Hide and Seek: how parton distribution functions can conceal new physics

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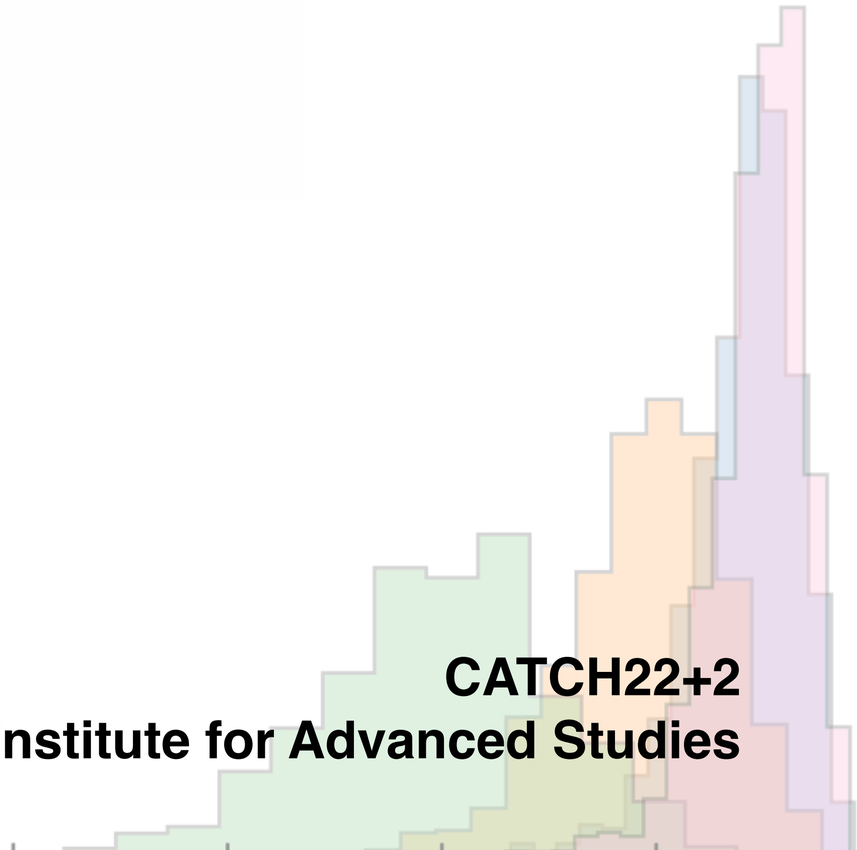
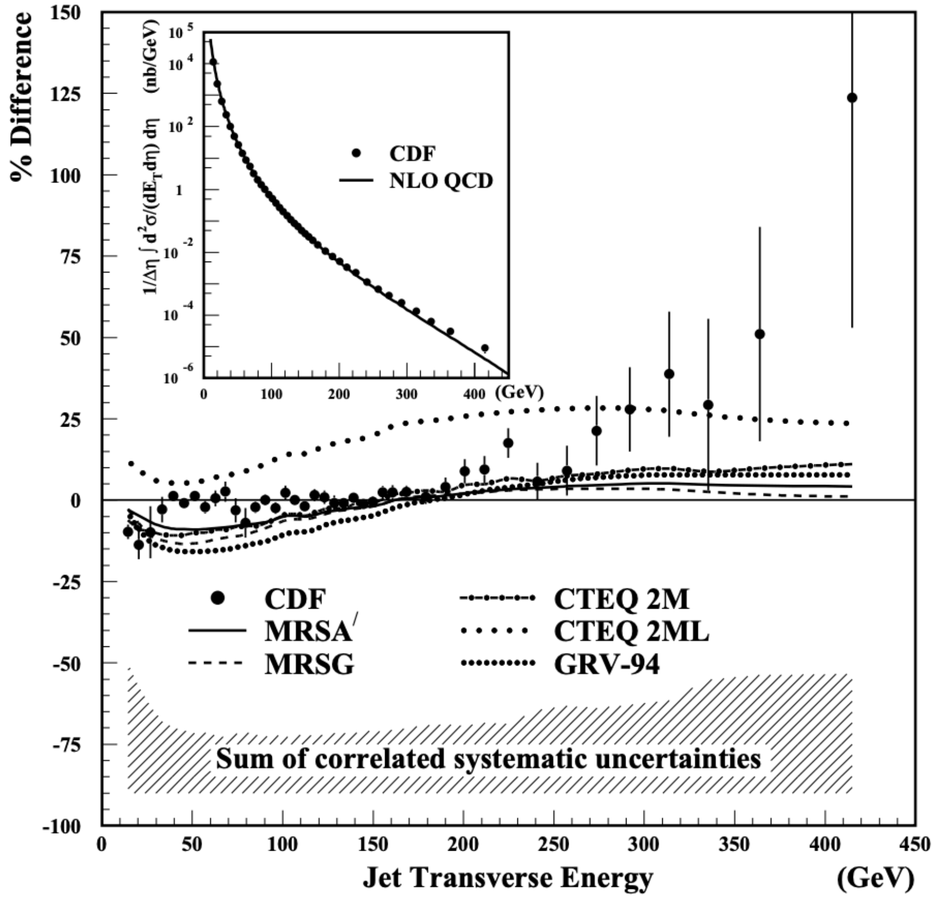


CATCH22+2
Dublin Institute for Advanced Studies



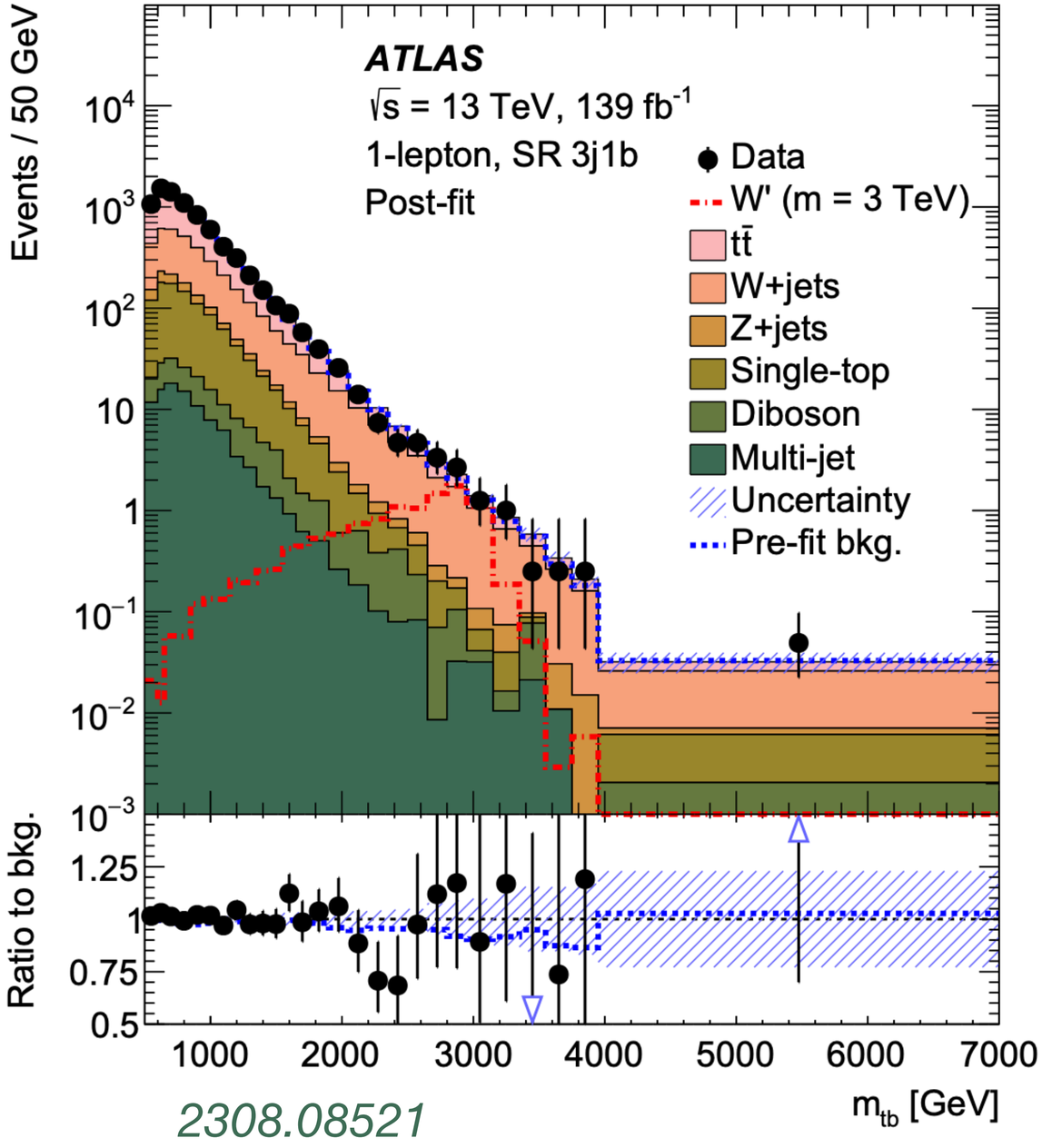
hep-ex/9601008

CDF collaboration measured a deviation at high transverse momentum

However, this was not new physics

- deviation went away with improvements to large-*x* gluon PDFs

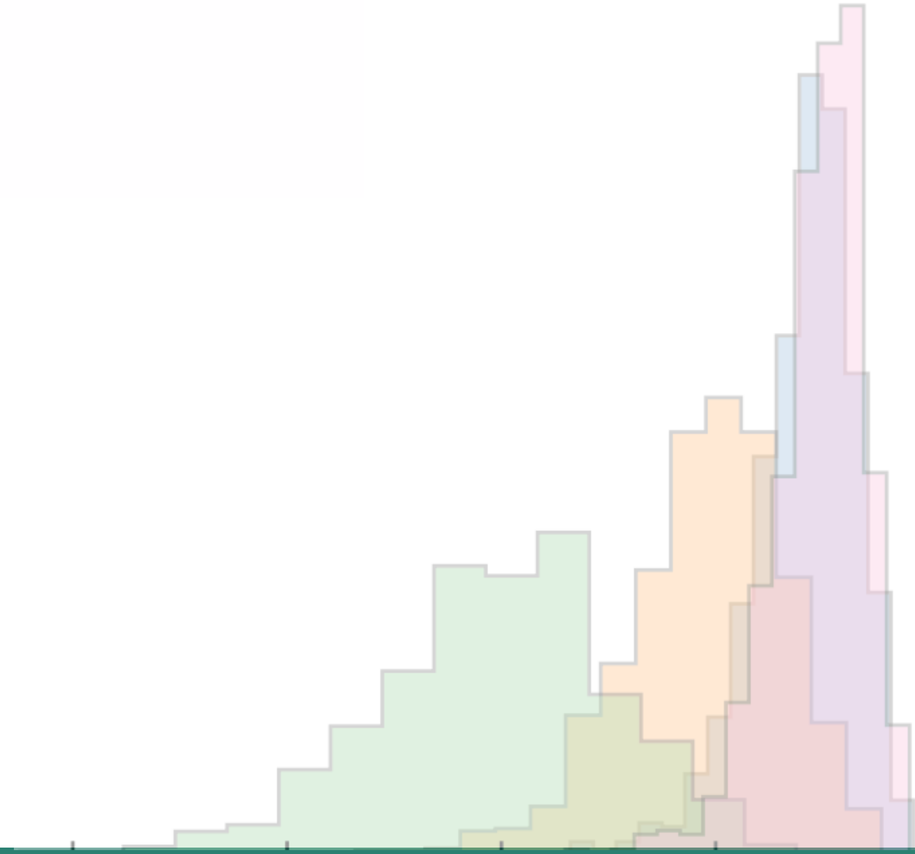
What if no new physics is observed…



2308.08521

…because it has been **absorbed by the PDFs**?

PDF-EFT Interplay



PDF-EFT Interplay

Wilson coefficients: c
PDF parameters: θ

$$\sigma = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{q_1,q_2} f_{q_1}(x_1, Q^2) f_{q_2}(x_2, Q^2) \hat{\sigma}(x_1, x_2)$$

Both PDFs and SMEFT are determined by fitting from data

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:

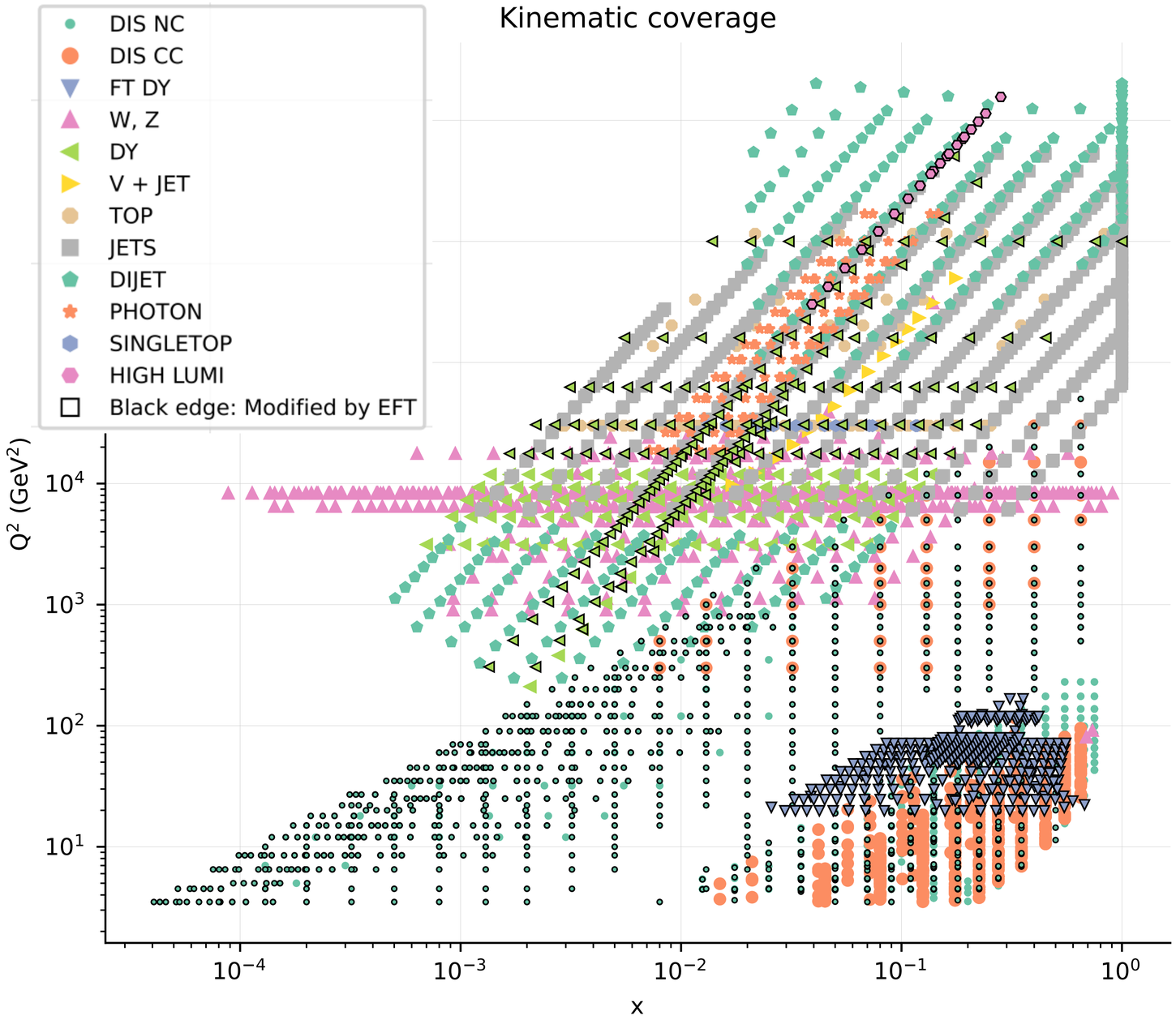
$$\sigma(c, \bar{\theta}) = f_1(\bar{\theta}) \otimes f_2(\bar{\theta}) \otimes \hat{\sigma}(c)$$

PDFs used in SMEFT fits rely on SM assumptions

Data overlap

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

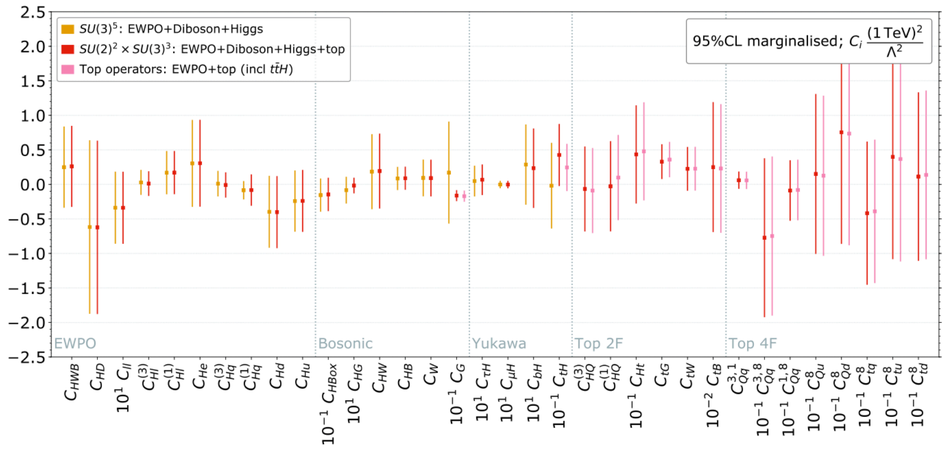
This overlap will grow as we continue to take a global approach to constraining the SMEFT and PDFs.



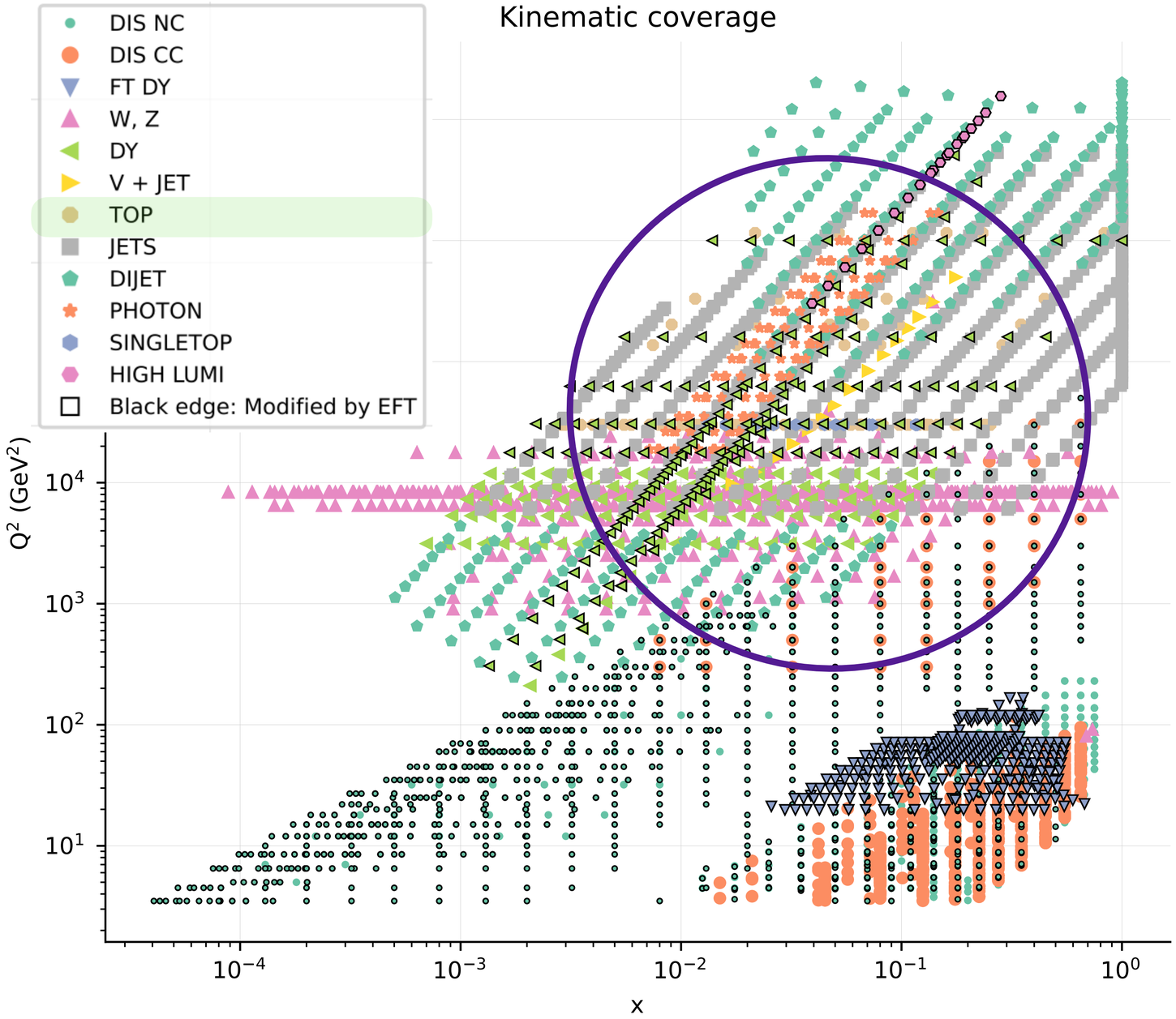
Data included in our study

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*



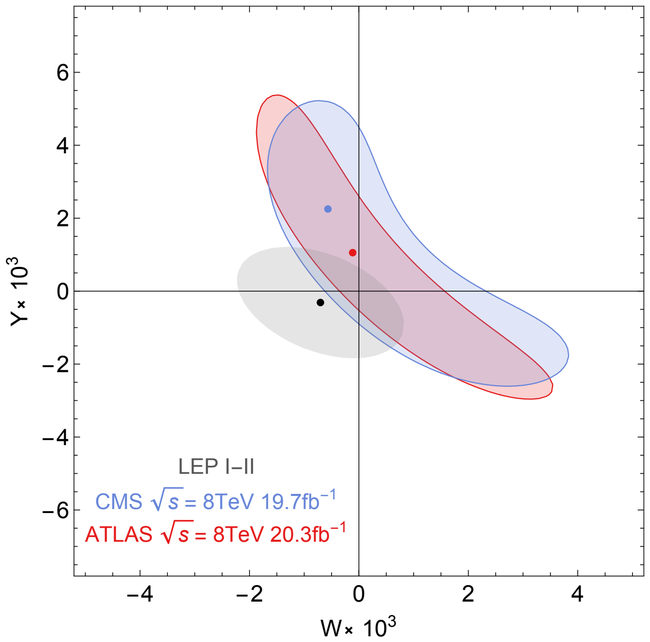
Kinematic coverage



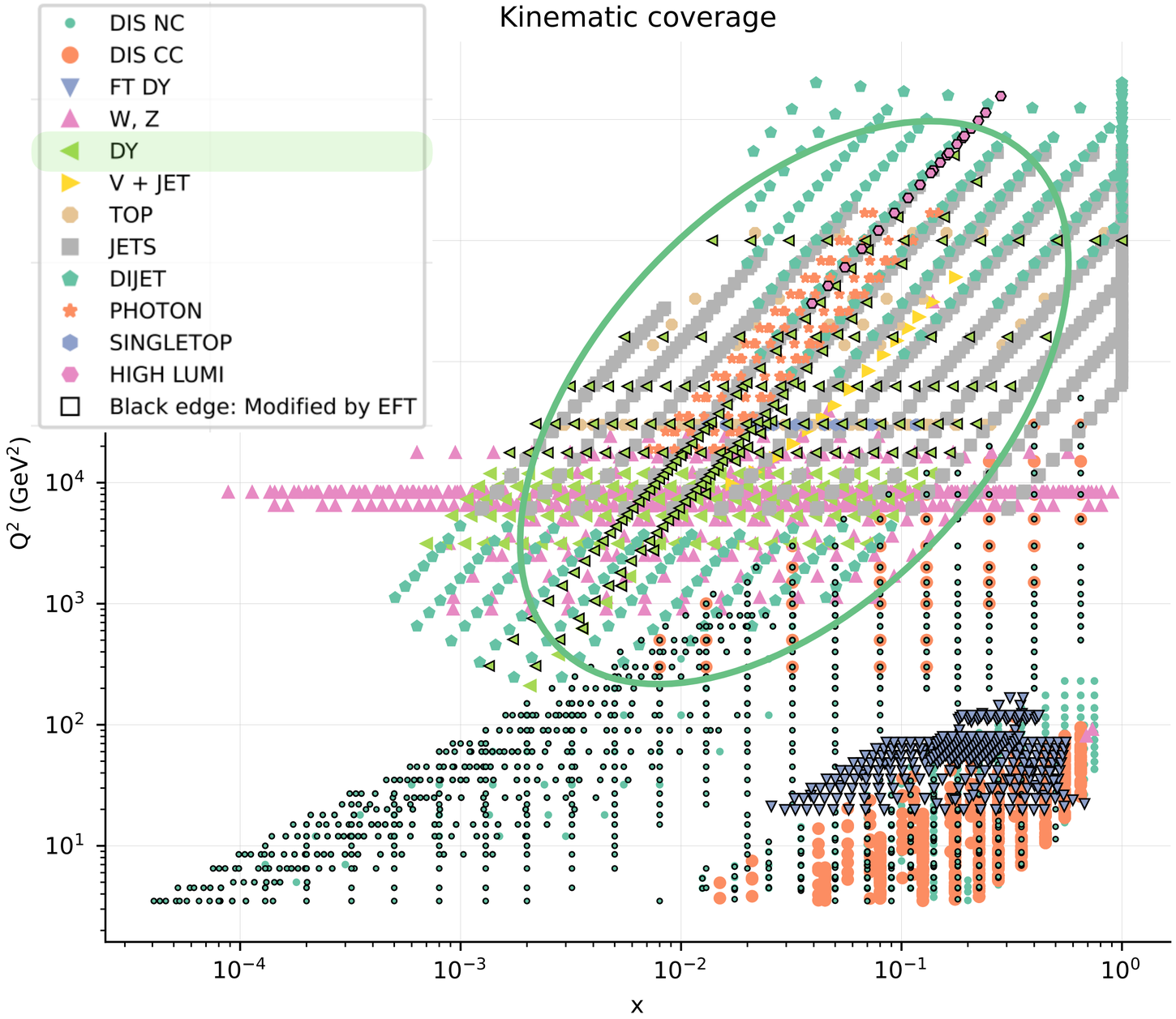
Data included in our study

Data overlap

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



Kinematic coverage



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?

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

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

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

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

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

Generate Monte Carlo pseudodata according to this underlying law:

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

Contaminated PDFs

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Perform a PDF fit: **fit only the SM parameters** $\theta_{\rm SM}$ using the NNPDF4.0 methodology *2109.02653*

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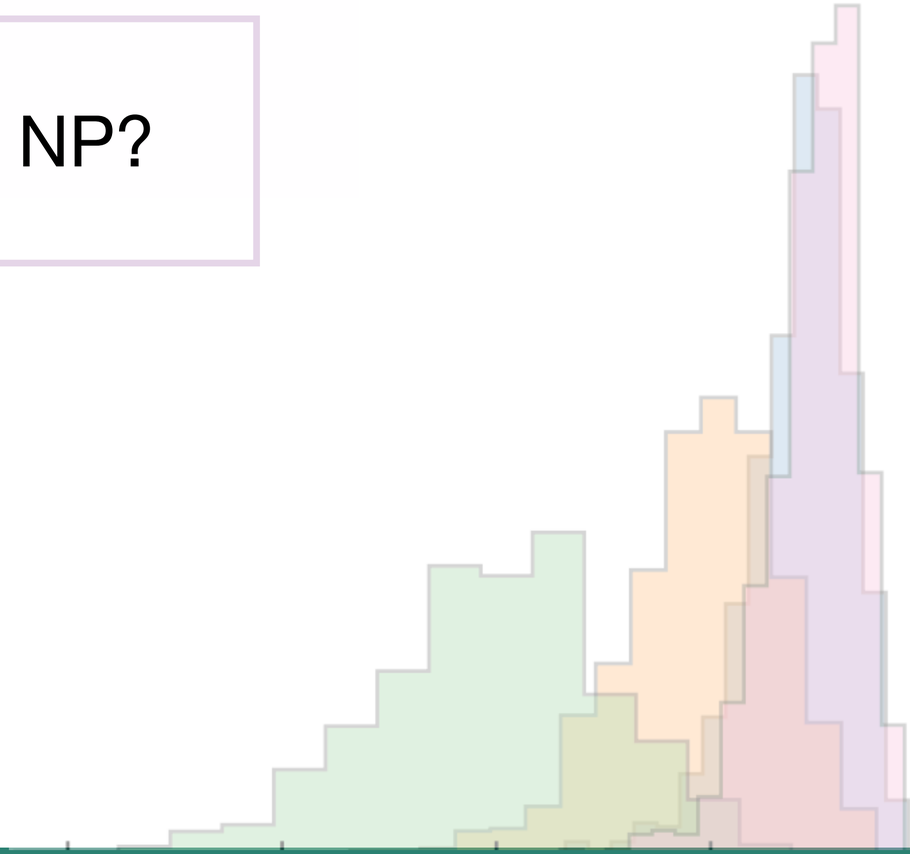
Perform a PDF fit: fit only the SM parameters $\theta_{\rm SM}$ using the NNPDF4.0 methodology *2109.02653*

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

Can PDFs be contaminated by NP?



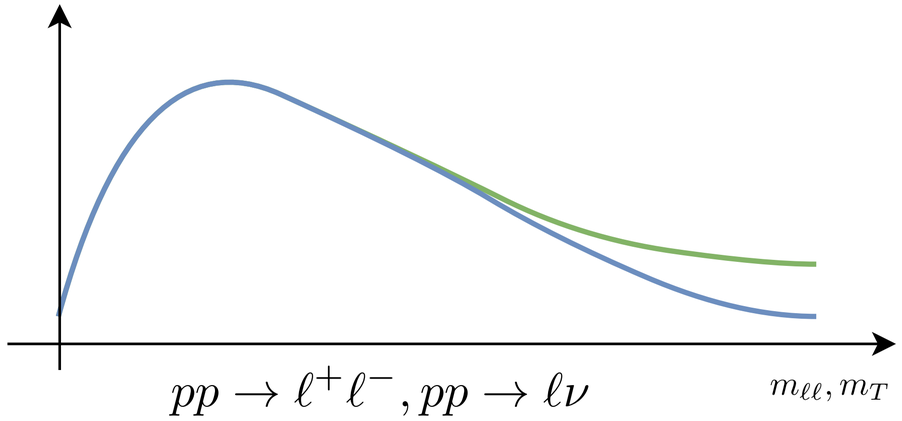
Data

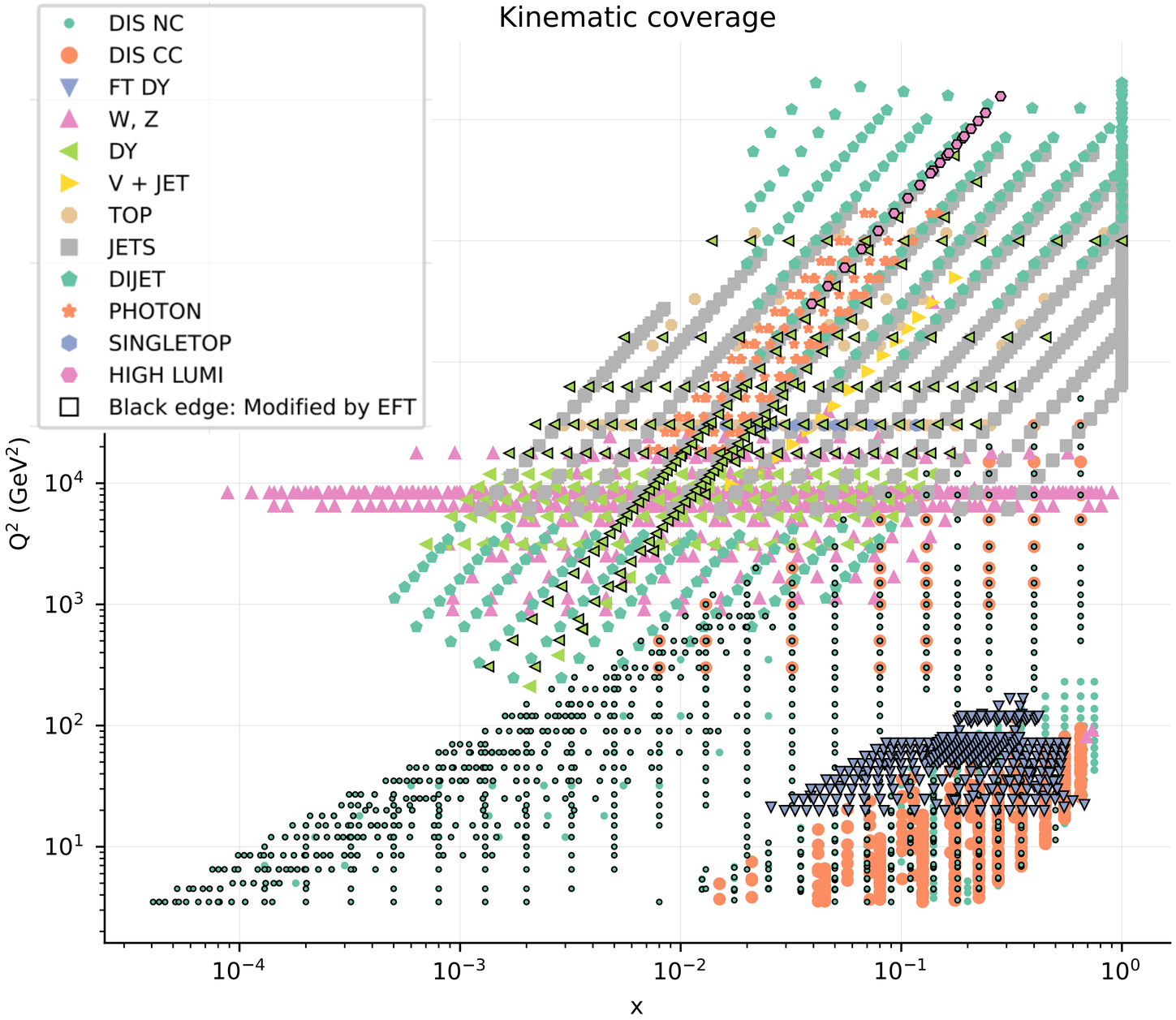
- We generate MC pseudodata for all datasets included in NNPDF 4.0

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

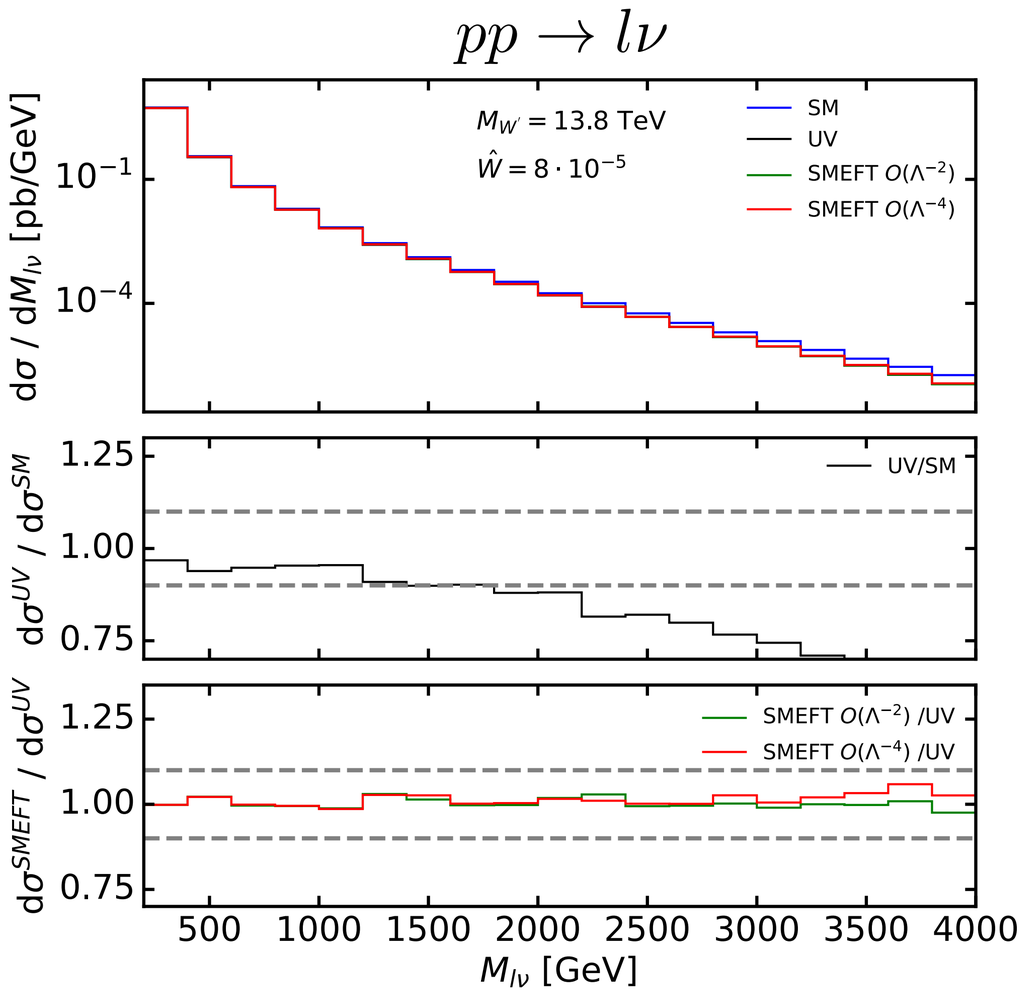
- Flavour universal W’

EFT approximation

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

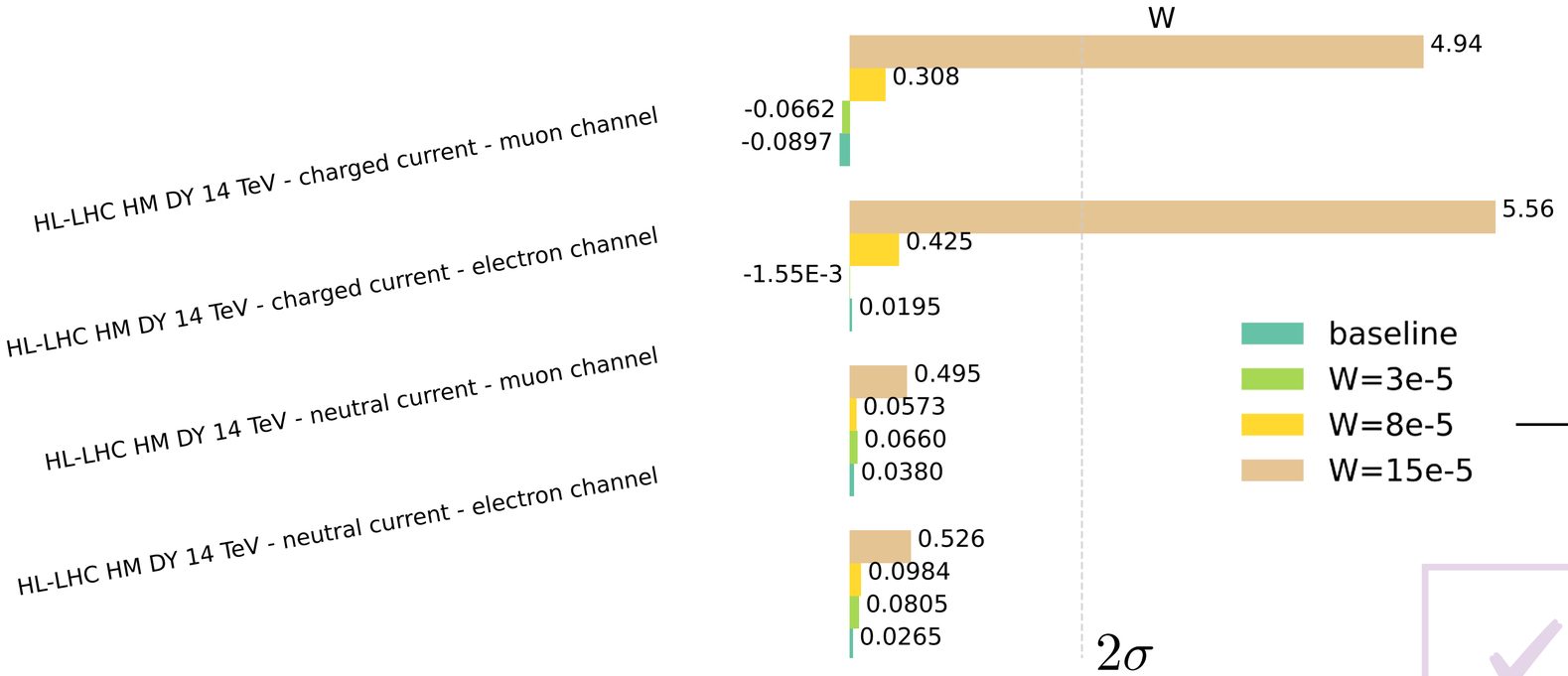
$$J_L^\mu = \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L$$

- Impacts NC and CC DY



Do our contaminated fits pass the selection criteria?

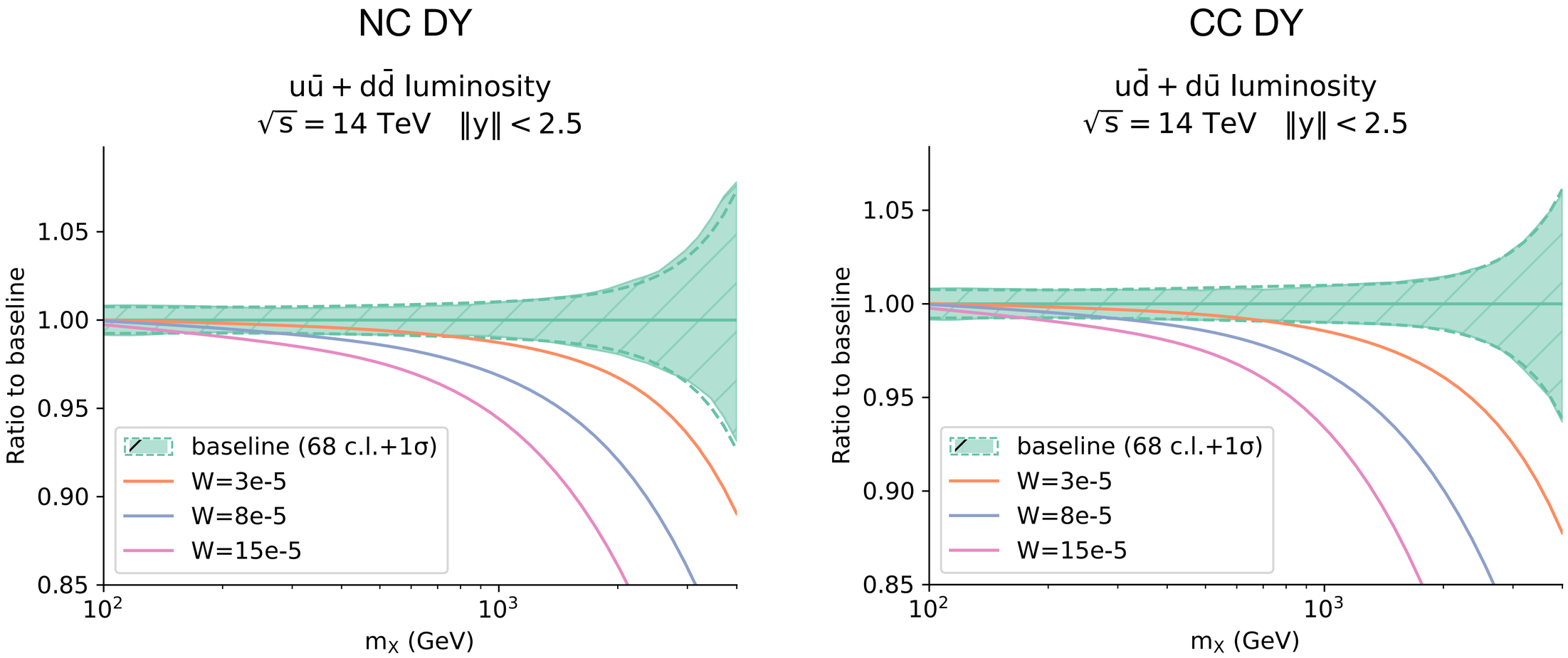
$$n_\sigma = \frac{\chi^2 - 1}{\sigma_{\chi^2}}$$



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

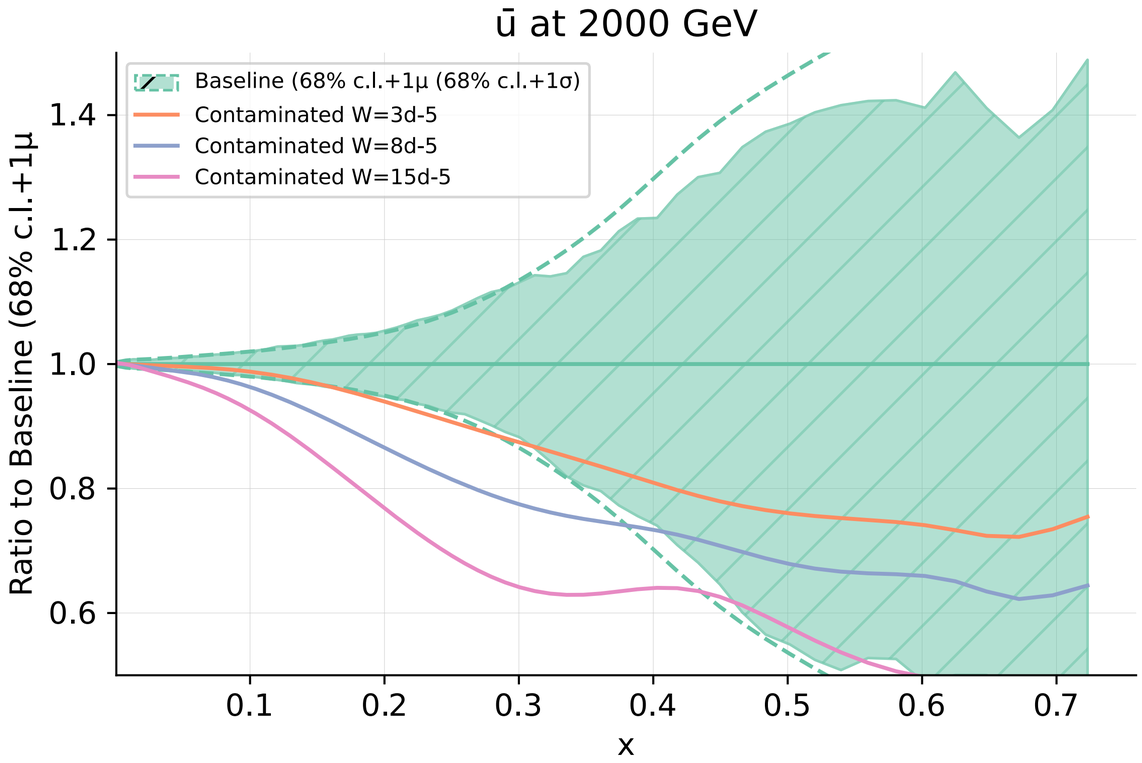
✓ ***Yes: PDFs absorb new physics***

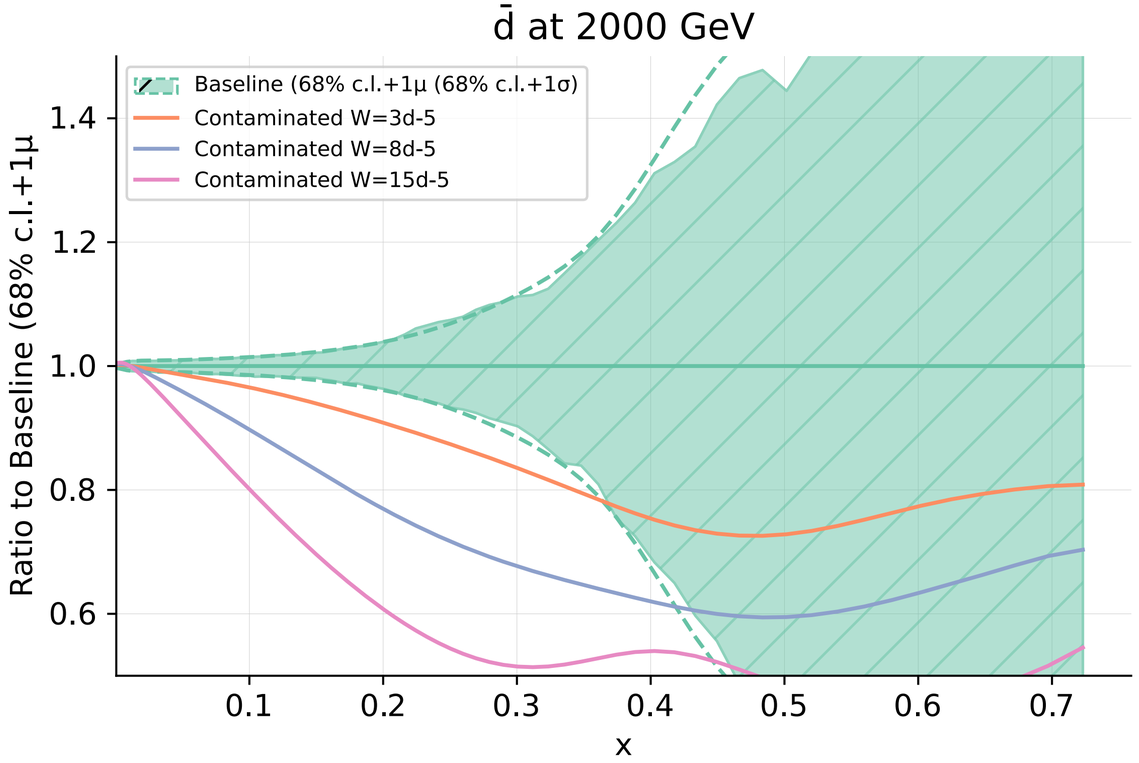
W’-contaminated PDFs



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

W’-contaminated PDFs



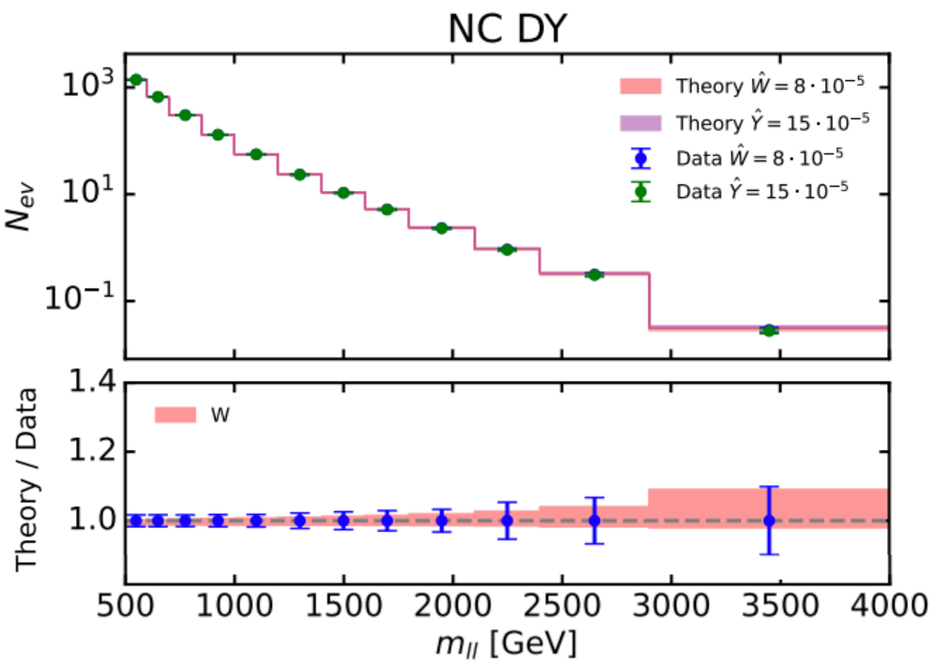


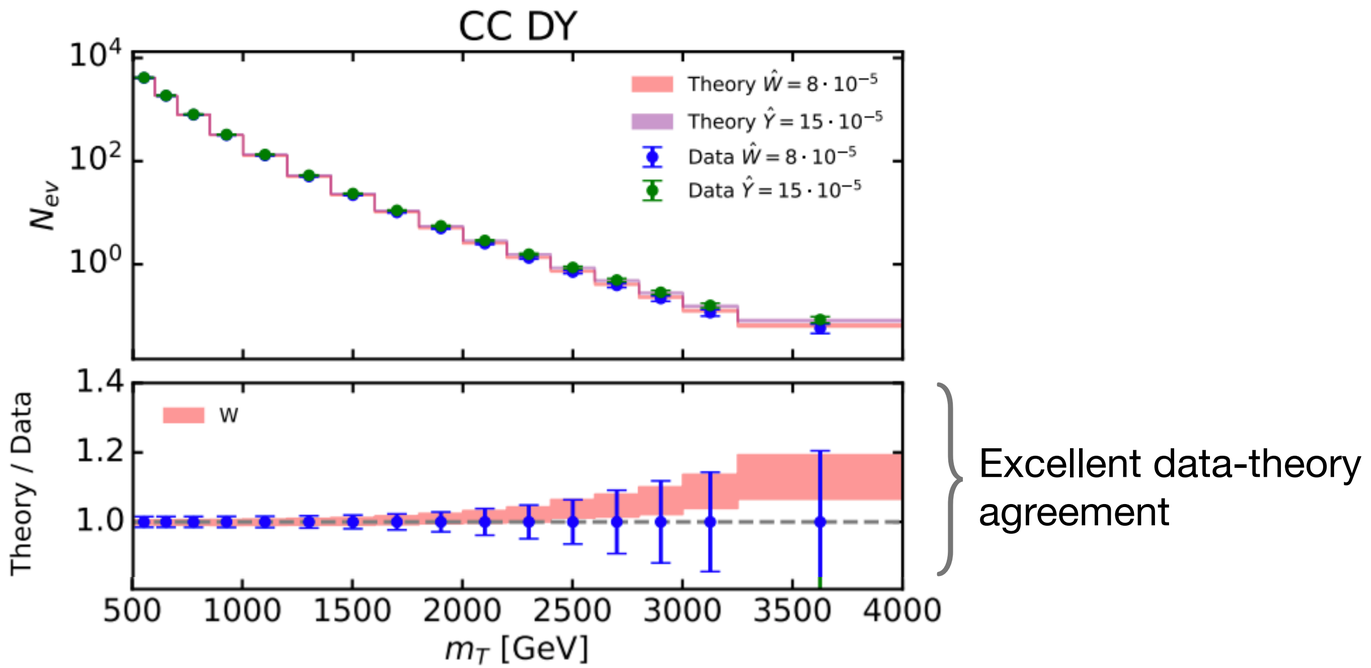
Fewer constraints on the **large-x antiquark PDFs** allow freedom to shift away from the baseline

What is the impact on observables?

Impact on Drell-Yan

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 on EW processes

Data: ‘true’ PDF ⊗ SM
Theory: contaminated PDF ⊗ SM

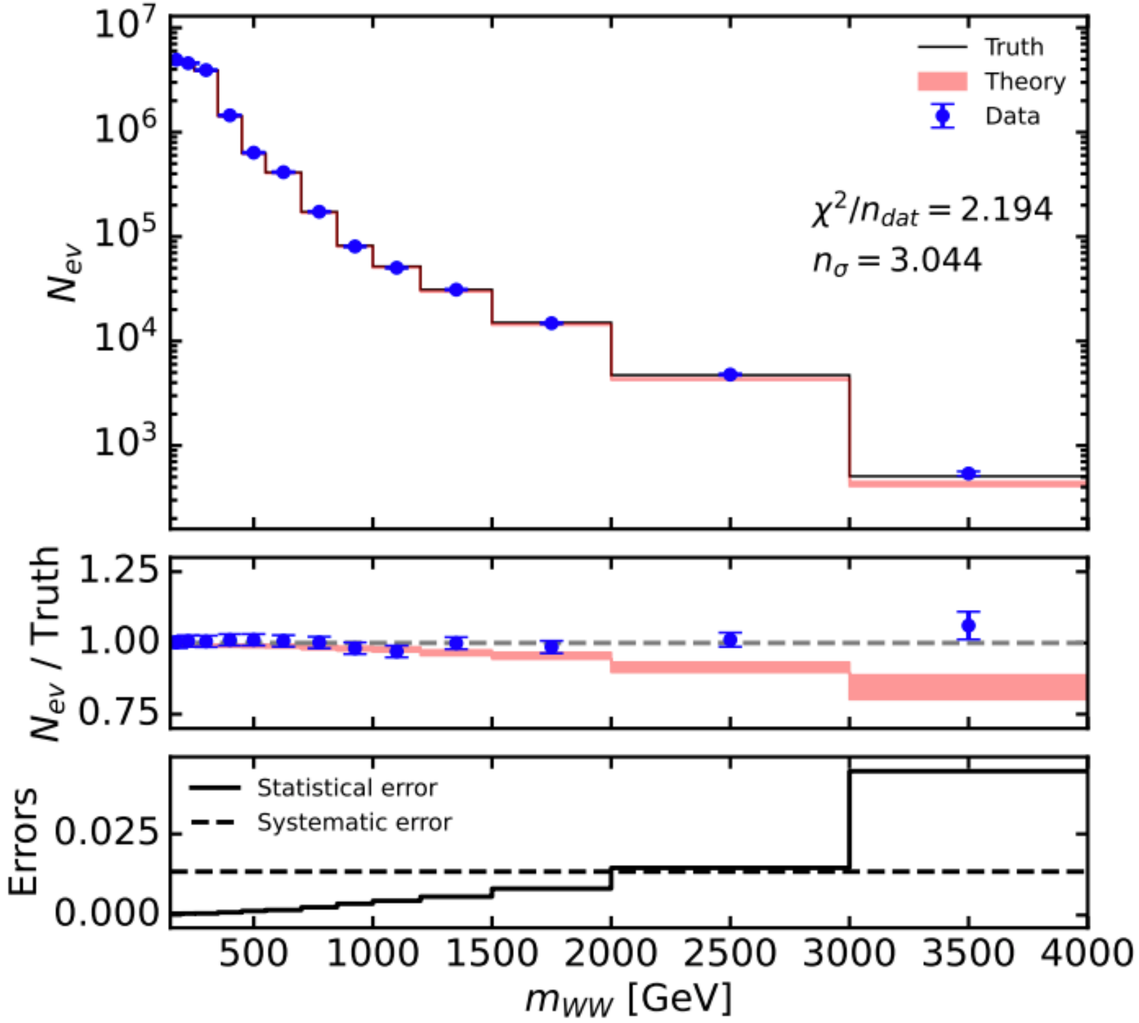
The PDF then causes **spurious NP effects** in other observables e.g.

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

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

the deviation is in the PDF

HL-LHC projections



Impact on EW processes

Data: ‘true’ PDF ⊗ SM
Theory: contaminated PDF ⊗ SM

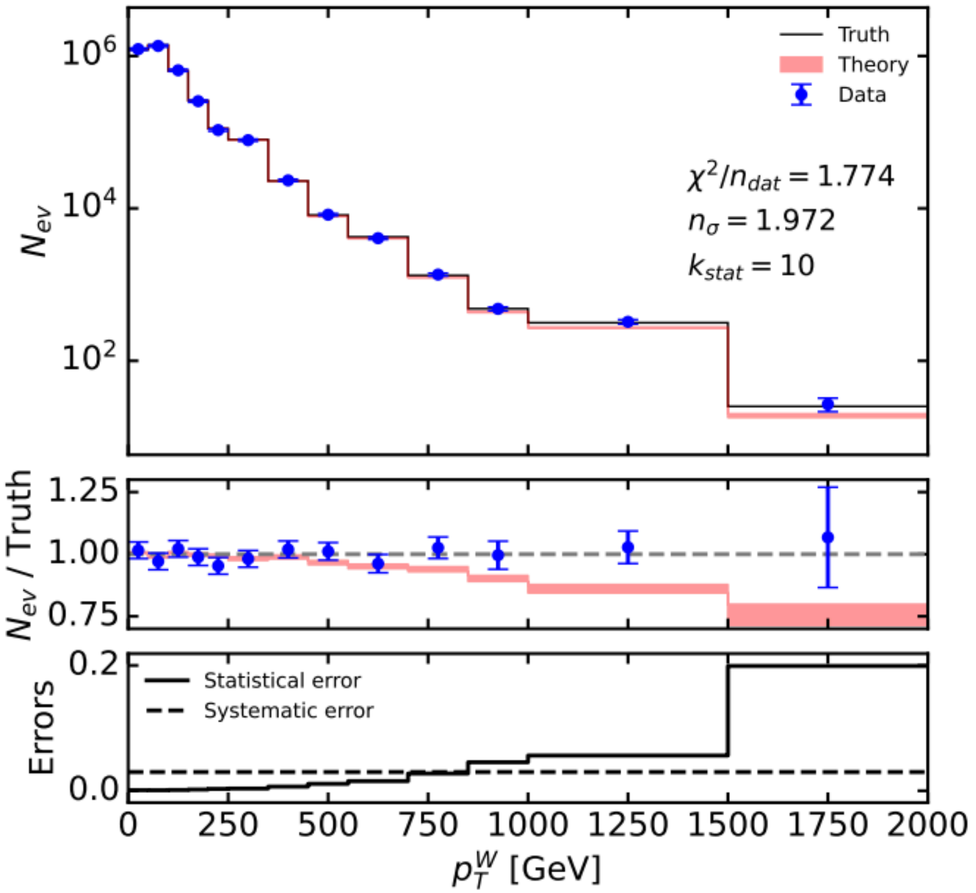
The PDF then causes **spurious NP effects** in other observables e.g.

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

- Data appears to disagree with SM at 2σ
- However, WH is unaffected by W’ model:

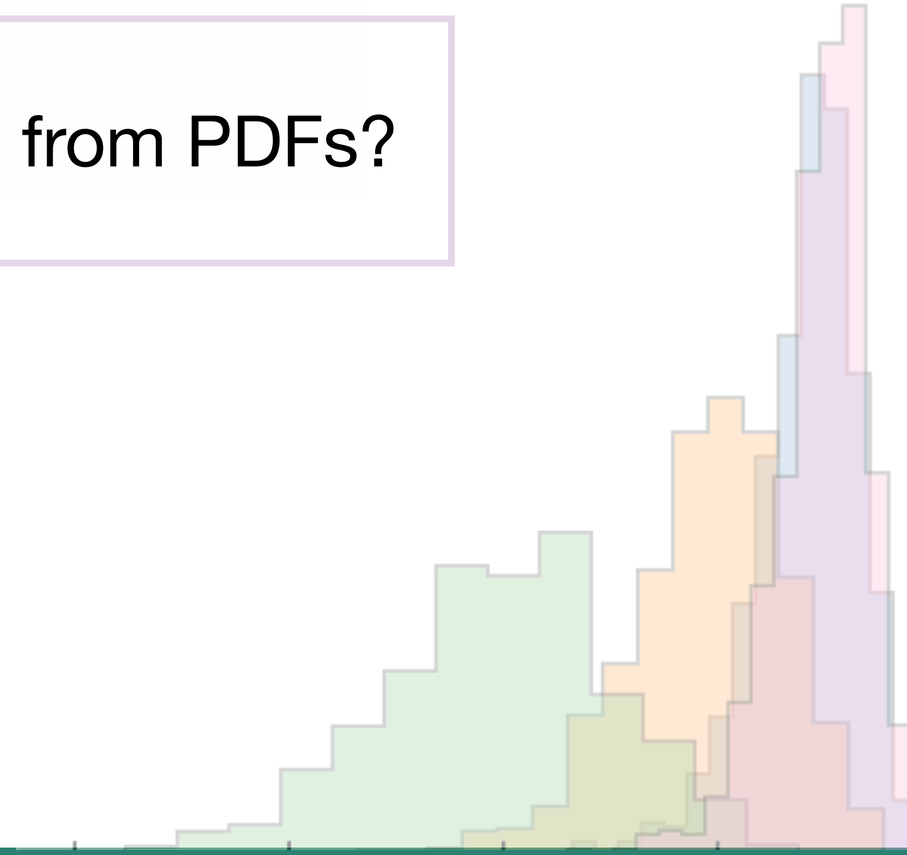
the deviation is in the PDF

HL-LHC projections



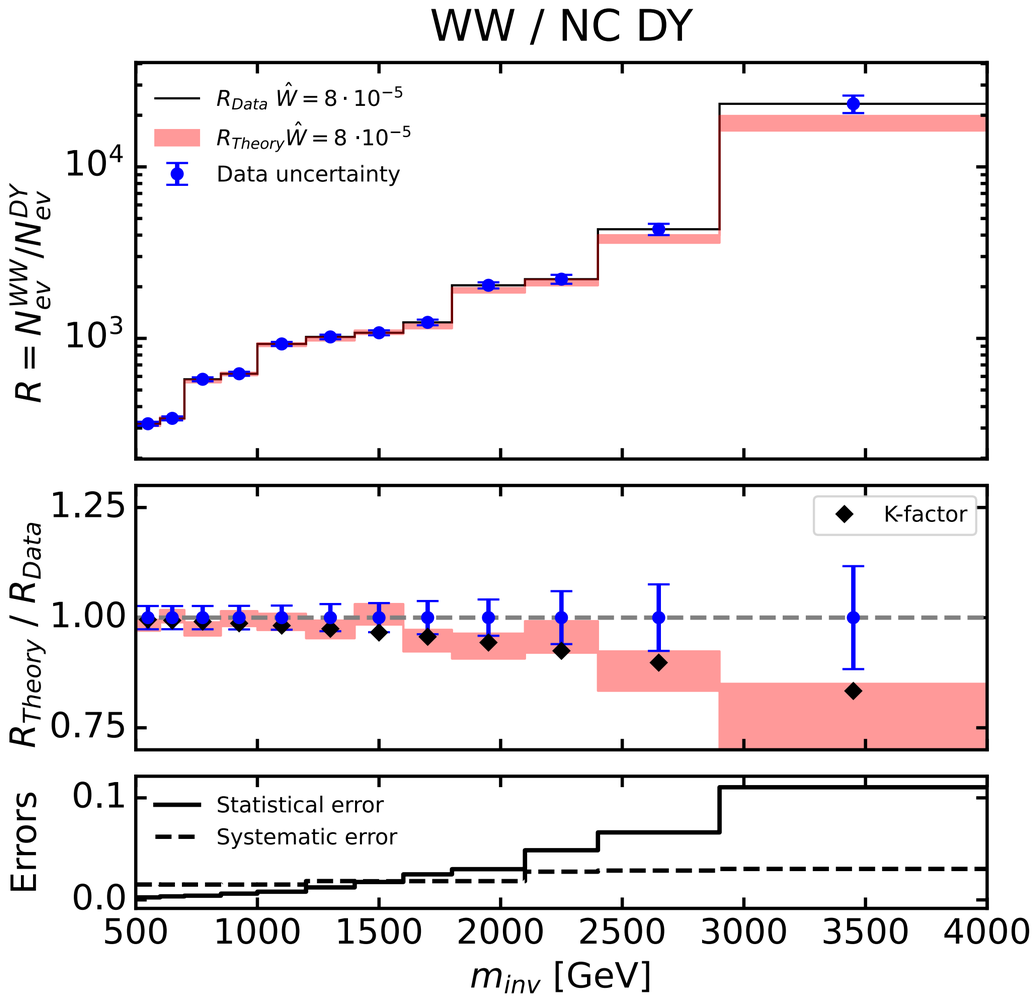
statistics improved by a factor of 10

Can we disentangle the effect of NP from PDFs?



Opportunities to disentangle PDF and SMEFT effects

Ratio observables:



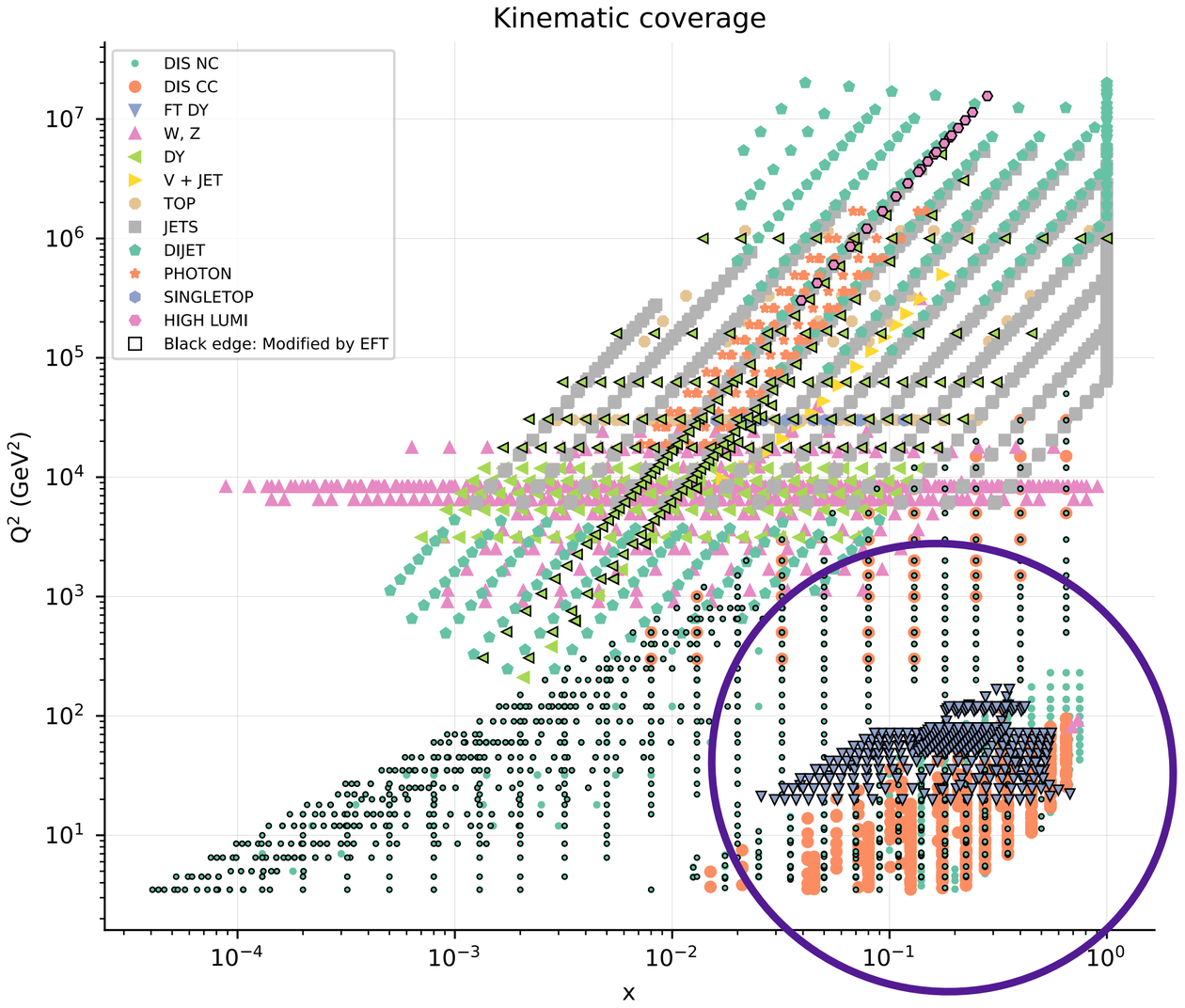
Opportunities to disentangle PDF and SMEFT effects

Ratio observables:

Low-energy precision measurements sensitive to high-x PDFs

➡ add precision here:

work in progress by E. Hammou, M. Ubiali



Opportunities to disentangle PDF and SMEFT effects

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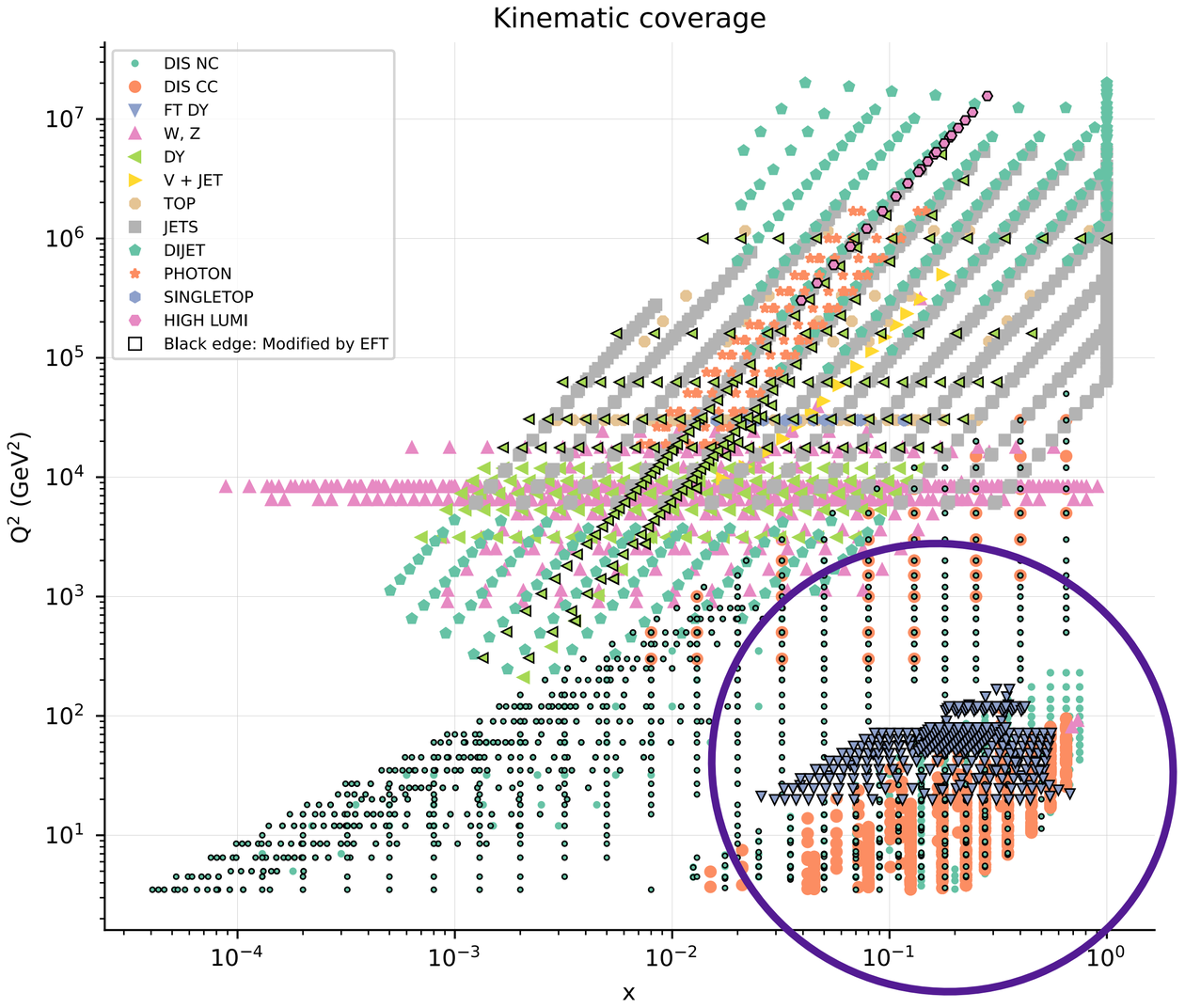
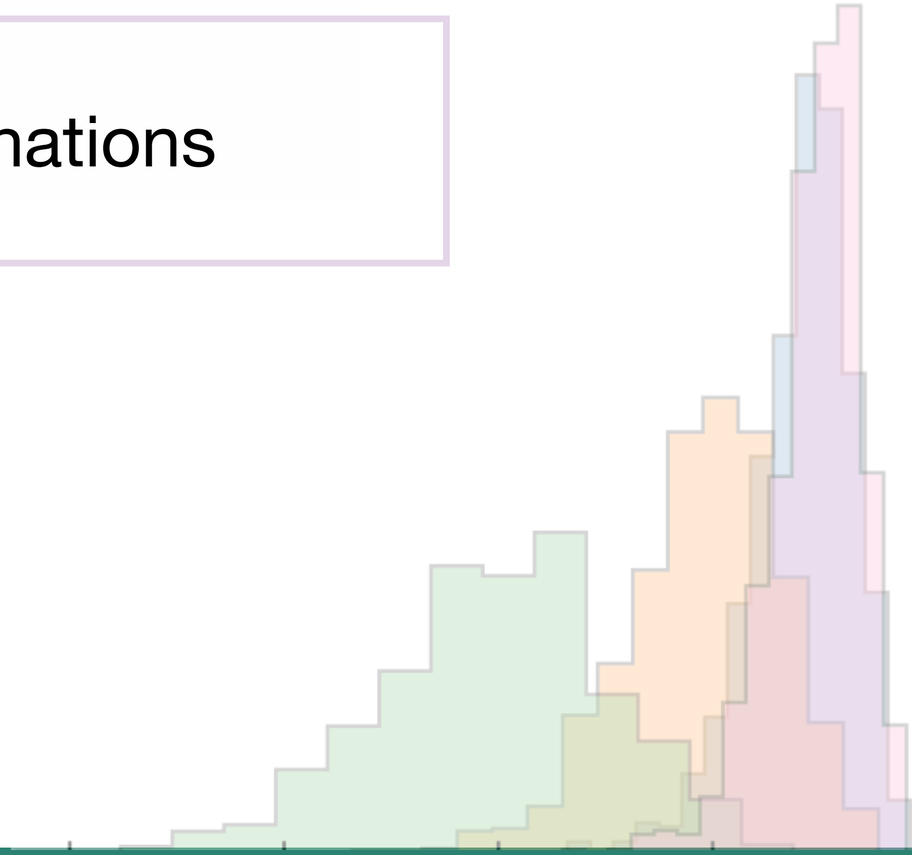
Simultaneous PDF and SMEFT determinations



Simultaneous PDF-EFT Determinations

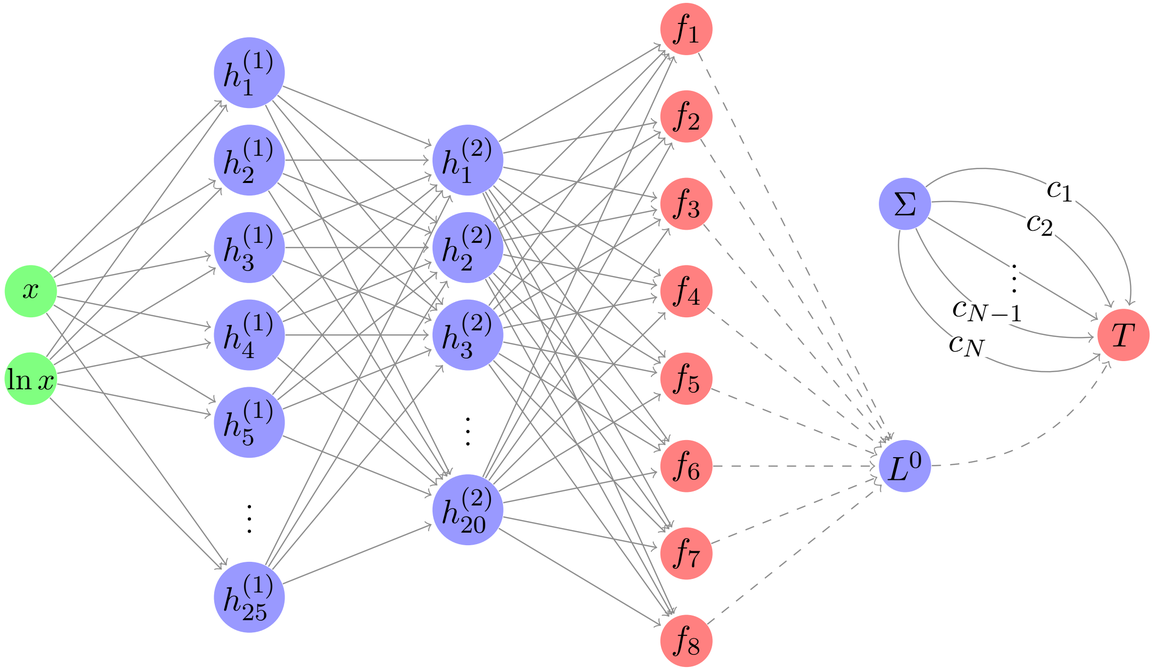


Simultaneous fit of PDFs and SMEFT with simuNET

S. Iranipour, M. Ubiali, 2201.07240

Public release: *2402.03308*, https://hep-pbsp.github.io/SIMUnet

M. N. Constantini, E. Hammou, Z. Kassabov, MM, L. Mantani, J. Moore, M. Morales Alvarado, M. Ubiali



Fast and efficient **simultaneous determinations** of PDFs and Wilson coefficients

Places PDF parameters and Wilson coefficients on the same footing

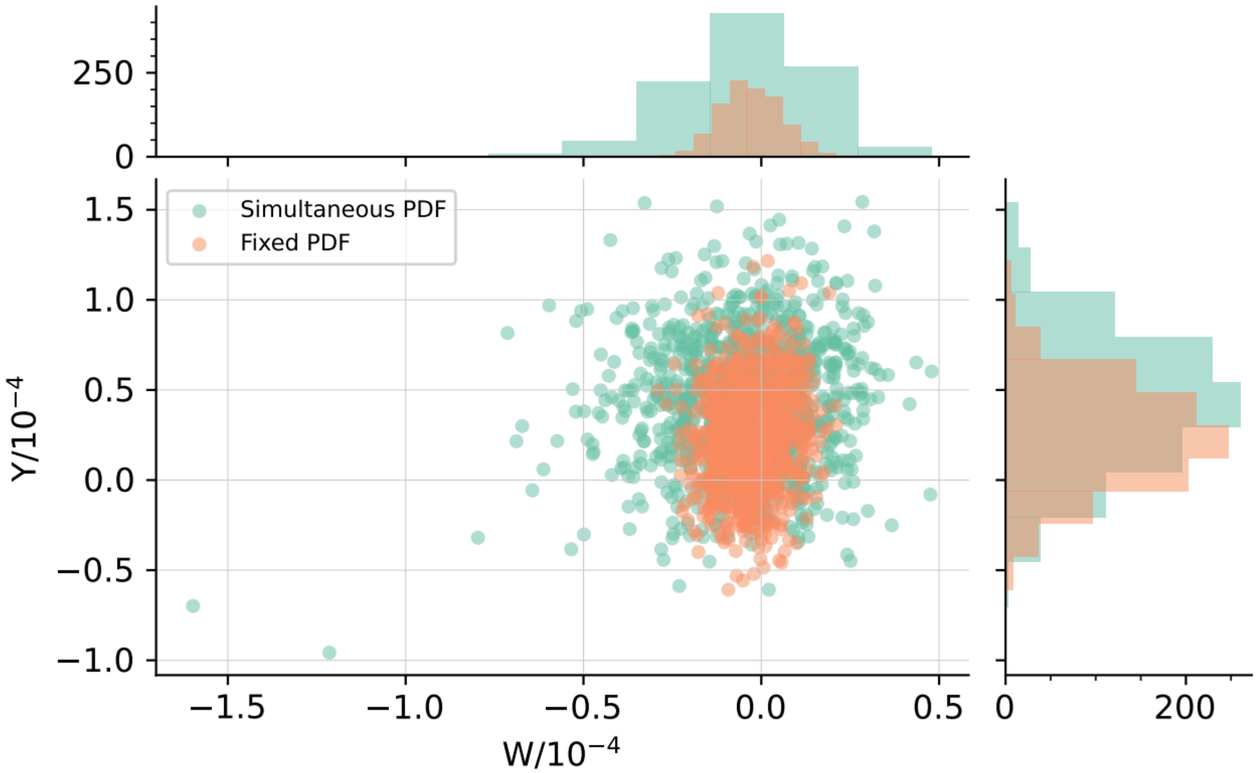
some examples: ⟶

Simultaneous fit of PDFs and SMEFT in high mass DY

S. Iranipour, M. Ubiali, 2201.07240

Including **HL-LHC projections** for NC and CC Drell-Yan:

Neglecting PDF-EFT interplay leads to a significant overestimate of the EFT constraints.



Simultaneous fit of PDFs and SMEFT in the top sector

Z. Kassabov et. al , 2303.06159

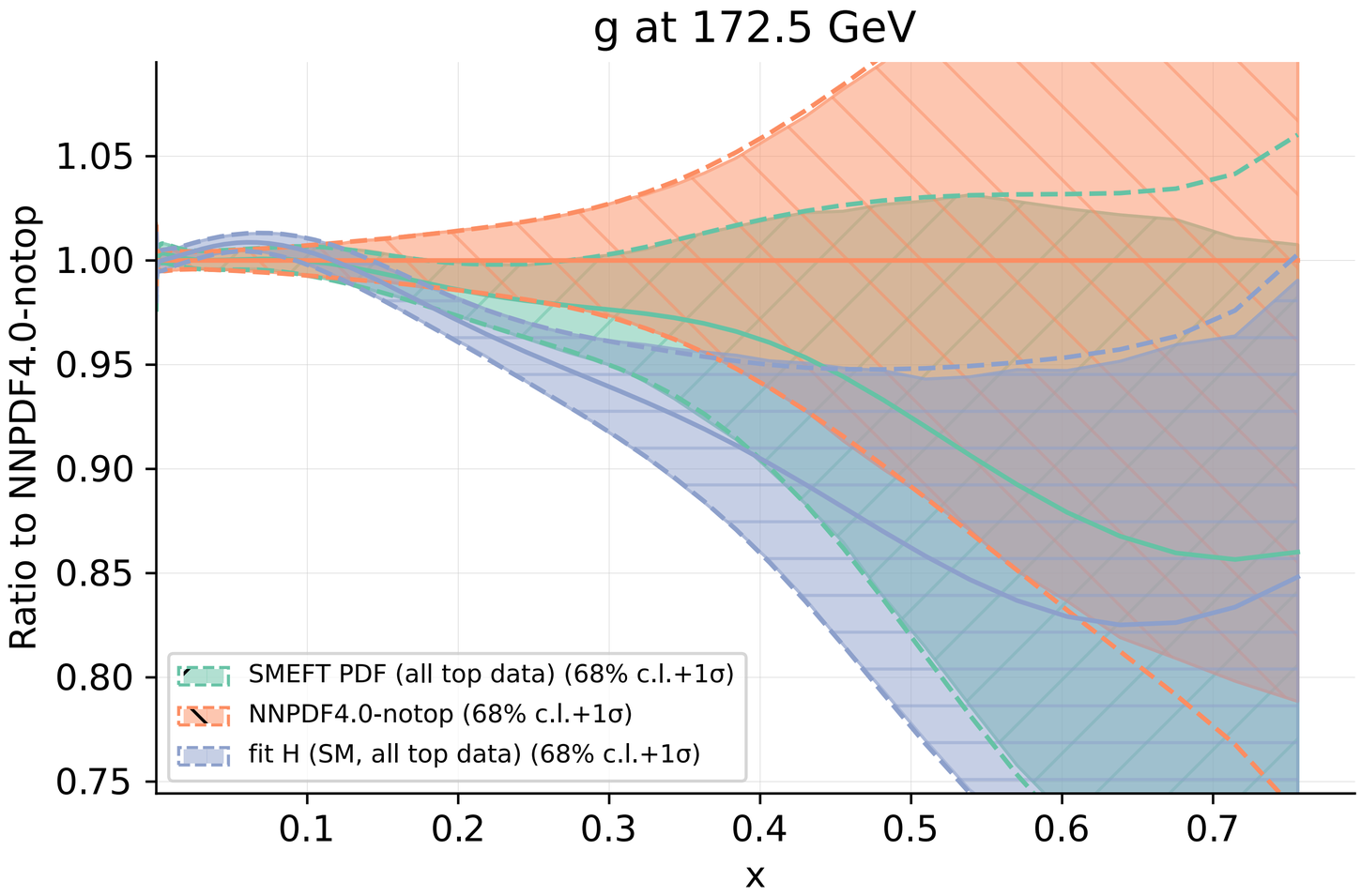
Including **top quark data** from LHC Run II:

A simultaneous fit shows better agreement with the no-top fit:

- the impact of top data is **diluted** by the inclusion of the SMEFT

Uncertainties increase relative to the *SM, all top data* PDF fit

- reflecting the increase in number of fitted parameters



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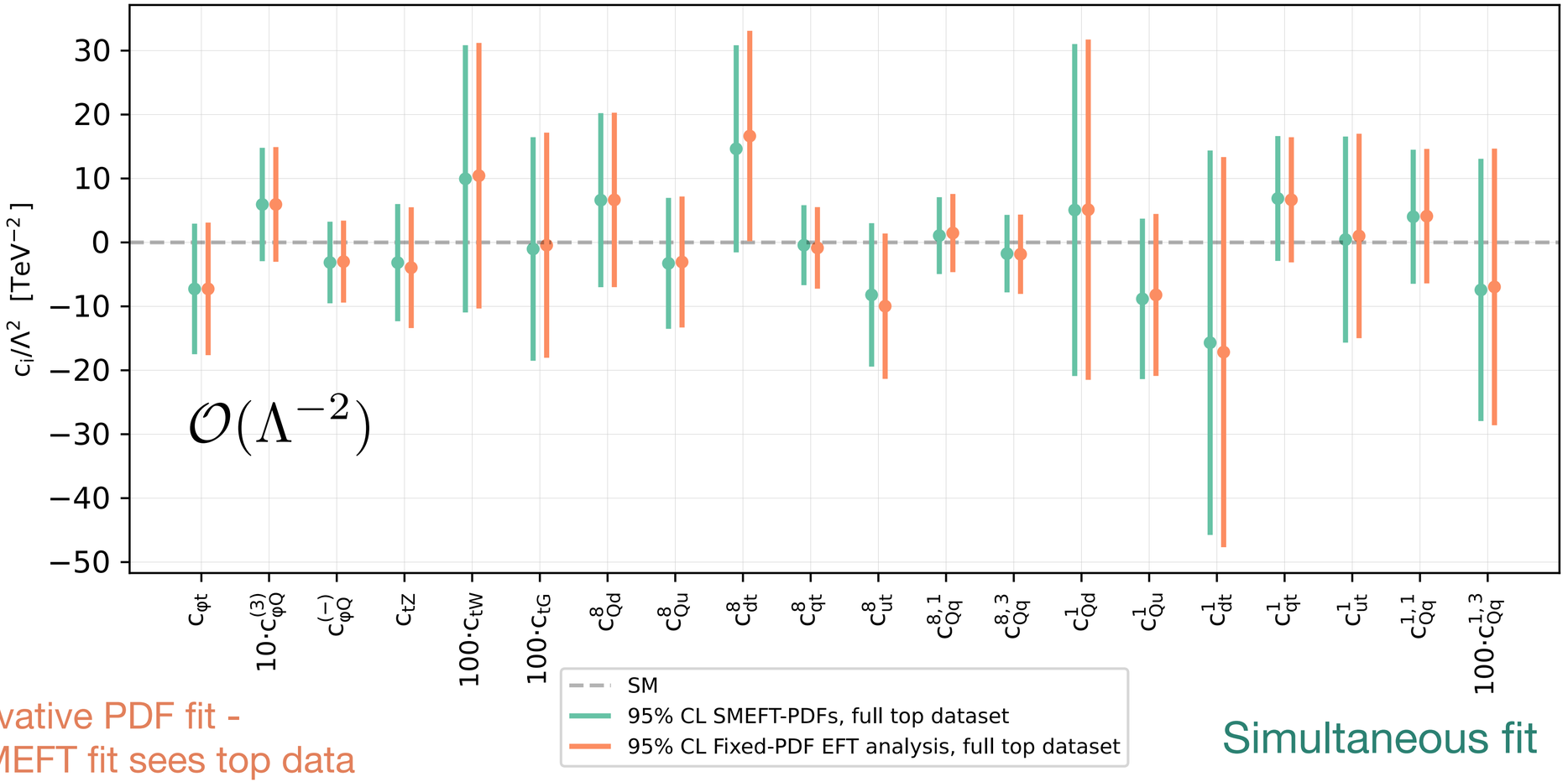

Conservative PDF fit -
only SMEFT fit sees top data

Simultaneous fit

Conclusions

Discovering new physics will rely on an unbiased and accurate understanding of the parton distribution functions

- Parton distribution functions have the potential to **conceal new physics:**
  - Contaminated PDFs may translate signs of new physics into Higgs+EW processes
  - Disentangling post-fit is not guaranteed: future low-energy precision measurements of high-x antiquarks, e.g. from the EIC, will provide crucial inputs to future PDF fits

- Tools to investigate contaminated PDF fits in other BSM scenarios are publicly available: https://www.pbsp.org.uk/contamination/
- SIMUnet public release: https://hep-pbsp.github.io/SIMUnet

Conclusions

Thank you for listening!

Discovering new physics will rely on an unbiased and accurate understanding of the parton distribution functions

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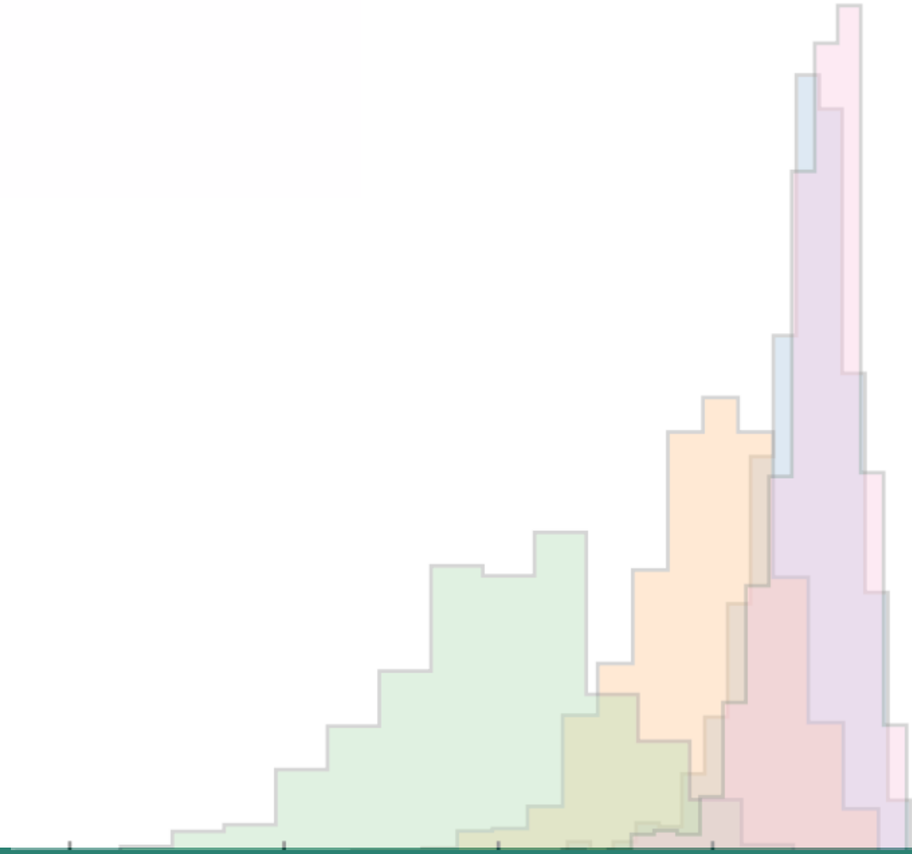
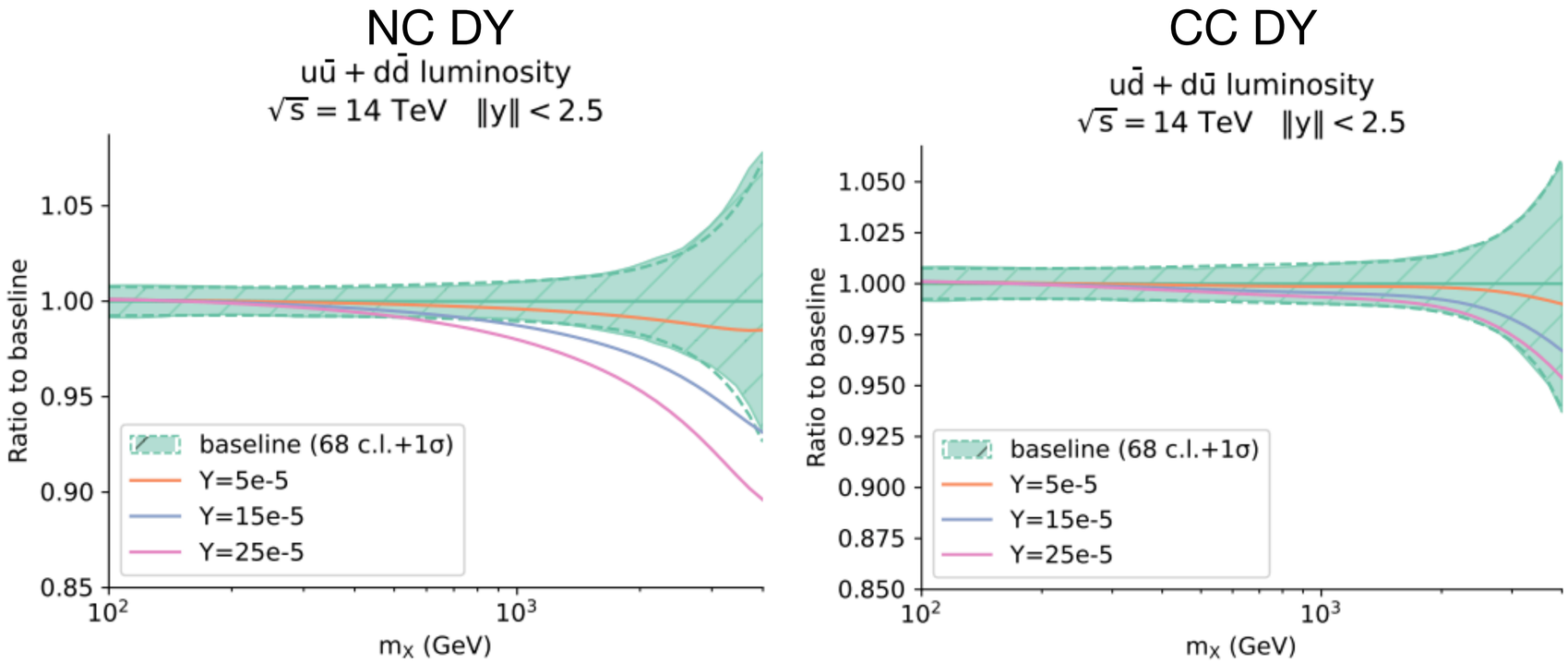
Backup



Z’-contaminated PDFs

Data: ‘true’ PDF ⊗ SM + Z’
Theory: contaminated PDF ⊗ SM



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 ⊗ SM + Z’
Theory: contaminated PDF ⊗ SM