Durham seminar, 4th October 2018

Implications of Decoupling New Physics

Tevong You

UNIVERSITY OF CAMBRIDGE

The Branco Weiss Fellowship
Society in Science

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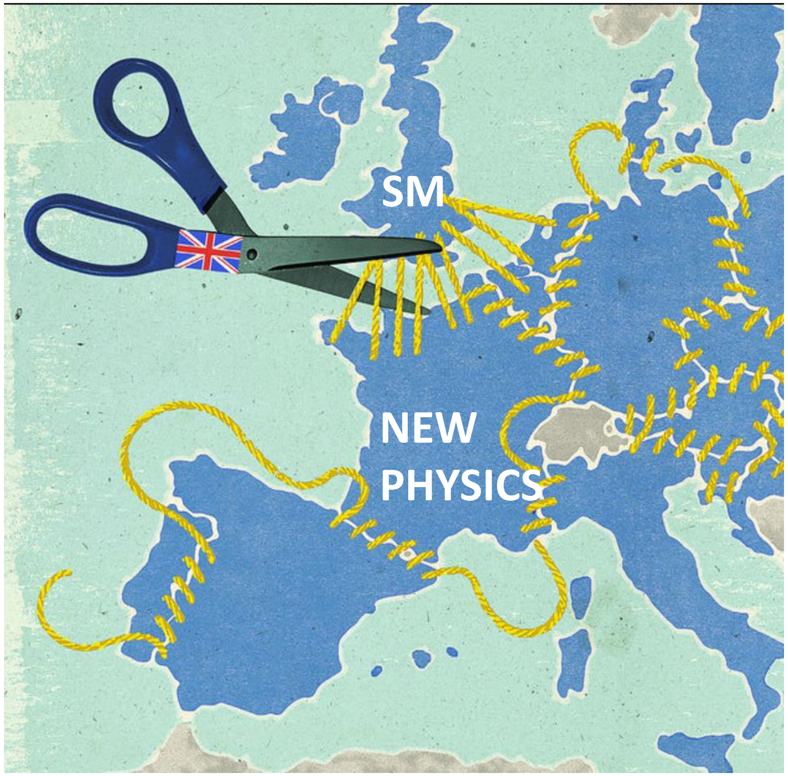
SMEXIT

Implications of decoupling new physics



Introduction

- **Soft** exit from the SM: New physics around the corner
  - Usual *low-scale SUSY/compositeness/extra-dimensions*… just a bit more fine-tuned
  - *Neutral naturalness/Twin Higgs*… hidden naturalising sector
- **Hard** exit from the SM: New physics decoupled
  - Accept fine-tuning while *SUSY/compositeness/extra-dimensions* resolve other problems at heavier scales
  - *Anthropic landscape, censorship-type approaches…*
  - *Cosmological relaxation, clockwork…*
- Phenomenological framework: **SM EFT**

Outline

- **Part I: SM EFT**
  - A phenomenological framework for decoupled new physics
- **Part 2: B Anomalies**
  - Signs of a non-zero Wilson coefficient?
- **Part 3: Cosmological Relaxation**
  - A new approach to decoupling new physics without fine-tuning

- **Part I: SM EFT**
- Part 2: B Anomalies
- Part 3: Cosmological Relaxation

Why SM EFT?

Include only experimentally discovered degrees of freedom in our theory

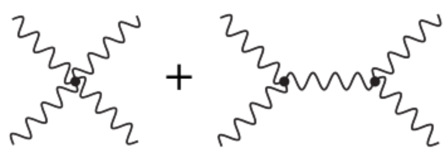
The TeV Scale

What effective theory captures everything we know experimentally about weak interactions?

1933–1982 4-fermion interactions

$\sim G_F E^2 \qquad \Rightarrow \; \Lambda \sim \text{TeV}$

1982–2011 SM without Higgs



$\sim \dfrac{g^2 E^2}{m_W^2} \quad \Rightarrow \; \Lambda \sim \text{TeV}$

2012-now SM + higher-dimension operators?

$\Rightarrow \Lambda \lesssim M_P?$

Markus Luty PASCOS 2015 slide

Why SM EFT?

Take a step back: recall the situation before 2012

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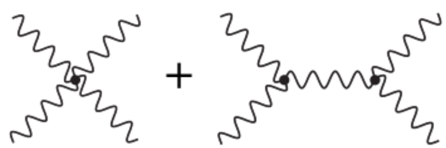

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2012-now SM + higher-dimension operators?

$\Rightarrow \Lambda \lesssim M_P$?

Markus Luty PASCOS 2015 slide

Beyond the Standard Model?

- A priori many ways to break electroweak symmetry!

- Technicolor
- 2HDM
- Higgs + SUSY
- NMSSM
- Composite 2HDM

- Fundamental Scalar (SM Higgs)
- Composite Higgs
- Extra Dimensions
- Walking Technicolor
- Little Higgs

- New scalars could also be something other than a Higgs

EFT for weak bosons

- **1980s-2012**: Discovery of weak bosons. Non-linear effective Lagrangian for spontaneously-broken global symmetry (*breaking mechanism unknown!)*

- Global symmetry-breaking pattern gives low-energy effective theory regardless of UV mechanism responsible for it

$$\boxed{SU(2) \times SU(2) \rightarrow SU(2)_V \qquad (\rho \equiv M_W/M_Z \cos\theta_w \sim 1)}$$

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma - m_i \bar{\psi}_L^i \Sigma \psi_R^i + \mathrm{h.c.}$$

$$\Sigma = \exp\left(i \frac{\sigma^a \pi^a}{v} \right)$$

EFT for weak bosons + scalar

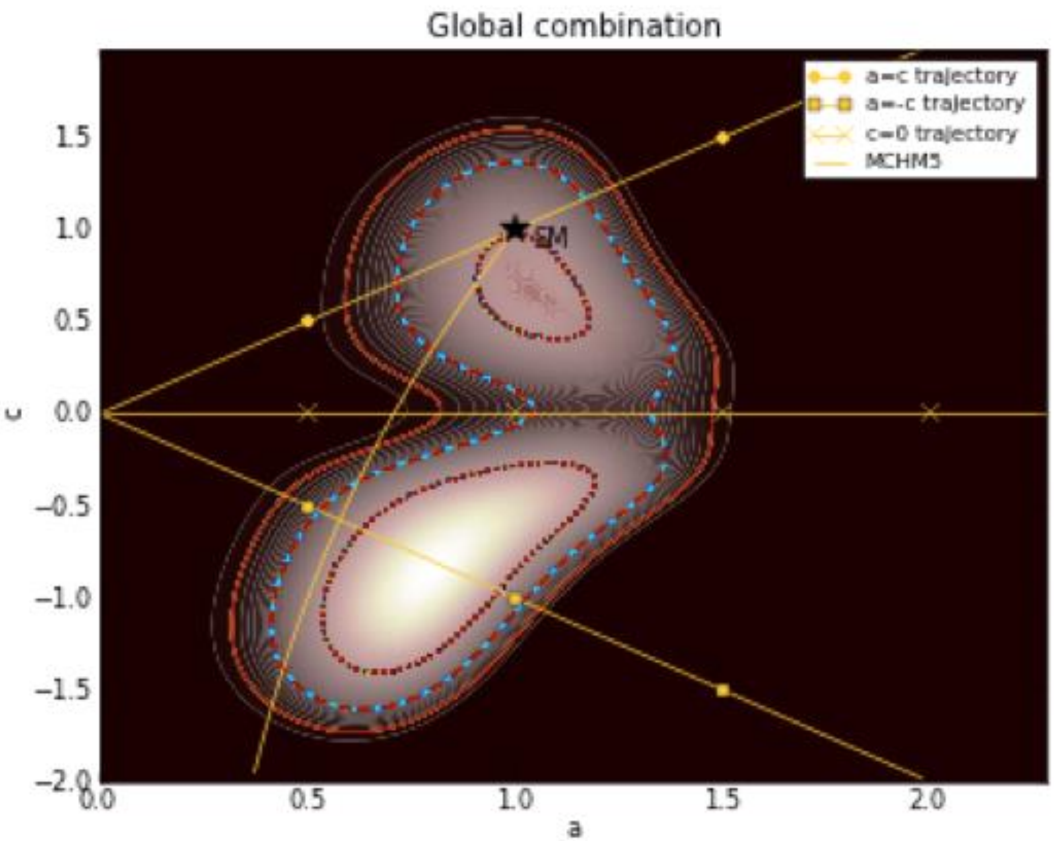
- 2012: Non-linear electroweak Lagrangian + general couplings to singlet scalar

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) - m_i\bar{\psi}^i_L\Sigma\left(1 + c\frac{h}{v} + \ldots\right)\psi^i_R + \mathrm{h.c.}$$
$$+ \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right)$$

Fit experimental data to couplings

- Could have had very different coupling



March 2012 pre-discovery
J. Ellis and T.Y. [arXiv:1204.0464]

Fit experimental data to couplings

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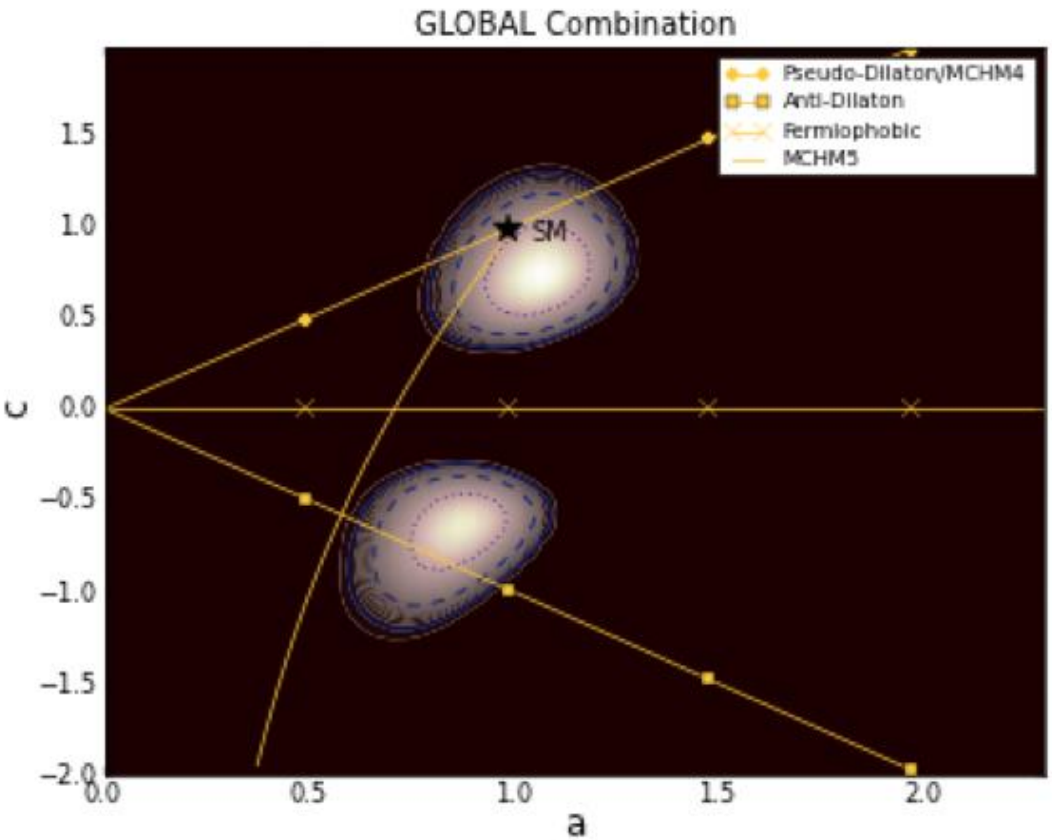

July 2012 post-discovery
J. Ellis and T.Y. [arXiv:1207.1693]

Fit experimental data to couplings

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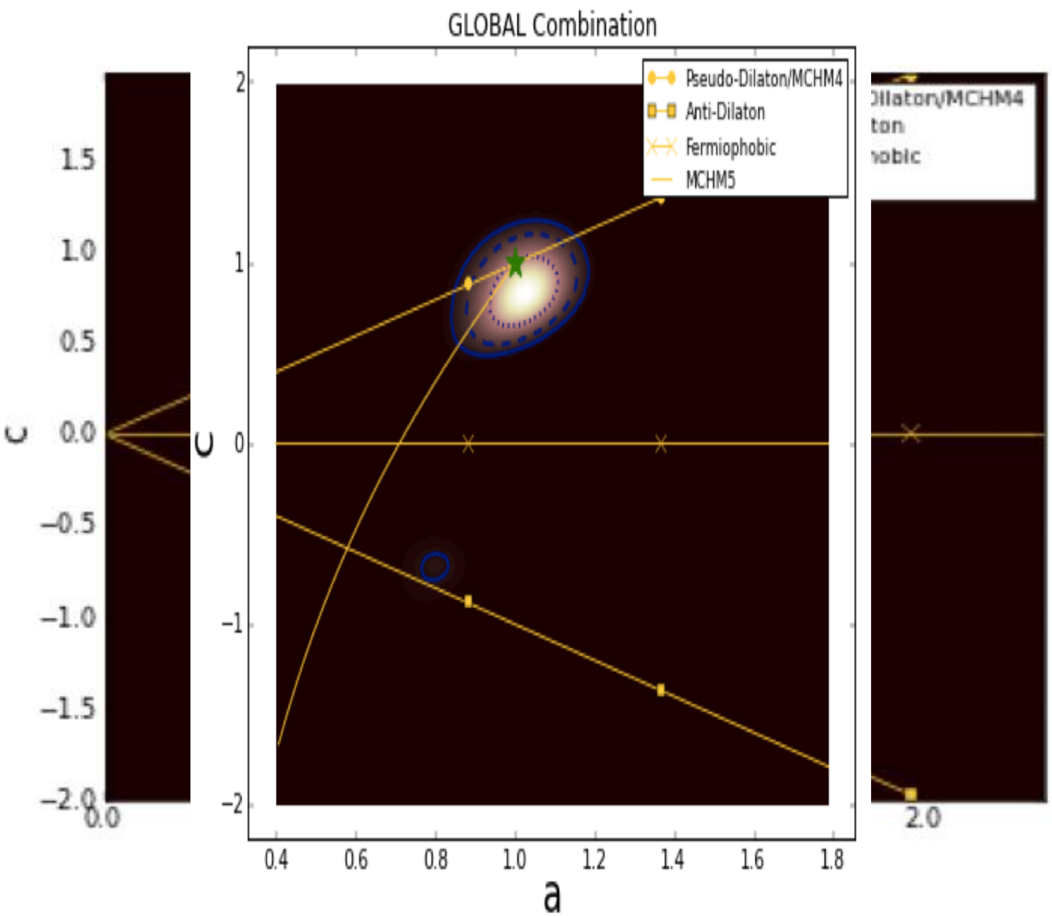

Moriond 2013

J. Ellis and T.Y. [arXiv:1303.1879]

Why SM EFT?

Assuming a SM Higgs and decoupled new physics at higher energies, the SM EFT is the next phenomenological framework

The TeV Scale

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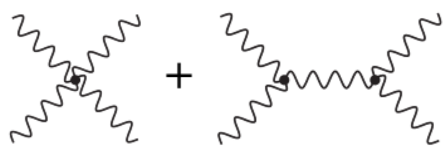

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2012-now SM + higher-dimension operators?

$\Rightarrow \Lambda \lesssim M_P$?

Markus Luty PASCOS 2015 slide

SMEFT framework

- New physics appear to be decoupled at higher energies
- Given particle content, write down *all* terms allowed by symmetries…

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
q_R^u	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$
q_R^d	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$
L_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
l_R	$\mathbf{1}$	$\mathbf{1}$	-1
ϕ	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R$$
$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu}$$
$$\mathcal{L}_H = (D_\mu^L\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$
$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q_R^d + y_u\bar{Q}_L\phi^c q_R^u + y_L\bar{L}_L\phi l_R + \text{h.c.} \quad ,$$

- …Including **higher-dimensional** operators!

$$+ \quad \boxed{\mathcal{L}_{\text{SM}}^{\text{dim-6}} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i}$$

- Generated by new physics at scale $\Lambda \gg v$

Tevong You (Cambridge)

SMEFT framework

- Unique dim-5 Weinberg operator, violates lepton number, predicts neutrino masses
- Modulo flavour structure, there are **59** dim-6 (CP-even) operators in a **non-redundant** basis

Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
Gradkowski et al [arXiv:1008.4884]

- ~**19** operators relevant for EWPT, TGC, and Higgs physics

EWPTs	Higgs Physics	TGCs
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$		
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$		$\mathcal{O}_{3W} = g\frac{\epsilon_{abc}}{3!} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	
$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	
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$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

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Combinations of operators constrained in EWPT more easily set to zero in Higgs and TGCs

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Operators constrained by measurements at per cent level or worse

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

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Operators benefit from per mille precision at LEP

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

LEP EWPT Example

- (Pseudo-)Observables

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_\ell + 3\Gamma_\nu \qquad R_\ell = \frac{\Gamma_{had}}{\Gamma_\ell} \qquad \sigma_{had} = 12\pi \frac{\Gamma_e \Gamma_{had}}{\hat{m}_Z^2 \Gamma_Z^2} \qquad A_{FB}^f = \frac{3}{4} A_e A_f \qquad M_W = c_W M_Z$$

$$R_q = \frac{\Gamma_q}{\Gamma_{had}}$$

- Depends on

$$\Gamma_f = \frac{\sqrt{2} G_F M_Z^2 \hat{M}_Z}{6\pi}\left[(g_L^f)^2 + (g_R^f)^2\right] \qquad A_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

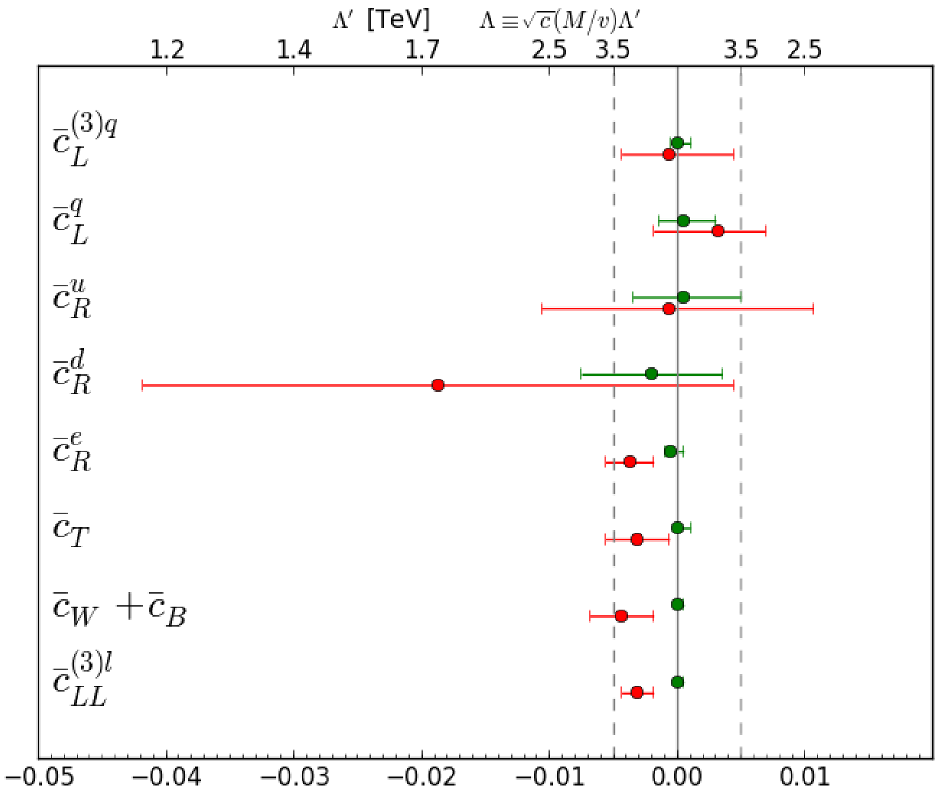
$$g^f = T_f^3 - Q_f s_W^2 \qquad s_W^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2}}$$

- Dim-6 operators can modify observables directly through Zff couplings contributions or indirectly through redefinitions of input observables

$$m_Z^2 = (m_Z^2)^0 (1 + \Pi_{ZZ}) \qquad G_F = G_F^0 (1 - \Pi_{WW}^0) \qquad \alpha(m_Z) = \alpha^0(m_Z)(1 + \Pi'_{\gamma\gamma})$$

LEP EWPT Example

- Individual (green) and marginalised (red) 95% CL limits



Ellis, Sanz and T.Y. 1410.7703

- 8 (combinations of) operators probed by EWPT

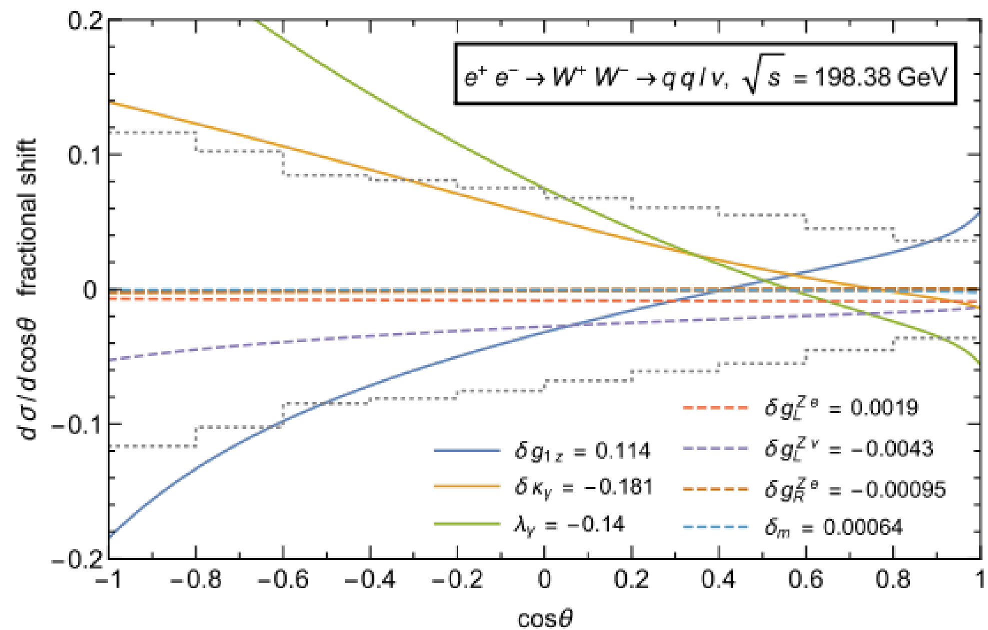
Triple-Gauge-Couplings in Diboson

- Assume SM Z and W couplings to fermions in diboson measurements
- Interpret in anomalous TGC framework:

$$\begin{aligned}\mathcal{L}_{\rm TGC} =& \\ & ig\left\{(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})\left[(1+\delta g_{1z})\,c_\theta Z^\nu + s_\theta A^\nu\right]\right. \\ & +\frac{1}{2}W^+_{[\mu,}W^-_{\nu]}\left[(1+\delta\kappa_z)\,c_\theta Z^{\mu\nu} + (1+\delta\kappa_\gamma)\,s_\theta A^{\mu\nu}\right] \\ & \left.+\frac{1}{m_W^2}W_\mu^{+\nu}W_\nu^{-\rho}(\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu)\right\},\end{aligned}$$

Z. Zhang, 1610.01618

- Justified at LEP:



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$$
\begin{aligned}
\mathcal{L}_{\mathrm{TGC}} = \\
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& + \frac{1}{m_W^2} W_\mu^{+\nu} W_\nu^{-\rho} (\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu) \Big\},
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$$

Z. Zhang, 1610.01618

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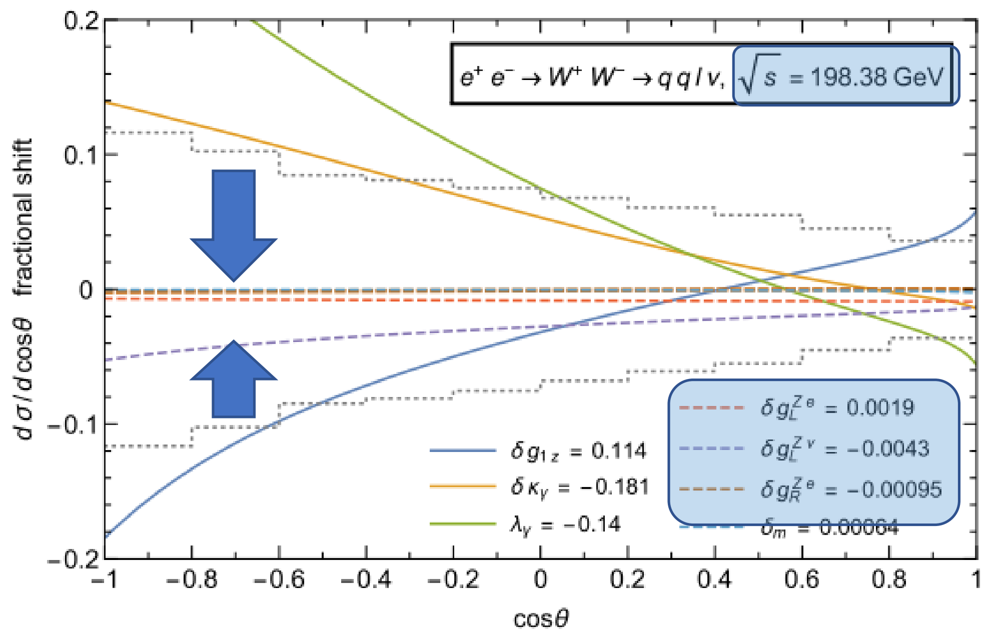

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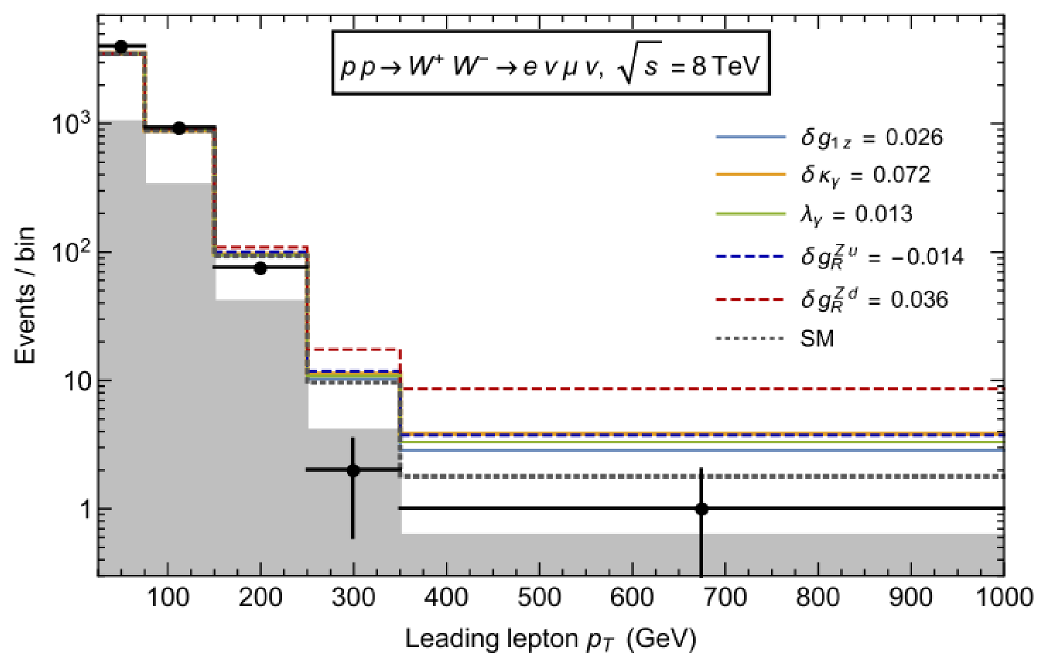
$$\mathcal{L}_{\mathrm{TGC}} = ig\Big\{(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})\big[(1+\delta g_{1z})\,c_\theta Z^\nu + s_\theta A^\nu\big] + \frac{1}{2}W^+_{[\mu,}W^-_{\nu]}\big[(1+\delta\kappa_z)\,c_\theta Z^{\mu\nu} + (1+\delta\kappa_\gamma)\,s_\theta A^{\mu\nu}\big] + \frac{1}{m_W^2}W_\mu^{+\nu}W_\nu^{-\rho}(\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu)\Big\},$$

- But not at high pT:

Z. Zhang, 1610.01618



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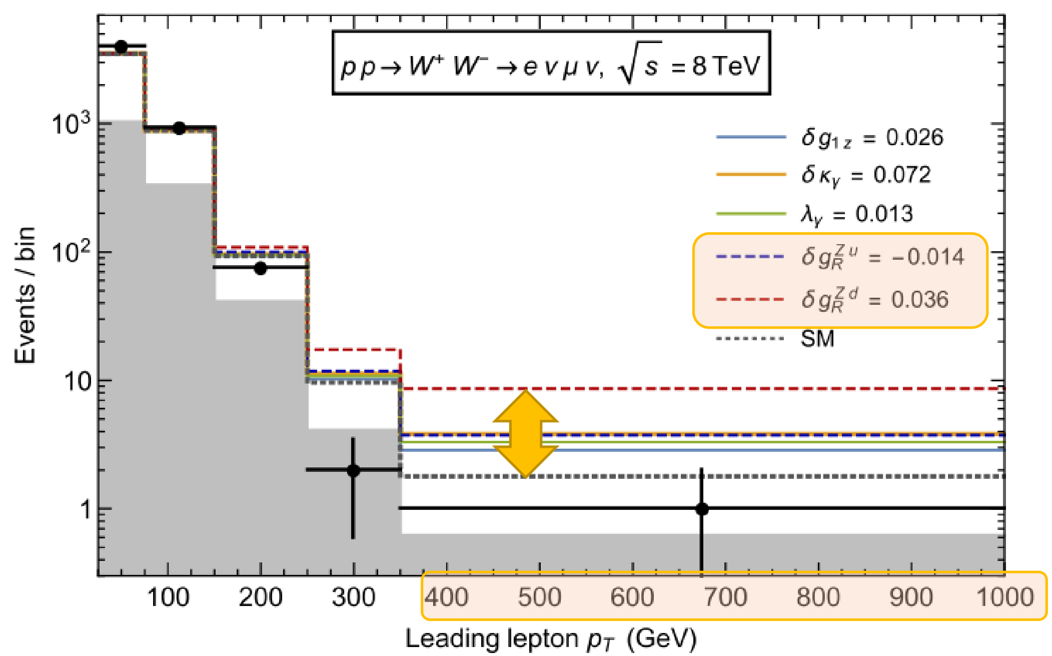
- But not at high pT:

Note: quadratic dim-6 effect unless diboson SM-BSM interference recovered

Azatov et al 1607.05236, 1707.08060, Panico, Riva, Wulzer 1708.07823, Bellazzini, Riva 1806.09640

Z. Zhang, 1610.01618



Updated Global SMEFT Fit

J. Ellis, C. Murphy, V. Sanz and TY, 1803.03252

- Combine **EWPT, diboson, Higgs** data
- Fit to 20 dim-6 CP-even operators **simultaneously**
- Present results in **Warsaw** and **SILH** basis
- Match to **simplified models**

Updated Global SMEFT Fit

- SILH basis

$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}}^{\text{SILH}} \supset\ & \frac{\bar{c}_W}{m_W^2}\frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu} + \frac{\bar{c}_B}{m_W^2}\frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu} + \frac{\bar{c}_T}{v^2}\frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
& + \frac{\bar{c}_{ll}}{v^2} 2(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L) + \frac{\bar{c}_{He}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R) + \frac{\bar{c}_{Hu}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R) \\
& + \frac{\bar{c}_{Hd}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R) + \frac{\bar{c}'_{Hq}}{v^2}(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L) \\
& + \frac{\bar{c}_{Hq}}{v^2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L) + \frac{\bar{c}_{HW}}{m_W^2} ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu} + \frac{\bar{c}_{HB}}{m_W^2} ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_{3W}}{m_W^2} g^3\epsilon_{abc}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu} + \frac{\bar{c}_g}{m_W^2} g_s^2|H|^2 G^A_{\mu\nu}G^{A\mu\nu} + \frac{\bar{c}_\gamma}{m_W^2} g'^2|H|^2 B_{\mu\nu}B^{\mu\nu} \\
& + \frac{\bar{c}_H}{v^2}\frac{1}{2}(\partial^\mu|H|^2)^2 - \sum_{f=e,u,d}\frac{\bar{c}_f}{v^2} y_f|H|^2\bar{F}_L H^{(c)} f_R \\
& + \frac{\bar{c}_{3G}}{m_W^2} g_s^3 f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho - \frac{\bar{c}_{uG}}{m_W^2} 4 g_s y_u H^\dagger\cdot\bar{Q}_L\gamma^{\mu\nu}T_a u_R G^A_{\mu\nu}\,. \qquad (6)
\end{aligned}
$$

Updated Global SMEFT Fit

- Warsaw basis

$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}}^{\text{Warsaw}} \supset\ & \frac{\bar{C}^{(3)}_{Hl}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}^{(1)}_{Hl}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l) \\
&+ \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2} H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu} \\
&+ \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d) \\
&+ \frac{\bar{C}^{(3)}_{Hq}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}^{(1)}_{Hq}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}}^{\text{Warsaw}} \supset\ & \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H}) \\
&+ \frac{\bar{C}_G}{v^2} f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\, G^A_{\mu\nu} \\
&+ \frac{\bar{C}_{HW}}{v^2} H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2} H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2} H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.
\end{aligned}
$$

Observables

- LEP and SLC EWPTs, M_W from ATLAS, Tevatron

Observable	Measurement	Ref.	SM Prediction	Ref.
Γ_Z [GeV]	2.4952 ± 0.0023	[39]	2.4943 ± 0.0005	[38]
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	[39]	41.488 ± 0.006	[38]
R^0_ℓ	20.767 ± 0.025	[39]	20.752 ± 0.005	[38]
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	[39]	0.01622 ± 0.00009	[114]
$\mathcal{A}_\ell\,(P_\tau)$	0.1465 ± 0.0033	[39]	0.1470 ± 0.0004	[114]
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	[39]	0.1470 ± 0.0004	[114]
R^0_b	0.021629 ± 0.00066	[39]	0.2158 ± 0.00015	[38]
R^0_c	0.1721 ± 0.0030	[39]	0.17223 ± 0.00005	[38]
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	[39]	0.1031 ± 0.0003	[114]
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	[39]	0.0736 ± 0.0002	[114]
$\mathcal{A}_b$	0.923 ± 0.020	[39]	0.9347	[114]
$\mathcal{A}_c$	0.670 ± 0.027	[39]	0.6678 ± 0.0002	[114]
M_W [GeV]	80.387 ± 0.016	[40]	80.361 ± 0.006	[114]
M_W [GeV]	80.370 ± 0.019	[94]	80.361 ± 0.006	[114]

- LEP WW measurements
- ATLAS WW high pT overflow bin

Observables

- ATLAS+CMS Higgs Run 1

Production	Decay	Signal Strength	Production	Decay	Signal Strength
ggF	$\gamma\gamma$	$1.10^{+0.23}_{-0.22}$	Wh	$\tau\tau$	-1.4 ± 1.4
ggF	ZZ	$1.13^{+0.34}_{-0.31}$	Wh	bb	1.0 ± 0.5
ggF	WW	0.84 ± 0.17	Zh	$\gamma\gamma$	$0.5^{+3.0}_{-2.5}$
ggF	$\tau\tau$	1.0 ± 0.6	Zh	WW	$5.9^{+2.6}_{-2.2}$
VBF	$\gamma\gamma$	1.3 ± 0.5	Zh	$\tau\tau$	$2.2^{+2.2}_{-1.8}$
VBF	ZZ	$0.1^{+1.1}_{-0.6}$	Zh	bb	0.4 ± 0.4
VBF	WW	1.2 ± 0.4	tth	$\gamma\gamma$	$2.2^{+1.6}_{-1.3}$
VBF	$\tau\tau$	1.3 ± 0.4	tth	WW	$5.0^{+1.8}_{-1.7}$
Wh	$\gamma\gamma$	$0.5^{+1.3}_{-1.2}$	tth	$\tau\tau$	$-1.9^{+3.7}_{-3.3}$
Wh	WW	$1.6^{+1.2}_{-1.0}$	tth	bb	1.1 ± 1.0
pp	$Z\gamma$	$2.7^{+4.6}_{-4.5}$	pp	$\mu\mu$	0.1 ± 2.5

Observables

- ATLAS+CMS Higgs Run 2

	Production	Decay	Sig. Stren.		Production	Decay	Sig. Stren.
[96]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$	[105]	pp	$\mu\mu$	-0.1 ± 1.4
[97]	Zh	$b\bar{b}$	0.9 ± 0.5	[106]	Zh	$b\bar{b}$	$0.69^{+0.35}_{-0.31}$
[97]	Wh	$b\bar{b}$	1.7 ± 0.7	[106]	Wh	$b\bar{b}$	$1.21^{+0.45}_{-0.42}$
[98]	$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$	[107]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[99]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	[108]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[99]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	[108]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[99]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	[108]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[100]	$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$	[108]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[100]	$t\bar{t}h$	3ℓ	$1.0^{+0.8}_{-0.7}$	[108]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[100]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$	[108]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[101]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[109]	VBF	WW	$1.7^{+1.1}_{-0.9}$
[101]	1-jet	WW	1.1 ± 0.4	[109]	Wh	WW	$3.2^{+4.4}_{-4.2}$
[101]	2-jet	WW	1.3 ± 1.0	[110]	$\mathrm{B}(h \to \gamma\gamma)/\ \mathrm{B}(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[101]	VBF 2-jet	WW	1.4 ± 0.8	[110]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[101]	Vh 2-jet	WW	$2.1^{+2.3}_{-2.2}$	[110]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[101]	Wh 3-lep	WW	-1.4 ± 1.5	[110]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[102]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[110]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[102]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[110]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[102]	$t\bar{t}h$	$\gamma\gamma$	2.2 ± 0.9	[110]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[102]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[110]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[103]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$	[110]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[104]	0-jet	$\tau\tau$	0.84 ± 0.89	[110]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[104]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$				
[104]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$				

Observables

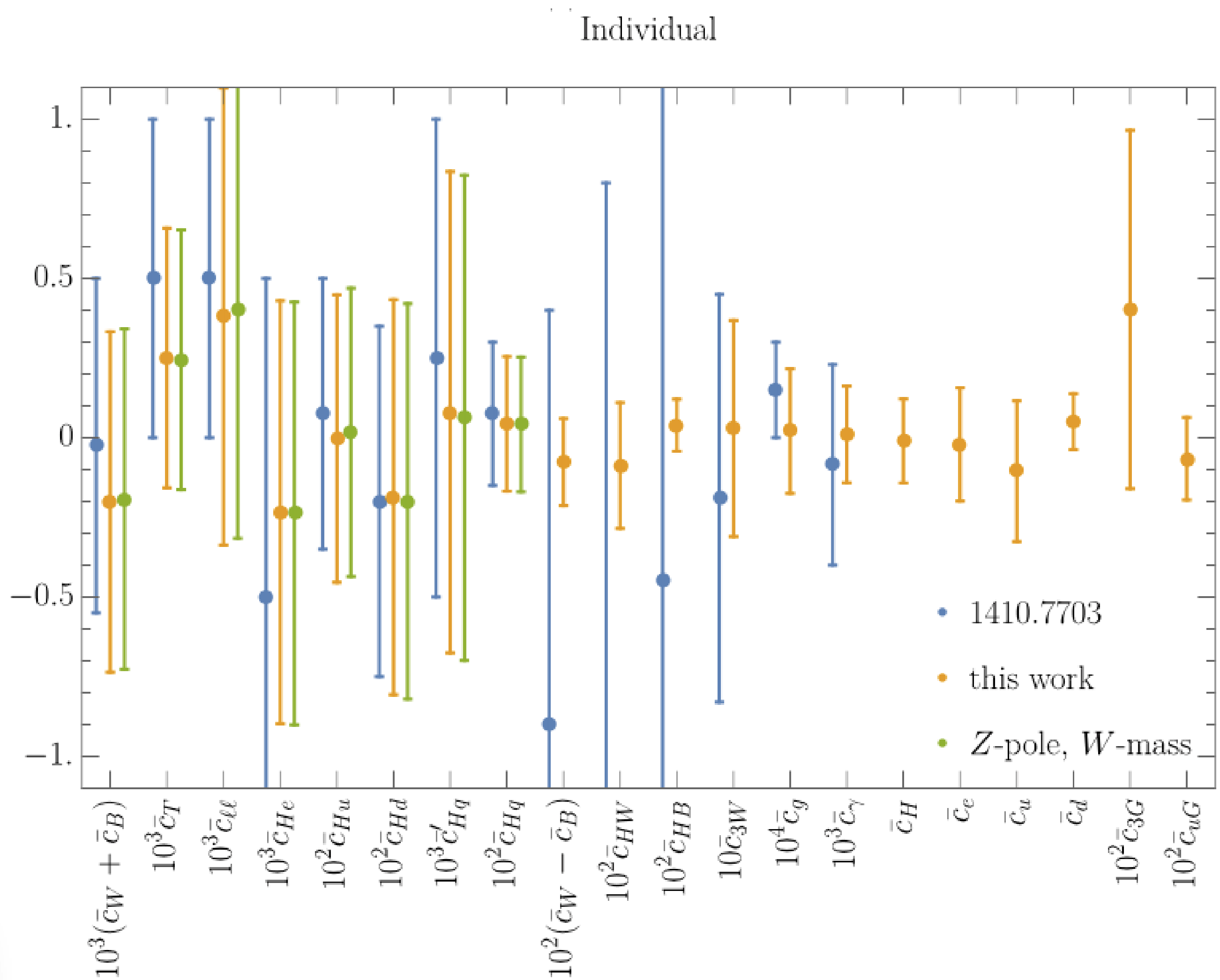
- ATLAS+CMS Higgs Run 2

Including kinematical information facilitated by **STXS**

	Production	Decay	Sig. Stren.		Production	Decay	Sig. Stren.
[96]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$	[105]	pp	$\mu\mu$	-0.1 ± 1.4
[97]	Zh	$b\bar{b}$	0.9 ± 0.5	[106]	Zh	$b\bar{b}$	$0.69^{+0.35}_{-0.31}$
[97]	Wh	$b\bar{b}$	1.7 ± 0.7	[106]	Wh	$b\bar{b}$	$1.21^{+0.45}_{-0.42}$
[98]	$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$	[107]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[99]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	[108]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[99]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	[108]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[99]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	[108]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[100]	$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$	[108]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[100]	$t\bar{t}h$	3ℓ	$1.0^{+0.8}_{-0.7}$	[108]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[100]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$	[108]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[101]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[109]	VBF	WW	$1.7^{+1.1}_{-0.9}$
[101]	1-jet	WW	1.1 ± 0.4	[109]	Wh	WW	$3.2^{+4.4}_{-4.2}$
[101]	2-jet	WW	1.3 ± 1.0	[110]	$\mathrm{B}(h \to \gamma\gamma)/\ \mathrm{B}(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[101]	VBF 2-jet	WW	1.4 ± 0.8	[110]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[101]	Vh 2-jet	WW	$2.1^{+2.3}_{-2.2}$	[110]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[101]	Wh 3-lep	WW	-1.4 ± 1.5	[110]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[102]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[110]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[102]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[110]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[102]	$t\bar{t}h$	$\gamma\gamma$	2.2 ± 0.9	[110]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[102]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[110]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[103]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$	[110]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[104]	0-jet	$\tau\tau$	0.84 ± 0.89	[110]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[104]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$				
[104]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$				

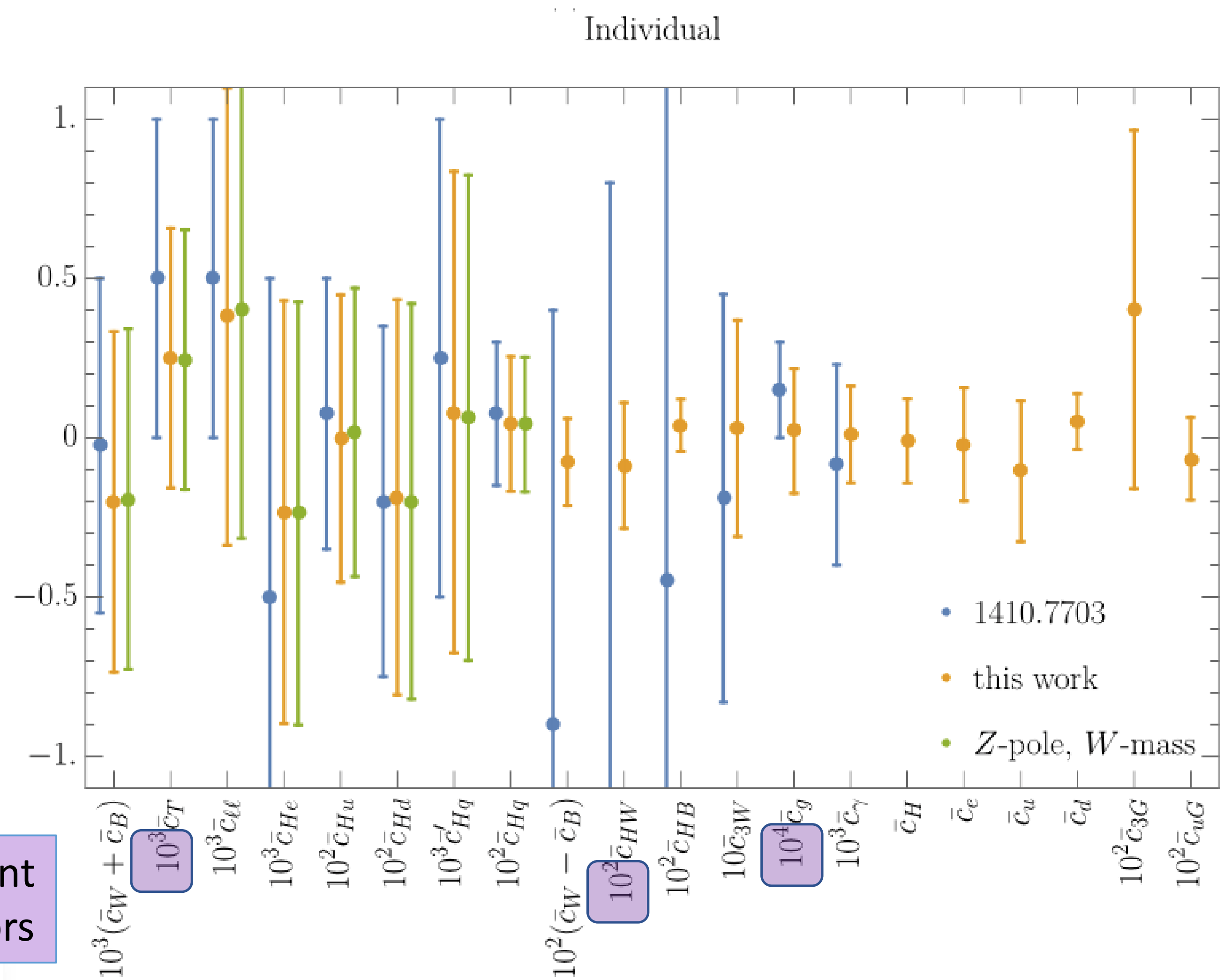
Results

- **SILH** basis, fit each operator **individually**



Results

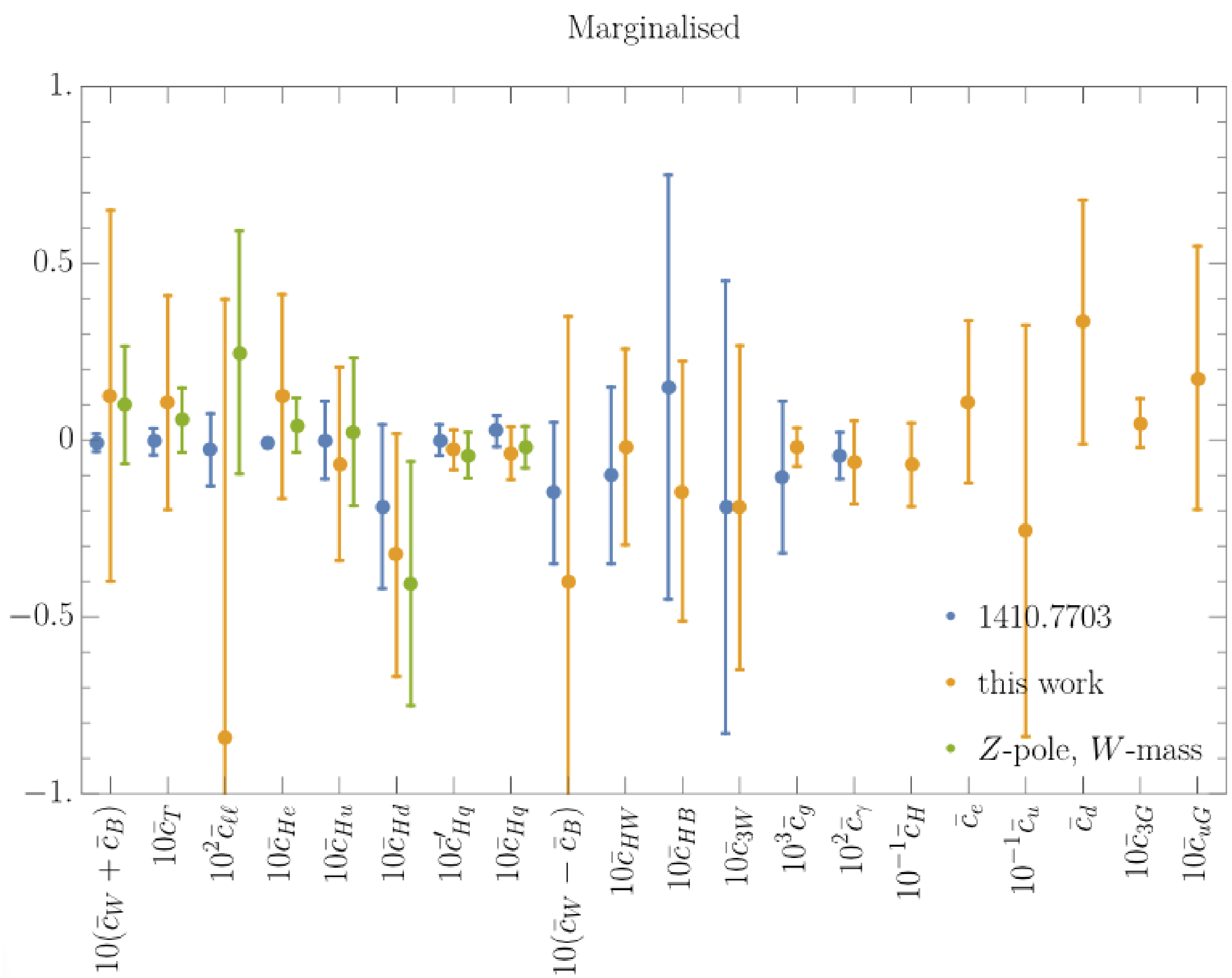
- **SILH** basis, fit each operator **individually**



Note different scaling factors

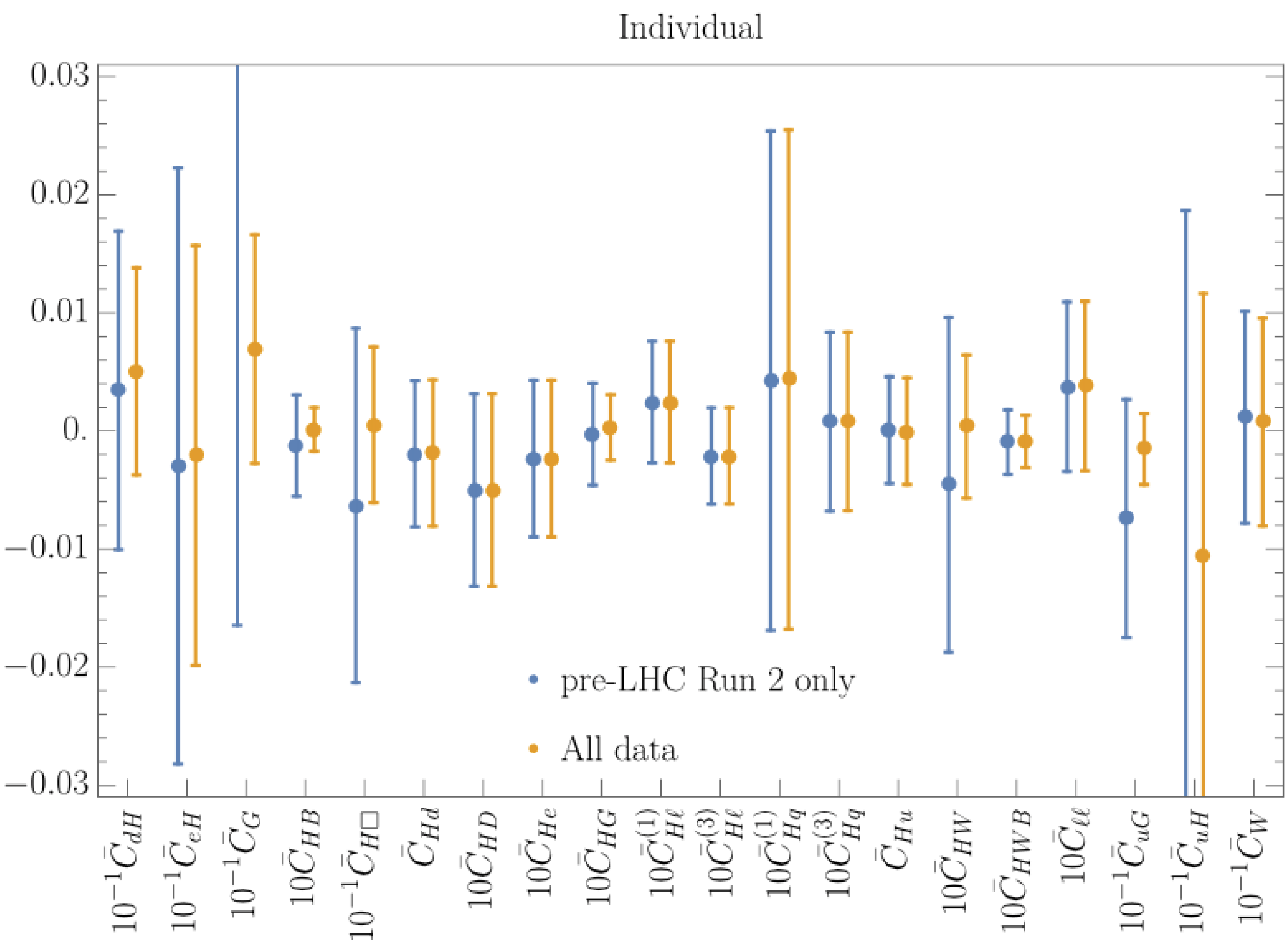
Results

- **SILH** basis, fit *all* operators **simultaneously**



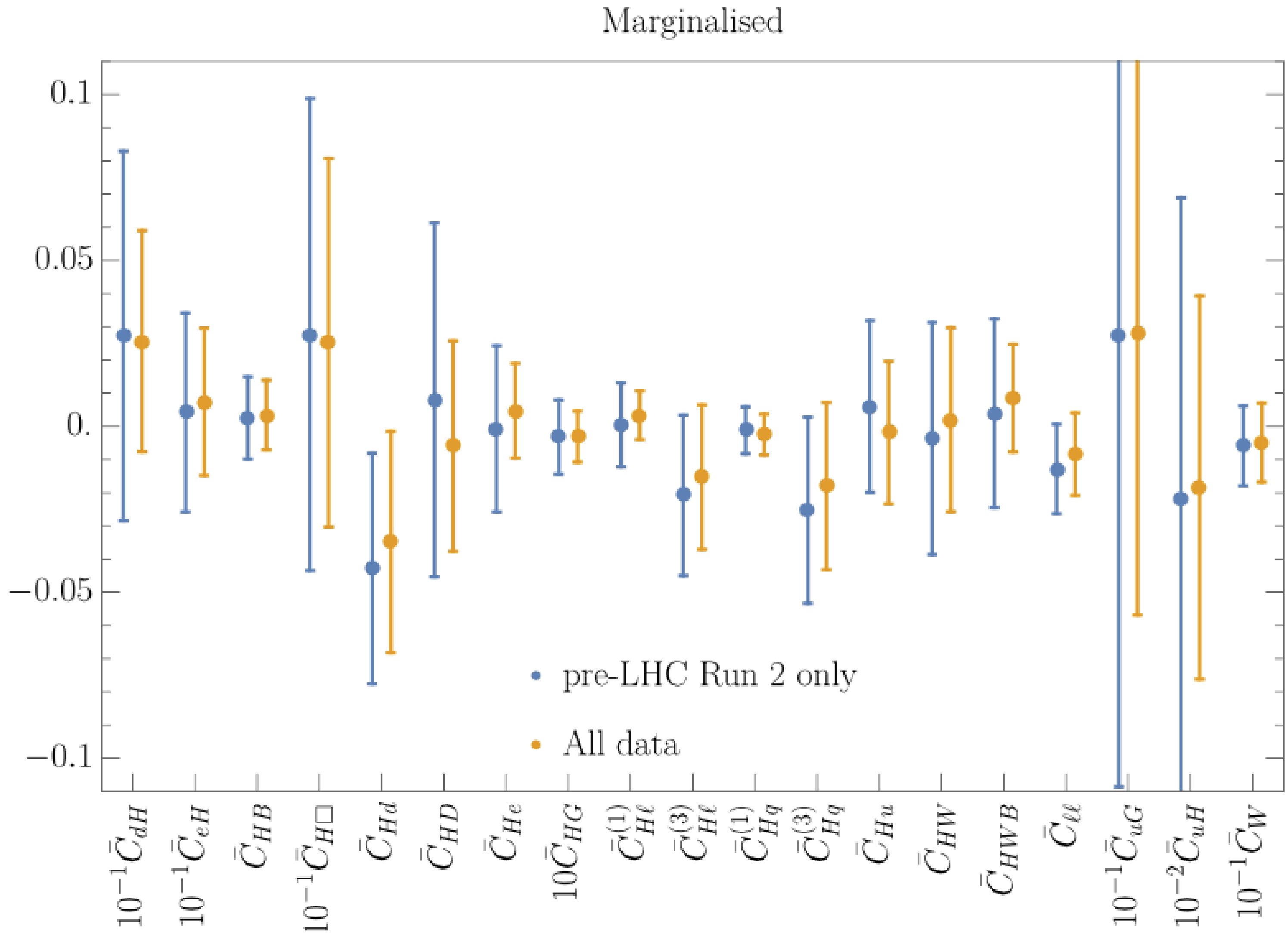
Results

- **Warsaw** basis, fit each operator **individually**



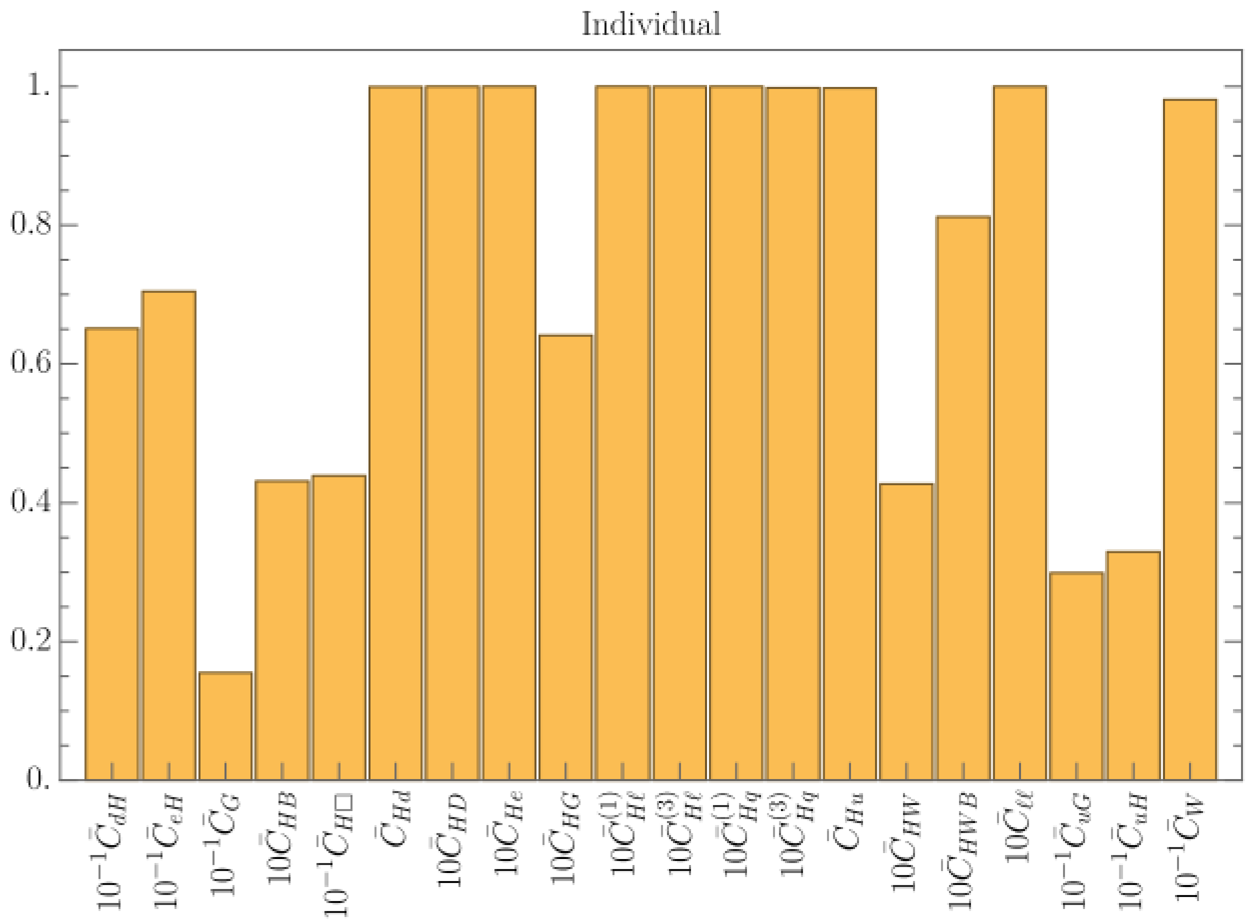
Results

- **Warsaw** basis, fit *all* operators **simultaneously**



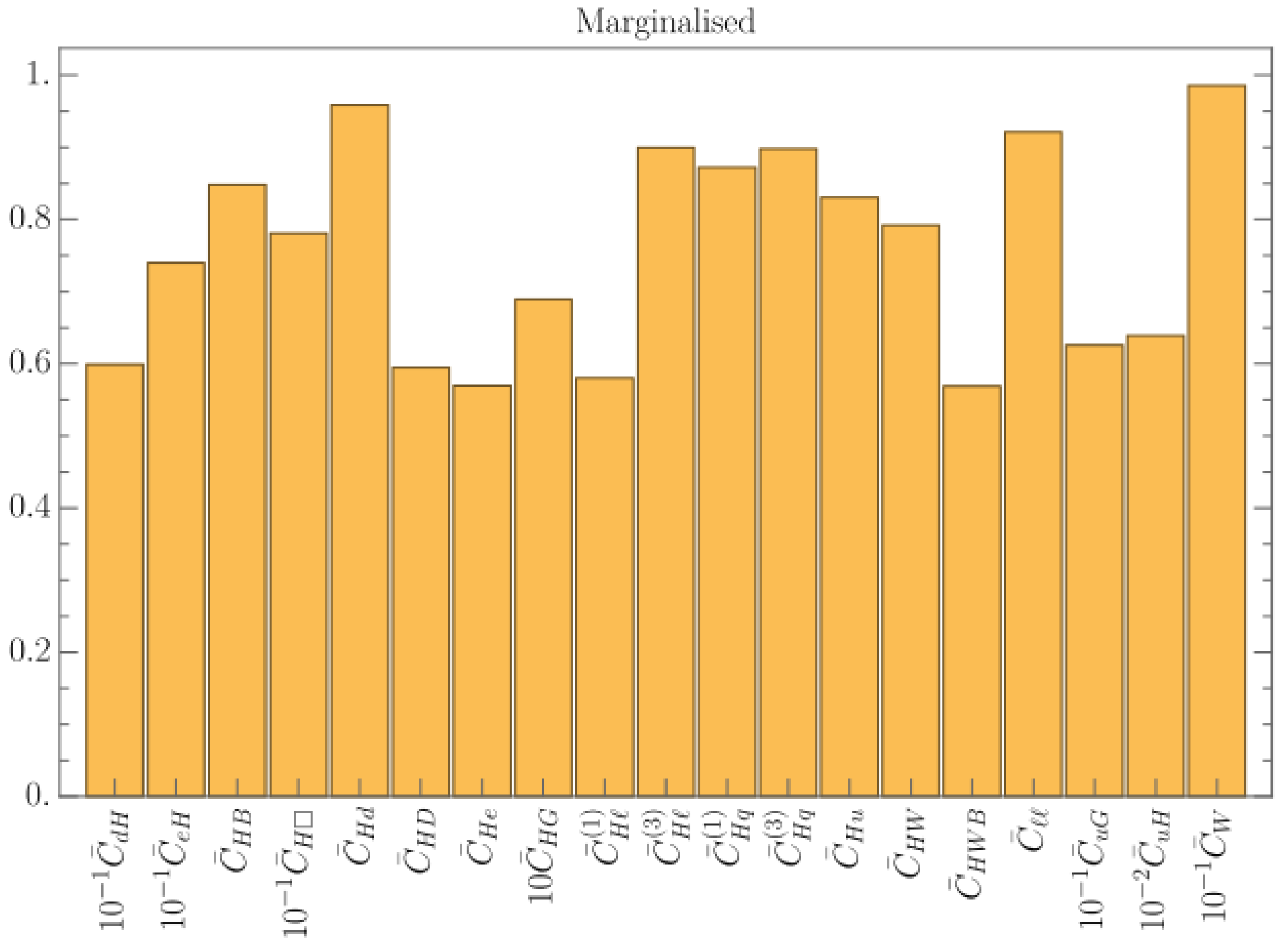
Results

- **Warsaw** basis, improvement from Run 1 to 2 (lower is better) for **individual** fit



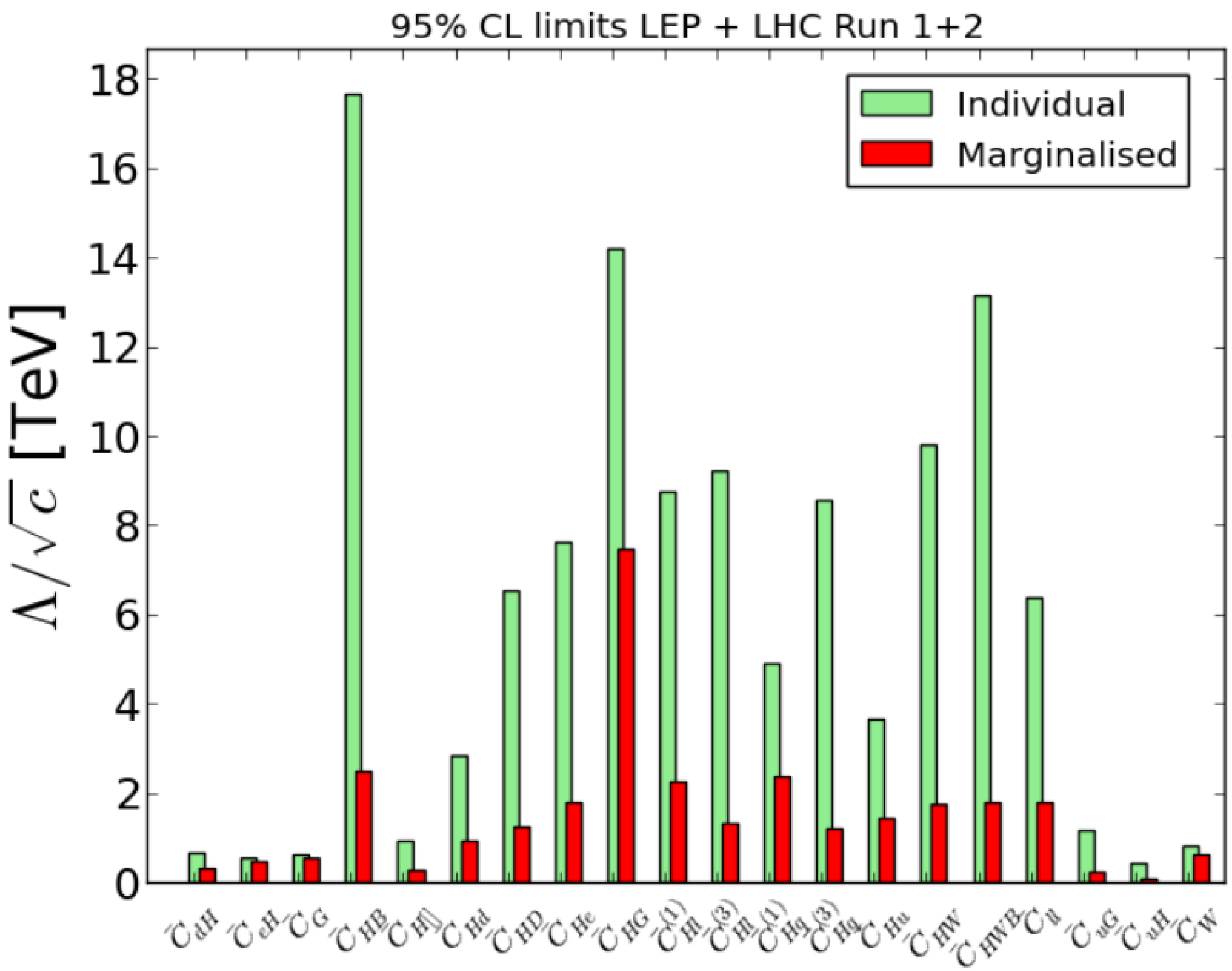
Results

- **Warsaw** basis, improvement from Run 1 to 2 (lower is better) for **marginalised** fit



Results

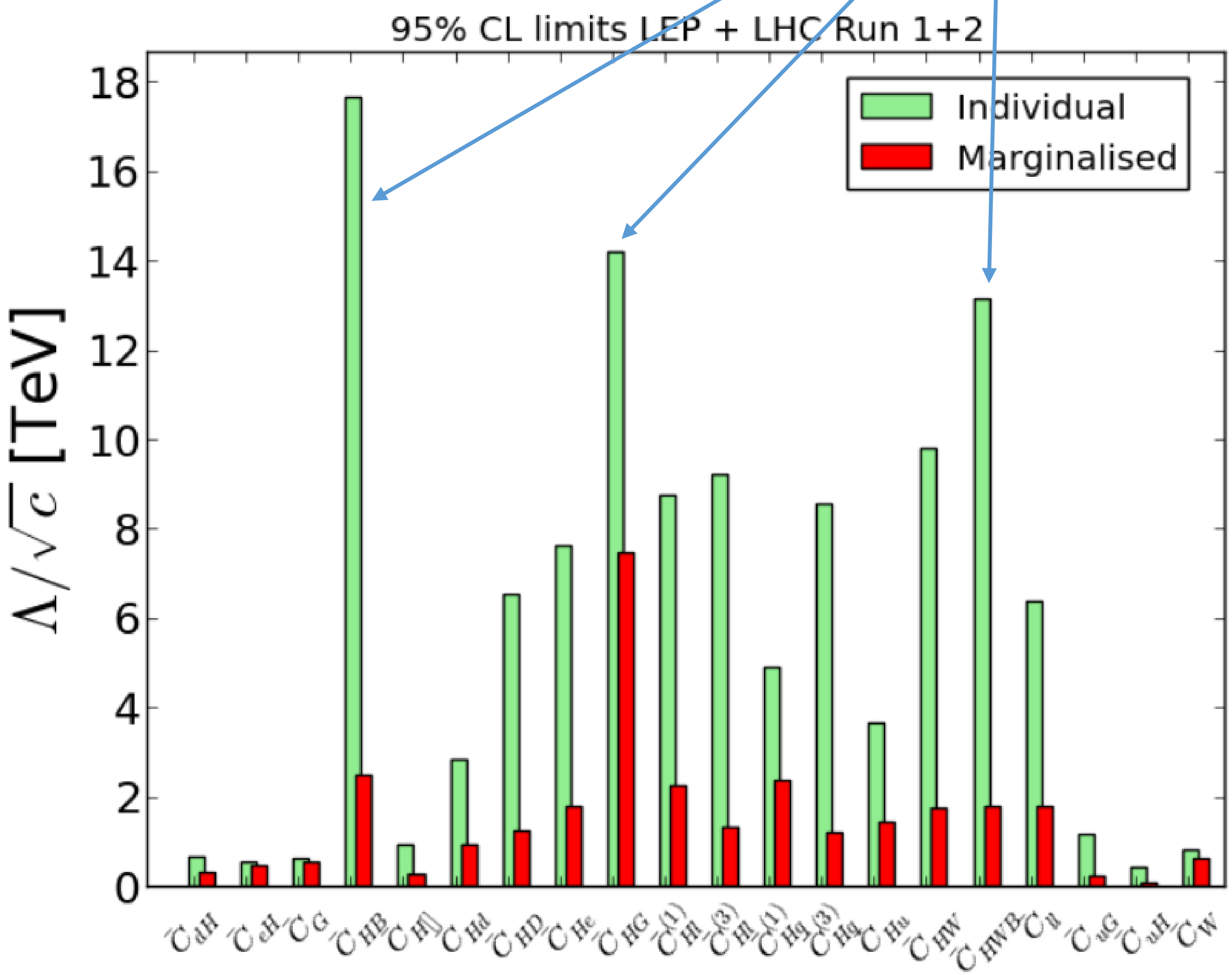
- **Warsaw** basis, summary



Results

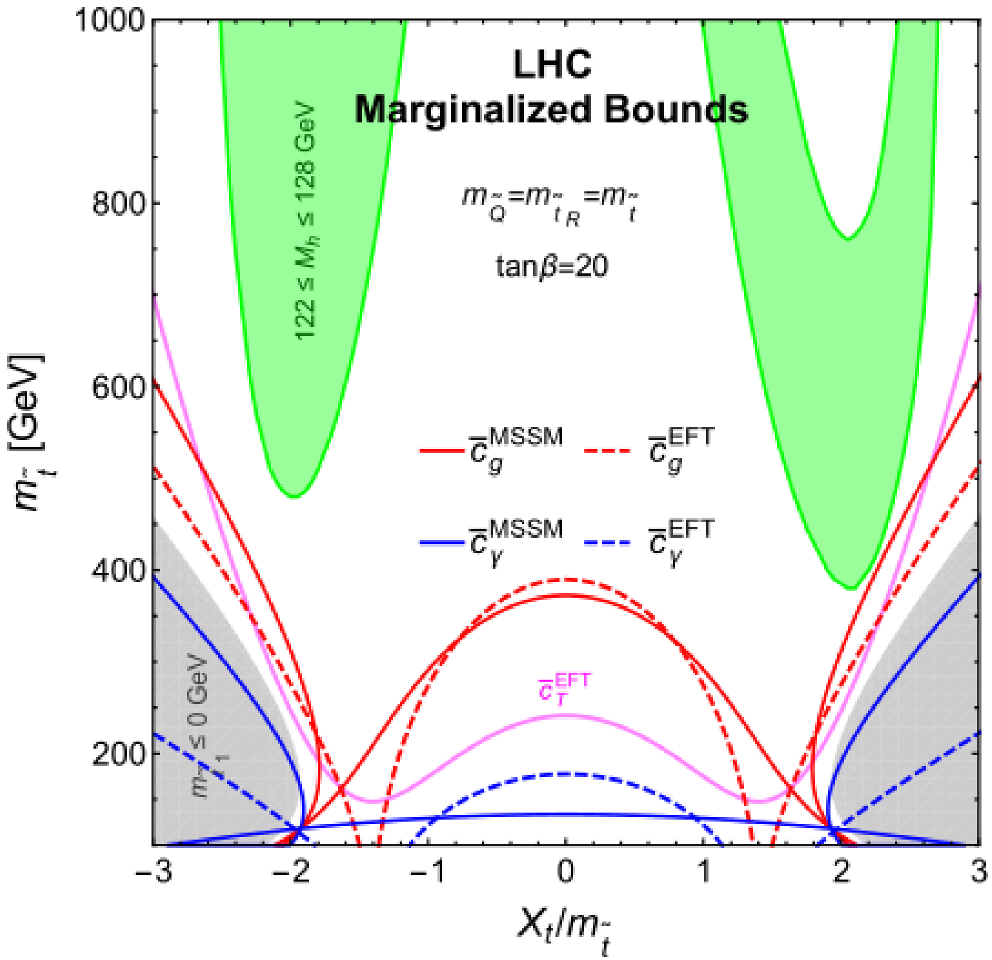
- **Warsaw** basis, summary

Loop-induced
$H\gamma\gamma$ and Hgg



Results

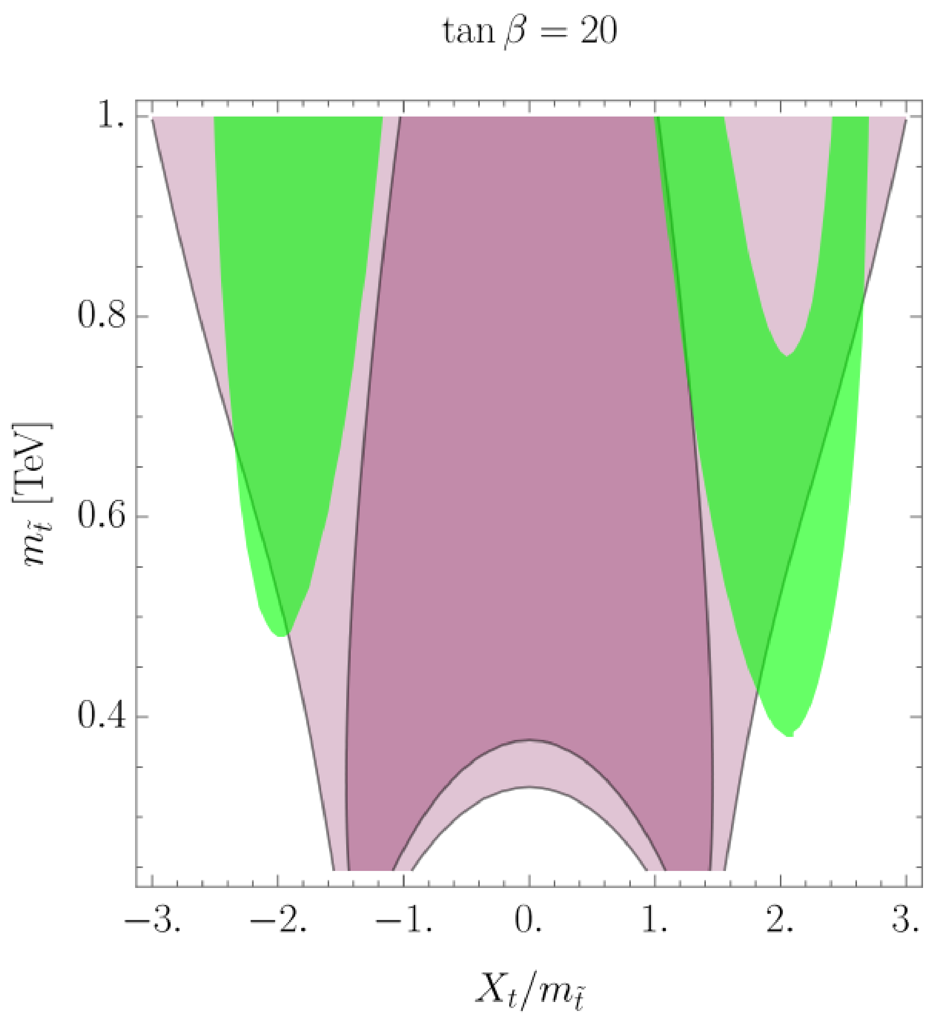
- Simplified models: **stops** (Run 1)



Drozd, Ellis, Quevillon and T.Y.
1504.02409

Results

- Simplified models: **stops** (Run 2)



Results

- Simplified models: **renormalisable SM extensions**

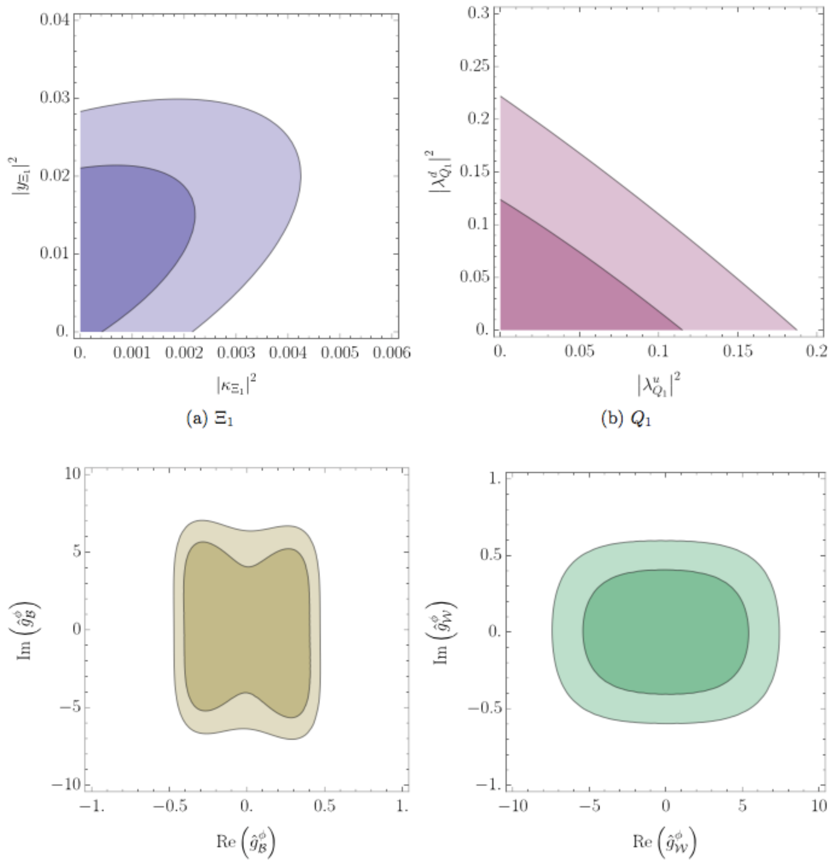
Name	Spin	$SU(3)$	$SU(2)$	$U(1)$	Name	Spin	$SU(3)$	$SU(2)$	$U(1)$
$\mathcal{S}$	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
$\mathcal{S}_1$	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
$\mathcal{B}$	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
$\mathcal{B}_1$	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
$\mathcal{W}$	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
$\mathcal{W}_1$	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$

- Classification and tree-level matching dictionary

De Blas, Criado, Perez-Victoria, Santiago [1711.10391]

Results

- Simplified models: **renormalisable SM extensions**



(a) Ξ_1 (b) Q_1

(c) $\mathcal{B}$, no ψ^4 operators (d) $\mathcal{W}$, no ψ^4 operators

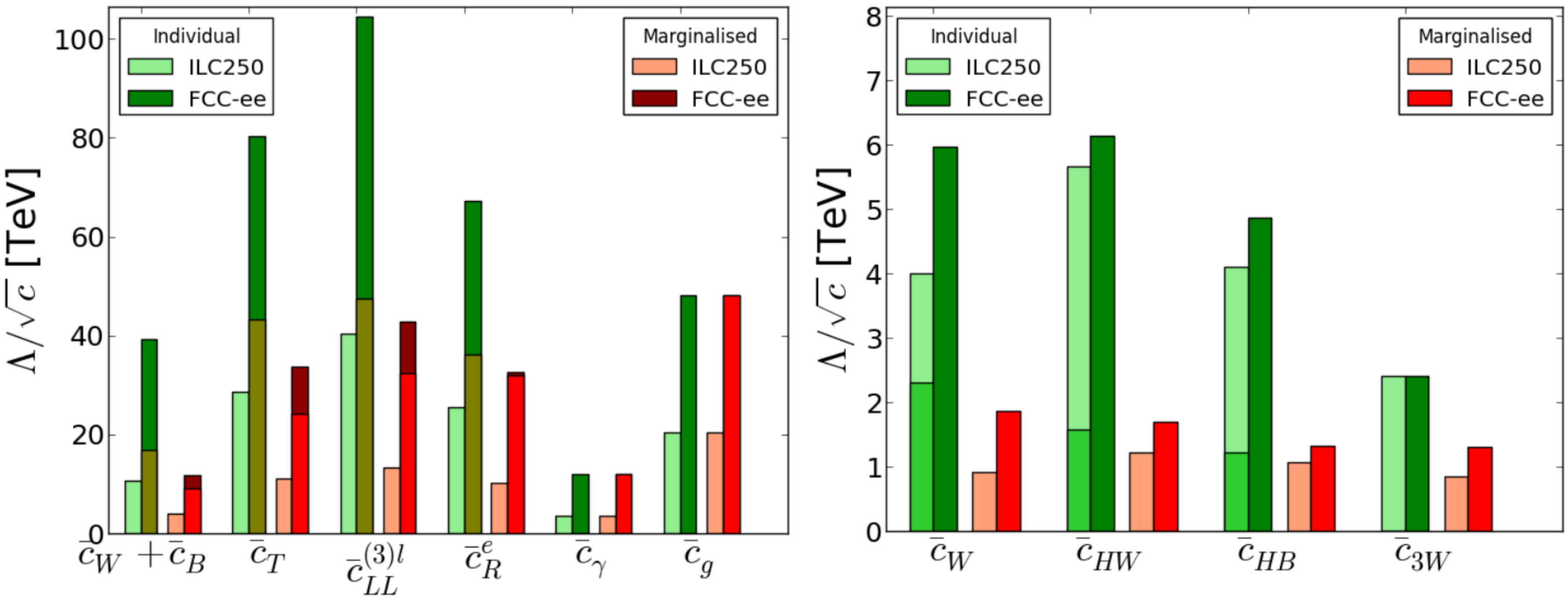
Model	χ^2	χ^2/n_d	Coupling	Mass / TeV
SM	157	0.987	-	-
$\mathcal{S}_1$	156	0.986	$\|y_{\mathcal{S}_1}\|^2 = (6.3 \pm 5.9) \cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.0,\ 49)$
φ, Type I	156	0.986	$Z_6 \cdot \cos\beta = -0.64 \pm 0.59$	$M_\varphi = (0.9,\ 4.3)$
Ξ	155	0.984	$\|\kappa_\Xi\|^2 = (4.2 \pm 3.4) \cdot 10^{-3}$	$M_\Xi = (12,\ 35)$
N	155	0.978	$\|\lambda_N\|^2 = (1.8 \pm 1.2) \cdot 10^{-2}$	$M_N = (5.8,\ 13)$
$\mathcal{W}_1$	155	0.984	$\left\|\hat{g}^\phi_{\mathcal{W}_1}\right\|^2 = (3.3 \pm 2.7) \cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
E	157	0.993	$\|\lambda_E\|^2 < 1.2 \cdot 10^{-2}$	$M_E > 9.2$
Δ_3	156	0.990	$\|\lambda_{\Delta_3}\|^2 < 1.9 \cdot 10^{-2}$	$M_{\Delta_3} > 7.3$
Σ	157	0.992	$\|\lambda_\Sigma\|^2 < 2.9 \cdot 10^{-2}$	$M_\Sigma > 5.9$
Q_5	156	0.990	$\|\lambda_{Q_5}\|^2 < 0.18$	$M_{Q_5} > 2.4$
T_2	157	0.992	$\|\lambda_{T_2}\|^2 < 7.1 \cdot 10^{-2}$	$M_{T_2} > 3.8$
$\mathcal{S}$	157	0.993	$\|y_\mathcal{S}\|^2 < 0.32$	$M_\mathcal{S} > 1.8$
Δ_1	157	0.993	$\|\lambda_{\Delta_1}\|^2 < 5.7 \cdot 10^{-3}$	$M_{\Delta_1} > 13$
Σ_1	157	0.993	$\|\lambda_{\Sigma_1}\|^2 < 7.3 \cdot 10^{-3}$	$M_{\Sigma_1} > 12$
U	157	0.993	$\|\lambda_U\|^2 < 2.8 \cdot 10^{-2}$	$M_U > 6.0$
D	157	0.993	$\|\lambda_D\|^2 < 1.4 \cdot 10^{-2}$	$M_D > 8.4$
Q_7	157	0.993	$\|\lambda_{Q_7}\|^2 < 7.7 \cdot 10^{-2}$	$M_{Q_7} > 3.6$
T_1	157	0.993	$\|\lambda_{T_1}\|^2 < 0.13$	$M_{T_1} > 3.0$
$\mathcal{B}_1$	157	0.993	$\left\|\hat{g}^\phi_{\mathcal{B}_1}\right\|^2 < 2.4 \cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

- Streamlines process of interpreting limits on BSM parameter space

Future e+e- Constraints

J. Ellis and T.Y. [arXiv:1510:04561]

ILC and FCC-ee



- Future precision sensitive to TeV scale, even for loop-induced operators

- One-loop matching simplified by a **Universal One-Loop Effective Action**

Henning, Lu, Murayama, 1412.1837;
Drozd, J. Ellis, Quevillon, TY, 1512.03003;
S.A.R. Ellis, Quevillon, TY, Z. Zhang, 1604.02445, 1706.07765.

- Part I: SM EFT
- **Part 2: B Anomalies**
- Part 3: Cosmological Relaxation

B anomalies

$$\mathcal{O}^l_{ij} = (\bar{s}\gamma^\mu P_i b)(\bar{l}\gamma_\mu P_j l)$$

- Anomalies in processes involving $\mathrm{b} \to s\, \mu^+\mu^-$ transitions:

- LHCb 3.4 σ in P5' angular distribution of $\mathrm{B} \to K^*\, \mu^+\mu^-$ (2 σ for Belle)
- Various other kinematic observables in $\mathrm{b} \to s\, \mu^+\mu^-$
- 3.2 σ in $B_s \to \varphi\, \mu^+\mu^-$
- ~4 σ non-zero Wilson coefficient in global fit to these "messy" observables

- 2.5 σ in "clean" observable R_K
- 2.5 σ in "clean" observable R_K^*
- ~4 σ non-zero Wilson coefficient in combined fit to just these two clean observables

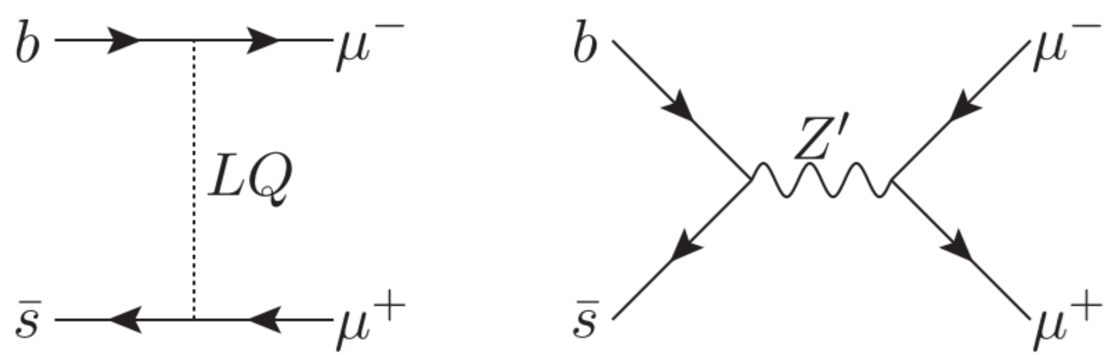
- *Consistency* of all these various anomalies is non-trivial

Motivation for future colliders

- If $b \to s\mu^+\mu^-$ anomalies are confirmed, can we *definitely* discover directly the source (i.e. LQ/Z') at higher energies?

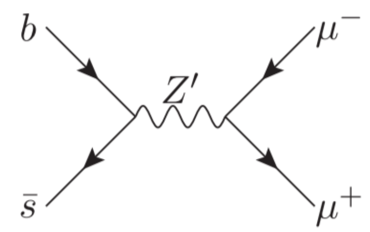
(80 TeV unitarity limit = **no general no-lose theorem** at FCC-hh)
Di Luzio, Nardecchia [1706.01868]

- Consider sensitivity to most **pessimistic** scenario: only include minimal couplings required to explain $b \to s\mu^+\mu^-$ anomalies

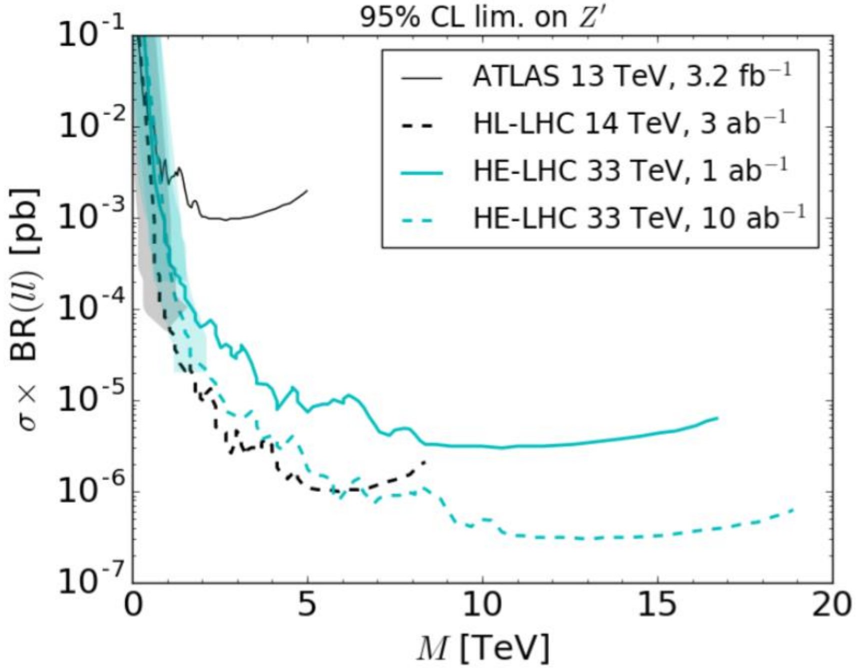


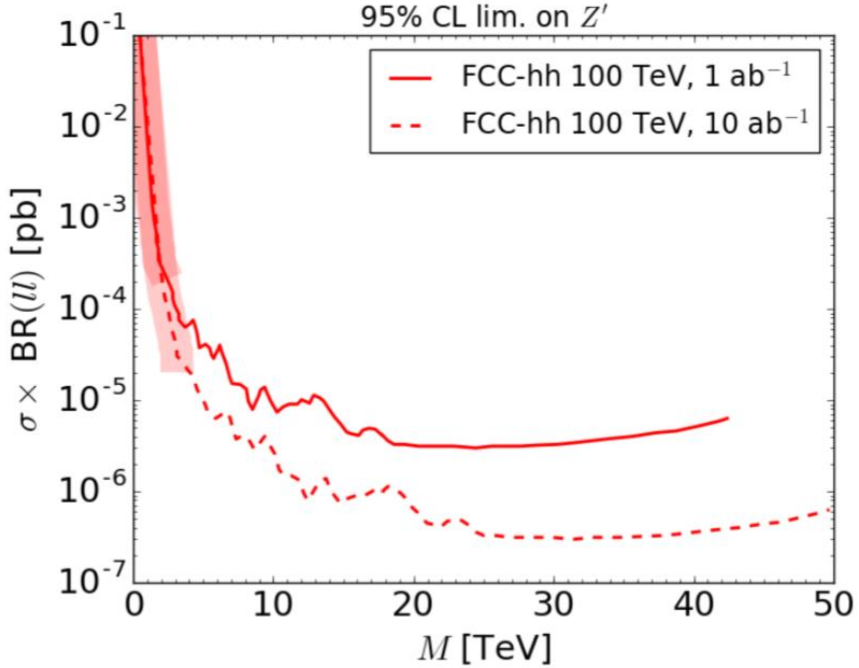
- More realistic models will only be *easier* to discover

Z′ Sensitivity



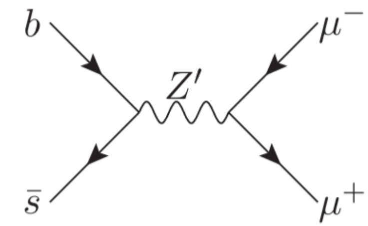
- Extrapolate current 13 TeV di-muon search:





- Actual limits depend on Z′ couplings in signal x-section

Z' Sensitivity



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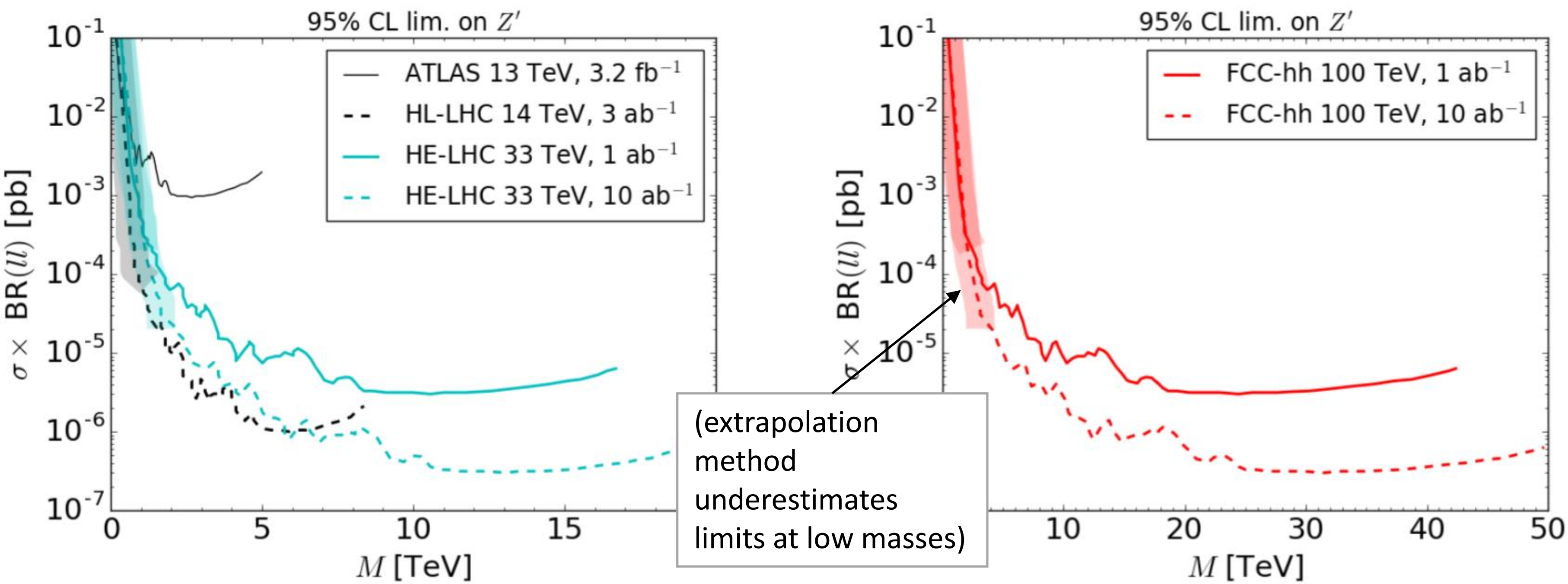

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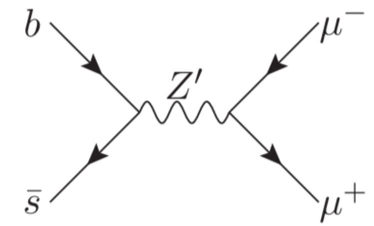

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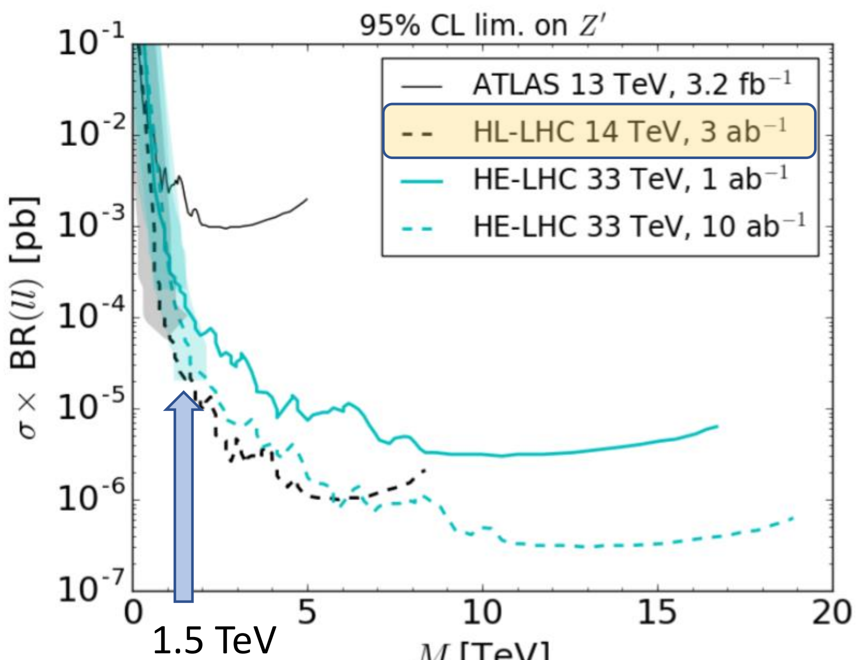

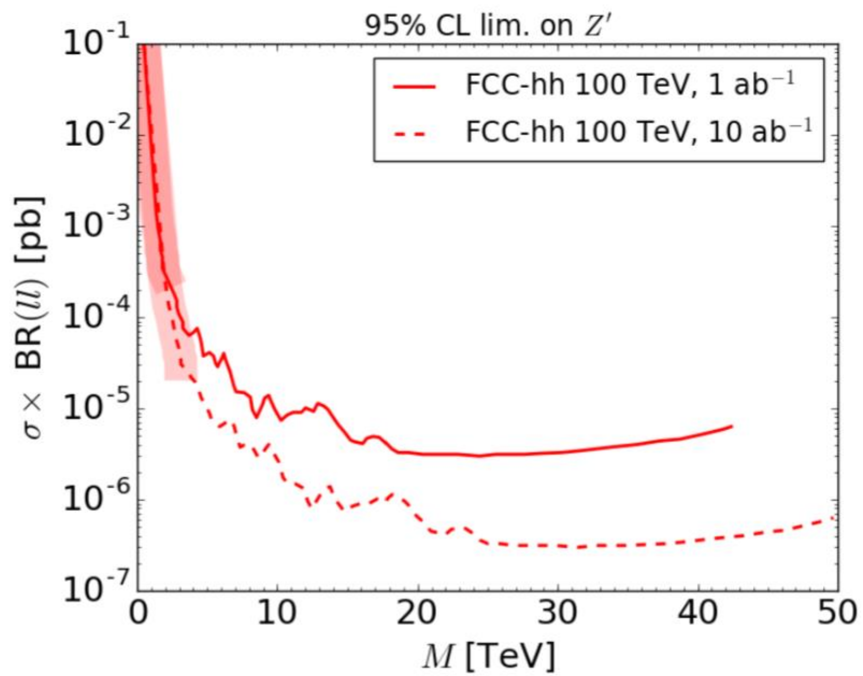

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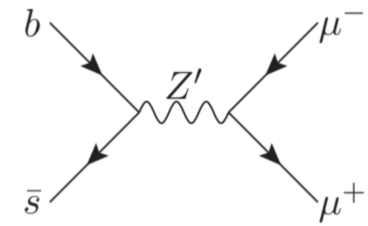

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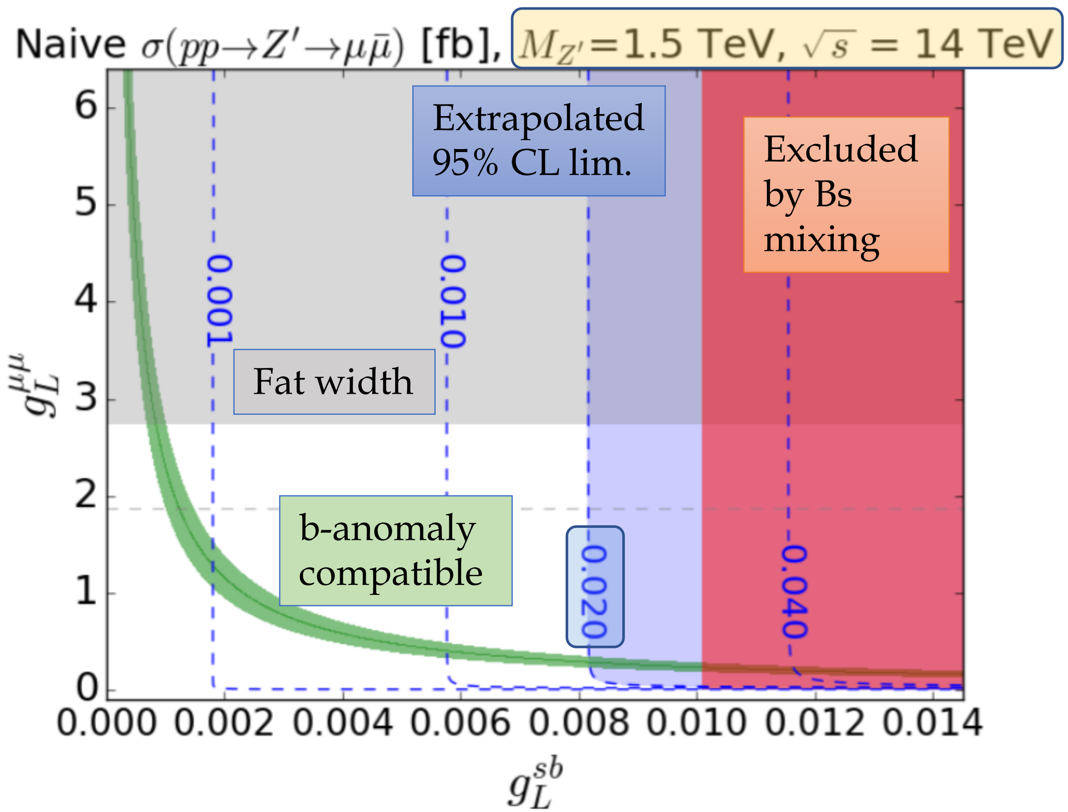

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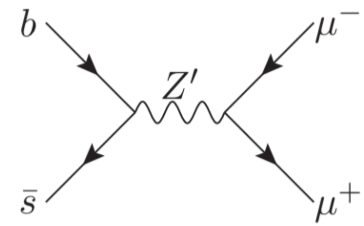

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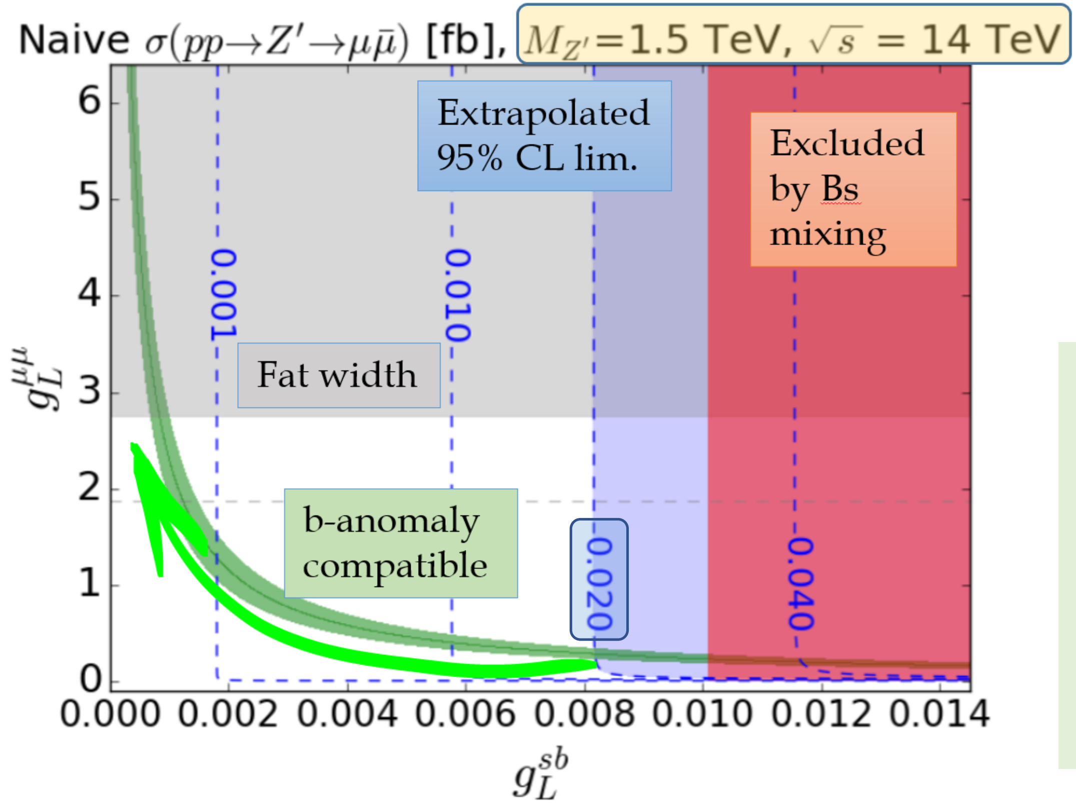
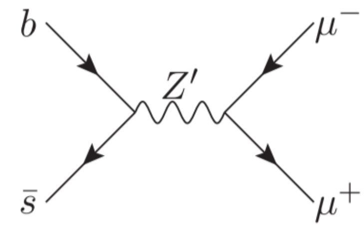


Summary of Z' coverage: For each $M_{Z'}$, plot vertically the anomaly-compatible region

- Actual limits depend on Z' couplings in signal x-section

Z′ Sensitivity



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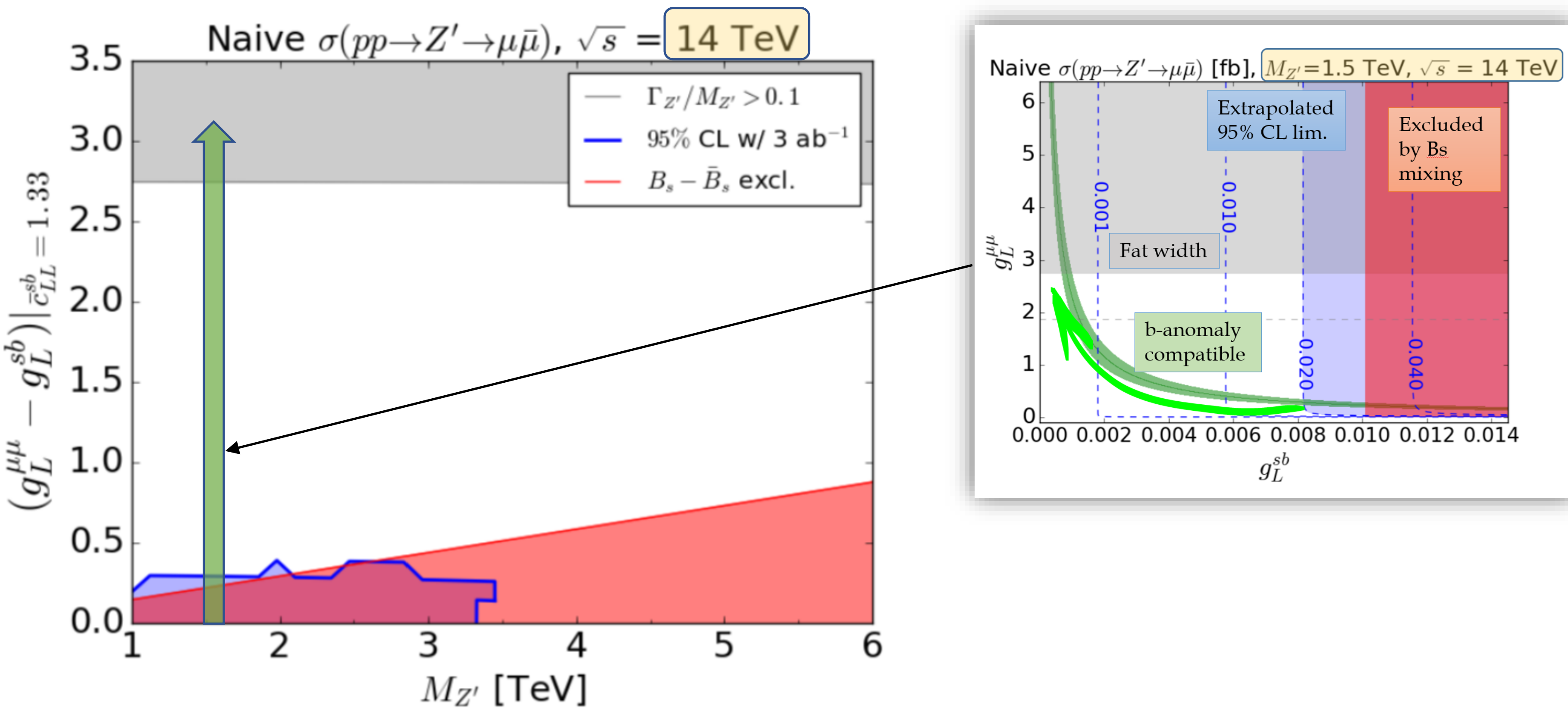

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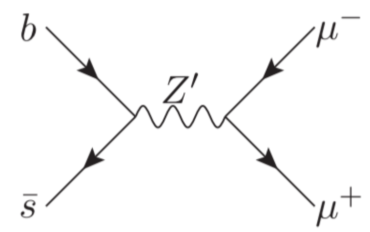

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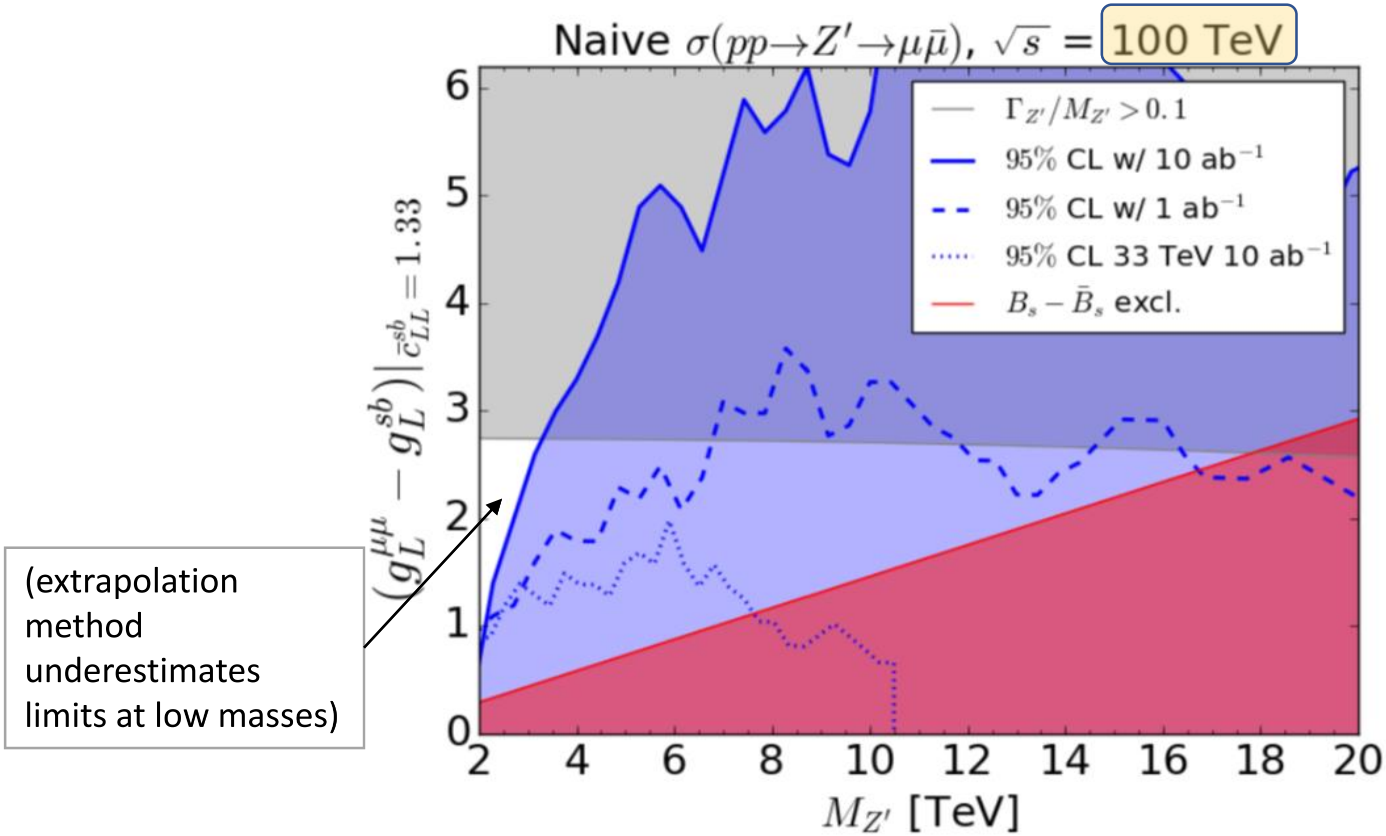
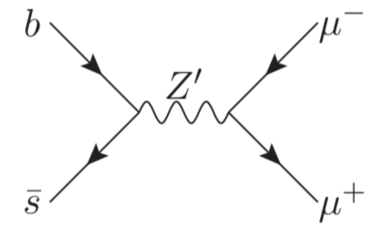


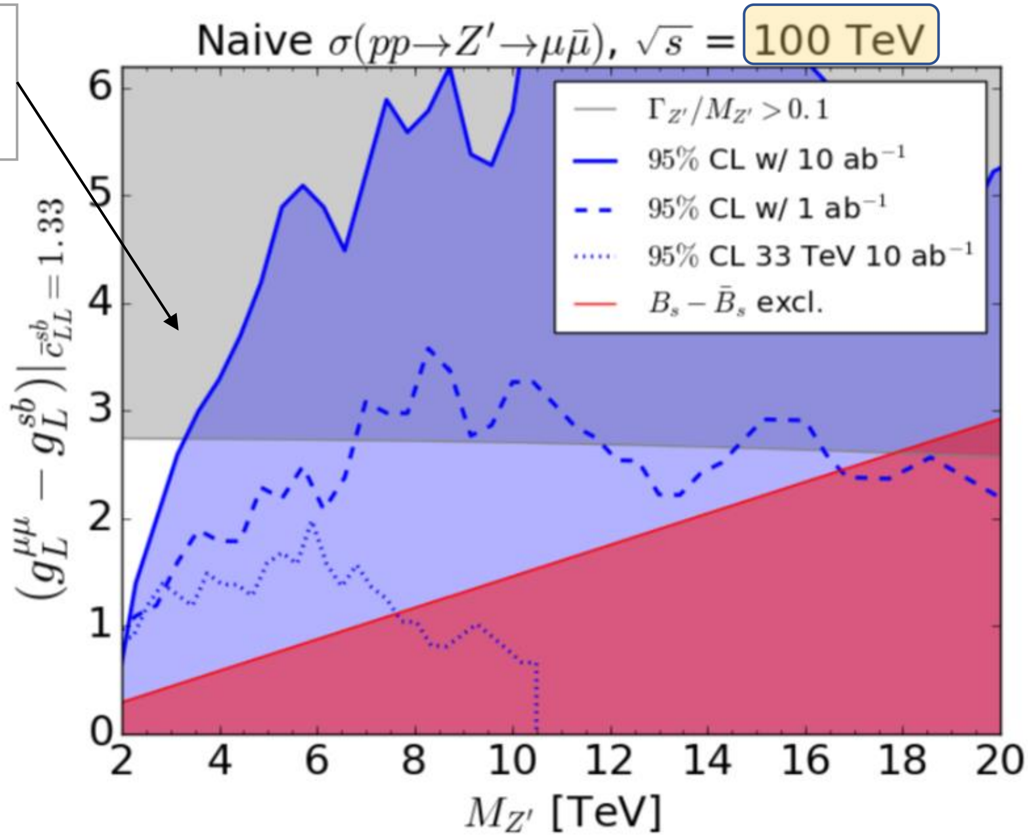
- 100 TeV can cover **all** parameter space of most *pessimistic* scenario

Z' Sensitivity



- Extrapolate current 13 TeV di-muon search:

Narrow width approximation no longer valid!

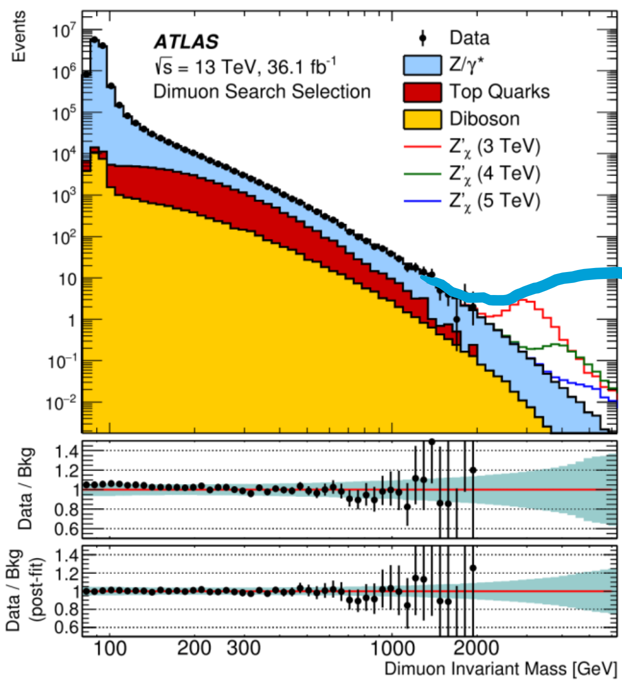


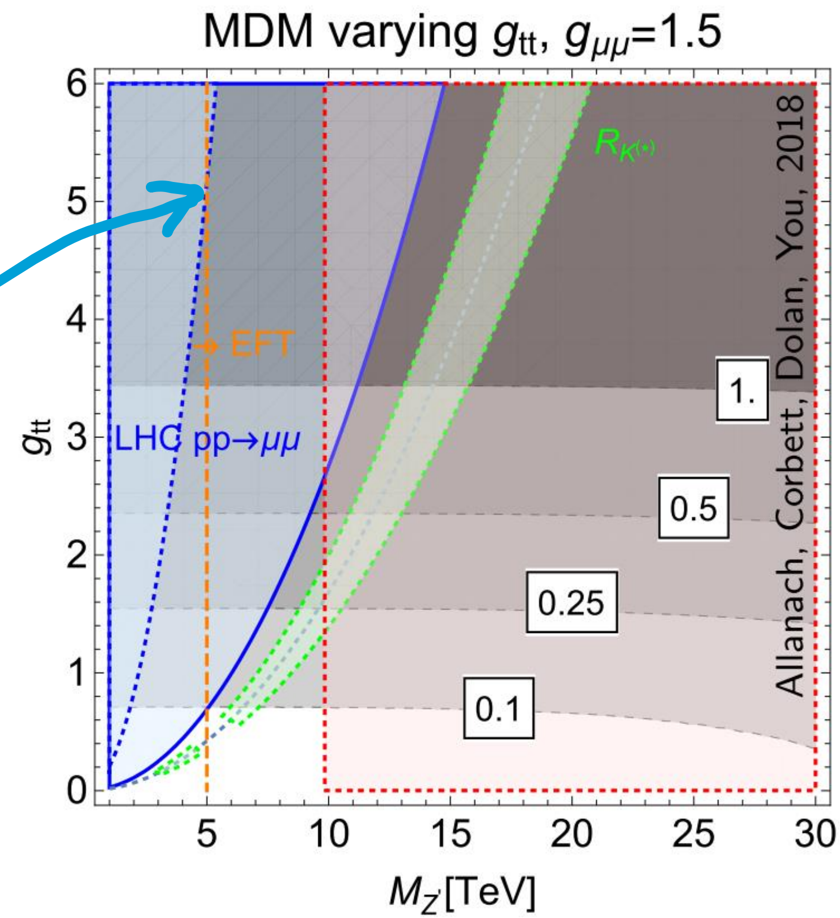
- 100 TeV can cover **all** parameter space of most *pessimistic* scenario

Z' Sensitivity

Allanach, Corbett, Dolan, **TY** [1810.tomorrow]

- **Indirect effects** from effective operators in LHC di-muon tail would point towards **fat Z'** at higher energies

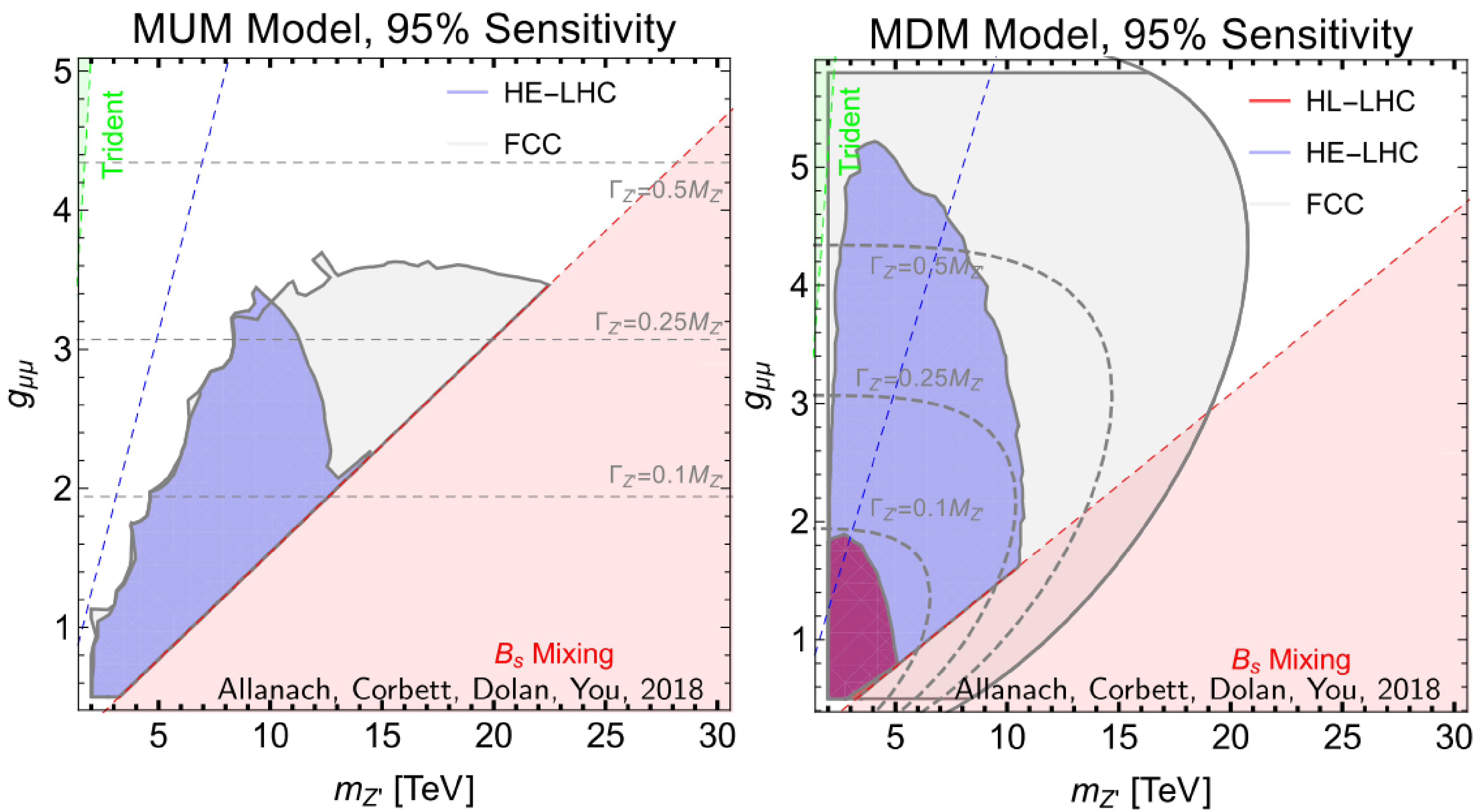




Z′ Sensitivity

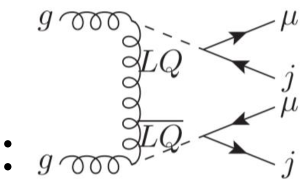
Allanach, Corbett, Dolan, **TY** [1810.tomorrow]

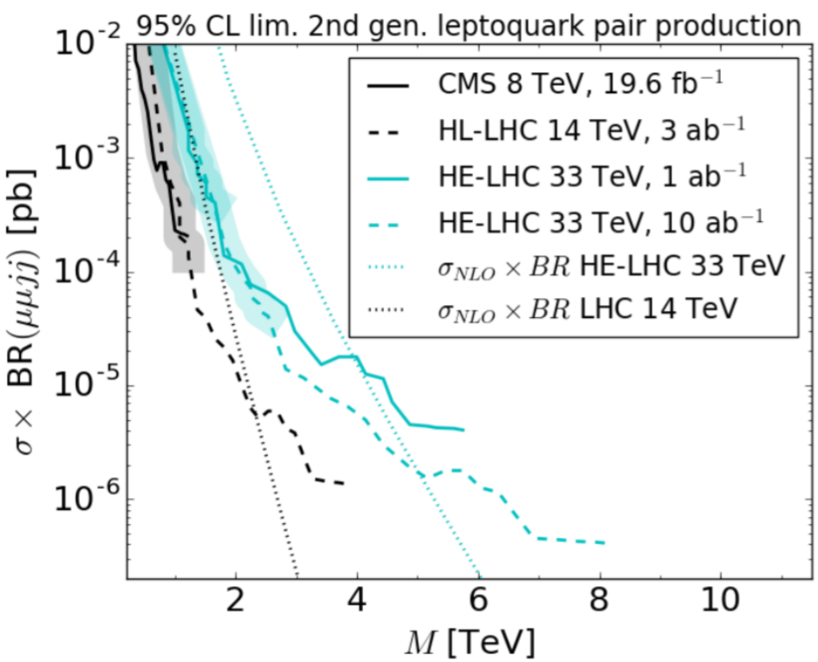
- Improved study including **large widths**:

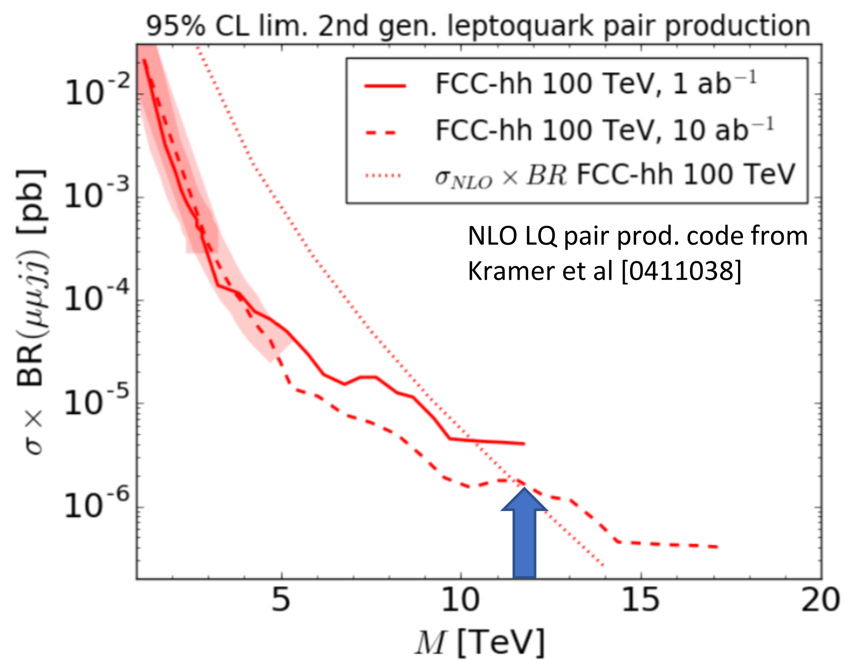


Leptoquark Sensitivity

- Extrapolate current 8 TeV LQ di-muon+di-jet search:

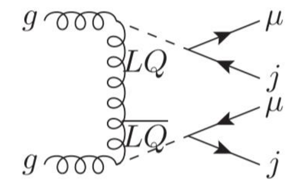






- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

Leptoquark Sensitivity



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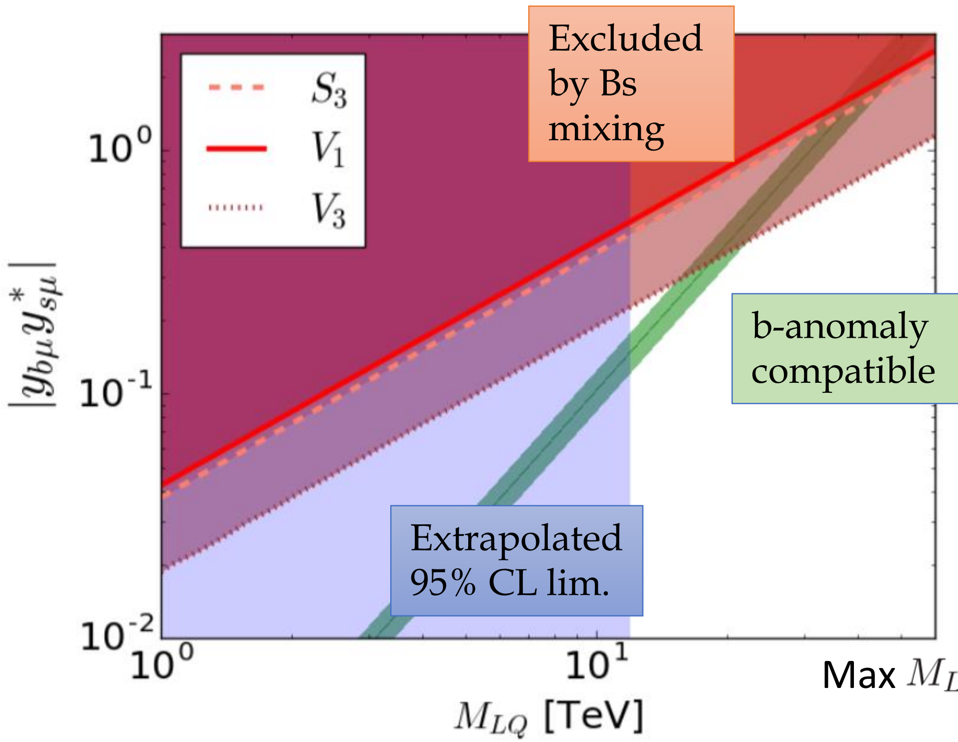


Max $M_{LQ} = 37, 41, 18$ TeV for S_3, V_1, V_3

- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

Take-home message

- Complete coverage of Z′ models at 100 TeV FCC-hh
- Contrived LQ models may still survive FCC-hh
- Future studies: consider backgrounds, other channels, more realistic benchmark models, etc.
- Even if anomalies vanish, motivates **direct** discovery potential of future hadron colliders and interplay with **indirect** sensitivity from B physics

- Part I: SM EFT
- Part 2: B Anomalies
- **Part 3: Cosmological Relaxation**

Beyond the Standard Model?

- **Hierarchy problem is still a problem**: $(m_h)^2_{tree} + (m_h)^2_{radiative} = (m_h)^2_v$

$$\delta m_\phi^2 \propto m_{\rm heavy}^2, \quad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\rm heavy}}{\mu}\right)$$

- Earliest example of an unnatural, arbitrary feature of a fundamental theory:

$$m_{inertial} = q_{gravity}$$

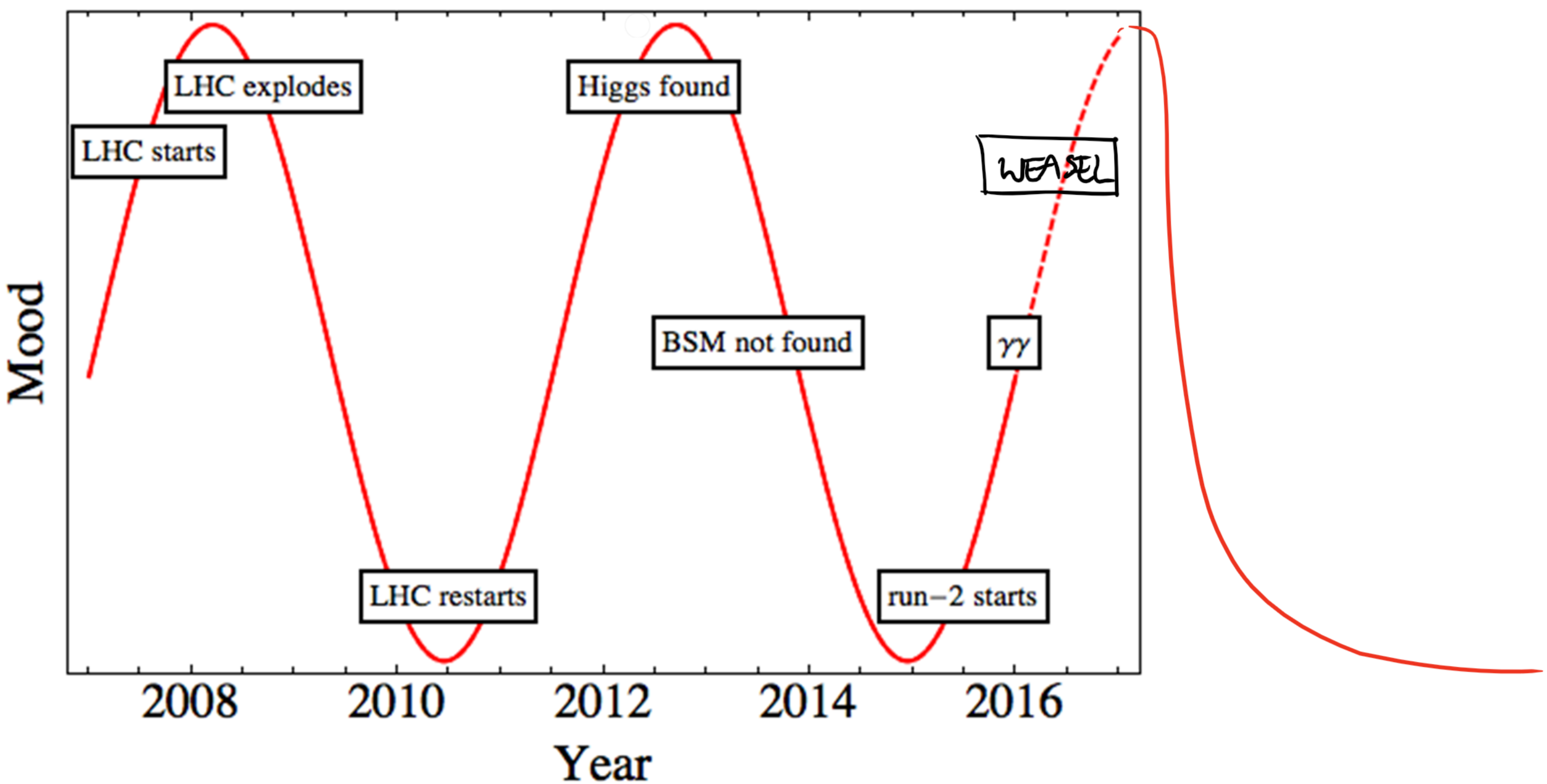
- Classical electromagnetism fine-tuning:

$$(m_e c^2)_{\rm obs} = (m_e c^2)_{\rm bare} + \Delta E_{\rm coulomb}, \qquad \Delta E_{\rm coulomb} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

- Pions cut-off also at natural scale

- Higgs? Expect **underlying explanation** => fine-tuned unless new physics close to weak scale (just try writing down a model with a calculable Higgs potential...)

Beyond the Standard Model?



http://resonaances.blogspot.com.es/2016/01/do-or-die-year.html

- Maybe Nature is trying to tell us we are missing something in the way we think about the hierarchy problem

Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

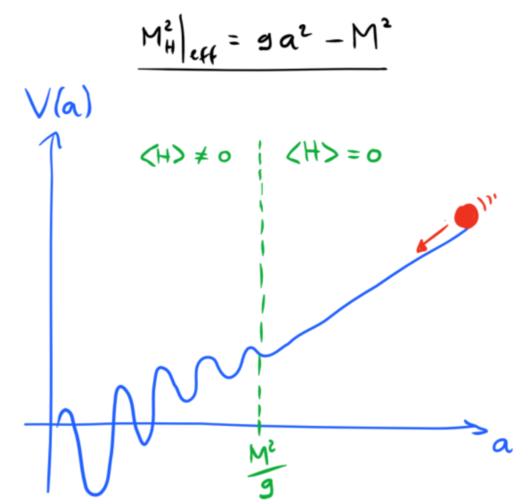
$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter *g*

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



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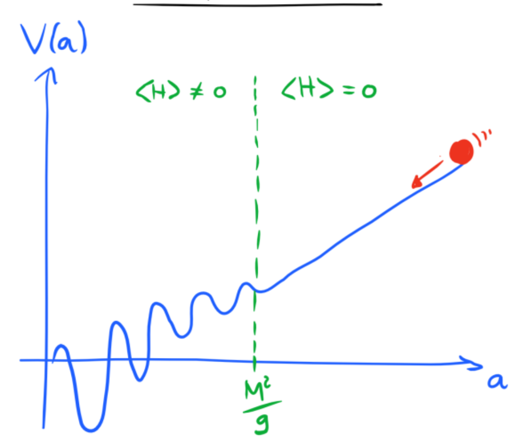
$M_H^2\big|_{\rm eff} = g a^2 - M^2$



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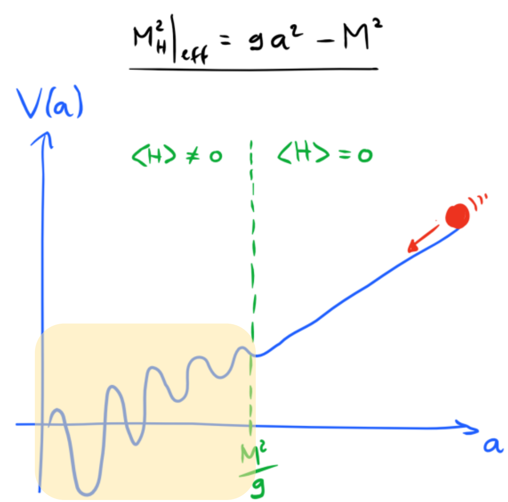

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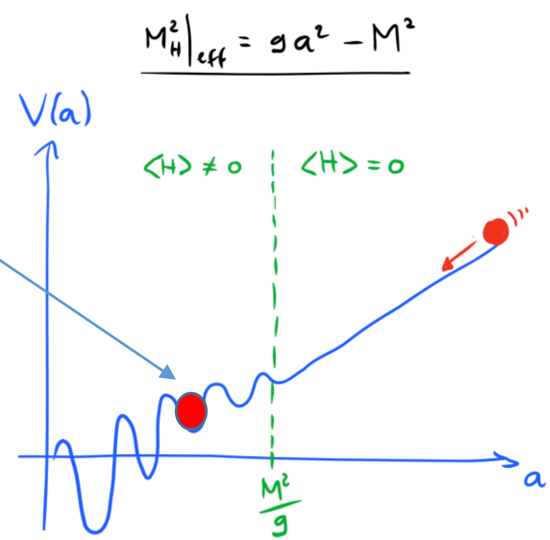
$$gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$

- Technically-natural for v << M



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Constraints: H < v, classical rolling vs quantum, inflaton energy density dominates relaxion, etc.

Very small *g* and natural scanning range lead to super-planckian field excursions, exponential e-foldings…

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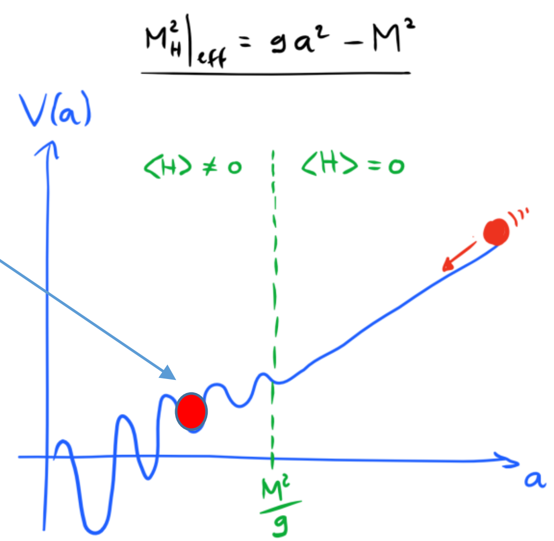

Relaxation Models (apologies for lack of references)

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  - G=QCD: Need additional ingredients to overcome strong-CP problem
  - New gauge group G: new physics at weak scale + coincidence problem

- **n=2 models** Espinosa et al [arXiv:1506.09217]
  - G can be at higher scales, raises M cut-off too
  - Requires second scalar to relax relaxion barriers: double-scanning mechanism

- **n=0 models** Hook and Marques-Tavares [arXiv:1607.01786], **TY** [arXiv:1701.09167]
  - More promising, make use of axial gauge coupling $\mathcal{L} = \frac{1}{32\pi^2}\frac{a}{f}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}G_{\mu\nu}G_{\rho\sigma}$

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Relaxation backreaction on inflation

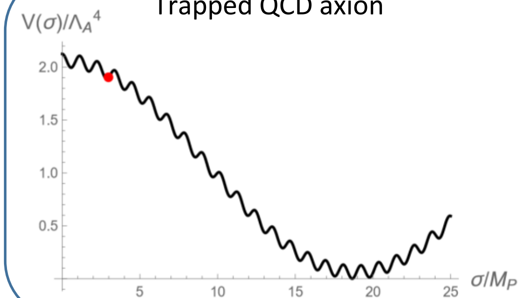
TY [arXiv:1701.09167]

- Minimal relaxion setup, **no v-dependence in relaxion sector**

$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + ... + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \,,$$

- Backreaction instead ends inflation
  - e.g.

Trapped QCD axion



Inflating with electroweak dissipation:

$$\mathcal{L} \supset -\frac{\alpha}{f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\ddot{\sigma} + 3H\dot{\sigma} + V'_\sigma(\sigma) = -I\frac{\alpha}{f}\left(\frac{H}{\xi}\right)^4 e^{2\pi\xi} \,,$$

$$\xi \equiv \frac{\alpha}{2f}\frac{\dot{\sigma}}{H}$$

See e.g. Anber and Sorbo 0908.4089

- Hubble falls
- Dark dissipation increases
- Relaxion loses KE and is trapped

	M	g	H_I	H_c	N_e	Λ_G	f_ϕ	f_D/α_D
$\sim$ [GeV]	10^8	10^{-11}	10^{-2}	10^{-5}	10^{18}	$10^{3.5}$	10^9	10^{15}

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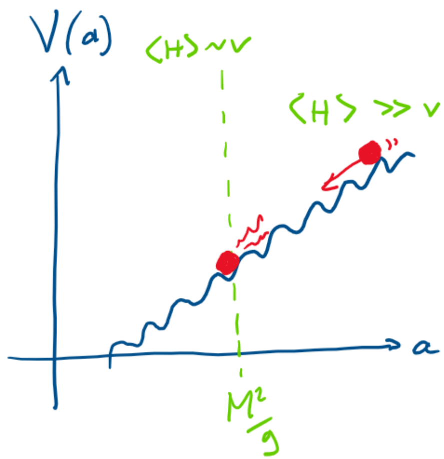
Relaxation backreaction on particle production

Hook and Marques-Tavares [arXiv:1607.01786]

- v-dependence in gauge particle production

$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + \ldots + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \,,$$



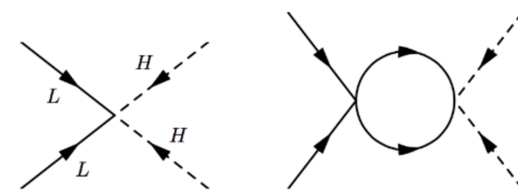
- For M ~ 10-100 TeV sub-Planckian field excursions, no tiny parameters
- Model can be realised before, during, or after inflation

Relaxation backreaction on particle production

- Relaxation after inflation: **relaxion can reheat universe** but low T

- **Leptogenesis during reheating**: L and CP violation by higher-dimensional operators parametrising decoupled new physics

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\lambda_{1,ij} H H \bar{L}_j^c L_i + \frac{1}{\Lambda_2^2}\lambda_{2,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{L}_k\gamma_\mu L_l) + \frac{1}{\Lambda_3^2}\lambda_{3,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{E}_k\gamma_\mu E_l) + h.c.$$



Hamada & Kawana [arXiv:1510.05186]

- Attractive features in **reheating leptogenesis for cosmological relaxation with particle production**

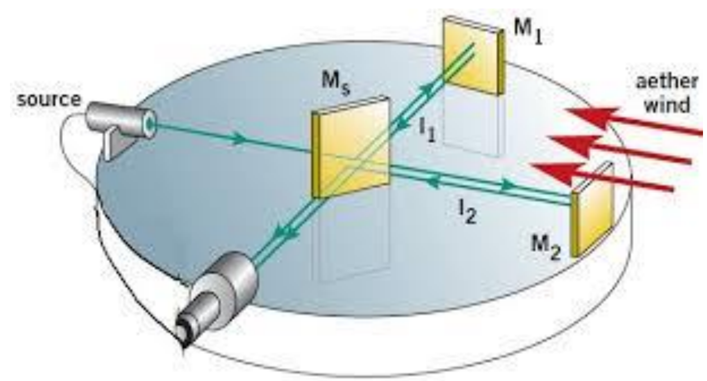
Minho Son, Fang Ye, **TY** [1804.06599]

- **Minimal EFT setup** for naturally decoupled new physics

Conclusion

- A SM-like Higgs boson and no direct signs of new physics may turn out to be a significant experimental **null result**

- Null results may still lead to **deeper understanding**



- *No new physics at the TeV scale could be our "Michelson-Morley" moment*

- Experiment will *always* play a key role: **need future colliders**!

Lose theorem: If we *don't* go to higher energies we definitely *won't* have any direct knowledge of what fundamental physics may lie at 10 TeV

Conclusion

- Decoupled new physics motivates an SM EFT approach to phenomenology
- Future precision may probe even loop-induced operators at the TeV scale
- B anomalies could be the first indirect signs of new physics at accessible energy scales
- A desert above the weak scale has interesting implications for naturalness and model-building
- Cosmological relaxation mechanisms one possible avenue to explore

Observables

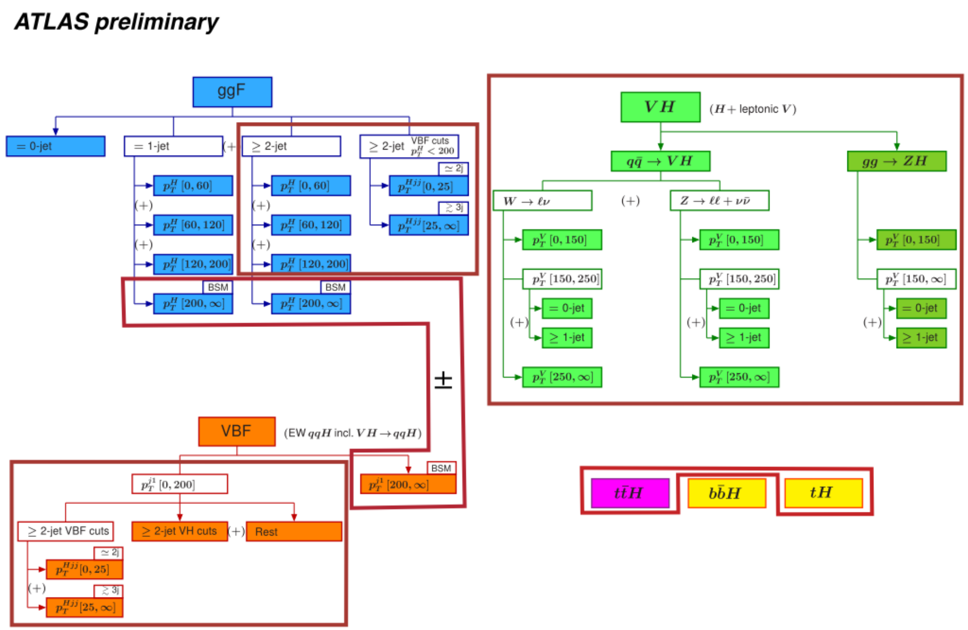
- ATLAS+CMS Higgs Run 2

Including kinematical information facilitated by **STXS**

	Production	Decay	Sig. Stren.		Production	Decay	Sig. Stren.
[96]	1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$	[105]	pp	$\mu\mu$	-0.1 ± 1.4
[97]	Zh	$b\bar{b}$	0.9 ± 0.5	[106]	Zh	$b\bar{b}$	$0.69^{+0.35}_{-0.31}$
[97]	Wh	$b\bar{b}$	1.7 ± 0.7	[106]	Wh	$b\bar{b}$	$1.21^{+0.45}_{-0.42}$
[98]	$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$	[107]	$t\bar{t}h$	$b\bar{b}$	$0.84^{+0.64}_{-0.61}$
[99]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	[108]	$t\bar{t}h$	$2\ell os + 1\tau_h$	$1.7^{+2.1}_{-1.9}$
[99]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	[108]	$t\bar{t}h$	$1\ell + 2\tau_h$	$-0.6^{+1.6}_{-1.5}$
[99]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	[108]	$t\bar{t}h$	$3\ell + 1\tau_h$	$1.6^{+1.8}_{-1.3}$
[100]	$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$	[108]	$t\bar{t}h$	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[100]	$t\bar{t}h$	3ℓ	$1.0^{+0.8}_{-0.7}$	[108]	$t\bar{t}h$	3ℓ	$1.8^{+0.9}_{-0.7}$
[100]	$t\bar{t}h$	4ℓ	$0.9^{+2.3}_{-1.6}$	[108]	$t\bar{t}h$	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
[101]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[109]	VBF	WW	$1.7^{+1.1}_{-0.9}$
[101]	1-jet	WW	1.1 ± 0.4	[109]	Wh	WW	$3.2^{+4.4}_{-4.2}$
[101]	2-jet	WW	1.3 ± 1.0	[110]	$B(h \to \gamma\gamma)/\ B(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
[101]	VBF 2-jet	WW	1.4 ± 0.8	[110]	0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
[101]	Vh 2-jet	WW	$2.1^{+2.3}_{-2.2}$	[110]	1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
[101]	Wh 3-lep	WW	-1.4 ± 1.5	[110]	1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
[102]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[110]	1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
[102]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[110]	2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
[102]	$t\bar{t}h$	$\gamma\gamma$	2.2 ± 0.9	[110]	"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
[102]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[110]	VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
[103]	ggF	4ℓ	$1.20^{+0.22}_{-0.21}$	[110]	Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
[104]	0-jet	$\tau\tau$	0.84 ± 0.89	[110]	$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
[104]	boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$				
[104]	VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$				

STXS

- Simplified Template Cross-Sections
- Sub-division into kinematic regions for production processes

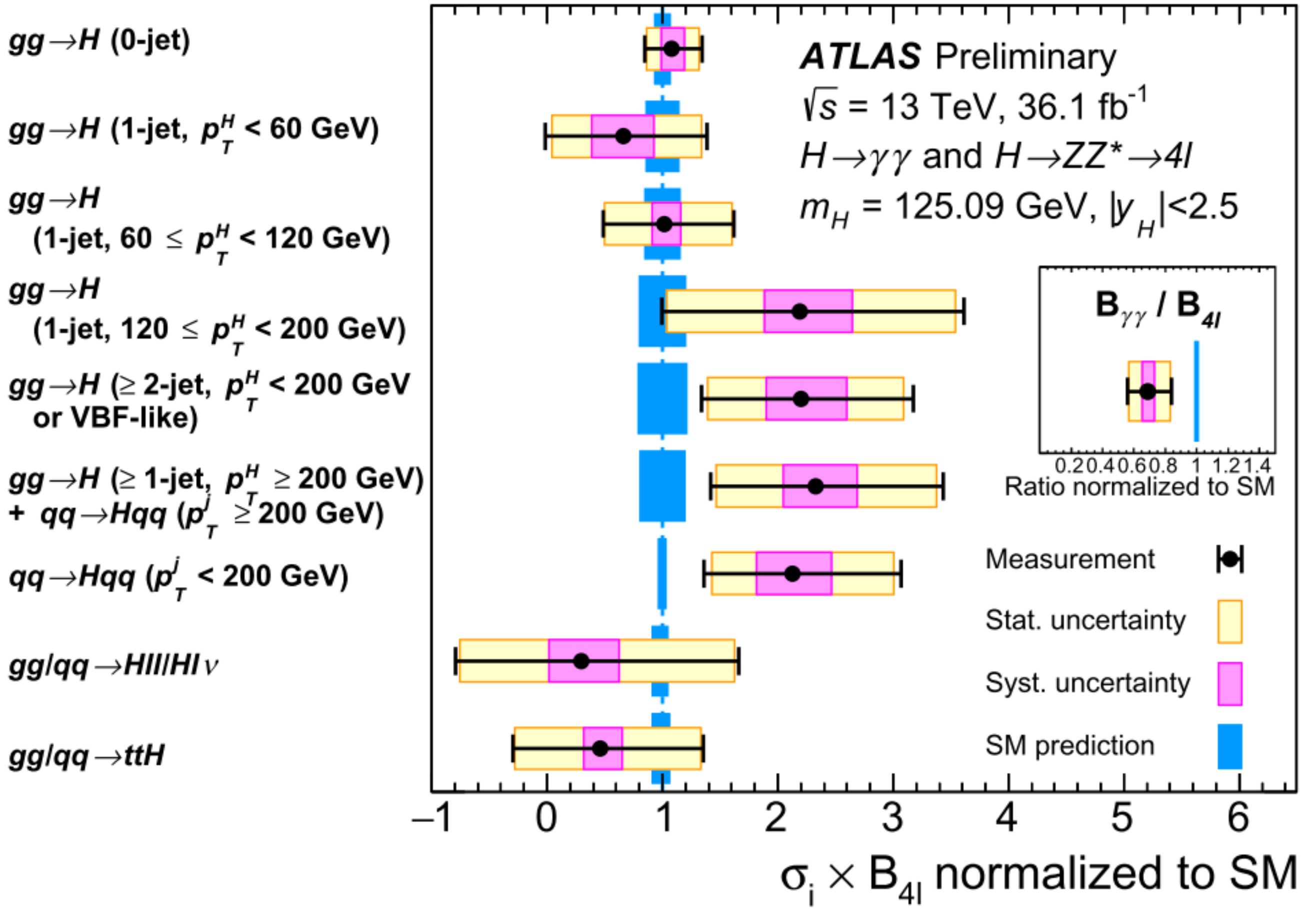


ATLAS-CONF-2017-047

- Facilitates combination and interpretation

STXS

- STXS measurements



ATLAS-CONF-2017-047

STXS

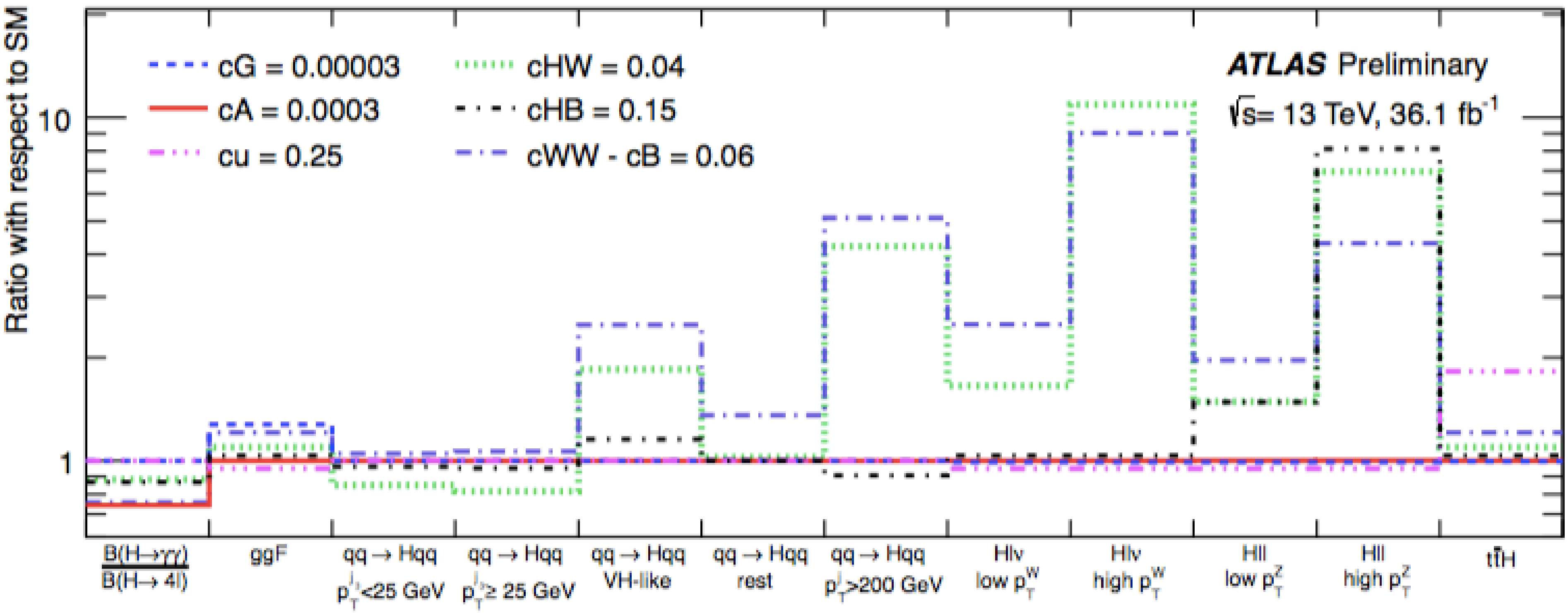
- STXS dim-6 predictions

Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet) $gg \to H$ (1-jet, $p_T^H < 60$ GeV) $gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g$
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 18\mathrm{c3G} + 11\mathrm{c2G}$
$gg \to H$ (1-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 52\mathrm{c3G} + 34\mathrm{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g + 8\mathrm{c3G} + 7\mathrm{c2G}$
$gg \to H$ ($\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 23\mathrm{c3G} + 18\mathrm{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 90\mathrm{c3G} + 68\mathrm{c2G}$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} < 25$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j_3} \geq 25$ GeV)	$56c'_g + 9\mathrm{c3G} + 8\mathrm{c2G}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} < 25$ GeV)	$-1.0\mathrm{cH} - 1.0\mathrm{cT} + 1.3\mathrm{cWW} - 0.023\mathrm{cB} - 4.3\mathrm{cHW}$ $-0.29\mathrm{cHB} + 0.092\mathrm{cHQ} - 5.3\mathrm{cpHQ} - 0.33\mathrm{cHu} + 0.12\mathrm{cHd}$
$qq \to Hqq$ (VBF-like, $p_T^{j_3} \geq 25$ GeV)	$-1.0\mathrm{cH} - 1.1\mathrm{cT} + 1.2\mathrm{cWW} - 0.027\mathrm{cB} - 5.8\mathrm{cHW}$ $-0.41\mathrm{cHB} + 0.13\mathrm{cHQ} - 6.9\mathrm{cpHQ} - 0.45\mathrm{cHu} + 0.15\mathrm{cHd}$
$qq \to Hqq$ ($p_T^j \geq 200$ GeV)	$-1.0\mathrm{cH} - 0.95\mathrm{cT} + 1.5\mathrm{cWW} - 0.025\mathrm{cB} - 3.6\mathrm{cHW}$ $-0.24\mathrm{cHB} + 0.084\mathrm{cHQ} - 4.5\mathrm{cpHQ} - 0.25\mathrm{cHu} + 0.1\mathrm{cHd}$
$qq \to Hqq$ ($60 \leq m_{jj} < 120$ GeV)	$-0.99\mathrm{cH} - 1.2\mathrm{cT} + 7.8\mathrm{cWW} - 0.19\mathrm{cB} - 31\mathrm{cHW}$ $-2.4\mathrm{cHB} + 0.9\mathrm{cHQ} - 38\mathrm{cpHQ} - 2.8\mathrm{cHu} + 0.9\mathrm{cHd}$
$qq \to Hqq$ (rest)	$-1.0\mathrm{cH} - 1.0\mathrm{cT} + 1.4\mathrm{cWW} - 0.028\mathrm{cB} - 6.2\mathrm{cHW}$ $-0.42\mathrm{cHB} + 0.14\mathrm{cHQ} - 6.9\mathrm{cpHQ} - 0.42\mathrm{cHu} + 0.16\mathrm{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathrm{cH} + 2.9\mathrm{cu} + 0.93\mathrm{cG} + 310\mathrm{cuG}$ $+27\mathrm{c3G} - 13\mathrm{c2G}$

Hays, Sanz, Zemaityte
[LHCHXSWG-INT-2017-01]

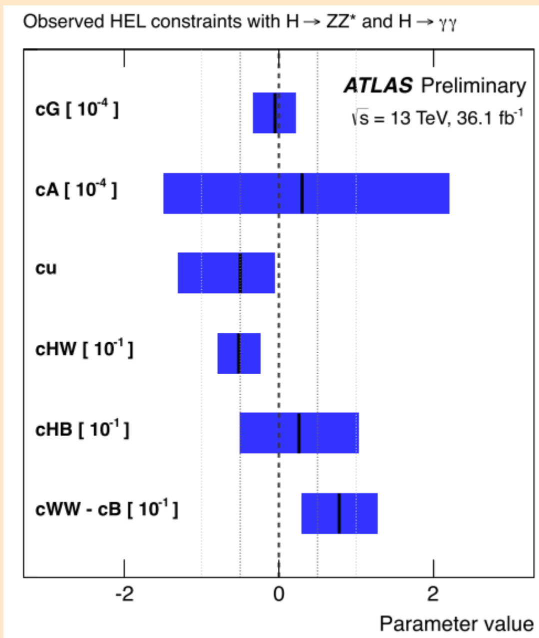
STXS

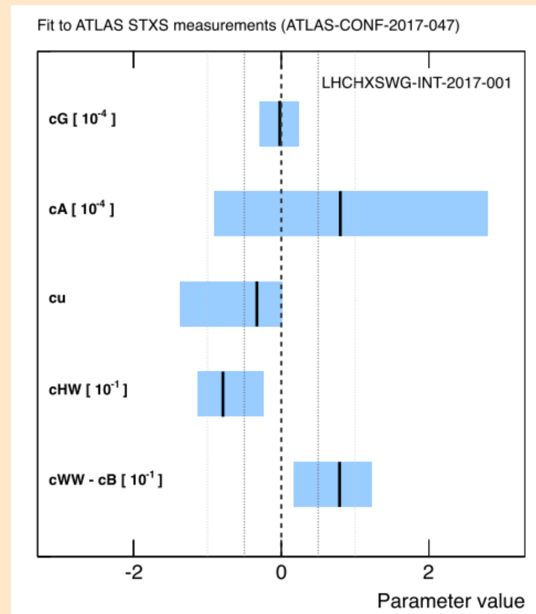
- STXS dim-6 predictions



STXS

- Good agreement with optimised non-STXS fit





ATLAS fit uses more categories than measured STXS

Fit to STXS measurement can only constrain five parameters

https://indico.cern.ch/event/682466/contributions/2796820/attachments/1573120/2482936/WG211Dec2017.pdf

27 Mar 2018 C. Hays, Oxford University 13

- Though more information lost in VH case

De Blas, Lohwasser, Musella, Mimasu
[in progress]