Hide and seek: how PDFs can conceal new physics

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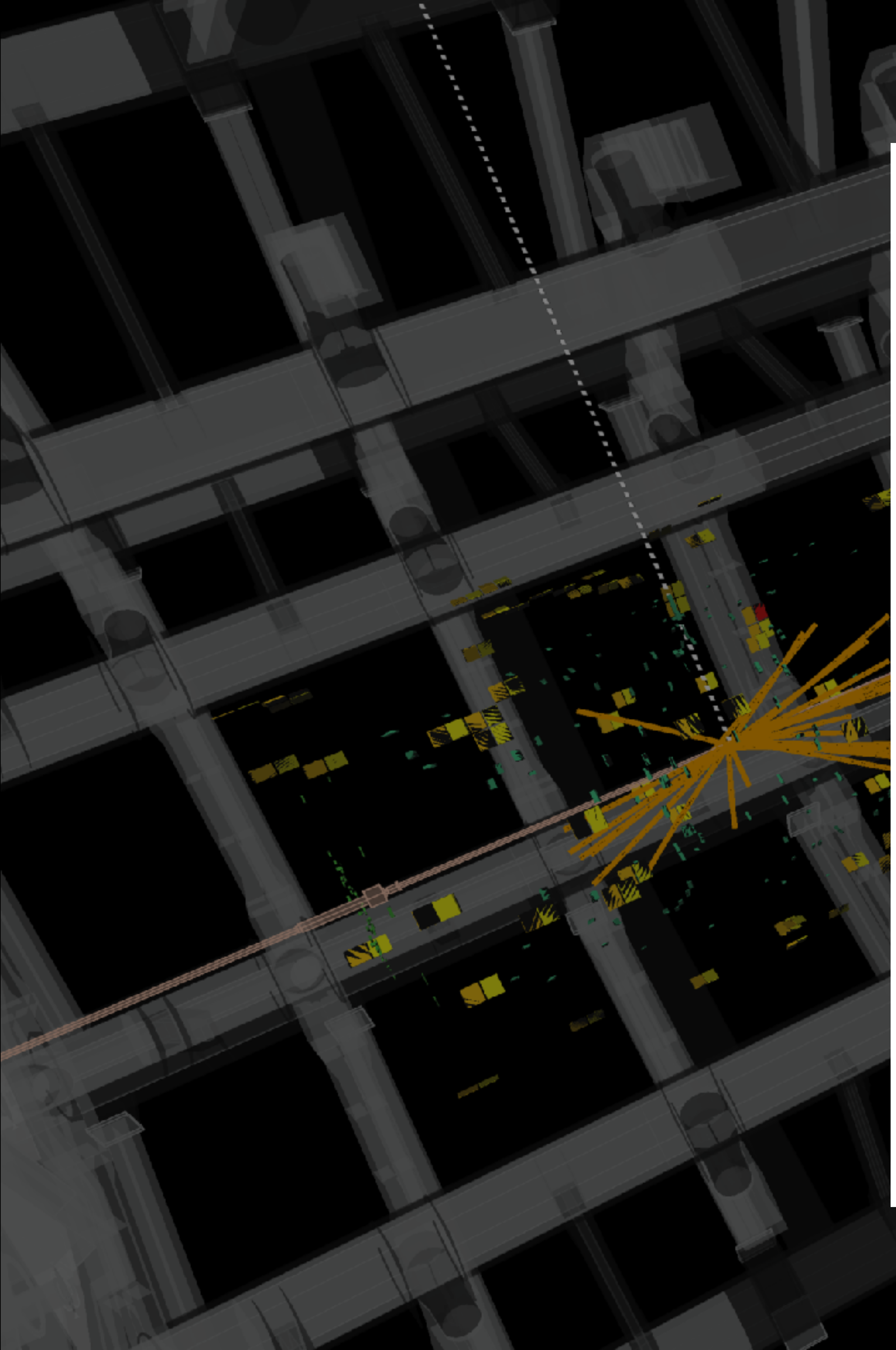
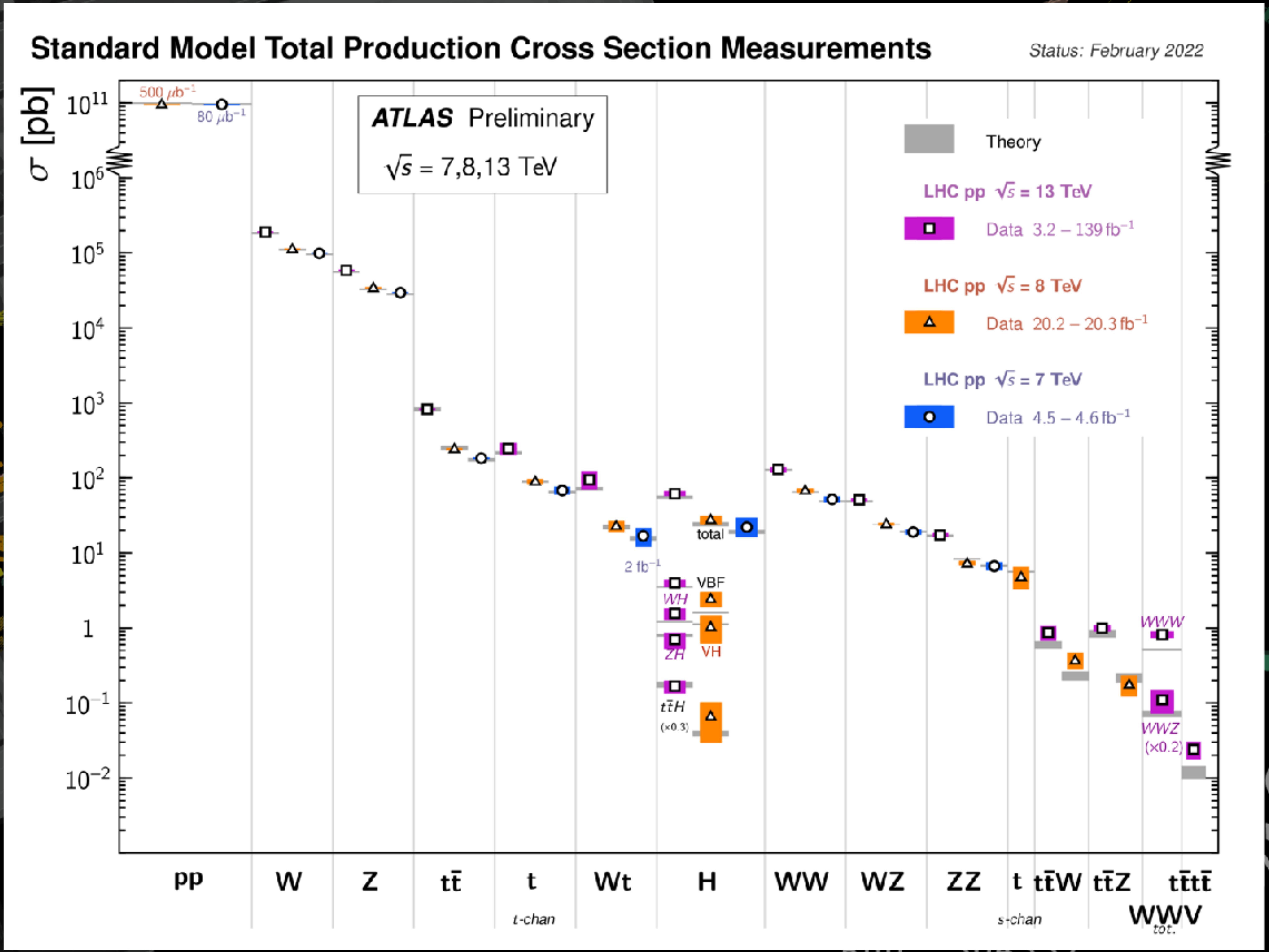
CP3, Université catholique de Louvain, 16.04.24

Data driven era of particle physics

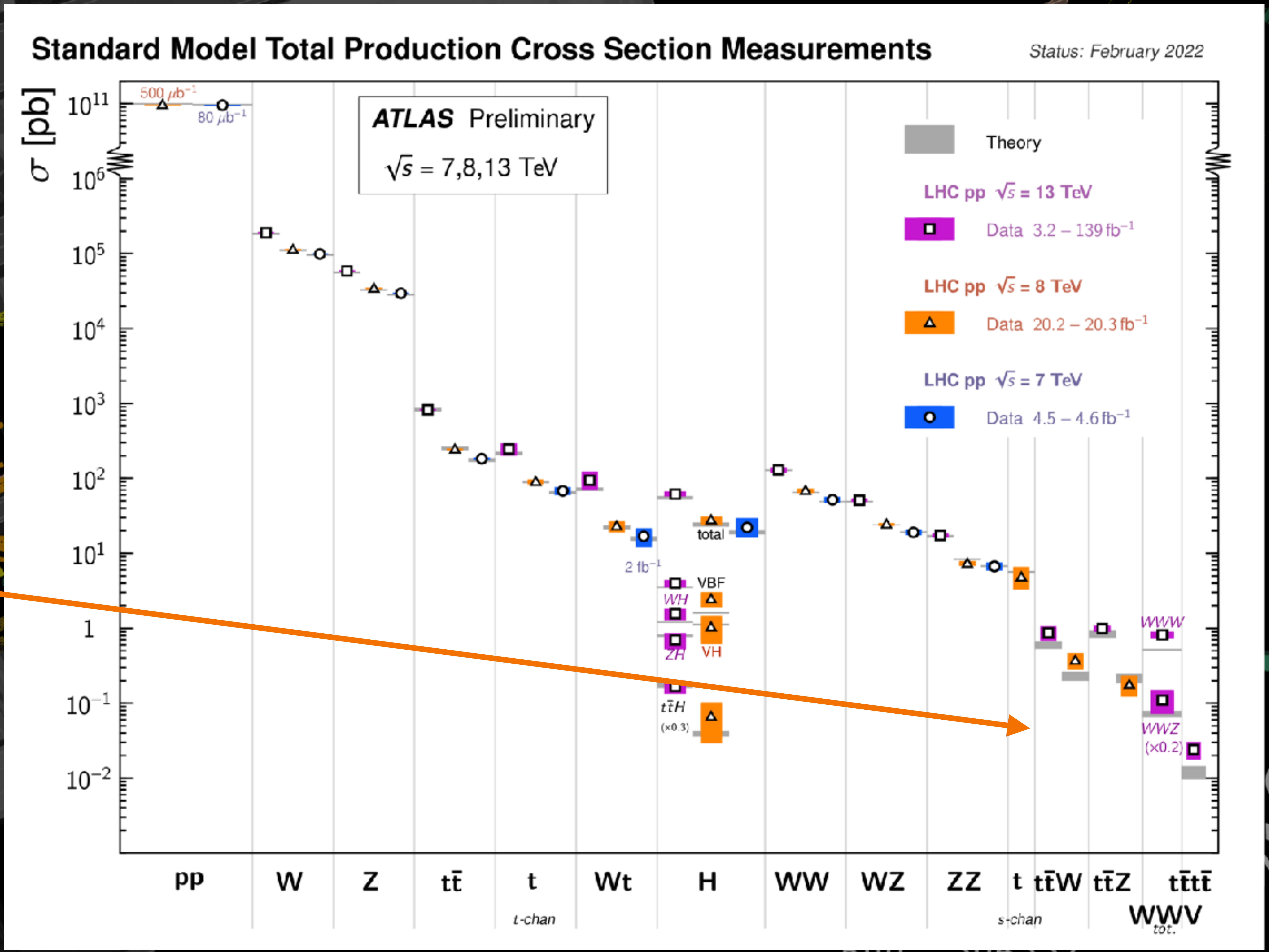
vast quantity of data → precision measurements


Event: 588288156
2016-07-23 19:55:07 CES


Standard Model Total Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
$\sqrt{s}$ = 7,8,13 TeV
σ [pb]
Theory
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 139 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.6 fb^{-1}
500 μb^{-1}
80 μb^{-1}
2 fb^{-1}
total
VBF
WH
ZH
VH
$t\bar{t}H$
(×0.3)
WWW
WWZ
(×0.2)
pp
W
Z
$t\bar{t}$
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
$t\bar{t}W$
$t\bar{t}Z$
$t\bar{t}t\bar{t}$
WWV
tot.

Agreement between data and the Standard Model

New channels probed in Run II



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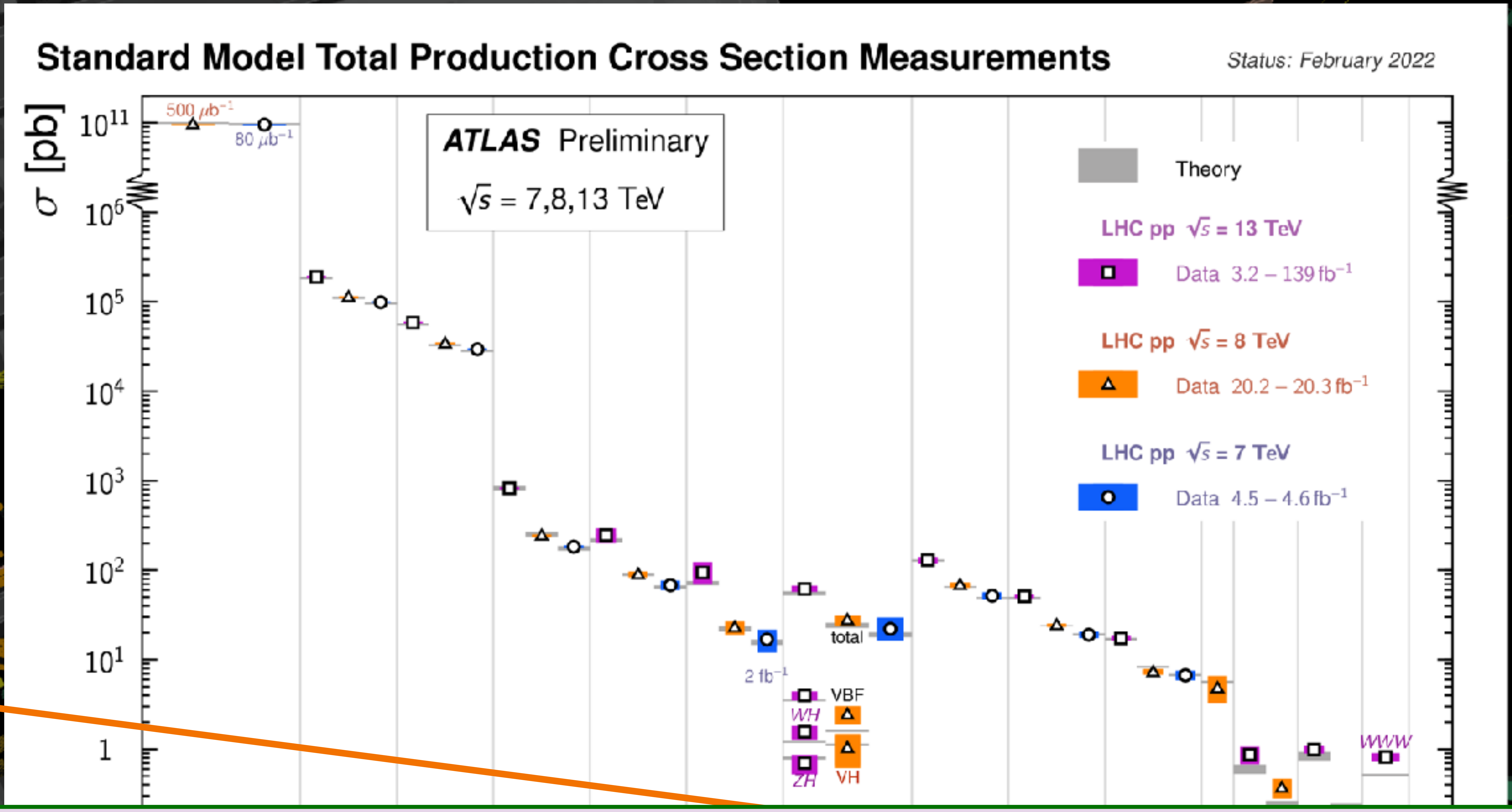


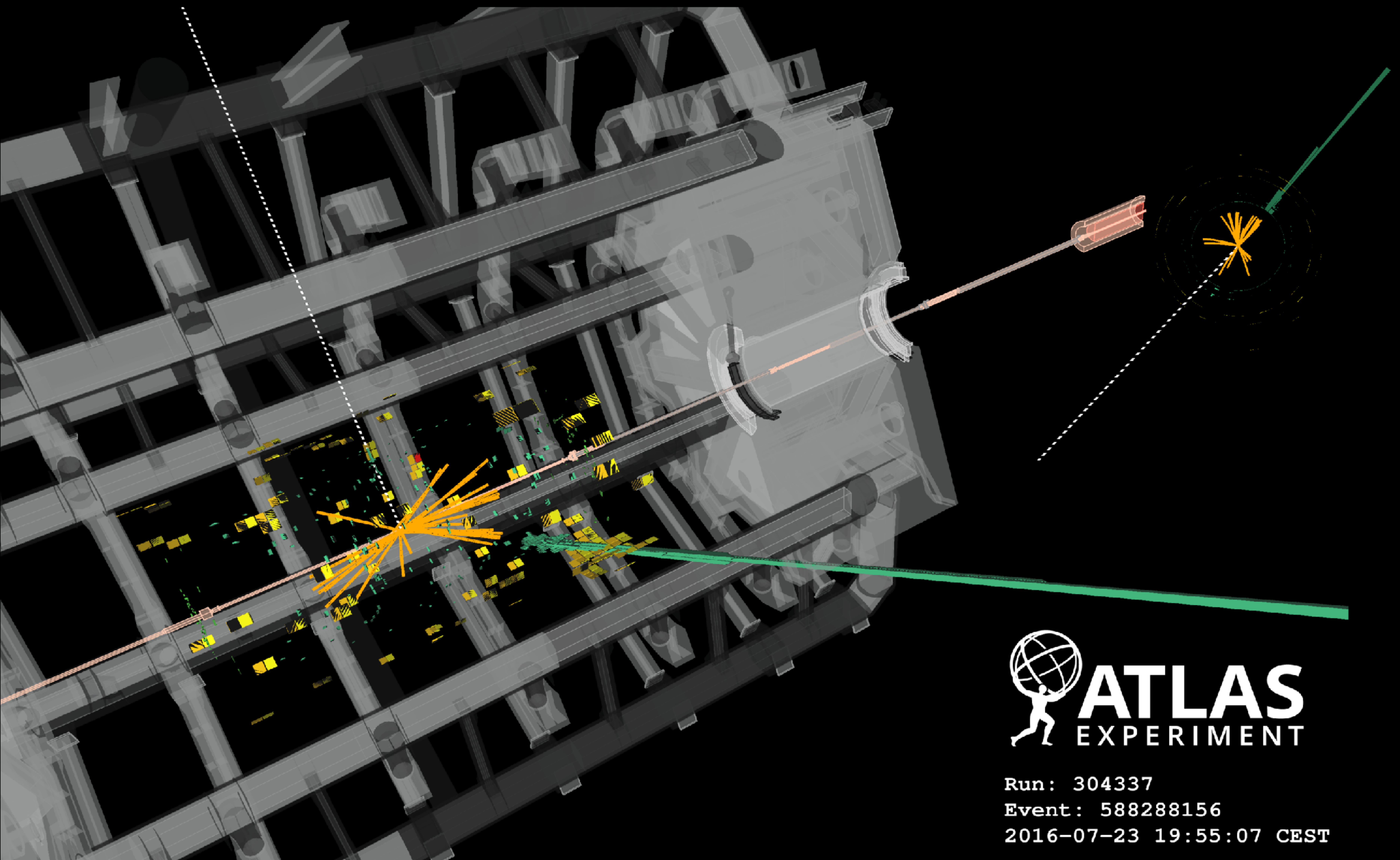
Where is the new physics beyond the Standard Model?

Evidence comes from neutrino oscillations, dark matter, ….

Event: 588288156
2016-07-23 19:55:07 CES

ATLAS Search for a new heavy gauge boson decaying into a lepton + missing transverse momentum

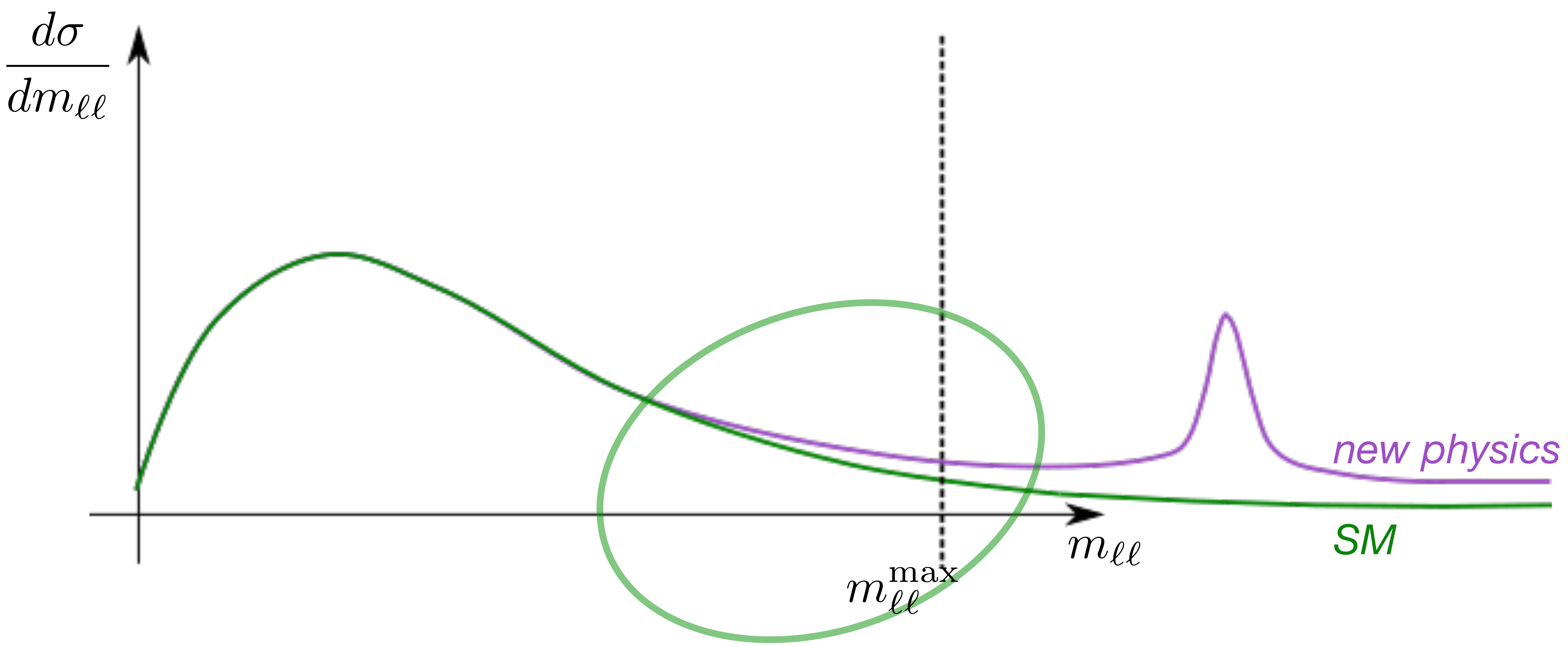
1706.04786



W or W’ ?

Indirect searches for new physics

Could BSM particles be heavy and out of reach? $\Lambda_{\mathrm{NP}} \gg E$



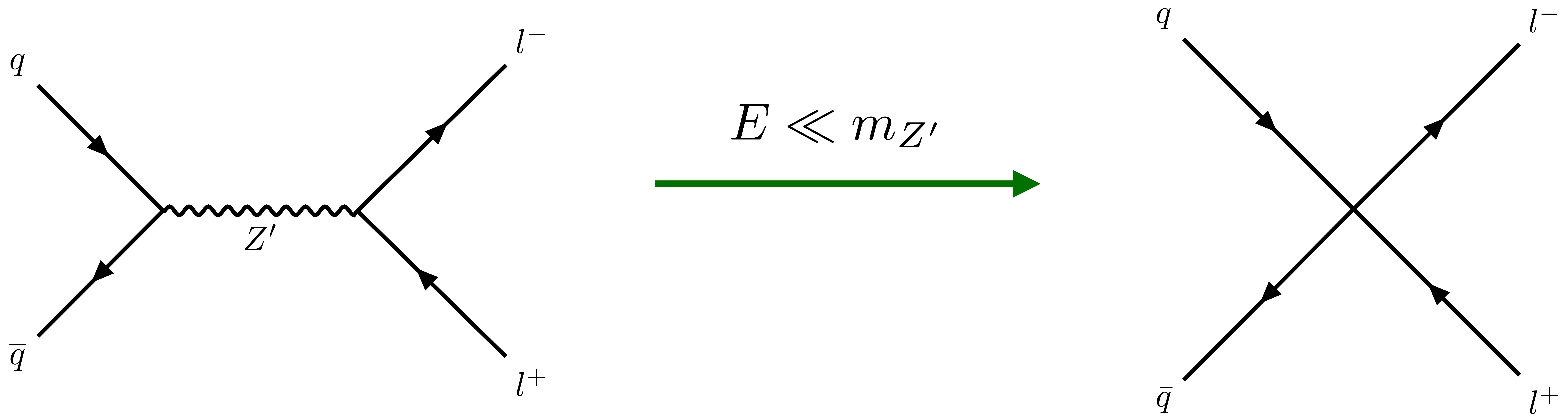
Indirect searches benefit from **precision** measurements.

e.g. high-mass Drell-Yan tails

The Standard Model Effective Field Theory

Assume new physics is **heavy**: $\Lambda \gg E$

Integrate out the new physics particle to obtain interactions of the SM fields.



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Assume **SM symmetries** continue to hold and write down all possible interactions of **SM fields:**

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{C^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

Compute observables as a systematically improvable expansion in E/Λ

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this talk

Compute observables as a systematically improvable expansion in E/Λ

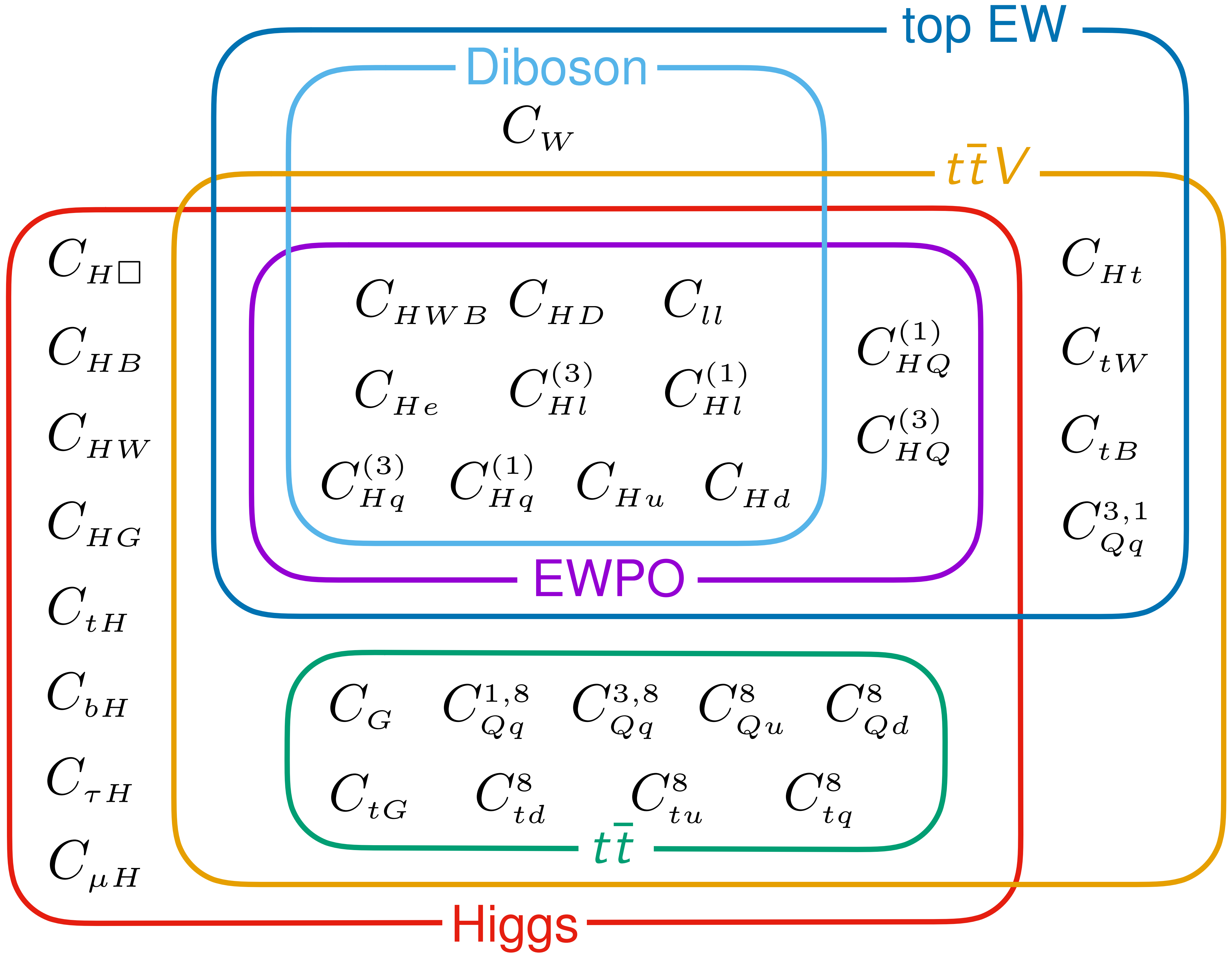
SMEFT

At dimension 6: 2499 operators

X^3		H^6 and H^4D^2		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 H^2$		$\psi^2 X H$		$\psi^2 H^2 D$	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$				

SMEFT

At dimension 6: 2499 operators



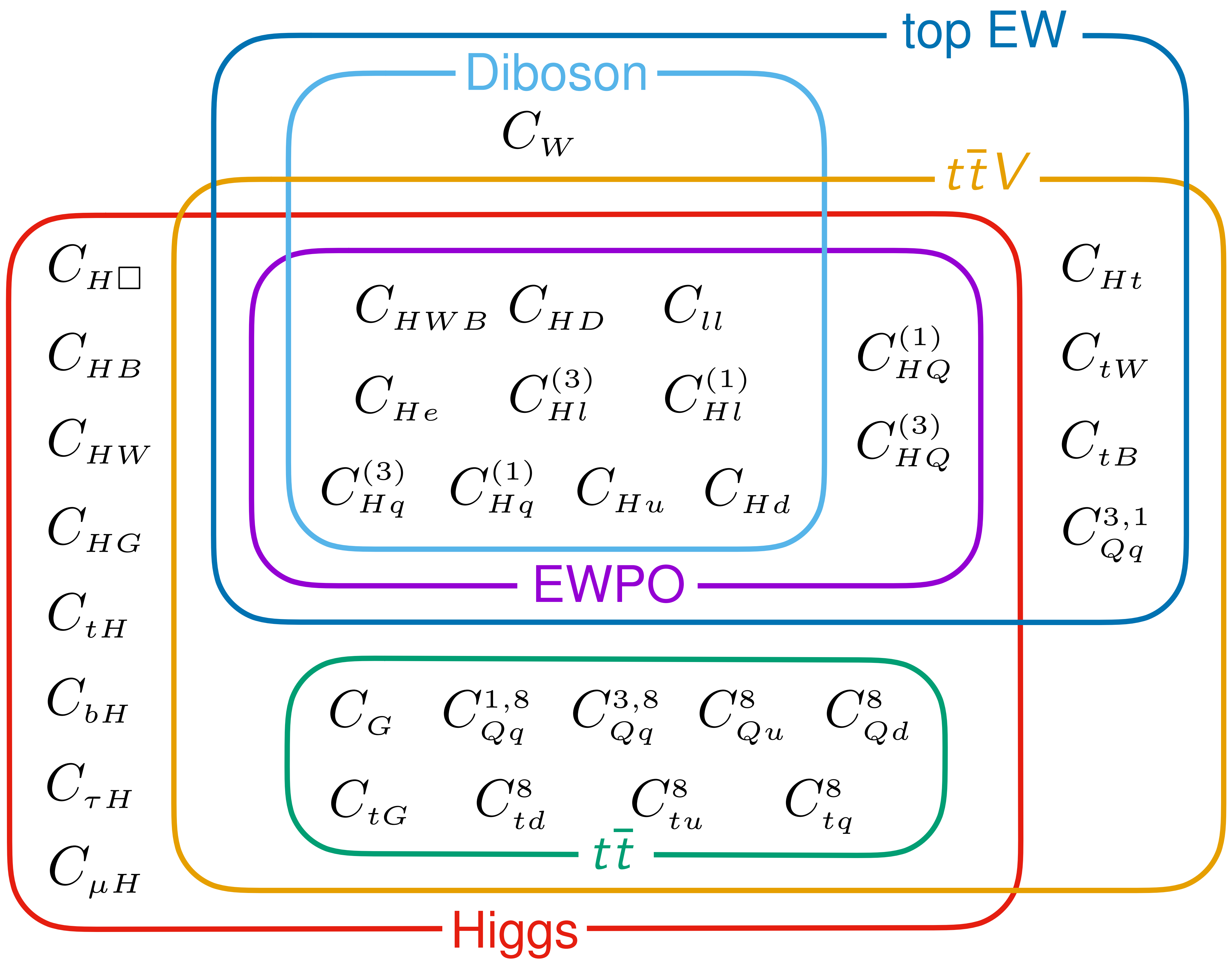
2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

SMEFT

At dimension 6: 2499 operators

The SMEFT framework connects different sectors of observables measured at the LHC.

We need to take a **global approach,** including as many relevant datasets as possible.



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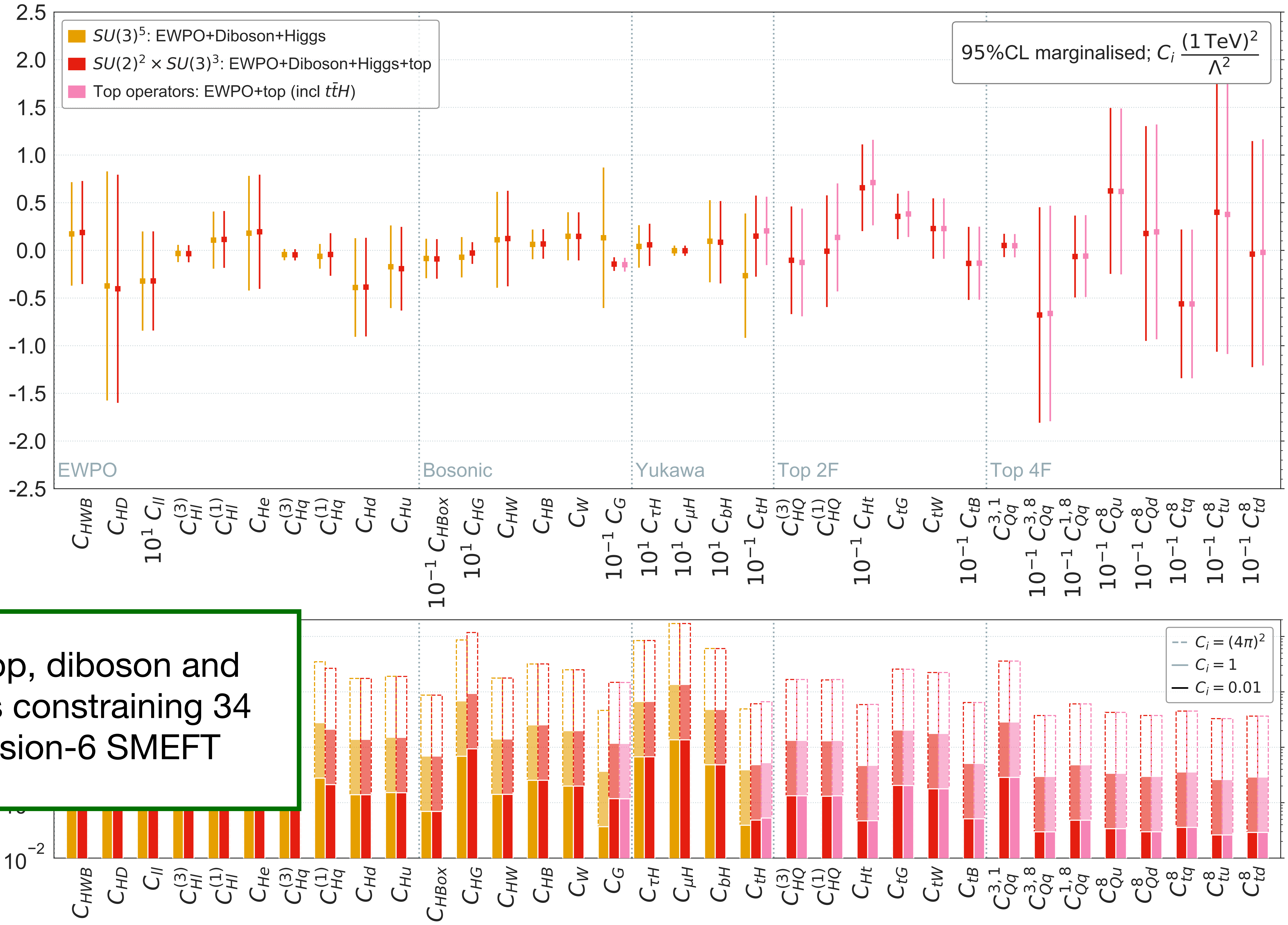
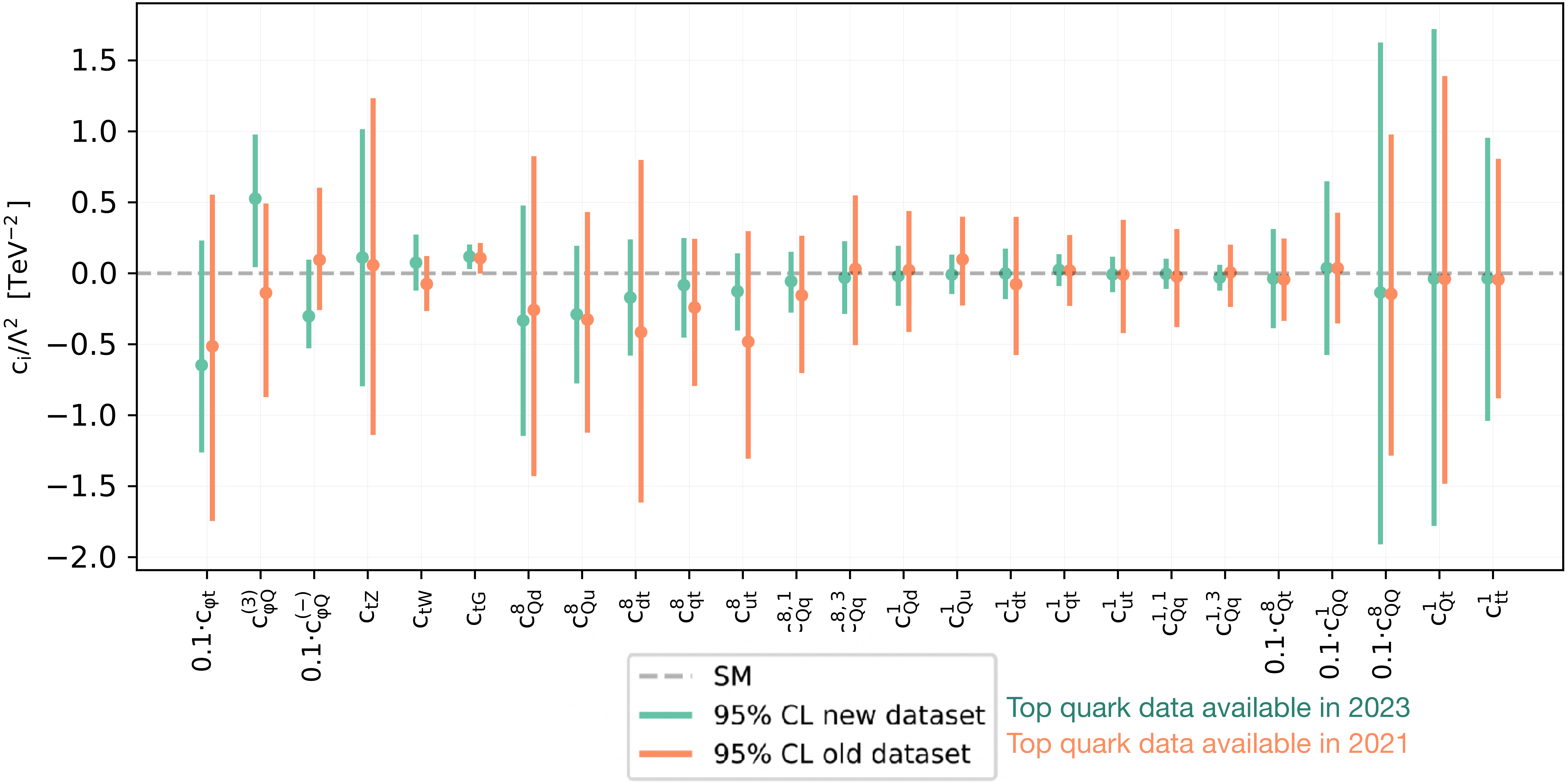


Combination of Higgs, top, diboson and electroweak observables constraining 34 coefficients of the dimension-6 SMEFT

The top sector after Run II

Z. Kassabov et. al , 2303.06159



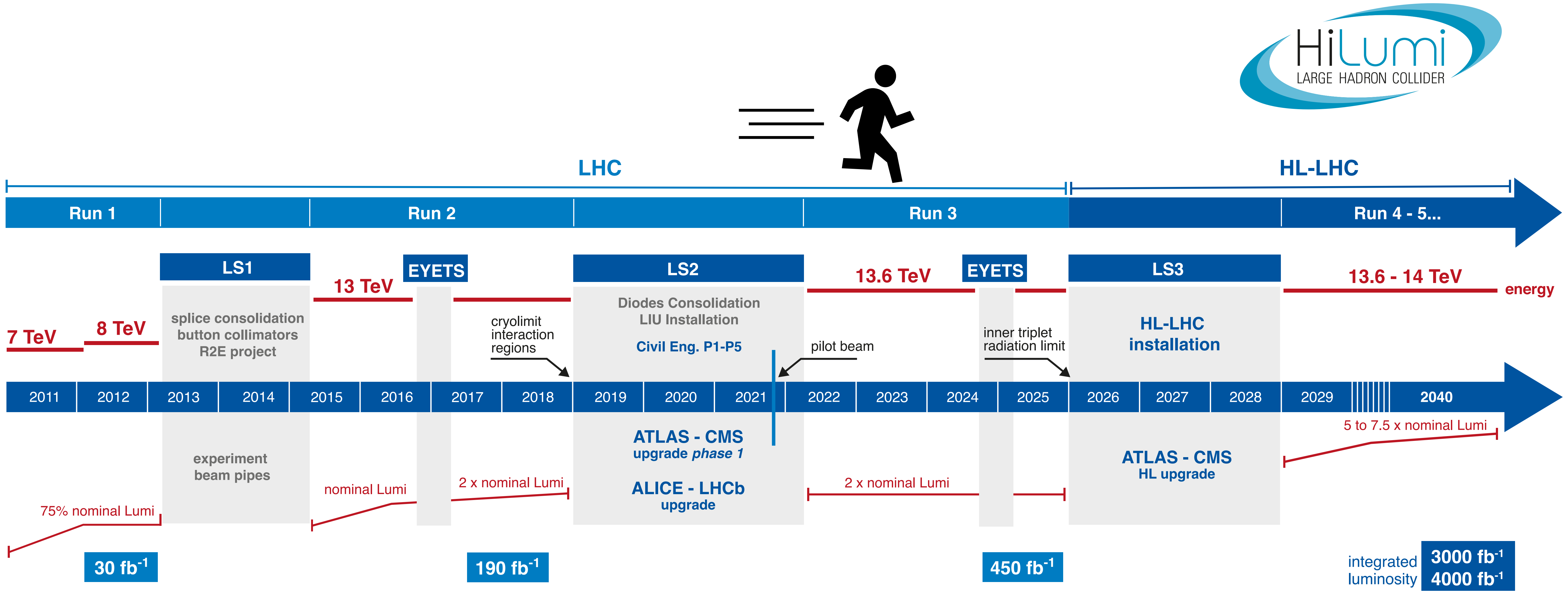
Top quark data available in 2023

Top quark data available in 2021

Looking forward

Run II data already provides precise constraints on the top quark sector of the SMEFT

As constraints improve, subleading effects may no longer be negligible



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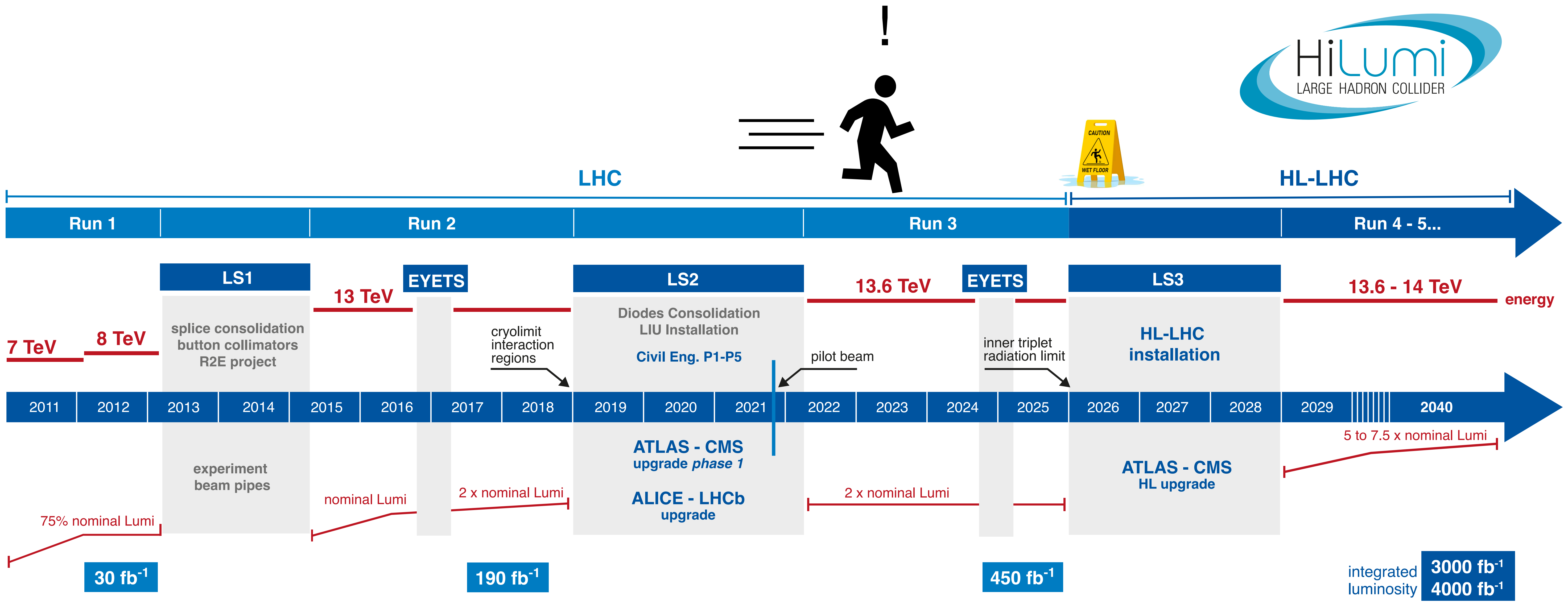
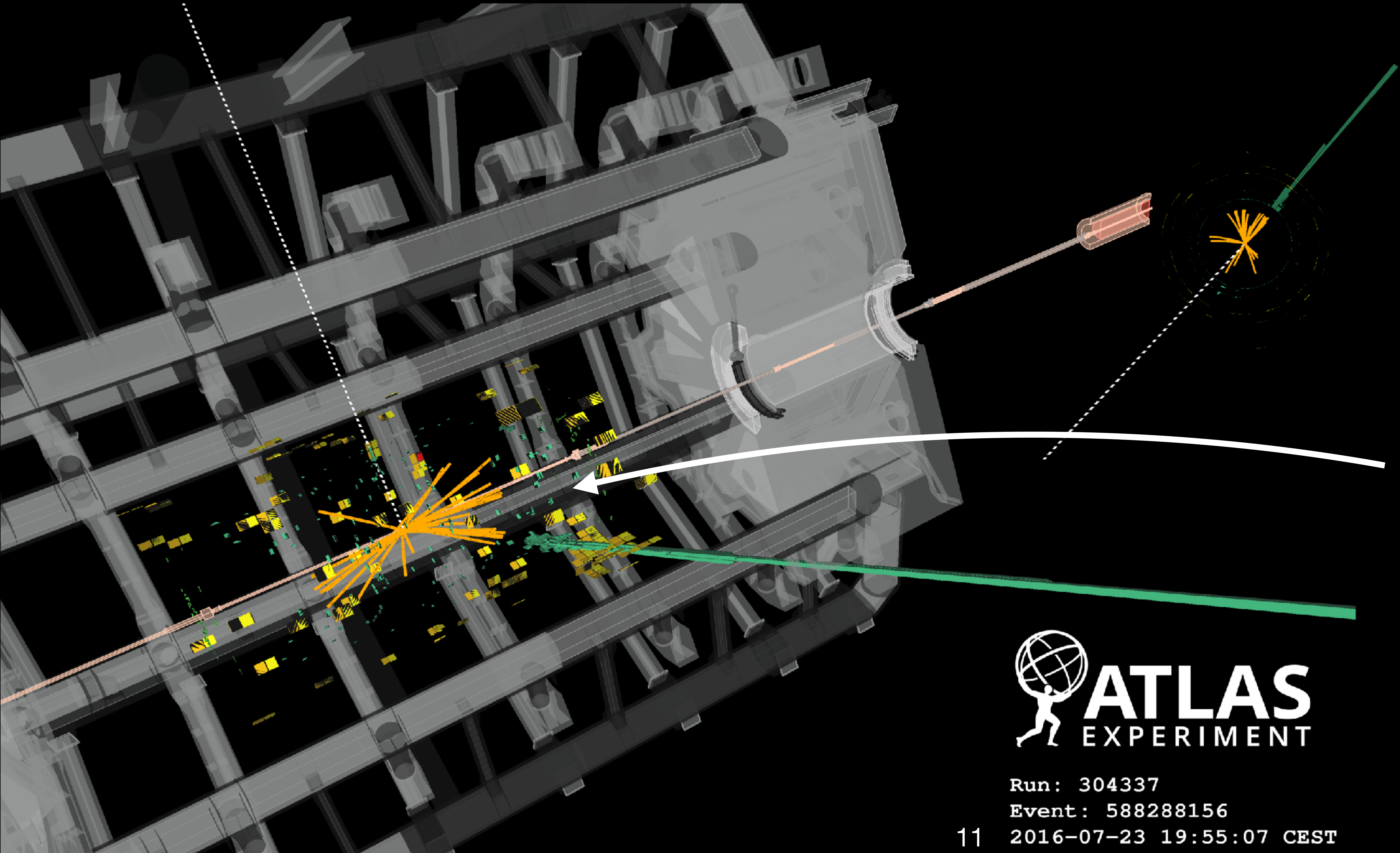
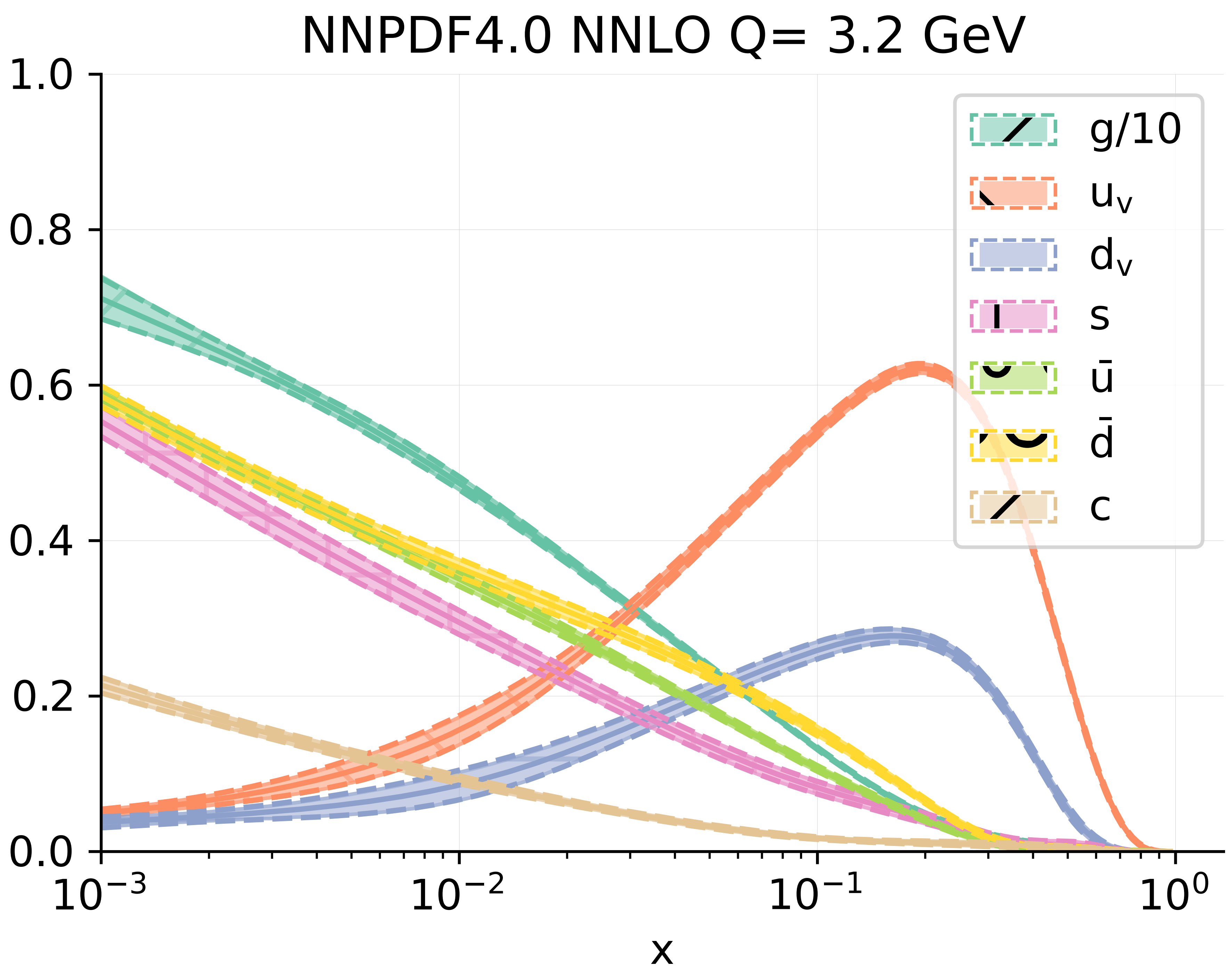


Parton distribution functions



Parton distribution functions

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



Parton distribution functions

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The SMEFT enters here: $\hat{\sigma} = \hat{\sigma}_{\mathrm{SM}} + \frac{C}{\Lambda^2}\hat{\sigma}_{\mathrm{SMEFT}} + \ldots$

Parton distribution functions

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

Both PDFs and SMEFT are determined by fitting from data

PDF-EFT Interplay

Wilson coefficients: c
PDF parameters: θ

PDF fits

SMEFT parameters are kept fixed:

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

SMEFT Fits

PDF parameters are fixed:

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

PDF-EFT Interplay

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Typically PDF fits assume the SM:

$$\bar{c} = 0$$

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SMEFT Fits

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

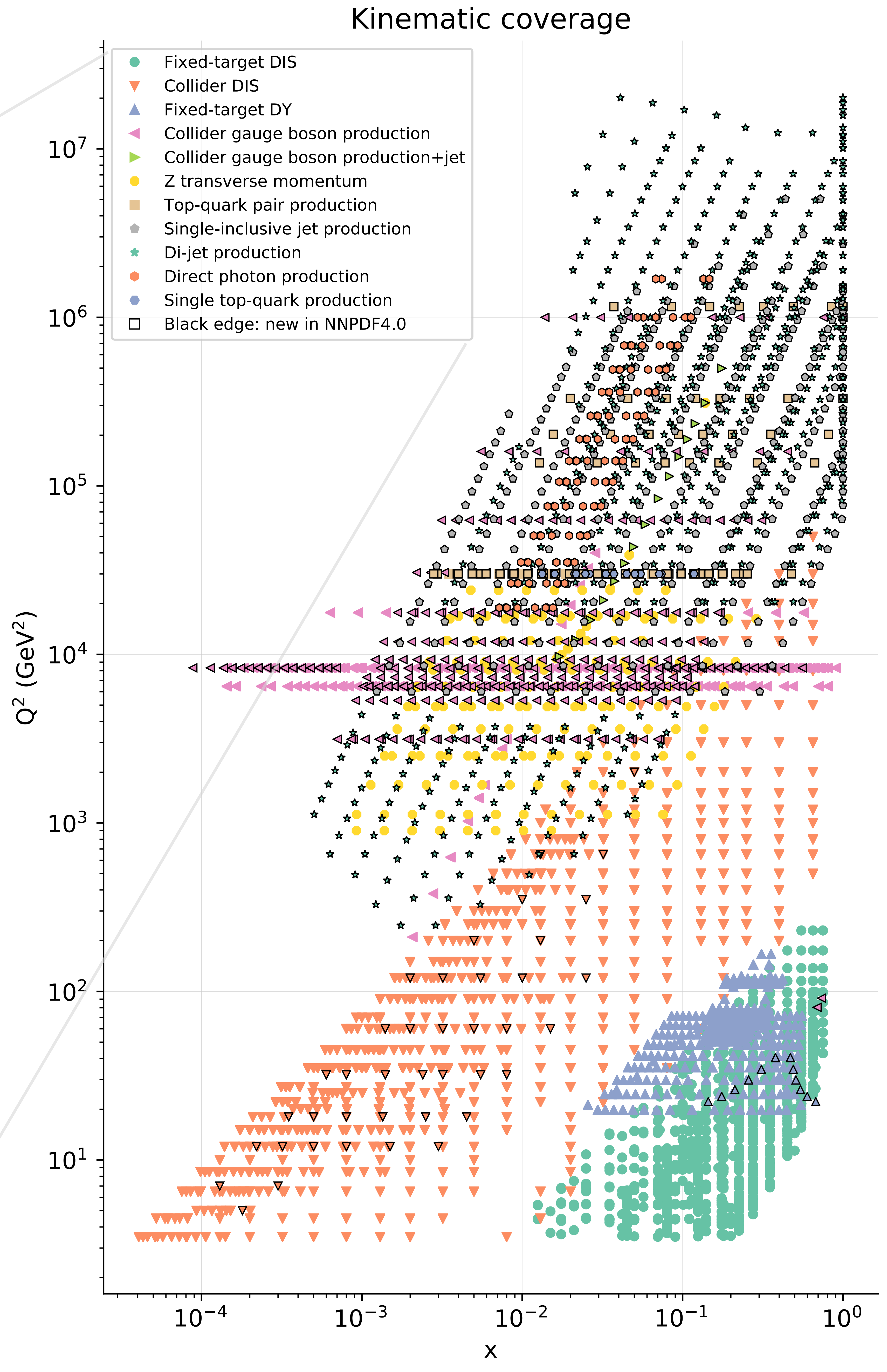
Data overlap

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

This overlap will grow as we take the global approach to constraining the SMEFT.

Data included in NNPDF4.0, [2109.02653]:

- Fixed-target DIS
- Collider DIS
- Fixed-target DY
- Collider gauge boson production
- Collider gauge boson production+jet
- Z transverse momentum
- Top-quark pair production
- Single-inclusive jet production
- Di-jet production
- Direct photon production
- Single top-quark production
- Black edge: new in NNPDF4.0



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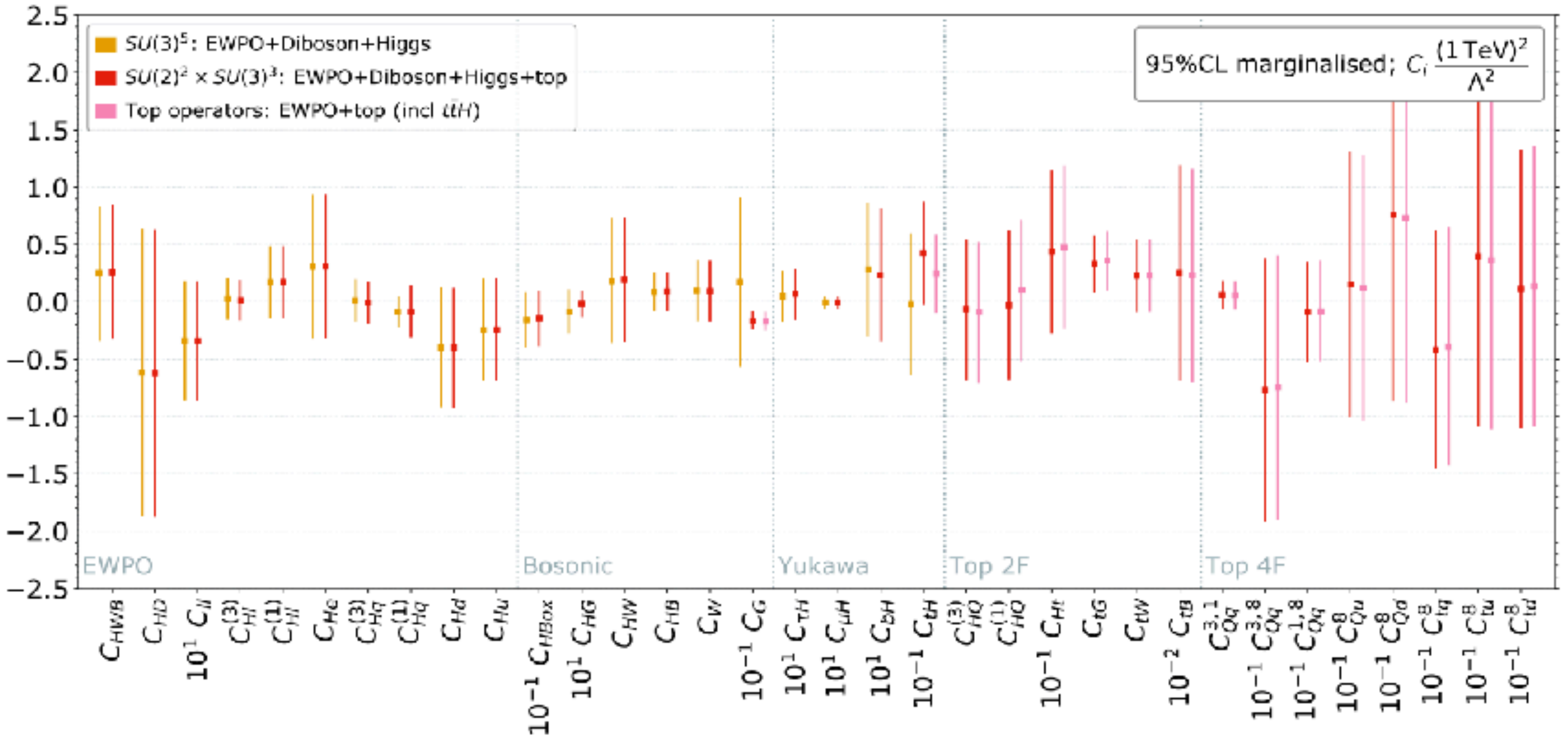
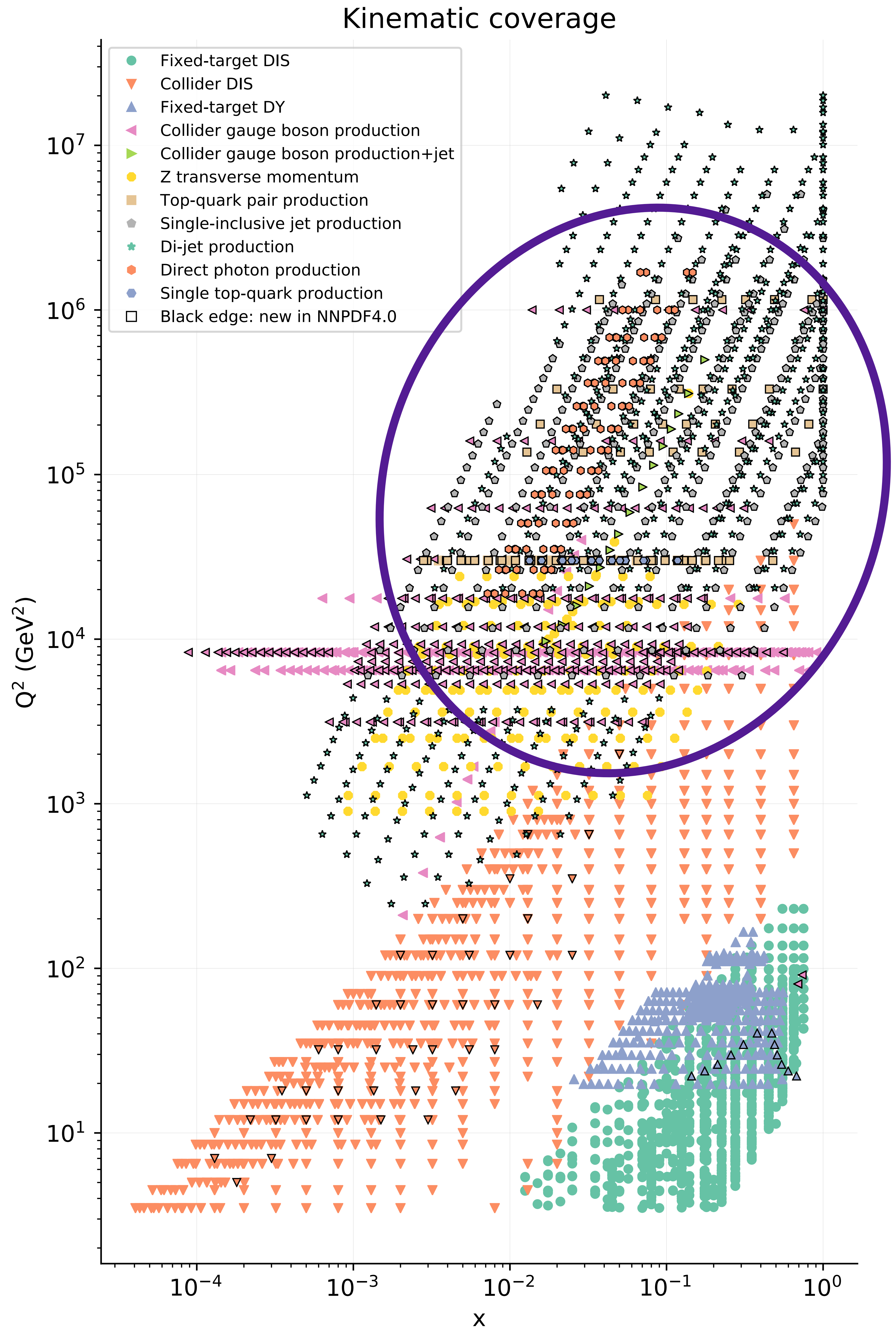
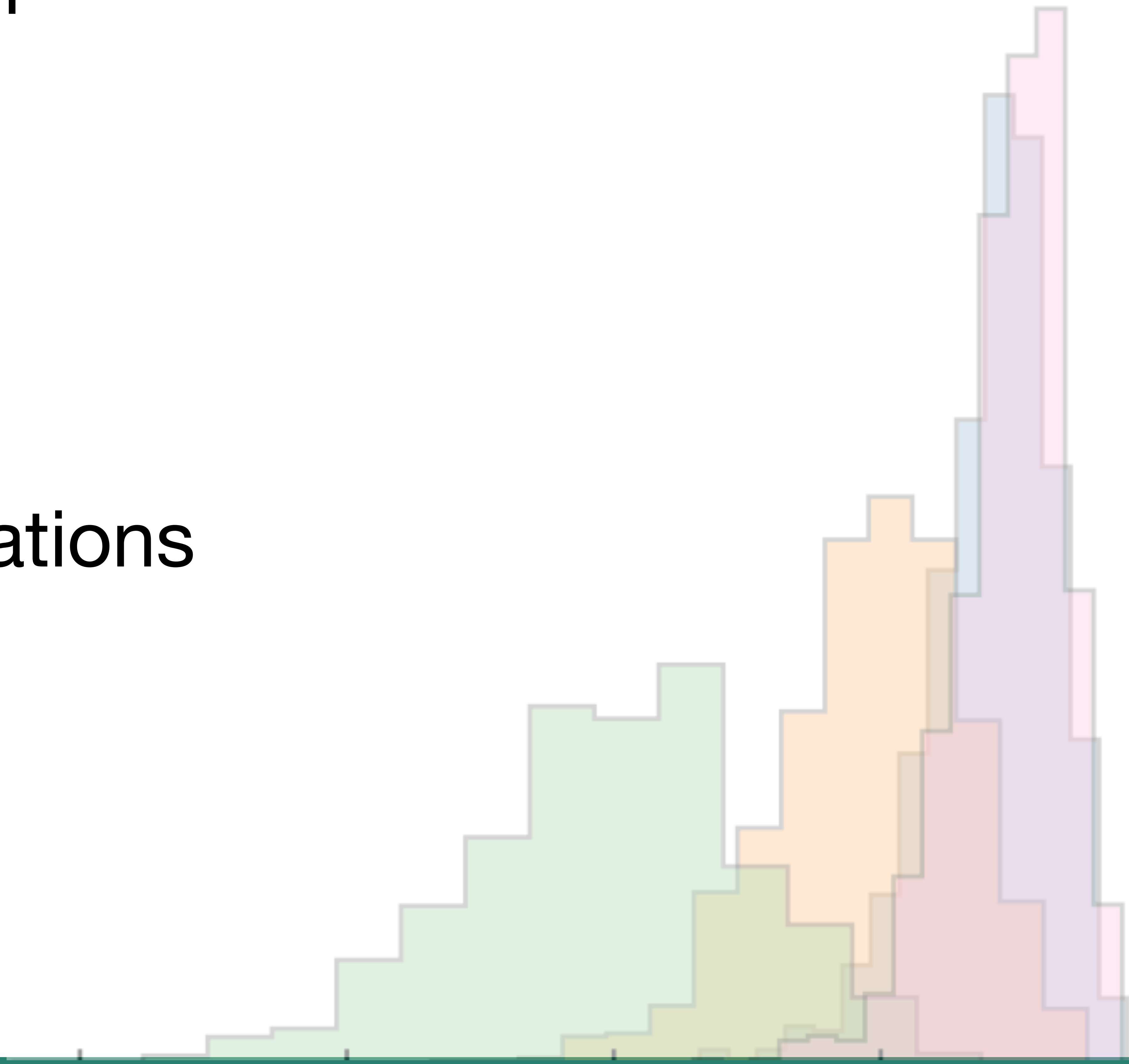
- e.g. Top quark data used to fit the SMEFT in the global fit of *2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You*





Overview

1. PDF-EFT interplay in high-mass Drell-Yan
2. Can PDFs absorb new physics?
3. Simultaneous PDF and SMEFT determinations



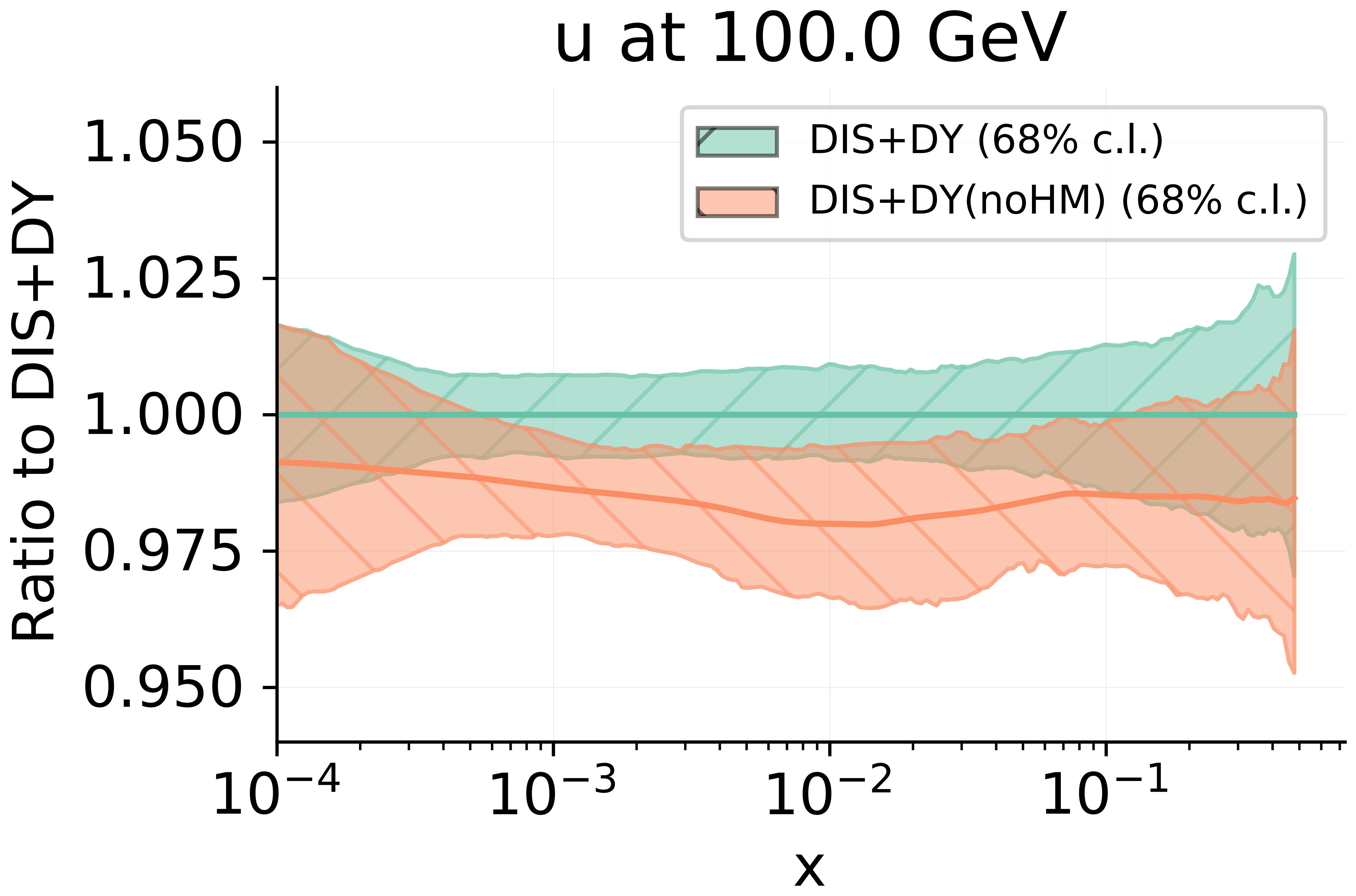
PDF-EFT interplay in high-mass Drell-Yan

Greljo et. al 2104.02723

PDF-EFT interplay **in high-mass Drell-Yan**

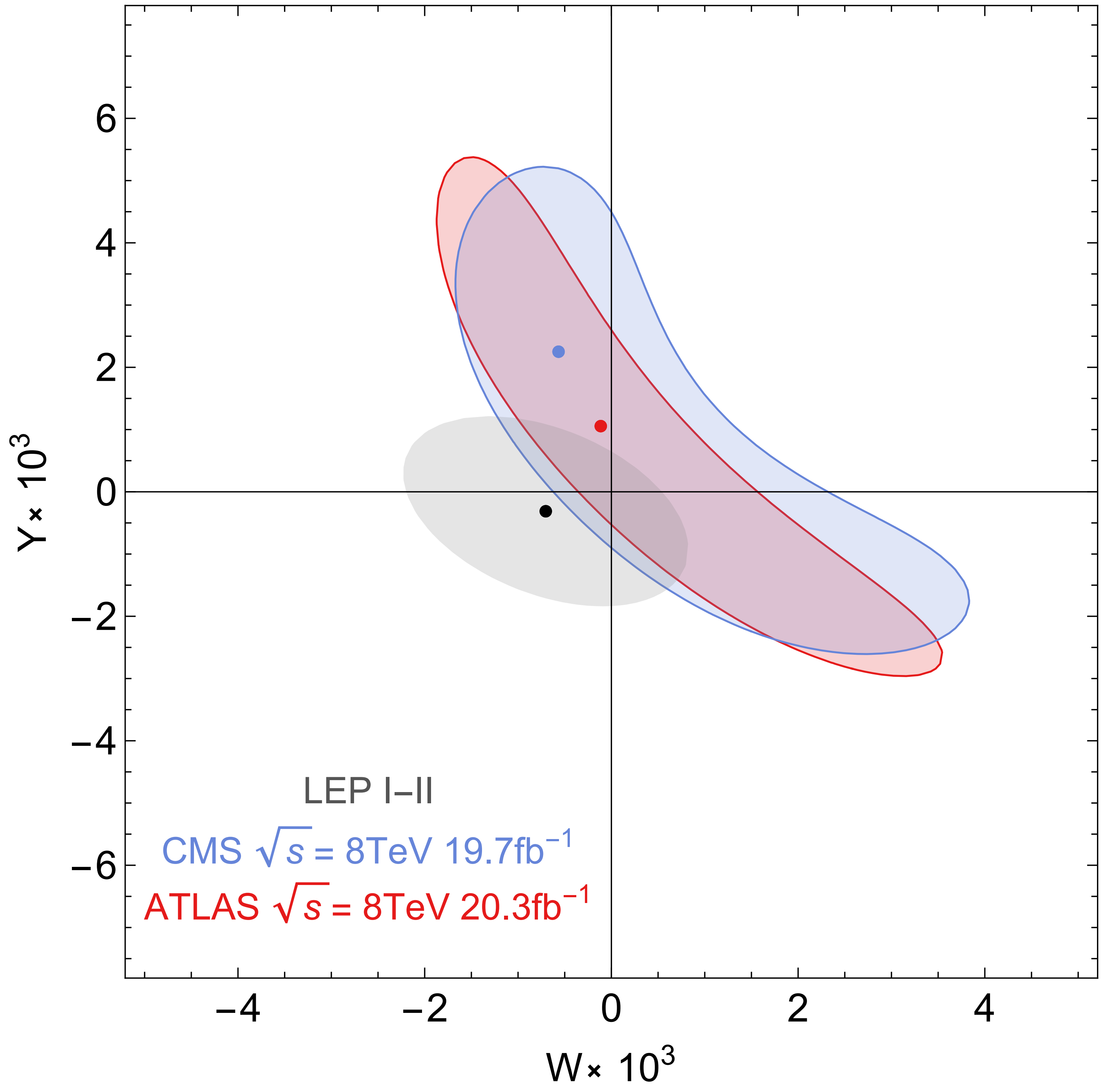
Greljo et. al 2104.02723

Constraints on the large-*x* region of the u and d PDFs:



Greljo et. al 2104.02723

Constraints on 4-fermion operators of the SMEFT:

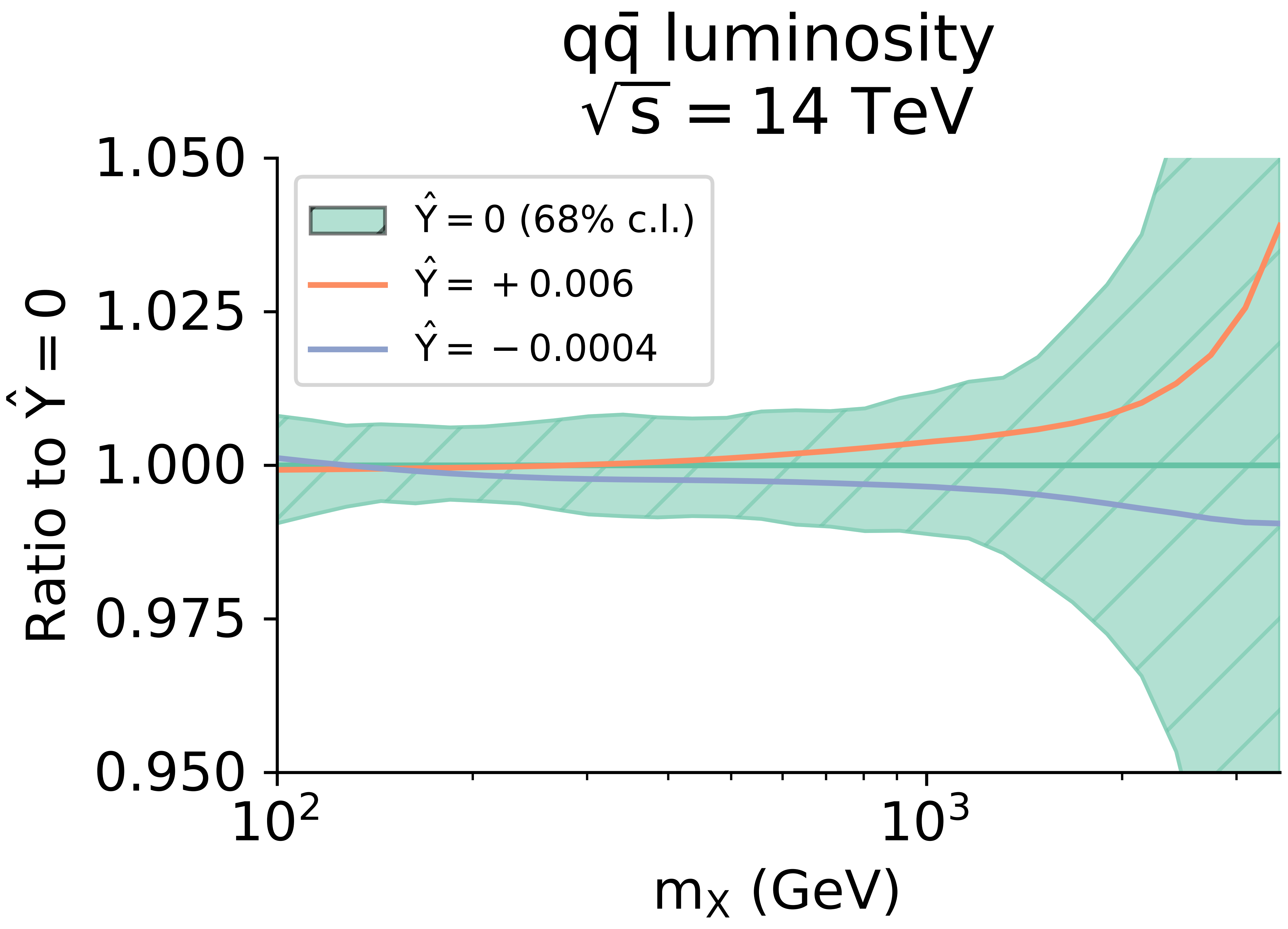


Farina et. al 1609.08157

PDF-EFT interplay **in high-mass Drell-Yan**

Greljo et. al 2104.02723

Excluding HL-LHC projections for NC and CC Drell-Yan:



PDF fits under the assumption of nonzero SMEFT coefficients:

We see a **moderate shift** of the PDF central values, and **no change** to the PDF uncertainties.

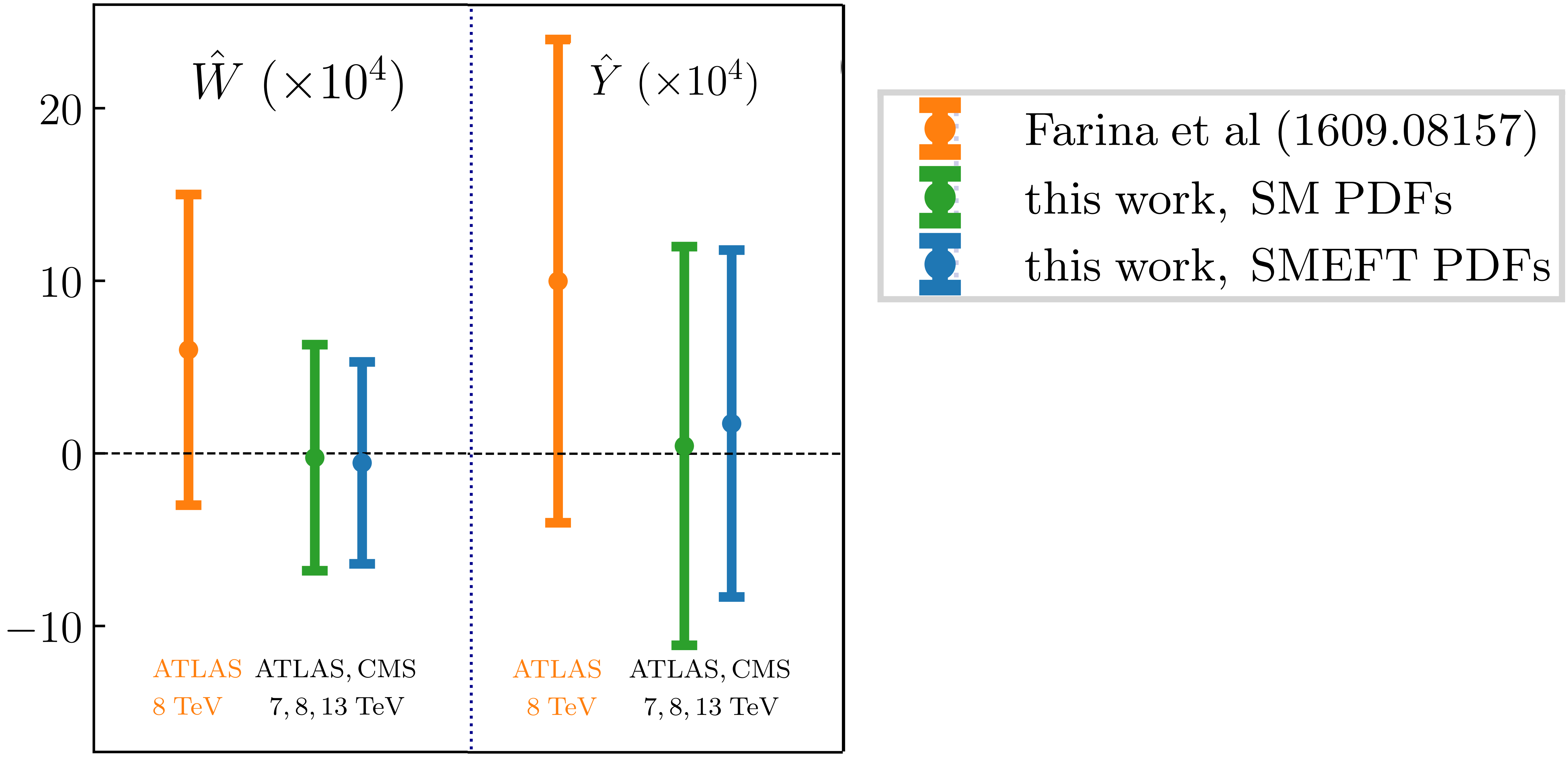
PDF-EFT interplay **in high-mass Drell-Yan**

Greljo et. al 2104.02723

Excluding HL-LHC projections for NC and CC Drell-Yan:

SMEFT constraints are **stable:**

moderate shifts when using SMEFT vs SM PDFs



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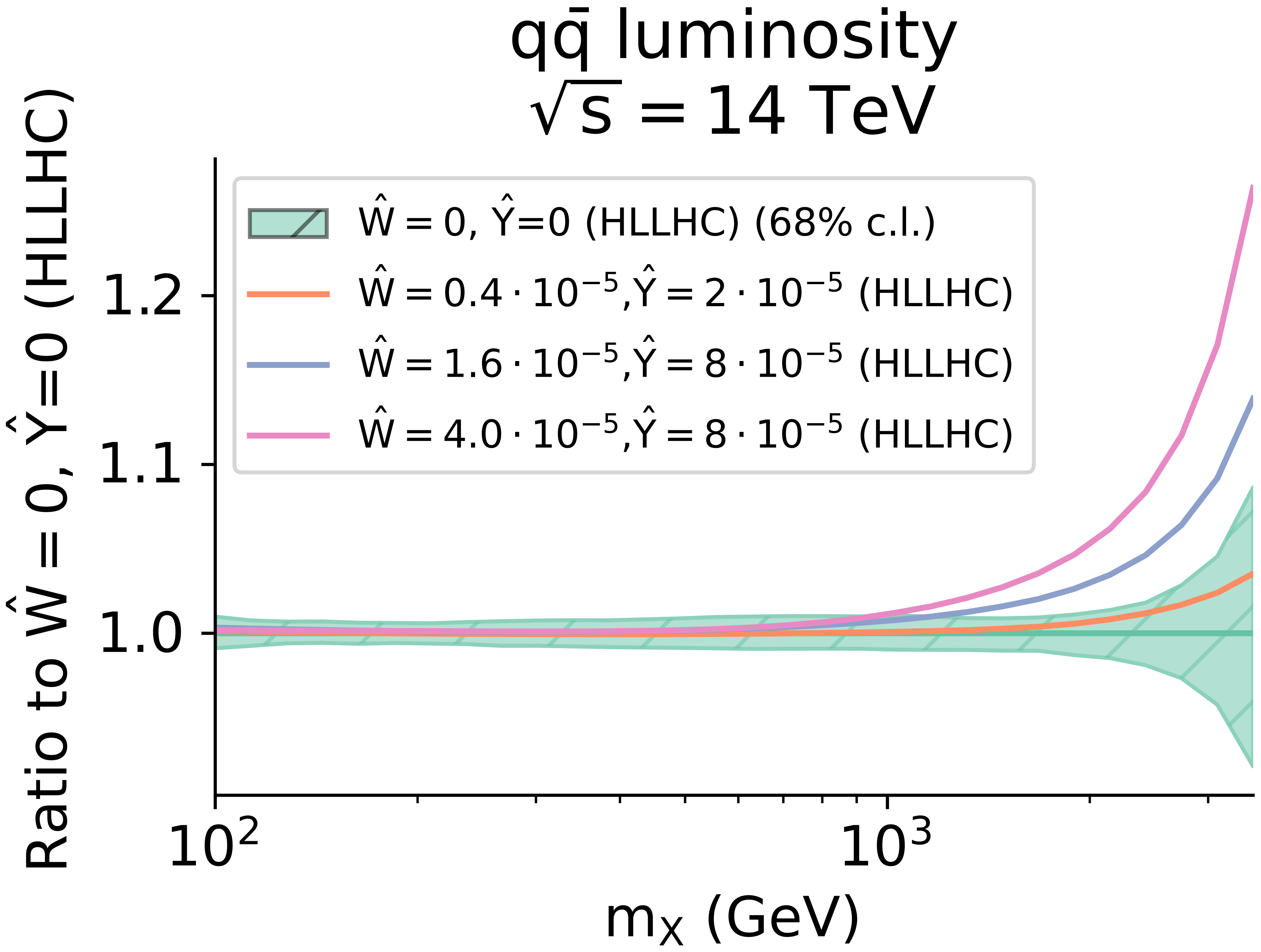


PDF fits under the assumption of nonzero SMEFT coefficients:

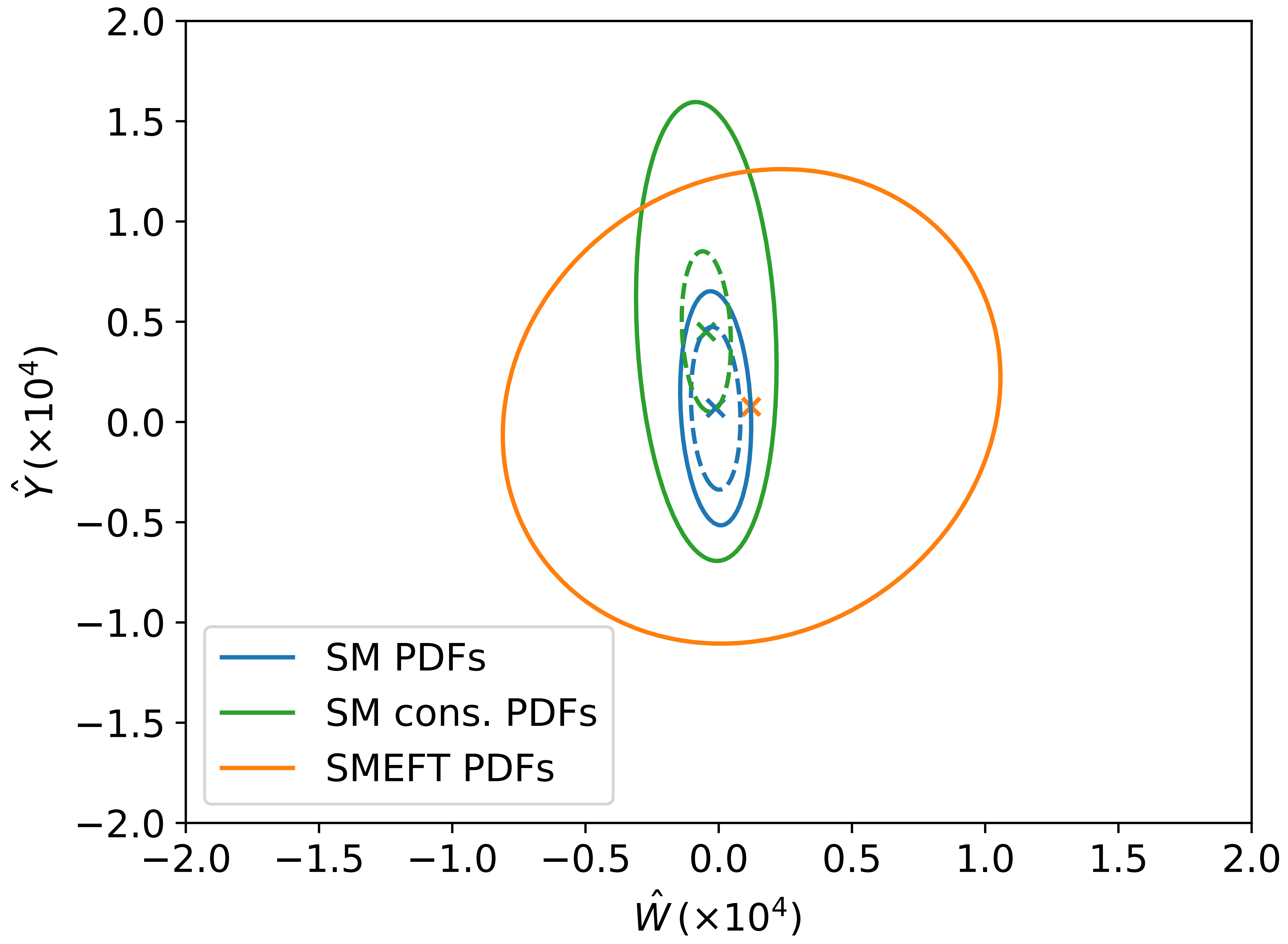
We see a **large shift** of the PDF central values, in some cases beyond PDF uncertainties

PDF-EFT interplay **in high-mass Drell-Yan**

Greljo et. al 2104.02723

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

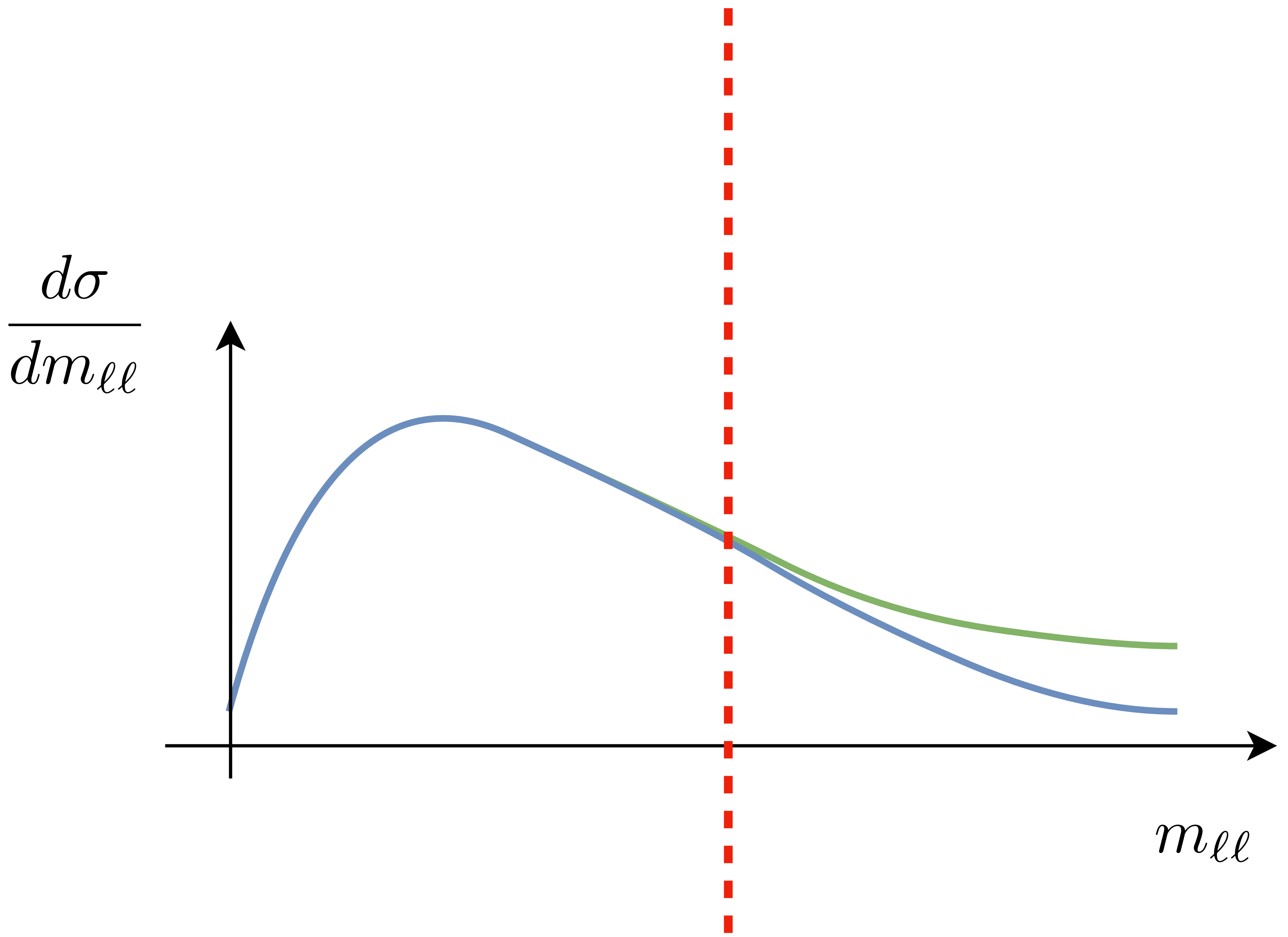
Neglecting PDF-EFT interplay leads to a significant overestimate of the EFT constraints.



Conservative PDFs

Could we improve the SM PDF fits by removing the high-mass data from PDF fits?

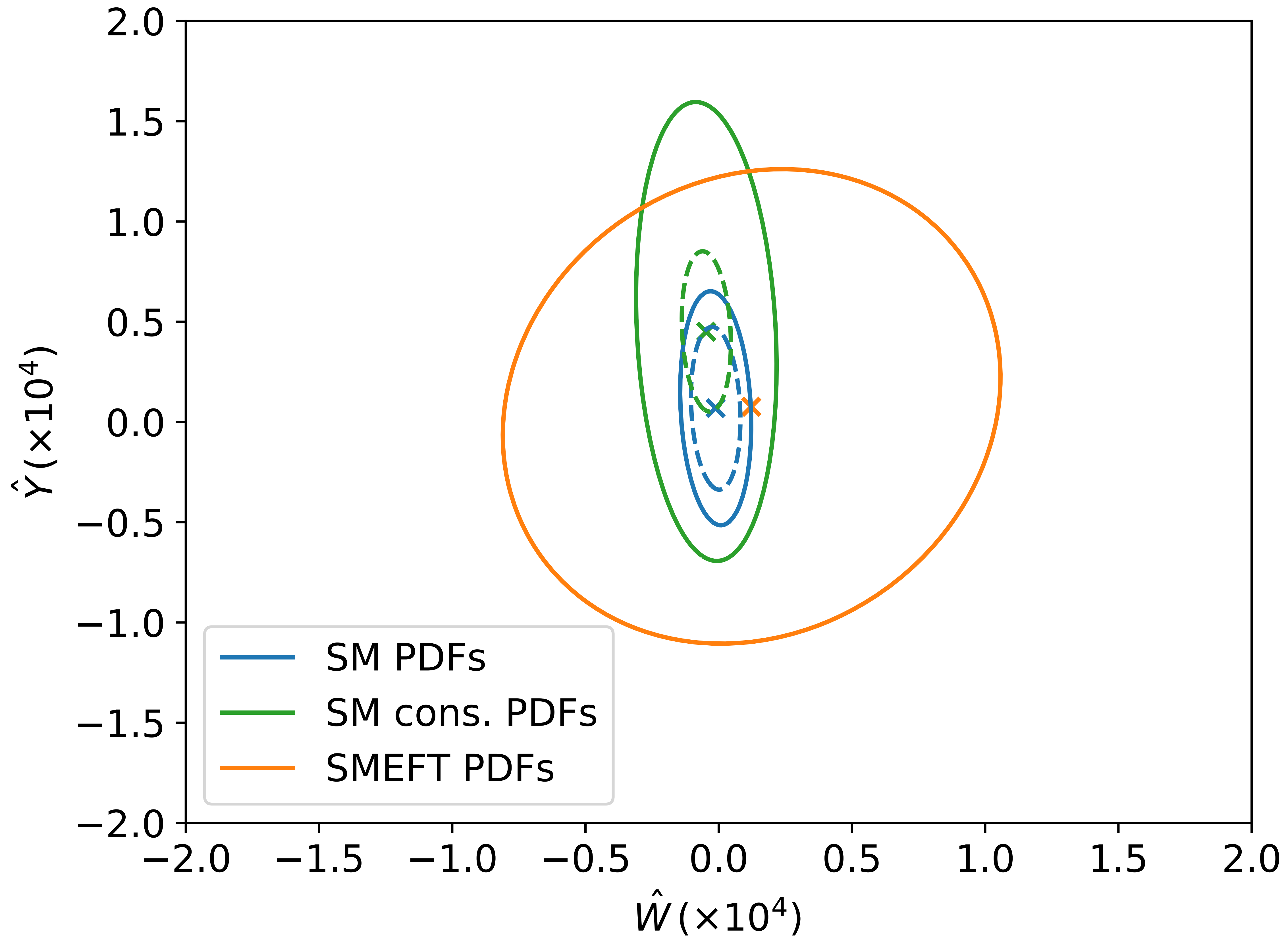
- not in the spirit of global fits
- still have a theoretical inconsistency due to SM assumptions
- **but** much easier than doing a simultaneous PDF-SMEFT fit



Simultaneous PDF and SMEFT fit **results**

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

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

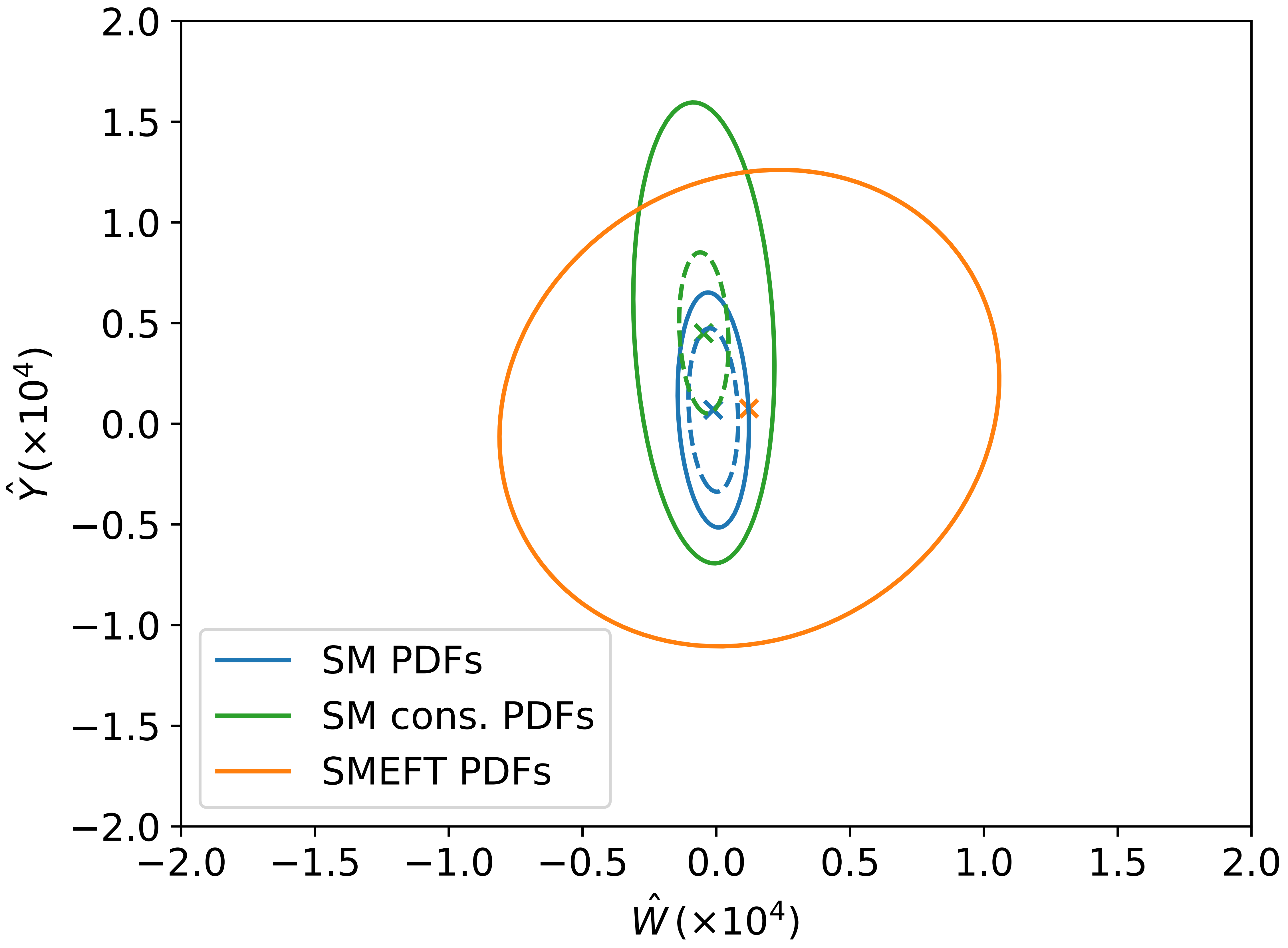


Simultaneous PDF and SMEFT fit **results**

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

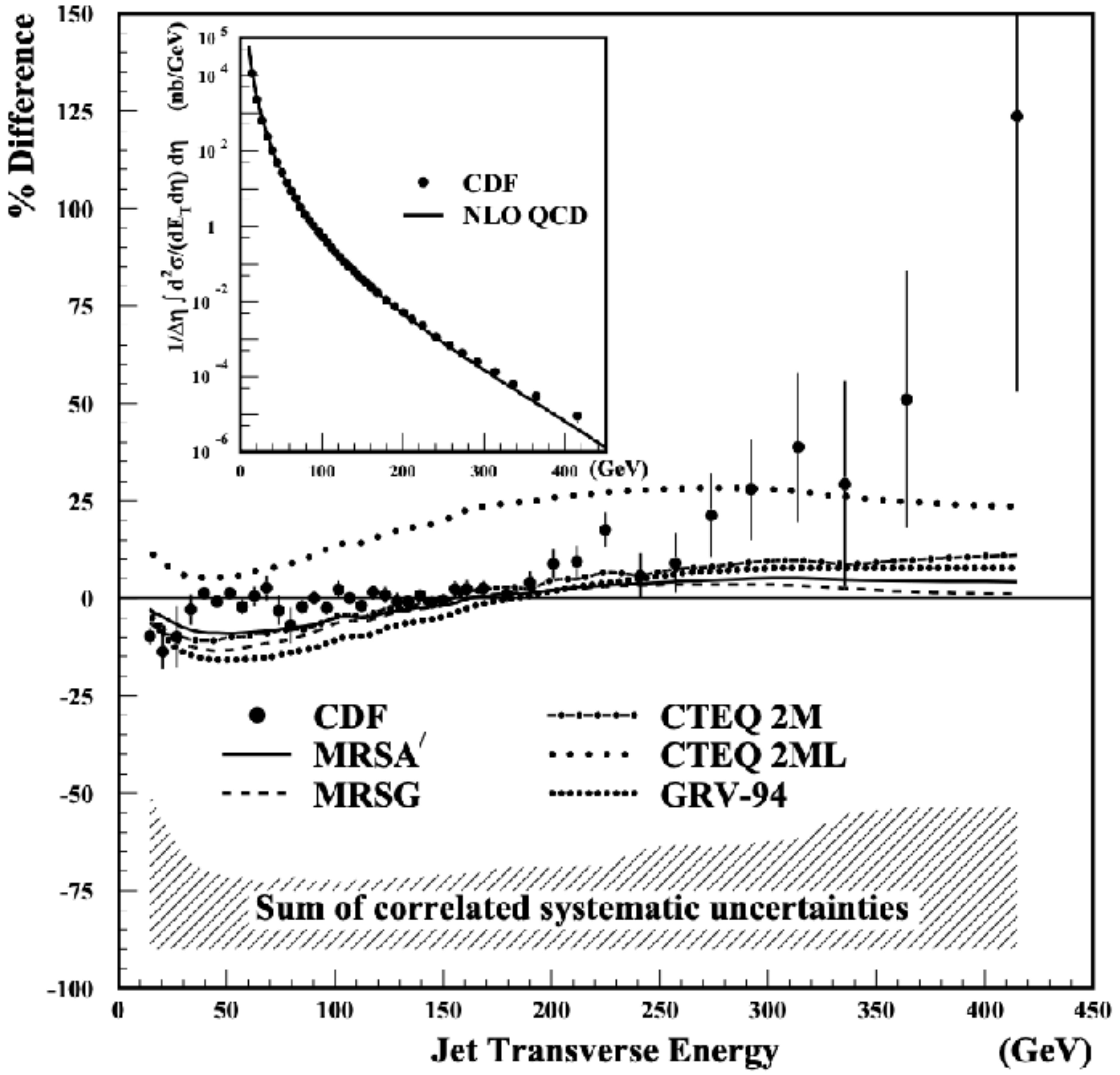
Neglecting PDF-EFT interplay leads to a significant overestimate of the EFT constraints.

what does this mean for searches for new physics?



Can PDFs Absorb New Physics?

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



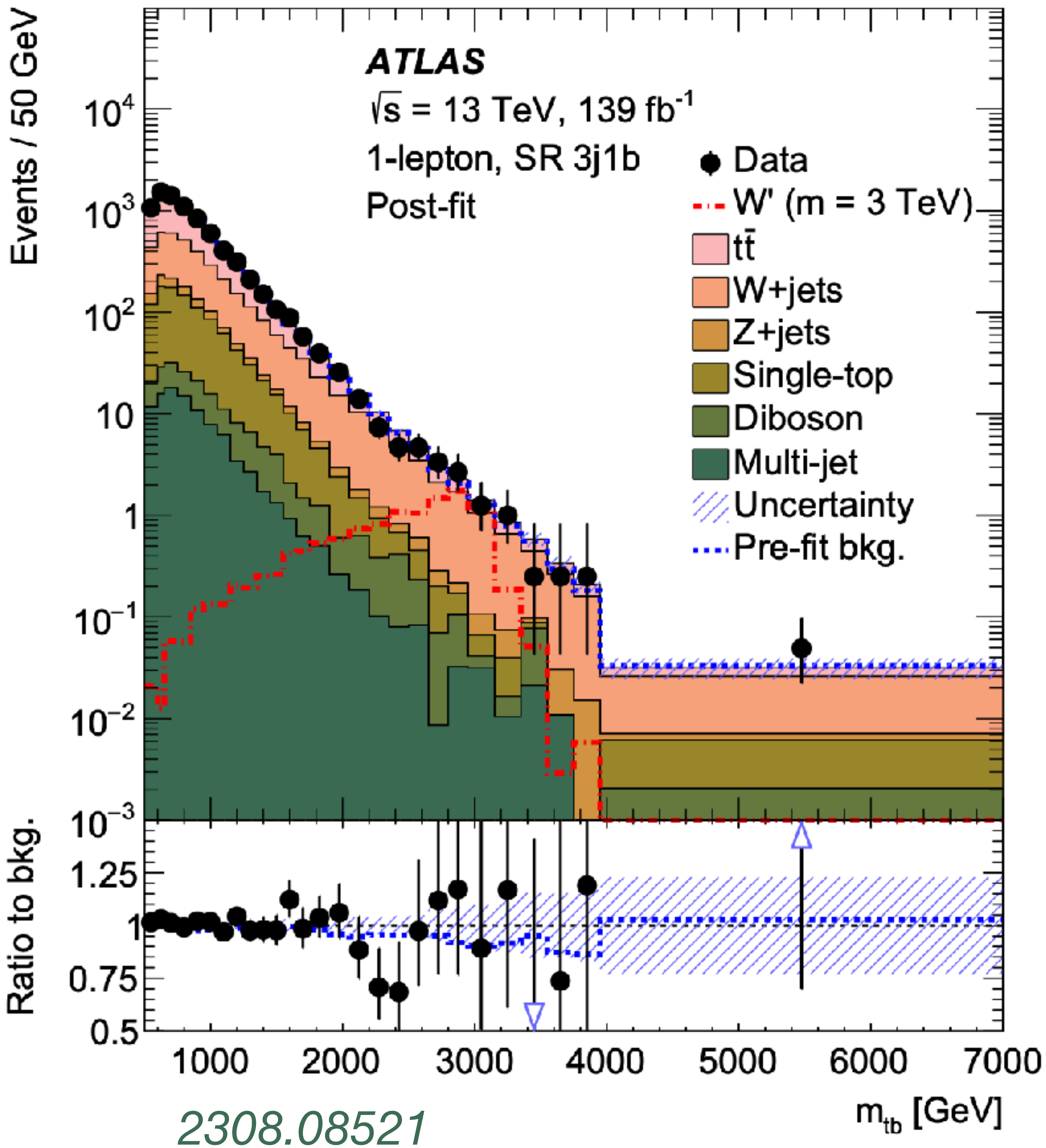
hep-ex/9601008

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**?

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

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

Contaminated PDFs

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

Generate Monte Carlo pseudodata according to this underlying law:

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

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

2109.02653

Contaminated PDFs

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

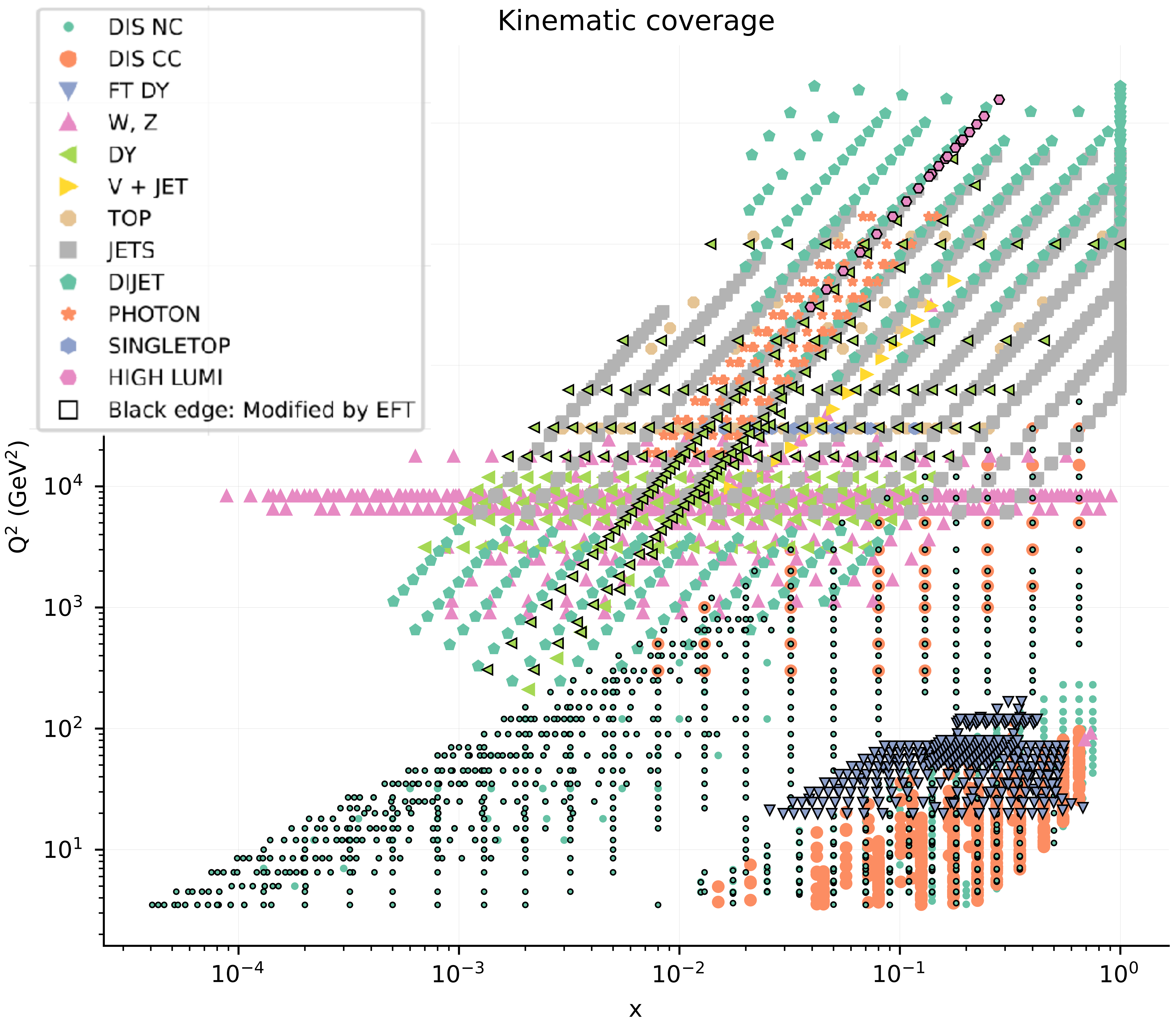
Data

- 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: Z’

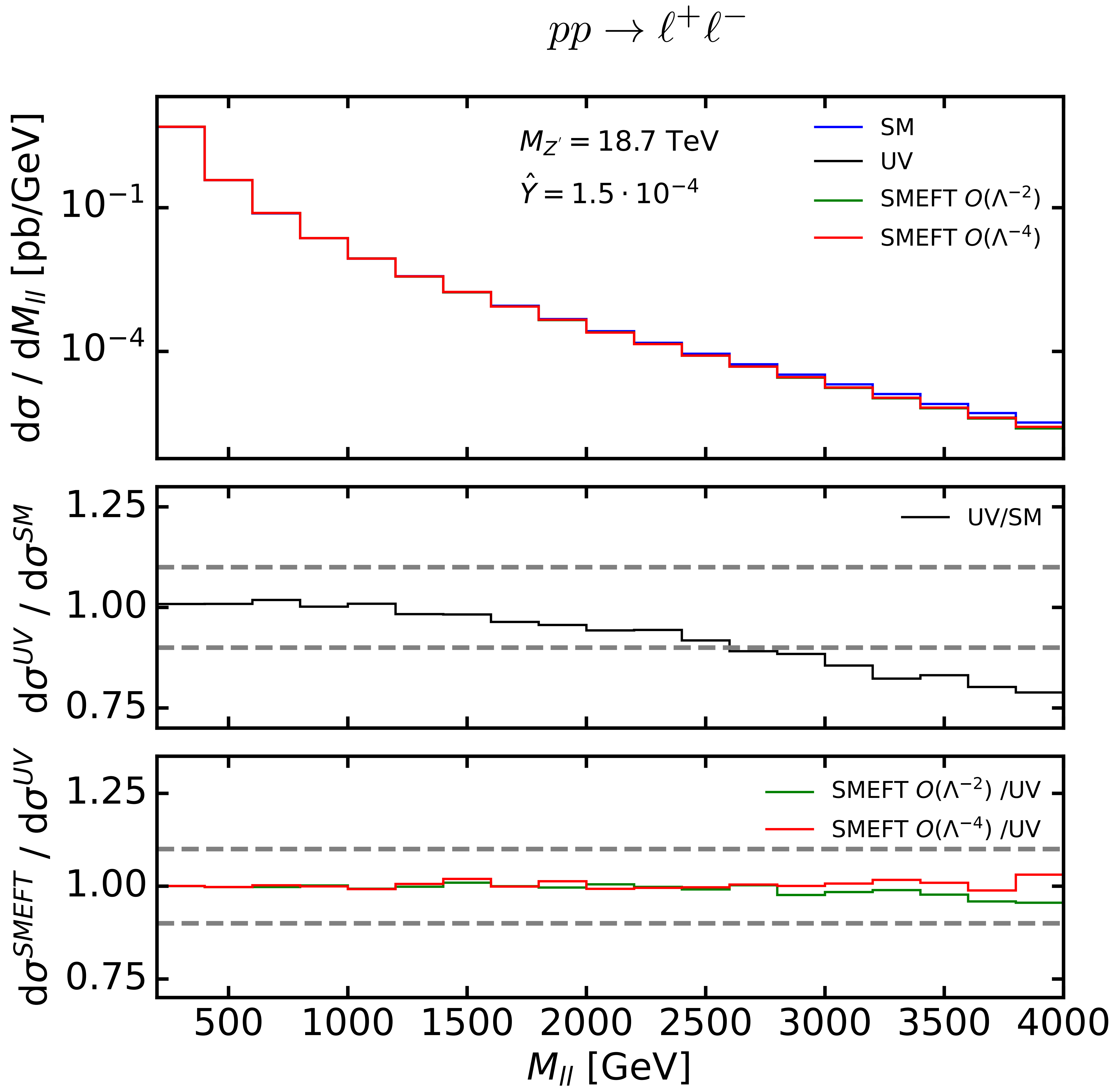
- Flavour universal Z’

EFT approximation

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

$$J_L^\mu = \sum_f Y_f \bar{f}\gamma^\mu f$$

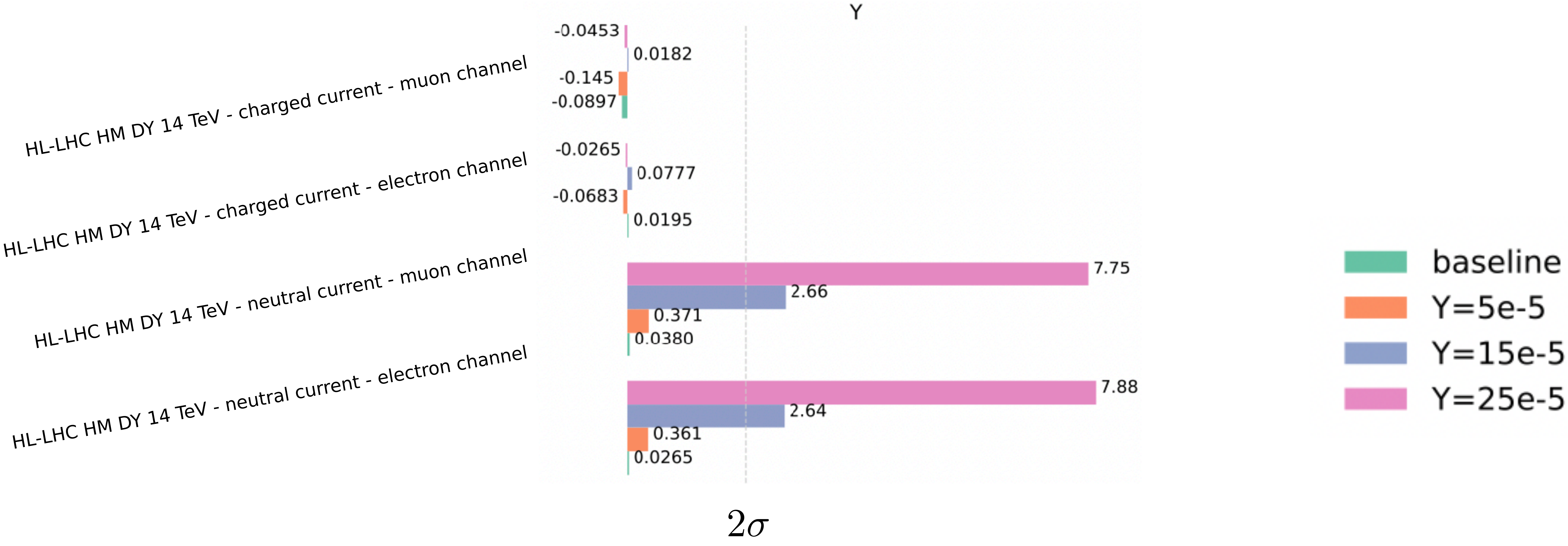
- Impacts NC DY



Do our contaminated fits pass the selection criteria?

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

➡ **Z' scenario**



$m_{Z'} \approx 30$ TeV

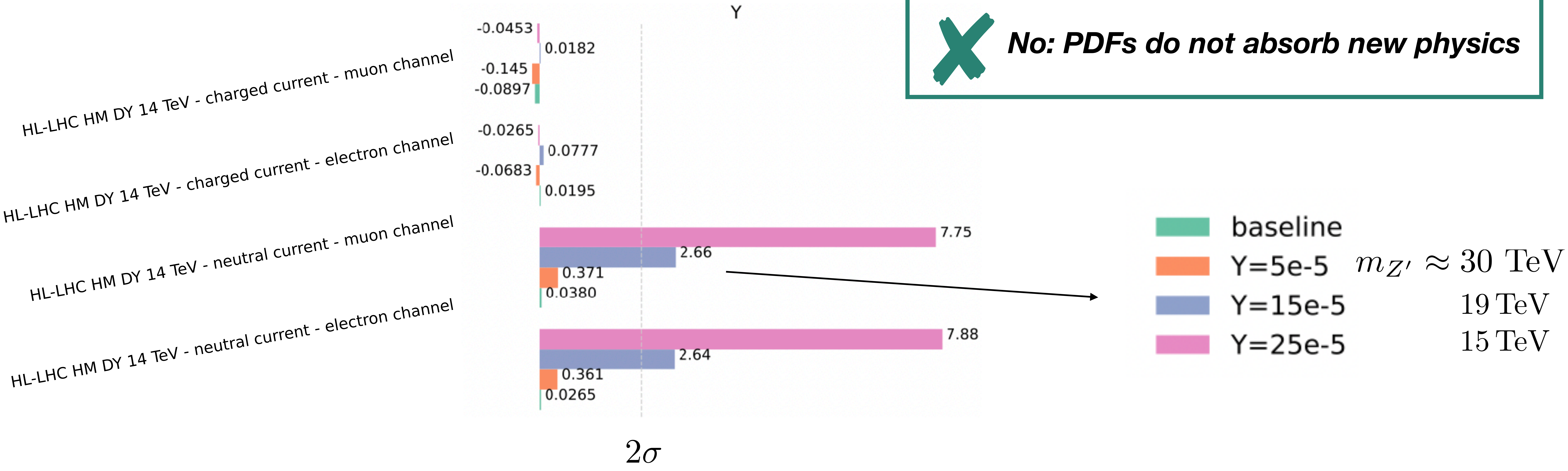
19 TeV

15 TeV

Do our contaminated fits pass the selection criteria?

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

➡ **Z' scenario**

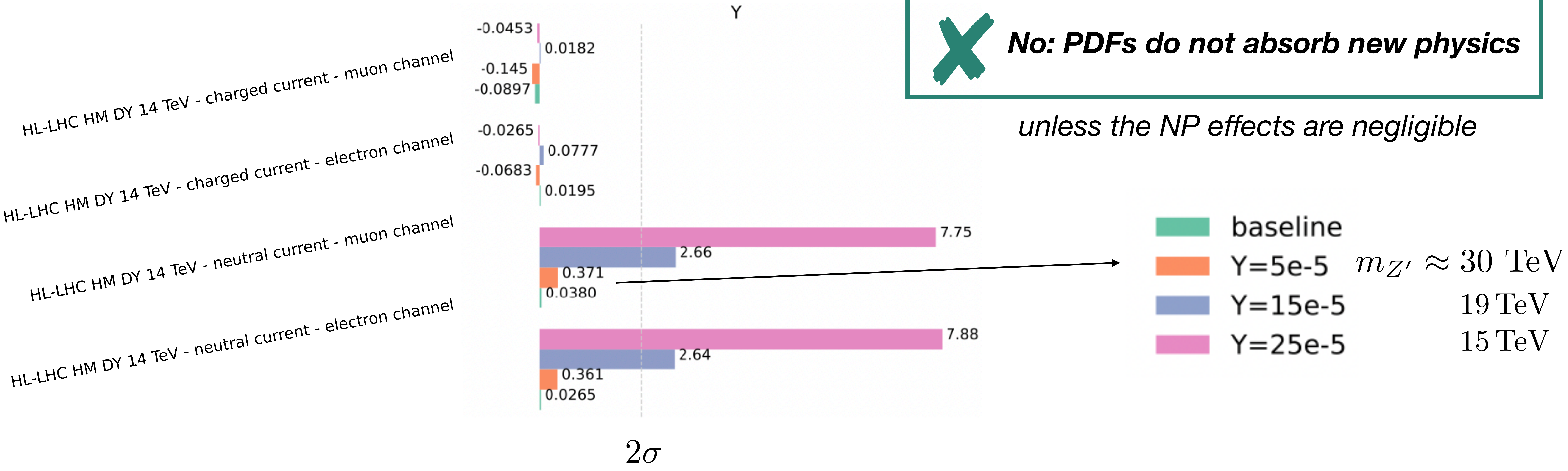


✗ *No: PDFs do not absorb new physics*

Do our contaminated fits pass the selection criteria?

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

➡ **Z' scenario**

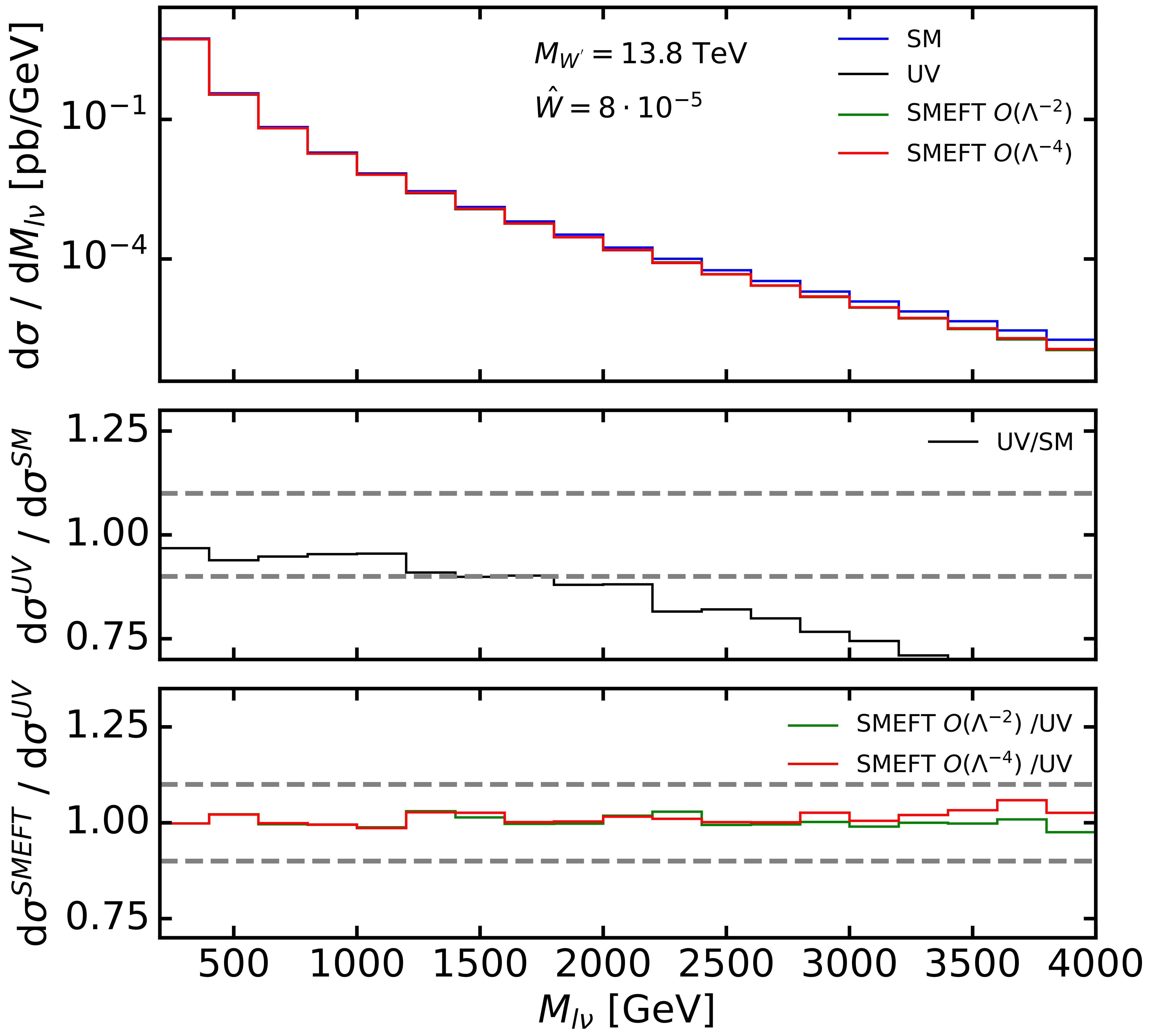


No: PDFs do not absorb new physics

unless the NP effects are negligible

BSM scenario: W’

$pp \to l\nu$



- Flavour universal W’

EFT approximation

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

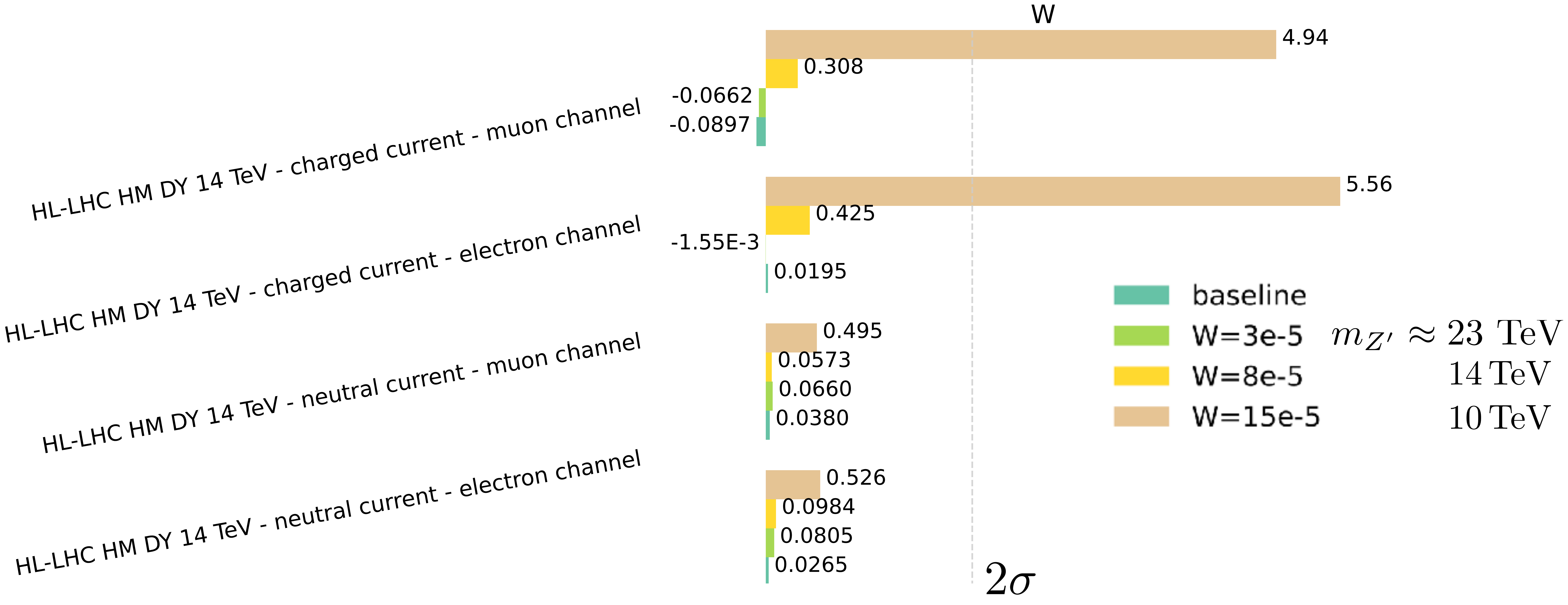
$$J_L^{\mu} = \sum_{f_L} \bar{f}_L T^a \gamma^{\mu} f_L$$

- Impacts NC **and CC DY**

Do our contaminated fits pass the selection criteria?

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

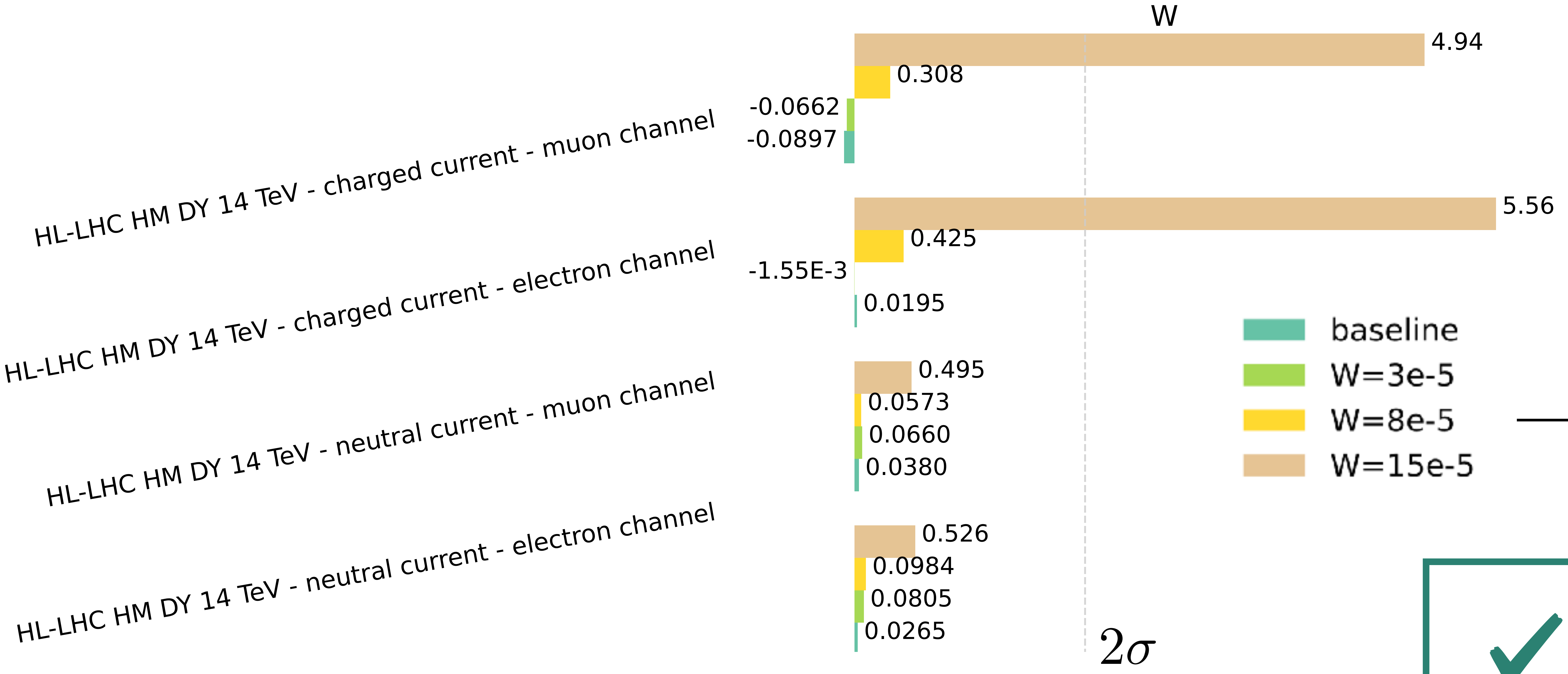
➡ W' scenario



Do our contaminated fits pass the selection criteria?

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

➡ W' scenario

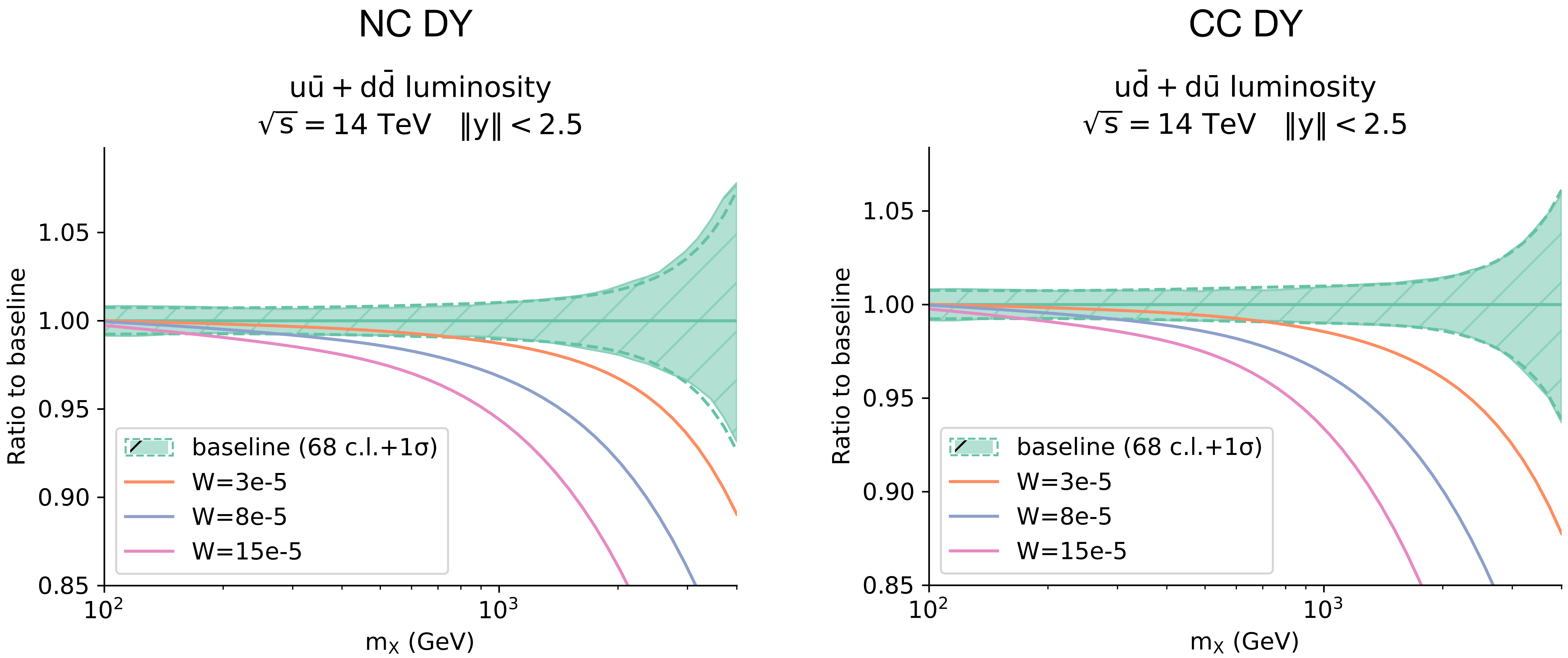


→ $\hat{W} = 8 \cdot 10^{-5}, \quad M_{W'} \approx 14 \text{ TeV}$

✔ ***Yes: PDFs absorb new physics***

W'-contaminated PDFs

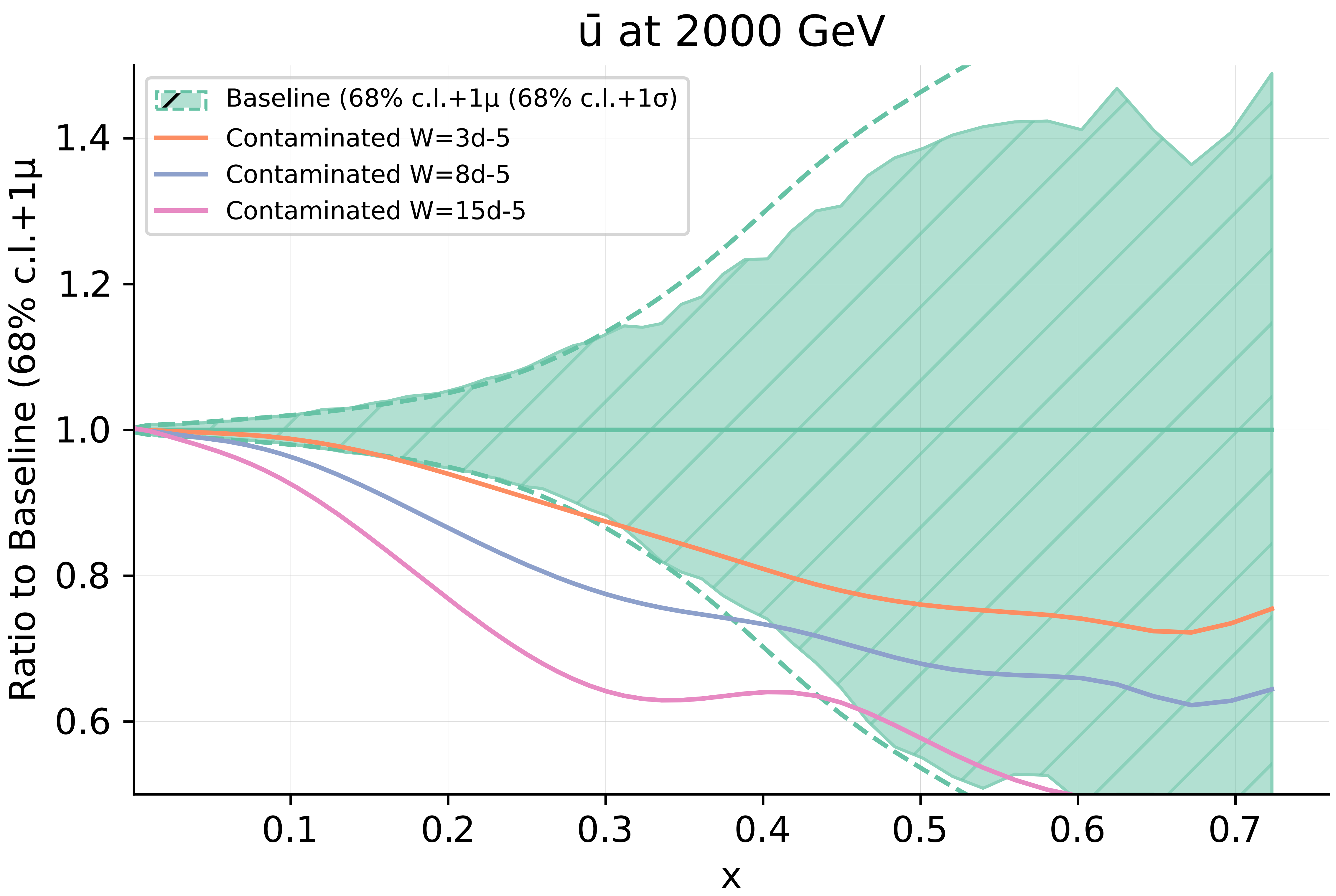
$$\mathcal{L}_{q\bar{q}} = \sum_{q,\bar{q}} \int_{\tau}^{1} \frac{dx}{x} f_q(x) f_{\bar{q}}(\tau/x)$$

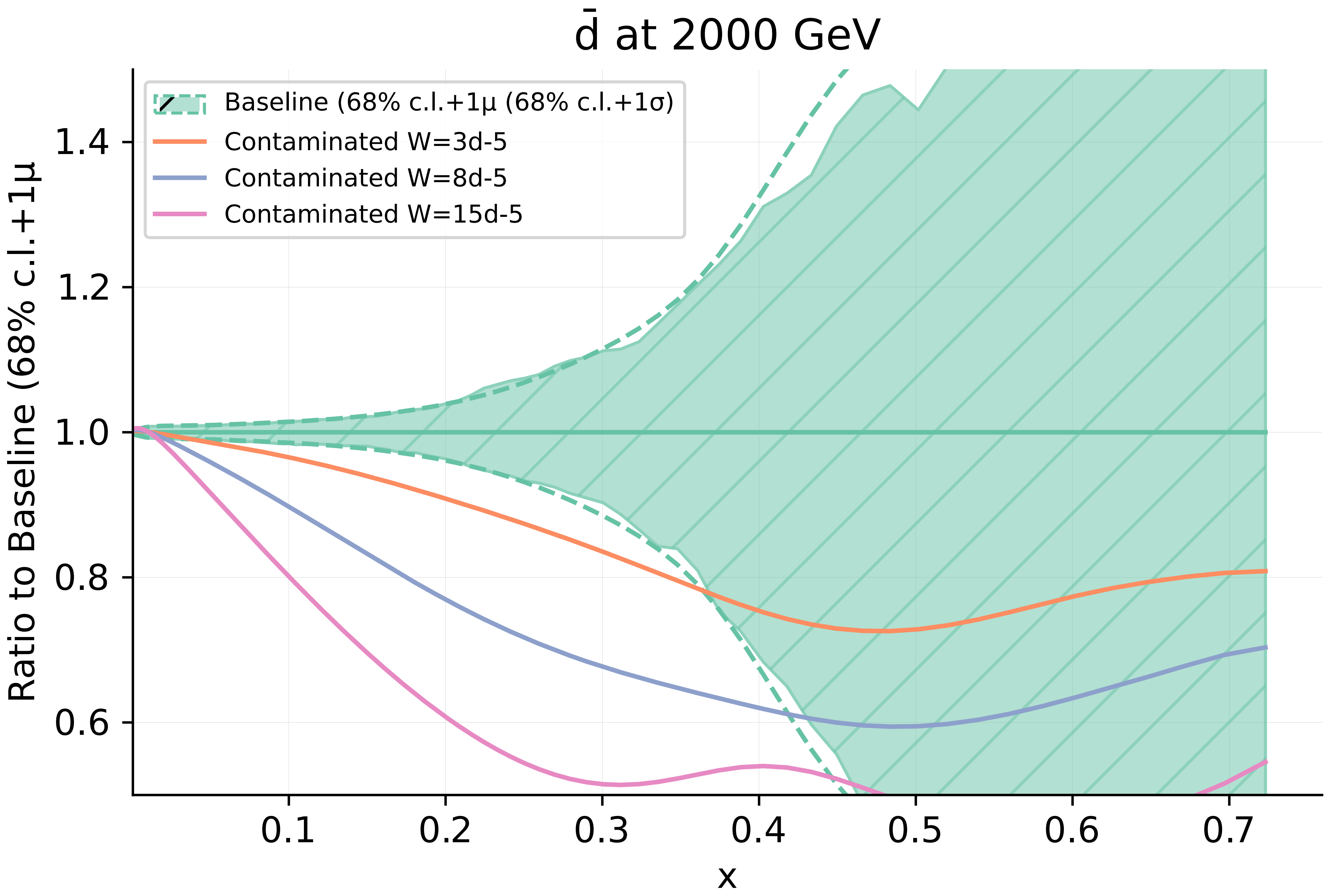


Fewer constraints on the **large-x antiquark PDFs** allow freedom to shift away from the baseline

W'-contaminated PDFs

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

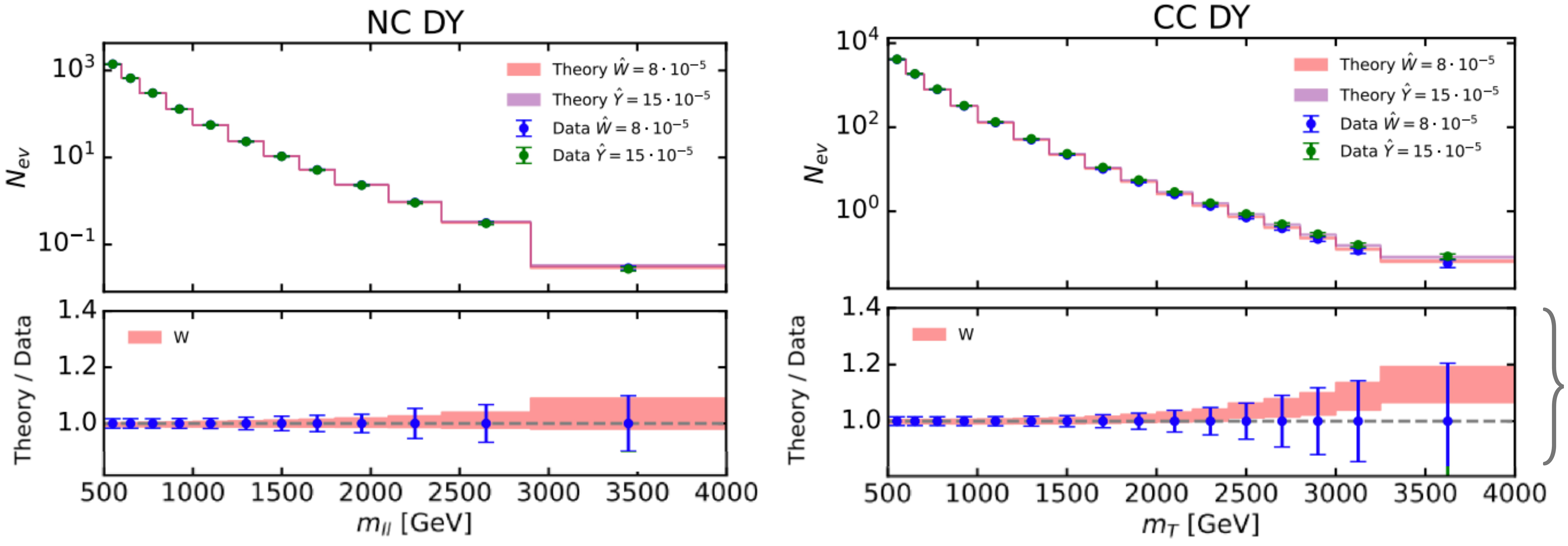




Fewer constraints on the **large-x antiquark PDFs** allow freedom to shift away from the baseline

Impact on Drell-Yan

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

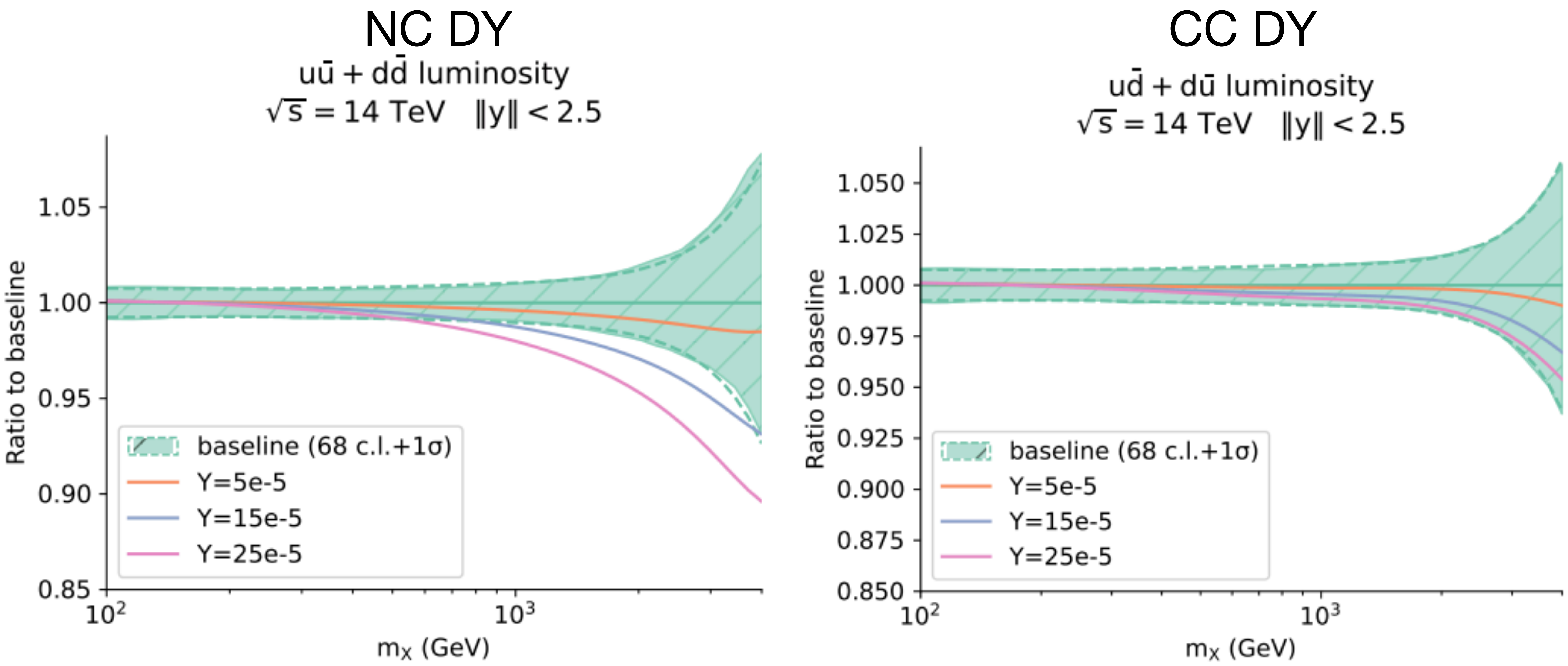


Excellent data-theory agreement

- 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

Z'-contaminated PDFs

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



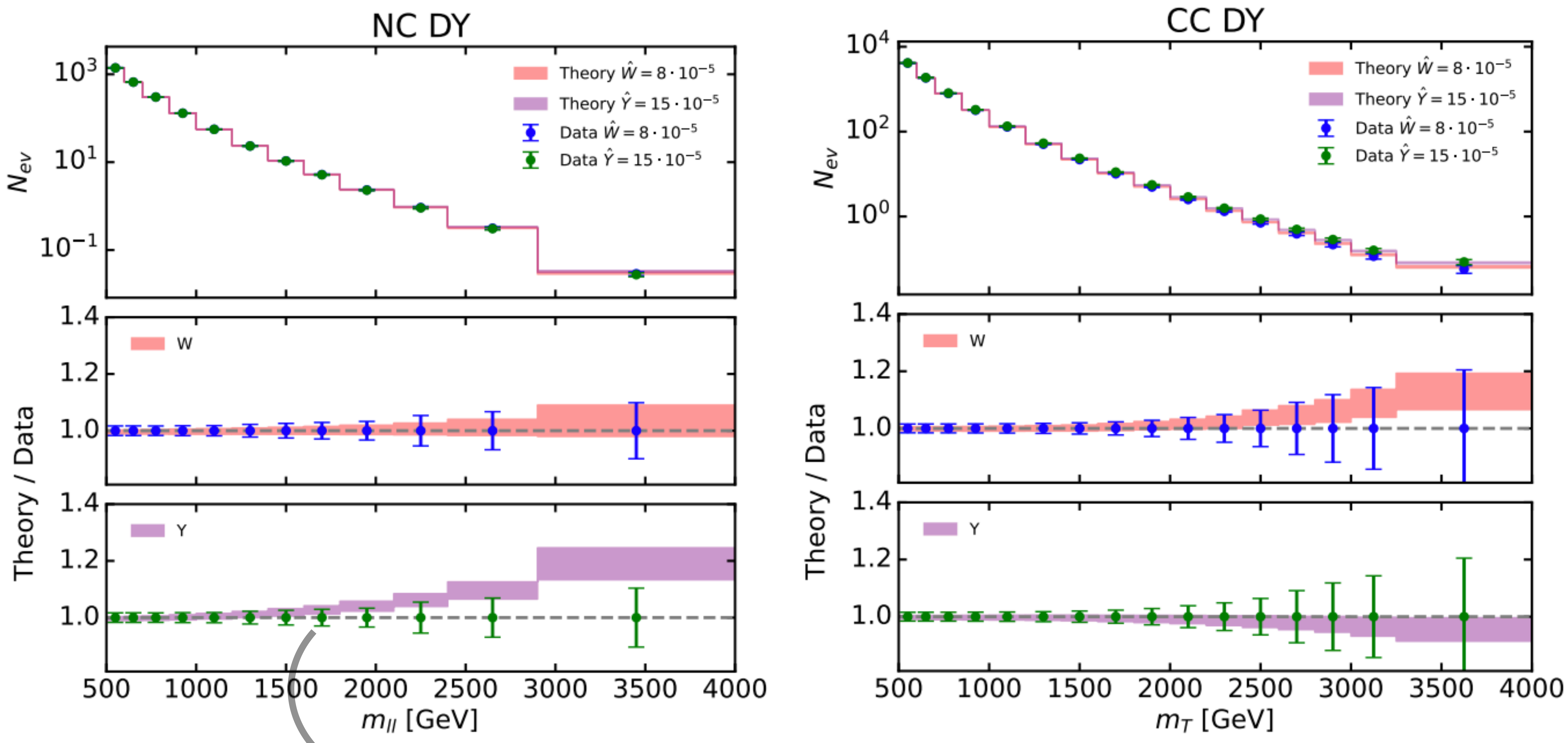
Charged current DY is not impacted by the Z' model

➡ 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 $\otimes$ SM + Z’
Theory: contaminated PDF $\otimes$ SM



PDFs remain SM-like: discrepancy with Z’ in NC DY data

Impact on EW processes

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

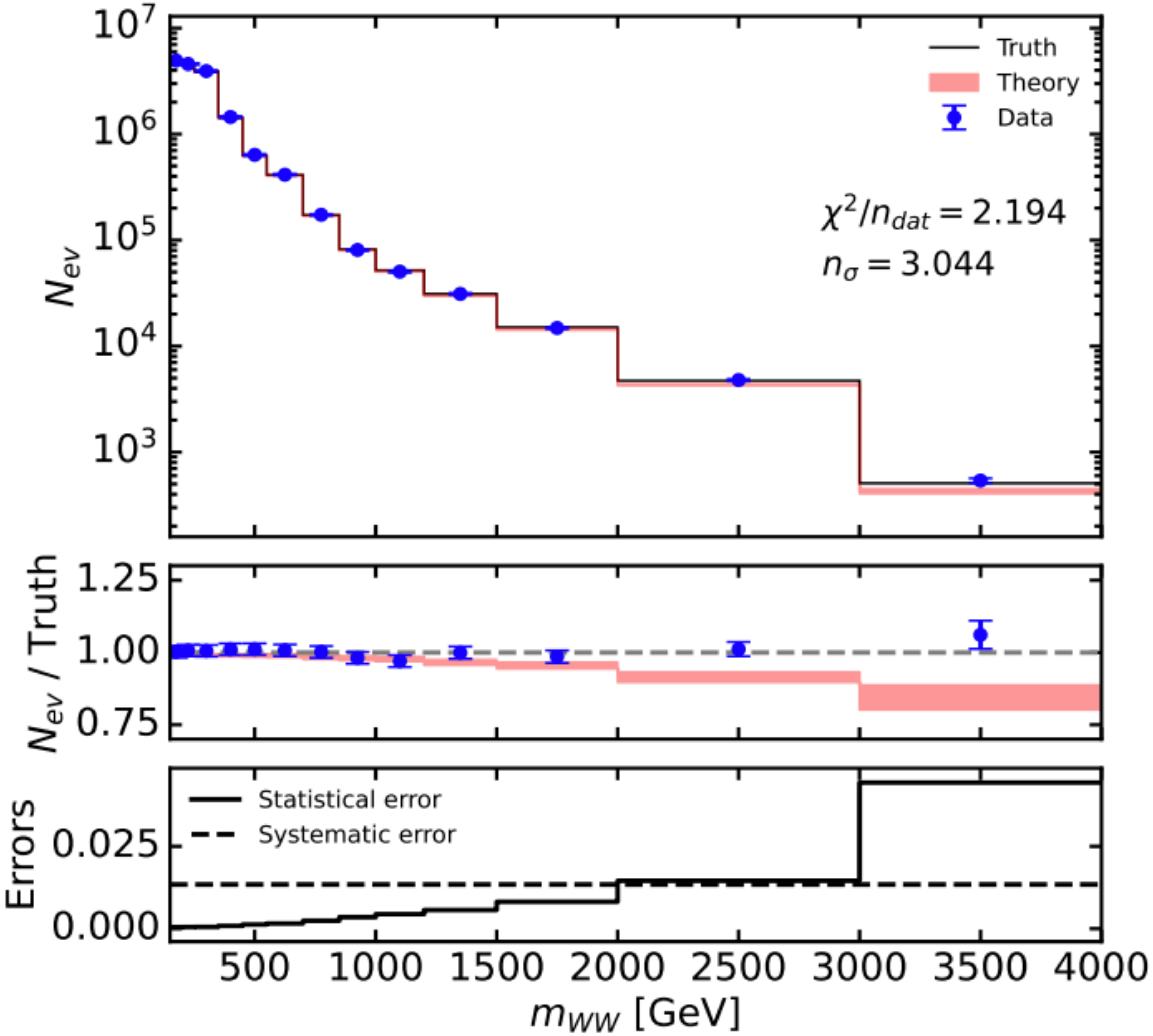
The PDF then causes **spurious NP effects** in other observables e.g.

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

- 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 $\otimes$ SM
Theory: contaminated PDF $\otimes$ SM

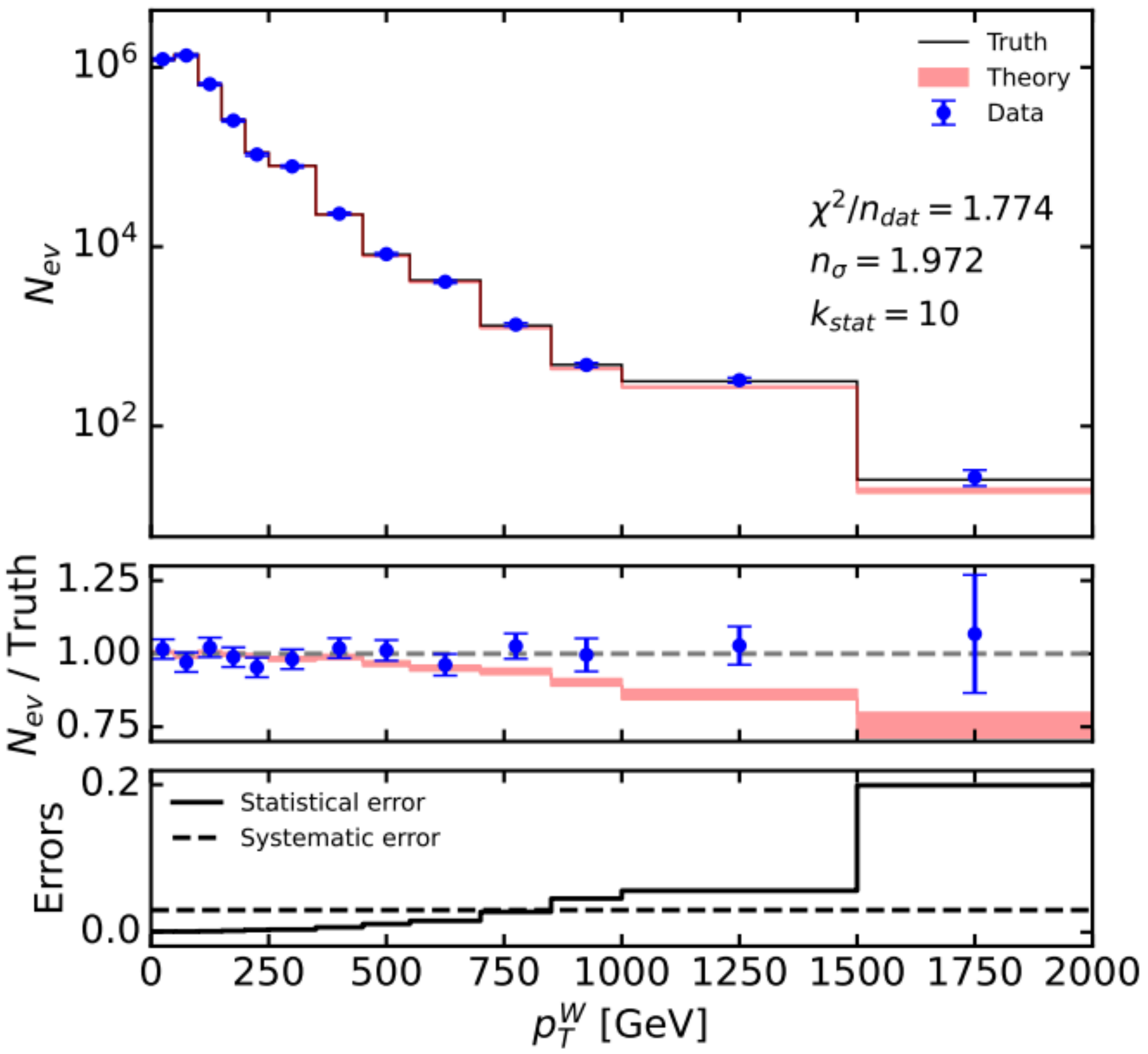
The PDF then causes **spurious NP effects** in other observables e.g.

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

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

  the deviation is in the PDF

HL-LHC projections

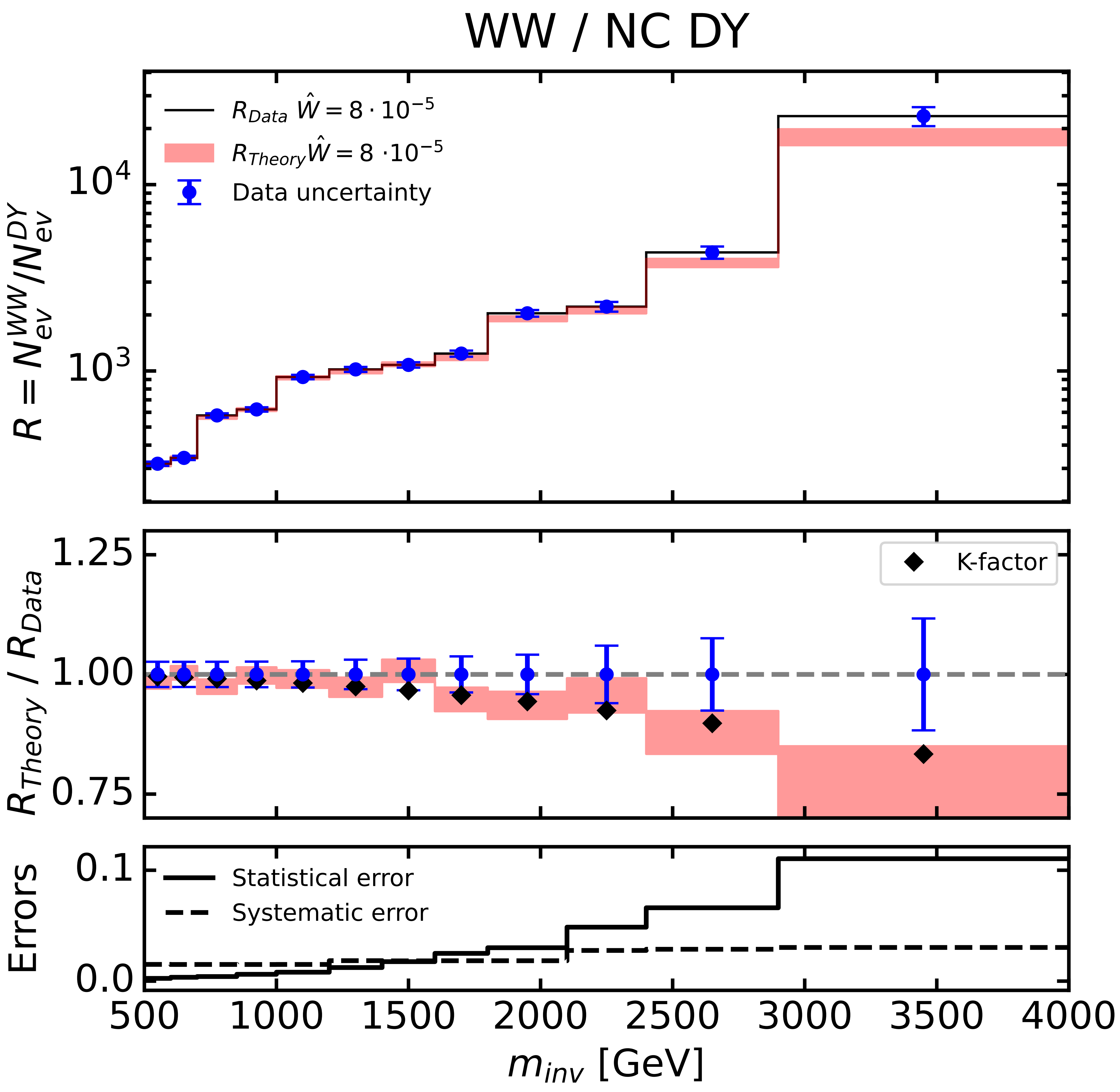


statistics improved by a factor of 10

Opportunities to disentangle PDF and SMEFT effects

Opportunities to disentangle PDF and SMEFT effects

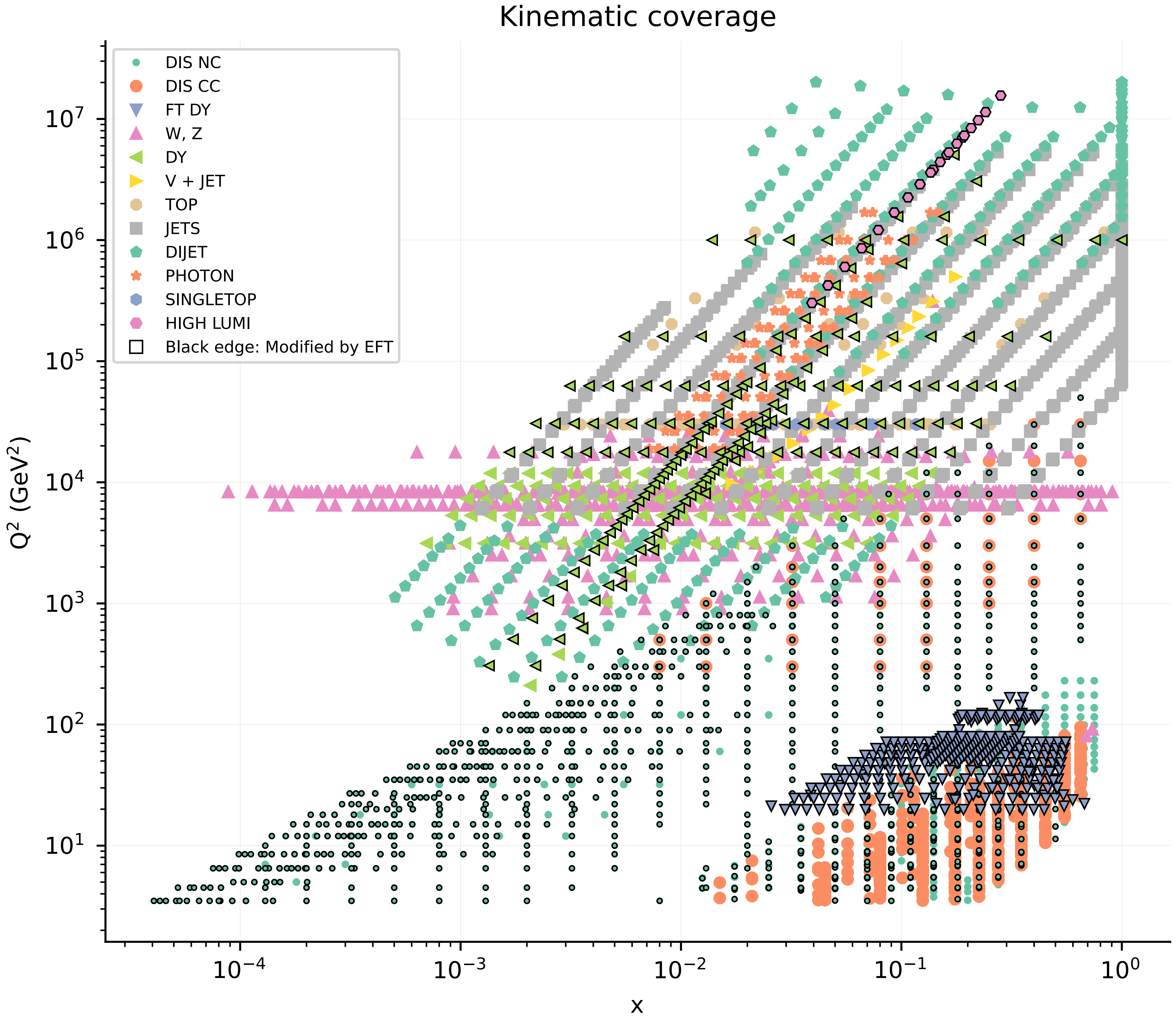
Ratio observables:



Opportunities to disentangle PDF and SMEFT effects

Ratio observables:

Low-energy precision measurements sensitive to high-x PDFs

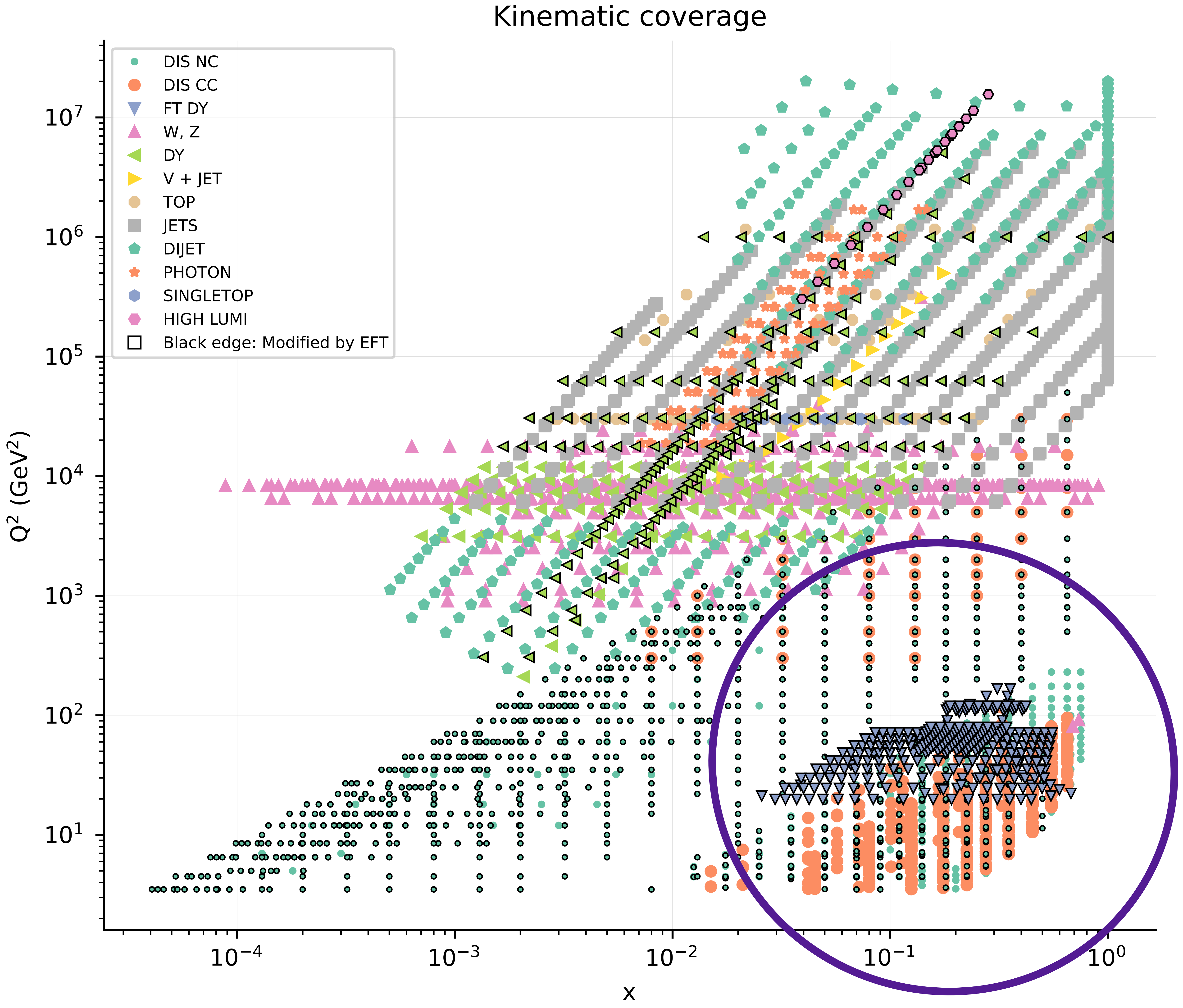


Opportunities to disentangle PDF and SMEFT effects

Ratio observables:

Low-energy precision measurements sensitive to high-x PDFs

➡ add precision here:



Opportunities to disentangle PDF and SMEFT effects

Ratio observables:

Low-energy precision measurements sensitive to high-x PDFs

→ **what about simultaneous PDF and SMEFT determinations?**

The SIMUnet Methodology

S. Iranipour, M. Ubiali, 2201.07240

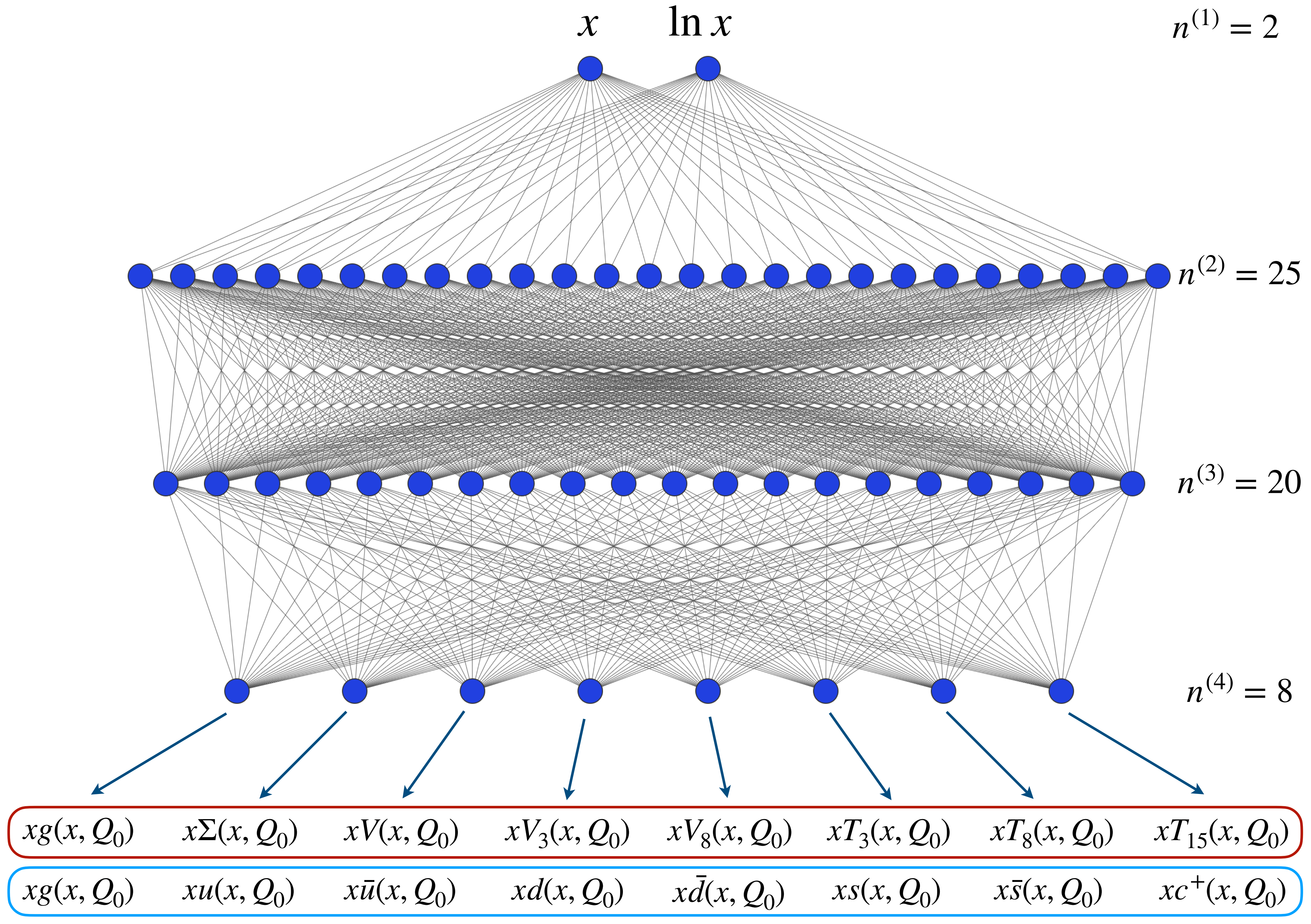
Public release: ***2402.03308,*** **https://hep-pbsp.github.io/SIMUnet**

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

The SIMUnet methodology

An extension of the NNPDF framework

- PDFs parameterised by a neural network

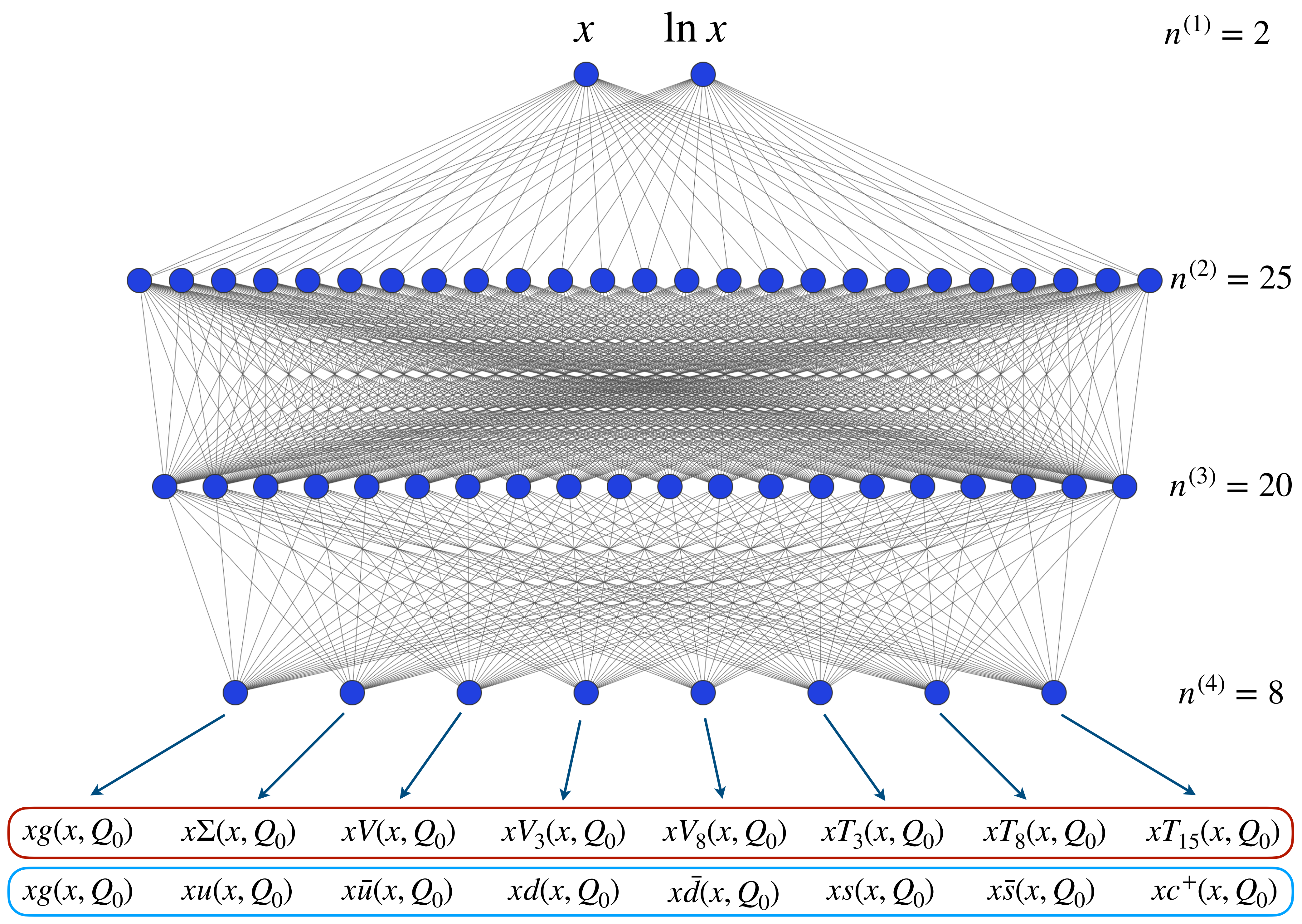


Ball et. al, NNPDF4.0, 2109.02653

The SIMUnet methodology

An extension of the NNPDF framework

- PDFs parameterised by a neural network
- Propagates uncertainties from data to NN parameters using the Monte Carlo replica method



Ball et. al, NNPDF4.0, 2109.02653

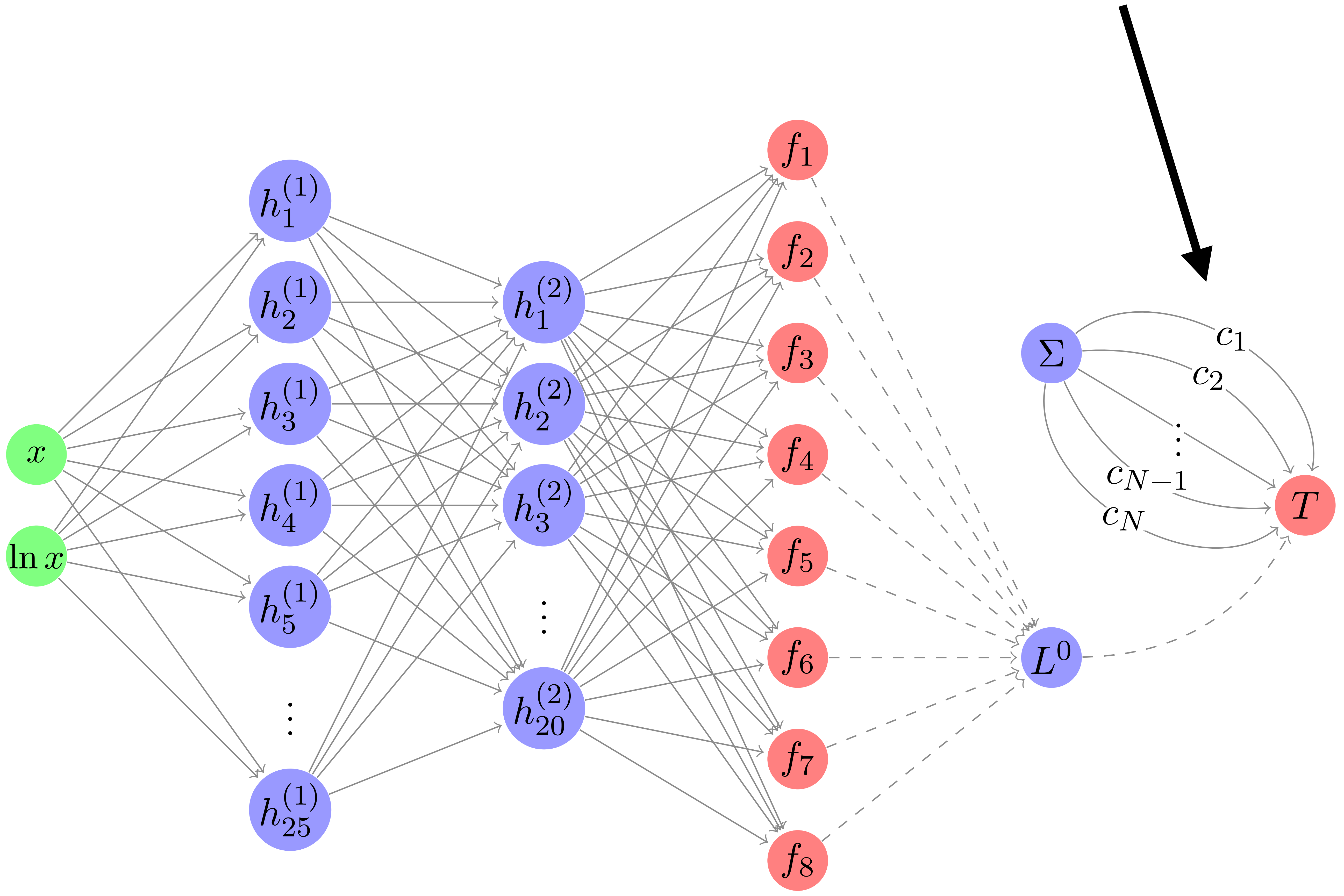
The SIMUnet methodology

Additional layer incorporates SMEFT Wilson coefficients

An extension of the NNPDF framework

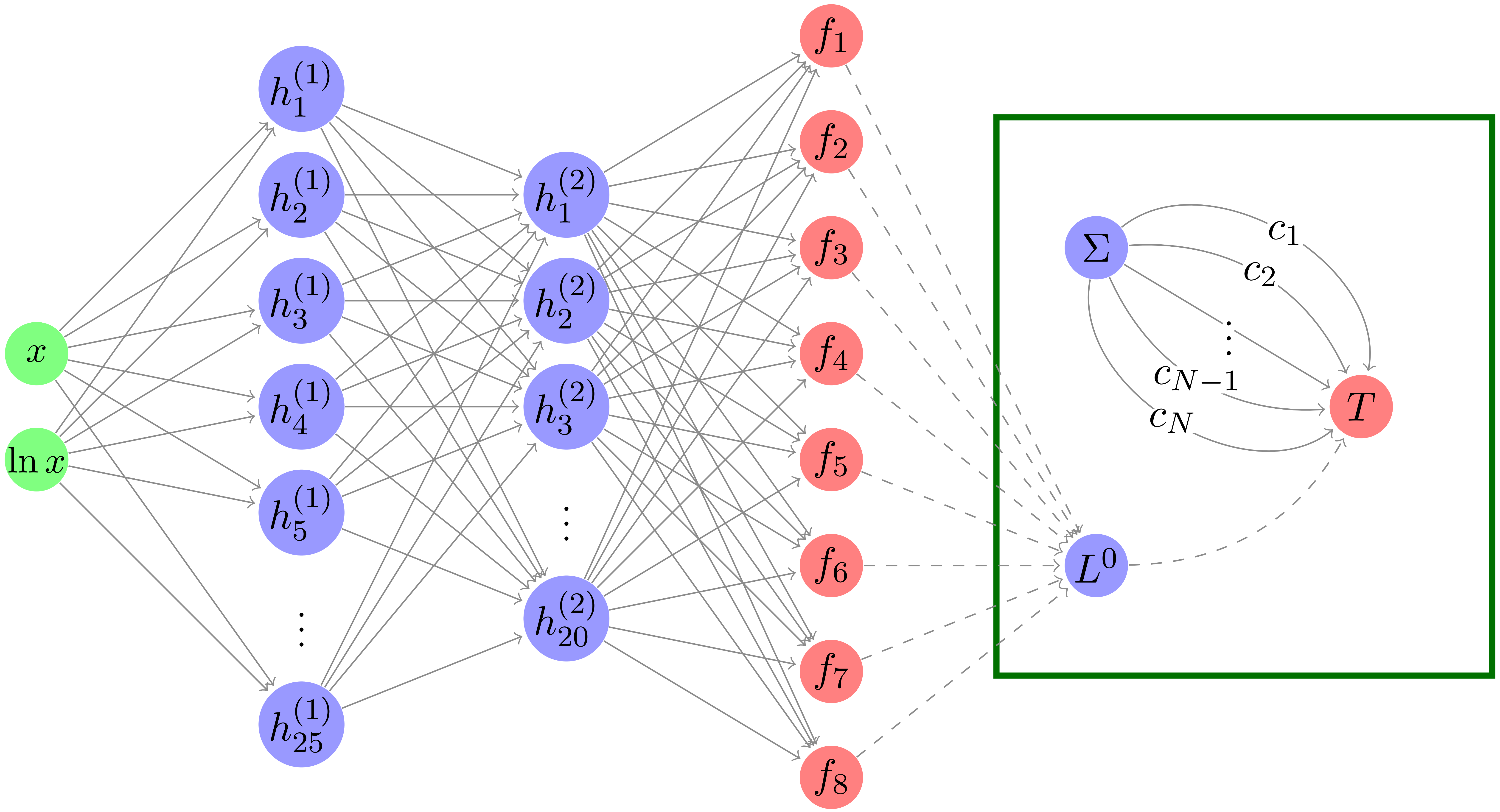
- PDFs parameterised by a neural network

- Propagates uncertainties from data to NN parameters using the Monte Carlo replica method



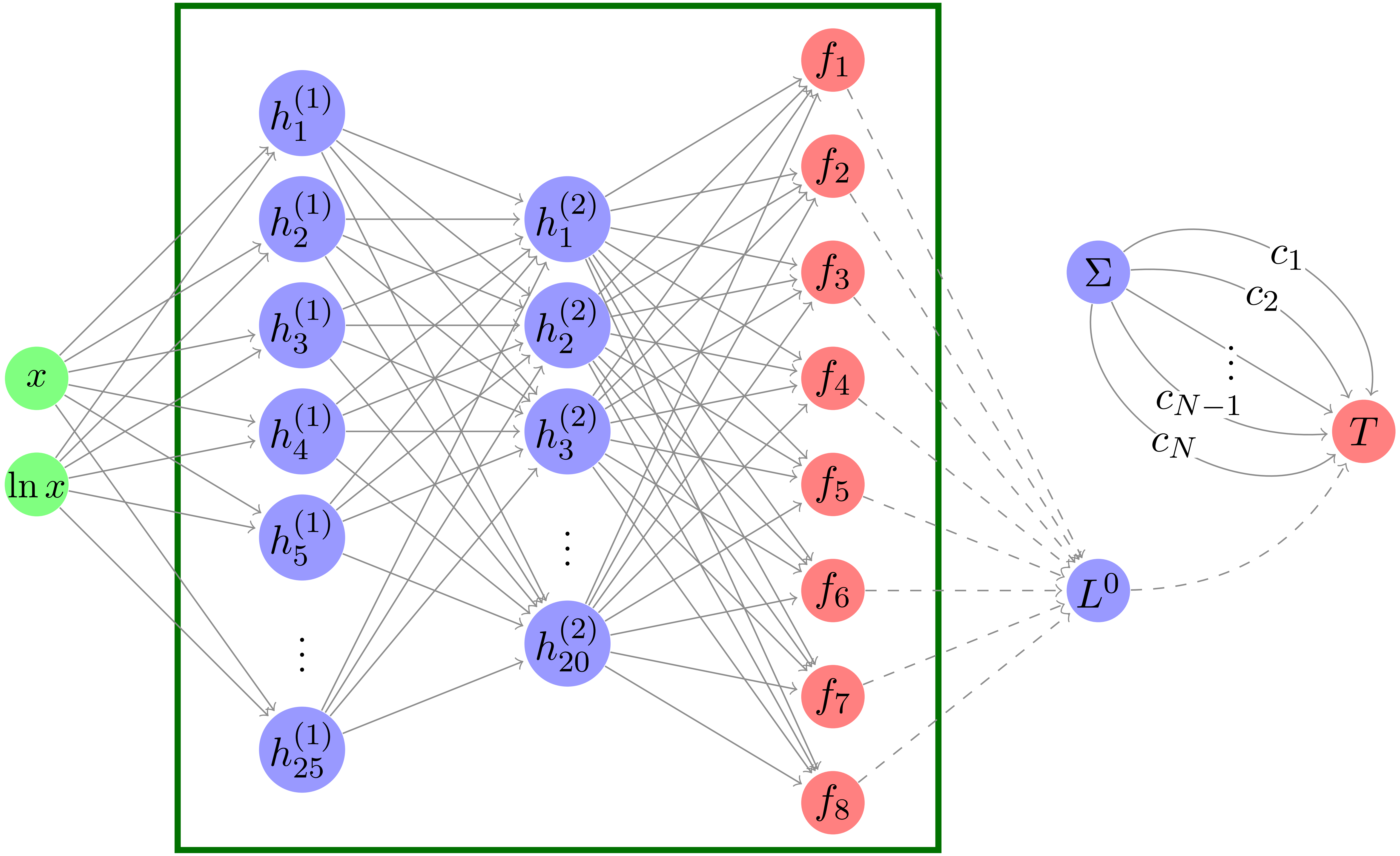
The SIMUnet methodology

Train only the final layer: reproduce SMEFT fits



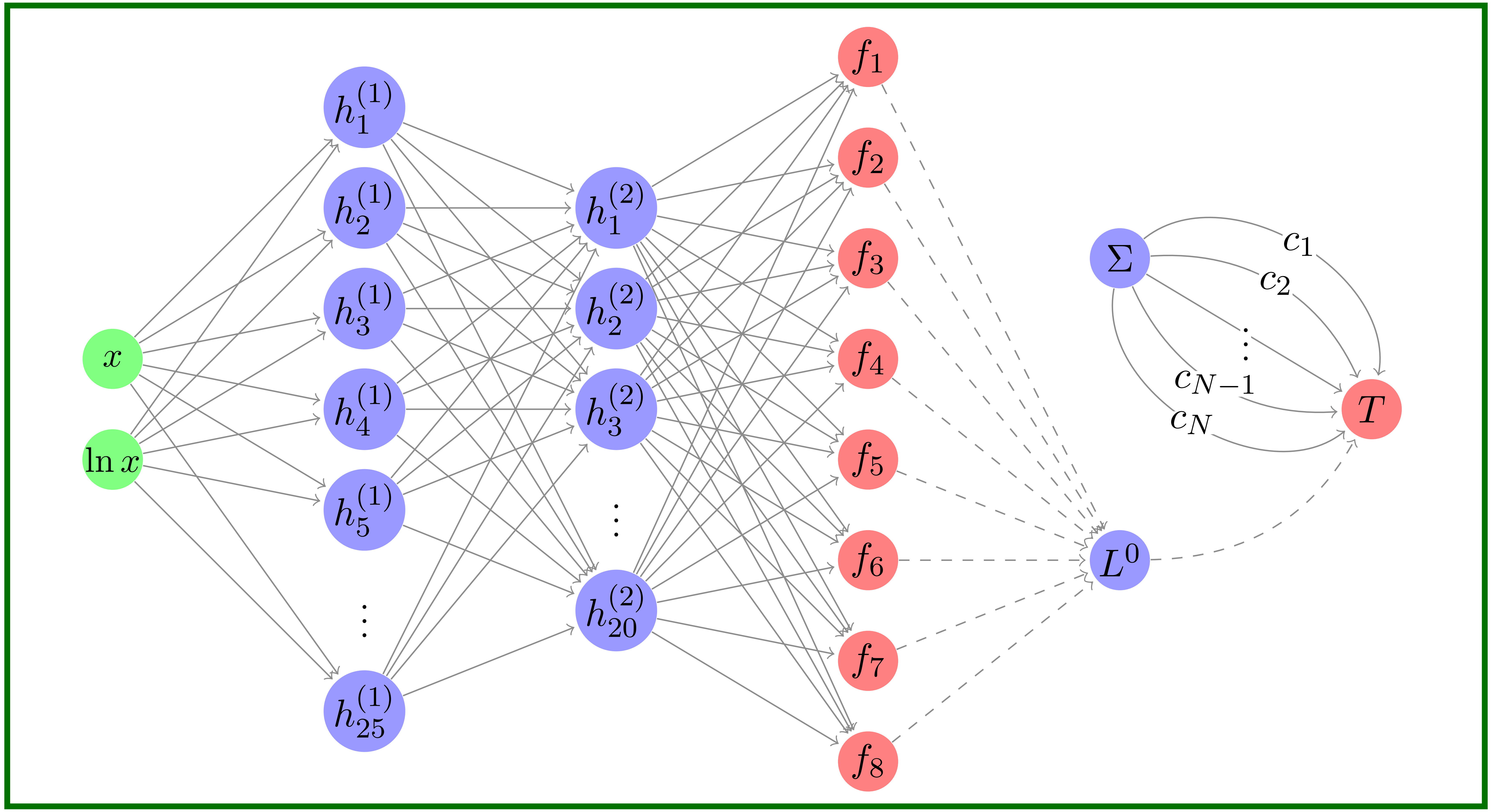
The SIMUnet methodology

Train only the PDF NN weights on all data: reproduce NNPDF



The SIMUnet methodology

Train everything: **simultaneous fit**



The SIMUnet release

- Simultaneous fits of PDFs and linear SMEFT effects
- + Fits of linear combinations of Wilson coefficients
- PDF-independent observables
- Tests for new physics absorption

https://hep-pbsp.github.io/SIMUnet/

+ new data from the Higgs, diboson, electroweak, Drell-Yan and top sectors

+ Tutorials, website and documentation

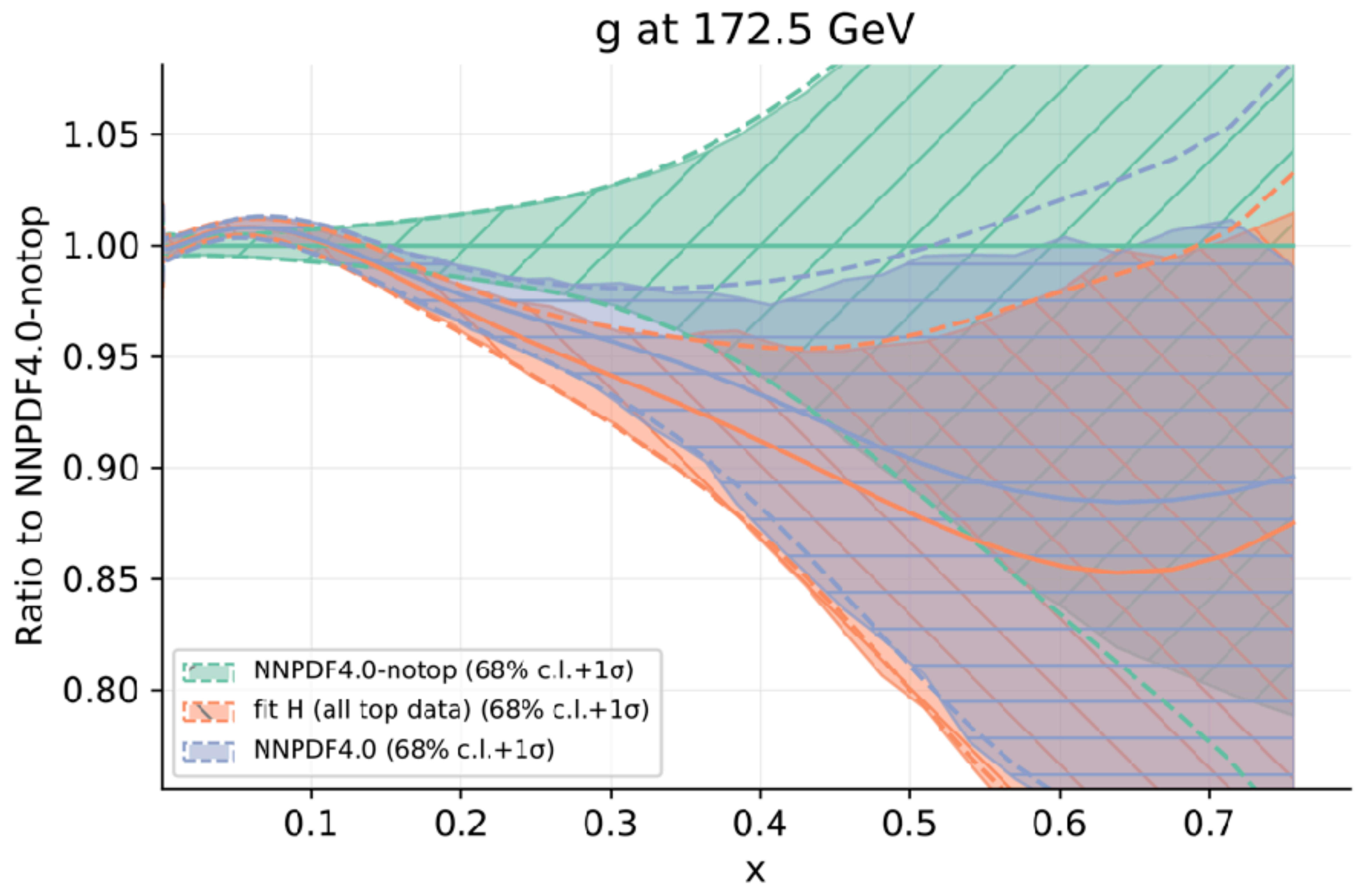
Simultaneous PDF and SMEFT determination in the top sector

Z. Kassabov, MM, L. Mantani, J. Moore, M. Morales Alvarado, J. Rojo, M. Ubiali 2303.06159

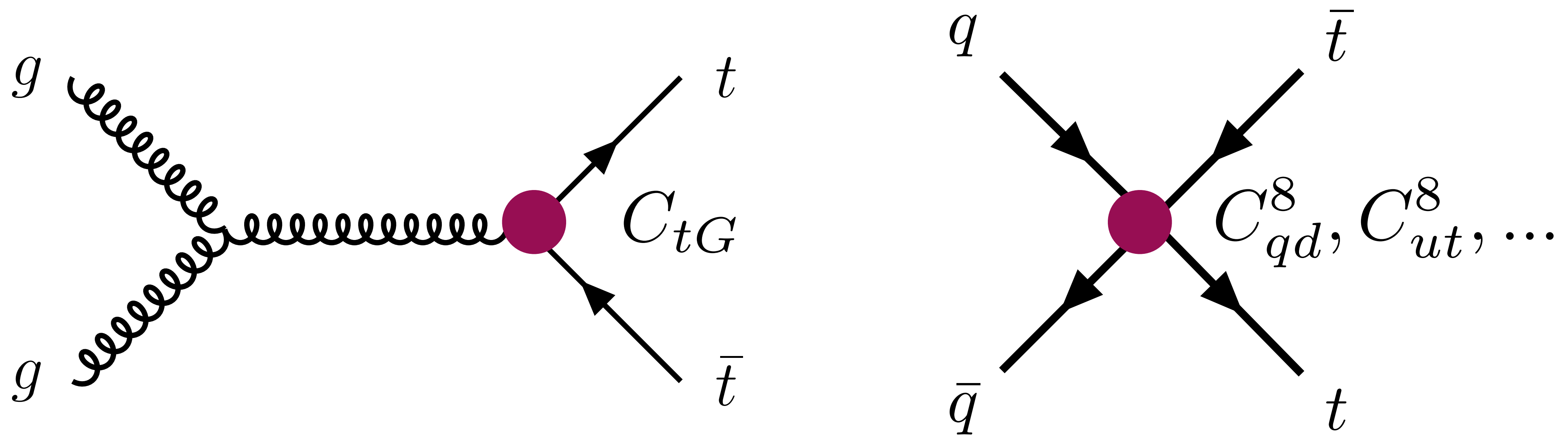
PDF-EFT interplay **in the top sector**

Top quark data provides important constraints on the large-*x* region of the gluon PDF.

This impact is largely driven by **top quark pair production** cross sections and differential distributions.
e.g. Czakon et. al, 1303.7215, 1611.08609, 1912.08801

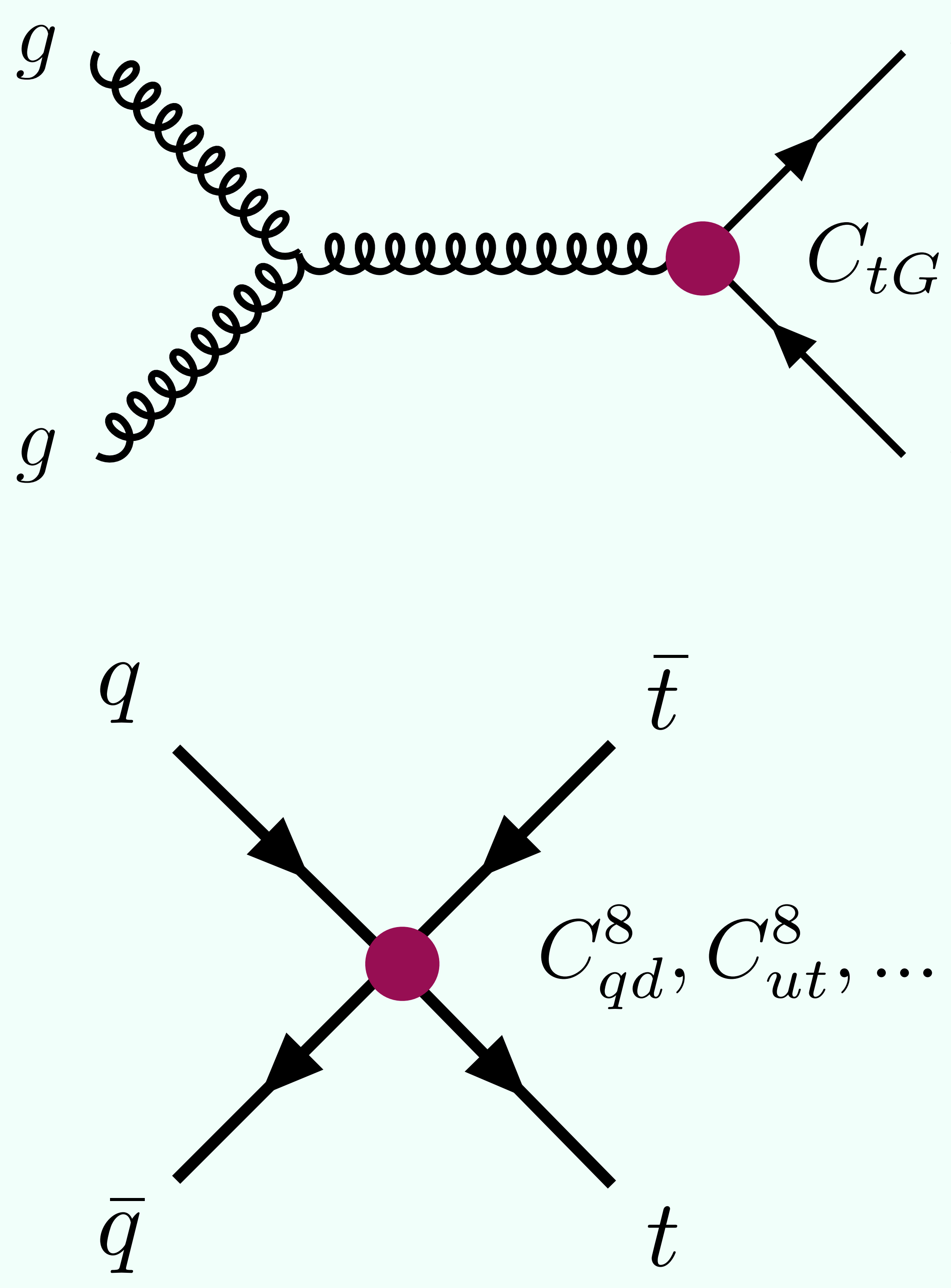


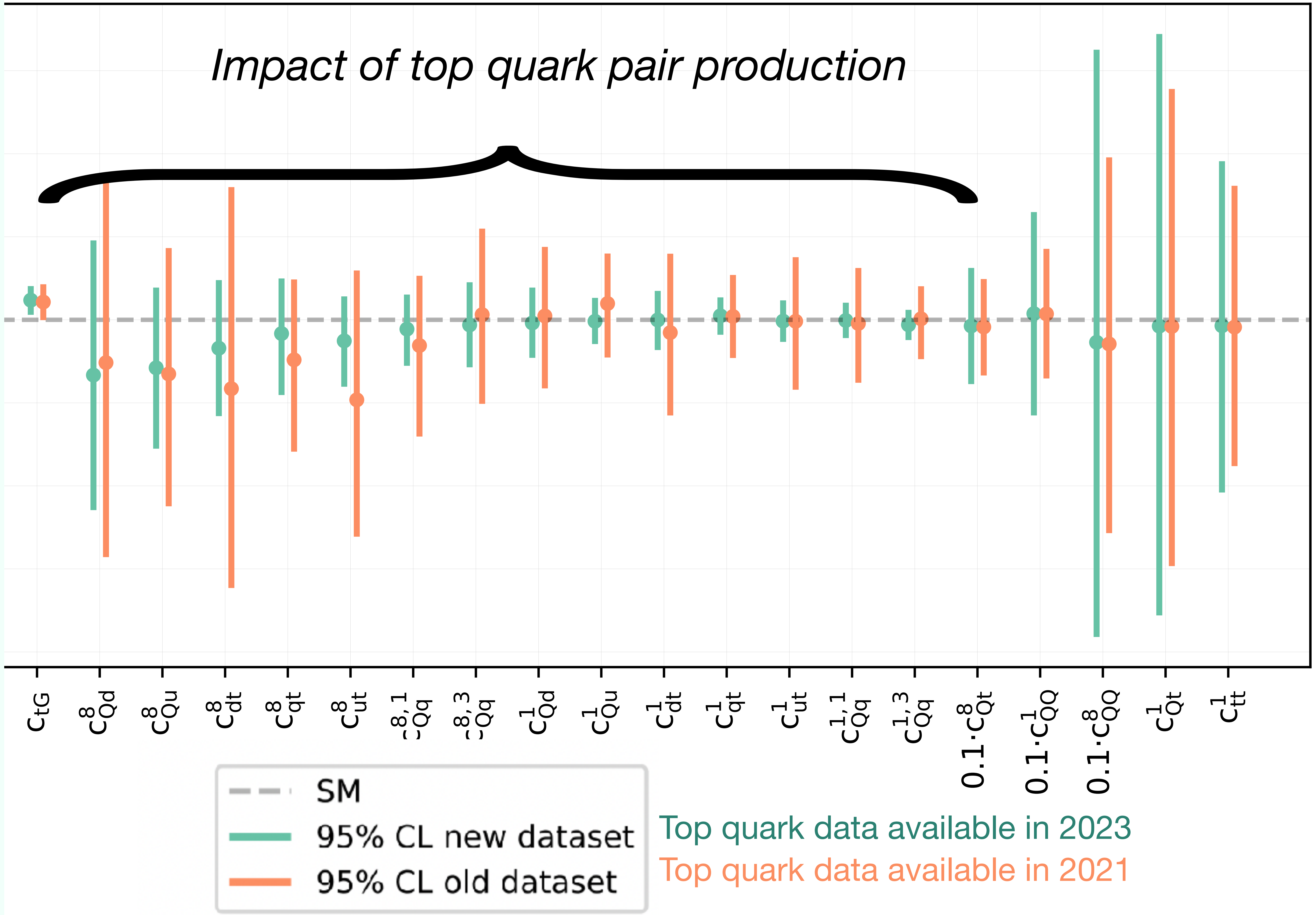
Potential for interplay between **gluon PDF** and coefficients modifying top quark pair production:



The top sector of the SMEFT

Z. Kassabov et. al , 2303.06159





Top quark data available in 2023

Top quark data available in 2021

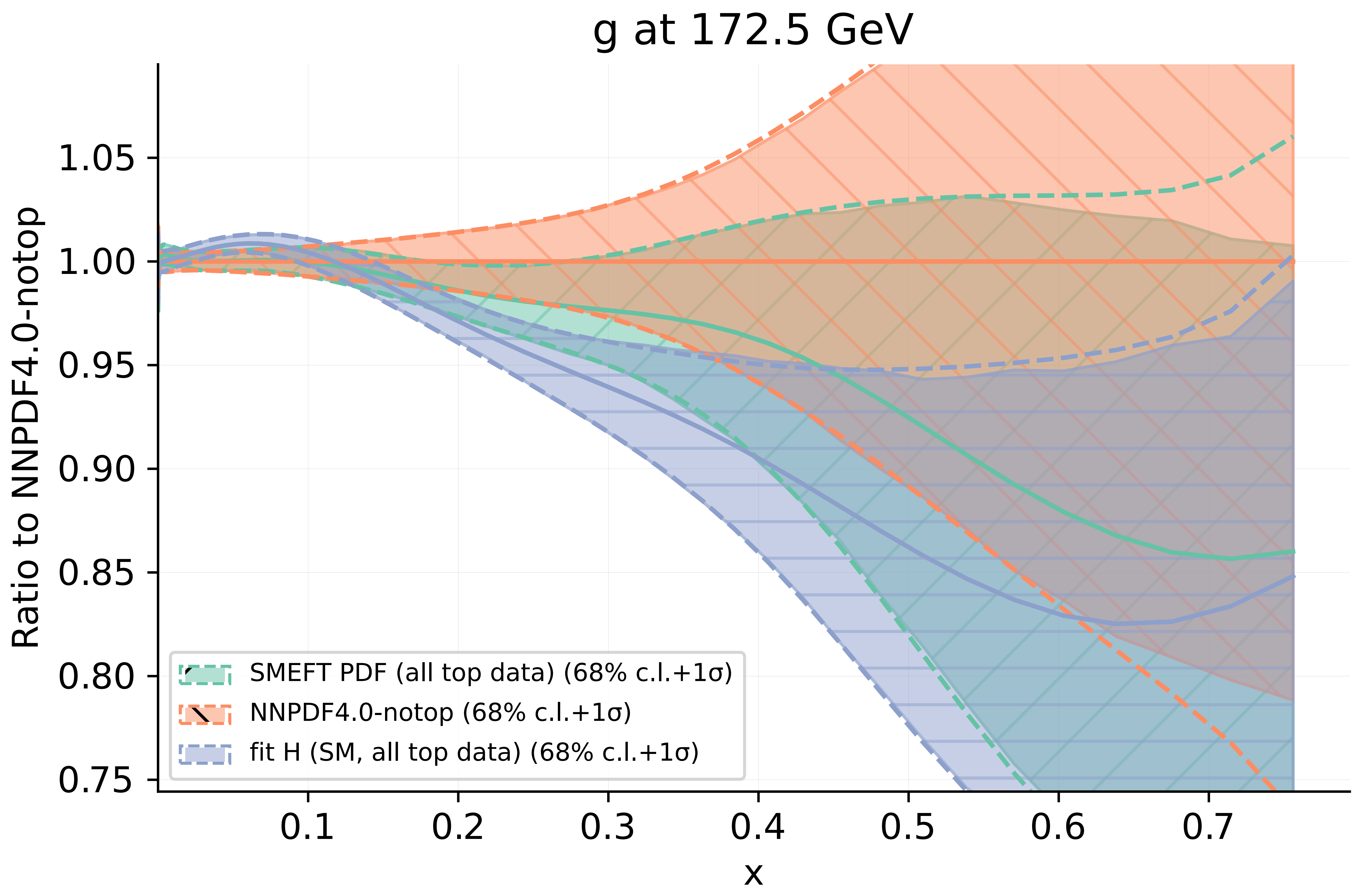
Simultaneous fit

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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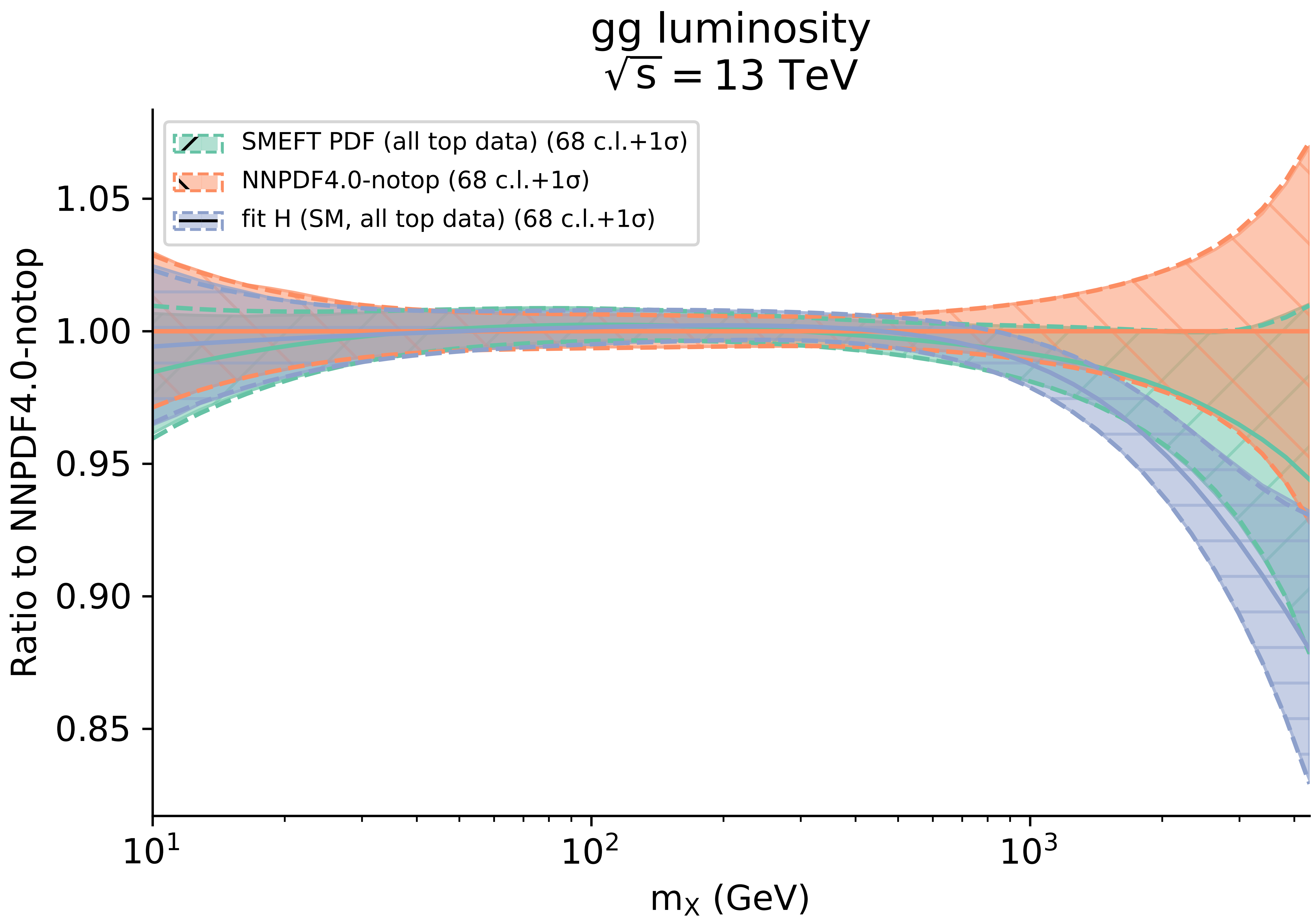
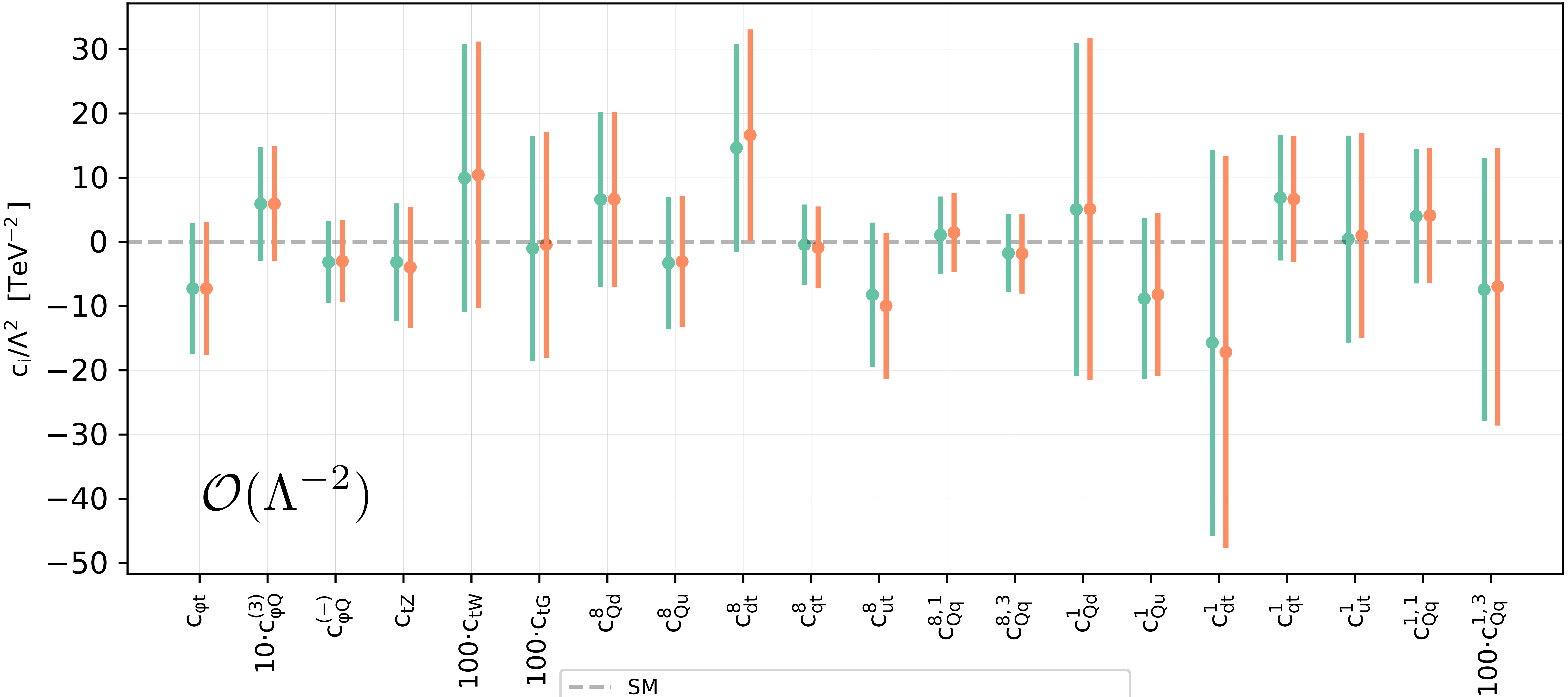


Simultaneous fit of the top sector

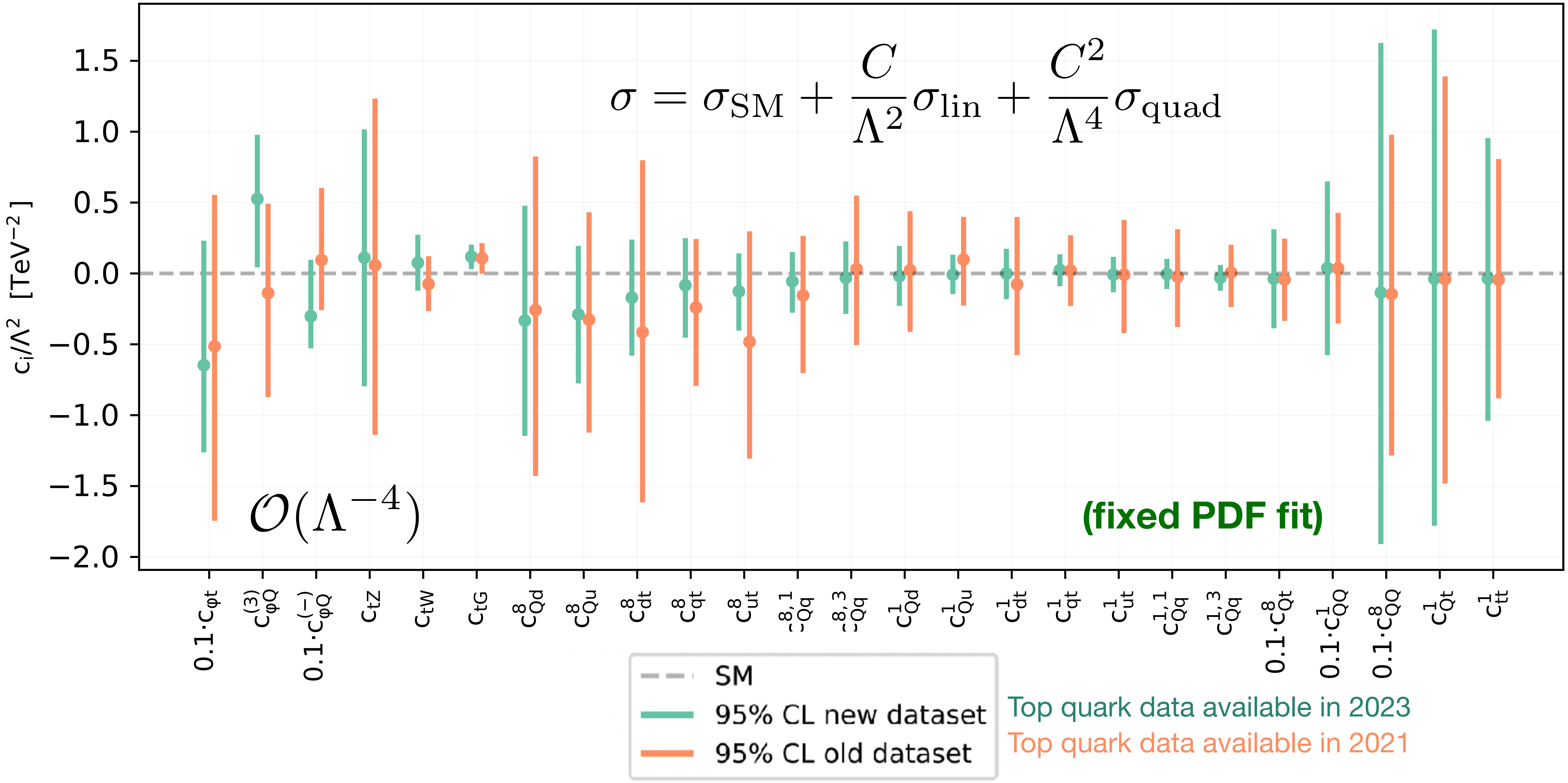
Constraints on the Wilson coefficients are **stable**, despite differences in PDFs



Conservative PDF fit -
only SMEFT fit sees top data

Simultaneous fit

What about quadratic EFT effects?

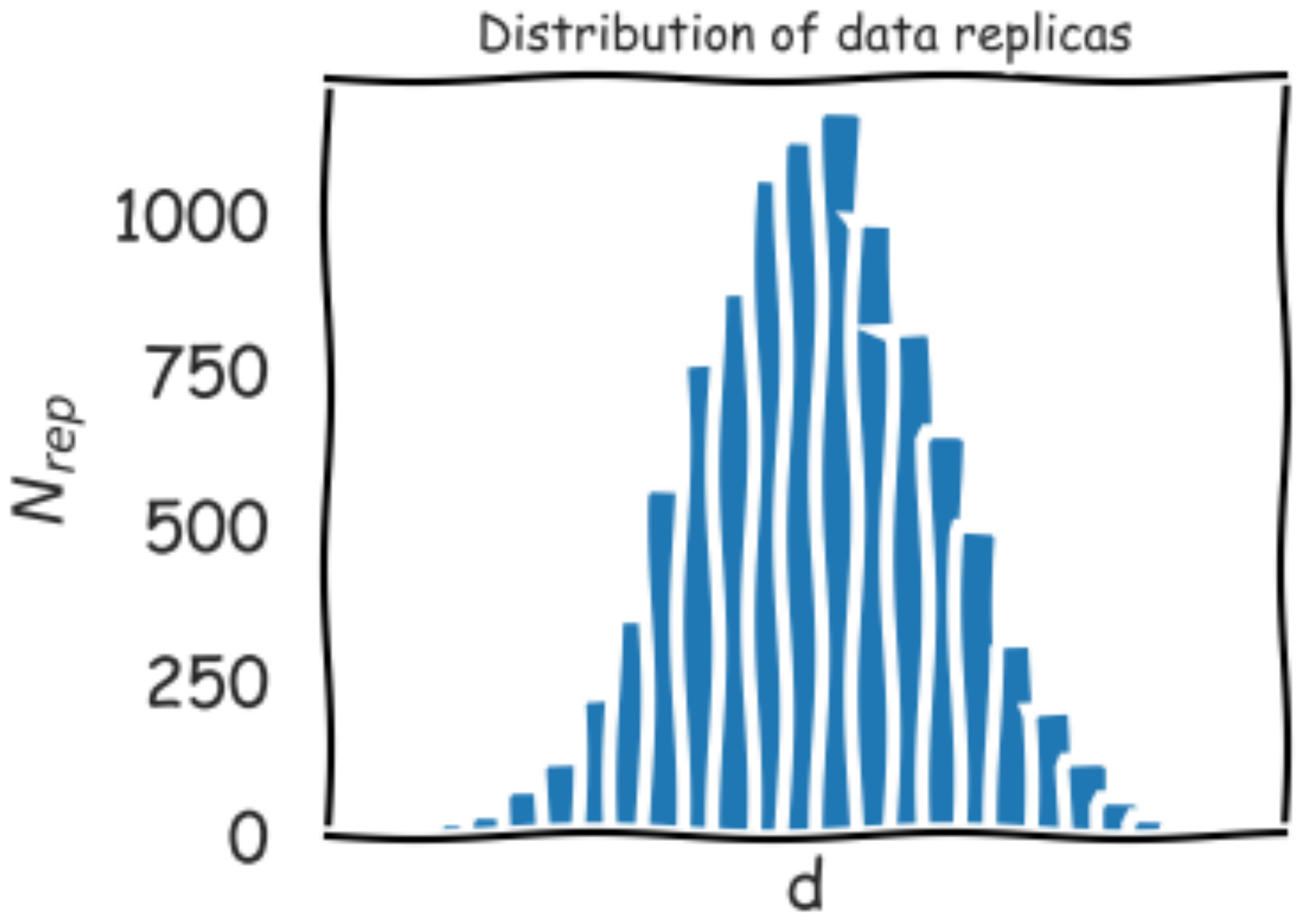


Top quark data available in 2023

Top quark data available in 2021

Monte Carlo Replica Method

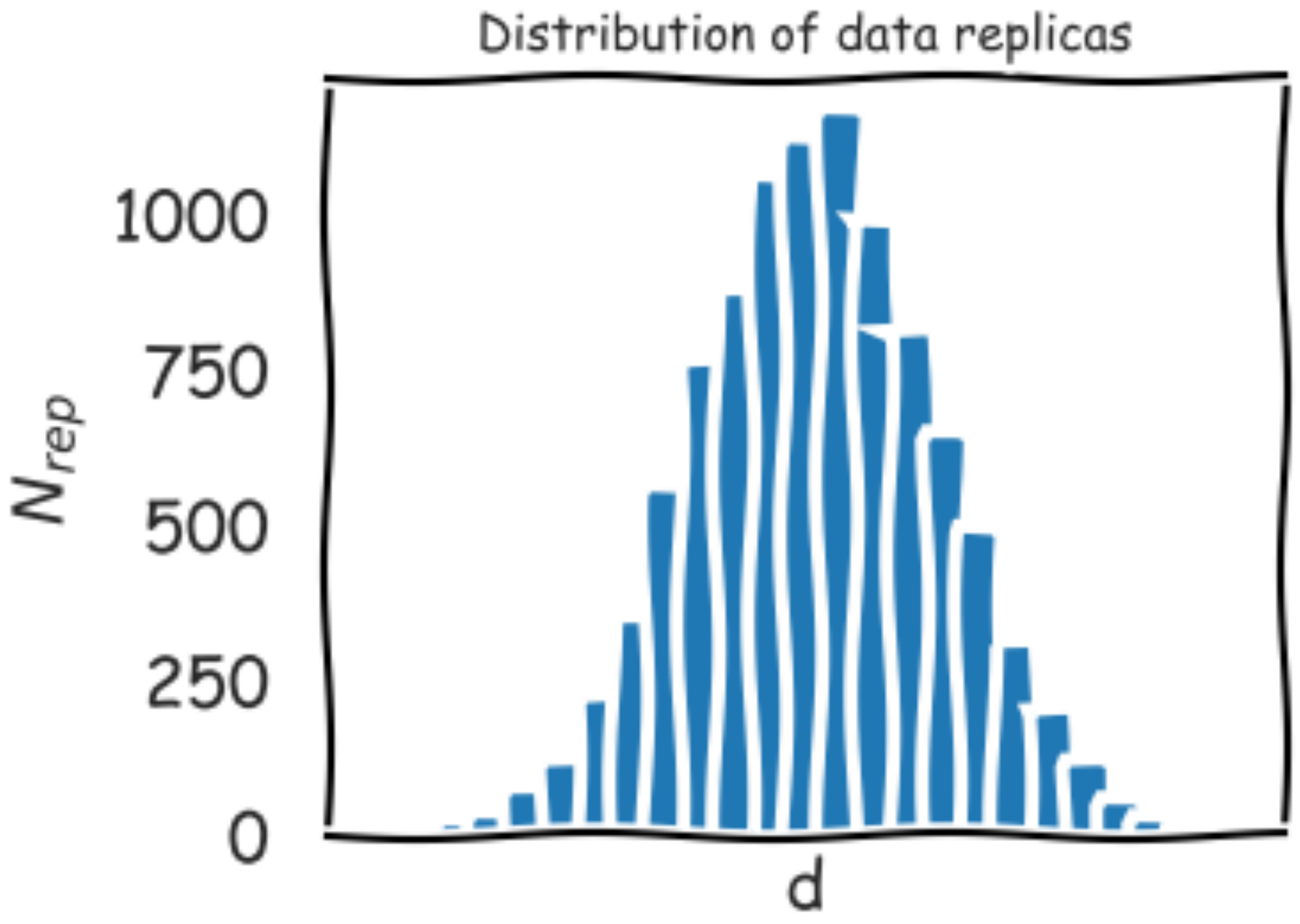
Consider a measurement *d,* with uncertainty σ

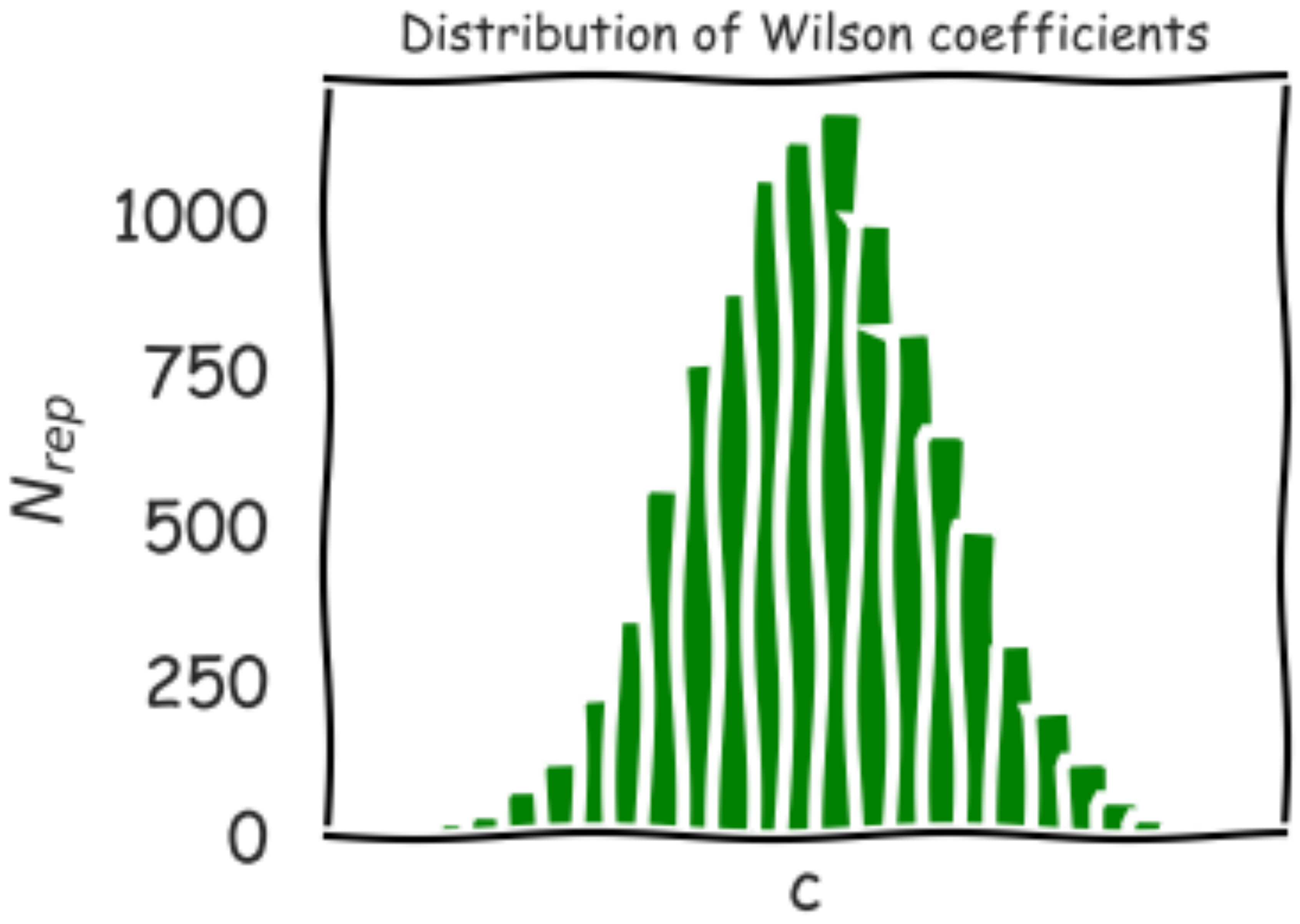


$$d_k \sim \mathcal{N}(d, \sigma)$$

Monte Carlo Replica Method

Consider a measurement *d,* with uncertainty σ





$$d_k \sim \mathcal{N}(d, \sigma) \longrightarrow c_k = \arg\min_c \chi^2(c, d_k)$$

Monte Carlo Replica Method: caveat

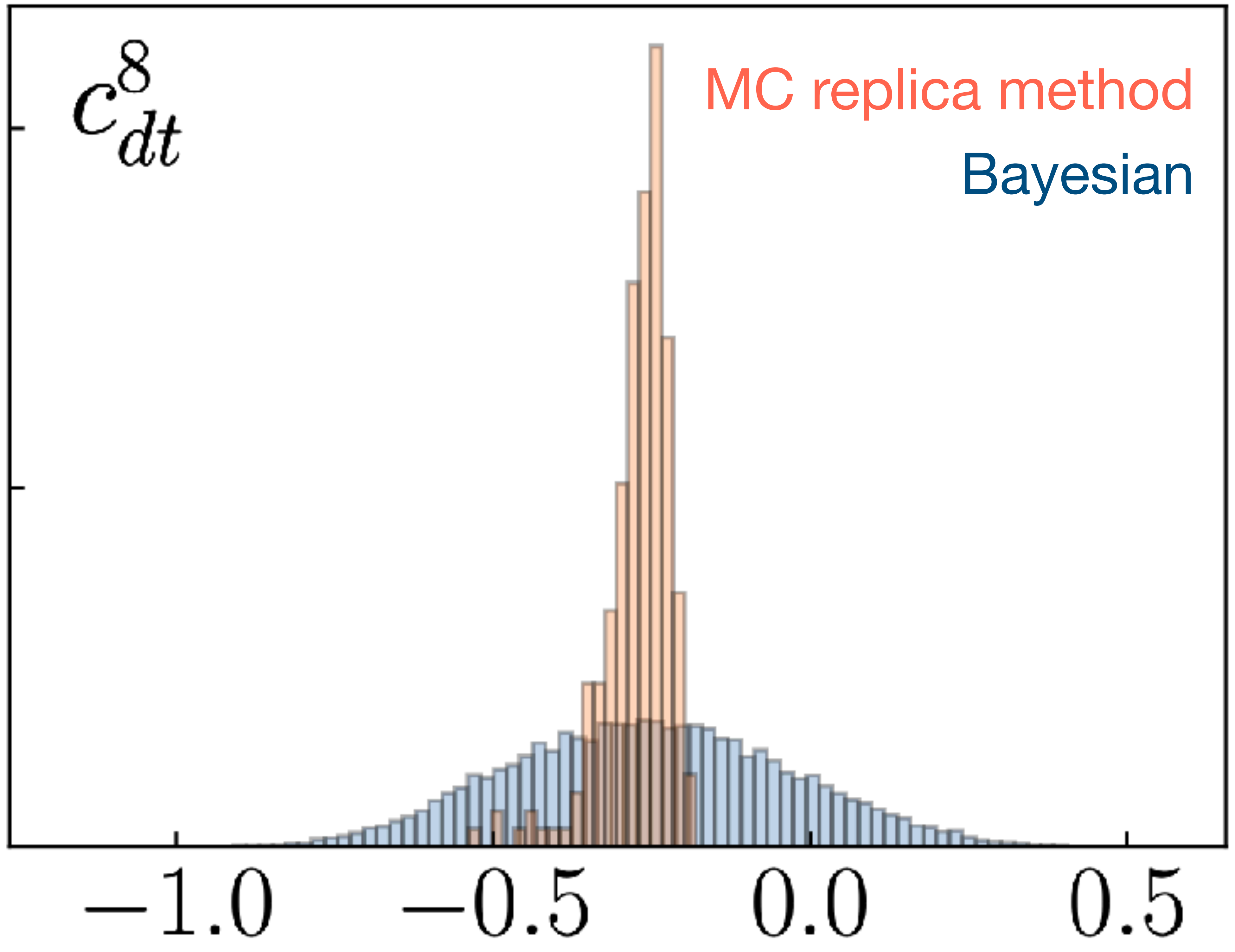
This methodology only provides reliable confidence intervals for linear SMEFT

$$\sigma(c) = \sigma_{\rm SM} + \sigma_{\rm lin} c + \sigma_{\rm quad} c^2$$

Inclusion of the quadratic term may lead to an artificial 'spiked' distribution

Work in progress assess the implications for PDF uncertainties

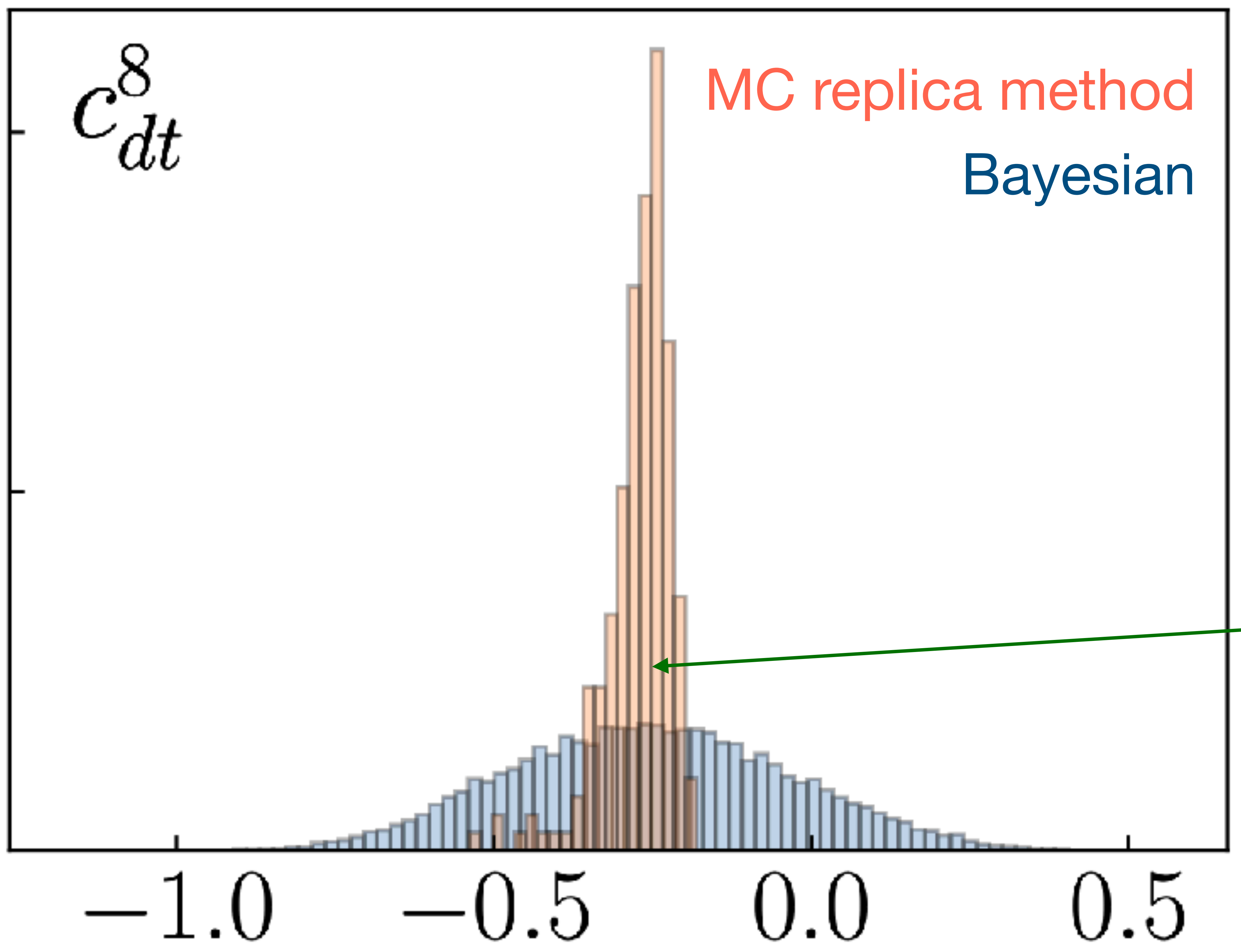
M.N.Constantini, MM, L. Mantani, J. Moore (arXiv tomorrow!)

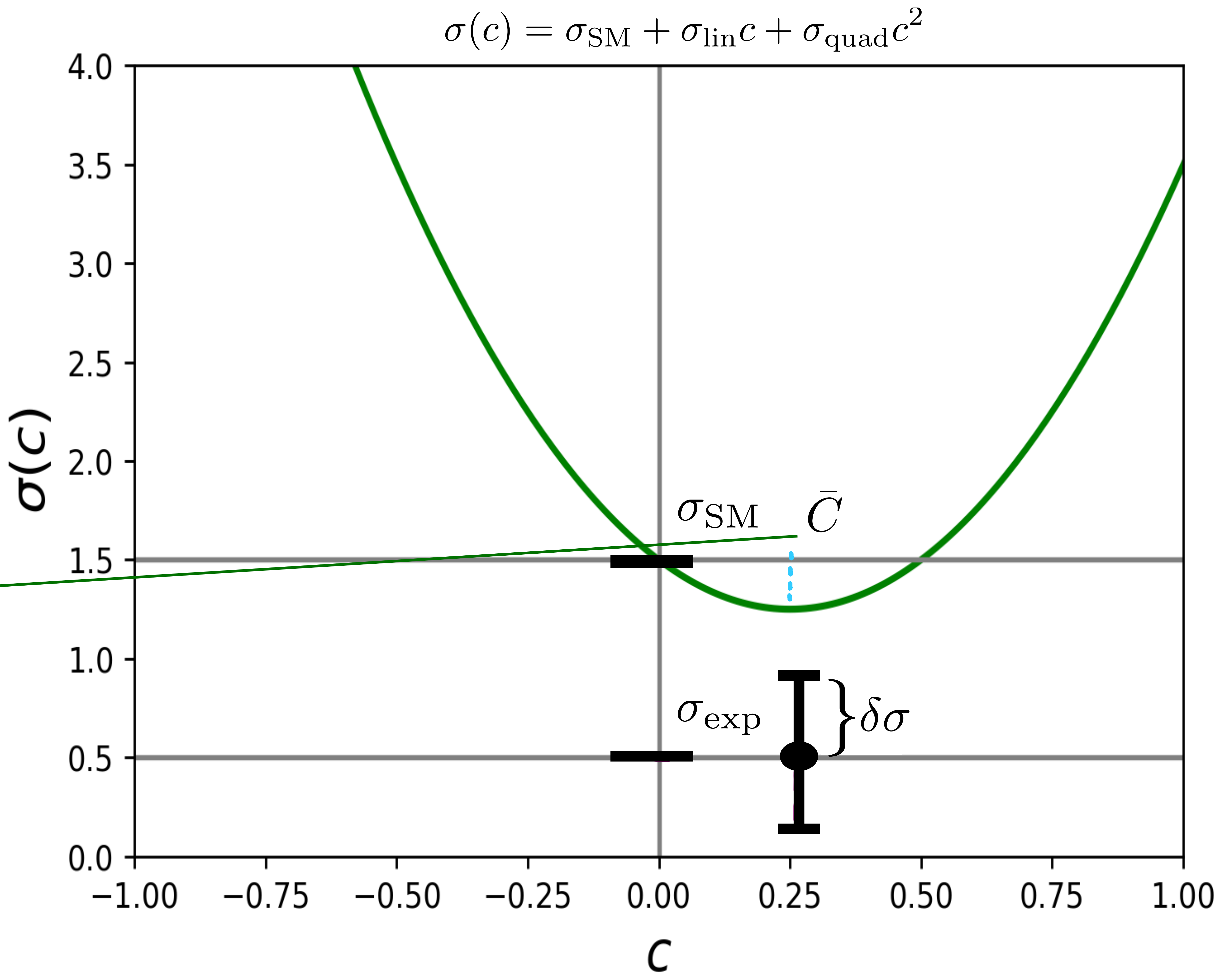


Z. Kassabov et. al , 2303.06159

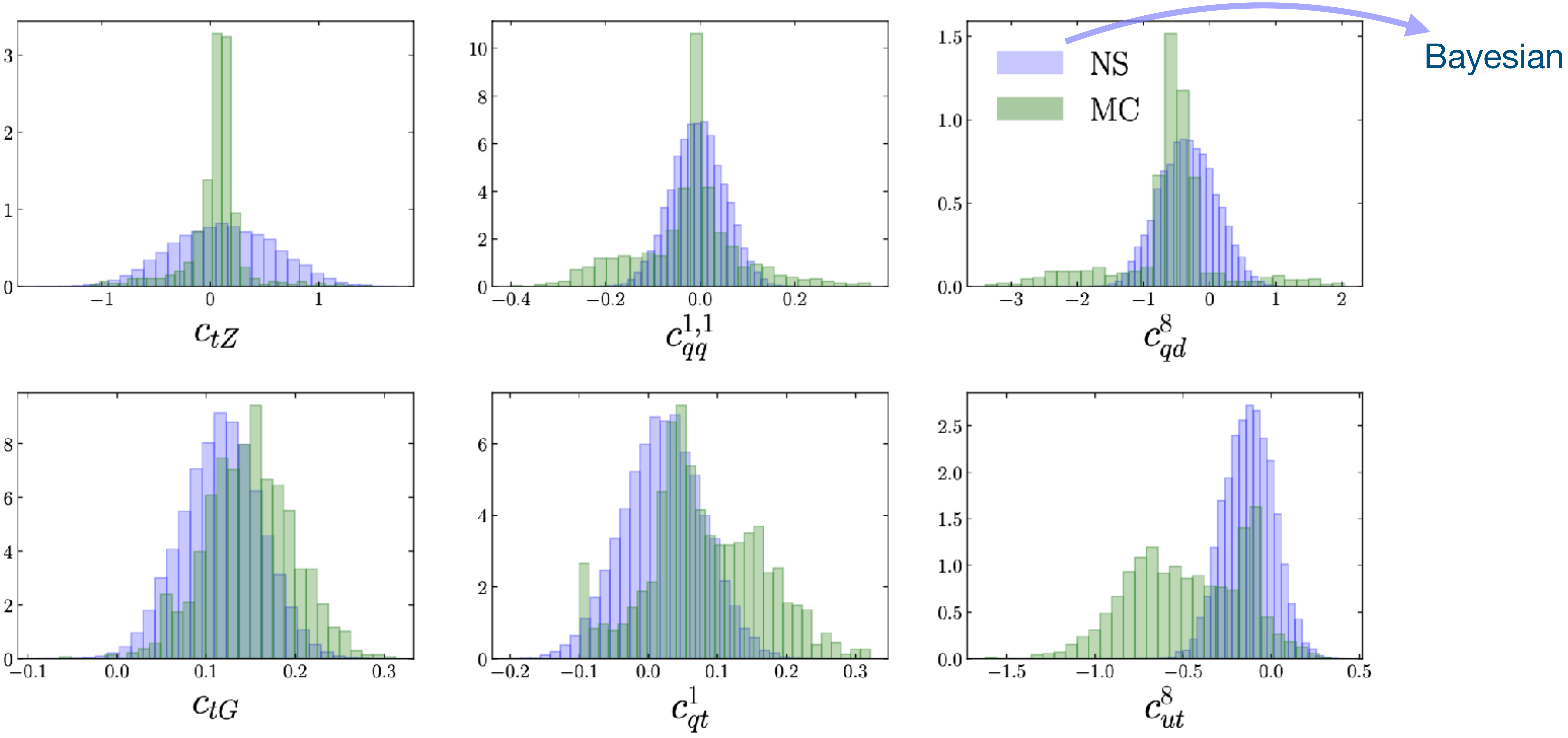
Monte Carlo Replica Method: caveat

Problem: in the presence of a quadratic theory, often the minimum χ^2 will be given by the same $\bar{c}$.



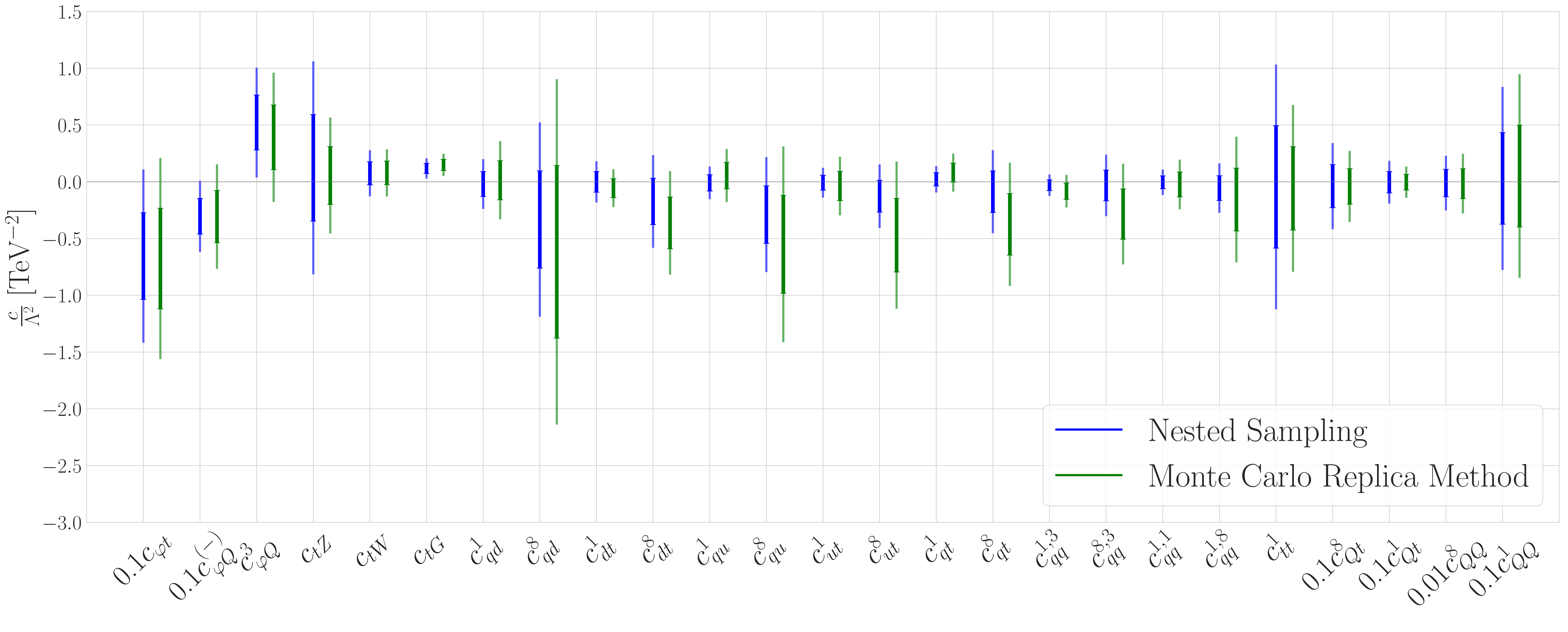


Monte Carlo Replica Method: issues in SMEFT fits



M.N.Constantini, MM, L. Mantani, J. Moore

Monte Carlo Replica Method: issues in SMEFT fits



M.N.Constantini, MM, L. Mantani, J. Moore

Conclusions

The discovery of 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 these effects post-fit is not guaranteed

PDF-EFT interplay is moderate in current LHC data, but may become **significant at the HL-LHC**

Simultaneous PDF and SMEFT determinations are crucial for the assessment of the extent of PDF-EFT interplay in current LHC data.

Conclusions

Thank you for listening!

The discovery of 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 these effects post-fit is not guaranteed

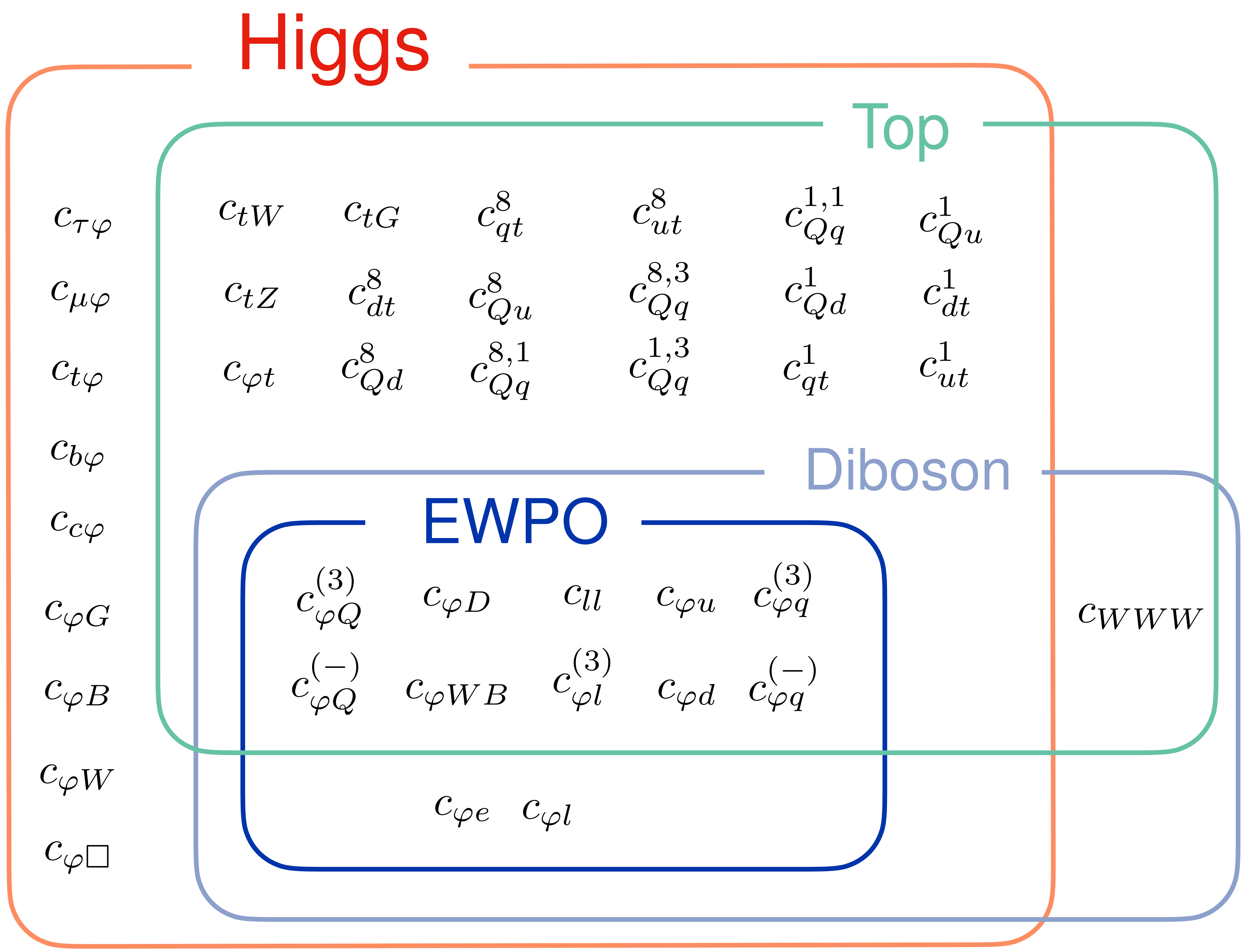
PDF-EFT interplay is moderate in current LHC data, but may become **significant at the HL-LHC**

Simultaneous PDF and SMEFT determinations are crucial for the assessment of the extent of PDF-EFT interplay in current LHC data.

Backup

Going more global

M. N. Constantini, E. Hammou, Z. Kassabov, MM, L. Mantani, J. Moore, M. Morales Alvarado, J. Rojo, M. Ubiali 2402.03308



Significant overlap between the Higgs, diboson, EWPO and top sectors of the SMEFT

See also:

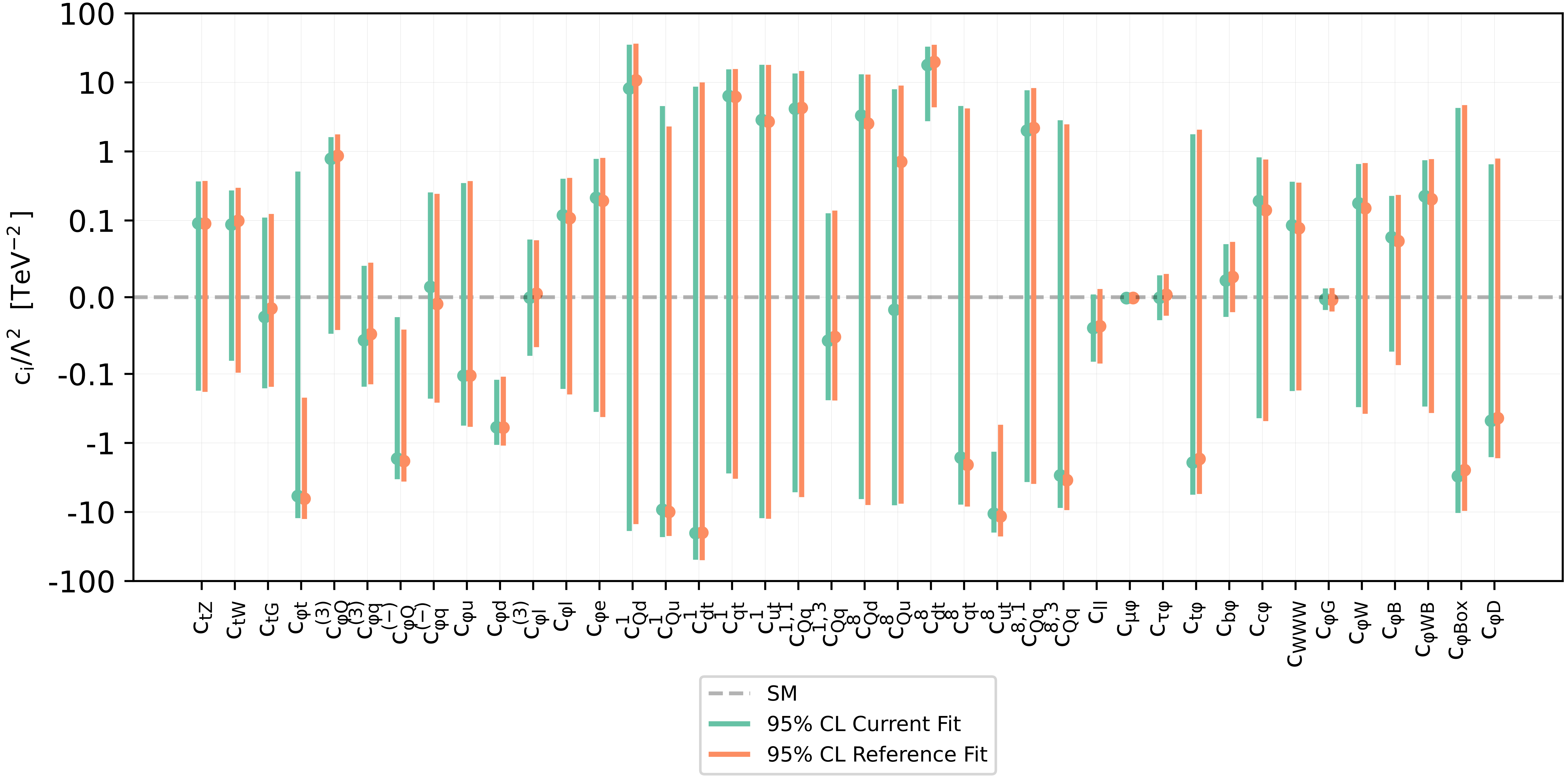
2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You

J. Ethier et. al, 2105.00006

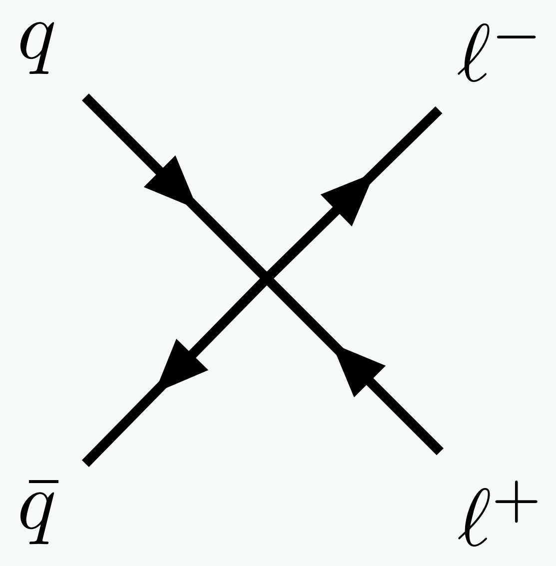
Going more global

M. N. Constantini, E. Hammou, Z. Kassabov, MM, L. Mantani, J. Moore, M. Morales Alvarado, J. Rojo, M. Ubiali 2402.03308

Constraints on the Wilson coefficients are **stable**, as in the top sector

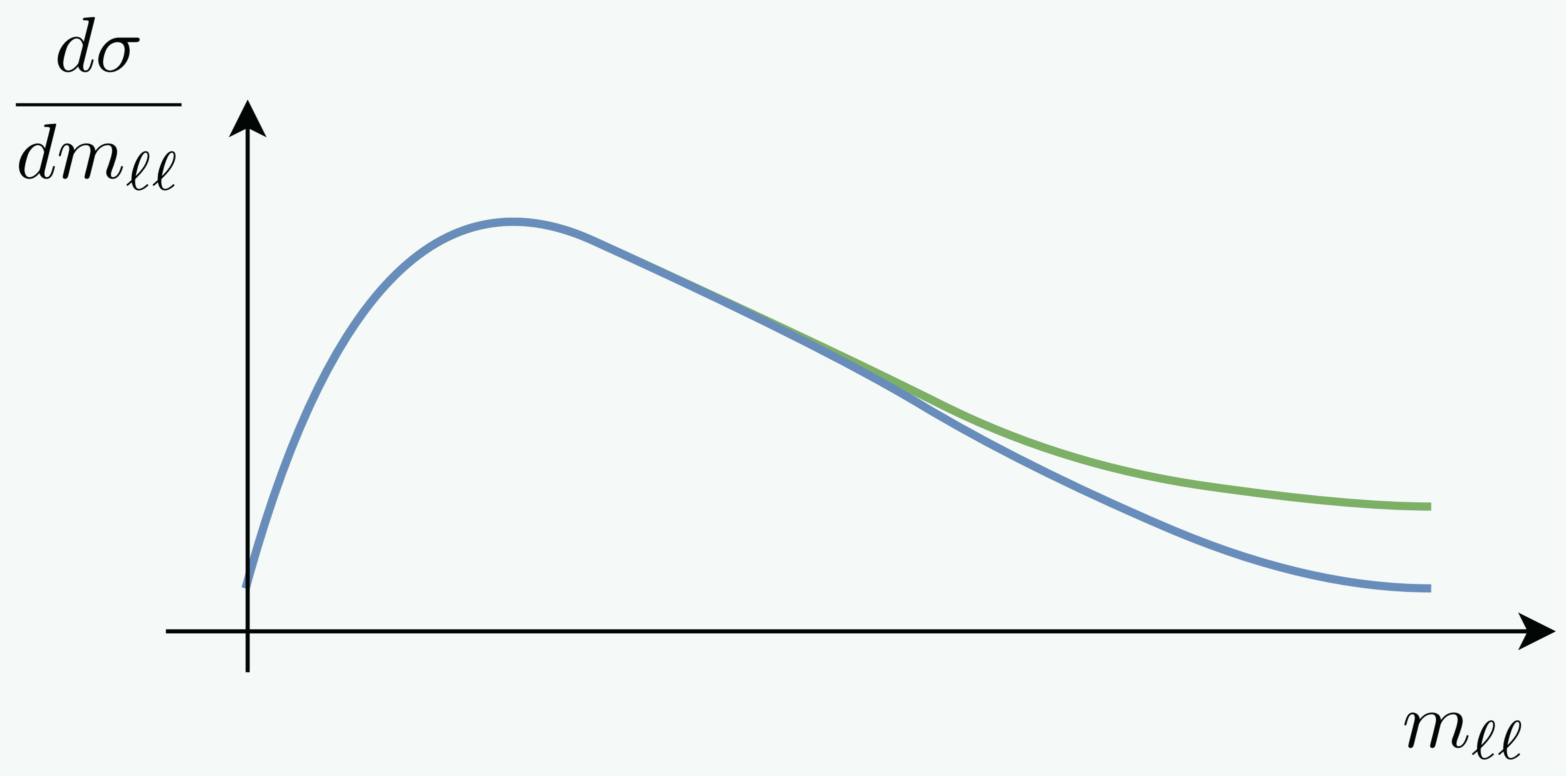


PDF-EFT interplay **in high-mass Drell-Yan**

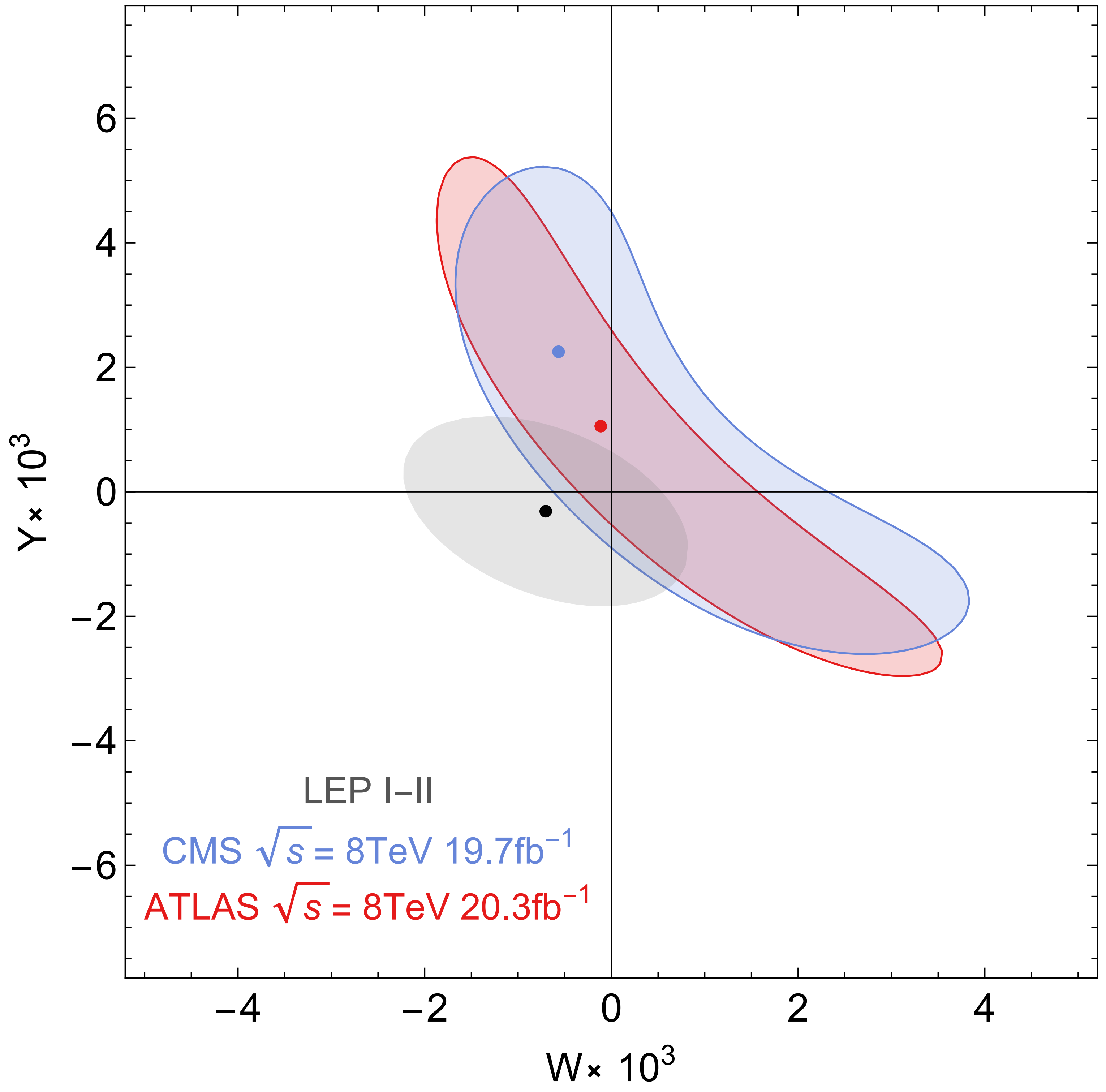


$$\mathcal{A} \sim \mathcal{A}_{\rm SM} + C\frac{E^2}{\Lambda^2}$$

Energy-growing 4-fermion operators manifest as a smooth distortion of the high-mass tail:



Constraints on 4-fermion operators of the SMEFT:



Farina et. al 1609.08157

Simultaneous PDF and SMEFT fit

Data

Deep inelastic scattering + Drell-Yan

- including high-mass DY:

Exp.	$\sqrt{s}$ (TeV)	Ref.	$\mathcal{L}$ (fb^{-1})	Channel	1D/2D	$n_{\rm dat}$	$m_{\ell\ell}^{\rm max}$ (TeV)
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Total						**270 (313)**	

+ High Luminosity projections

Theory benchmarks

Electroweak oblique parameters $\hat{W}, \hat{Y}$

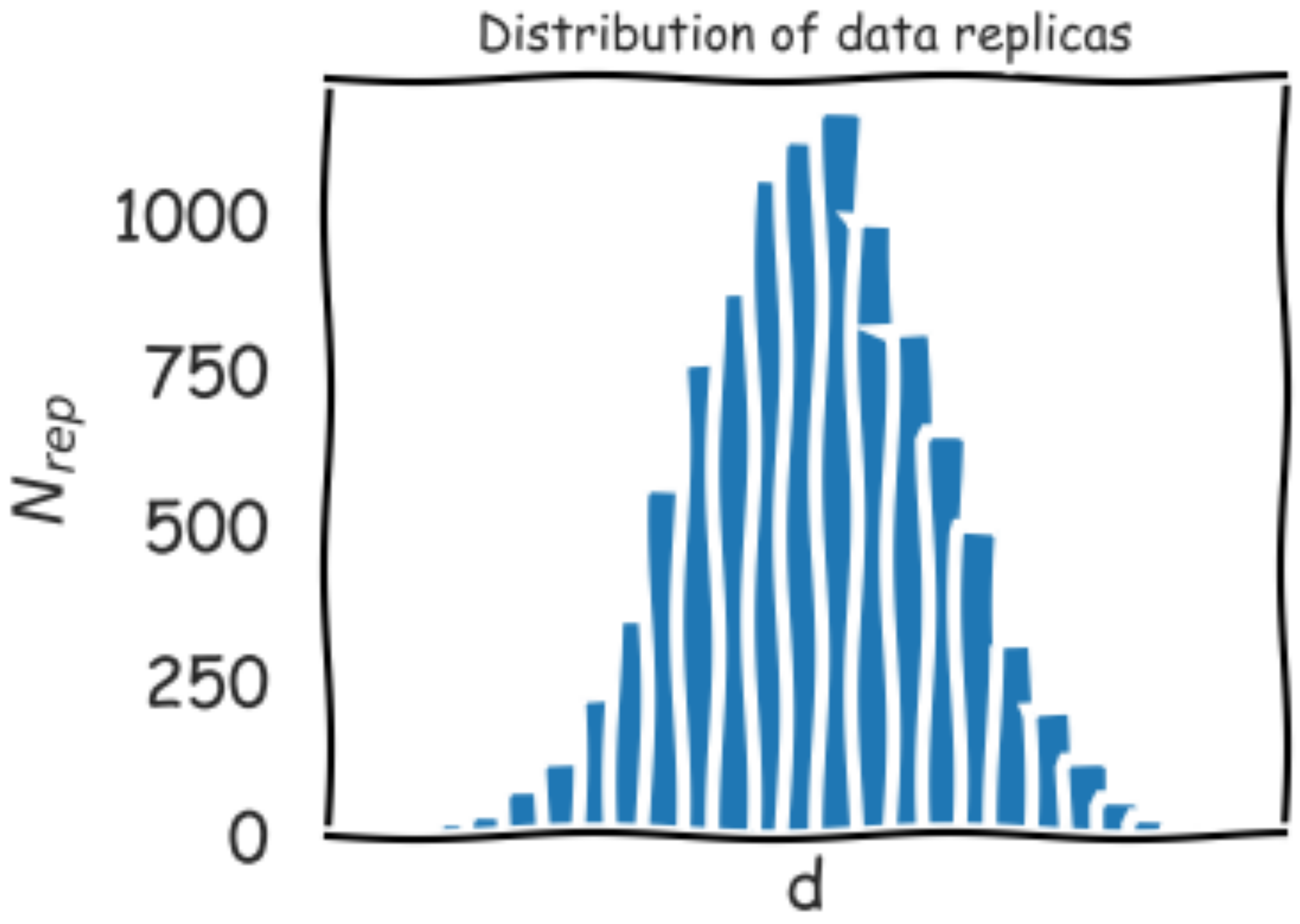
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} - \frac{g^2\hat{W}}{4m_W^2}\mathcal{O}_{lq}^{(3)} - \frac{g_Y^2\hat{Y}}{m_W^2}\Big(Y_lY_d\,\mathcal{O}_{ld} + Y_lY_u\,\mathcal{O}_{lu} + Y_lY_q\,\mathcal{O}_{lq}^{(1)} + Y_eY_d\,\mathcal{O}_{ed} + Y_eY_u\,\mathcal{O}_{eu} + Y_eY_q\,\mathcal{O}_{qe}\Big)$$

parametrises the impact of a flavour universal **W'**

parametrises the impact of a flavour universal **Z'**

Monte Carlo Replica Method

Consider a measurement *d,* with uncertainty σ



$$d_k \sim \mathcal{N}(d, \sigma)$$

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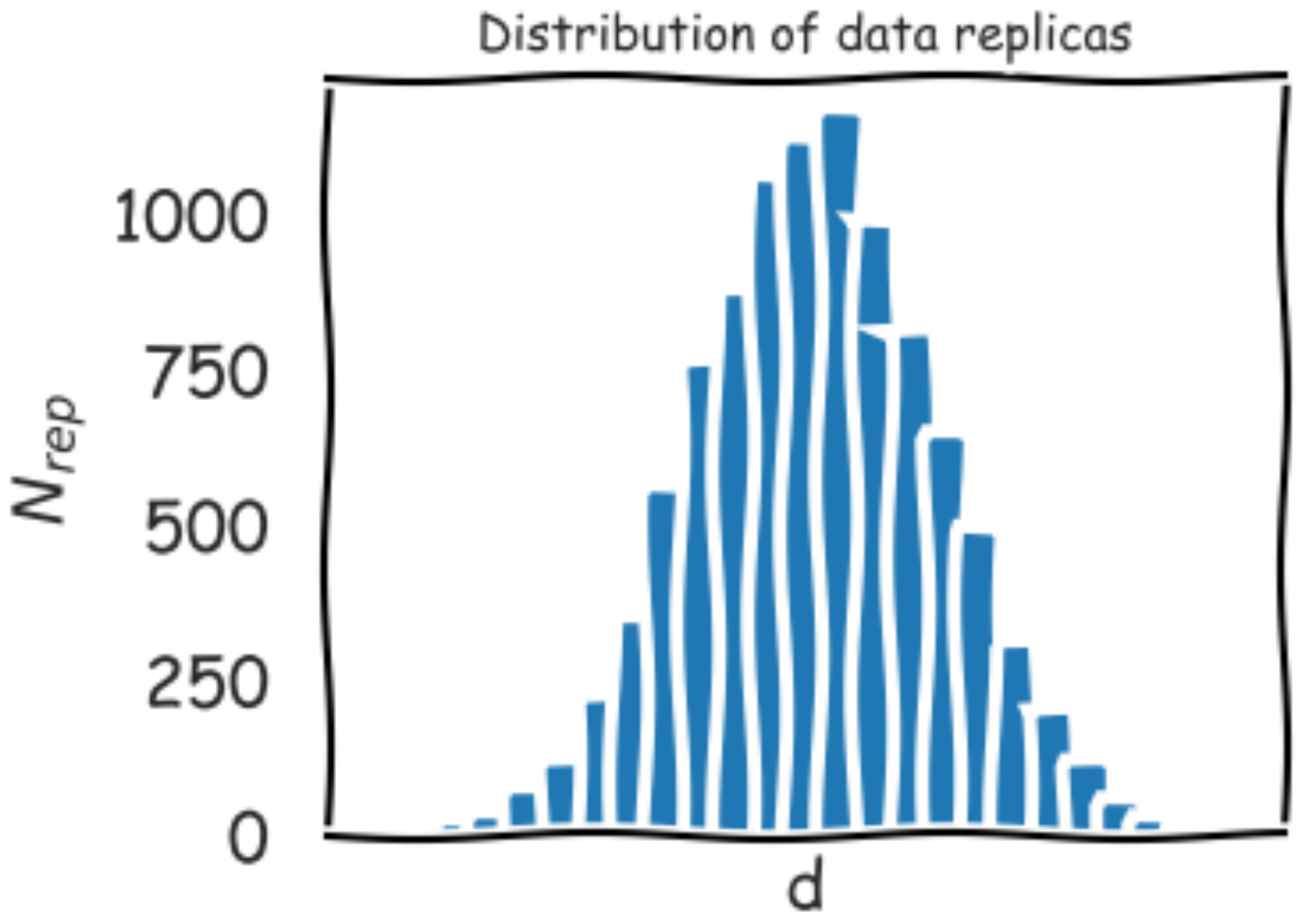
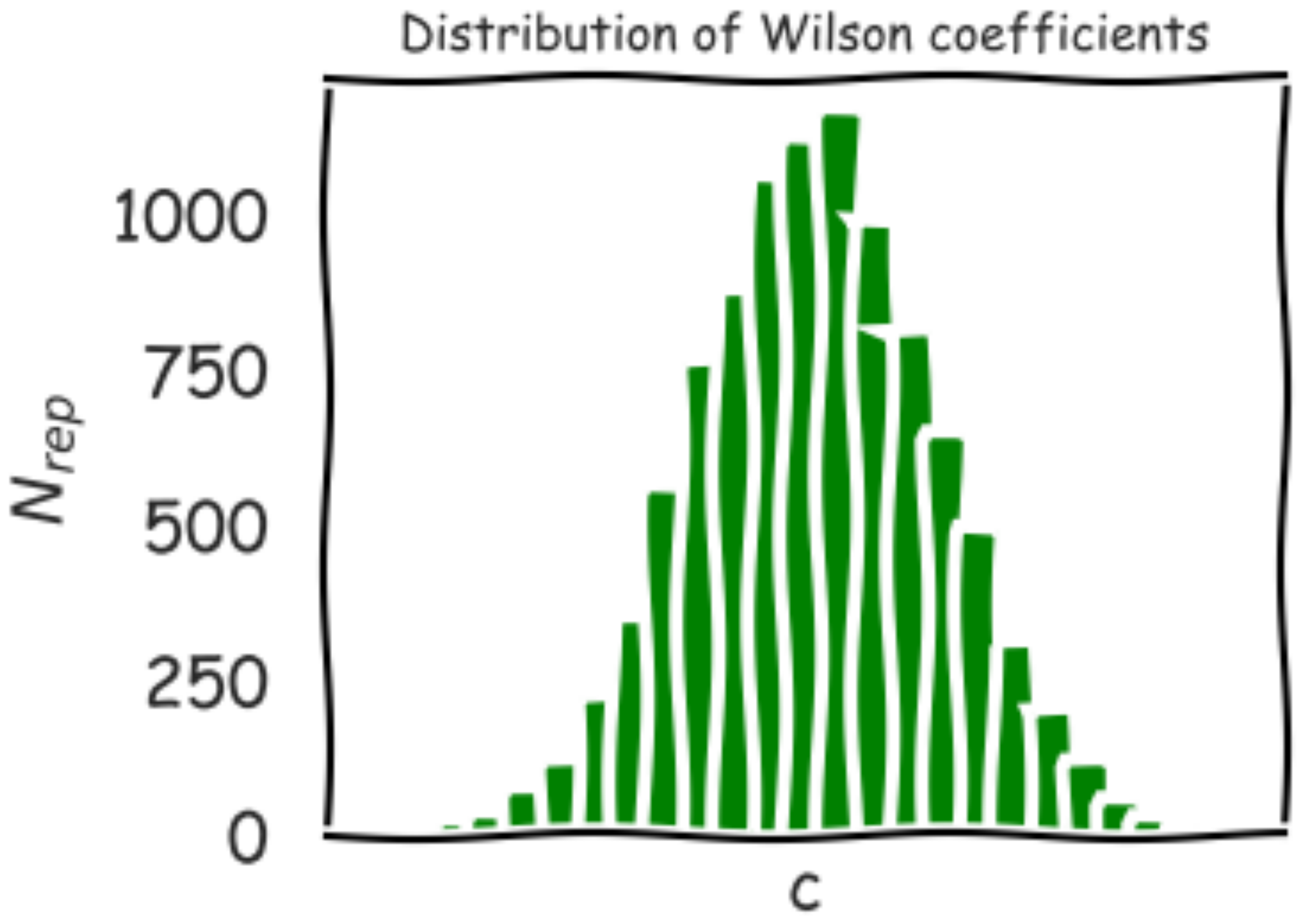




$$d_k \sim \mathcal{N}(d, \sigma) \longrightarrow c_k = \arg\min_c \chi^2(c, d_k)$$

Monte Carlo Replica Method: caveat

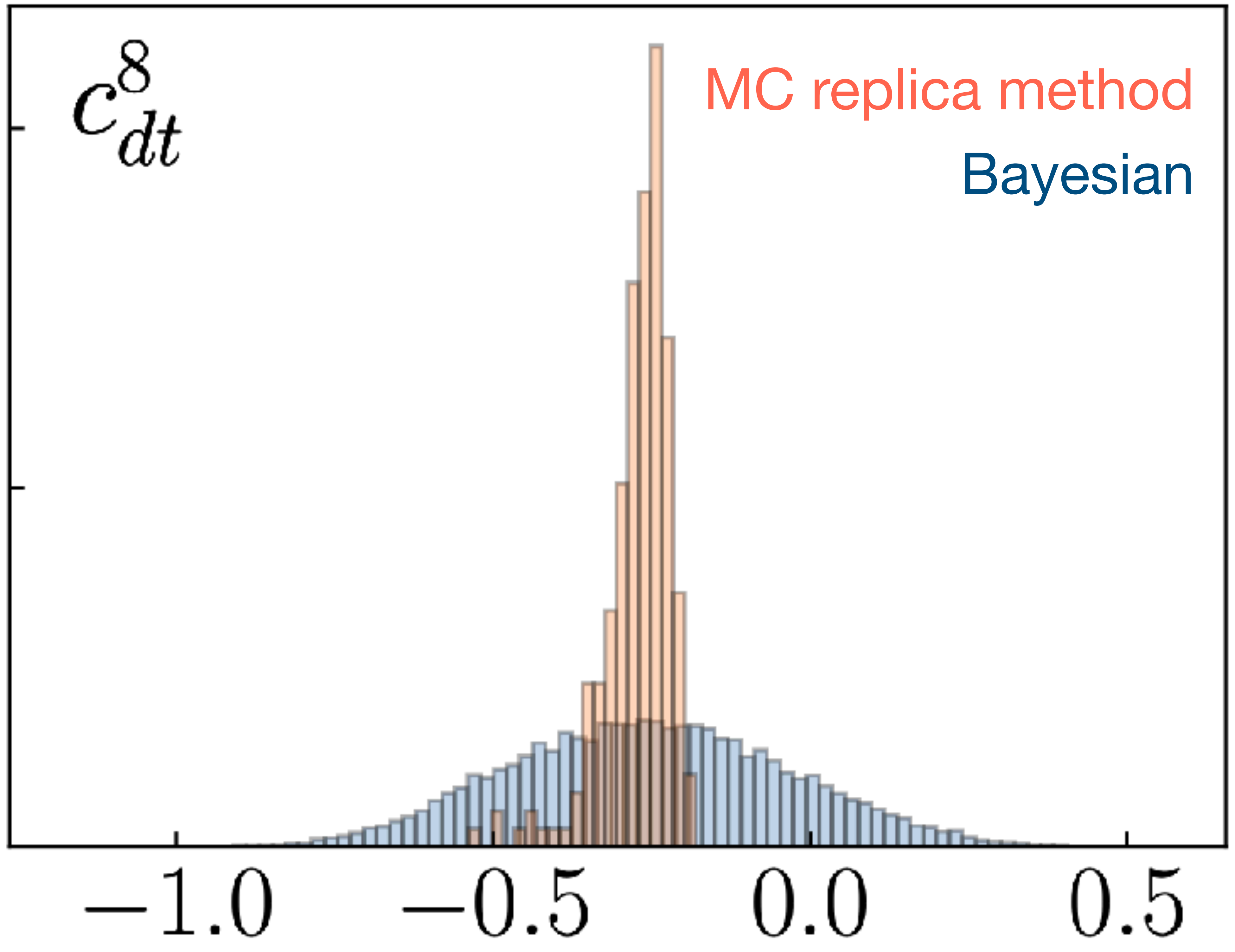
This methodology only provides reliable confidence intervals for linear SMEFT

$$\sigma(c) = \sigma_{\rm SM} + \sigma_{\rm lin} c + \sigma_{\rm quad} c^2$$

Inclusion of the quadratic term may lead to an artificial 'spiked' distribution

Work in progress will assess the implications for PDF uncertainties

M.N.Constantini, MM, L. Mantani, J. Moore

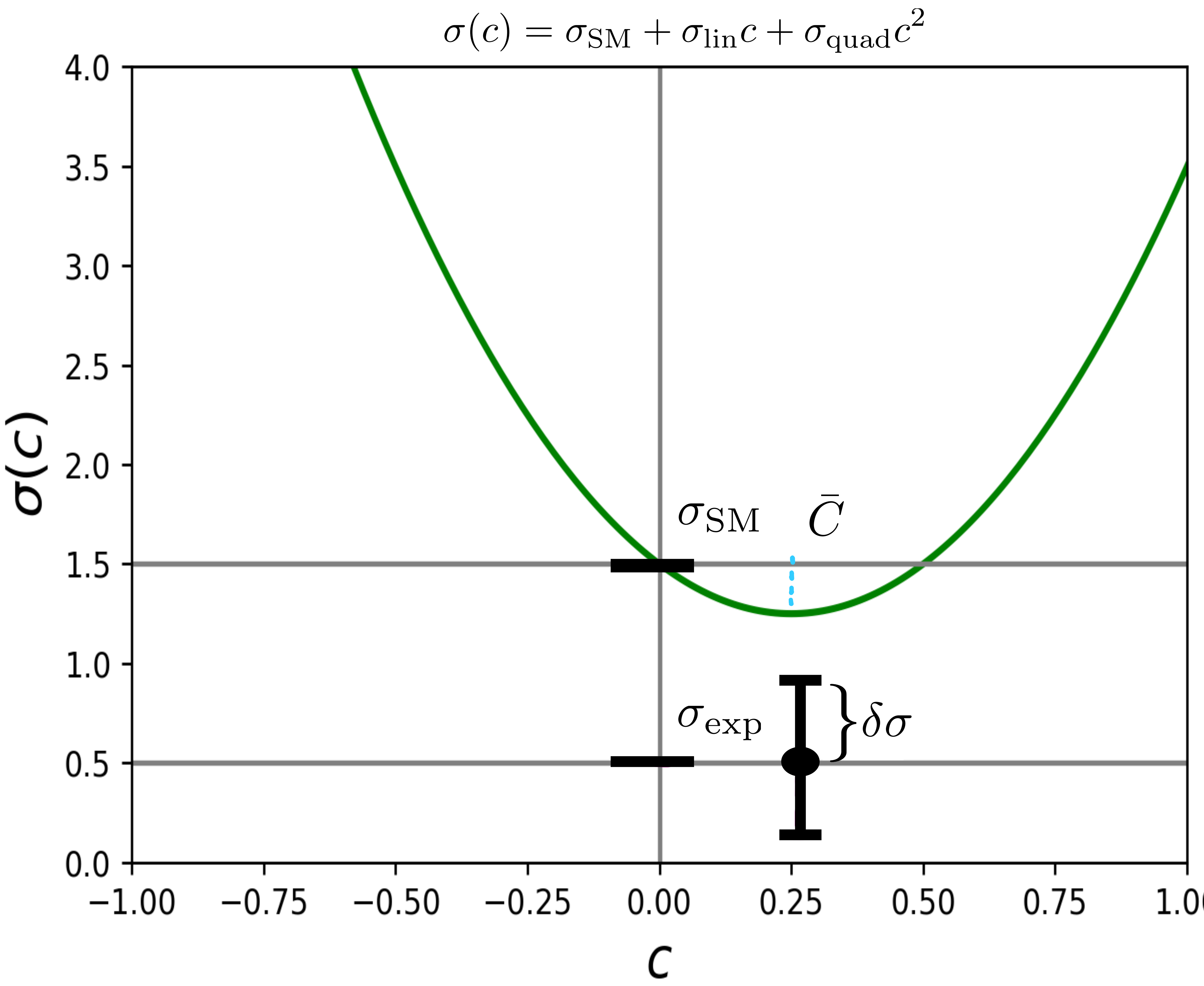


The Monte Carlo Replica Method

MC replicas

Problem: in the presence of a quadratic theory, often the minimum χ^2 will be given by the same $\bar{c}$.

2. Minimise: $$\bar{c} = \arg\min_c \frac{(\sigma(c) - \tilde{\sigma}_{\text{exp}})^2}{\delta\sigma^2}$$



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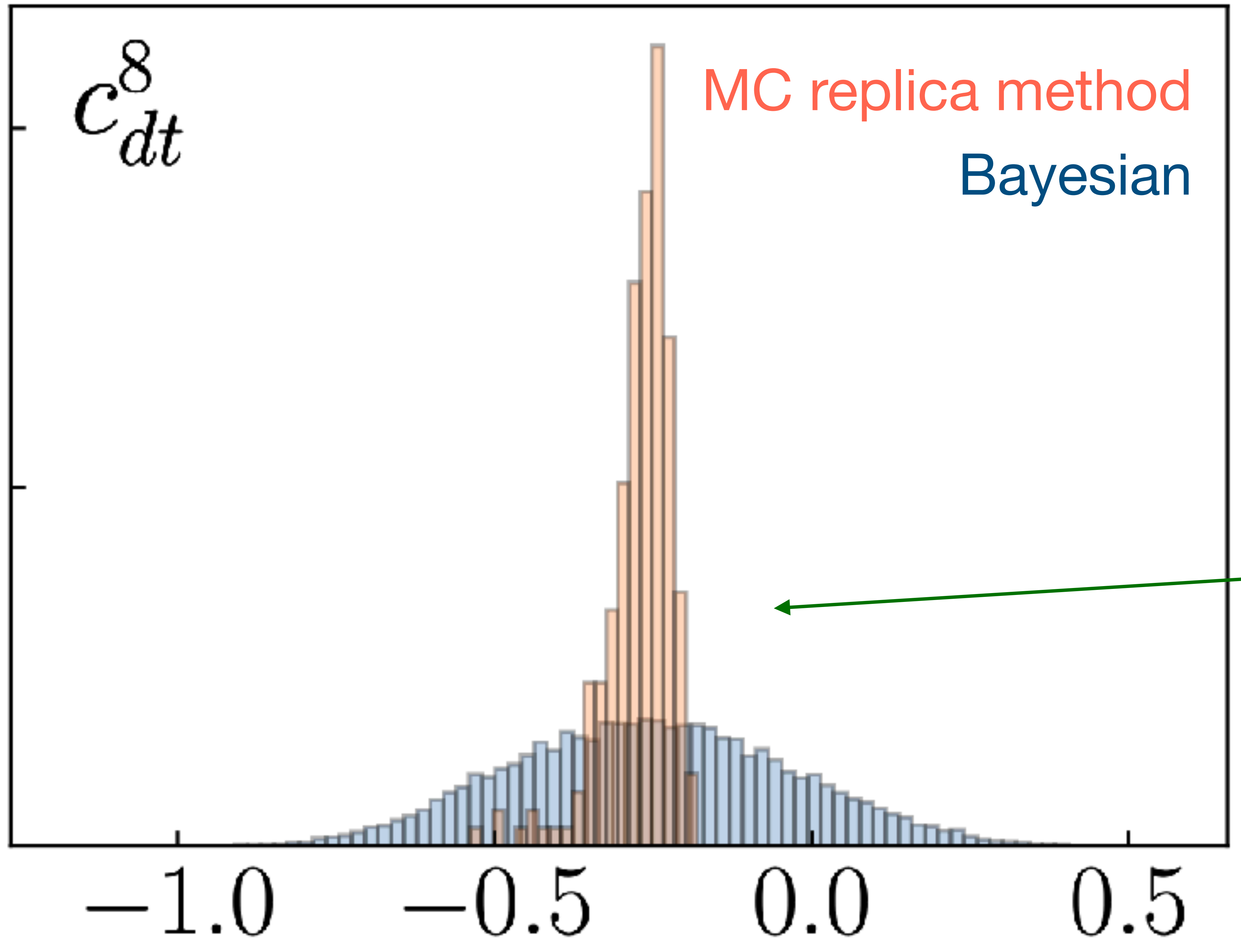
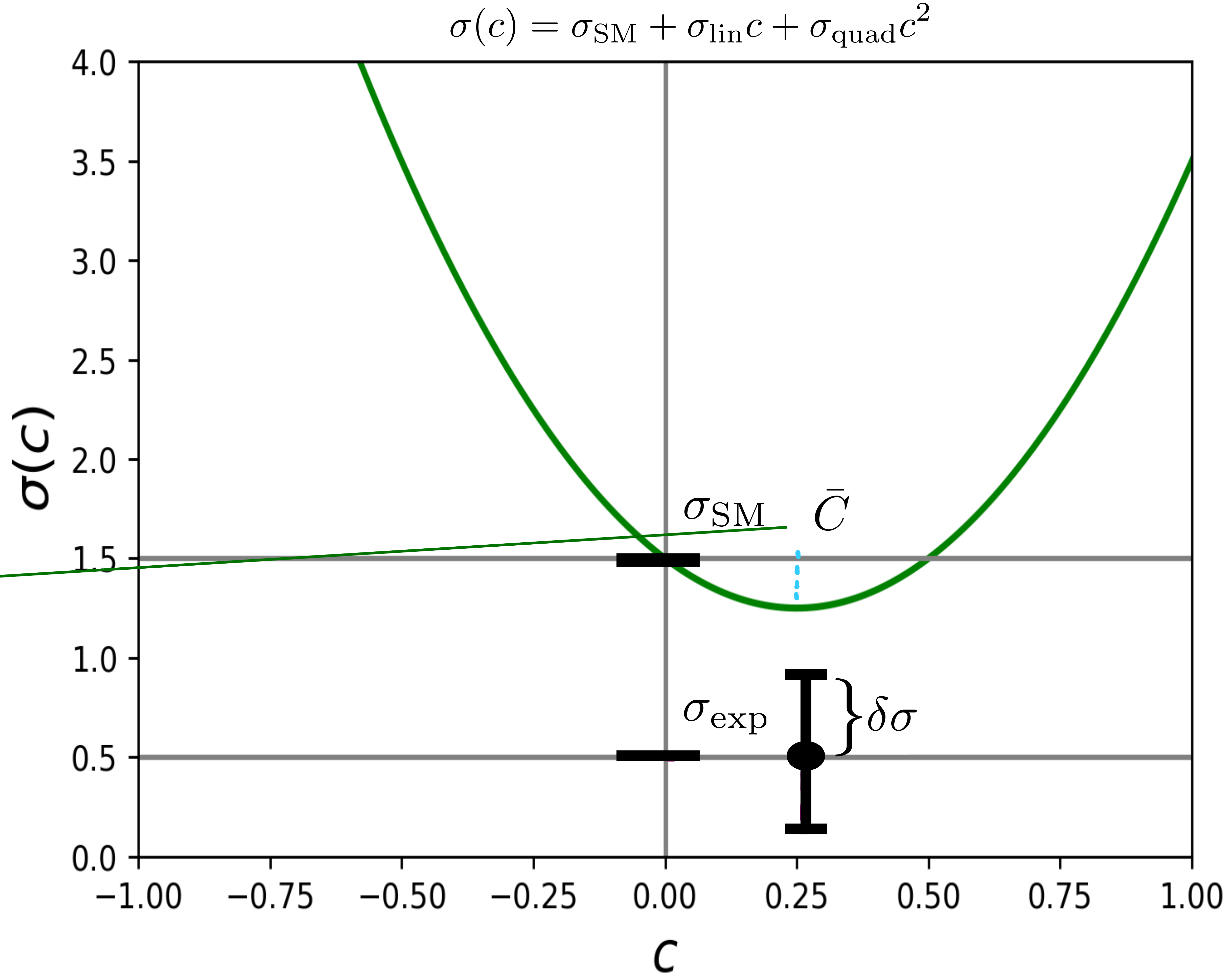
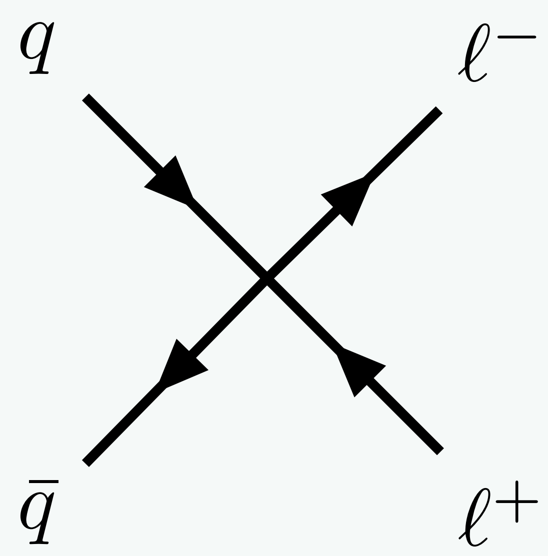




PDF-EFT interplay **in high-mass Drell-Yan**



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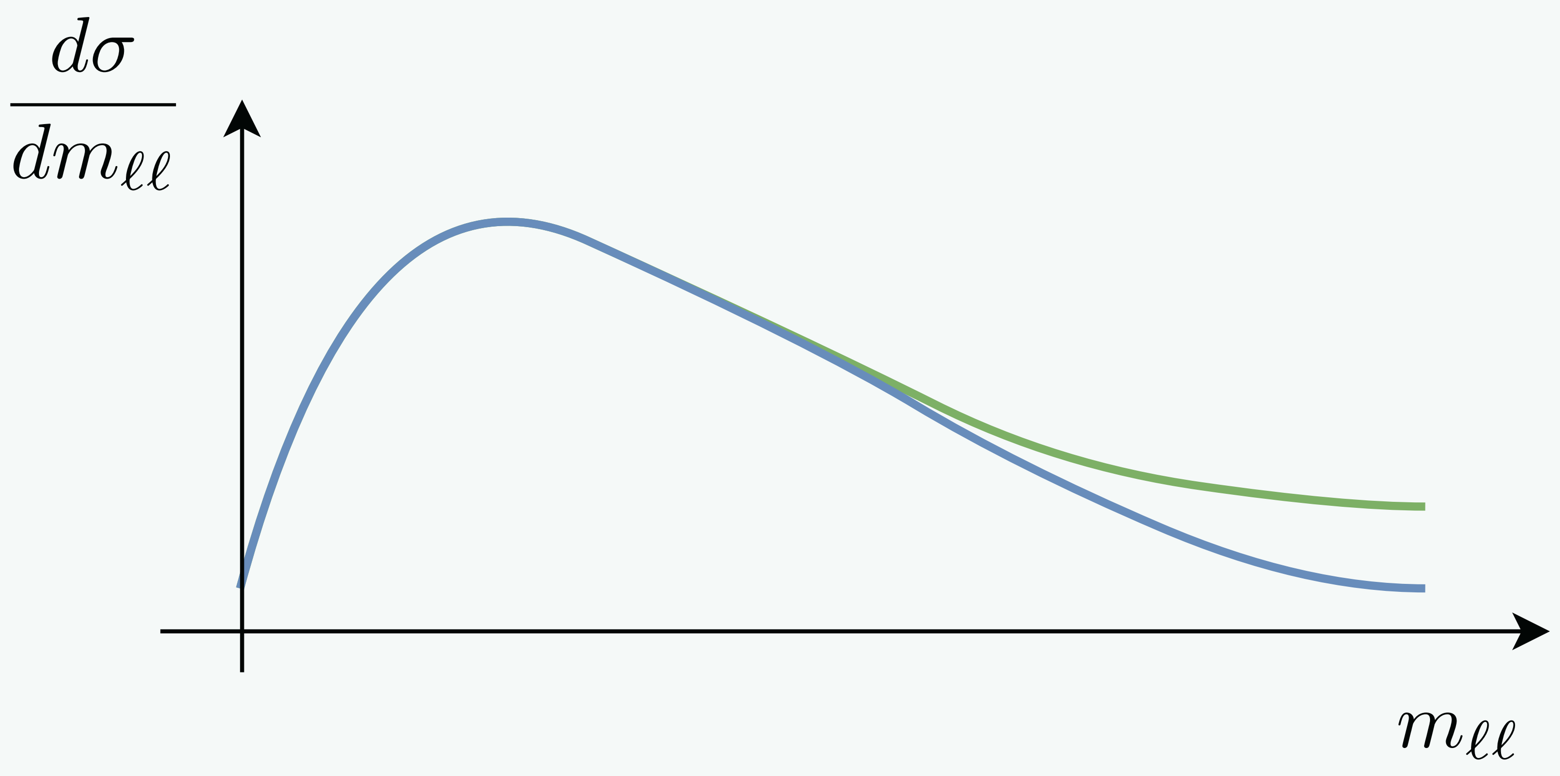
Energy-growing 4-fermion operators manifest as a smooth distortion of the high-mass tail:

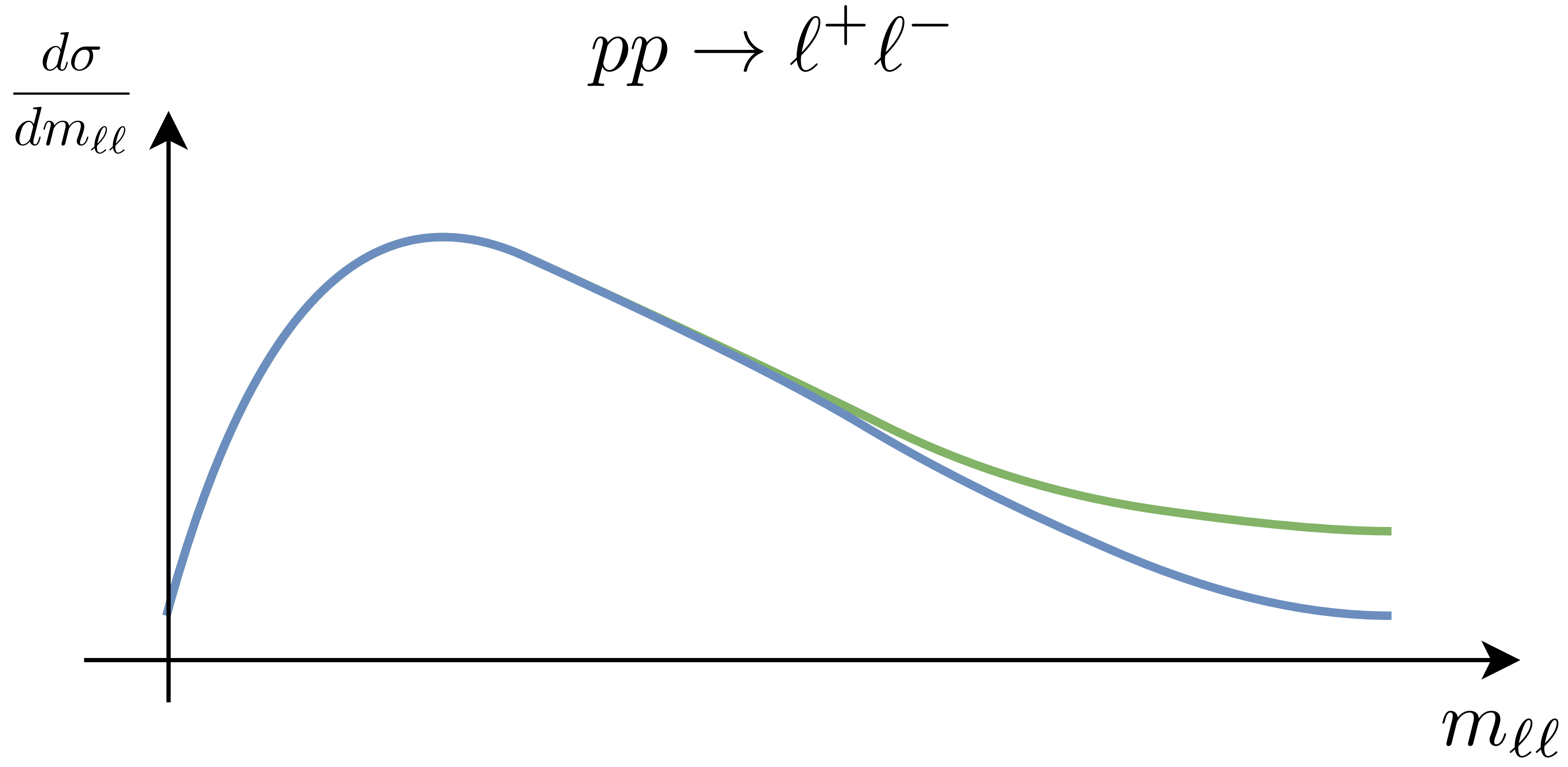


e.g. Z'

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

$$J_L^\mu = \sum_f Y_f \bar{f}\gamma^\mu f$$

Impacts **only** neutral-current DY:



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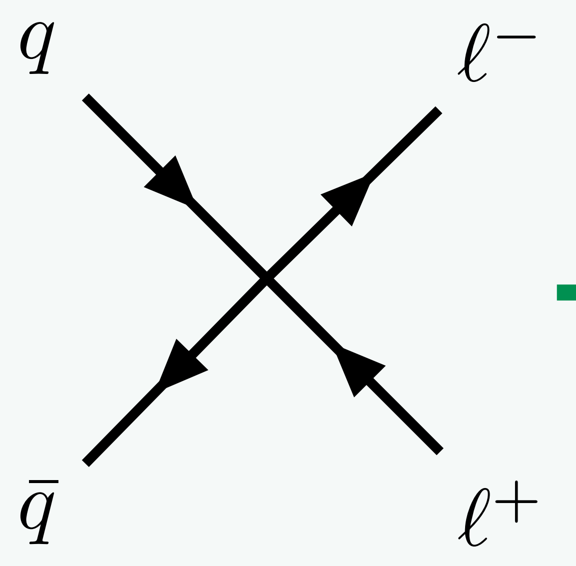

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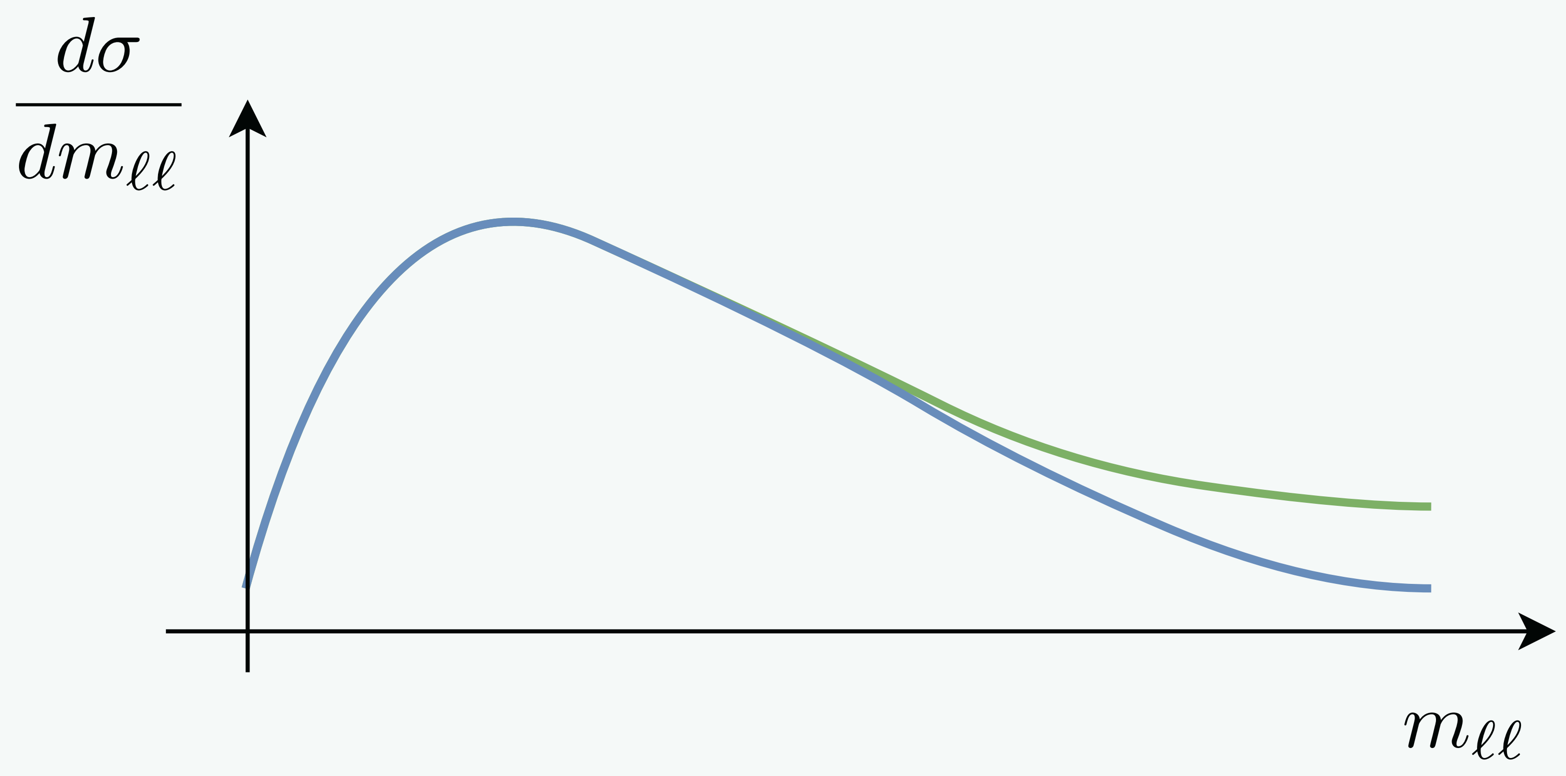


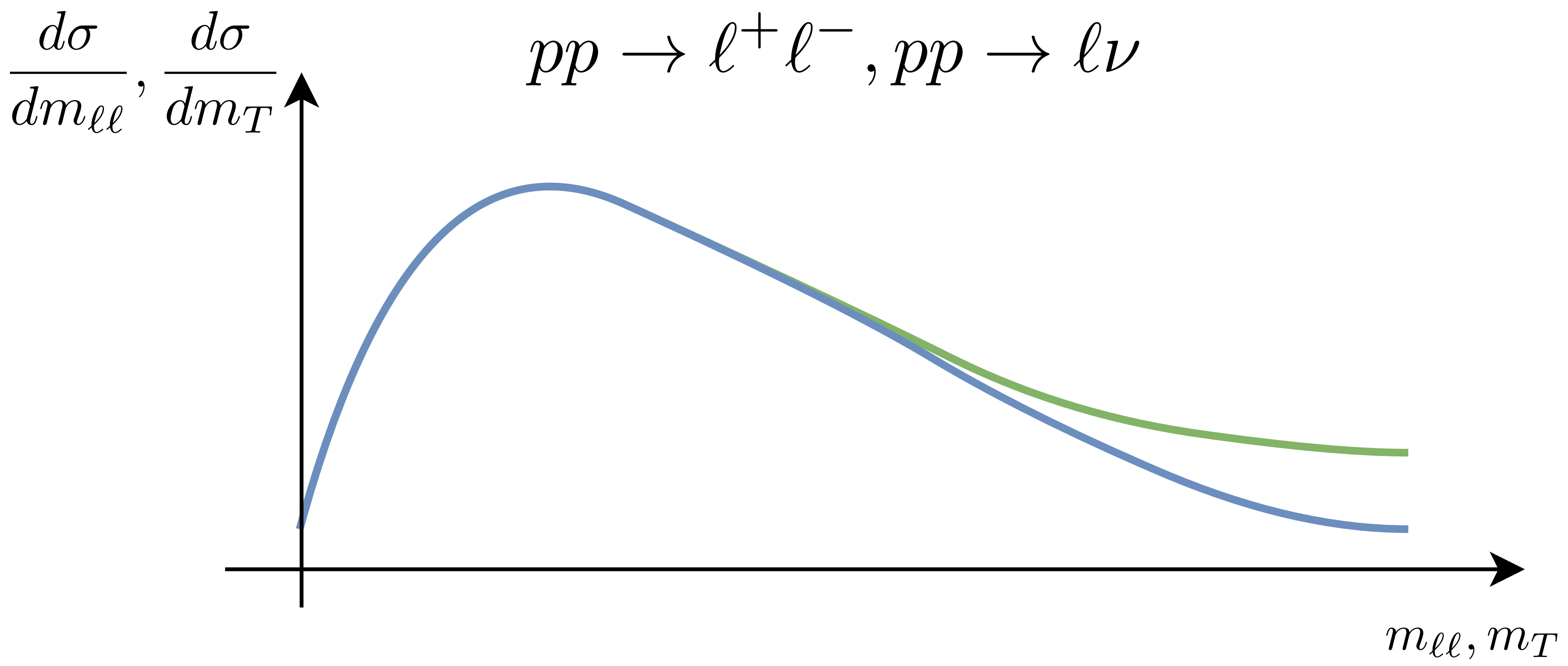
e.g. W'

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

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

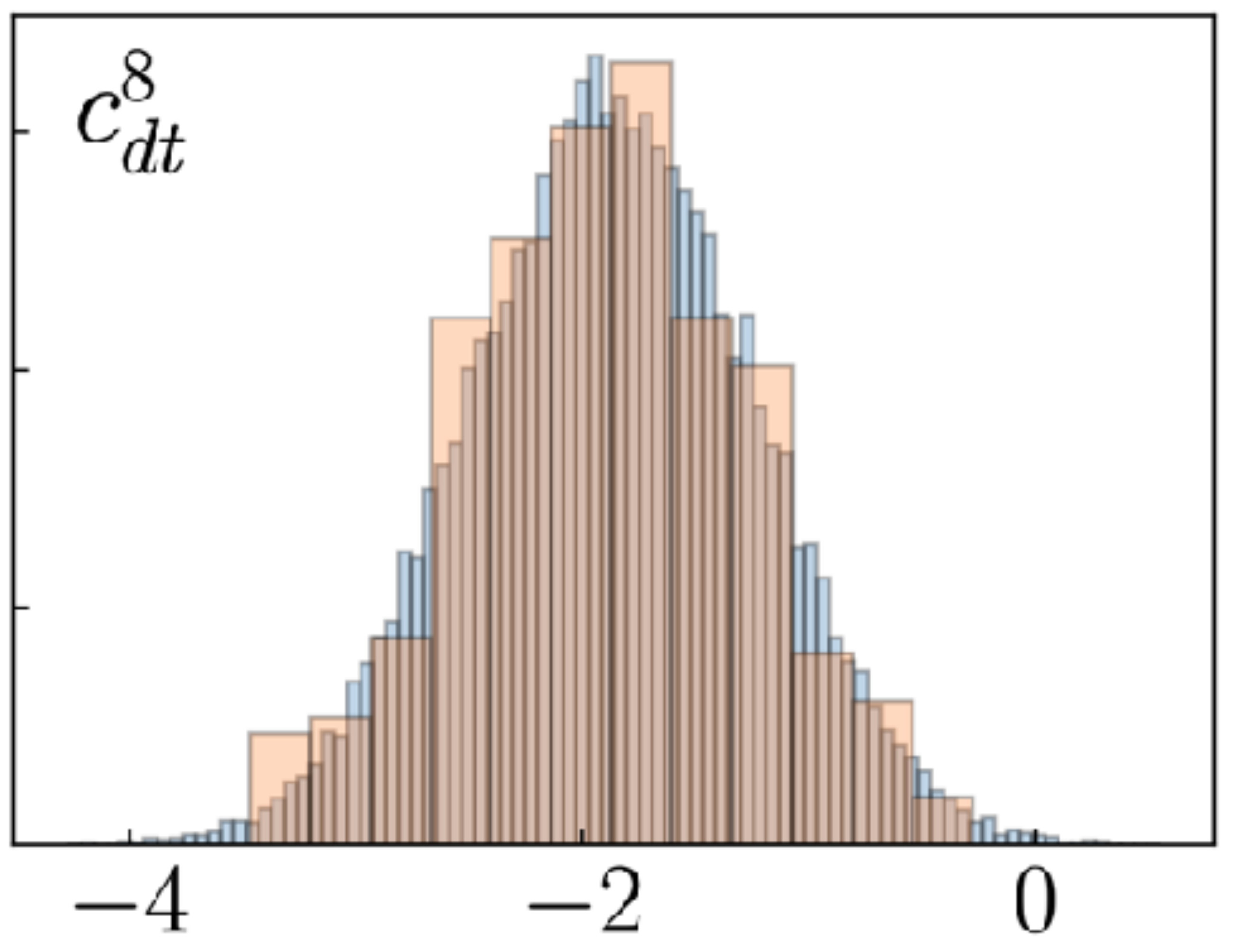
Impacts **both** neutral and charged-current DY:

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



The Monte Carlo Replica Method

Consider fitting 1 Wilson coefficient *c* to 1 datapoint σ_{exp}: define $\chi^2 = \dfrac{(\sigma(c) - \sigma_{\text{exp}})^2}{\delta\sigma^2}$



1. Resample: $\tilde{\sigma}_{\text{exp}} \sim \mathcal{N}(\sigma_{\text{exp}}, \delta\sigma)$

2. Minimise: $\bar{c} = \arg\min_c \dfrac{(\sigma(c) - \tilde{\sigma}_{\text{exp}})^2}{\delta\sigma^2}$

3. Repeat, and treat the sample $\{\bar{c}\}$ as a sample from the Bayesian posterior $p(c|D)$

- Often used in the context of PDF fitting and SMEFT fitting, e.g. 2109.02653, 1901.05965

The Monte Carlo Replica Method

Problem: in the presence of a quadratic theory, often the minimum χ^2 will be given by the same $\bar{c}$.

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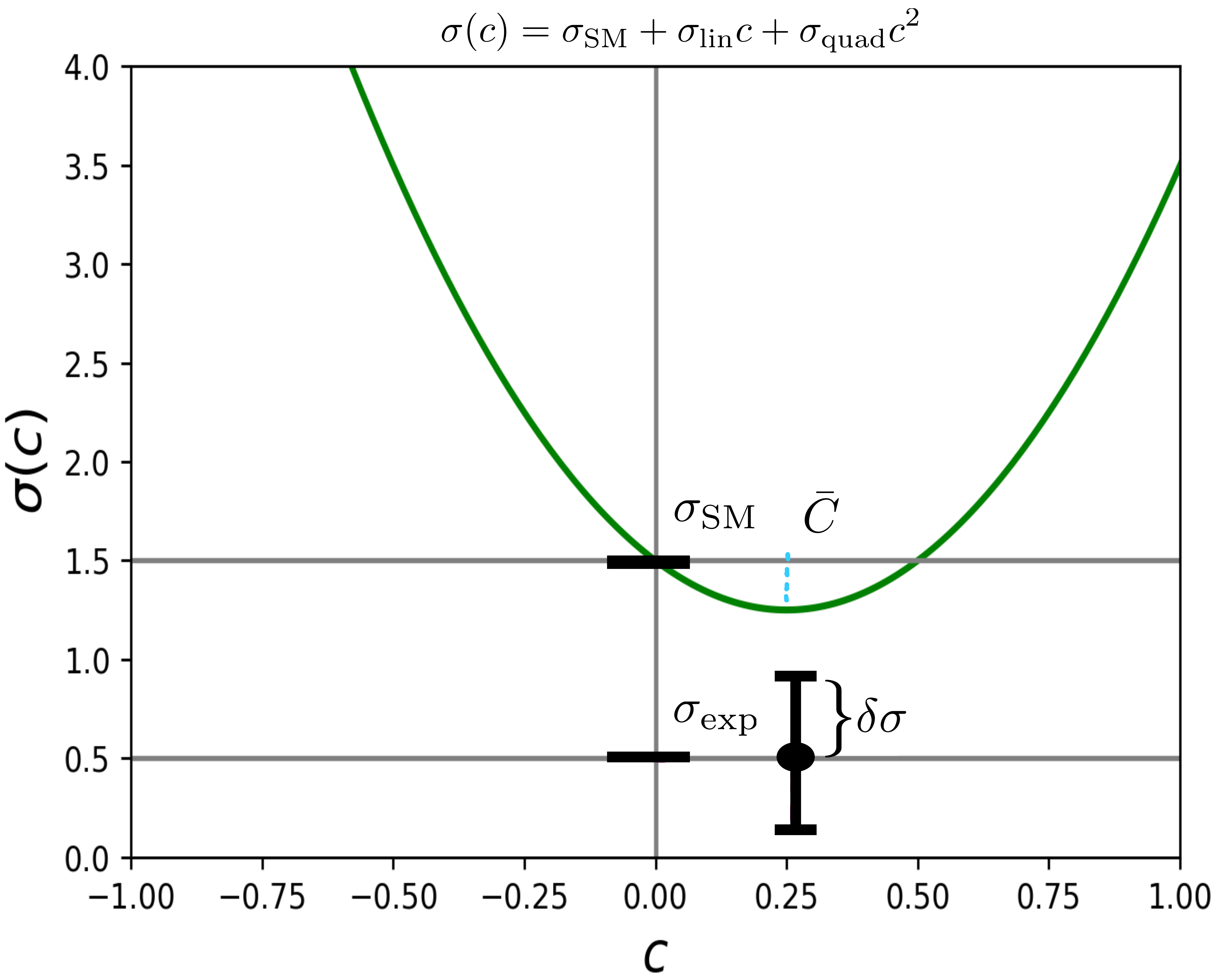

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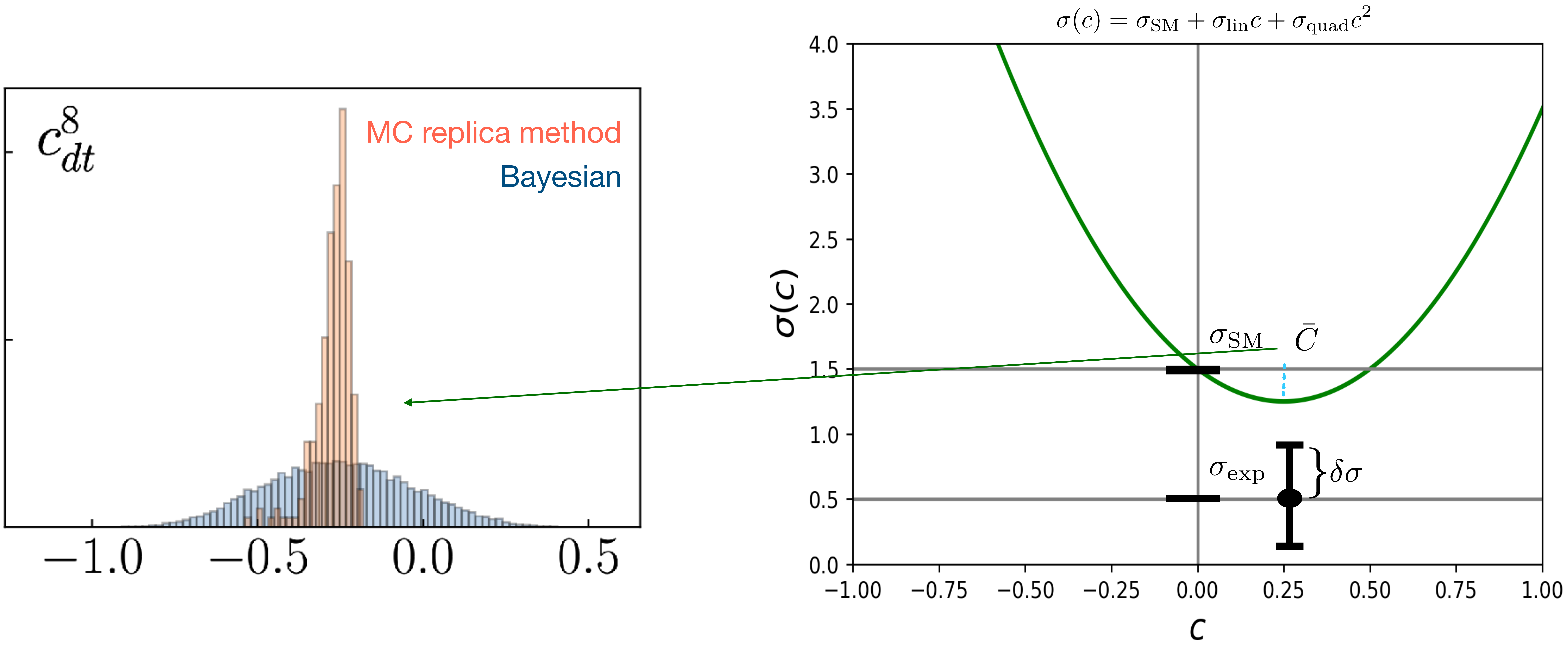


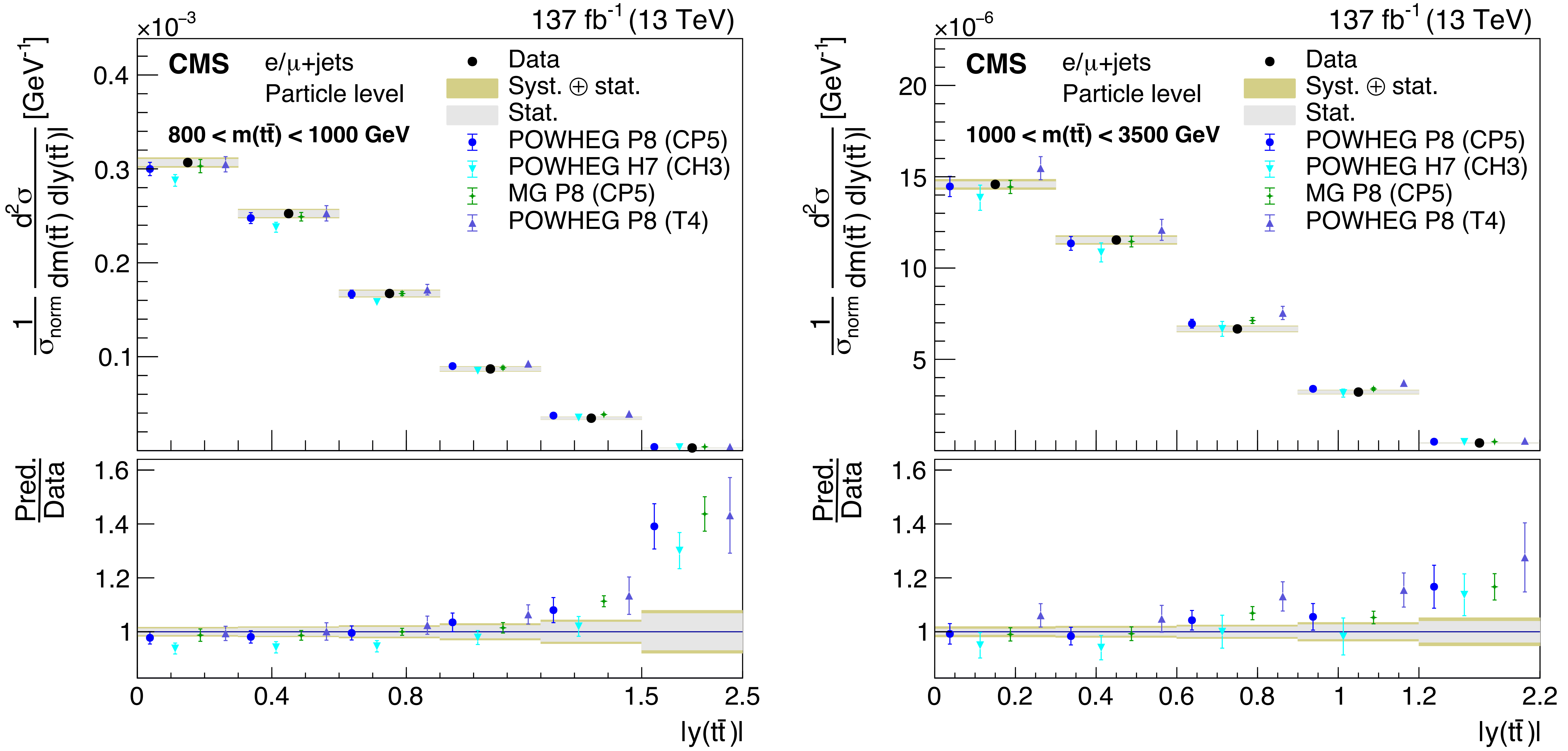
Data

[CMS, Phys. Phys. Rev. D 104 (2021) 092013]

175 datapoints:

a superset of measurements in

`fitmaker` `SMEFiT` `NNPDF`



$t\bar{t}$ — $t\bar{t}+V$ — charge asymmetry A_C — $t\bar{t}t\bar{t}, t\bar{t}b\bar{b}$ — single top, tW

Theory

SM
NLO QCD using MG5_aMC@NLO

Where available, NNLO QCD using k-factors from HighTea: *Czakon et. al, 2304.05993*
https://www.precision.hep.phy.cam.ac.uk/hightea/

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SMEFT

25 Wilson coefficients at NLO QCD using `SMEFT@NLO` *Degrande et. al, 2008.11743*

Dipoles: C_{tW}, C_{tZ}, C_{tG}

Currents: $C_{\phi Q}^{(1)}$, $C_{\phi Q}^{(3)}$, $C_{\phi t}$

4-fermion octets: C_{ut}^{8}, C_{Qu}^{8}, C_{qt}^{8}, $C_{Qq}^{8,3}$, $C_{Qq}^{8,1}$, C_{Qd}^{8}, C_{dt}^{8}

4-fermion singlets: $C_{Qq}^{1,3}$, $C_{Qq}^{1,1}$, C_{Qd}^{1}, C_{dt}^{1}, C_{Qu}^{1}, C_{qt}^{1}, C_{ut}^{1}

4-heavy: C_{tt}^{1}, C_{Qt}^{8}, C_{Qt}^{1}, C_{QQ}^{1}, C_{QQ}^{8}

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