How to disentangle Parton Distribution Functions and new physics signals?

[PBSP, 2307.10370, JHEP]

[PBSP, 2402.03308]

[Hammou et Ubiali, 2410.00963]

[PBSP, forthcoming]

European Research Council
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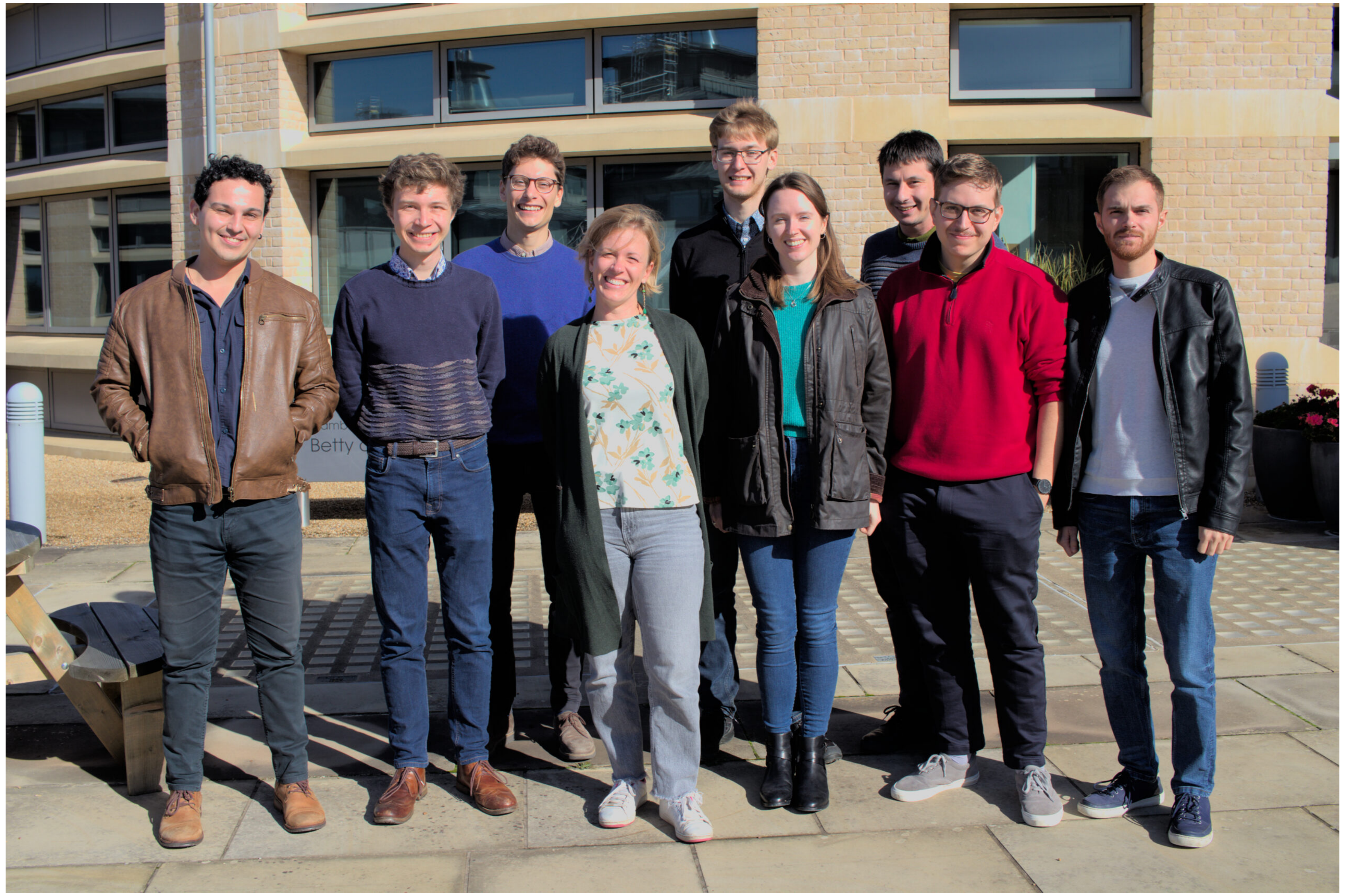
PBSP

Elie Hammou
Seminar, Genova, Nov 2024

Our group: PBSP

Physics Beyond the Standard Proton

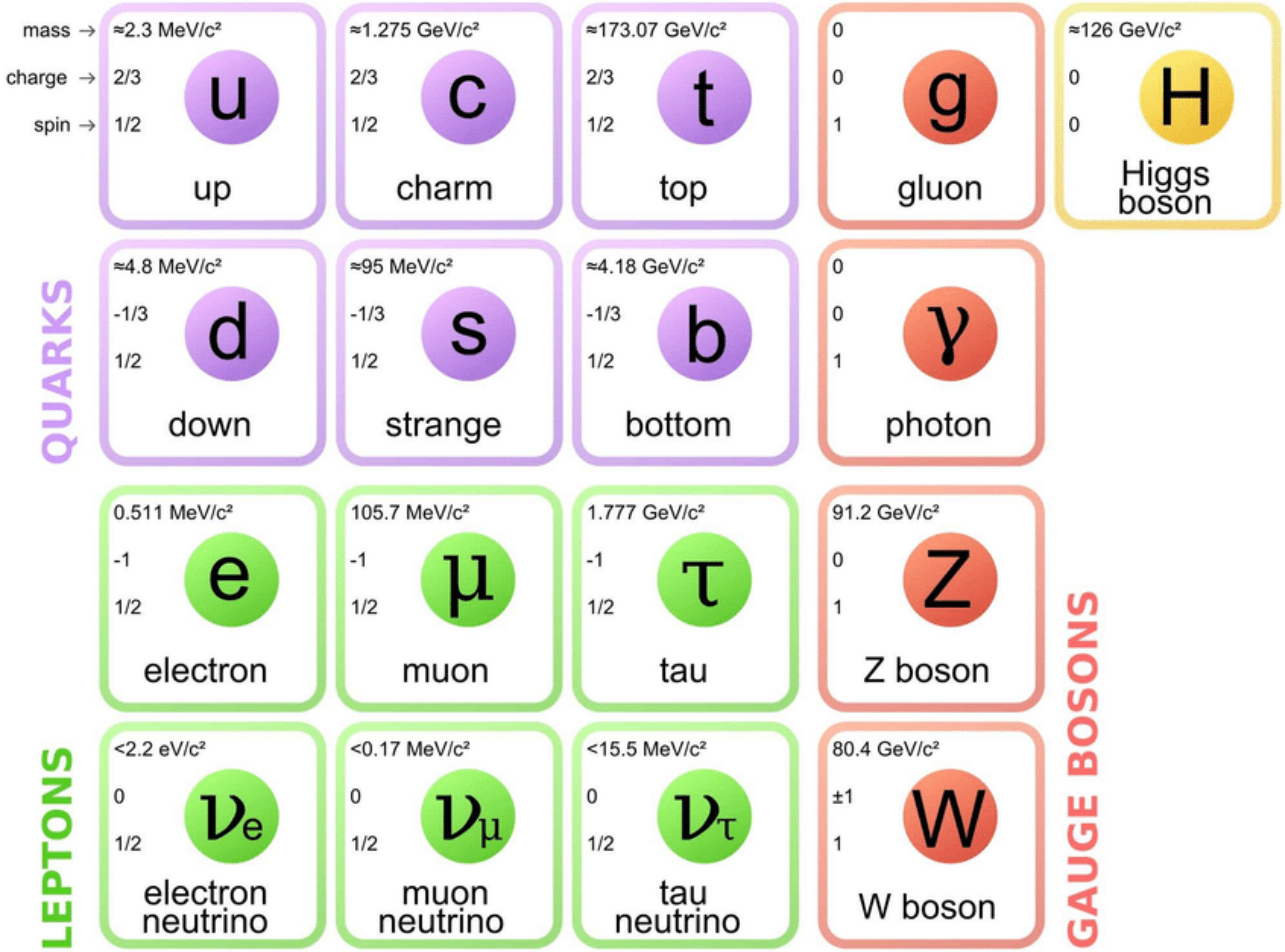


- Led by Maria Ubiali
- Based in Cambridge
- Focus on:
  - Indirect search for heavy new physics
  - Investigate robust fitting methods
  - Interplay with PDFs

The Standard Model

$$\mathcal{G} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

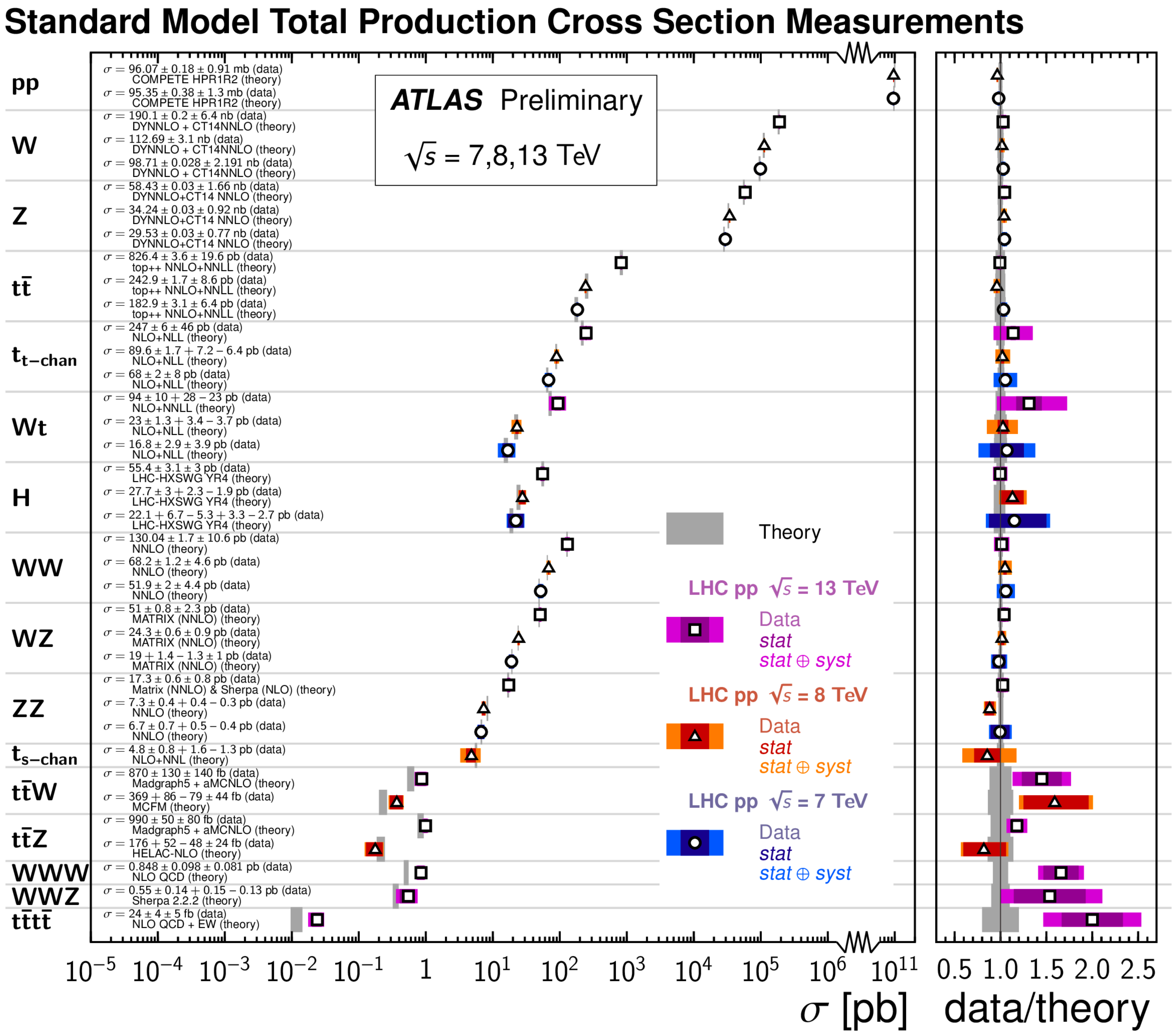
$$\begin{aligned}\mathcal{L} = &-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i \bar{\psi} \not{D} \psi + h.c. \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi)\end{aligned}$$



SM very successful

- Very precise measurements
- Lot of progress in theoretical calculations
- Overall strong agreement between the two

➡ <u>The end of the story?</u>



Beyond the Standard Model?

Limits and unsolved puzzles: motivation for new physics

Motivation for BSM physics:

- Dark matter
- Matter/anti-matter asymmetry
- Flavour structure and anomalies
- CP problem
- Hierarchy problem…

A fair amount of questions

Extension of the Lagrangian:

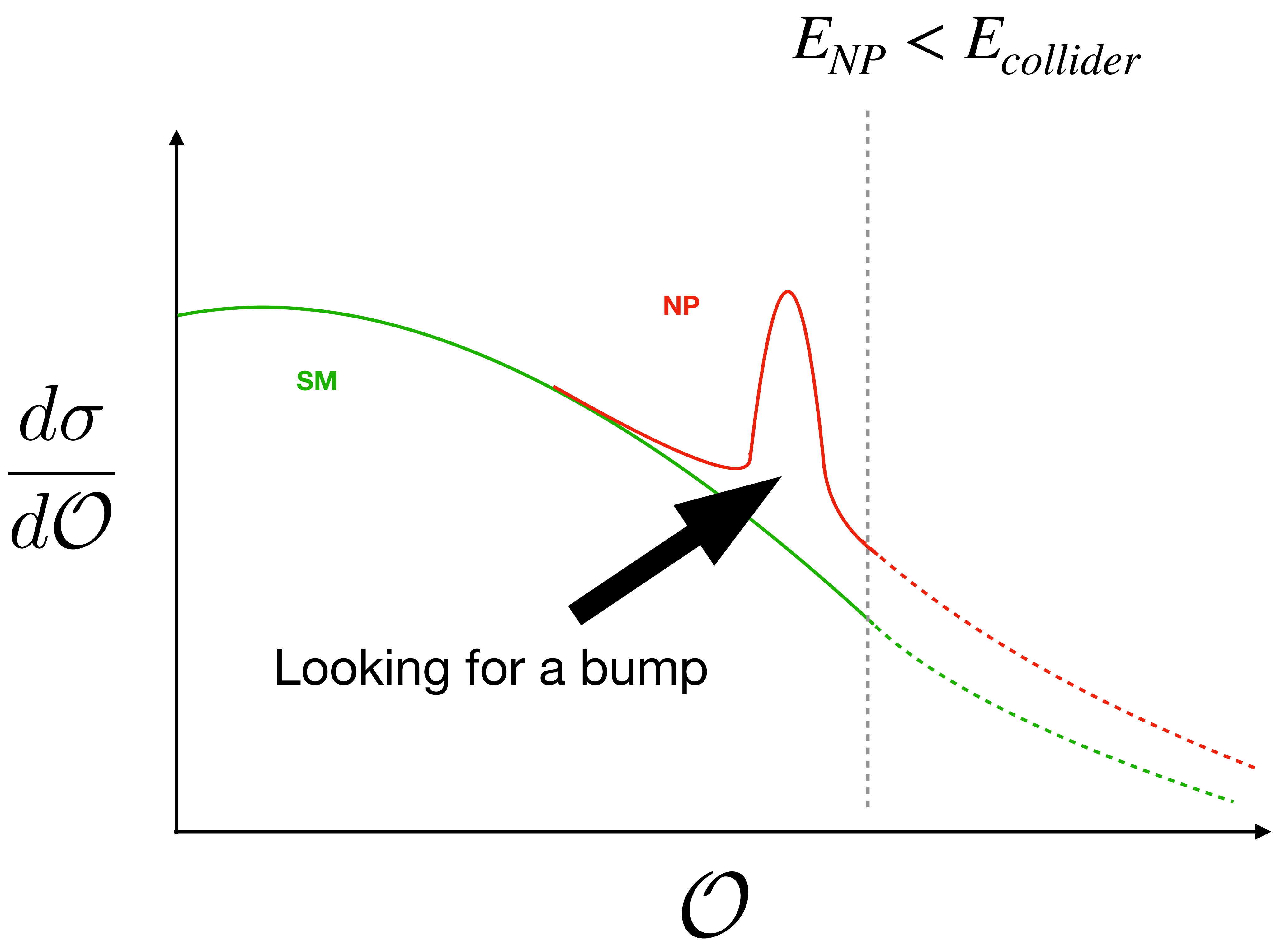
- New gauge symmetry?
- Right-handed neutrino?
- More Higgs?
- GUT?
- ALPs?…

A lot of possible models

New physics searches

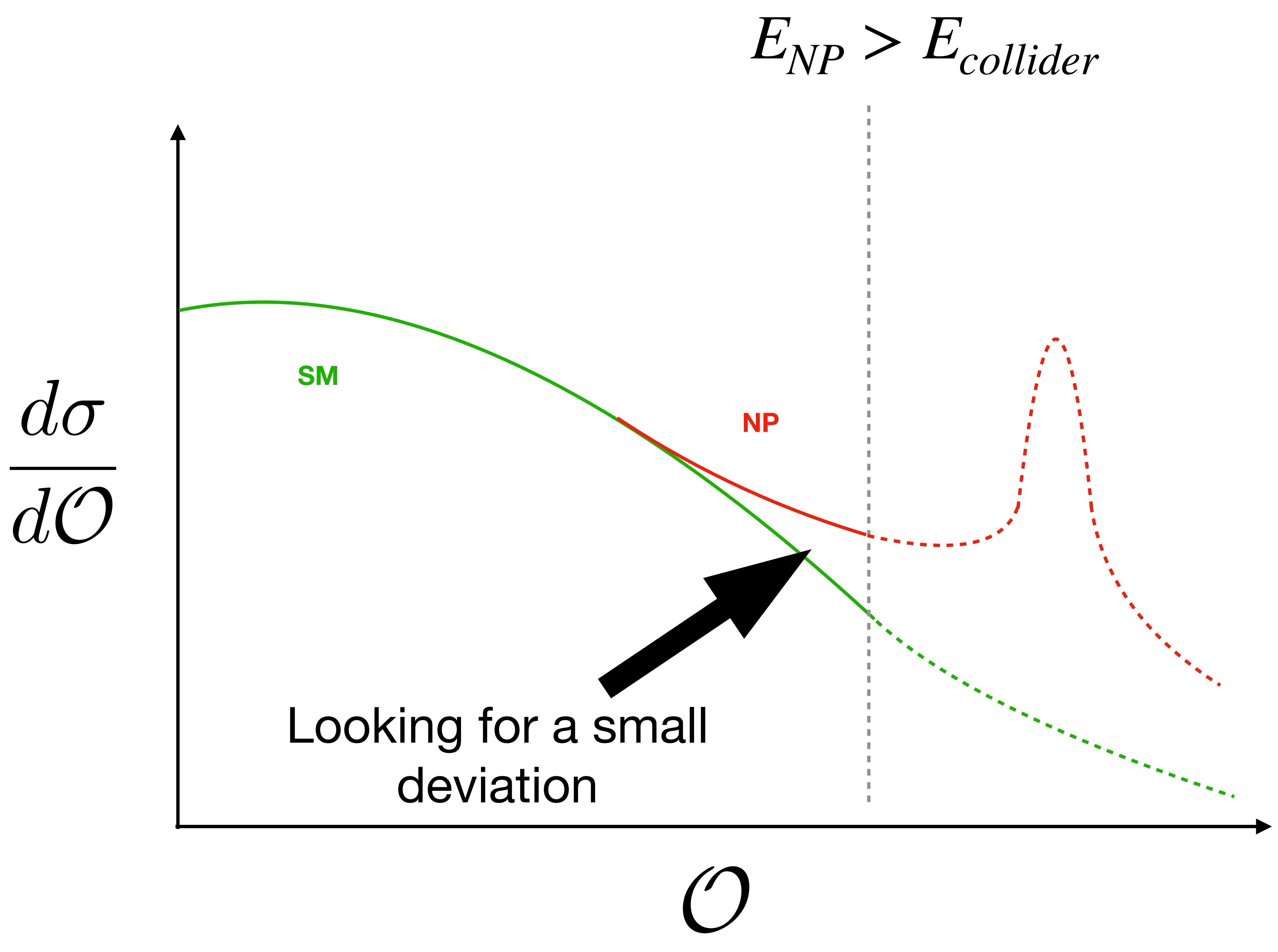
Looking toward higher energy scales and indirect searches

Direct searches



No luck so far…

Indirect searches



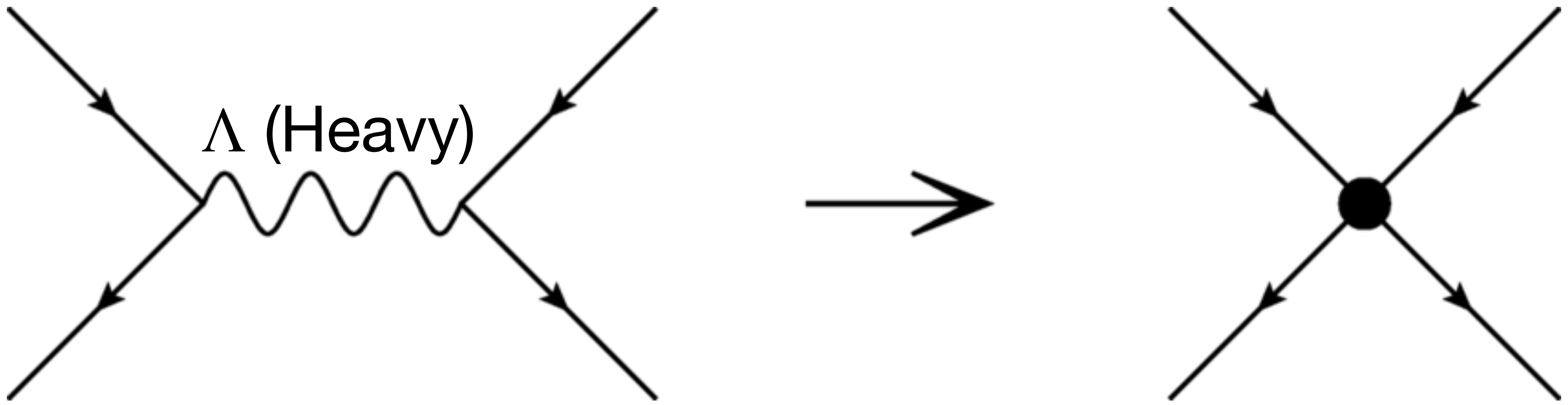
Requires precision

Indirect searches and Effective Field Theories

The Standard Model EFT (SMEFT)

Integrate heavy fields out:

UV Model



EFT Model

[10.1007/s10773-021-04723-1]

Obtain model independent Lagrangian:

$$\mathscr{L}^{\text{UV}} = \mathscr{L}^{\text{SM}} + \mathscr{L}^{\text{Heavy}} \longrightarrow \mathscr{L}^{\text{SMEFT}} = \mathscr{L}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

- Dim 6 EFT operators with SM fields: $\mathcal{O}_i^{(6)}$
- Wilson coefficients fittable from data: $\frac{c_i}{\Lambda^2}$

The SMEFT

Dimension-6 operators

Operator basis

2499 operators
[Grzadkowski et al, arXiv:1008.4884]

Reduced with symmetry assumptions:

- e.g. baryon number conservation : 59 operators

Presented in the Warsaw basis

Corrections

$$\mathcal{L}^{\text{SMEFT}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}$$

$$\sigma^{\text{SMEFT}} = \sigma^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}|\mathcal{A}^{SM}\mathcal{A}^{\mathcal{O}_i}| + \sum_{i,j} \frac{c_i c_j}{\Lambda^4}|\mathcal{A}^{\mathcal{O}_i}\mathcal{A}^{\mathcal{O}_j}|$$

Linear

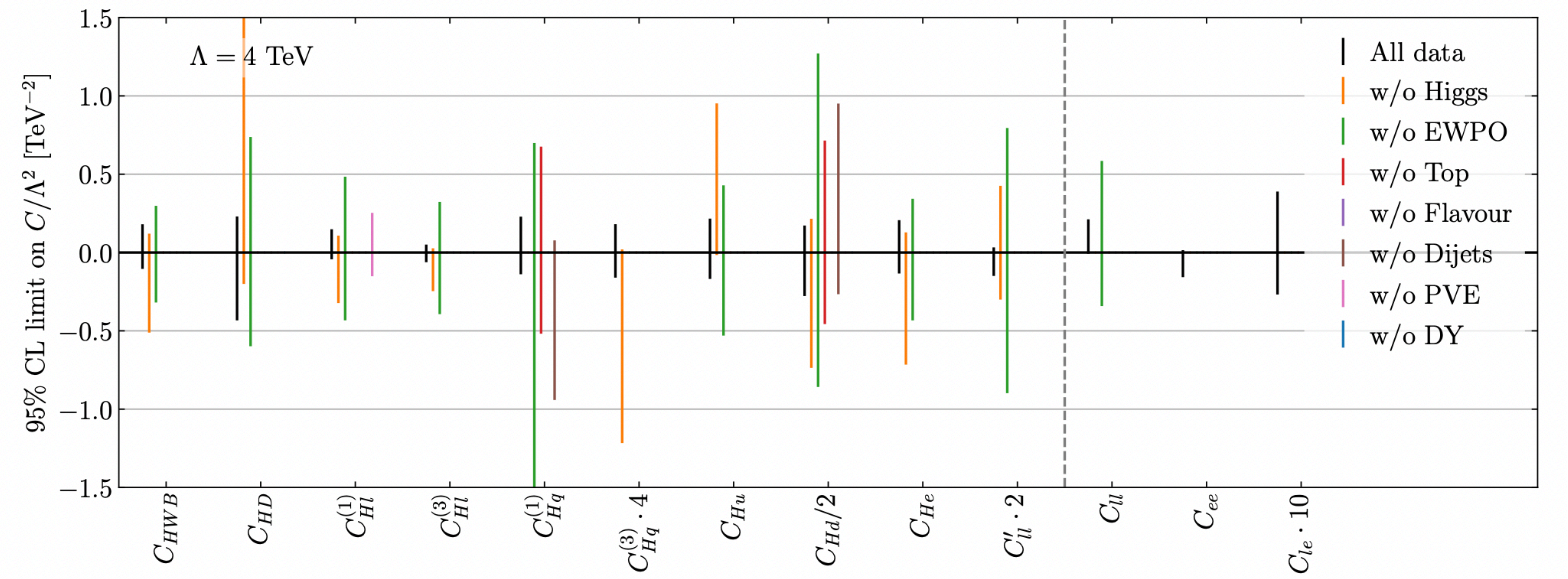
$$\mathcal{O}\left(\frac{c_i}{\Lambda^2}\right)$$

Quadratic

$$\mathcal{O}\left(\frac{c_i c_j}{\Lambda^4}\right)$$

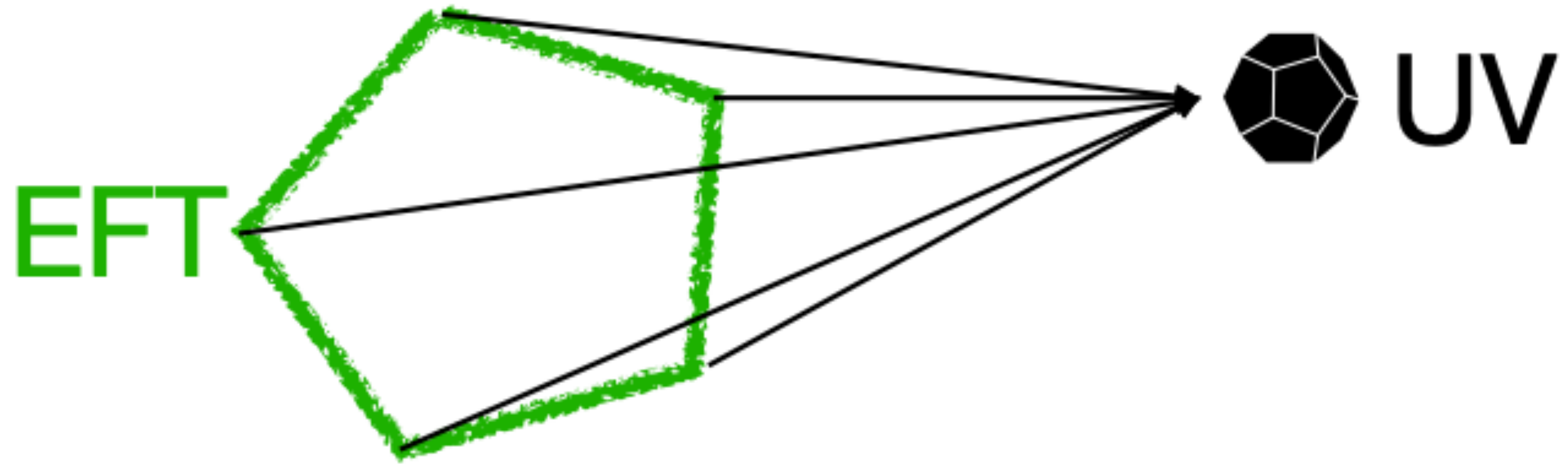
SMEFT fit from data

[SMEFiT, 2302.06660]



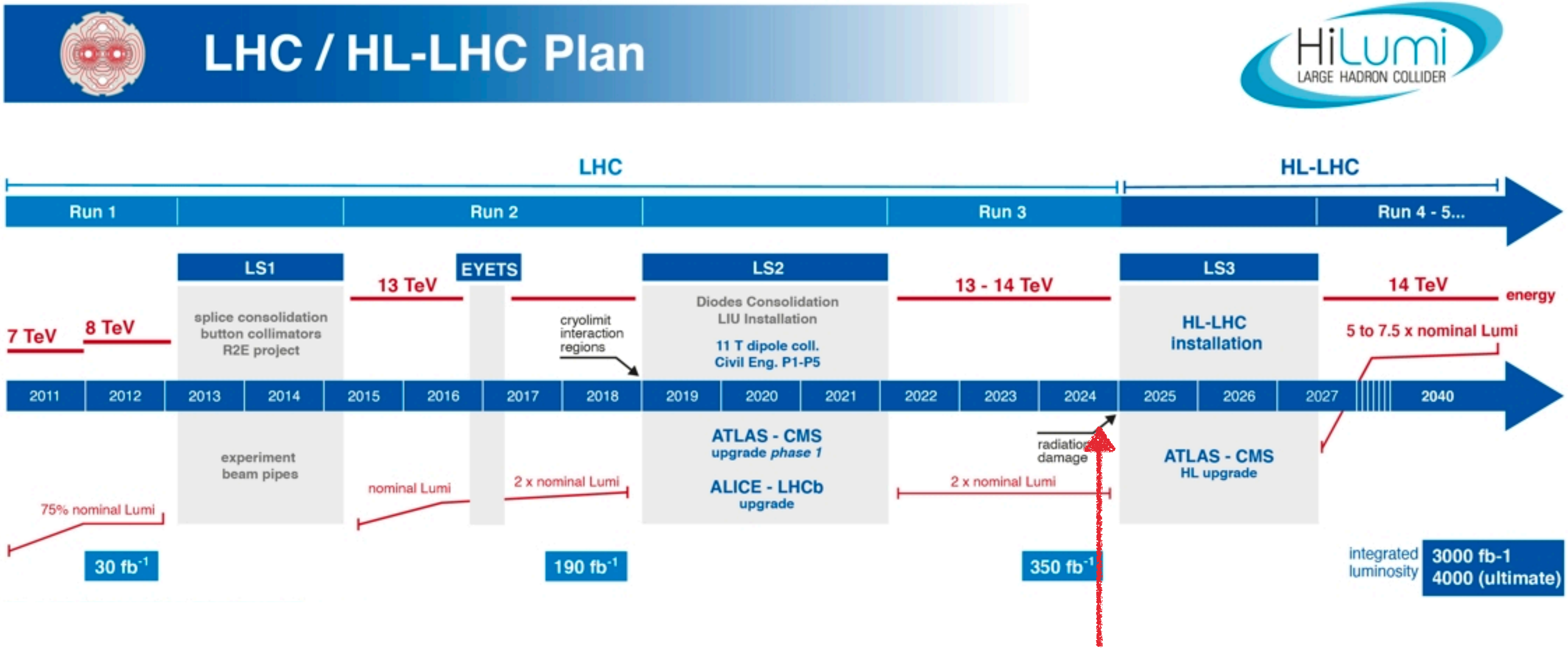
Can fit $\{\frac{c_i}{\Lambda^2}\}$:

➡ can then be matched to a UV model



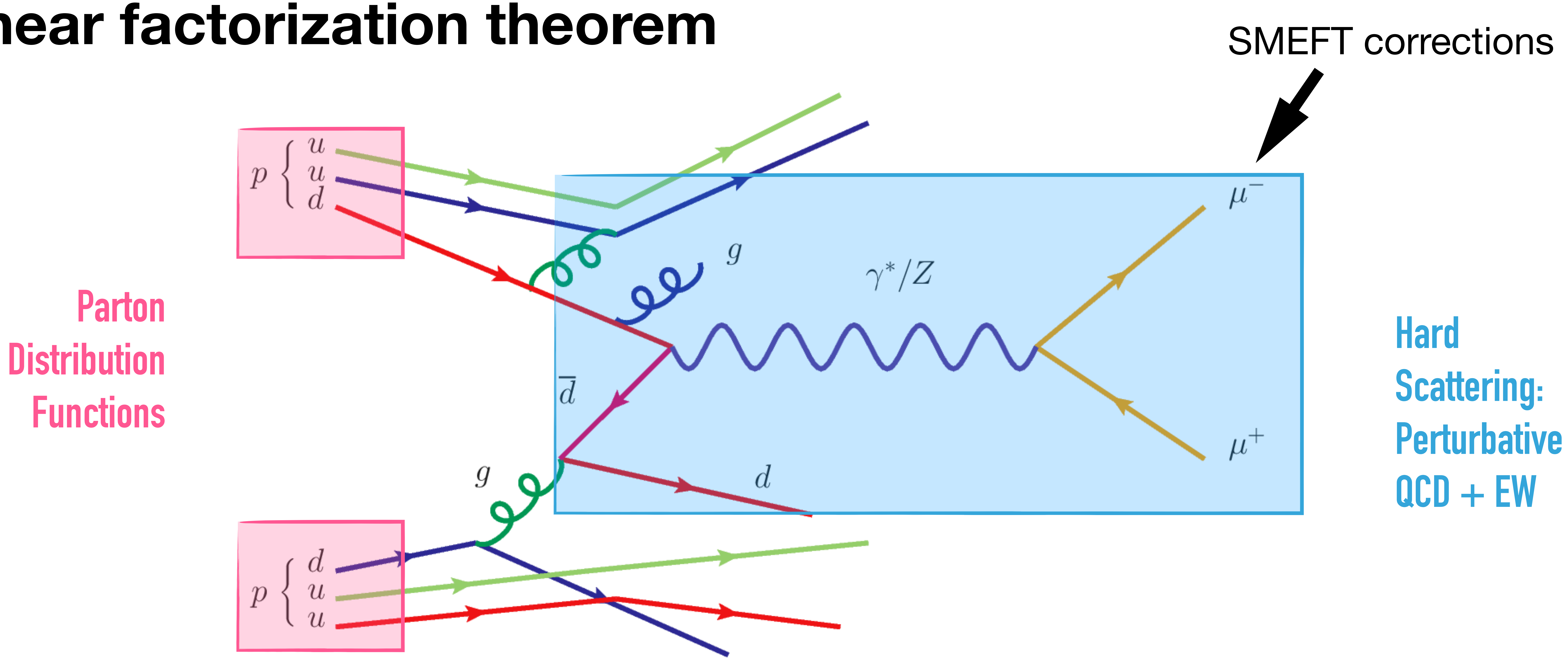
Exploring high energies at the LHC

Toward the high-luminosity run



Hadron colliders and PDFs

Collinear factorization theorem



$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

PDFs overview

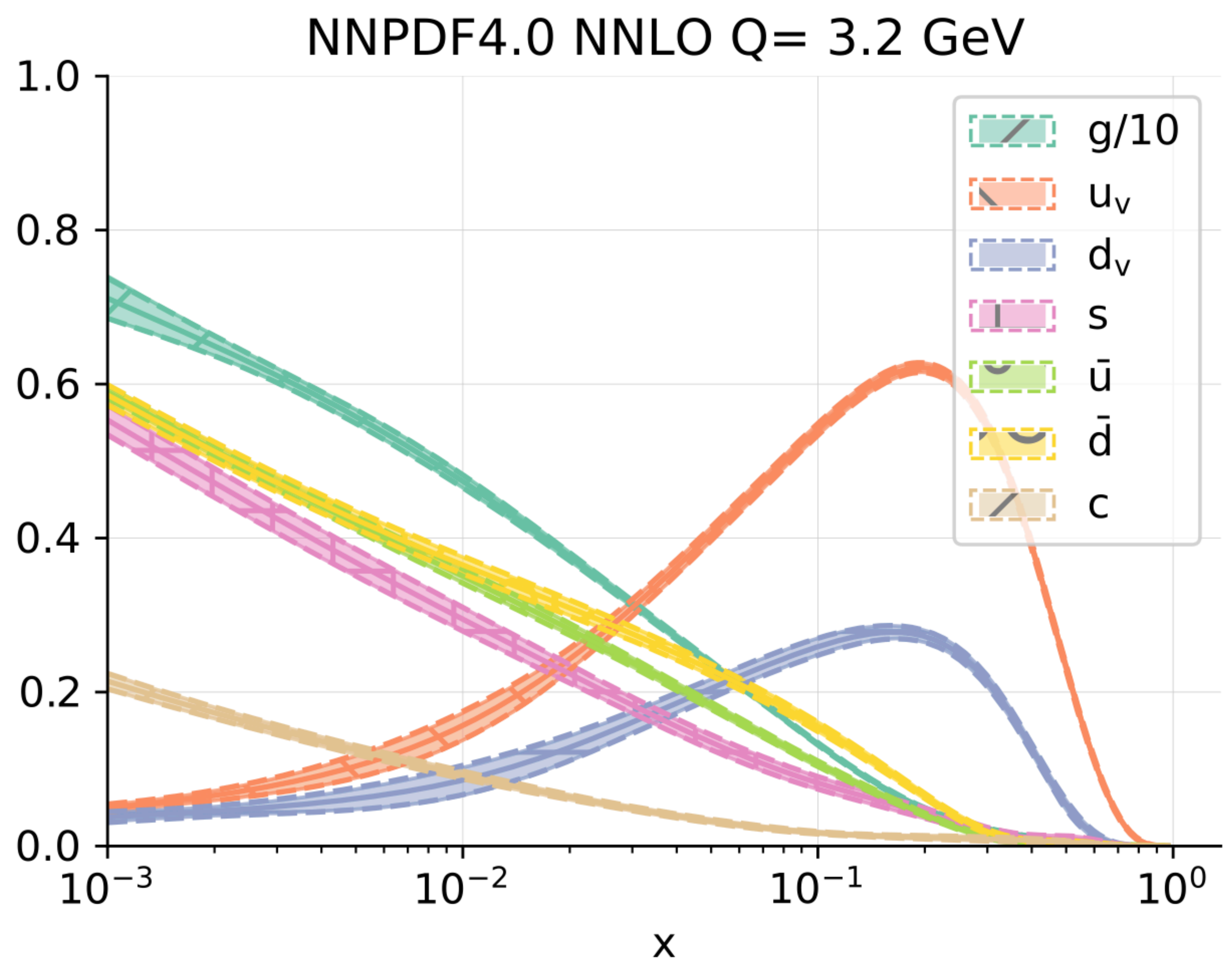
Hadron collider observable: $\sigma = f_1 \otimes f_2 \otimes \hat{\sigma}$

PDFs in a nutshell:

- describe proton in terms of partonic content
- $f(x, Q)$
- x dependance: non-perturbative QCD

➡ **Fitted from data**

Using NNPDF methodology

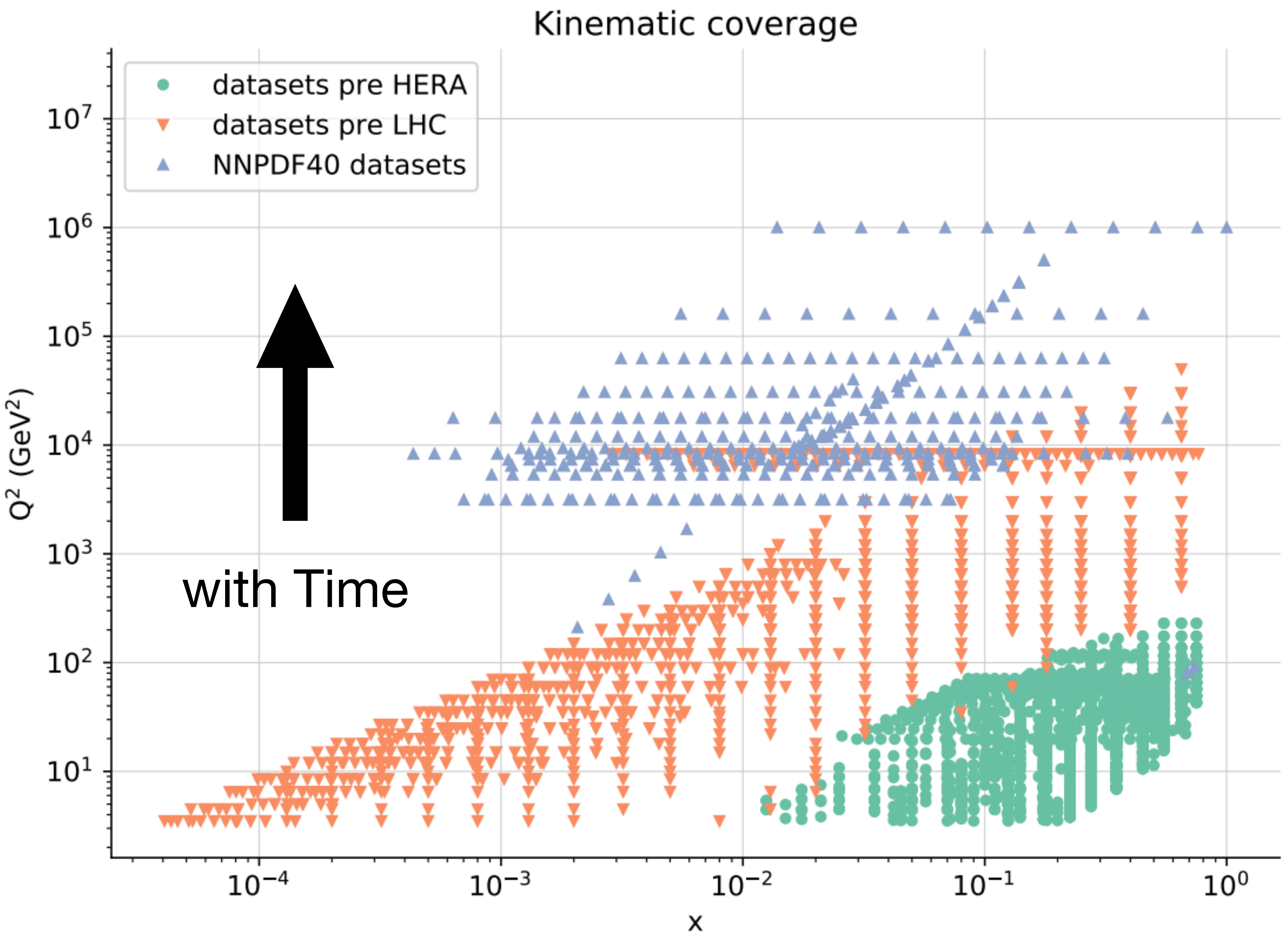


[Ball et al., NNPDF4.0, 2109.02653]

NNPDF methodology

Fitting PDF from data

The dataset used by NNPDF



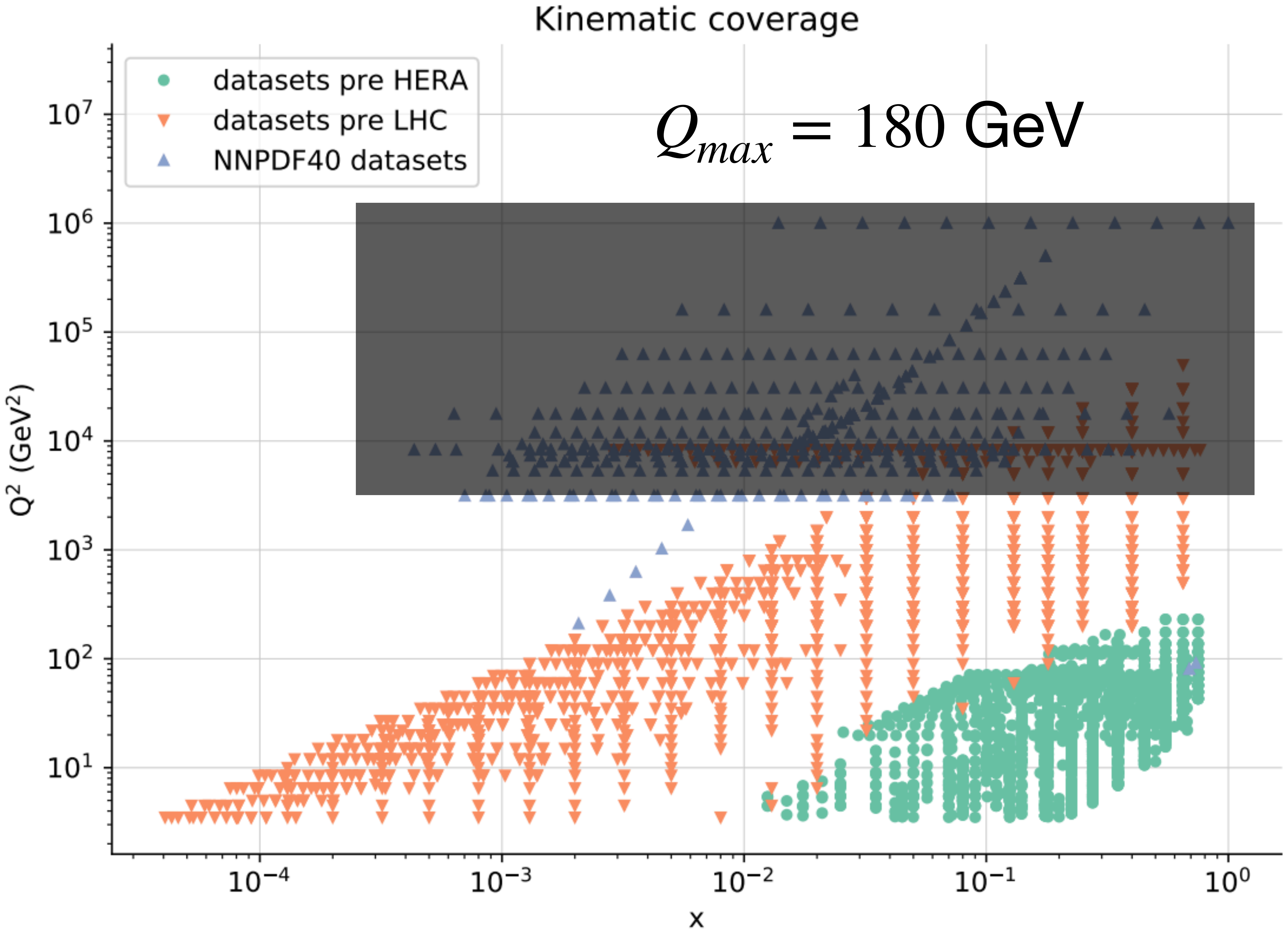
Evolution of the dataset through time:

- Moved toward higher energies
- 30% is LHC data
- More to come with HL-LHC run

[Ball et al., NNPDF4.0, 2109.02653]

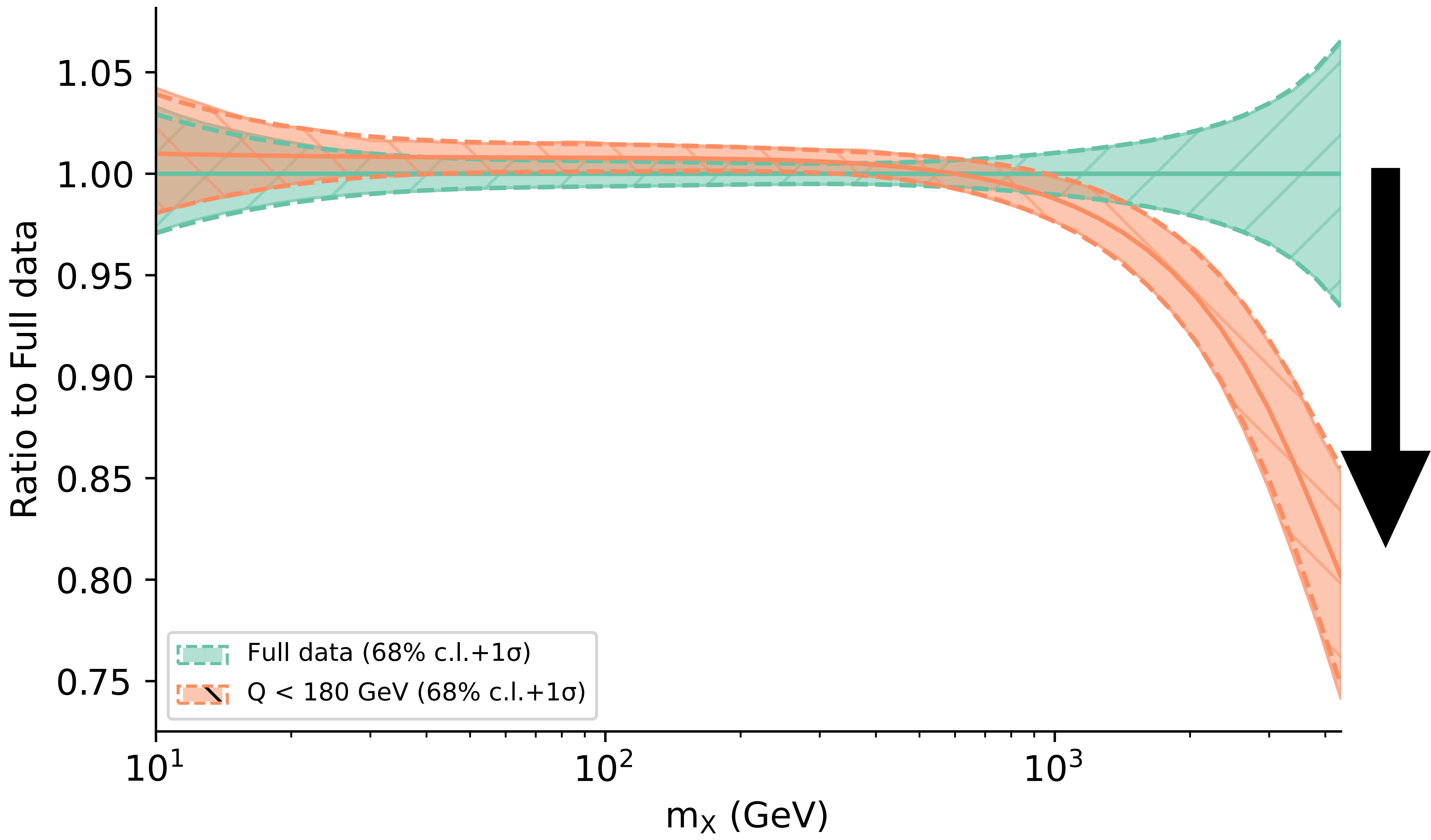
Discrepancy between low and high-energy data fits

Comparison of full data and no LHC PDF fit



Impact of energy cut

gg luminosity $\sqrt{s} = 13$ TeV $\mathscr{L}_{gg} = f_g \otimes f_g$



Risk of absorbing new physics in PDFs?

Methodology for risk assessment

Perform a "Contamination test":

1. Choose a BSM model
2. Produce BSM pseudodata
3. Fit PDFs from pseudodata assuming SM
4. Compare results with baseline PDFs (no BSM physics)

[PBSP, 2307.10370]

Contamination criteria:

- Incompatible with baseline
- Fit quality does not deteriorate

➡ $$\chi^2 = (Dat - Th)^{\mathsf{T}} \cdot \Sigma_{cov}^{-1} \cdot (Dat - Th)$$

PDF contamination:

➡ **PDFs have absorbed new physics signals**

New physics scenarios: W'

From UV to the SMEFT

Heavy triplet under $SU(2)_L$: W'

$$\mathscr{L}_{UV}^{W'} = \mathscr{L}_{SM} - \frac{1}{4} W'^{a}_{\mu\nu} W'^{a,\mu\nu} + \frac{1}{2} M^2_{W'} W'^{a}_{\mu} W'^{a,\mu} - g_{W'} W'^{a,\mu} \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L - g_{W'} (W'^{a,\mu} \varphi^\dagger T^a i D_\mu \varphi + \text{h.c.})$$

➡ Creates two charged particles: W'^{+} / W'^{-} and a neutral one: W'_3

<u>Matching to the SMEFT:</u>

$$\mathscr{L}_{SMEFT}^{W'} = \mathscr{L}_{SM} - \frac{g^2_{W'}}{2M^2_{W'}} J_L^{a,\mu} J^a_{L,\mu} \qquad J_L^{a,\mu} = \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L$$

$$\rightarrow \quad \mathscr{L}_{SMEFT}^{W'} = \mathscr{L}_{SM} - \frac{g^2 \hat{W}}{2m^2_W} J_L^{a,\mu} J^a_{L,\mu} \qquad \hat{W} = \frac{g^2_{W'}}{g^2} \frac{m^2_W}{M^2_{W'}} \propto \frac{c}{\Lambda^2}$$

New physics parameter

New physics scenarios: W' $pp \to l^- \bar{\nu}$ $M_{W'} = 13.8$ TeV

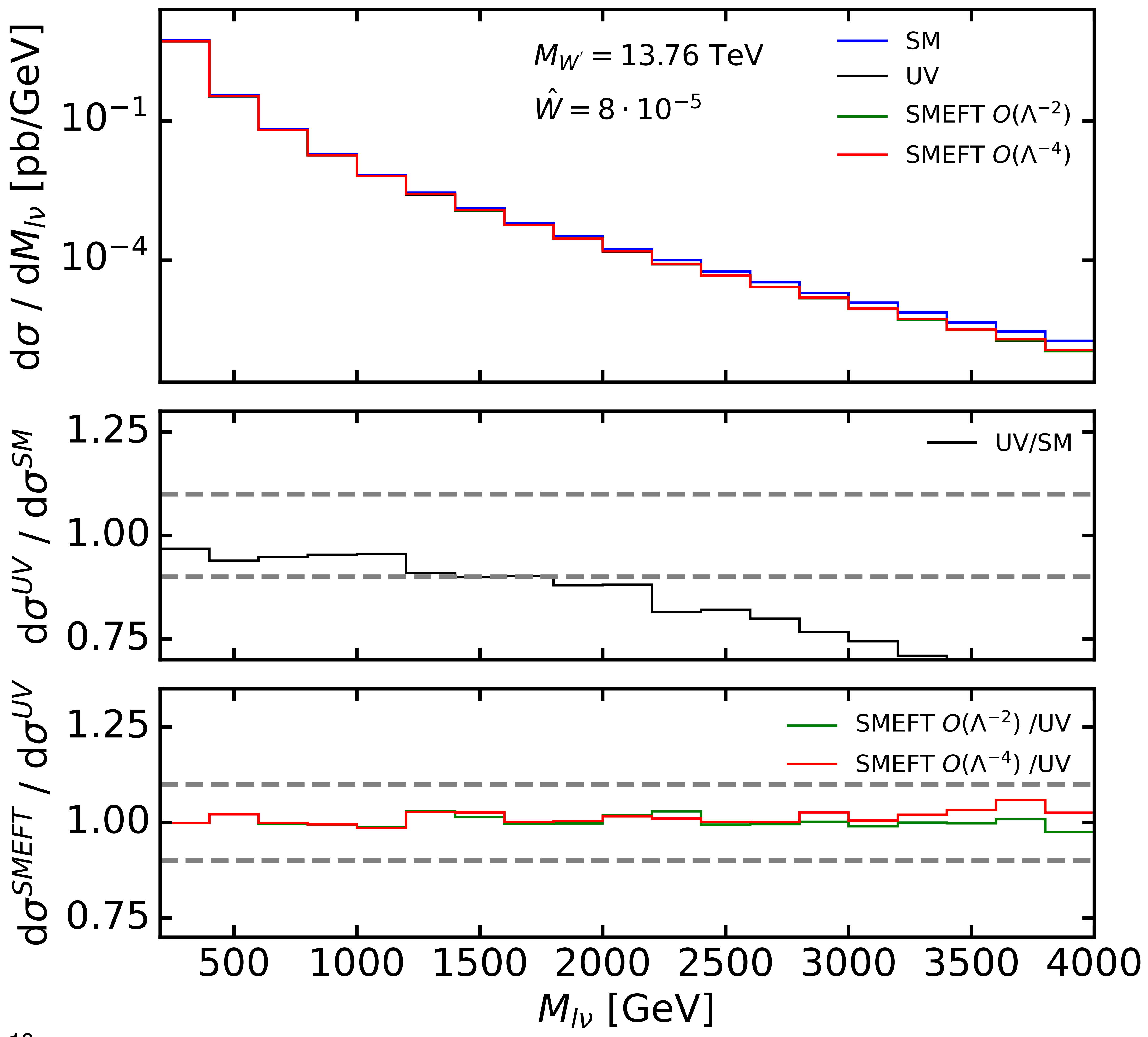
Generation of the pseudodata

$$\hat{W} \leftrightarrow M_{W'} \quad (g_{W'} = 1)$$

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

➡ Impacts CC and NC Drell-Yan

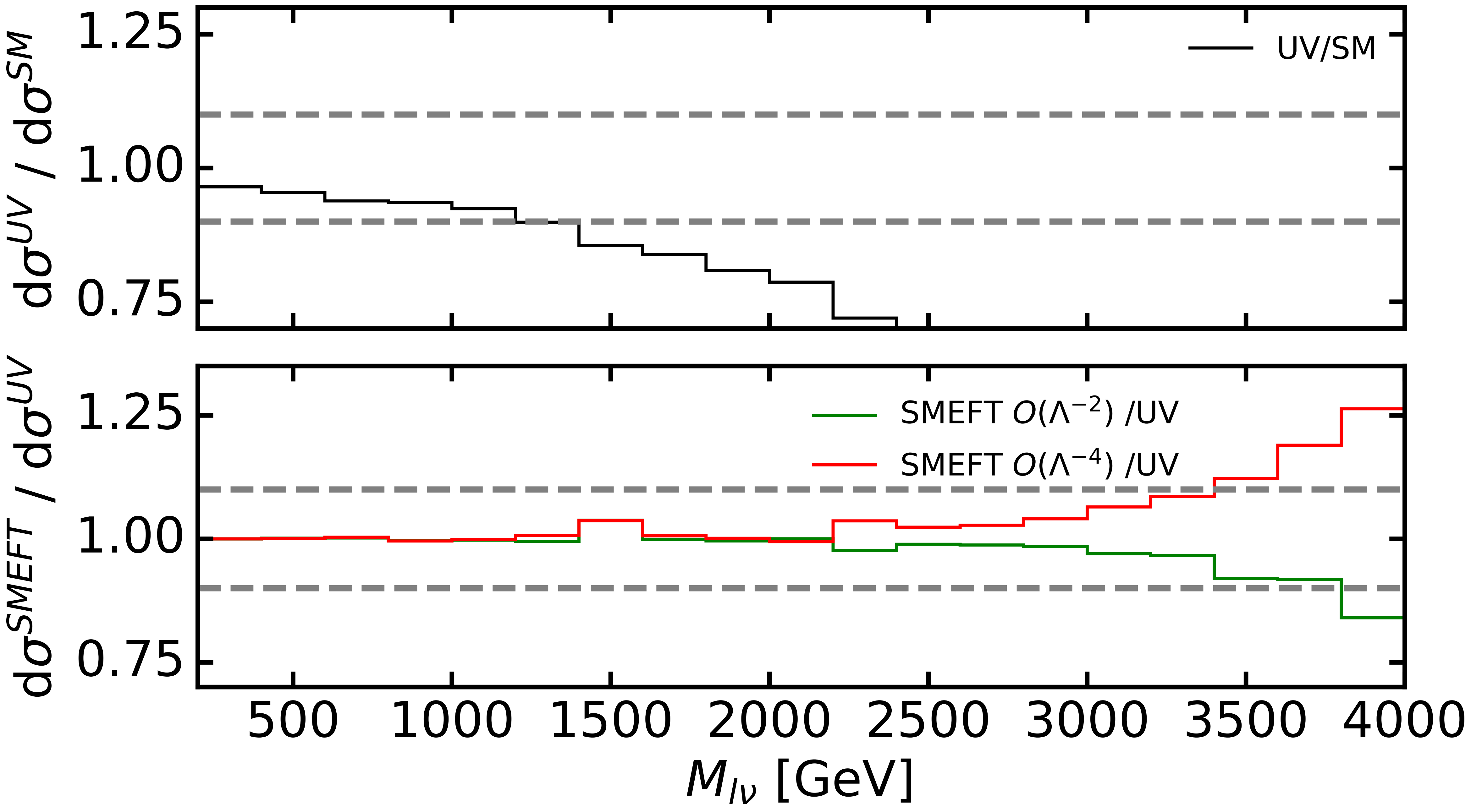
HL-LHC Projections



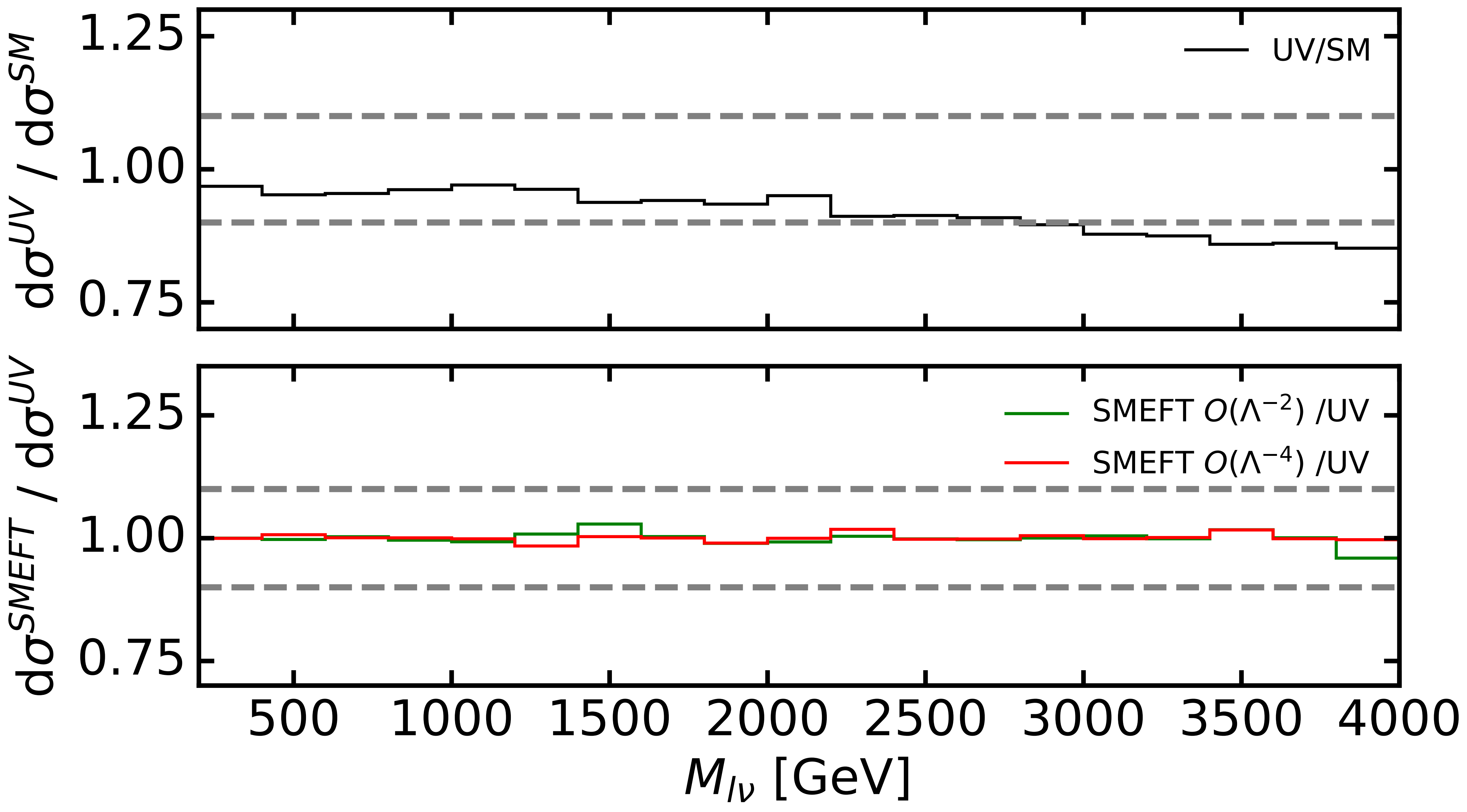
New physics scenarios: W'

Consideration of different masses

$M_{W'} = 10$ TeV



$M_{W'} = 22.5$ TeV



New physics scenarios: Z'

From UV to the SMEFT

Heavy boson charged under $U(1)_Y : Z'$

$$\mathscr{L}^{Z'}_{\text{UV}} = \mathscr{L}_{\text{SM}} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu - g_{Z'} Z'_\mu \sum_f Y_f \bar{f} \gamma^\mu f - Y_\varphi g_{Z'} (Z'_\mu \varphi^\dagger i D^\mu \varphi + \text{h.c.})$$

➡ Creates one neutral particle

<u>Matching to the SMEFT:</u>

$$\mathscr{L}^{Z'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2_{W'}}{2M^2_{W'}} J^{a,\mu}_Y J^a_{Y,\mu} \qquad J^{a,\mu}_L = \sum_{f_L} Y_f \bar{f}_L \gamma^\mu f_Y$$

$$\to \quad \mathscr{L}^{Z'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2 \hat{Y}}{2m^2_W} J^{a,\mu}_Y J^a_{Y,\mu} \qquad \hat{Y} = \frac{g^2_{Z'}}{g^2} \frac{m^2_W}{M^2_{Z'}} \propto \frac{c}{\Lambda^2}$$

New physics parameter

New physics scenarios: Z'

$p\bar{p} \to l^+l^-$

$M_{Z'} = 18.7$ TeV

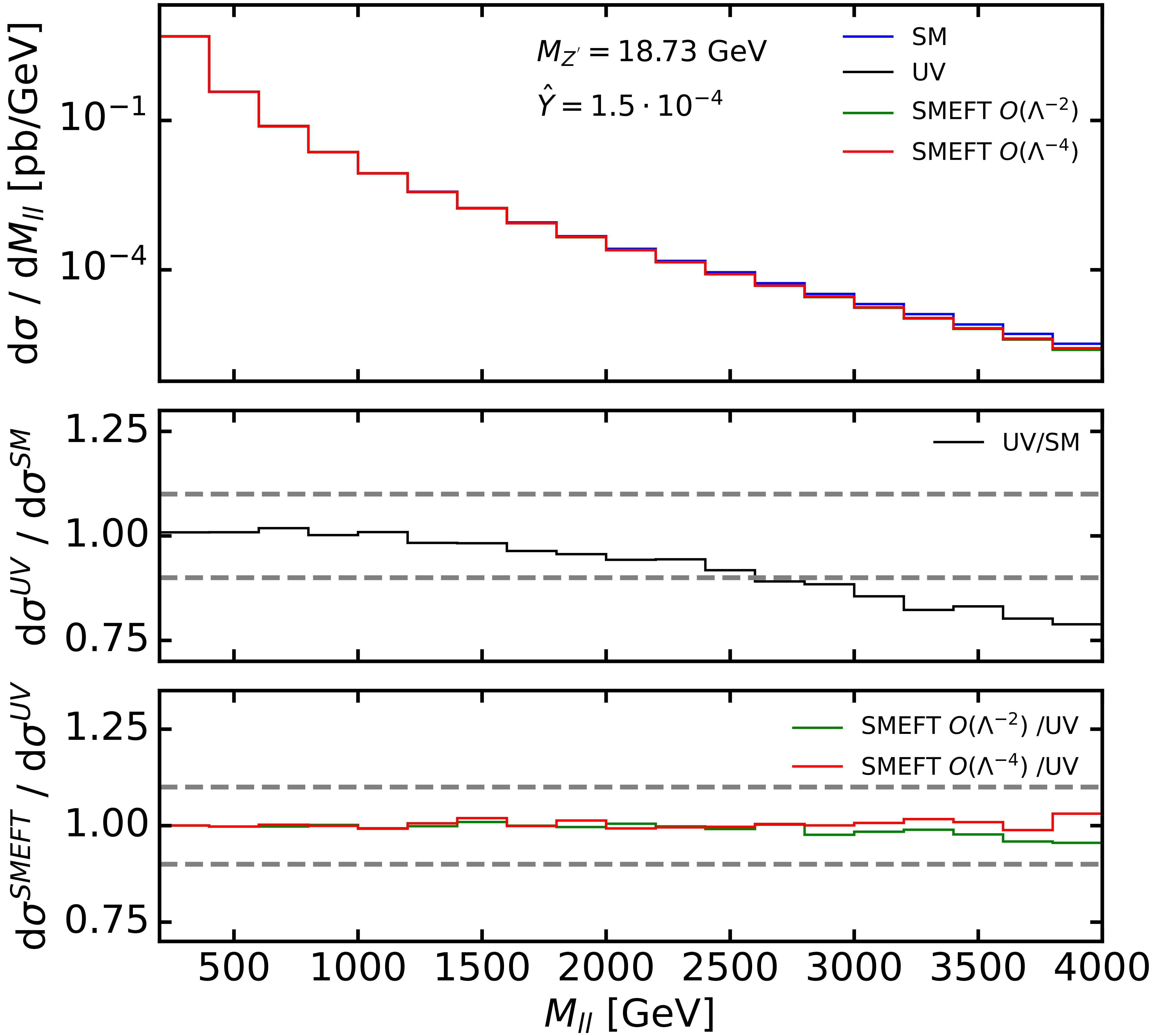
Generation of the pseudodata

$$\hat{Y} \leftrightarrow M_{Z'} \qquad (g_{Z'} = 1)$$

$$\mathscr{L}^{Z'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g_{Z'}^2}{2M_{Z'}^2} J^{\mu}_{Y} J_{Y,\mu}$$

➡ Impacts neutral-current Drell-Yan

HL-LHC Projections



PDF fitting: selection criteria

Exclusion of incompatible datasets (NNPDF criteria)

Two criteria:

$$\chi^2 = (D - T_{SM})^T \cdot V_{cov}^{-1} \cdot (D - T_{SM})$$

- χ^2-statistics:
  - $\frac{\chi^2}{n_{dat}} > 1.5$ → excluded

- n_σ standard deviation:
  - $n_\sigma > 2$ → excluded

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

PDF fitting: selection test

Do our contaminated datasets pass the selection criteria?

Z'

Selection test: ✗

➡ Excluded from PDF fit

No impact on PDFs

W'

Selection test: ✓

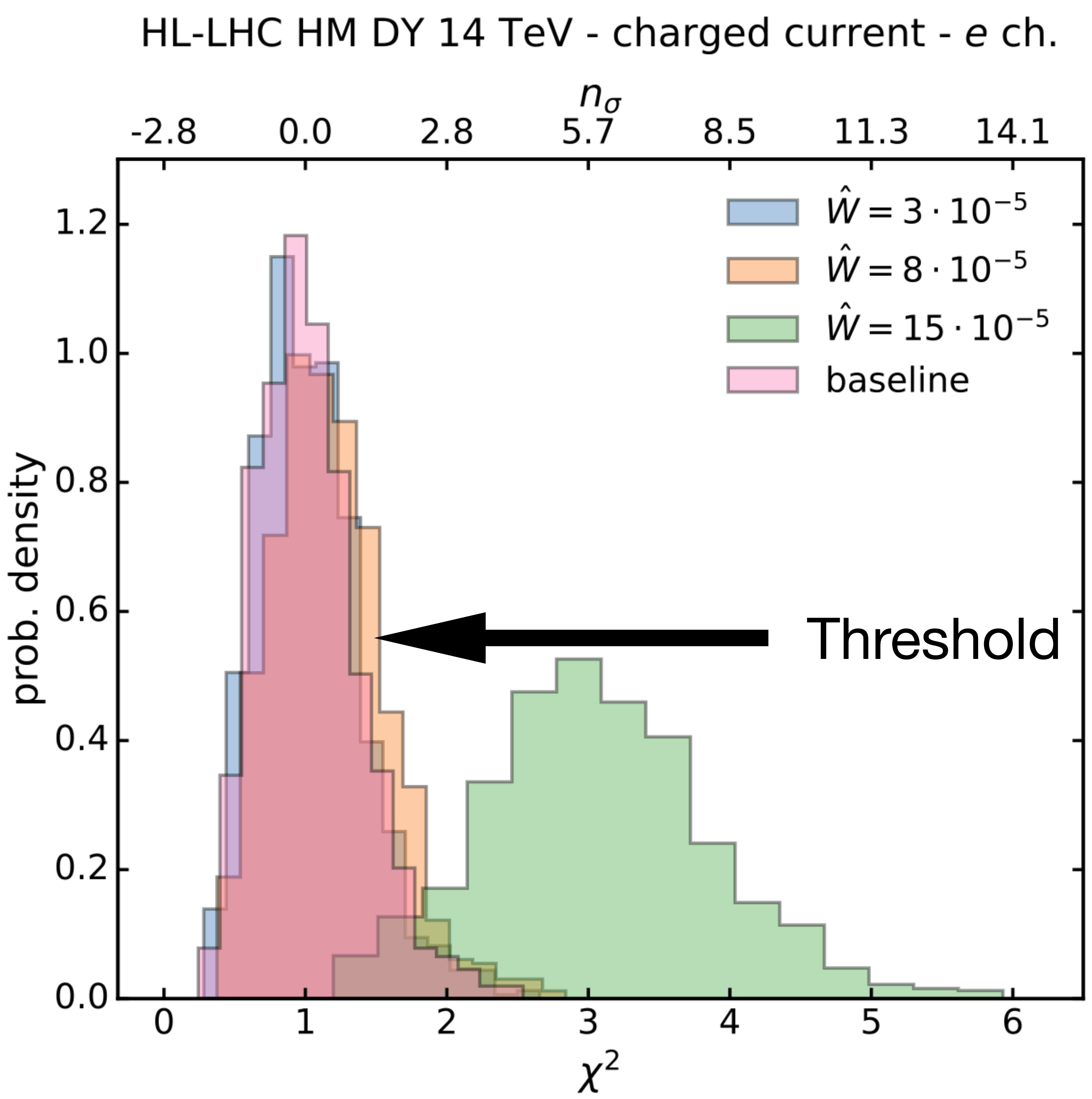
➡ Included in PDF fit

PDFs contaminated

Impact of contamination: the PDFs

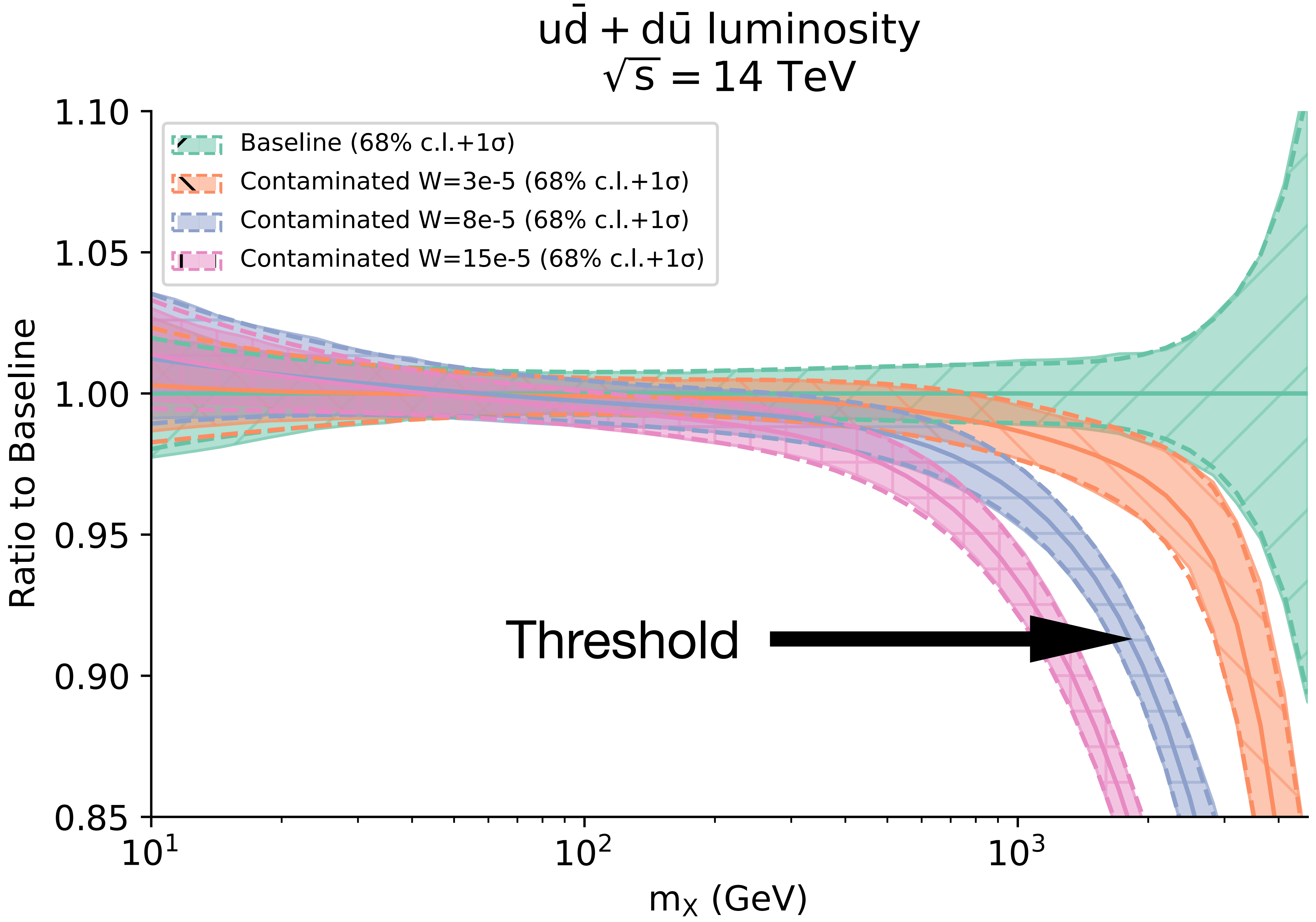
Comparison between contaminated and Baseline PDFs

Fit quality



$M_{W'} = 13.8$ TeV

Impact on PDFs

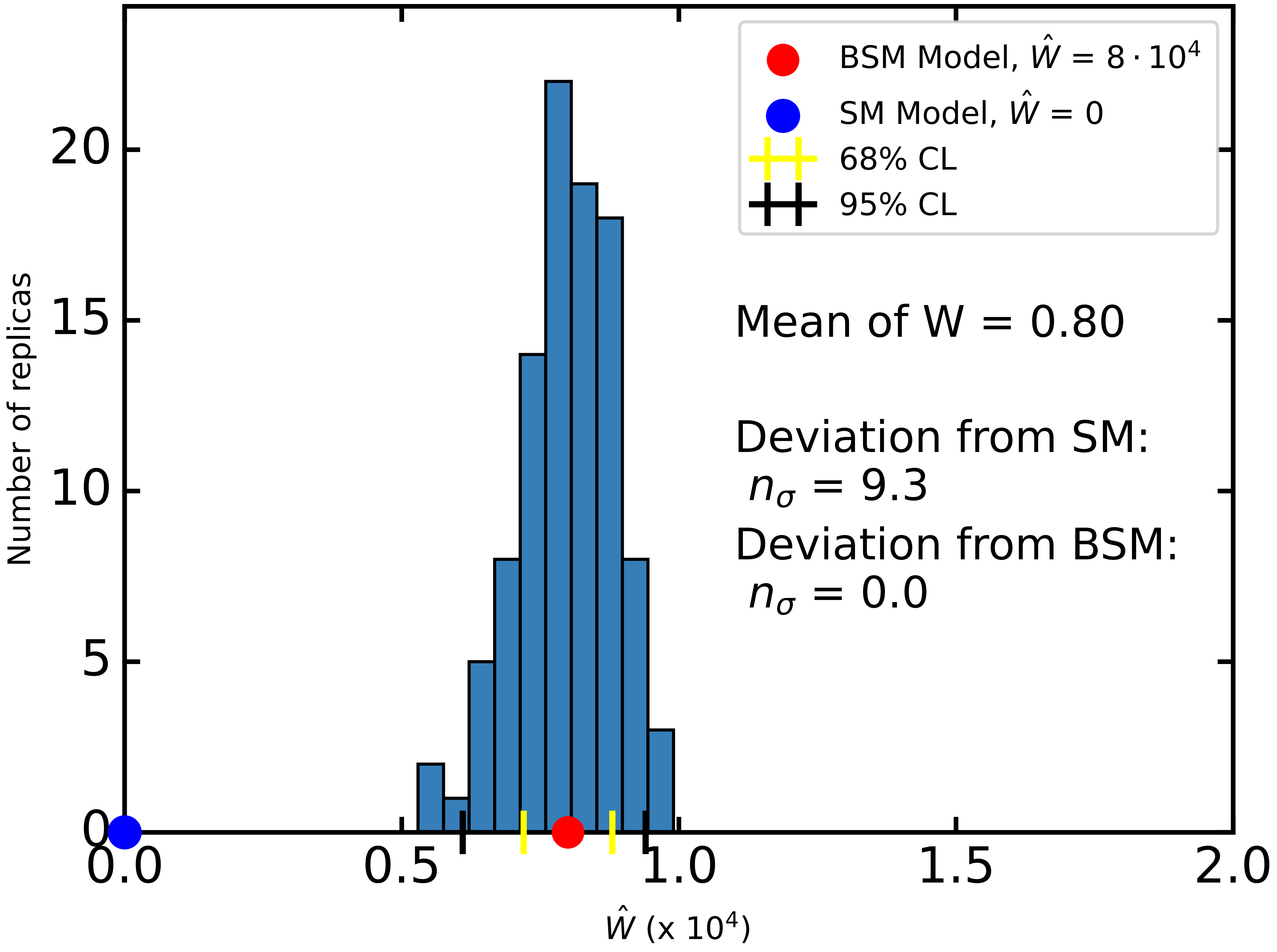


$$\hat{\sigma}_{BSM} \otimes \mathscr{L}_{SM} \approx \hat{\sigma}_{SM} \otimes \mathscr{L}_{cont}$$

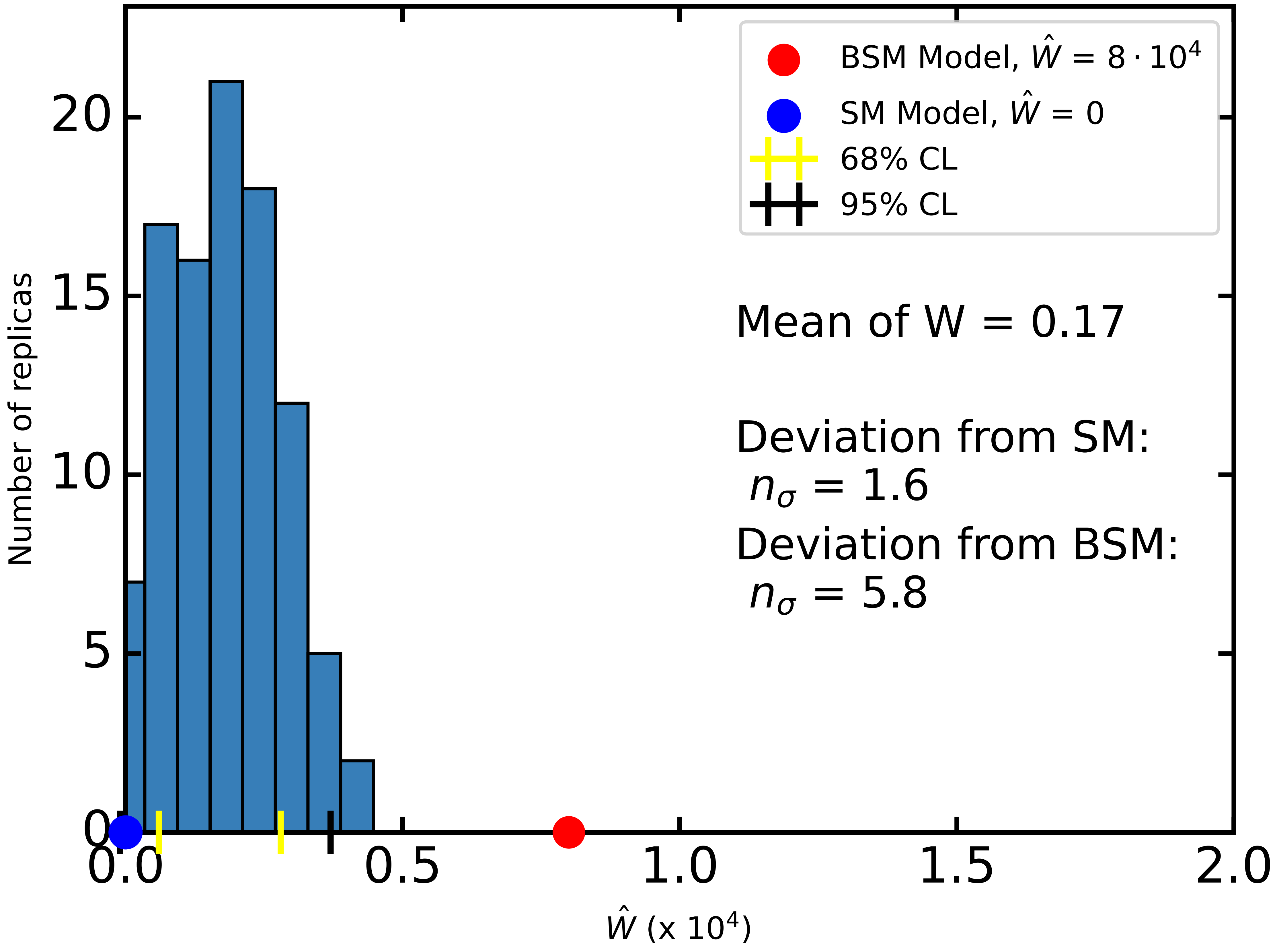
Impact of contamination: missing new physics

Comparison between SMEFT fits using different PDFs

True PDFs



Contaminated PDFs



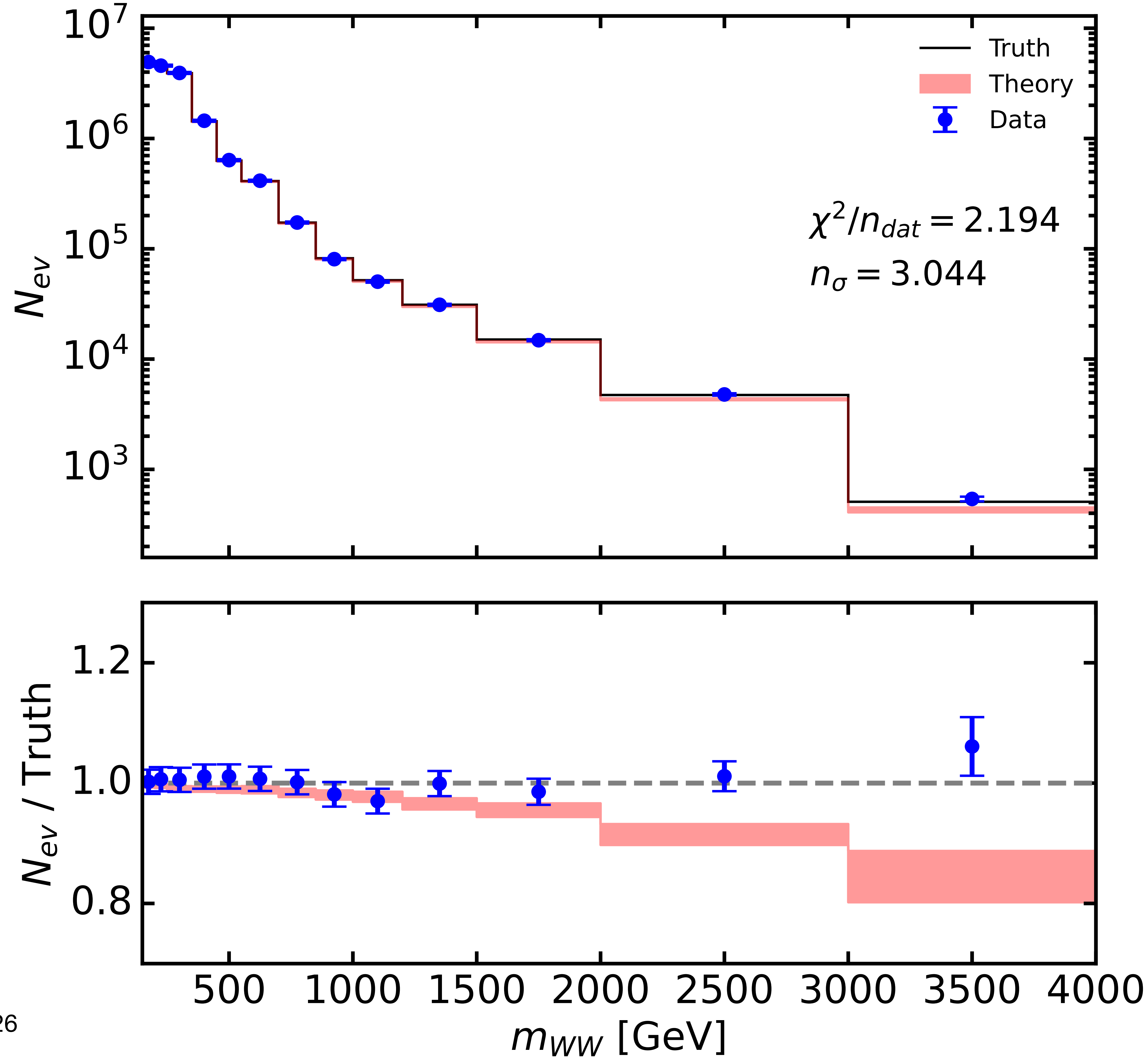
Impact of contamination: fake deviations

$pp \to W^+W^-$ (SM)

SM predictions with:

- Contaminated PDFs (red)
- True PDFs (black)

➡ Fake deviation in other sectors



Also seen in:

WH, WZ, ZH production

HL-LHC Projections

PDF contamination: summary

- BSM data in PDF fit:
  - At best: BSM data flagged and excluded
  - At worst: BSM signal absorbed by the PDF

- Consequences of PDF contamination:
  - New physics is hidden (model can be rules out)
  - Introduced fake deviations in other sectors

➡ Possible solutions?

Synergy of high and low-energy data

Adding low-energy dataset constraining the large-x region

Excessive antiquark PDF flexibility in large-x region:

➡ Accommodates real data and BSM pseudodata

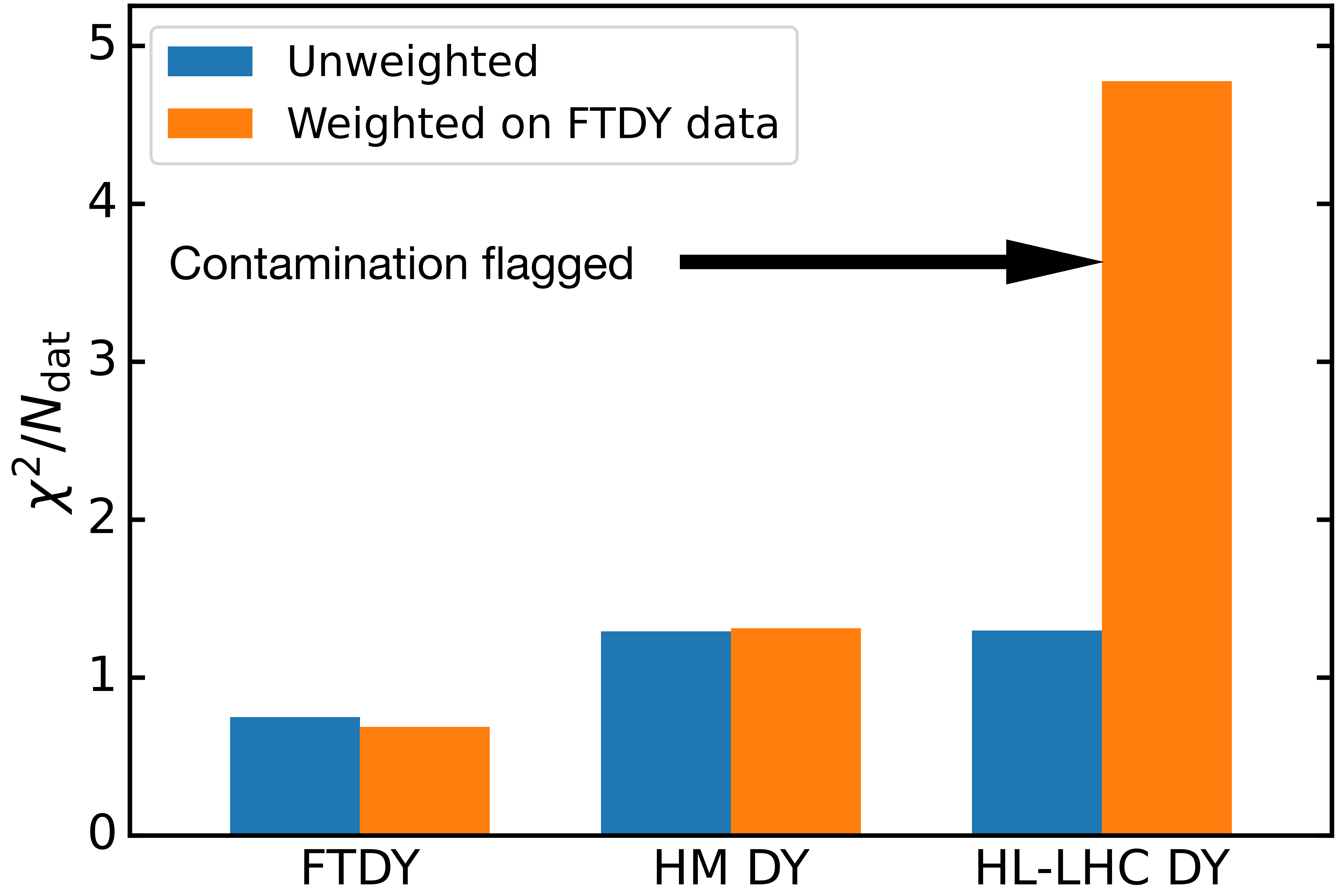
➡ Allows contamination

Including low-energy large-x data:

- Constraint large-x region
- Safe from BSM contamination

[Hammou et Ubiali, 2410.00963]

FTDY data weighted



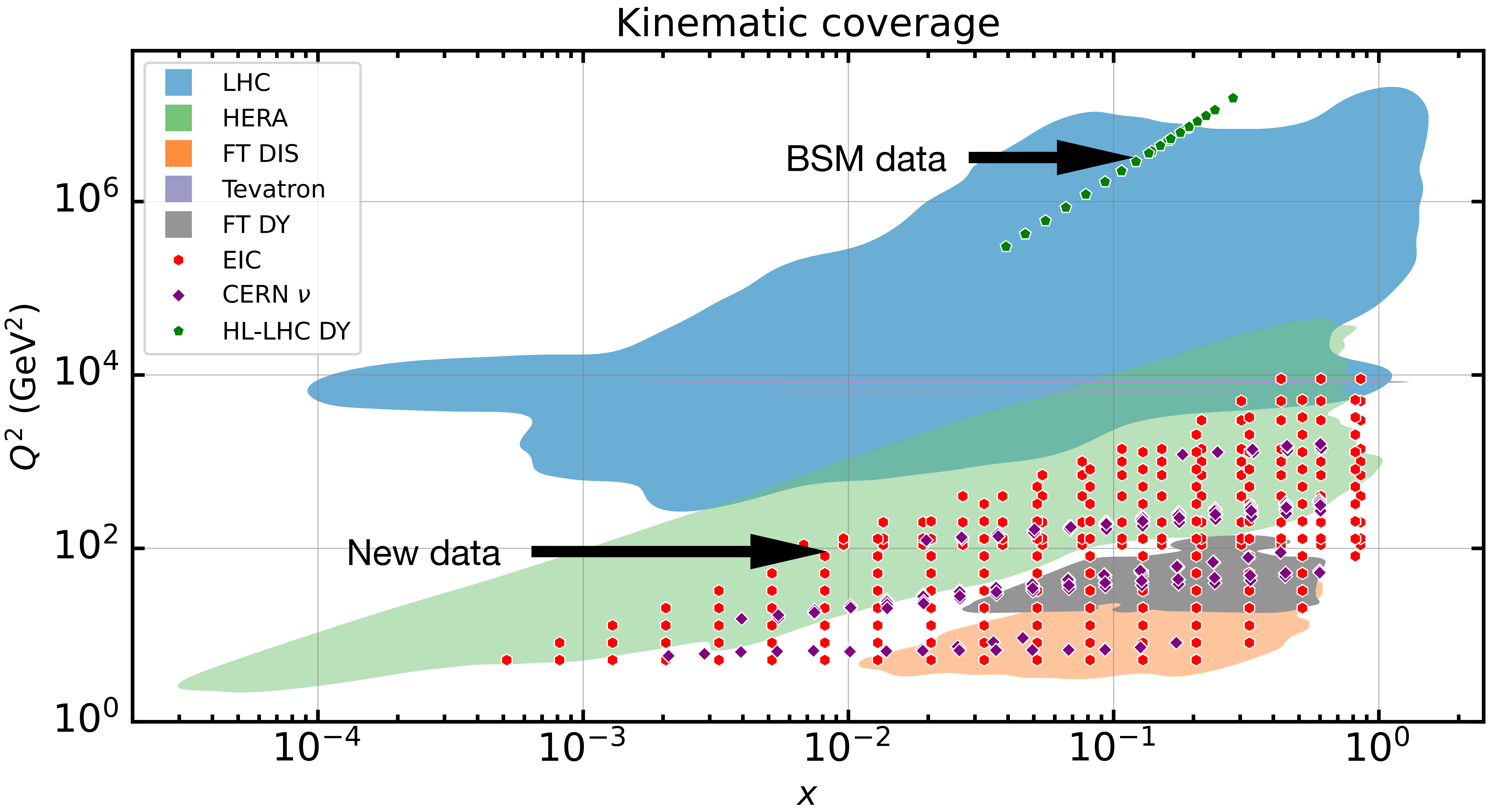
Future low energy data

Kinematic coverage

<u>Projection data:</u>

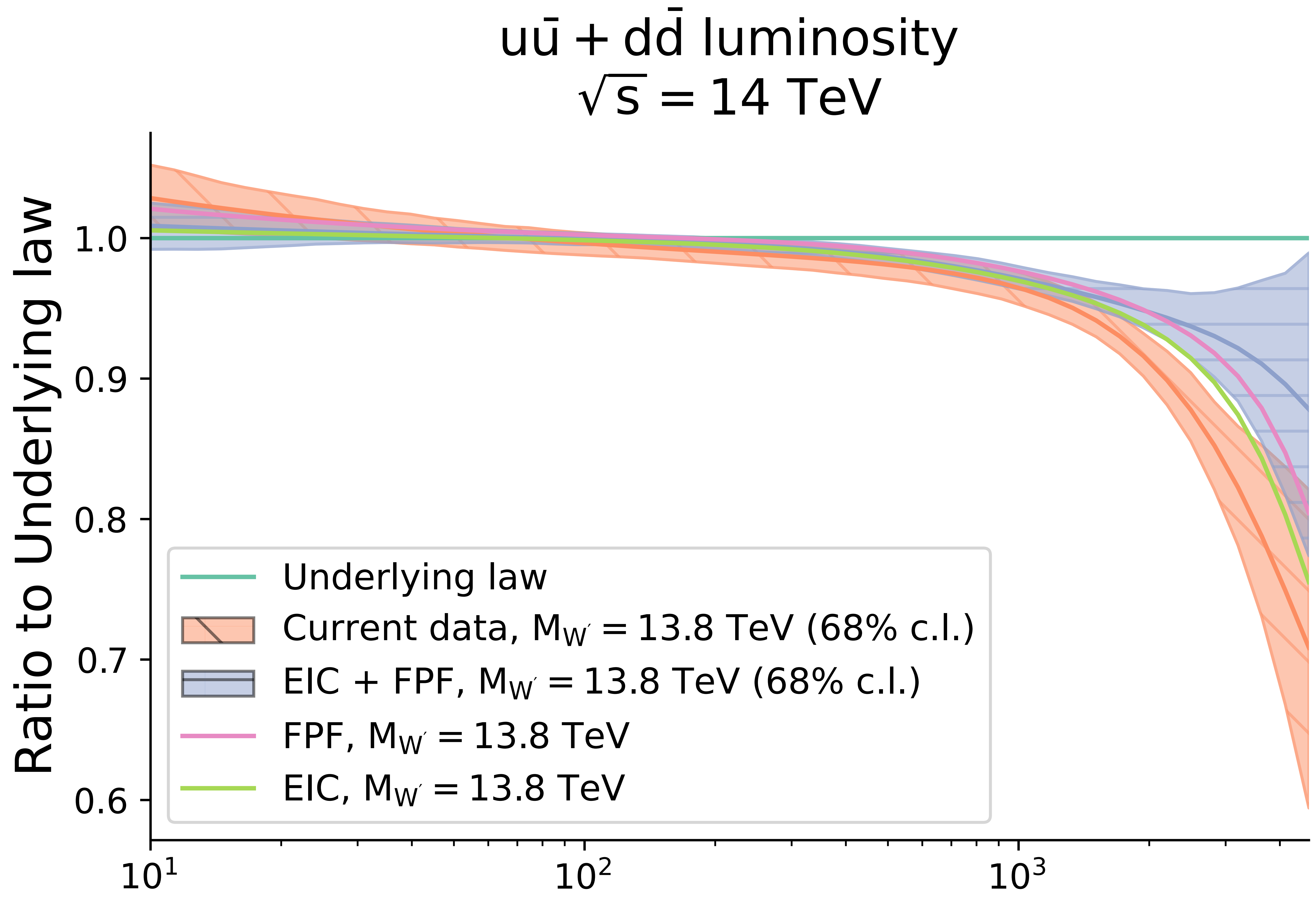
- Electron Ion Collider (EIC)
- Forward Physics Facility (FPF)

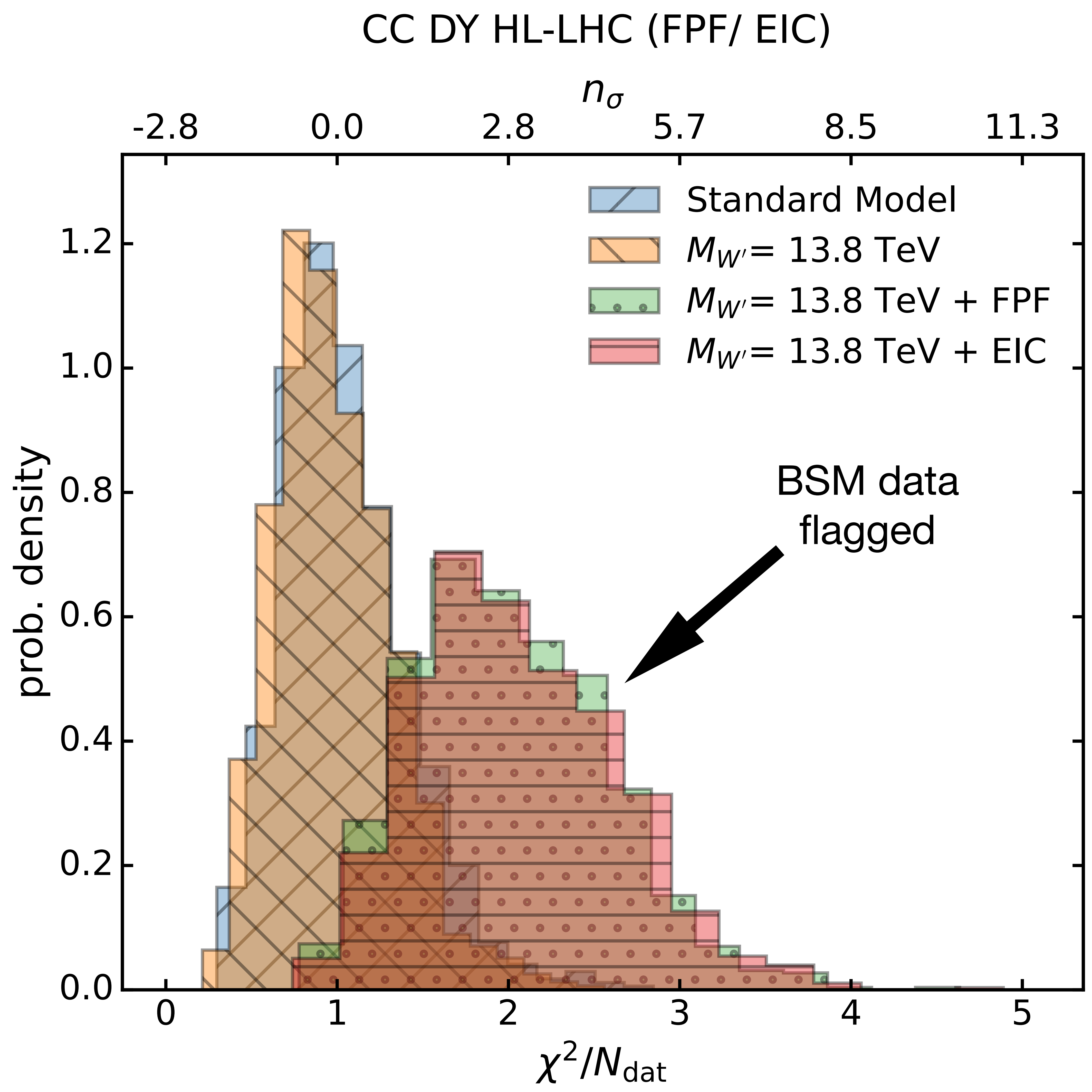
  (neutrino DIS)



Impact on the PDF contamination

Flagging the BSM data





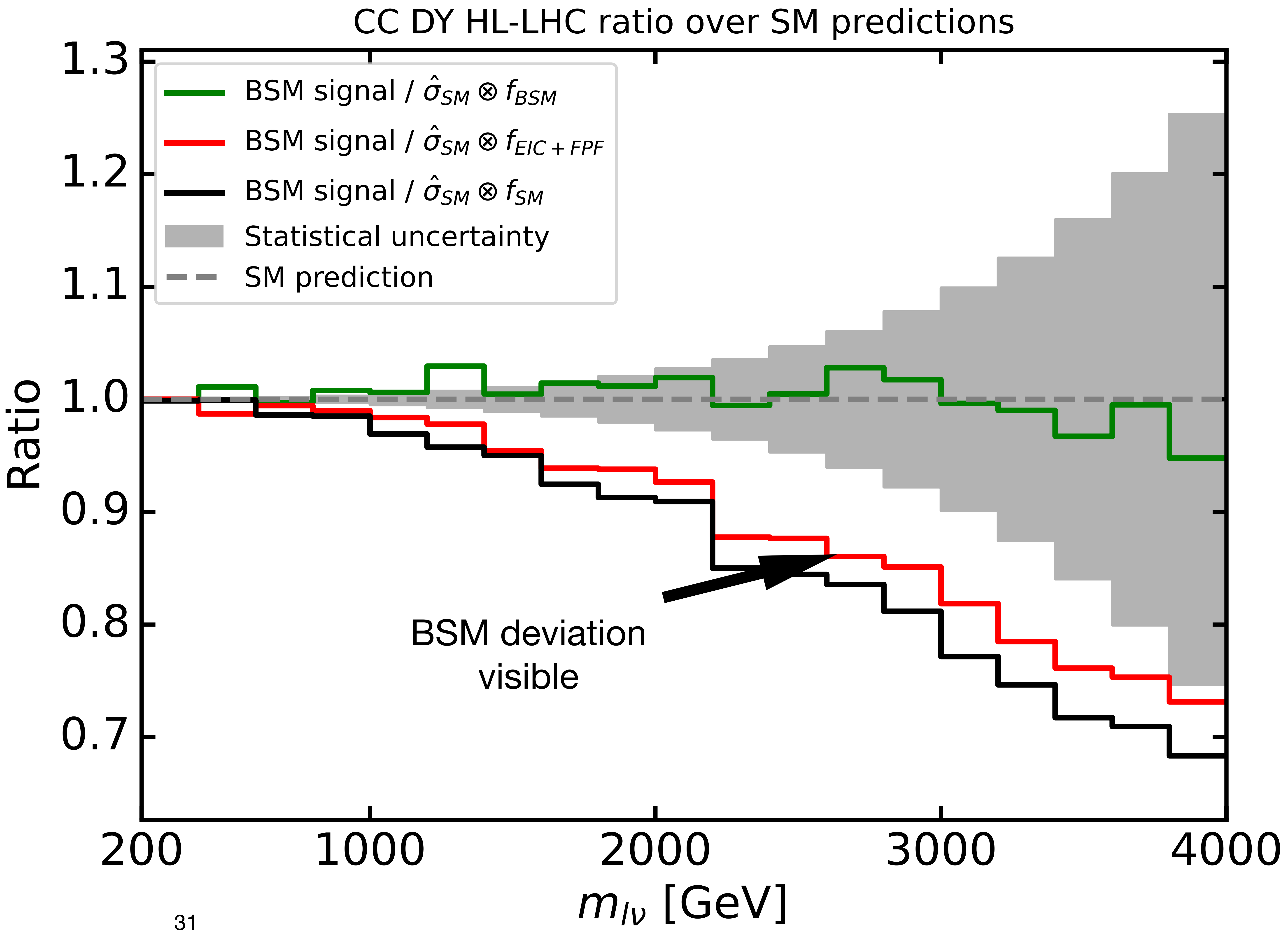
Recovering the signs of new physics

BSM data versus SM theory predictions

$$\hat{\sigma}_{BSM} \otimes \mathscr{L}_{SM} \approx \hat{\sigma}_{SM} \otimes \mathscr{L}_{cont}$$

$$\hat{\sigma}_{BSM} \otimes \mathscr{L}_{SM} \neq \hat{\sigma}_{SM} \otimes \mathscr{L}_{EIC+FPF}$$

$M_{W'}$: 13.8 TeV



Shift of the contamination threshold

From the fit quality

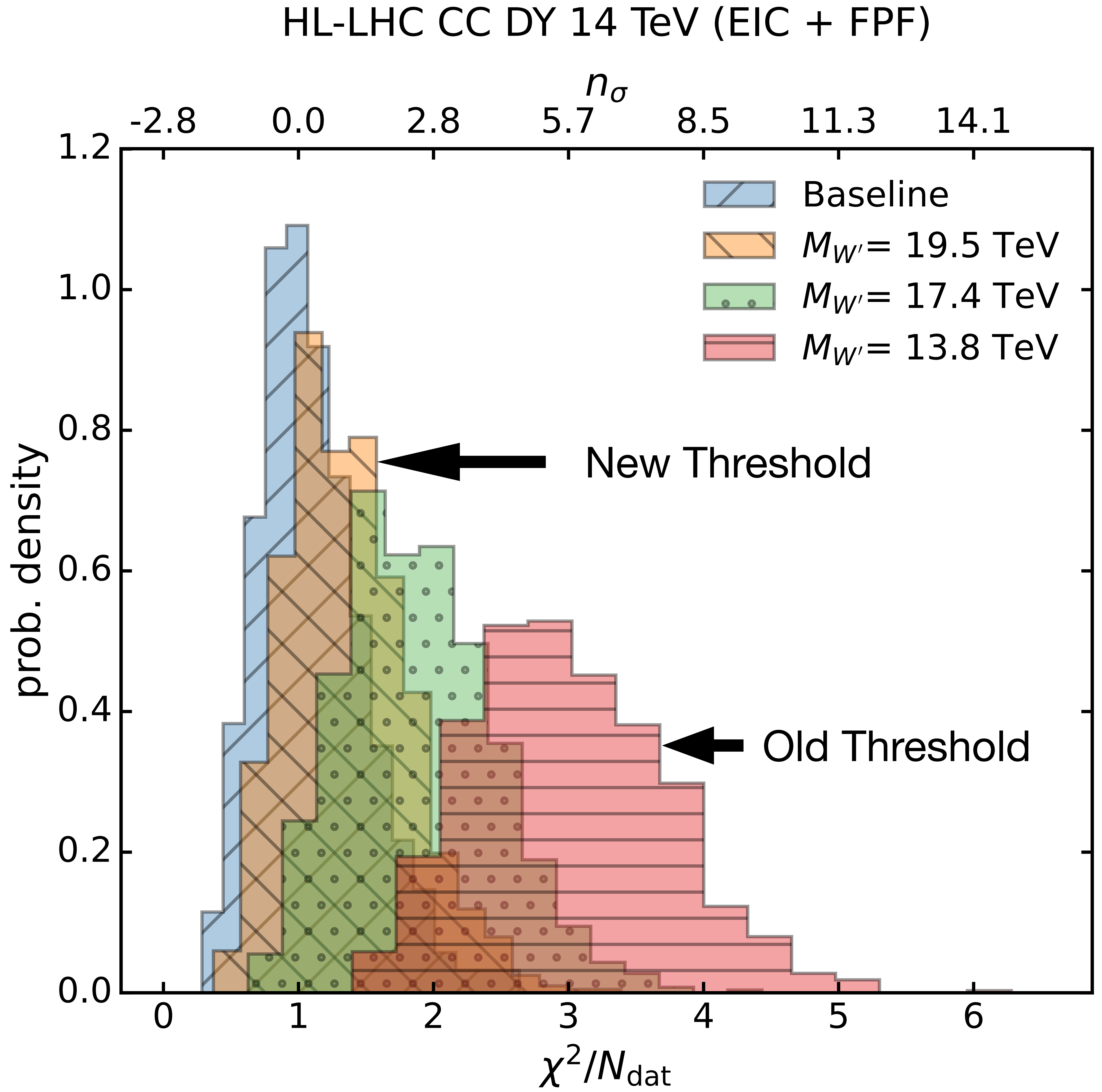
Not a complete solution:

Smaller deviations can still be absorbed

➡ risk at higher BSM mass

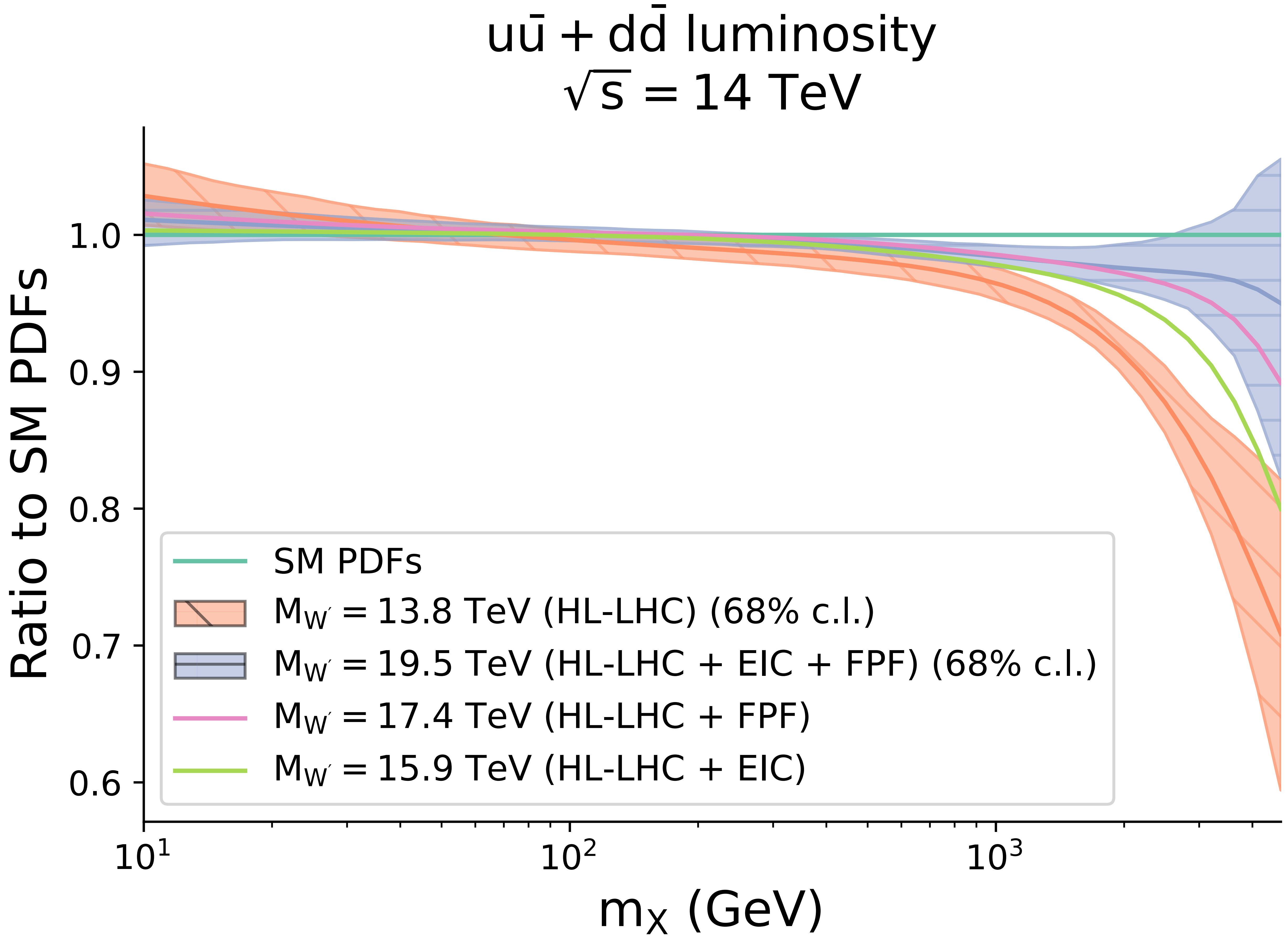
Reduction of the “blindspot”:

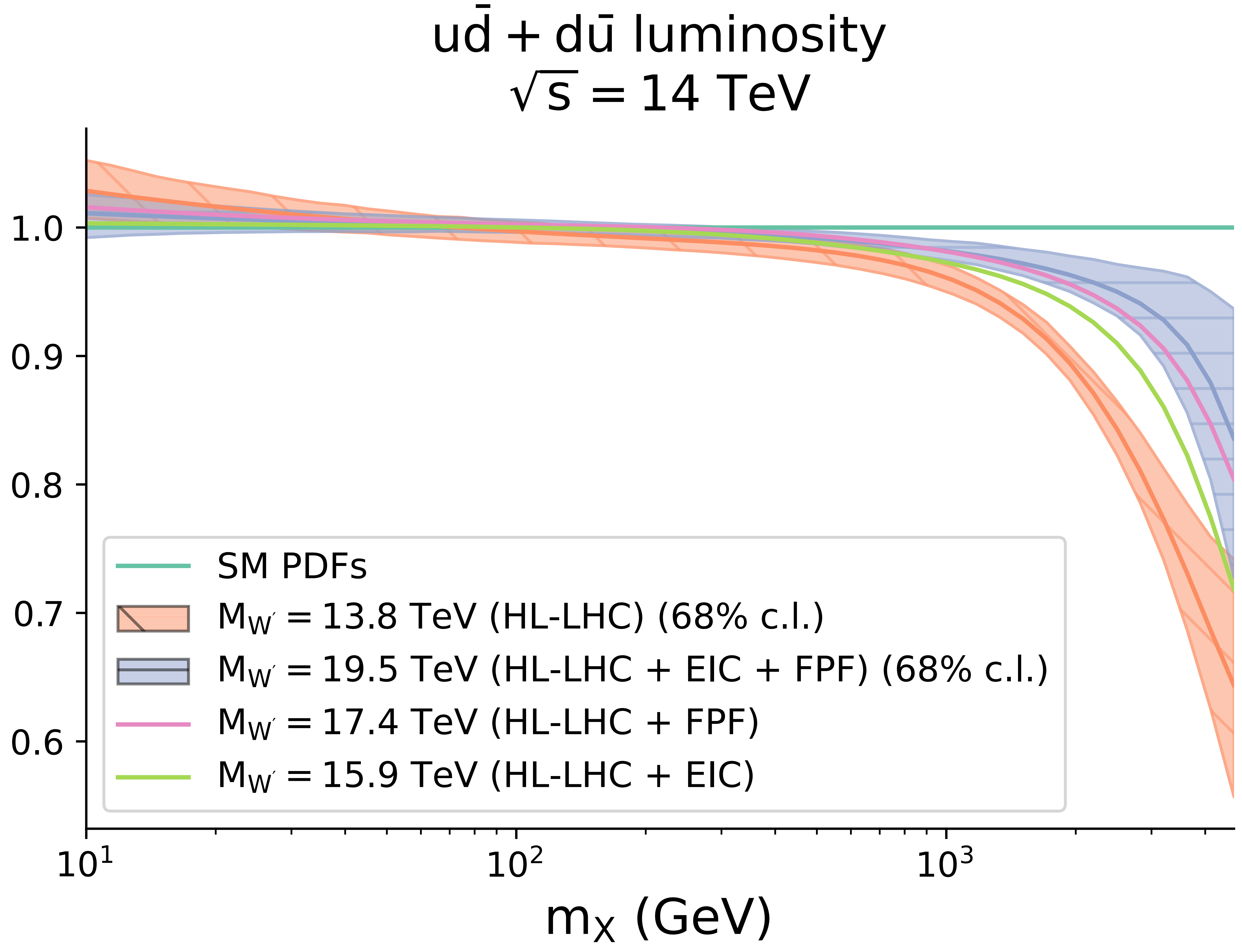
$M_{W'}$: 13.8 → 19.5 TeV



Shift of the contamination threshold

Impact on PDF luminosities





Adding large-x low-energy data: summary

- Adding data from future colliders:
  - Electron Ion Collider (EIC)
  - Forward Physics Facility (FPF)

- Impact on PDF contamination:
  - Solves situation we showed initially
  - Moves contamination threshold to higher energies

Simultaneous fit of PDF and new physics

Separate versus simultaneous fits

Separate fits

PDF fit:

$$T(\{\theta\}, \{c = 0\}) = \text{PDF}(\{\theta\}) \otimes \hat{\sigma}(\{c = 0\})$$

$\rightarrow \bar{\theta}$

Assumes SM:
source of contamination

SMEFT fit:

$$T(\{\theta = \bar{\theta}\}, \{c\}) = \text{PDF}(\{\theta = \bar{\theta}\}) \otimes \hat{\sigma}(\{c\})$$

$\rightarrow \bar{c}$

Simultaneous fits

$$T(\{\theta\}, \{c\}) = \text{PDF}(\{\theta\}) \otimes \hat{\sigma}(\{c\})$$

$\rightarrow \{\bar{\theta}, \bar{c}\}$

Removes assumption-based bias

Simultaneous fit of PDF and new physics

Presentation of the tool: SIMUnet

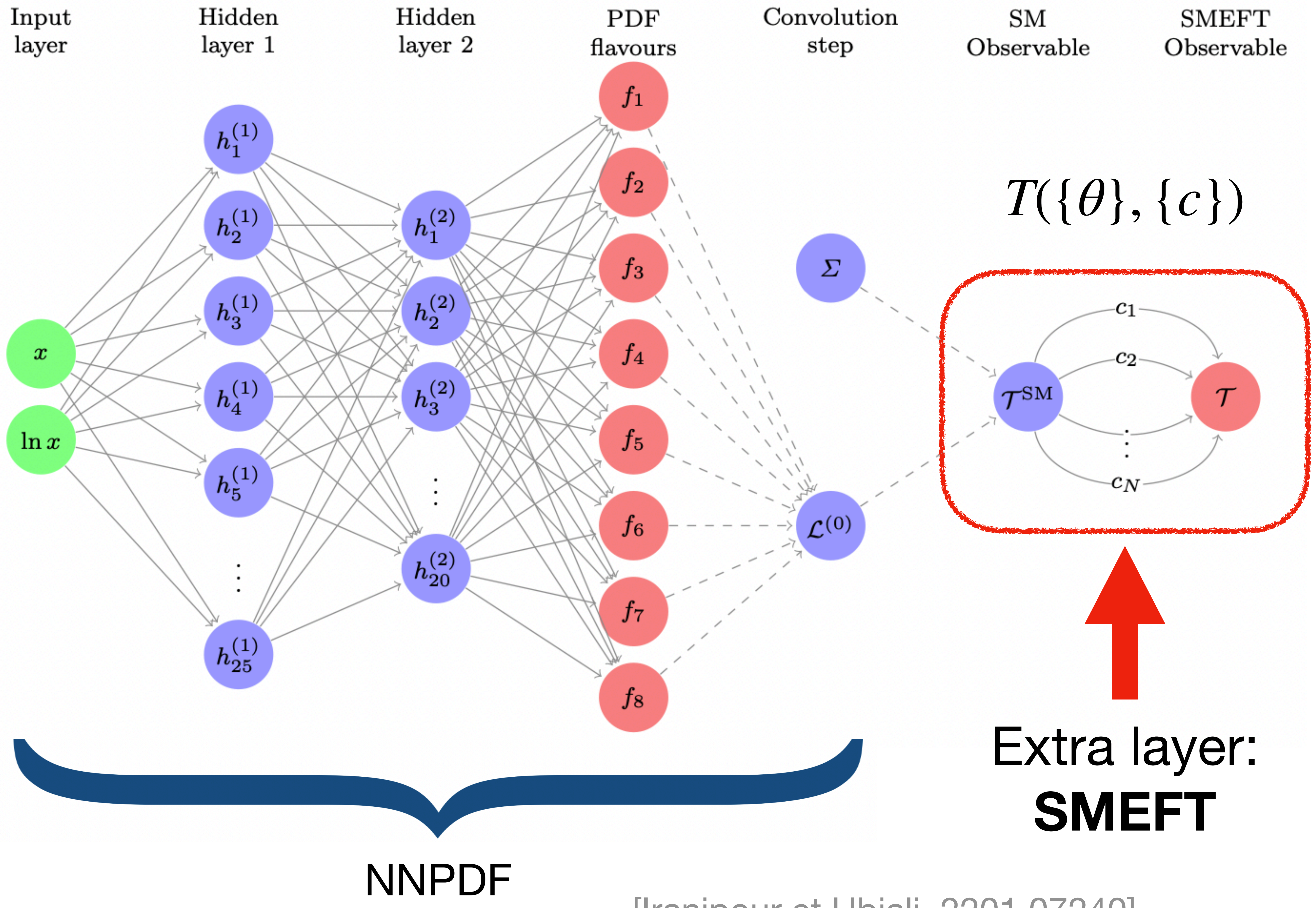
<u>SIMUnet:</u>

- Open-source tool:
  github.com/HEP-PBSP/SIMUnet

  [PBSP, 2402.03308]

- Fits PDFs and WC simultaneously

- Performs contaminated PDF fits

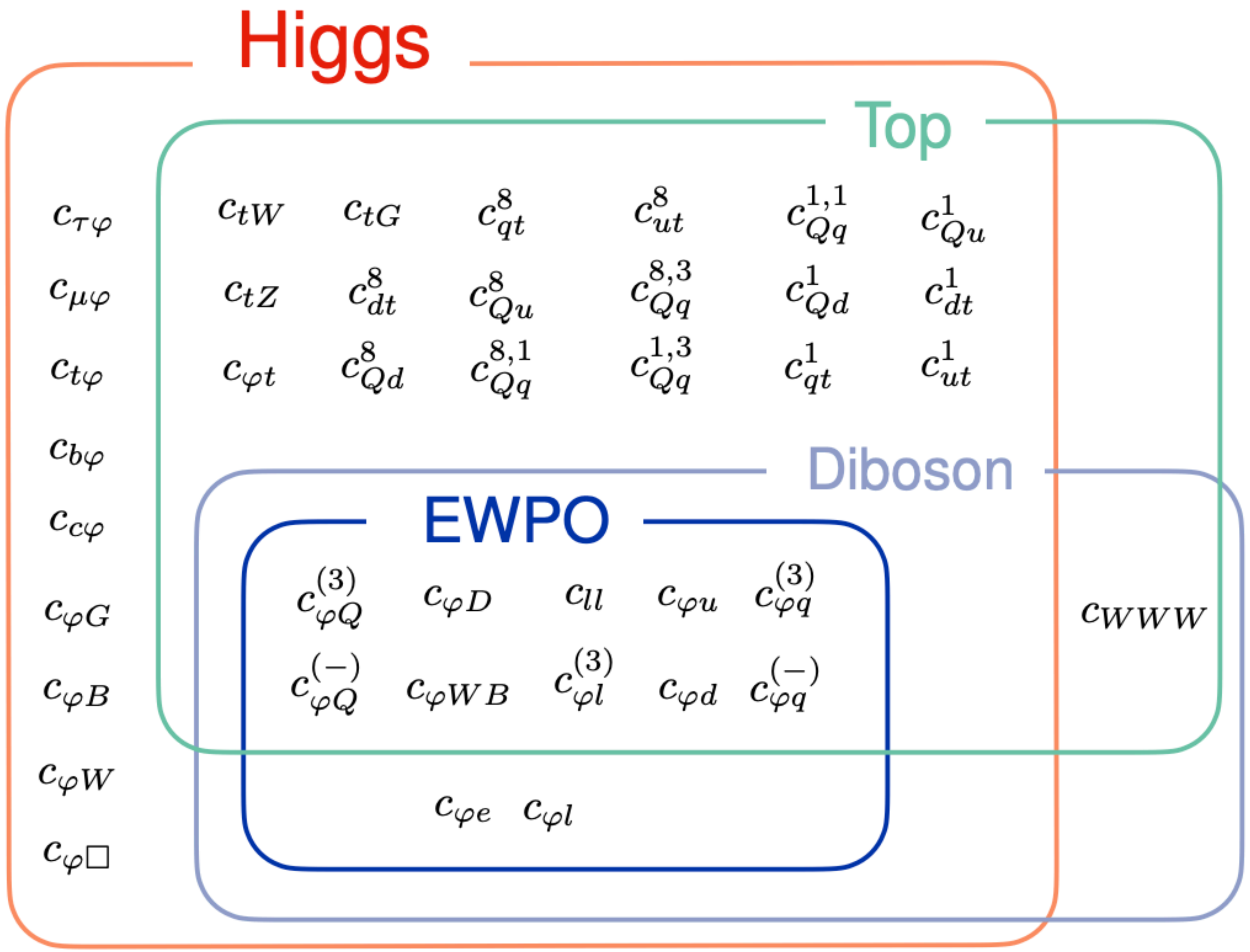


[Iranipour et Ubiali, 2201.07240]

Simultaneous fit of PDF and new physics

SMEFT operators implemented

- 40 operators implemented
- Observables:
  - top sector
  - diboson
  - Higgs
  - Drell-Yan
  - EW Precision Observables

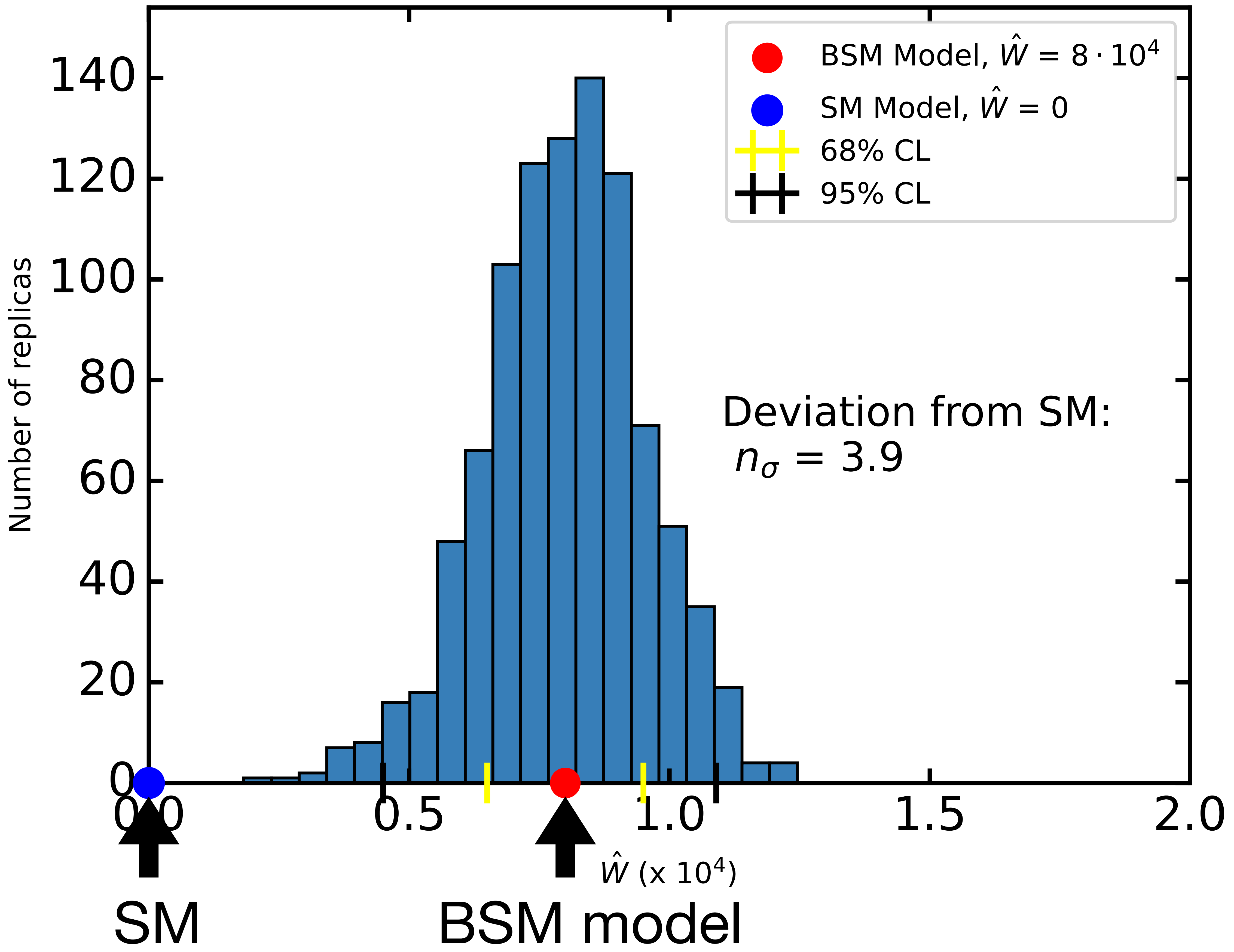


Application to the Drell-Yan sector

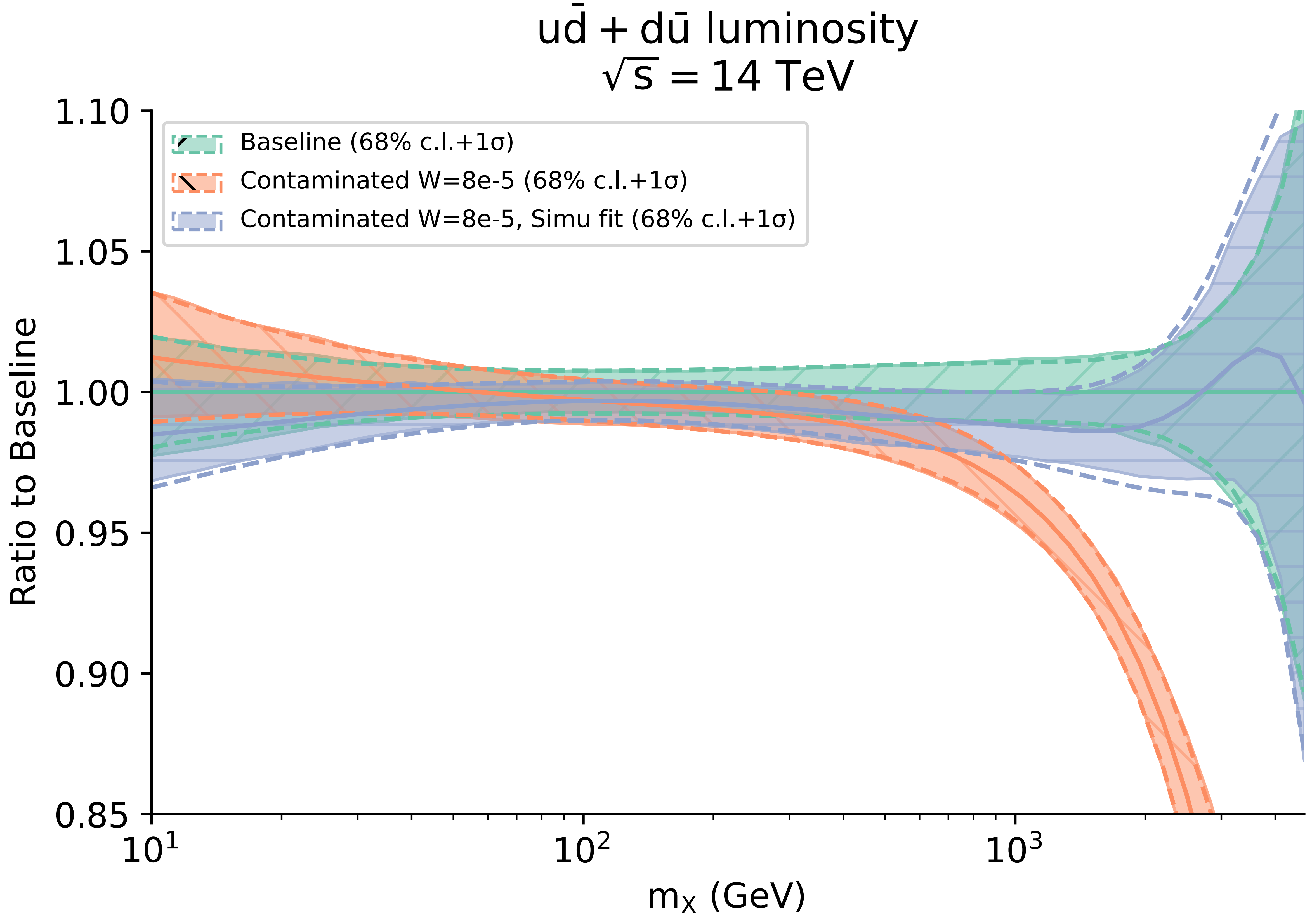
Disentangling PDF contamination

[PBSP, forthcoming]

SMEFT Fit



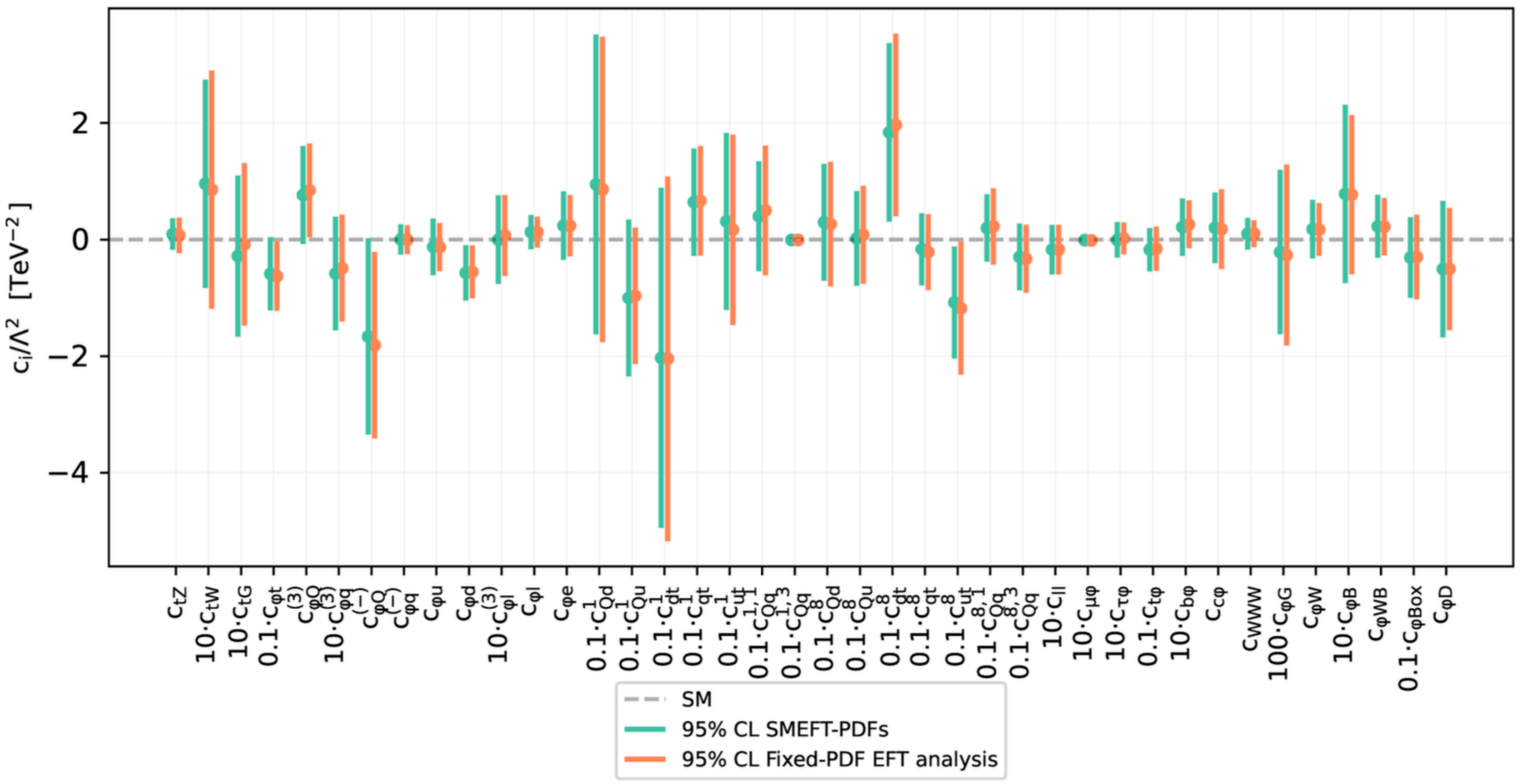
PDF Fit



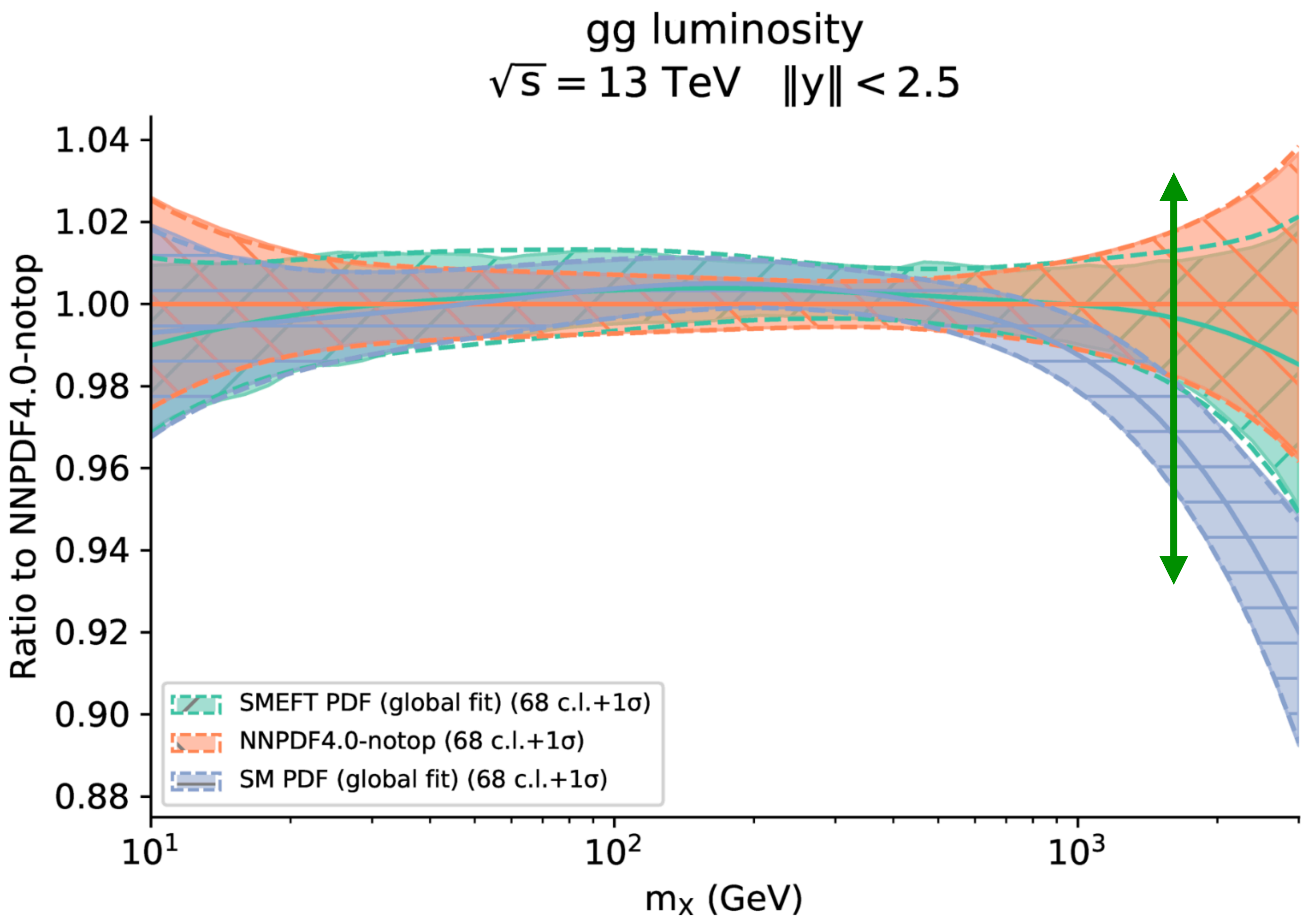
Application to the top sector (real data)

In progress

SMEFT Fit



PDF Fit



Limits of the simultaneous fits

- Technical limits:
  - Can only fit linear SMEFT corrections (fitting method)
    - Working on an alternative bayesian method
- Fundamental limits:
  - More difficult than PDF fit
  - Need to choose SMEFT operators [PBSP, forthcoming]
  - PDF still universal?

Summary and outlook

- PDF contamination: BSM model dependant
    - Not seen for Z'
    - Ongoing study for gluon sector
- Signs of W' got fitted away in PDF parametrisation
    - Missed new physics
    - Introduced fake deviations in other sectors
- Solution to prevent contamination:
    - Add precise large-x low-energy datasets into fits: FTDY, FPF, EIC…
    - Fitting simultaneously PDF and new physics: **SIMUnet** tool available

Thank you for your attention!

Extra slides

PARTON DISTRIBUTION FUNCTIONS $f_i(x,\mu)$

Perturbative QCD

$$\frac{d}{dt}\begin{pmatrix} q_i(x,t) \\ g(x,t) \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \sum_{j=q,\bar{q}} \frac{d\xi}{\xi} \begin{pmatrix} P_{ij}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{ig}\left(\frac{x}{\xi},\alpha_s(t)\right) \\ P_{gj}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{gg}\left(\frac{x}{\xi},\alpha_s(t)\right) \end{pmatrix} \otimes \begin{pmatrix} q_j(\xi,t) \\ g(\xi,t) \end{pmatrix}$$

Dokshitzer - Gribov - Lipatov - Altarelli - Parisi

DGLAP evolution equation

- Impressive progress in amplitude computations leading towards solution of DGLAP evolution equations up to N^{3}LO in perturbative QCD, plus NLO-coupled QED. Many ingredients made available, some still missing

➡ 4-loop DGLAP Splitting Functions P_{ij} to evolve PDFs

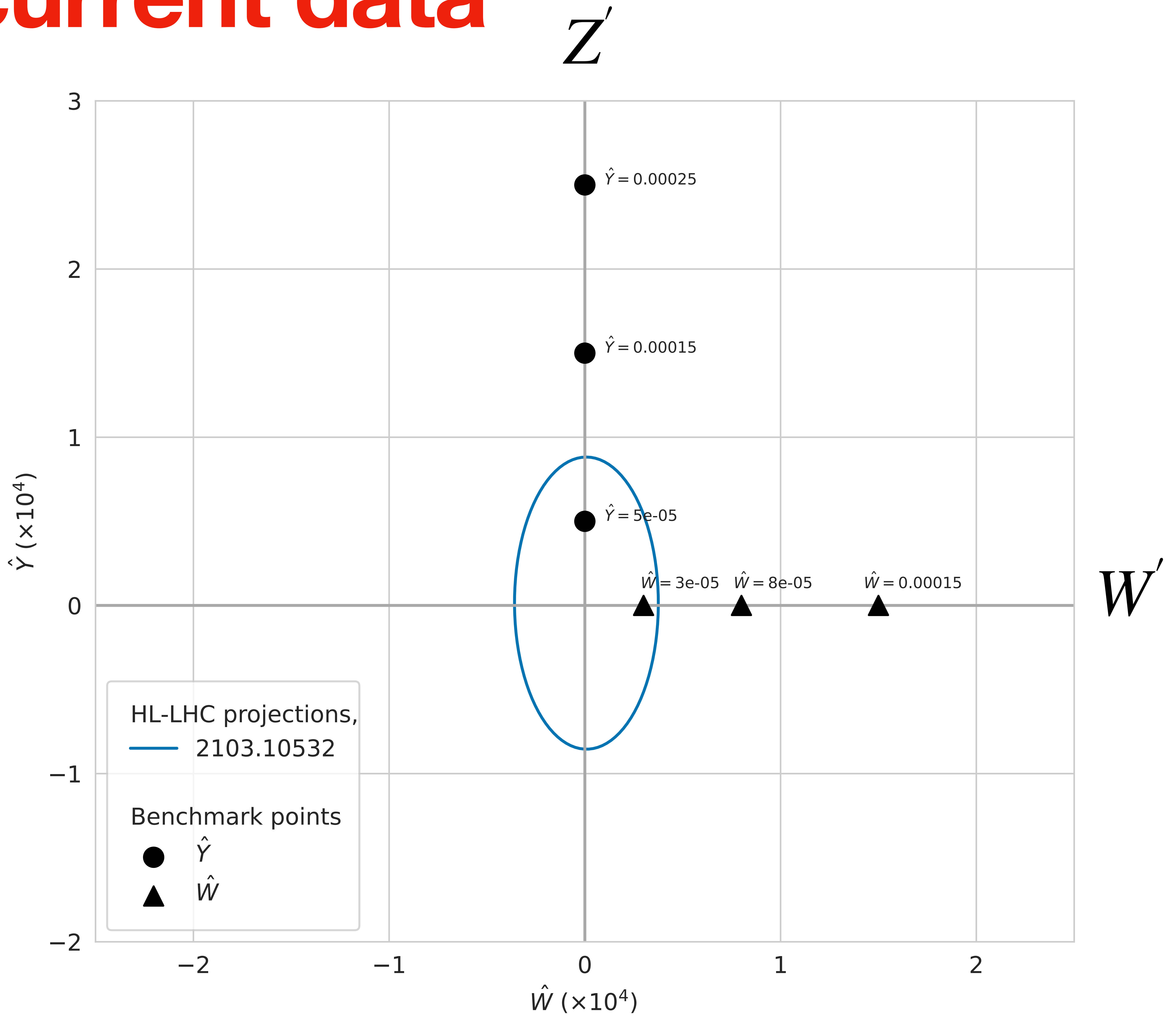
non-singlet - large n_F limit [NPB 915 (2017) 335; arXiv:2308.07958]
- small-x [JHEP 08 (2022) 135] and large-x [JHEP 10 (2017) 041] limits
- lowest 8 Mellin moments [JHEP 06 (2018) 073]

singlet - large n_F limit [NPB 915 (2017) 335; arXiv:2308.07958, arXiv:2310.01245]
- small-x [JHEP 06 (2018) 145] and large-x [NPB 832 (2010) 152; JHEP 04 (2020) 018; JHEP 09 (2022) 155] limits
- lowest 5 (10) Mellin moments [PLB 825 (2022) 136853; ibid. 842 (2023) 137944; ibid. 846 (2023) 138215]

➡ Deep Inelastic Structure Functions (hard scattering coefficient functions for DIS)
- DIS NC (massless) [NPB 492 (1997) 338; PLB 606 (2005) 123; NPB 724 (2005) 3]
- DIS CC (massless) [NPB 813 (2009) 220]
- Massive from param. combining known limits and damping functions [NPB 864 (2012) 399]

Constraints from current data

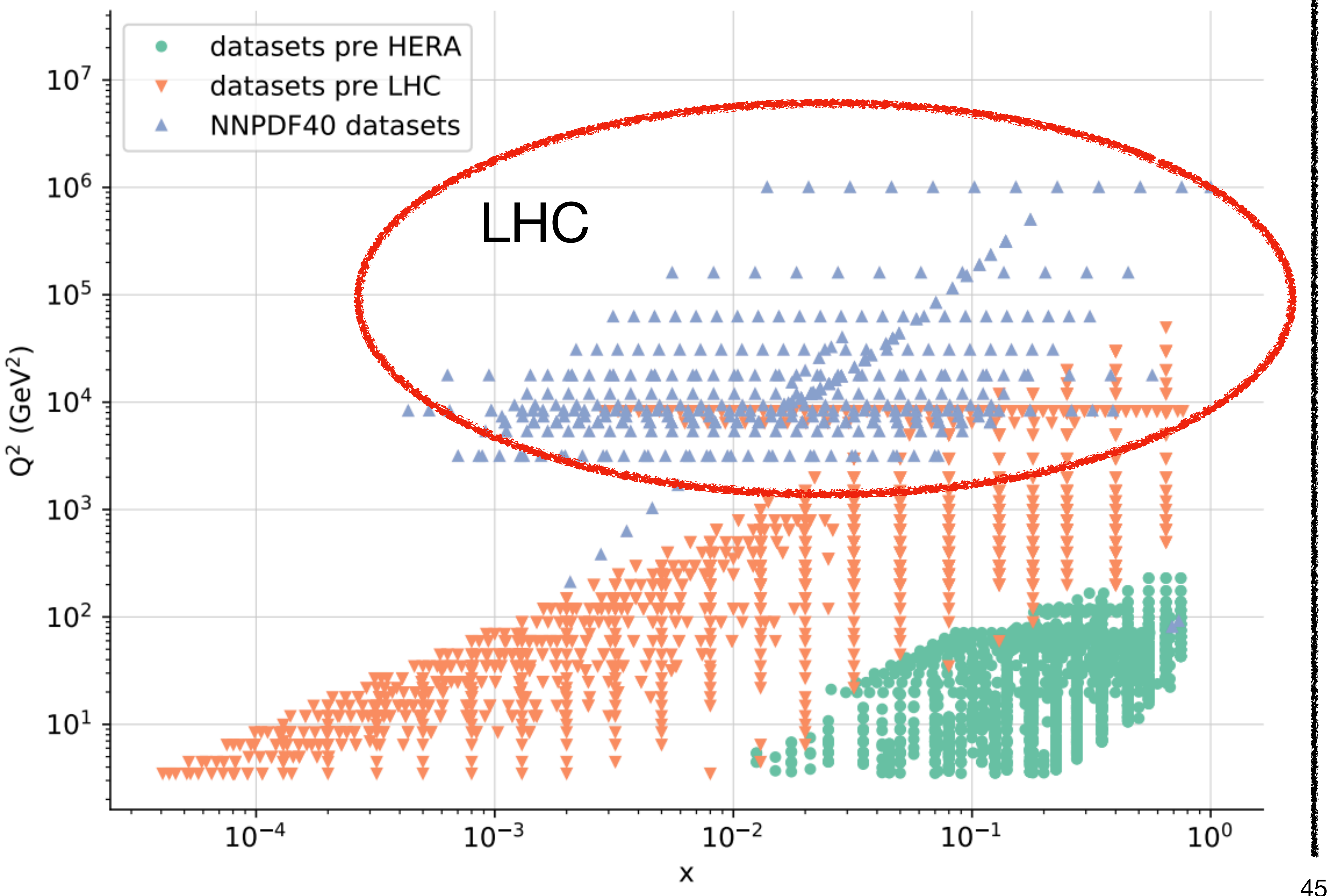
- New physics scenarios compared to constraints at 95% CL



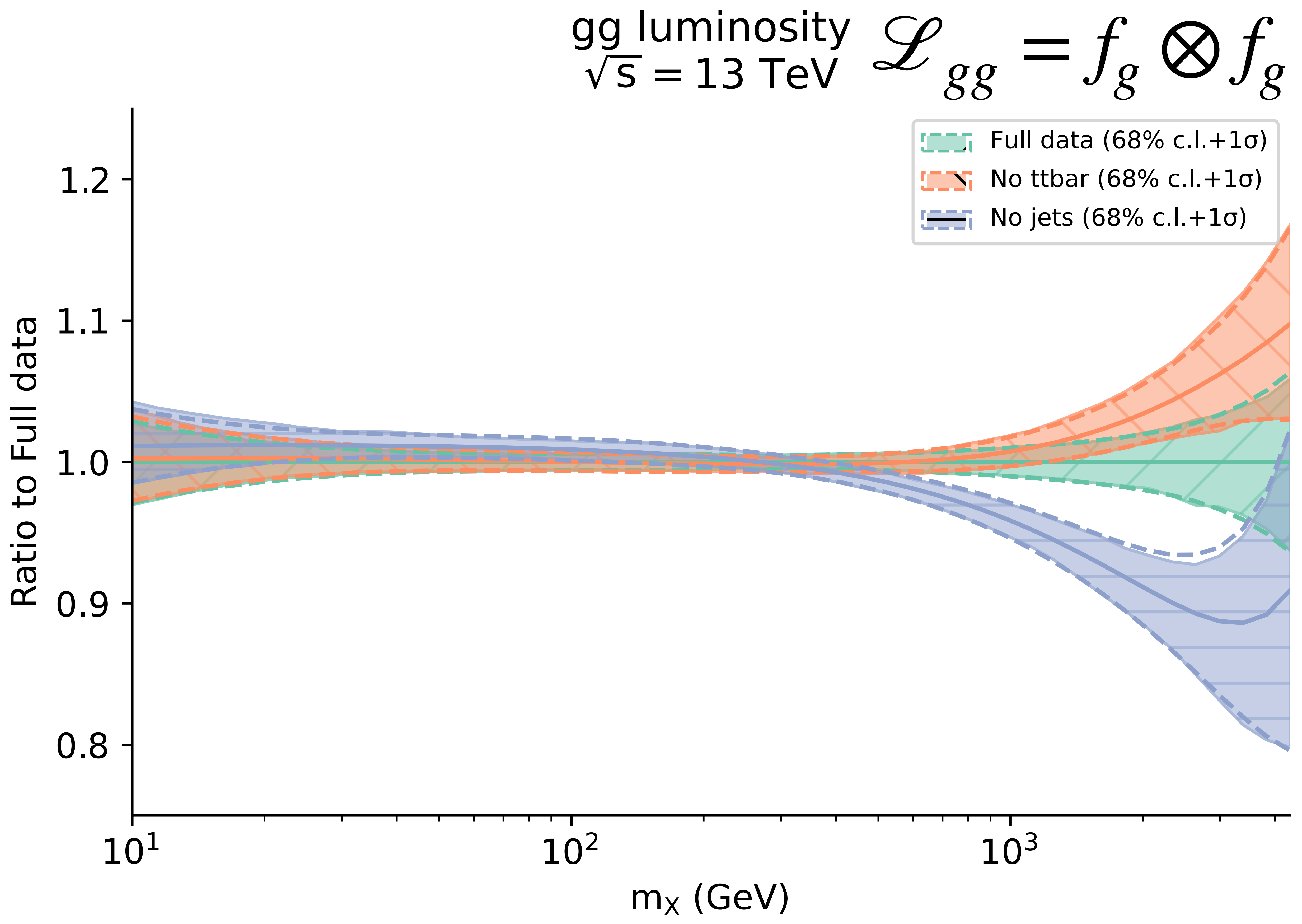
Incompatibility between top and jet data

Comparison of PDFs trained on different datasets

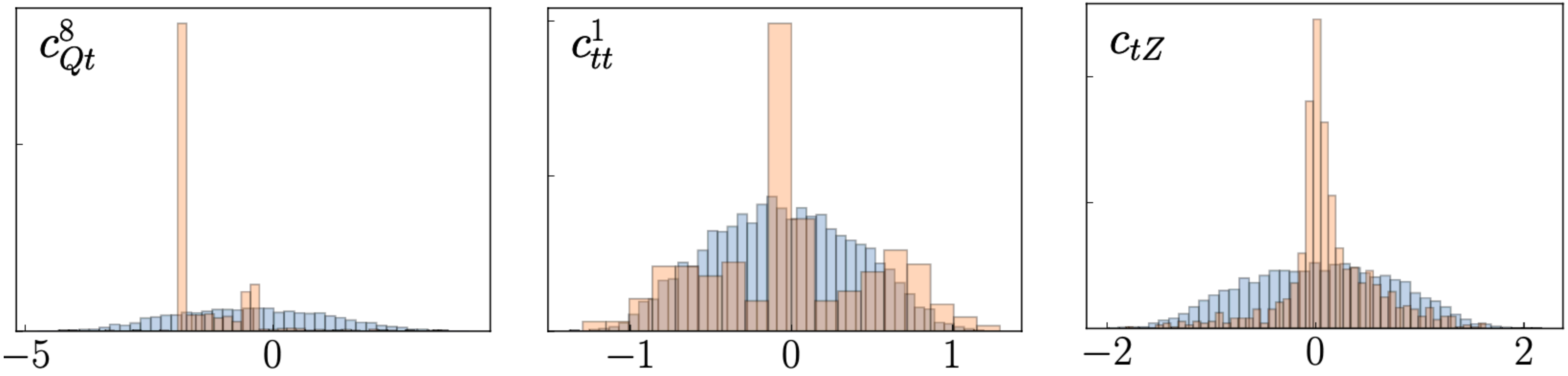
Full data kinematic coverage



PDFs' process dependance…



BEYOND MONTE CARLO AND NEURAL NETWORKS



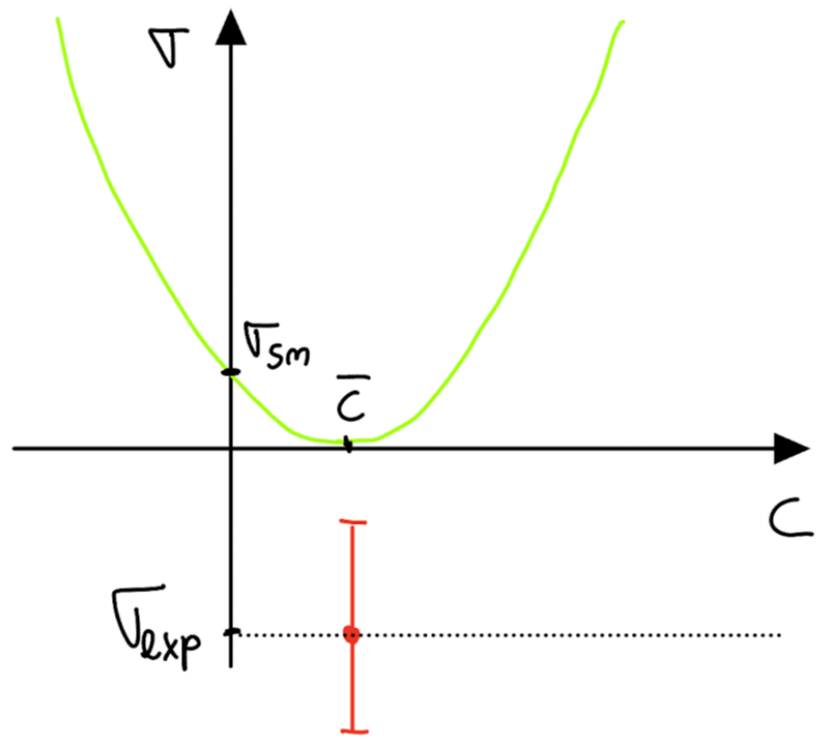
- In the quadratic SMEFT fit observed disagreement between MC method and Bayesian method. Very different posterior (hence different CLs)

- Study of MC versus Bayesian method based on nested sampling for PDF fits and SMEFT fits [Costantini, Madigan, Mantani, Moore arXiv:2404.10056]

- Towards a general Bayesian methodology for simultaneous fits [Costantini, Mantani, MU, in progress]

Let's consider a simple scenario: 1 operator, 1 datapoint

$$\chi^2 = \frac{(\sigma(c) - \sigma_{exp})^2}{\delta\sigma^2} \qquad \Delta\chi^2 = \chi^2 - \chi_{min} = 1 \quad \rightarrow \quad [c_-, c_+]$$



SIMUNET: INPUT DATA

Exp.	$\sqrt{s}$ (TeV)	Observable	$\mathcal{L}$ (fb^{-1})	n_{dat}
ATLAS and CMS	7 and 8	$\mu_{H\to\mu^+\mu^-}$	5 and 20	22
CMS	13	μ_H	35.9	24
ATLAS	13	μ_H	80	25
ATLAS	13	$\mu_{H\to Z\gamma}$	139	1
ATLAS	13	$\mu_{H\to\mu^+\mu^-}$	139	1

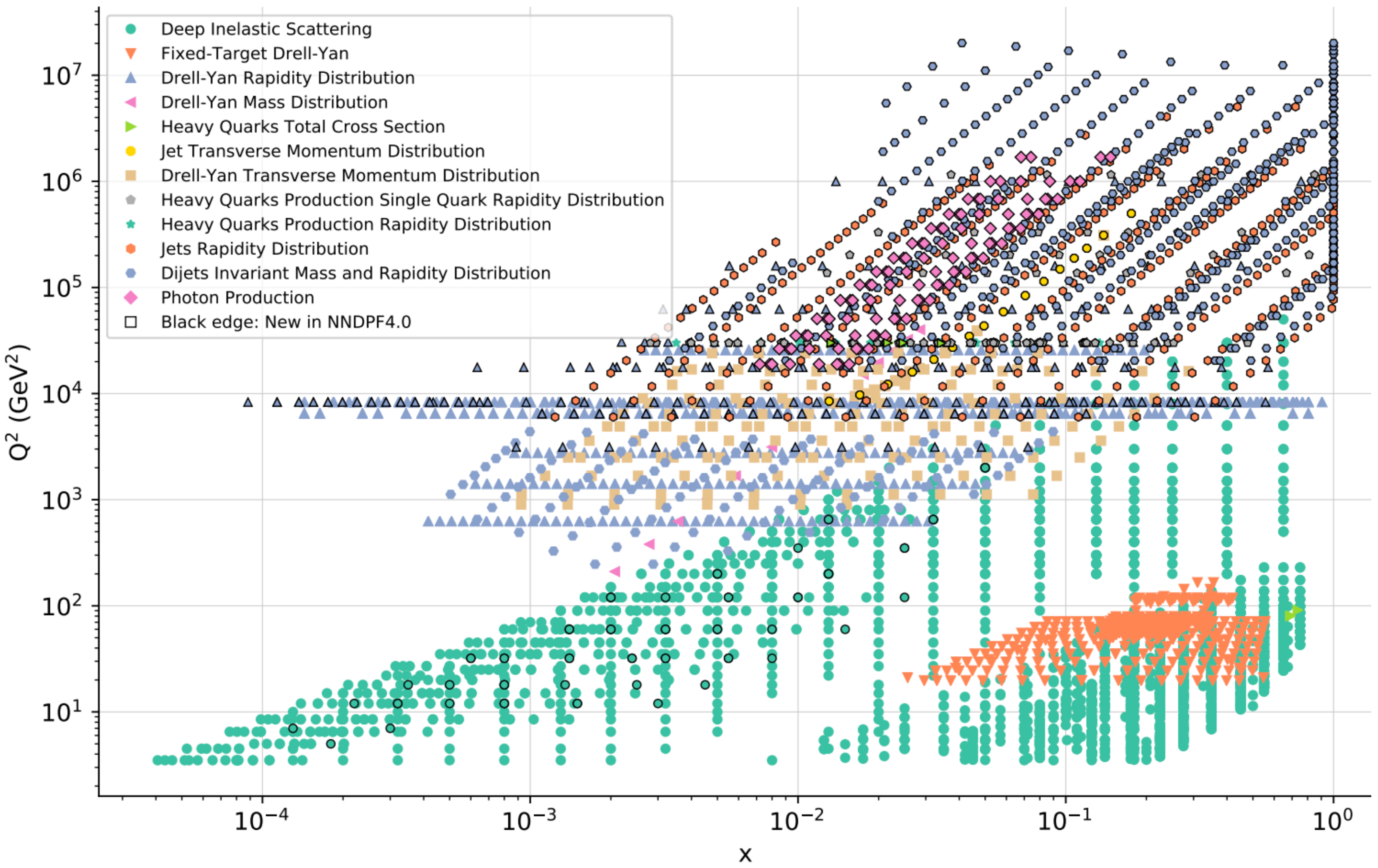
Higgs signal strength SMEFT only

Exp.	$\sqrt{s}$ (TeV)	Observable	$\mathcal{L}$ (fb^{-1})	n_{dat}
LEP	0.182	$d\sigma_{WW}/dcos(\theta_W)$	0.164	10
LEP	0.189	$d\sigma_{WW}/dcos(\theta_W)$	0.588	10
LEP	0.198	$d\sigma_{WW}/dcos(\theta_W)$	0.605	10
LEP	0.206	$d\sigma_{WW}/dcos(\theta_W)$	0.631	10
ATLAS	13	$d\sigma_{W^+W^-}/dm_{e\mu}$	36.1	13
ATLAS	13	$d\sigma_{WZ}/dm_T$	36.1	6
ATLAS	13	$d\sigma(Zjj)/d\Delta\phi_{jj}$	139	12
CMS	13	$d\sigma_{WZ}/dp_T$	35.9	11

Di-boson SMEFT only

Exp.	$\sqrt{s}$ (TeV)	Observable	$\mathcal{L}$ (fb^{-1})	n_{dat}
LEP	0.250	Z observables		19
LEP	0.196	$\mathcal{B}(W\to l^-\bar{v}_l)$	3	3
LEP	0.189	$\sigma(e^+e^-\to e^+e^-)$	3	21
LEP	0.209	$\hat{\alpha}^{(5)}(M_Z)$	3	1

EWPO SMEFT only

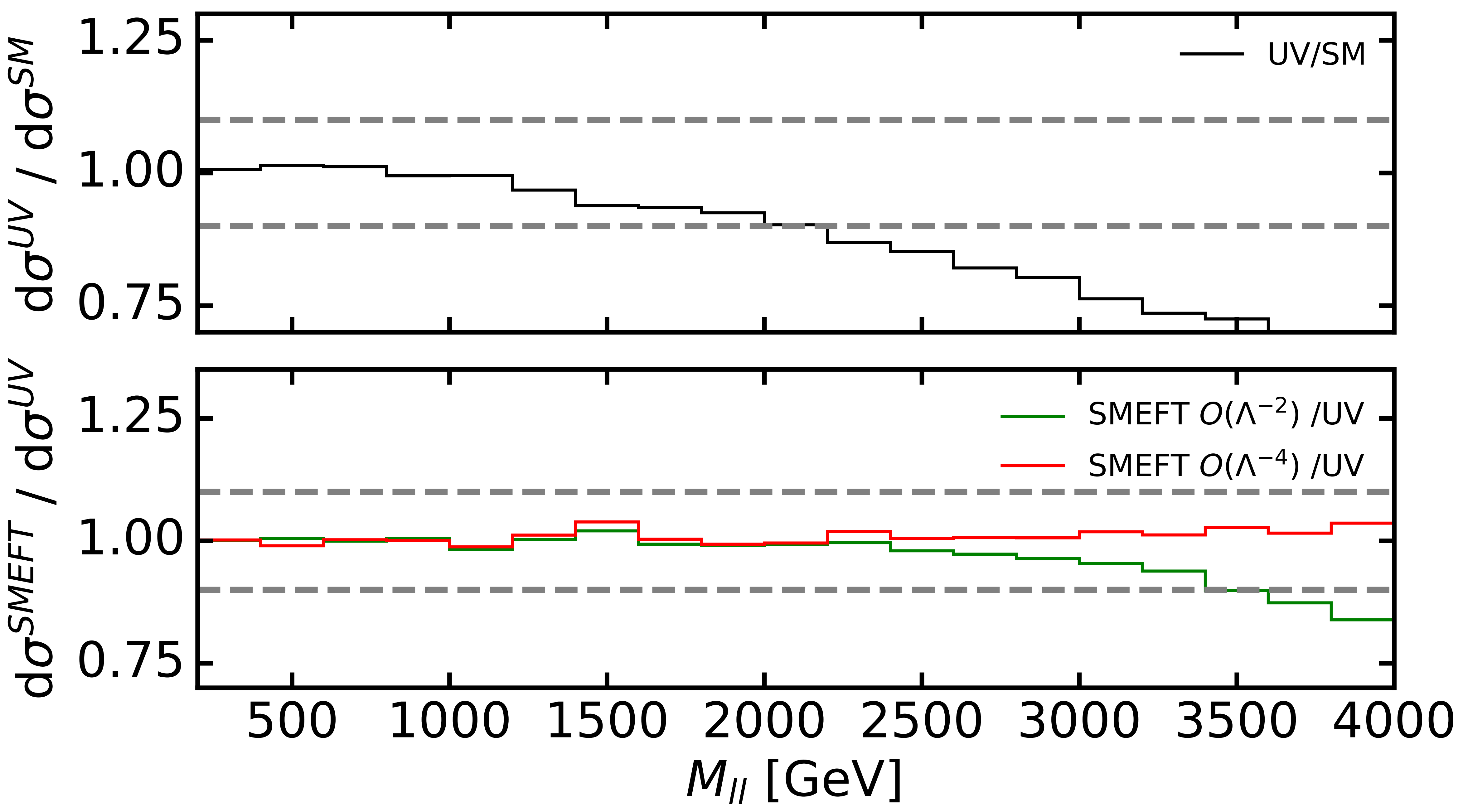


Total of ~ 5000 input datapoints, some constraining only SMEFT, some only PDFs, some both SMEFT & PDFs

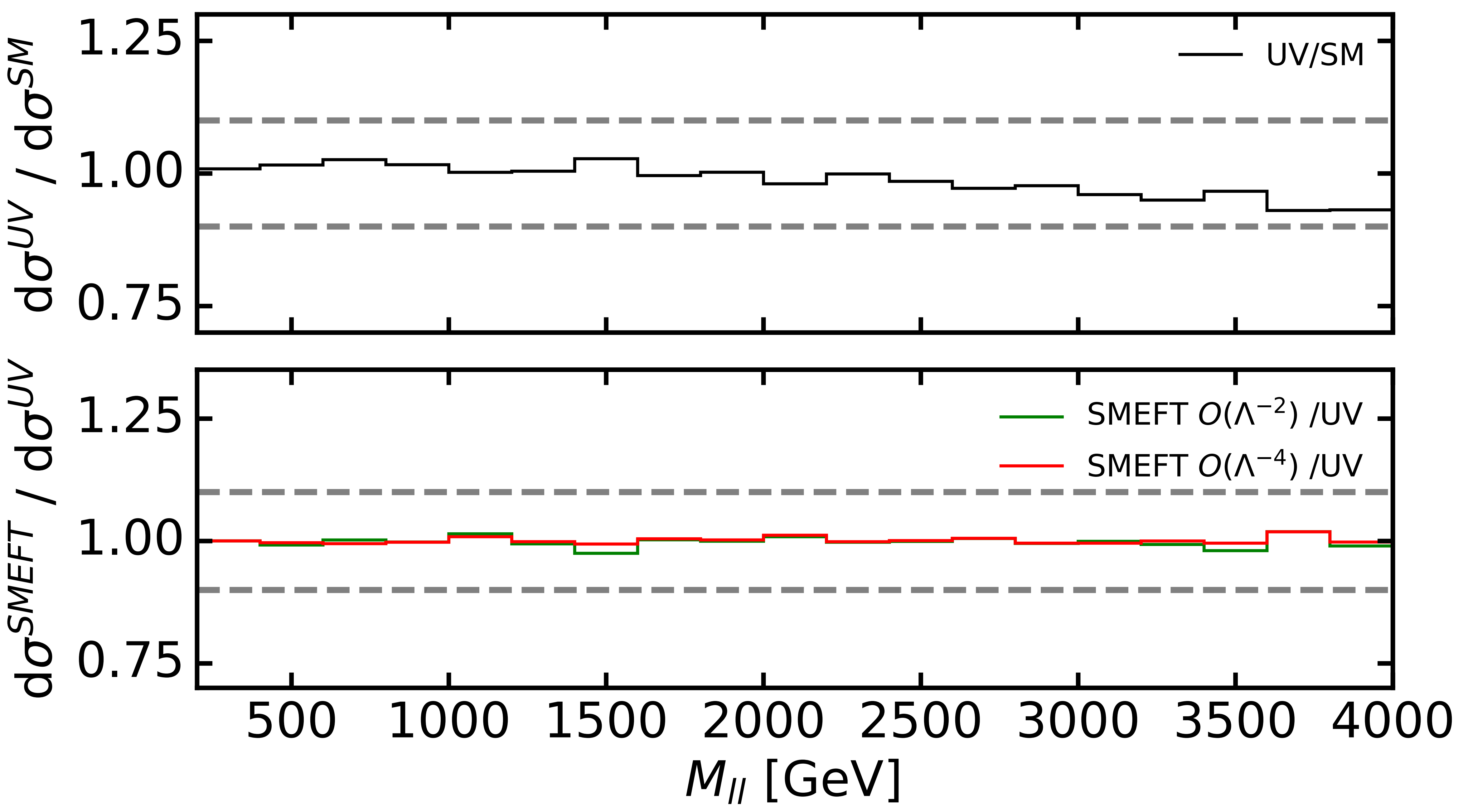
+O(4000) data from DIS, DY, jets, di-jets, W and Z production, Z pT - PDF only

New physics scenarios: Z'

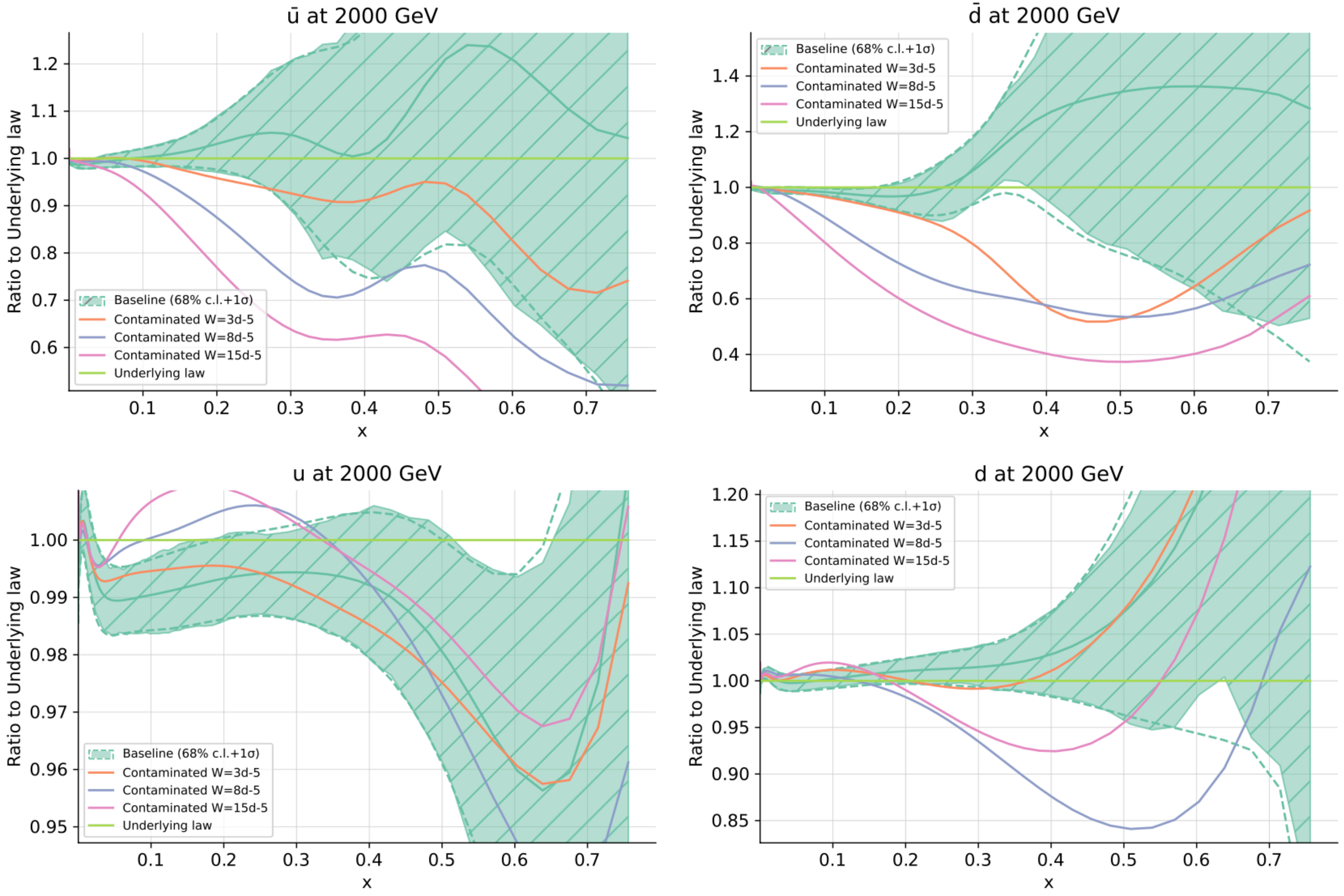
$M_{Z'} = 14.5$ TeV



$M_{Z'} = 32.5$ TeV



Quarks PDF


ū at 2000 GeV
Ratio to Underlying law
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x
Baseline (68% c.l.+1σ)
Contaminated W=3d-5
Contaminated W=8d-5
Contaminated W=15d-5
Underlying law
d̄ at 2000 GeV
Ratio to Underlying law
1.4
1.2
1.0
0.8
0.6
0.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x
Baseline (68% c.l.+1σ)
Contaminated W=3d-5
Contaminated W=8d-5
Contaminated W=15d-5
Underlying law
u at 2000 GeV
Ratio to Underlying law
1.00
0.99
0.98
0.97
0.96
0.95
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x
Baseline (68% c.l.+1σ)
Contaminated W=3d-5
Contaminated W=8d-5
Contaminated W=15d-5
Underlying law
d at 2000 GeV
Ratio to Underlying law
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x
Baseline (68% c.l.+1σ)
Contaminated W=3d-5
Contaminated W=8d-5
Contaminated W=15d-5
Underlying law

List of deviations

	HL-LHC		Stat. improved	
Dataset	χ^2/n_{dat}	n_σ	χ^2/n_{dat}	n_σ
W^+H	1.17	0.41	1.77	1.97
W^-H	1.08	0.19	1.08	0.19
W^+Z	1.08	0.19	1.49	1.20
W^-Z	0.99	-0.03	1.02	0.05
ZH	1.19	0.44	1.67	1.58
W^+W^-	2.19	3.04	2.69	4.31
VBF $\rightarrow$ H	0.70	-0.74	0.62	-0.90