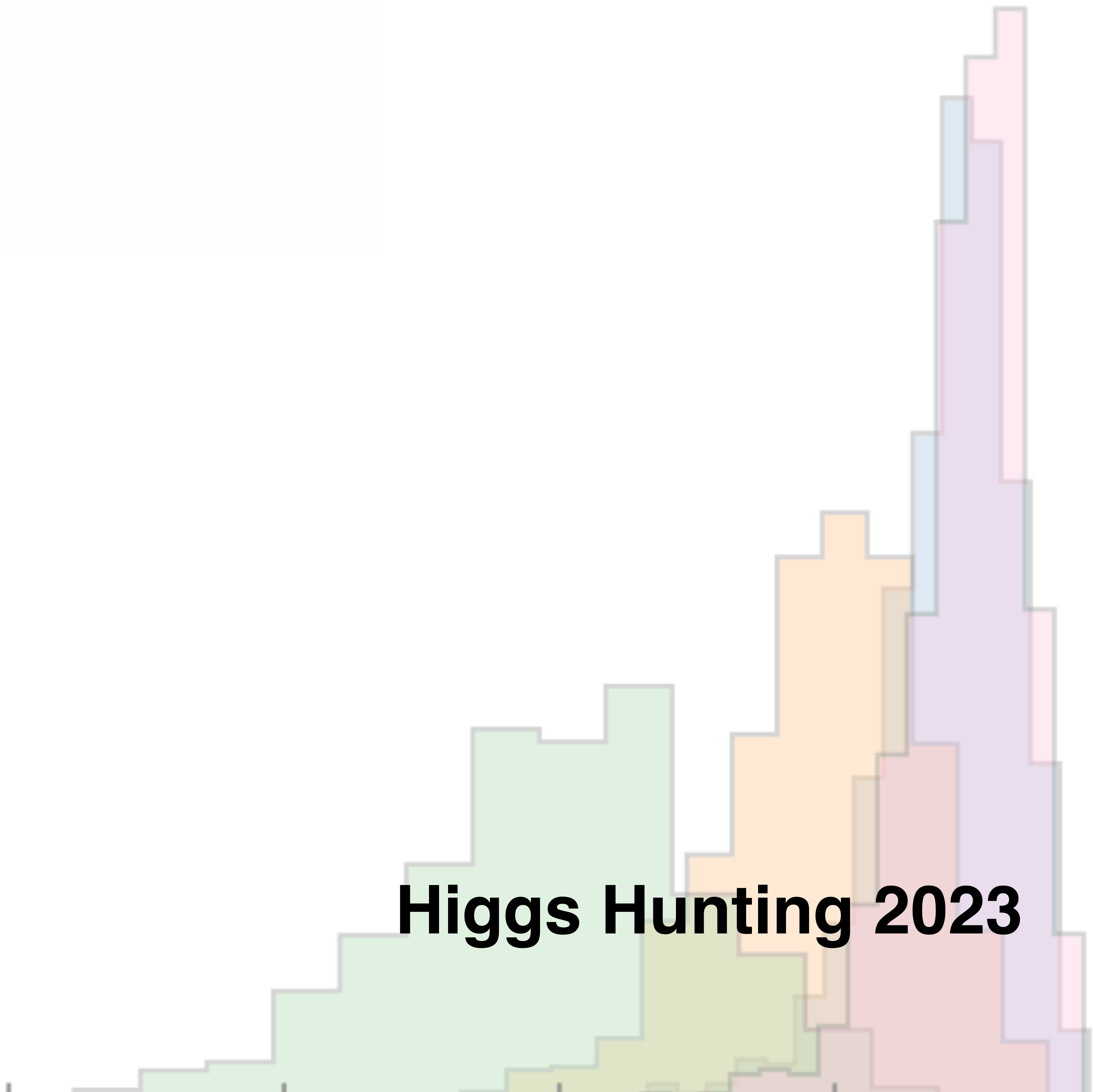
Standard Model Effective Field Theory:

Higgs fits and their interplay with other sectors

Maeve Madigan
Heidelberg University

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



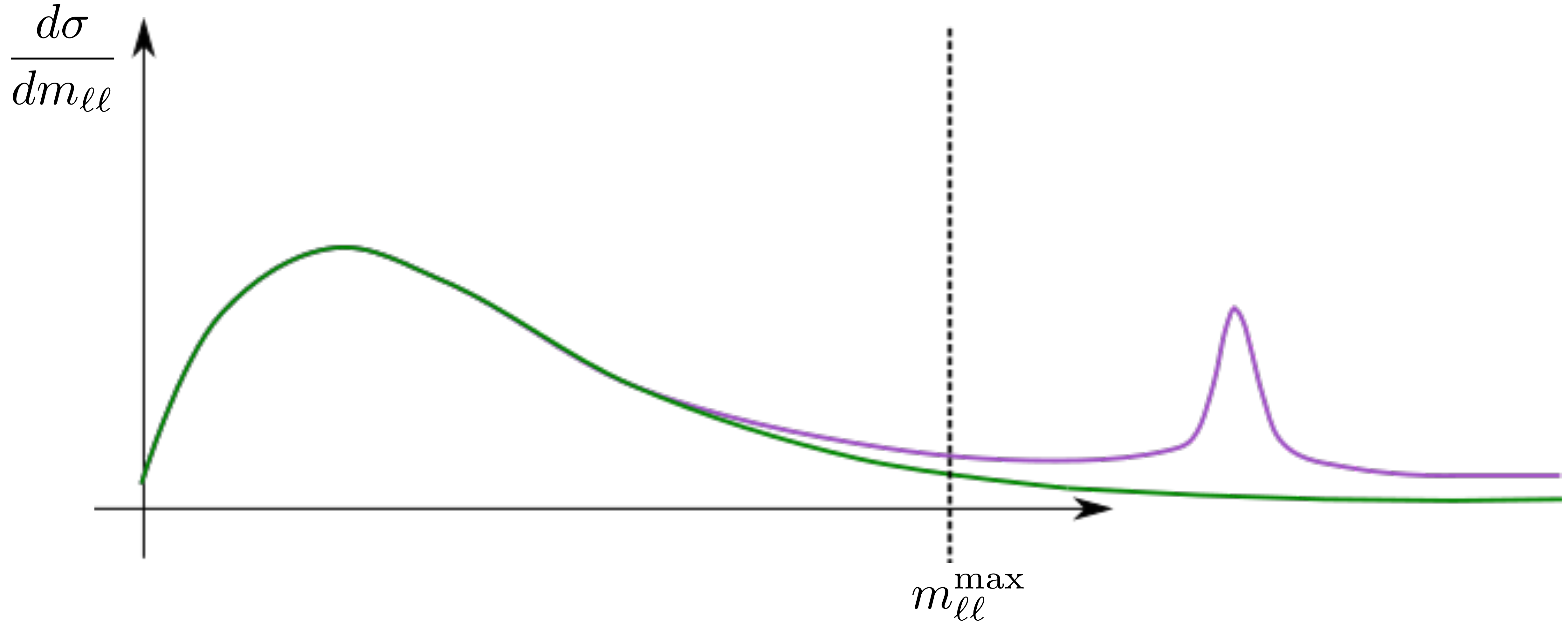
Higgs Hunting 2023

The Standard Model Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

this talk

- Assuming $\Lambda \gg E$
- A powerful theoretical framework for capturing the indirect effect of NP on LHC observables



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

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

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

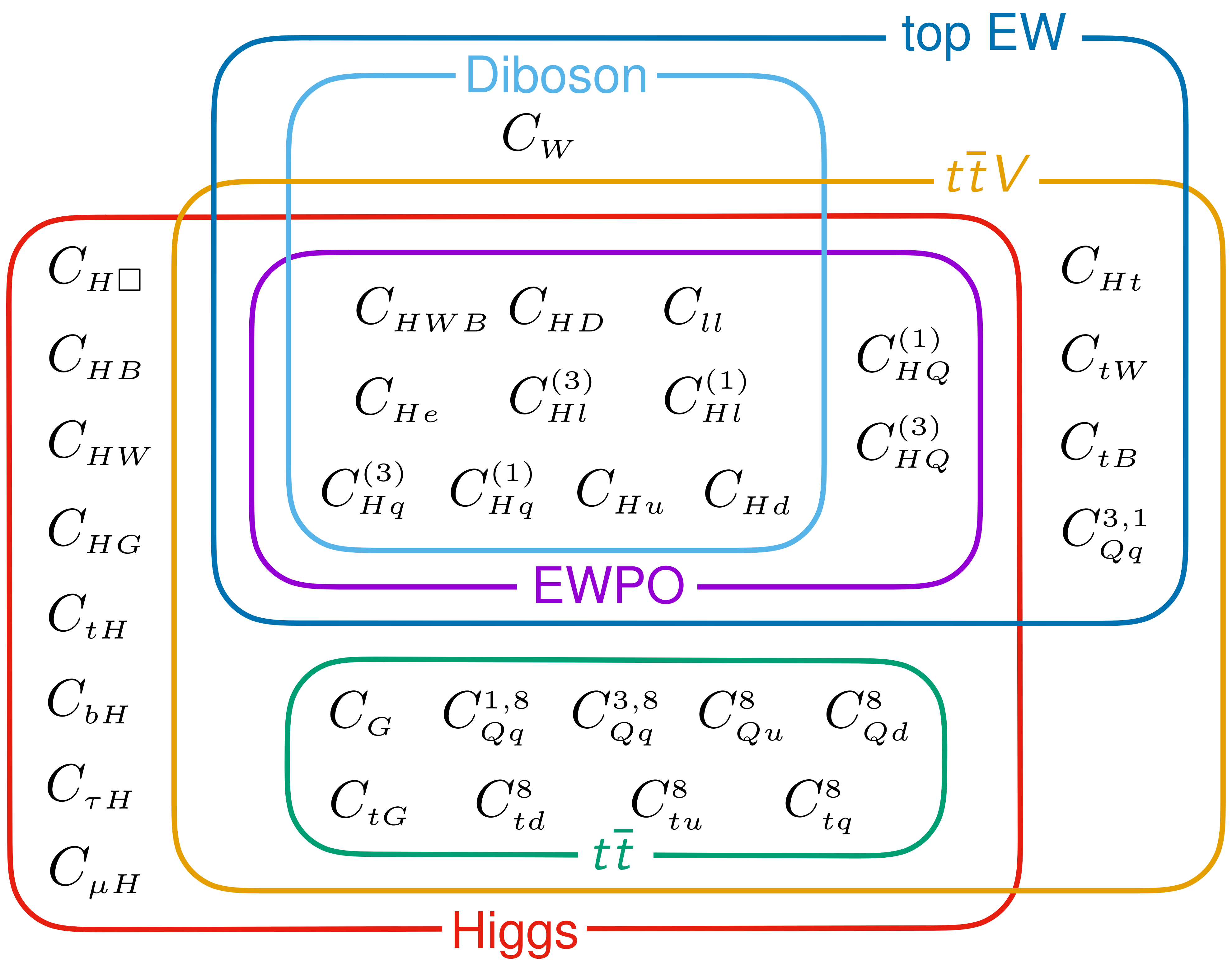
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j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

Global SMEFT interpretations

The SMEFT framework connects different sectors of observables measured at the LHC.

We need to take a **global approach,** including as many datasets as possible

→ Model-independent interpretation of BSM physics in LHC data



2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

see talk by Víctor Miralles for more on Higgs fits

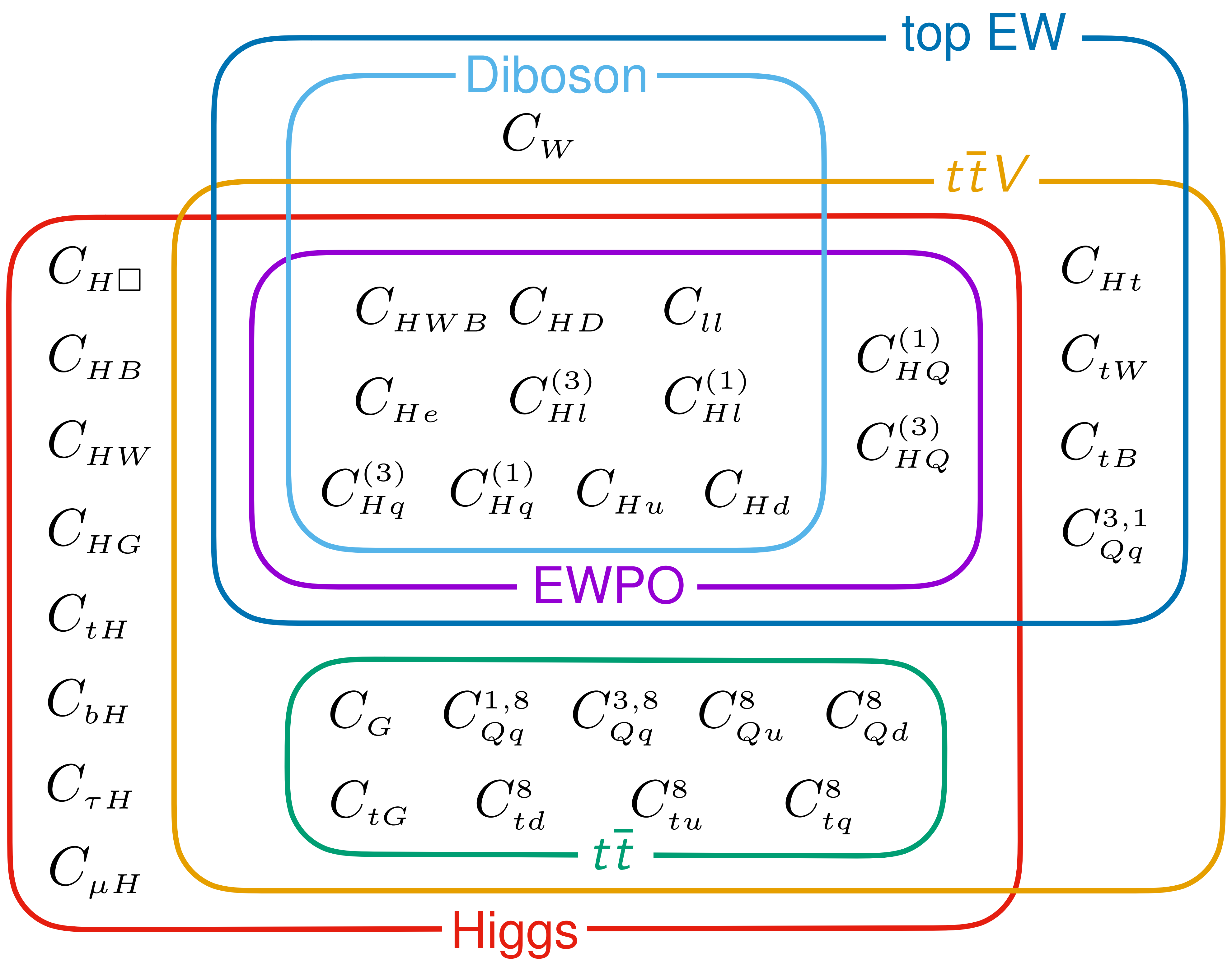
Global SMEFT interpretations

Is the overlap between data sectors visible in a global fit?

- **Top-Higgs interplay**

The same data is used to constrain SMEFT and PDFs: what is the impact?

- **PDF-SMEFT interplay**



2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

see talk by Víctor Miralles for more on Higgs fits

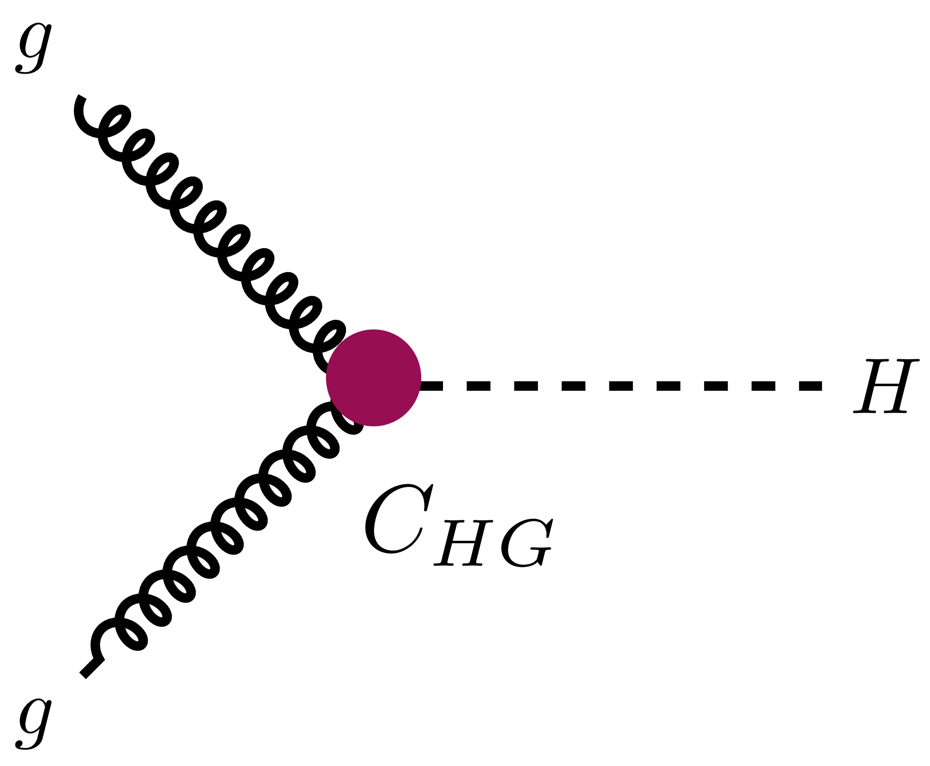
Top-Higgs interplay

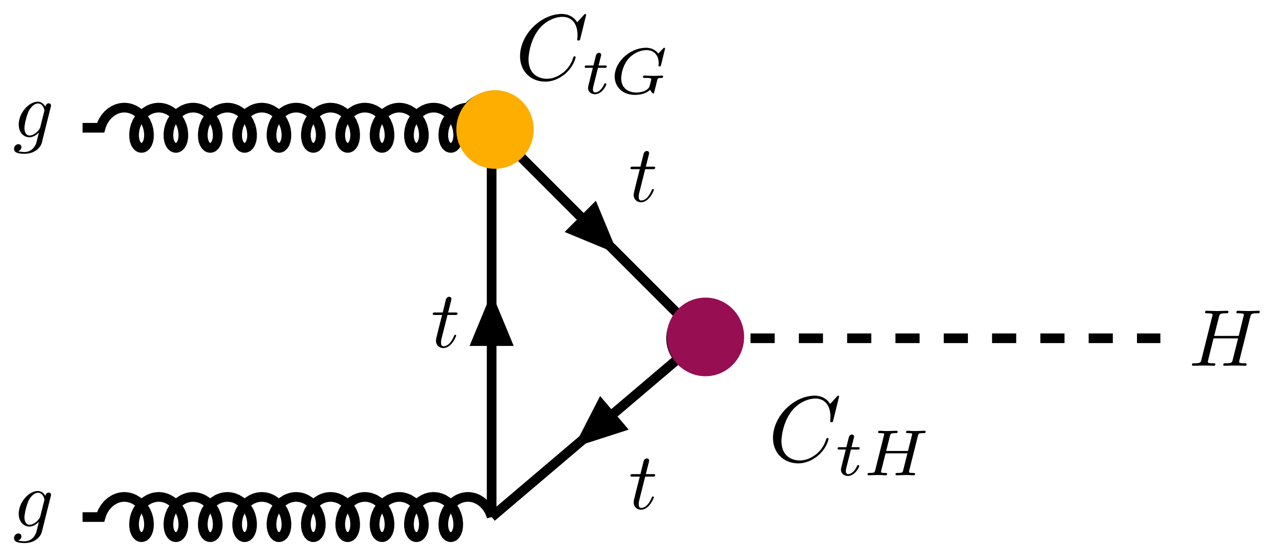
2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

Top-Higgs Interplay

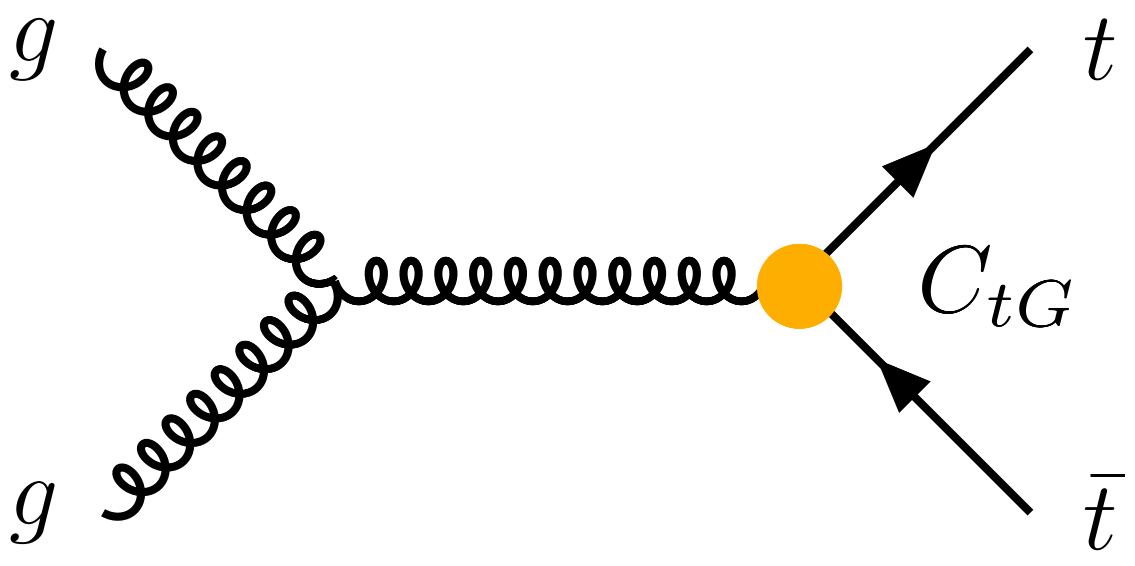
E.g. between ggF production of the Higgs, and top quark pair production

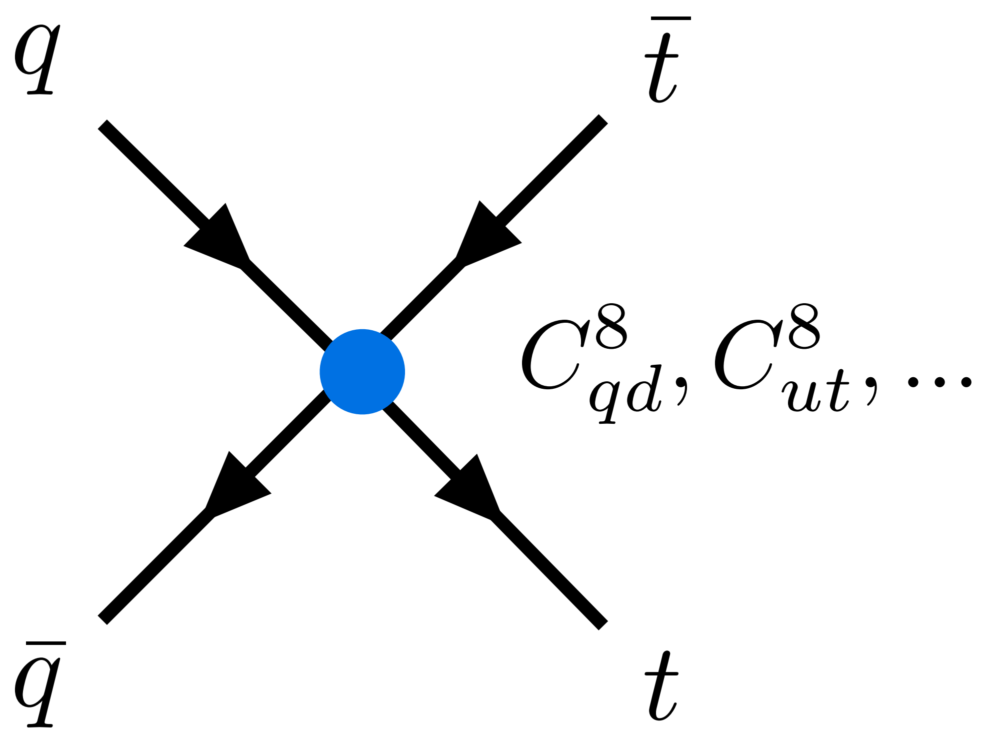
Higgs ggF:

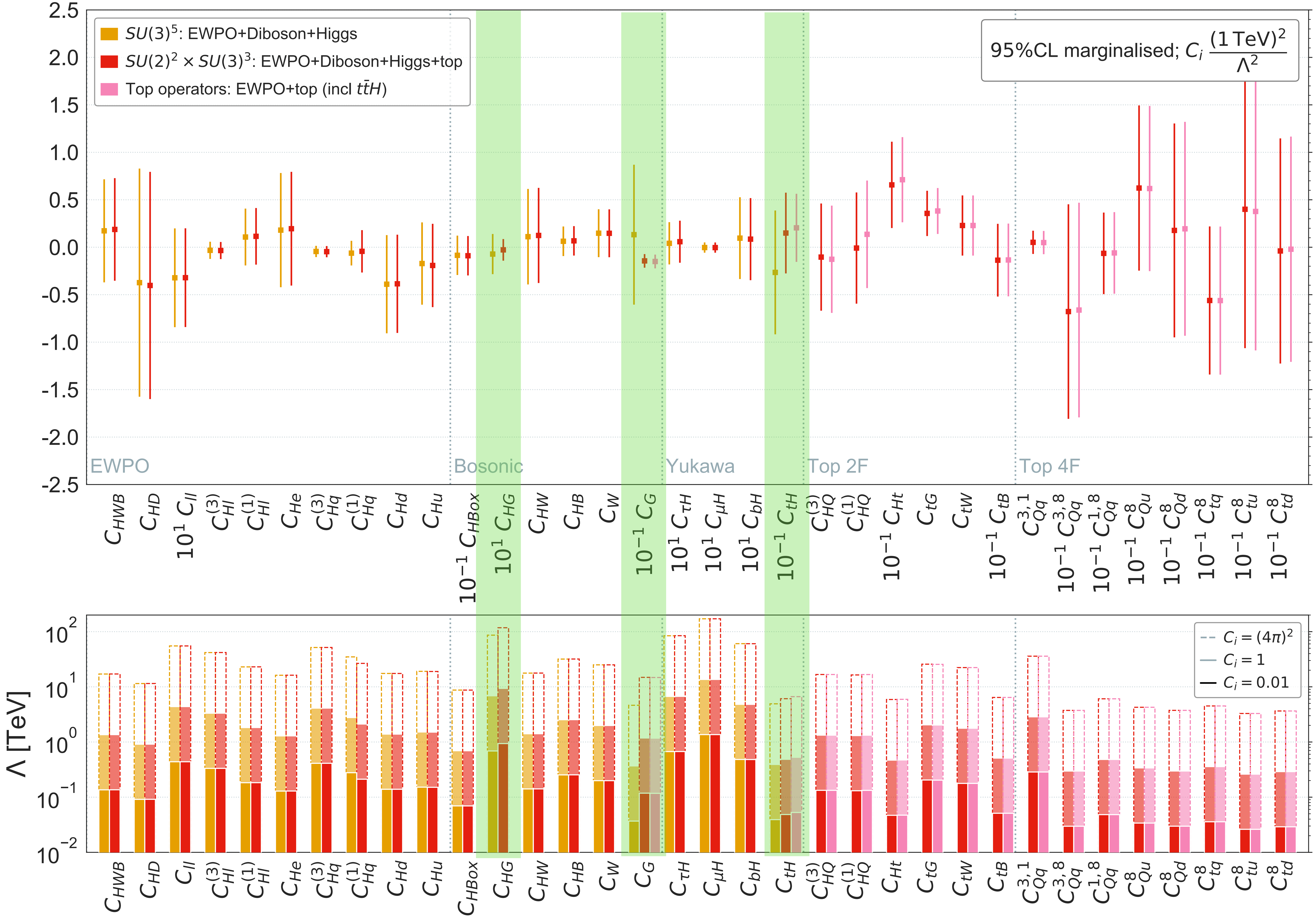




Top pair production:







- 34 dimension-6 SMEFT ops constrained
- top-specific flavour symmetry, following the *LHC top WG 1802.07237*
- RED: the full fit
- ORANGE: by removing the top data we see some shift in the constraints, particularly on

$$C_{HG}, C_G, C_{tH}$$

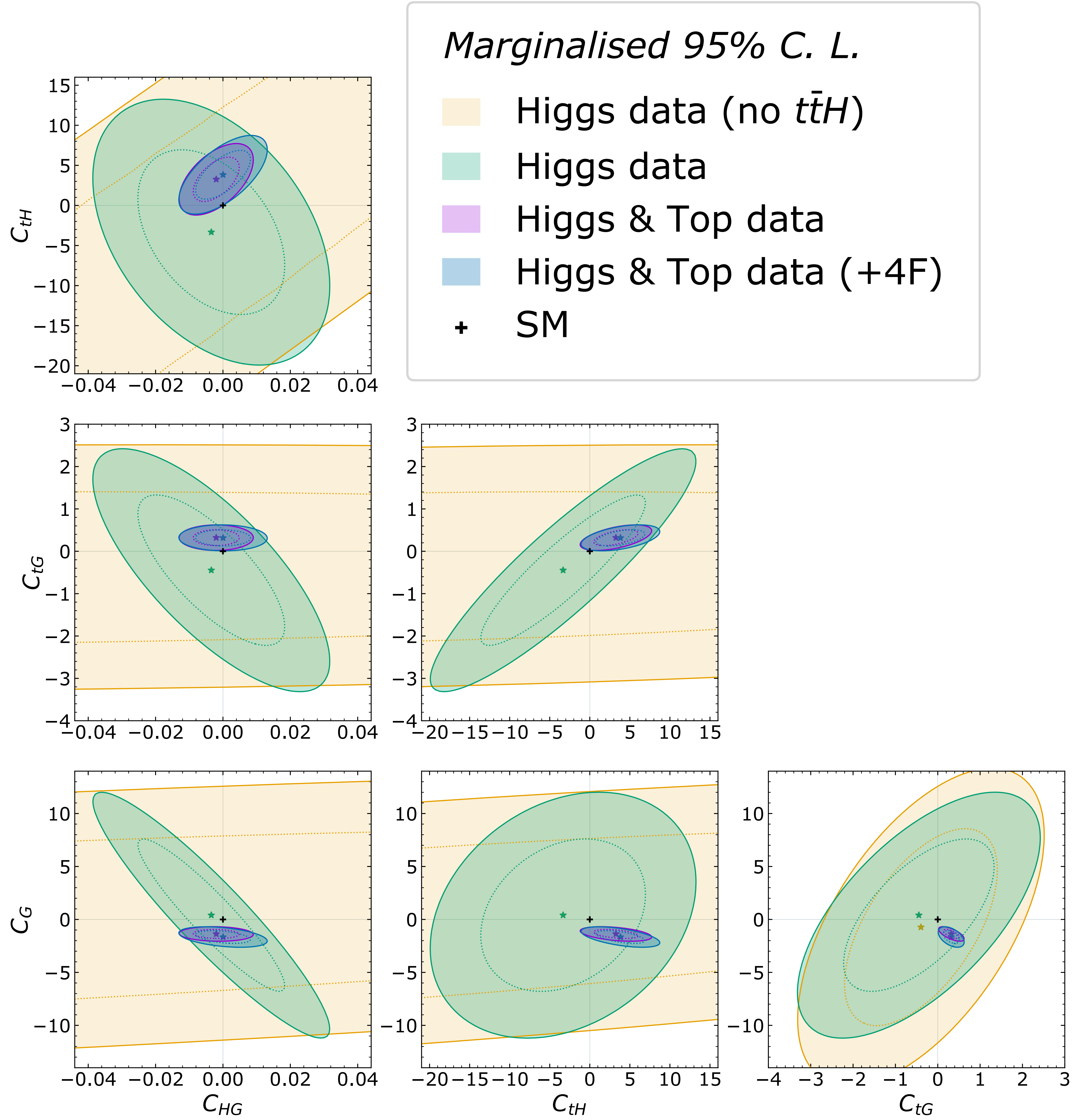
important for both ggF and $t\bar{t}$

Top-Higgs interplay

How do the constraints on $C_{HG}, C_{tG}, C_G, C_{tH}$ change as we include more top quark data?

We marginalise over
$C_{H\Box}, C_{HW}, C_{HB}, C_{bH}, C_{\tau H}, C_{\mu H} (+\text{ 4-fermion operators})$

- *ttH* removes the degeneracy between C_{HG}, C_{tH}.
- top quark data substantially **reduces the area** constrained at 95 % CL and **suppresses some correlations**.
- this is true even when marginalising over all 4-fermion operators involving top quarks.



PDF-SMEFT interplay

2307.10370: E. Hammou, Z. Kassabov, MM, M. L. Mangano, L. Mantani, J. Moore, M. Morales Alvarado, M. Ubiali

PDF-EFT Interplay

Wilson coefficients: c
PDF parameters: θ

Parton distribution function fits

Wilson coefficients are kept fixed:

$$\sigma(\bar{c}, \theta) = f_1(\theta) \otimes f_2(\theta) \otimes \hat{\sigma}(\bar{c})$$

SMEFT Fits and BSM searches

PDF parameters are fixed:

$$\sigma(c, \bar{\theta}) = f_1(\bar{\theta}) \otimes f_2(\bar{\theta}) \otimes \hat{\sigma}(c)$$

PDF-EFT Interplay

Wilson coefficients: c
PDF parameters: θ

Parton distribution function fits

Wilson coefficients are kept fixed:

$$\sigma(\bar{c}, \theta) = f_1(\theta) \otimes f_2(\theta) \otimes \hat{\sigma}(\bar{c})$$

Typically PDF fits assume the SM:
$\bar{c} = 0$

SMEFT Fits and BSM searches

PDF parameters are fixed:

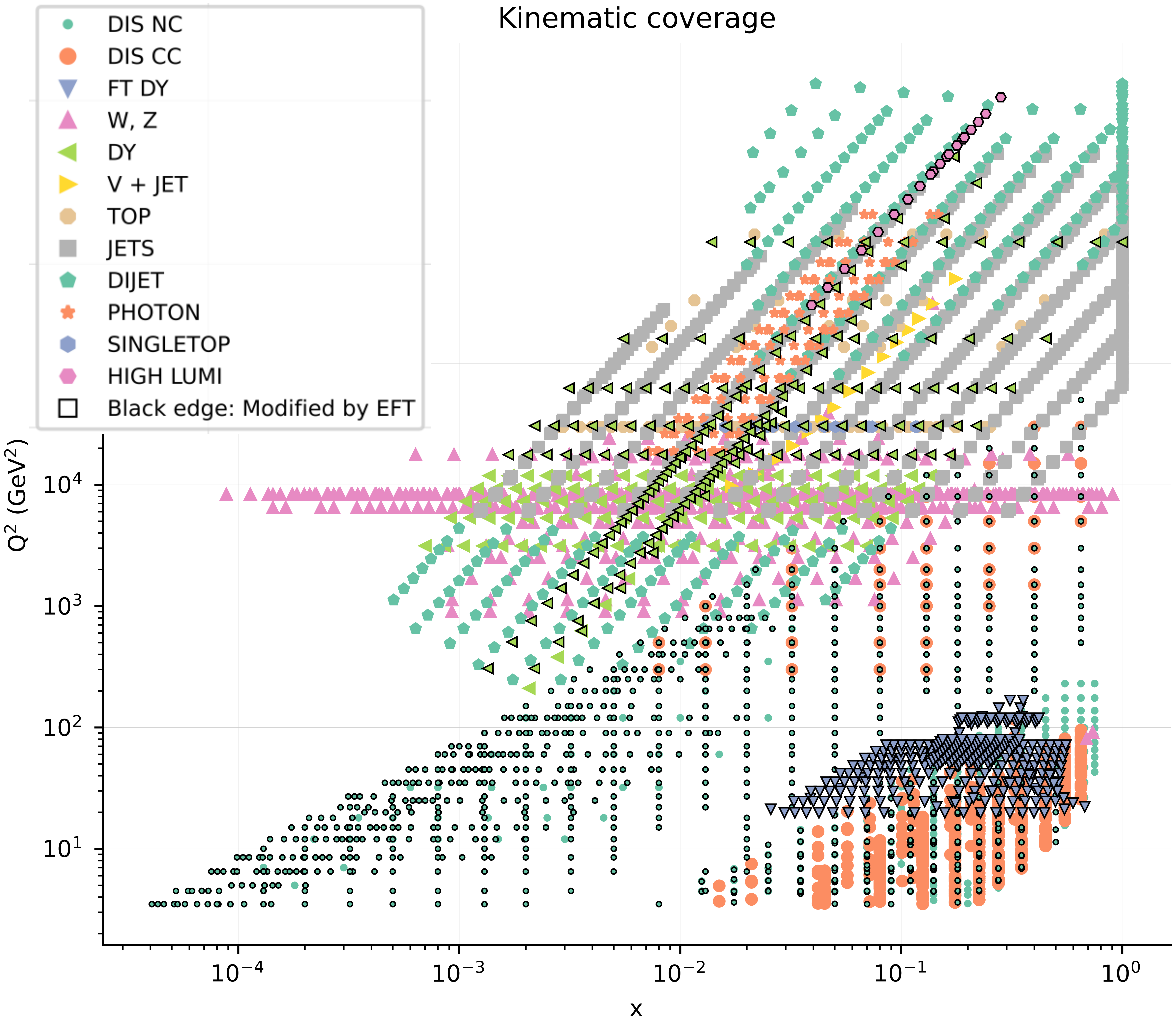
$$\sigma(c, \bar{\theta}) = f_1(\bar{\theta}) \otimes f_2(\bar{\theta}) \otimes \hat{\sigma}(c)$$

PDFs used in SMEFT fits rely on SM assumptions

Data overlap

Often the data used in PDF fits are also used in EFT fits.

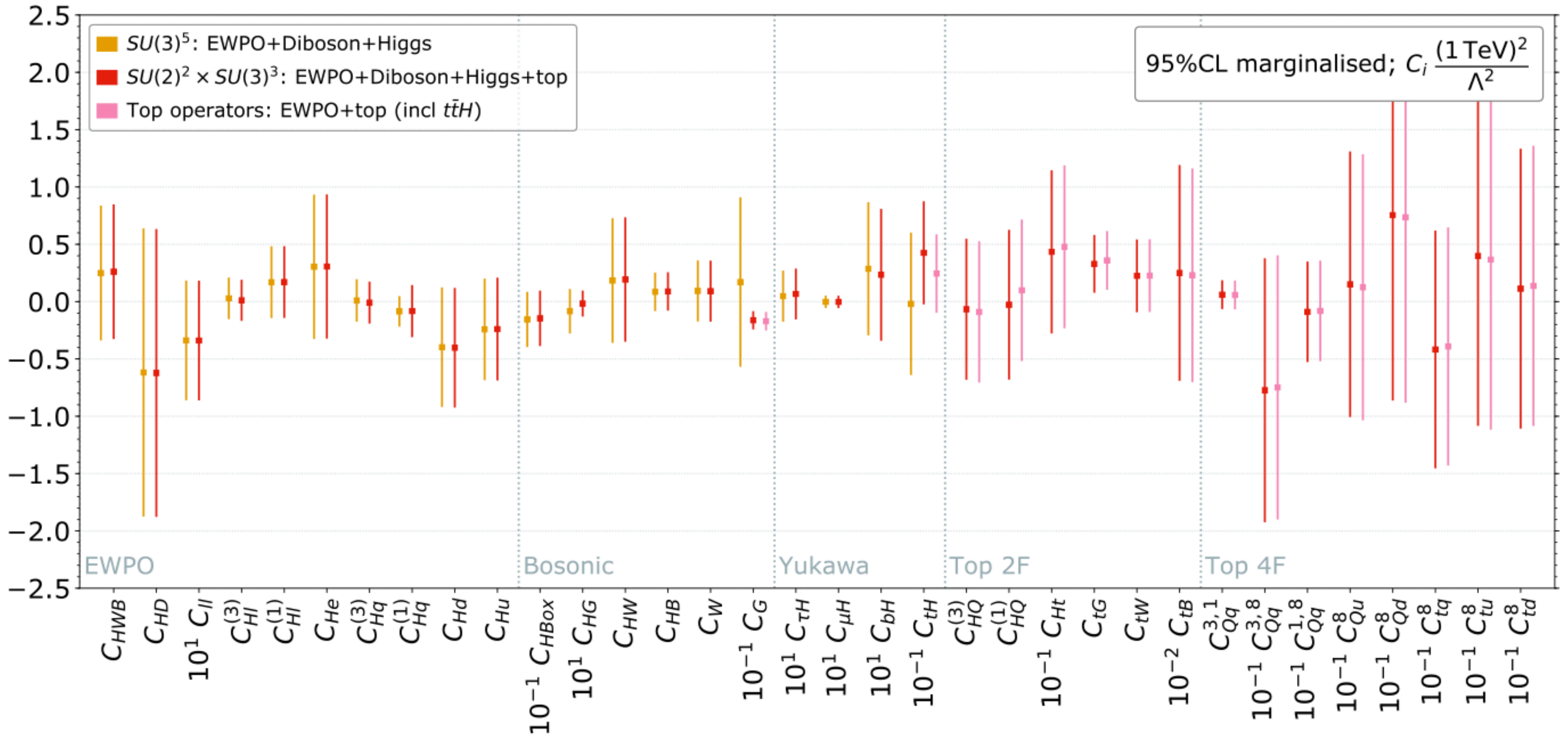
This overlap will grow as we continue to take a global approach to constraining the SMEFT.

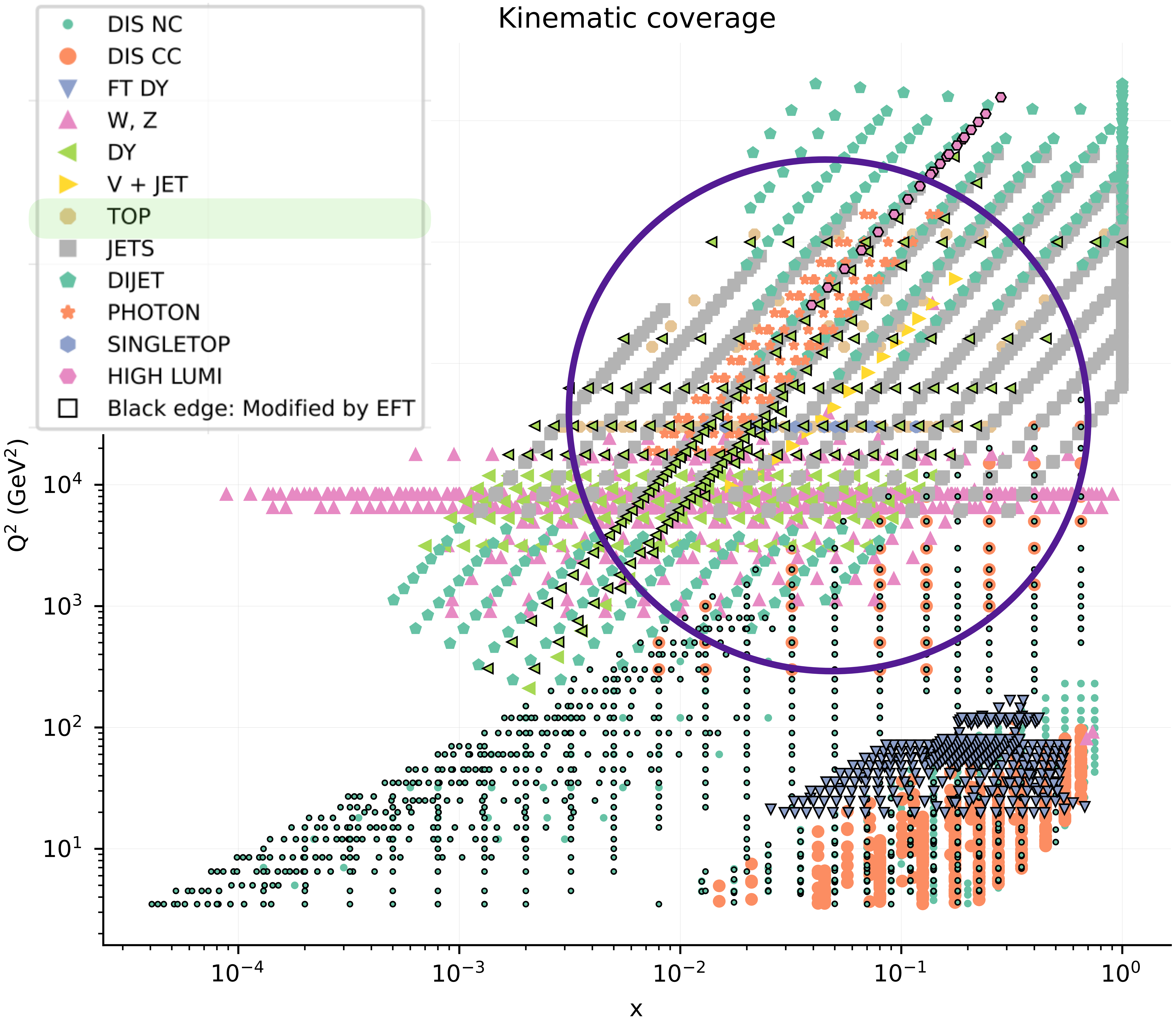


Data included in our study

Data overlap

- e.g. Top quark data used to fit the SMEFT in the global fit of *2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You*

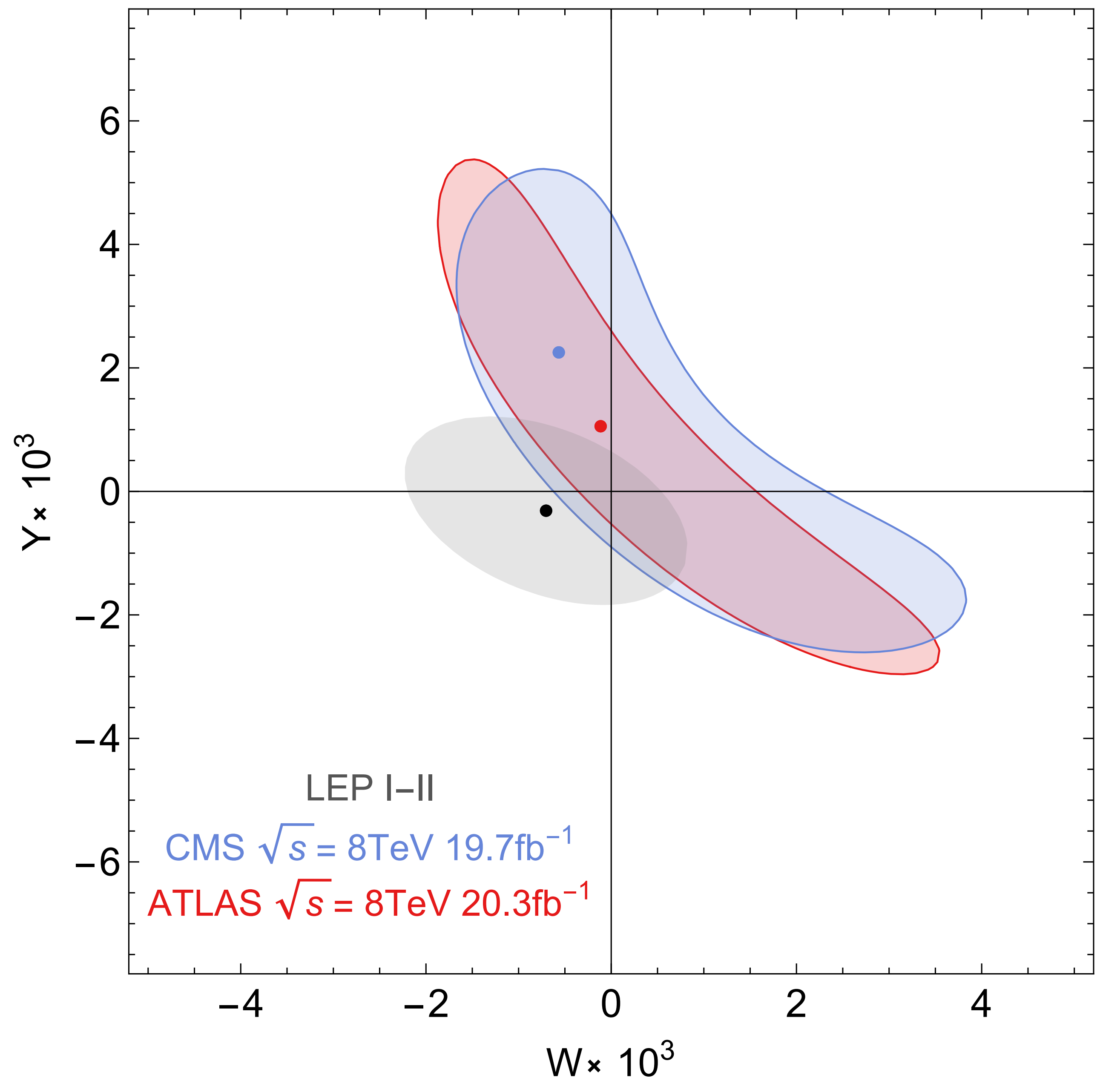


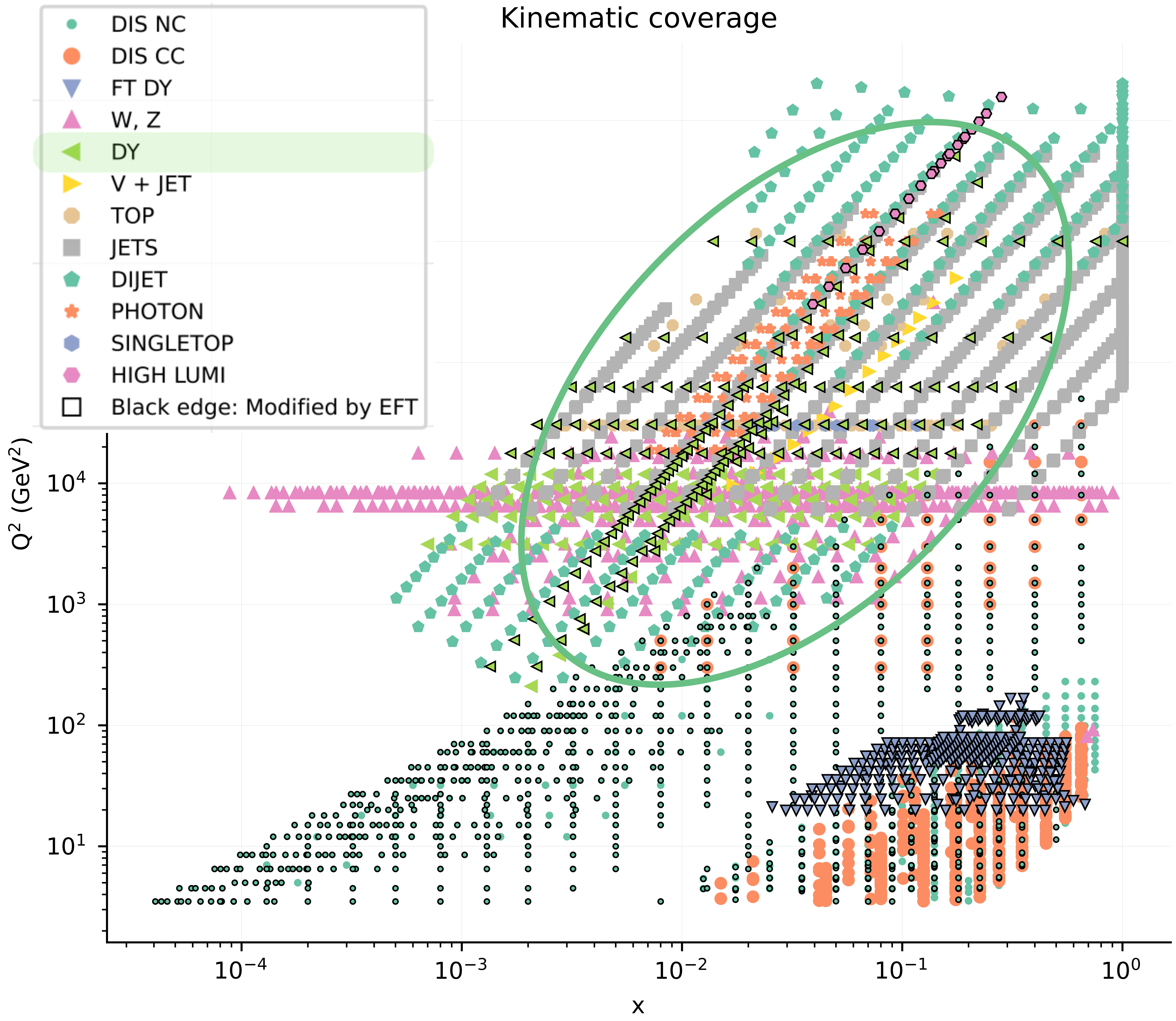


Data included in our study

Data overlap

- e.g. High-mass Drell-Yan data used to fit the SMEFT 4-fermion operators in *Farina et. al 1609.08157*





Data included in our study

Understanding PDF-EFT Interplay

Simultaneous PDF-EFT determinations:

- Deep Inelastic Scattering data
  Carrazza et al.: PRL 123 (2019) 13, 132001
- DIS + high-mass Drell-Yan tails
  Greljo et. al 2104.02723
- Top quark data
  Kassabov et. al: 2303.06159
  See also 2201.06586, 2211.01094

Contaminated PDF fits:

What are the consequences of performing a SM PDF fit in the presence of new physics?

Contaminated PDFs

closely follows the *closure test methodology* developed by NNPDF, 1410.8849

Assume that we know the **true underlying law of nature**: SM + UV model

$$T = T(\theta_{\mathrm{SM}}, \theta_{\mathrm{NP}})$$

PDF parameters

Parameters of the BSM model

Contaminated PDFs

closely follows the *closure test methodology* developed by NNPDF, 1410.8849

Assume that we know the true underlying law of nature: SM + UV model

$$T = T(\theta_{\text{SM}}, \theta_{\text{NP}})$$

Generate Monte Carlo pseudodata according to this underlying law:

$$D \sim \mathcal{N}(T(\theta_{\text{SM}}, \theta_{\text{NP}}), \Sigma)$$

Contaminated PDFs

closely follows the *closure test methodology* developed by NNPDF, 1410.8849

Assume that we know the true underlying law of nature: SM + UV model

$$T = T(\theta_{\rm SM}, \theta_{\rm NP})$$

Generate Monte Carlo pseudodata according to this underlying law:

$$D \sim \mathcal{N}(T(\theta_{\rm SM}, \theta_{\rm NP}), \Sigma)$$

Perform a PDF fit: **fit only the SM parameters** $\theta_{\rm SM}$ using the NNPDF4.0 methodology

2109.02653

Contaminated PDFs

closely follows the *closure test methodology* developed by NNPDF, 1410.8849

Assume that we know the true underlying law of nature: SM + UV model

$$T = T(\theta_{\rm SM}, \theta_{\rm NP})$$

Generate Monte Carlo pseudodata according to this underlying law:

$$D \sim \mathcal{N}(T(\theta_{\rm SM}, \theta_{\rm NP}), \Sigma)$$

Perform a PDF fit: fit only the SM parameters $\theta_{\rm SM}$ using the NNPDF4.0 methodology

2109.02653

PDF has **absorbed new physics** if the fit quality is good $$n_\sigma = \frac{\chi^2 - 1}{\sigma_{\chi^2}} < 2$$

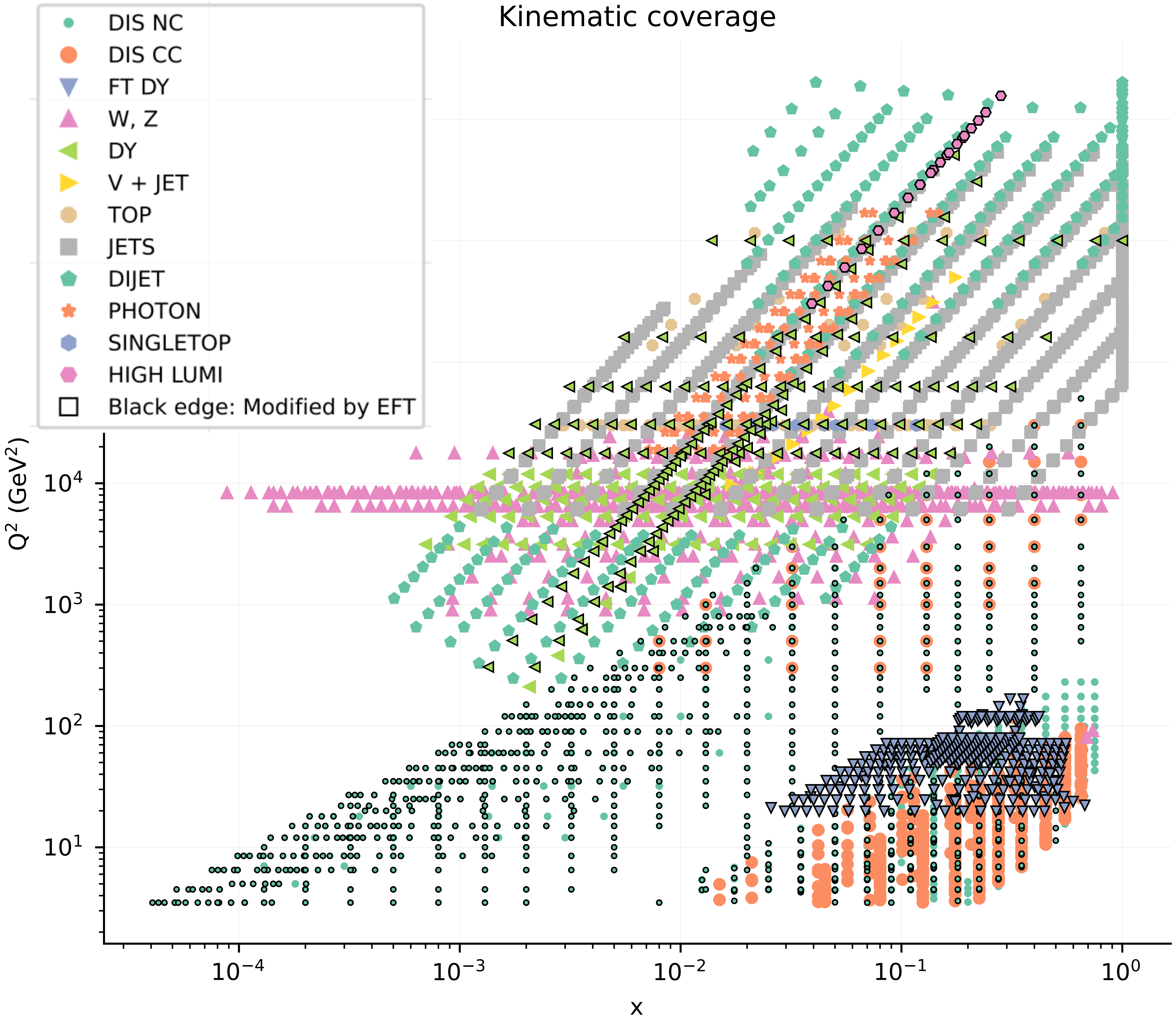
Data

- We generate MC pseudodata for all datasets included in NNPDF 4.0

  2109.02653

- Additionally, we include **HL-LHC** projections for neutral current and charged current DY

  as in Greljo et. al 2104.02723



BSM scenario: W'

See 2307.10370 for a flavour universal Z' scenario

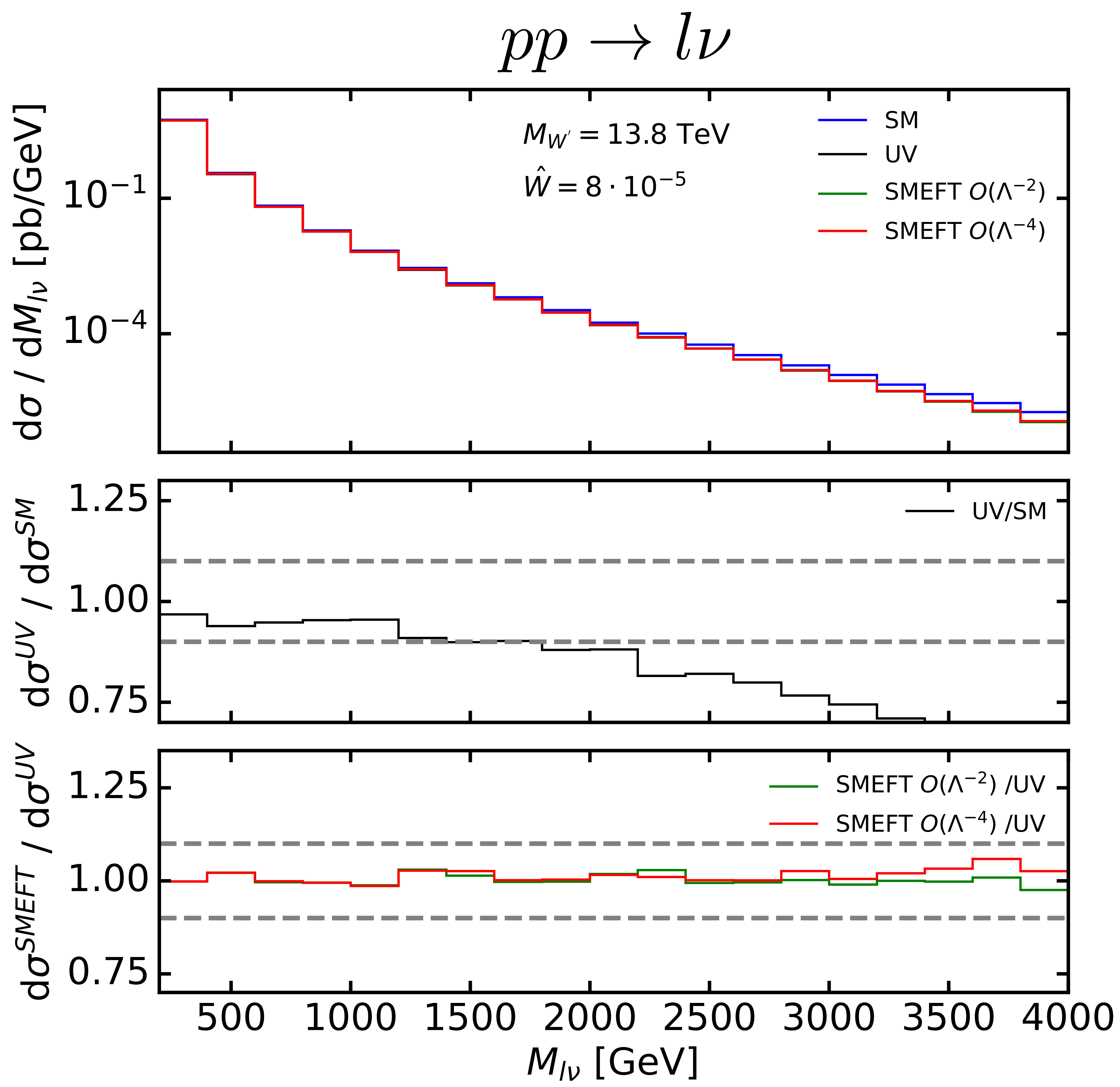
- Flavour universal W'

EFT approximation

$$\mathcal{L}_{\text{SMEFT}}^{W'} = \mathcal{L}_{\text{SM}} - \frac{g^2 \hat{W}}{2m_W^2} J_L^{\mu} J_{L,\mu}$$

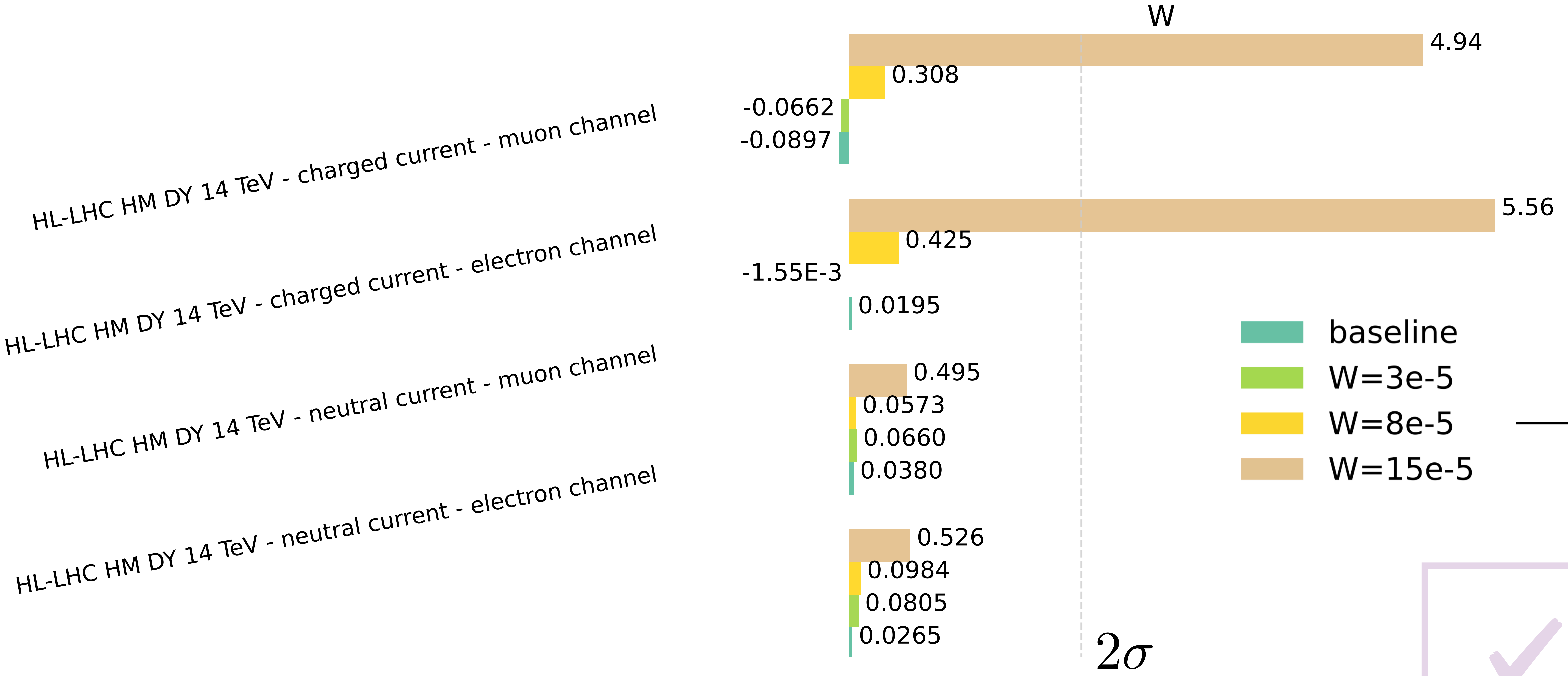
$$J_L^{\mu} = \sum_{f_L} \bar{f}_L T^a \gamma^{\mu} f_L$$

- Impacts NC and CC DY



Do our contaminated fits pass the selection criteria?

$$n_\sigma = \frac{\chi^2 - 1}{\sigma_{\chi^2}}$$



$\longrightarrow \hat{W} = 8 \cdot 10^{-5}, \quad M_{W'} \approx 14$ TeV

✓ ***Yes: PDFs absorb new physics***

Impact on EW processes

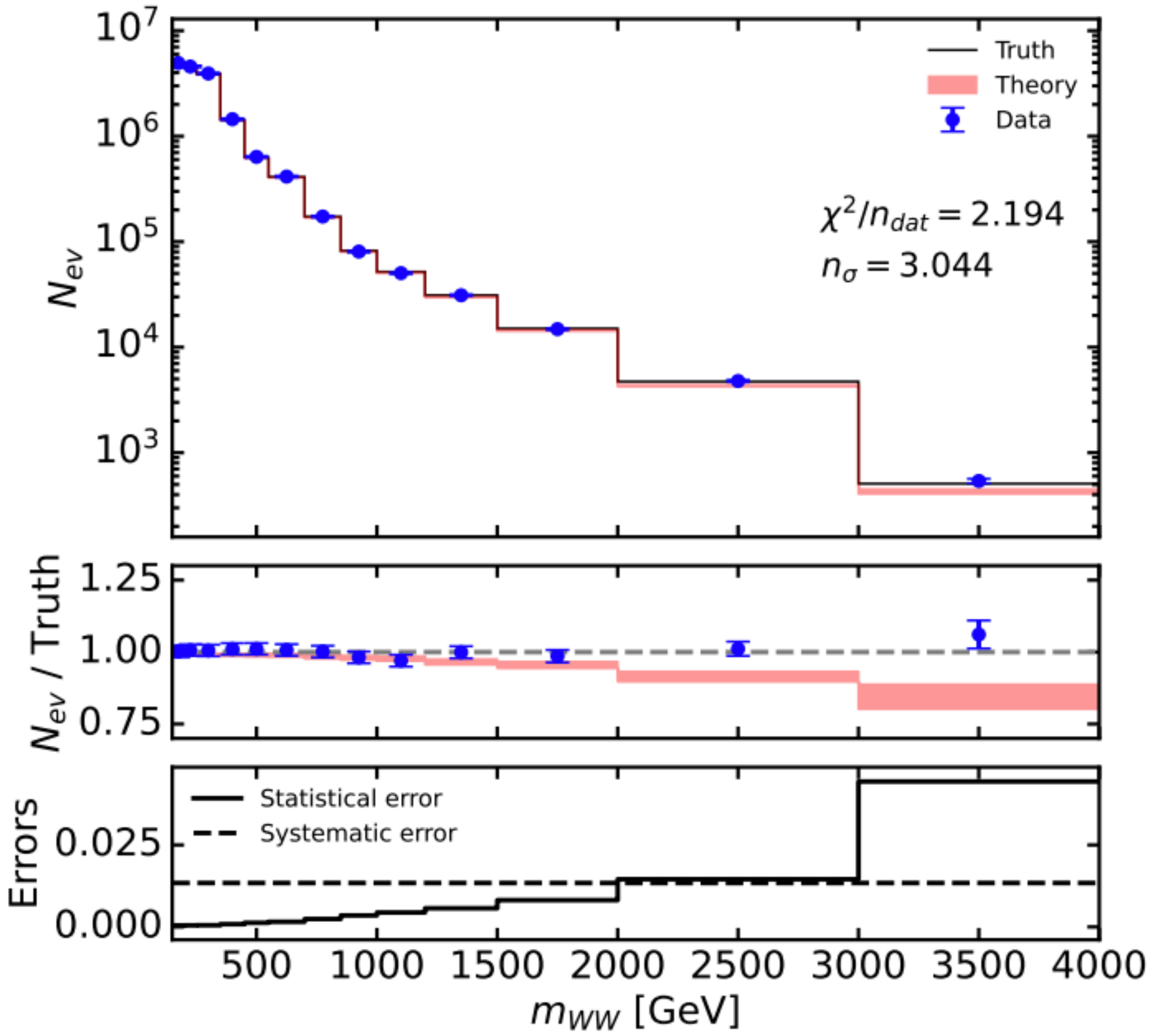
Data: 'true' PDF $\otimes$ SM
Theory: contaminated PDF $\otimes$ SM

The PDF then causes **spurious NP effects** in other observables e.g.

$$q\bar{q} \to W^+W^-$$

- Data appears to disagree with SM at 3σ
- However, W^+W^- is unaffected by W' model:

the deviation is in the PDF



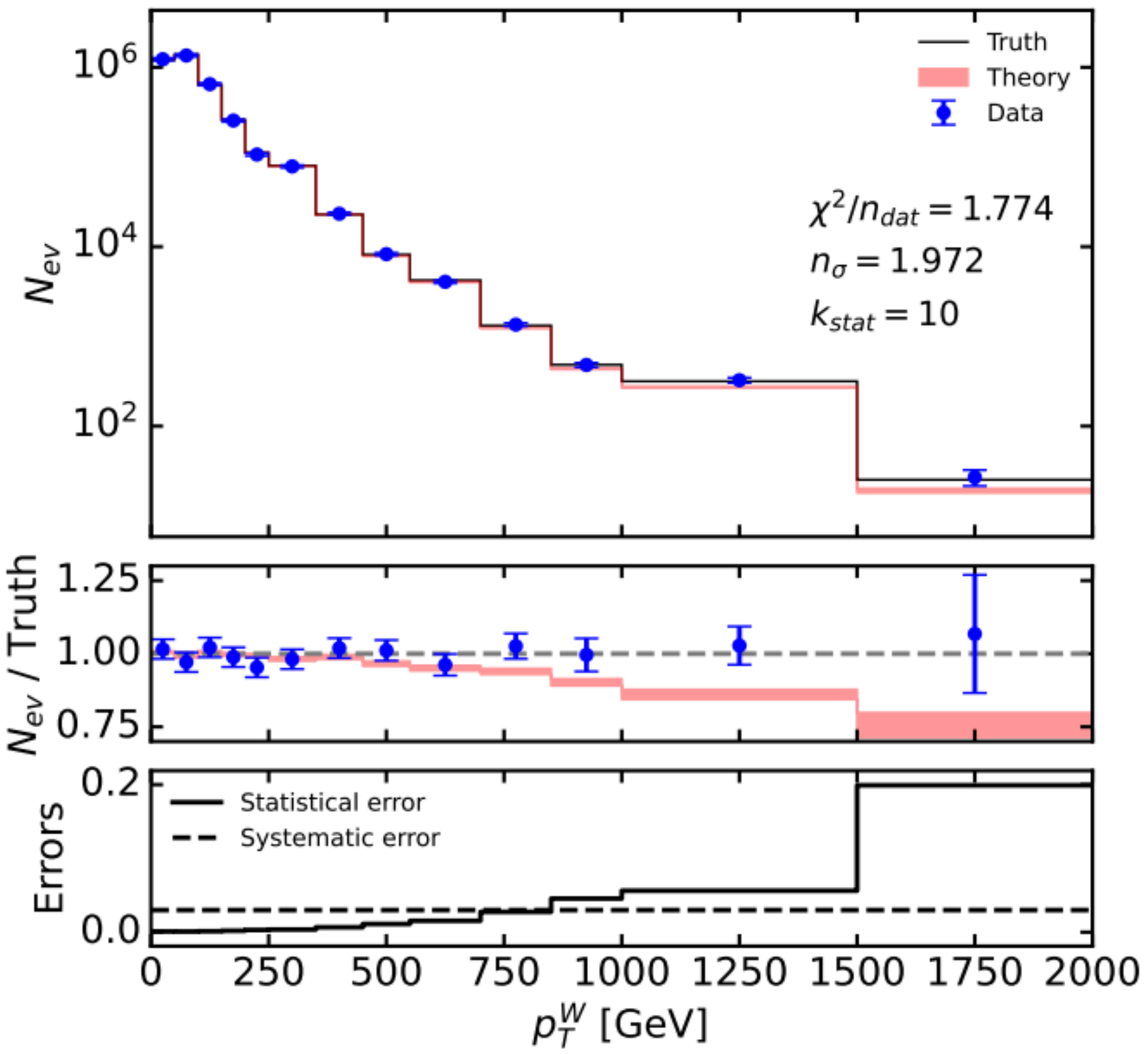
Impact on EW processes

Data: 'true' PDF $\otimes$ SM
Theory: contaminated PDF $\otimes$ SM

The PDF then causes **spurious NP effects** in other observables e.g.

$$q\bar{q} \to WH$$

- Data appears to disagree with SM at 2σ
- However, WH is unaffected by W' model:
  the deviation is in the PDF



statistics improved by a factor of 10

Conclusions

- SMEFT fits of LHC Run II data provide precise constraints on the Higgs sector of the SMEFT
- We observe an interplay between Higgs and top sectors - global SMEFT interpretations are necessary to obtain accurate SMEFT constraints
- **Looking to HL-LHC:** PDF-EFT interplay may be significant
    - PDFs have the potential to absorb NP signals from DY observables, and translate this into Higgs + EW process
    - Future low-energy precision measurements of high-x antiquark PDFs will provide crucial inputs to PDF fits to disentangle this interplay
- Tools to investigate contaminated PDF fits in other BSM scenarios are publicly available: https://www.pbsp.org.uk/contamination/

Conclusions

Thank you for listening!

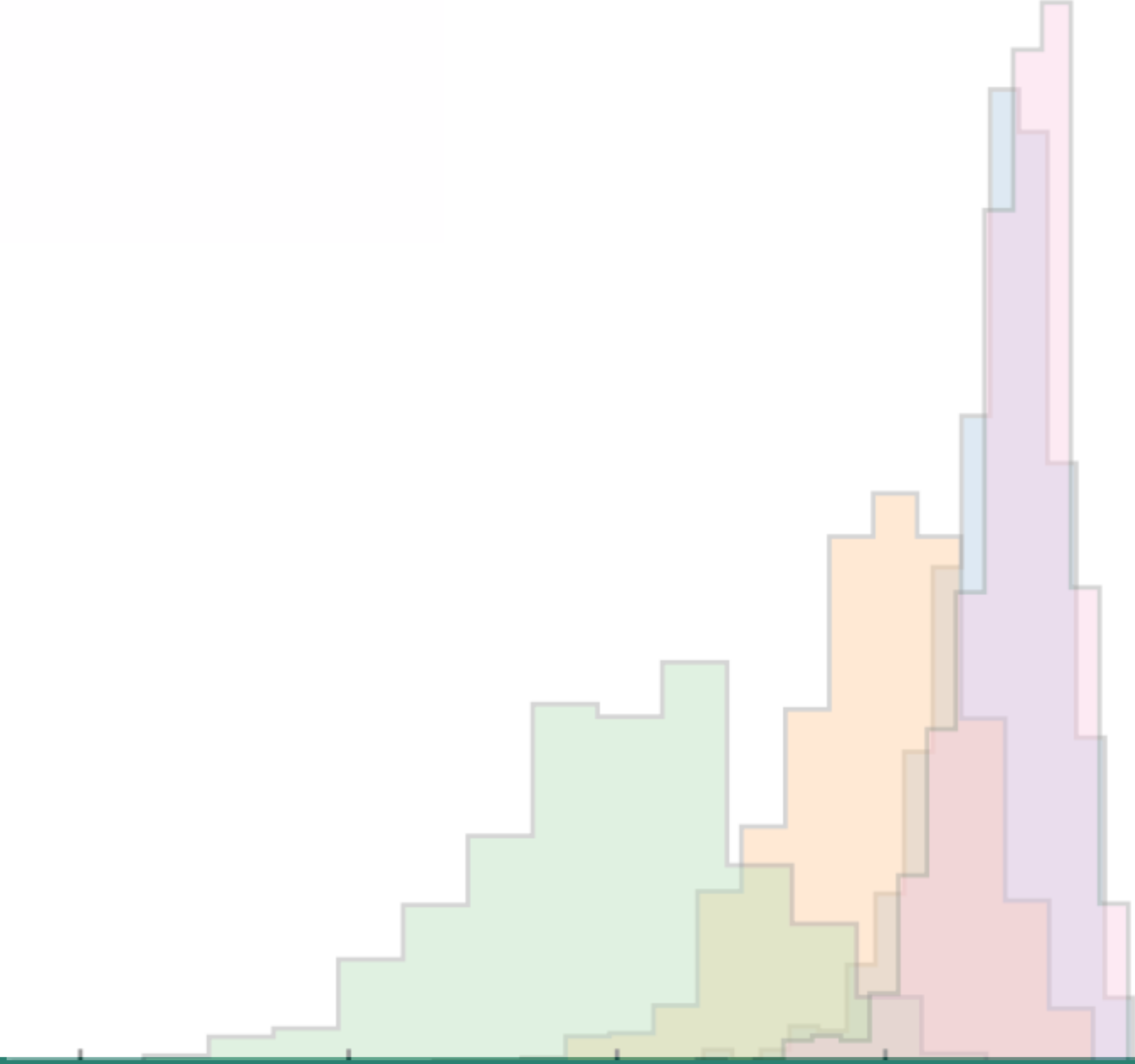
- SMEFT fits of LHC Run II data provide precise constraints on the Higgs sector of the SMEFT

- We observe an interplay between Higgs and top sectors - global SMEFT interpretations are necessary to obtain accurate SMEFT constraints

- **Looking to HL-LHC:** PDF-EFT interplay may be significant
  - PDFs have the potential to absorb NP signals from DY observables, and translate this into Higgs + EW process
  - Future low-energy precision measurements of high-x antiquark PDFs will provide crucial inputs to PDF fits to disentangle this interplay

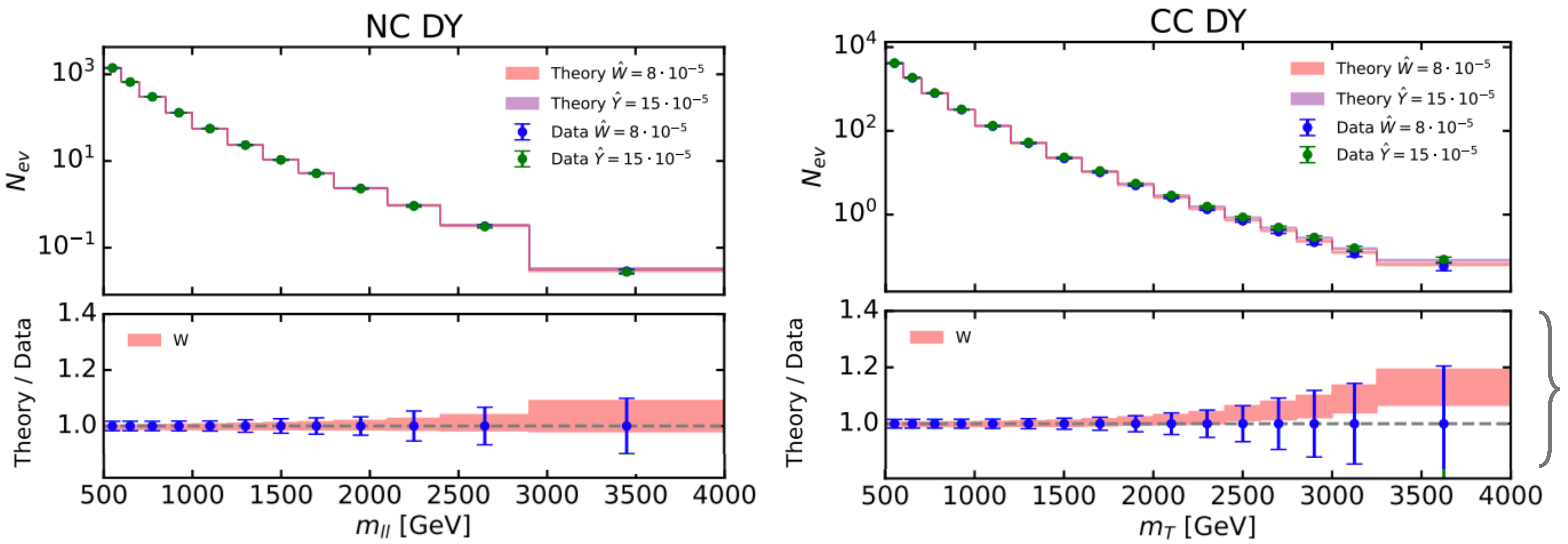
- Tools to investigate contaminated PDF fits in other BSM scenarios are publicly available: https://www.pbsp.org.uk/contamination/

Backup



W'-contaminated PDFs

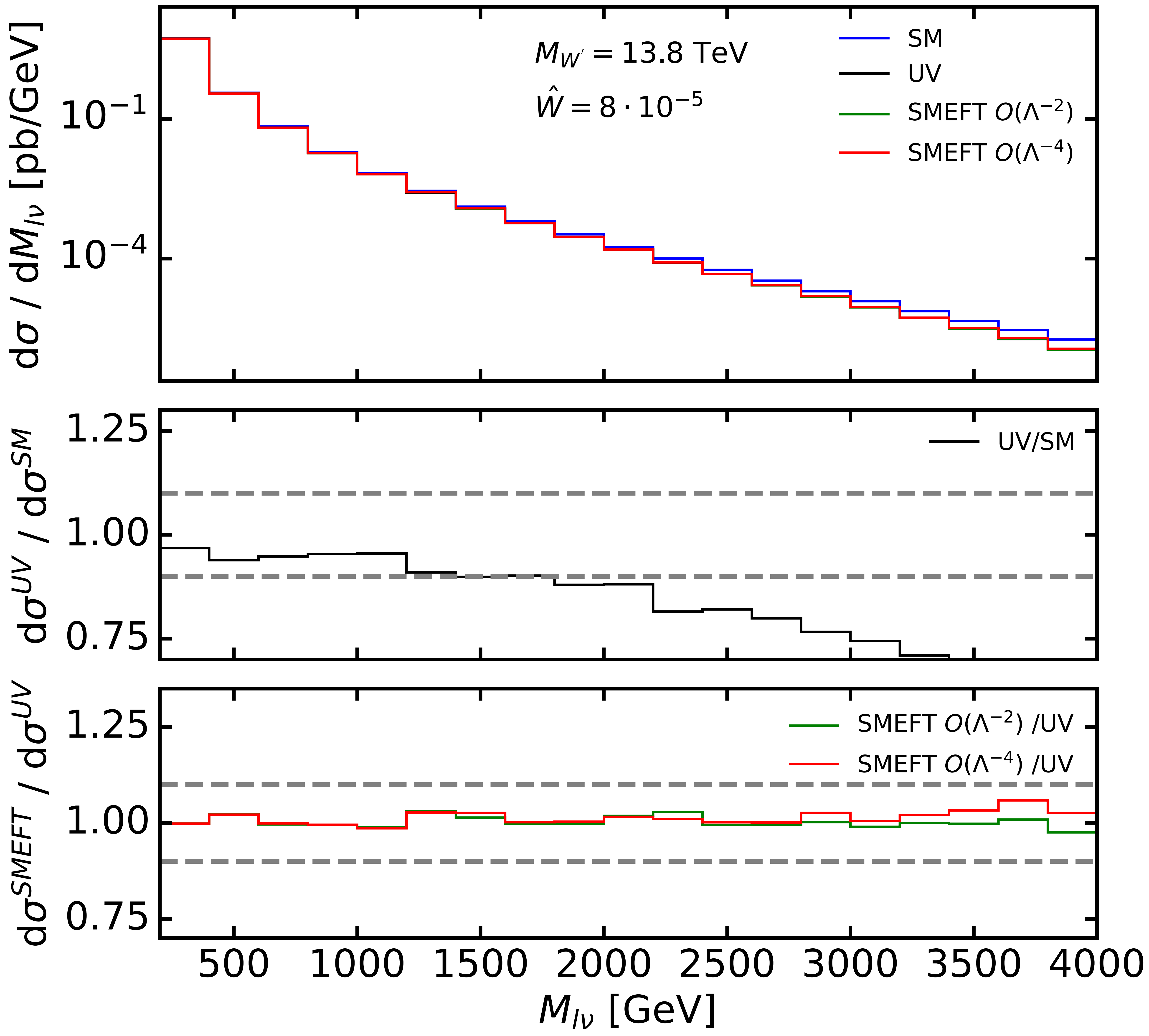
Data: 'true' PDF ⊗ SM + W'
Theory: contaminated PDF ⊗ SM



Excellent data-theory agreement

- The data appears to agree well with the SM
- **The shift in the PDFs compensates the NP effects**
- The effects of NP are completely missed

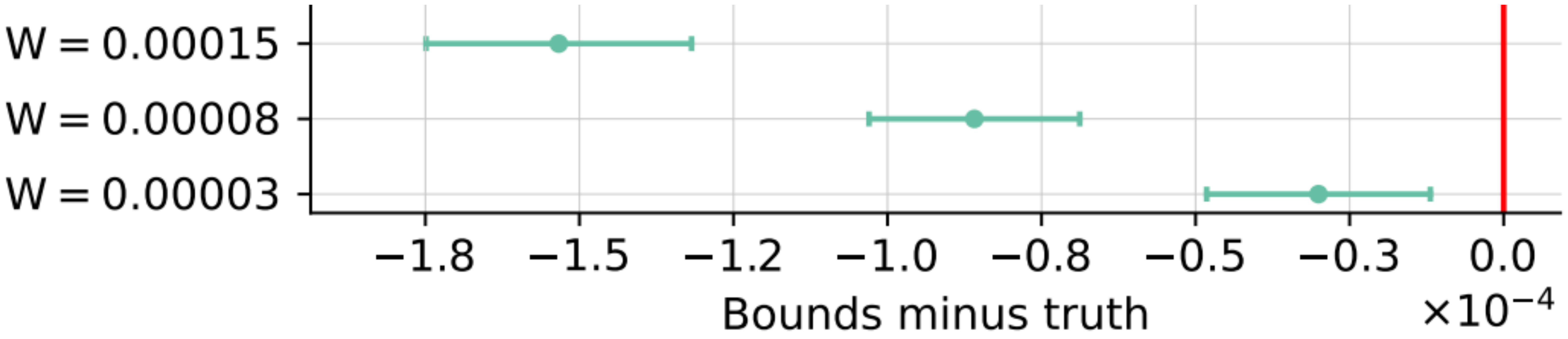
Impact of W' model



Impact on DY of W'-contaminated PDFs

The high-mass DY data **appears** to agree well with the SM

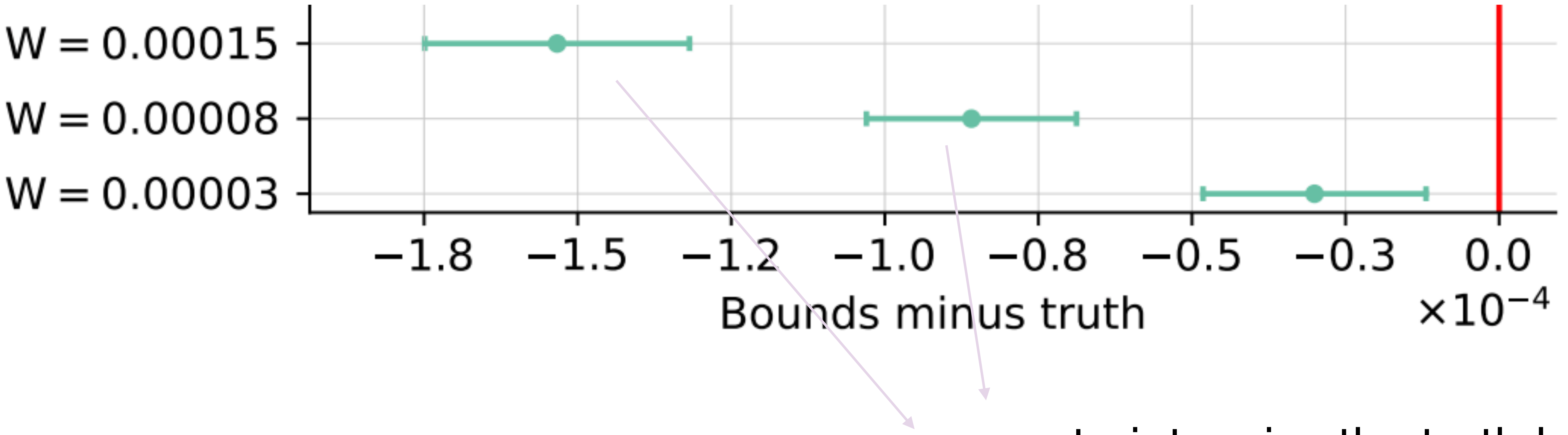
This leads to constraints on the W' which **miss the truth:**



Impact on DY of W’-contaminated PDFs

The high-mass DY data **appears** to agree well with the SM

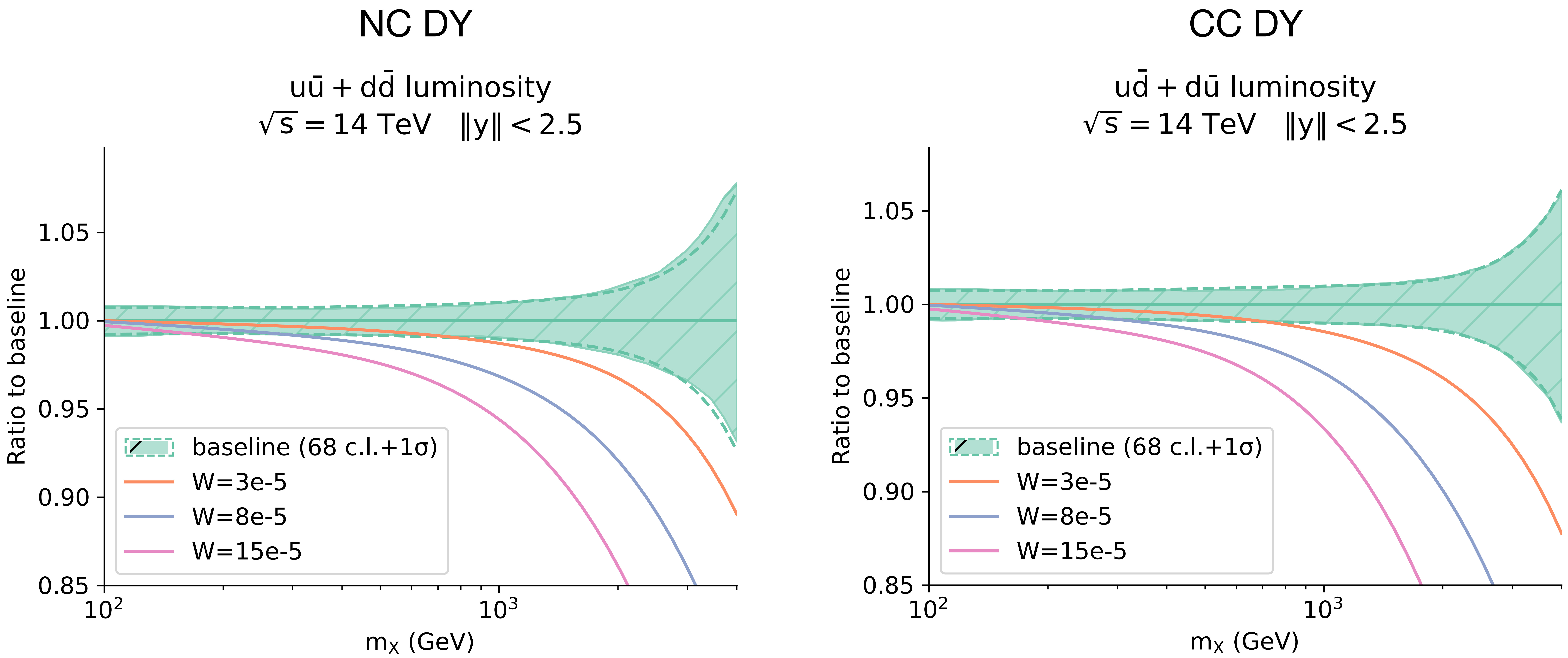
This leads to constraints on the W’ which **miss the truth:**



constraints miss the truth by $> 2\sigma$

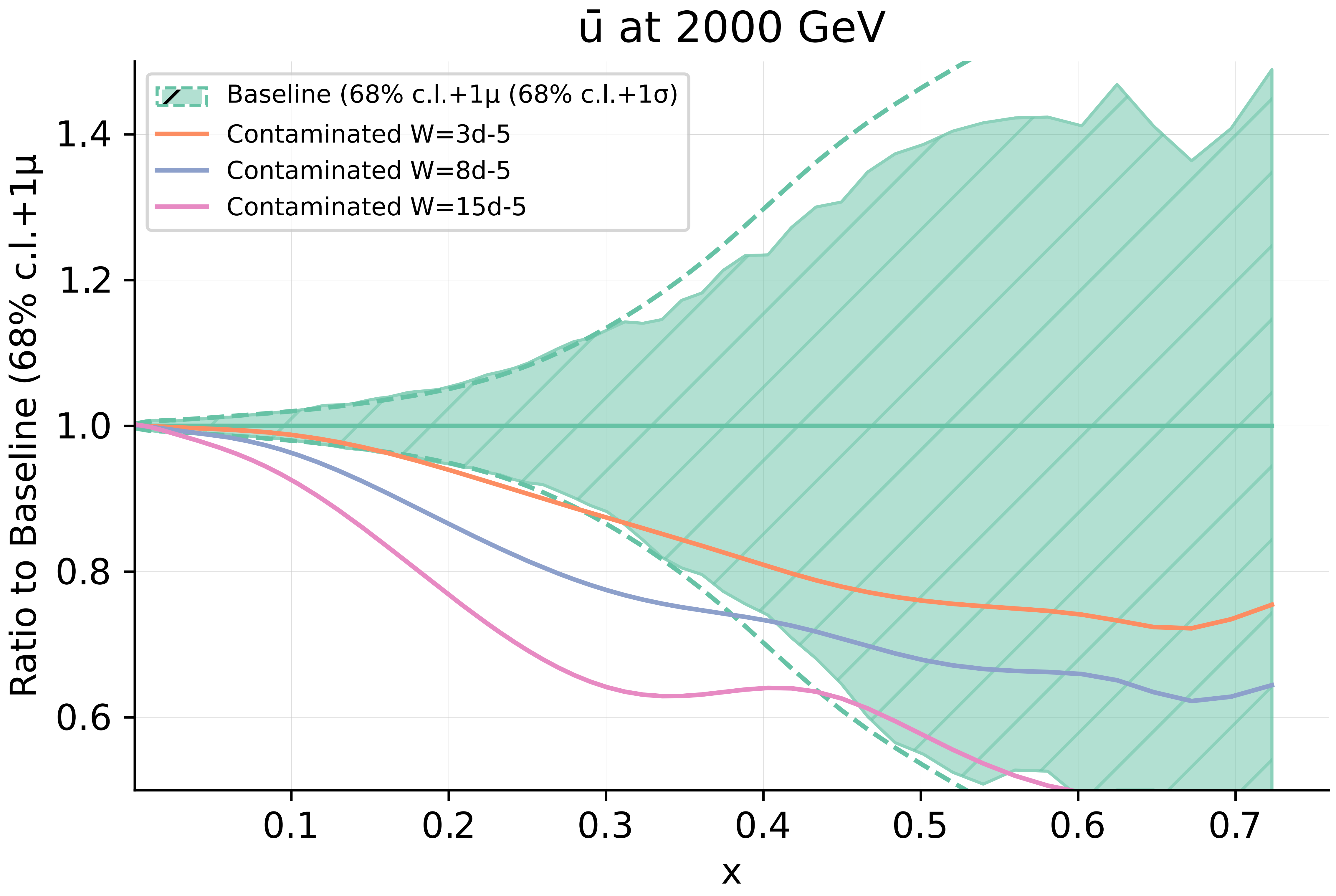
W'-contaminated PDFs

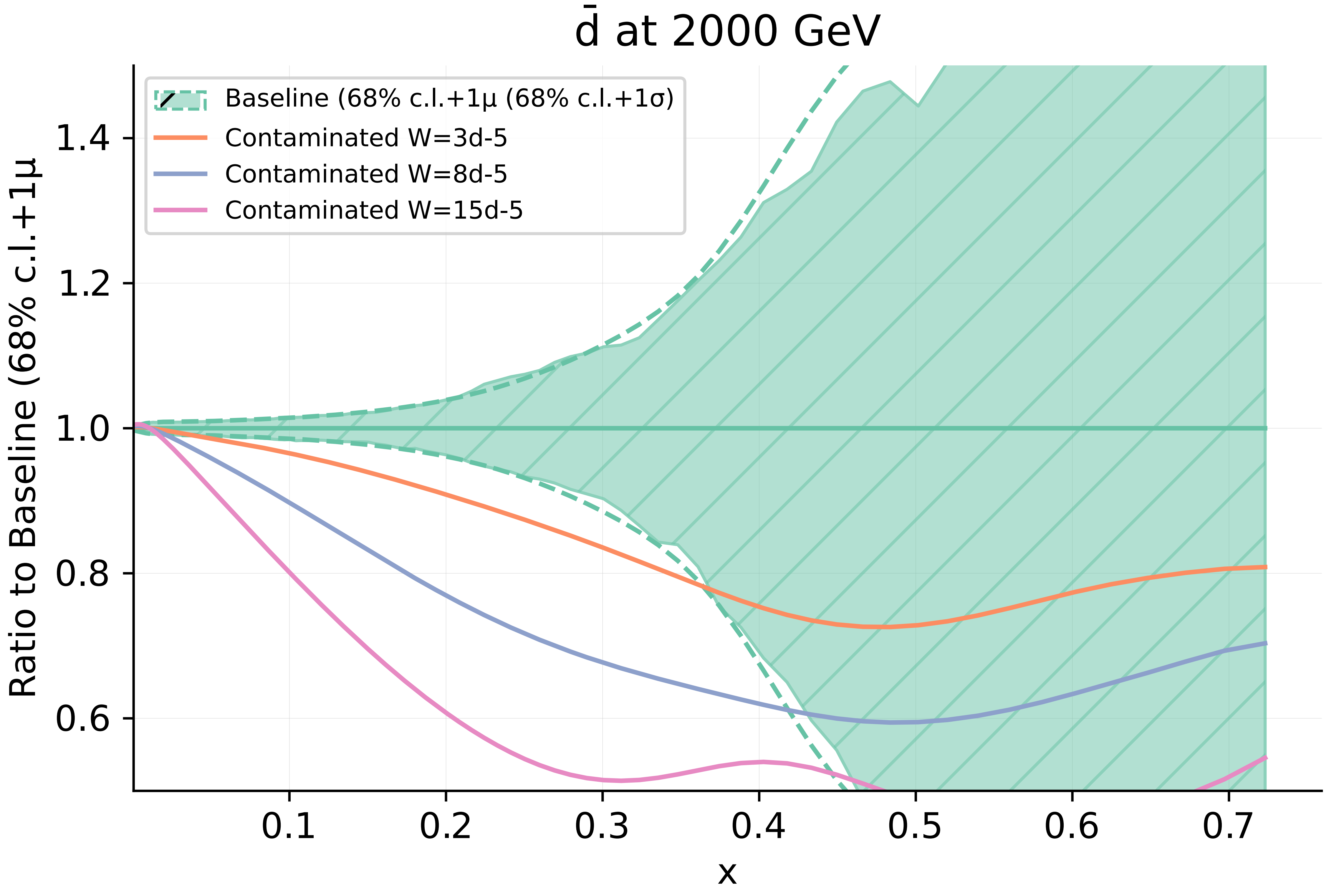
Data: 'true' PDF $\otimes$ SM + W'
Theory: contaminated PDF $\otimes$ SM



Fewer constraints on the **large-x antiquark PDFs** allow freedom to shift away from the baseline

W’-contaminated PDFs



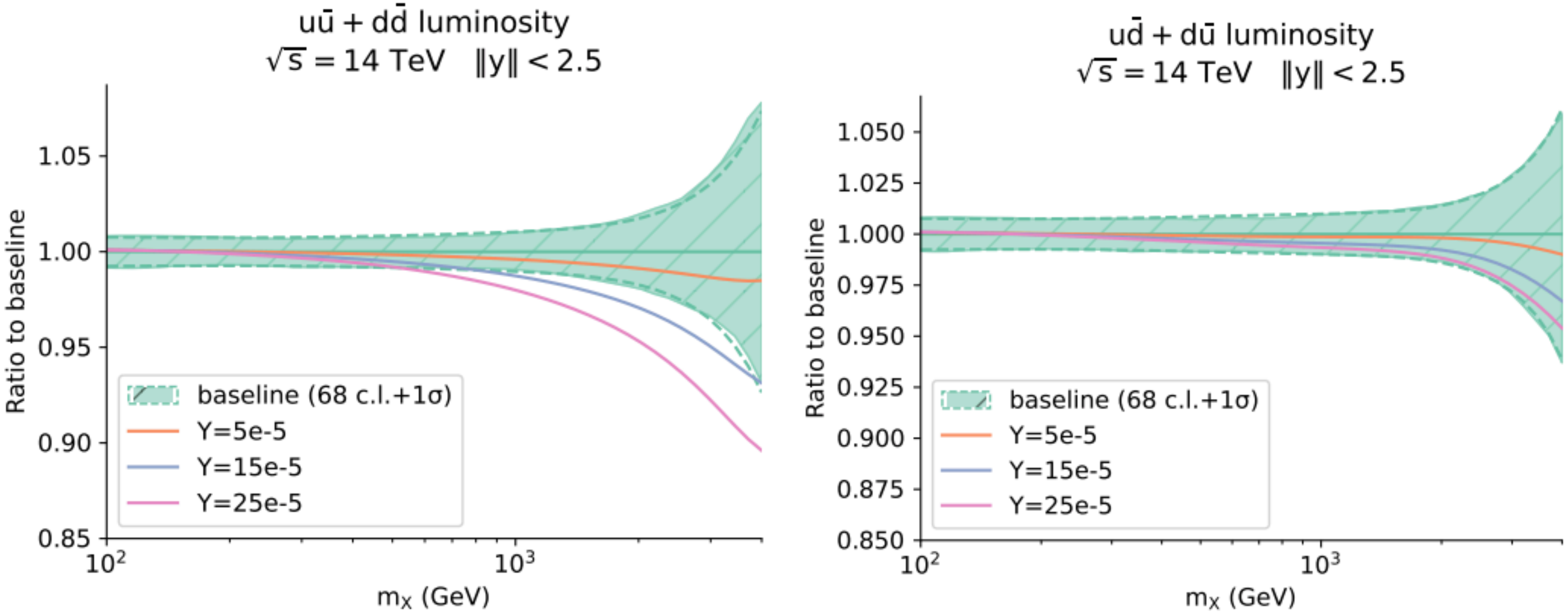


Z'-contaminated PDFs

Data: 'true' PDF $\otimes$ SM + Z'
Theory: contaminated PDF $\otimes$ SM

NC DY

CC DY



Charged current DY is not impacted by the Z' model

➡ CC DY data constrains the large-x quark and antiquark PDFs to be SM-like

➡ PDFs cannot shift enough to absorb NP effects in neutral current DY

Z'-contaminated PDFs

Data: 'true' PDF $\otimes$ SM + Z'
Theory: contaminated PDF $\otimes$ SM