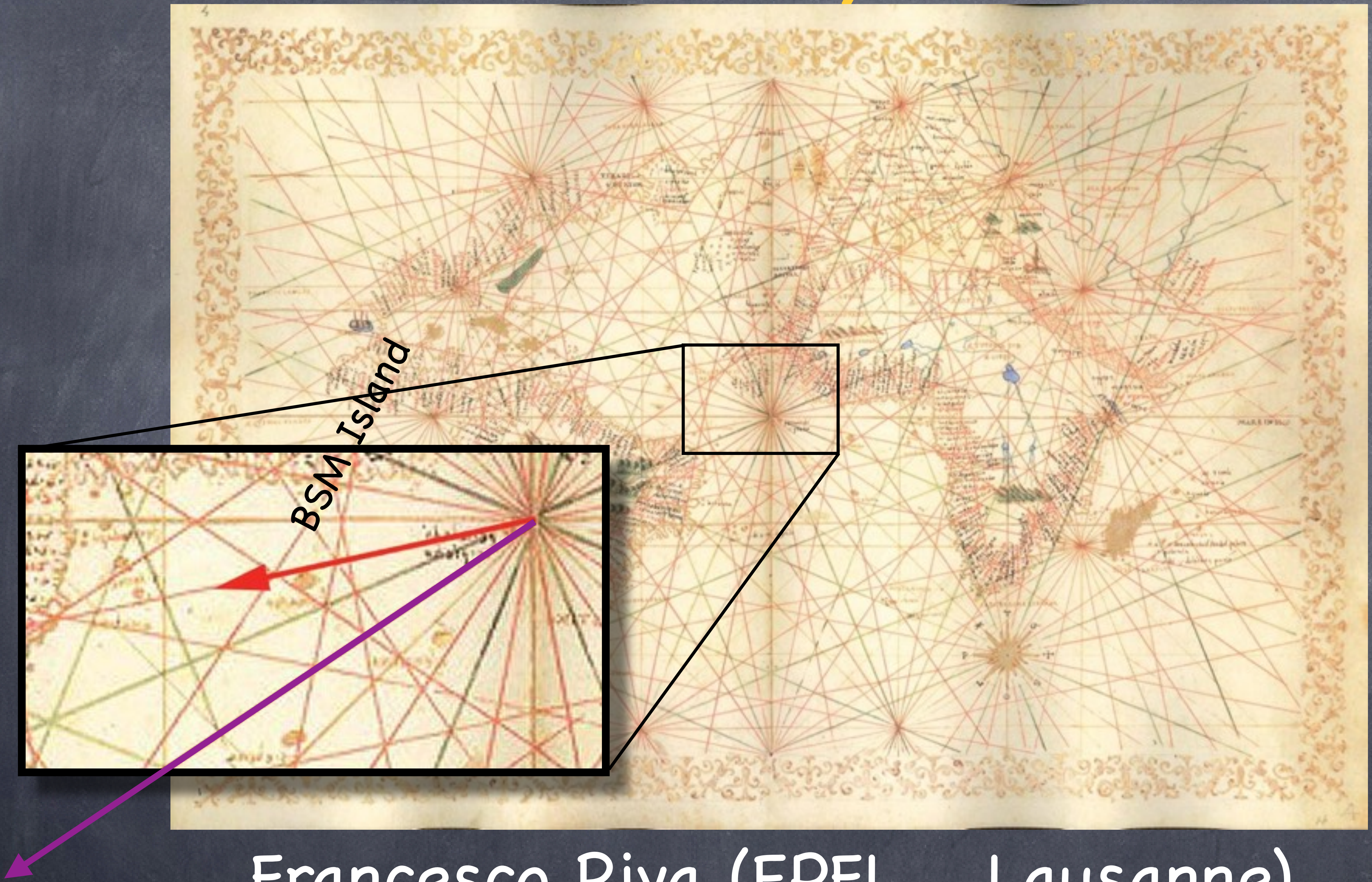
BSM Primary Effects



Francesco Riva (EPFL - Lausanne)

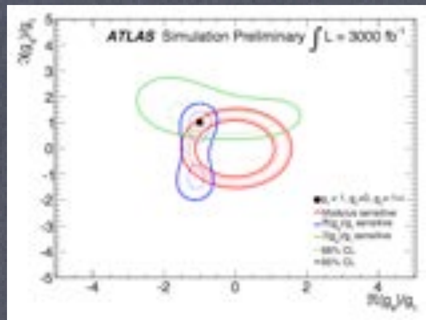
In Collaboration with:

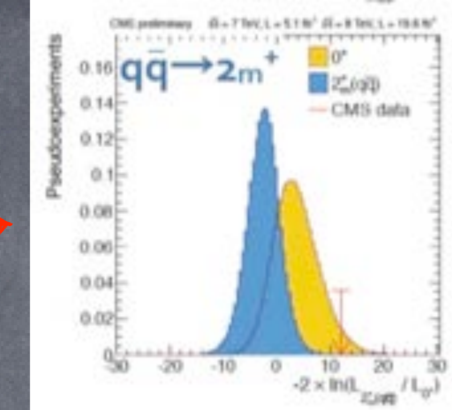
Pomarol, Gupta, Liu, Falkowski, Masso, Espinosa, Elias-Miro, Rattazzi, Biekötter, Knochel, Krämer

(1308.2803 ,1308.1879, 1405.0181, 1406.7320, 1411.0669, 150x.xxxx)

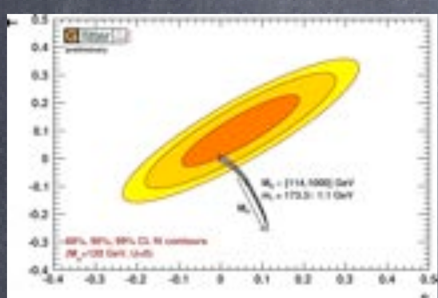
Motivation

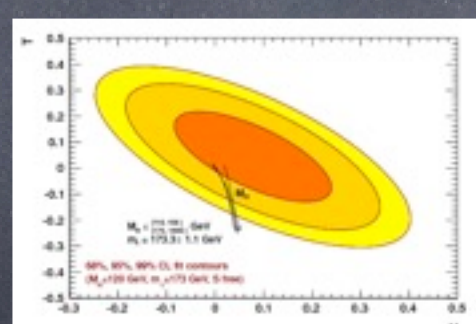
Precision Searches for New Physics

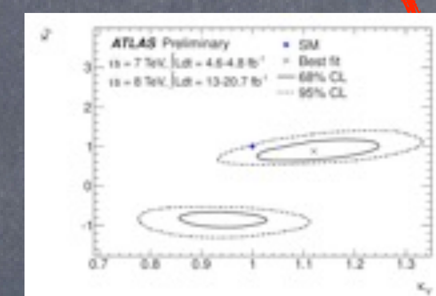


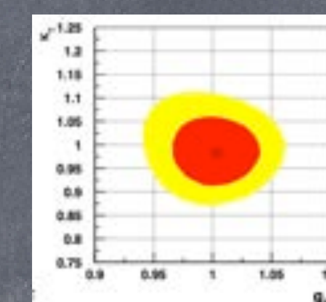


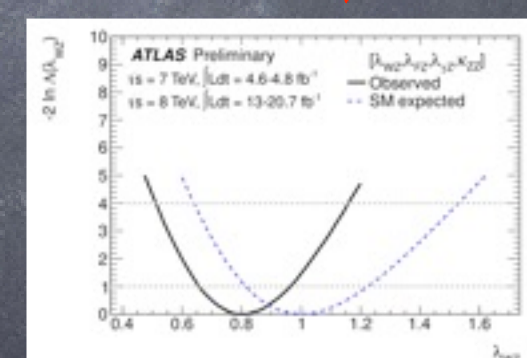
$\mathcal{L}^{SM}$

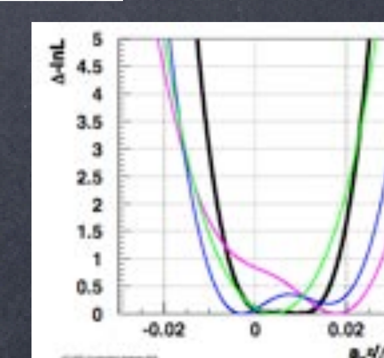






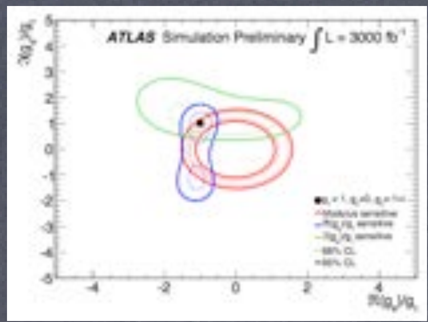


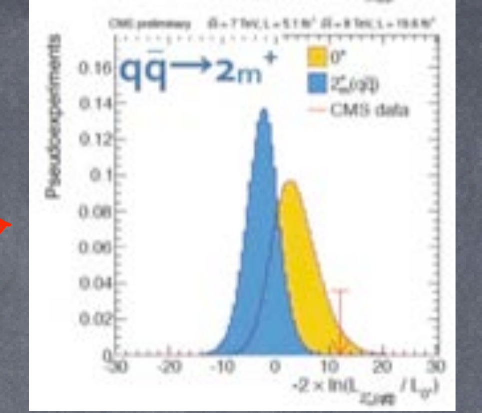




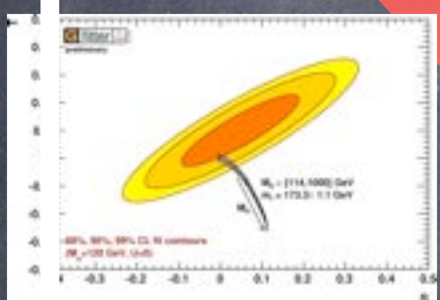
Motivation

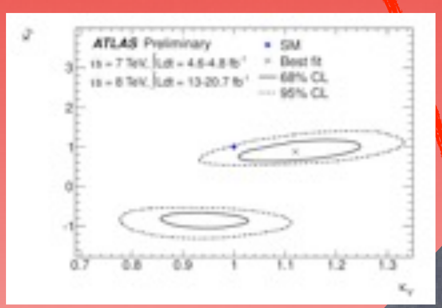
Precision Searches for New Physics

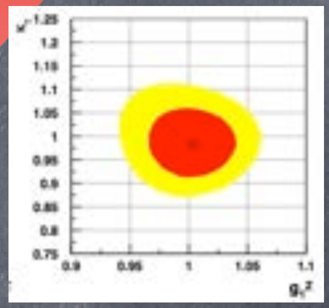


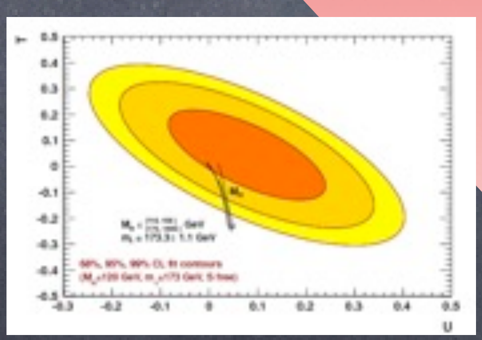


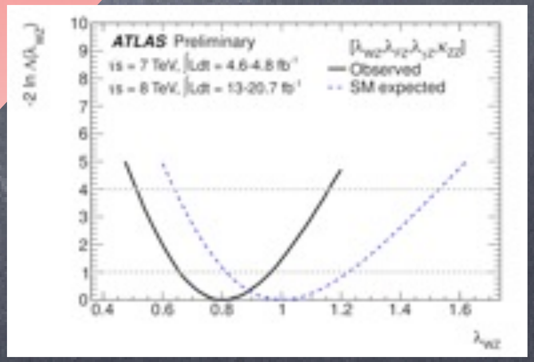
$\mathcal{L}^{SM}$



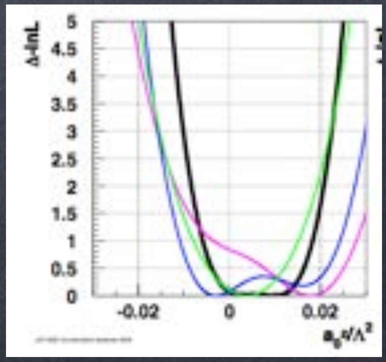








$\mathcal{L}^{UV}$



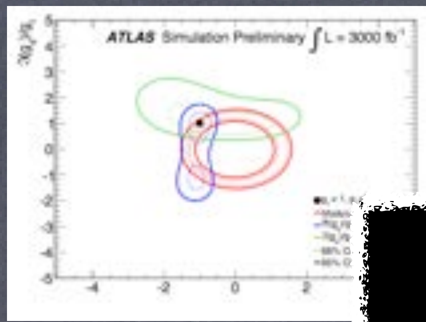
Expansion

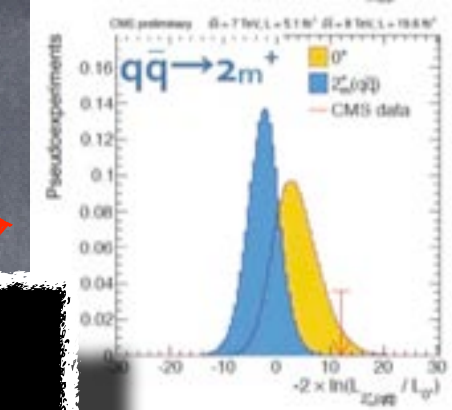
1) E/Λ

2) H/f

3) Y_U, Y_D, Y_E

Motivation

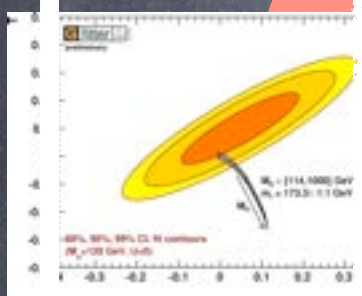


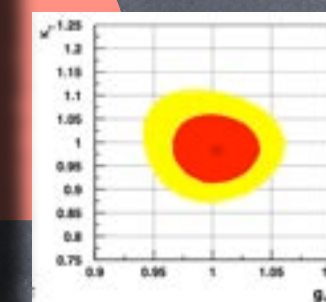


$\mathcal{L}^{SM} \equiv$

1) No direct findings: $M^i_{new} \sim \Lambda \gg m_W$

→ Expansion in D_μ/Λ





Expansion

1) E/Λ

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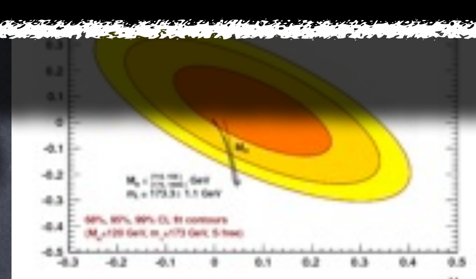
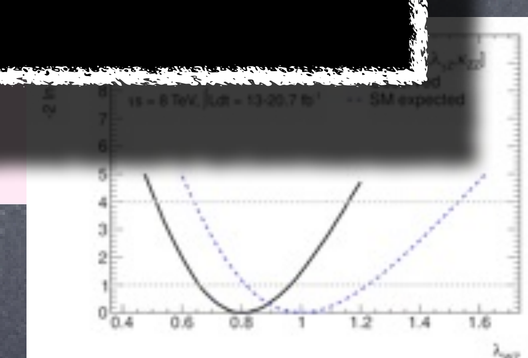
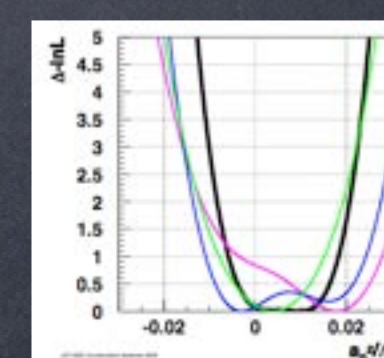
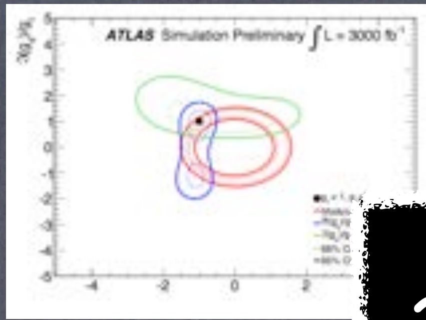


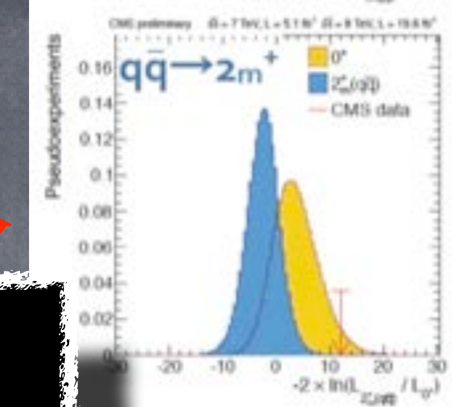


$\mathcal{L}^{UV}$

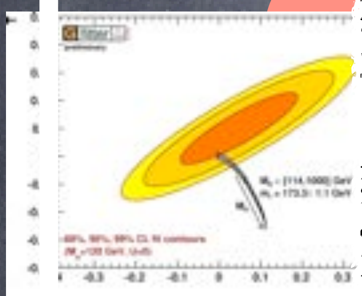


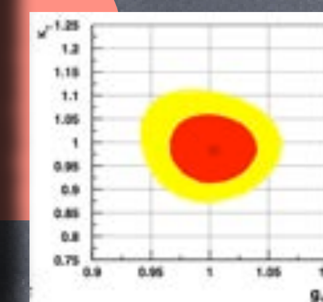
Motivation

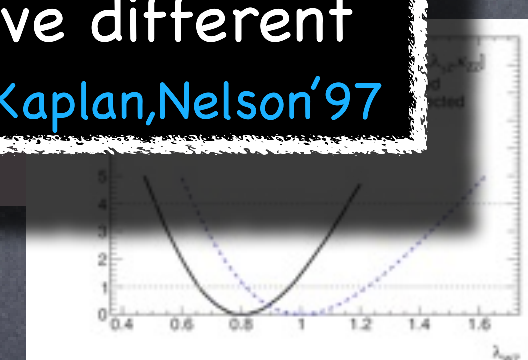


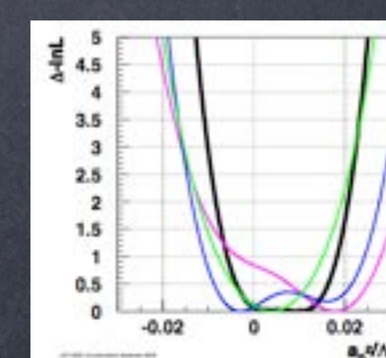


$\mathcal{L}^{SM} \equiv$

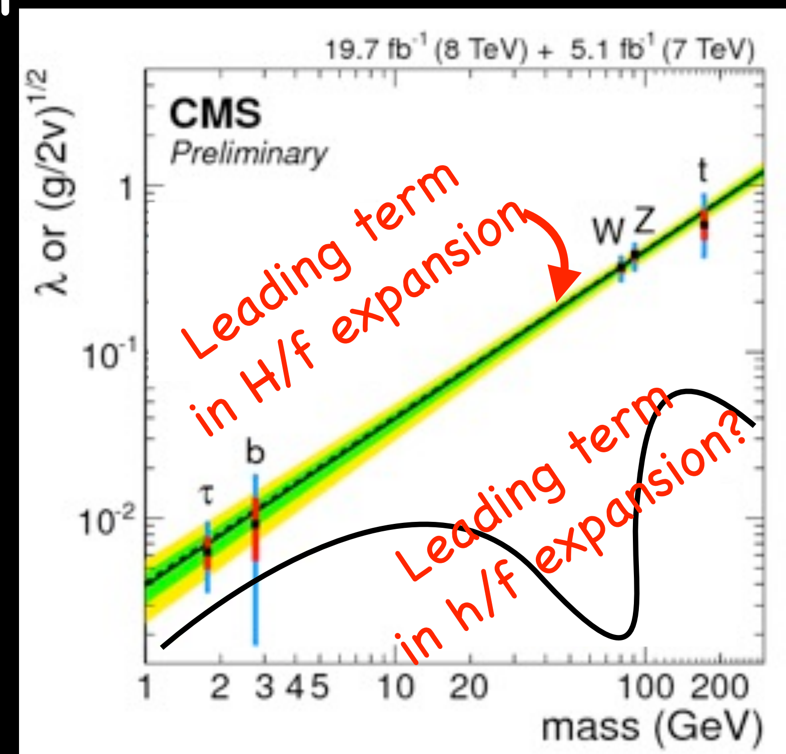








2) BEH scalar is excitation around EWSB vacuum

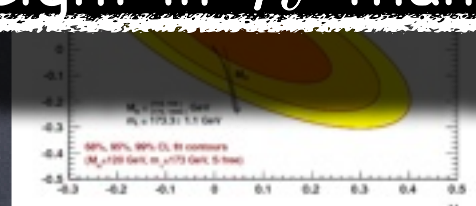


$v + h$

→ Expansion in H/f

$(f \equiv \Lambda/g_*)$

Some BSM coupling (necessary, since fields have different weight in $\hbar$ than derivatives) e.g. Cohen,Kaplan,Nelson'97



Expansion

1) E/Λ

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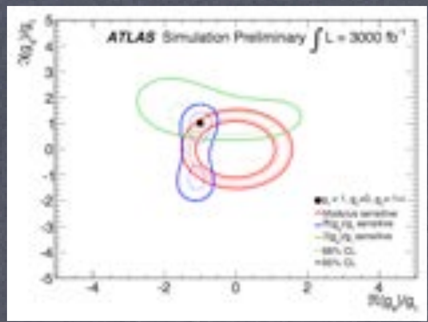
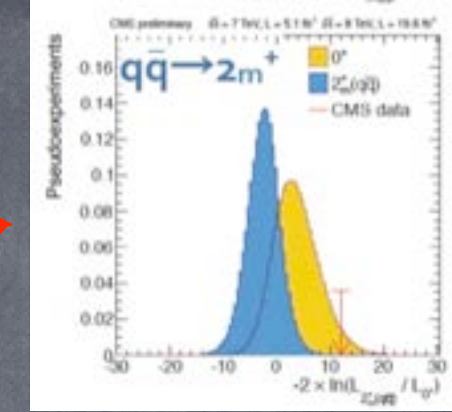
$\mathcal{L}^{UV}$

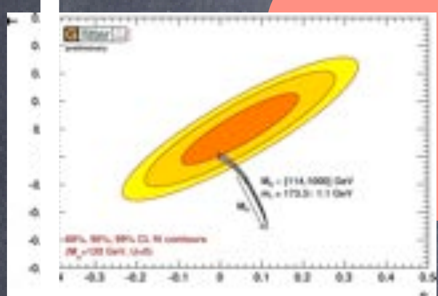
Motivation

Precision Searches for New Physics

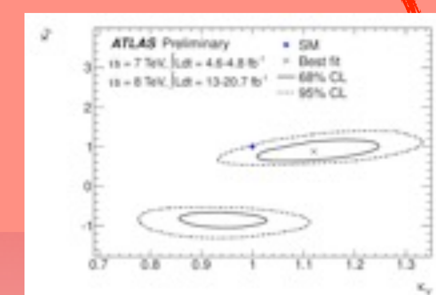


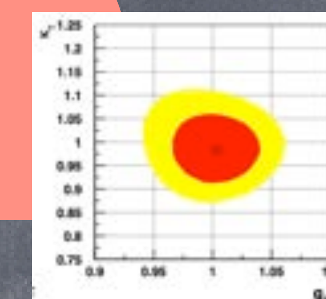


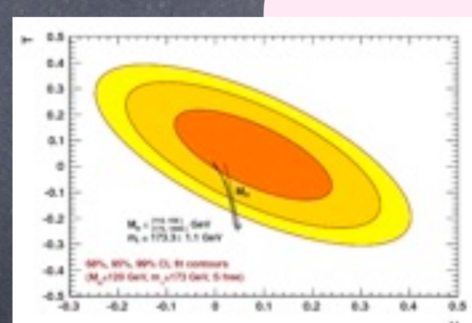
$\mathcal{L}^{SM} \equiv \mathcal{L}^4$



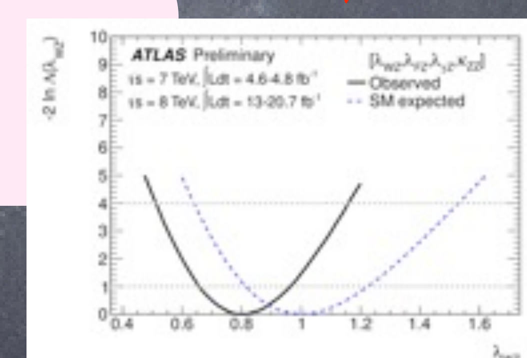
$\mathcal{L}^6$



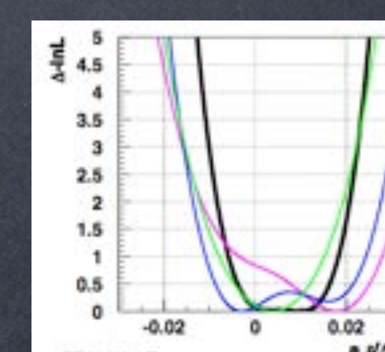




$\mathcal{L}^8$



$\mathcal{L}^{UV}$



Expansion

1) E/Λ

2) H/f

3) Y_U, Y_D, Y_E

Motivation (short)

- Provide a meaningful parametrization of departures from SM (in form of Effective Field Theory - EFT)

  BSM inspired: interpretable as search

- What are the most important parameters to search for?

- Where can the LHC provide genuine New Information?

Motivation (short)

- Provide a meaningful parametrization of departures from SM (in form of Effective Field Theory - EFT)
  - ➜ BSM inspired: interpretable as search

- What are the most important parameters to search for?

- Where can the LHC provide genuine New Information?

Motivation

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\,\frac{g_* H}{\Lambda}\,,\,\frac{g_* f_{L,R}}{\Lambda^{3/2}}\,,\,\frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots\,,$$

SM → $\mathcal{L}_4$

$\mathcal{L}_6$ ← $\sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$

Buchmuller,Wyler'86;
Giudice et al '07
Grzadkowski et al'10
Alonso et al'13

$$\mathcal{L}^{SM} \equiv \mathcal{L}^4$$

What defines SM?

(from an experiment's point of view)

Motivation

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}, \frac{g_* H}{\Lambda}, \frac{g_* f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots,$$

SM → $\mathcal{L}_4$

$\sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$ → $\mathcal{L}_6$

Buchmuller,Wyler'86;
Giudice et al '07
Grzadkowski et al'10
Alonso et al'13

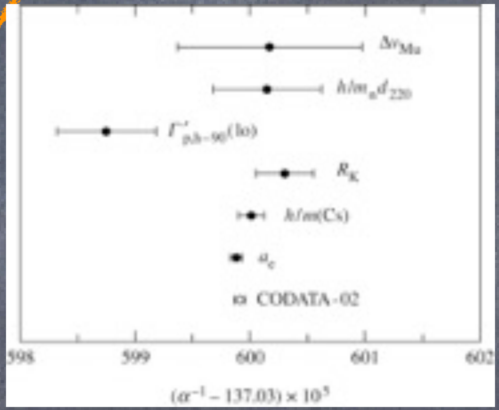
$$\mathcal{L}^{SM} \equiv \mathcal{L}^4$$

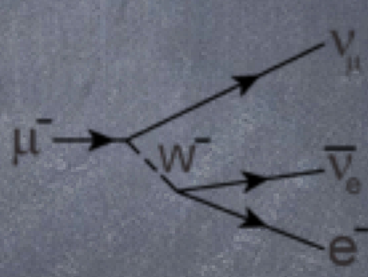
Fixed by 19 most precise experiments

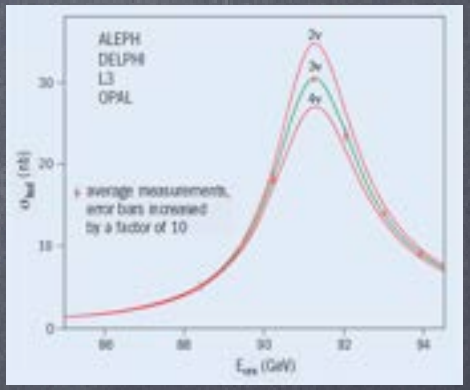
What defines SM?

(from an experiment's point of view)

- Parameters: 19 in $\mathcal{L}_4 \equiv \mathcal{L}_{SM}$







Motivation

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}, \frac{g_* H}{\Lambda}, \frac{g_* f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots ,$$

SM → $\mathcal{L}_4$; $\mathcal{L}_6$ ← $\sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$

Buchmuller,Wyler'86;
Giudice et al '07
Grzadkowski et al'10
Alonso et al'13

$$\mathcal{L}^{SM} \equiv \mathcal{L}^4$$

What defines SM?

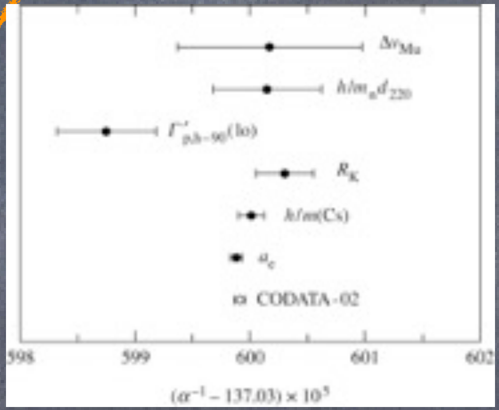
(from an experiment's point of view)

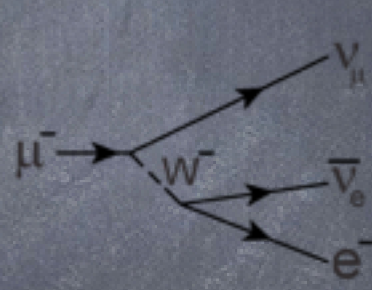
- Parameters: 19 in $\mathcal{L}_4 \equiv \mathcal{L}_{SM}$
- Accidental relations (due to d=4 Lagrangian)

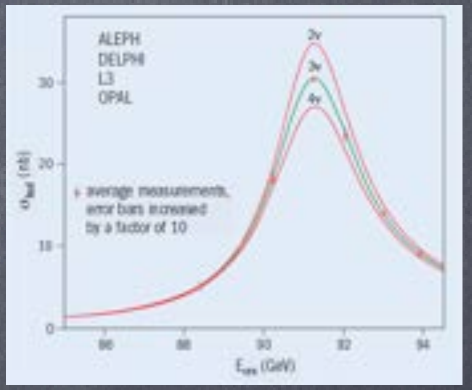
e.g. $m_W = m_Z \cos\theta_W$

$g_{h\bar{f}f} = m_f/v$

Fixed by 19 most precise experiments







Predictions for other experiments

Motivation

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}, \frac{g_* H}{\Lambda}, \frac{g_* f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots,$$

SM → $\mathcal{L}_4$; $\mathcal{L}_6$ ← $\sum_i \frac{c_i}{\Lambda^2} O_i$

Buchmuller,Wyler'86;
Giudice et al '07
Grzadkowski et al'10
Alonso et al'13

$$\mathcal{L}^{SM} \equiv \mathcal{L}^4$$

$$\mathcal{L}^{BSM} \simeq \mathcal{L}^6$$

What defines SM?

- Parameters: 19 in $\mathcal{L}_4 \equiv \mathcal{L}_{SM}$
- Accidental relations (due to d=4 Lagrangian)

e.g. $m_W = m_Z \cos\theta_W$

$g_{h\bar{f}f} = m_f/v$

What defines BSM?

- Parameters: 76 dimension-6 ops.
- Accidental relations ?

Motivation

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}, \frac{g_* H}{\Lambda}, \frac{g_* f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots,$$

SM → $\mathcal{L}_4$; $\mathcal{L}_6$ ← $\sum_i \frac{c_i}{\Lambda^2} O_i$

Buchmuller,Wyler'86;
Giudice et al '07
Grzadkowski et al'10
Alonso et al'13

$$\mathcal{L}^{SM} \equiv \mathcal{L}^4 \qquad \mathcal{L}^{BSM} \simeq \mathcal{L}^6$$

This Talk: BEH Scalar PHYSICS
(one family, CP conserving)

What defines SM?

- Parameters: 1...
- Accidental r...
  (due to d=4 Lagrangian)

e.g. $m_W = m_Z \cos\theta_W$

$g_{h\bar{f}f} = m_f/v$

...defines BSM?

- Parameters: ~~76~~ 17 dimension-6 ops.
- Accidental relations ?

PART 1
17 BSM Parameters:

(Counting independent dimension-6 terms
that can affect BEH scalar physics*)

*=all Wilson coefficients evaluated at $\mu \sim m_W$

For running to UV see e.g.
Elias-Miro,Espinosa,Masso,Pomarol'13; (Alonso,Grojean),Jenkins,Manohar,Trott'13,Elias-Miro,Grojean,Gupta,Marzocca'13

Parameters for BSM: BEH-only

BEH scalar Physics Only

$\langle h \rangle = v$

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

In the vacuum <h>=v, operators $|H|^2 \times \mathcal{L}_{SM}$ only redefine SM parameters! ➔ Observable only in BEH-scalar physics!

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

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

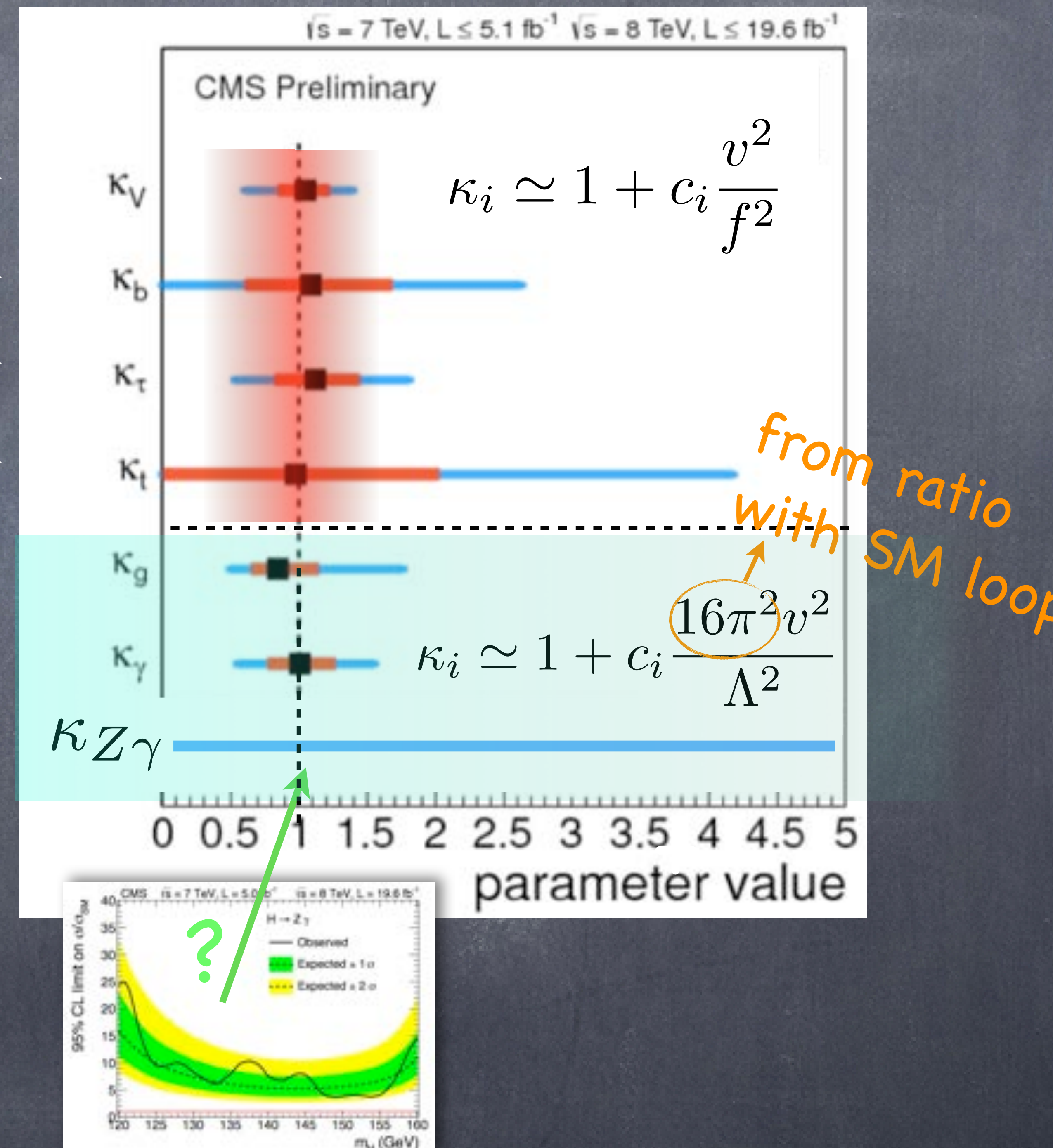
Parameters for BSM: BEH-only

BEH scalar Physics Only

$\langle h \rangle = v$

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

h^3?



→ 8 Parameters fixed by BEH scalar physics experiments!

Elias-Miro,Espinosa,Masso,Pomarol13; Gupta,Pomarol,FR'14

Parameters for BSM: BEH+EW

BEH scalar Physics Only		EW and BEH physics
$\mathcal{O}_r = \|H\|^2 (D_\mu H)^\dagger (D^\mu H)$		$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$		$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$		$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
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Parameters for BSM: BEH+EW

In the vacuum <h>=v, these operators can be measured!

7 of these operators modify:

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

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

All tightly constrained by LEP1 1/1000

EW and BEH physics

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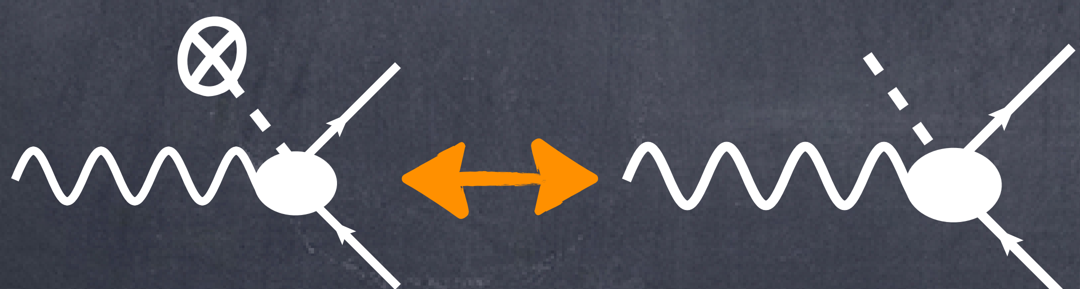
Preview:



Impact of these operators in BEH-physics is small

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2 of these modify TGCs: $g_Z^1 \quad \kappa_\gamma$

Hagiwara,Hikasa, Peccei,Zeppenfled'87

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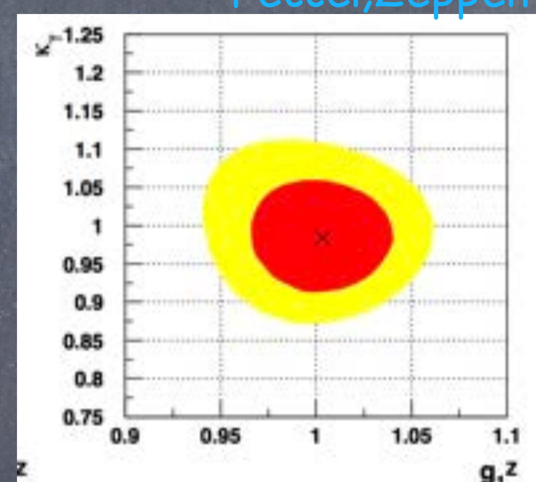
LEP2(ee->WW) constrained* $\sim$5/100



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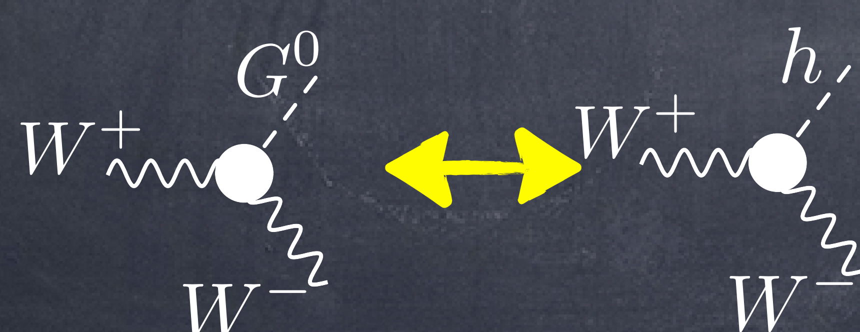

Small Summary: Parameters

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$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_G, \kappa_{\gamma\gamma}, \kappa_{Z\gamma}, \kappa_{h^3}$

g_Z^1, κ_γ

$\delta g_{ZeL}, \delta g_{ZeR}, \delta g_{Z\nu}, \delta g_{ZuL}, \delta g_{ZdL}, \delta g_{ZuR}, \delta g_{ZdR}$

Might as well use these as parameters, to keep relations between observables manifest!

- "BSM Primaries" & "Higgs-Basis"

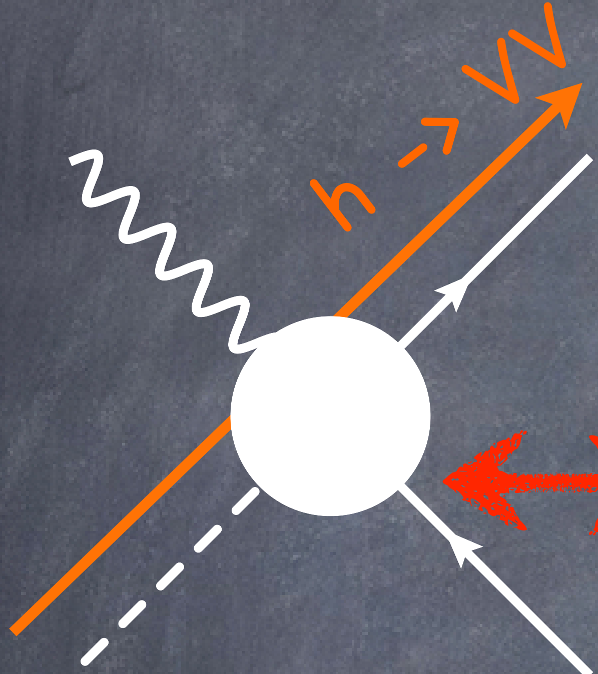
Gupta,Pomarol,FR'14 HXSWG'15

PART 2
Some Relations

BSM Relations for Run 2

Deviations in different. distr. of $h \to Z\bar{f}f$ or $h \to W\bar{f}f$

See e.g. Isidori,(Manohar),Trott'13; Pomarol,FR'13; Falkowski,Vega-Morales'14

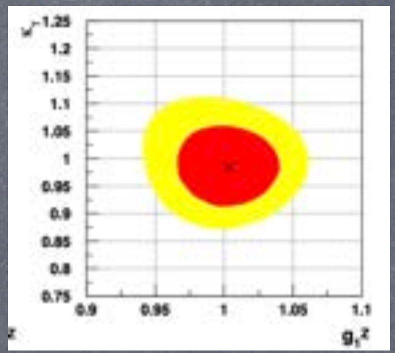


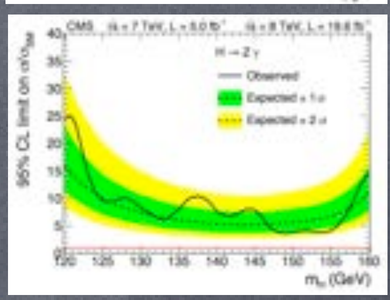
LEP 1

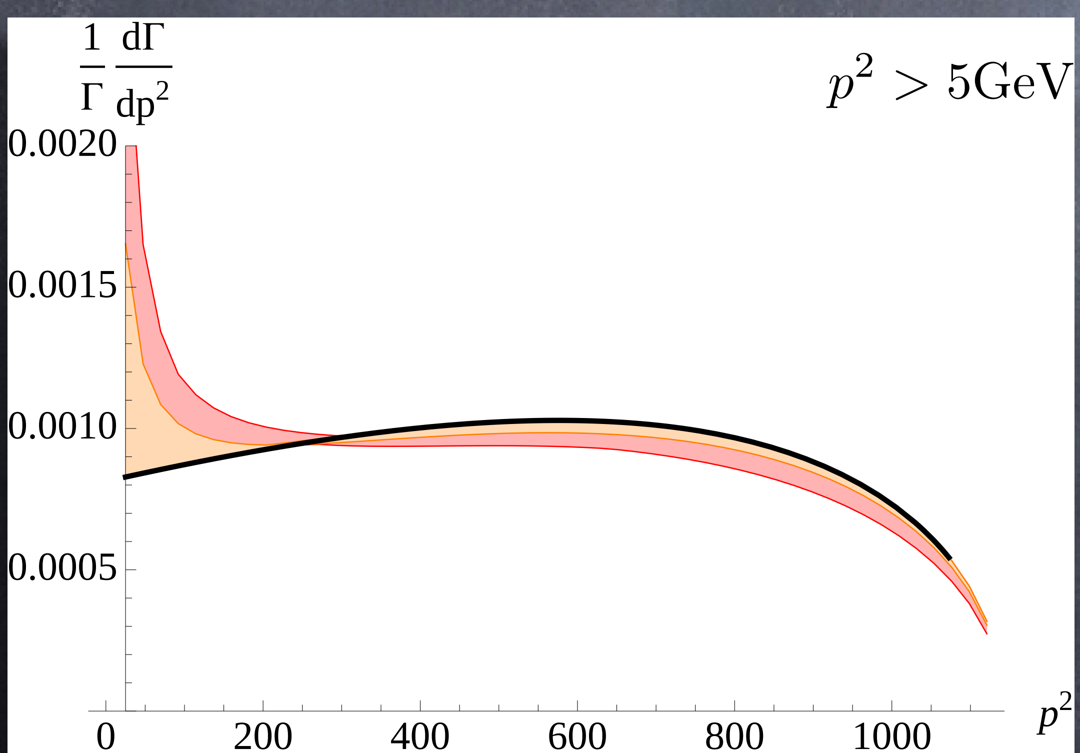
~~Related with Zff couplings~~

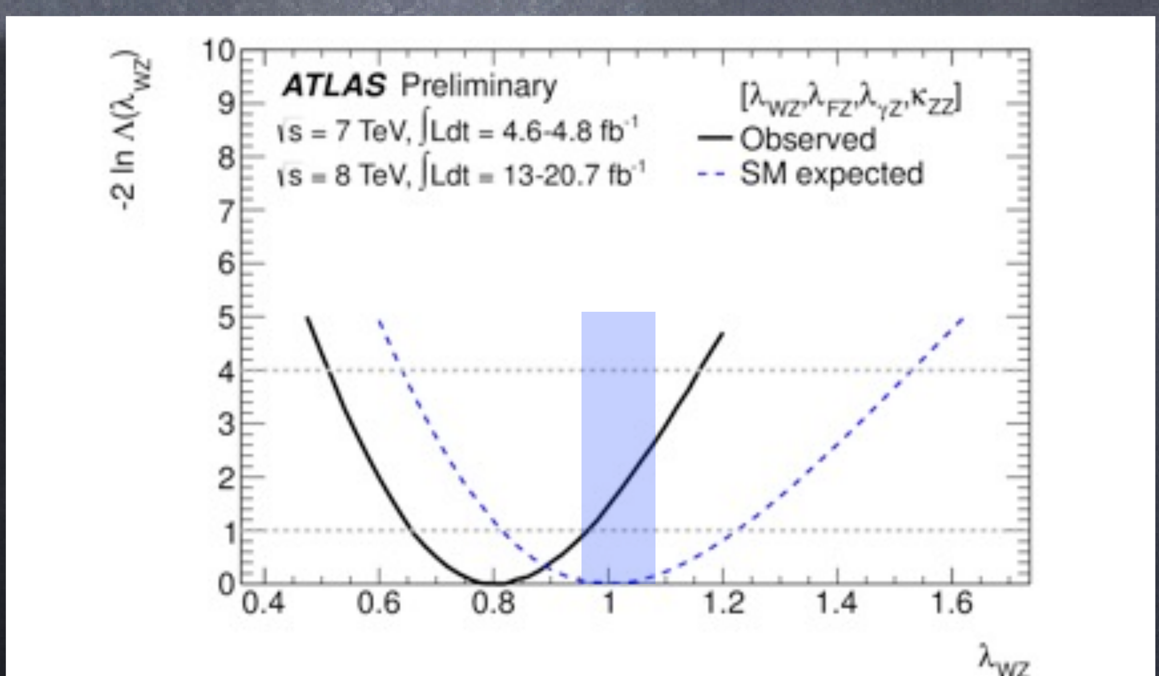
Related with Triple Gauge Coupling

Related with $h \to Z\gamma, \gamma\gamma$









$$\lambda_{WZ}^2 - 1 \simeq 0.6\delta g_1^Z - 0.5\delta\kappa_\gamma - 1.6\kappa_{Z\gamma}$$

Pomarol,FR'13; Gupta et al' to Appear

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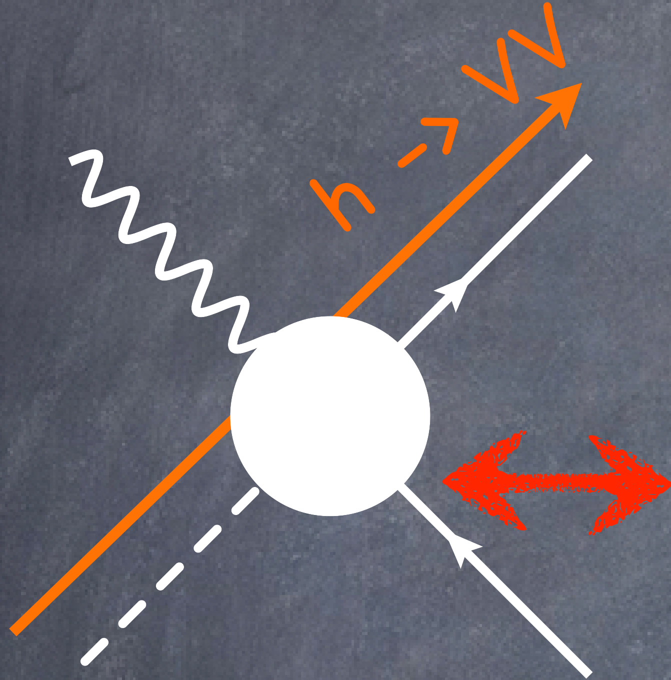

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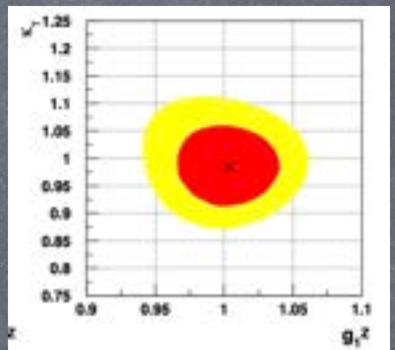

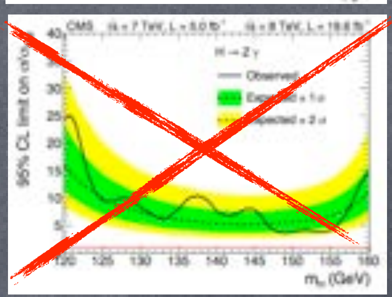

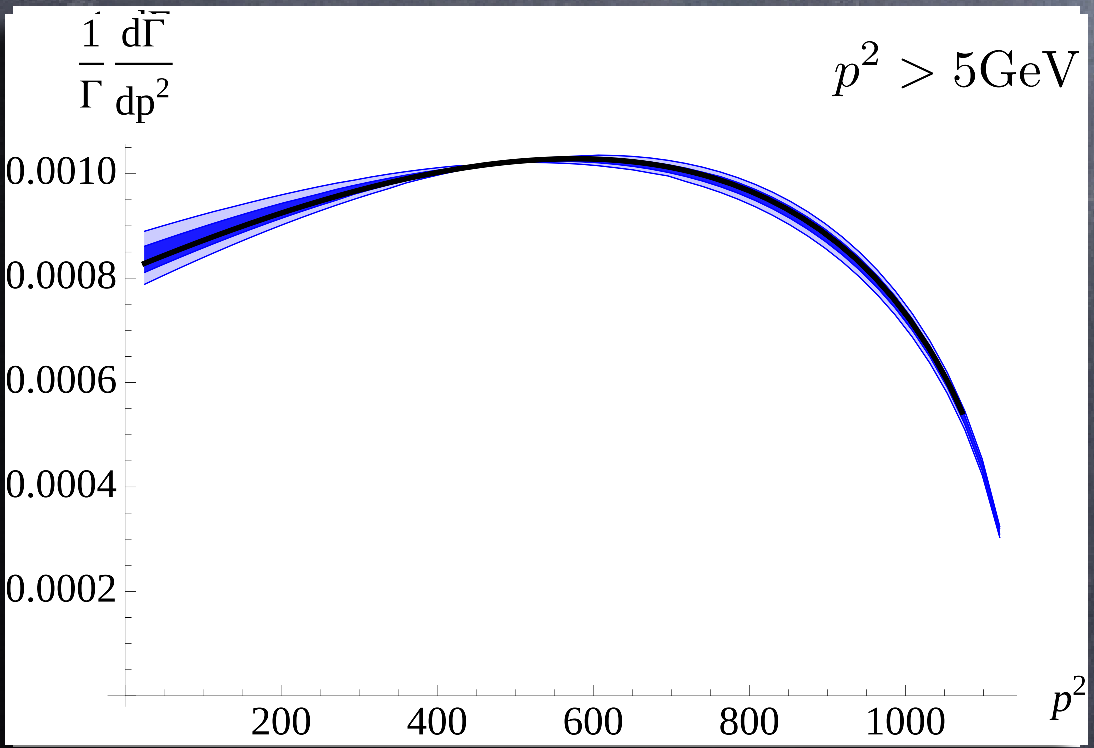

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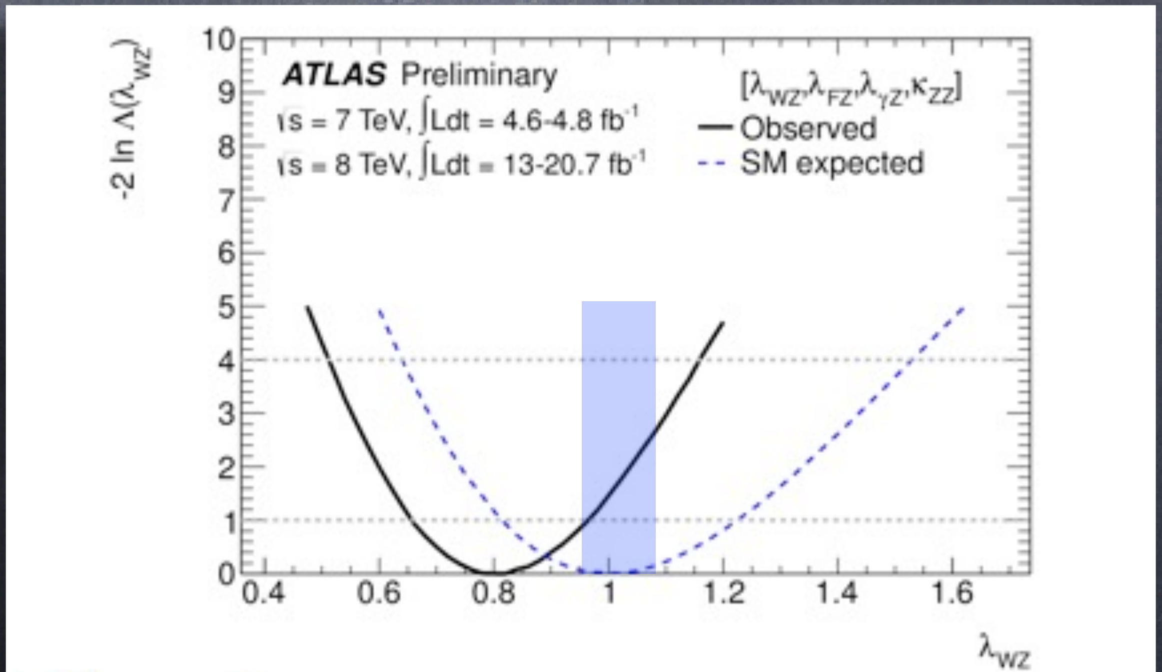

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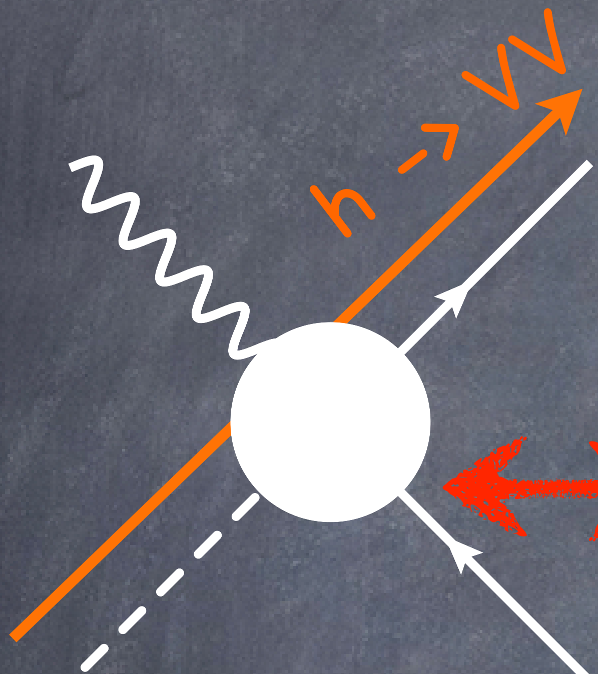

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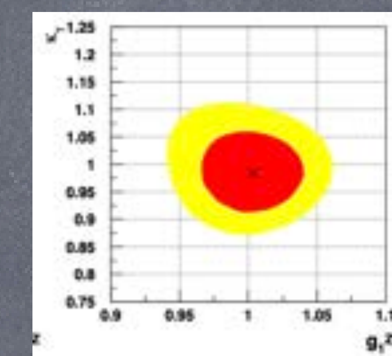
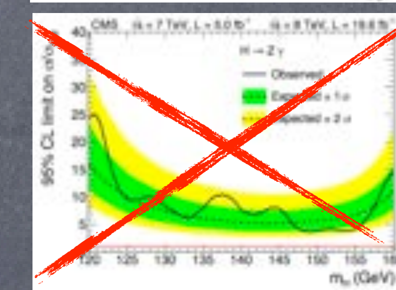
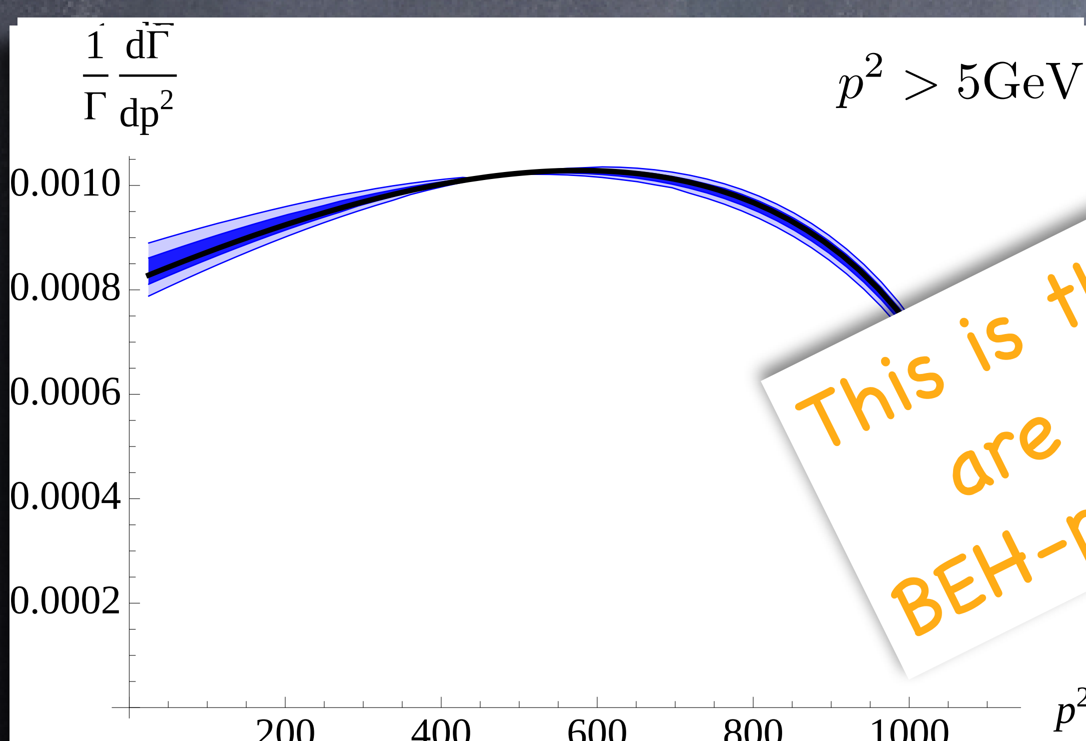
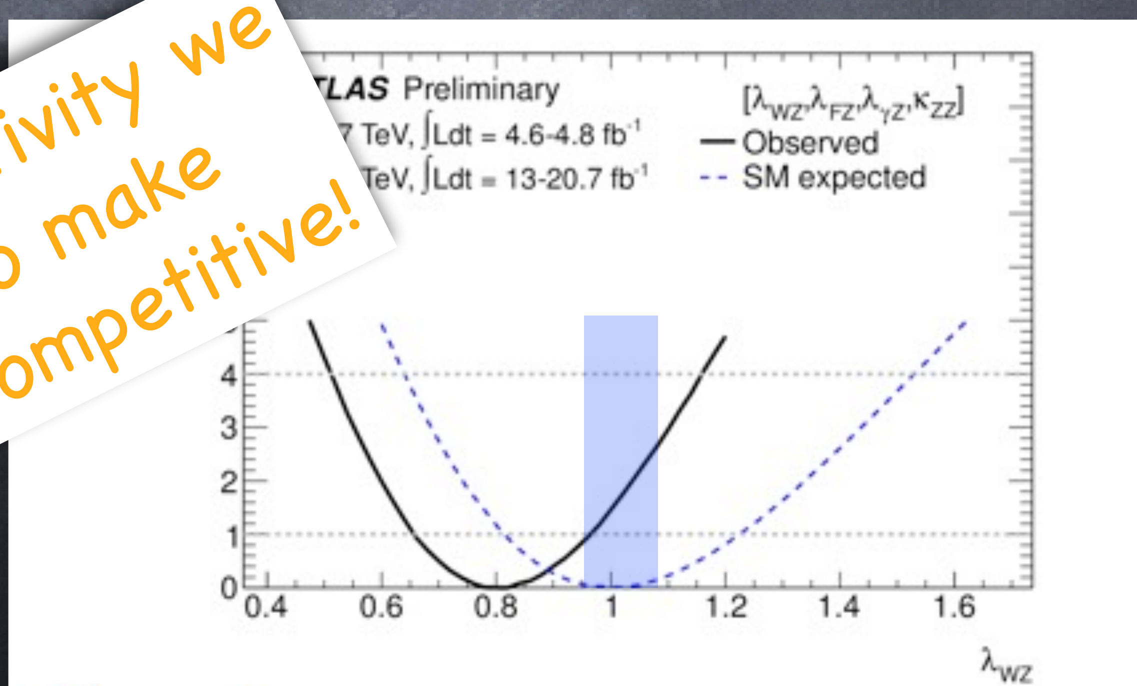






This is the sensitivity we are aiming to make BEH-physics competitive!



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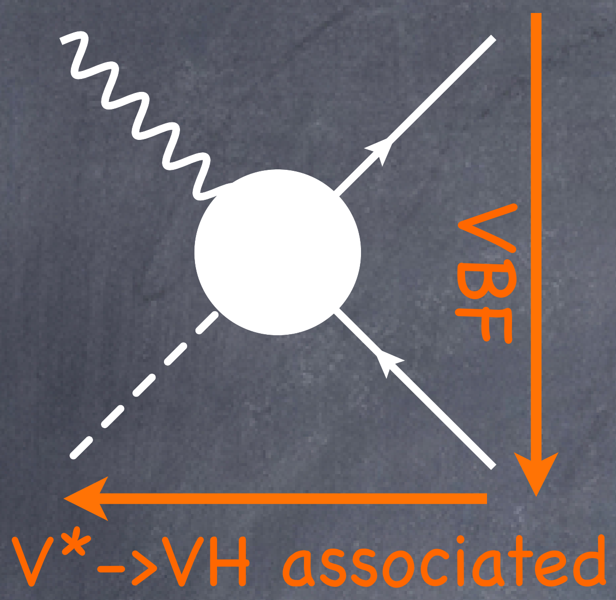
...but at High Energy LHC improves



Some BSM effects grow with energy:

$$\sim \int d\cos\theta |\mathcal{M}_L|^2 \underset{(s \gg m_W)}{\longrightarrow} \frac{g^4}{6}\left(1 + 4\frac{\hat{s}}{g^2\Lambda_{g1z}^2} + \cdots\right)^2$$

Biekötter,Knochel,Krämer,Liu,FR '14
Isidori,Trott'13;Corbett, et al 12-13;
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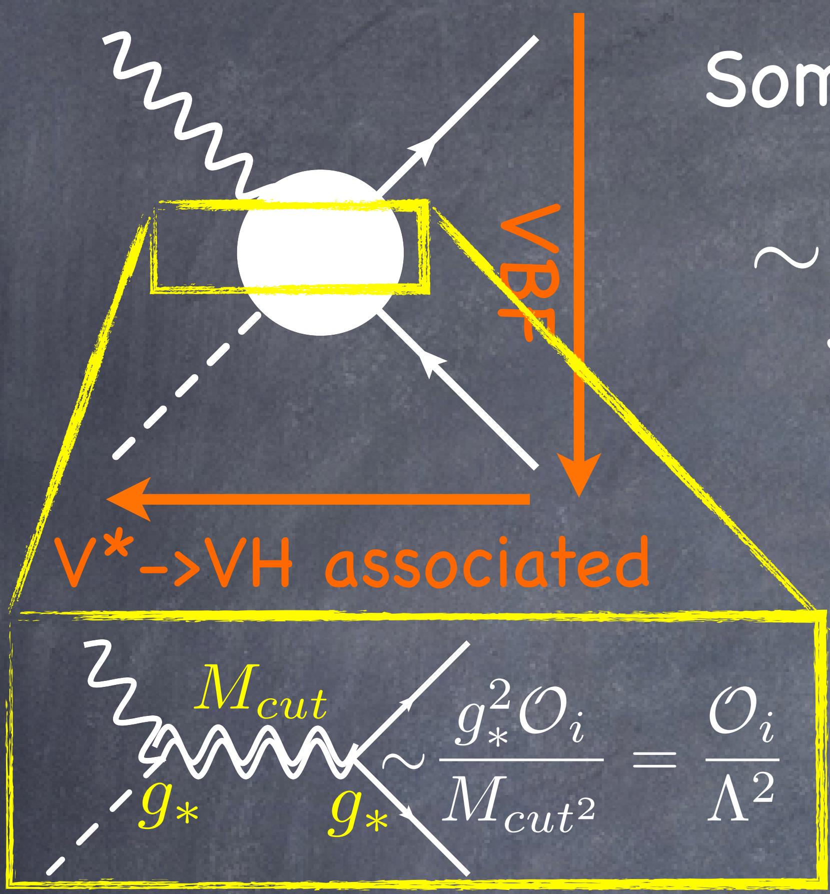

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- EFT must be used consistently: events with $E > M_{cut}$ cannot be used (conservatively)
- Information about Λ and the cut-off M_{cut} (or BSM coupling g_*) necessary (similar to DM and EFT!)

Giudice,Grojean,Pomarol,Rattaz

Biekötter,Knochel,Krämer,Liu,FR '14
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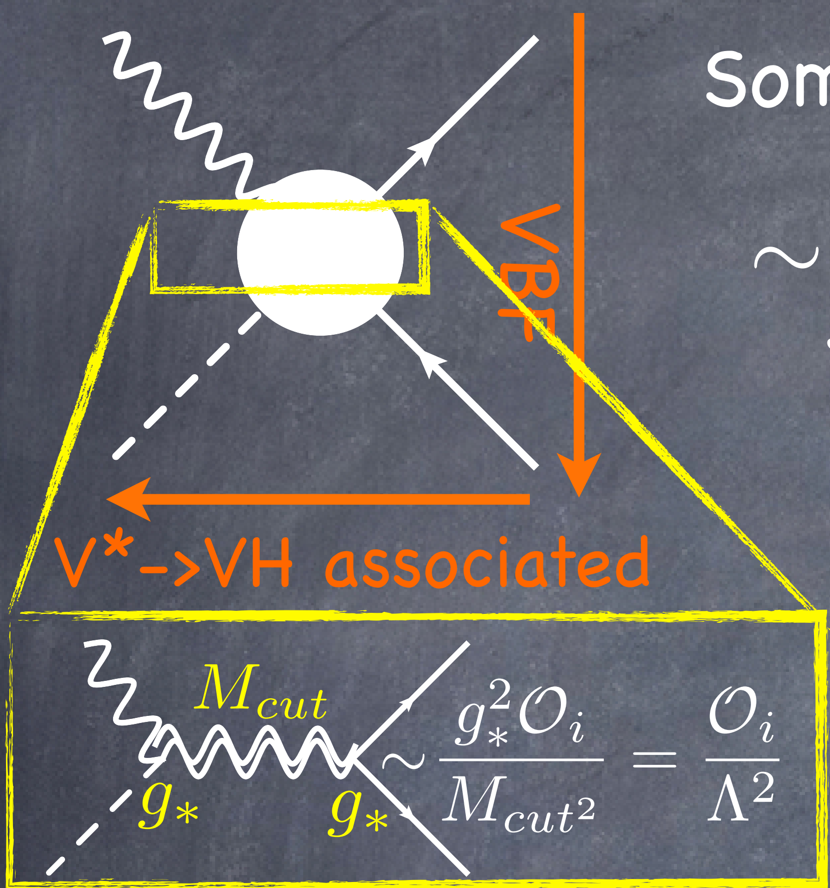

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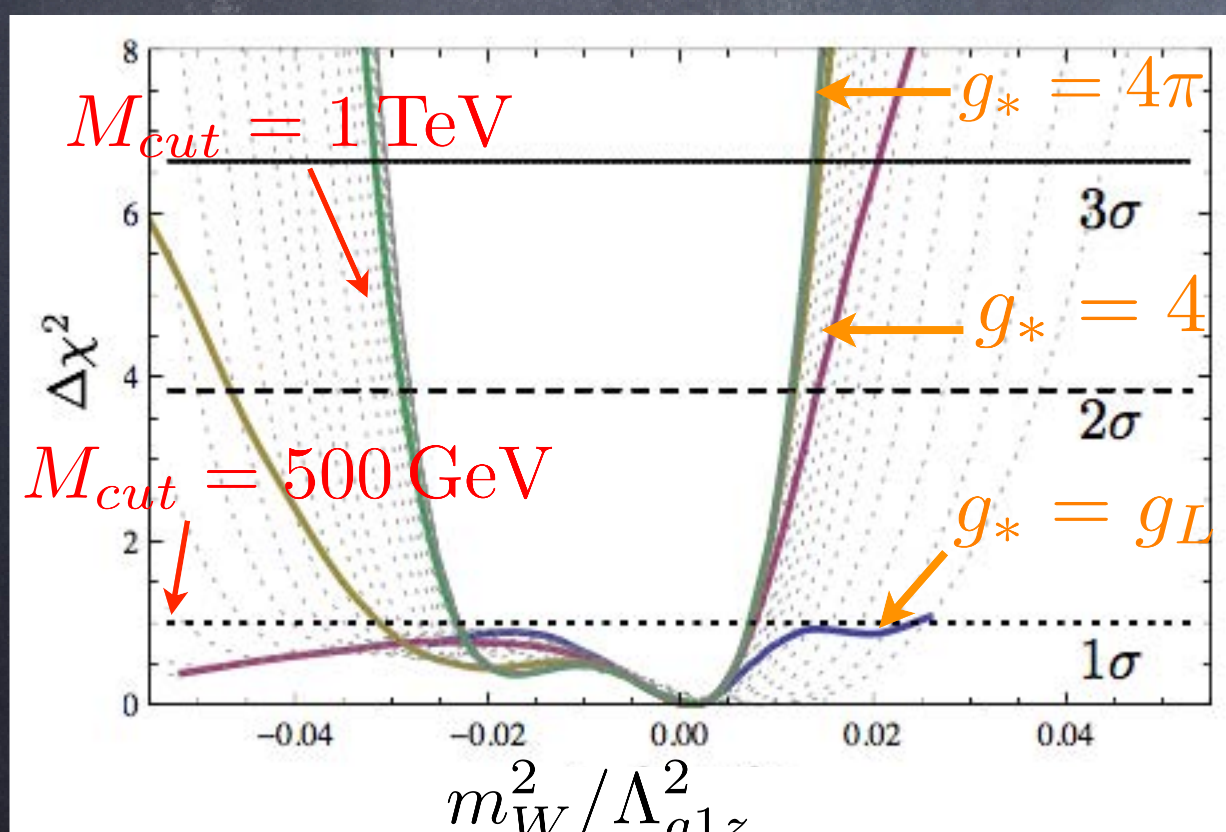

Biekötter,Knochel,Krämer,Liu,FR '14

Very strongly coupled BSM

Large-N/Holography Composite Higgs

Weakly coupled Z',...

Biekötter,Knochel,Krämer,Liu,FR '14
Isidori,Trott'13;Corbett, et al 12-13;
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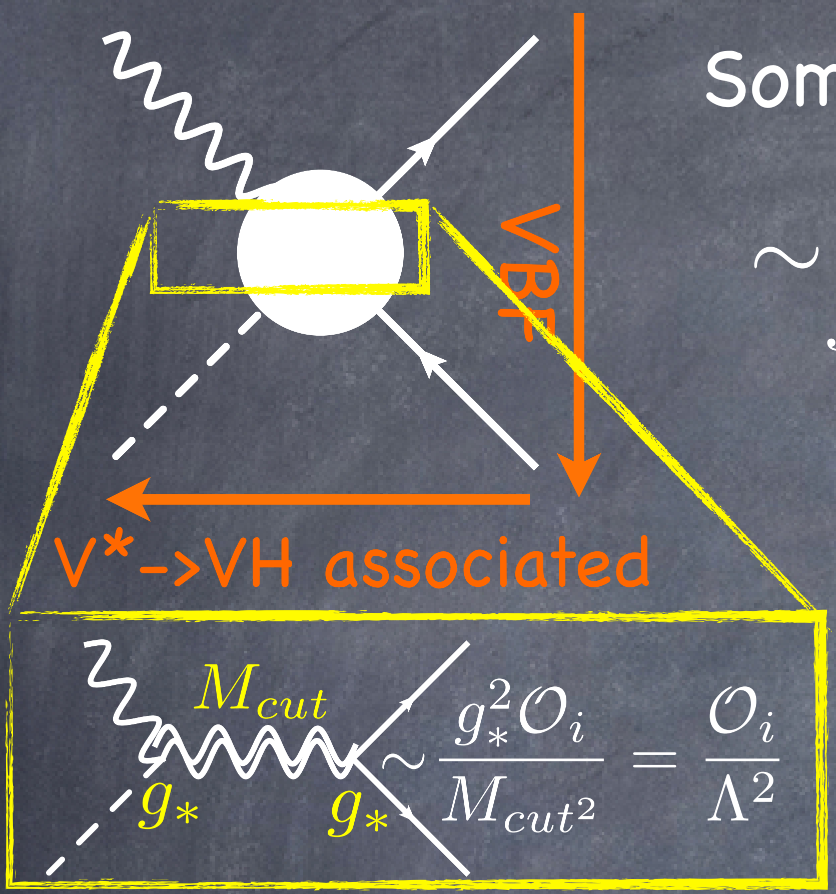

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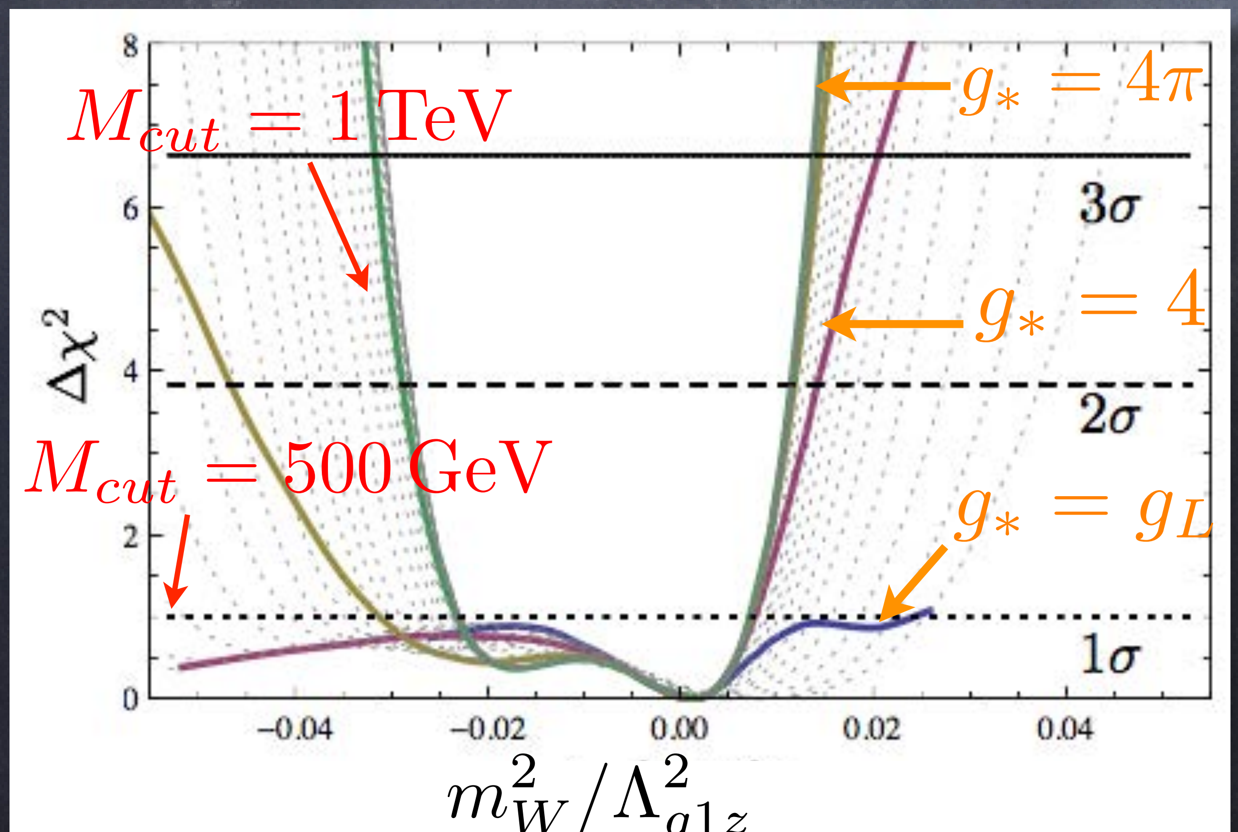

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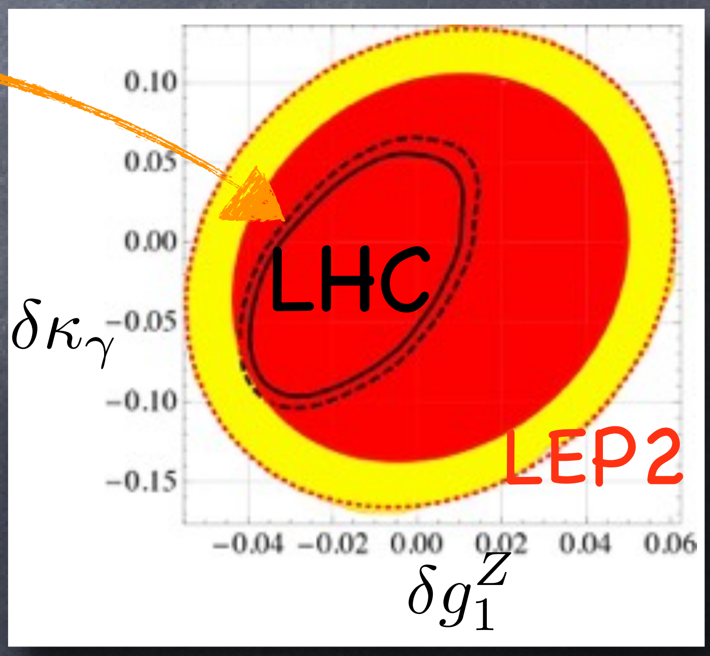

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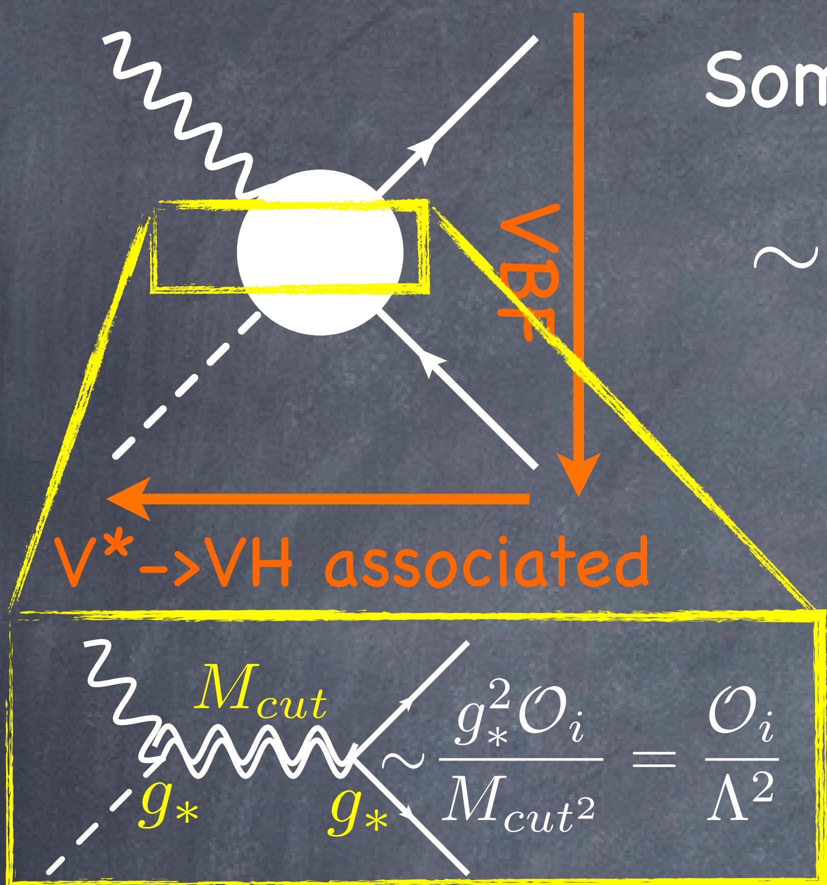

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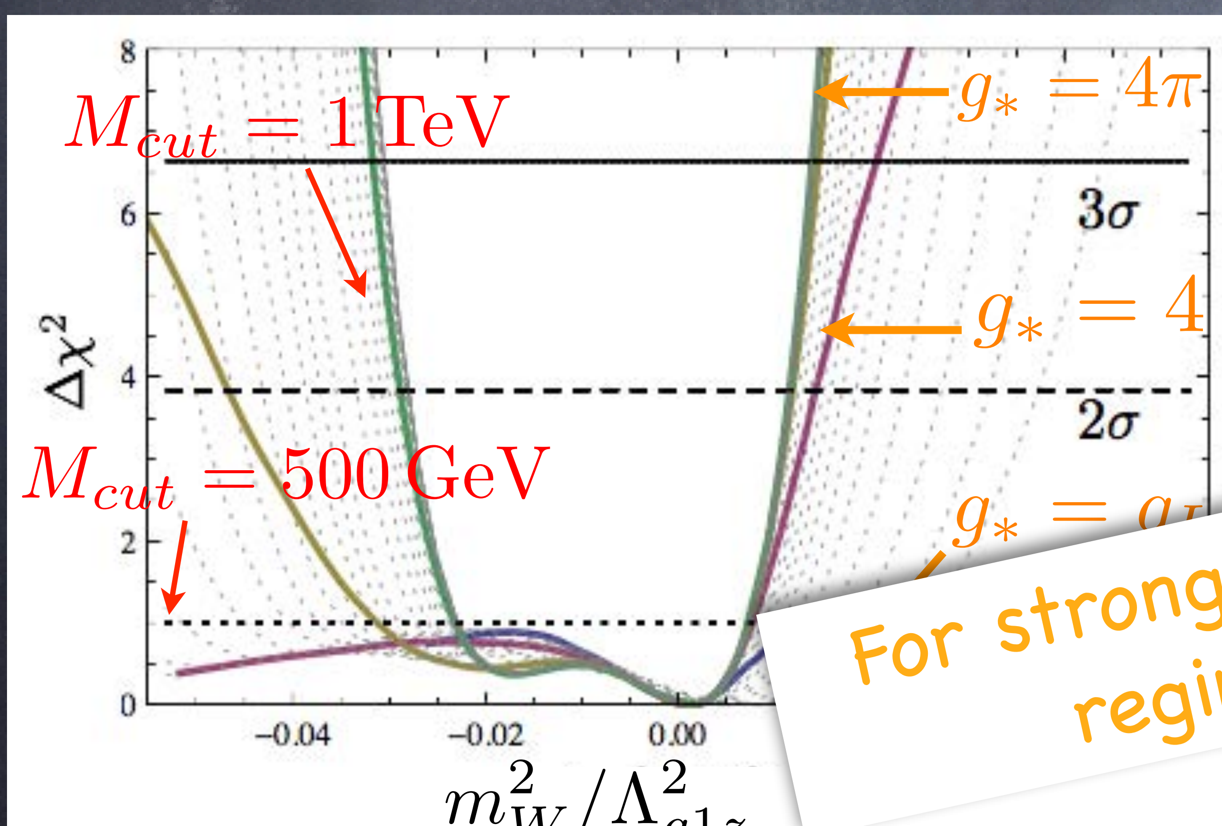
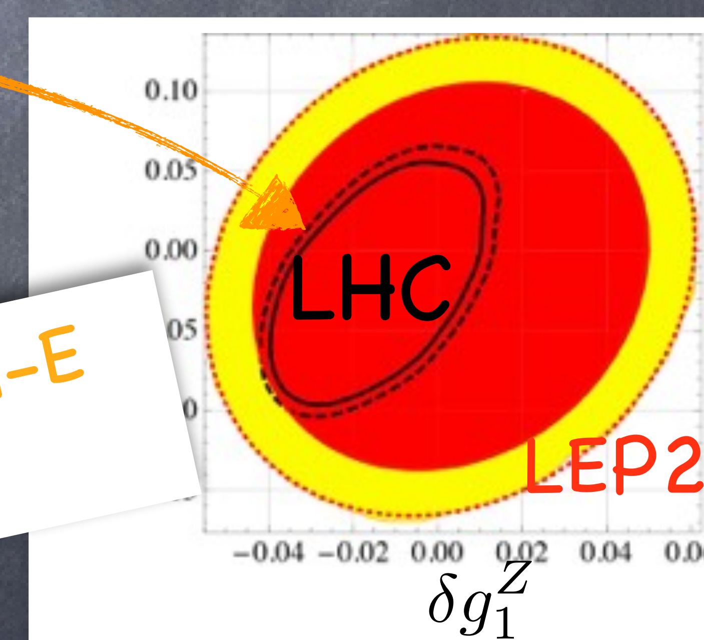


Very strongly coupled BSM

Large-N/Holography Composite Higgs

For strongly coupled BSM, High-E regime very sensitive...



Biekötter,Knochel,Krämer,Liu,FR '14

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Conclusions

BSM, early 2012:

Conclusions

BSM, early 2015: 

Conclusions

BSM, early 2015:

Generic SM
precision tests

Conclusions

BSM, early 2015:

Generic SM precision tests

EFT: BSM Inspired precision searches ("fare la scarpetta")

Conclusions

- EFT: - Consistent framework to search for leading BSM effects
  - Motivation for precision tests

- Parametrization of BSM for Higgs physics:

7 $\{\delta g_{ZeL}, \delta g_{ZeR}, \delta g_{Z\nu}, \delta g_{ZuL}, \delta g_{ZdL}, \delta g_{ZuR}, \delta g_{ZdR}\}$ LEP1

2 $\{g_1^Z, \kappa_\gamma\}$ TGCs (LEP2)

VH/VBF (LHC High-E)

8 $\{\kappa_{gg}, \kappa_{\gamma\gamma}, \kappa_{Z\gamma}, \delta g^h_{V_\mu V^\mu}, \delta g^h_{\bar{t}t}, \delta g^h_{\bar{b}b}, \delta g^h_{\bar{\tau}\tau}, \delta g^h_{h^3}\}$ BEH-physics (LHC)

➜ Focusing on the most relevant parameters (combining different experiments) increases the sensitivity to new physics

- High-E regime valuable (at present only for strongly coupled BSM), but different assumptions on M_{cut} necessary for consistent constraints on Λ