How much room is there for discoveries?

Maeve Madigan
Heidelberg University
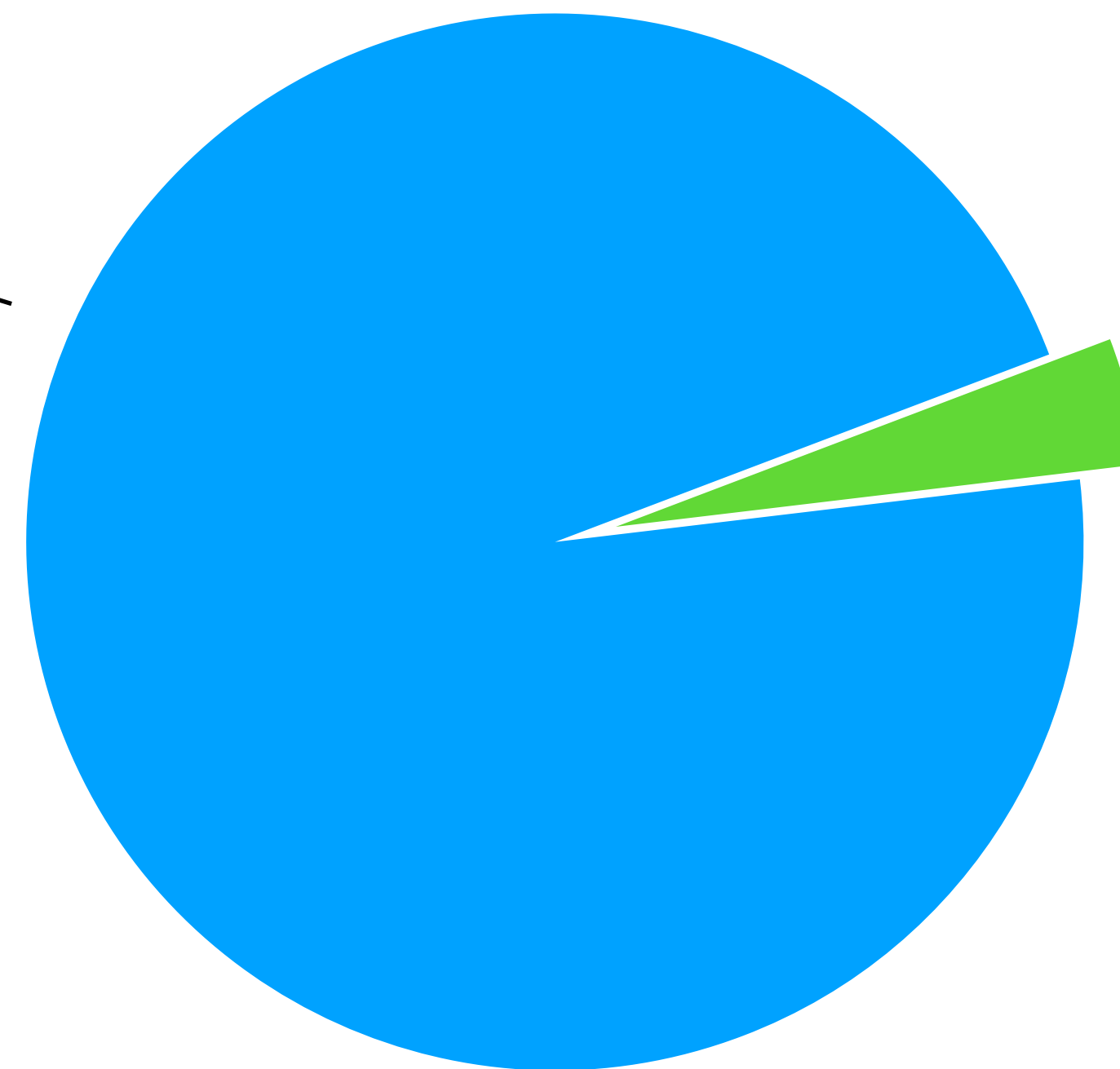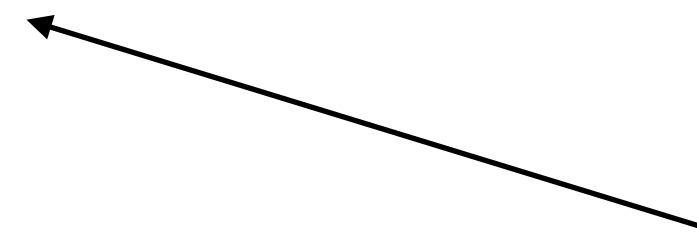
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

How much room is there for discoveries?

room for discoveries

this talk
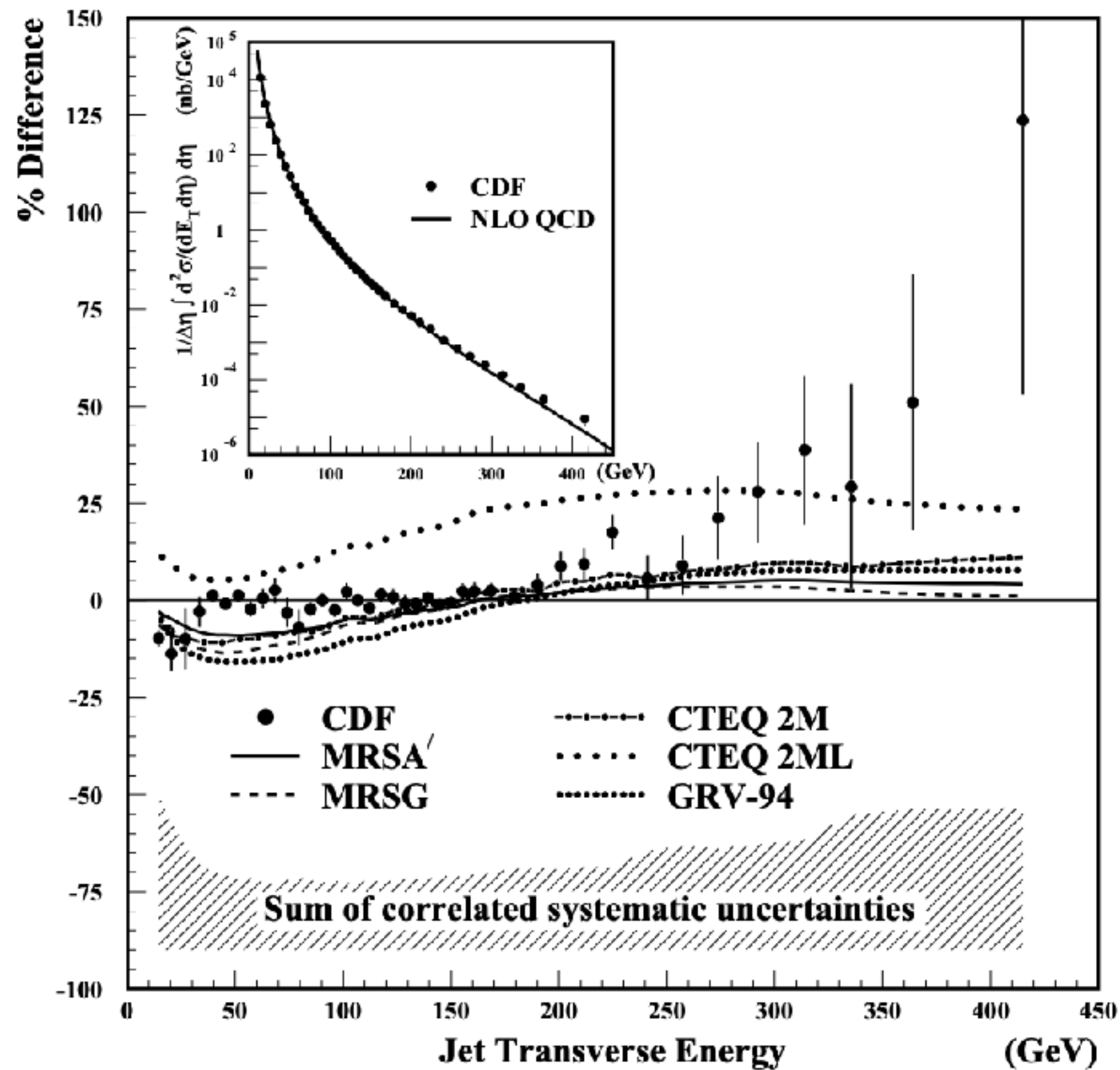
hep-ex/9601008

CDF collaboration measured a deviation at high transverse momentum

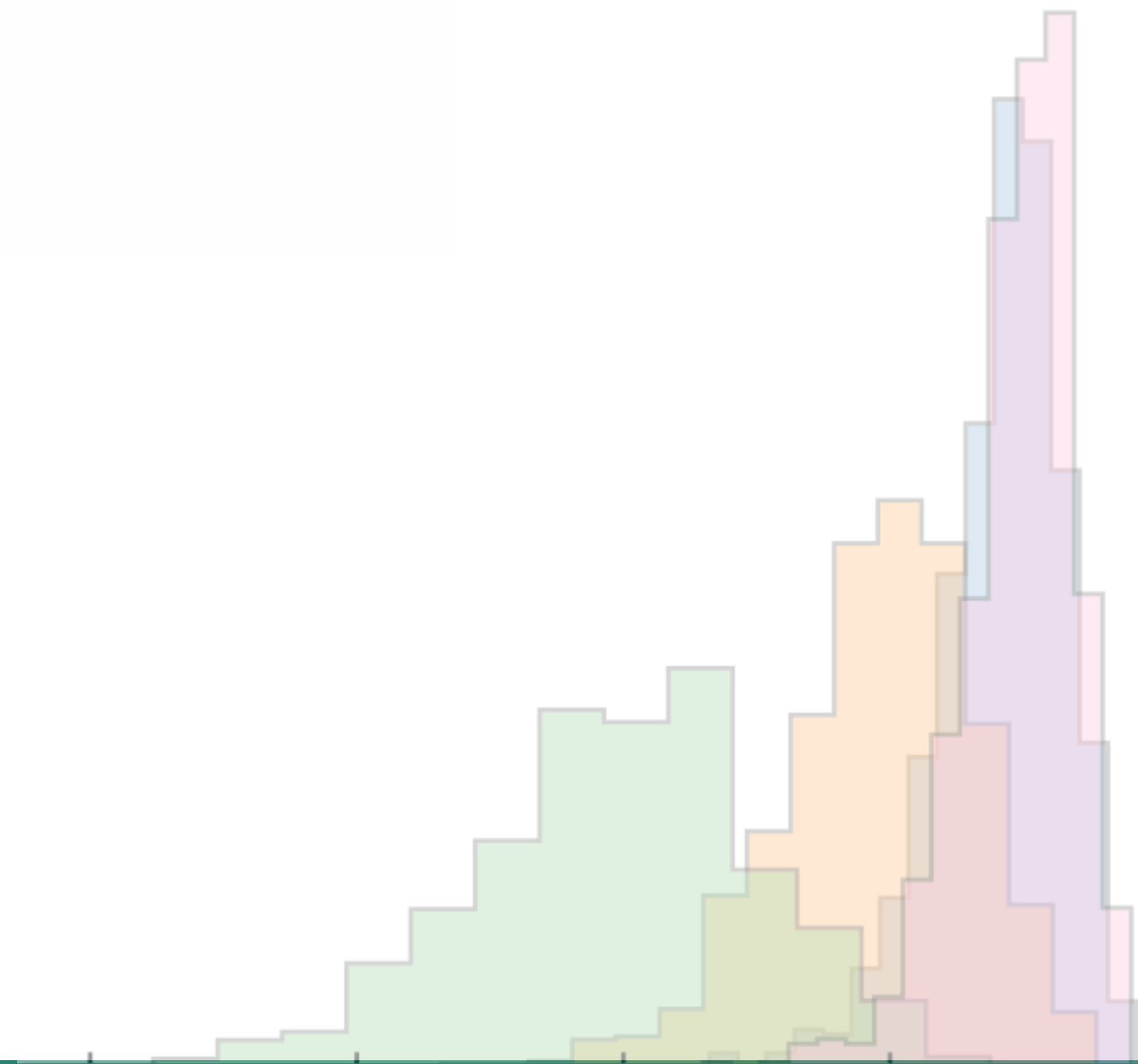**However,** this was not new physics

- deviation went away with improvements to large-x gluon PDFS

What if no new physics is observed…

2308.08521
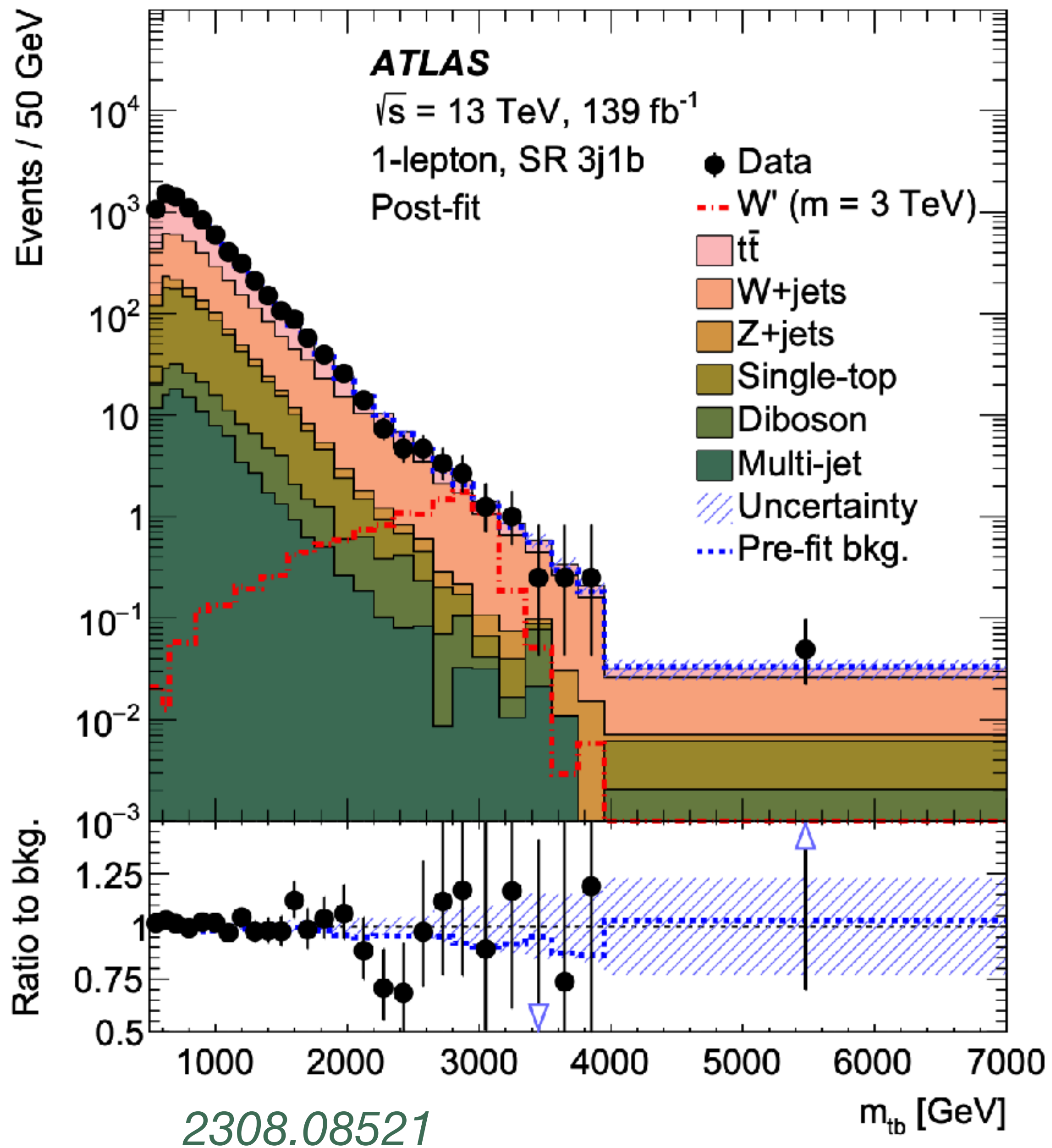
…because it has been **absorbed by the PDFs**?

PDF-EFT Interplay

PDF-EFT Interplay

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

Parton distribution function fits

Wilson coefficients are kept fixed:

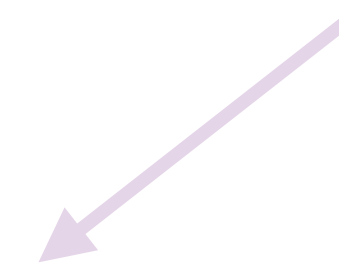$$\sigma(\bar{c}, \theta) = f_1(\theta) \otimes f_2(\theta) \otimes \hat{\sigma}(\bar{c})$$

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

SMEFT Fits and BSM searches

PDF parameters are fixed:

$$\sigma(c, \bar{\theta}) = f_1(\bar{\theta}) \otimes f_2(\bar{\theta}) \otimes \hat{\sigma}(c)$$
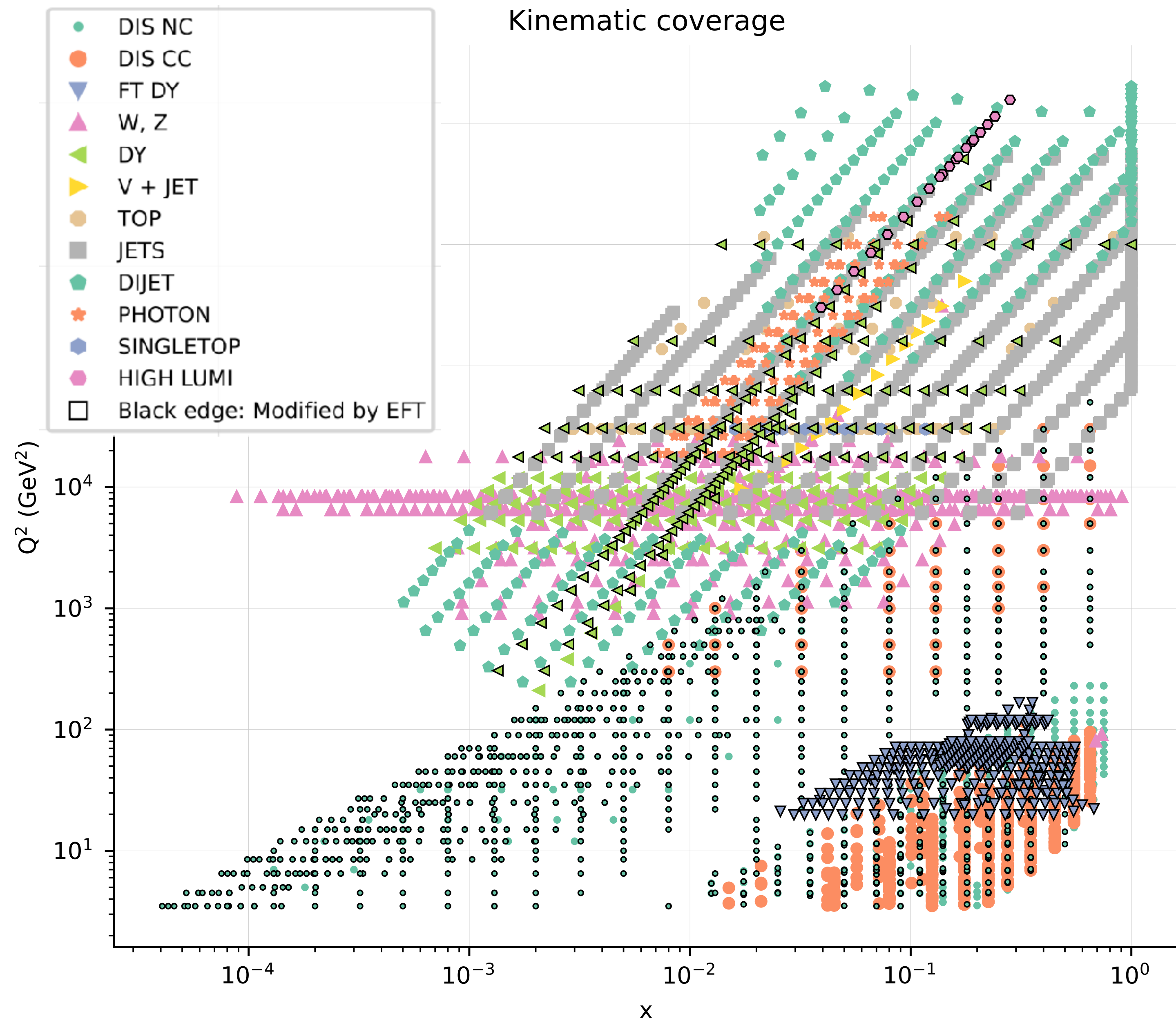
PDFs used in SMEFT fits rely on SM assumptions

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.

Kinematic coverage

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
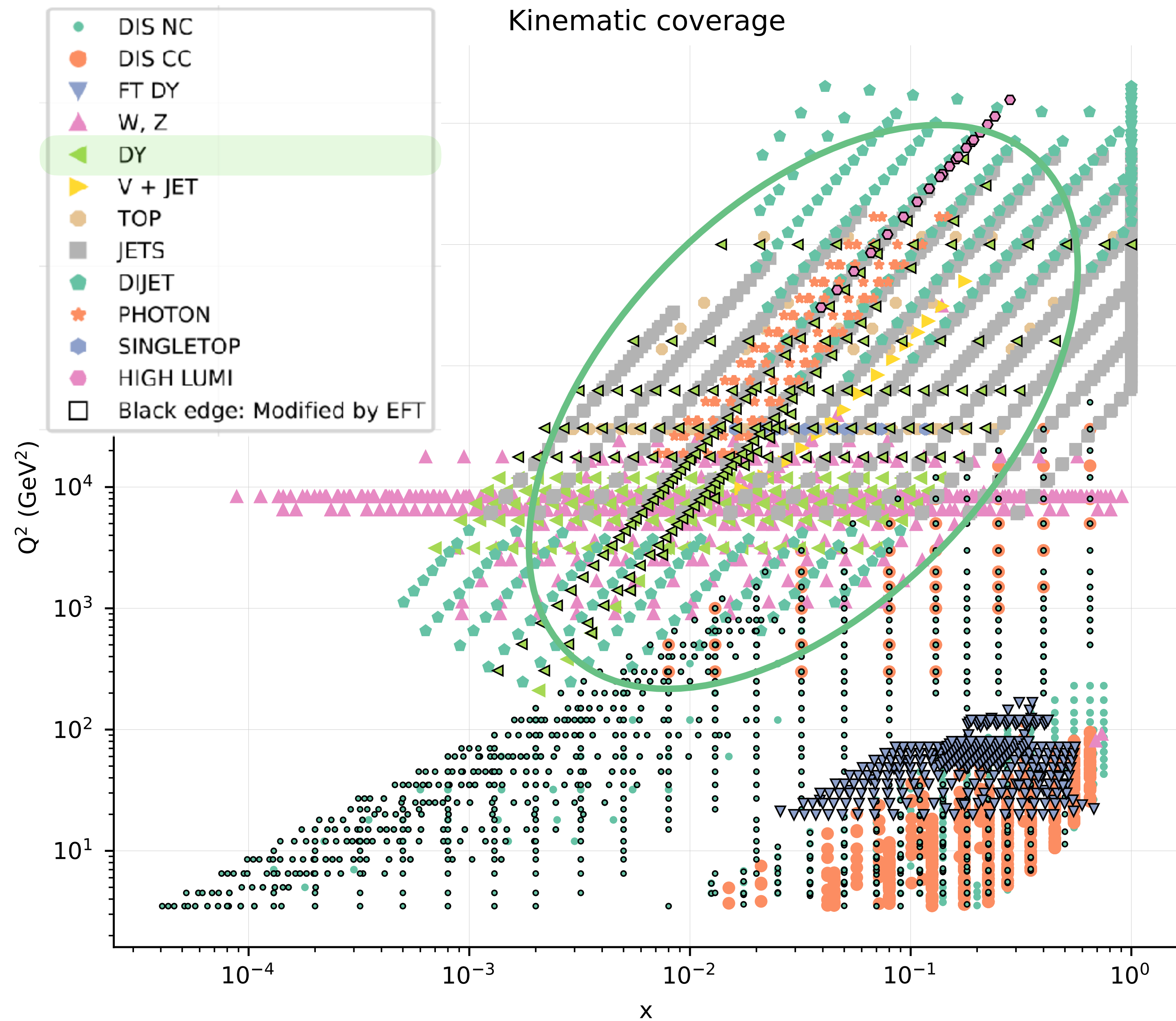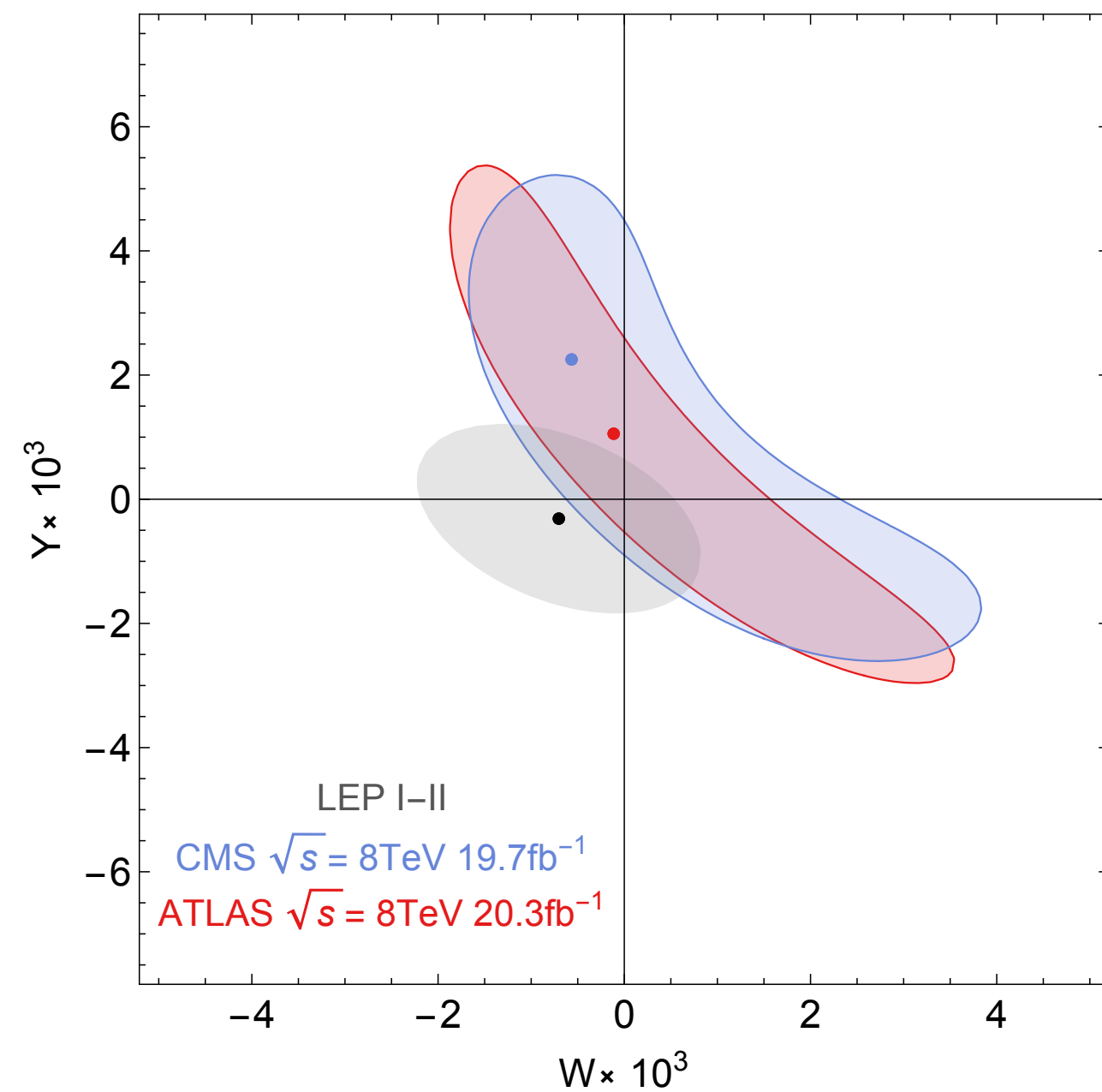
Data included in our study

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
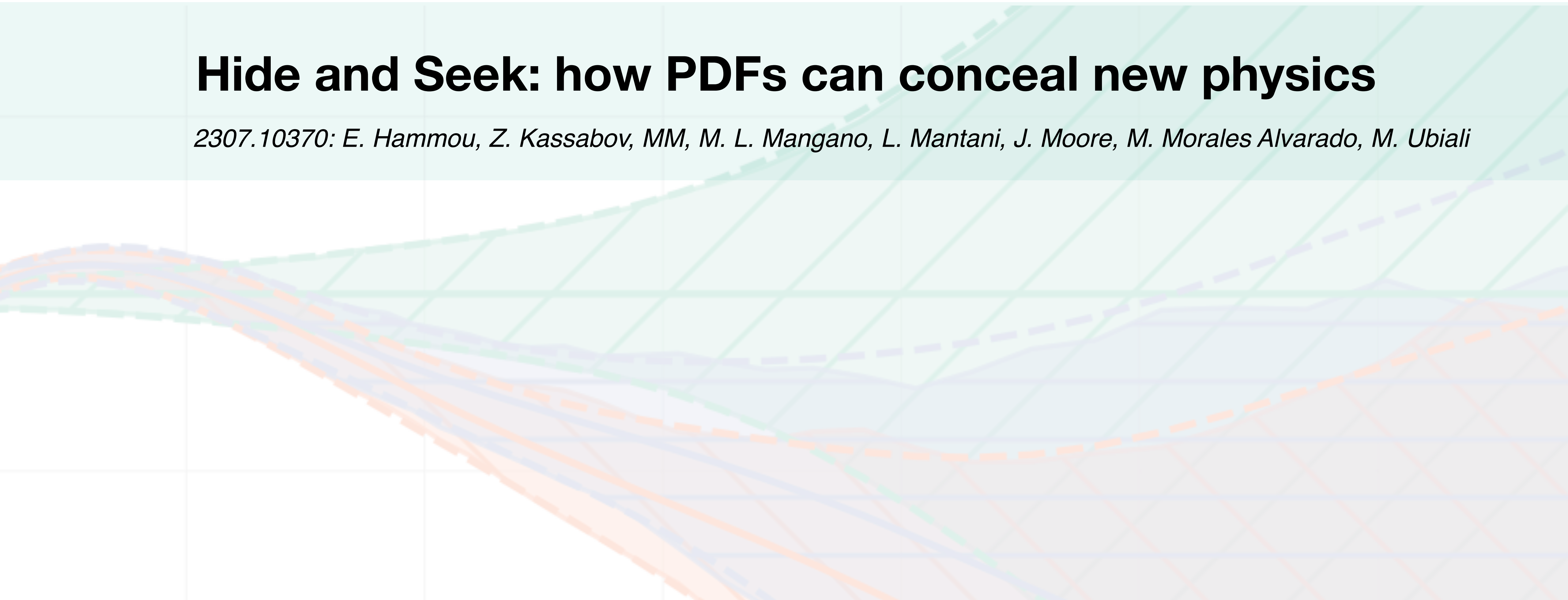 *See also 2201.06586, 2211.01094*

Contaminated PDF fits:

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

Hide and Seek: how PDFs can conceal new physics

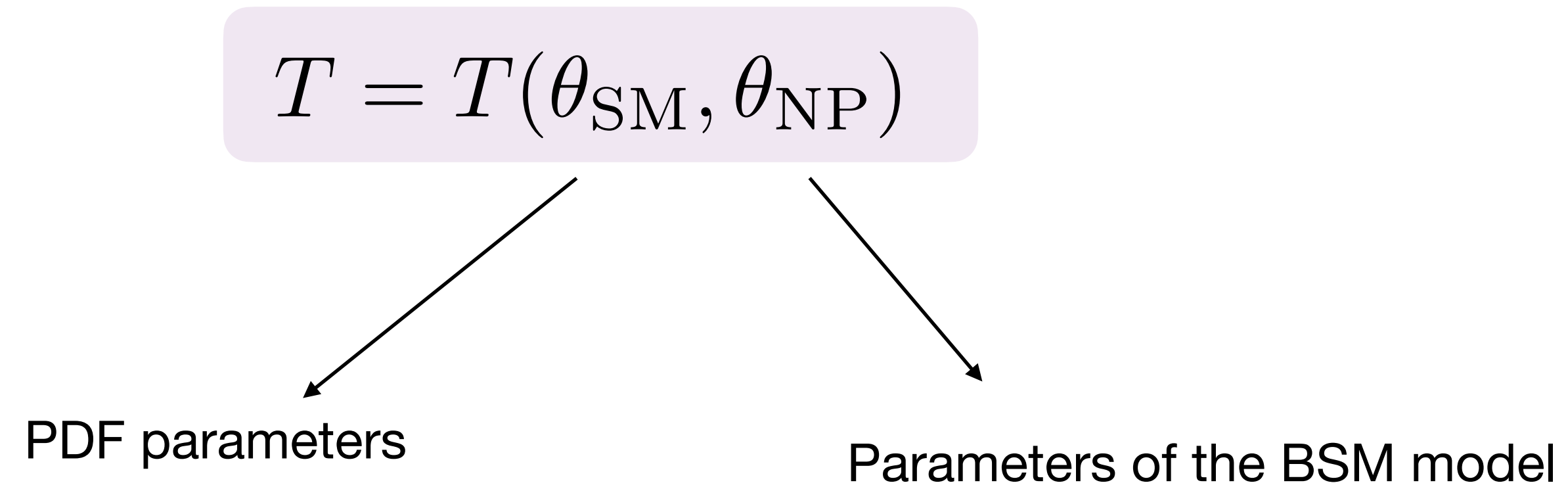*2307.10370: E. Hammou, Z. Kassabov, MM, M. L. Mangano, L. Mantani, J. Moore, M. Morales Alvarado, M. Ubiali*

Contaminated PDFs

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

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

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

Generate Monte Carlo pseudodata according to this underlying law:

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

Contaminated PDFs

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Perform a PDF fit: **fit only the SM parameters** θ_{SM} using the NNPDF4.0 methodology

2109.02653

Contaminated PDFs

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

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

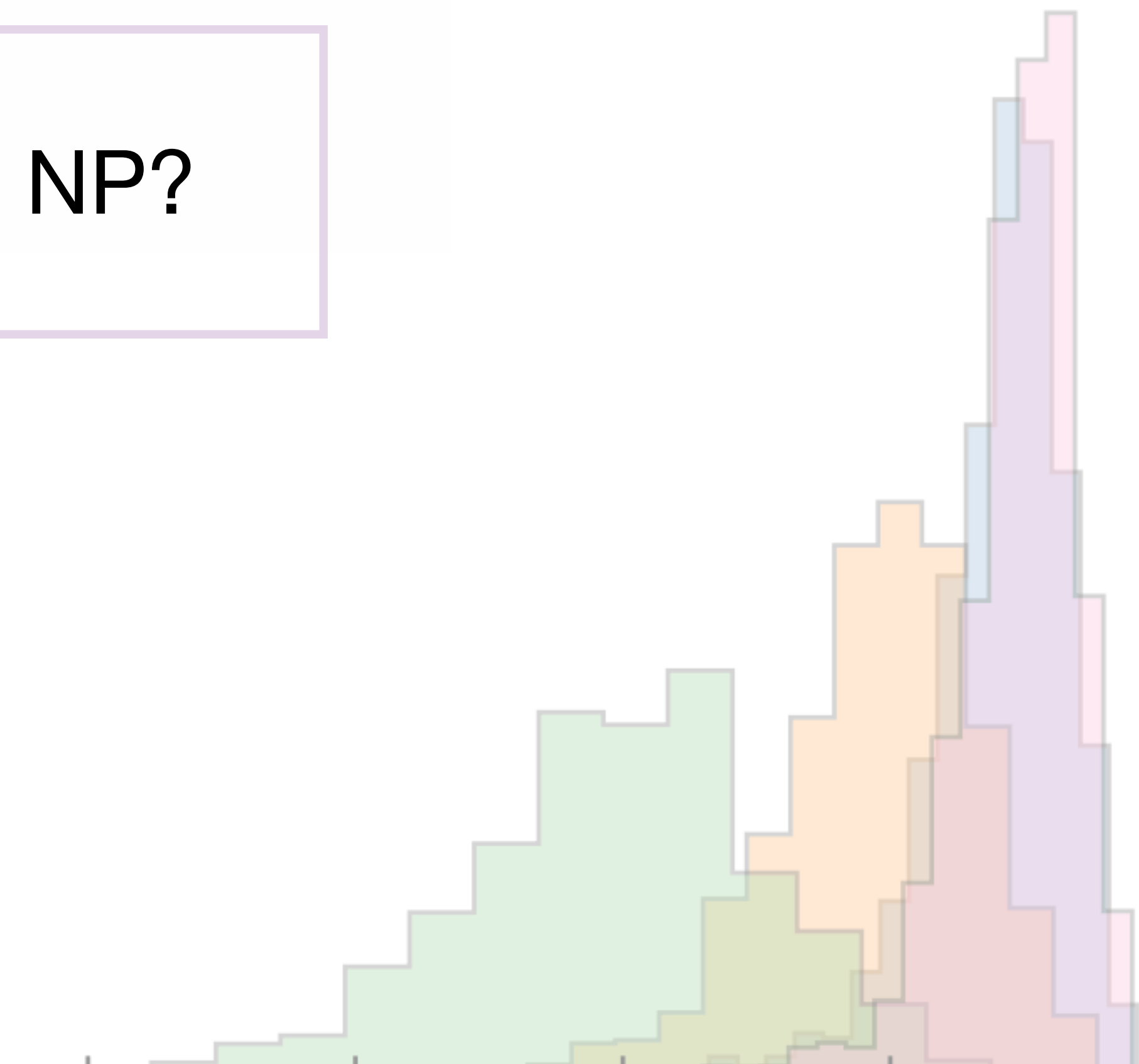Generate Monte Carlo pseudodata according to this underlying law:

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

Perform a PDF fit: fit only the SM parameters θ_{SM} using the NNPDF4.0 methodology

2109.02653

PDF has **absorbed new physics** if the fit quality is good $n_\sigma = \dfrac{\chi^2 - 1}{\sigma_{\chi^2}} < 2$
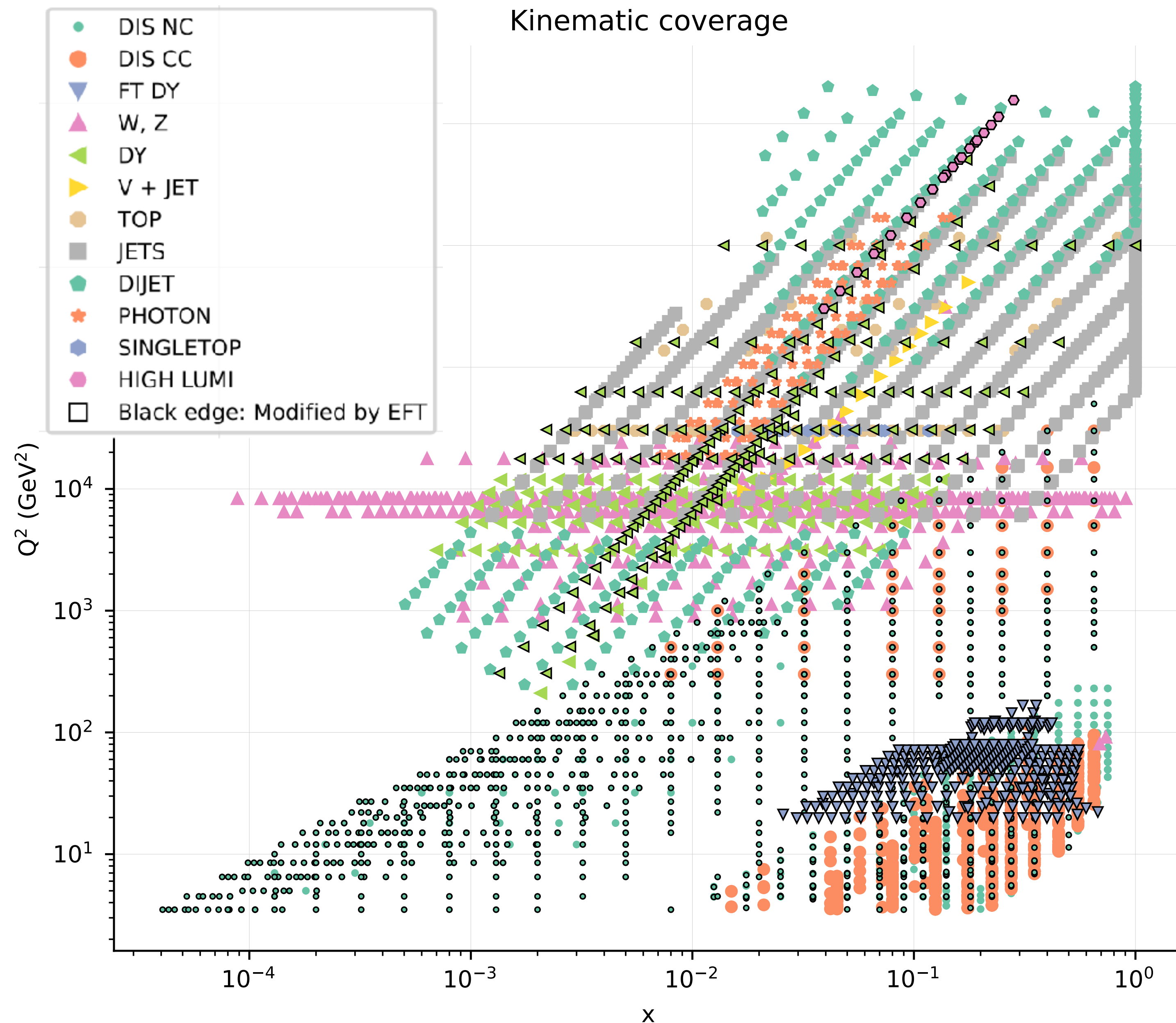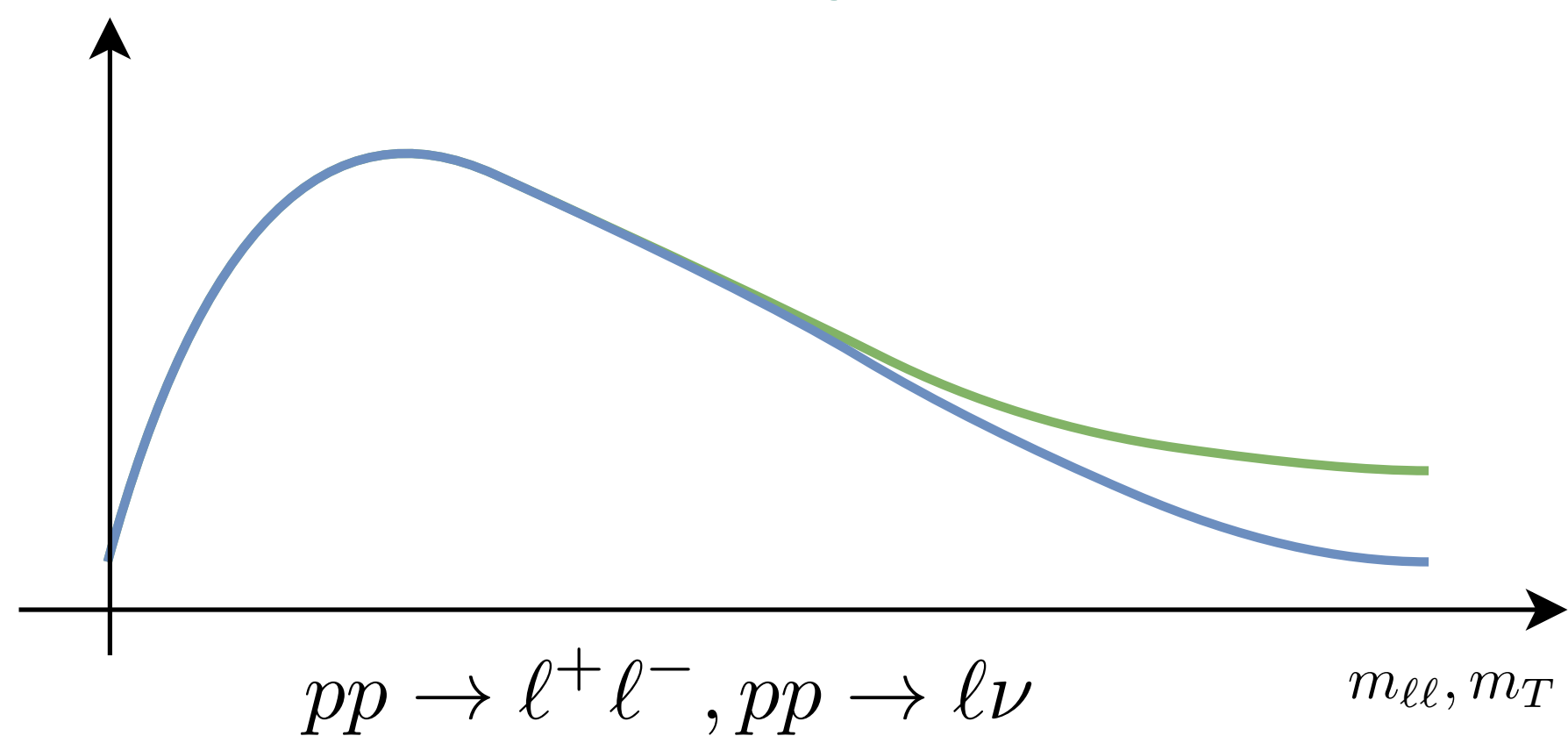
Can PDFs be contaminated by NP?

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

$$pp \rightarrow \ell^+\ell^-, pp \rightarrow \ell\nu$$

$m_{\ell\ell}, m_T$

Kinematic coverage

BSM scenario: W'

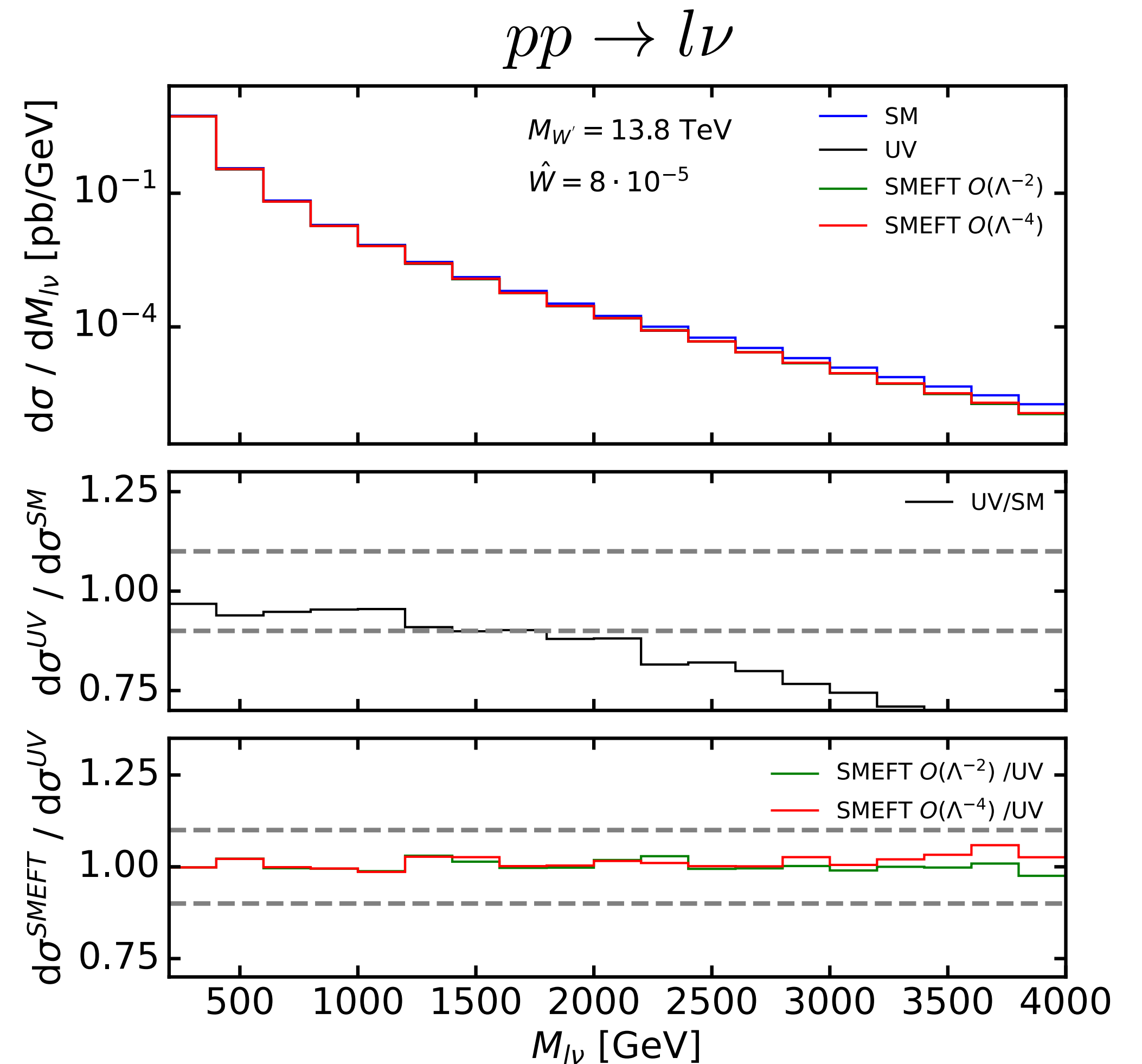- Flavour universal W'

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

$pp \rightarrow l\nu$

$M_{W'} = 13.8$ TeV
$\hat{W} = 8 \cdot 10^{-5}$

SM
UV
SMEFT $O(\Lambda^{-2})$
SMEFT $O(\Lambda^{-4})$

UV/SM

SMEFT $O(\Lambda^{-2})$ /UV
SMEFT $O(\Lambda^{-4})$ /UV

1.66
0.771
1.39

3.20
0.865
0.164
0.145

2.03
0.268
0.0889
-0.188

baseline
W=3e-5
W=8e-5
W=15e-5

$$\sigma = \dfrac{}{\sigma_{\chi^2}}$$

W

HL-LHC HM DY 14 TeV - charged current - muon channel

HL-LHC HM DY 14 TeV - charged current - electron channel

HL-LHC HM DY 14 TeV - neutral current - muon channel

HL-LHC HM DY 14 TeV - neutral current - electron channel

baseline
W=3e-5
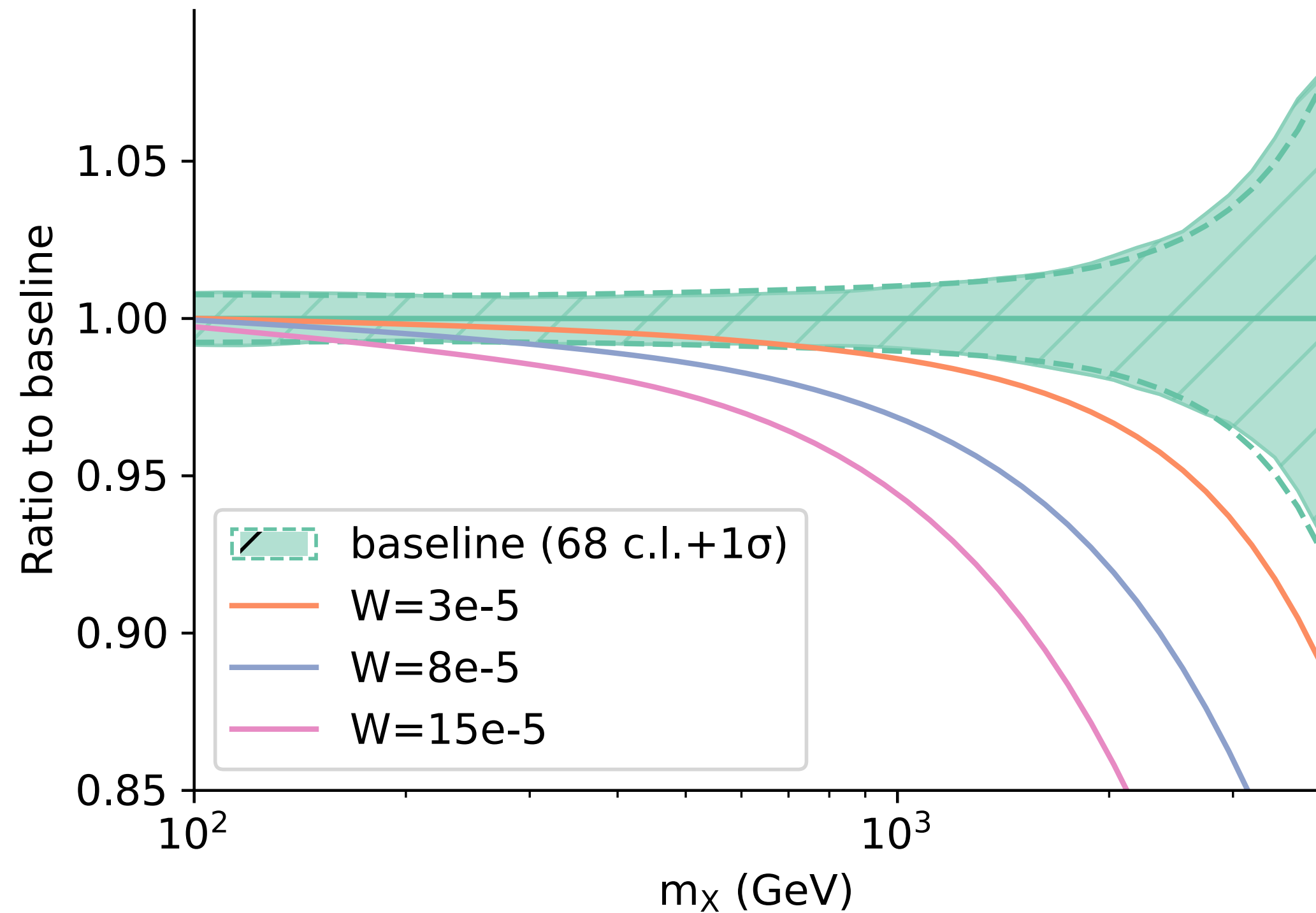W=8e-5
W=15e-5
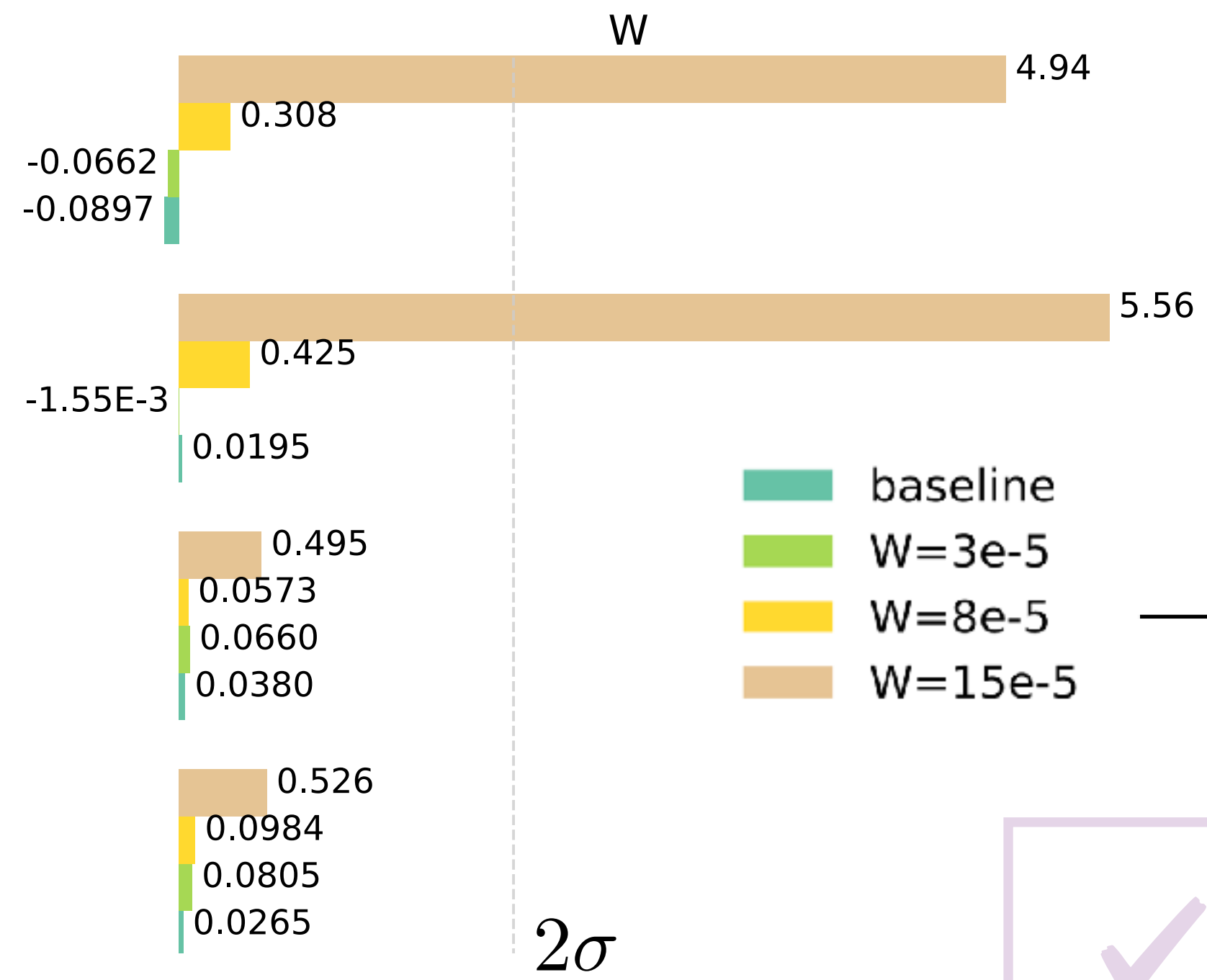
$-5, \ M_{W'} \approx 14 \text{ TeV}$

rb new physics

W'-contaminated PDFs

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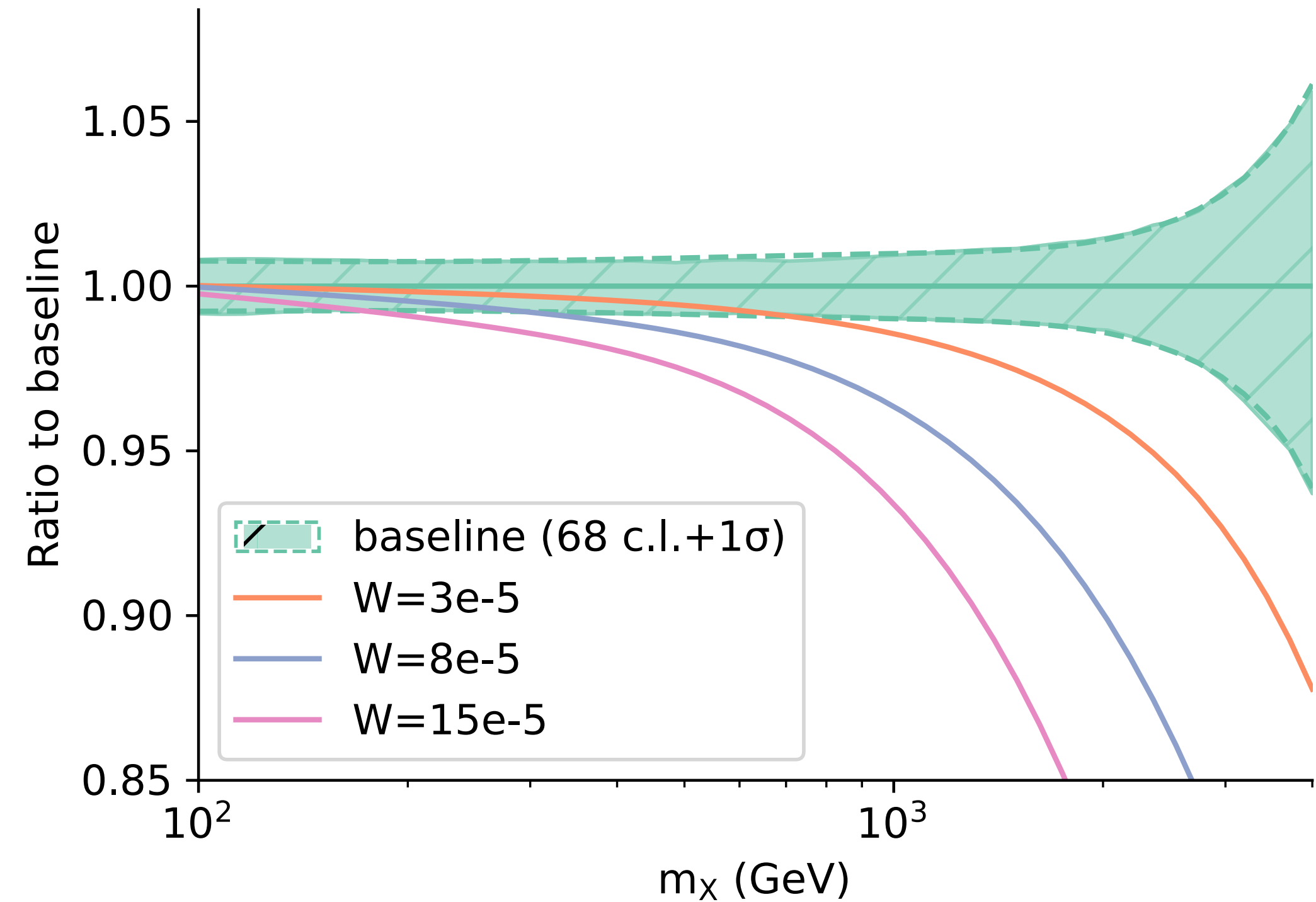Theory: contaminated PDF $\otimes$ SM

NC DY

$u\bar{u} + d\bar{d}$ luminosity
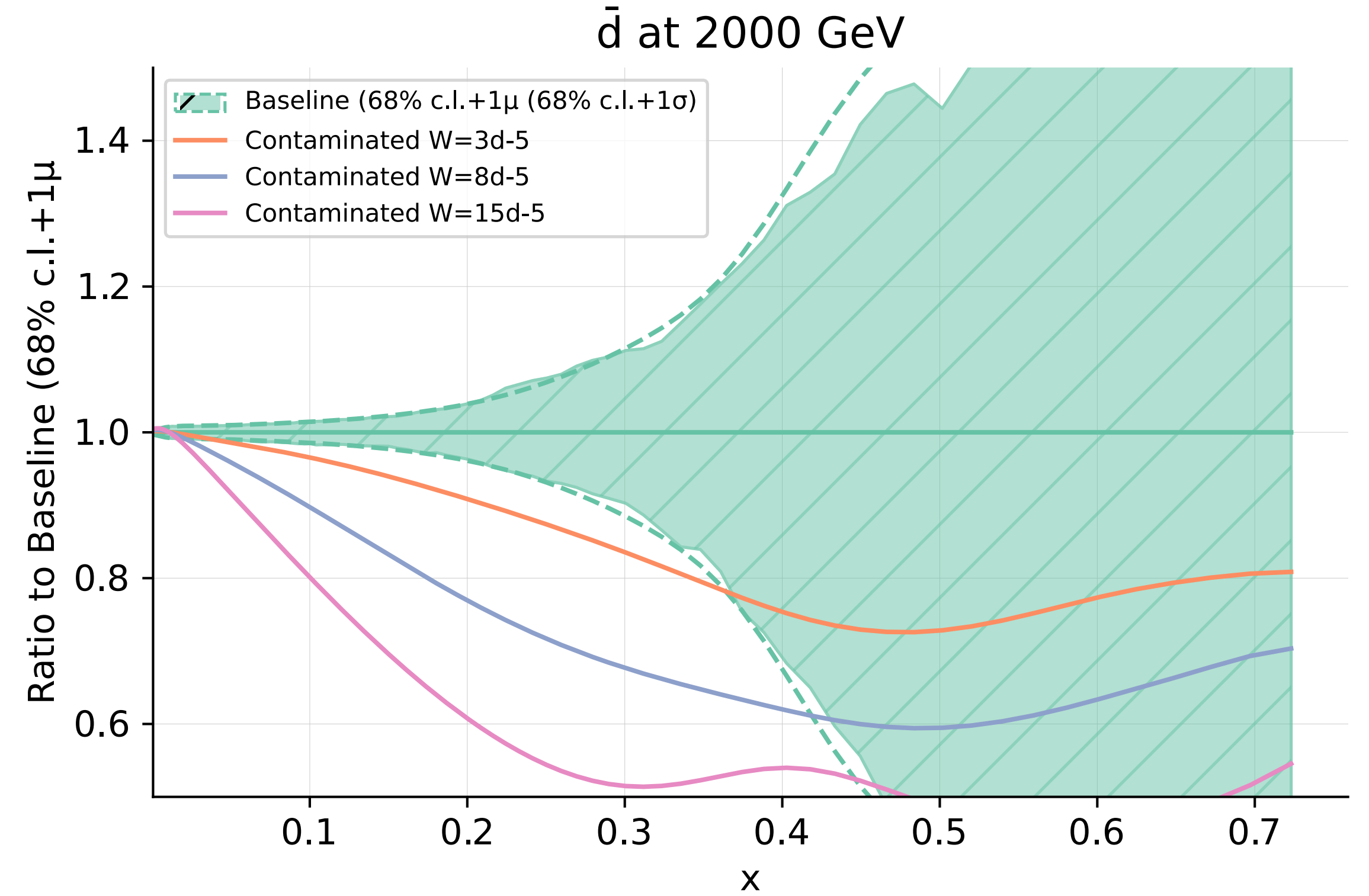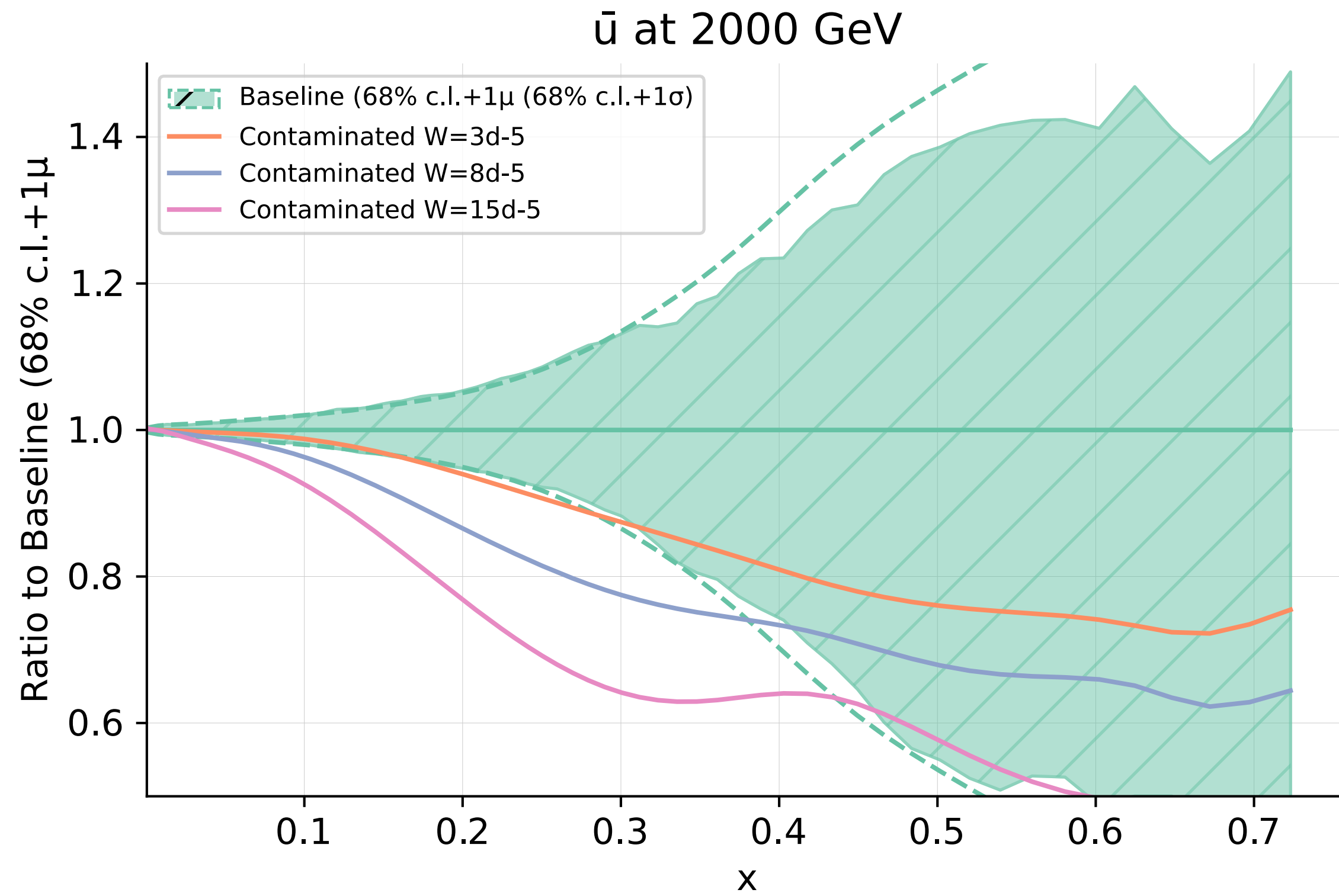$\sqrt{s} = 14$ TeV $\|y\| < 2.5$

CC DY

$u\bar{d} + d\bar{u}$ luminosity
$\sqrt{s} = 14$ TeV $\|y\| < 2.5$

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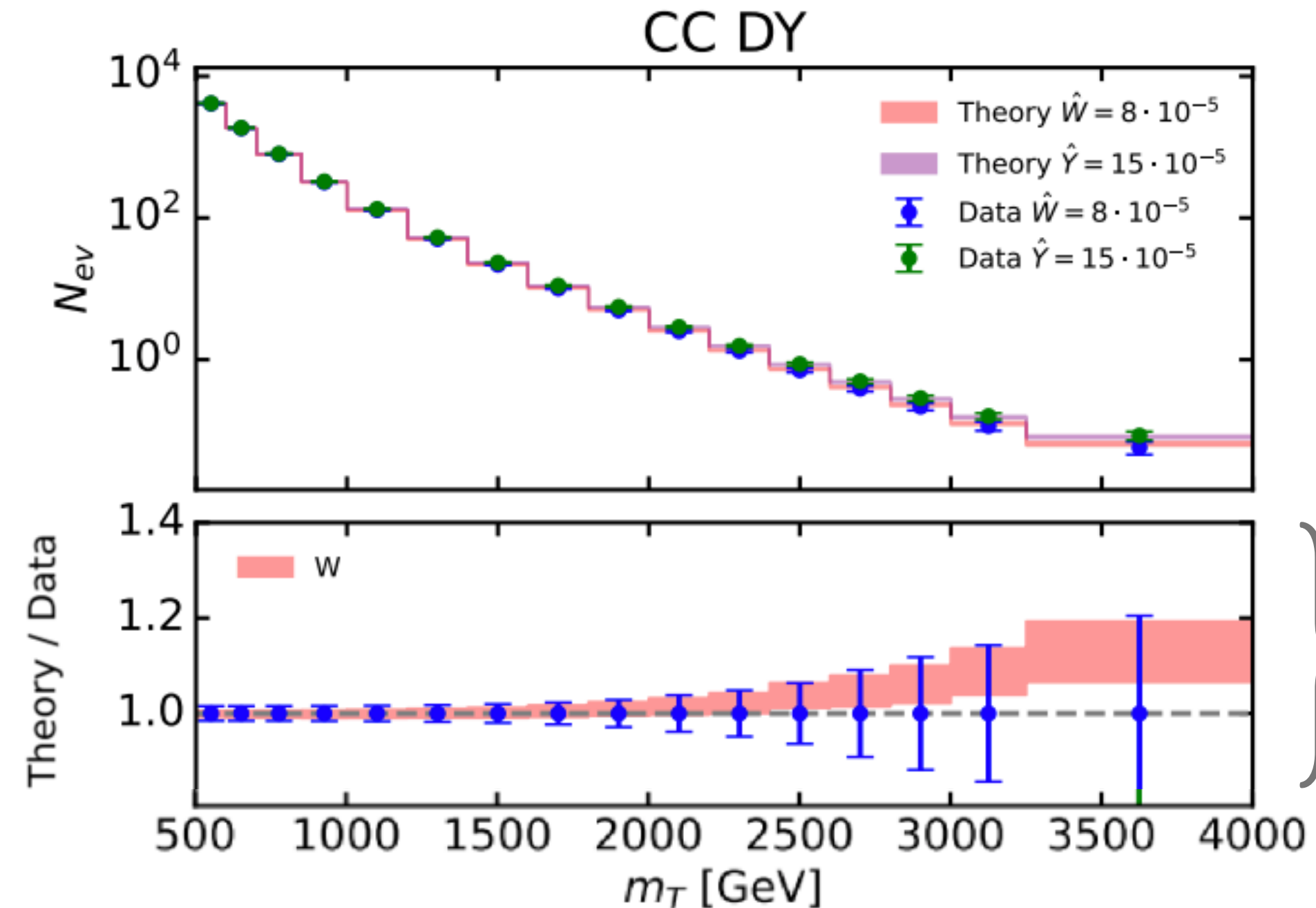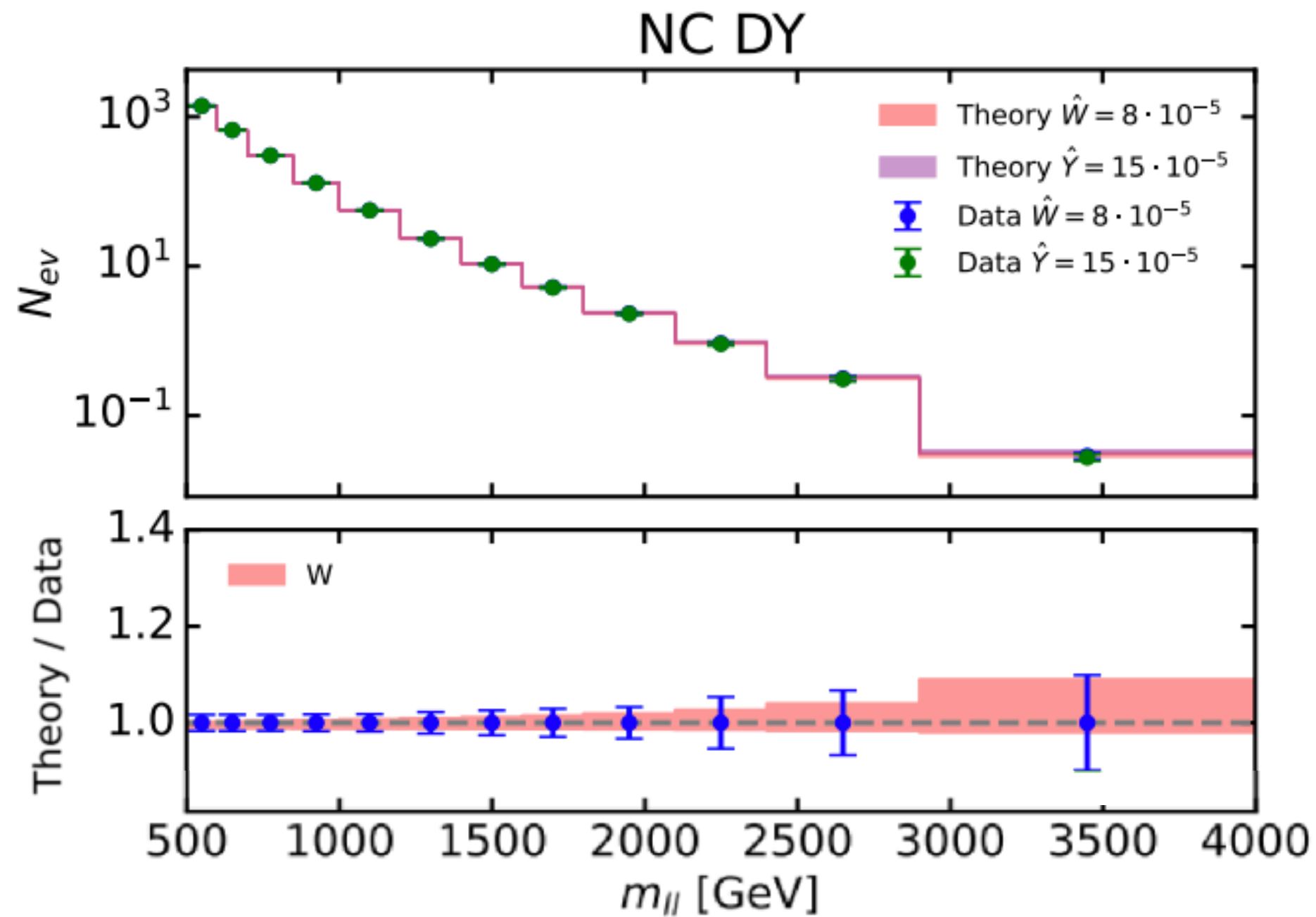
W'-contaminated PDFs

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

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

HL-LHC projections

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

$\chi^2/n_{dat} = 2.194$

$n_\sigma = 3.044$
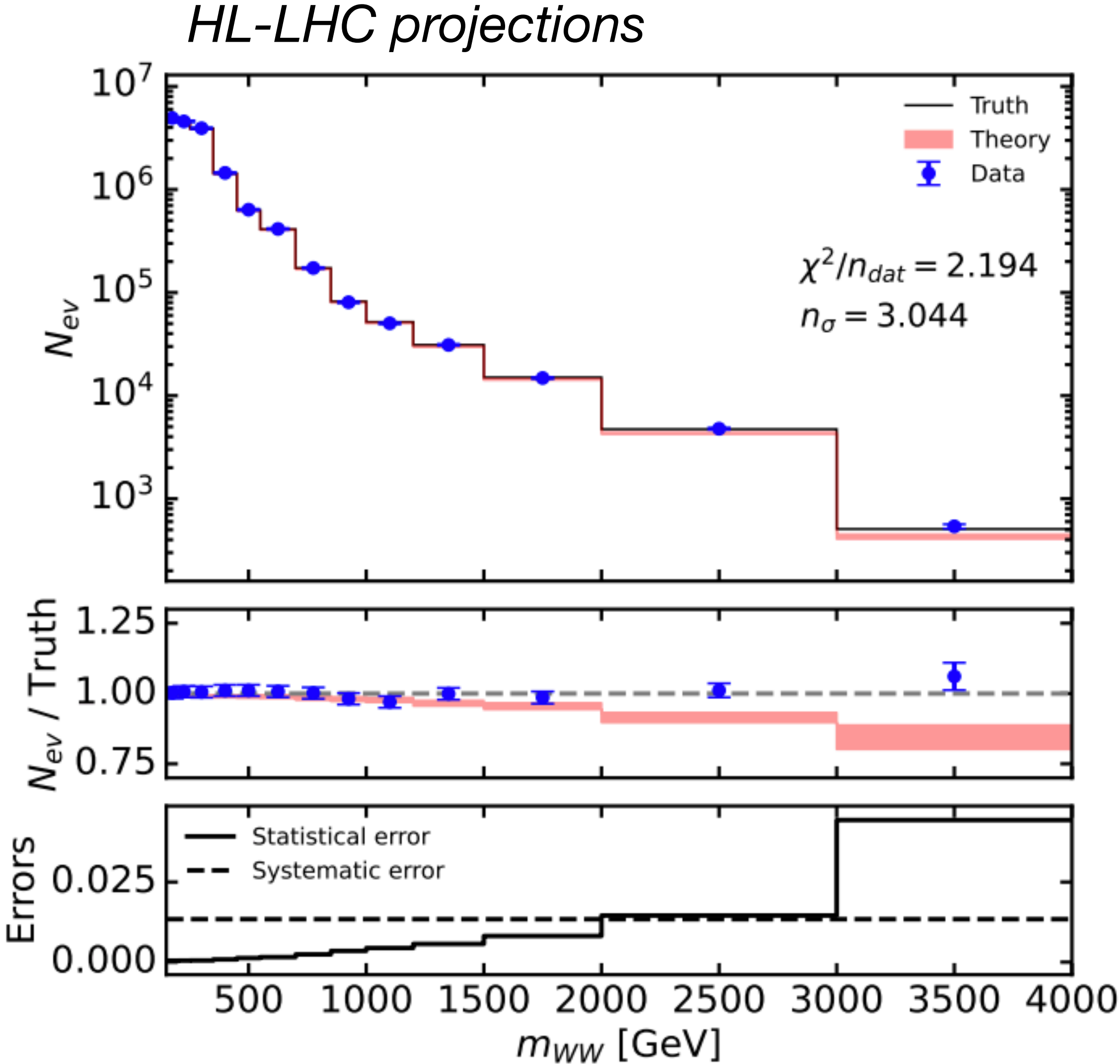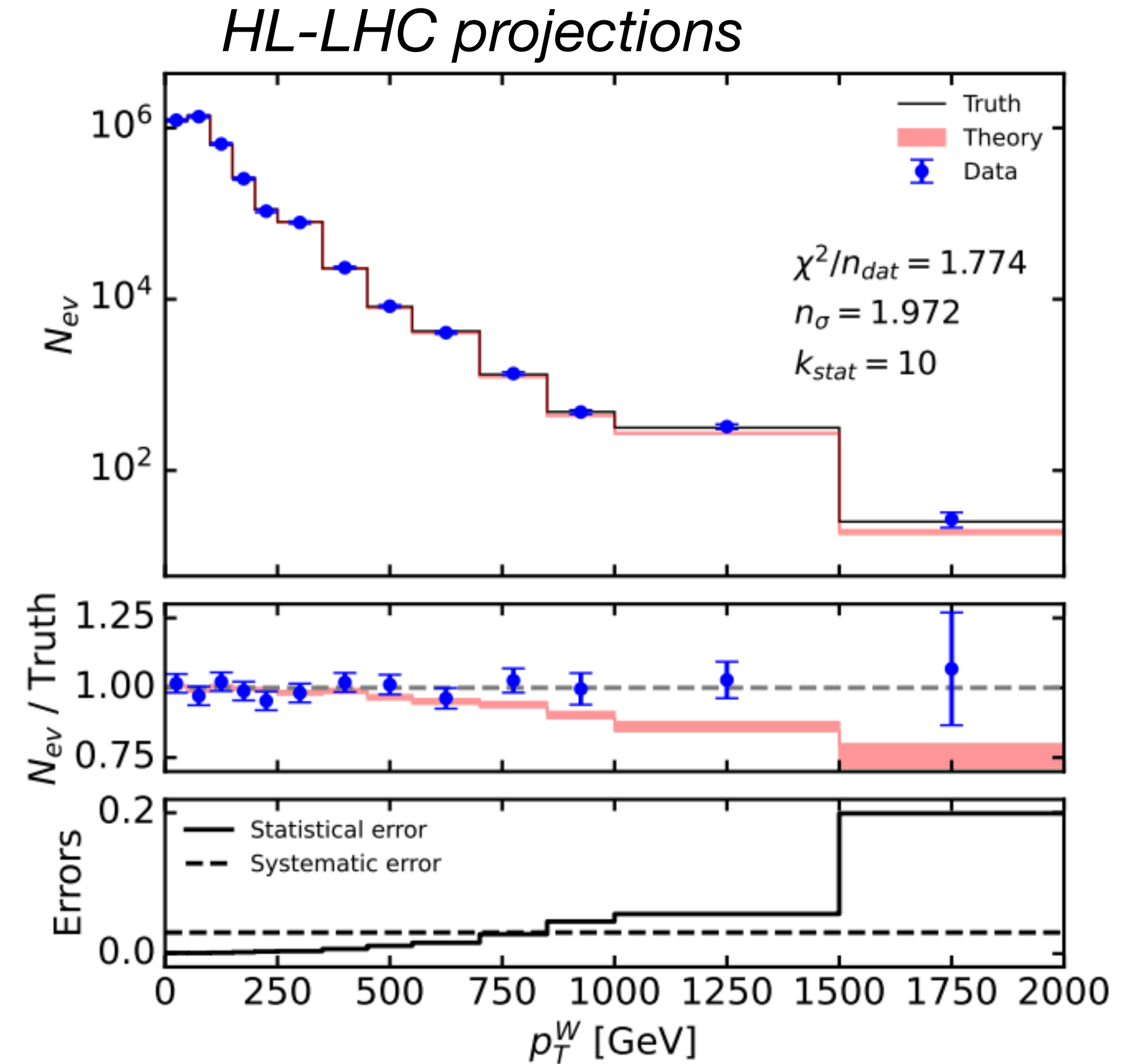
Impact on EW processes

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

$$q\bar{q} \rightarrow WH$$

- Data appears to disagree with SM at 2σ

- However, WH is unaffected by W' model:

  the deviation is in the PDF

HL-LHC projections

$\chi^2/n_{dat} = 1.774$
$n_\sigma = 1.972$
$k_{stat} = 10$

statistics improved by a factor of 10

Can we disentangle the effect of NP from PDFs?

Disentangling new physics effects post-fit

see 2307.10370 for other disentangling strategies

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

HL-LHC projections for **forward Z production** at LHCb:

$$60 < m_{\ell\ell} < 120 \text{ GeV} \qquad p_T^\ell > 20 \text{ GeV}$$

$$2 < |y_Z| < 4.5$$

NC DY

$\chi^2/n_{dat} = 1.060$
$n_\sigma = 0.135$

However no discrepancy between data and theory is observed
▸ PDF-EFT interplay is not disentangled

Disentangling new physics effects post-fit

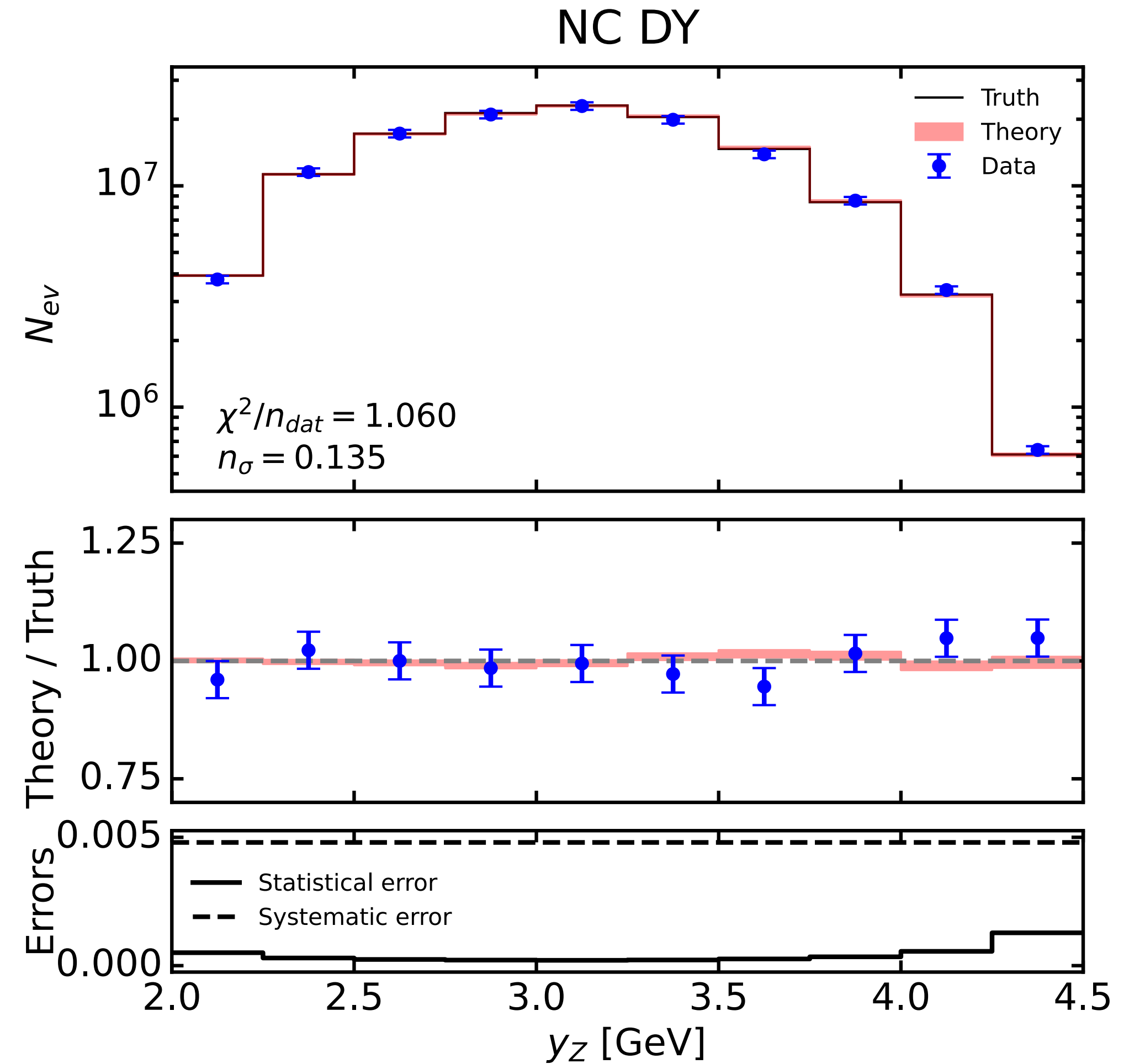*see 2307.10370 for other disentangling strategies*

HL-LHC projections for **forward Z production** at LHCb:

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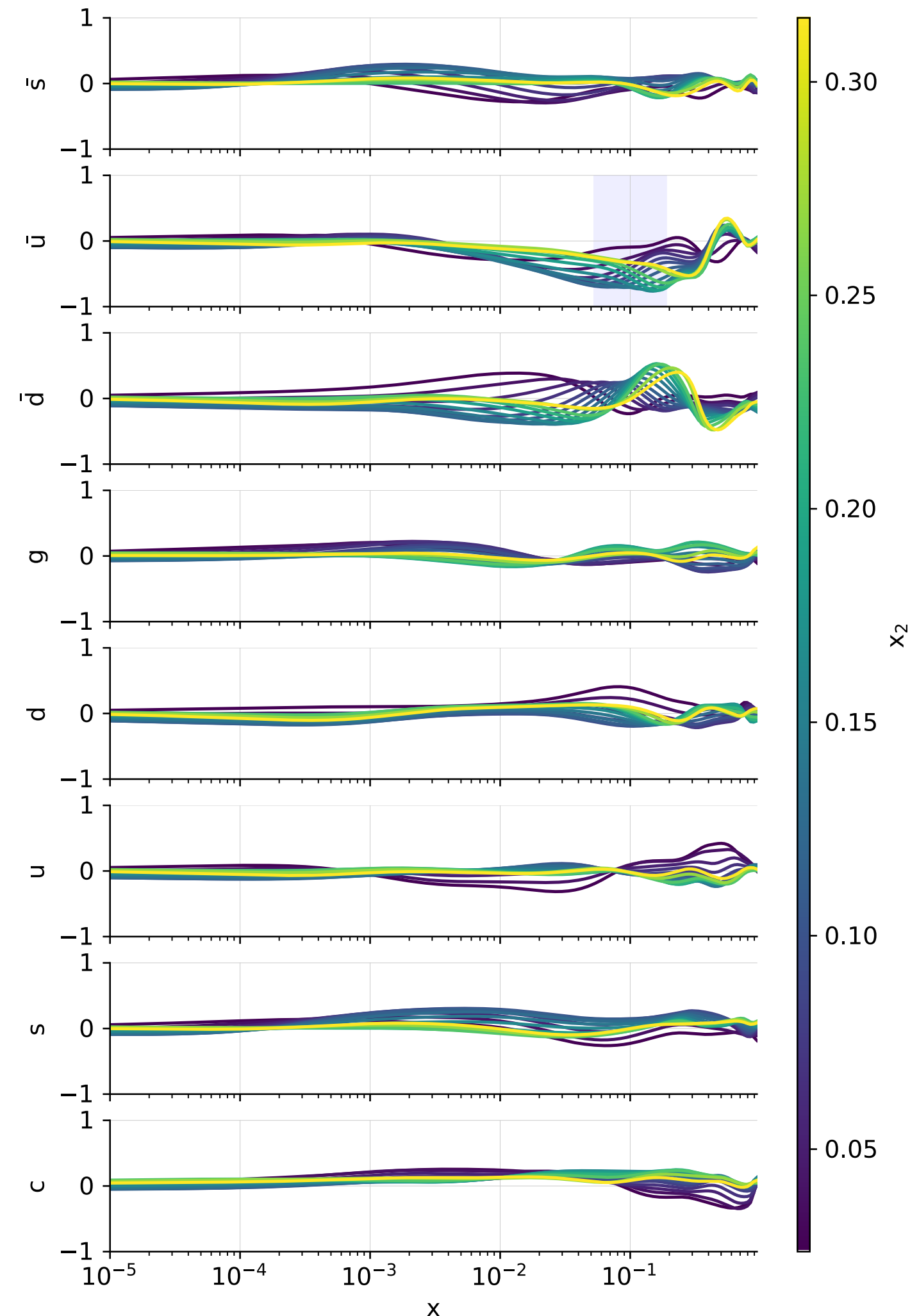
$$2 < |y_Z| < 4.5$$

However no discrepancy between data and theory is observed
  ‣ PDF-EFT interplay is not disentangled

Disentangling new physics effects post-fit

see 2307.10370 for other disentangling strategies

DYE 866 $\sigma_{DY}^{d}/\sigma_{DY}^{p}$
[Baseline fit]

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

Low-Q^2 measurements sensitive to large-x antiquarks may help

➡ independent of NP effects

e.g.NuSea collaboration fixed target DY [hep-ex/0103030]

Disentangling new physics effects post-fit

see 2307.10370 for other disentangling strategies

DYE 866 $\sigma_{DY}^d/\sigma_{DY}^p$
[Baseline fit]

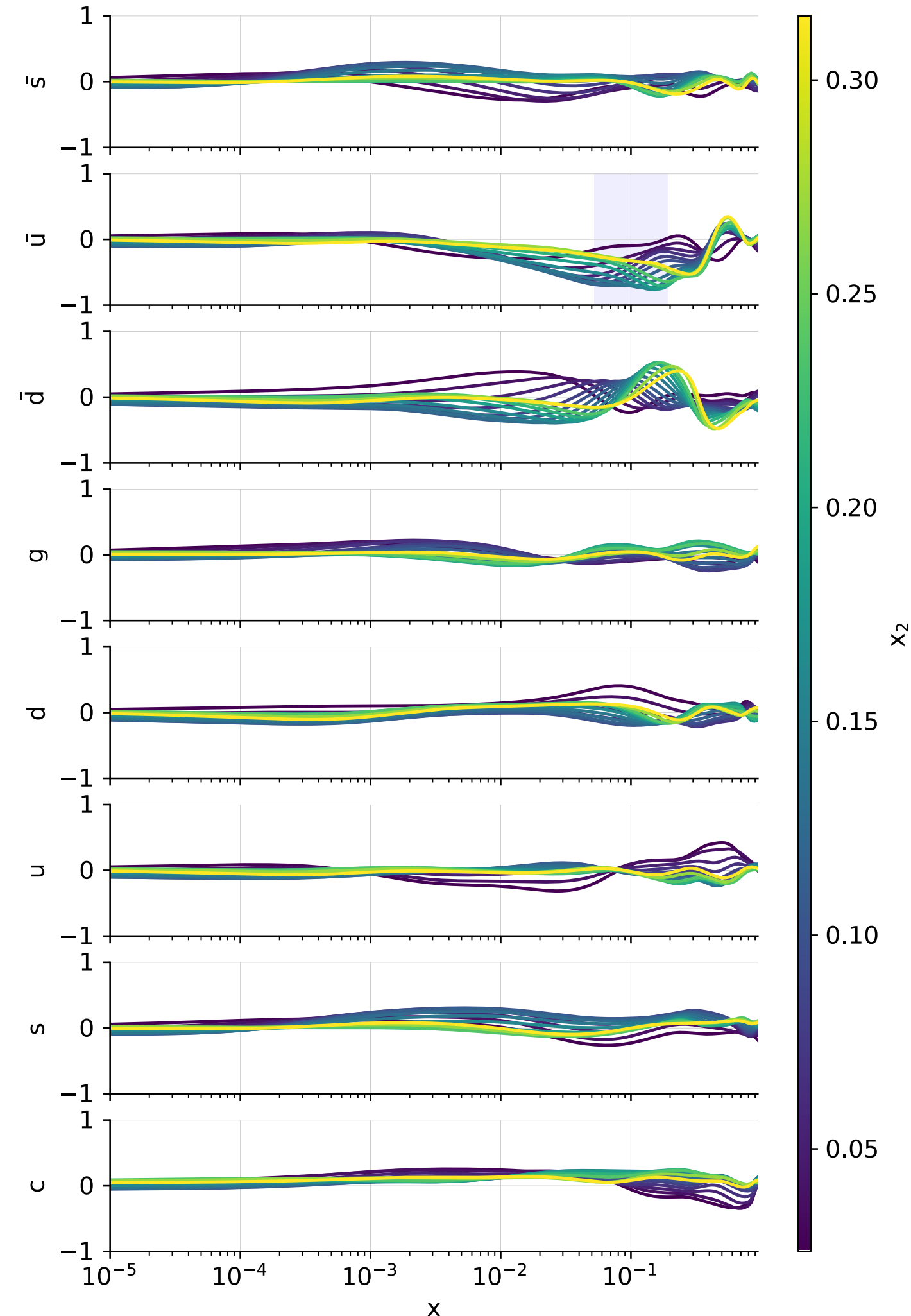Fewer constraints on the **large-x antiquark PDFs** allow freedom to shift away from the baseline

Low-Q^2 measurements sensitive to large-x antiquarks may help

➡️independent of NP effects

*e.g.NuSea collaboration fixed target DY [hep-ex/0103030]*

However:
- data currently included in the fit is not precise enough to disentangle this effect

- Future low-energy measurements, e.g. **the EIC programme**, will provide crucial inputs to PDF fits

Simultaneous PDF-EFT Determinations
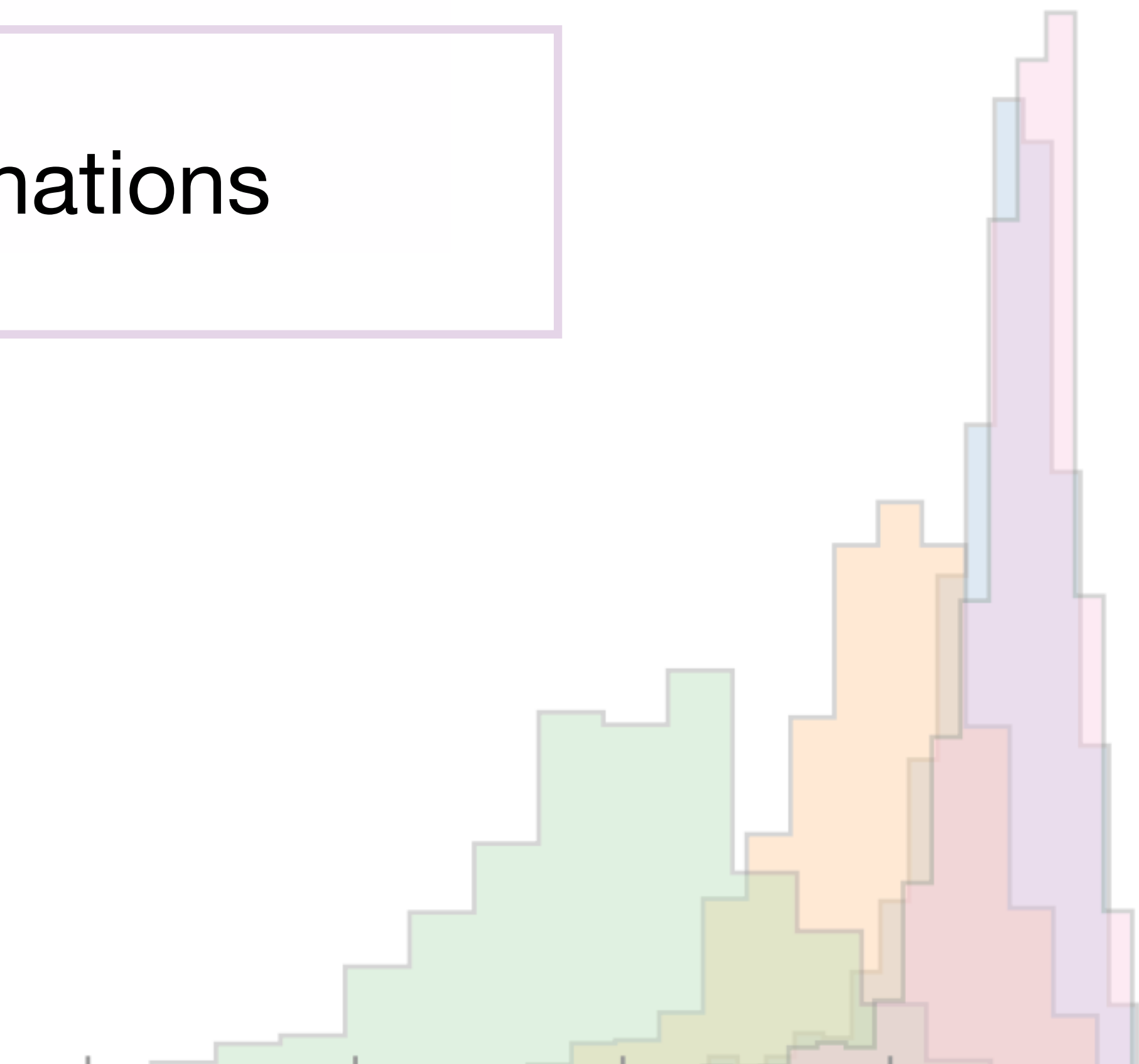
Simultaneous fit of PDFs and SMEFT with simuNET

S. Iranipour, M. Ubiali, 2201.07240

public code release coming soon
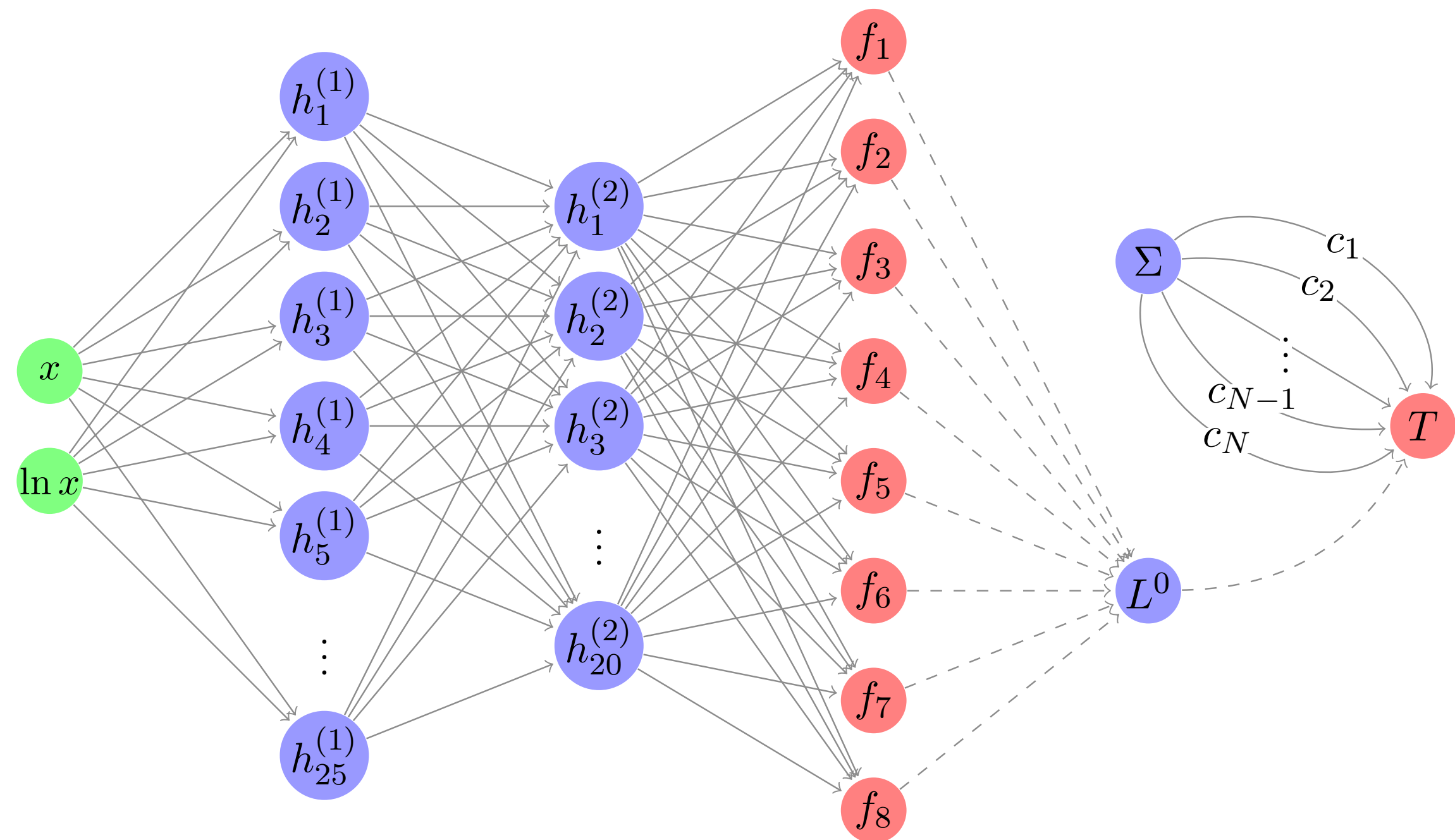
Fast and efficient **simultaneous determinations** of PDFs and Wilson coefficients

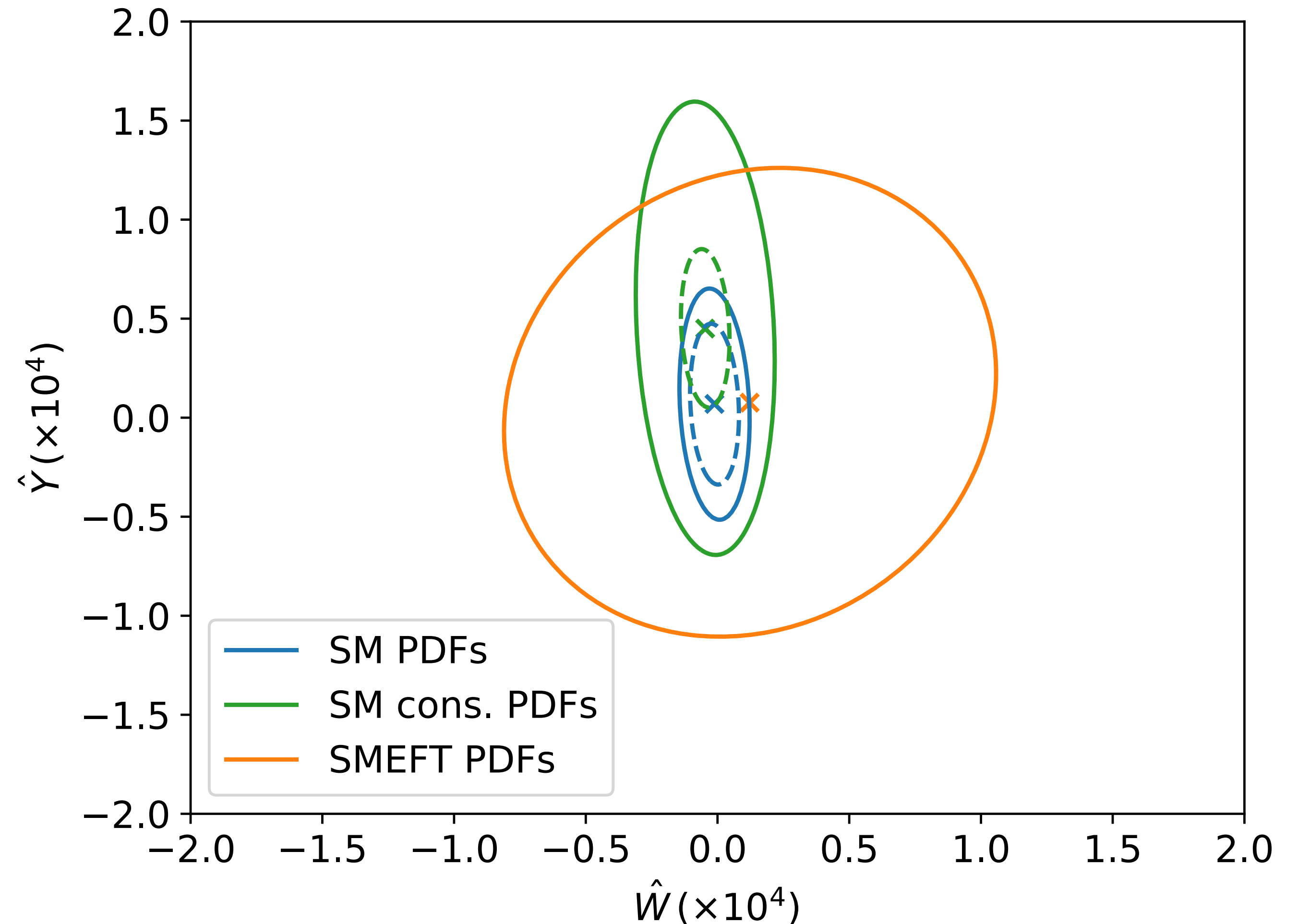Places PDF parameters and Wilson coefficients on the same footing

some examples: ⟶

Simultaneous fit of PDFs and SMEFT in high mass DY

Greljo et. al 2104.02723

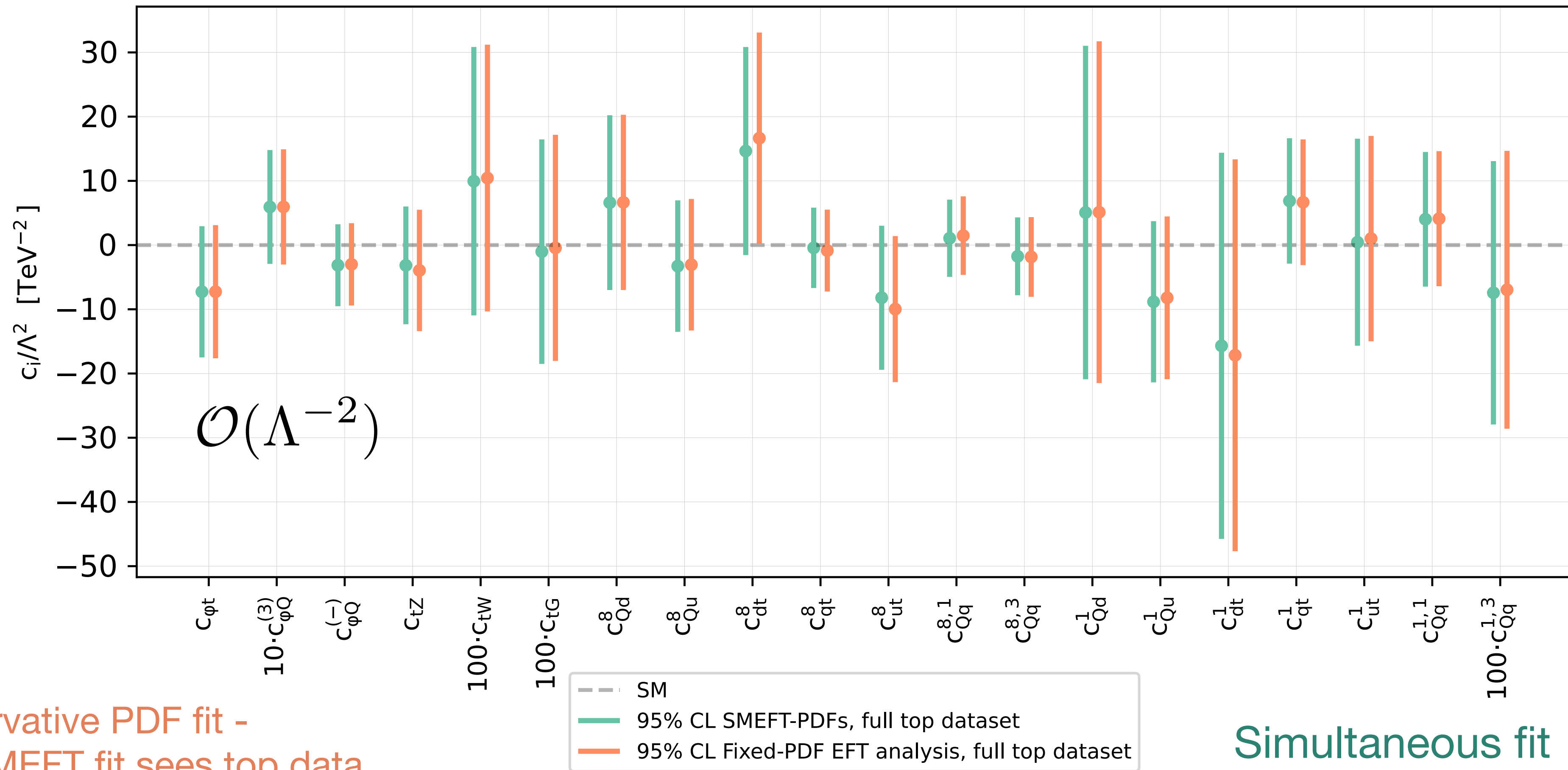Including **HL-LHC projections** for NC and CC Drell-Yan:

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:

$$\mathcal{O}(\Lambda^{-2})$$

Conservative PDF fit - only SMEFT fit sees top data

Simultaneous fit

Legend:
- — — SM
- — 95% CL SMEFT-PDFs, full top dataset
- — 95% CL Fixed-PDF EFT analysis, full top dataset

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:
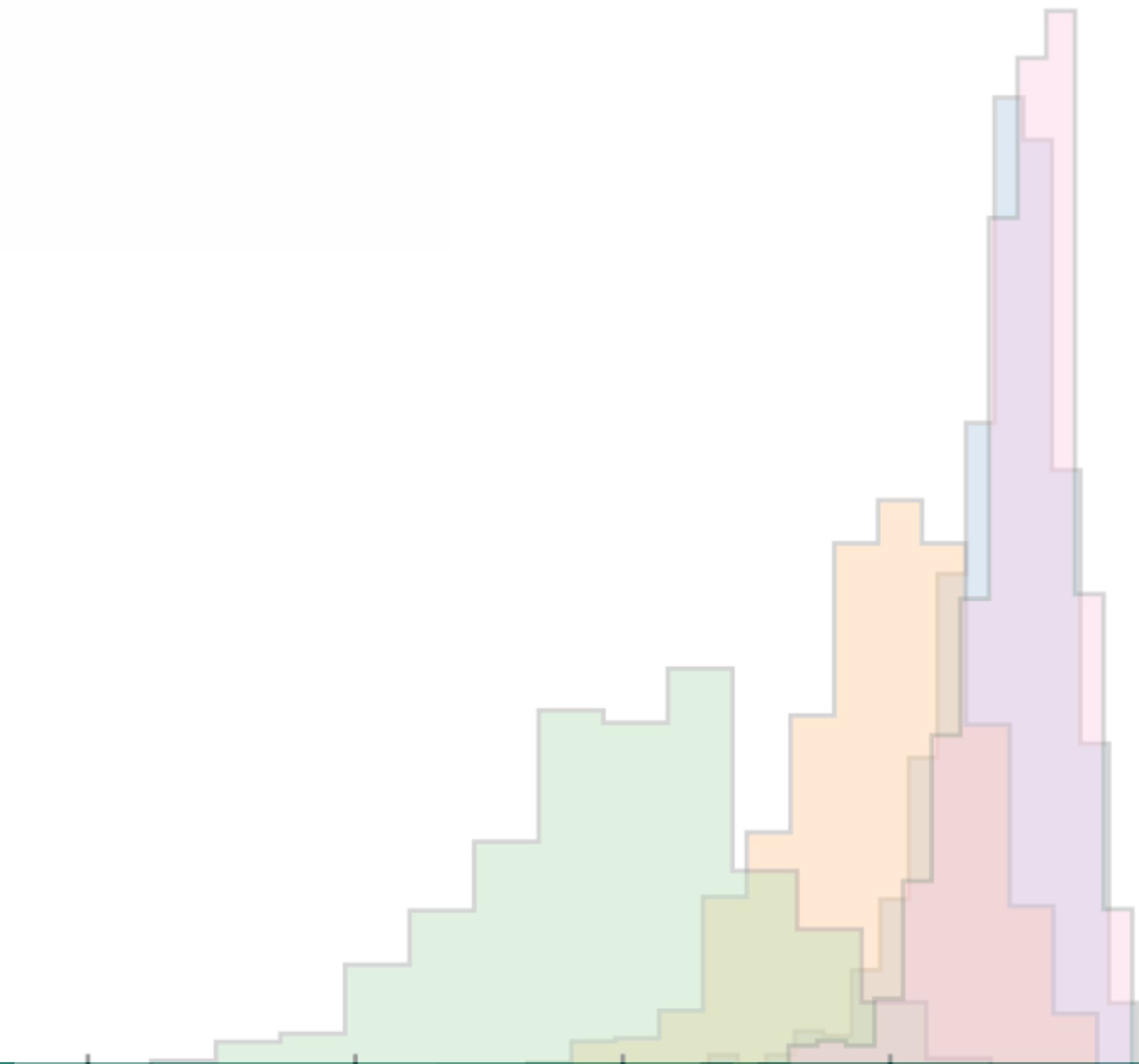
  https://www.pbsp.org.uk/contamination/

Conclusions

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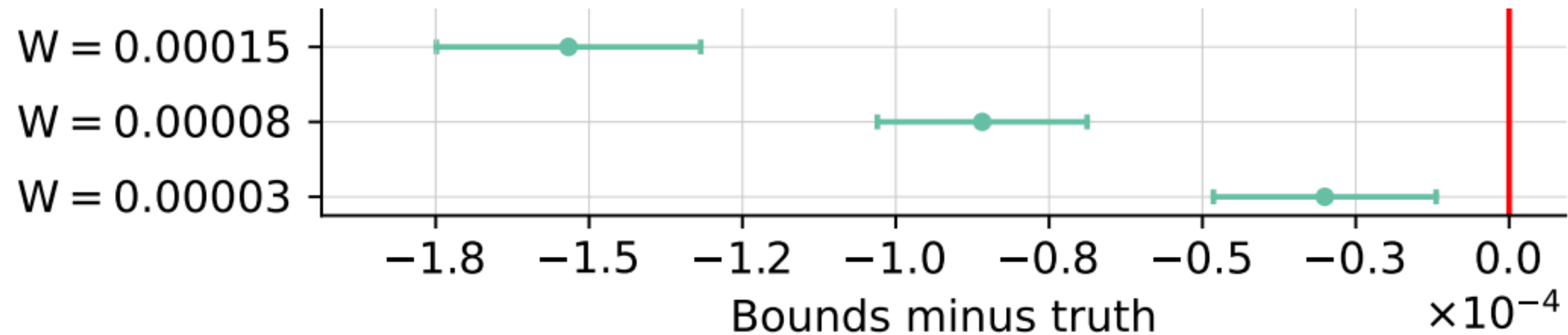
  https://www.pbsp.org.uk/contamination/

Backup

Impact on DY of W'-contaminated PDFs

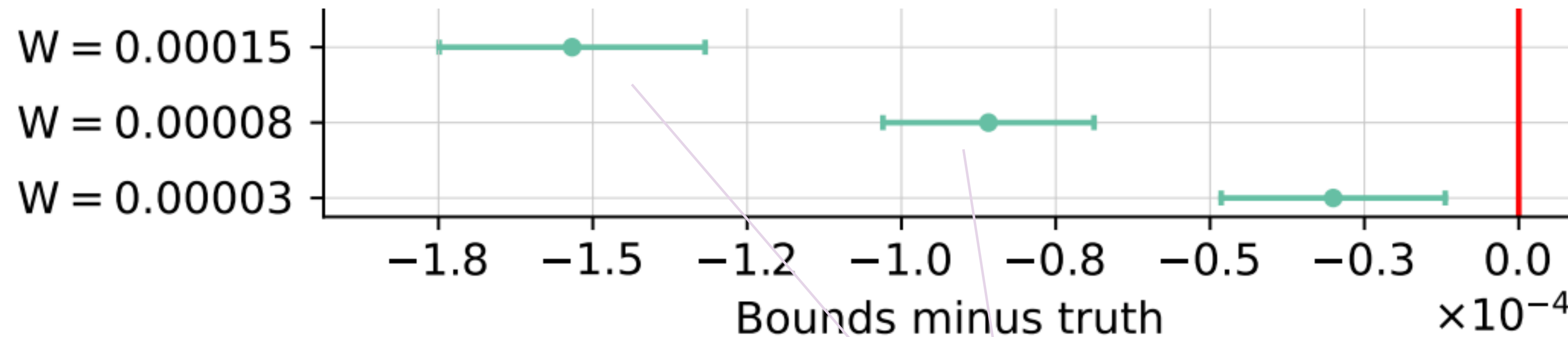The high-mass DY data **appears** to agree well with the SM

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:**
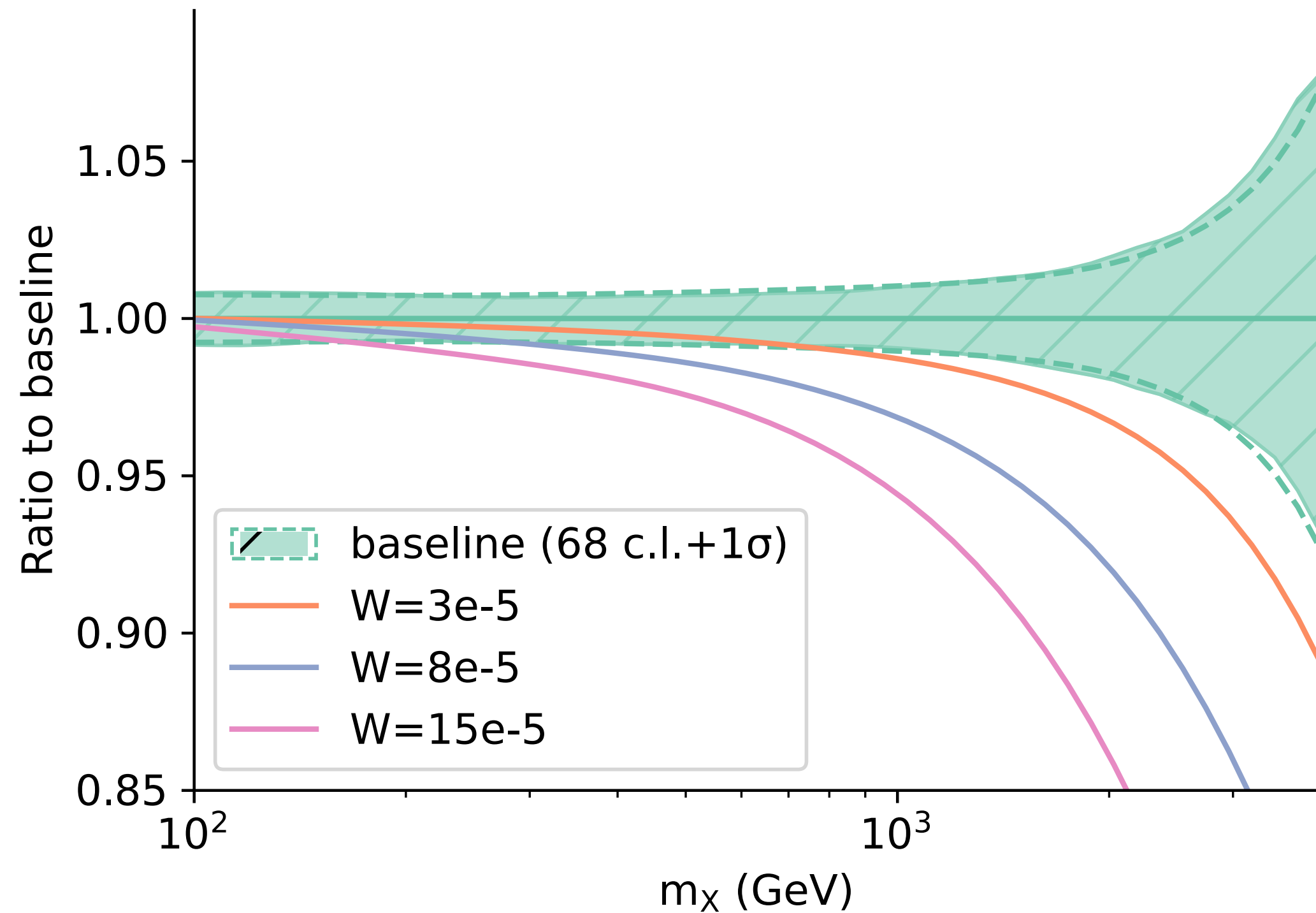

constraints miss the truth by $> 2\sigma$

W'-contaminated PDFs

NC DY

$u\bar{u} + d\bar{d}$ luminosity
$\sqrt{s} = 14$ TeV $\|y\| < 2.5$

Legend:
- baseline (68 c.l.+1σ)
- W=3e-5
- W=8e-5
- W=15e-5

Ratio to baseline vs m_X (GeV)

CC DY

$u\bar{d} + d\bar{u}$ luminosity
$\sqrt{s} = 14$ TeV $\|y\| < 2.5$

Legend:
- baseline (68 c.l.+1σ)
- W=3e-5
- W=8e-5
- W=15e-5

Ratio to baseline vs m_X (GeV)

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

W'-contaminated PDFs

ū at 2000 GeV

d̄ at 2000 GeV

Z'-contaminated PDFs
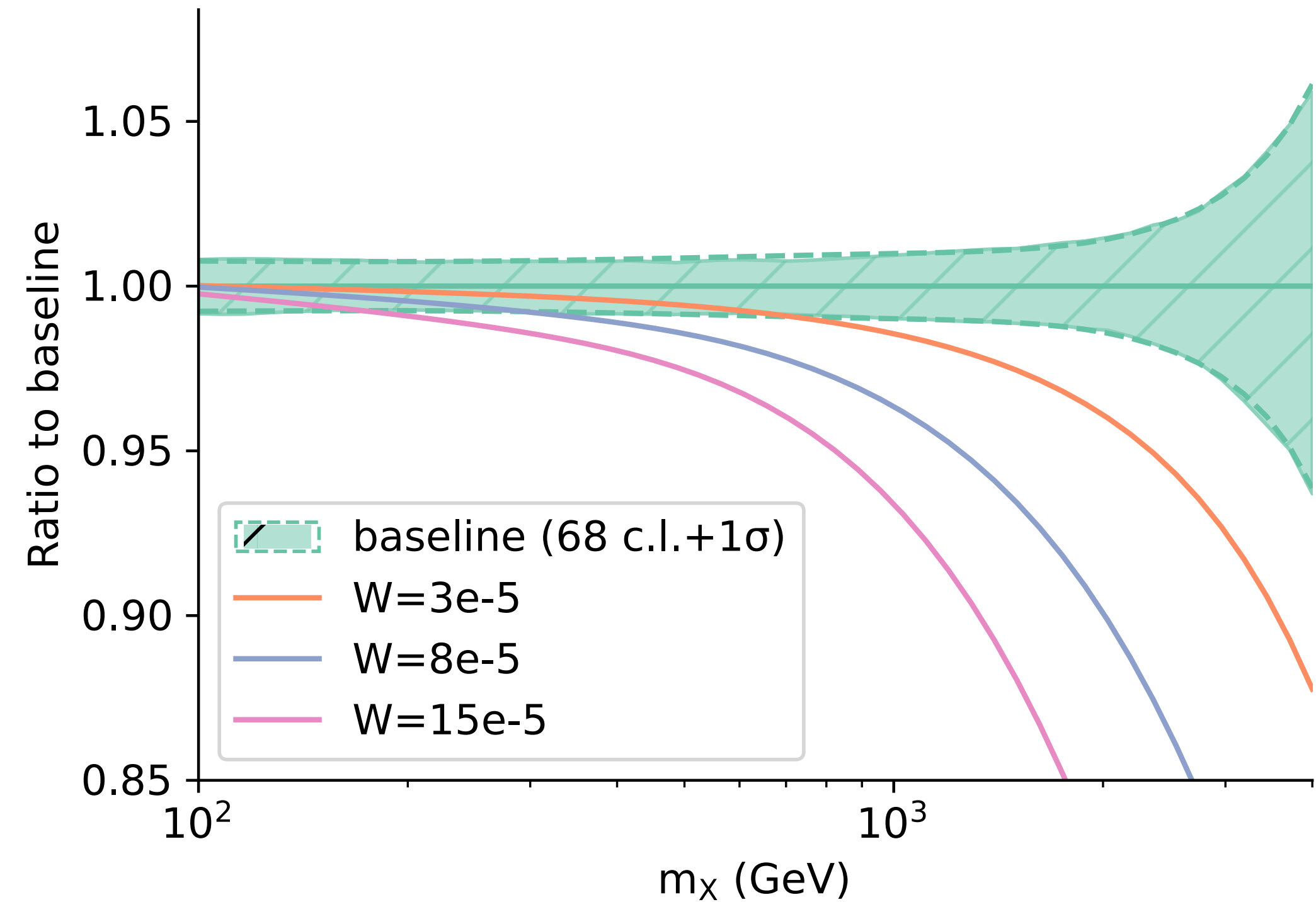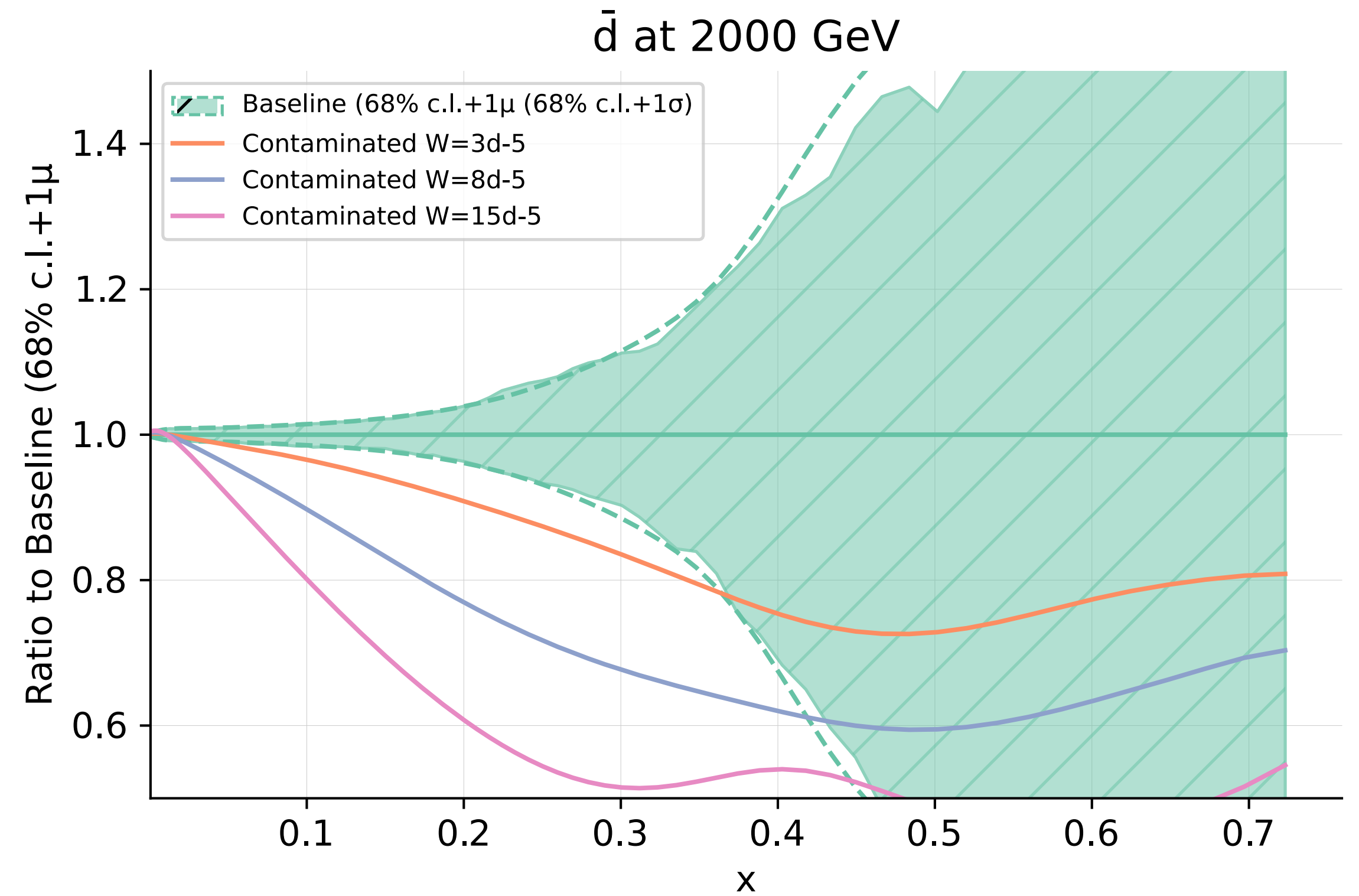
NC DY

$u\bar{u} + d\bar{d}$ luminosity
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CC DY

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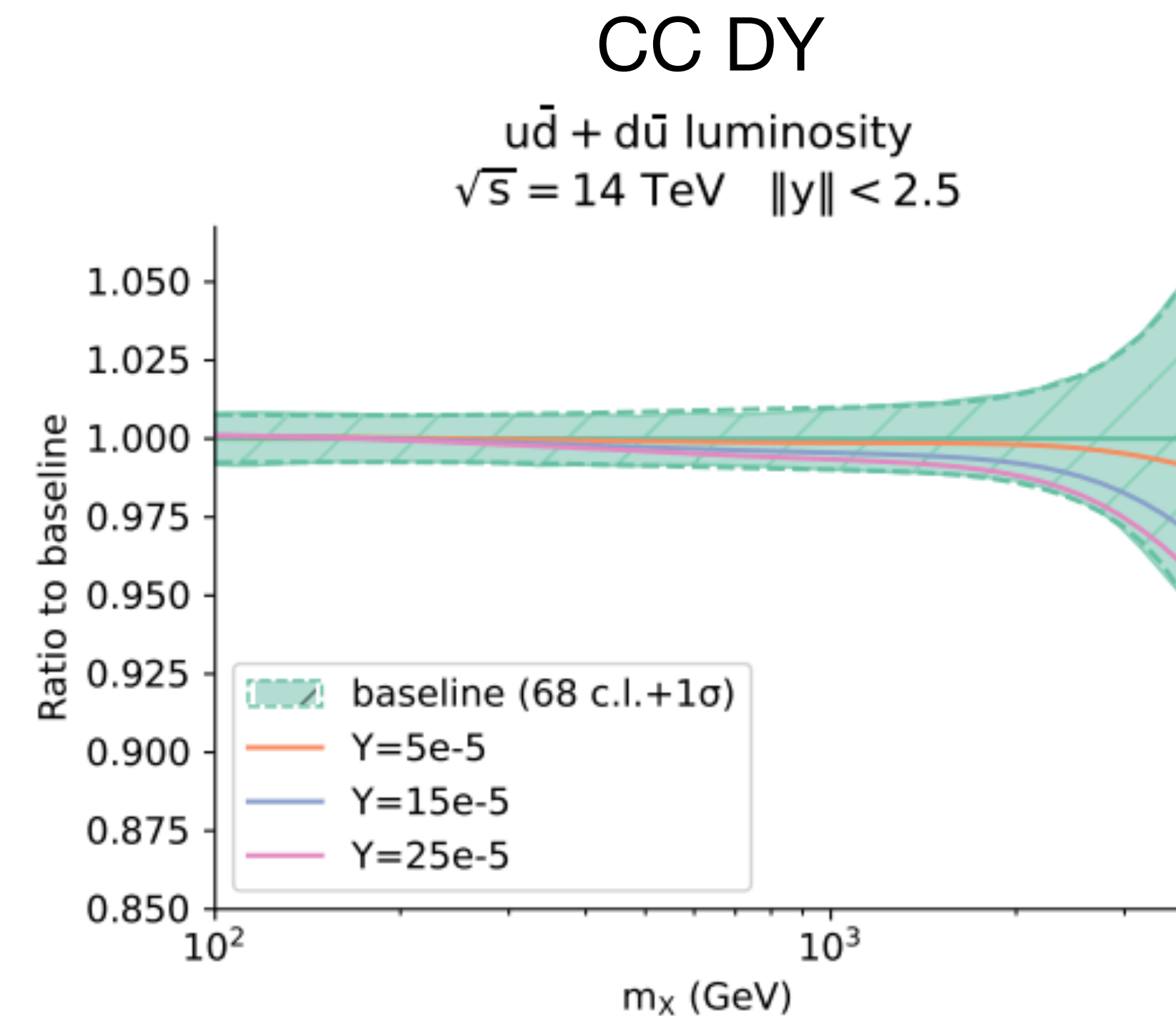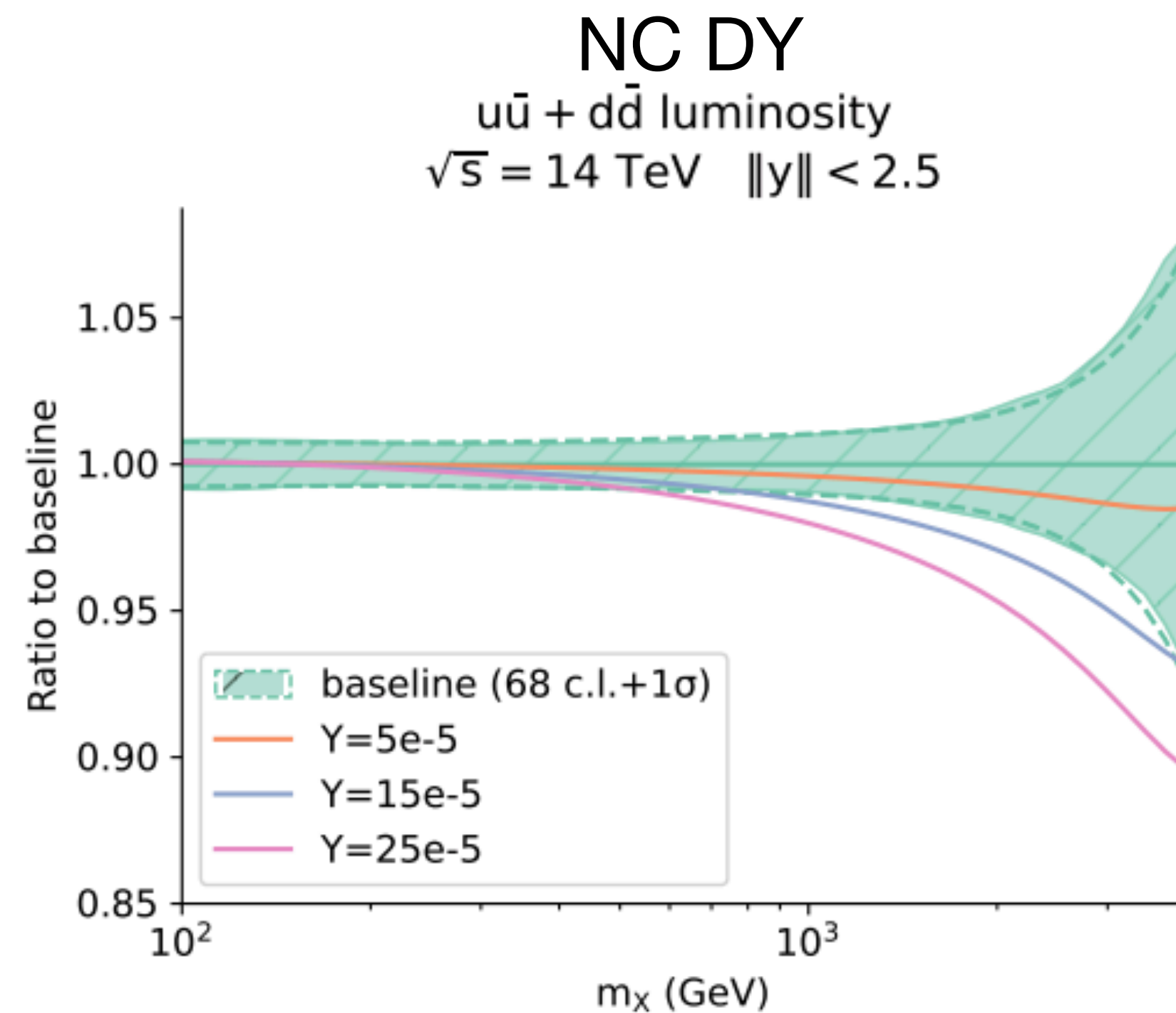$\sqrt{s} = 14$ TeV $\|y\| < 2.5$

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
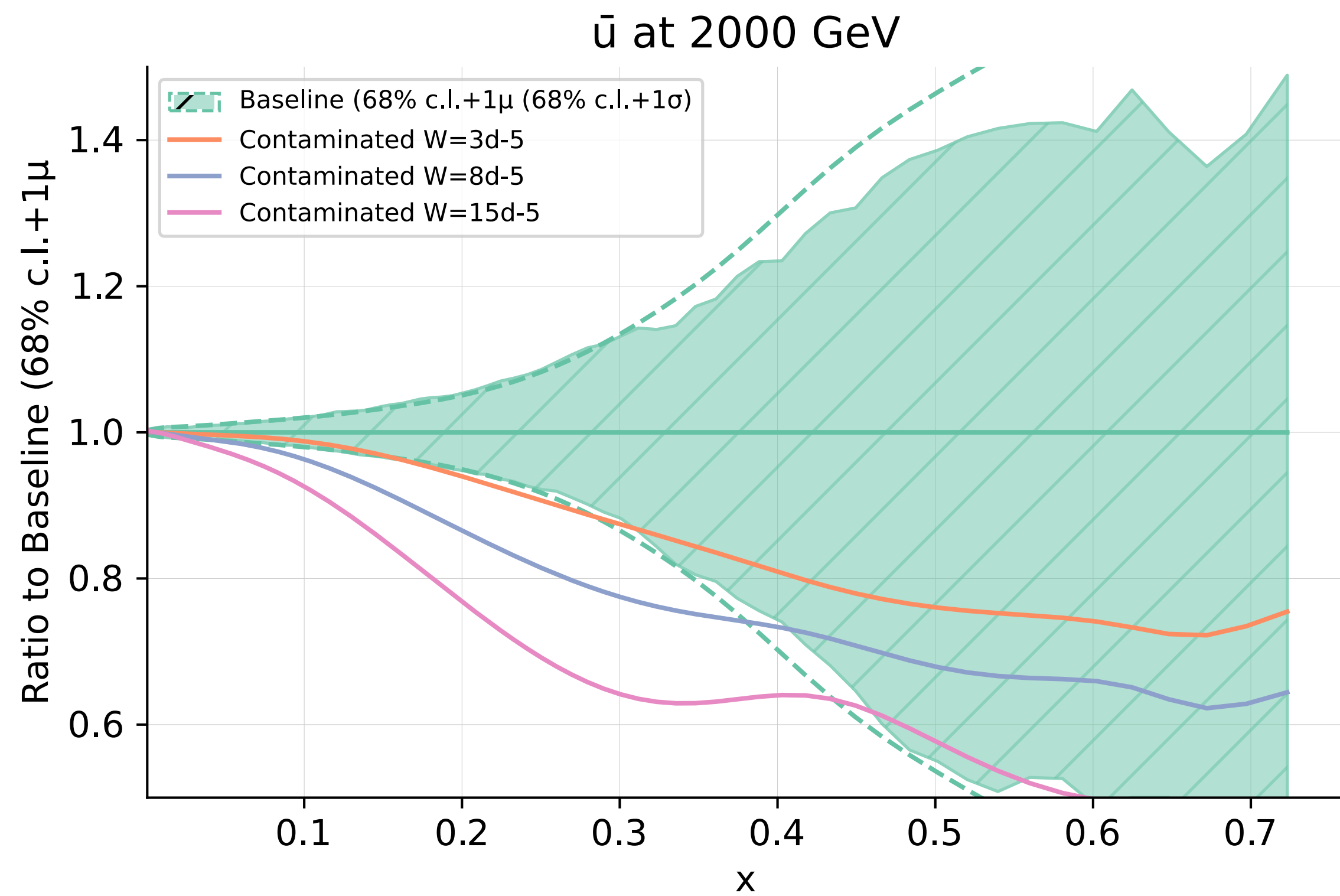
Z'-contaminated PDFs

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