LHCP2020
May 25-30, 2020

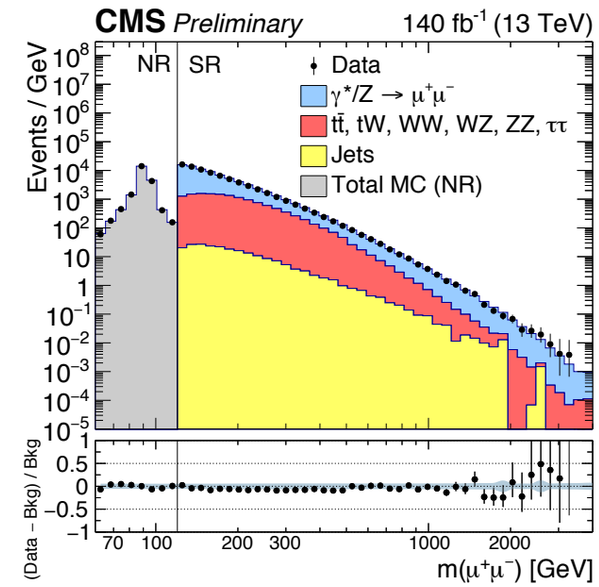
SMEFT and searches for new physics

Ken Mimasu
CP3, UCLouvain
28th May 2020

UCLouvain

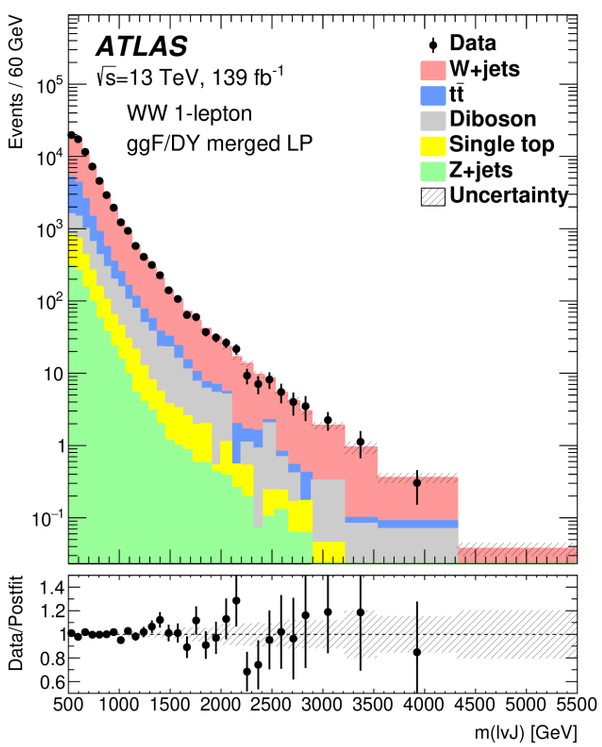
[CMS-PAS-EXO-19-019]

Where are we?

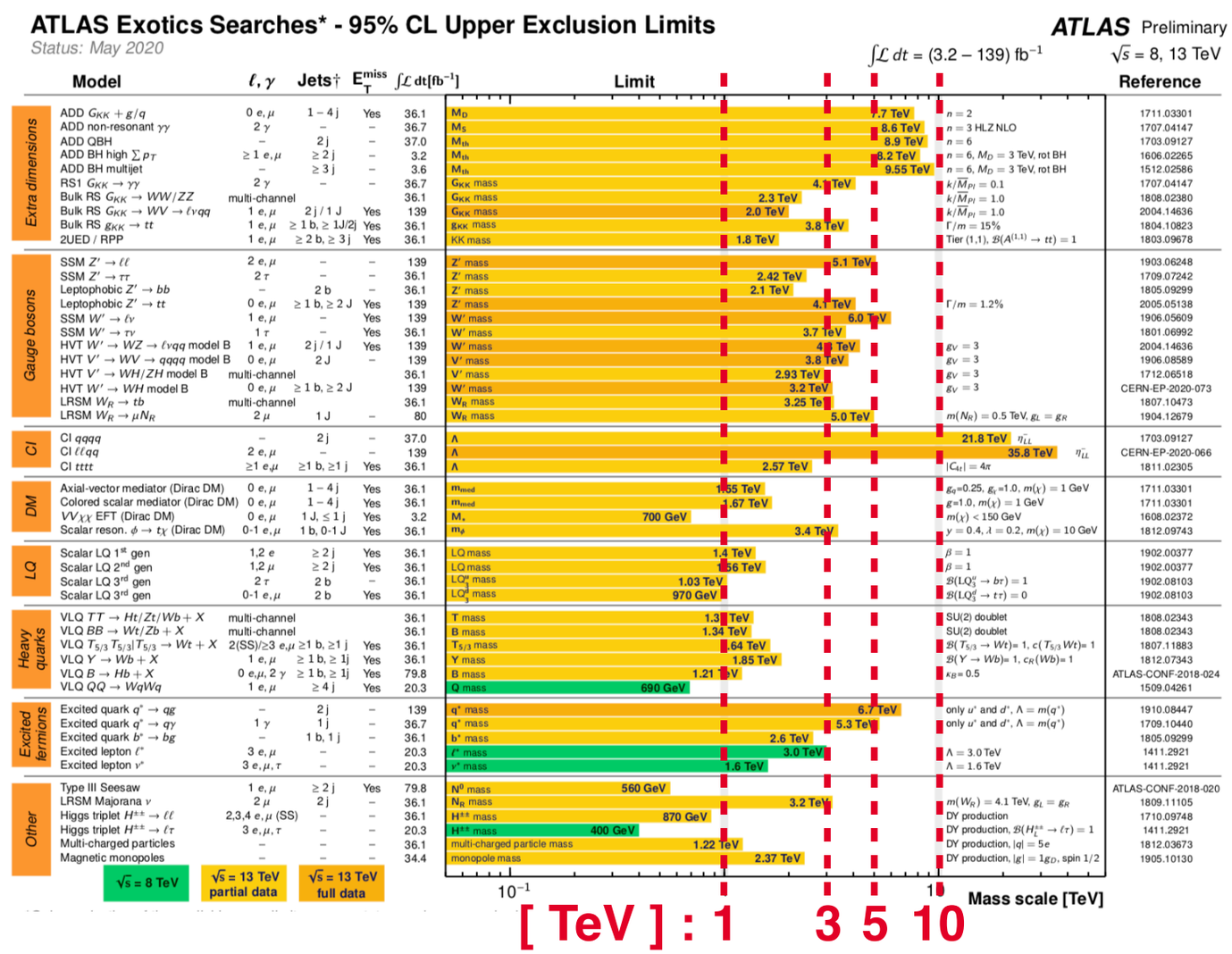


10 years since the start of LHC run 1

- No clear sign of TeV scale new physics
- Direct searches have saturated the energy frontier



[CERN-EP-2020-049]



What do we know?

BSM states are either too…

Weakly coupled *rate limited*	Room for improvement with increasing luminosity Still 20x more data to come
Exotic *we aren't looking in the right place*	Limited by our creativity Work for theorists & experimentalists to motivate & enable searches for new signatures
Heavy *kinematically out of reach*	Worst-case scenario from direct search point of view Forced into the business of indirect searches

The indirect way

Not only direct searches…

LHC's #1 objective (Higgs discovery) has been achieved

We are in the midst of a huge programme of precision measurements of SM interactions up to the TeV scale

Thanks to the efforts of th. and exp. colleagues, the LHC can equally be used as a precision machine

Big question: Origin of the Electroweak scale

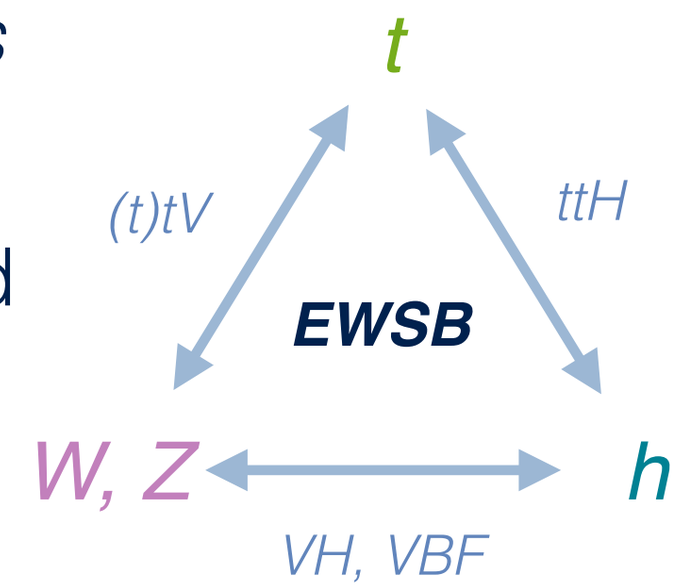
Where to look: Interactions among the key players

Higgs, EW gauge bosons, top quark,…

Pinning down EWSB

Independent of the outcome of direct NP searches

LHC legacy = precise set of measurements of the interactions that govern EWSB



Gauge/Higgs: all components of Higgs field

- Connects gauge and Goldstone boson interactions
- Equivalence of longitudinal modes at high energy

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} -iG^+ \\ v + h + iG^0 \end{pmatrix} \qquad \begin{array}{l} \partial_\mu G^+ \leftrightarrow W^+_\mu \\ \partial_\mu G^0 \leftrightarrow Z_\mu \end{array}$$

The top is special yet relatively poorly measured

- Being most strongly coupled to the Higgs has strong BSM implications
- The LHC is a top factory

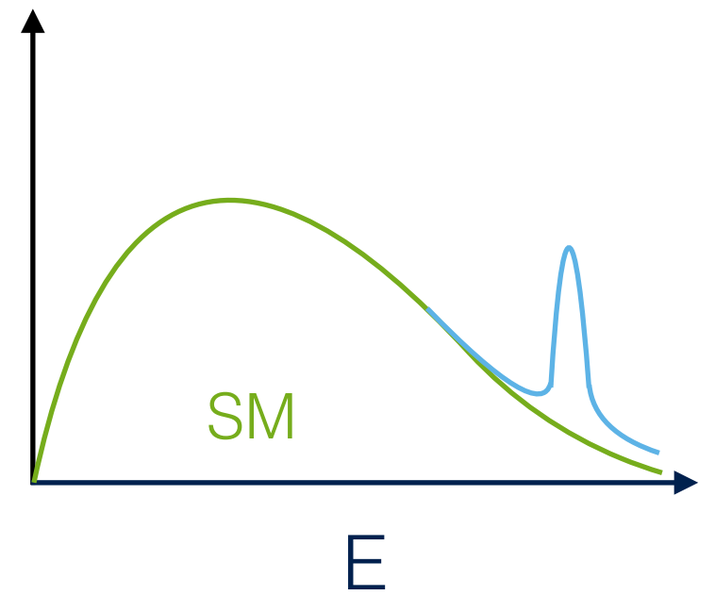
Marrying energy & precision

Paradigm shift at the energy frontier for BSM searches

Direct (bump hunts)

Indirect (measuring tails)

⇒ New physics is heavy



Heavy new physics
Precision measurements
High energy

→ **Standard Model Effective Field Theory (SMEFT)**

A parameter space for BSM interactions between SM particles

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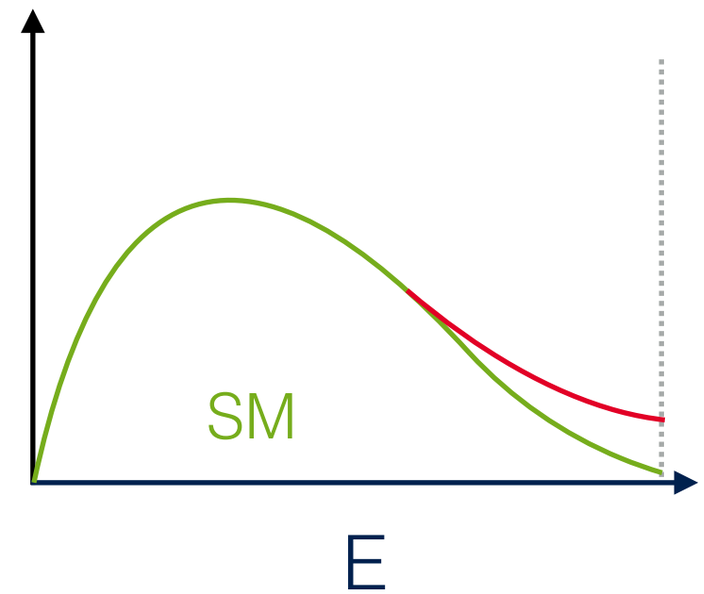

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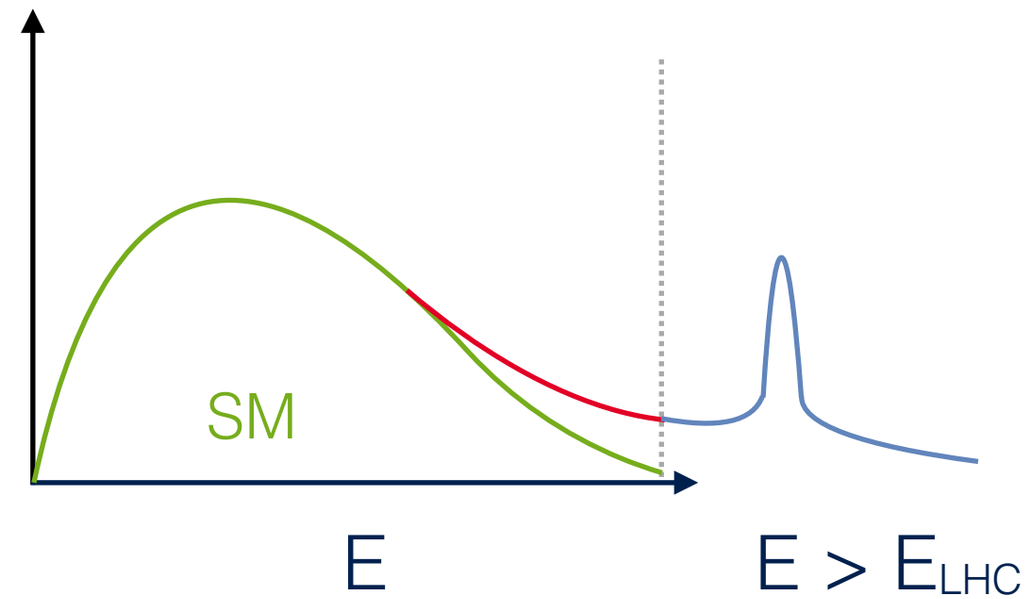

Heavy new physics
Precision measurements
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A parameter space for BSM interactions between SM particles

SMEFT: SM v2.0

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

We have access to a low energy effective description

- SM: all relevant & marginal (D ≤ 4) operators
- + EFT: tower of irrelevant (D > 4) operators

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

SM gauge symmetry & linear EWSB

More than 'just' a parametrisation of ignorance

- **Unlike** 'Anomalous Couplings'
- Finite energy range < Λ (NP)
- Renormalisable QFT (order-by-order)
- Well-defined matching procedure

aTGC y_f λ_h ffV

$$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\ \rho}$$

$$H^6 : (\varphi^\dagger \varphi)^3$$

$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i\, u_j\, \tilde{\varphi})$$

$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$$

$$X^2 H^2 : (\varphi^\dagger \varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$$

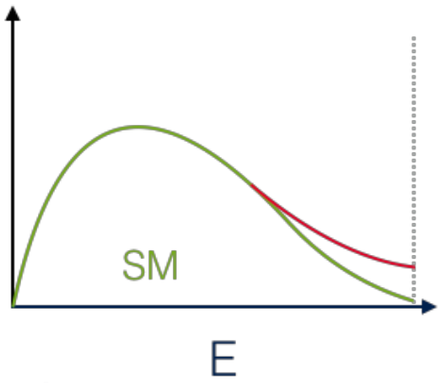
$$H^4 D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$$

$$\psi^2 X H : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$$

$$\psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$$

ggh(h) δM$_Z$ 'dipole' 4F

Energy growth



Higher dimensional operators mean energy growth

Dim-6

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(\boxed{1 + c_i \frac{v^2}{\Lambda^2}} + \boxed{c_j \frac{v\,E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2}}\right)$$

'Energy helps accuracy'

[Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated

Increasingly high-energy measurements scale with lumi.

Outlines a systematically improvable process for improving our understanding of the D>4 parameters of the SM

Slightly complicated by interference structure w/ A_{SM}

- Cross sections contain terms up to order $1/\Lambda^4$
- Different energy growth/symmetries can mix the hierarchy in EFT expansion
- Dim-8 operators generally not studied

Global Fits

SMEFT seeks model independence

- **Only requirement:** BSM physics lives sufficiently above experimental energy
- Don't know *a priori* which operators NP will generate

Ultimate goal: complete likelihood for general SMEFT

- Start small.. realistic subsets of measurements/operators (exploit symmetries)

EWPO, Higgs, Diboson, top, DY, flavor,…

LS2 is an opportune time to take stock

- Legacy papers coming out with full Run II dataset
- SMEFT fit is a fantastic benchmarking & data preservation exercise
- Progress in many complementary directions
- Good to have several groups working in parallel
- Expect many fit papers in 2020/21!

Where do we stand and where to look next?

hints, blind/weak directions,…

see also [Hartmann, Shepherd & Trott; JHEP 03 (2017) 060]
& Will Shepherd's talk from Monday

EWPO at NLO in SMEFT

[Dawson & Giardino; PRD 101 (2020) 1, 013001]

QCD & EW corrections to Z & W pole observables

- First 'complete NLO' SMEFT fit result

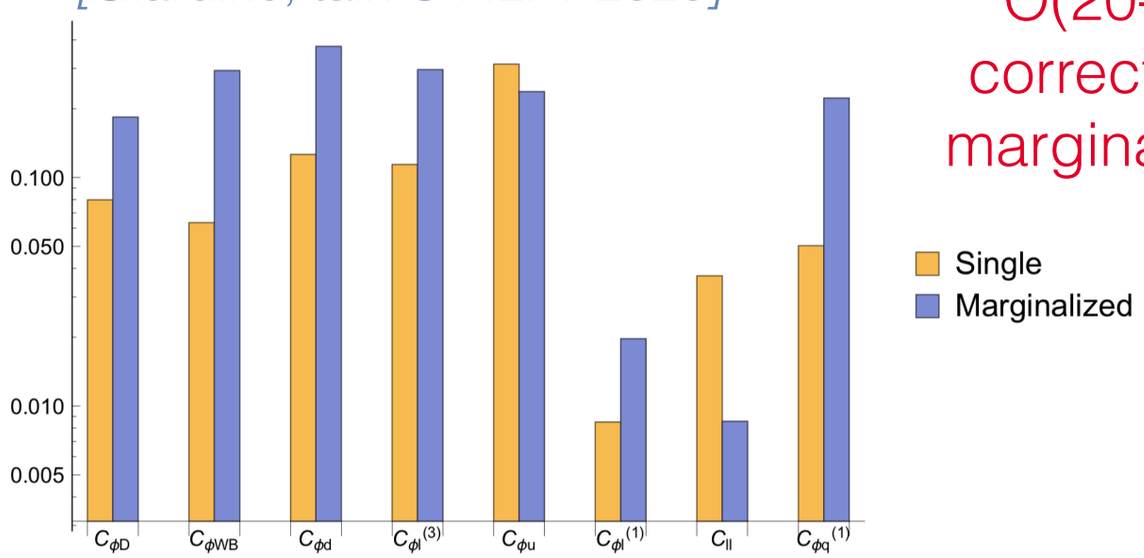
LO	10 operators* 8 constraints

→

NLO	32 operators 10 constraints

- LO blind directions closed by adding in Diboson/Higgs data
- NLO fit nowhere near self-contained

[Giardino; talk @ HEFT 2020]



O(20-30%) corrections in marginalised fit

Coefficient	LO	NLO
$\mathcal{C}_{\phi D}$	$[-0.034, 0.041]$	[-0.039,0.051]
$\mathcal{C}_{\phi WB}$	$[-0.080, 0.0021]$	$[-0.098, 0.012]$
$\mathcal{C}_{\phi d}$	$[-0.81, -0.093]$	$[-1.07, -0.03]$
$\mathcal{C}_{\phi l}^{(3)}$	$[-0.025, 0.12]$	$[-0.039, 0.16]$
$\mathcal{C}_{\phi u}$	$[-0.12, 0.37]$	$[-0.21, 0.41]$
$\mathcal{C}_{\phi l}^{(1)}$	$[-0.0086, 0.036]$	$[-0.0072, 0.037]$
$\mathcal{C}_{ll}$	$[-0.085, 0.035]$	$[-0.087, 0.033]$
$\mathcal{C}_{\phi q}^{(1)}$	$[-0.060, 0.076]$	$[-0.095, 0.075]$

Combined Higgs/EW

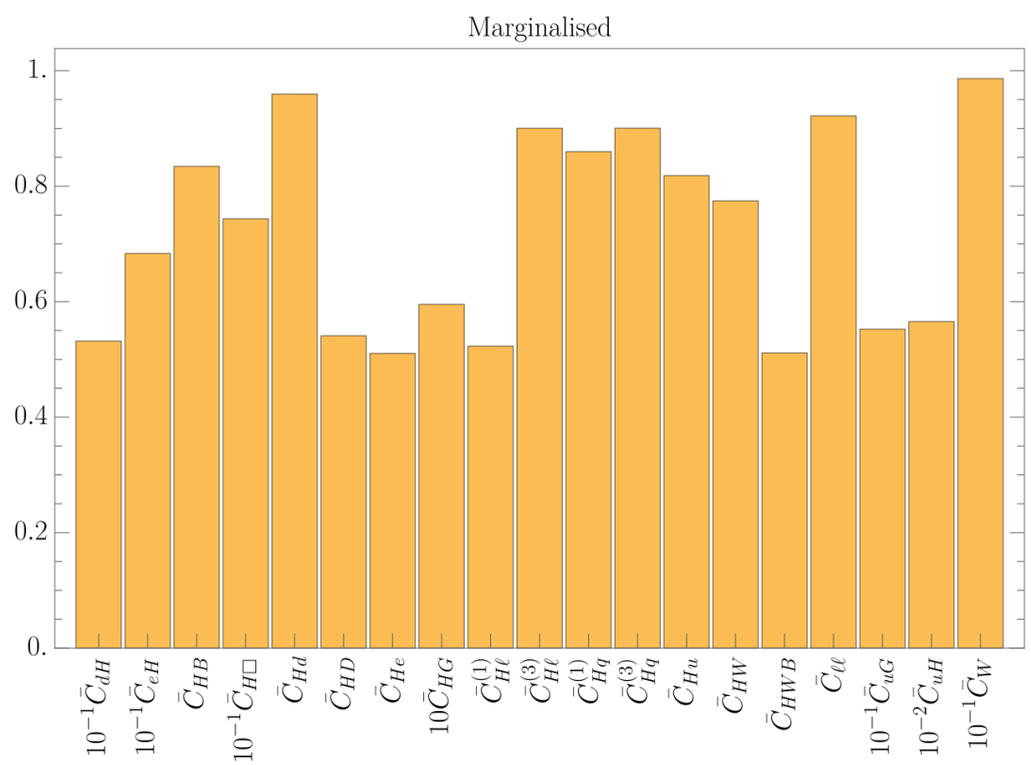
[Ellis, Murphy, Sanz & You; JHEP 06 (2018)146]

Recent global analysis of LEP + LHC Run I & II data

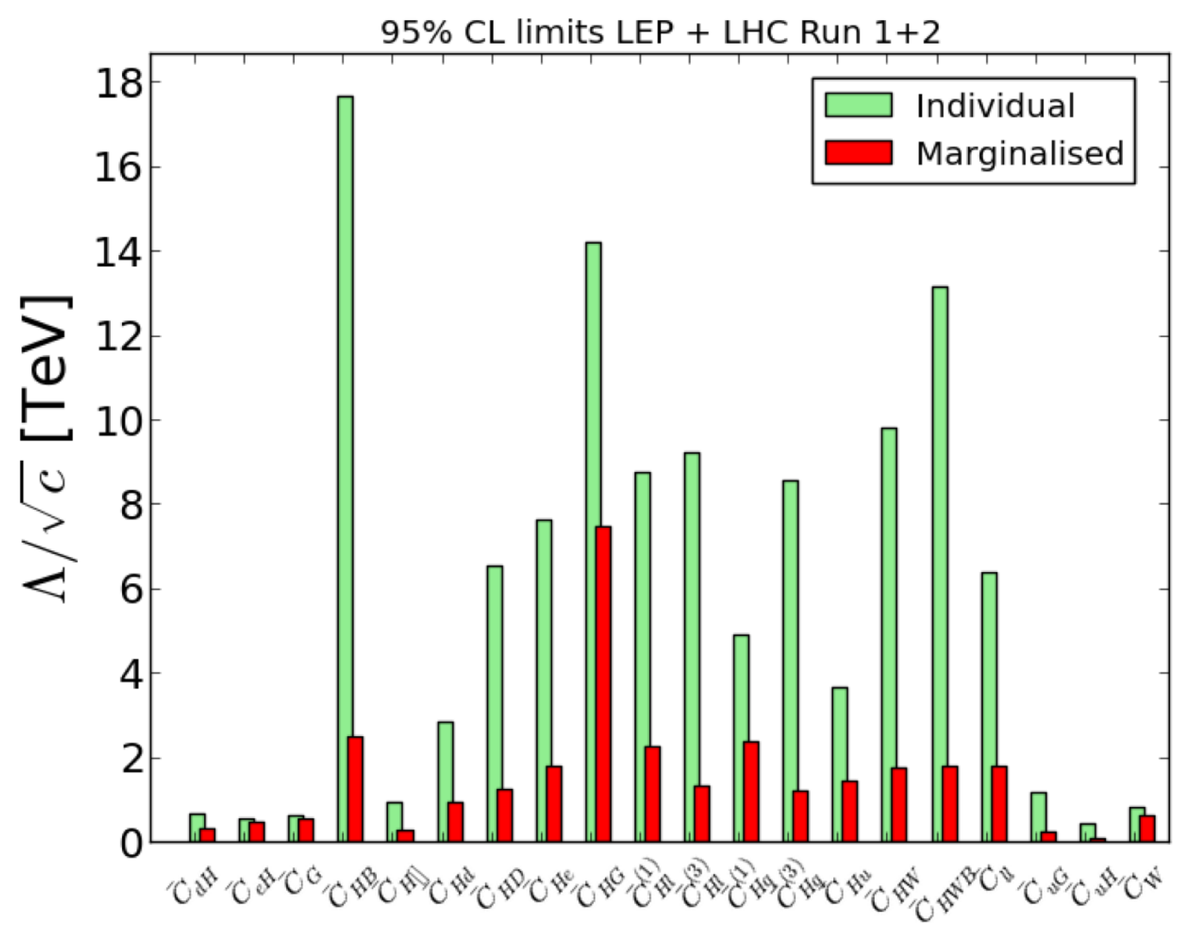
- LO & linear; flavour universal assumption $U(3)^5$ + Yukawa operators

Includes differential information for Higgs

- Stage 1 simplified template cross sections (STXS) for Higgs production
- High-p_T WW measurement



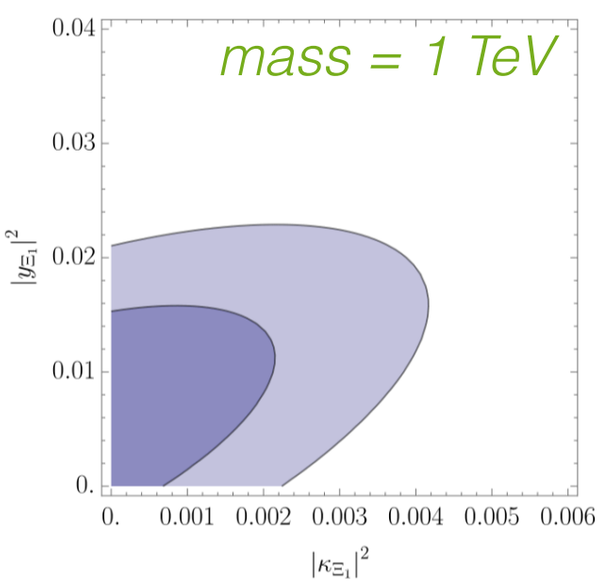
Improvement after adding Run II data

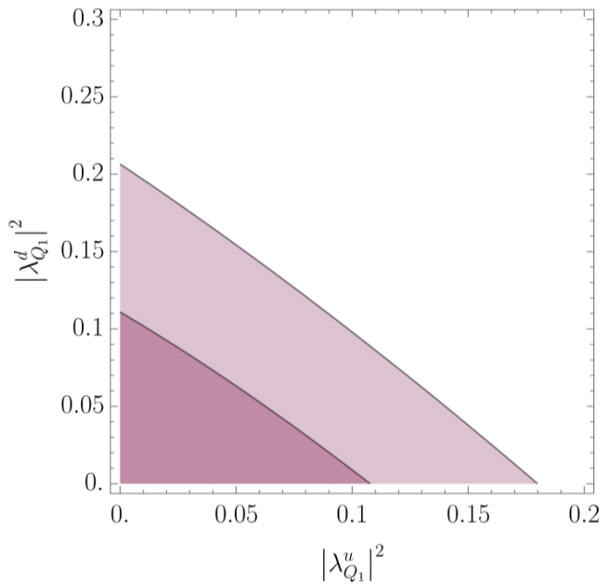


[Ellis et al.; JHEP 06 (2018)146]

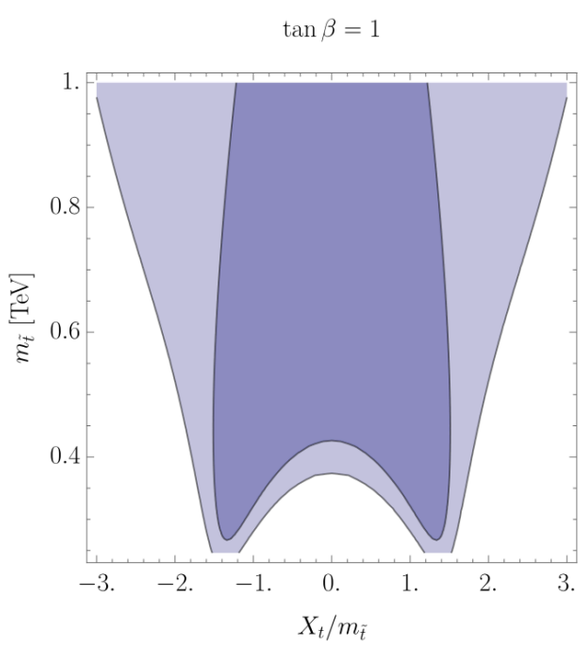
Map to UV models

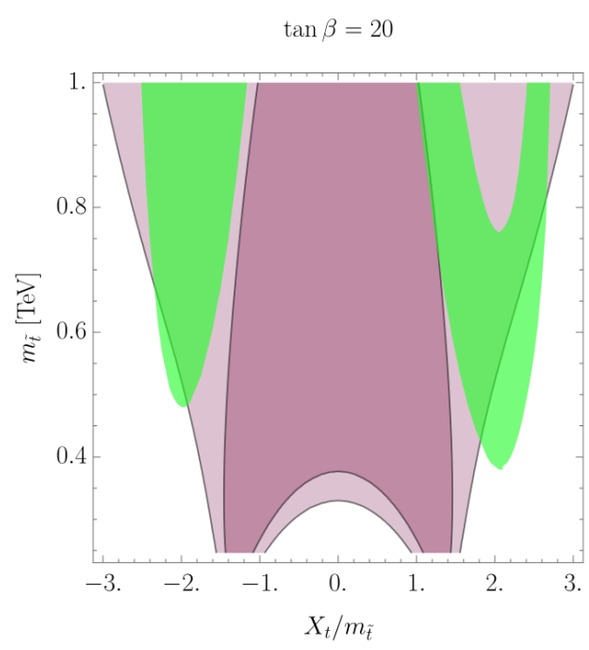
Tree-level: scalar EW triplet & vector-like quark doublet





Loop-level: MSSM w/ degenerate stops





Fit results are interesting & useful in and of themselves

- Real interpretation starts here

UV matching quasi-automated

- Complete tree-level dictionary

  [de Blas et al.; JHEP 03 (2018) 109]
- Universal 1-loop effective action

  [Henning, Lu & Murayama; JHEP 01 (2016) 023]

  [Drozd et al.; JHEP 03 (2016) 180]

UV interpretations will usually involve subsets of full basis

- Better constrained than full SMEFT
- Need to retain likelihoods to re-fit
- Important to have an 'agile' framework

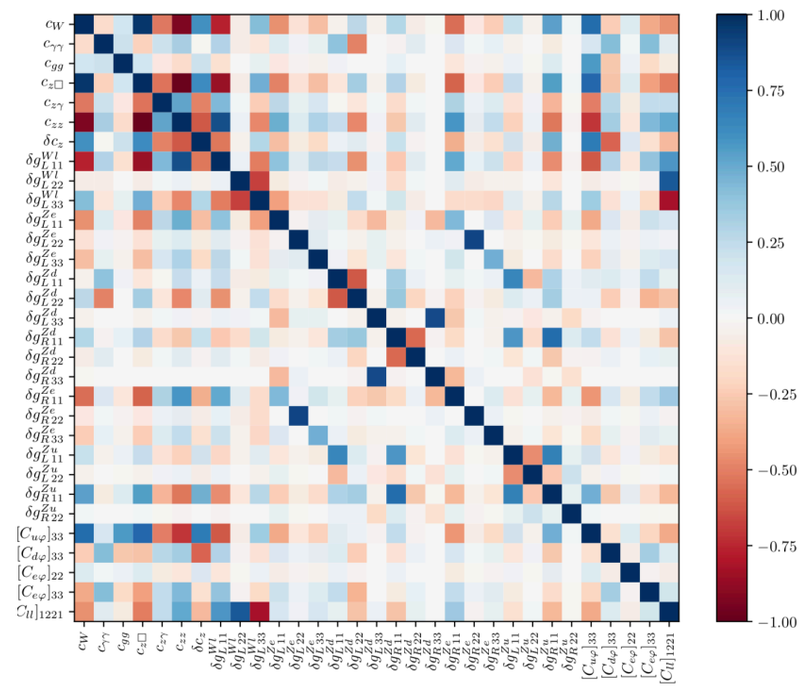
Flavorful Higgs/EW fit

[Falkowski & Straub.; JHEP 04 (2020) 066]

Relaxation to non-universal flavour assumption

- An important evolution direction for global analyses
- Separate 3 fermion gens.
- 19 → 31 parameters
- Custodial vector triplet interpretation

$$\mathcal{L} \supset \frac{1}{2} V_\mu^I \Big(i g_H H^\dagger \tau^I D_\mu H - i g_H D_\mu H^\dagger \tau^I H + \sum_i g_{l_i} \bar{l}_i \tau^I \gamma^\mu l_i + \sum_i g_{q_i} \bar{q}_i \tau^I \gamma^\mu q_i \Big)$$



$$\frac{g_H}{M} = 0.231^{+0.067}_{-0.107}\ \mathrm{TeV}^{-1}, \quad \frac{g_{l_1}}{g_H} = 0.054 \pm 0.040, \quad \frac{g_{l_2}}{g_H} = 0.100 \pm 0.060, \quad \frac{g_{l_3}}{g_H} = 0.009 \pm 0.068,$$

multi-TeV

$$\frac{g_{q_1}}{g_H} = -0.05 \pm 0.25, \quad \frac{g_{q_2}}{g_H} = 0.11 \pm 0.27, \quad \frac{g_{q_3}}{g_H} = -0.027 \pm 0.094.$$

Coeff.	central	unc.	pull [σ]
C_W	0.19	± 1.9	0.1
$c_{\gamma\gamma}$	−0.056	± 0.11	0.5
c_{gg}	−0.017	± 0.014	1.2
$c_{z\Box}$	4.9	± 6.2	0.8
$c_{z\gamma}$	−0.6	± 0.63	1.0
c_{zz}	−12.0	± 16.0	0.8
δc_z	0.49	± 1.5	0.3
$\delta g^{Wl}_{L\,11}$	−0.09	± 0.053	1.7
$\delta g^{Wl}_{L\,22}$	−0.24	± 0.083	2.9
$\delta g^{Wl}_{L\,33}$	0.26	± 0.1	2.6
$\delta g^{Ze}_{L\,11}$	−0.0074	± 0.0052	1.4
$\delta g^{Ze}_{L\,22}$	−0.0014	± 0.018	0.1
$\delta g^{Ze}_{L\,33}$	−0.0054	± 0.01	0.5
$\delta g^{Zd}_{L\,11}$	−0.17	± 0.66	0.3
$\delta g^{Zd}_{L\,22}$	0.43	± 0.57	0.8
$\delta g^{Zd}_{L\,33}$	0.052	± 0.027	1.9
$\delta g^{Zd}_{R\,11}$	1.5	± 1.0	1.4
$\delta g^{Zd}_{R\,22}$	0.27	± 0.73	0.4
$\delta g^{Zd}_{R\,33}$	0.33	± 0.11	3.1
$\delta g^{Ze}_{R\,11}$	−0.0086	± 0.0056	1.5
$\delta g^{Ze}_{R\,22}$	−0.0018	± 0.021	0.1
$\delta g^{Ze}_{R\,33}$	0.0084	± 0.01	0.8
$\delta g^{Zu}_{L\,11}$	0.14	± 0.5	0.3
$\delta g^{Zu}_{L\,22}$	−0.027	± 0.072	0.4
$\delta g^{Zu}_{R\,11}$	1.3	± 0.85	1.5
$\delta g^{Zu}_{R\,22}$	−0.056	± 0.084	0.7
$[C_{u\varphi}]_{33}$	−0.18	± 2.7	0.1
$[C_{d\varphi}]_{33}$	0.016	± 0.049	0.3
$[C_{e\varphi}]_{22}$	0.004	± 0.0054	0.8
$[C_{e\varphi}]_{33}$	−0.0018	± 0.019	0.1
$[C_{ll}]_{1221}$	−0.68	± 0.2	3.3

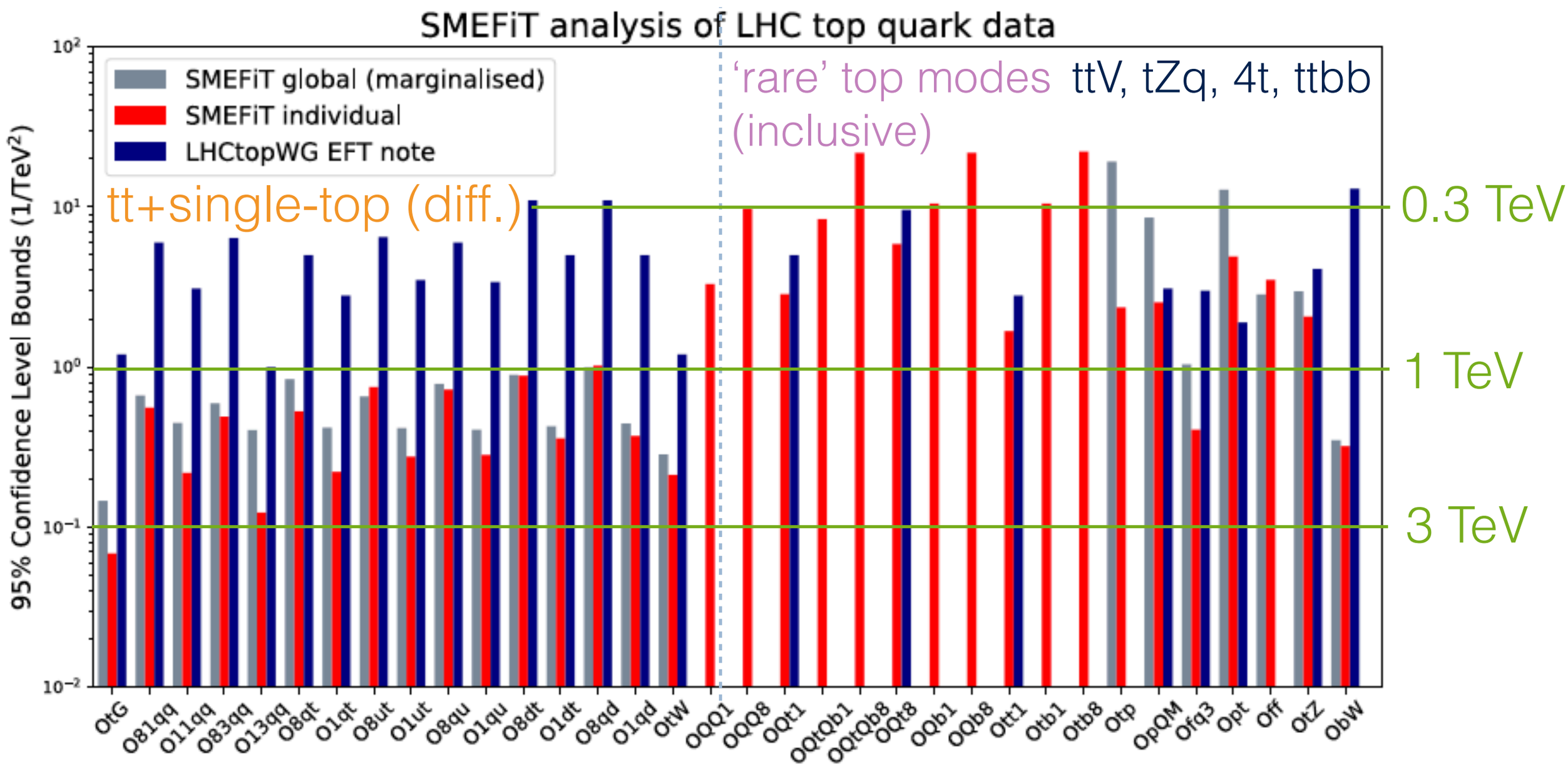
Results & likelihood available through **smelli**

- Global SMEFT likelihood tool *[Aebischer et al.; EPJ C79 (2019) no.6, 509]* https://smelli.github.io

Top sector

[Hartland et al.; JHEP 1904 (2019)100]

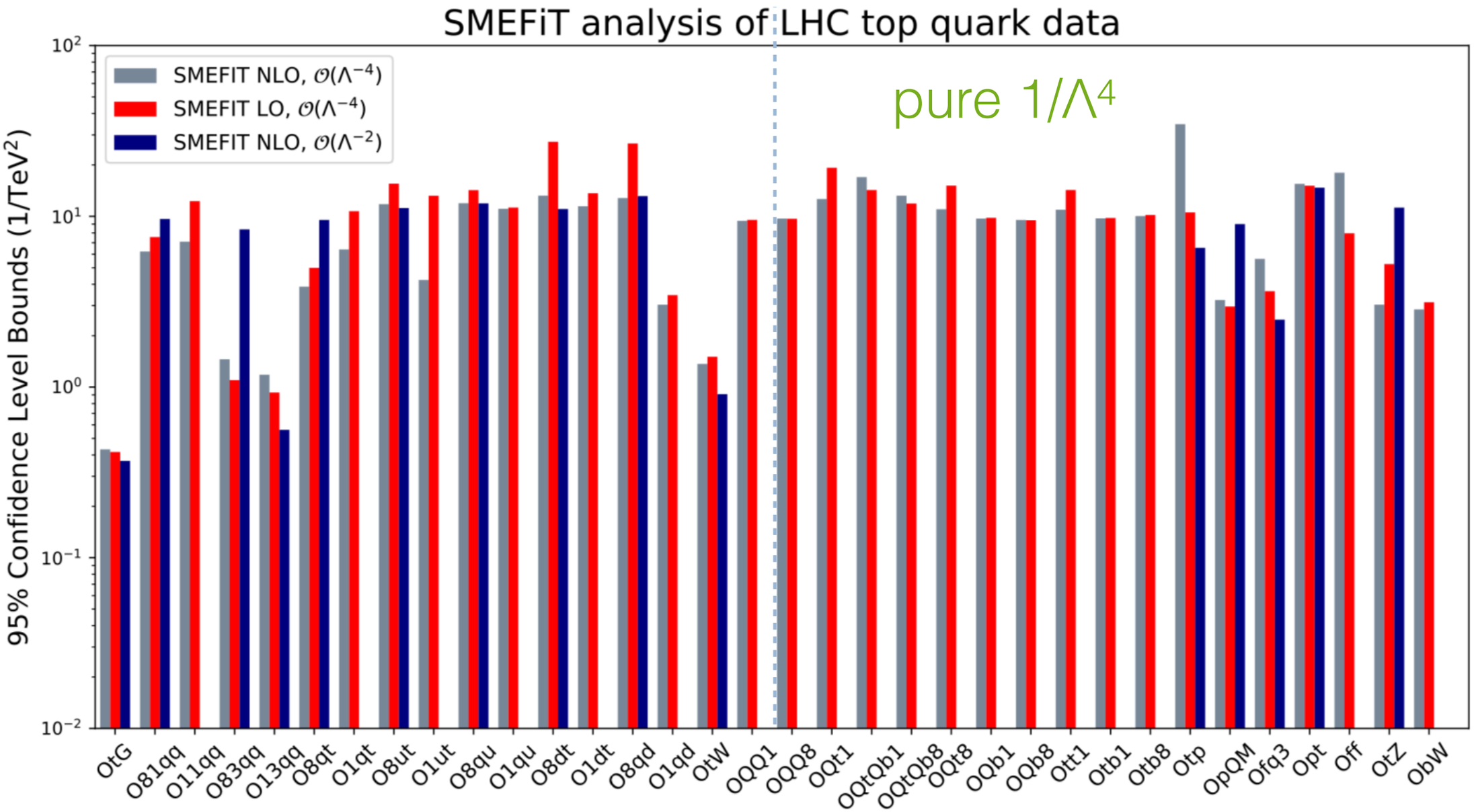
- (N)NLO QCD predictions for SM
- Mostly **NLO QCD for SMEFT**
- 34 Wilson coefficients (many 4F)



See also [Brivio et al.; JHEP 02 (2020) 131]

Higher orders

$$\mathcal{O} = \mathcal{O}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\rm int} + \sum_{i,j} \frac{c_i\, c_j}{\Lambda^4}\mathcal{O}^{ij}_{\rm sq}$$



Impact of NLO and $1/\Lambda^4$ LO vs NLO $1/\Lambda^2$ vs $1/\Lambda^4$

Experimental fits

[CERN-EP-2020-034] & [CMS-PAS-HIG-19-005]

see talks by:
Efe Yazgan (Tues)
Elizaveta Shabalina (Tues)
Andrea Gabrielli (Tues)
Giacomo Zecchinelli (Tues)
Luca Fiorini (Weds)

Enthusiasm for SMEFT percolated to the exp. community

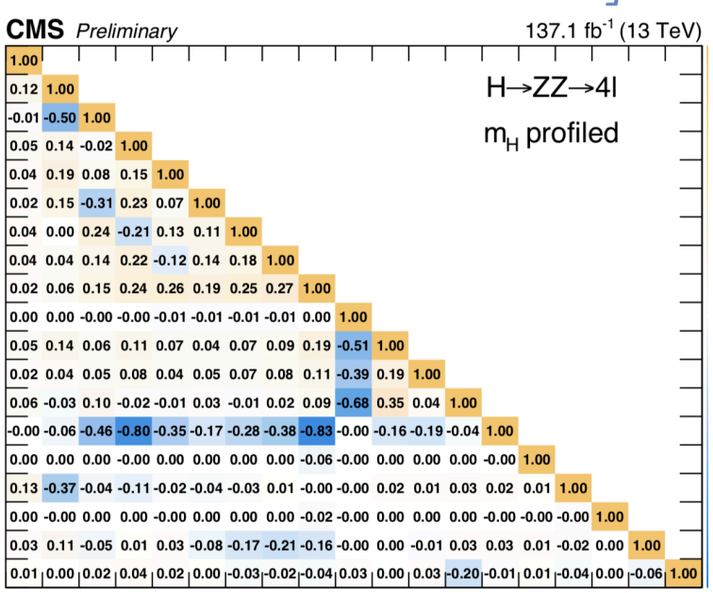
- Too many results to cover here
- One Higgs example here (honorable mention to the many top results)

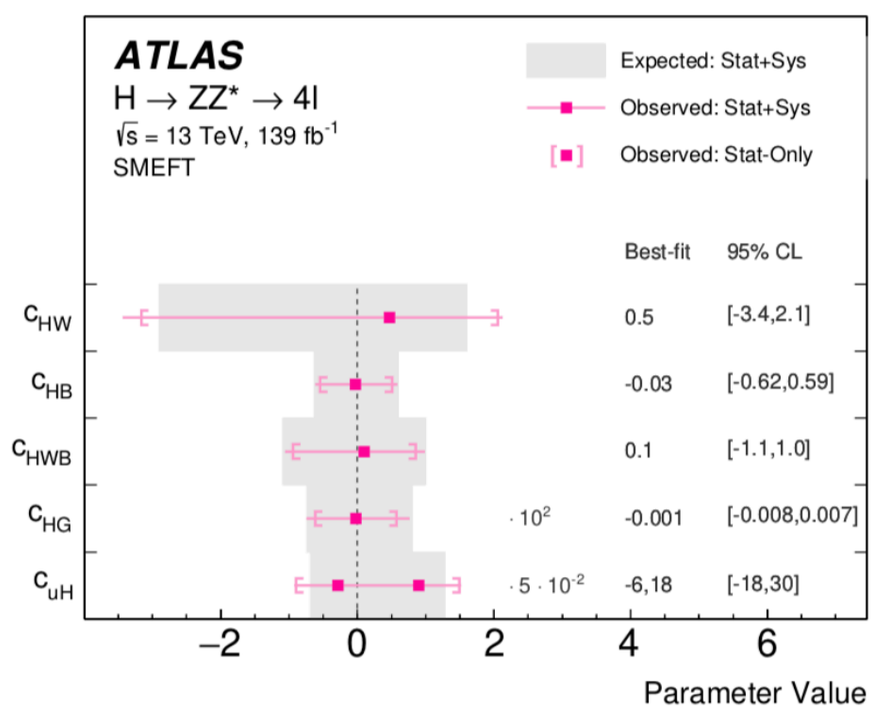
SMEFT interpretations of STXS measurements

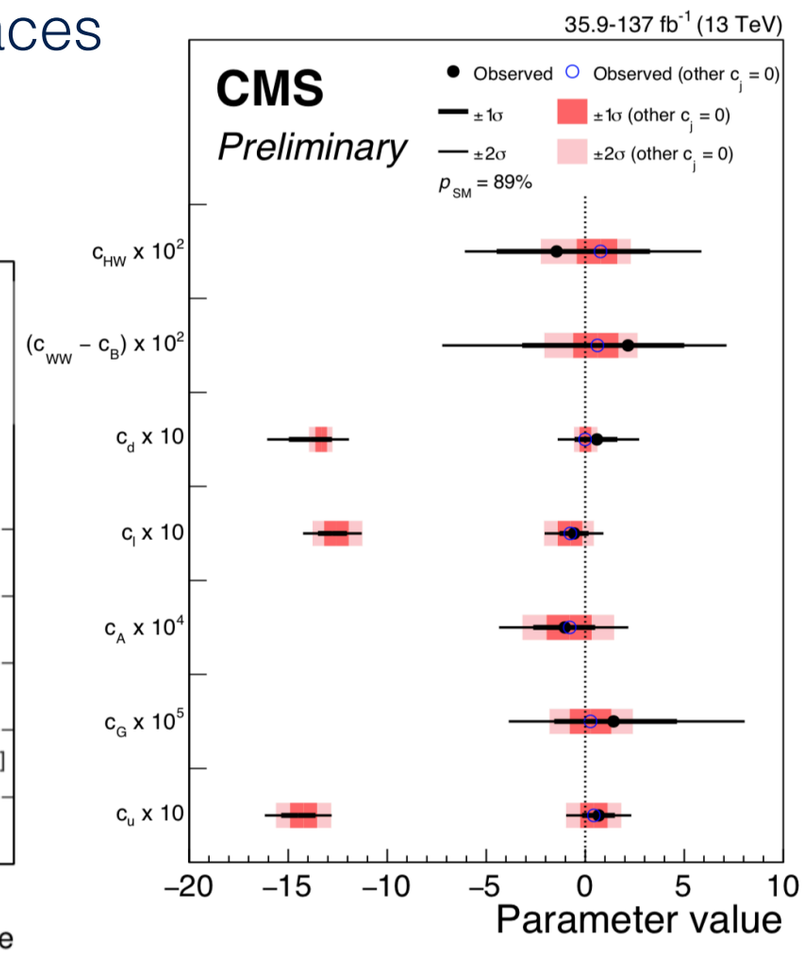
dedicated session (Fri)

- Experiments typically consider smaller parameter spaces
- Better handle on uncertainties/correlations

CMS-PAS-HIG-19-001]







Going forward

Fits are not ‘fun’… a slog of data creation/curation

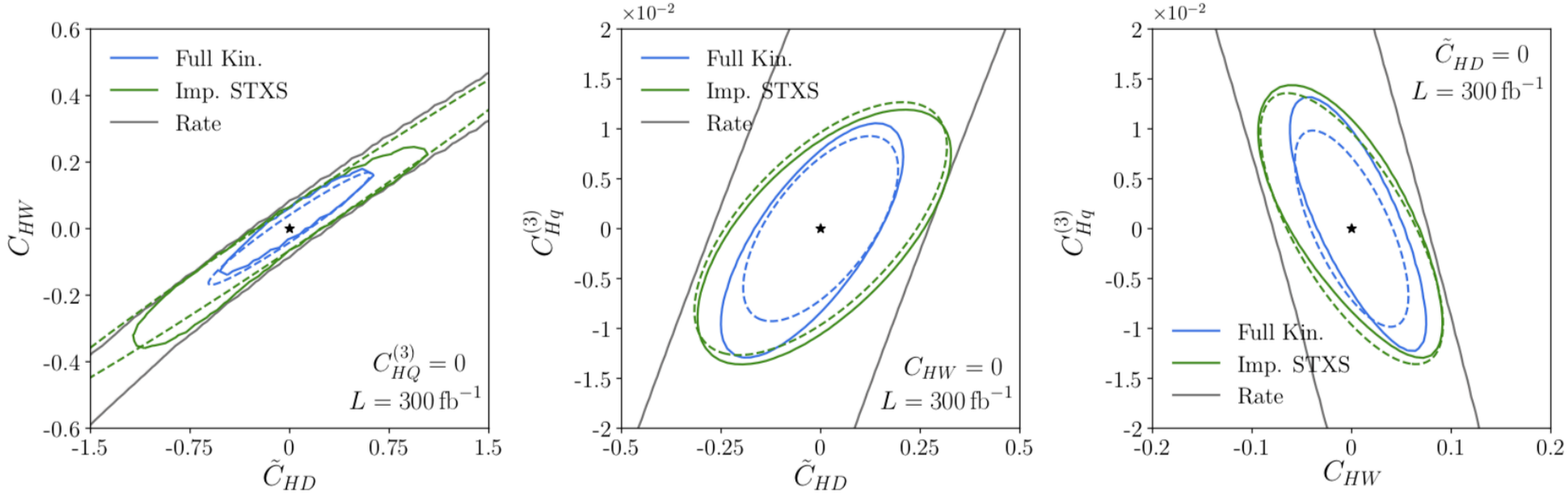
- Beware of statistical overlap between datasets, correlated uncertainties

Legacy stage 1.1 STXS papers are out → next gen. fits

- Represent a controlled evolution towards combined, fully differential data
- Best **compromise** for ease of interpretation and global sensitivity
- Caveat: SM kinematics/acceptance assumed

Important to study their information content w.r.t SMEFT

[Brehmer et al.; JHEP 11 (2019) 034]



Compare WH STXS to ‘perfect’ info

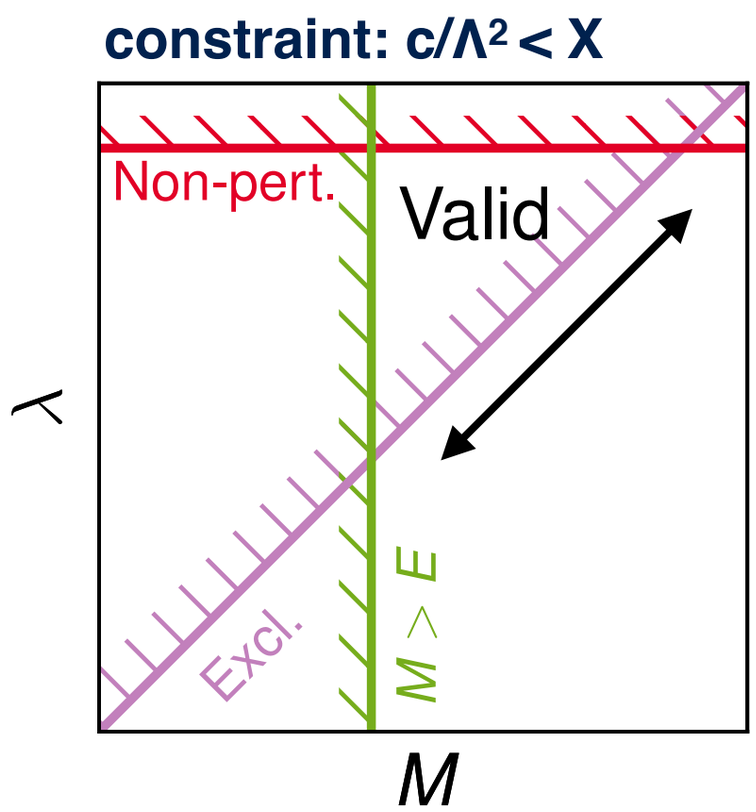
proposal for improved STXS

SMEFT & BSM today

SMEFT-UV connection is model dependent by construction

- Implications on heavy new physics & validity of EFT is ***a posteriori***
- Depends on sensitivity & energy scale probed by data
- Bottom-up philosophy: new physics scale unknown

arbitrary dimensionful parameter $\frac{c_S}{\Lambda^2} = \frac{\lambda^2}{M^2}$ *coupling/mass scale of new physics*



Difficult to address in a general way

- Today we are probing TeV scale new physics
- Hierarchies in sensitivity EWPO > Higgs > top (EW)
- Moderate-to-strong coupling scenarios most safe
- Generic NP in loops looks challenging for the LHC
- Concrete models should be better constrained
- We should widen enough to test **realistic models**

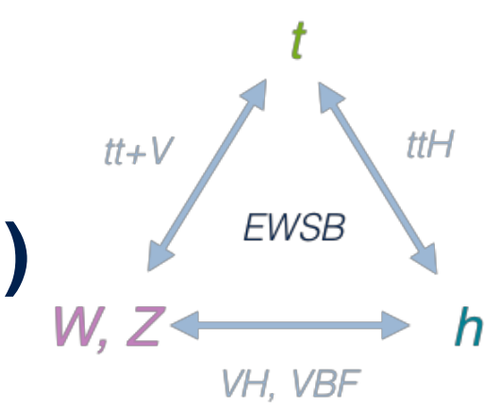
Next up: Top/Higgs/EW fit

Conspicuous split between top & Higgs/EW sector fits

- Several such results will appear soon *see Peter Galler's talk on Friday*
- Dedicated 'top+Higgs' parallel session at this workshop

If we are thinking about the origin of the weak scale, we should fit to SMEFT for full EWSB sector

Especially timely given recent measurement of relevant processes connecting the three sectors



ttH + 'rare'/EW top production (tZj, 4top,…)

Unclear to what extent the two sectors will talk beyond ttH

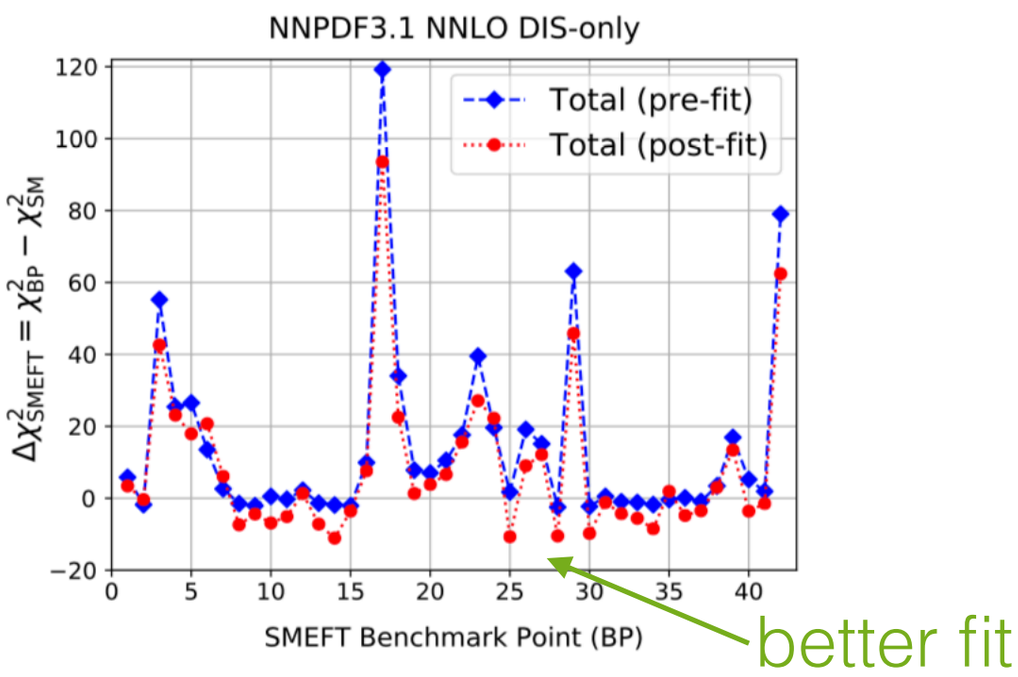
- Top measurements are important for H, Hj, HH
- LHC should observe tHj process toward the end of its lifetime

SMEFT in the proton

[Carazza et al,; PRL 123 (2019) 13, 132001]

Q: Can the PDF extraction procedure absorb NP effects?

- Slew of LHC data being used to determine them, some at high energy
- In principle, one should fit them together with the Wilson coefficients
- Proof of concept using DIS data & qqll contact operators



	Individual	Marginalized: no PDF unc	Marginalized: w PDF unc
a_u	$[-0.1, +0.4]$	$[-2.3, +1.4]$	$[-3.6, +2.7]$
a_d	$[-1.6, +0.4]$	$[-13, +3.9]$	$[-19, +11]$
a_s	$[-2.8, +4.2]$	$[-18, +29]$	$[-36, +47]$
a_c	$[-2.6, +1.2]$	$[-13, +7.0]$	$[-21, +15]$

fixed PDFs

	Individual	Marginalised
a_u	$[0.0, +0.5]$	$[-0.4, +2.4]$
a_d	$[-1.1, +0.8]$	$[-4.4, +4.5]$
a_s	$[-4.5, +3.6]$	$[-61, +39]$
a_c	$[-2.4, +0.7]$	$[-29, +2.7]$

simultaneous extraction

Related issue: impact of SMEFT on α_S determination

- Not yet studied: Lattice, e^+e^-, PDFs, ….

Adding flavor constraints

[Aoude et al,; arXiv:2003.05432] & [Hurth et al,; JHEP 06 (2019) 029]

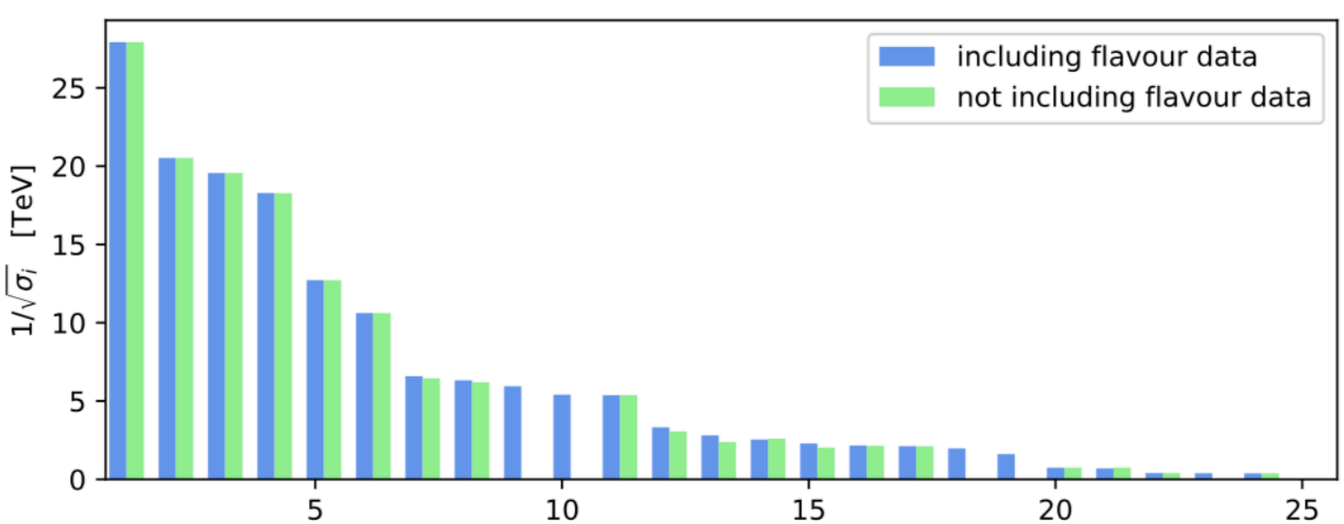
Imposing flavor symmetry in SMEFT avoids tree-FCNC

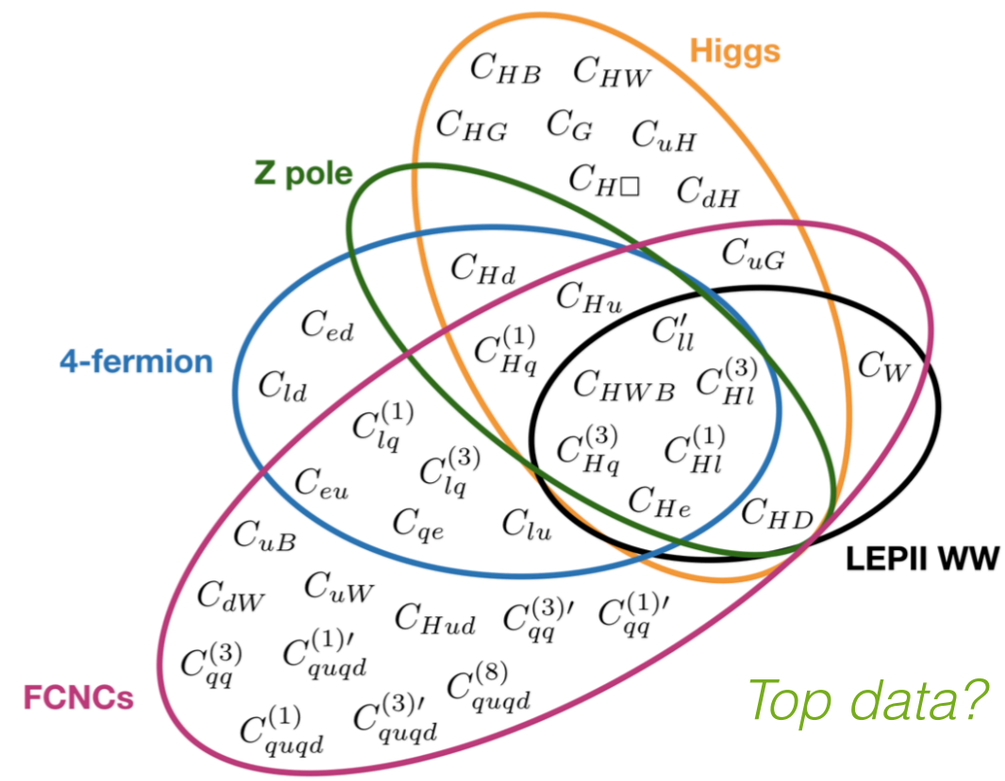
- Flavor violation induced by SM interactions at loop level
- Down type FCNC processes at low energy: B-decay/mixing and some Kaon

SMEFT (Λ) → WET (v) → Flavour experiments

- Translate existing constraints on WET coefficients to SMEFT
  - Combined with fit to EWPO/diboson/Higgs
  - 5 new constrained directions

Minimal Flavor Violation
[D'Ambrosio et al.; Nucl. Phys. B645 (2002) 155]



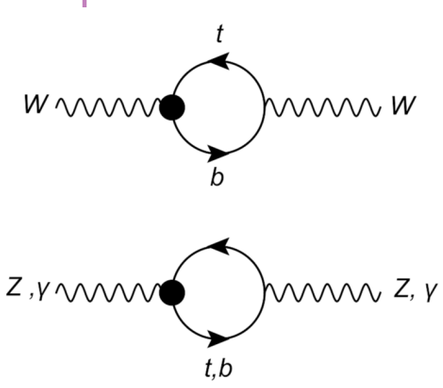


SMEFT in loops

Recent progress: top operators in EW loops

- Relatively poorly-known EW top quark interactions contributing to precisely measured observables
- Loop suppression overcome by ‘large’ allowed values for Wilson coefficients

Z-pole observables



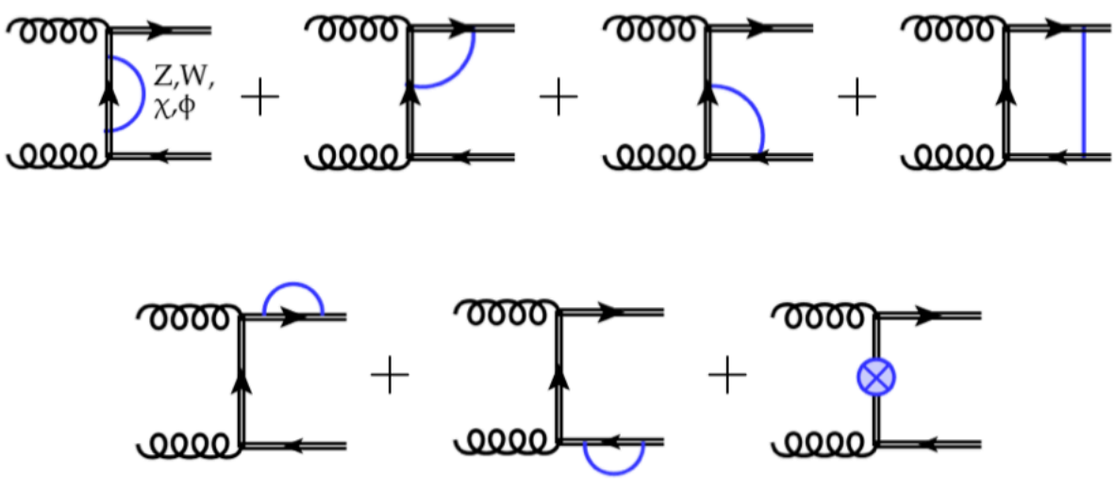
[Zhang, Greiner & Willenbrock; PRD 86 (2012) 014024]

EW Higgs production & decay

[Zhang & Vryonidou; JHEP 08 (2018) 036]

1) competitive sensitivity
2) marginalisation headache

Top pair production



[Martini & Schulze; JHEP 04 (2020) 017*]*

See talk by Till Martini on Friday

Tools for SMEFT in loops

One-loop predictions in the SMEFT

- NLO QCD corrections / loop induced predictions
- Precision & scale uncertainties / new sensitivity
- Non-flat K-factors in EFT space

Recent results on NLO QCD corrections

- DY & VH *[Alioli et al.; JHEP 08 (2018) 205]* http://powhegbox.mib.infn.it
- VH & VV *[Baglio et al.; PRD 100 (2019) 11, 113010 & arXiv:2003.07862]*

Automated framework for Madgraph5_aMC@NLO

SMEFTatNLO *[Degrande et al.; in preparation]*
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- Process independent, complete SMEFT, in top-specific flavor limit
- 4 fermion operators not yet public

See talks by Alessandro Da Rold & Ruchi Gupta

SMEFTatNLO

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; in preparation]

Preliminary results for di/triboson production @ NLO QCD

- Recent evidence for tri-boson by ATLAS & CMS
- Like VBS, sensitive to quartic gauge couplings (dimension-8)
- Potential additional probe of gauge fermion and TGC at dimension-6

$W^+W^+W^-$

σ[fb]	LO	NLO	K-factor
σ_{SM}	$79.38(5)^{+0.1\%}_{-0.6\%}$	$142.8(9)^{+6.7\%}_{-5.2\%}$	1.80
$\sigma_{\phi WB}$	$0.192(2)^{+0.0\%}_{-0.3\%}$	$0.403(3)^{+8.3\%}_{-6.6\%}$	2.10
$\sigma_{\phi WB,\phi WB}$	$0.04959(6)^{+2.3\%}_{-2.4\%}$	$0.0591(1)^{+2.7\%}_{-2.1\%}$	1.19
$\sigma_{\phi W}$	$2.93(2)^{+0.0\%}_{-0.3\%}$	$4.07(3)^{+3.9\%}_{-3.0\%}$	1.39
$\sigma_{\phi W,\phi W}$	$2.517(3)^{+6.2\%}_{-5.5\%}$	$2.522(5)^{+1.1\%}_{-1.4\%}$	1.00
σ_{WWW}	$0.4(2)^{+8.0\%}_{-10.4\%}$	$-10.8(2)^{+21.1\%}_{-16.4\%}$	-26.52
$\sigma_{WWW,WWW}$	$254.6(3)^{+10.4\%}_{-8.7\%}$	$215.7(4)^{+1.9\%}_{-0.9\%}$	0.85
$\sigma_{\phi D}$	$-0.0746(8)^{+2.0\%}_{-2.8\%}$	$-0.016(1)^{+66.2\%}_{-80.3\%}$	0.21
$\sigma_{\phi D,\phi D}$	$0.005286(8)^{+0.0\%}_{-0.5\%}$	$0.00696(1)^{+3.1\%}_{-2.3\%}$	1.32
$\sigma_{d\phi}$	$0.43(1)^{+1.4\%}_{-2.1\%}$	$0.606(2)^{+3.4\%}_{-2.5\%}$	1.41
$\sigma_{d\phi,d\phi}$	$0.01668(2)^{+0.7\%}_{-1.3\%}$	$0.02057(3)^{+2.0\%}_{-1.5\%}$	1.23
$\sigma_{\phi q_i^{(-)}}$	$1.55(5)^{+1.4\%}_{-1.6\%}$	$1.99(6)^{+3.7\%}_{-2.8\%}$	1.29
$\sigma_{\phi q_i^{(-)},\phi q_i^{(-)}}$	$36.03(3)^{+8.8\%}_{-7.4\%}$	$34.04(5)^{+1.3\%}_{-1.5\%}$	0.94
$\sigma_{\phi q_i^{(3)}}$	$44.11(9)^{+0.4\%}_{-0.8\%}$	$66.3(1)^{+5.0\%}_{-3.9\%}$	1.50
$\sigma_{\phi q_i^{(3)},\phi q_i^{(3)}}$	$121.2(1)^{+9.1\%}_{-7.7\%}$	$111.7(2)^{+1.4\%}_{-1.4\%}$	0.92

ZZW^+

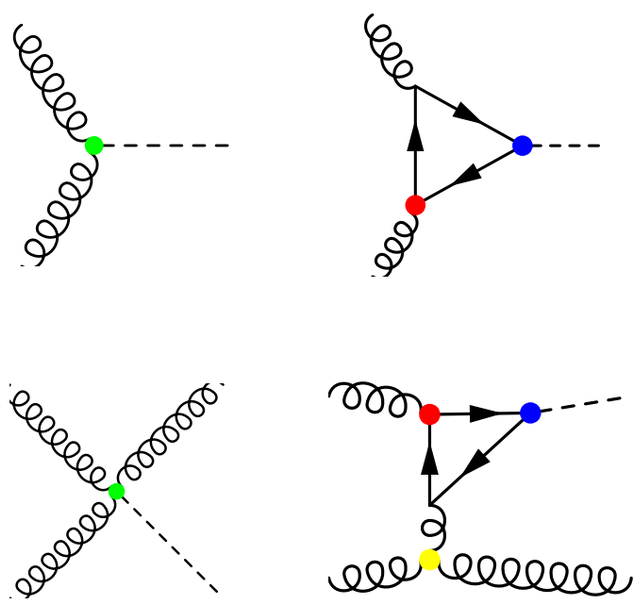
σ[fb]	LO	NLO	K-factor
σ_{SM}	$19.15(2)^{+1.0\%}_{-1.4\%}$	$37.43(2)^{+8.7\%}_{-6.9\%}$	1.95
$\sigma_{\phi WB}$	$2.176(2)^{+1.1\%}_{-1.5\%}$	$4.308(6)^{+8.8\%}_{-6.9\%}$	1.98
$\sigma_{\phi WB,\phi WB}$	$0.1859(3)^{+5.2\%}_{-4.7\%}$	$0.2634(6)^{+5.3\%}_{-4.5\%}$	1.42
$\sigma_{\phi W}$	$0.687(4)^{+1.9\%}_{-2.1\%}$	$0.996(7)^{+5.7\%}_{-4.5\%}$	1.45
$\sigma_{\phi W,\phi W}$	$1.029(2)^{+7.6\%}_{-6.5\%}$	$1.072(2)^{+1.4\%}_{-1.5\%}$	1.04
$\sigma_{\phi B}$	$-0.017(1)^{+0.0\%}_{-0.4\%}$	$-0.0305(2)^{+7.0\%}_{-5.6\%}$	1.79
$\sigma_{\phi B,\phi B}$	$0.0004755(7)^{+1.2\%}_{-1.5\%}$	$0.000555(1)^{+2.3\%}_{-1.7\%}$	1.17
σ_{WWW}	$0.65(4)^{+1.9\%}_{-3.3\%}$	$-4.52(7)^{+24.6\%}_{-19.1\%}$	-6.95
$\sigma_{WWW,WWW}$	$120.0(2)^{+11.3\%}_{-9.3\%}$	$117.5(3)^{+2.2\%}_{-1.2\%}$	0.98
$\sigma_{\phi D}$	$0.84(1)^{+1.2\%}_{-1.6\%}$	$1.831(1)^{+9.8\%}_{-7.8\%}$	2.18
$\sigma_{\phi D,\phi D}$	$0.0215(5)^{+1.1\%}_{-1.5\%}$	$0.04175(5)^{+8.5\%}_{-6.8\%}$	1.94
$\sigma_{d\phi}$	$0.0789(3)^{+0.0\%}_{-0.4\%}$	$0.1193(7)^{+5.1\%}_{-4.0\%}$	1.51
$\sigma_{d\phi,d\phi}$	$0.005092(8)^{+0.8\%}_{-1.2\%}$	$0.00598(1)^{+2.2\%}_{-1.6\%}$	1.18
$\sigma_{\phi q_i^{(-)}}$	$1.801(4)^{+0.5\%}_{-0.9\%}$	$2.477(5)^{+4.0\%}_{-3.0\%}$	1.38
$\sigma_{\phi q_i^{(-)},\phi q_i^{(-)}}$	$0.4757(8)^{+0.8\%}_{-1.2\%}$	$0.729(1)^{+5.4\%}_{-4.3\%}$	1.53
$\sigma_{\phi q_i^{(3)}}$	$15.94(5)^{+2.1\%}_{-2.3\%}$	$23.79(6)^{+5.7\%}_{-4.5\%}$	1.49
$\sigma_{\phi q_i^{(3)},\phi q_i^{(3)}}$	$42.53(9)^{+10.3\%}_{-8.5\%}$	$43.8(1)^{+1.8\%}_{-1.6\%}$	1.03

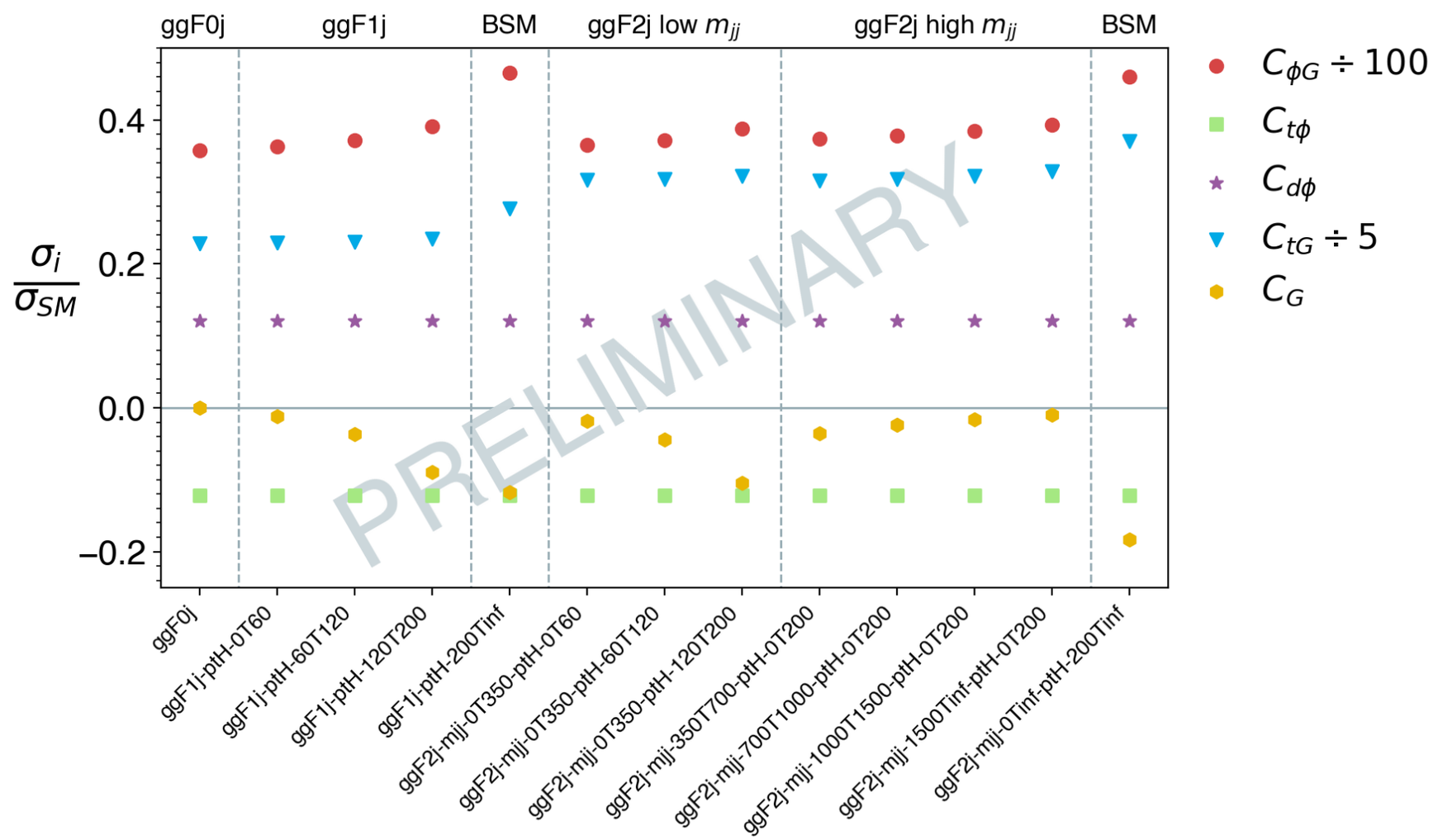
Improving fits

[Ellis, Madigan, KM, Sanz, You; in preparation]

STXS for ggF: one-loop is LO for the SM

- Tree-EFT x loop-SM and loop-EFT x loop-SM interference terms
- Heavy top limit OK for 0-jet, breaks down for high-p_T





Higher orders in Λ

[Li et al.; 2005.00008] & [Murphy; arXiv: 2005.00059]

EFTs are systematically improvable in 1/Λ

- Dimension-6 is the LO for baryon/lepton number conserving operators

Important to think about possible dim-8 effects

- Theoretical uncertainties / validity of the EFT expansion
- Some measurements are dominated by quadratic dim-6 effects ($1/\Lambda^4$)
- Small/no interference due to symmetry, helicity selection, color structure,…

Operator counting known to arbitrary dimensions

2, 84, 30, 993, 560, 15456, 11962, 261485, . . .: *[Henning et al.; JHEP 08 (2017) 016]*
higher dimension operators in the SM EFT *[Lehman & Martin; JHEP 02 (2016) 081]*

New result: complete dimension 8 basis written down

- 44807 operators encoded in 1029 Lagrangian terms
- Paves the way for more exploratory studies of importance & unique pheno

First-principles positivity constraints applicable (e.g. VBS)

High energy & multiplicity

How can we improve with increasing statistics?

- Target energy growth (energy helps accuracy)

more differential
higher multiplicity

Dim-6 operators don't guarantee energy growth

Operator contribution to a given process:

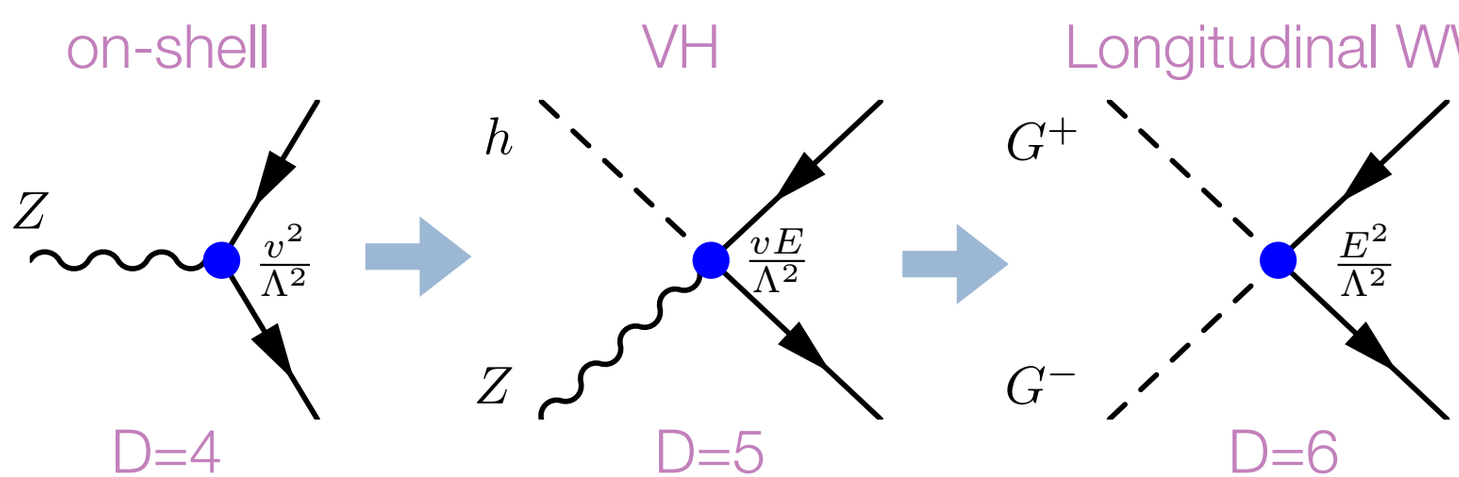
(a) **May not** grow maximally with energy (E^2)

(b) Have **suppressed** interference w/ SM

[Azatov et al.; PRD 95 (2017) no. 6, 065014]

There will always be **some** scattering amplitude that displays maximal (E^2) growth w.r.t the SM

$$(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{f}_i \gamma^\mu f_j)$$



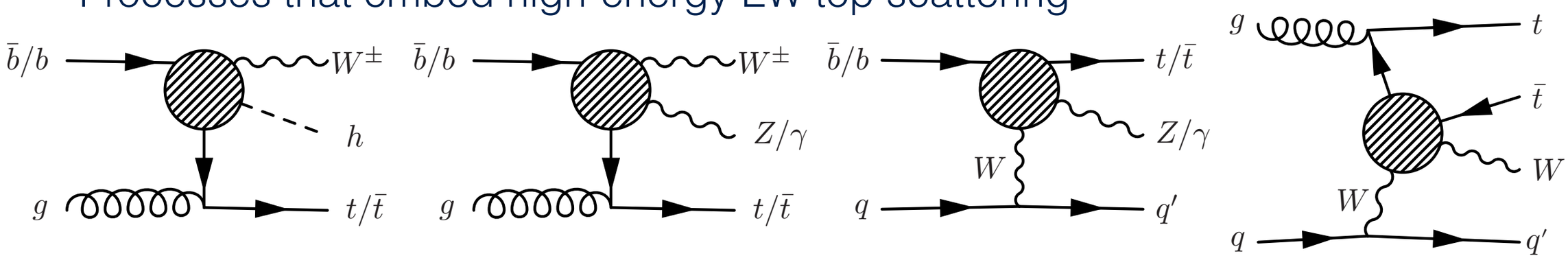
SM interference

High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production

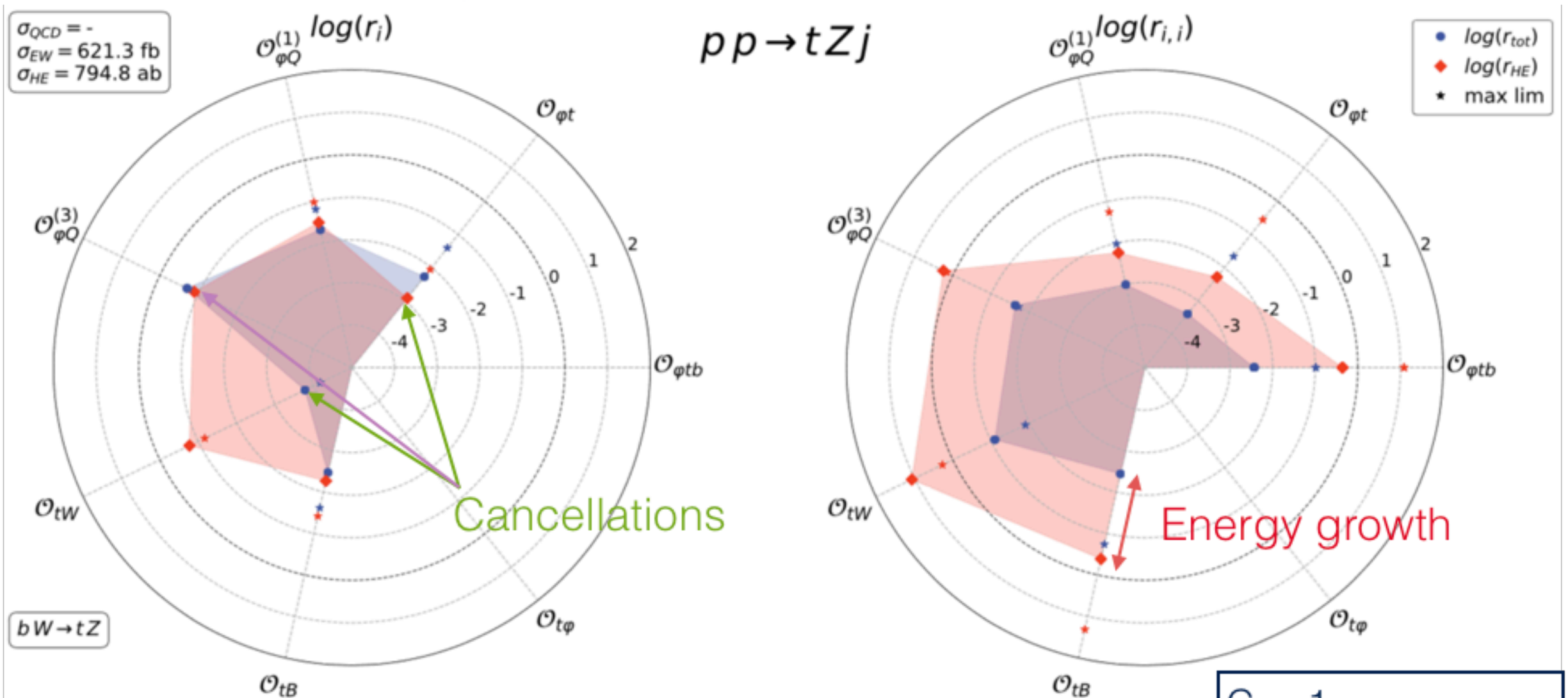
- Processes that embed high-energy EW top scattering



High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production



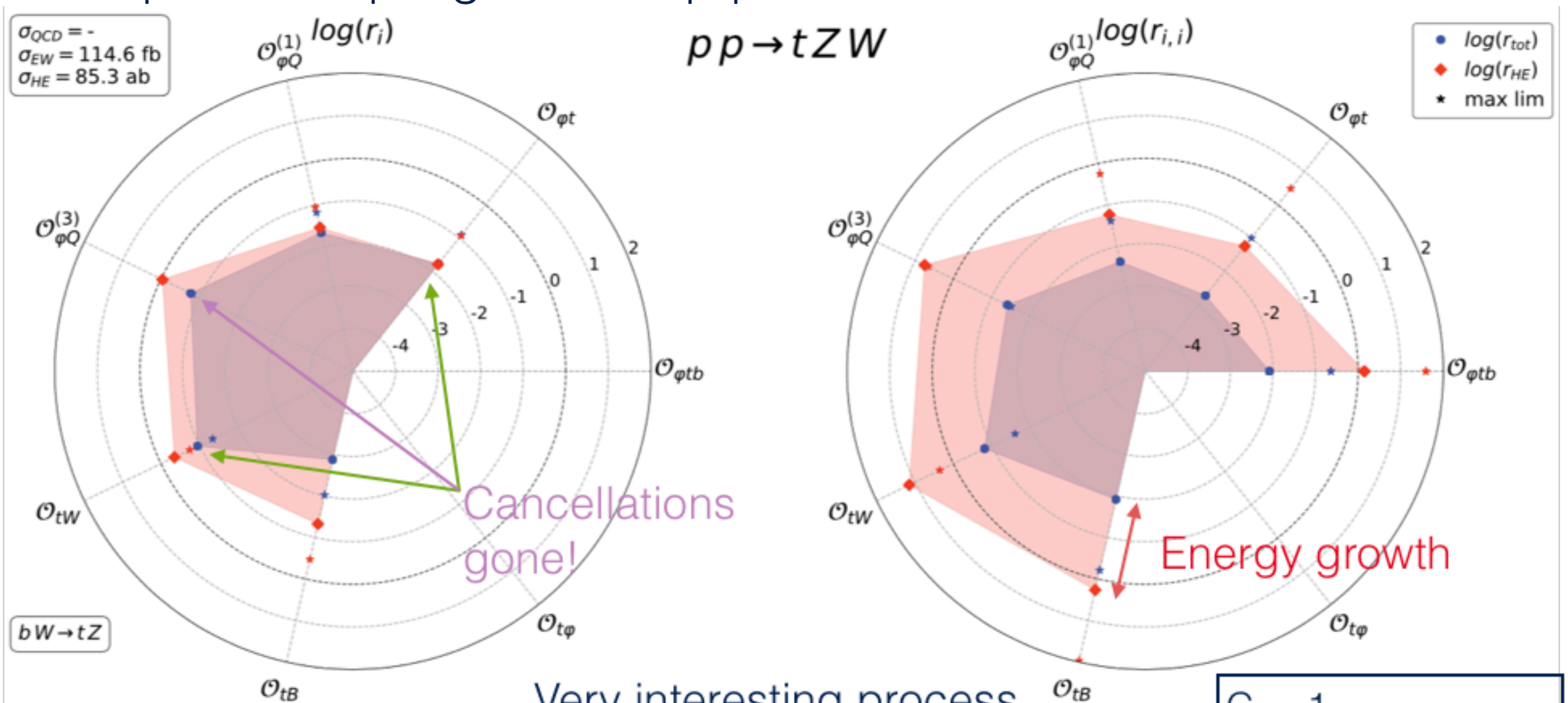
$C_i = 1$
Inclusive
$p_T(Z) > 500$ GeV

Expected growth from 2→2 absent!

High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production



Expected growth is there!

Very interesting process that should be measured at the LHC

C_i = 1
Inclusive
p_T (W,Z)> 500 GeV

High energy & multiplicity

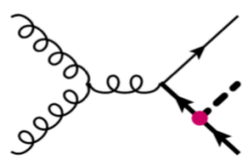
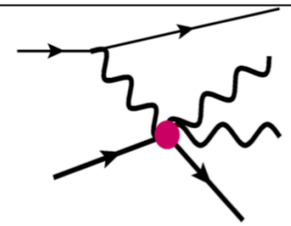
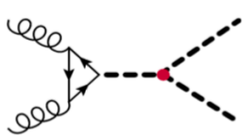
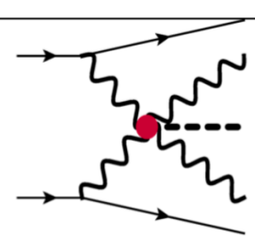
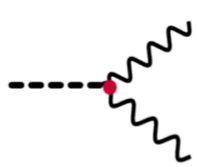
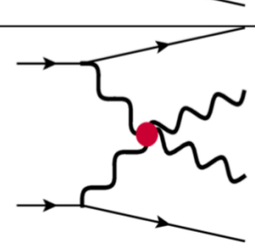
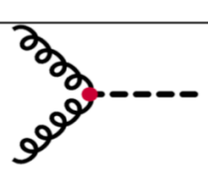
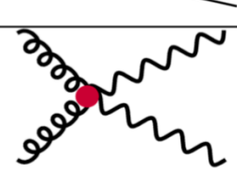
[Henning et al.; PRL 123 (2019), no.18 181801]

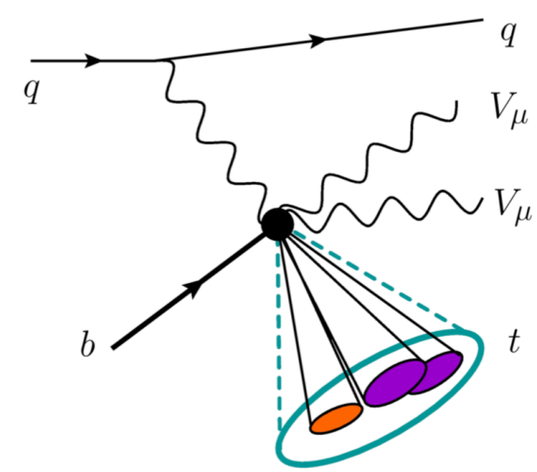
Higgs couplings… without the Higgs

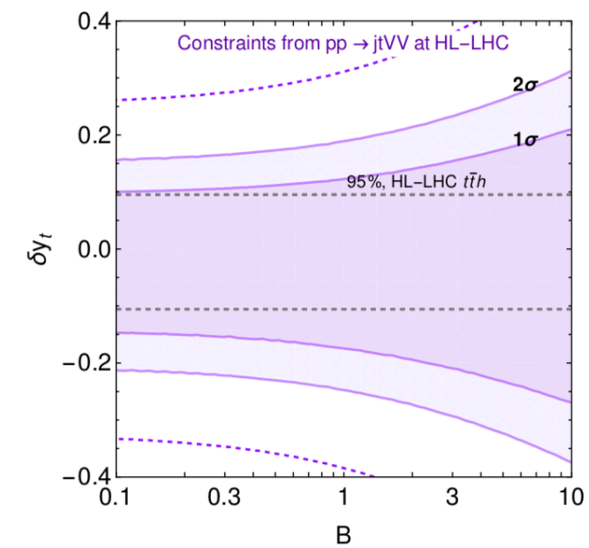
$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6$$

- Operators that affect Higgs signal strengths contain

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$





Modified EWSB sector interactions

Energy growth in high-multiplicity final states of Higgs, top & longitudinal gauge bosons

Promising avenue for the future

Conclusions

SMEFT is truly well established in the HEP community

- On the path to measuring the SM parameters up to dimension-6
- Extend the reach of the LHC beyond nominal energy
- Multi-TeV scale within reach, next step: more realistic models

Much work to do towards the global SMEFT likelihood

- Precision tools available
- Progress in many directions
- High energy & multiplicity as a roadmap for the future

Big part of the LHC legacy

Other important topics

- B-anomalies & SMEFT/BSM talk by Admir Greljo on Tuesday
- Overlap of signal & background in global analyses
- Interplay between Di-Higgs & other measurements in global fits
- CPV violation in SMEFT see Elina Fuchs' talk just now
- Applying on-shell techniques (basis construction, RGEs, non-renormalisation)

LHC EFT working group

LHC EFT working group

Clear interest in EFT interpretation across multiple existing LHC working groups (HXSWG, Top, EW,…)

New, dedicated working group in the pipeline

- Centralised forum for exchange & discussion
- General aspects & common methodologies across WGs
- Tools, benchmarking, theoretical aspects,…
- Leading to recommendations on coherent & consistent EFT interpretations

A natural & welcome development

- Reinforces the global nature of the EFT approach
- Coordinated effort among all groups will lead to better scientific outcomes
- Facilitate combinations measurements for experimentalists and/or theorists

Thank you

UCLouvain

European Commission

Thank you

Zoom room:
https://universityofsussex.zoom.us/j/8579312707?pwd=VHZWaHdLTUNrYlY5L3JhWUM4NkIIdz09

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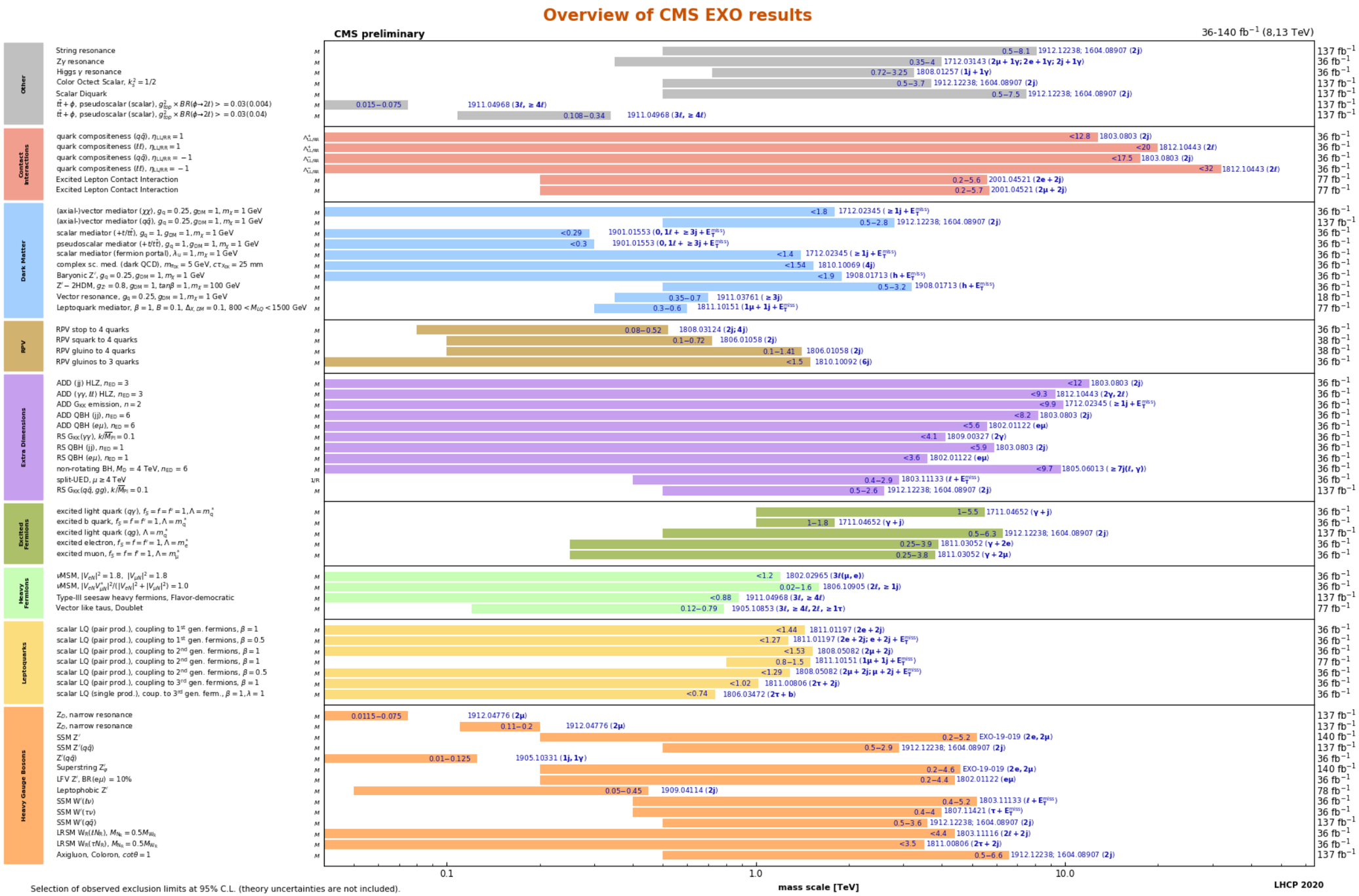
CMS exotic summary



D=6 operators

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

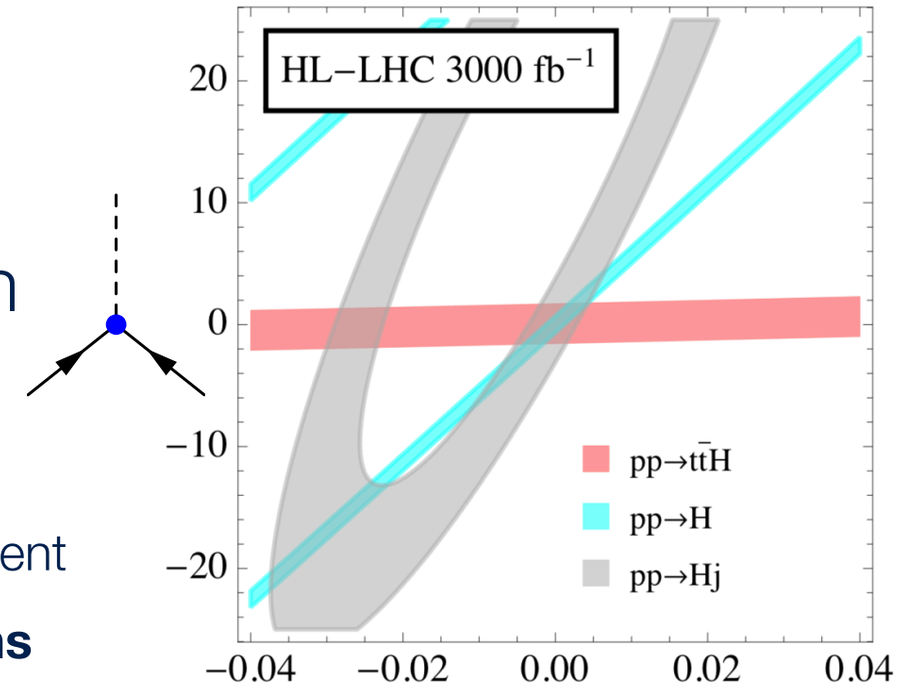
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

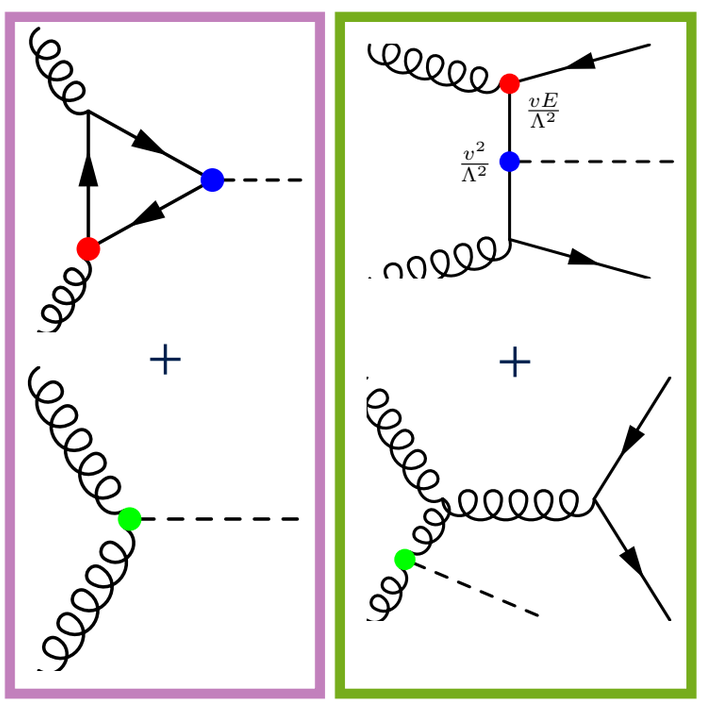
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

[Maltoni, Vryonidou & Zhang; JHEP 10 (2016) 123]
[Azatov, Grojean, Paul & Salvioni; JHEP 09 (2016) 123]

SMEFT

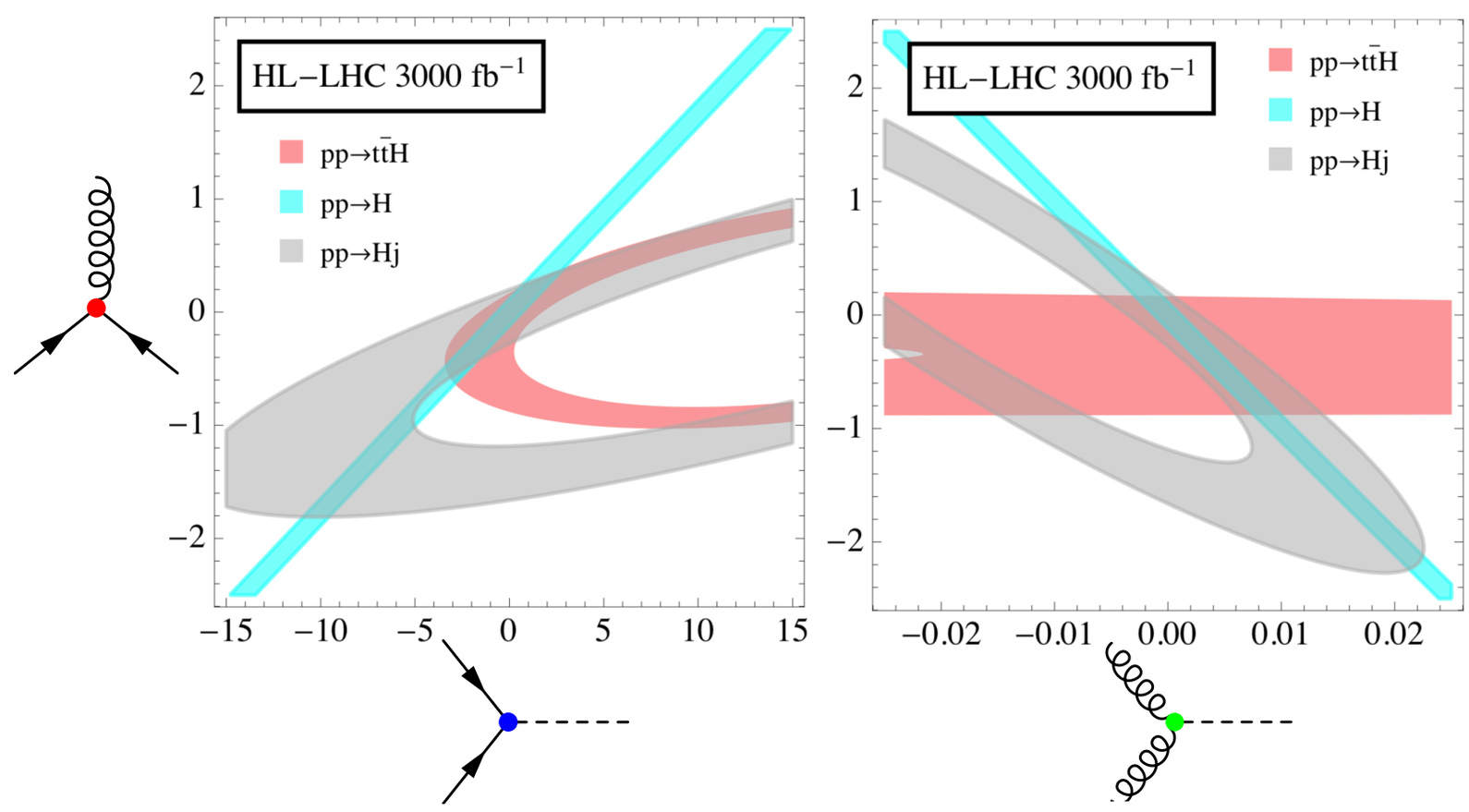
Direct ttH measurement breaks **degeneracy** among y_t, ggH and dipole in gg-fusion





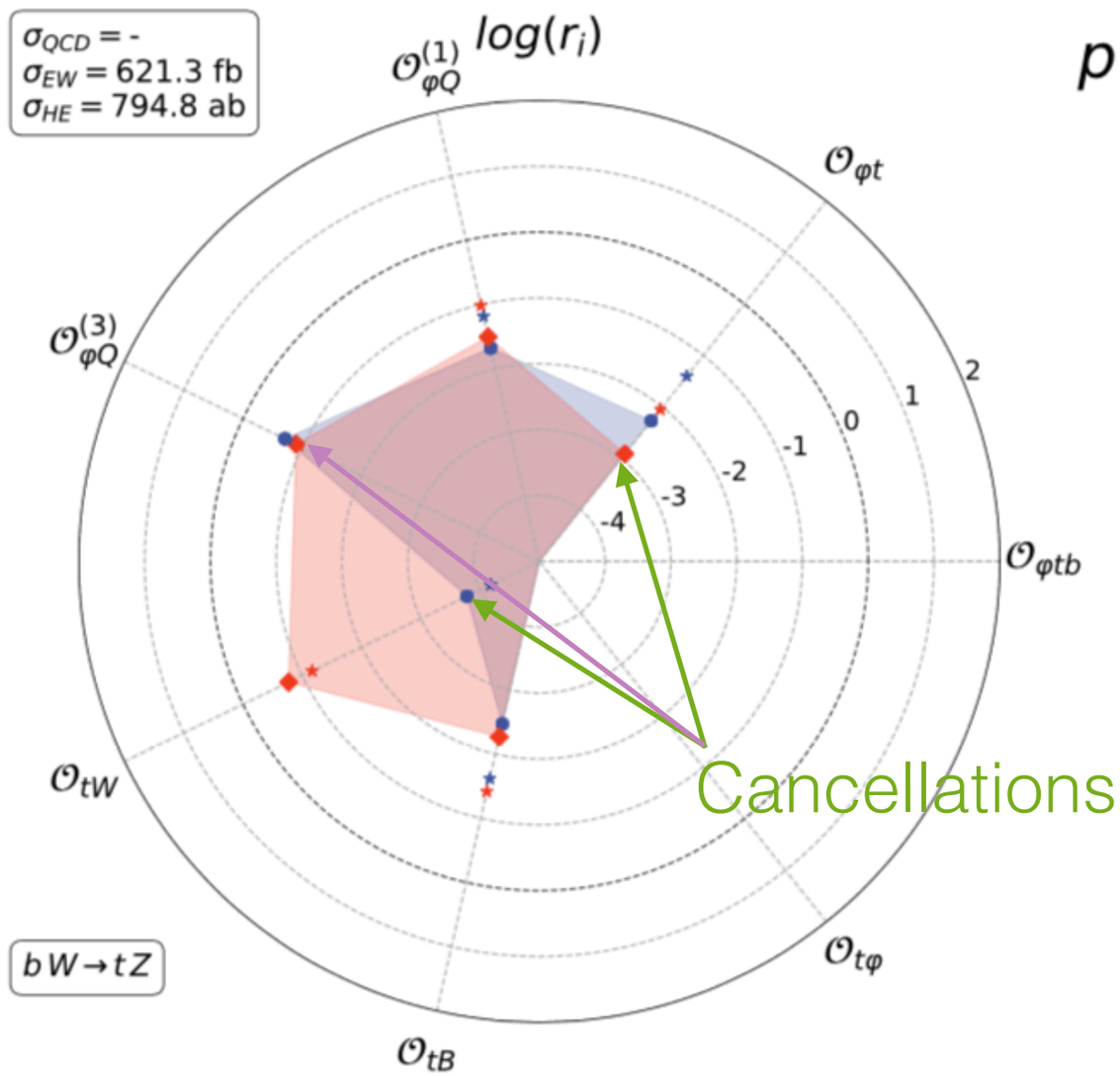
Pin down heavy coloured particles in the loop

Single measurement
=
Blind directions



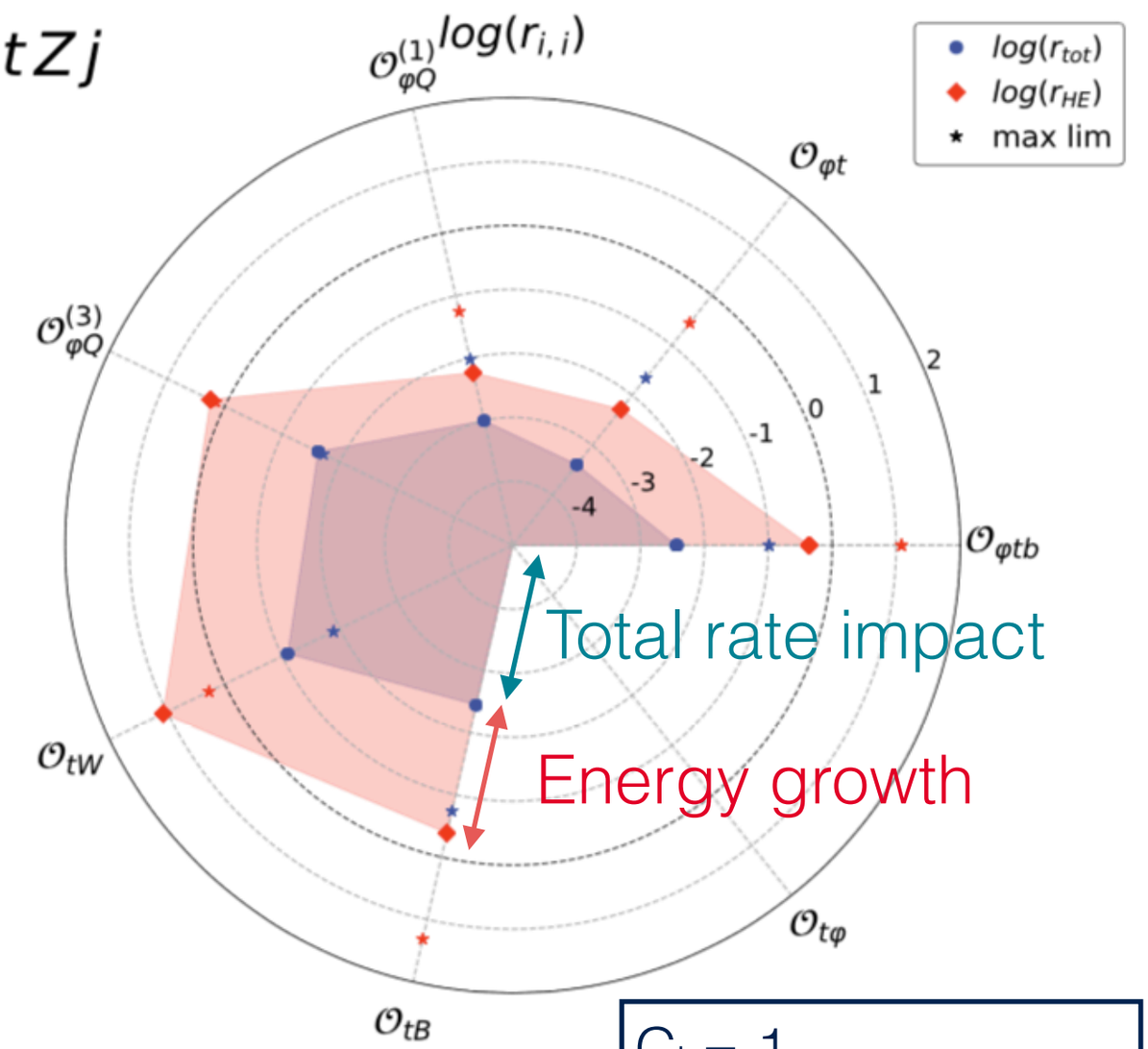
tZj total & high energy xs

interference/SM



$pp \to tZj$

square/SM

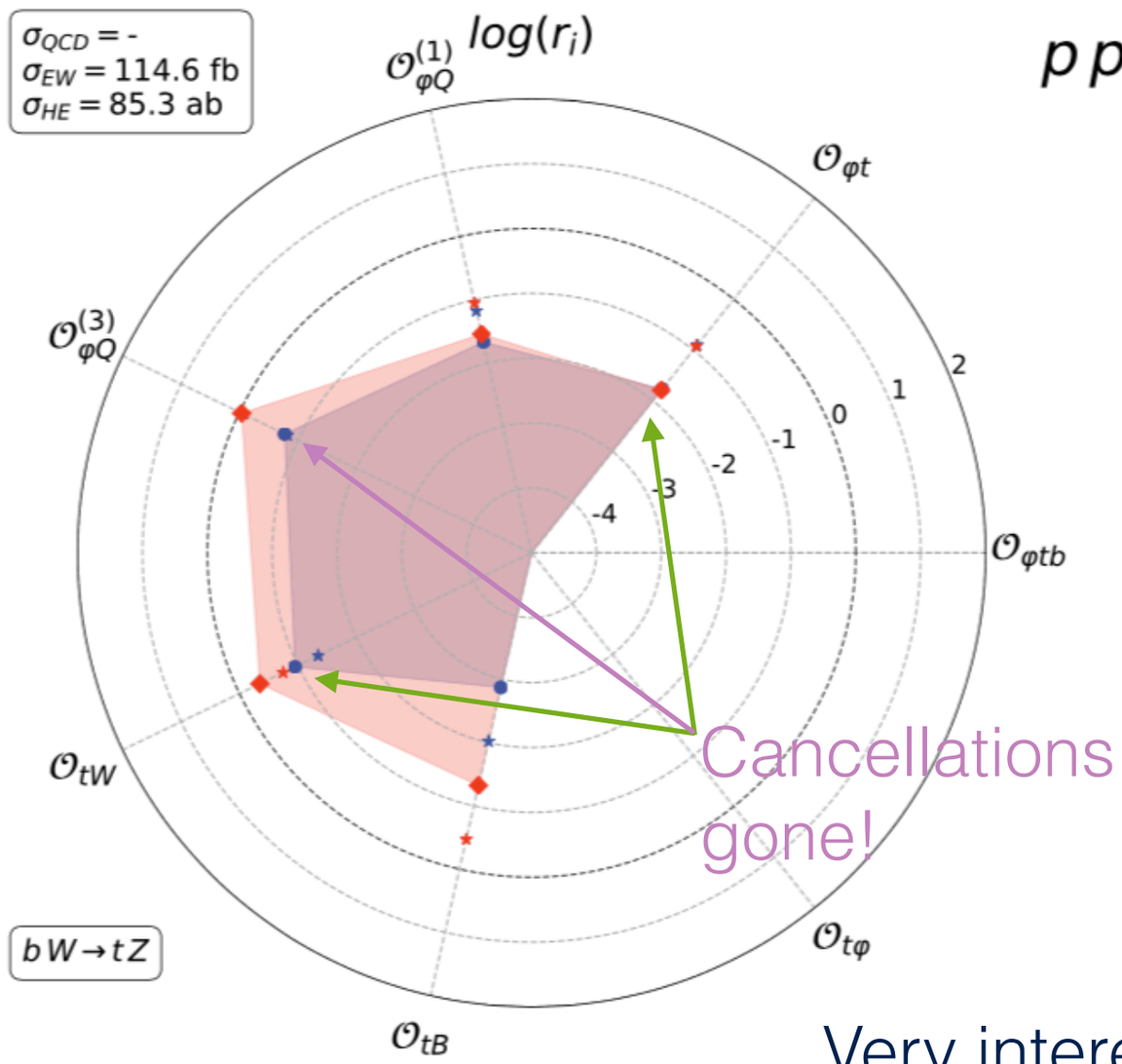


$C_i = 1$
Inclusive
$p_T(Z) > 500$ GeV

Expected growth from 2→2 absent!

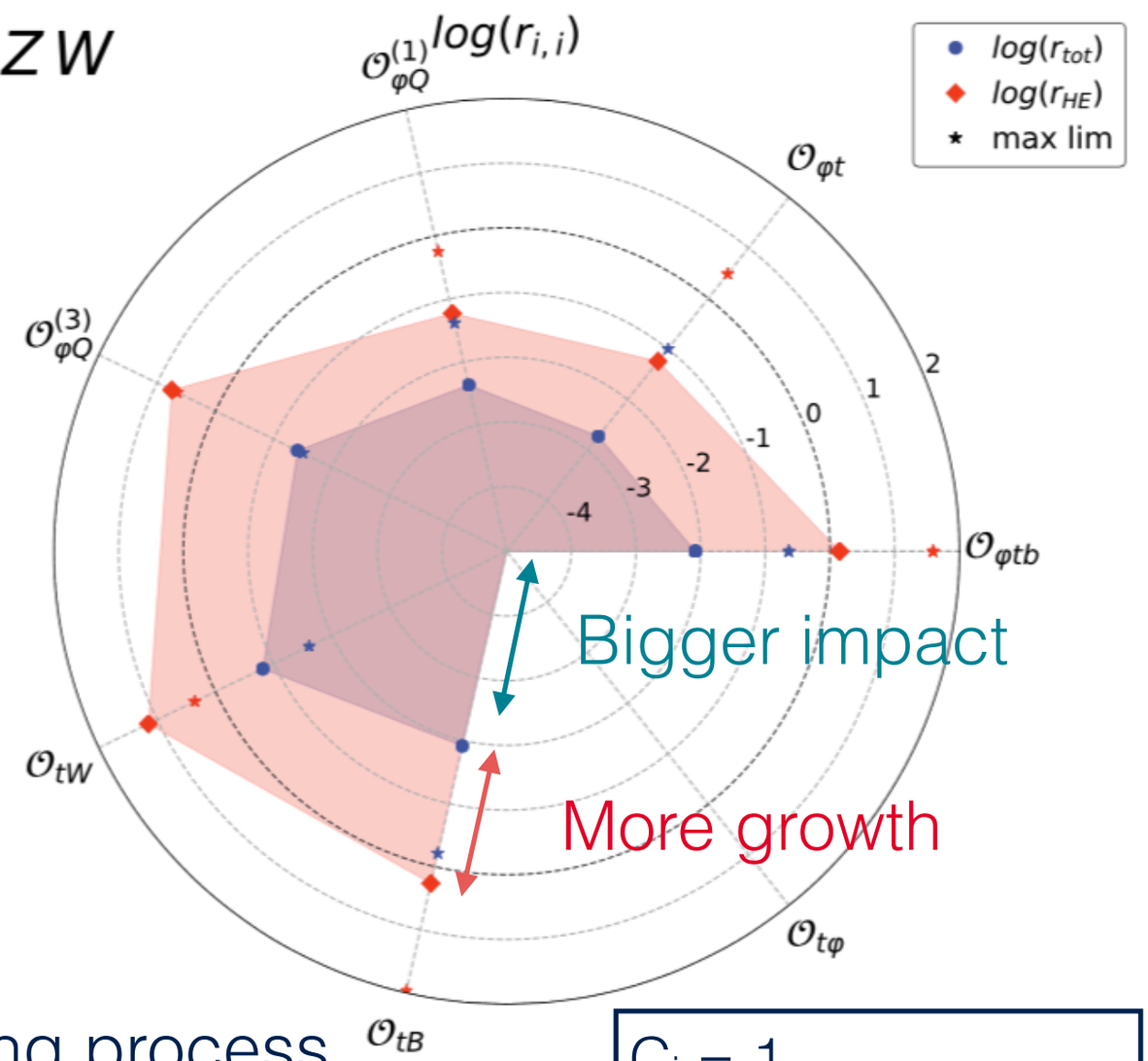
tZW total & high energy xs

interference/SM



$pp \to tZW$

square/SM

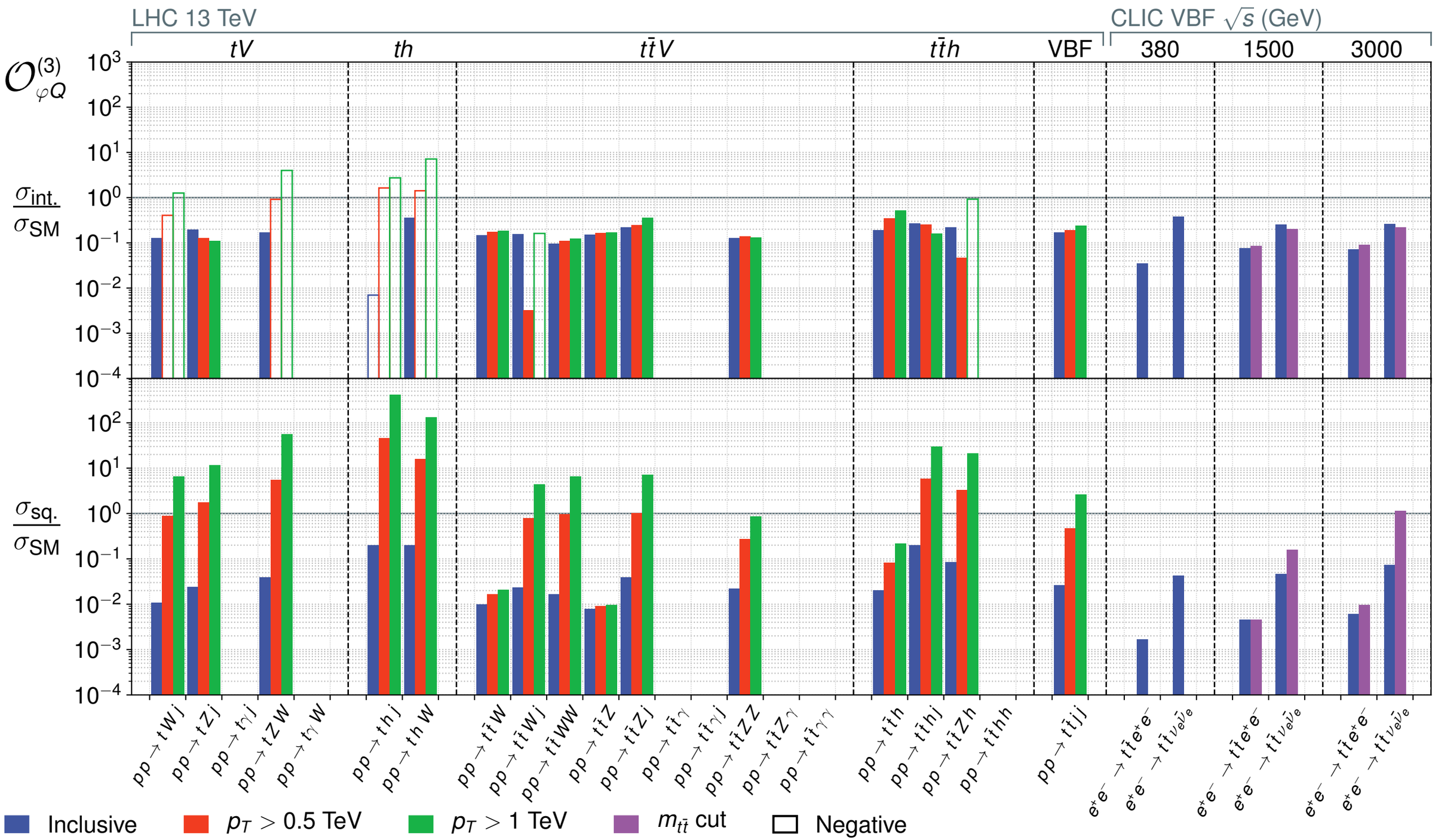


Expected growth is there!

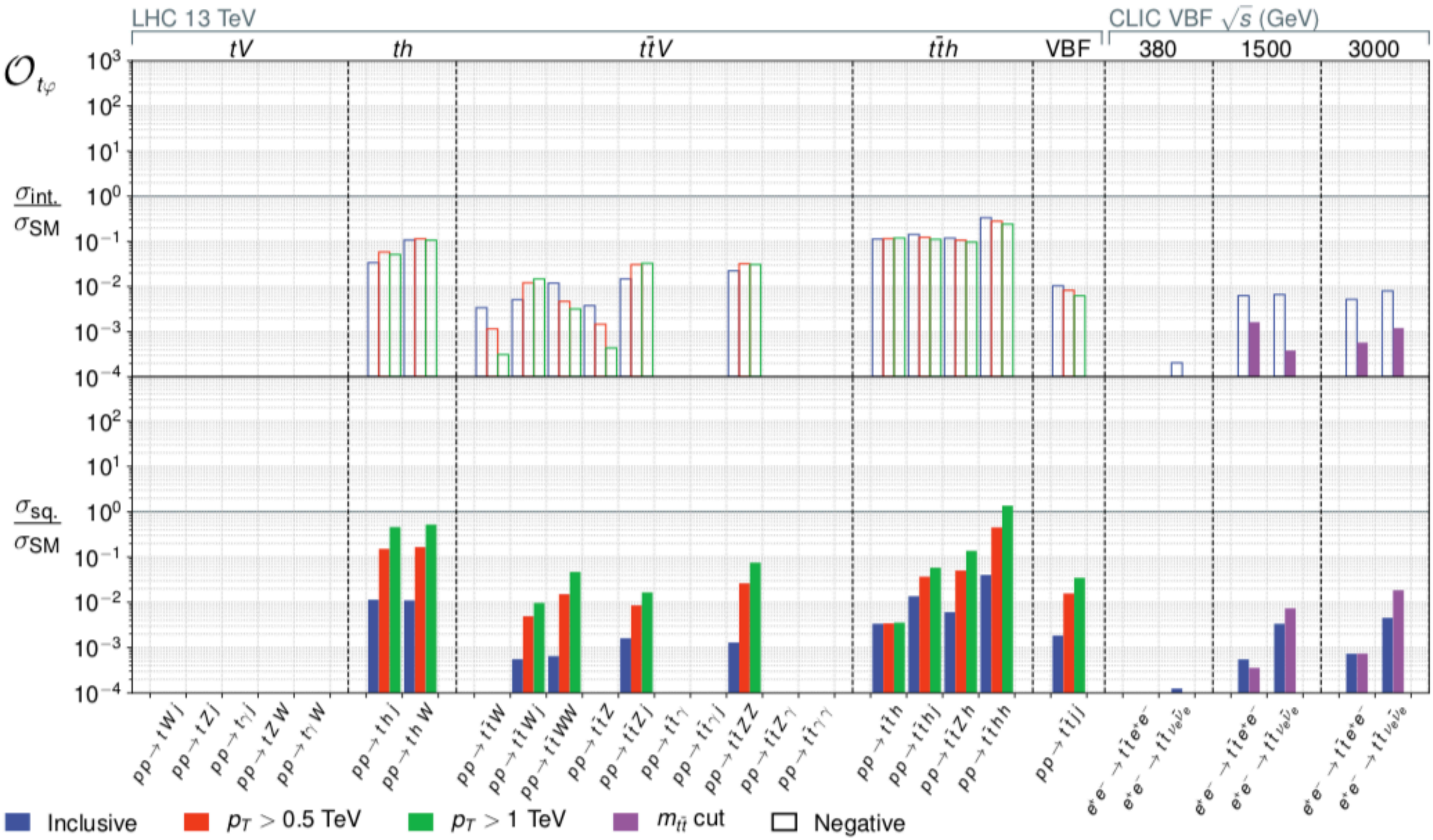
Very interesting process that should be measured at the LHC/FCC

C_i = 1
Inclusive
p_T (W,Z)> 500 GeV

Charged current operator



Yukawa operator



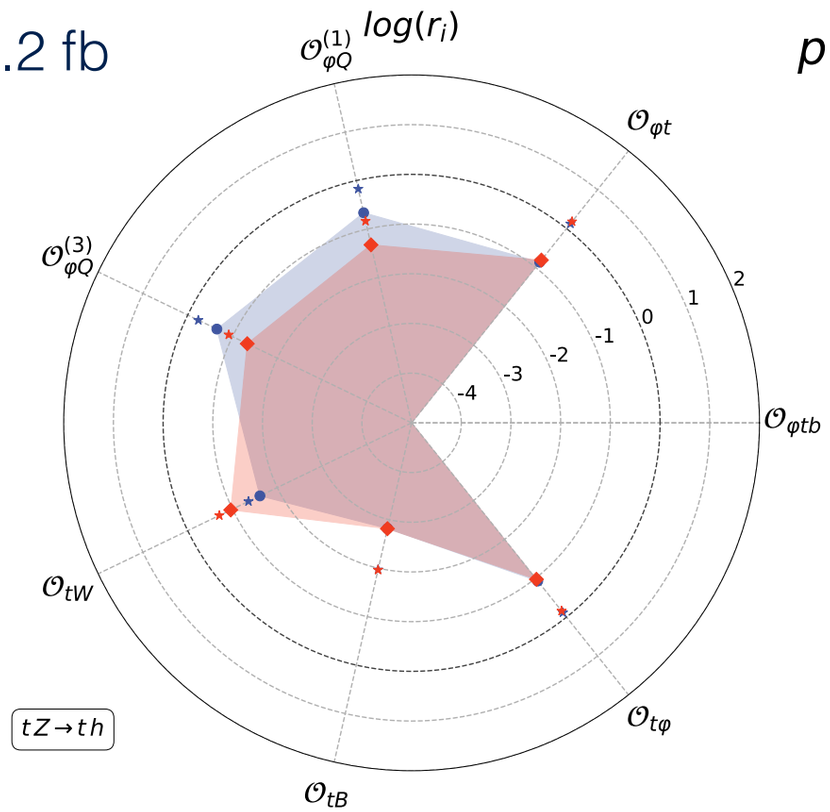
ttZh: LHC vs FCC-hh

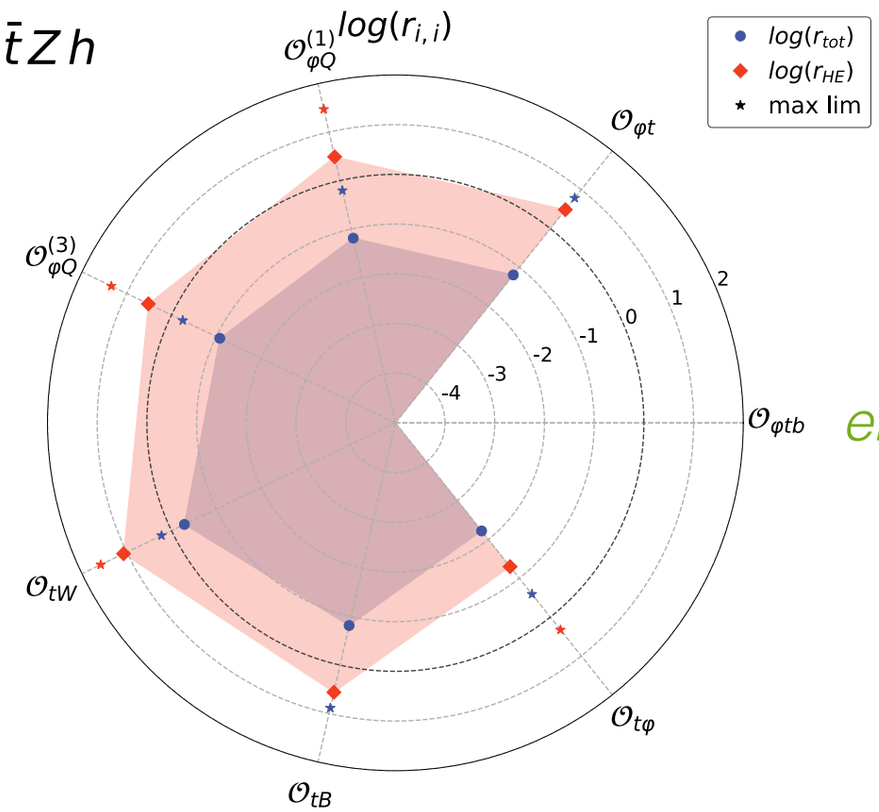
High energy: p_T (Z,h) > 500 GeV

σ_{13} = 1.2 fb

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

Interference: phase space cancellations



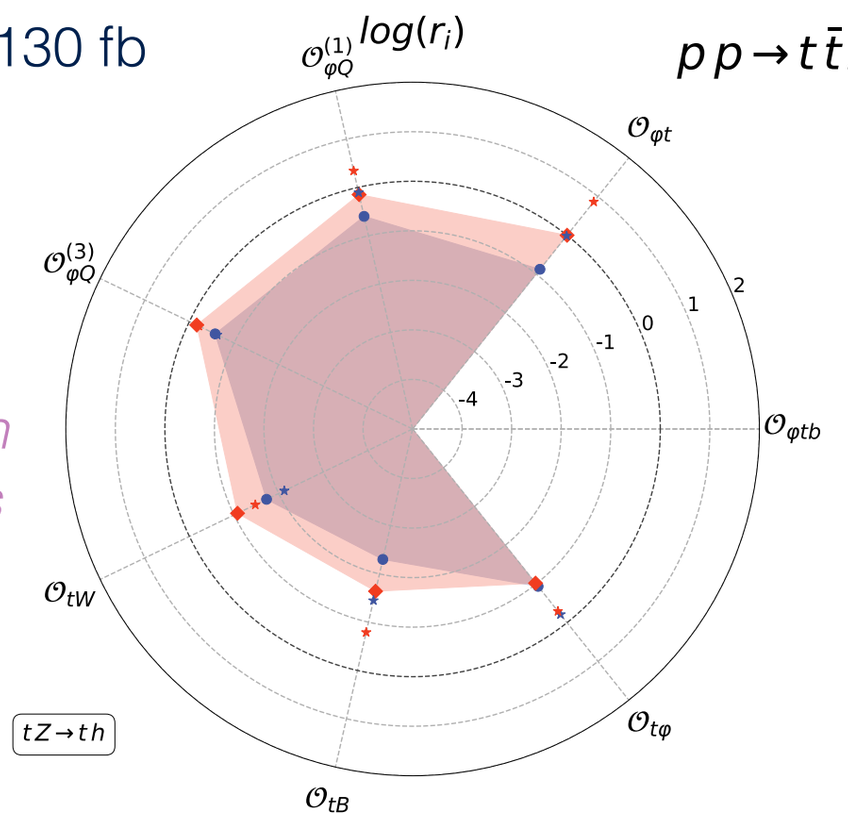


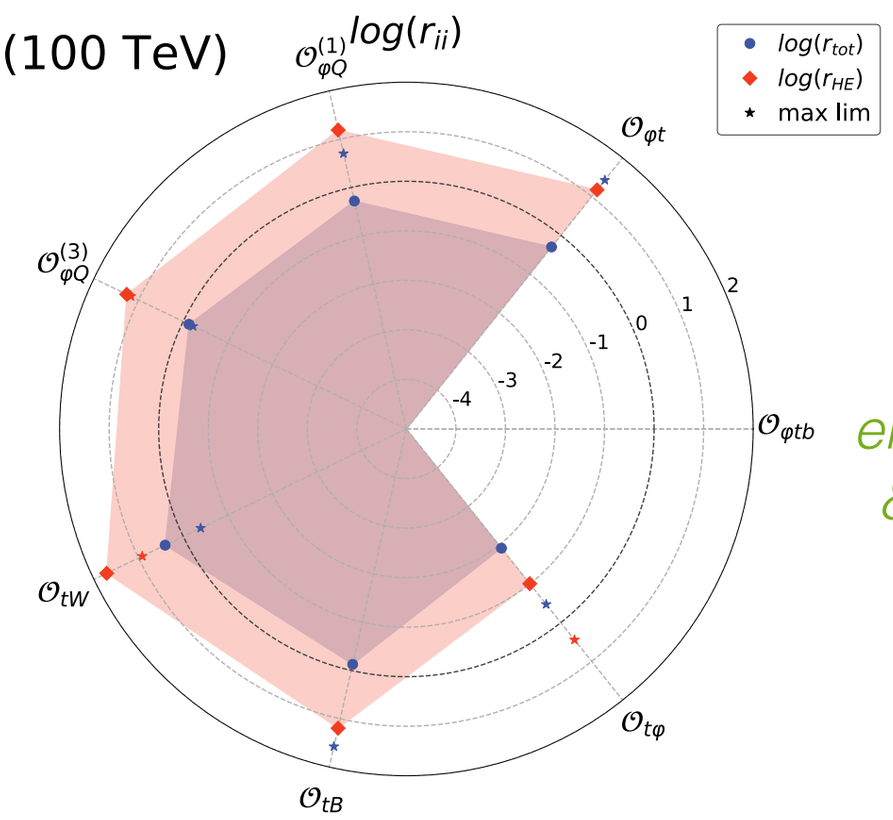
Quadratic: energy growth & O(1-10)

σ_{100} = 130 fb

$pp \to t\bar{t}Zh$ (100 TeV)

Interference: energy growth & O(1) effects





Quadratic: energy growth & O(10-100)