UNIVERSITY OF CAMBRIDGE

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THE LHC RUN II TOP QUARK DATA LEGACY ON GLOBAL PDF AND SMEFT ANALYSES

MANUEL MORALES ALVARADO

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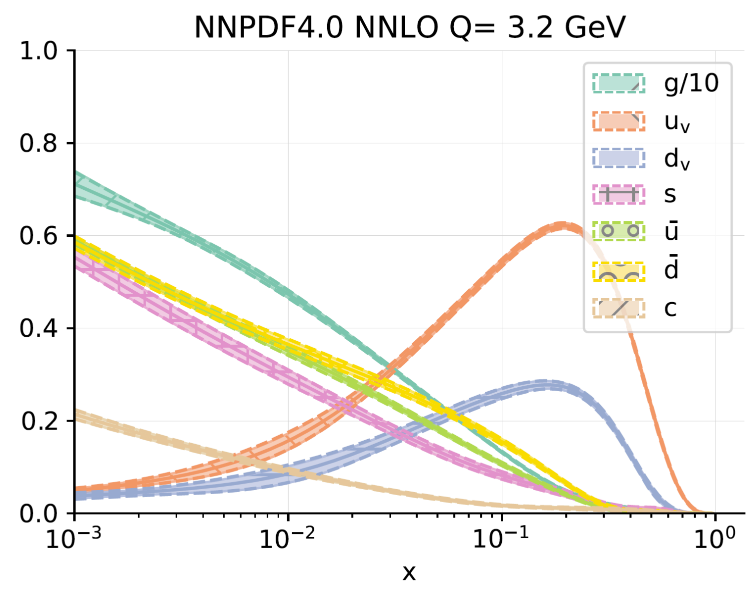
MANUEL MORALES ALVARADO

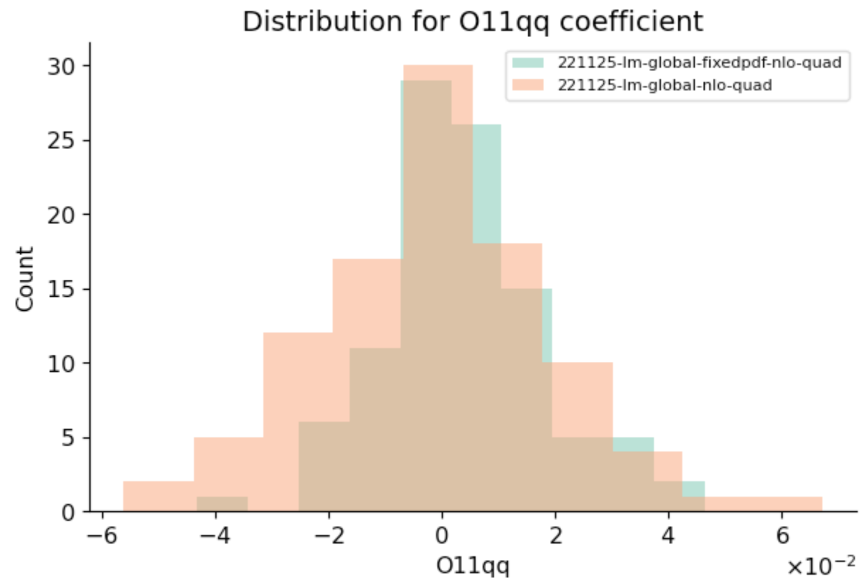
Thanks to J. Moore and M. Madigan for some of the slides!

OUTLINE



$$+ \frac{c_i}{\Lambda^2}$$

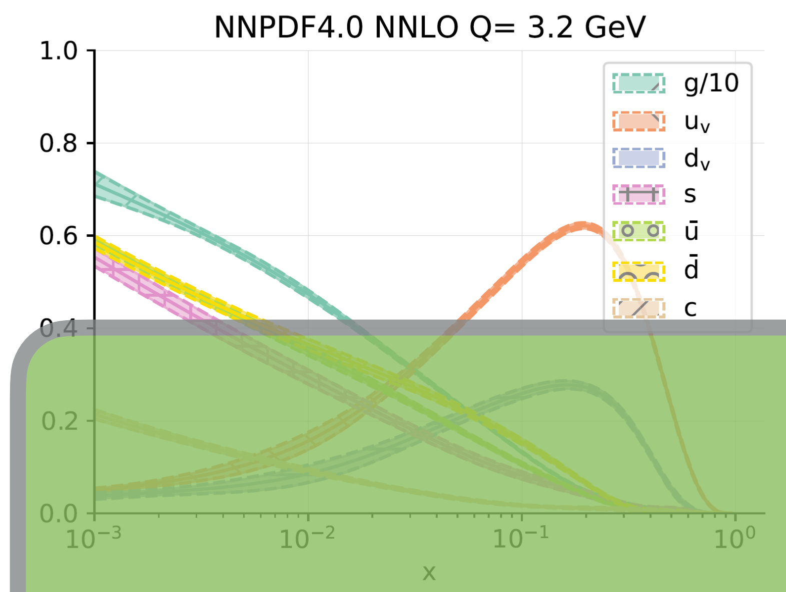
Background: PDFs and SMEFT



PDF-SMEFT interplay - DY & Top

Conclusions and outlook

OUTLINE



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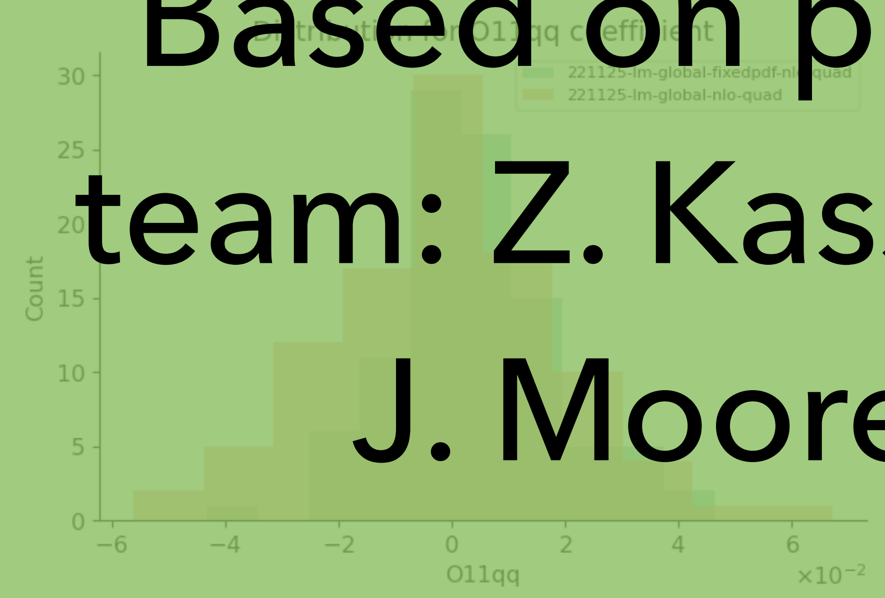
Background: PDFs and SMEFT

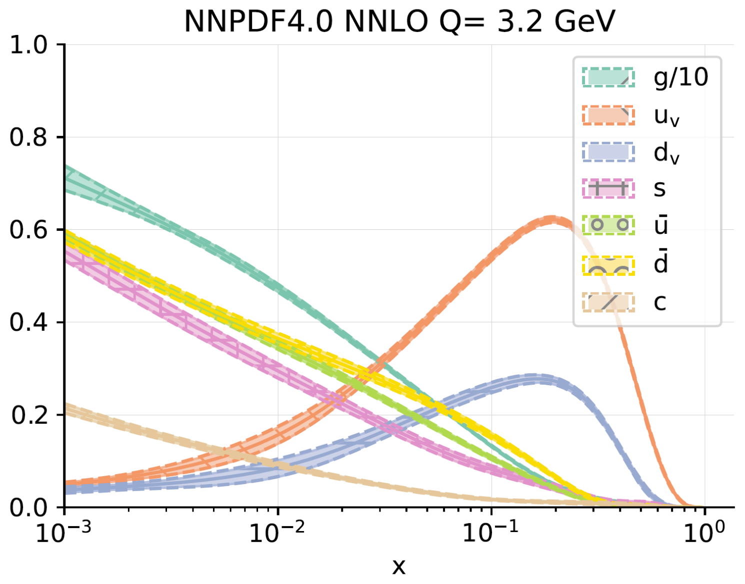


PDF-SMEFT interplay

Conclusions and outlook

Based on preliminary work with the PBSP team: Z. Kassabov, M. Madigan, L. Mantani, J. Moore, MMA, M.Ubiali & J. Rojo

OUTLINE



$$+ \quad \frac{c_i}{\Lambda^2}$$

Background: PDFs and SMEFT

PDF-SMEFT interplay - DY & Top

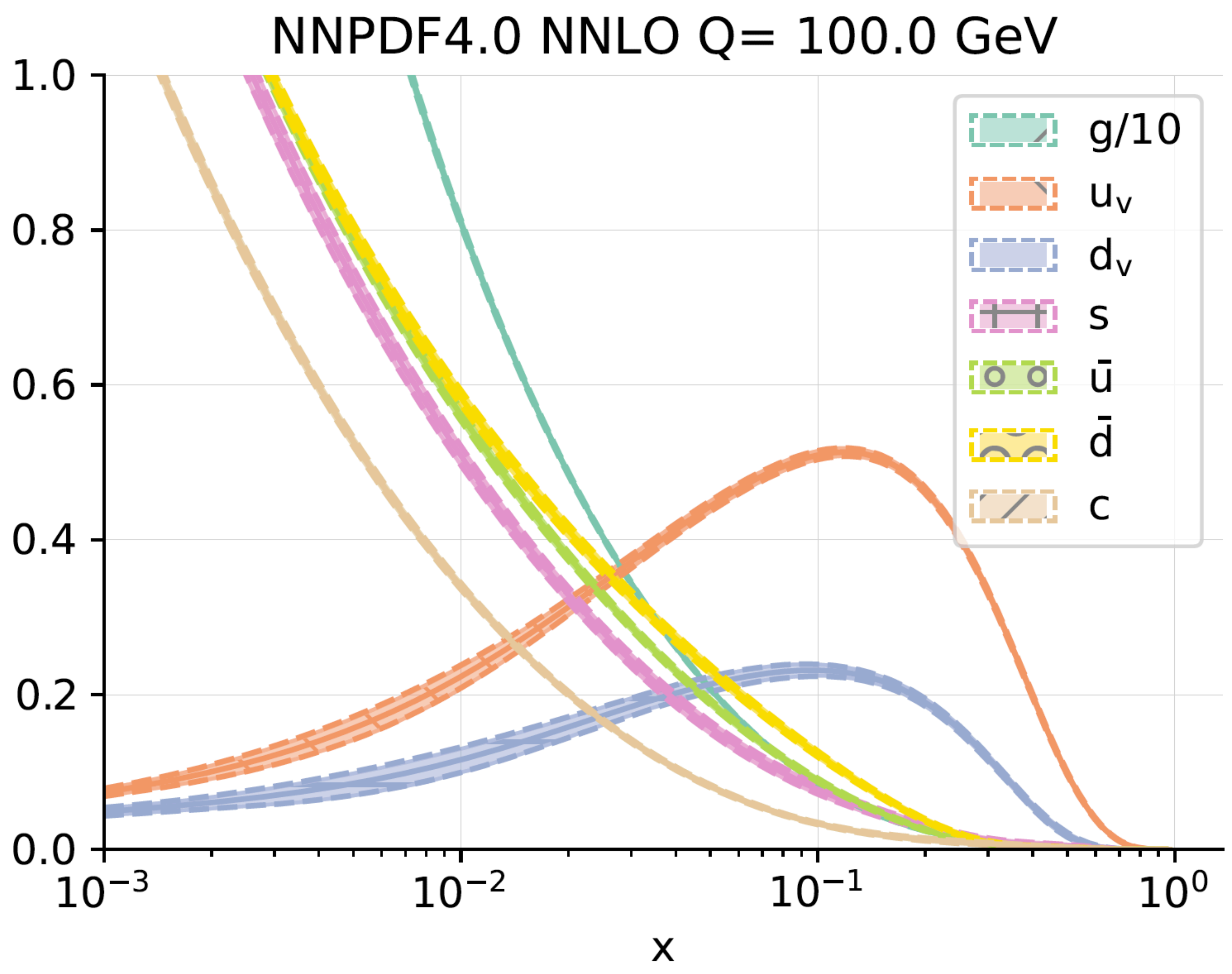
Conclusions and outlook

PARTON DISTRIBUTION FUNCTIONS

Parton distribution functions (PDFs) are important ingredients in LHC phenomenology

$$f(x, Q^2)$$

$$\sigma = \hat{\sigma} \otimes f$$



Ball et al. arXiv: 2109.02653

Recent global PDF fits include:

- NNPDF 4.0: Ball et al., 2109.02653
- CT18: Hou et al., 1912.10053
- MSHT20: Bailey et al., 2012.04684

PARTON DISTRIBUTION FUNCTIONS

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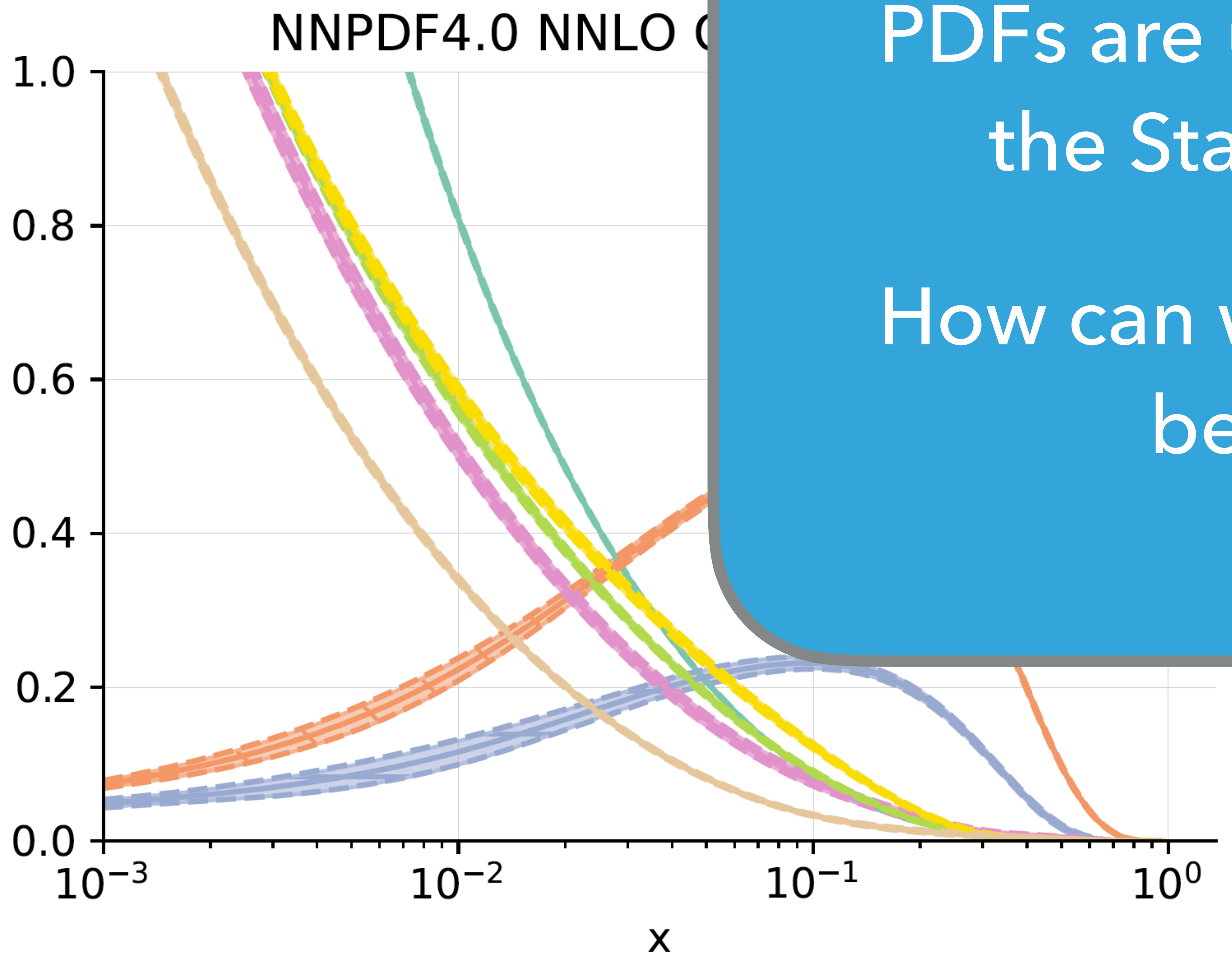

Ball et al. arXiv: 2109.02653

PDFs are usually determined in the Standard Model (SM)

How can we account for effects beyond the SM?

…lude:

- …2109.02653
- …10053
- MSHT20: Bailey et al., 2012.04684

STANDARD MODEL EFFECTIVE FIELD THEORY (SMEFT)

In the SMEFT we supplement the SM Lagrangian with towers of higher dimensional operators

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} Q_i^{(6)} + \cdots$$

With

c_i	Wilson coefficient (WC)
$\{Q_i^{(6)}\}$	Dimension 6 operators
Λ	High energy scale

In the SMEFT:

- There is a clear separation of scales Λ
- The only light degrees of freedom are the SM ones
- The gauge group still is $SU(3)_c \times SU(2)_L \times U(1)_Y$

STANDARD MODEL EFFECTIVE FIELD THEORY (SMEFT)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} Q_i^{(6)} + \cdots$$

B. Grzadkowski et al., 1008.4884
W. Buchmuller, D. Wyler, Nucl. Phys. B268 (1986) 621-653

We will parametrise the SMEFT using the Warsaw basis (59 operators without generation indices)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

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In the SMEFT we supplement the SM Lagrangian with towers of higher dimensional operators

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} Q_i^{(6)} + \cdots$$

B. Grzadkowski et al., 1008.4884
W. Buchmuller, D. Wyler, Nucl. Phys. B268 (1986) 621-653

We will parametrise the SMEFT using ... ices)

How can PDFs be related to the SMEFT?

X^3		φ^6 an…			
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ			
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi$…		
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D$…		
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		ψ^2…			
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi \widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi \widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
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… $\bar R R)$		$(\bar L L)(\bar R R)$	
	… $)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
	… $)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
	… $)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
	… $)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
	… $)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
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$(\bar L R)(\bar R L)$ and $(\bar L R)(\bar L R)$		B-violating	
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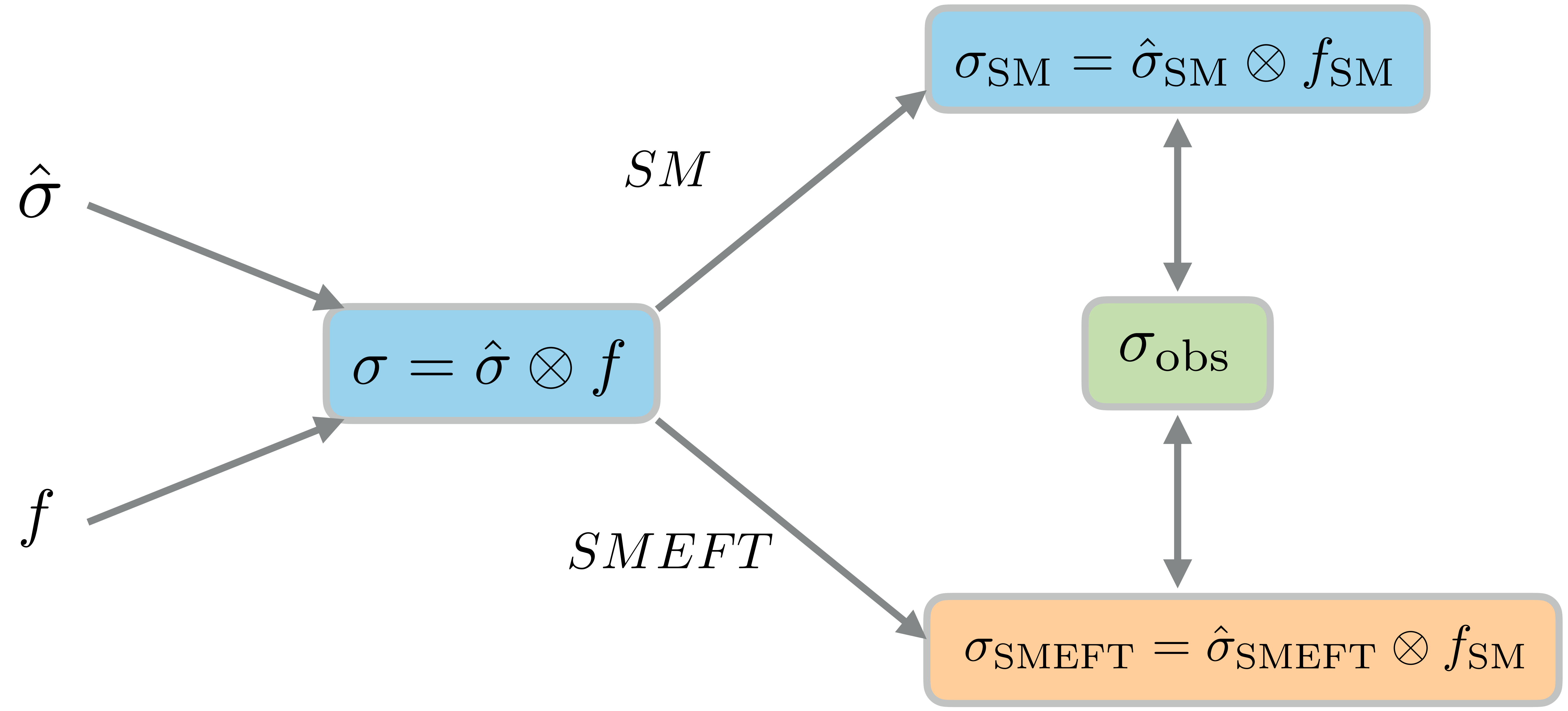
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

PDFS AND SMEFT

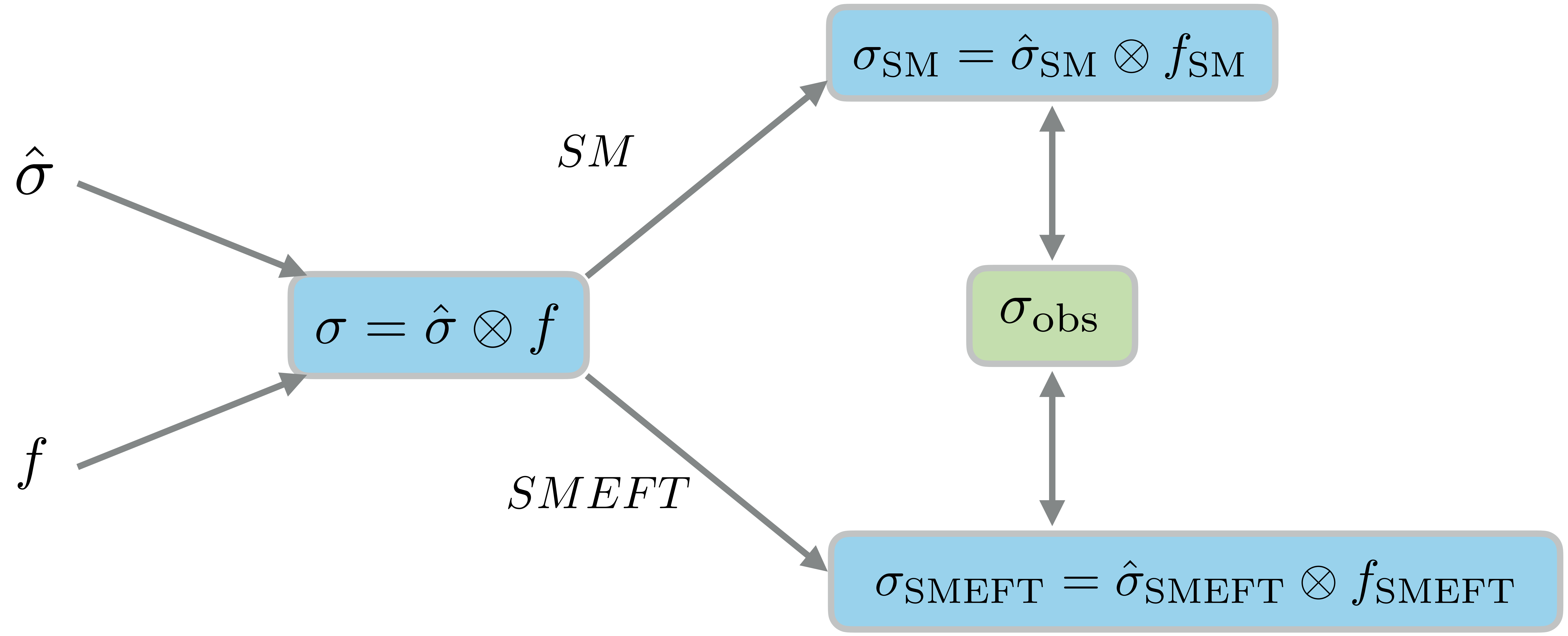
From partonic cross sections and PDFs to observables:



Possible inconsistency in our theoretical calculations

PDFS AND SMEFT

From partonic cross sections and PDFs to observables:

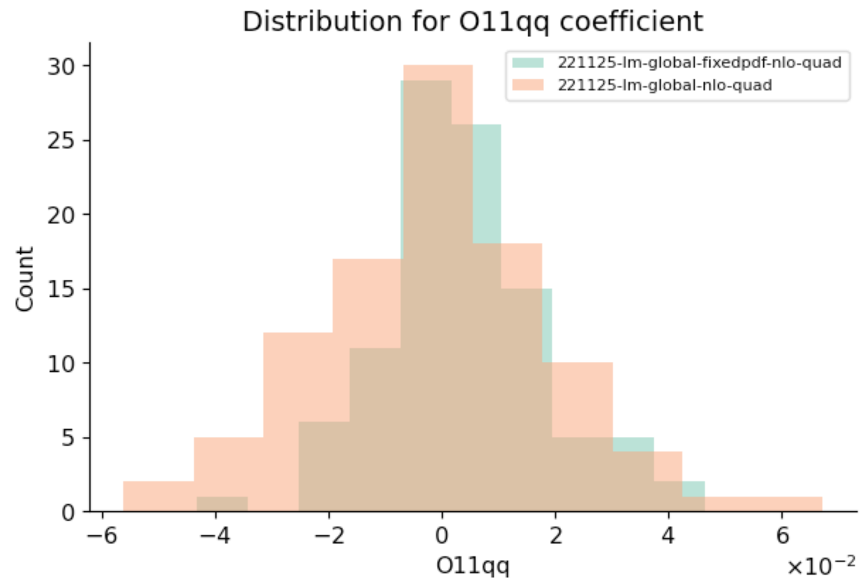


✅ We include the PDF-SMEFT interplay

OUTLINE

$$+ \frac{c_i}{\Lambda^2}$$

Background: PDFs and SMEFT



PDF-SMEFT interplay - DY & Top

Conclusions and outlook

EXTRACTION OF PHYSICAL PARAMETERS FROM DATA

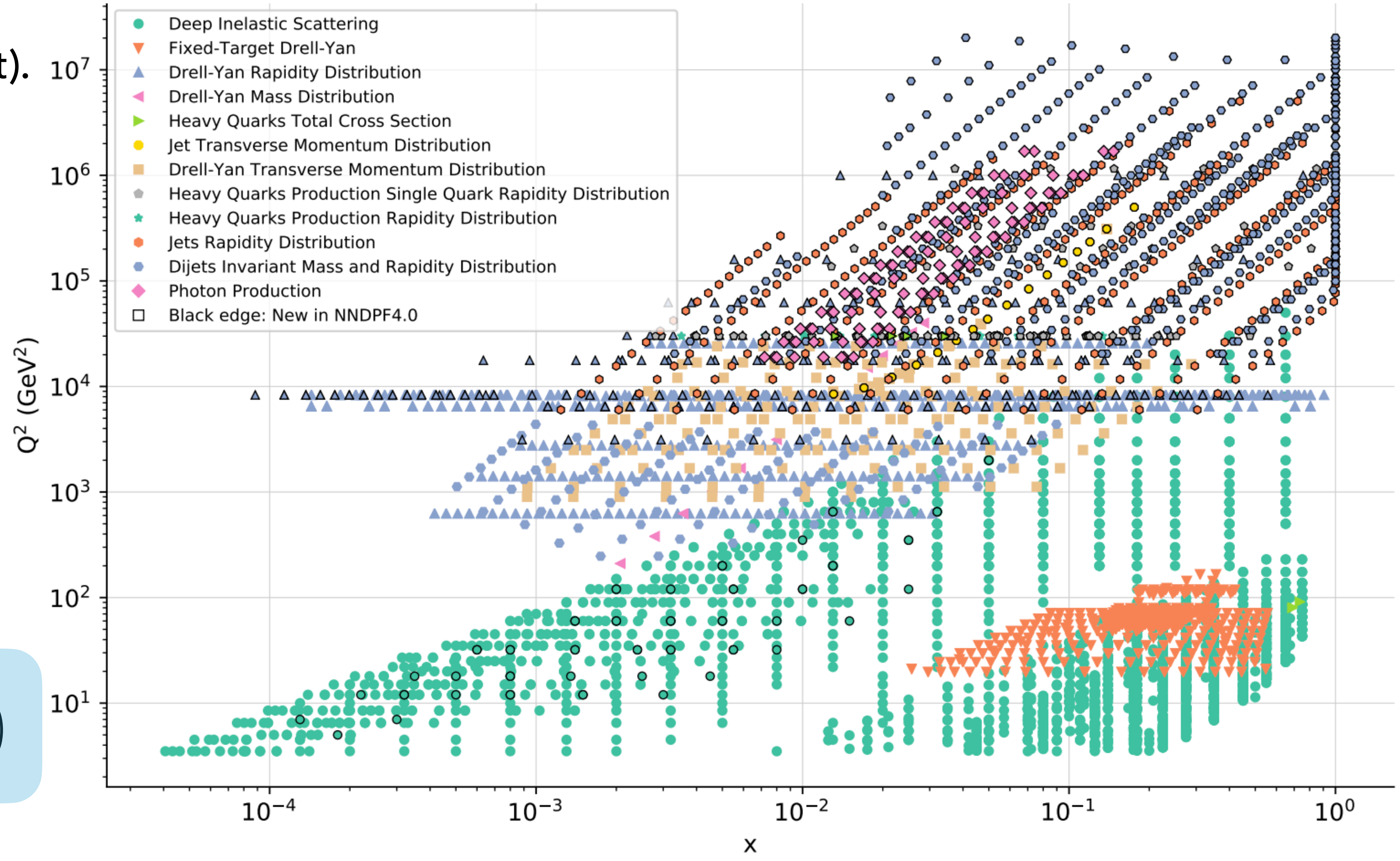
PDFs cannot be calculated from first principles (yet).
They have to be extracted from data.

$$f \to f(\{\theta\})$$

SMEFT predictions depend on $\{c\}$.

We extract the parameters $\{\theta\}$ and $\{c\}$ that minimise

$$\chi^2 = \frac{1}{N_{dat}} \sum_{i}^{N_{dat}} \Big(T_i(\{\theta\},\{c\}) - D_i \Big) \mathrm{cov}_{ij}^{-1} \Big(T_j(\{\theta\},\{c\}) - D_j \Big)$$

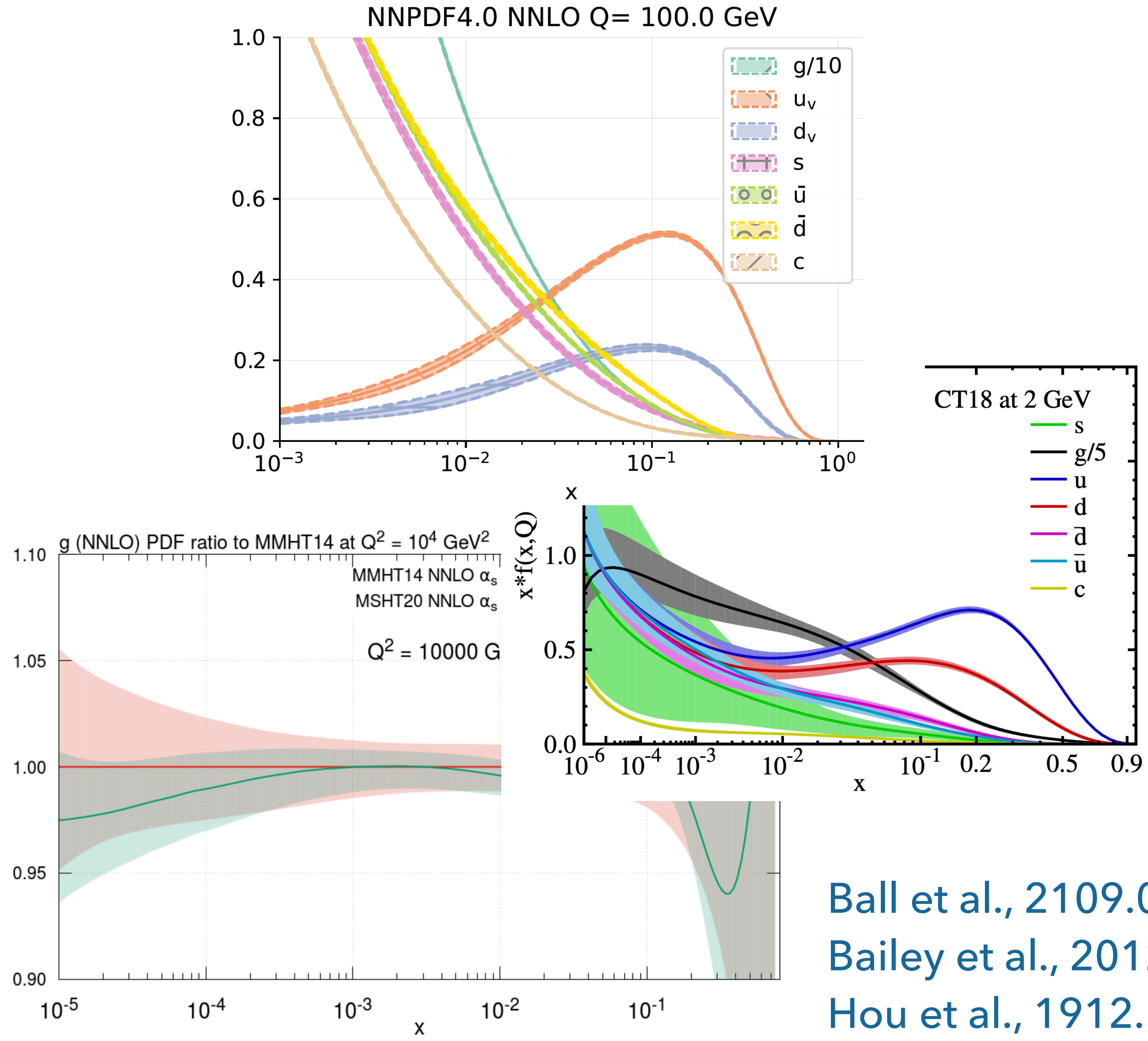


Ball et al. arXiv: 2109.02653

EXTRACTION OF PHYSICAL PARAMETERS FROM DATA

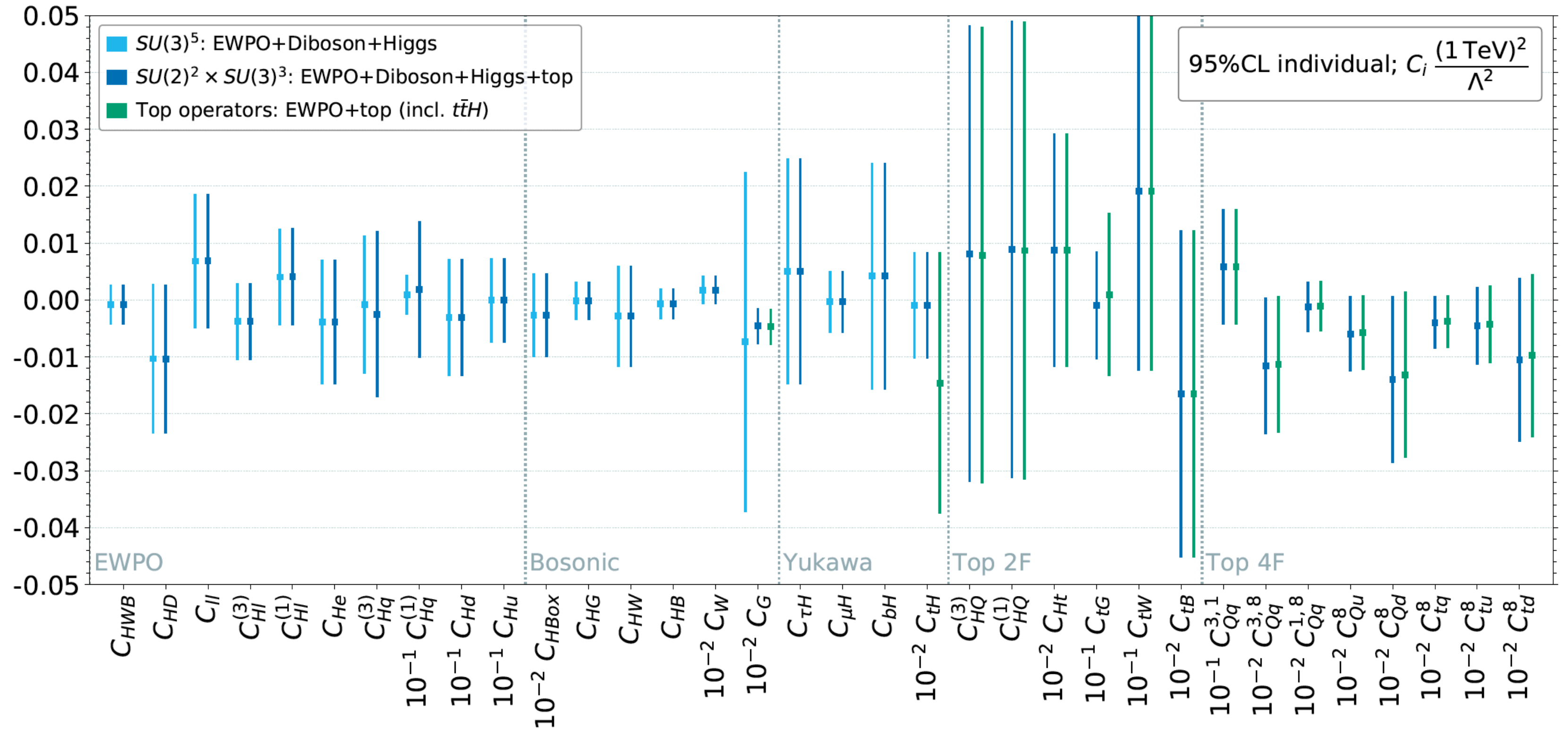
In this way we obtain

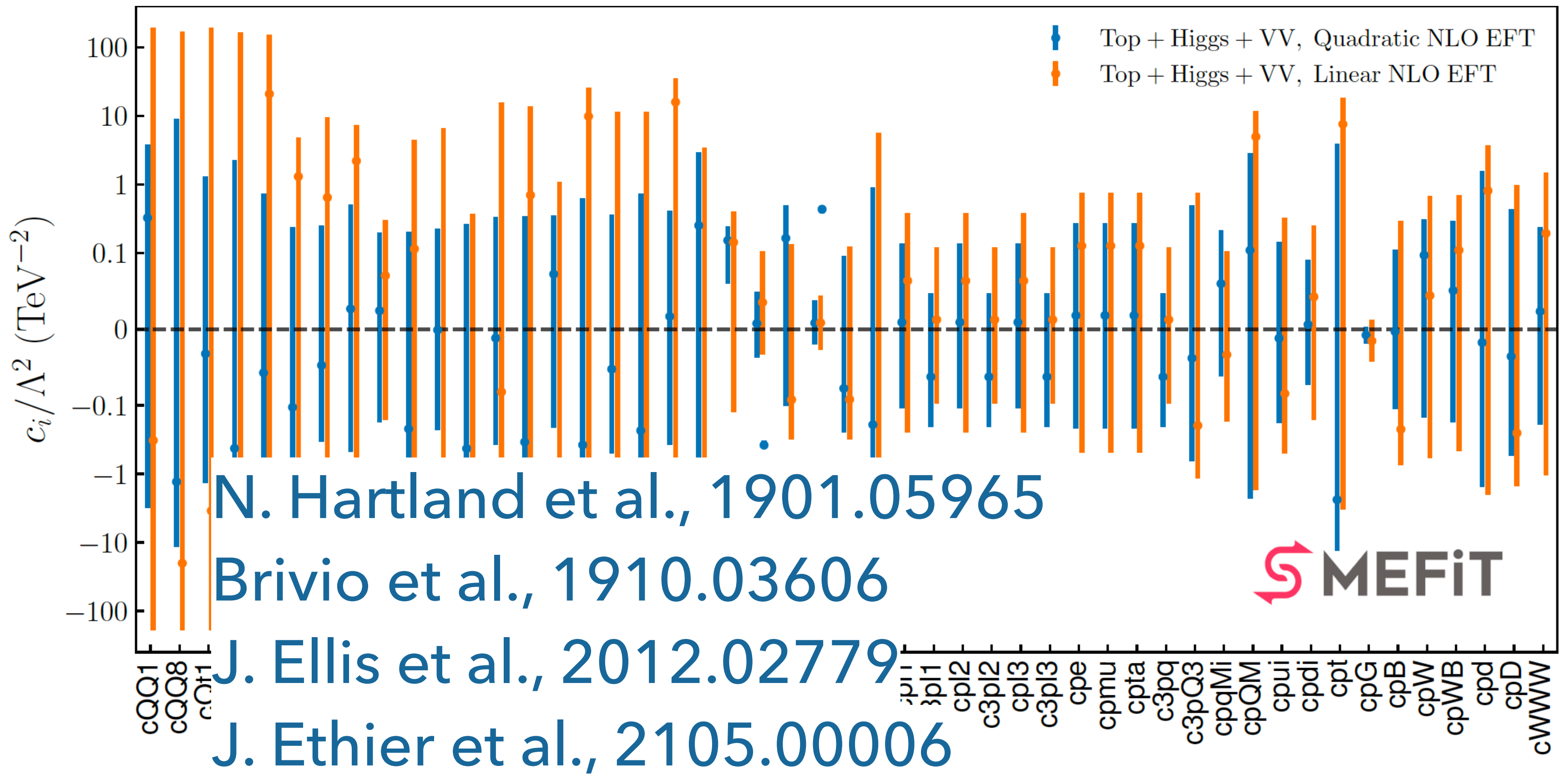
PDFs



Ball et al., 2109.02653
Bailey et al., 2012.04684
Hou et al., 1912.10053

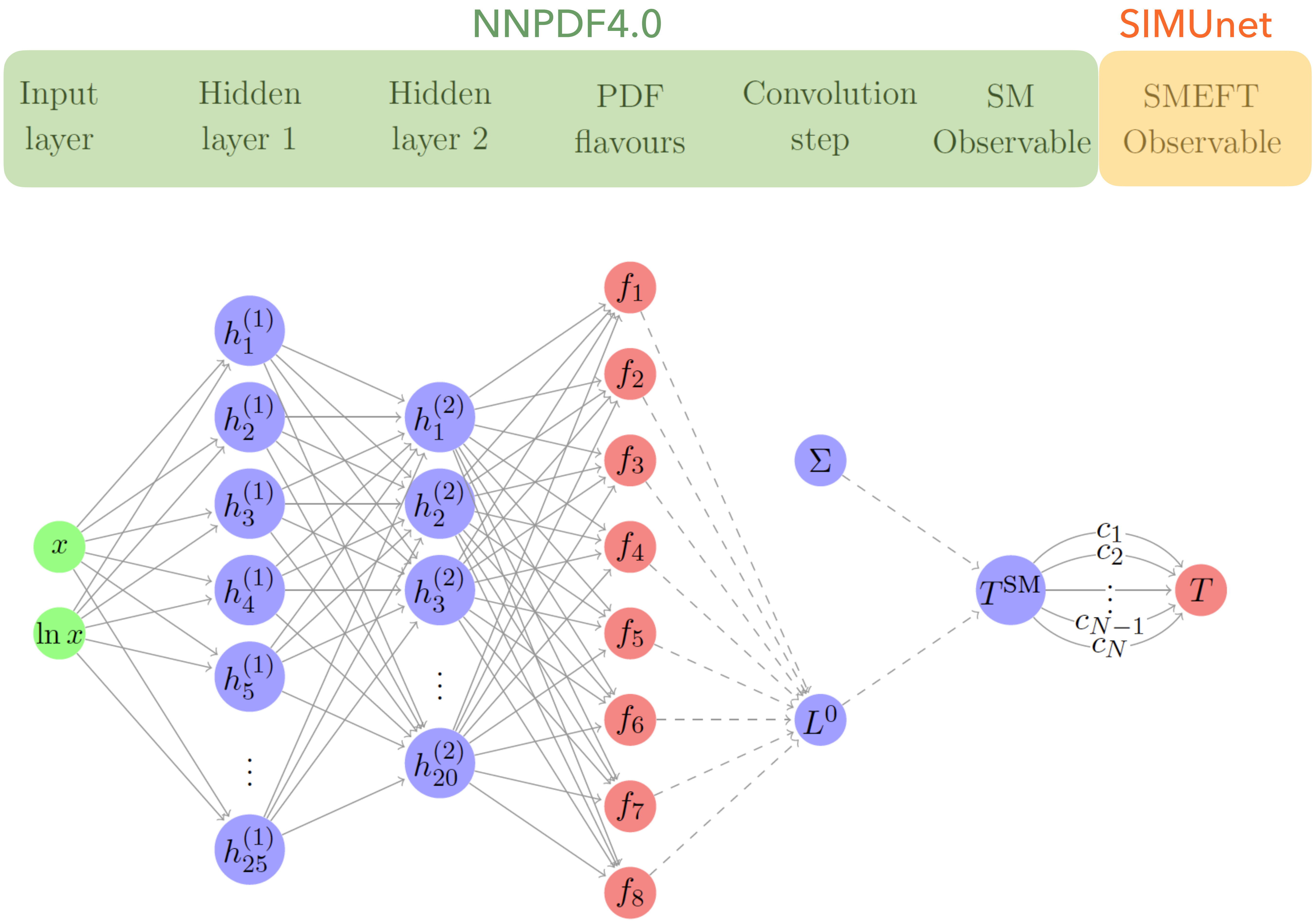
SMEFT Wilson coefficients





N. Hartland et al., 1901.05965
Brivio et al., 1910.03606
J. Ellis et al., 2012.02779
J. Ethier et al., 2105.00006

SIMULTANEOUS PDF-SMEFT FITS: SIMUNET



- Methodology based on NNPDF4.0. It uses neural networks to perform SM PDF fits by optimising θ
- It takes the SM prediction T^{SM} and maps into T by calling on the $\{c_i\}$ trainable parameters (Wilson coefficients)
- The parameters $\{c_i\}$ and the PDF parameters θ can be optimised simultaneously

Iranipour, Ubiali, 2201.07240

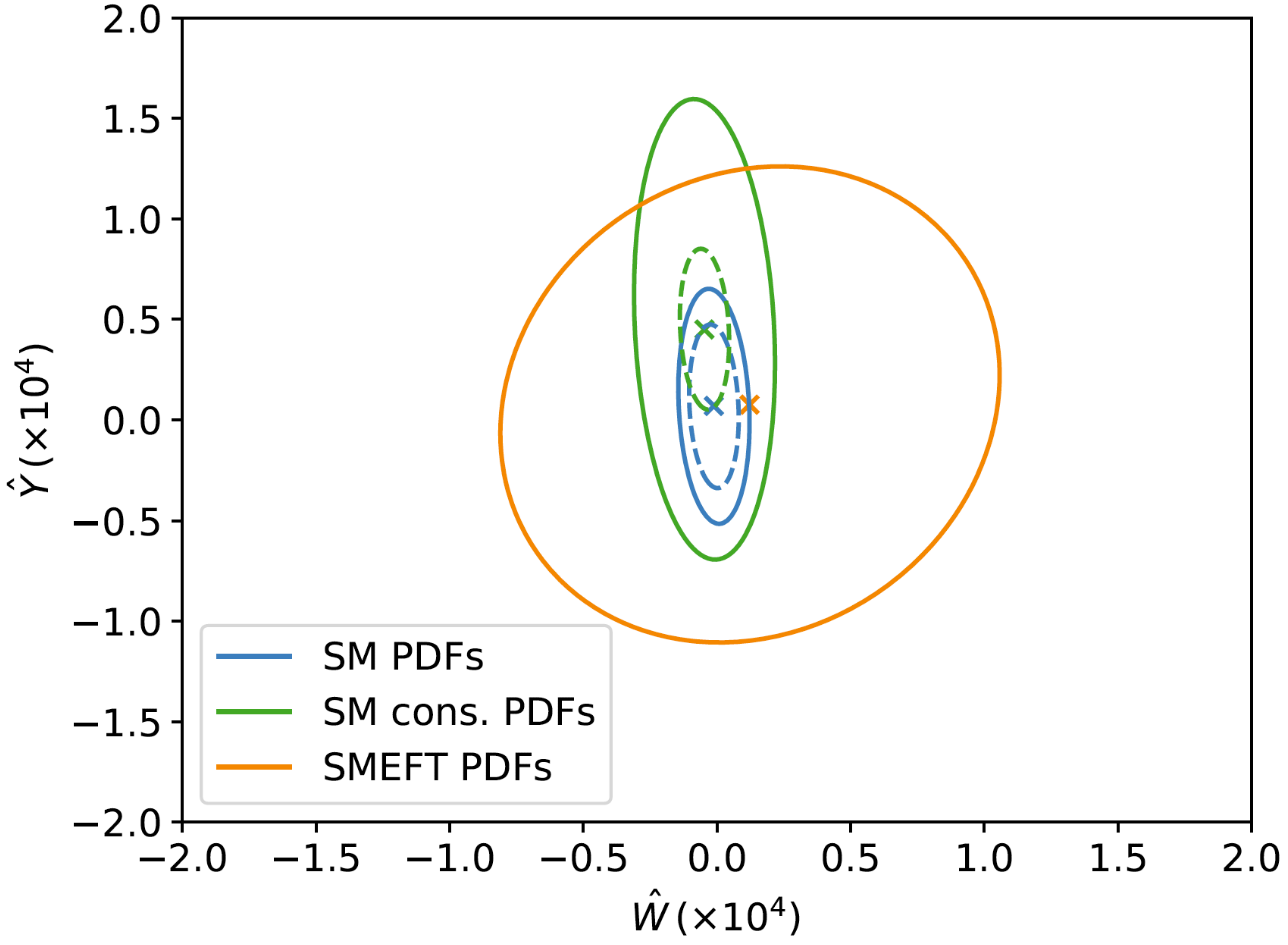
PDF-SMEFT FITS IN DRELL-YAN DATA

The PDF-SMEFT interplay is not negligible.

Greljo et al, 2104.02723

Carrazza et al, 1905.05215
Greljo et al, 2104.02723
Liu et al, 2201.06586
CMS 2111.10431

$$\mathcal{L}_{\rm SMEFT} \supset \mathcal{L}_{\rm SM} - \frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



- Failing to consider the PDF-SMEFT interplay can lead to an overestimation of the constraints on the Wilson coefficients

PDF-SMEFT FITS IN TOP DATA

N. Hartland et al., 1901.05965
Brivio et al., 1910.03606
J. Ellis et al., 2012.02779
J. Ethier et al., 2105.00006

- The top sector has received a lot of attention over the last couple of years
- We study the PDF-SMEFT interplay in the top sector
- Considerable effort has been made to include the broadest set of top data points from Runs I and II:

~200 data points from

ATLAS and CMS!

- We study the effect of 25 SMEFT operators (linear and quadratic contributions)

$$\sigma = \sigma^{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \sigma_i^{\mathrm{SMEFT}} + \sum_{i,j} \frac{c_i}{\Lambda^2} \frac{c_j}{\Lambda^2} \sigma_{ij}^{\mathrm{SMEFT}}$$

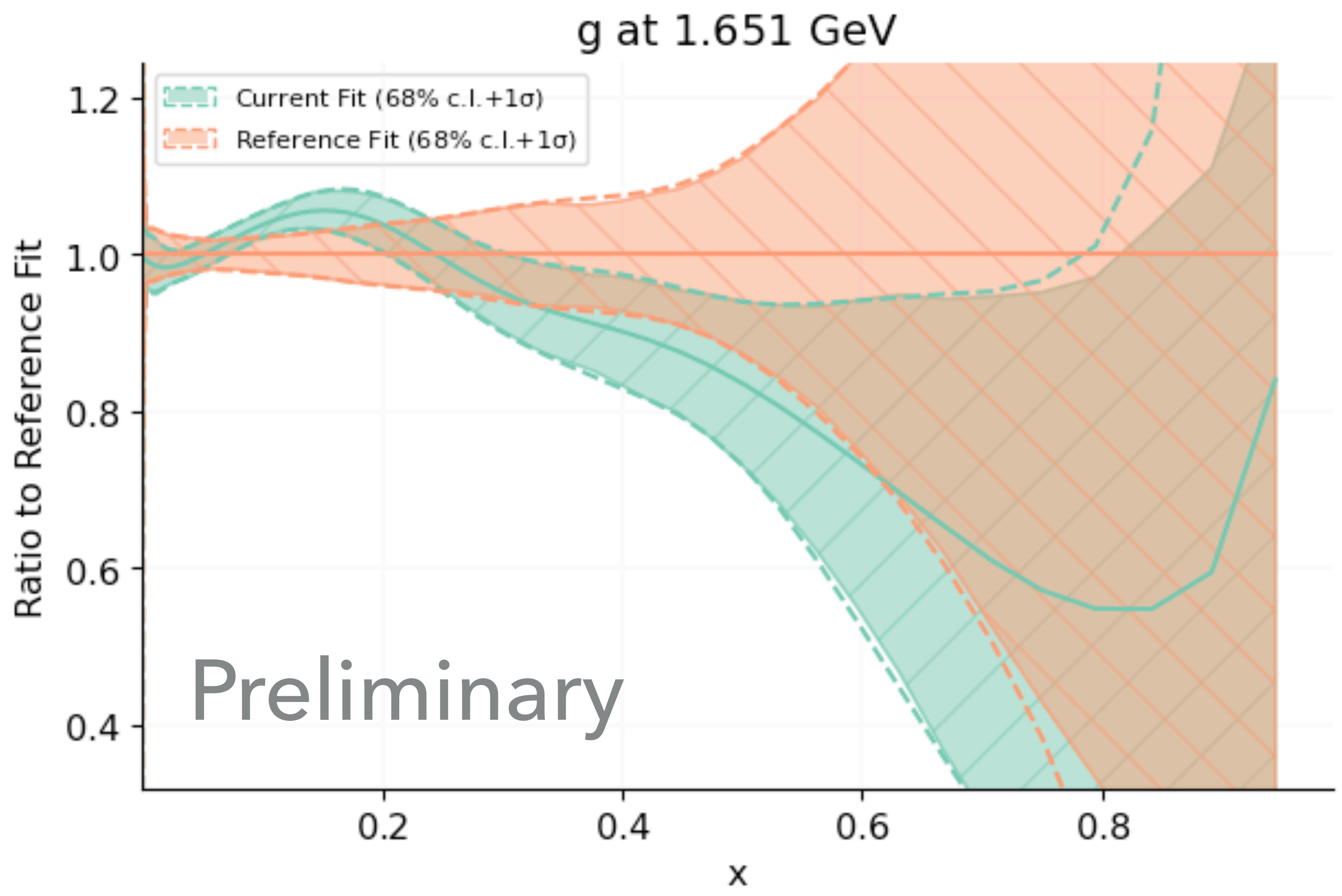
PDF-SM FITS IN TOP DATA

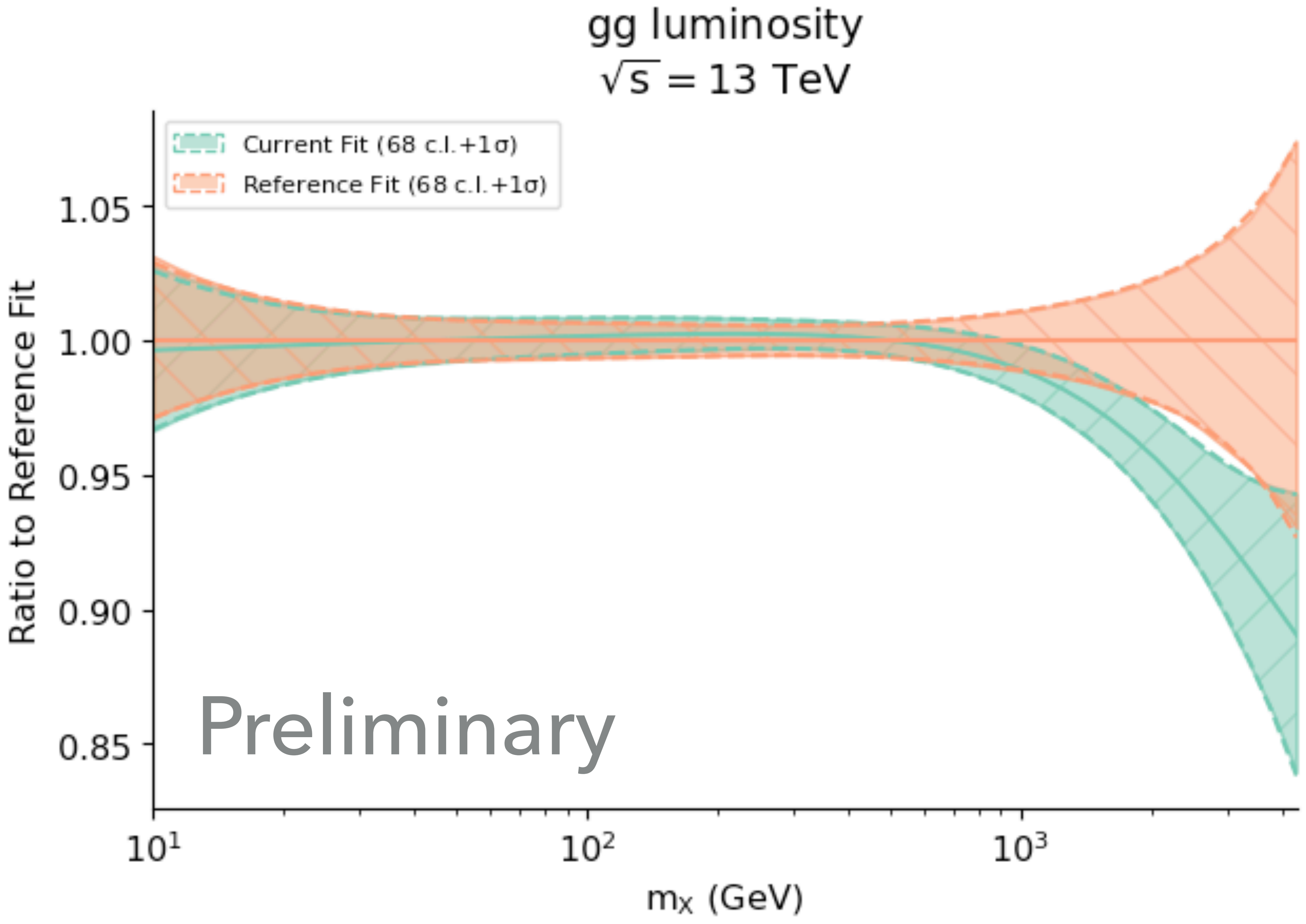
- With the new data, the SM PDFs change.

Orange: no-top data

Green: including top data

$$\mathcal{L}_{ij}(\tau, M_X^2) = \int_\tau^1 \frac{dx}{x} f_i(x, M_X^2) f_j(\tau/x, M_X^2)$$





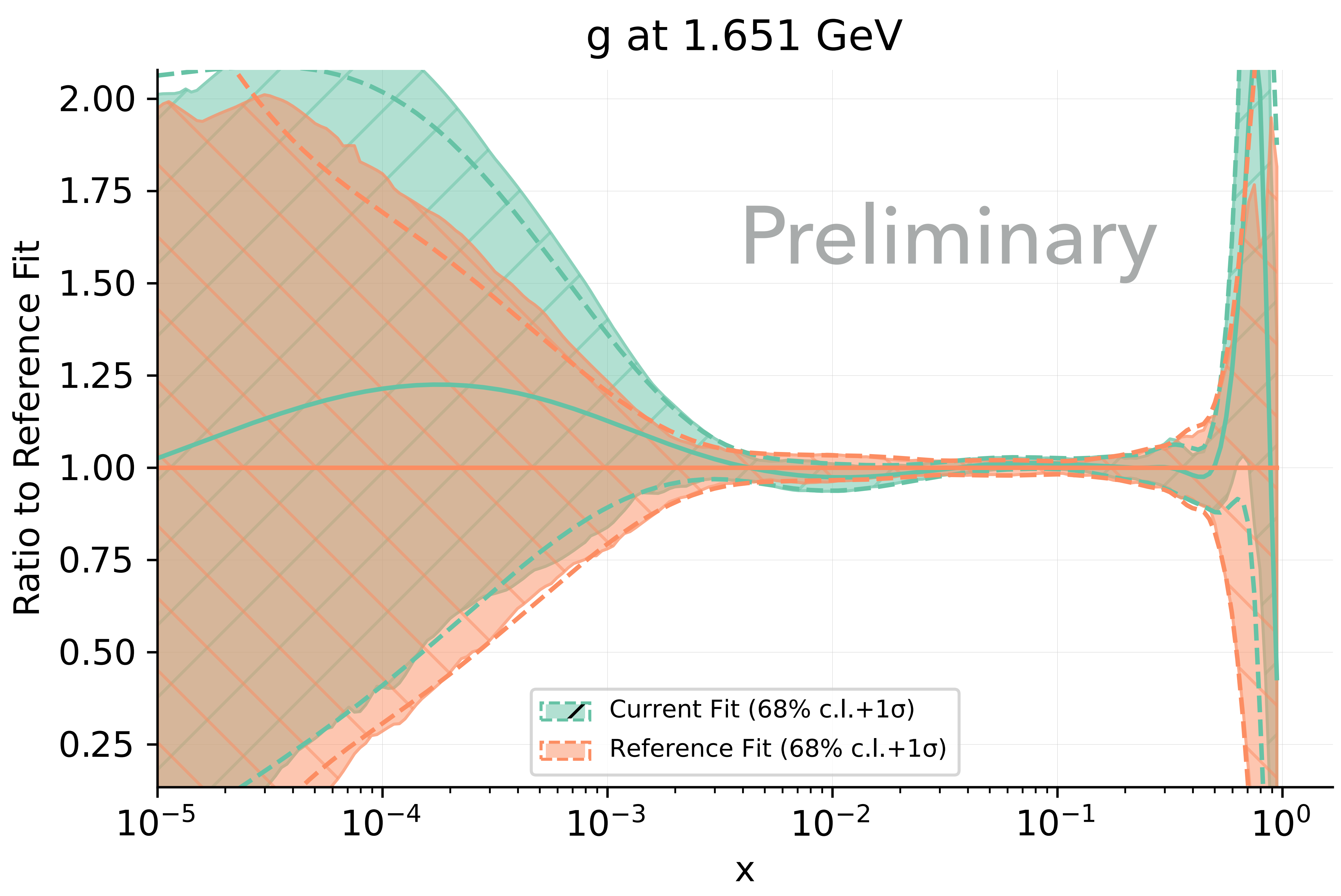
PDF-SMEFT FITS IN TOP DATA

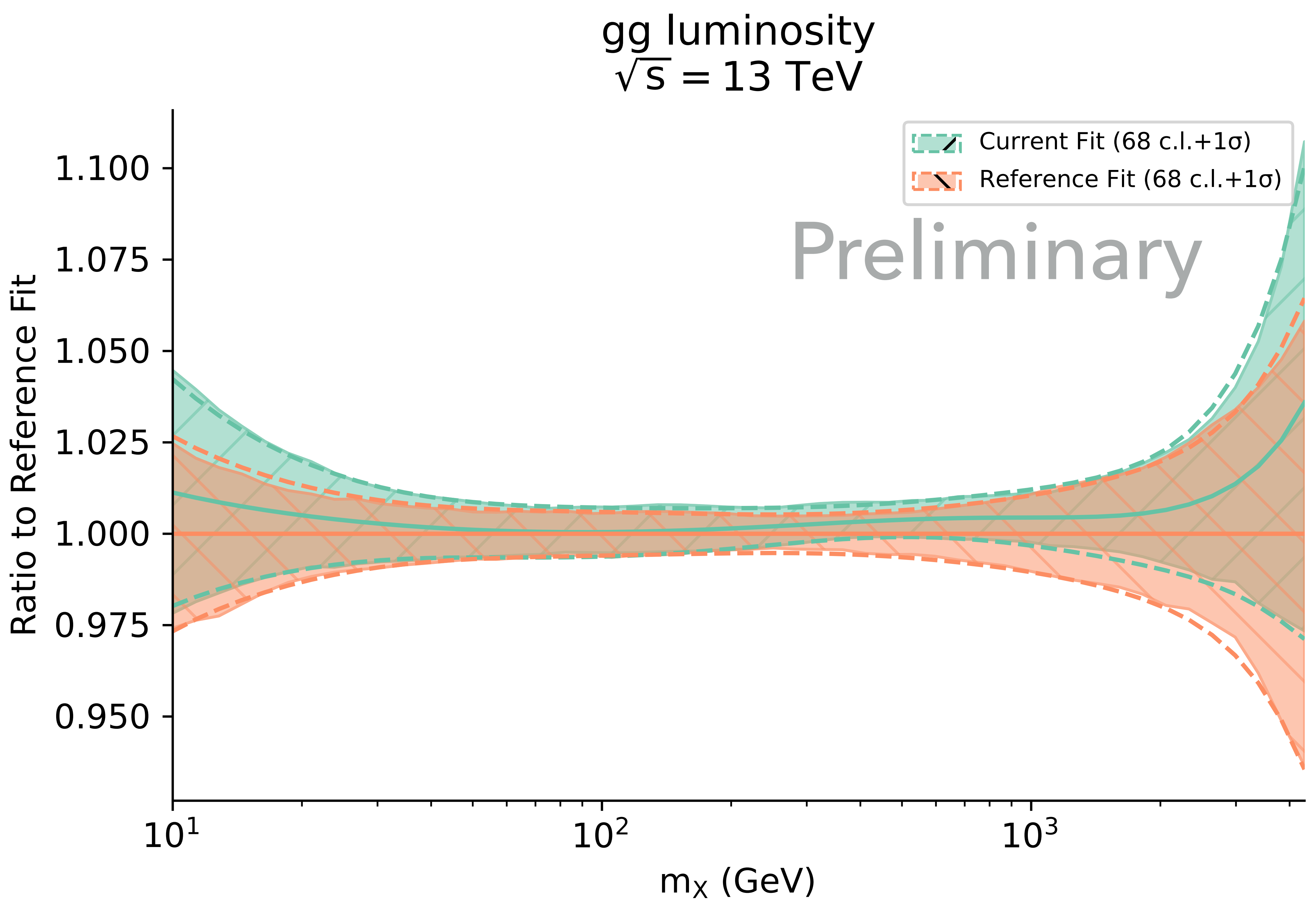
- The PDFs change when we perform a simultaneous fit with Wilson coefficients

Green: PDF-only fit

Orange: PDF-SMEFT simultaneous fit

(With global top dataset)



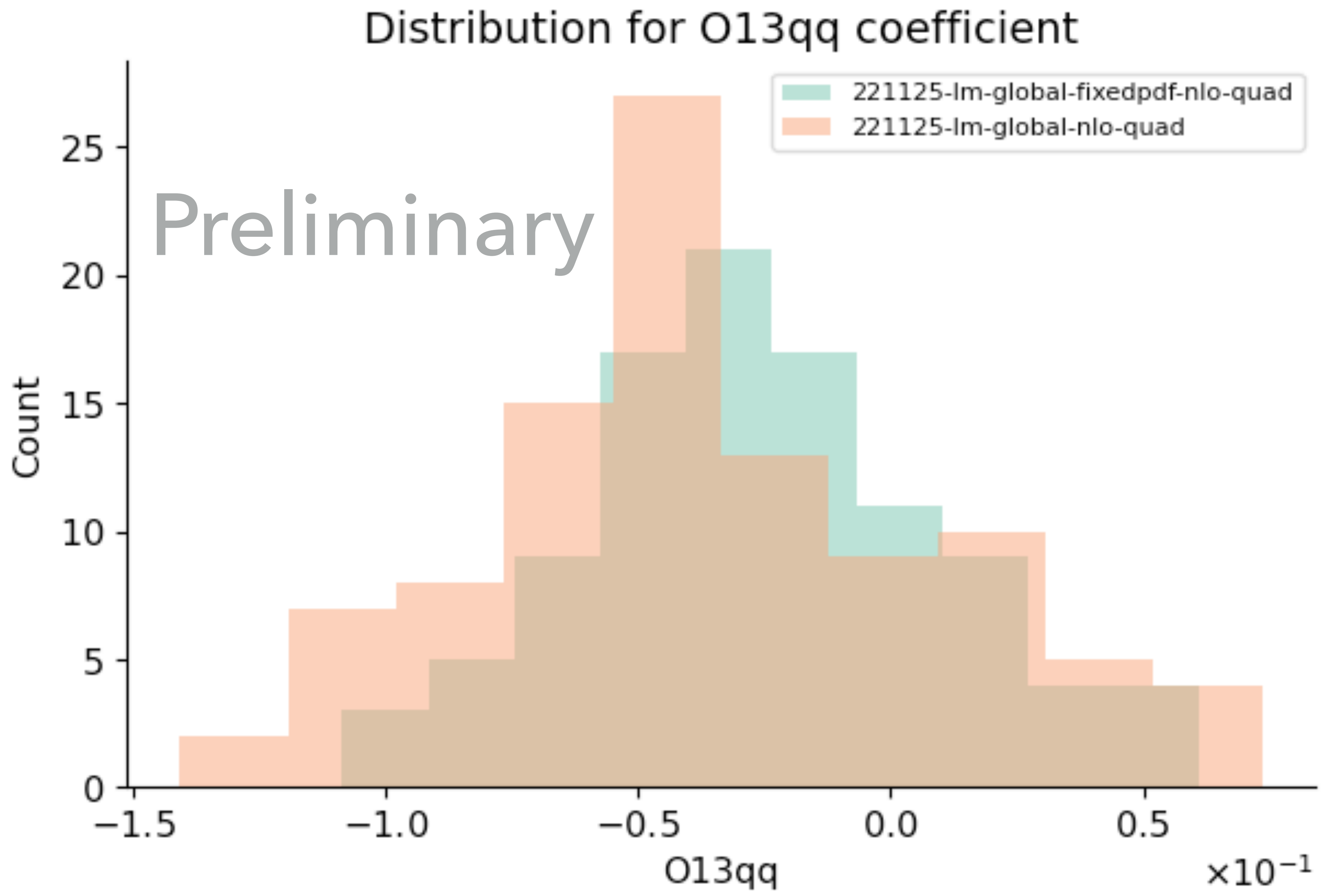


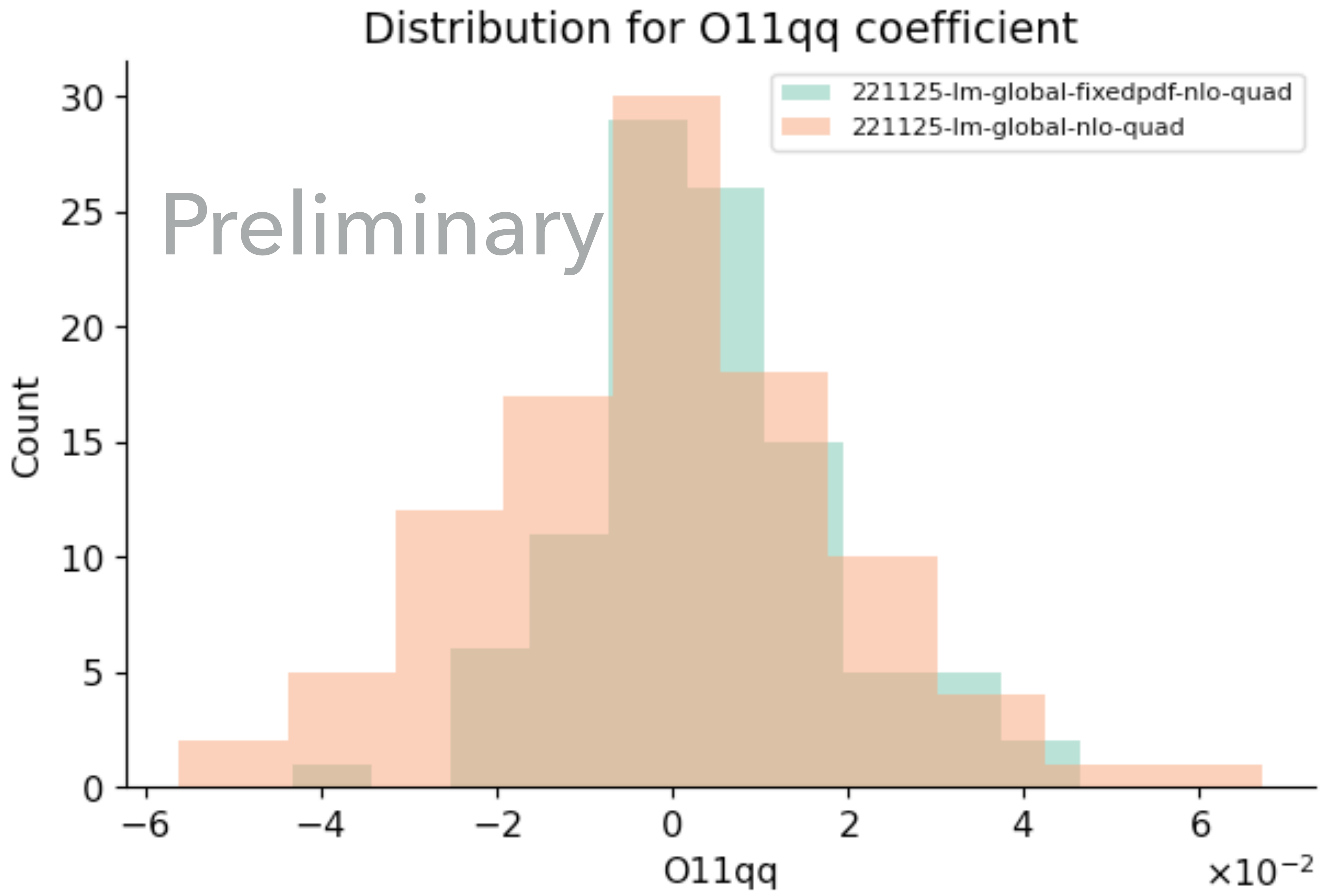
PDF-SMEFT FITS IN TOP DATA

- In a simultaneous PDF-SMEFT fit the constraints on the Wilson are slightly relaxed (~20% broadening)

Green: fixed PDF fit

Orange: simultaneous PDF-SMEFT fit



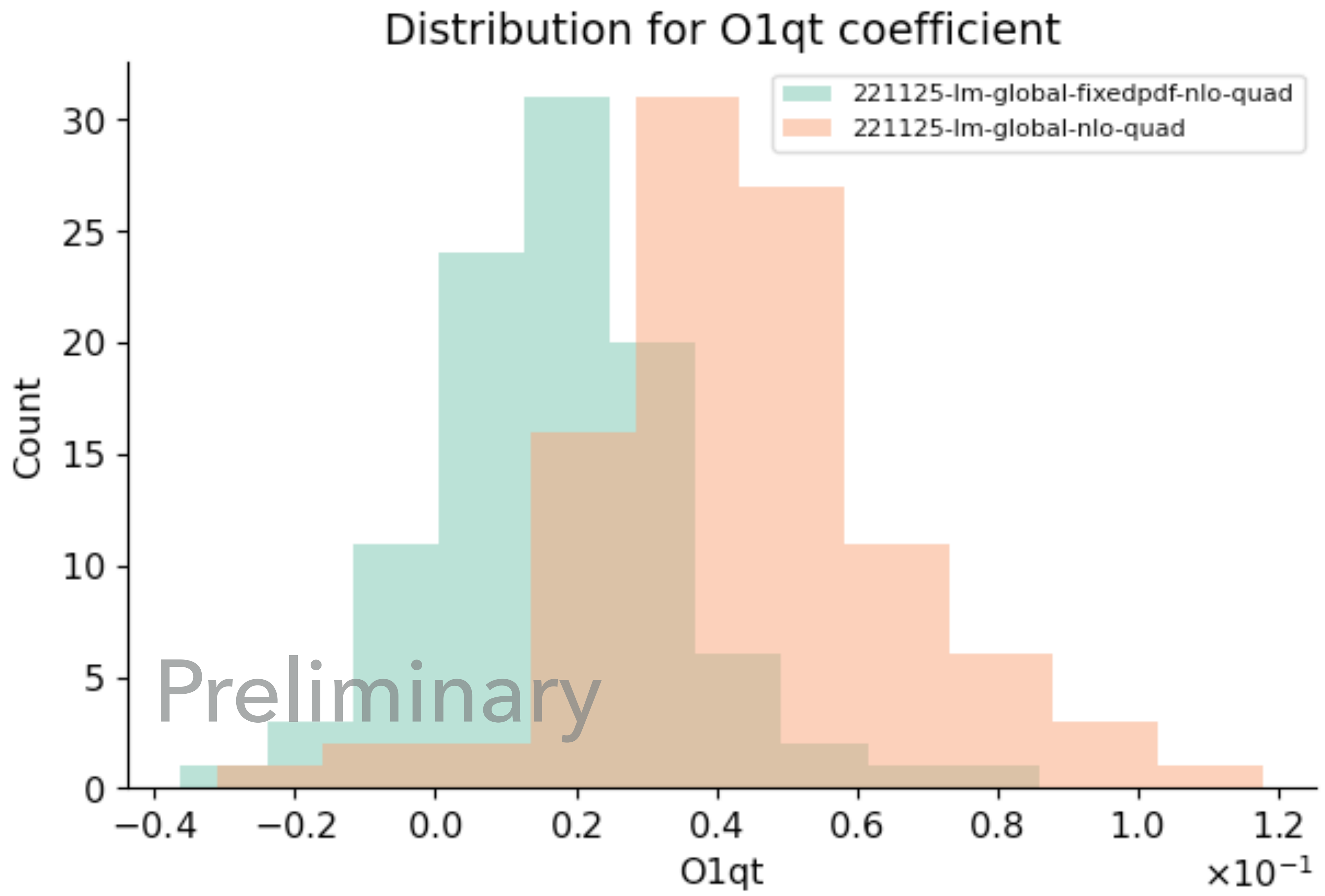


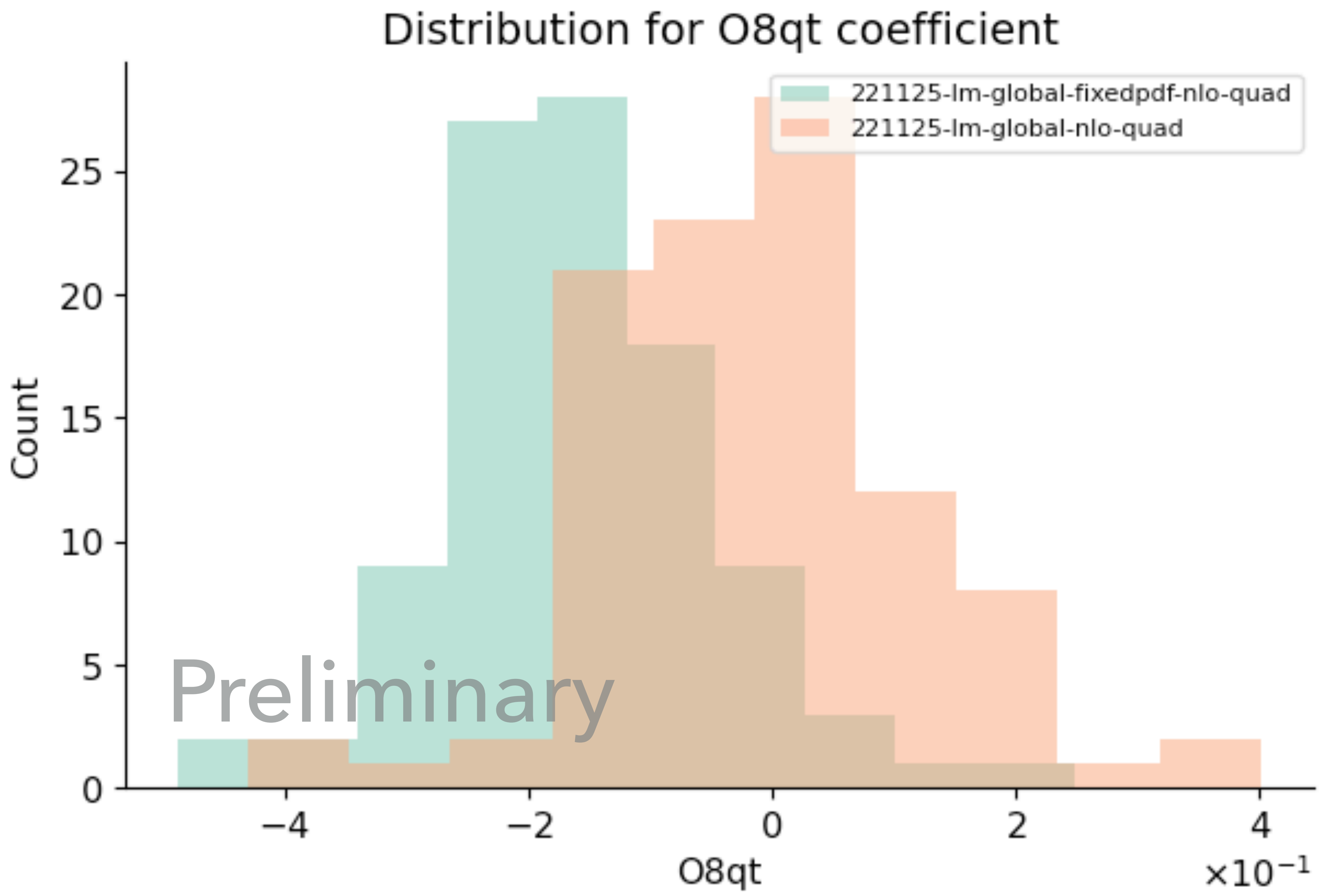
PDF–SMEFT FITS IN TOP DATA

- In a simultaneous PDF-SMEFT fit the central values of the Wilson coefficients can shift

Green: fixed PDF fit

Orange: simultaneous PDF-SMEFT fit



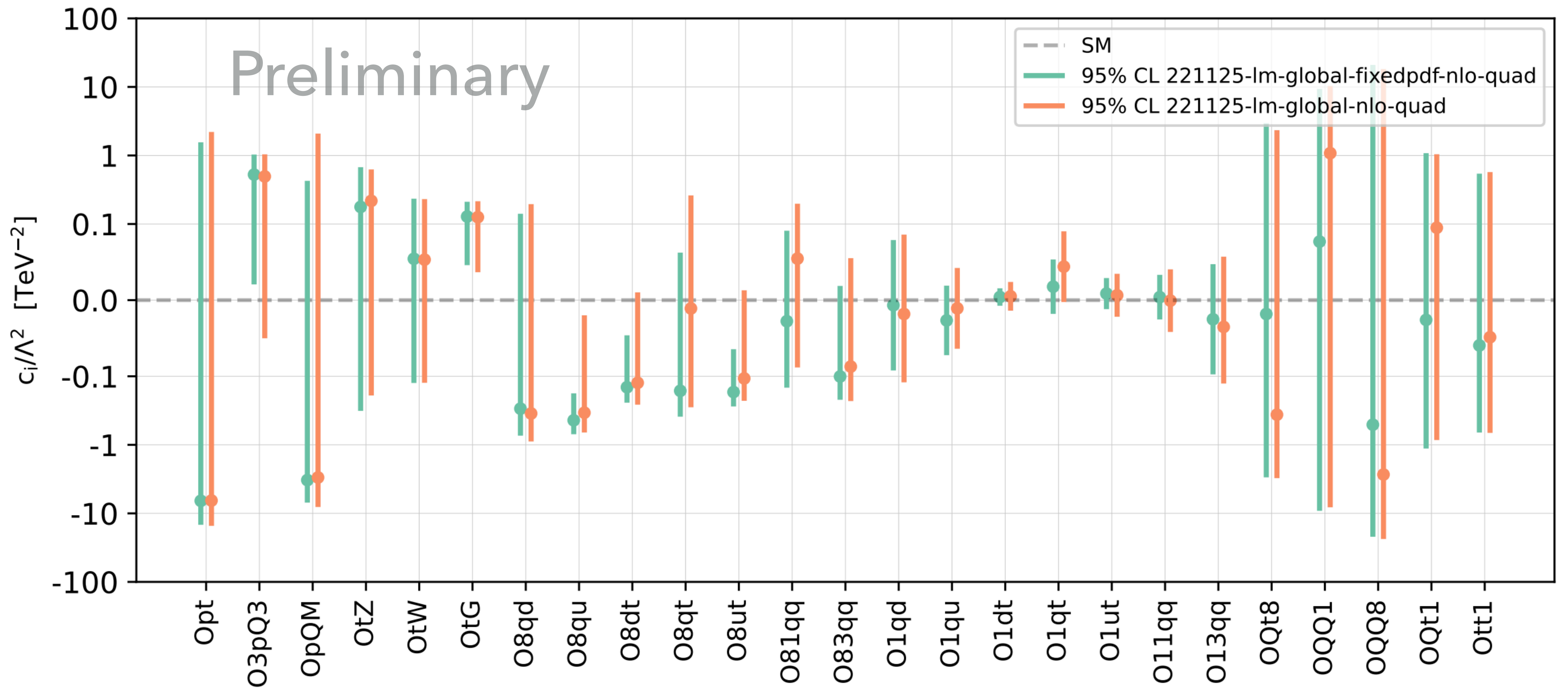


PDF-SMEFT FITS IN TOP DATA

- We constrain 25 SMEFT operators

Green: fixed PDF fit

Orange: simultaneous PDF-SMEFT fit



OUTLINE

$$+ \frac{c_i}{\Lambda^2}$$

Background: PDFs and SMEFT

PDF-SMEFT interplay - DY & Top

Conclusions and outlook

CONCLUSIONS AND OUTLOOK

- We discussed the PDF-SMEFT interplay:

  - ☑ We have a developed SIMUnet: a methodology to perform simultaneous PDF-SMEFT fits and fixed-PDF SMEFT fits
  - ☑ The PDF-SMEFT interplay has to be addressed in BSM searches
  - ☑ We are currently working in the top sector: fitting 25 operators with the broadest dataset up-to-date

- In the future:

  - ☐ Assess other sectors (EW, top, Higgs, …)
  - ☐ Include RGE effects
  - ☐ Map constraints to UV theories
  - ☐ …

Thank you for your attention