The SM EFT & new physics

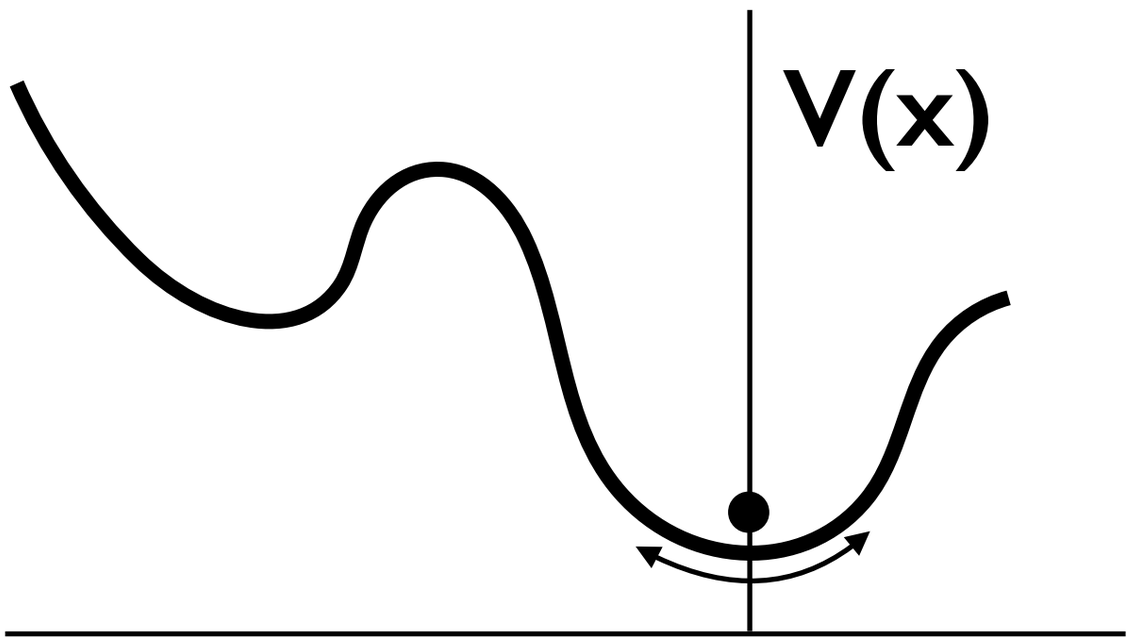
LHC indirect searches for BSM

Alex Pomarol UAB & IFAE (Barcelona)

What's the SM EFT?

Effective Field Theory

Similarly as in Classical mechanics



Expanding around the minimum:

$$V(x) = k\,x^2/2 + \ldots$$

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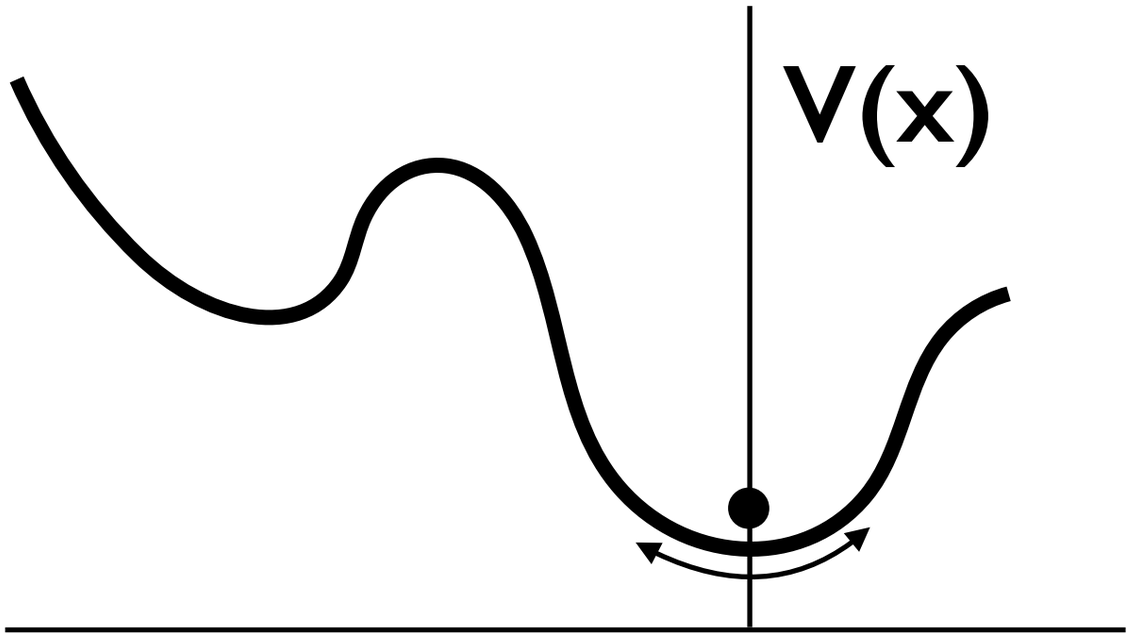


Expanding around the minimum:

$$V(x) = k\,x^2/2 + \ldots$$

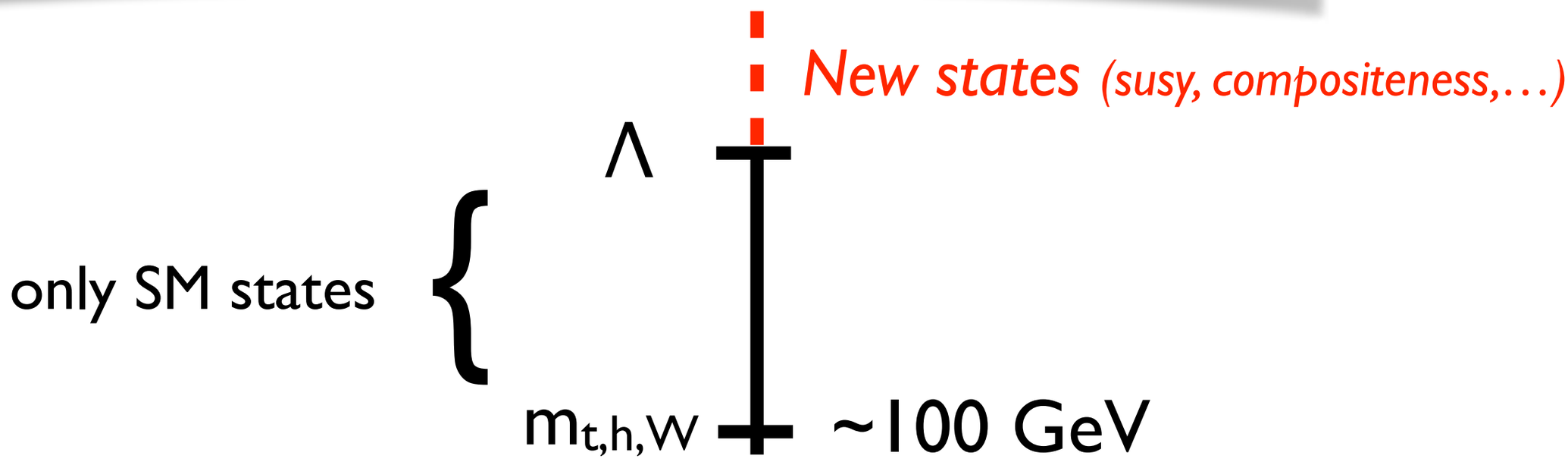
$$\Downarrow$$

universal behaviour:

$$F = -k\,x$$ Hooke's law

(valid only for small oscillations)

Assuming only the SM states below some Λ:



We can then Taylor expand (SM fields and derivative over Λ):

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

dimension-4 terms:

The SM ☛ predictive model *(but not fundamental)*

(e.g. universal gauge couplings)

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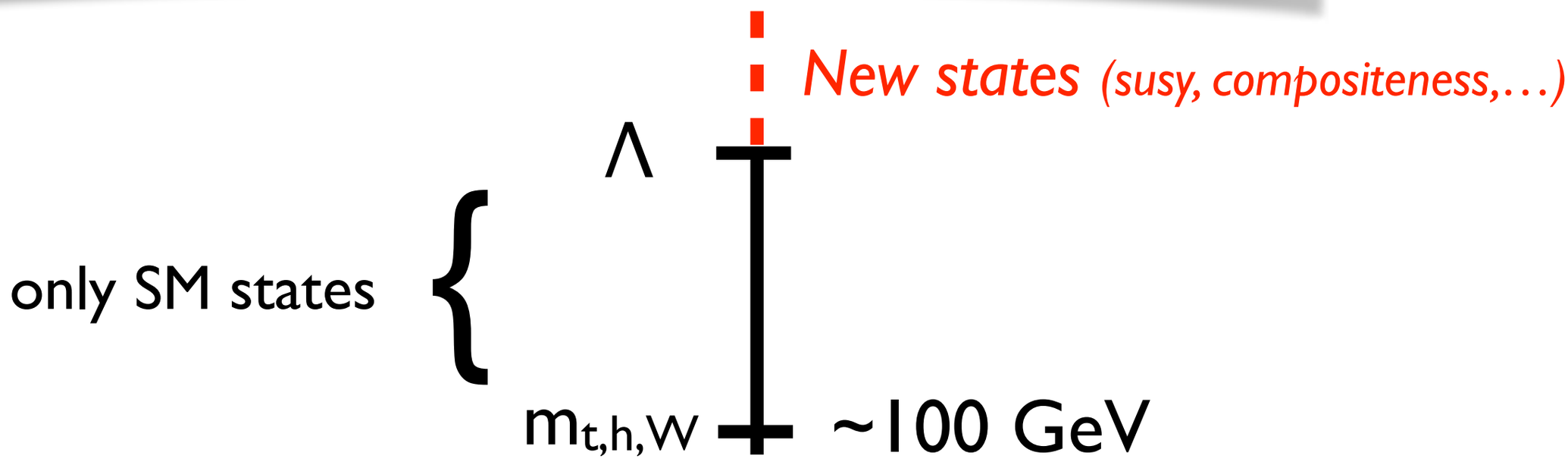

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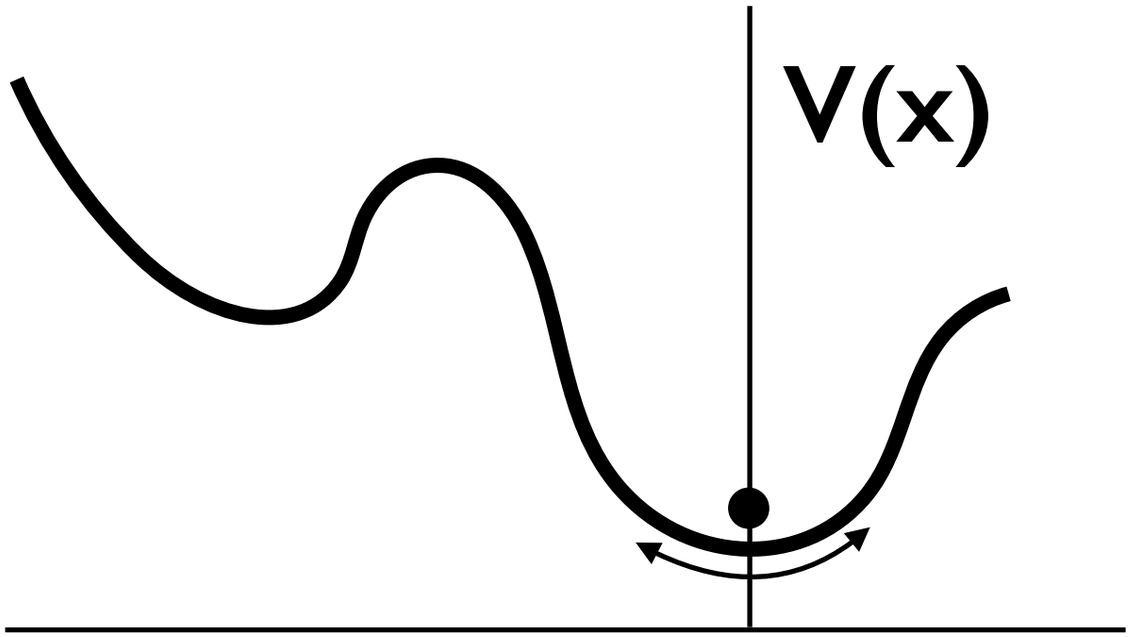
Valid for E≲Λ !

Similarly as in Classical mechanics



Expanding around the minimum:

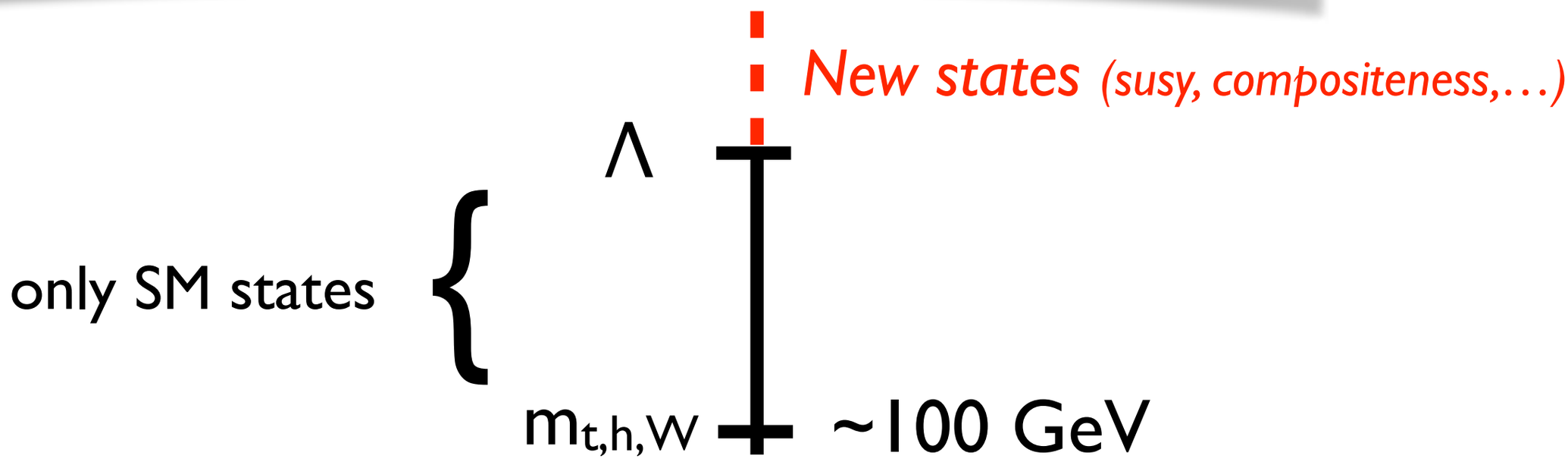
$$V(x) = k\,x^2/2 + c_1\,x^3/3 + \ldots$$

$$\Downarrow$$

$$F = -k\,x - c_1\,x^2$$

leading deviations
from Hooke's law

Assuming only the SM states below some Λ:



We can then Taylor expand (SM fields and derivative over Λ):

(assuming lepton & baryon number)

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

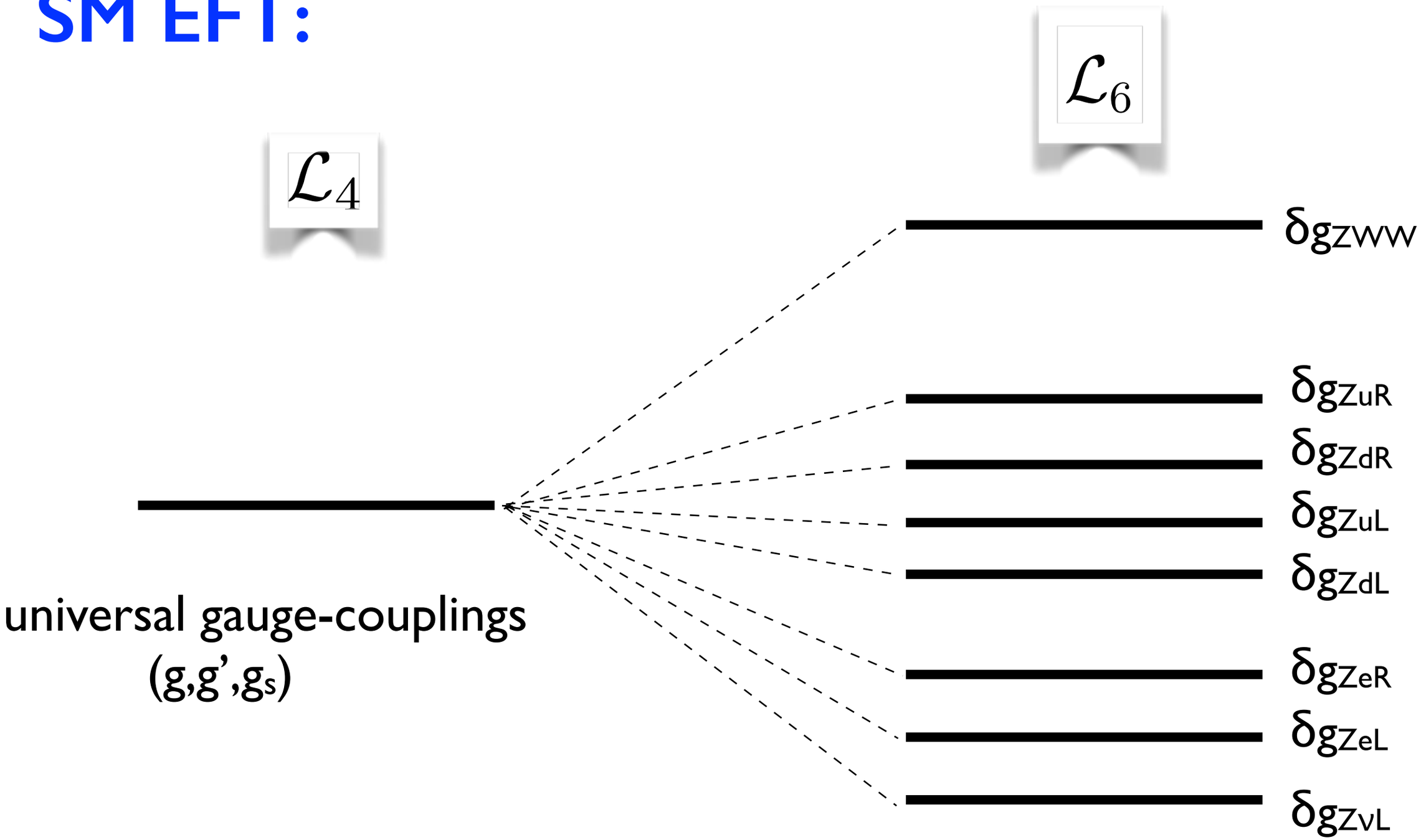
dimension-4 terms:

The SM

dimension-6 terms:

Leading deviations from the SM

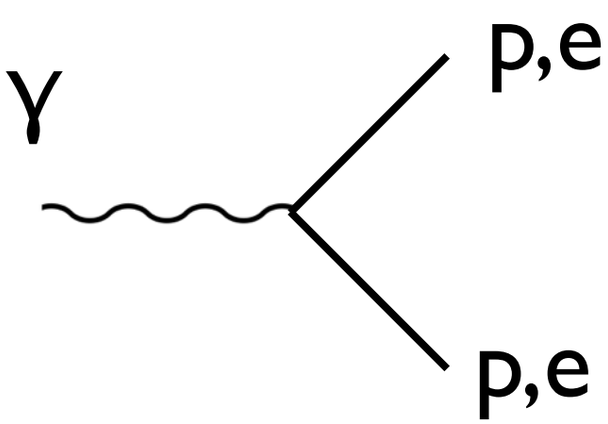
SM EFT:

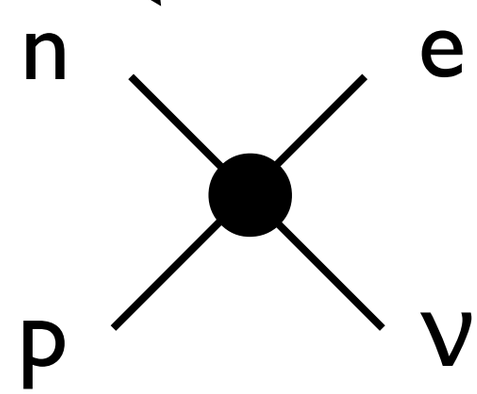


small splittings $\sim v^2/\Lambda^2$ (visible if $\Lambda \sim$ TeV)

Expansion seen at work already many times…

in the 30': $\mathcal{L}_{\rm EM} + \mathcal{L}_{\rm Fermi} + \cdots$





$\propto \frac{1}{\Lambda^2}$

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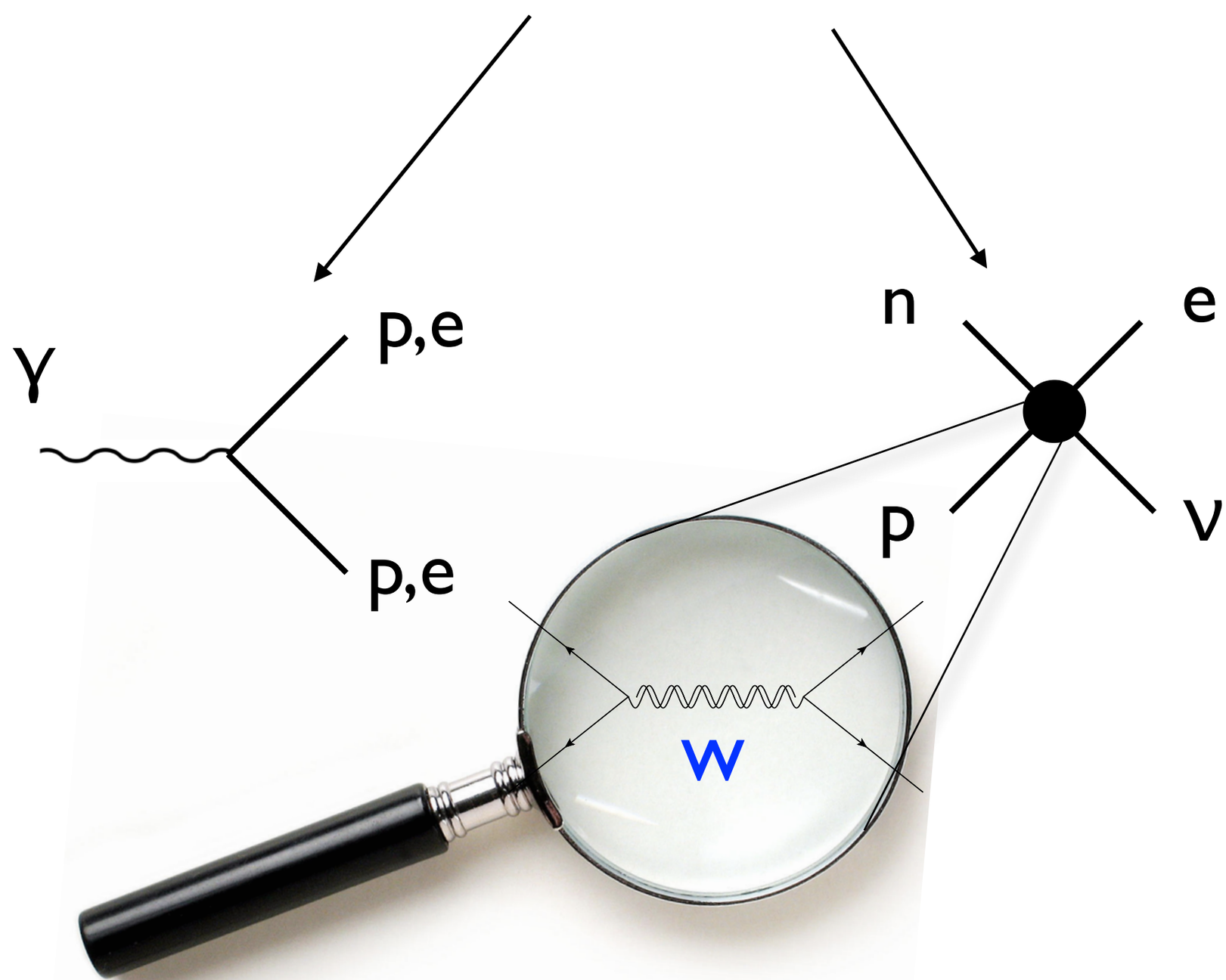


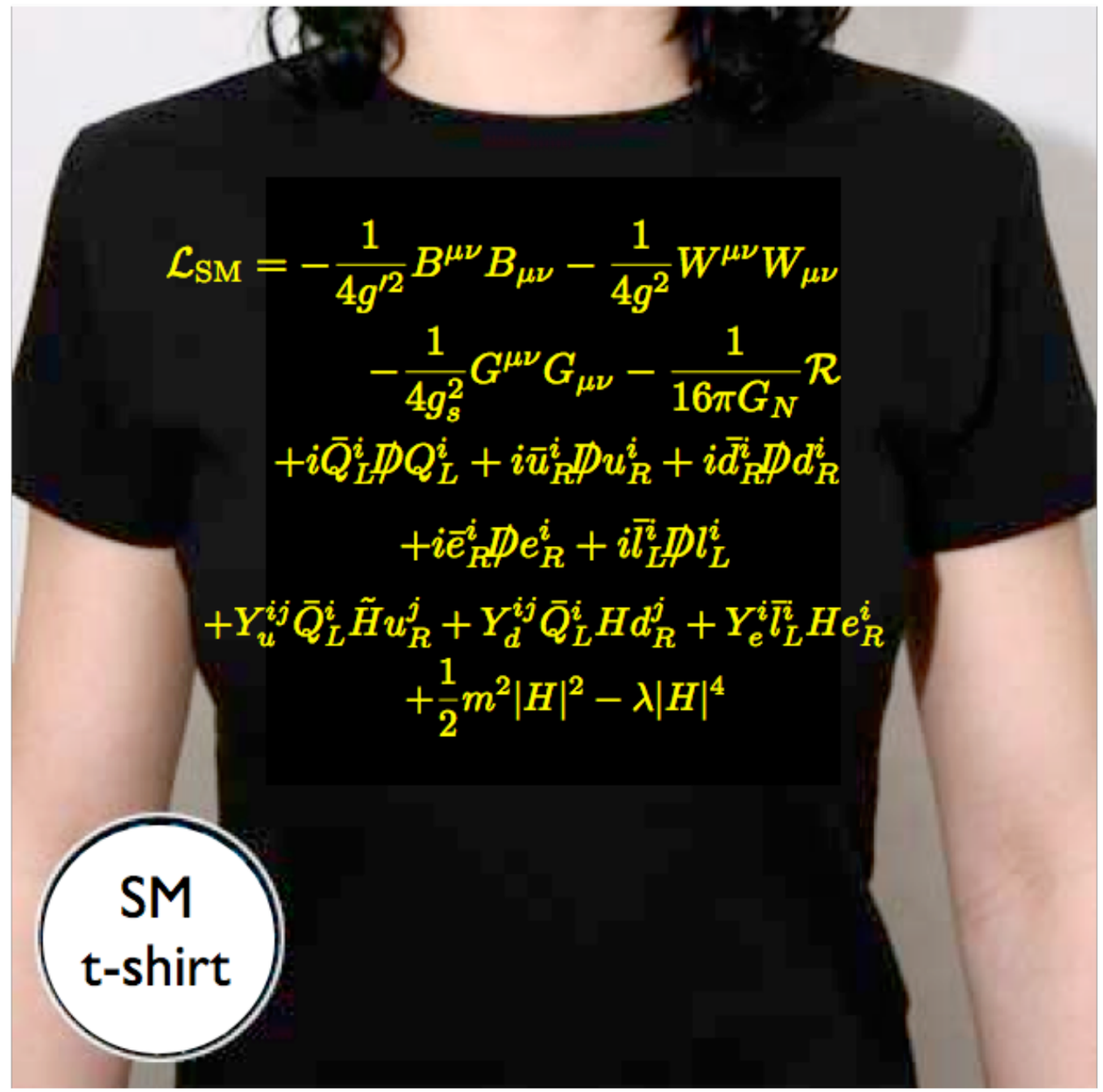
$\propto \dfrac{1}{\Lambda^2}$

$\Lambda = m_W/g$

SM EFT:

$\mathcal{L}_4$ can fit in a t-shirt:

Dimension-4 operators



SM EFT:

$$\mathcal{L}_6$$

Grzadkowski et.al. JHEP 1010 (2010) 085

assuming L & B

Dimension-6 operators

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

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

$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

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

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^{B}_{\nu\rho} G^{C\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{u}_R \gamma^\mu T^A u_R)$ $\mathcal{O}^u_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{Q}_L \gamma^\mu T^A Q_L)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma^\mu d_R)$ $\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{d}_R \gamma^\mu T^A d_R)$ $\mathcal{O}^d_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}^e_{RR} = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}^l_{LL} = (\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L)$
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Too many terms to understand the implications?

A more intuitive parametrization of leading BSM effects

Flavor & CP conserving

☛ **Which departures predict from the SM ?**

A more intuitive parametrization of leading BSM effects

Flavor & CP conserving

Shifts from the SM couplings:

Higgs couplings:

- hVV, hff, h^3

Z couplings:

- Zf_Lf_L, Zf_Rf_R, ZWW

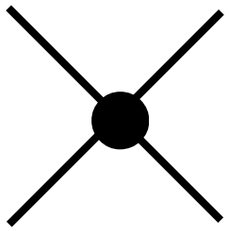
New type of couplings:

- $h\gamma\gamma$, hGG, $hZ\gamma$
- Wd_Ru_R

Dipole-type:

- Wf_Lf_R, γWW
- WWW, GGG

4-fermion contact-interactions



(25 of them)

R.S.Gupta, AP, F. Riva [arXiv:1405.0181 [hep-ph]]

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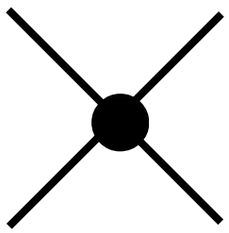

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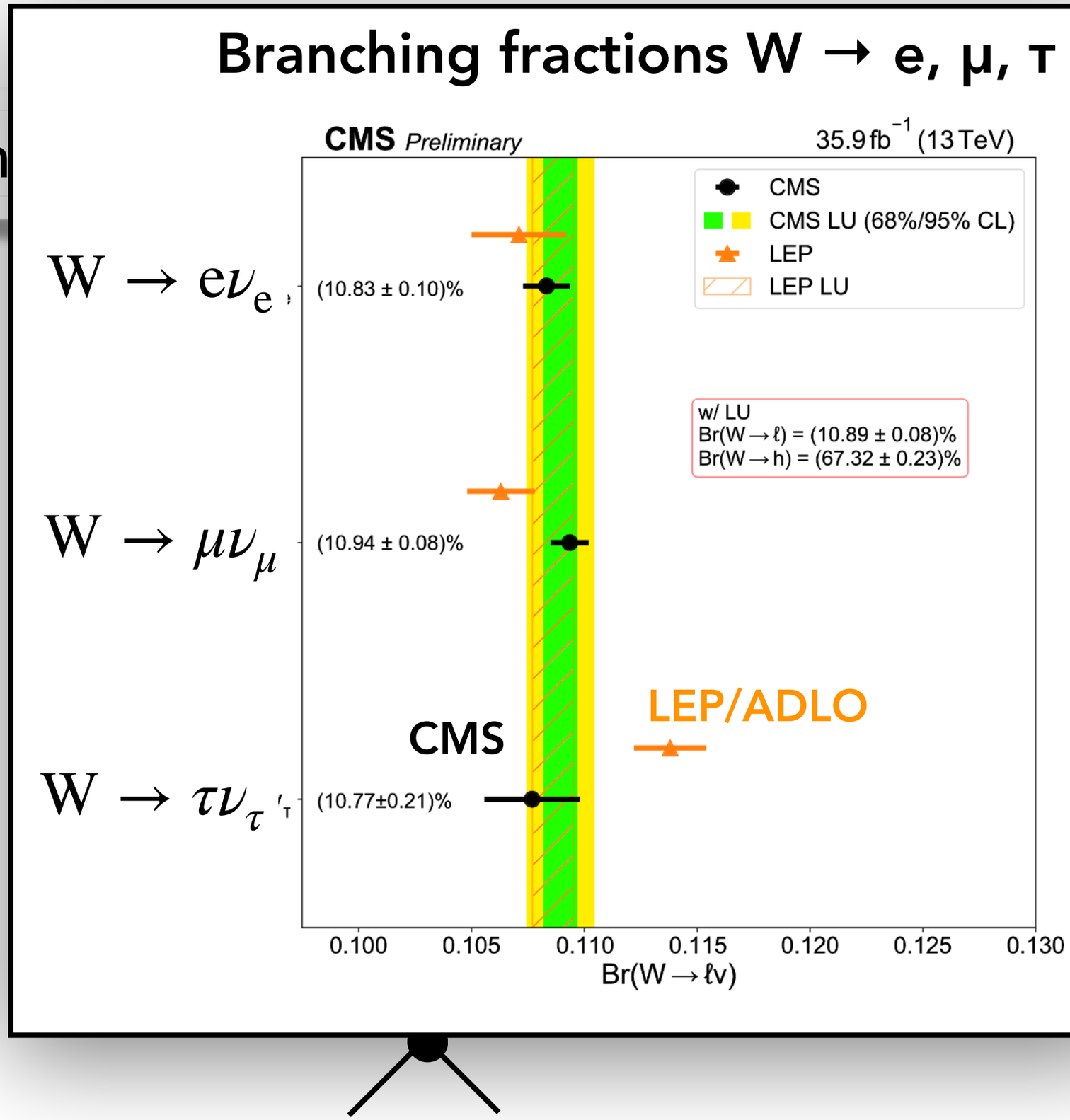

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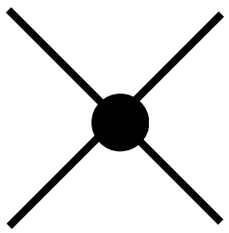

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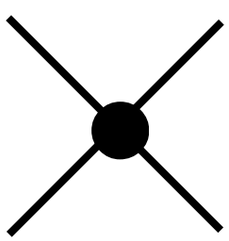
From LEP ☛ Z physics
From LHC ☛ Higgs & top
} **almost all couplings measured ~ few %**

related! Wf_Lf_L'

- WWW, GGG

4-fermion contact-interactions (25 of them)



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Dipole-type:

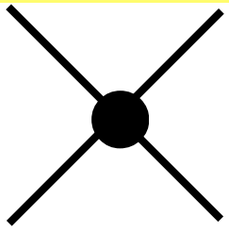
but (few) important couplings still to unravel

- WWW, GGG

related! Wf_Lf_L'

4-fermion contact-interactions

(25 of them)



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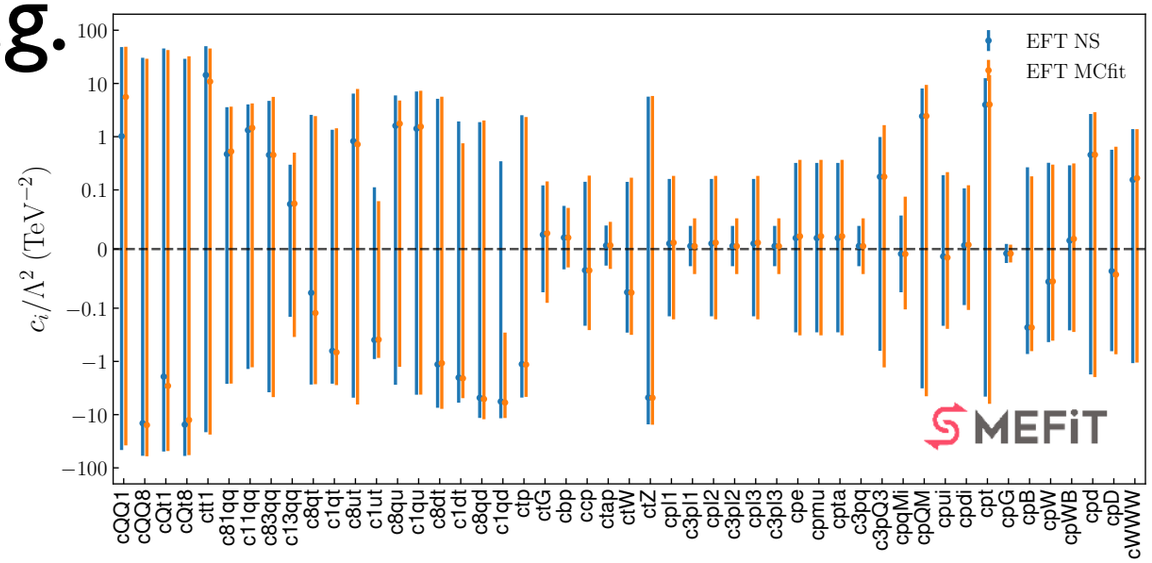
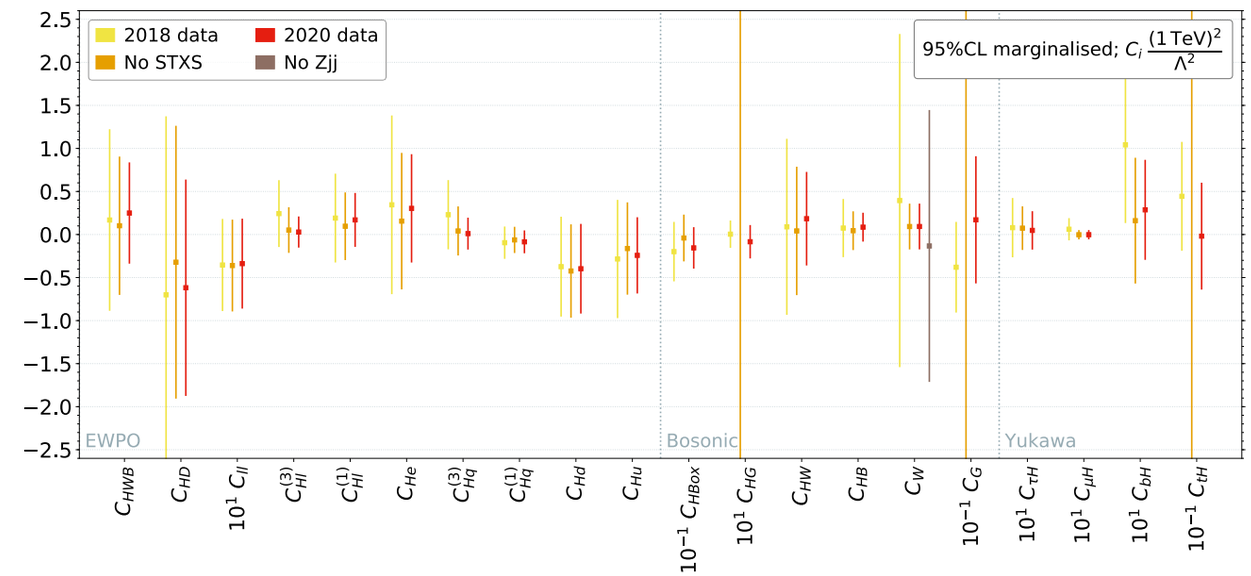
A lot of effort to combine all data to place bounds on the coefficients of the new terms:

e.g.





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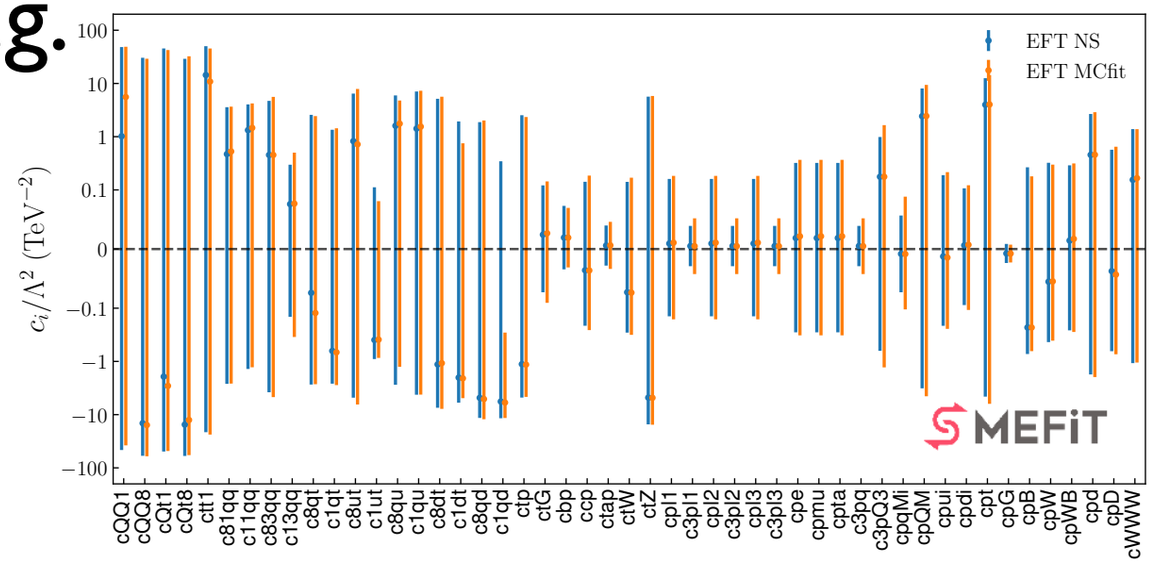
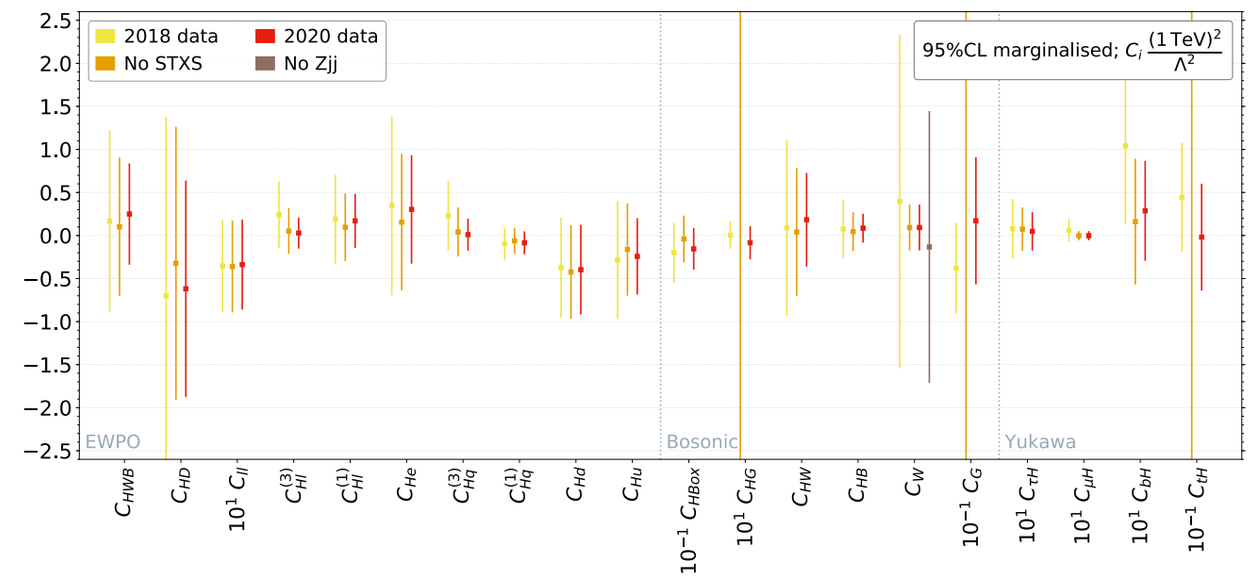




To understand the **impact on** certain **new physics**,
a small set of bounds on SM couplings is enough

(not need of global fits)

Here I'll present few examples of **LHC best tests**:

Higgs couplings ⊕ top couplings ⊕ High-energy probes

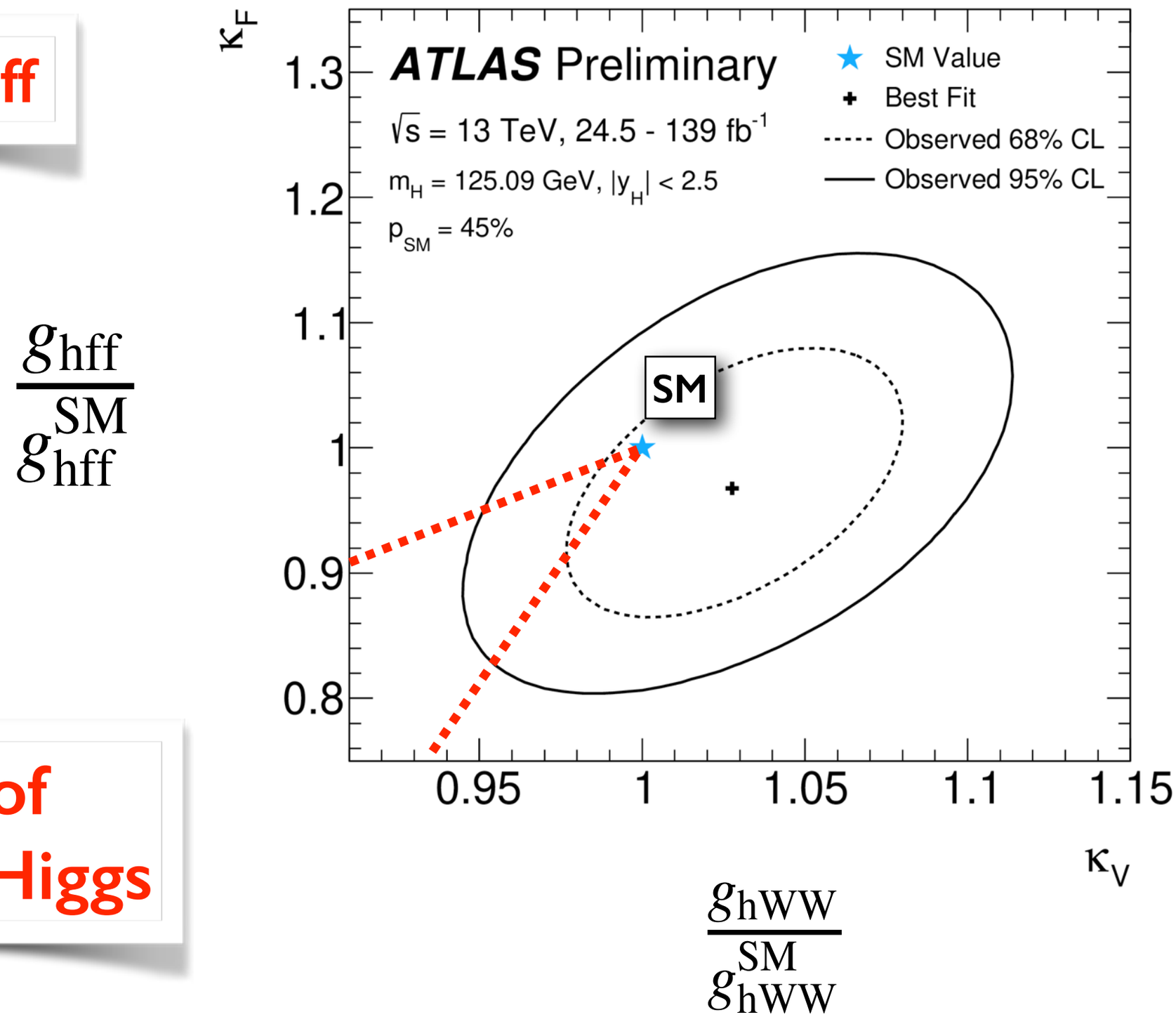
Higgs couplings

Still the main *destroyer* of BSM addressing the hierarchy problem

Expected largest corrections to Higgs couplings:

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√					√
NMSSM	√	√	√	√	√	√
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

hWW, hZZ & hff

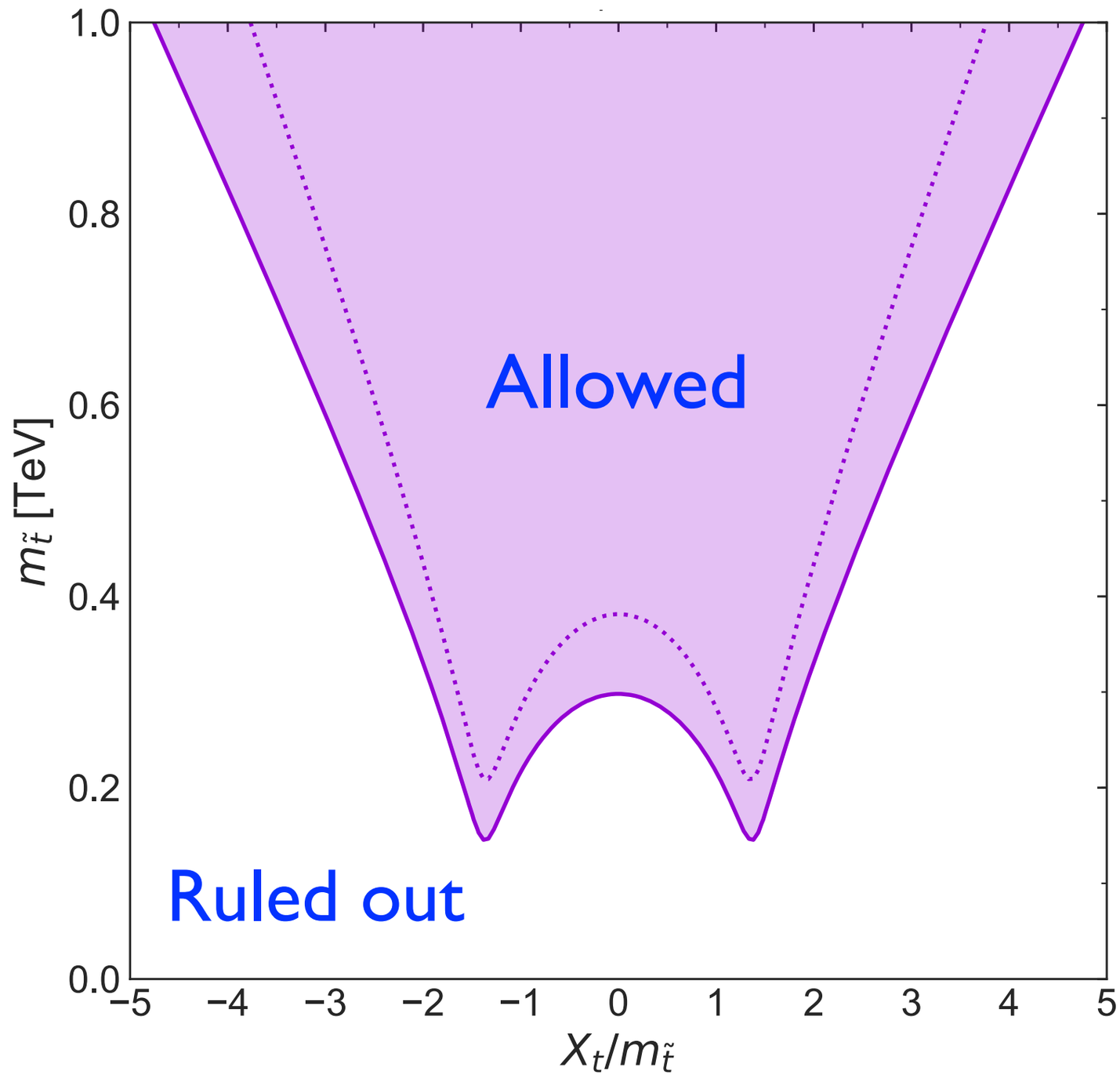


No sign of Composite Higgs

scale of compositeness≳ 2-3 TeV

hGG & hγγ

bound on stops

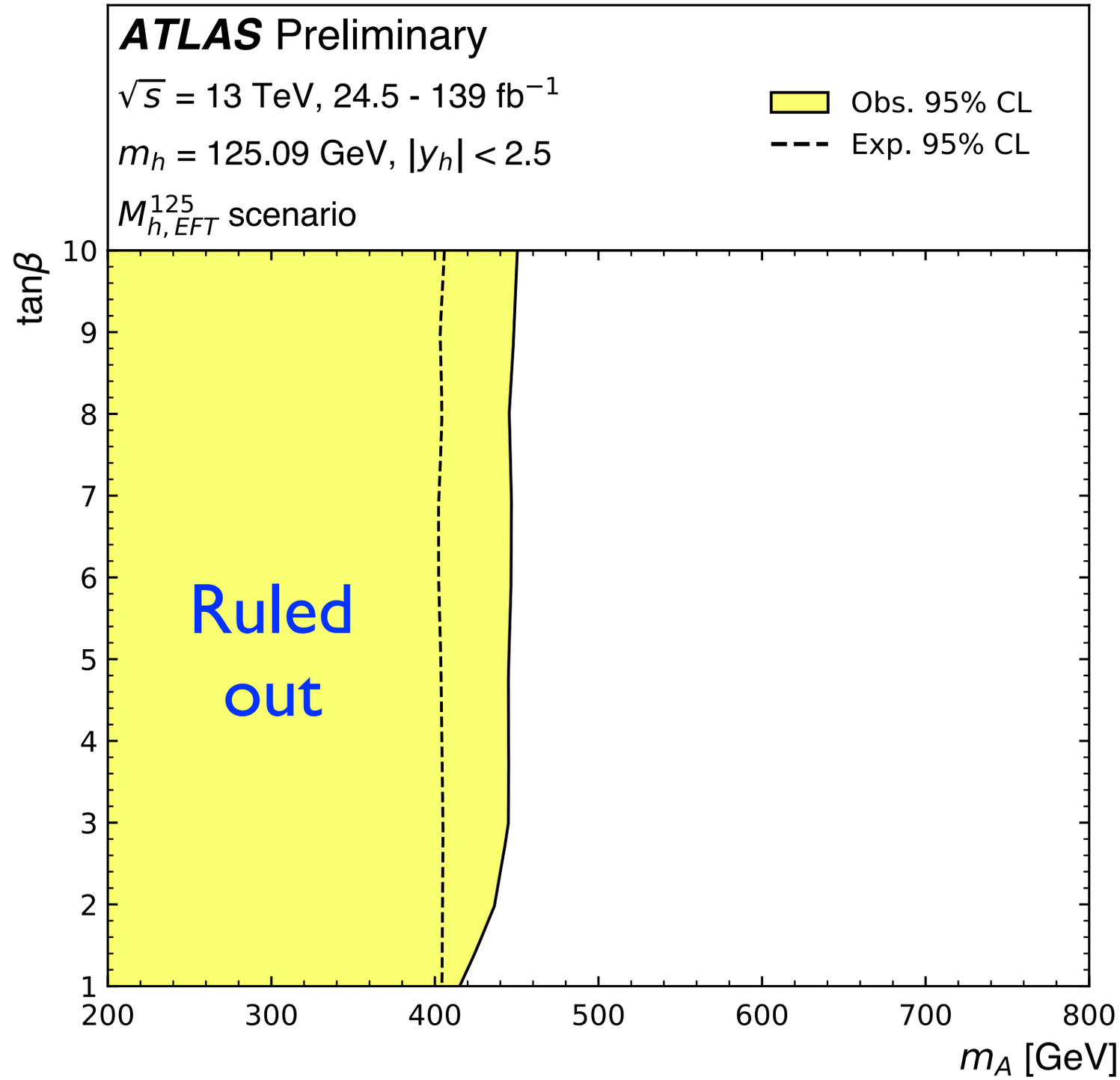


No sign of stops

J.Ellis,M.Madigan,K.Mimasu,V.Sanz,T,You arXiv:2012.02779

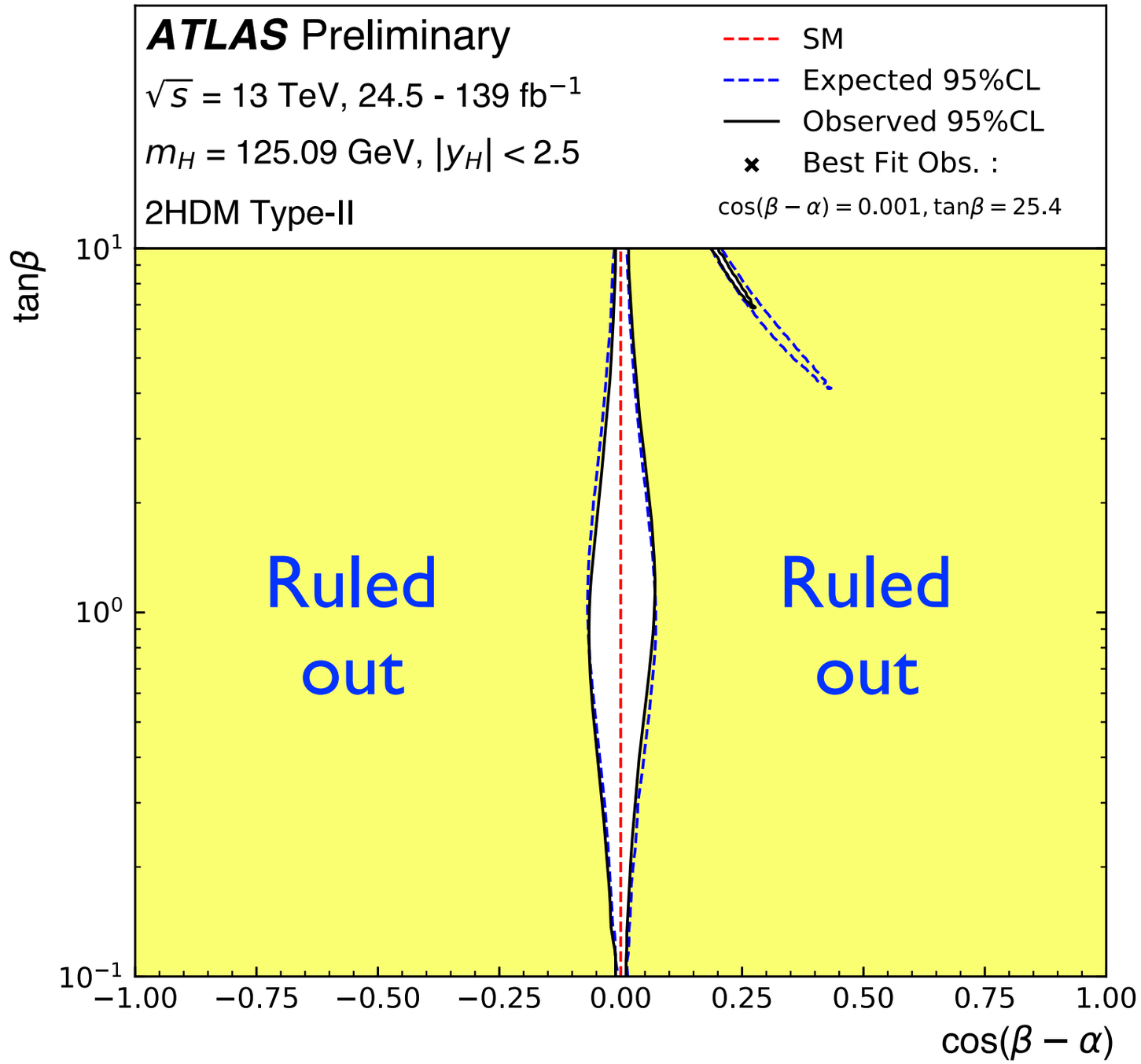
htt, hbb & hττ

No sign of extra Higgs (as in susy models)



htt, hbb & hττ

as a function of the parameters of the MSSM:



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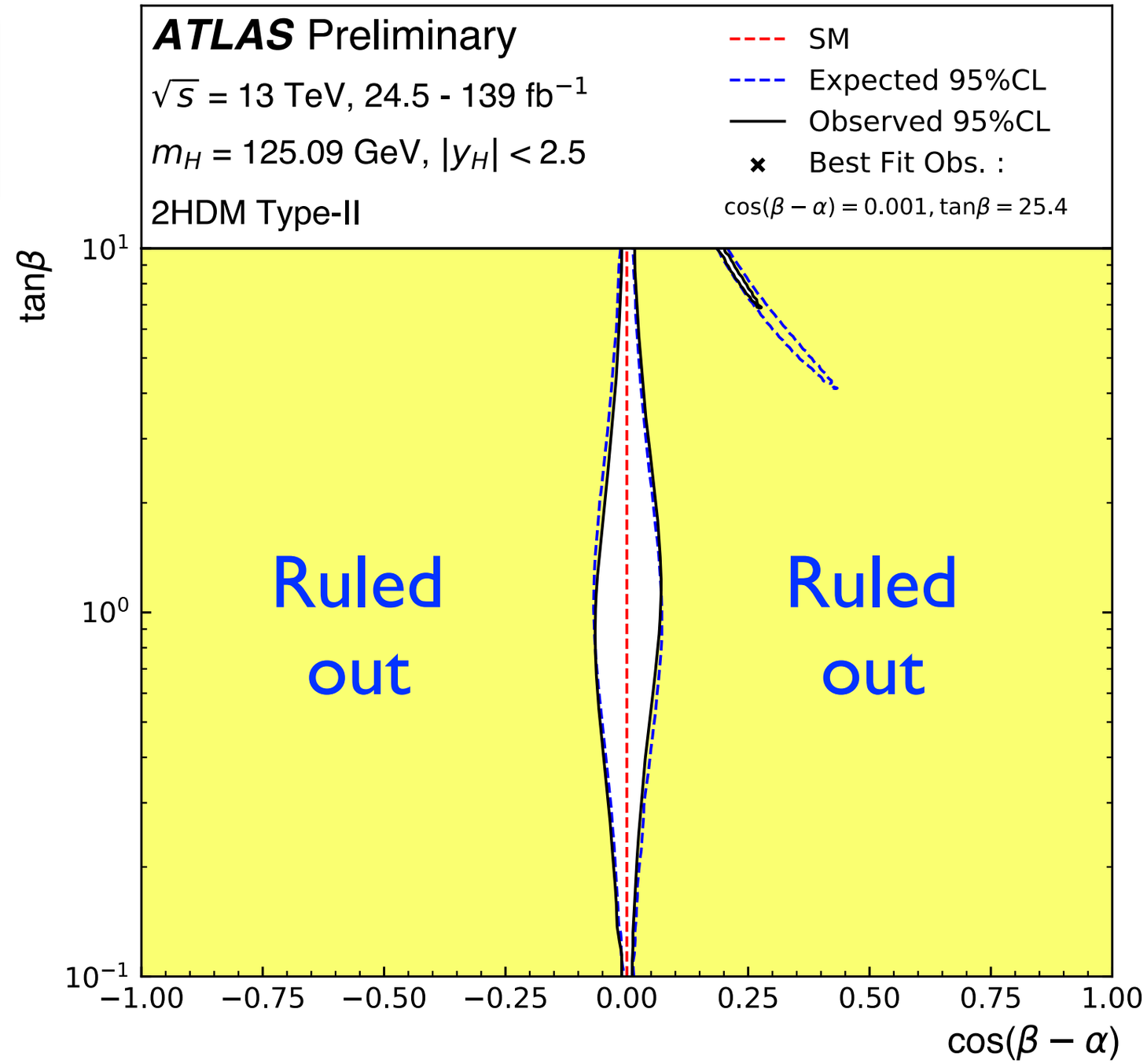
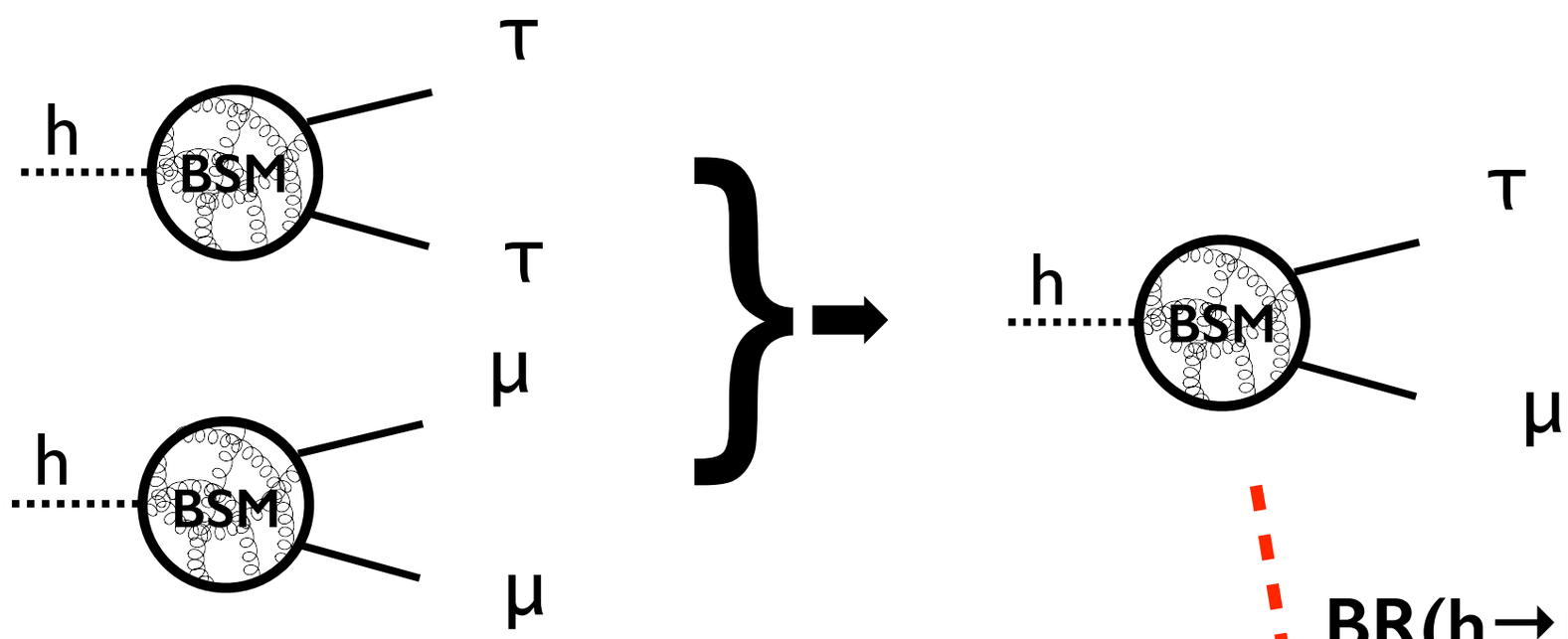


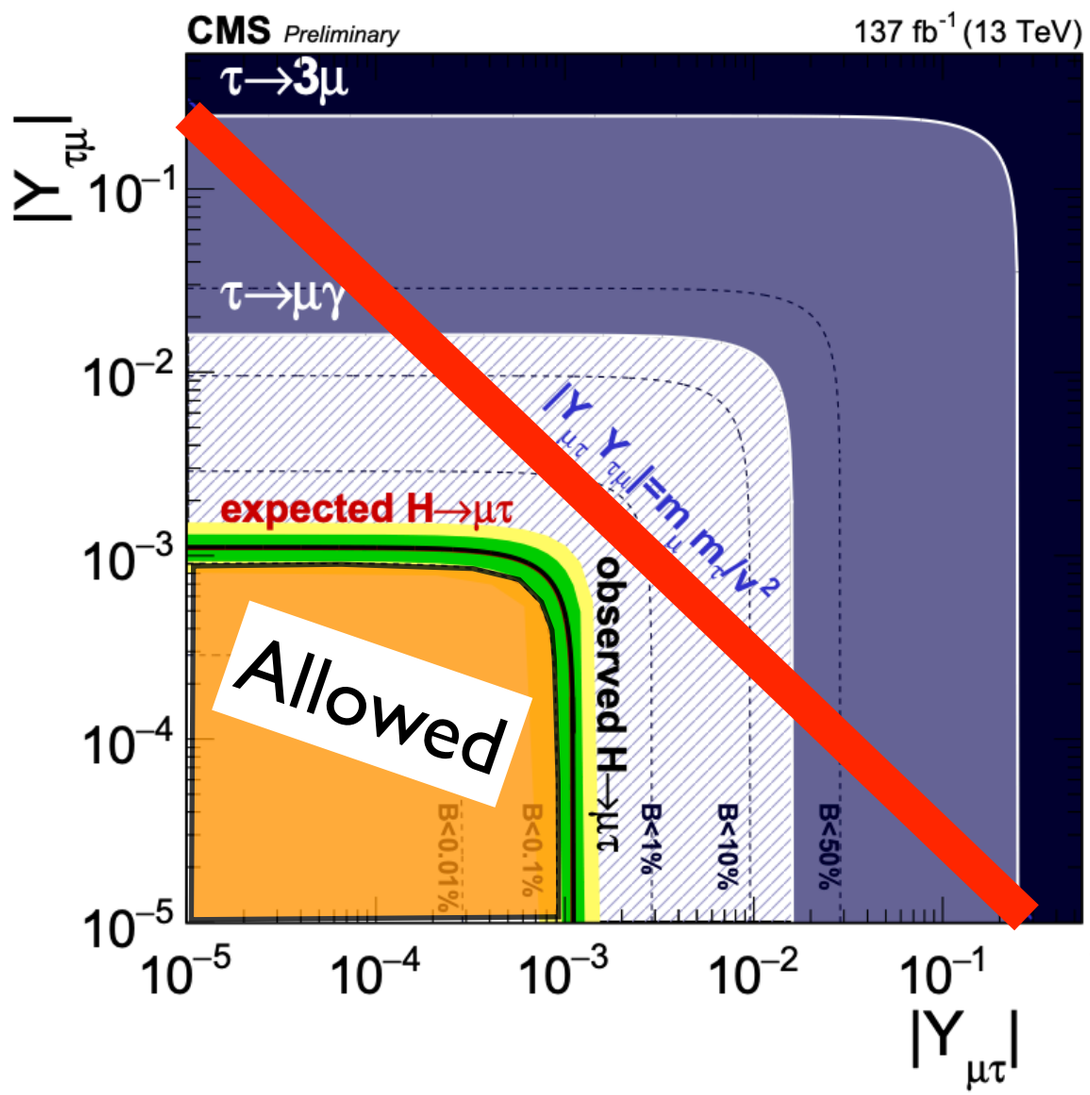
Small regions left for the MSSM

hτμ

Excluding the possibility of some **flavor models:**

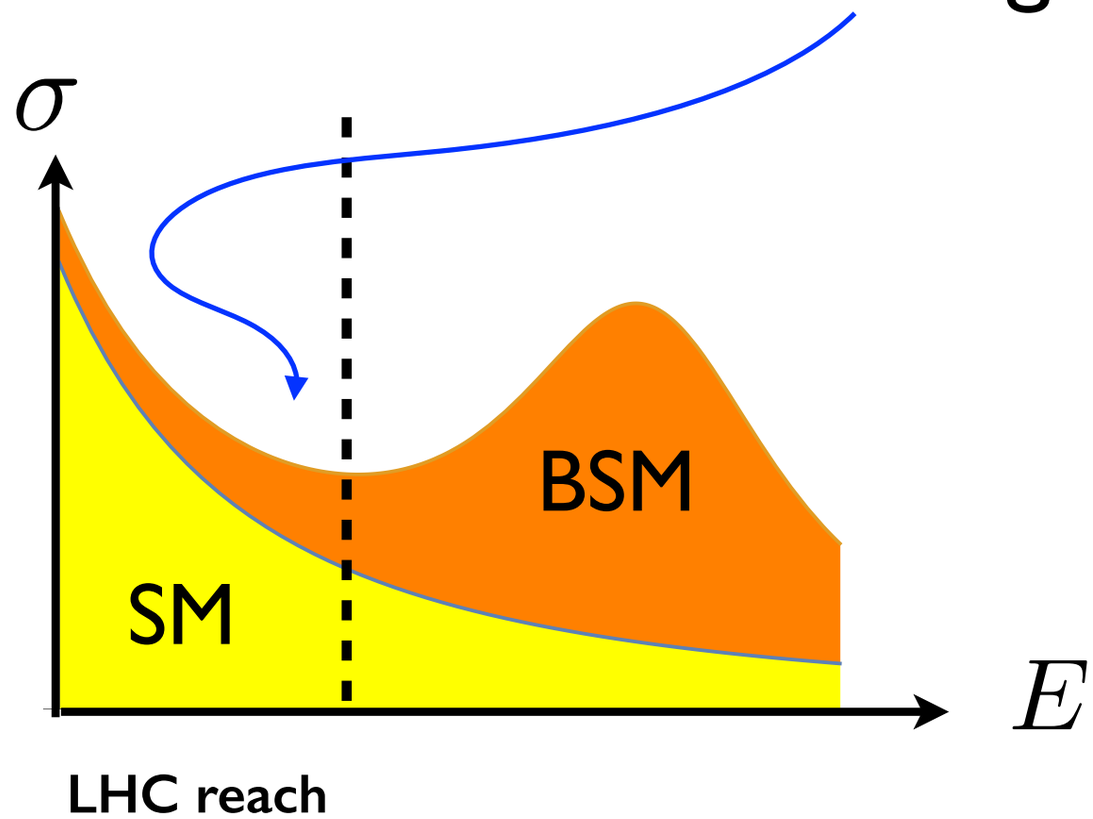


BR(h→μτ)>1%



LHC main player

Measuring couplings at high-energies
where deviations can be larger

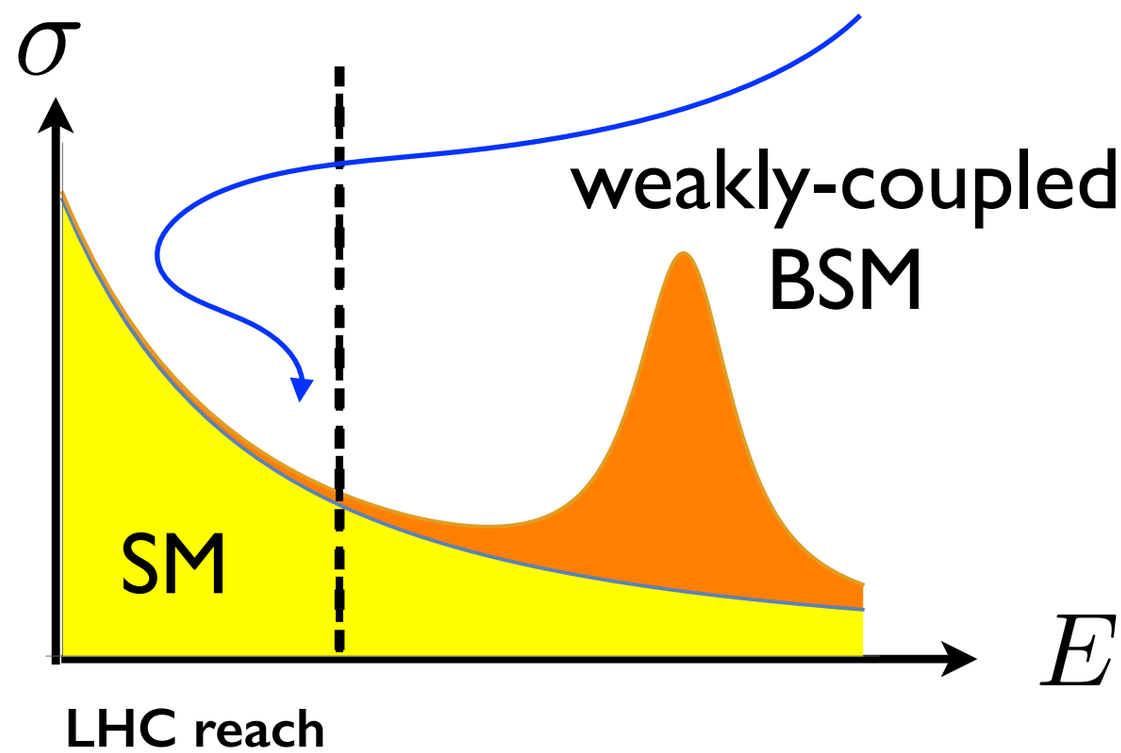


Possibility to do
better than LEP
even in Z physics

if you cannot get the resonance,
try to get its tail

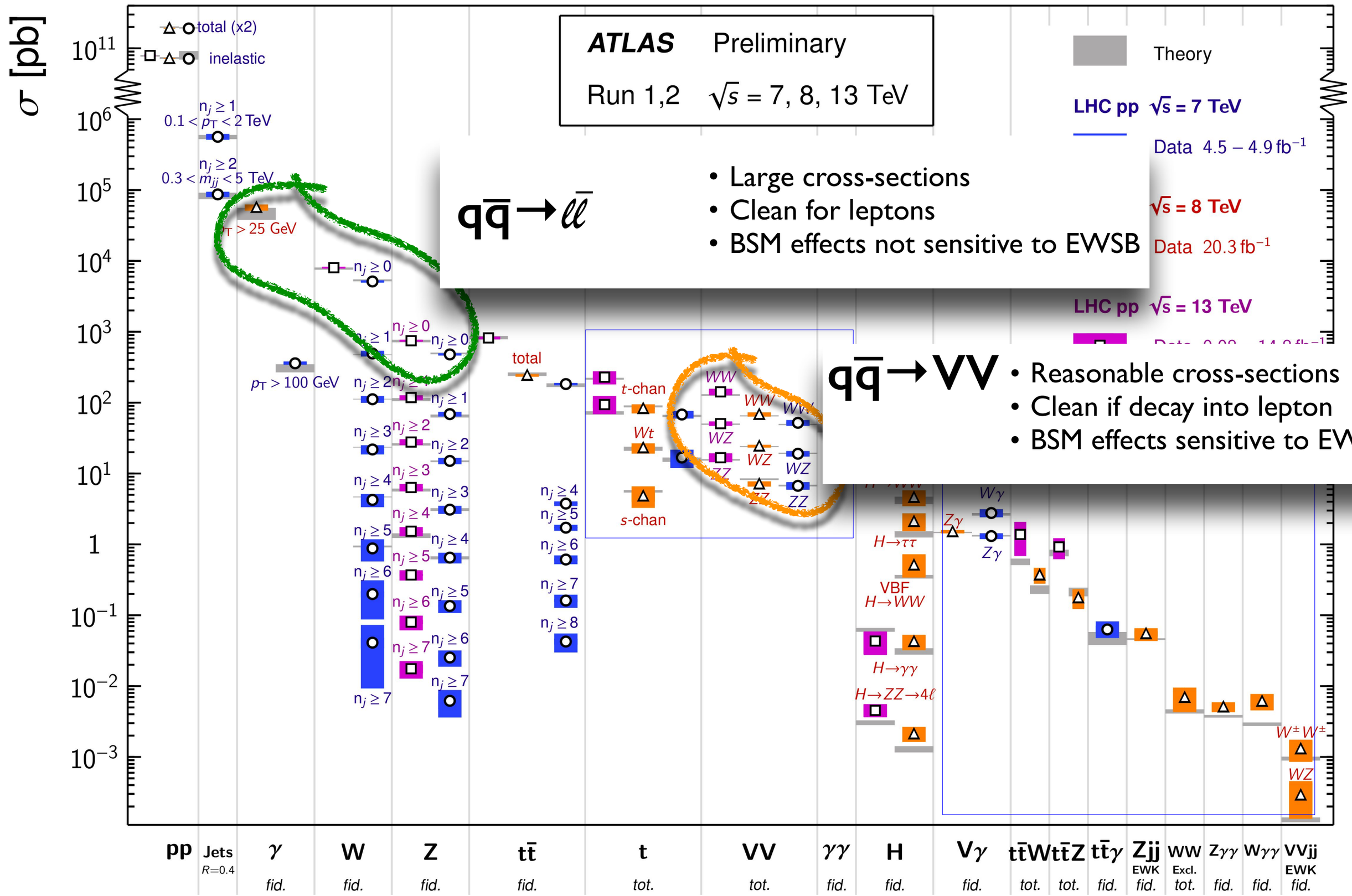
LHC main player

Measuring couplings at high-energies
where deviations can be larger



Energy & accuracy
needed
to catch up
different BSM!

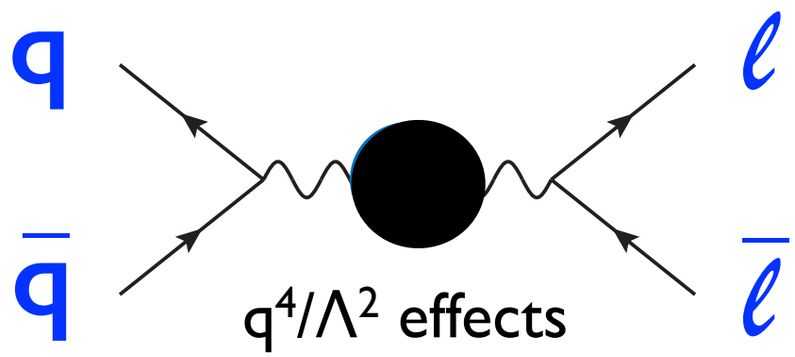
if you cannot get the resonance,
try to get its tail


Standard Model Production Cross Section Measurements
Status: August 2016
σ [pb]
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
√s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
total (x2)
inelastic
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
VVjj EWK fid.
total
t-chan
s-chan
Wt
WW
WZ
ZZ
Wγ
Zγ
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
W±W±
WZ
pT > 25 GeV
pT > 100 GeV
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
qq̄→ℓℓ̄
• Large cross-sections
• Clean for leptons
• BSM effects not sensitive to EWSB
qq̄→VV
• Reasonable cross-sections
• Clean if decay into lepton
• BSM effects sensitive to EWSB

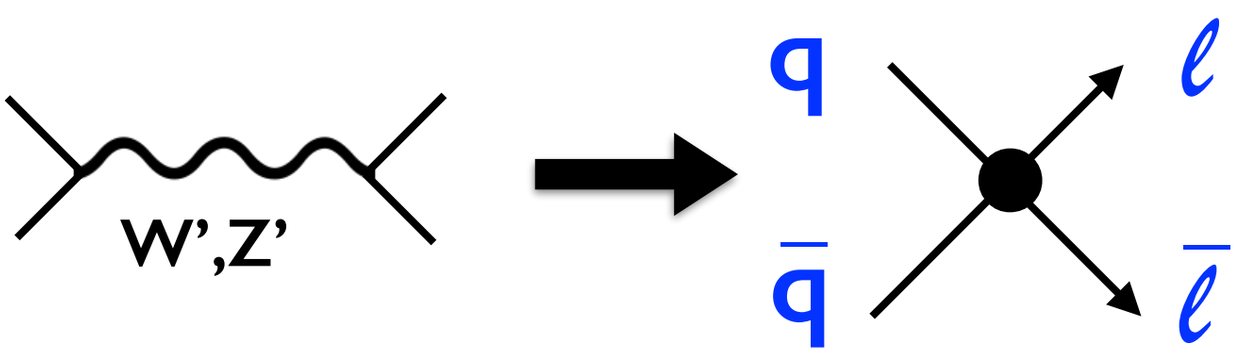
$q\bar{q} \to \ell\bar{\ell}, \ell\bar{\nu}$:

Can be sensitive to oblique-corrections or extra bosons:

a)



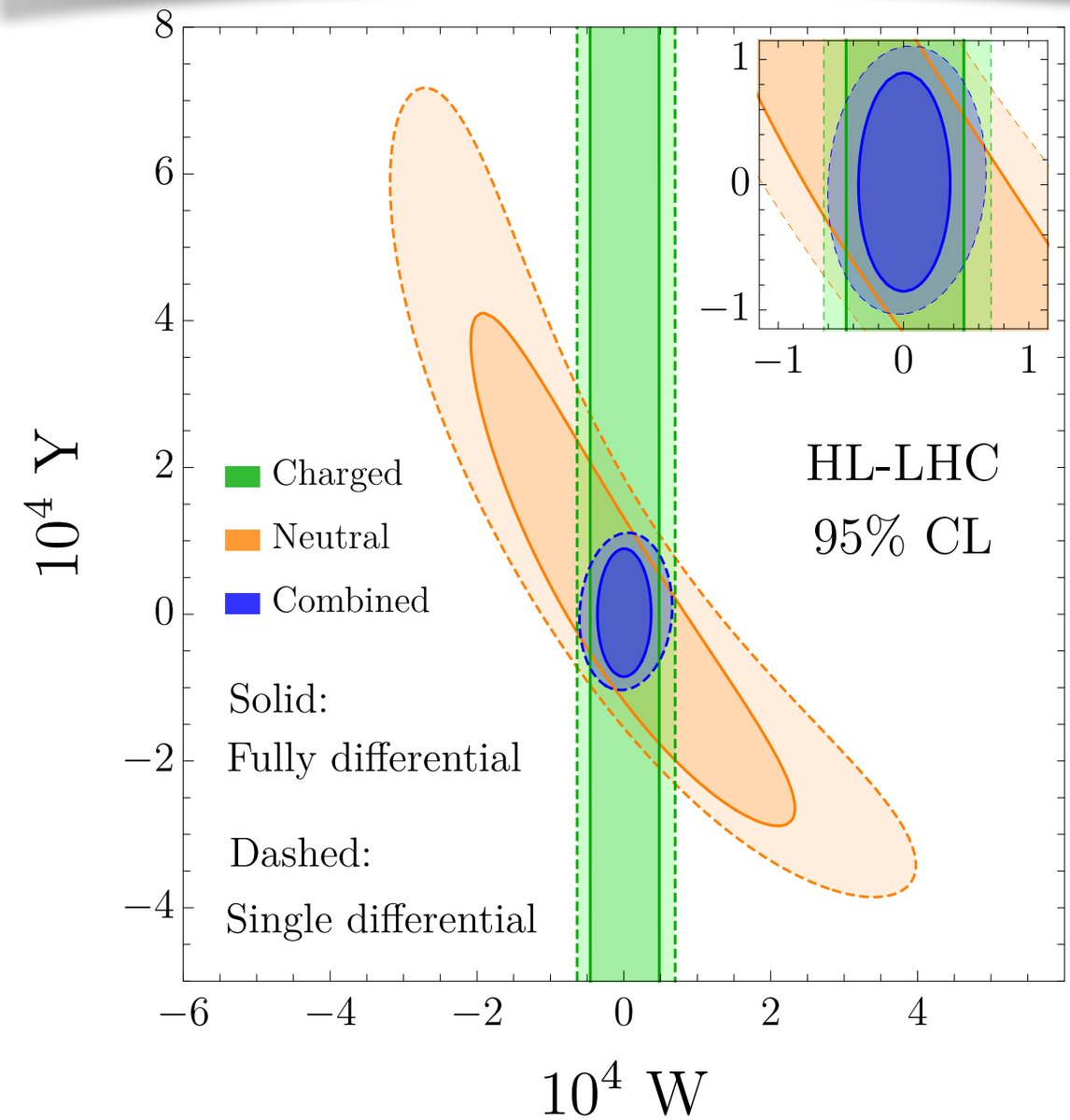
b)



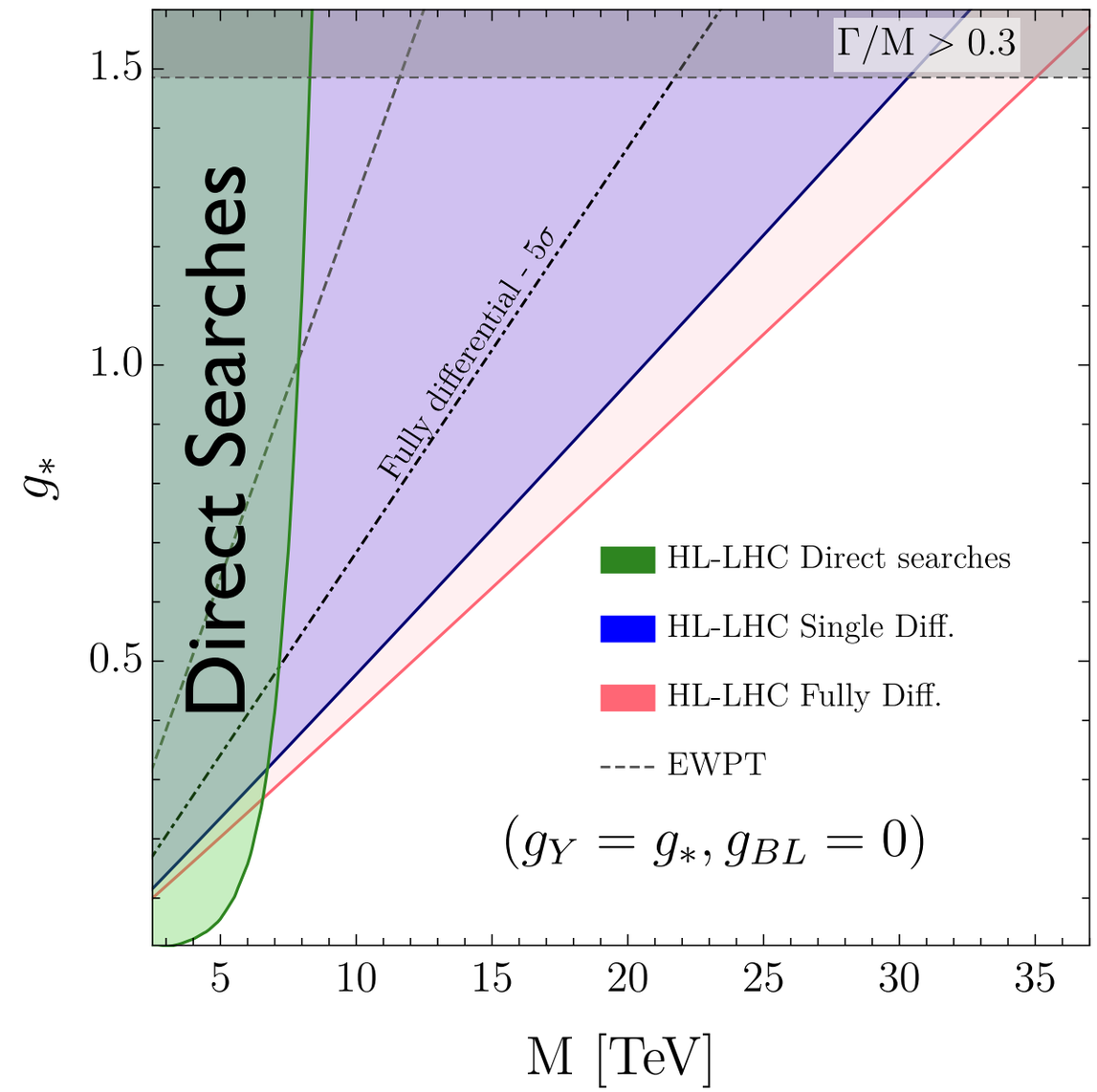
$$\frac{\delta\mathcal{M}}{\mathcal{M}^{\rm SM}} \simeq 1 + c\frac{\hat{s}}{\Lambda^2}$$

☛ effects can be seen in the differential cross-sections $\dfrac{d\sigma}{dm^2_{\ell\ell}}$ at large inv. masses

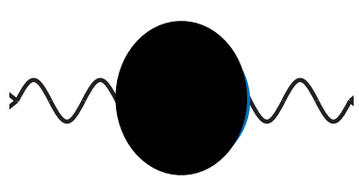
bounds on oblique corrections



bounds on Z'

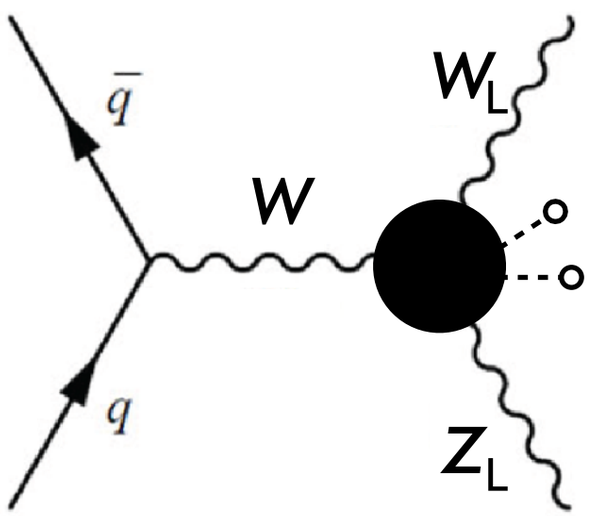


constraints of O(10^{-4}) on

q^4/Λ^2 effects 

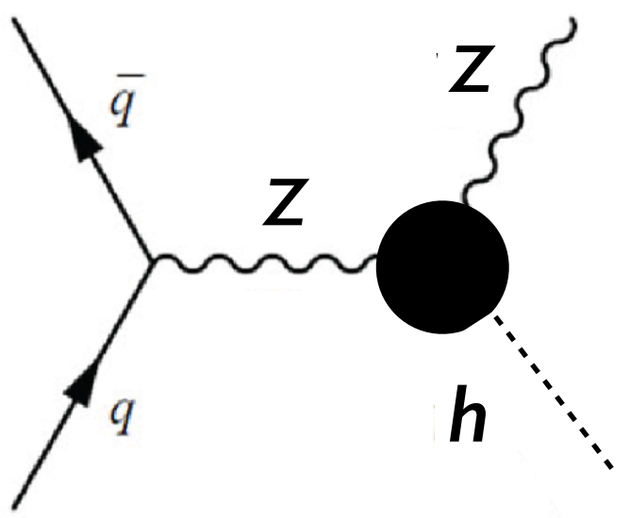
G.Panico,L.Ricci, A.Wulzer arXiv:2103.10532

$q\bar{q} \to V_L V_L(h)$



$$\frac{\delta\mathcal{M}_{LL}}{\mathcal{M}_{LL}^{\rm SM}} \simeq 1 - \frac{\hat{s}}{m_Z^2}\delta g_1^Z \qquad \text{for } \hat{s} \gg m_Z^2$$

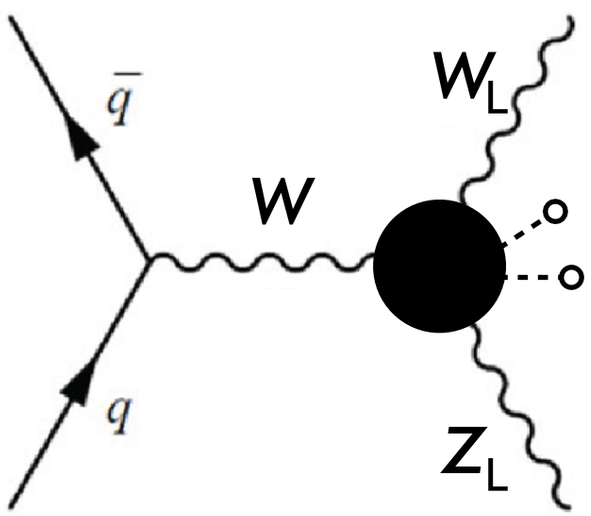
Shift of the SM **WWZ-coupling**



$$\frac{\delta\mathcal{M}_{Zh}}{\mathcal{M}_{Zh}^{\rm SM}} \simeq 1 - c_q\frac{\hat{s}}{m_Z^2}\kappa_{ZZ} \qquad \text{for } \hat{s} \gg m_Z^2$$

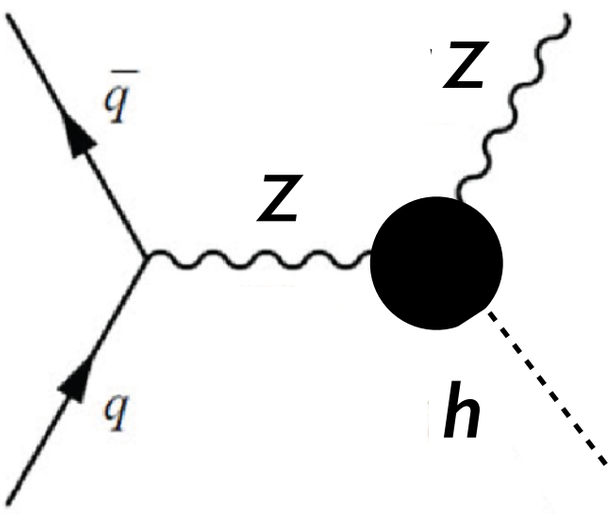
New type of **hZZ** interaction: $hZ^{\mu\nu}Z_{\mu\nu}$

$q\bar{q} \to V_L V_L(h)$



$$\frac{\delta\mathcal{M}_{LL}}{\mathcal{M}_{LL}^{\rm SM}} \simeq 1 - \frac{\hat{s}}{m_Z^2}\delta g_1^Z \qquad \text{for } \hat{s} \gg m_Z^2$$

Shift of the SM **WWZ-coupling**



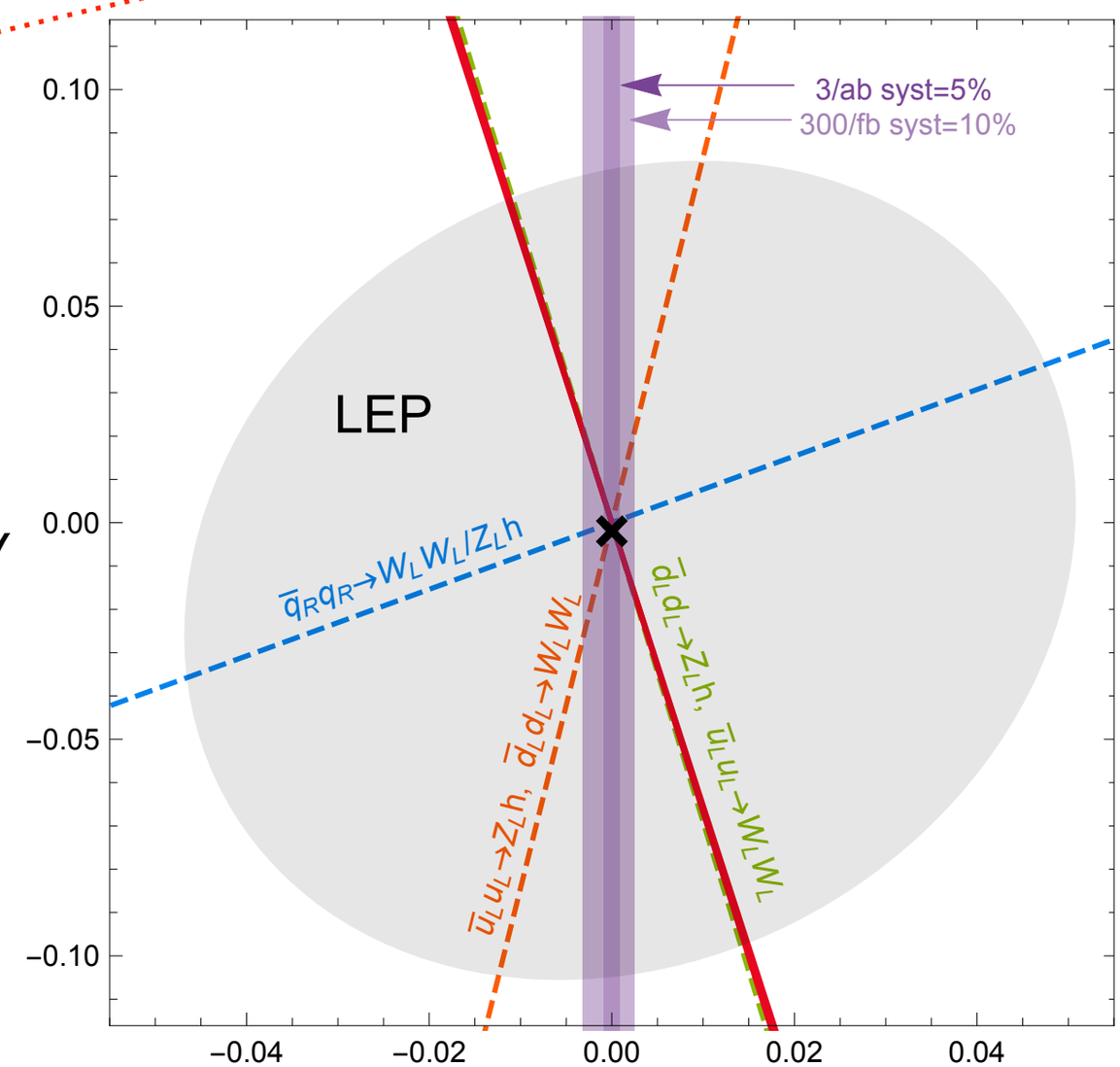
$$\frac{\delta\mathcal{M}_{Zh}}{\mathcal{M}_{Zh}^{\rm SM}} \simeq 1 - c_q\frac{\hat{s}}{m_Z^2}\kappa_{ZZ} \qquad \text{for } \hat{s} \gg m_Z^2$$

TGC: EM dipole of a **W** ($\delta\kappa_\gamma$) $\xleftrightarrow{\text{related}}$ New type of **hZZ** interaction: $hZ^{\mu\nu}Z_{\mu\nu}$

prediction of the SM EFT!

pp→WZ

HL-LHC



$\delta\kappa_\gamma$

EM dipole of a **W**

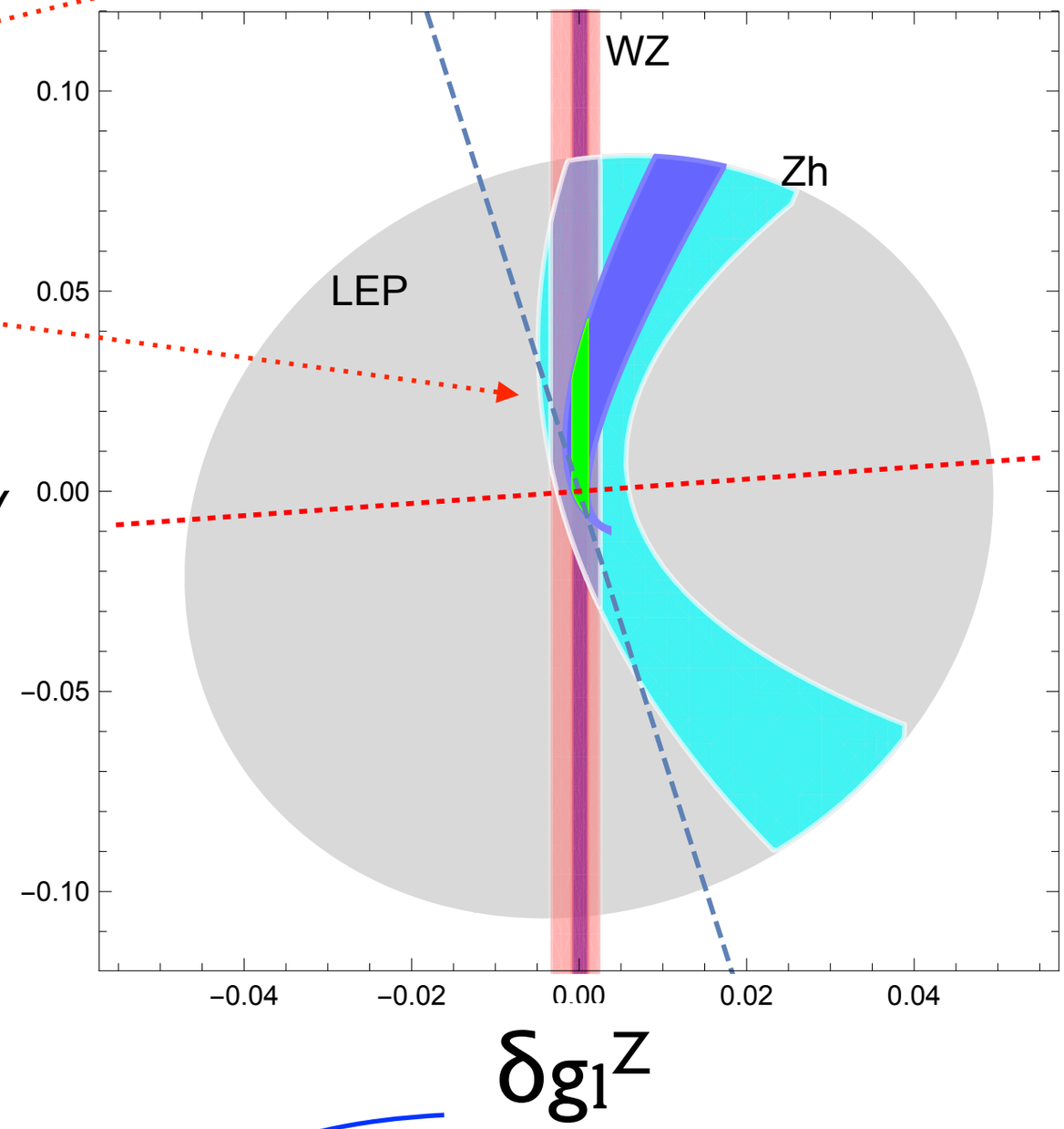
δg_1^Z

Shift of the SM **WWZ-coupling**

R. Franceschini, G.Panico, AP, F. Riva, A. Wulzer arXiv:1712.01310

pp→WZ

pp→Zh



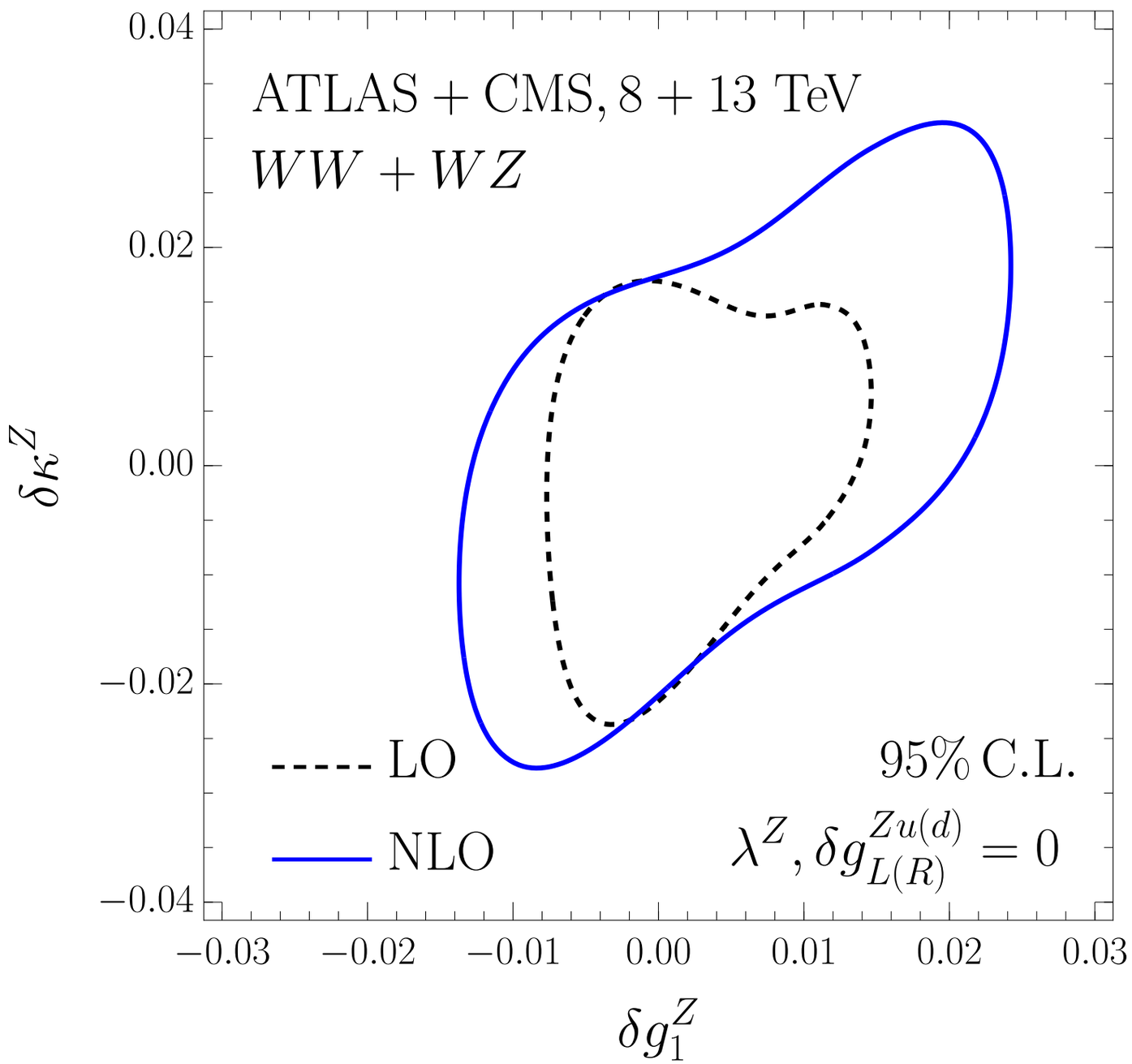
HL-LHC

EM dipole of a **W**

Shift of the SM **WWZ-coupling**

S.Banerjee, C.Englert, R.Gupta, M.Spannowsky 1807.01796

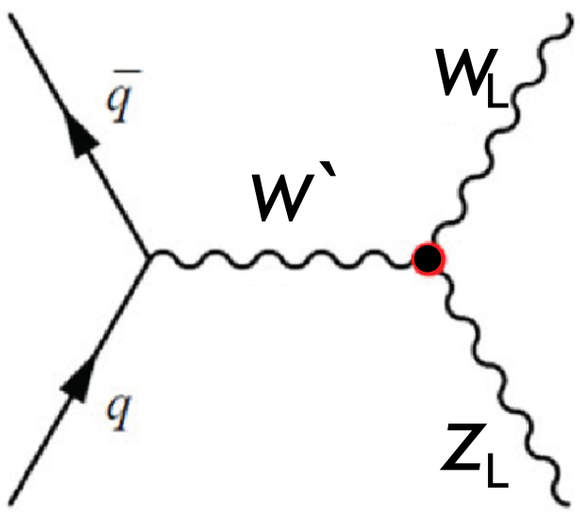
Beating already LEP ($\delta g_1^Z \lesssim 0.05$)

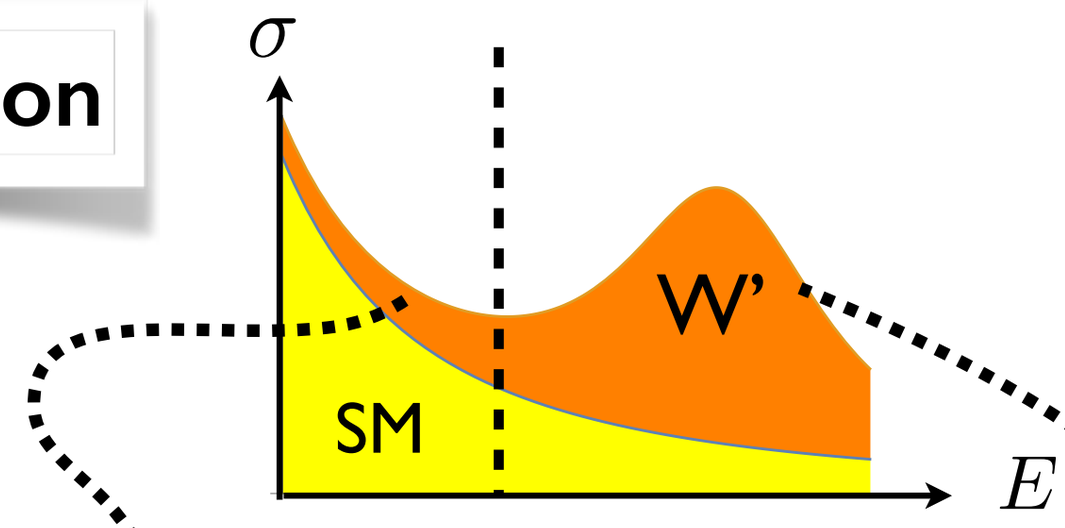


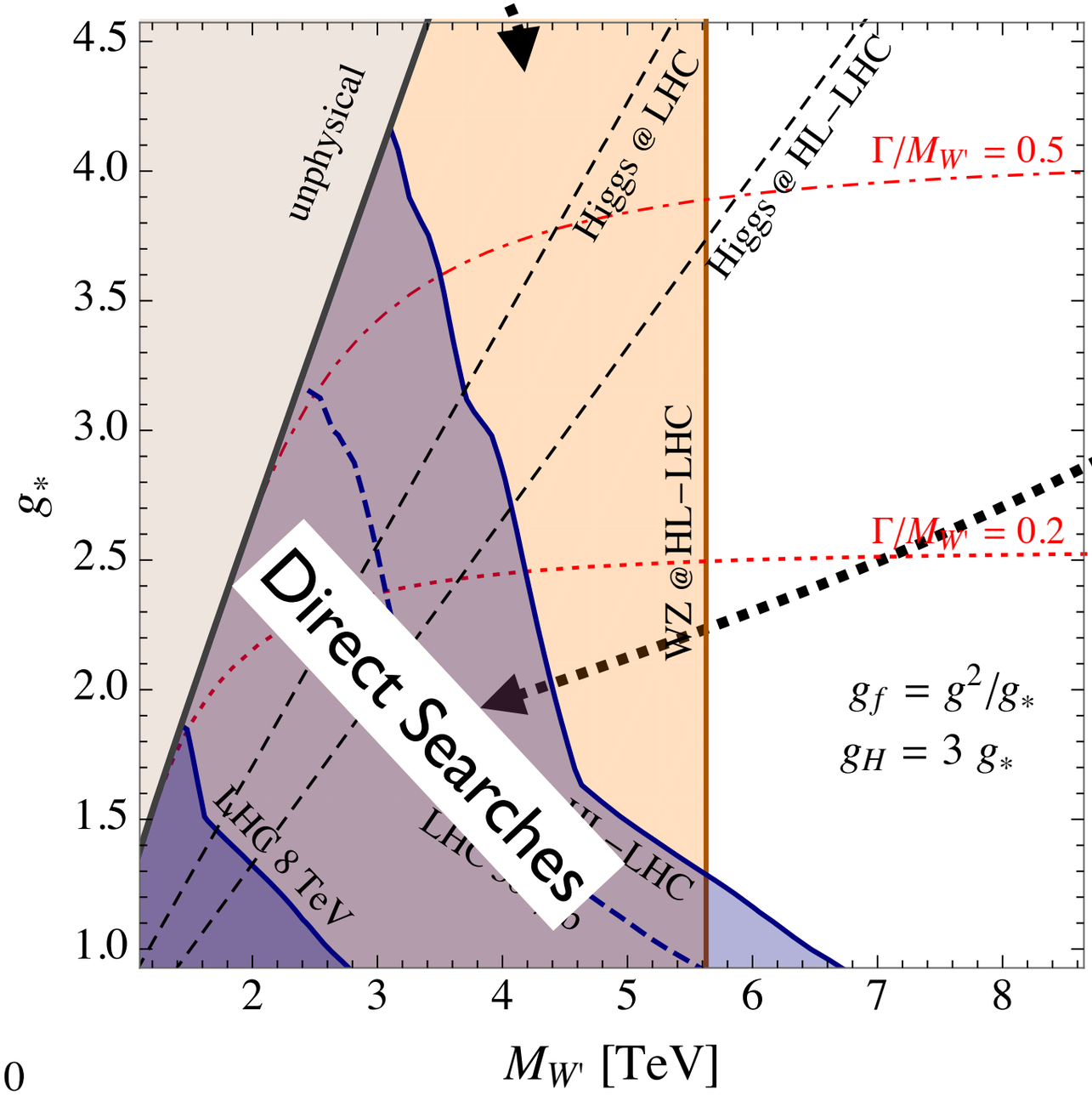
$$\delta\kappa^Z = \delta g_1^Z - t_W^2 \delta\kappa^\gamma$$

J.Baglio,S.Dawson,S.Homiller arXiv:1909.11576

"tail" vs "bump" competition







No winners: Complementary of **indirect** and **direct** searches

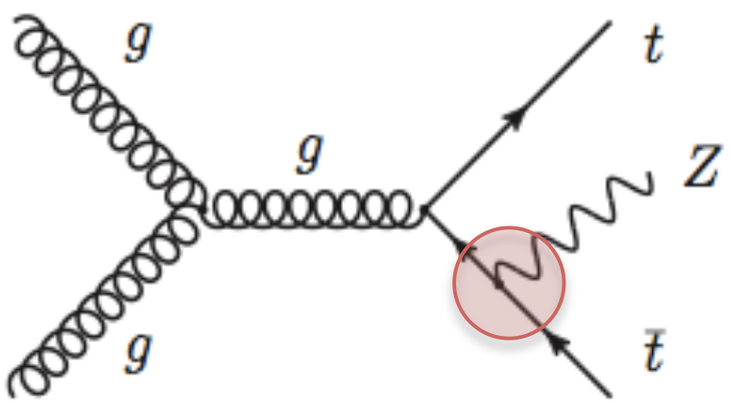
R. Franceschini, G.Panico,
AP, F. Riva, A. Wulzer arXiv:1712.01310

t_R : one of the less known state of the SM

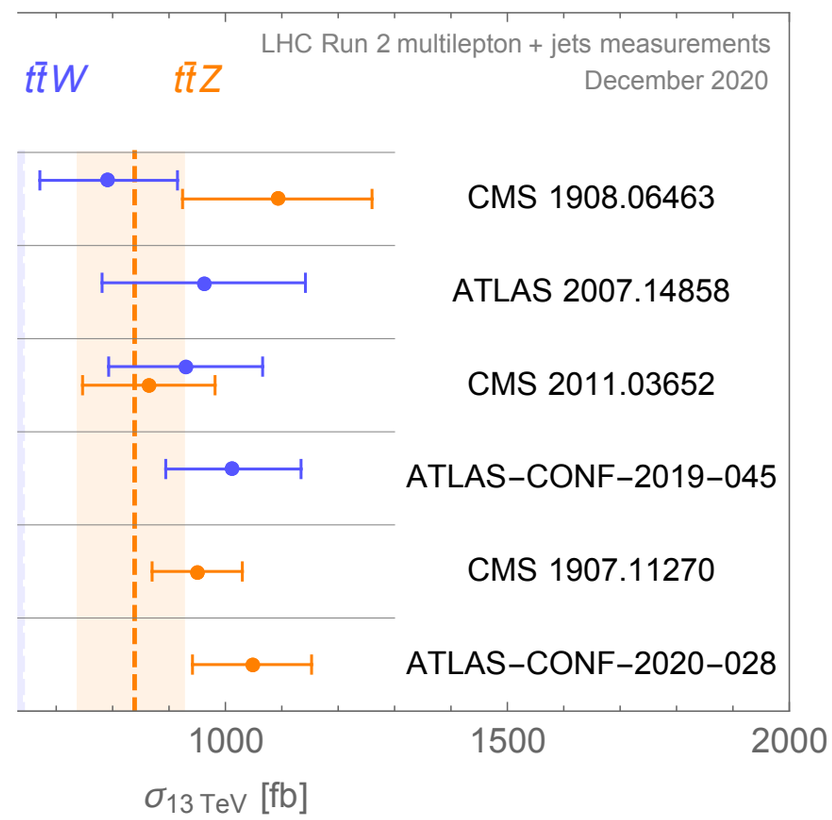
Even that we produce a lot of top pairs,
they do not provide much relevant information on the nature of t_R

SM EFT ☛ BSM encoded in $\delta g_{Zt_Rt_R}$ & $t_Rt_Rt_Rt_R$ contact-int.

- Zt_Rt_R difficult to bound:



no growth with energy



arXiv:2010.05915

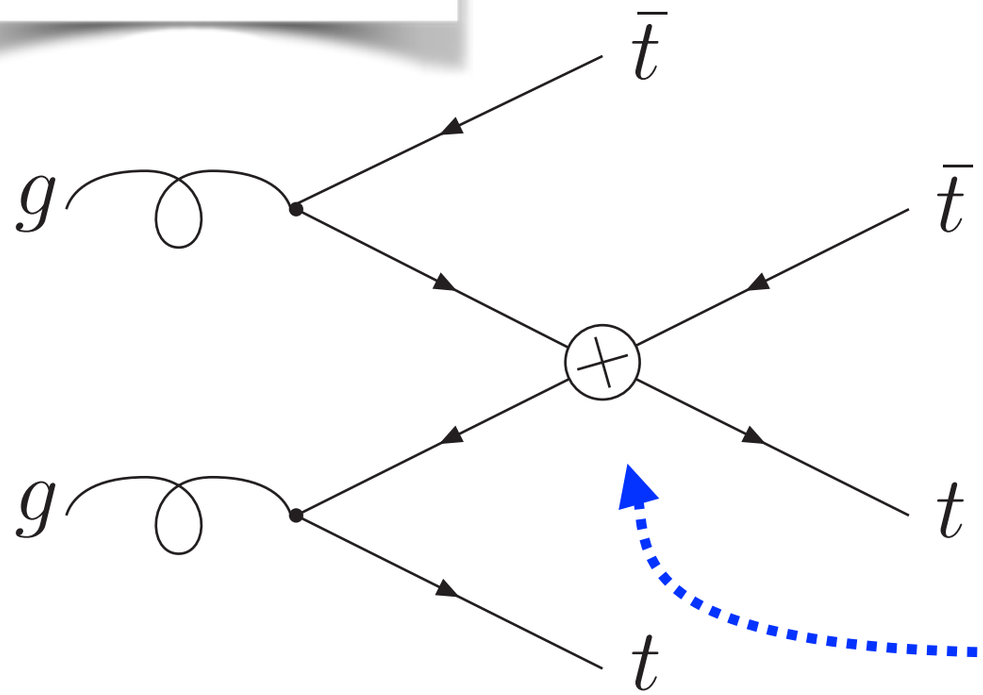
~some excess

- Best probe: 4 top contact-interaction:

$$pp \to t\bar{t}t\bar{t}$$ ☛ effects grow with E

AP,J.Serra, Phys.Rev.D78(2008)074026

$$pp \to t\bar{t}t\bar{t}$$



$$\frac{1}{\Lambda^2}(\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma^\mu t_R)$$

CMS: $\sigma_{t\bar{t}t\bar{t}} = 9.4^{+6.2}_{-5.6}$ fb

ATLAS: $\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}$ fb

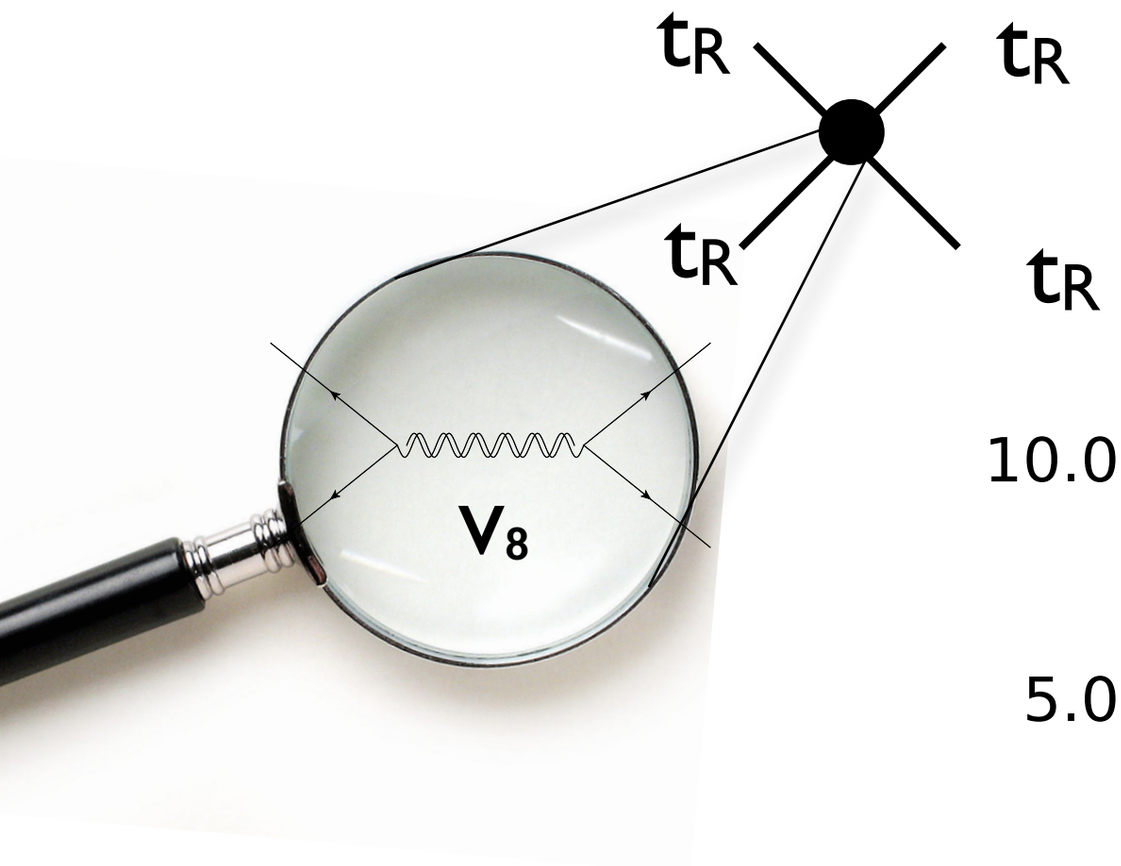
some excess

$\left(\sigma^{\rm SM}_{t\bar{t}t\bar{t}} = 12.0^{+18\%}_{-21\%}\right)$

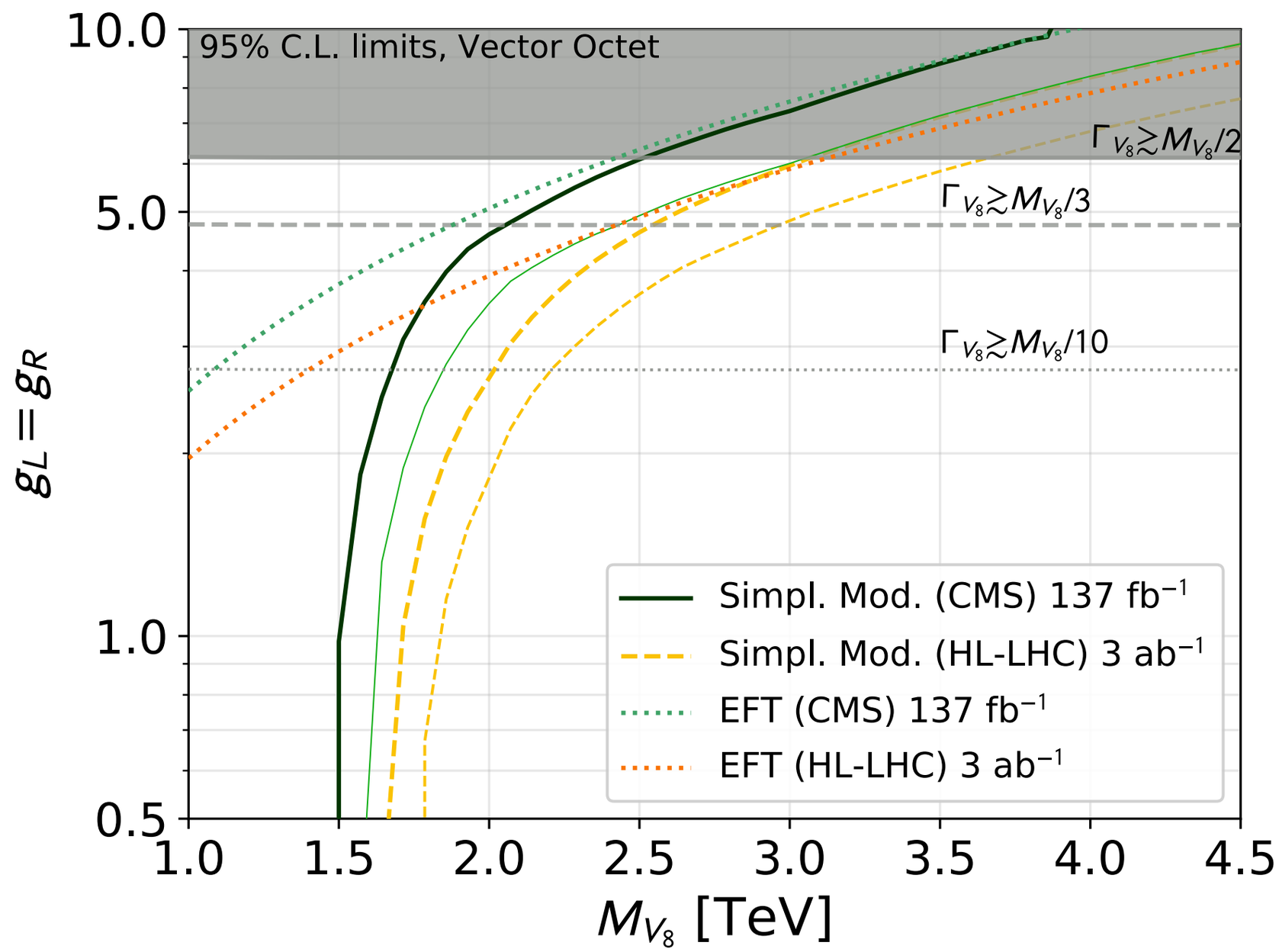
Present: $\Lambda \gtrsim$ 0.75 TeV

HL-LHC: $\Lambda \gtrsim$ 1.3 TeV

G.Banelli,E.Salvioni,J.Serra,T.Theil,A.Weiler arXiv:2010.05915



Example of bounds on particles generating 4-tops:



L.Darme, B.Fuks,F.Maltoni arXiv:2104.0951

Conclusions

- **The SM is an EFT:** dimension-6 interactions are there *waiting* to be discovered (not clear though at which scale)

- LHC main strong impact:
  Higgs couplings ⊕ top couplings ⊕ certain high-energy 2→2
  (e.g. di-lepton, di-bosons)

- No serious sign of deviations from the SM
  ☛ Important BSM constraints (susy, compositeness,…)

- **LCH legacy** on SM tests will be very useful & essential to understand future strategies

Null results are also important to make progress!
(e.g. Michelson-Morley)


RESTRICTED
AREA
NO UNAUTHORIZED
PERSONNEL
BEYOND THIS POINT