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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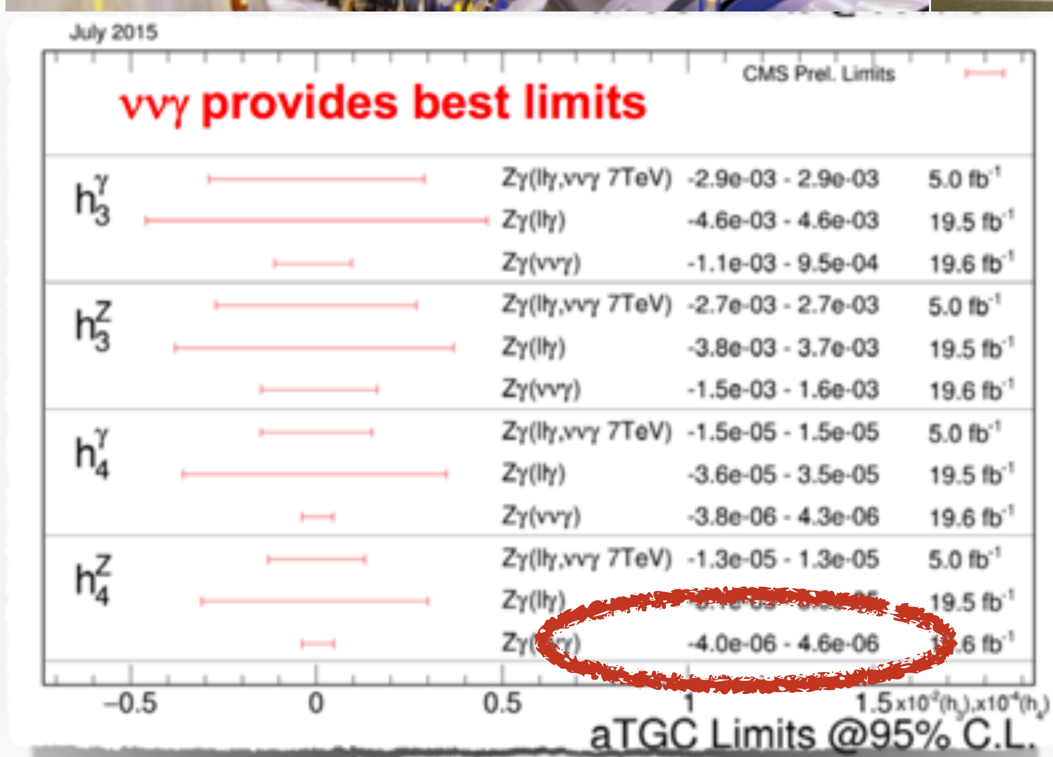

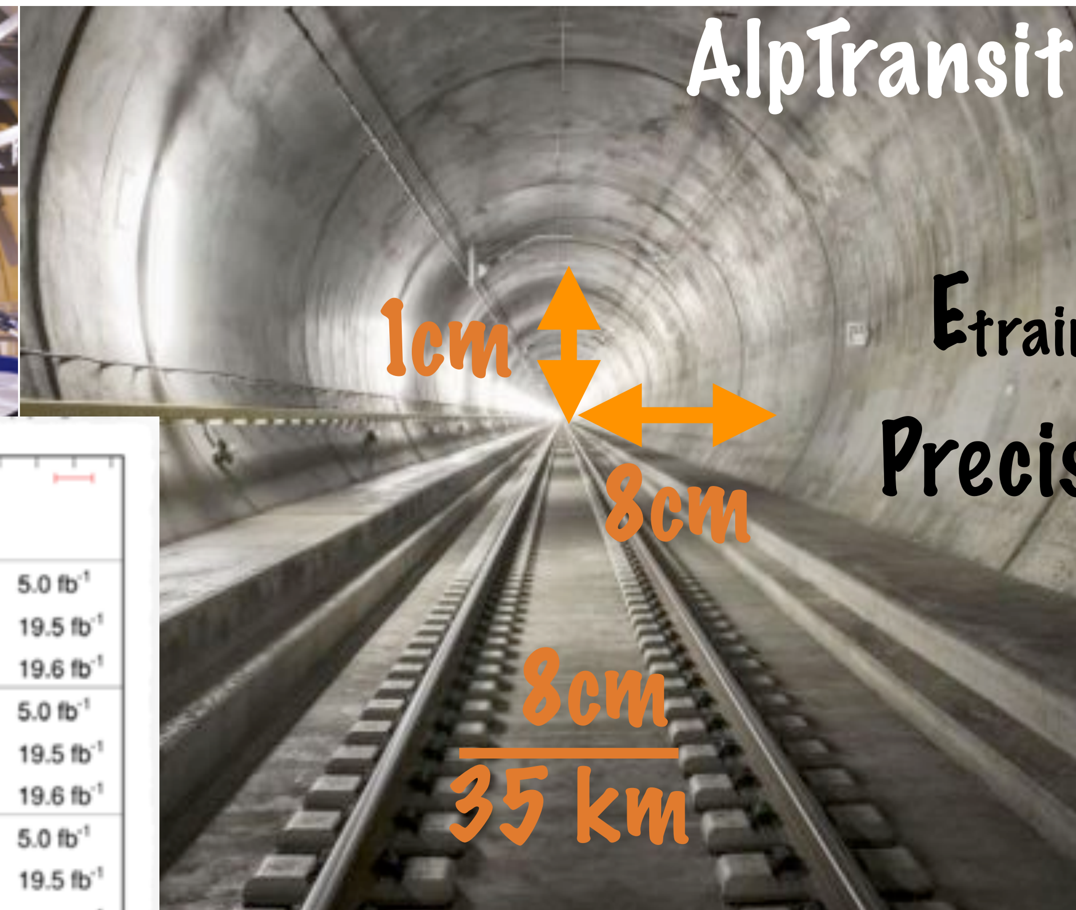

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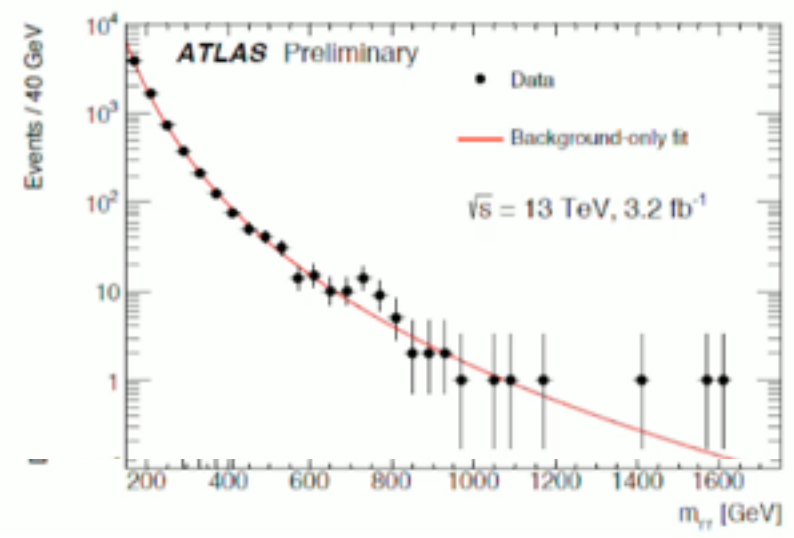
Two modes of exploration at LHC:

A) Direct Searches:



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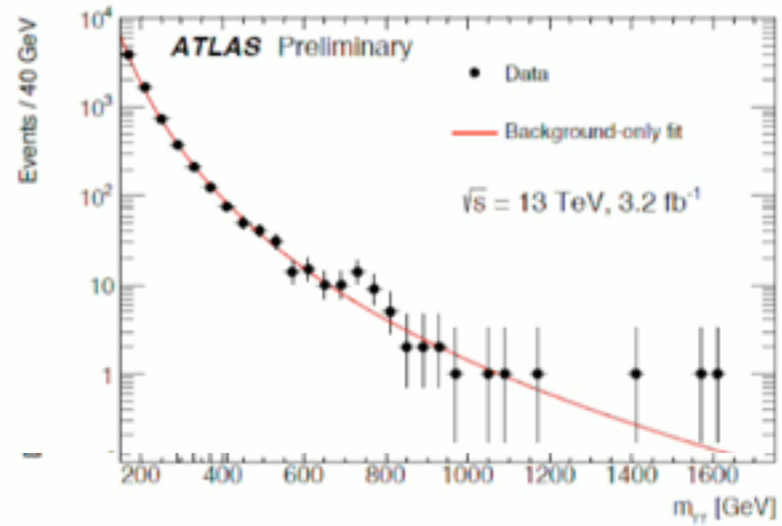
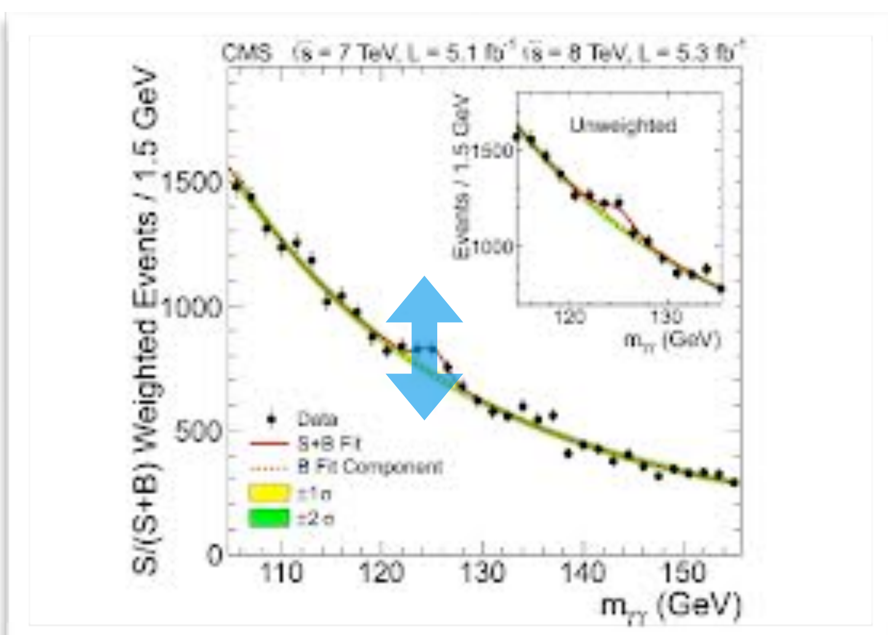
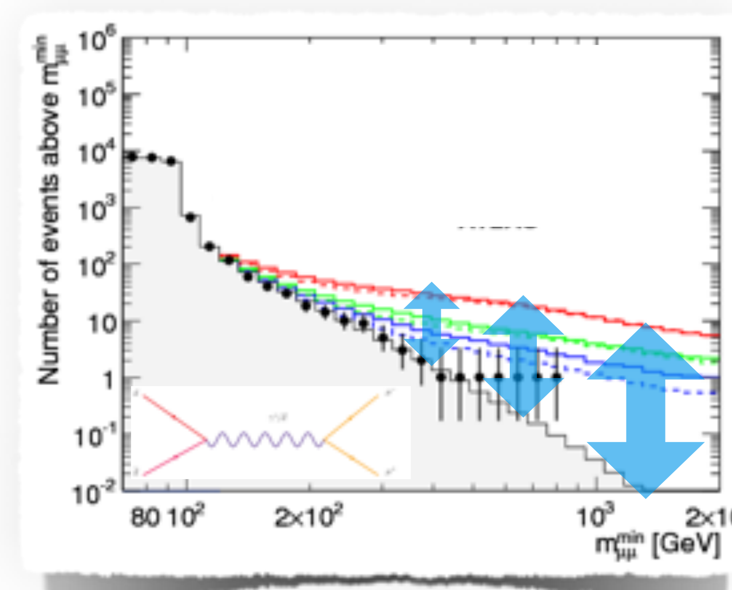


B) Indirect Searches:





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

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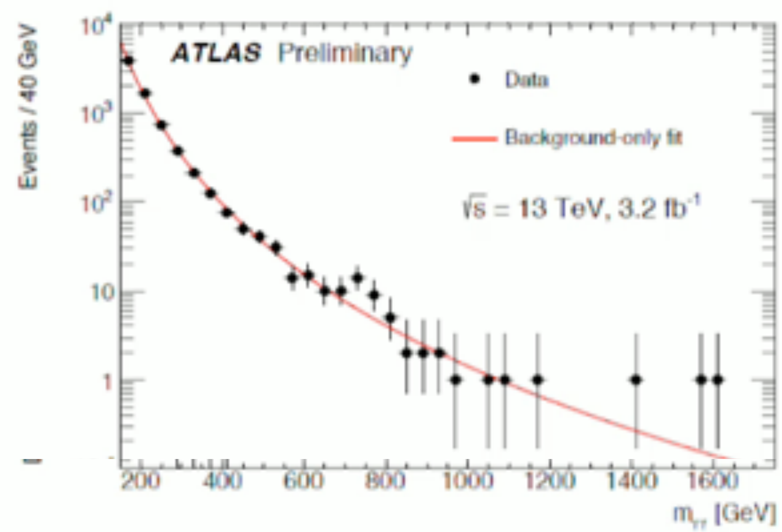

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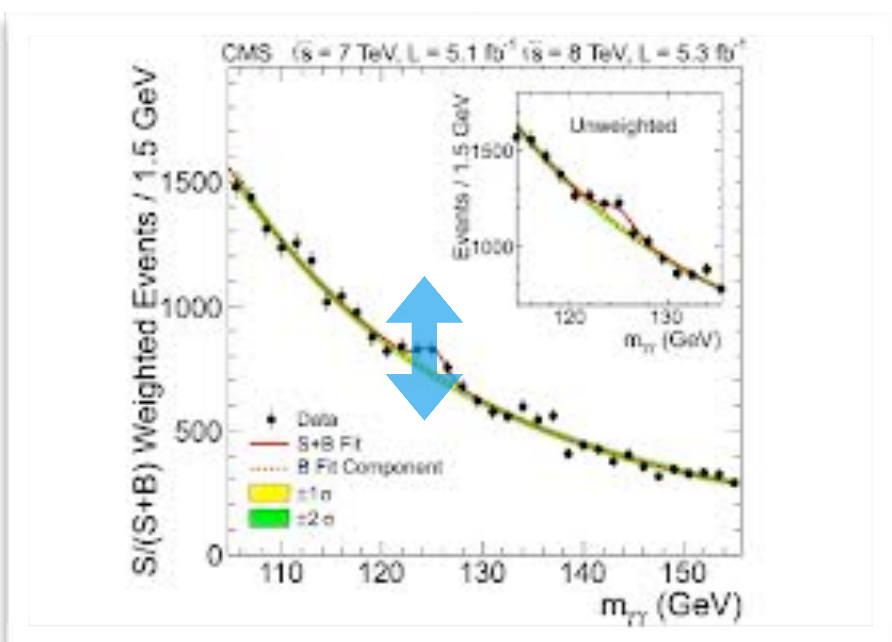

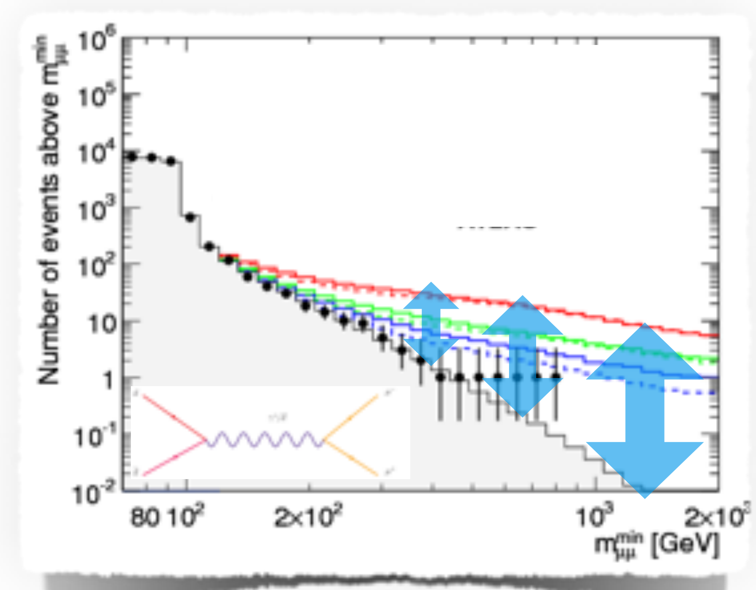

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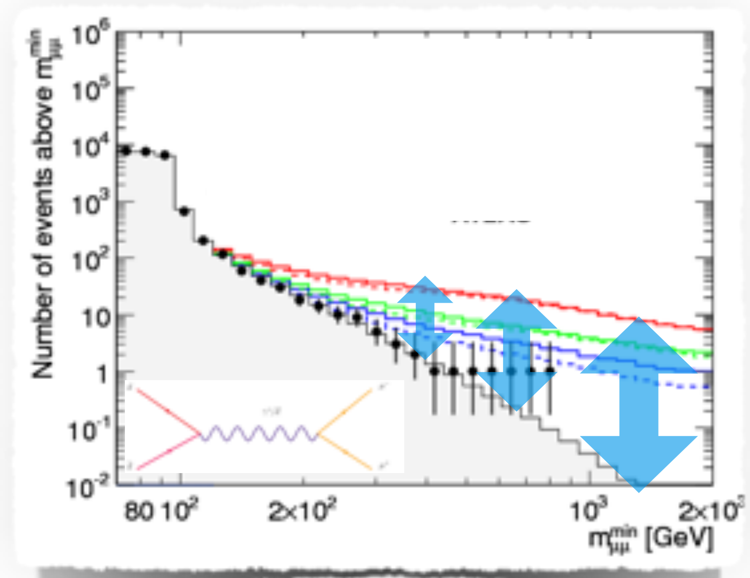
2) Off SM resonance $E \gg m_Z, m_h$

- Less precise (small statistics)
- Relies on large signals!

Two modes of exploration at LHC:

This talk: $\bar{q}q \to VV'\,(V'')$

$V^{(\prime)} = W^{\pm}, Z, \gamma$



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(tri)Dibosons at LHC $\bar{q}q \to VV'(V'')$

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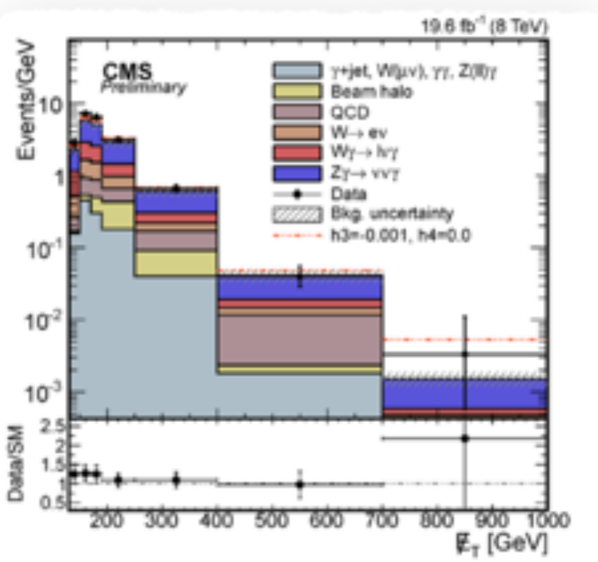
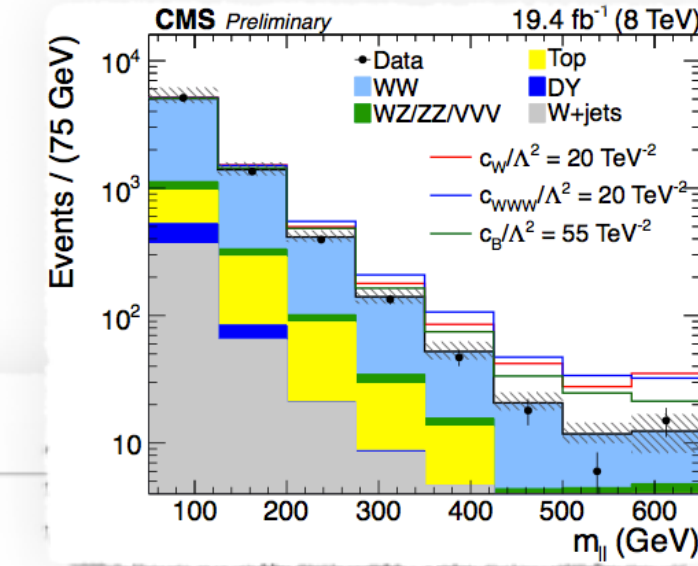
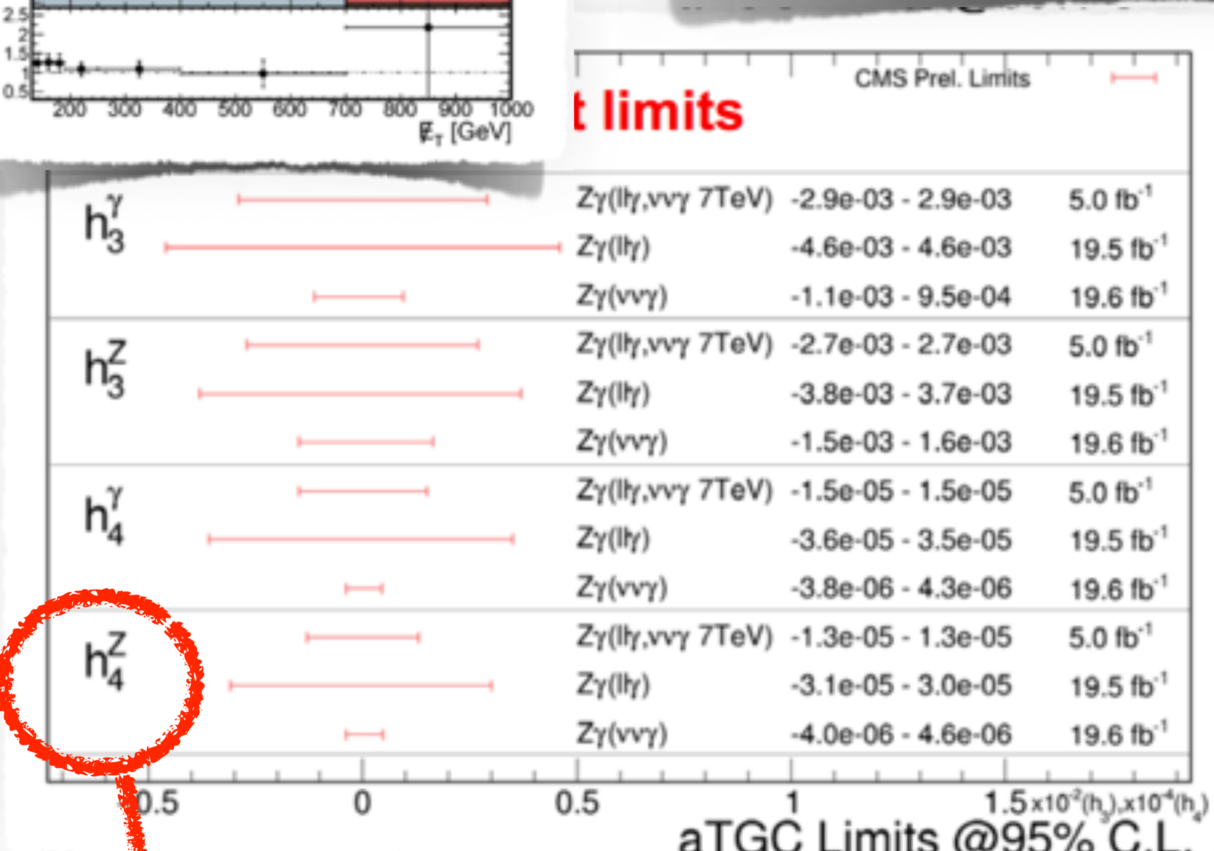
Plenty of Data:

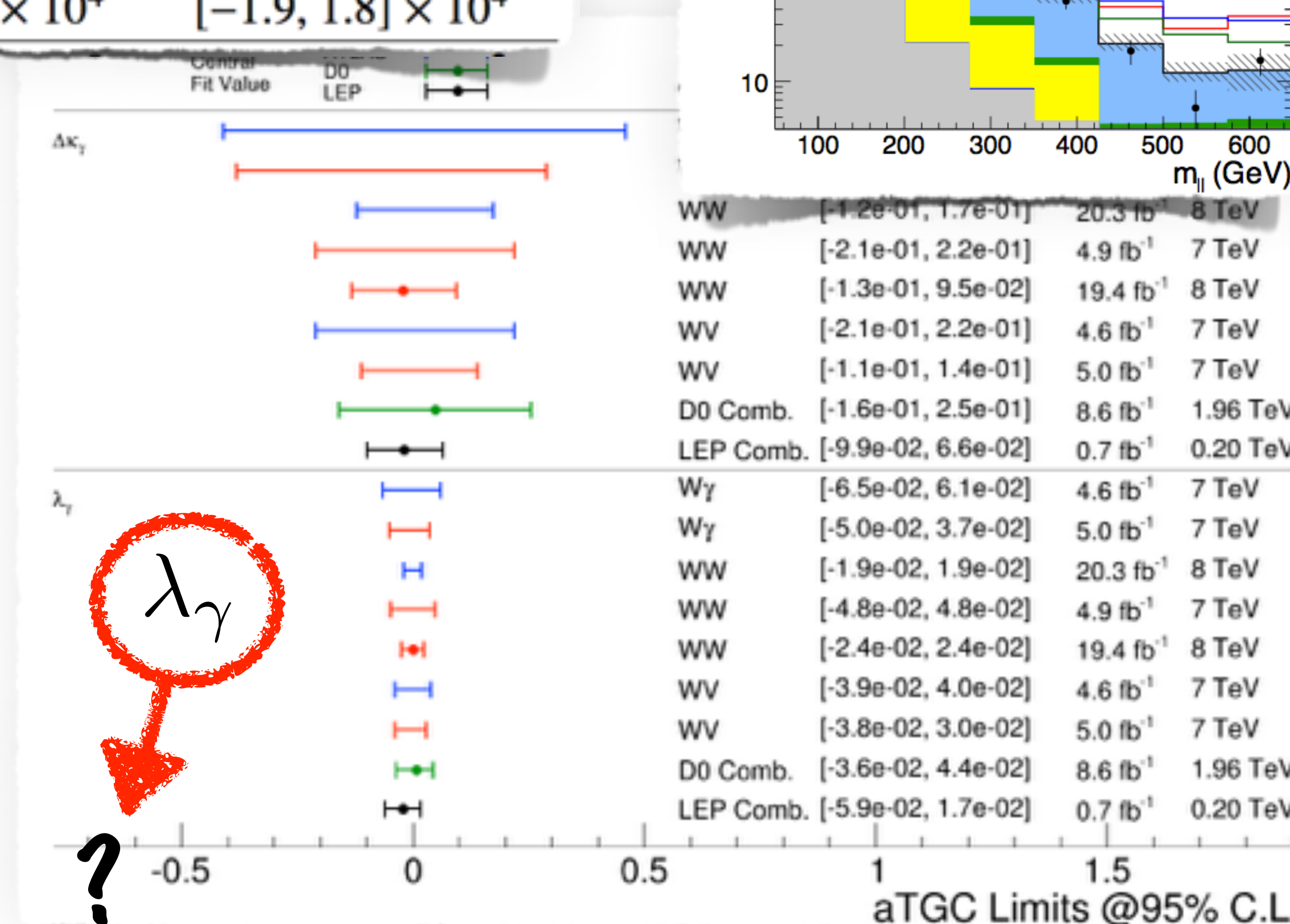


		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$

?







Why nobody cares?

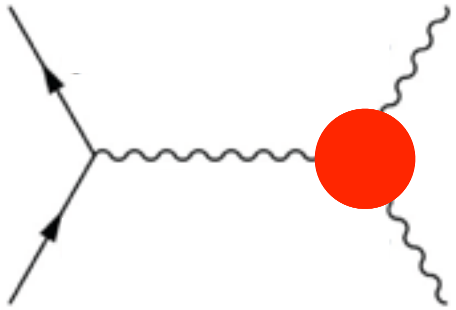
Part 1

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**	$H^\dagger D_\mu H \, D_\rho B_\nu^\rho \tilde{B}^{\mu\nu}$
$f_{T,0} \leftrightarrow$		$W_{\mu\nu}^4$



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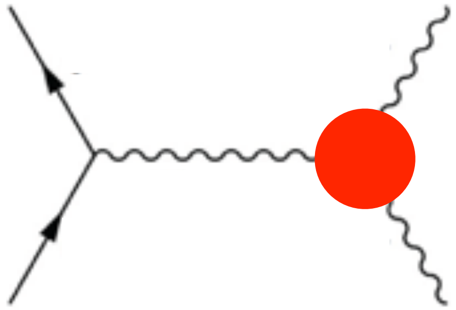
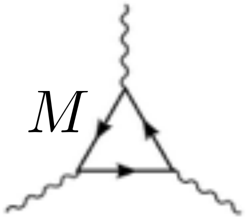


In popular models (e.g. SUSY, CH), V_T elementary, these are tiny:

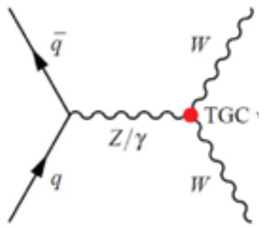


$$g\lambda_\gamma \sim \frac{g^3}{16\pi^2}\frac{m_W^2}{M^2}$$

SILH: Giudice,Grojean,Pomarol,Rattazzi'2007

2 Inconsistent

These couplings are tested in high-energy processes:



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

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

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

(see Contino's talk)

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

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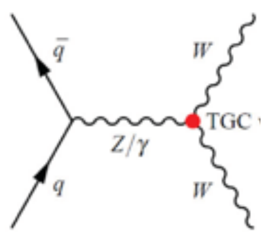

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- There is in fact a fundamental obstruction to measure weakly coupled theories consistently with hypothesis of scale separation...

3 Non-Interference for BSM_6 amplitudes

Azatov,Contino,Machado,FR'16

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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Theorem:

Any BSM dim-6 operator

A_4	$\|h(A_4^{SM})\|$	$\|h(A_4^{BSM})\|$
$VVVV$	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

Massless limit + tree level + at least one transverse vector

- SM and BSM_6 contribute to different helicity amplitudes
- No interference

why nobody cares

3 Non-Interference for BSM$_6$ amplitudes

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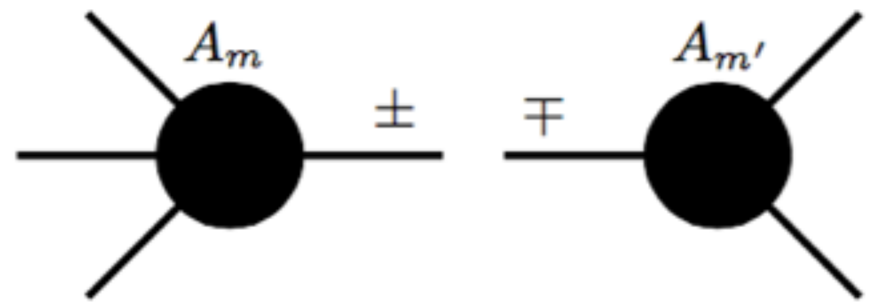
How?

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

n=m+m'-2 legs



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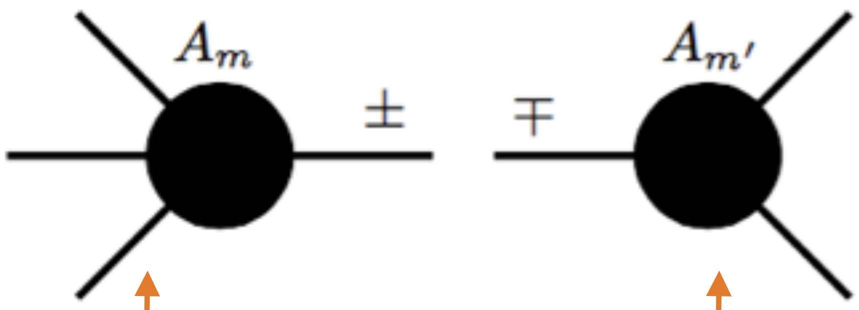

$p \in \mathbb{C}$ so that on-shell condition $p^2 = 0$ satisfied also for A_3

SM or BSM_6 (*)

(*)=In a basis where all effects proportional to the Equations od Motion have been eliminated

why nobody cares

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How?

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

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

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$$v_+(p) = (|p]_a, 0) \quad \epsilon^\mu_+(p;q) = \frac{\langle q|\gamma^\mu|p]}{\sqrt{2}\langle qp\rangle}$$

$$v_-(p) = (0, |p\rangle^{\dot{a}})$$

$$-\not{p} = |p\rangle[p| + |p]\langle p|$$

irreps of $SU(2) \times SU(2) \simeq SO(3,1)$

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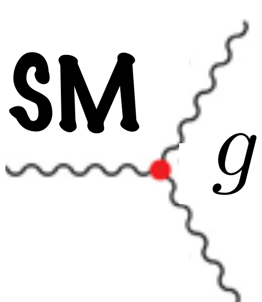
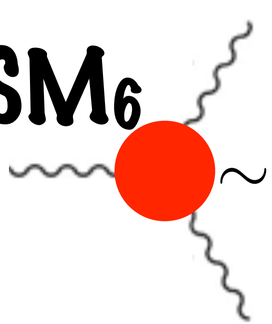
▶ $A_3(1^{h_1}2^{h_2}3^{h_3}) = g\langle 12\rangle^{h_3-h_1-h_2}\langle 13\rangle^{h_2-h_1-h_3}\langle 23\rangle^{h_1-h_2-h_3}$ **uniquely fixed**

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

BSM$_6$  $\sim \frac{1}{M^2} \Rightarrow |h^{BSM}| = 3$

why nobody cares

3 Non-Interference for BSM_6 amplitudes

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How?

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

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 doublett))

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Grisaru,Pendleton,vanNieuwenhuizen'77

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

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

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

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

BSM : Operators with transverse V not supersymmetrizable

Elias-Miro,Espinosa,Pomarol'14

why nobody cares

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

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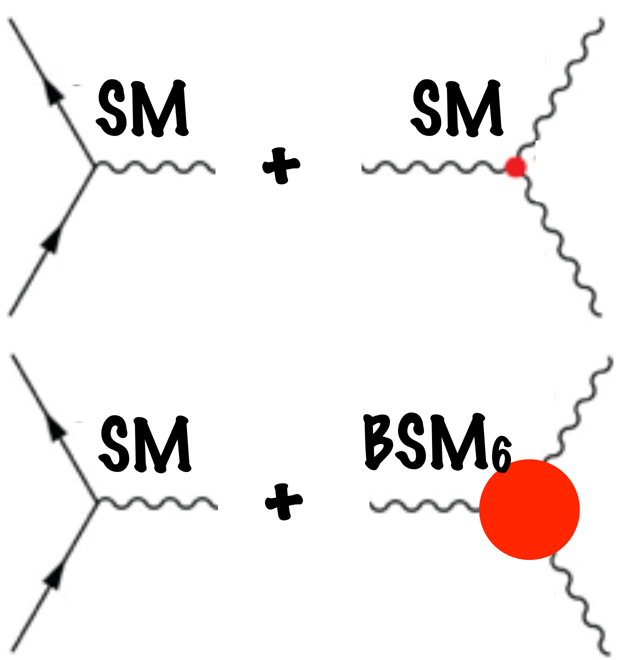

$$h^{tot} = 1 - 1 = 0$$

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

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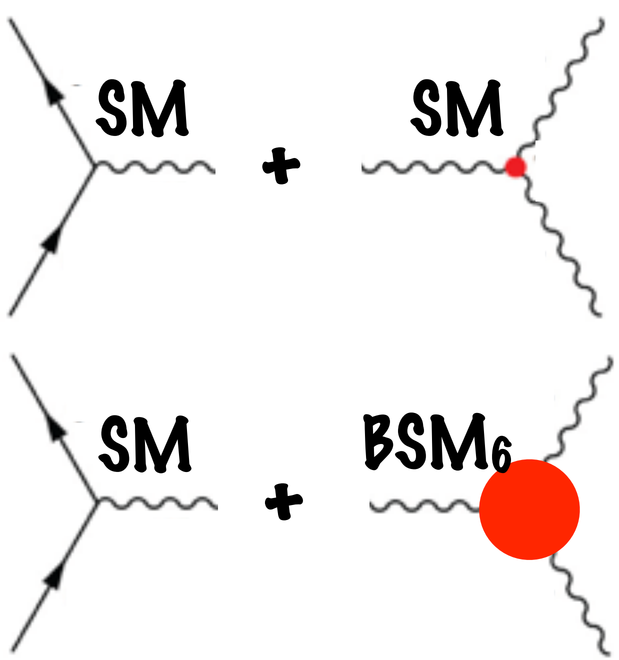

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No Interference
(dim-6, 4-point)

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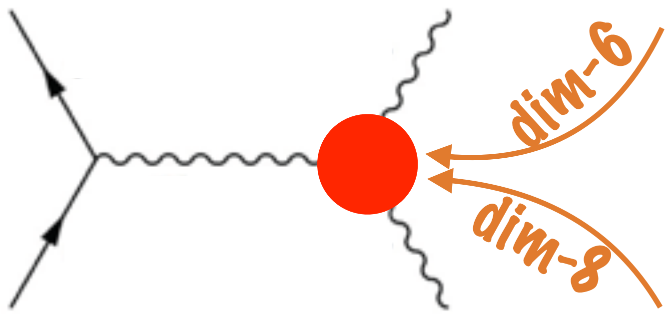
Implications?

$$\bar{q}q \to VV'$$

$V^{(\prime)} = W^{\pm}, Z, \gamma$



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

$$\frac{g_*}{M^4}\epsilon_{abc}\Box\, W_{\mu}^{a\,\nu}W_{\nu\rho}^{b}W^{c\,\rho\mu}$$

(3-point vertex has dimension of coupling → weight with g_* for illustration)

why nobody cares

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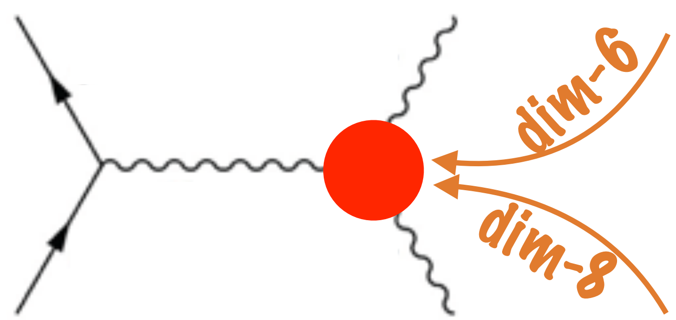

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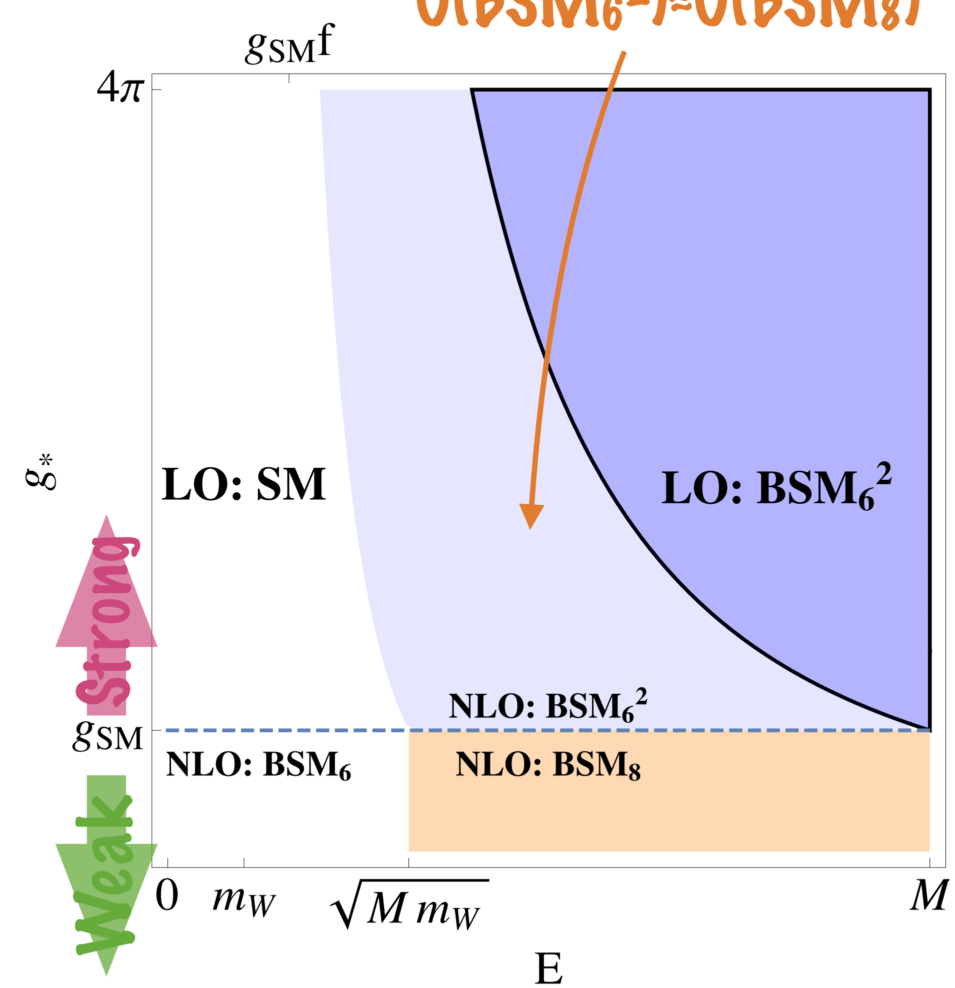
$$\frac{g_*}{M^4}\epsilon_{abc}\Box W_{\mu}^{a\,\nu}W_{\nu\rho}^{b}W^{c\,\rho\mu}$$

(3-point vertex has dimension of coupling → weight with g* for illustration)

$$\sigma_T \sim \frac{g_{SM}^4}{E^2}\Big[1 + \overbrace{\frac{g_*}{g_{SM}}\frac{m_W^2}{\Lambda^2}}^{\text{BSM}_6\times\text{SM}} + \overbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}}^{\text{BSM}_6{}^2} + \underbrace{\frac{g_*}{g_{SM}}\frac{E^4}{\Lambda^4}}_{\text{BSM}_8\times\text{SM}} + \dots\Big]$$

Non-interference:
O(BSM$_6^2$)≈O(BSM$_8$)



why nobody cares?

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

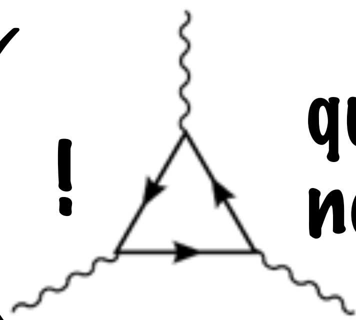
Part 2

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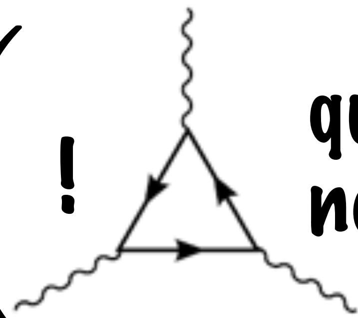
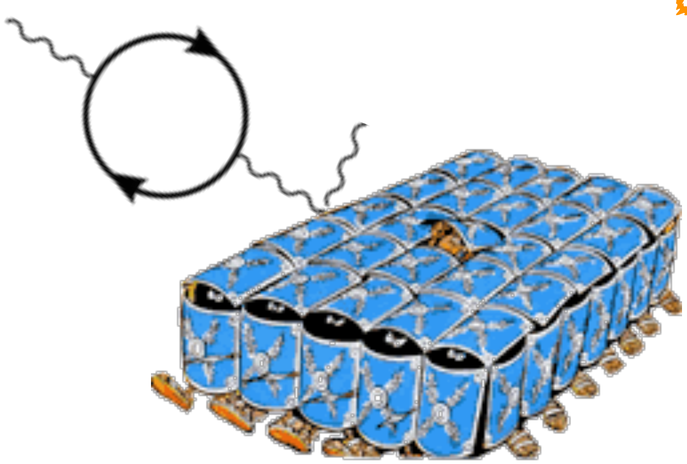
(!  quantum effects generally propagate new couplings to the whole SM !)

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



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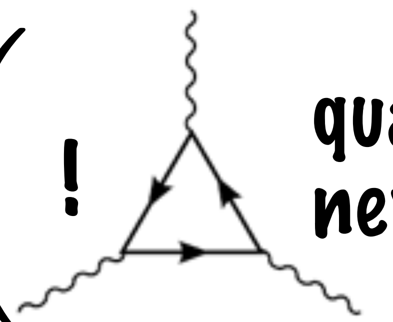
(!  quantum effects generally propagate new couplings to the whole SM !)

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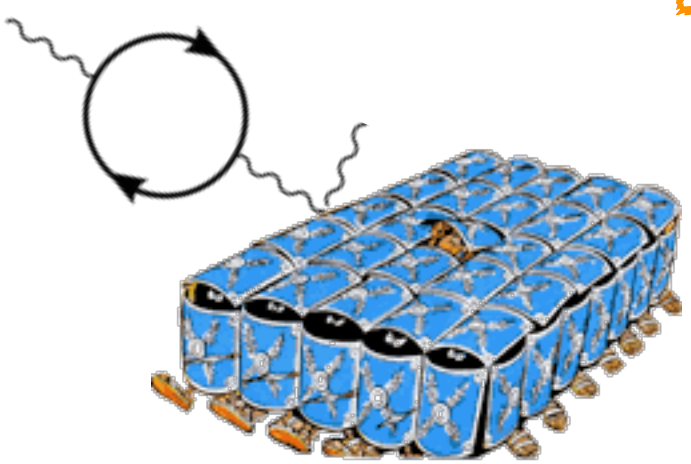
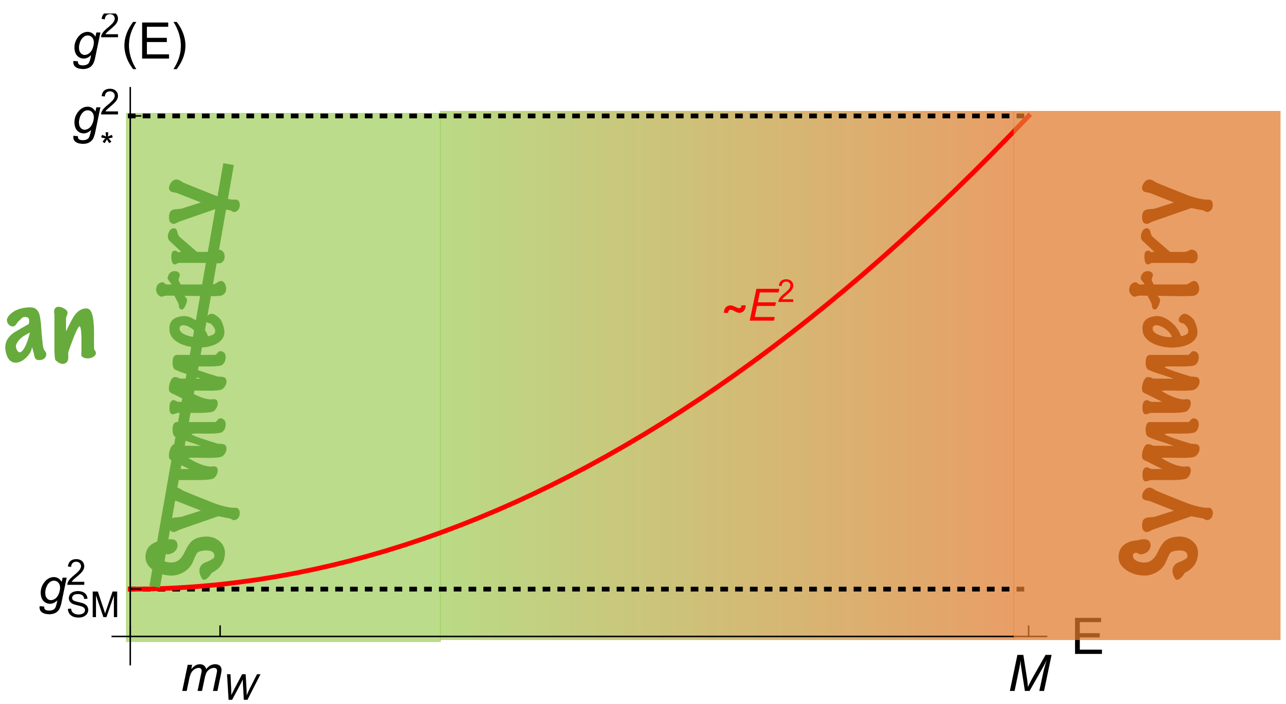


$$A \simeq g_{SM}^2 \left(1 + \frac{g_*^2}{g_{SM}^2}\frac{E^2}{M^2}\right) \equiv g^2(E)$$

SM Lagrangian (dim-4)



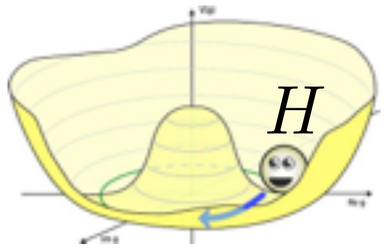
Higher-dim operators (dim-6, sim-8…)

Strongly Coupled BSM and Approximate Symmetries

Scalars: Composite Higgs

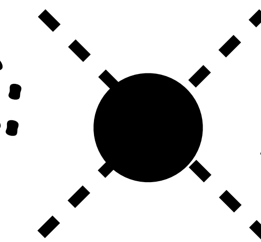
Higgs is a Pseudo Goldstone boson from new strong sector (symm=SO(5)/SO(4))

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



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

- $\frac{g_*^2}{M^2}(\partial_\mu |H|^2)^2$ **large**
- $\lambda |H|^4$ **small**
- **Large effects $V_L V_L \to V_L V_L$ at high-E:**



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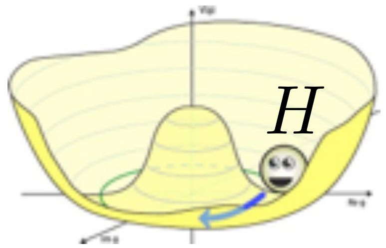

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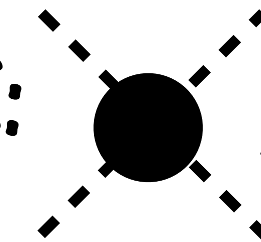

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Fermions: (partially) Composite fermions

Symmetry: Chiral (or Non-linear SUSY)

Eichten,Lane,Peskin'83 Bardeen,Visnjic'82, Bellazzini,FR'soon

- **Large effects in, e.g. dijets at LHC**

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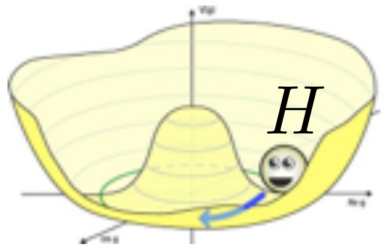

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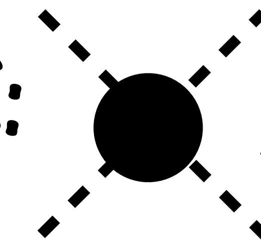

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Vectors: ?

Strong transverse vectors at high-E

Problem: Gauge bosons associated with weak SM coupling $(\partial_\mu + igA_\mu)$ how compatible with g*>>g ?

(Even if composite, $g = \frac{4\pi}{\sqrt{N}}$ it would never appear strong)

Liu,Pomarol,Rattazzi,FR'16

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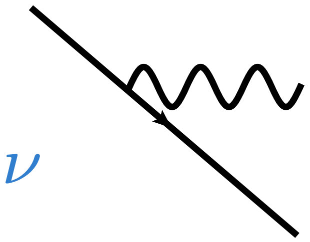
However:
Two ways a particle can couple to gauge boson:

$g\bar{\psi}_{\text{new}} A_\mu \gamma^\mu \psi_{\text{new}}$ monopole/dipole $g_* \bar{\psi}_{\text{new}} \sigma^{\mu\nu} \psi_{\text{new}} F_{\mu\nu}$ 

Liu,Pomarol,Rattazzi,FR'16

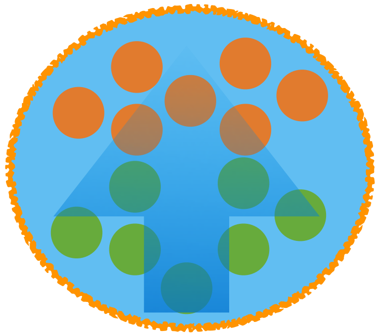
Strong transverse vectors at high-E

$g = 0$

- A_μ composite, g*
- No light charged d.o.f

$$\mathcal{L} = \frac{M^4}{g_*^2} L\left(\frac{\partial_\mu}{M}, g_* \frac{\hat{F}_{\mu\nu}}{M^2}, \Phi\right)$$

(Euler-Heisenberg)



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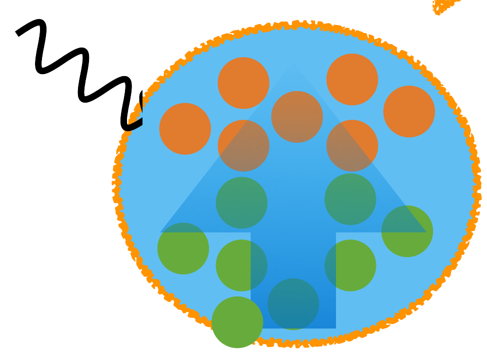

$q = \frac{g}{g_*}$

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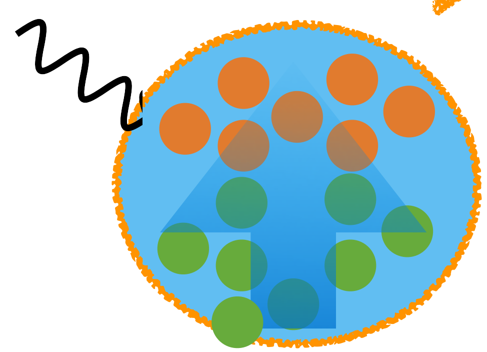

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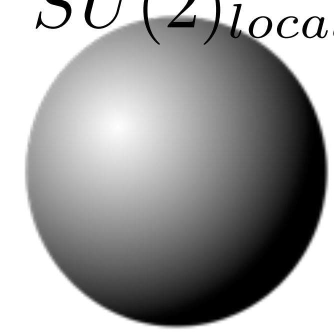
Non-abelian

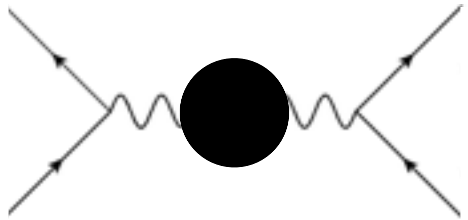
$U(1)^3_{local} \times SU(2)_{global}$ ⟵ $SU(2)_{local}$



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

Liu,Pomarol,Rattazzi,FR'16

Strong transverse vectors: Implications

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

Barbieri,Pomarol,Rattazzi,Strumia'04

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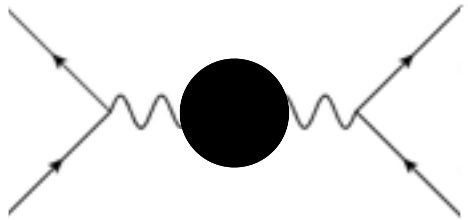

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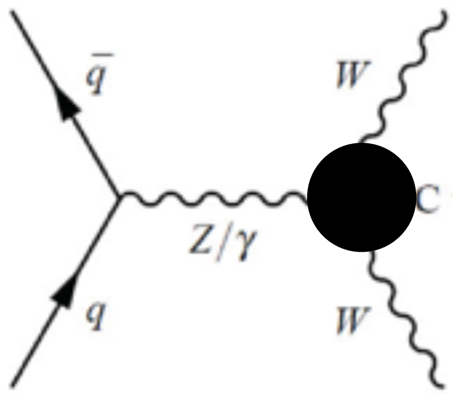
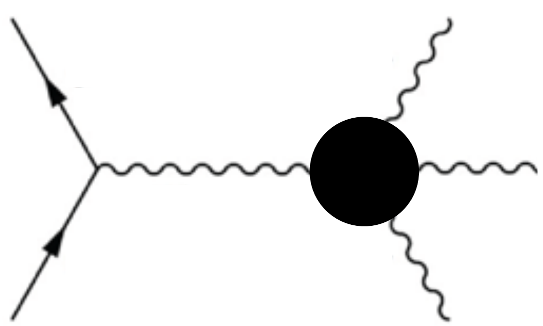


$\lambda_\gamma \approx g_* \frac{m_W^2}{M^2}$ $M \gtrsim \sqrt{\frac{g_*}{4\pi}}\ 2.2\ \text{TeV}$

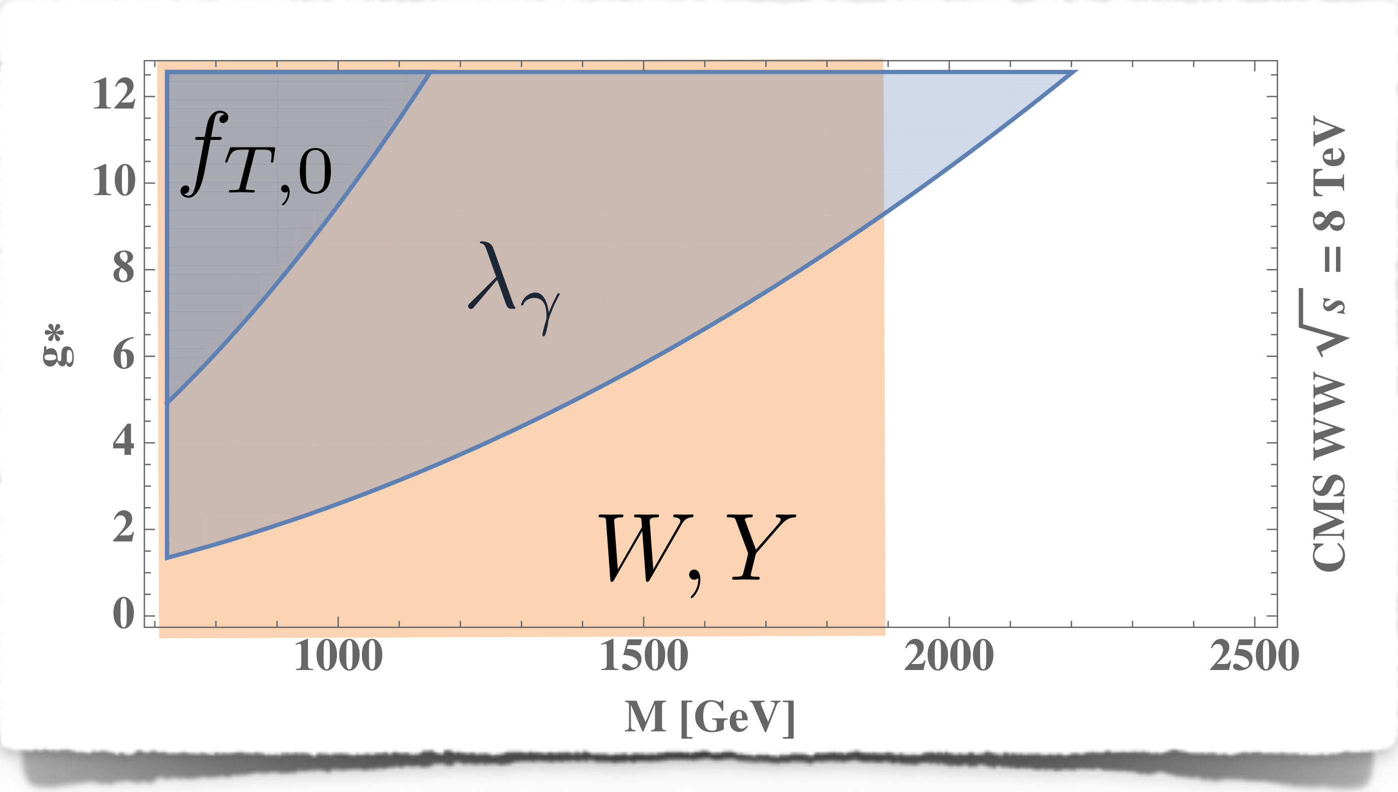
- $\frac{g_*^2}{M^4}W_{\mu\nu}^4$



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

So far the only models that motivate these searches consistently

Strong transverse vectors: Implications



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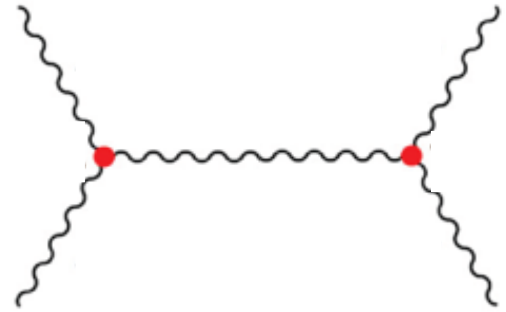
W_T scattering

SM



$\sim g^2$

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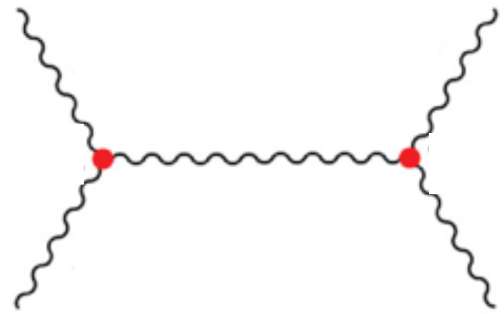

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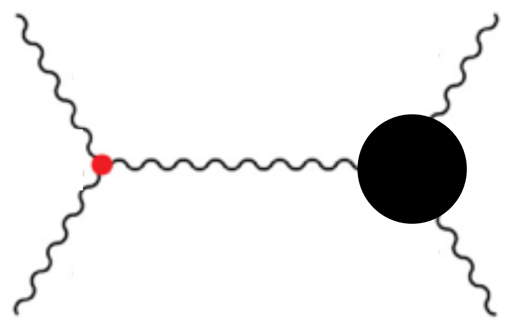

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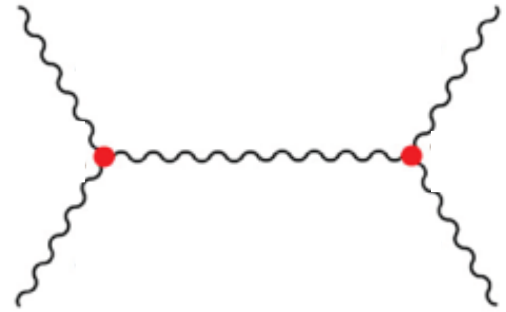

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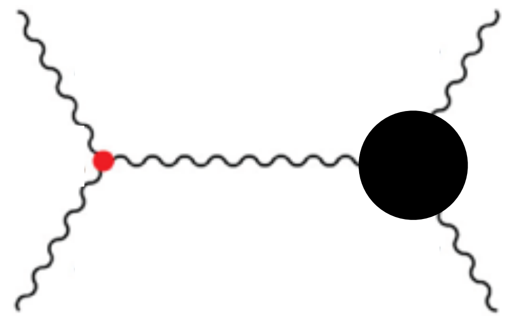

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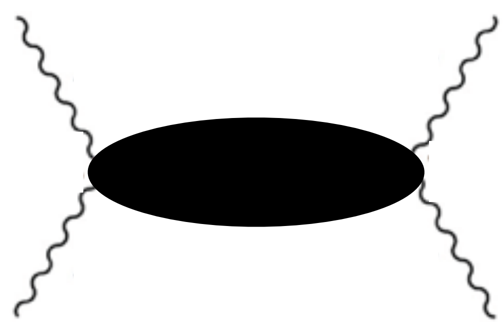

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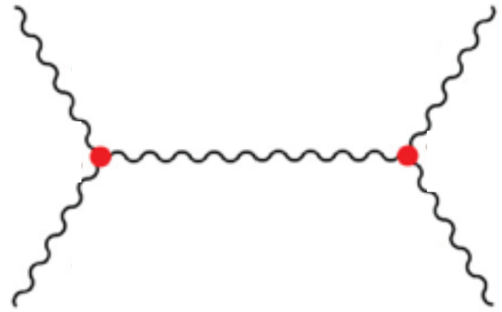

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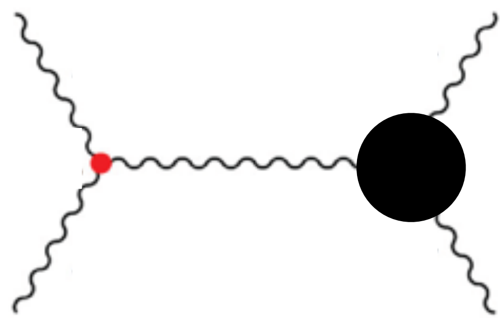

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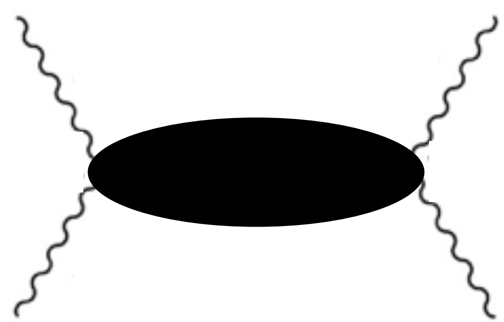

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- $\frac{\delta \mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \lesssim 1$ **dimension-6 analysis ok**

Strong transverse vectors: Implications

W_T scattering

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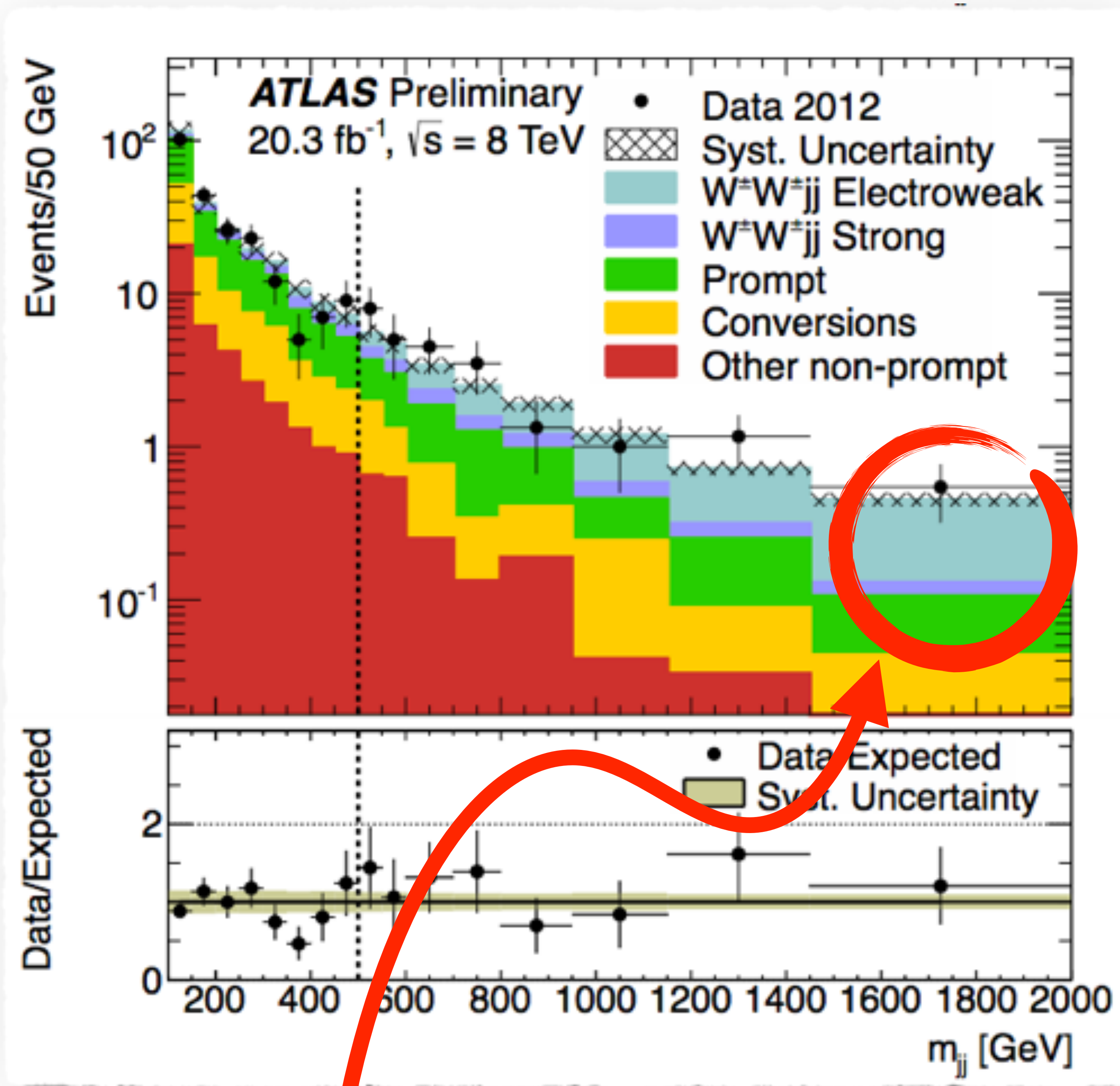

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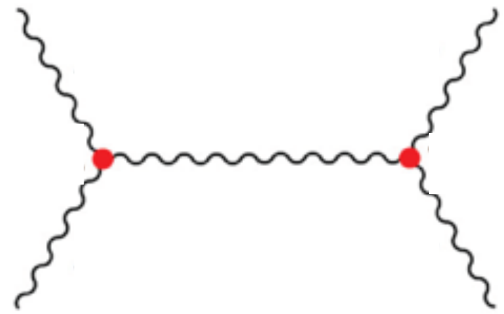

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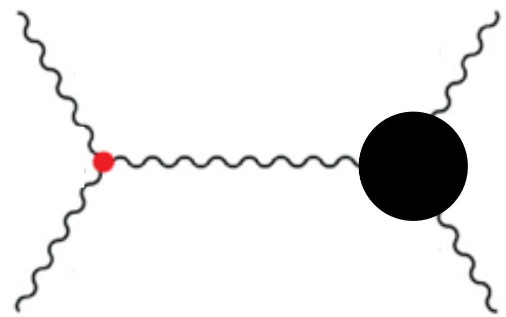

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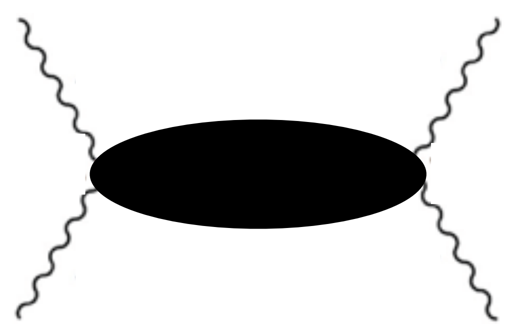

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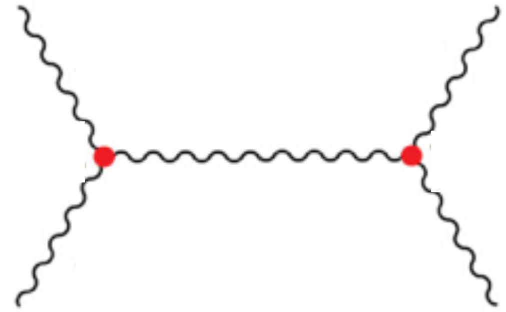

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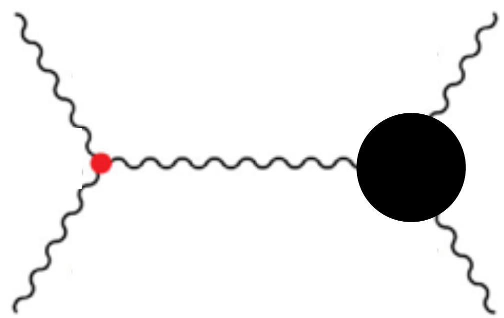

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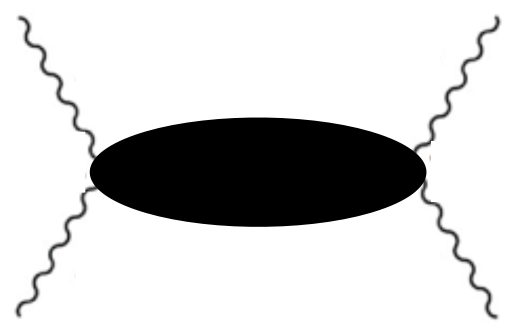

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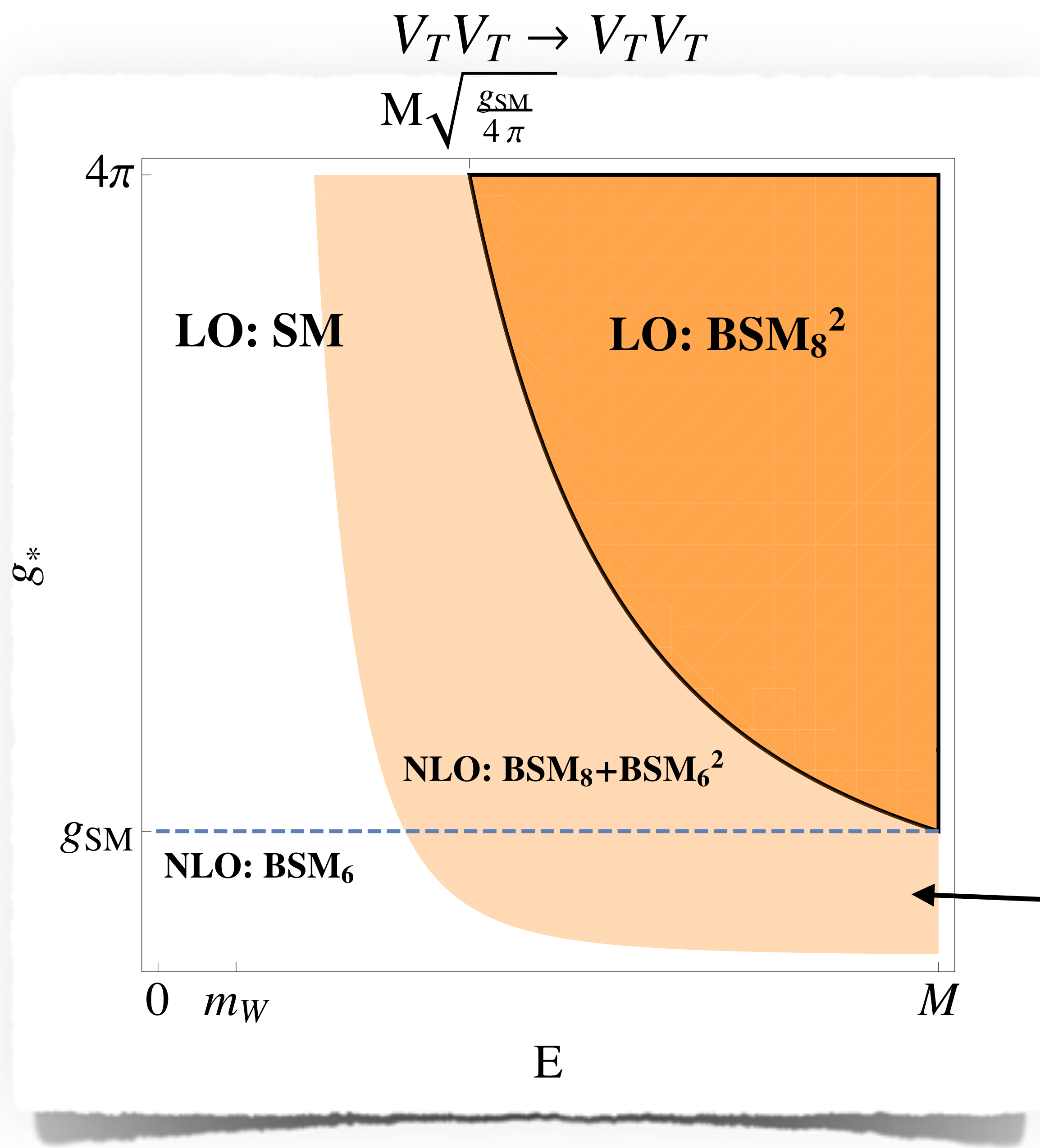
- $\frac{\delta\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \gtrsim 1$ dim-6 not ok! dim-8 dominate!

(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)

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)

...

Conclusions

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

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

Need structurally robust scenario for strong coupling

- Remedios:
  - 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

Conclusions