REMEDIOS

- LHC precision tests (di/tri-boson): what is being searched for? -

L=27km

E_{beam}=362MJ

Precision=??

L=35km

E_{train}=362MJ

Precision=10^{-6}

Francesco Riva
(CERN)

In collaboration with
Liu, Pomarol, Rattazzi 1603.03064,
Azatov, Contino, Machado 1607.05236

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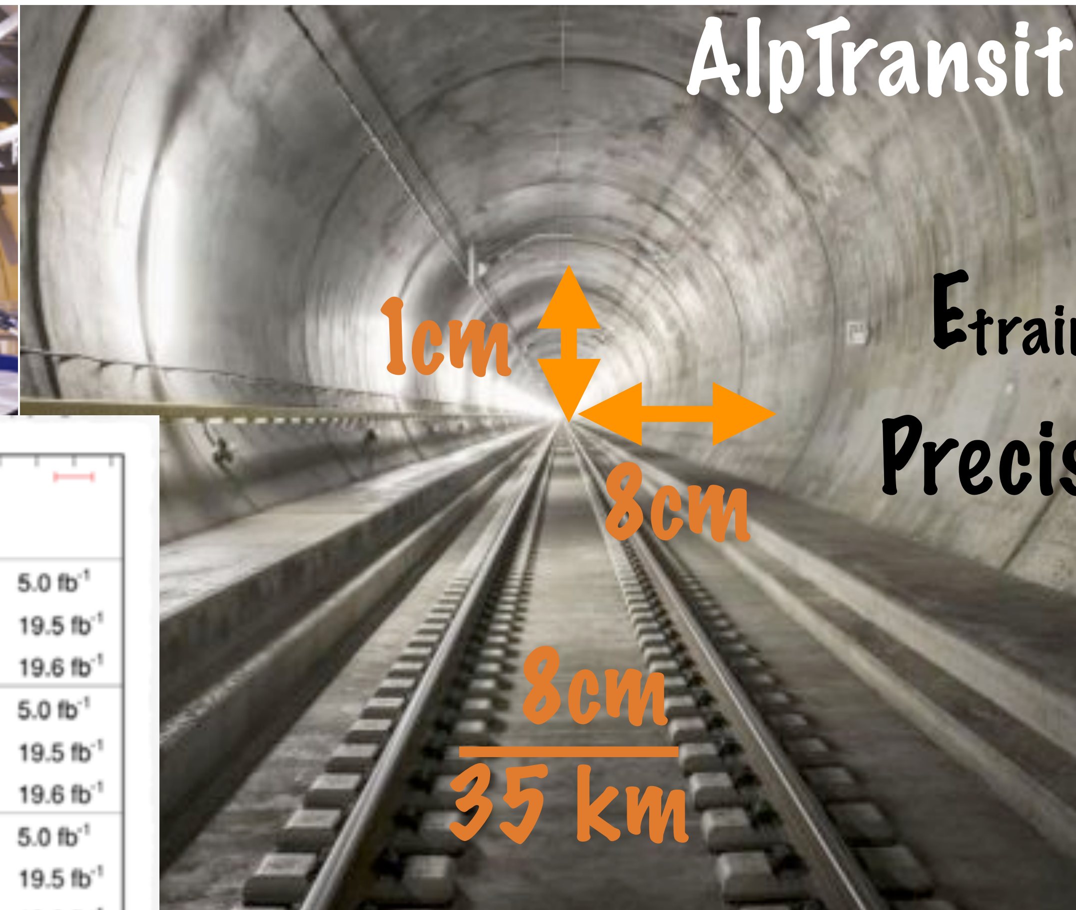

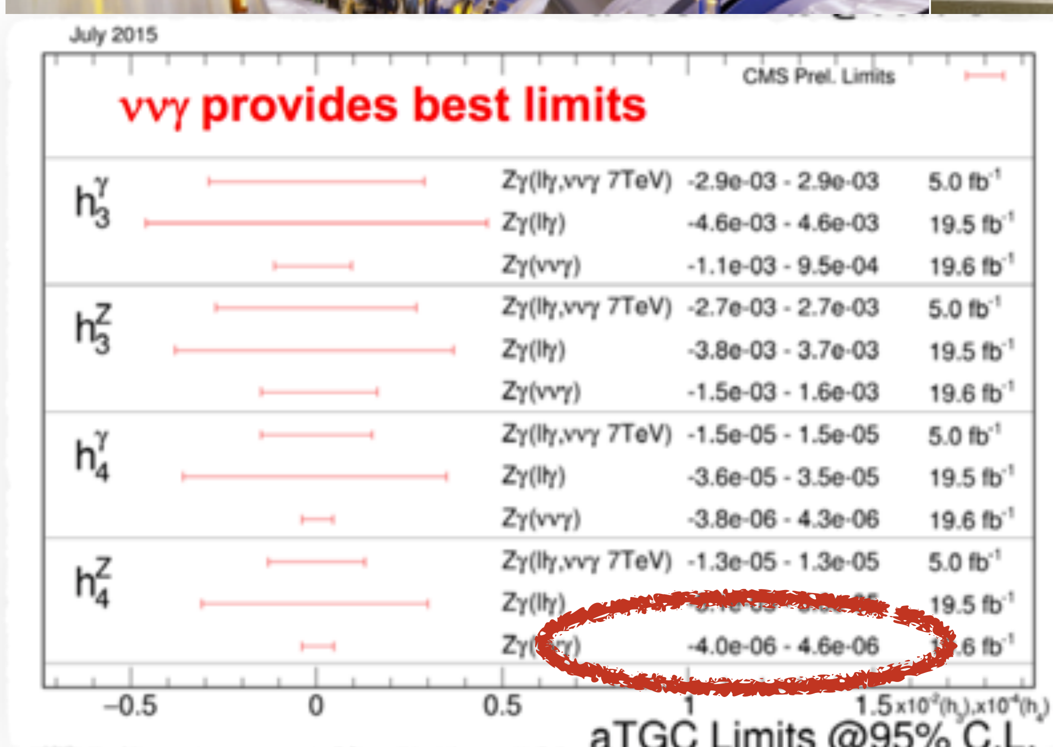

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Two modes of exploration at LHC:

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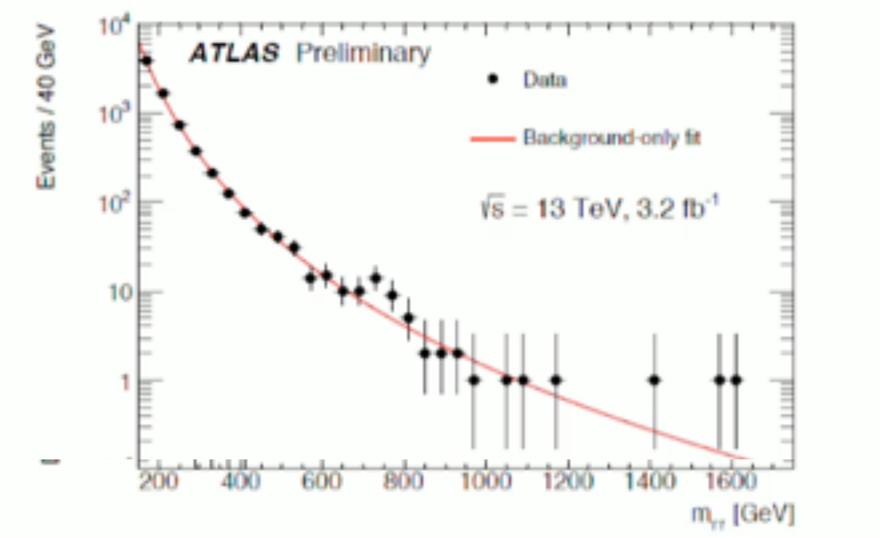

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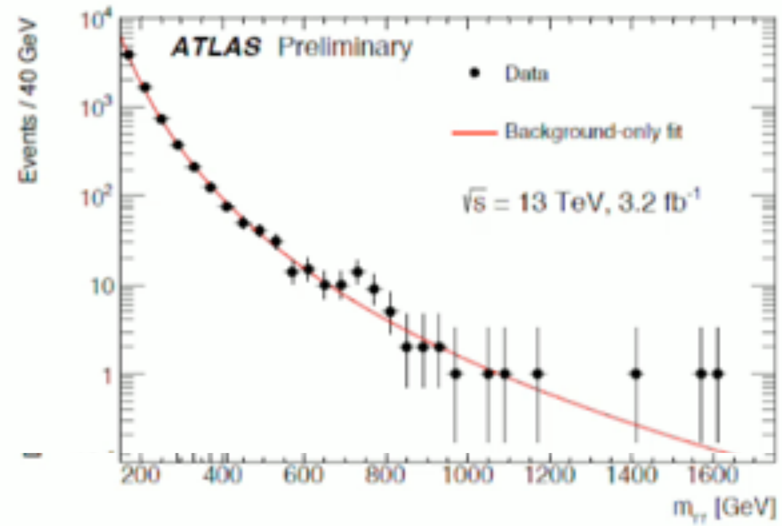

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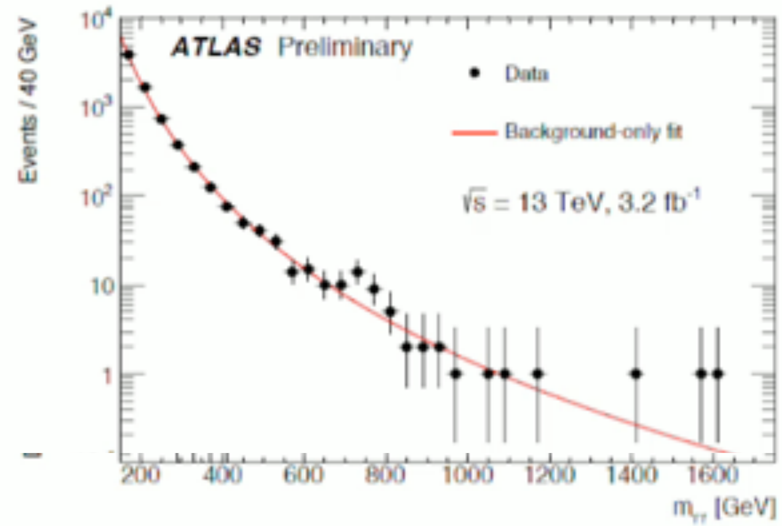

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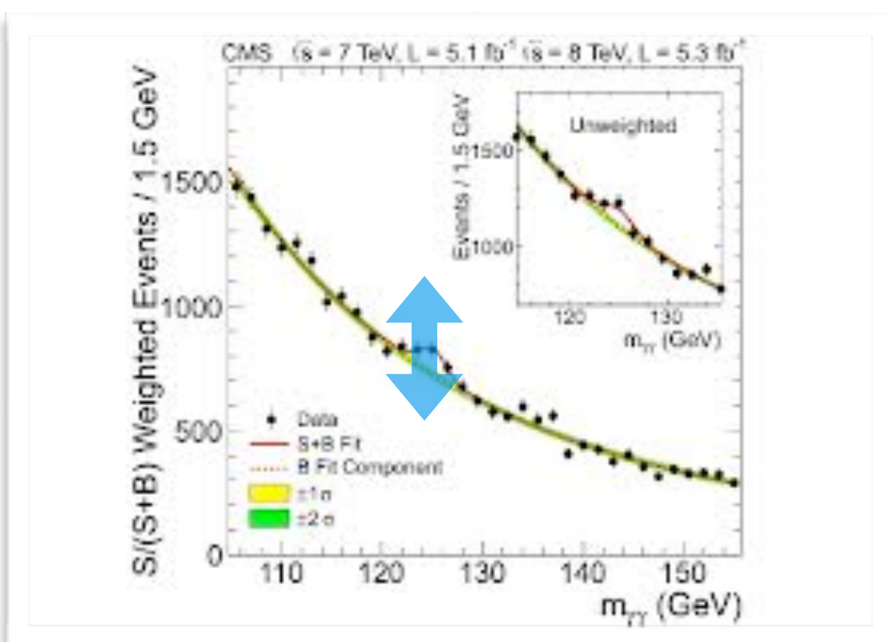

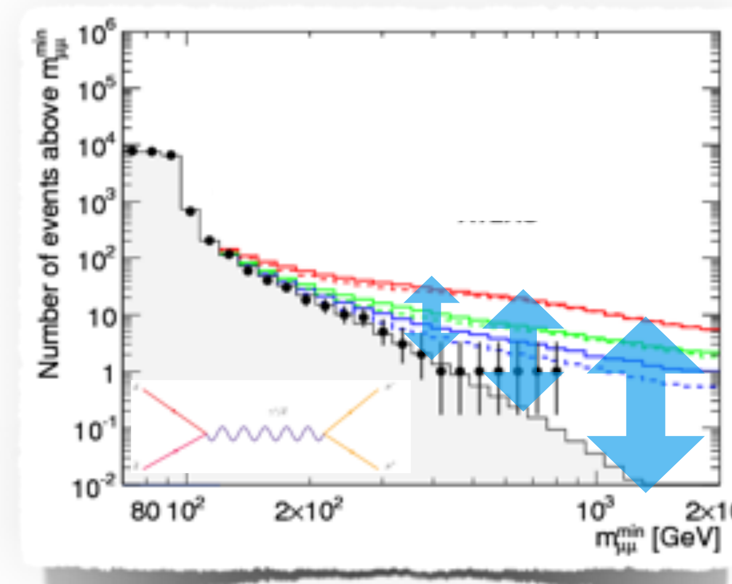

1) On SM resonance $E = m_Z, m_h$

2) Off SM resonance $E \gg m_Z, m_h$

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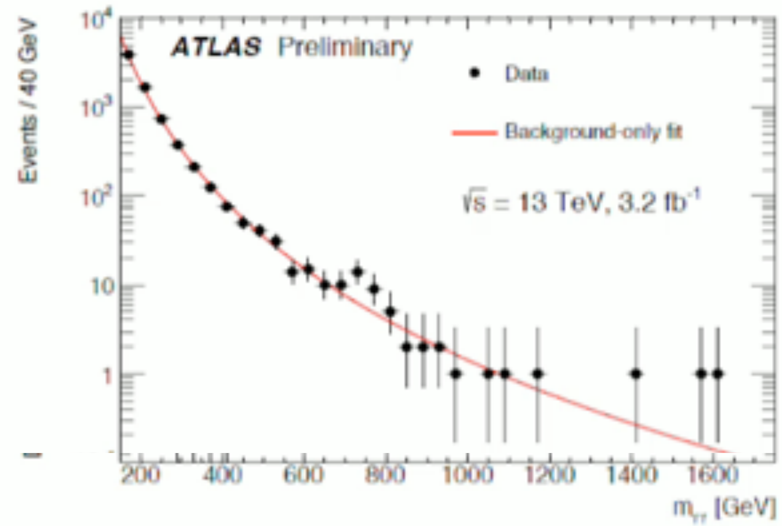

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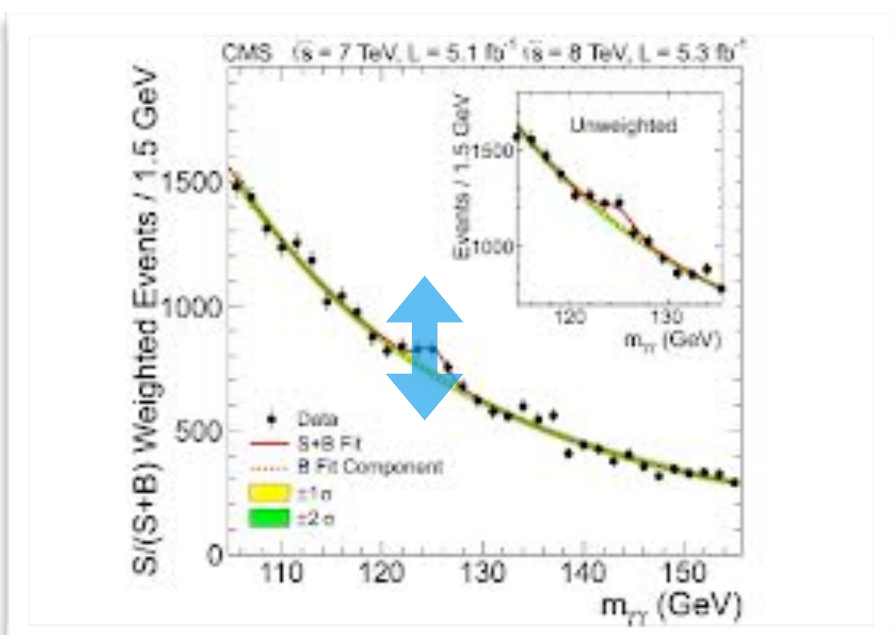
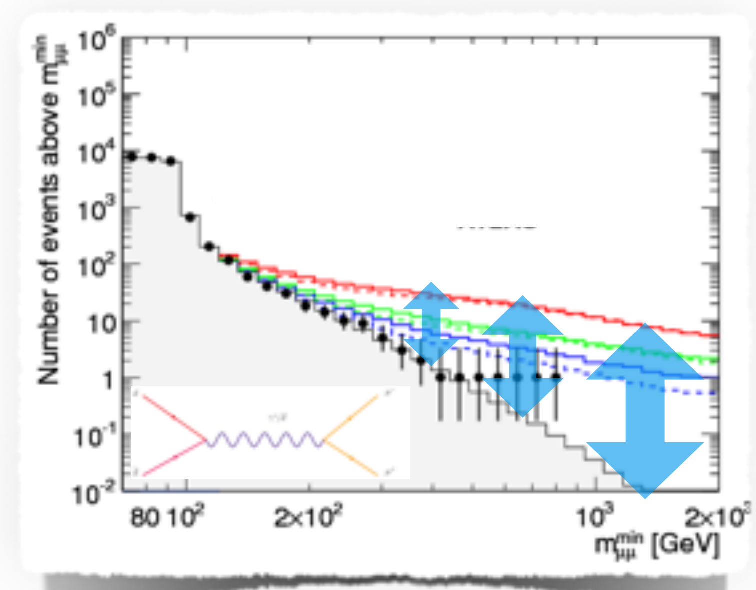




1) On SM resonance $E = m_Z, m_h$

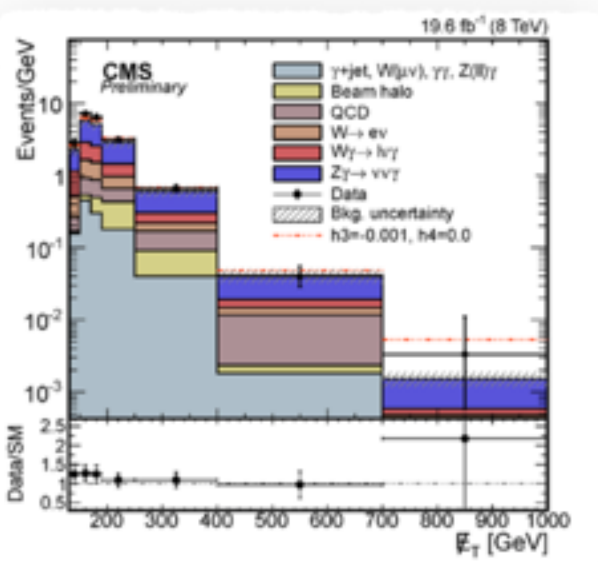
2) Off SM resonance $E \gg m_Z, m_h$

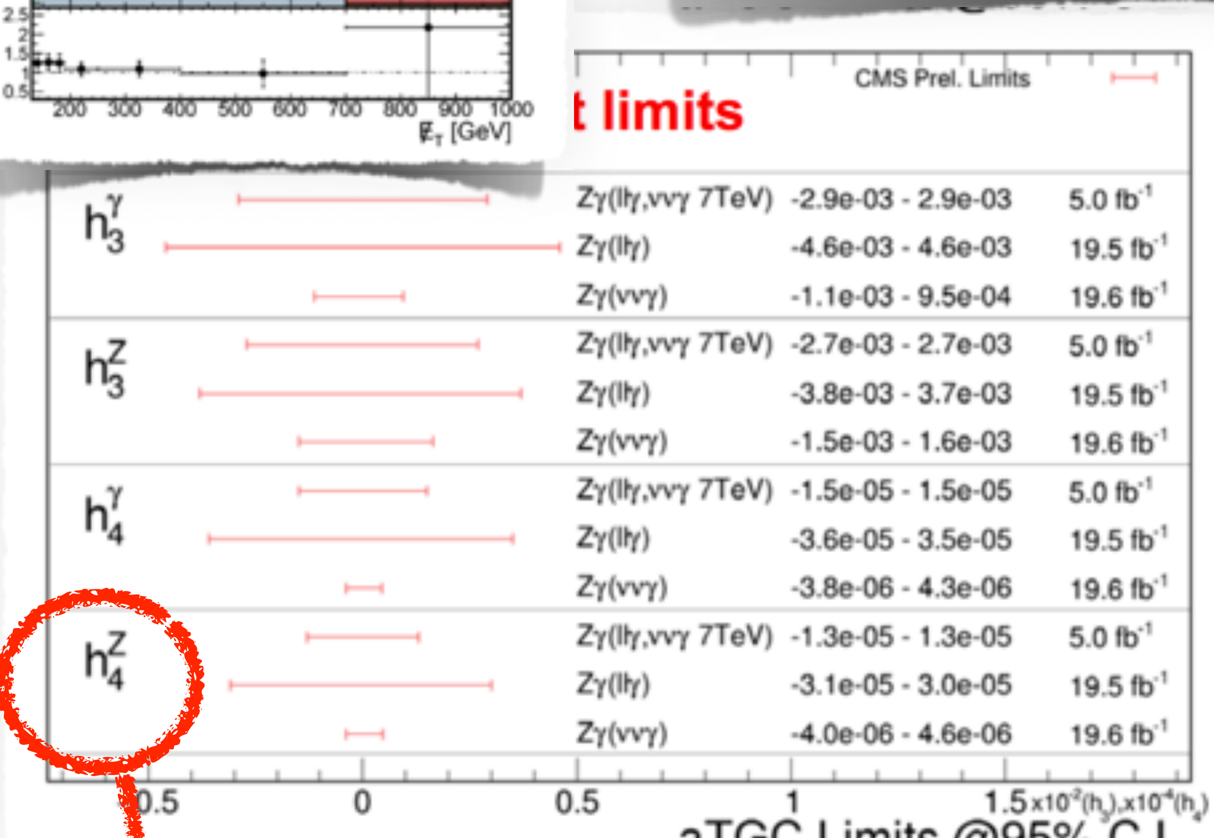
From LHC

Plenty of Data in multiboson processes:

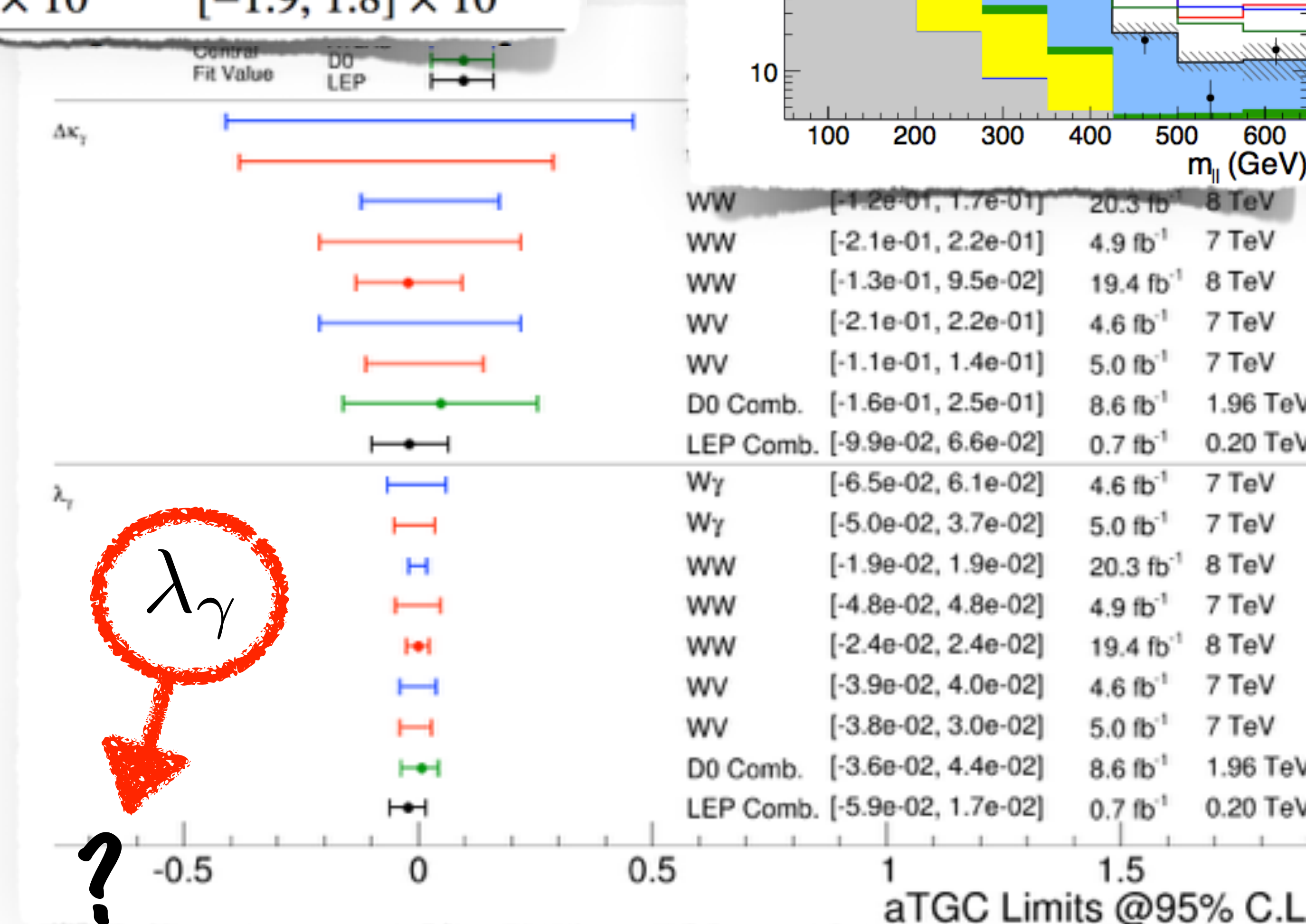
?

		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$



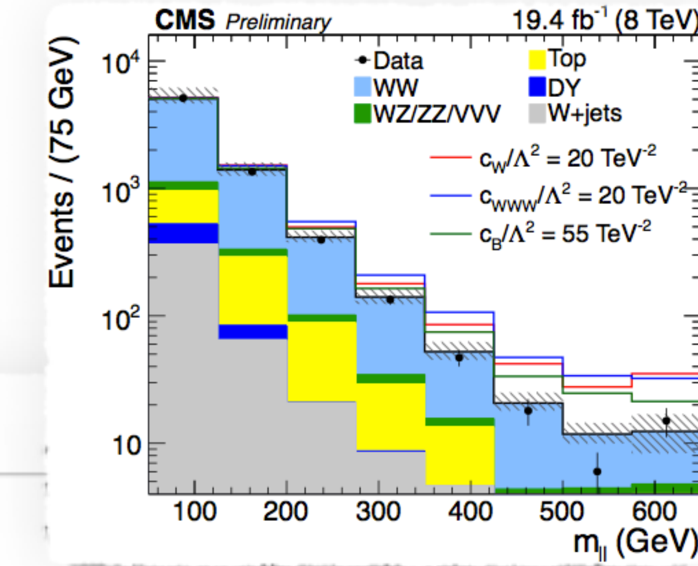


?



λ_γ

?



Why nobody cares?

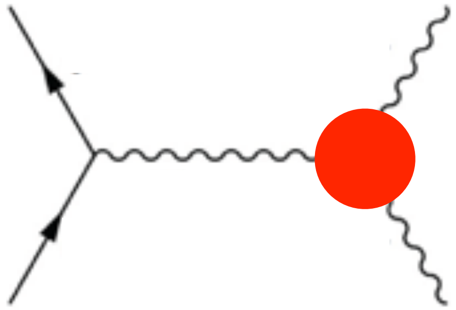
Part 1

why nobody cares

1 Smallness

These parameters $\leftrightarrow$ EFT coefficients:

$\lambda_\gamma \leftrightarrow$	**dim-6**	$\epsilon_{abc} W_\mu^{a\,\nu} W_{\nu\rho}^b W^{c\,\rho\mu}$
$h_3^Z \leftrightarrow$	**dim-8**	$H^\dagger D_\mu H \, D_\rho B_\nu^\rho \tilde{B}^{\mu\nu}$
$f_{T,0} \leftrightarrow$		$W_{\mu\nu}^4$



Involve the transverse polarizations of vectors

$\boxed{1}$ Smallness

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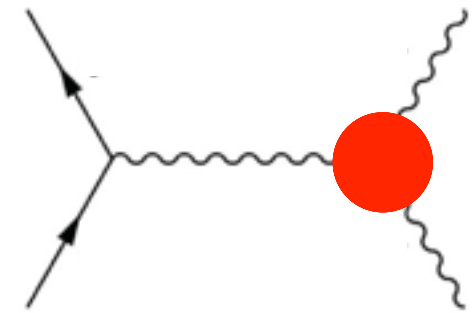
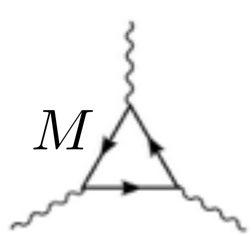


Involve the transverse polarizations of vectors

In popular models (e.g. SUSY, CH), V_T elementary, these are tiny:



$$g\lambda_\gamma \sim \frac{g^3}{16\pi^2} \frac{m_W^2}{M^2}$$

SILH: Giudice,Grojean,Pomarol,Rattazzi'2007

2 Non-Interference for BSM_6 amplitudes

Azatov,Contino,Machado,FR'16

There is in fact one more obstruction to test transverse vectors:

For $E \gg m_W$ states have well defined helicity h

Amplitudes for 2→2 with different h_{tot} don't interfere

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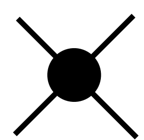
Selection Rule:



Any BSM dim-6 operator

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

tree level + at least one transverse vector ▸ No interference

why nobody cares

2 Non-Interference for BSM$_6$ amplitudes

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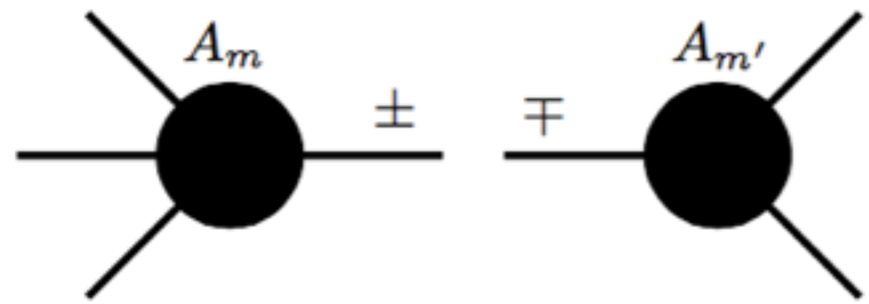
How? **i) Helicity sums:** $h(A_n) = h(A_m) + h(A_{m'})$

n=m+m'-2 legs



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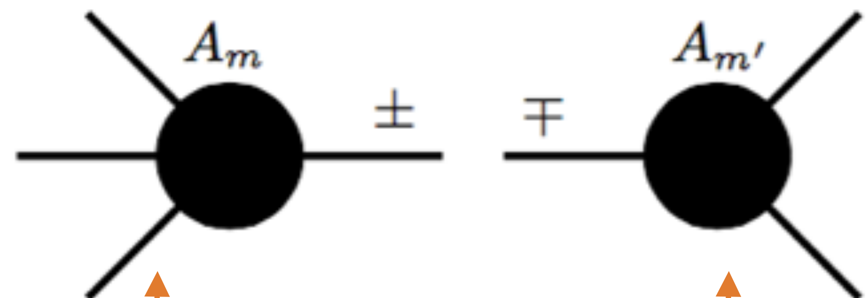

$p \in \mathbb{C}$ so that on-shell condition $p^2 = 0$ satisfied also for A$_3$

SM or BSM$_6$

2 Non-Interference for BSM$_6$ amplitudes

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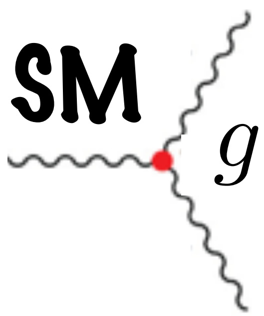
How?

ii) Helicity of 3-point$\leftrightarrow$coupling dimension:

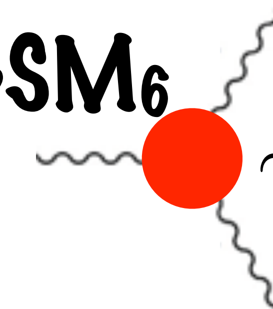
$$|h(A_3)| = 1 - [g]$$

SM



$g \Rightarrow |h^{SM}| = 1$

BSM$_6$



$\sim \frac{1}{\Lambda^2} \Rightarrow |h^{BSM}| = 3$

From: Little group scaling + dimensional analysis

(see e.g. Elvang,Huang'13)

why nobody cares

2 Non-Interference for BSM$_6$ amplitudes

Azatov,Contino,Machado,FR'16

How?

iii) SUSY* Ward Identities: $|h(A_4^{SM})| < 2$ (except $\psi^+\psi^+\psi^+\psi^+$)

(aka Ultra Helicity Violation)

why nobody cares

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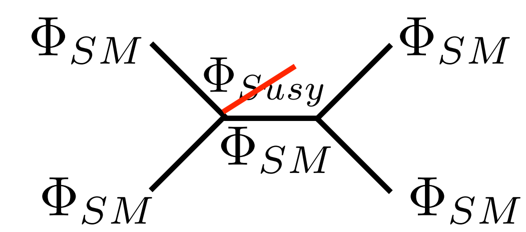
*in the limit of either y_u=0 or y_d=y_l=0:

SM upliftable to SUSY+R-parity (with 1 Higgs doublet)

Grisaru,Pendleton,vanNieuwenhuizen'77



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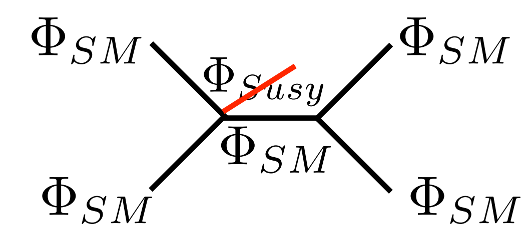

→ **e.g.** $0 = \langle 0|[Q,\Psi^+V^+V^+V^+]|0\rangle = \sum_i \langle 0|\Psi^+ ... [Q,V^+]...V^+|0\rangle \propto \langle 0|V^+V^+V^+V^+|0\rangle$

$[Q,\psi] \sim V \quad [Q,V] \sim \psi \qquad \psi^+\psi^+\cdots = 0$

$$SM : A(V^+V^+V^+V^-) = A(V^+V^+\psi^+\psi^-) = A(V^+V^+\phi\phi) = A(V^+\psi^+\psi^+\phi) = 0$$

why nobody cares

$\boxed{2}$ Non-Interference for BSM$_6$ amplitudes

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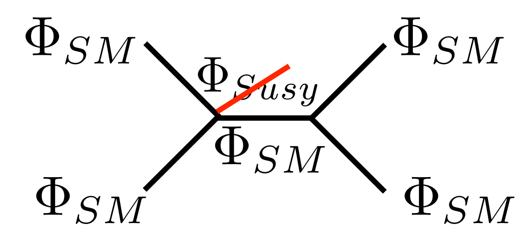

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BSM : **Operators with transverse V not supersymmetrizable**

Elias-Miro,Espinosa,Pomarol'14

why nobody cares

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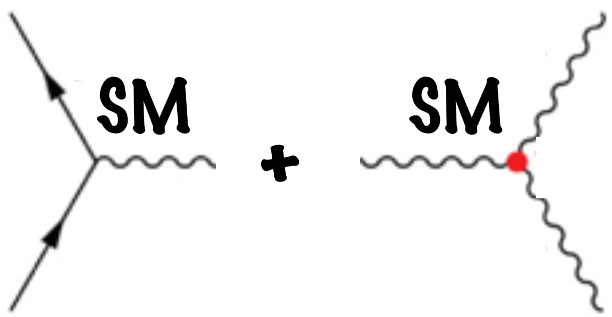

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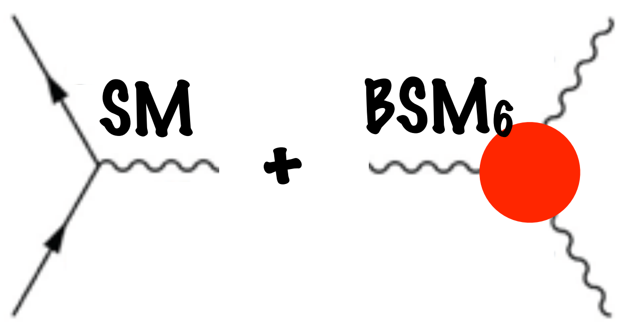

$$h^{tot} = 1 \pm 3 = 2, 4$$

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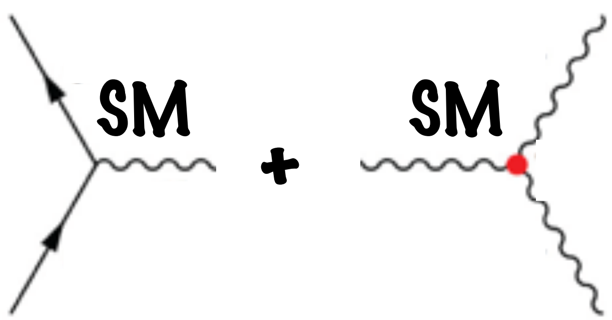

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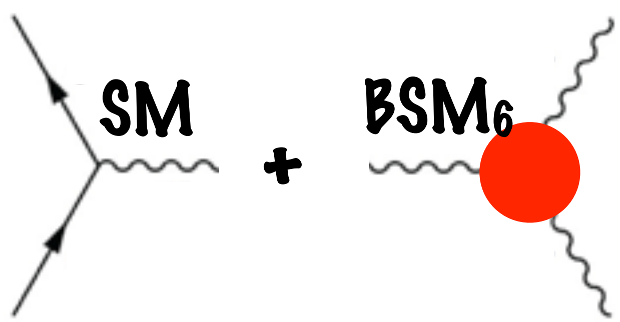

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No Interference
(dim-6, 4-point)

why nobody cares

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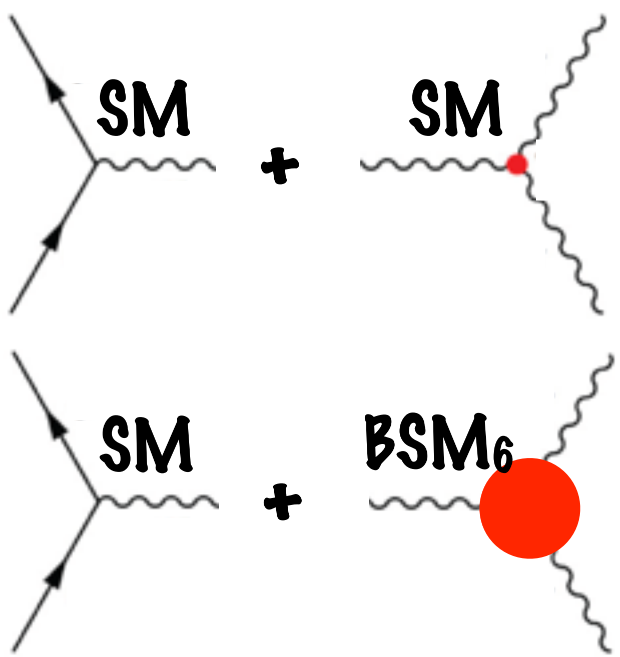


$h^{tot} = 1 - 1 = 0$

$h^{tot} = 1 \pm 3 = 2, 4$

No Interference
(dim-6, 4-point)

interference vanishes

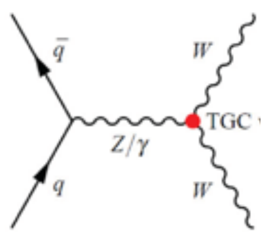
- $\sigma \propto \sum |Amp|^2 \simeq SM^2(1 + c_i \cancel{\frac{E^2}{M^2}} + c_i^2 \frac{E^4}{M^4})$

$\boxed{\text{Small effects, are even smaller!}}$

why nobody cares

Non-Interference+Smallness

Present constraints:



LEP2: $E = 130 - 209\,\mathrm{GeV}$

$$\lambda\gamma \in [-0.059, 0.017] \sim \frac{g^2}{16\pi^2}\frac{m_W^2}{M^2} \quad \Rightarrow M \gtrsim 30\ \mathrm{GeV}$$

95%C.L. (LEP EW: 1302.3415)

LHC: $E \gtrsim 1\mathrm{TeV}$ ...

$$\lambda_\gamma \in [-0.019, +0.019]$$

...so small that is doesn't even make sense as an EFT.

why nobody cares?

Because there is no structured scenario
where these searches are self-consistent
(need strong coupling)

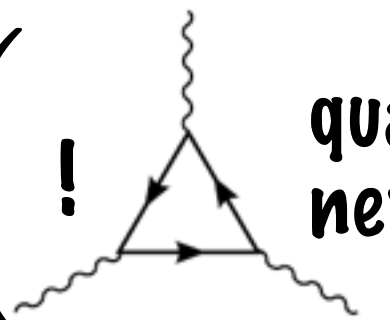
Part 2

why caring

(Remedios)

Strongly Coupled BSM?

How can SM be light and weakly coupled at $E<m_W$ and strongly coupled at $E\gg m_W$?

(!  quantum effects generally propagate new couplings to the whole SM !)

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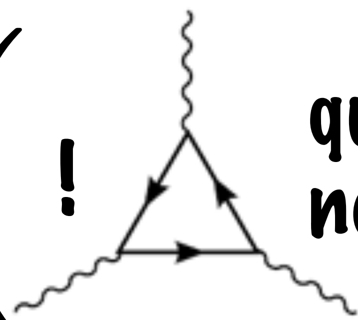
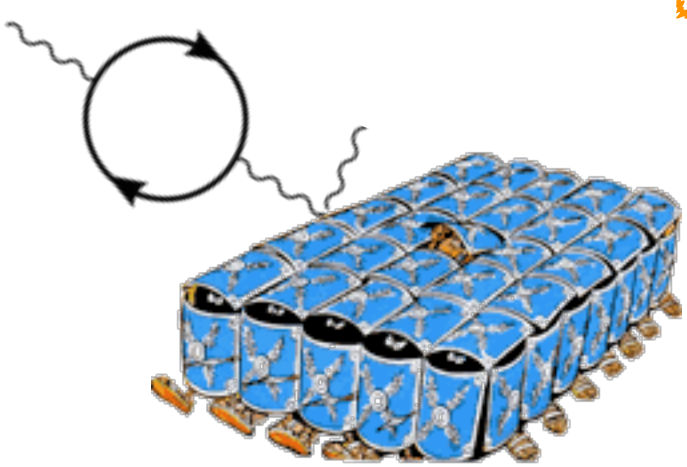
(!  quantum effects generally propagate new couplings to the whole SM !)

Need shielding: **Approximate Symmetries broken in SM**



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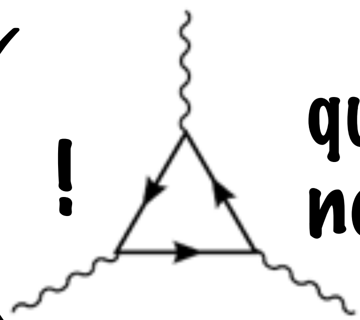

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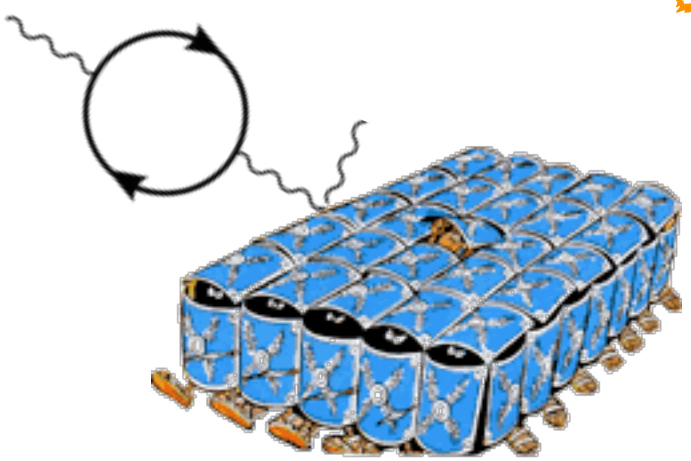
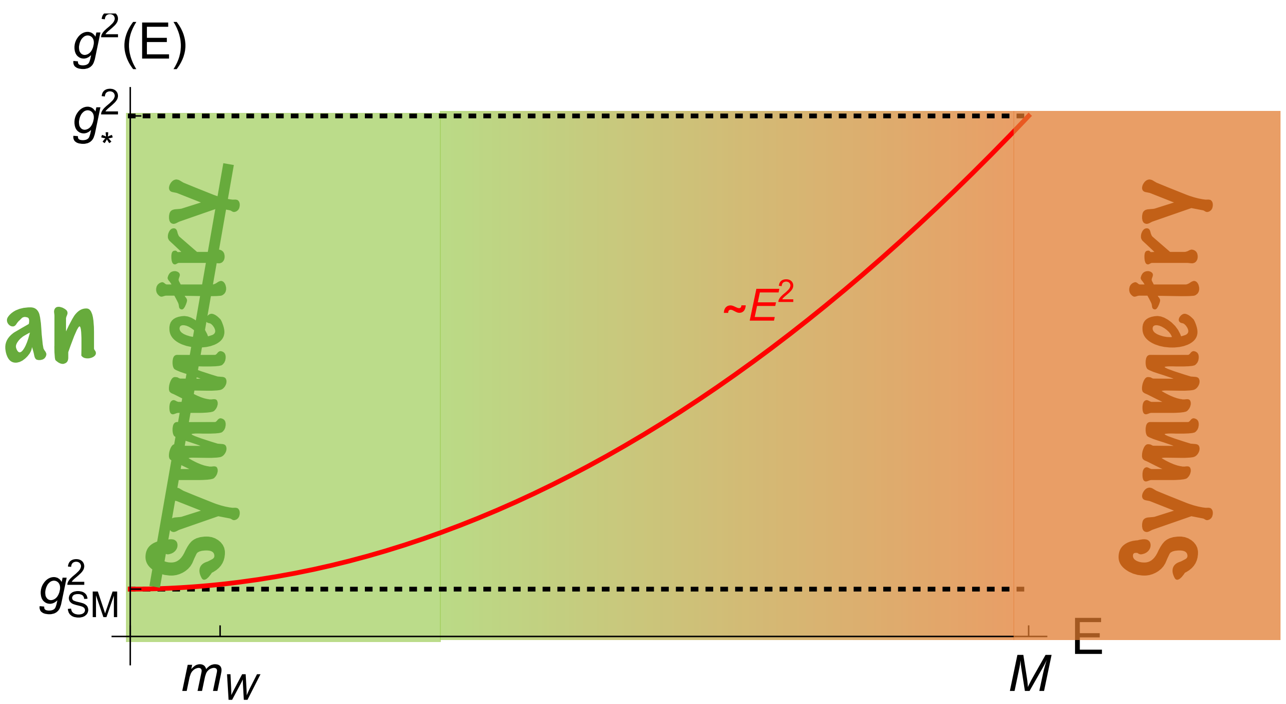


$$A \simeq g_{SM}^2\left(1+\frac{g_*^2}{g_{SM}^2}\frac{E^2}{M^2}\right)\equiv g^2(E)$$

g_{SM} weak

SM Lagrangian (dim-4)

Marginal



g* strong

Higher-dim operators (dim-6, sim-8...)

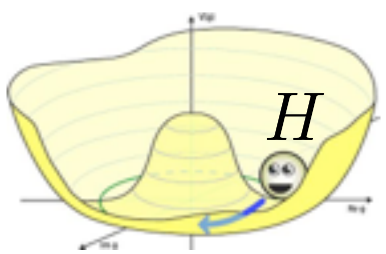
Irrelevant

Strongly Coupled BSM and Approximate Symmetries

Scalars: Composite Higgs

Higgs is a Pseudo Goldstone boson from new strong sector (symm=SO(5)/SO(4))

Georgi,Kaplan'84; Agashe,Contino,Nomura,Pomarol'04; Giudice,Grojean,Pomarol,Rattazzi'07;...



Shift Symm: $H \to H + c_{+\text{n.l.}}$ $\qquad g_*\partial_\mu H_{+\text{n.l.}}$ $\qquad \epsilon H$

~~symmetry~~

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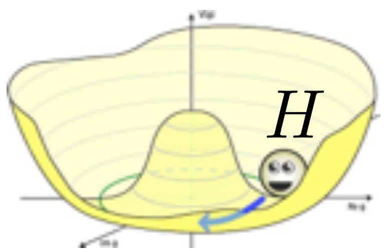

Shift Symm: $H \to \underset{+\text{n.l.}}{H + c}$ $\qquad g_* \partial_\mu \underset{+\text{n.l.}}{H}$ ✓ $\qquad \epsilon H$ ✗ ~~symmetry~~

- $\dfrac{g_*^2}{M^2}(\partial_\mu |H|^2)^2$ **large**
- $\lambda |H|^4$ **small**

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Higgs is a Pseudo Goldstone boson from new strong sector (symm=SO(5)/SO(4))

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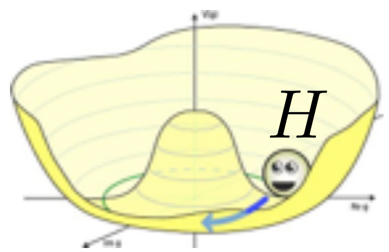
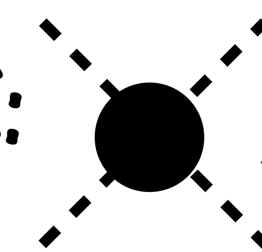


Shift Symm: $H \to H + c$ $_{+\text{n.l.}}$ $\quad g_* \partial_\mu H$ $_{+\text{n.l.}}$ ✓ $\quad \epsilon H$ ✗ ~~symmetry~~

- $\dfrac{g_*^2}{M^2}(\partial_\mu |H|^2)^2$ **large** $\quad$ - $\lambda |H|^4$ **small**
- **Large effects $V_L V_L \to V_L V_L$ at high-E:**  $A \sim \lambda \left(1 + \dfrac{g_*^2}{\lambda}\dfrac{E^2}{M^2}\right)$

Strongly Coupled BSM and Approximate Symmetries

Scalars: Composite Higgs

Higgs is a Pseudo Goldstone boson from new strong sector (symm=SO(5)/SO(4))

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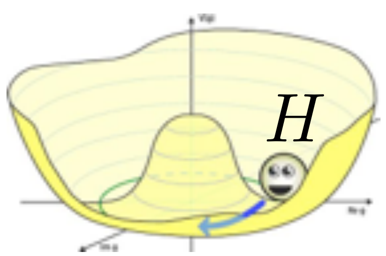

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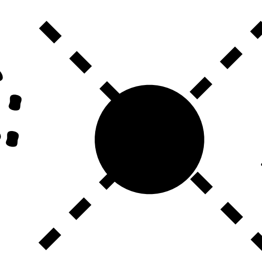
- **Large effects $V_L V_L \to V_L V_L$ at high-E:**  $A \sim \lambda \left(1 + \dfrac{g_*^2}{\lambda}\dfrac{E^2}{M^2}\right)$

Vectors: ?

Strong transverse vectors at high-E

Problem: Naively, contrary to scalars, gauge bosons couple universally

Gauge bosons: weak SM coupling ($\partial_\mu + igA_\mu$)

Liu,Pomarol,Rattazzi,FR'16

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Gauge bosons: weak SM coupling $(\partial_\mu + igA_\mu)$

However:

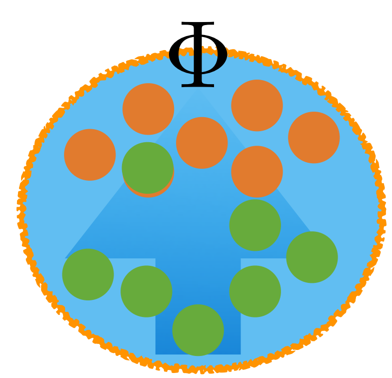
$\boxed{g = 0}$

- A_μ composite, g*

- No light charged d.o.f
(but large dipoles possible)

$$\mathcal{L} = L\left(\frac{\partial_\mu}{M}, g_* \frac{\hat{F}_{\mu\nu}}{M^2}, \Phi\right)$$

(Euler-Heisenberg)



- Strong higher-d interactions

Liu,Pomarol,Rattazzi,FR'16

Strong transverse vectors at high-E

Problem: Naively, contrary to scalars, gauge bosons couple universally
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$\boxed{g=0}$ ⟵ $\boxed{g \neq 0}$

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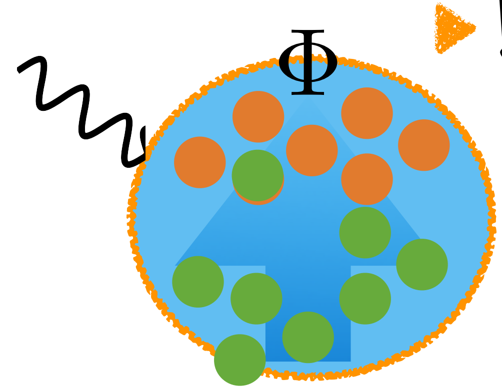


$q = \frac{g}{g_*}$

- Light d.o.f. with charge $\frac{g}{g_*} \ll 1$

$$\mathcal{L} = L\left(\frac{\partial_\mu + igA_\mu}{M}, g_* \frac{F_{\mu\nu}}{M^2}, \Phi\right)$$

- Weak marginal interactions

Liu,Pomarol,Rattazzi,FR'16

Strong transverse vectors at high-E

What symmetry is broken by g and not by g_*? none...

Multipole interactions (field strengths)

$g_* F^a_{\mu\nu}$

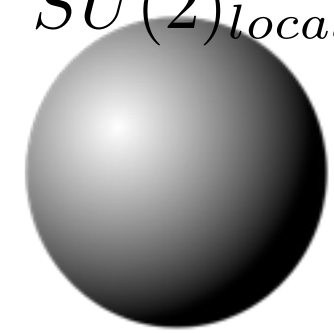
Monopole interactions (covariant derivative)

$\partial_\mu + i g A^a_\mu T^a$

Non-abelian

$U(1)^3_{local} \times SU(2)_{global}$

$SU(2)_{local}$

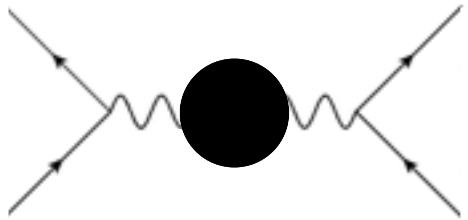


Inonu-Wigner Contraction ('53)
#generators invariant
(Like Poincaré->Galilei)

- **Symmetry deformation:** a new selection rule to build EFTs (different from spurions)

Liu,Pomarol,Rattazzi,FR'16

Strong transverse vectors: Implications

- $\frac{1}{M^2}(D_\rho W^{a,\nu}_\mu)^2$  $W, Y \simeq \frac{m_W^2}{M^2} \lesssim 10^{-3}$ → $\boxed{M \gtrsim 2\,\mathrm{TeV}}$

Barbieri,Pomarol,Rattazzi,Strumia'04

Strong transverse vectors: Implications

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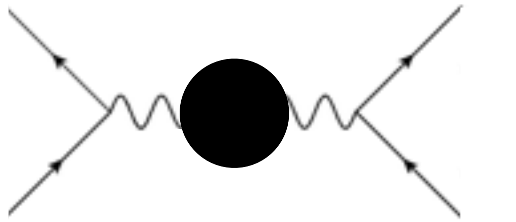

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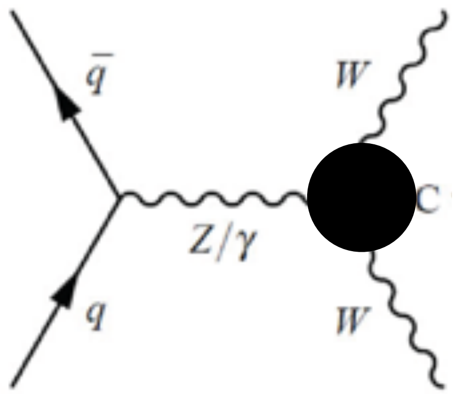
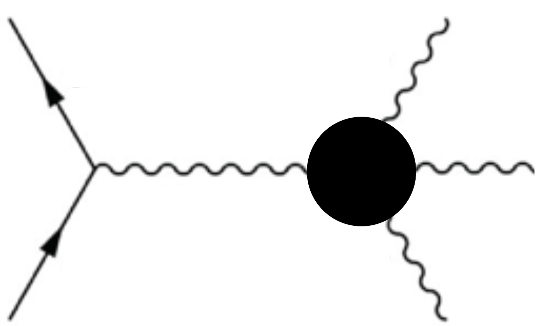
- $\frac{g_*}{M^2}\epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$



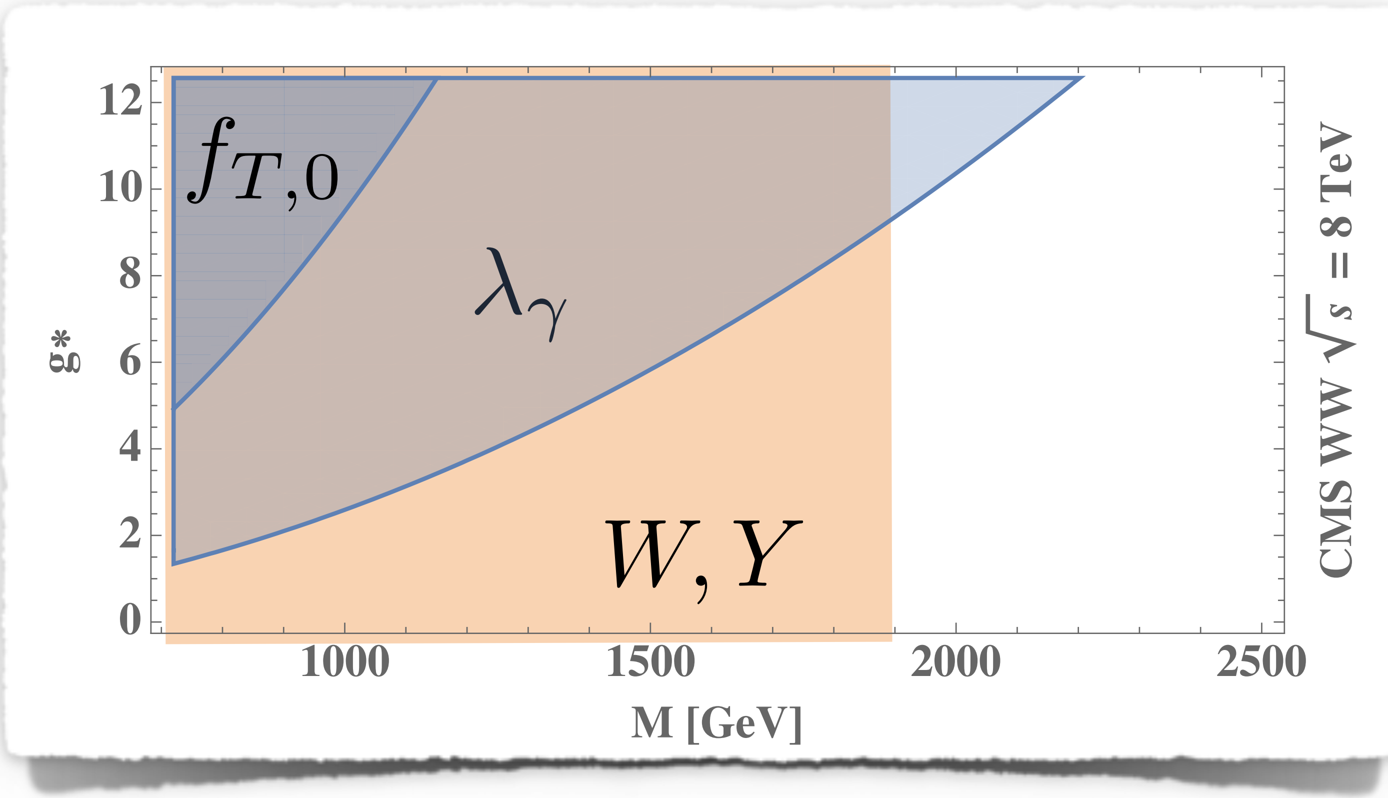
$\lambda_\gamma \approx g_* \frac{m_W^2}{M^2}$ $\boxed{M \gtrsim \sqrt{\frac{g_*}{4\pi}}\ 2.2\ \text{TeV}}$

- $\frac{g_*^2}{M^4} W^4_{\mu\nu}$



$f_{T,0} \approx \frac{g_*^2}{M^4}$ $\boxed{M \gtrsim \sqrt{\frac{g_*}{4\pi}}\ 1.1\ \text{TeV}}$

Strong transverse vectors: Implications



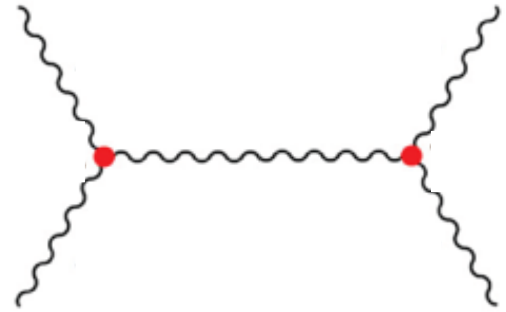
So far the only models that motivate these searches consistently

Remedios (Remedios the Beauty was not a creature of this world- Gabriel Garcia Marquez)

Strong transverse vectors: Implications

$\boxed{W_T \text{ scattering}}$

SM



$\sim g^2$

Strong transverse vectors: Implications

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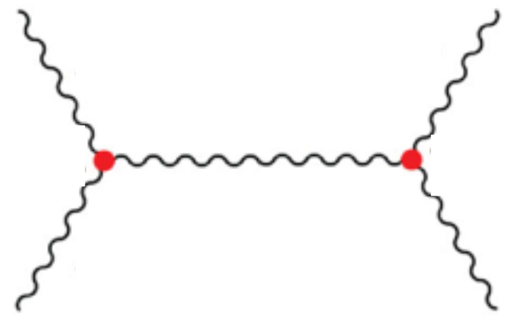

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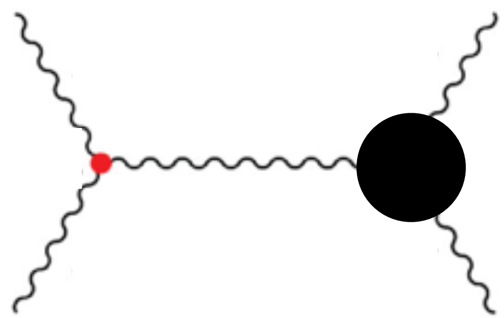
Strong vectors:

D6 $\frac{g_*}{M^2}\epsilon_{abc}W_\mu^{a\,\nu}W_{\nu\rho}^{b}W^{c\,\rho\mu}$



$\sim g g_* \frac{E^2}{M^2}$

Strong transverse vectors: Implications

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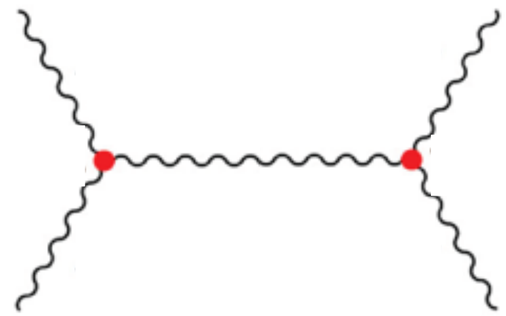

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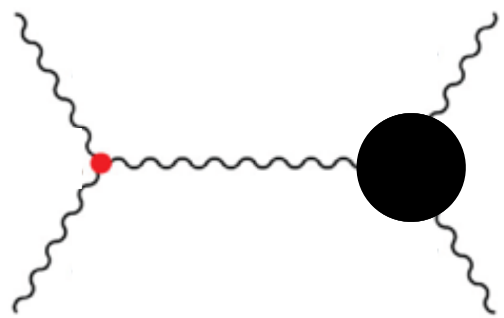

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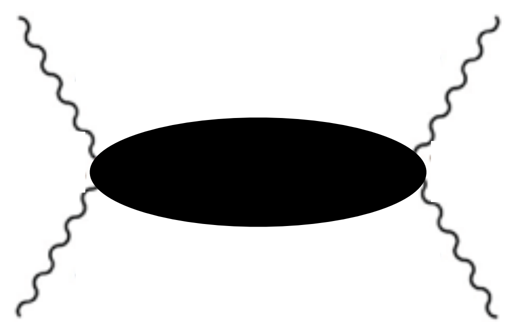
(NDA: 4-point vertex≈ coupling²)



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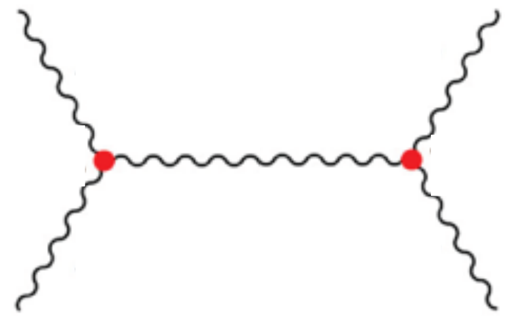

$\sim g^2$

$$\frac{g_*}{g}\frac{E^2}{M^2} \lesssim 1$$

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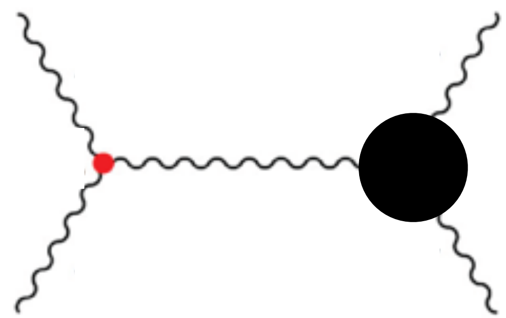

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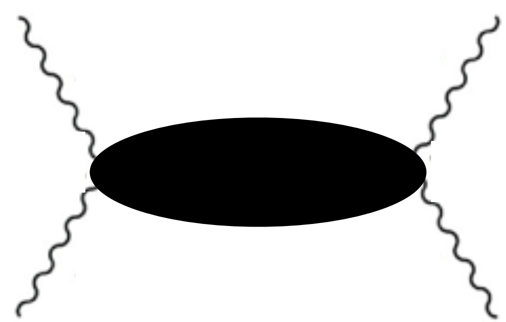

$\sim g_*^2\frac{E^4}{M^4}$

- $\frac{\delta \mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \lesssim 1$ **dimension-6 analysis ok**

Strong transverse vectors: Implications

W_T scattering

SM

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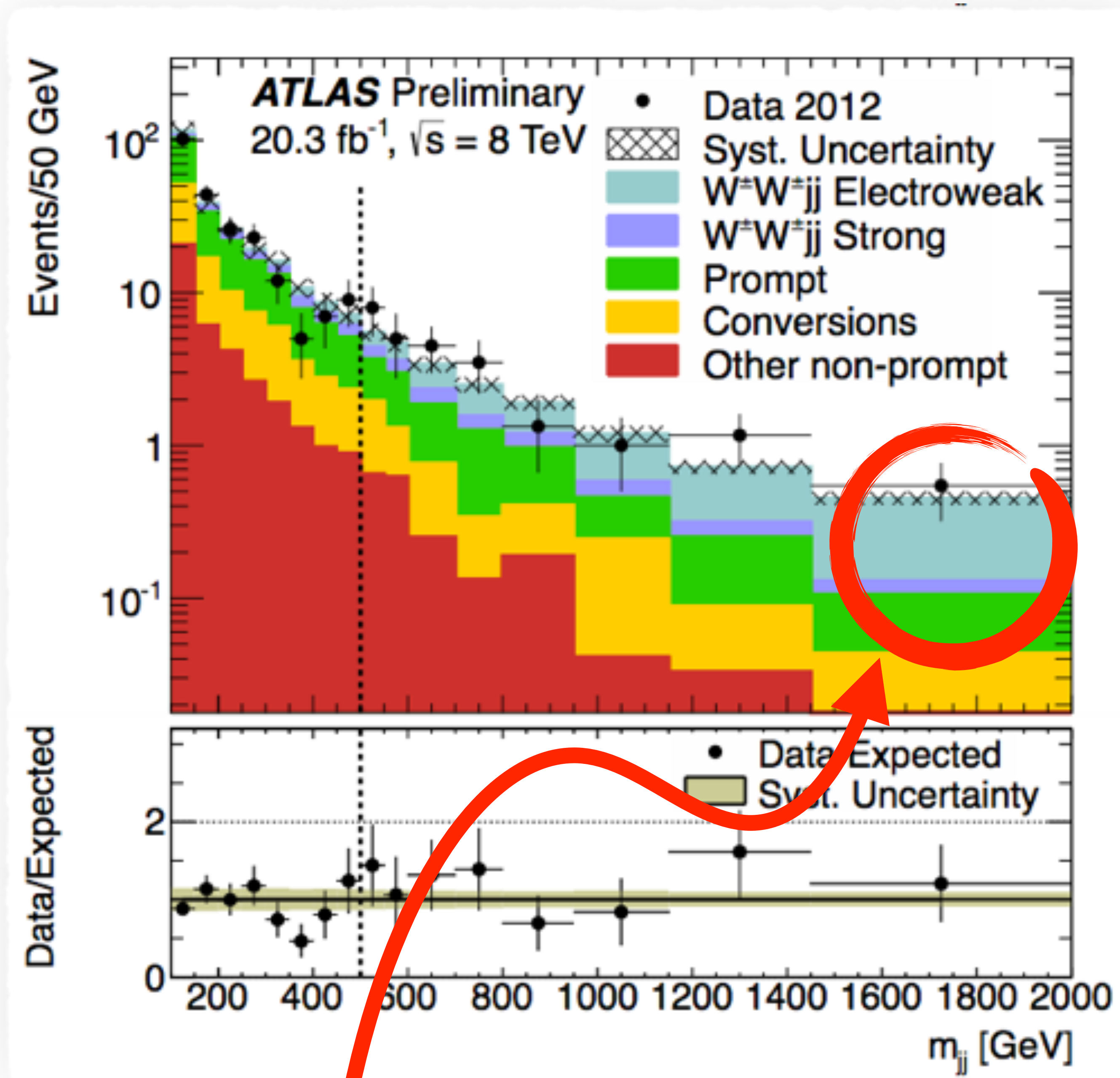

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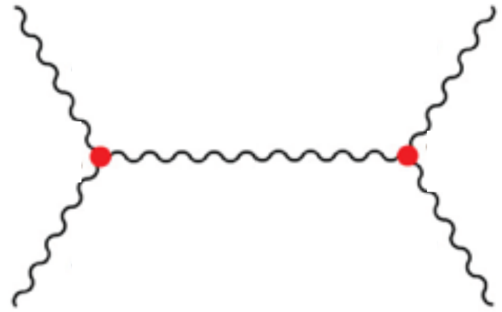

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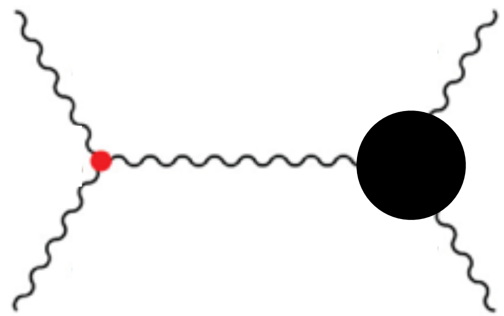

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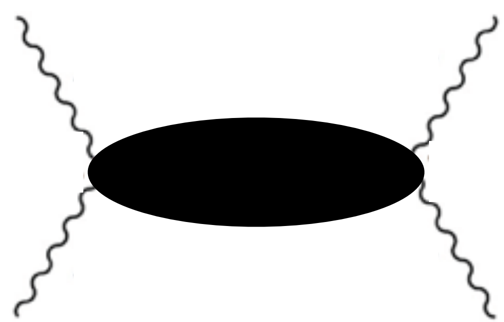

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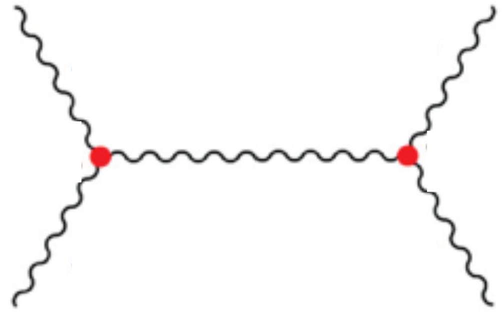

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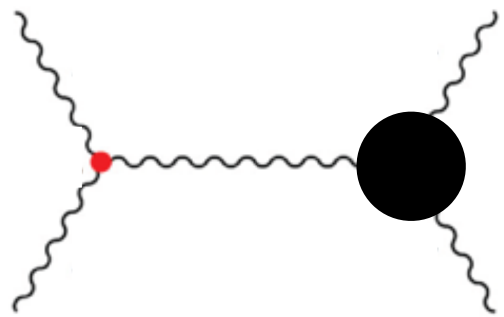

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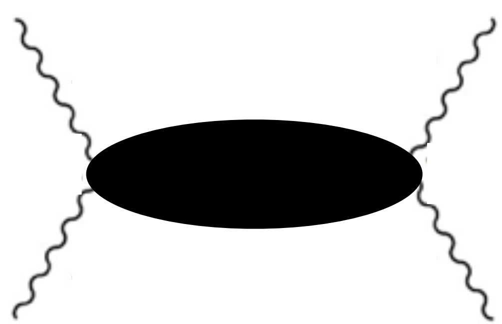


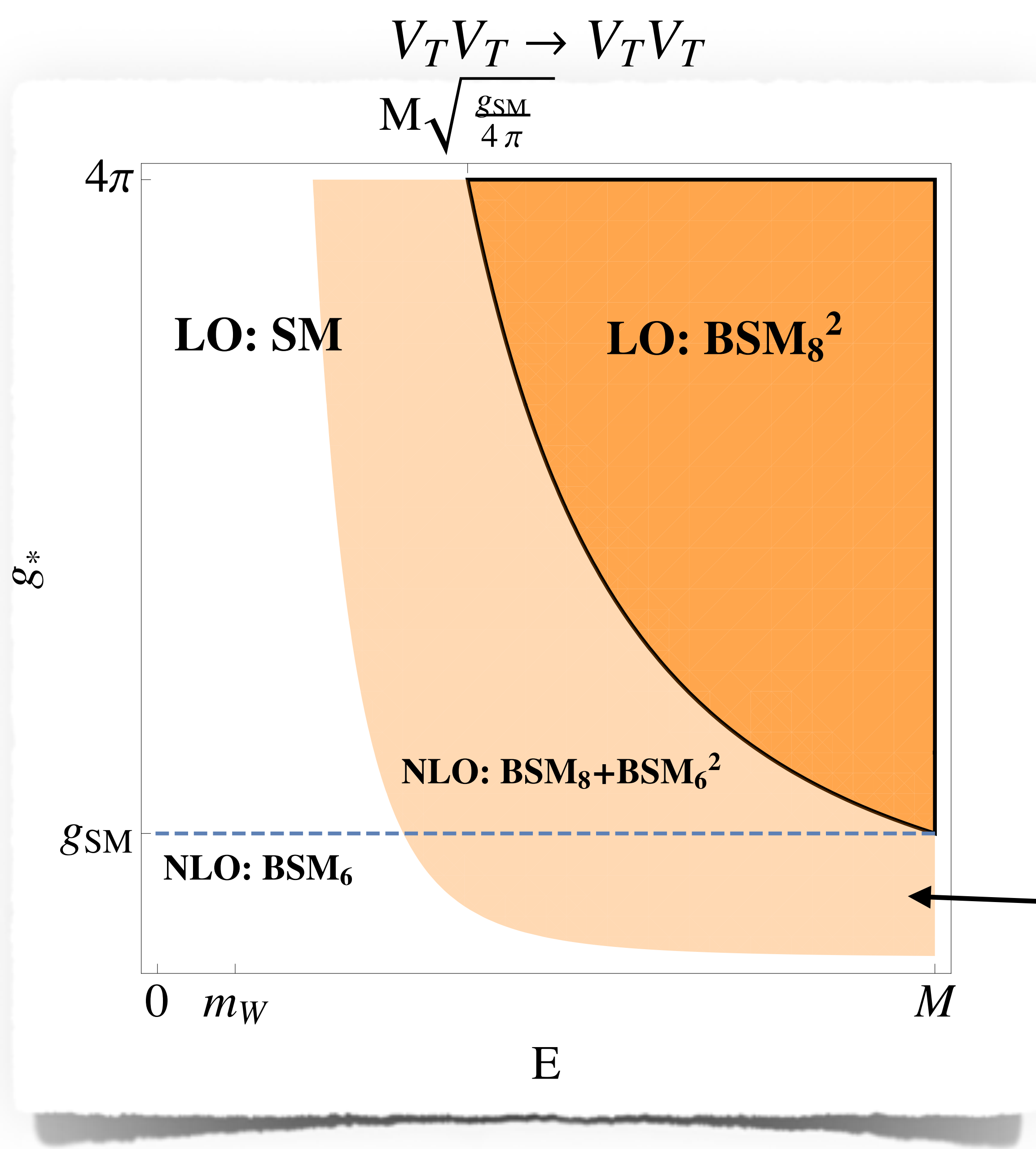
$\sim g_*^2\frac{E^4}{M^4}$

▸ $\frac{\delta \mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \gtrsim 1$ **dim-6 not ok! dim-8 dominate!**

(EFT E/M expansion still valid: dimension-10 small)

Strong transverse vectors: Implications

W_T scattering



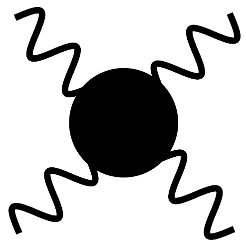
Non-interference: even at low-E D8>D6

dim-8 always large for WW scattering

(EFT E/M expansion still valid: dimension-10 small)

Dimension-8 Liu,Pomarol,Rattazzi,FR'16

Approximate (Non-linear) symmetries go beyond shielding the SM...

	Dim-8	Dim-6
▸ **Remedios Model:** 	$\frac{g_*^2}{M^4}(W^a_{\mu\nu})^4$	$g \ll g_*$ $\cancel{\frac{g g_*}{M^2} W_\mu^{a\,\nu} W_{\nu\rho}^{b} W^{b\mu} W^{a\rho}}$

(dimension-10 smaller by E^2/M^2)

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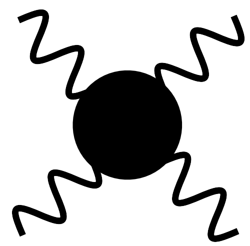
$\boxed{\text{Dim-8}}$ $\boxed{\text{Dim-6}}$

- **Remedios Model:**

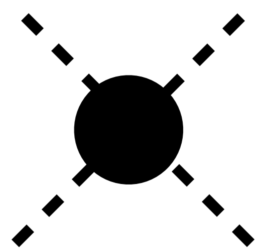


$$\frac{g_*^2}{M^4}(W^a_{\mu\nu})^4 \qquad \cancel{\frac{g g_*}{M^2} W^{a\,\nu}_{\mu} W^b_{\nu\rho}} \, W^{b\mu} W^{a\rho} \qquad g \ll g_*$$

- **Composite Higgs: (flat coset)**

$$H \in ISO(4)/SO(4) \qquad ISO(4) = SO(4) \rtimes T_4$$

$$H \to H + c\,, \qquad H \to RH\,,$$



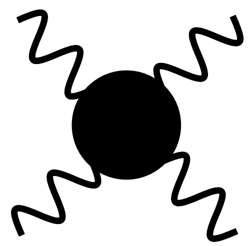
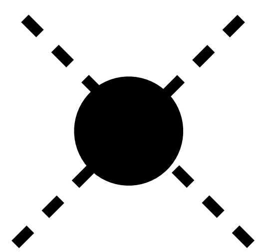
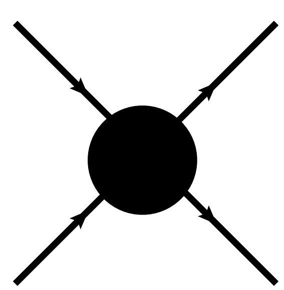
$$\frac{g_*^2}{M^4}(D_\mu H^\dagger D_\nu H)^2 \qquad \cancel{\epsilon_c \frac{g_*^2}{M^2}(H^\dagger D_\mu H)^2}$$

Proportional to coset curvature

(dimension-10 smaller by E^2/M^2)

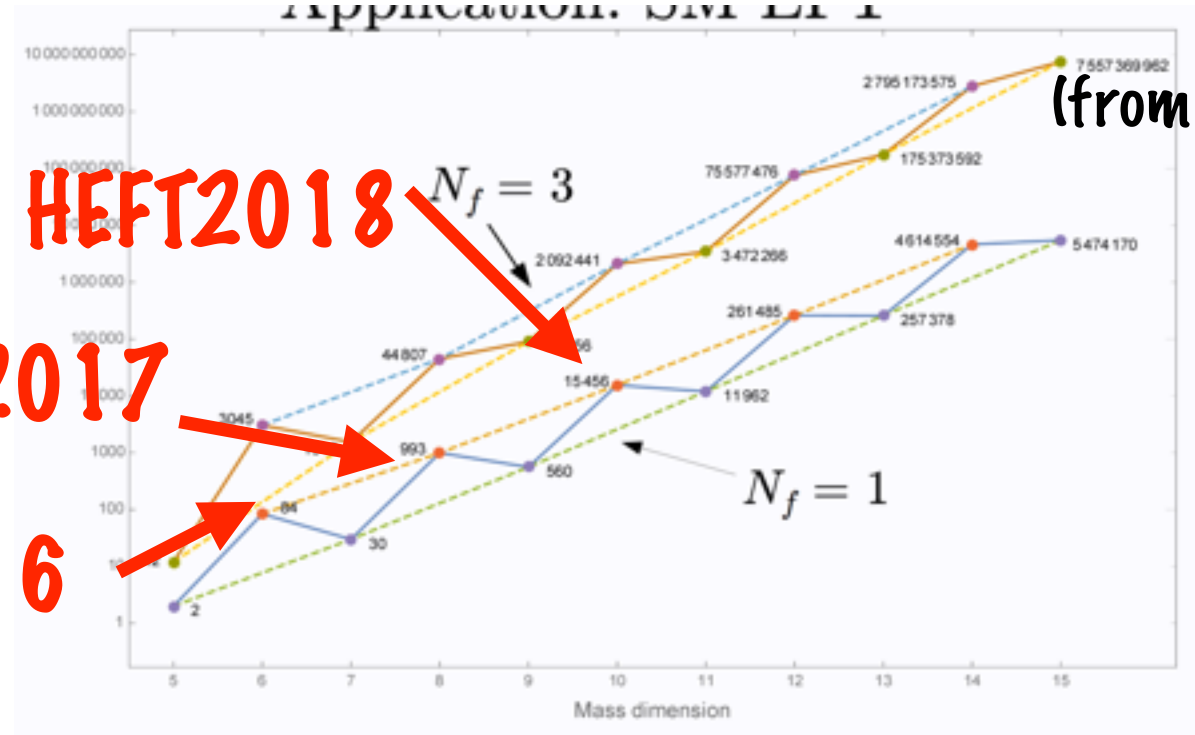
Dimension-8 Liu,Pomarol,Rattazzi,FR'16

Approximate (Non-linear) symmetries go beyond shielding the SM...

		Dim-8	Dim-6
Remedios Model:		$\frac{g_*^2}{M^4}(W^a_{\mu\nu})^4$	$g \ll g_*$ $\cancel{\frac{g g_*}{M^2} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{b\mu} W^{a\rho}}$
Composite Higgs: (flat coset)	$H \in ISO(4)/SO(4)$, $ISO(4) = SO(4) \rtimes T_4$ $H \to H + c\,,\quad H \to RH\,,$ 	$\frac{g_*^2}{M^4}(D_\mu H^\dagger D_\nu H)^2$	Proportional to coset curvature $\cancel{\epsilon_c \frac{g_*^2}{M^2}(H^\dagger D_\mu H)^2}$
Fermions as Pseudo-Goldstinos Bardeen, Visnjic'82; Bellazzini,FR'soon	$\delta\psi = \xi + \frac{i}{2F^2}\partial_\mu \psi(\bar\psi\bar\gamma^\mu\xi - \bar\xi\bar\gamma^\mu\psi)$ 	$\frac{g_*^2}{M^4}(\partial_\mu\bar\psi\gamma^\mu\psi)^2$	$\cancel{\epsilon_{\cancel{\rm SUSY}} \frac{g_*^2}{M^2}(\bar\psi\gamma^\mu\psi)^2}$

(dimension-10 smaller by E^2/M^2)

HEFT 993, 15456,...



(from Brian)

HEFT2018

HEFT2017

HEFT2013-2016

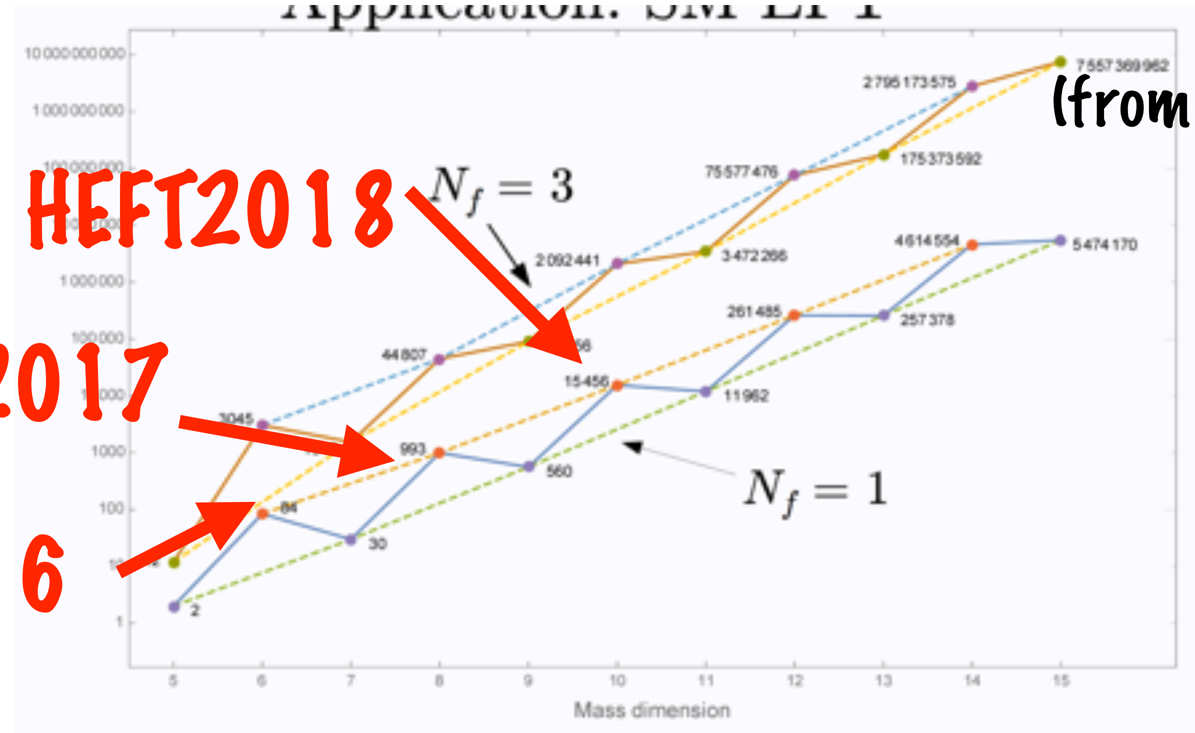
fear not...

HEFT 993, 15456,...

HEFT2018

HEFT2017

HEFT2013-2016



(from Brian)

fear not...

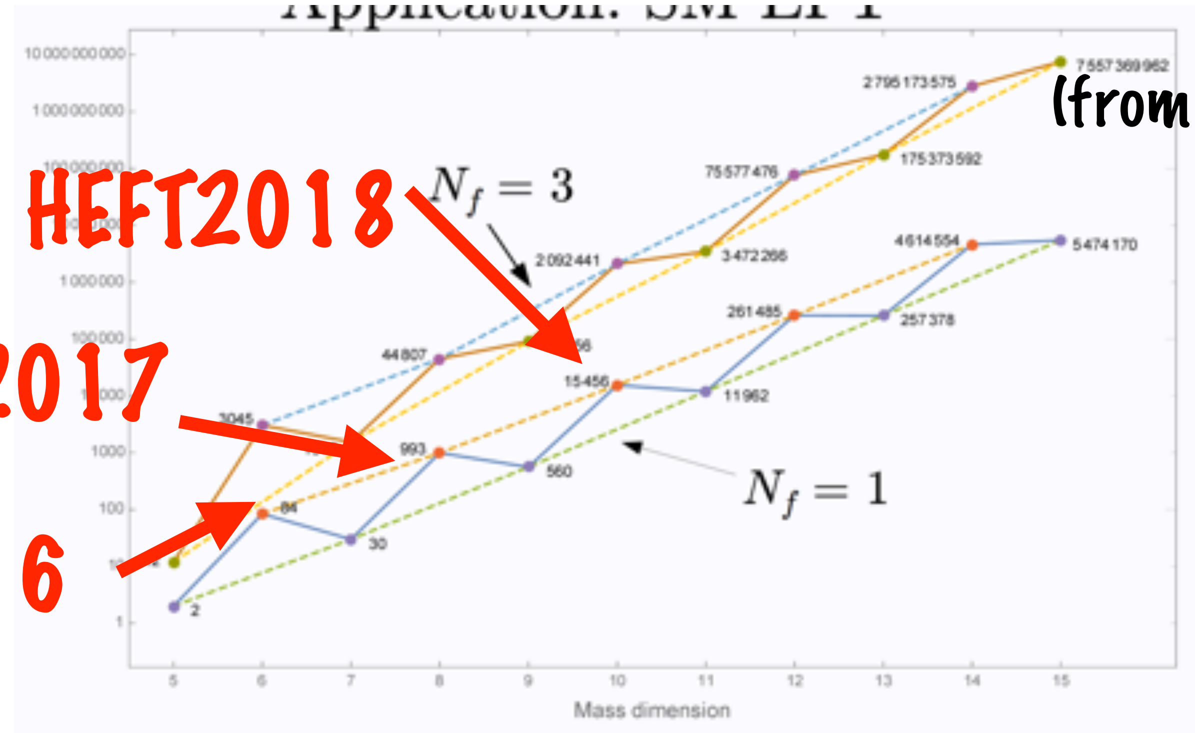
Can there be symmetries that protect dimension-10 in 2→2 processes?

HEFT 993, 15456,...

HEFT2018

HEFT2017

HEFT2013-2016



(from Brian)

fear not...

Can there be symmetries that protect dimension-10 in 2→2 processes?

NO! Positivity constraints from analyticity,unitarity,crossing symm.:

Adams,Arkani-hamed,Dubovsky,Nicolis,Rattazzi'06; Bellazzini'16;...

$$\boxed{c_8 > 0}$$

$$\mathcal{L} = \partial_\mu \pi \partial^\mu \pi + \frac{c_8}{M^4}(\partial_\mu \pi \partial^\mu \pi)^2 + \frac{c_{10}}{M^6}(\partial_\mu \pi \partial_\nu \partial^\mu \pi)^2$$

- A symmetry that protects dim-10 can never be considered exact

Conclusions

LHC/LEP: many €€resources€€ to test transverse vectors

- Not BSM motivated (non-interference, smallness in ordinary models)

Henning,Lu,Melia,Murayama'15; Lehman,Martin'15

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Remedios: structurally robust scenario for strong coupling

- large multipoles/small monopoles
- deformed symmetry

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- deformed symmetry

Approximate symmetries can lead to dim-8 domination in 2→2 processes

Motivation for some QGC searches

Motivation for dim-8 operator classification

Henning,Lu,Melia,Murayama'15; Lehman,Martin'15

- New patterns for deviations from the SM

Conclusions

LHC/LEP: many €€resources€€ to test transverse vectors

- Not BSM motivated (non-interference, smallness in ordinary models)

Remedios: structurally robust scenario for strong coupling

- large multipoles/small monopoles
- deformed symmetry

Approximate symmetries can lead to dim-8 domination in 2→2 processes

Motivation for some QGC searches

Motivation for dim-8 operator classification

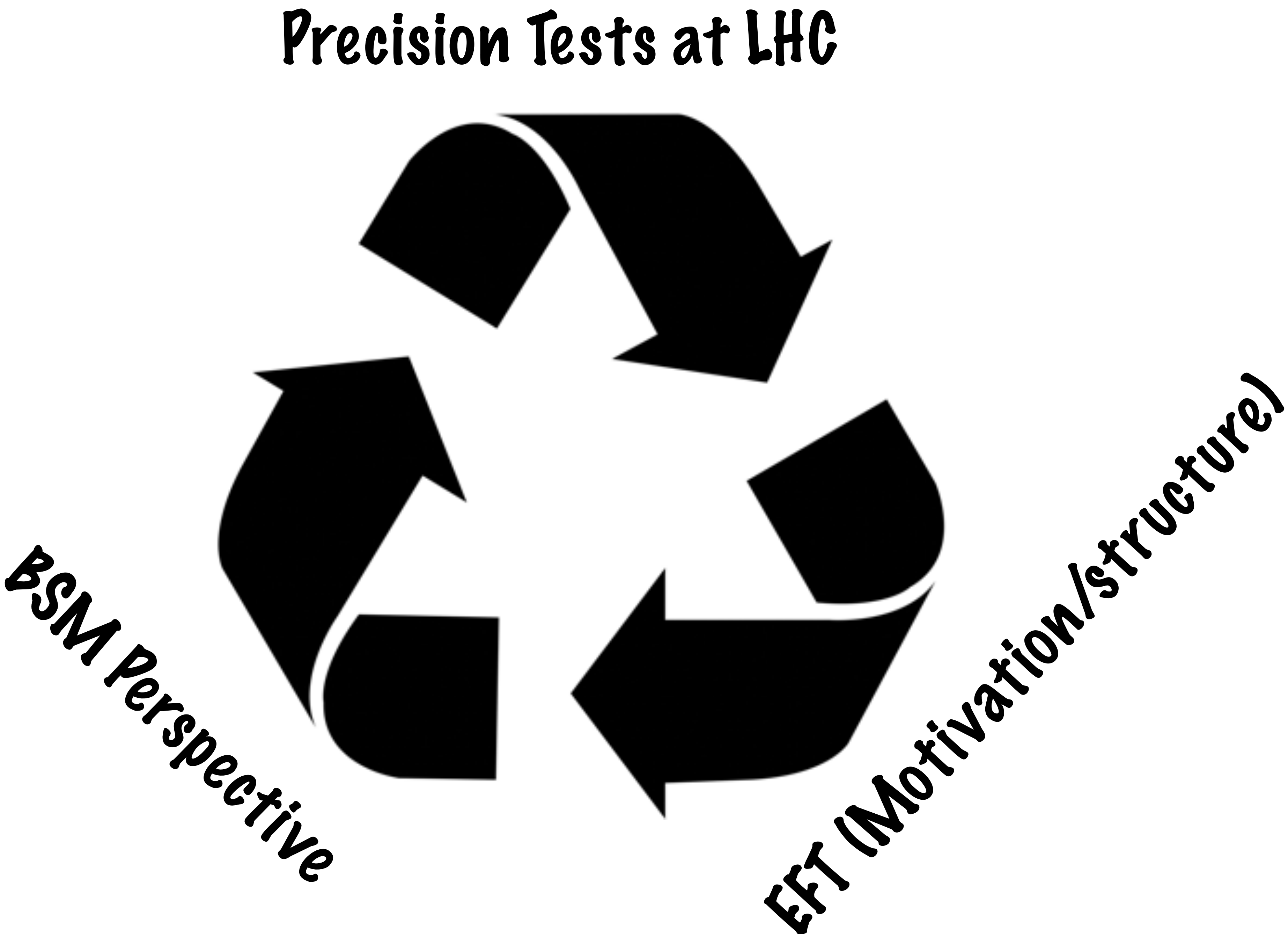
Henning,Lu,Melia,Murayama'15; Lehman,Martin'15

- New patterns for deviations from the SM

So far the hierarchy problem has shaped our picture of TeV-physics.

Here "Data-driven": what can we learn from well-measured quantities?

Conclusions



Strong transverse vectors: UV?

Through Partial Compositeness?

$$\mathcal{L}_{mix} = \epsilon_A A_\mu J^\mu + \epsilon_F F_{\mu\nu} \mathcal{O}^{\mu\nu}$$

Marginal $dim[J] = 3$

Relevant if $dim[\mathcal{O}] < 2$

Unitarity $dim[\mathcal{O}] \geq 2$

Ferrara,Gatto,Grillo'74,Mack'79

- Either free or irrelevant

- No CFT or Warped Extra-D model exists

Strong transverse vectors: UV?

Through P

- No C

Strong transverse vectors=Remedios

Remedy to motivate (some) LHC searches

No warped UV model

(Remedios the Beauty was not a creature of this world-
Gabriel Garcia Marquez)

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