Interpreting top quark LHC measurements in SMEFT

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Particle Physics Seminar, Universität Wien

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New physics through tops

What is the origin of electroweak symmetry breaking?

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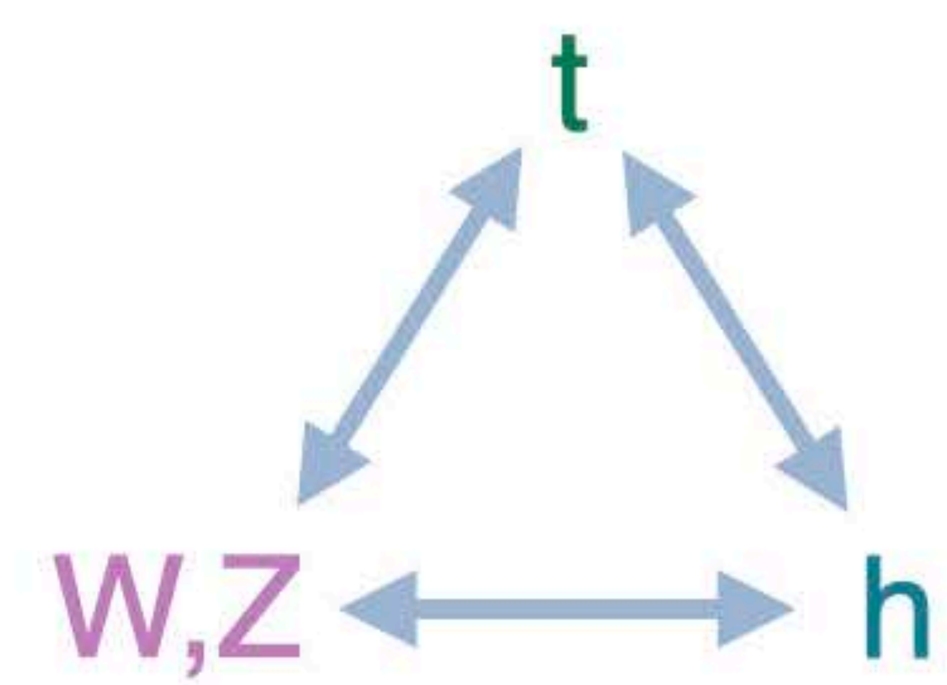
Who are the main players?

- Higgs boson, EW gauge bosons & **top quark**
- Most **massive** ⇔ **strongly coupled** to the Higgs



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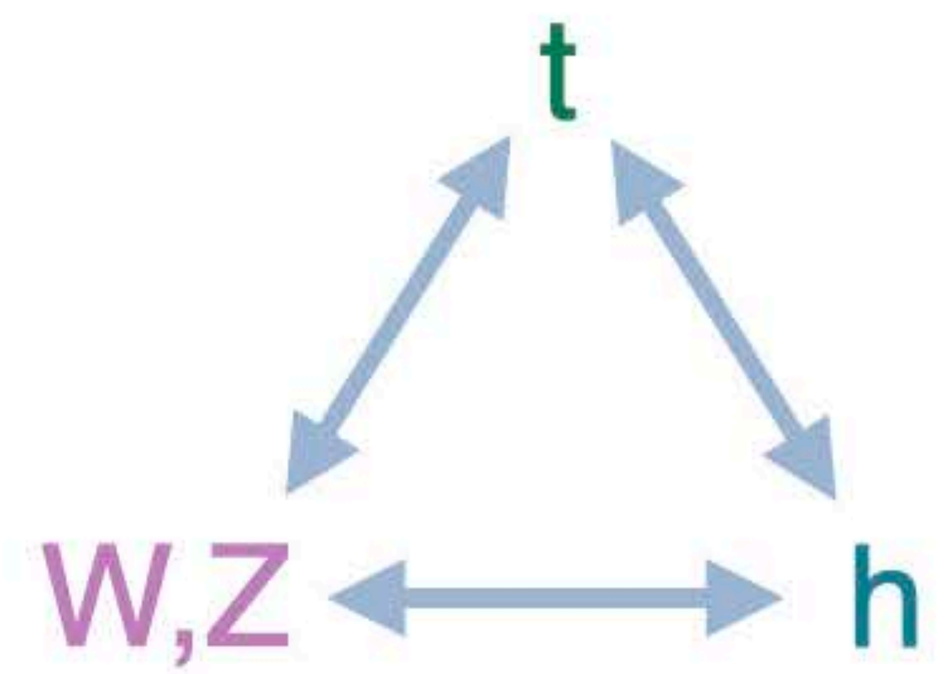
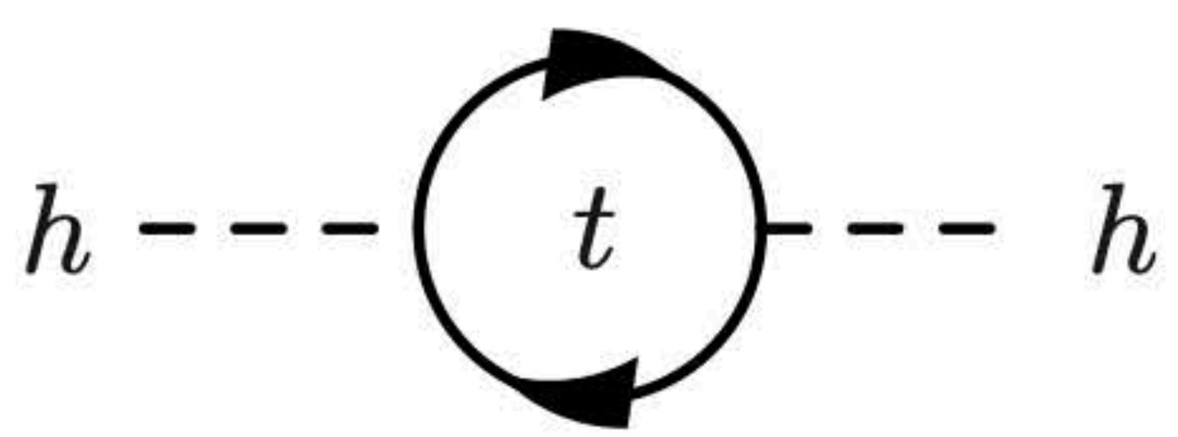
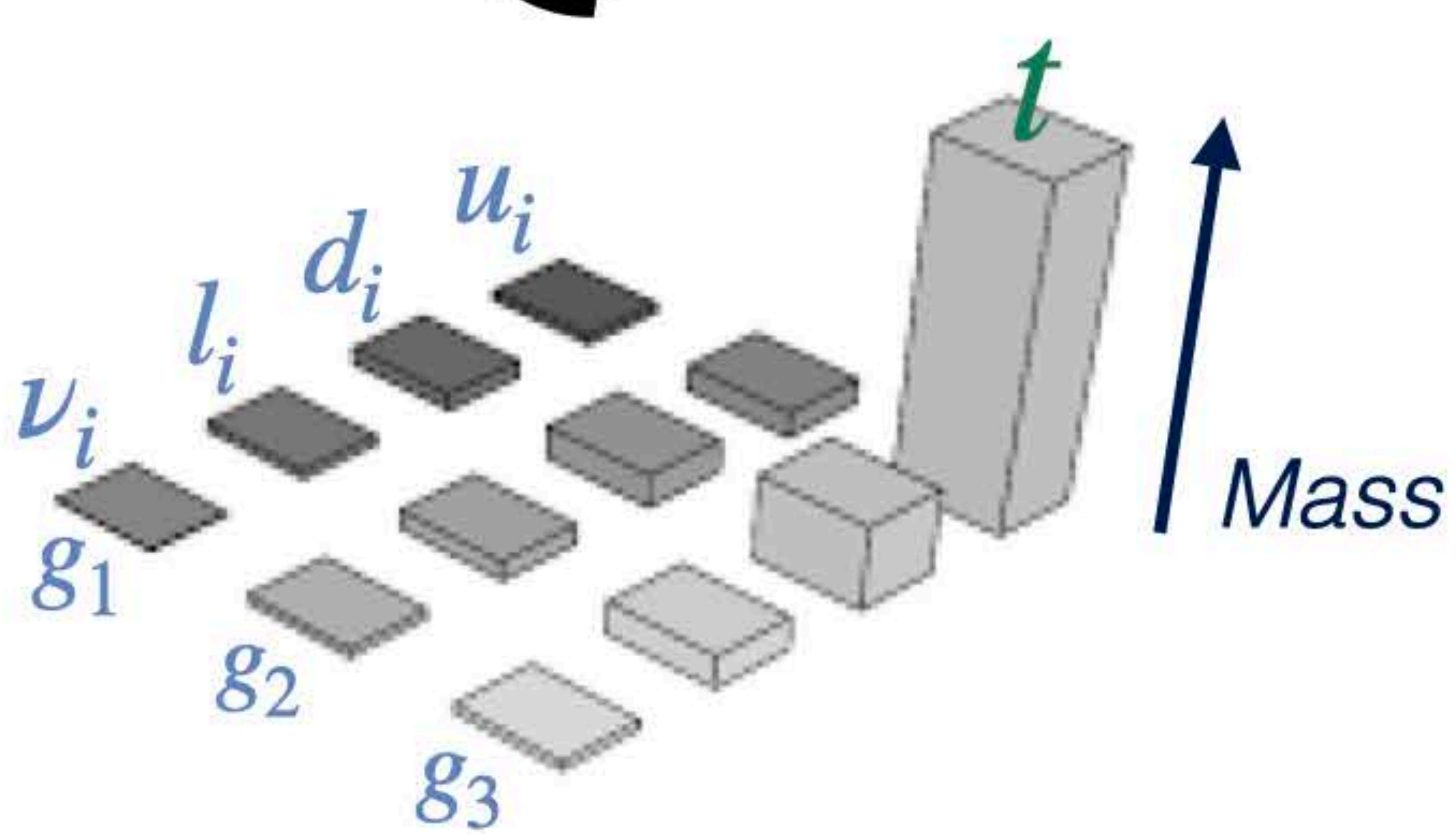
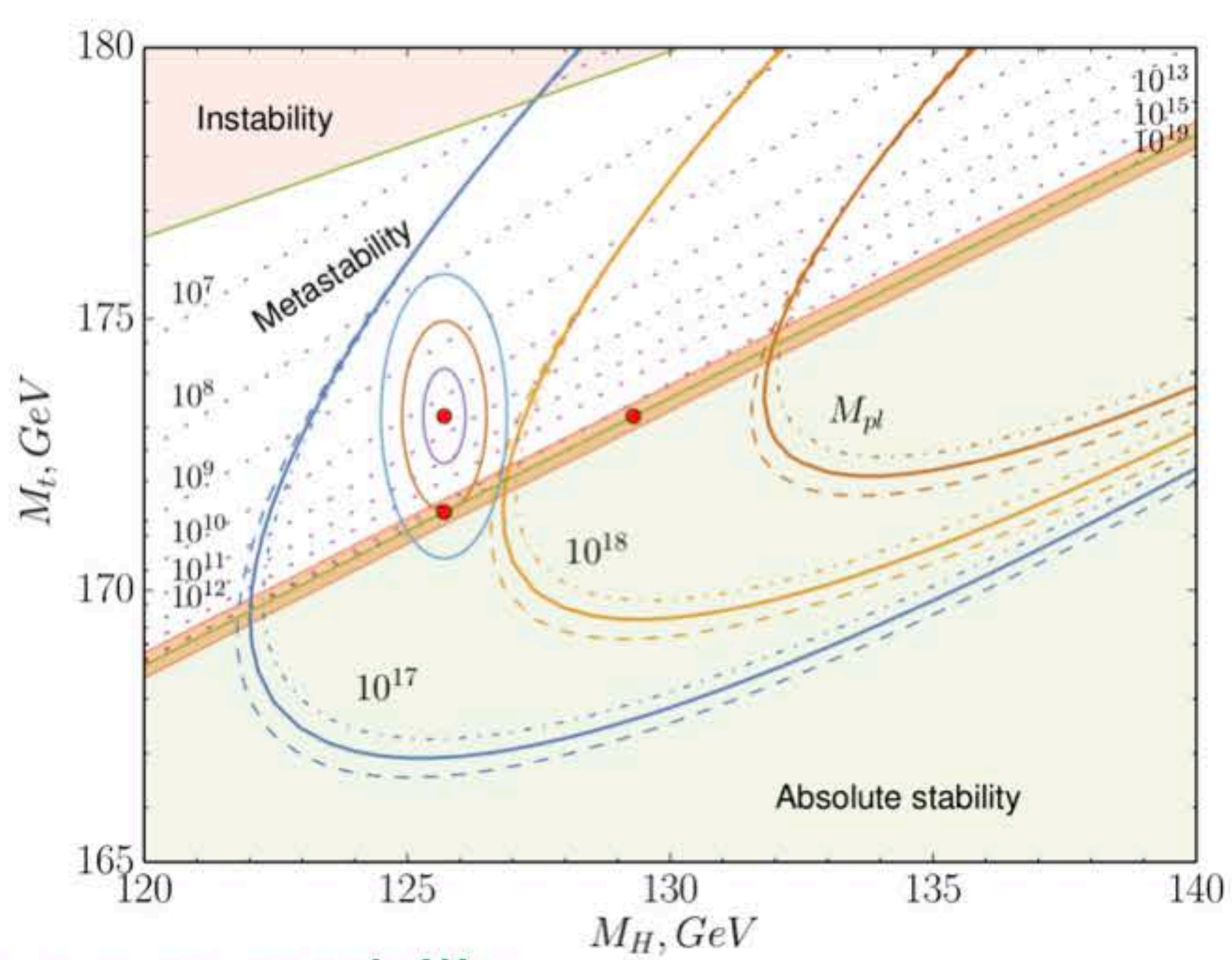


The **top is special** for many reasons



naturalness & hierarchies

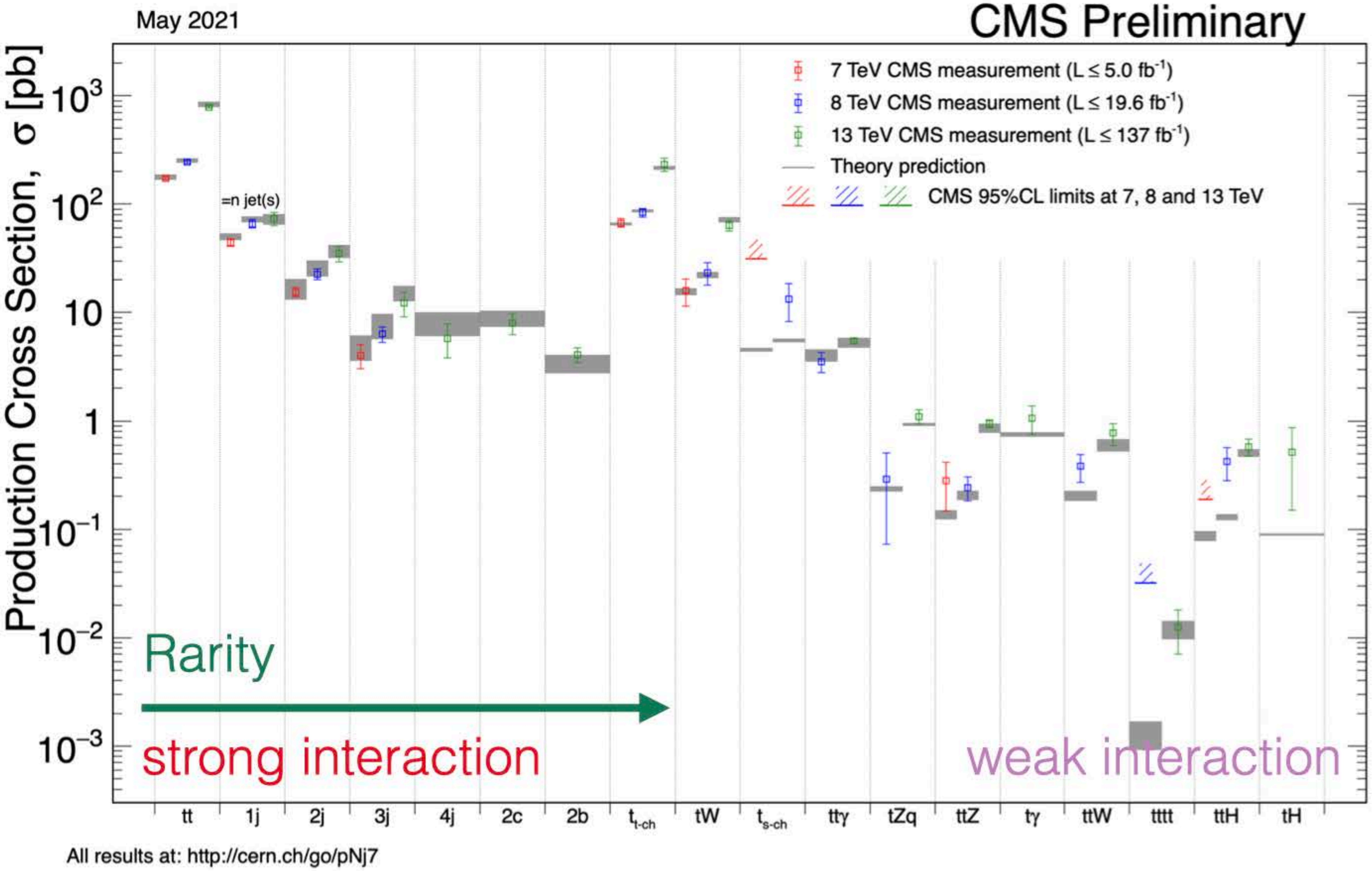




EW vacuum stability

[Bednyakov et al.; PRL 115 (2015) 201802],…

The LHC is a top factory



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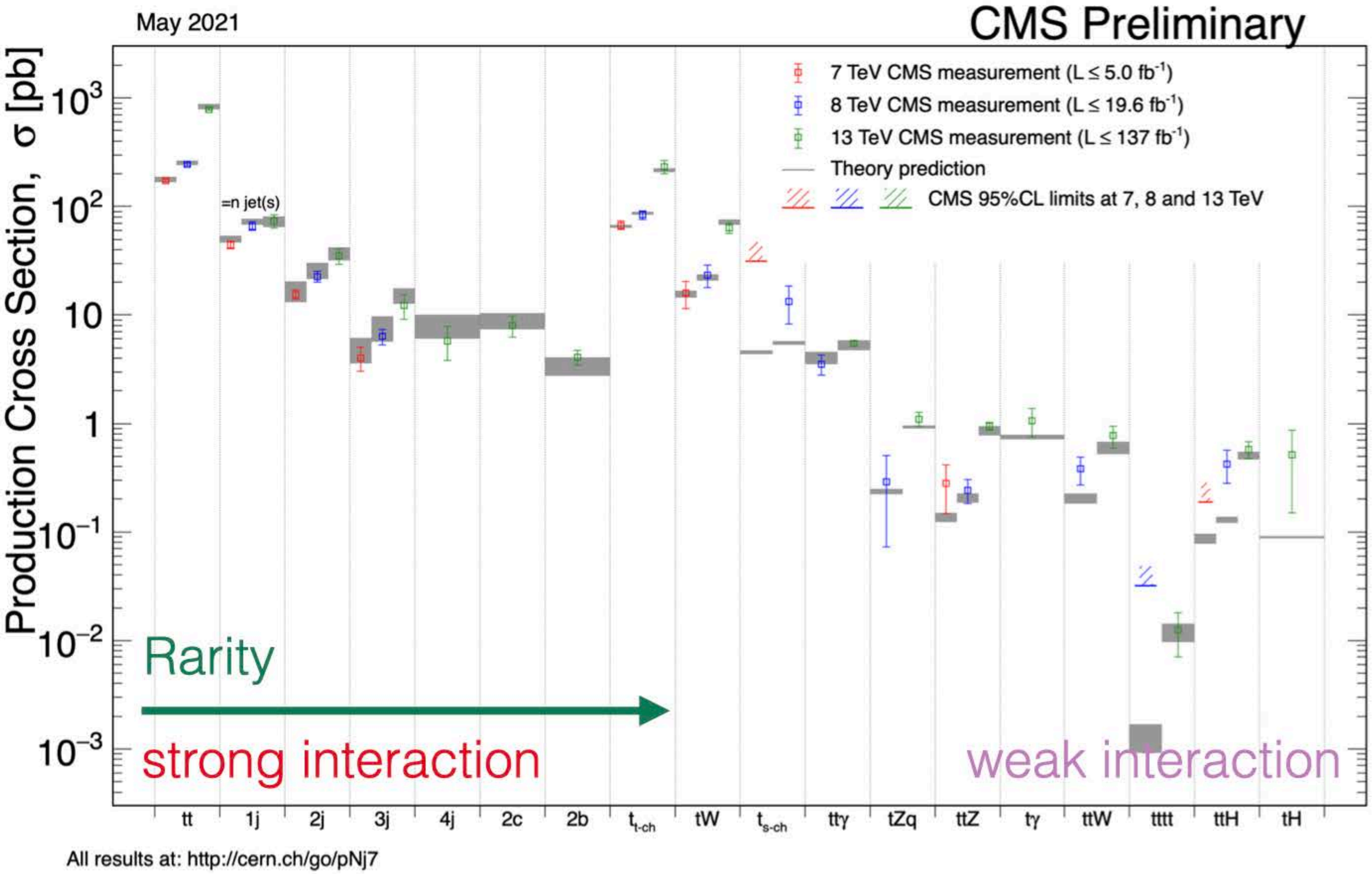

$t\bar{t}:\ 10^9$

$tj, tW, tb:\ 10^8$

$t\bar{t}+Z/W/\gamma:\ 10^7$

$t\bar{t}H:\ 10^6$

$t\bar{t}t\bar{t}:\ 10^4$

$\mathscr{L}^{\text{int.}} \sim 3\,\text{ab}^{-1}$

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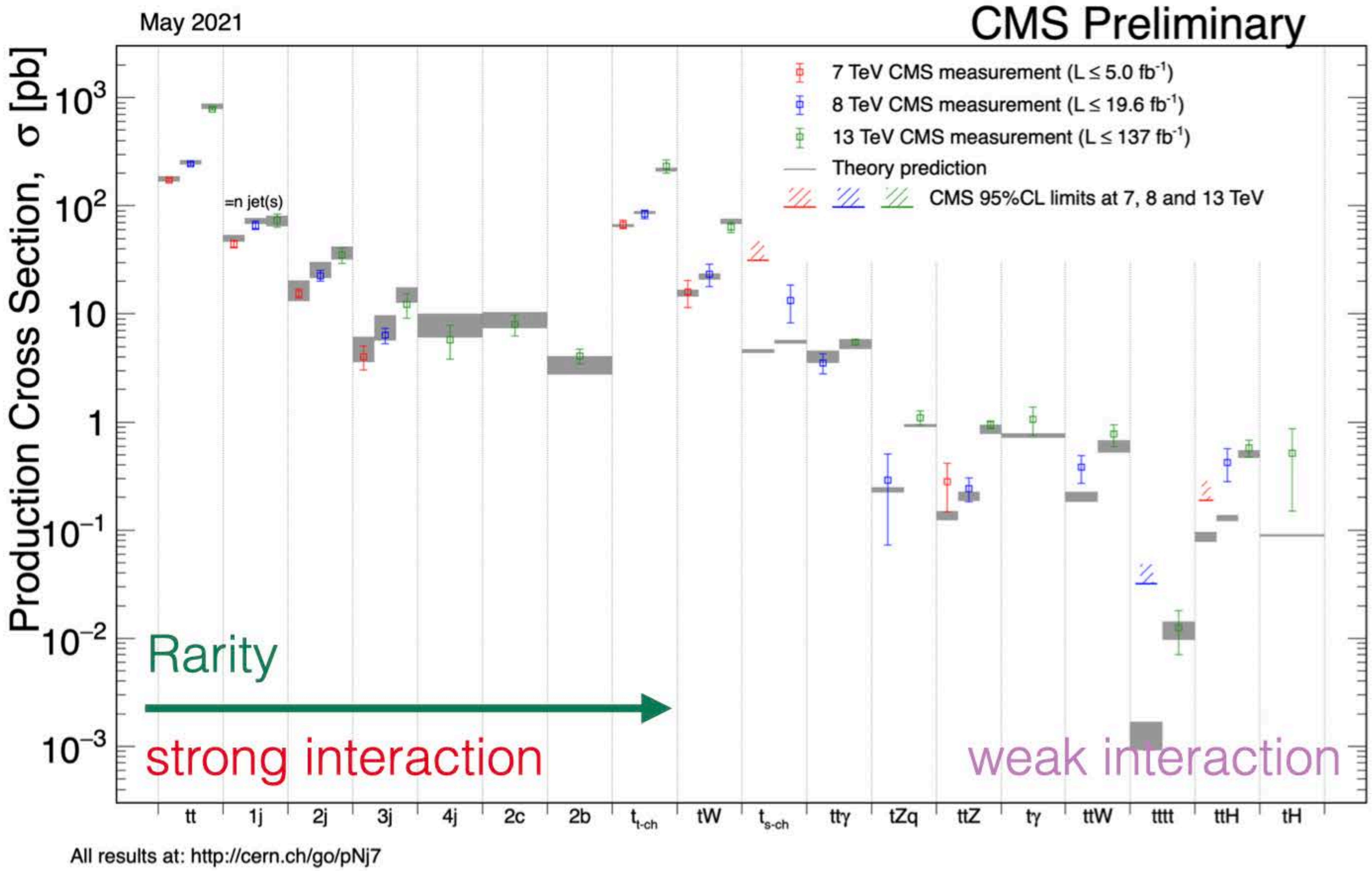

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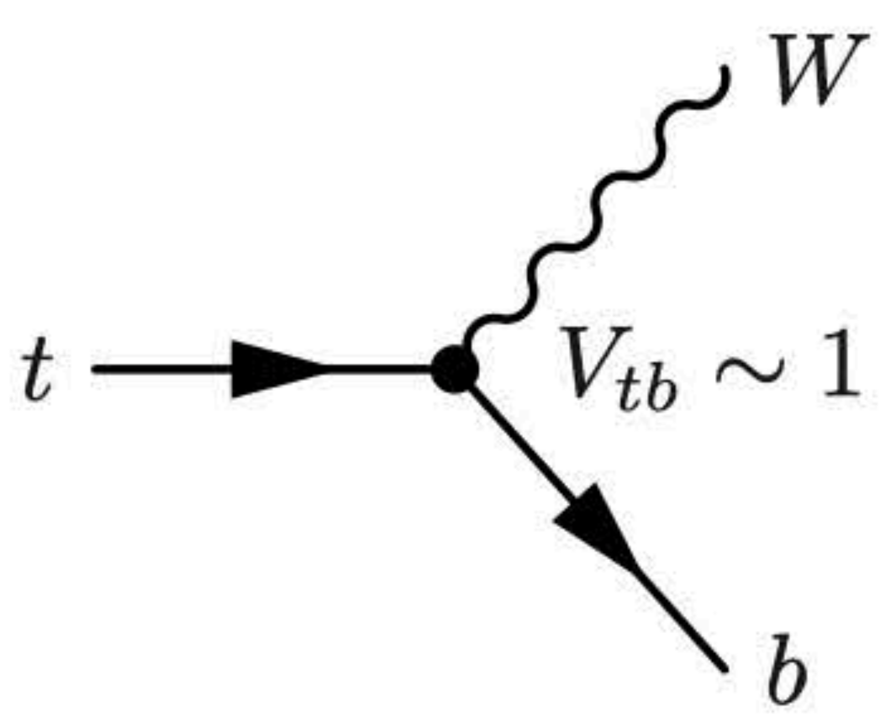
Decays before hadronising

- Spin/helicity information preserved



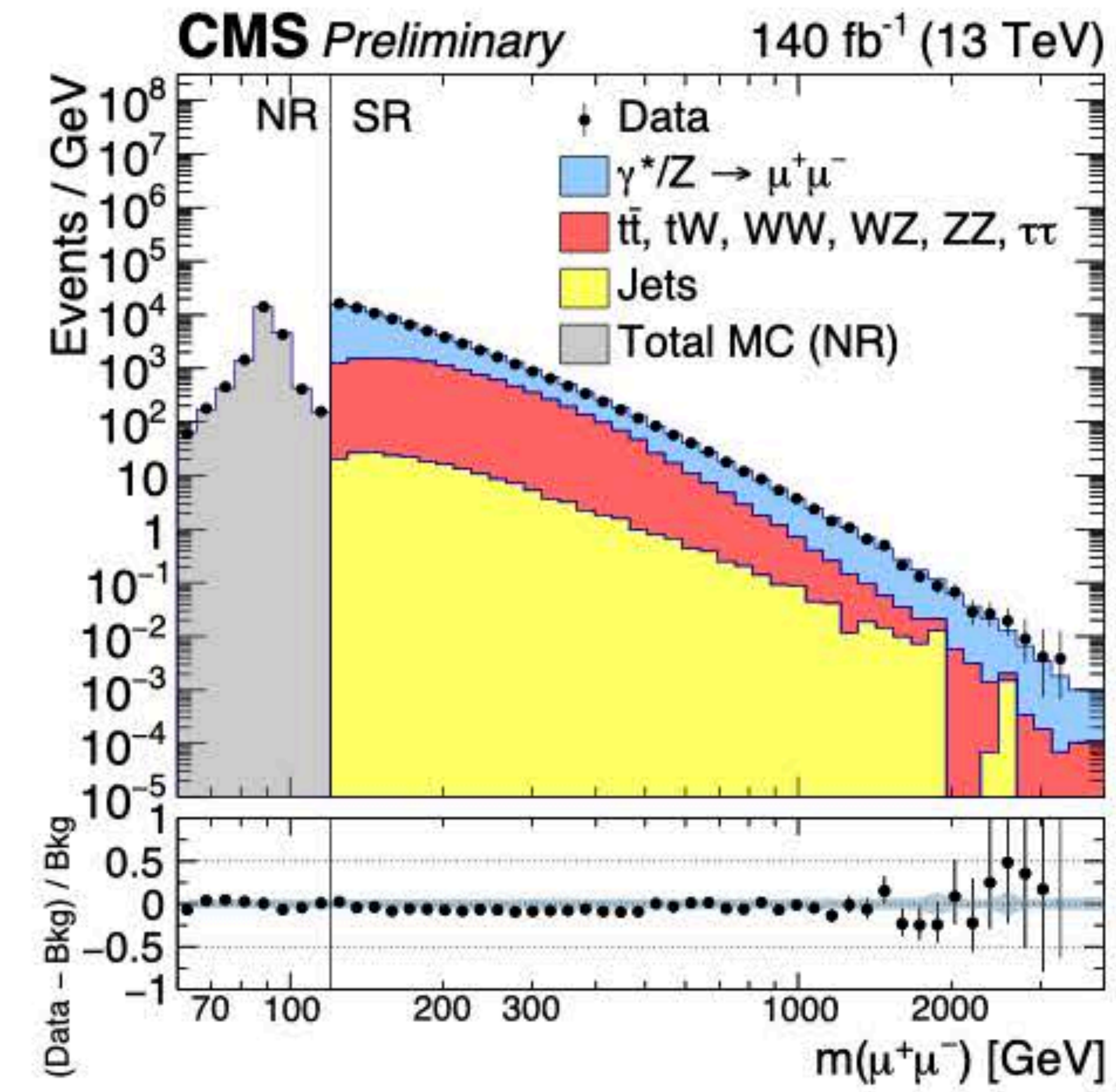
$$\frac{1}{\Gamma_t}\frac{d\Gamma_{t_\pm}}{d\cos\theta_\ell} \propto (1 \pm \cos\theta_\ell)$$

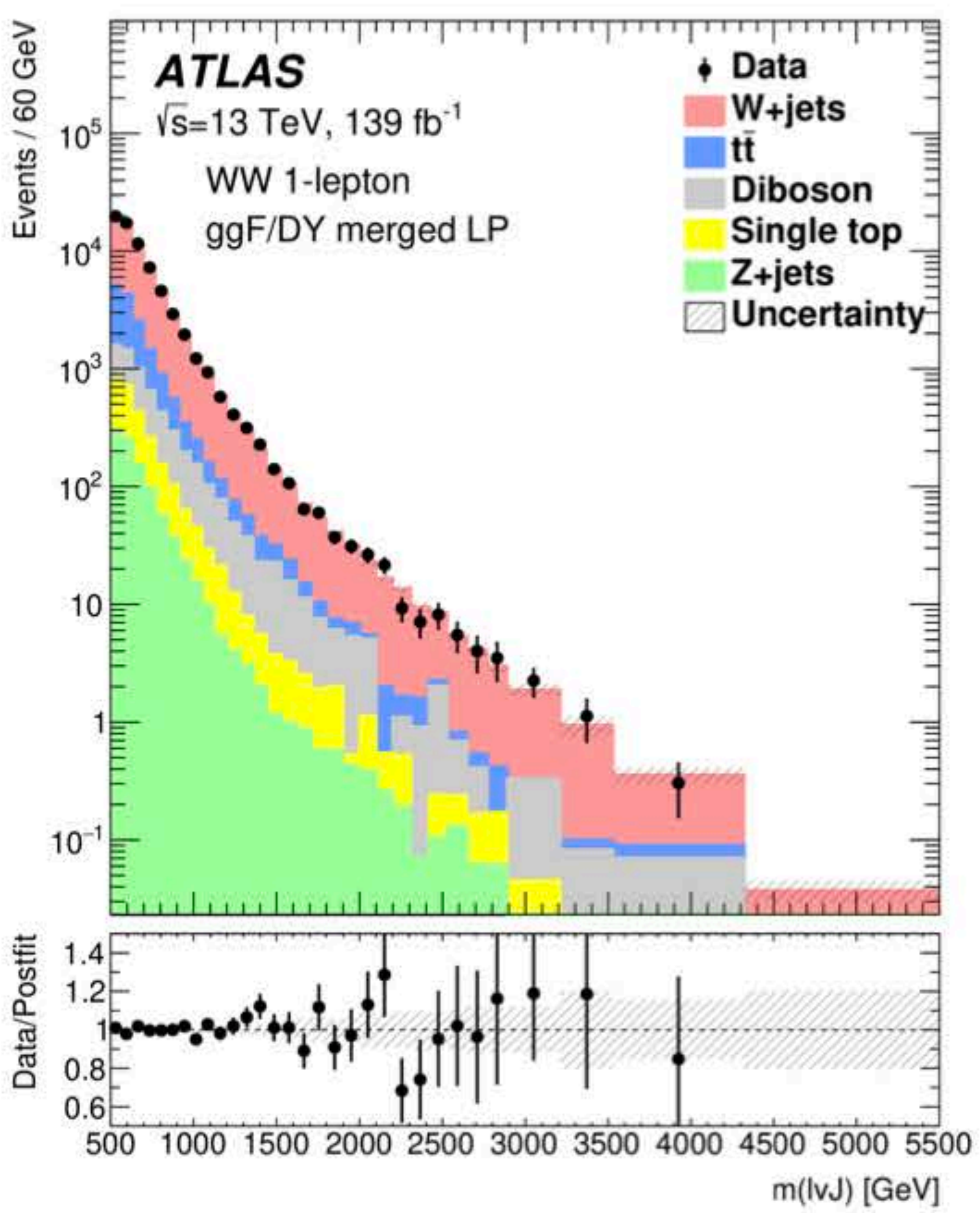
[CMS-PAS-EXO-19-019]

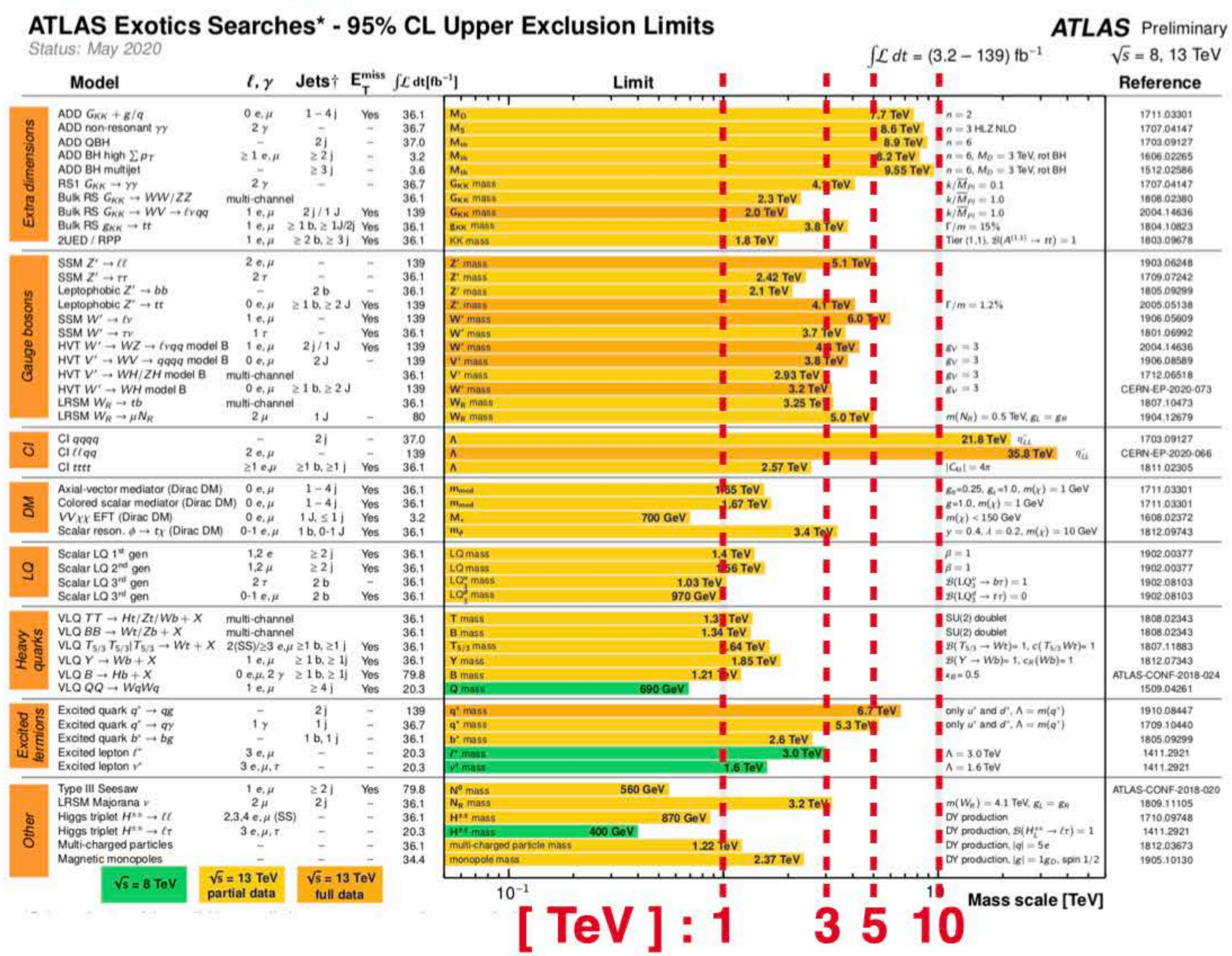
Where are we?

~10 years since the start of LHC Run 1

- No clear sign of new physics at the TeV scale
- Direct searches are saturating the energy frontier







What have we learnt?

BSM: new states are too…

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Weakly coupled

rate limited

Room for improvement
With increasing integrated luminosity

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Exotic

we aren't looking in the right place

Limited by our creativity

Work for theorists & experimentalists:
Motivate & enable searches for new signatures

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Weakly coupled *rate limited*	Room for improvement With increasing integrated luminosity
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Heavy *kinematically out of reach*	Worst-case scenario …from direct search point of view Complemented by indirect searches

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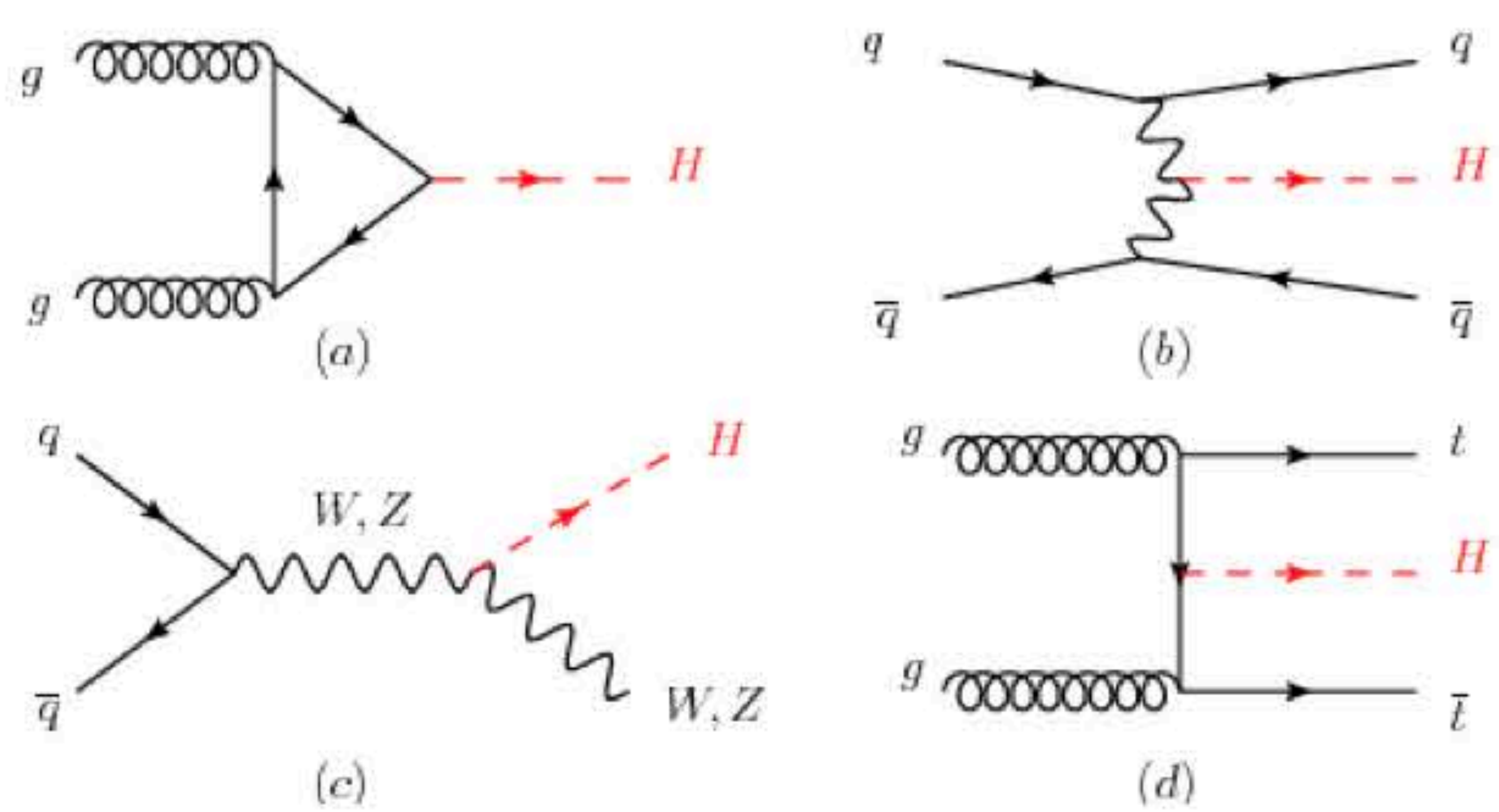
SM: a tremendous amount!

- Higgs discovery & properties ⇒ precision LHC programme

The LHC explorer

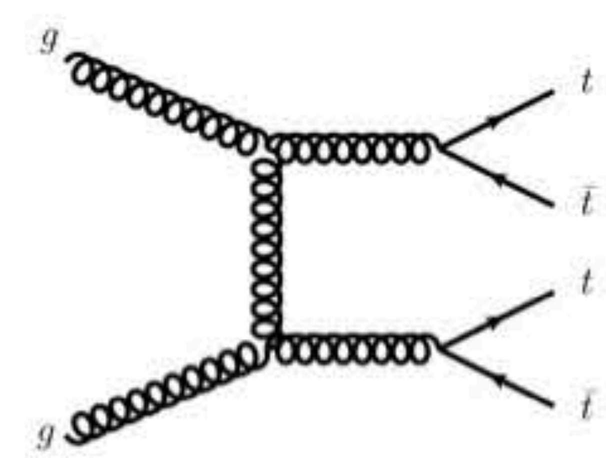
Many new processes observed at the LHC for the first time

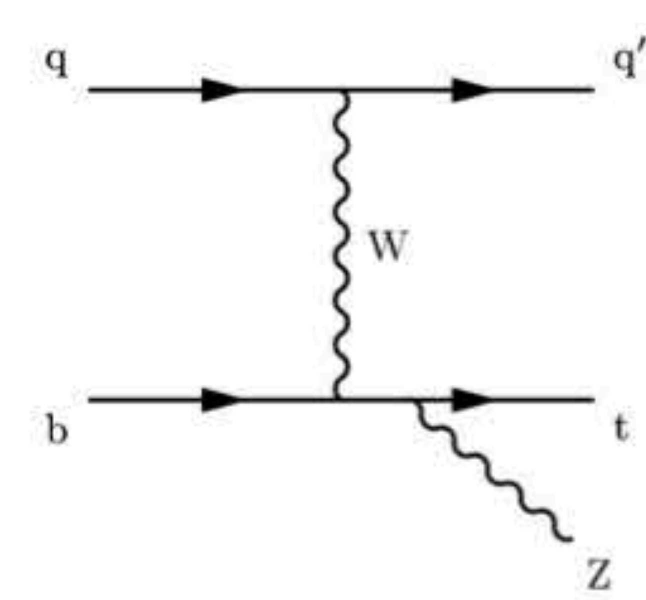
Main Higgs production modes



ggF, VH, VBF, ttH

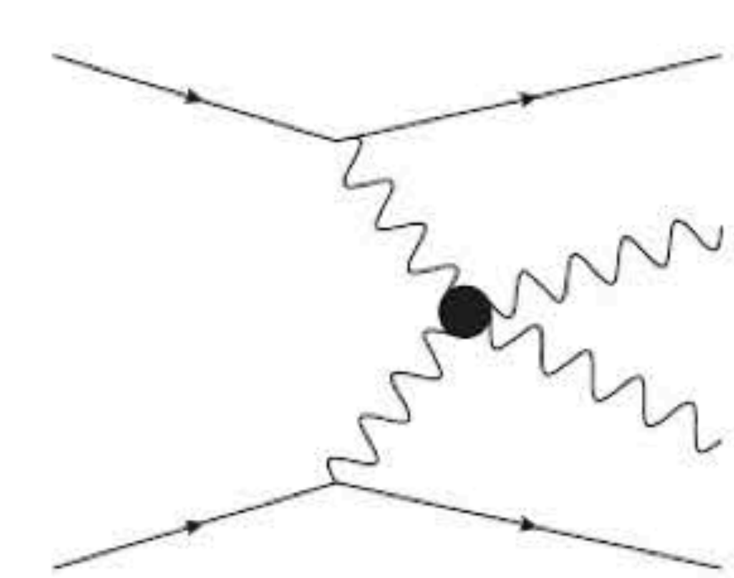
Rare top production

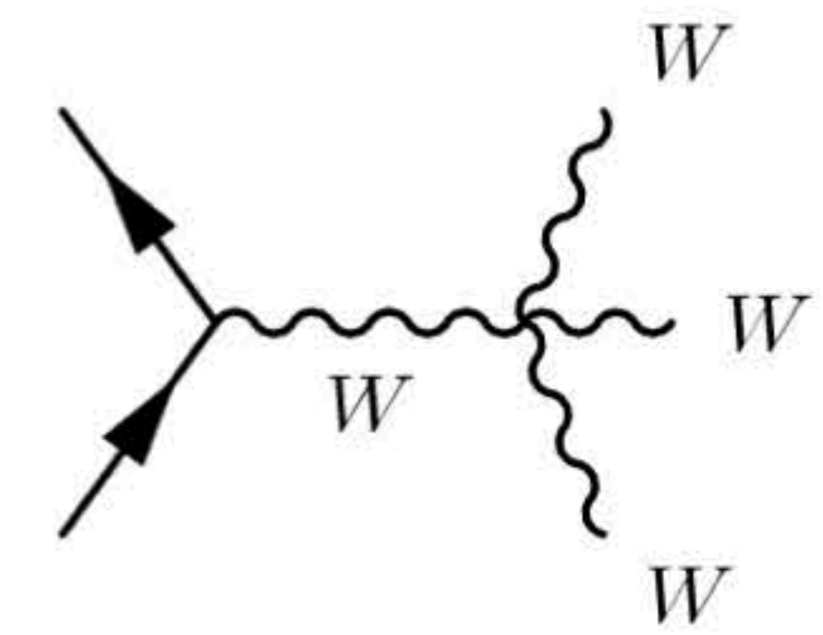




tttt, ttbb *ttV, tW, tZ*

Weak boson scattering





VBS, VVV

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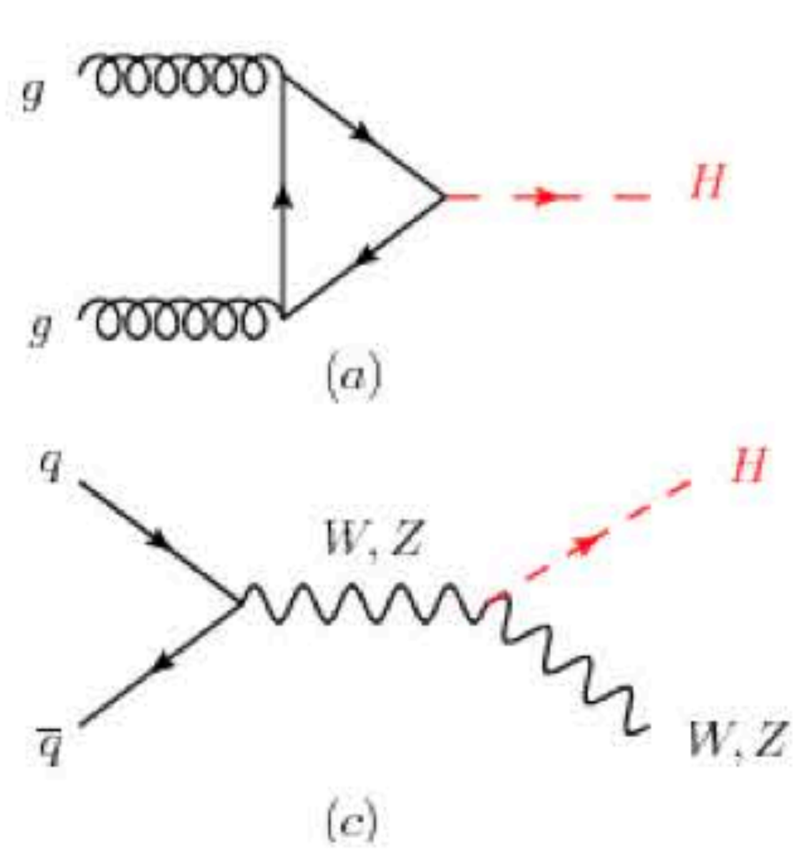

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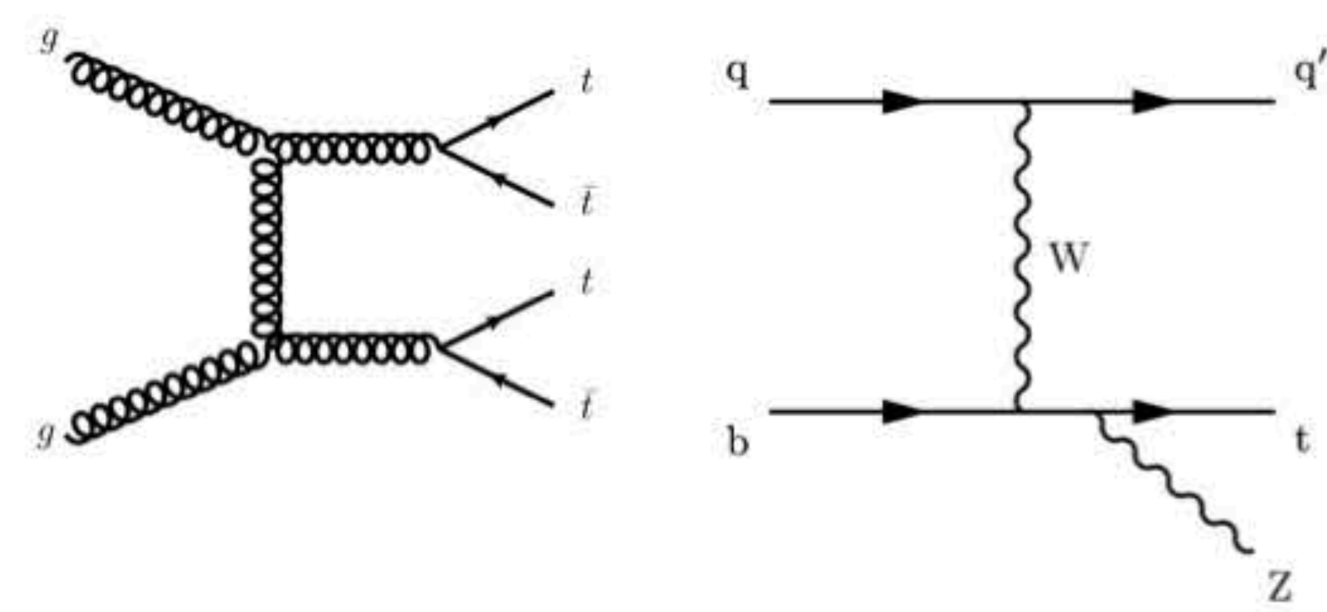

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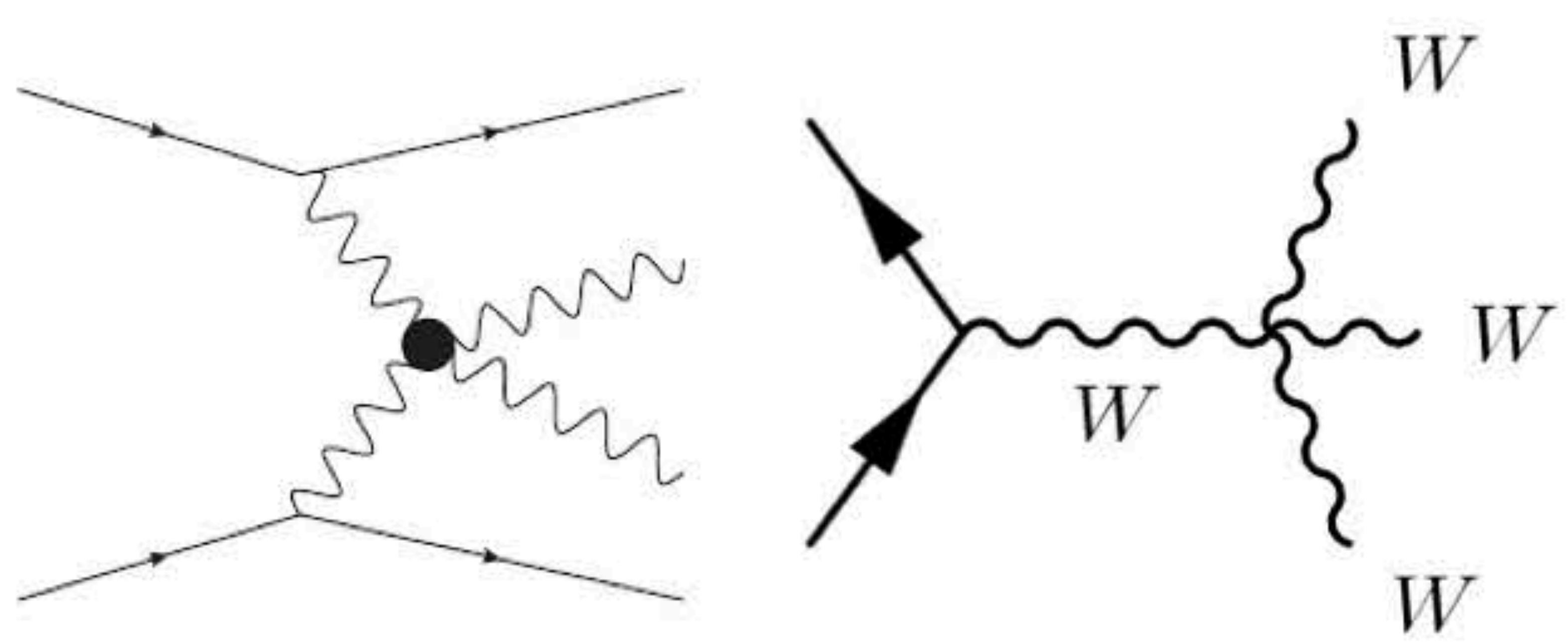


VBS, VVV

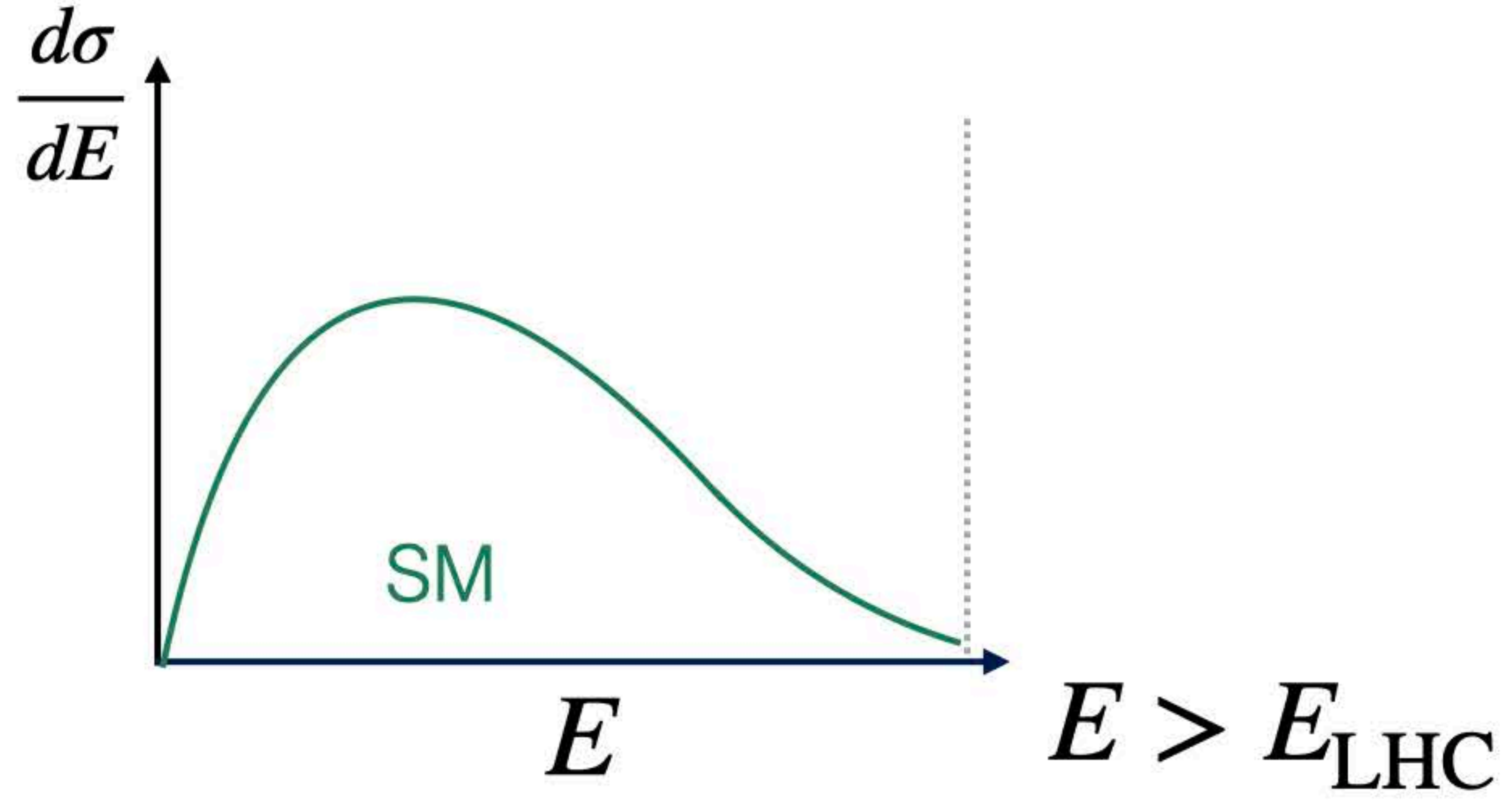
Each opens a new window, through which we can

Improve our understanding of the SM

- Search for new physics via new interactions

Energy & precision

Paradigm shift at the energy frontier for BSM searches



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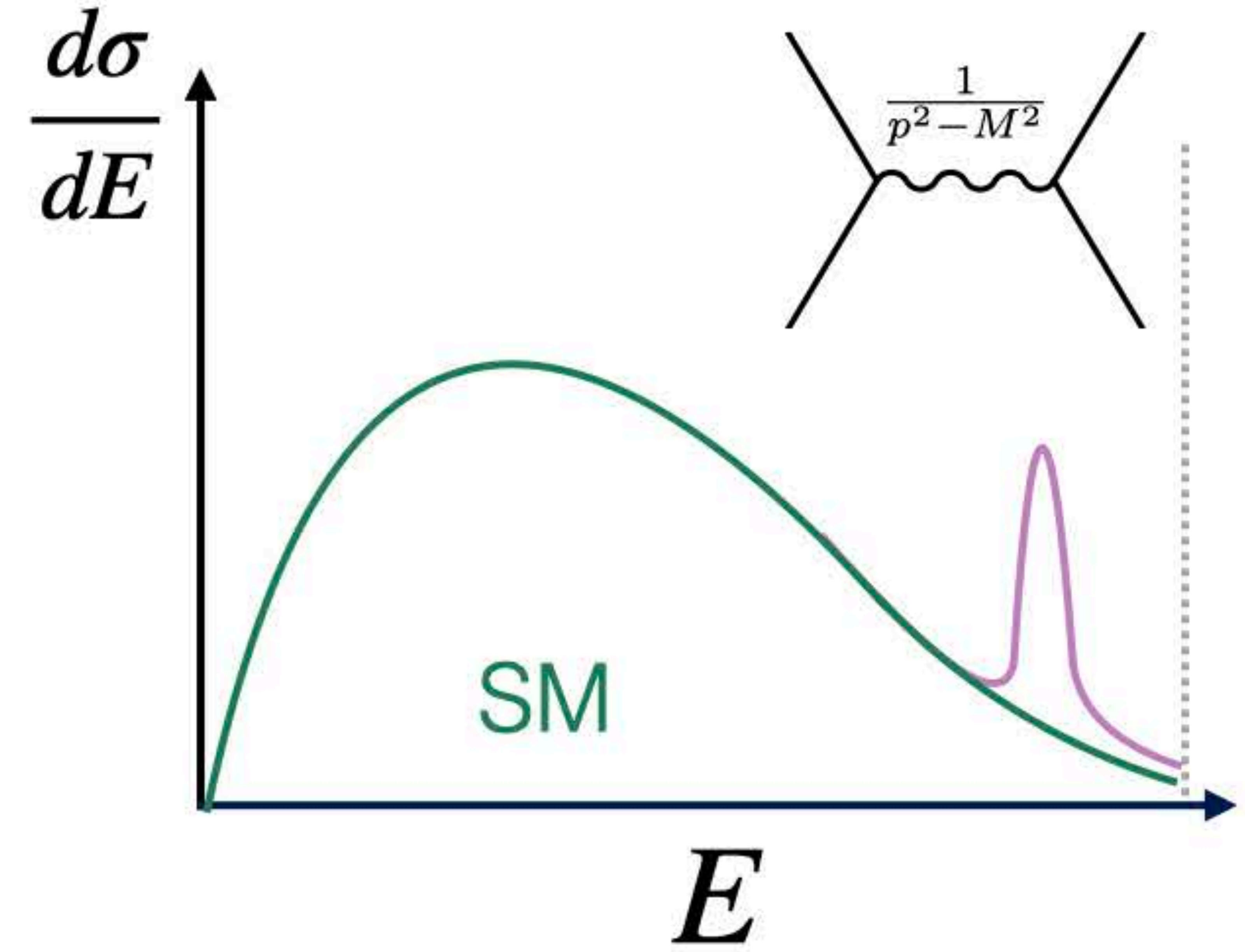
Direct (bumps)



$E > E_{\text{LHC}}$

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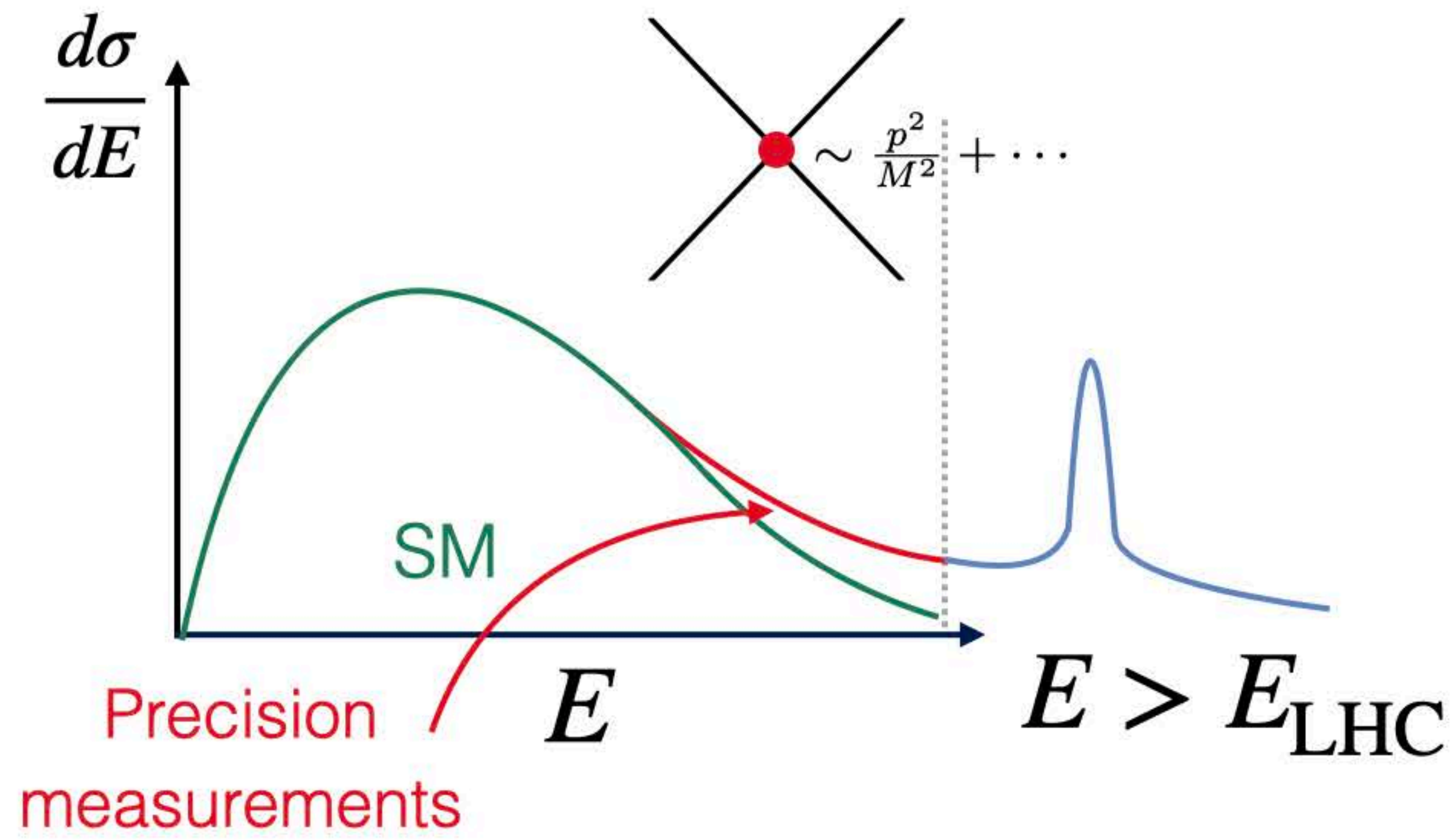
Direct (bumps)

Indirect (tails)

⇒ New physics is heavy



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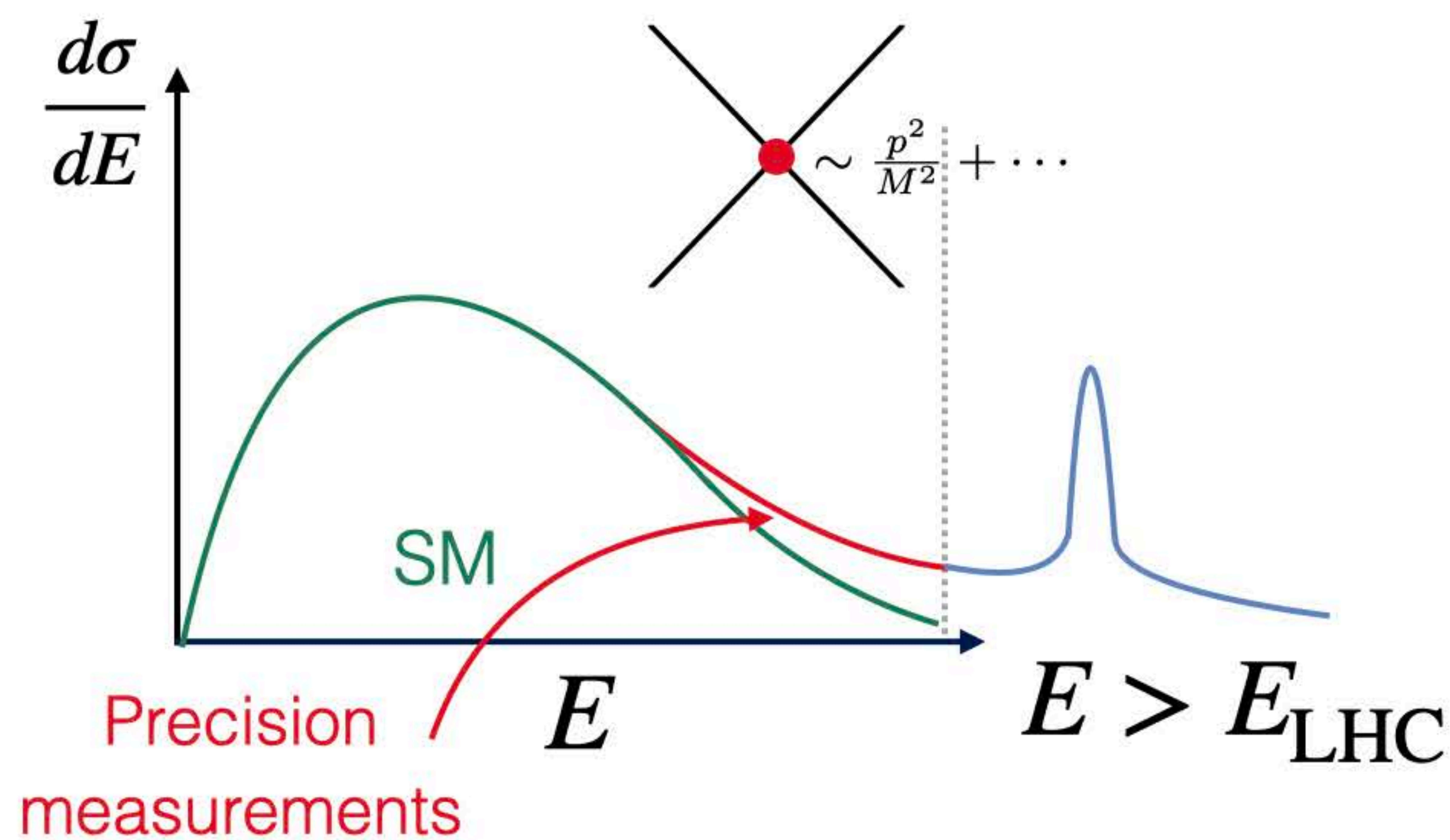

Heavy new physics
Precision measurements
High energy

→ **Effective Field Theory (EFT)**

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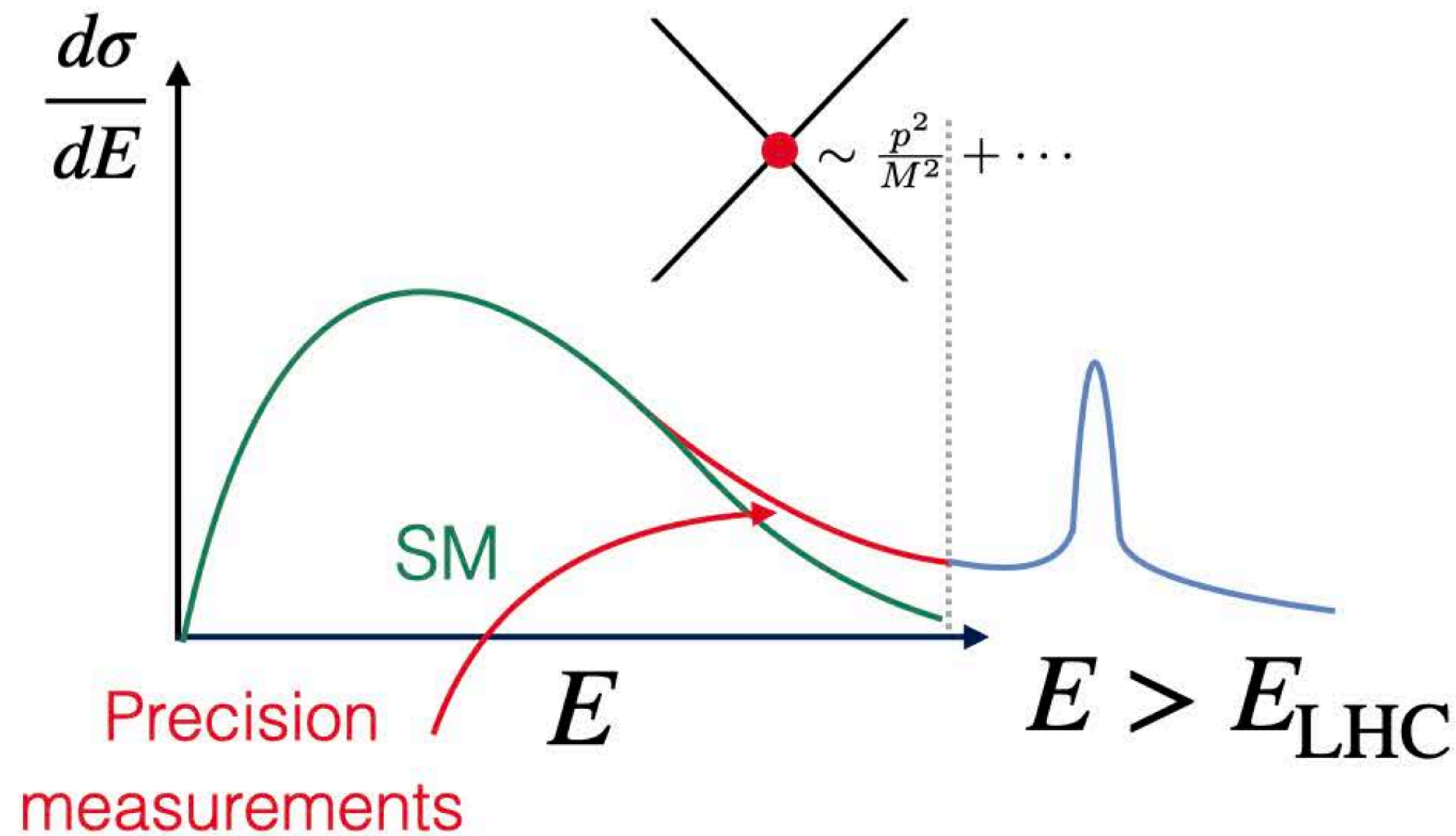

Heavy new physics
Precision measurements
High energy

→ **Effective Field Theory (EFT)**

$$\mathcal{A}^n_{\mathrm{BSM}}(E, M) \sim E^{4-n}\left(a_0 + a_1\frac{E}{M} + a_2\frac{E^2}{M^2} + \cdots\right), \quad E \ll M$$

SMEFT: SM v2.0

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

SM = low energy effective description

- New physics = tower of irrelevant (D>4) operators
- Respecting low energy field content & symmetries

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

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

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λ_h	$H^6 : (\varphi^\dagger\varphi)^3$	$H^4D^2 : (\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$	δM_Z
y_f	$\psi^2H^3 : (\varphi^\dagger\varphi)^2(\bar{q}_i\, u_j\, \tilde{\varphi})$	$\psi^2XH : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi})B_{\mu\nu}$	'dipole'
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More than 'just' a parametrisation of ignorance

- Unlike anomalous couplings
- Finite energy range ($\sim\Lambda$)
- Renormalisable QFT (order-by-order)
- Well defined matching procedure

SMEFT is…

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

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$

SM field content & gauge symmetries

Linear EWSB: Higgs = doublet

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Systematically improvable

- Double expansion *higher dim.* $\frac{E^2}{\Lambda^2}$ & $\{g_S,\, g,\, g'\}$ *more loops*

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- **Model independence:** we don't know what operators NP will generate
- Patterns & correlations among observables are key

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EWPO, Higgs, multiboson, top, DY, flavor,…

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$\mathscr{L}(c_i) \Rightarrow$ **indirectly constrain many UV models**

SMEFT interpretation

$\boldsymbol{o_n}$
observables

$$\Delta o_n = o_n^{\rm EXP} - o_n^{\rm SM} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

SMEFT interpretation

Improving new physics reach means improving…

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As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

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Sensitivity
Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

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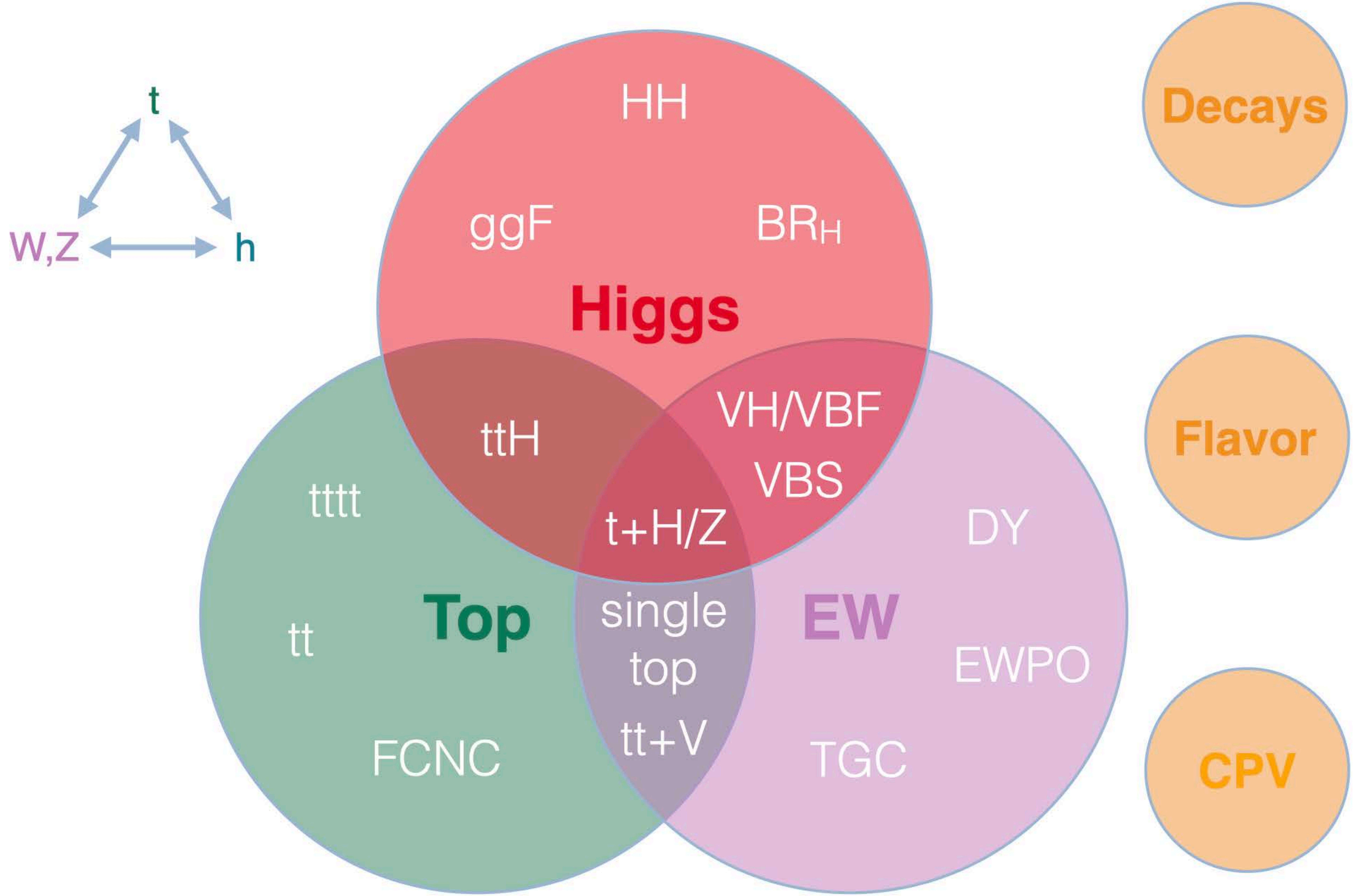
Interpretation
Relies on accurate knowledge of the size & correlation among a_i

Determining $c_i^{(6)}$ requires most precise available SMEFT predictions ⇒ **NLO**

The wealth of data



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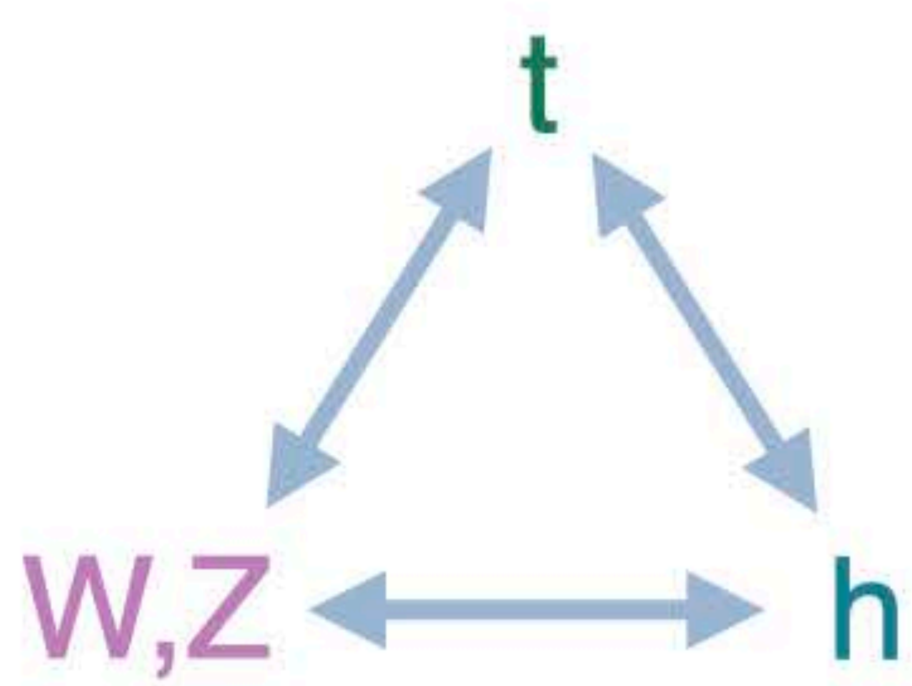
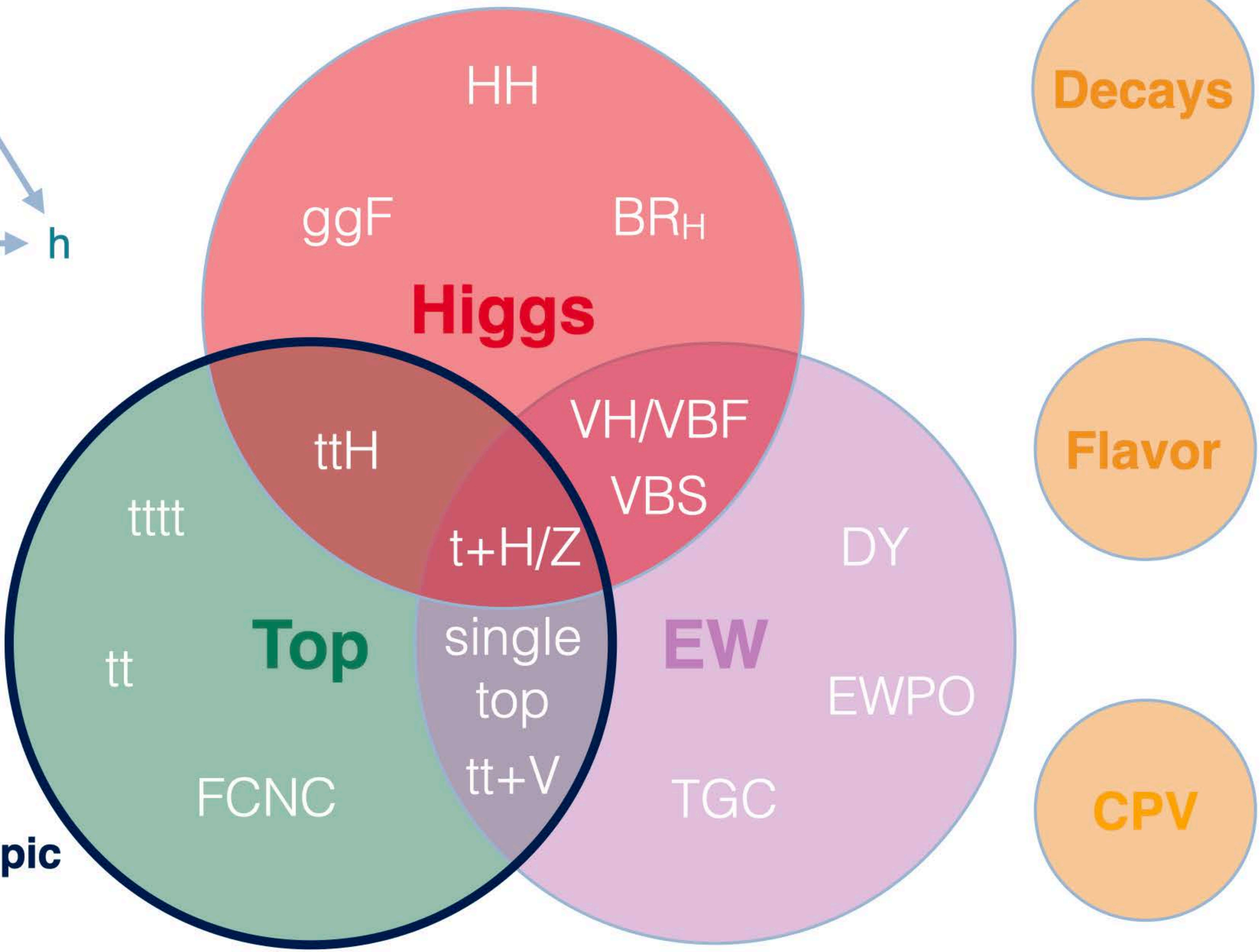


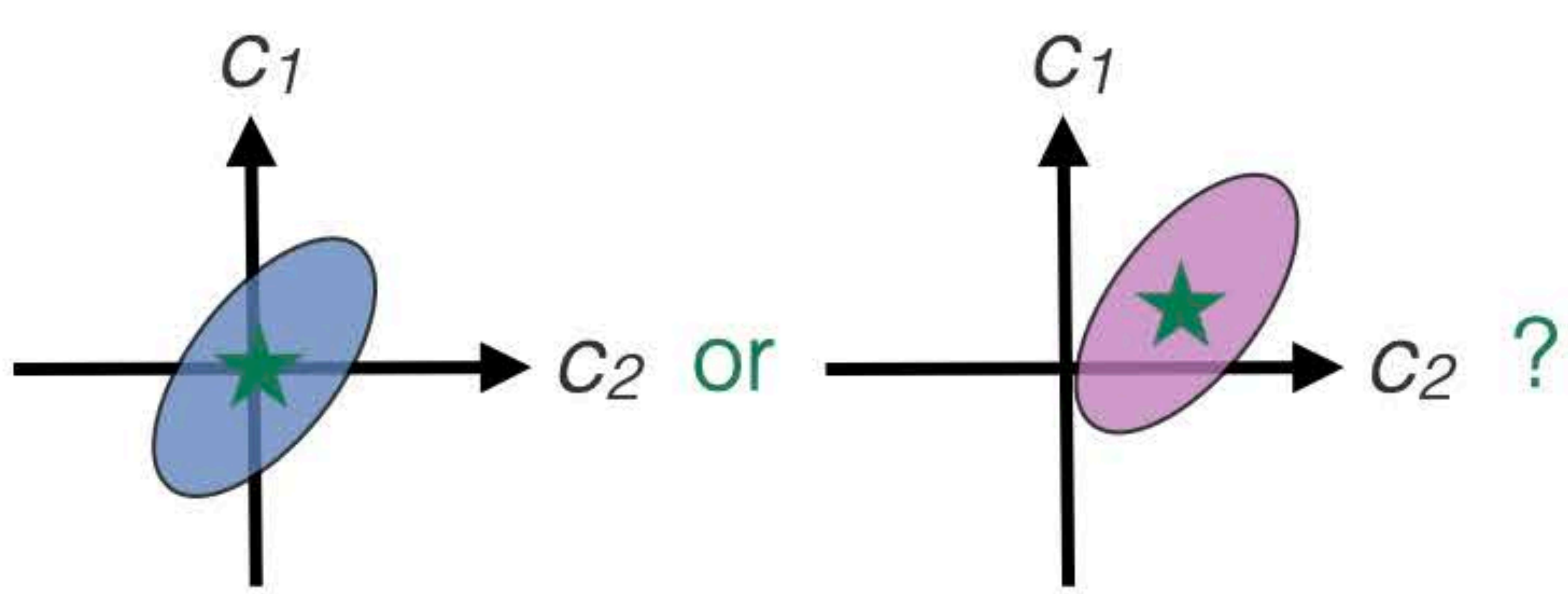


Today's topic

The importance of top data

Likelihood ⇔ Fit to the Wilson coefficients

- Search for deviations from the SM: $\dfrac{C_i}{\Lambda^2} = 0$
- Find hints for heavy new physics
- LHC top data has a vital role in this programme



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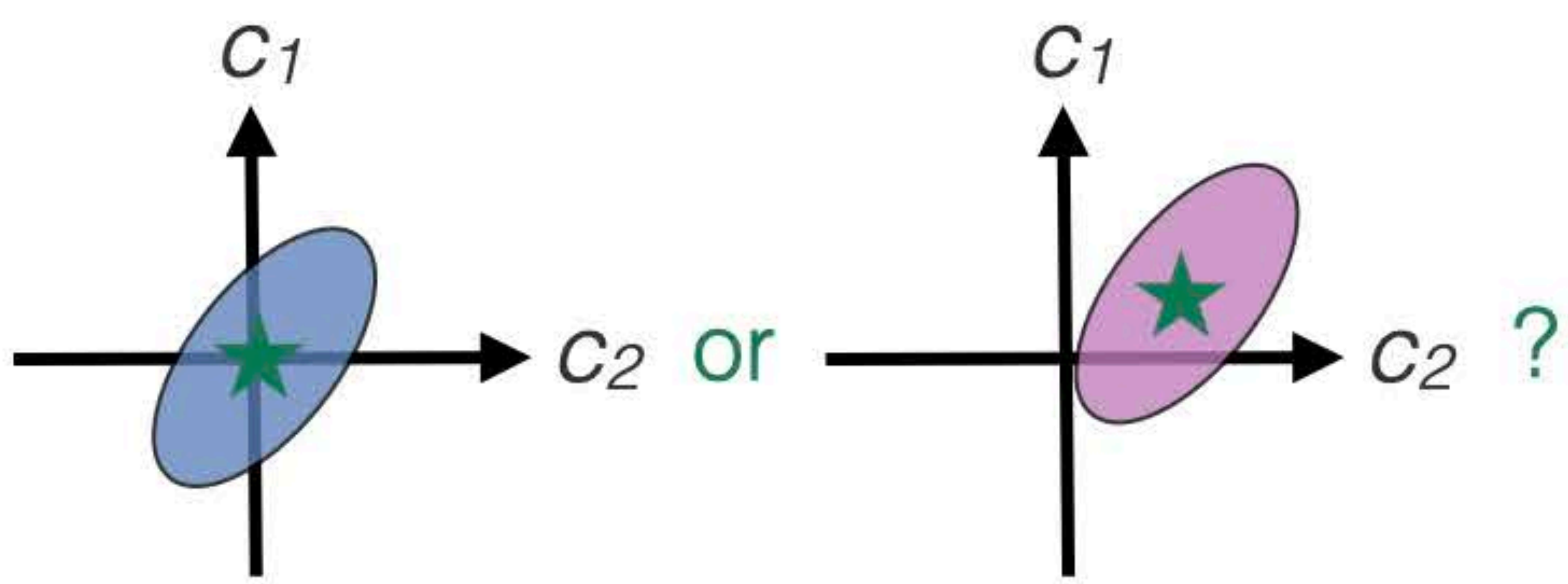
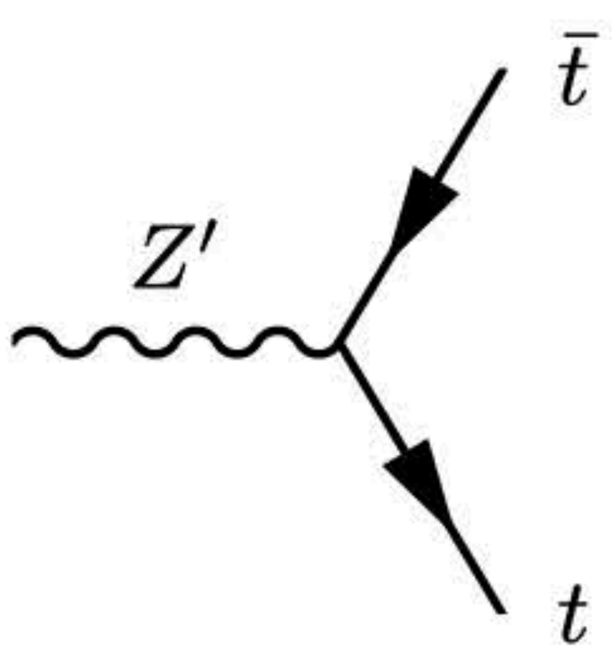


By itself: individual bounds; top data alone

- Determine top quark properties/interactions
- Probe heavy new physics that couples preferentially to tops



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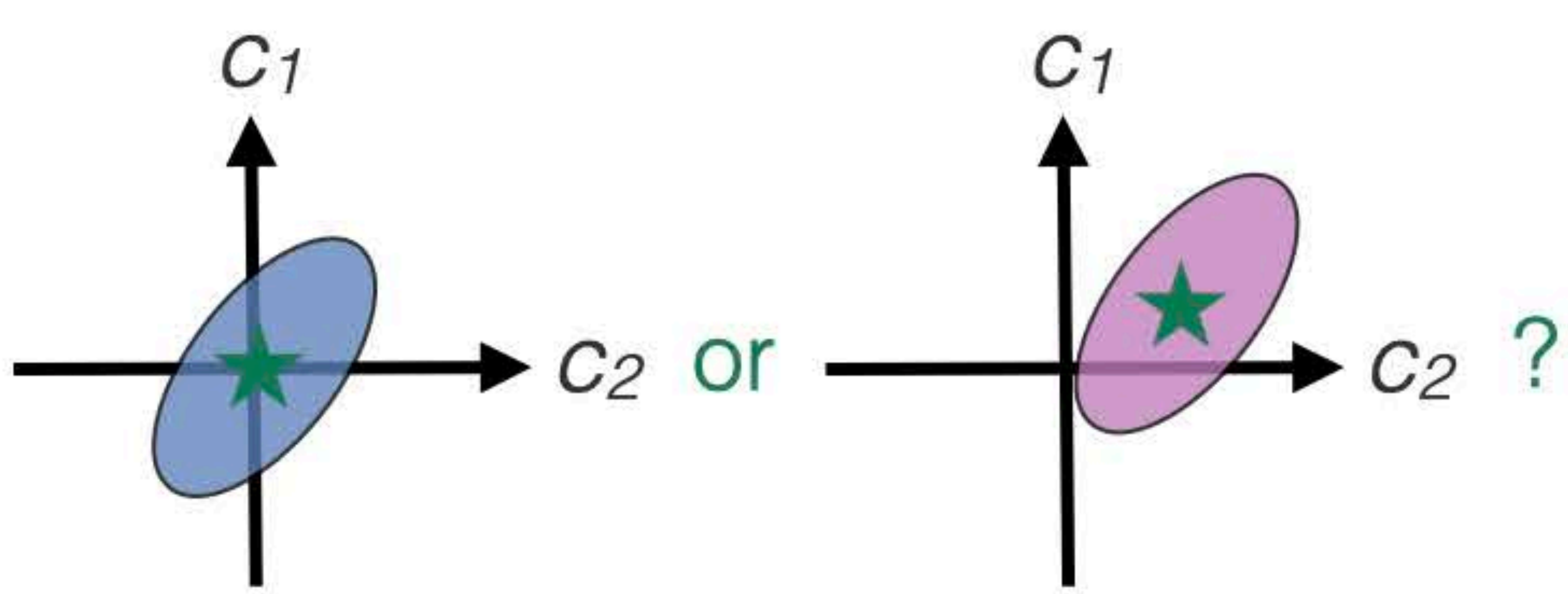

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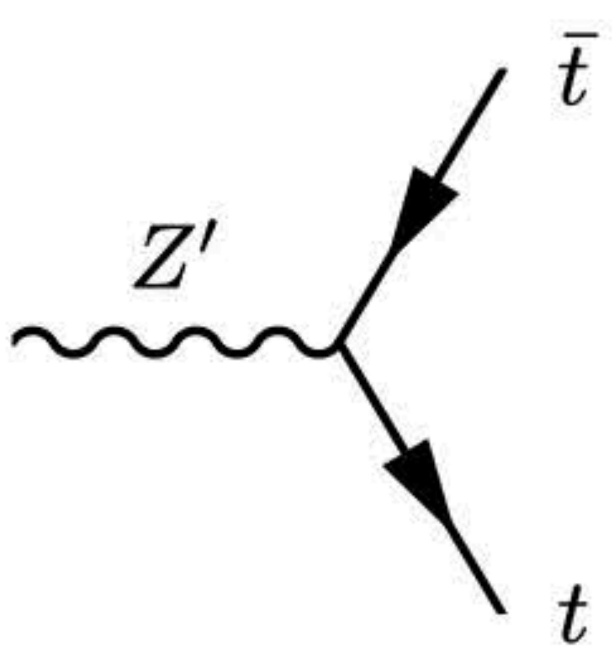
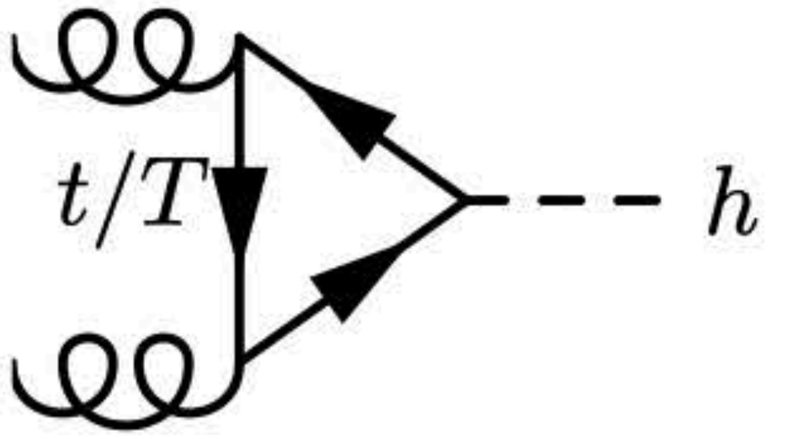


Globally: marginalised; top, Higgs, diboson, LEP, … data

- Influence determination of other couplings in EW sector,…
- Probe more realistic models connected to the EWSB puzzle



Top operator glossary

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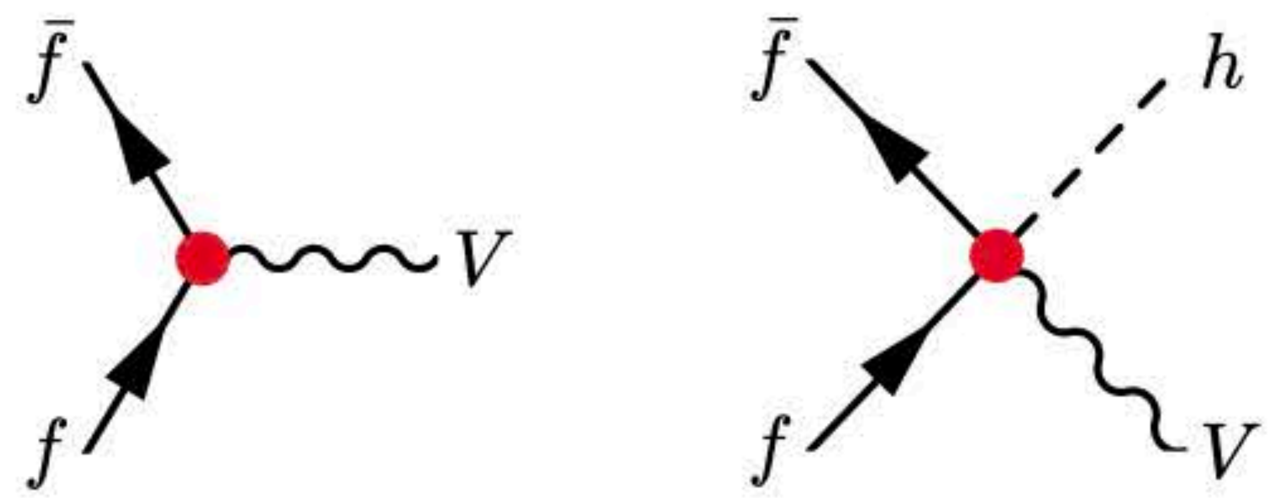
currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

Top operator glossary

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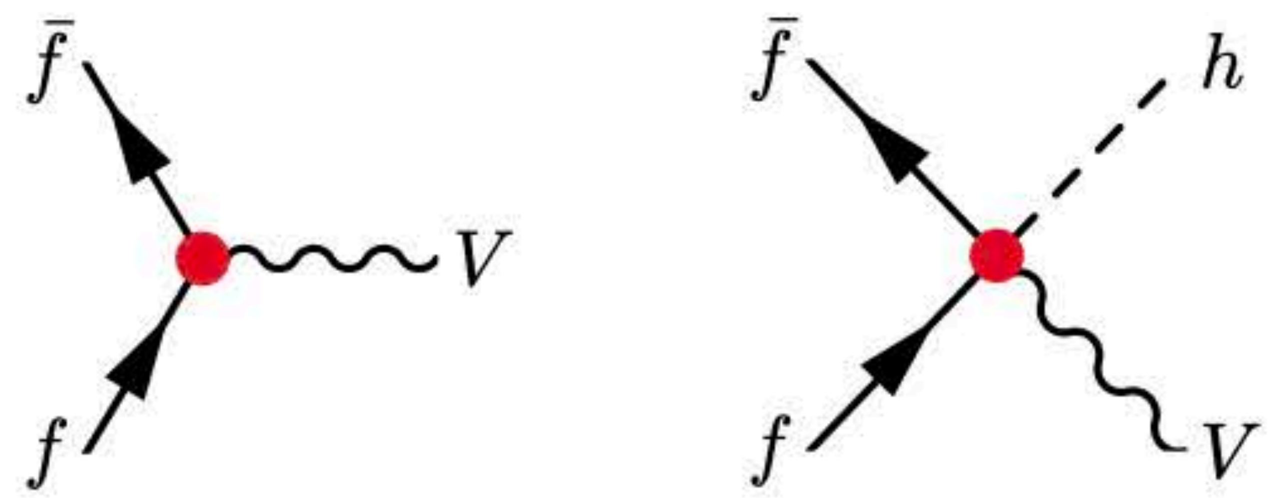
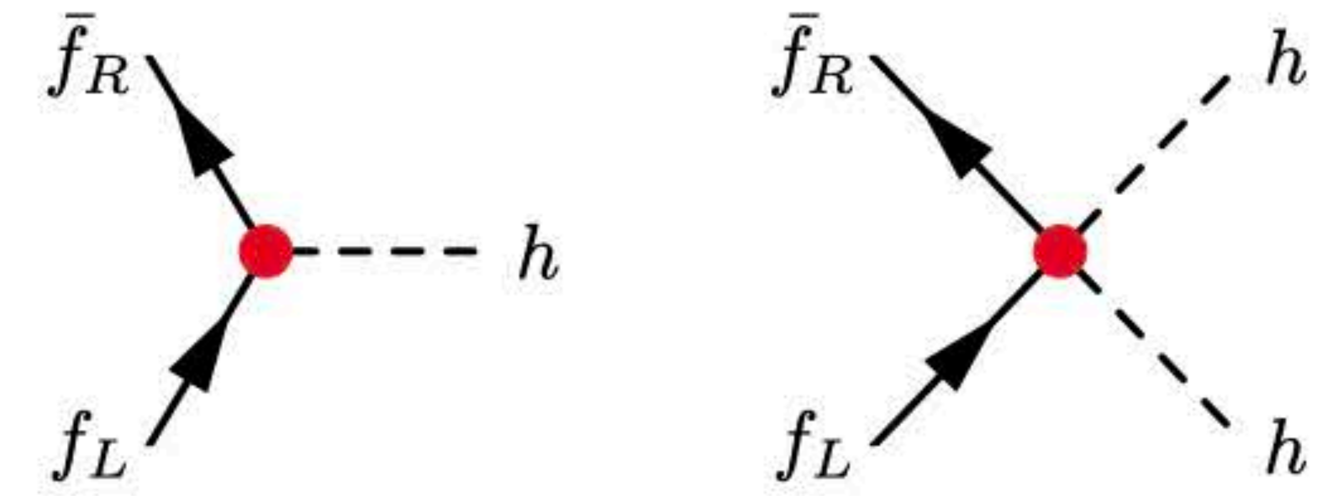


$C_{\phi f}$

- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

Yukawa $(\bar{q}\, t\, \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

- Decouple m_t & y_t
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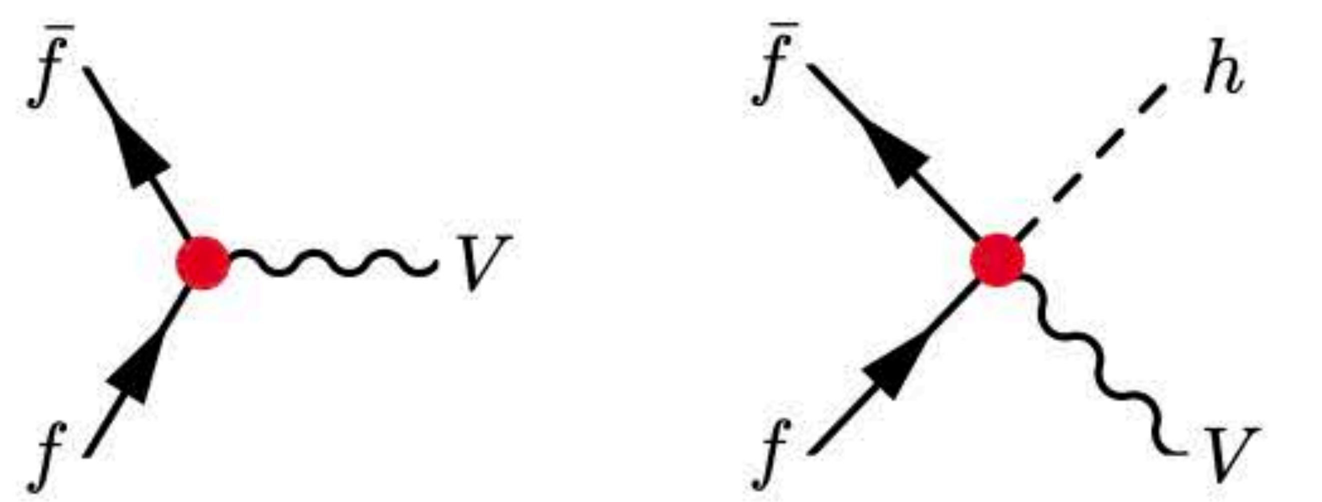

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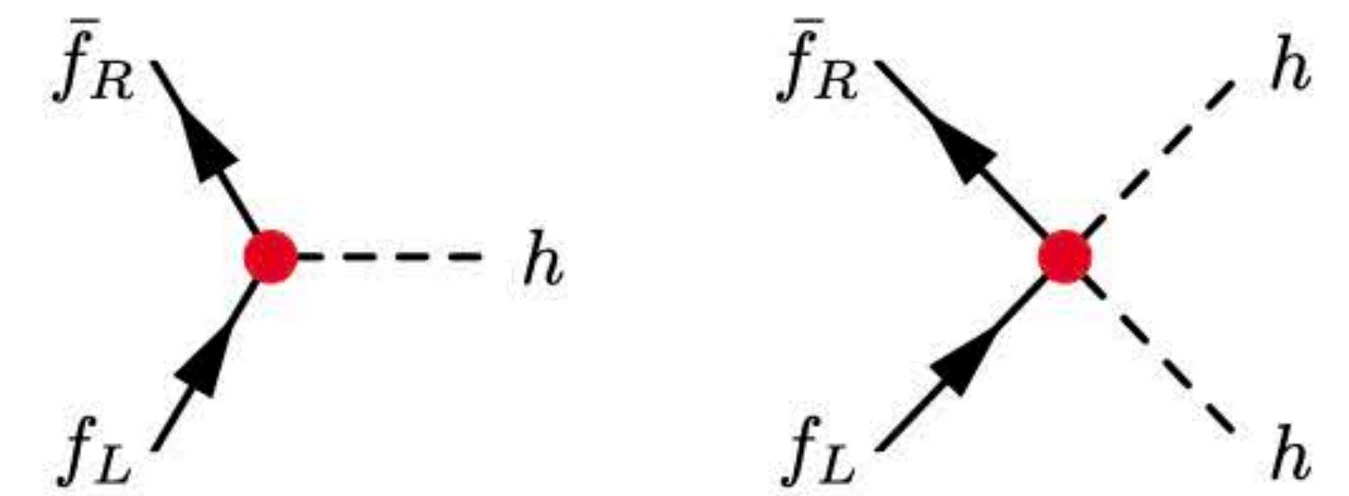

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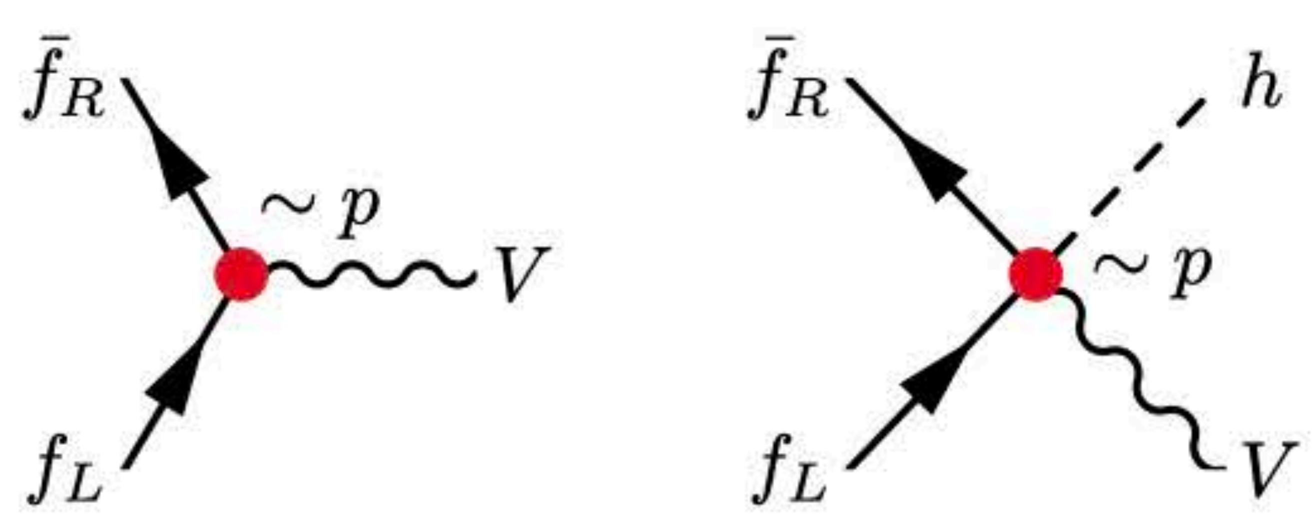
dipole $(\bar{q}\, \sigma_{\mu\nu}\, t\, \tilde{\varphi})V^{\mu\nu}$



C_{tV}

- Chirality flipping $f\bar{f}V$ couplings
- $f\bar{f}V(V)h$ contact interactions
- W, B & G fields

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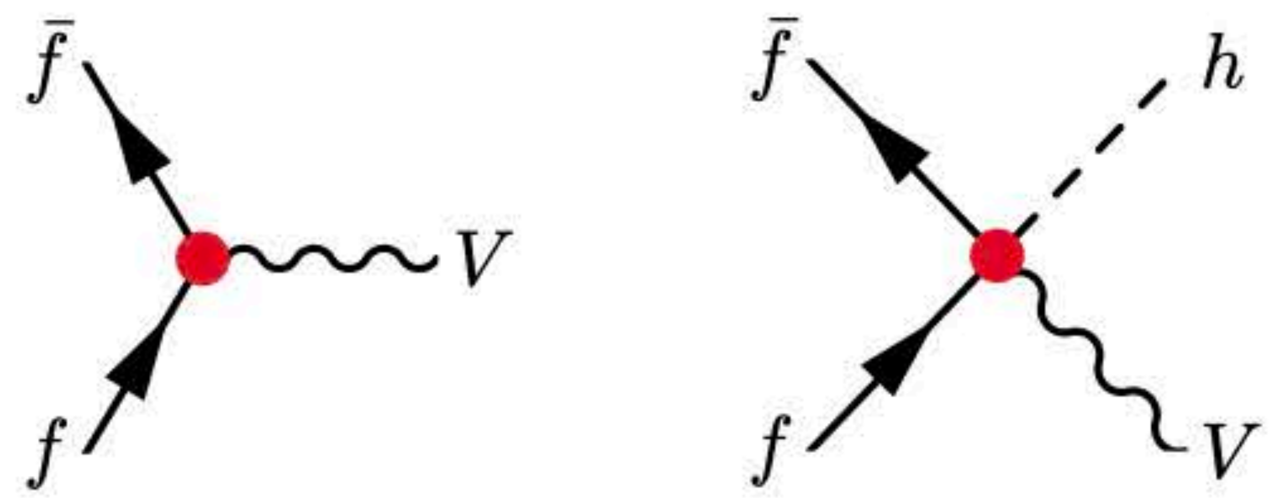

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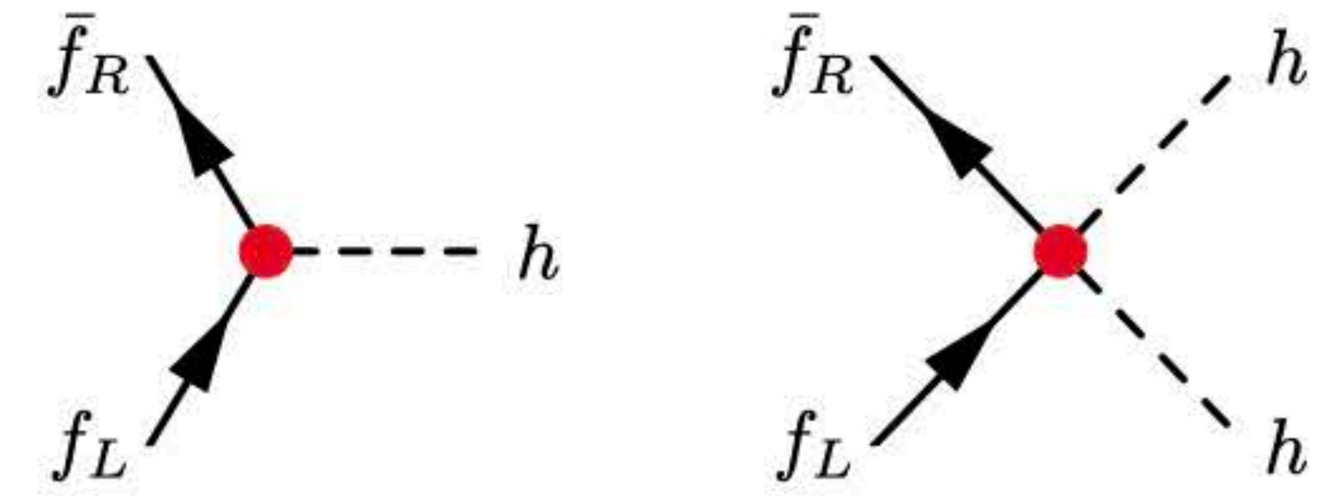

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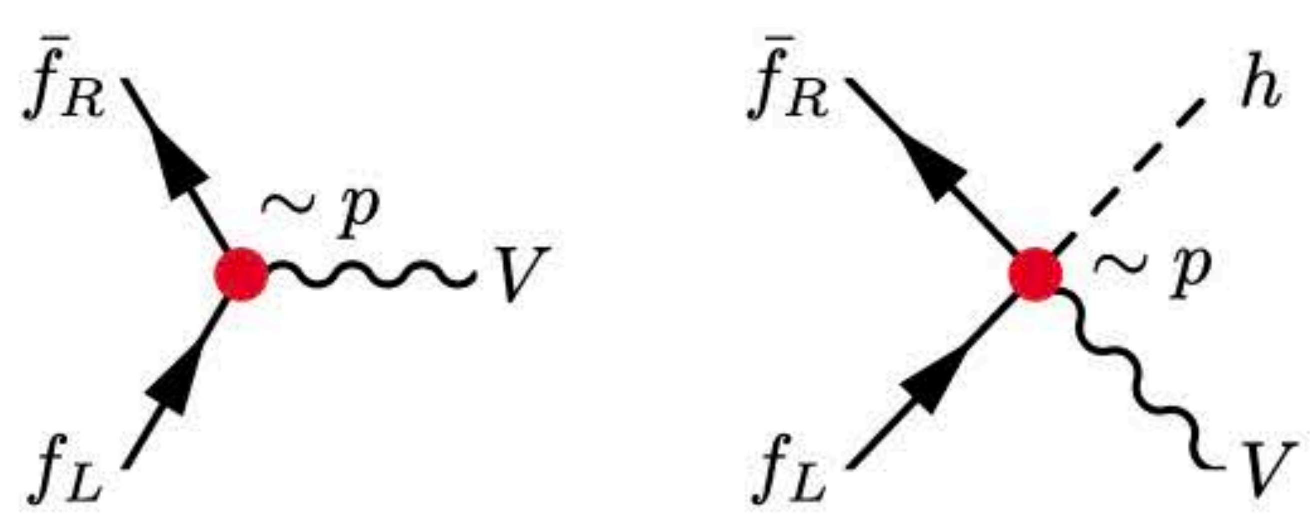

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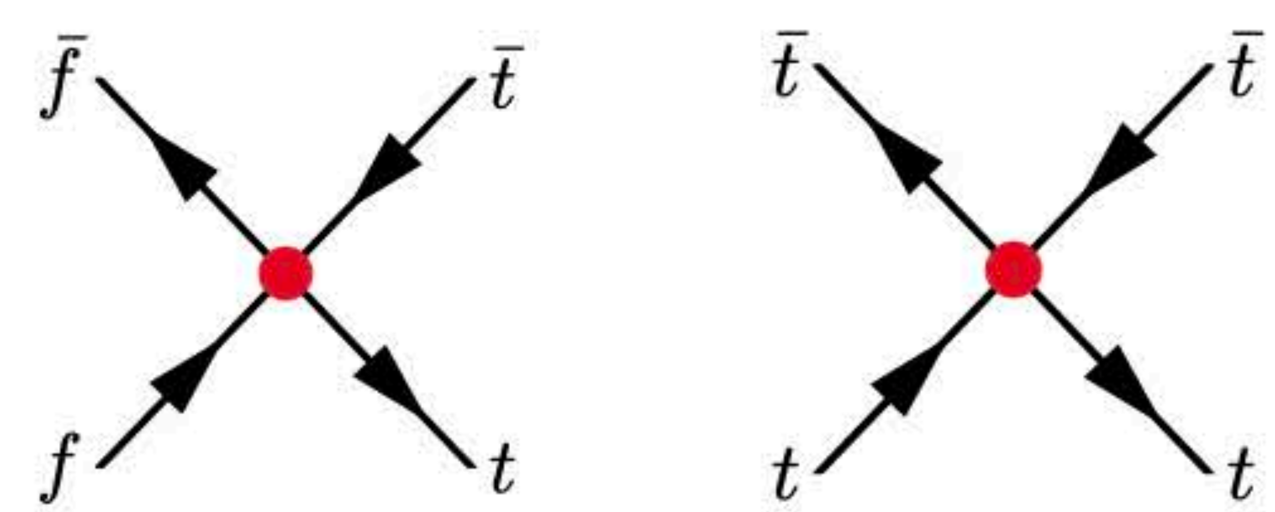

C_{ft}

- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous (~O(20) w/ top)

Fits: status & developments

Many SMEFT interpretations in experimental analyses

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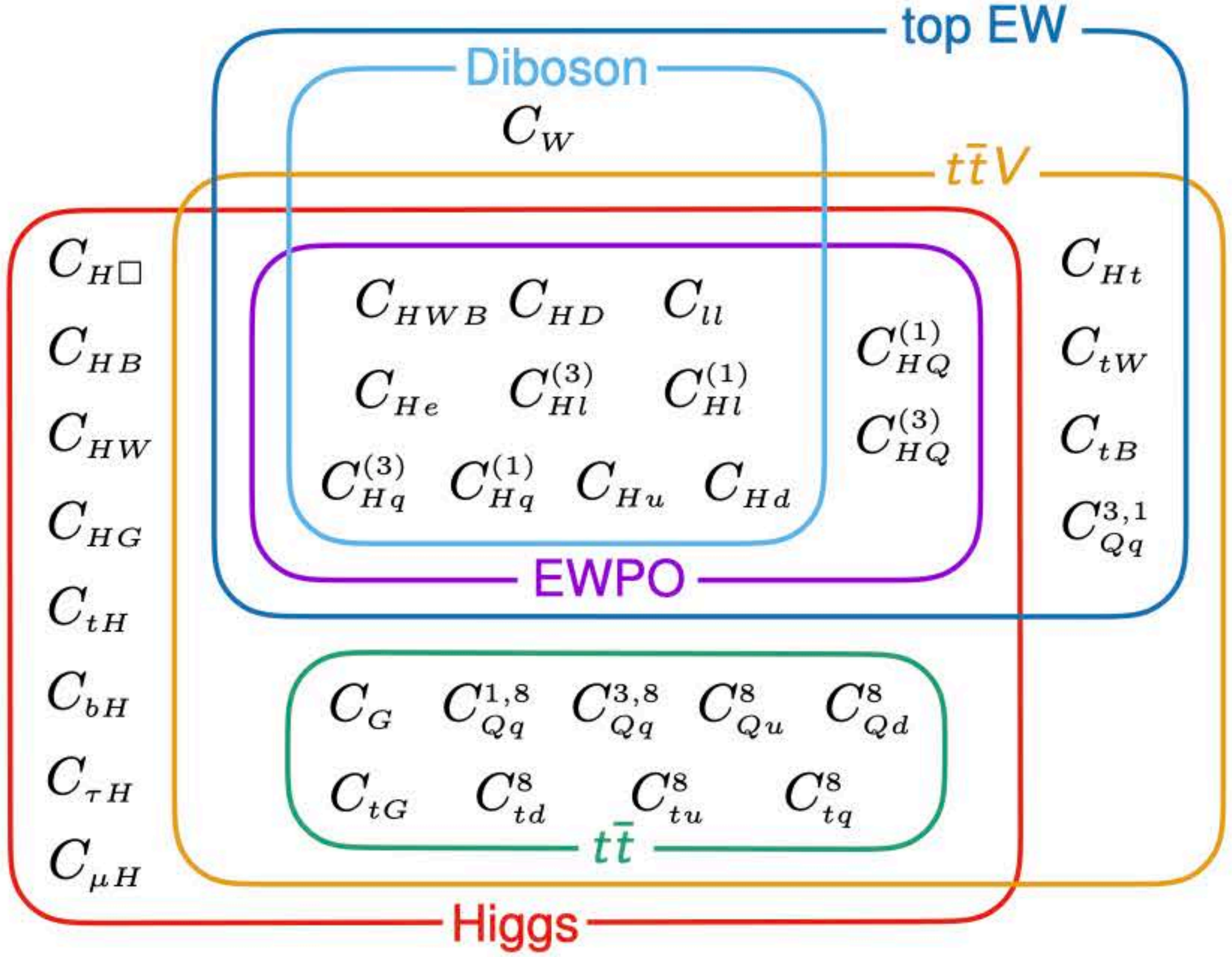
Many SMEFT interpretations in experimental analyses

Global interpretations

- **Size:** 100s of data points & 10s of operators
- **Precision:** Inclusion of NLO QCD corrections & loop sensitivity
- **Breadth:** First combinations of top, Higgs & EW precision data

[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]



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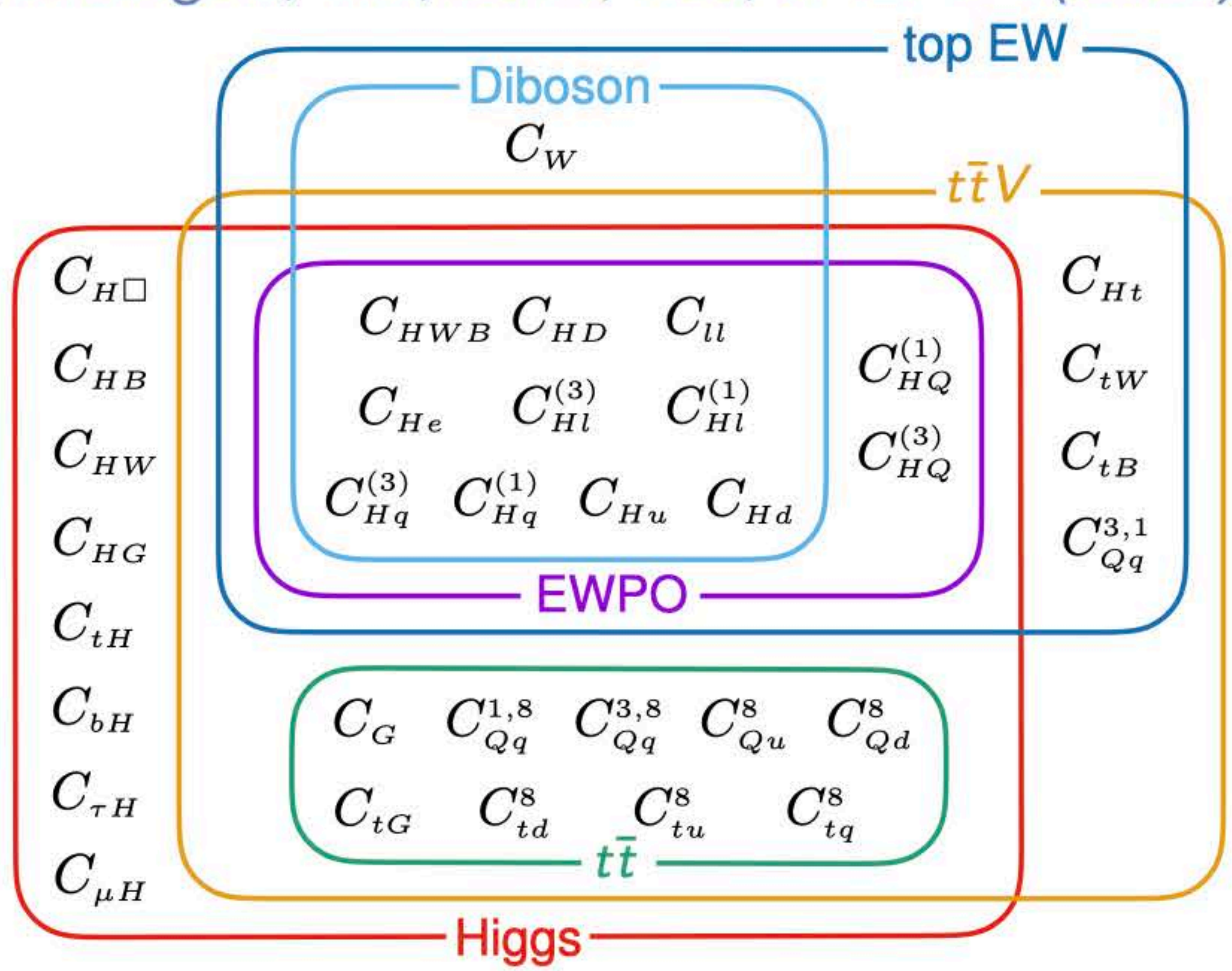

Take home message

- Top sector probed around TeV scale
- NLO effects can be significant
- EW top couplings weakly constrained
- EFT validity should be studied

Status in a nutshell

Global new physics searches via high precision/energy

- Z & W-pole data: handle on the EW gauge sector *[Han & Skiba; PRD 71 (2005) 075009]* *[Falkowski & Riva; JHEP 02 (2015) 039]*
- LHC: thriving Higgs & top programmes
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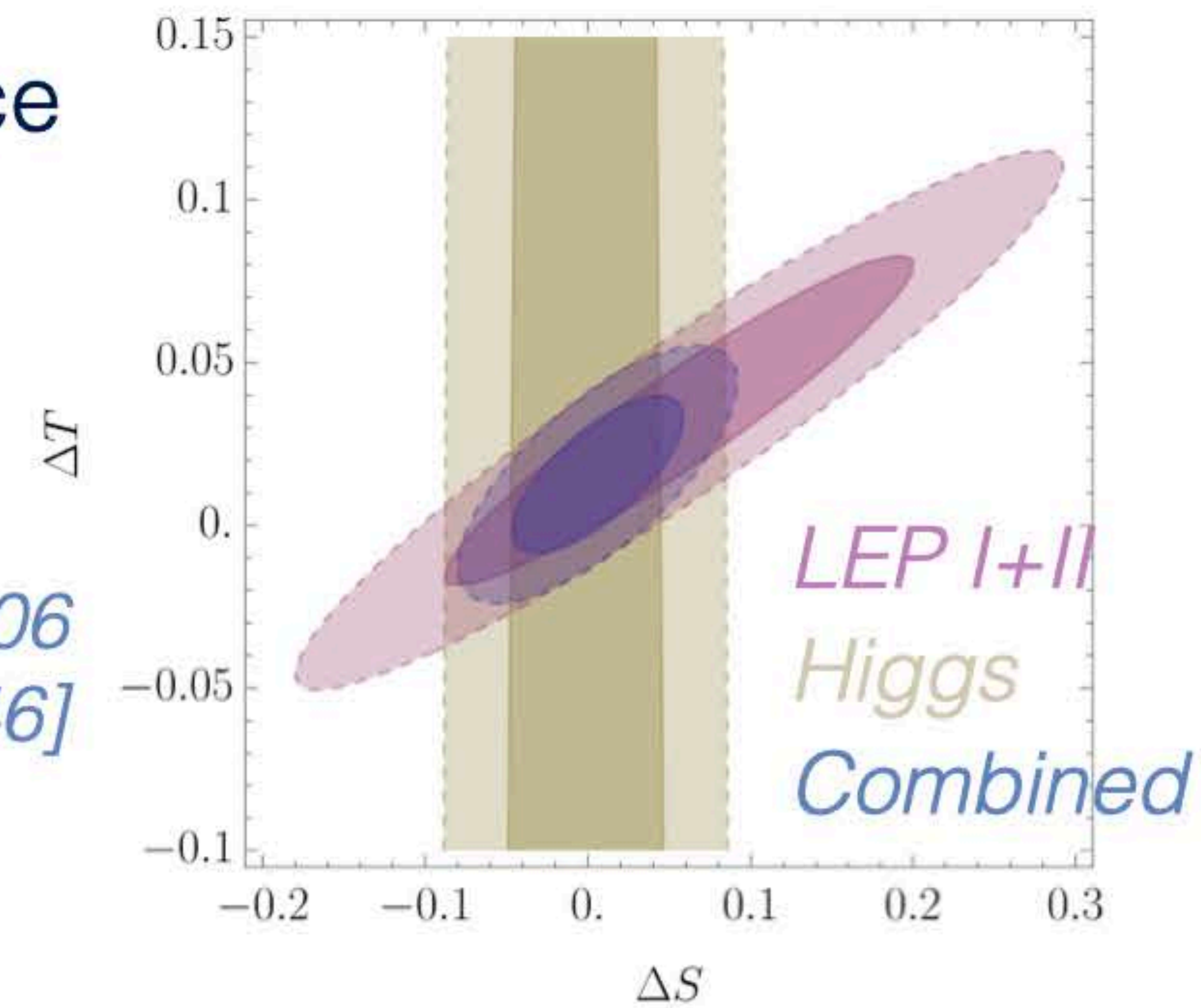
How much cross-talk? Where does being global matter?

We know that Higgs data greatly complements LEP

- Access unconstrained directions in parameter space
- Allows for a closed fit to flavor-universal SMEFT
- Crucial to combine EWPO, Diboson & Higgs data

[Corbett et al.; PRD 87 (2013) 015022]
[Pomarol & Riva; JHEP 01 (2014) 151]
[Ellis, Sanz & You; JHEP 03 (2015) 157]
[Biekötter, Corbett & Plehn; SciPost Phys 6 (2019) 6, 064]…
[Ellis et al.; JHEP 06 (2018) 146]



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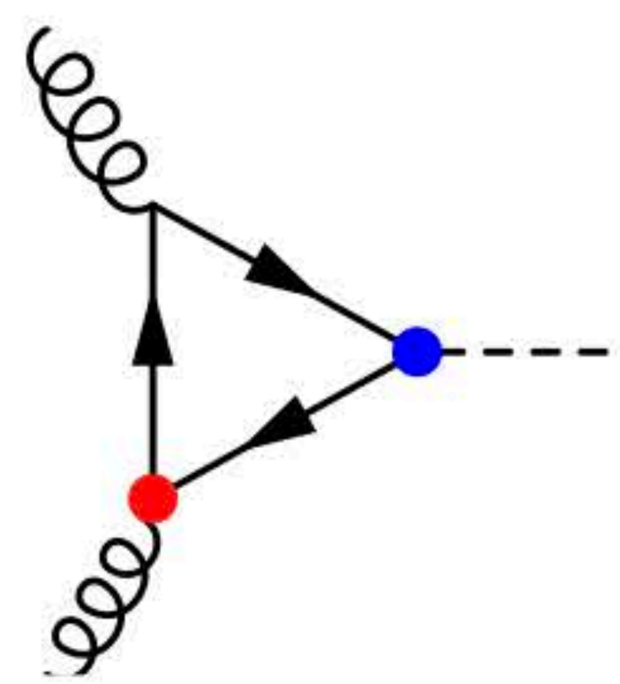

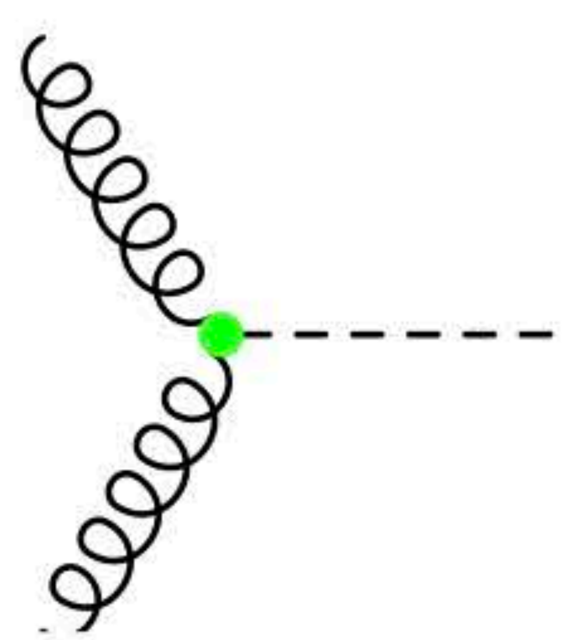

Blind direction in BSM scenarios
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Effective coupling degeneracy

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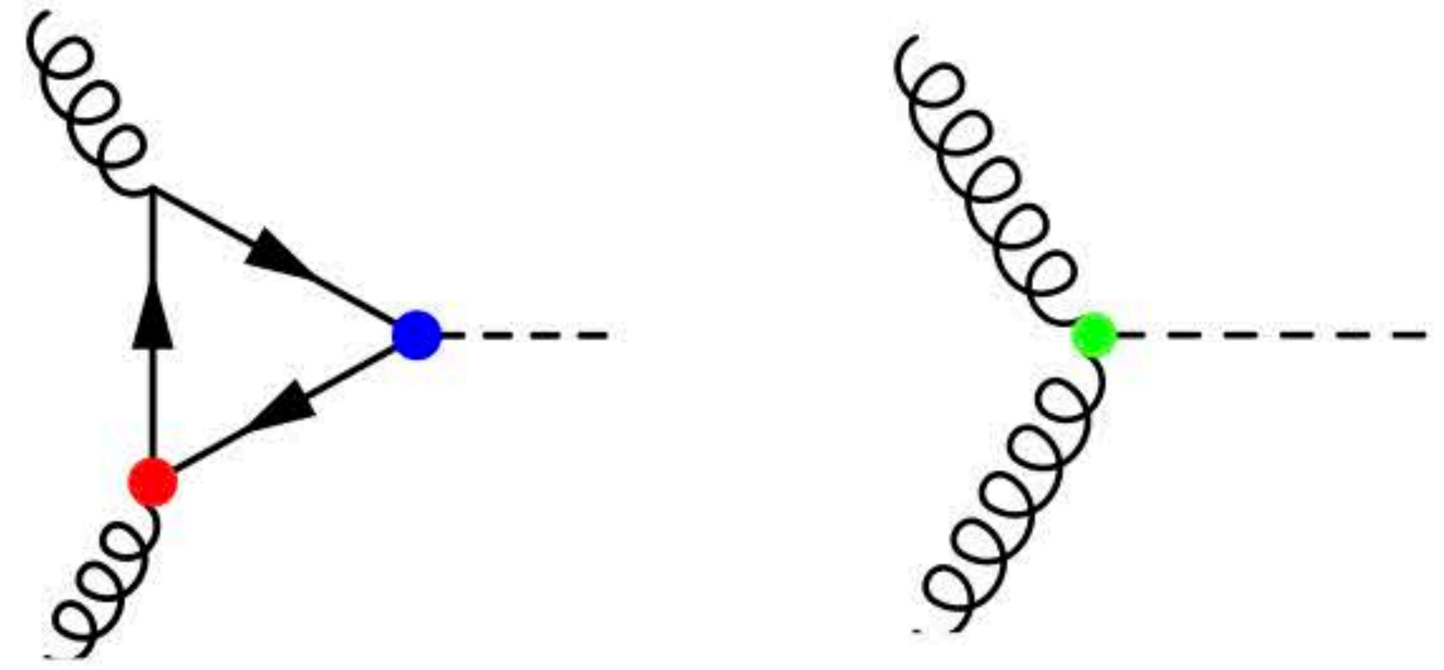

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Need more data to break degeneracy

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

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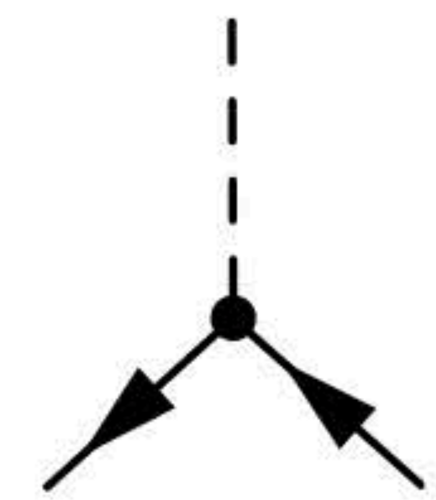

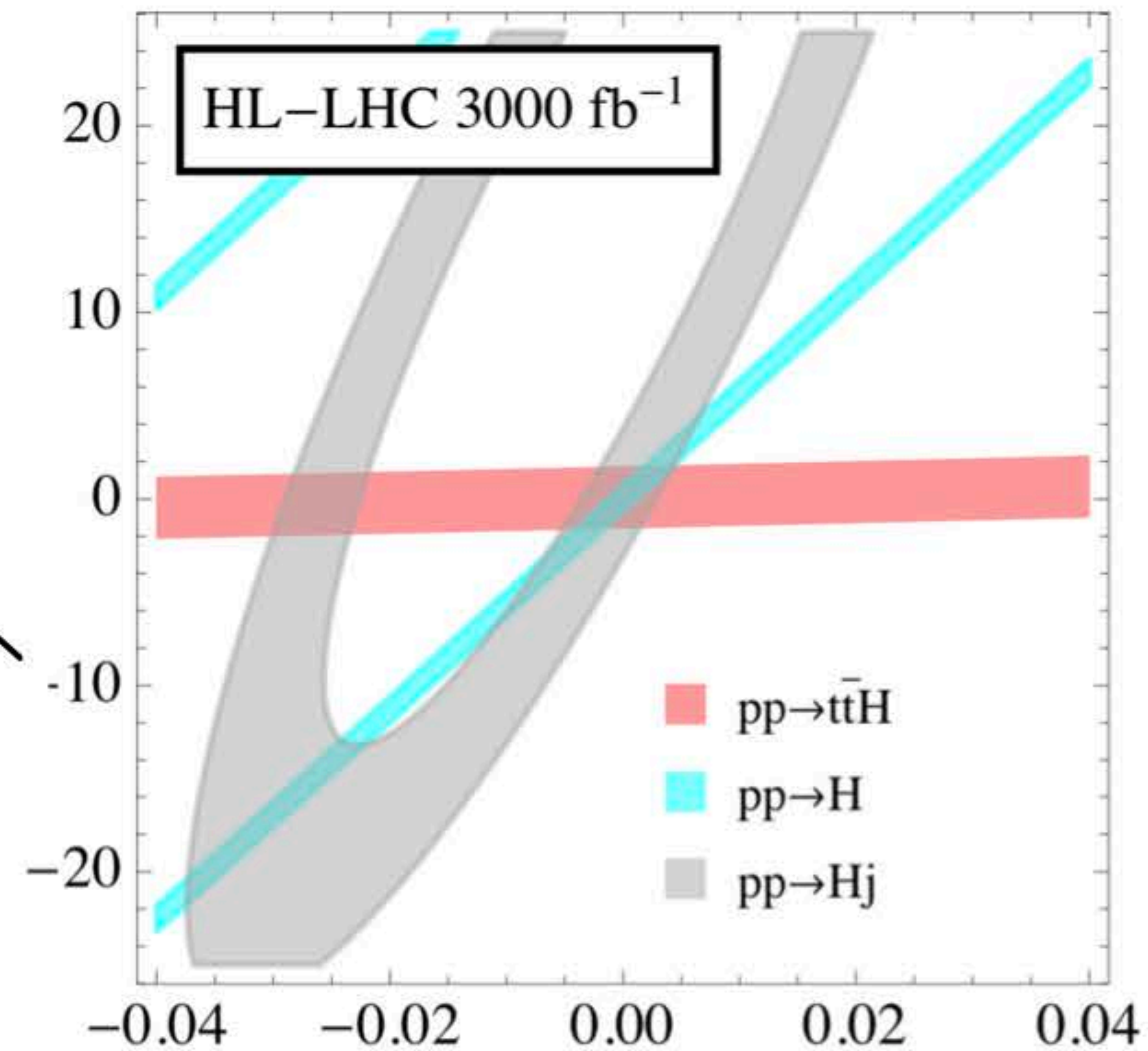

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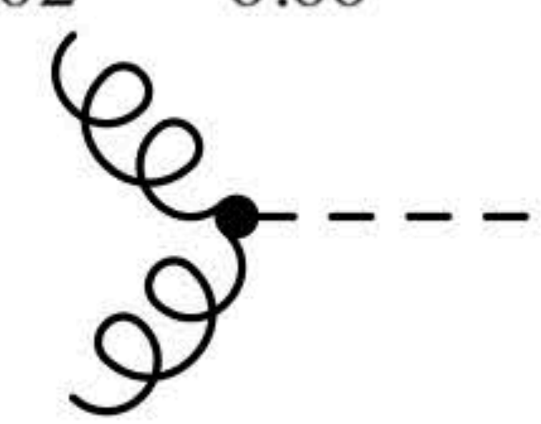

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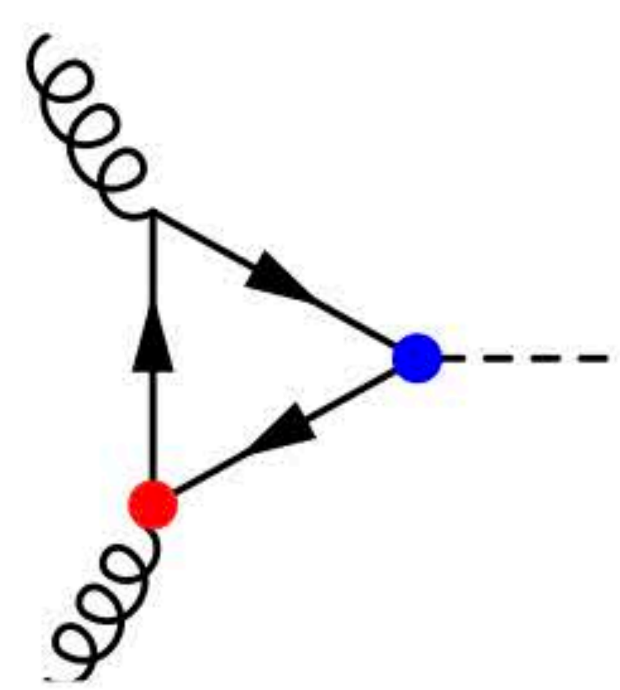

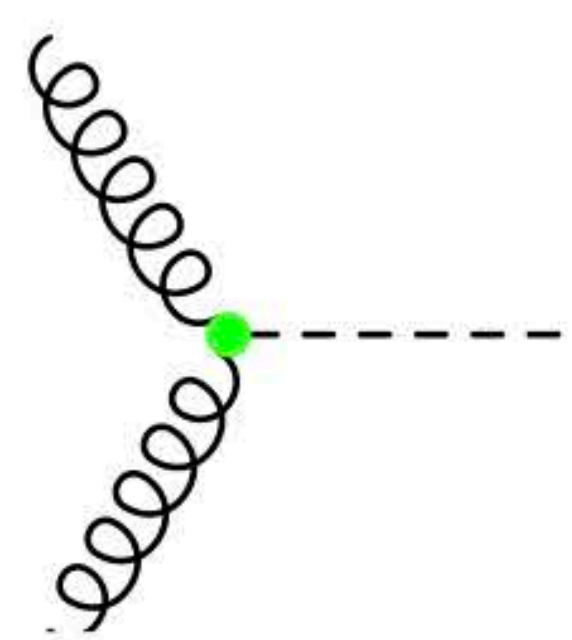

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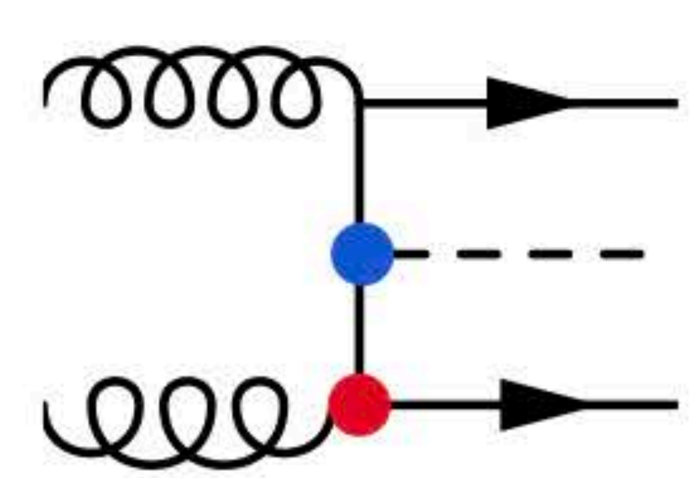
- $t\bar{t}H$ production for direct Yukawa measurement



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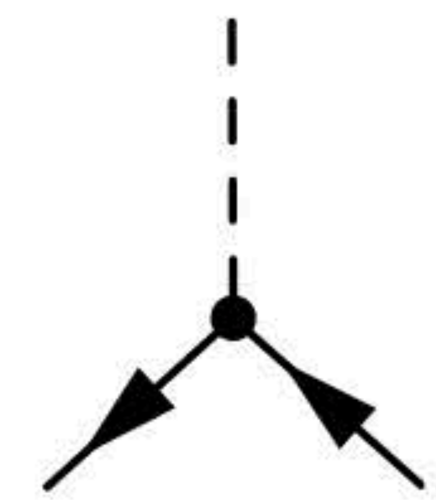

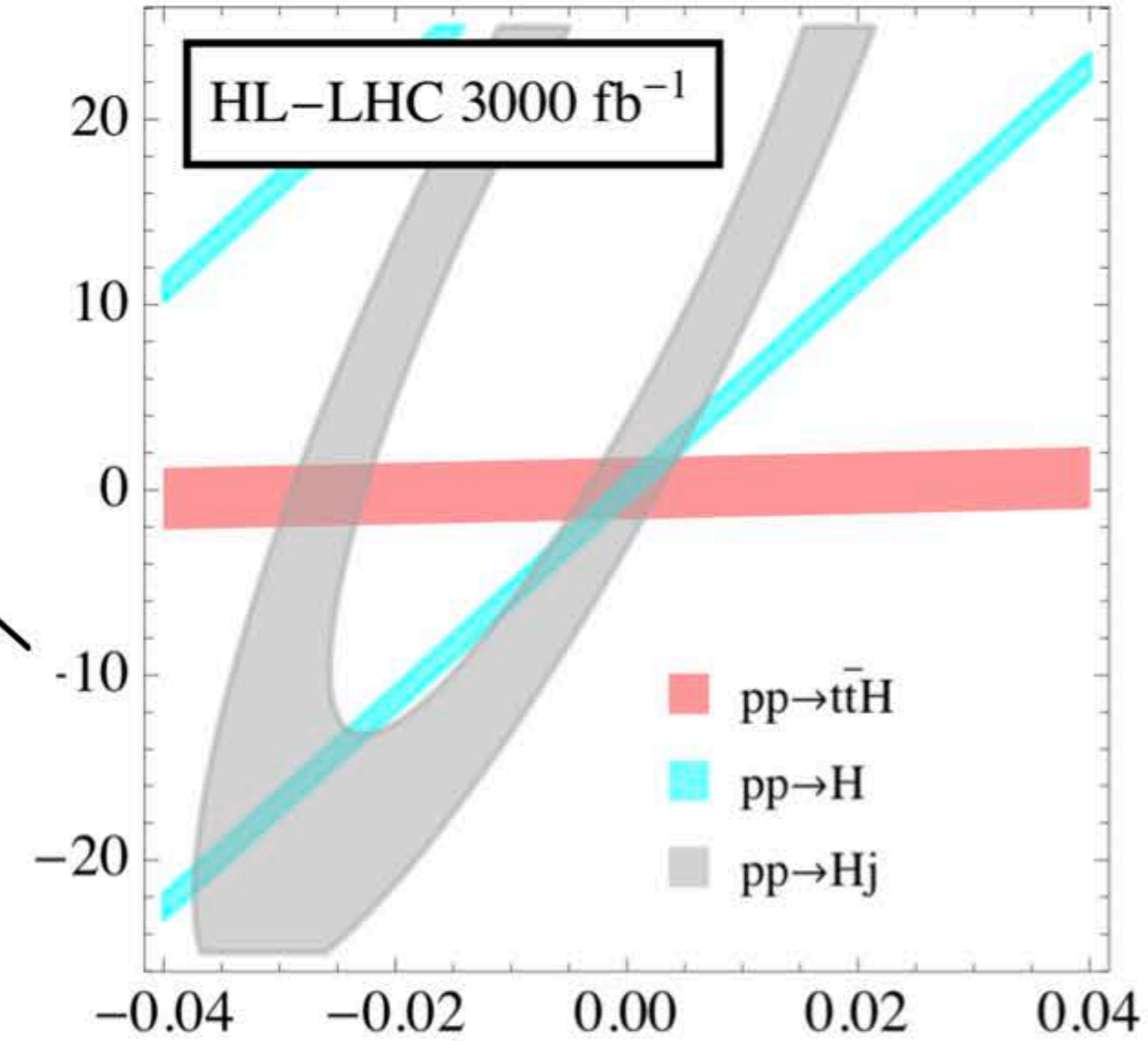

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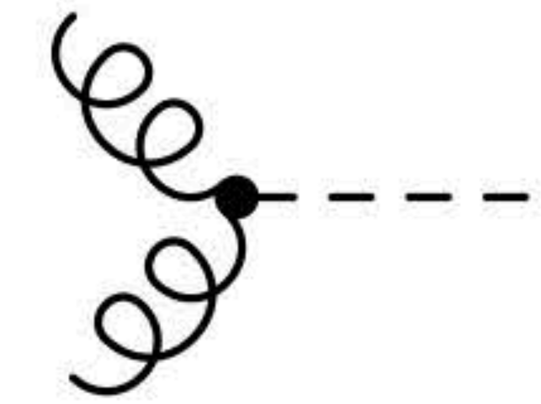

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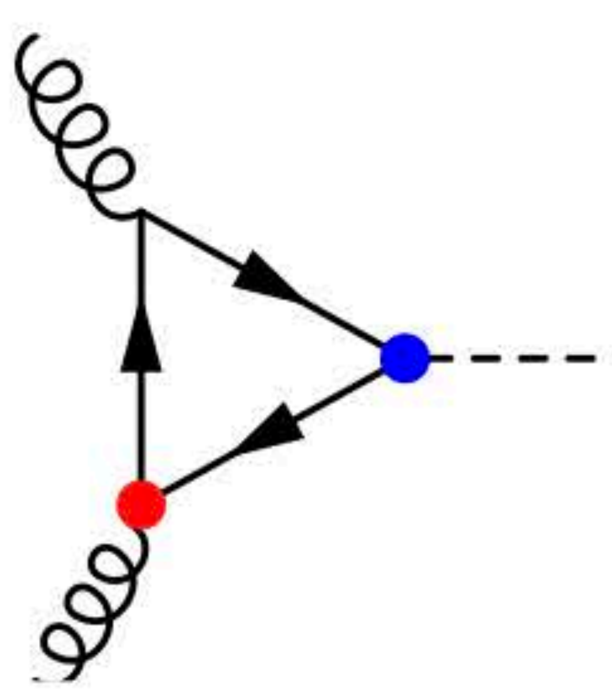

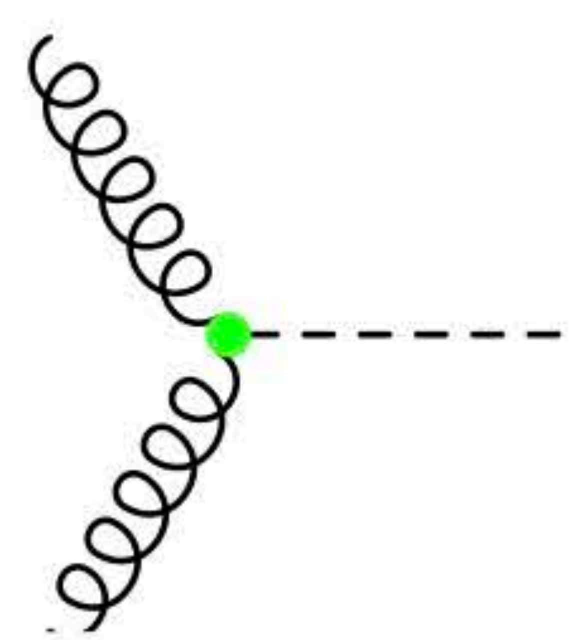

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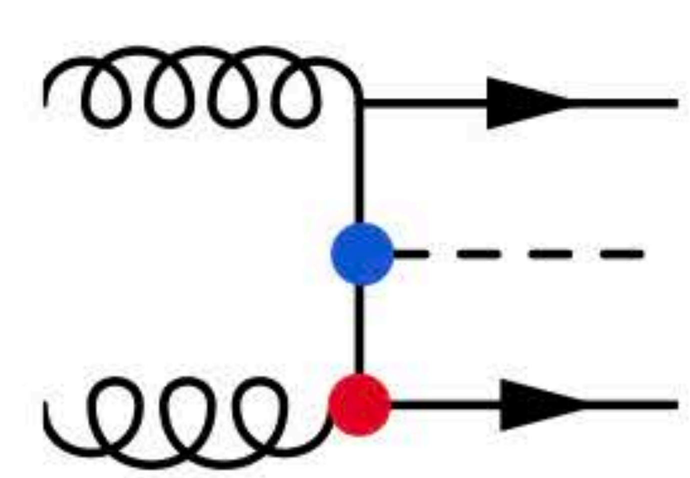
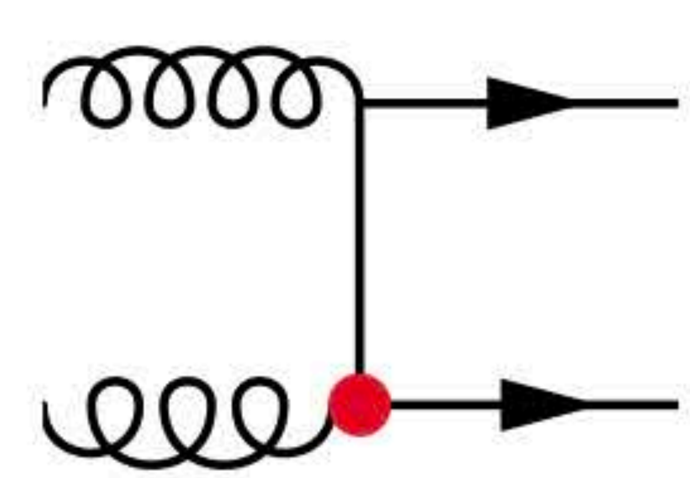
- $t\bar{t}$ data to constrain dipole

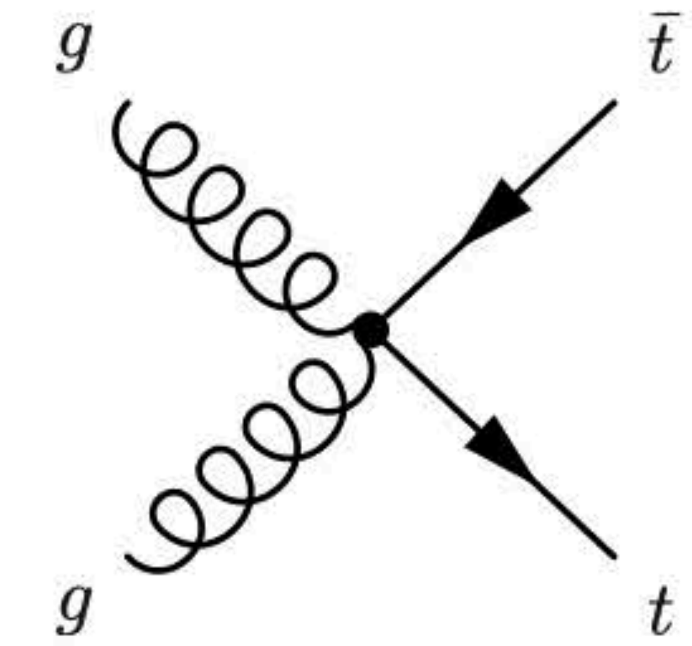




The role of top data

$t\bar{t}$ cross section measurements constrain C_{tG}

- Indirectly improve bounds on C_{HG} and C_{tH}



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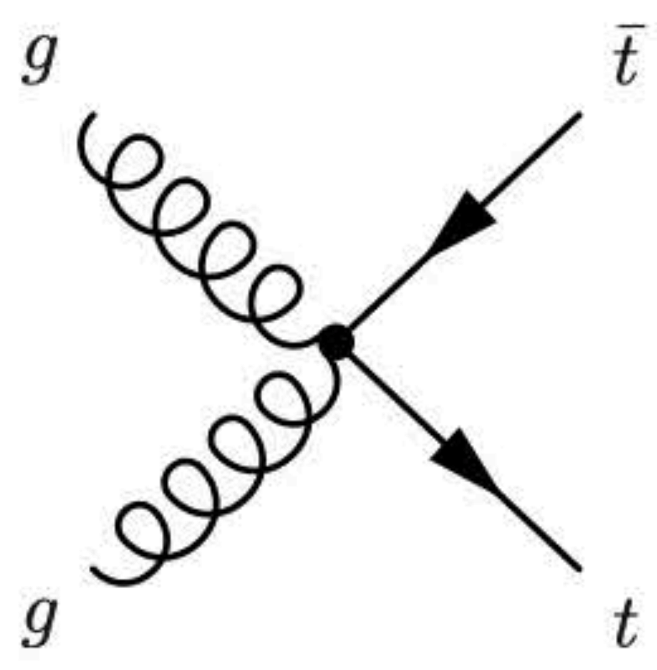

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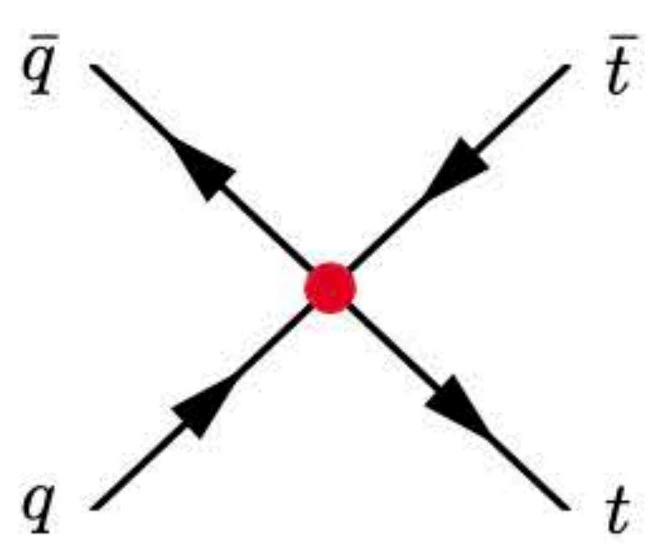

Several other new interactions can affect $t\bar{t}$

- Notably $q\bar{q}t\bar{t}$ operators, of which there are many (14)
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?

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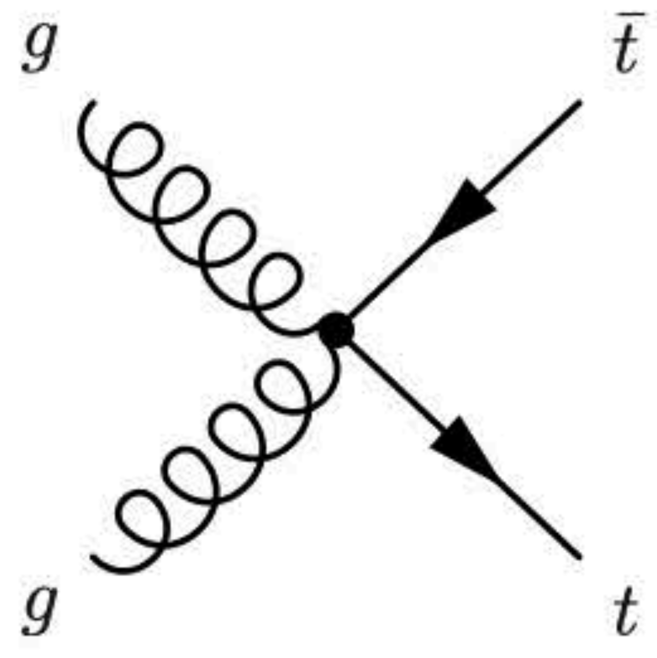

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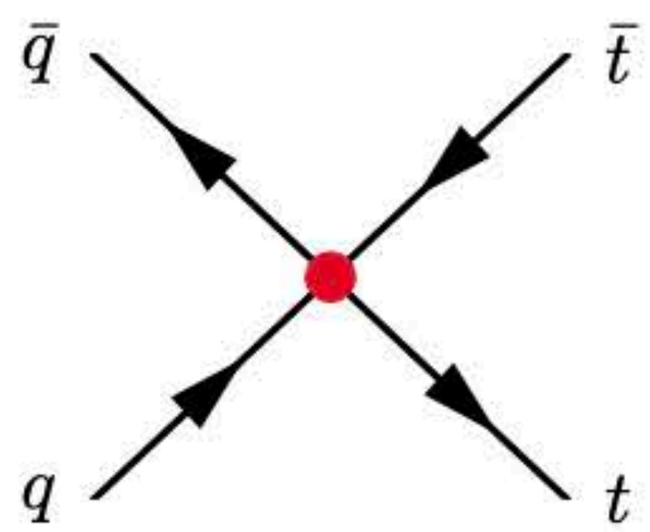

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Can only be addressed in combined fit

- Beyond tree-level (at least for ggF)

[Degrande et al.; PRD 103 (2021) 9, 096024]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- Identify other cross-talk (non-trivial correlations)
- Crystallisation of knowledge gained after LHC Run 2
- Broaden range of applicability to UV models

The fit

fitmaker https://gitlab.com/kenmimasu/fitrepo
public-friendly version w/ example notebooks in progress

Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

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Global SMEFT interpretation of 4 categories of data

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

14 • Electroweak Precision Observables (EWPO): Z-pole & W-mass

118 • LEP2 & LHC diboson production: differential WW, WZ, Zjj

72 • Higgs measurements: signal strengths & STXS

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Big thanks to authors of SMEFiT analysis [JHEP 04 (2019) 100] for sharing some of their top predictions

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341 measurements across categories

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Linear EFT approximation: $$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Degrees of freedom

Flavor scenario			
Universal	EWPO:	$\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}^{(3)}_{Hl}\,,\ \mathcal{O}^{(1)}_{Hl}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}^{(3)}_{Hq}\,,\ \mathcal{O}^{(1)}_{Hq}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,;$	
	Bosonic:	$\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$	
	Yukawa:	$\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,$	20
'Top specific'	Top 2F:	$\mathcal{O}^{(3)}_{HQ}\,,\ \mathcal{O}^{(1)}_{HQ}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$	
	Top 4F:	$\mathcal{O}^{3,1}_{Qq}\,,\ \mathcal{O}^{3,8}_{Qq}\,,\ \mathcal{O}^{1,8}_{Qq}\,,\ \mathcal{O}^{8}_{Qu}\,,\ \mathcal{O}^{8}_{Qd}\,,\ \mathcal{O}^{8}_{tQ}\,,\ \mathcal{O}^{8}_{tu}\,,\ \mathcal{O}^{8}_{td}\,.$	+14

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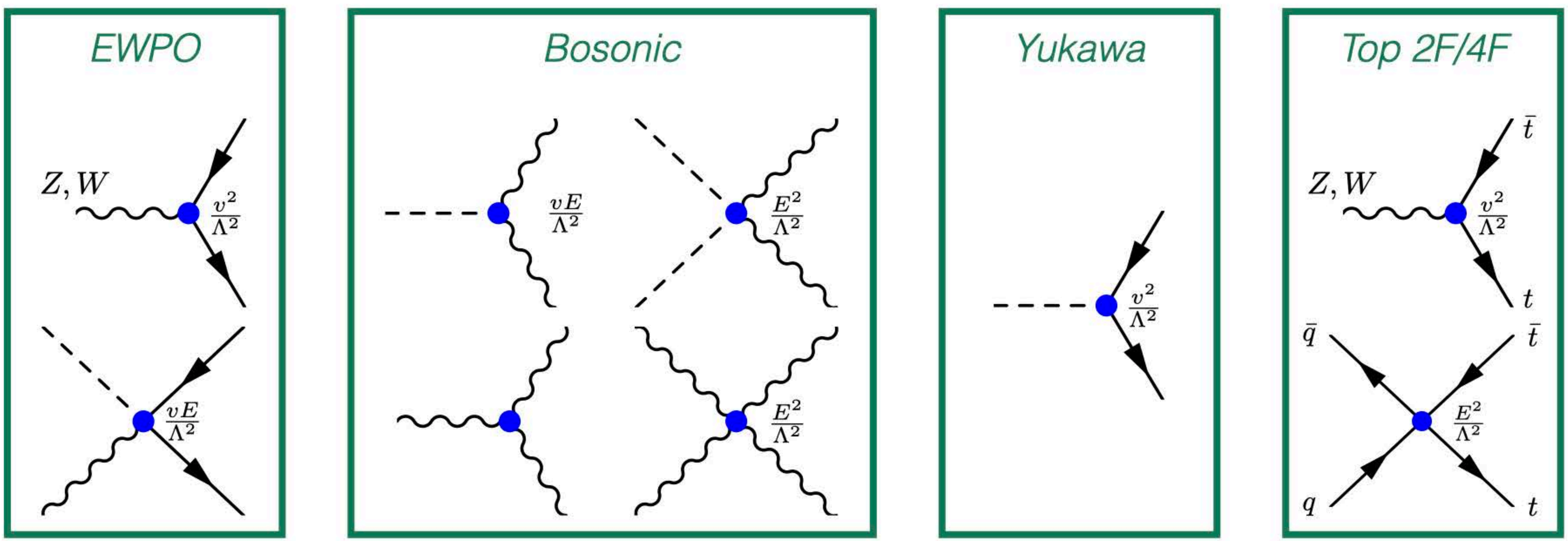
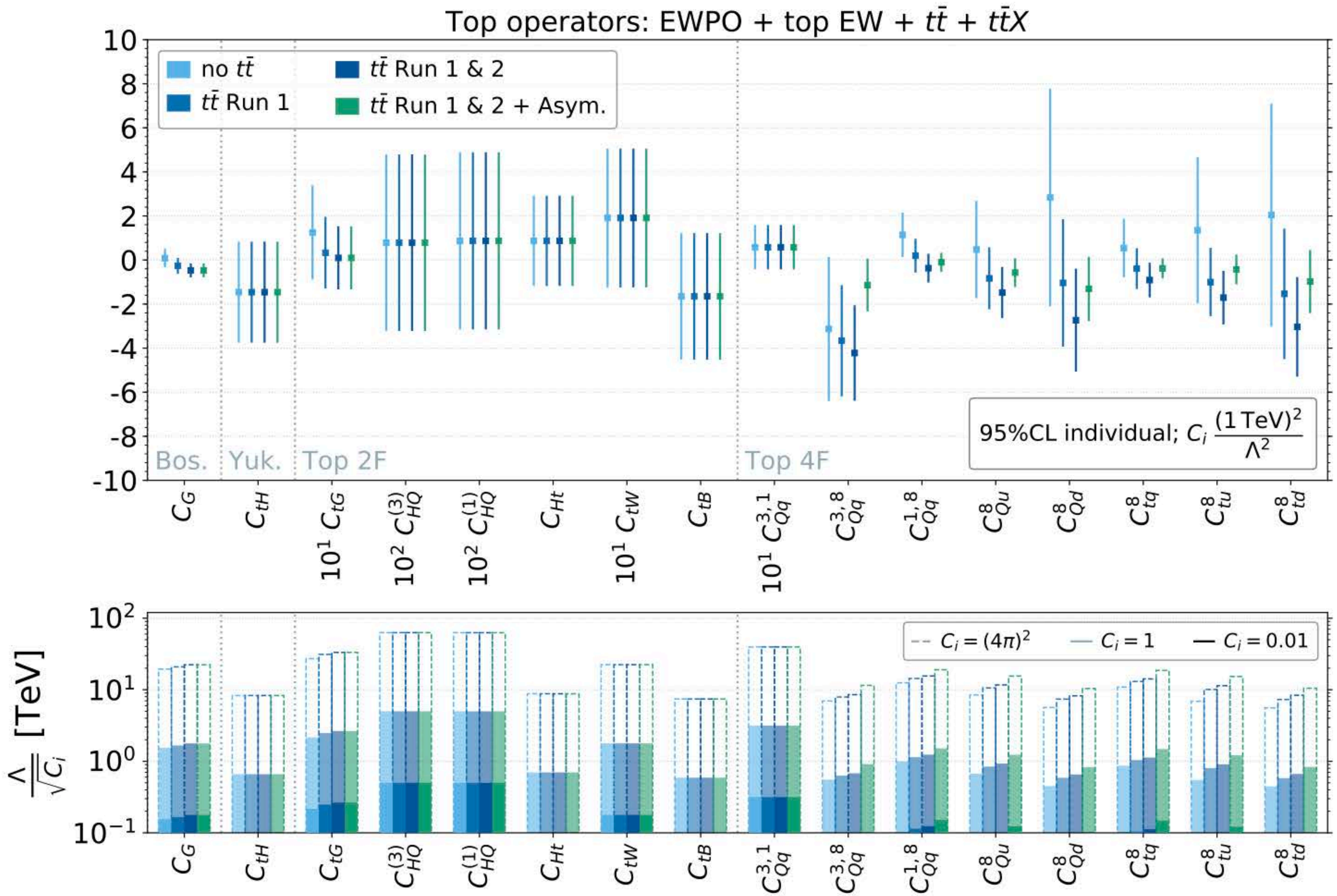


Top-only: top + EWPO individual



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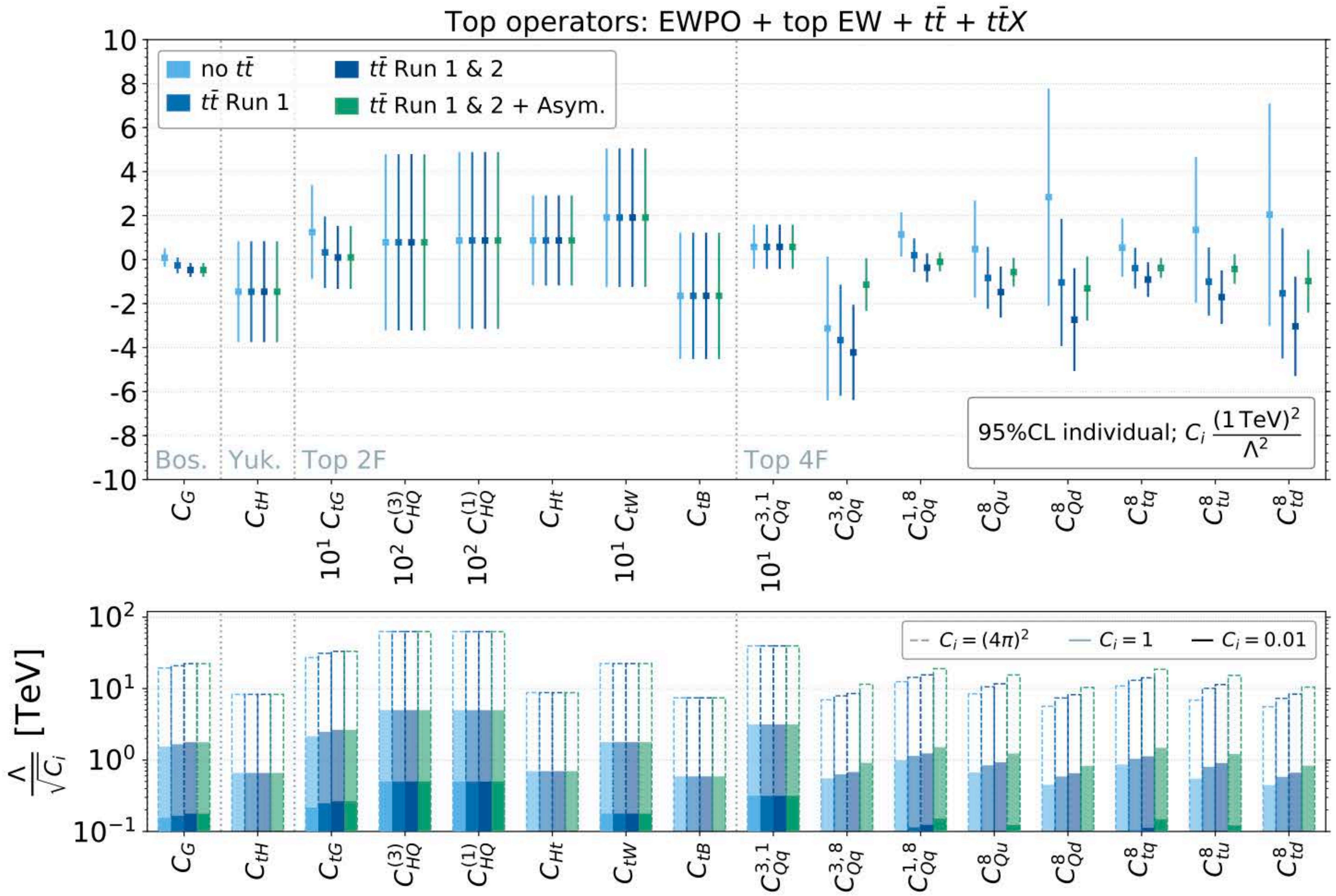
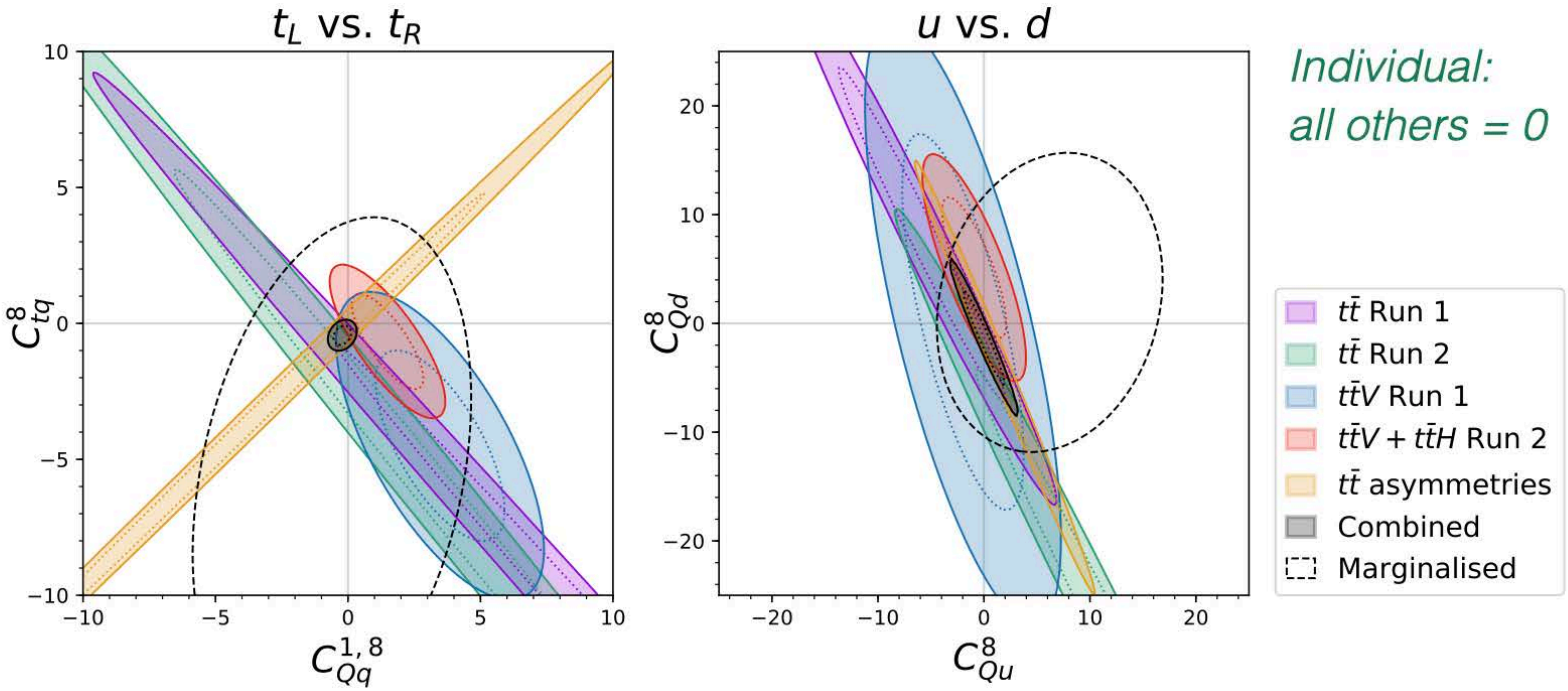


- Some tension in $t\bar{t}$ data
- Asymmetries help to improve agreement

See also dedicated top fits: SMEFiT [Hartland et al.; JHEP 04 (2019) 100]
SFitter [Brivio et al.; JHEP 02 (2020) 131]

Top-only: breakdown

4F ($\bar{t}t\bar{q}q$) operators



Individual:
all others = 0

Top-only: breakdown

4F ($\bar{t}t\bar{q}q$) operators

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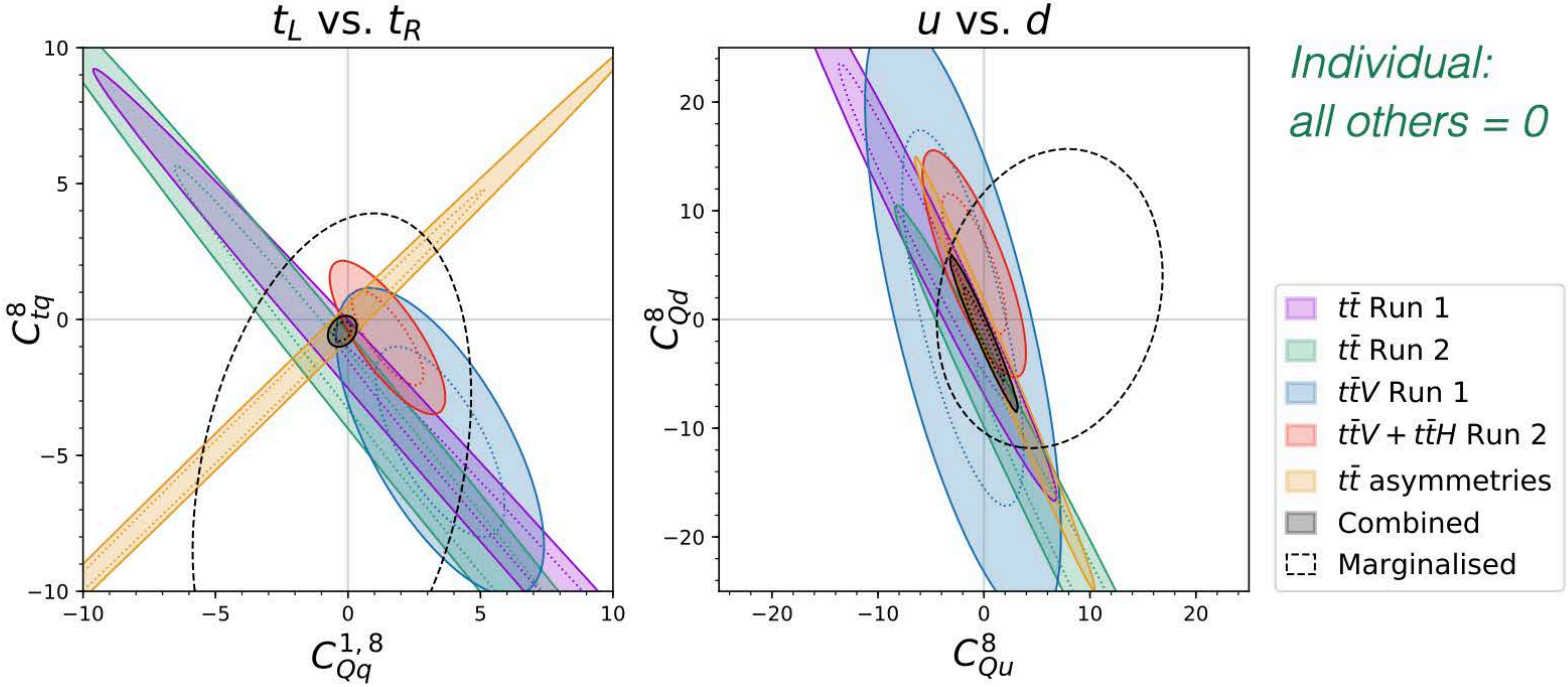

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- $t\bar{t}V$ & $t\bar{t}H$ help to close the space

Top-only: breakdown

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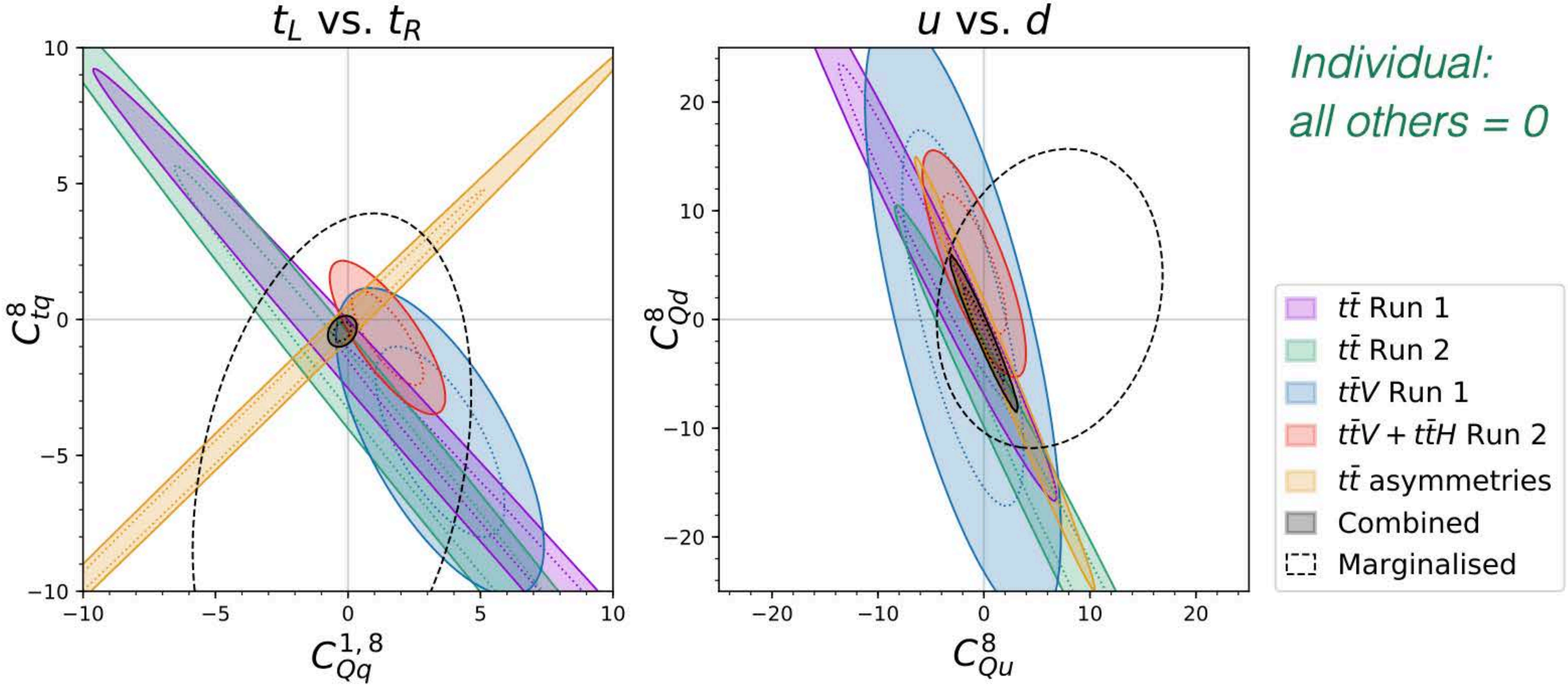

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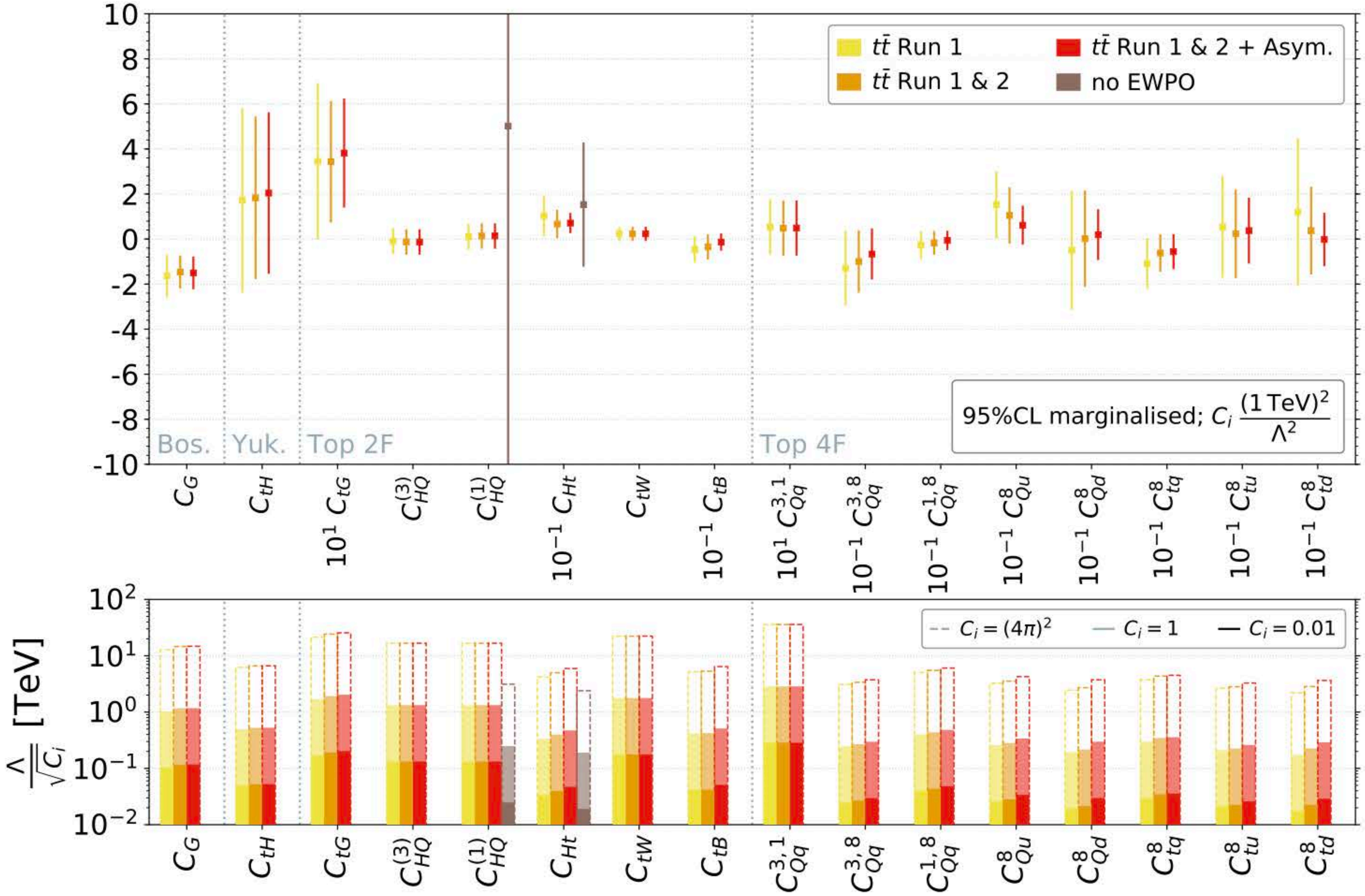
- Marginalised linear sensitivity: $C_{4F}\left[\frac{1\,\mathrm{TeV}^2}{\Lambda^2}\right] \sim (5-15)$ significant $\frac{1}{\Lambda^4}$ effects

Top-only: top + EWPO marginalised



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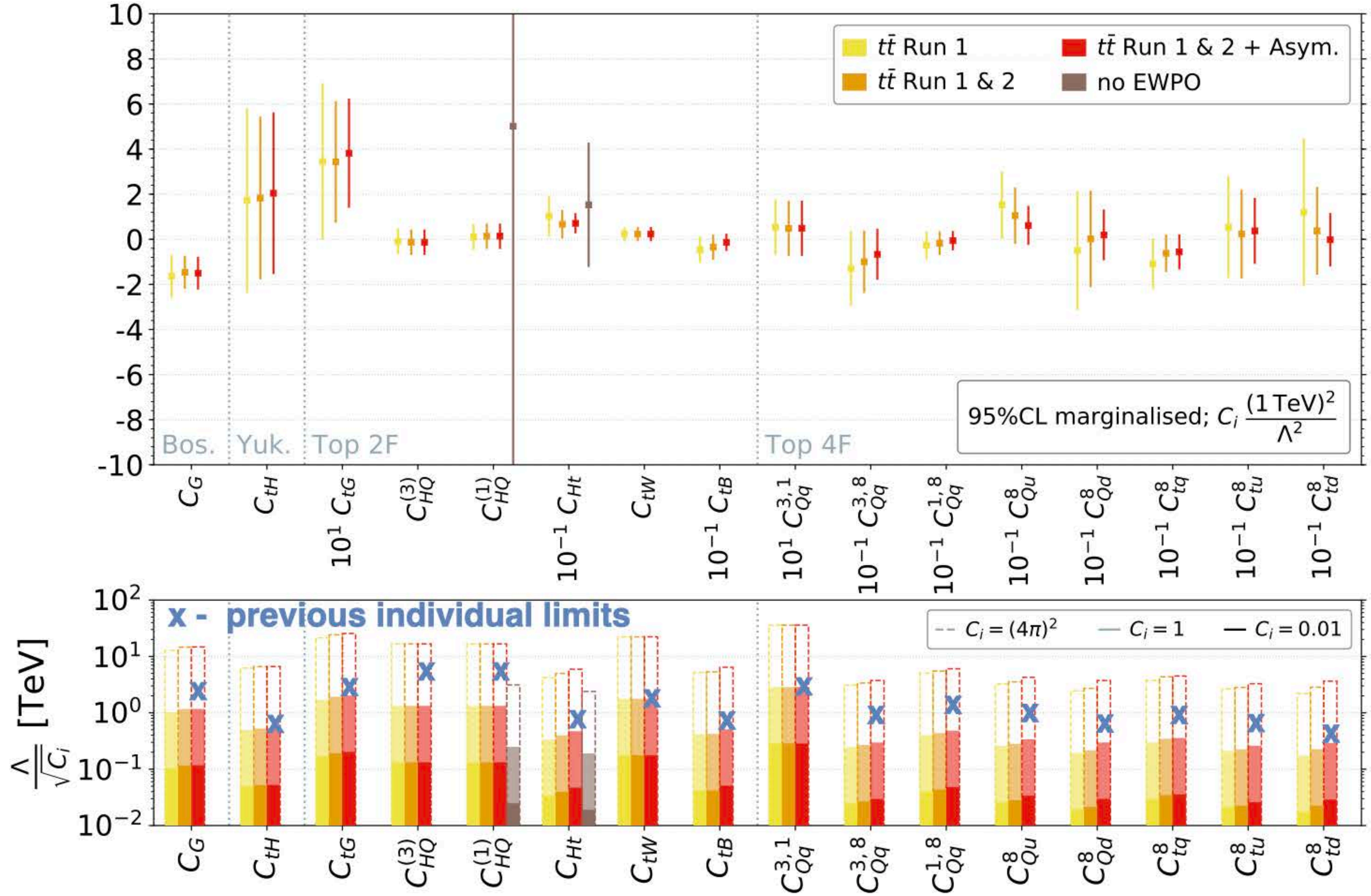

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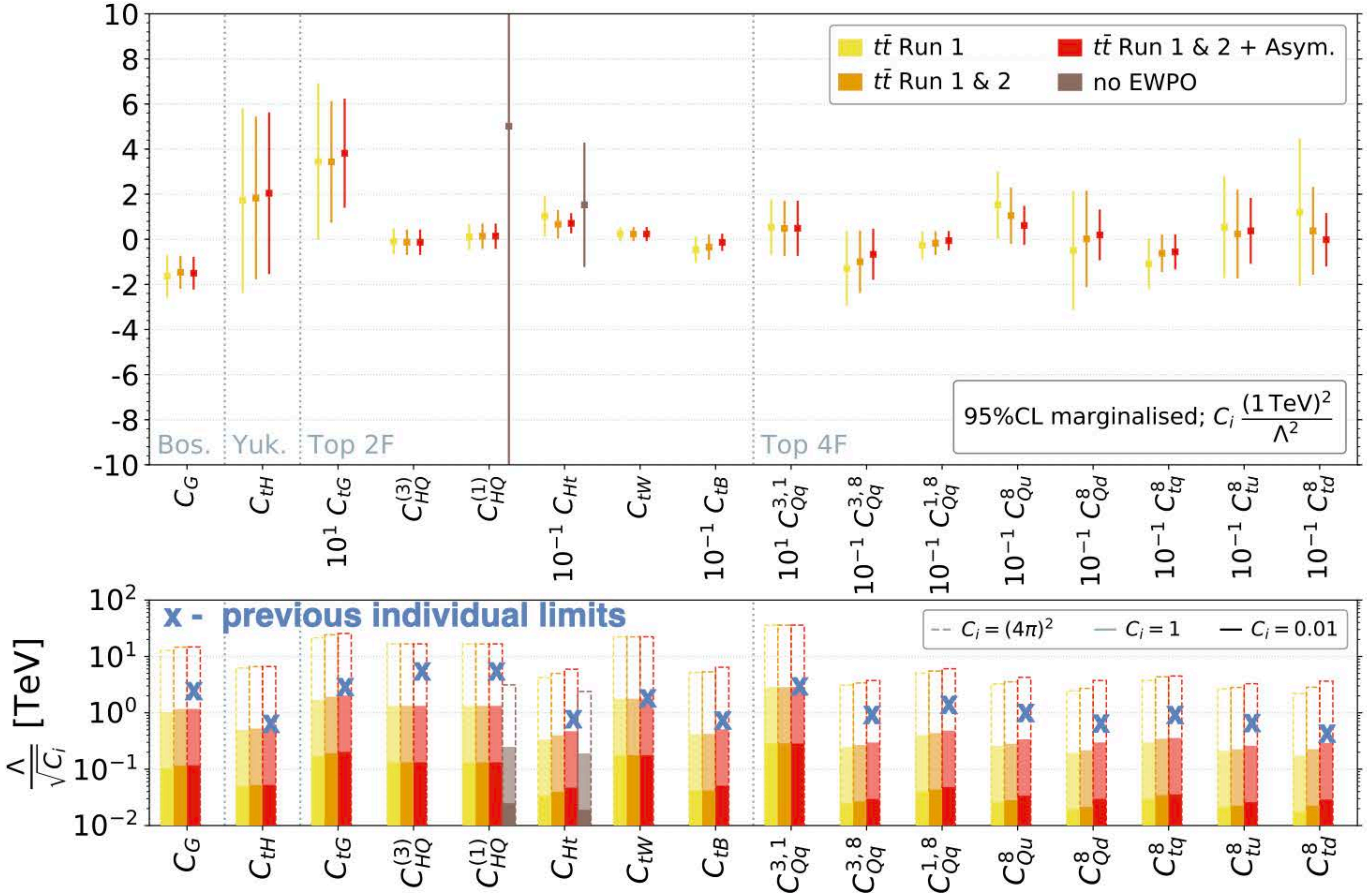

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- C_{tG}: Strong constraint but tension with SM
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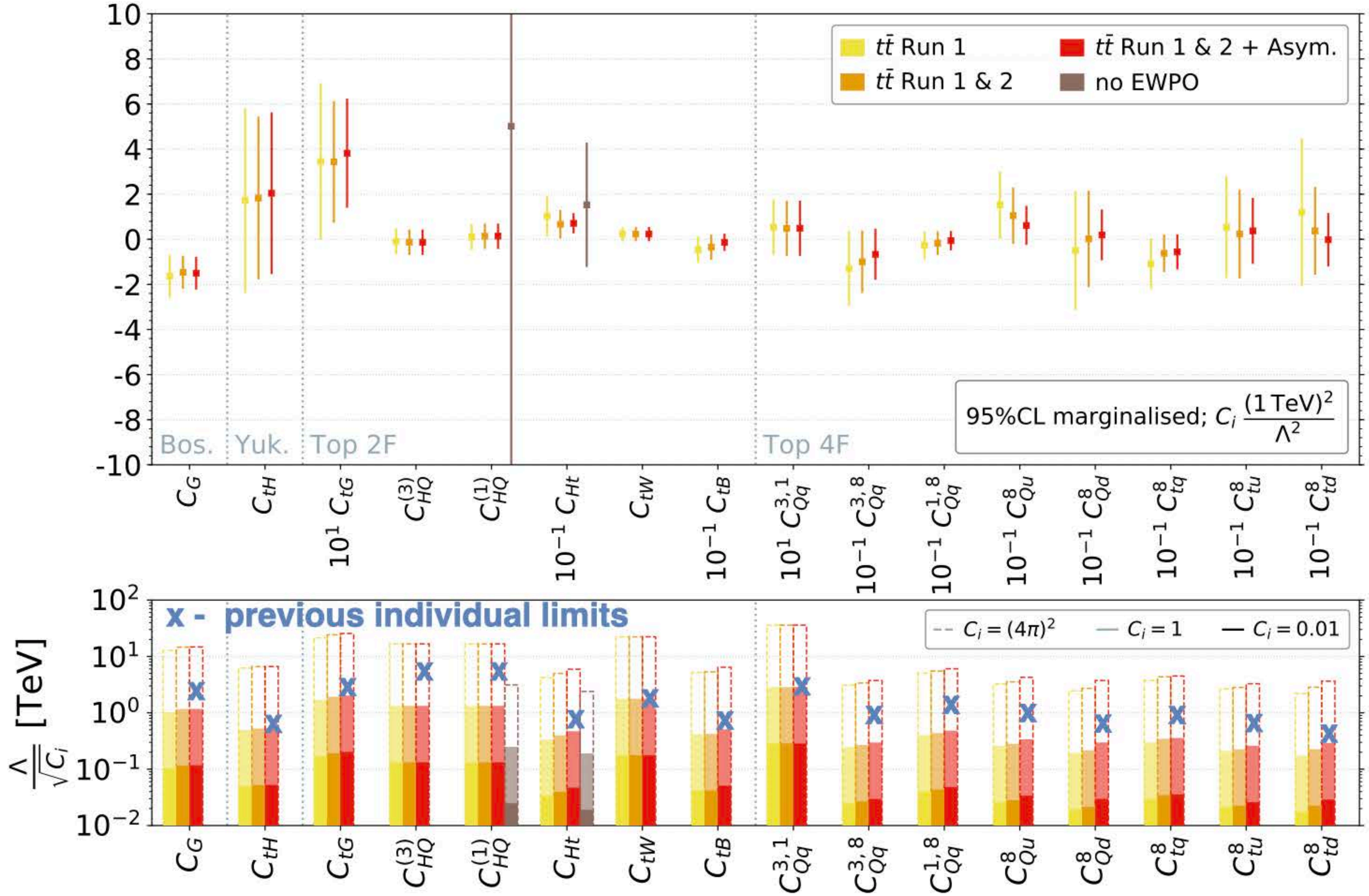

- C_{tH}: $t\bar{t}H$ bound alone is quite weak
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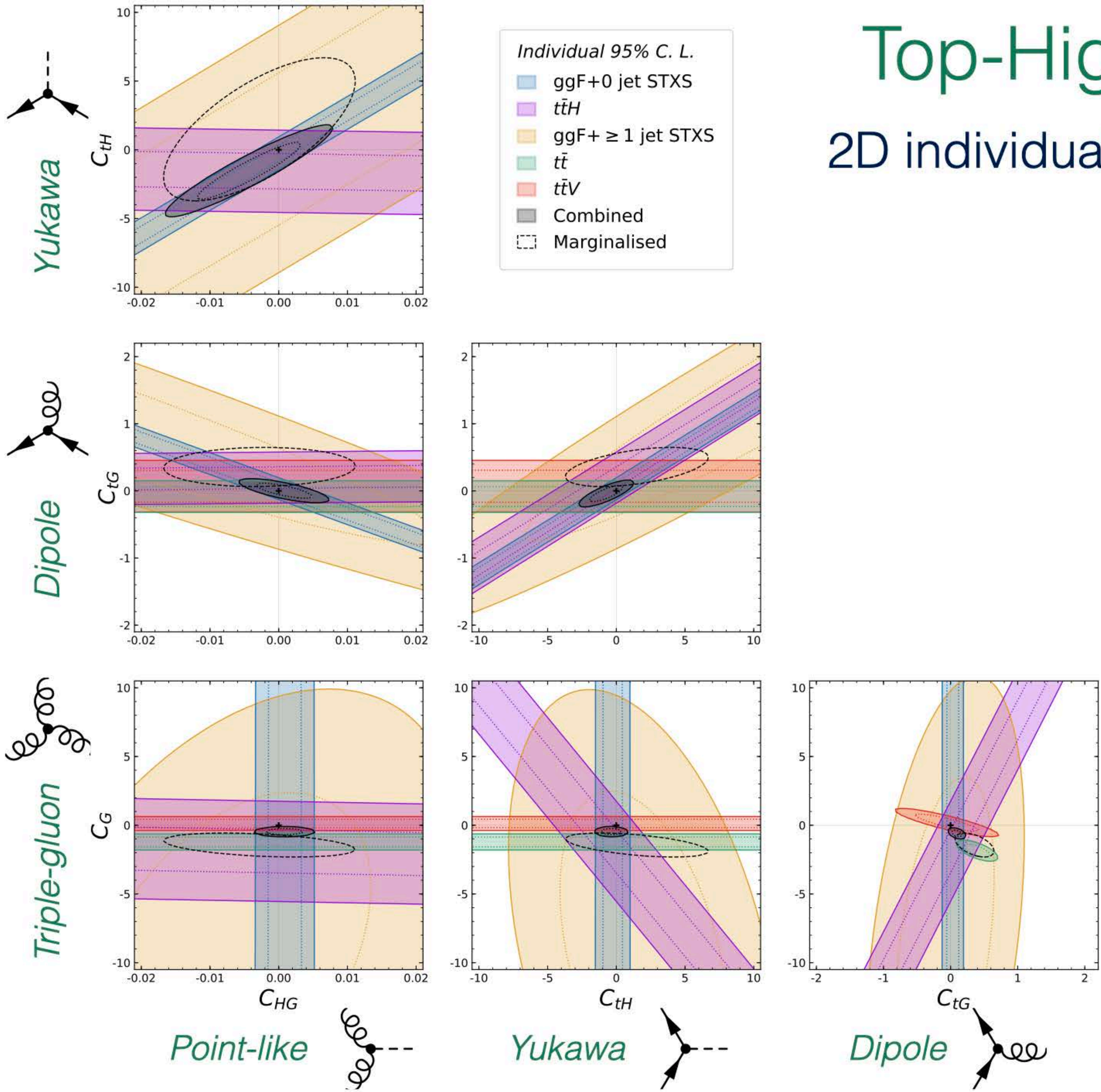
- EWPO closes $Zb\bar{b}$ coupling direction
- Impact of asymmetries in 4F
- Somewhat low scales (validity?)

Top-Higgs interplay

2D individual constraints



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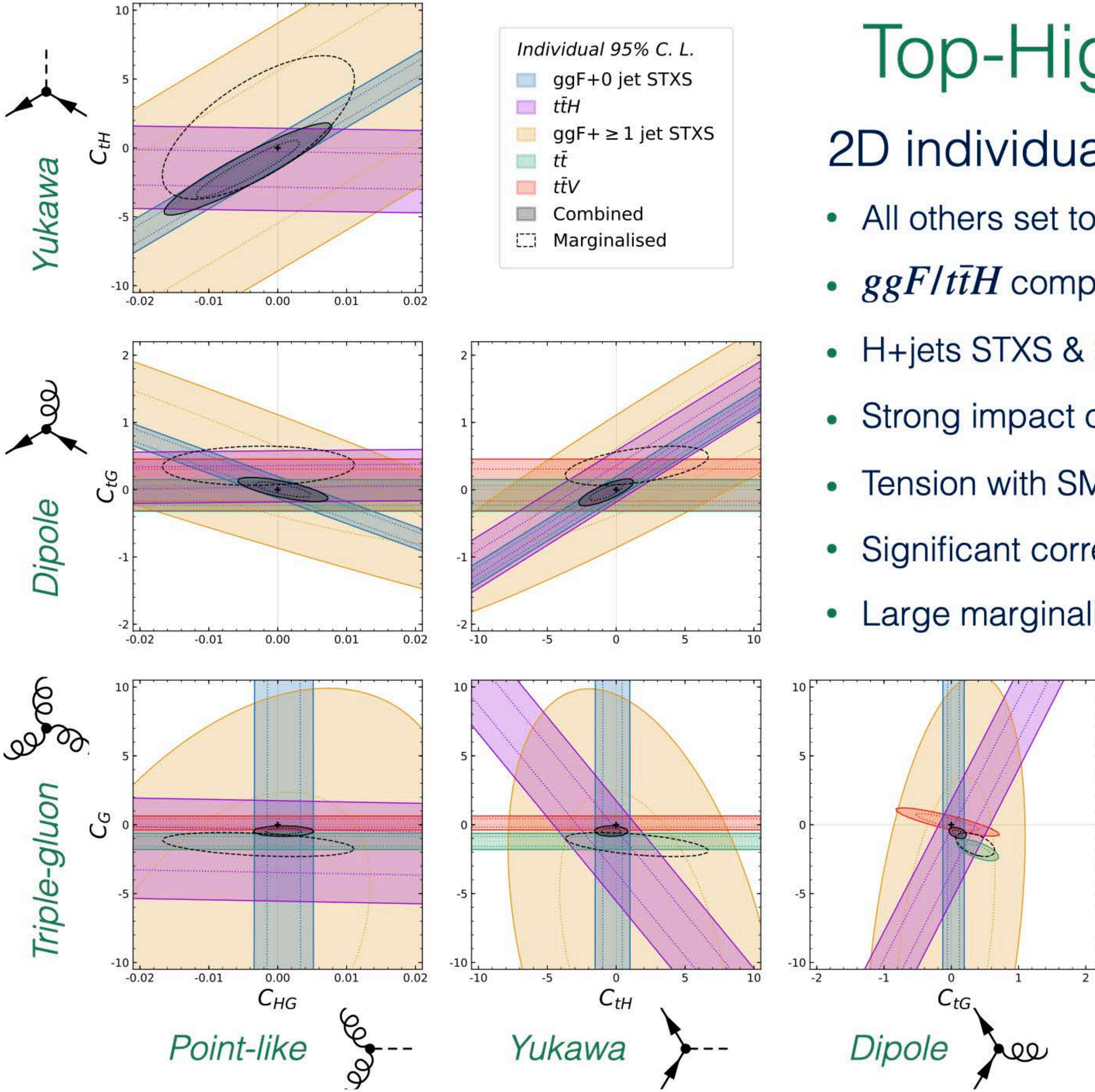

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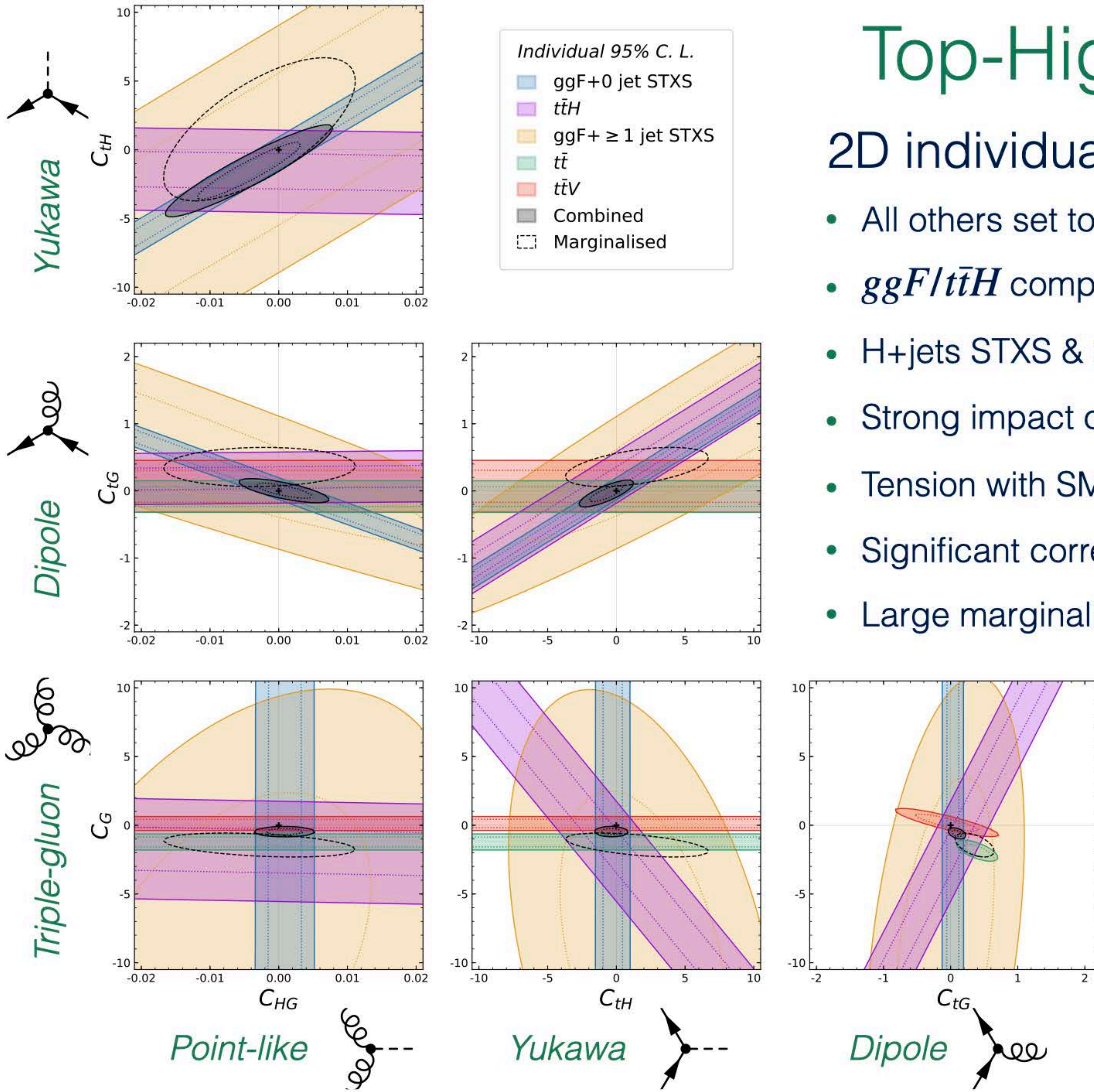

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What is the concrete impact of 4F?

4F impact

Fit to 'Higgs-only' subspace

$C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H}$
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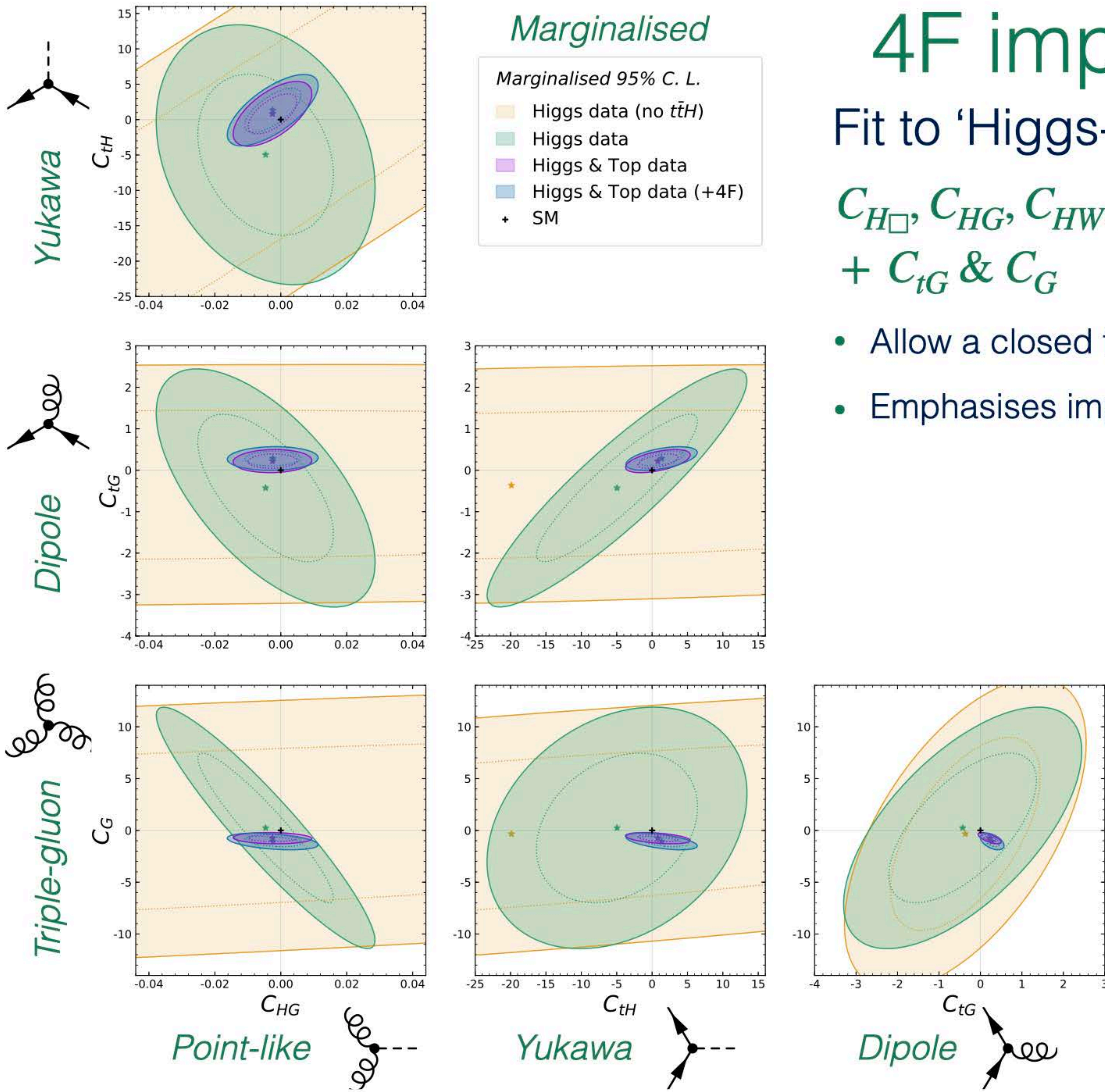

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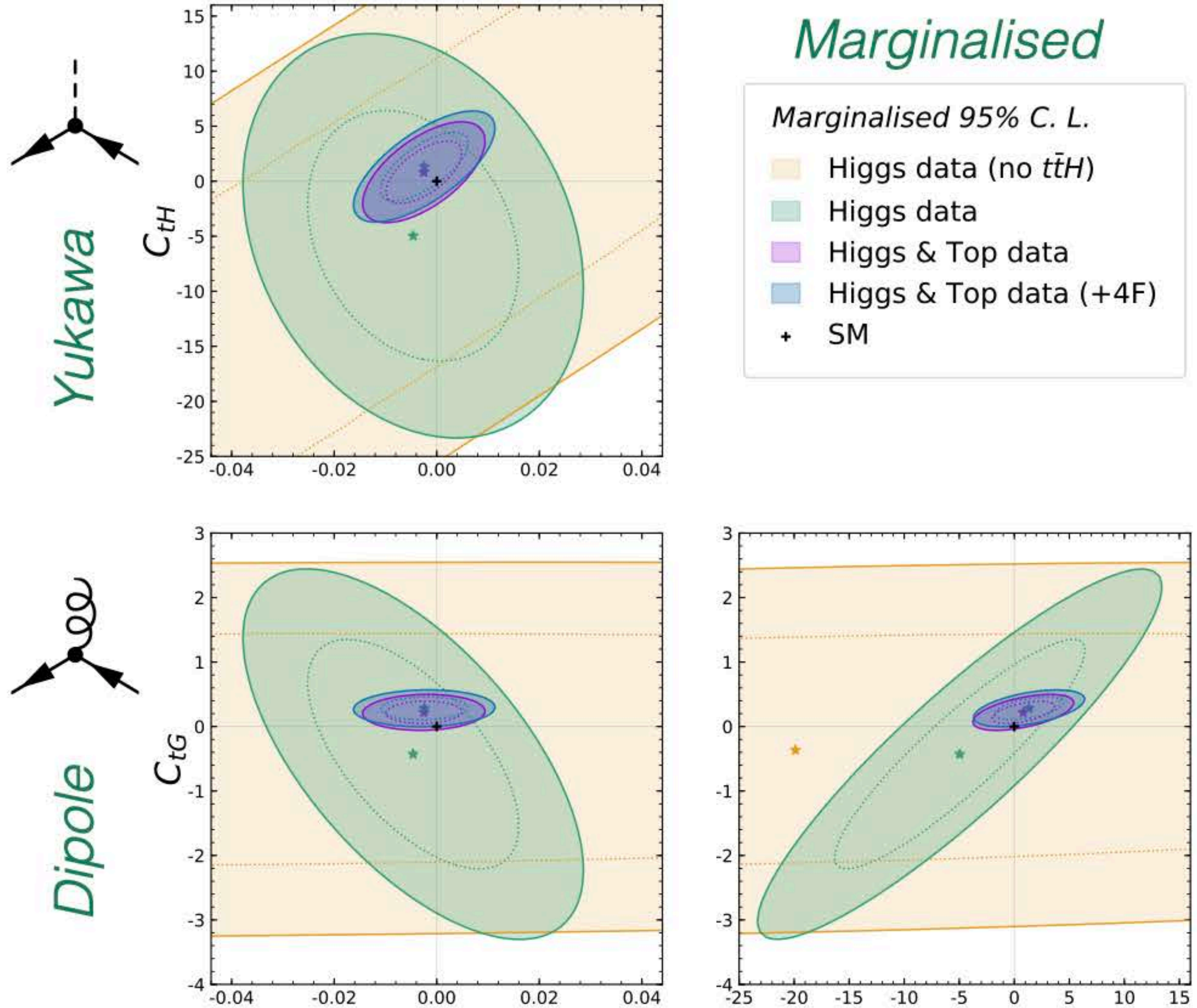

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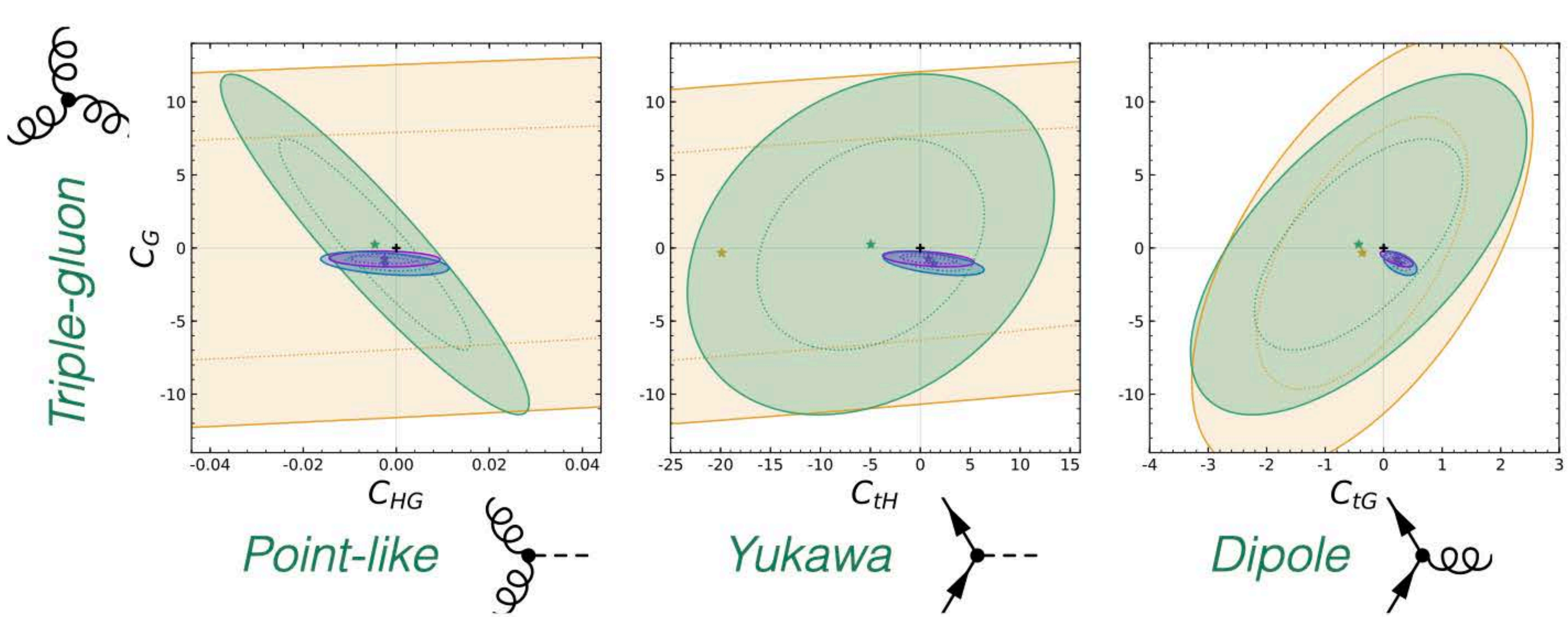
Now add in $t\bar{t}$ 4F operators

$+ \, C_{Qq}^{3,8}, C_{Qq}^{1,8}, C_{Qu}^{8}, C_{Qd}^{8}, C_{tq}^{8}, C_{tu}^{8}, C_{td}^{8}$



- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

  C_{tG} : low $m_{t\bar{t}}$

  $4F$: high $m_{t\bar{t}}$
- Able to constrain them independently

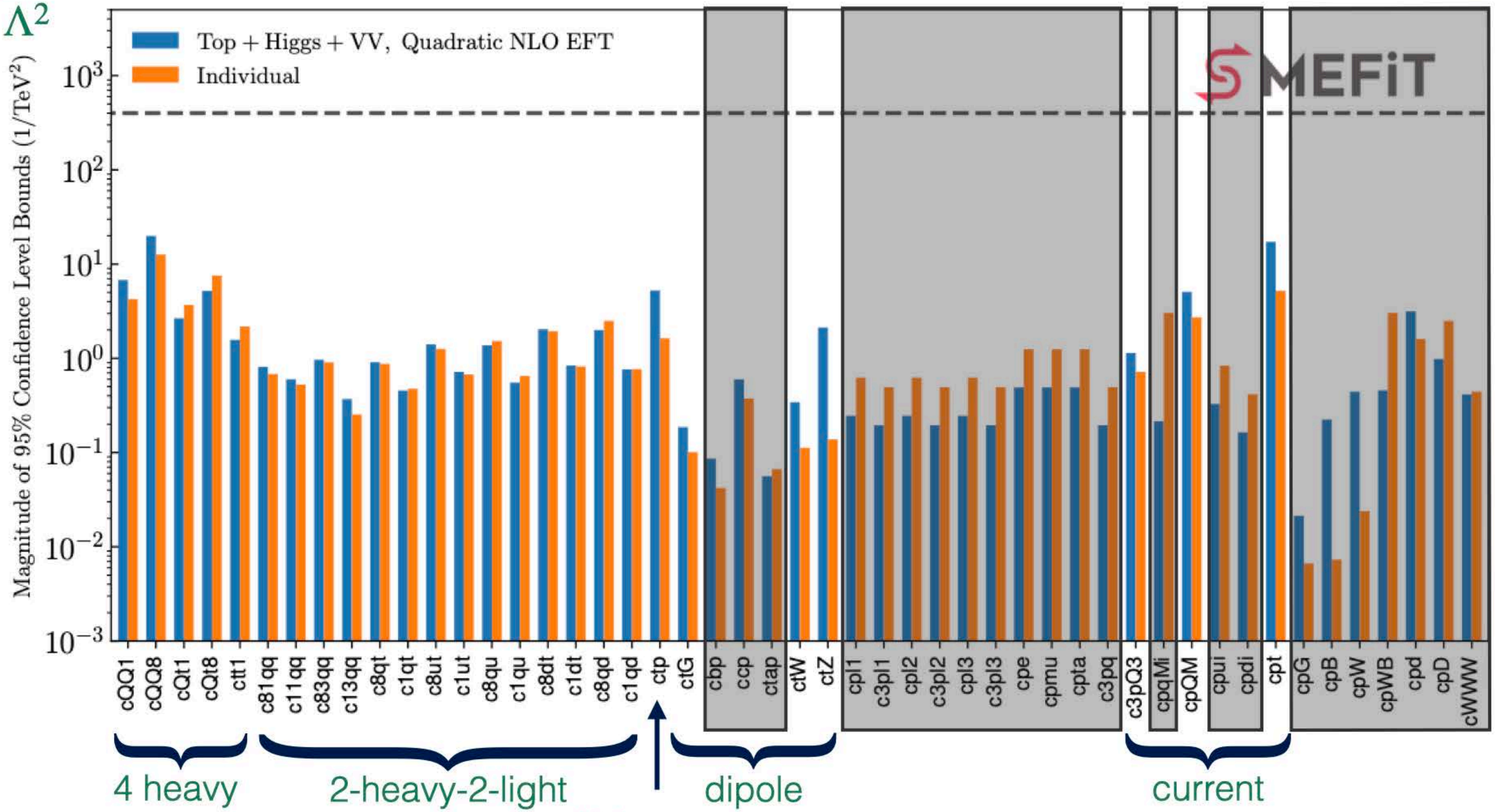
SMEFiT

[Ethier et al.; JHEP 11 (2021) 089]
see also: [Brivio et al.; JHEP 02 (2020) 131]
[Brown et al.; PoS ICHEP2020 (2021) 322]

Top, Higgs & Diboson w/ 'perfect' EWPO

- NLO QCD
- top loop sensitivity

$\frac{C_i}{\Lambda^2}$



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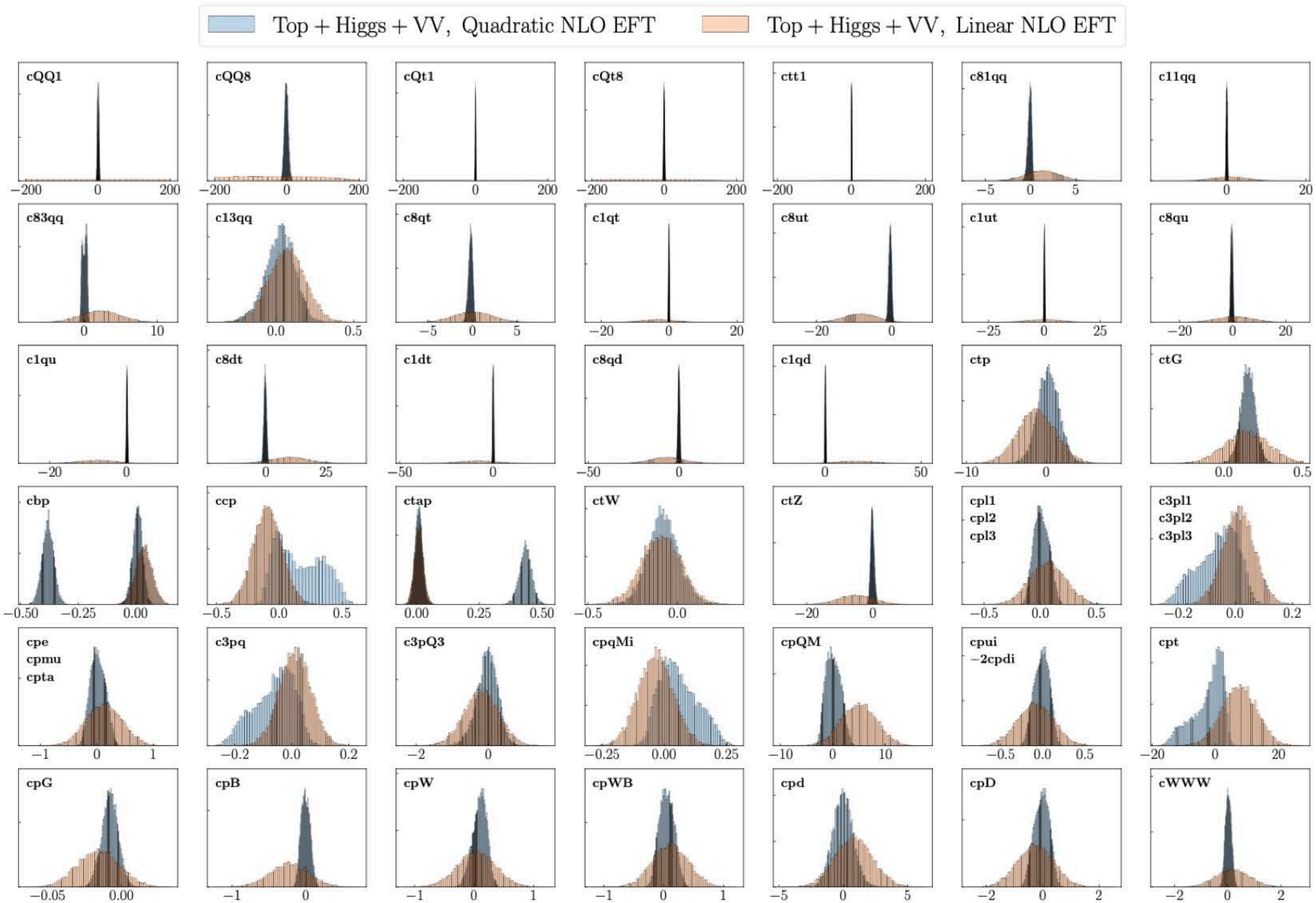

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Some bounds purely $O(\Lambda^{-4})$

1) imprecise data

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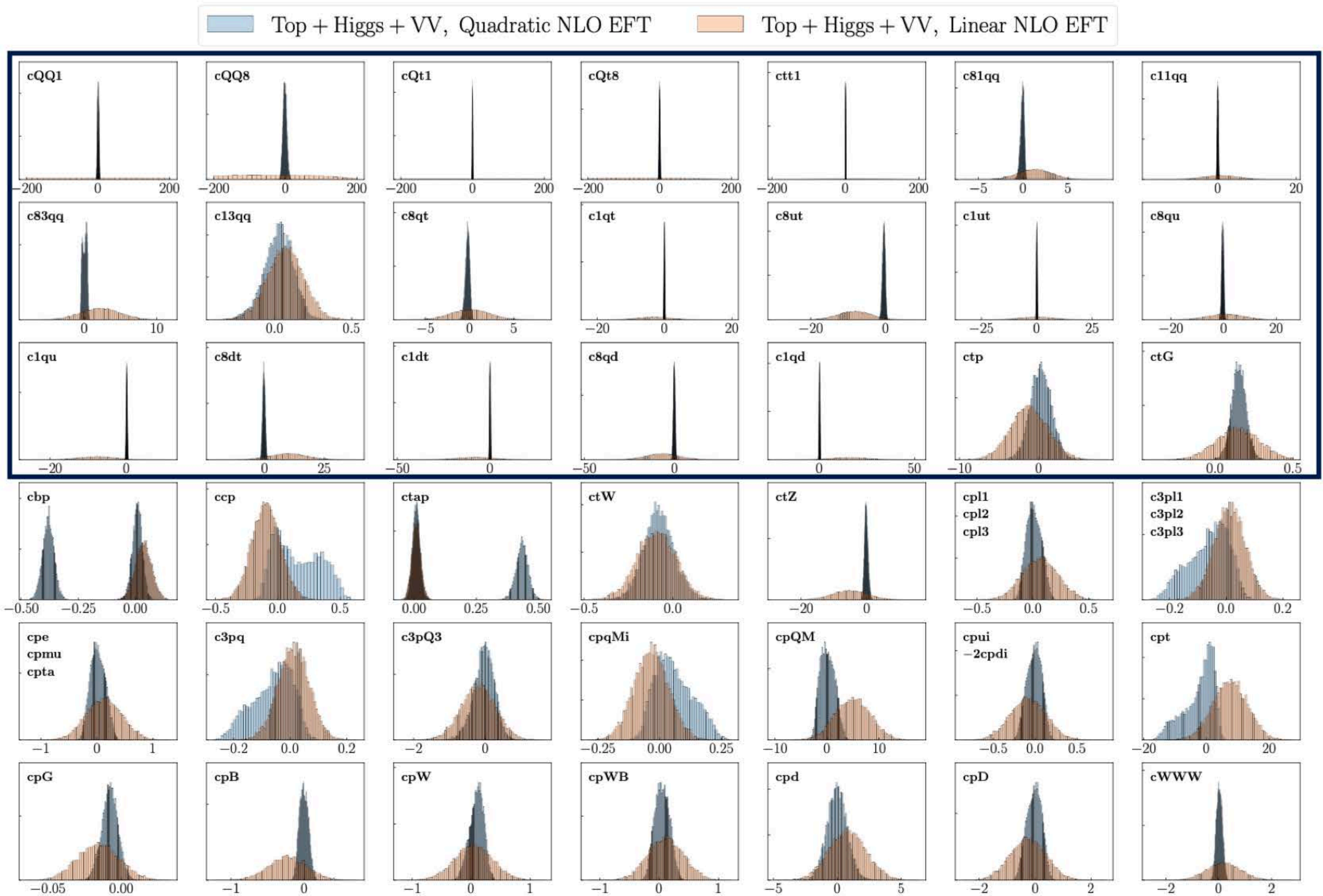

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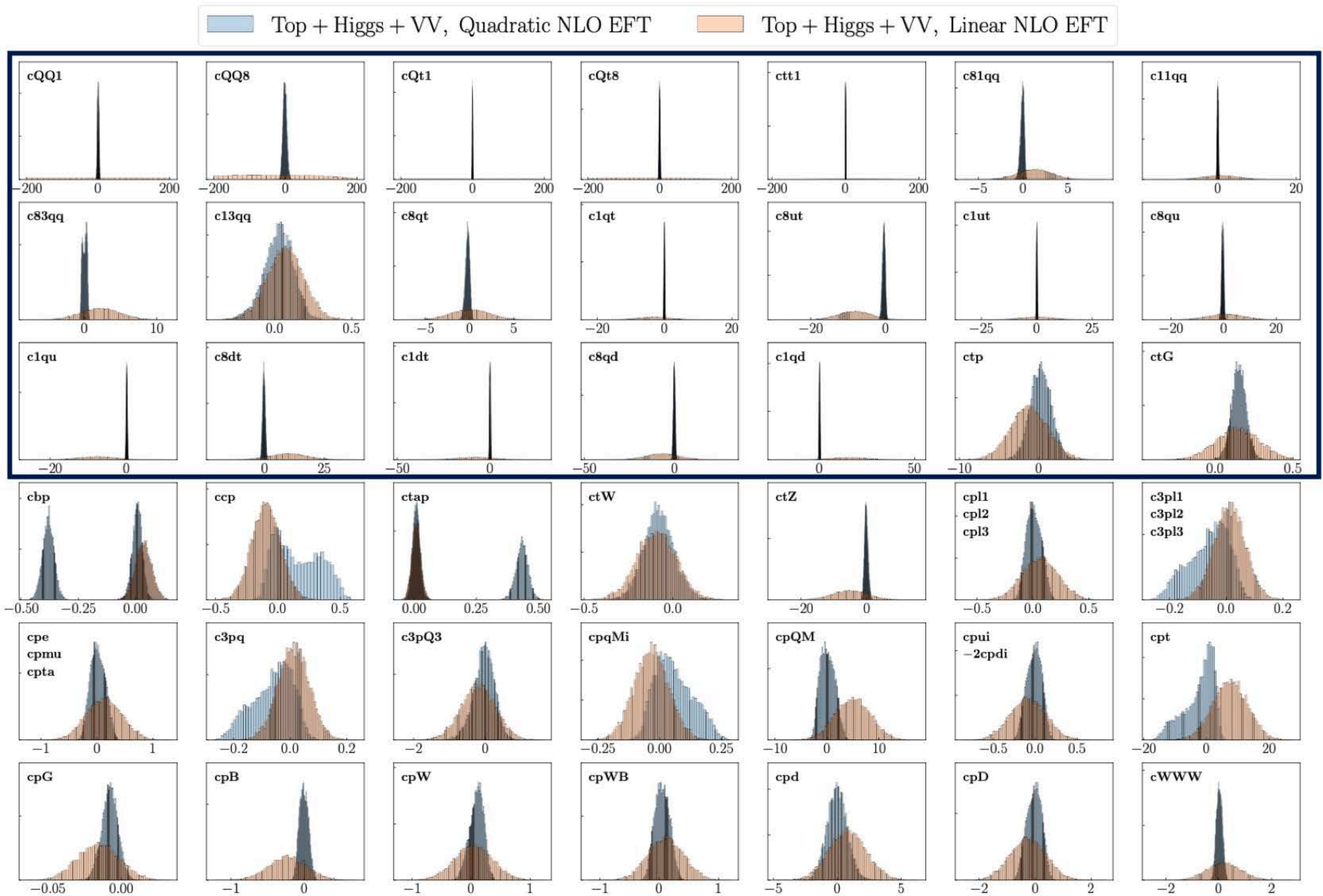

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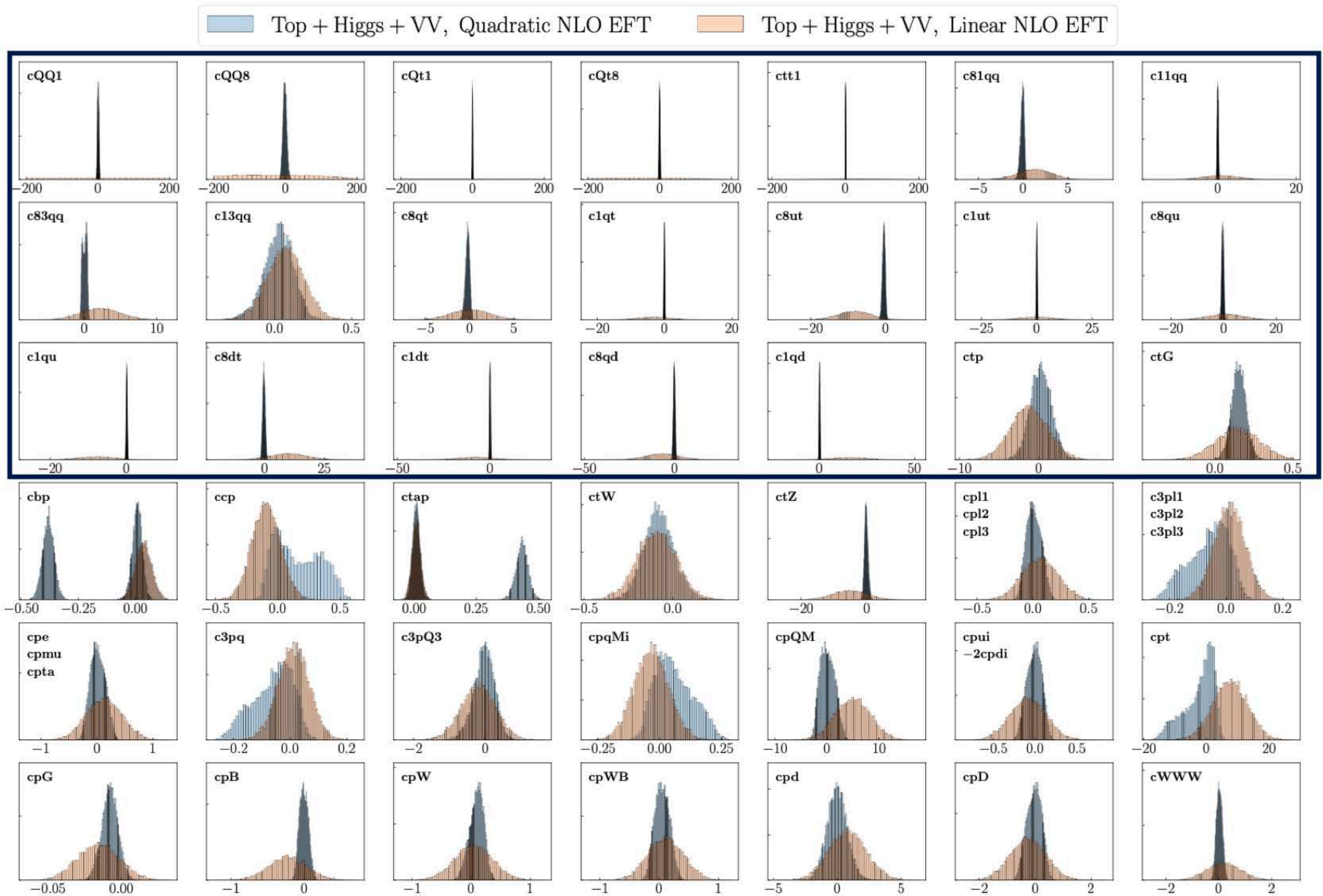
Dim-8 effects? EFT validity?



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[Ethier et al.; JHEP 11 (2021) 089]

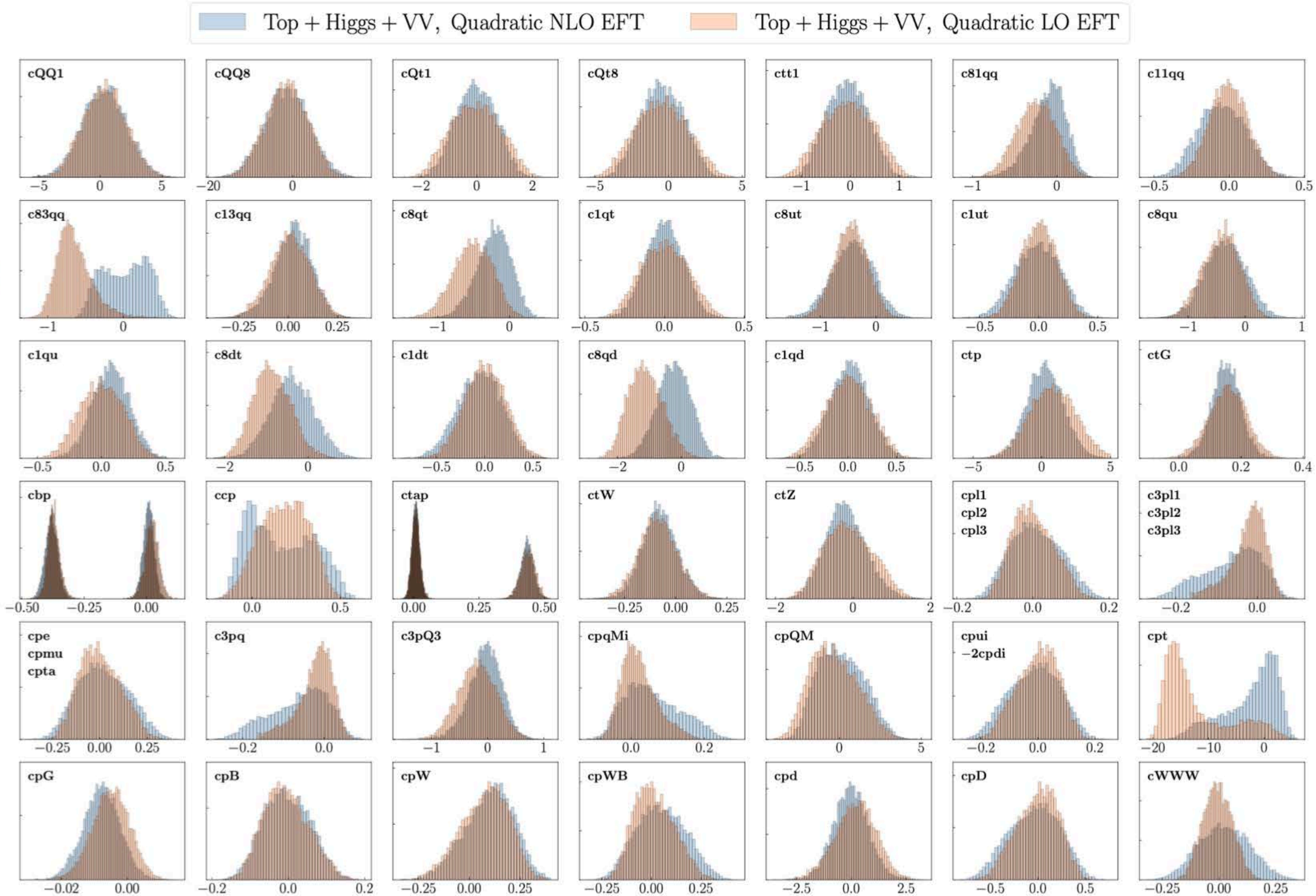
SMEFTatNLO

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

[Degrande et al.; PRD 103 (2021) 9, 096024]

Top is coloured

Non-trivial QCD corrections



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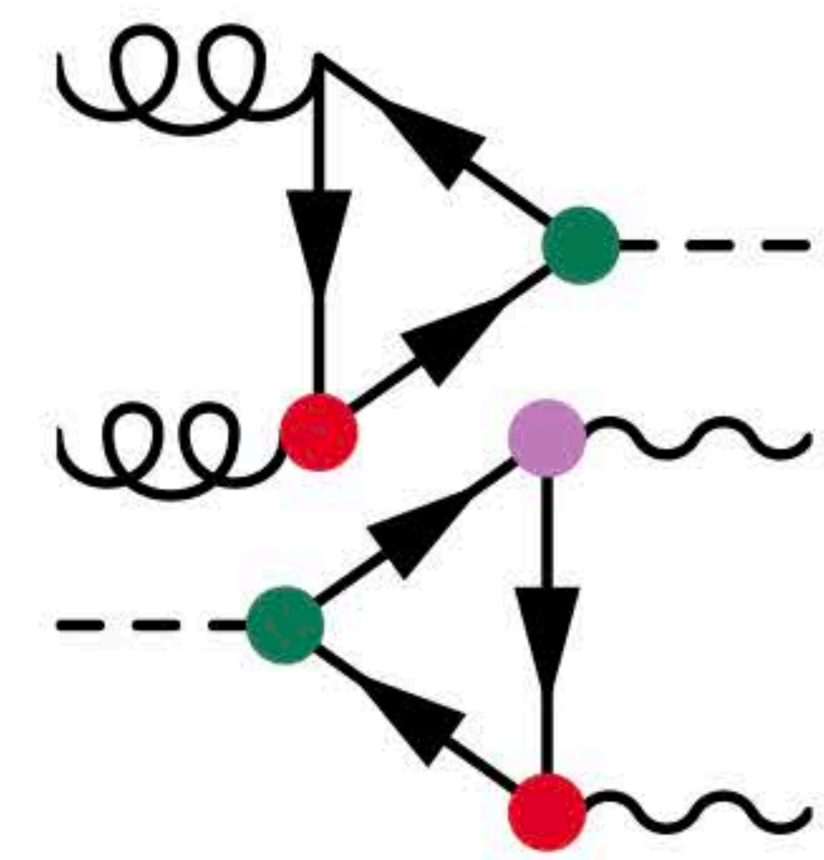

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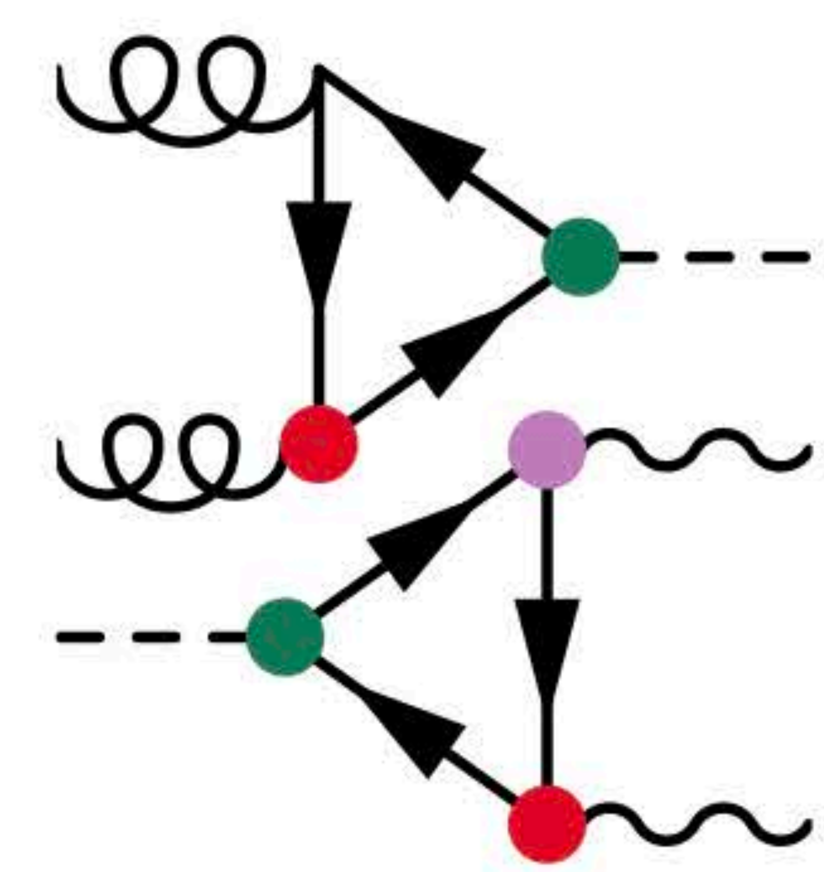

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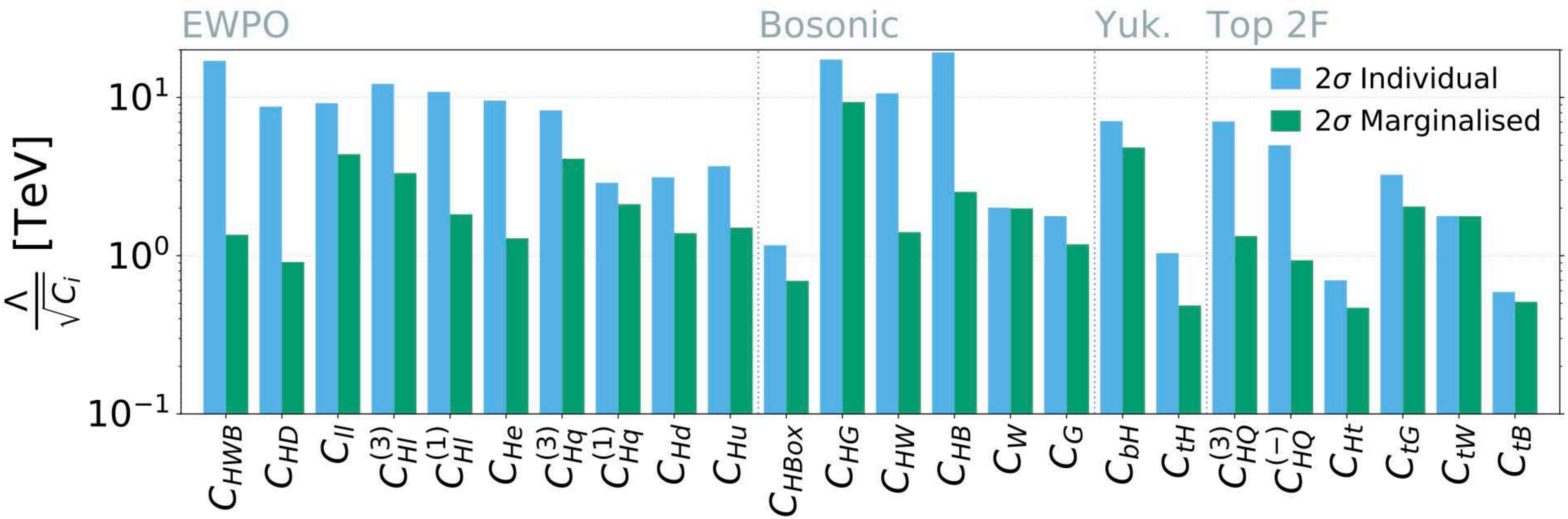
SMEFiT: individual bounds dominated by Higgs data!

- Weak dipoles & $Z\bar{t}t$ current operators $\left(C_{tW}, C_{tZ}, C^{(-)}_{\varphi Q}, C^{3}_{\varphi Q}, C_{\varphi t}\right)$
- Also contributions to $gg \to Zh/ZZ/Z\gamma/WW$
- Complementary indirect sensitivity from non-top data

Top EW interactions



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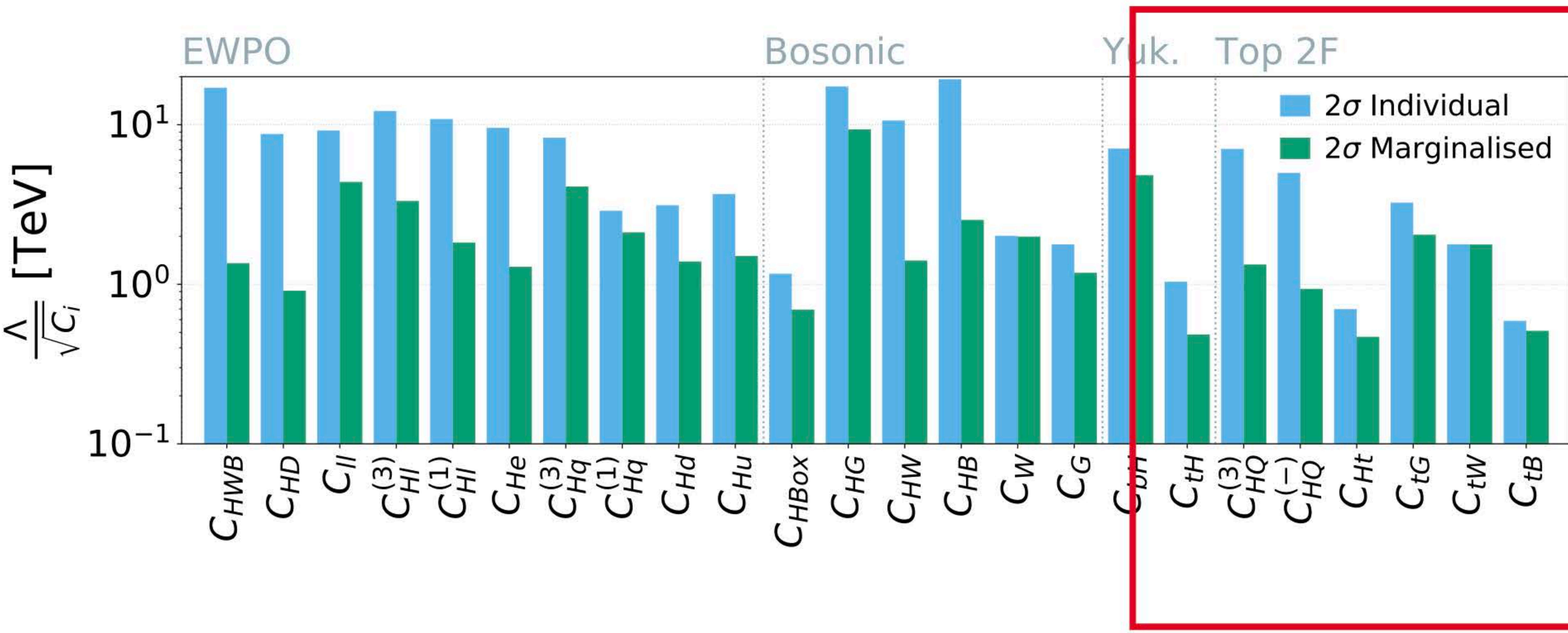

[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]

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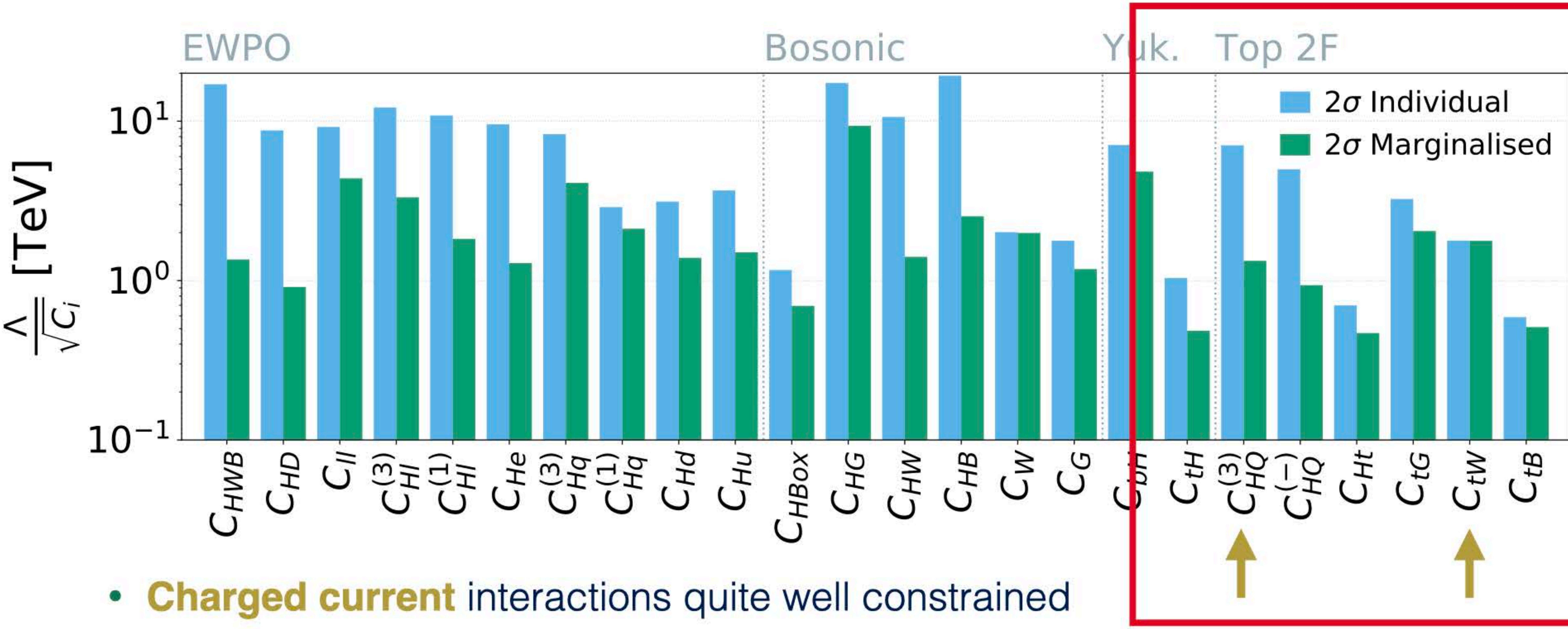

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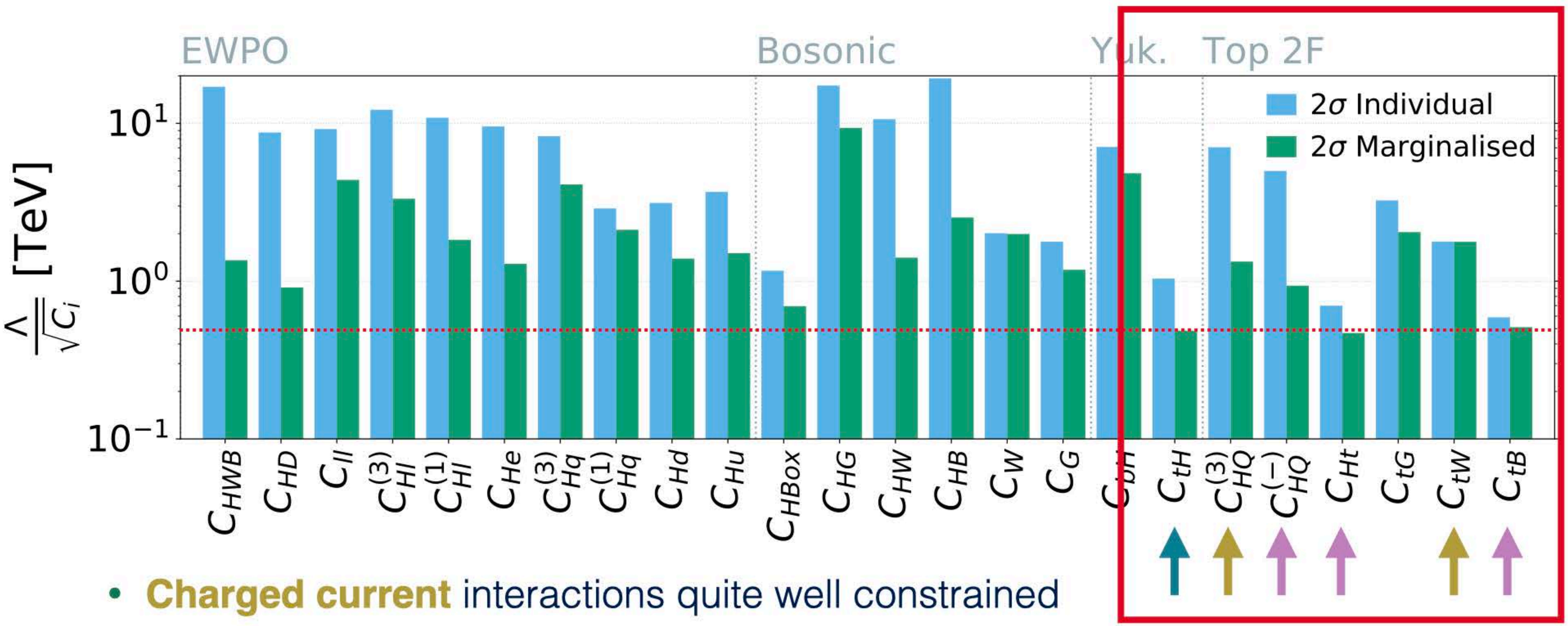

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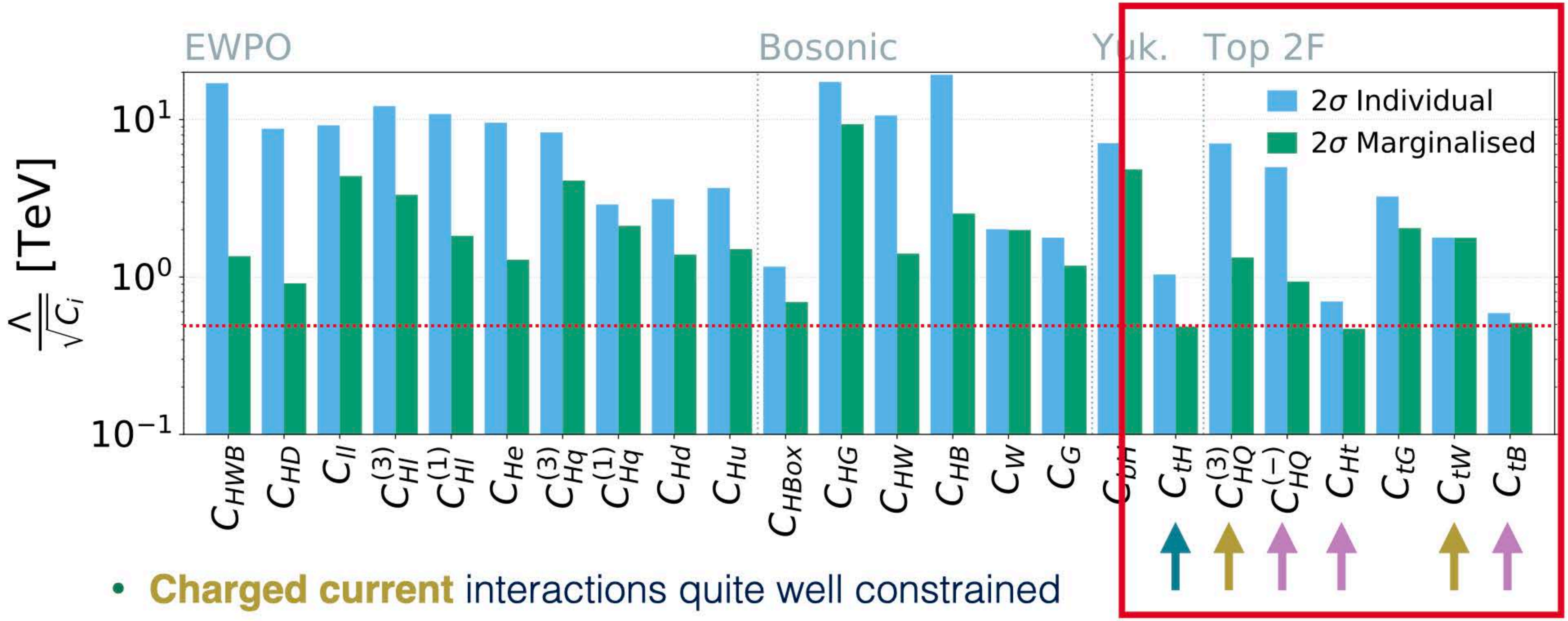

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How can we improve?

High energy & multiplicity

Improving sensitivity = collect more data. Is it enough?

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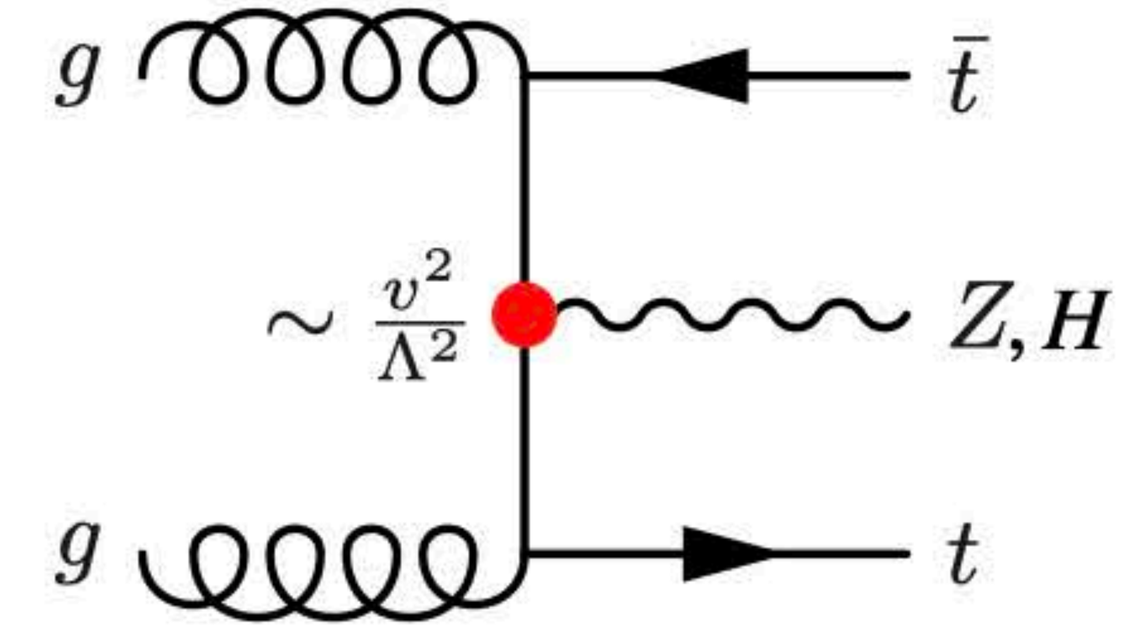
$t\bar{t}X$ for Yukawa & neutral current operators



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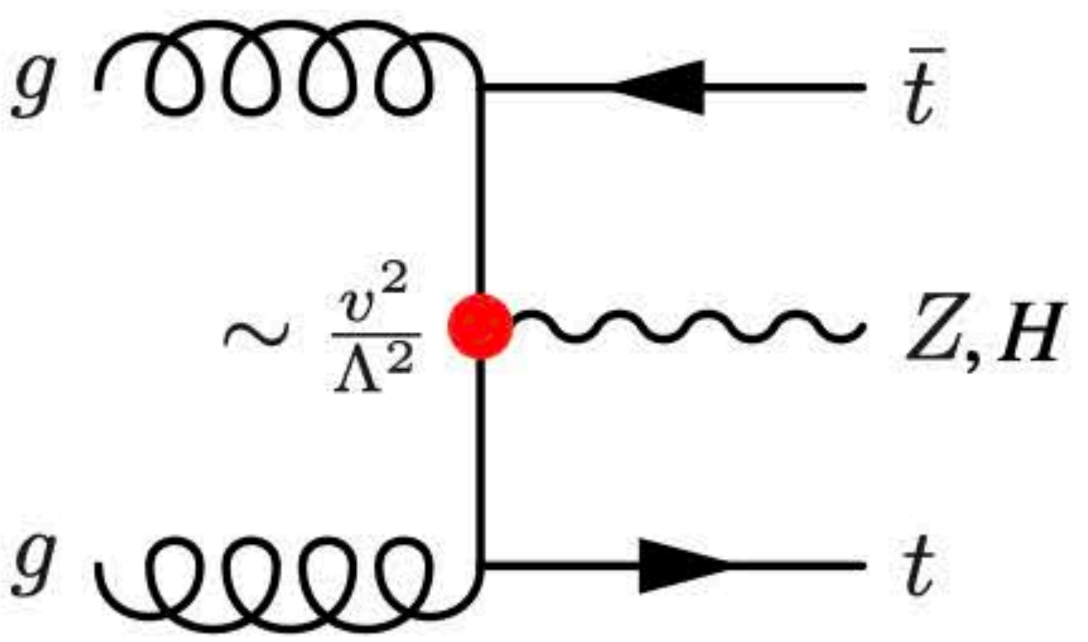

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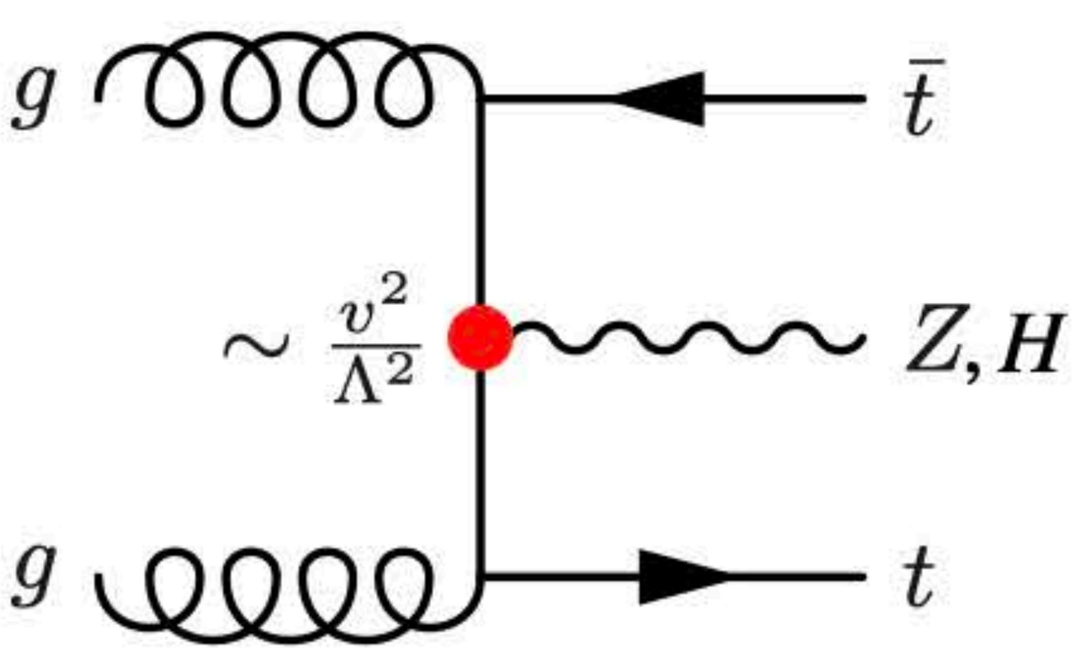

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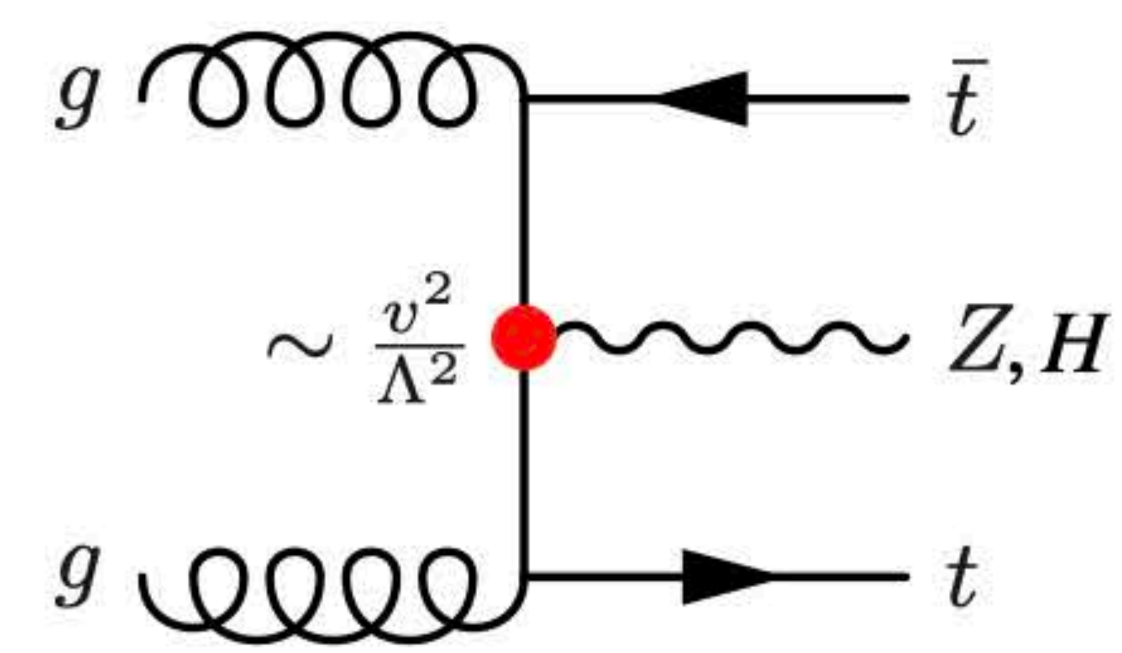

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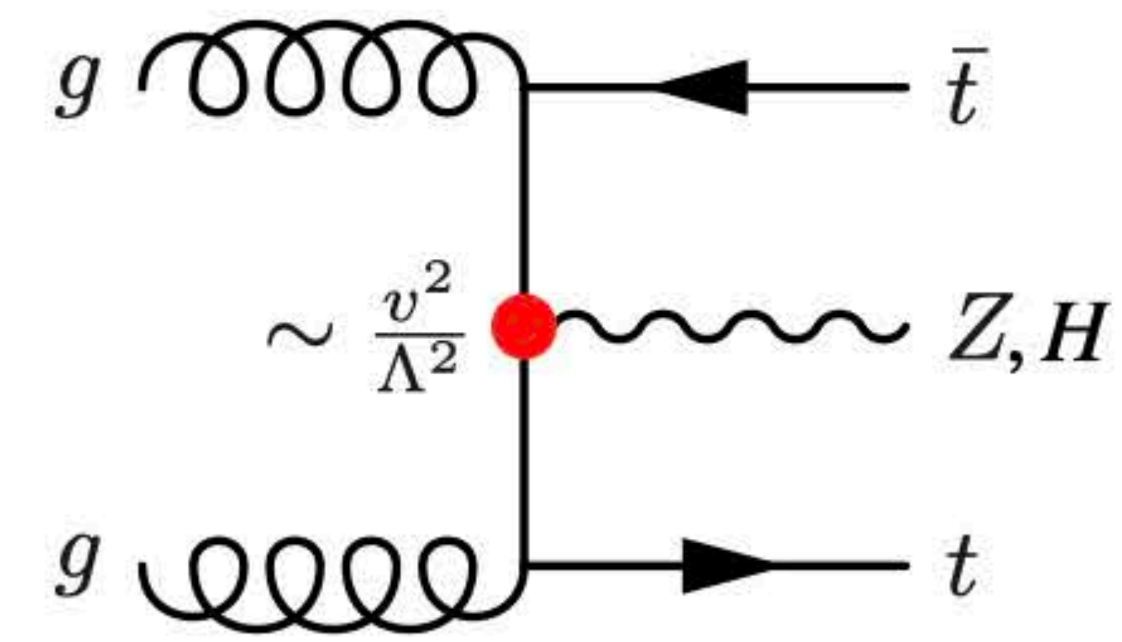

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Increasingly high-energy measurements scale with lumi.

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

[Dror et al.; JHEP 01 (2016) 071]
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Finding the right process

Gauge invariance +
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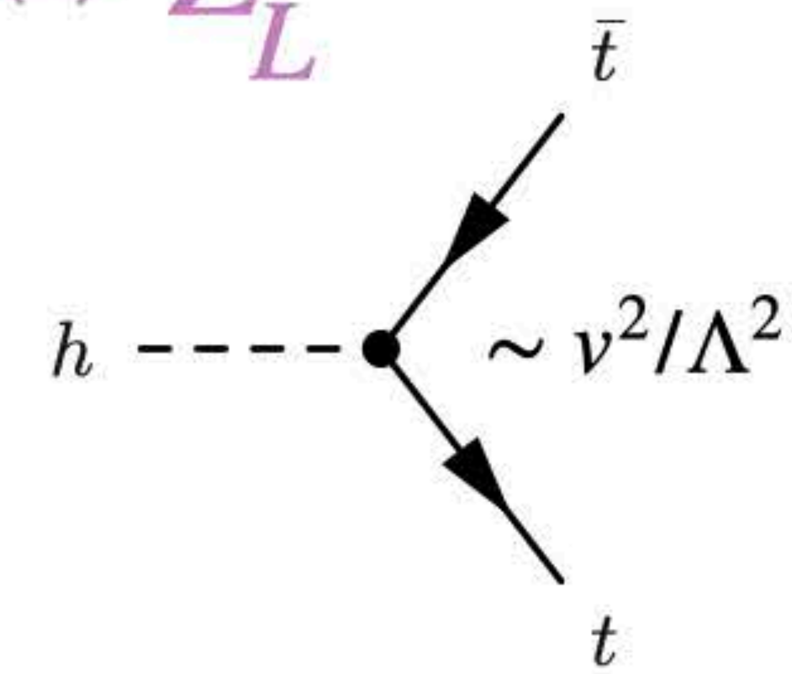

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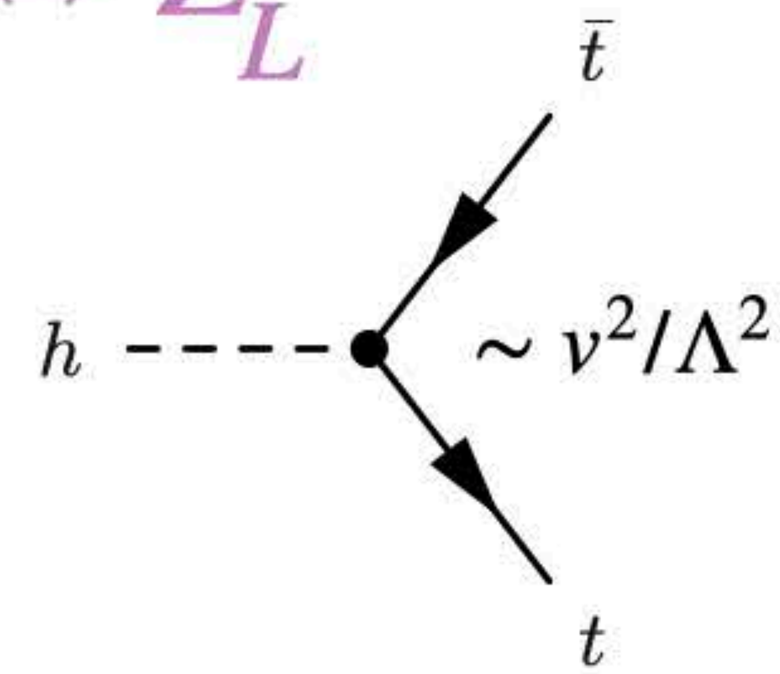

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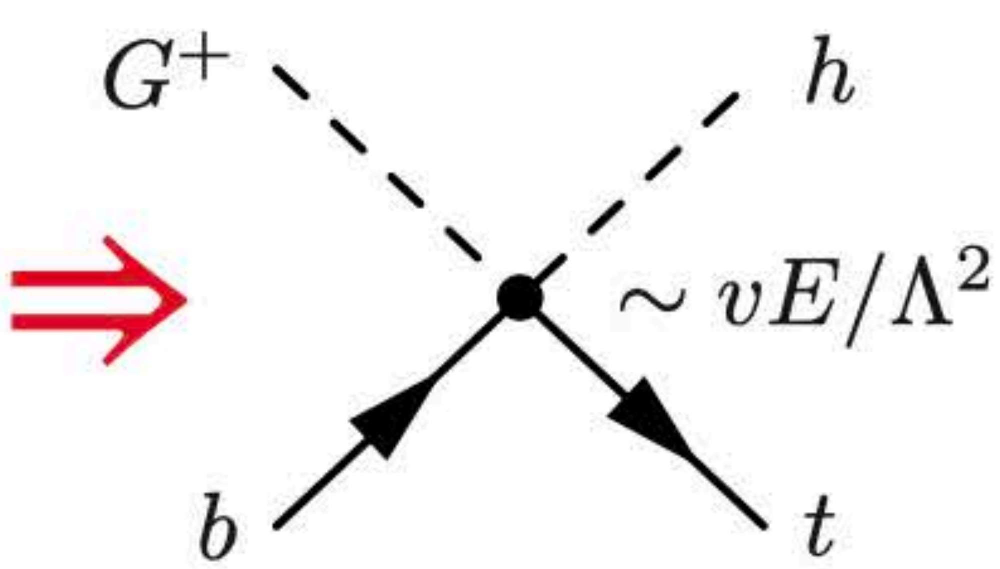

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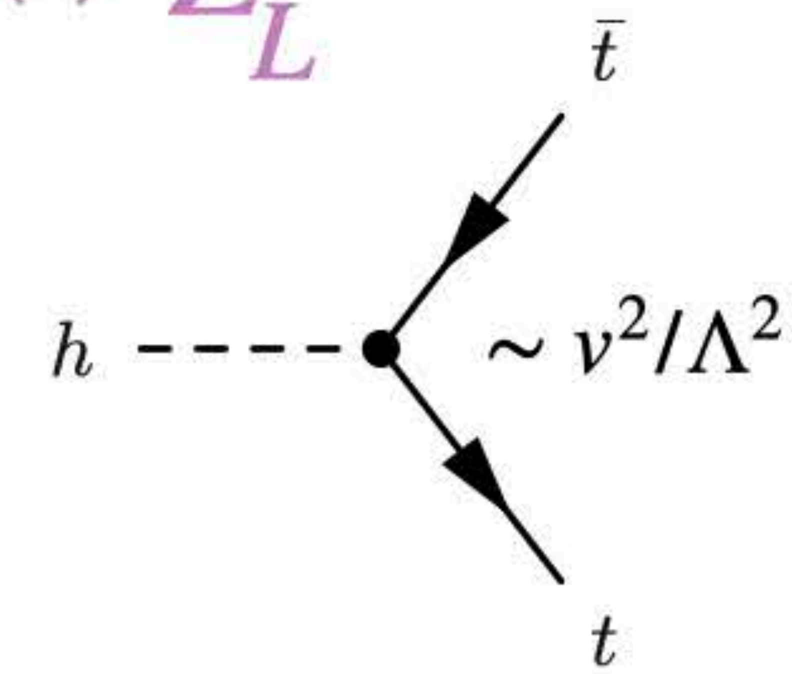

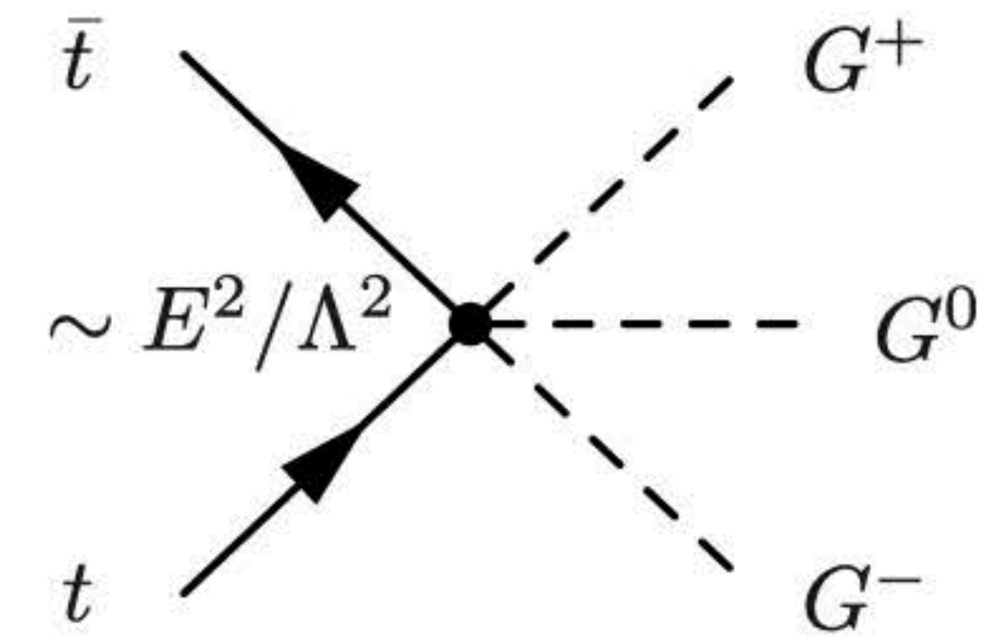

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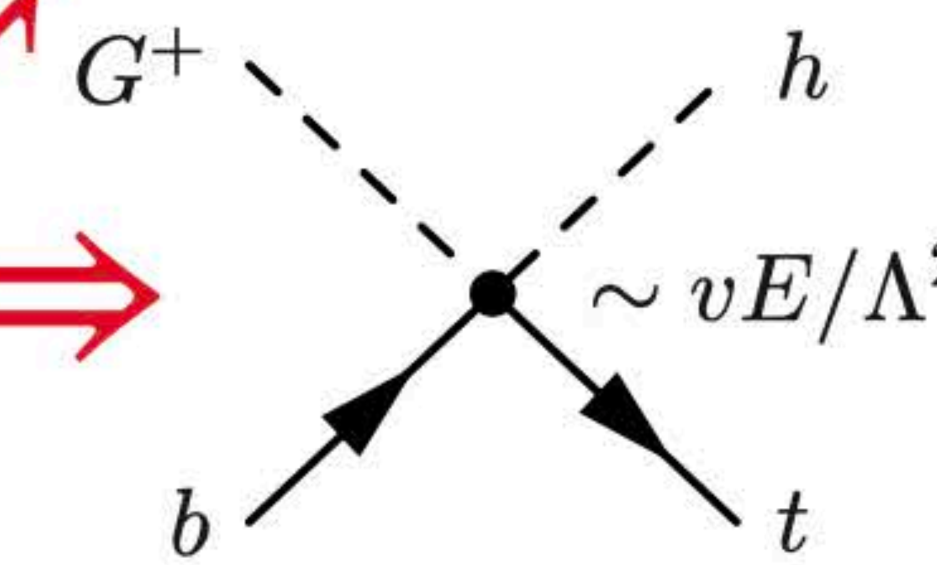

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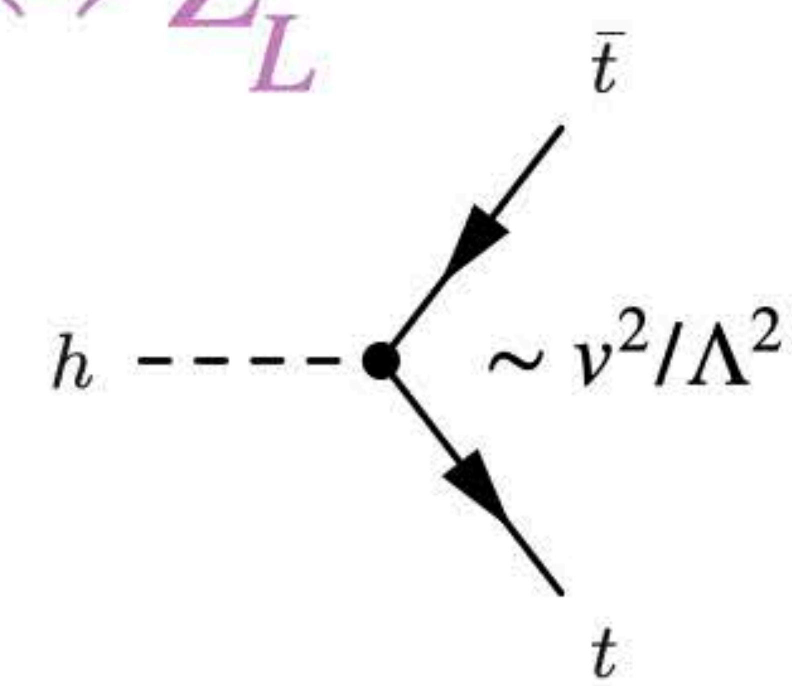

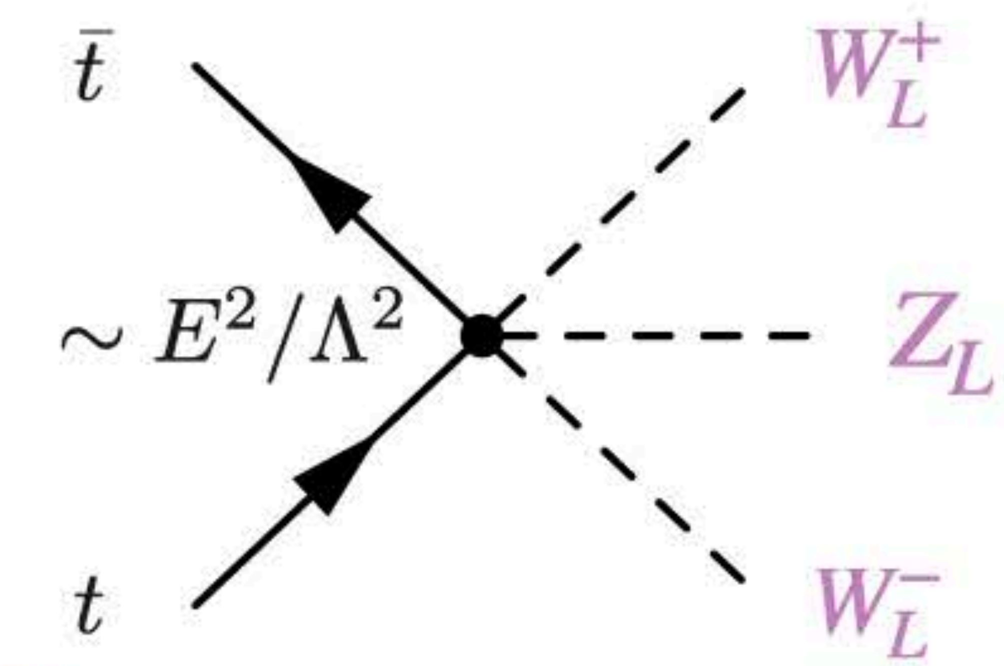

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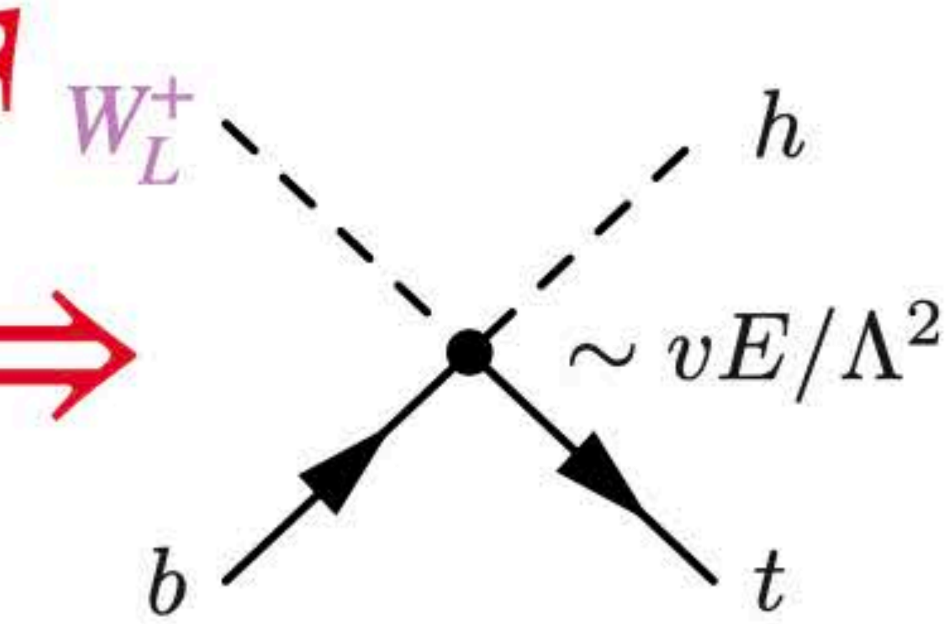

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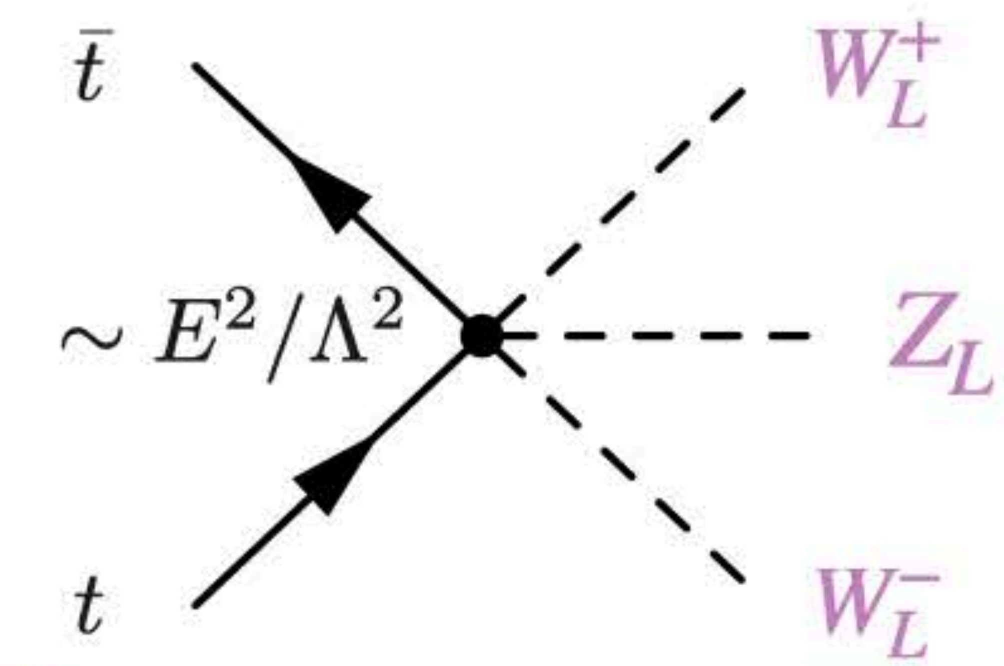

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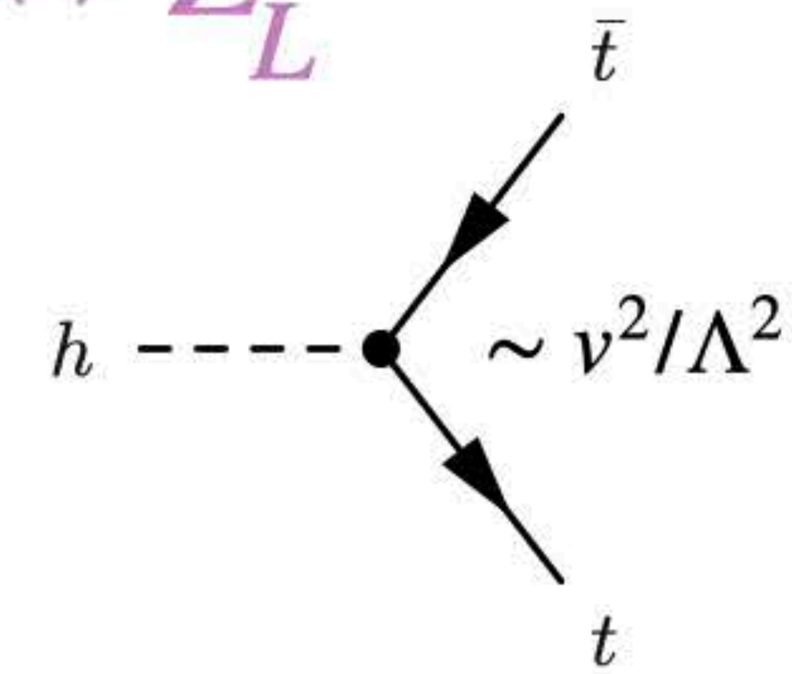

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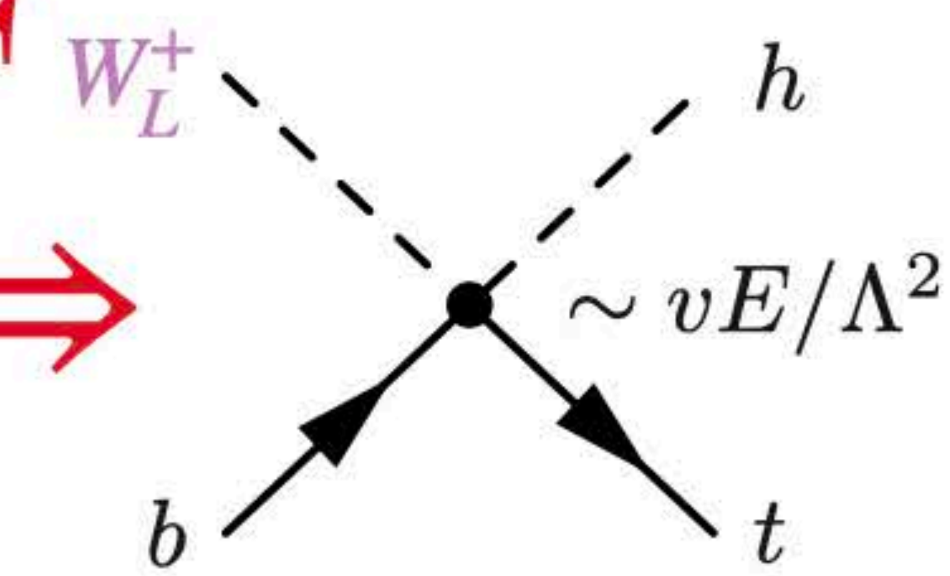
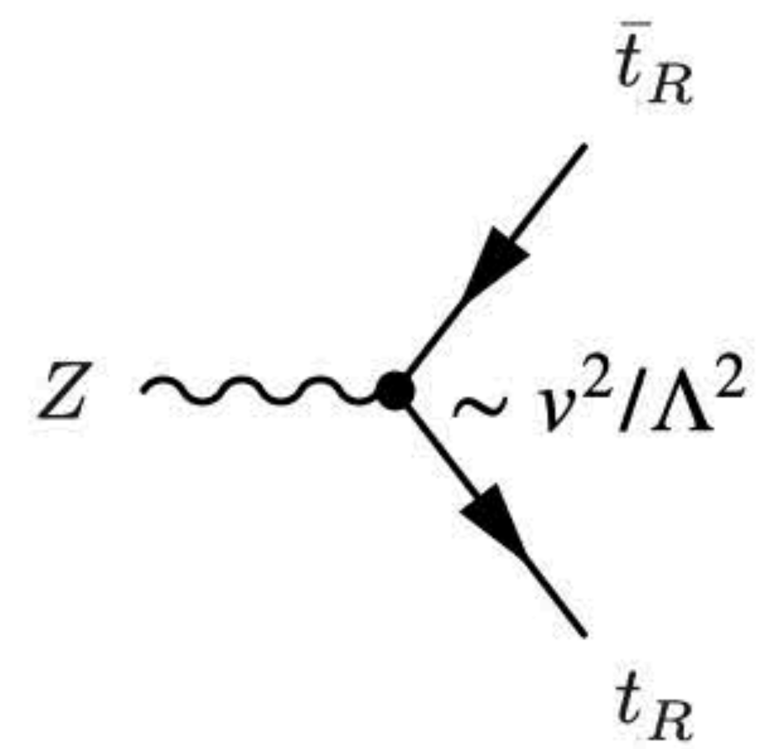


$C_{Ht}\, i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R\gamma^\mu t_R) \quad \Rightarrow$



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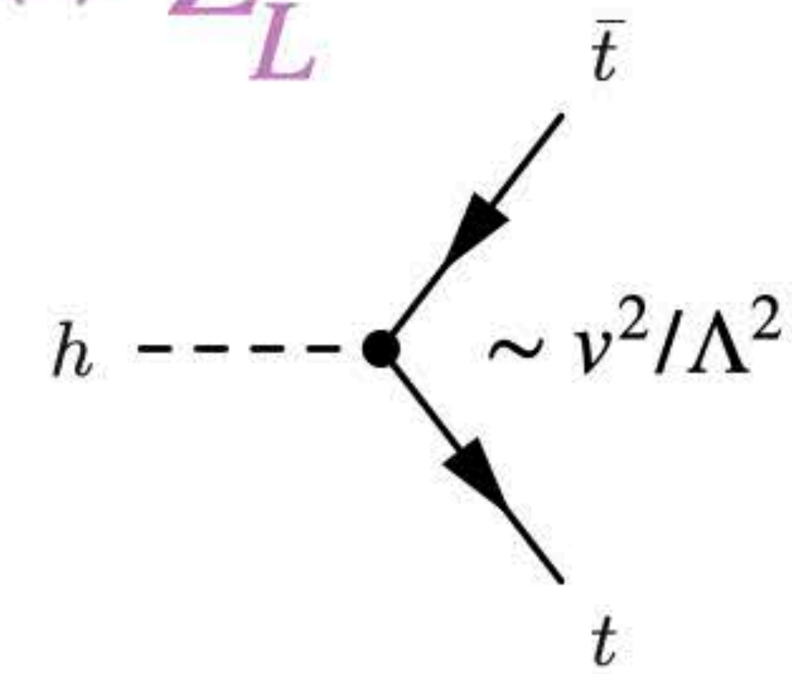
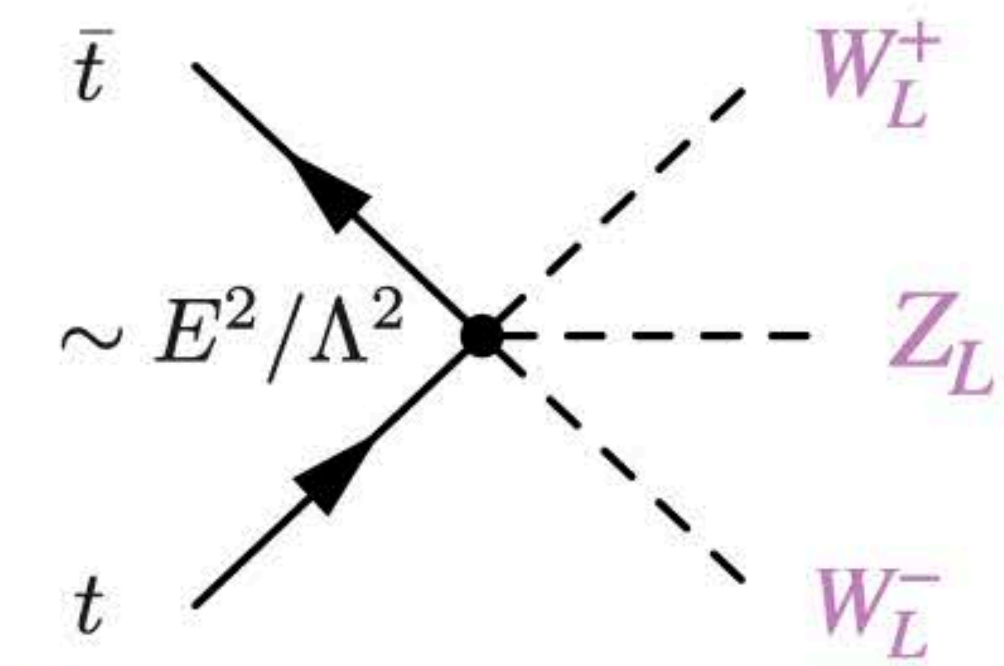
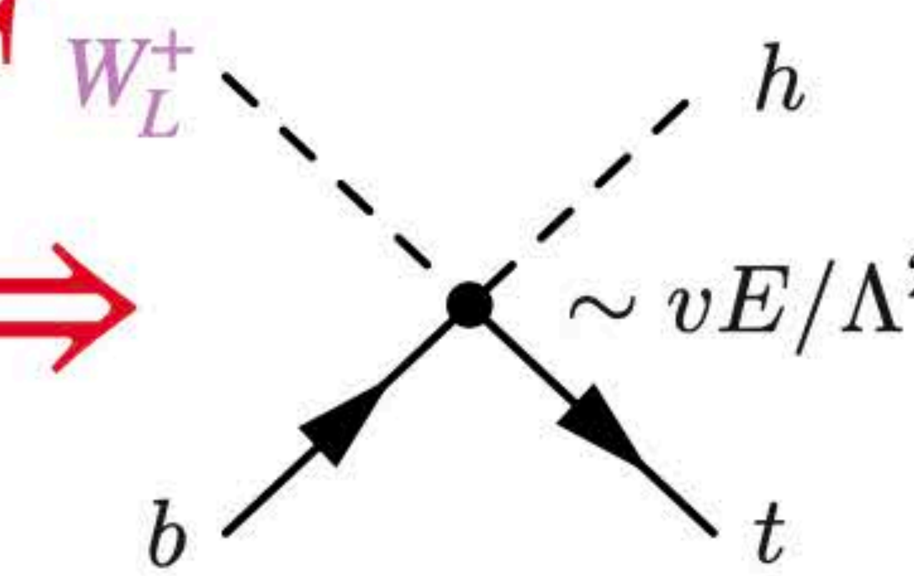
$C_{tH}(H^\dagger H)(\bar{Q}t\tilde{H})$ $\quad \langle H^\dagger H\rangle = v^2 \quad \Rightarrow$

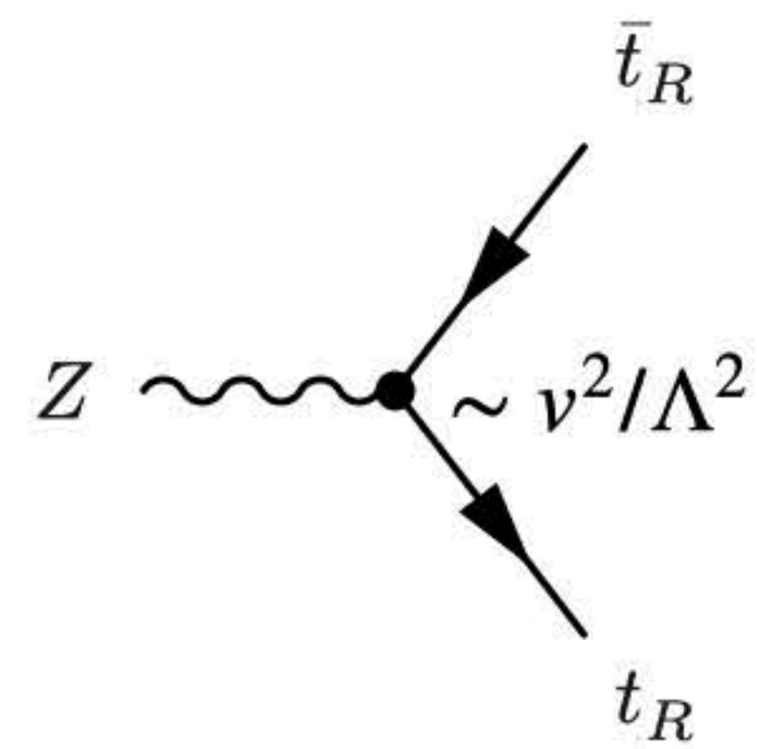




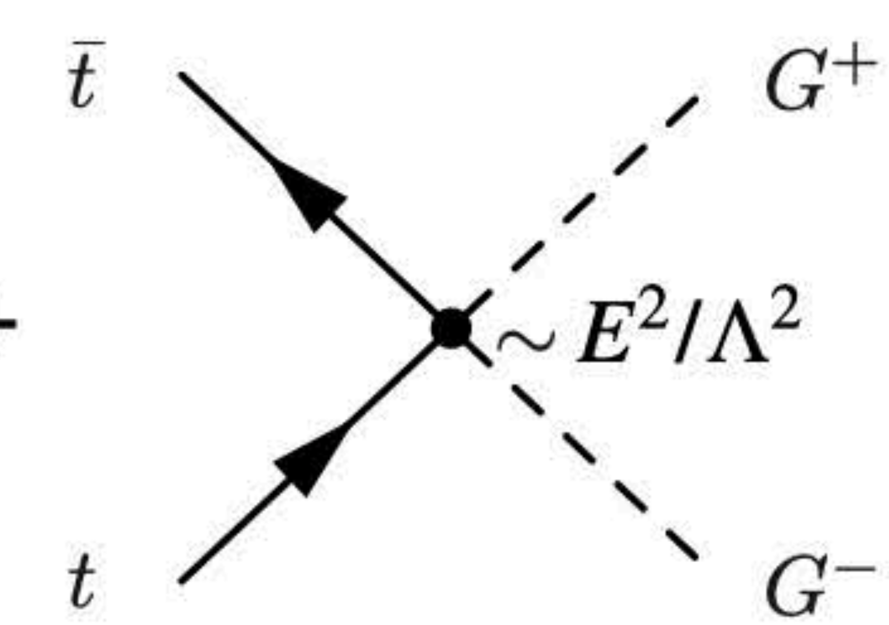
Feynman gauge $\quad \langle H^\dagger H\rangle = v^2 + 2vh + h^2 + G^+G^- + G_0^2 \quad \Rightarrow$



$C_{Ht}\, i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R\gamma^\mu t_R) \quad \Rightarrow$



+

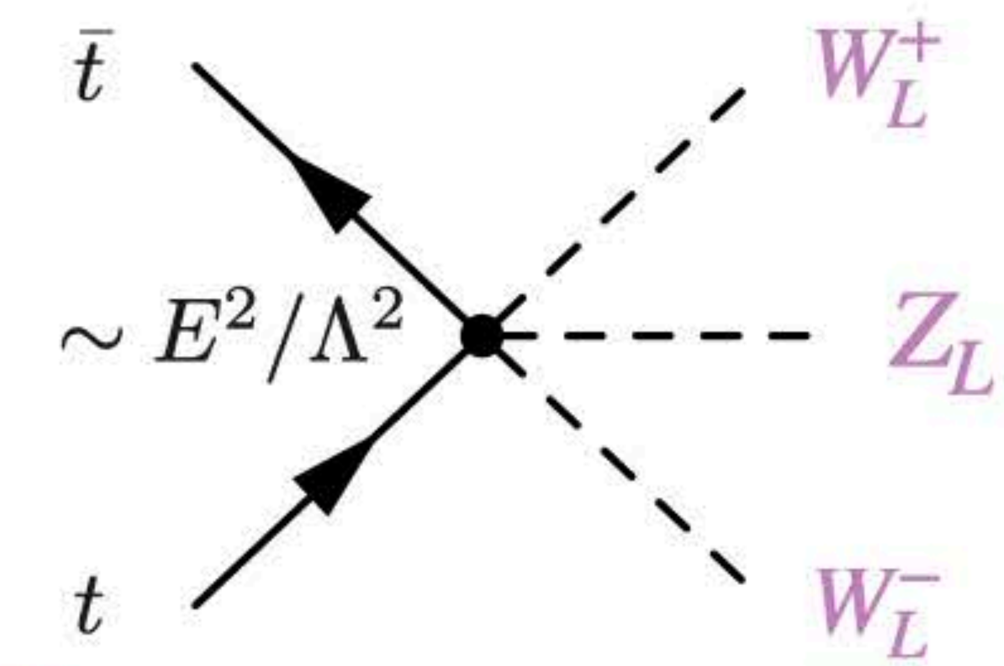


$$\boxed{\begin{array}{c} t\,W_L \to t\,W_L \\ t\,Z_L \to t\,h \\ b\,W_L \to t\,Z_L \\ b\,W_L \to t\,h \end{array}}$$

[Dror et al.; JHEP 01 (2016) 071]
[Mantani, Maltoni & KM; JHEP 10 (2019) 004]

Finding the right process

Gauge invariance +
Goldstone equivalence theorem: $\partial^\mu G \leftrightarrow Z_L^\mu$



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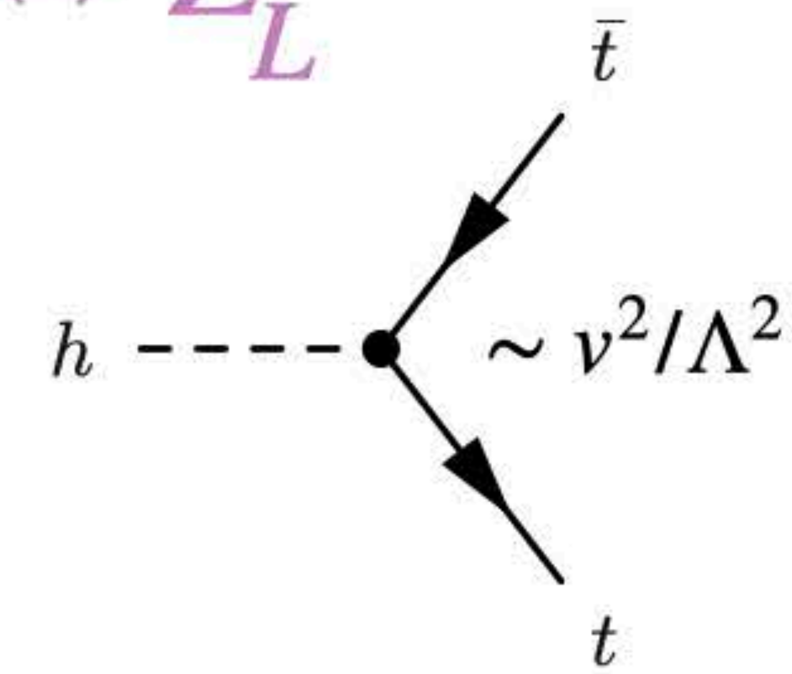

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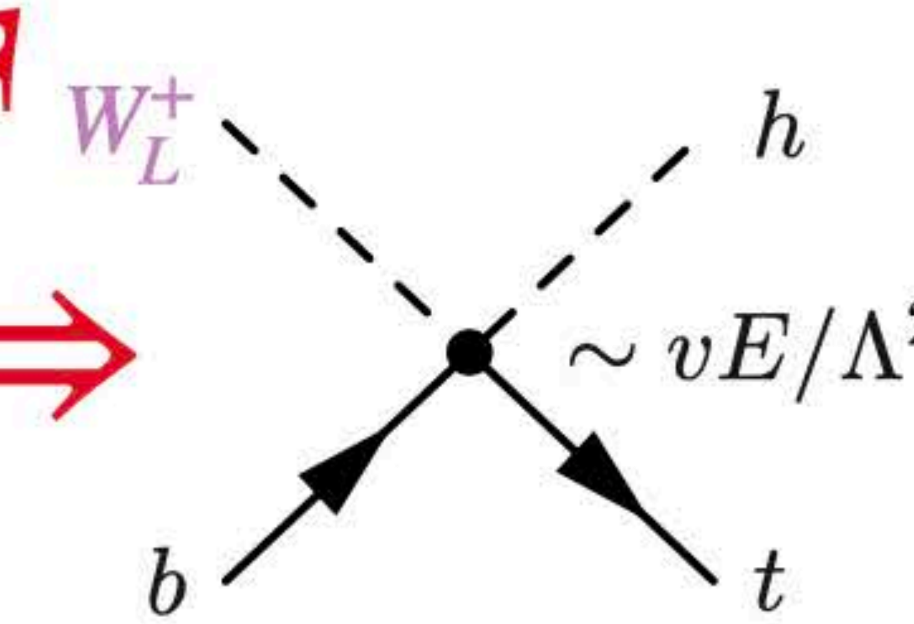

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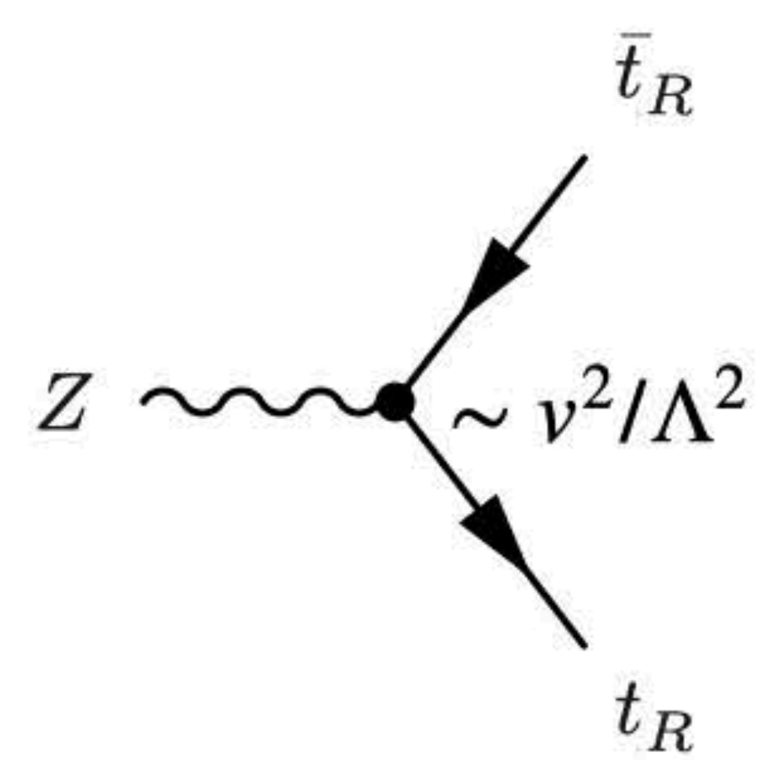

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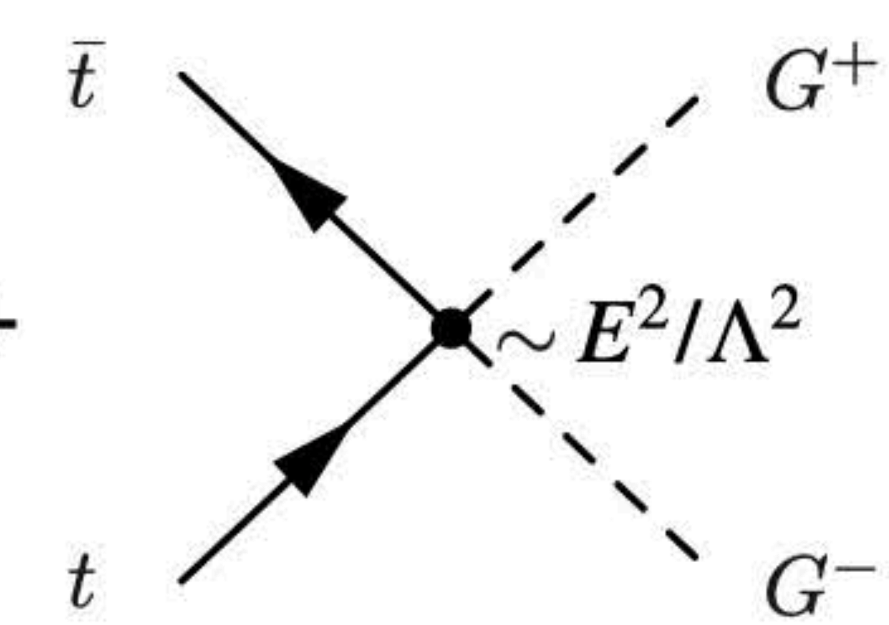

$$\boxed{\begin{array}{c} t\,W_L \to t\,W_L \\ t\,Z_L \to t\,h \\ b\,W_L \to t\,Z_L \\ b\,W_L \to t\,h \end{array}}$$

Unitarity non-cancellations in scattering amplitudes $\Leftrightarrow$ **Non-renormalisable contact interactions with Goldstones**

[Dror et al.; JHEP 01 (2016) 071]
[Mantani, Maltoni & KM; JHEP 10 (2019) 004]

Finding the right process

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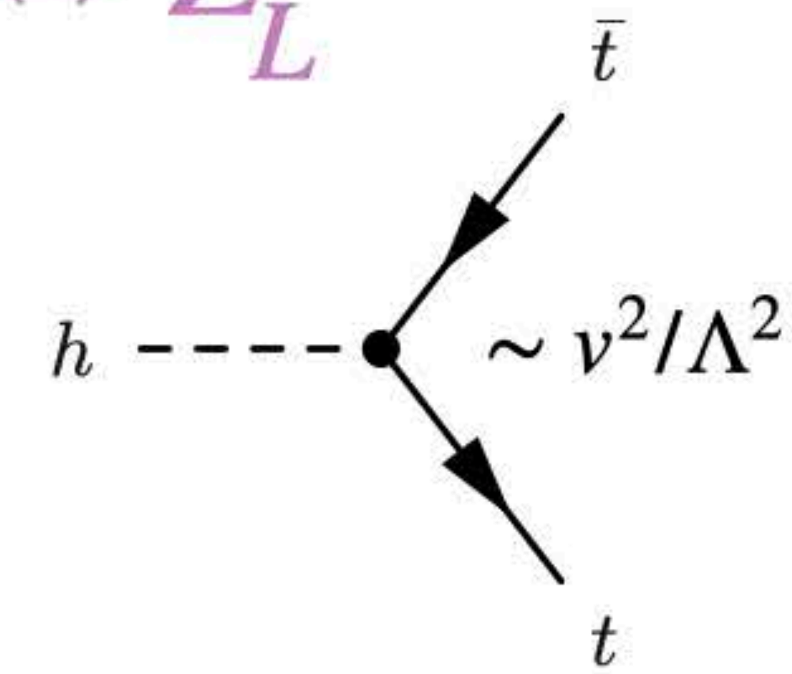

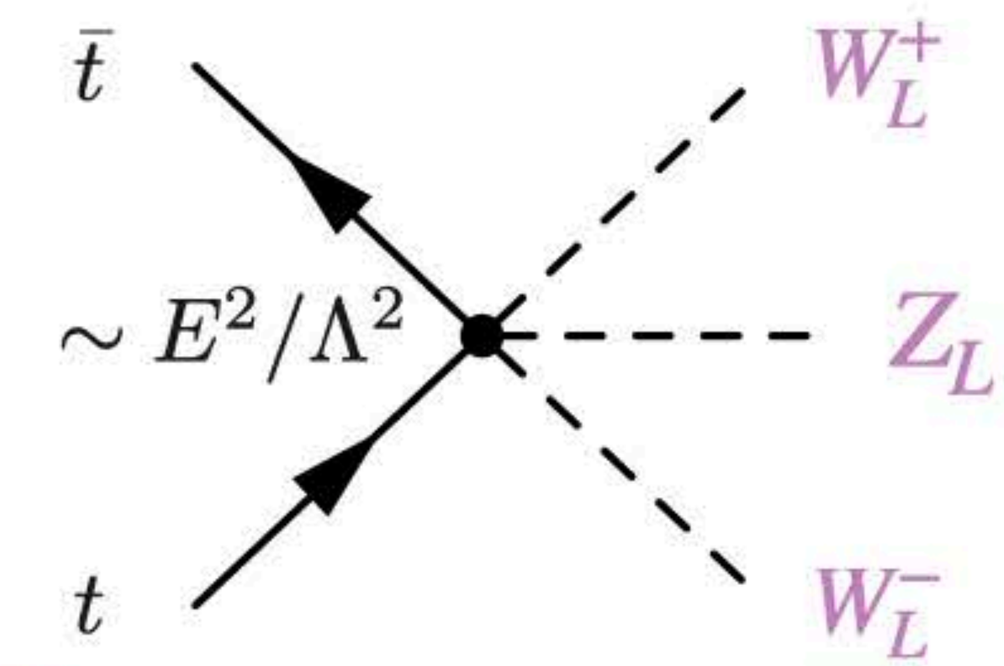

$\Uparrow$

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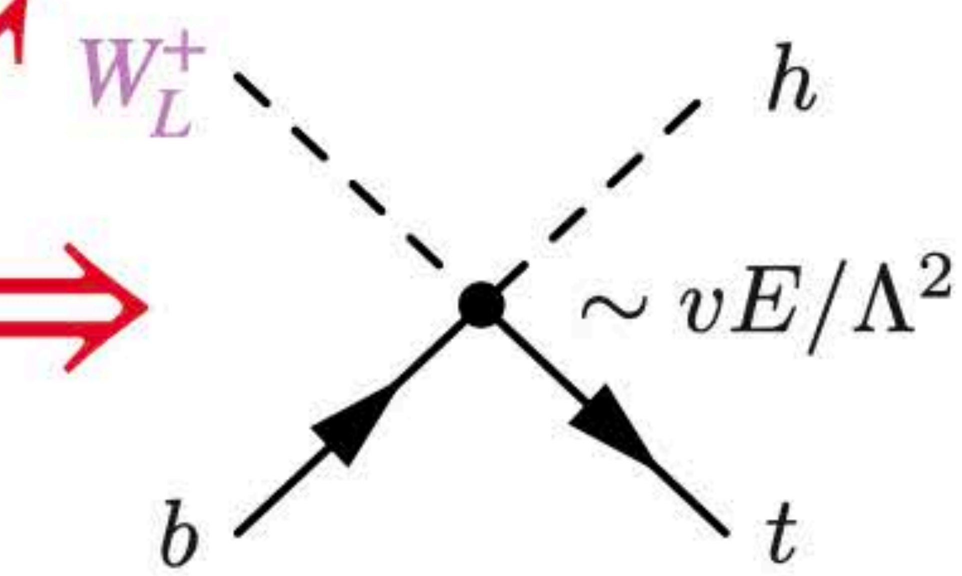

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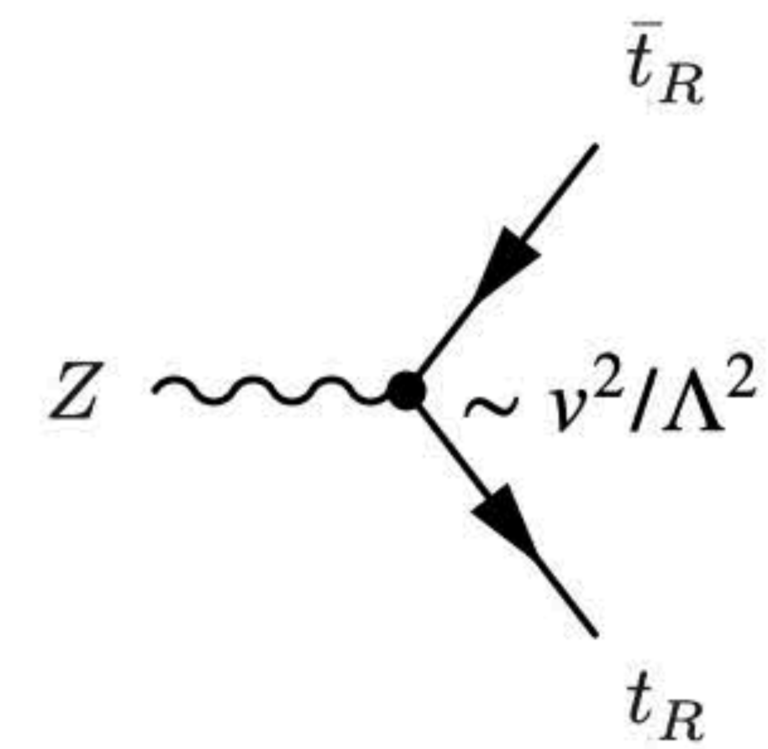

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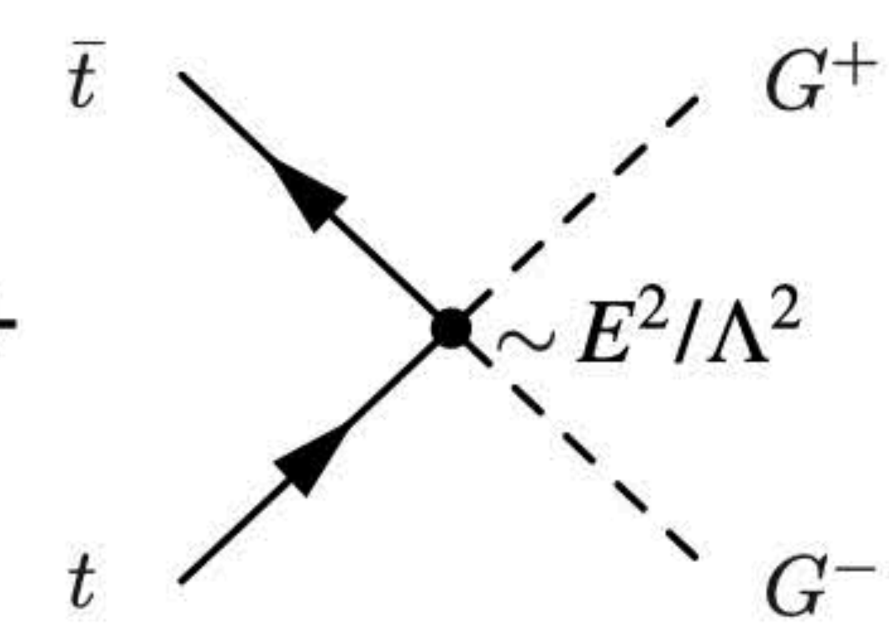


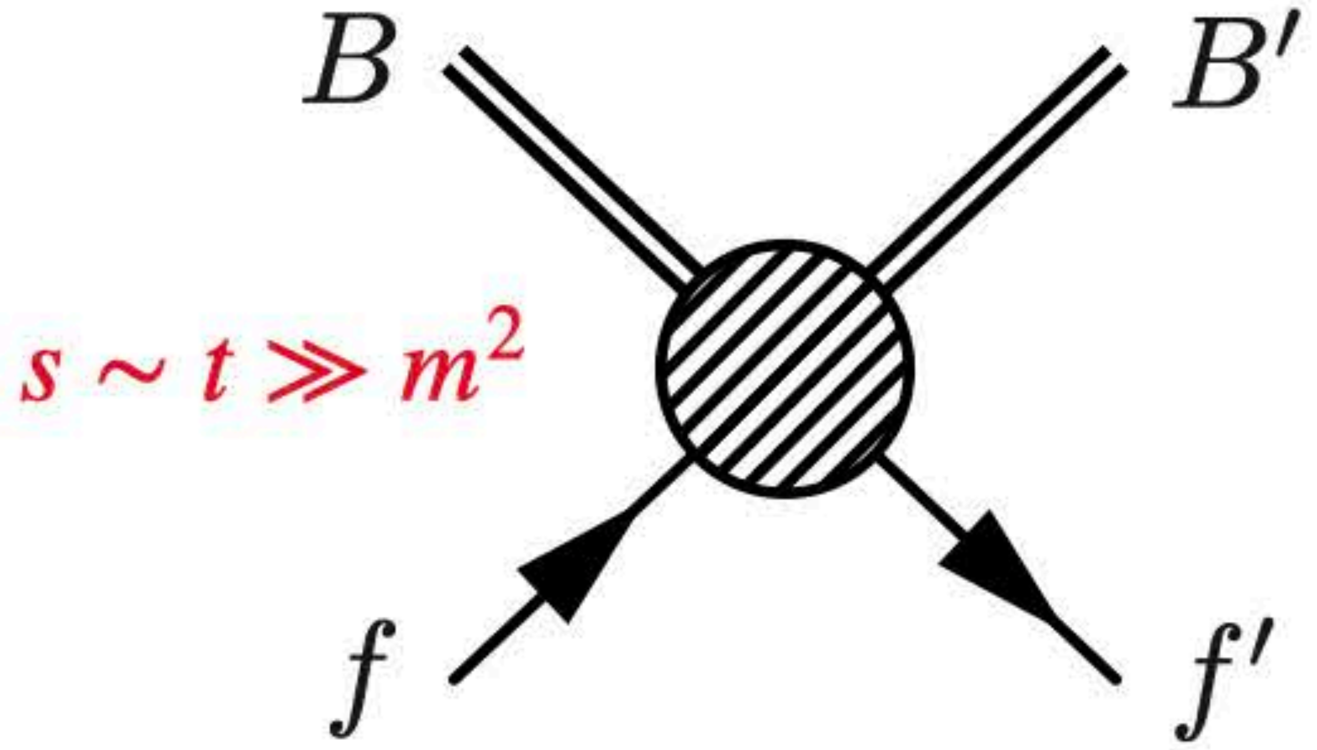
$$\boxed{\begin{array}{c} t\,W_L \to t\,W_L \\ t\,Z_L \to t\,h \\ b\,W_L \to t\,Z_L \\ b\,W_L \to t\,h \end{array}}$$

Unitarity non-cancellations in scattering amplitudes $\Leftrightarrow$ **Non-renormalisable contact interactions with Goldstones**

c.f. 'Higgs without Higgs' [Henning et al.; PRL 123 (2019) 181801]

Less vevs, more legs! (AKA multiplicity)

EW top scattering



	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
w/ Higgs	$b\,W \to t\,h$	$t\,(Z/\gamma) \to t\,h$ $t\,h \to t\,h$

$2 \to 2$ *top EW scattering amplitudes in high energy limit:*
study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT

[Dror et al.; JHEP 01 (2016) 071]
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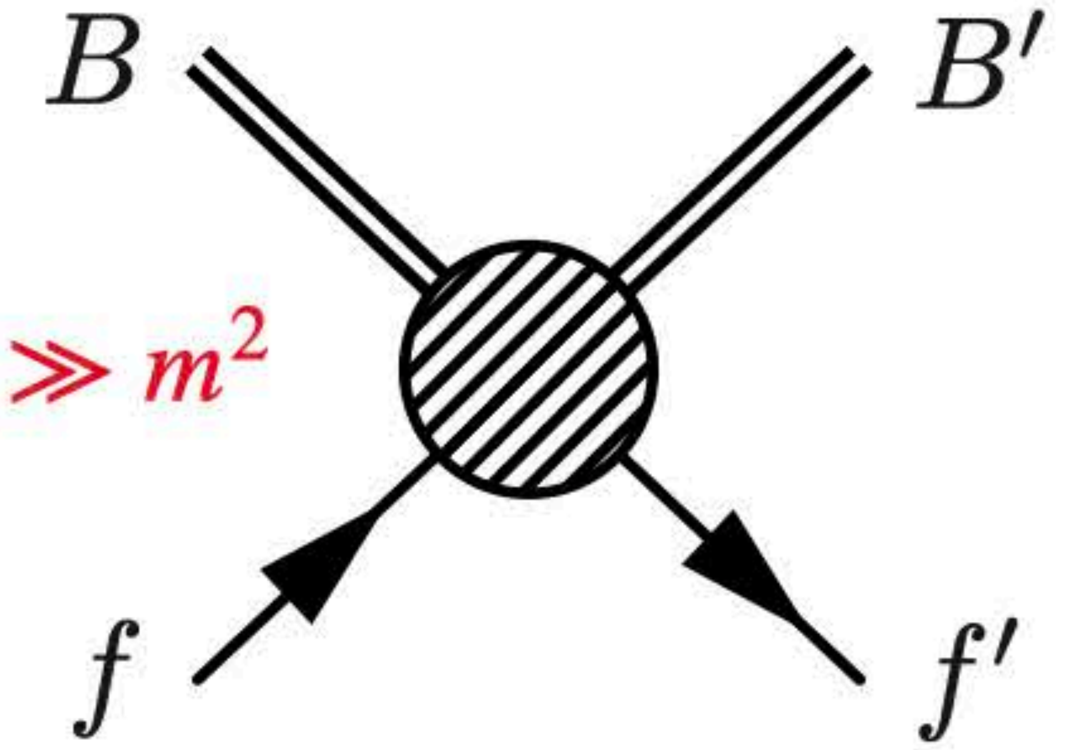

	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
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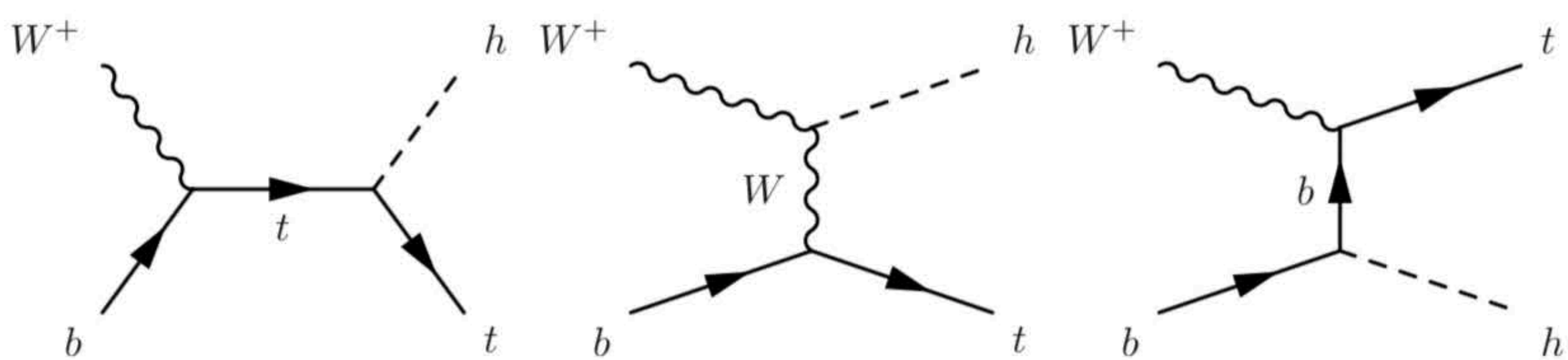

e.g. $bW \to th$

[Dror et al.; JHEP 01 (2016) 071]
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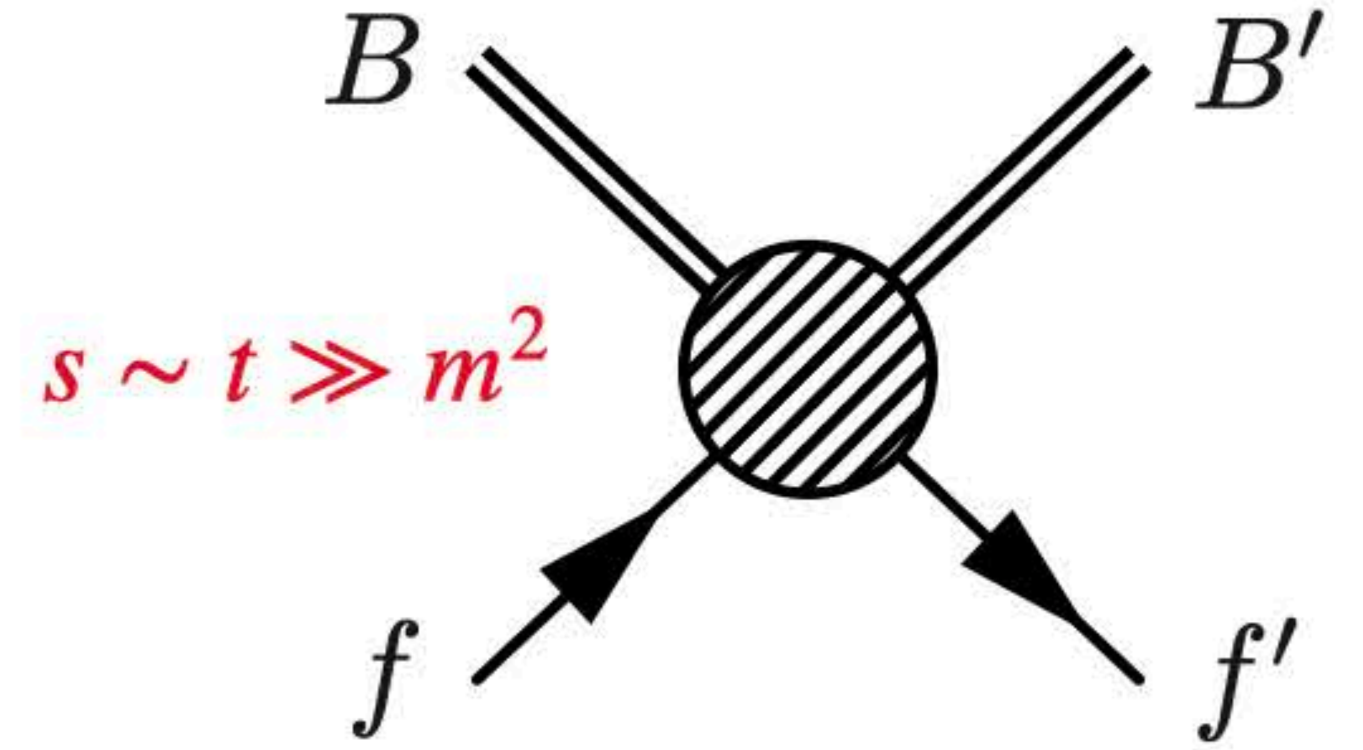
EW top scattering



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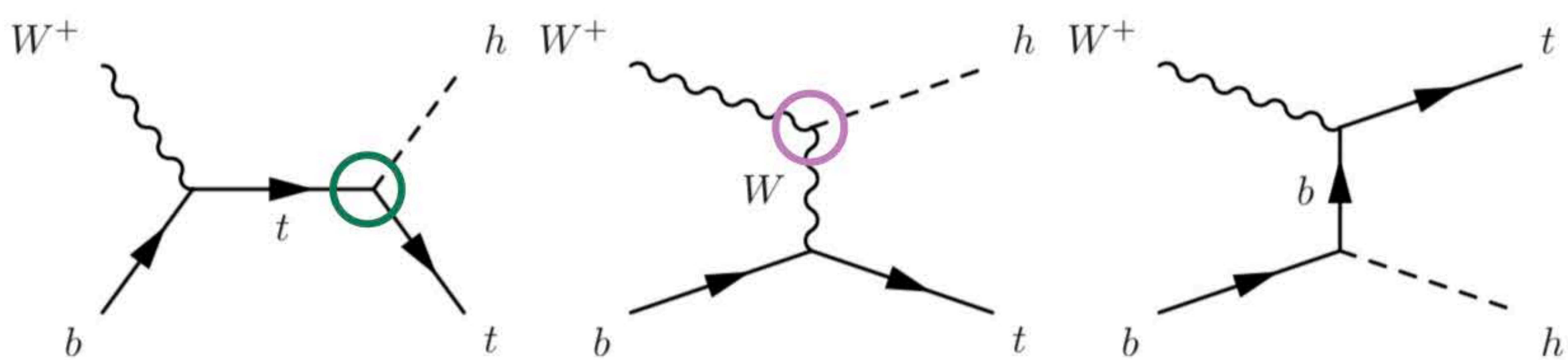
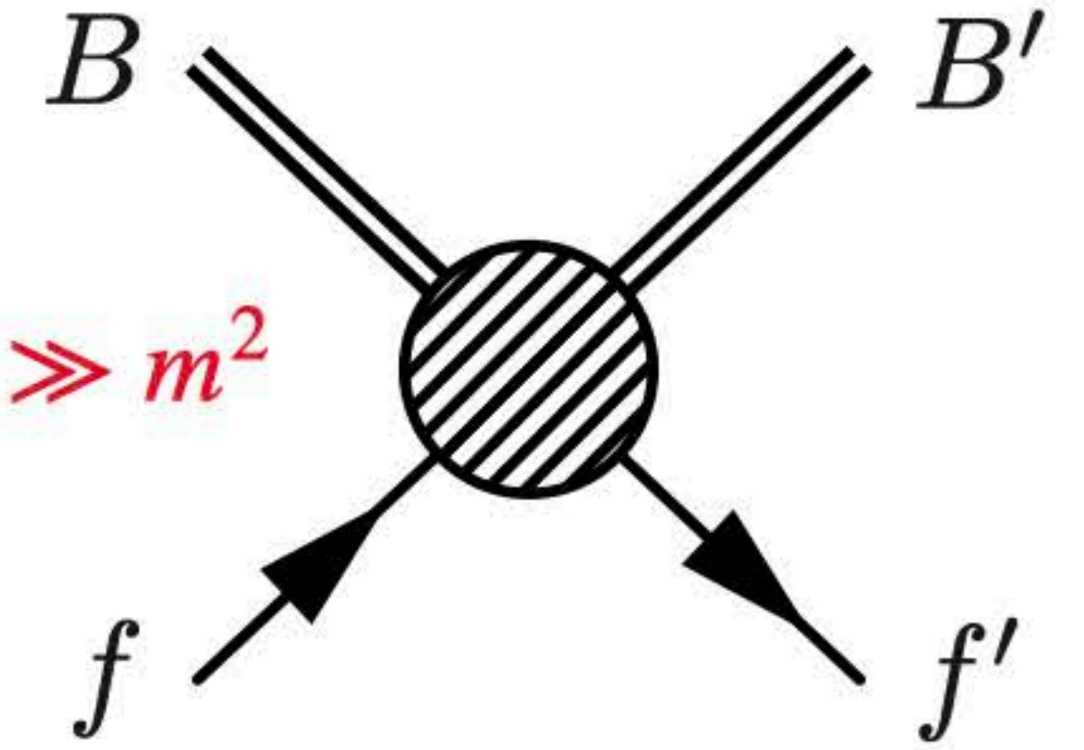


$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 \boxed{g_{th}} - \boxed{g_{Wh}} m_t)$$

e.g. $bW \to th$

EW top scattering



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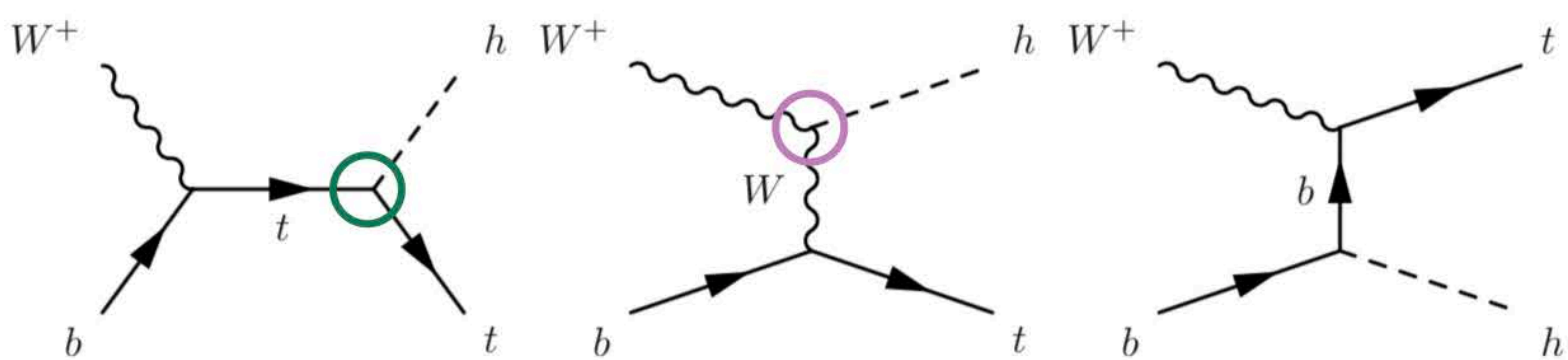

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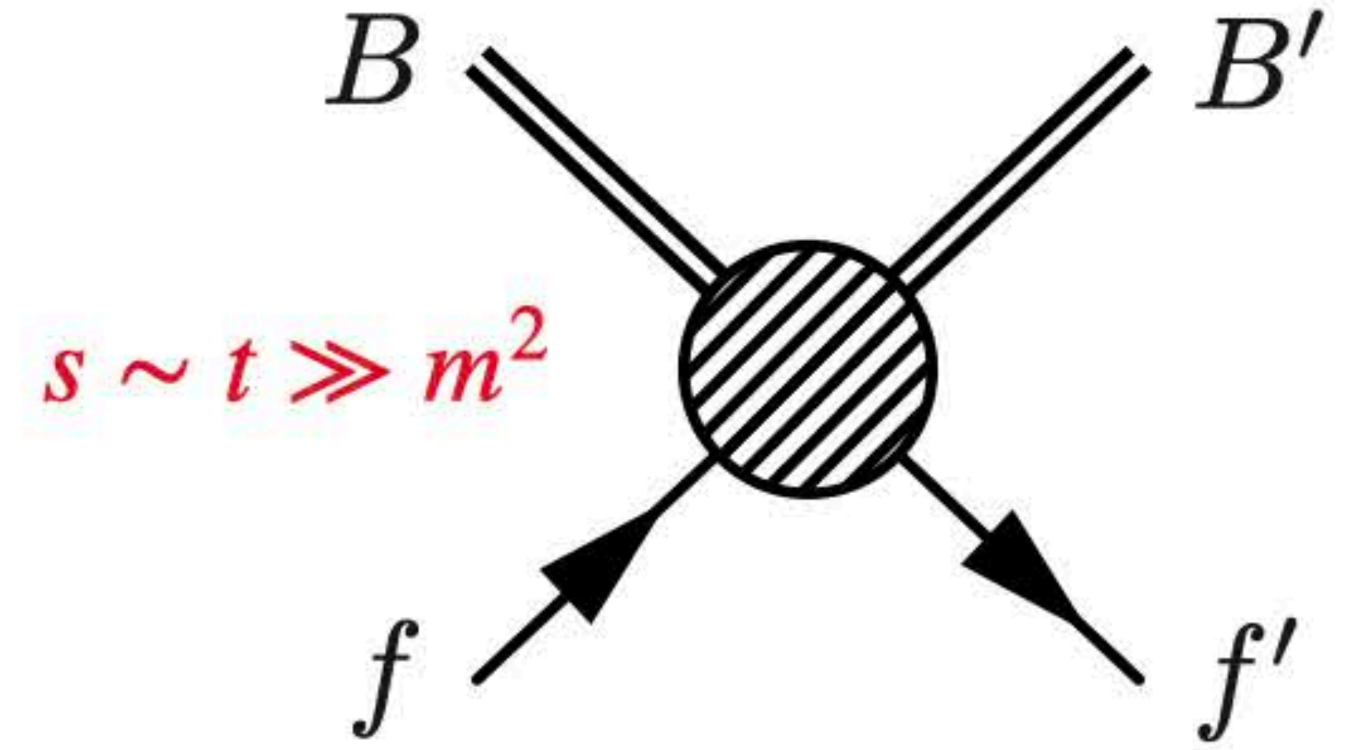
e.g. $bW \to th$ SMEFT $\Rightarrow$

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	–	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	–	–	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	–	–	$\sqrt{-t}m_t$	–	–	–
$+, 0, +$	–	–	$\sqrt{s(s+t)}$	–	–	–

EW top scattering



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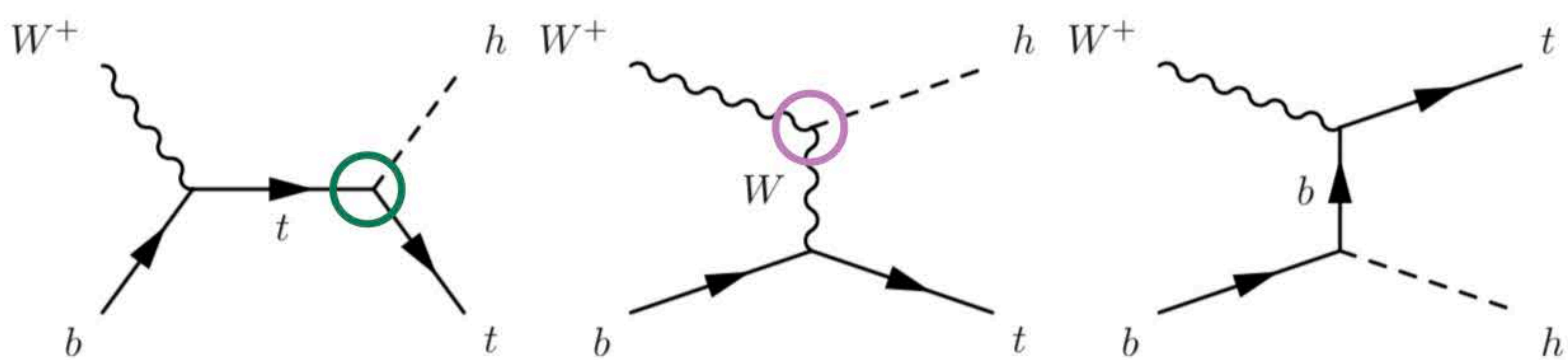

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e.g. $bW \to th$ SMEFT ⇒

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	s^0	s^0	$-$	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$

Where is max-growth?
Behaviour of interference?

Overview of results

Energy-growing interference

gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/ Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

Overview of results

Energy-growing interference

gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/ Higgs

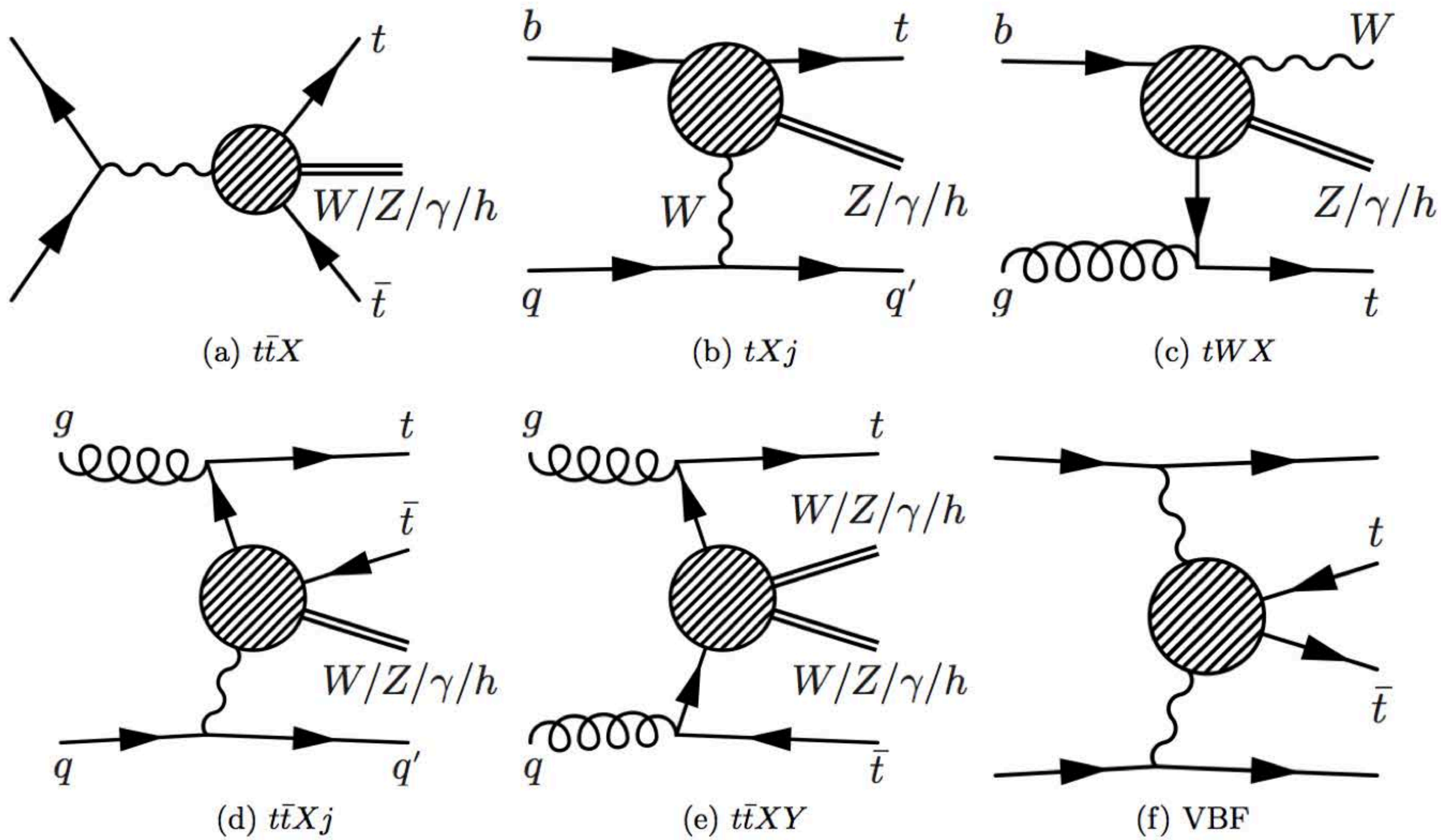
	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

Most top operators show max growth somewhere

- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)

Embedding the amplitudes

Collider processes: **high multiplicity, EW top production**



Embedding the amplitudes

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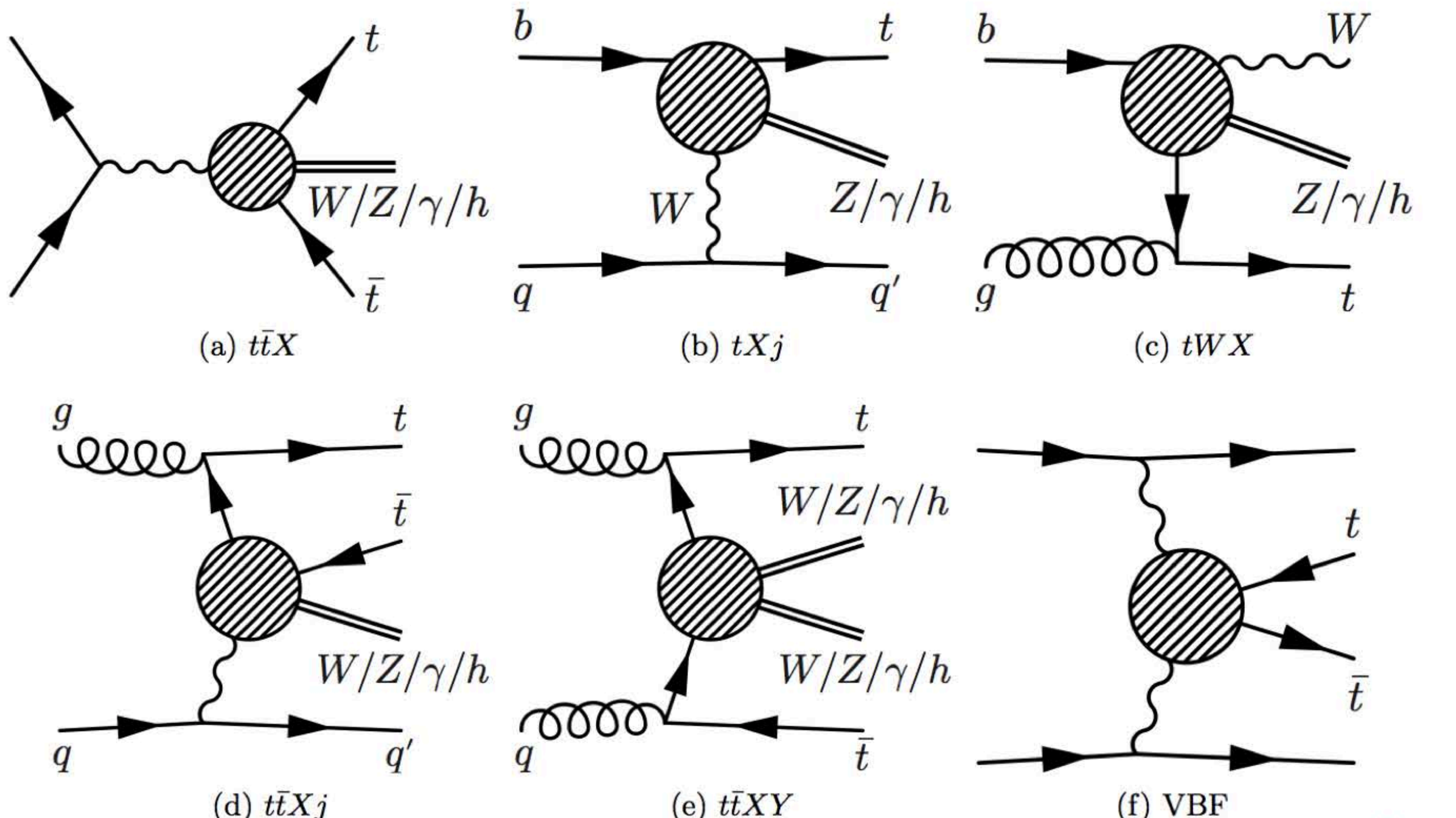
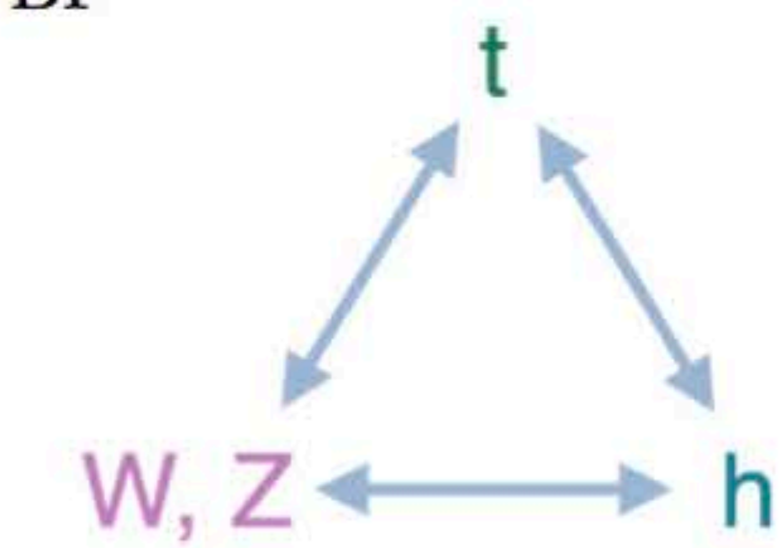


(a) $t\bar{t}X$ (b) tXj (c) tWX

(d) $t\bar{t}Xj$ (e) $t\bar{t}XY$ (f) VBF

Couplings $\left\{\begin{array}{l}\text{top EW}\\ \text{Higgs}\\ \text{triple gauge}\end{array}\right.$ $\Rightarrow$ Heart of EWSB sector



Top EW scattering pheno

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

single-top

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

two-top w/o Higgs

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

two-top w/ Higgs

Top EW scattering pheno

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

single-top

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

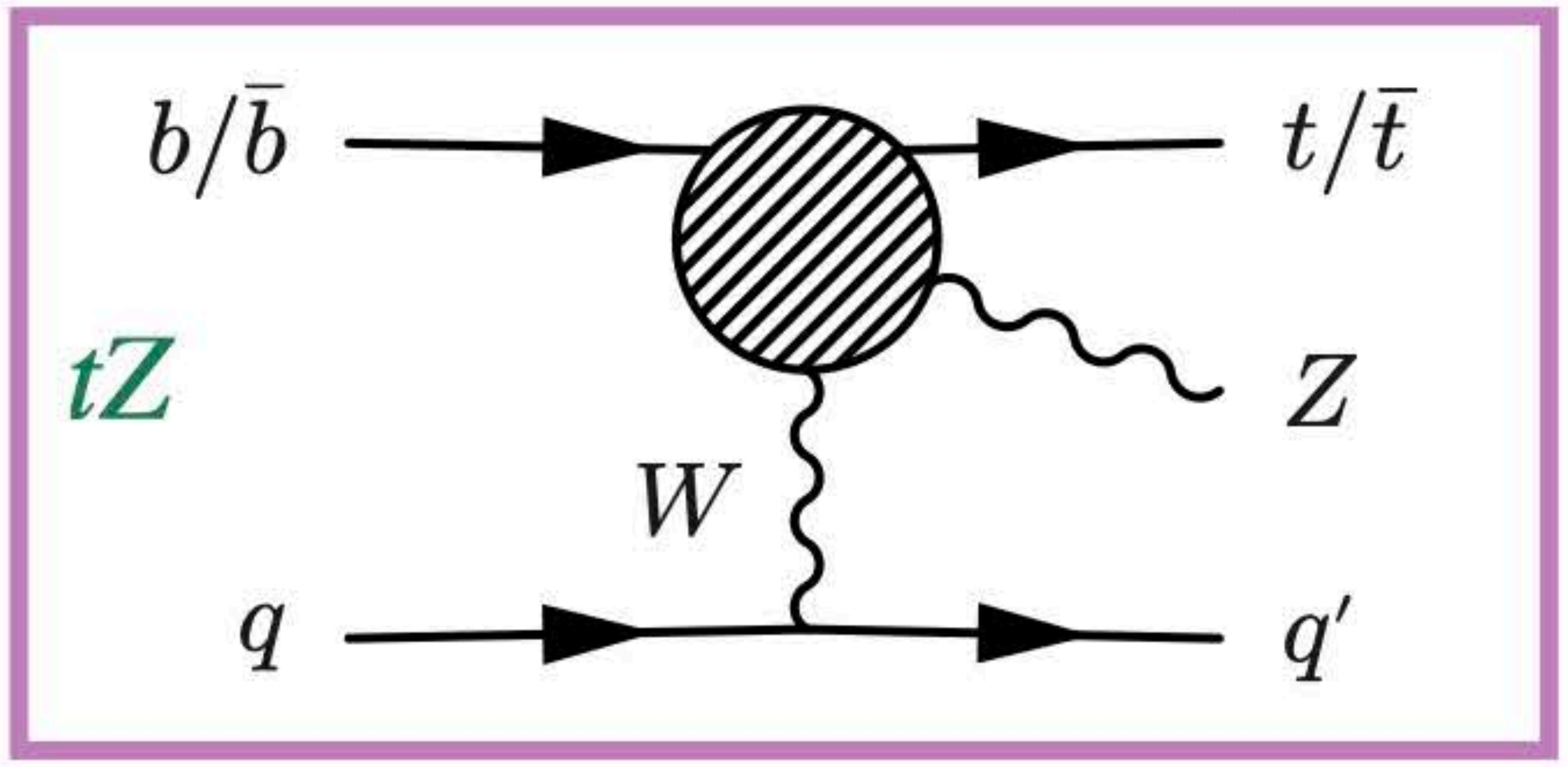
two-top w/o Higgs

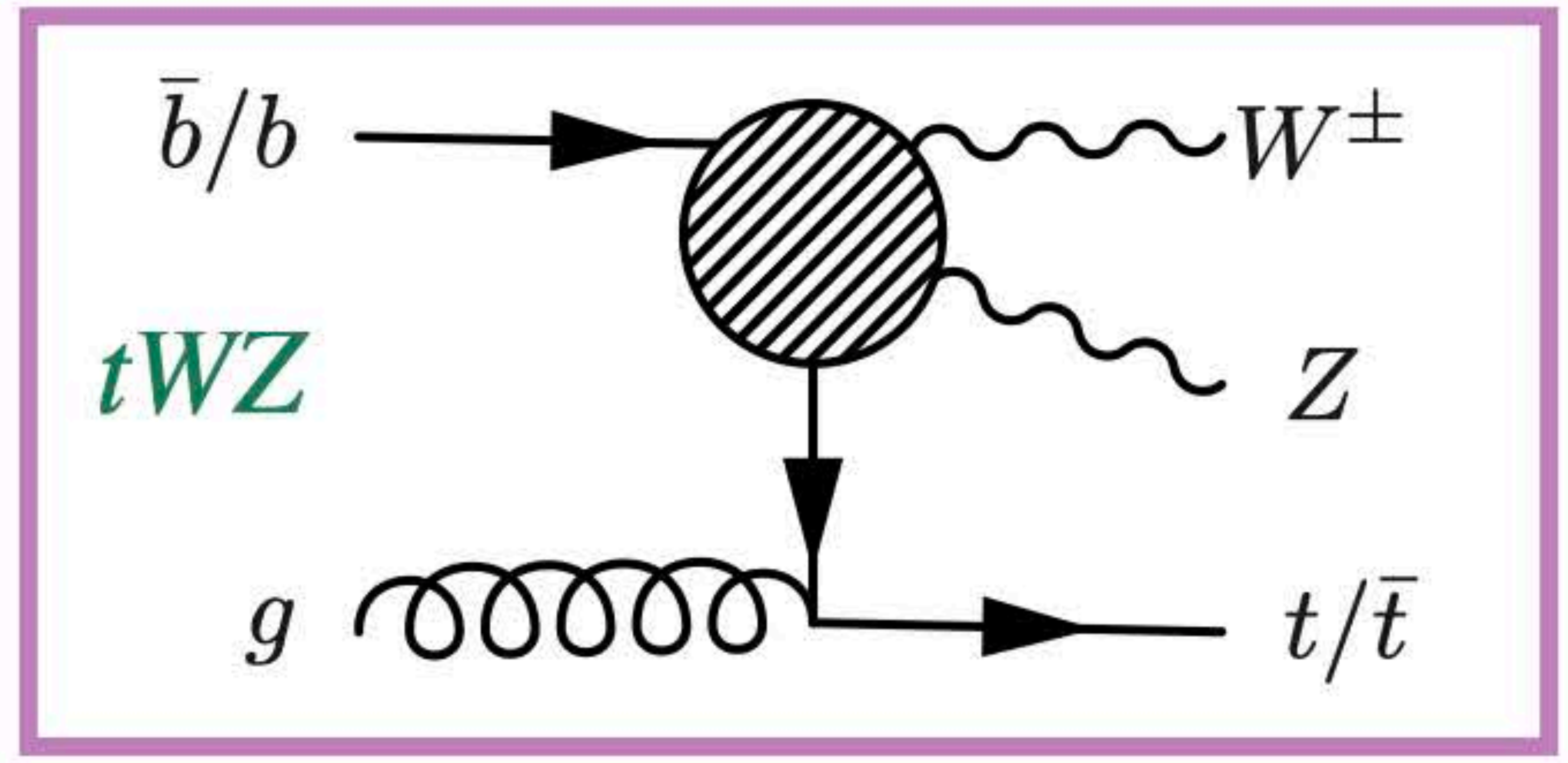
	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

two-top w/ Higgs

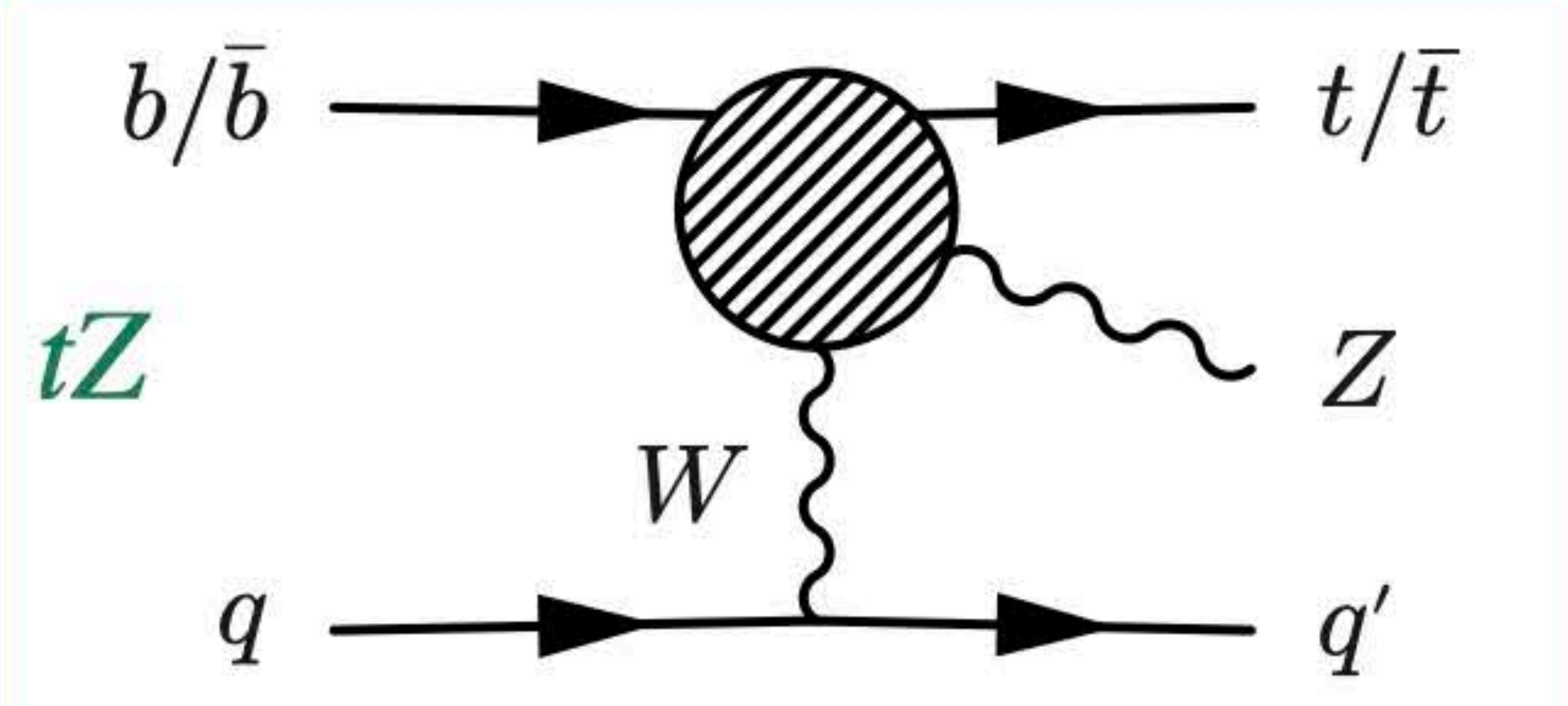
See, e.g.,
tZj/tHj *[Degrande, Maltoni, KM, Vryonidou & Zhang; JHEP* 01 (2022) 100*]*
tWZ *[El Faham, Maltoni, KM & Zaro; JHEP* 01 (2022) 100*]*

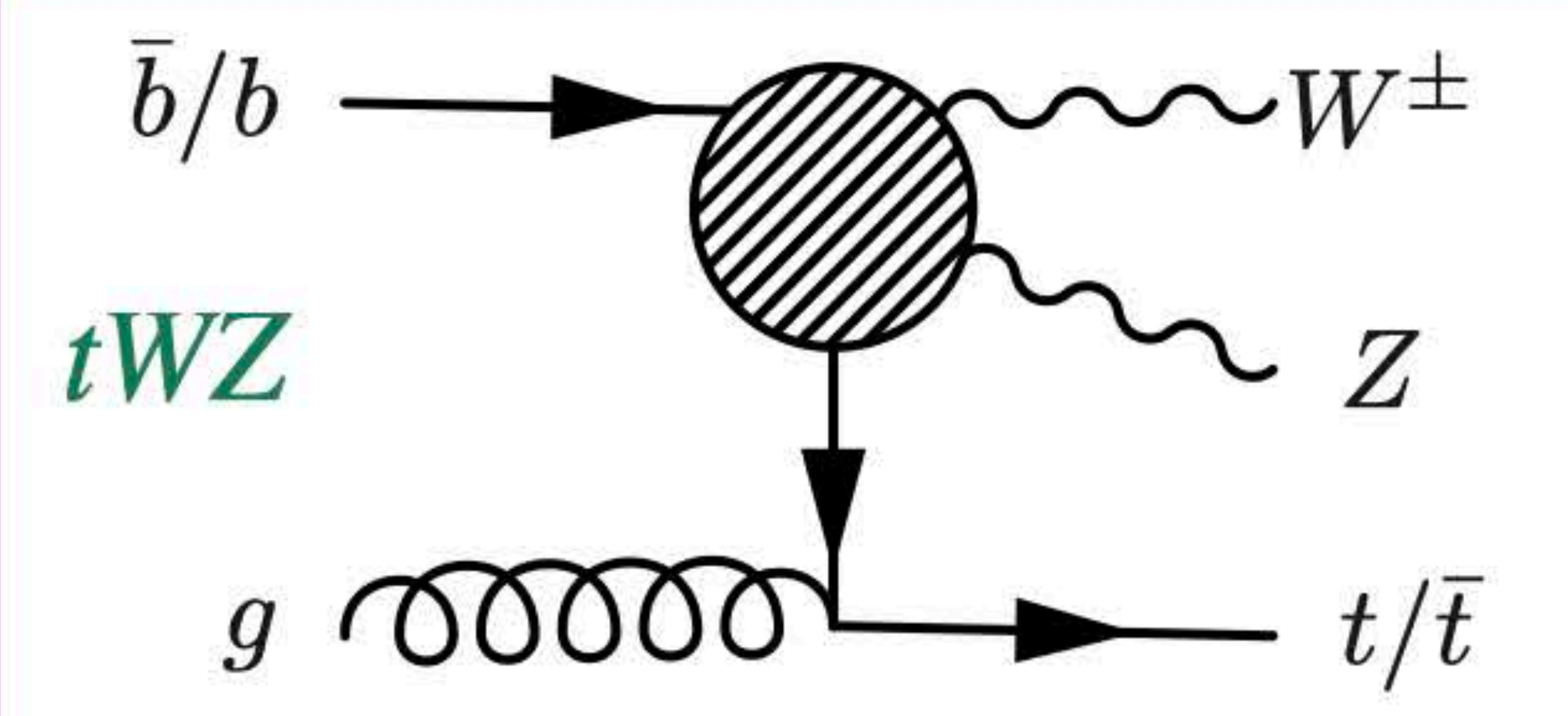
Rare single top modes





Rare single top modes





$$b\,W \to t\,Z$$

neutral & charged current top quark gauge interactions

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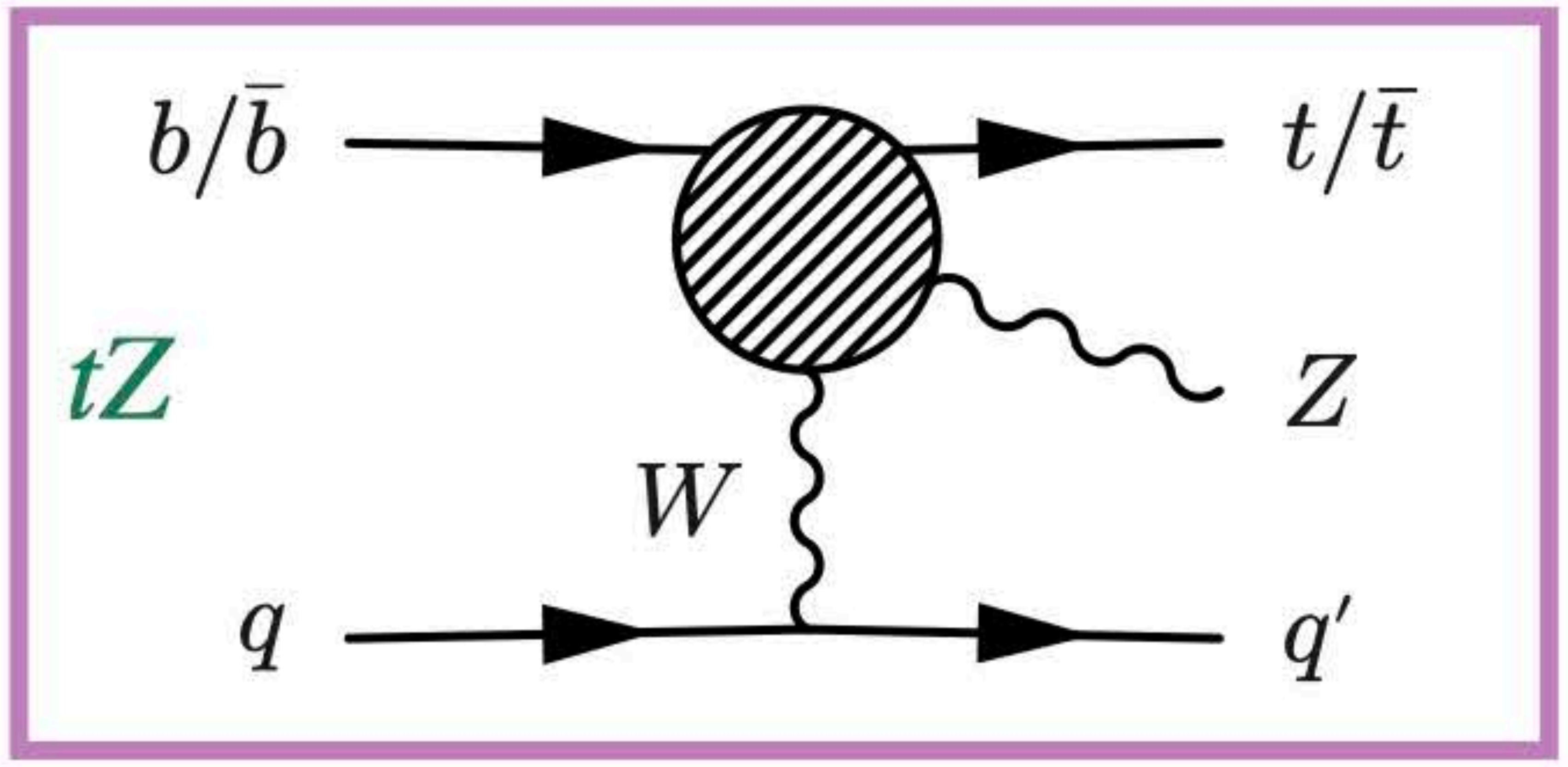

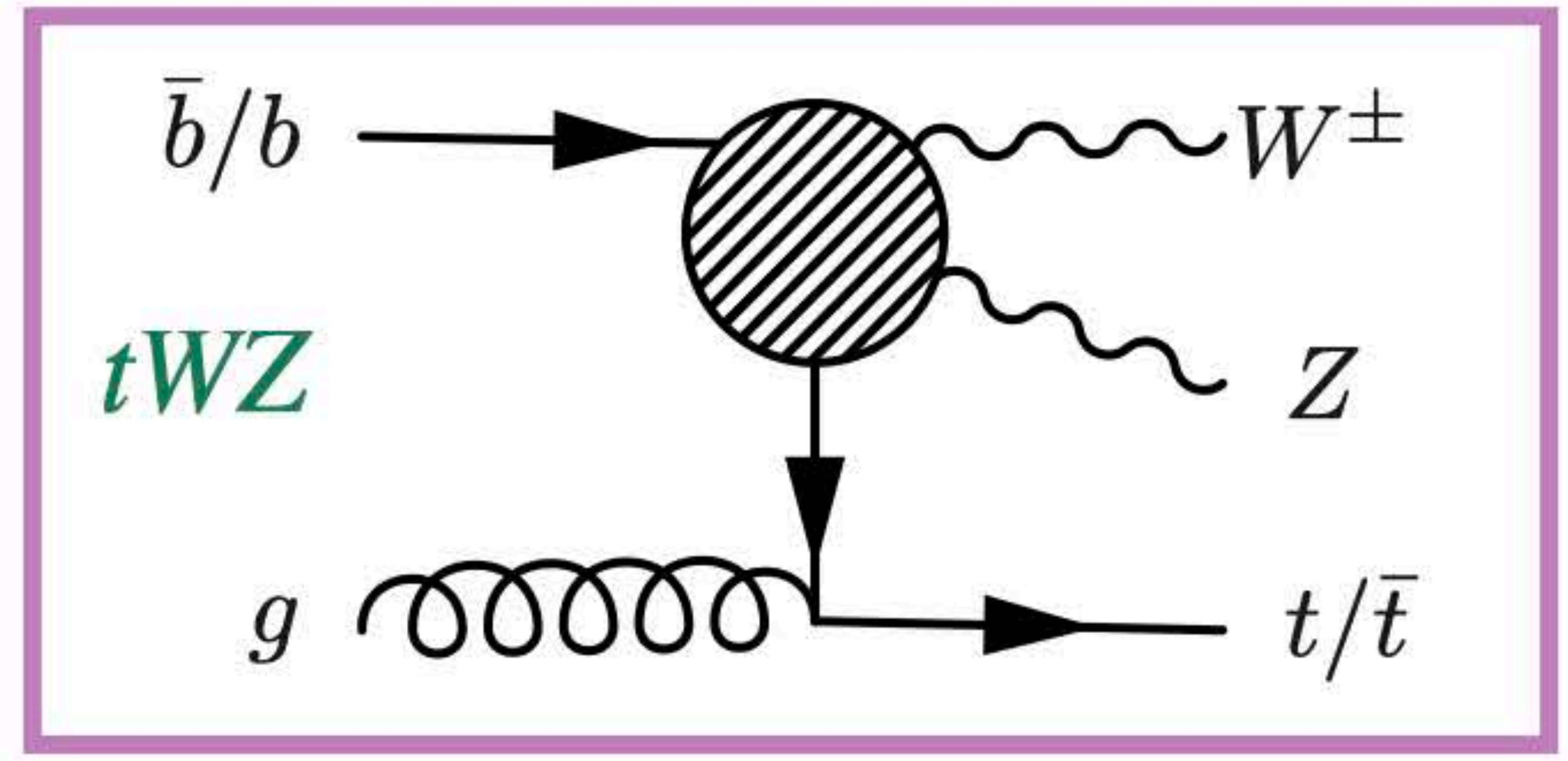

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Energy-growing interference

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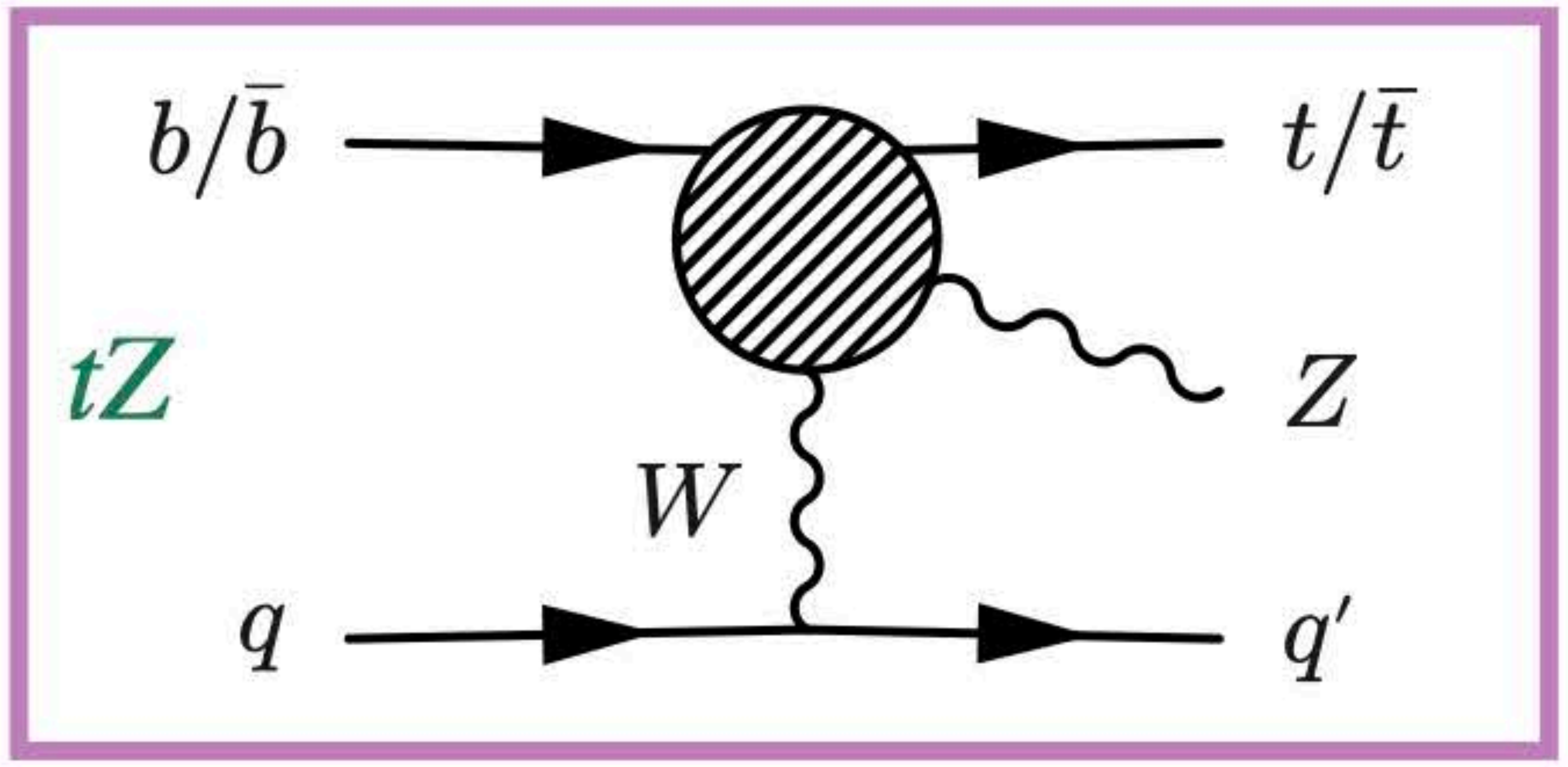

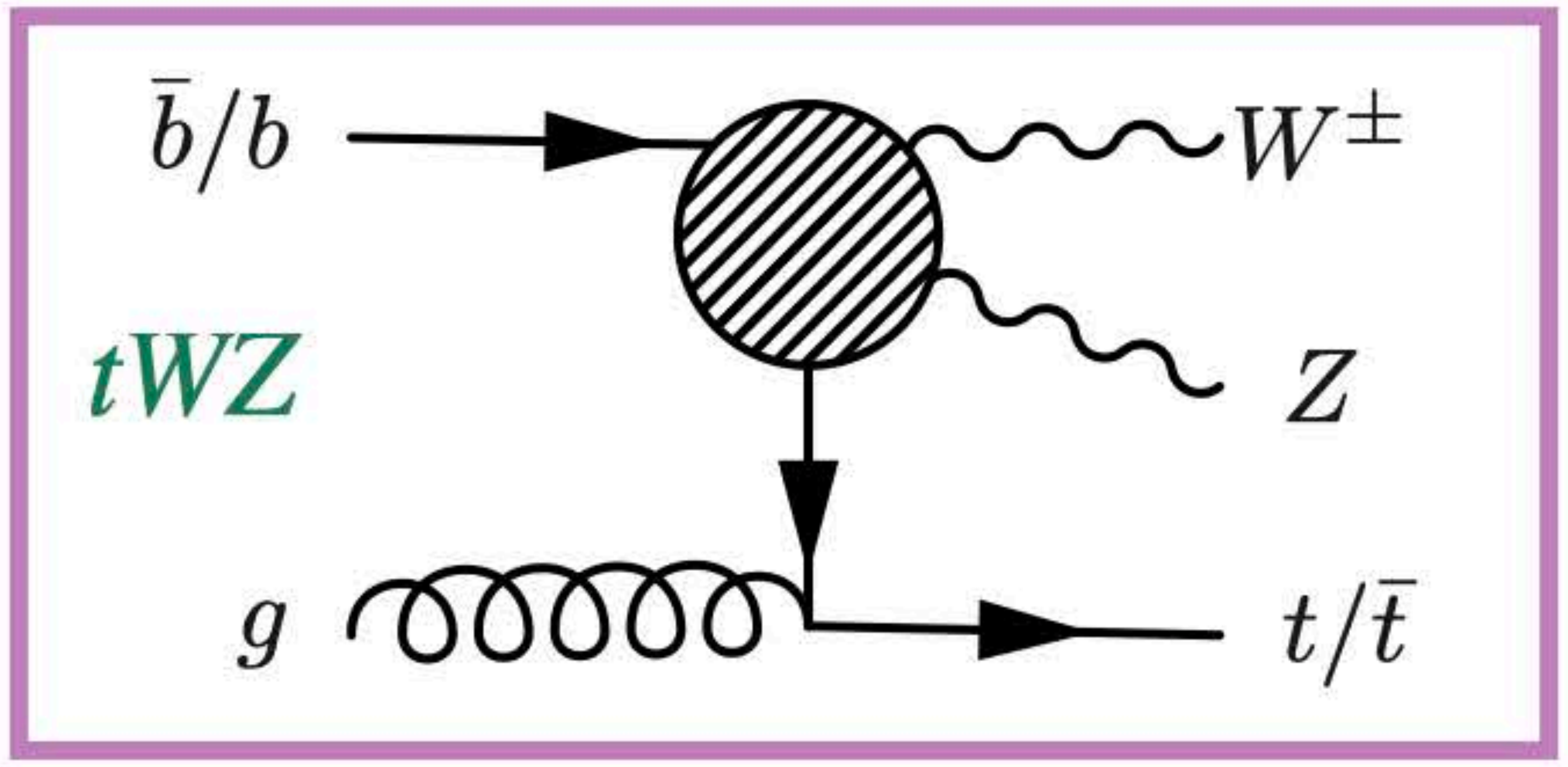

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Dedicated *tZj* study:

[Degrande, Maltoni, KM, Vryonidou & Zhang; JHEP 10 (2018) 005]

- Larger rate, differential measurements available
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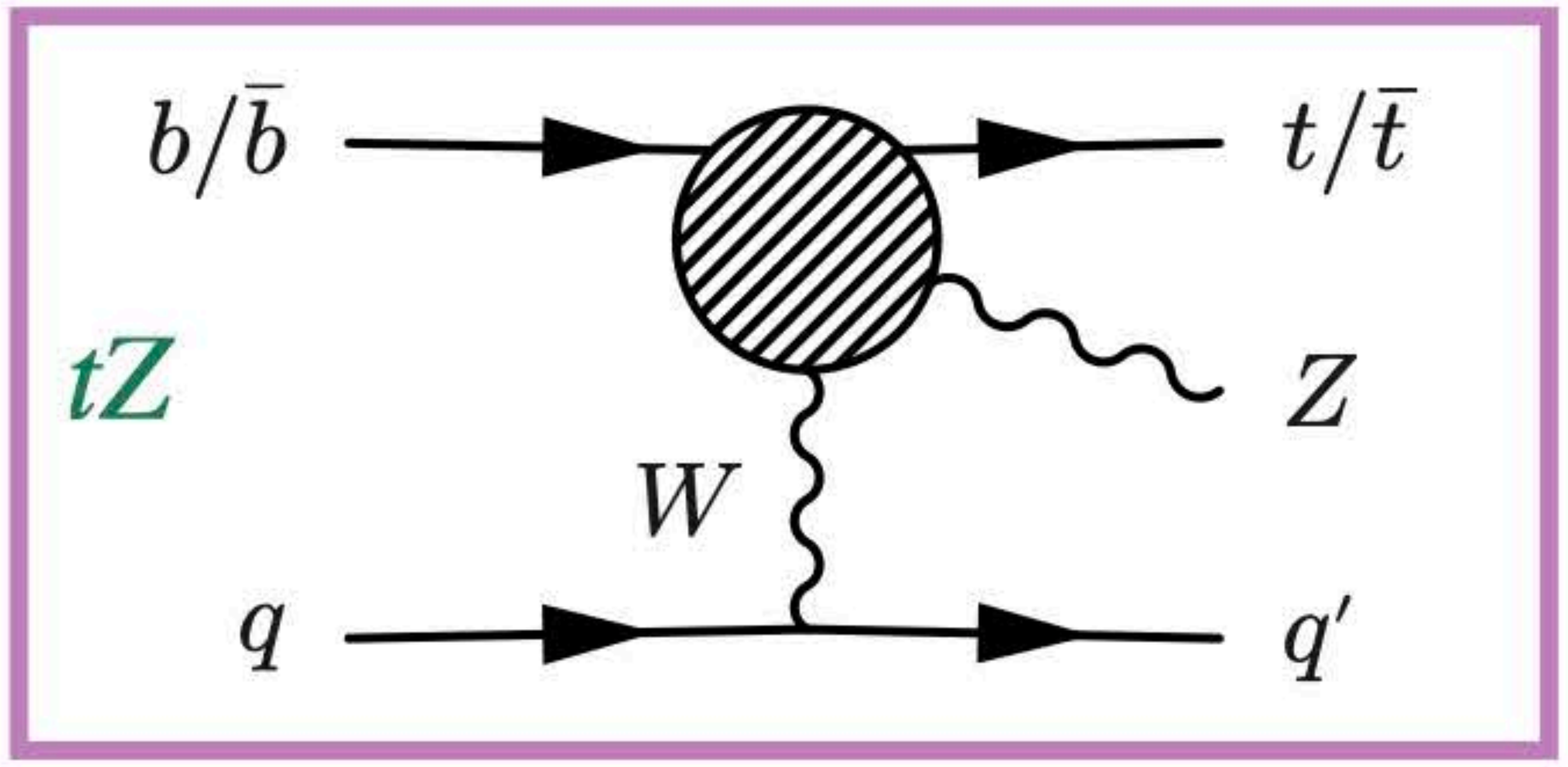

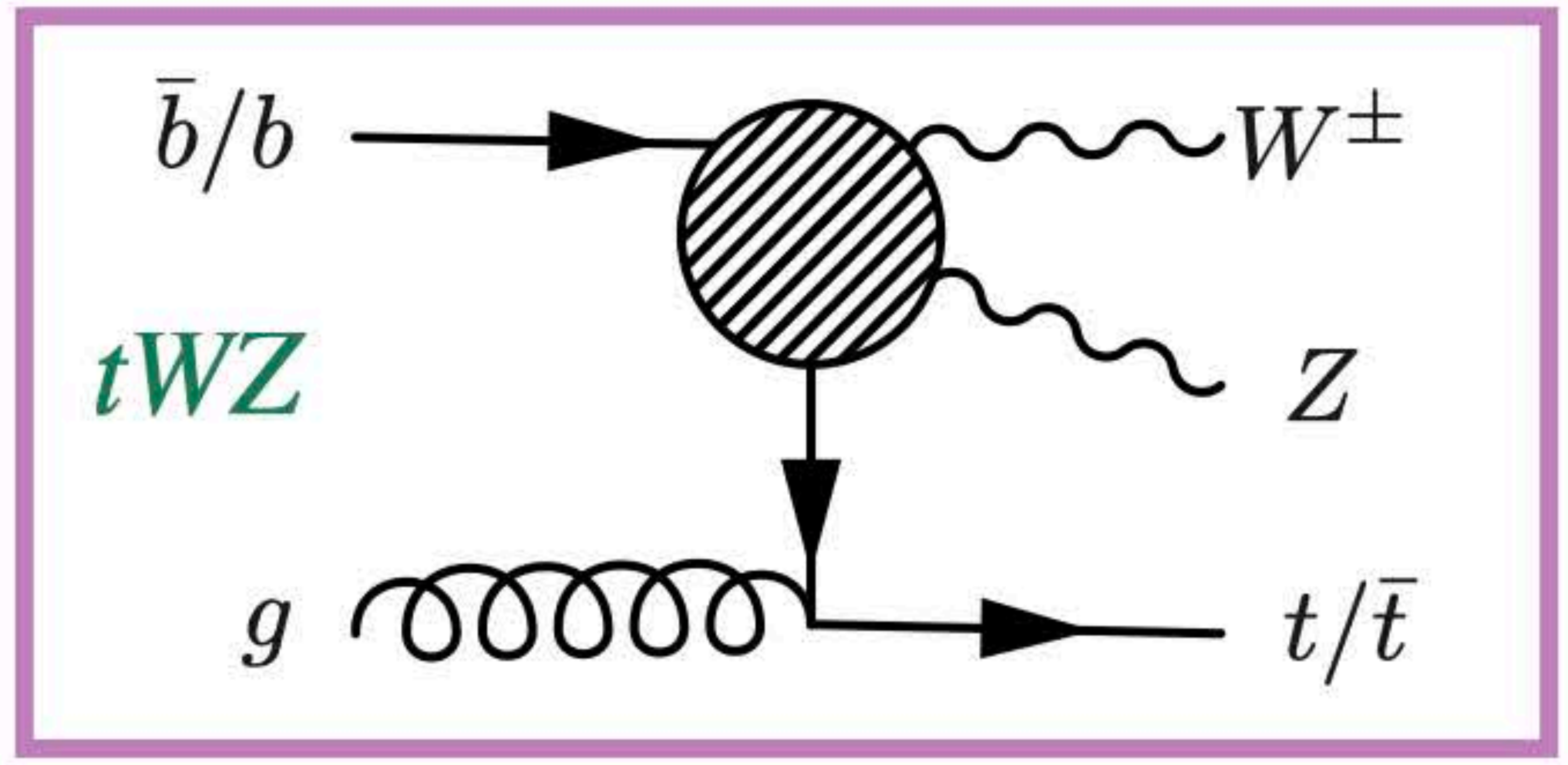

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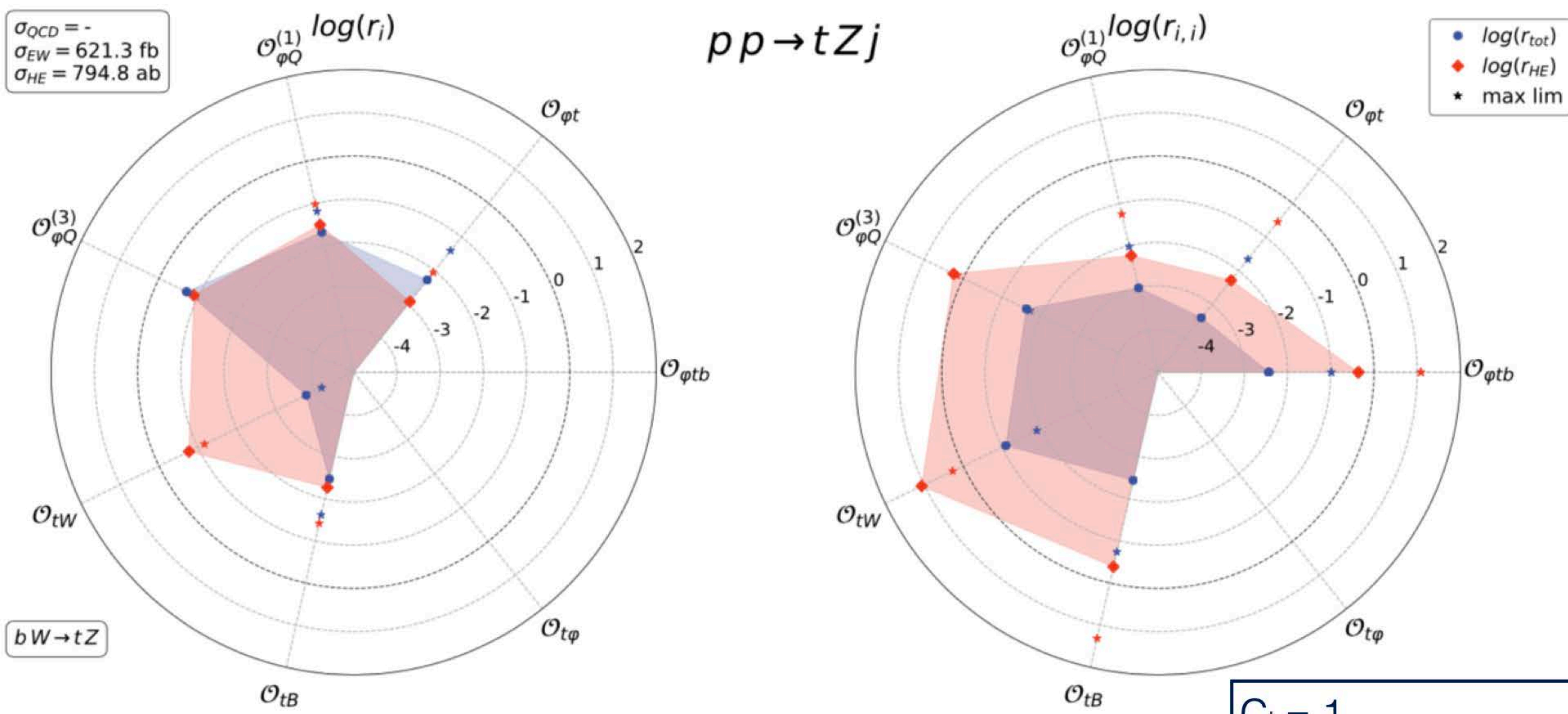
Growth recovered in tWZ

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

- Generally larger relative effect of all BSM interactions

tZ radar plot

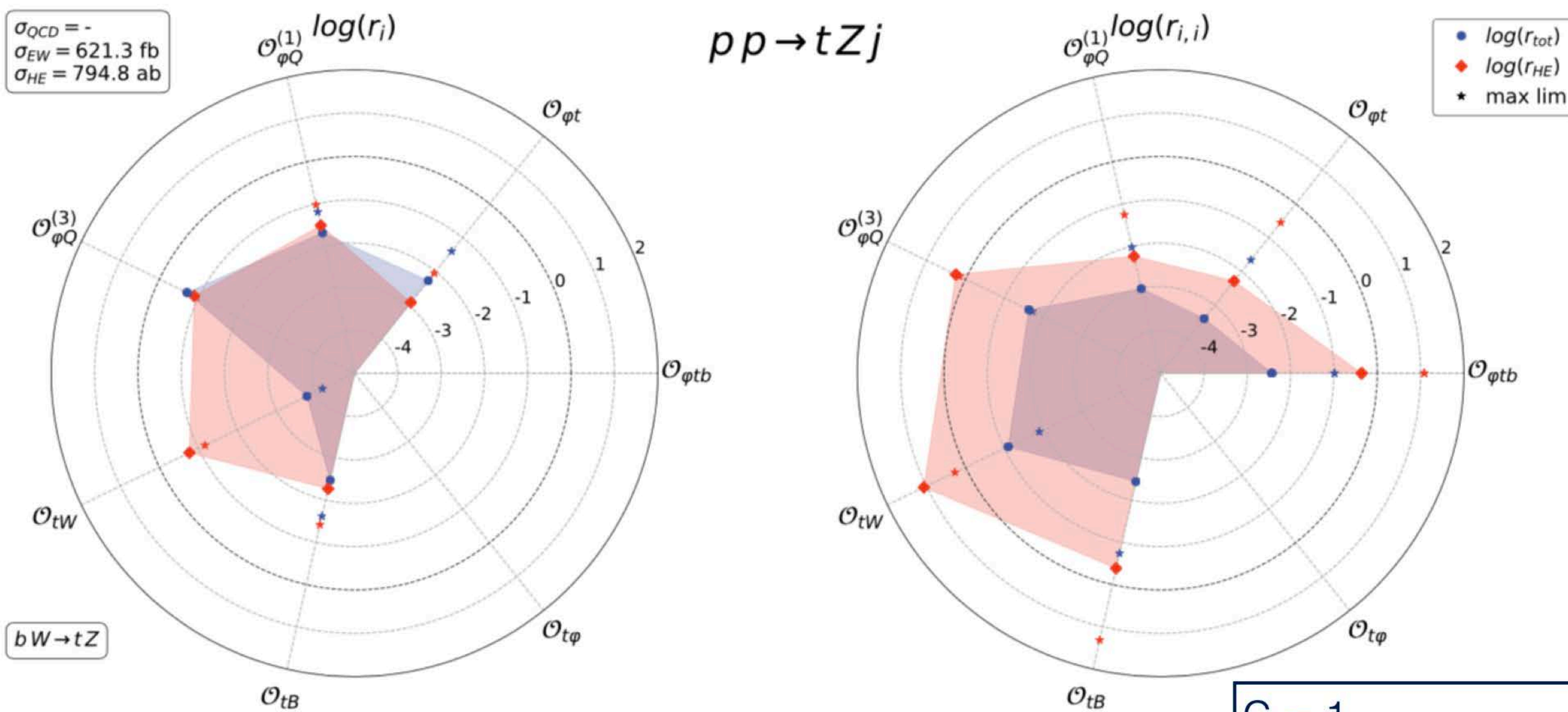


C_i = 1
Inclusive
p_T (Z)> 500 GeV

tZ radar plot

interference/SM

square/SM



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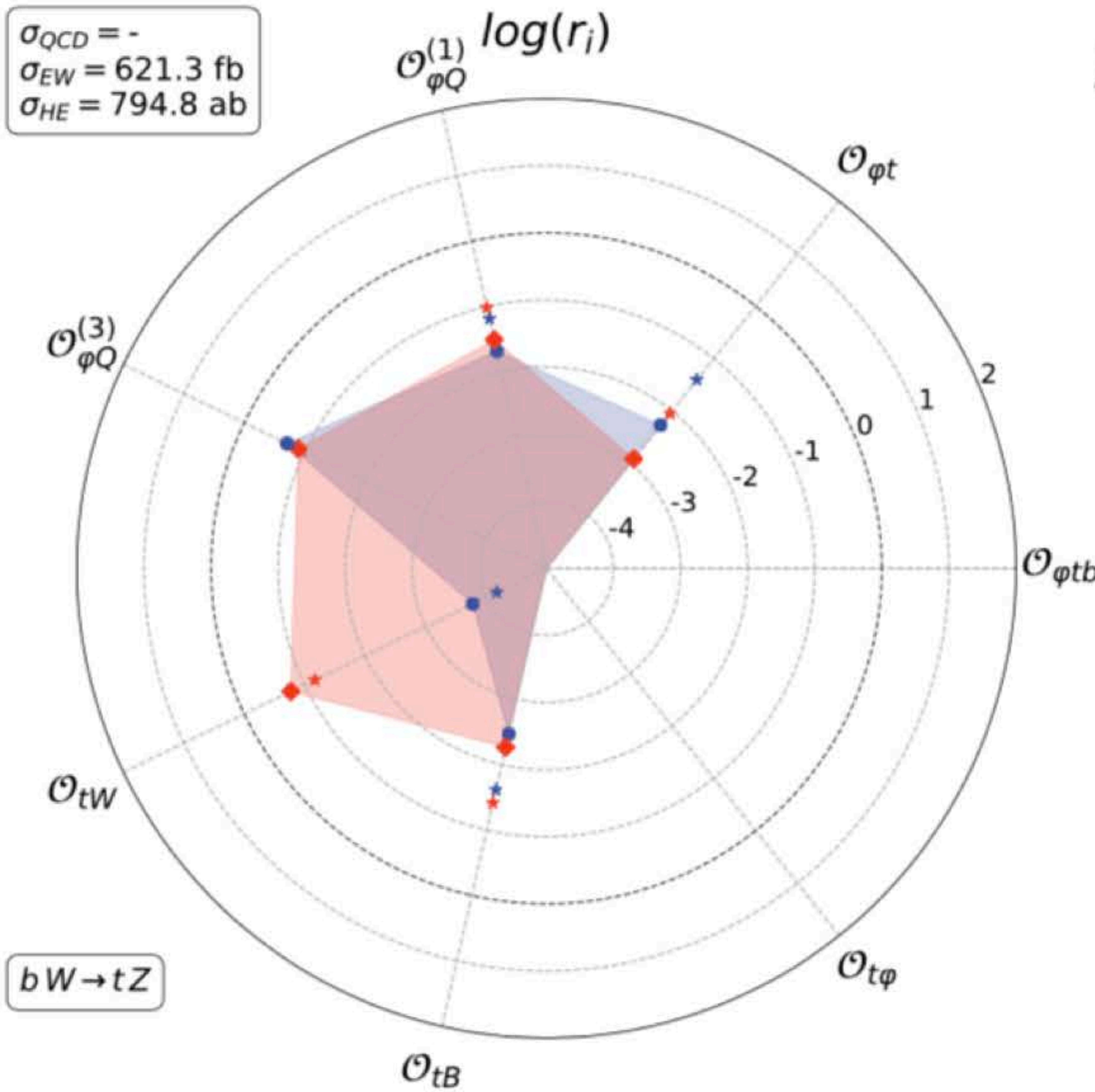

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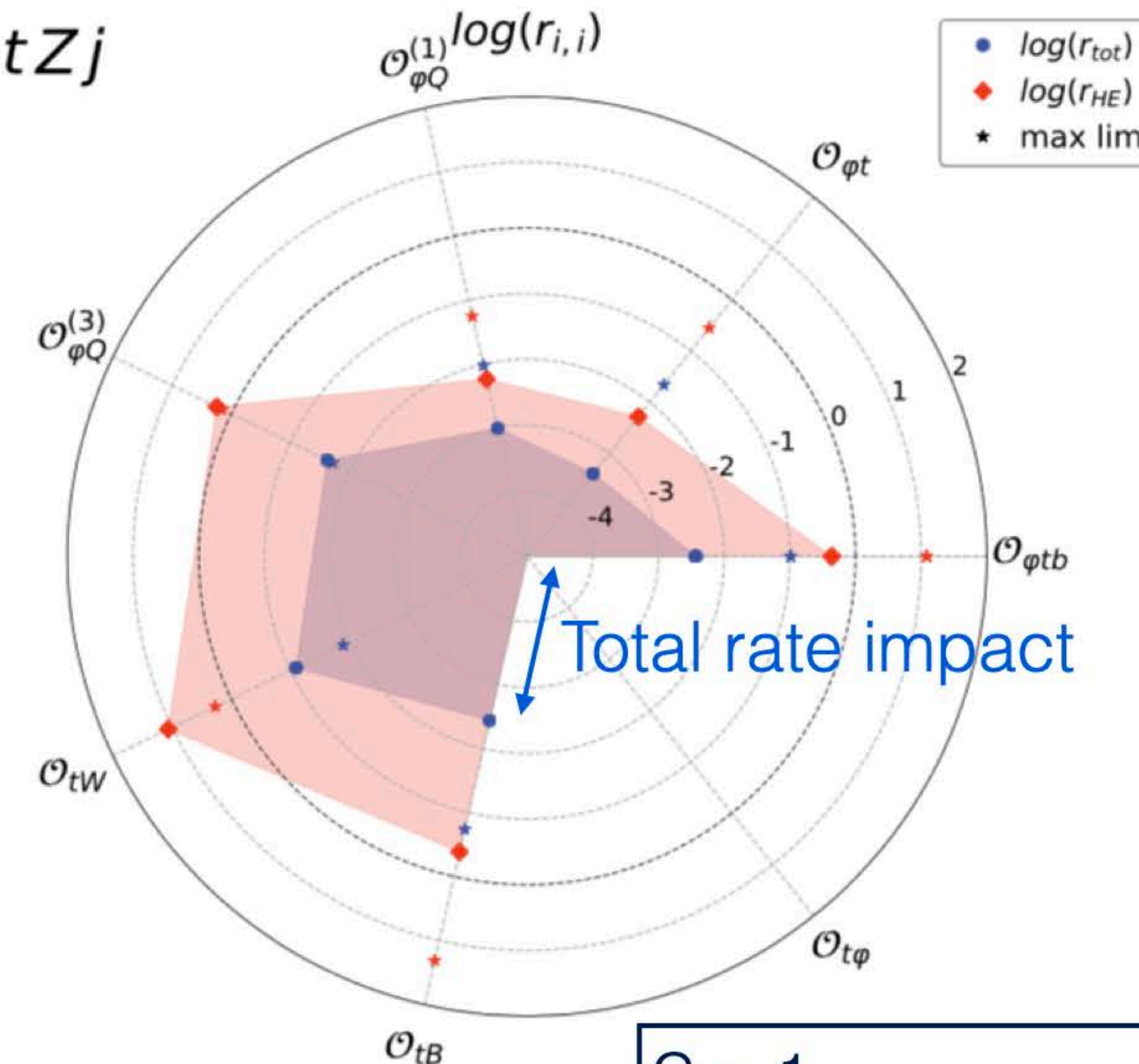

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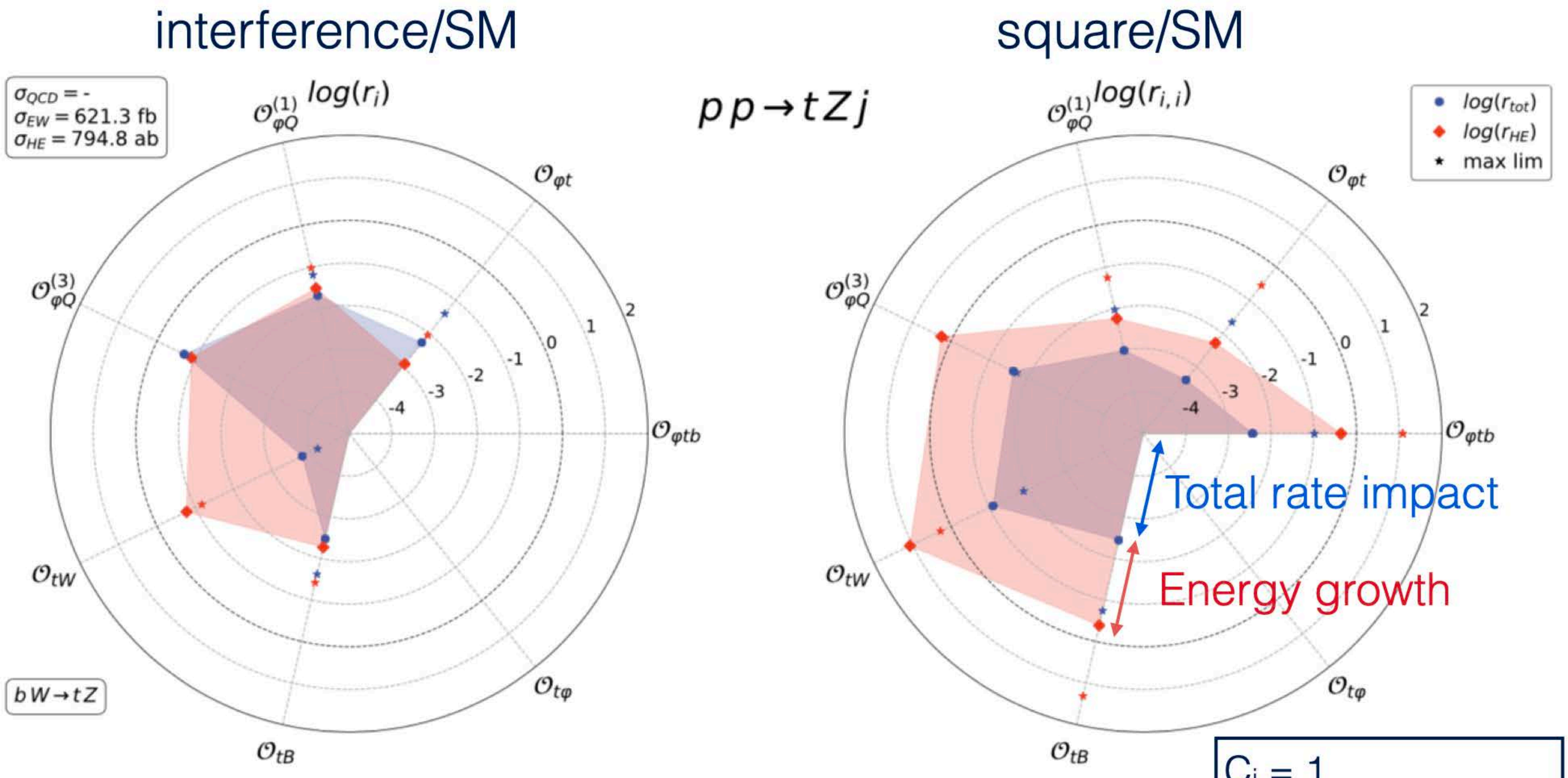

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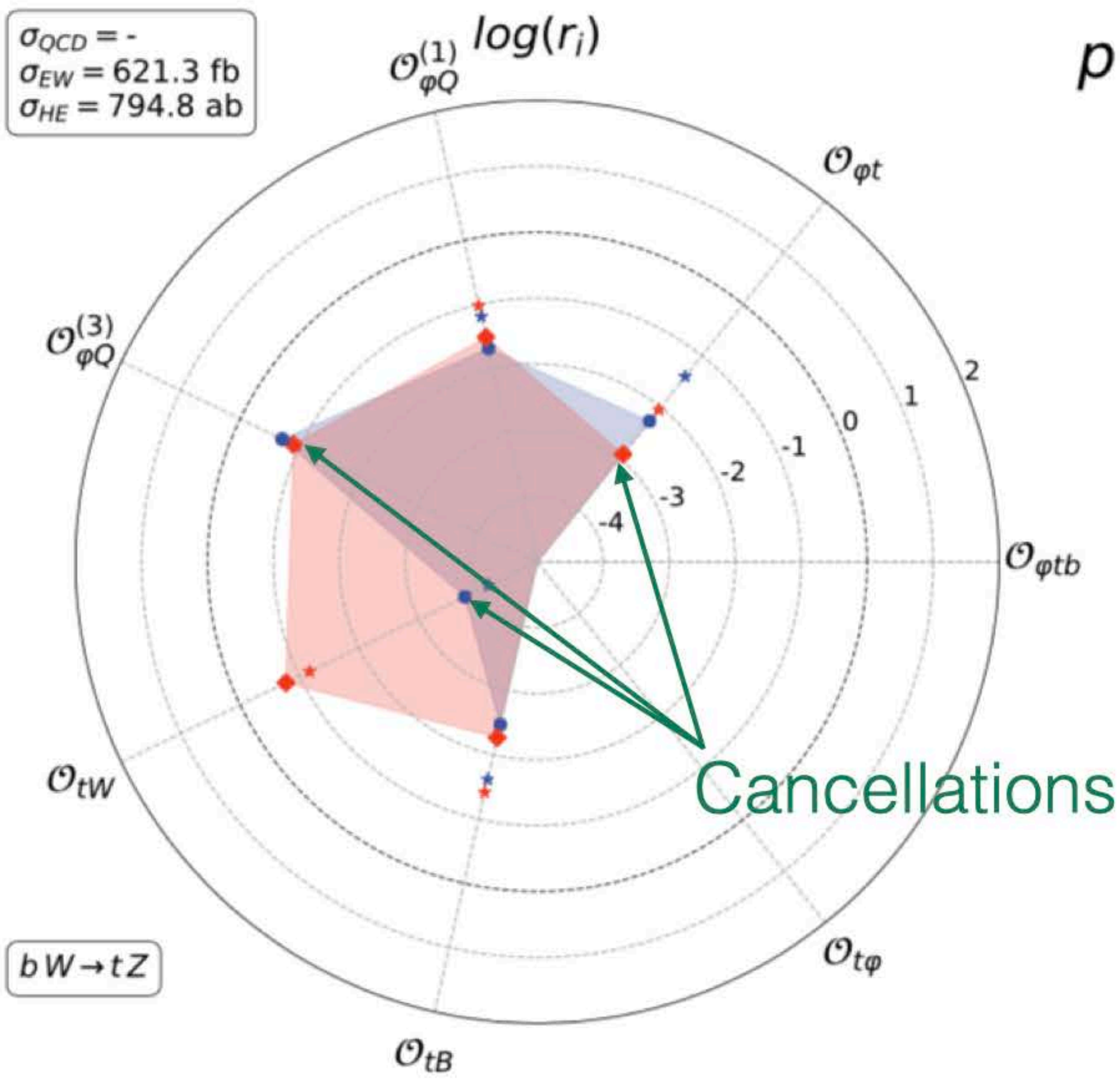

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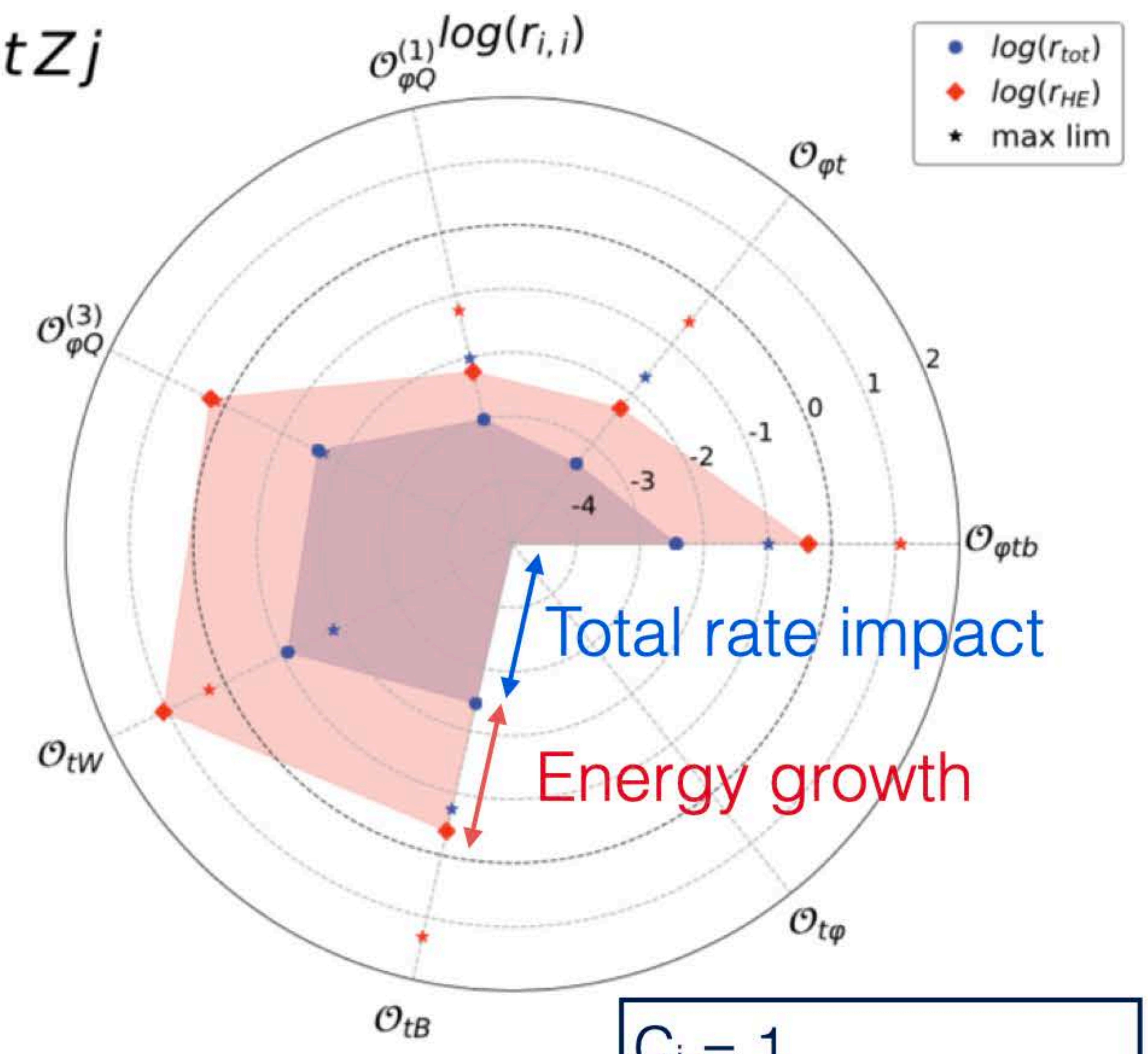

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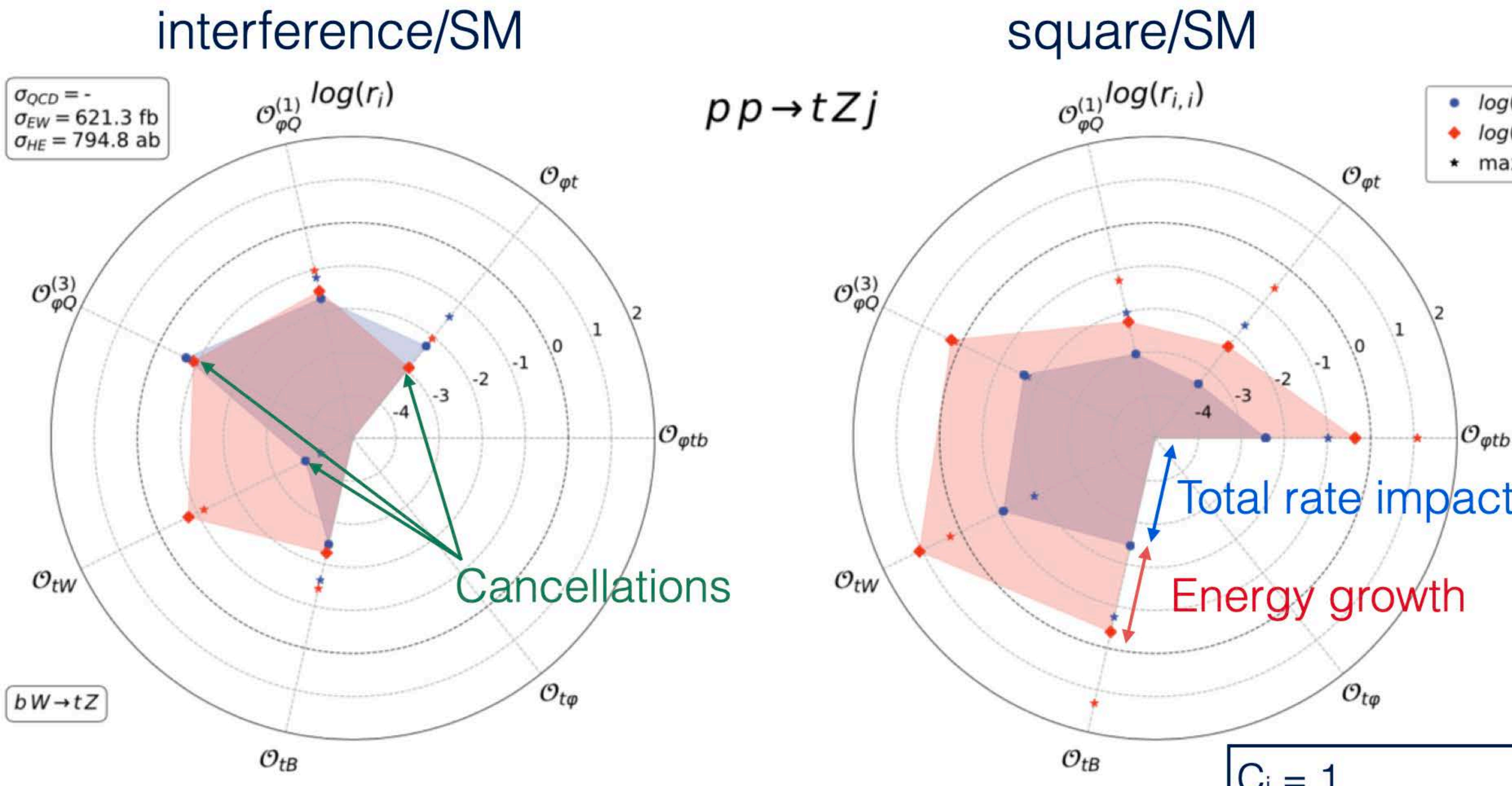

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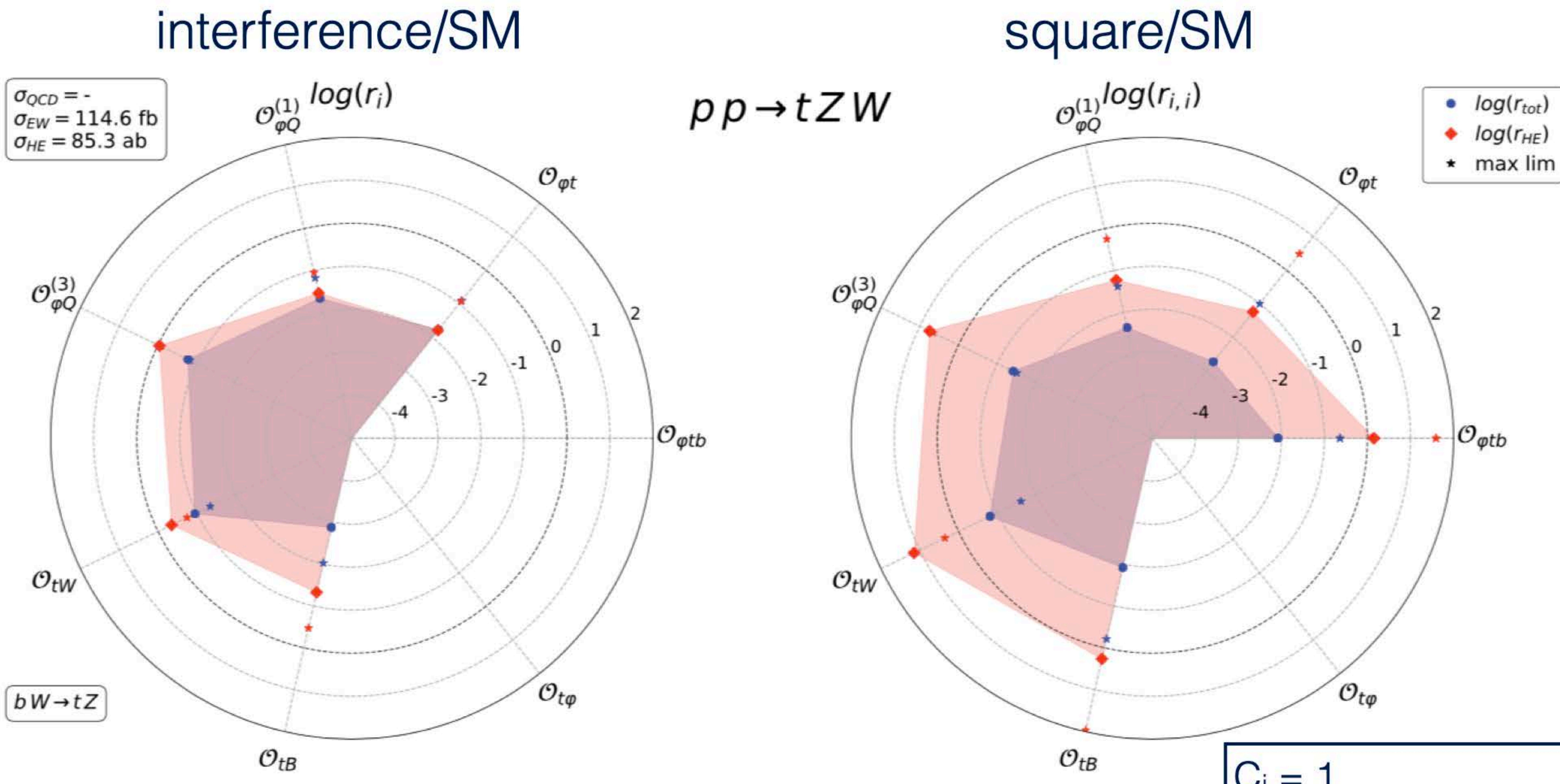
Expected growth from 2→2 absent!

tZW radar plot



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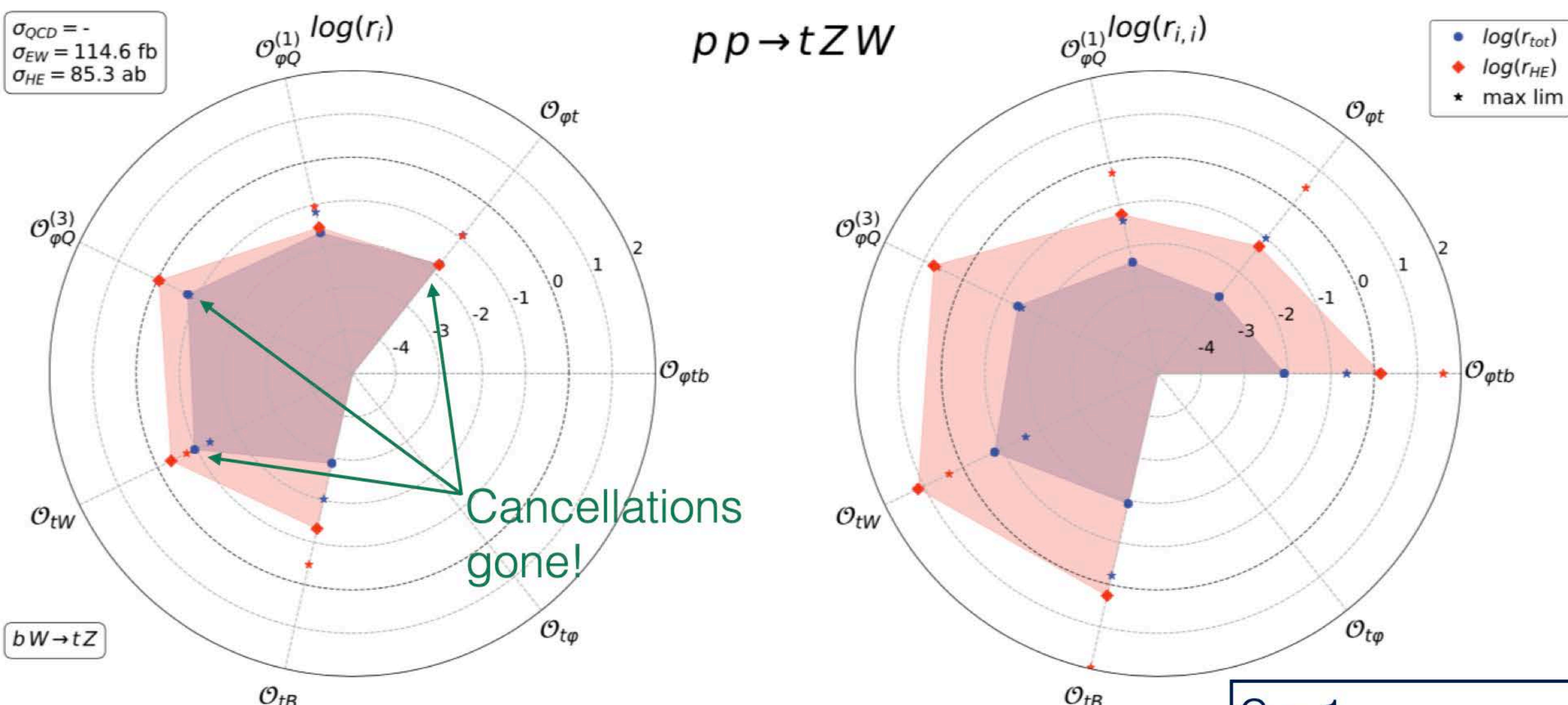

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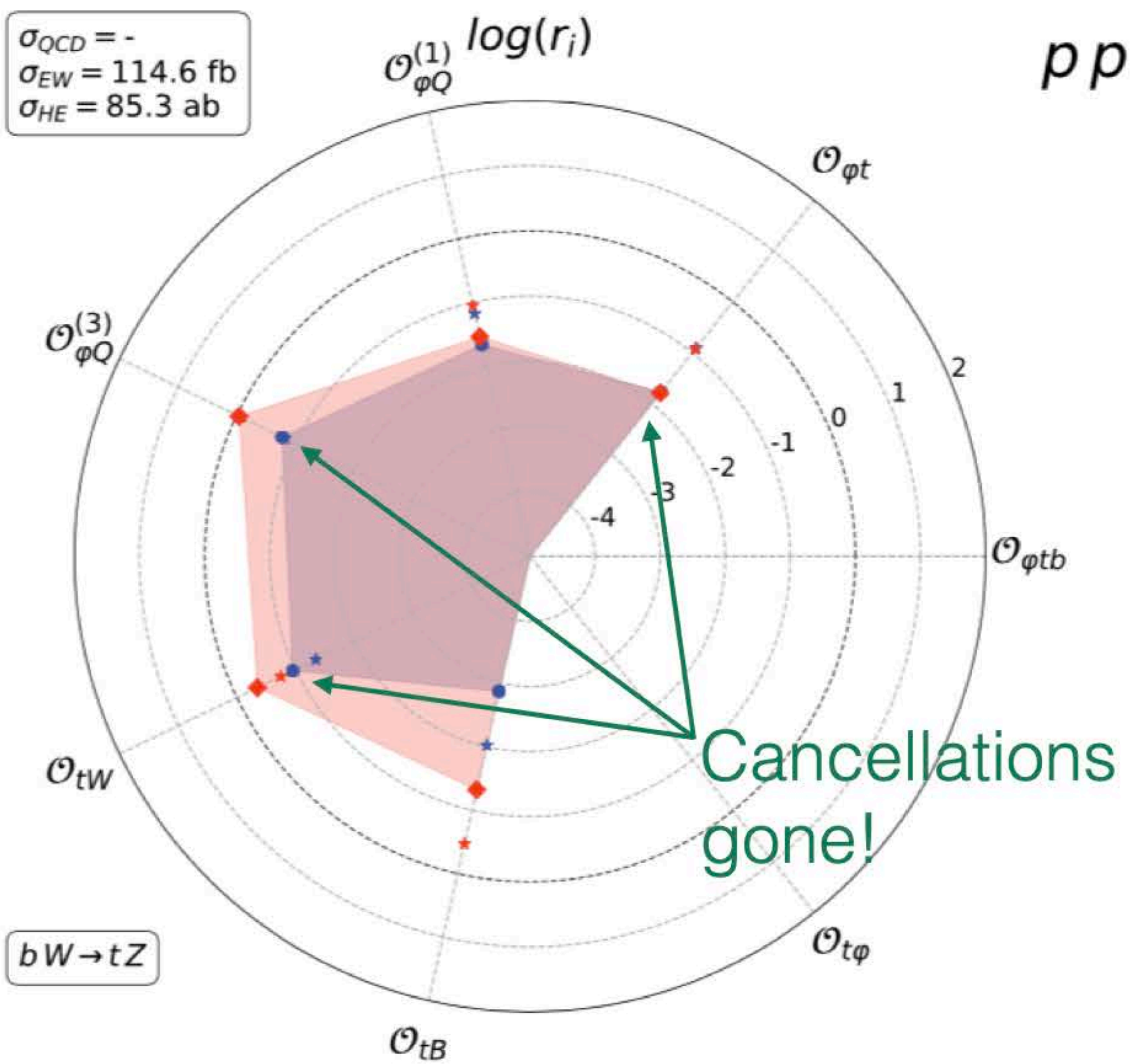

$pp \to tZW$

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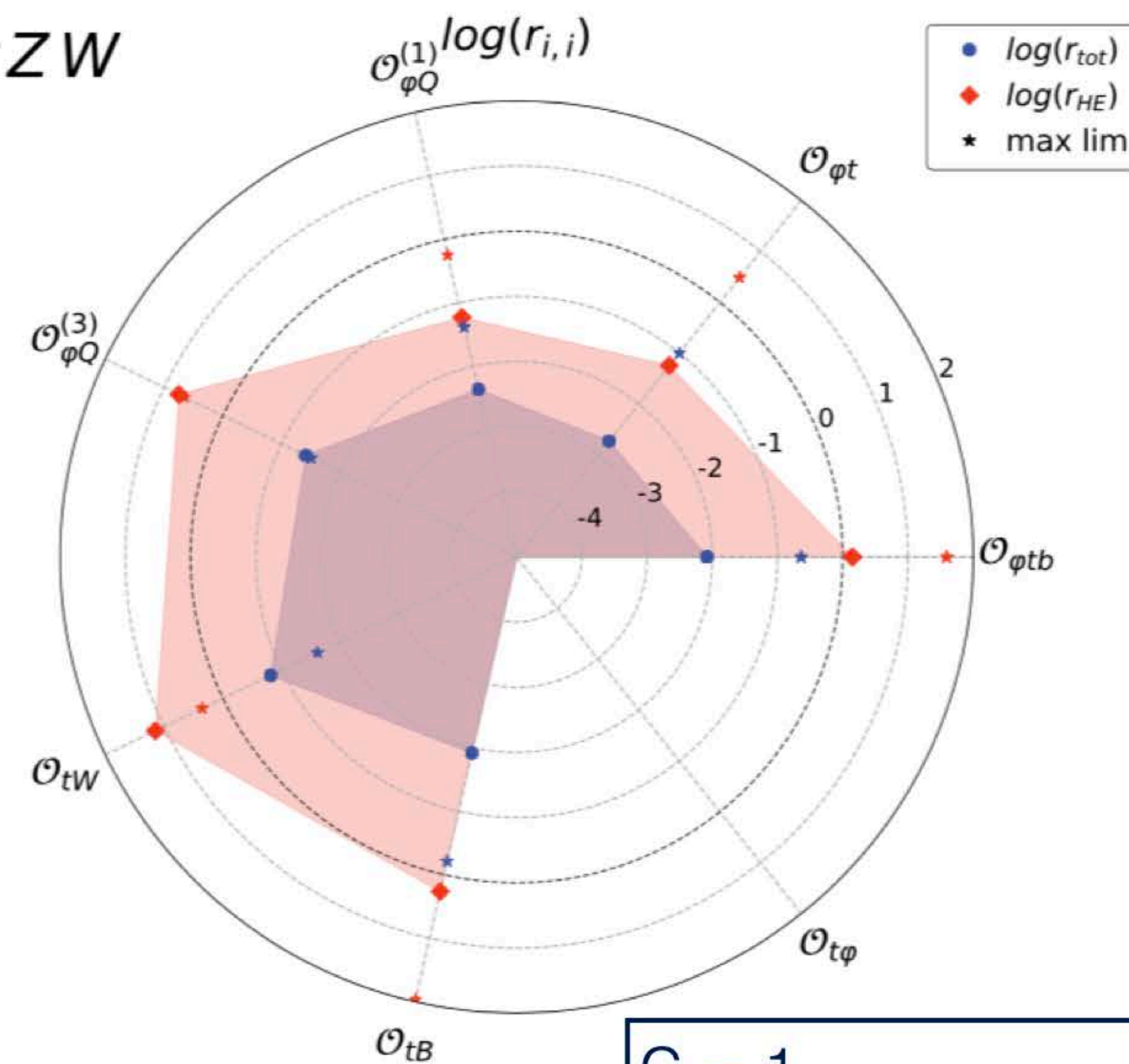

Expected growth is there!

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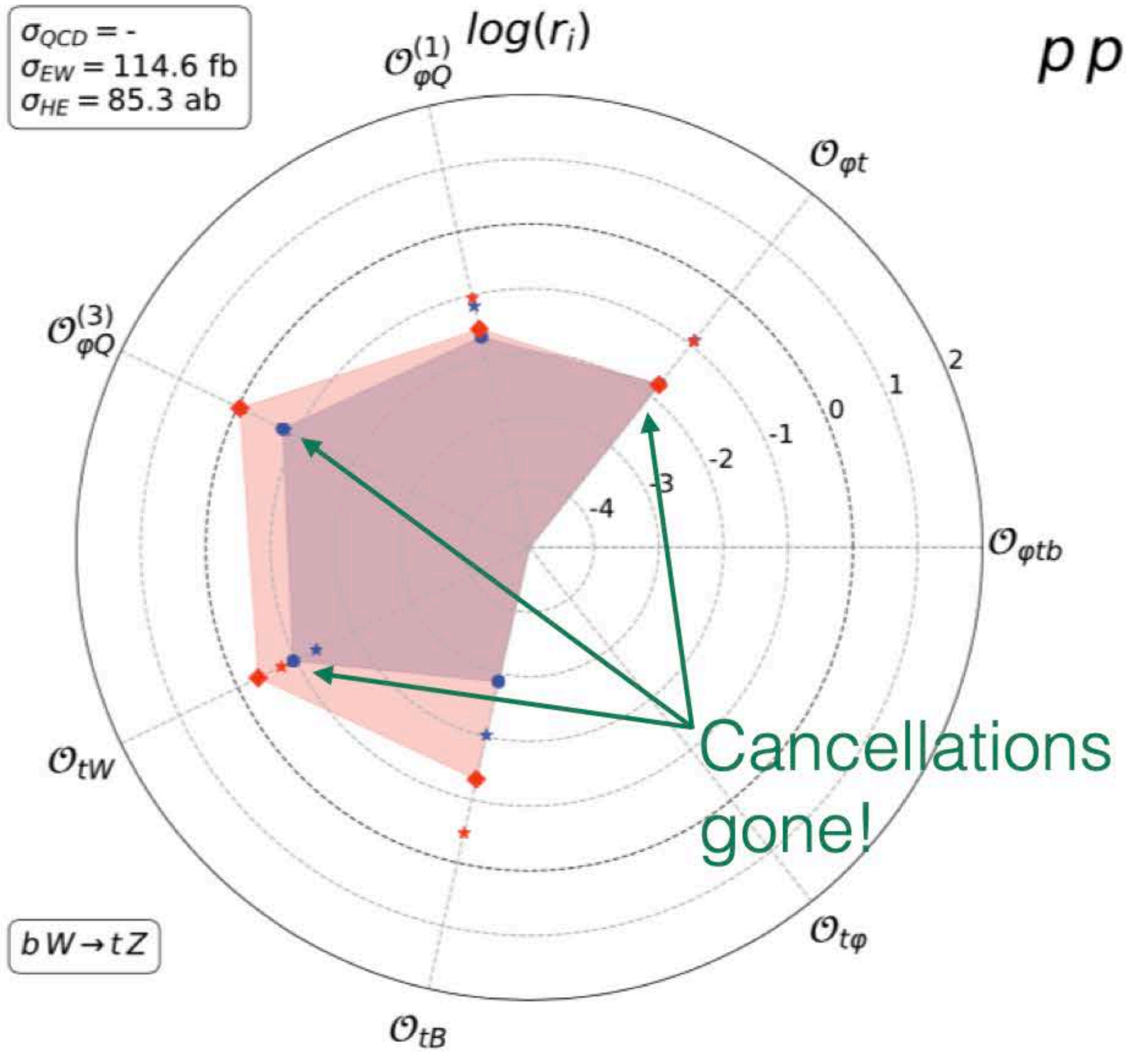

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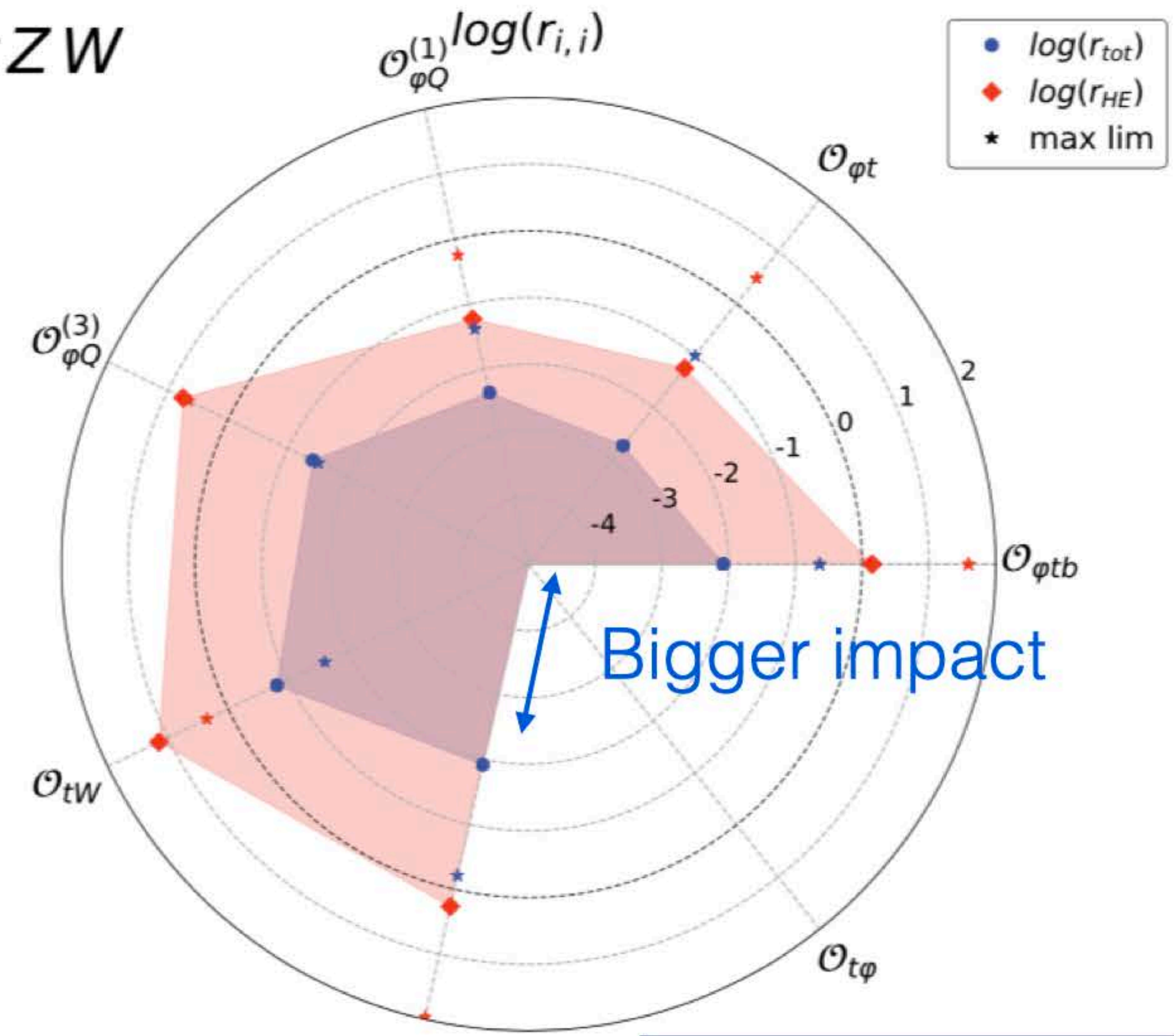

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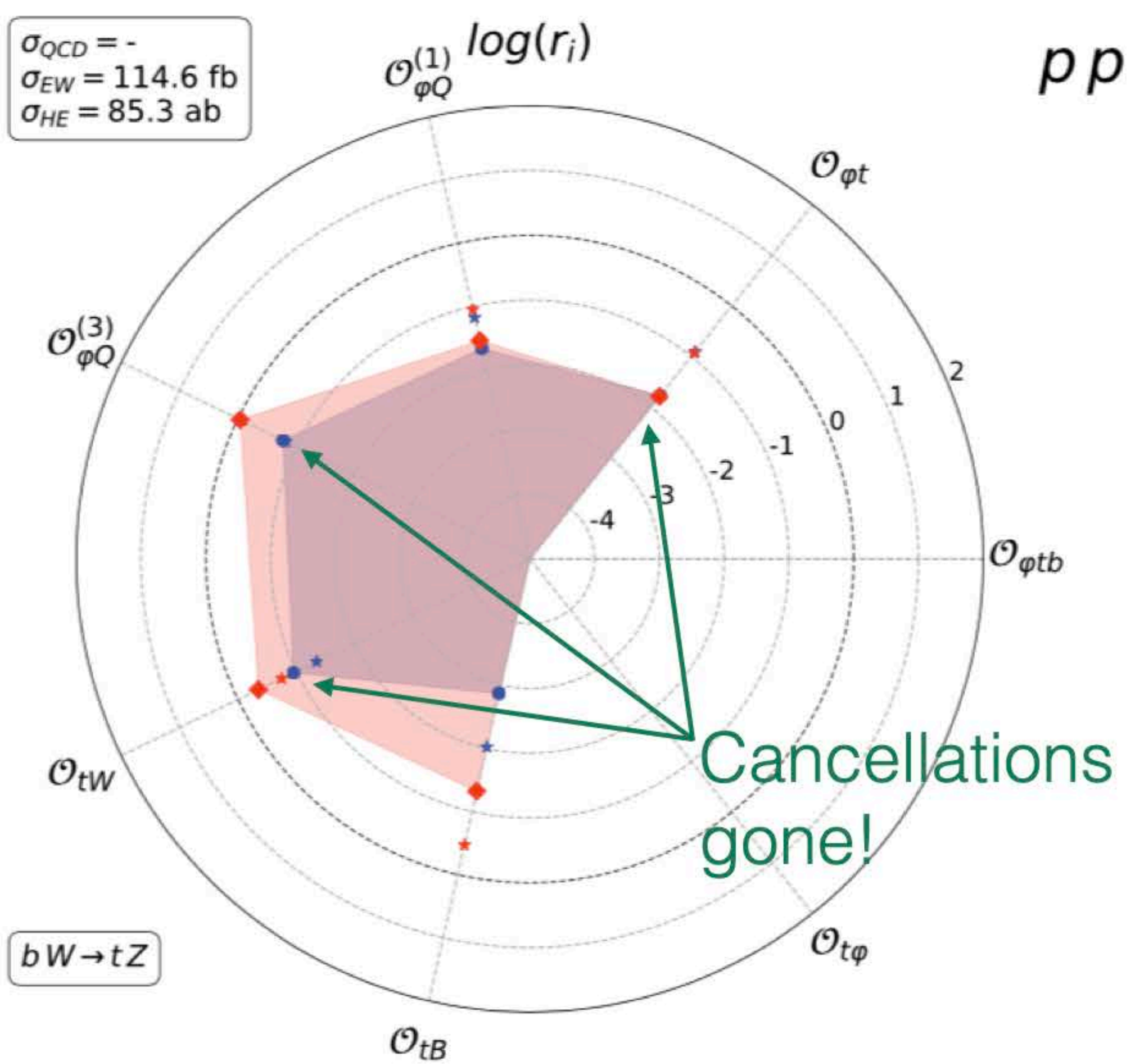

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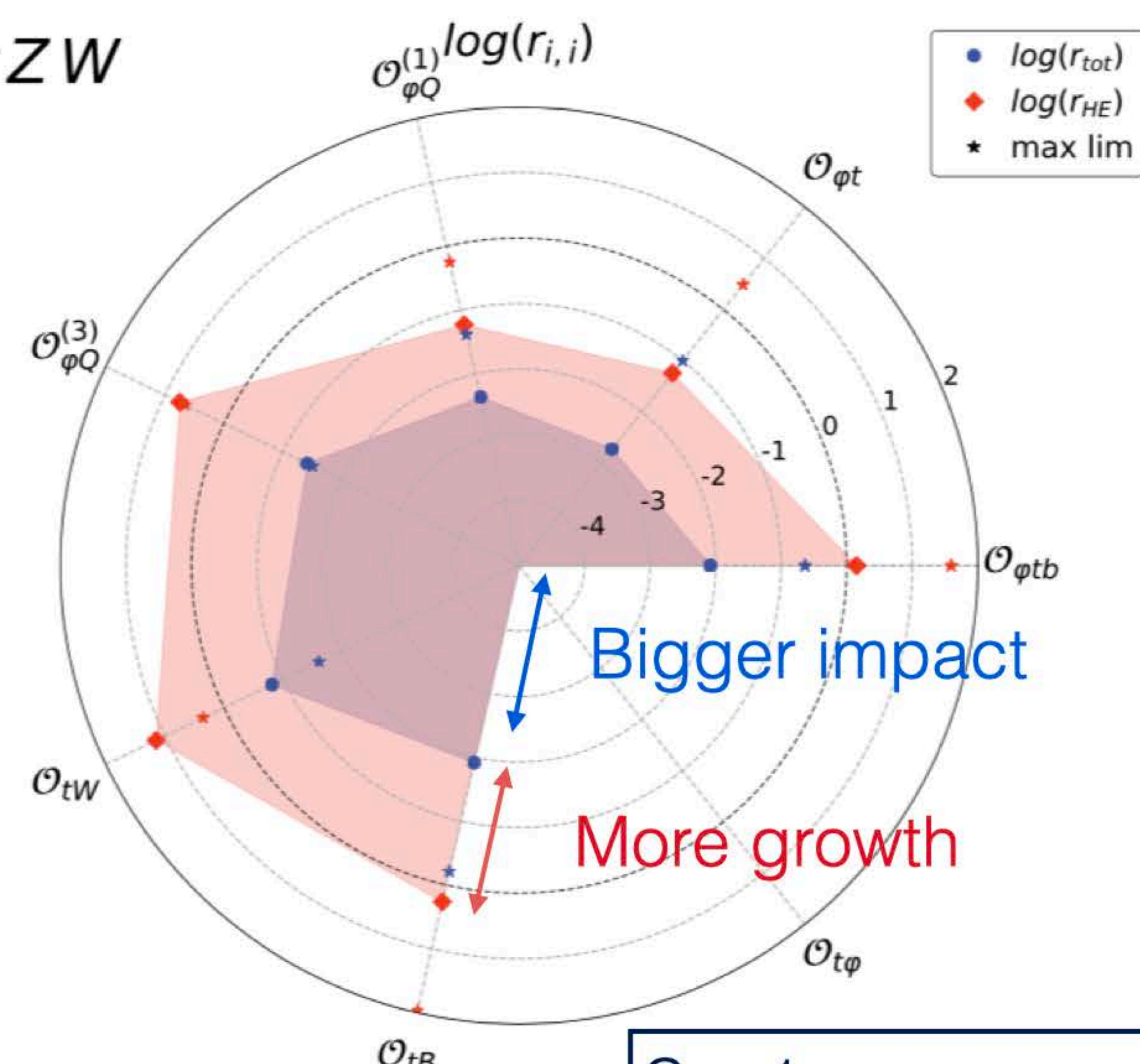

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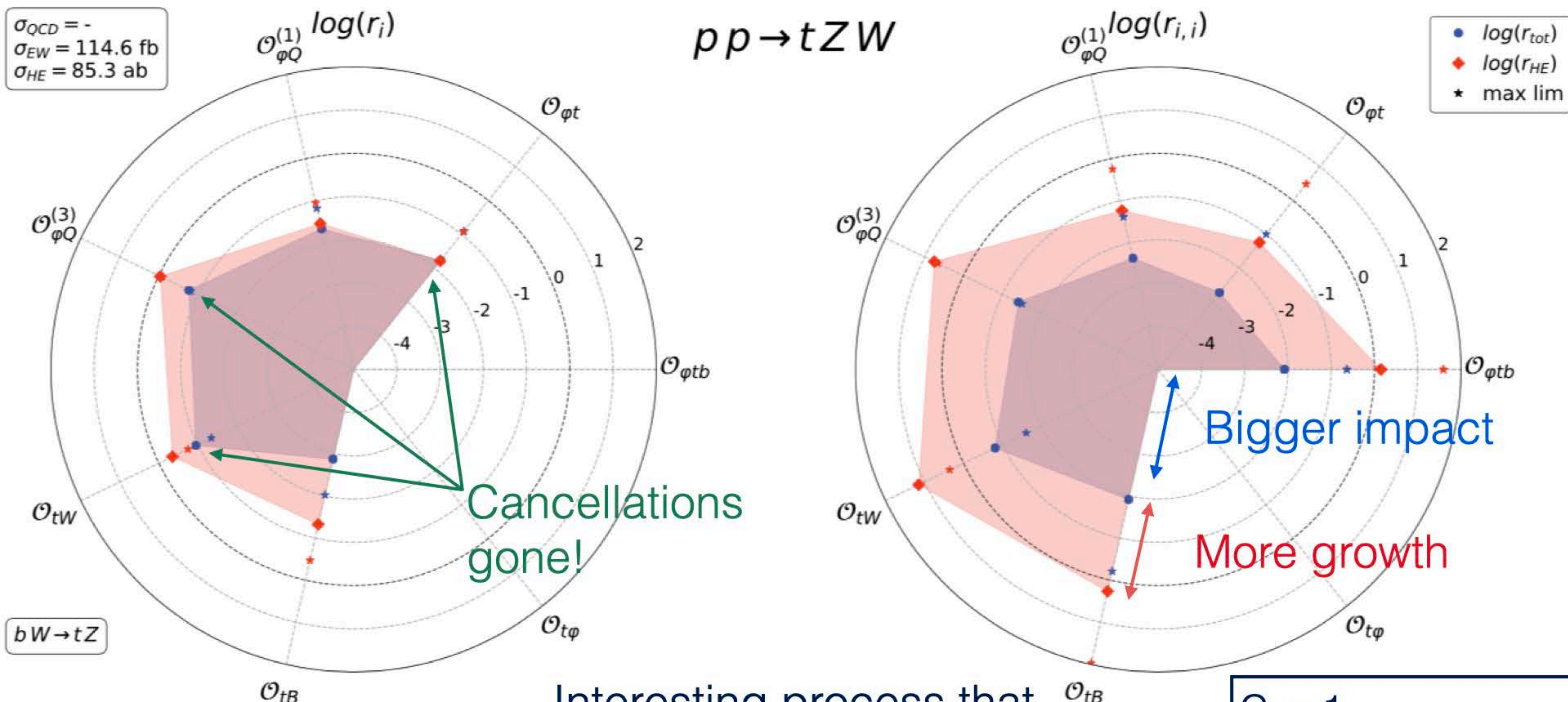

Expected growth is there!

Interesting process that should be accessible at the LHC

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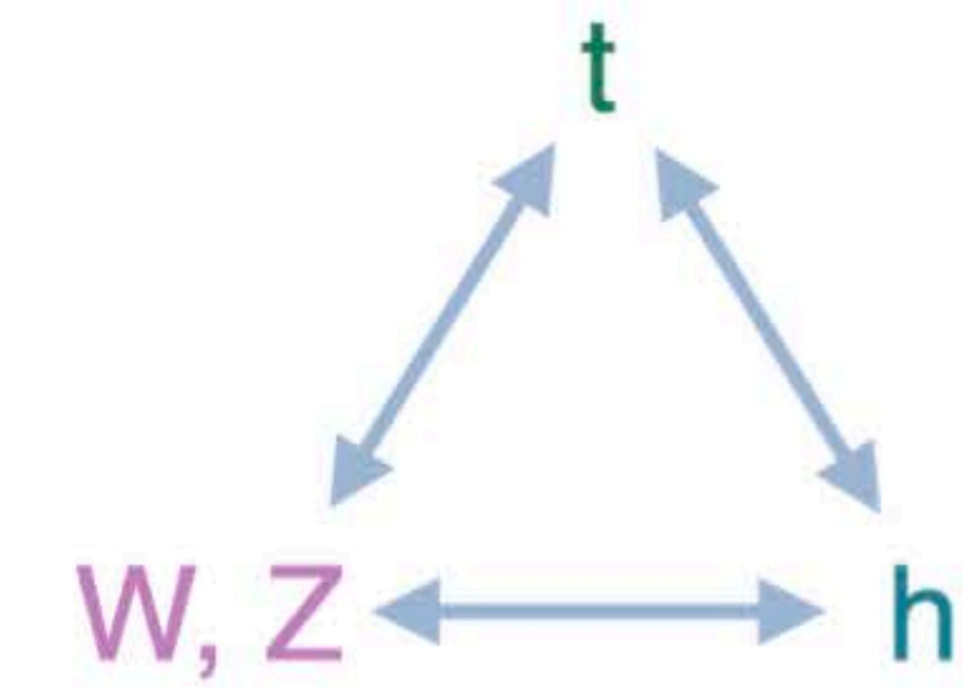
[Maltoni, KM, El Faham & Zaro; JHEP 01 (2022) 100]

New physics in tWZ



Rare top production with promising BSM sensitivity

- Precision differential predictions for SM & EFT

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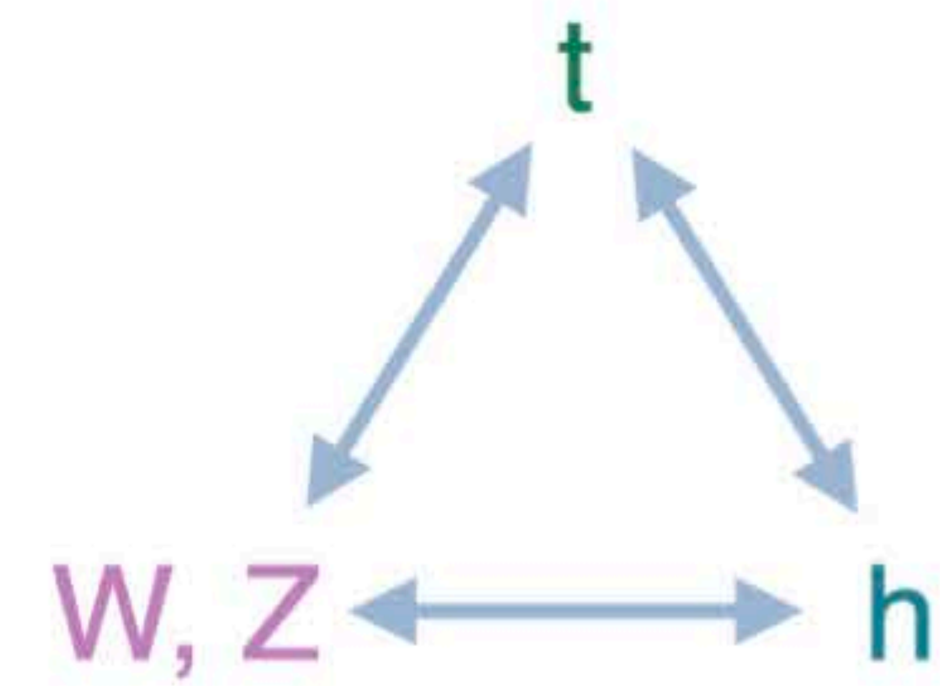

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Well-defined NLO calculation

- Control uncertainties & check stability of BSM impact (SMEFT K-factors)
- tWZ non-trivial: **overlap** with other processes

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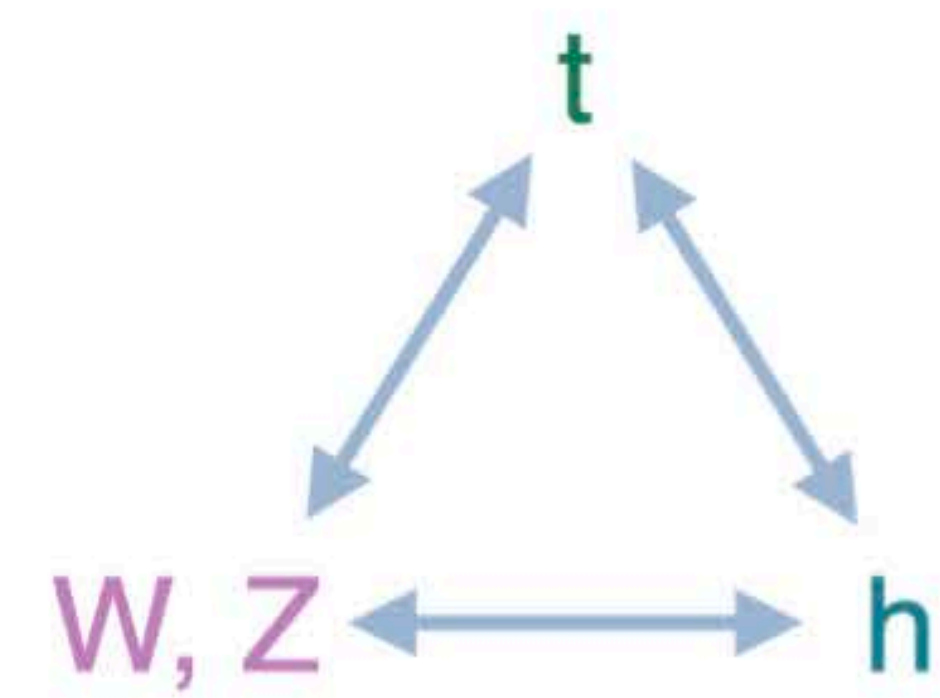

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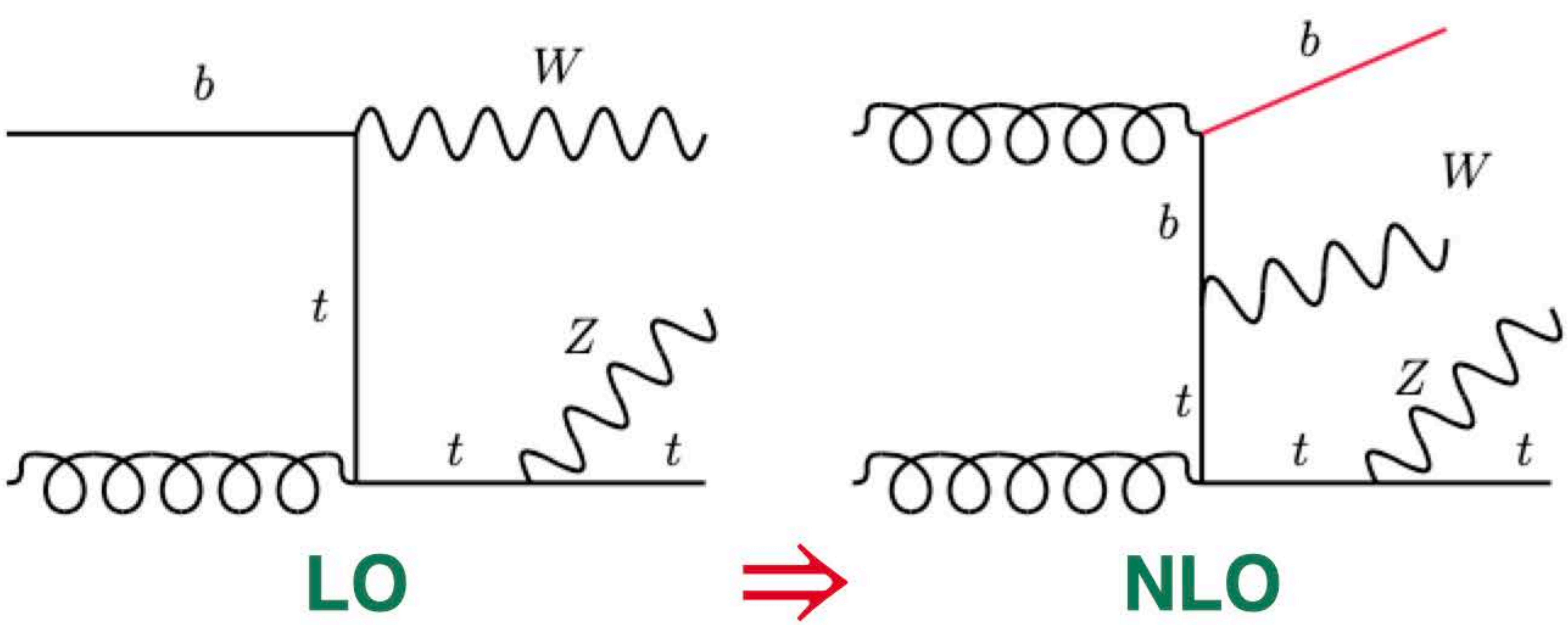
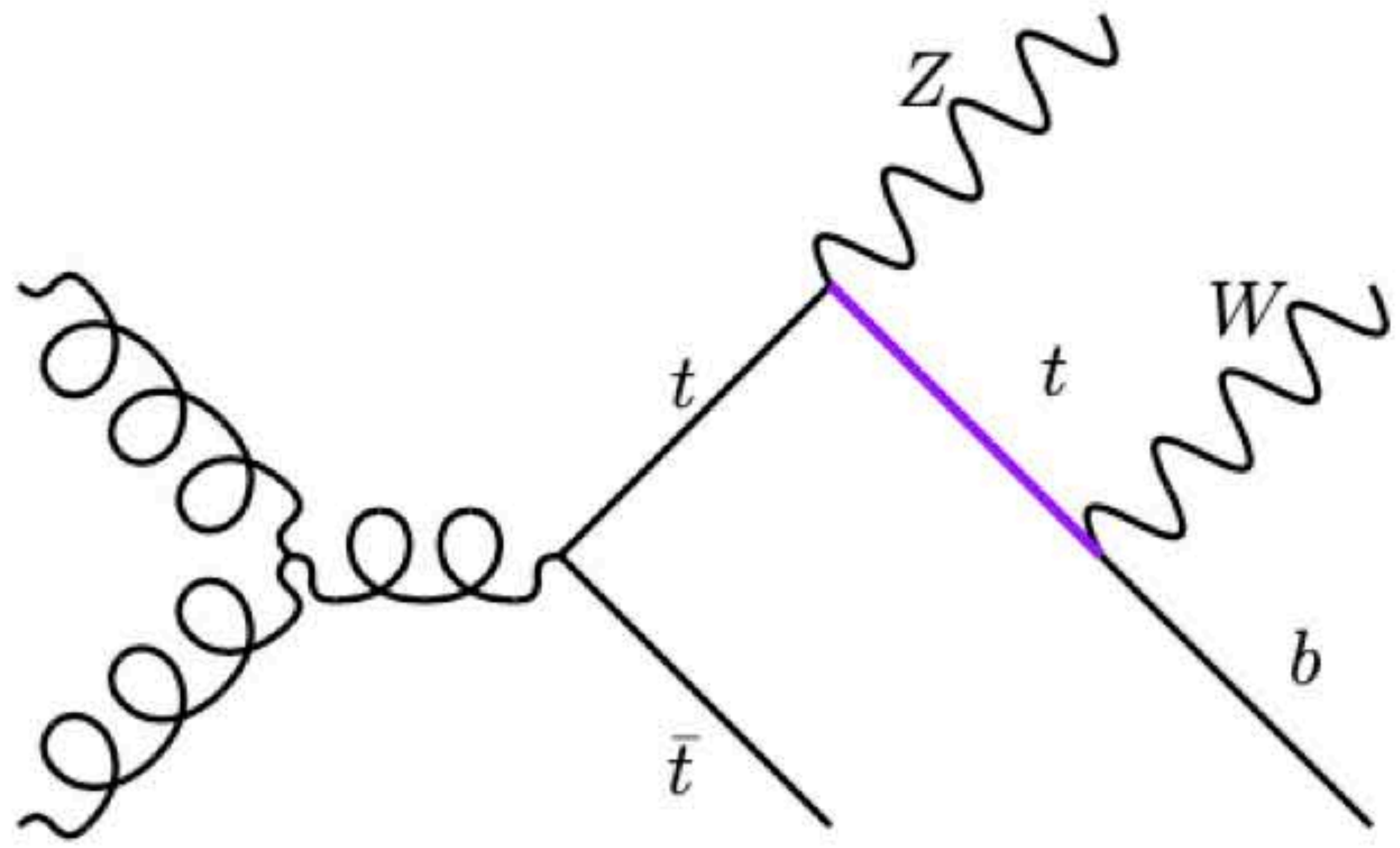
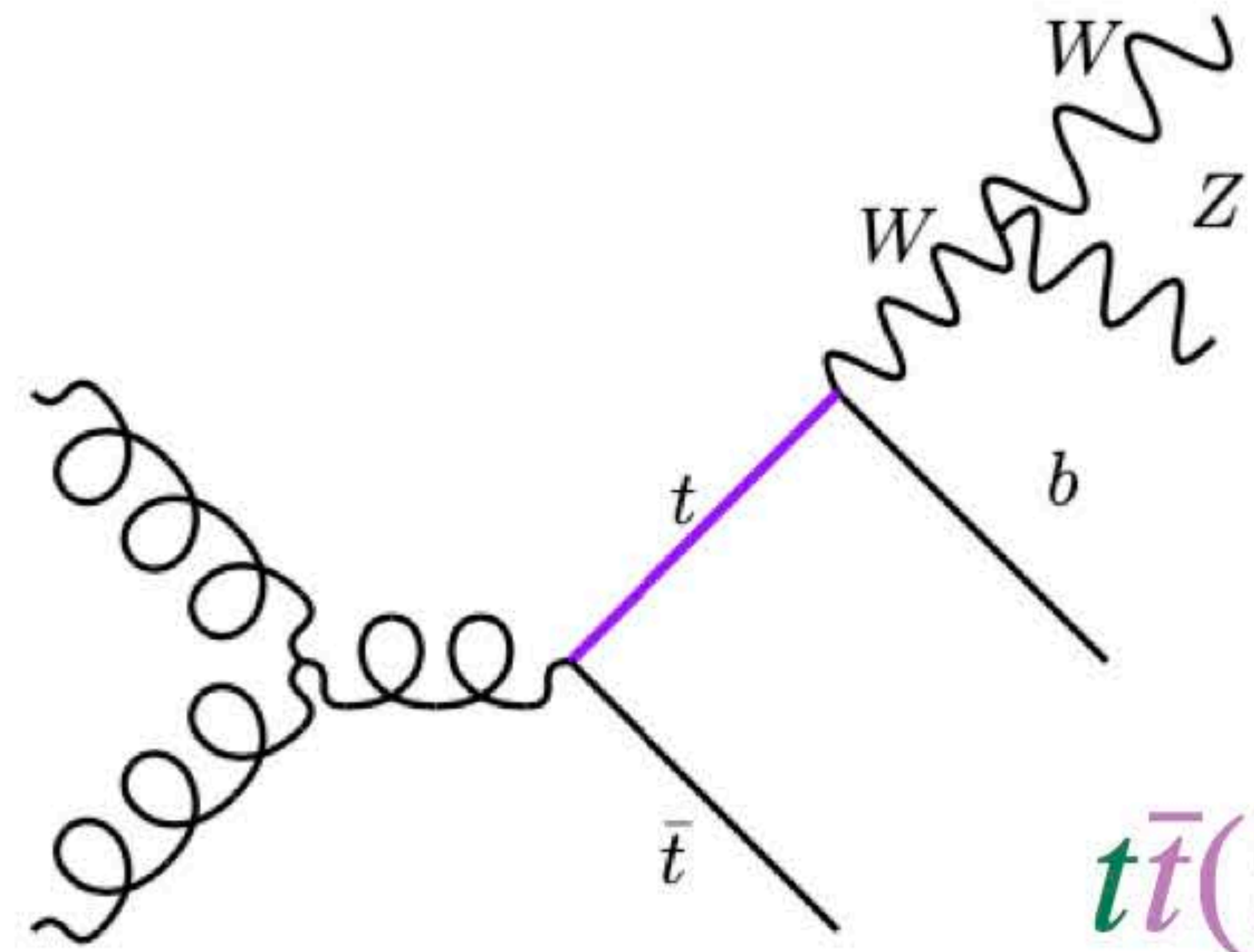


NLO 5FS: real-emission includes $tWZ\bar{b}$ final state

Overlap in tWZ

$t\bar{t}Z(\bar{t} \to W\bar{b})$





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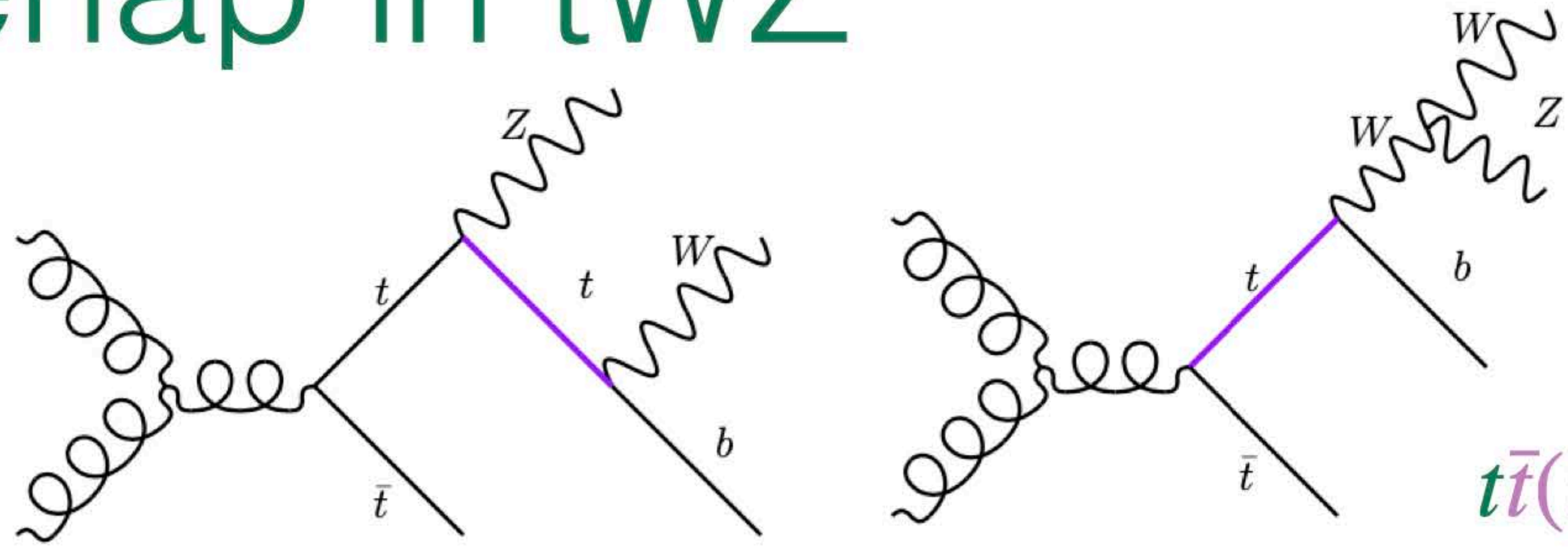

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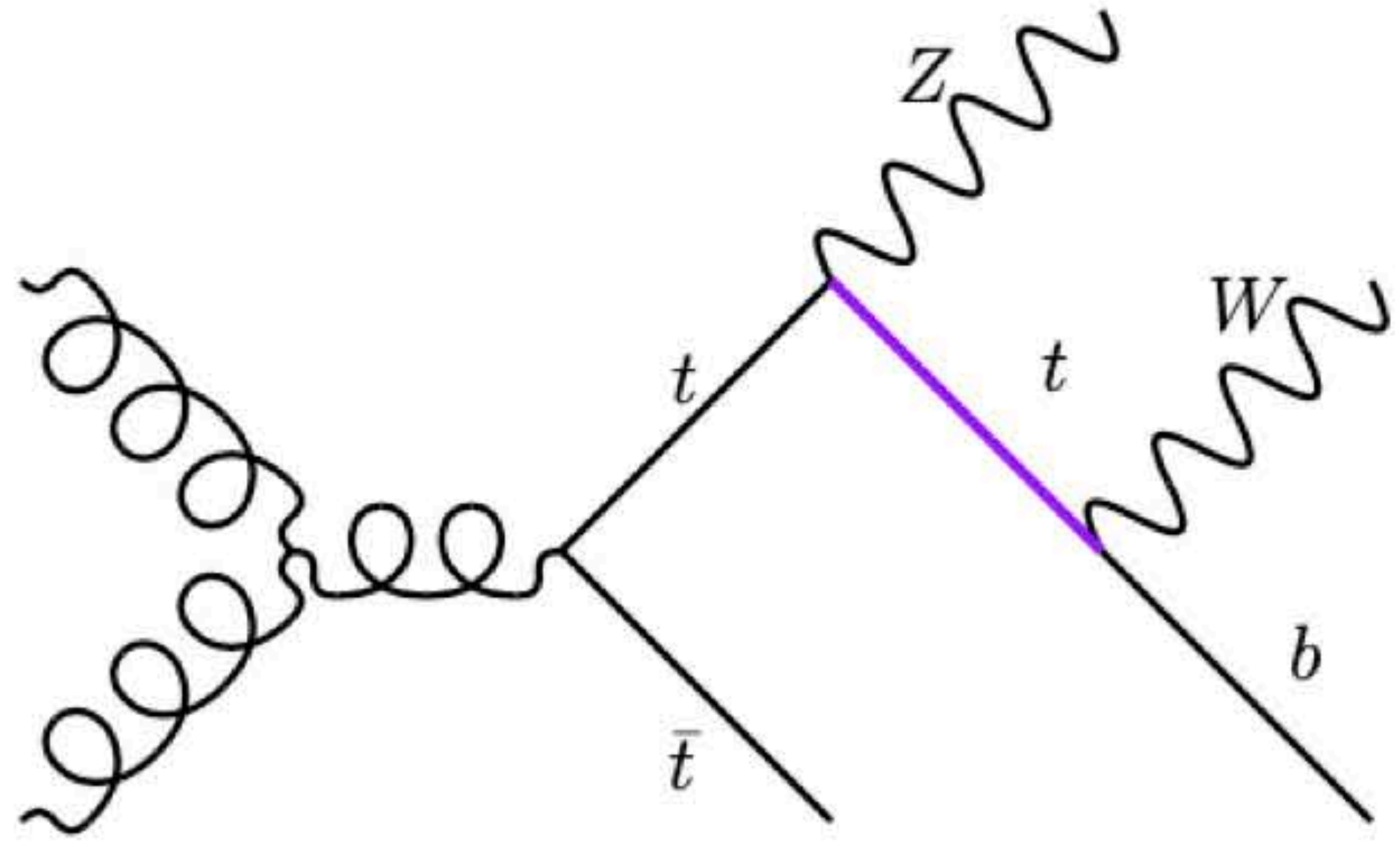

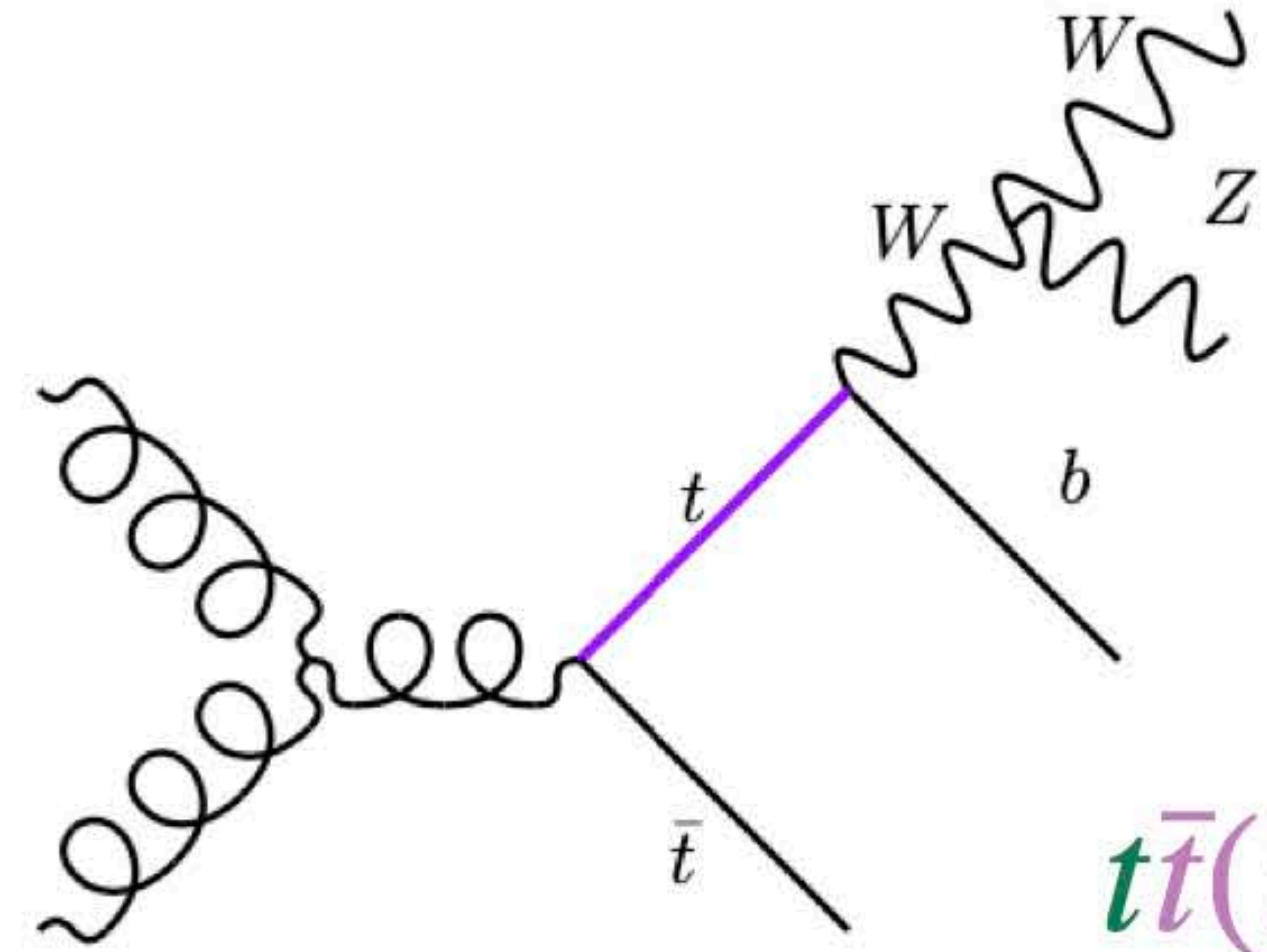

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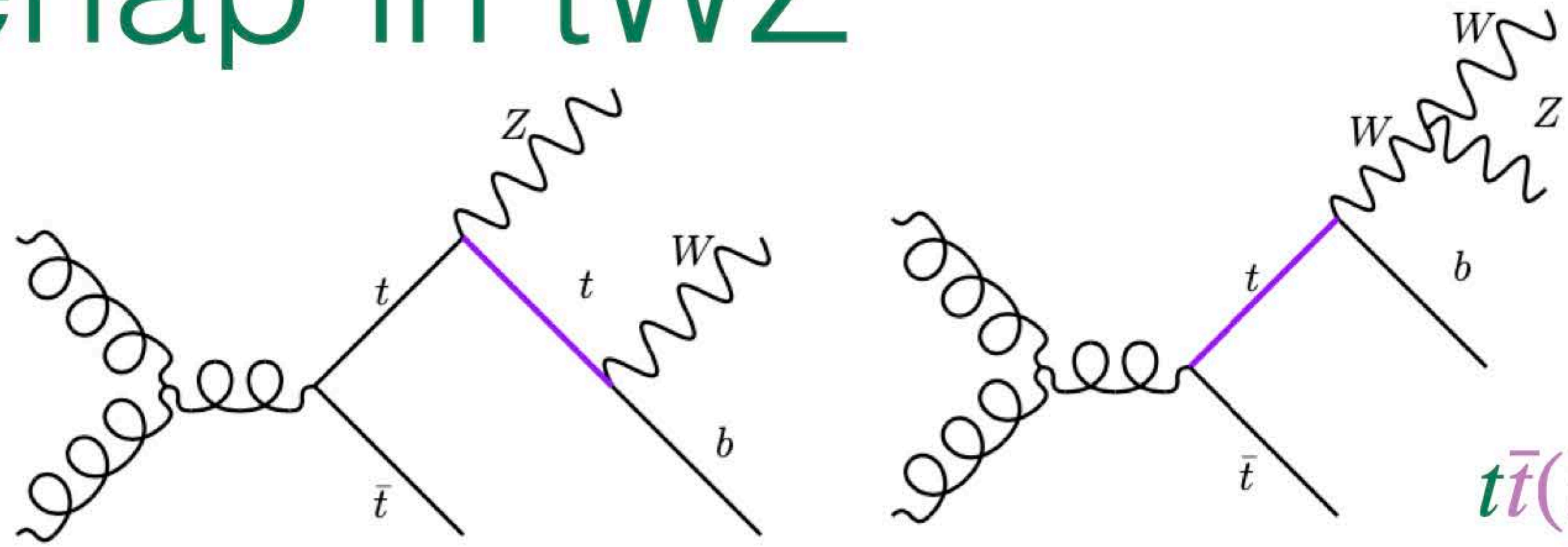

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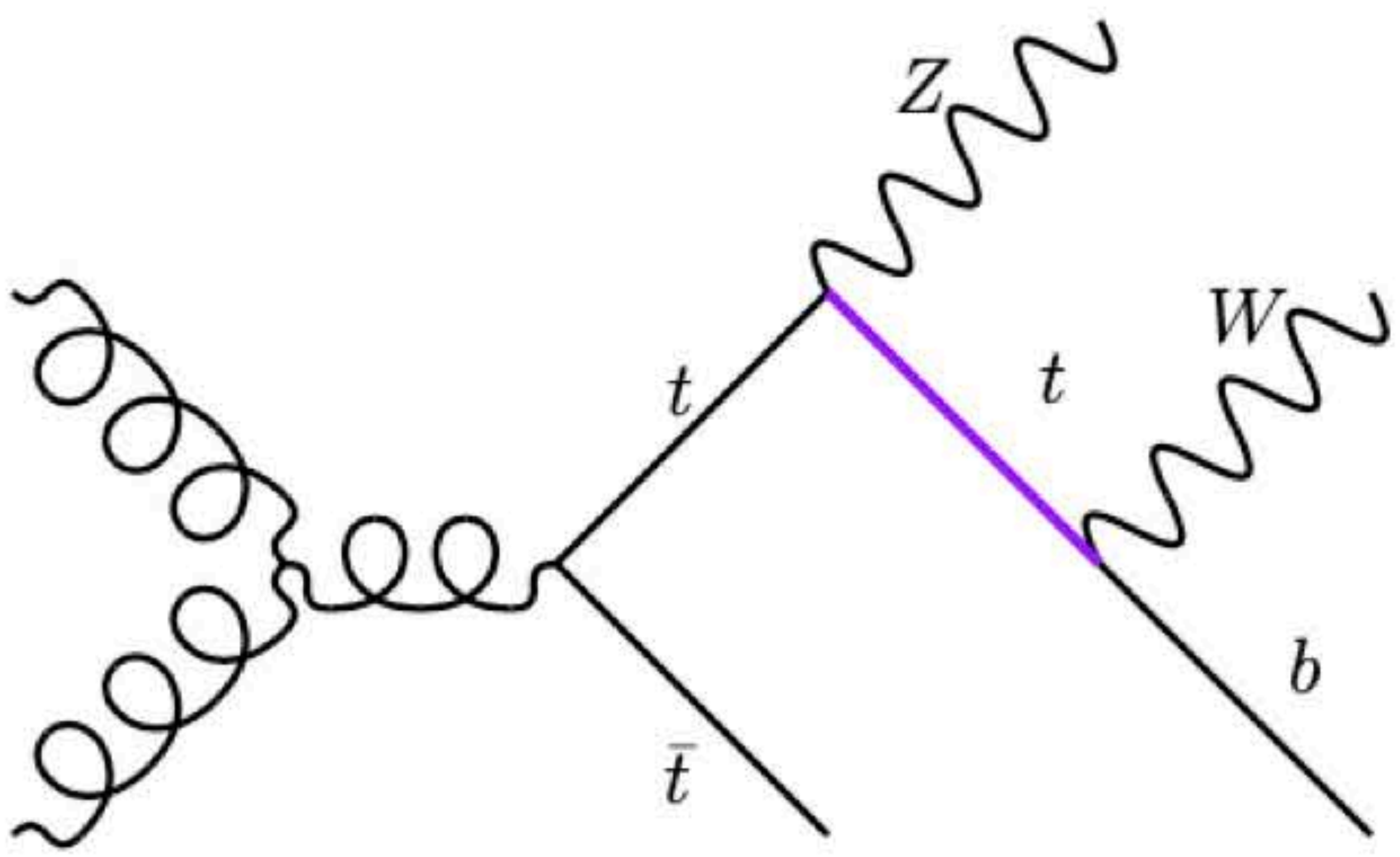

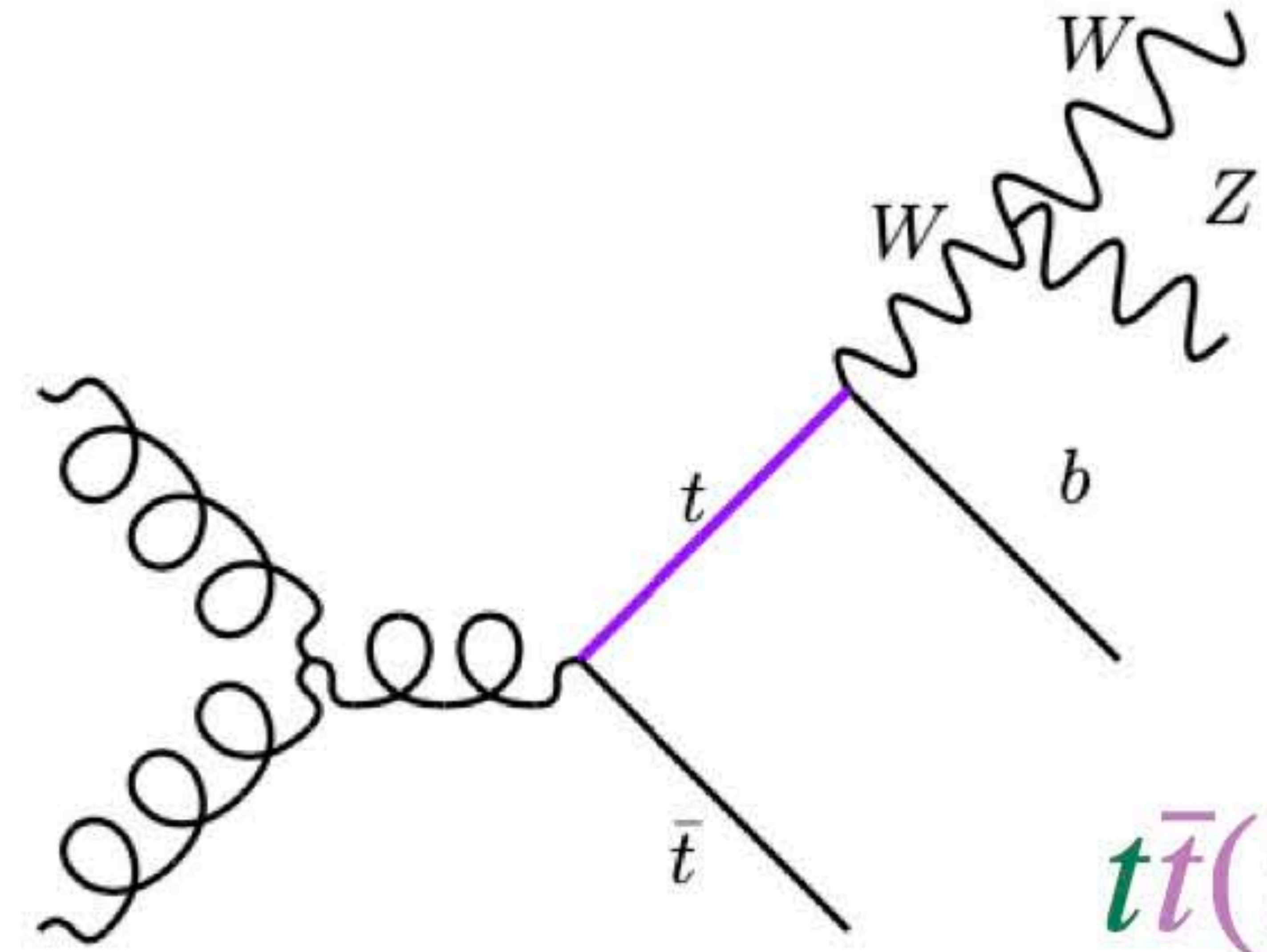

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A. Full final state, 4FS: $pp \to b\bar{b}W^+W^-Z$ *! NLO computationally intensive !*
   [Bevilacqua et al.; JHEP 11 (2019) 001] *! Resonant 'backgrounds' known to NNLO !*

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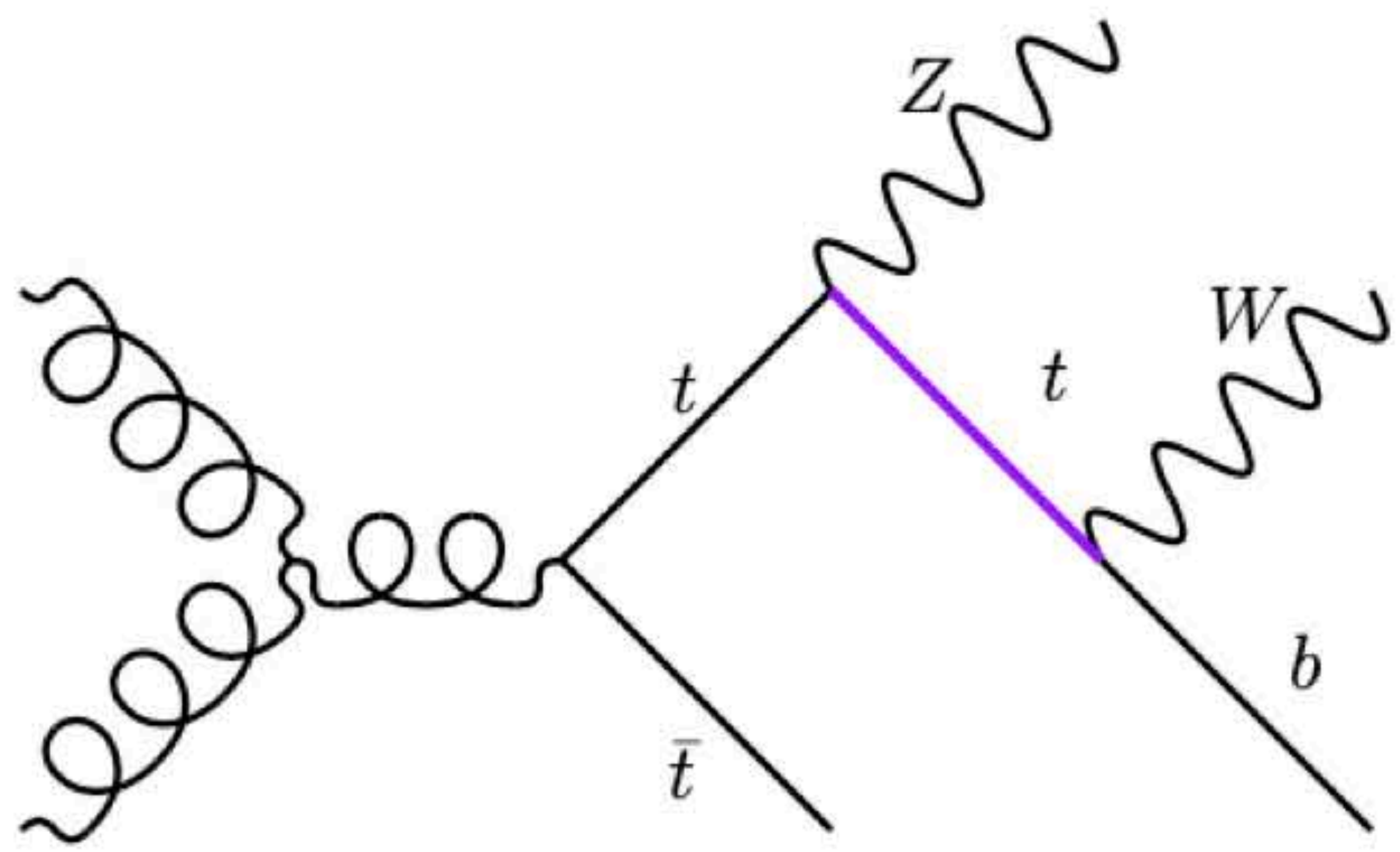

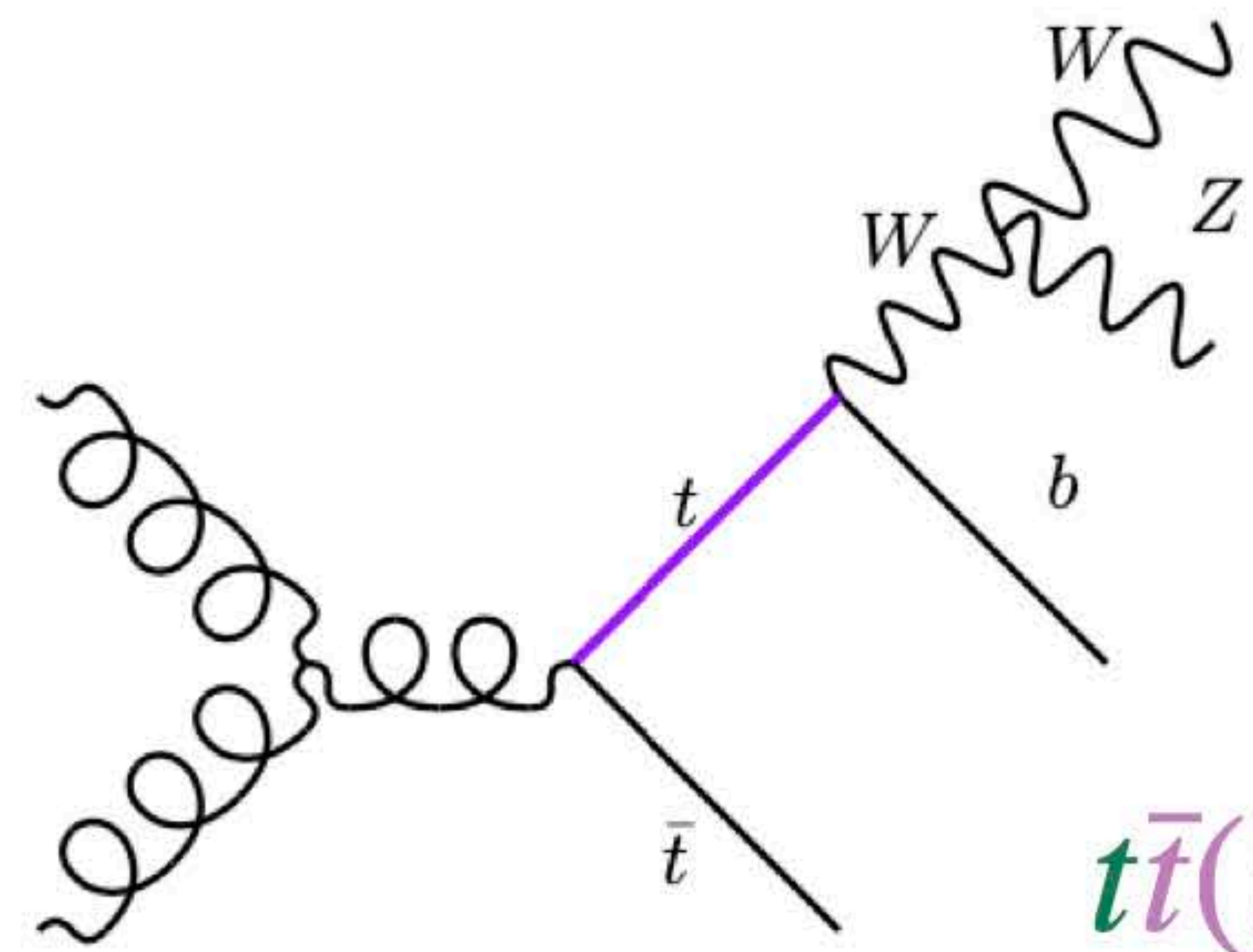

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B. Subtract resonant contributions: operative definition of signal region @ NLO

tWZ in the SM

$tWZ \to tW\ell\ell$: resonant overlap = 1→2(3) & 1→3(4) decays

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$$p_T > 30\,\mathrm{GeV}$$
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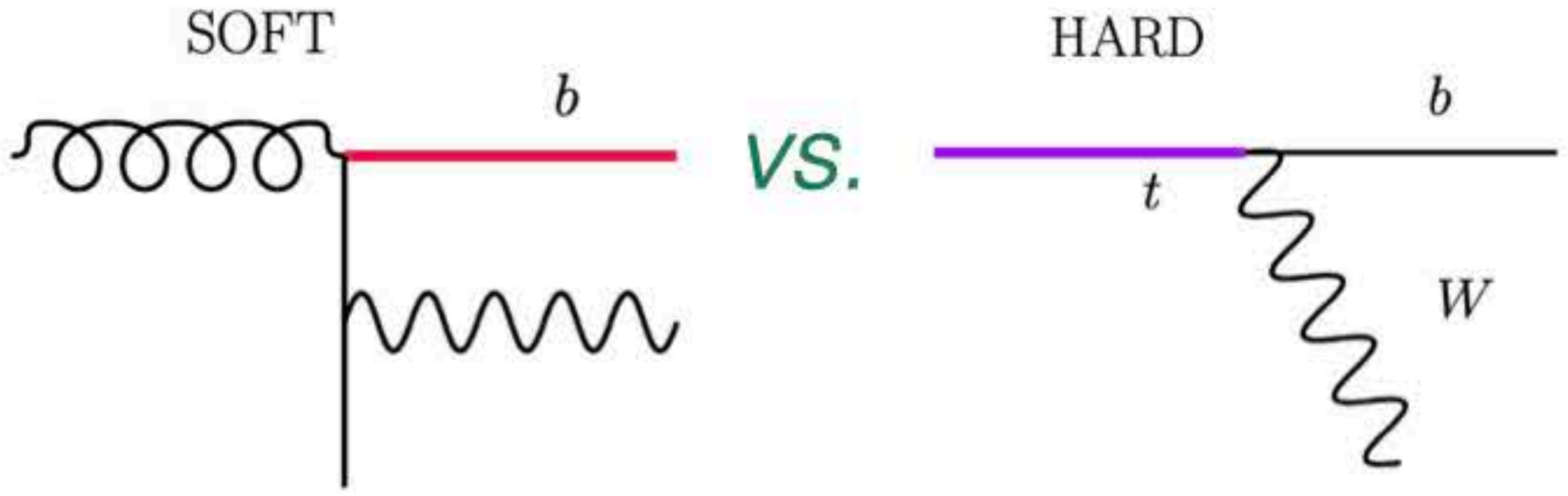

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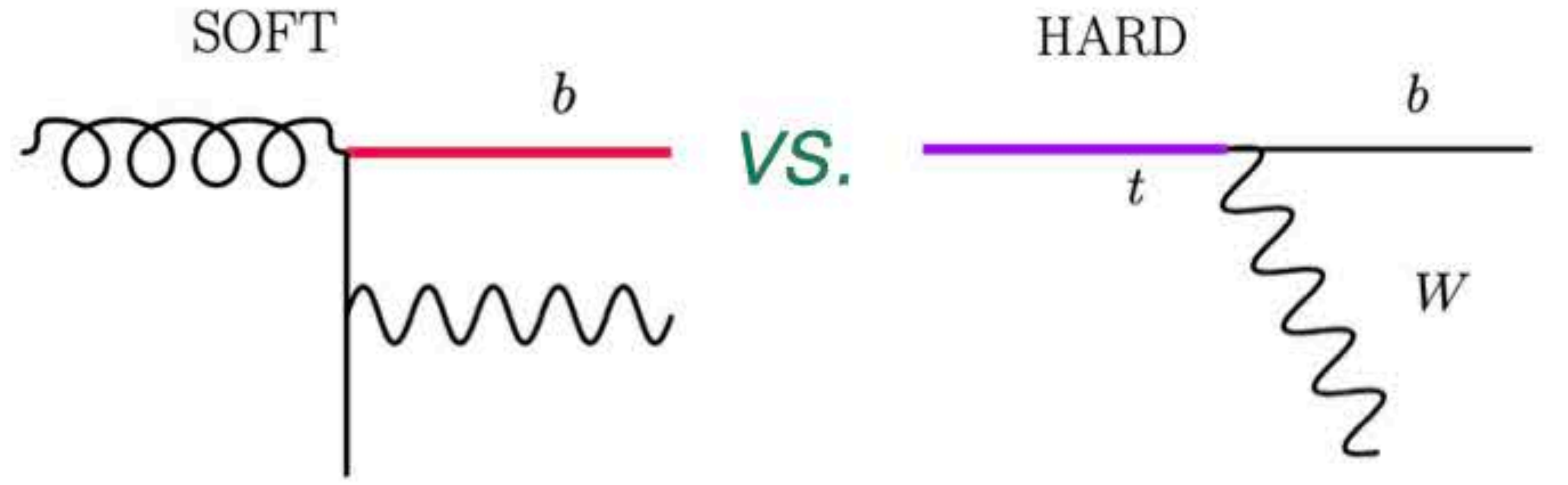

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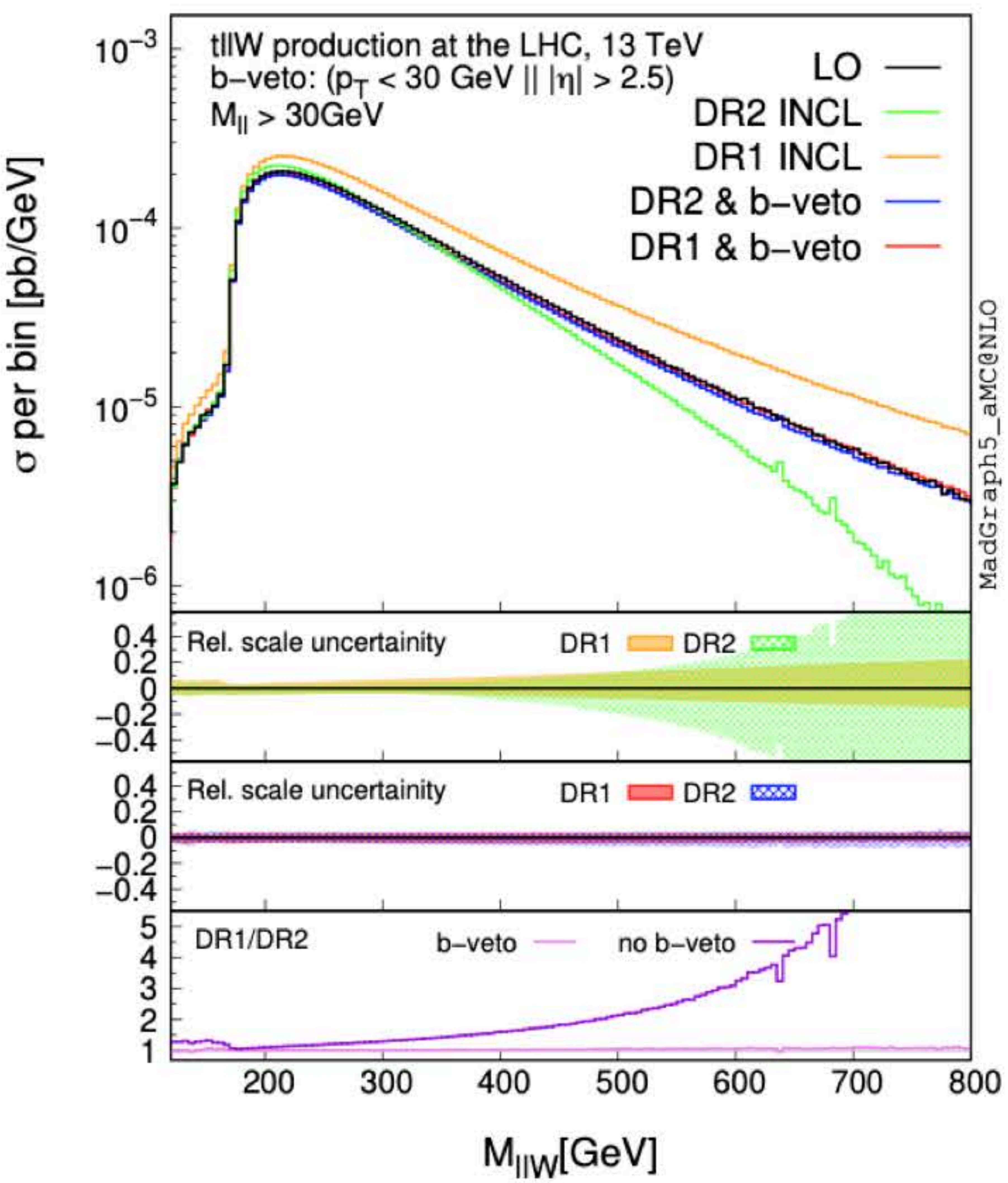
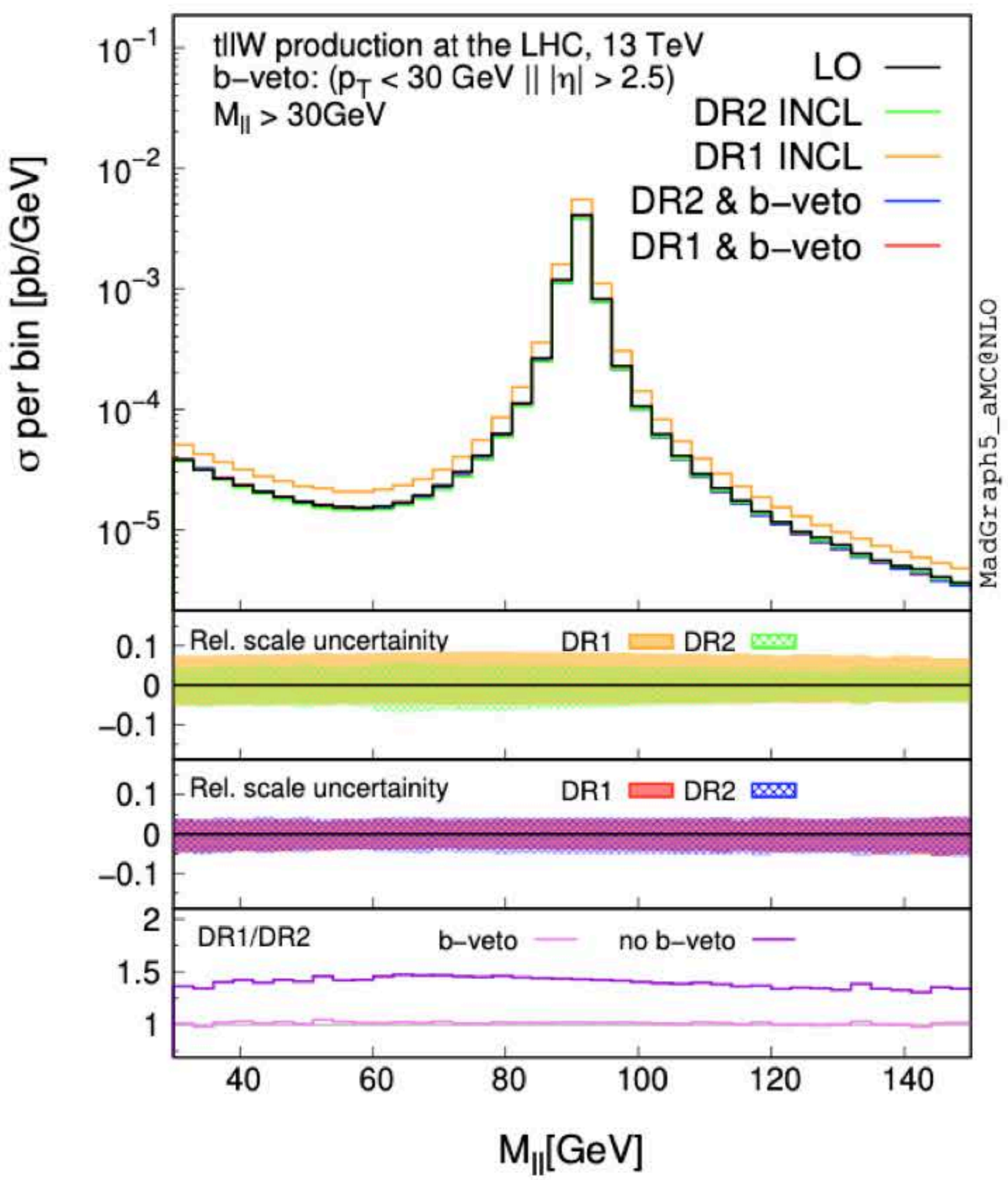




High mass & Z-pole

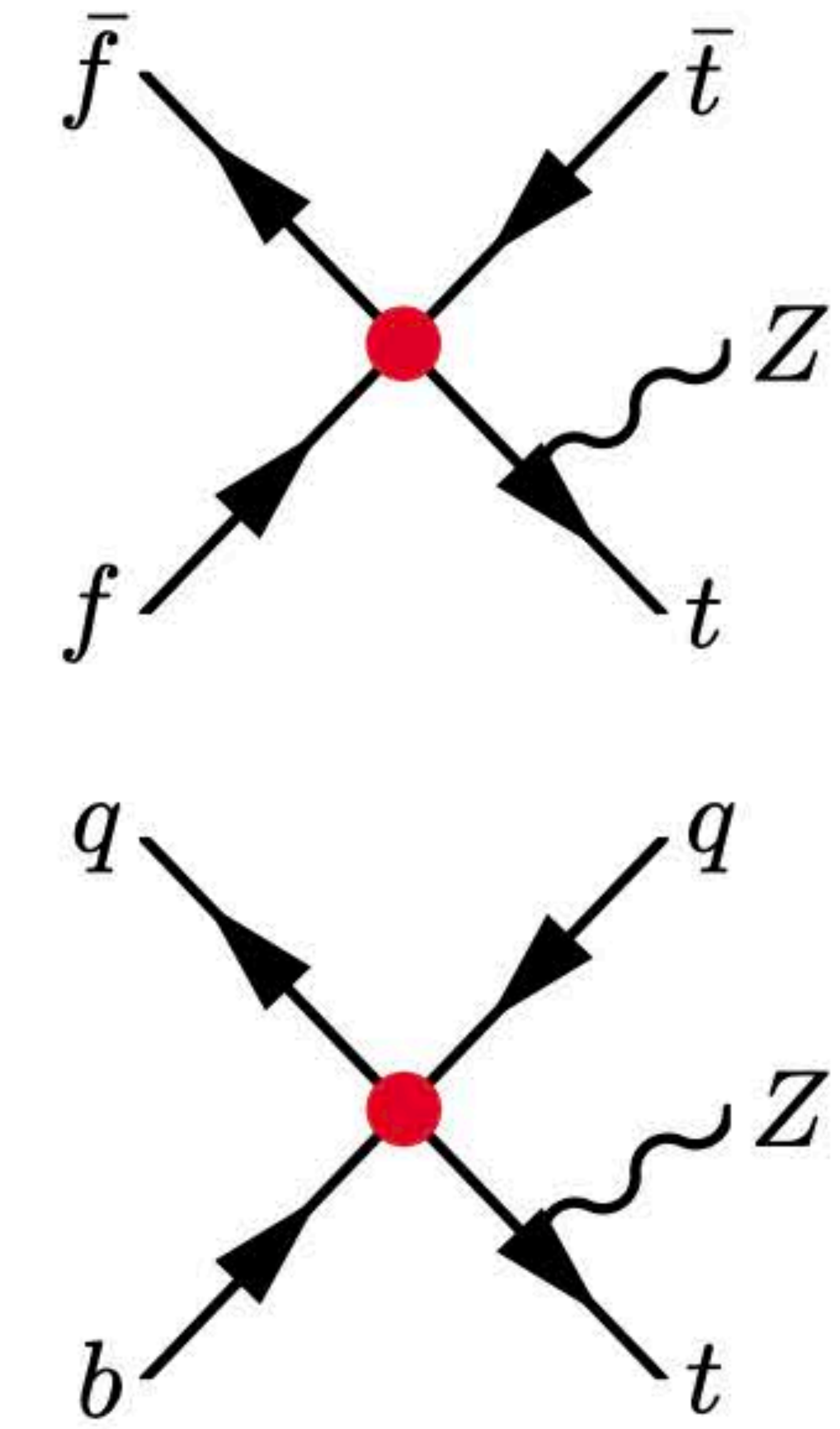
w/o b-veto:
DR1/DR2 diverge at high energy.
Gauge invariance issues…

w/ b-veto:
DR1/DR2 agree.
Uncertainty under control.

tWZ in the SMEFT

Pros

- Sensitive to unitarity violation in $bW \to tZ$ scattering
- Energy growth found to be more pronounced w.r.t. tZj, tWj,…
- No LO contribution from 4F operators, unlike $t\bar{t}Z$ & tZj
- Global fit: help to de-correlate 4F from top EW couplings



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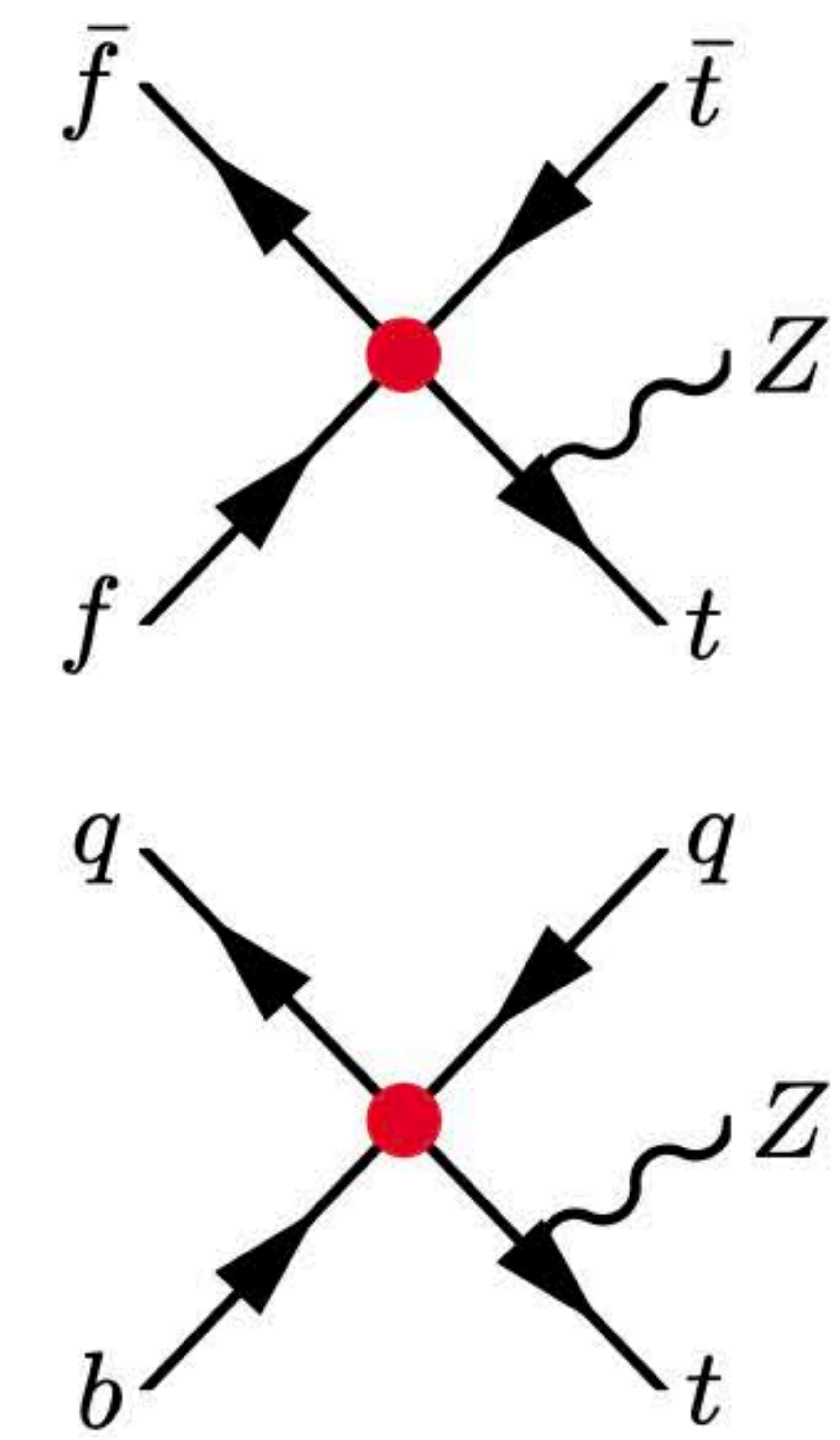

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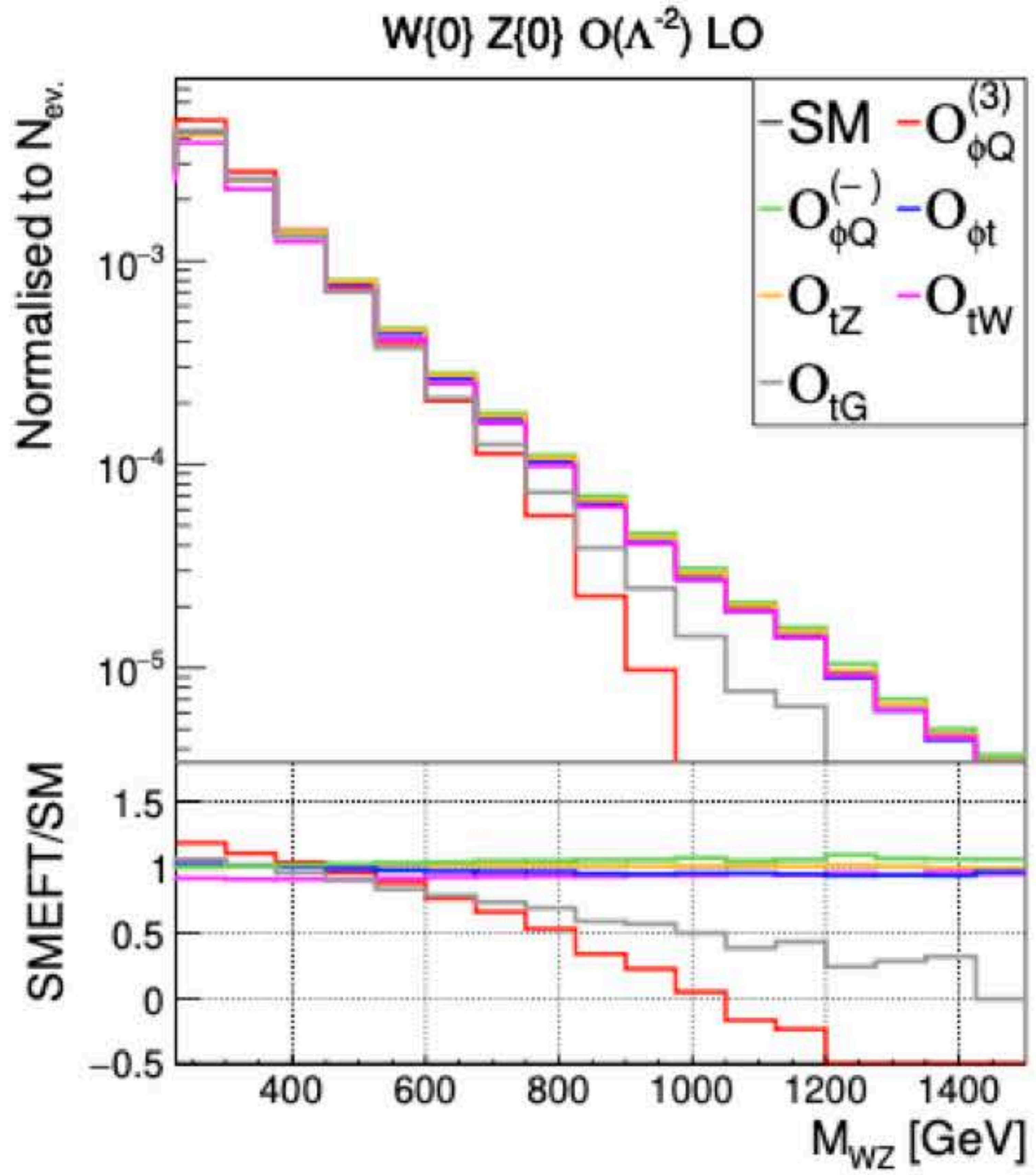
Cons

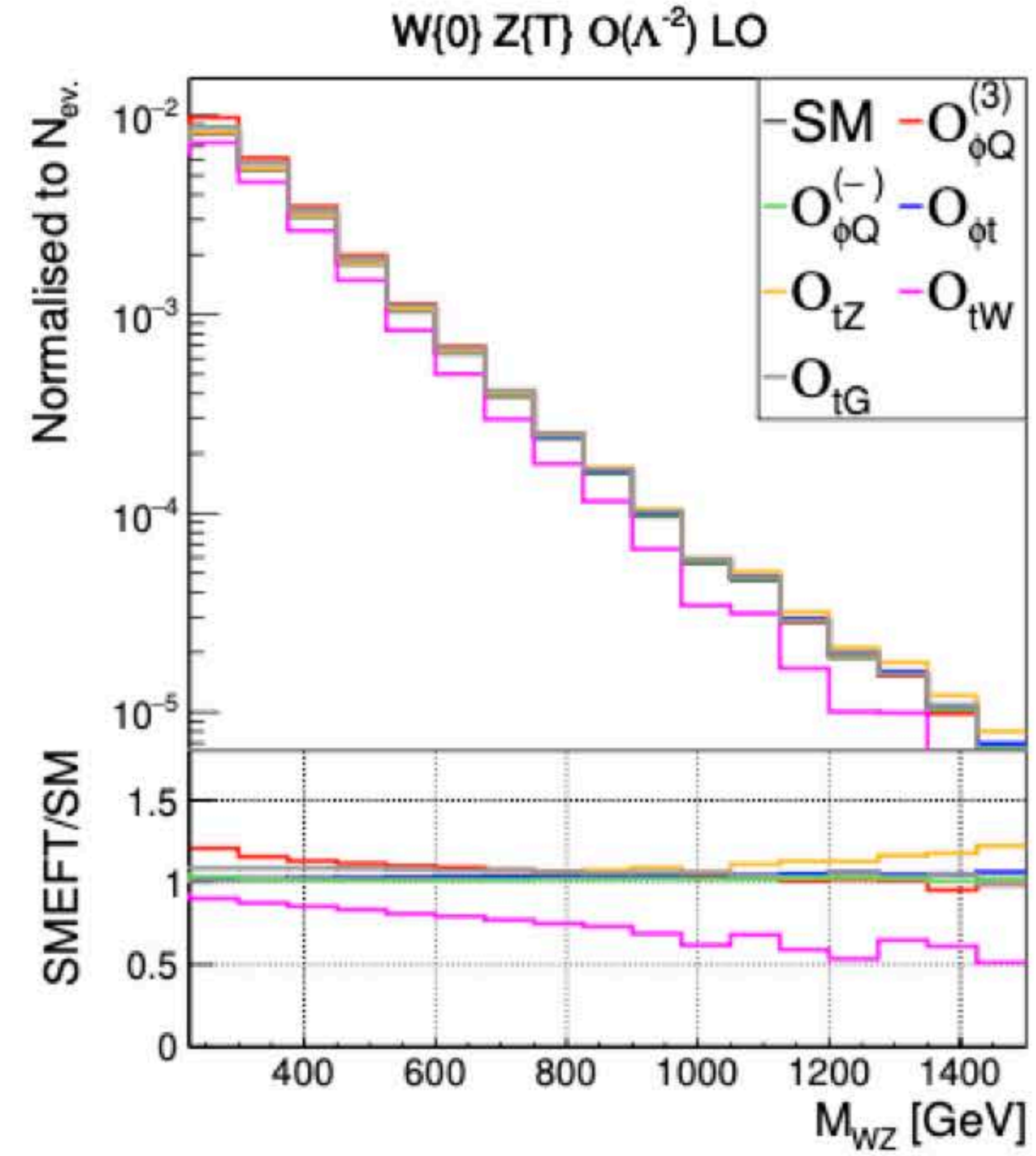
- Rare process ~100 fb before decays
- Not yet observed
- Overlap with resonant backgrounds
- Challenging to disentangle from other rate top processes
- $tW, t\bar{t}Z, t\bar{t}W, tZj, \ldots$

$\mathcal{O}(\Lambda^{-2})$

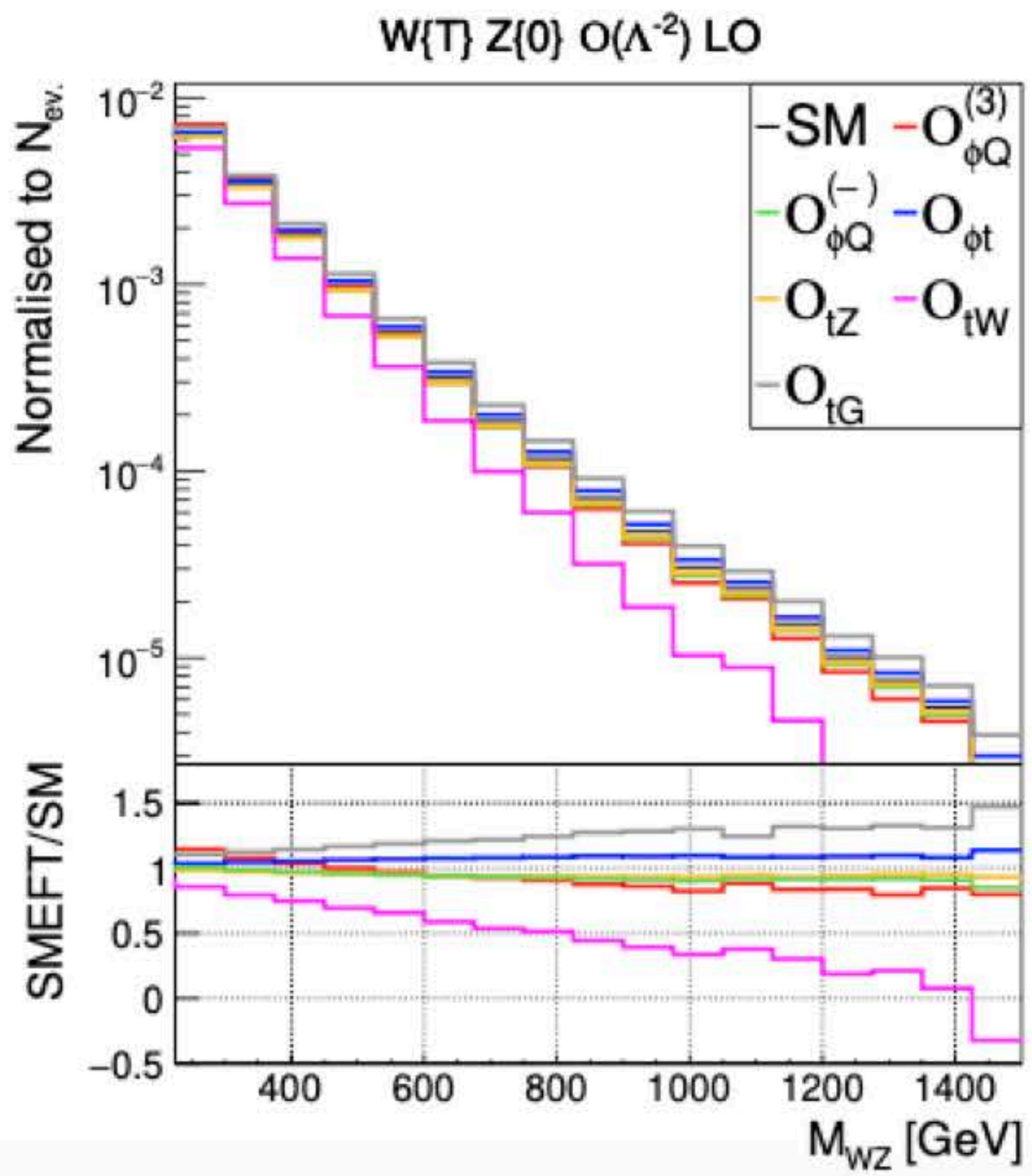
W_L, Z_L



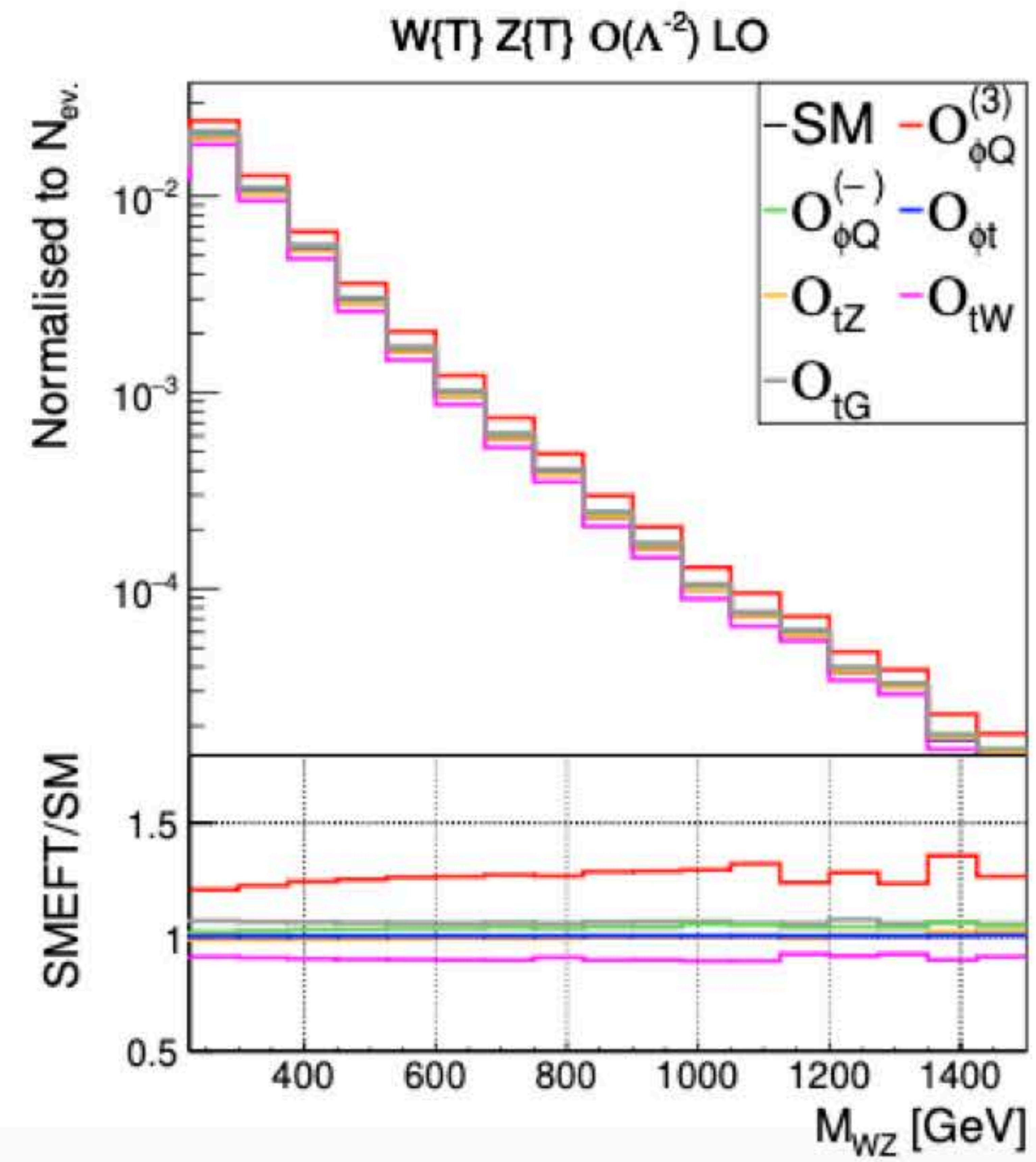
W_L, Z_T



W_T, Z_L



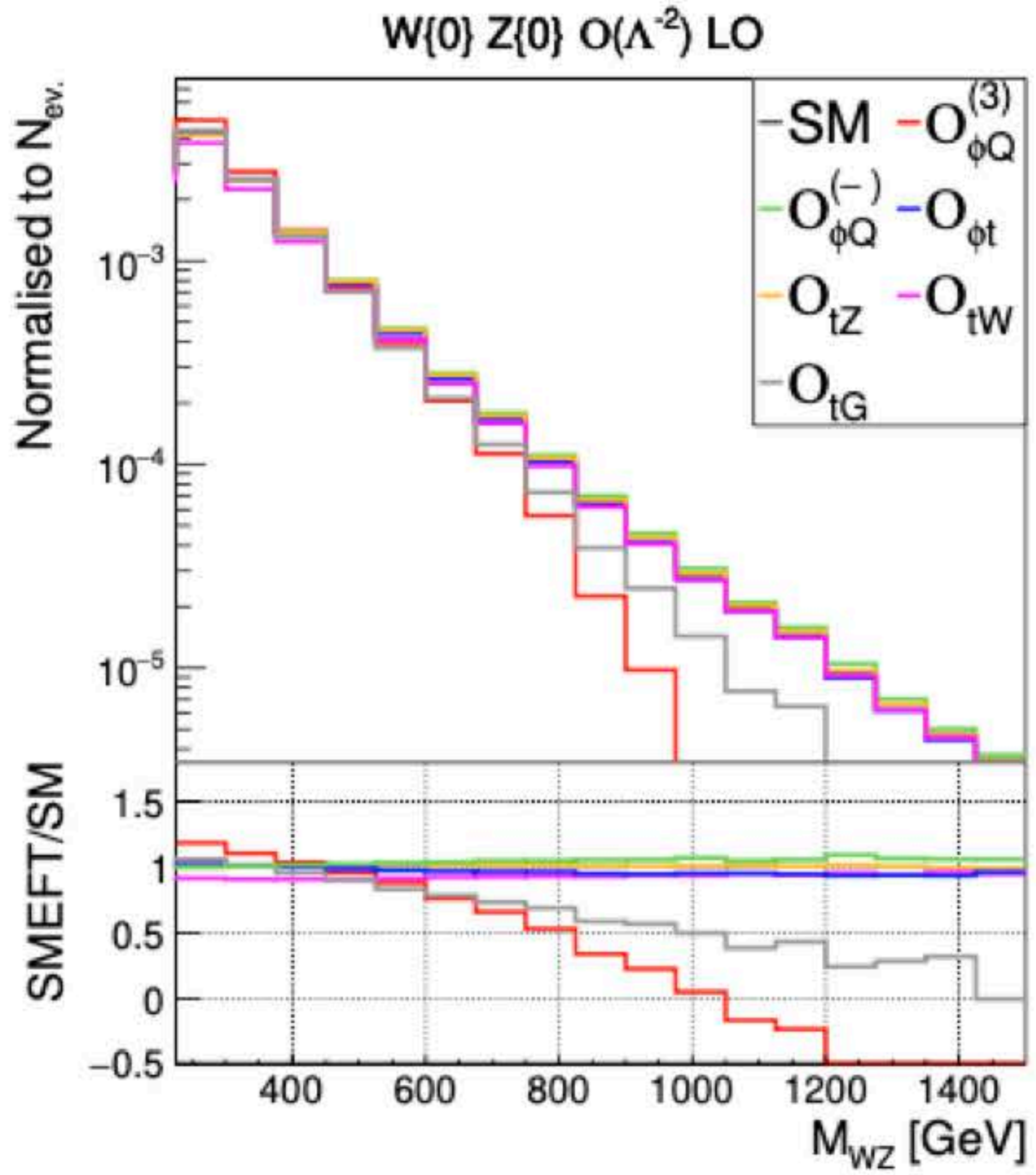
W_T, Z_T



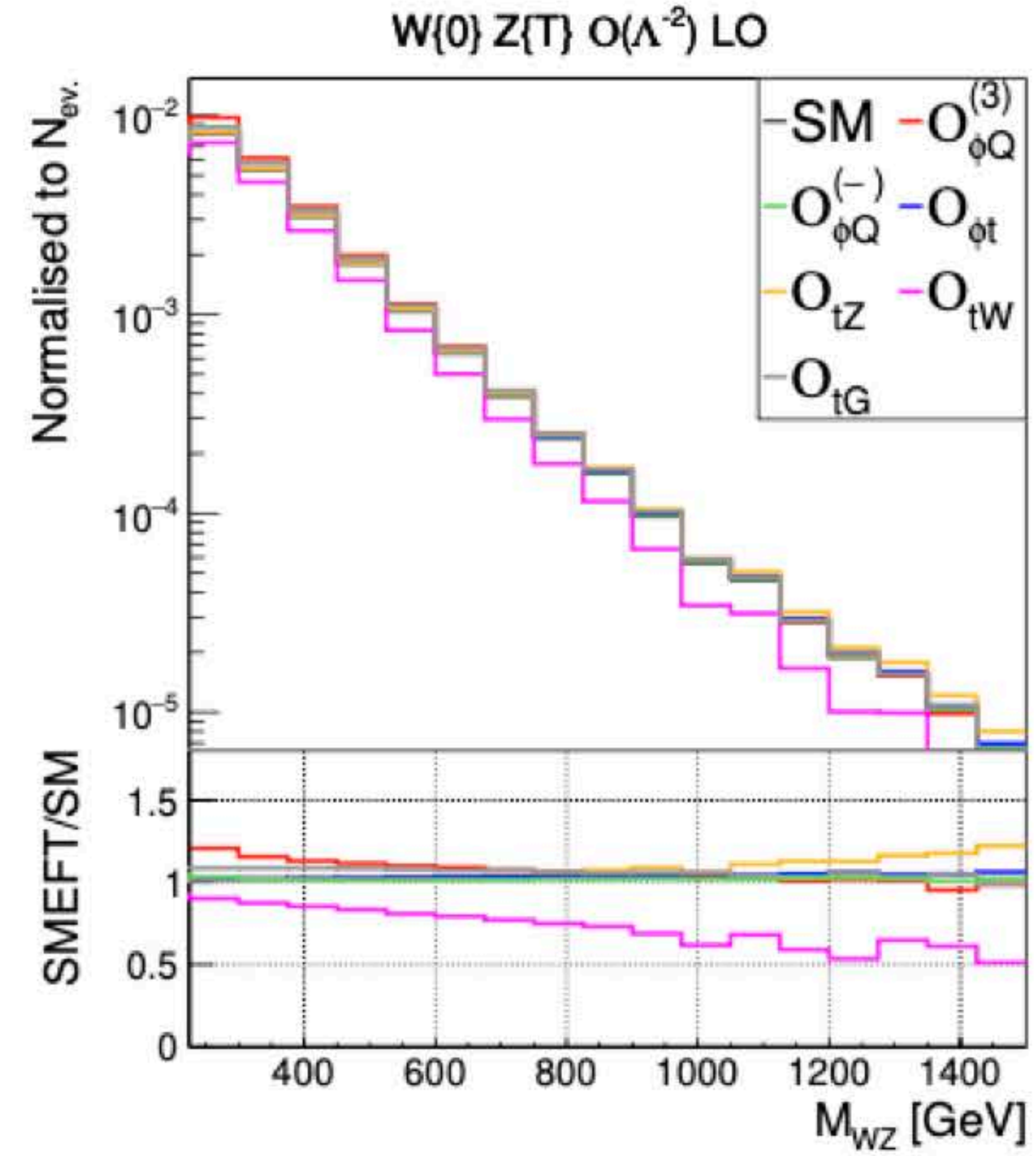
$\mathcal{O}(\Lambda^{-2})$

W_L, Z_L

Expected E-growing interference

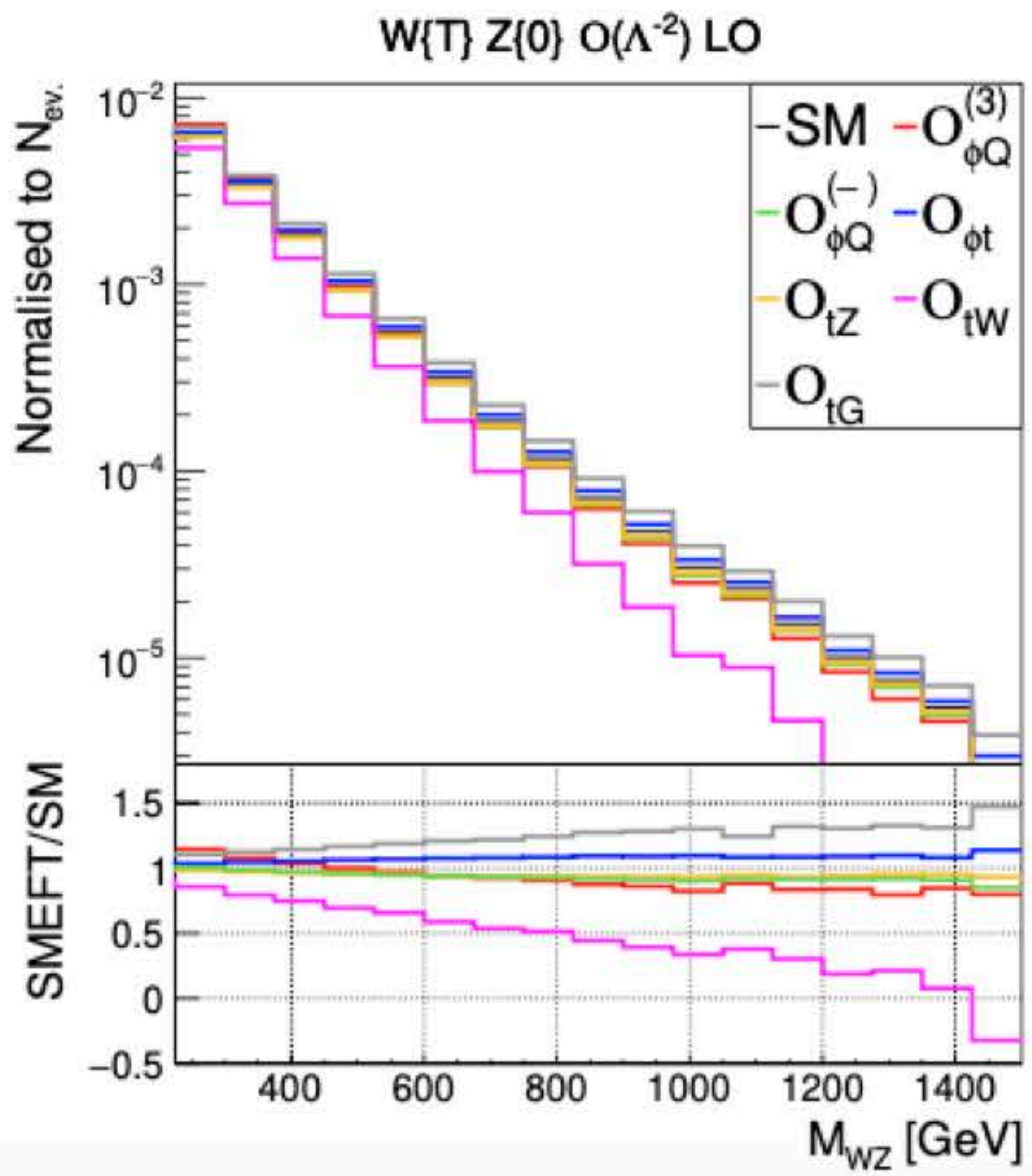


W_L, Z_T

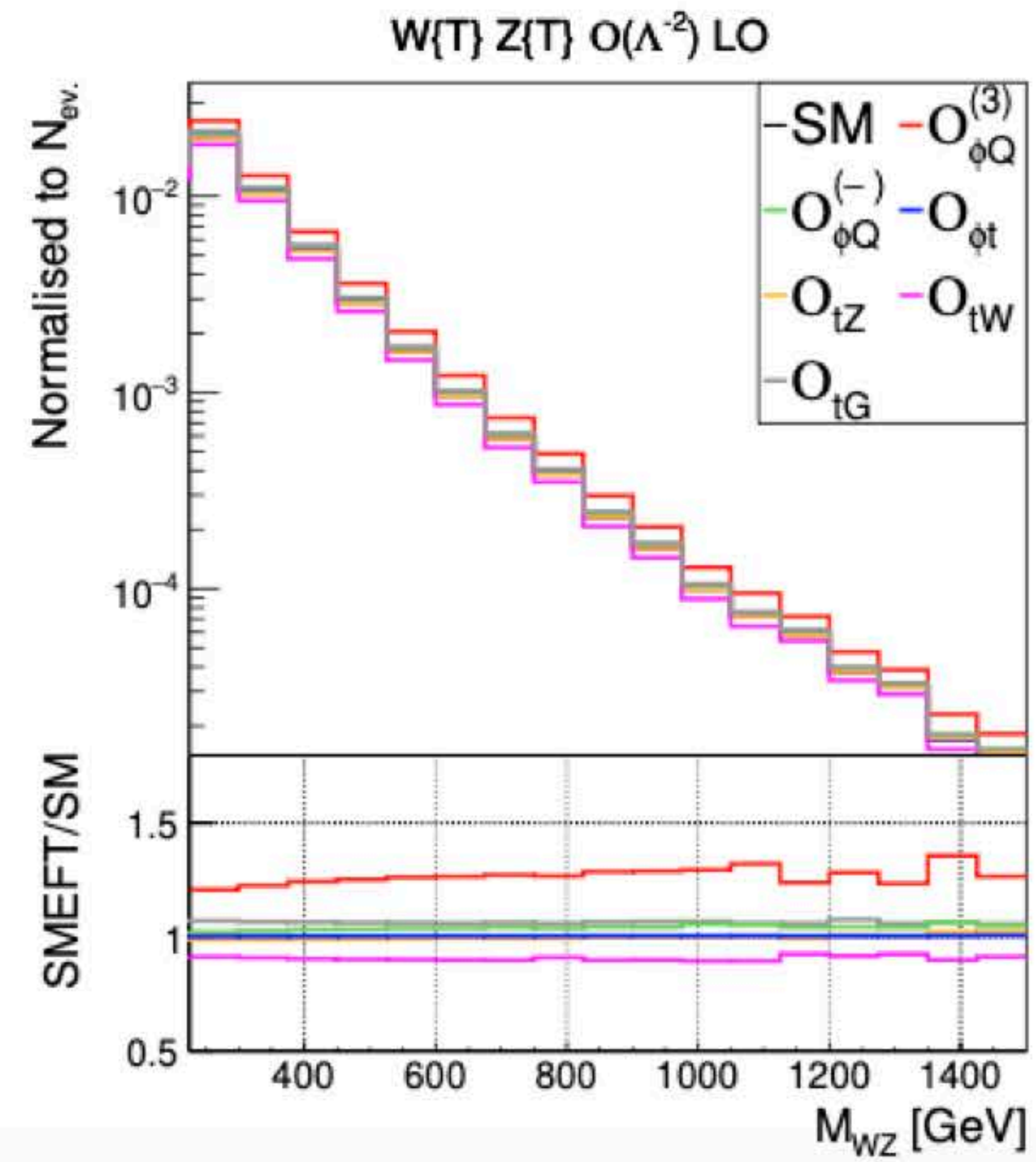


W_T, Z_L

Other unexpected ones… finite mass effects?

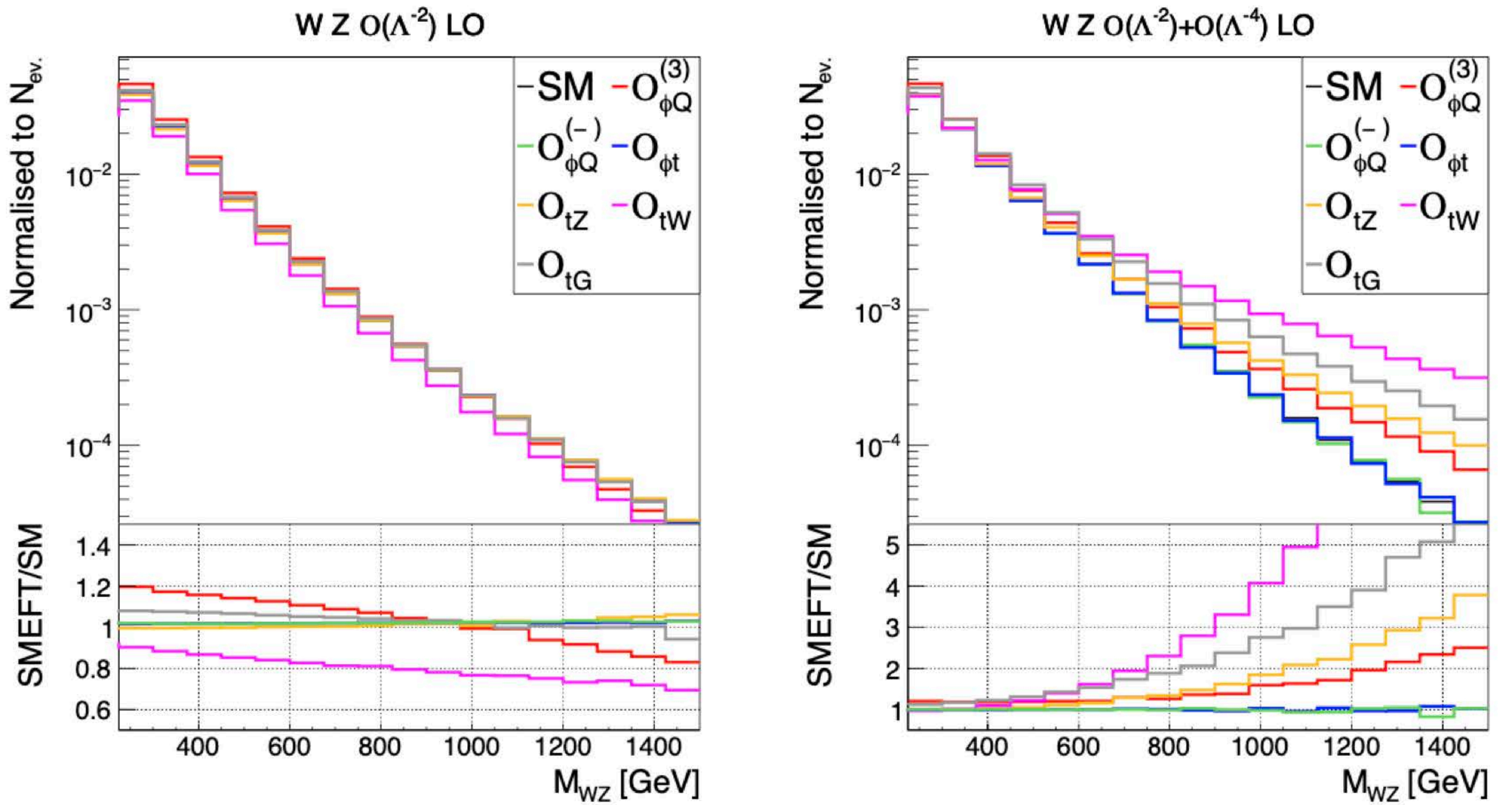


W_T, Z_T



LO, unpolarised $\Lambda = 1\,\mathrm{TeV}, C_i = 1$

SM: TT=56 fb, TL=47 fb & LL = 13 fb



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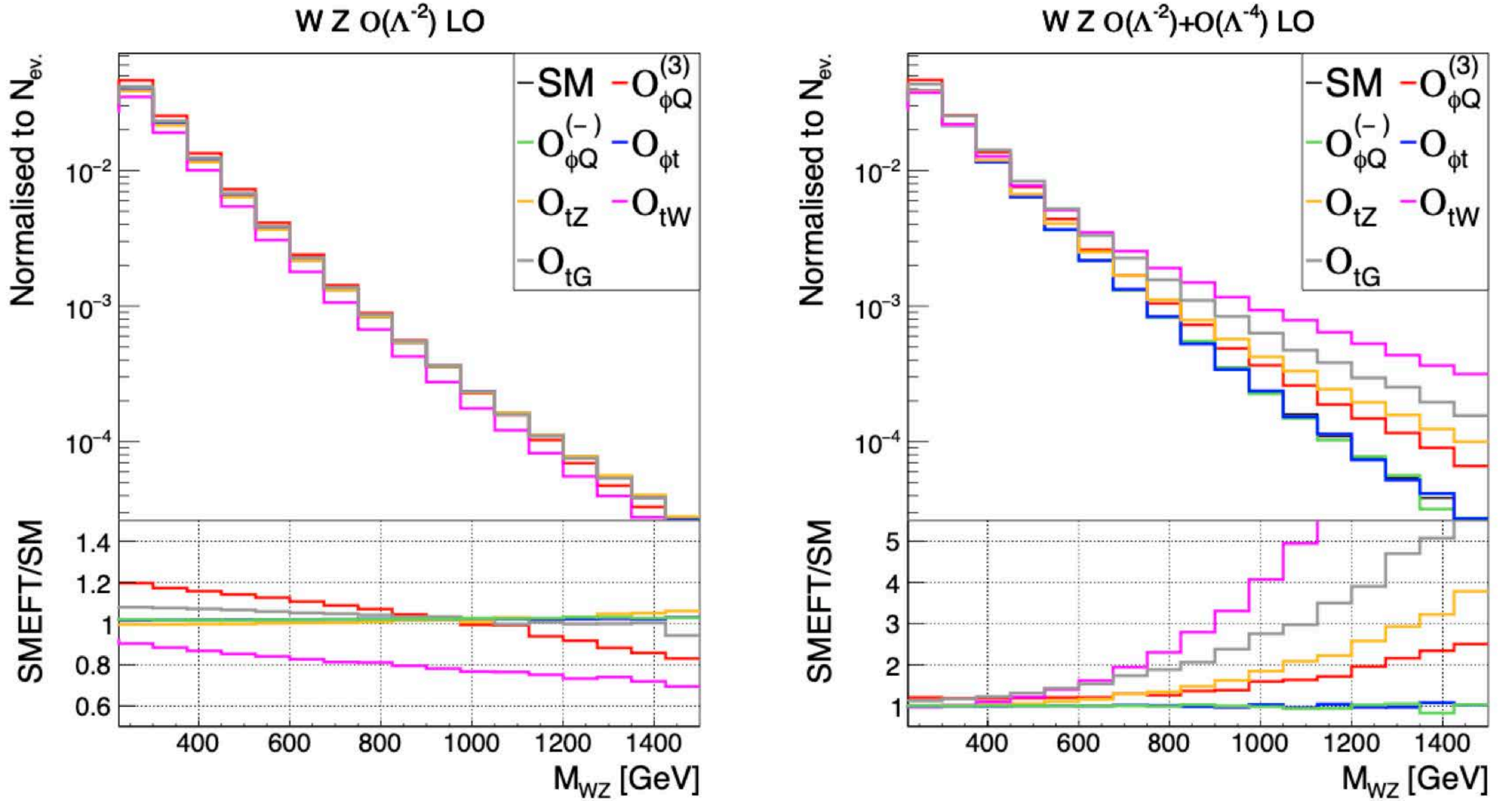

$C_{\phi Q}^{(-)}, C_{\phi t}$ no energy growth: expected in interference, too mild in square

NLO inclusive

$\Lambda = 1\,\mathrm{TeV}, \mathrm{C_i} = 1$

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

	Inclusive			**High-Energy** $\equiv p_T^{Z,W} > 500\,\mathrm{GeV}$		
	LO	NLO DR1	NLO DR2	LO	NLO DR1	NLO DR2
SM	$103.36(4)^{+12.76\%}_{-12.82\%}$	$106.70(15)^{+4.97\%}_{-6.28\%}$	$106.80(9)^{+5.04\%}_{-5.62\%}$	$0.073(0)^{+15.92\%}_{-14.23\%}$	$0.048(0)^{+10.86\%}_{-18.35\%}$	$0.036(0)^{+26.82\%}_{-45.63\%}$

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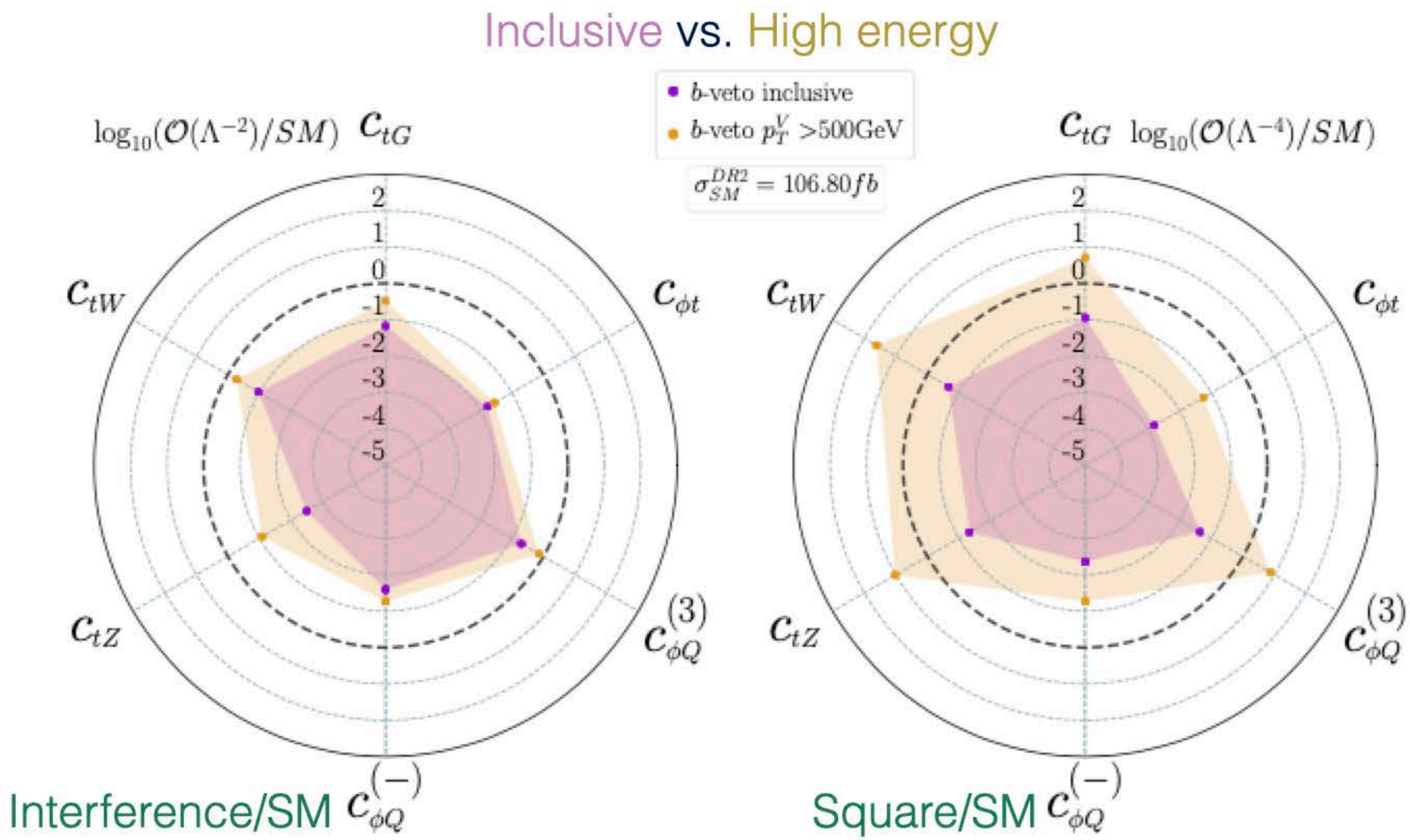
c_i	Inclusive $\mathcal{O}(\Lambda^{-2})$			Inclusive $\mathcal{O}(\Lambda^{-4})$		
	LO	**NLO DR1**	**NLO DR2**	**LO**	**NLO DR1**	**NLO DR2**
$c^{(3)}_{\varphi Q}$	$19.78(1)^{+12.98\%}_{-13.02\%}$	$21.20(2)^{+5.66\%}_{-6.13\%}$	$21.37(3)^{+5.90\%}_{-6.27\%}$	$4.94(1)^{+10.53\%}_{-10.62\%}$	$4.71(2)^{+4.88\%}_{-6.37\%}$	$4.72(2)^{+4.90\%}_{-6.50\%}$
$c^{(-)}_{\varphi Q}$	$2.19(0)^{+12.65\%}_{-12.72\%}$	$2.69(1)^{+8.92\%}_{-8.18\%}$	$2.74(1)^{+8.52\%}_{-8.17\%}$	$0.44(0)^{+12.18\%}_{-12.29\%}$	$0.48(0)^{+5.89\%}_{-5.89\%}$	$0.48(0)^{+5.86\%}_{-6.03\%}$
$c_{\varphi t}$	$1.77(0)^{+13.11\%}_{-13.13\%}$	$1.81(0)^{+4.81\%}_{-5.53\%}$	$1.84(0)^{+5.08\%}_{-5.74\%}$	$0.19(0)^{+11.44\%}_{-11.61\%}$	$0.18(0)^{+4.45\%}_{-7.08\%}$	$0.17(0)^{+5.09\%}_{-7.54\%}$
c_{tW}	$-11.34(1)^{+12.27\%}_{-12.15\%}$	$-11.49(2)^{+5.84\%}_{-5.57\%}$	$-11.68(1)^{+5.72\%}_{-5.41\%}$	$24.06(3)^{+10.53\%}_{-9.90\%}$	$23.38(5)^{+4.15\%}_{-5.18\%}$	$22.79(3)^{+4.59\%}_{-6.41\%}$
c_{tZ}	$-0.26(0)^{+11.03\%}_{-11.01\%}$	$-0.35(2)^{+4.99\%}_{-6.66\%}$	$-0.34(1)^{+5.47\%}_{-7.06\%}$	$5.23(1)^{+10.53\%}_{-10.05\%}$	$4.90(2)^{+4.59\%}_{-6.69\%}$	$4.94(1)^{+4.64\%}_{-6.57\%}$
c_{tG}	$7.95(0)^{+13.00\%}_{-13.04\%}$	$7.36(1)^{+4.00\%}_{-5.01\%}$	$7.26(1)^{+4.65\%}_{-6.29\%}$	$15.04(3)^{+11.61\%}_{-11.22\%}$	$12.19(8)^{+6.97\%}_{-11.93\%}$	$12.17(7)^{+6.95\%}_{-11.96\%}$

Good DR1/DR2 agreement: stick to DR2 henceforth

NLO inclusive

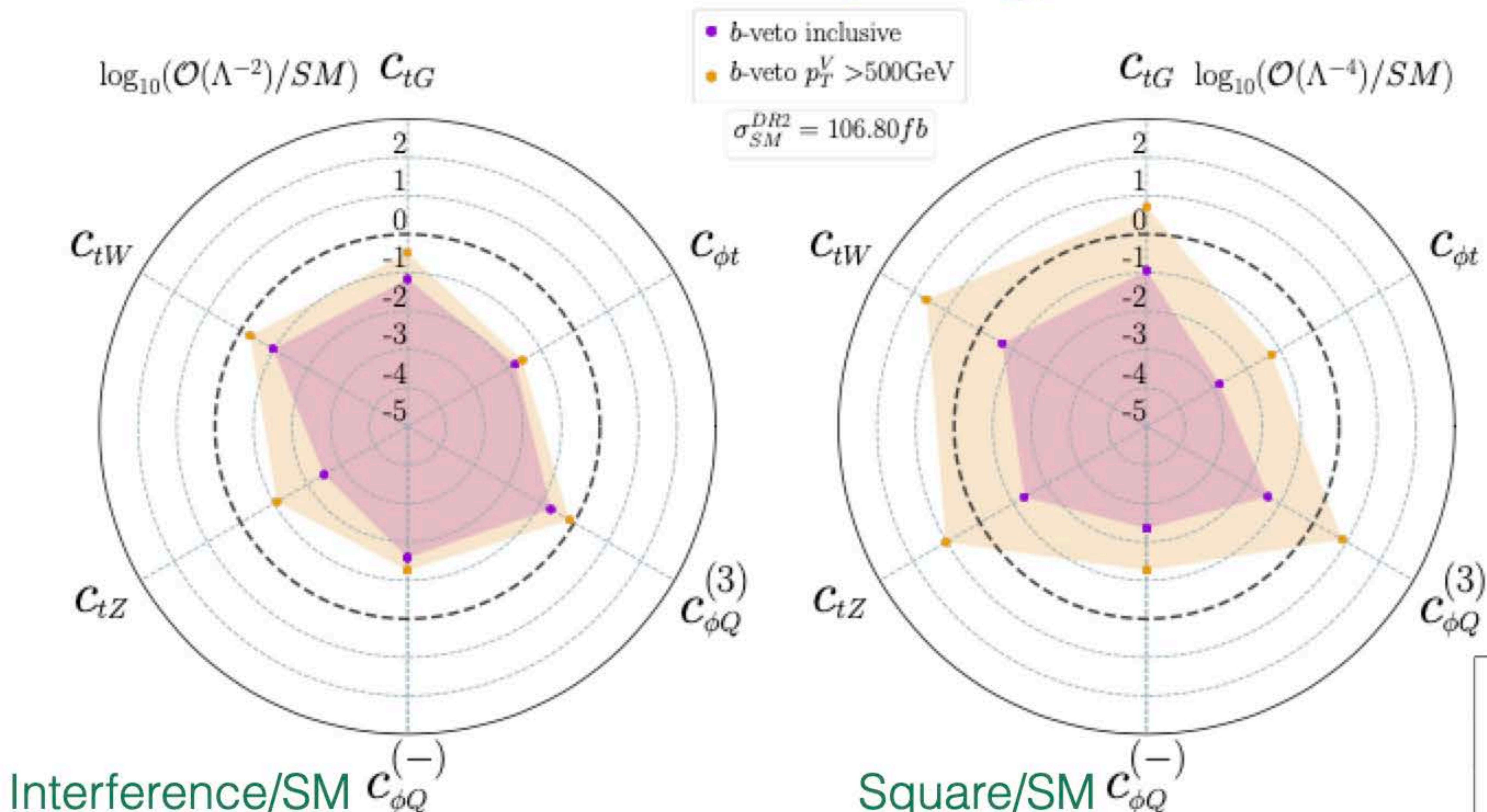
$\Lambda = 1\,\mathrm{TeV}, \mathrm{C_i} = 1$



NLO inclusive

$\Lambda = 1\,\mathrm{TeV}, C_i = 1$

Inclusive vs. High energy



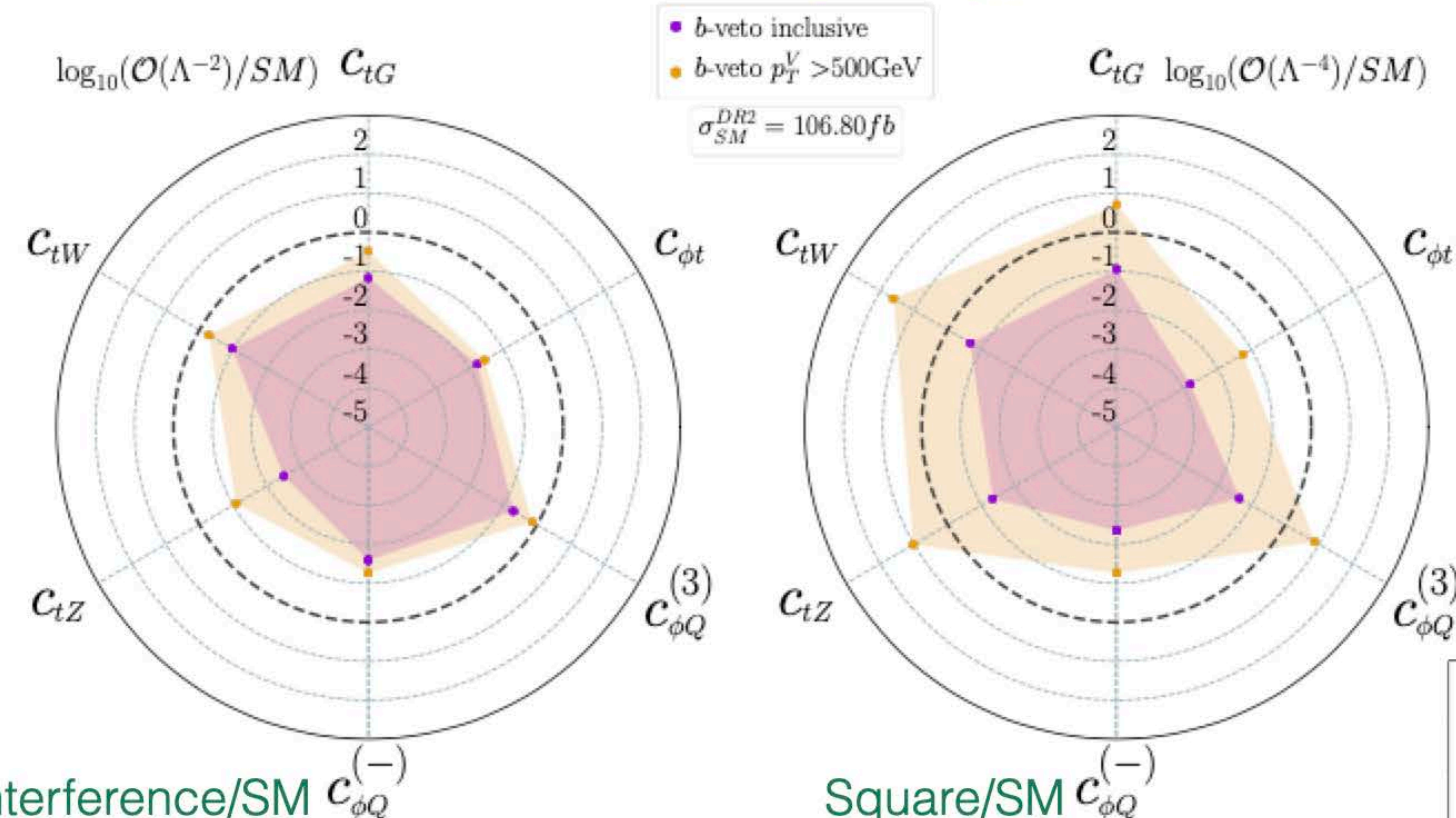
c_i	Inclusive					
	$\mathcal{O}(\Lambda^{-2})$			$\mathcal{O}(\Lambda^{-4})$		
	LO	NLO	K	LO	NLO	K
$c_{\varphi Q}^{(3)}$	0.191	0.200	1.05	0.048	0.044	0.92
$c_{\varphi Q}^{(-)}$	0.021	0.026	1.24	0.004	0.004	1.00
$c_{\varphi t}$	0.017	0.017	1.00	0.002	0.002	1.00
c_{tW}	−0.110	−0.109	0.99	0.233	0.213	0.91
c_{tZ}	−0.003	−0.003	1.00	0.051	0.046	0.90
c_{tG}	0.077	0.068	0.88	0.145	0.114	0.79

c_i	High-Energy					
	$\mathcal{O}(\Lambda^{-2})$			$\mathcal{O}(\Lambda^{-4})$		
	LO	NLO	K	LO	NLO	K
$c_{\varphi Q}^{(3)}$	−0.870	−0.715	0.82	5.626	7.476	1.33
$c_{\varphi Q}^{(-)}$	0.028	0.056	2.00	0.058	0.057	0.98
$c_{\varphi t}$	0.017	0.023	1.35	0.056	0.054	0.96
c_{tW}	−0.528	−0.524	0.99	30.905	40.695	1.32
c_{tZ}	0.098	0.076	0.78	7.739	10.482	1.35
c_{tG}	−0.232	−0.354	1.53	7.488	5.242	0.70

NLO inclusive

$\Lambda = 1\,\mathrm{TeV}, C_i = 1$

Inclusive vs. High energy



Interference/SM

Square/SM

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	LO	NLO	K	LO	NLO	K
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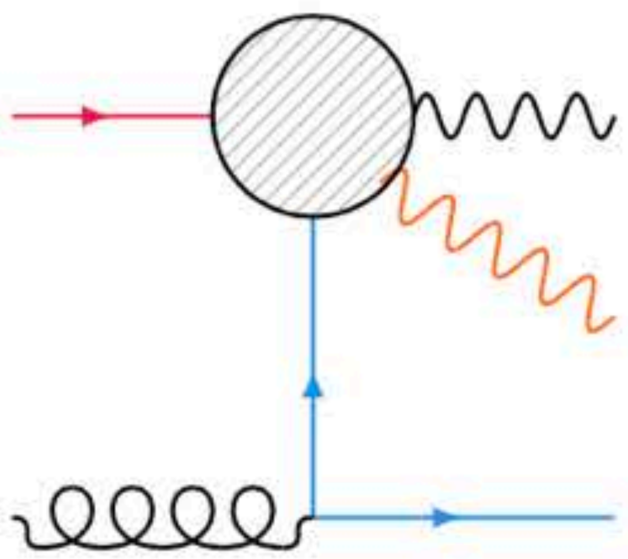
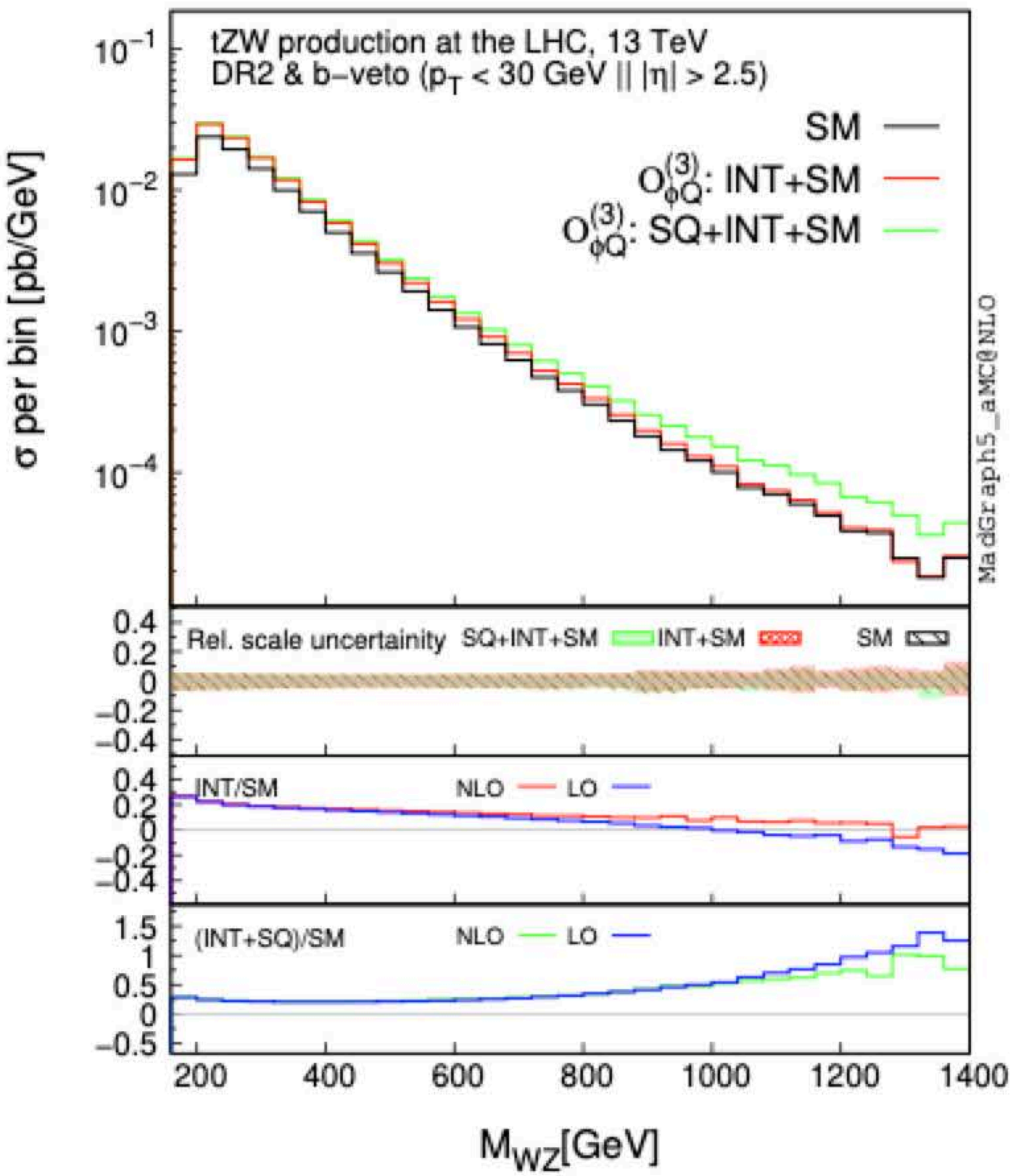
b-veto: LO/NLO have different phase space

- "K-factor" ill defined: compute for relative impacts
- Some non-trivial NLO QCD corrections

NLO differential

Fixed order: relative impact stable under NLO QCD

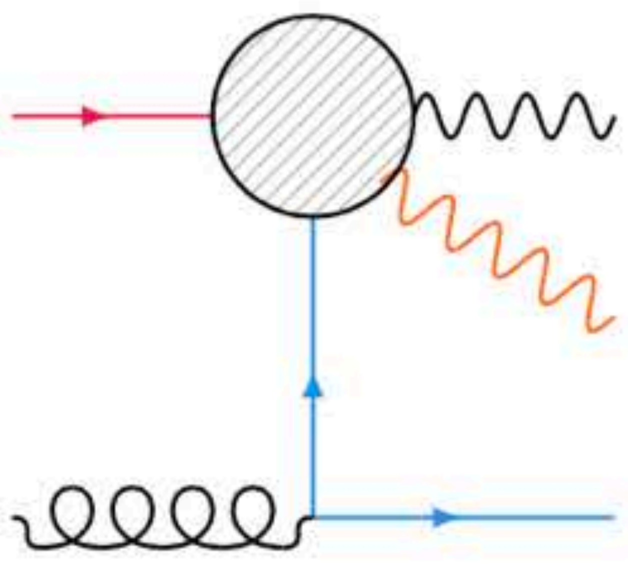


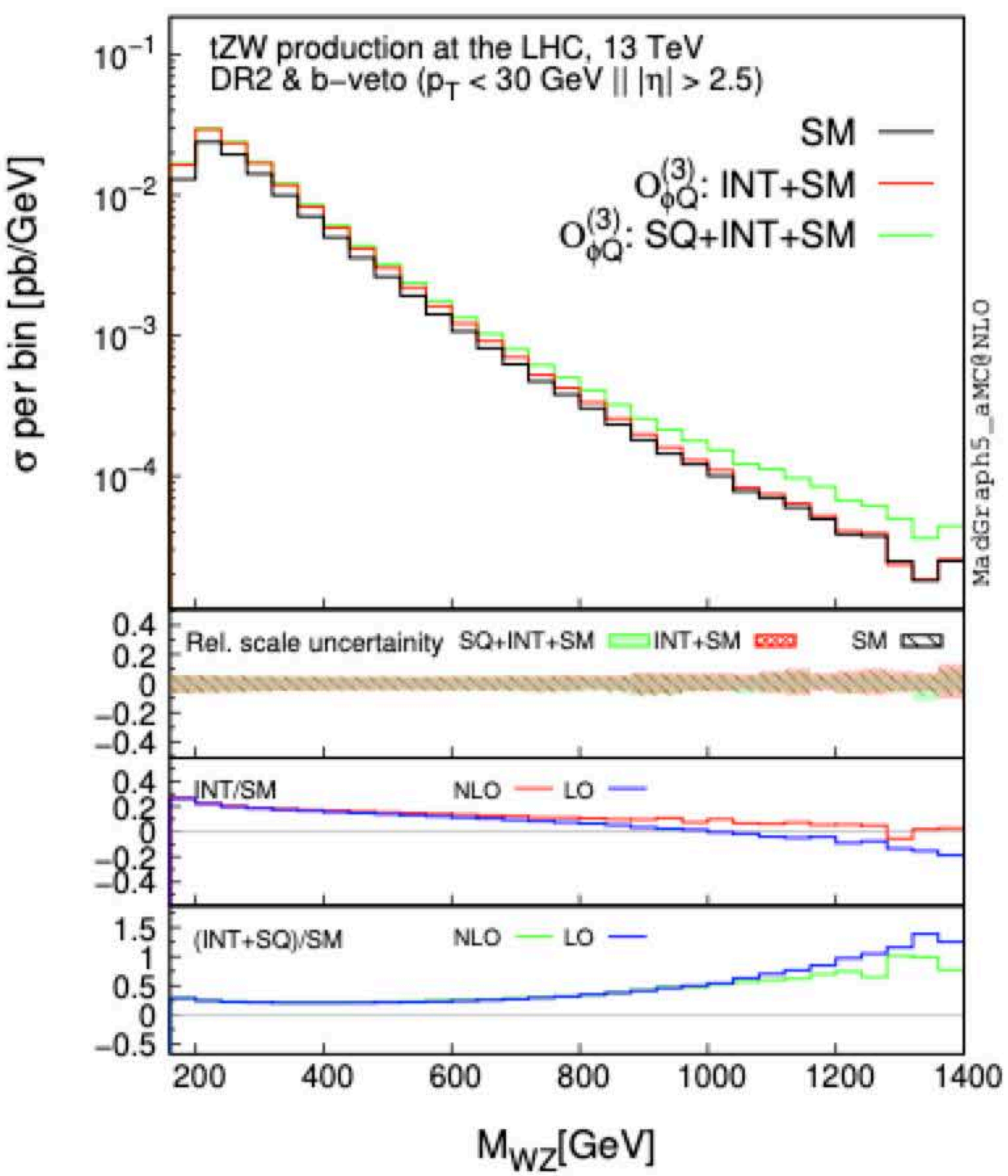


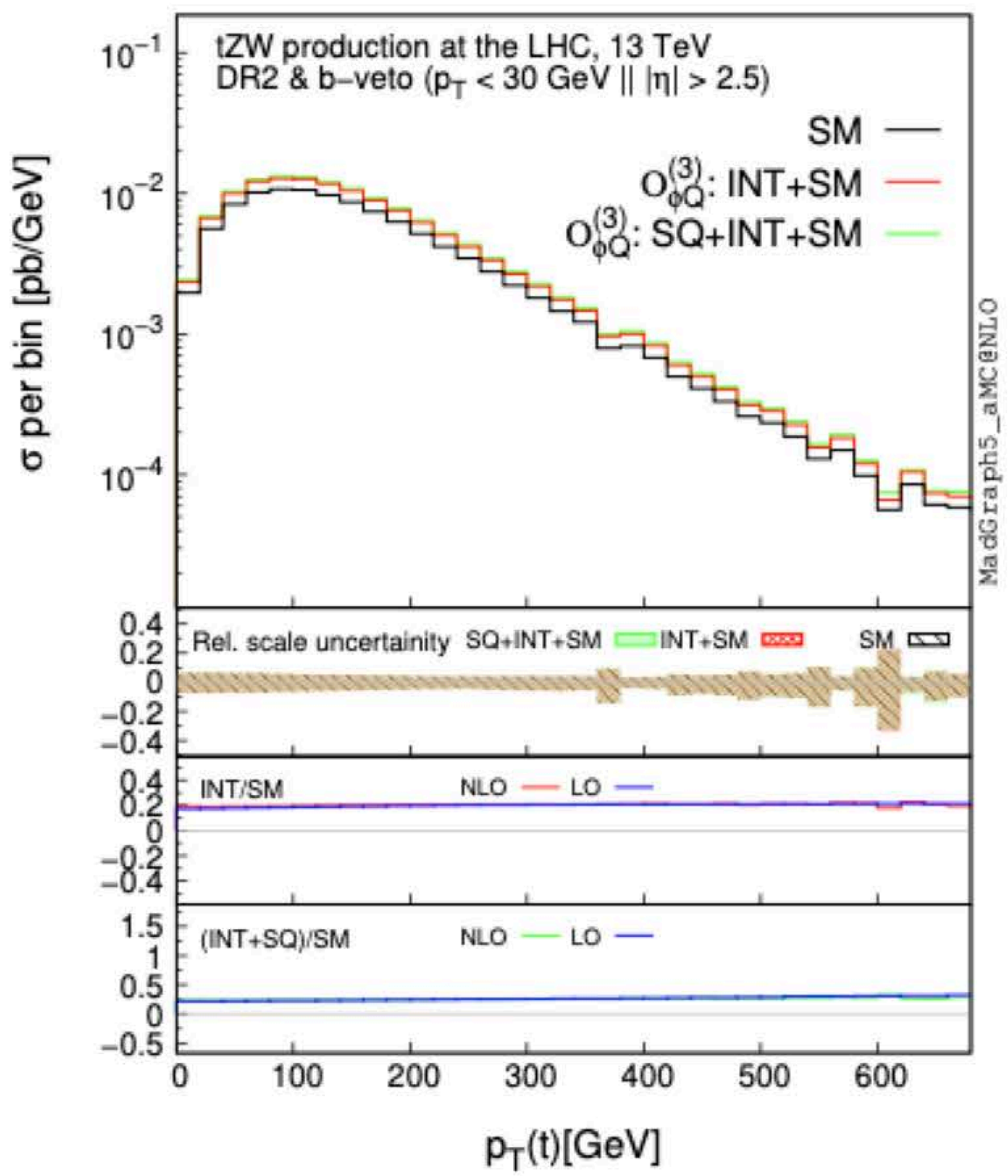
NLO differential

Fixed order: relative impact stable under NLO QCD

- top p_T not sensitive, not in relevant $tb \to WZ$ sub-amplitude







NLO differential

Dipoles, dominated by quadratic

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- Omitted other current operators due to lack of growth
- Potential sensitivity to gluon dipole (quite constrained by $t\bar{t}$)

NLO differential

SMEFT contribution to suppressed overlap processes included!

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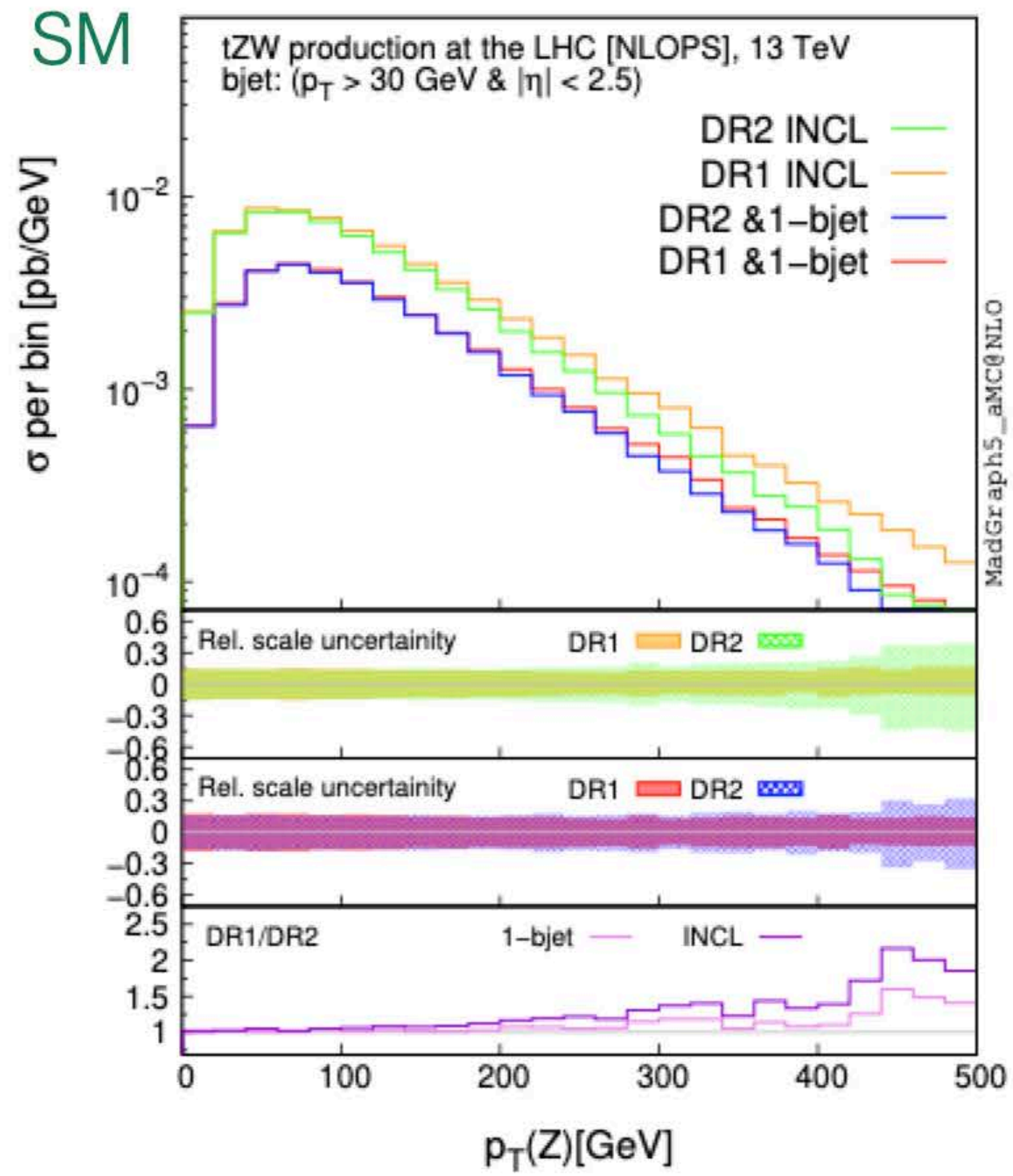
NLO+PS

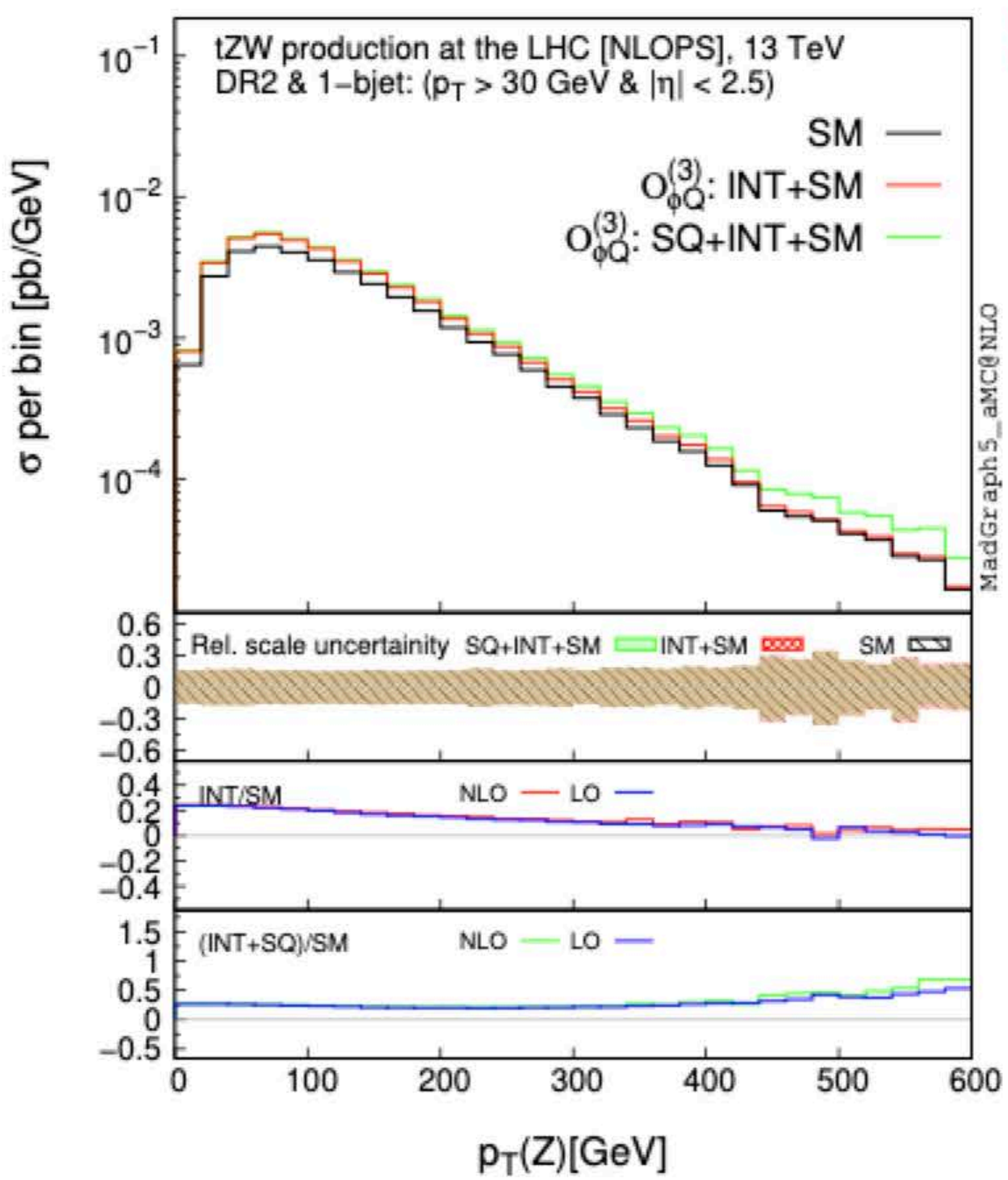
Allow tops to decay, keep W & Z stable

- Now require exactly one b-jet (veto applied to additional b-jet)
- Assumes 100% b-tagging efficiency within $|\eta| < 2.5$

SM



SMEFT



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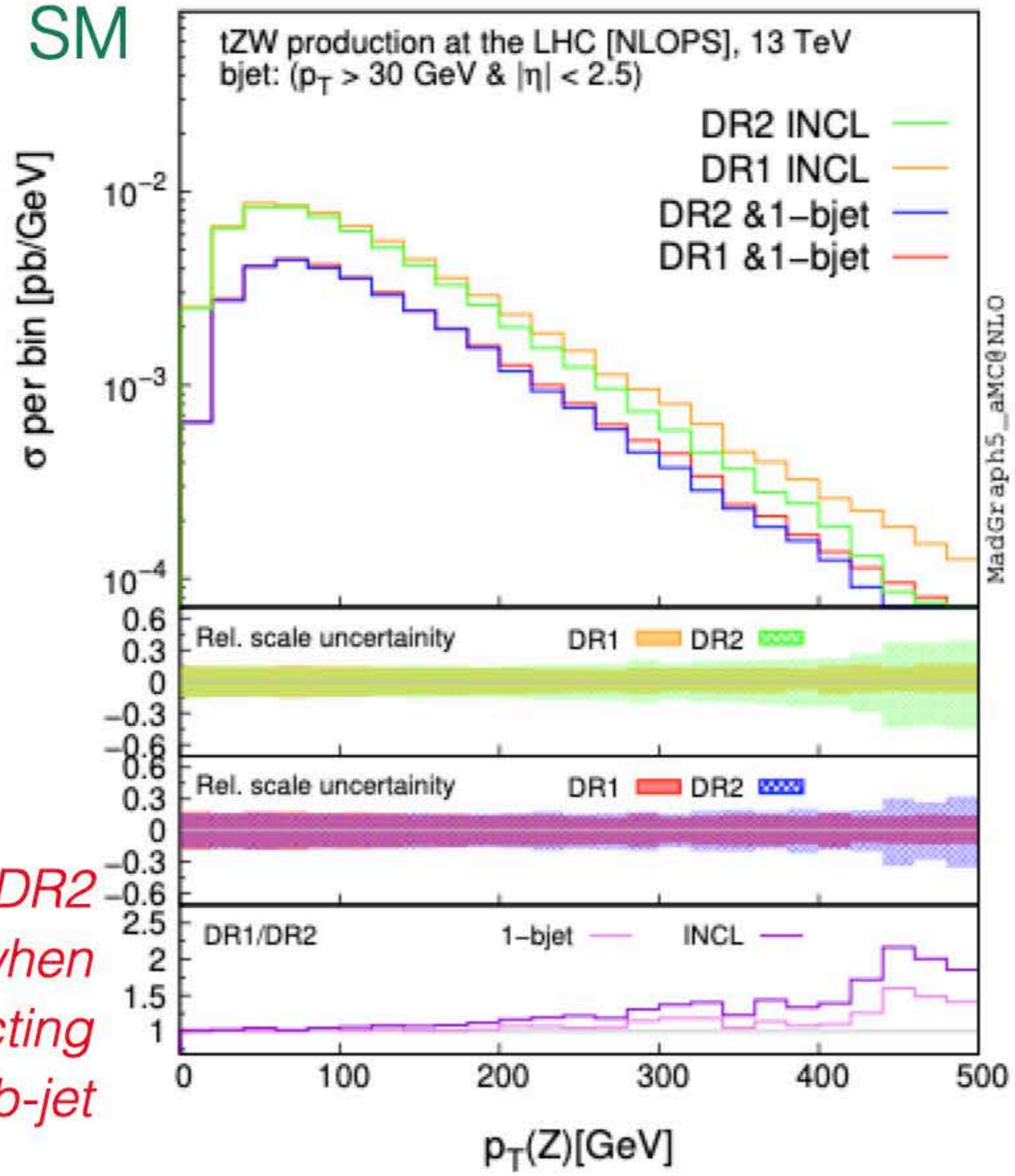
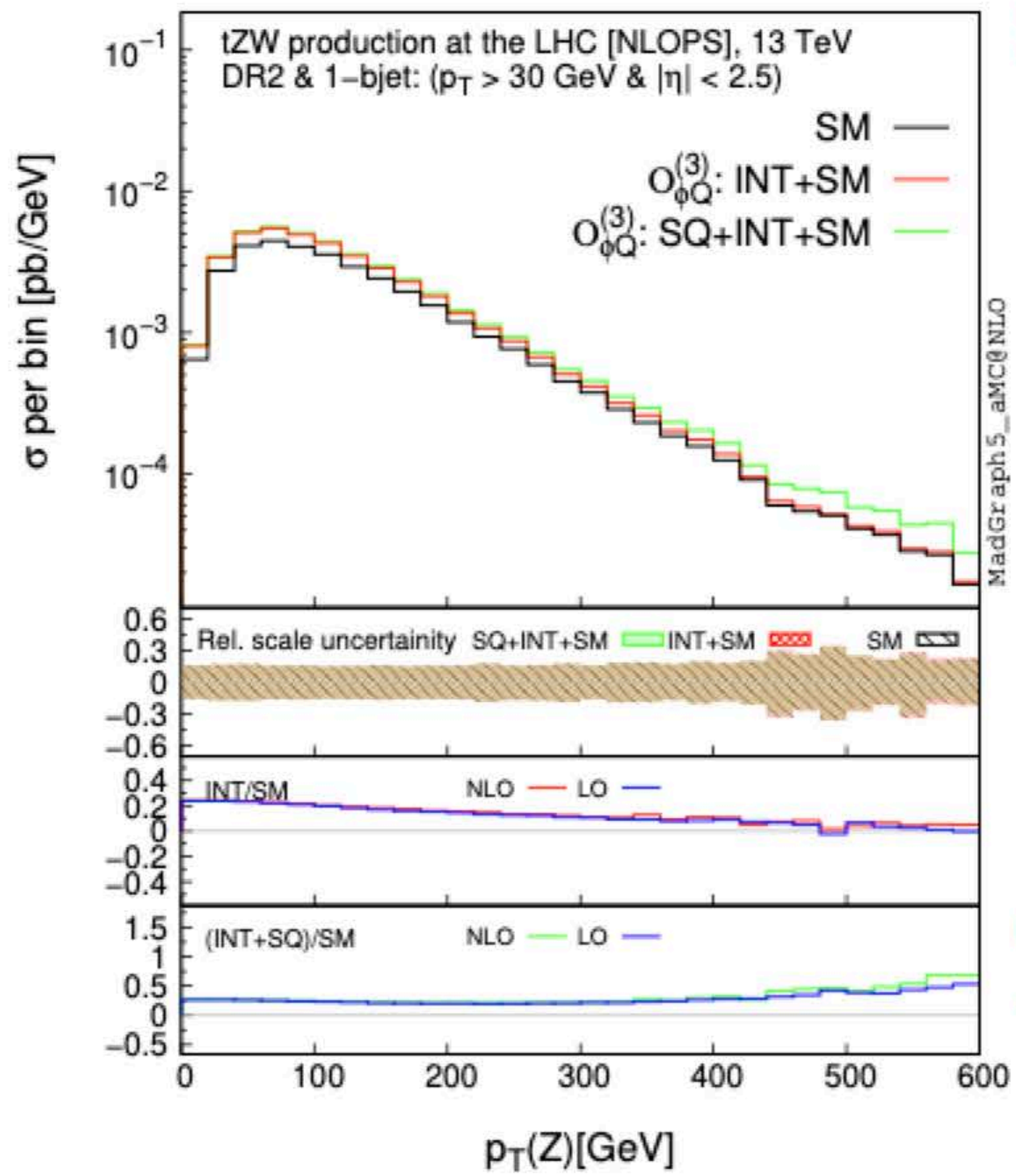


SMEFT



Some DR1/DR2 difference when selecting 'wrong' b-jet

Otherwise NLO stable!

Prospects & challenges

EW top scattering: promising avenue for EW top couplings

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EW top scattering: promising avenue for EW top couplings

- Go beyond rate measurements & access energy growth/unitarity violation
- Increasingly high energy & multiplicity processes: future-proof
- Rare EW top modes: probe complimentary directions in SMEFT space
- Some already measured or within LHC reach ($t\bar{t}Wj, tHj, tWZ, \ldots$)
- Others challenging, dedicated pheno studies required…

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Sig.	Bkg.
$t\bar{t}Z(\ell^+\ell^-)$	$t\bar{t}W$, $t\bar{t}H$, tZj, WZ,...
$t\bar{t}H(b\bar{b})$	$t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
$t\bar{t}H(\gamma\gamma)$	$t\bar{t}$, $b\bar{b}H$, tHj, tHW
$t\bar{t}H(\tau^+\tau^-)$	$t\bar{t}W(W)$, $t\bar{t}Z$,...
tZj	$t\bar{t}V$, tHj, tHW, tZW,...
tHj	$t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
$t\bar{t}t\bar{t}$	$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$,...

Sig/Bkg. overlap $\Rightarrow$ global measurements

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$t\bar{t}H(\gamma\gamma)$	$t\bar{t}$, $b\bar{b}H$, tHj, tHW
$t\bar{t}H(\tau^+\tau^-)$	$t\bar{t}W(W)$, $t\bar{t}Z$,...
tZj	$t\bar{t}V$, tHj, tHW, tZW,...
tHj	$t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
$t\bar{t}t\bar{t}$	$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$,...

Sig/Bkg. overlap ⇒ global measurements

- SMEFT contributes everywhere… blurs the lines
- Challenging to incorporate into global likelihood
- From individual to simultaneous measurements
- Signal regions based on final state properties

Conclusions

The future is bright for top physics in SMEFT

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- Rare EW top production: high energy & high multiplicity
- Towards global measurements for global fits

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Things I couldn't mention!

- Future direction: global study on CP violating operators in top data
- Fantastic progress in UV model interpretations of global fits
- Automated matching tools available
- Very important for testing validity