Higgs Physics and Beyond the Standard Model

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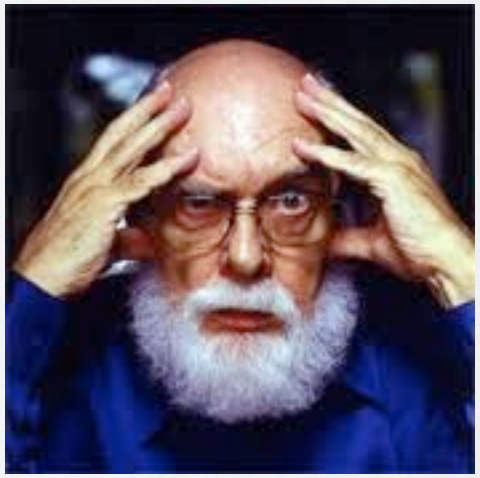
"Absence of evidence is not evidence of absence."

The BSM mantra..

You can't prove a negative.

- James Randi



Outline.

First session:

- Review of probes of Beyond the Standard model, pre LHC, and lessons learned. (Not much Higgs.)
- Briefly on BSM searches at LHC. (What we did not find.)

Second session:

- The Higgs discovery and the O(1) lessons learned there. (What we did find.)

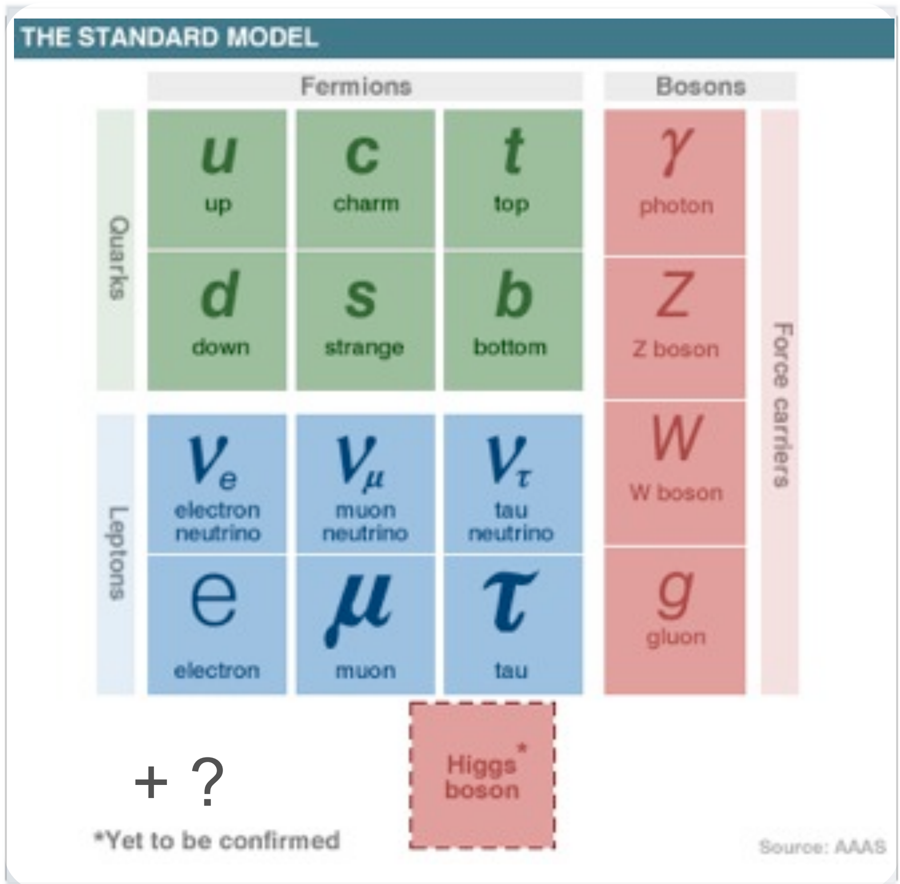
Third session:

- Prospects for precision studies of the Higgs like resonance, frameworks and recent progress.
- Systematic development of the SMEFT.

The Standard model ...

- The SM, an SU(3) xSU(2)xU(1) gauge theory:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i \not{D}\, \psi$$
$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$



- We can count the number of parameters present in the theory.

$m_e,\ m_\mu,\ m_\tau,\ m_u,\ m_d,\ m_c,\ m_s,\ m_t,\ m_b$: 9 masses

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

N^2 real parameters in NxN

$2N-1$ relative phases

$(N-1)^2$ physical parameters

The Standard model ...

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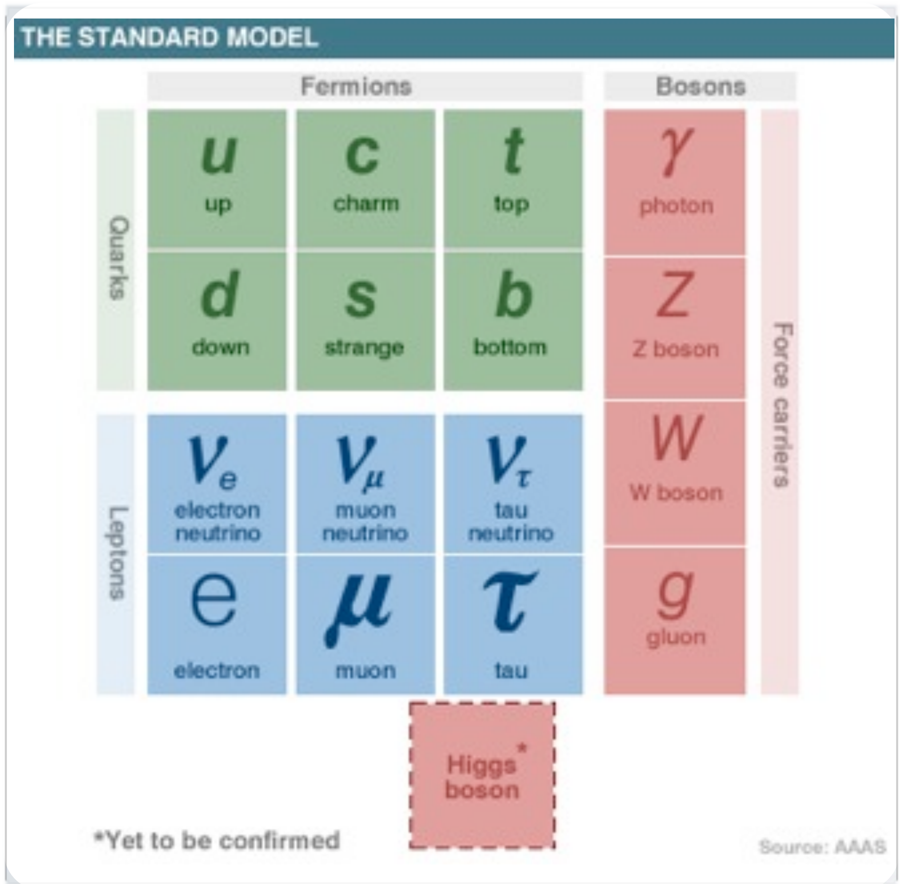


- We can count the number of parameters present in the theory.

$m_e,\ m_\mu,\ m_\tau, m_u,\ m_d,\ m_c,\ m_s,\ m_t,\ m_b$: 9 masses

$\theta_{12}, \theta_{13}, \theta_{23}, \delta$: 4 quark mixing

$g_1,\ g_2,\ g_3$: 3 couplings

v, λ : 2 EW sym breaking

This is the 18 parameters you hear about...

....and beyond...

- What is the meaning of parameters?

  The bare parameters in the Lagrangian renormalized in perturbation theory. Parameters related to low energy experiments. Measurements are on the asymptotic states of the theory.

- The SM is an EFT, and the intuitive idea at work is that the low energy (long distance) physics is independent of the high energy (short distance) physics.

  This statement strongly depends on the concept of LOCALITY. An EFT is a local interacting field theory with a factorization between short distance Wilson coefficients and long distance matrix elements.

(for nima)

If locality has to go... this is a challenge for a revolution.. to actually calculate precisely.

Known unknowns in BSM

- High energy physics modifies the low energy coupling constants of the EFT, and can place symmetry constraints on the EFT.

- Decoupling does NOT mean that higher scales have no effect on lower scale physics.

Nice Ex from Manohar EFT review:
hep-ph/9606222

$$m_t \frac{d}{d\,m_t}\left(\frac{1}{\alpha}\right) = -\frac{1}{3\,\pi}$$

Hydrogen energy levels DO depend on top mass. Change top mass while fixing the EM coupling constant.

Practically irrelevant if α, m_e, m_p fixed in low energy experiments around same scale.

- Lesson: BSM physics is already measured, and encoded in SM parameters.

Symmetries in the SM and SMEFT

- If BSM already present in measurements, simply need to make more precise measurements, or go to higher scales (or both) to unravel it. This will require ever more precise theory - EFT techniques essential.

- BSM physics can also place non trivial sym constraints on the low energy EFT. Effective symmetries offer further insight.

$\phi_q \to e^{i\,\phi_q}\,\phi_q$	global U(1) of baryon number
$\phi_\ell \to e^{i\,\phi_\ell}\,\phi_\ell$	global U(1) of lepton number

- Other approx symmetries:

$SU(2)_L \times SU(2)_R \to SU(2)_c$	custodial, preserved in simple Higgs sector broken by Yukawas and hypercharge
$U(3)^5$	flavour symmetry broken only by Yukawas in the SM - “MFV”

Baryon Number

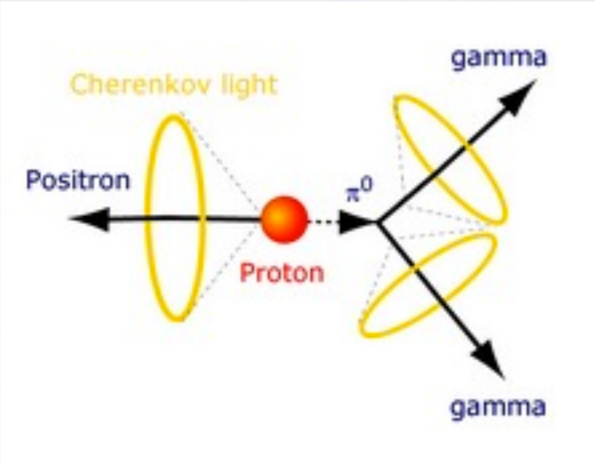
- Baryon number is conserved at the classical level in the SM as an *accidental* Global symmetry:

$$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$$

This implies the stability of the lightest Baryon (the proton) in the SM.

Well, not quite. Not good enough to have a classical sym.

$$\partial_\mu \, J^\mu_B = \frac{g^2}{16\,\pi^2}\,\mathrm{Tr} F^{\mu\,\nu}\,\tilde{F}_{\mu\,\nu}$$



This allows instanton based B violation prop to: $e^{-\frac{2\,\pi}{\alpha}}\,Q\,Q\,Q\,L$

Highly suppressed in the SM alone at low temp.

Exp lifetime constraints on the order of: $\geq 8.2 \times 10^{33}$ years (superK)

Baryon Number

- In the SMEFT one can have dimension 6 decay of the proton through the operators

$$
\begin{aligned}
Q^{duq\ell}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(d^{\alpha}_{p} C u^{\beta}_{r})(q^{i\gamma}_{s} C \ell^{j}_{t}),\\
Q^{qque}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(q^{i\alpha}_{p} C q^{j\beta}_{r})(u^{\gamma}_{s} C e_{t}),\\
Q^{qqq\ell}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(q^{i\alpha}_{p} C q^{j\beta}_{r})(q^{k\gamma}_{s} C \ell^{l}_{t}),\\
Q^{duue}_{prst} &= \epsilon_{\alpha\beta\gamma}(d^{\alpha}_{p} C u^{\beta}_{r})(u^{\gamma}_{s} C e_{t}),
\end{aligned}
$$

Although an anomalous symmetry, the RGE of these operators respects Baryon number, so the B violating operators only mix among themselves.

1405.0486 Alonso, Chiang, Jenkins, Manohar, Shotwell
L. Abbott and M. B. Wise, Phys.Rev. D22, 2208 (1980)

Decays go as : $\Gamma_p \approx c^2 \dfrac{m_p^5}{\Lambda^4}$ exp limit: $\geq 8.2 \times 10^{33}$ yrs

leads to: $\Lambda \gtrsim 10^{16}\,\mathrm{GeV}$

BSM Baryon Number

- What does this mean?

  Extreme interpretation is that - nothing is present, no BSM sector, to this very high scale. Weak support for this view.
  Is SM accidental Global sym unique? NO.

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$	Couples to
I	1	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R\ Q_L$
II	8	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R\ Q_L$
III	1	2	-1/2	$(1,3,\bar{3})$	$\bar{d}_R\ Q_L$
IV	8	2	-1/2	$(1,3,\bar{3})$	$\bar{d}_R\ Q_L$
V	3	1	-4/3	(3,1,1)	$u_R\ u_R$
VI	$\bar{6}$	1	-4/3	$(\bar{6},1,1)$	$u_R\ u_R$
VII	3	1	2/3	(1,3,1)	$d_R\ d_R$
VIII	$\bar{6}$	1	2/3	$(1,\bar{6},1)$	$d_R\ d_R$
IX	3	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R\ u_R$
X	$\bar{6}$	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R\ u_R$
XI	3	1	-1/3	$(1,1,\bar{6})$	$Q_L\ Q_L$
XII	$\bar{6}$	1	-1/3	(1,1,3)	$Q_L\ Q_L$
XIII	3	3	-1/3	(1,1,3)	$Q_L\ Q_L$
XIV	$\bar{6}$	3	-1/3	$(1,1,\bar{6})$	$Q_L\ Q_L$

Baryon number conservation from gauge symmetry. Baryon number 0.

Baryon number -2/3.

Gauge symmetries protect proton decay alone.

Lepton flavour sym to protect the proton.

arXiv:0911.2225 Arnold, Pospelov, Trott, Wise

BSM Baryon Number

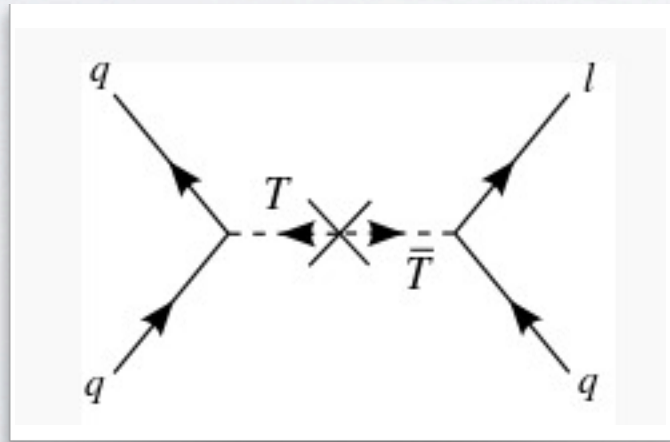
- Further can gauge baryon number - see arXiv:1002.1754, 1105.3190,1106.0343 Perez, Wise

  Generically one has to introduce new fermion,scalar multiplets for anomaly cancelation.

- Note in doing this B number cannot be completely preserved, one Sakarov condition for Baryogenesis is B number violation. So if gauged has to also be spontaneously broken.

- Baryon number is a particular problem for popular solutions to the Hierarchy problem. Phys Rev Lett 32 (1974) 438 Georgi, Glashow

  GUTs such as Georgi-Glashow SU(5) group quarks and leptons into irreps. Interactions in the GUT in general do not preserve B number.



$$T : (3,1)_{-1/3}$$

BSM Baryon/Lepton Number

- SUSY is also challenged by baryon number:

Minimal MSSM gives proton decay suppressed by $\frac{1}{m^2_{SUSY}}$

To fix this, for SUSY motivated by the hierarchy problem $m_{susy} \sim \mathrm{TeV}$
R parity (matter parity imposed)

$$P_R = (-1)^{3B+3L+2s}$$

s spin, L lepton number, B baryon number

Good: LSP then stable, DM candidate.
Bad: LSP stable so large missing energy signature expected at LHC. None seen.

- In the minimal SM, also *accidental* Global symmetries in lepton number(s) also present. Not just $U(1)_L$ also $U(1)_{e,\mu,\tau}$

Neutrino oscillations clear indication minimal SM incomplete and these Global symmetries broken in UV.

BSM Lepton Number

- Model independent minimal extension of the SM to accommodate neutrino mass and observed oscillations. Leading operator that can violate Lepton number of dim 5:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{I\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i \not{D}\, \psi$$
$$- \lambda \left(H^\dagger H - \frac{1}{2} v^2 \right)^2 - \left[H^{\dagger j} \overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j} \overline{u}\, Y_u\, q_j + H^{\dagger j} \overline{e}\, Y_e\, l_j + \text{h.c.} \right], \; + \frac{1}{2\,\Lambda} \left[(\tilde{H}^\dagger\, \ell_i) C_{ij} (\tilde{H}^\dagger\, \ell_j) + h.c \right]$$

- Again, does not mean no BSM untill scale of suppression of this operator (which is $\Lambda_{\Delta L} = 10^{16}\,\mathrm{GeV}$). Just no L violation.

- In this case new parameters are present breaking a global symmetry so these effects are not just absorbed in renormalization for low scale experiments.

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- Number of parameters augmented to...

$m_e,\, m_\mu,\, m_\tau,\, m_u,\, m_d,\, m_c,\, m_s,\, m_t,\, m_b$	: 9 masses
$\theta_{12}, \theta_{13}, \theta_{23}, \delta$	: 4 quark mixing
$g_1,\, g_2,\, g_3$	: 3 couplings
v, λ	: 2 EW sym breaking
$s_{12},\, s_{13},\, s_{23},\, \delta_\nu, m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau}$	: 7 neutrino parameters

Flavour Symmetry

- The global flavour symmetry of the SM is

$$\mathrm{G_F} = \mathrm{U}(3)^5 = \mathrm{S_Q} \otimes \mathrm{S_L} \otimes \mathrm{U}(1)^5$$

$$q \to U_q q, \qquad l \to U_l l, \qquad u \to U_u u, \qquad d \to U_d d, \qquad e \to U_e e.$$

here $S_Q = \mathrm{SU}(3)_{\mathrm{Q_L}} \otimes \mathrm{SU}(3)_{\mathrm{U_R}} \otimes \mathrm{SU}(3)_{\mathrm{D_R}}$ $\quad S_L = \mathrm{SU}(3)_{\mathrm{L_L}} \otimes \mathrm{SU}(3)_{\mathrm{E_R}}$

Talked about the $U(1)$ now on to the $\mathrm{SU}(3)$

- In the SM a well defined sense in which this flavour symmetry is restored:

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{G_F} + g_u^{ij}\, \bar{u}_R^i\, H^T\, \epsilon\, Q_L^j - g_d^{ij}\, \bar{d}_R^i\, H^\dagger\, Q_L^j + h.c.$$

$$g_u^{ij} \to 0 \qquad g_d^{ij} \to 0$$

Technically you can think of the Yukawas as symmetry breaking spurions

$$g_u^{ij} \sim (3, 1, \bar{3}) \quad g_d^{ij} \sim (1, 3, \bar{3})$$

Flavour Symmetry

- Can make separate rotations on the left and right handed fermion fields to diagonalize all interactions in the G_F limit, while leaving the kinetic terms in the Lagrangian invariant:

$$\mathcal{L}_{kin} = \bar{Q}_L^i \, i \not\partial \, Q_L + \bar{L}_L^i \, i \not\partial \, L_L + \bar{u}_R \, i \not\partial \, u_R + \bar{d}_R \, i \not\partial \, d_R$$

- When Yukawa's turned on the inability to simultaneously diagonalise the yukawas and charged current interactions leads to flavour violation. Both renormalizable interactions set by scale $\sim v$

- Diagonalize the fermion masses and different components of the doublets rotated

$$\begin{pmatrix} U_L \\ D_L \end{pmatrix} = \mathcal{U}(U,L) \begin{pmatrix} U_L' \\ \mathcal{U}(U,L)^\dagger \, \mathcal{U}(D,L) D_L' \end{pmatrix}$$

V_{CKM}

Flavour Symmetry

- Structure of the breaking of G_F is what is important.

- NO flavour changing neutral currents at tree level in the SM.

  Flavour changing charged currents allowed and present.

$$\frac{g_2}{\sqrt{2}} W^+ \bar{u}_L \gamma^\mu d_L = \frac{g_2}{\sqrt{2}} W^+ \bar{u'}_L \gamma^\mu V_{CKM} d'_L$$

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

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$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\,\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\,\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

Here rephased the quark fields to go down to $(N-1)^2$ real parameters AND implemented an expansion (Wolfenstein parameterization)

CKM matrix should be unitary. This leads to a number of unitarity triangles:

$$V_{ud}\,V_{ub}^\star + V_{cd}\,V_{cb}^\star + V_{td}\,V_{tb}^\star = 0$$

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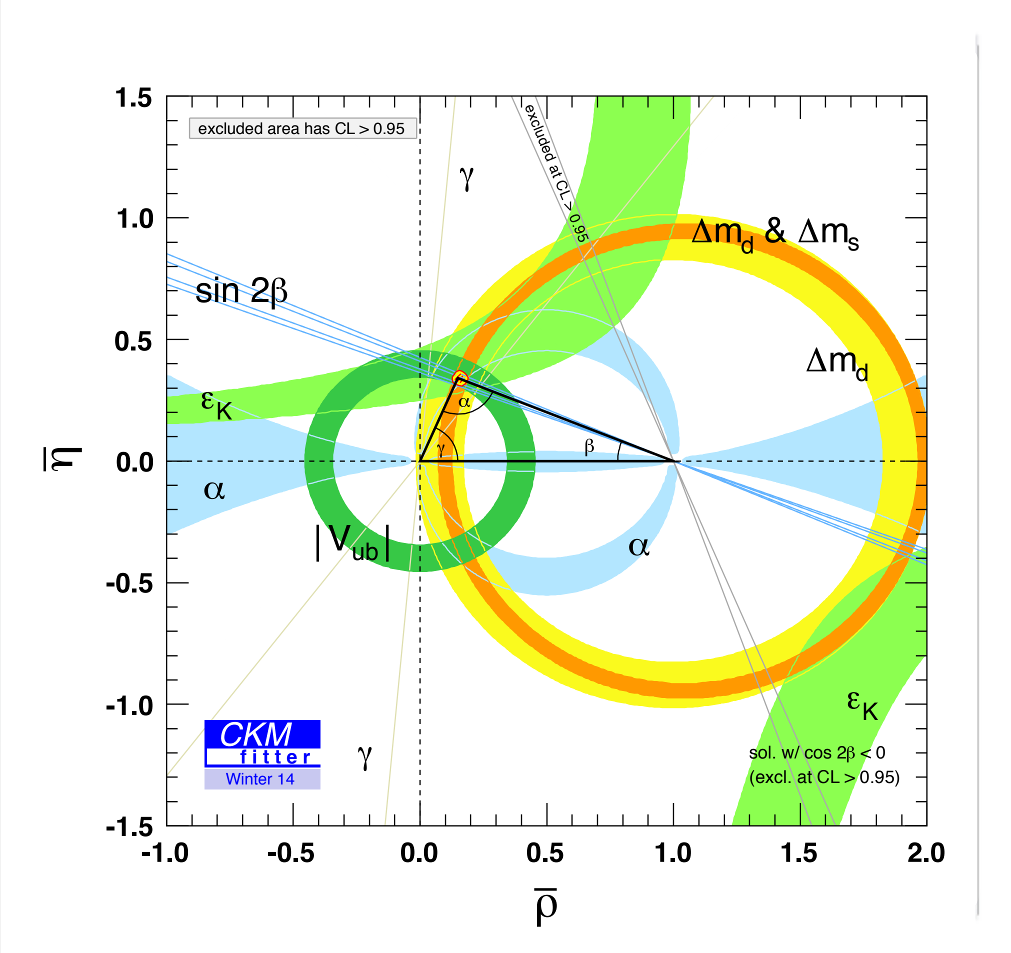
Flavour Symmetry



$$A\,\lambda^3(\rho + i\eta) - A\lambda^3 + A\lambda^3(1-\rho-i\eta) = 0$$

One of many equivalent "CKM triangles" (any column times row gives a relation)

For CP violation better to think in invariants

$$J_{CP} = \pm \mathrm{Im}\left(V_{ik}\,V_{jl}\,V_{il}^\star\,V_{jk}^\star\right) \approx A^2\lambda^6\,\eta$$

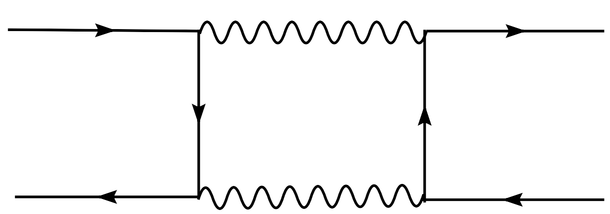
$$(i \neq j, l \neq k)$$

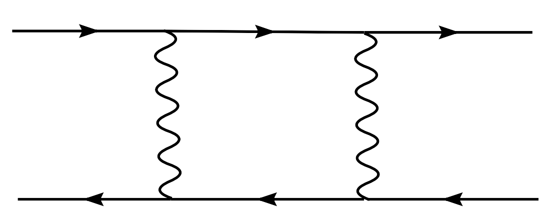
CP violation tiny in SM! (but seen)

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\,\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\,\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

- Exp facts that: $\lambda \sim 0.22$ flavour violation, and CP violation could have been larger

Flavour Symmetry





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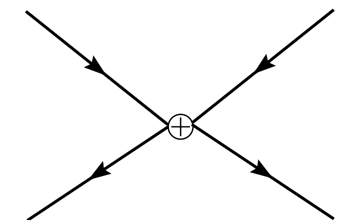


Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^\star\,V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

SM PATTERN has GIM suppression,
CKM suppression , and loop suppression

$\lambda \sim 0.2$ so $\lambda^8 \sim 10^{-6}$ $\lambda^4 \sim 10^{-3}$

Integrate out your desired NP states/sector

$$O_{ij} = \frac{c_{ij}}{\Lambda^2}\,(\bar{Q}_L^i\,\gamma^\mu\,Q_L^j)^2$$

- Pretty much need MFV for TeV scale new physics to be robust.
- Flavour breaking in these operators proportional to

$$(g_u^\dagger\,g_u) \to V_Q\;(g_u^\dagger\,g_u)\;V_Q^\dagger \qquad \left(g_d^\dagger\,g_d\right) \to V_Q\;\left(g_d^\dagger\,g_d\right)\;V_Q^\dagger$$

as up and down not simultaneously diagonalized

These flavour breaking operators are $(Q_L\Gamma_1\,Q_L)(Q_L\Gamma_2\,Q_L)$

Flavour Symmetry

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$	12		7.1×10^{-3}		$pp\to tt$

- Pretty much need MFV for TeV scale new physics to be robust.

hep-ph/0207036 D'Ambrosio, Giudice, Isidori, Strumia

Effective MFV

- Minimal flavour violation is a symmetry breaking pattern.

- Symmetries, and symmetry breaking lead to constraints on an S matrix. Can constrain low energy EFTs that reproduce the IR physics of some S matrix elements

However: $y_t(\mu = v) = \frac{\sqrt{2}\, m_t}{v} \sim 0.996$

Expanding in 1 is not wise. On the other hand $\lambda \sim 0.2$

- LINEAR MFV expands in $g_u^\dagger \, g_u$ and assumes the corresponding unknown constants of the expansion are small

- Non-LINEAR MFV resums powers of $g_u^\dagger \, g_u \quad g_d^\dagger \, g_d$

Effective MFV:linear vs nonlinear

- Functionally using LINEAR MFV: $g_u^{ij} \sim (3,1,\bar{3})$ $g_d^{ij} \sim (1,3,\bar{3})$

  Write everything down in a manner that is invariant under the full G_F

  This holds for higher d operators

$$(Q_L \Gamma_1 Q_L)(Q_L \Gamma_2 Q_L) \longrightarrow (Q_L \Gamma_1 Q_L)(Q_L \Gamma_2 Q_L)\ F((g_u^\dagger g_u)^n,\ (g_d^\dagger g_d)^m)$$

  Even the SM interactions get promoted to all possible insertions of the flavour matricies

$$\begin{aligned} Y_U{}^j_i &= \eta_U\, g_U{}^j{}_i + \eta_U'\, g_U{}^j{}_k [(g_U^\dagger)^k{}_l\ (g_U)^l{}_i] + \cdots, \\ Y_D{}^j_i &= \eta_D\, g_D{}^j{}_i + \eta_D'\, g_D{}^j{}_k [(g_U^\dagger)^k{}_l\ (g_U)^l{}_i] + \cdots. \end{aligned}$$

  Even new field content can be added that is flavour non-trivial

$$S_8 \to V_D\, S_8\, V_D^\dagger.$$

$$(\mathbf{1}, \mathbf{8}, \mathbf{1})$$

$$\begin{aligned} \mathcal{L}_Y &= \bar{u}_R^i\, \hat{Y}_U{}^l{}_i\, (g_D^\dagger)^o{}_l\, (T^a)^n{}_o\, (g_D)^j{}_n\, Q_{Lj}\, S_8^a, \\ &\quad + \bar{d}_R^i\, (T^a)^m_i\, (\hat{Y}_D)^j{}_m Q_{Lj}\, S_8^{\dagger\,a} + \text{h.c.} \end{aligned}$$

Effective MFV:linear vs nonlinear

- Not a guarantee you can always do this! Recall B violating ops:

$$
\begin{aligned}
Q^{duq\ell}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(d^{\alpha}_p C u^{\beta}_r)(q^{i\gamma}_s C \ell^j_t)\,,\\
Q^{qque}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(q^{i\alpha}_p C q^{j\beta}_r)(u^{\gamma}_s C e_t)\,,\\
Q^{qqq\ell}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(q^{i\alpha}_p C q^{j\beta}_r)(q^{k\gamma}_s C \ell^l_t)\,,\\
Q^{duue}_{prst} &= \epsilon_{\alpha\beta\gamma}(d^{\alpha}_p C u^{\beta}_r)(u^{\gamma}_s C e_t)\,,
\end{aligned}
$$

1405.0486 Alonso, Chiang, Jenkins, Manohar, Shotwell

Nice proof: all ops transform under $SU(3)_i$ with n_i upper indicies and m_i lower indicies

All B number violating ops satisfy: $\sum_{i=1}^{5}(n_i - m_i) \equiv 1\,(mod\,3)$

Can't form a flavour singlet, MFV spurions have $(n_i - m_i) \equiv 0\,(mod\,3)$

With massive neutrinos can extend MFV and include these ops..

Effective MFV:linear vs nonlinear

- Nonlinear formulation   0903.1794 Kagan, Perez, Volansky, Zupan

When the SM spurions take on their background field values
the break the flavour group. This breaking is strongly hierarchical:

$$y_t \gg y_b \gg y_i$$

$$g_u^{ij} \sim (3,1,\bar{3}) \longrightarrow g_u = \mathrm{diag}(0,0,y_t) + \cdots$$

$$g_d^{ij} \sim (1,3,\bar{3}) \longrightarrow g_d = \mathrm{diag}(0,0,y_b) + \cdots$$

$$G_F \to H_{res}$$

$$H_{res} = U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_3$$

$$\bar{d}_L^i \left[(a_1 + a_2 y_t^2)\xi_{ij}^t + a_1 \xi_{ij}^c\right] d_L^j + \left[b_2 y_b^2\, \bar{d}_L^i \xi_{ib}^t b_L + h.c.\right] = c_b(\overline{\tilde{d}_L^{(2)}}\chi \tilde{b}_L + h.c) + c_t \overline{\tilde{d}_L^{(2)}}\chi\chi^\dagger \tilde{d}_L^{(2)} + c_c \overline{\tilde{d}_L^{(2)}}\phi_u \phi_u^\dagger \tilde{d}_L^{(2)}$$

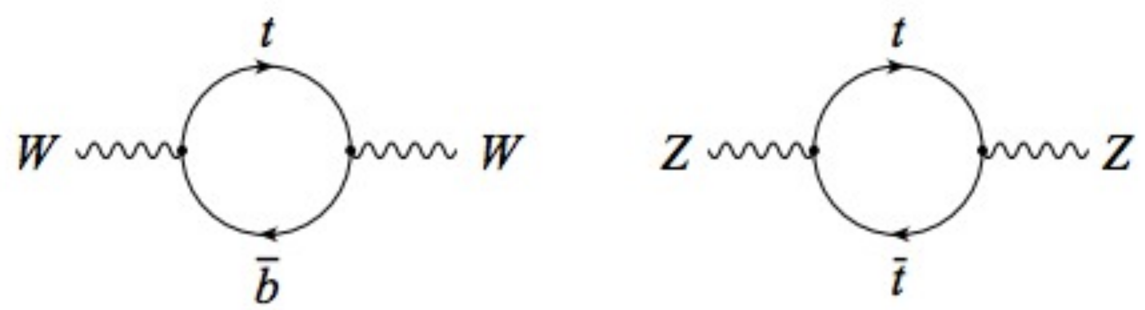
$$c_b \simeq (a_1 y_t^2 + a_2 y_t^4 + b_2 y_b^2),\ c_t \simeq a_1 y_t^2 + a_2 y_t^4 \qquad \xi_{ij}^k = y_k^2 V_{ki}^* V_{kj}$$

$$Y_u = V_{\mathrm{CKM}}^\dagger \mathrm{diag}\,(m_u, m_c, m_t),\ Y_d = \mathrm{diag}\,(m_d, m_s, m_b). \quad \chi^\dagger = i(V_{td}, V_{ts}), \qquad \phi_u = V_{\mathrm{CKM}}^{(2)\dagger}\,\mathrm{diag}\,(\frac{m_u}{m_t}, \frac{m_c}{m_t}).$$

Custodial Symmetry in the SM

- The $d \leq 4$ Scalar part of the SM has a larger symmetry group, even when the Higgs gets a vev. Reviewed in Pich's lectures.

Breaking due to SU(2) doublets:



$$\hat{\rho} \approx 1 + \frac{3G_F}{8\pi^2\sqrt{2}}\left(m_t^2 + m_b^2 - 2\frac{m_t^2 m_b^2}{m_t^2 - m_b^2}\ln\frac{m_t^2}{m_b^2}\right)$$

The top mass was able to be indirectly inferred in this manner before direct discovery.

Custodial Symmetry in the SM

- The $d \leq 4$ Scalar part of the SM has a larger symmetry group, even when the Higgs gets a vev. Reviewed in Pich's lectures.

Hypercharge breaking:

$$-\frac{11 G_F M_Z^2 \sin^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}\,.$$

Similarly the higgs mass was indirectly inferred from the 2 point functions.

We see custodial breaking in precision measurements:

$$\rho_0 \equiv \frac{M_W^2}{M_Z^2\,\hat{c}_Z^2\,\hat{\rho}}\,,$$

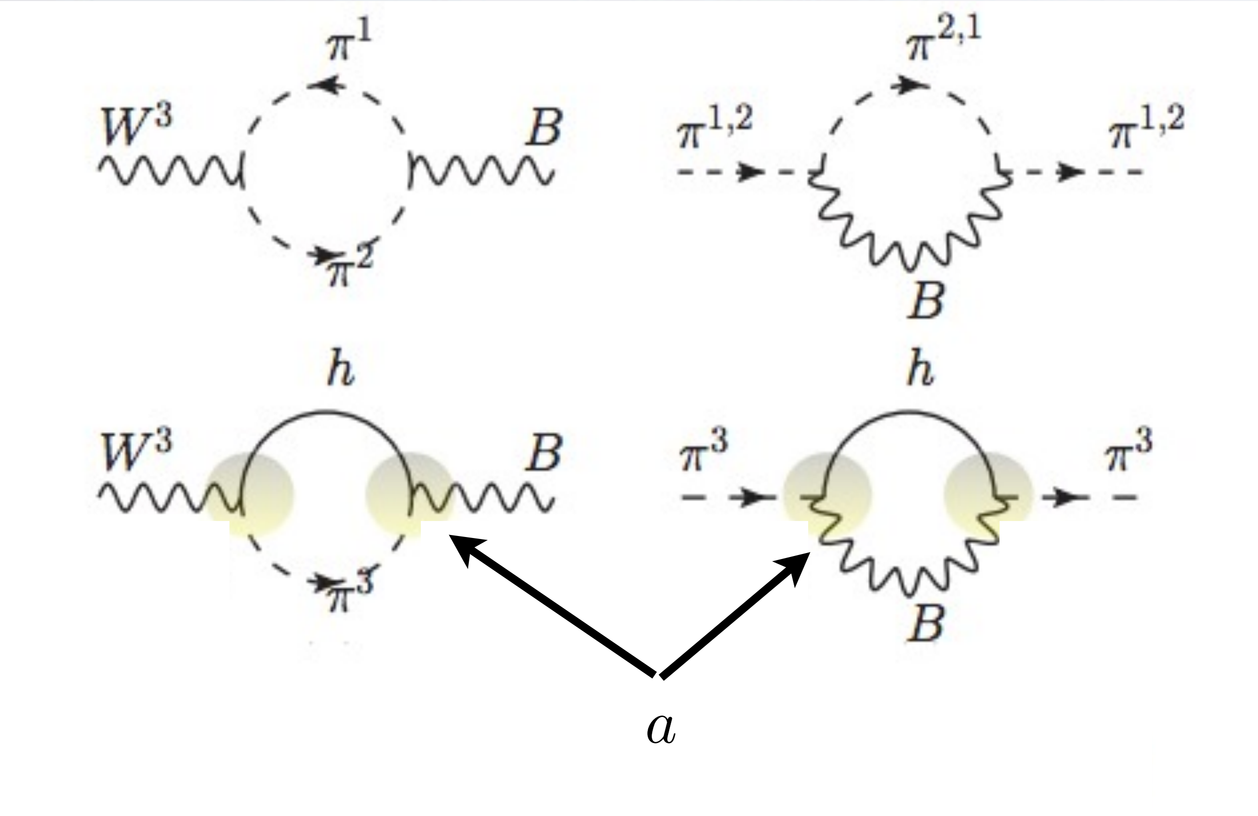
$$\rho_0 = 1.00040 \pm 0.00024\,,$$
$$\alpha_s(M_Z) = 0.1194 \pm 0.0017,$$

Custodial symmetry has been a manifestly usefull probe.

EWPD

- The traditional STU parameterization of EWPD characterized shifts in a number of observables in terms of common contributions to 2 point functions. Will get back to EWPD in the next session.

Some divergences no longer cancel as in the SM in the non linear chiral Lagrangian:



- With EWPD parameters characterizing deviations from the SM:

$$\hat{\alpha}(M_Z)\,T \equiv \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\frac{\hat{\alpha}(M_Z)}{4\,\hat{s}_Z^2\,\hat{c}_Z^2}\,S \equiv \frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} - \frac{\hat{c}_Z^2 - \hat{s}_Z^2}{\hat{c}_Z\,\hat{s}_Z}\frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

- This leads to the result that when a is not 1: $\Delta S \approx -\frac{(1-a^2)}{6\,\pi}\,\log\frac{m_h}{\Lambda}$

Barbieri, Bellazzini, Rychkov, Varagnolo **arXiv:0706.0432**

Why go beyond the SM?

- Where is dark matter in this theory?
- Where is inflation in this theory?

  (minimal) Higgs inflation does not work - ask me later.

- Where is baryogenesis in this theory?

  Leptogenesis at a high scale might be right.

- What is the origin of neutrino mass? Beyond the dim 5 op.
- It is clear that the SM breaks down at some scale.
  Where are the corrections, where is everyone?

That Hierarchy Problem

Unknown UV — characteristic scale $\mu \sim \Lambda$ — scalars $\frac{\Lambda^2}{16\,\pi^2}\,h^2$

- Singlet scalars should be proximate to the cut off scale of the theory.

  This statement is basically dimensional analysis.

- We now have a scalar with mass $m_h \sim 125\,\mathrm{GeV}$

  reasonable to expect $\Lambda \sim few\,\mathrm{TeV}$

- LHC is about to restart at 14 TeV, but practical discovery reach to excite new particles $\lesssim 14/6 \sim 2\,\mathrm{TeV}$

  (rule of thumb due to PDF suppression)

- Corrections expected on the order of $\frac{v^2}{\Lambda^2} \sim few\,\%$
  (LEP data few % to 0.1 % precise)

- Good news! This means that the impressive chart makes sense.

The Traditional approach

- What are the ideas to fix this naturalness problem?

No Higgs!

~~$\mu^2 H^\dagger H$~~

- Replace the Higgs with scaled up QCD - Technicolour

Weinberg, Susskind

- That would have made sense...

The Traditional approach

- What are the ideas to fix this naturalness problem?

Techni-theories.

$\mu^2 \, H^\dagger H$

Lower the cut off scale

- $\mu \sim \mathrm{TeV}$

Extra Dimensions

Dvali, Dimopoulous, Arkani-Hamed, Randall, Sundrum

The Traditional approach

- What are the ideas to fix this naturalness problem?

Techni-theories.

$\mu^2 H^\dagger H$

Lower the cut off scale

$\mathrm{H} \rightarrow H + \epsilon\, c$

A Shift Symmetry, a Pseudo-Goldstone Higgs

Georgi and Collaborators

- That would forbid all the Higgs interactions and the self coupling.

- Collective symmetry breaking and Little Higgs possible, not very nice.

Georgi, Cohen, Arkani-Hamed

The Traditional approach

- What are the ideas to fix this naturalness problem?

Techni-theories.

$\mu^2 H^\dagger H$

Lower the cut off scale

$\mathrm{H} \to H + \epsilon\, c$

A Shift Symmetry, a PGH

$\mathrm{H} \to H + \epsilon A$

Relate the higgs to a gauge field.

Arkani-Hamed, Cheung, Dobrescu, Hall

- Use gauge symmetry to forbid a mass.
- Extra-Dimension scenarios.

The Traditional approach

- What are the ideas to fix this naturalness problem?

Techni-theories.

$\mu^2 H^\dagger H$

Lower the cut off scale

$\mathrm{H} \rightarrow H + \epsilon\, c$

A Shift Symmetry, a PGH

$\mathrm{H} \rightarrow H + \epsilon A$

Extra-Dimensions.

$\mathrm{H} \rightarrow H + \epsilon \Psi$

Relate the higgs to
a fermion field.
Use chiral symmetry
to protect the mass
SUPERSYM!

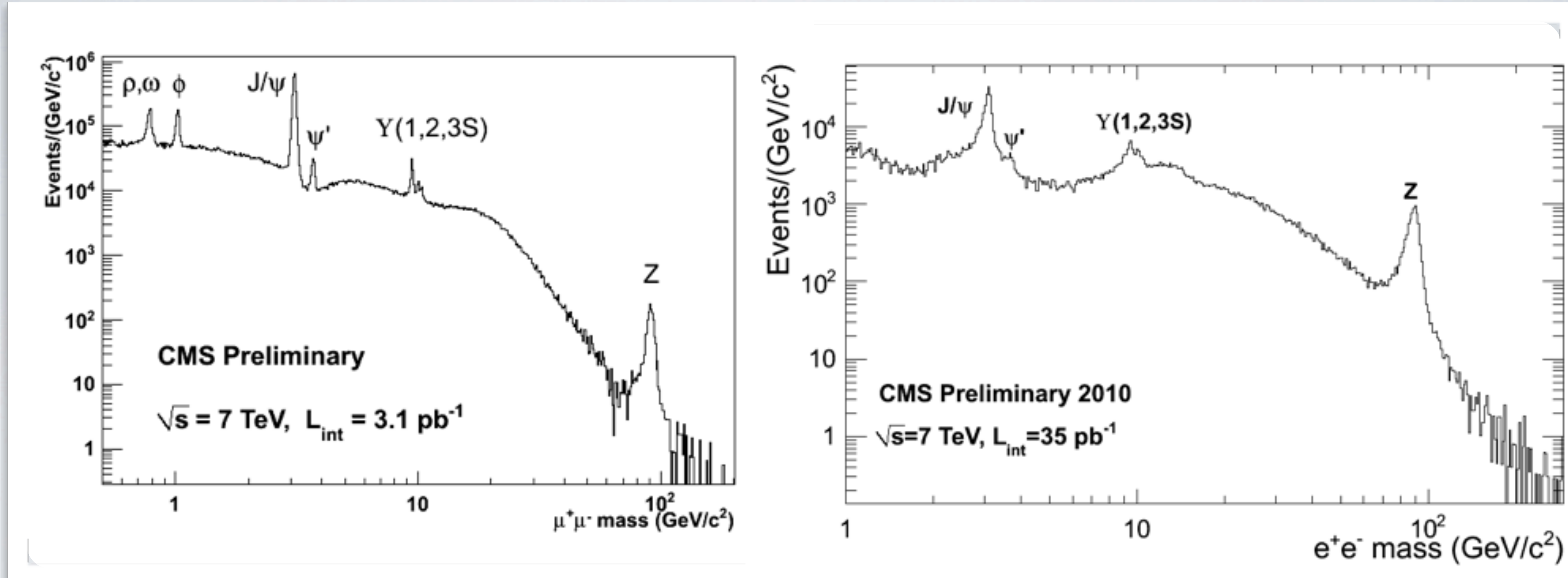
- The symmetry predicts new states that should show up at ~ TeV.
  We have all these great arguments LHC is running what do you got!

Hierarchy motivated states found.

- Other than this h field...

Can the damn machine find anything?

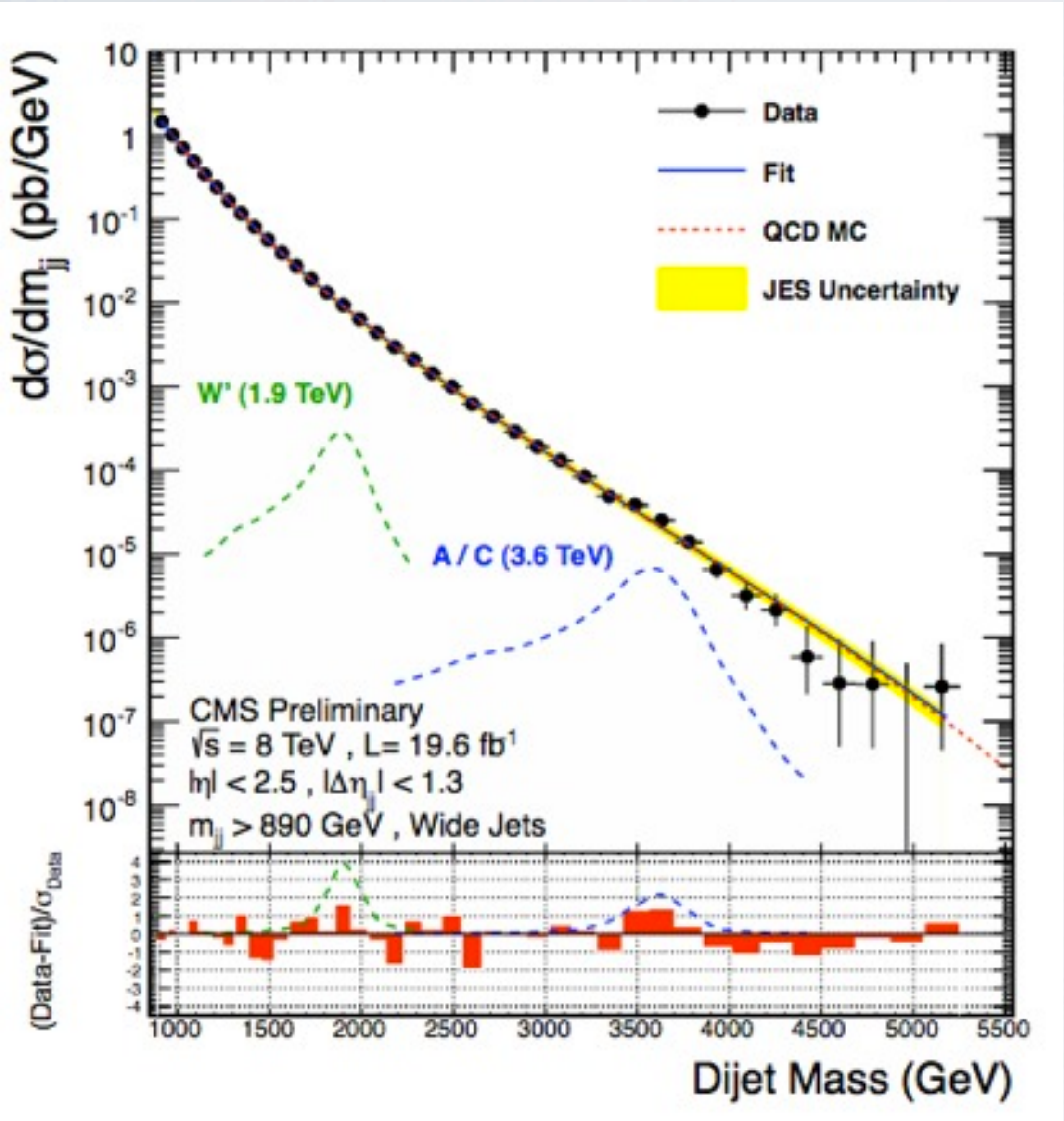
- Yes of course, dimuon searches rediscovering the SM.

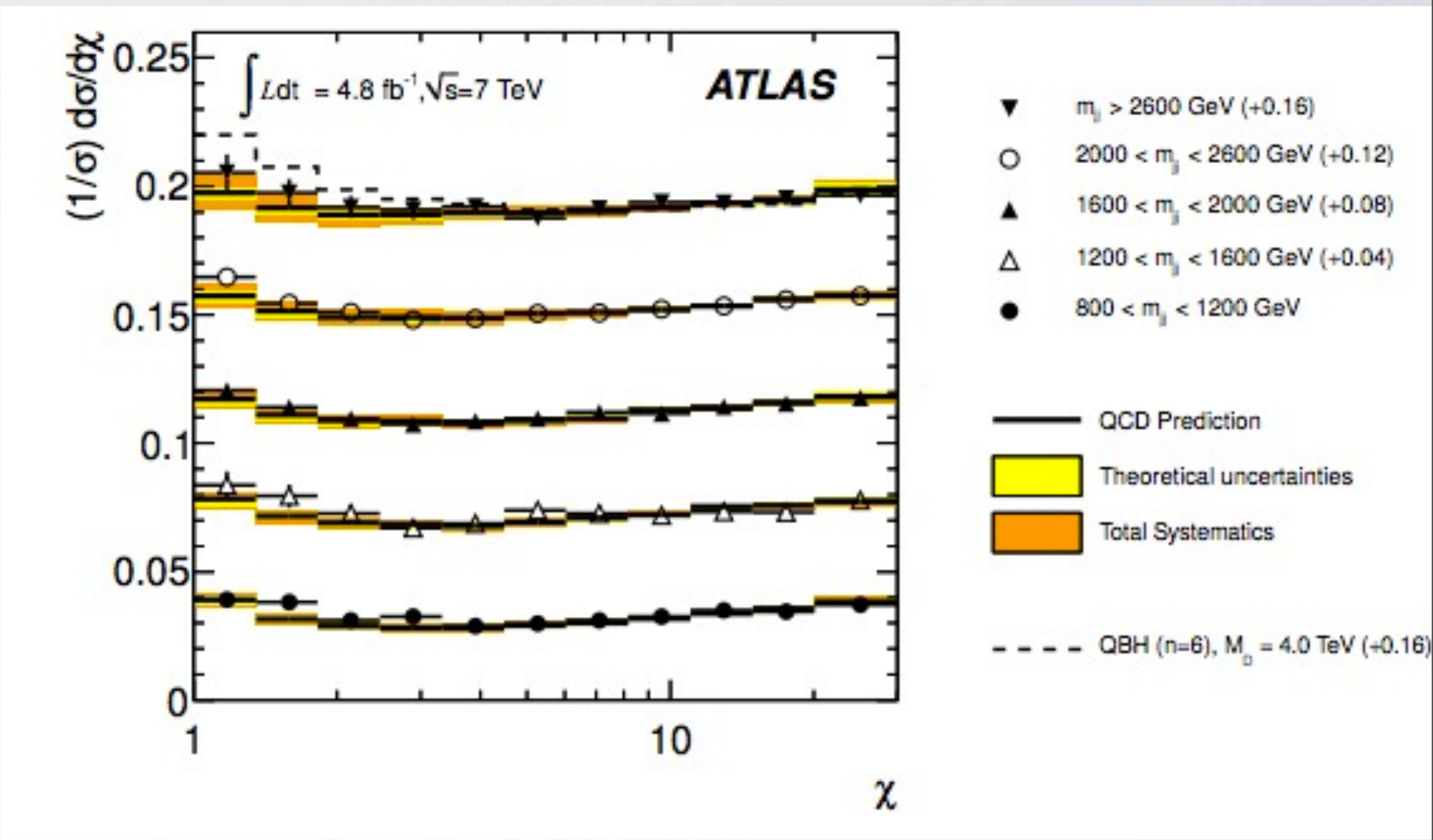


Null search results in dimuon Resonances in the initial run - but AMAZING results!

Dijet searches, the O(1) discovery mode

- One of the best probes of states coupling to quarks are dijet searches terrific reach and statistics:





arXiv:1302.4794 CMS narrow resonance

- Angular $\chi \equiv (1+|\cos\theta|)/(1-|\cos\theta|)$ measure (more sensitive to scalars)

1210.1718.pdf Atlas dijets and anglular distributions

Dijet searches, the O(1) discovery mode

- Somewhat more usefull formulation of dijet bounds:

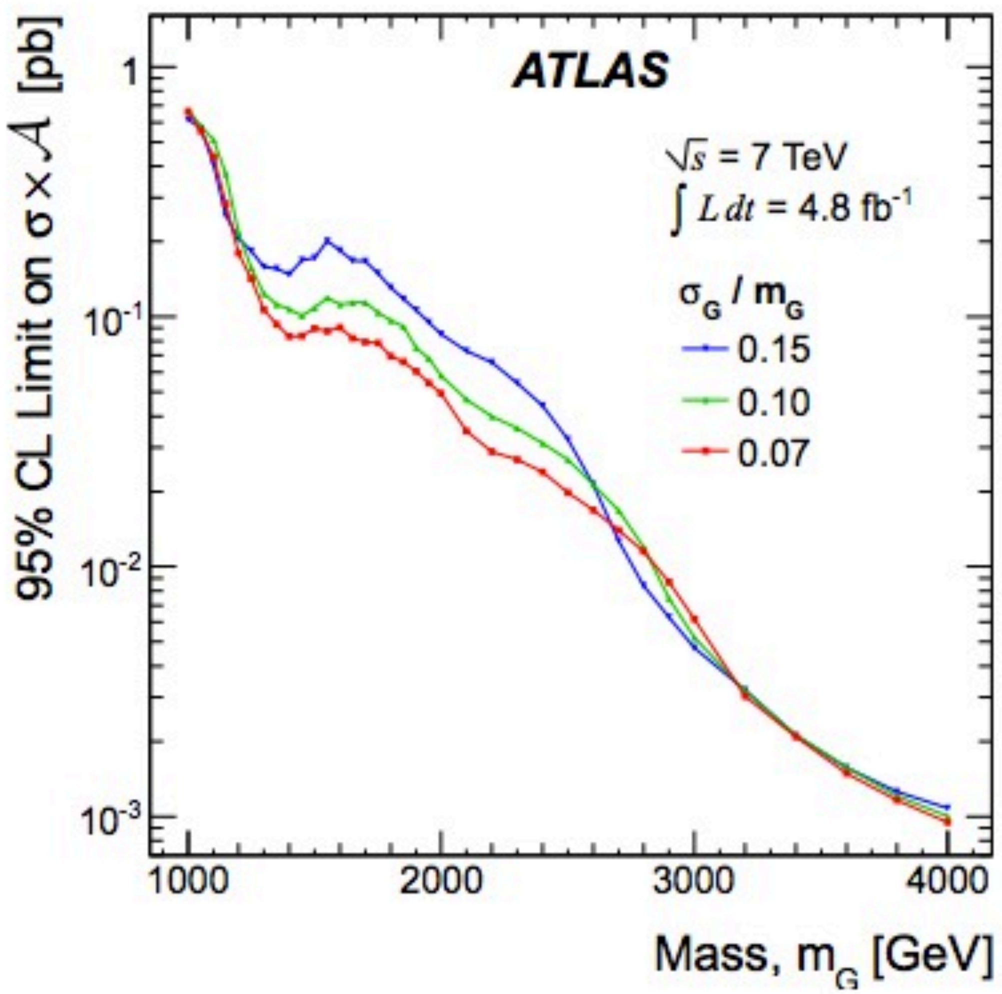


Figure 6. The 95% CL upper limits on $\sigma \times \mathcal{A}$ for a simple Gaussian resonance decaying to dijets as a function of the mean mass, m_G, for three values of σ_G/m_G, taking into account both statistical and systematic uncertainties.

Dijet searches, the O(1) discovery mode

- Not as bad as you think.
  Any quark resonance is limiting $\dfrac{c^2}{p^2 - m_r^2}$

S_V^3 Mass	TeV M_{jj}	LHC M_{jj}	TeV χ	LHC χ	S_{VI} Mass	TeV M_{jj}	LHC M_{jj}	TeV χ	LHC χ
300	1.0	-	1.2	1.1	300	0.3	-	0.4	0.5
500	1.2	n.b.	0.5	0.9	500	0.3	2.2	0.2	0.5
700	2.0	0.7	0.7	0.6	700	0.6	0.2	0.2	0.2
900	2.5	0.3	0.6	0.5	900	0.7	0.1	0.2	0.2
1100	2.8	0.4	0.5	0.6	1100	1.4	0.1	0.2	0.1
1300	4.0	0.5	1.3	0.6	1300	1.6	0.1	0.7	0.1
1500	6.0	0.6	1.6	0.3	1500	1.8	0.1	0.8	0.1
1700	n.b.	0.6	1.8	0.5	1700	2.0	0.1	0.8	0.1
1900	n.b.	0.6	2.0	0.4	1900	2.6	0.1	0.9	0.1
2100	n.b.	0.7	2.1	0.6	2100	3.0	0.1	1.0	0.1

- Bounds degraded by backgrounds, QCD uncertainties, width dependence, etc.. but not good for TEV states.

Natural SUSY, leading contender

- Minimal "natural" susy spec:

Field	Spin	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$\tilde{Q}_L = \left(\tilde{t}_L, \tilde{b}_L\right)$	0	$(\mathbf{3}, \mathbf{2}, 1/6)$
$\tilde{t}_R^*$	0	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
$H_u = (H_u^+, H_u^0)$	0	$(\mathbf{1}, \mathbf{2}, +1/2)$
$H_d = (H_d^0, H_d^-)$	0	$(\mathbf{1}, \mathbf{2}, -1/2)$
$\tilde{H}_u = \left(\tilde{H}_u^+, \tilde{H}_u^0\right)$	1/2	$(\mathbf{1}, \mathbf{2}, +1/2)$
$\tilde{H}_d = \left(\tilde{H}_d^0, \tilde{H}_d^-\right)$	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$
$\tilde{g}$	1/2	$(\mathbf{8}, \mathbf{1}, 0)$

- Generic susy has all superpartners at the SUSY soft breaking scale

$$M_i \sim M_{susy}$$

- Limits have risen to roughly

$$1.5\,\mathrm{Tev}/\mathcal{O}(100's)\,\mathrm{GeV}$$

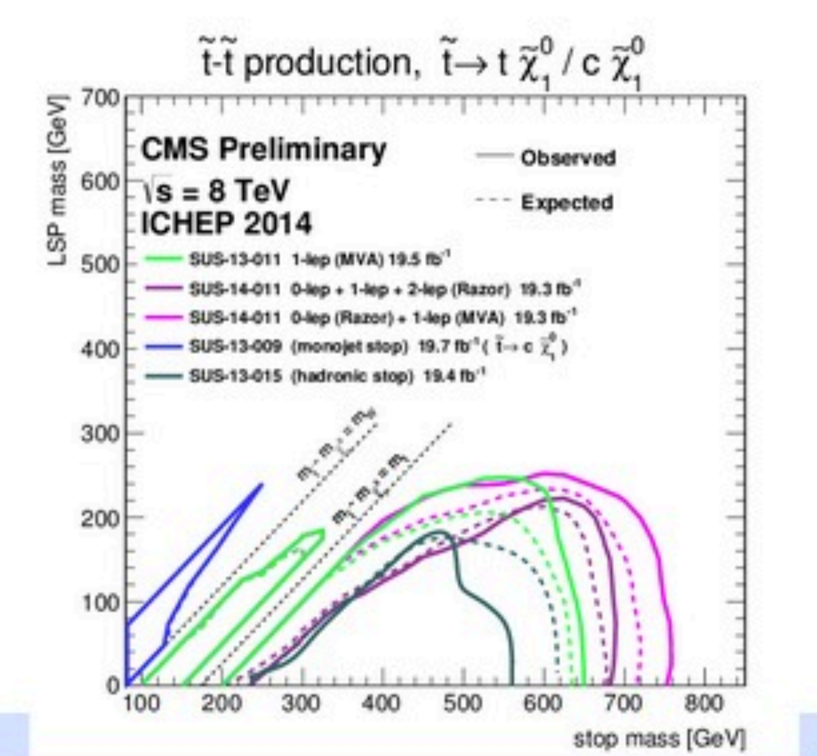
for coloured/electroweak susy state. So minimal spectrum more appealing.

- stops directly feed into Higgs mass so have to be light. sbottom (components) forced to be light due to $SU(2)_L$ soft masses

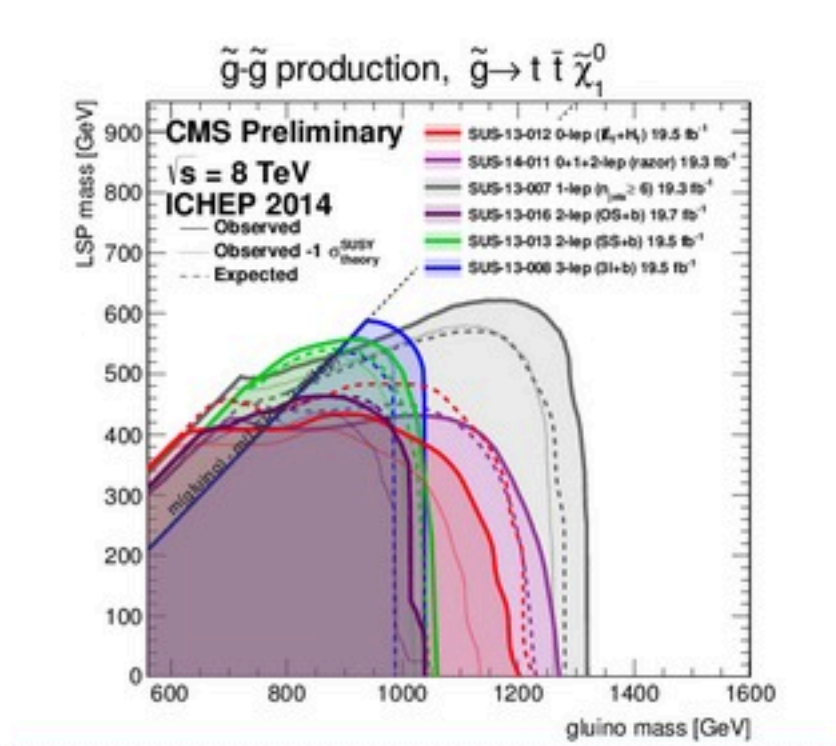
- μ^2 higgsino masses tied to the higgs mass

- gluino masses at 2 loops feed into the higgs mass

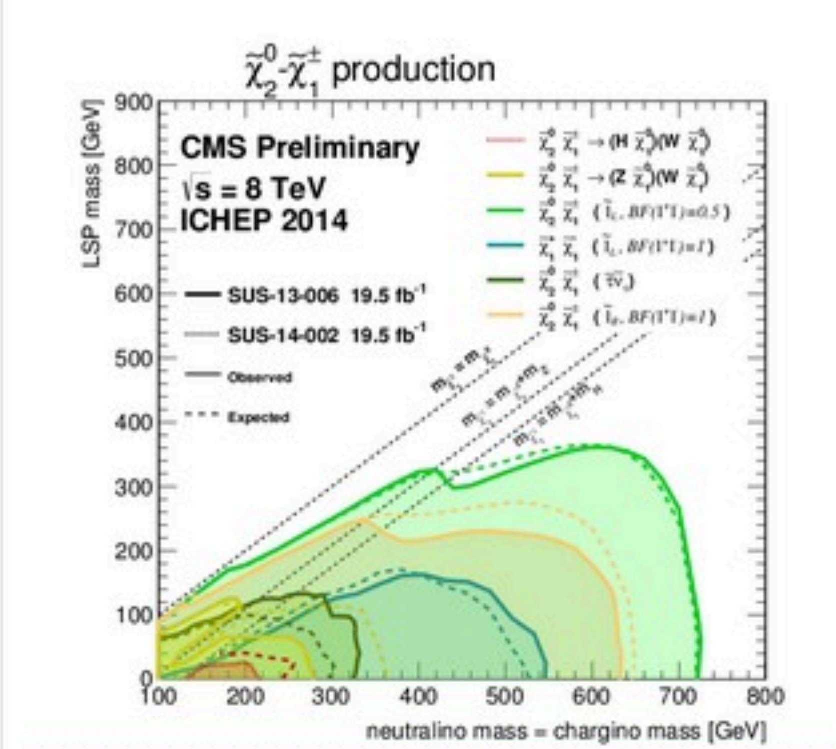
Natural SUSY, leading contender



Summary of limits for direct stop searches



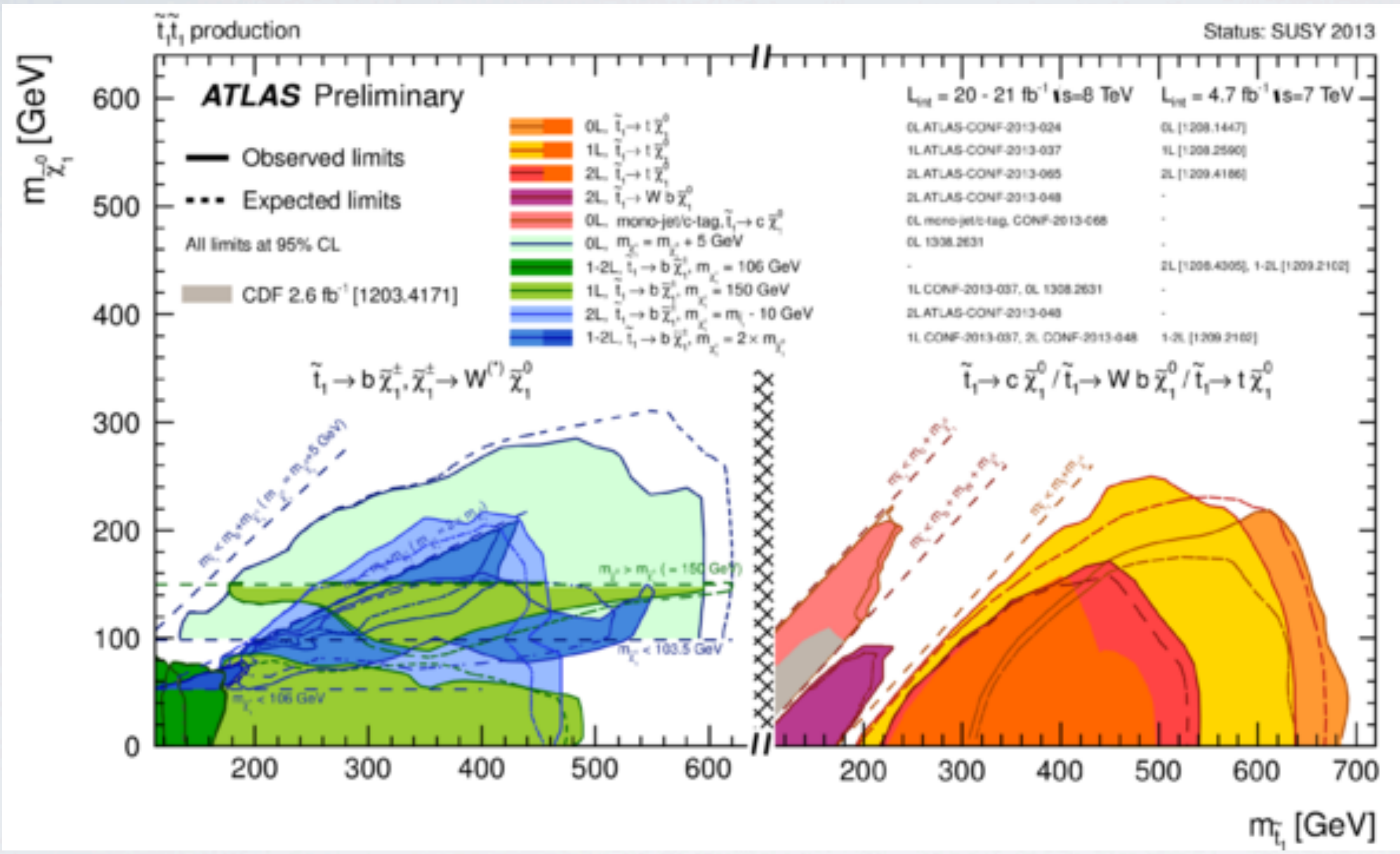
Summary of observed and expected limits for gluino pair production with gluino decaying via the 3-body decay top anti-top neutralino



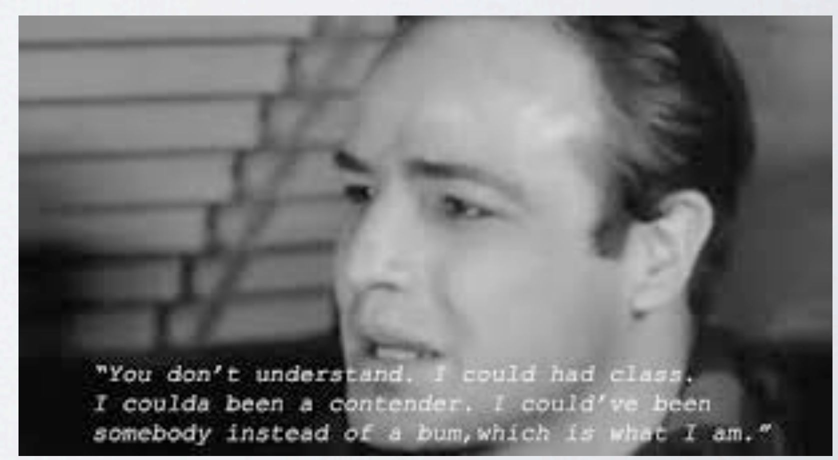
Summary of observed limits for EWKino models

- No matter which experiment you look at....

Natural SUSY, leading contender



- Natural SUSY is looking rough...
- However stops are quite difficult.



Stops and hitting sbottom

- Stops are hard to see in the collider, sbottoms are easier.

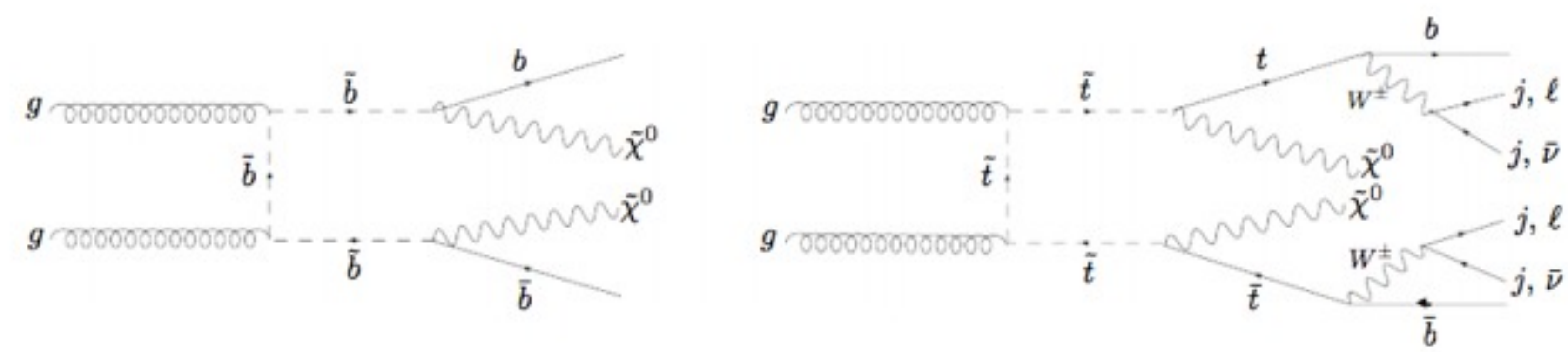


FIG. 4: Direct production and decay of $\tilde{b}\,\tilde{b}$ and $\tilde{t}\,\tilde{t}$.

$$m_{\tilde{b}_1}^2 \approx \cos^2\theta_{\tilde{t}}\, m_{\tilde{t}_1}^2 + \sin^2\theta_{\tilde{t}}\, m_{\tilde{t}_2}^2 - m_t^2 - m_W^2 \cos(2\,\beta).$$

$$\Delta\rho_0^{SUSY} \approx \frac{3\,G_F \cos^2\theta_{\tilde{t}}}{8\sqrt{2}\,\pi^2}\left\{-\sin^2\theta_{\tilde{t}}\, F_0[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2] + F_0[m_{\tilde{t}_1}^2, m_{\tilde{b}_1}^2] + \tan^2\theta_{\tilde{t}}\, F_0[m_{\tilde{t}_2}^2, m_{\tilde{b}_1}^2]\right\}.$$

- sbottoms linked to stop masses by custodial sym limits

$$F_0[x,y] = x + y - \frac{2\,x\,y}{x-y}\log\frac{x}{y}.$$

Natural SUSY, leading contender

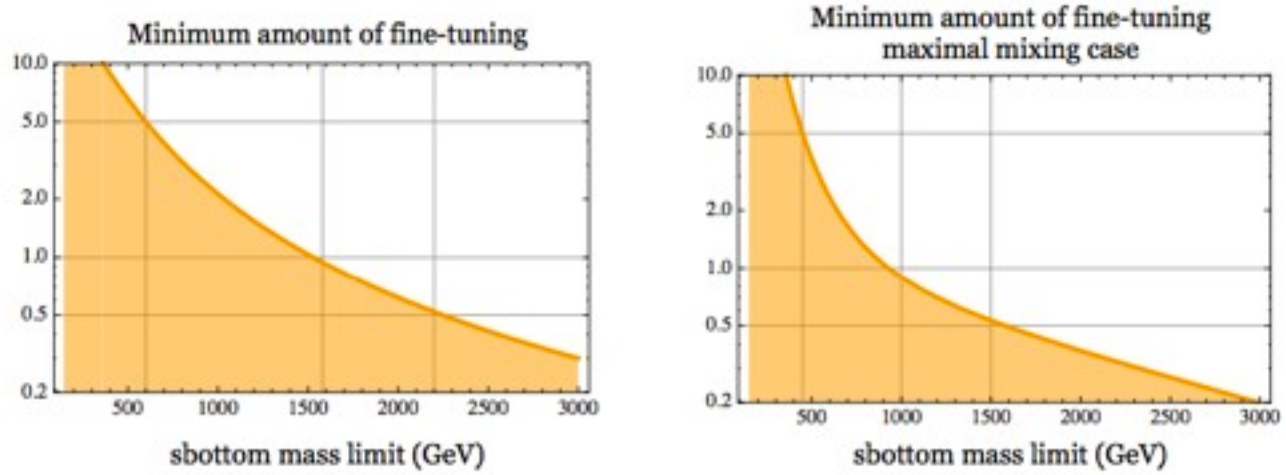


FIG. 2: Fine-tuning measure (in %) for different bounds on sbottom particles. Left: general case. Right: maximal mixing case. Here $\tan\beta = 10$ and $\Lambda = 100$ TeV.

Bounding the sbottom pushes up the fine tuning measure of the NSUSY spectrum directly

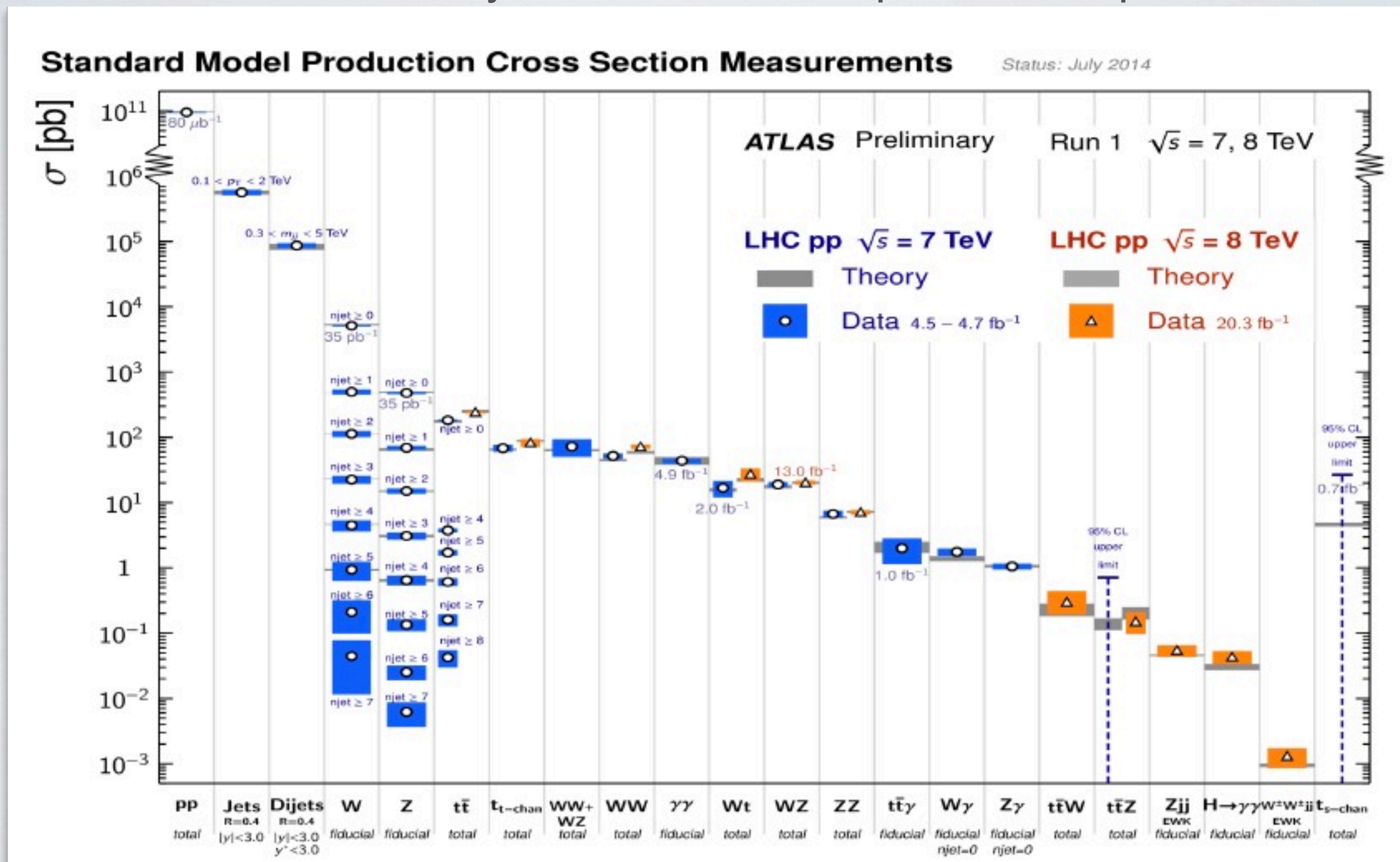
	Sbottom For $p_T^b < 670$ GeV $\epsilon_{b,tag} \simeq 60 - 80\%$ [52] $\epsilon_{mistag} \simeq 1 - 10\%$ [52].	**Stop, non boosted** SM $t\,\bar{t}$ similar. Considering only lepton isolation criteria $\Delta R > 0.7$.	**Stop, boosted** Top-tagging eff.$\gtrsim$40% if $p_T^t \in [600, 1600]$ GeV [51]
	$\epsilon_{p_T^b<670}$	$\epsilon_{\Delta R>0.7}$	$\epsilon_{p_T^{top}>600}$
$<$ 300 GeV	1	$>$ 0.50	$<$ 0.01
300-700 GeV	$\simeq$ 1	0.50-0.25	0.01-0.1
700-1000 GeV	>0.78	<0.25	0.1-0.3

TABLE I: Estimated efficiencies ϵ_i for basic cuts in searches for sbottoms and stops, for LHC at 8 TeV.

1204.0802, Lee, Sanz, Trott

Where we stand after run 1

- The SM is an extremely successful description of the public data



The ~~Higgs~~ discovery and O(1) lessons

"Higgs like boson"

How is the cut off scale working?

- Why should a 0^+ state be part of the nature of EW symmetry breaking?
  The EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{\psi} i D \psi$$

$$+ \left[\frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) - \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c., \right]$$

T. Appelquist and C. Bernard, Phys. Rev. D22 (1980) 200.
A. Longhitano, Phys. Rev. D22 (1980) 1166; Nucl. Phys. B188 (1981) 118.

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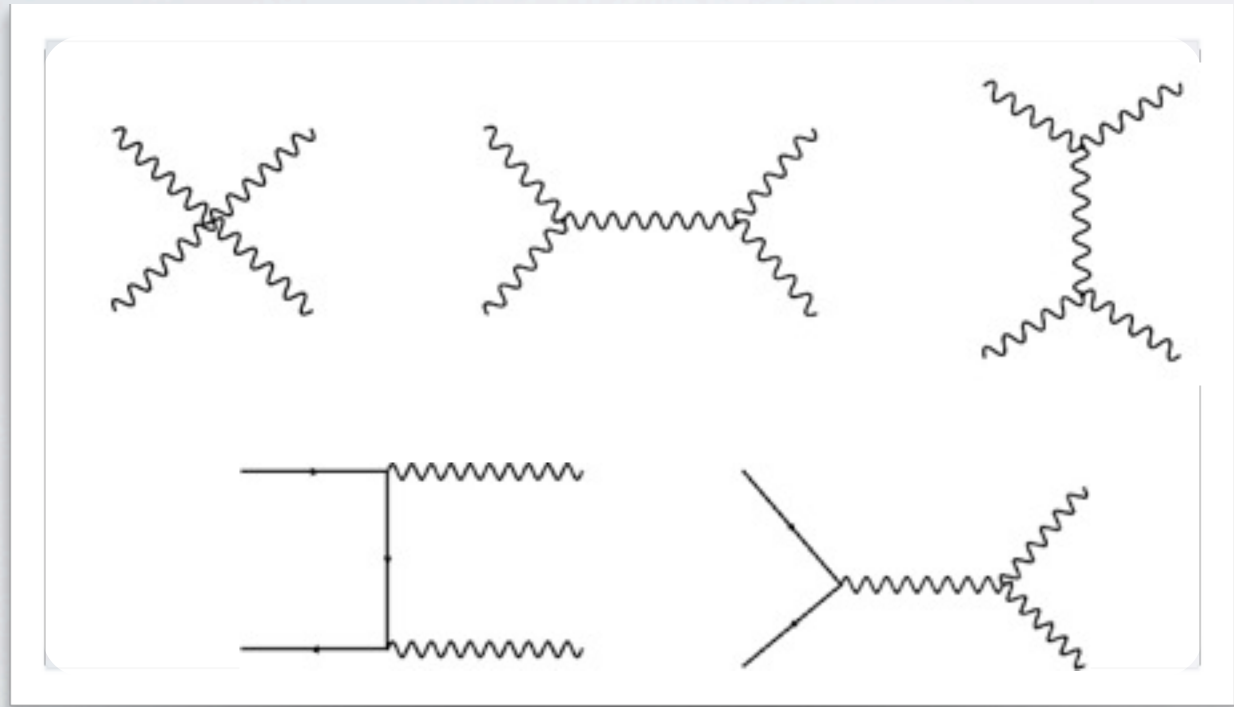
$$+ M_w^2 W_\mu^+ W \mu_- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu - \bar{\psi}_L M \psi_R + h.c. \; + \cdots$$



$$W_L^+ W_L^- \rightarrow W_L^+ W_L^- \; : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2} (s+t)$$

$$\epsilon_L^\mu \simeq p^\mu / m_W$$

$$\psi \, \bar{\psi} \rightarrow W_L^+ \, W_L^- \; : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}$$

Lee, Quigg, Thacker Phys.Rev.D 16 (1977) 1519 **Cornwall, Levin,Tiktopoulos** Phys.Rev.D 10 (1974) 1145
Chanowitz,Gaillard Nucl.Phys. B261 (1985) 379 **Vayonakis** Lett.Nouvo Cim 17 (1976) 383
Appelquist,Chanowitz, Phys. Rev. Lett. 59, 2405 (1987) [Erratum-ibid. 60, 1589 (1988)].
Chanowitz, Furman, Hinchliffe Phys. Lett. B78, 285 (1978), Nucl Phys B153, 402 (1979)

Why unitarity?

- If the amplitudes grow with energy too fast, partial wave unitarity is violated.

" SO WHAT? Does the universe cease to exist?"

- Hamiltonian constructed from (approximate low energy) real Lagrangian density is Hermitian. So unitary by definition. If unitarity fails an approximation fails, usually the approximation is that the low energy effective theory is taken beyond its regime of validity.

- This regime of validity is approximated by the cut off scale Λ present in the EFT power counting.

- Beyond this scale, the EFT is not expected to reproduce the s matrix of the full theory.

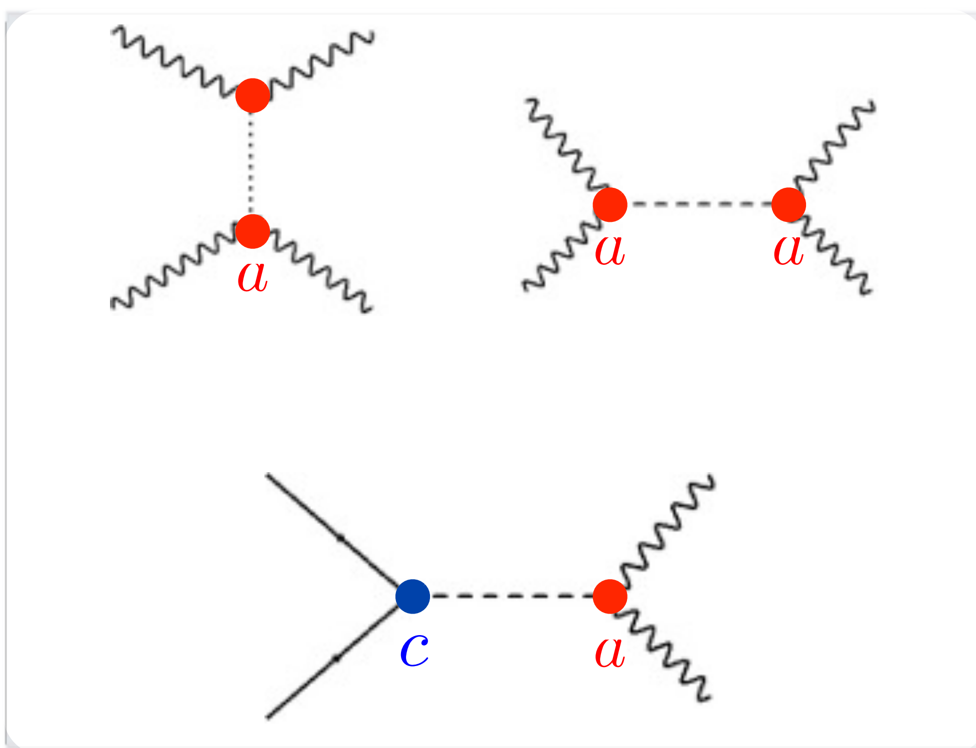
- New states are usually required with mass scale proximate (and below) Λ

How is the cut off scale working?

- Why should a 0^+ state be part of the nature of EW symmetry breaking?
The EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{\psi} i D \psi$$

$$+ \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) - \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c.,$$



$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4 m_W^2} (s+t)(1-a^2)$$

$$\psi \bar{\psi} \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2} (1 - a\, c)$$

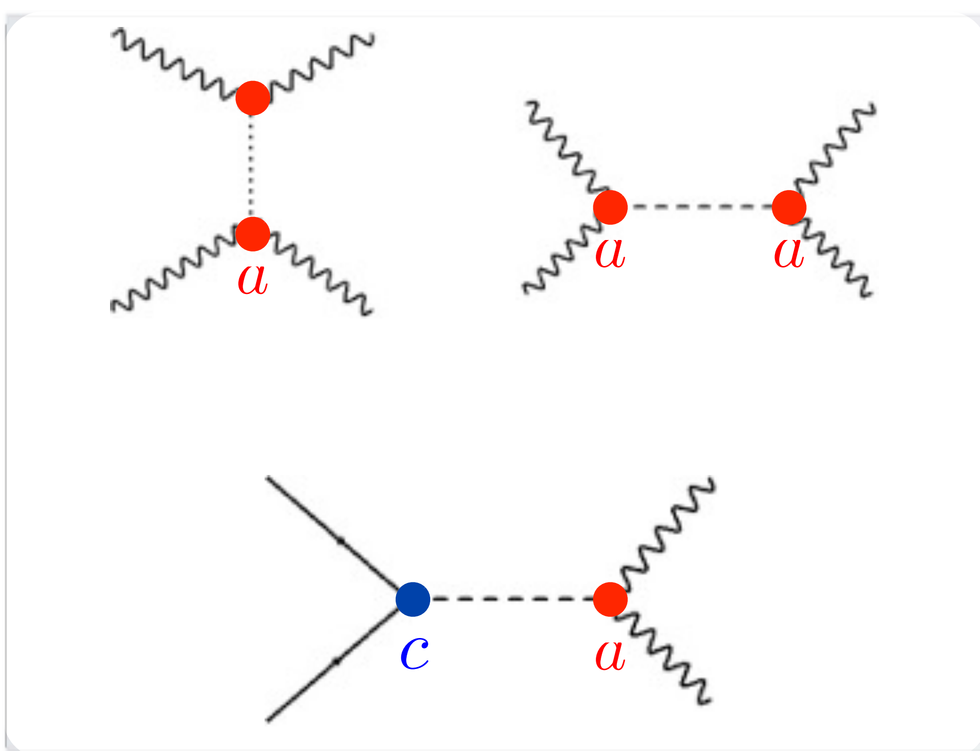
Introduce a 0^+ scalar with general couplings, sets the correction to be such that the cut off scale will be pushed up.

How is the cut off scale working?

- Why should a 0^+ state be part of the nature of EW symmetry breaking?
  The EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{\psi} i D\psi$$

$$+ \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) - \frac{v}{\sqrt{2}} (\bar{u}^i_L \bar{d}^i_L) \Sigma \begin{pmatrix} y^u_{ij} u^j_R \\ y^d_{ij} d^j_R \end{pmatrix} + h.c.,$$



$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4 m_W^2} (s+t)(1 - a^2) \to 0$$

Case of SM Higgs.

$$\psi \bar{\psi} \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2} (1 - a\, c) \to 0$$

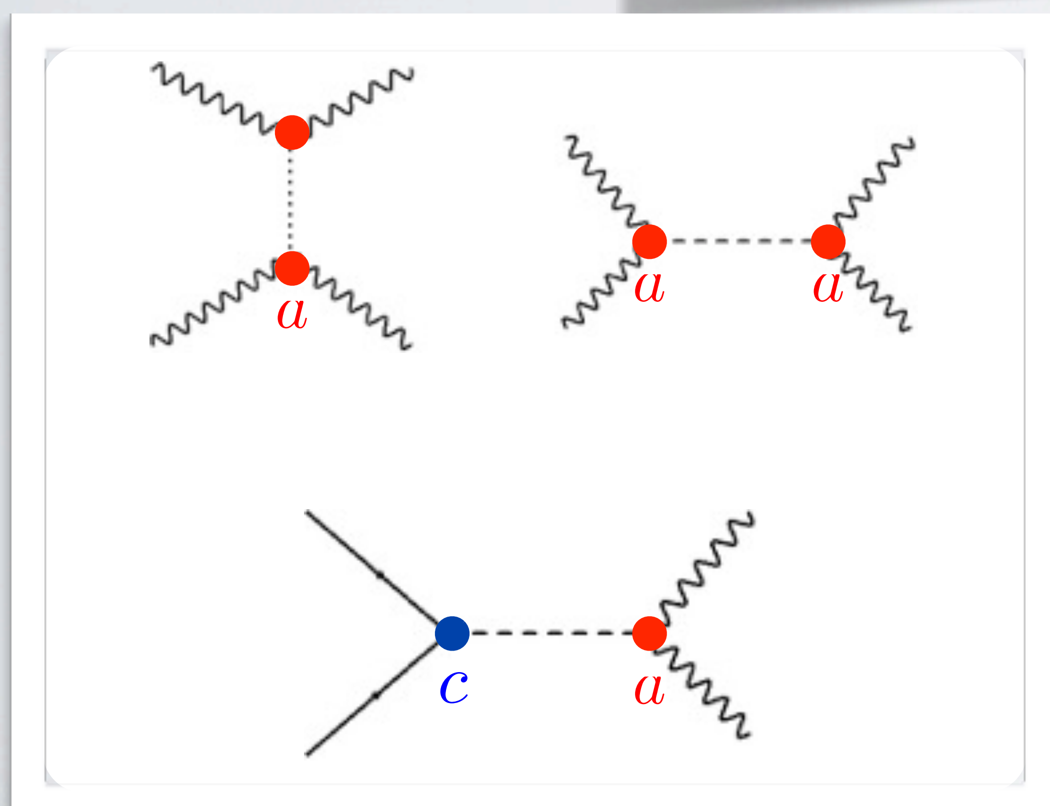
Introduce a 0^+ scalar with general couplings, sets the correction to be such that the cut off scale will be pushed up.

How is the cut off scale working?

- Why should a 0^+ state be part of the nature of EW symmetry breaking?
  The EFT consistent with what we knew (80‘s -00‘s) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{\psi} i D \psi$$

$$+ \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) - \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c.,$$



- For WW scattering the cut off scale for the EFT with the addition of a scalar is raised:

$\Lambda \simeq 4\pi v$ ..raised to... $\Lambda \simeq 4\pi v / \sqrt{|1 - a^2|}$

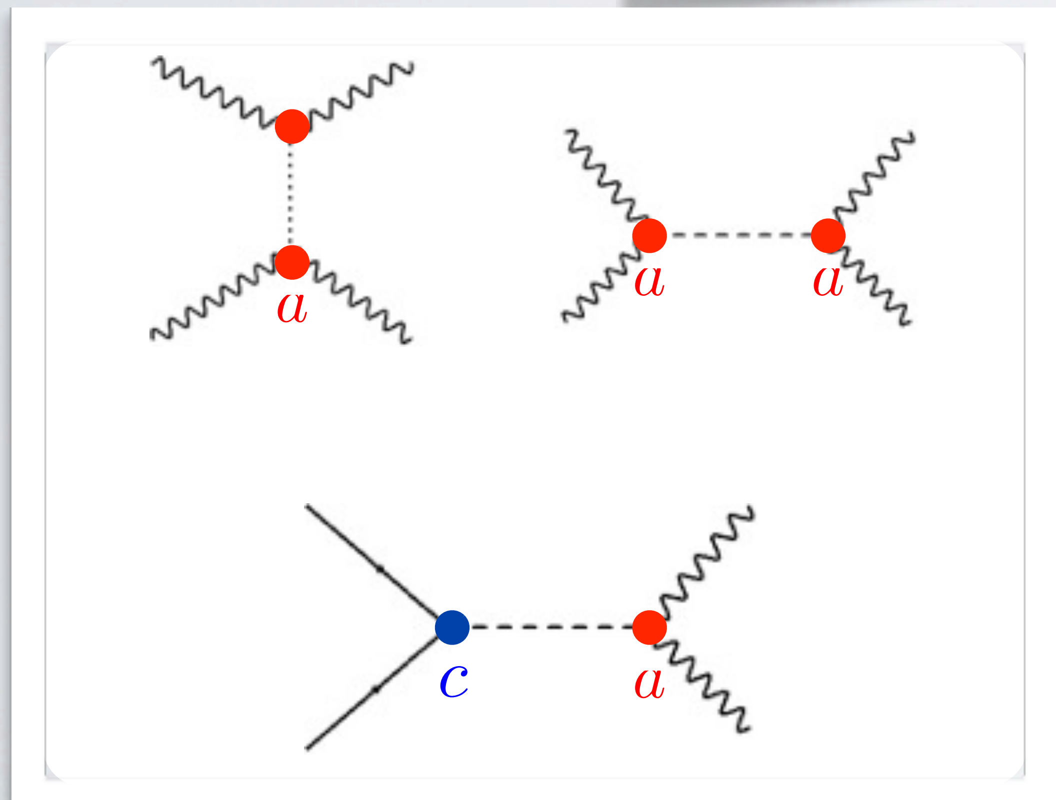
We see a Higgs like boson, with no other states (to date) at low scales. That just fundamentally --- makes sense. Consistent with precision tests.
(For energies up to a couple TeV.)

How is the cut off scale working?

- Why should a 0^+ state be part of the nature of EW symmetry breaking?
  The EFT consistent with what we knew (80's -00's) did not extrapolate to arbitrary high energies:

$$\mathcal{L} = -\frac{1}{4}W^{\mu\nu}W_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \bar{\psi}iD\psi$$

$$+ \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma) - \frac{v}{\sqrt{2}}(\bar{u}^i_L \bar{d}^i_L)\,\Sigma \begin{pmatrix} y^u_{ij}\, u^j_R \\ y^d_{ij}\, d^j_R \end{pmatrix} + h.c.,$$



- For WW scattering the cut off scale for the EFT with the addition of a scalar is raised:

$\Lambda \simeq 4\pi v$ ..raised to... $\Lambda \simeq 4\pi v/\sqrt{|1-a^2|}$

Couplings within 10% of the SM, in this case, cut off scale 7 TeV...

General EFT: Nonlinear chiral+ singlet

- General EFT : Nonlinear SU(2)xU(1) + Singlet scalar* $\Sigma = e^{i\sigma_a \pi^a/v}$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\, a_{W,Z}\,\frac{h}{v} + b_{Z,W}\,\frac{h^2}{v^2} + b_{3,Z,W}\,\frac{h^3}{v^3} + \cdots\right],$$

$$-\frac{v}{\sqrt{2}}\,(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_i^{u,d}\,\frac{h}{v} + c_{2,j}^{u,d}\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c.,$$

$$V(h) = \frac{1}{2}\,m_h^2\, h^2 + \frac{d_3}{6}\left(\frac{3\, m_h^2}{v}\right) h^3 + \frac{d_4}{24}\left(\frac{3 m_h^2}{v^2}\right) h^4 + \cdots .$$

- Also higher dimensional operators: (hats -dual fields)

$$\mathcal{L}_{HD}^5 = c_g\, g_3^2 \frac{h}{v}\, G_{\mu\nu}\, G^{\mu\nu} + c_W\, g_2^2 \frac{h}{v}\, W_{\mu\nu}\, W^{\mu\nu} + c_B\, g_1^2 \frac{h}{v}\, B_{\mu\nu}\, B^{\mu\nu},$$

$$+\hat{c}_W\, g_2^2 \frac{h}{v}\, \hat{W}_{\mu\nu}\, W^{\mu\nu} + \hat{c}_B\, g_1^2 \frac{h}{v}\, \hat{B}_{\mu\nu}\, B^{\mu\nu} + \hat{c}_G\, g_3^2 \frac{h}{v}\, \hat{G}_{\mu\nu}\, G^{\mu\nu}$$

* Grinstein/Trott 0704.1505, see also Bagger et al 9306256, Feruglio 9301281 for Technicolour sigma version, informed discussion in Burgess et al hep-ph/9912459

General EFT: Nonlinear chiral+ singlet

- EFT gives model independence. One can reduce parameters at the cost of restricting UV. This can break degeneracies in the data with a theory prior.

General case: $\Sigma \to U_L \, \Sigma \, U_Y^\dagger$

Custodial case: $\Sigma \to U_L \Sigma \, U_R^\dagger$

Also assuming consistency with MFV:

$$\mathcal{L} \;\; = \;\; \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger \, D^\mu \Sigma) \left[1 + 2\, a \, \frac{h}{v}\right] - \frac{v}{\sqrt{2}} \, (\bar{u}_L^i \bar{d}_L^i) \, \Sigma \, \left[1 + c^{u,d} \, \frac{h}{v}\right] \left(\begin{array}{c} y_{ij}^u \, u_R^j \\ y_{ij}^d \, d_R^j \end{array} \right) + h.c.,$$

Also higher dimensional operators: - assuming no large BSM CP violation

$$\mathcal{L}^5_{HD} = c_g \, g_3^2 \frac{h}{v} \, G_{\mu\,\nu} \, G^{\mu\,\nu} + c_W \, g_2^2 \frac{h}{v} \, W_{\mu\,\nu} \, W^{\mu\,\nu} + c_B \, g_1^2 \frac{h}{v} \, B_{\mu\,\nu} \, B^{\mu\,\nu}$$

- Can draw physical conclusions for sym theories with current data. Still have degeneracies. Not a model independent operator analysis- a hypothesis test.

What did we learn in Run I?

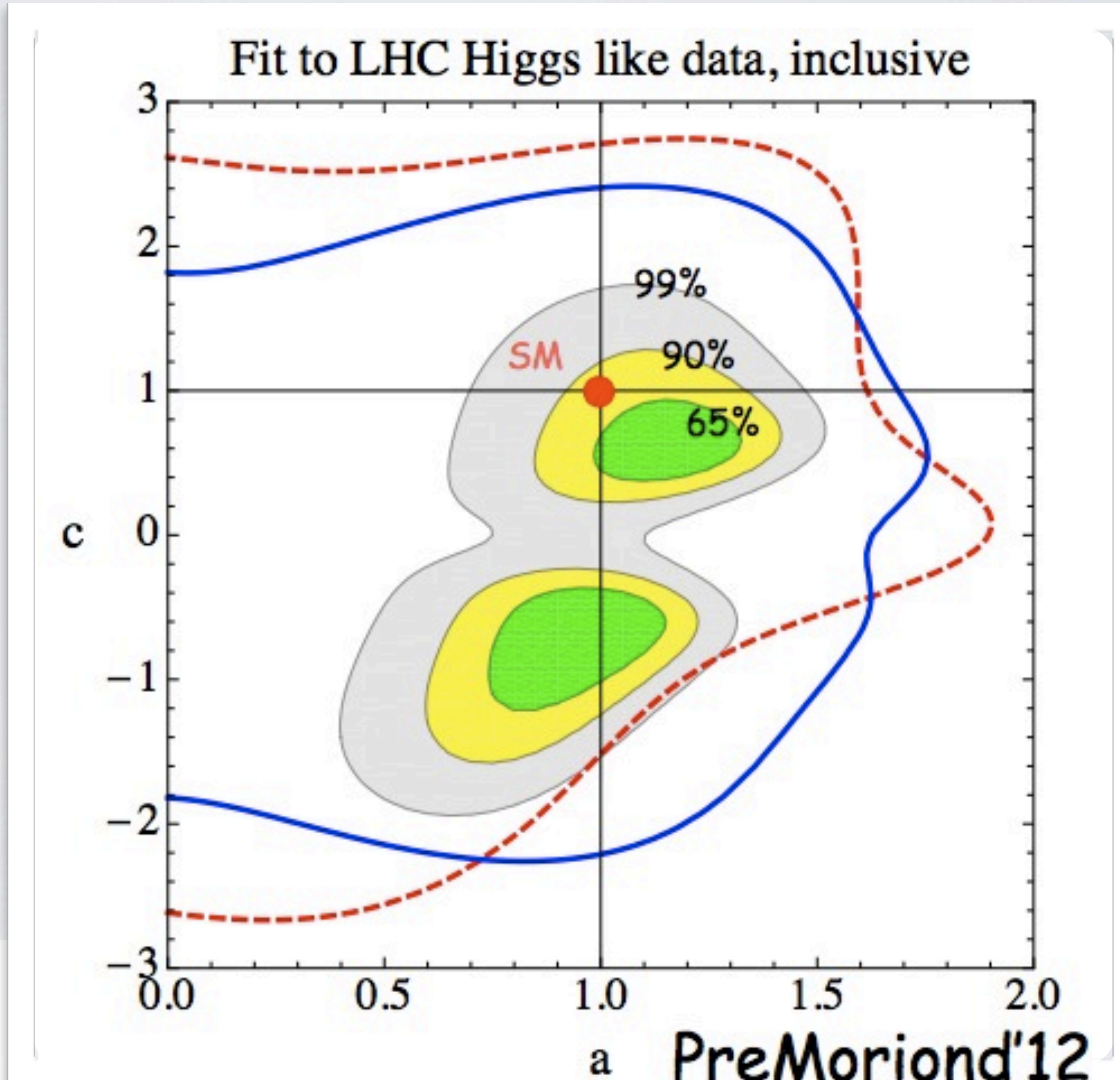
- First (important) question on scalar- is it converging on the SM case to raise the cut off scale?

SM 82%CL away from best fit point

Two minima:

(a,c)=(1.13,0.58)
χ^2=2.86

(a,c)=(0.96,-0.64)
χ^2=1.96



Atlas 95%CL exclusion

CMS 95%CL exclusion

65% CL

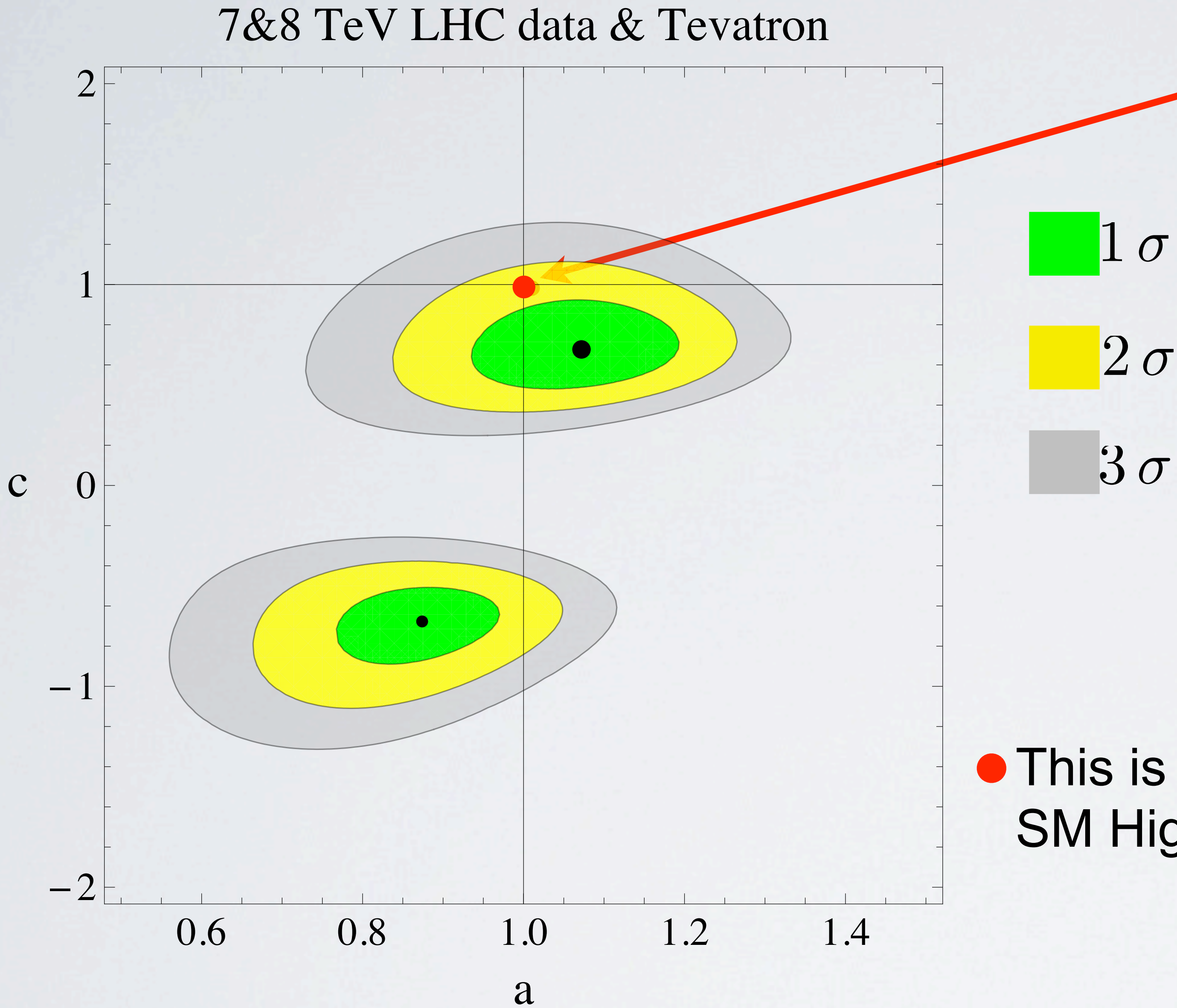
90% CL

99% CL

Espinosa,Grojean, Mull,Trott arXiv:1202.3697

Fastest paper of my life.

It got better.



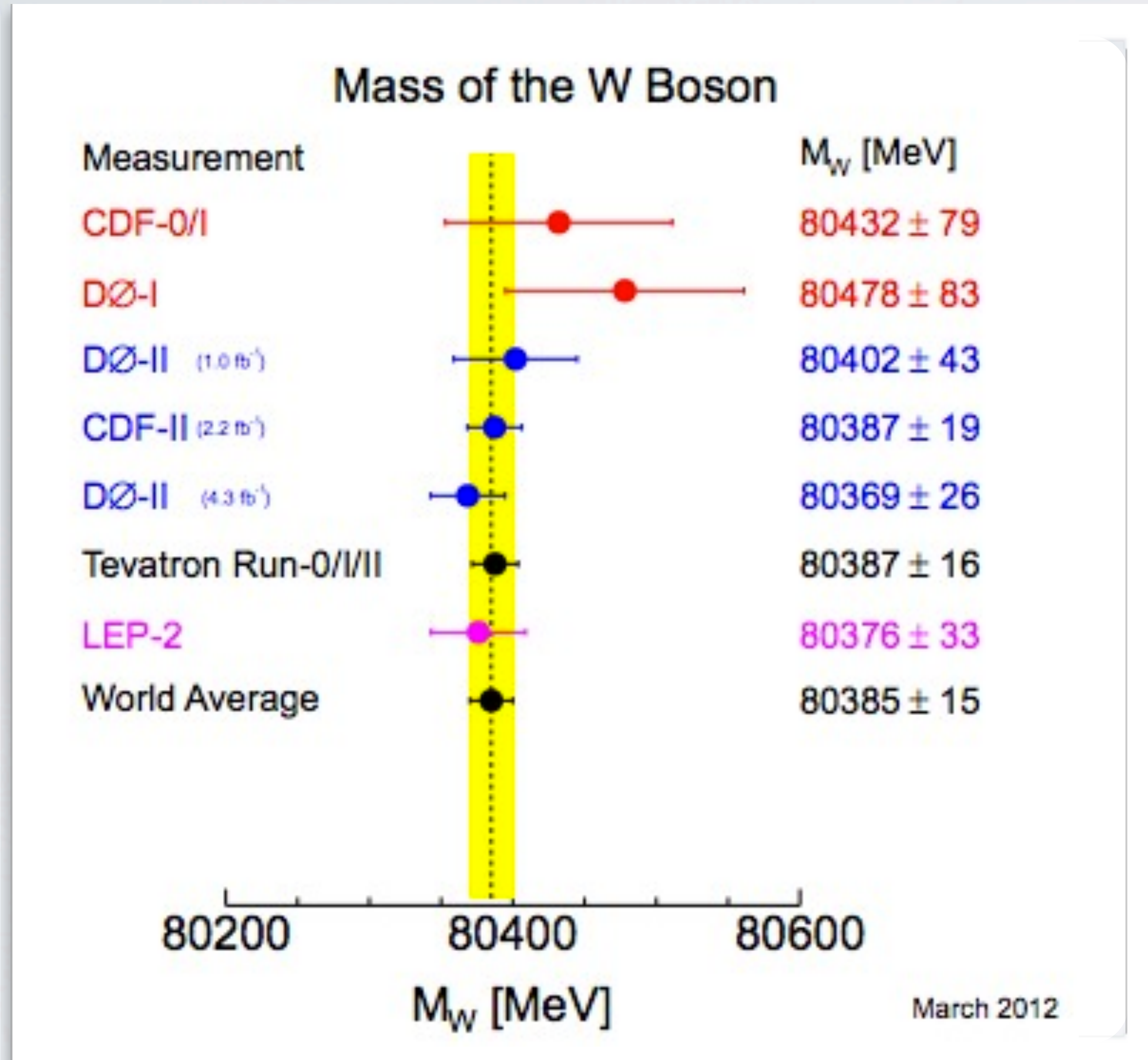
Espinosa,Grojean,Muhlleitner,Trott
JHEP 1205 (2012) 097 arxiv:1207.1717

GWS is here, is the data there as well?

- This is a direct (and minimal) way to test - is it the SM Higgs with no other NP from the discovery data.
- The discovery of the Higgs Like Boson must be placed in the context of precision EW measurements at LEP (and other facilities)

and better....

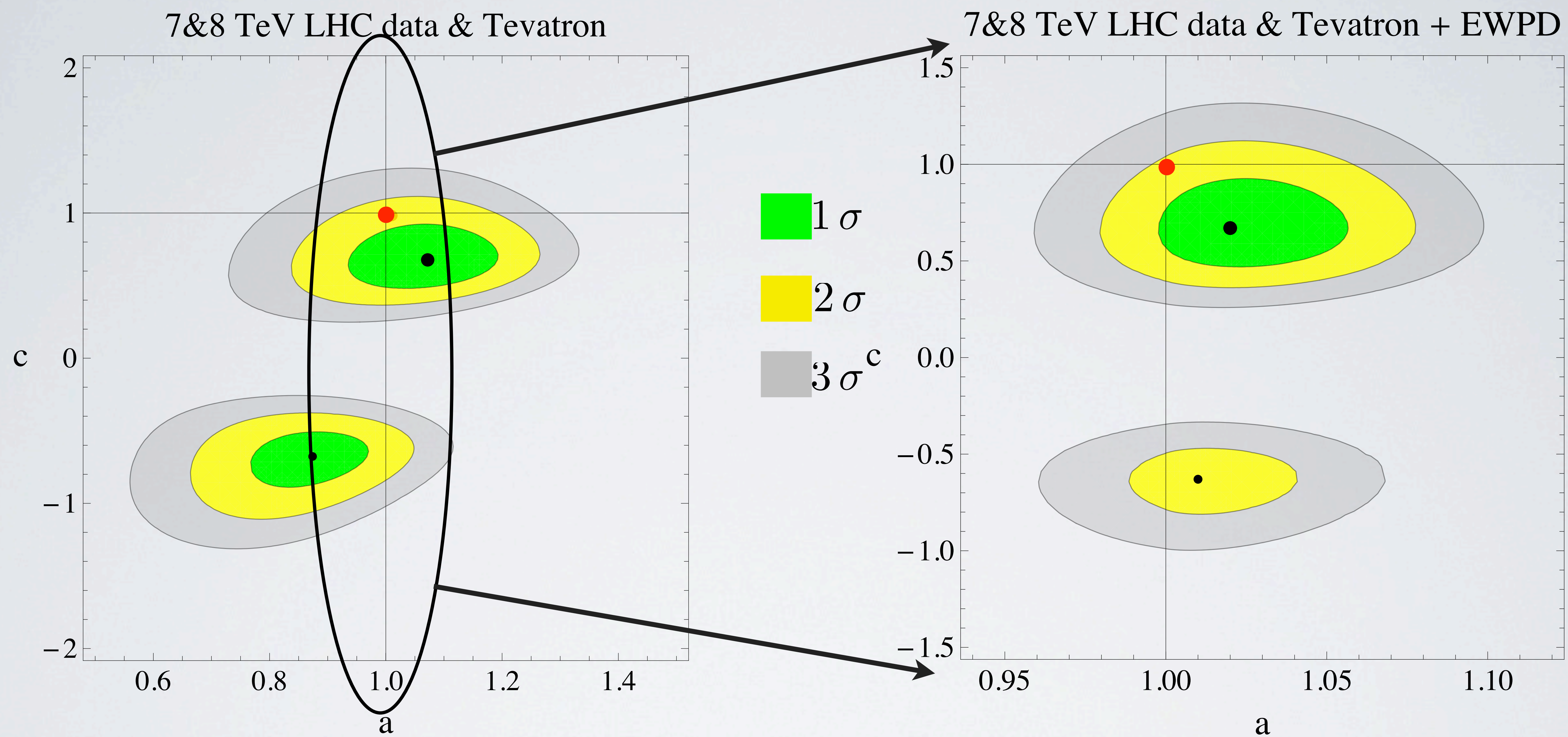
- Precision EW measurements have also improved with input from the Tevatron on the W mass combined into the world average $80.385 \pm 0.015\mathrm{GeV}$



- One of the lasting important legacies of the Tevatron, a powerful measurement! Most important "Higgs" data from the Tevatron (I.M.O.) is the W mass.

2012 Update of the Combination of CDF and D0
Results for the Mass of the W Boson, Tevatron EW working group, arXiv:1204.0042

hypothesis testing the SM.



Notice "a" scale changed significantly

- Used the recent updated W mass measurement at the Tevatron.*

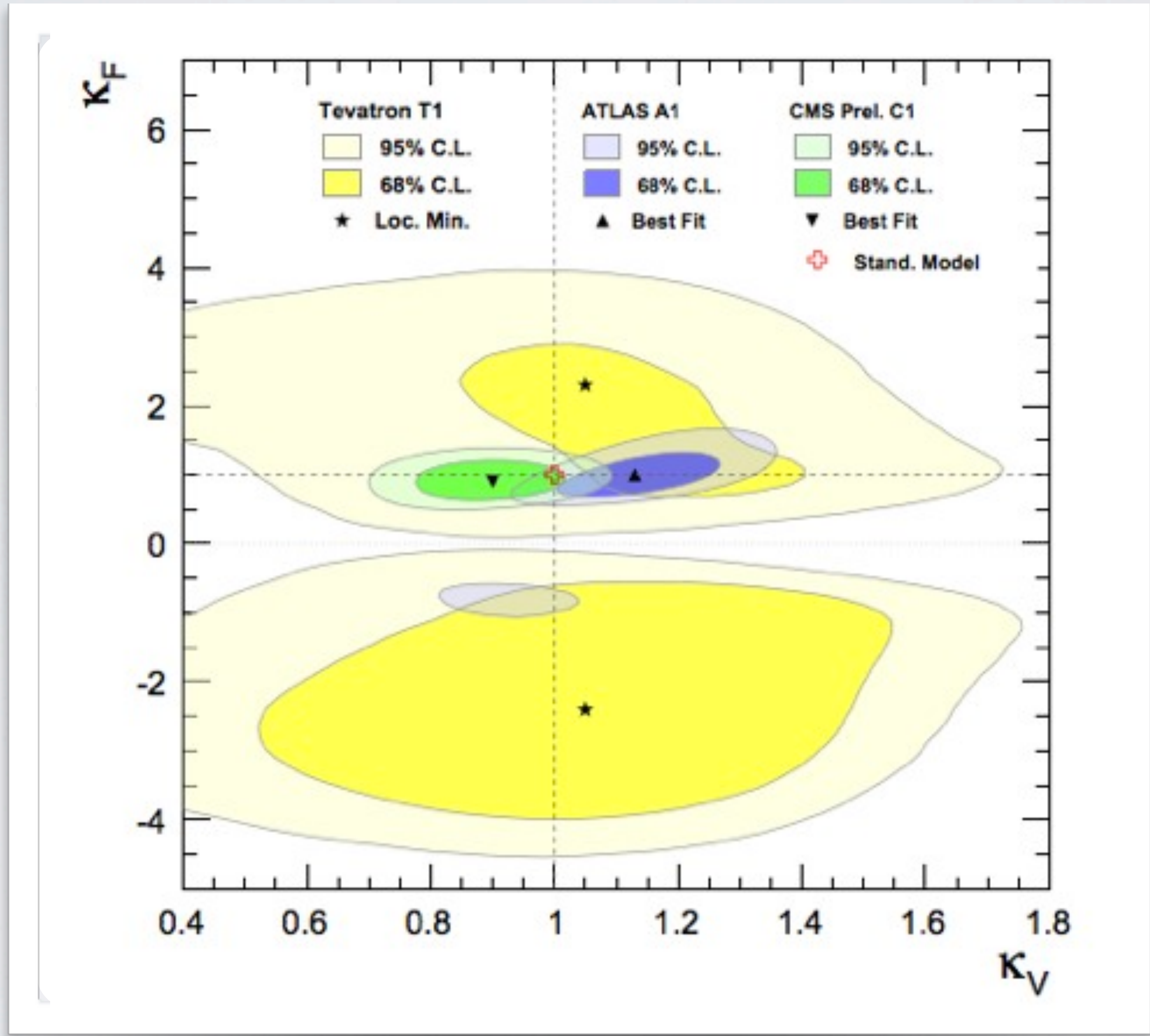
Espinosa,Grojean,Muhlleitner,Trott **JHEP 1205 (2012) 097 arXiv:1207.1717**

*Thanks to J. Erler for provided the EWPD fit output on short notice.

Now the standard analysis.

- Current version of this analysis handed off the the experimentalists: (statistical error domination reduced, systematics and subtleties in combining experiments more serious issues)

From the PDG:



Note this analysis was also reproduced by many other authors. Too many to list here.

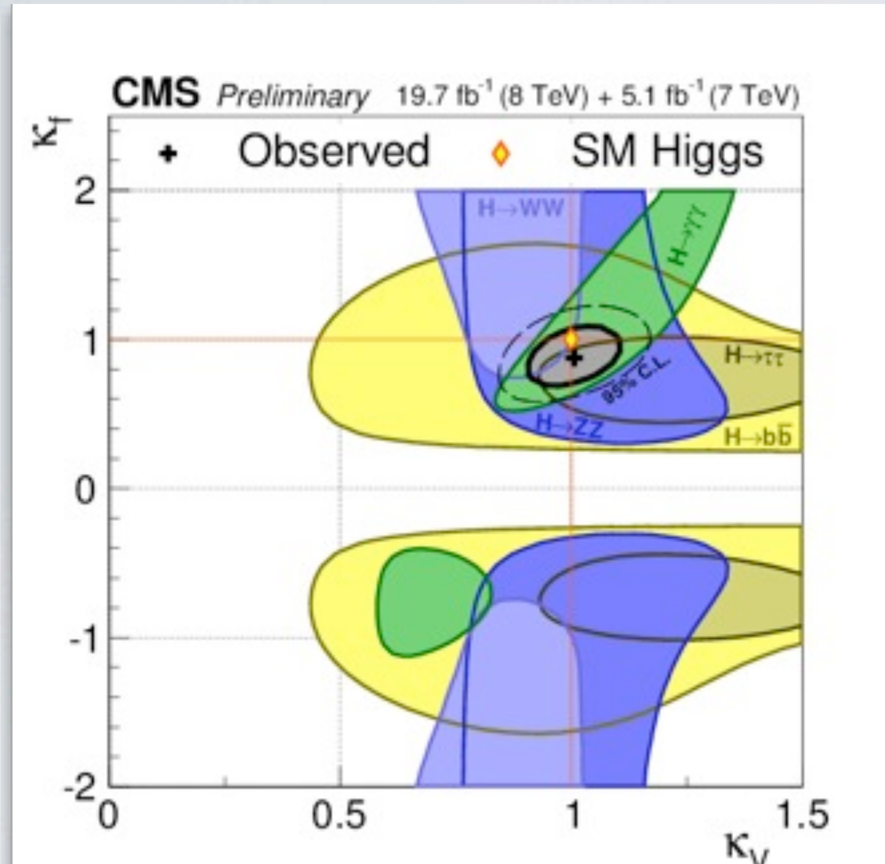
24 hours

Carmi,Falkowski,Kuflik,Volansky arXiv:1202.3144
Azatov,Contino,Galloway arXiv:1202.3415
Espinosa,Grojean,Muhlleitner,Trott arXiv:1202.3697

Curiously, initial work uncited in PDG.

Recent slight revisions in data

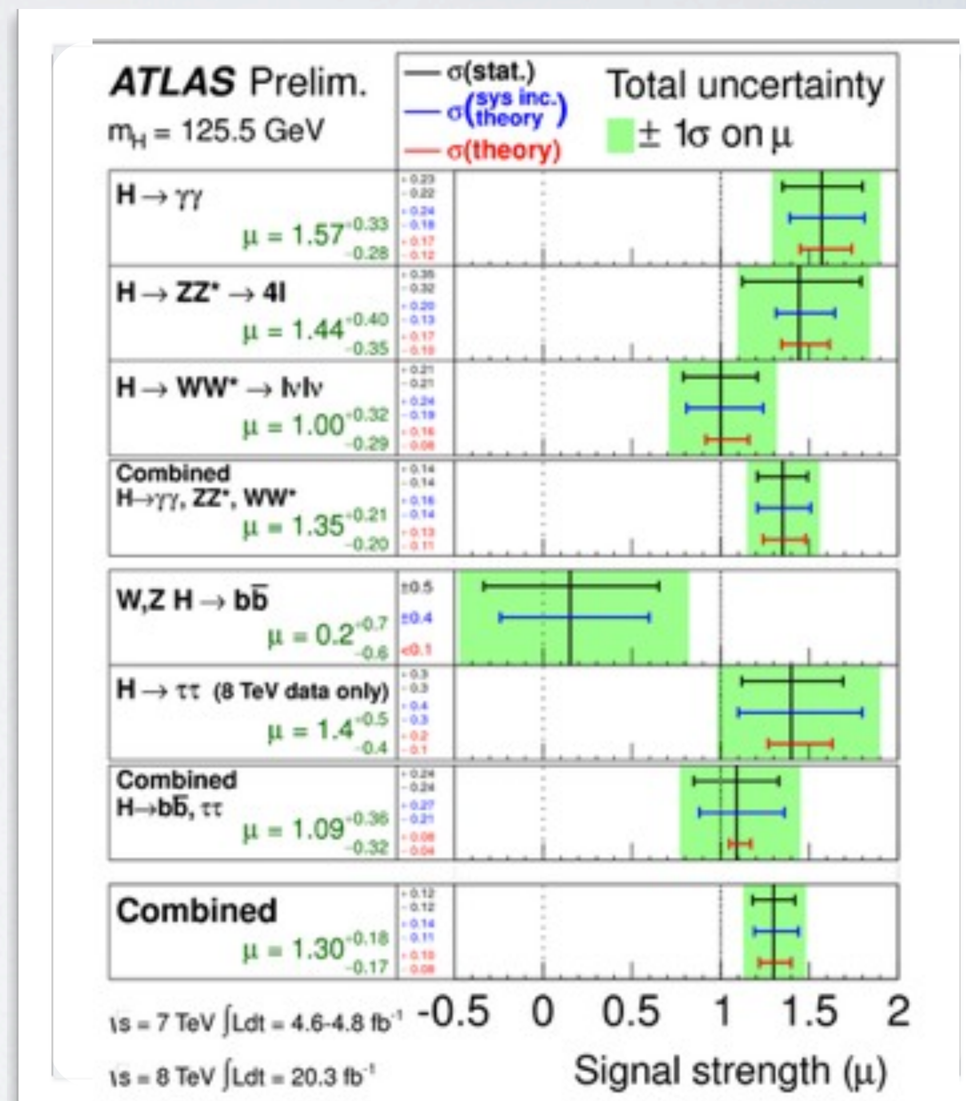
- Current Higgs data:



Facility	LHC	HL-LHC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	10,000+2600
κ_γ	5 – 7%	2 – 5%	1.45%
κ_g	6 – 8%	3 – 5%	0.79%
κ_W	4 – 6%	2 – 5%	0.10%
κ_Z	4 – 6%	2 – 4%	0.05%
κ_ℓ	6 – 8%	2 – 5%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	0.69%

- Pushing LHC to be as precise as possible in predictions and measurements essential to reach expected deviations. This is just barely the machine we need.

- We are just NOW getting into the interesting region for Higgs measurements.



How to use the data.

- Higgs LHC data has been traditionally supplied in one of three forms - signal strengths (the good)
  CLS “blue band” plots (the bad)
  full likelihood (the ugly)

- Most usefull data is a signal strength

This is the framework that leads to generalizing the SM predictions with tree level rescalings of the cross section and branching ratios:

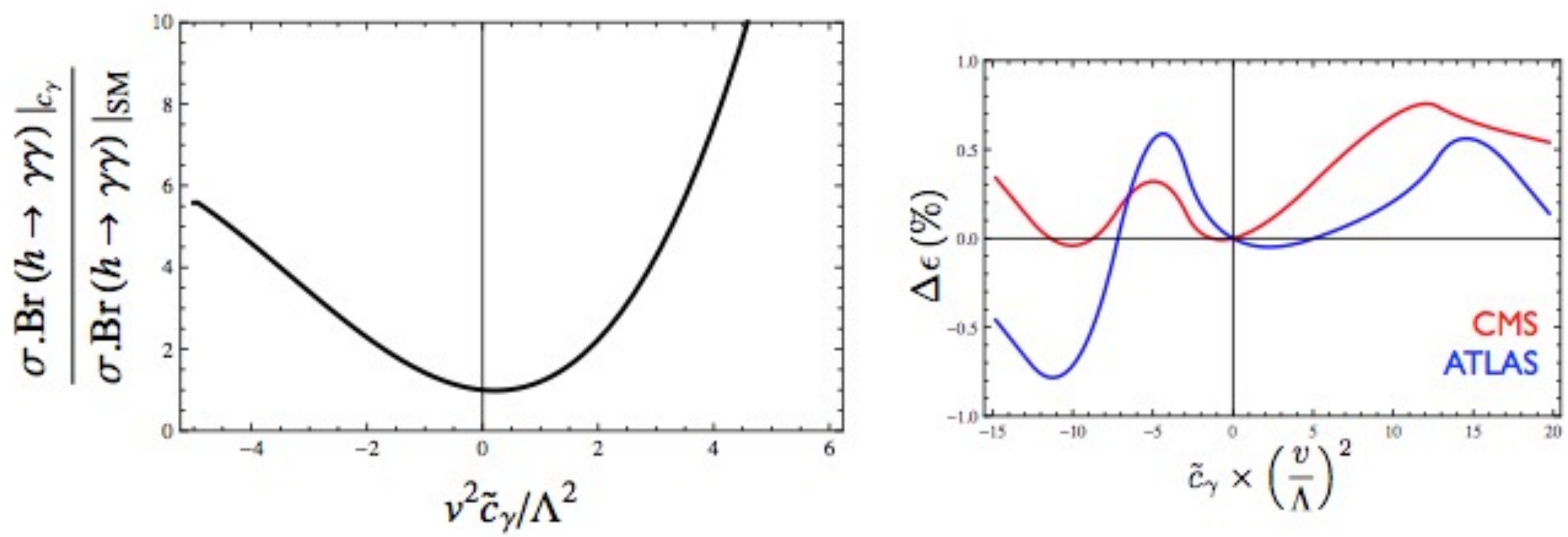
$$\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}}\,, \qquad \chi^2(\mu_i) = \sum_{i=1}^{N_{ch}} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

This should be generalized to a full off diagonal error matrix including correlations. But such information is not supplied (for the most part) from the experiments.

This modifies $\mu^i_{SM} \to \mu^i(a,c)$ but what about efficiency corrections?

How to use the data.

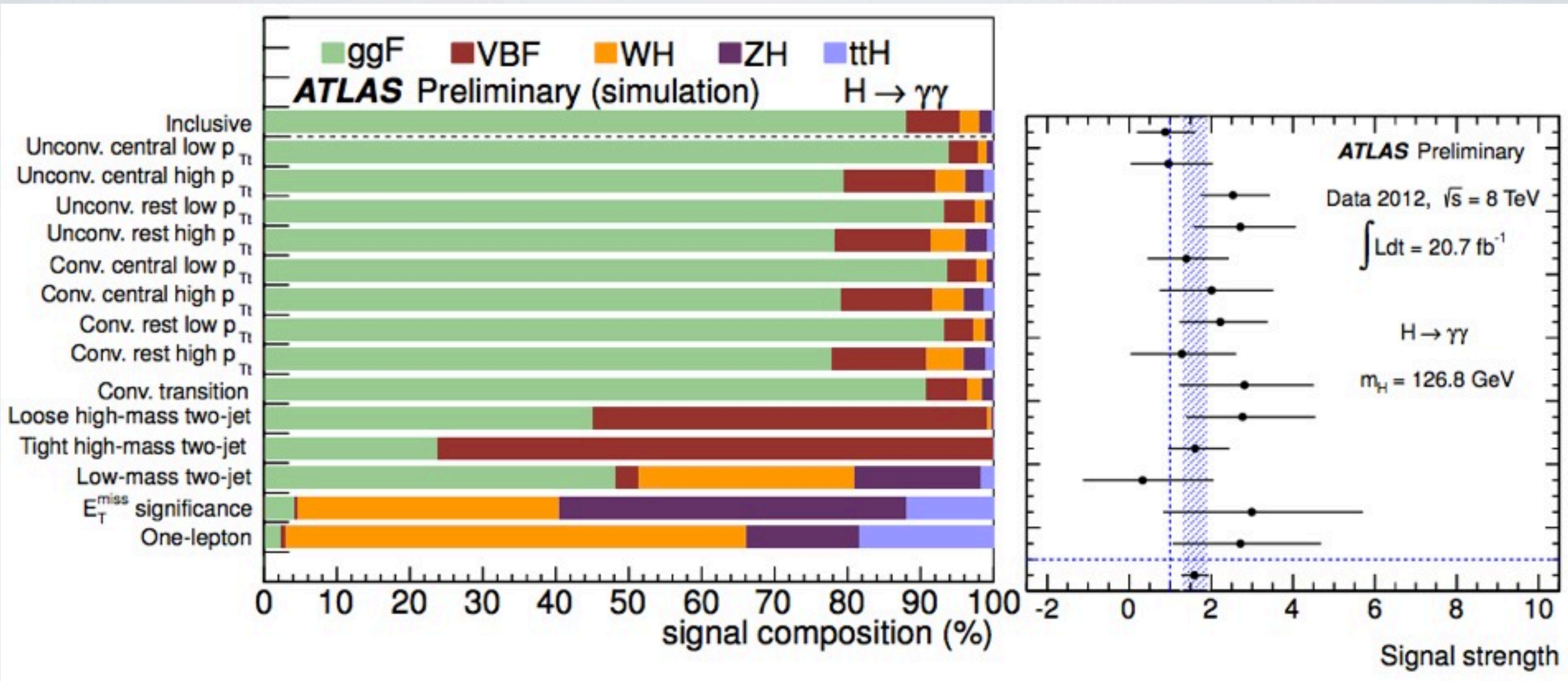
- Event rates will only change if a kinematic distribution is changed significantly we have checked that in a number of cases as well eff corrections can be safely neglected:



- The reason this works is most signals are dominated by one production mechanism, check if there is significant subleading production to make sure you don't screw up.

How to use the data.

- Example of dominance of single production mode:



Simple limit methodology

What is this statistics #$@!*$ in your paper, it is just equivalent to a damn χ^2 as far as i am concerned!

-another charitable physicist.

Each signal strength measurement can be approx:

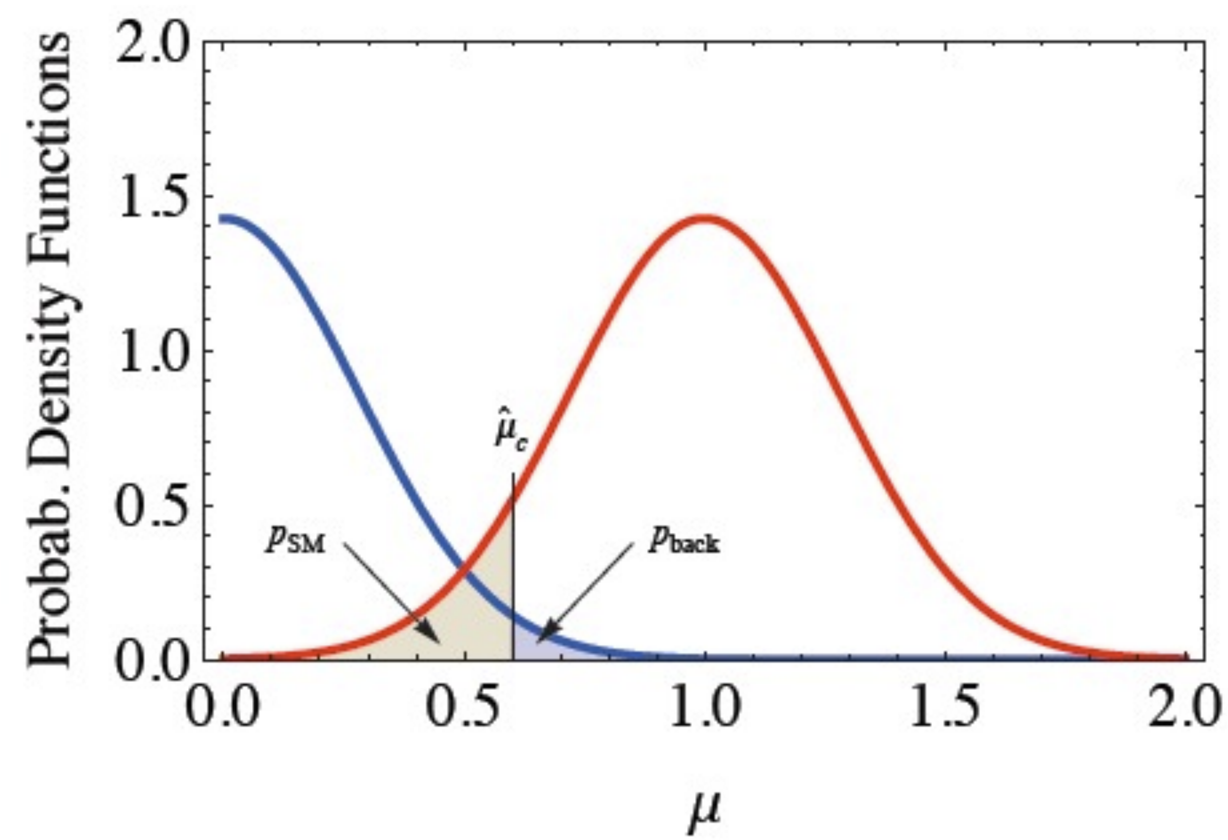
$$pdf_i(\mu, \hat{\mu}_i, \sigma_i) \approx e^{-(\mu-\hat{\mu}_i)^2/(2\sigma_i^2)}$$

The PDF's can be combined to get global PDF's

$$pdf(\mu, \hat{\mu}_c, \sigma_c) \propto \prod_i^{N_{ch}} pdf_i(\mu, \hat{\mu}_i, \sigma_i) = \mathcal{N}_c\, e^{-(\mu-\hat{\mu}_c)^2/(2\,\sigma_c^2)}$$

Where you have the combination variables:

$$\frac{1}{\sigma_c^2} = \sum_i^{N_{ch}} \frac{1}{\sigma_i^2}, \qquad \frac{\hat{\mu}_c}{\sigma_c^2} = \sum_i^{N_{ch}} \frac{\hat{\mu}_i}{\sigma_i^2}\,.$$



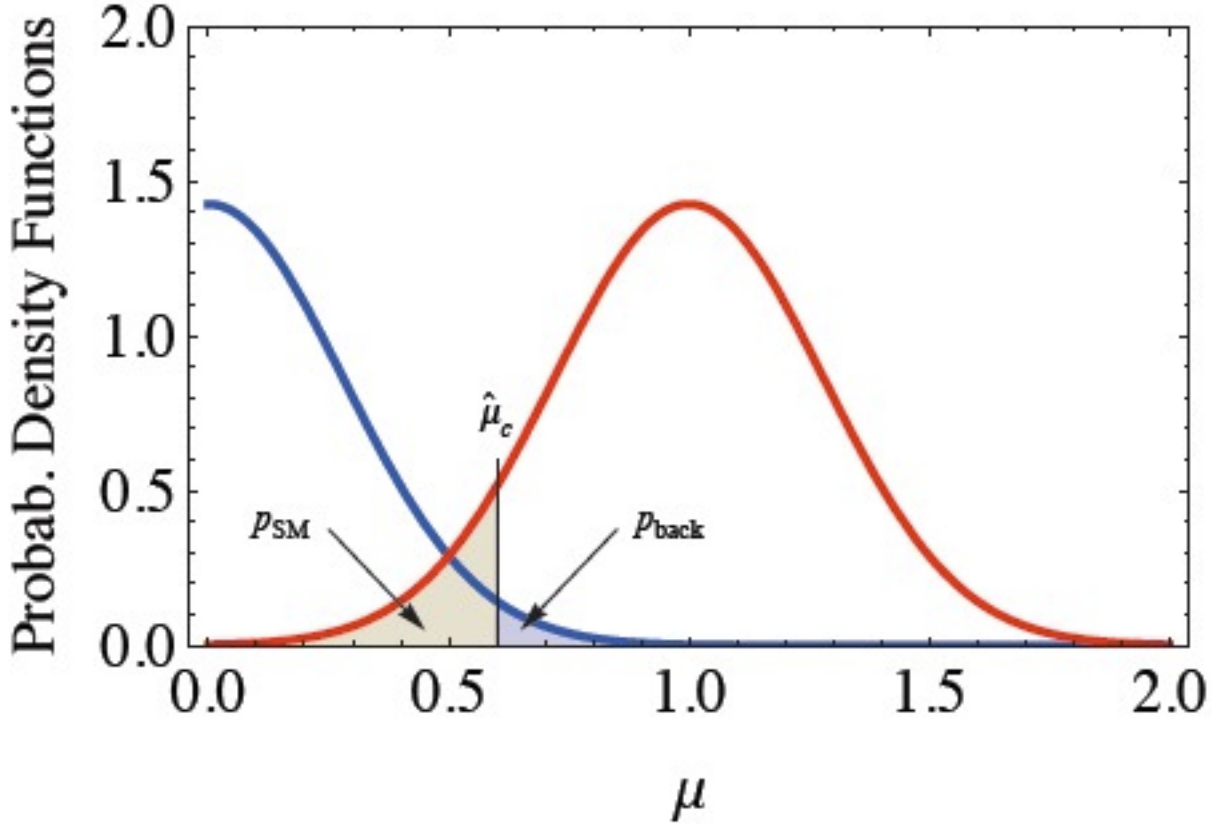
(note: correlations neglected here)

PDF's make clear one can set upper, lower and consistency limits on signal strength values.

Simple limit methodology

The invisible branching ratio is great as it is a universal shift on signal strengths.

$$\mathrm{Br}(h \to f) \equiv \frac{\Gamma(h \to f)}{\Gamma_{\rm SM} + \Gamma_{inv}} = (1 - \mathrm{Br}_{inv}) \times \mathrm{Br}_{SM}(h \to f).$$



In terms of the gaussian combination variables

$$\frac{1}{\sigma_c^2} = \sum_i^{N_{ch}} \frac{1}{\sigma_i^2}, \qquad \frac{\hat{\mu}_c}{\sigma_c^2} = \sum_i^{N_{ch}} \frac{\hat{\mu}_i}{\sigma_i^2}.$$

The invisible branching ratio is expressed as: $\mathrm{Br}_{inv} = 1 - \hat{\mu}_c.$

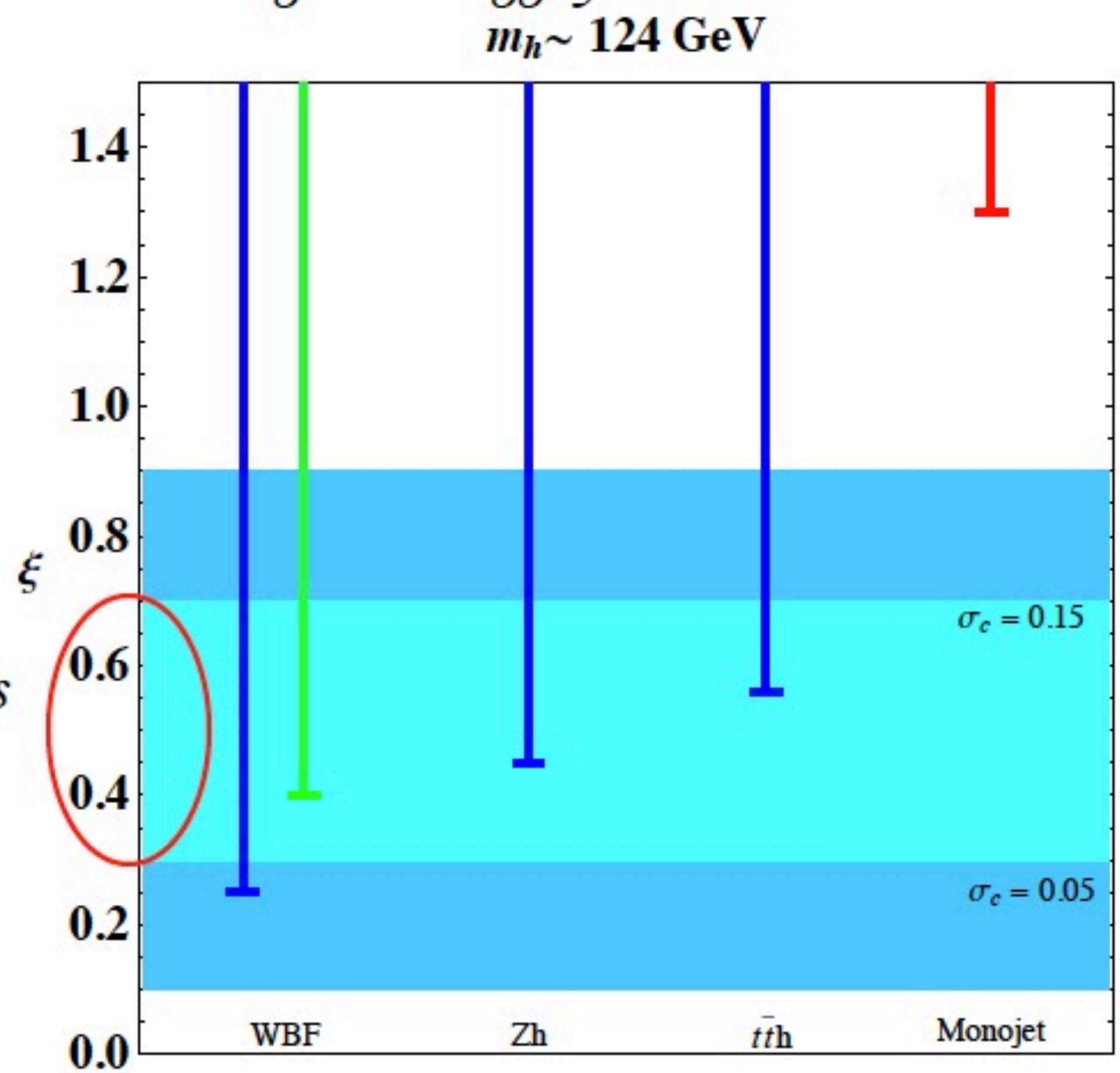
One can fit to it using the SUPPLIED COMBINED SIGNAL STRENGTHS

Pre-LHC this was considered one of the hardest BSM parameters to bound.

Post 1205.6790 Espinosa, Mull, Grojean, Trott understood to be one of the easiest.

Witness the power of "N"

Strength of indirect tests in global Higgs fits:



Sensitivity this year ~ 2 σ

Direct reach in Higgs global fits for $\xi = \mathrm{Br}_{\mathrm{inv}}$ various channels -vertical 95% CL

Indirect reach in Higgs global fits for $\xi = \mathrm{Br}_{\mathrm{inv}}$ -horizontal

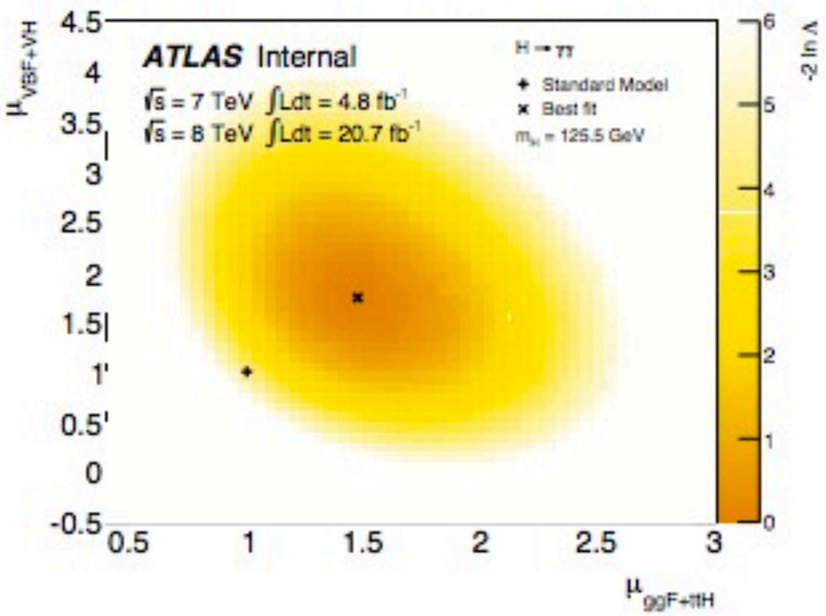
Espinosa,Muhlleitner,Grojean,Trott arXiv:1205.6790

Witness the power of N, when you combine N channels in fits!

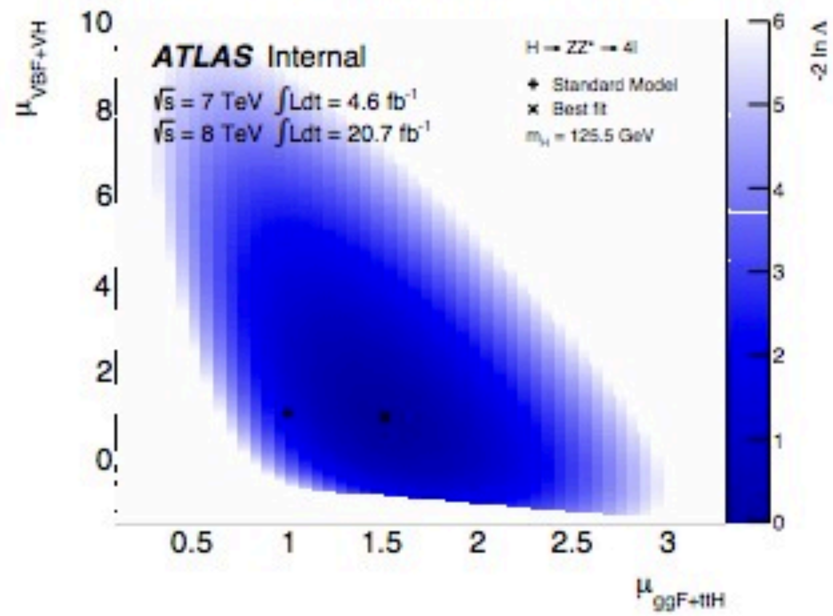
How to use the data.

- Correlations are NOT supplied in a sufficient manner. Stopgaps are:

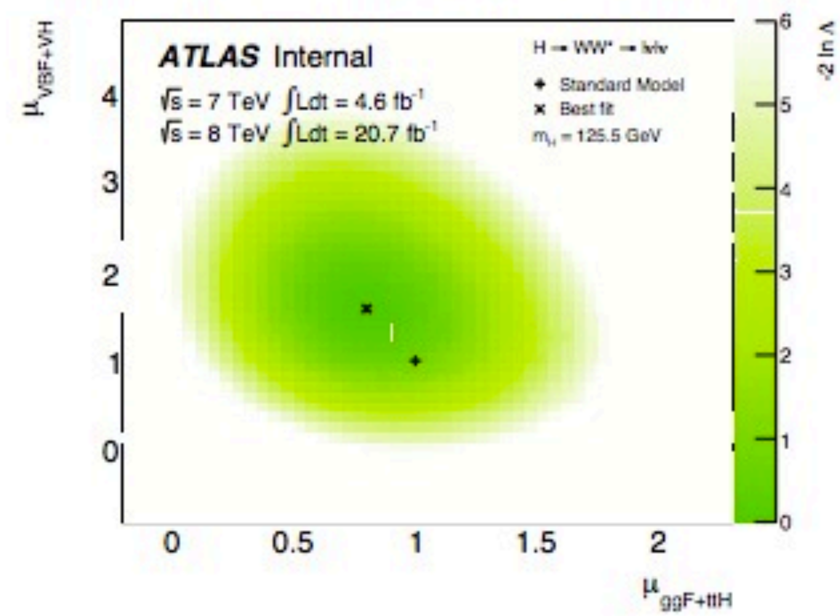
http://doi.org/10.7484/INSPIREHEP.DATA.A78C.HK44



http://doi.org/10.7484/INSPIREHEP.DATA.RF5P.6M3K



http://doi.org/10.7484/INSPIREHEP.DATA.26B4.TY5F



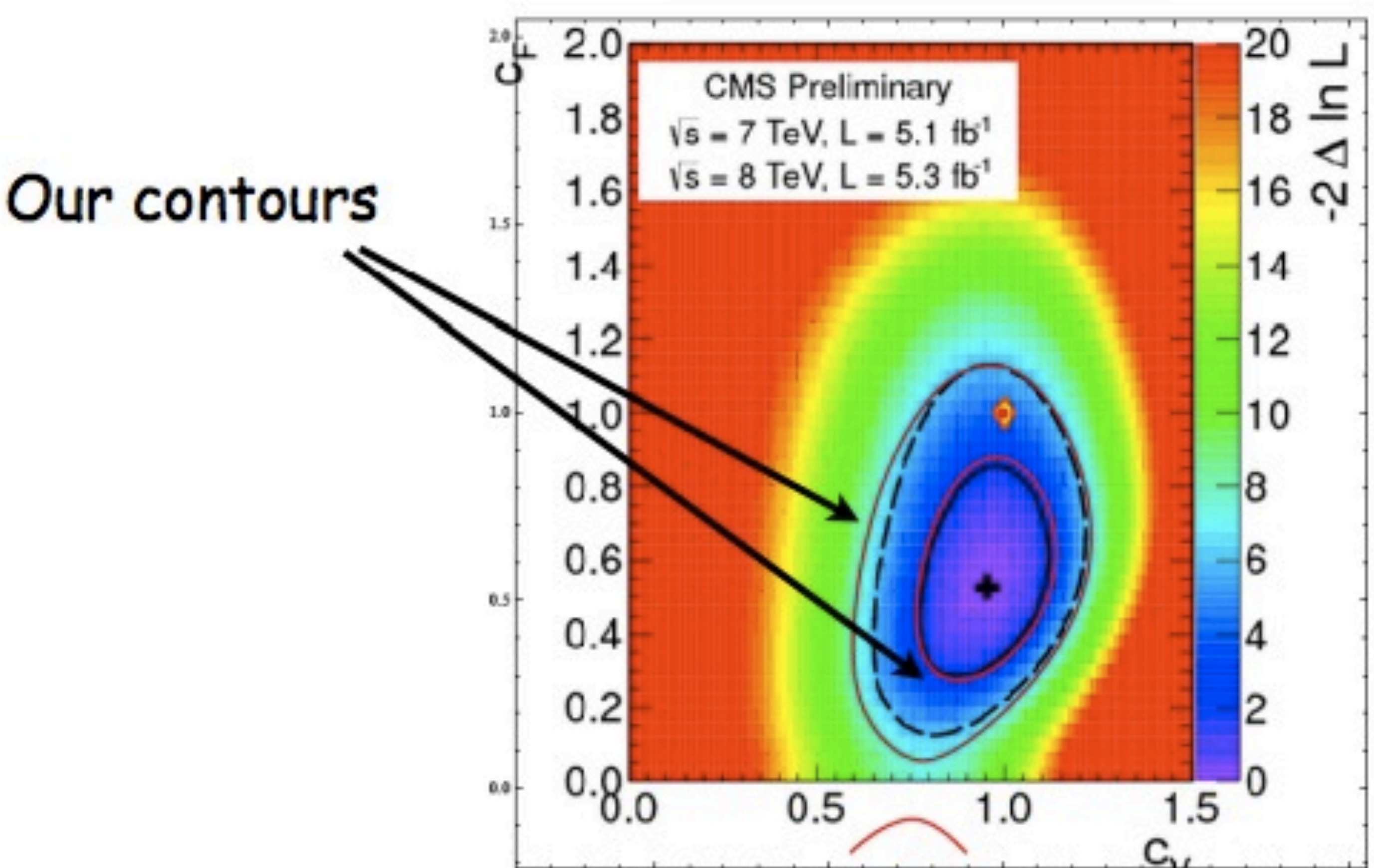
- Incorporate partial correlations through reading the 45% angle in combined plots of this form

- Use a program like HiggsBounds and just accept the output.

The data can be usable

Comparison with CMS "official" fit

CMS imposed a prior c > 0
(it doesn't affect χ^2, but it modifies $\Delta\chi^2$)



Your χ^2 is too damn good !
-our friendly competition

This means that:

a) We are not badly screwing up.

b) correlations do not matter (summer)

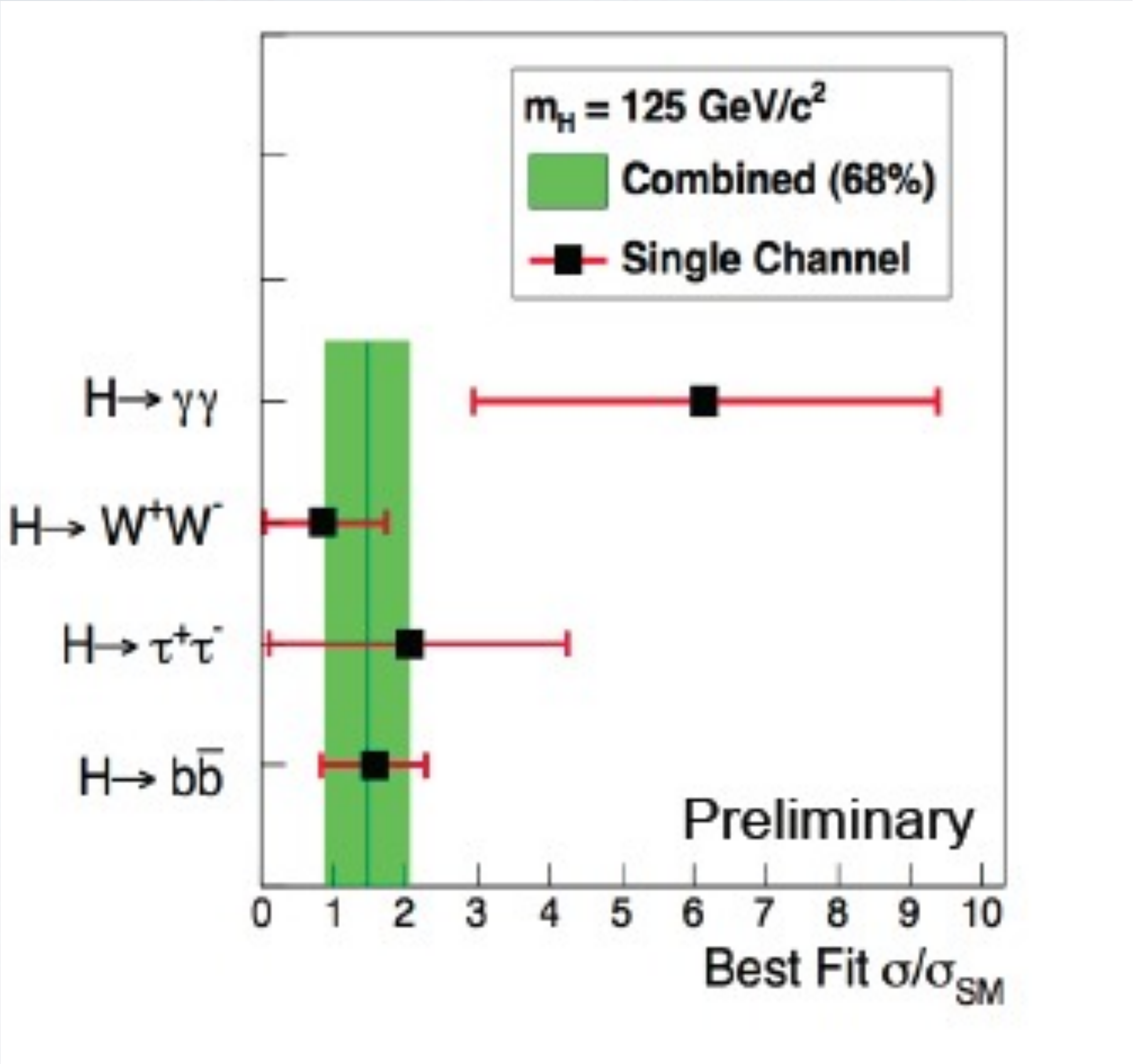
or

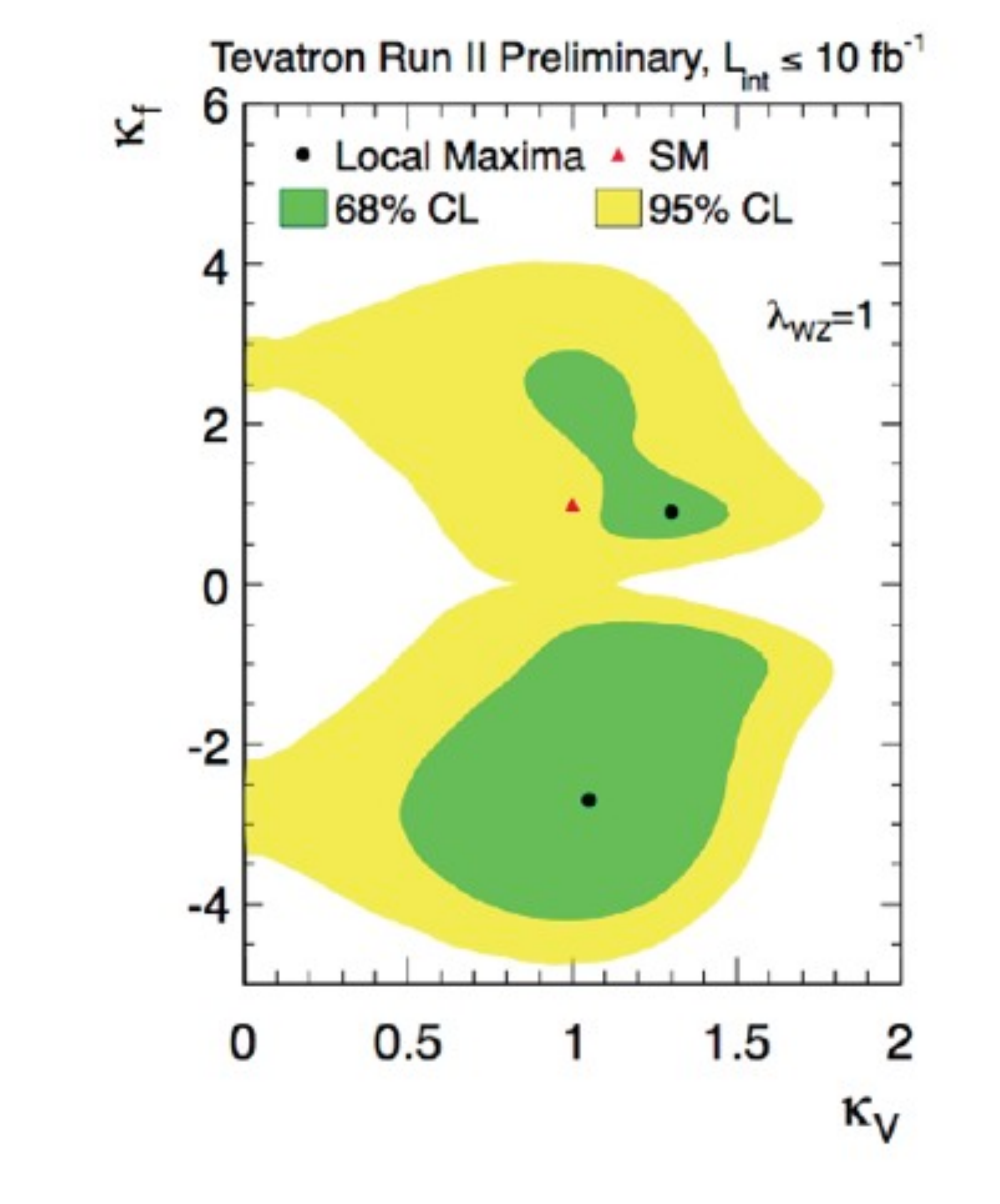
b) they do matter but CMS is as lost on estimating them correctly as we are.

Conclusion: You can trust some theorists to do this (for now).

The data can be un-usable

- Some of the public data is extremely problematic as it is statistically marginal





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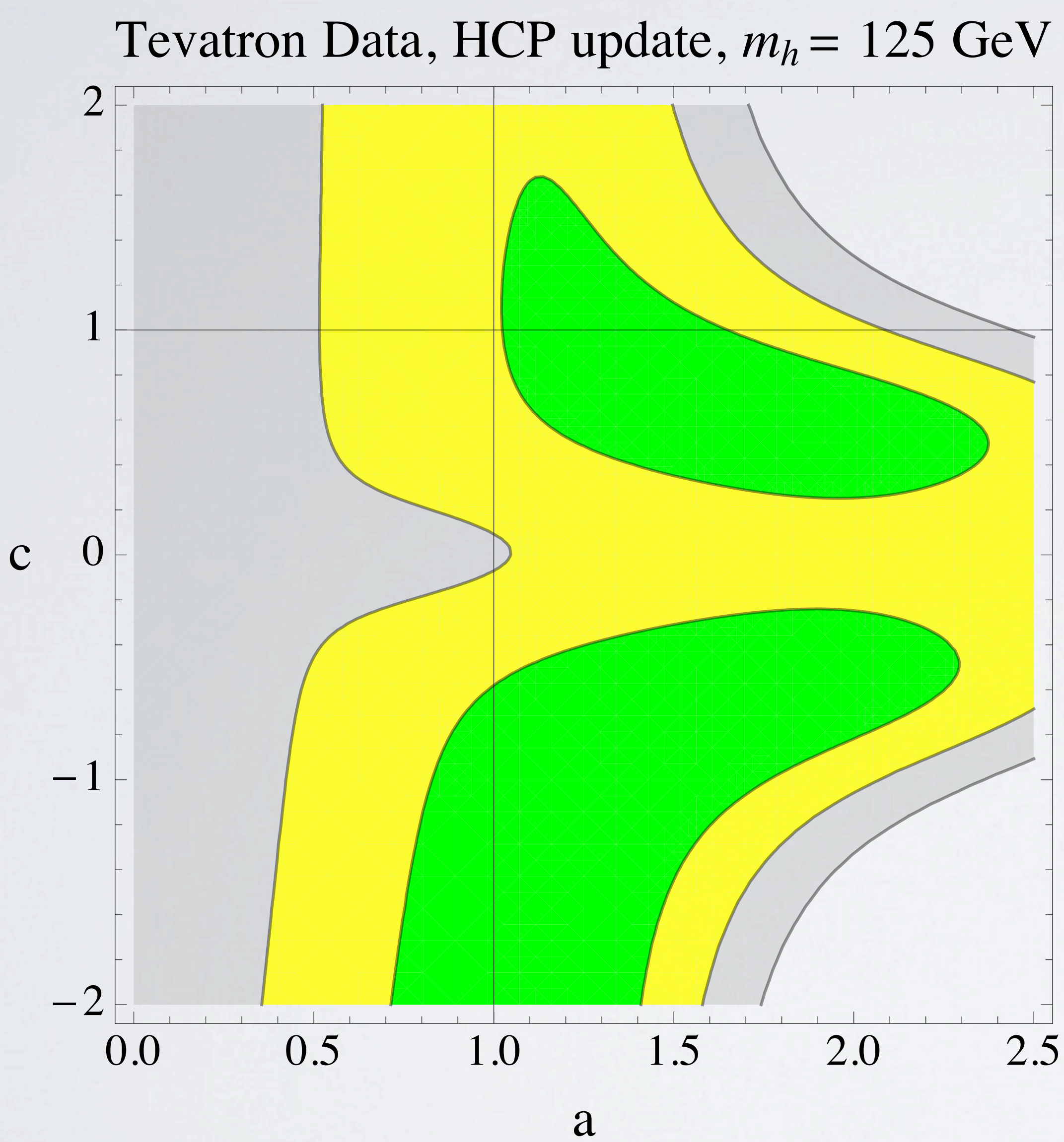
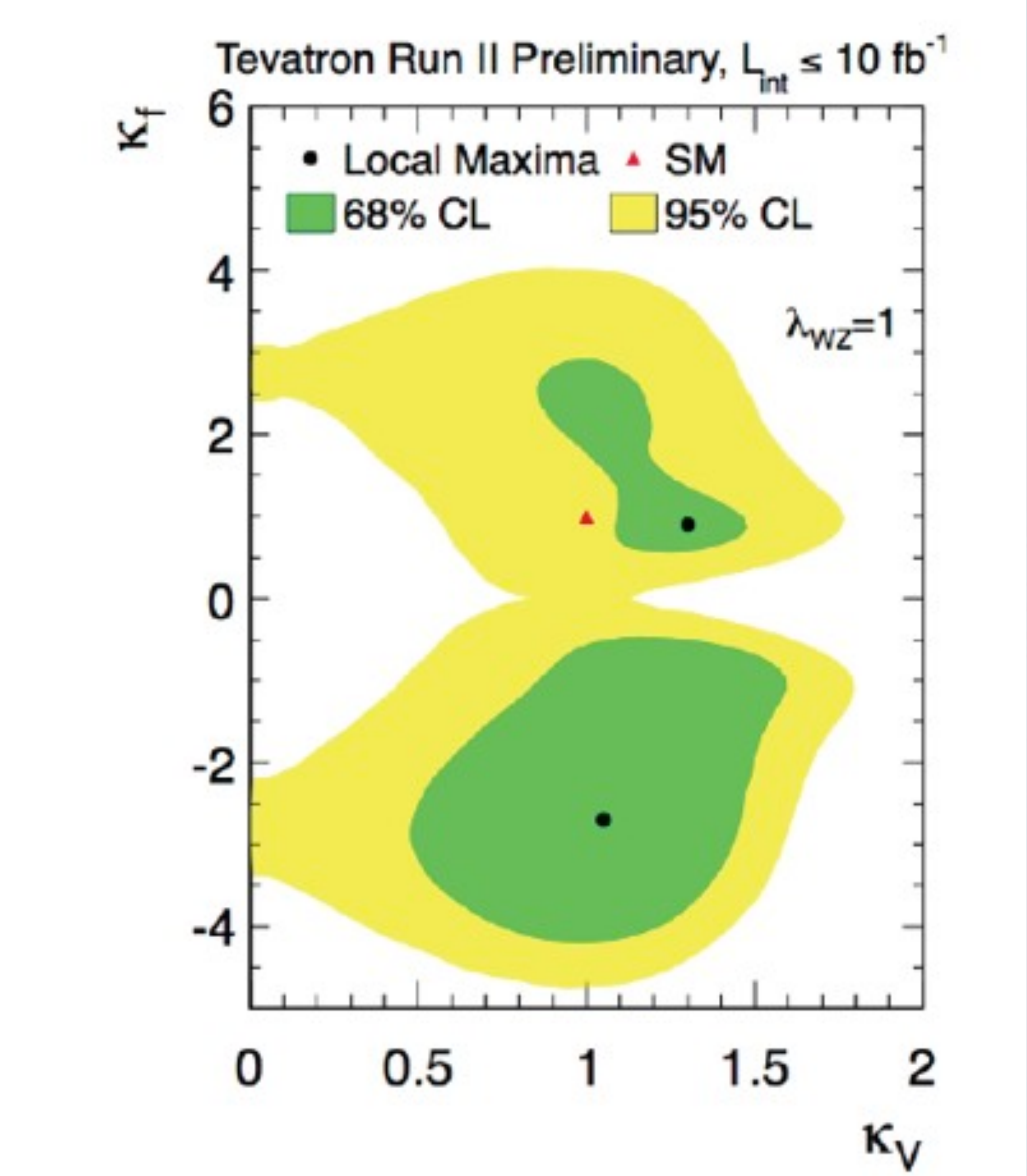




.....different scales....but still the public info not sufficient. Info will have to be further resolved so that broad physics conclusions can be drawn by theorists from Higgs data.

What is the theory?

Unknown UV

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{pr\cdots}}{\Lambda^2} C_i^{pr\cdots}$$

$SU(2)\times U(1)$ linearly realized

$SU(2)\times U(1)$ nonlinearly realized more general

IDEA: arXiv:0704.1505 Grinstein Trott

$$\Sigma = e^{i\sigma_a\,\pi^a/v}$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a_{W,Z}\frac{h}{v} + b_{Z,W}\frac{h^2}{v^2} + b_{3,Z,W}\frac{h^3}{v^3} + \cdots\right],$$

$$-\frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_i^{u,d}\frac{h}{v} + c_{2,j}^{u,d}\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c.,$$

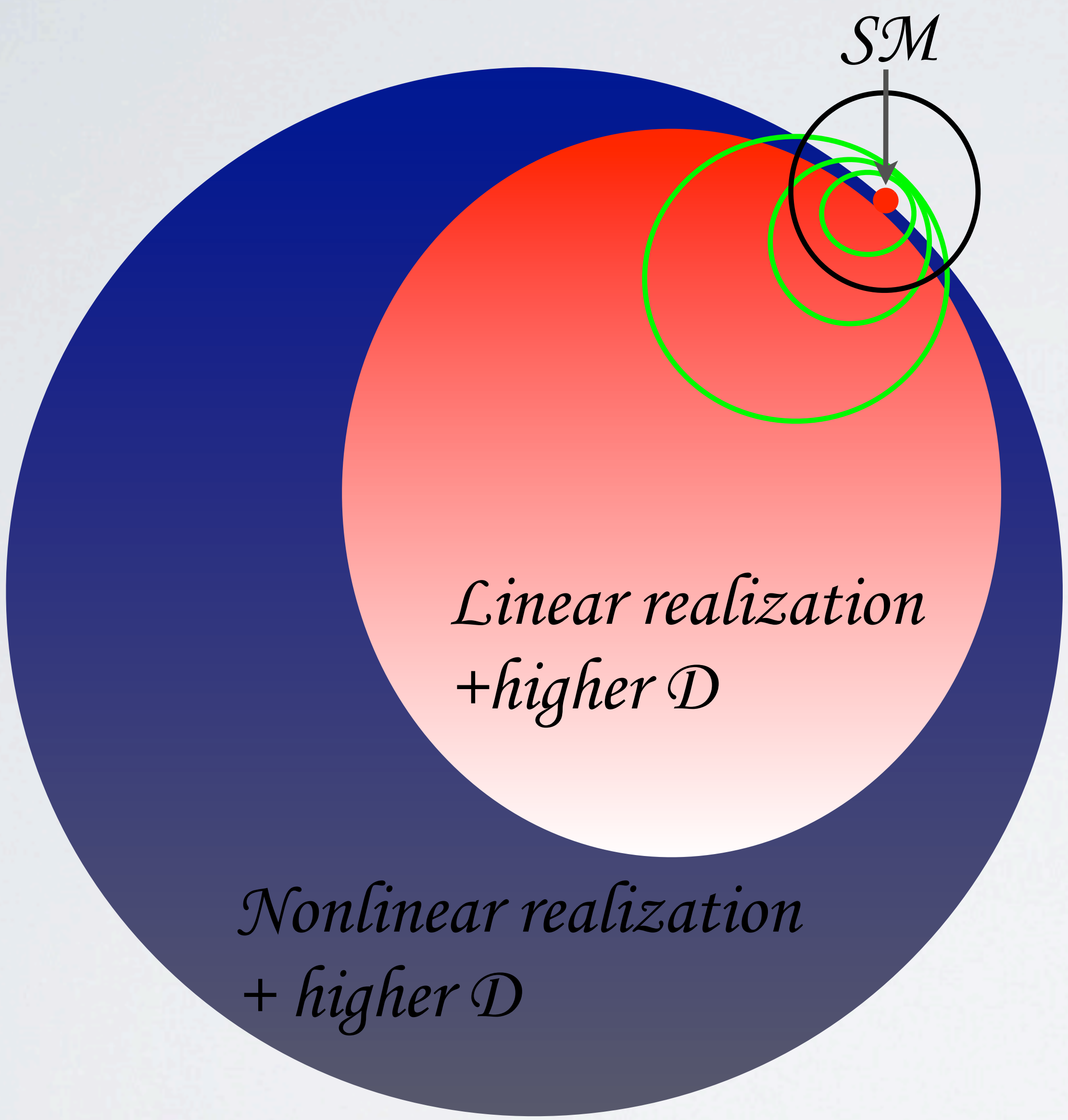
$$V(h) = \frac{1}{2}m_h^2 h^2 + \frac{d_3}{6}\left(\frac{3\,m_h^2}{v}\right)h^3 + \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots .$$

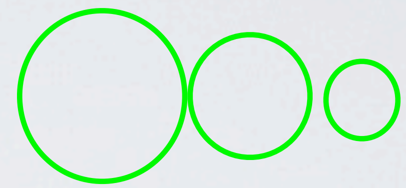
Notation:
R. Contino, et al. JHEP 1005 (2010) 089.

- The question is not is the Higgs doublet or mechanism present. The question is “do we have interactions in the UV that force us to use a nonlinear formalism to reproduce the IR”.

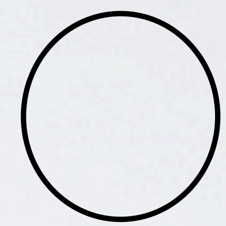
- This is the theory used in the fits to Higgs data as more general.

What is the picture?





Cut off scale raising above the ew scale



Run I LHC

The SM EFTs approach in one venn diagram.

- Linear EFT $H \supset h$ and relations between measurements that follow from this hold
- Non-Linear EFT, singlet h in formalism. Broader range of relations between measurements.

- Known unknown UV works this way - gravity non linearizes the EFT $\xi \frac{\bar{X}}{M_{pl}}$

arXiv:1402.1467Burgess, Patil, Trott

Test the derivative expansion

Lets assume the SM eventually fails.

Next step:

- Need to test the EFT's to sub-leading order. First define nonlinear one:

  Alonso,Gavela,Merlo,Rigolin,Yepes arXiv:1212.3305
  see also Contino et al. arXiv:1202.3415
  Buchalla, Cata arXiv:1203.6510, +Krause arXiv:1307.5017

  Linear EFT non-redundant basis took to 1008.4884 Grzadkowski et al.

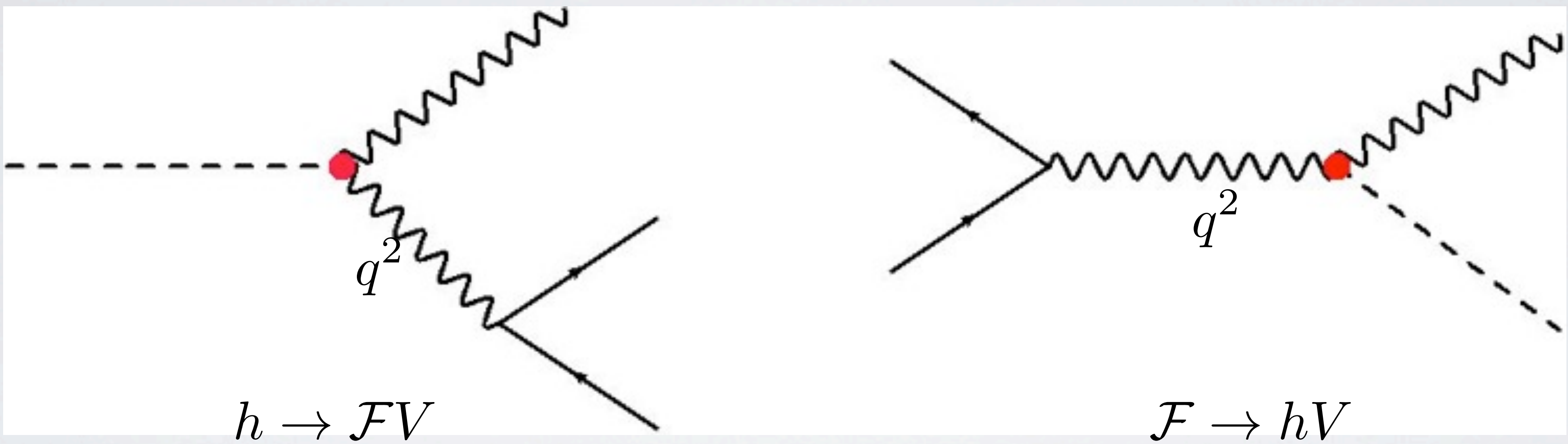
- Can establish what the formalism is by looking for evidence that the linear realization cannot (directly) accommodate the data going forward.

  Discussion on this has (re)started: Grinstein/Trott arXiv:0704.1505, Contino et al arXiv:1303.3876,1309.7038, Manohar, Isidori, Trott arXiv:1305.0663, Isidori Trott arXiv:1307.4051, Brivio et all arXiv:1311.1823.

Test the derivative expansion

- We are not evolving towards characterizing differential pseudo-observables from the data and using them to bound the SMEFT

  Consider the following processes with non-SM interactions involving the "h":



Manohar, Isidori, Trott arXiv:1305.0663, Isidori Trott arXiv:1307.4051

Both of these processes are governed by the same lorentz invariant structures.

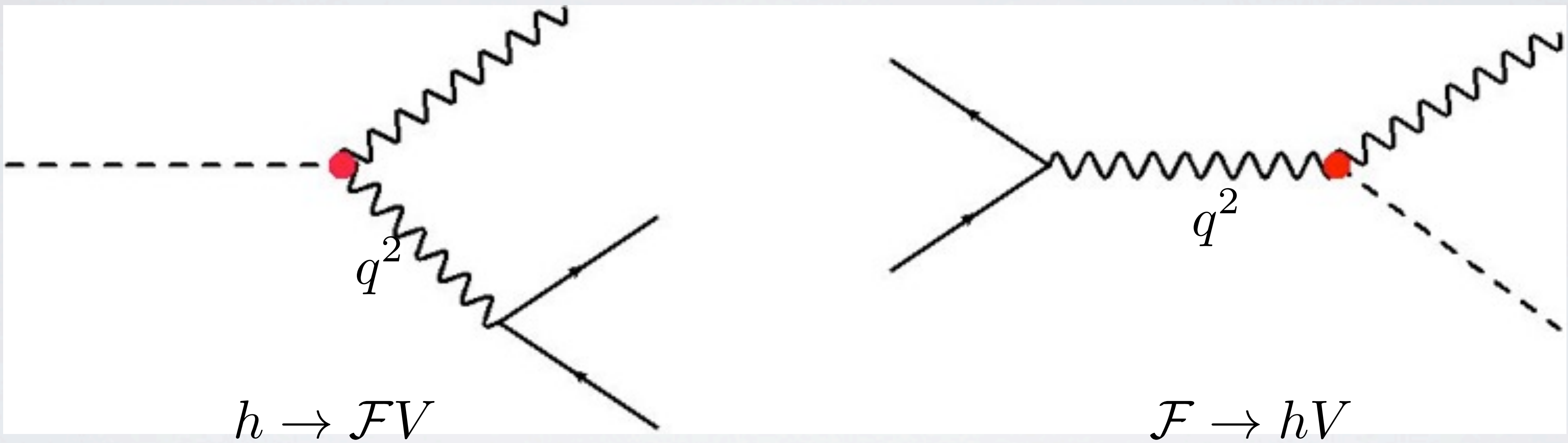
Of course we now know that : $m_h < 2\, m_V$

- hVV just does NOT exist onshell. We probe (approximately) hVF greens functions. So incorporate non-SM effects in EFT into these greens functions.

Test the derivative expansion

- We are not evolving towards characterizing differential pseudo-observables from the data and using them to bound the SMEFT

  Consider the following processes with non-SM interactions involving the "h":



With this current normalization:
$$\mathcal{L}_J^{\rm SM} = \frac{e}{\sqrt{2}\,\sin\theta_W} J_\mu^\pm W_\pm^\mu + \frac{e}{\sin\theta_W \cos\theta_W} J_\mu^0 Z^\mu = \sum_V C_V g_V J_\mu^V V^\mu \, .$$

The F-> hV process is:
$$\mathcal{A}_V^{\mathcal{F}} = \mathcal{A}[h \to V(\tilde{\epsilon}, p)\mathcal{F}(q)] = \frac{C_V g_V^z m_V}{(q^2 - m_V^2)} \tilde{\epsilon}_\mu J_\nu^{\mathcal{F}_V} T_V^{\mu\nu} \, ,$$
$$T_V^{\mu\nu} = \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu + f_3^V(q^2)(p\cdot q \, g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right] \, .$$

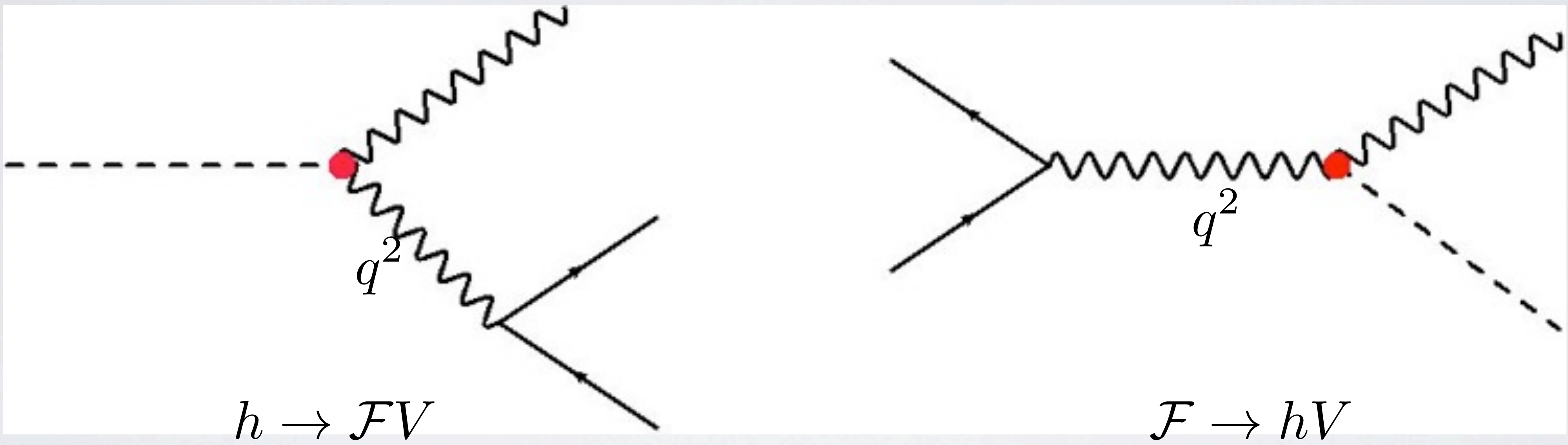
While h-> VF is
$$\mathcal{A}\left[\bar{\psi}\psi(q) \to h\, V(\tilde{\epsilon}, -p)\right] = \mathcal{A}_V^{\psi\bar{\psi}},$$

- Differential form factors are PSEUDO-OBSERVABLES like the signal strengths.

Test the derivative expansion

- We are not evolving towards characterizing differential pseudo-observables from the data and using them to bound the SMEFT

  Consider the following processes with non-SM interactions involving the "h":



Probes the form factors for:

$$\frac{q^2}{m_v^2} \ll 1$$

Short term, this is being constructed by the experimentalists right now.

Probes the form factors for:

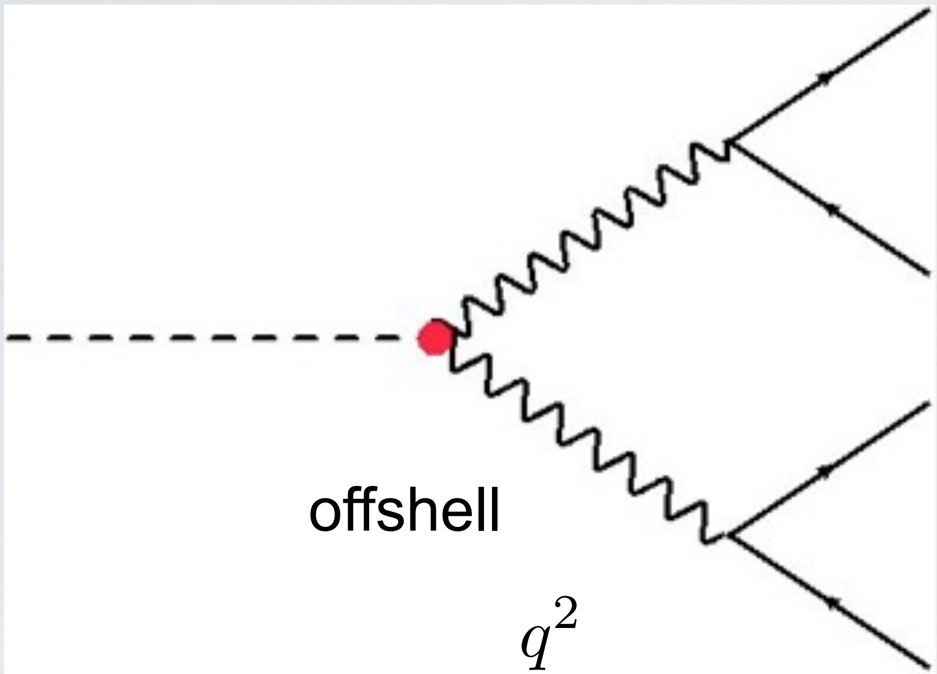
$$\frac{q^2}{m_v^2} \gg 1$$

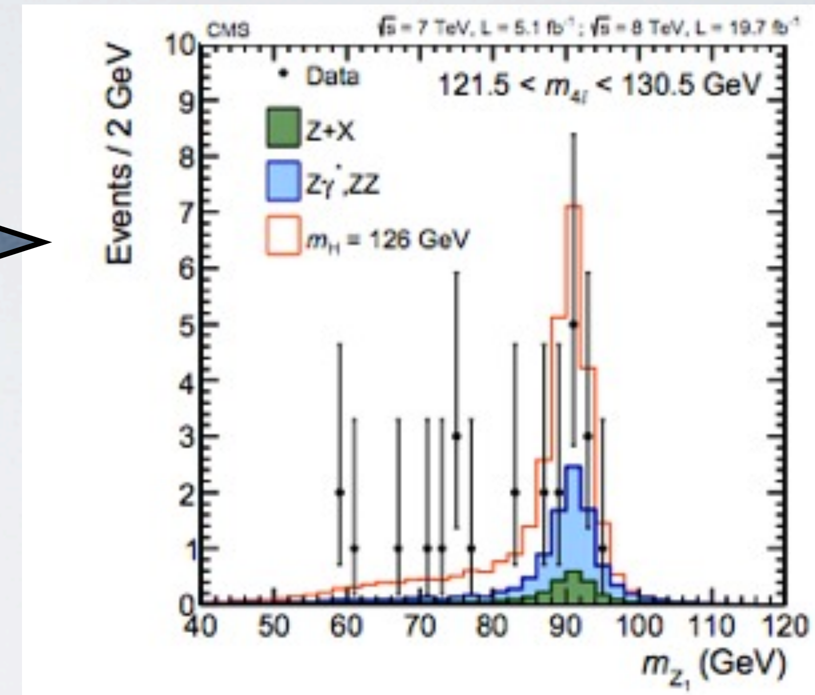
More sensitivity, but also close to EFT expansion failing (also an issue in TGC)

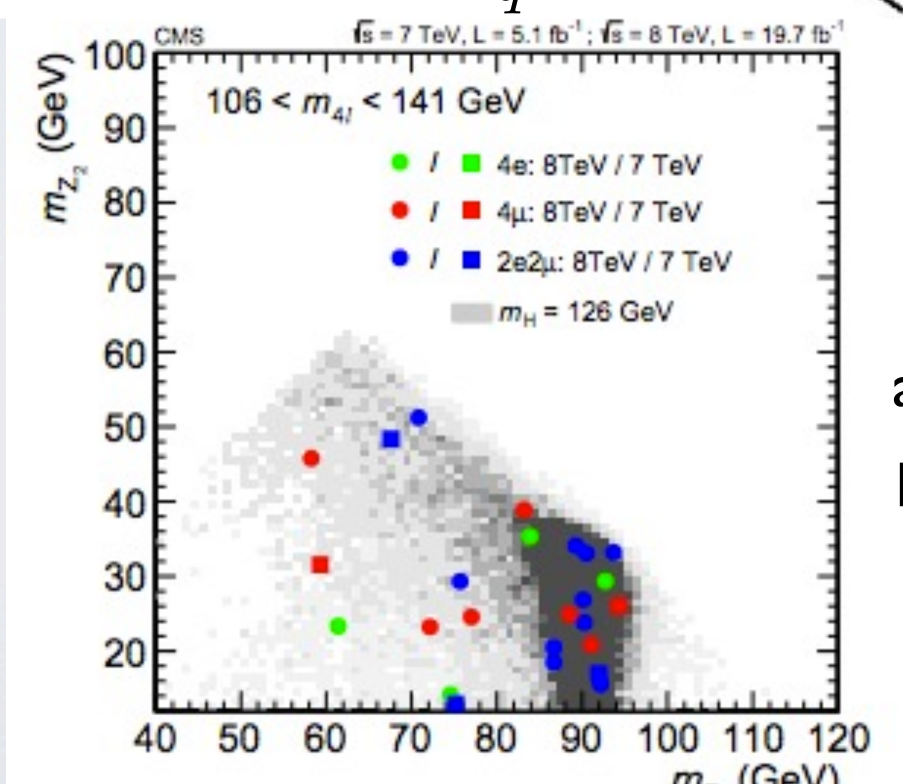
Longer term, need more events.

Establish the EFT in the golden channel

Consider the following processes with non-SM interactions involving the "h":

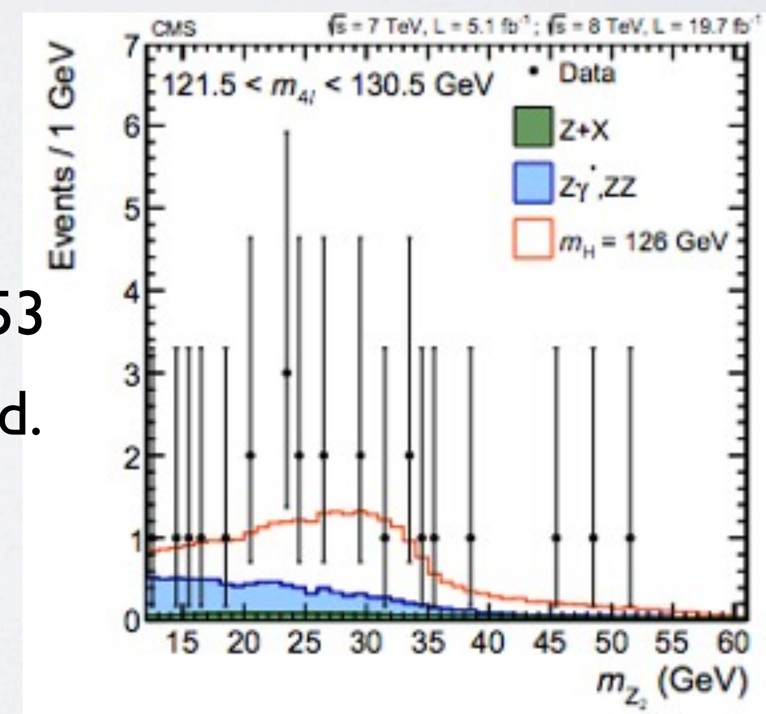




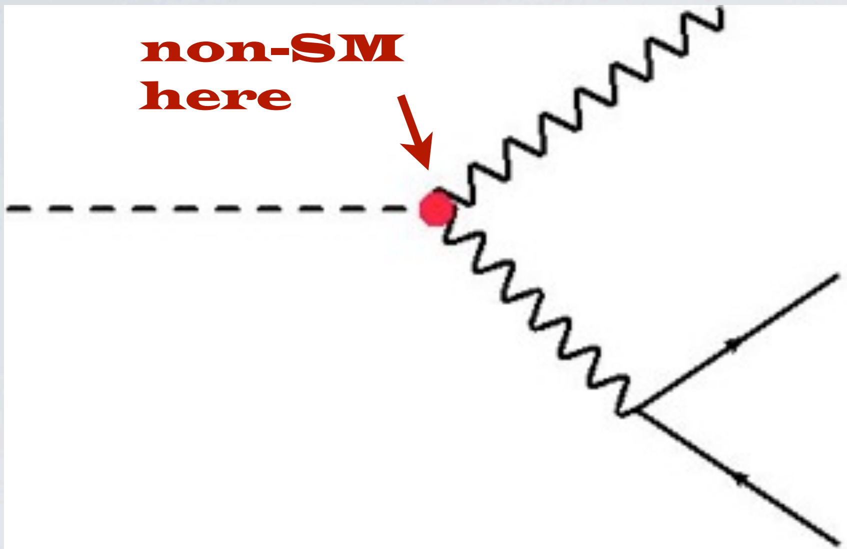


Recent CMS analysis 1312.5353

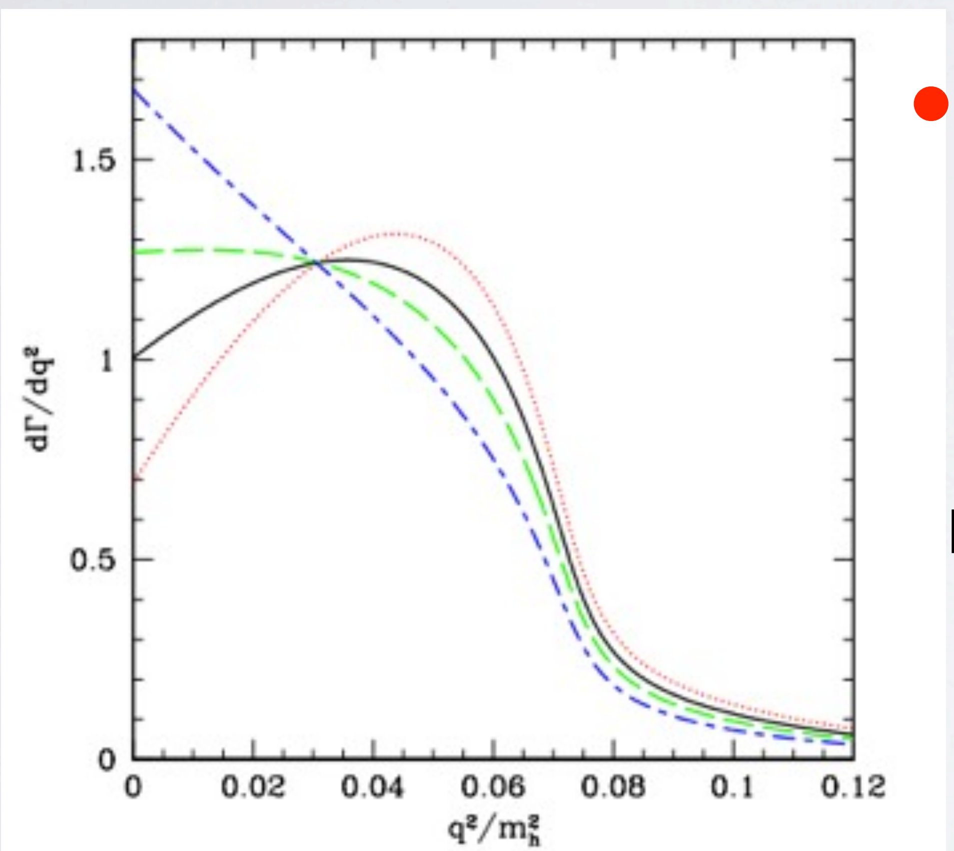
Event rate limited.



Establish the EFT in the golden channel

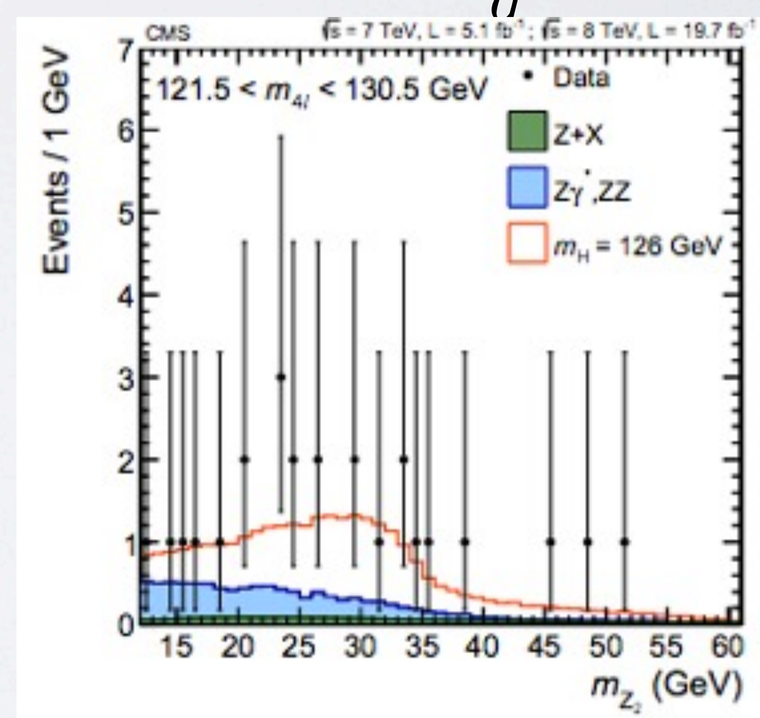


With sufficient data, a tight cut on the reconstructed on shell vector mass, study the 3 body distribution (can then combine vector decay modes)



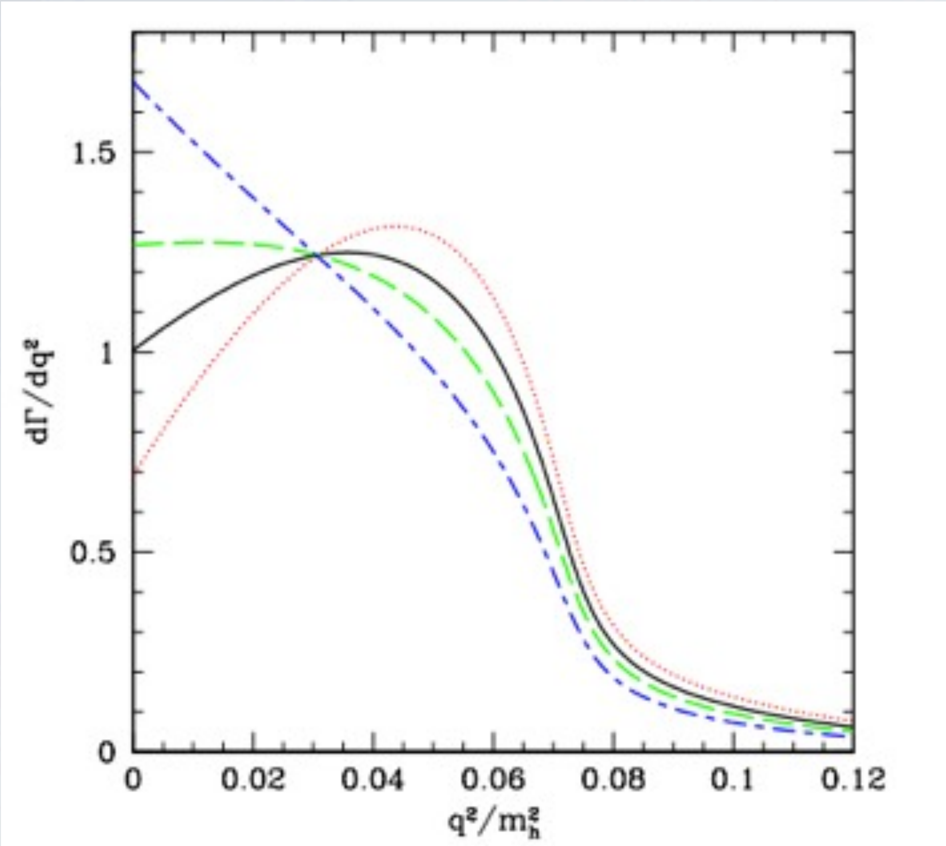
- Total signal strength the same, significant shape variations possible in offshell q^2 spec. (Photon pole neglected here).

Need more data!
But we are going to get it!



Another nice paper on this spec (light states focus)
M Gonzalez-Alonso, G Isidori arXiv:1403.2648.

Establish the EFT in the golden channel



- In the linear realization deviations in this spectra are bounded by higgs processes.

- In the nonlinear realization, when h is just a singlet, the deviations related to greens functions with the h field not related to non h processes (at tree level)

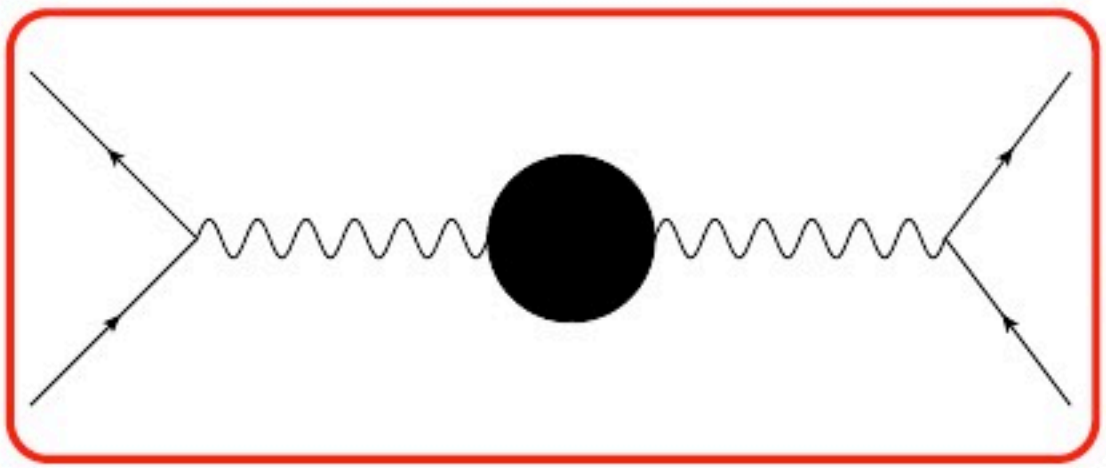
- For this reason, consistency checking any deviations against all other SMEFT constraints a very hot topic.

- Much debate in the literature: See 1308.2803 Pomarol, Riva. 1411.0669 Falkowski, Riva. Isidori Trott arXiv:1307.4051 1409.7605 Trott

If any deviations seen can check consisteny

- In performing such analyses recently some subtleties have appeared.

- Observable directly related to an S matrix element. Relations between observables basis independent.
- Constructed observable related to measurements with defining conditions. Relations involving constructed observables are NOT basis independent -- unless the defining conditions are imposed on the field theory.
- The most well know constructed observable - the S parameter.



Measured observable

If any deviations seen can check consisteny

- In performing such analyses recently some subtleties have appeared.

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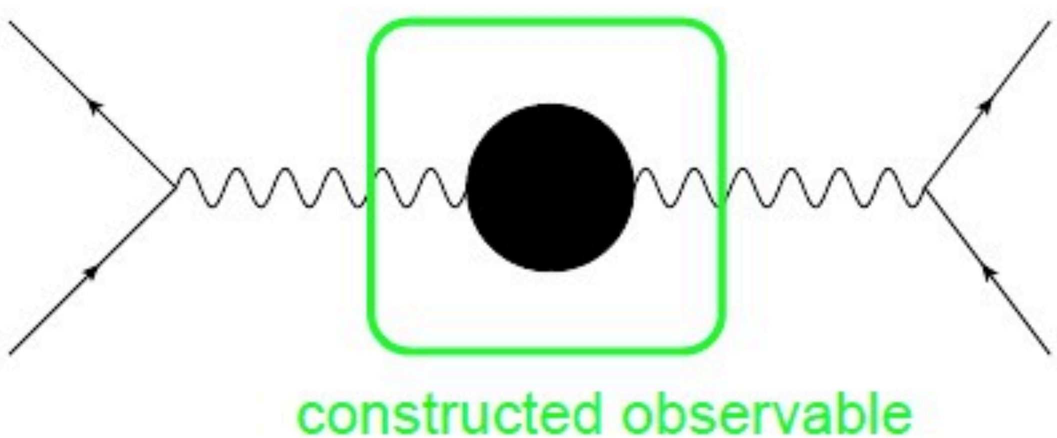


- Defining condition possible vertex corrections PHYSICALLY vanish.

S parameter defining conditions

- In terms of operators

$$Q_{HW} = H^\dagger H\, W^I_{\mu\nu} W_I^{\mu\nu}, \quad Q^{(1)}_{\substack{H\ell \\ pr}} = (H^\dagger i \overleftrightarrow{D}_\mu H)\, \bar{\ell}_p \gamma^\mu \ell_r, \quad Q_{HWB} = H^\dagger \tau_I H\, W^I_{\mu\nu} B^{\mu\nu},$$

$$Q^{(3)}_{\substack{H\ell \\ pr}} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)\, \bar{\ell}_p \tau^I \gamma^\mu \ell_r, \quad Q_{HD} = (H^\dagger D^\mu H)^\star (H^\dagger D_\mu H).$$

- However could also choose a basis:

$$\mathcal{O}_{HW} = -i\, g_2\, (D^\mu H)^\dagger \tau^I (D^\nu H)\, W^I_{\mu\nu}, \qquad \mathcal{O}_{HB} = -i\, g_1\, (D^\mu H)^\dagger (D^\nu H)\, B_{\mu\nu},$$

$$\mathcal{O}_W = -\frac{i\, g_2}{2} (H^\dagger \overleftrightarrow{D}^I_\mu H)(D^\nu W^I_{\mu\nu}), \qquad \mathcal{O}_B = -\frac{i\, g_1}{2} (H^\dagger \overleftrightarrow{D}^\mu H)(D^\nu B_{\mu\nu}),$$

$$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}^\mu H).$$

- Where has the defining condition gone as a constraint on the field theory?

S parameter defining conditions

- Operator relations

$$
\begin{aligned}
g_1\, g_2\, Q_{HWB} &= 4\,\mathcal{O}_B - 4\,\mathcal{O}_{HB} - 2\,\mathsf{y}_H\, g_1^2\, Q_{HB}, \\
g_2^2\, Q_{HW} &= 4\,\mathcal{O}_W - 4\,\mathcal{O}_B - 4\,\mathcal{O}_{HW} + 4\,\mathcal{O}_{HB} + 2\,\mathsf{y}_H\, g_1^2\, Q_{HB}, \\
g_1^2\, \mathsf{y}_\ell\, Q^{(1)}_{\underset{tt}{Hl}} &= 2\,\mathcal{O}_B + \mathsf{y}_H\, g_1^2\, \mathcal{O}_T - g_1^2 \left[\mathsf{y}_e Q_{\underset{rr}{He}} + \mathsf{y}_q Q^{(1)}_{\underset{rr}{Hq}} + \mathsf{y}_u Q_{\underset{rr}{Hu}} + \mathsf{y}_d Q_{\underset{rr}{Hd}}\right], \\
g_2^2\, Q^{(3)}_{\underset{tt}{Hl}} &= 4\,\mathcal{O}_W - 3\, g_2^2\, Q_{H\Box} + 2\, g_2^2 m_h^2\, (H^\dagger\, H)^2 - 8\, g_2^2\, \lambda\, Q_H - g_2^2\, Q^{(3)}_{Hq}, \\
&\quad - 2\, g_2^2 \left([Y_u^\dagger]_{rr} Q_{\underset{rr}{uH}} + [Y_d^\dagger]_{rr} Q_{\underset{rr}{dH}} + [Y_e^\dagger]_{rr} Q_{\underset{rr}{eH}} + h.c.\right).
\end{aligned}
$$

- Consistency in the field theory $\mathcal{L}^{(6)} = \sum_i C_i\, Q_i = \sum_i \mathcal{P}_i\, \mathcal{O}_i.$

$$
\mathcal{P}_B \to \frac{4}{g_1\, g_2} C_{HWB} - \frac{4}{g_2^2} C_{HW} + \frac{2}{g_1^2\, \mathsf{y}_\ell} C^{(1)}_{\underset{tt}{H\ell}}, \qquad \mathcal{P}_W \to \frac{4}{g_2^2} C_{HW} + \frac{4}{g_2^2} C^{(3)}_{\underset{tt}{H\ell}},
$$

$$
\mathcal{P}_{HB} \to -\frac{4}{g_1\, g_2} C_{HWB} + \frac{4}{g_2^2} C_{HW}, \qquad \mathcal{P}_{HW} \to -\frac{4}{g_2^2} C_{HW}.
$$

- Naively use S parameter bound $\mathcal{P}_{HB} = -\mathcal{P}_B \quad \mathcal{P}_{HW} = -\mathcal{P}_W$

S parameter defining conditions

- It (should) go without saying - no preferred operator basis for the oblique parameters

$$S_Q = -\frac{16\,\pi\,v_T^2}{g_1\,g_2}\,C_{HWB}. \qquad\qquad S_{\mathcal{O}} = -4\,\pi\,v_T^2\,(\mathcal{P}_B + \mathcal{P}_W)$$

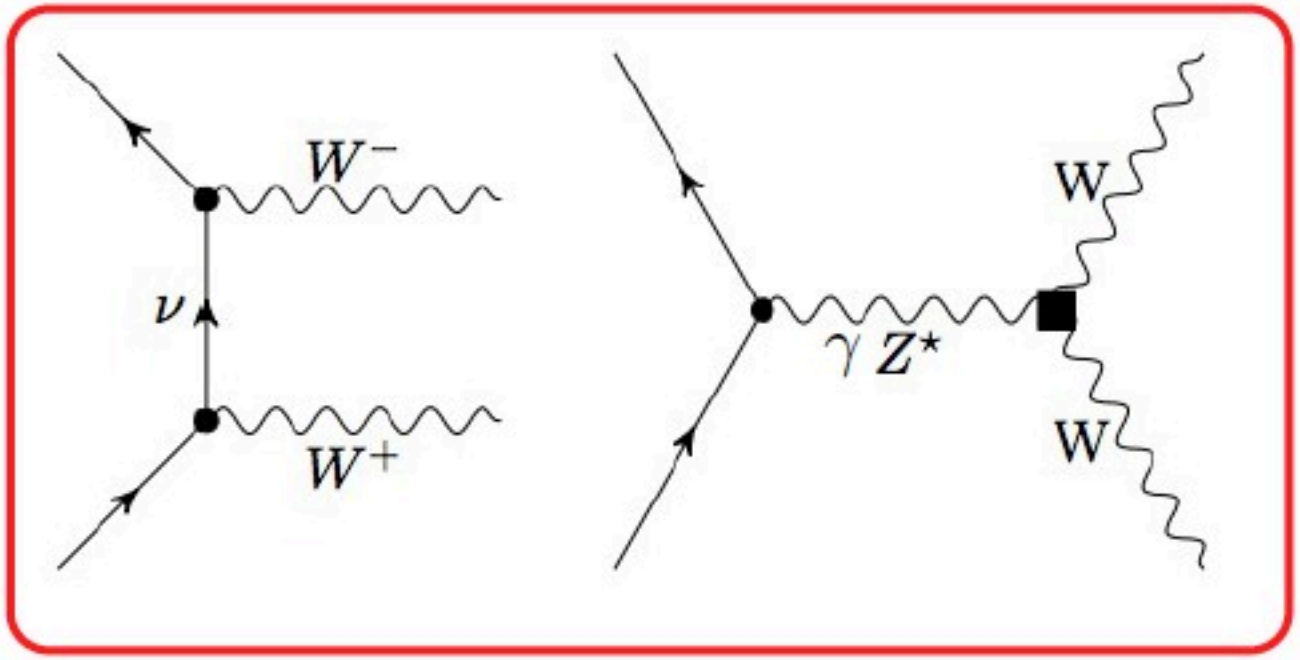
$$-4\pi\,v_T^2\,(\mathcal{P}_B + \mathcal{P}_W) \rightarrow -\frac{16\,\pi\,v_T^2}{g_1\,g_2}\,C_{HWB} - \frac{8\,\pi\,v_T^2}{g_1^2\,\mathsf{y}_\ell}\,C^{(1)}_{\substack{H\ell \\ tt}} - \frac{16\,\pi\,v_T^2}{g_2^2\,\mathsf{y}_\ell}\,C^{(3)}_{\substack{H\ell \\ tt}}$$

hep-ph/0602154, Skiba, Terning et al.
(and others..)

- Does not follow that the EFT is less constrained due to an operator basis choice (obviously) if one is consistent.

Constructed collider observables

- An observable in a collider environment is non trivial. Same lesson holds. Consider TGC bounds:

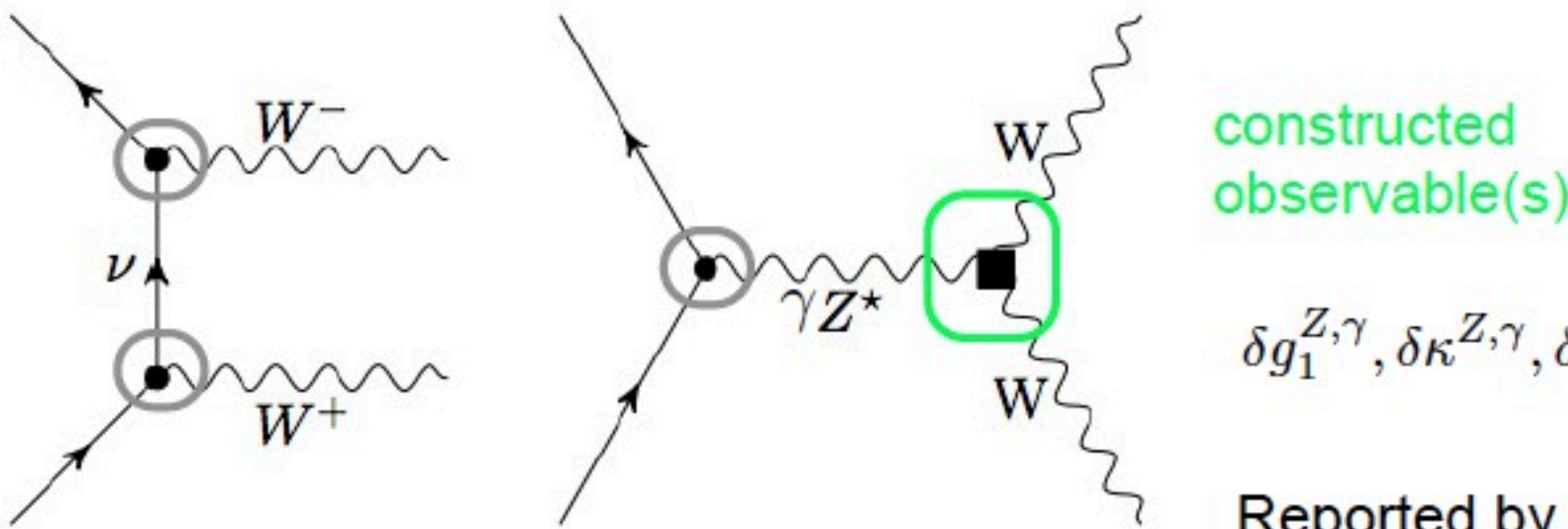


Measured observable(s)

$$\sigma(e^+e^- \to W^+W^-) \quad \frac{d\sigma}{d\Omega}$$

Constructed collider observables

- An observable in a collider environment is non trivial. Same lesson holds. Consider TGC bounds:



$\delta g_1^{Z,\gamma}, \delta\kappa^{Z,\gamma}, \delta\lambda^{Z,\gamma}$

Reported by the LEP experiments! Be careful.

- Defining condition SM like coupling of W,Z to fermions.

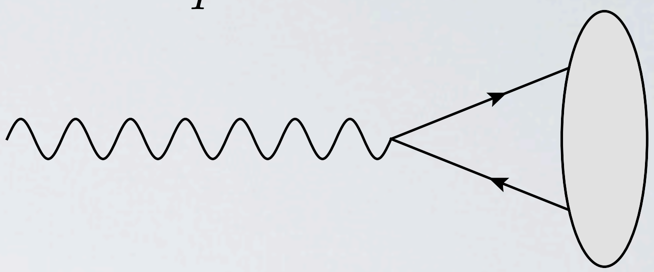
  ◯ physically as in the SM

- Getting this right you find that the relation between TGC and the golden channel vanishes. 1409.7605 Trott

Exclusive decays of the Higgs

Rare pseudo-scalar decays: - then the current is proportional to $J^\mu \propto q^\mu$

Manohar, Isidori, Trott arXiv:1305.0663



This gives access to another combination of form factors:

$$\mathcal{M}_P^{\mu\nu} = \left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{m_V^2}\right) \left|f_1 + q^2 f_2\right|^2 .$$

i.e. another combination of wilson coefficients in the EFT.

These are small Br, but not impossible to find in the future if dedicated studies

$$\frac{\Gamma(h \to VP)}{\Gamma(h \to VP)^{\rm SM}} = \left|c_1 + g_2^2(c_2 + c_3)\right|^2$$

Exclusive decays of the Higgs

- The SM rates of some exclusive modes..

VP mode	$\mathcal{B}^{\rm SM}$	VP^* mode	$\mathcal{B}^{\rm SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	0.4×10^{-5}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	0.4×10^{-5}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.4×10^{-5}

TABLE I: SM branching ratios for selected $h \to VP$ and $h \to VP^*$ decays.

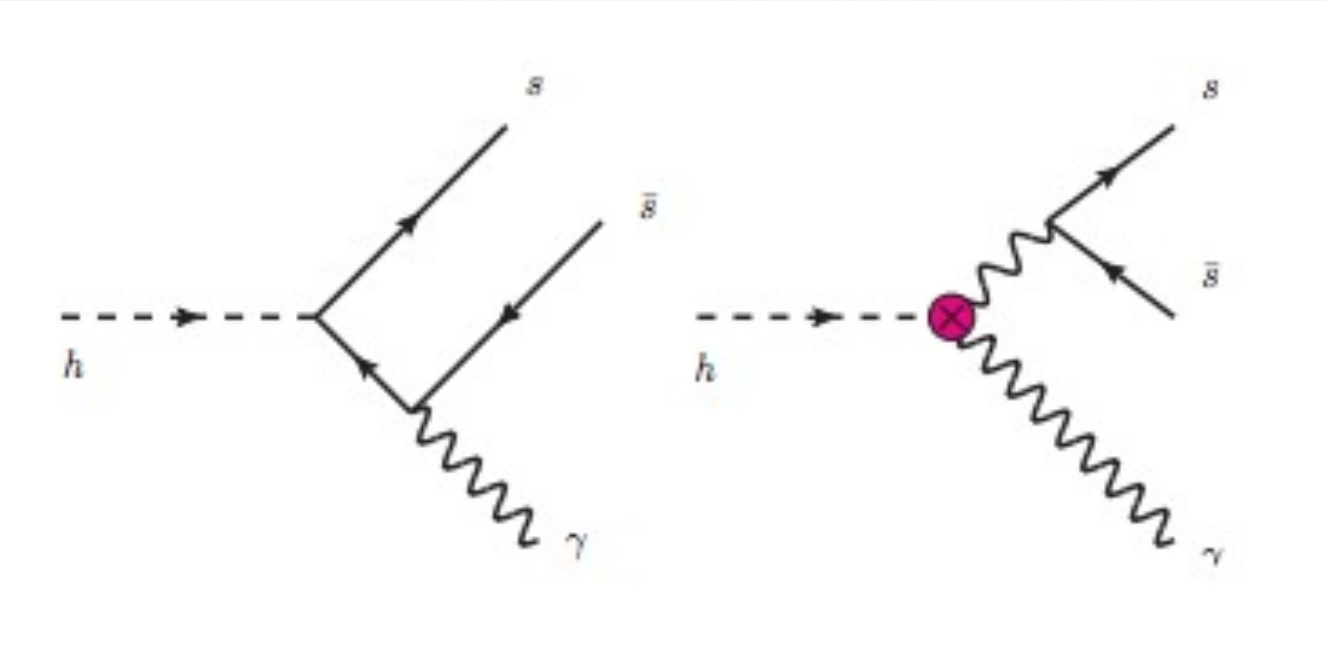
- Now a hot topic since we pointed this out 1305.0663 Isidori, Manohar, Trott

1410.7475 Mangano, Melia, 1406.1722 Kagan et al.

Exclusive decays of the Higgs

- Part of the reason this is a hot area is due to the potential to extract couplings of the higgs to light quarks

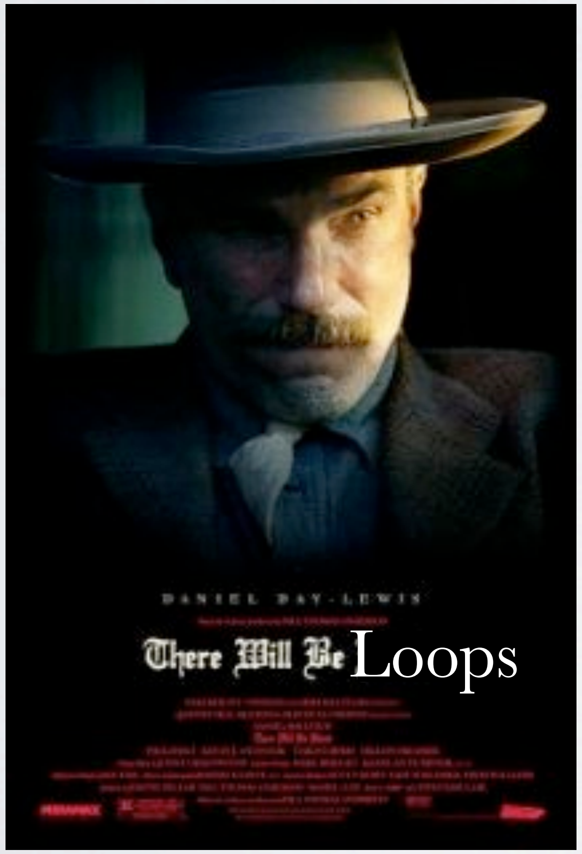
1306.5770 Bodwin, Petriello, Stoynev, Velasco
1406.1722 Kagan et al.



- Lesson - always get all the leading tree level diagrams!

- Going forward we want every drop of information we can get form the experiments projected onto the SMEFT in a consistent fashion.

Systematics of the SMEFT



- and a heck of alot of operators....
  But lets leave that to the next session.

What is the theory?

- (Probably) our lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \cdots$
- 1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek
  operator basis FULLY reduced by SM EOM.

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

6 gauge dual ops

28 non dual operators

25 four fermi ops

59 + h.c. operators

NOTATION:

$\widetilde X_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$

$\widetilde\varphi^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$

$\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$

$\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I\right)\varphi$

What is the theory?

- Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

- Initial work in the 80's: Leung,Love, Rao 1984, Buchmuller Wyler 1986

over 20 years?!
700 citations?
...for shame...

Timelines of developments.

(Probably) our Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \cdots$

- Timeline a bit interesting:

Glashow 1961, Weinberg 1967 (Salam 1967)

Weinberg 1977

Leung, Love, Rao 1984, Buchmuller Wyler 1986,
Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

Weinberg 1979

Lehman 2014 (student at Notre Dame)

arXiv:1410.4193 L. Lehman

Timelines of developments.

(Probably) our Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \cdots$

- Running timeline:

(red circle) 1973 Wilczek, Gross, Politzer, Many others remaining SM terms (**Khriplovich 69, t'hooft 72)**

(blue circle) Babu, Leung, Pantaleone (complete) 1993 + many others for partial

(green circle) Alonso, Jenkins, Manohar, Trott (complete) 2013, + many others for partials

(cyan circle) Alonso, Chiang, Jenkins, Manohar, Shotwell (complete) 2014 + many others for partials

(black circle) somebody is working on it somewhere...

Can actually treat this as a real EFT.

- Complexity is scaling up:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \cdots$$

14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

1 operator, and 7 extra parameters

59 + h.c operators, or 2499 parameters (or 76 with flavour symmetry)

Alonso,Jenkins,Manohar
Trott arXiv:1312.2014

4 operators, or 408 parameters (all violate B number)

arXiv:1405.0486 Alonso, Cheng, Jenkins, Manohar, Shotwell

20 operators, (all violate L number, 7 violate B number) arXiv:1410.4193 L. Lehman

Don’t use a redundant basis!

- A redundant operator basis is a basis that has not been full reduced by the SM EOM to a minimal set of operators.

  - 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek
    operator basis FULLY reduced by SM EOM. No Redundant operators here.

  <u>Why are redundant operators a bad idea?</u>

  They lead to massive confusion in some quarters. Mistakes abound.

  You have completely calculate S matrix elements, and use the EOM on the result. Only then will the unphysical redundant parameters drop out.

  Anomalous dimension calculations in a redundant operator basis are GAUGE and SCHEME dependent.

  - USE ANY (complete, well defined) BASIS YOU WANT.
    But best to not have a redundant one.

old problem, see:
hep-ph/9708306 Bauer, Manohar
hep-ph/0109117 Pineta

What is the plan?

- So what do we do? We try and prove which formalism is correct - TOUGH!
  And we systematically develop these theories to interpret and discovered deviations in the future.

What does any deviation mean in terms of the underlying theory?

- In the lack of any directly discovered new states - there is no other option!
  (Other than switching to cosmology/DM.)
- Recall the NSUSY case:

Consider a minimal natural SUSY.

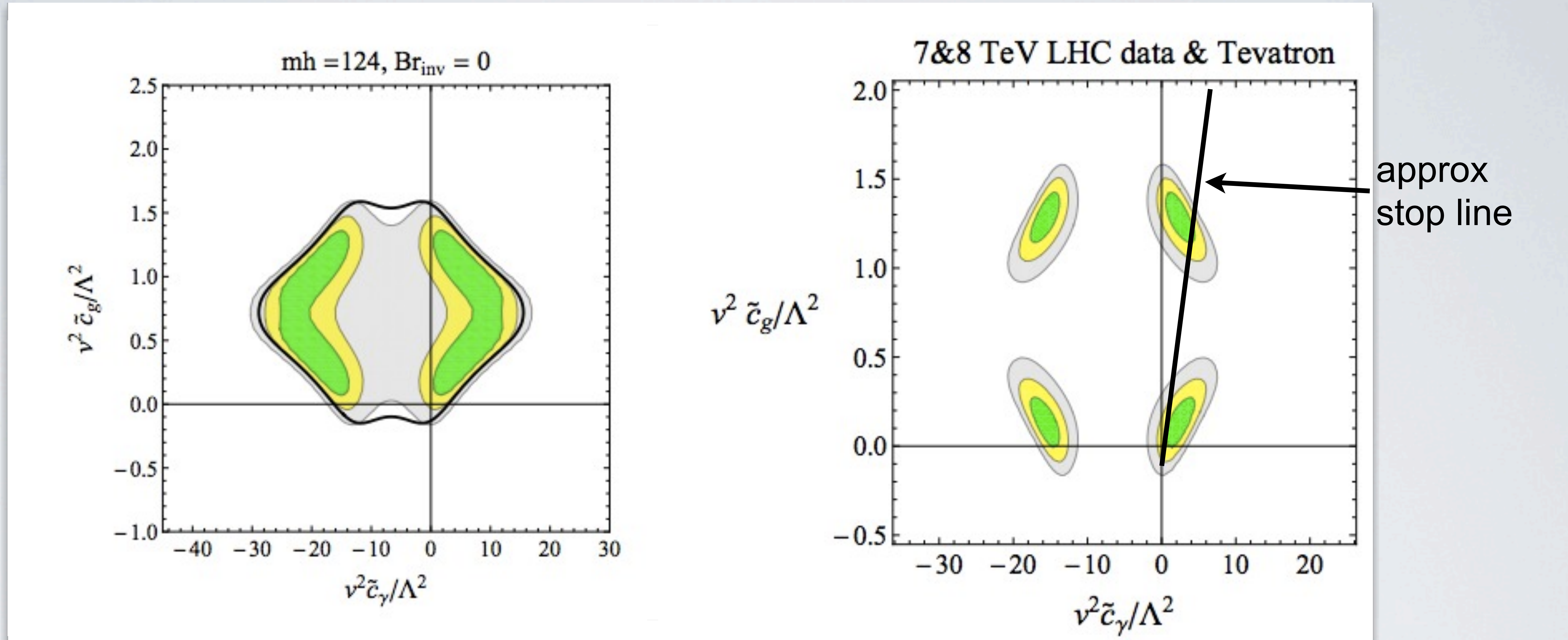
Field	Spin	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$\tilde{Q}_L = (\tilde{t}_L, \tilde{b}_L)$	0	$(\mathbf{3}, \mathbf{2}, 1/6)$
$\tilde{t}^*_R$	0	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
$H_u = (H_u^+, H_u^0)$	0	$(\mathbf{1}, \mathbf{2}, +1/2)$
$H_d = (H_d^0, H_d^-)$	0	$(\mathbf{1}, \mathbf{2}, -1/2)$
$\tilde{H}_u = (\tilde{H}_u^+, \tilde{H}_u^0)$	1/2	$(\mathbf{1}, \mathbf{2}, +1/2)$
$\tilde{H}_d = (\tilde{H}_d^0, \tilde{H}_d^-)$	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$
$\tilde{g}$	1/2	$(\mathbf{8}, \mathbf{1}, 0)$

$$\sigma_{gg\to h} \approx \sigma^{SM}_{gg\to h}\left|1 + \frac{2}{F_g^{SM}}\frac{v^2\,\tilde{c}_g}{\Lambda^2}\right|^2, \quad \Gamma_{h\to\gamma\gamma} \approx \Gamma^{SM}_{h\to\gamma\gamma}\left|1 + \frac{1}{F_\gamma^{SM}}\frac{v^2\,\tilde{c}_\gamma}{\Lambda^2}\right|^2.$$

$$\frac{v^2\,\tilde{c}_g}{\Lambda^2} \simeq C_g(\alpha_s)\,\frac{F_g}{2}, \qquad \frac{v^2\,\tilde{c}_\gamma}{\Lambda^2} \simeq N_c\,Q_{\tilde{t}}^2\,C_\gamma(\alpha_s)\,F_g$$

$$C_g(\alpha_s) = 1 + \frac{25\,\alpha_s}{6\,\pi}, \qquad C_\gamma(\alpha_s) = 1 + \frac{8\,\alpha_s}{3\,\pi}.$$

What about models?



- Rapidly this parameter space has been (and will be) resolved in the future. This is also why we need to develop the SMEFT.
- Line is matching without running. The corrections already matter, need to systematically improve for models too.

$$\frac{\tilde{c}_g}{\tilde{c}_\gamma} = \frac{1}{2N_c Q_{\tilde{t}}^2} \frac{C_g(\alpha_s)}{C_\gamma(\alpha_s)} = \frac{3}{8}\left(1 + \frac{3\,\alpha_s}{2\,\pi}\right)$$

If we find a pattern of deviations

- What about the mixing? The matching perturbative correction is already important!
- Adding extra operators to the SM, generalizes the SM predictions.
- But it is not trivial. This violently changes the UV divergence structure of the theory.
  A different field theory that has to reproduce the IR of the UV theory if we are serious.

Effective Theory:

$$\mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_i c.t.$$

Renormalize it.

MUST reproduce the IR of the full theory.

Need all effects of order:

$$\frac{g^2}{16\,\pi^2}\,\frac{v^2}{\Lambda^2}$$

Run the ops.

As we don't see other NP effects at low scales

LHC run 1

Matching

Full Theory:

$$\mathcal{L}_{SM} + \mathcal{L}_{please\,exist} + \sum_i c.t.$$

Renormalize it.

Michael Trott, Niels Bohr Institute, Nov 25th 2014

Linear EFT renormalization program.

Why else should you renormalize?

- impress our (non german, non russian) friends, 100s of diagrams, 59 operators,EOM subtleties. 2499x2499 matrix that depends on

$$\frac{1}{16\pi^2} \times \{1, g^2, \lambda, y^2, g^4, g^2\lambda, g^2y^2, \lambda^2, \lambda y^2, y^4, g^6, g^4\lambda, g^6\lambda\}$$

- required to precisely understand measurements at different scales if the SM is an EFT (and it is)

$$c_i(m_h) = \left(\delta_{ij} - \gamma_{ij} \log\left(\frac{\Lambda}{m_h}\right)\right) c_j(\Lambda)$$

- Loop corrections in SM EFT. Need to include all

$$\frac{1}{16\pi^2} \times \{1, g^2, \lambda, y^2, g^4, g^2\lambda, g^2y^2, \lambda^2, \lambda y^2, y^4, g^6, g^4\lambda, g^6\lambda\}$$

corrections to precisely compare to data as well. RGE is a guide to the loops.

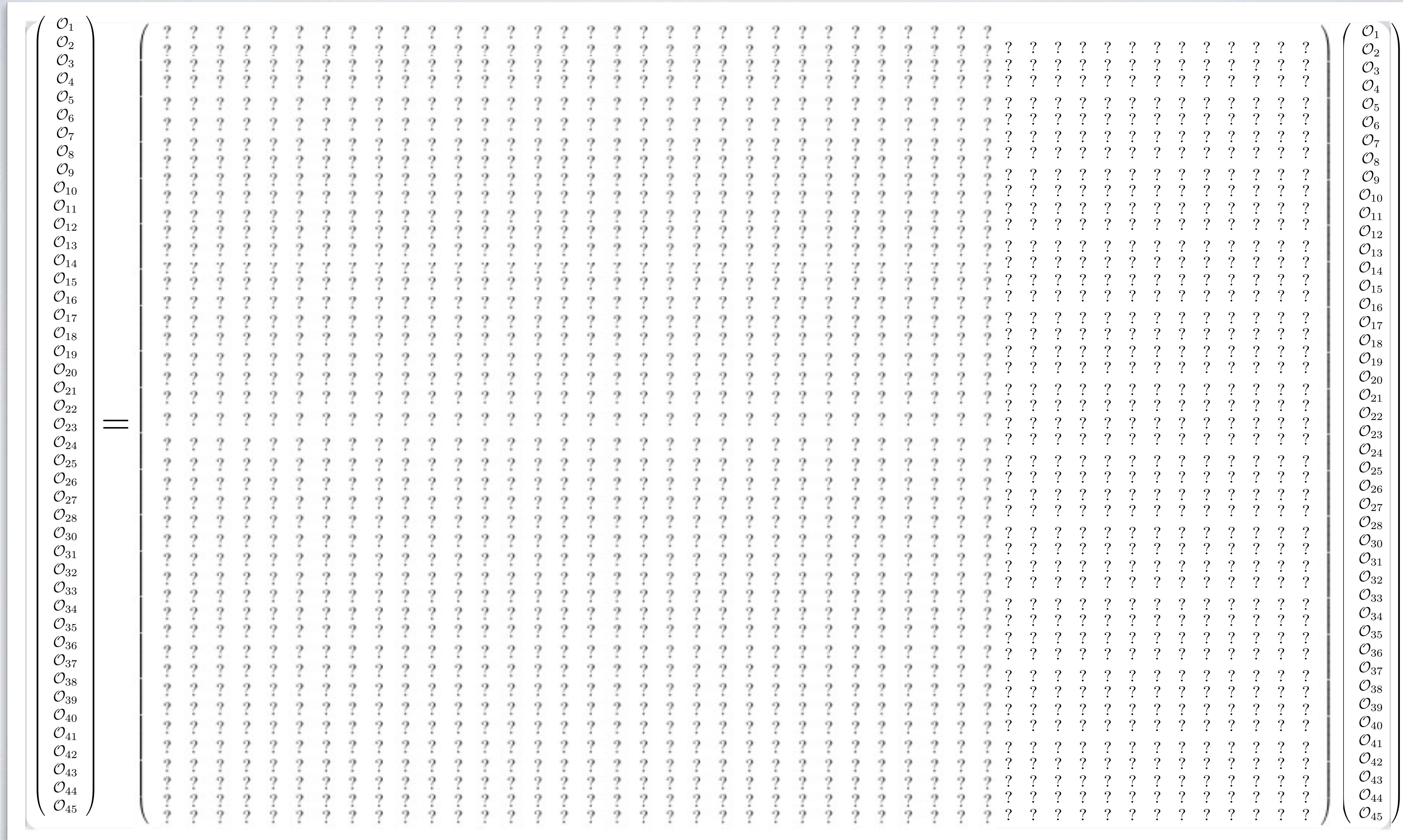
- If Basis is wrong, renormalization can uncover a problem. Good check of formalism.

1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek got it right!

Linear EFT renormalization program.

Why should you not renormalize?

Interesting fact, Latexit will not even display a 59x59 dim matrix. Here is a 45x45 one:



It is the SMEFT not Higgs EFT.

- It does not really make sense to think of just RGE improving a sector like "the Higgs sector". We need the whole RGE evolution.

Consider the SM equations of motion:

Higgs:

$$D^2 H_k - \lambda v^2 H_k + 2\lambda (H^\dagger H) H_k + \overline{q}^j \, Y_u^\dagger \, u \epsilon_{jk} + \overline{d} \, Y_d \, q_k + \overline{e} \, Y_e \, l_k = 0$$

Gauge field:

$$i\not{D}\, q_j = Y_u^\dagger \, u \, \widetilde{H}_j + Y_d^\dagger \, d \, H_j \,, \qquad i\not{D}\, d = Y_d \, q_j \, H^{\dagger j} \,, \qquad i\not{D}\, u = Y_u \, q_j \, \widetilde{H}^{\dagger j}$$

$$i\not{D}\, l_j = Y_e^\dagger \, e H_j \,, \qquad i\not{D}\, e = Y_e \, l_j H^{\dagger j} \,,$$

Fermion:

$$[D^\alpha, G_{\alpha\beta}]^A = g_3 j_\beta^A, \qquad [D^\alpha, W_{\alpha\beta}]^I = g_2 j_\beta^I, \qquad D^\alpha B_{\alpha\beta} = g_1 j_\beta,$$

$$j_\beta^A = \sum_{\psi = u,d,q} \overline{\psi} T^A \gamma_\beta \psi \,,$$

$$j_\beta^I = \frac{1}{2} \overline{q} \, \tau^I \gamma_\beta q + \frac{1}{2} \overline{l} \, \tau^I \gamma_\beta l + \frac{1}{2} H^\dagger \, i \overleftrightarrow{D}_\beta^I H \,,$$

$$j_\beta = \sum_{\psi = u,d,q,e,l} \overline{\psi} \, \mathsf{y}_i \gamma_\beta \psi + \frac{1}{2} H^\dagger \, i \overleftrightarrow{D}_\beta H \,,$$

- I used to say Higgs EFT all the time. No longer!

EOM effects essential in RGE

- The EOM have been used EXTENSIVELY in reducing the basis to 59 operators.
  Our intuition does not accommodate that, but it is a fact.
  Here is one way this non-intuitive physics shows up.

You renormalize and obtain a divergence, for example

(People met this in flavour physics Gilman-Wise Phys.Rev. D20 (1979) 2392)

$$E_{H\Box} = [H^\dagger H][H^\dagger (D^2 H) + (D^2 H^\dagger) H]$$

This operator form is not retained in the basis, so remove it:

$$\mathcal{L}_{SM} + \frac{c}{\Lambda^2} E_{H\Box} \to \mathcal{L}_{SM} + \frac{c}{\Lambda^2} \tilde{E}_{H\Box} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

via field redefinition

$$H \to H + \frac{c}{\Lambda^2}(H^\dagger H) H$$

$$\tilde{E}_{H\Box} = 2\lambda v^2 (H^\dagger H)^2 - 4\lambda Q_H - \left([Y_u^\dagger]_{rs} \, Q_{\substack{uH \\ rs}} + [Y_d^\dagger]_{rs} \, Q_{\substack{dH \\ rs}} + [Y_e^\dagger]_{rs} \, Q_{\substack{eH \\ rs}} + \text{h.c.}\right)$$

- An operator O_1 can mix with an operator O_2 when

NO 1PI diagram exists that corresponds to the mixing.

EOM terms essential

- Contributions to the giant anom dim matrix, via possible EOM terms:

		g^3X^3 1	H^6 2	H^4D^2 3	$g^2X^2H^2$ 4	$y\psi^2H^3$ 5	$gy\psi^2XH$ 6	ψ^2H^2D 7	ψ^4 8
g^3X^3	1	0	0	0	1	0	0	0	0
H^6	2	$g^6\lambda$	0	$g^2\lambda, \lambda^2$	λg^4	λy^2	0	$\lambda g^2, \lambda y^2$	0
H^4D^2	3	g^6	0	g^2	g^4	0	g^2y^2	g^2	0
$g^2X^2H^2$	4	g^4	0	0	0	0	0	0	0
$y\psi^2H^3$	5	g^6	0	g^2, λ, y^2	g^4	y^2	$g^2\lambda, g^2y^2$	g^2, λ, y^2	λ, y^2
$gy\psi^2XH$	6	g^4	0	0	0	0	g^2, y^2	1	1
ψ^2H^2D	7	g^6	0	g^2	g^4	0	g^2y^2	g^2, y^2	g^2, y^2
ψ^4	8	g^6	0	0	0	0	g^2y^2	g^2, y^2	g^2, y^2

- No direct 1PI diagram. Why are these contributions here?

  Mathematical consistency with field redefinitions to remove redundancy.
  The EFT reproduces the S matrix in some momentum regime of validity.
  The S matrix does not only correspond to 1PI diagrams.

All terms combined

- Contributions to the giant anom dim matrix, via direct 1PI diagrams:

		g^3X^3	H^6	H^4D^2	$g^2X^2H^2$	$y\psi^2H^3$	$gy\psi^2XH$	ψ^2H^2D	ψ^4
		1	2	3	4	5	6	7	8
g^3X^3	1	g^2	0	0	1	0	0	0	0
H^6	2	0	λ, g^2	$g^4, g^2\lambda, \lambda^2$	$g^6, g^4\lambda$	y^4	0	y^4	0
H^4D^2	3	0	0	g^2, λ	g^4	y^2	0	y^2	0
$g^2X^2H^2$	4	g^4	0	1	g^2, λ	0	y^2	1	0
$y\psi^2H^3$	5	0	0	g^2, y^2	g^4	g^2, λ, y^2	$g^2\lambda, g^4, g^2y^2$	g^2, λ, y^2	y^2
$gy\psi^2XH$	6	g^4	0	0	g^2	1	g^2, y^2	1	1
ψ^2H^2D	7	0	0	y^2	g^4	y^2	g^2y^2	g^2, λ, y^2	y^2
ψ^4	8	0	0	0	0	0	g^2y^2	y^2	g^2, y^2

- These are “possible” entries in that you can draw a one loop diagram
- The EOM terms and IPI terms combine in a non trivial way to close the op basis at one loop in the RGE

NDA explains some structure

		g^3X^3	H^6	H^4D^2	$g^2X^2H^2$	$y\psi^2H^3$	$gy\psi^2XH$	ψ^2H^2D	ψ^4
		1	2	3	4	5	6	7	8
g^3X^3	1	g^2	0	0	1	0	0	0	0
H^6	2	$g^6\lambda$	λ, g^2, y^2	$g^4, g^2\lambda, \lambda^2$	$g^6, g^4\lambda$	$\lambda y^2, y^4$	0	$\lambda y^2, y^4$	0
H^4D^2	3	g^6	0	g^2, λ, y^2	g^4	y^2	g^2y^2	g^2, y^2	0
$g^2X^2H^2$	4	g^4	0	1	g^2, λ, y^2	0	y^2	1	0
$y\psi^2H^3$	5	g^6	0	g^2, λ, y^2	g^4	g^2, λ, y^2	$g^2\lambda, g^4, g^2y^2$	g^2, λ, y^2	λ, y^2
$gy\psi^2XH$	6	g^4	0	0	g^2	1	g^2, y^2	1	1
ψ^2H^2D	7	g^6	0	g^2, y^2	g^4	y^2	g^2y^2	g^2, λ, y^2	y^2
ψ^4	8	g^6	0	0	0	0	g^2y^2	g^2, y^2	g^2, y^2

Combined results. This pattern in an arbitrary EFT is now better understood.

Normalize ops using NDA: $f^2\Lambda^2 \left(\frac{\phi}{f}\right)^A \left(\frac{\psi}{f\sqrt{\Lambda}}\right)^B \left(\frac{gX}{\Lambda^2}\right)^C \left(\frac{D}{\Lambda}\right)^D$

Entries follow the rule: $\left(\frac{g^2}{16\pi^2}\right)^{n_g} \left(\frac{y^2}{16\pi^2}\right)^{n_y} \left(\frac{\lambda}{16\pi^2}\right)^{n_\lambda}, \quad N = n_g + n_y + n_\lambda$

Where: $N = L + w - \sum_k w_k \equiv L + \Delta.$

Jenkins, Manohar, Trott arXiv: 1309.0819
(nice follow up) Buchalla et al. arXiv: 1312.5624

The ω is the power of f^2 in the operator normalization.

Terms that have to vanish

w	operators
2	H^6
1	$H^4D^2,\ y\psi^2H^3,\ \psi^2H^2D,\ \psi^4$
0	$g^2X^2H^2,\ gy\psi^2XH$
-1	g^3X^3

$$\begin{array}{c} \\ \{2\} \\ \{3,5,7,8\} \\ \{4,6\} \\ \{1\} \end{array} \begin{array}{c} \{2\} \quad \{3,5,7,8\} \quad \{4,6\} \quad \{1\} \\ \begin{pmatrix} 1 & 2 & 3 & 4 \\ 0 & 1 & 2 & 3 \\ -1 & 0 & 1 & 2 \\ -2 & -1 & 0 & 1 \end{pmatrix} \end{array}$$

Have to vanish in anom dim.

- Anomalous dimensions cannot have inverse powers of couplings (provided no couplings are included in the operator normalization).
- Alternate suggestions for structure of the anomalous dimension matrix, based on “minimal coupling” and some “no tree-loop” mixing rule.

arXiv:1302.5661 Elias-Miro, Espinosa, Masso, Pomarol

Results of full calculation

- Can check against full result now known:

	H^6	H^4D^2	$y\psi^2H^3$	ψ^2H^2D	ψ^4	$g^2X^2H^2$	$gy\psi^2XH$	g^3X^3
Class	2	3	5	7	8	4	6	1
NDA Weight	2	1	1	1	1	0	0	-1
H^6	λ, y^2, g^2	$\lambda^2, \lambda g^2, g^4$	$\lambda y^2, y^4$	$\lambda y^2, \lambda g^2$, ~~y^4~~	0	$\lambda g^4, g^6$	0	~~λg^6~~
H^4D^2	0	λ, y^2, g^2	~~y^2~~	y^2, g^2	0	~~g^4~~	~~y^2g^2~~	~~g^6~~
$y\psi^2H^3$	0	λ, y^2, g^2	λ, y^2, g^2	λ, y^2, g^2	λ, y^2	g^4	~~$g^2\lambda$~~, g^4, g^2y^2	~~g^6~~
ψ^2H^2D	0	g^2, y^2	~~y^2~~	g^2, ~~λ~~, y^2	g^2, y^2	~~g^4~~	~~g^2y^2~~	~~g^6~~
ψ^4	0	0	0	g^2, y^2	g^2, y^2	0	g^2y^2	~~g^6~~
$g^2X^2H^2$	0	~~1~~	0	~~1~~	0	λ, y^2, g^2	y^2	g^4
$gy\psi^2XH$	0	0	~~1~~	~~1~~	1	g^2	g^2, y^2	g^4
g^3X^3	0	0	0	0	0	~~1~~	0	g^2

- Crossed hatched entries vanish despite naive degree of divergence, or through cancelations

Blue is explicit one loop “tree-loop” mixing even in weakly coupled renormalizable UV theories

“No tree loop mixing” is just wrong.

- NDA offers an explanation as to why some terms have to vanish at a loop order, but does not explain an accidental vanishing that can still occur if NDA allowed.

- ”No Tree-loop” mixing does not work to understand the anomalous dimension matrix.

  Here is the explicit example:

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} C_{\underset{pr}{eB}} = \frac{1}{16\pi^2}\left[4 g_1 N_c \left(\mathsf{y}_u + \mathsf{y}_q\right) C^{(3)}_{\underset{prst}{lequ}} [Y_u]_{ts}\right] + \ldots$$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} C_{\underset{pr}{eW}} = \frac{1}{16\pi^2}\left[-2 g_2 N_c C^{(3)}_{\underset{prst}{lequ}} [Y_u]_{ts}\right] + \ldots$$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} C_{\underset{pr}{uB}} = \frac{1}{16\pi^2}\left[4 g_1 \left(\mathsf{y}_e + \mathsf{y}_l\right) C^{(3)}_{\underset{stpr}{lequ}} [Y_e]_{ts}\right] + \ldots$$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} C_{\underset{pr}{uW}} = \frac{1}{16\pi^2}\left[-2 g_2 C^{(3)}_{\underset{stpr}{lequ}} [Y_e]_{ts}\right] + \ldots ,$$

  Can be generated by (3,2,7/6) scalars. Even for weakly coupled renormalizable theories, this is the case at one loop.

- Recent interesting suggestion is that holomorphy is approximately respected at one loop. See Alonso, Jenkins and Manohar hep/1409.0868
  However, it is not exact, yukawas violate this scheme at one loop as well.

Tree and loop operator classification

- IF underlying theory is weakly coupled and renormalizable can classify operators based on “tree” or “loop” integrating out of BSM particles -Artz Einhorn Wudka 93. In some basis choices, operators with field strengths can be considered “loop”. Tree and loop operators mix at one loop even so. This also happens in the SM.

- Attempts to generalize this thinking to strongly coupled non-renormalizable UV theories used “minimal coupling” at an operator level in EFT, and made very strong and general claims. This is the SILH: hep-ph/0703164 Giudice, Grojean, Pomarol, Rattazzi

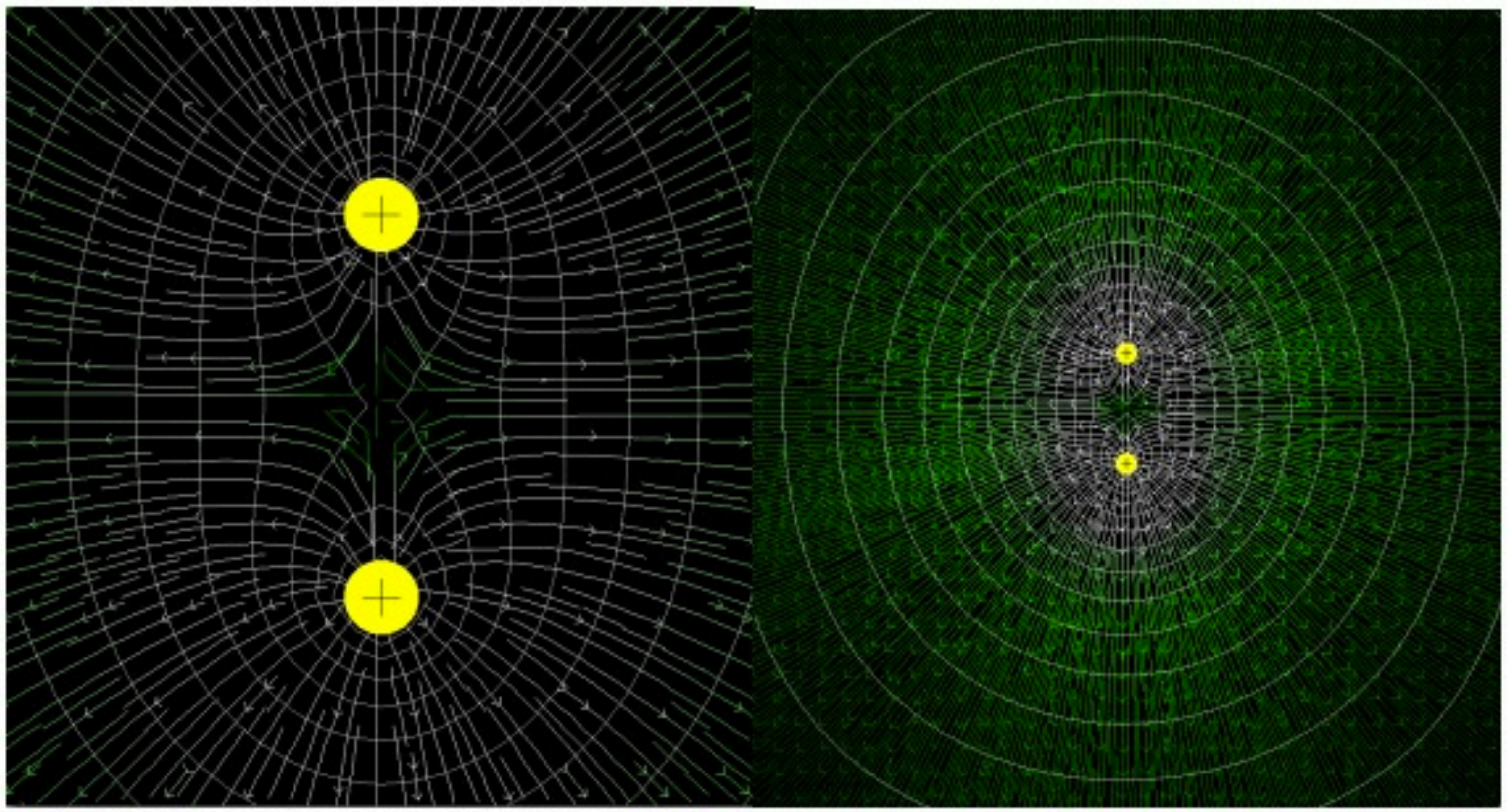
- For recent comments (corrections) to SILH see also 1412.6356.pdf Buchalla et al.

- Minimal coupling is ill defined in an EFT at an operator level, and even in quantum mechanics. See - **Jenkins, Manohar,Trott arXiv: 1305.0017** or Weinberg in the 70’s or H. Weyl in the 30’s.

$$i\partial_\mu \to iD_\mu = i\partial_\mu - eqA_\mu. \qquad [\partial^\mu, \partial^\nu] = 0, \text{ but } [D^\mu, D^\nu] = ieqF^{\mu\nu}$$

Related point on what operators are(not)

- An EFT captures the IR physics of some underlying sector by definition. This does NOT just correspond to heavy particle exchange.



The field far away looks just like a point charge.

- Consider the electrostatics multipole expansion

$$V(r) = \frac{1}{r} \sum c_{lm} Y_{lm}(\Omega) \left(\frac{a}{r}\right)^l$$

- By adding a series of terms (operators) like the dipole quadrapole etc one approx the field
- HQET and SCET multiple exp critical

- In the SMEFT these correspond to “cut off scale effects” that are not generally small in a strongly interacting theory. Reason is resonance exchange prox in mass to cut off in a predictive EFT of a strong sector.

Non trivial running

- One of the Yukawa results, full 3 generation result, nontrivial flavour structure in the RGEs :

$$
\begin{aligned}
\dot C^{(1)}_{\underset{prst}{qq}} =\; & \frac{1}{2}[Y_u^\dagger Y_u - Y_d^\dagger Y_d]_{pr} C^{(1)}_{\underset{st}{Hq}} + \frac{1}{2}[Y_u^\dagger Y_u - Y_d^\dagger Y_d]_{st} C^{(1)}_{\underset{pr}{Hq}} \\
& + \frac{1}{4\,N_c}\left([Y_u^\dagger]_{pv}\,[Y_u]_{wr}\,C^{(8)}_{\underset{stvw}{qu}} + [Y_u^\dagger]_{sv}\,[Y_u]_{wt}\,C^{(8)}_{\underset{prvw}{qu}}\right) + \frac{1}{4\,N_c}\left([Y_d^\dagger]_{pv}\,[Y_d]_{wr}\,C^{(8)}_{\underset{stvw}{qd}} + [Y_d^\dagger]_{sv}\,[Y_d]_{wt}\,C^{(8)}_{\underset{prvw}{qd}}\right) \\
& - \frac{1}{8}\left([Y_u^\dagger]_{pv}\,[Y_u]_{wt}\,C^{(8)}_{\underset{srvw}{qu}} + [Y_u^\dagger]_{sv}\,[Y_u]_{wr}\,C^{(8)}_{\underset{ptvw}{qu}}\right) - \frac{1}{8}\left([Y_d^\dagger]_{pv}\,[Y_d]_{wt}\,C^{(8)}_{\underset{srvw}{qd}} + [Y_d^\dagger]_{sv}\,[Y_d]_{wr}\,C^{(8)}_{\underset{ptvw}{qd}}\right) \\
& + \frac{1}{16N_c}\left([Y_d]_{wt}\,[Y_u]_{vr}\,C^{(8)}_{\underset{pvsw}{quqd}} + [Y_d]_{wr}\,[Y_u]_{vt}\,C^{(8)}_{\underset{svpw}{quqd}}\right) + \frac{1}{16N_c}\left([Y_d^\dagger]_{sw}\,[Y_u^\dagger]_{pv}\,C^{(8)*}_{\underset{rvtw}{quqd}} + [Y_d^\dagger]_{pw}\,[Y_u^\dagger]_{sv}\,C^{(8)*}_{\underset{tvrw}{quqd}}\right) \\
& + \frac{1}{16}\left([Y_d]_{wt}\,[Y_u]_{vr}\,C^{(8)}_{\underset{svpw}{quqd}} + [Y_d]_{wr}\,[Y_u]_{vt}\,C^{(8)}_{\underset{pvsw}{quqd}}\right) + \frac{1}{16}\left([Y_d^\dagger]_{sw}\,[Y_u^\dagger]_{pv}\,C^{(8)*}_{\underset{tvrw}{quqd}} + [Y_d^\dagger]_{pw}\,[Y_u^\dagger]_{sv}\,C^{(8)*}_{\underset{rvtw}{quqd}}\right) \\
& - \frac{1}{2}[Y_u^\dagger]_{pv}\,[Y_u]_{wr}\,C^{(1)}_{\underset{stvw}{qu}} - \frac{1}{2}[Y_d^\dagger]_{pv}\,[Y_d]_{wr}\,C^{(1)}_{\underset{stvw}{qd}} - \frac{1}{2}[Y_u^\dagger]_{sv}\,[Y_u]_{wt}\,C^{(1)}_{\underset{prvw}{qu}} - \frac{1}{2}[Y_d^\dagger]_{sv}\,[Y_d]_{wt}\,C^{(1)}_{\underset{prvw}{qd}} \\
& - \frac{1}{8}[Y_d]_{wt}\,[Y_u]_{vr}\,C^{(1)}_{\underset{pvsw}{quqd}} - \frac{1}{8}[Y_d^\dagger]_{sw}\,[Y_u^\dagger]_{pv}\,C^{(1)*}_{\underset{rvtw}{quqd}} - \frac{1}{8}[Y_d]_{wr}\,[Y_u]_{vt}\,C^{(1)}_{\underset{svpw}{quqd}} - \frac{1}{8}[Y_d^\dagger]_{pw}\,[Y_u^\dagger]_{sv}\,C^{(1)*}_{\underset{tvrw}{quqd}} \\
& + \gamma^{(Y)}_{\underset{pv}{q}}\,C^{(1)}_{\underset{vrst}{qq}} + \gamma^{(Y)}_{\underset{sv}{q}}\,C^{(1)}_{\underset{prvt}{qq}} + C^{(1)}_{\underset{pvst}{qq}}\,\gamma^{(Y)}_{\underset{vr}{q}} + C^{(1)}_{\underset{prsv}{qq}}\,\gamma^{(Y)}_{\underset{vt}{q}} \qquad \text{(A.36)}
\end{aligned}
$$

Jenkins, Manohar,Trott arXiv: 1310.4838

$$\dot A = 16\,\pi^2 \mu\,\frac{dA}{d\mu}$$ (dot notation used at times)

Non trivial running

- Flat directions in LEP care about it, which is surprising:

  Following an analysis as in Pomarol Riva arXiv:1308.2803 introduce

$$\mathcal{S} = \frac{v_T^2\, C_{HBW}}{\bar{g}_1\, \bar{g}_2}, \qquad \mathcal{T} = \frac{1}{2} v_T^2\, C_{HD}.$$

$$\frac{\delta\alpha_{ew}}{(\alpha_{ew})_{SM}} = -2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S},$$

$$\frac{\delta G_F}{(G_F)_{SM}} = -\frac{v_T^2}{2}\left(C_{\underset{\mu e e \mu}{ll}} + C_{\underset{e \mu \mu e}{ll}}\right) + v_T^2\left(C^{(3)}_{\underset{ee}{Hl}} + C^{(3)}_{\underset{\mu\mu}{Hl}}\right),$$

$$\frac{\delta m_Z^2}{(m_Z^2)_{SM}} = \mathcal{T} + 2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S}.$$

Flavour dependent cancelation

LEP data:

$$\frac{\delta\Gamma_Z^{L(t)}}{\Gamma_Z^L} = \frac{1}{\bar{c}_{2\theta}^2}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 4\bar{s}_\theta^2\, \bar{g}_2^2\, \mathcal{S}\right) + \frac{2\, v_T^2}{2\,\bar{s}_\theta^2 - 1}\left(C^{(1)}_{\underset{tt}{H\ell}} + C^{(3)}_{\underset{tt}{H\ell}}\right),$$

$$\frac{\delta\Gamma_Z^R}{\Gamma_Z^R} = -\frac{1}{\bar{c}_{2\theta}}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\,\bar{g}_2^2\, \mathcal{S}\right) - \frac{v_T^2\, C_{He}}{\bar{s}_\theta^2},$$

$$\frac{\delta\Gamma_Z^\nu}{\Gamma_Z^L} = \mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\, v_T^2\left(C^{(1)}_{\underset{tt}{H\ell}} - C^{(3)}_{\underset{tt}{H\ell}}\right),$$

$$\frac{\delta m_W}{m_W} = \frac{1}{2\,\bar{c}_{2\theta}}\left(\bar{c}_\theta^2 \mathcal{T} + \bar{s}_\theta^2\left(\frac{\delta G_F}{(G_F)_{SM}} + 2\bar{g}_2^2\, \mathcal{S}\right)\right).$$

Non trivial flat direction:

$$2\, C^{(3)}_{Hl} = C_{ll}, \qquad v_T^2\, C^{(3)}_{H\ell} = \frac{\mathcal{T}}{2} + \frac{\delta G_F}{2\,(G_F)_{SM}}.$$

Makes clear it is essential to separately probe the W coupling to leptons robustly to close all remaining flat directions. 1409.7605 Trott

Non trivial running

- Flat directions in LEP care about it, which is surprising:

  Following an analysis as in Pomarol Riva arXiv:1308.2803 introduce

$$\mathcal{S} = \frac{v_T^2\, C_{HBW}}{\bar{g}_1\, \bar{g}_2}, \qquad \mathcal{T} = \frac{1}{2} v_T^2\, C_{HD}.$$

$$\begin{aligned} \frac{\delta\alpha_{ew}}{(\alpha_{ew})_{SM}} &= -2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S}, \\ \frac{\delta G_F}{(G_F)_{SM}} &= -\frac{v_T^2}{2}\left(C_{\underset{\mu e e\mu}{ll}} + C_{\underset{e\mu\mu e}{ll}}\right) + v_T^2\left(C^{(3)}_{\underset{ee}{Hl}} + C^{(3)}_{\underset{\mu\mu}{Hl}}\right), \\ \frac{\delta m_Z^2}{(m_Z^2)_{SM}} &= \mathcal{T} + 2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S}. \end{aligned}$$

Flavour dependent cancelation

LEP data:

$$\begin{aligned} \frac{\delta\Gamma_Z^{L(t)}}{\Gamma_Z^L} &= \frac{1}{\bar{c}^2_{2\theta}}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 4\bar{s}_\theta^2\, \bar{g}_2^2\, \mathcal{S}\right) + \frac{2\, v_T^2}{2\,\bar{s}_\theta^2 - 1}\left(C^{(1)}_{\underset{tt}{H\ell}} + C^{(3)}_{\underset{tt}{H\ell}}\right), \\ \frac{\delta\Gamma_Z^R}{\Gamma_Z^R} &= -\frac{1}{\bar{c}_{2\theta}}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\,\bar{g}_2^2\, \mathcal{S}\right) - \frac{v_T^2\, C_{He}}{\bar{s}_\theta^2}, \\ \frac{\delta\Gamma_Z^\nu}{\Gamma_Z^L} &= \mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\, v_T^2\left(C^{(1)}_{\underset{tt}{H\ell}} - C^{(3)}_{\underset{tt}{H\ell}}\right), \\ \frac{\delta m_W}{m_W} &= \frac{1}{2\,\bar{c}_{2\theta}}\left(\bar{c}_\theta^2 \mathcal{T} + \bar{s}_\theta^2\left(\frac{\delta G_F}{(G_F)_{SM}} + 2\bar{g}_2^2\, \mathcal{S}\right)\right). \end{aligned}$$

Non trivial flat direction:

$$2\, C^{(3)}_{Hl} = C_{ll}, \qquad v_T^2\, C^{(3)}_{H\ell} = \frac{\mathcal{T}}{2} + \frac{\delta G_F}{2\,(G_F)_{SM}}.$$

As flavour matters, how many parameters for the leptons in general?

$$\frac{1}{4}\left(8 + 15 n_g^2 + 2 n_g^3 + 3 n_g^4\right) = 110$$

Set $\Gamma_z^2/M_z^2 \sim 10^{-3} \rightarrow 0$ Then 29.

Flavour dependent LEP fit feasible, and relevant.

Scale dependence of parameters

- Remember i started talking about that! It matter to break flat directions.
  With this chosen direction the leading breaking is:

$$\mu \frac{d}{d\,\mu}(C_{HD} - 2\,C_{Hl}^{(3)}) = \frac{12\,\lambda}{16\,\pi^2}\,C_{HD} + \cdots$$

$$\mu \frac{d}{d\,\mu}(C_{HD} - C_{ll}) = \frac{3}{4\,\pi^2}\,(\lambda + y_t^2)\;C_{HD} + \cdots$$

1409.7605 Trott

(neglecting mixing)

- It actually matters to treat the scale dependence carefully in global analyses. Percent level breaking of flat directions for precision observables doing so at LEP.

- In this sense, the LHC vector bosons are not your fathers (or mothers) vector bosons.

- Path is starting to emerge to globally constrain the SMEFT accounting for the scale dependence of the operators.

  Recent excellent study on $\mu \to e\,\gamma$:Pruna, Signer arXiv:1408.3565

SM parameters run differently

The complete anomalous dimension matrix is known, but also the running of the SM parameters is modified due to the dimension 6 operators (in dim reg).

This is just like quark mass terms in RGEs in flavour physics.

$$\mu \frac{d}{d\,\mu} C_{d\leq 4} \propto m_h^2 \sum_{i=1..59} C^i_{d=6}$$

When you run SM parameters, this is the same order as explicit (loop) operator insertions.

The SM EFT has an explicit scale in it, v -- we expand around that background field value.

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\lambda = \frac{m_H^2}{16\pi^2}\Big[12C_H + \Big(-32\lambda + \frac{10}{3}g_2^2\Big)C_{H\Box} + \Big(12\lambda - \frac{3}{2}g_2^2 + 6g_1^2\mathsf{y}_H^2\Big)C_{HD} + 2\eta_1 + 2\eta_2$$
$$+ 12g_2^2 c_{F,2}C_{HW} + 12g_1^2\mathsf{y}_H^2 C_{HB} + 6g_1g_2\mathsf{y}_H C_{HWB} + \frac{4}{3}g_2^2 C^{(3)}_{\underset{tt}{Hl}} + \frac{4}{3}g_2^2 N_c C^{(3)}_{\underset{tt}{Hq}}\Big],$$

$$\eta_1 = \Big(\frac{1}{2}N_c C_{\underset{rs}{dH}}[Y_d]_{sr} + \frac{1}{2}N_c C_{\underset{rs}{uH}}[Y_u]_{sr} + \frac{1}{2}C_{\underset{rs}{eH}}[Y_e]_{sr}\Big) + h.c.\,,$$

$$\eta_2 = -2N_c C^{(3)}_{\underset{rs}{Hq}}[Y_u^\dagger Y_u]_{sr} - 2N_c C^{(3)}_{\underset{rs}{Hq}}[Y_d^\dagger Y_d]_{sr} + N_c C_{\underset{rs}{Hud}}[Y_d Y_u^\dagger]_{sr} + N_c C^*_{\underset{rs}{Hud}}[Y_u Y_d^\dagger]_{rs} - 2C^{(3)}_{\underset{rs}{Hl}}[Y_e^\dagger Y_e]_{sr}\,,$$

SM parameters run differently

- Full effect of dim 6 ops on running of SM parameters:

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\lambda = \frac{m_H^2}{16\pi^2}\Big[12C_H + \left(-32\lambda + \frac{10}{3}g_2^2\right)C_{H\Box} + \left(12\lambda - \frac{3}{2}g_2^2 + 6g_1^2\mathsf{y}_H^2\right)C_{HD} + 2\eta_1 + 2\eta_2$$
$$+ 12g_2^2 c_{F,2}C_{HW} + 12g_1^2\mathsf{y}_H^2 C_{HB} + 6g_1g_2\mathsf{y}_H C_{HWB} + \frac{4}{3}g_2^2 C^{(3)}_{\substack{Hl\\tt}} + \frac{4}{3}g_2^2 N_c C^{(3)}_{\substack{Hq\\tt}}\Big],$$

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}m_H^2 = \frac{m_H^4}{16\pi^2}\left[-4C_{H\Box} + 2C_{HD}\right],$$

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}[Y_u]_{rs} = \frac{m_H^2}{16\pi^2}\Big[3C^*_{\substack{uH\\sr}} - C_{H\Box}[Y_u]_{rs} + \frac{1}{2}C_{HD}[Y_u]_{rs} - [Y_u]_{rt}\left(C^{(1)}_{\substack{Hq\\ts}} + 3C^{(3)}_{\substack{Hq\\ts}}\right) + C_{\substack{Hu\\rt}}[Y_u]_{ts}$$
$$- C_{\substack{Hud\\rt}}[Y_d]_{ts} - 2\left(C^{(1)*}_{\substack{qu\\sptr}} + c_{F,3}C^{(8)*}_{\substack{qu\\sptr}}\right)[Y_u]_{tp} - C^{(1)*}_{\substack{lequ\\ptsr}}[Y_e^*]_{tp} + N_c C^{(1)*}_{\substack{quqd\\srpt}}[Y_d]^*_{tp}$$
$$+ \frac{1}{2}\left(C^{(1)*}_{\substack{quqd\\prst}} + c_{F,3}C^{(8)*}_{\substack{quqd\\prst}}\right)[Y_d]^*_{tp}\Big],$$

$$\mu\frac{\mathrm{d}g_3}{\mathrm{d}\mu} = -4\frac{m_H^2}{16\pi^2}g_3C_{HG}, \qquad \mu\frac{\mathrm{d}g_2}{\mathrm{d}\mu} = -4\frac{m_H^2}{16\pi^2}g_2C_{HW}, \qquad \mu\frac{\mathrm{d}g_1}{\mathrm{d}\mu} = -4\frac{m_H^2}{16\pi^2}g_1C_{HB},$$
$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\theta_3 = -\frac{4m_H^2}{g_3^2}C_{H\widetilde{G}}, \qquad \mu\frac{\mathrm{d}}{\mathrm{d}\mu}\theta_2 = -\frac{4m_H^2}{g_2^2}C_{H\widetilde{W}}, \qquad \mu\frac{\mathrm{d}}{\mathrm{d}\mu}\theta_1 = -\frac{4m_H^2}{g_1^2}C_{H\widetilde{B}},$$

Implications of threshold terms

- Contributions of this form modify predicted SM processes at the LHC if input parameters inferred from low scale measurements.

  Consider a measurement of the b quark mass in B decays used to predict the Higgs width:

Shift in the prediction:

$$\Gamma(h \to \bar{b}\, b) = \frac{(\mathcal{Y}_b + \Delta\mathcal{Y}_b)^2\, m_H\, N_c}{8\,\pi} \left(1 - 4\frac{m_b^2}{m_H^2}\right)^{3/2}$$

$$\Delta\mathcal{Y}_b = \frac{m_H^2}{16\pi^2} \log\left(\frac{m_H}{m_b}\right) C_1 + \frac{m_H^2}{16\pi^2} \log\left(\frac{m_H}{\Lambda}\right) C_2.$$

$$C_2 = \frac{1}{2\sqrt{2}\lambda}[Y_d]_{33}\left(\dot{C}_{H\Box} - \frac{1}{4}\dot{C}_{HD}\right) - \frac{3}{4\lambda}\dot{C}^*_{\substack{dH\\33}}$$

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}[Y_d]_{rs} = \frac{m_H^2}{16\pi^2}\Bigg[3C^*_{\substack{dH\\sr}} - C_{H\Box}[Y_d]_{rs} + \frac{1}{2}C_{HD}[Y_d]_{rs} + [Y_d]_{rt}\left(C^{(1)}_{\substack{Hq\\ts}} + 3C^{(3)}_{\substack{Hq\\ts}}\right) - C_{\substack{Hd\\rt}}[Y_d]_{ts}$$
$$- [Y_u]_{ts}C^*_{\substack{Hud\\tr}} - 2\left(C^{(1)*}_{\substack{qd\\sptr}} + c_{F,3}C^{(8)*}_{\substack{qd\\sptr}}\right)[Y_d]_{tp} + C_{\substack{ledq\\ptrs}}[Y_e]^*_{pt} + N_c C^{(1)*}_{\substack{quqd\\ptsr}}[Y_u]^*_{tp}$$
$$+ \frac{1}{2}\left(C^{(1)*}_{\substack{quqd\\sptr}} + c_{F,3}C^{(8)*}_{\substack{quqd\\sptr}}\right)[Y_u]^*_{tp}\Bigg].$$

We should probably see h to tau mu

Intimidation equation

$$[\dot{Y}_e]_{rs} = \frac{m_H^2}{16\pi^2}\Big[3C^*_{\underset{sr}{eH}} - C_{H\Box}[Y_e]_{rs} + \frac{1}{2}C_{HD}[Y_e]_{rs} + [Y_e]_{rt}\Big(C^{(1)}_{\underset{ts}{Hl}} + 3C^{(3)}_{\underset{ts}{Hl}}\Big) - C_{\underset{rt}{He}}[Y_e]_{ts}$$

$$- 2C^*_{\underset{sptr}{le}}[Y_e]_{tp} + N_c C^*_{\underset{srpt}{ledq}}[Y_d]_{pt} - N_c C^{(1)*}_{\underset{srpt}{lequ}}[Y_u]^*_{tp}\Big],$$

$$\dot{C}_{\underset{rs}{eH}} = 2(\eta_1+\eta_2+i\eta_5)[Y_e^\dagger]_{rs} + [Y_e^\dagger Y_e Y_e^\dagger]_{rs}(C_{HD}-6C_{H\Box}) + 2C^{(1)}_{\underset{rt}{Hl}}[Y_e^\dagger Y_e Y_e^\dagger]_{ts} - 2[Y_e^\dagger Y_e Y_e^\dagger]_{rt}C_{\underset{ts}{He}}$$

$$+ 8C_{\underset{rpts}{le}}[Y_e^\dagger Y_e Y_e^\dagger]_{pt} - 4C_{\underset{rspt}{ledq}}N_c[Y_d^\dagger Y_d Y_d^\dagger]_{tp} + 4C^{(1)}_{\underset{rstp}{lequ}}N_c[Y_u Y_u^\dagger Y_u]_{pt} + 4C_{\underset{rt}{eH}}[Y_e Y_e^\dagger]_{ts} + 5[Y_e Y_e^\dagger]_{rt}C_{\underset{ts}{eH}}$$

$$+ 3\gamma_H^{(Y)}C_{\underset{rs}{eH}} + \gamma^{(Y)}_{\underset{rv}{l}}C_{\underset{vs}{eH}} + C_{\underset{rv}{eH}}\gamma^{(Y)}_{\underset{vs}{e}} + \lambda\Big[24\,C_{\underset{rs}{eH}} + 4C^{(1)}_{\underset{rt}{Hl}}[Y_e]^*_{st} + 12C^{(3)}_{\underset{rt}{Hl}}[Y_e]^*_{st} - 4[Y_e]^*_{tr}C_{\underset{ts}{He}}$$

$$- 4\,[Y_e]^*_{sr}C_{H\Box} + 2[Y_e]^*_{sr}C_{HD} - 8C_{\underset{rpts}{le}}[Y_e]^*_{tp} + 4N_c C_{\underset{rspt}{ledq}}[Y_d]^*_{tp} - 4N_c C^{(1)}_{\underset{rspt}{lequ}}[Y_u]_{tp}\Big] \qquad (3.54)$$

In a realistic model, this probably matters.

$$- 3g_1\Big[-4y_e\,y_H[Y_d^\dagger]_{ws}\,C^3_{\underset{rw}{Hl}} - (-2y_H+5y_L-y_Q)\,[Y_e^\dagger]_{rv}\,C_{\underset{vs}{eB}} + 8g_1^2y_H^2\,(y_e+y_L)\,C_{\underset{rs}{eB}}$$

$$+ 3y_e[Y_e^\dagger]_{ws}\,C_{\underset{rw}{eB}} - (y_e+y_H-2y_L+y_Q)\,[Y_e^\dagger]_{rw}[Y_e^\dagger]_{vs}C^\dagger_{\underset{vw}{eB}} - 4g_1y_Hy_L[Y_e^\dagger]_{rv}\,C_{\underset{vs}{He}}$$

$$- 4g_1y_ey_H[Y_e^\dagger]_{ws}\,C^1_{\underset{rw}{Hl}} + g_1^2\,(3y_e^2-4y_ey_L+3y_L^2)\;C_{\underset{rs}{eH}} - 8g_1y_ey_L[Y_e^\dagger]_{rs}C_{HB}$$

due to EOM...

$$- 4g_1y_H^2[Y_e^\dagger]_{rs}C_{HB} - 2g_1y_H^2[Y_e^\dagger]_{rs}C_{HD}\Big]$$

$$+ \frac{g_2}{12}\Big[16g_2[Y_e^\dagger]_{rs}\Big(C^1_{\underset{aa}{Hl}} + C^3_{\underset{aa}{Hl}}\Big) + 36[Y_e^\dagger]_{rv}C^1_{\underset{vs}{eW}} + 36g_2[Y_e^\dagger]_{rv}C^1_{\underset{vs}{He}} + 20g_2[Y_e^\dagger]_{rs}C_{H\Box}$$

$$- 9g_2[Y_e^\dagger]_{rs}C_{HD} + 54g_2[Y_e^\dagger]_{rs}C_{HW}\Big] - \frac{81g_2^2}{12}C_{\underset{rs}{eH}}$$

$$- 6g_1\,g_2\Big(g_2y_HC_{\underset{rs}{eB}} + 2g_1y_H(y_e+y_L)C_{\underset{rs}{eW}} - (y_e+y_H)[Y_e^\dagger]_{rs}C_{HWB}\Big).$$

Final comments on precision

- What the mixing tells us is that at the one loop level (to properly account for the scale dependence of the SMEFT) extensive corrections.
- Logs were calculated in the "unbroken phase" of the theory where all SM masses (other than higgs set to 0)
- These logs correspond to the logs that are in one loop diagrams in the SMEFT. But such diagrams also have finite terms that are not log enhanced.
- As the logs are about 4, the finite terms have to be determined as well. This is in progress...

Conclusions:

- It remains to be proven (experimentally) what the right EFT formalism is, future studies of $h \to V\mathcal{F}$ will be informative on this.

- The complete, 3 generation anomalous dimension matrix is now known for dimension six operators in the SM EFT.

  As is the mixing down effect of these operators to the SM parameters.

- Extensive mixing. Unlikely that this is irrelevant in a realistic model (IMO). Need to sort out all finite terms for precision phenomenology to really map to high scale.

- RGE is a very important guide to this growing effort, it has all EOM effects incorporated.

- The precision SMEFT era has begun!