# Indirect new physics searches with 1,2 & 3 bosons

Ken Mimasu
University of Southampton

*[E. Celada, G. Durieux, KM, E. Vryonidou; 240X.XXXXX]*

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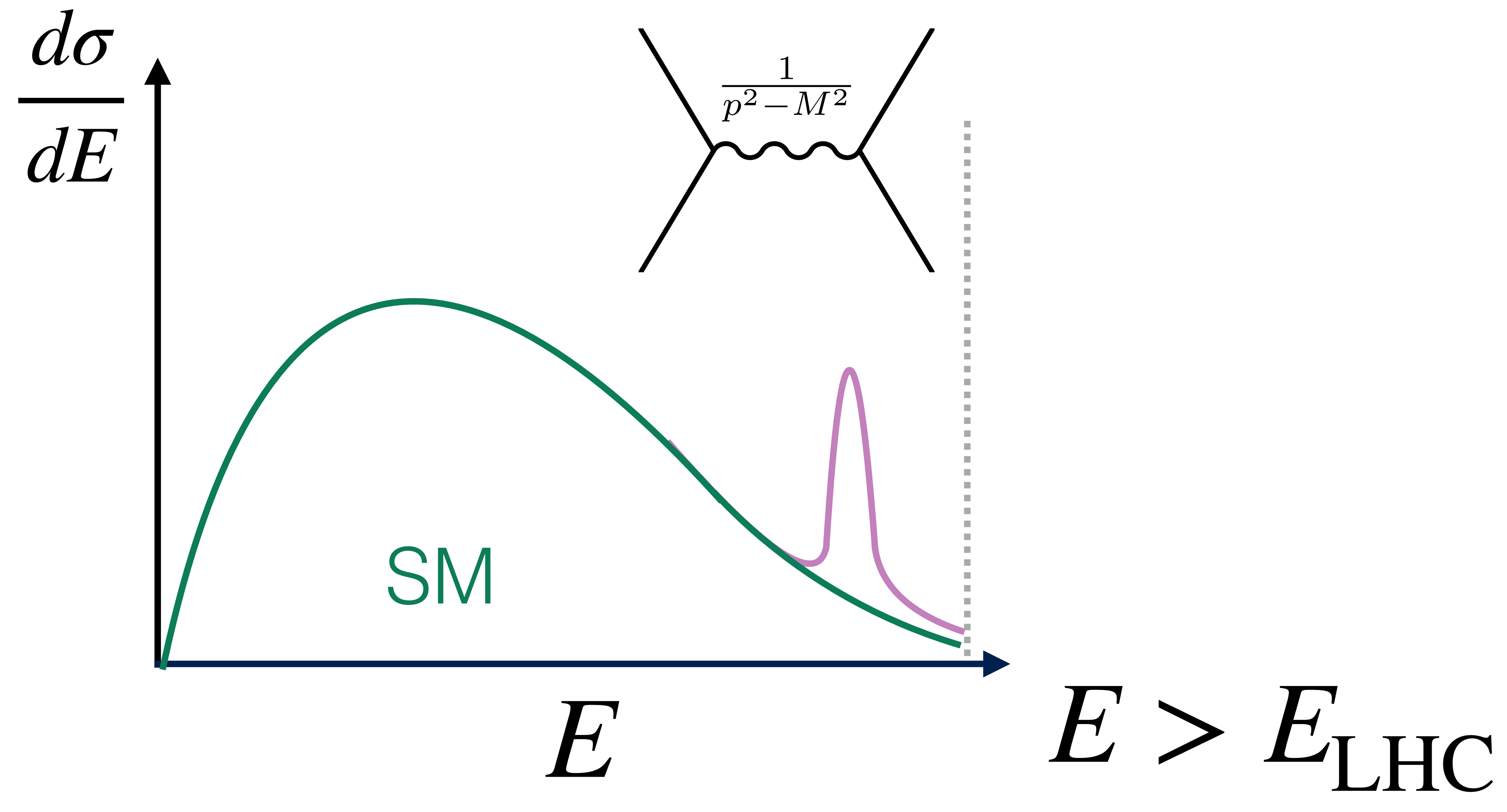
Science and Technology Facilities Council

University of Southampton

# Energy & precision for BSM

**2010s: energy**

Direct (bumps)



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**2020s: intensity**
Indirect (tails/precision)

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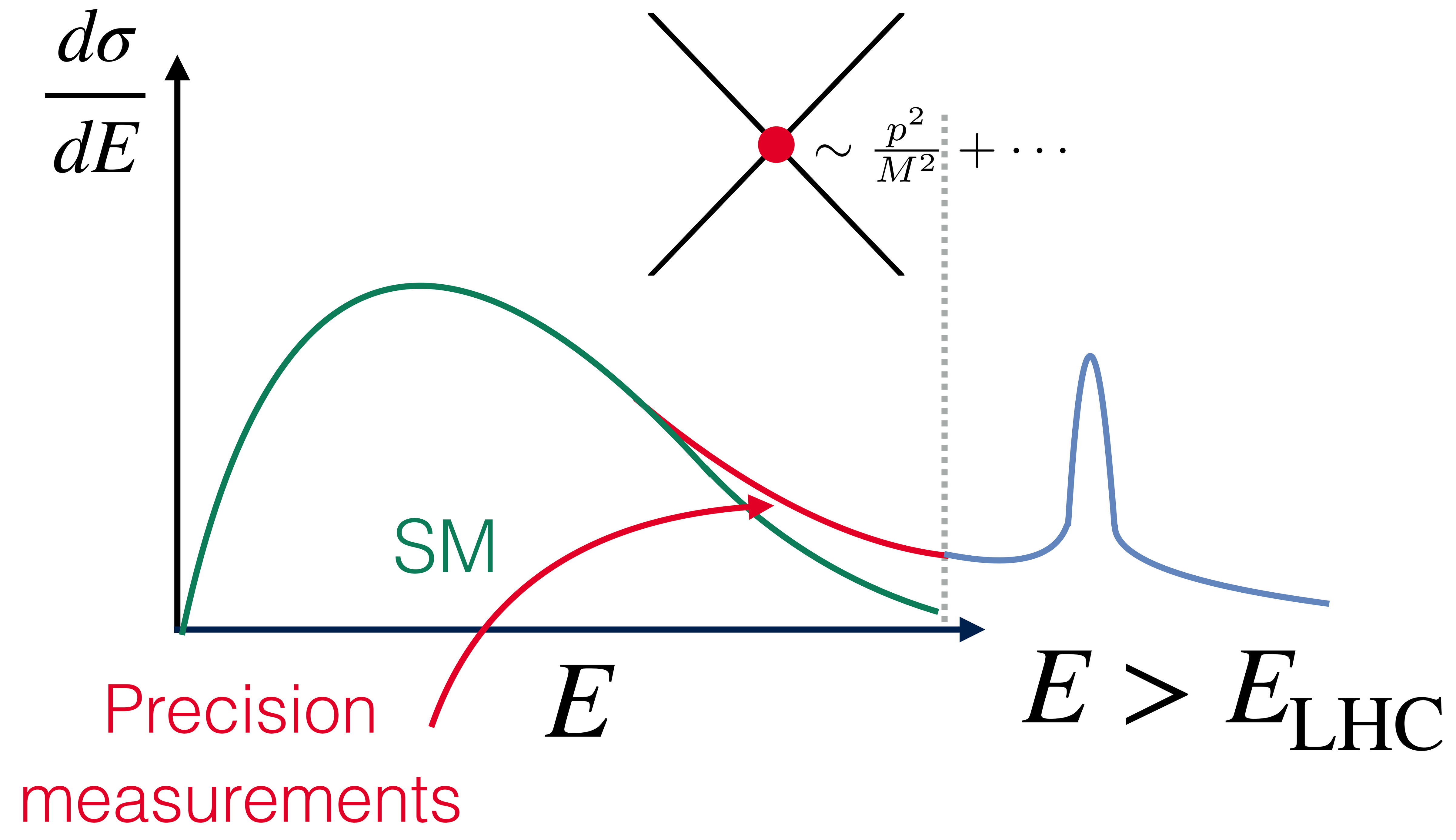

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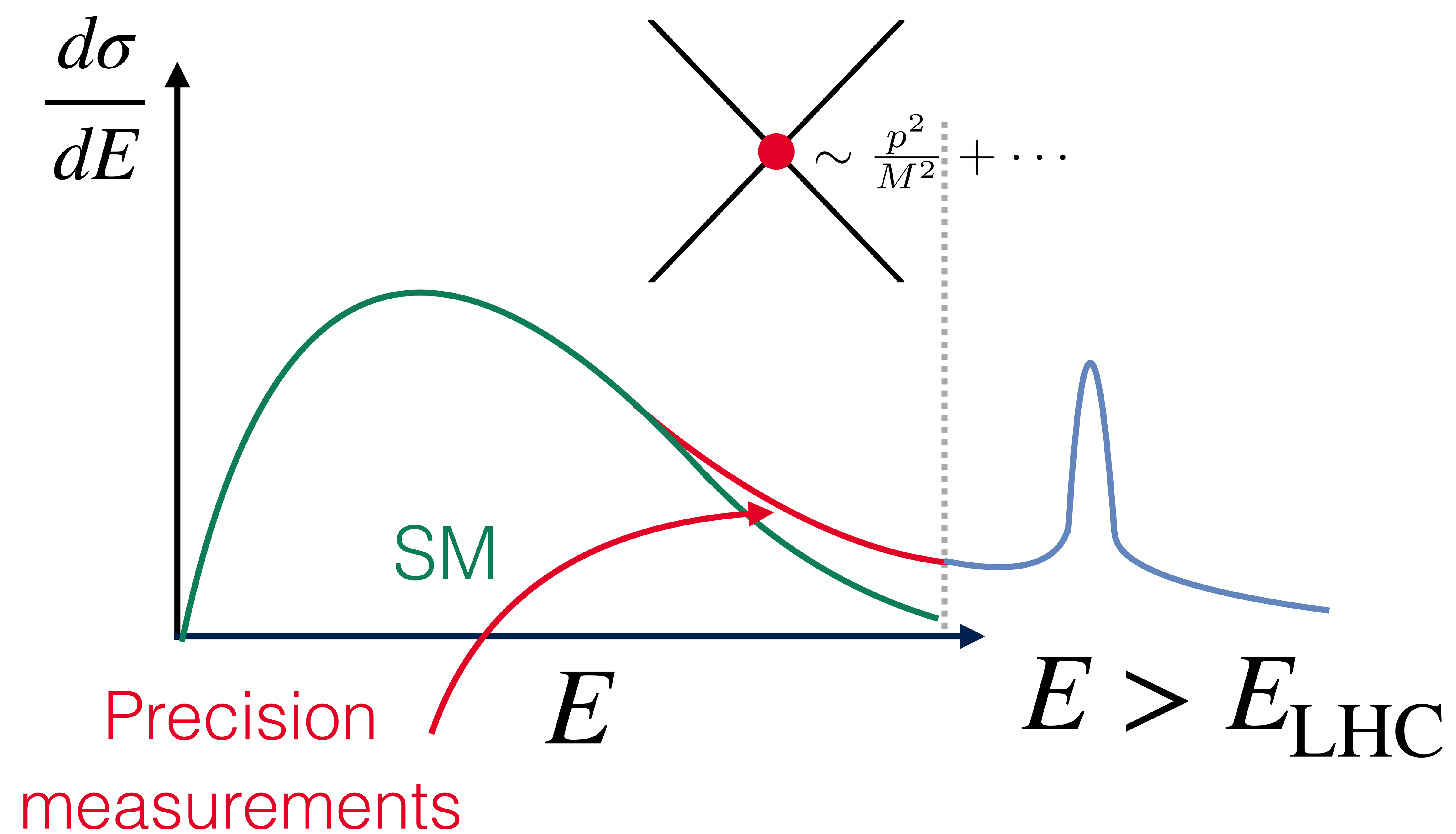


Heavy new physics
Precision measurements
High energy

→ **Effective Field Theory (EFT)**

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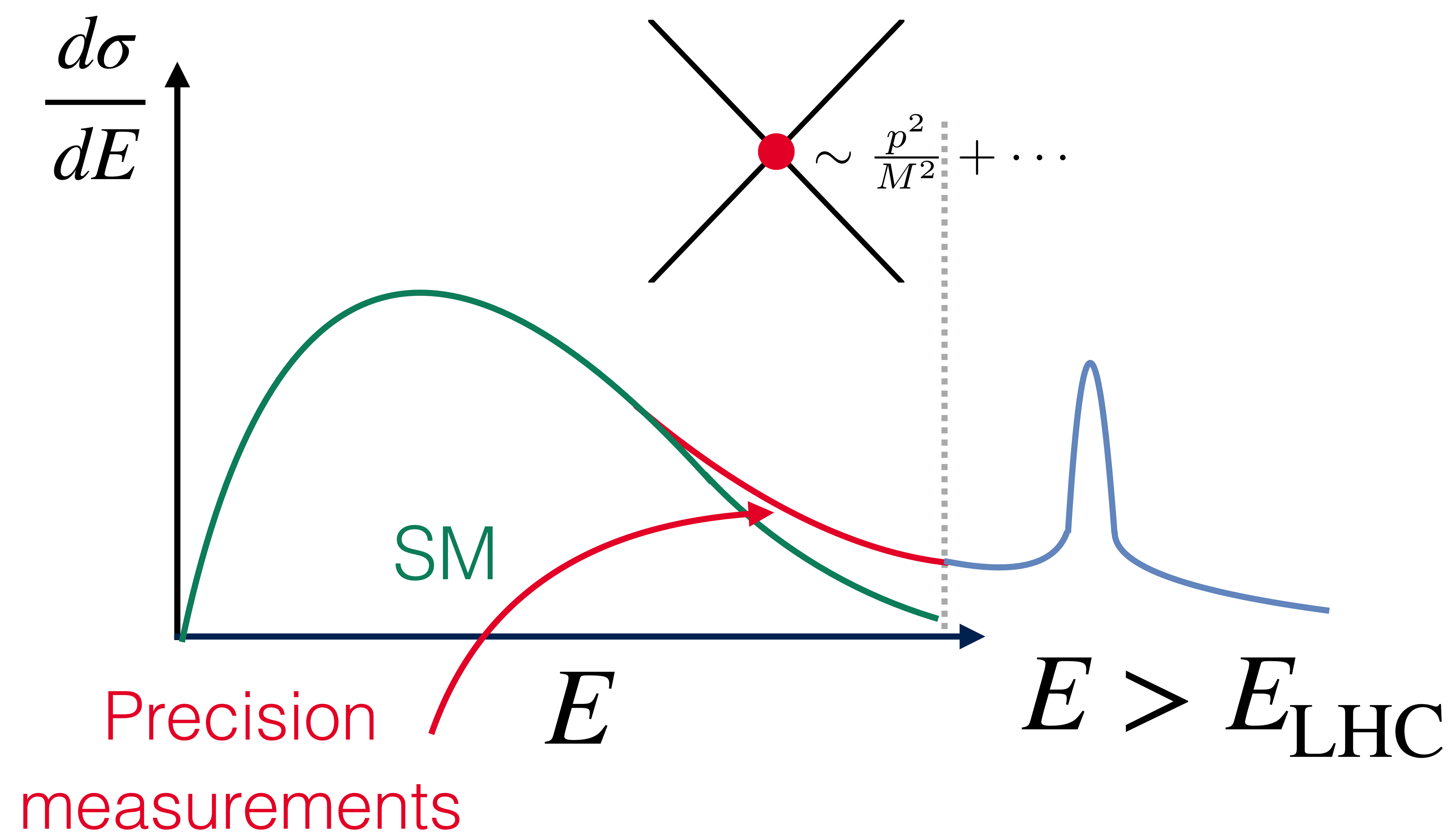


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**Effective Field Theory (EFT)**

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

# SMEFT is…

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

## Model independent

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

*SM field content & gauge symmetries*

*Linear EWSB: Higgs = doublet*

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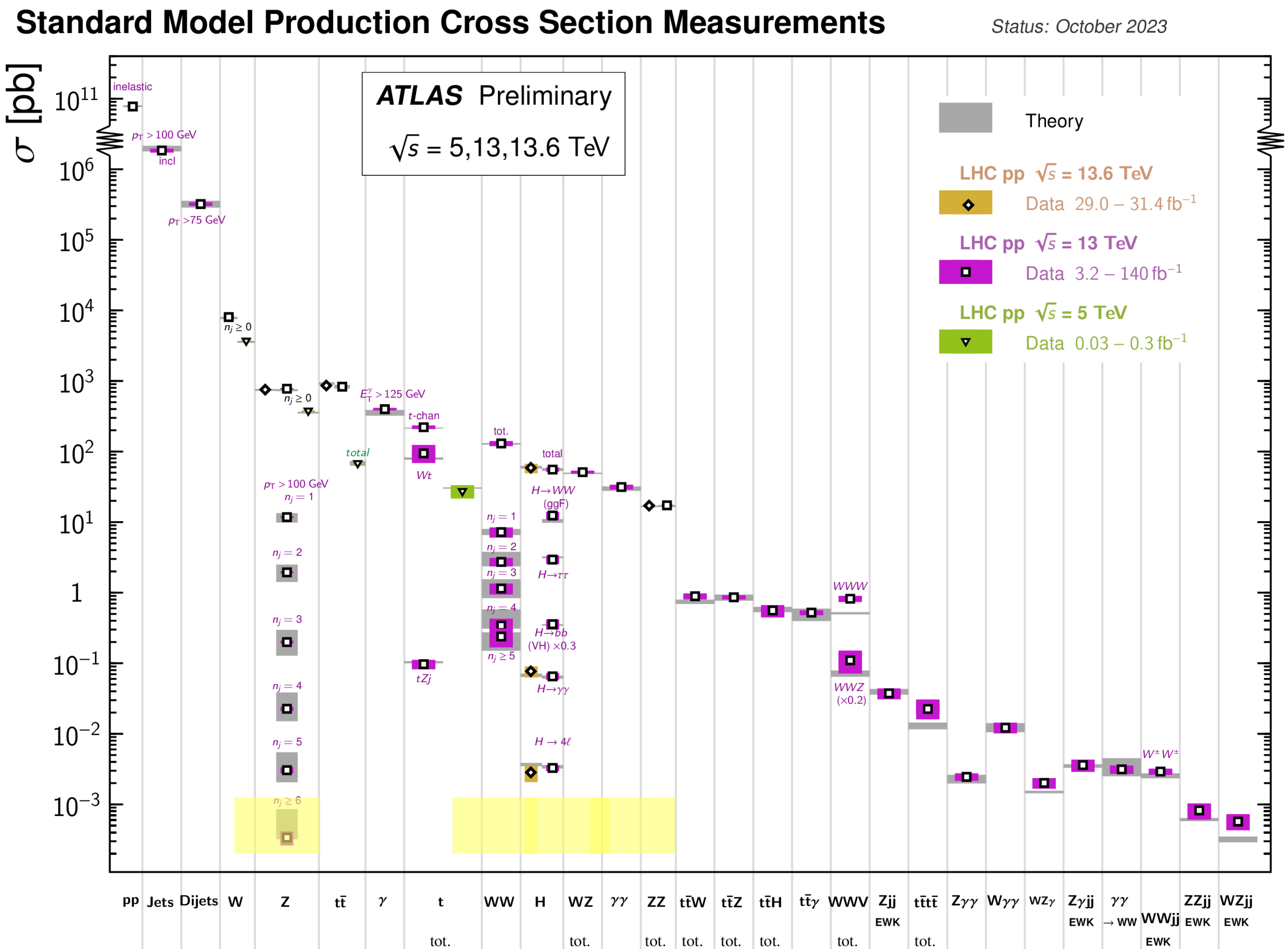
$\mathscr{L}(c_i) \Rightarrow$ **indirectly constrain many UV models**

# Energy & multiplicity



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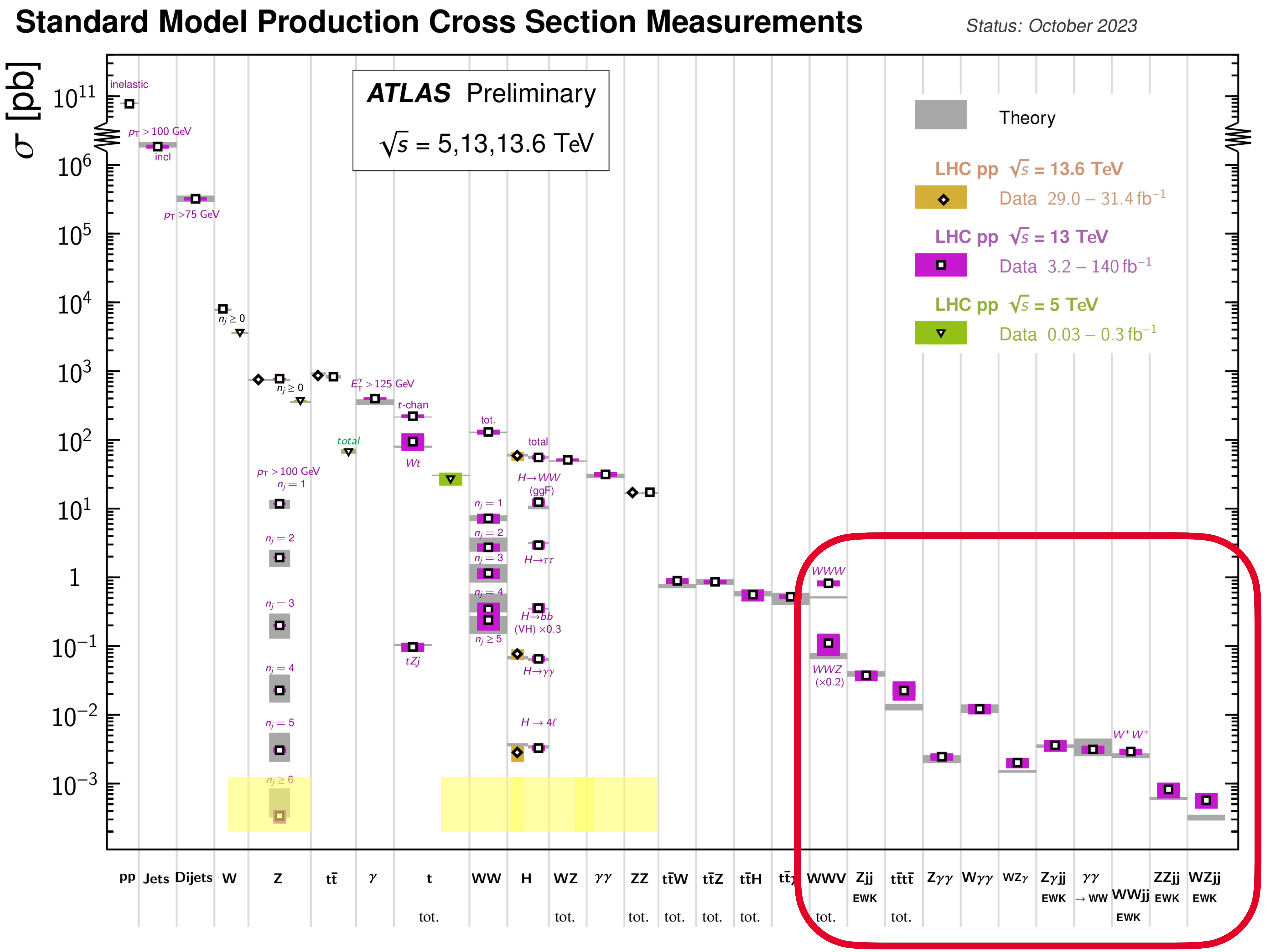

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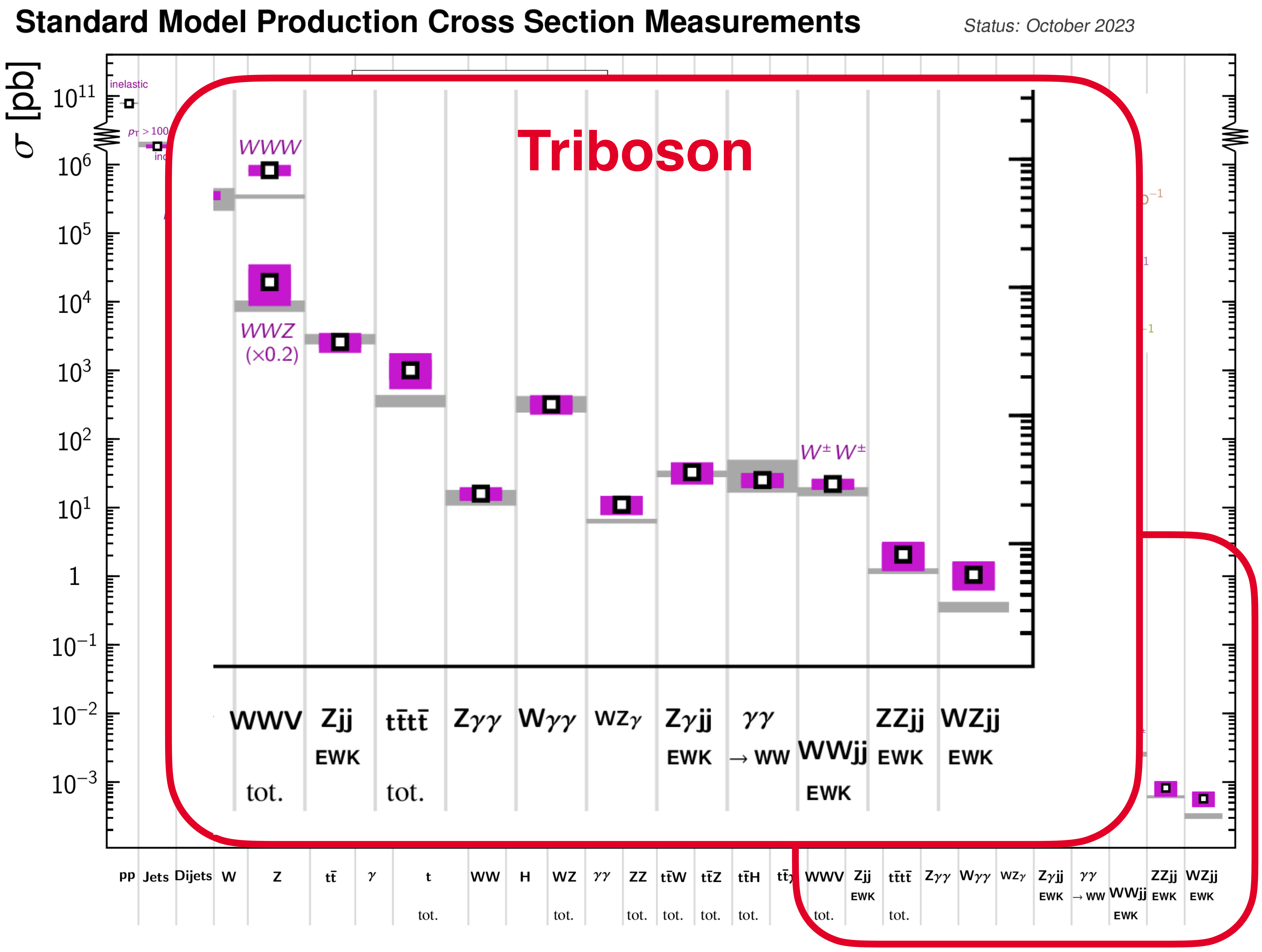
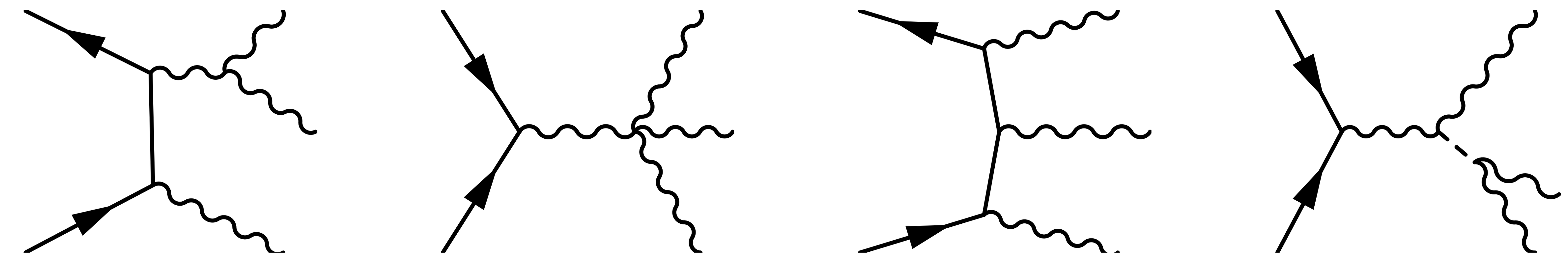
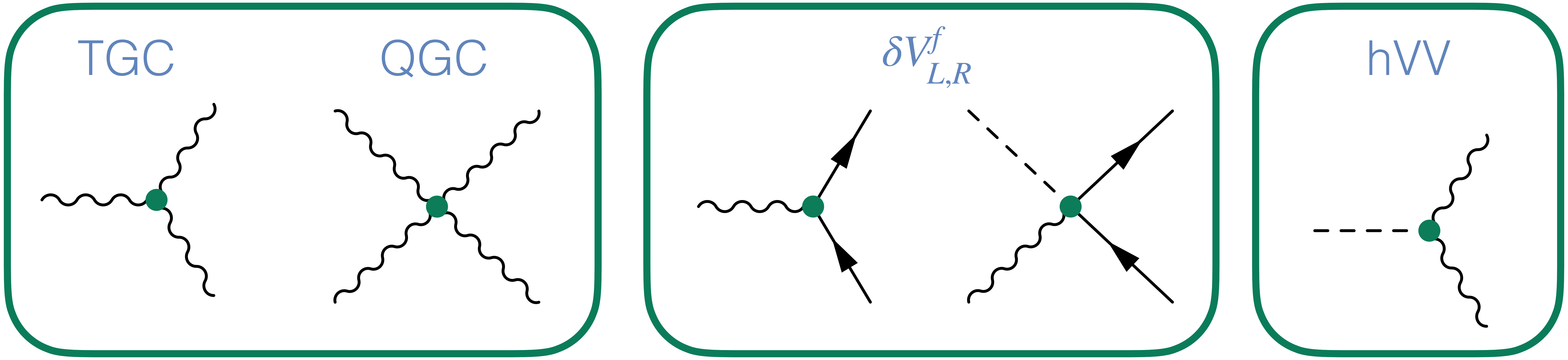


# New physics probes with triboson

$pp \to VVV, \ V = W^{\pm}, Z, \gamma$





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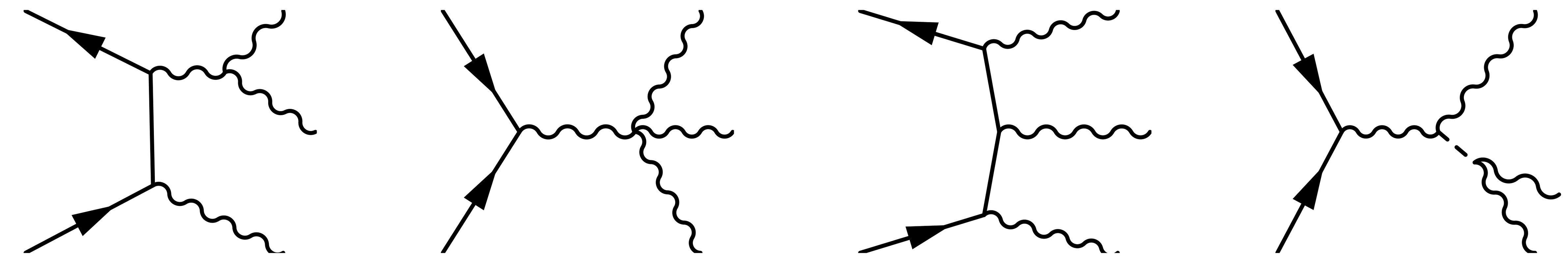
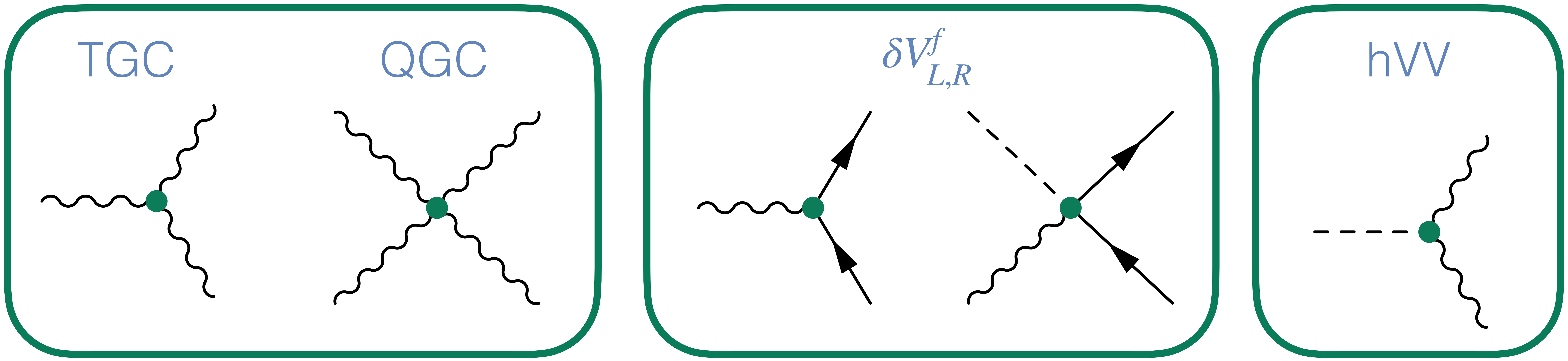
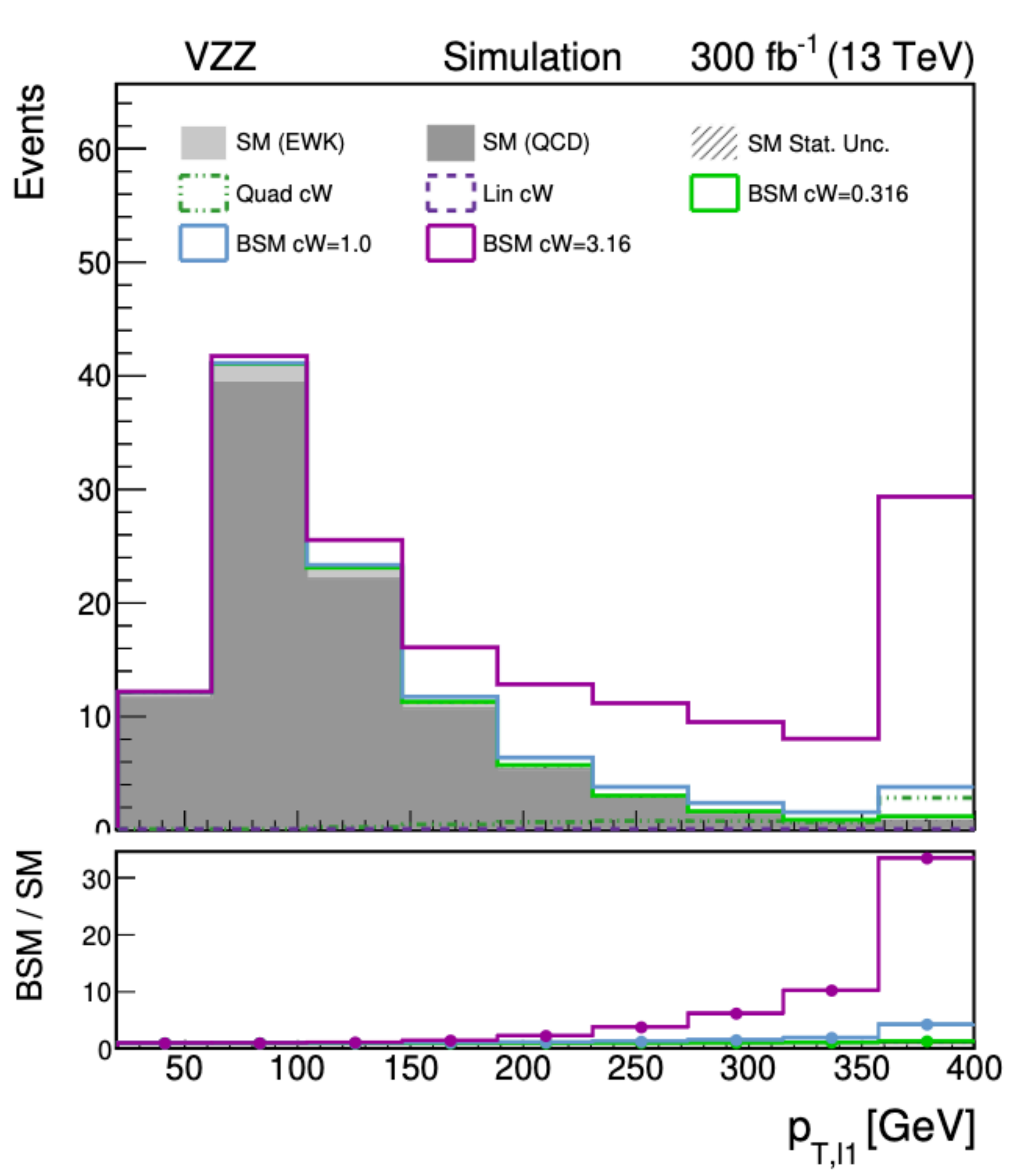
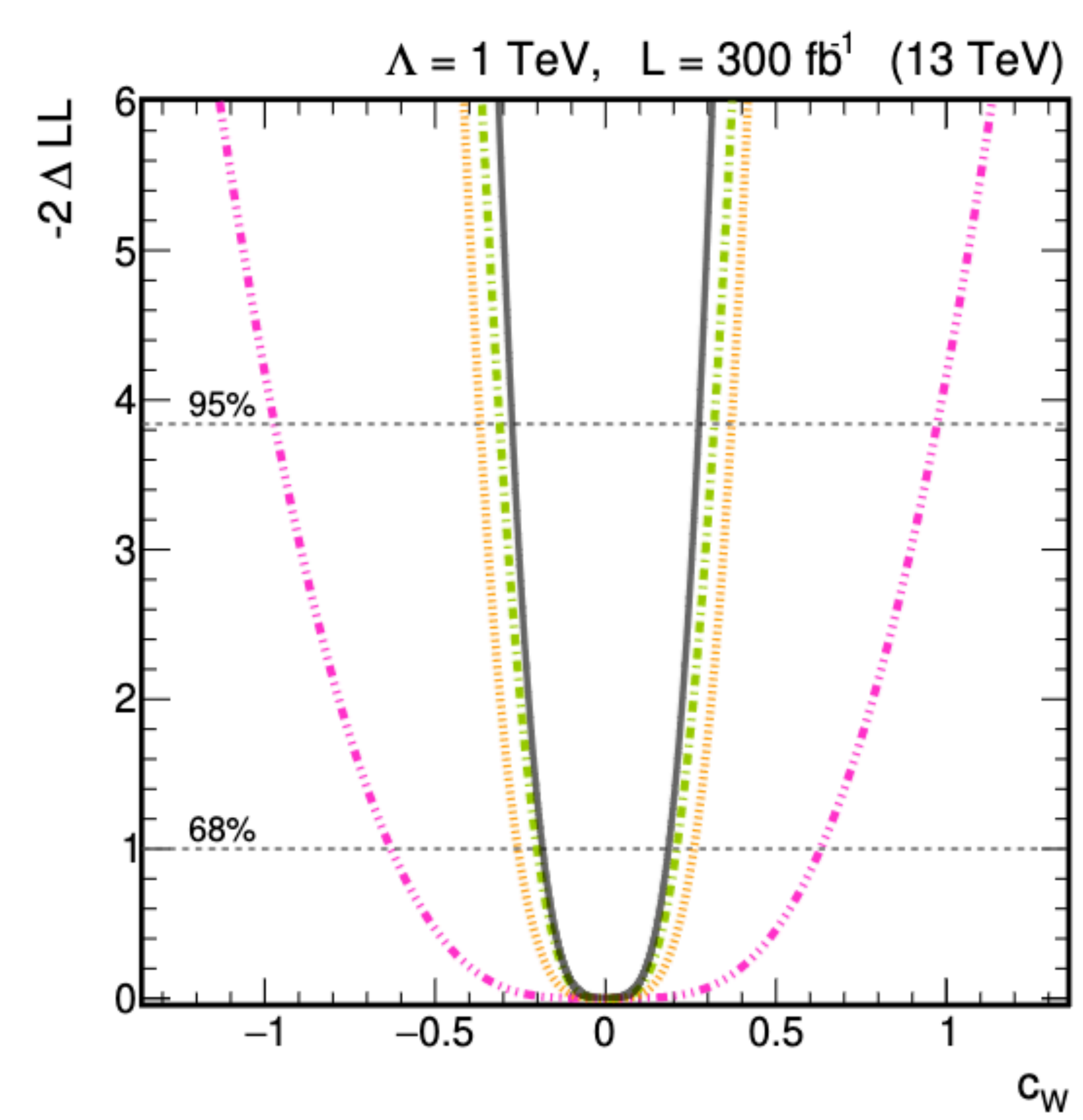





[Bellan et al; JHEP 08 (2023) 158]



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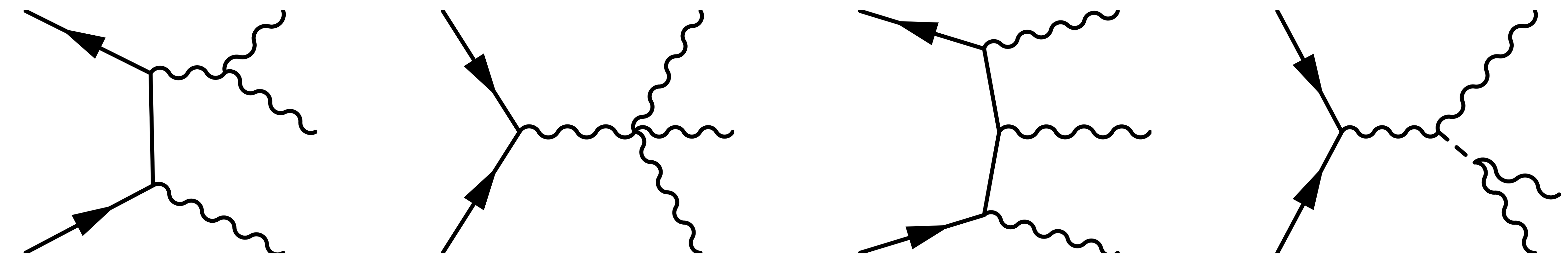

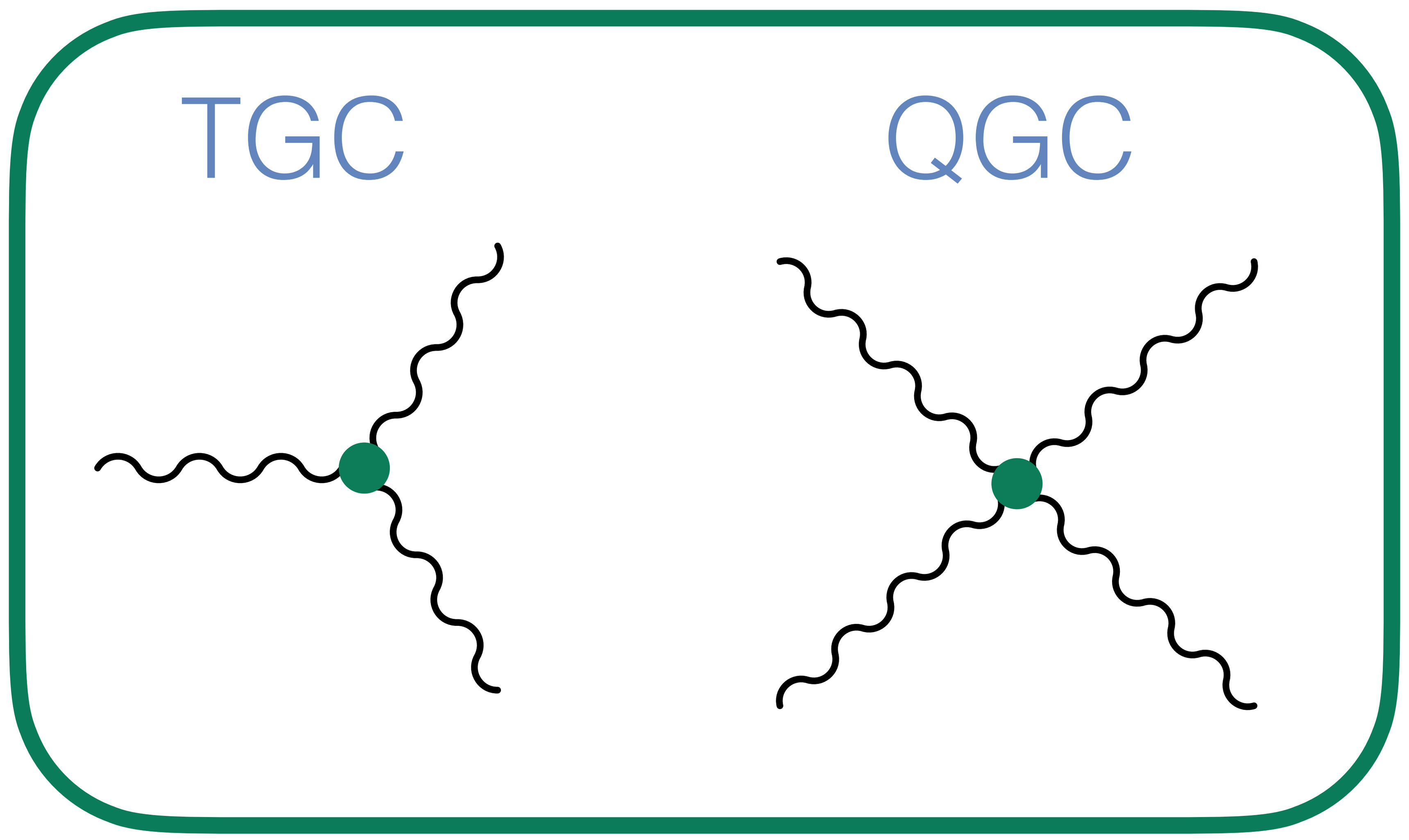


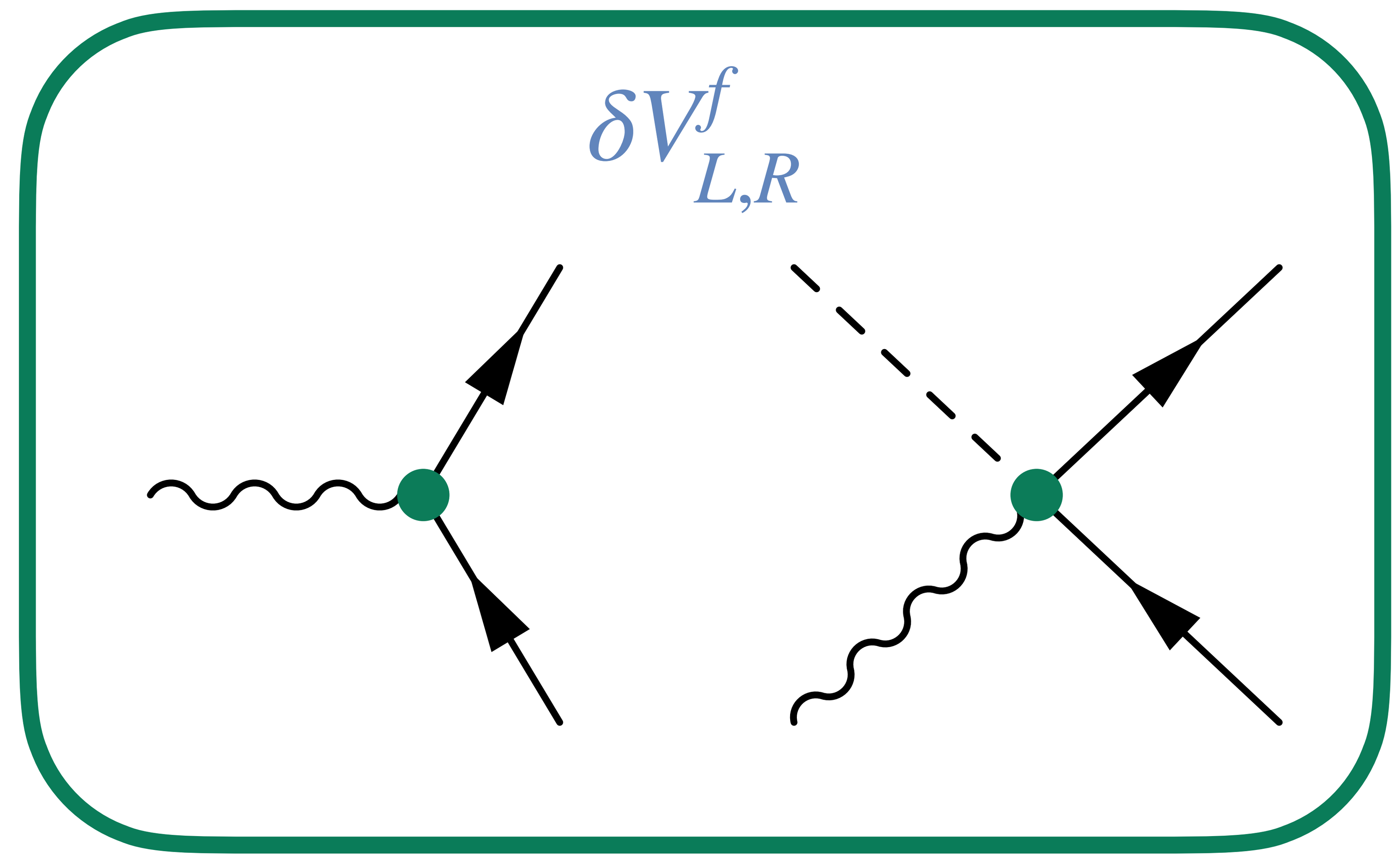


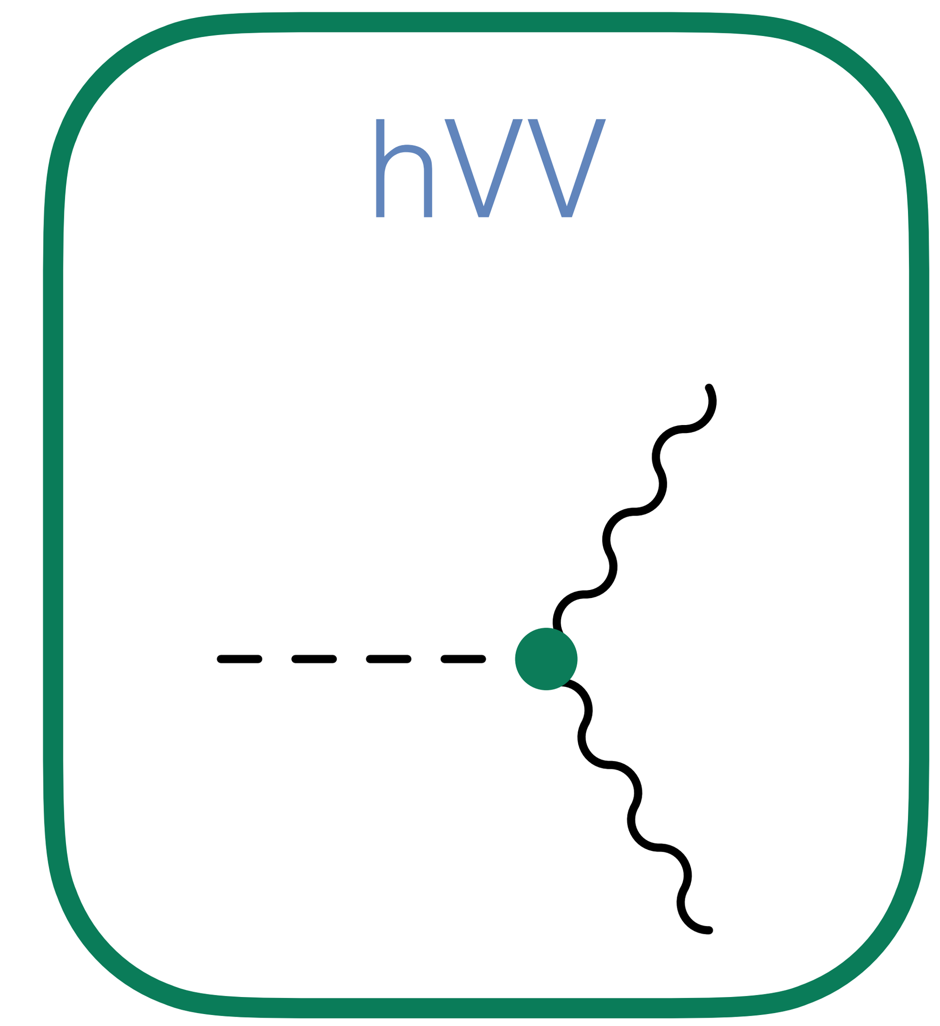


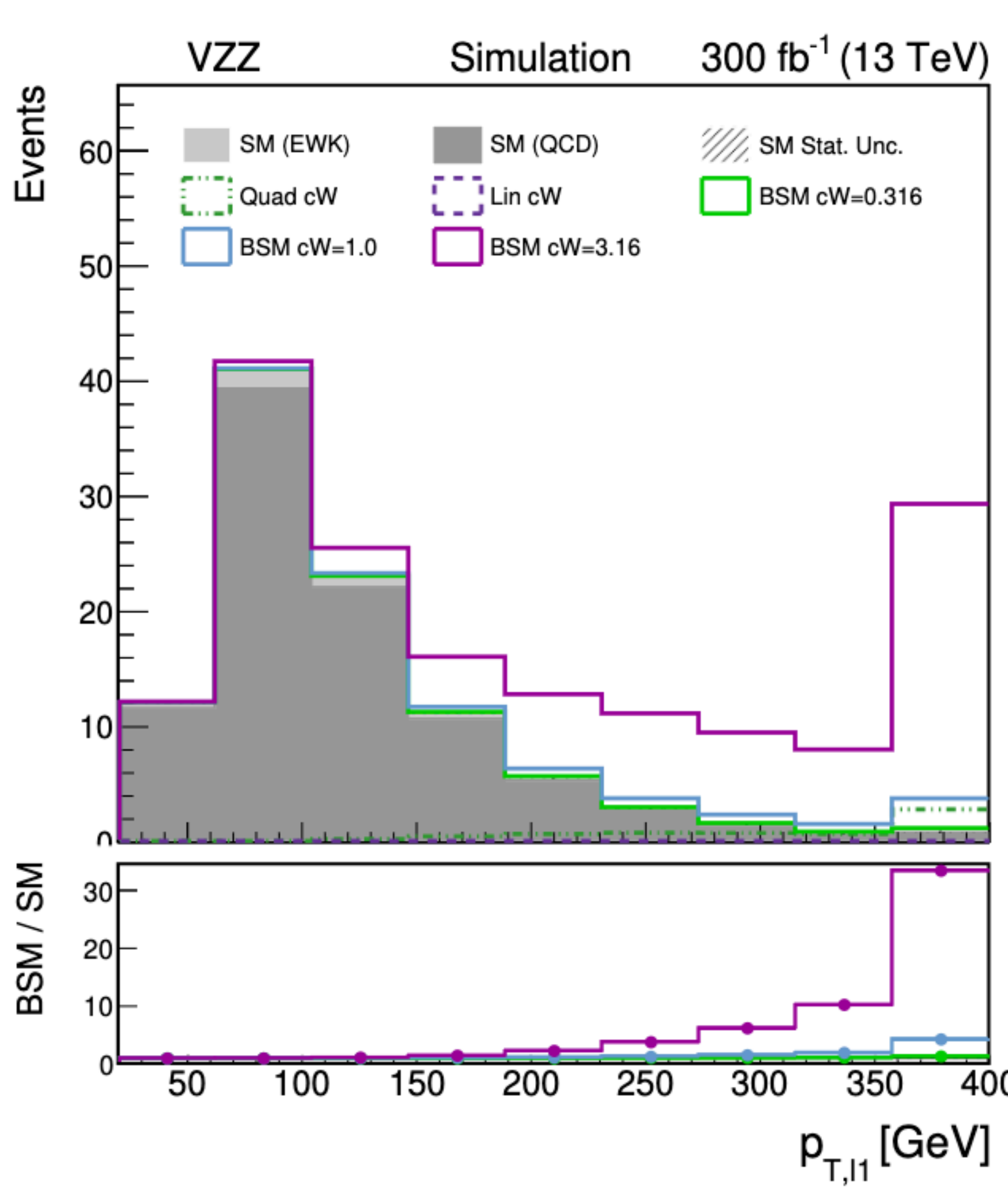


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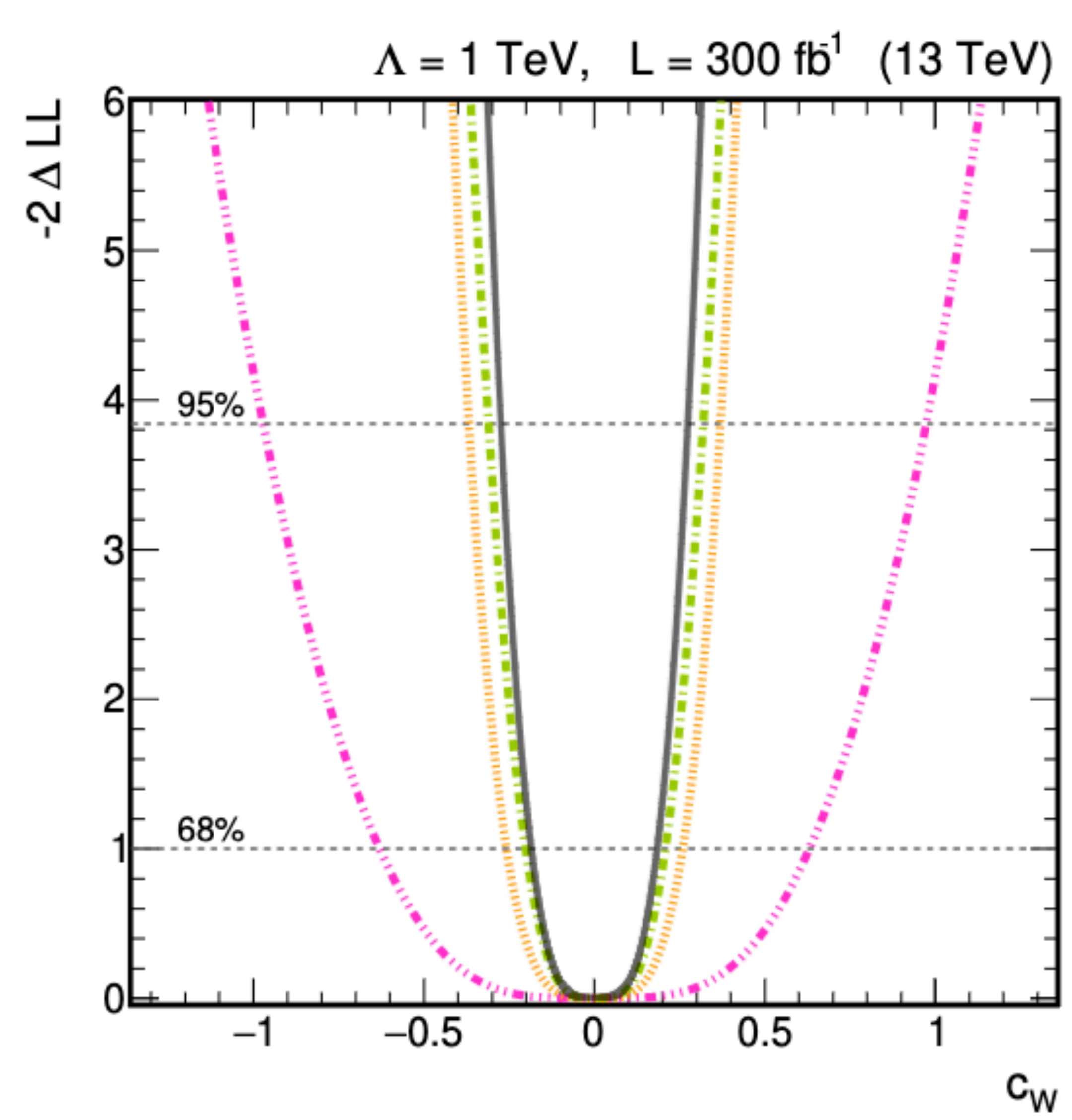
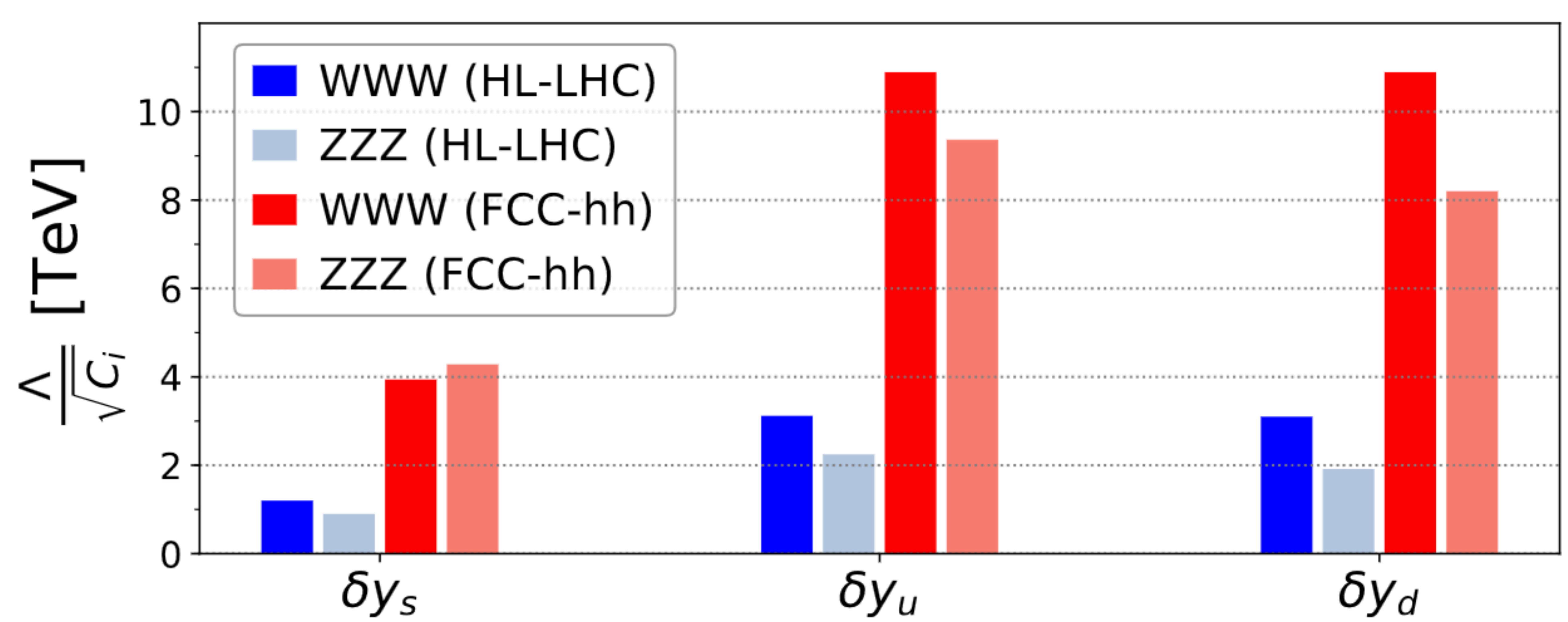



Light quark Yukawas

[Henning et al.; PRL 123 (2019) 181801]
[Falkowski et al; JHEP 04 (2021) 023]



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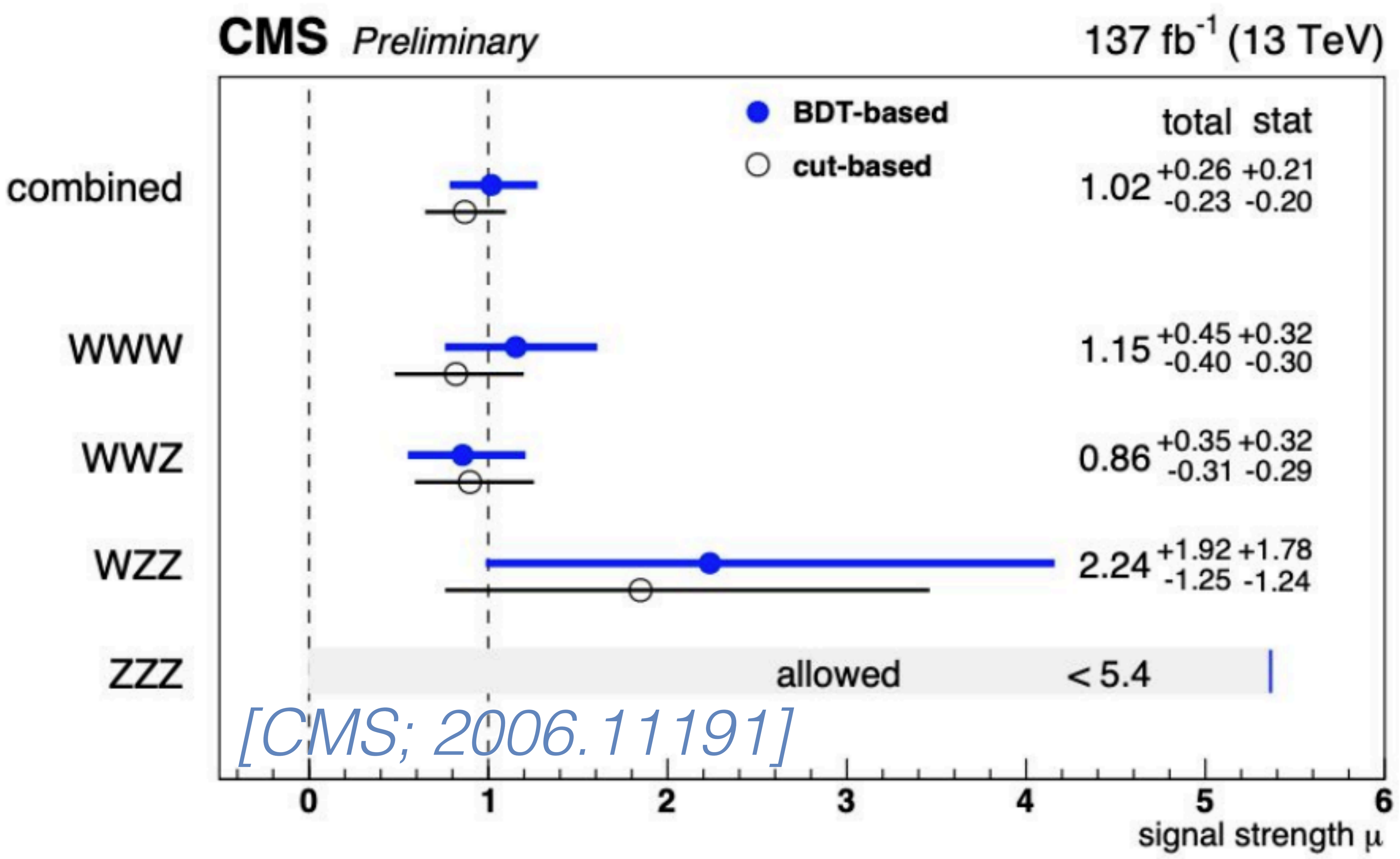


[CMS; 2006.11191]

$\mu_{WWW} = 1.61 \pm 0.19 \pm 0.16$ [ATLAS; 2201.13045]

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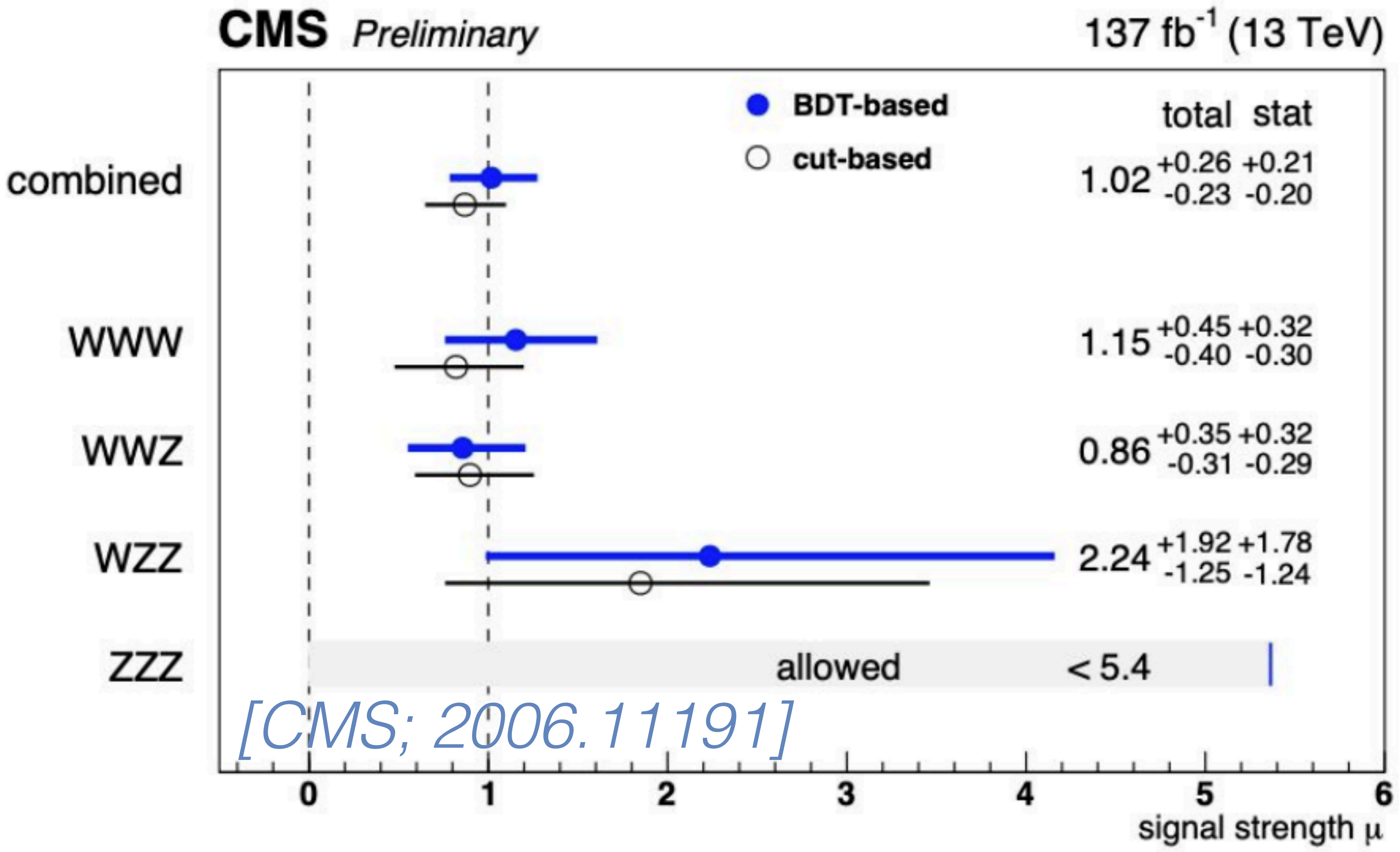


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- EWPO, LHC & LEP diboson, Higgs programme $\delta_{EWPO} \sim 1 - 0.1\,\%$ $\delta_h \sim 10\,\%$
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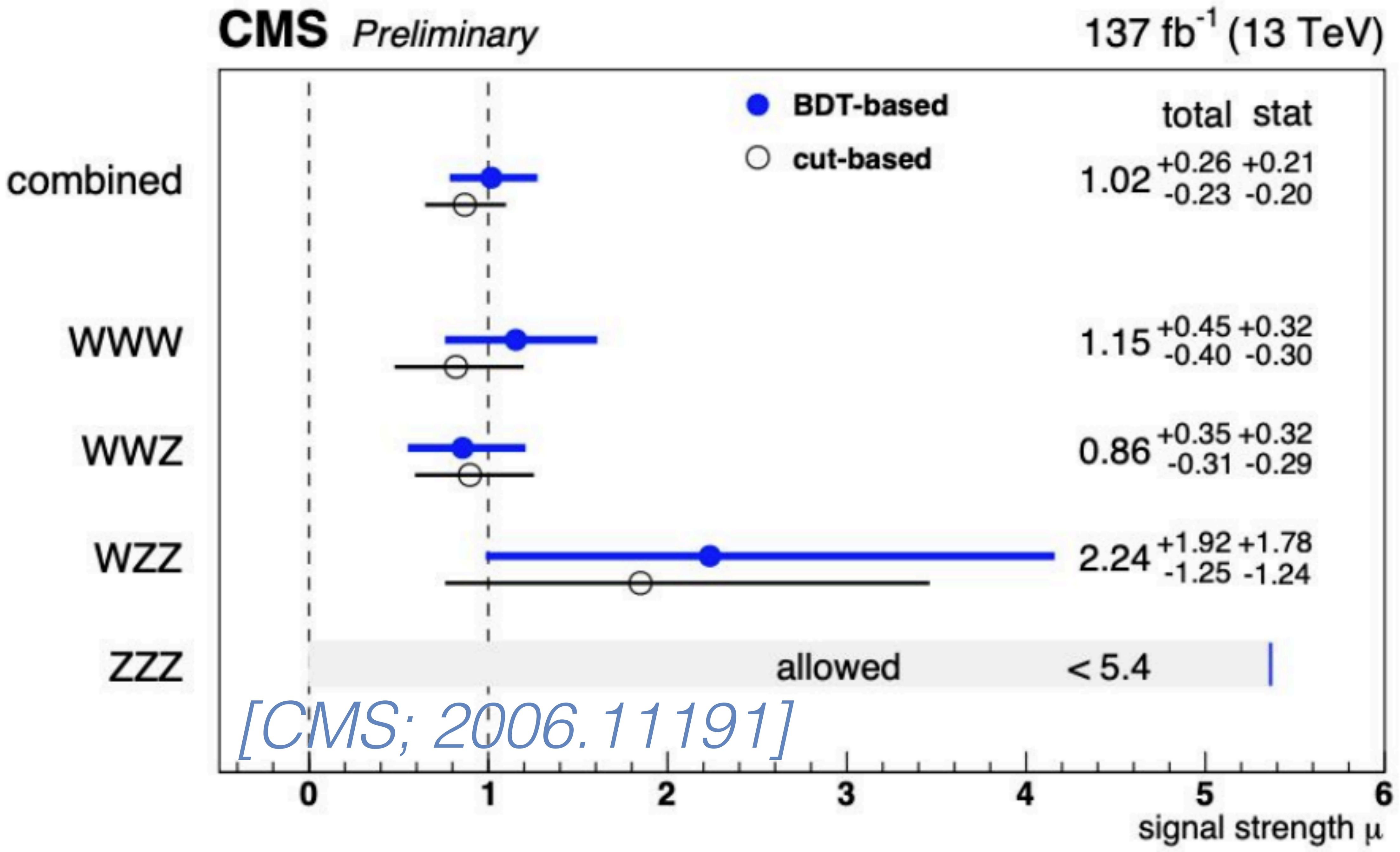


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## What new information does triboson offer?

- Naively not much… do a fit to find out! [E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

# 1,2 & 3 bosons: data

+ VVV signal strengths from before

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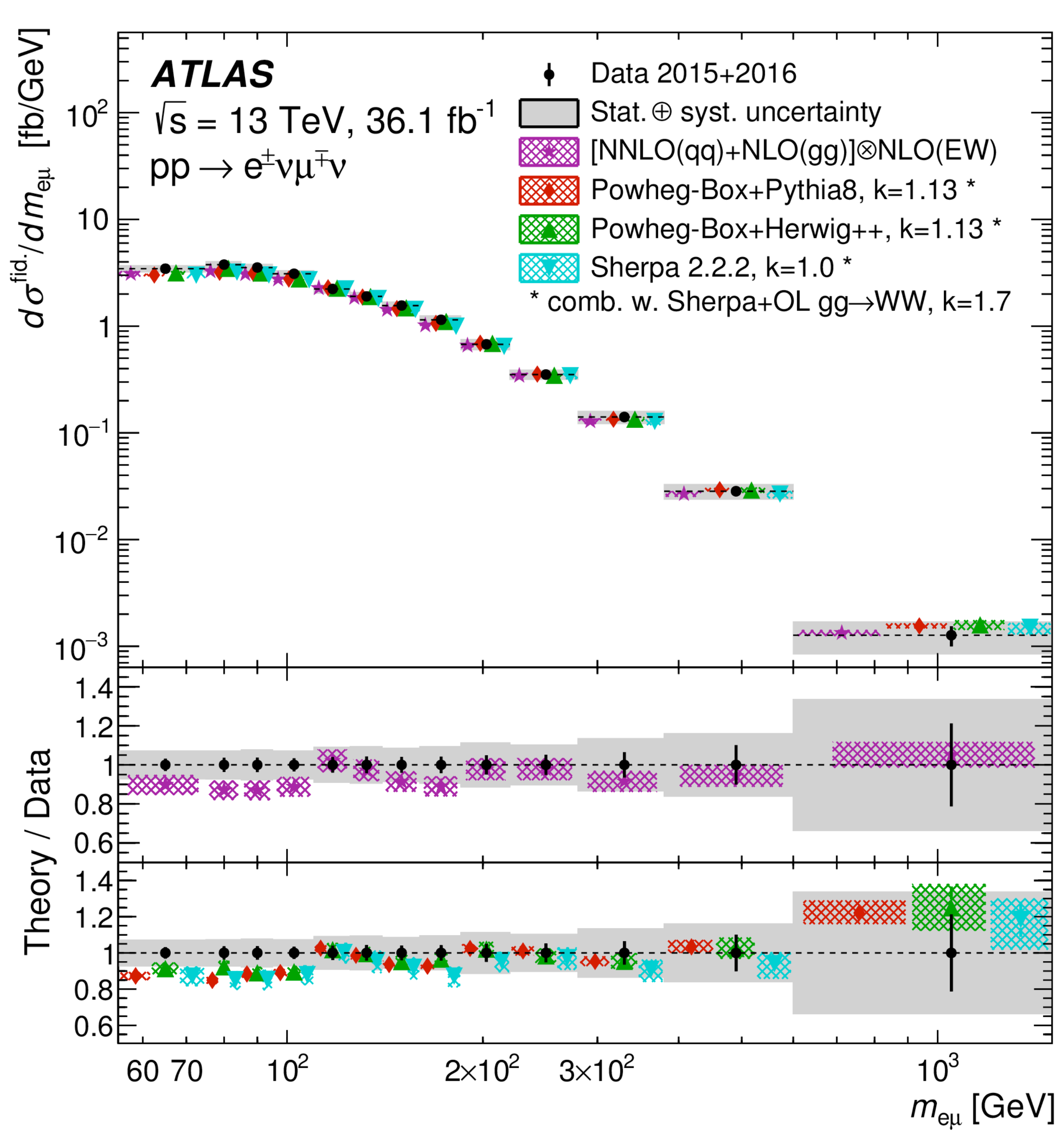
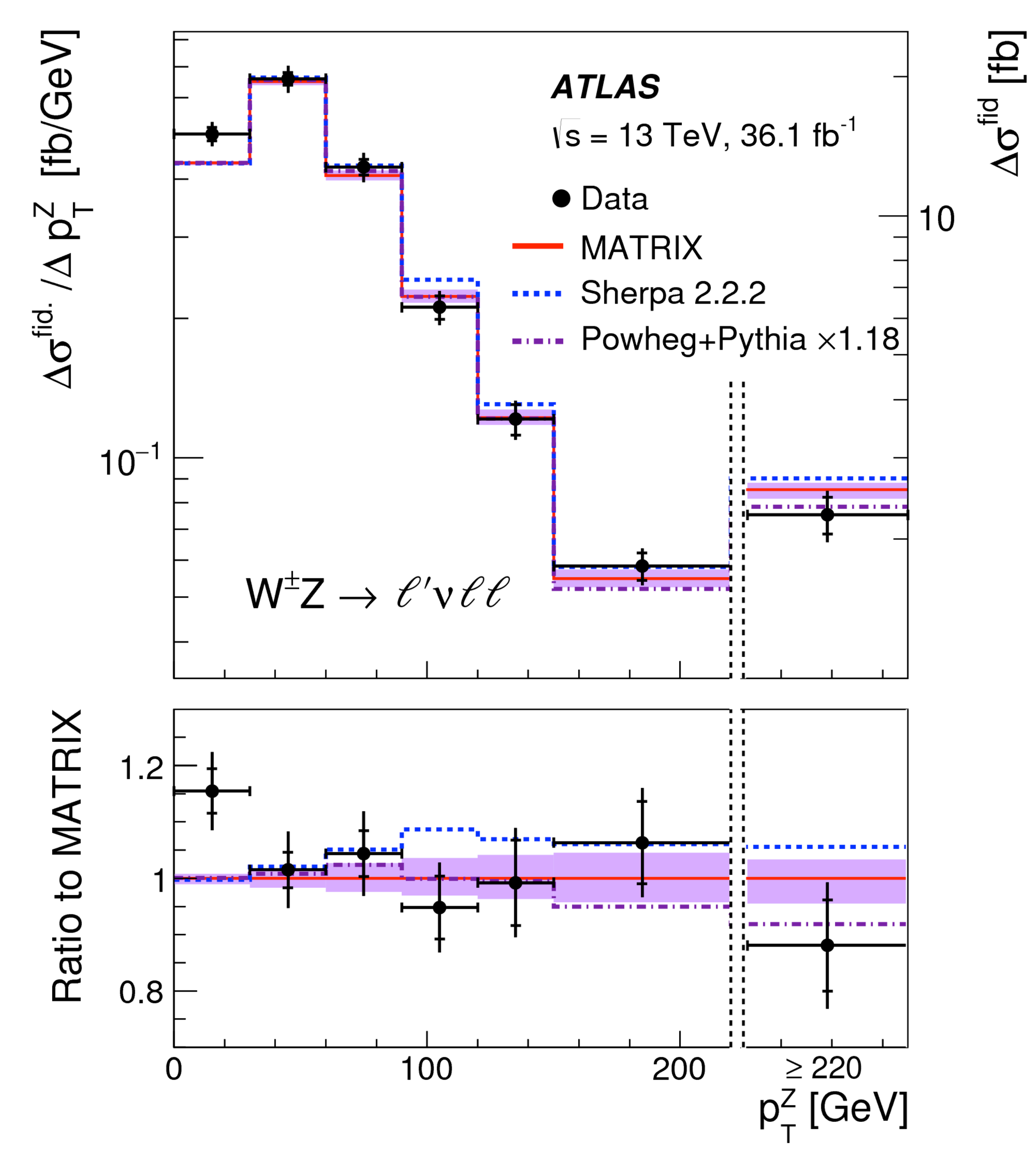
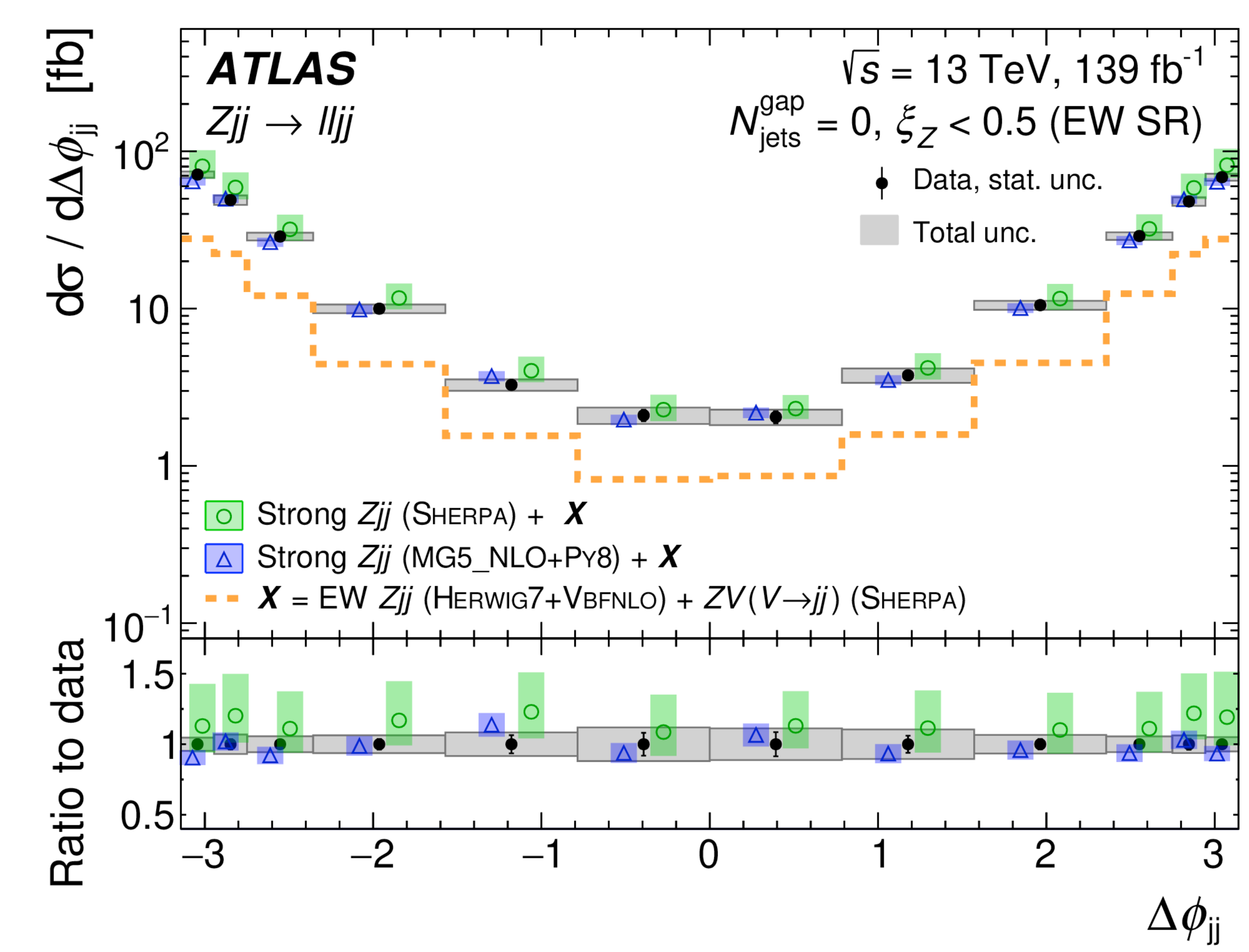
LHC VV $pp @ \sqrt{s} = 13\ TeV$ $\quad pp \to W^+W^-/WZ/Zjj$



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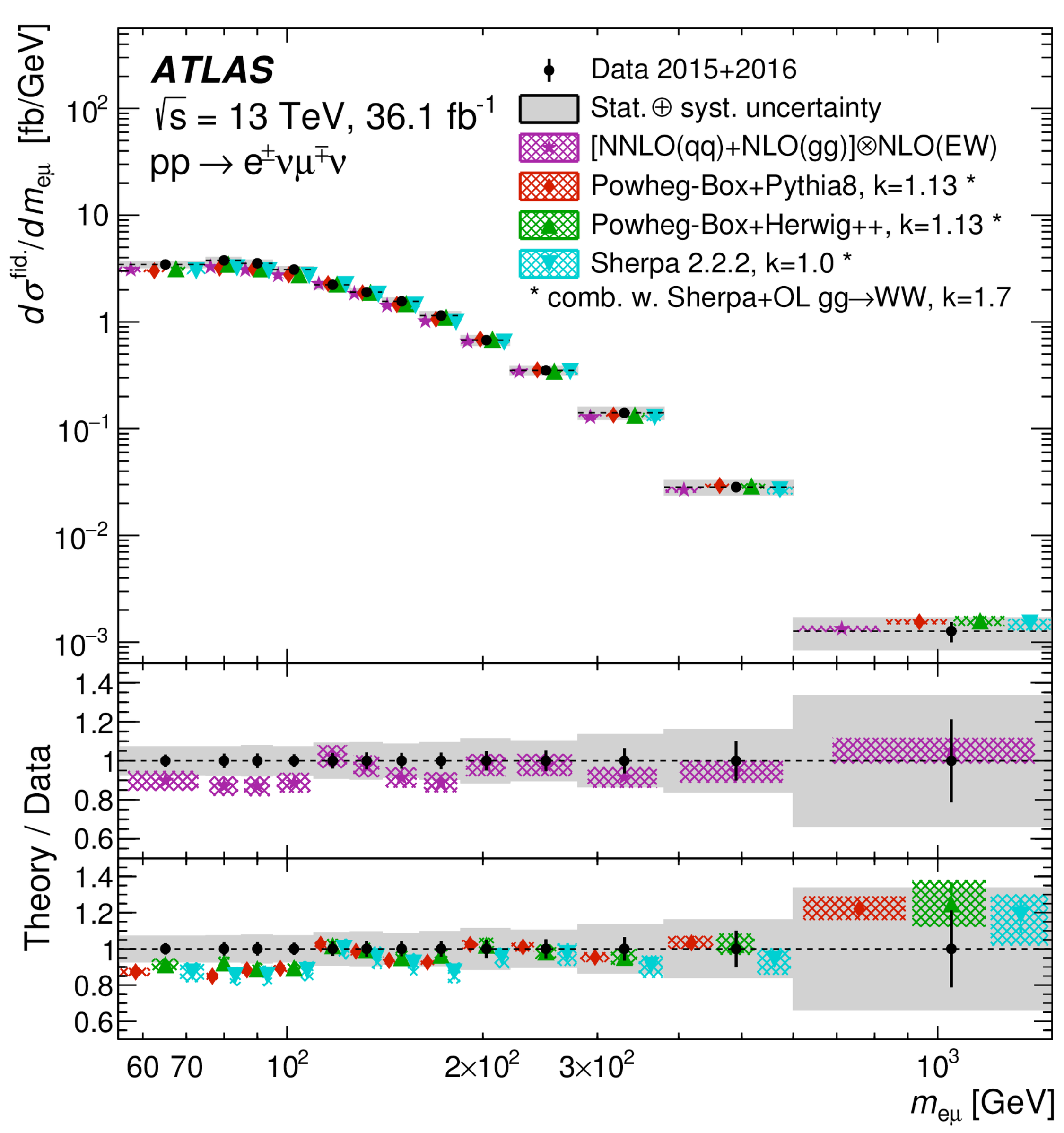


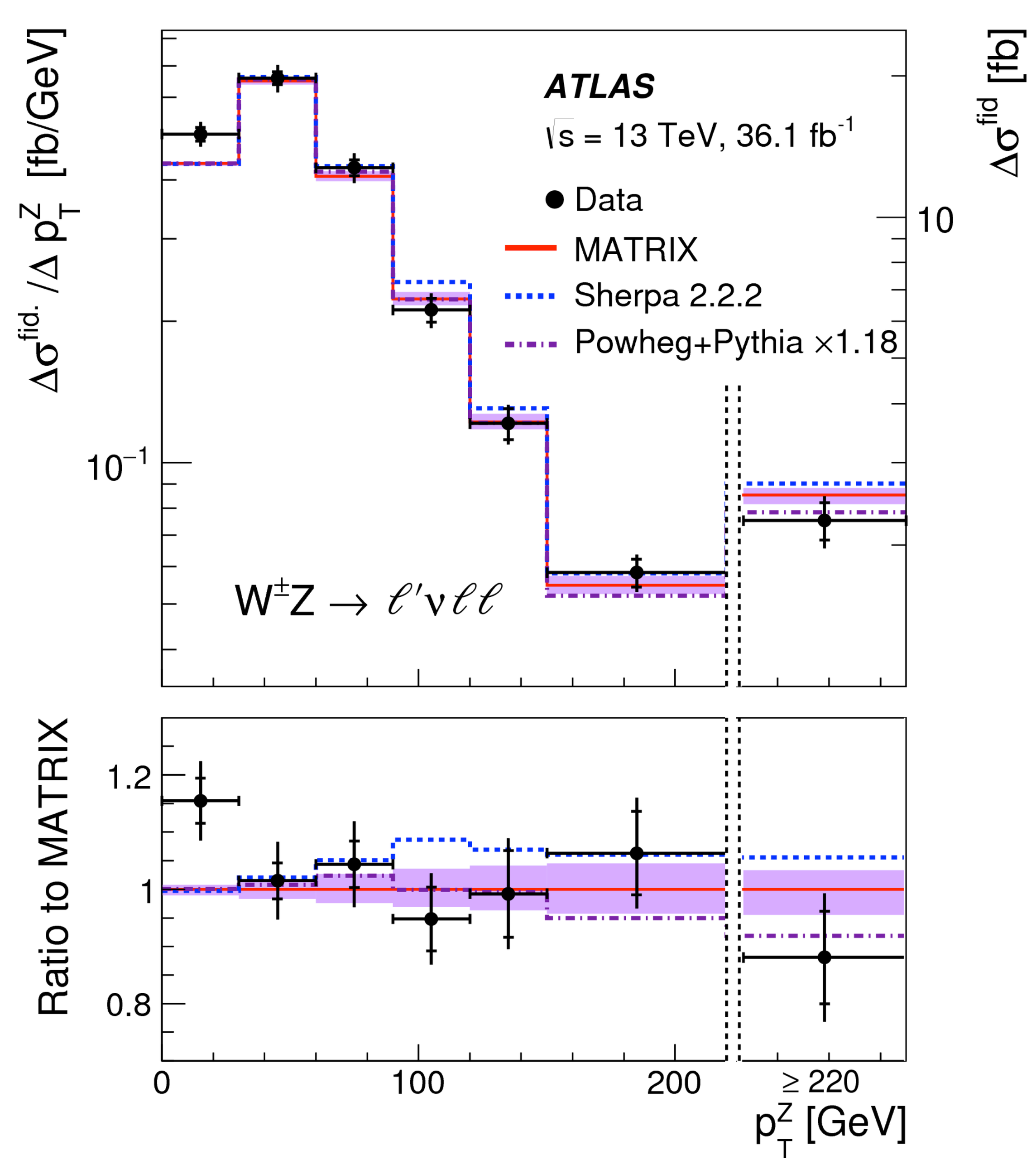


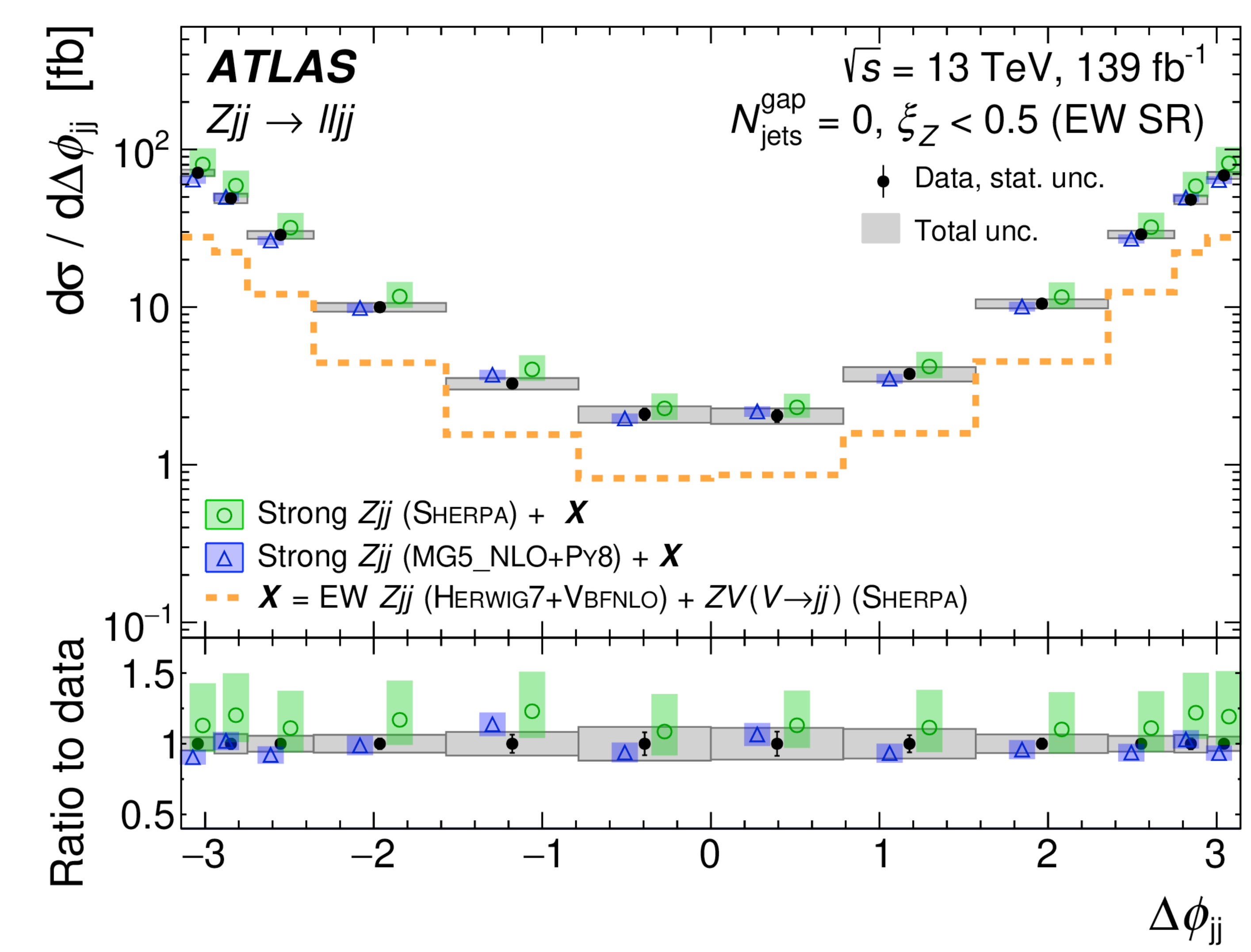


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a) linear $O(\Lambda^{-2})$

b) quadratic $O(\Lambda^{-4})$

# 1,2 & 3 bosons: model

| 11 parameters | Operator | Definition |
|---|---|---|
| | **bosonic** | |
| $\delta\alpha, \delta g_Z$ & hVV | $\mathcal{O}_{\phi D}$ | $(\phi^\dagger D^\mu \phi)^\dagger(\phi^\dagger D_\mu \phi)$ |
| | $\mathcal{O}_{\phi WB}$ | $(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$ |
| TGC | $\mathcal{O}_{WWW}$ | $\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_\rho$ |
| | **two-fermion** | |
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| | $\mathcal{O}_{\phi e}$ | $i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$ |
| | **four-fermion** | |
| $\delta\alpha$ | $\mathcal{O}_{\ell\ell}$ | $(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$ |

fitmaker: [Ellis et al.; 2012.02779]
SMEFT@NLO: [Degrande et al.; 2008.11743]

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# Results

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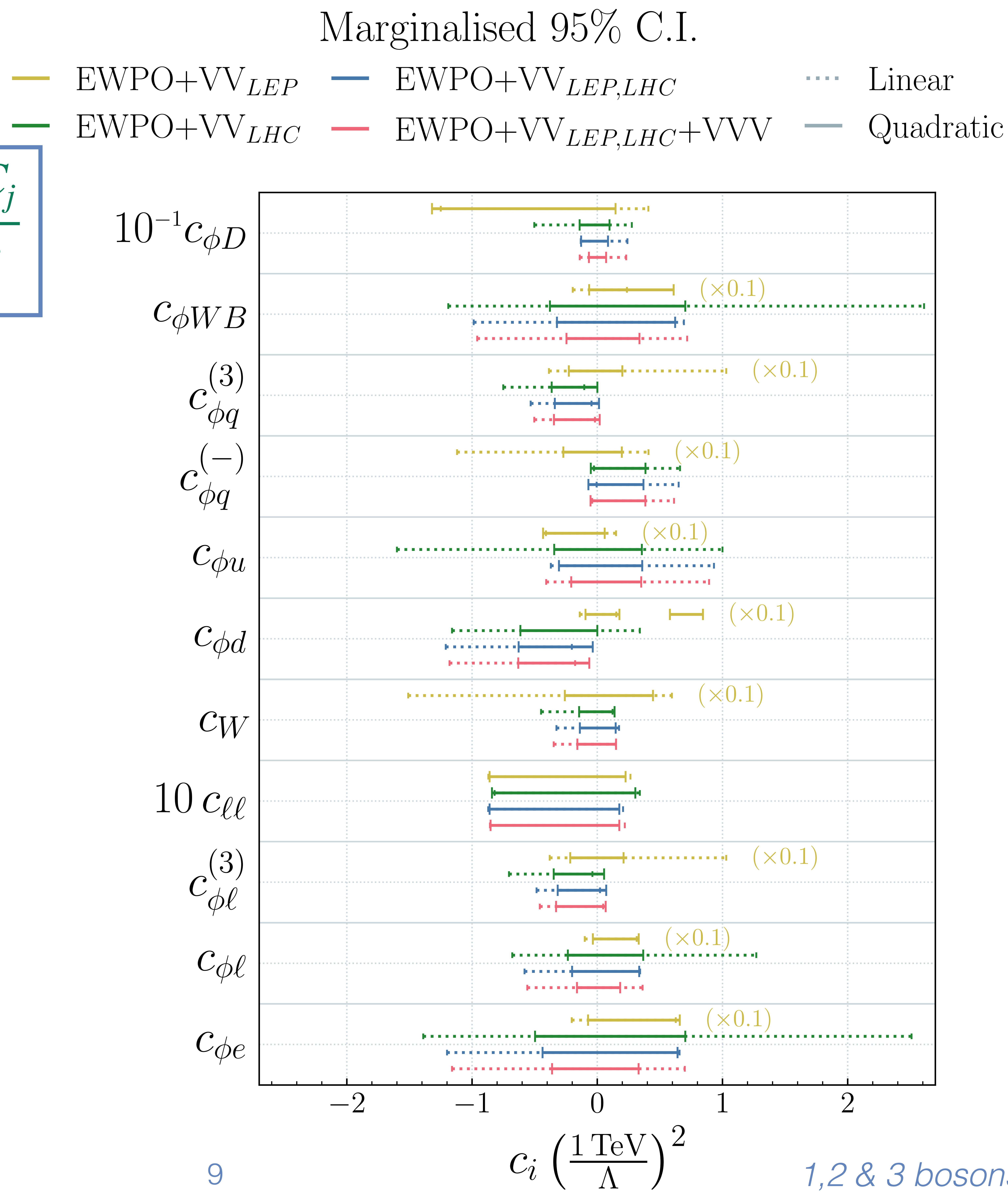

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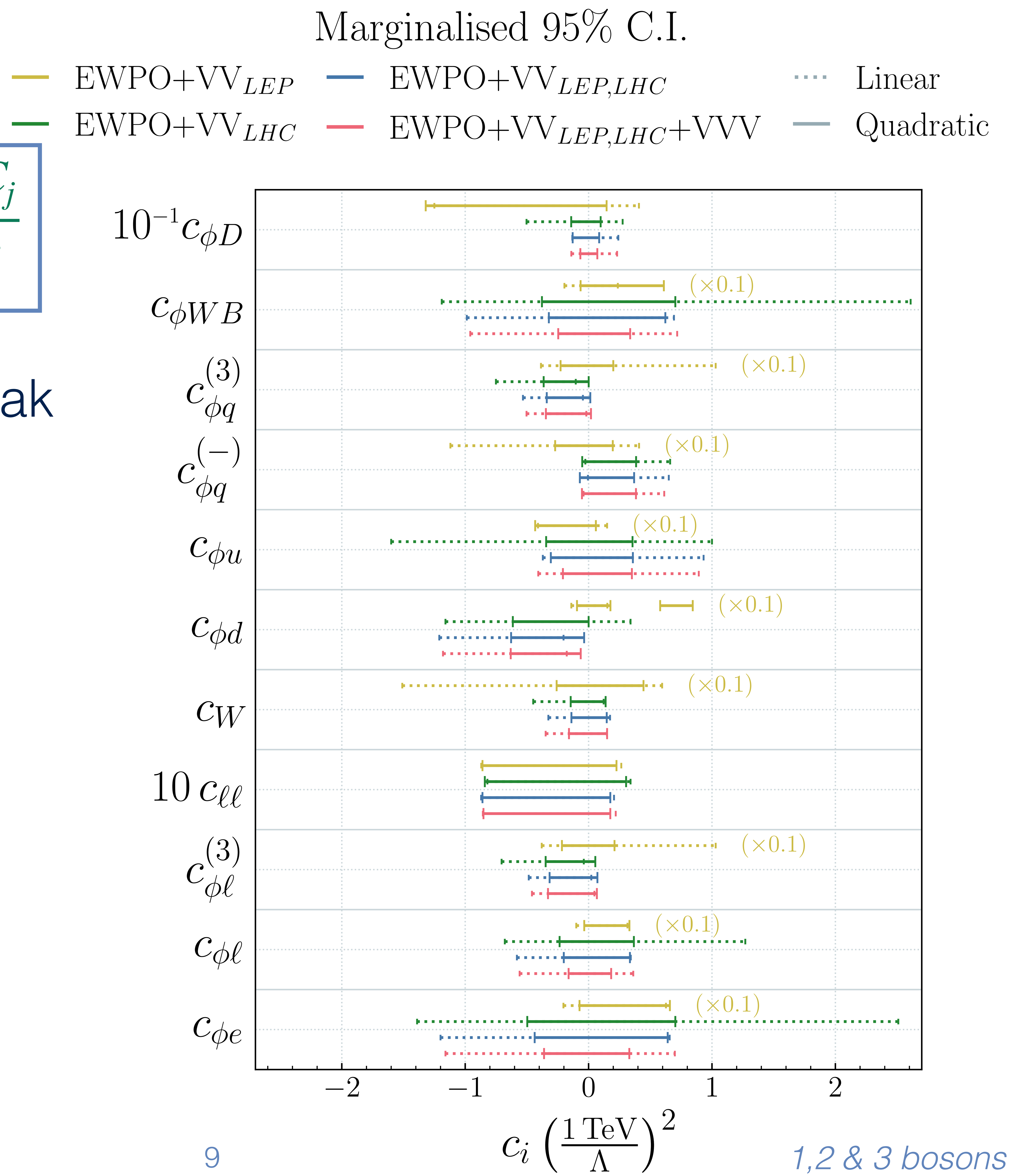
- Significant quadratic effects



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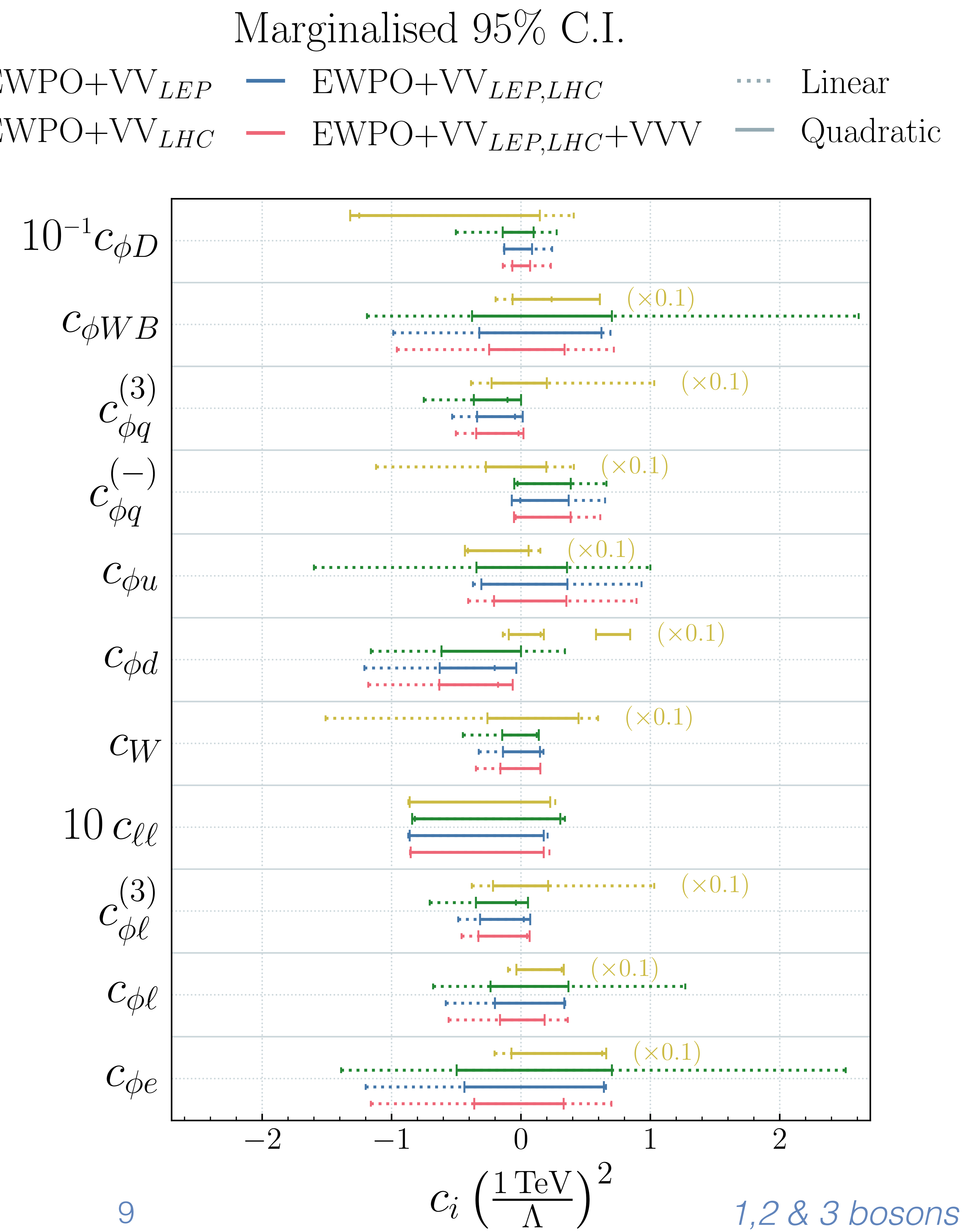

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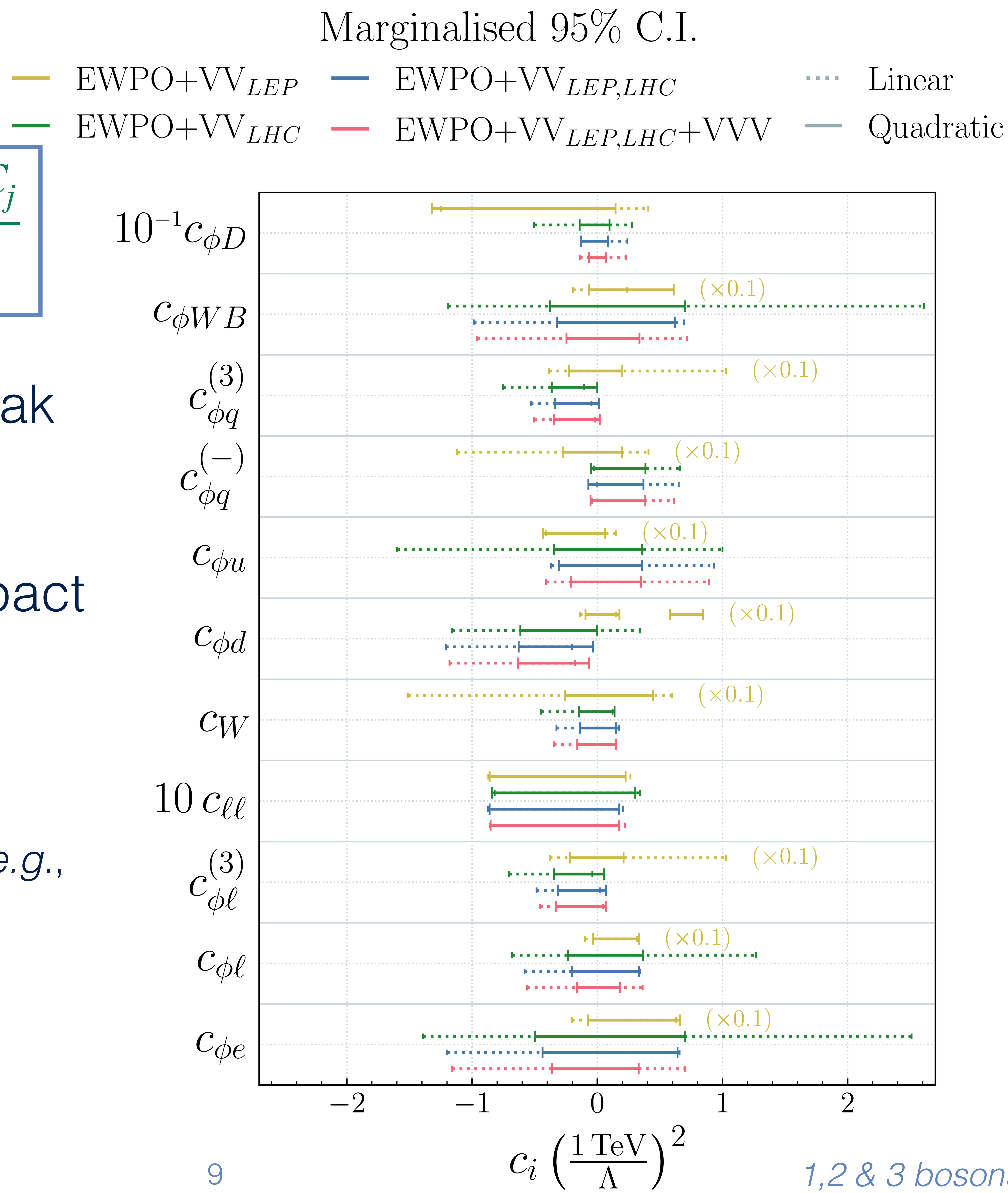
## VVV makes a difference

- Apparently $\sim 50\,\%$ effect in, *e.g.*, $c_{\phi D}$, $c_{\phi WB}$, $c_{\phi \ell}$, $c_{\phi e}$
- Quadratic only



# Interpretation

[De Rujula et al.; Nucl. Phys. B 384 (1992) 3-58]
[Degrande et al.; 1205.4231]
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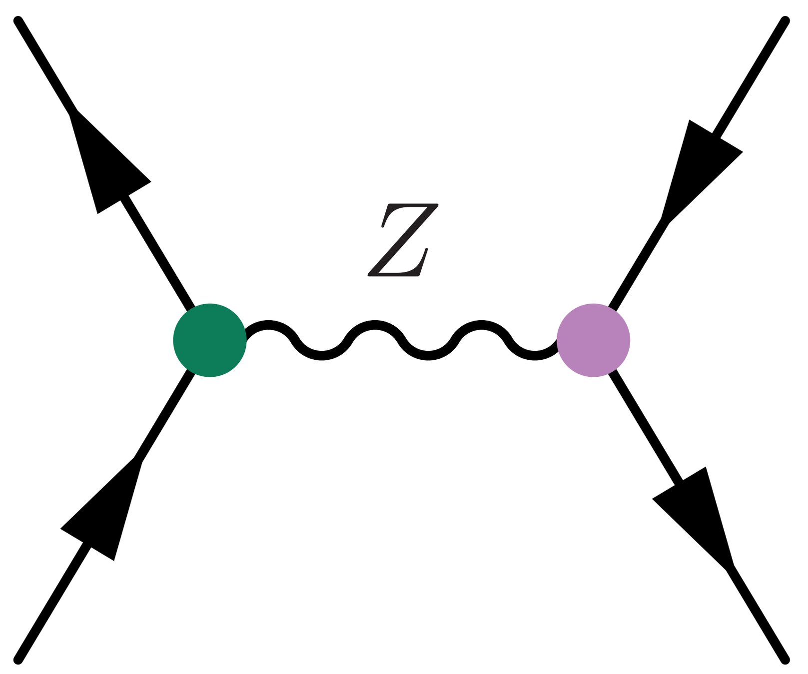
- Not sensitive to TGC & has 2 additional flat directions
- Constrains 8 out of 11 combinations of $C_i$



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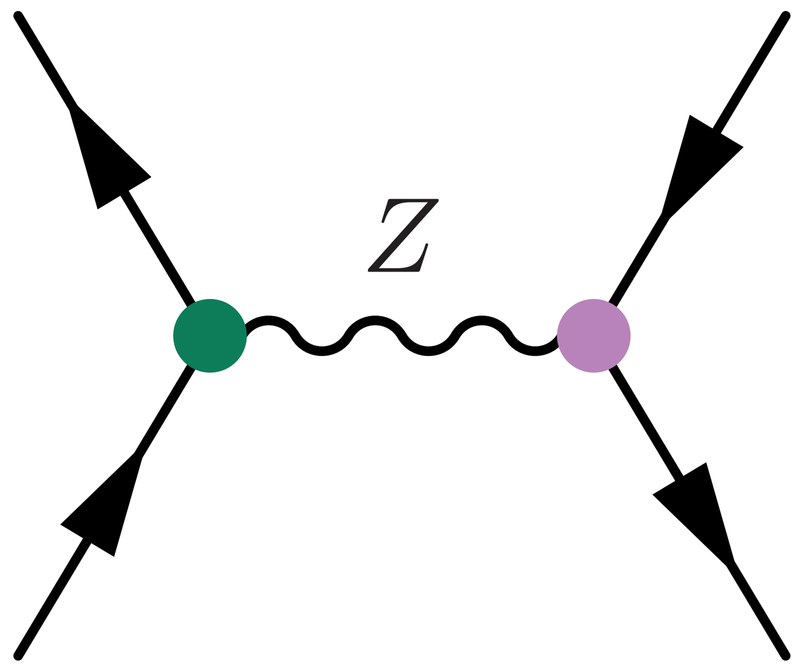


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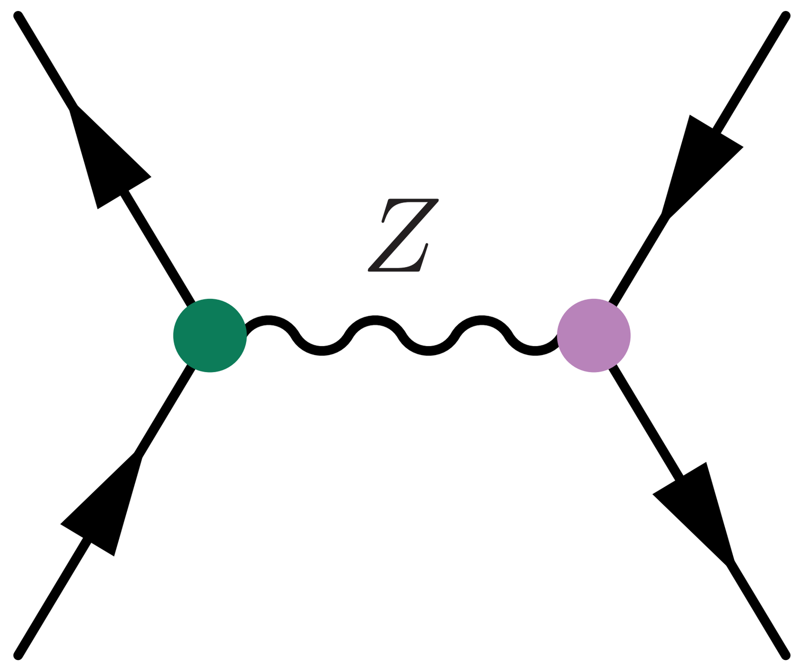


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## Eigenvectors of the Fisher information, $\hat{e}_i$

$$\vec{\mu} = \vec{\mu}_{SM} + \mathbf{H}\cdot\vec{c}$$

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- Unconstrained directions: $\hat{e}_{1,2} = a_{1,2}\,\hat{\omega}_B + b_{1,2}\,\hat{\omega}_B$
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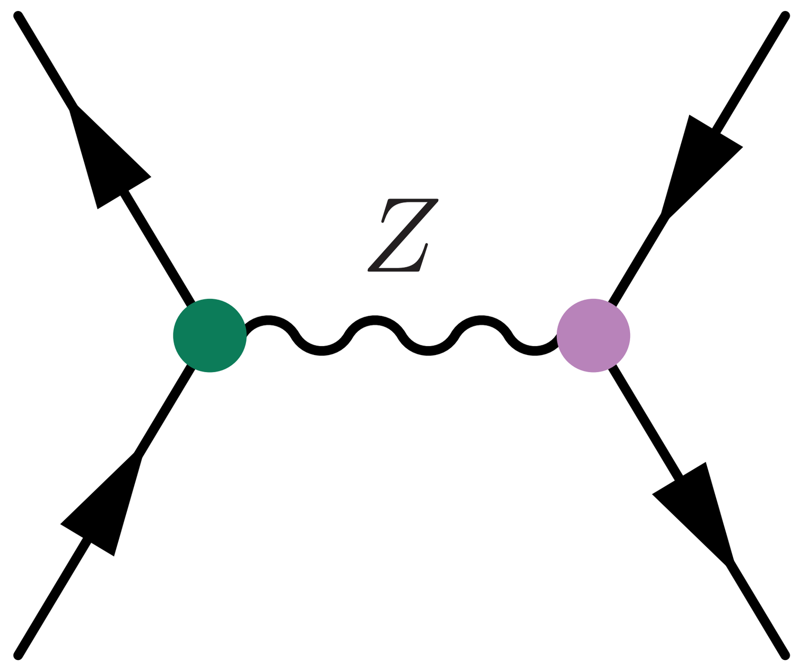


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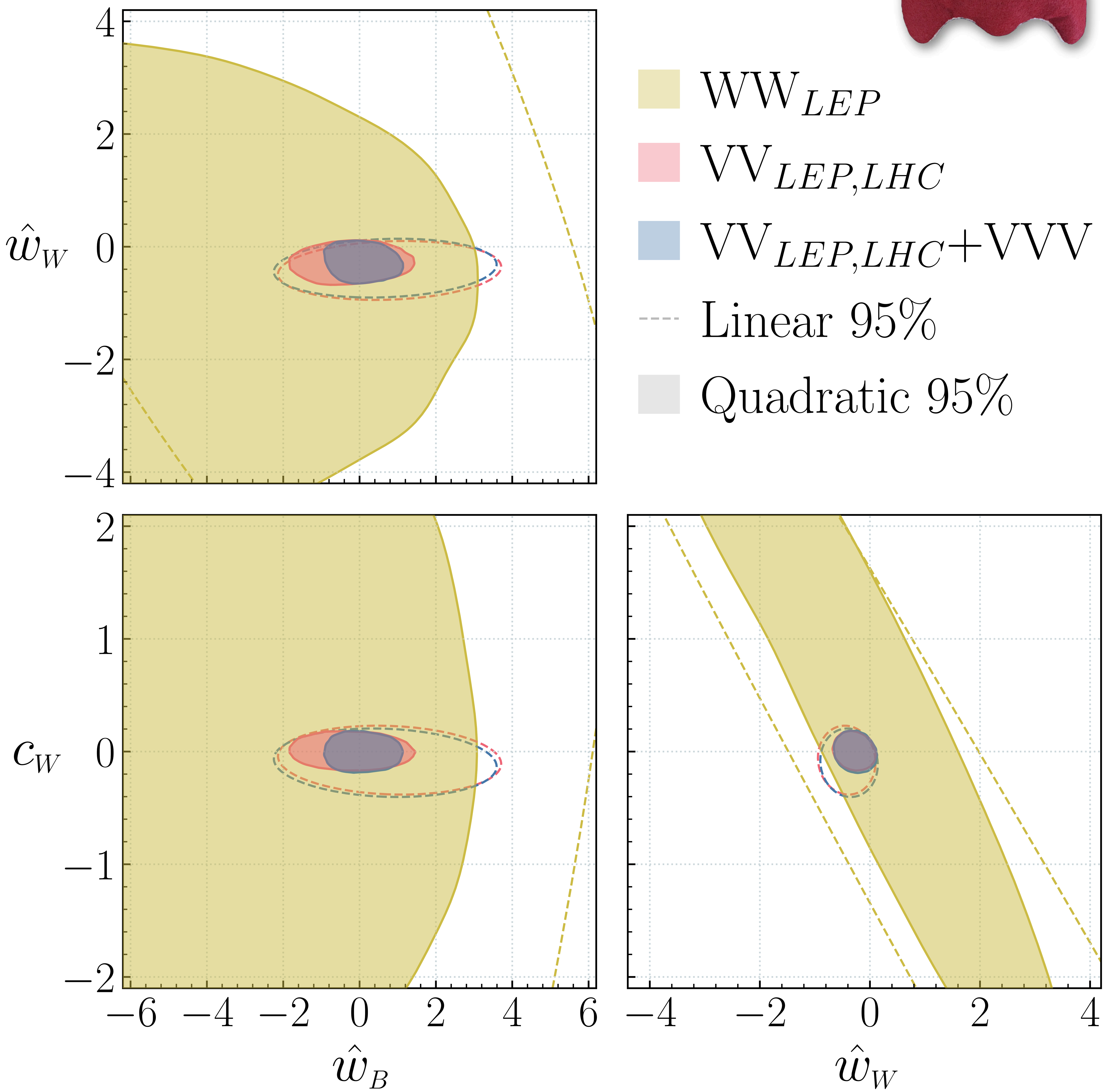
**Global:** bounds limited by the sensitivity of the extra data

# EWPO blind space




## Sufficient to study 3D space

- TGC + 2 flat directions
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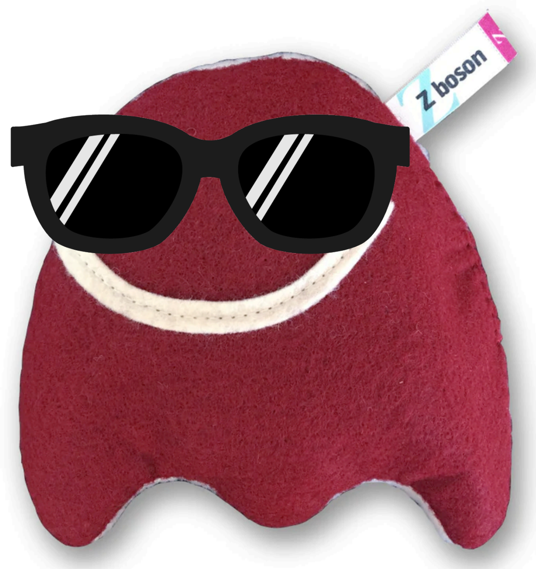

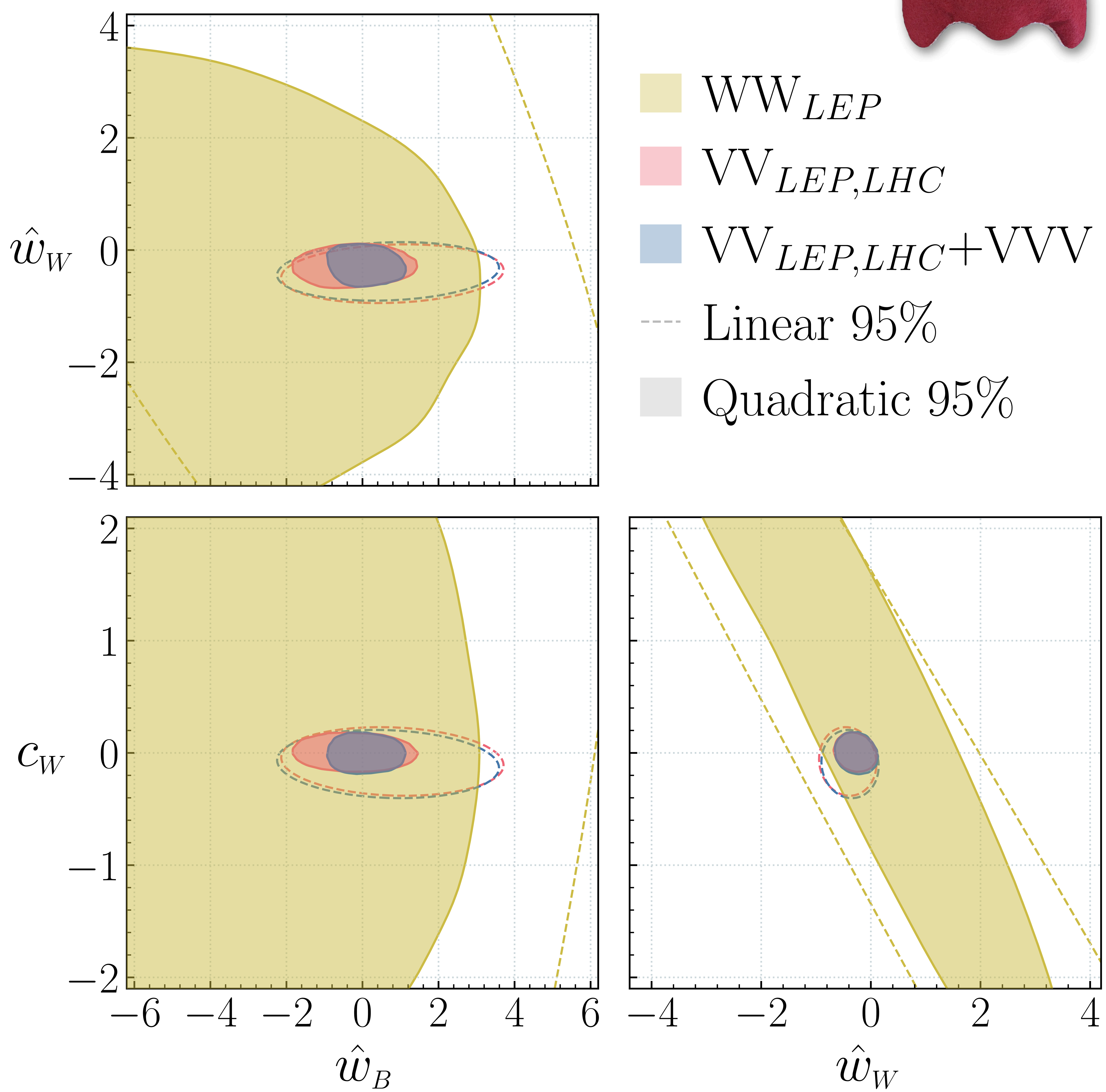


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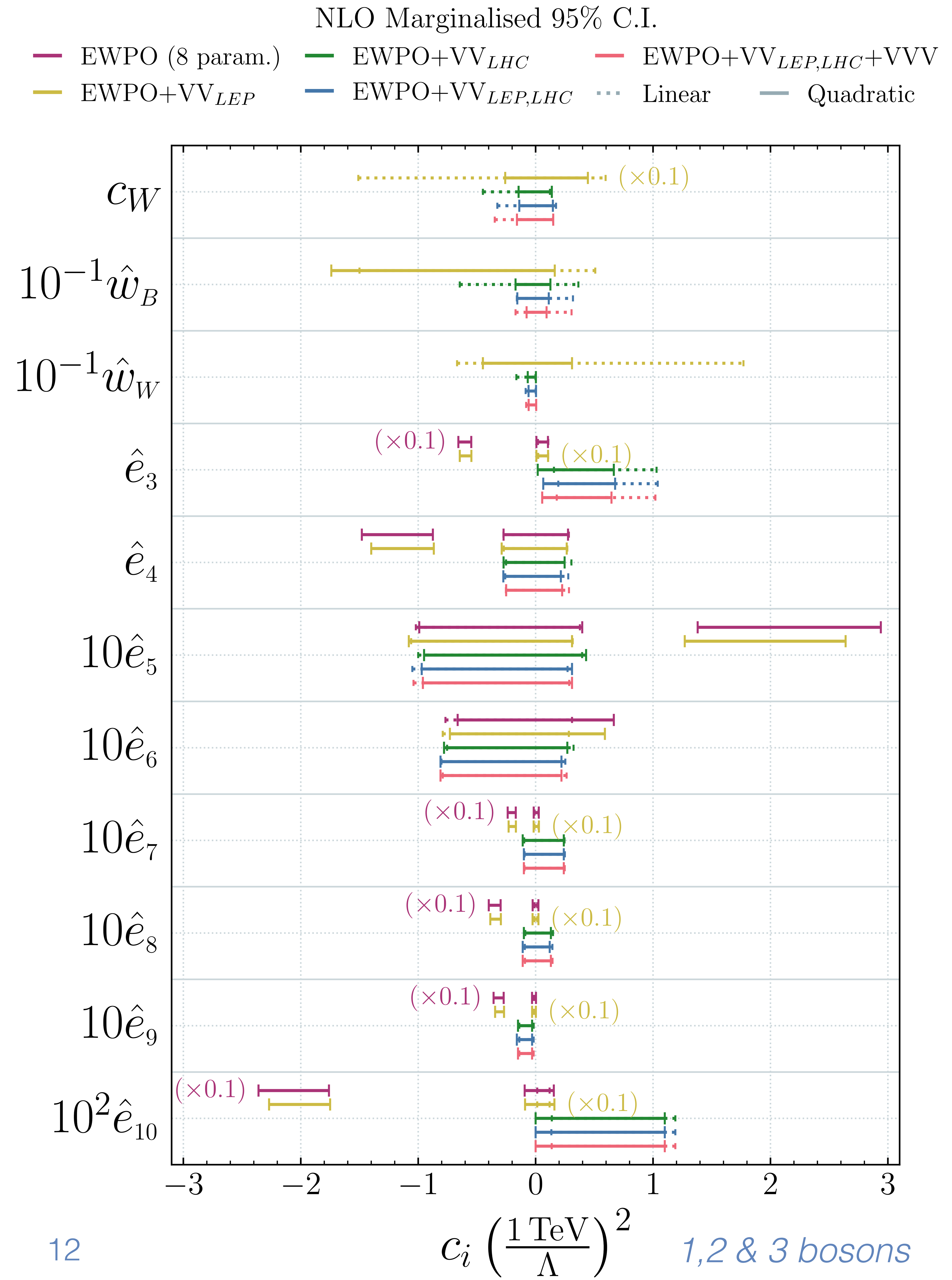
## VVV: purely $O(\Lambda^{-4})$ effect

- Significant quadratics everywhere
- Propagate into any global analysis that combines EWPO with other things
- EFT validity?

# Other $\hat{e}_i$?

## Rotated results to eigenbasis

- Compare to 8 parameter EWPO fit
- Significant quadratic effects
- Secondary minima



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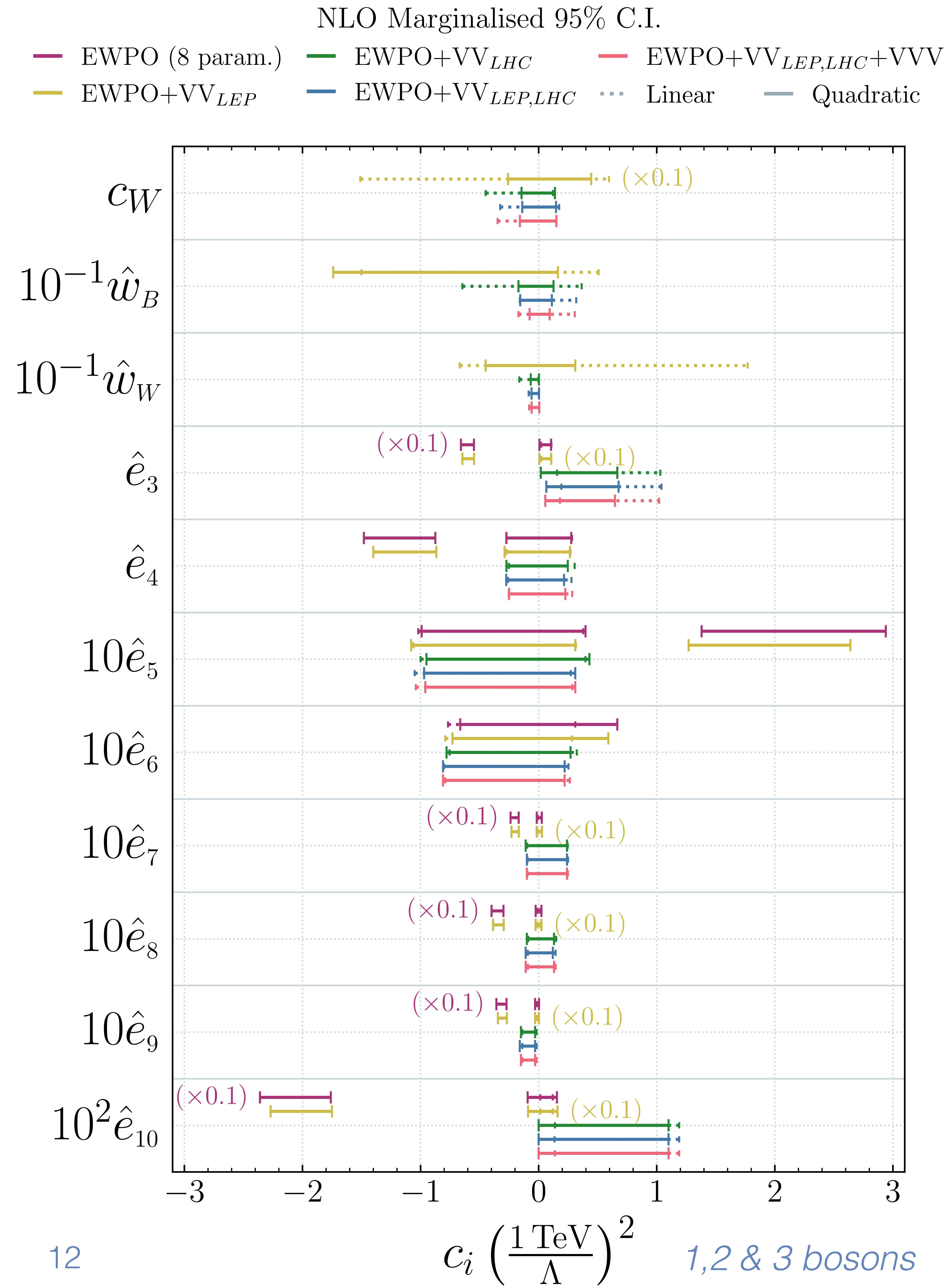




1,2 & 3 bosons

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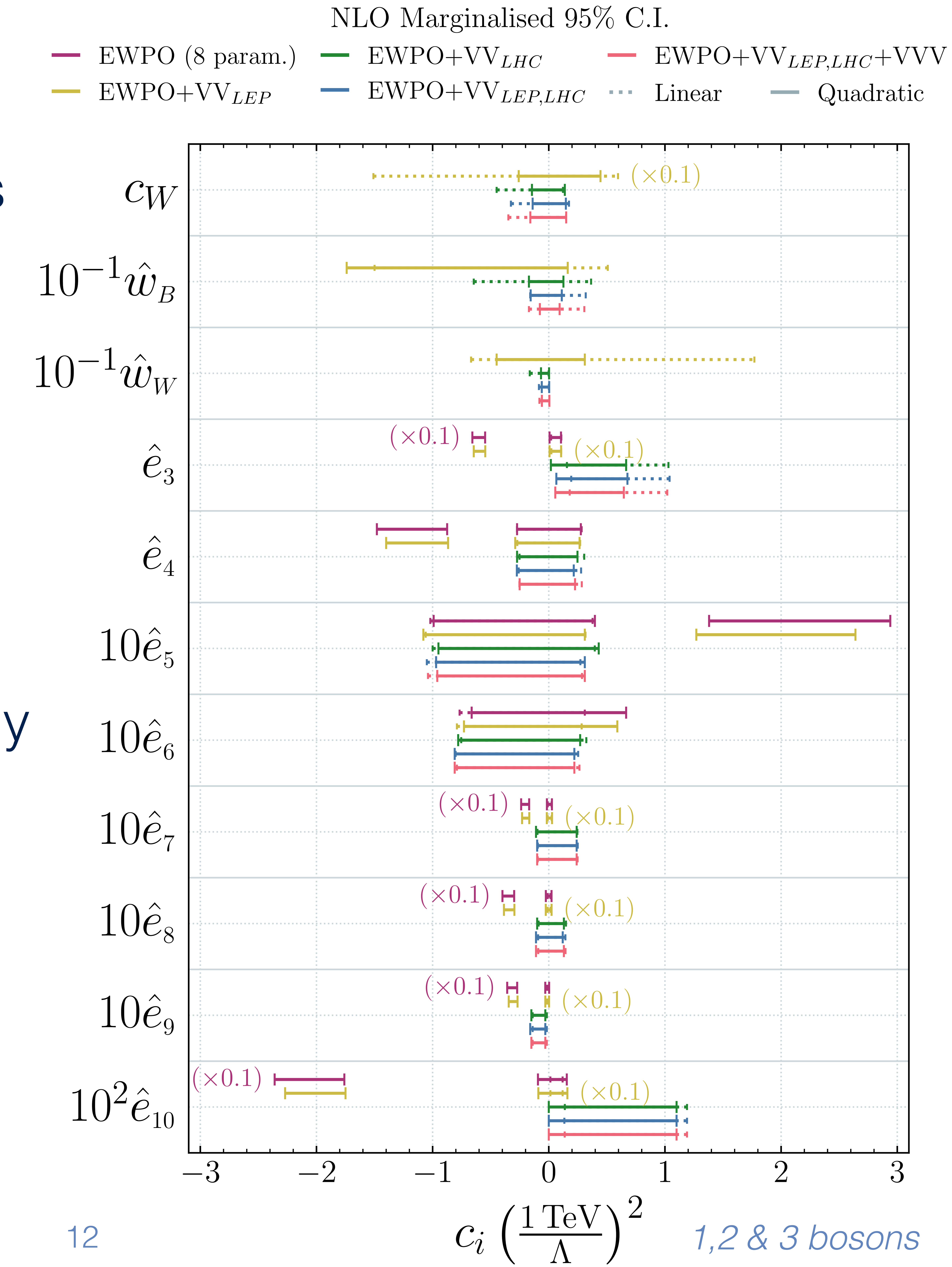
## LEP WW has little impact

## LHC VV improves significantly

- Lifts secondary minima
- No further impact from VVV



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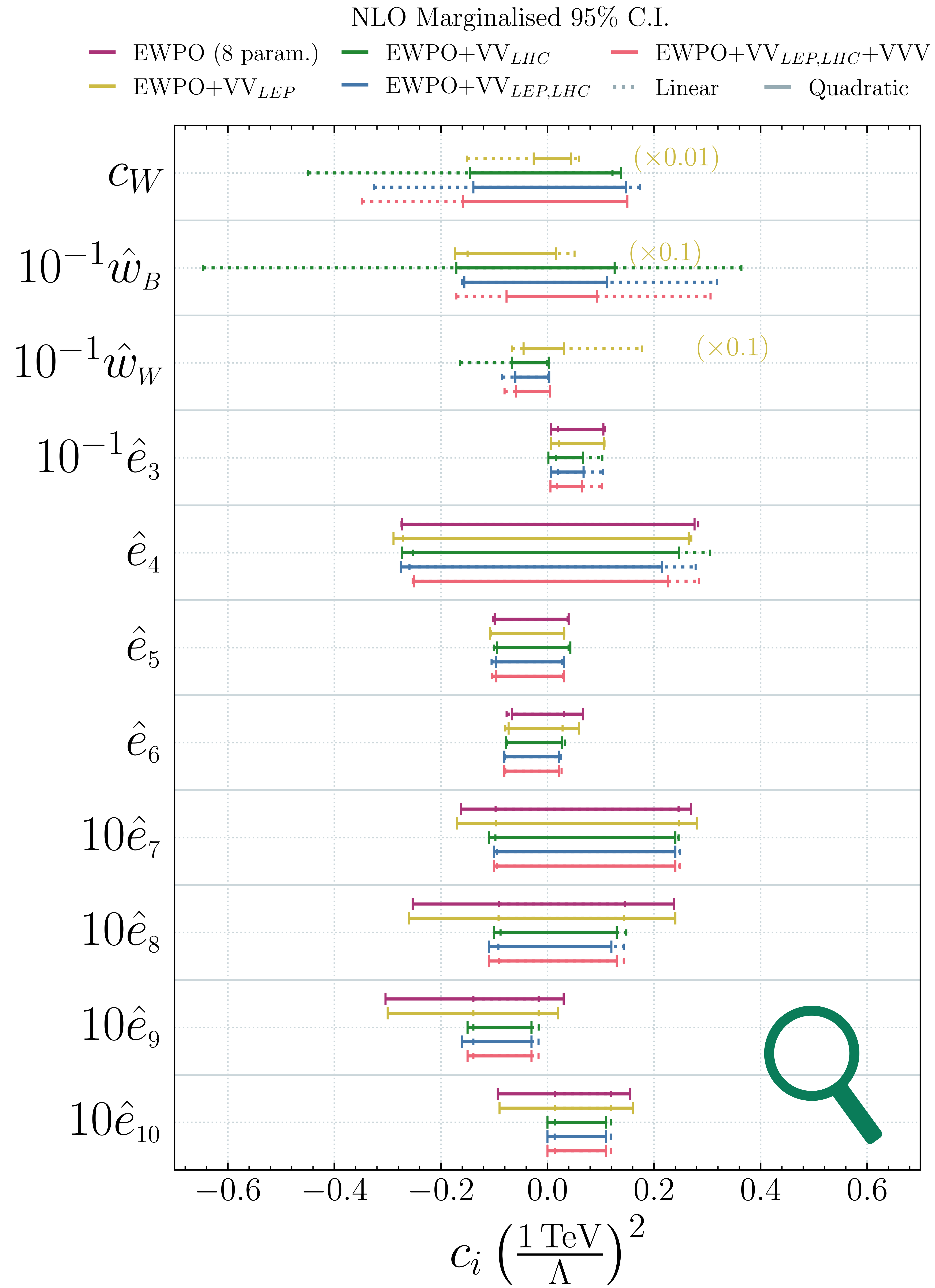
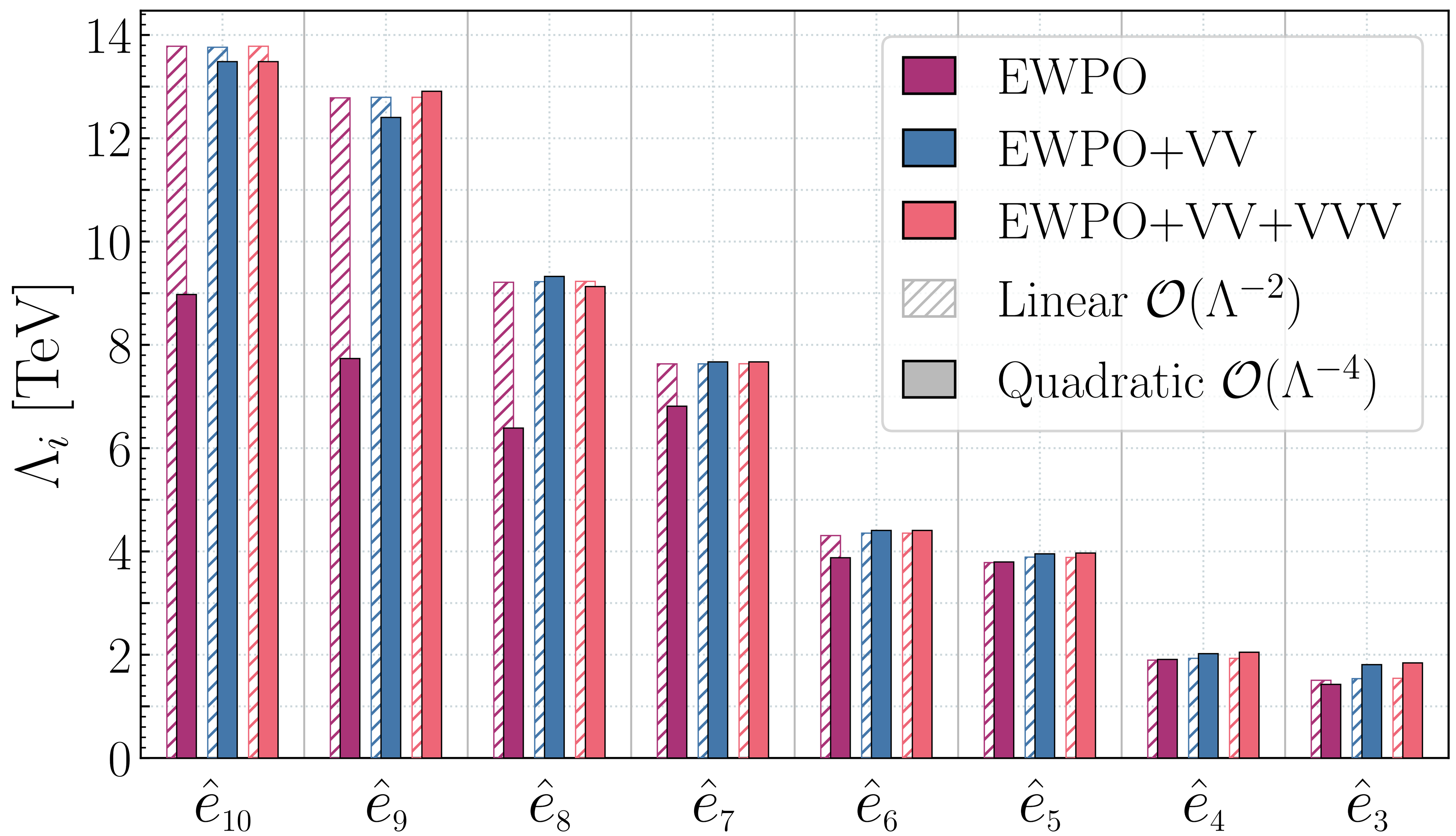


NLO Marginalised 95% C.I.
EWPO (8 param.)
EWPO+VV$_{LHC}$
EWPO+VV$_{LEP,LHC}$+VVV
EWPO+VV$_{LEP}$
EWPO+VV$_{LEP,LHC}$
Linear
Quadratic
$c_W$
(×0.01)
$10^{-1}\hat{w}_B$
(×0.1)
$10^{-1}\hat{w}_W$
(×0.1)
$10^{-1}\hat{e}_3$
$\hat{e}_4$
$\hat{e}_5$
$\hat{e}_6$
$10\hat{e}_7$
$10\hat{e}_8$
$10\hat{e}_9$
$10\hat{e}_{10}$
−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
$c_i \left(\frac{1\,\text{TeV}}{\Lambda}\right)^2$

# Other $\hat{e}_i$?

$$\Lambda_i = \left(\Delta\hat{e}_i^{95}\right)^{-\frac{1}{2}}$$



K. Mimasu - CATCH22+2 - 05/05/2024

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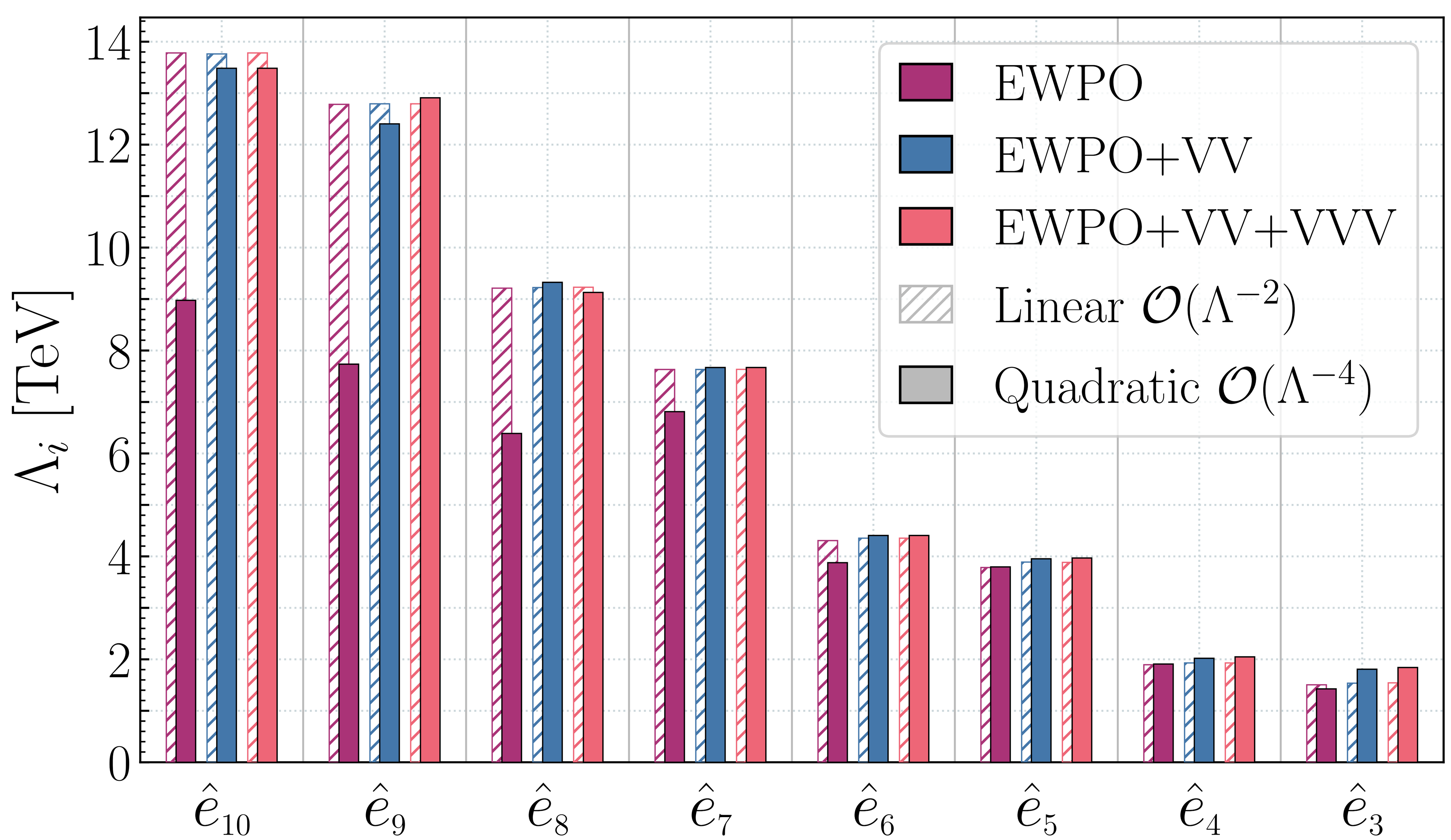
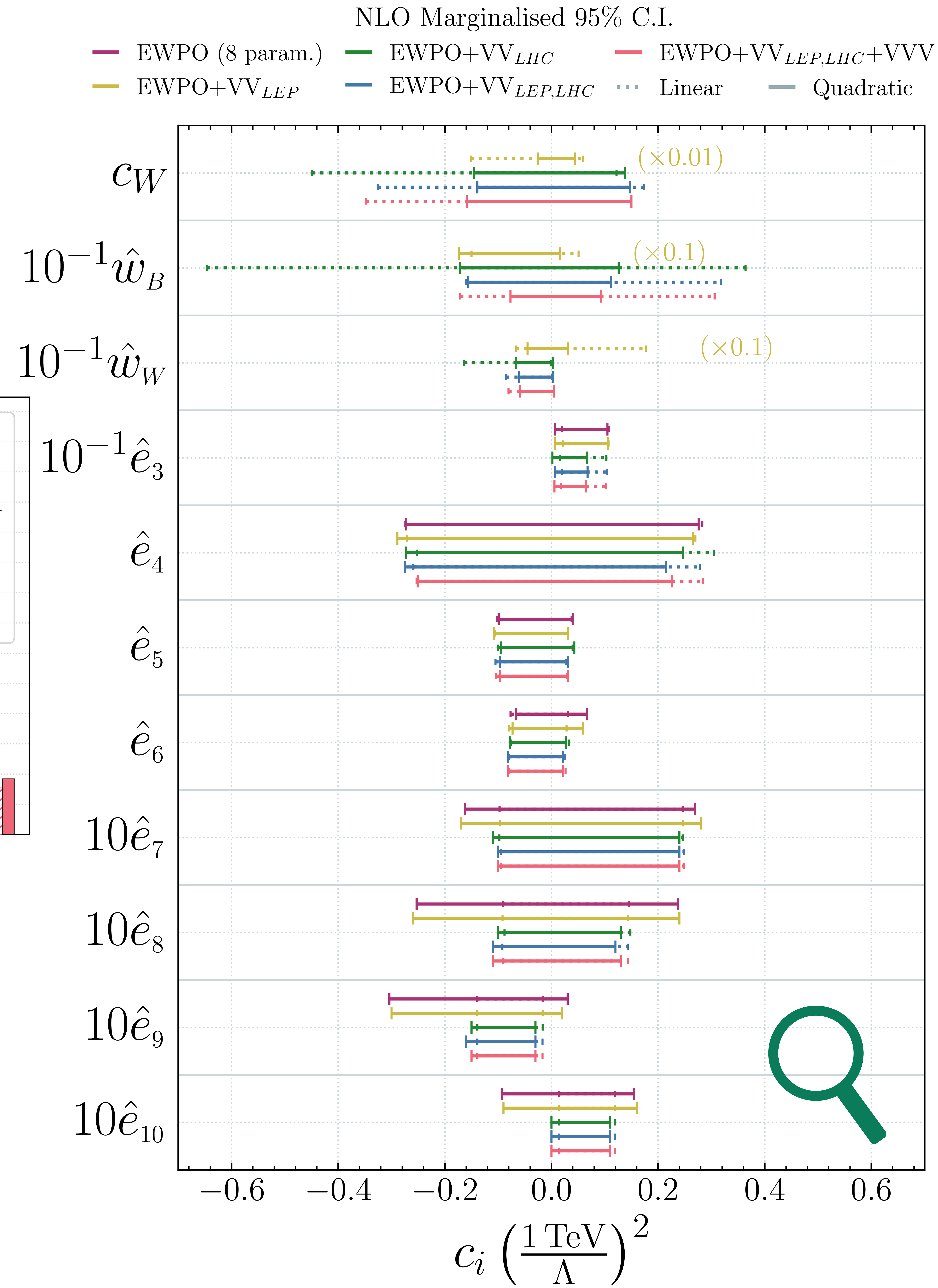



LHC data is crucial in solidifying the EFT validity in these directions

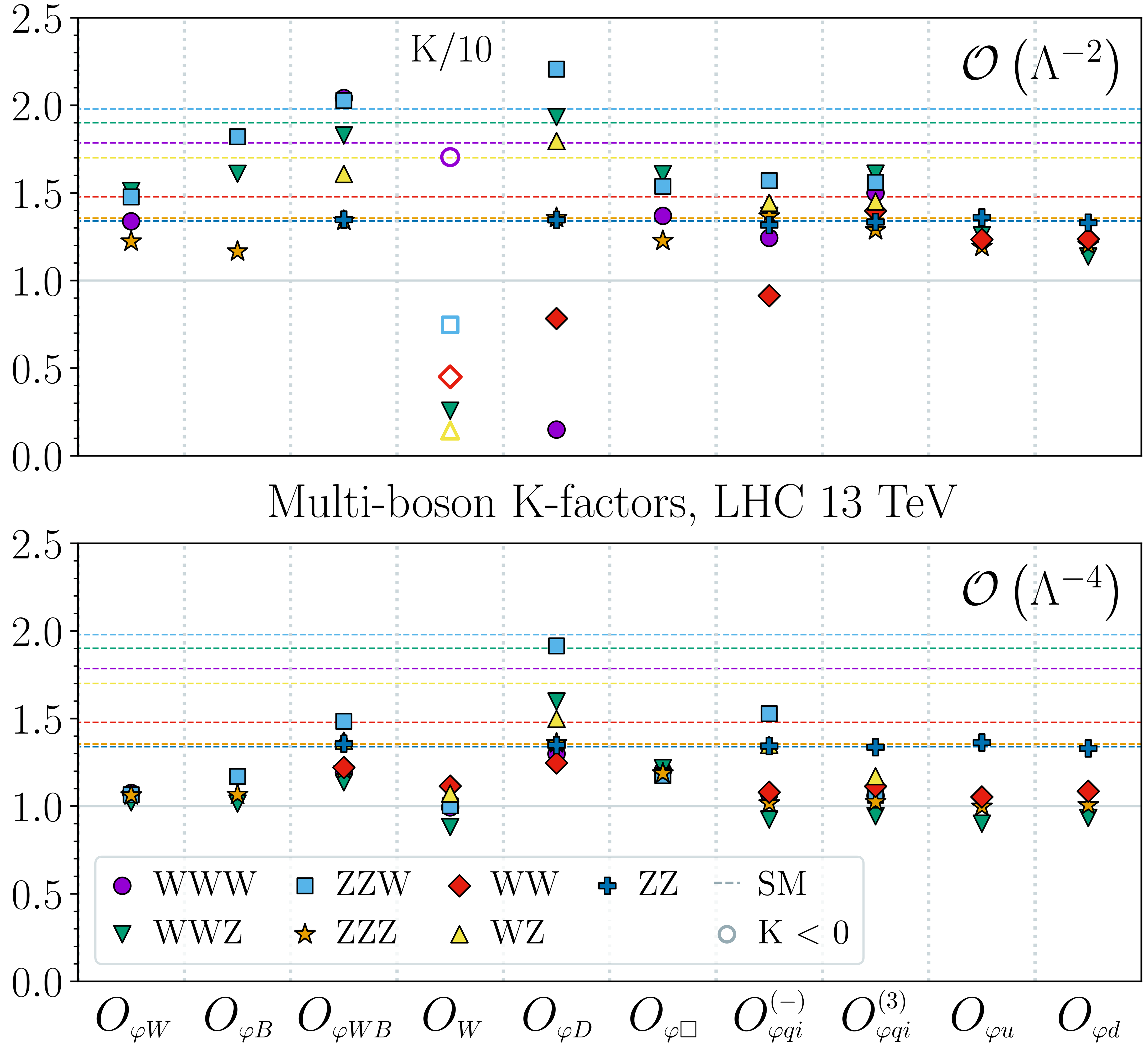


# NLO vs LO

https://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO
[Degrande et al.; 2008.11743]

## **SMEFTatNLO**: QCD corrections to SMEFT predictions

------ : SM K-factor ● : $c_i$ K-factor



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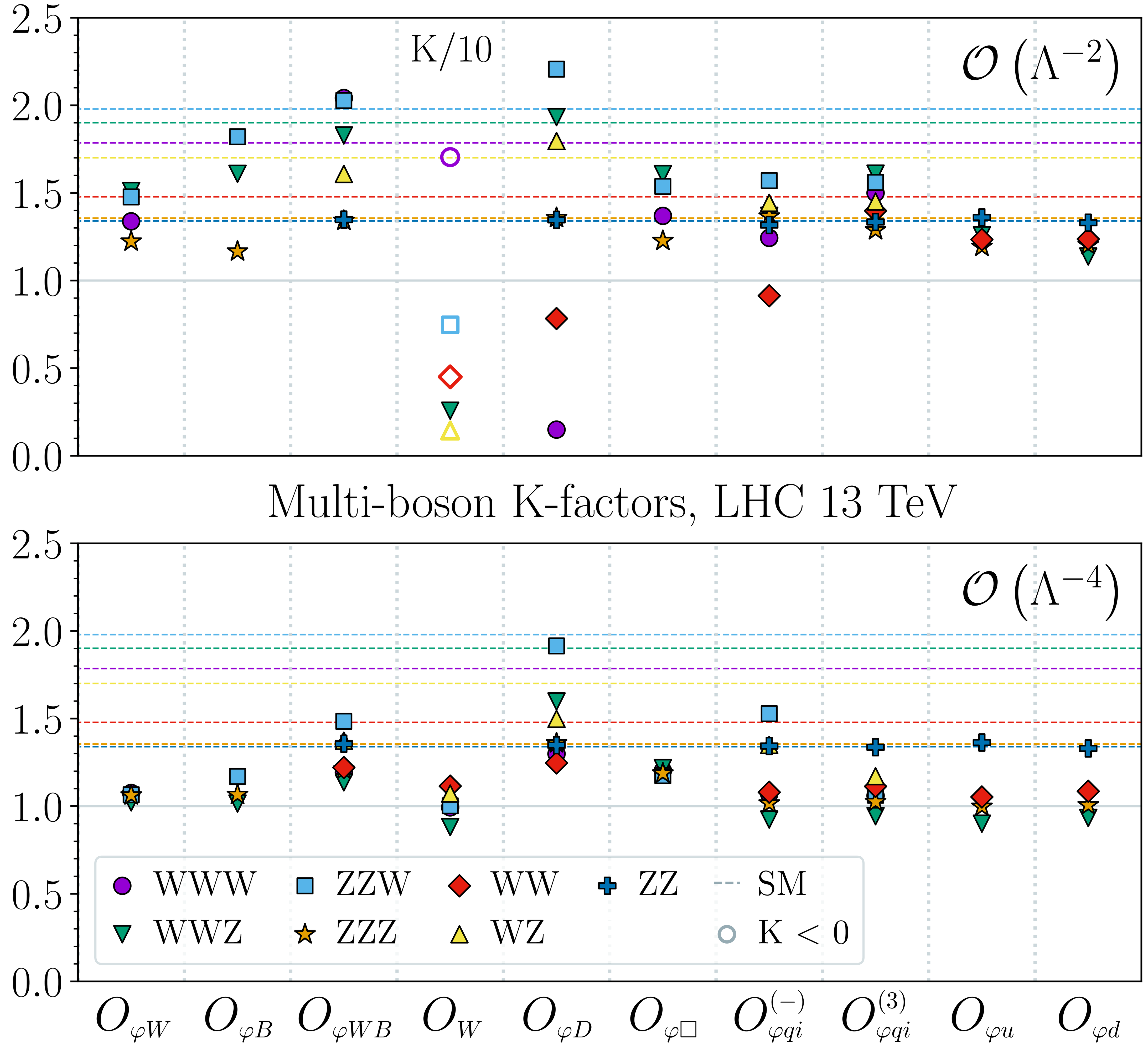
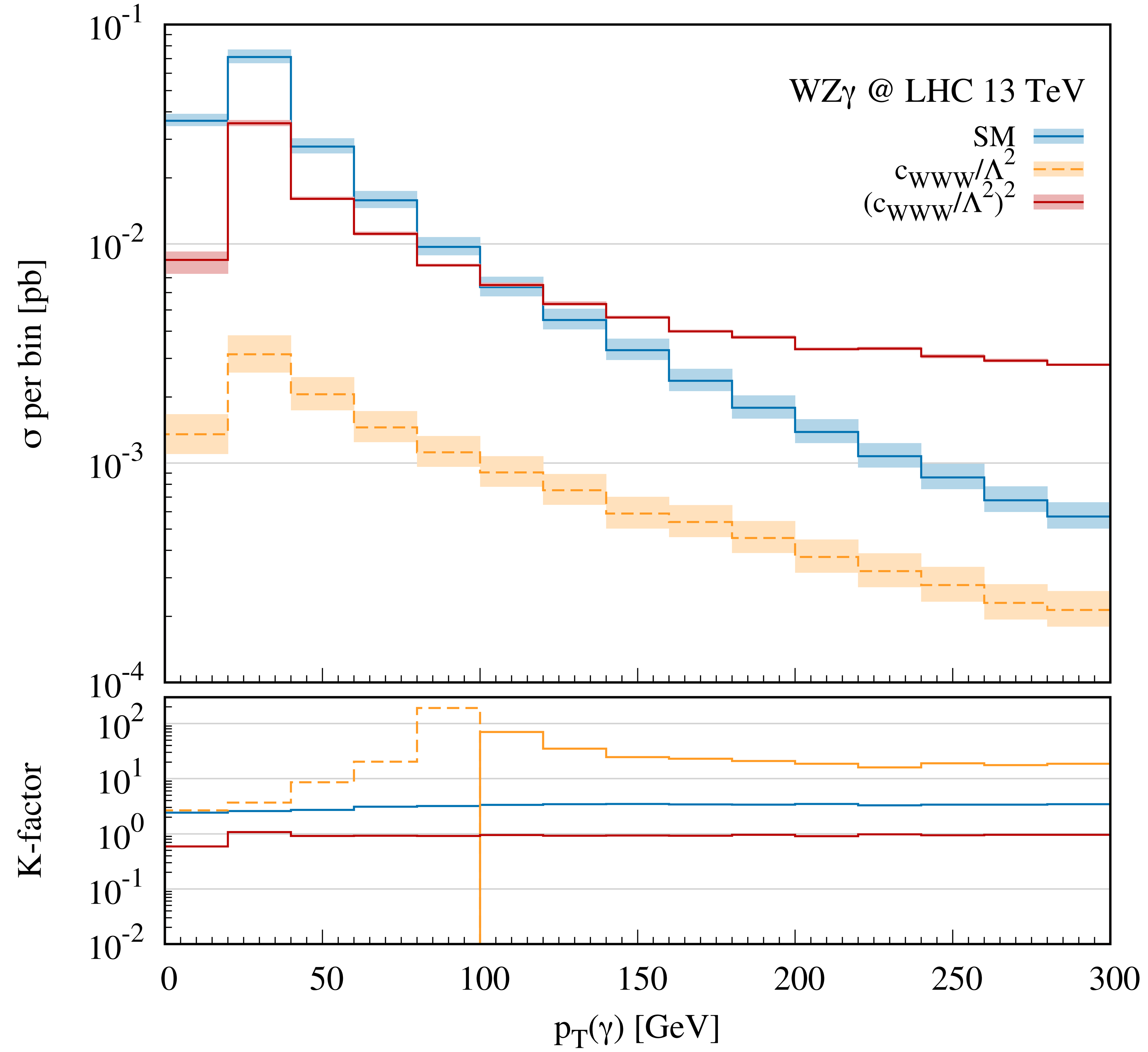



*TGC operator: $c_W$*



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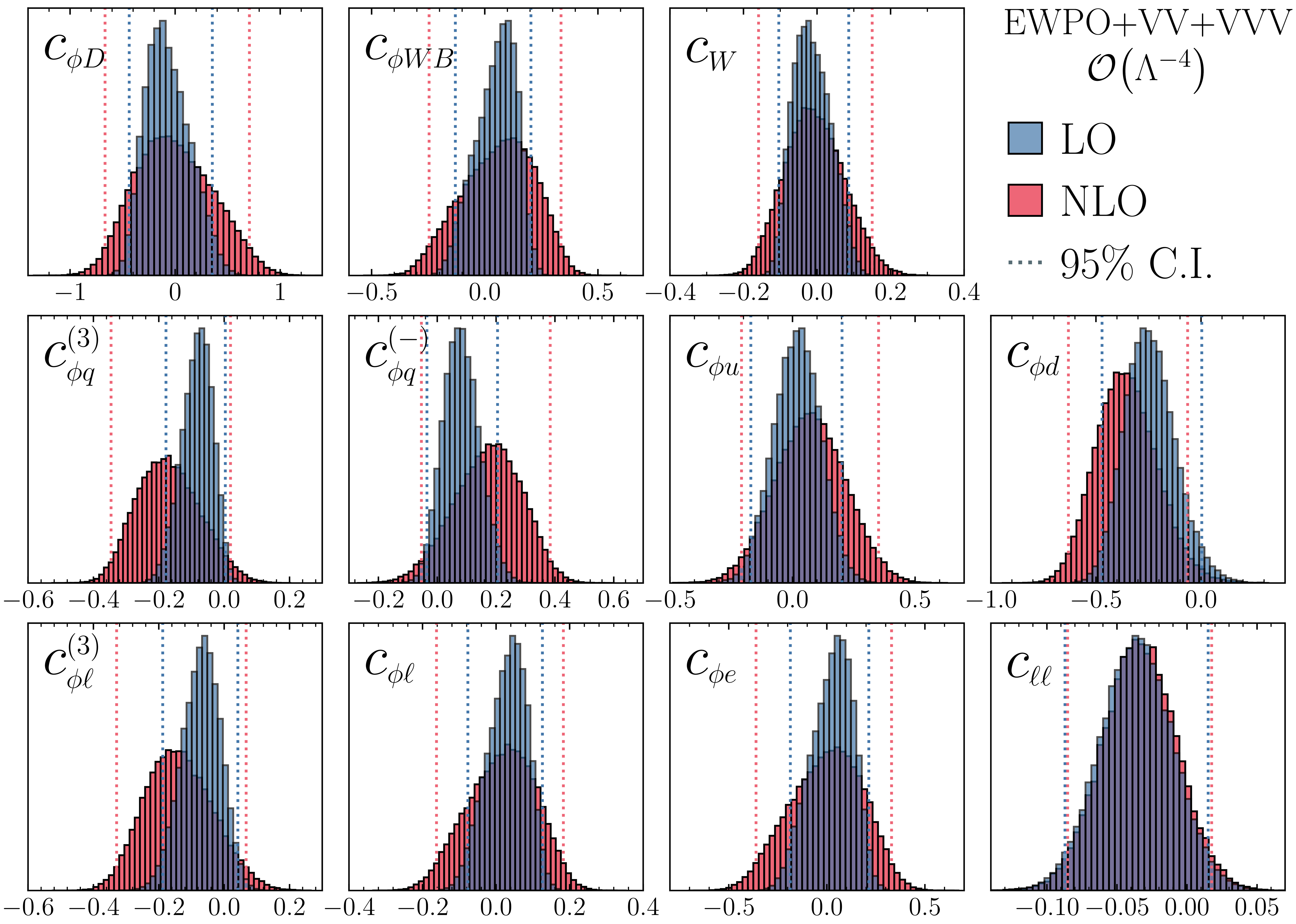
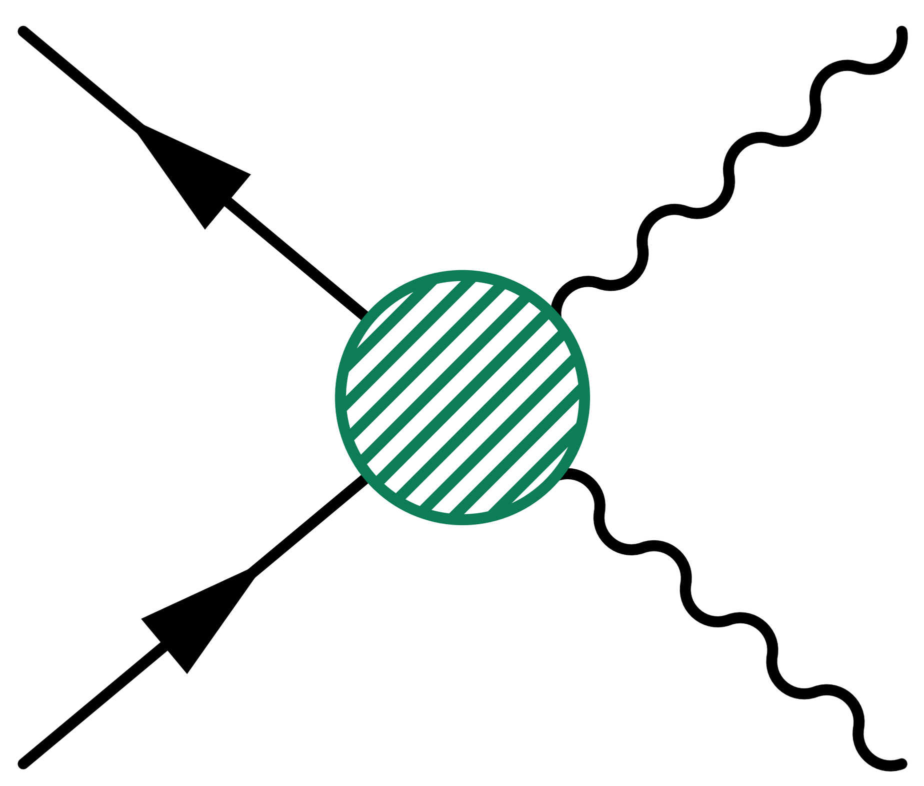


$c_{\phi D}$
$c_{\phi WB}$
$c_W$
EWPO+VV+VVV
$\mathcal{O}(\Lambda^{-4})$
LO
NLO
95% C.I.
$c_{\phi q}^{(3)}$
$c_{\phi q}^{(-)}$
$c_{\phi u}$
$c_{\phi d}$
$c_{\phi \ell}^{(3)}$
$c_{\phi \ell}$
$c_{\phi e}$
$c_{\ell\ell}$

# $pp \to VV$ @ NLO

[Campanario, Englert & Spannowsky; PRD82 (2010) 054015 & PRD 83 (2011) 074009]
[Campanario, Roth & Zeppenfeld; PRD 91 (2015) 054039]
[Baglio et al.; PRD 101 (2020) 115004]



$$\mathscr{A}_{EFT} \sim \frac{p_T^2}{\Lambda^2}$$

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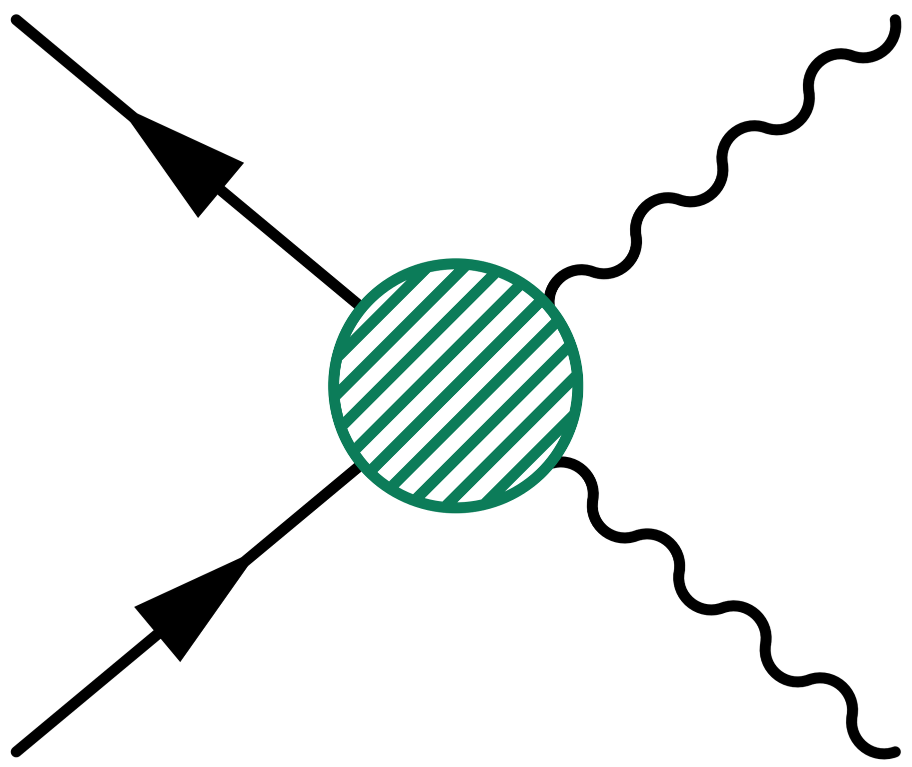

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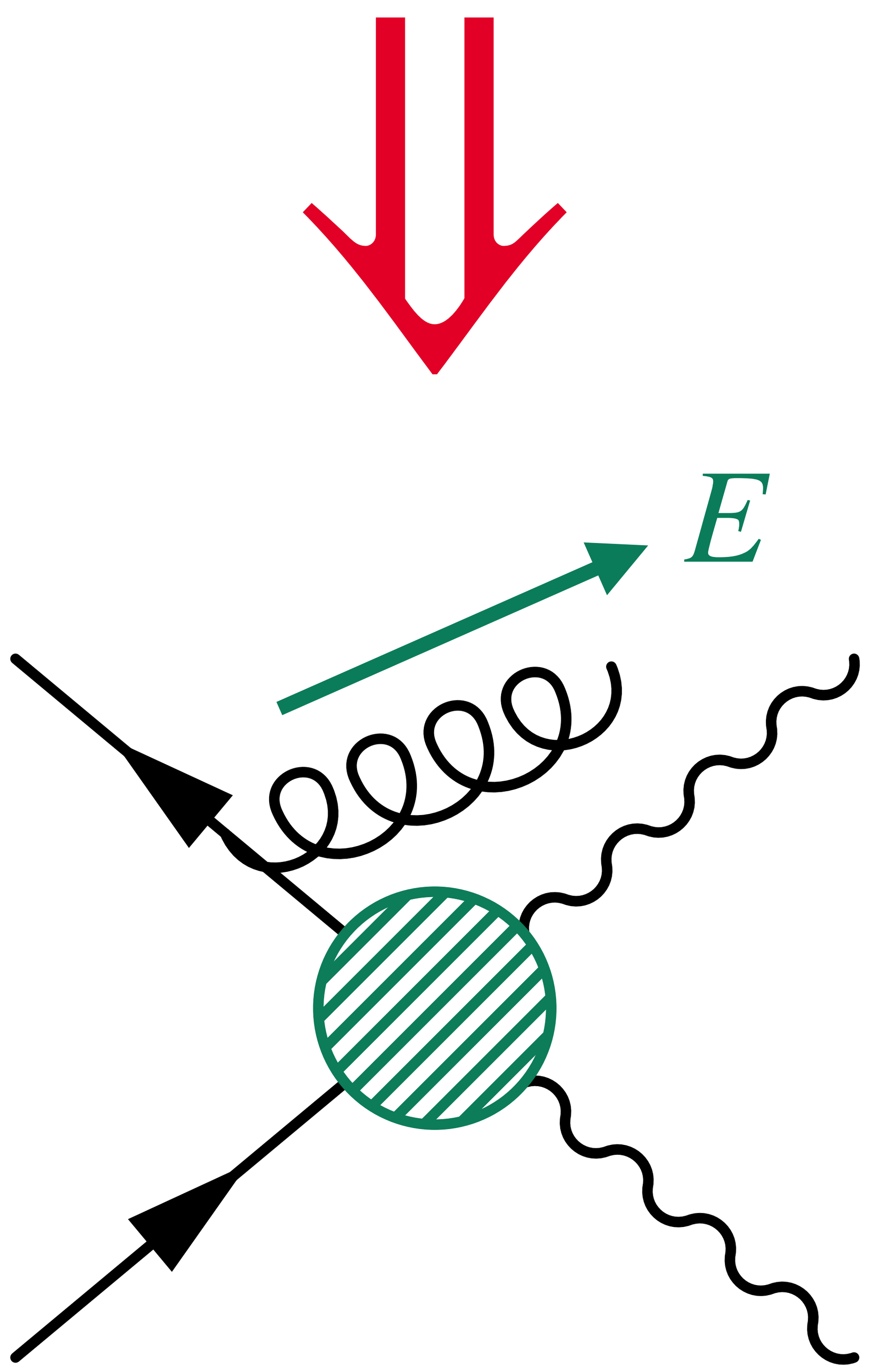

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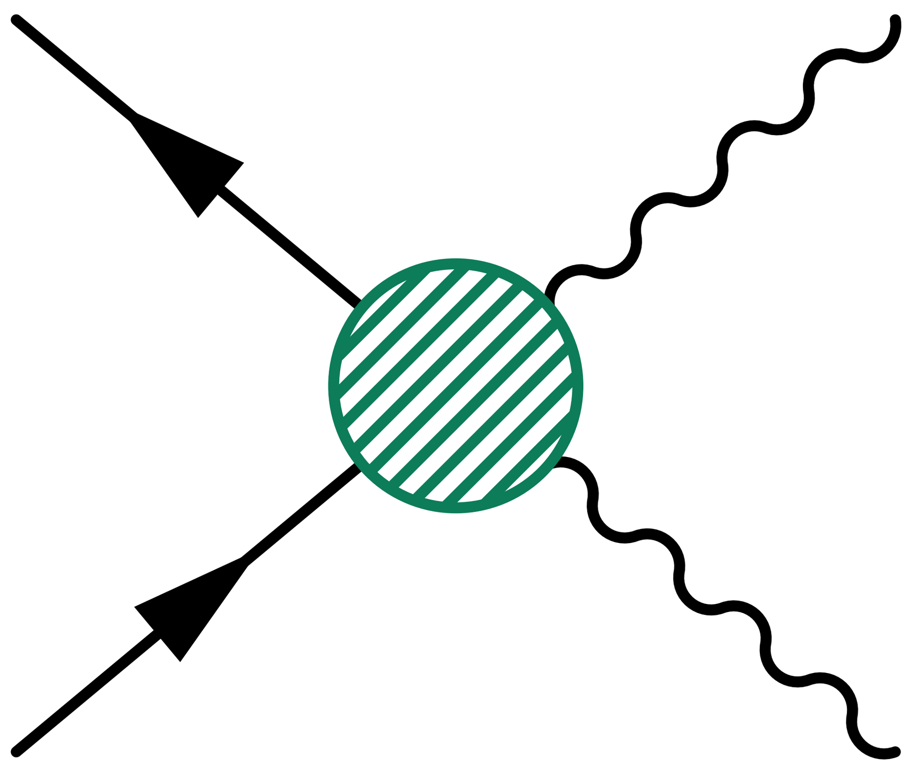

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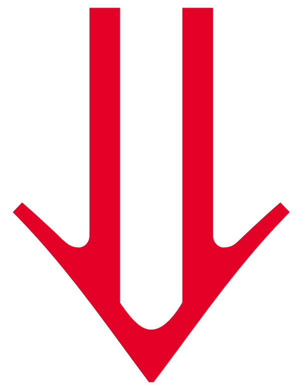

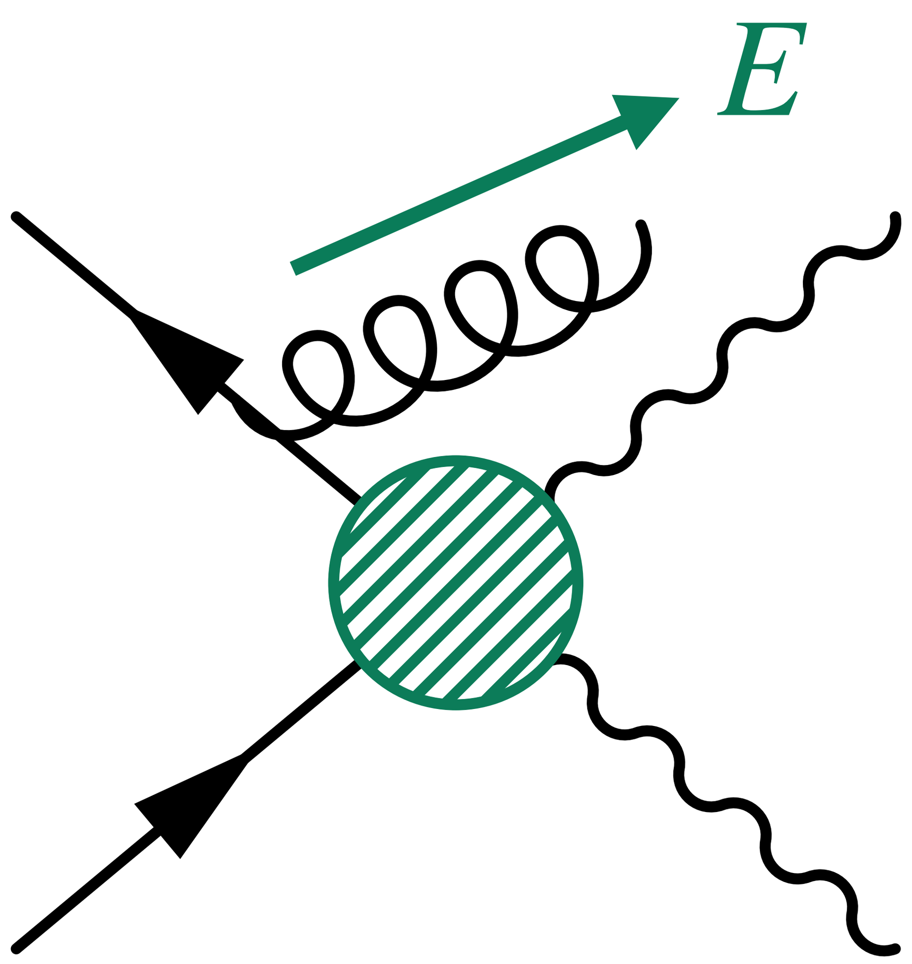


$$\mathscr{A}_{EFT} \sim \frac{q^2 < p_T^2}{\Lambda^2}$$

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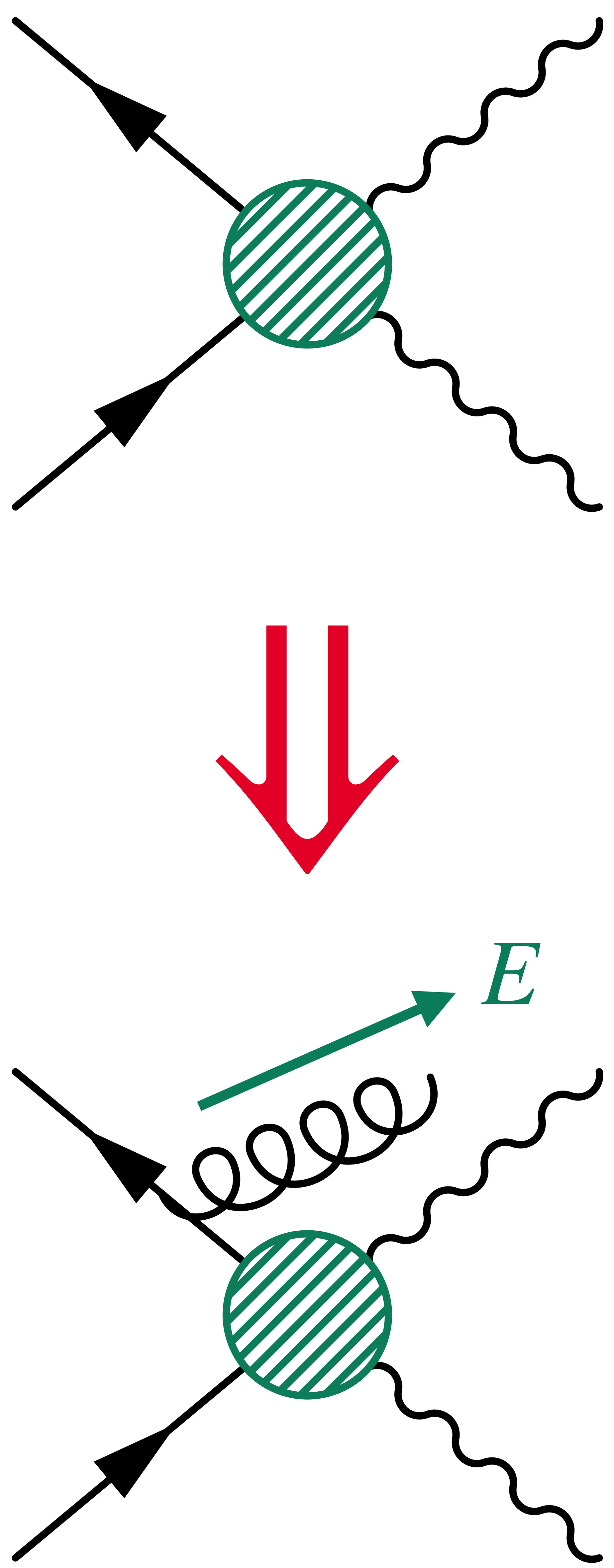


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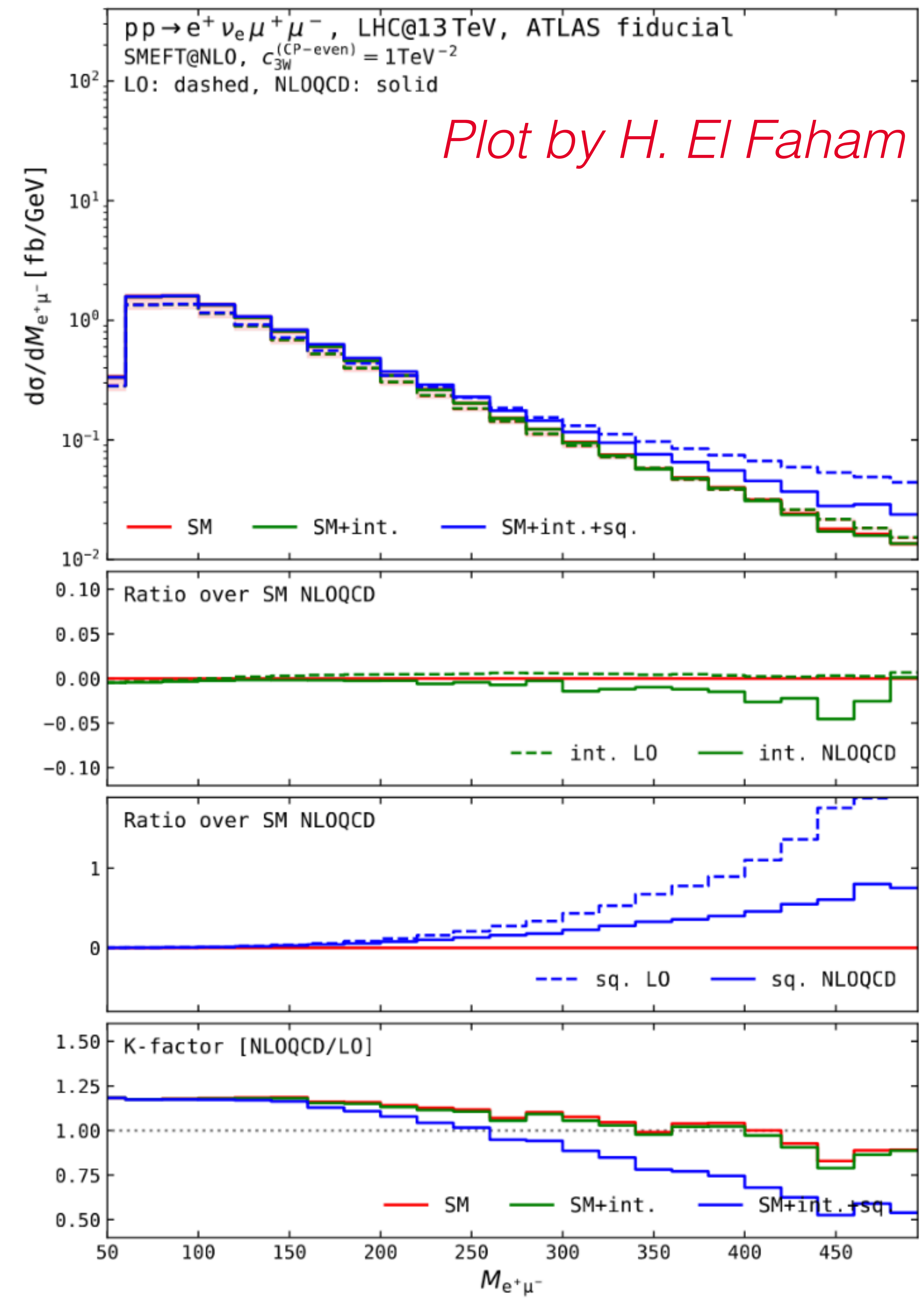


(b) ATLAS fiducial

# Conclusions

Minimal global analysis of indirect NP sensitivity of triboson

- Reference sensitivity: EWPO & LEP & LHC diboson data
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## More data needed!

- Higgs, VBS, other rare EW processes?

# Backup

# SMEFT: SM v2.0

$(\bar{F}\sigma_{\mu\nu}f\tilde{\varphi})V^{\mu\nu}$

$(\bar{f}\gamma_\mu f)(\bar{F}\gamma^\mu F)$

$(\bar{F}f\tilde{\varphi})(\varphi^\dagger\varphi)$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,D} \frac{c_i^{(D)}\mathcal{O}_i^{(D)}}{\Lambda^{D-4}}$$

$(\varphi^\dagger\varphi)^3$

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

$(\varphi^\dagger\varphi)V^{\mu\nu}V_{\mu\nu}$

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*BSM particle masses* $M$ ⇔ *Generic new physics scale* $\Lambda$

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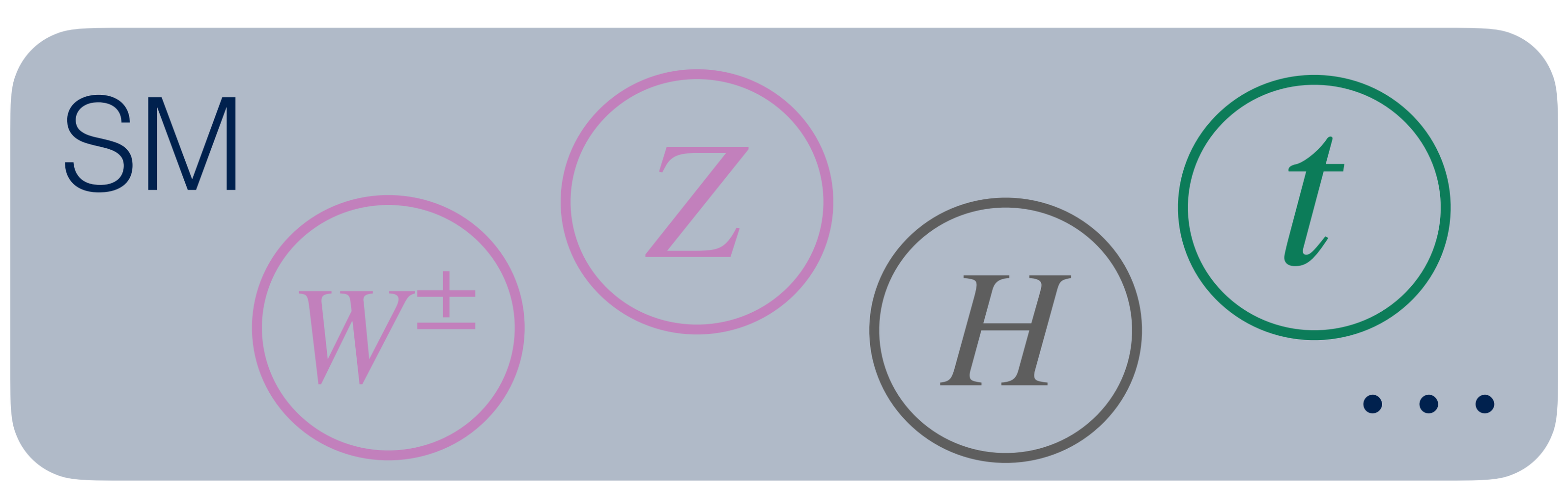
*BSM particle masses $M$* $\Leftrightarrow$ *Generic new physics scale $\Lambda$*

*Taylor expansion of $\mathscr{A}_{BSM}$* $\Leftrightarrow$ *Tower of operators $\mathcal{O}_i^{(D)}$*

$\mathcal{O}_i^{(D)} \supset$




*Low energy (SM) fields & symmetries*

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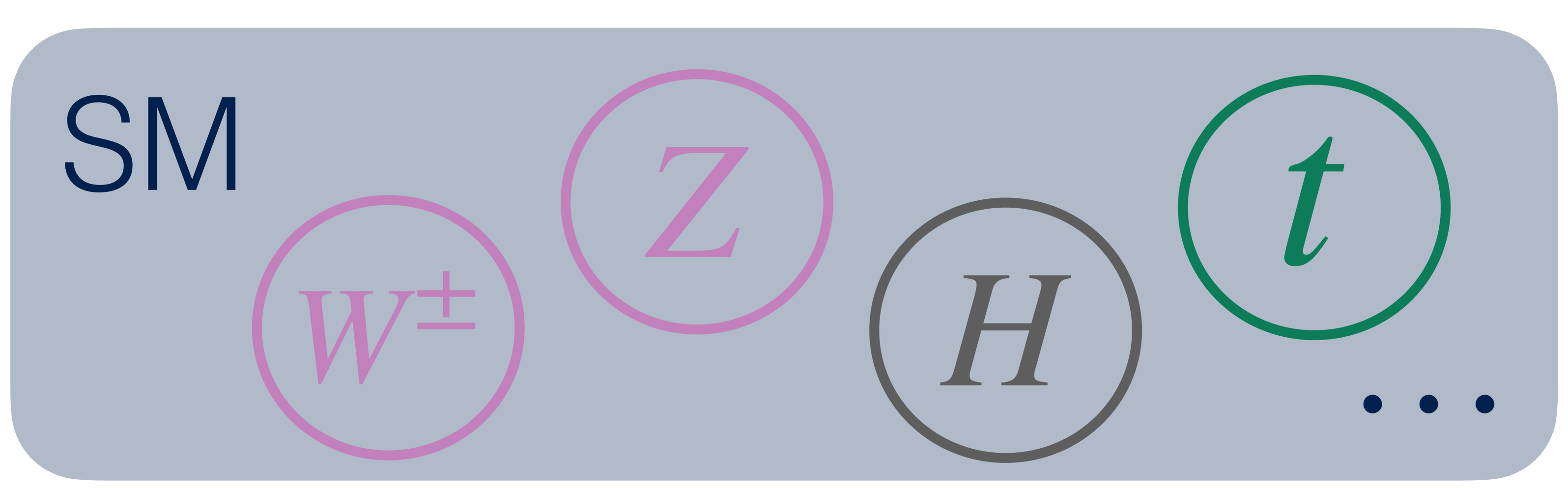
$\mathcal{O}_i^{(D)} \supset$ 


*Low energy (SM) fields & symmetries*

*Model parameters $\{g^i_{\rm BSM}, M_k\}$* ⇔ *Wilson coefficients $\frac{c_j^{(D)}}{\Lambda^{D-4}}(g^i_{\rm BSM}, M_k)$*

*measure $g_i$ : new physics model parameters*

"Matching"

*measure $c_i$ : coupling strengths of new BSM interactions*

# SMEFT interpretation (fits)

$o_n$
*observables*

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

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Improving new physics reach means improving…

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**Global nature**

As many observables as possible

Identify patterns & correlations in fits

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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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*Theory*:

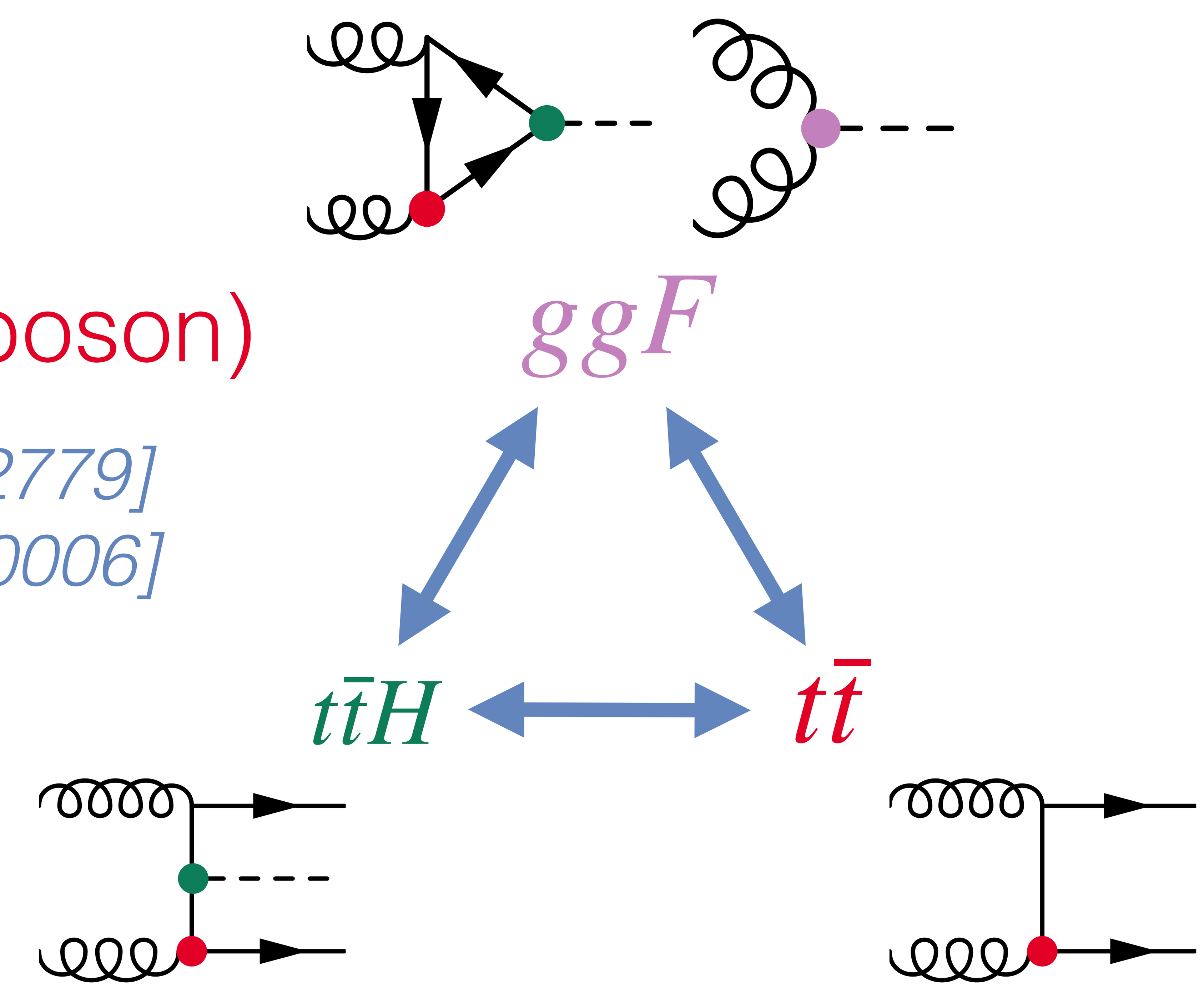
Best available predictions for observables (NLO, NNLO, N3LO,…)

**Interpretation**

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

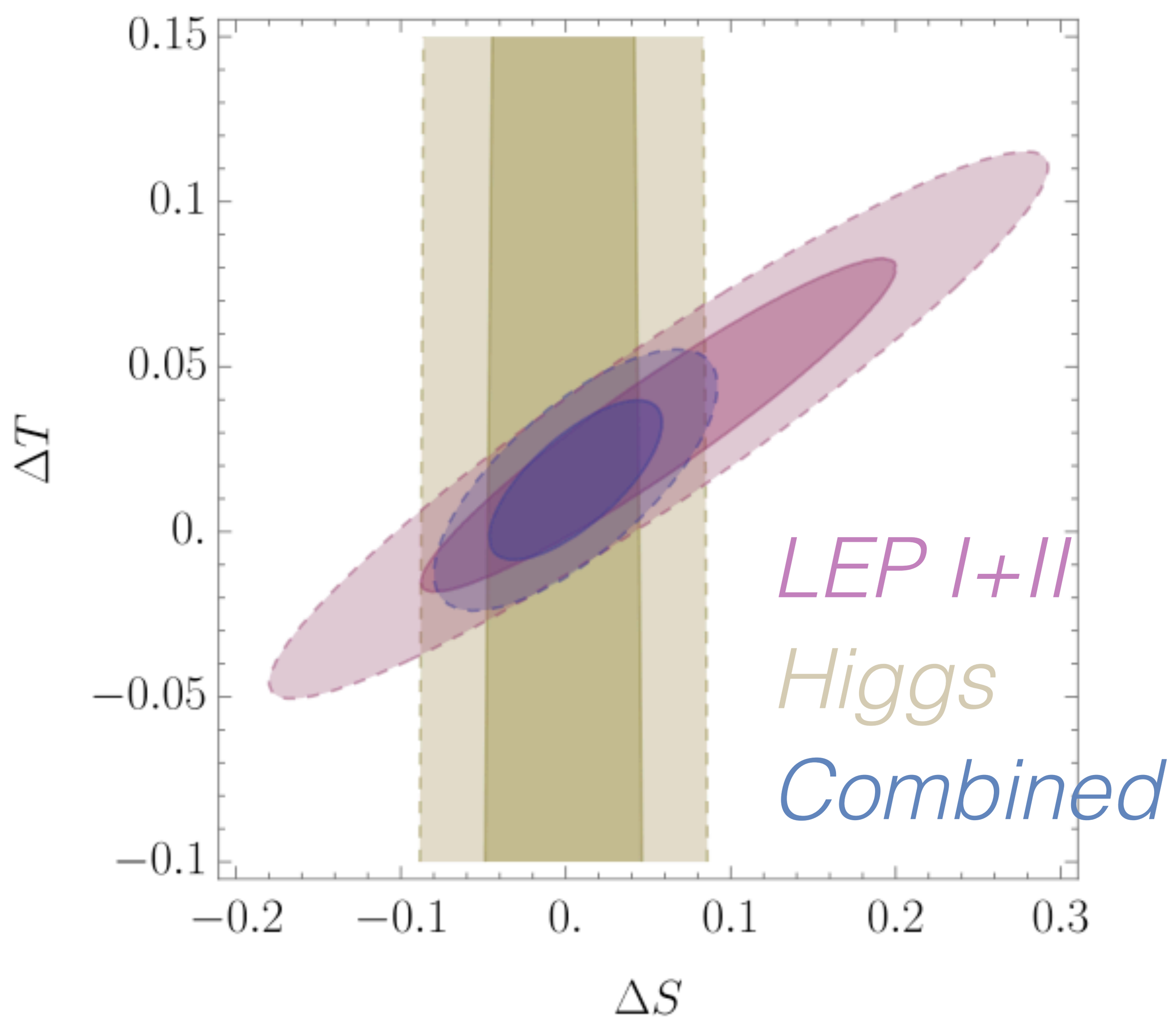
Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

# Interplay




## Higgs & EWPO

*[Ellis et al.; 1803.03252]*



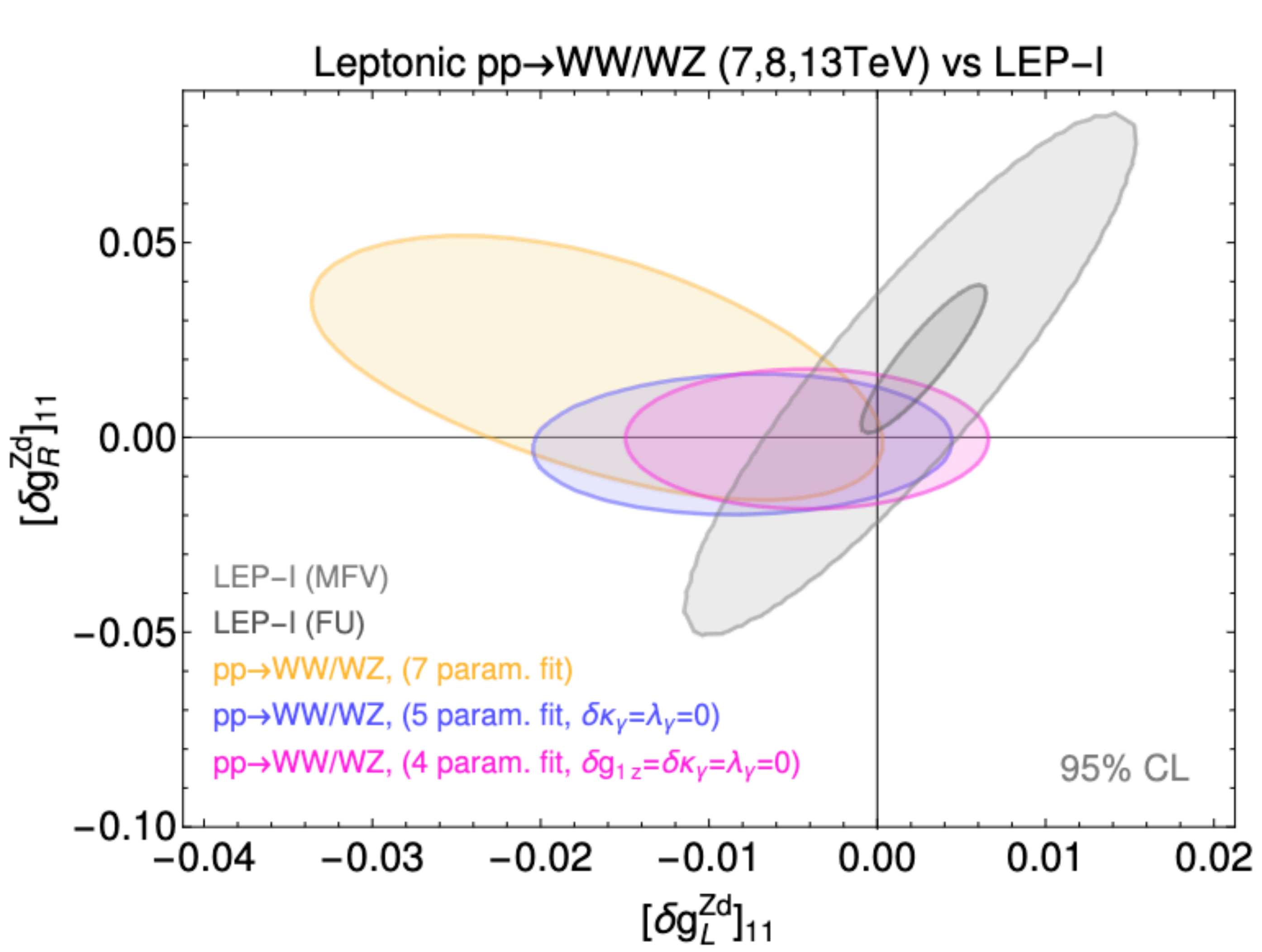

## Top & Higgs (EWPO, Diboson)

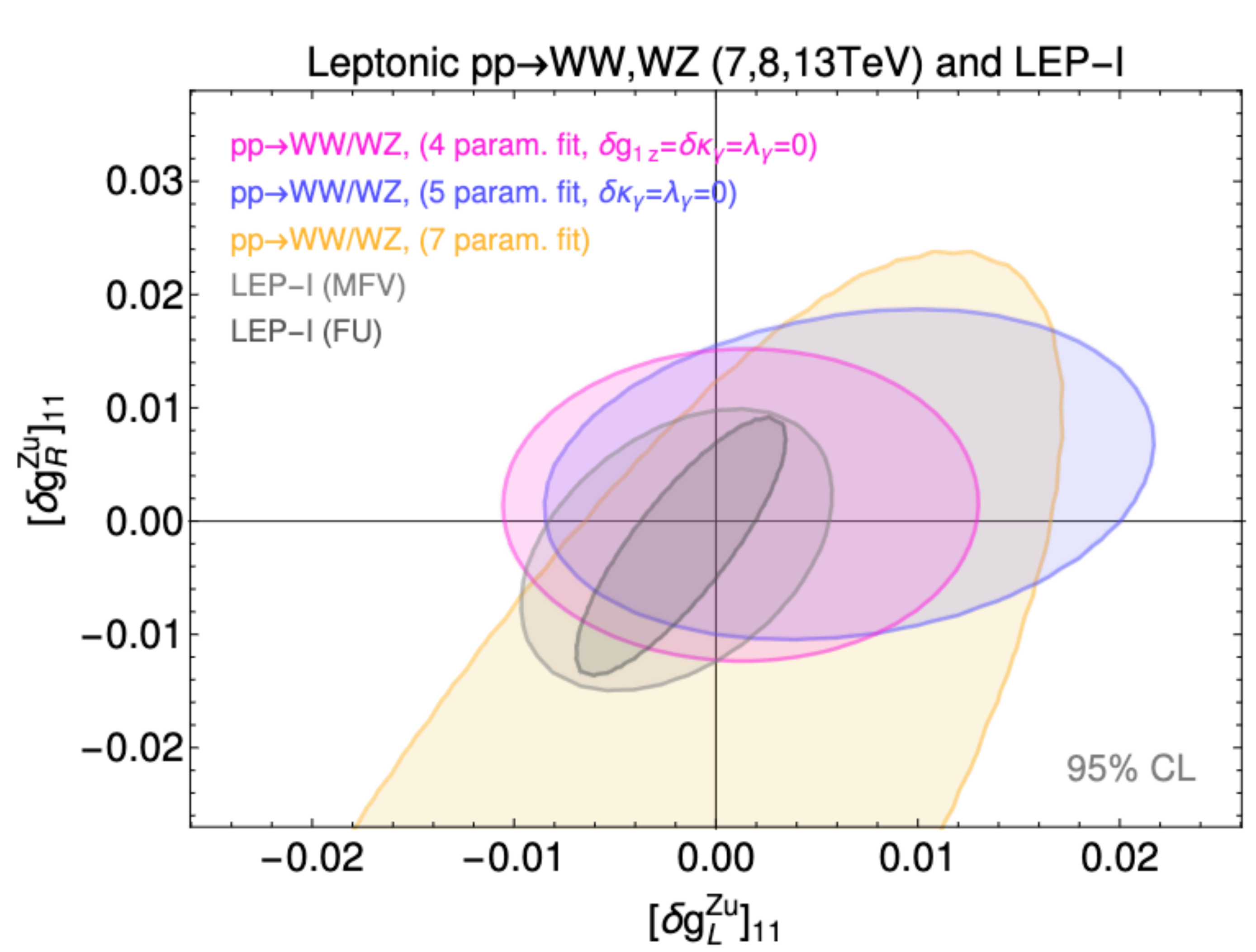
*fitmaker: [Ellis et al.; 2012.02779]*
*SMEFiT: [Ethier et al; 2105.00006]*

**Where does being global matter?**

## Diboson & EWPO

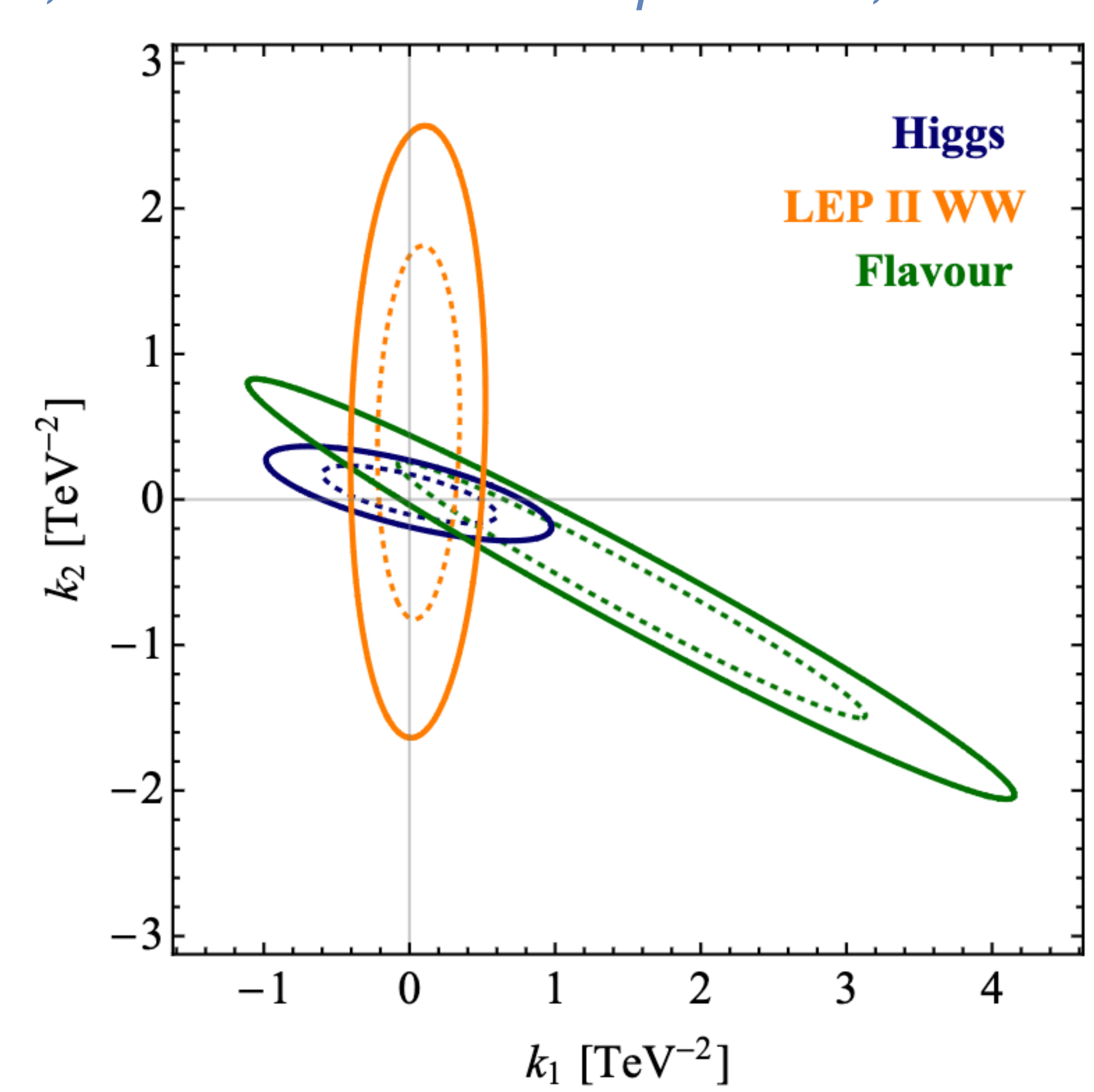
*[Grojean, Montull & Riembau; 1810.05149]*



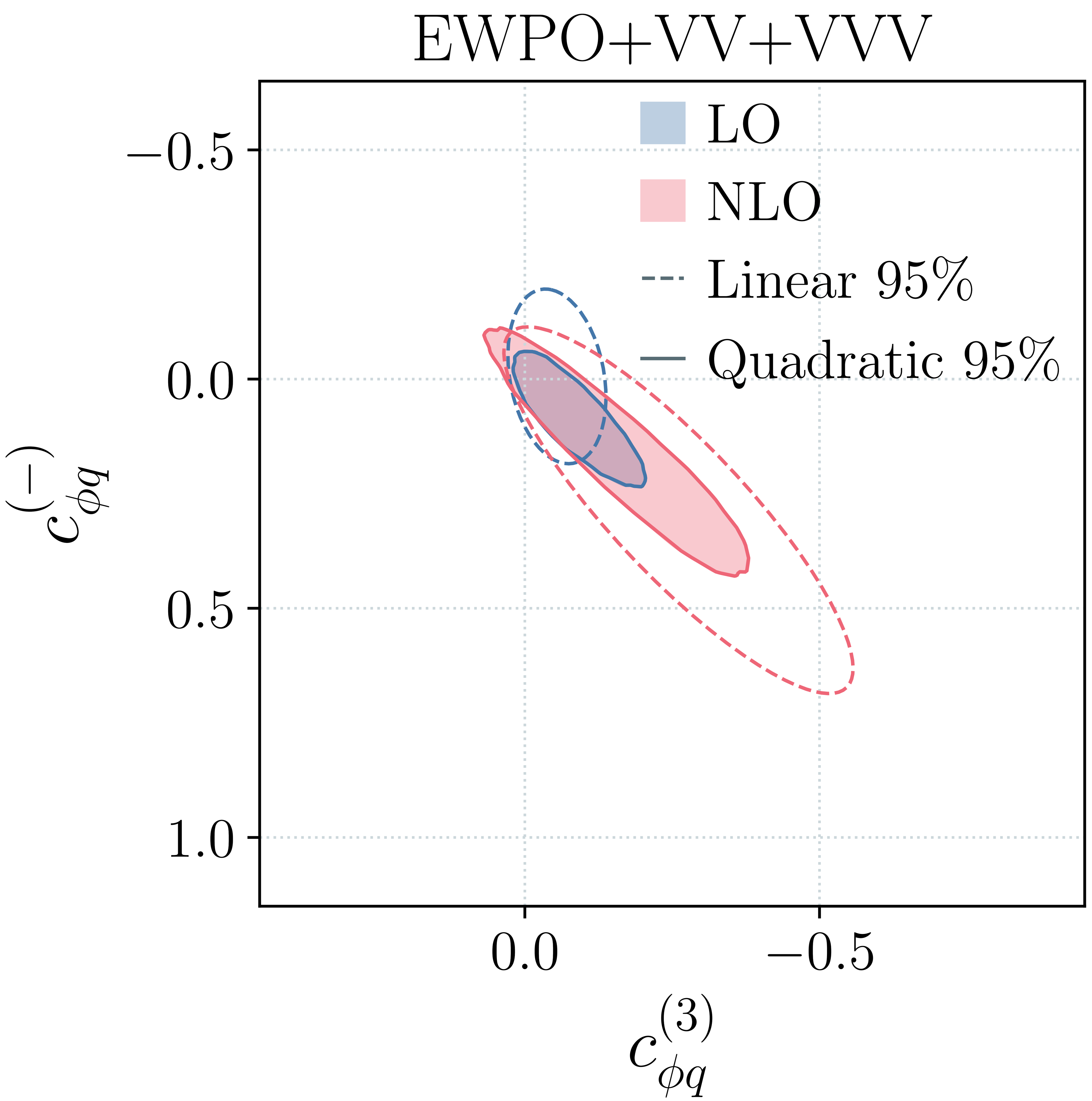



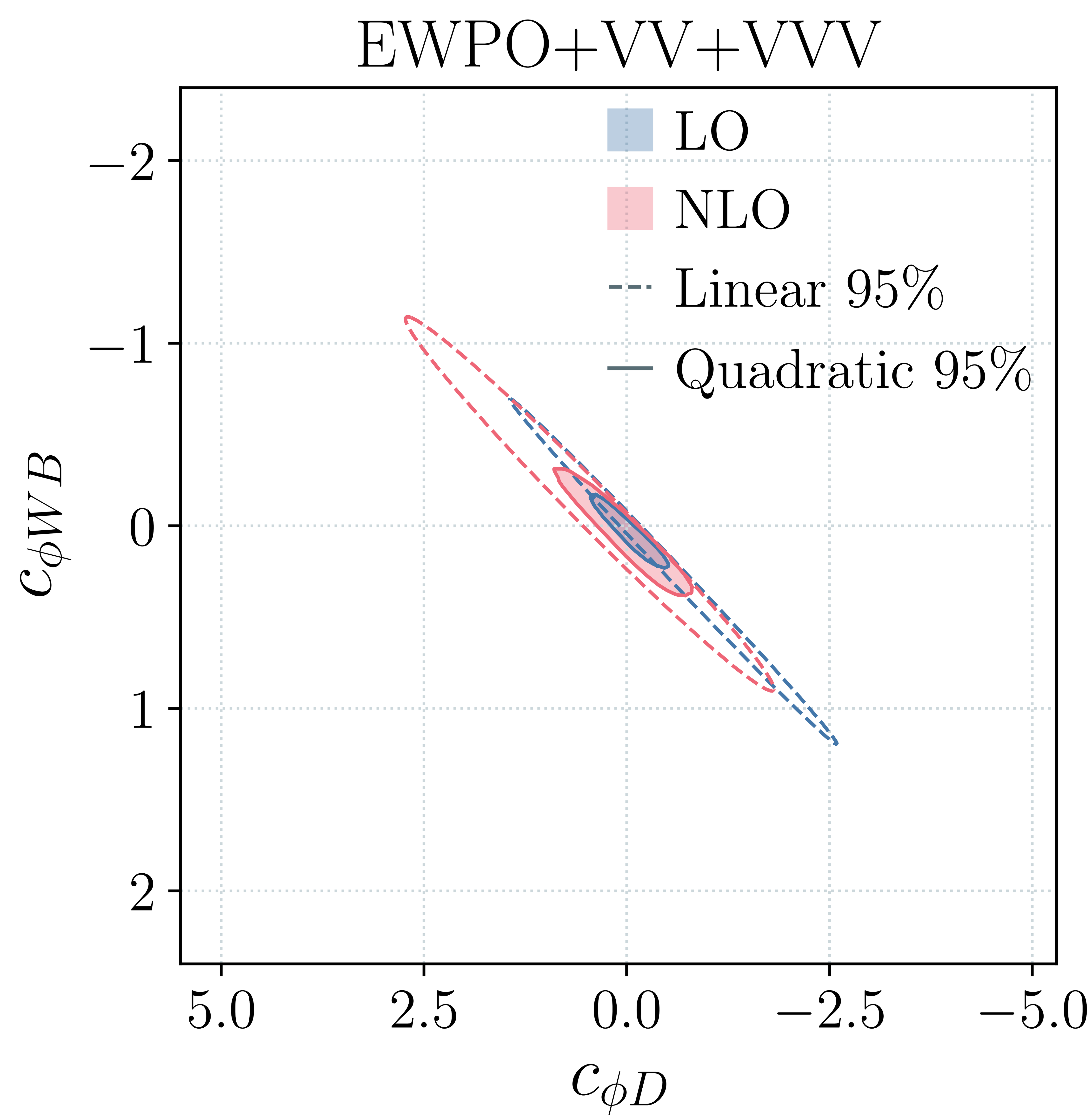

## Flavor, LEP II & Higgs

*[Aoude, Hurth, Renner & Shepherd; 2003.05432]*



# NLO vs LO


EWPO+VV+VVV
LO
NLO
Linear 95%
Quadratic 95%
−0.5
0.0
0.5
1.0
0.0
−0.5
$c_{\phi q}^{(-)}$
$c_{\phi q}^{(3)}$


EWPO+VV+VVV
LO
NLO
Linear 95%
Quadratic 95%
−2
−1
0
1
2
5.0
2.5
0.0
−2.5
−5.0
$c_{\phi WB}$
$c_{\phi D}$