Looking Beyond the Standard Model with the SMEFT

"…the direct method may be used…but indirect methods will be needed in order to secure victory…."

"The direct and the indirect lead on to each other in turn. It is like moving in a circle…."

Who can exhaust the possibilities of their combination?"

Sun Tzu, *The Art of War*

John Ellis

KING'S College LONDON

Where are we?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},\text{-}1)$
E_R	$e^-_R \; , \; \mu^-_R \; , \; \tau^-_R$	$(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	$u_R \; , \; c_R \; , \; t_R$	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	$d_R \; , \; s_R \; , \; b_R$	$(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} \;\; = & \;\; -\frac{1}{4} F^a_{\mu\nu} F^{a\;\mu\nu} \\ & + \;\; i\bar{\psi} \; \not{D} \psi + h.c. \\ & + \;\; \psi_i y_{ij} \psi_j \phi + h.c. \\ & + \;\; |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

gauge interactions

matter fermions

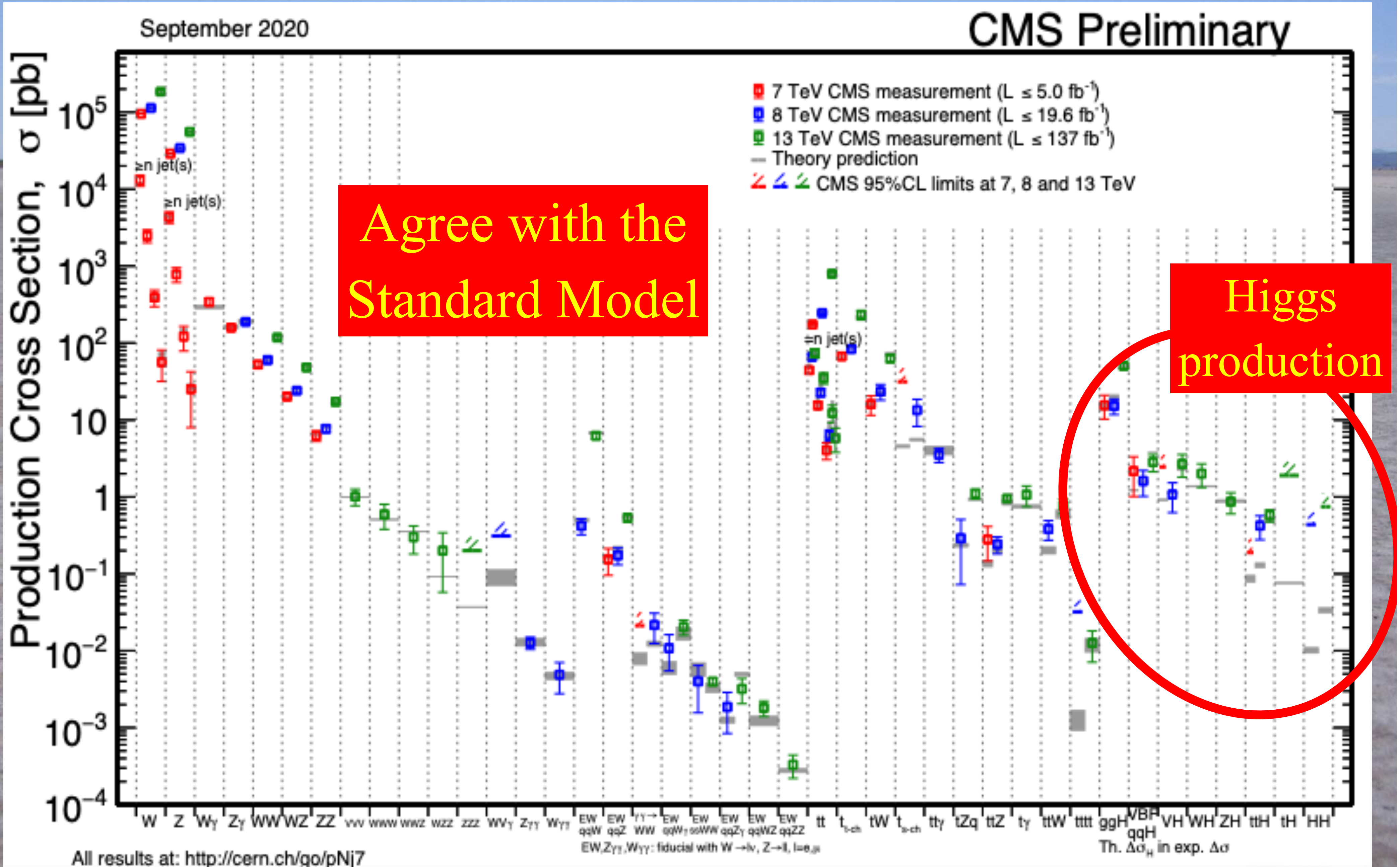
Yukawa interactions

Higgs potential

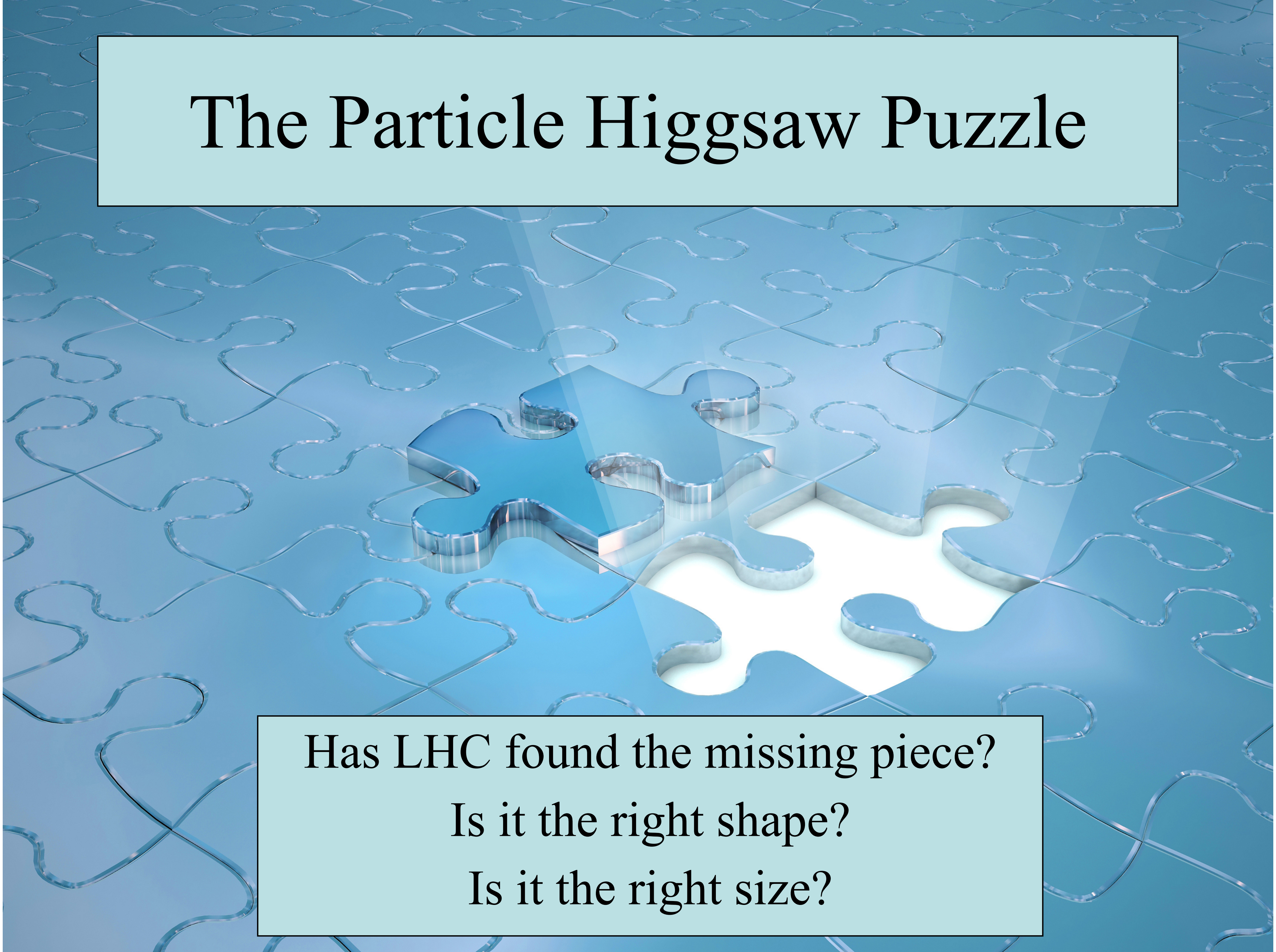
Tested < 0.1% before LHC

Testing now in progress

LHC Measurements



The Particle Higgsaw Puzzle



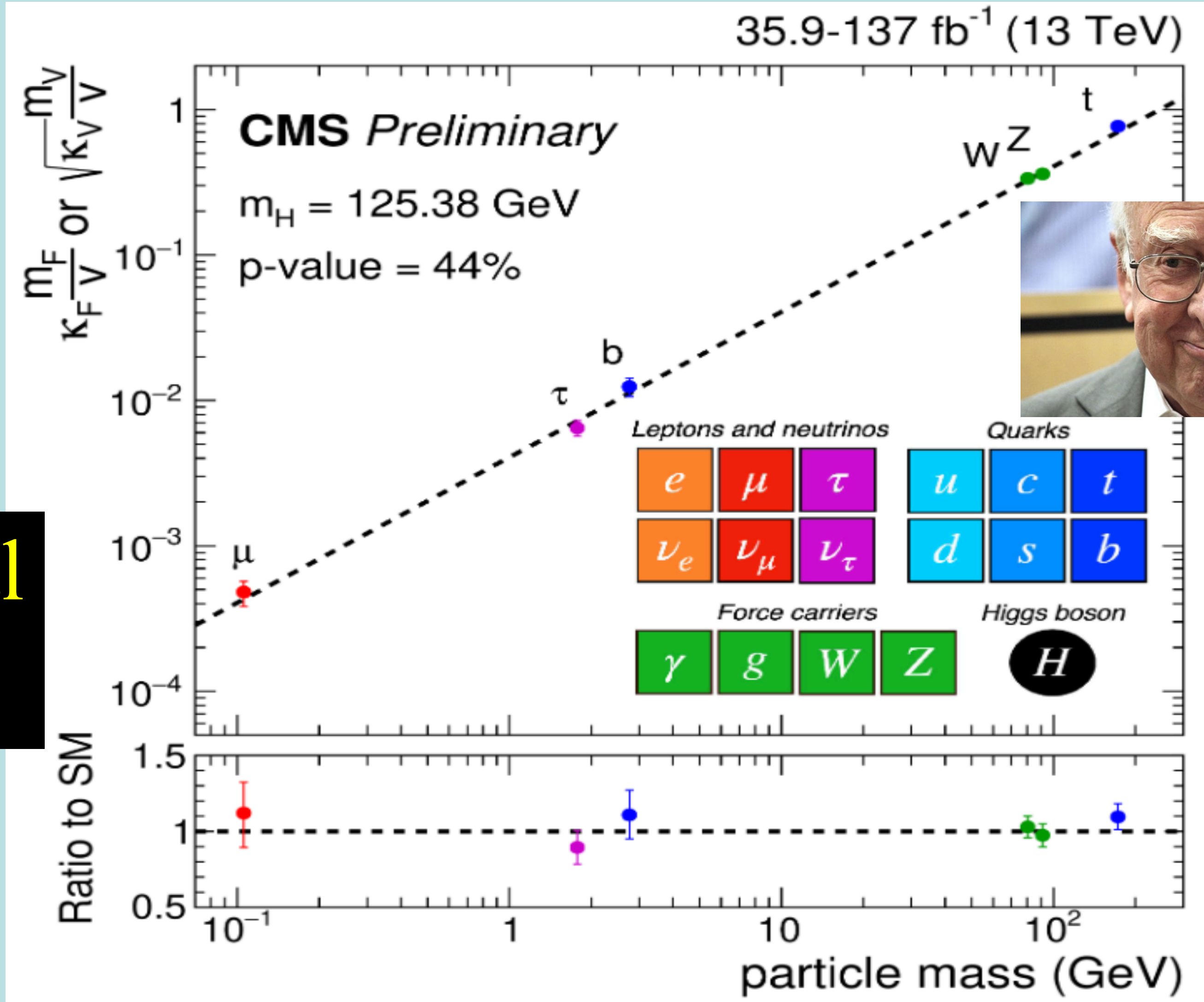
Has LHC found the missing piece?

Is it the right shape?

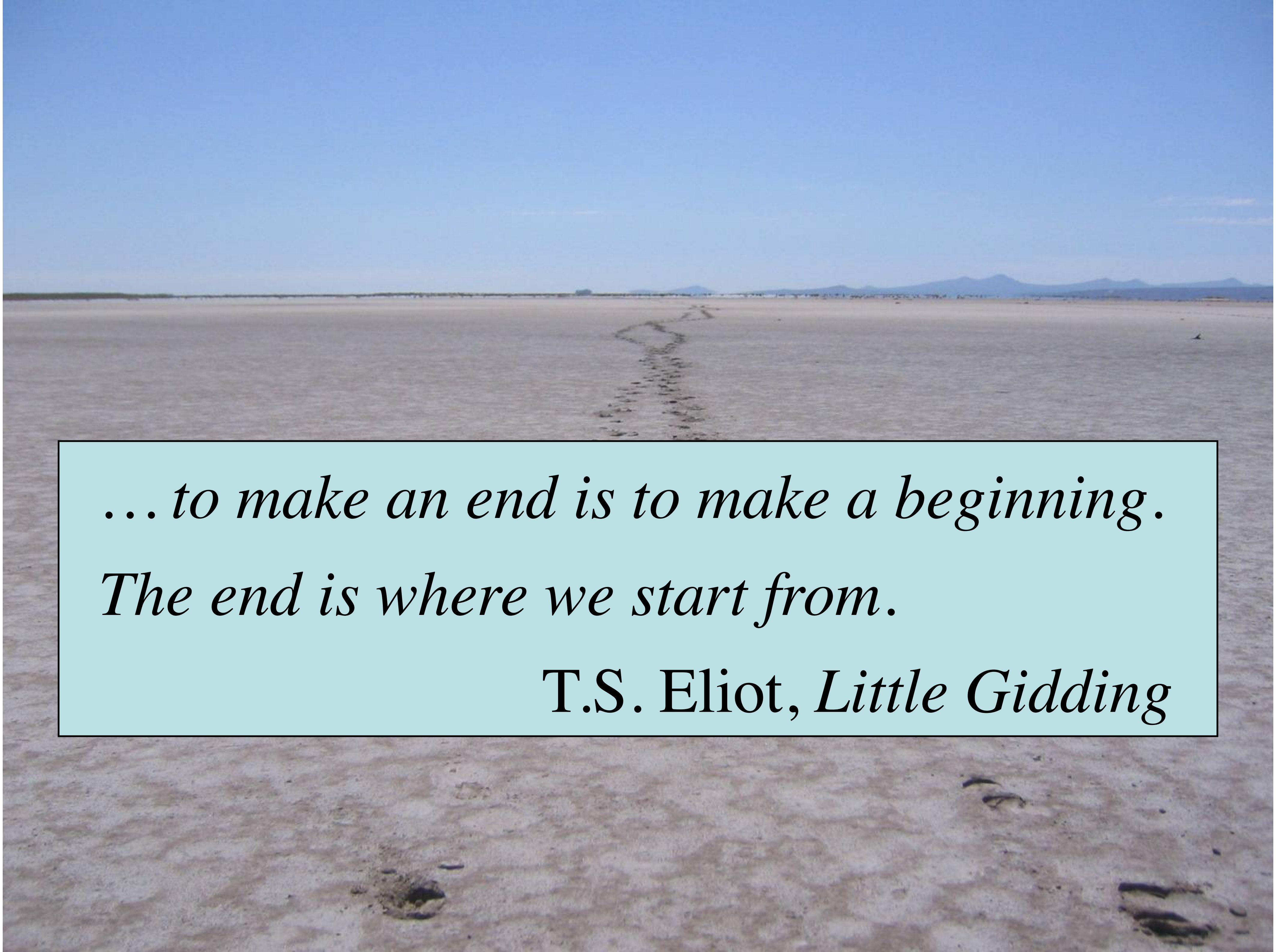
Is it the right size?

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?



Global fit



…to make an end is to make a beginning.
The end is where we start from.

T.S. Eliot, *Little Gidding*

Everything about Higgs is Puzzling

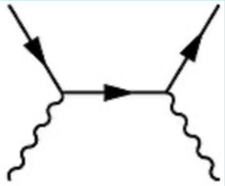
$$\boxed{\mathcal{L} \; = \; yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0} \; \boxed{+ \ldots}$$

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

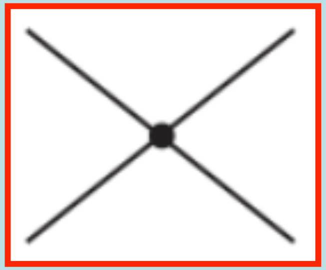
Higher-dimensional interactions?

Effective Field Theories (EFTs)
a long and glorious History

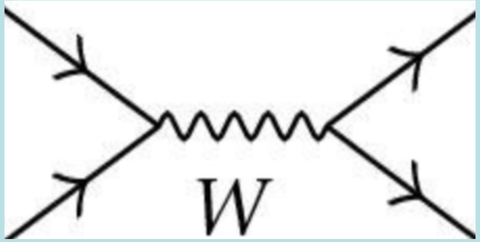
- 1930's: "Standard Model" of QED had d=4



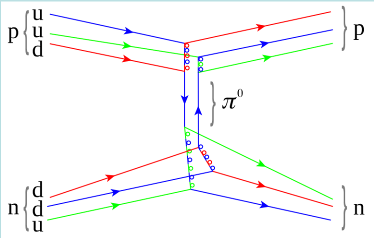
- **Fermi's four-fermion theory of the weak force**



- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?



- V-A ➔ massive vector bosons ➔ gauge theory
- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? ➔ pions



- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue ➔ QCD

Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Summarize Analysis Framework

- Include all leading dimension-6 operators?

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 Operators in Detail

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate $SU(3)^5$ symmetry
- Important when including top observables

X^3		H^6 and H^4D^2		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star\left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		$\psi^2 XH$		$\psi^2 H^2 D$	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

Flavour anomalies

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

Baryon decay

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Operators included in Global Fit

- 20 operators in flavour-universal $SU(3)^5$ fit

$$
\begin{aligned}
&\text{EWPO:} && \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,\\
&\text{Bosonic:} && \mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,\\
&\text{Yukawa:} && \mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.
\end{aligned}
$$

Indicating which sectors constrain which operators

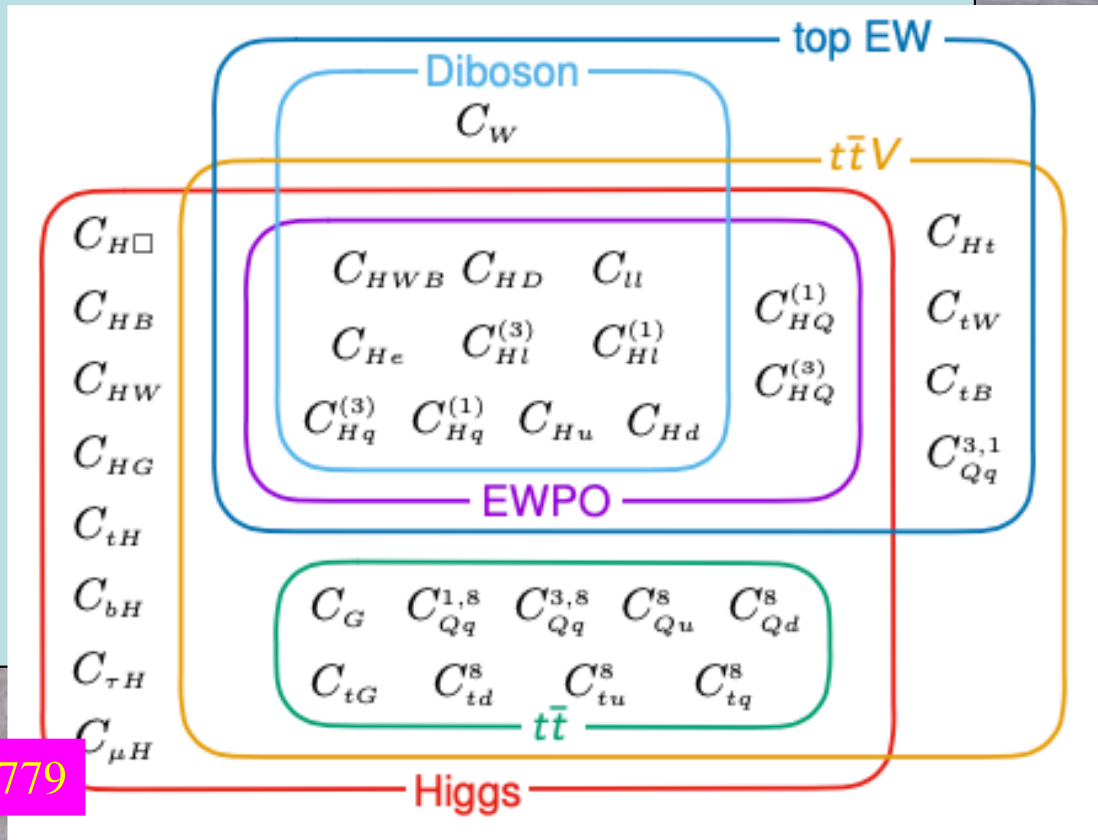
- 34 operators in top-specific $SU(2)^2 \times SU(3)^3$ fit

$$
\begin{aligned}
&\text{EWPO:} && \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,\\
&\text{Bosonic:} && \mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,\\
&\text{Yukawa:} && \mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,\\
&\text{Top 2F:} && \mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,\\
&\text{Top 4F:} && \mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.
\end{aligned}
\tag{2.12}
$$

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

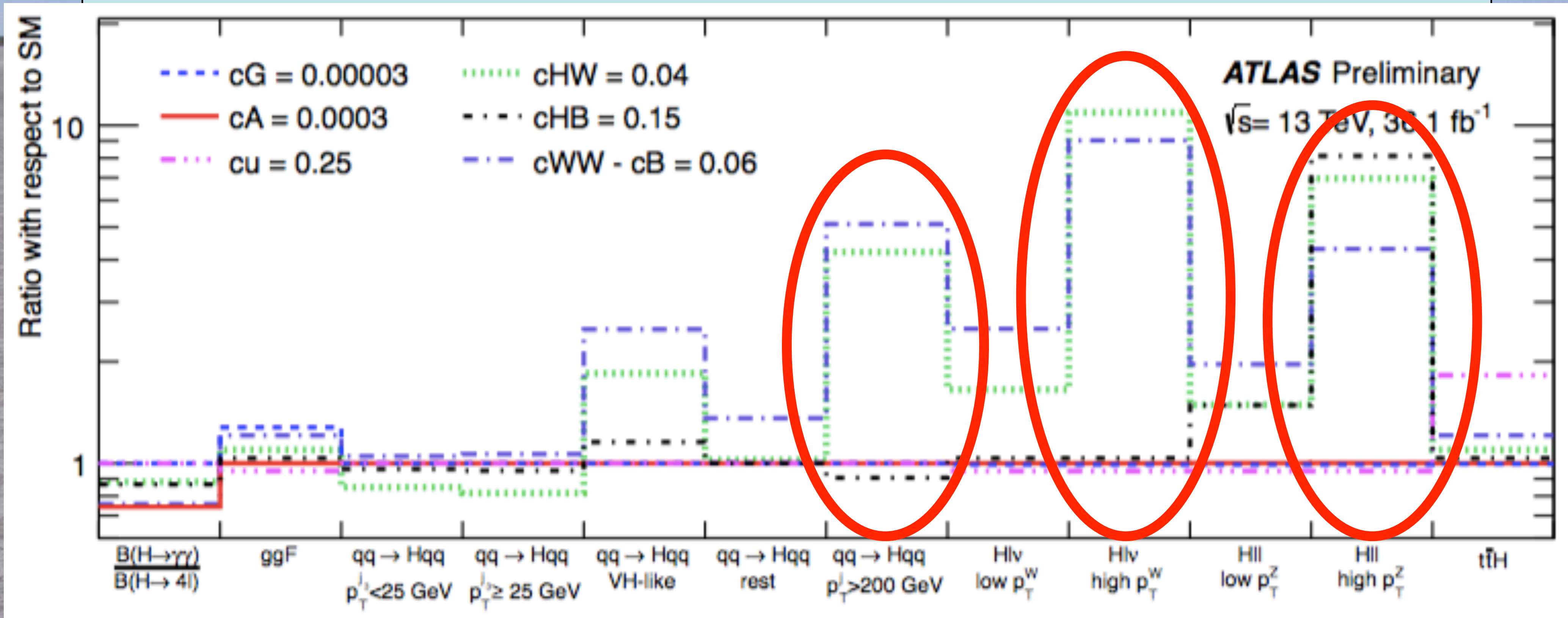
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1 and 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Sensitivities to Operators

- Rate relative to SM with different operators



- **Higher sensitivity at higher p_T**
- **But lower statistics**

Data included in Global Fit

EW precision observables		Ref.
Precision electroweak measurem… Γ_Z, $\sigma^0_{\rm had.}$, R^0_ℓ, A^ℓ_{FB}, A_ℓ(SLD), A…		
Combination of CDF and D0 W…		
LHC run 1 W boson mass meas…		

Diboson LEP & LHC
W^+W^- angular distribution m…
W^+W^- total cross section meas… final states for 8 energies
W^+W^- total cross section meas… $qqqq$ final states for 7 energies
W^+W^- total cross section mea… & $qqqq$ final states for 8 energies
ATLAS W^+W^- differential cr… $p_T > 120$ GeV overflow bin
ATLAS W^+W^- fiducial differe… $\frac{d\sigma}{dp^T_{\ell_1}}$
ATLAS $W^\pm Z$ fiducial differential cross section in the ℓ^+… $\frac{d\sigma}{dp^T_Z}$
CMS $W^\pm Z$ normalised fiducial differential cross section… channel, $\frac{1}{\sigma}\frac{d\sigma}{dp^T_Z}$
ATLAS Zjj fiducial differential cross section in the $\ell^+\ell^-$…

LHC Run 1 Higgs
ATLAS and CMS LHC Run 1 combination of Higgs sig… Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$
ATLAS inclusive $Z\gamma$ signal strength measurement

LHC Run 2 Higgs …		Ref.
ATLAS combination … including ratios of bra…		
Signal strengths|coars…		
CMS LHC combinatio… Production: ggF, VB… Decay: $\gamma\gamma$, ZZ, W^+W…		
CMS stage 1.0 STXS… 13 parameter fit | 7 pa…		
CMS stage 1.0 STXS…		
CMS stage 1.1 STXS…		
CMS differential cross… tion in the $WW^* \to \ell$… $\frac{d\sigma}{dn_{\rm jet}}$ | $\frac{d\sigma}{dp^T_H}$		
ATLAS $H \to Z\gamma$ sign…		
ATLAS $H \to \mu^+\mu^-$ si…		

Tevatron & Run 1 top	$n_{\rm obs}$	Ref.
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]
ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$		
ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS… $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS… dilept…		
ATLA… dilept…		
ATLA… $A_C(m$…		
CMS… $\frac{d\sigma}{dm_{t\bar{t}}dy}$		
ATLA… decay.		
ATLA… f_0, f_L…		
CMS… f_0, f_L…		
ATLA…		
CMS…		
ATLA… $\frac{d\sigma}{dp^T_t}$		
CMS…		
CMS… $\frac{d\sigma}{dp^T_{t+\bar{t}}}$		
CMS… $\sigma_t\,\vert\,\sigma_{\bar{t}}\,\vert\,\sigma_{t+\bar{t}}\,\vert\,R_t$.		
ATLAS s-channel single-top cross section measurement.		
CMS tW cross section measurement.	1	[33]
ATLAS tW cross section measurement in the single lepton channel…	1	[34]
ATLAS tW cross section measuremen…		

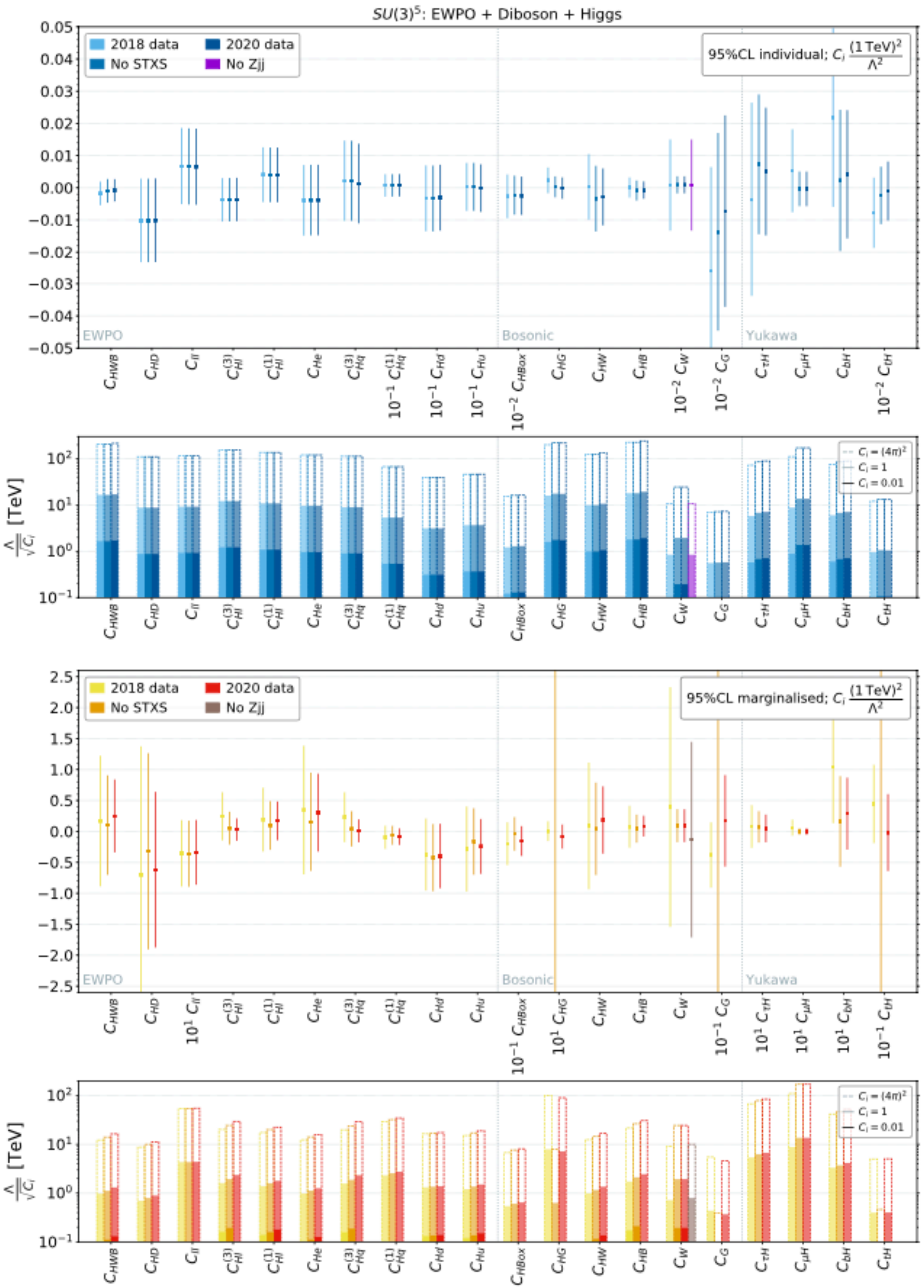
Run 2 top	$n_{\rm obs}$	Ref.
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 231]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\vert\sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\vert\sigma_{t\bar{t}Z}$	1|1	[40]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp^T_Z}$ | $\frac{d\sigma}{d\cos\theta^*}$	4|4	[41]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $R_t\,(p^T_{t+\bar{t}})$	5|5	[42]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & R_t.	4	[43]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t\,\vert\,\sigma_{\bar{t}}\,\vert\,\sigma_{t+\bar{t}}\,\vert\,R_t$.	1|1|1|1	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $\frac{d\sigma}{d\vert y_{t+\bar{t}}\vert}$	4|4	[45]
ATLAS tW cross section measurement.		
CMS tZ cross section measurement.		
CMS tW cross section measurement.		
ATLAS tZ cross section measurement.		
CMS $tZ\,(Z \to \ell^+\ell^-)$ cross section measurement		

328 measurements included in global analysis

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

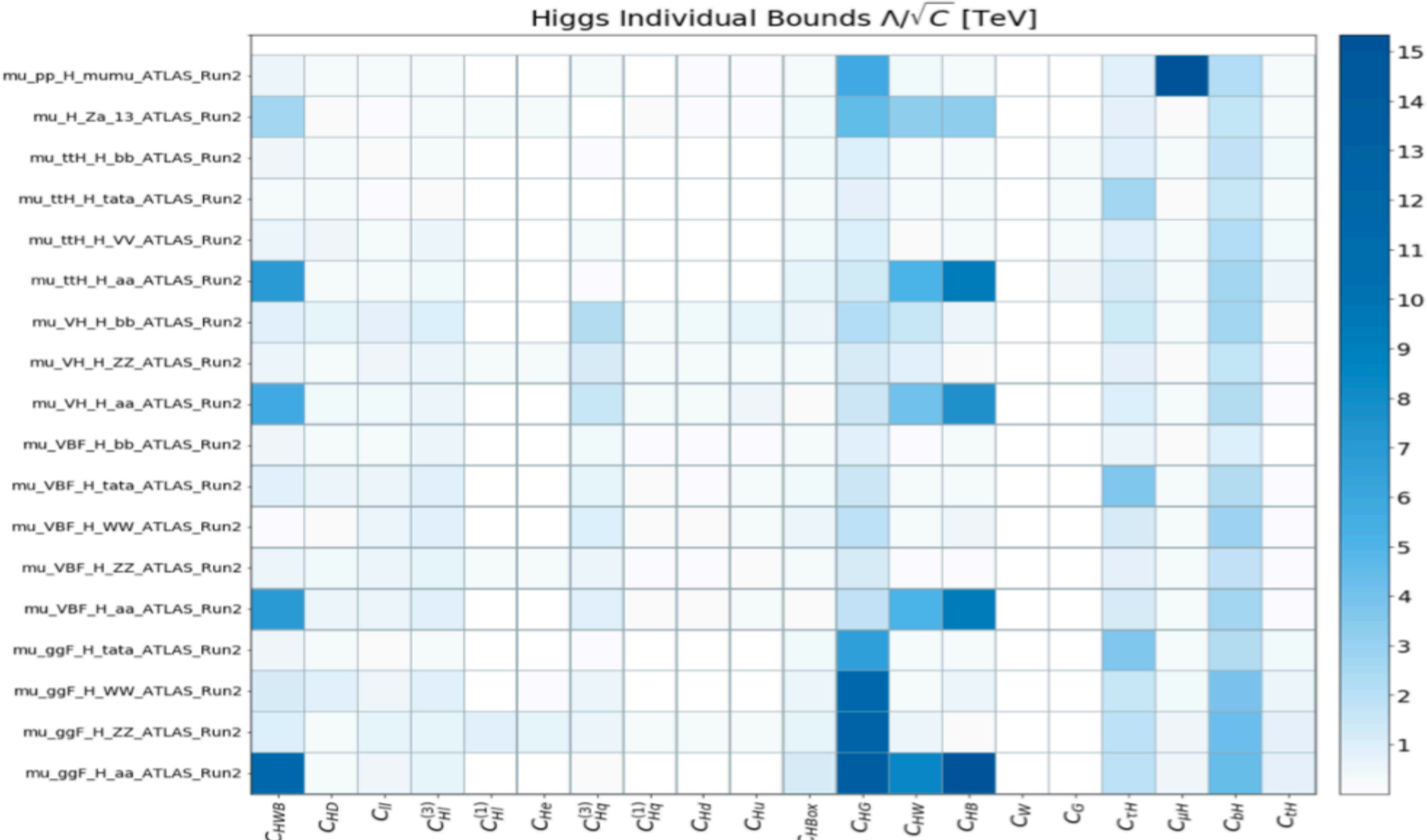
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Impacts of Measurements

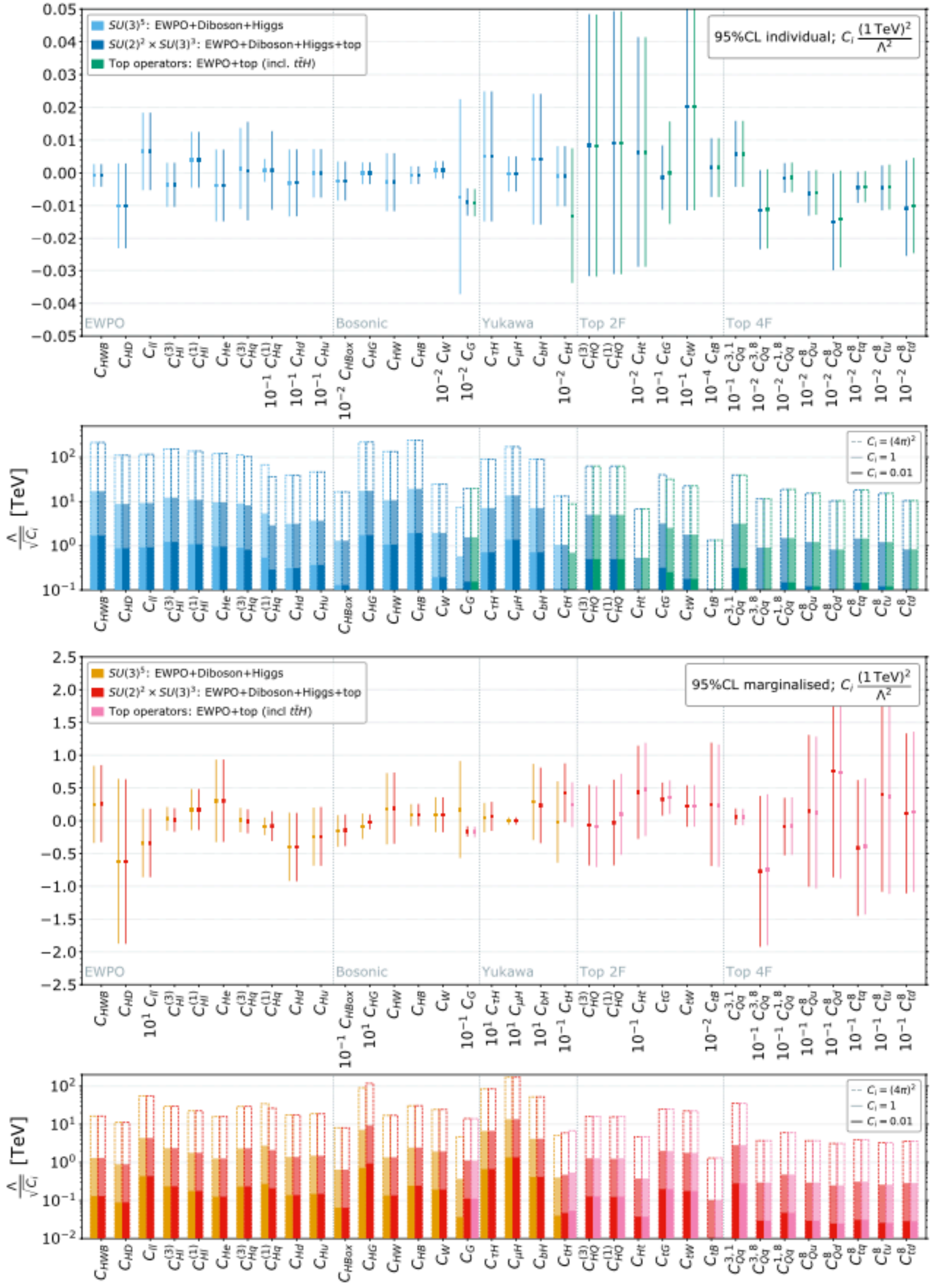
$$\frac{X}{X_{SM}} = 1 + \sum_i \boxed{a_i^X} \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\cancel{\frac{1}{\Lambda^4}}\right)$$



Which measurements constrain which operator coefficients?

Dimension-6 Constraints with Top-Specific $SU(2)^2 \times SU(3)^3$

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



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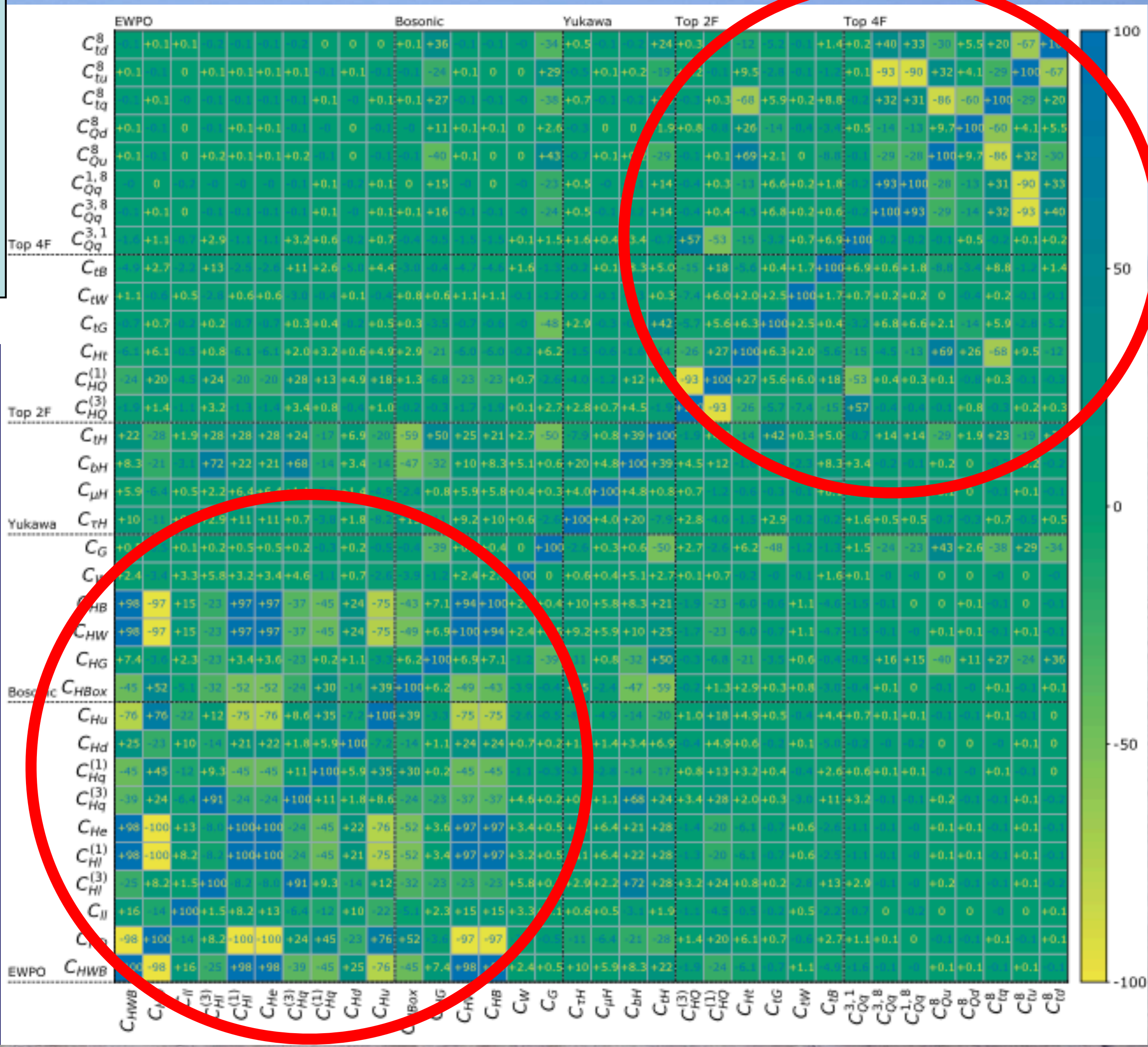
Correlation Analysis

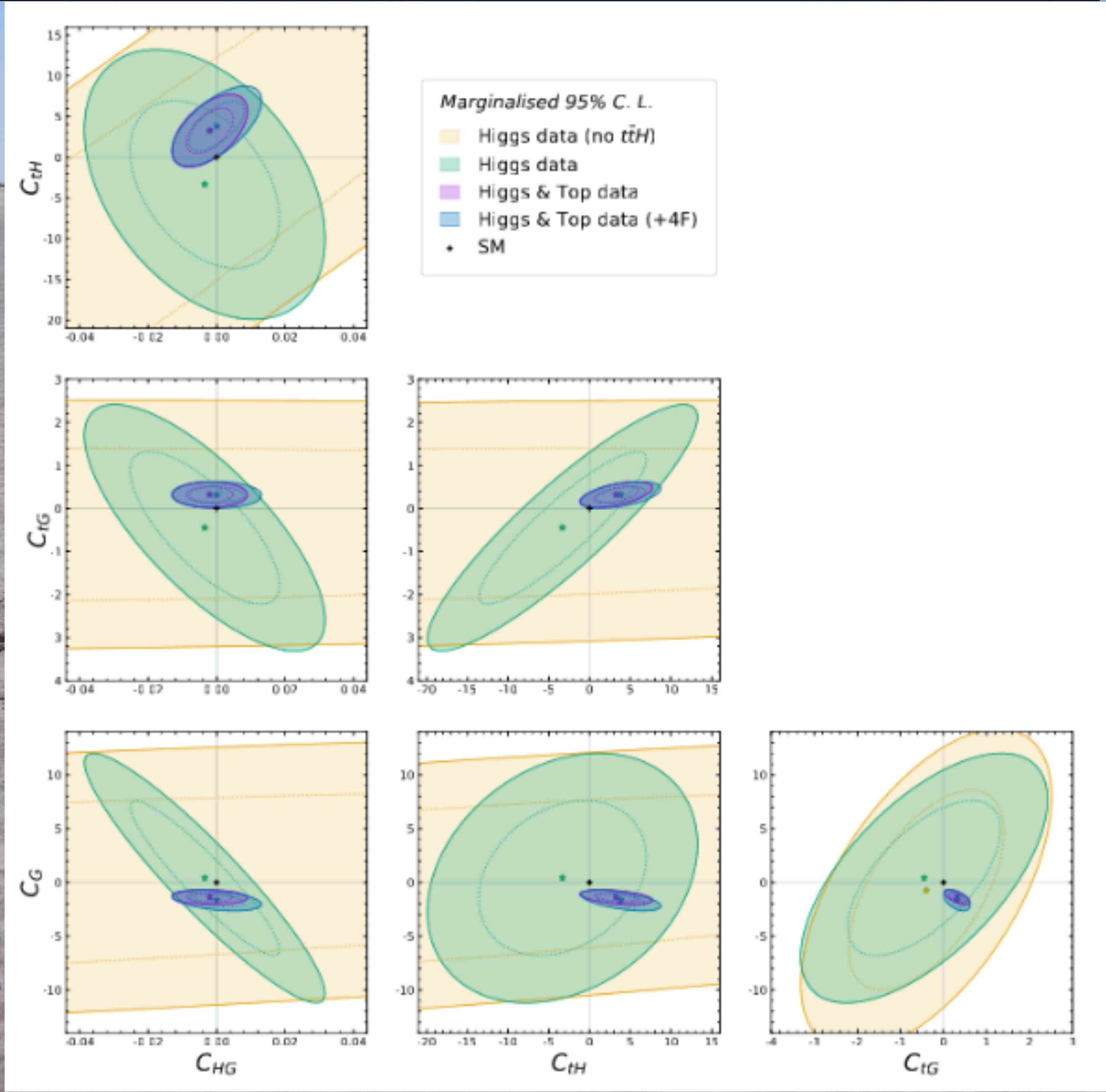


- EWPO and boson sectors correlated
- Also within top sector
- Weaker correlations between sectors

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

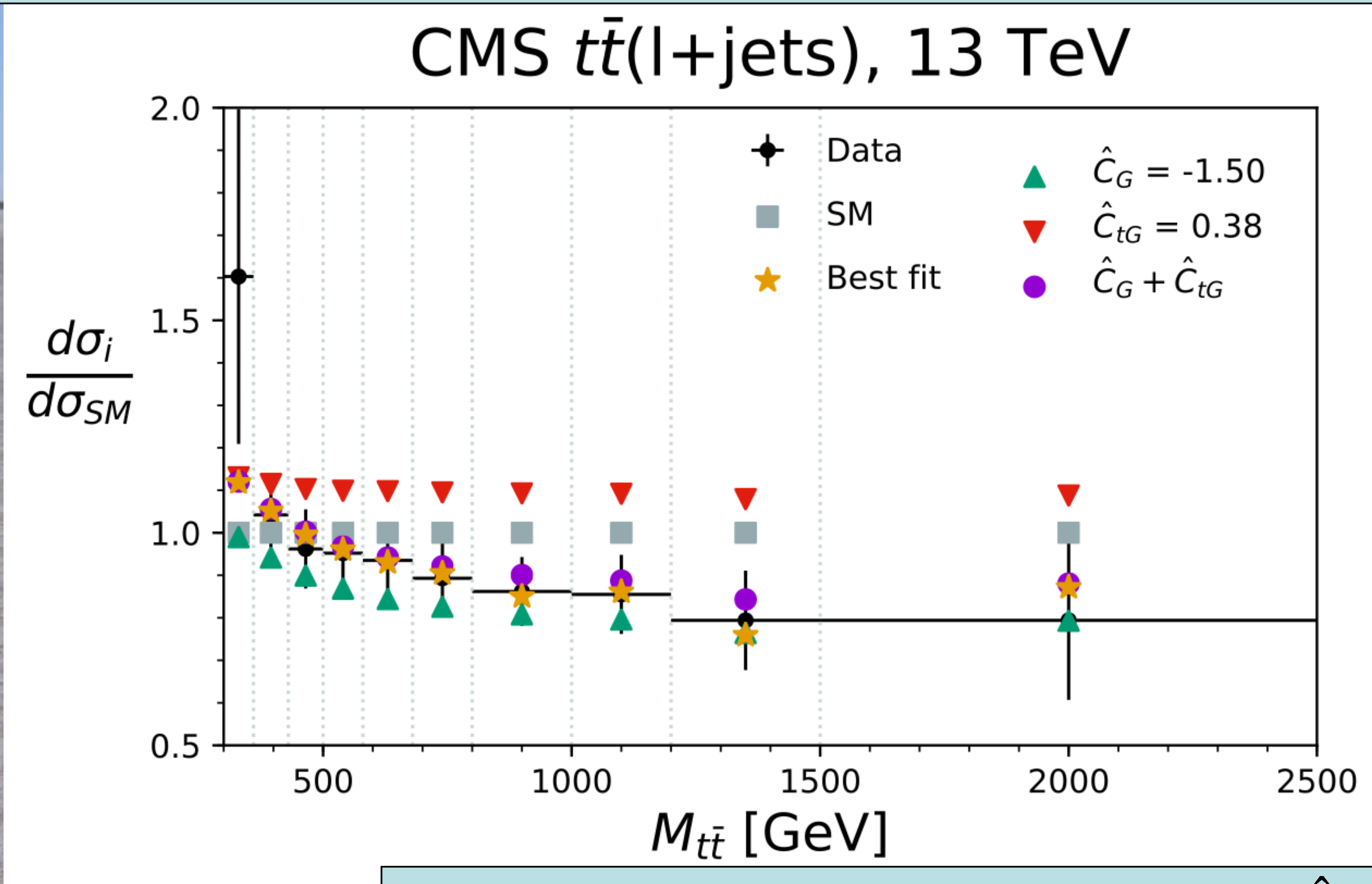
Example of Interplay between Data Sets

- Higgs data
- Include ttH
- Include top data
- Global analysis



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Biggest Discrepancy with Standard Model



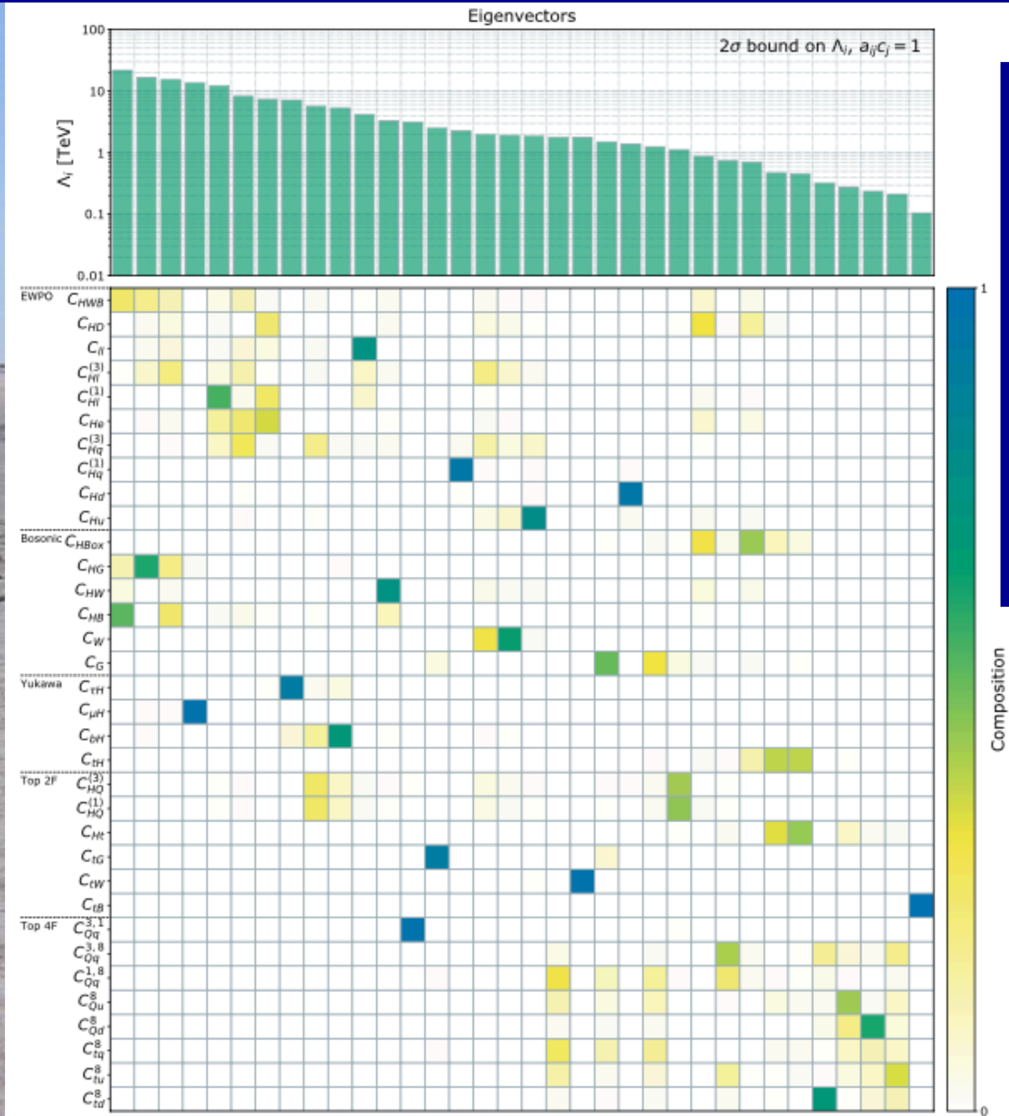
- $t\bar{t}$ invariant mass distribution favours $\hat{C}_G \neq 0$
- But jet data favour small $\hat{C}_G \simeq 0$

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Principal Component Analysis

- Diagonalise correlation matrix
- Analyze eigenvectors and eigenvalues
- Scales from 20 TeV to 100 GeV
- Strongest constraints from Electroweak, H

Less constrained operator combinations ➔



EWPO	6	35	59	–	99	97	99	–	73	25	75	–	–	–	91	8	8	60	–	–	–	90	–	–	3	–	3	1	–	–	–	–	–	–
LEP WW	–	–	–	–	–	–	–	–	–	–	24	–	–	–	2	9	3	8	–	–	–	6	–	–	5	–	4	–	–	–	–	–	–	–
Run 1, μ_H	15	13	7	5	–	–	–	21	2	7	–	6	–	1	1	6	3	3	–	–	–	–	1	–	25	–	12	10	6	–	–	–	–	–
Run 2, μ_H	29	28	16	94	–	–	–	45	5	17	–	90	–	14	2	14	6	5	–	–	8	–	11	2	37	2	30	26	17	–	–	–	–	–
STXS	50	23	18	1	–	–	–	33	19	50	–	2	–	6	3	24	11	17	–	–	4	1	4	–	12	–	19	12	8	–	–	–	–	–
LHC WW	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	1	3	–	–	–	–	–	–	9	–	4	–	–	–	–	–	–	–
LHC Zjj	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	30	66	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$t\bar{t}$	–	–	–	–	–	–	–	–	–	–	–	–	–	71	–	1	–	–	99	84	72	–	72	10	7	12	19	11	27	97	98	100	99	1
single top	–	–	–	–	–	–	–	–	–	–	–	–	100	–	–	2	1	–	–	14	–	1	2	76	1	6	–	6	8	–	–	–	–	96
$t\bar{t}V$	–	–	–	–	–	–	–	–	–	–	–	–	–	8	–	–	–	–	–	–	15	–	9	10	–	79	8	31	33	3	–	–	–	–

Relative constraining power (%)

Relative importance (%)

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Single-Field Extensions of the Standard Model

Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	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	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
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	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Contributions to SMEFT Coefficients

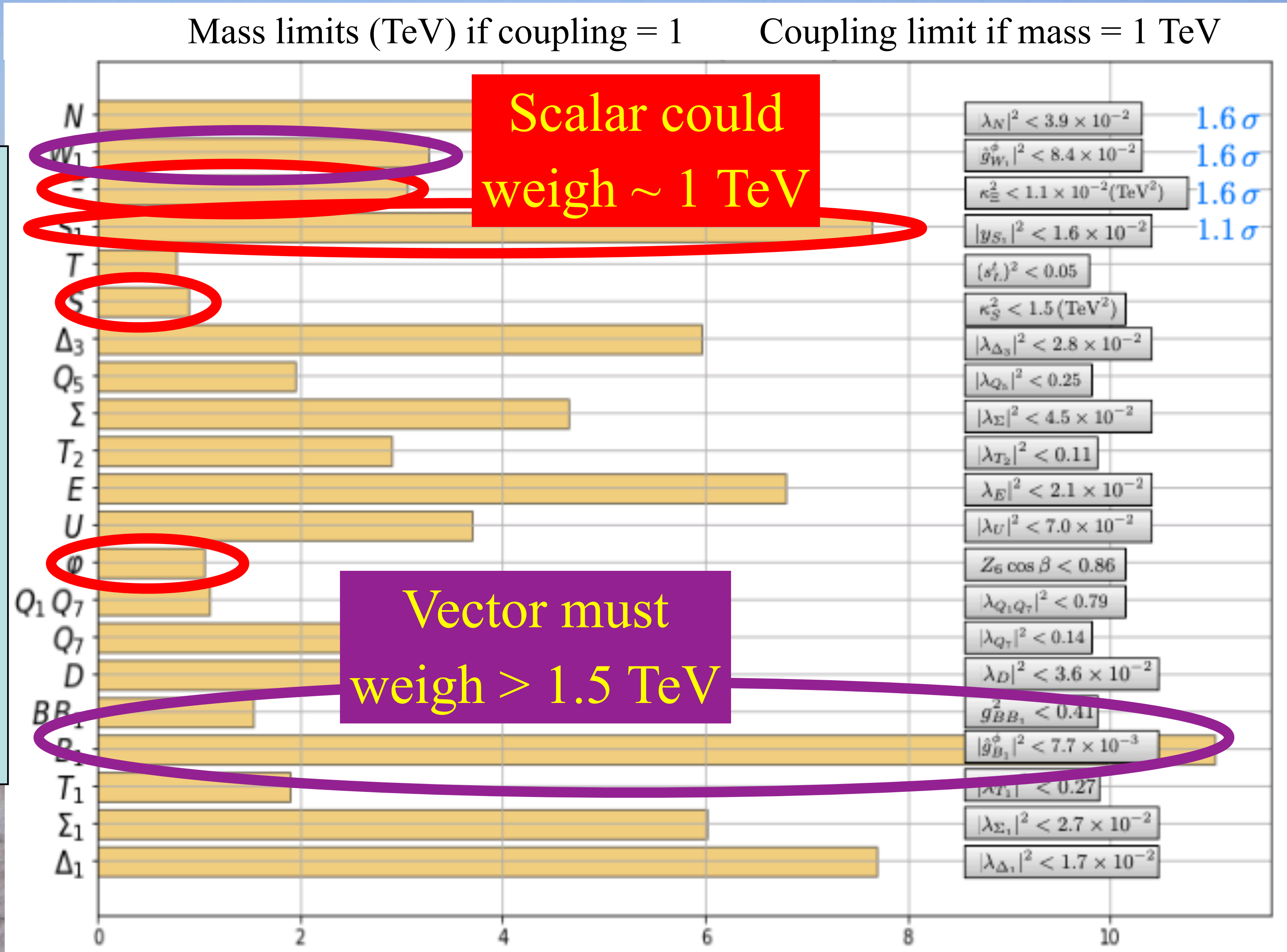
Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
Spin zero S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Spin zero Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1 Vector	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
Spin zero φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$ Vector						1	y_τ	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

Model	C_{HG}	C^3_{Hq}	C^1_{Hq}	$(C^3_{Hq})_{33}$	$(C^1_{Hq})_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}
U		$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$	
D		$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$
Q_5							$-\frac{1}{2}$		$\frac{y_b}{2}$
Q_7						$\frac{1}{2}$		$\frac{y_t}{2}$	
T_1		$-\frac{5}{8}$	$-\frac{3}{16}$	$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$
T_2		$-\frac{5}{8}$	$\frac{3}{16}$	$-\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$
T	$-\frac{M_T^2}{v^2}\frac{\alpha_s(0.02)}{8\pi}$			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$	

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Constraints on Single-Field BSM Scenarios

- No significant pulls away from SM
- Any single-field extension of SM must have mass scale > 800 GeV if coupling = 1



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Constraints on Light Stops

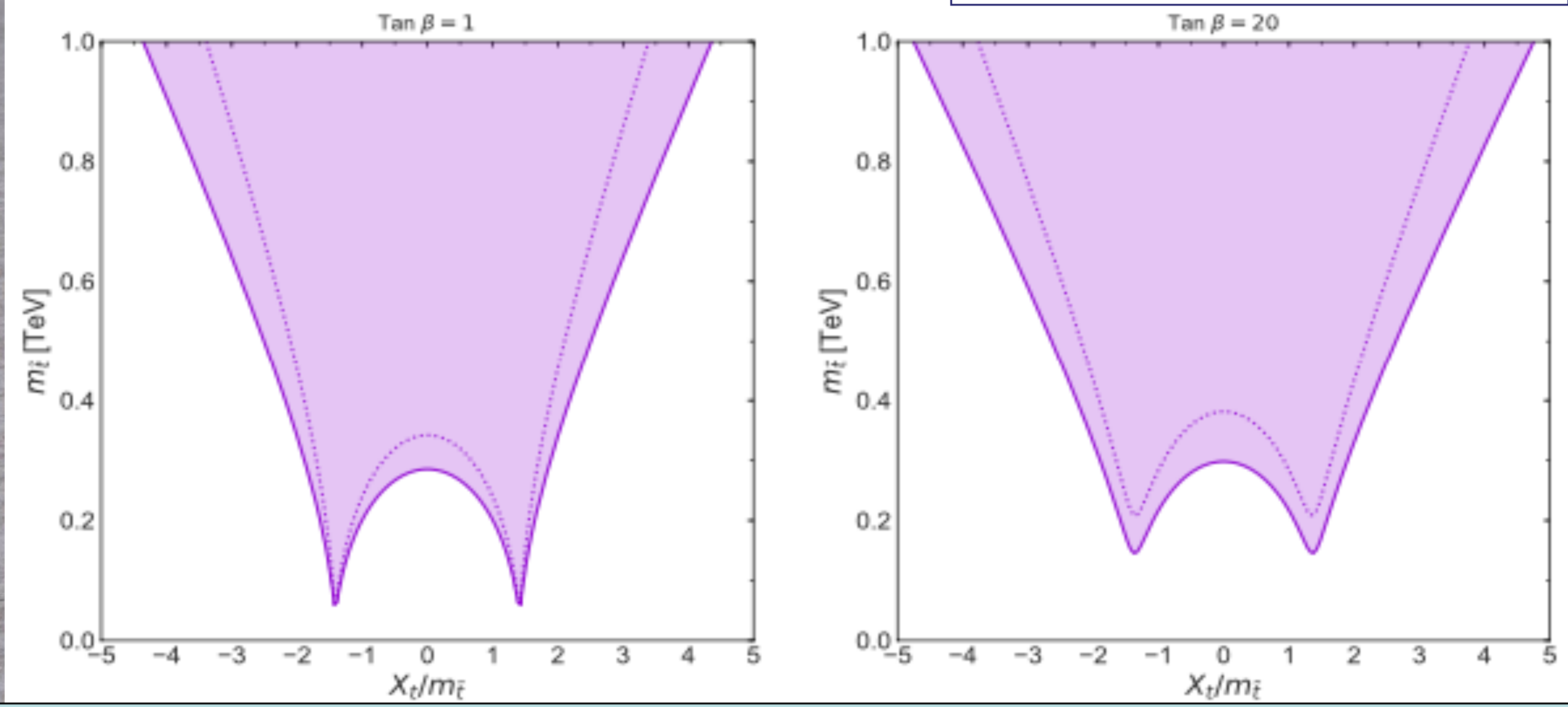
From quantum loop corrections:

$$C_{HG} = \frac{g_s^2}{12}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{1}{12}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\Big],$$

$$C_{HB} = \frac{17g'^2}{144}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{31}{102}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{38}{85}\frac{X_t^2}{m_{\tilde{t}}^2}\Big],$$

$$C_{HW} = \frac{g^2}{16}\frac{h_t^2}{(4\pi)^2}\Big[(1-\frac{1}{6}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{2}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\Big],$$

$$C_{HWB} = -\frac{gg'}{24}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{1}{2}\frac{c_{2\beta}g^2}{h_t^2}) - \frac{4}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\Big],$$

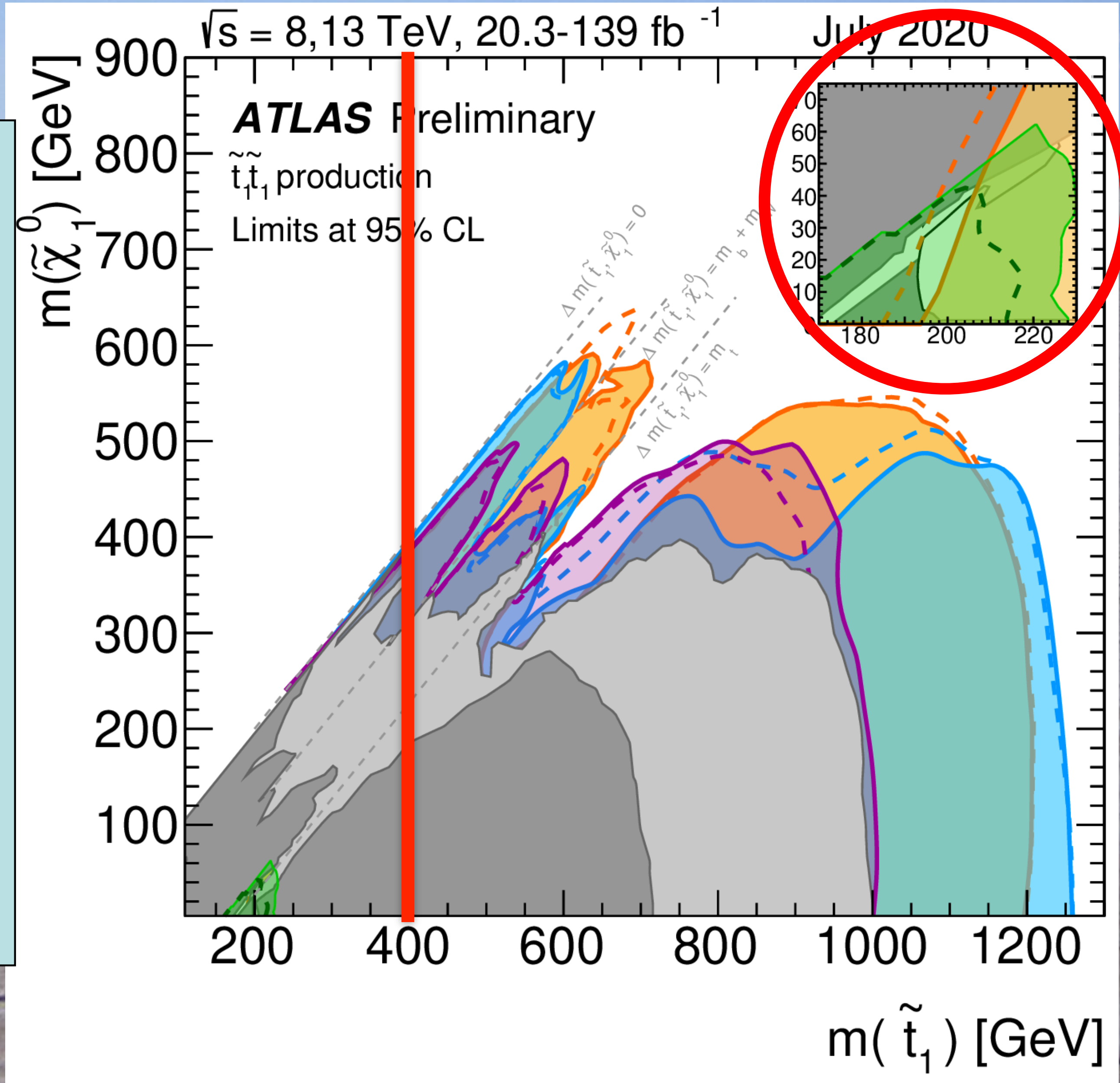


(Almost) model-independent lower limit on stop squark mass

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

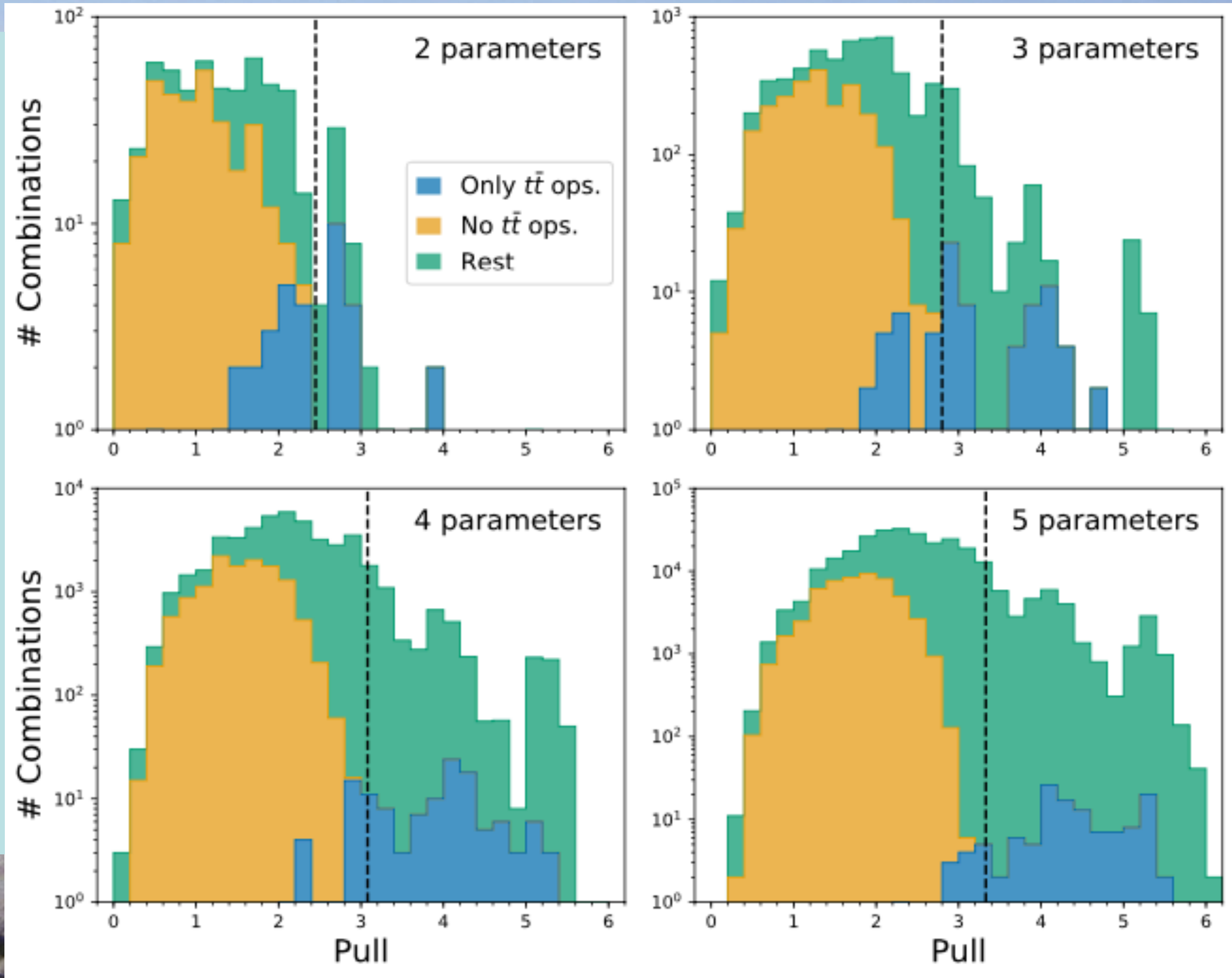
Direct Search Constraints on Light Stops

- Patchwork of many model-dependent searches
- Indirect constraint excludes low-mass region (almost) model-independently



Model-Independent BSM Survey

- **Top-less sector fits SM very well**
- Top sector does not fit so well
- Overall, pulls not excessive
- **No hint of BSM**

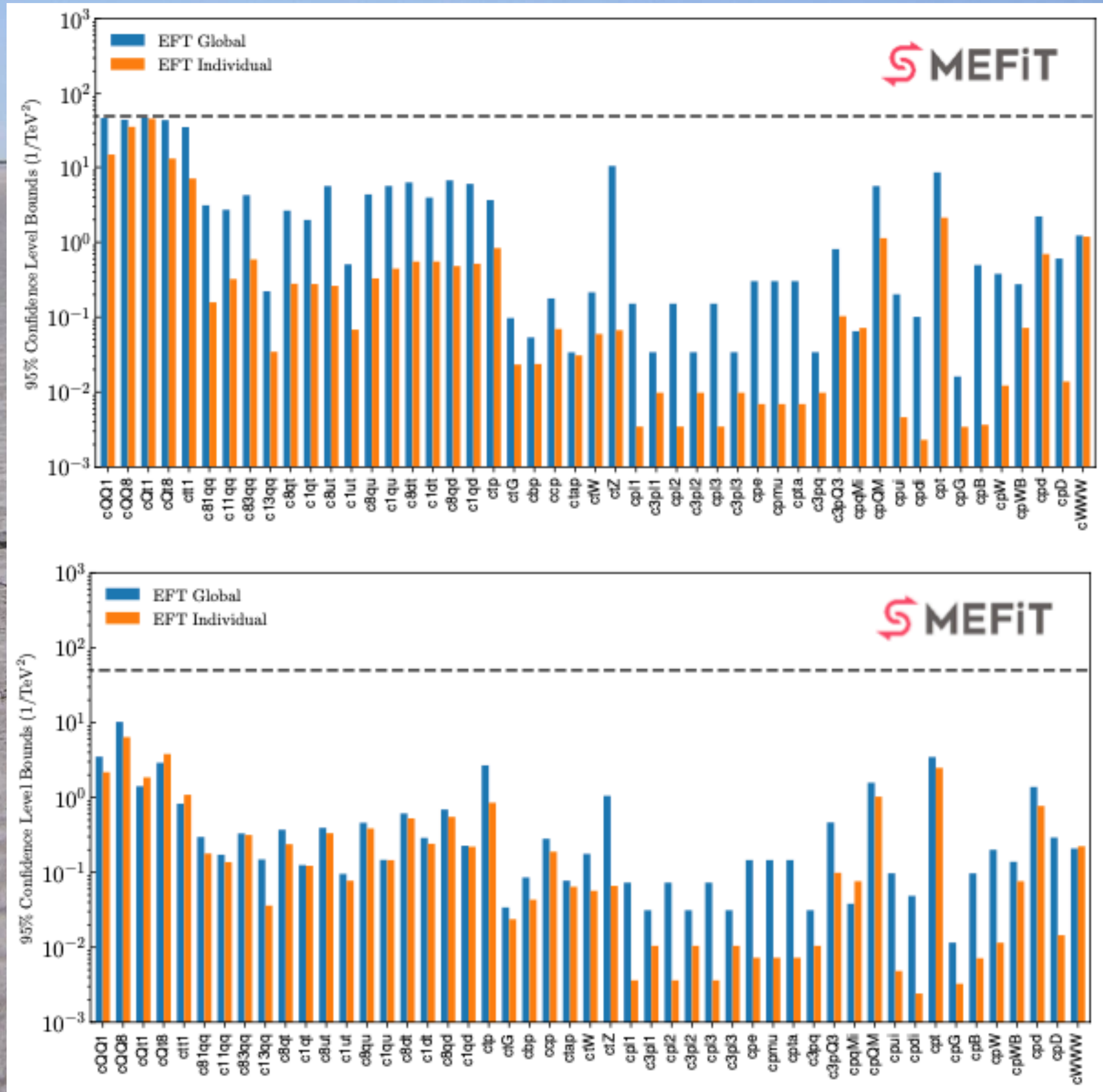


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Comparison of Linear and Quadratic Fits

- Quadratic dimension 6 contribute at $\mathcal{O}(1/\Lambda^4)$
- Fit assuming EW data = Standard Model
- Tighter constraints in general
- Fitting process slower, difficult to make broad BSM survey
- **How about dimension 8, also contribute at $\mathcal{O}(1/\Lambda^4)$?**

Ethier et al., arXiv:2105.00006



How about Dimension 8?

Some windows of opportunity:

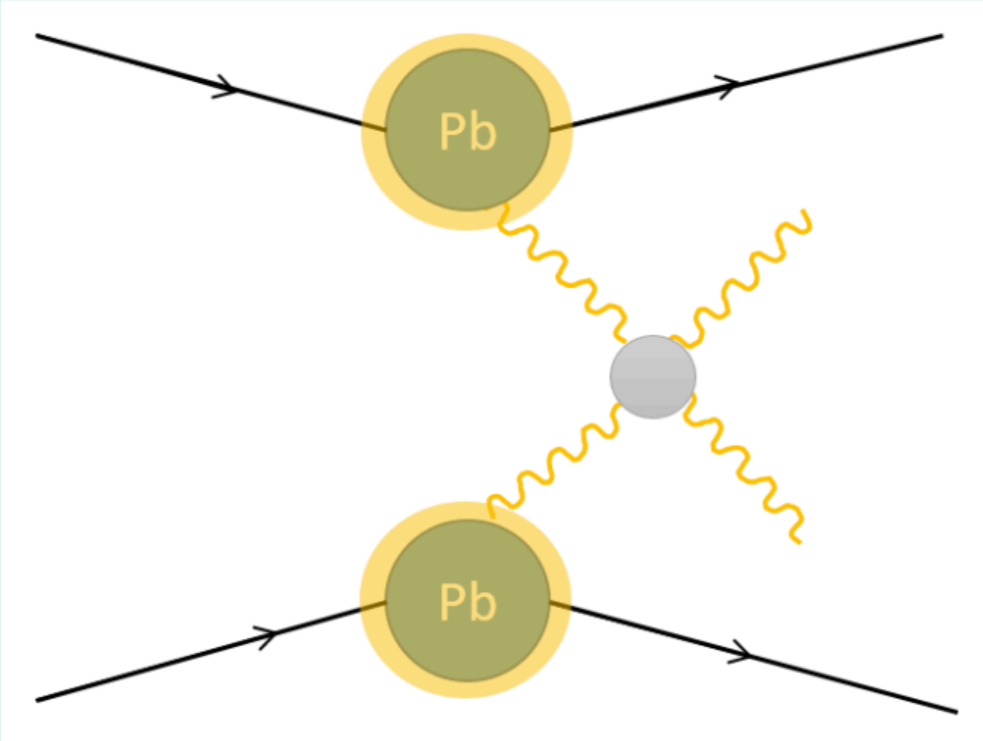
Light-by-light scattering

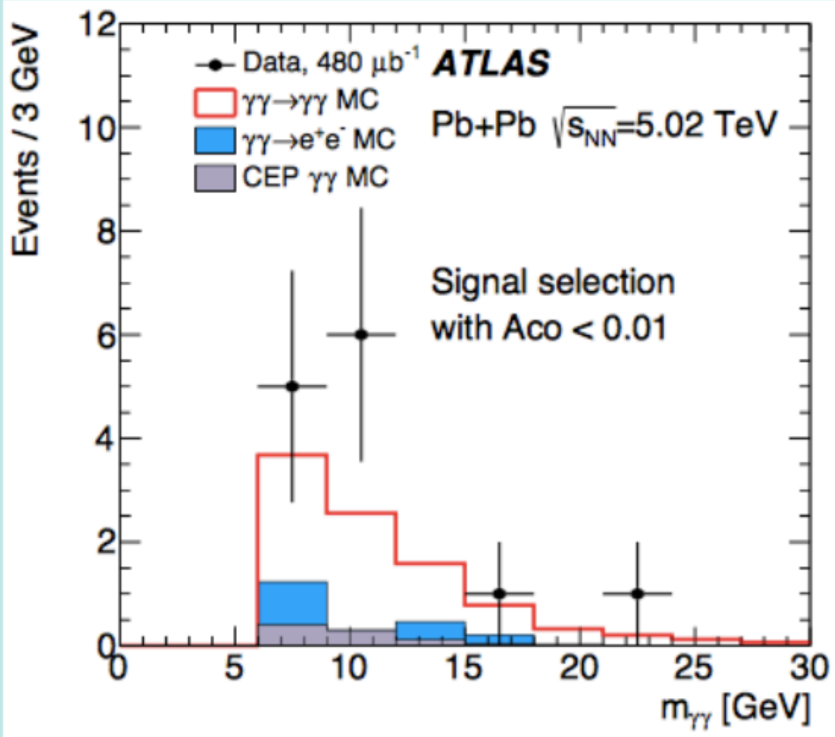
$$gg \to \gamma\gamma, Z\gamma$$

Neutral triple-gauge couplings

First Measurement of Light-by-Light Scattering

- Peripheral heavy-ion collisions at the LHC: $\gamma\gamma \rightarrow \gamma\gamma$





- Expected in ordinary QED from fermion loops
- ATLAS measurement agrees with QED

Heisenberg & Euler 1936

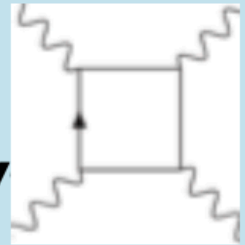
- Can be used to constrain nonlinearities in Born-Infeld

JE, Mavromatos & You: arXiv:1703.08450

Supplement on dimension-8 operators

Light-by-Light Scattering in QED

- Electron (charged particle) loops induce light-by-light scattering: γ



- First calculations:

Bemerkungen zur Diracschen Theorie des Positrons.

Von **W. Heisenberg** in Leipzig.

(Eingegangen am 21. Juni 1934.)

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2) + \frac{e^2}{h c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}$$

Born-Infeld Theory

Foundations of the New Field Theory.

By M. Born and L. Infeld,† Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 26, 1934.)

- Original Born-Infeld modification of QED:

$$L = b^2\left(\sqrt{1 + \frac{1}{b^2}(H^2 - E^2)} - 1\right).$$

- Based on "unitarian" idea of maximum electromagnetic field, cf, velocity of light
- Limit on Coulomb potential

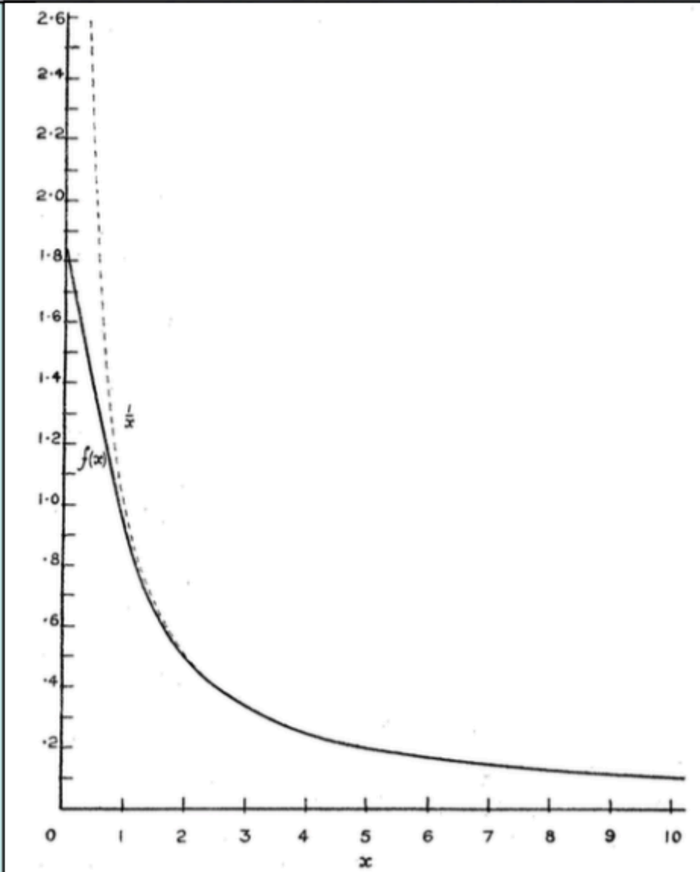


Fig. 1.

Born-Infeld & String Theory

- Original Born-Infeld modification of QED: Born & Infeld 1934

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow \mathcal{L}_{\rm BI} = \beta^2\left(1-\sqrt{1+\frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu}-\frac{1}{16\beta^4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2}\right)$$

- Derived from string theory: Fradkin & Tseytlin 1985

  in D dimensions: $\int d^D y \left[\det\left(\delta_{\mu\nu}+2\pi\alpha' F_{\mu\nu}\right)\right]^{1/2}$

  4 dimensions: $[\det(\delta_{\mu\nu}+\bar{F}_{\mu\nu})]^{1/2} = [1+\frac{1}{2}\bar{F}^2_{\mu\nu}+\frac{1}{16}(\bar{F}_{\mu\nu}\bar{F}^*_{\mu\nu})^2]^{1/2}$

- Limiting gauge field ⇔ brane velocity = light

$$\mathcal{L}_{BI} \propto \sqrt{1-(2\pi\alpha' e\mathbf{E})^2} \quad \leftrightarrow \quad \mathcal{L}_{particle} \propto \sqrt{1-v^j v_j}$$

Bachas, hep-th/9511043

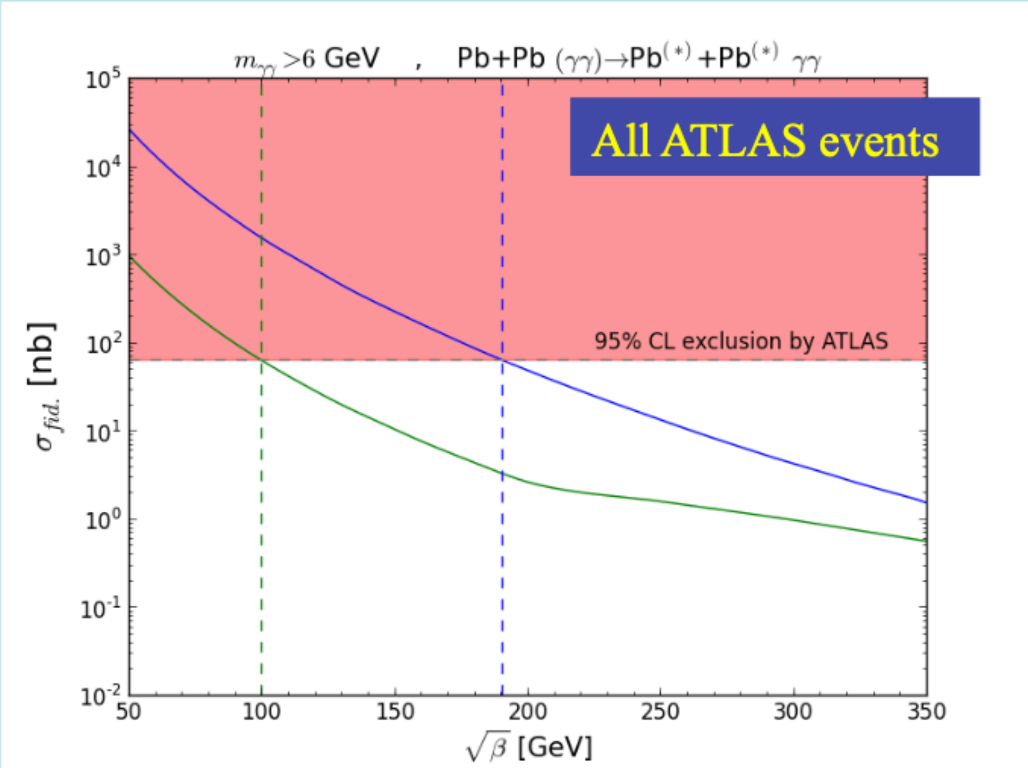
- Mass scale M = $\sqrt{\beta}$

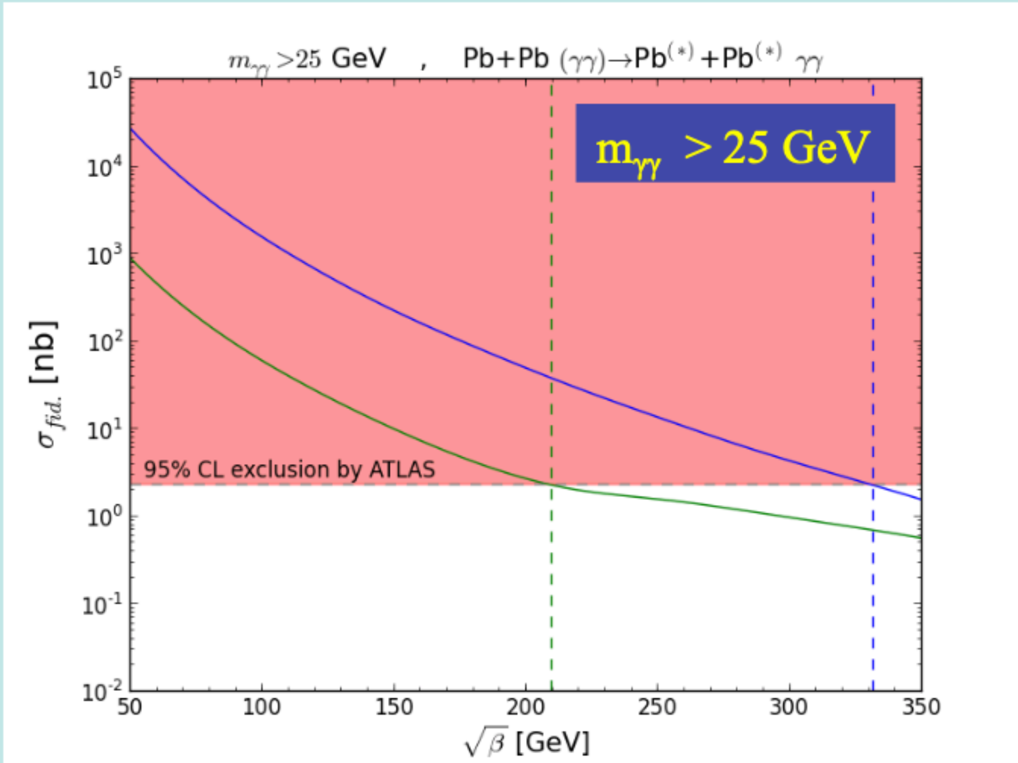
  ⇔ 1/distance between branes, ≥ TeV?

Constraint on Born-Infeld Scale

JE, Mavromatos & You, arXiv:1703.08450

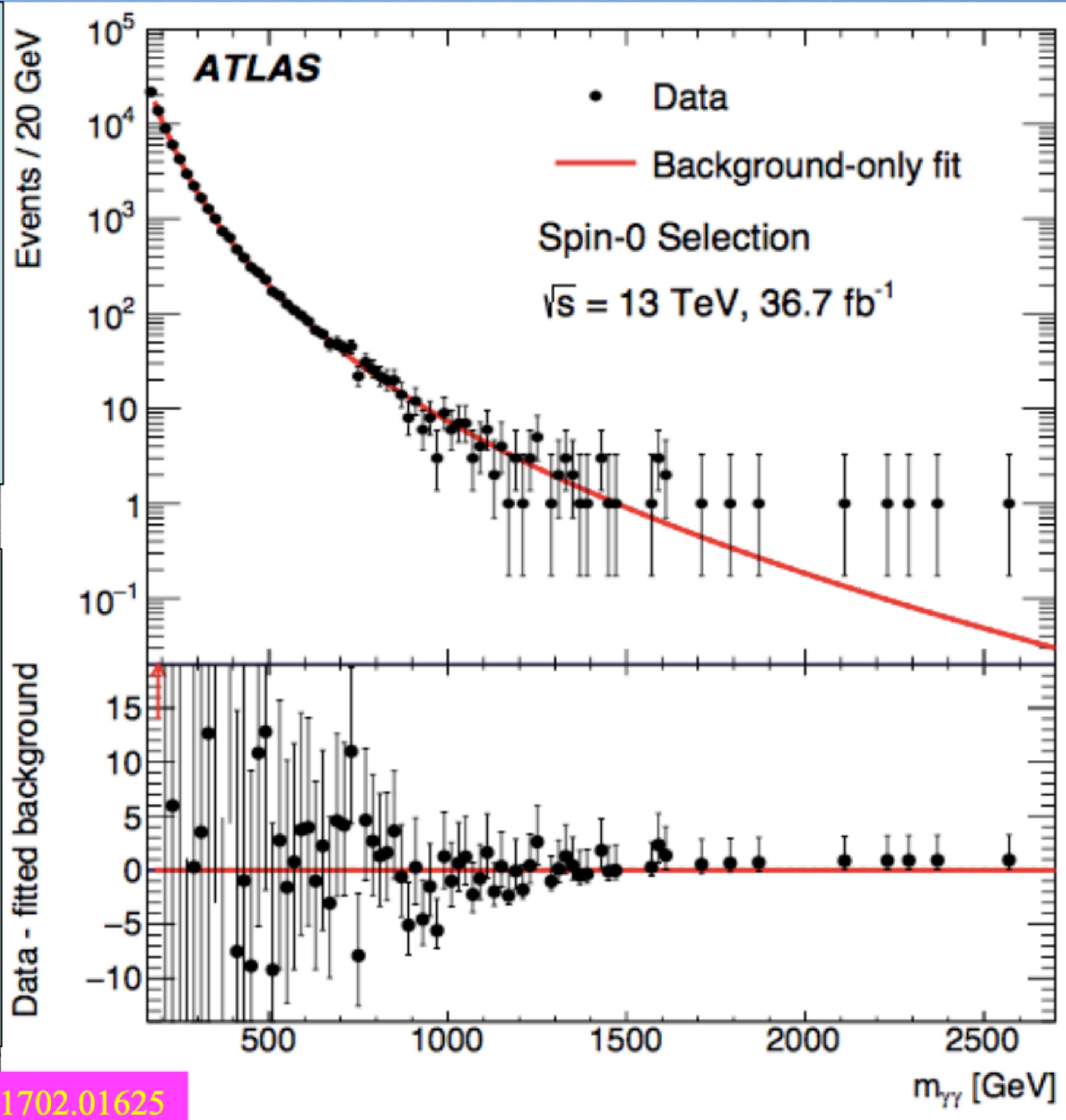
- ATLAS constraint on σ(γγ→γγ) constrains $M = \sqrt{\beta}$





- All events with $m_{\gamma\gamma} \leq M$: limit $M \approx 100, 210$ GeV
- Assume $\sigma = 1/m_{\gamma\gamma}^2$ at higher masses: $M \approx 190,330$ GeV
- **Entering range of low-scale brane models**

Production of Isolated γγ at LHC



- Data agree with SM
- Can be used to constrain dimension-8 ggγγ operators

ATLAS Collaboration, arXiv:1702.01625

JE & Ge, arXiv:1802.02416

Effects of Dimension-8 ggγγ Operators

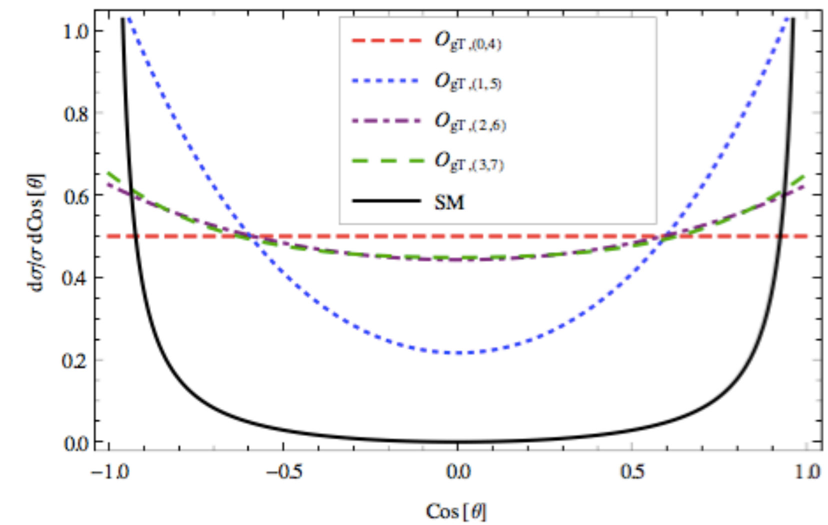
Dimension-8 operators

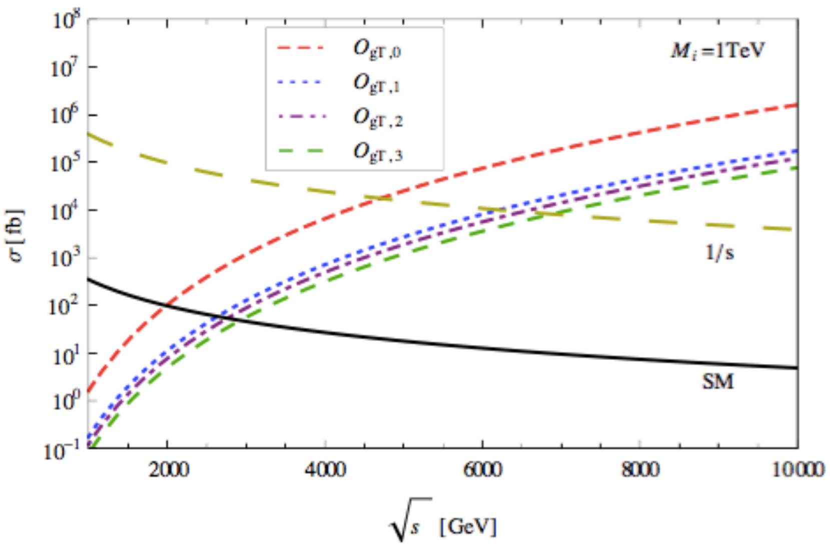
$$\mathcal{O}_{gT,0} = \sum_a G^a_{\mu\nu} G^{a,\mu\nu} \times \sum_i W^i_{\alpha\beta} W^{i,\alpha\beta},$$
$$\mathcal{O}_{gT,1} = \sum_a G^a_{\alpha\nu} G^{a,\mu\beta} \times \sum_i W^i_{\mu\beta} W^{i,\alpha\nu},$$
$$\mathcal{O}_{gT,2} = \sum_a G^a_{\alpha\mu} G^{a,\mu\beta} \times \sum_i W^i_{\nu\beta} W^{i,\alpha\nu},$$
$$\mathcal{O}_{gT,3} = \sum_a G^a_{\alpha\mu} G^a_{\beta\nu} \times \sum_i W^{i,\mu\beta} W^{i,\nu\alpha},$$
$$\mathcal{O}_{gT,4} = \sum_a G^a_{\mu\nu} G^{a,\mu\nu} \times B_{\alpha\beta} B^{\alpha\beta},$$
$$\mathcal{O}_{gT,5} = \sum_a G^a_{\alpha\nu} G^{a,\mu\beta} \times B_{\mu\beta} B^{\alpha\nu},$$
$$\mathcal{O}_{gT,6} = \sum_a G^a_{\alpha\mu} G^{a,\mu\beta} \times B_{\nu\beta} B^{\alpha\nu},$$
$$\mathcal{O}_{gT,7} = \sum_a G^a_{\alpha\mu} G^a_{\beta\nu} \times B^{\mu\beta} B^{\nu\alpha},$$

Born-Infeld

$$\beta^2 \left[1 - \sqrt{1 + \sum_{\lambda=1}^{12} \frac{F^\lambda_{\mu\nu} F^{\lambda,\mu\nu}}{2\beta^2} - \left(\sum_{\lambda=1}^{12} \frac{F^\lambda_{\mu\nu} \widetilde{F}^{\lambda,\mu\nu}}{4\beta^2} \right)^2 } \right]$$

Cross sections

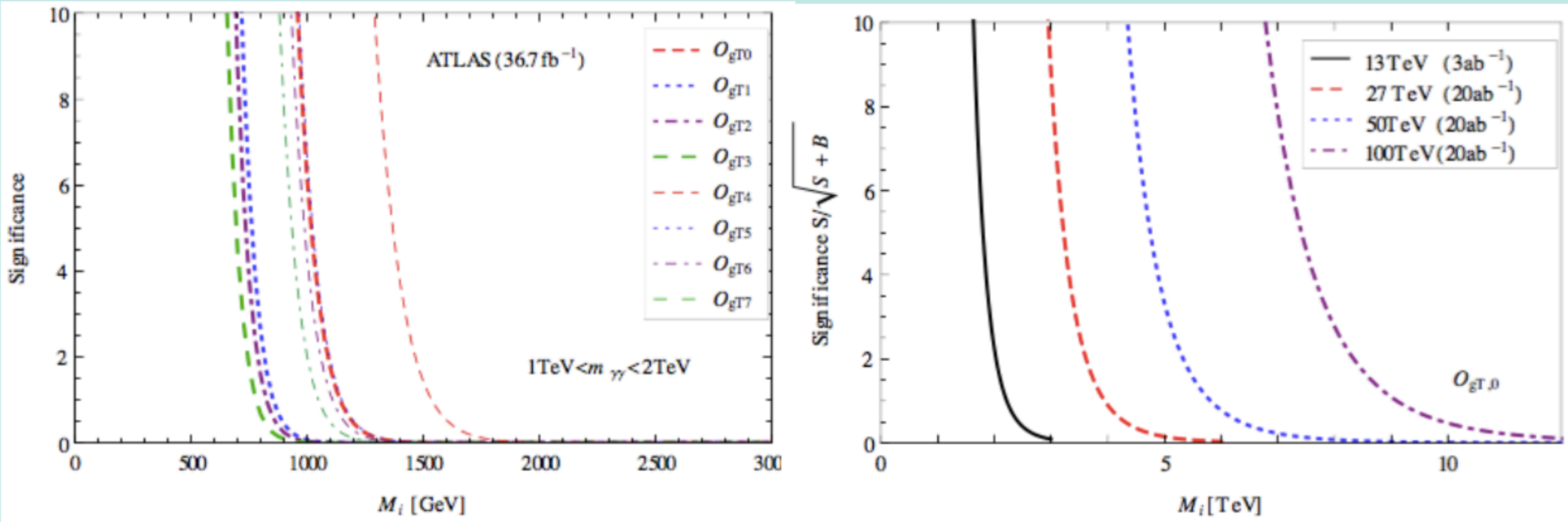




JE & Ge, arXiv:1802.02416

Constraints from Collider Data

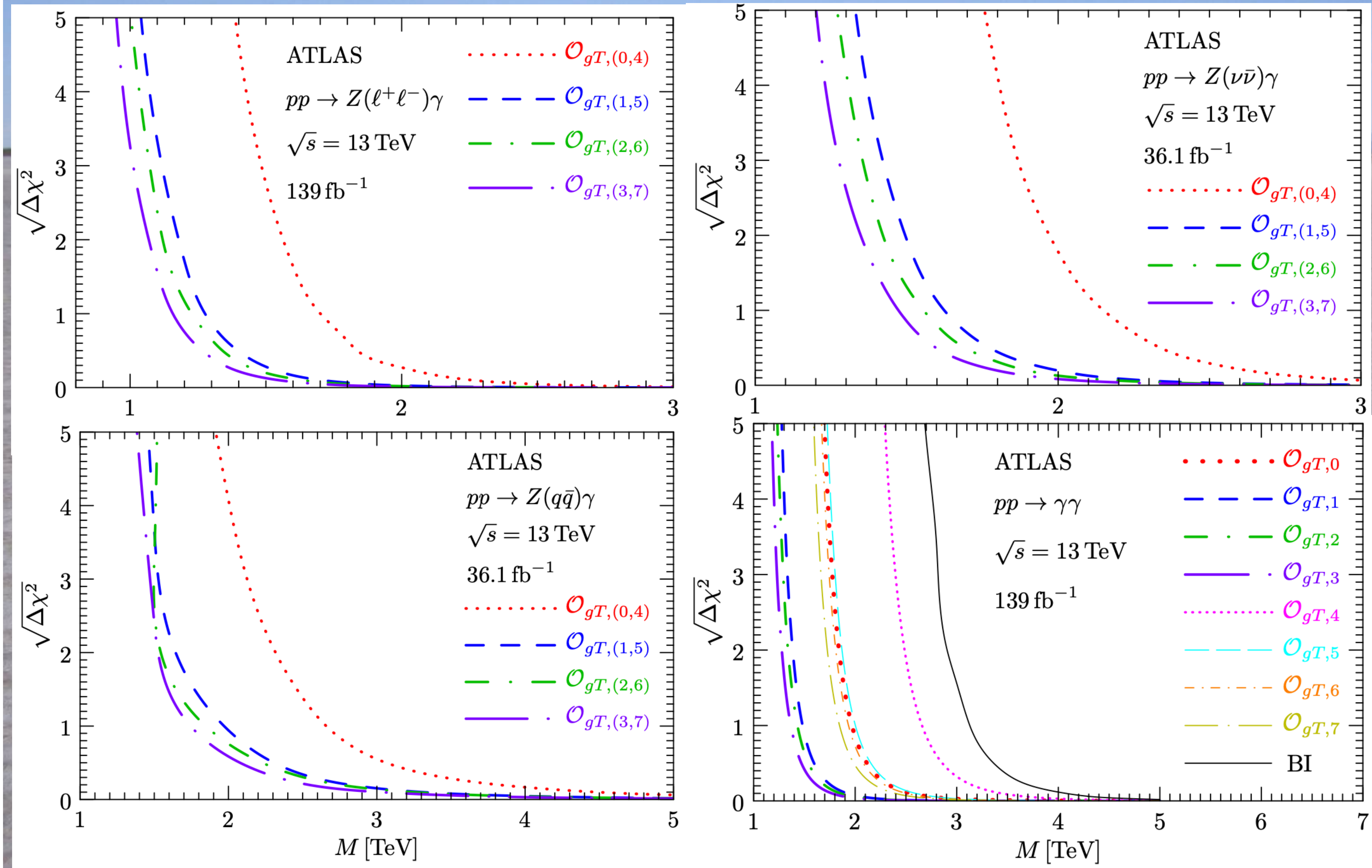
- ATLAS: 95% CL lower limits in TeV range



- Prospective sensitivities of future colliders in multi-TeV range
- **Unique window on dimension-8 physics**

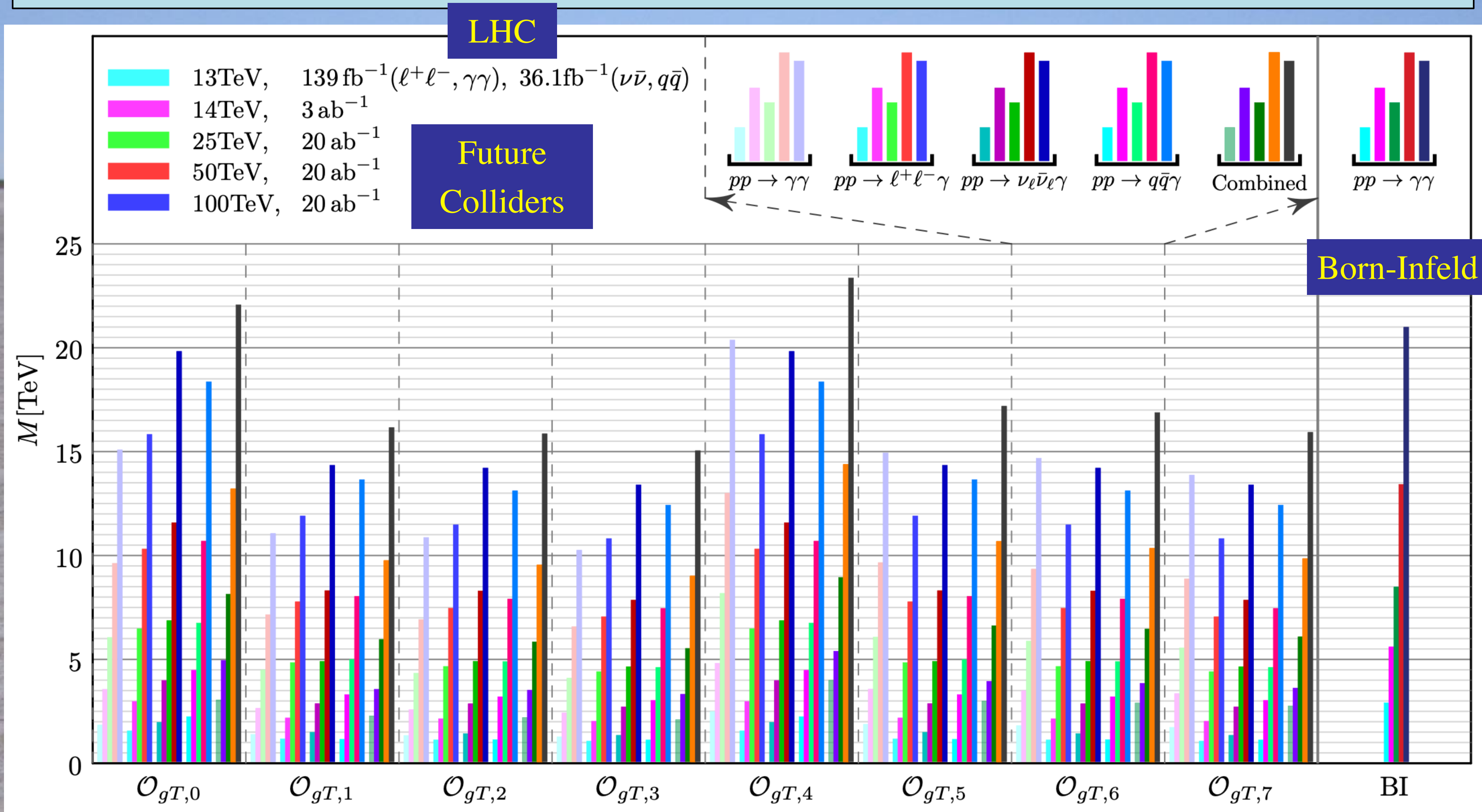
JE, Ge & Ma, arXiv:2112.06729

Also $gg \to Z(\to \ell^+\ell^-, \nu\bar{\nu}, q\bar{q})\gamma$ at the LHC



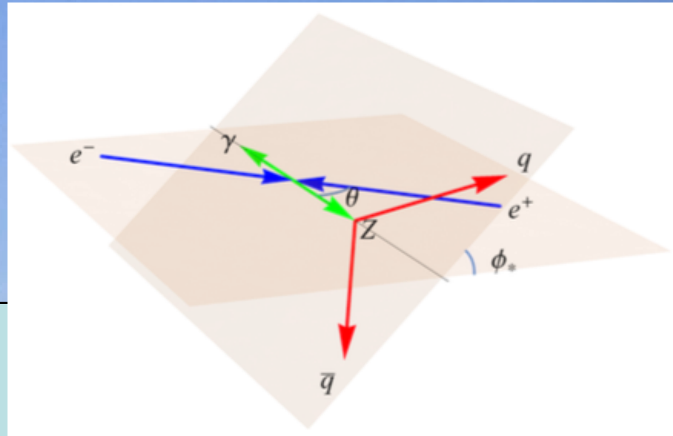
JE, Ge & Ma, arXiv:2112.06729

Compilation of $gg \to Z(\to \ell^+\ell^-, \nu\bar{\nu}, q\bar{q})\gamma, \gamma\gamma$ Constraints



Sensitivities to new physics scales at LHC and future colliders

Another Window on Dimension 8



- Neutral triple gauge couplings
  have no dimension-4, -6 contributions
- Appear first at dimension-8:

$$g\mathcal{O}_{G+} = \widetilde{B}_{\mu\nu}W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho})$$

$$g\mathcal{O}_{G-} = \widetilde{B}_{\mu\nu}W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho})$$

$$\mathcal{O}_{\widetilde{B}W} = \mathrm{i}\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H$$

$$\mathcal{O}_{C+} = \widetilde{B}_{\mu\nu}W^{a\mu\rho}[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L) + D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)]$$

- Probe in $e^+e^- \rightarrow Z\gamma$, using hadronic Z decays:

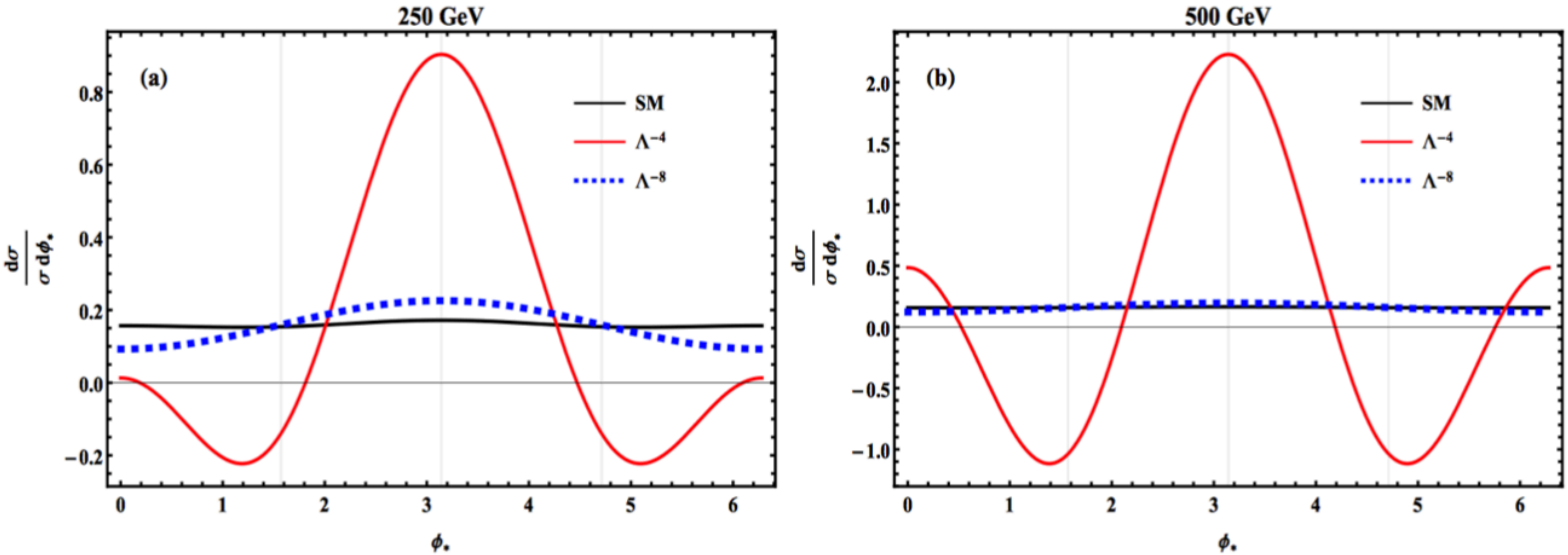
$\sqrt{s}$	$\Lambda^{2\sigma}_{G+}$	$\Lambda^{5\sigma}_{G+}$	$\Lambda^{2\sigma}_{G-}$	$\Lambda^{5\sigma}_{G-}$	$\Lambda^{2\sigma}_{\widetilde{B}W}$	$\Lambda^{5\sigma}_{\widetilde{B}W}$	$\Lambda^{2\sigma}_{C+}$	$\Lambda^{5\sigma}_{C+}$
0.25	(1.3, 1.6)	(1.0, 1.2)	(0.9, 1.1)	(0.72, 0.89)	(1.2, 1.3)	(0.97, 1.0)	(1.2, 1.6)	(0.97, 1.2)
0.5	(2.3, 2.7)	(1.9, 2.2)	(1.3, 1.7)	(1.1, 1.3)	(1.8, 1.9)	(1.4, 1.4)	(1.8, 2.2)	(1.4, 1.7)
1	(3.9, 4.7)	(3.2, 3.7)	(1.9, 2.4)	(1.6, 1.9)	(2.6, 2.6)	(2.0, 2.1)	(2.6, 2.9)	(2.0, 2.4)
3	(9.2, 11.0)	(7.2, 8.6)	(3.3, 4.2)	(2.7, 3.3)	(4.3, 4.5)	(3.5, 3.6)	(4.4, 5.2)	(3.4, 4.1)
5	(13.4, 15.9)	(10.8, 12.7)	(4.4, 5.5)	(3.4, 4.4)	(5.7, 5.9)	(4.5, 4.7)	(5.7, 6.8)	(4.5, 5.5)

- Unpolarized beams: $\Lambda >> E_{CM}$

JE, He & Xiao, arXiv:2008.04298
(JE, Ge, He & Xiao, arXiv:1902.06632)

Dimension-8 Operators in nTGCs

- Angular distributions in SM and with dim-8

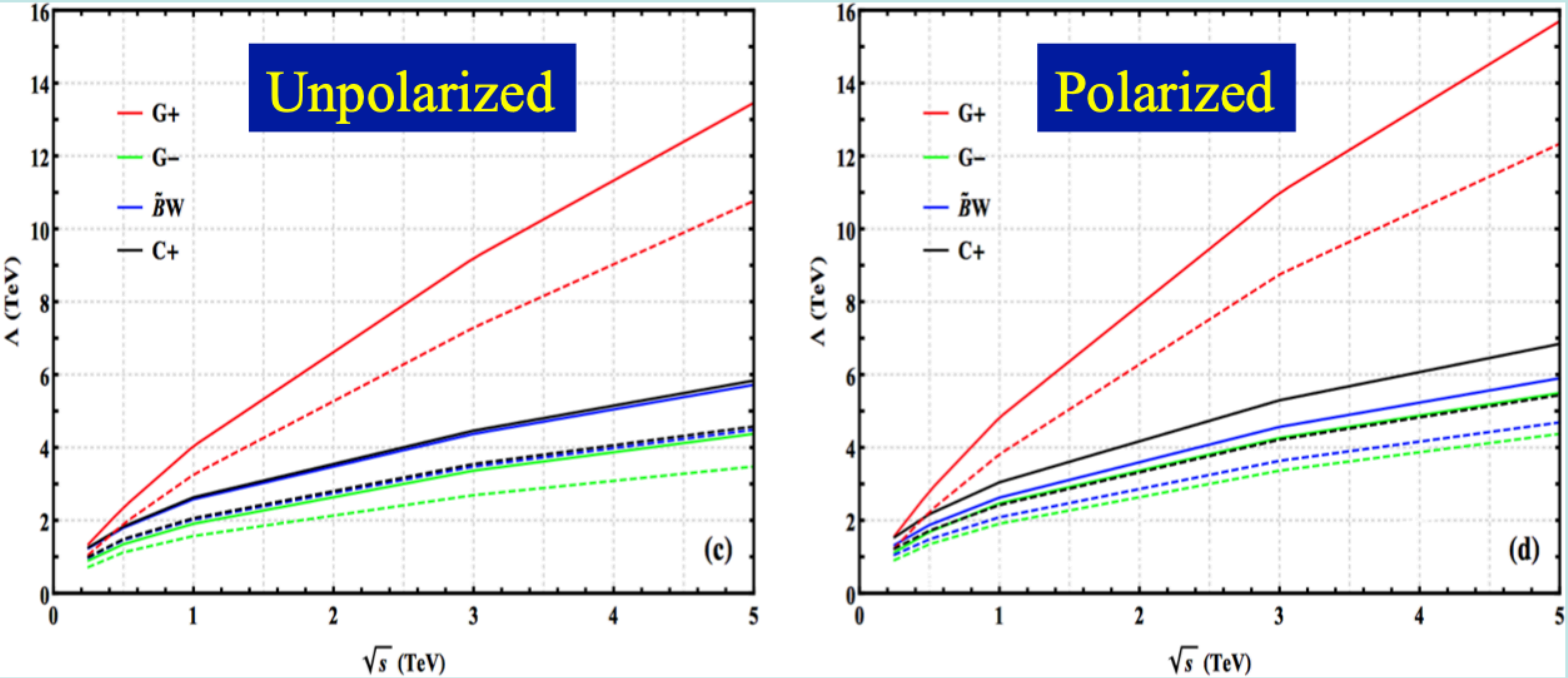


- Easy to distinguish dimension-8

JE, He & Xiao, arXiv:2008.04298
(JE, Ge, He & Xiao, arXiv:1902.06632)

Sensitivity to Dimension-8

- New physics scale Λ vs centre-of-mass energy

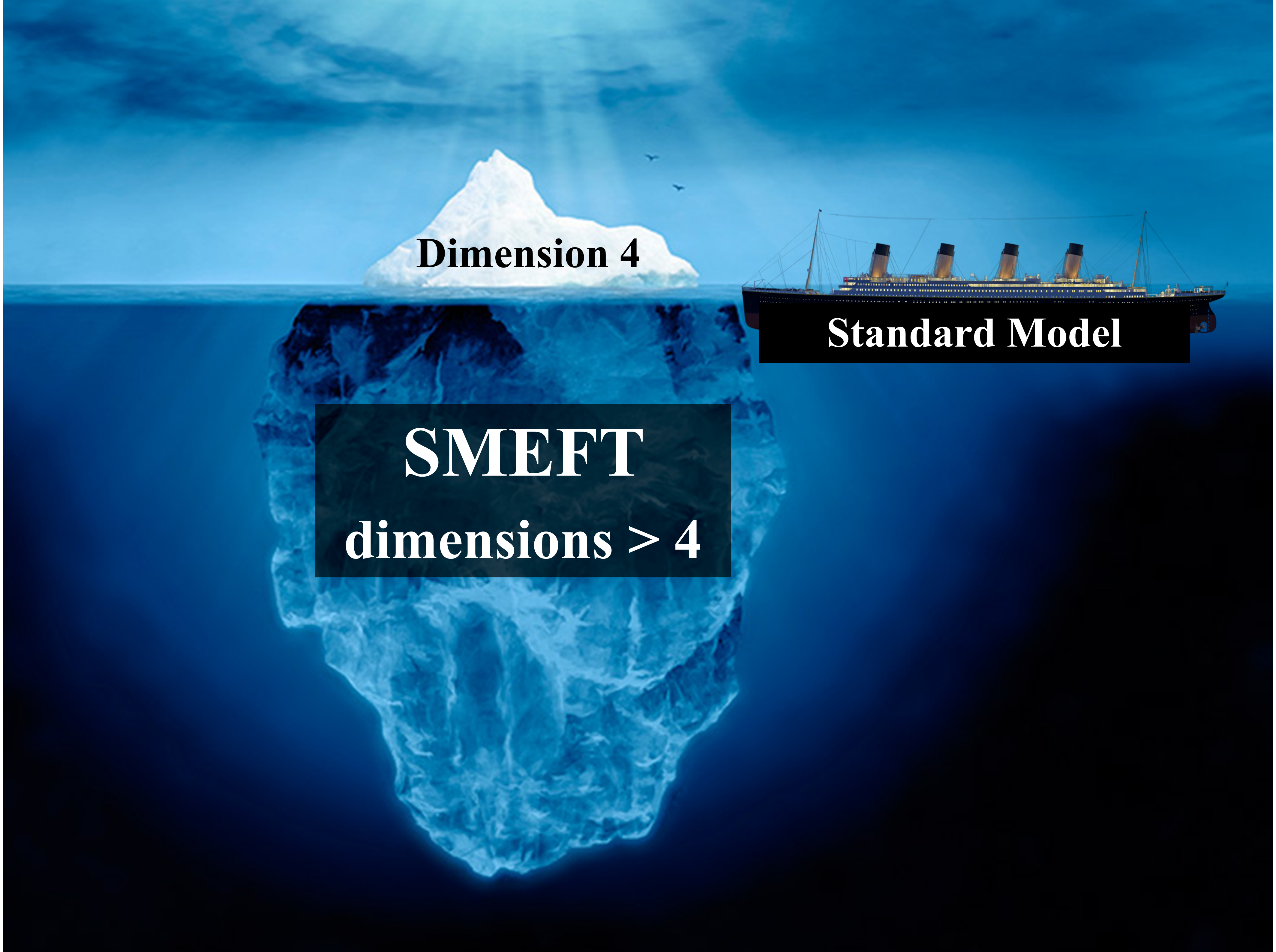


- Solid: 2-σ exclusion, dashed: 5-σ discovery

JE, He & Xiao, arXiv:2008.04298
(JE, Ge, He & Xiao, arXiv:1902.06632)

Summary

- **Remember Sun Tzu:** search for new physics indirectly as well as directly
- SMEFT is an effective, model-independent tool for probing indirectly possible physics beyond the SM
- It can be used to analyze jointly precision electroweak, diboson and top quark data from LHC and elsewhere
- Our current analysis indicates that the scale of new physics is probably > TeV
- Useful for assessing sensitivities of proposed future accelerators


Dimension 4
Standard Model
SMEFT
dimensions > 4