Precision Higgs

Swiss Tunnels:

L=27km

E_{beam}=362MJ

Precision=??

L=35km

E_{train}=362MJ

Precision=10^{-5}

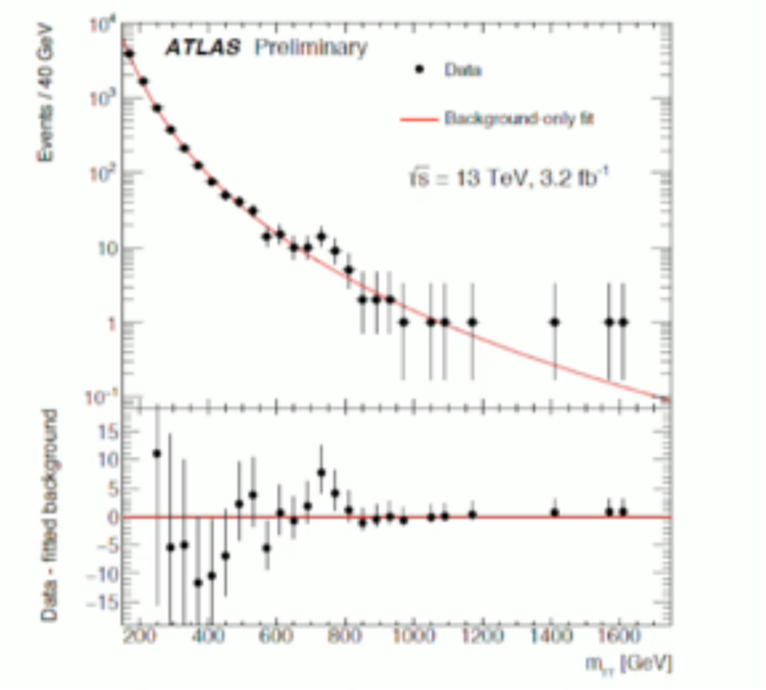
Francesco Riva
(CERN)

In collaboration with
Pomarol 1308.2803
Gupta, Pomarol 1405.0181
Biekotter, Knochel, Kramer, Liu 1406.7320
Falkowski 1411.0669
Liu, Pomarol, Rattazzi 1603.03064,
Contino,Falkowski,Goertz,Grojean, 1604.06444
Azatov, Contino, Machado 1607.05236

LHC Searches

Two modes of exploration at LHC:

A) Direct Searches:



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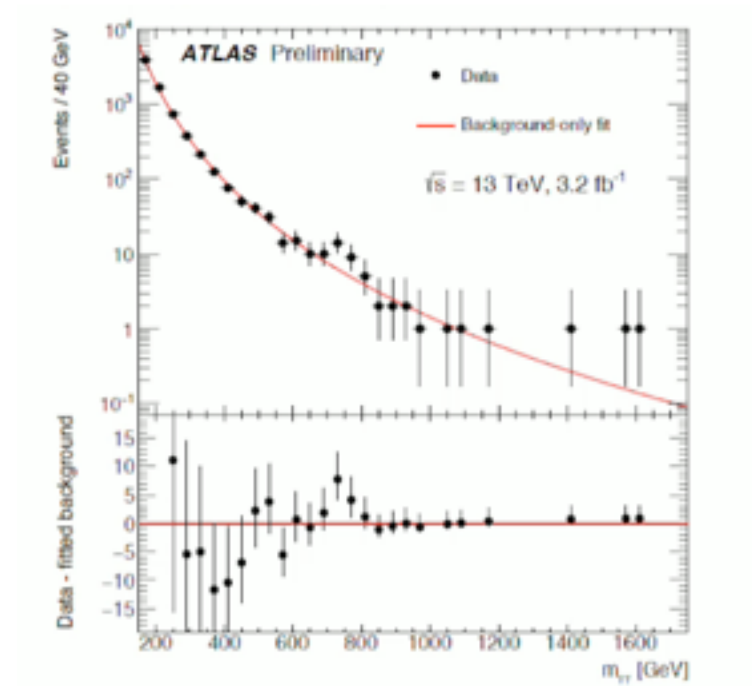
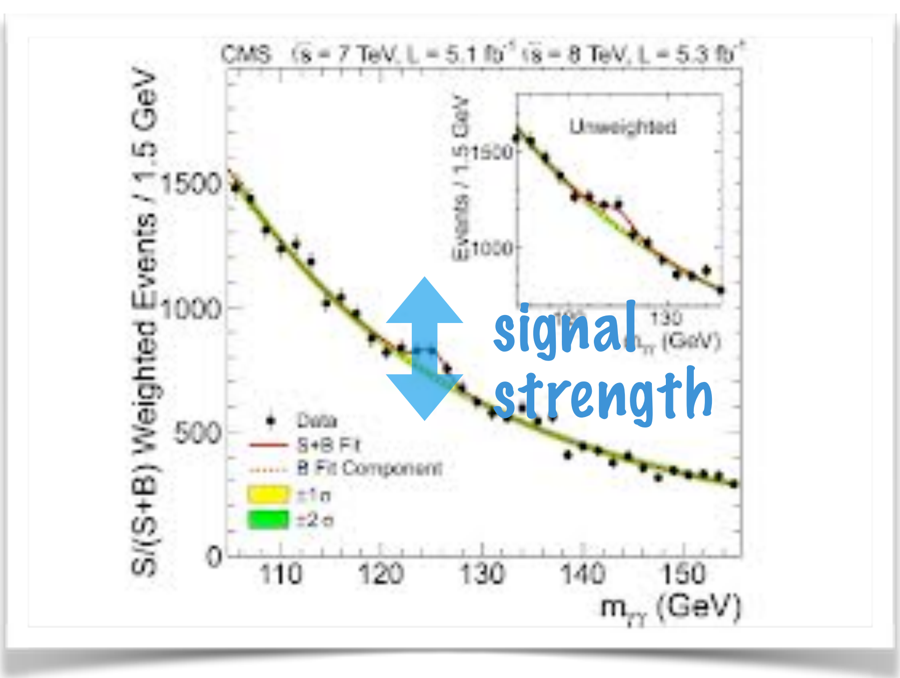
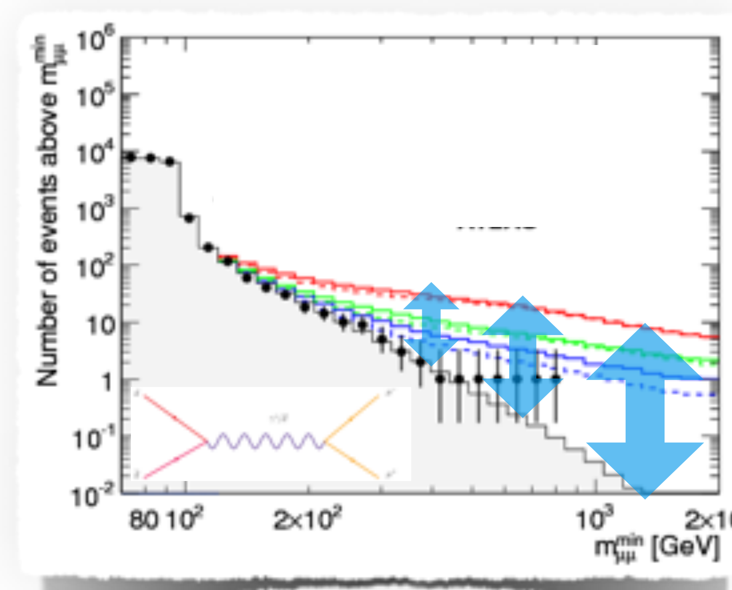


B) Indirect Searches:



1) On SM resonance

$E = m_{h,Z}$

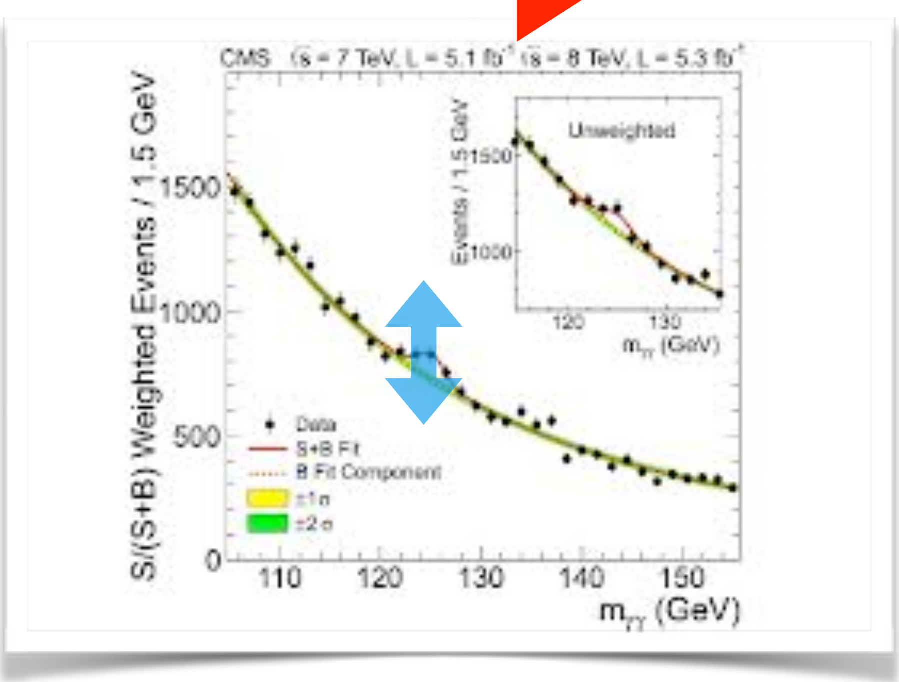


2) Off SM resonance

$E \gg m_{h,Z}$

LHC Searches

B) Indirect Searches:



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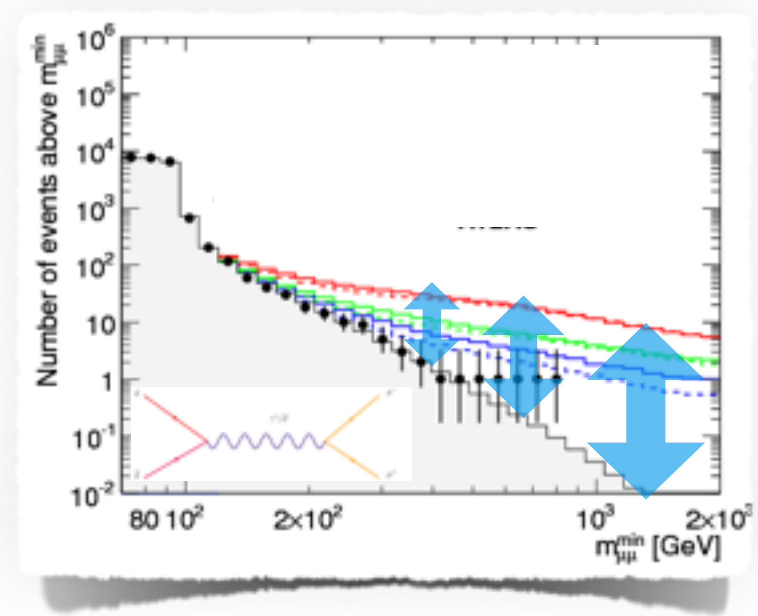

2) Off (SM) resonance
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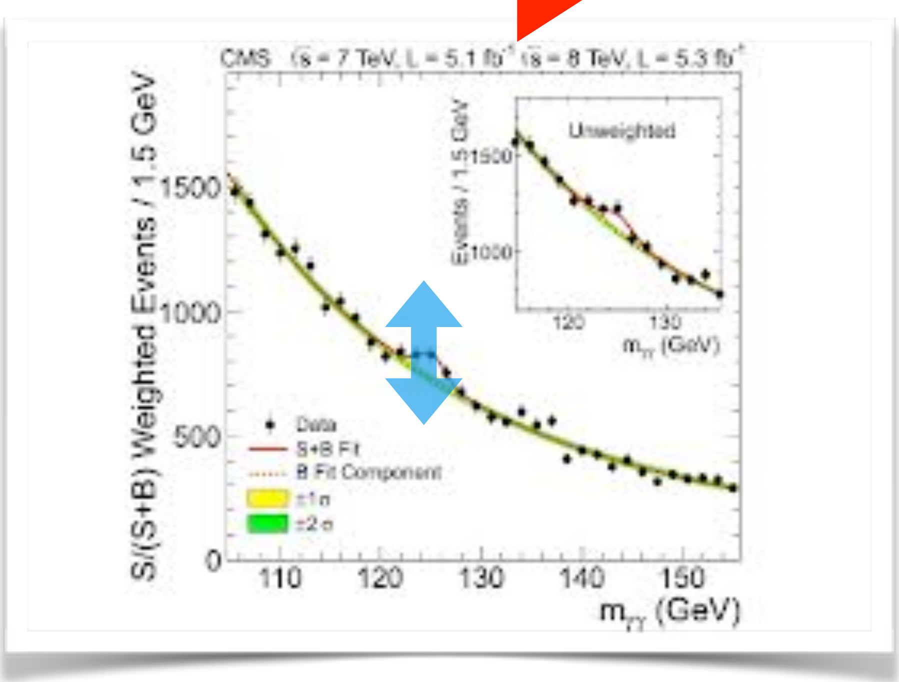
LHC Searches

Why can we call these "searches"?

B) Indirect Searches:



1) On (SM) resonance
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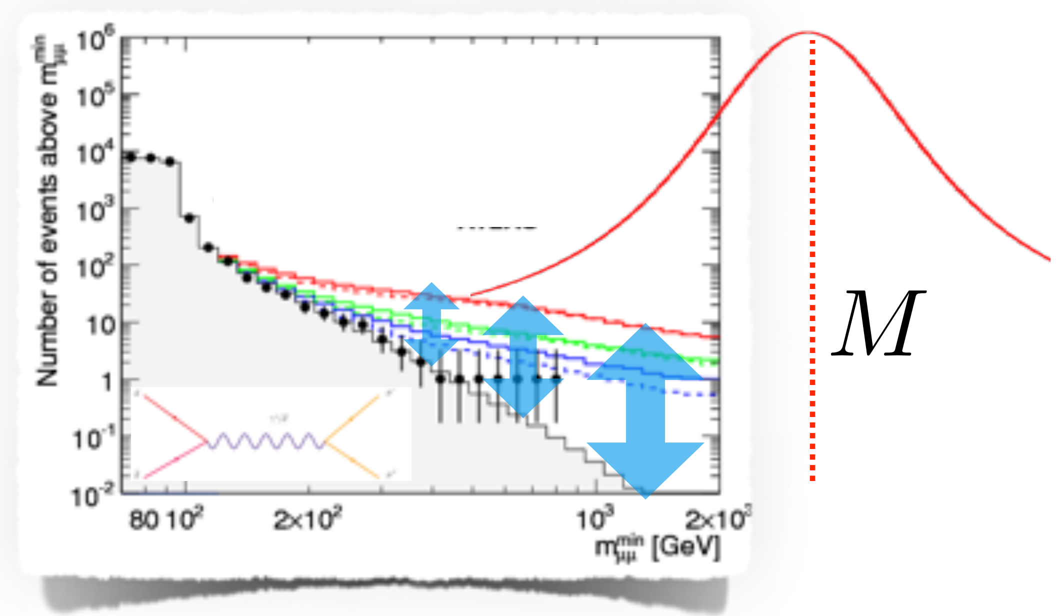
We miss the resonance, but get its tail

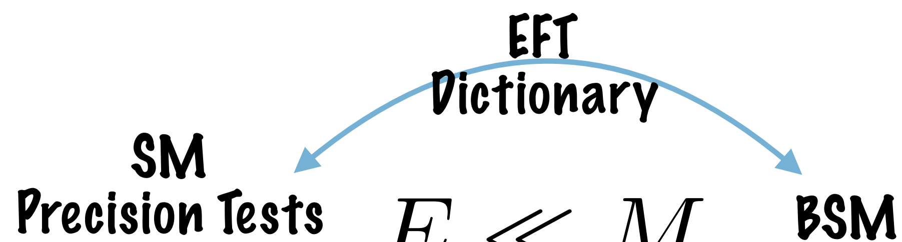


2) Off (SM) resonance
$E \gg m_{h,Z}$

Effective Field Theories

Why can we call these "searches"?

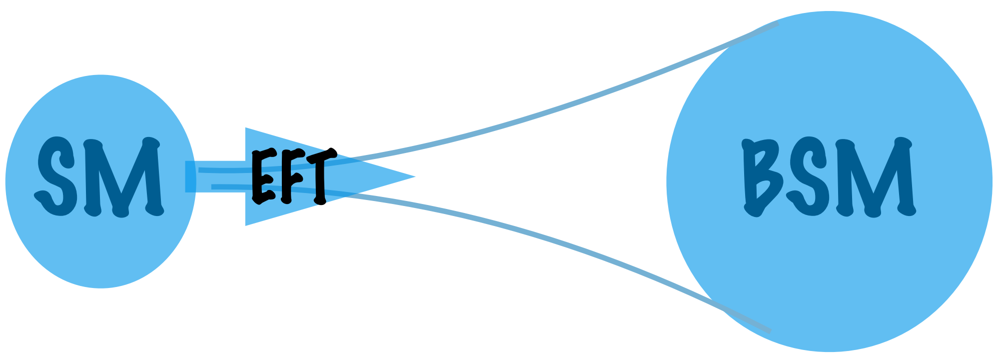
Effective Field Theories provide the correct framework for



$$E \ll M$$

$$\mathcal{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathcal{L}_{\text{eff}} \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

$$\mathcal{L}_6 \leftarrow \sum_i c_i \frac{\mathcal{O}_i}{M^2}$$



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EFT Dictionary

SM Precision Tests $E \ll M$ BSM

$$\mathcal{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathcal{L}_{\rm eff} \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

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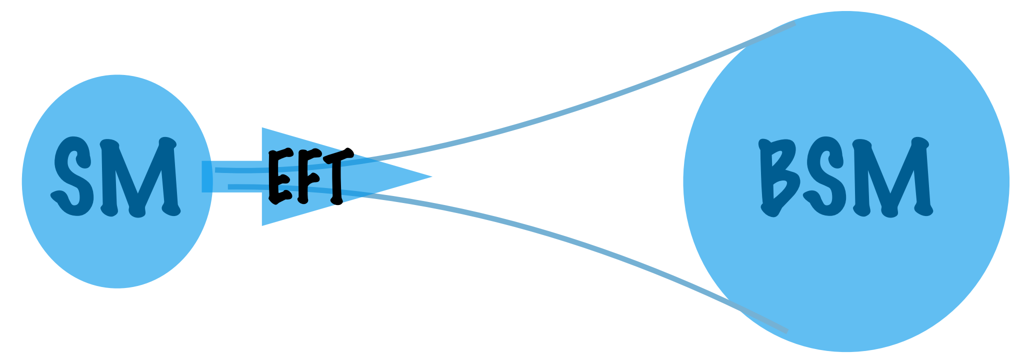


In practice it's an expansion in fields and derivatives

New BSM couplings (power-counting) → g_*; New BSM mass → M

$$\frac{g_* \Phi}{M} \qquad \frac{D_\mu}{M}$$

2 expansion parameters:

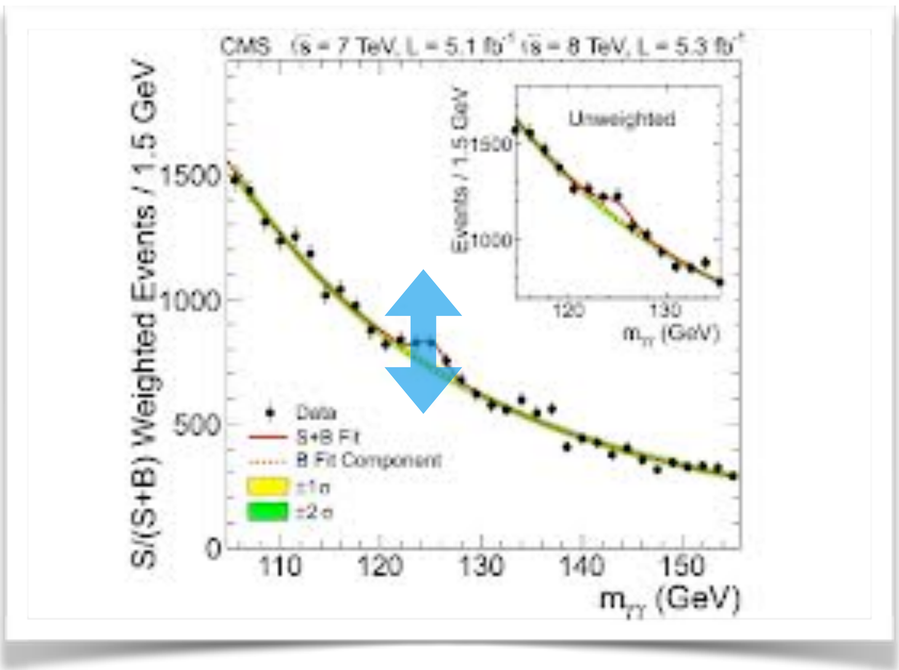
Higgs couplings to BSM (g_*), Higgs vev (v)

$$\frac{g_* v}{M} \ll 1 \qquad \frac{E}{M} \ll 1$$

(in technicolor-like theories the field expansion fails -> "non-linear" EFT)

Alonso,Brivio,Gavela,Merlo,Rigolin,Yepes'14, Buchalla,Cata,Krause'14-15

Indirect Searches



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- Exploits resonant enhancement of SM process to measure it precisely

- Tests departures from SM couplings

$$\frac{\delta g}{g} \sim \frac{g_* v}{M}$$

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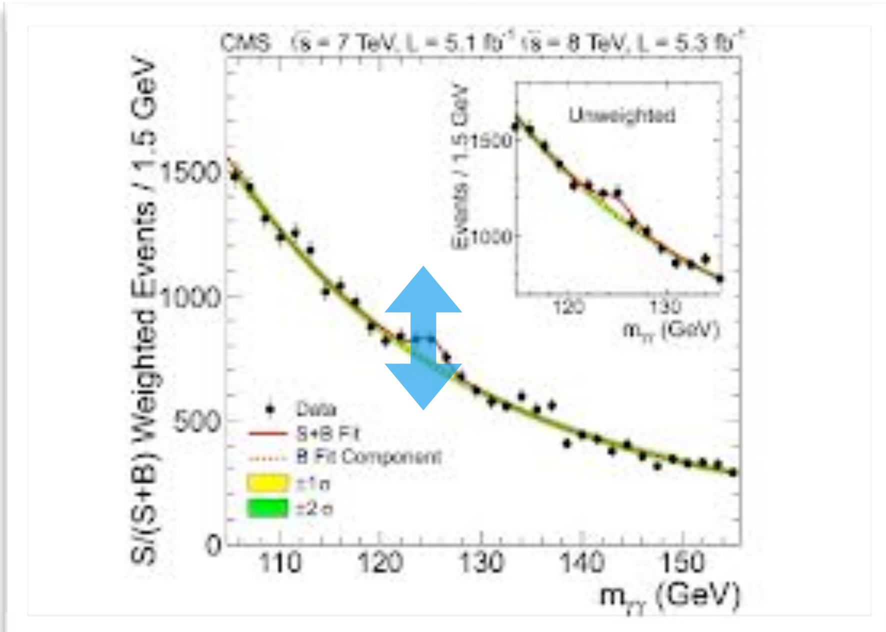

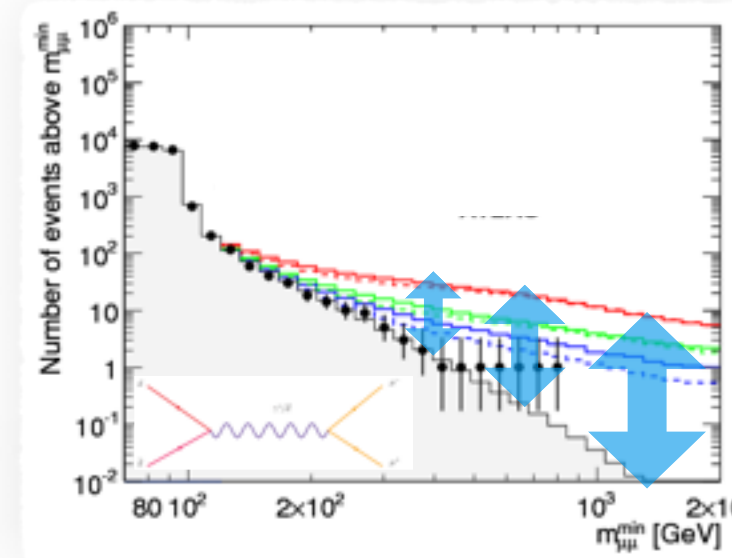

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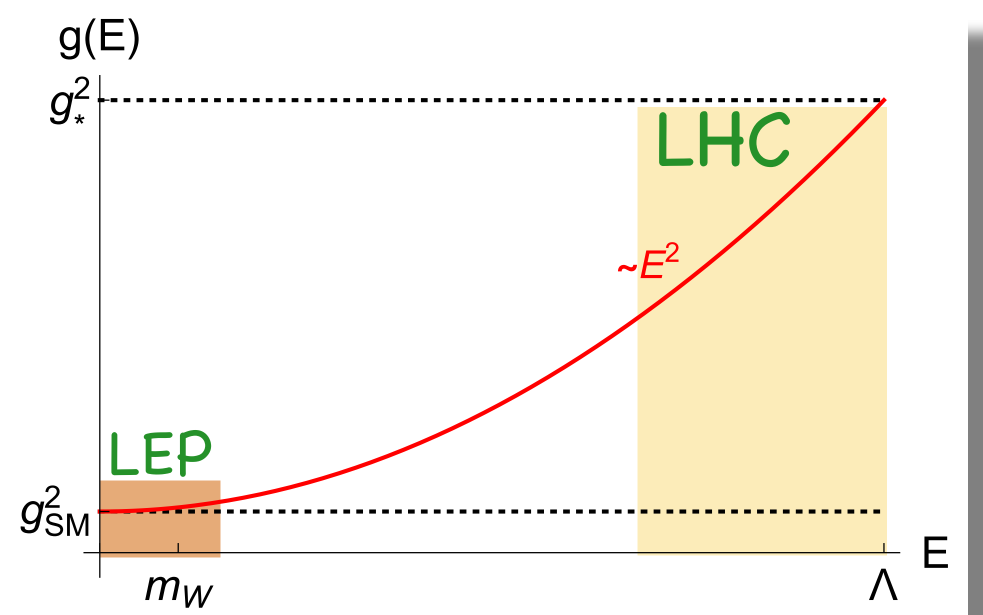
2) Off (SM) resonance

$E \gg m_{h,Z}$

- Less precise
- Tests new coupling structures



$$\left.\frac{\delta g}{g}\right|_{E \gg m_Z} \propto \frac{E^2}{M^2}$$

1) On-shell processes and implications for h-physics

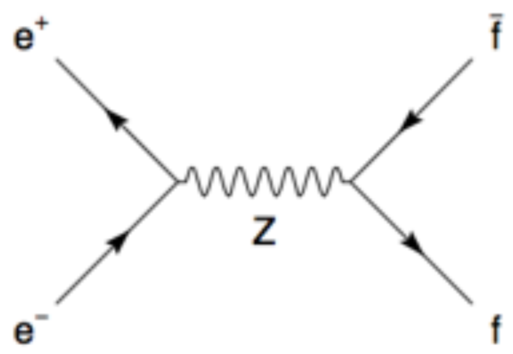
(assume CP-preserving, flavour universal new physics)

$E = m_Z$

Z-resonance (LEP1)

Measures deviations from SM Z-couplings to fermions

Experiment



How Many parameters? 7

$Z\bar{\nu}\nu \quad Z\bar{e}_L e_L \quad Z\bar{e}_R e_R$

$Z\bar{u}_L u_L \quad Z\bar{u}_R u_R \quad Z\bar{d}_L d_L \quad Z\bar{d}_R d_R$

What precision?
≈1/1000

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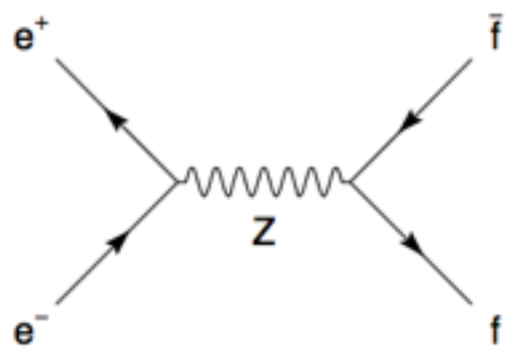

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Theory

$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$
$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\sigma^a\gamma^\mu L_L)$

At given order in 1/M, combinations of operators proportional to EoM redundant
→ Different equivalent bases

(translator: Falkowski,Fuks,Mawatari, Mimasu,FR,Sanz '14)

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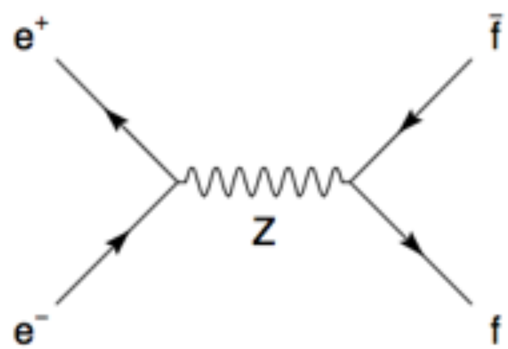

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What precision?

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$$\frac{g_*^2 v^2}{M^2}\begin{pmatrix} \tilde{c}_{HL} \\ \hat{c}_{HL} \\ \hat{c}_{HE} \\ \tilde{c}_{HQ} \\ \hat{c}_{HQ} \\ \hat{c}_{HU} \\ \hat{c}_{HD} \\ \hat{c}_{ll} \end{pmatrix} = \begin{pmatrix} -1.9 \pm 1.1 \\ 1.1 \pm 0.7 \\ 0.1 \pm 0.6 \\ -4.7 \pm 1.9 \\ 0.2 \pm 2.0 \\ 7.0 \pm 6.9 \\ -31.3 \pm 10.3 \\ -4.7 \pm 3.5 \end{pmatrix} \cdot 10^{-3},$$

Falkowski,FR '14

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erent equivalent bases

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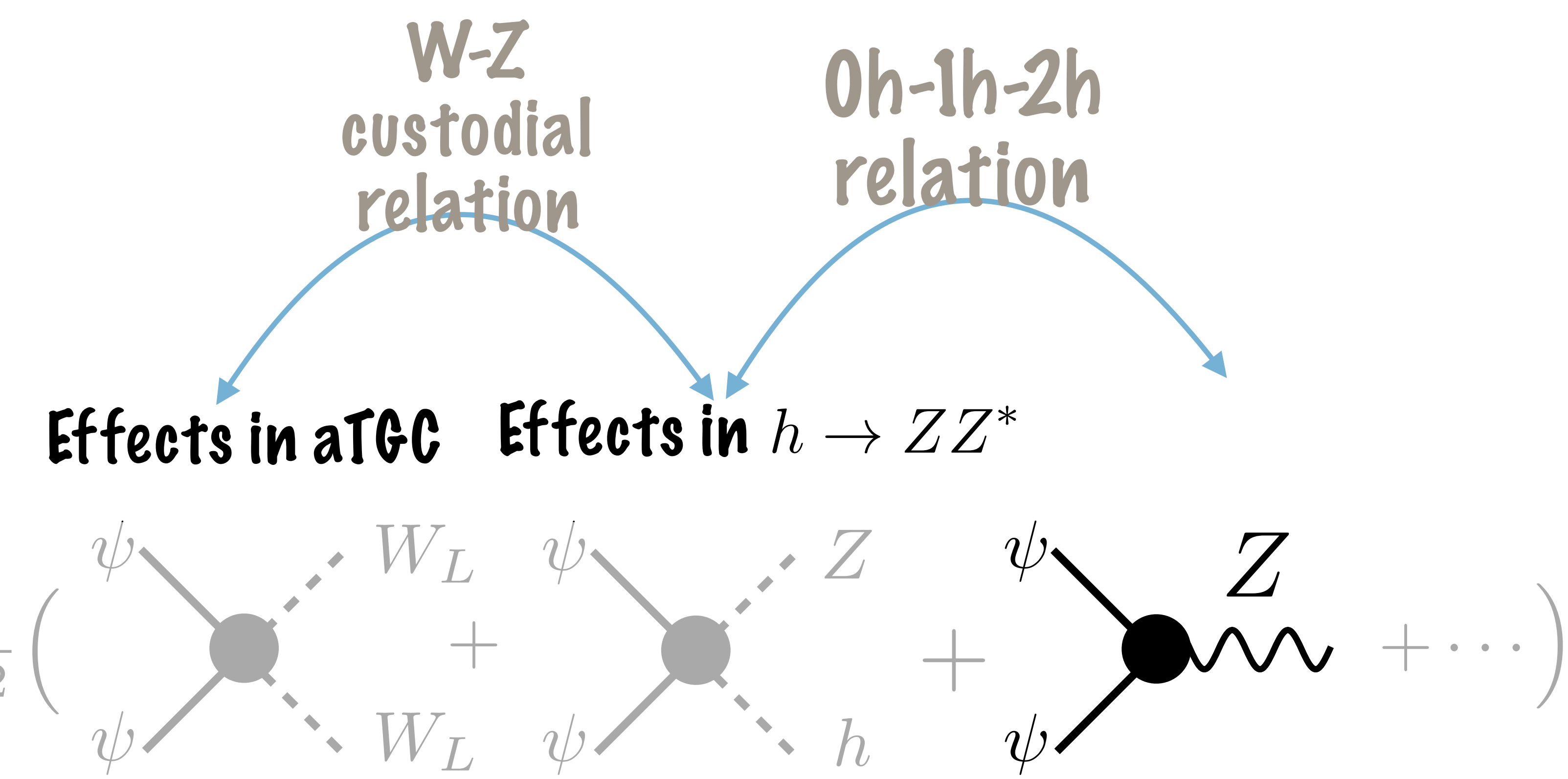
Z-resonance (LEP1)

Implications of EFT perspective:*

- Relation with new physics scale: $\frac{M}{g_*} \geq 2.5~\text{TeV}$
- Relation with h-physics and W-physics

(testing $\frac{\delta g}{g} \sim \frac{g_* v}{M}$ expansion)



$$\frac{g_*^2}{M^2} H^\dagger D_\mu H \bar{\Psi} \gamma^\mu \Psi = \frac{g_*^2}{M^2} \left(\cdots \right)$$

*=since here the #experimental parameters is finite, EFT expansion not necessarily needed (see parametrization m_Z, A_{FB} ,...)

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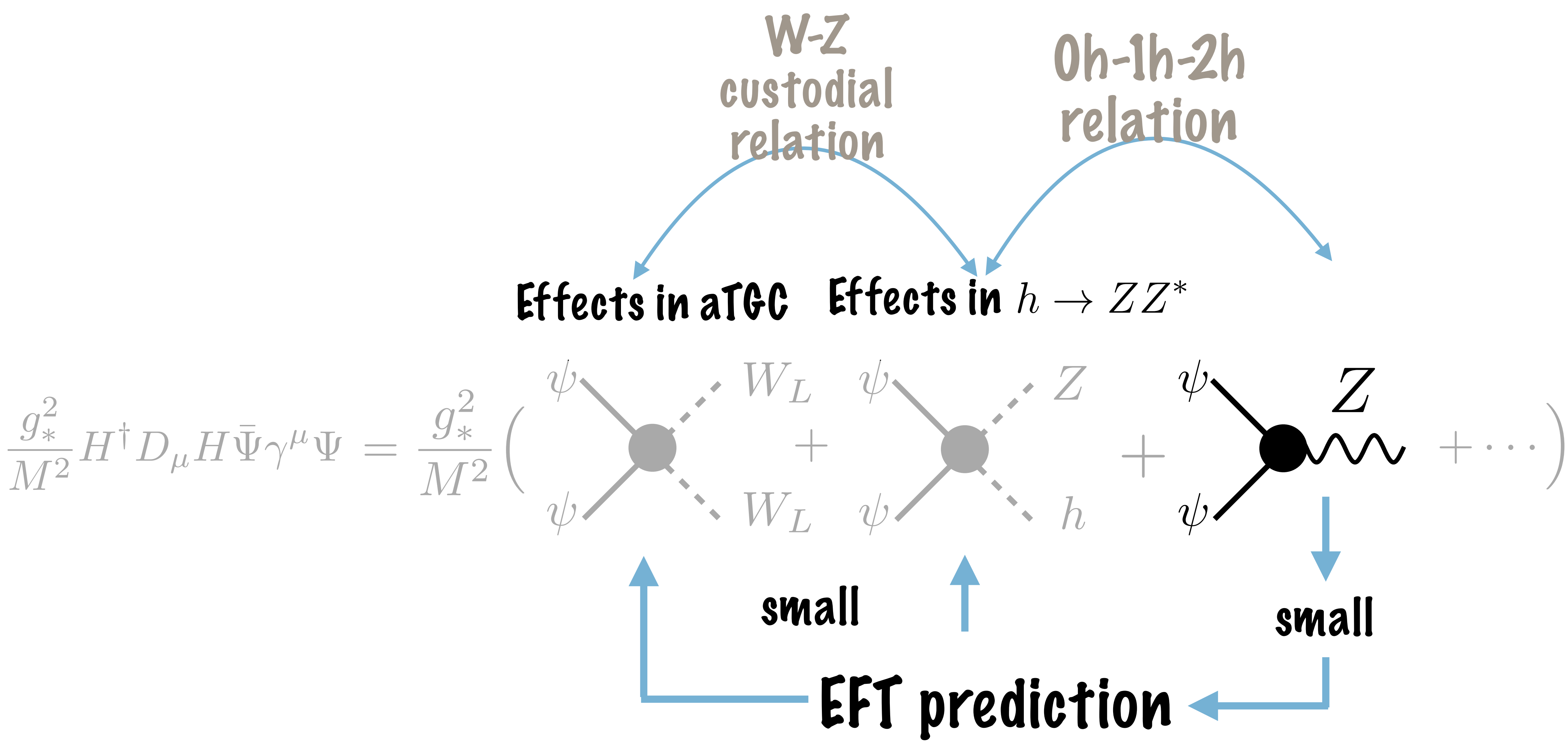

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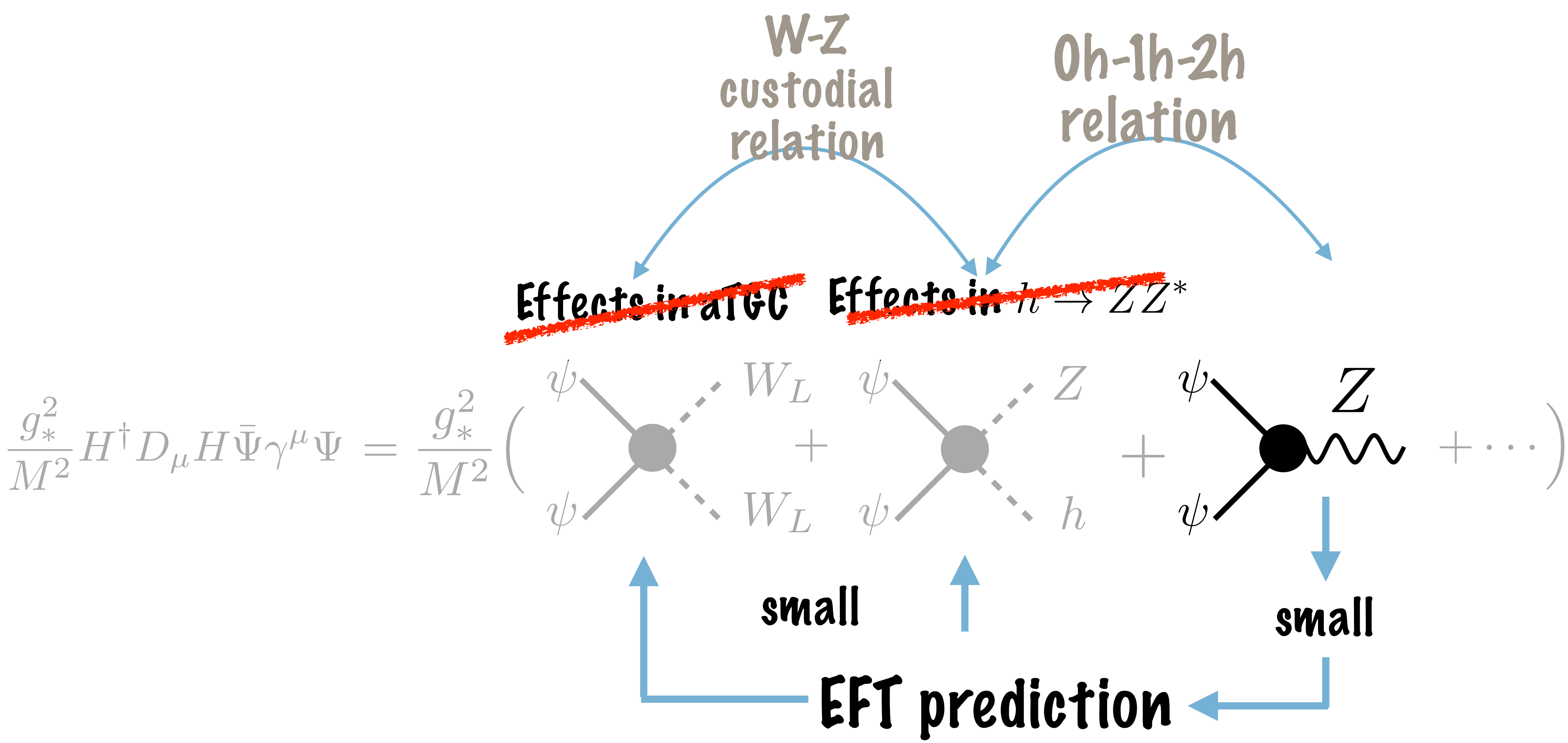

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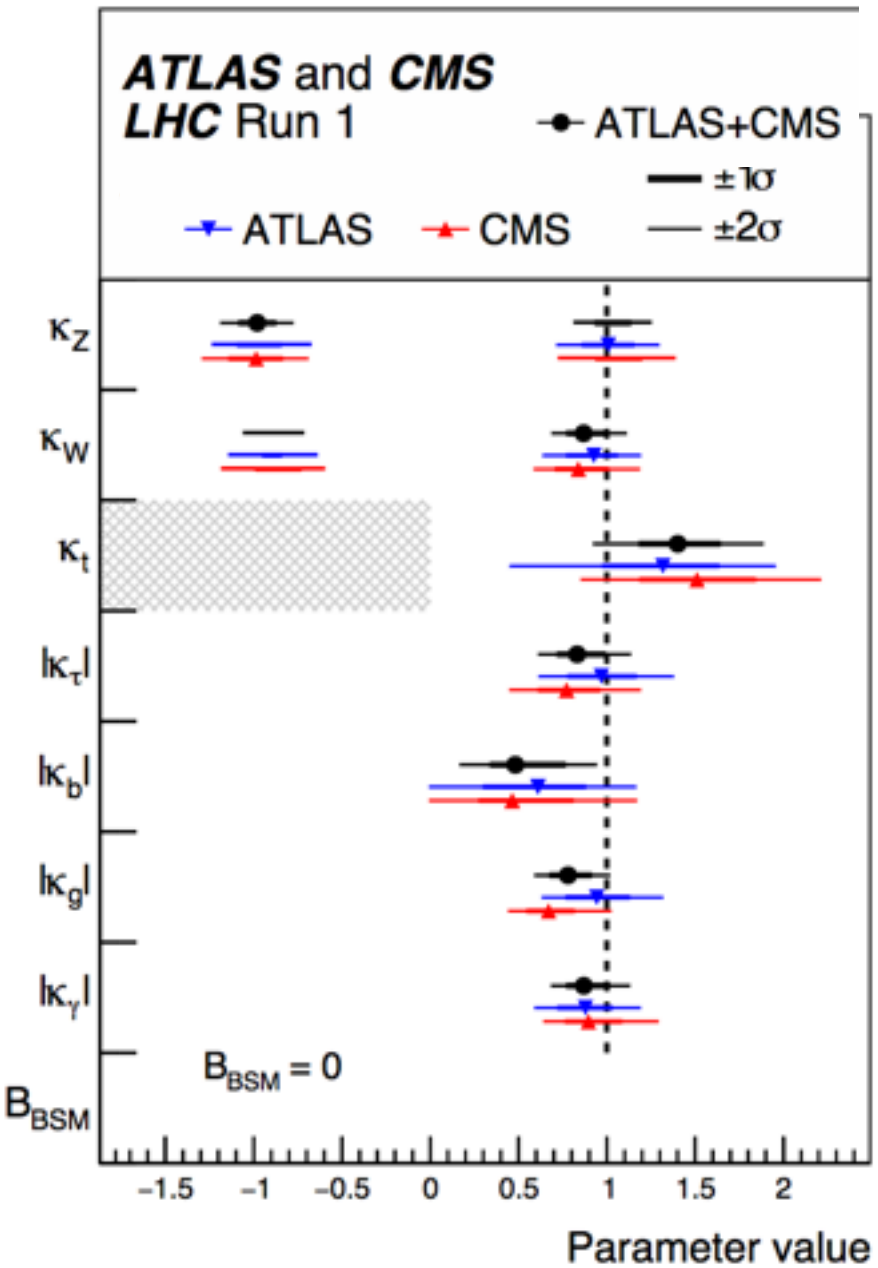
$E = m_h$

h-resonance (LHC)

Measures deviations from SM h-couplings

Experiment



Future: h^3, $hZ\gamma$

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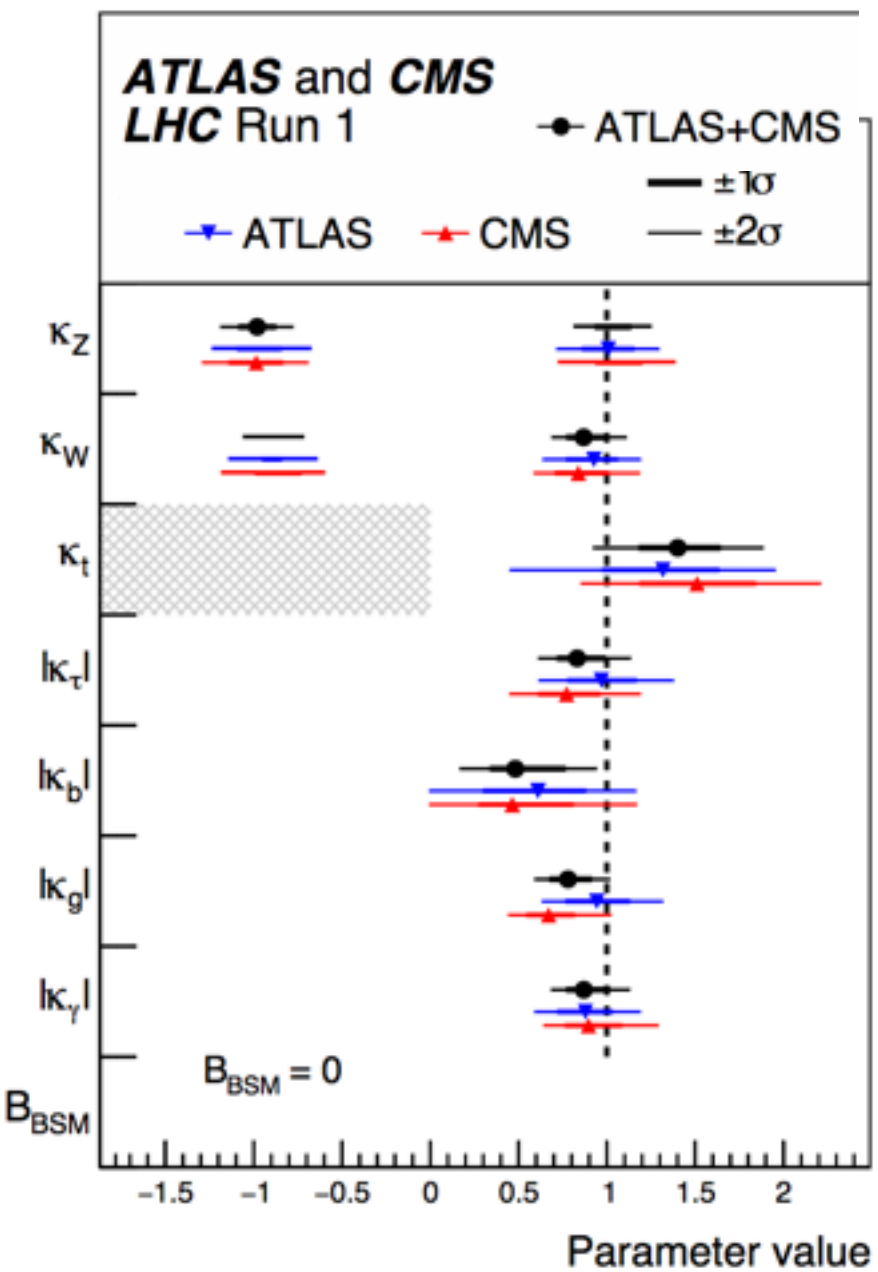
h-resonance (LHC)

Measures deviations from SM h-couplings

Experiment



Future: h³, hZγ

Theory

$\langle h \rangle = v$

v	$\longleftarrow$	$\mathcal{O}_r = \lvert H\rvert^2 (D_\mu H)^\dagger (D^\mu H)$
m_d	$\longleftarrow$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$
m_e	$\longleftarrow$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
m_u	$\longleftarrow$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$
g_s	$\longleftarrow$	$\mathcal{O}_{GG} = \frac{g_s^2}{4} \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$
g'	$\longleftarrow$	$\mathcal{O}_{BB} = \frac{g'^2}{4} \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$
g	$\longleftarrow$	$\mathcal{O}_{WW} = \frac{g^2}{4} \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$
m_h	$\longleftarrow$	$\mathcal{O}_6 = \lambda \lvert H\rvert^6$

In vacuum <h>=v, operators $|H|^2 \times \mathcal{L}_{SM}$ only redefine SM parameters!

- Observable only in Higgs physics!

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu}$$

Elias-Miro,Espinosa,Masso,Pomarol'13; Gupta,Pomarol,FR'14

h-resonance (LHC)

Implications of EFT perspective:*

- Relation between 1h-2h processes

- Custodial symmetry persists at d=6

  (accidental in the SM d=4)

$$\kappa_Z = \kappa_W$$

=since here the #experimental parameters is finite, POs (Greljo,Isidori,Marzocca '14-'15) can also be used to parametrize the on-shell decays, however (see later) for the off-shell h->ZZ an EFT perspective is necessary

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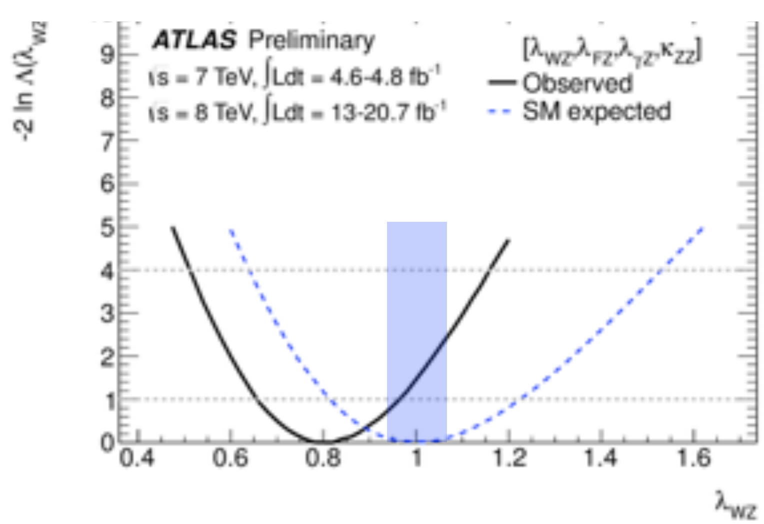
(accidental in the SM d=4)

$\kappa_Z = \kappa_W$

More precisely: since h->ZZ* , h->WW* are off-shell, custodial preserving, E-dependent, d=6 operators (see next) introduce effects sensitives to SM custodial breaking

$$\lambda^2_{WZ} - 1 \simeq s^2_{\theta_W}\left[0.9c_W - 2.6c_B + 3\kappa_{HW} - 3.9\kappa_{HB}\right]$$
$$\simeq 0.6\delta g_1^Z - 0.5\delta\kappa_\gamma - 1.6\kappa_{Z\gamma} \in [-6, 8]\times 10^{-2}$$

Pomarol,FR'13



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Is there an more info related with Higgs-physics?

2) ...off-shell $E >> m_h, m_Z$

Precision Searches at high-E

- Exemple 2->2 Processes

(LEP2, LHC) $\bar{\psi}\psi \to \bar{\psi}\psi$

$\bar{\psi}\psi \to W^+W^-$

(LHC) VBF, VH

- Important for Run2, FCC,...

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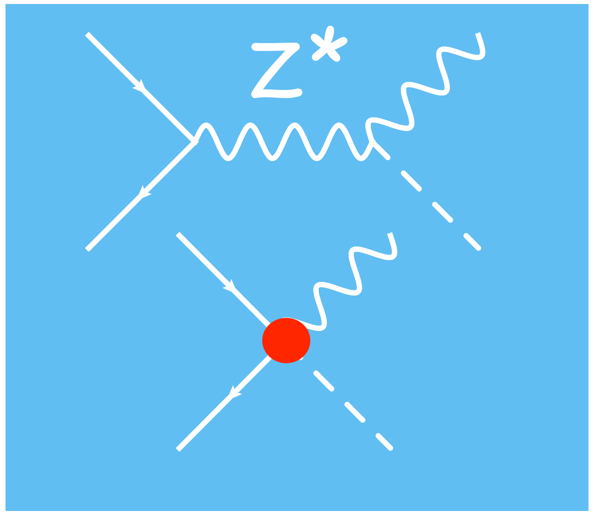
- Testing new (non-SM-like) interactions



$\sim \frac{1}{E^2}$

$\sim const$

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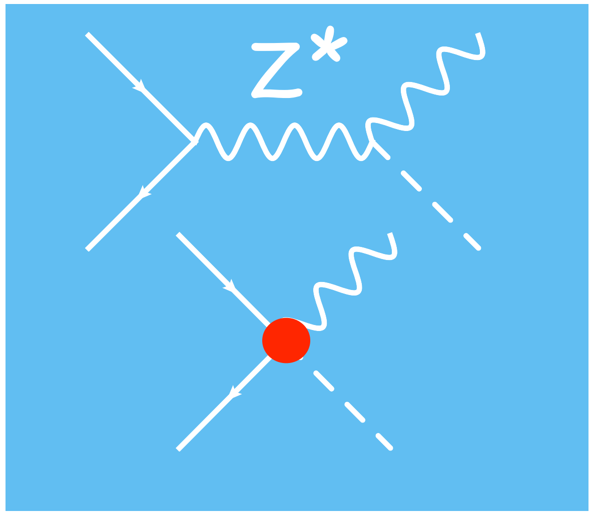


$\sim \dfrac{1}{E^2}$

$\sim const$

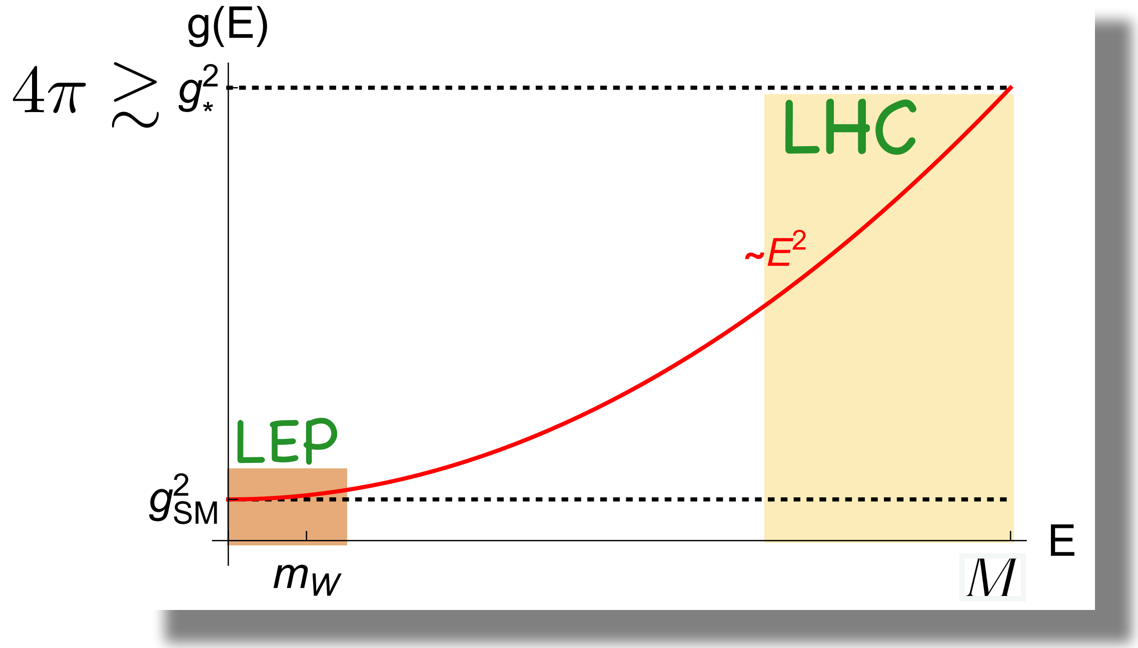
- Two operators with H still unconstrained by on-shell measurements:

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \qquad \mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

(more precisely, see Pomarol,FR'16; Gupta,Pomarol,FR'14)

Precision Searches at high-E

Amplitude for 2->2 has dimension of coupling² $A_{SM} \sim g^2_{SM}$



- We can think of these measurements as testing the E-growth of couplings

$$A_{BSM} \sim g^2_{SM}\left(1+\frac{g_*^2}{g^2_{SM}}\frac{E^2}{M^2}\right)+\cdots$$

Precision Searches at high-E

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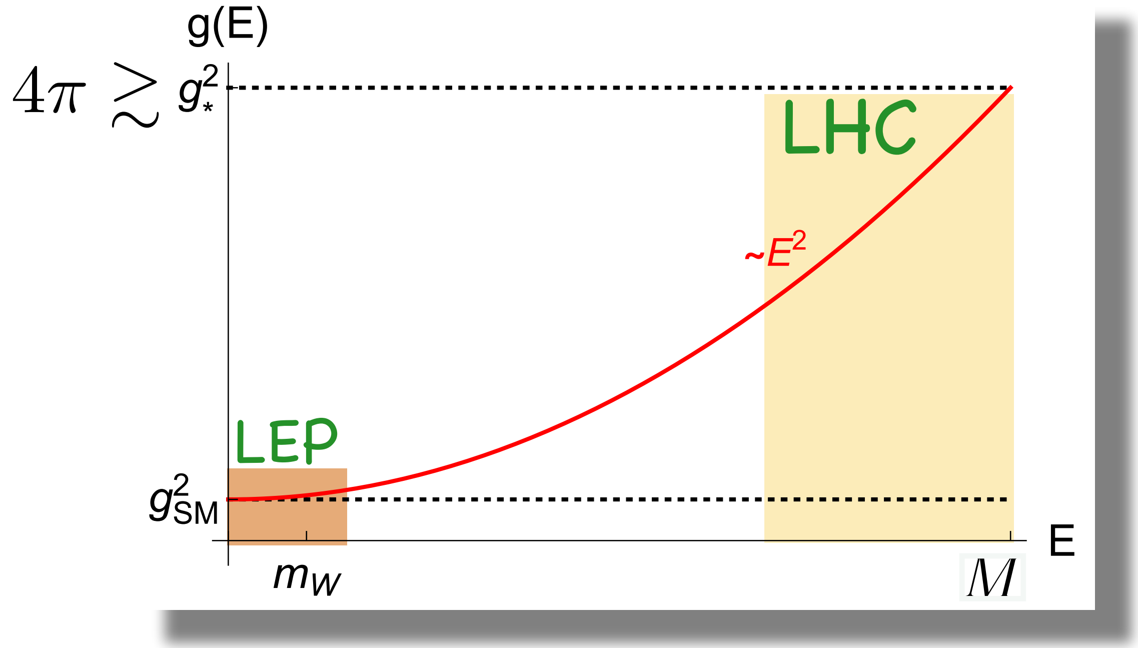

- **We can think of these measurements as testing the E-growth of couplings**

$$A_{BSM} \sim g_{SM}^2 \left(1 + \frac{g_*^2}{g_{SM}^2}\frac{E^2}{M^2}\right) + \cdots$$

<<1 for EFT expansion

Can be >>1 for g_{SM}<<g*<4pi

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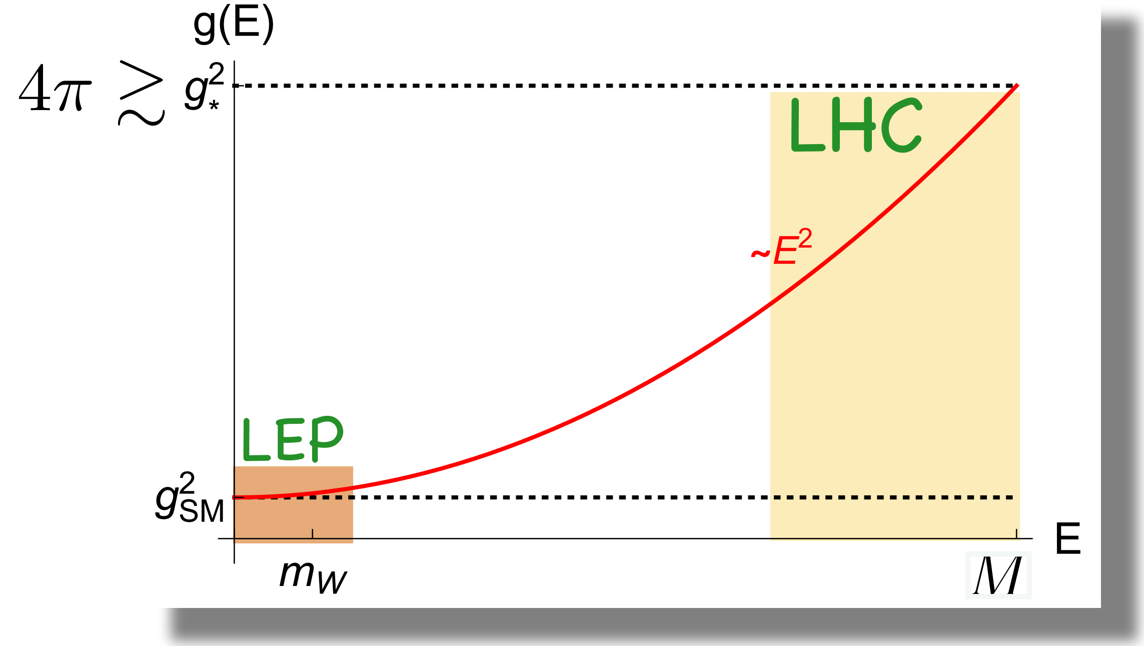

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<<1 for EFT expansion

Can be >>1 for g_{SM}<<g*<4pi

- For strongly coupled new physics there can be effects larger than SM,

$$\delta\sigma/\sigma_{SM} \gtrsim 1$$

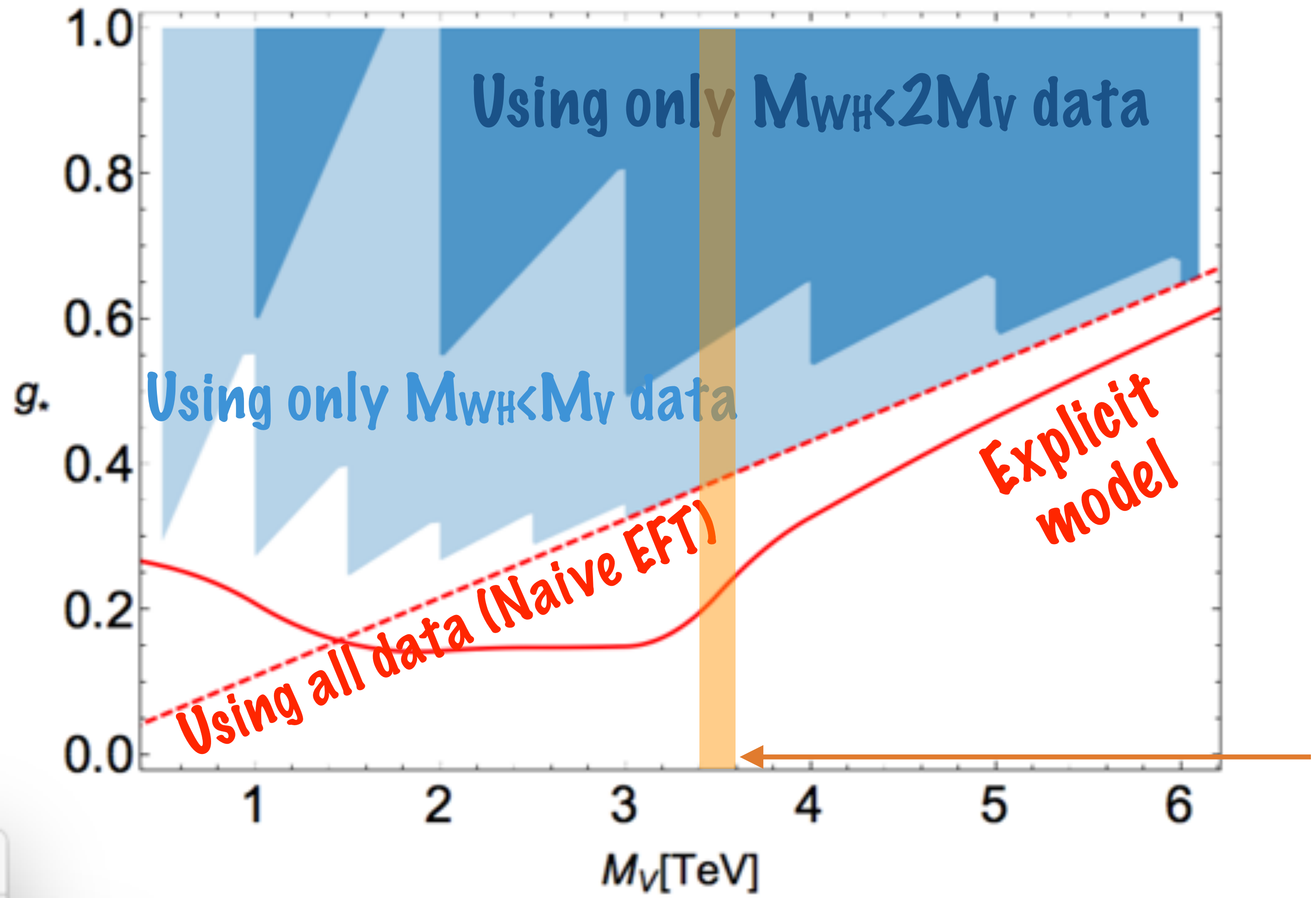
compatibly with EFT expansion E/M<<1 & with non observation at low-E

Precision Searches at high-E
In Practice

Measurements of $u\bar{d} \to W^+ h$

(fake data for illustration)

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
σ/σ_{SM}	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0



Resonance enter experimental reach:

Naive EFT analysis inconsistent

Consistent EFT analysis conservative

Contino,Falkowski,Grojean,Goertz,FR'16

Precision Searches at high-E
In Reality

- **2 remaining operators:**
  (in fact linear combinations with others)

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- **Give E-growing effects in**

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$$\bar\psi\psi \to hV$$

V=W,Z

$$\begin{pmatrix} h^+ \\ h + ih^0 \end{pmatrix} \quad h^0 \leftarrow Z_L$$

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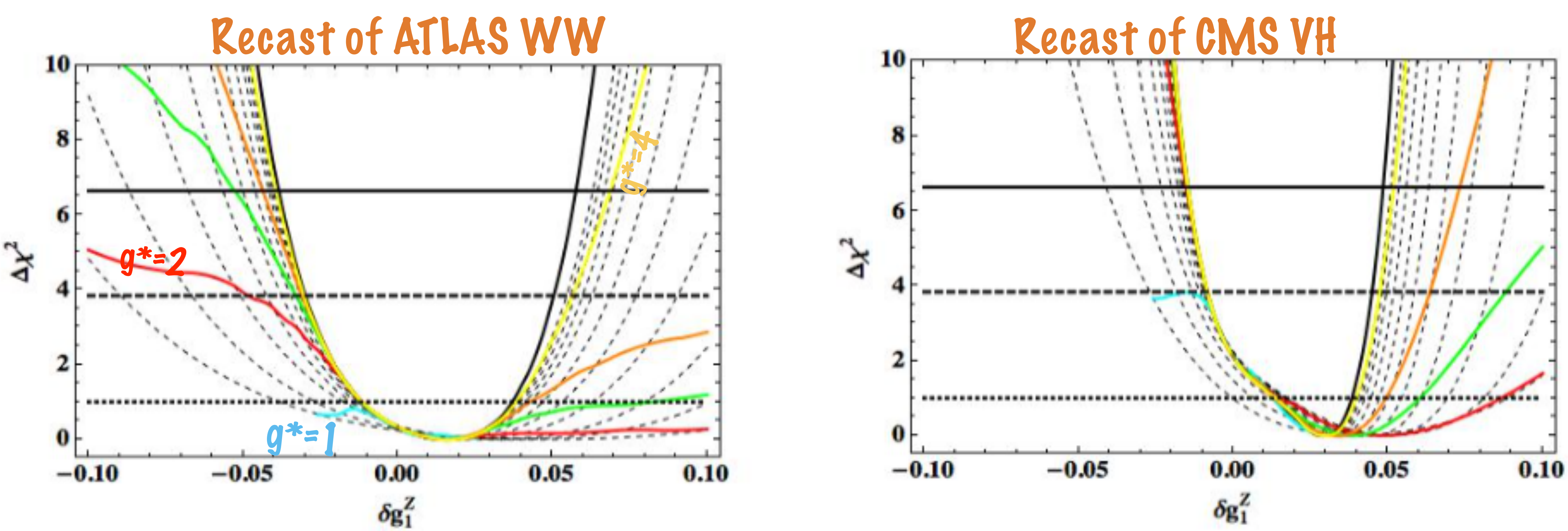

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Precision Searches at high-E
In Reality

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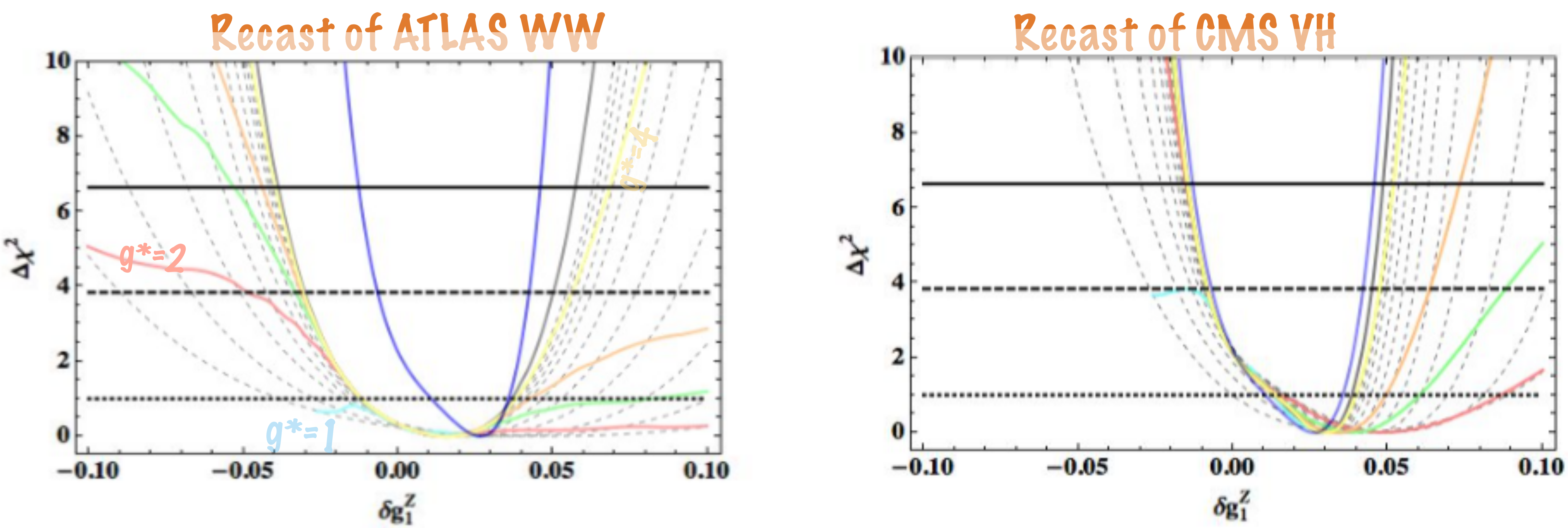

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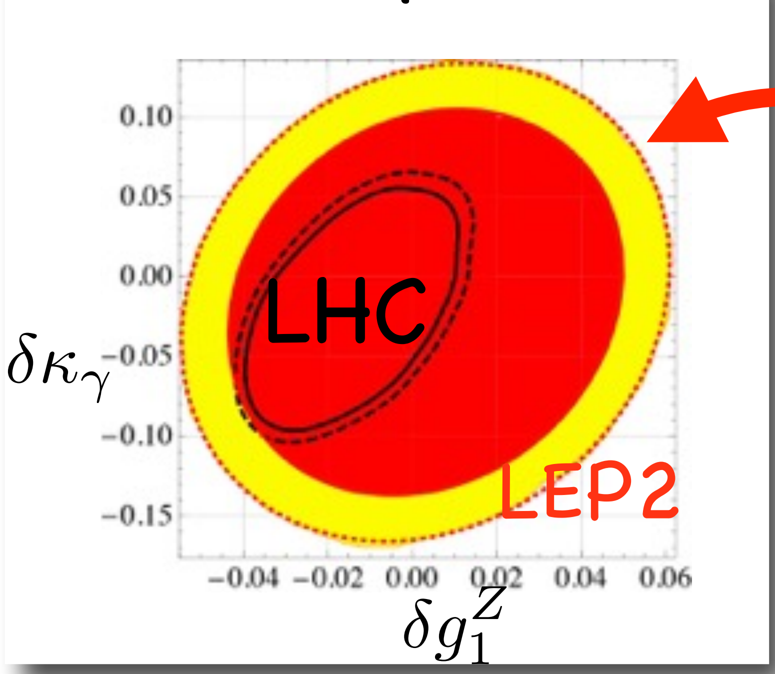
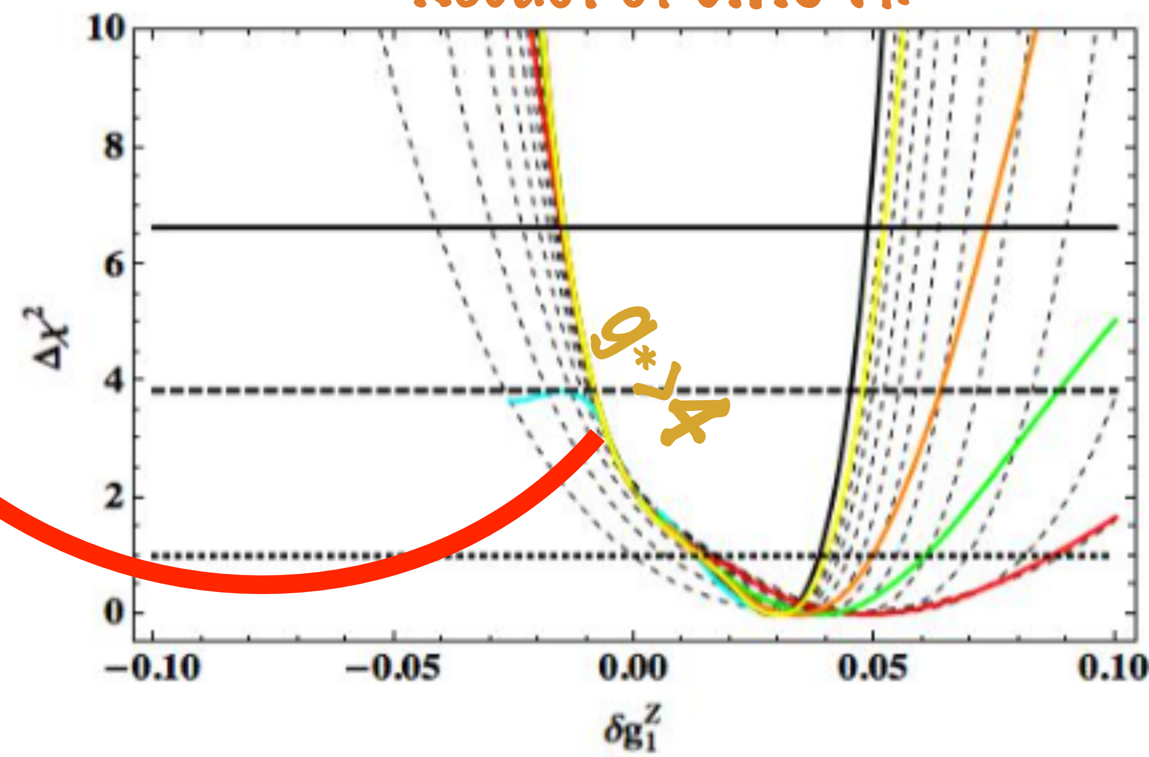
(because the same effect corresponds to a larger cut-off M so that a consistent analysis E<M contains more events)



Recast of CMS VH



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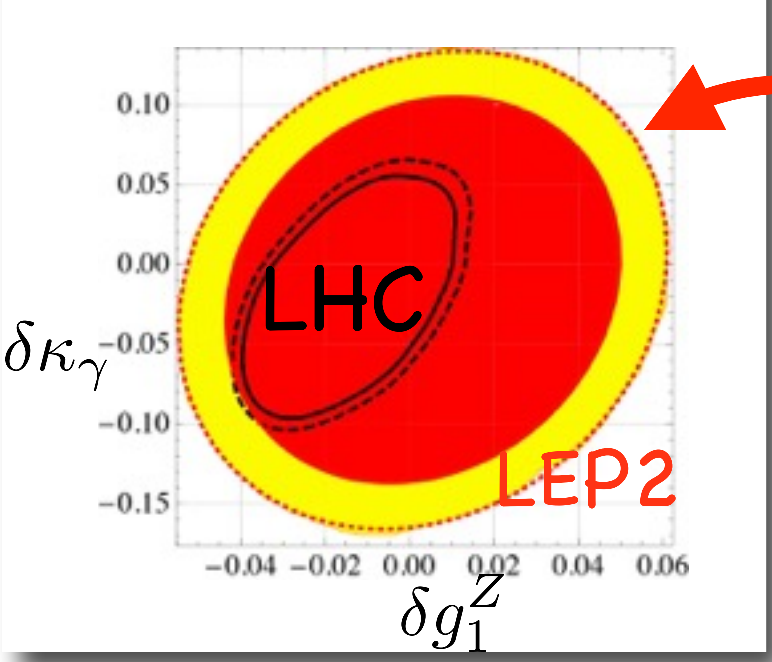

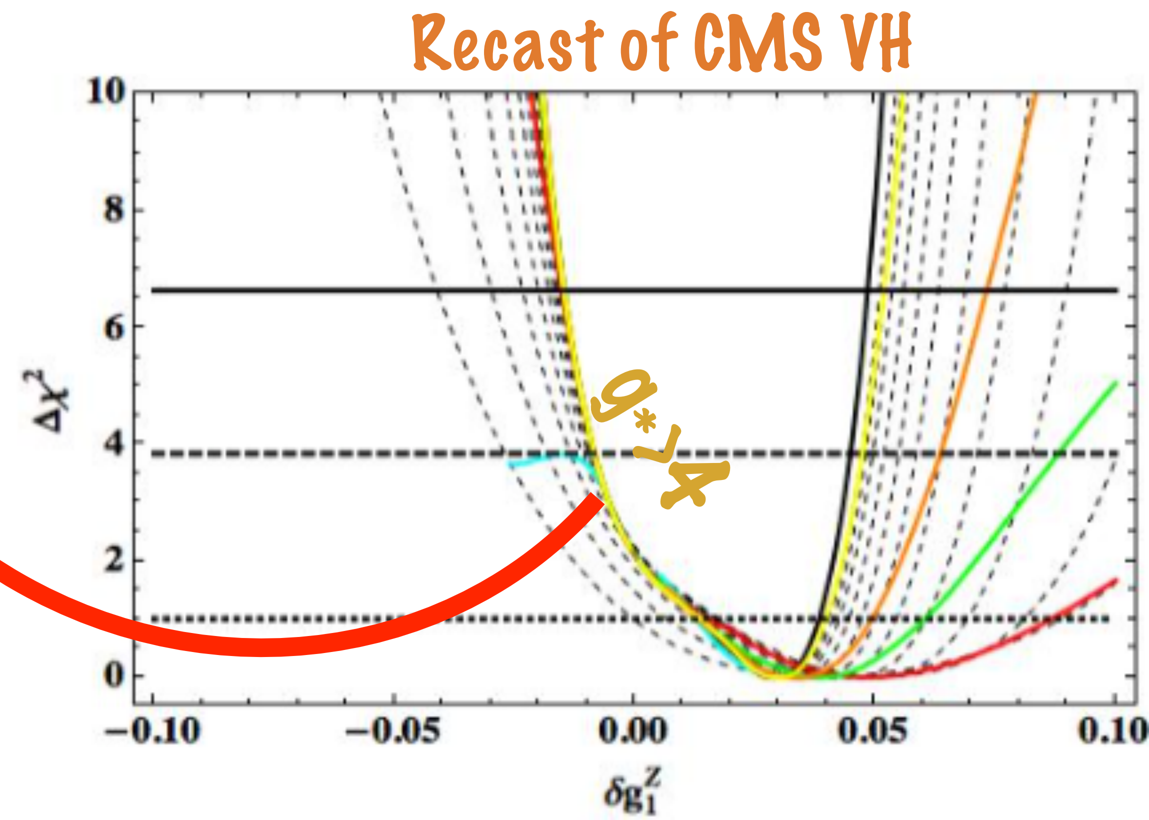

This is all very nice, but...

what is being tested?

what are these theories with a new strong coupling g*?

Biekötter,Knochel,Krämer,Liu,FR '14; Liu,Pomarol,Rattazzi,FR'to appear
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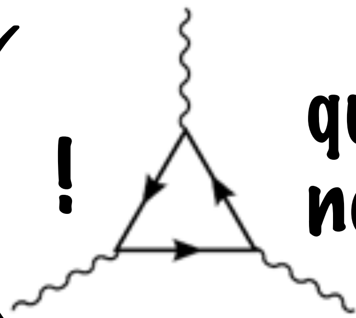
Strongly Coupled BSM?

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

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

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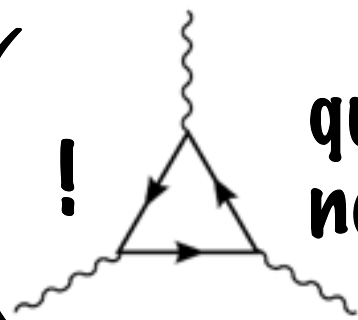
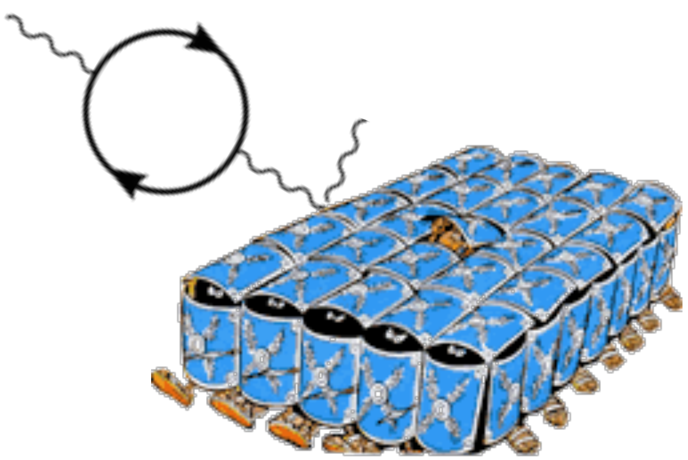
(!  quantum effects generally propagate new couplings to the whole SM !)

Need shielding: **Approximate Symmetries**



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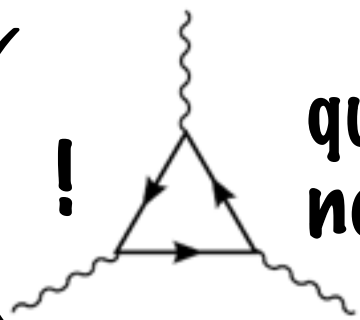
(!  quantum effects generally propagate new couplings to the whole SM !)

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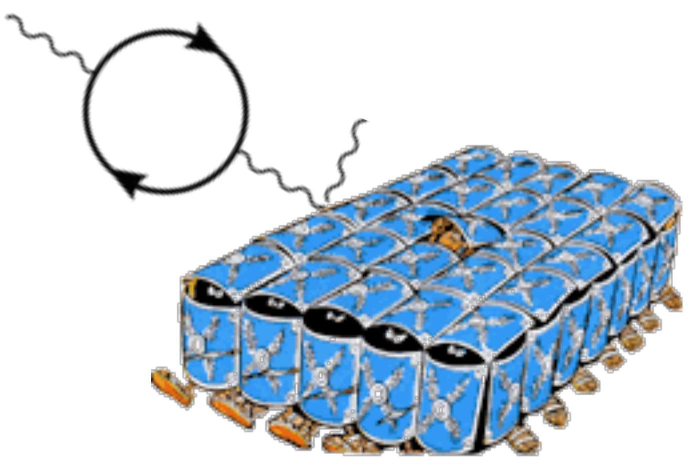
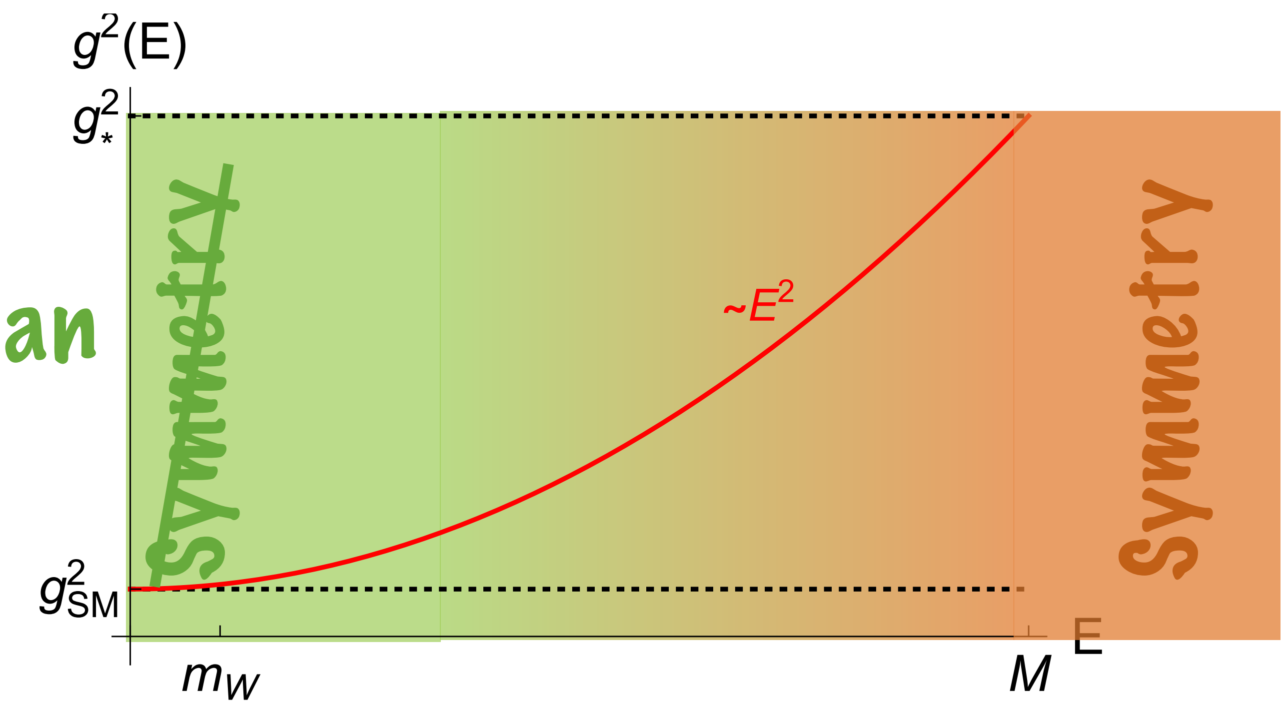


$$A \simeq g_{SM}^2 \left(1 + \frac{g_*^2}{g_{SM}^2}\frac{E^2}{M^2}\right) \equiv g^2(E)$$

SM Lagrangian (dim-4)



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

Strongly Coupled BSM?

How many examples of such approximate symmetries exist?

(situations where a New strong sector delivers naturally weakly coupled light states)

Scalars: 1) Composite Higgs

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

Higgs is a Pseudo Goldstone boson of a spontaneously broken global symmetry, e.g. SO(5)/SO(4)

Fermions: 2) Composite fermions

Eichten,Lane,Peskin'83

Chiral symmetry is broken by SM Yukawas

3) SM fermions as Goldstinos (non-linear SUSY)

Bardeen,Visnjic'82, Bellazzini,FR'soon

Vectors: 4) Strong dipoles

Liu,Pomaral,Rattazzi,FR'16

(Arguments based on unitarity/analicity show that no other approximate symmetries are possible)
Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi'06; Bellazzini,Martucci,Torre'14; Bellazzini'16

Example 1: (Composite) Higgs

- Higgs himself a (pseudo) Goldstone from New strongly interacting sector: (e.g. SO(5)/SO(4))

Georgi,Kaplan'84; Agashe,Contino,Nomura,Pomarol'04
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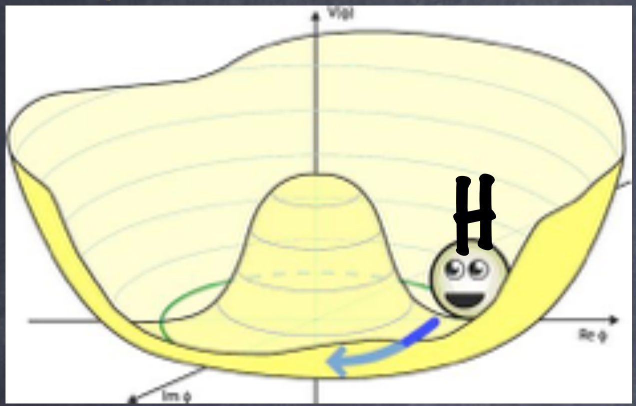

Shift symmetry:
$H \to H + c$

$g_* \partial_\mu H$ ✓
$+\text{n.l.}$

ϵH ✗

small symmetry breaking parameter

Callan,Coleman,Wess,Zumino'69

- $\frac{g_*^2}{M^2} (\partial_\mu |H|^2)^2$ big
- $\lambda (H^\dagger H)^2$ small

Implications:

- Small mass, but large effects in $W_L W_L$ scattering

(which is why the LHC was built)

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

e.g. Contino,Grojean,Moretti,Piccinini,Rattazzi'10

2. Composite Fermions

SM fermion interactions small because of chiral symmetry

(and because gauge bosons elementary)

$$\mathcal{L}_4 = y_\psi H \psi_L \psi_R$$

small since violates chiral symm

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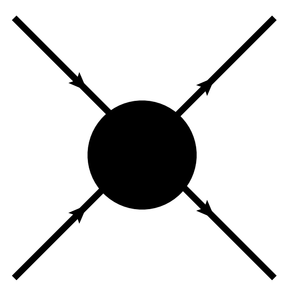
small since violates chiral symm

large since preserves chiral symm (but only sizable at high-E)

$$\mathcal{L}_6 = \frac{g_*^2}{M^2} \bar{\psi}\gamma_\mu \psi \bar{\psi}\gamma^\mu \psi + \cdots$$

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



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

2. Composite Fermions

SM fermion inter... ...mmetry

...auge bosons elementary)

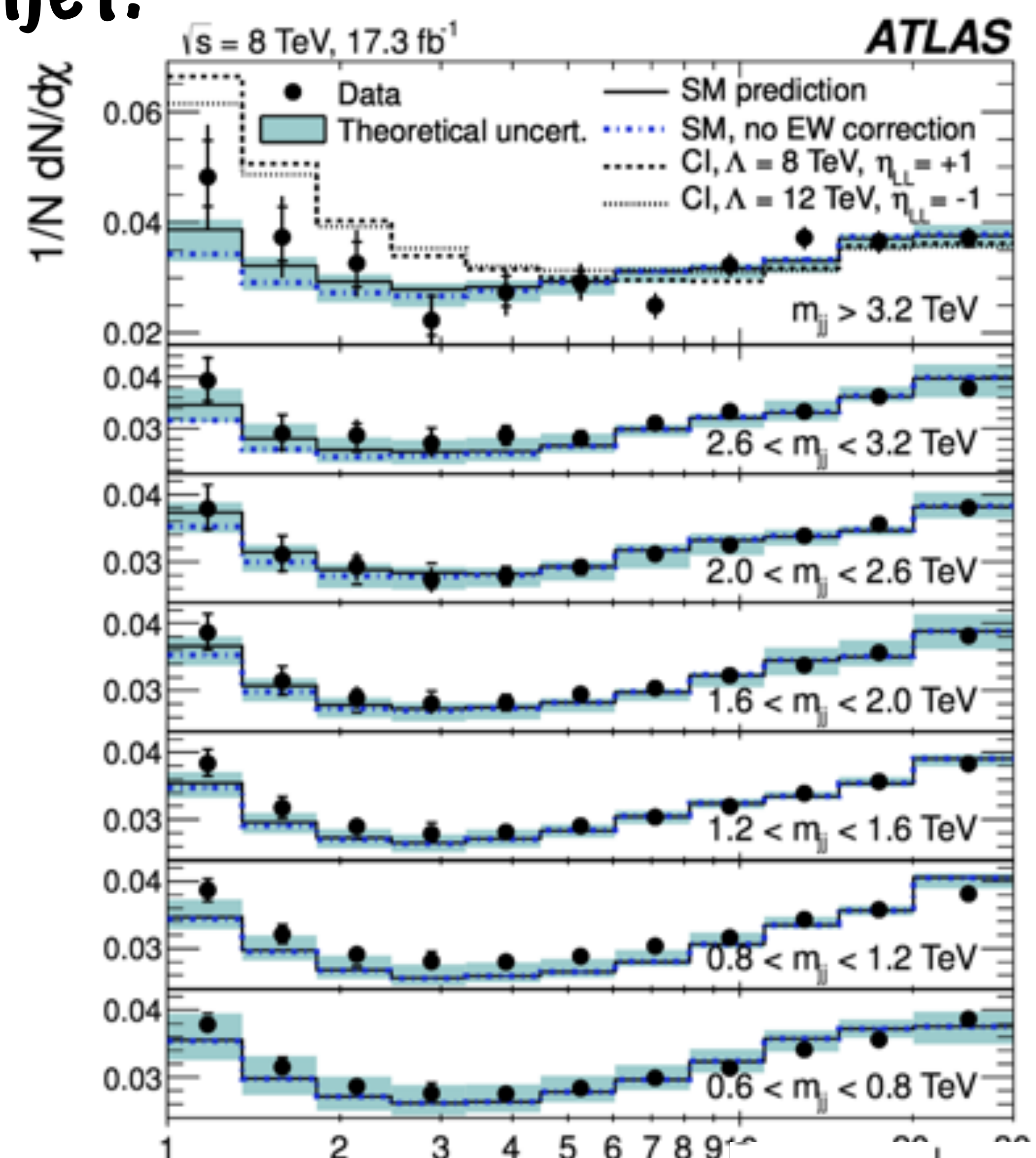
$\mathcal{L}_4 = y_i$ ...

...n (but only sizable at high-E)

$\mathcal{L}_6 = \frac{}{M}$ ...

- Large effects i... $g^2 \left(1 + \frac{g_*^2}{g^2}\frac{E^2}{M^2}\right)$

Dijet:



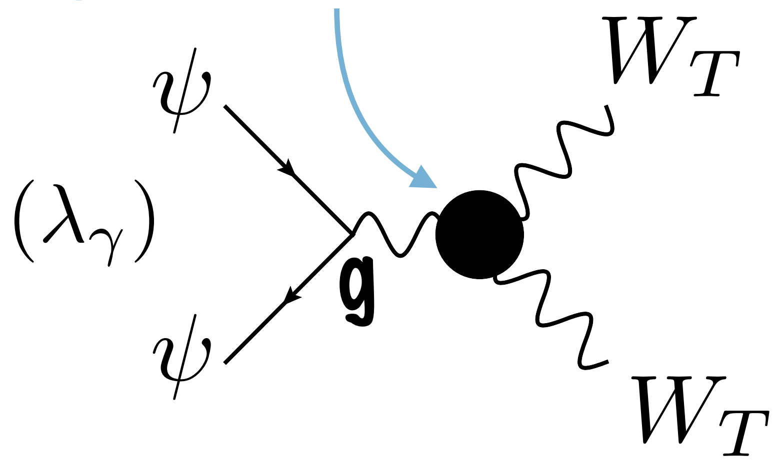
$\chi = e^{|y_1 - y_2|}$

$M \gtrsim (g_*/4\pi) 40\ \text{TeV}$

For light quarks

(see also Drell-Yann)

3. Strong transverse vectors?



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

Problem: Gauge bosons associated with weak SM coupling ($\partial_\mu + igA_\mu$) how can they couple with a different coupling g*>>g?

new new

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See 1603.03064

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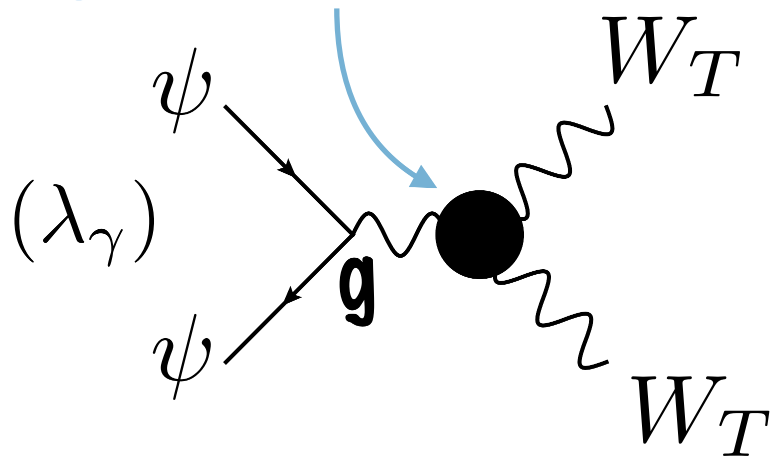

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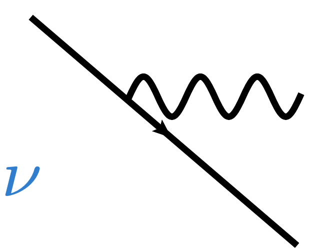
$g\bar{\psi}_{new}A_\mu\gamma^\mu\psi_{new}$ **monopole/dipole** $g_*\bar{\psi}_{new}\sigma^{\mu\nu}\psi_{new}F_{\mu\nu}$



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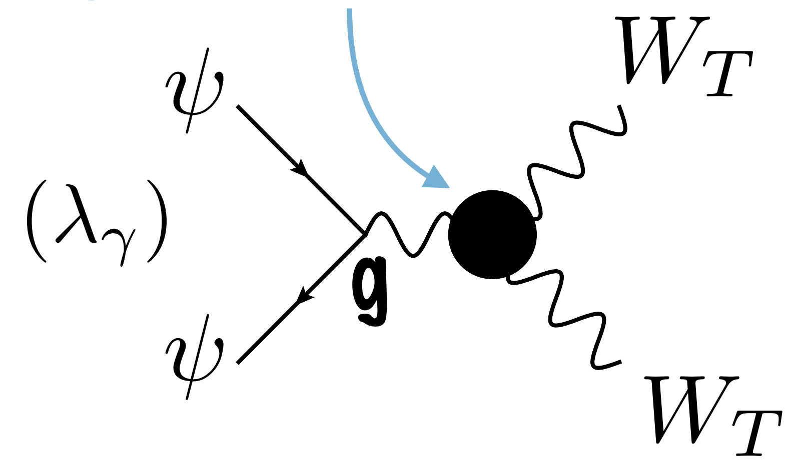

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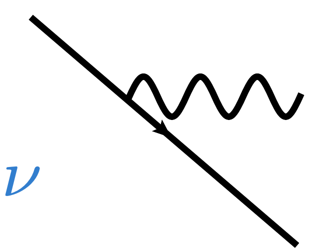
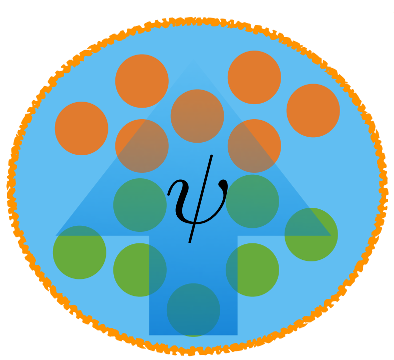


- Large dipoles $\frac{g_*}{g} \gg 1$ possible, even with small monopole



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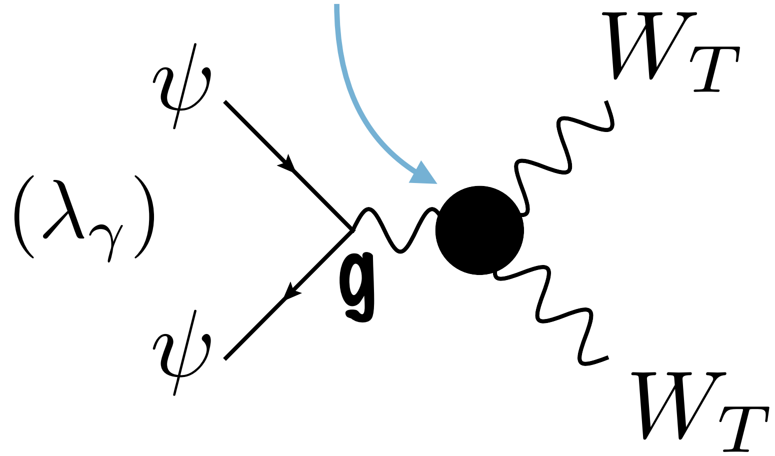

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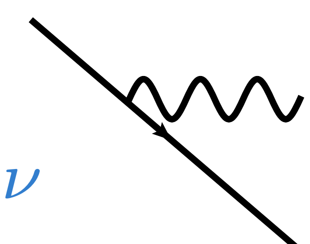

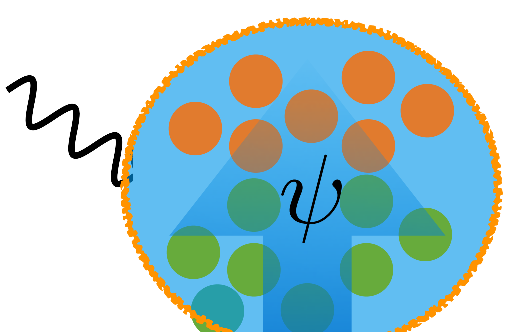

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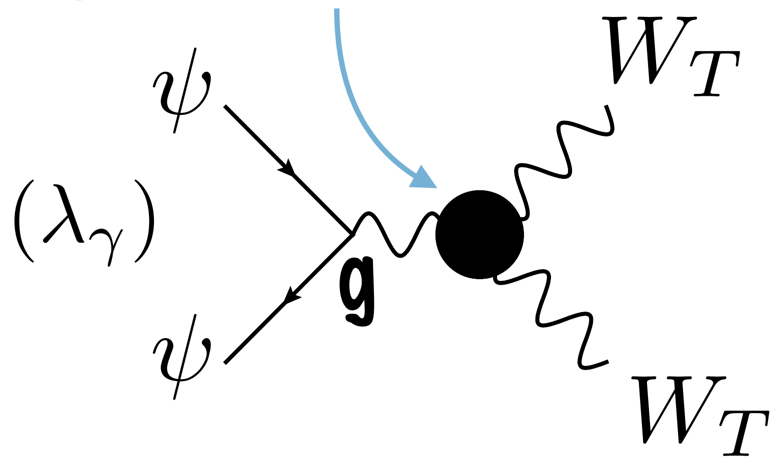

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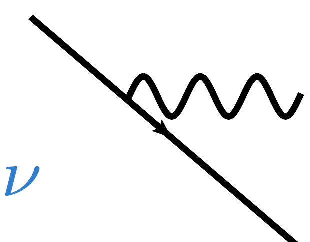

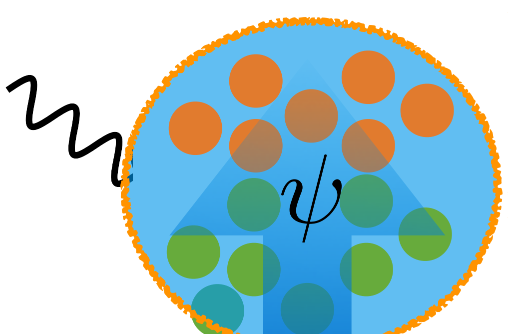

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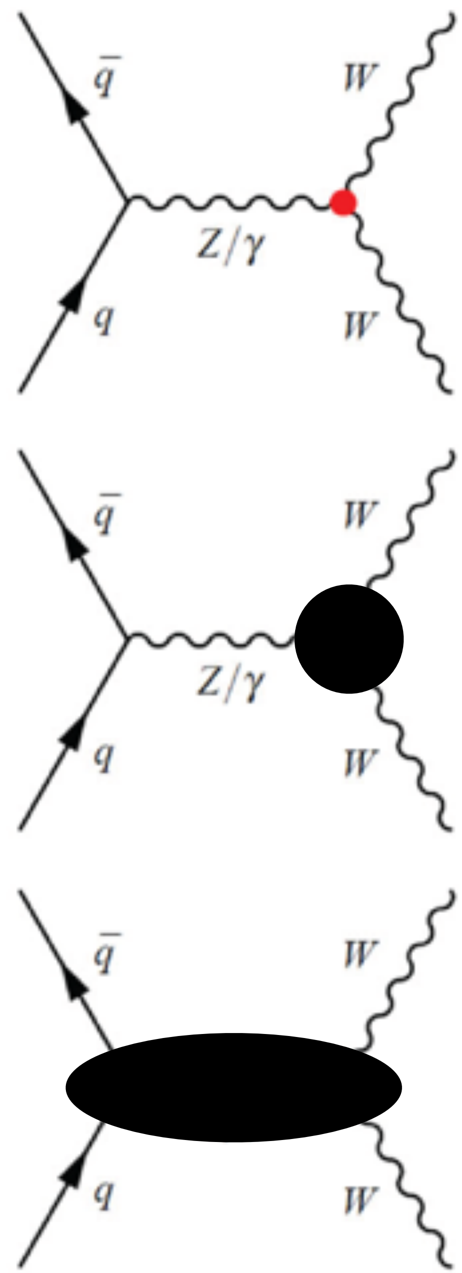
- Large dipoles $\frac{g_*}{g} \gg 1$ possible, even with small monopole
- Possible for operators involving $F^{\mu\nu}$ to be sizable, despite weak "covariant-derivative" interactions

See 1603.03064

3. Strong transverse vectors

SM



$$\sim g^2$$

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

Strong vectors:

BSM dimension-6

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

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...and strong fermions:

BSM dimension-8

$$\frac{g_*^2}{M^4}\bar{\psi}\gamma^{\mu}D_{\nu}\psi W^{a}_{\mu\rho}W^{a\nu\rho}$$

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

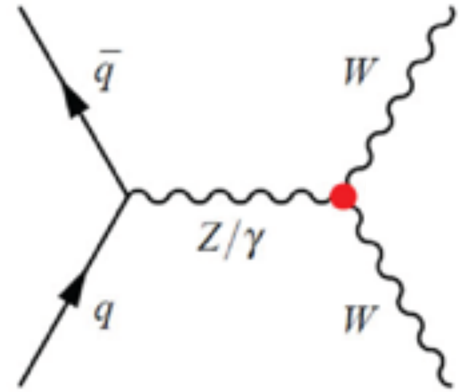
(remember: one coupling per field)

$$\frac{\delta \mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \lesssim 1$$

dimension-6 analysis ok

3. Strong transverse vectors

SM



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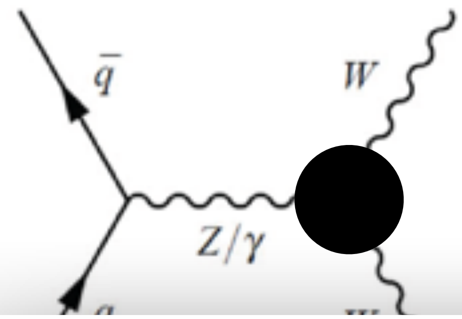

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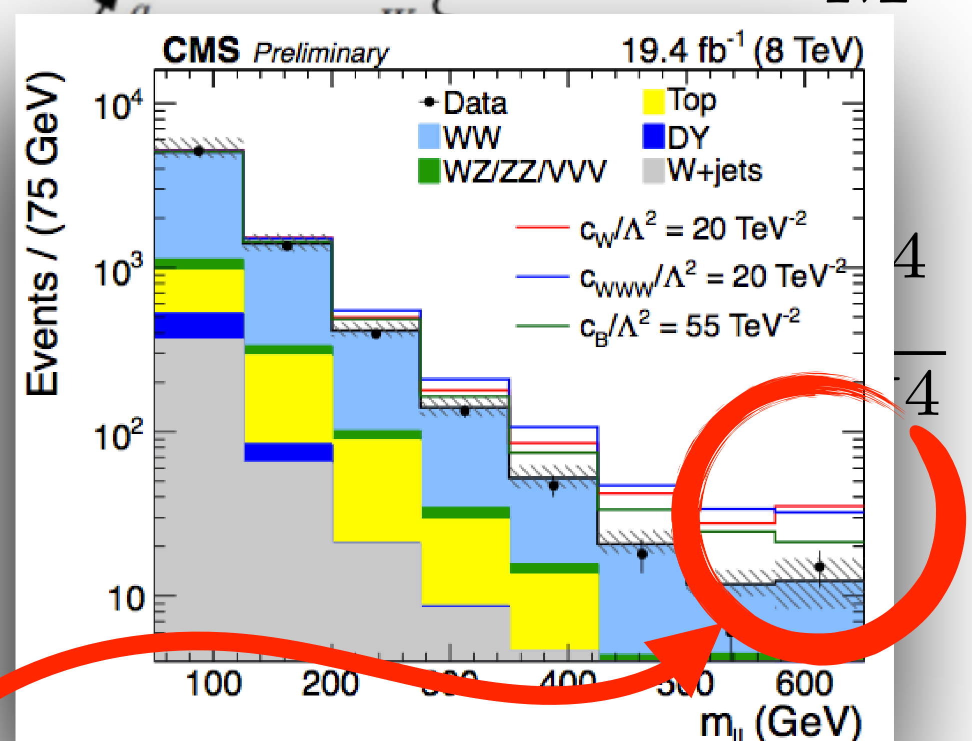

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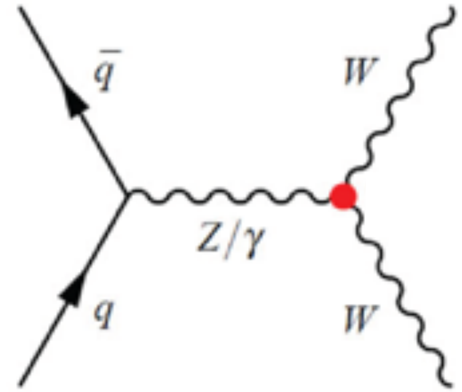
Strong transverse vectors: Implications

SM



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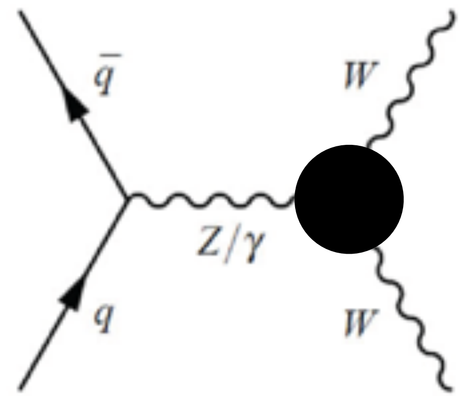

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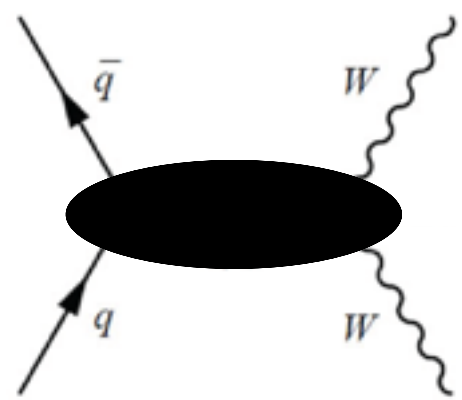

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$$\frac{g_*}{g}\frac{E^2}{M^2} \gtrsim 1$$

$$\frac{\delta\mathcal{A}_{BSM}}{\mathcal{A}_{SM}} \gtrsim 1$$

- **Some dimension-8 necessary due to coupling enhancement**
- **A rationale for neutral TGC studies (that already exploit d=8)**

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

Conclusions

Experiment

$E = m_{Z,h}$
(finite # observables)

- Measures modifications of SM couplings

$$\frac{g_* v}{M} \ll 1$$

  - EFT relates different observables (accidental d=6 custodial + 0h-1h-2h relation)
  - Relation with physical scale/couplings

Theory

$E \gg m_{Z,h}$
(infinite # observables)

- Measures E-growing effects
  - For g* strong $\delta\sigma/\sigma_{SM} \gtrsim 1$ compatibly with LEP and EFT
  - g* strong → approximate symmetries
- Consistent situations where dim-10<<dim-8>>dim-6

Conclusions

Precision Tests at LHC

BSM Perspective

EFT (Motivation/structure)