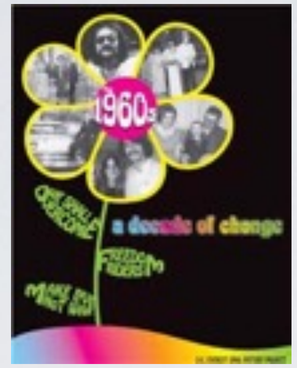
Past, 

present 

Michael Trott, Niels Bohr Institute, Copenhagen, Denmark.

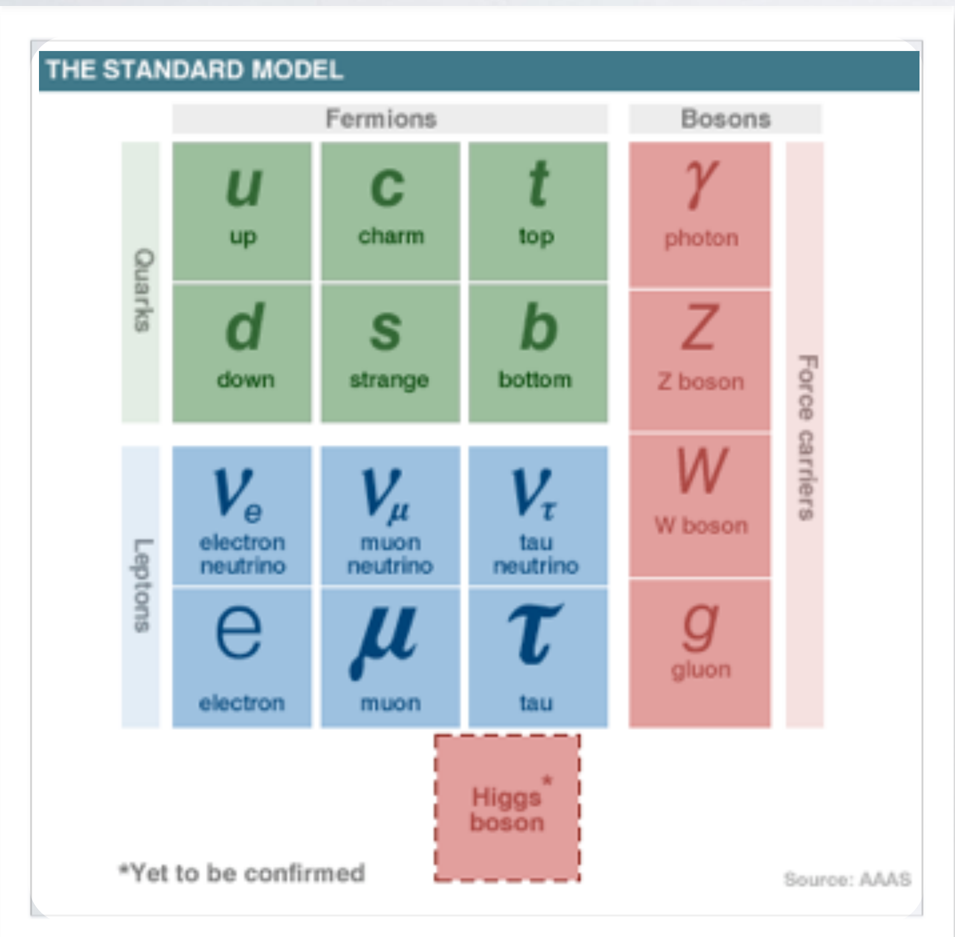
and the possible future 

in precision Higgs pheno.

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 scales in the theory
  There are at least 2:

$$\Lambda_{QCD} \sim 200\ \text{MeV}$$
$$v \sim 246\ \text{GeV}$$

- The QCD scale is generated dynamically, the EW one is put in by hand.

The Standard model ...

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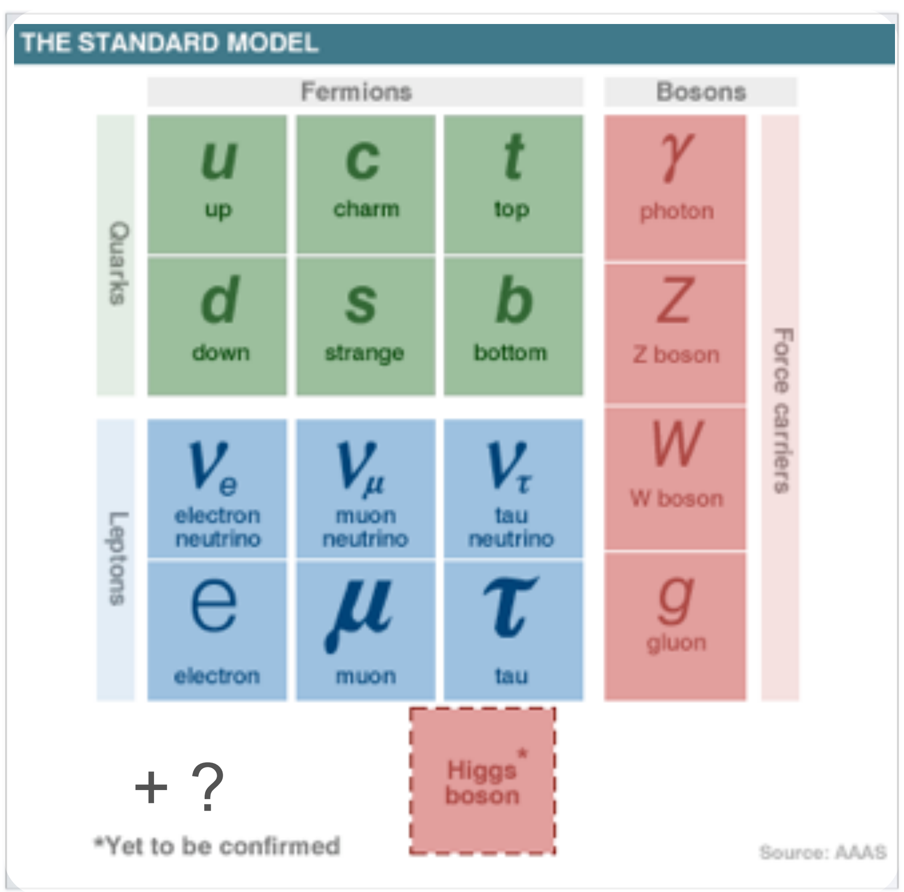
$$- \lambda \left(H^\dagger H - \frac{1}{2} v^2\right)^2 - \left[H^{\dagger j} \overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j} \overline{u}\, Y_u\, q_j + H^{\dagger j} \overline{e}\, Y_e\, l_j + \text{h.c.} \right],$$



- 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

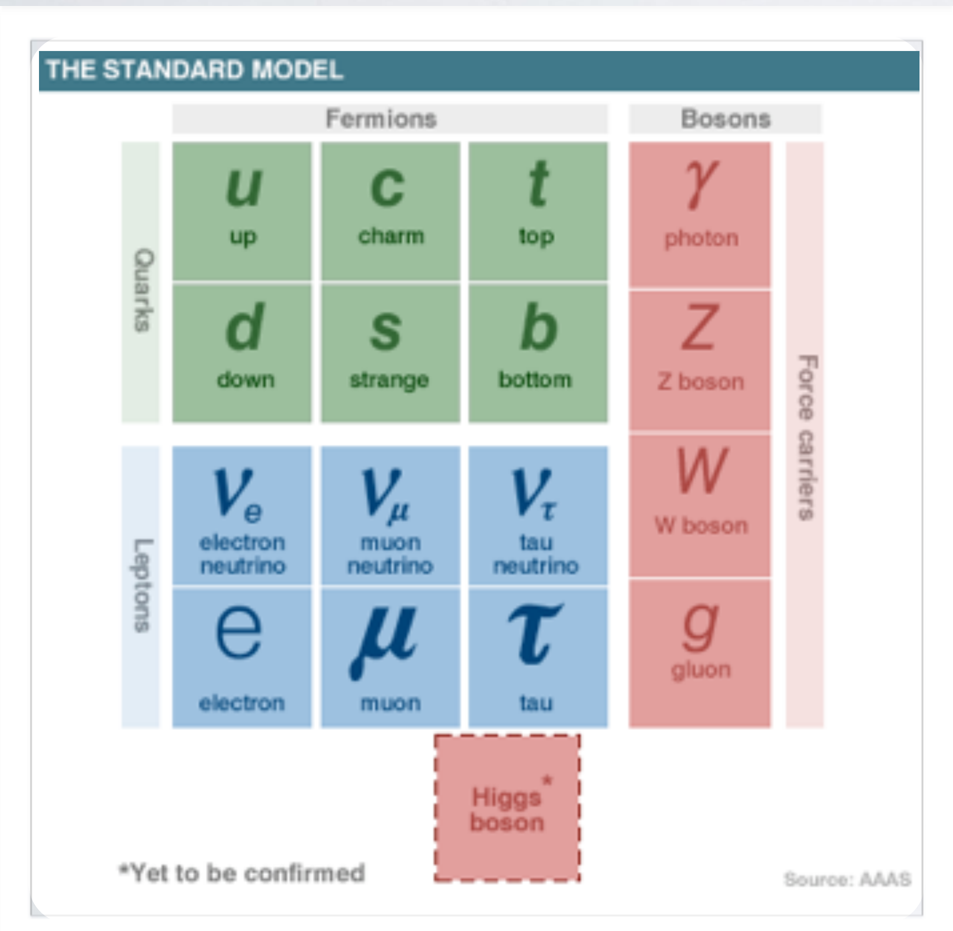
$2N-1$ relative phases

$(N-1)^2$ physical parameters

The Standard model ...

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

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



- 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

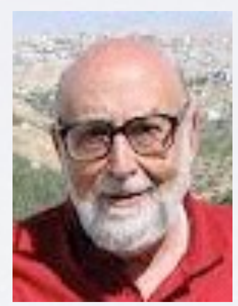
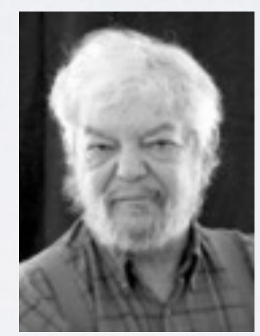
v, λ : 2 EW sym breaking

This is the 18 parameters you hear about...

Higgs Physics - the past motivation

- Swept under the rug in that discussion is the presence of massive vector bosons - the W,Z.

- Can you construct a renormalizable, spontaneously broken gauge theory that accommodates present data (massive vector bosons,etc.)

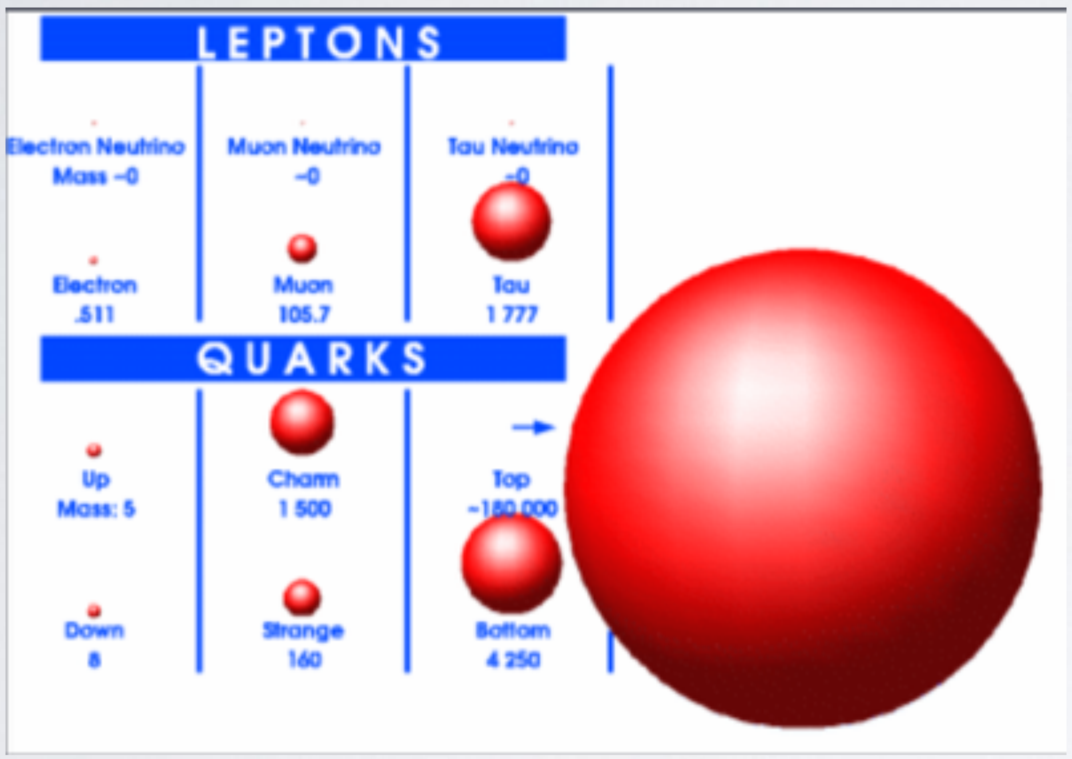
      

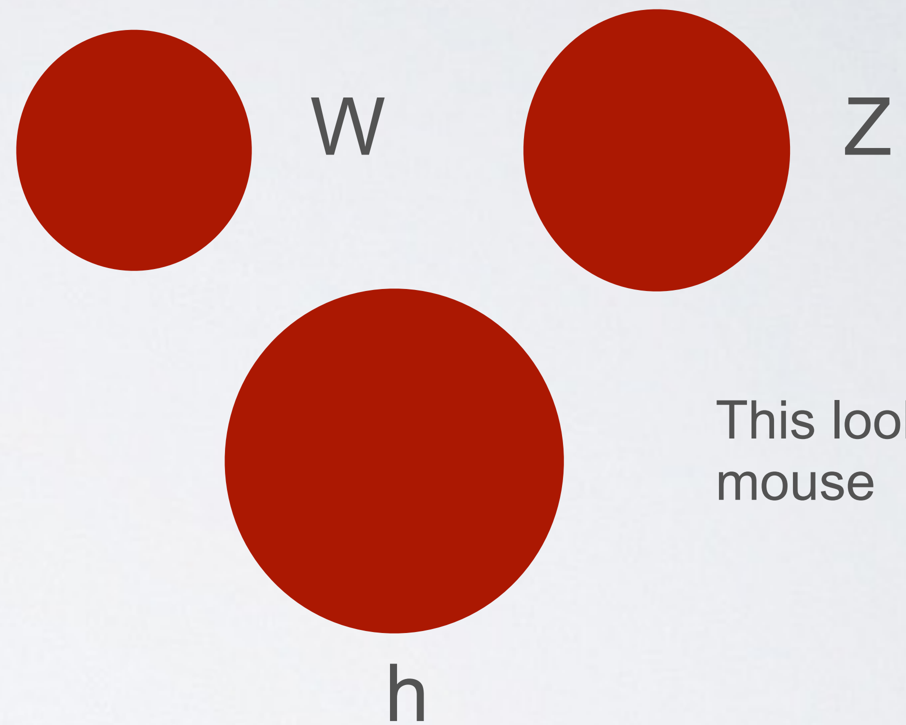
Yes we can!

$$+(D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i \not{D}\, \psi - \lambda \left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \mathrm{h.c.}\right],$$

Higgs Physics - the past motivation

- Does this explain the particle masses that are observed? Including the W and Z. (Yes and no.)





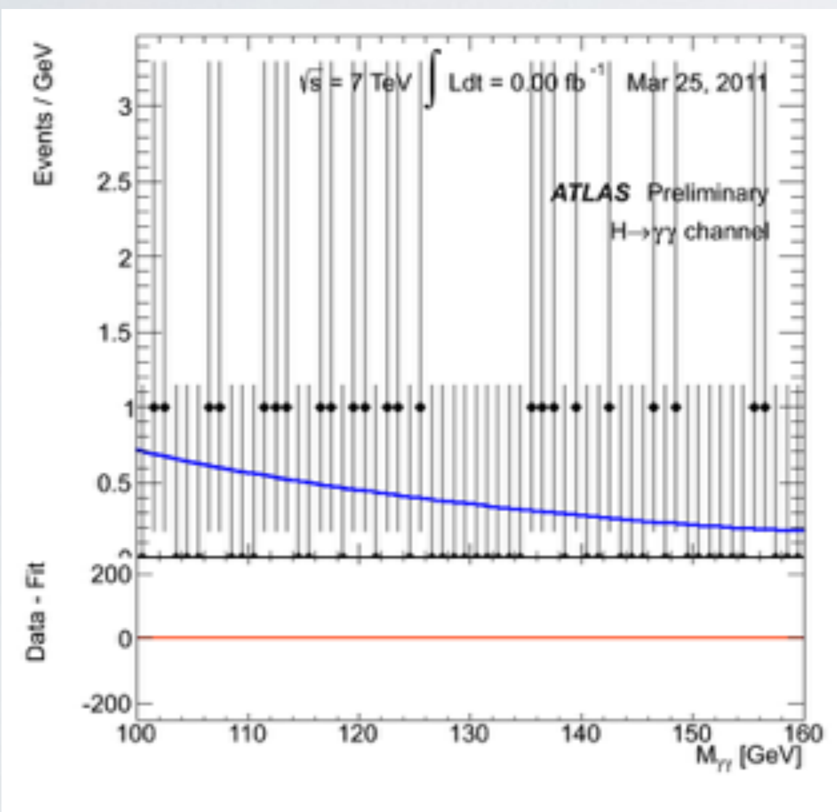
This looks like mickey mouse on purpose.

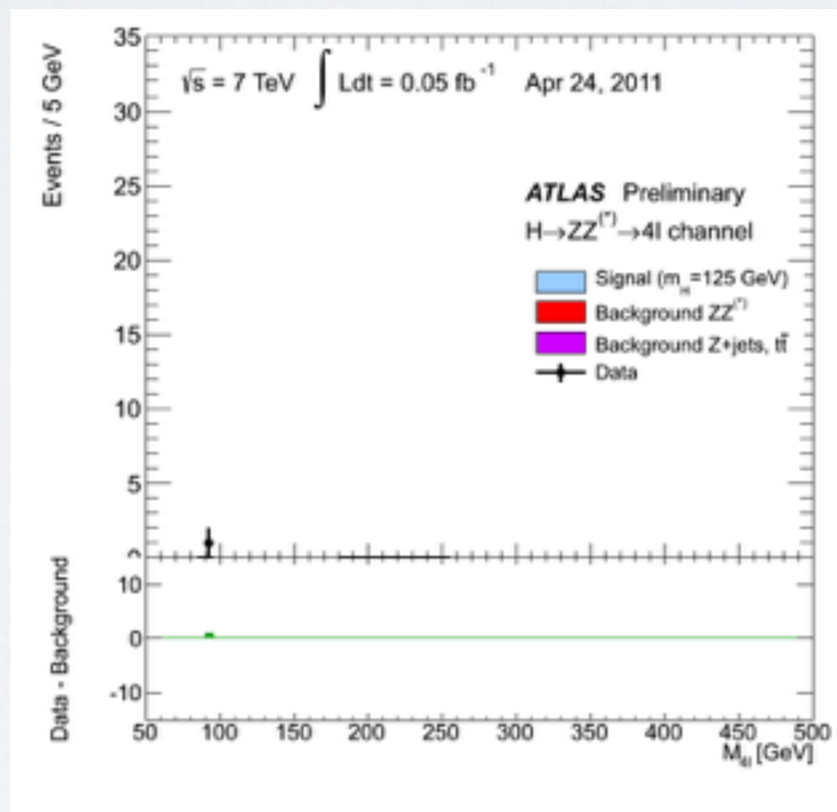
- Every mass that you see (can be) a coupling times the vacuum expectation value. (Neutrinos can be more complicated.)

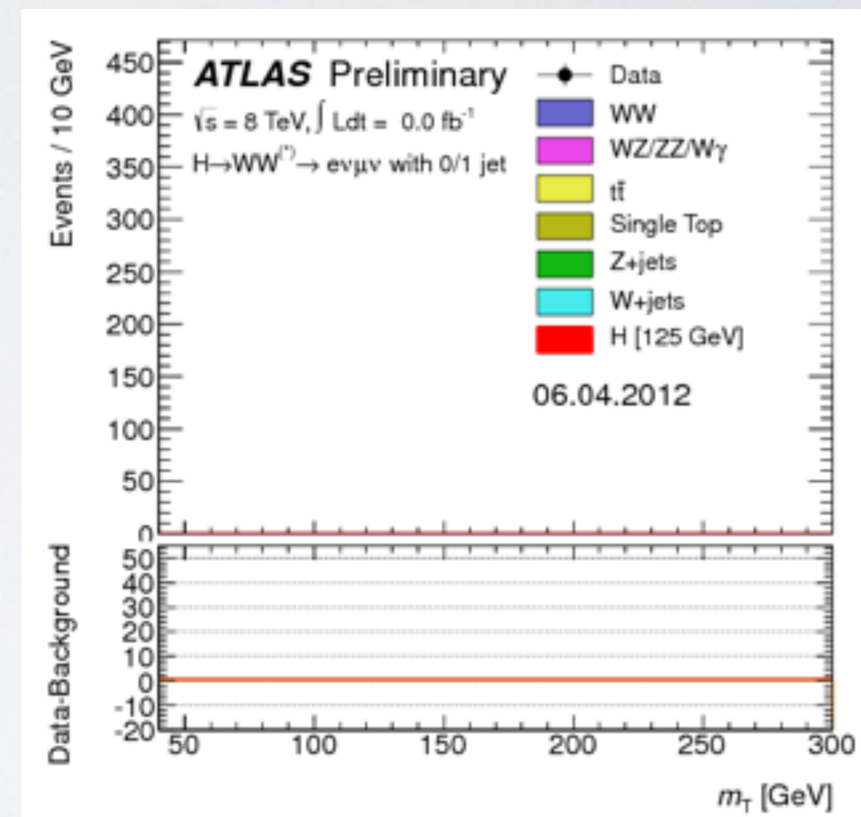
Ok, good job, can we find that?

BRIEF INTERMISSION.

1960's - 2012







All credit for these animations goes to ATLAS.

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 $\Lambda \sim few\,\mathrm{TeV}$

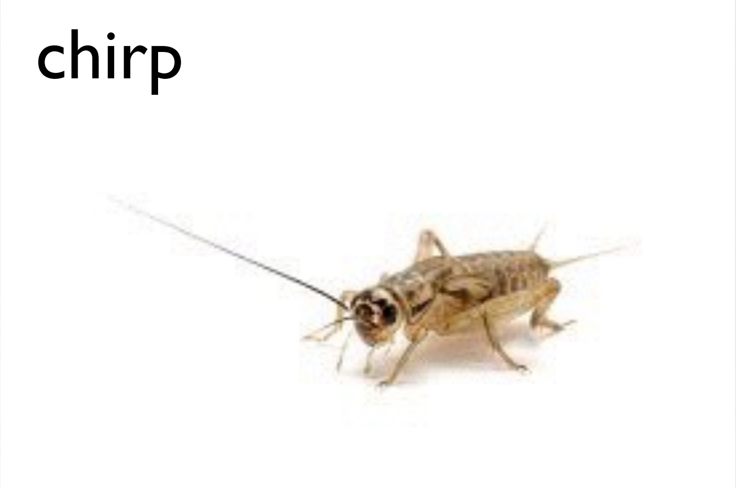
- LHC is about to restart at 14 TeV, but practical discovery reach to excite new particles $\lesssim 14/6 \sim 2\,\mathrm{TeV}$

  (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)

Hierarchy motivated states found.

- Other than this h field...



- Is it even clear we have exactly found THE higgs boson? Maybe not.
- In between the past and the present some things happened in physics

The "wilsonian" view of field theory and effective field theories put renormalizability in a new light. (Not a very flattering one.)

- Recent anti gauge symmetry (yes redundancy) insurgency as well. See jacobs talk.

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:

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

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

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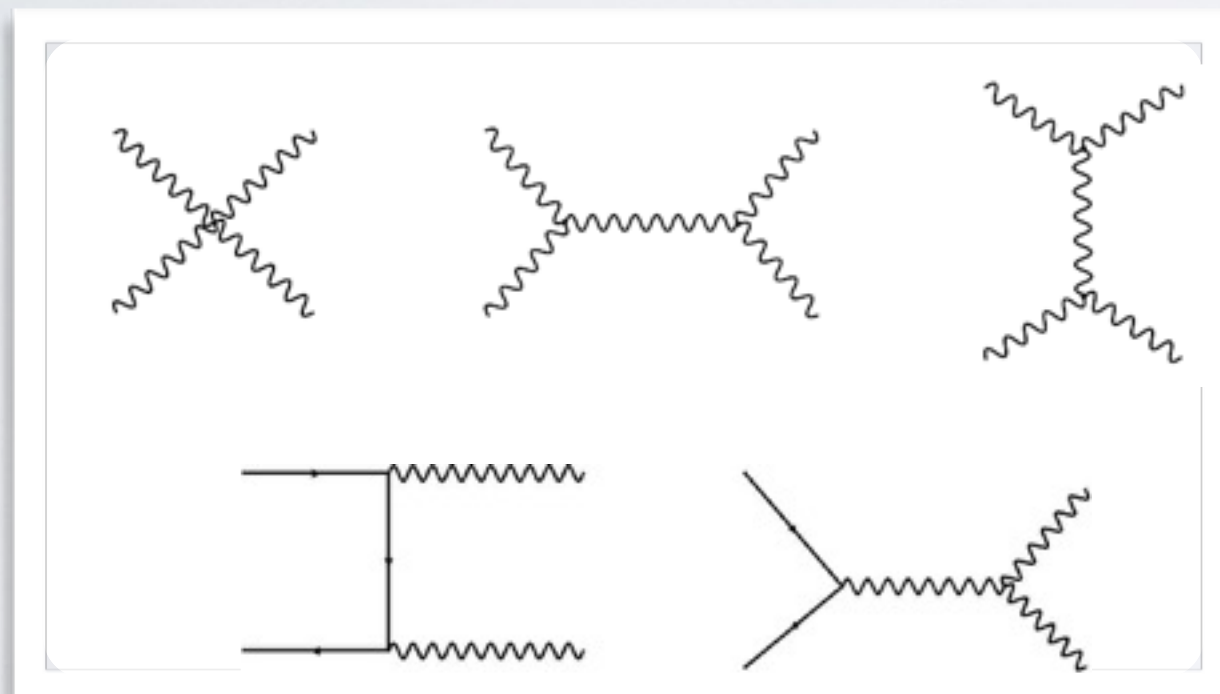
$$+ M_w^2 W_\mu^+ W \mu_- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu - \bar{\psi}_L M \psi_R + h.c. \; + \cdots$$



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

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

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

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)

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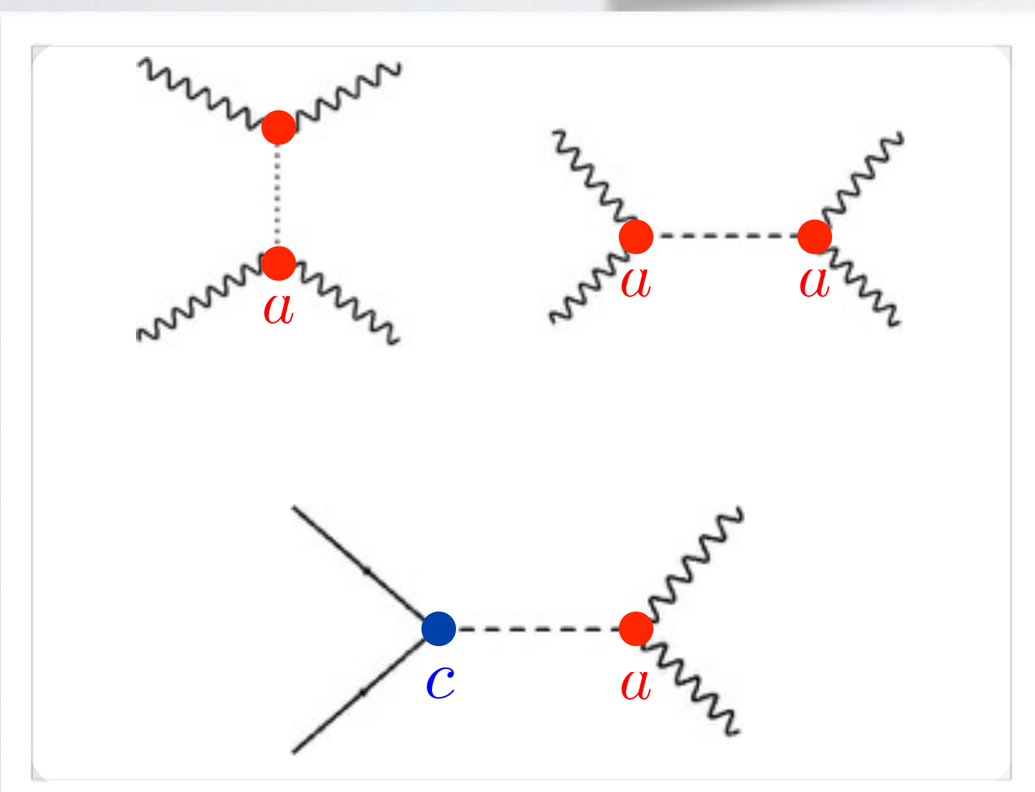
$$+ \boxed{\frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma) - \frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c.,}$$



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

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

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?

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  The EFT consistent with what we knew (80's -00's) did not extrapolate to arbitrary high energies:

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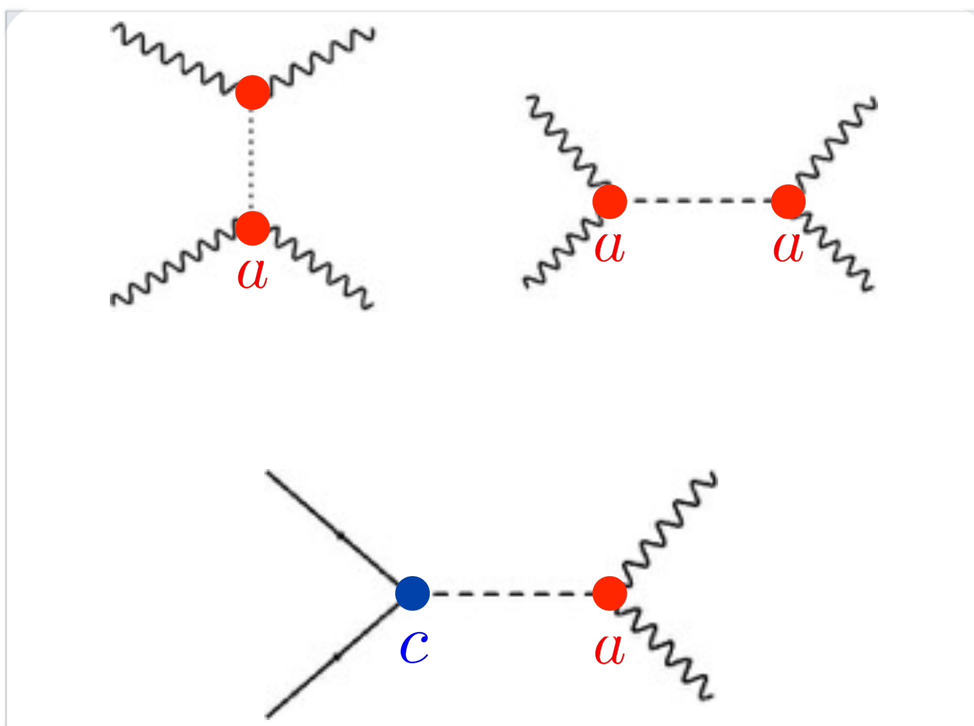

$$W_L^+ W_L^- \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2} (s+t)\, (\cancel{1 - a^2}) \to 0$$

Case of SM Higgs.

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

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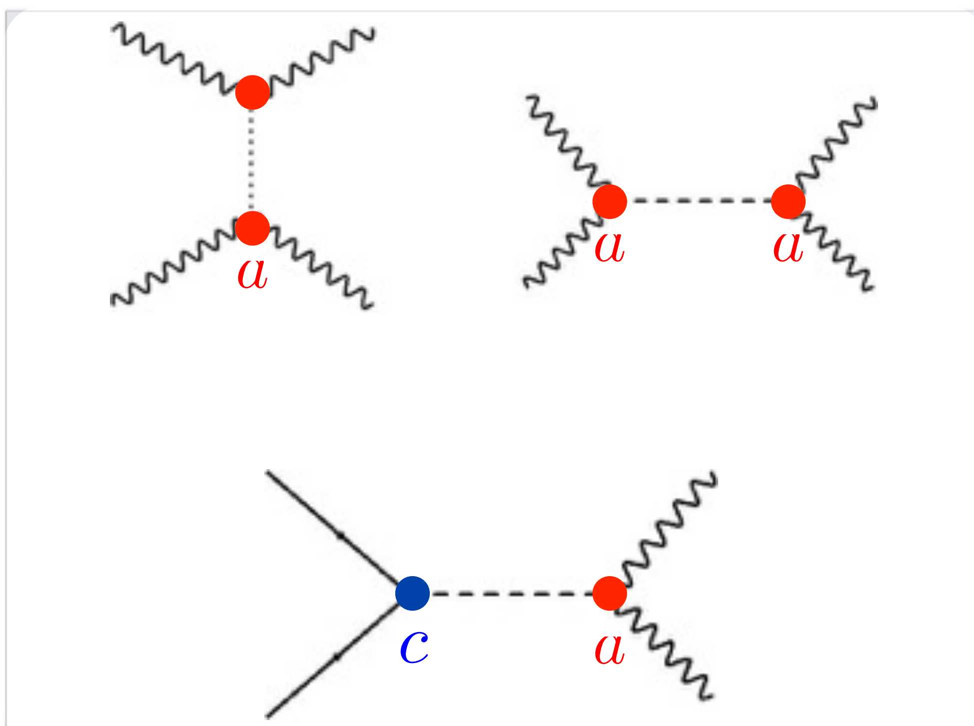

- For WW scattering the cut off scale for the EFT with the addition of a scalar is raised:

$\Lambda \simeq 4\pi v$ ..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?

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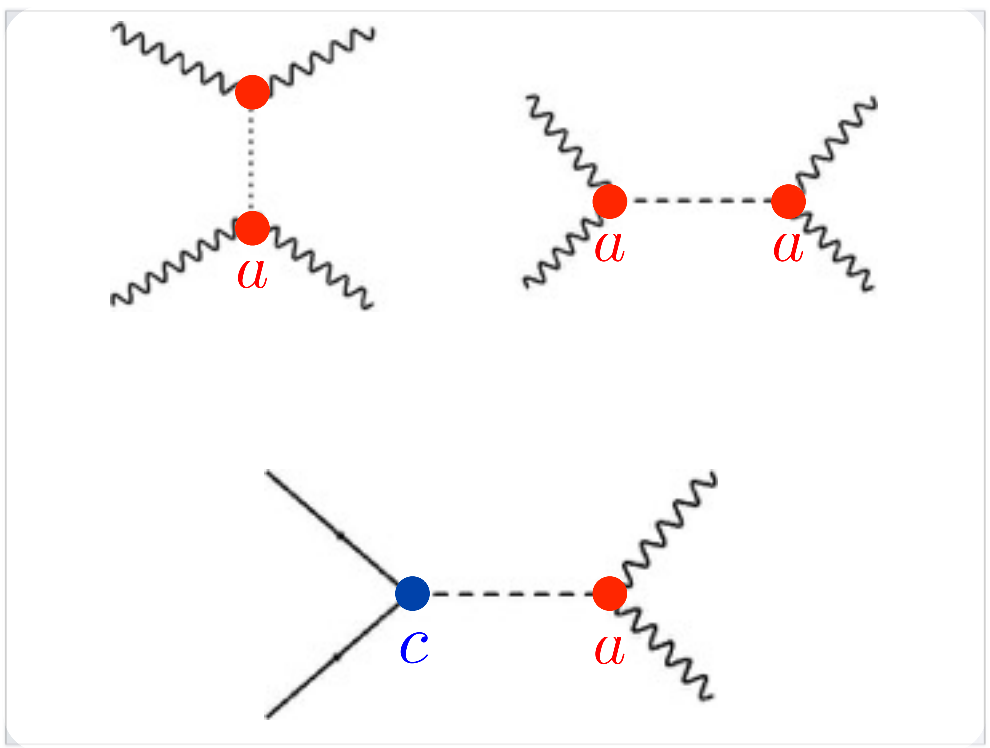
The EFT consistent with what we knew (80's -00's) did not extrapolate to arbitrary high energies:

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

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



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$\Lambda \simeq 4\pi v$ ..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...

Why unitarity?

- Why hold on to unitarity if relaxing local gauge symmetry and renormalizability concerns?

" 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

General EFT: Nonlinear chiral+ singlet

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

$$\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger\,D^\mu\Sigma)\left[1 + 2\,a_{W,Z}\,\frac{h}{v} + b_{Z,W}\,\frac{h^2}{v^2} + b_{3,Z,W}\,\frac{h^3}{v^3} + \cdots\right], \\
&\quad -\frac{v}{\sqrt{2}}\,(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_i^{u,d}\,\frac{h}{v} + c_{2,j}^{u,d}\,\frac{h^2}{v^2} + \cdots\right]\left(\begin{array}{c} y_{ij}^u\,u_R^j \\ y_{ij}^d\,d_R^j \end{array}\right) + h.c., \\
V(h) &= \frac{1}{2}\,m_h^2\,h^2 + \frac{d_3}{6}\left(\frac{3\,m_h^2}{v}\right)h^3 + \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots\,.
\end{aligned}$$

Recent development of this theory led by Gavela group in Madrid and Buchalla in Munich.

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

$$\begin{aligned}
\mathcal{L}_{HD}^5 = c_g\,g_3^2\frac{h}{v}\,G_{\mu\,\nu}\,G^{\mu\,\nu} + c_W\,g_2^2\frac{h}{v}\,W_{\mu\,\nu}\,W^{\mu\,\nu} + c_B\,g_1^2\frac{h}{v}\,B_{\mu\,\nu}\,B^{\mu\,\nu}, \\
+\hat{c}_W\,g_2^2\frac{h}{v}\,\hat{W}_{\mu\,\nu}\,W^{\mu\,\nu} + \hat{c}_B\,g_1^2\frac{h}{v}\,\hat{B}_{\mu\,\nu}\,B^{\mu\,\nu} + \hat{c}_G\,g_3^2\frac{h}{v}\,\hat{G}_{\mu\,\nu}\,G^{\mu\,\nu}
\end{aligned}$$

* 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

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

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

What did we learn in Run I?

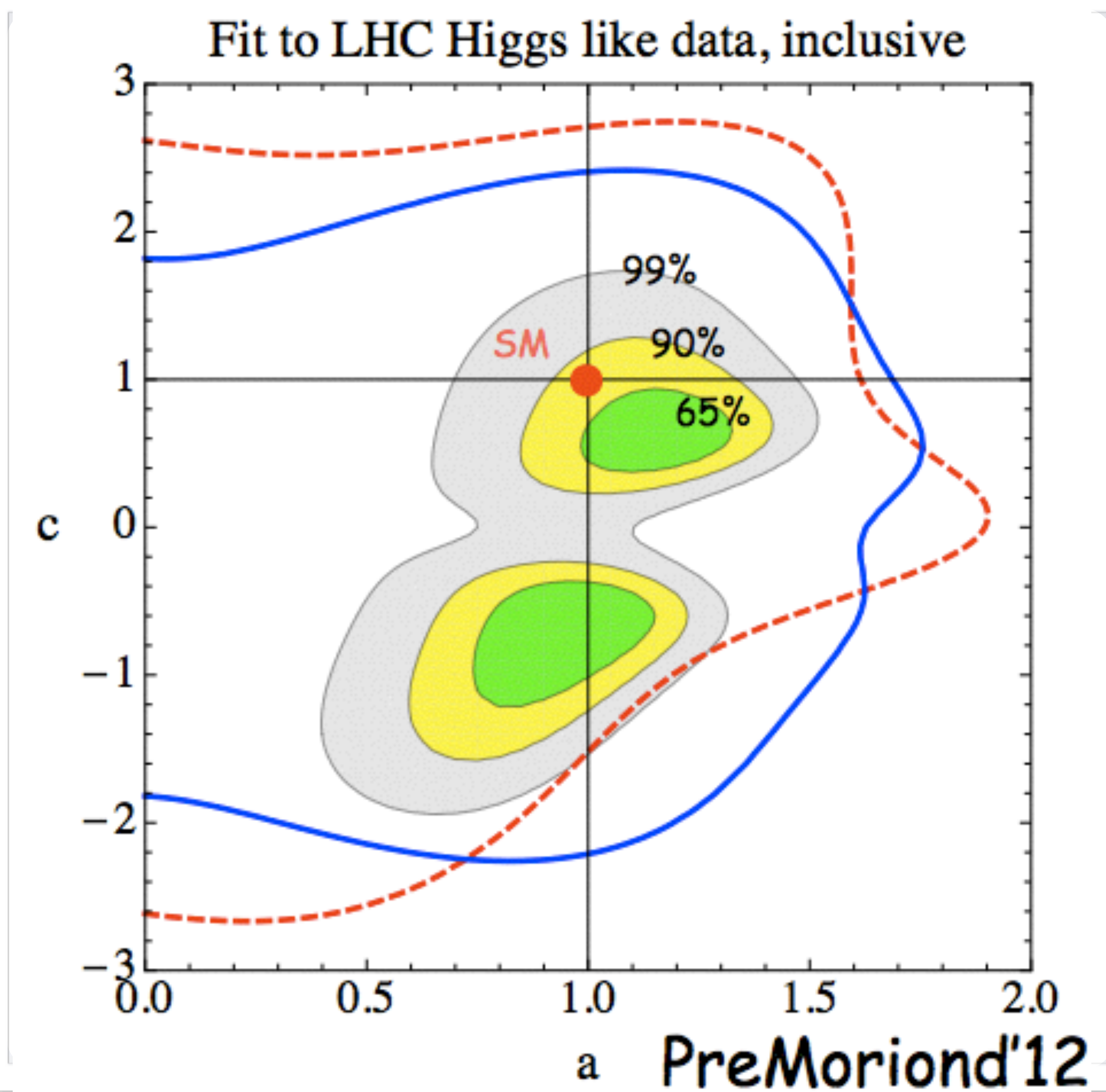
- First (important) question on scalar- is it converging on the SM case to raise the cut off scale?

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

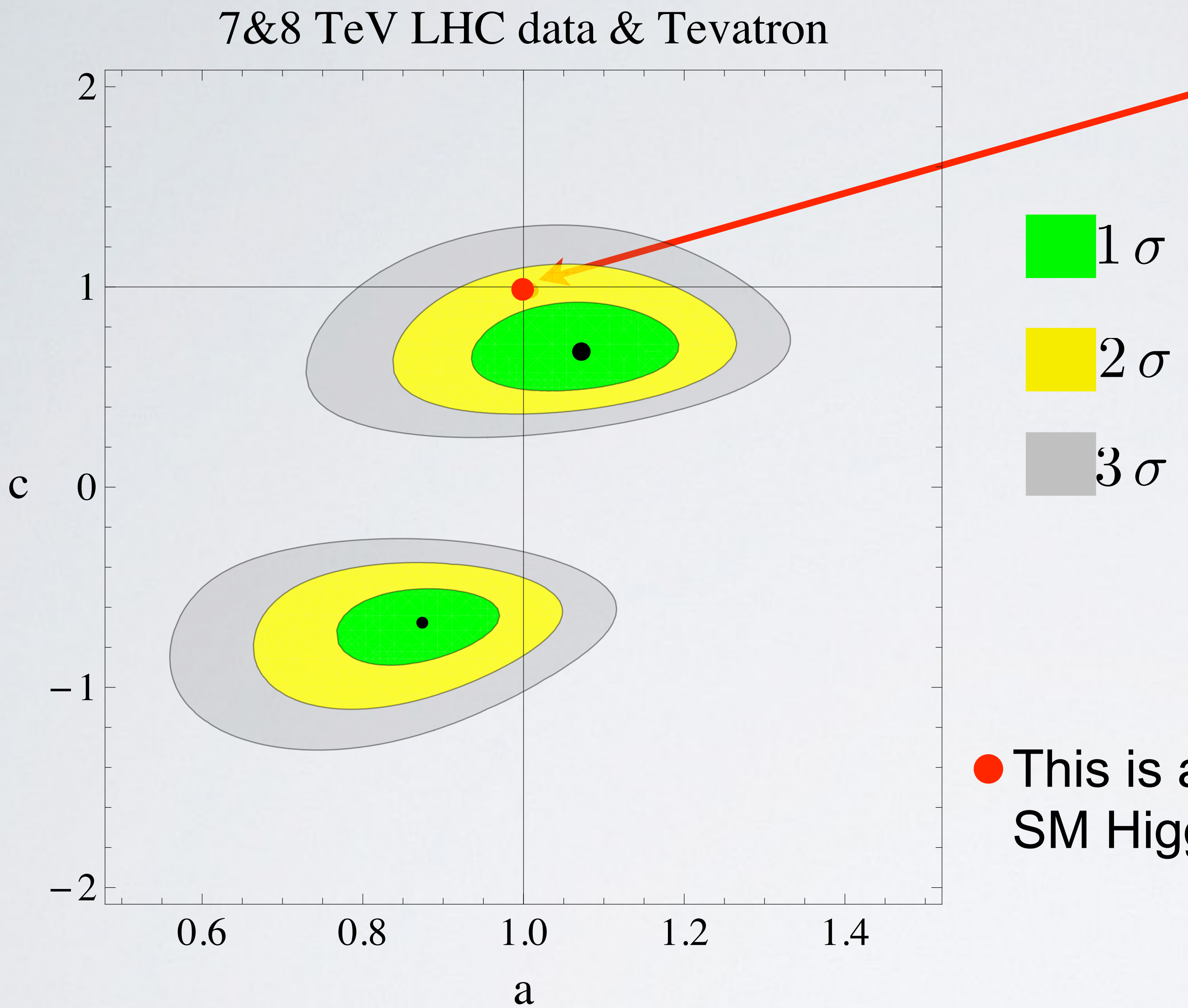
90% CL

99% CL

Espinosa, Grojean, Mull, Trott arXiv:1202.3697

Fastest paper of my life.

It got better.



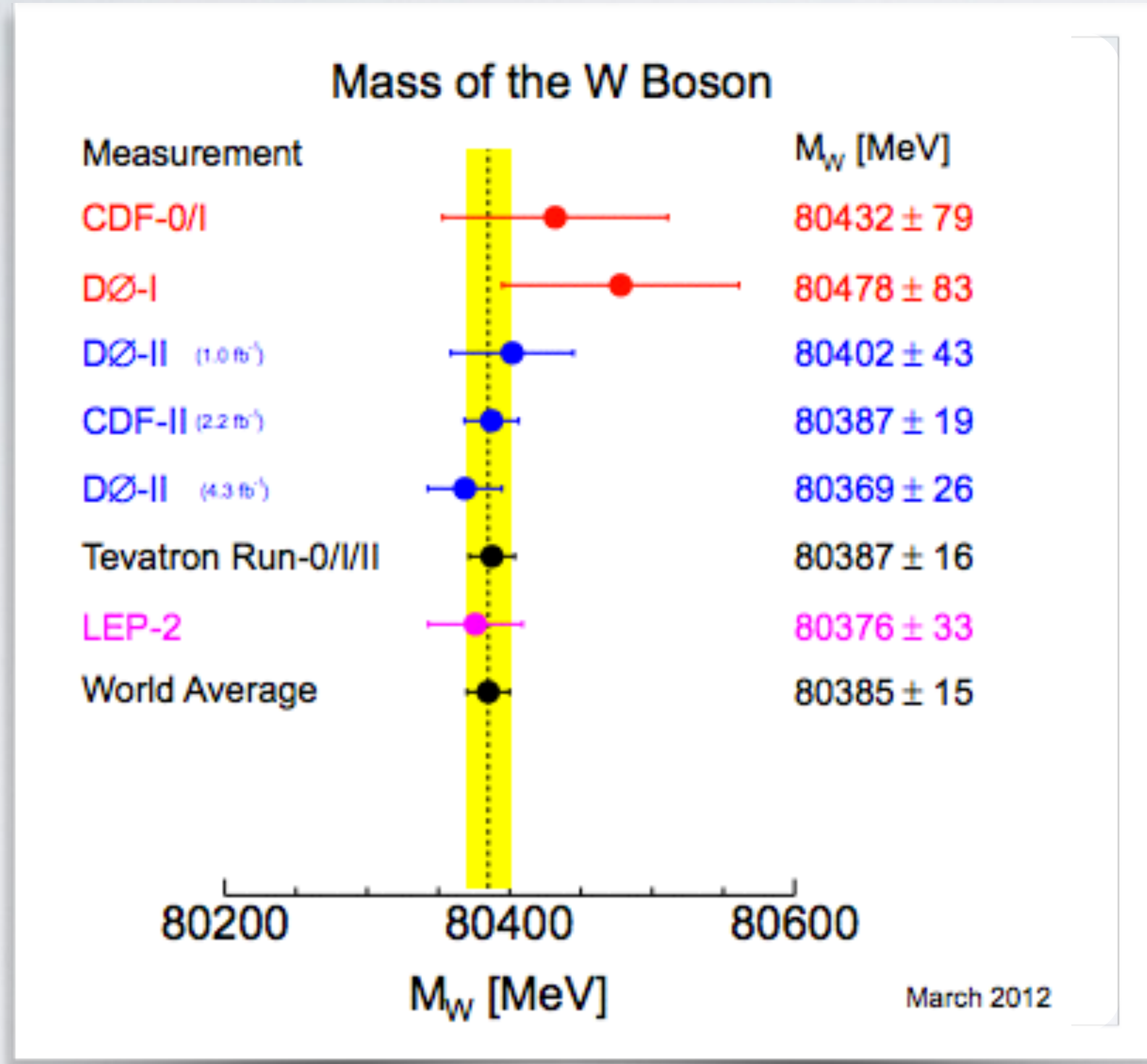
Espinosa,Grojean,Muhlleitner,Trott
JHEP 1205 (2012) 097 arxiv:1207.1717

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 $80.385 \pm 0.015\mathrm{GeV}$

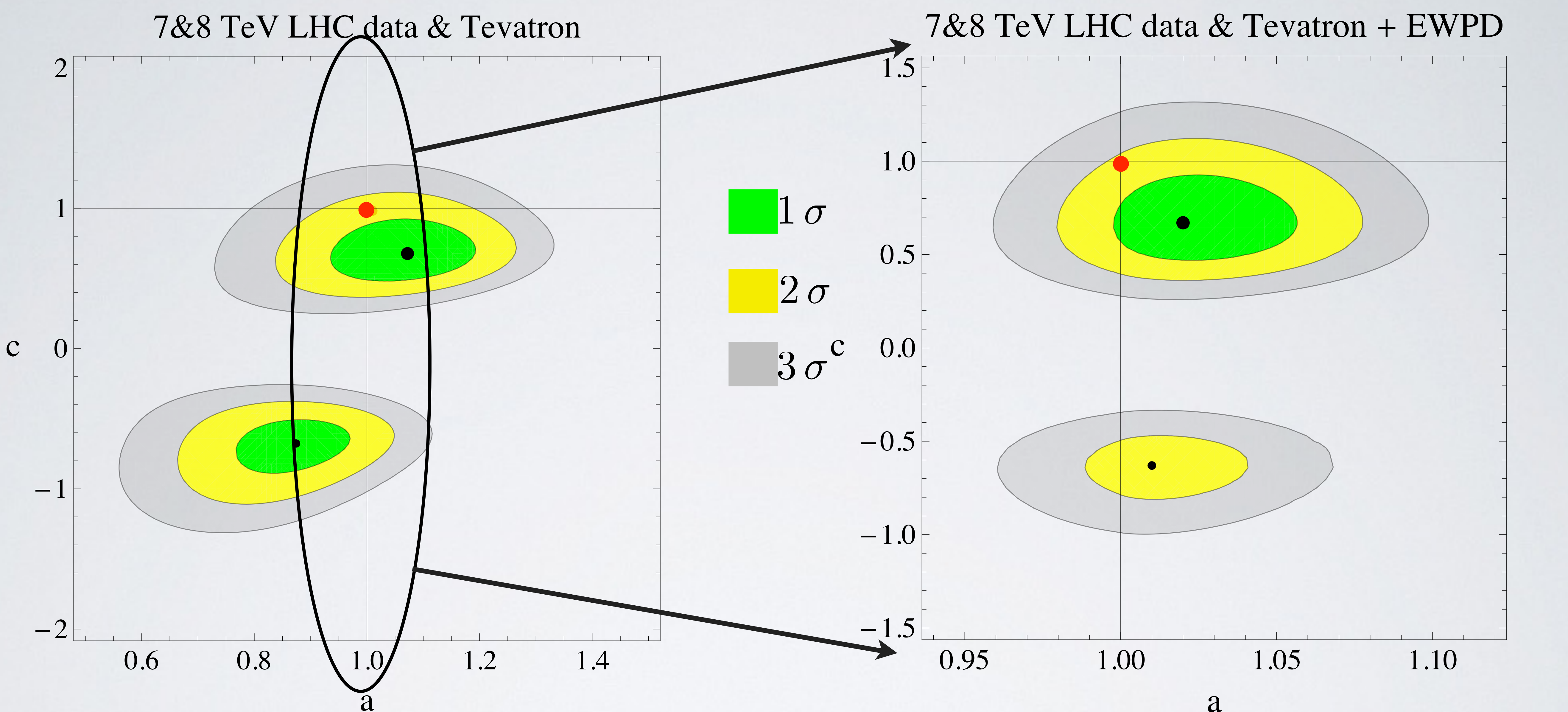


- One of the lasting important legacies of the Tevatron, a powerful measurement! Most important "Higgs" data from the Tevatron (I.M.O.) is the W mass.

- IMPORTANT LESSON - IT IS NOT JUST ABOUT THE HIGGS.

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.



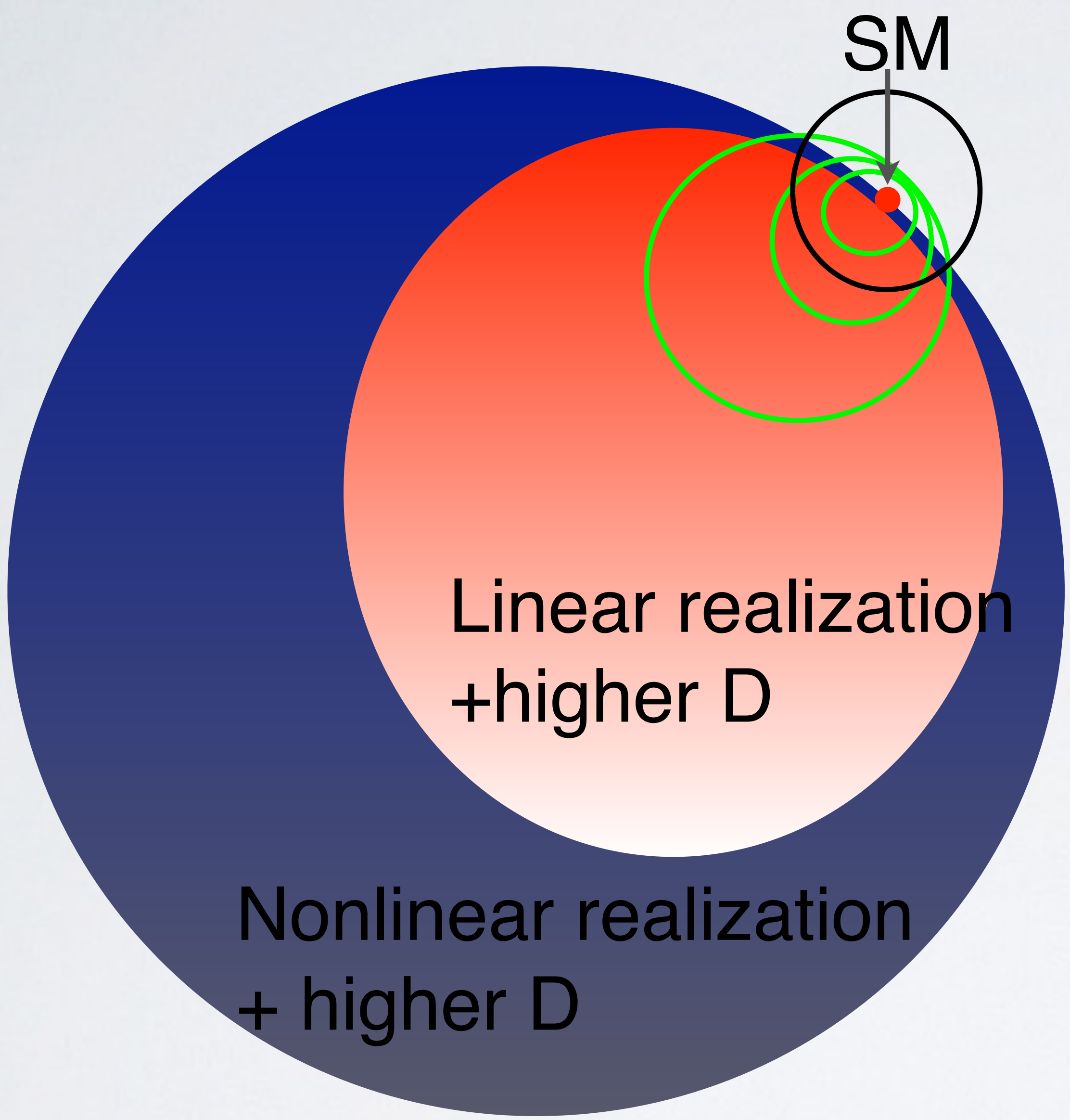
Notice “a” scale changed significantly

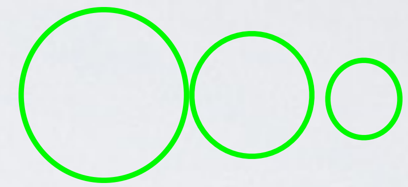
- Used the recent updated W mass measurement at the Tevatron.*

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

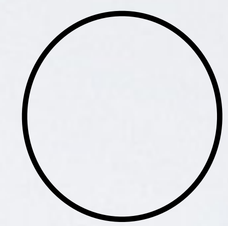
*Thanks to J. Erler for provided the EWPD fit output on short notice.

What is the picture?





Cut off scale raising above the ew scale



Run I LHC

The SM EFTs approach in one venn diagram.

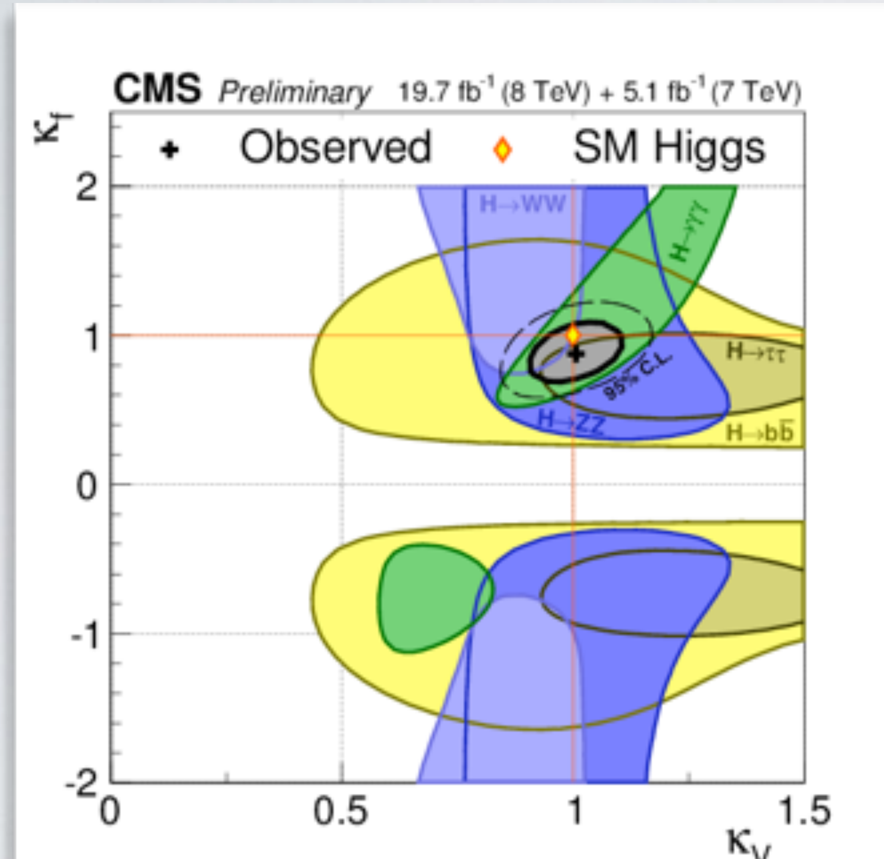
- Linear EFT $H \supset h$ and relations between measurements that follow from this hold
- Non-Linear EFT, singlet h in formalism. Broader range of relations between measurements.

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

arXiv:1402.1467 Burgess, Patil, Trott

Recent slight revisions in data

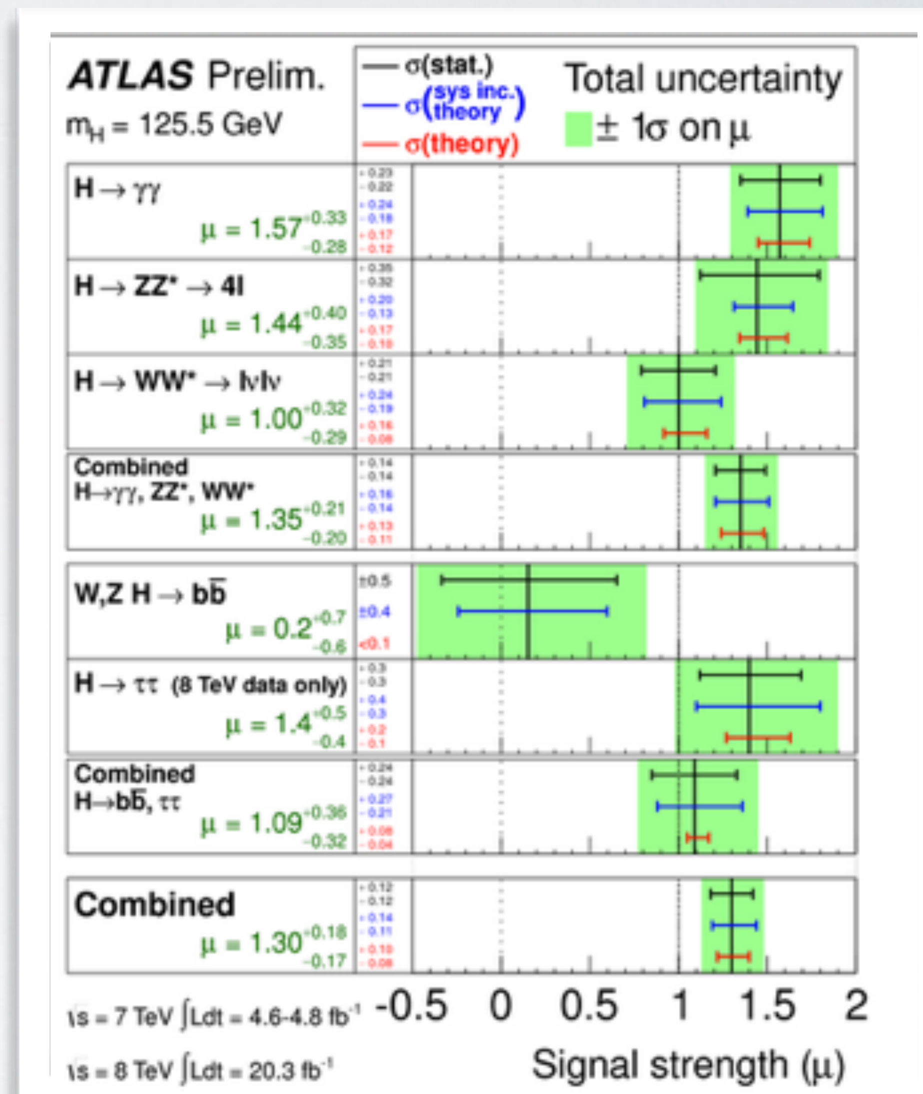
- Current Higgs data:



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.



Current state of Higgs 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 useful data is a signal strength (currently)

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

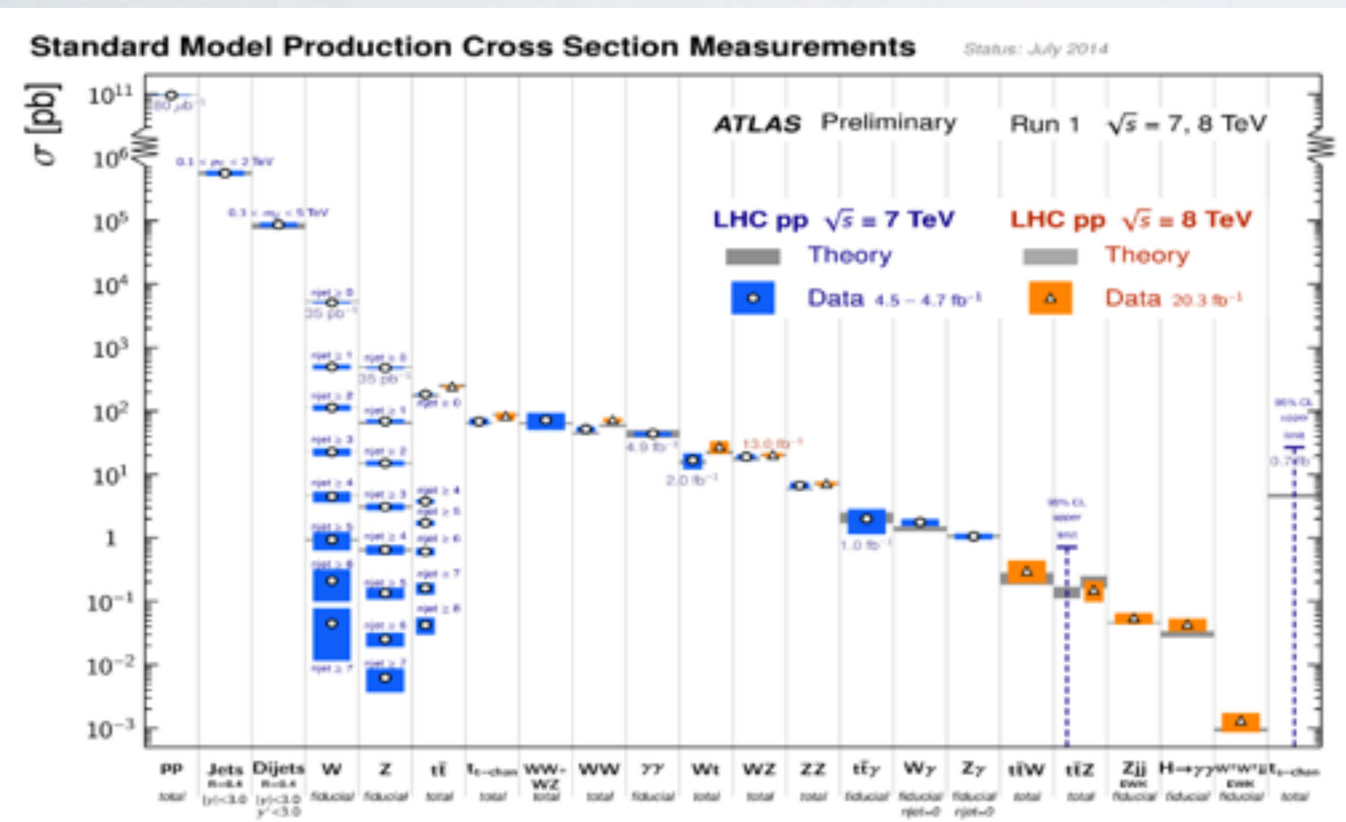
$$\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}} \,, \qquad \chi^2(\mu_i) = \sum_{i=1}^{N_{ch}} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

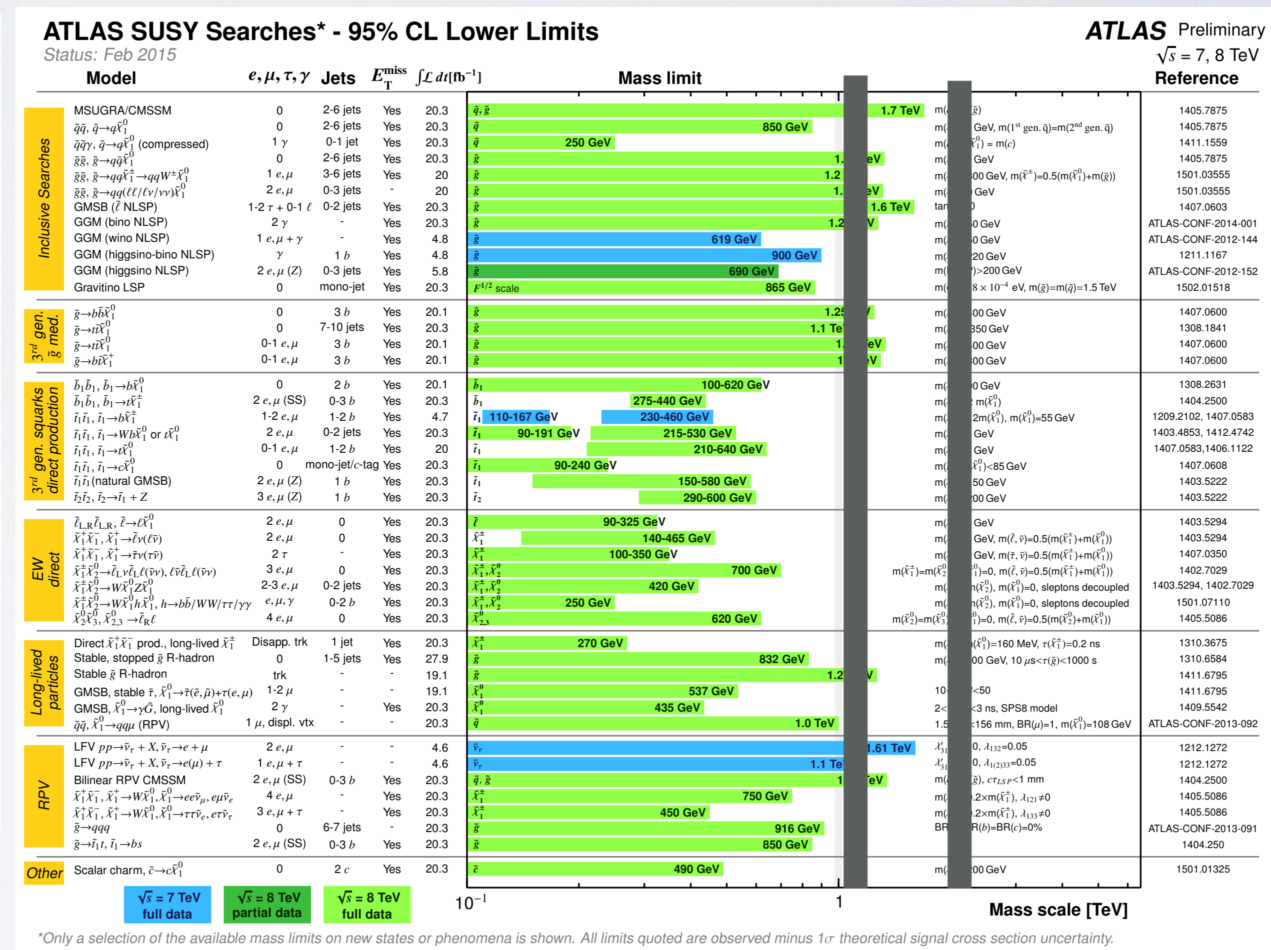
This should be generalized to a full off diagonal error matrix including correlations. But such information is not supplied (for the most part) from the experiments.

This modifies $\mu^i_{SM} \to \mu^i(a,c)$ and leads to the "kappa formalism".

Current state of affairs:

- Whatever is going on it involves a (mostly) 0^+ field.
- Deviations “naturally” expected not robustly ruled out, but very hopefull scenarios not looking good.





- Optimistic scenarios (remember LHC inverse problem?) out the window, hard grind to extract from the data the detailed story started.

Current state of affairs:

- What is the plan going forward:

> ...we just calmly laid out all the options,
> and failure was not one of them.
>
> *Jerry C. Bostick*
> *Flight Dynamics Officer (FDO) Apollo 13*

- Will talk about a couple things going on:

  Attempts to systematise data reporting in pseudo-observables

  Rare higgs modes in the SM and beyond.

  Developing precision constraints in the SMEFT

  Developing theoretical calculations to NLO in the SMEFT.

Test the derivative expansion

A lot more information in a Higgs decay than just the inclusive signal strength

In the EFT interpretation this corresponds to studying the derivative expansion:

- 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.

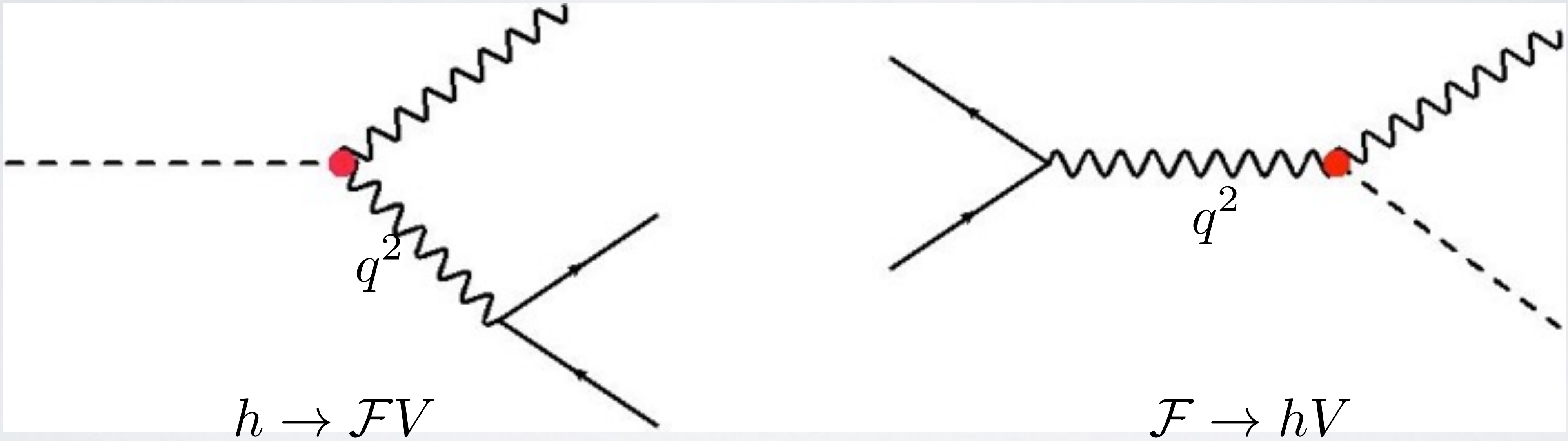
- Can establish what the formalism is by looking for evidence that the linear realization cannot (directly) accommodate the data going forward.

  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 now 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.

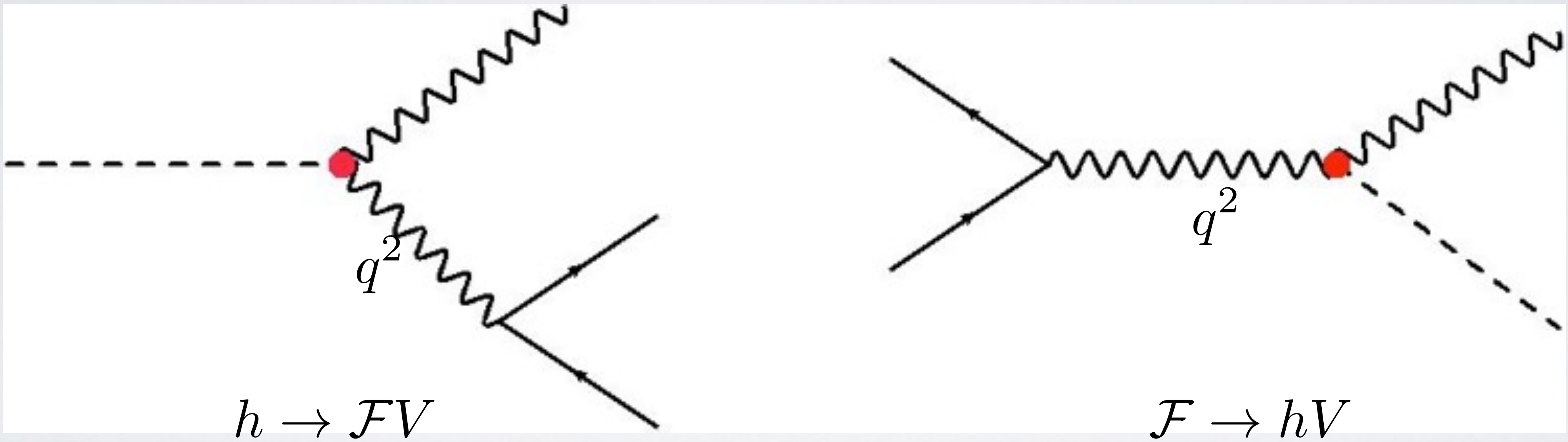
Of course we now know that : $m_h < 2\,m_V$

- 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 now 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: $$\mathcal{L}_J^{\rm SM} = \frac{e}{\sqrt{2}\,\sin\theta_W} J^{\pm}_{\mu} W^{\mu}_{\pm} + \frac{e}{\sin\theta_W \cos\theta_W} J^0_{\mu} Z^{\mu} = \sum_V C_V g_V J^V_{\mu} V^{\mu} \,.$$

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

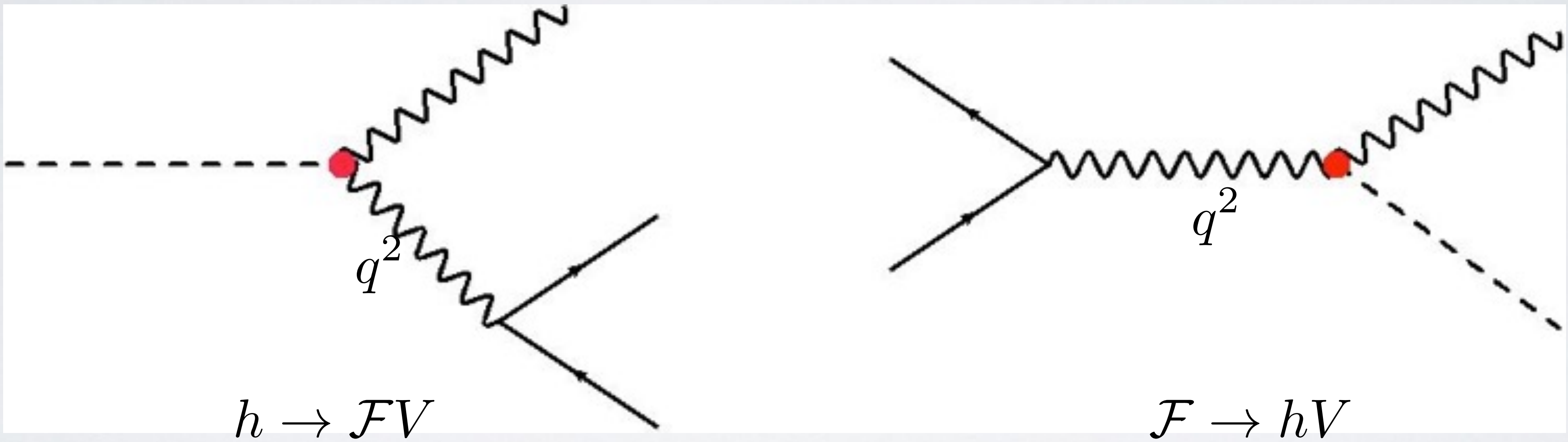
While h-> VF is $$\mathcal{A}\left[\bar{\psi}\psi(q) \to h\, V(\tilde{\epsilon}, -p)\right] = \mathcal{A}_V^{\psi\bar{\psi}},$$

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

Test the derivative expansion

- We are now 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:

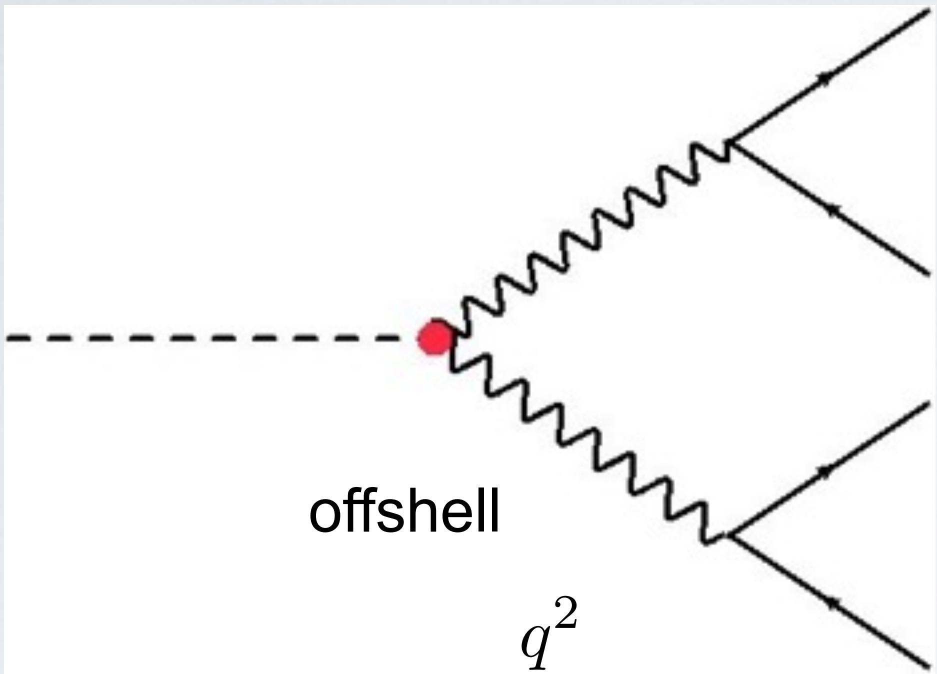
$$\boxed{\frac{q^2}{m_v^2} \gg 1}$$

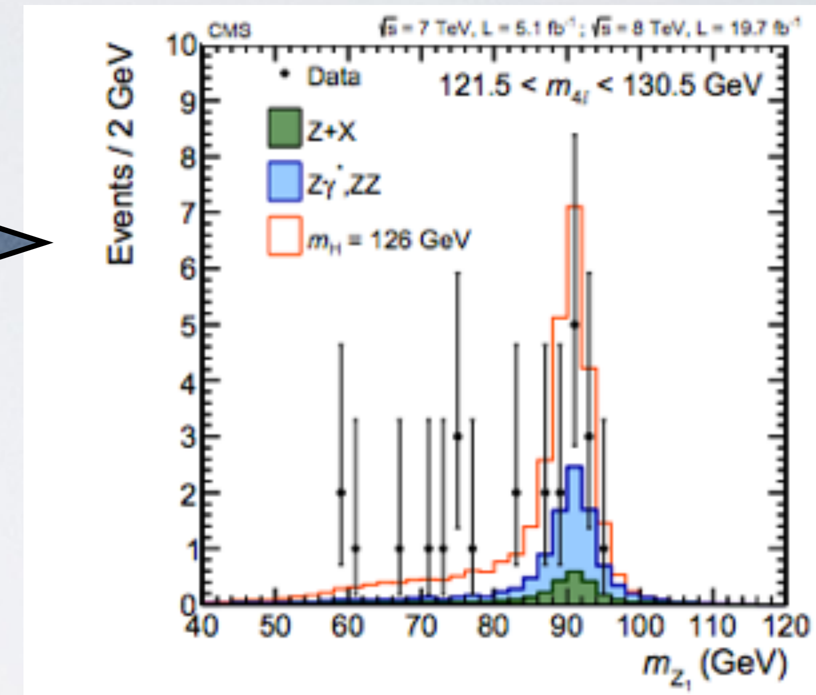
More sensitivity, but also close to EFT expansion failing (also an issue in TGC)

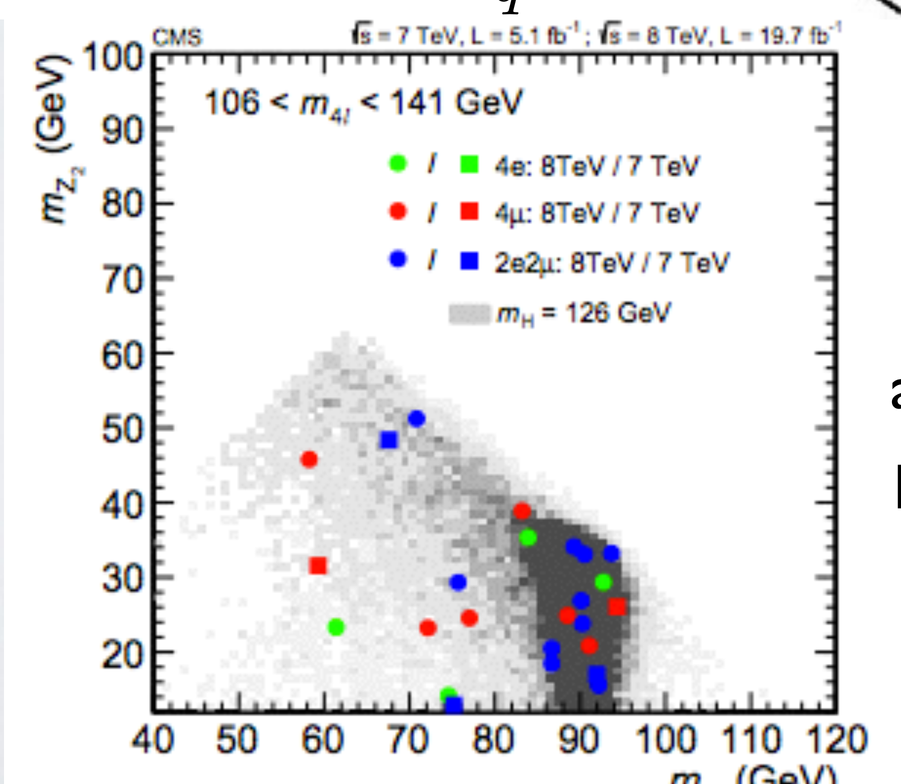
Longer term, need more events.

Establish the EFT in the golden channel

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

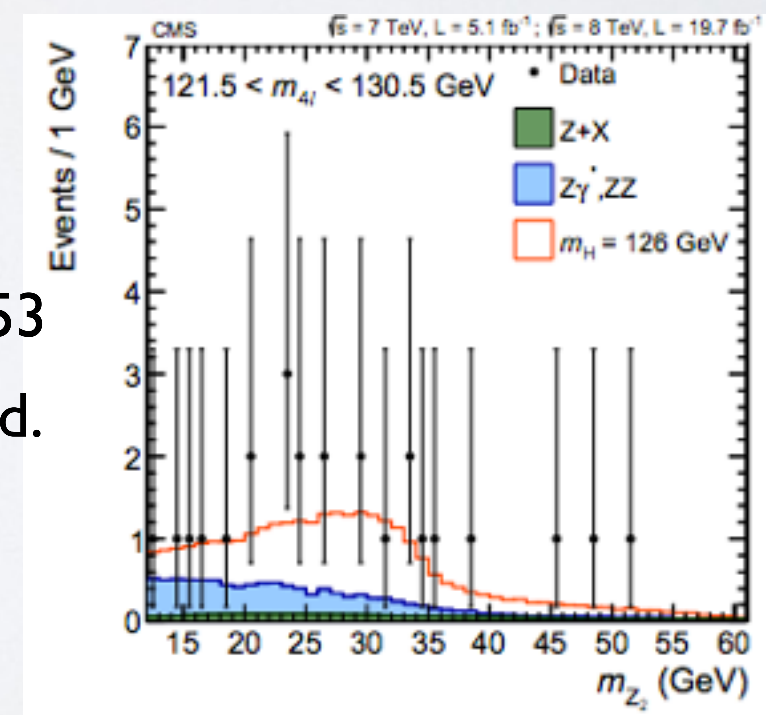




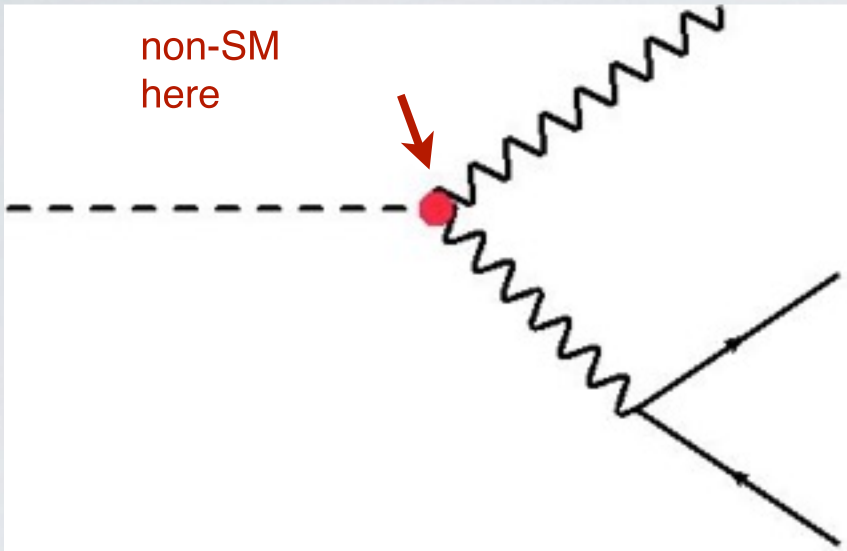


Recent CMS analysis 1312.5353

Event rate limited.

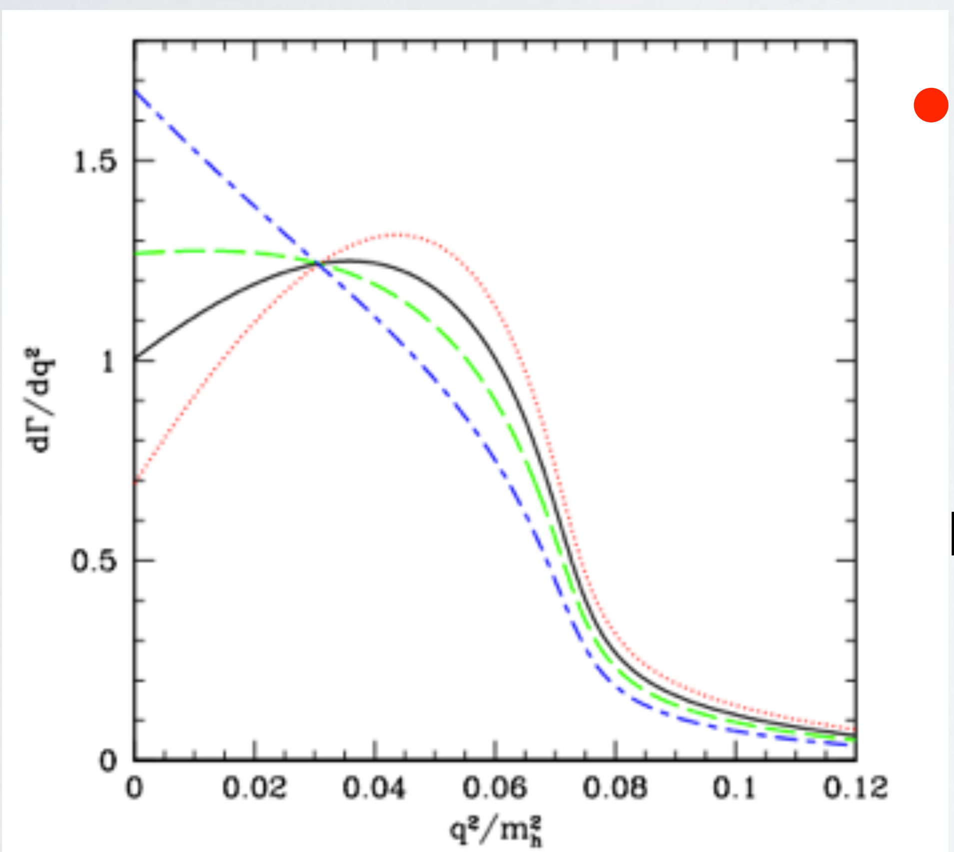


Establish the EFT in the golden channel



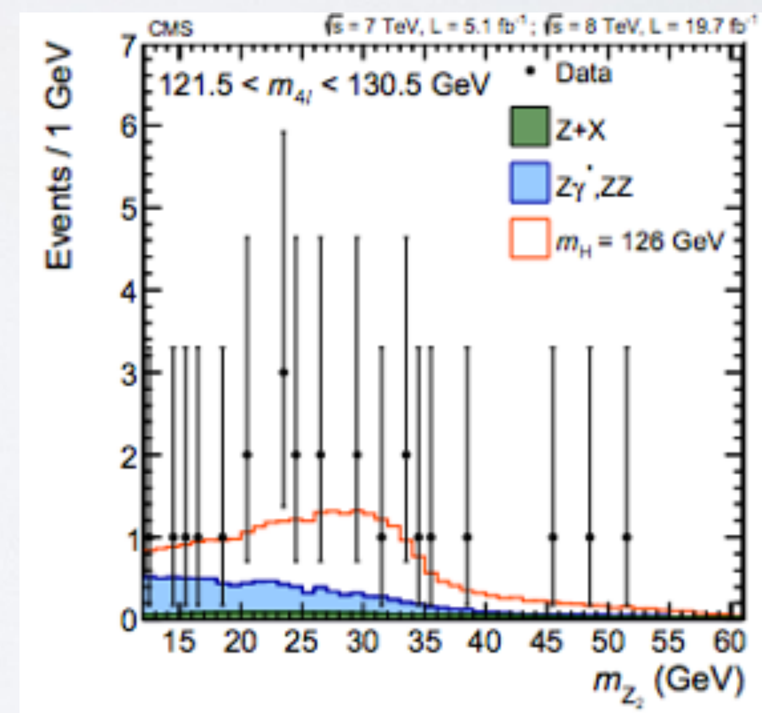
With sufficient data, a tight cut on the reconstructed on shell vector mass, study the 3 body distribution (can then combine vector decay modes)

shifted to
minimal
bi-lepton
distribution
(V reconstructed)



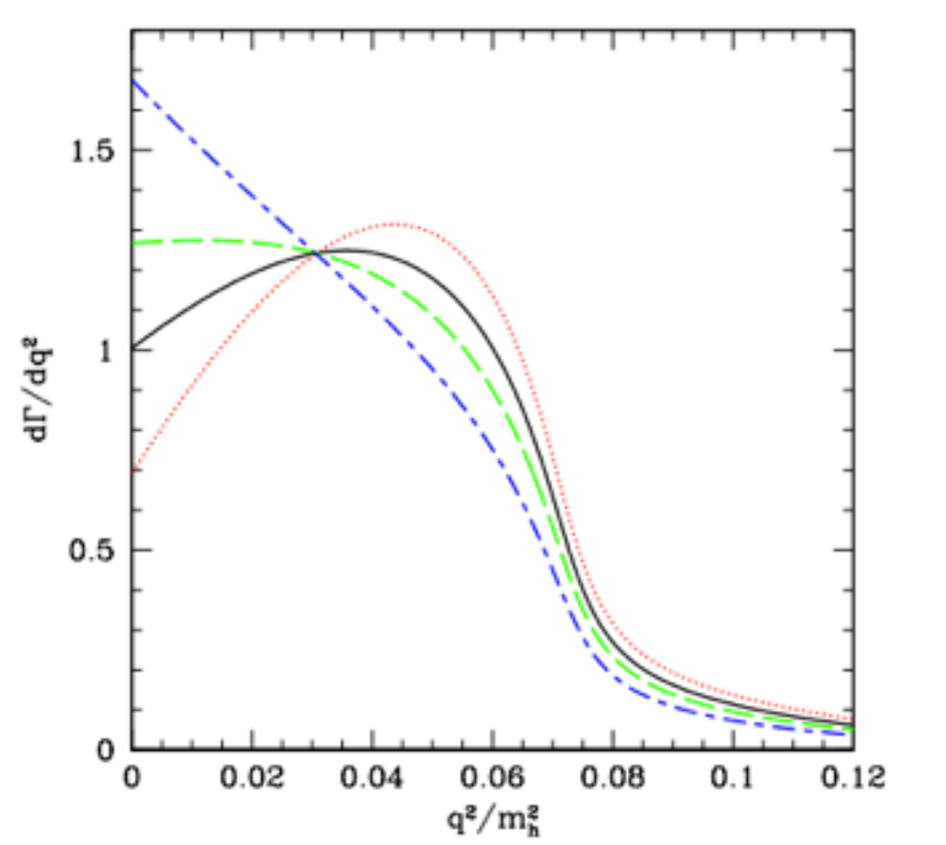
- Total signal strength the same, significant shape variations possible in offshell q^2 spec. (Photon pole neglected here).

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 SOME deviations in this spectra are bounded by non- 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)

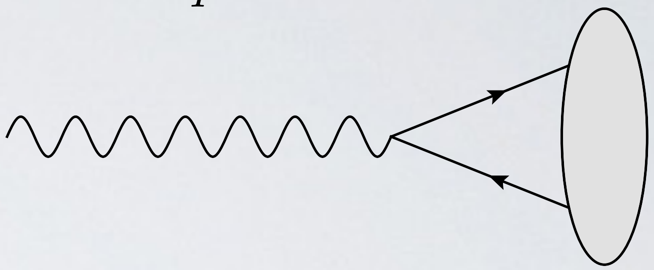
- For this reason, consistency checking any deviations against all other SMEFT constraints a very hot topic.

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

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.

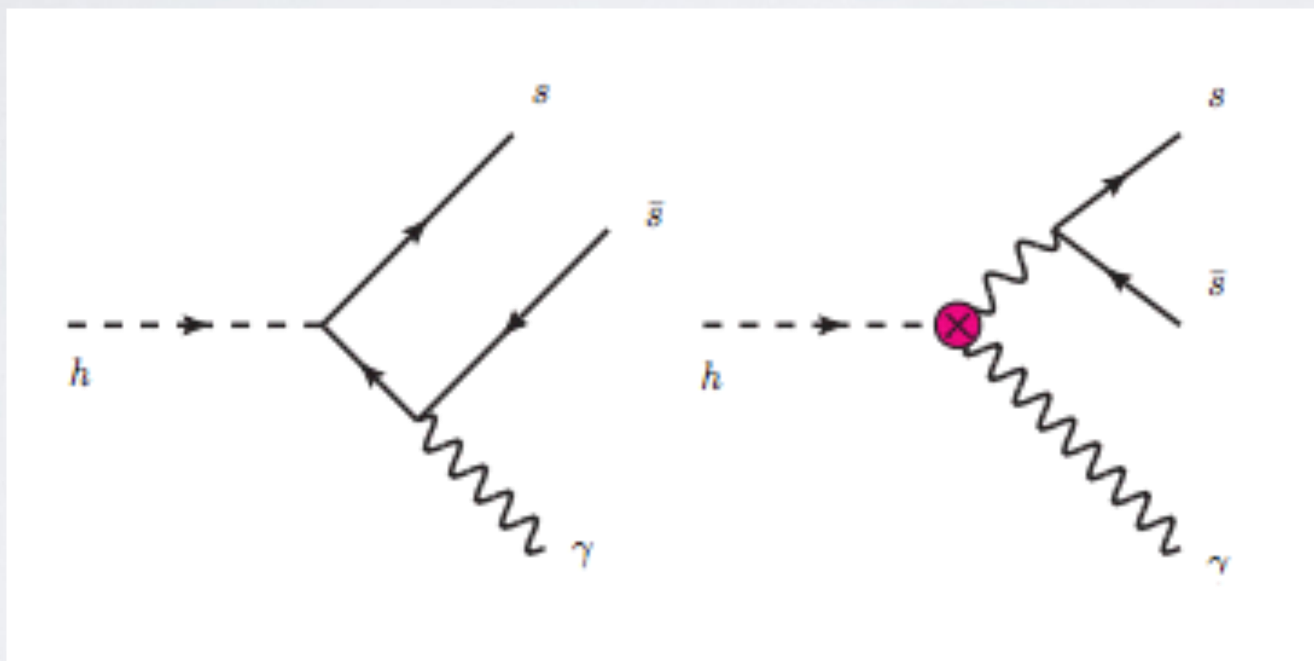
- These decays TEST the ratio of the two scales characterizing the breaking of SU(2)xU(1) How cool is that?
- Now a hot topic since 1305.0663 Isidori, Manohar, Trott

see: 1410.7475 Mangano, Melia, 1406.1722 Kagan et al. 1501.06569 Grossman 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.



EW part we calculated still dominant.

- 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 EFFICIENTLY.

NLO EFT - can we do it?

- (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}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

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

- 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:

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

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

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

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

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

What is the theory?

This seems fearsome. Lets add to the fear.

- 59+ h.c operators, but many have flavour indicies, take them seriously.

$$\left[107 n_g^4 + 2 n_g^3 + 135 n_g^2 + 60\right]/4$$

Alonso,Jenkins,Manohar
Trott arXiv:1312.2014

- for ng generations the total number of dim 6 CP even + CP odd parameters is

$n_g = 1$ total parameters 76

Need to use this to test MFV.

$n_g = 3$ total parameters 2499

This is the linear SMEFT.

- 

Practically can reduce the number of relevant parameters to about 50 or so using approximate flavour symmetry and neglecting CP violation, using scaling when near resonances..

If we find a pattern of deviations

- What does it MEAN? In terms of the underlying theory at a few TeV?
- 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.

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	$\lambda^2, \lambda g^2, g^4$	$\lambda y^2, y^4$	$\lambda y^2, \lambda g^2, \cancel{y^4}$	0	$\lambda g^4, g^6$	0	$\cancel{\lambda g^6}$
H^4D^2	0	λ, y^2, g^2	$\cancel{y^2}$	y^2, g^2	0	$\cancel{g^4}$	$\cancel{y^2 g^2}$	$\cancel{g^6}$
$y\psi^2H^3$	0	λ, y^2, g^2	λ, y^2, g^2	λ, y^2, g^2	λ, y^2	g^4	$\cancel{g^2}\lambda, g^4, g^2y^2$	$\cancel{g^6}$
ψ^2H^2D	0	g^2, y^2	$\cancel{y^2}$	$g^2, \cancel{\lambda}, y^2$	g^2, y^2	$\cancel{g^4}$	$\cancel{g^2 y^2}$	$\cancel{g^6}$
ψ^4	0	0	0	g^2, y^2	g^2, y^2	0	g^2y^2	$\cancel{g^6}$
$g^2X^2H^2$	0	$\cancel{1}$	0	$\cancel{1}$	0	λ, y^2, g^2	y^2	g^4
$gy\psi^2XH$	0	0	$\cancel{1}$	$\cancel{1}$	1	g^2	g^2, y^2	g^4
g^3X^3	0	0	0	0	0	$\cancel{1}$	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

Post Modern Discovery Physics

1502.02570 Berthier, Trott

- So what do we do NOW:

LHC
h pole

LEPII
4 fermions

Energy scale:

MFV

EDM's
flavour

80's-90's
colliders,

LEP I
z-pole

Constraint
vectors in
W coeff space

- the vectors rotate as you change scale..

1308.2803 Pomarol, Riva.
1411.0669 Falkowski, Riva.
1409.7605 Trott
1503.07872 Efrati et al.

- To combine the various constraints consistently take into account they rotate as you change scale..
- Any future discovery has to be projected back on these constraints to check consistency..

"Near pole" EWPD vs. TGC

- The Z pole measurements are not debatable - they range in precision from percent level to 10^{-3} precision.

- Due to near pole EWPD should we set non TGC parameters to 0 in a TGC measurement? My opinion - no.
  Why are past constraints too strong?

(this is the actual Dr. No.)

- It is well defined to construct a χ^2 from EWPD near pole data.

- Challenges are : Specifying the theoretical error in the SMEFT to build the χ^2 correctly. Perturbative corrections do matter.

  Past fit efforts ignored the theoretical error in the SMEFT (and sometimes in the SM) when fitting.

  Mapping χ^2 to space of C_i depends on $\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$

$$\chi^2 = \sum_i a_i C_i \frac{v^2}{\Lambda^2} + \sum_{ij} b_{ij} C_i C_j \frac{v^4}{\Lambda^4} + \cdots$$

Fit space dictated by terms treated inconsistently

People working hard

- Recent progress:

Constructed Observables: 1409.7605.pdf Trott

Towards consistent Electroweak Precision Data constraints in the SMEFT: 1502.02570.pdf

Berthier, Trott

LEP I
z-pole

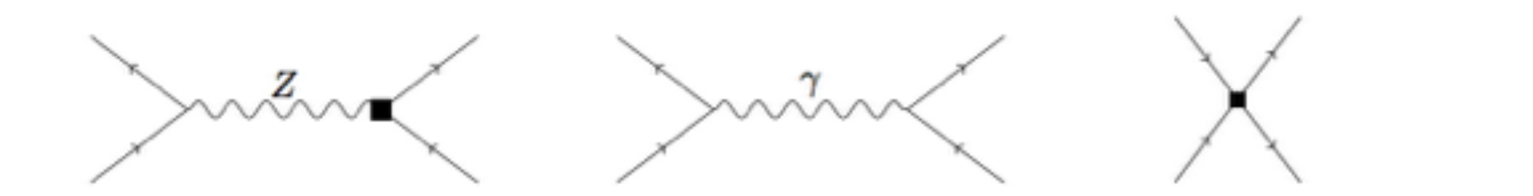
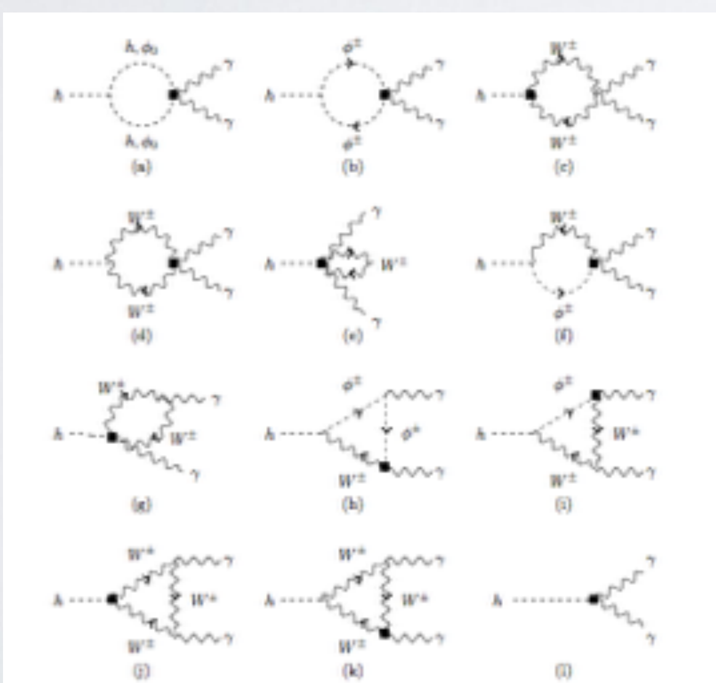


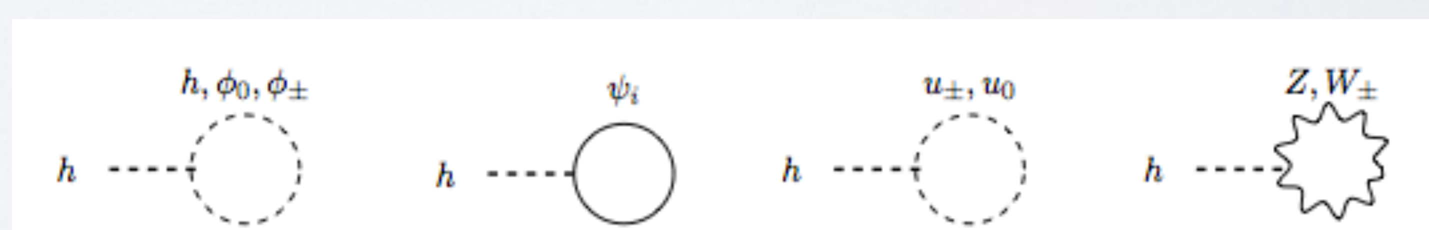
Figure 1. Diagrams contributing to near Z pole $2 \to 2$ scattering in the SMEFT. The black box indicates the insertion of $\mathcal{L}^{(6)}$.



Finite terms in h to Gamma Gamma: 150someday.pdf

LHC
h pole

Hartmann, Trott



The Big Picture going forward