Parton Distributions in the SMEFT: the top quark case

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Standard Model PDFs

Global PDF determinations are based on **Standard Model theoretical** calculations

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\ \mathscr{L}_{ij}(M, \sqrt{s}, \boldsymbol{\theta})\, \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M)) \qquad \hat{s} = M^2/s$$

SM hadronic cross-section

Theory prediction to compare with experiment

SM PDF Luminosity

Constrain from data

PDF parameters

SM partonic cross-section

NNLO QCD & NLO EW

$$\mathscr{L}_{ij}(M, \sqrt{s}, \boldsymbol{\theta}) = \frac{1}{s} \int_{-\ln\sqrt{s}/M}^{\ln\sqrt{s}/M} {\rm d}y\, f_i\left(\frac{Me^{y}}{\sqrt{s}}, \boldsymbol{\theta}\right) f_j\left(\frac{Me^{-y}}{\sqrt{s}}, \boldsymbol{\theta}\right) \qquad i, j = u, \bar{u}, g, \ldots$$

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PDF parameters from likelihood maximisation: BSM effects potentially ``**fitted away" into PDFs**

$$\chi^2\left(\boldsymbol{\theta}\right) = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{\rm i,th}(\boldsymbol{\theta}) - \sigma_{\rm i,exp}\right) \left({\rm cov}^{-1}\right)_{ij} \left(\sigma_{\rm j,th}(\boldsymbol{\theta}) - \sigma_{\rm j,exp}\right)$$

SMEFT PDFs

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SM hadronic cross-section — ***SM PDF Luminosity*** — **PDF parameters** — ***SM partonic cross-section***

In the case of new physics described within the **dimension-6 SMEFT framework:**

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X, \boldsymbol{c}, \Lambda) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\ \mathscr{L}_{ij}(M, \sqrt{s}, \boldsymbol{\theta})\, \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}) \left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}}{\Lambda^4} \right)$$

SMEFT PDF Luminosity — ***linear EFT corrections*** — ***quadratic EFT corrections***

SMEFT PDFs are defined as the PDFs extracted from the data when SMEFT cross-sections are used to describe the **partonic hard-scattering**

SM-PDFs vs SMEFT-PDFs

How different are **SM-PDFs** and **SMEFT-PDFs**, given current experimental constraints?

A significant difference between SM-PDFs and SMEFT-PDFs has two main consequences:

- Effects of higher-dimensional SMEFT operators **are partially reabsorbed into PDFs**, affecting indirectly prediction for other processes and **jeopardising validity of SM predictions**
- Bounds in **SMEFT operators will be modified** as compared to the assumption of SM-PDFs

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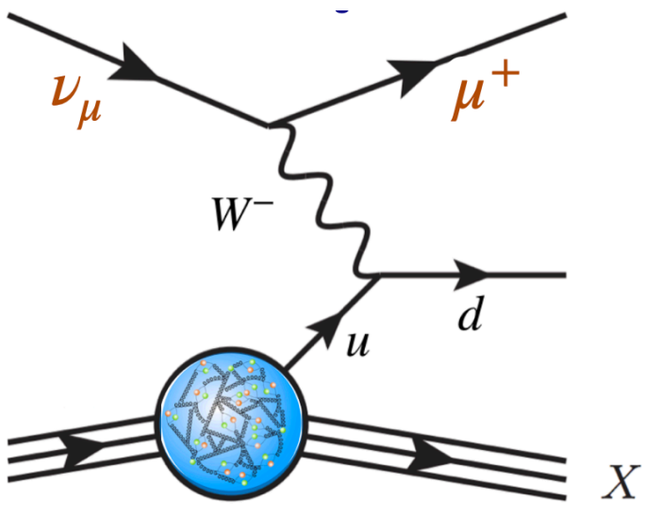
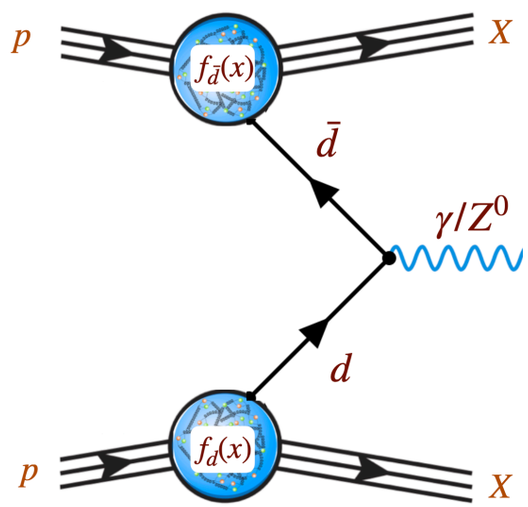
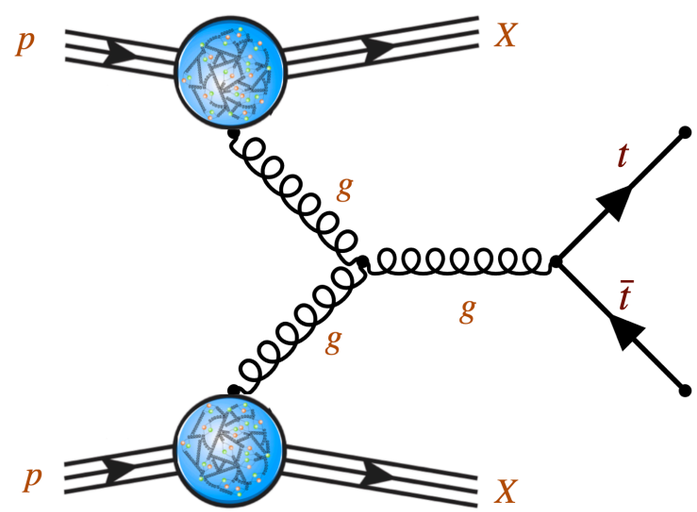
The answer depends on the **process** and on the **sensitivity** of available data. Needs to be studies on a case-by-case basis



Deep-Inelastic Scattering*: S. Carrazza, C. Degrande, S. Iranipour, JR, M. Ubiali, PRL 2019*

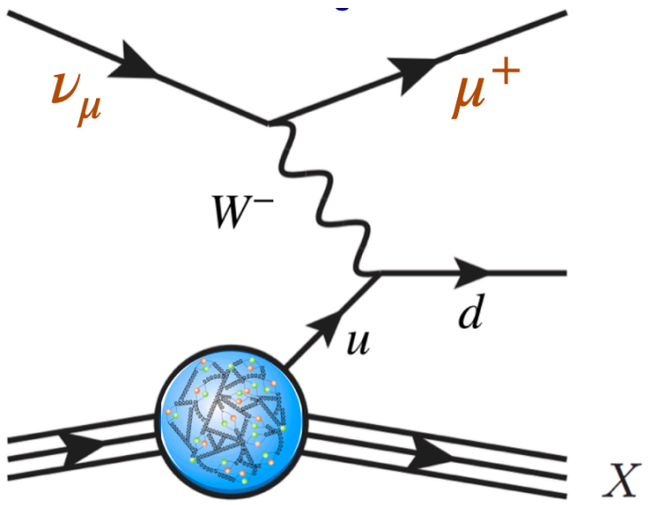


High-mass Drell-Yan: ***A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021***



Top quark sector: ***Z. Kassabov, M. Madigan, L. Mantani , J. Moore , M.Morales-Alvarado, JR , M. Ubiali,*** **JHEP 2023**

SMEFT PDFs from DIS



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- Constrain PDFs and **4-fermion operators** from DIS structure functions

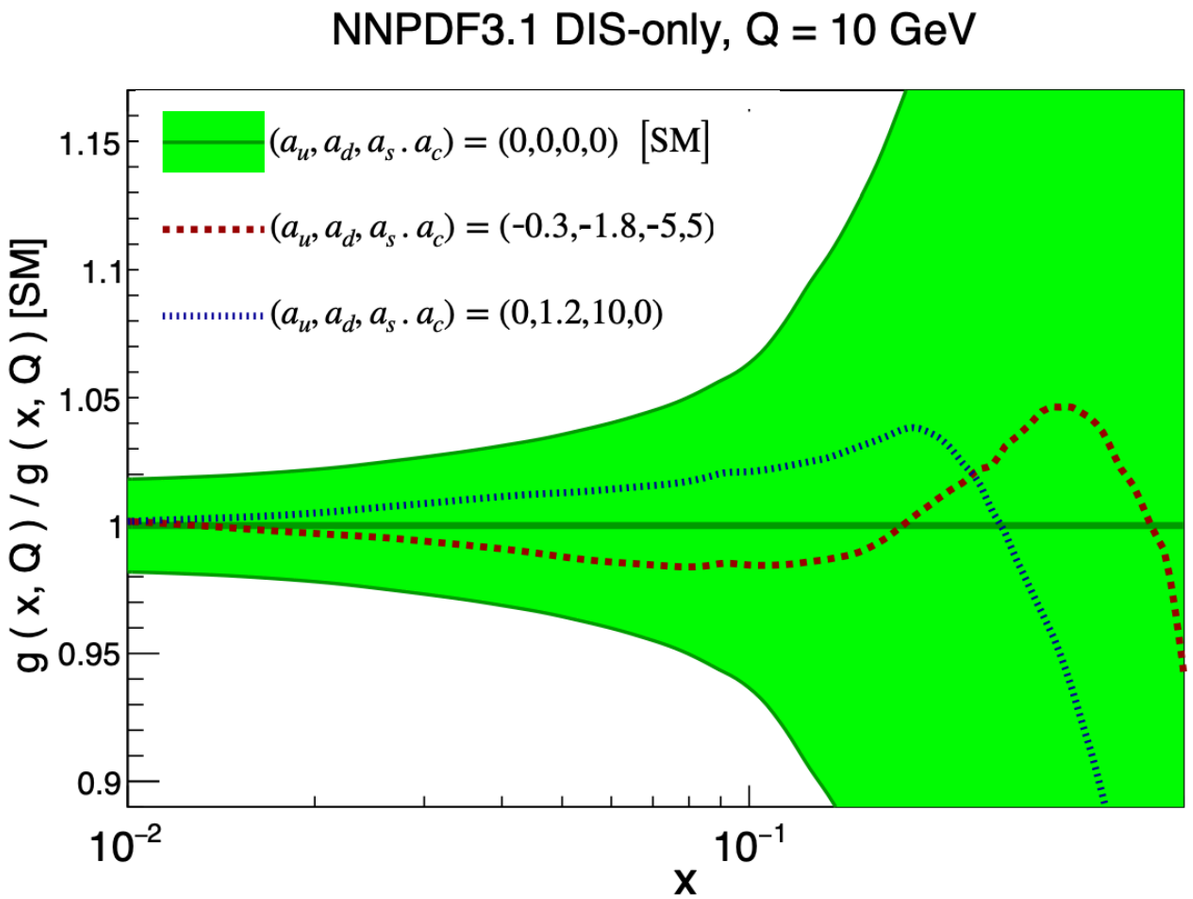
$$\mathcal{O}_{lq} = \left(\bar{l}_R \gamma^\mu l_R\right)\left(\bar{q}_R \gamma_\mu q_R\right)\ ,\ q = u, d, s, c\,,$$

- **Analytic calculation** of EFT corrections to structure functions

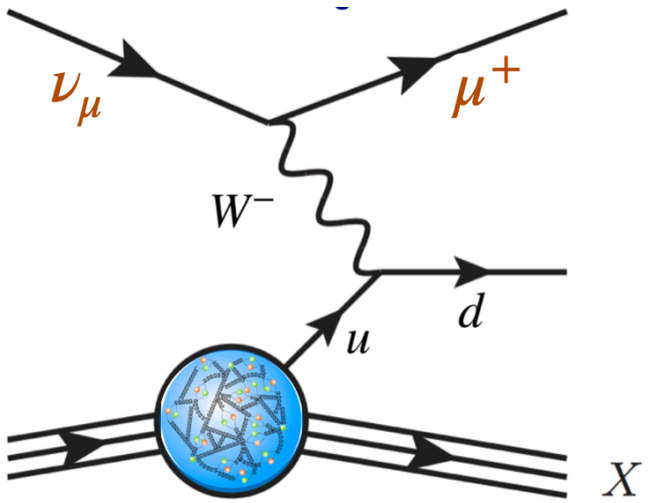
$$\Delta F_2^{\text{smeft}} \supset \frac{x}{12e^4}\left(4a_u e^2 \frac{Q^2}{\Lambda^2}(1 + 4K_Z s_W^4) + 3a_u^2 \frac{Q^4}{\Lambda^4}\right) \times \Big(u(x,Q^2) + \bar{u}(x,Q^2)\Big),$$

- Explore **parameter space of Wilson coefficients** allowed by current data: PDF shifts contained within PDF uncertainties

- SMEFT PDFs **similar** to their SM counterparts for DIS data (and the EFT operators considered)



SMEFT PDFs from DIS



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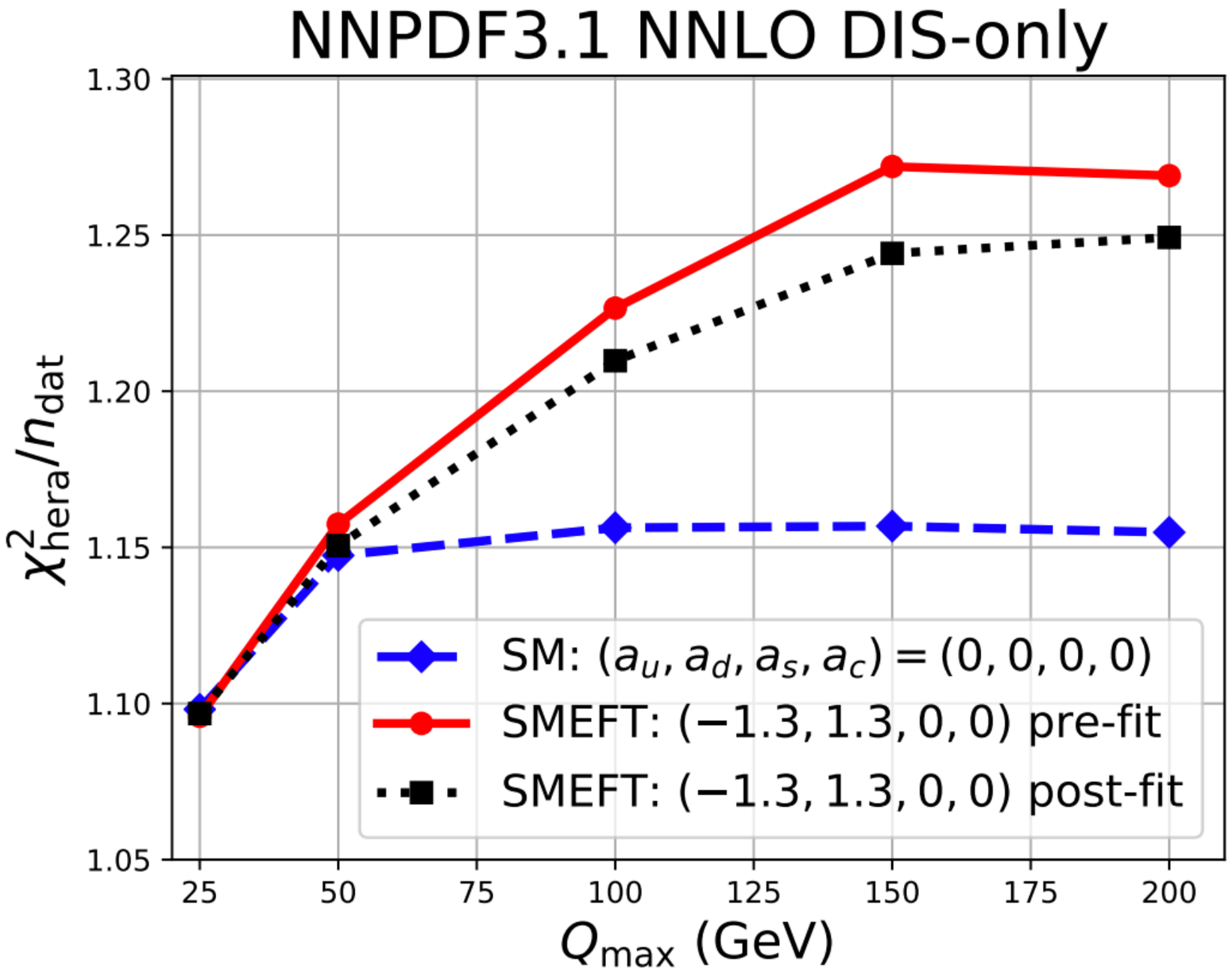
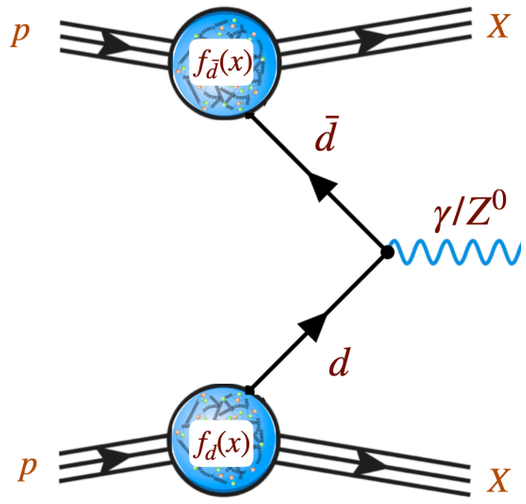
- **Presence of EFT effects** can be identified by their different energy dependence (power-like) as compared to QCD (logarithmic)
- Differential measurements sensitive to energy dependence key to **separate QCD from EFT dynamics**

In the presence of EFT effects, energy-growing effects arise



SMEFT PDFs from high-mass Drell-Yan



High-mass Drell-Yan: ***A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021***

Consider all available data on **high-mass Drell-Yan** together with a global dataset (**also on-peak data**)

Exp.	$\sqrt{s}$ (TeV)	Ref.	$\mathcal{L}$ (fb^{-1})	Channel	1D/2D	$n_{\rm dat}$	$m_{\ell\ell}^{\rm max}$ (TeV)
ATLAS	7	[120]	4.9	e^-e^+	1D	13	[1.0, 1.5]
ATLAS (*)	8	[86]	20.3	$\ell^-\ell^+$	2D	46	[0.5, 1.5]
CMS	7	[121]	9.3	$\mu^-\mu^+$	2D	127	[0.2, 1.5]
CMS (*)	8	[87]	19.7	$\ell^-\ell^+$	1D	41	[1.5, 2.0]
CMS (*)	13	[122]	5.1	e^-e^+, $\mu^-\mu^+$ $\ell^-\ell^+$	1D	43, 43 43	[1.5, 3.0]
Total						**270 (313)**	

Two **benchmark scenarios** distorting the high-mass DY distributions

oblique corrections

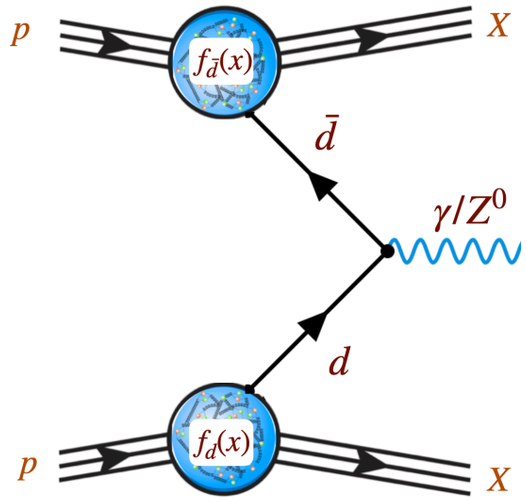
$$\mathcal{L}_{\rm SMEFT} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

translated to the Warsaw basis

left-handed muon-philic lepton-quark interactions

$$\mathcal{L}_{\rm SMEFT} \supset \frac{\mathbf{C}_{ij}^{U\mu}}{v^2}(\bar{u}_L^i\gamma_\mu u_L^j)(\bar{\mu}_L\gamma^\mu\mu_L) + \frac{\mathbf{C}_{ij}^{D\mu}}{v^2}(\bar{d}_L^i\gamma_\mu d_L^j)(\bar{\mu}_L\gamma^\mu\mu_L)$$

SMEFT PDFs from high-mass Drell-Yan



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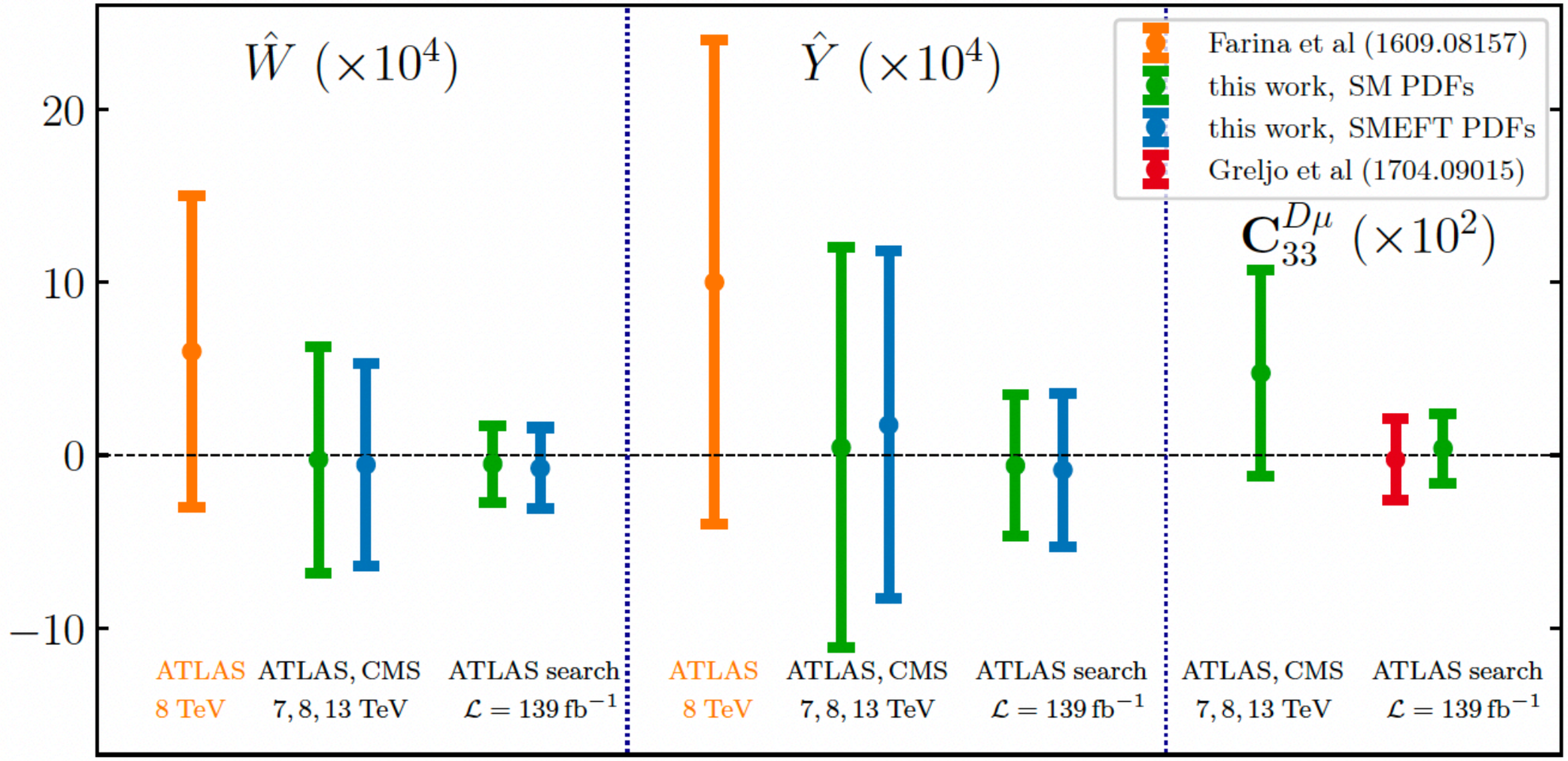
- Available data: **limited interplay** between PDF and EFT fits
- Best constraints from **searches,** but corresponding unfolded measurements not yet available
- SMEFT-PDFs modify bounds from SM-PDFs by around **10%**



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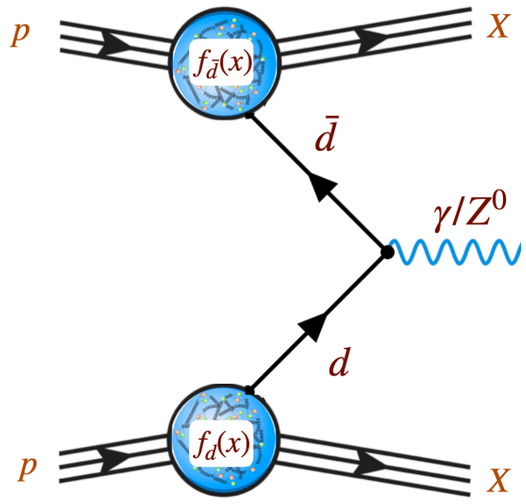

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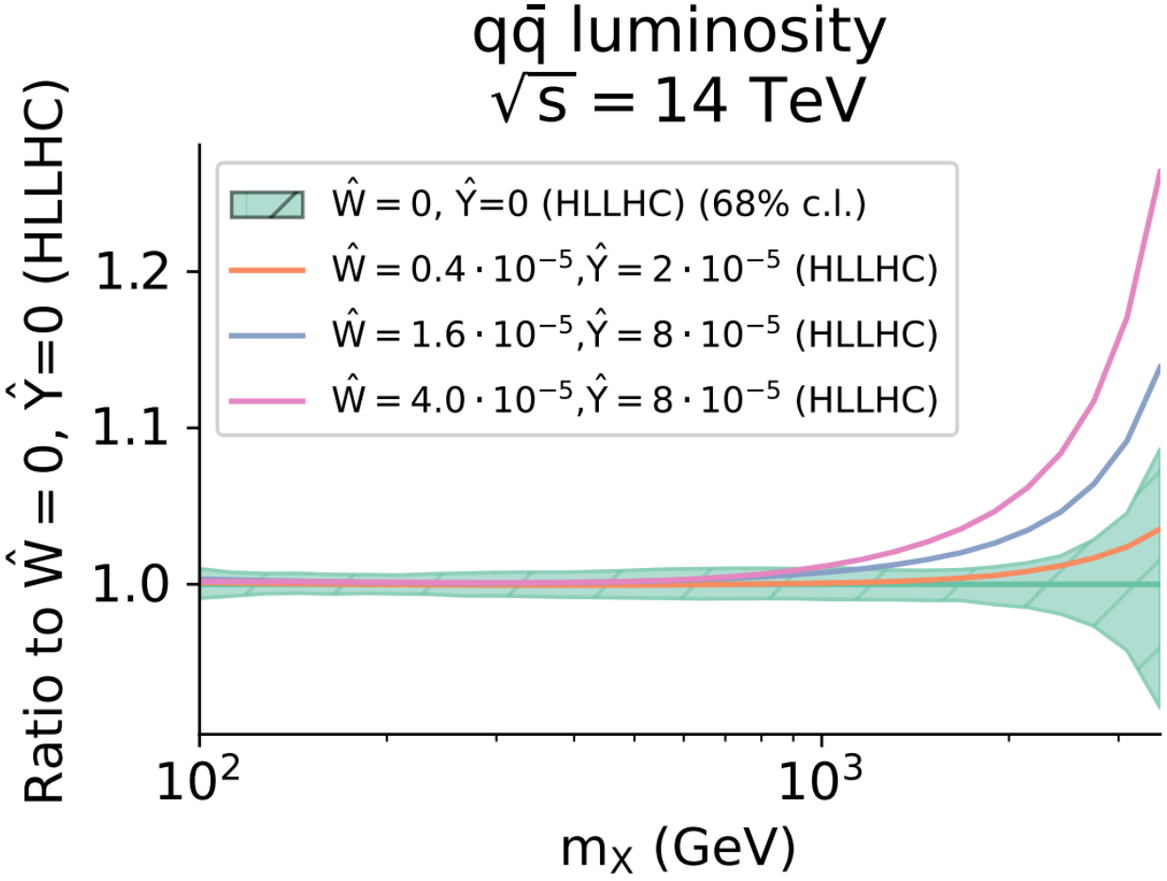
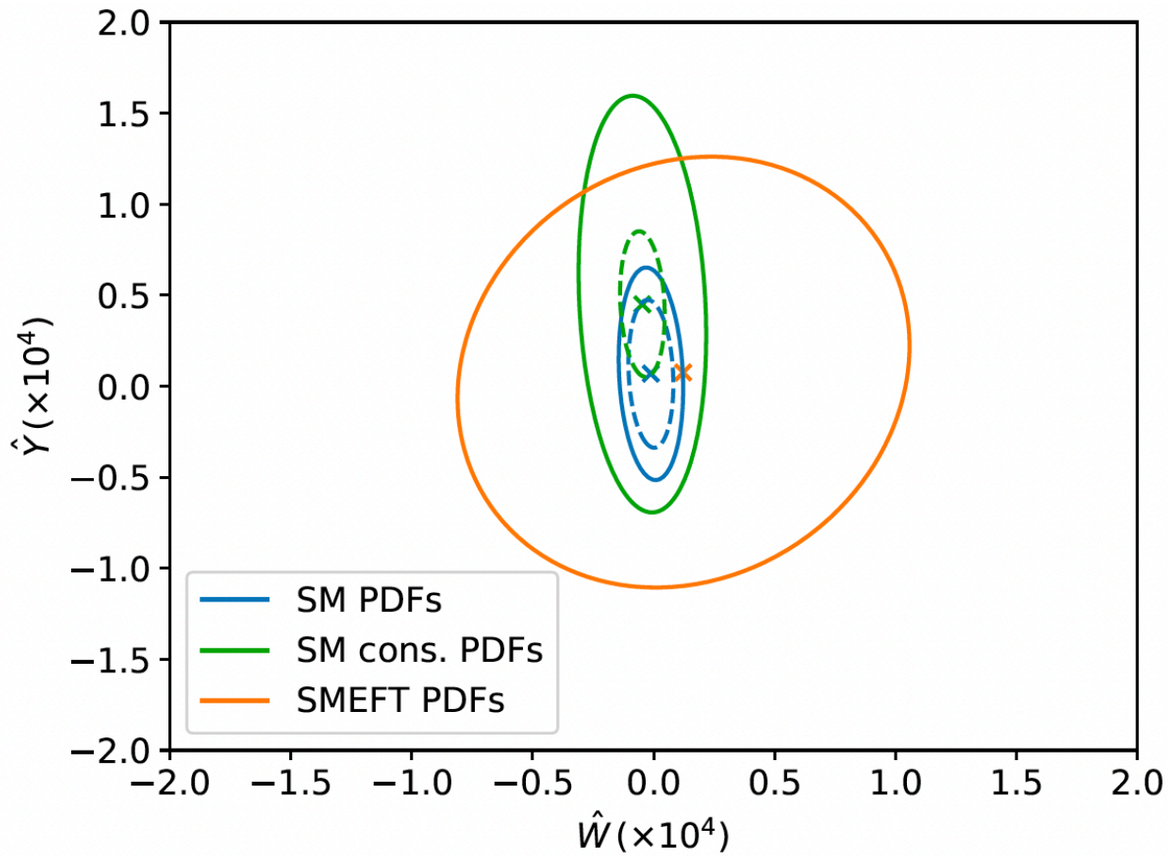
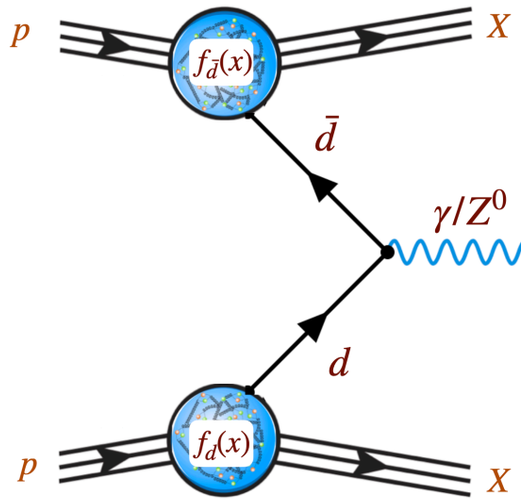
- HL-LHC projections: strong constraints on large-*x* antiquark PDFs, may be **reabsorbed into SMEFT PDFs**
- Bounds based on SM-PDFs **overly optimistic** as compared to those obtained from SMEFT-PDFs
- Emphasises importance of **SMEFT-PDF interplay** at the HL-LHC





relevant also for legacy Run III measurements

SMEFT PDFs from high-mass Drell-Yan



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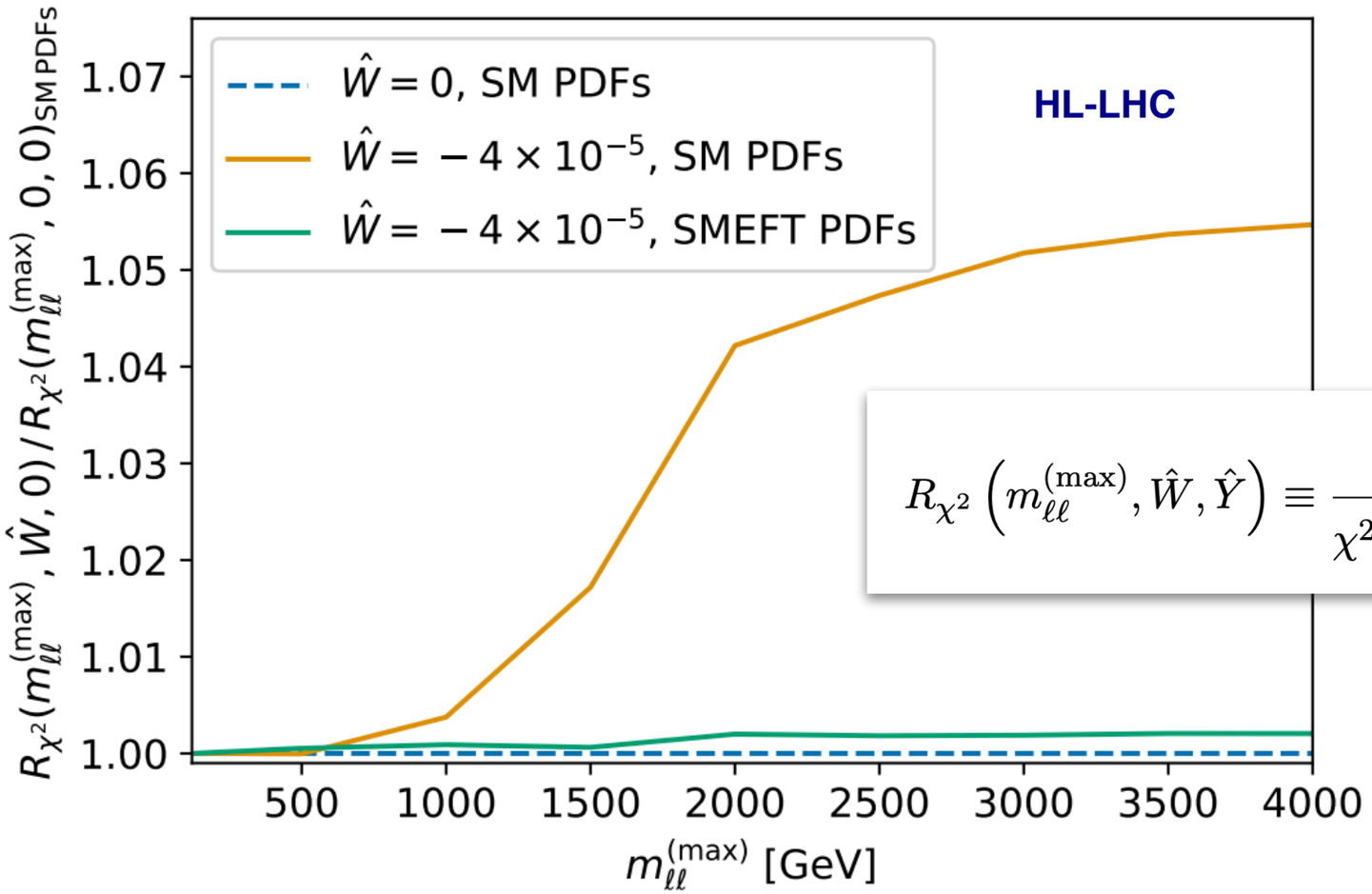
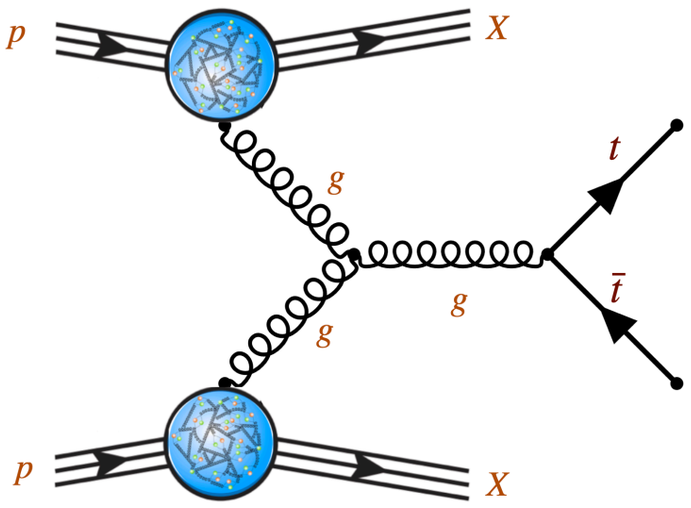
- HL-LHC projections: strong constraints on large-x antiquark PDFs, may be **reabsorbed into SMEFT PDFs**
- Bounds based on SM-PDFs **overly optimistic** as compared to those obtained from SMEFT-PDFs
- As for DIS, disentangle QCD from EFT effects from their different **energy dependence**



$$R_{\chi^2}\left(m_{\ell\ell}^{(\max)}, \hat{W}, \hat{Y}\right) \equiv \frac{\chi^2\left(m_{\ell\ell}^{(\max)}, \hat{W}, \hat{Y}\right)}{\chi^2\left(m_{\ell\ell}^{(\max)} = 120\ \text{GeV}, \hat{W}, \hat{Y}\right)}$$

SMEFT PDFs from top quark data

Consider all **available LHC top quark data** (including Run II legacy) and interpret them in terms of *i)* **SM-PDFs**, *ii)* **(fixed-PDF) EFT fit**, and *iii)* **SMEFT-PDFs**

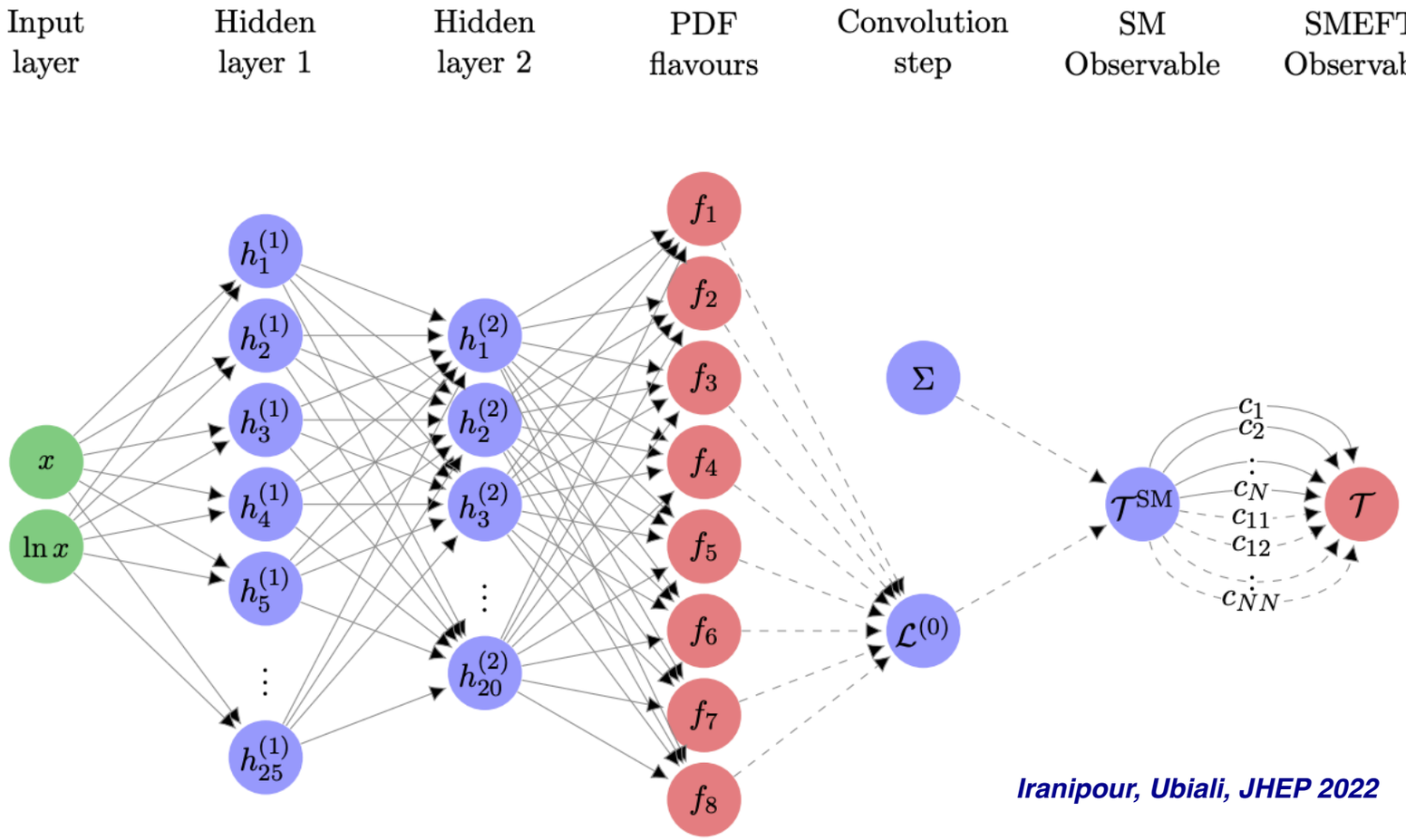


Top quark sector: ***Z. Kassabov, M. Madigan, L. Mantani , J. Moore , M.Morales-Alvarado, JR , M. Ubiali,*** **JHEP 2023**

- **SIMUnet** methodology allows joint determination of EFT coefficients (linear corrections) and PDF parameters
- Can also function as fixed-PDF EFT fitter, where it reproduces results based on public codes *e.g.* **SMEFiT**

Most extensive EFT (and PDF) interpretation of top quark data to date

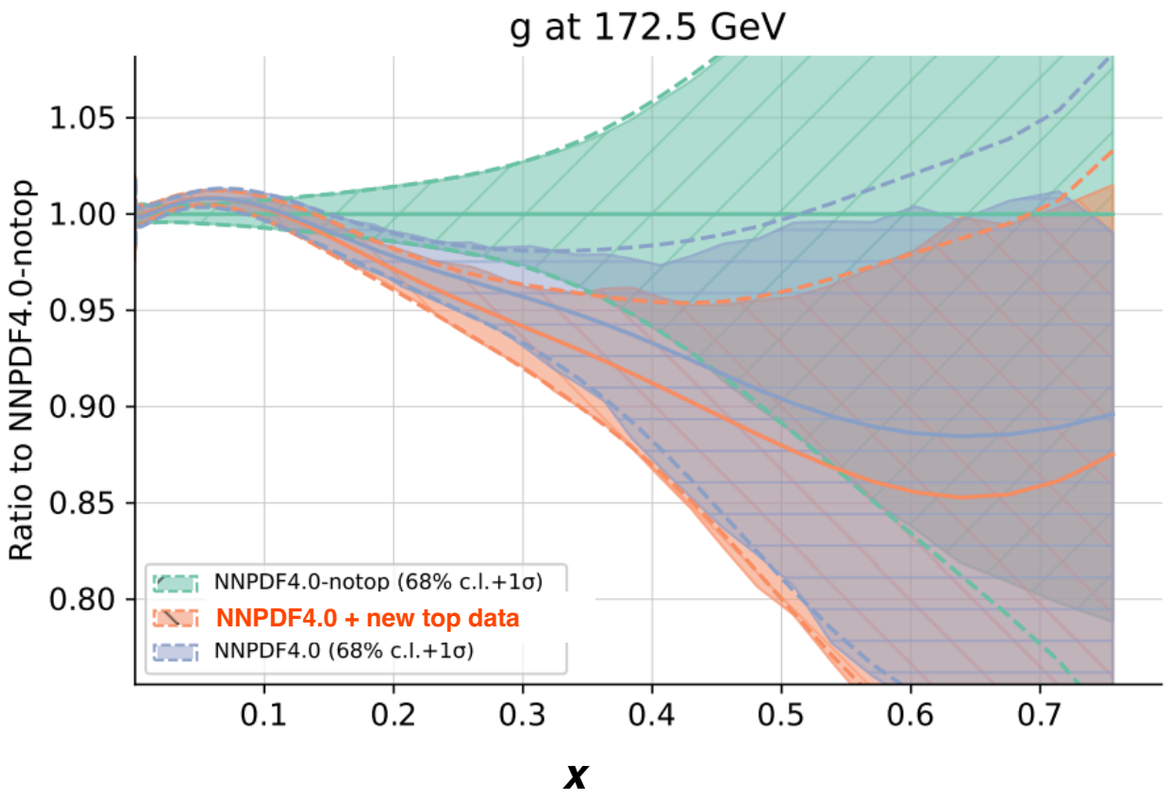
all measurements publicly available until Jan 2023

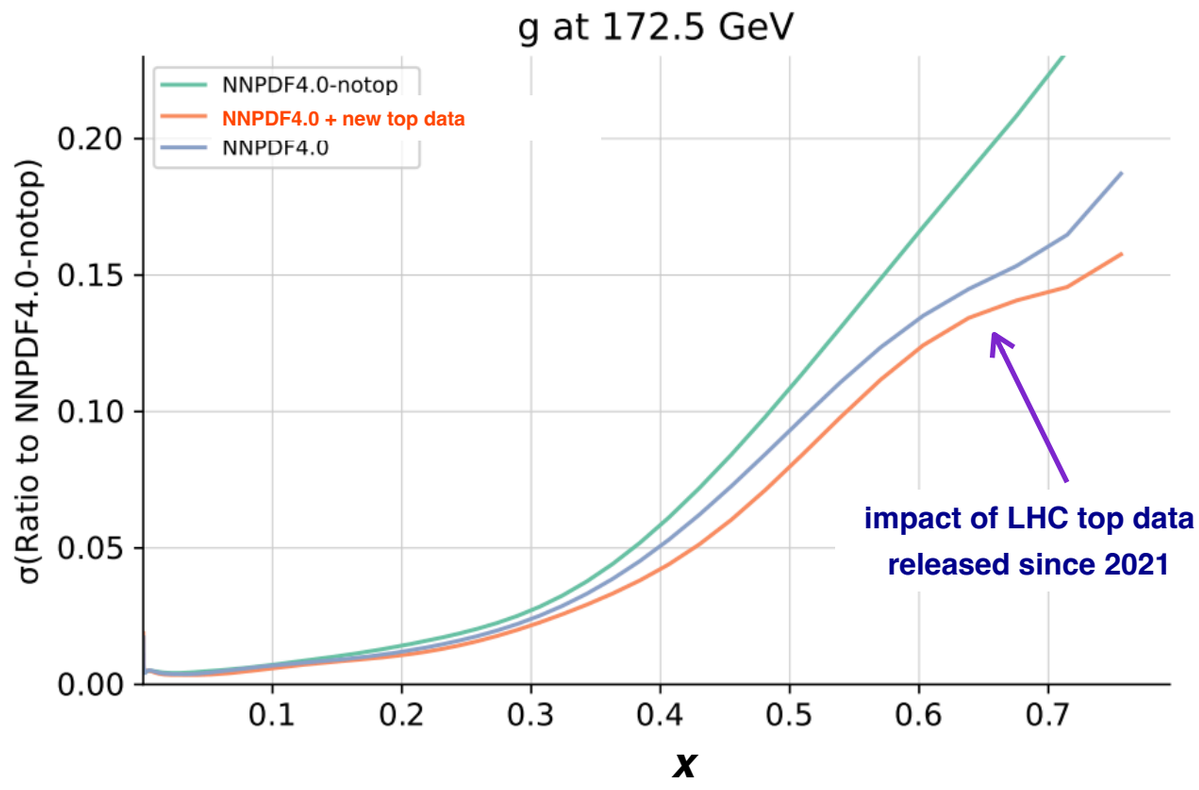


Iranipour, Ubiali, JHEP 2022

SMEFT PDFs from top quark data

SM-PDF results

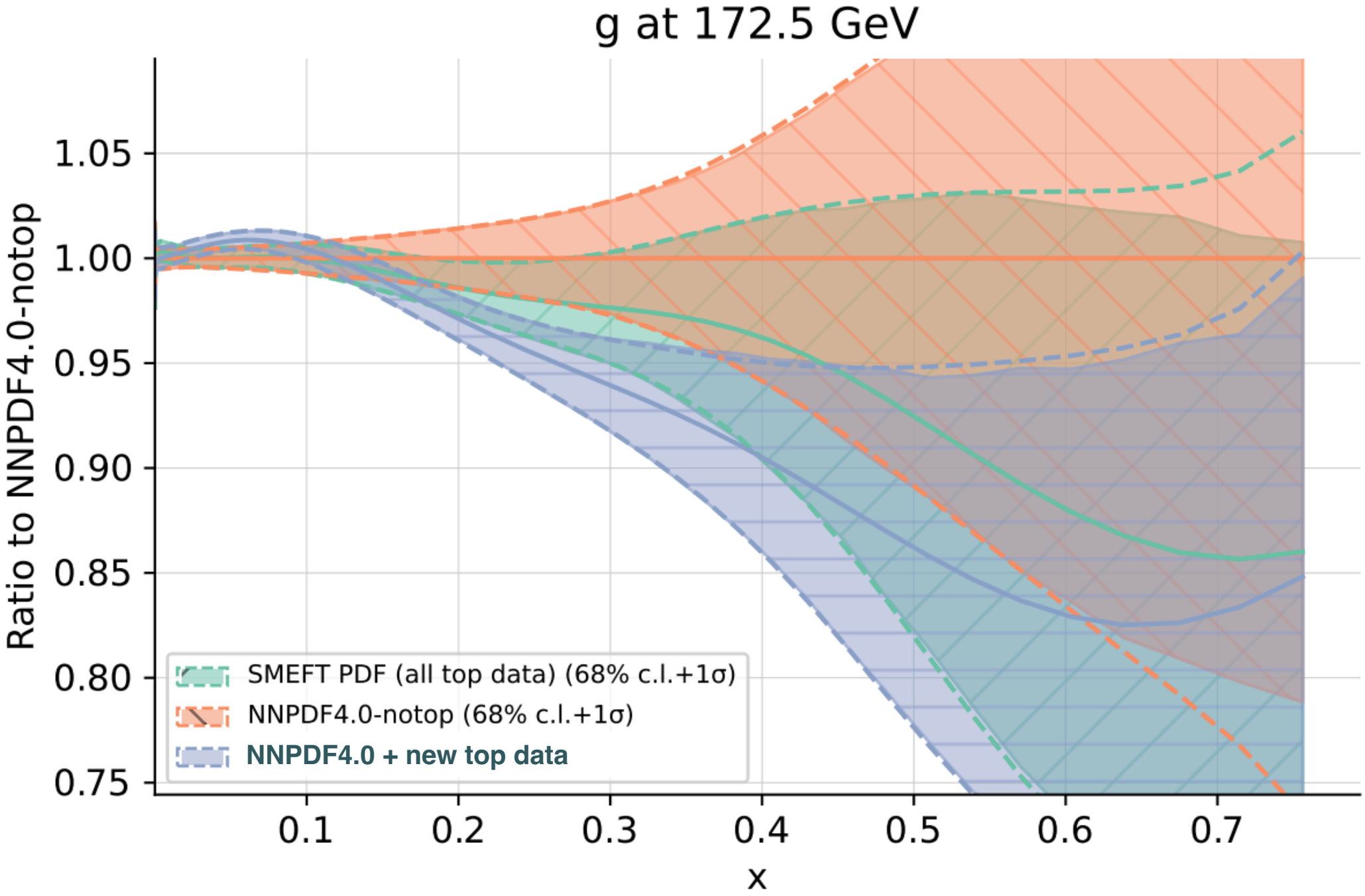




- New top data in addition to those measurements included in NNPDF4.0 leads to consistent pull with **suppression of large-*x* gluon**
- Sensitivity arises mostly from **m_{tt} distributions** in top quark pair production, which are also most affected by EFT effects
- What happens if now we **also fit EFT operators** distorting top quark production?

SMEFT PDFs from top quark data

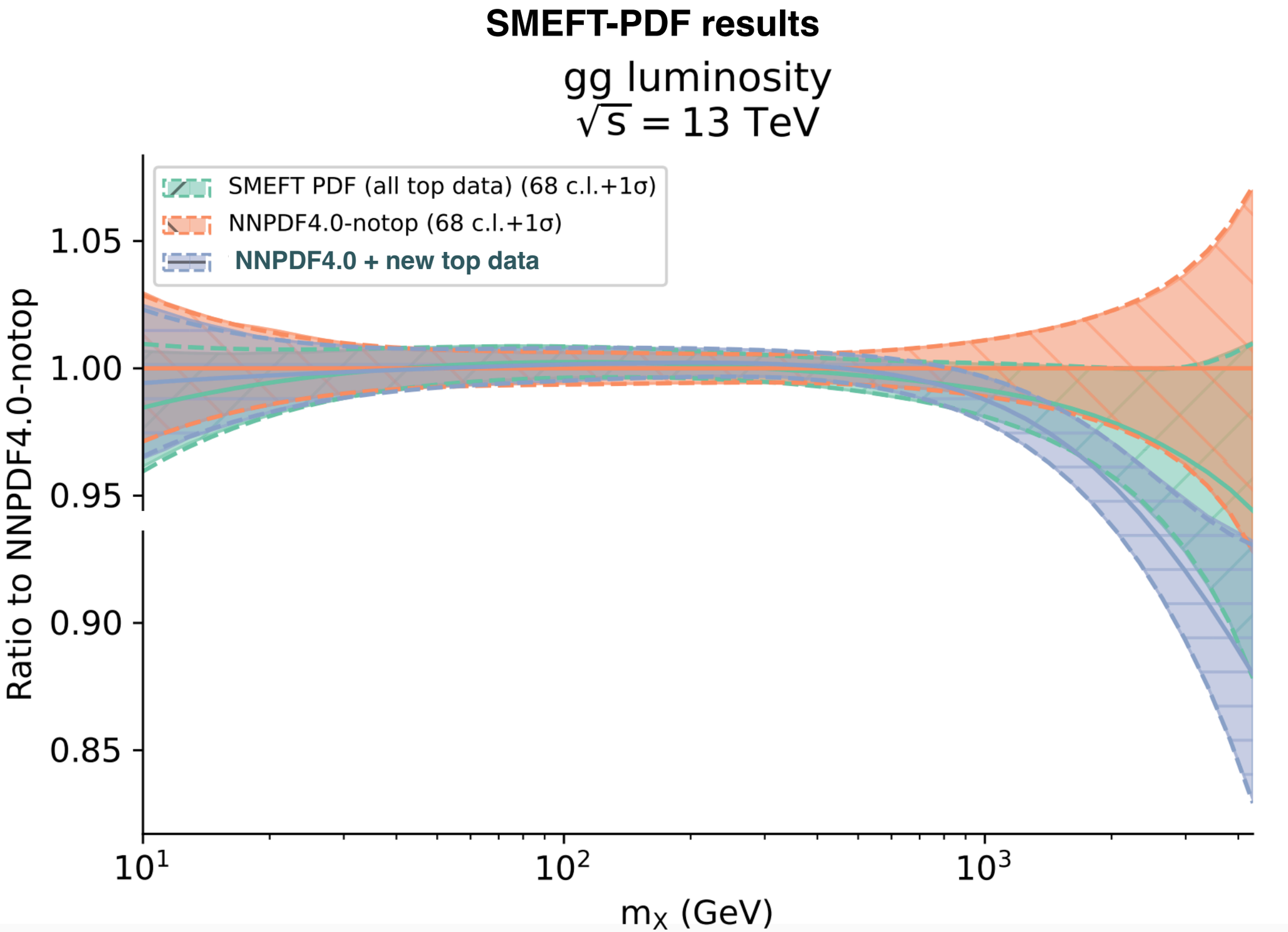
SMEFT-PDF results



Large-*x* gluon **distorted by EFT effects**, which partially absorb the data pulls

As a result, net effect of top quark data on PDFs **reduced** as compared to SM-PDFs

SMEFT PDFs from top quark data



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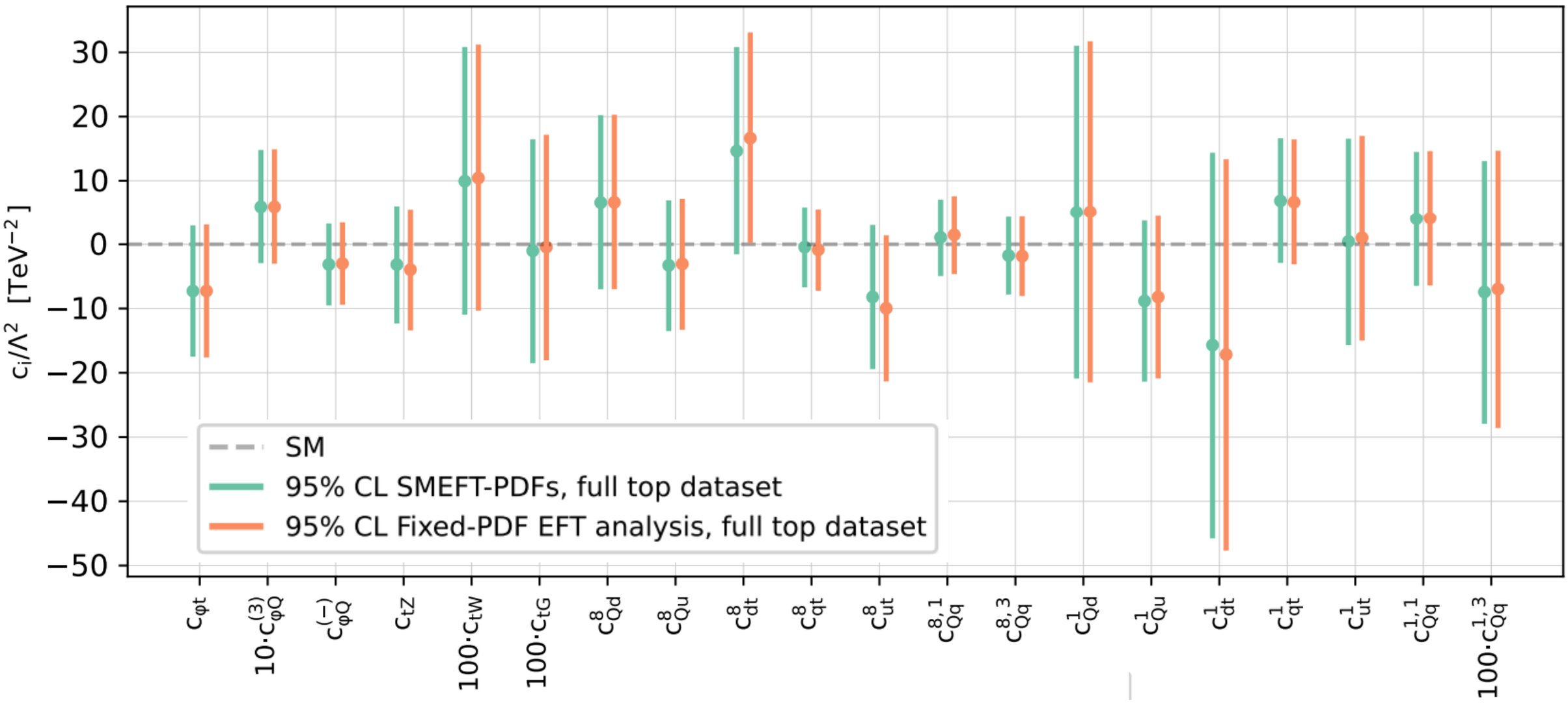

Despite differences between SMEFT-PDFs and SM-PDFs, **bounds on EFT coefficients stable**

PDF dependence **does not seem to affect** (for current data) EFT interpretations of top data

Summary and take-home messages

- The SMEFT framework provides a robust strategy to **interpret LHC data in terms of new BSM** phenomena while reducing model assumptions

- Newly developed techniques enable the **determination of SMEFT PDFs** that quantify the interplay between PDFs and EFT effects in LHC processes

- Conclusions depend on **process**, choice of **EFT operator basis**, and the **available data**

Overview of SMEFT-PDF studies based on the NNPDF & PBSP methodology

	SM-PDFs vs SMEFT-PDFs (current data)	SM-PDFs vs SMEFT-PDFs (HL-LHC)	Impact on EFT coefficients
Deep-Inelastic Scattering	differences << PDF uncertainties	to be studied (LHeC, EIC)	no effect
High-mass Drell-Yan	differences << PDF uncertainties	**differences >> PDF uncertainties**	10% effect on bounds for current data, **SMEFT-PDF bounds much broader for HL-LHC**
Top-quark production	**differences ≳ PDF uncertainties**	to be studied	**no effect** (linear EFT)