Composite Higgs models at the LHC and beyond

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Outline

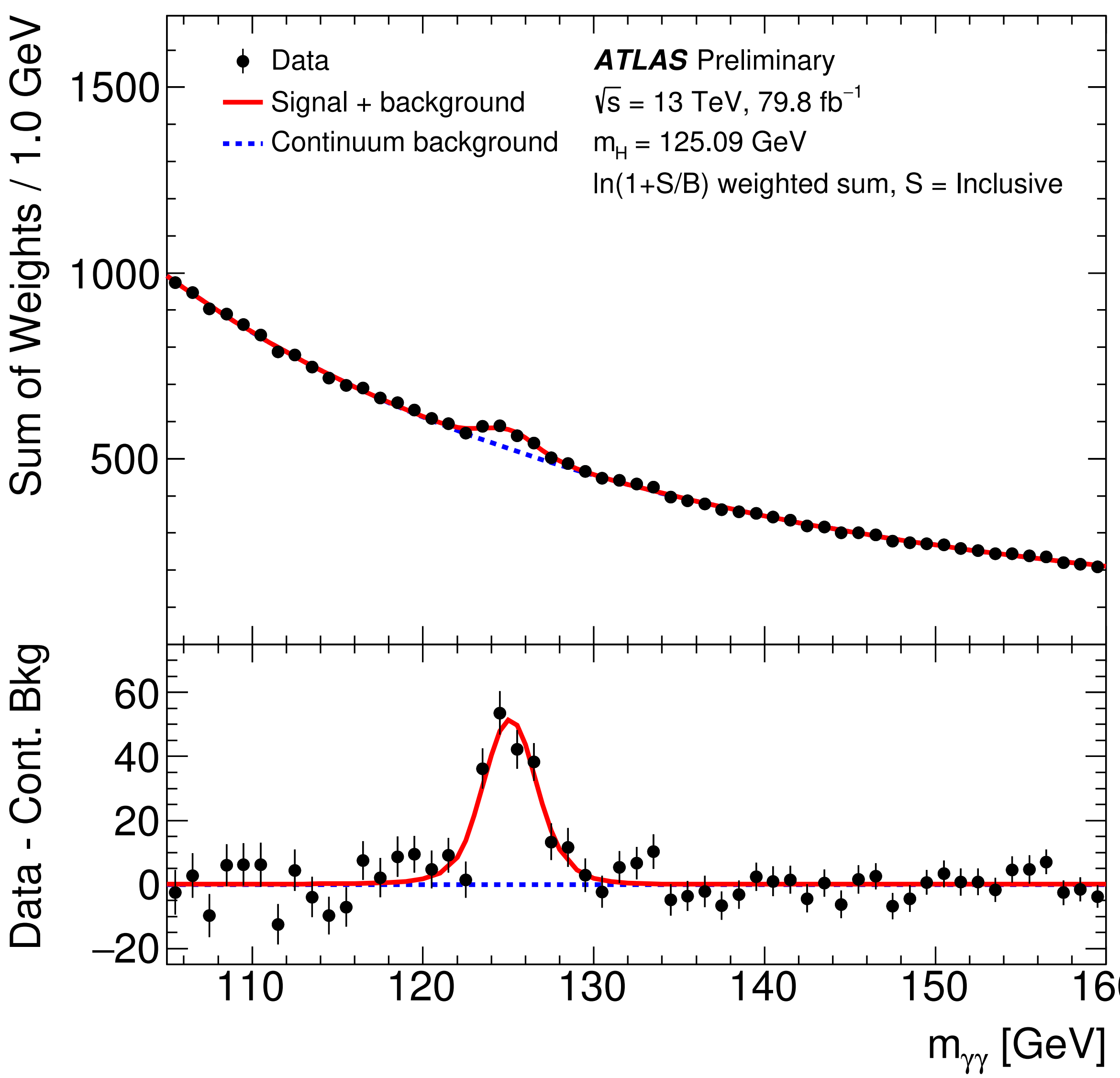
- Naturalness as guideline

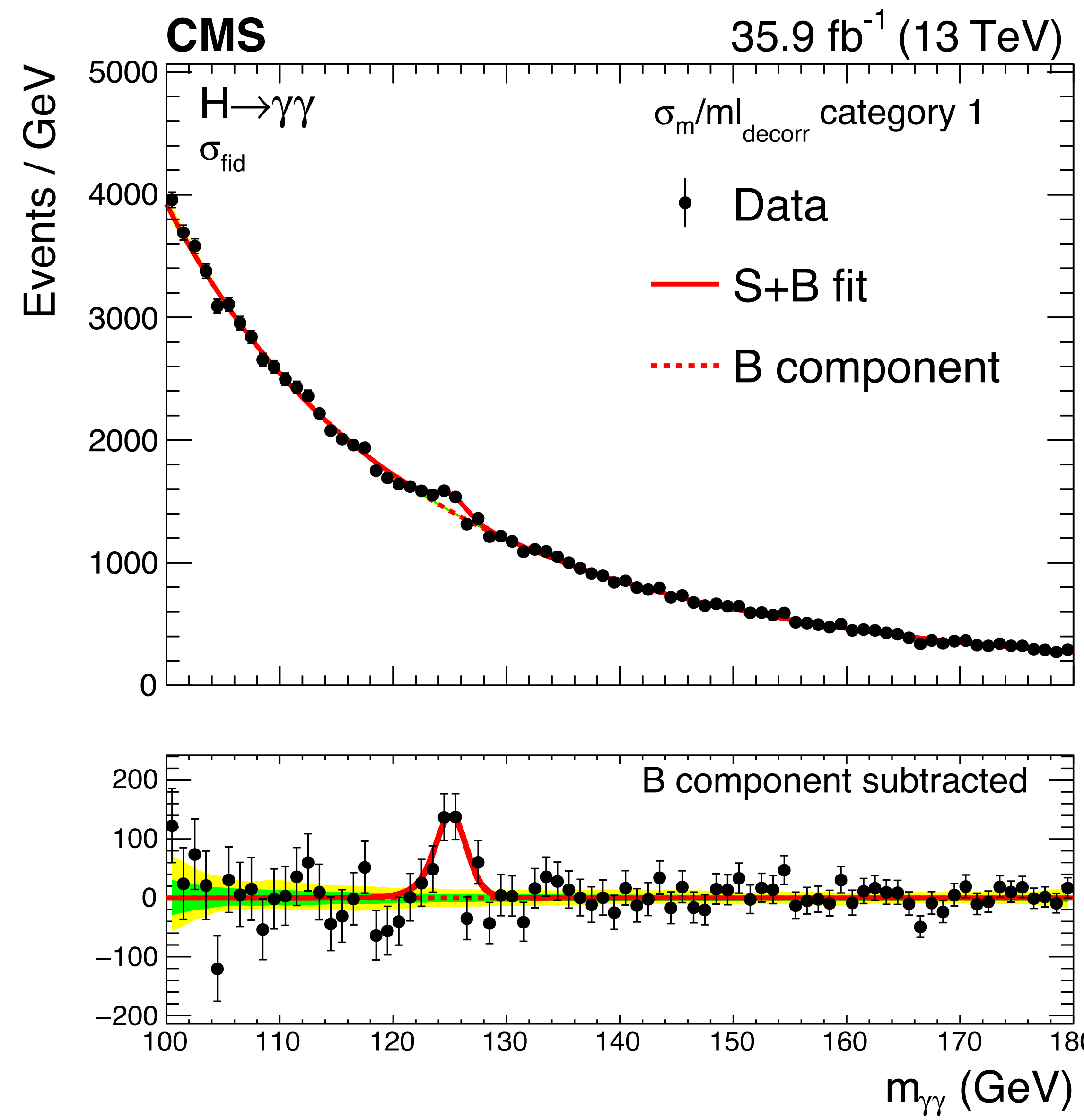
- Resonances in the composite Higgs models

- Indirect signatures

- Conclusion

Motivation





A first step towards the dynamics of EWSB!

t' Hooft Naturalness

A small parameter is natural
if setting it to zero leads to an enhanced symmetry

↓

Guideline for model building

t′ Hooft Naturalness

$$\mathcal{L} = -m_\psi \bar{\psi}_L \psi_R - m_\phi^2 \phi^\dagger \phi + g A_\mu \bar{\psi} \gamma^\mu \psi + y \phi \bar{\psi}_L \psi_R + \lambda (\phi^\dagger \phi)^2$$

- Enhanced photon number conservation

$$g = 0 \;\Rightarrow\; [N_\gamma, H] = 0$$

- Enhanced scalar number conservation

$$y = 0 \;\Rightarrow [N_\phi, H] = 0$$

t' Hooft Naturalness

$$\mathcal{L} = -m_\psi \bar{\psi}_L \psi_R - m_\phi^2 \phi^\dagger \phi + g A_\mu \bar{\psi} \gamma^\mu \psi + y \phi \bar{\psi}_L \psi_R + \lambda (\phi^\dagger \phi)^2$$

- Enhanced chiral symmetry

$$m_\psi = 0 \;\Rightarrow\; \psi_L \to e^{i\alpha} \psi_L, \phi \to e^{i\alpha} \phi$$

- Enhanced Shift symmetry

$$m_\phi = 0, \quad \lambda = 0 \;\Rightarrow\; \phi \to \phi + c$$

t' Hooft Naturalness

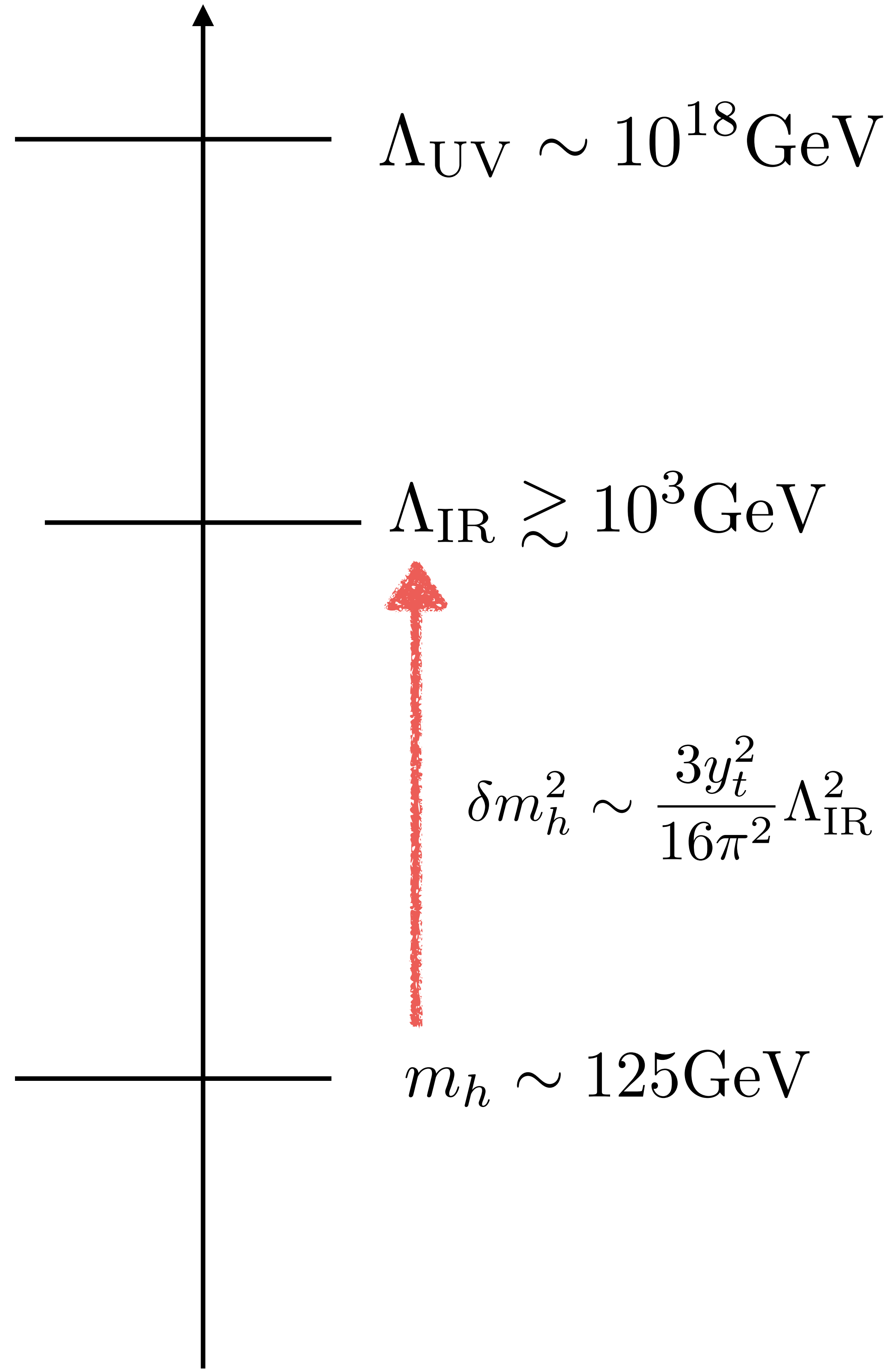
$$\mathcal{L} = -m_\psi \bar{\psi}_L \psi_R - m_\phi^2 \phi^\dagger \phi + g A_\mu \bar{\psi} \gamma^\mu \psi + y \phi \bar{\psi}_L \psi_R + \lambda (\phi^\dagger \phi)^2$$

- No enhanced symmetry

$$m_\phi = 0$$

- Small Higgs mass not natural

t' Hooft Naturalness



Naturalness as Guideline

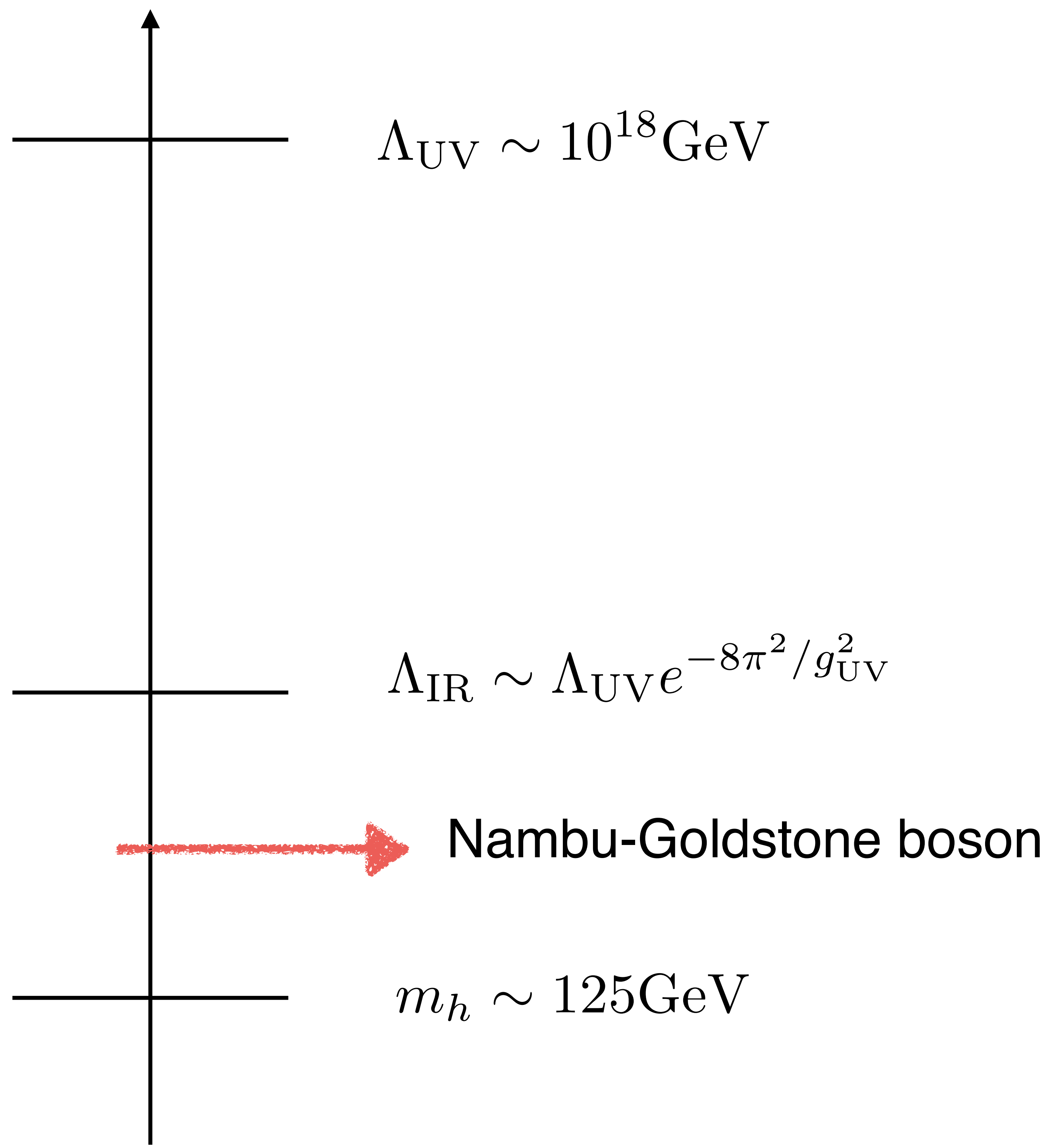
- Compositeness

$$\Lambda_{\rm IR} \sim \Lambda_{\rm UV} e^{-8\pi^2/g_{\rm UV}^2}$$

- Supersymmetry

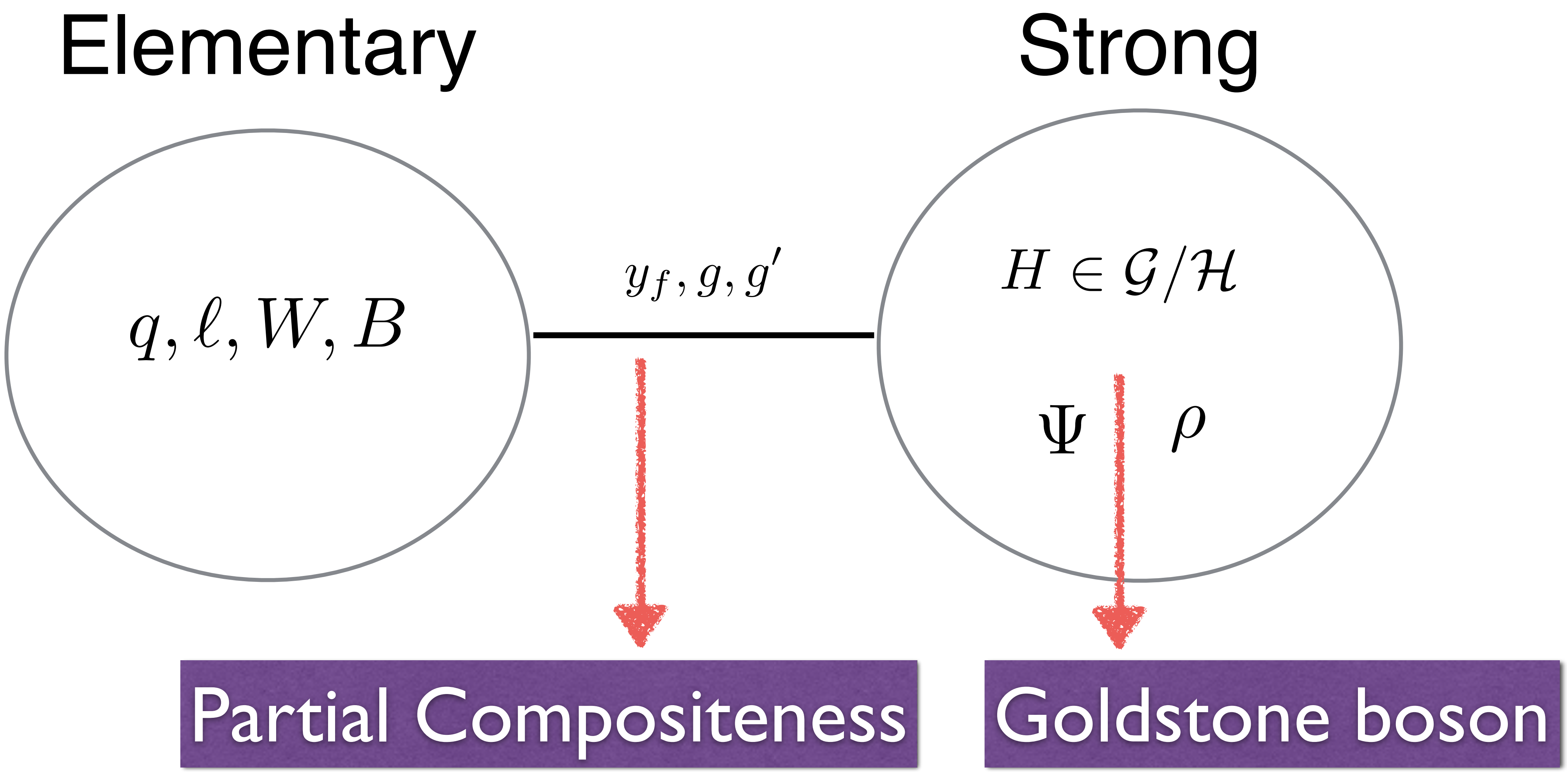
$$Q\left|\phi\right\rangle = \left|\psi\right\rangle \quad \Rightarrow \quad \text{Enhanced chiral symmetry}$$

Compositeness



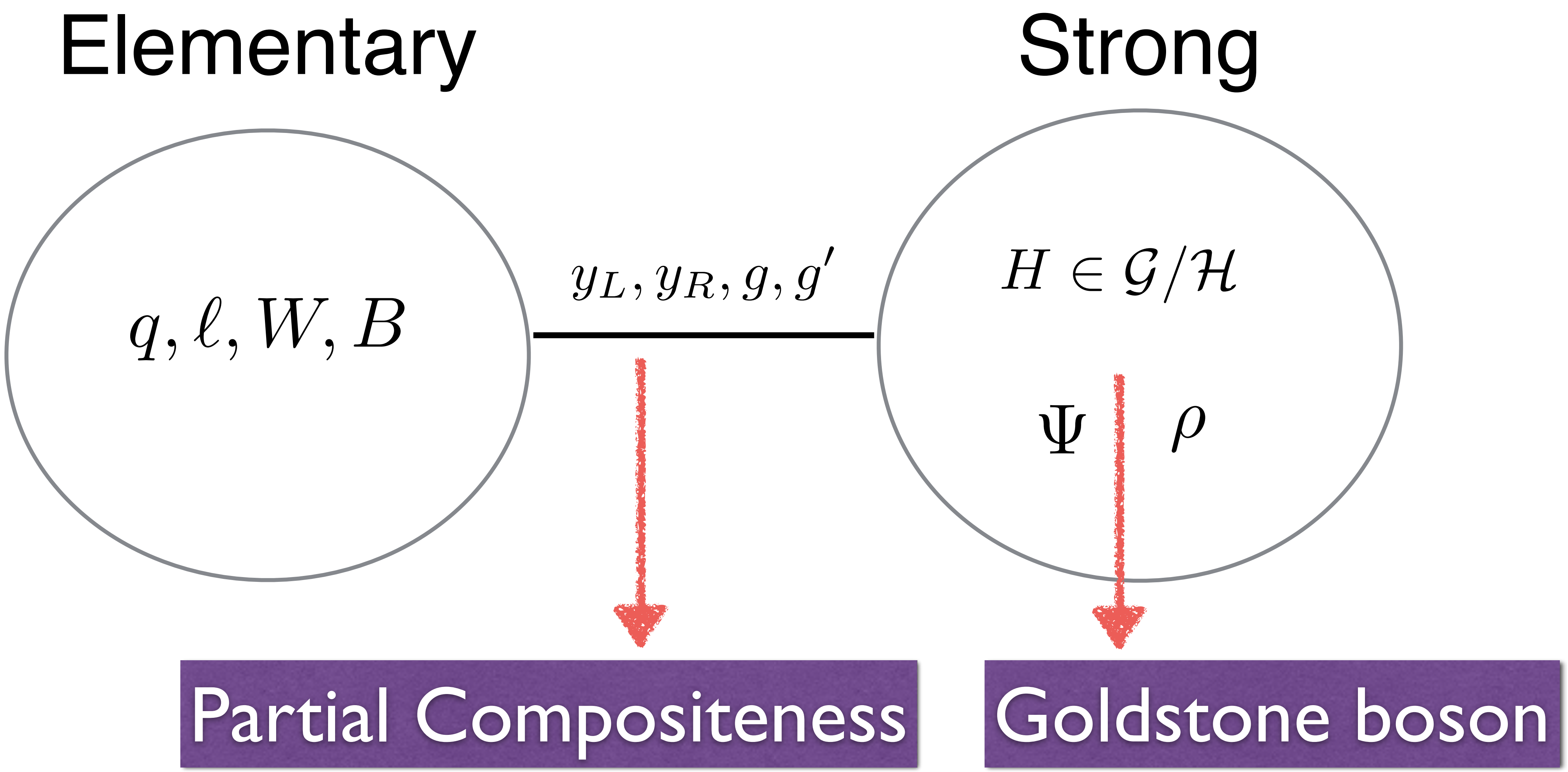
Enhanced shift symmetry!

Composite Higgs models



Kaplan, Georgi & Dimopoulos
Contino, Nomura and Pomarol
Agashe, Contino and Pomarol

Composite Higgs models



$$g_\Psi = \frac{M_\Psi}{f} \gg y_{L,R} \qquad\qquad g_\rho = \frac{M_\rho}{f} \gg g, g'$$

$$g_* \equiv g_\Psi, g_\rho$$

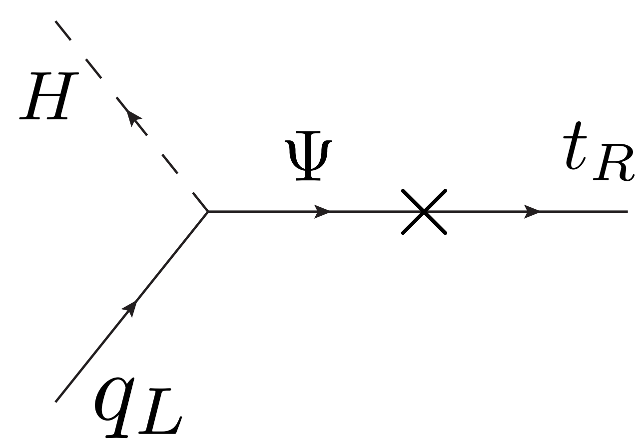
Partial compositeness

$$y_L \bar{q}_L^{I_L} \mathcal{O}_{I_L} + y_R \bar{t}_R^{I_R} \mathcal{O}_{I_R}$$

$$H \in \mathcal{G}/\mathcal{H}$$

$$SU(2)_L \times U(1)_Y \in \mathcal{H}$$

$$y_L \bar{q}_L H \Psi_R + y_R f \bar{t}_R \Psi_L$$

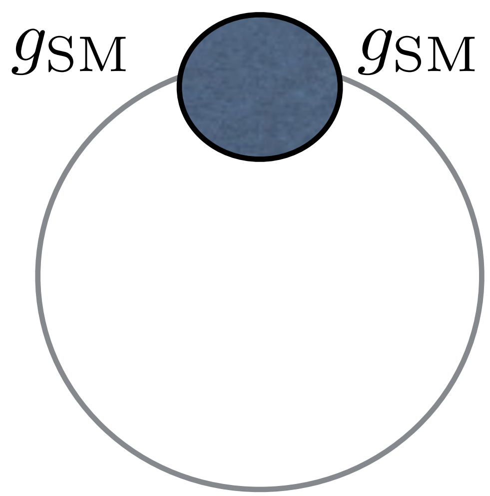


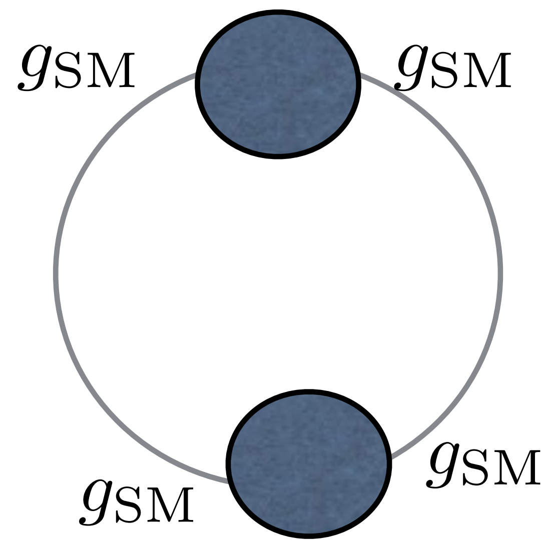
$$\frac{y_L y_R f}{M_\Psi} \bar{q}_L \tilde{H} t_R$$

$$y_t \sim \frac{y_L y_R}{g_*}$$

Light Higgs wants Light top partners

$$V(h) = \frac{N_c m_*^4 y_t^2}{16\pi^2 g_*^2}\left(-a\frac{h^2}{f^2} + \frac{b}{2}\frac{h^4}{f^4} + \frac{c}{3!}\frac{h^6}{f^6}\right)$$





$$v \sim f\sqrt{\frac{a}{b}}$$

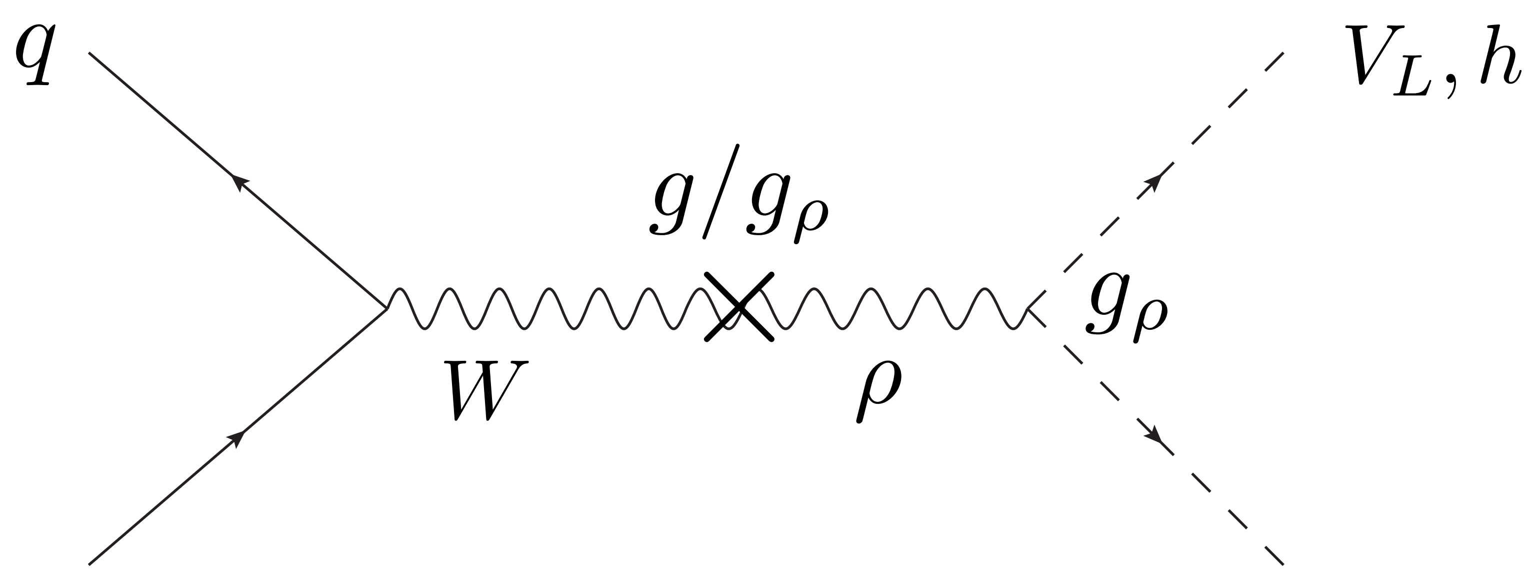
$$m_* \sim \frac{450\mathrm{GeV}}{\sqrt{a}}$$

$$\xi = \frac{v^2}{f^2}$$

Measure the fine-tuning

D.M, M.S &J.S '12; A.P & F.R '12
O.M, G.P & A.W '12; A.D.S, O.M, R.R & A.W '12

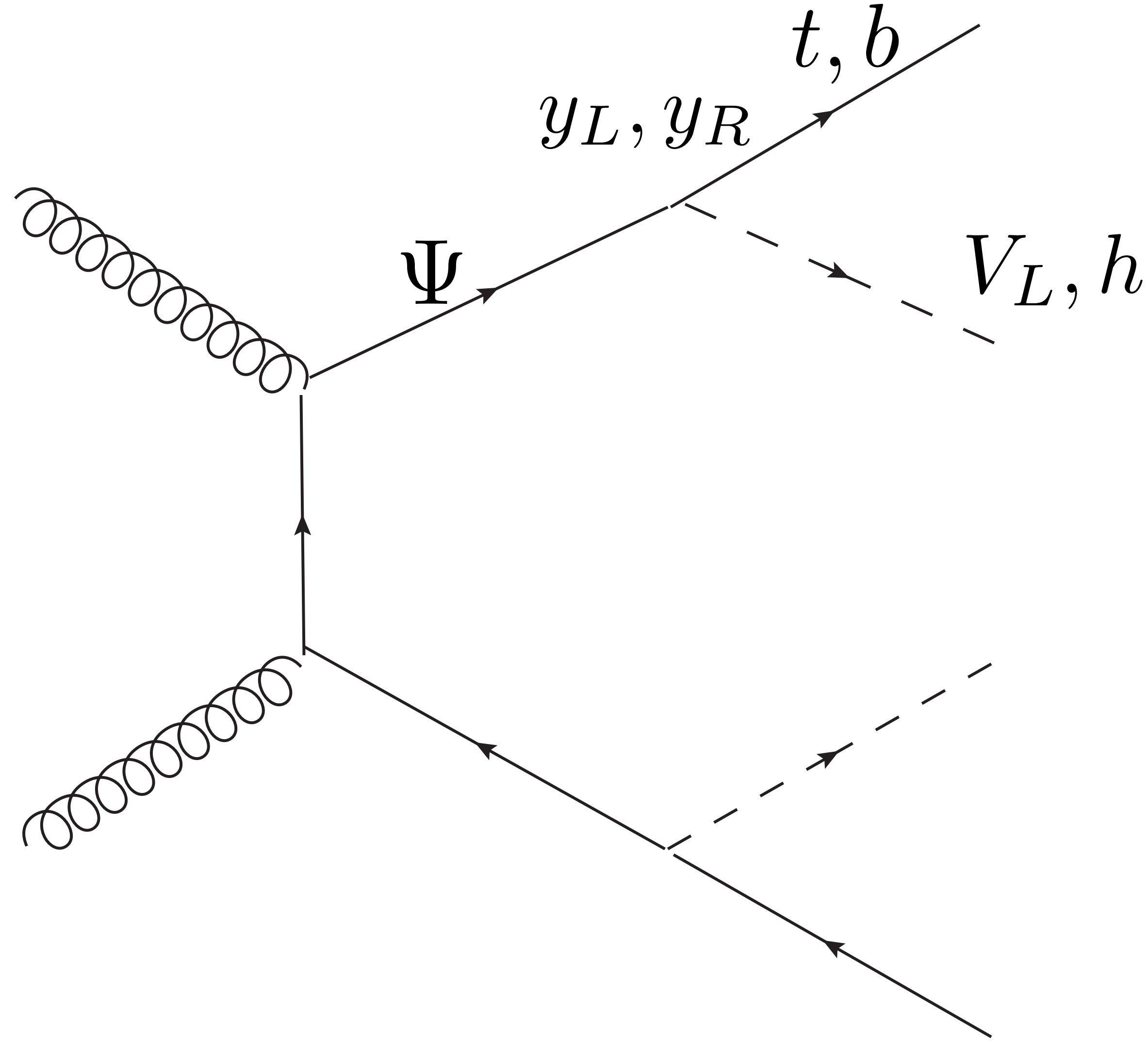
Direct searches: Spin-1



Dibosons provide the smoking gun!

Pappadopulo, Thamm, Torre and Wulzer

Direct searches: spin-1/2

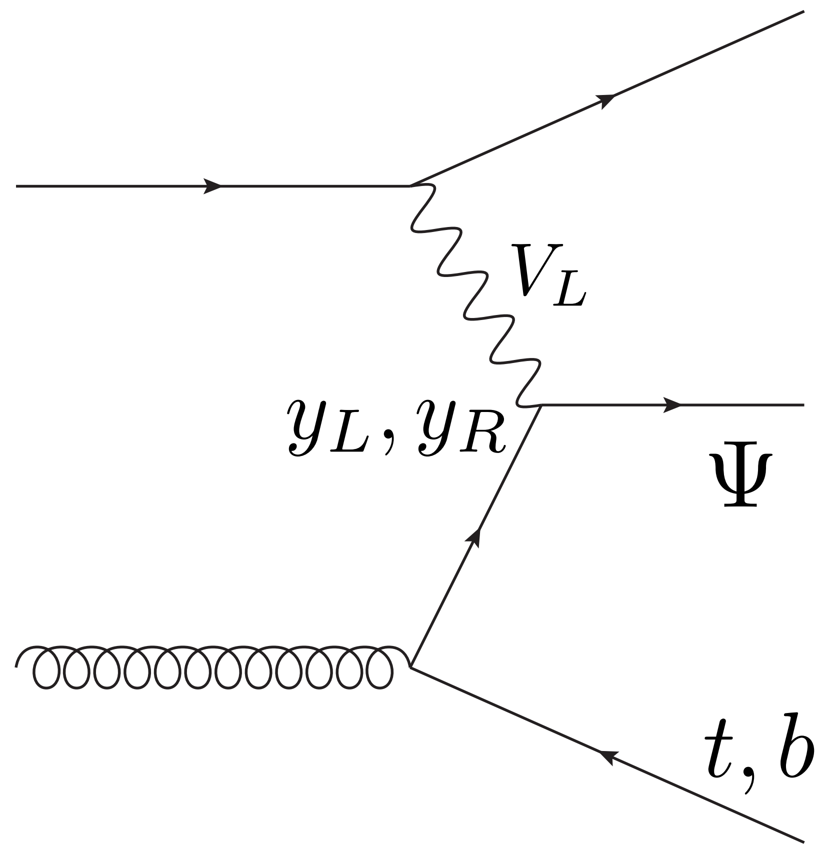


Top partners

$\Psi \equiv X_{5/3}, T, B$

Simone, Matsedonskyi, Rattazzi and Wulzer

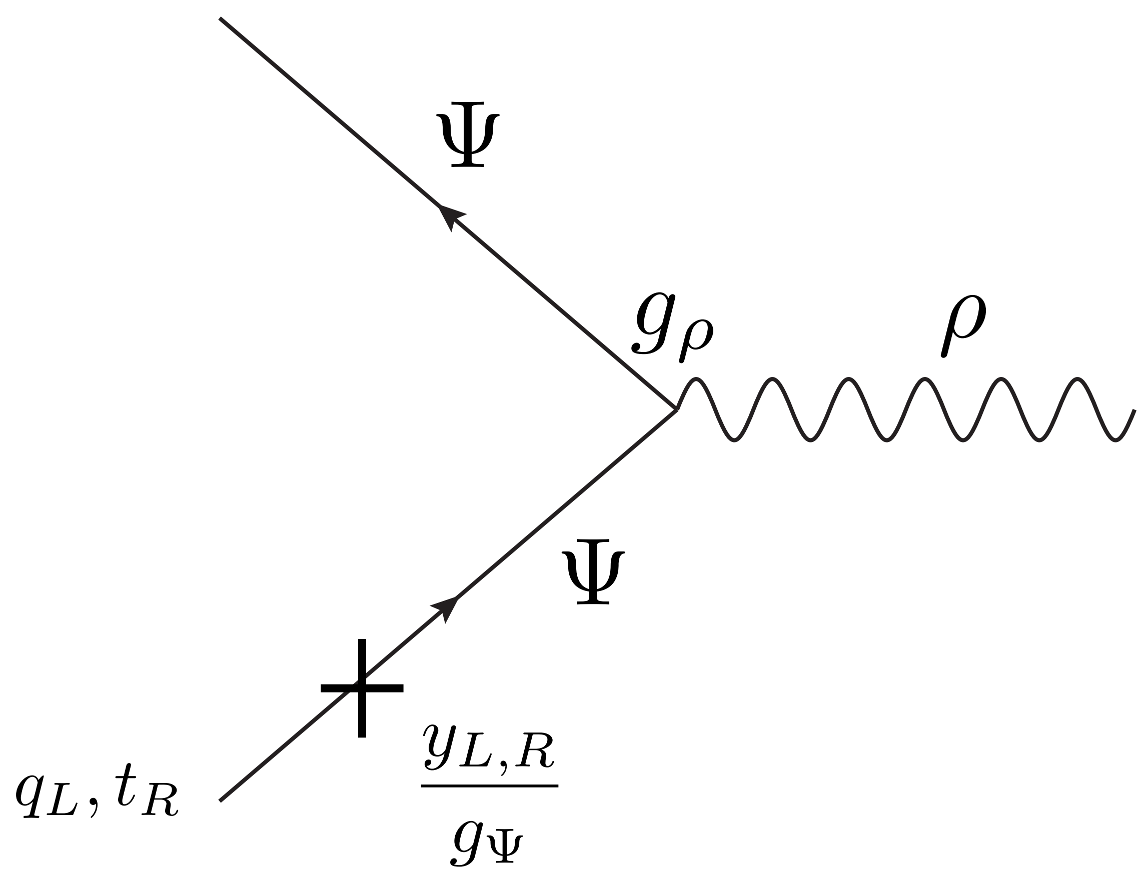
Direct searches: Single production



Lower mass threshold!

Simone, Matsedonskyi, Rattazzi and Wulzer

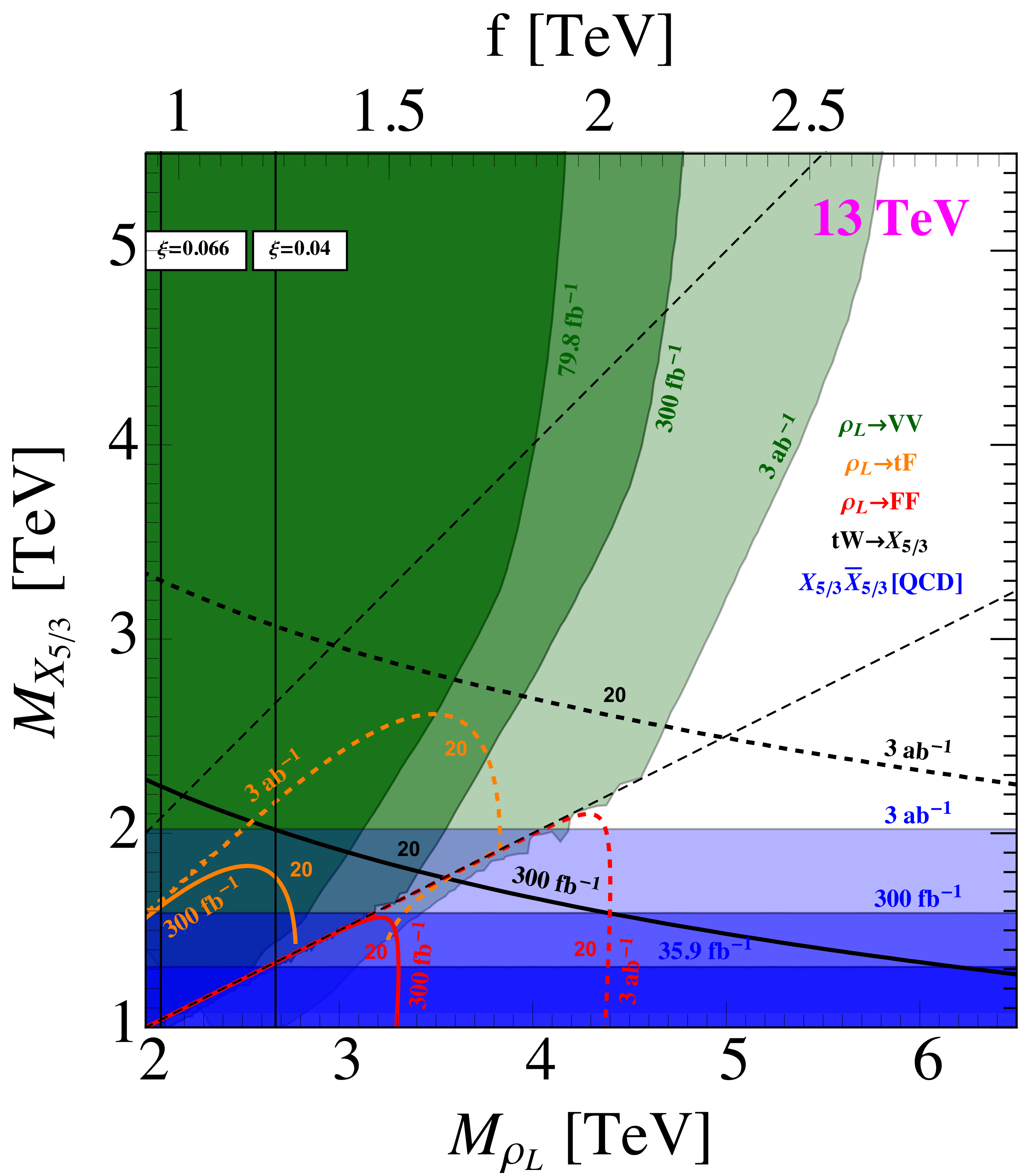
Cascade decays



Have kinematical advantage!

D. Greco and DL '14

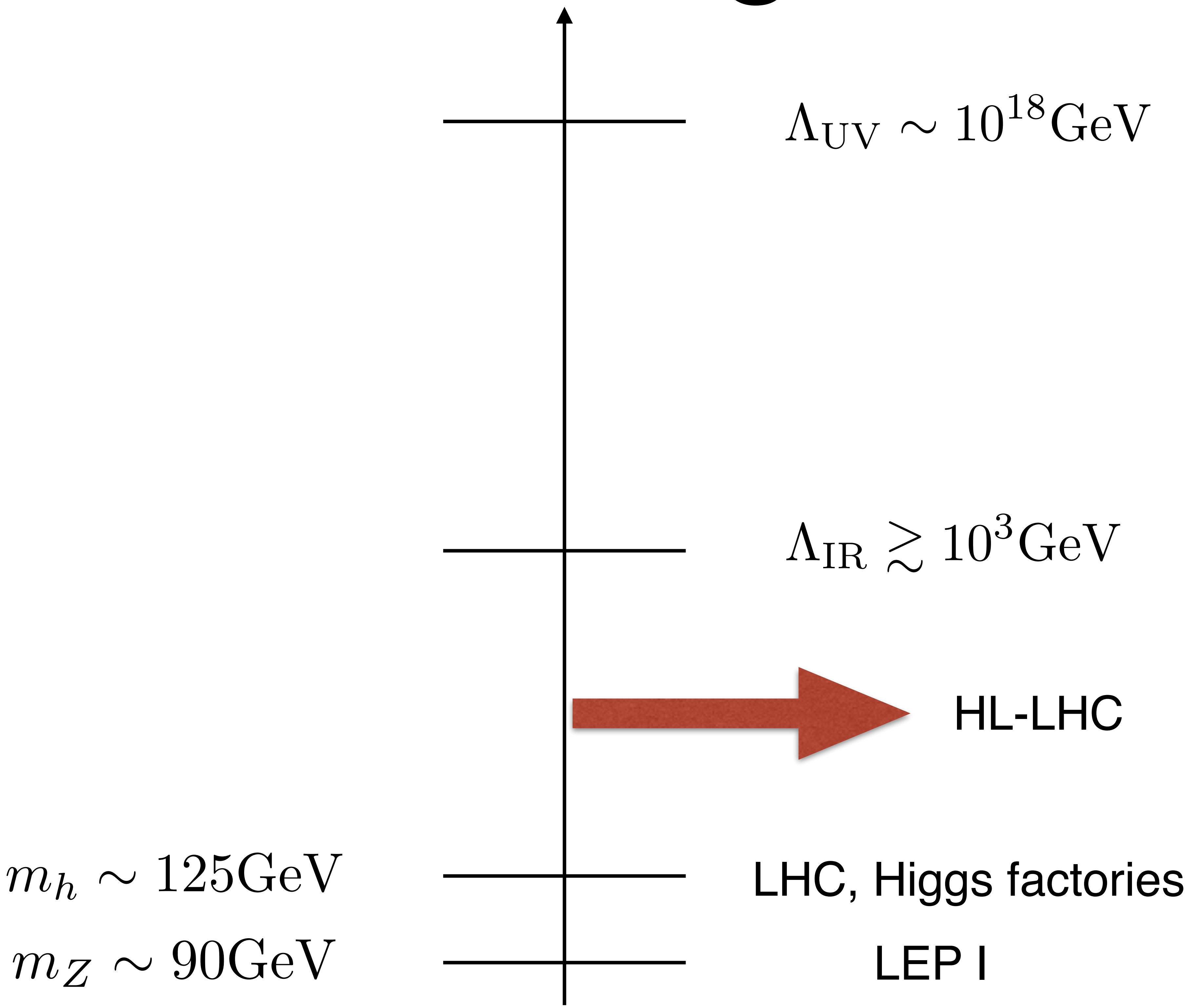
Bounds and Projections



DL, L.T. Wang and K. P. Xie '18

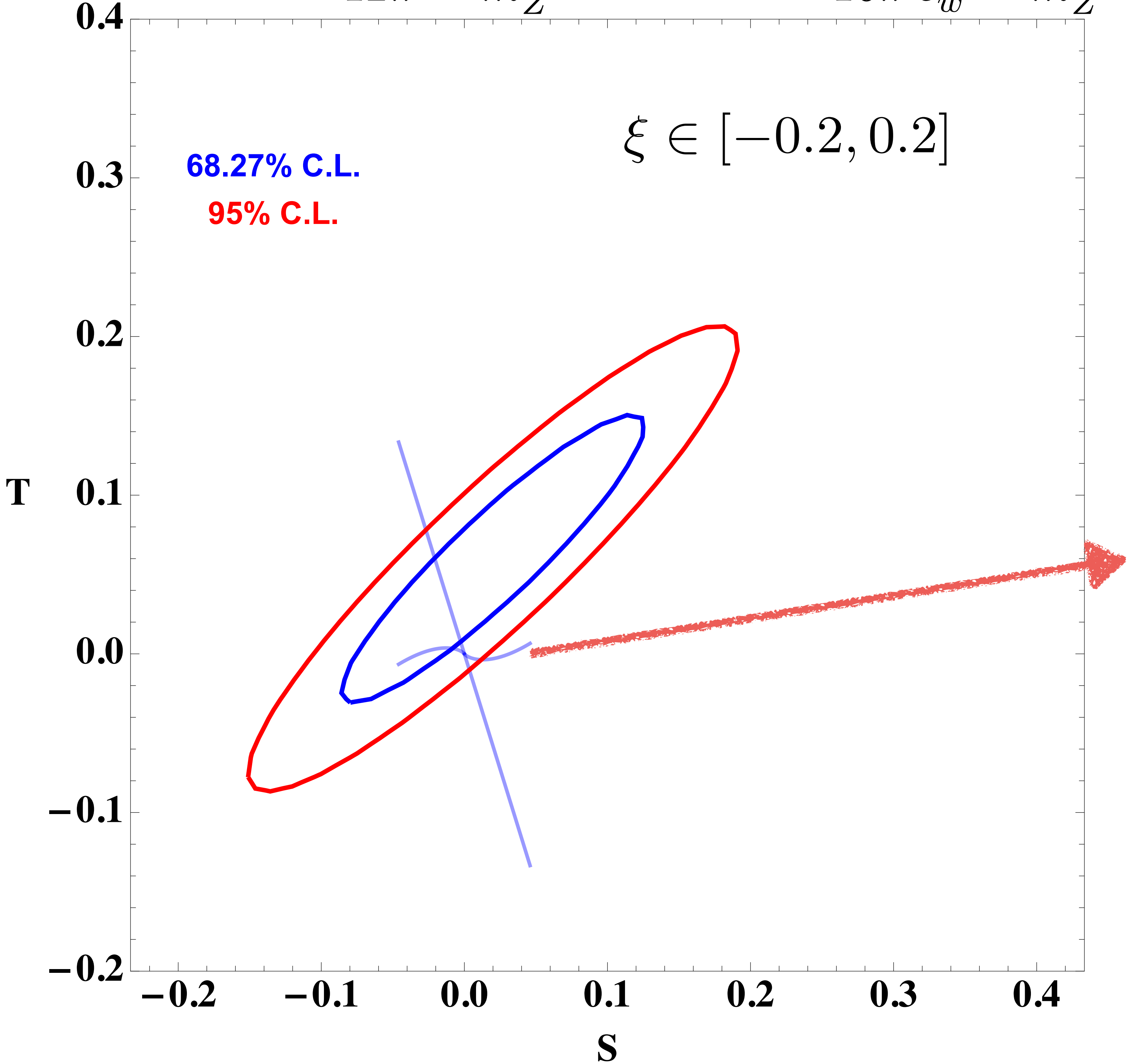
Indirect Signatures

Indirect Signatures



Electroweak Precision Test

$$S_H = \frac{\xi}{12\pi} \ln \frac{\Lambda^2}{m_Z^2}, \qquad T_H = -\frac{3}{16\pi} \frac{\xi}{c_w^2} \ln \frac{\Lambda^2}{m_Z^2}$$



$$\Delta T_f \sim \frac{3y_L^4}{64\pi^2 g_\Psi^2 \alpha_e} \xi$$

Indirect Signature

- Two expansions

$$\frac{H}{f} \qquad \frac{\partial}{m_*} \qquad\qquad m_* \sim g_* f$$

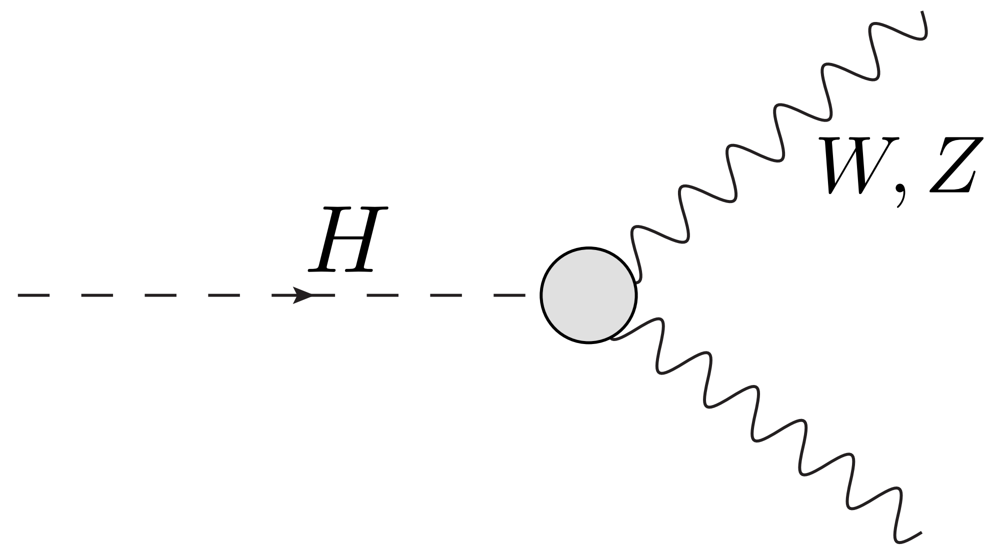
- A set of selection rules

  - Preserve the non-linearity: g_*
  - Explicit breaking

    $$y_f, g, g'$$

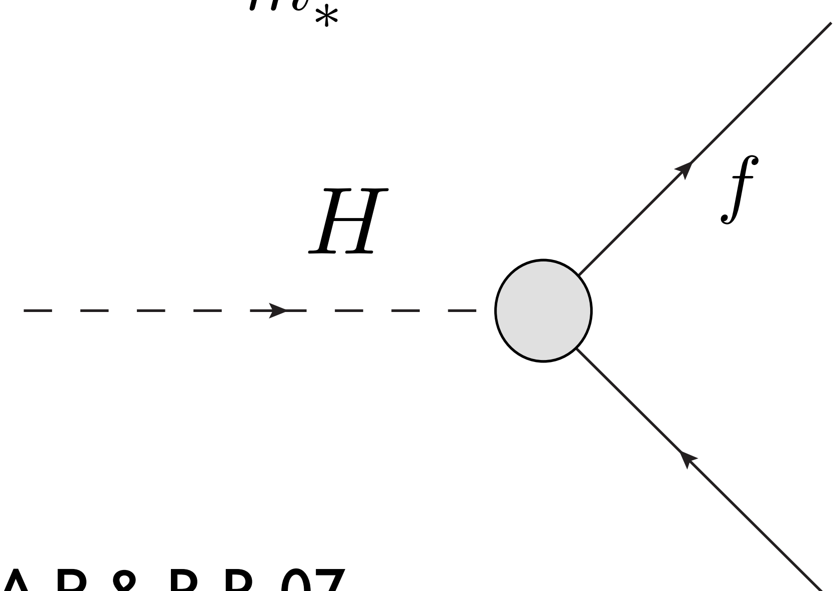
Indirect Signature

$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2m_*^2} \Rightarrow c_H \sim g_*^2$$



$$\sim -g_*^2 \, \frac{v^2}{2m_*^2}$$

$$\mathcal{O}_y = y_f \frac{H^\dagger H}{m_*^2} \bar{f}_L H f_R \Rightarrow c_y \sim g_*^2$$

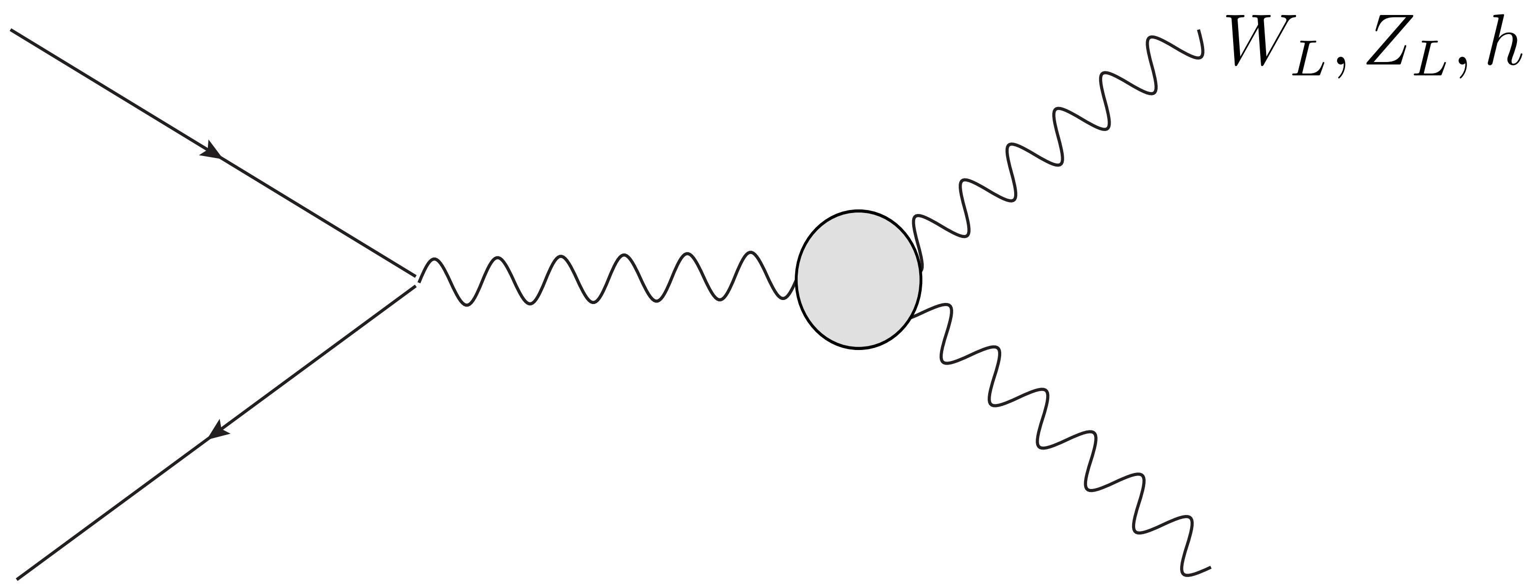


$$\sim -g_*^2 \, \frac{v^2}{2m_*^2}$$

SILH: G.F. G, C. G, A.P & R.R 07

Indirect Signature

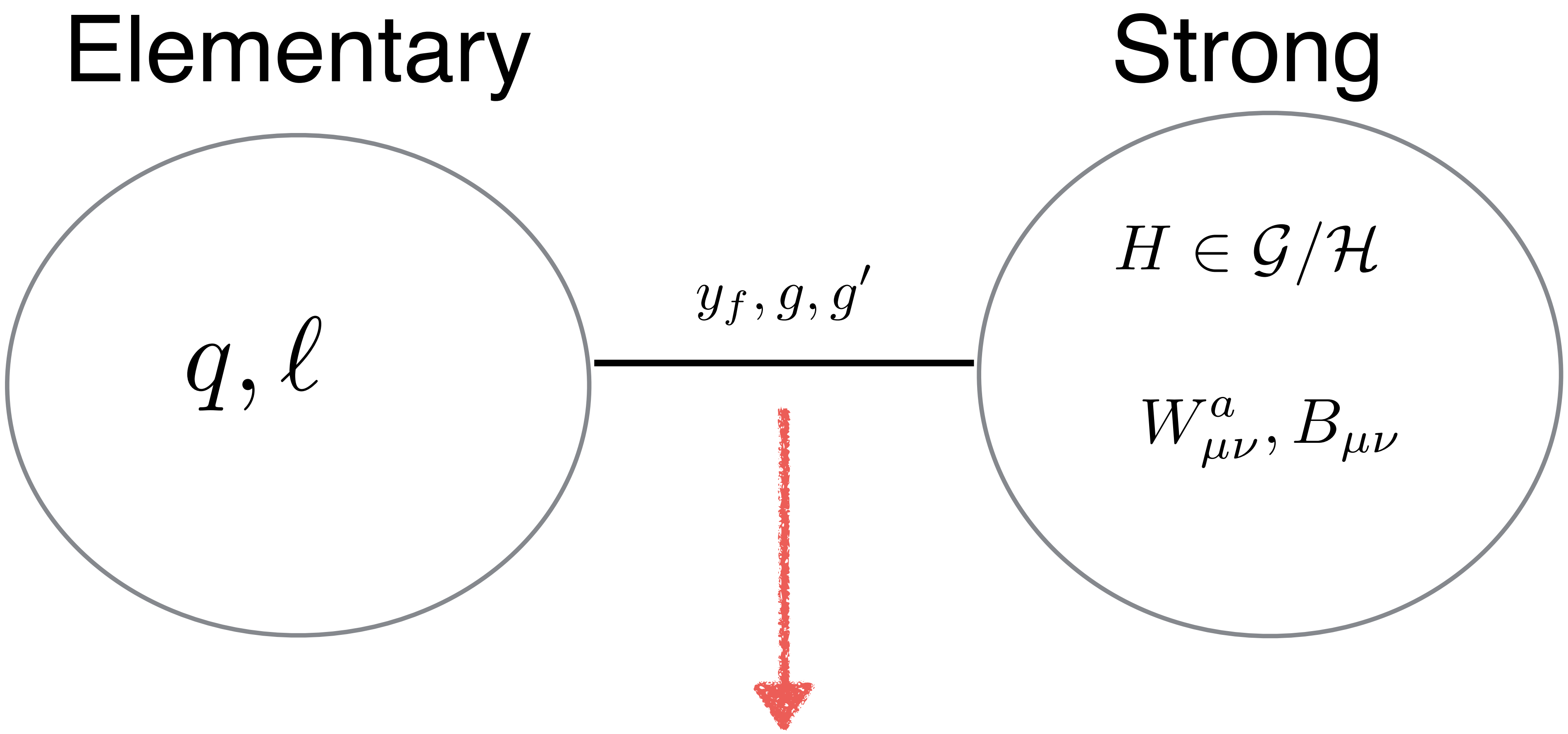
$$\mathcal{O}_W = \frac{ig}{2m_*^2}(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H) D^\nu W^a_{\mu\nu} \Rightarrow c_W \sim 1$$



$$\sim \frac{E^2}{m_*^2}$$

HL-LHC can play a role!

Strong multipole interactions



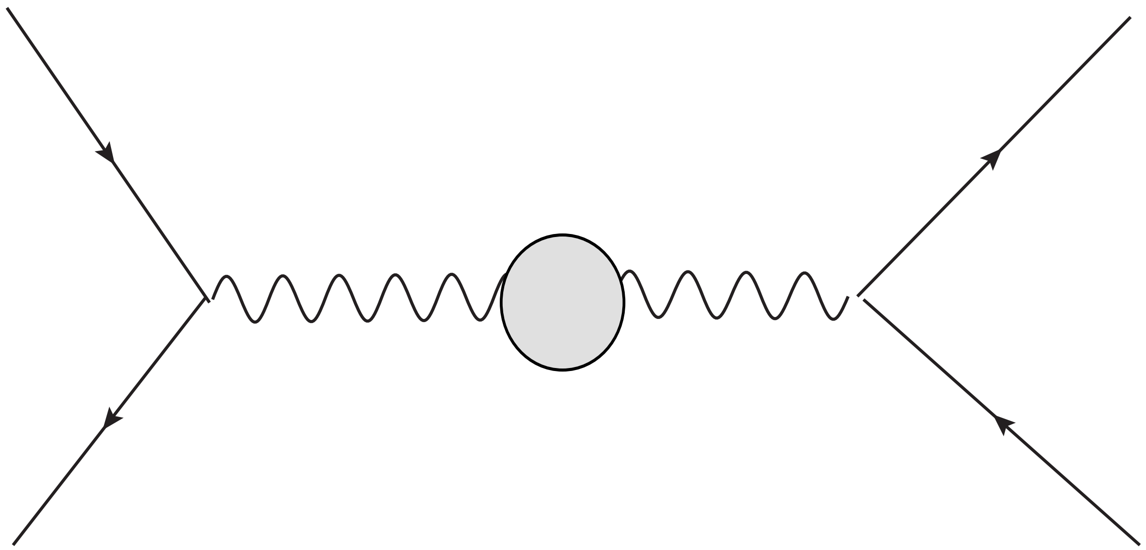
- New power-counting rules

$$W^a_{\mu\nu}, B_{\mu\nu} \,:\, g_*$$

DL, A. Pomarol, R. Rattazzi & F. Riva 16

Strong multipole interactions

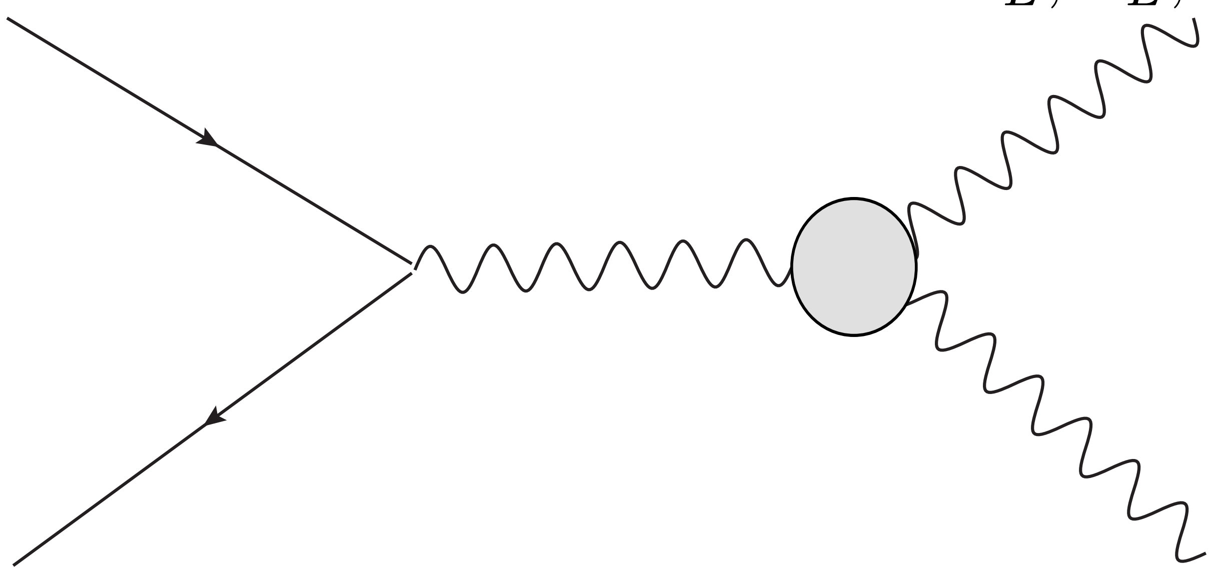
$$\mathcal{O}_{2W} = -\frac{1}{2m_*^2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu} \Rightarrow c_{2W} \sim \frac{g^2}{g_*^2} \qquad c_{2W} \sim 1$$



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

Strong multipole interactions

$$\mathcal{O}_{HW} = \frac{ig}{m_*^2}(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \Rightarrow c_{HW} \sim \frac{g_*^2}{16\pi^2}, \quad 1 \qquad \frac{g_*}{g}$$



$$\frac{g_*^2}{16\pi^2}\frac{E^2}{m_*^2} \qquad \frac{E^2}{m_*^2} \qquad \frac{g_*}{g}\frac{E^2}{m_*^2}$$

Mass scale reach HL-LHC

Model	Di-boson	S-parameter	LHC $h \to Z\gamma$	LHC $h \to \gamma\gamma$	LHC dilepton
SILH	4.0	2.5	$1.7\sqrt{\frac{g_*}{4\pi}}$	0.34	$0.69\sqrt{\frac{4\pi}{g_*}}$
Remedios	$10.6\sqrt{\frac{g_*}{4\pi}}$				13.4
Remedios+MCHM	$10.6\sqrt{\frac{g_*}{4\pi}}$	2.5	1.7	6.5	13.4
Remedios+$ISO(4)$	$17.6\sqrt{\frac{g_*}{4\pi}}$	2.5	$7.5\sqrt{\frac{g_*}{4\pi}}$	6.5	13.4

- Precision measurement at the HL-LHC will be very promising.
- A lot of data can make a big difference here!

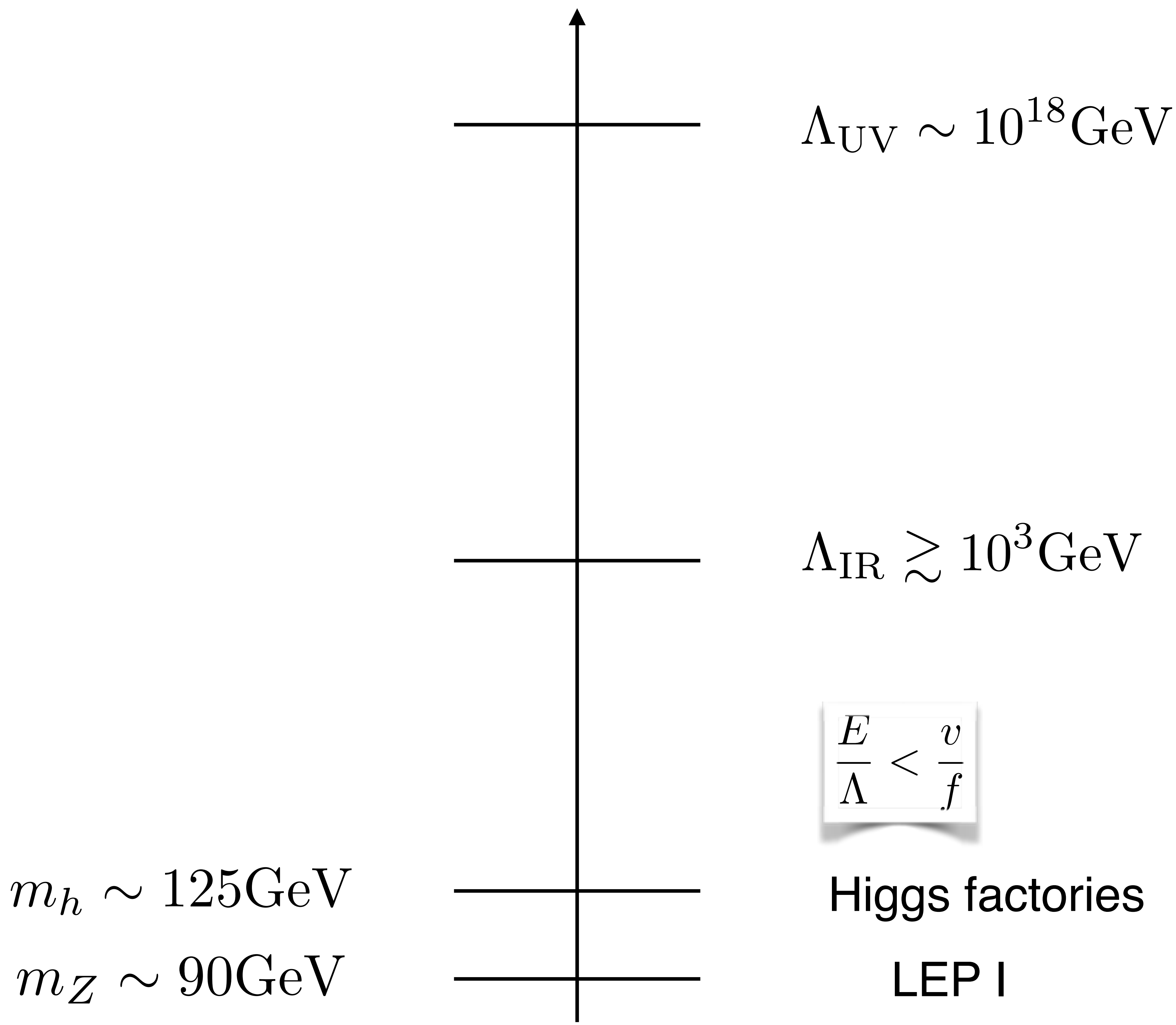
DL and L.T.Wang '18

see also R. Franceschini et al

Dilepton: M. Farina et al

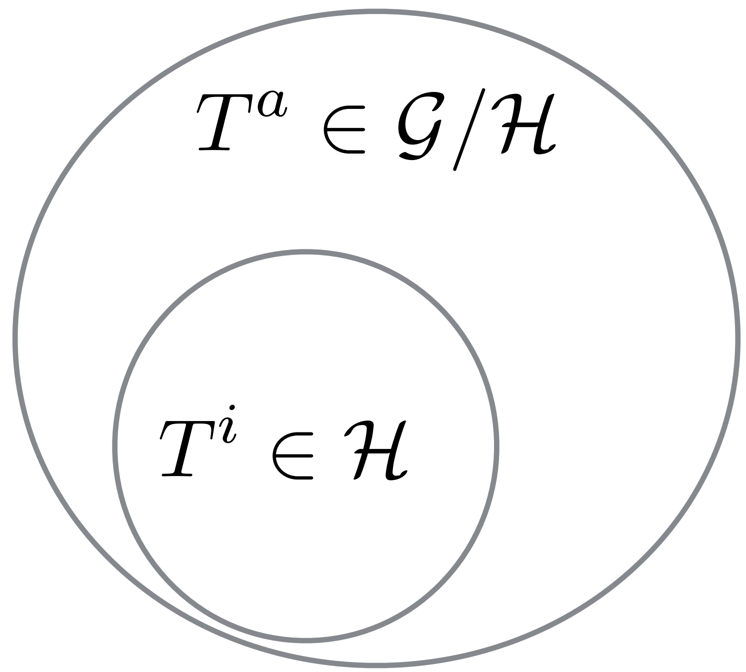
Beyond the LHC

Future lepton colliders



More from Higgs non-linearity

CCWZ



$$U = e^{i\frac{\pi^a}{f}T^a}$$

$$U \to gUh^\dagger(\pi^a(x))$$

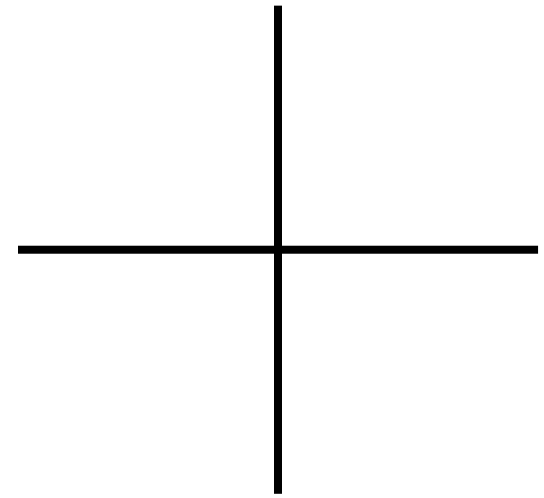
$$-iU^\dagger\partial_\mu U = d^a_\mu T^a + E^i_\mu T^i$$

$$d_\mu \to h(x)d_\mu h(x)^\dagger, \qquad E_\mu \to h(x)E_\mu h(x)^\dagger - ih(x)\partial_\mu h(x)^\dagger$$

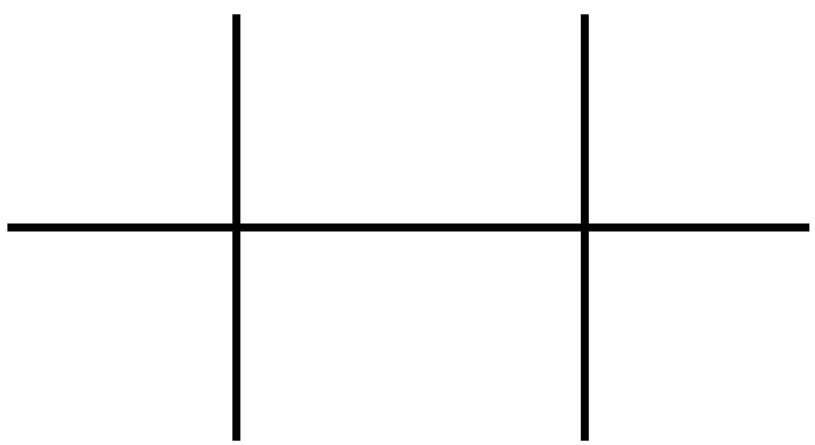
$$\mathcal{L}_2 \propto f^2\mathrm{Tr}[d_\mu d^\mu]$$

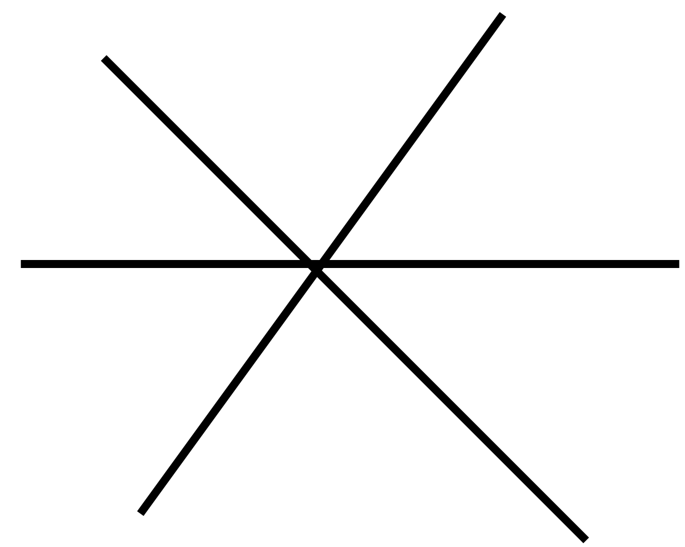
Soft bootstrap

Starting Point



$\partial^2\phi^2 F(\partial^\rho\phi)$



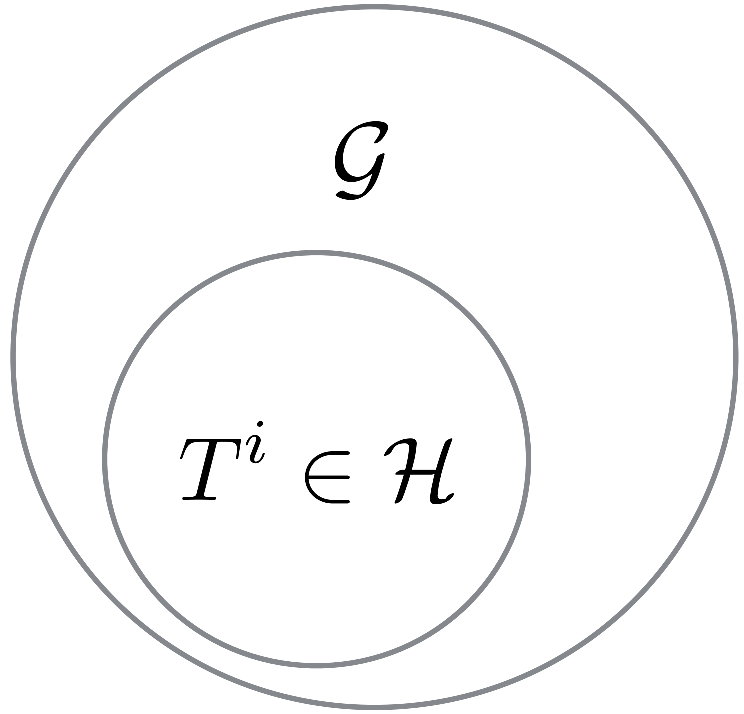


$$\lim_{p_i\to 0}\mathcal{A}_n(p_1,\cdots,p_n)=\mathcal{O}(p_i^\sigma)$$

$$\rho=0,\quad \sigma=1: \qquad \mathrm{NLSM}$$

C. Cheung, K. Kampf, J. Novotny, C.H. Shen and J. Trnka 16

Soft bootstrap



$$\mathcal{T}_{ab} = \frac{2}{f^2} T^i_{ac} T^i_{db} \pi^c \pi^d$$

Adler's zero condition ⟷ **Shift symmetry**

$$\pi^{a\,\prime} = \pi^a + [F_1(\mathcal{T})]_{ab}\ \epsilon^b\ , \quad [F_1(0)]_{ab} = \delta^{ab}$$

I. Low:1412.2145,1412.2146

Soft bootstrap

- Finding the covariant objects

$$d_\mu^a(\pi,\partial) = \frac{\sqrt{2}}{f}[F_2(\mathcal{T})]_{ab}\,\partial_\mu\pi^b \ , \quad E_\mu^i(\pi,\partial) = \frac{2}{f^2}\partial_\mu\pi^a[F_4(\mathcal{T})]_{ab}\,(T^i\pi)^b$$

- The solution is unique

$$F_1(\mathcal{T}) = \sqrt{\mathcal{T}}\cot\sqrt{\mathcal{T}}, \qquad F_2(\mathcal{T}) = \frac{\sin\sqrt{\mathcal{T}}}{\sqrt{\mathcal{T}}}, \qquad F_4(\mathcal{T}) = -\frac{2i}{\mathcal{T}}\sin^2\frac{\sqrt{\mathcal{T}}}{2}$$

I. Low:1412.2145,1412.2146

$\mathcal{O}(p^4)$ Lagrangian $SO(5)/SO(4)$

$$-iU^\dagger \partial_\mu U = d_\mu^a T^a + E_\mu^i T^i$$

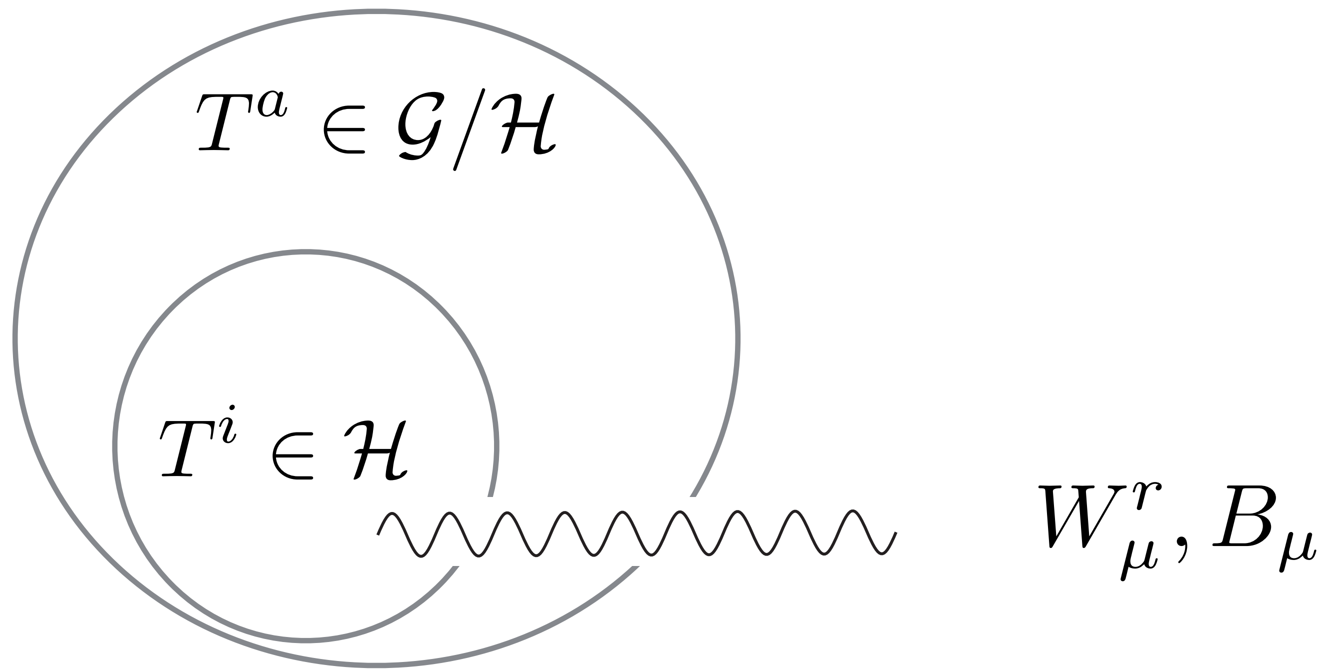
$$O_1 = \left(d_\mu^a d^{\mu a}\right)^2 \qquad O_2 = (d_\mu^a d_\nu^a)^2$$

$$O_3 = \left[\left(E_{\mu\nu}^L\right)^r\right]^2 - \left[\left(E_{\mu\nu}^R\right)^r\right]^2$$

$$\vdots \quad \vdots \quad \vdots$$

A set of unknown Wilson coefficients

More from Higgs non-linearity

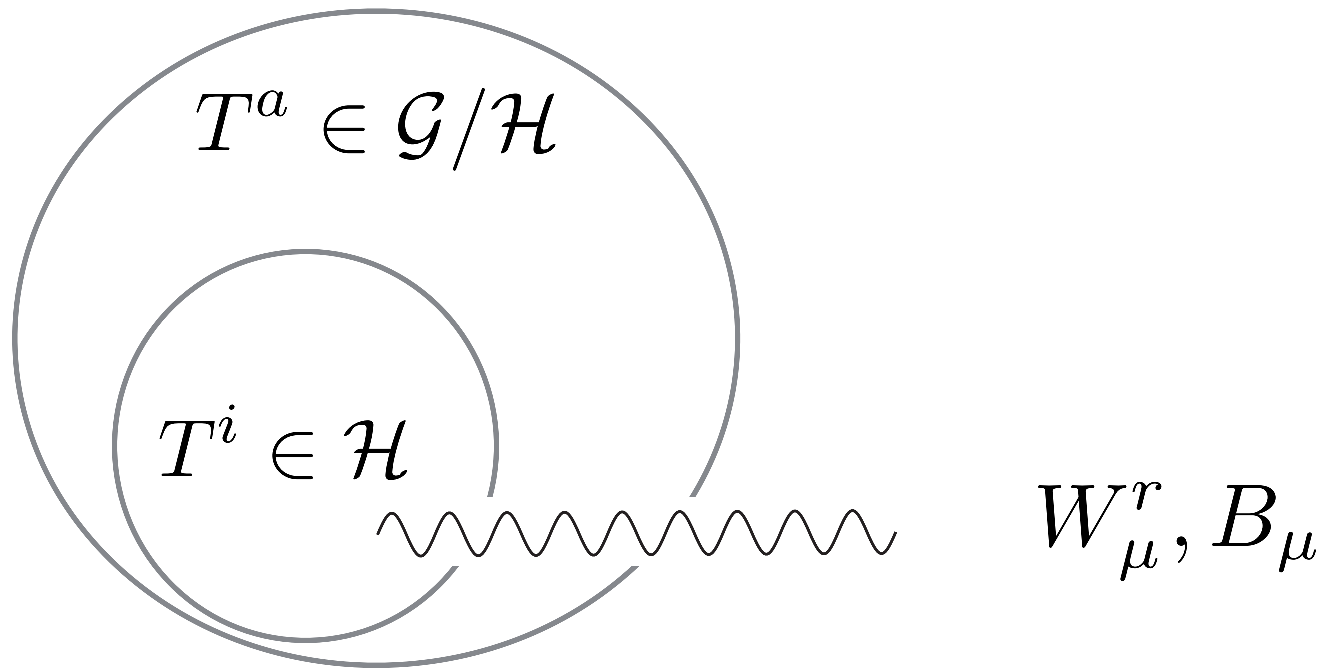


$$\partial_\mu \to \partial_\mu - igW^r_\mu T^{rL} - ig' B_\mu T^{3R}$$

$$d^a_\mu = \delta^{a4}\sqrt{2}\frac{\partial_\mu h}{f} + \frac{\delta^{ar}}{\sqrt{2}}\boxed{\sin(\theta + h/f)}(W^r_\mu - \delta^{r3} B_\mu)$$

Signs of Higgs non-linearity

More from Higgs non-linearity

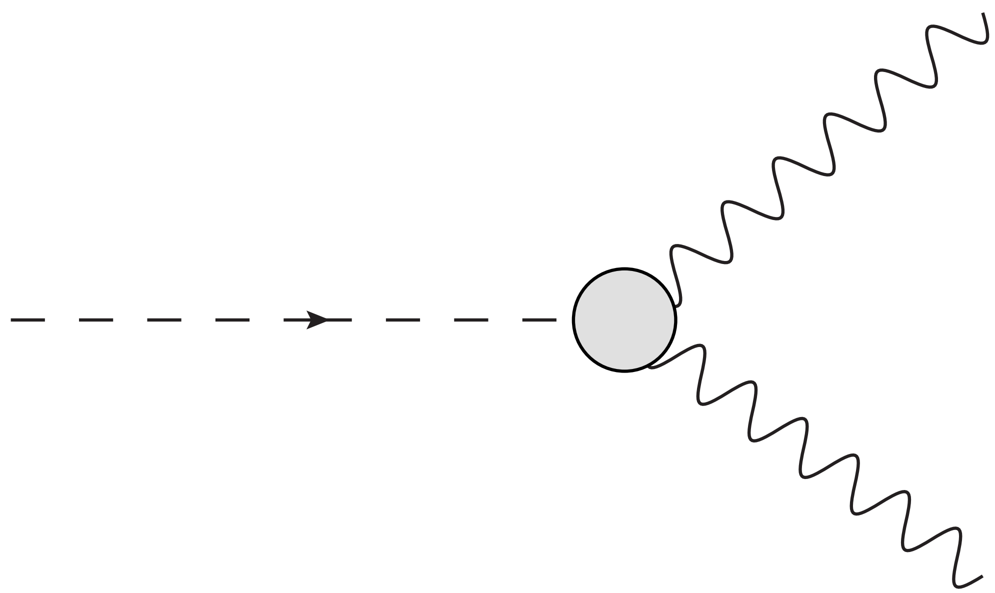


$$\partial_\mu \to \partial_\mu - igW_\mu^r T^{rL} - ig' B_\mu T^{3R}$$

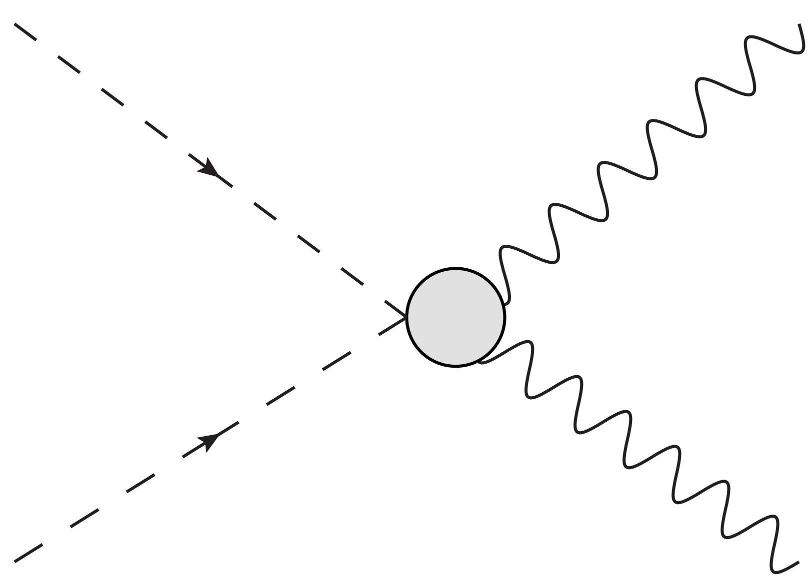
$$(E_\mu^{L/R})^r = \frac{1 \pm \cos(\theta + h/f)}{2} W_\mu^r + \frac{1 \mp \cos(\theta + h/f)}{2} B_\mu \delta^{r3}$$

Signs of Higgs non-linearity

Prediction from Higgs non-linearity



$$2a\frac{h}{v}\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)$$

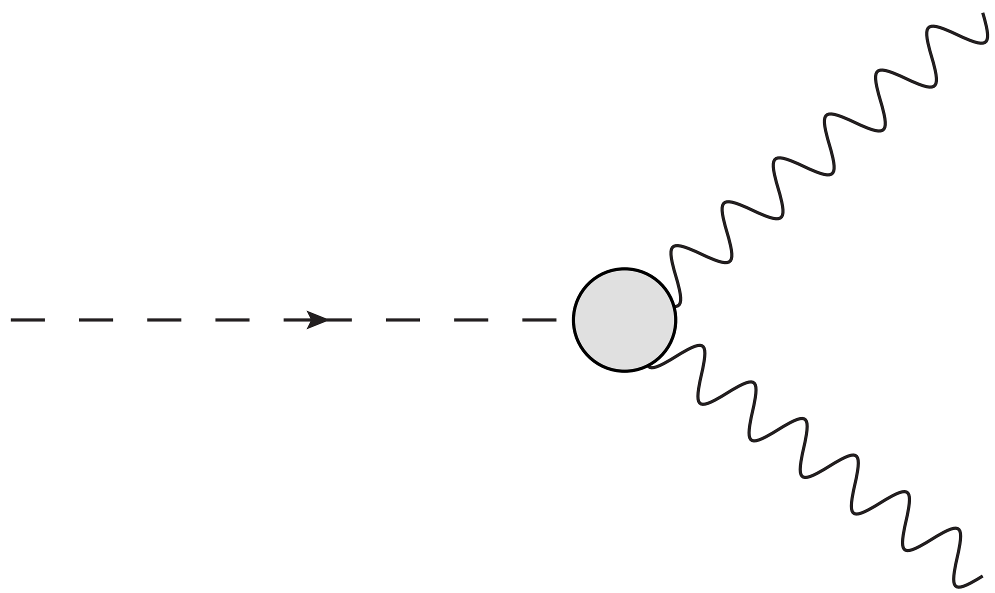


$$b\frac{h^2}{v^2}\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)$$

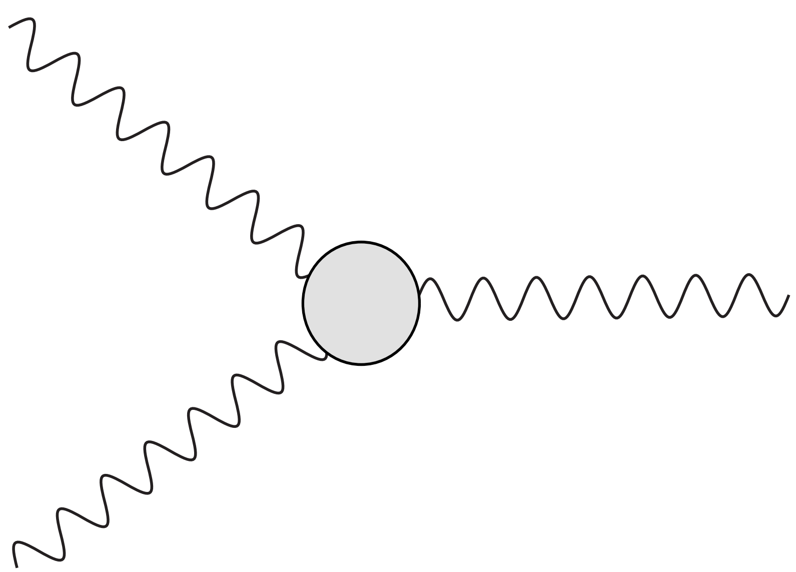
	SMEFT	Non-linearity
$\frac{1-b}{4(1-a)}$	1	$\frac{\xi}{2(1-\sqrt{1-\xi})} \sim 1 - \frac{1}{4}\xi$

D. Liu, I. Low and Z. Yin '18

Predictions from Higgs non-linearity



$$C_2^h \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu} \qquad C_4^h \frac{h}{v} Z_{\mu\nu} A^{\mu\nu}$$



$$\delta\kappa_\gamma ie W_\mu^+ W_\nu^- A^{\mu\nu}$$

	SMEFT	Non-linearity
$\dfrac{2c_w^2\, C_2^h - c_{2w}\, C_4^h/t_w}{\delta\kappa_\gamma}$	1	$\cos\theta = \sqrt{1-\xi}$

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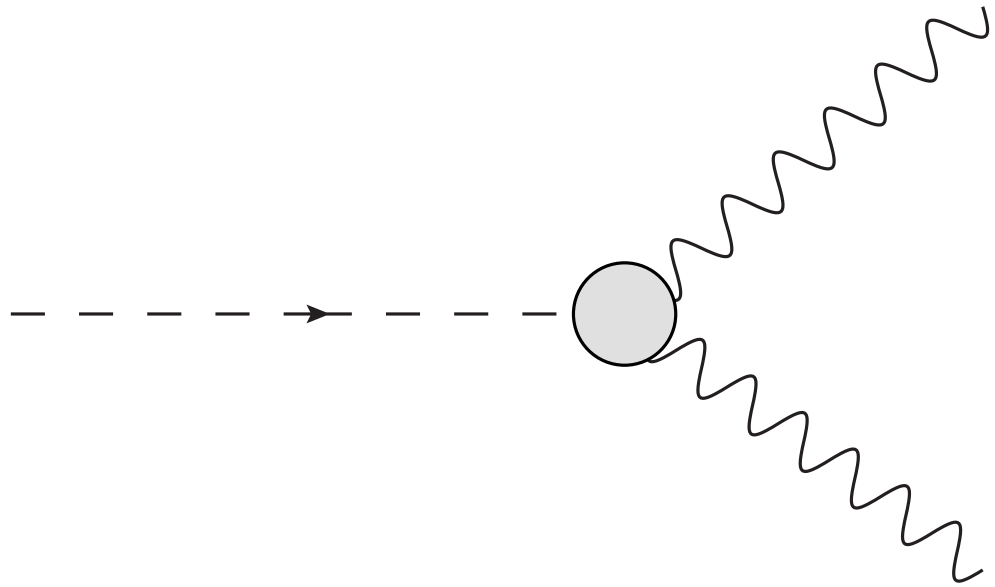
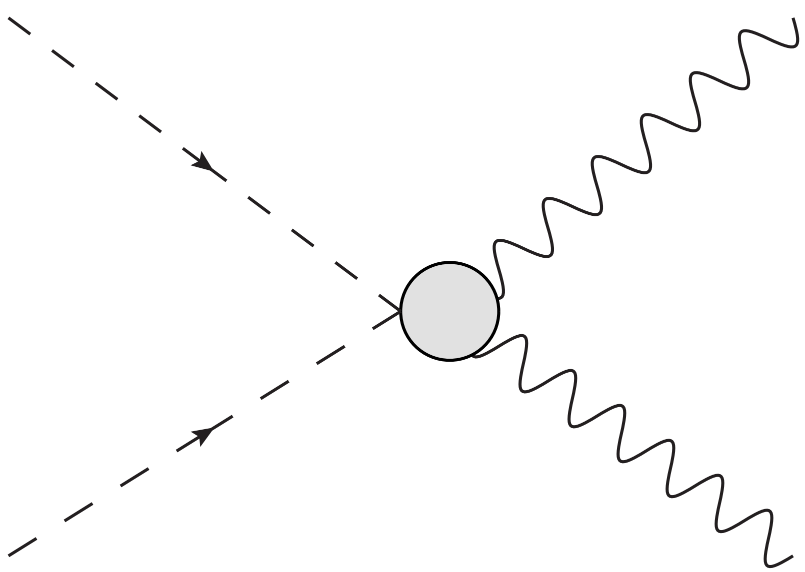
Prediction from Higgs non-linearity



$$C_3^h \frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} A_\nu \qquad C_4^h \frac{h}{v} Z_{\mu\nu} A^{\mu\nu}$$



$$C_3^{2h} \frac{h^2}{v^2} Z_\mu \mathcal{D}^{\mu\nu} A_\nu \qquad C_4^{2h} \frac{h^2}{v^2} Z_{\mu\nu} A^{\mu\nu}$$

		SMEFT	Non-linearity
$\frac{2C_3^{2h}}{C_3^h}$	$\frac{2C_4^{2h}}{C_4^h}$	1	$\cos\theta = \sqrt{1-\xi}$

D. Liu, I. Low and Z. Yin '18

Conclusion

- Compositeness is an elegant way to address the hierarchy problem.
- Resonance searches and precision measurement are both important.
- Higgs non-linearity predicts universal relations, can be probed in the future electron collider.

Back-up Slides

Effective Operators

We are focusing on the following dimension-six operators:

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu}, \qquad \mathcal{O}_{2B} = -\frac{1}{2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu}$$

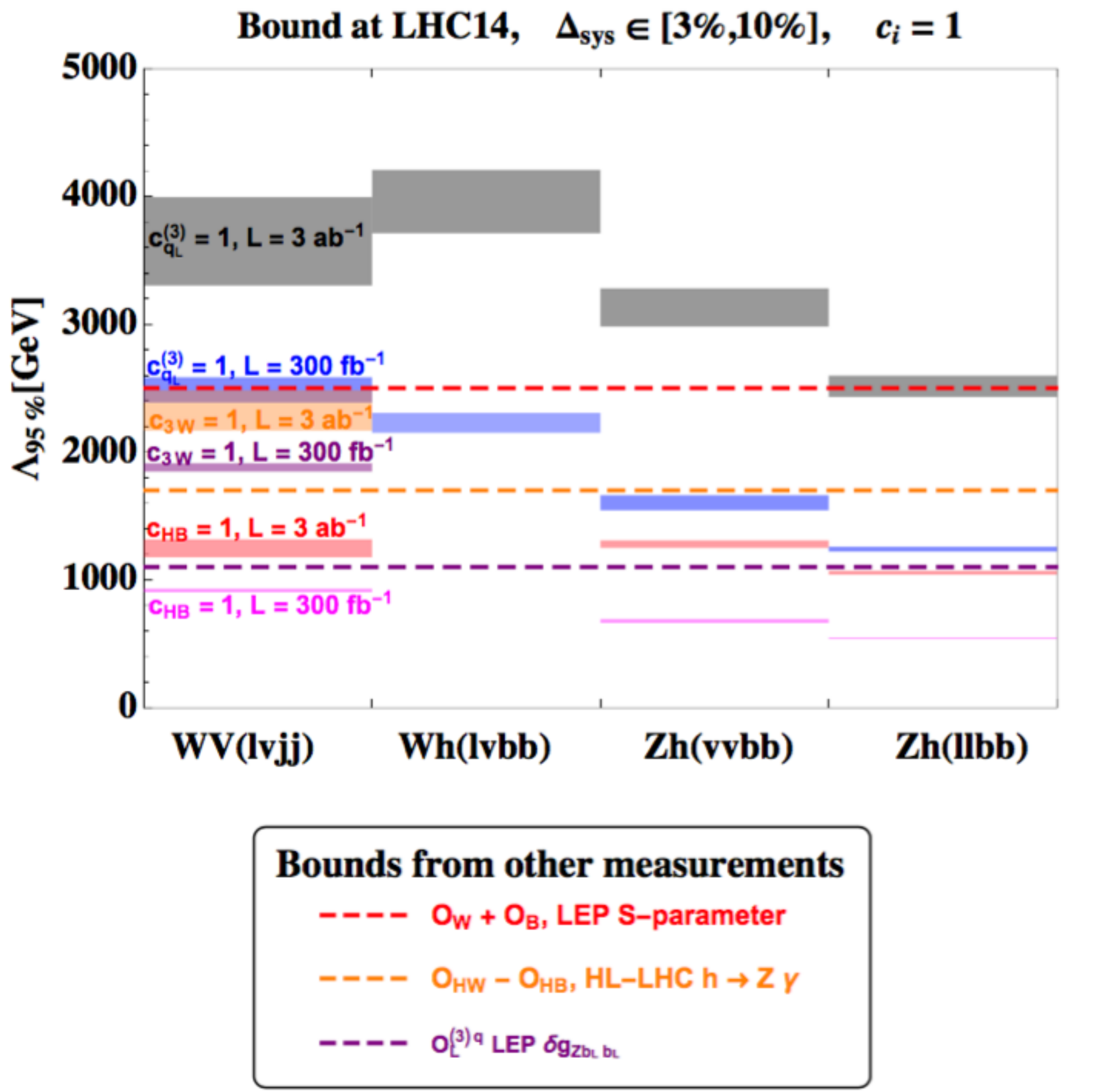
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}, \qquad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_{\mu} W^b_{\nu\rho} W^{c\rho\mu}, \qquad \mathcal{O}_T = \frac{g^2}{2}(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu) H$$

$$\mathcal{O}^u_R = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R, \qquad \mathcal{O}^d_R = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}^q_L = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L, \qquad \mathcal{O}^{(3)q}_L = ig^2 \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$



Bound at LHC14, $\Delta_{sys} \in [3\%,10\%]$, $c_i = 1$
5000
4000
3000
2000
1000
0
$\Lambda_{95\%}$[GeV]
$c^{(3)}_{q_L} = 1$, L = 3 ab^{-1}
$c^{(3)}_{q_L} = 1$, L = 300 fb^{-1}
$c_{3W} = 1$, L = 3 ab^{-1}
$c_{3W} = 1$, L = 300 fb^{-1}
$c_{HB} = 1$, L = 3 ab^{-1}
$c_{HB} = 1$, L = 300 fb^{-1}
WV(lvjj)
Wh(lvbb)
Zh(vvbb)
Zh(llbb)
Bounds from other measurements
$O_W + O_B$, LEP S–parameter
$O_{HW} - O_{HB}$, HL–LHC $h \to Z\gamma$
$O^{(3)q}_L$ LEP $\delta g_{Zb_L b_L}$

Helicity structure for WW

$$q_L\bar{q}_R \to W^+W^-$$

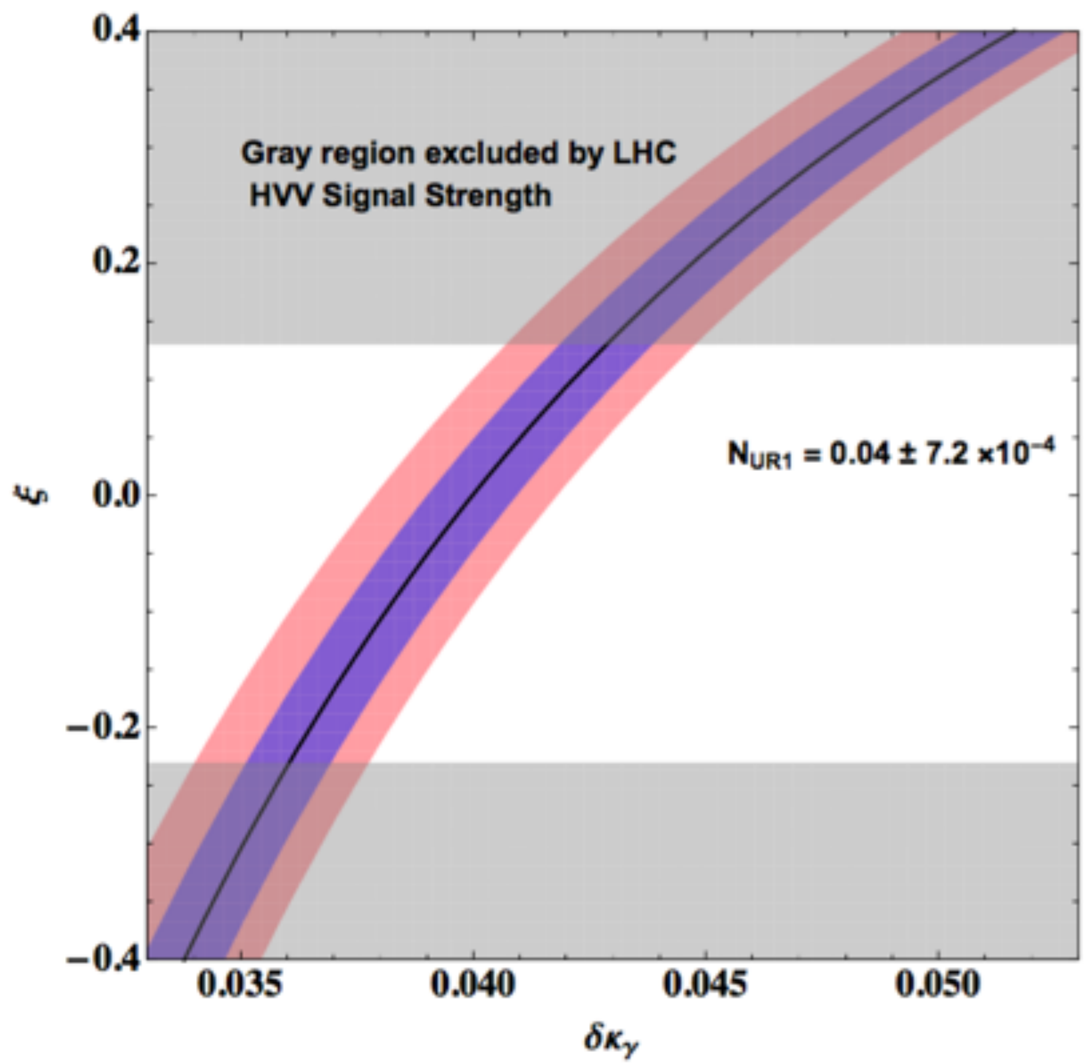
(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_B$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
$(\pm, \mp)$	1	0	0	0	0	0
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{Em_W}{\Lambda^2}$	$\frac{Em_W}{\Lambda^2}$	$\frac{Em_W}{\Lambda^2}$	$\frac{Em_W}{\Lambda^2}$	$\frac{Em_W}{\Lambda^2}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	$\frac{E^2}{\Lambda^2}$

$$q_R\bar{q}_L \to W^+W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_B$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
$(\pm, \mp)$	0	0	0	0	0	0
$(0, 0)$	1	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$	$\frac{Em_W}{\Lambda^2}$	$\frac{Em_W}{\Lambda^2}$	$\frac{Em_W}{\Lambda^2}$	$\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	$\frac{m_W^2}{\Lambda^2}$

$\mathcal{I}_i^h$	$\frac{m_W^2}{m_\rho^2} C_i^h(\text{ILC})$
(1) $h Z_\mu \mathcal{D}^{\mu\nu} Z_\nu / v$	5.83×10^{-4}
(2) $h Z_{\mu\nu} Z^{\mu\nu} / v$	3.93×10^{-4}
(3) $h Z_\mu \mathcal{D}^{\mu\nu} A_\nu / v$	
(4) $h Z_{\mu\nu} A^{\mu\nu} / v$	3.88×10^{-4}

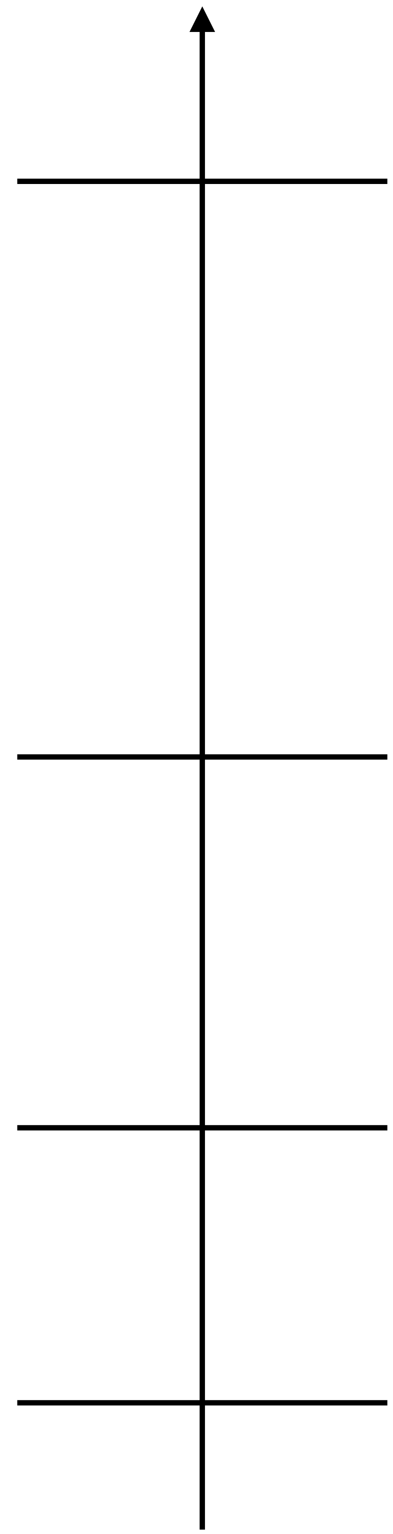
$\mathcal{I}_i^{3V}$	$\frac{m_W^2}{m_\rho^2} C_i^{3V}(\text{ILC})$
$(\delta g_1^Z) i\, g\, c_w W^{+\mu\nu} W_\mu^- Z_\nu + h.c.$	6.1×10^{-4}
$(\delta\kappa_\gamma) i\, e\, W_\mu^+ W_\nu^- A^{\mu\nu}$	6.4×10^{-4}



(a) Measured ξ as a function of $\delta\kappa_\gamma$, using N_{UR1} as an input.

$$\text{UR1} : \frac{N_{\text{UR1}}}{\delta\kappa_\gamma} = \sqrt{1-\xi}\ .$$

Conformal Technicolor



$$\Lambda_{\rm UV} \sim 10^{18}{\rm GeV}$$

$$d_H \sim 1 + \frac{1}{3}$$

$$\Lambda_t \sim \Lambda_{\rm EW} \left(\frac{\Lambda_{\rm EW}}{m_t} \right)^{\frac{1}{d_H - 1}} \sim 1.8 \times 10^4 {\rm TeV}$$

$$\Lambda_{\rm EW} \sim 4\pi v \sim 3.1{\rm TeV}$$

$$m_h \sim 125{\rm GeV}$$

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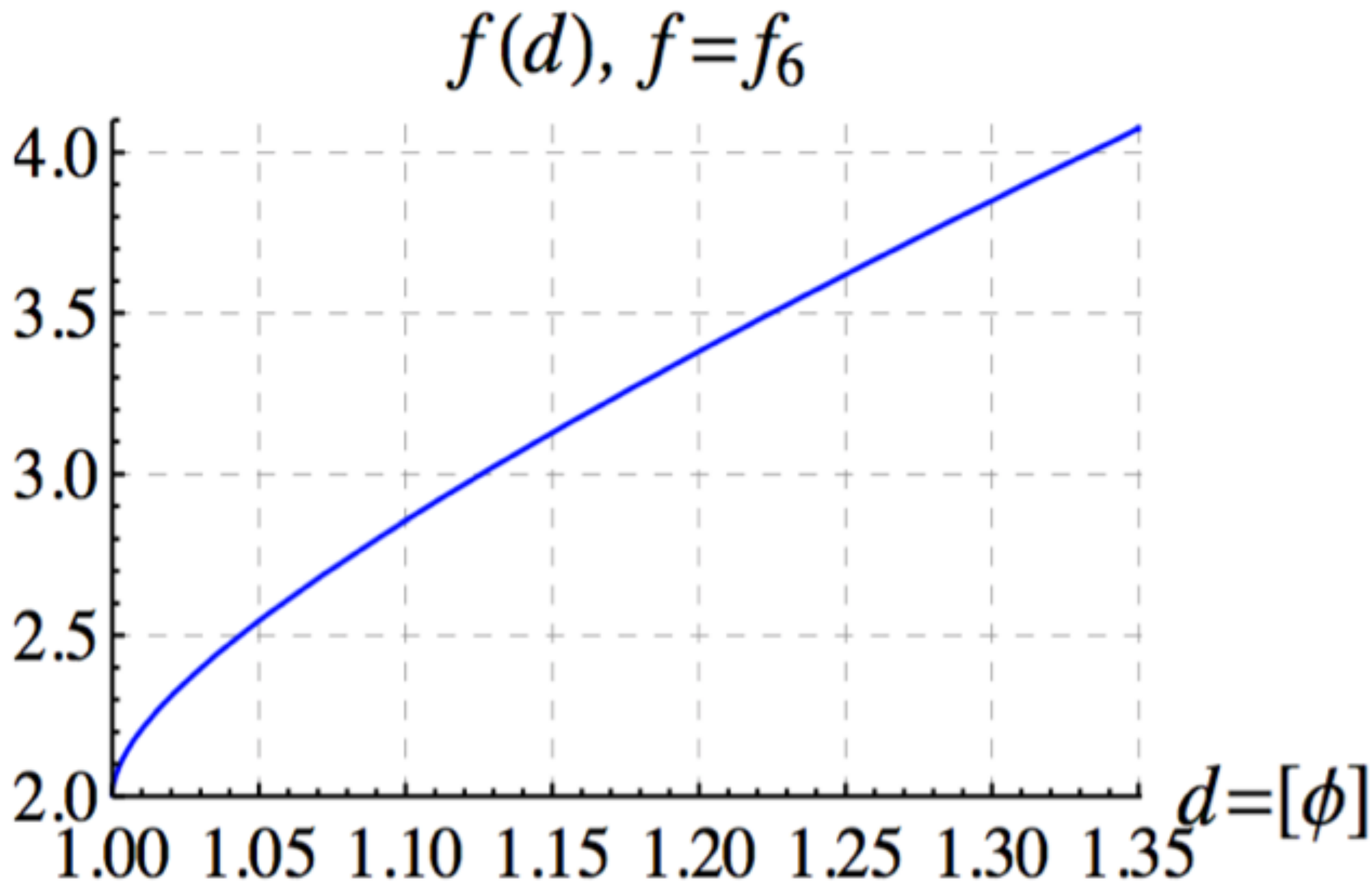

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