Simultaneous fits of PDFs and SMEFT in the top-sector

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PBSP

QCD@LHC 2023
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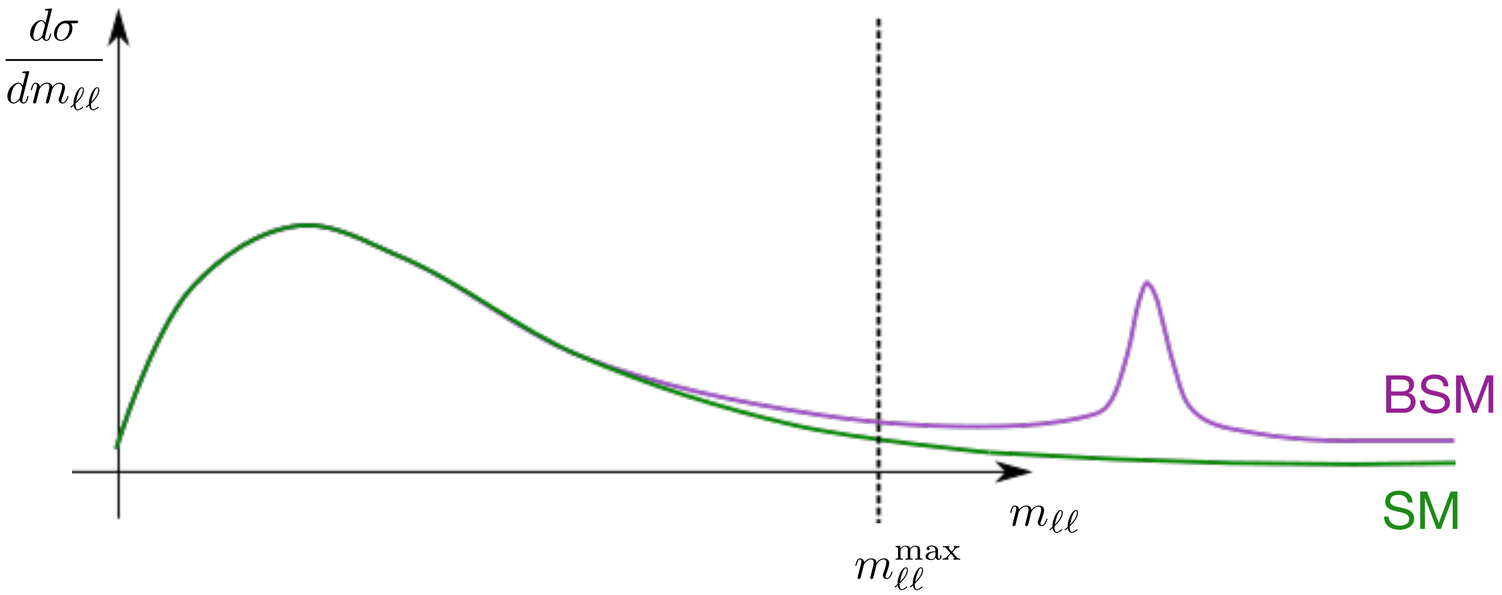
Global SMEFT interpretations

The **Standard Model Effective Field Theory:** a powerful framework for capturing deviations from the SM:

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

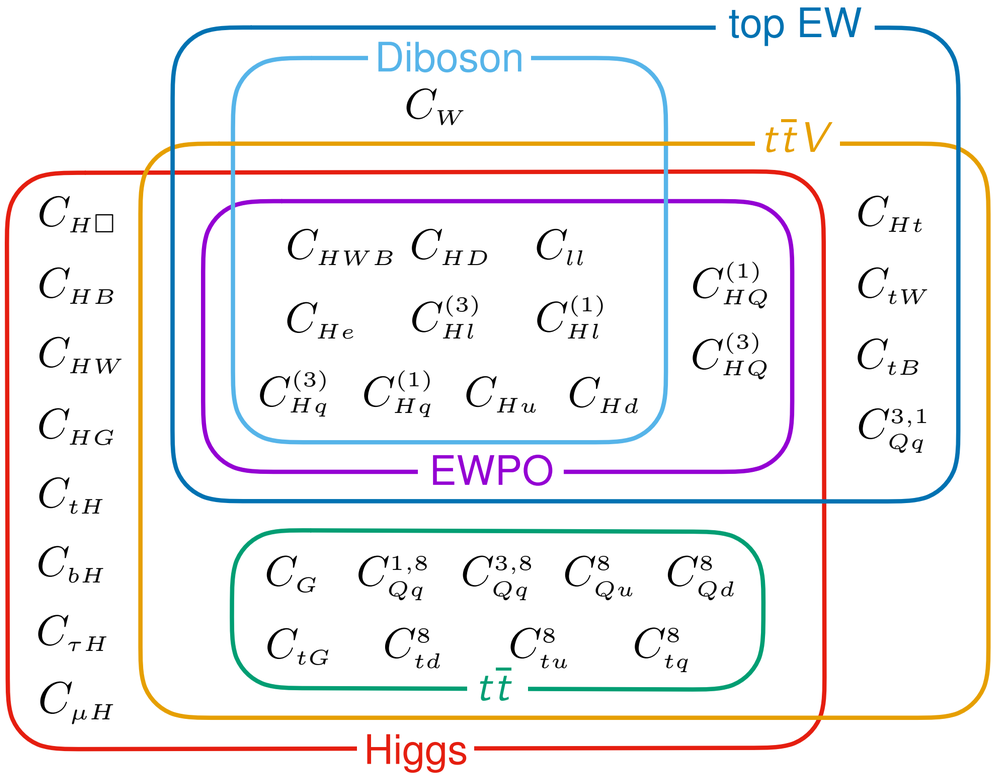


Global SMEFT interpretations

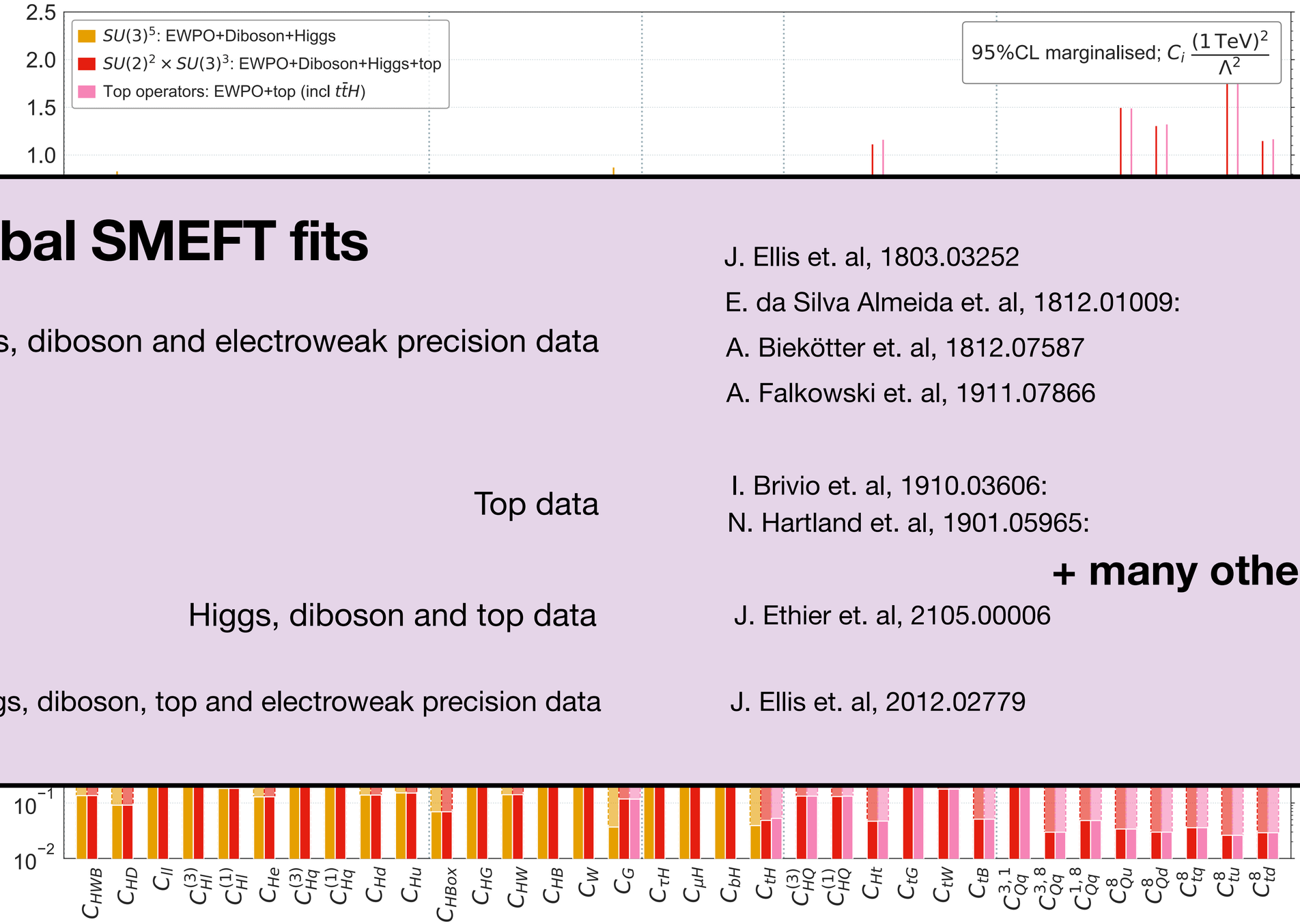
The SMEFT framework connects different sectors of observables measured at the LHC.

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

→ Model-independent interpretation of BSM physics in LHC data



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



Global SMEFT fits

Higgs, diboson and electroweak precision data

J. Ellis et. al, 1803.03252

E. da Silva Almeida et. al, 1812.01009:

A. Biekötter et. al, 1812.07587

A. Falkowski et. al, 1911.07866

Top data

I. Brivio et. al, 1910.03606:

N. Hartland et. al, 1901.05965:

+ many others….

Higgs, diboson and top data

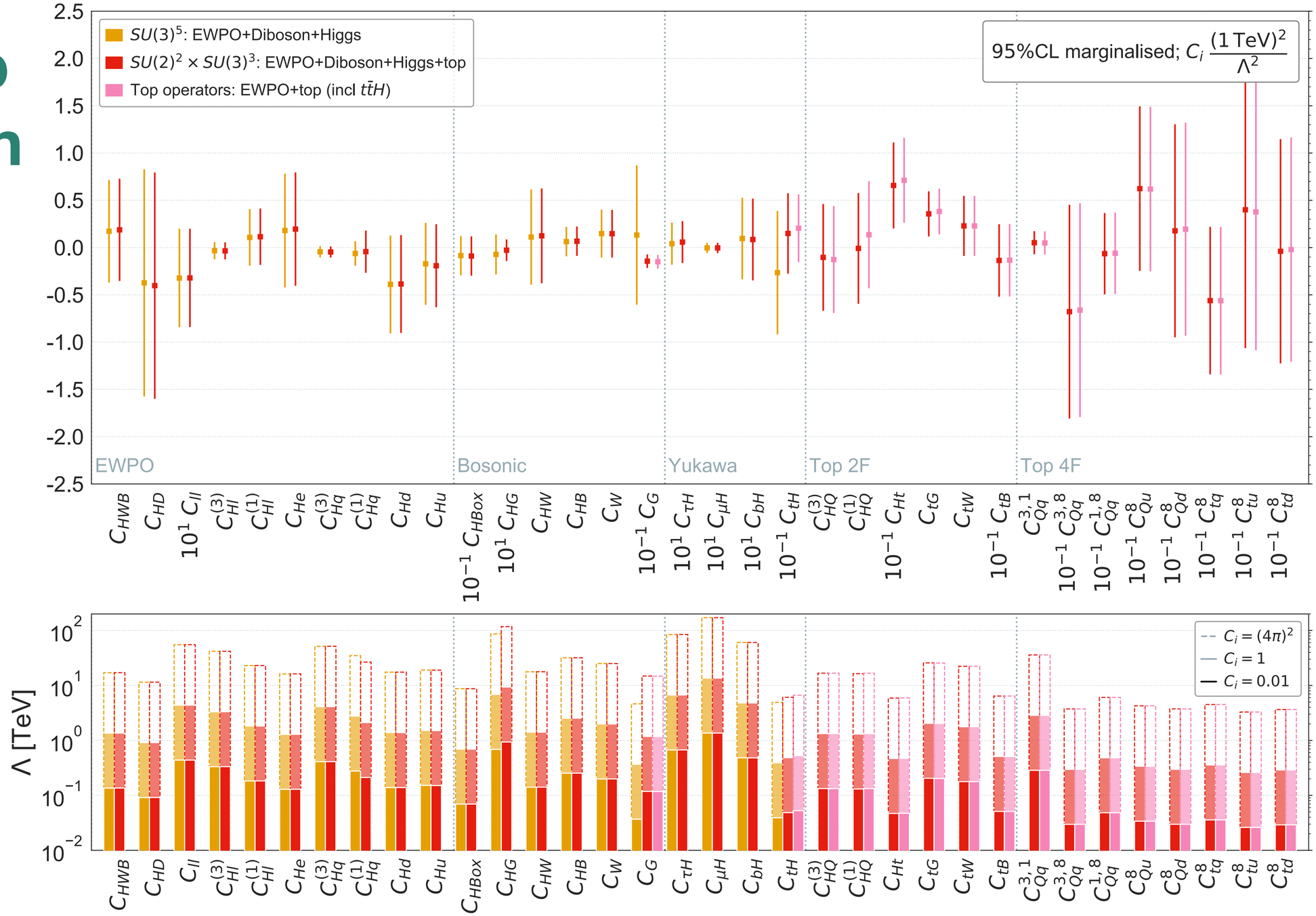
J. Ethier et. al, 2105.00006

Higgs, diboson, top and electroweak precision data

J. Ellis et. al, 2012.02779

Higgs & Top combination

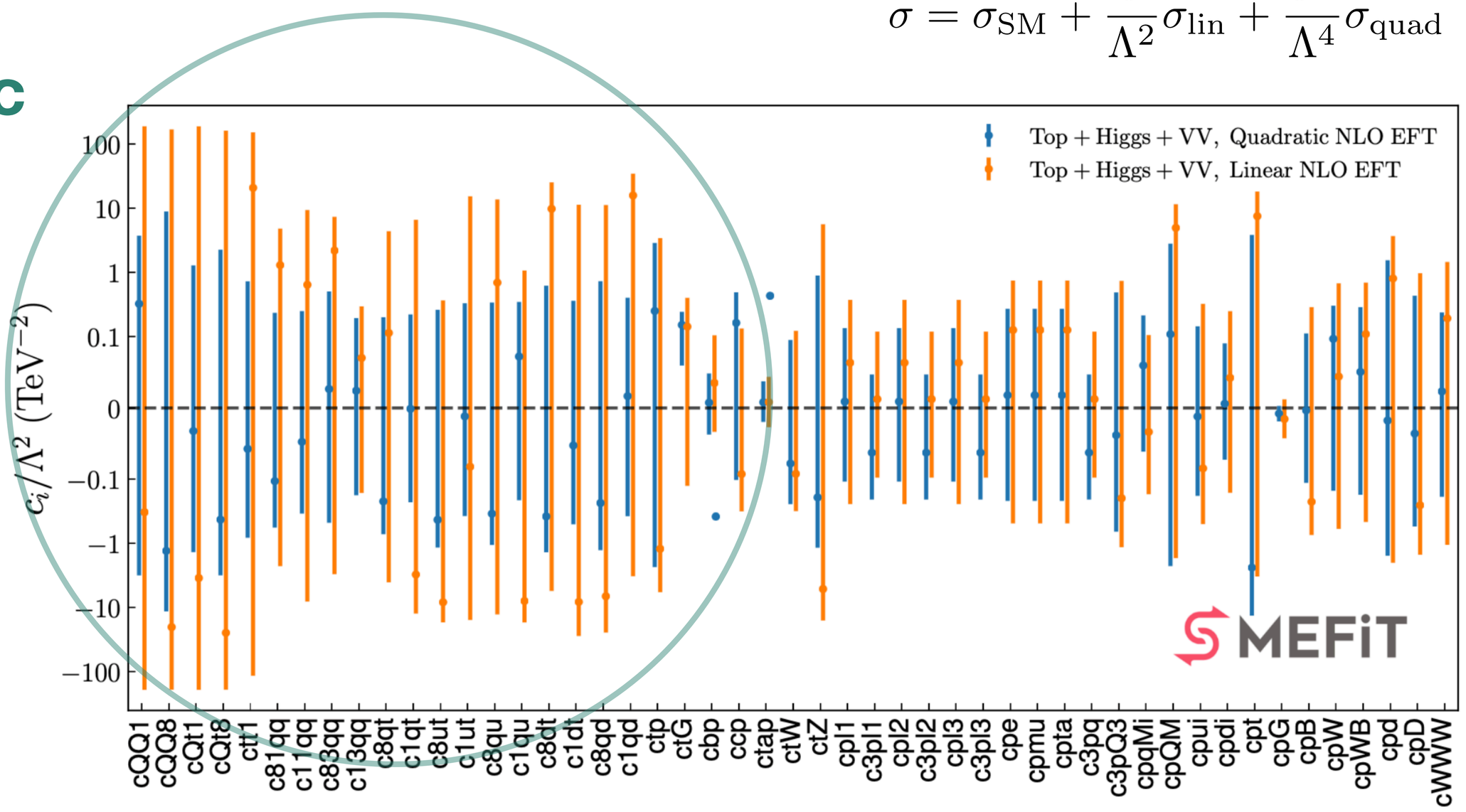
2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You



NLO and quadratic effects

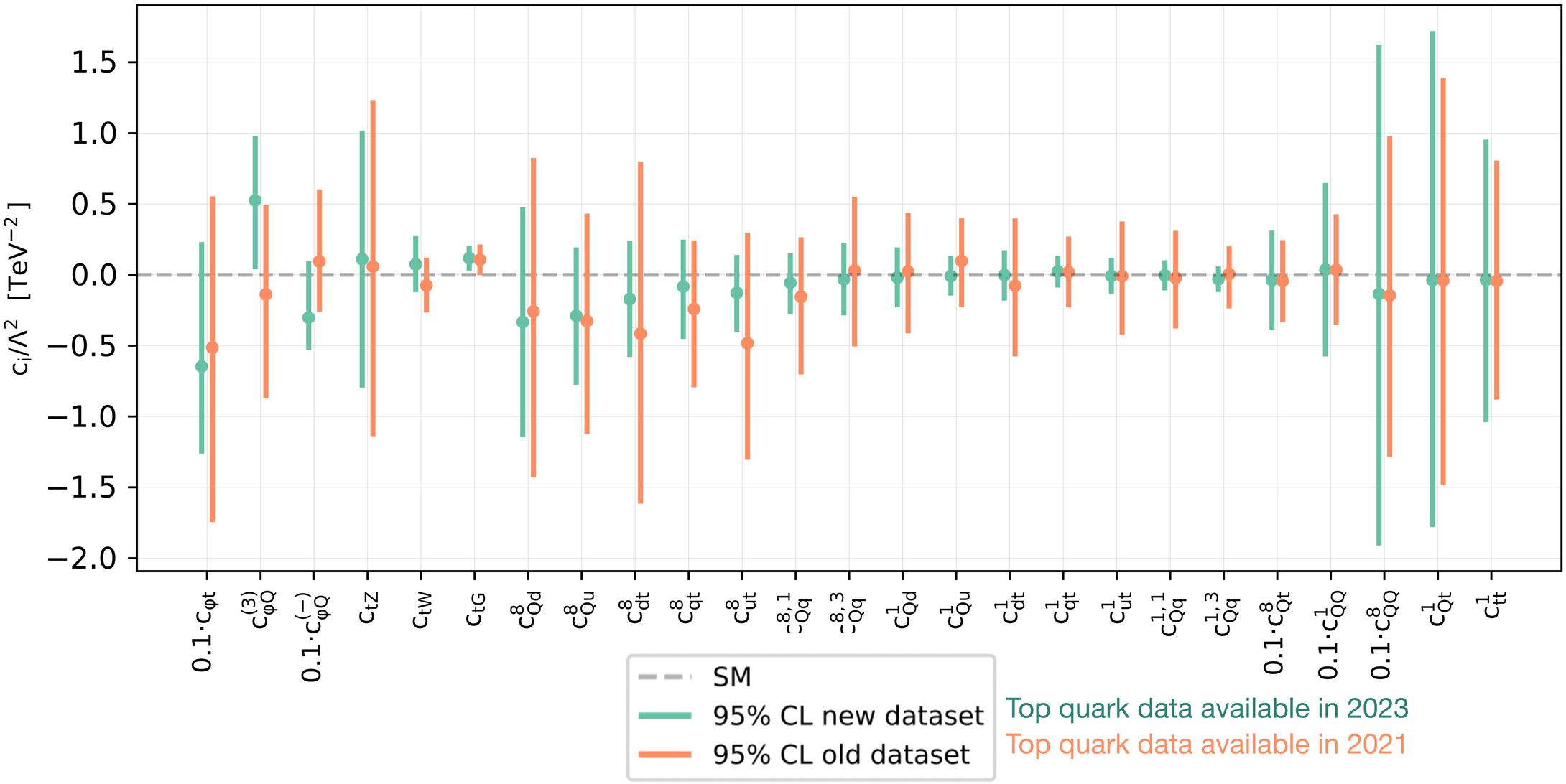
Ethier et. al, 2105.00006

$$\sigma = \sigma_{\rm SM} + \frac{C}{\Lambda^2}\sigma_{\rm lin} + \frac{C^2}{\Lambda^4}\sigma_{\rm quad}$$



The top sector after Run II

Z. Kassabov et. al , 2303.06159



Top quark data available in 2023

Top quark data available in 2021

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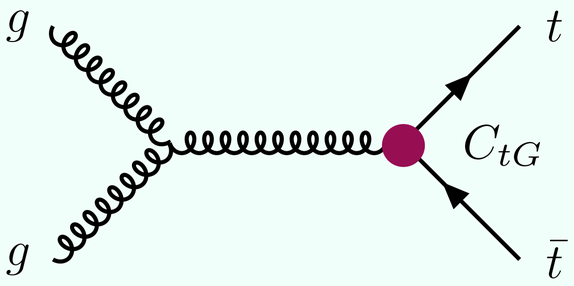
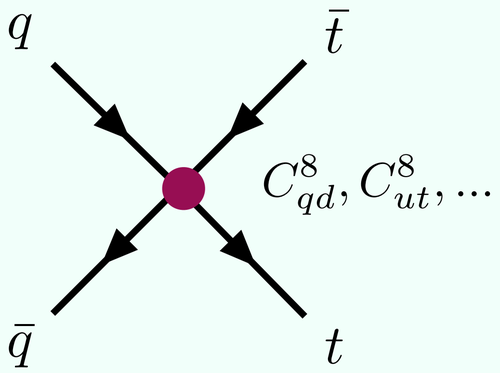
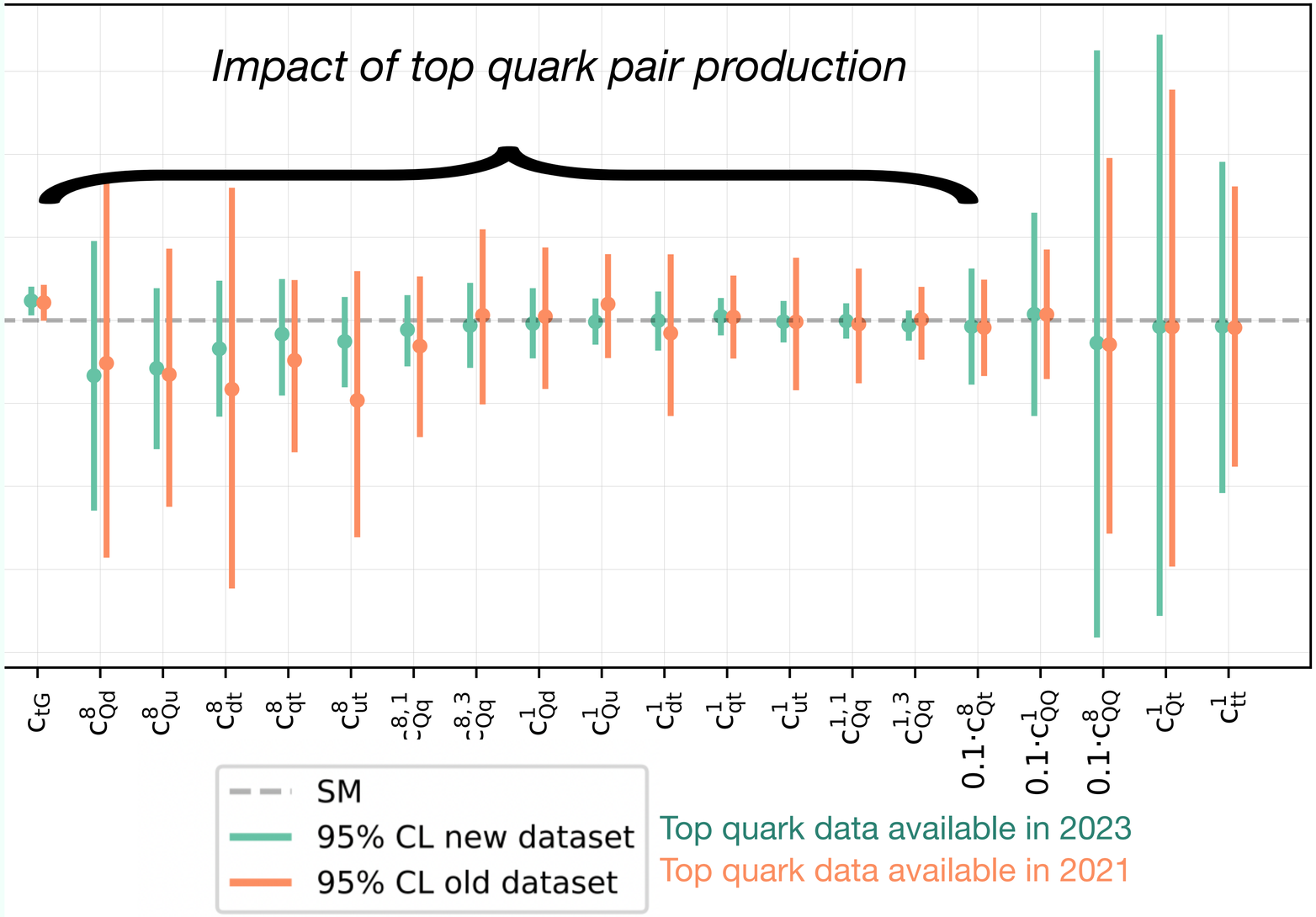


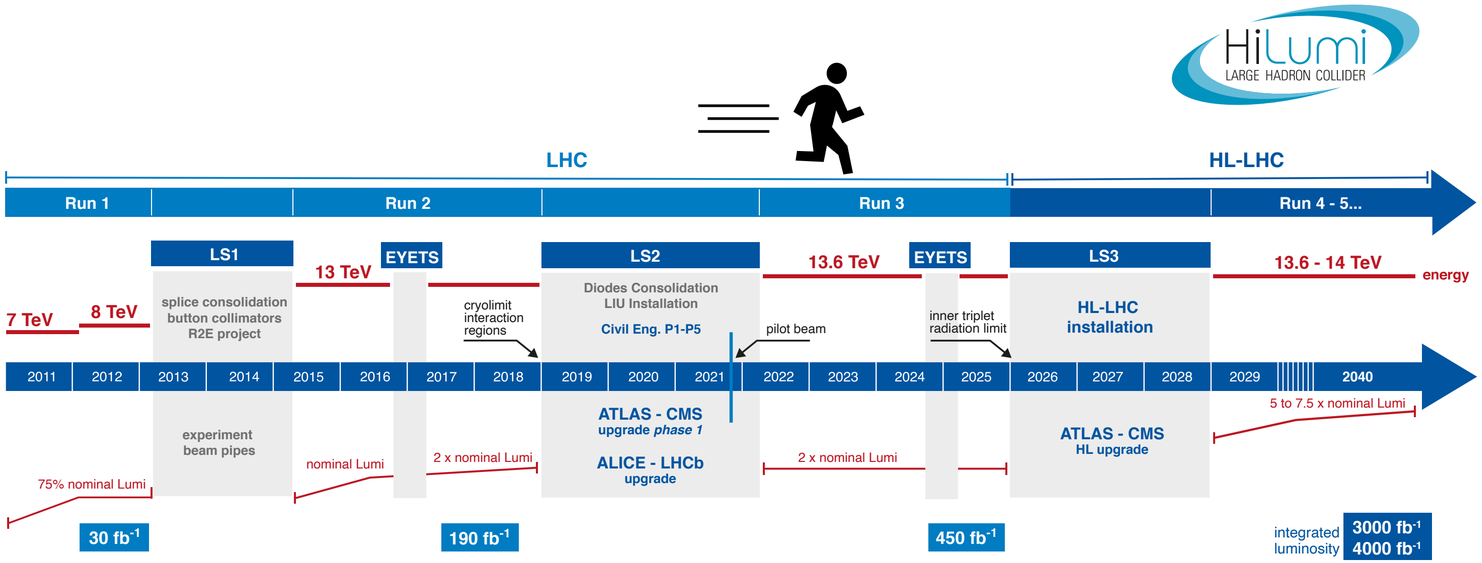




Looking forward

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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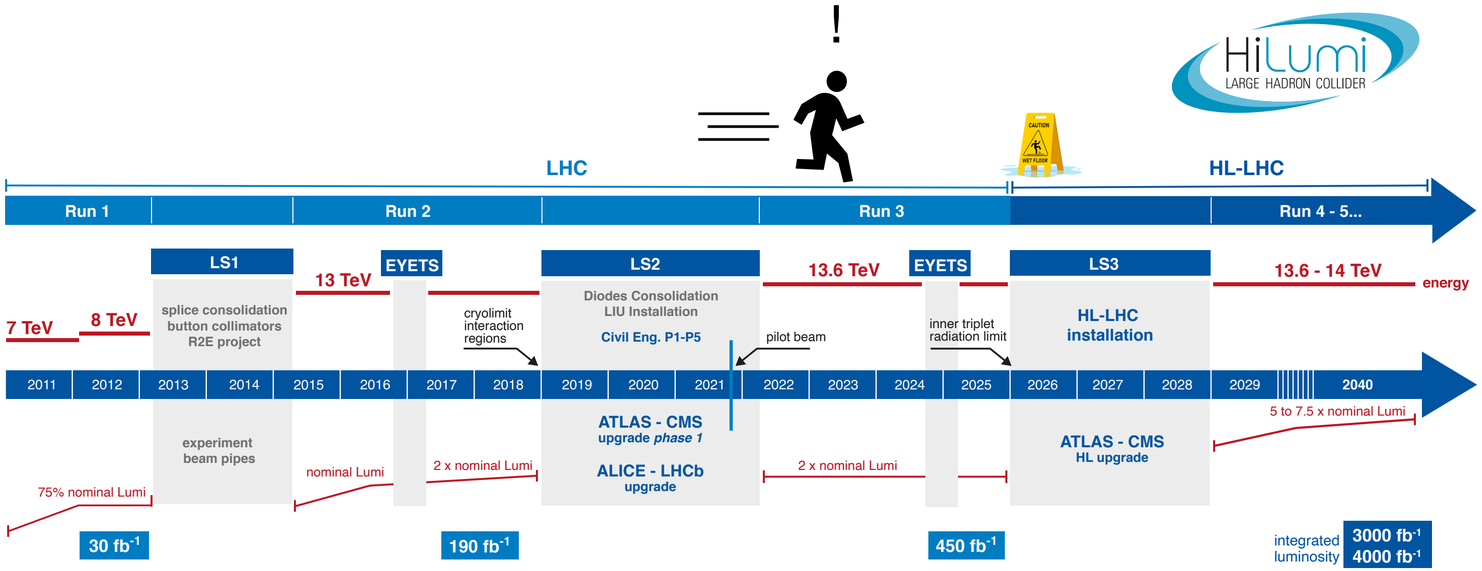

PDF-EFT Interplay

Wilson coefficients: c
PDF parameters: θ

PDF fits

SMEFT parameters are kept fixed:

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

Typically PDF fits assume the SM:

$$\bar{c} = 0$$

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PDFs used in SMEFT fits rely on SM assumptions

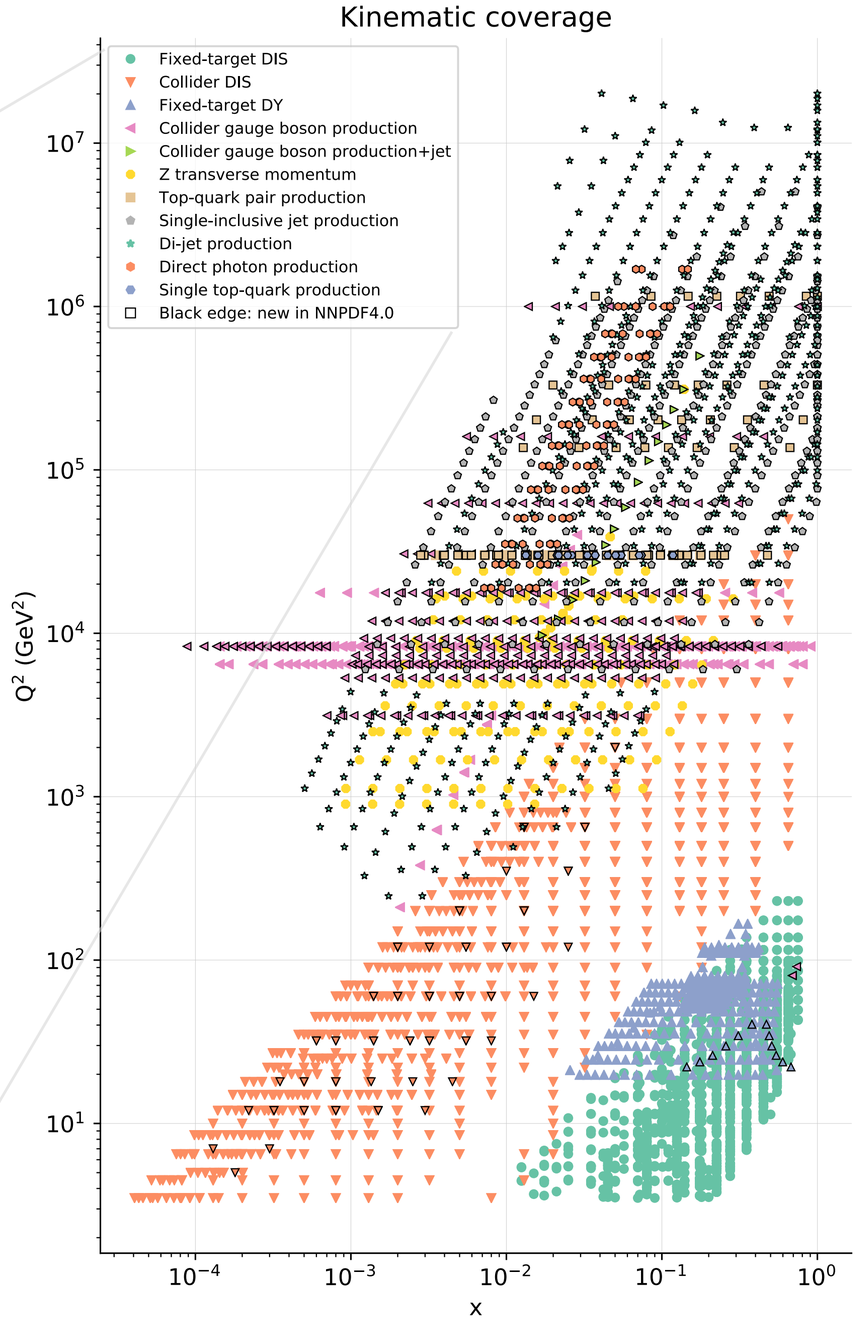
Data overlap

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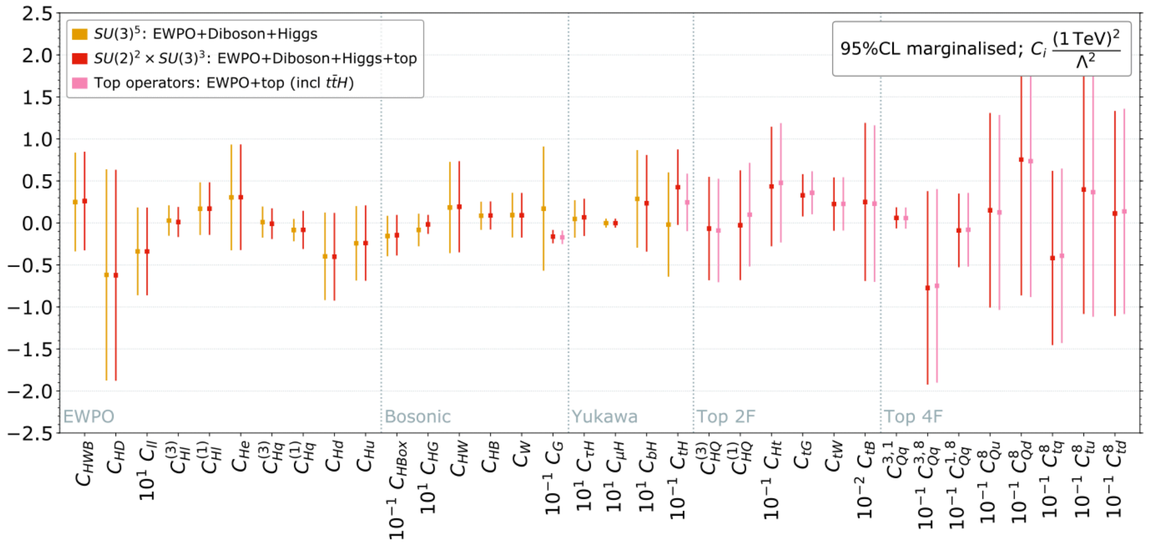
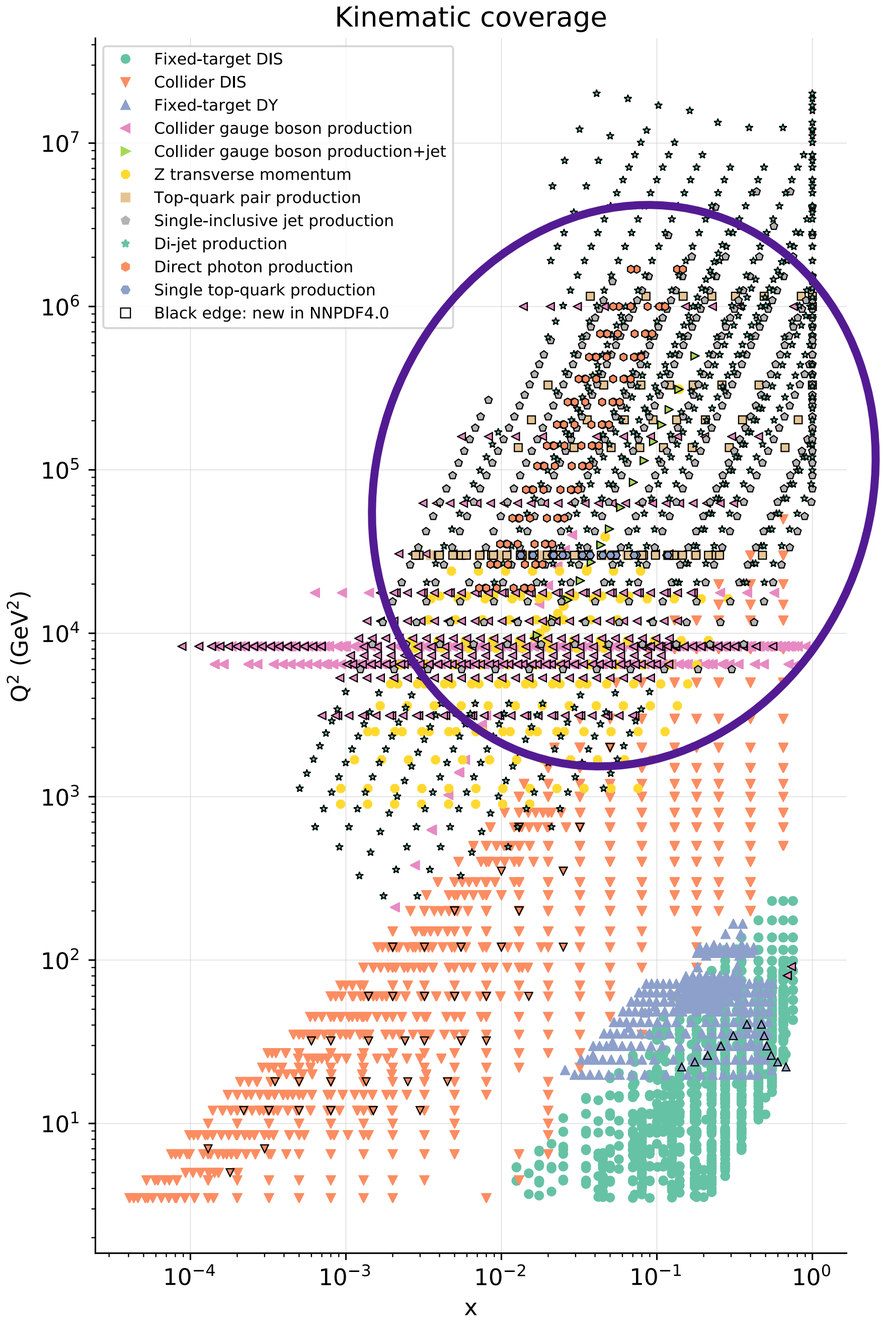
- e.g. Top quark data used to fit the SMEFT in the global fit of *2012.02779, J. Ellis, MM, K. Mimasu, V. Sanz, T. You*





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?

E. Hammou et. al, 2307.10370

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How do the constraints on the **SMEFT** change if we perform a simultaneous determination of the PDFs and SMEFT?

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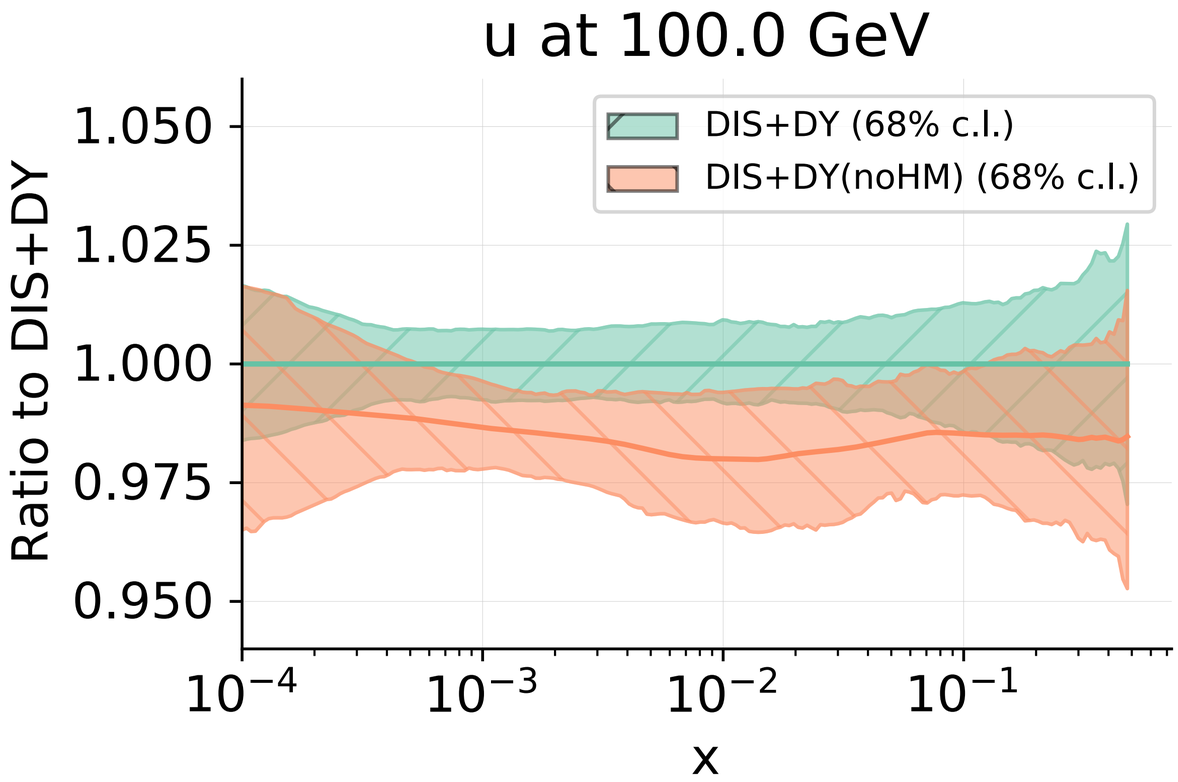
Could we be absorbing signs of new physics into the PDFs?

PDF-EFT interplay in high-mass Drell-Yan

Greljo et. al 2104.02723

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

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



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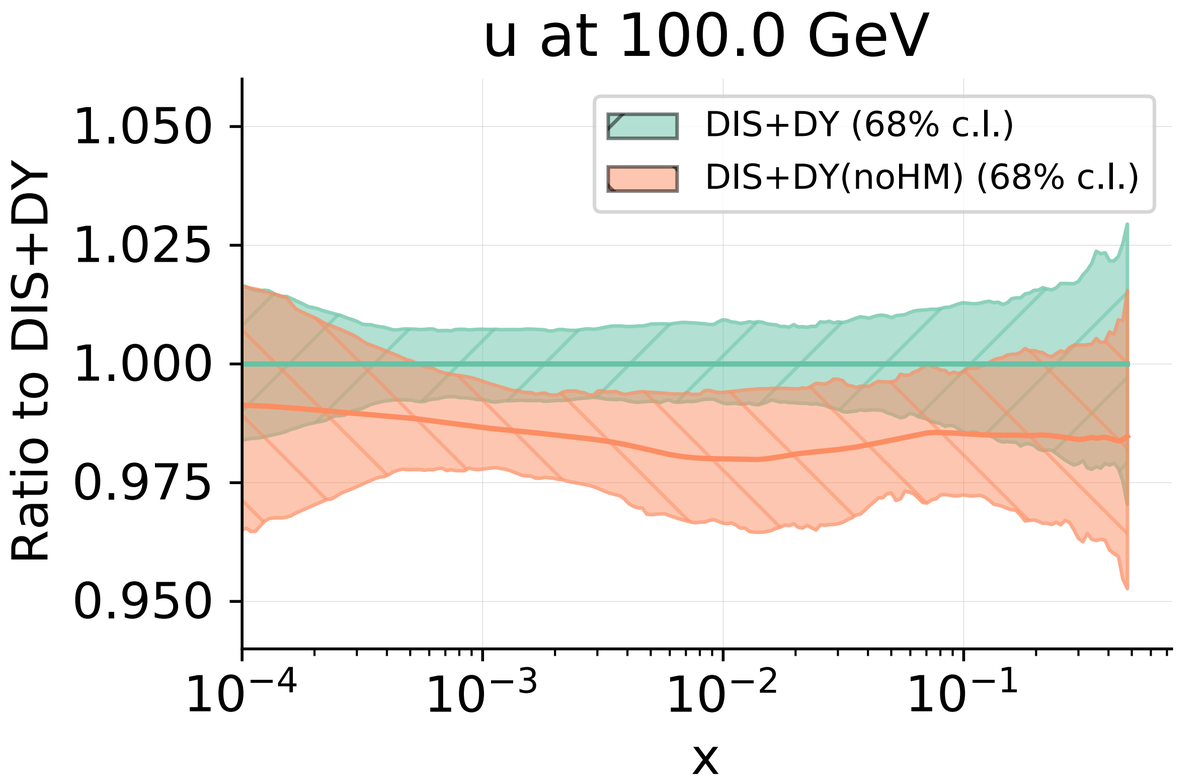

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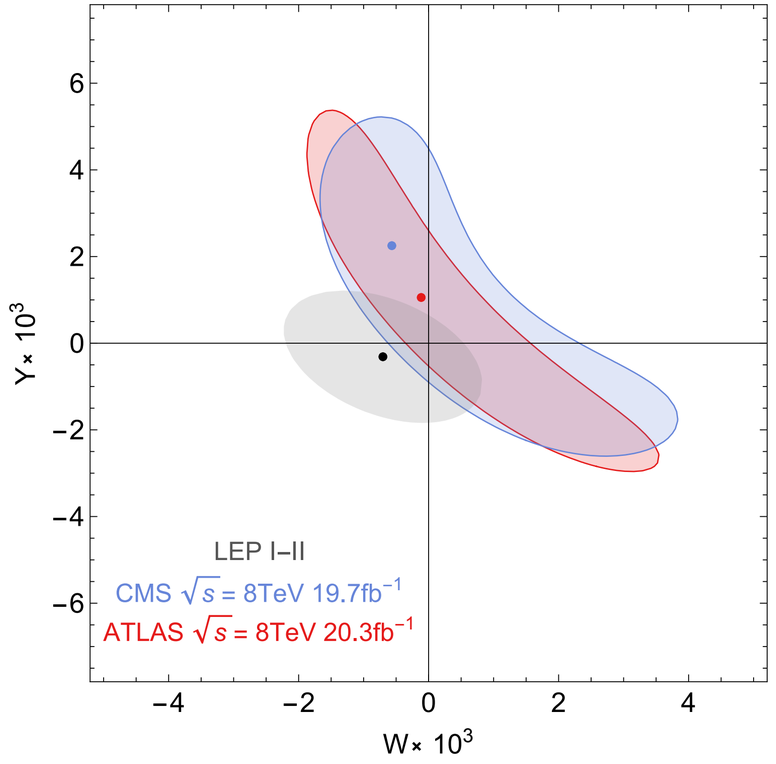
Constraints on 4-fermion operators of the SMEFT:



Farina et. al 1609.08157

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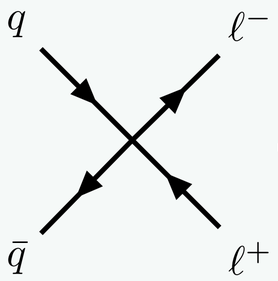
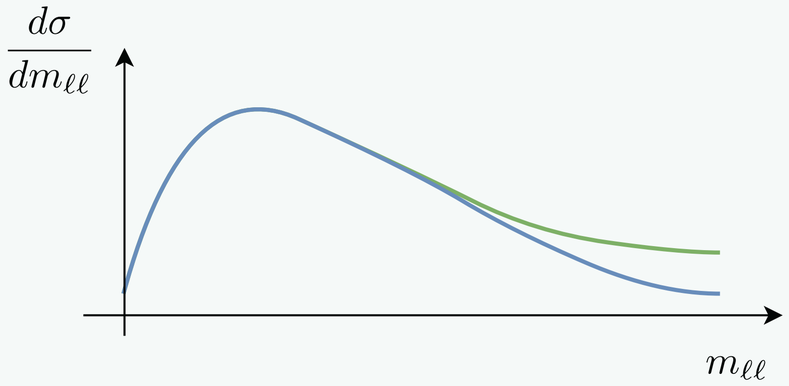


$$\mathcal{A} \sim \mathcal{A}_{\rm SM} + C\frac{E^2}{\Lambda^2}$$

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



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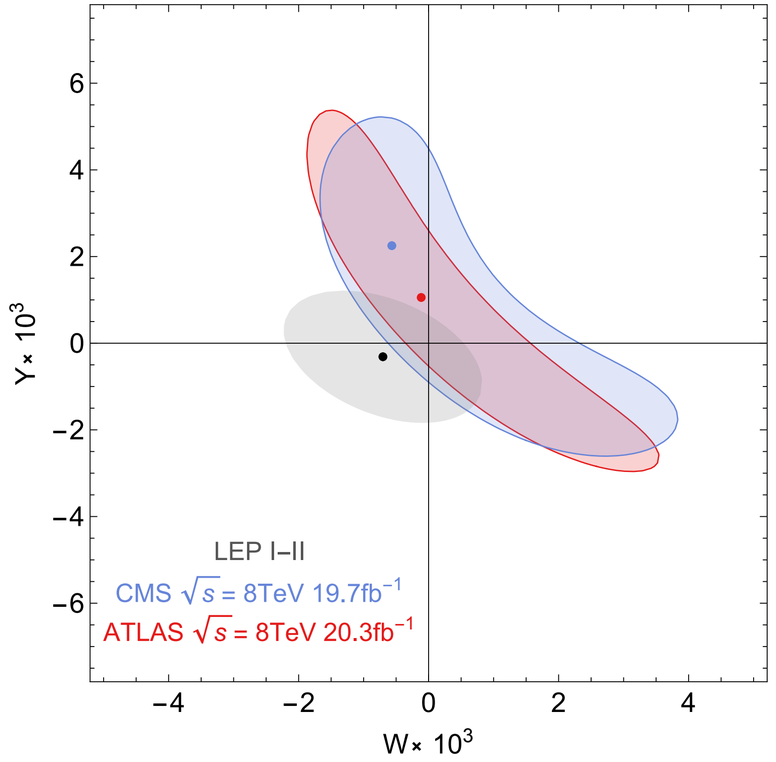

Farina et. al 1609.08157

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

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)
ATLAS	7	[120]	4.9	e^-e^+	1D	13	[1.0, 1.5]
ATLAS (*)	8	[86]	20.3	$\ell^-\ell^+$	2D	46	[0.5, 1.5]
CMS	7	[121]	9.3	$\mu^-\mu^+$	2D	127	[0.2, 1.5]
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CMS (*)	13	[122]	5.1	e^-e^+, $\mu^-\mu^+$ $\ell^-\ell^+$	1D	43, 43 43	[1.5, 3.0]
Total						**270 (313)**	

+ High Luminosity projections

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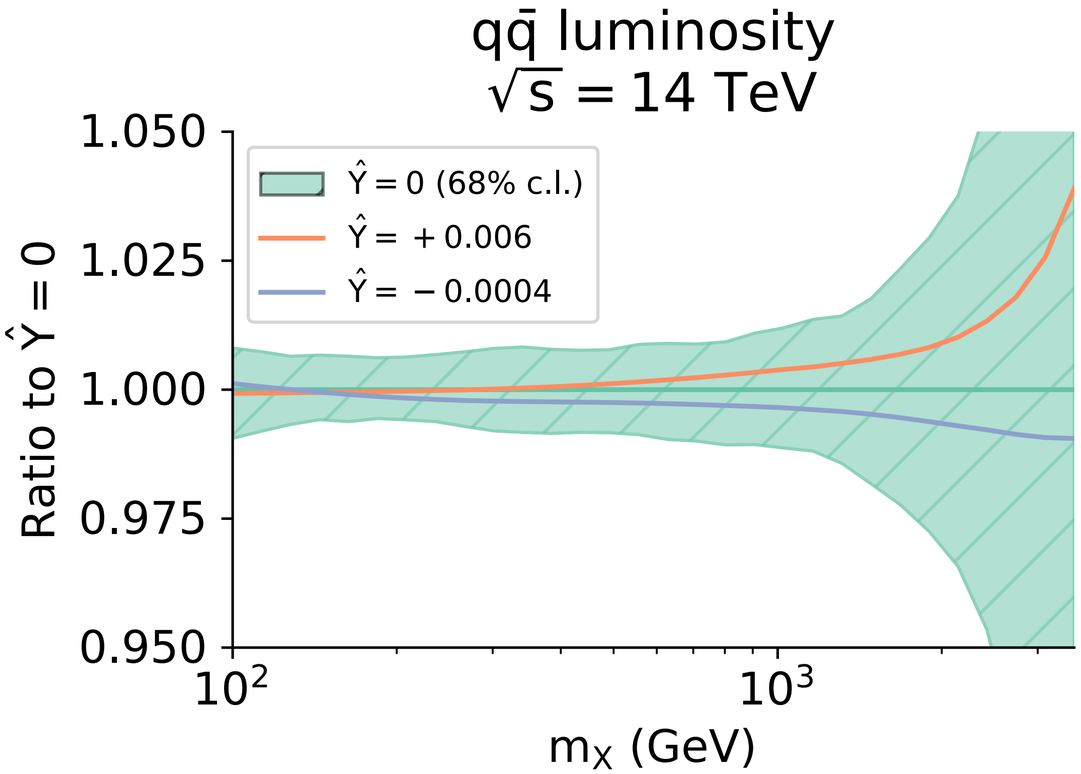
Theory benchmarks

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

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

See 2104.02723 for a flavourful benchmark

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



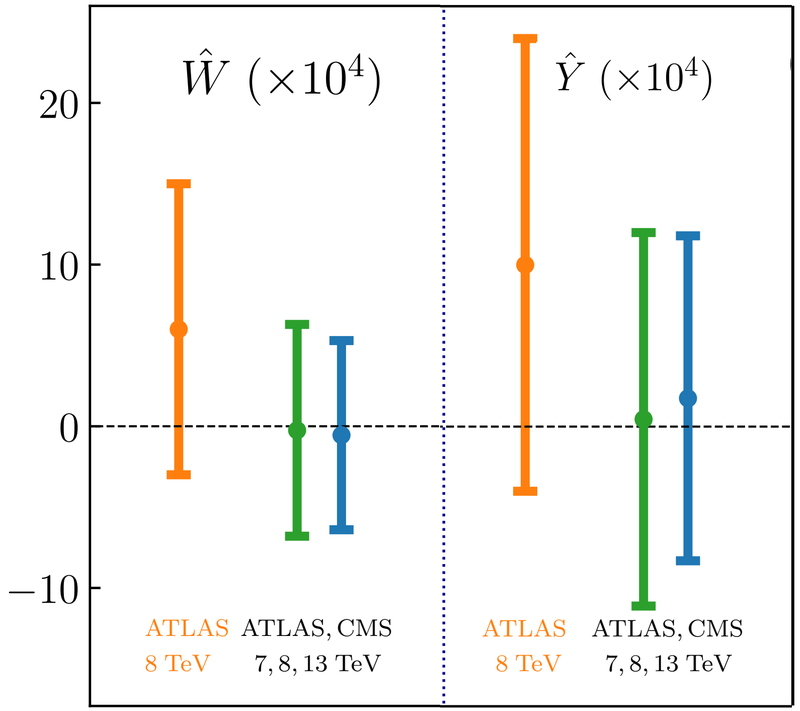
PDF fits under the assumption of nonzero SMEFT coefficients:

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**

SMEFT constraints are **stable:**

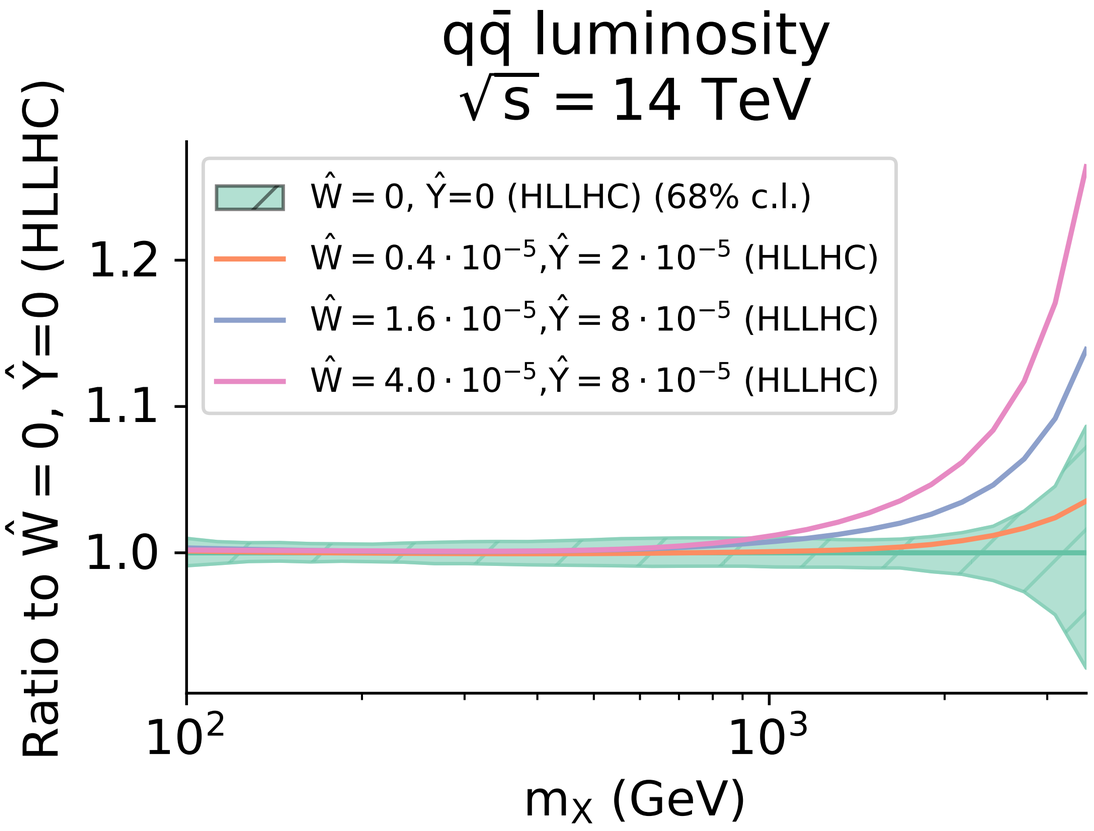
moderate shifts when using SMEFT vs SM PDFs



Farina et al (1609.08157)
this work, SM PDFs
this work, SMEFT PDFs

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

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



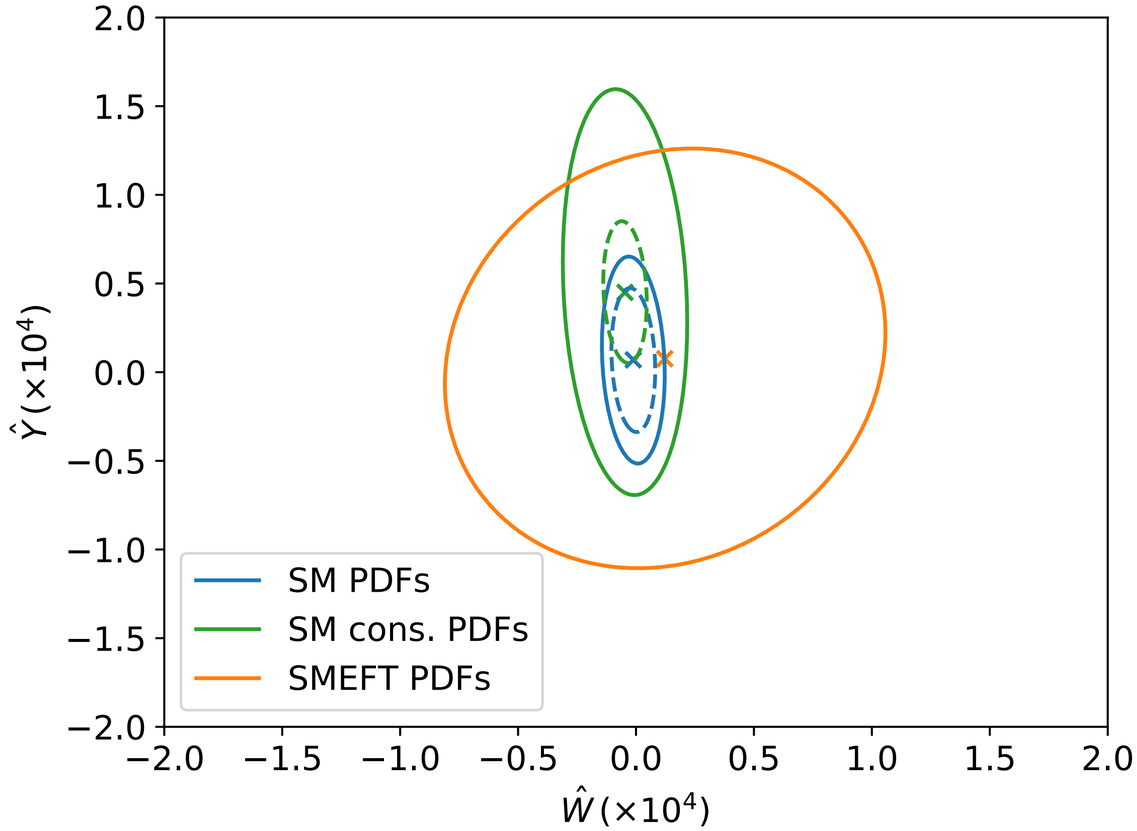
PDF fits under the assumption of nonzero SMEFT coefficients:

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

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

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

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



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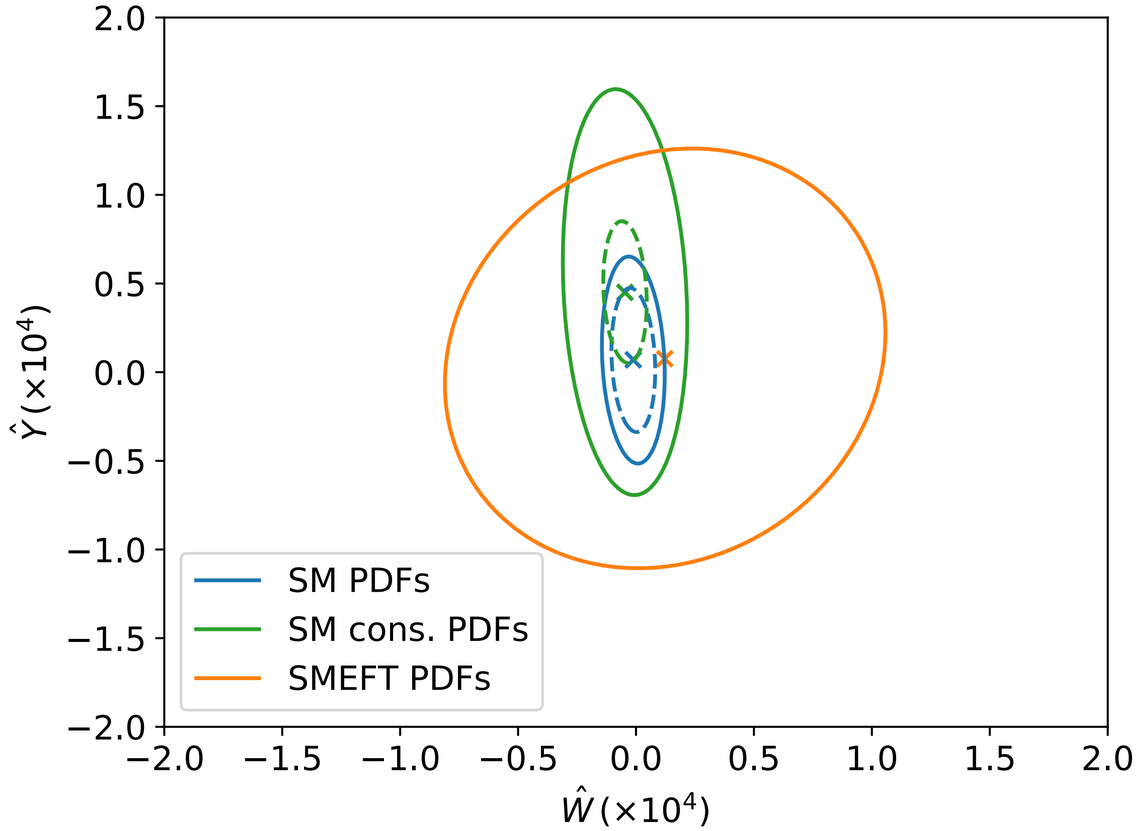
→ **what about the top sector?**



The SIMUnet Methodology

S. Iranipour, M. Ubiali, 2201.07240

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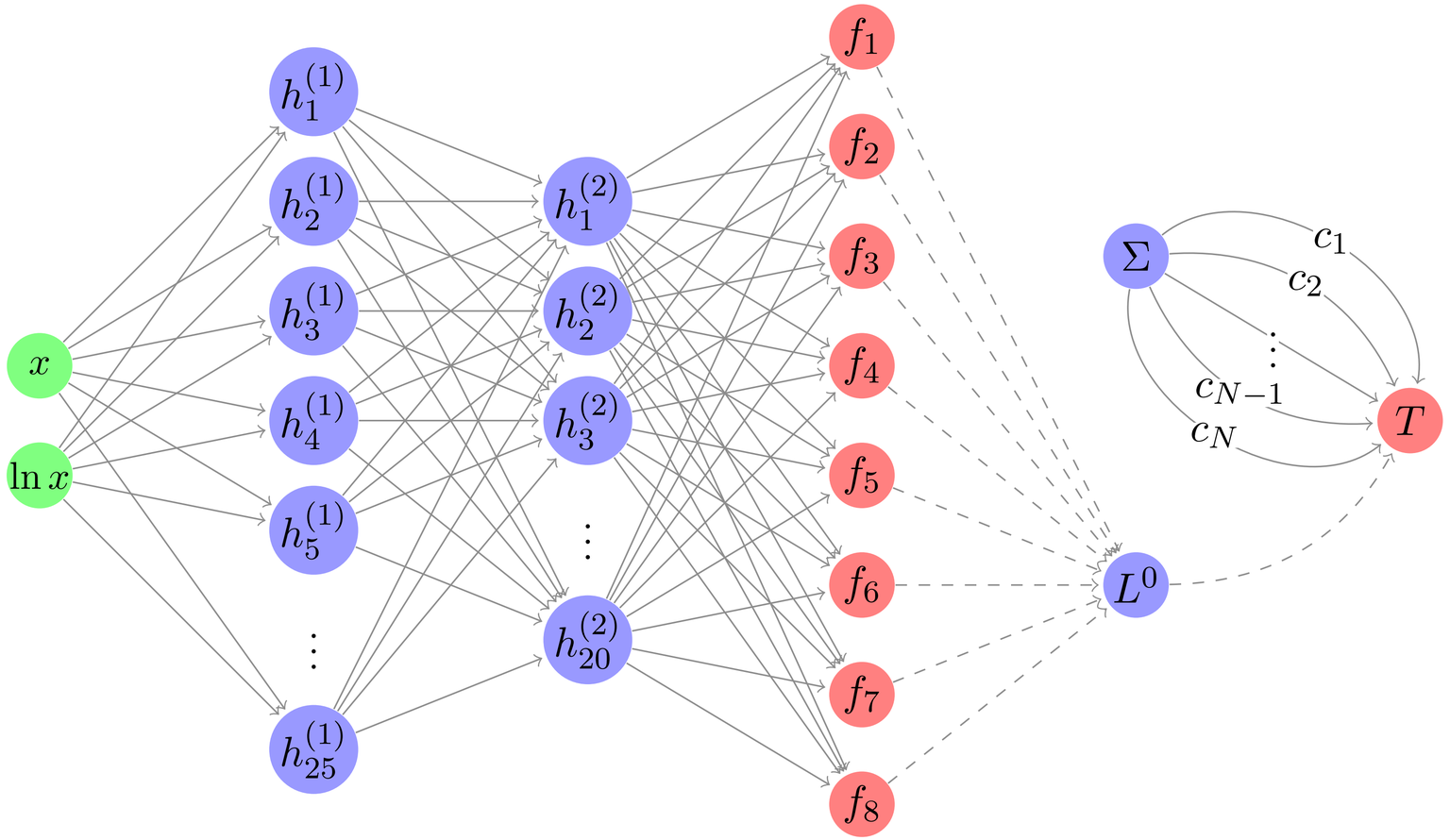
Propagates uncertainties from data to NN parameters using the Monte Carlo replica method



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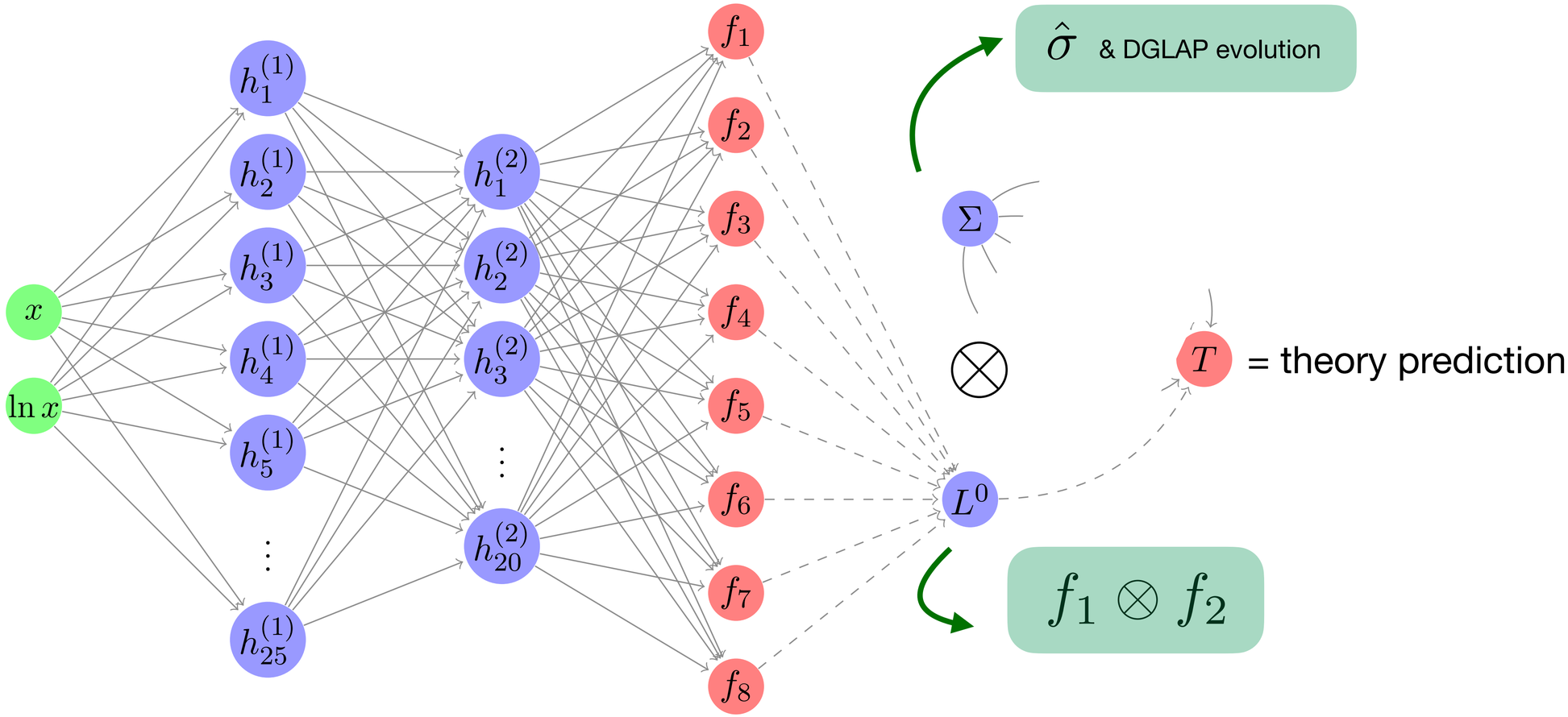
How does it work?



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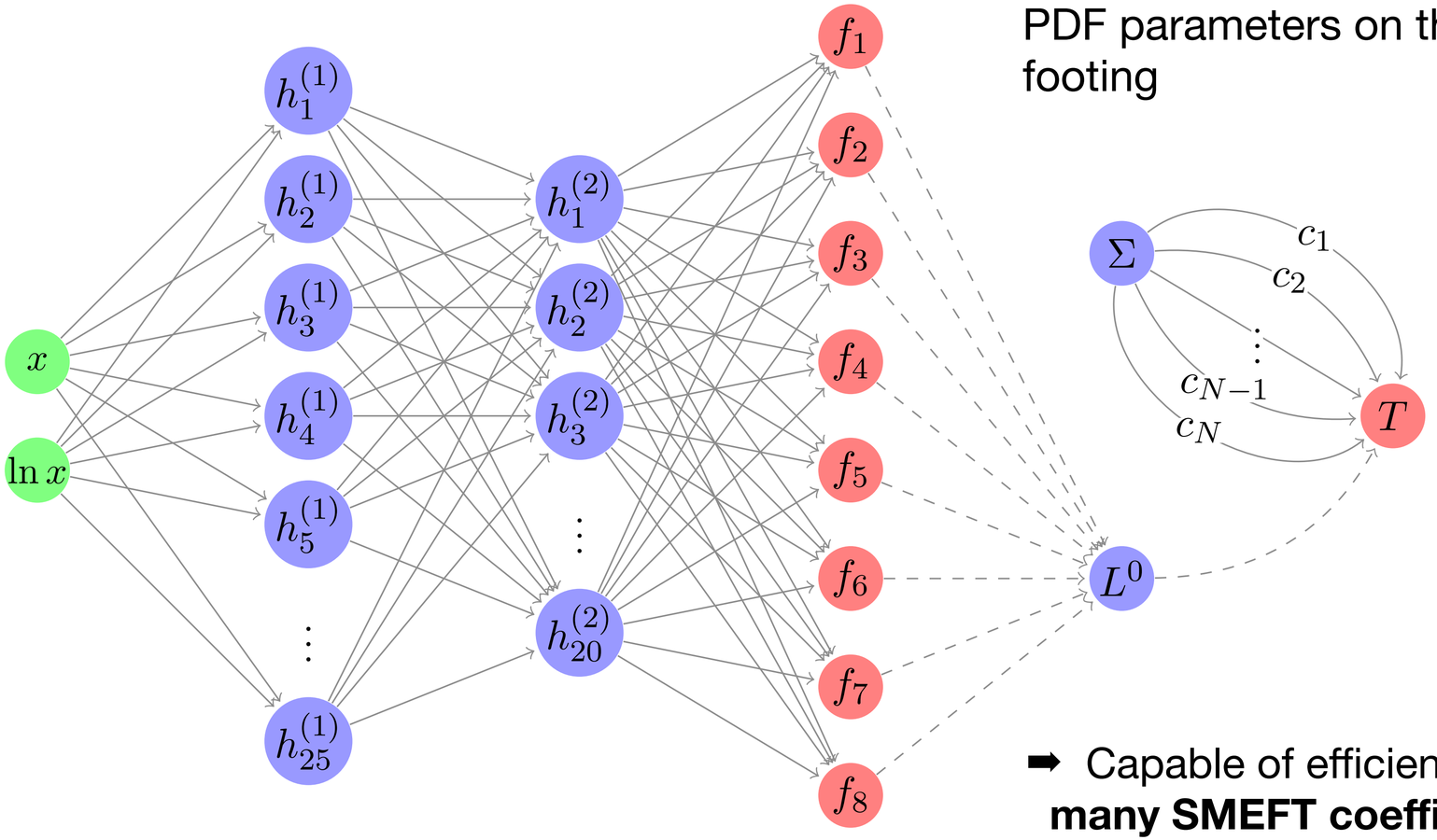

➡ places SMEFT parameters and PDF parameters on the same footing

➡ Capable of efficiently fitting **many SMEFT coefficients**

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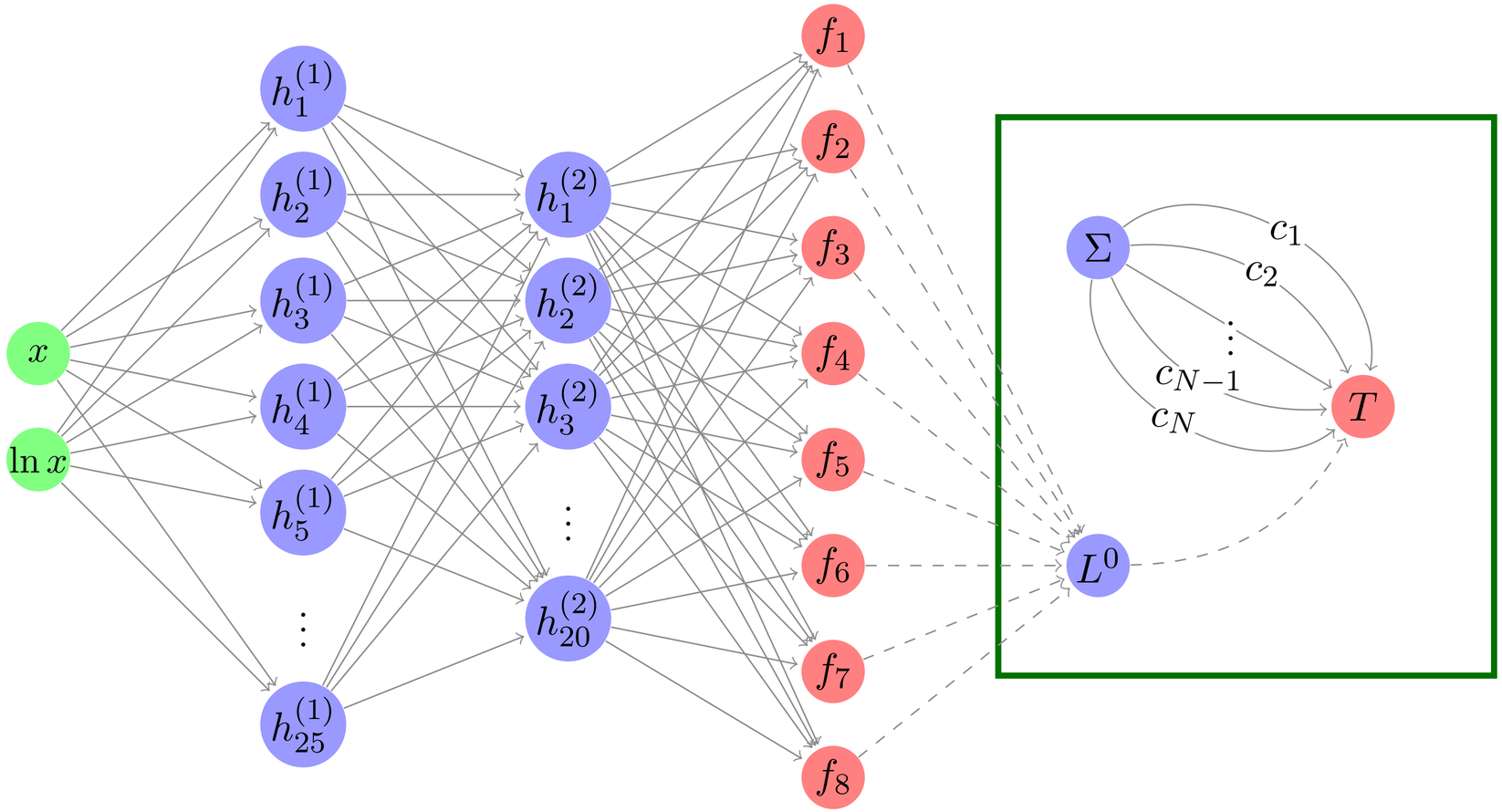
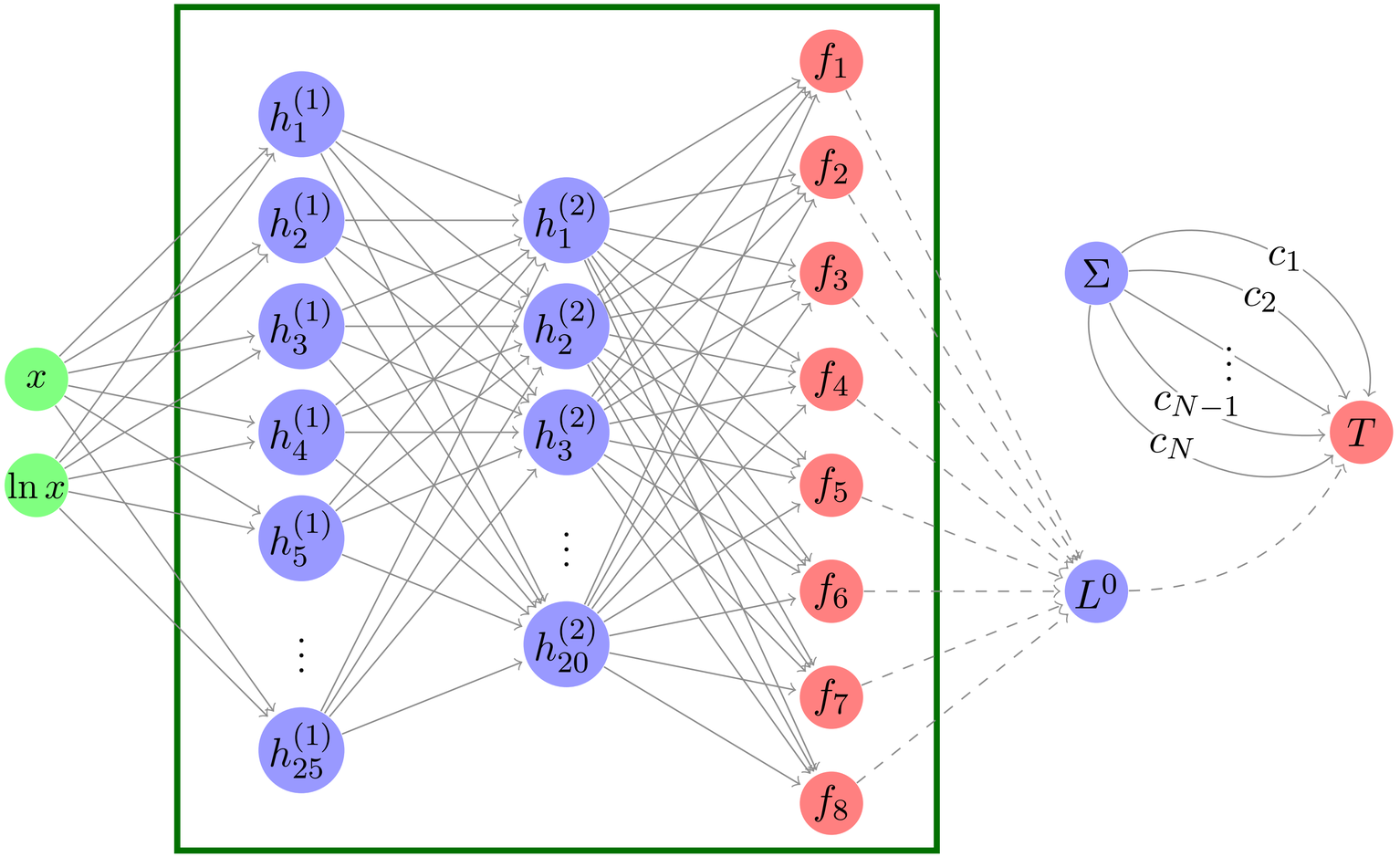
Train only the final layer: reproduce SMEFT fits



The SIMUnet methodology

S. Iranipour, M. Ubiali, 2201.07240

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



The SIMUnet methodology

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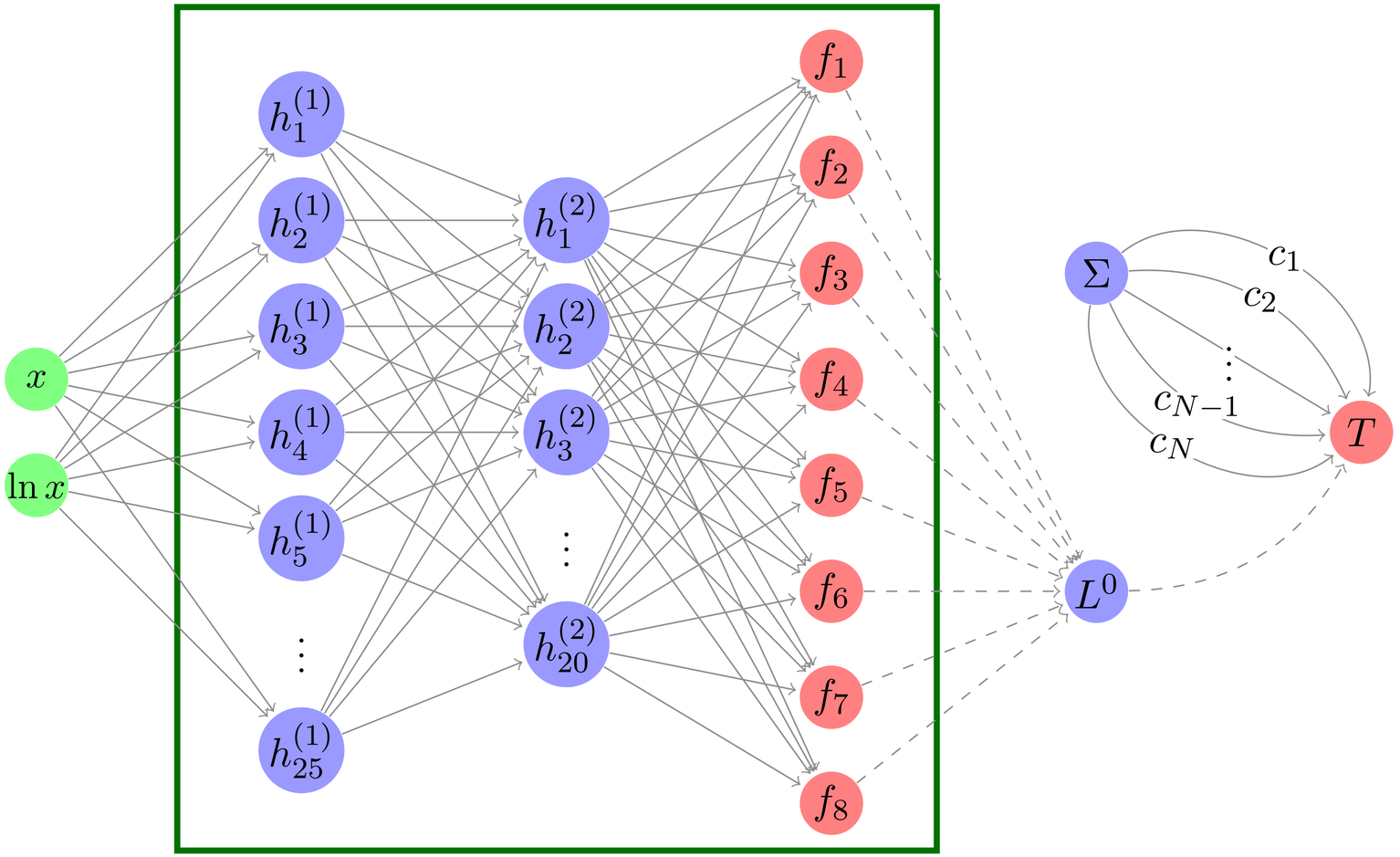
Train only the PDF NN weights on all data **except the top sector:** conservative PDFs



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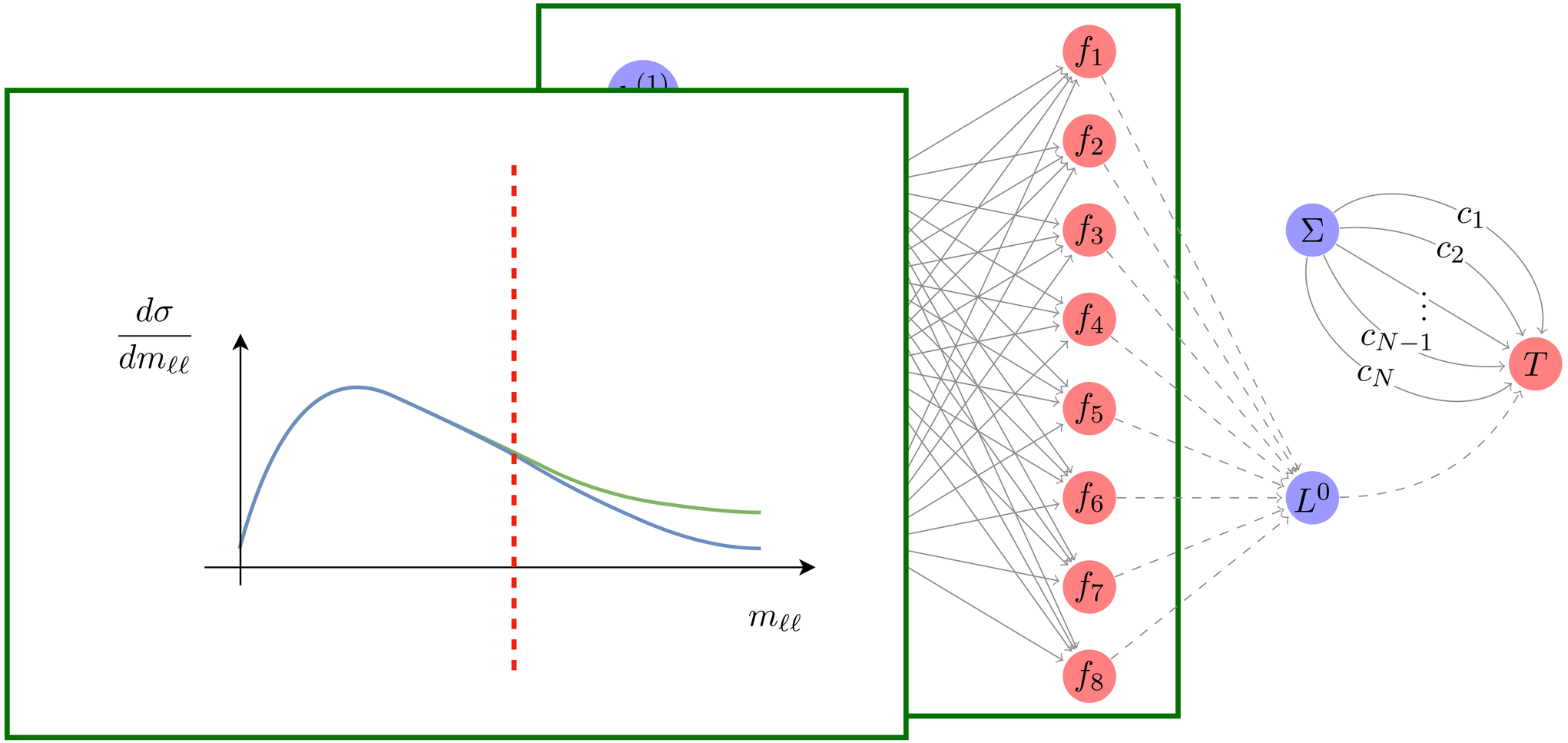

The SIMUnet methodology

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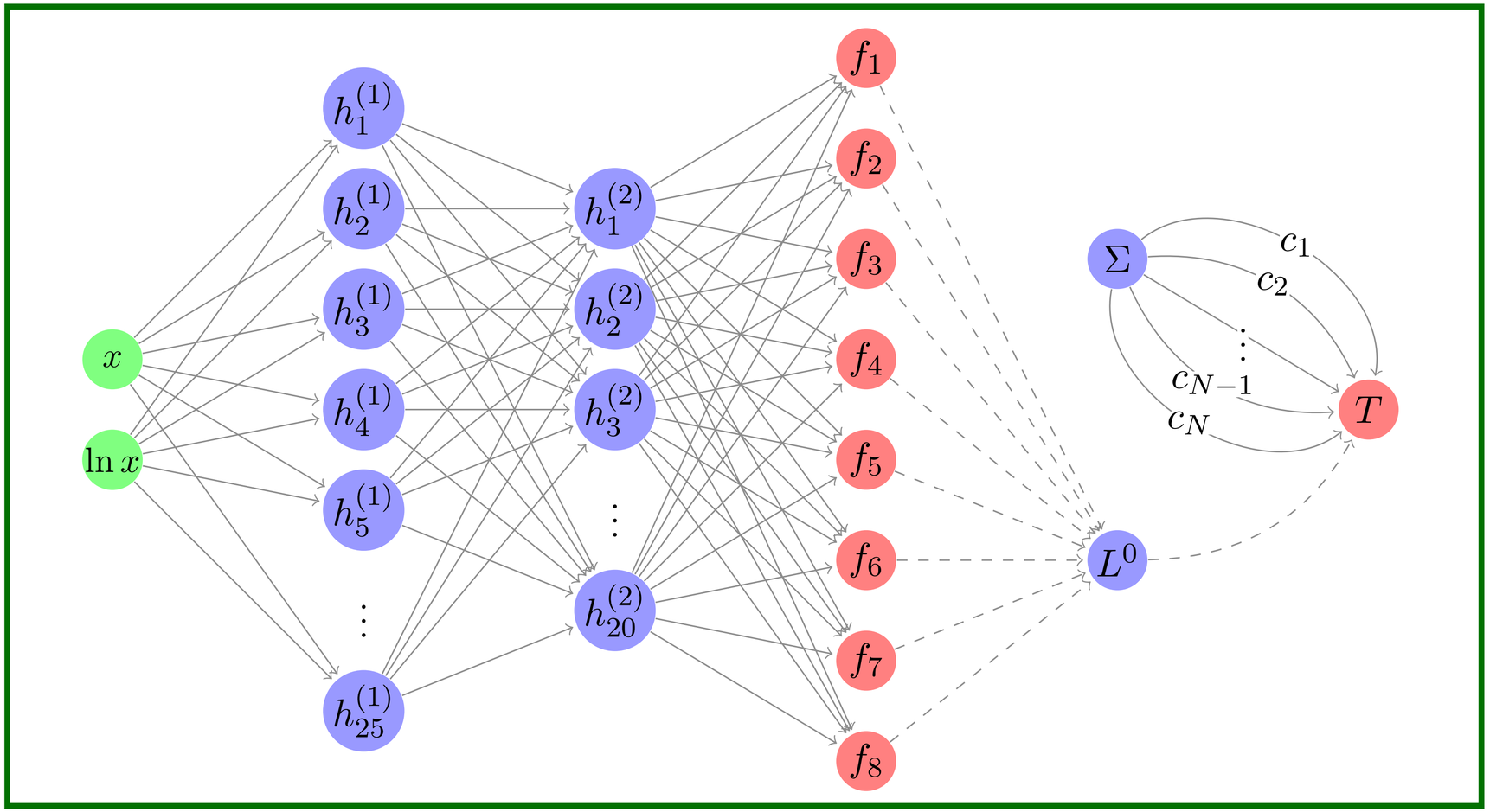
Train everything: **simultaneous fit**



PDF-EFT interplay in the top sector

Kassabov et. al: 2303.06159

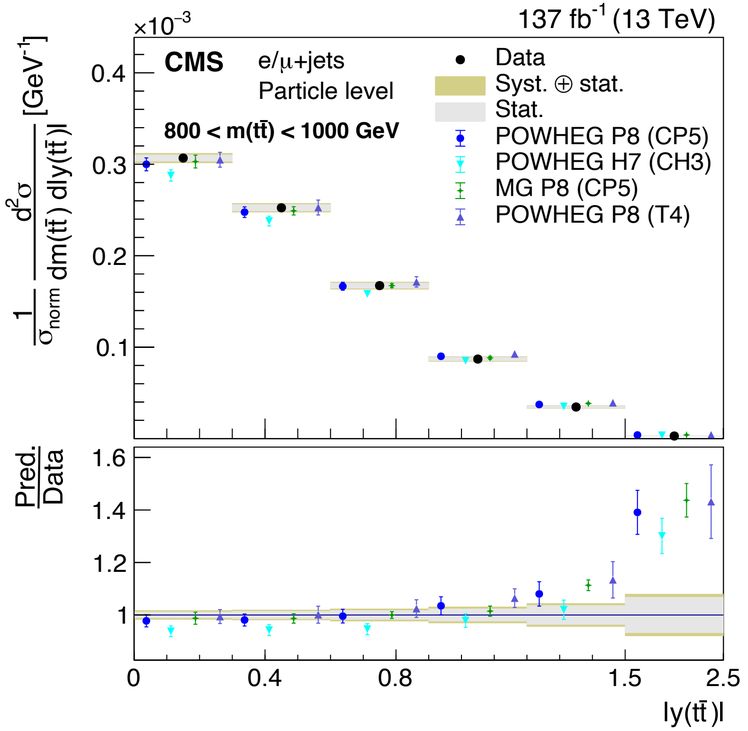
Data

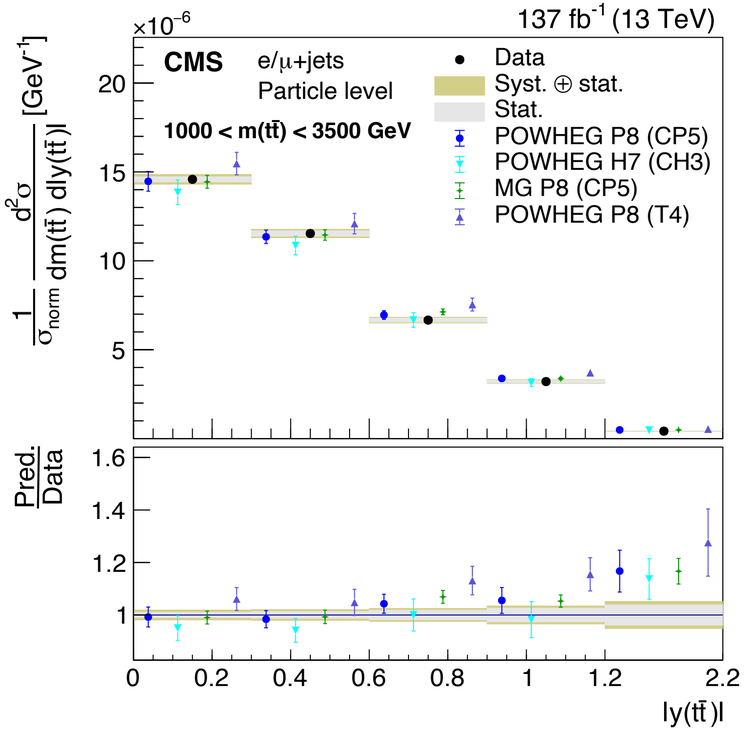
[CMS, Phys. Phys. Rev. D 104 (2021) 092013]

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}

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

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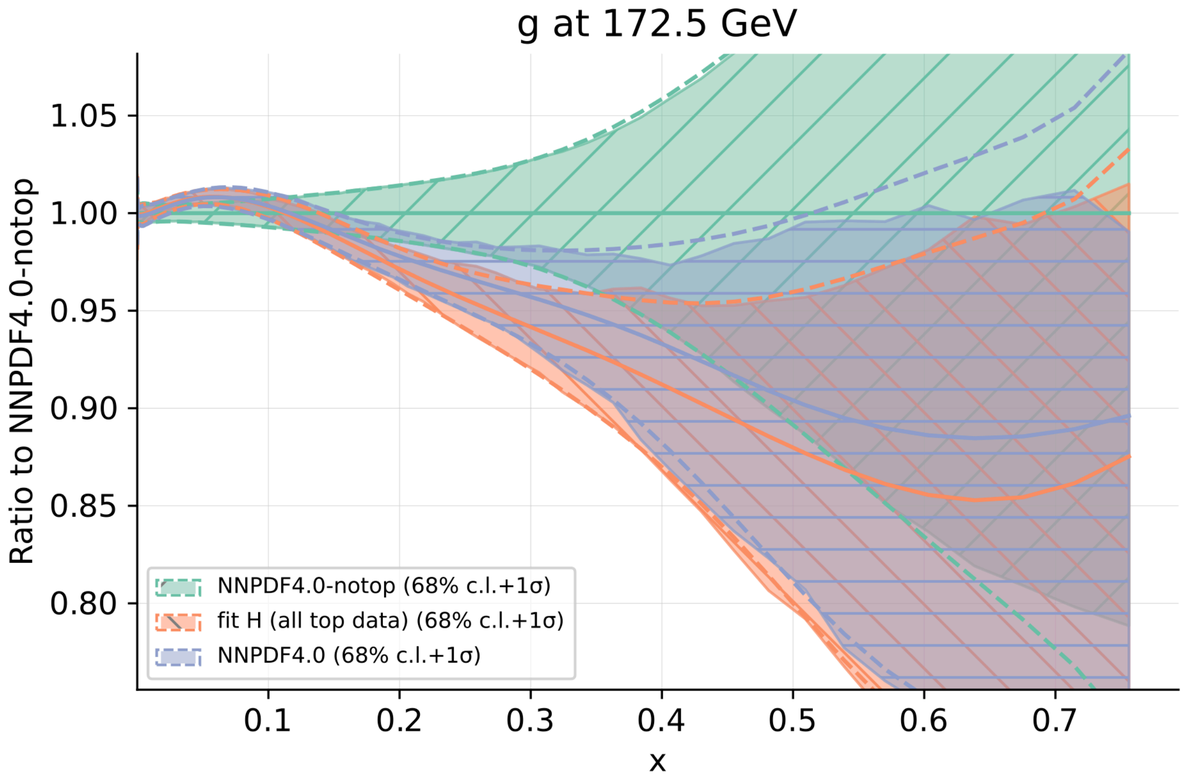

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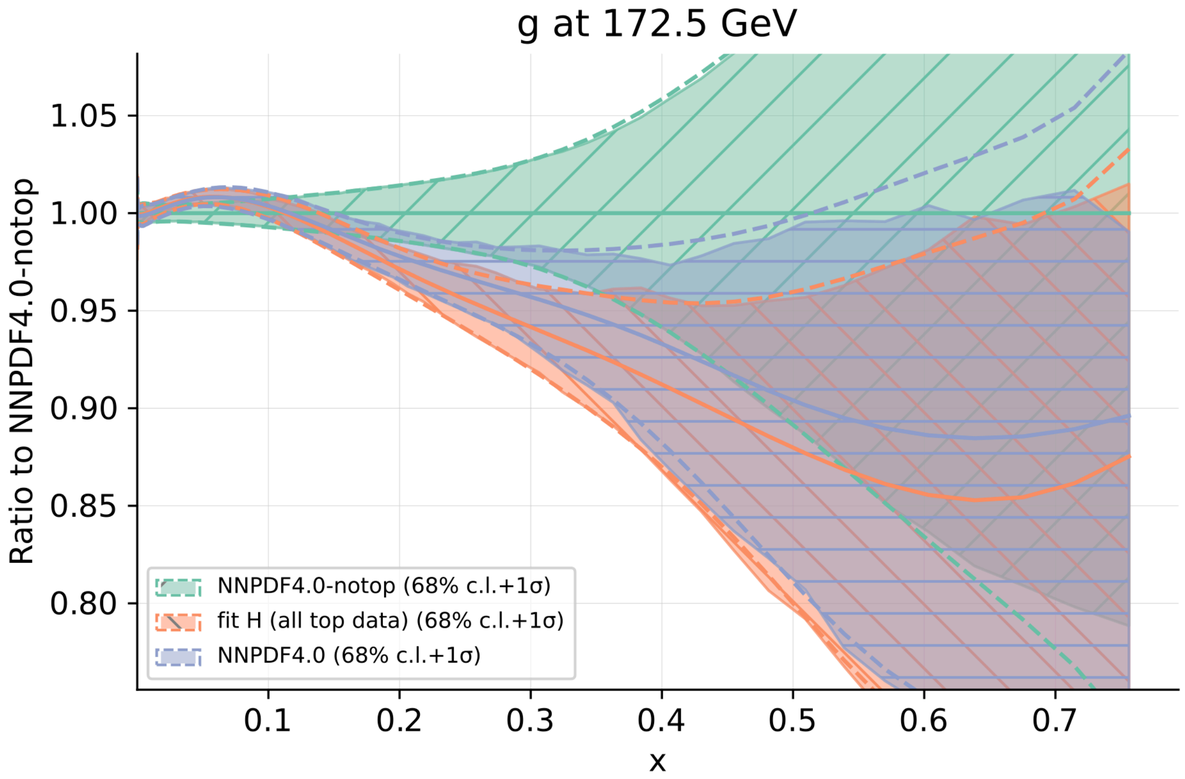
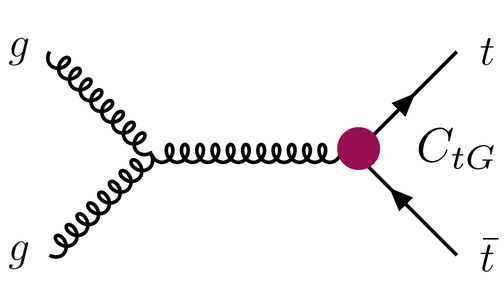
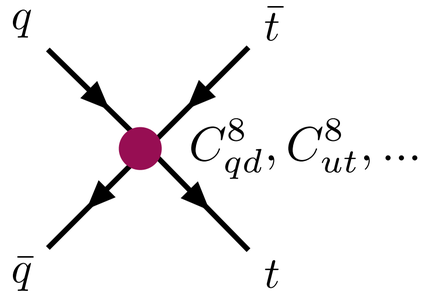


Potential for interplay between **gluon PDF** and coefficients modifying top quark pair production:

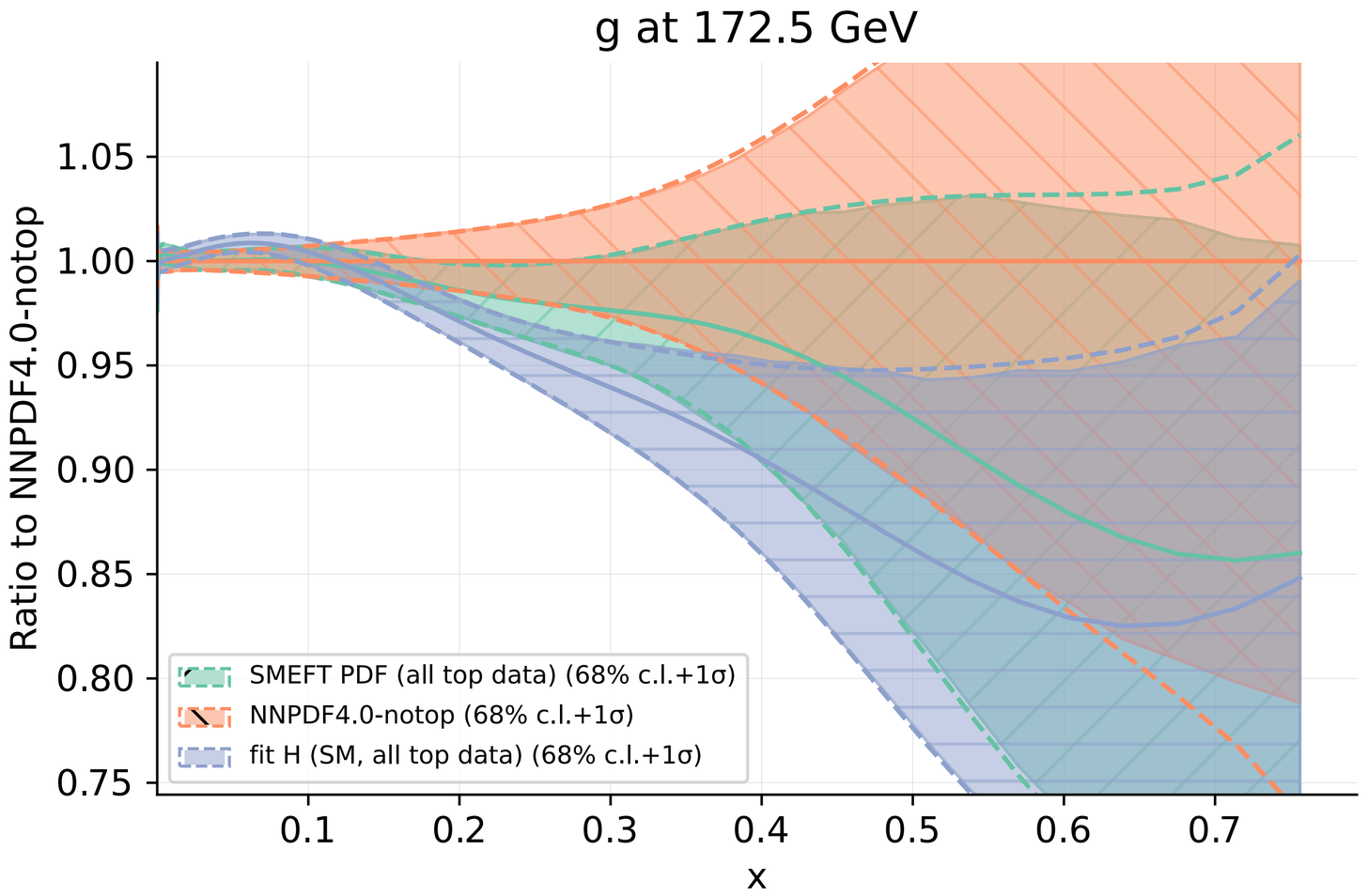




Simultaneous fit

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

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



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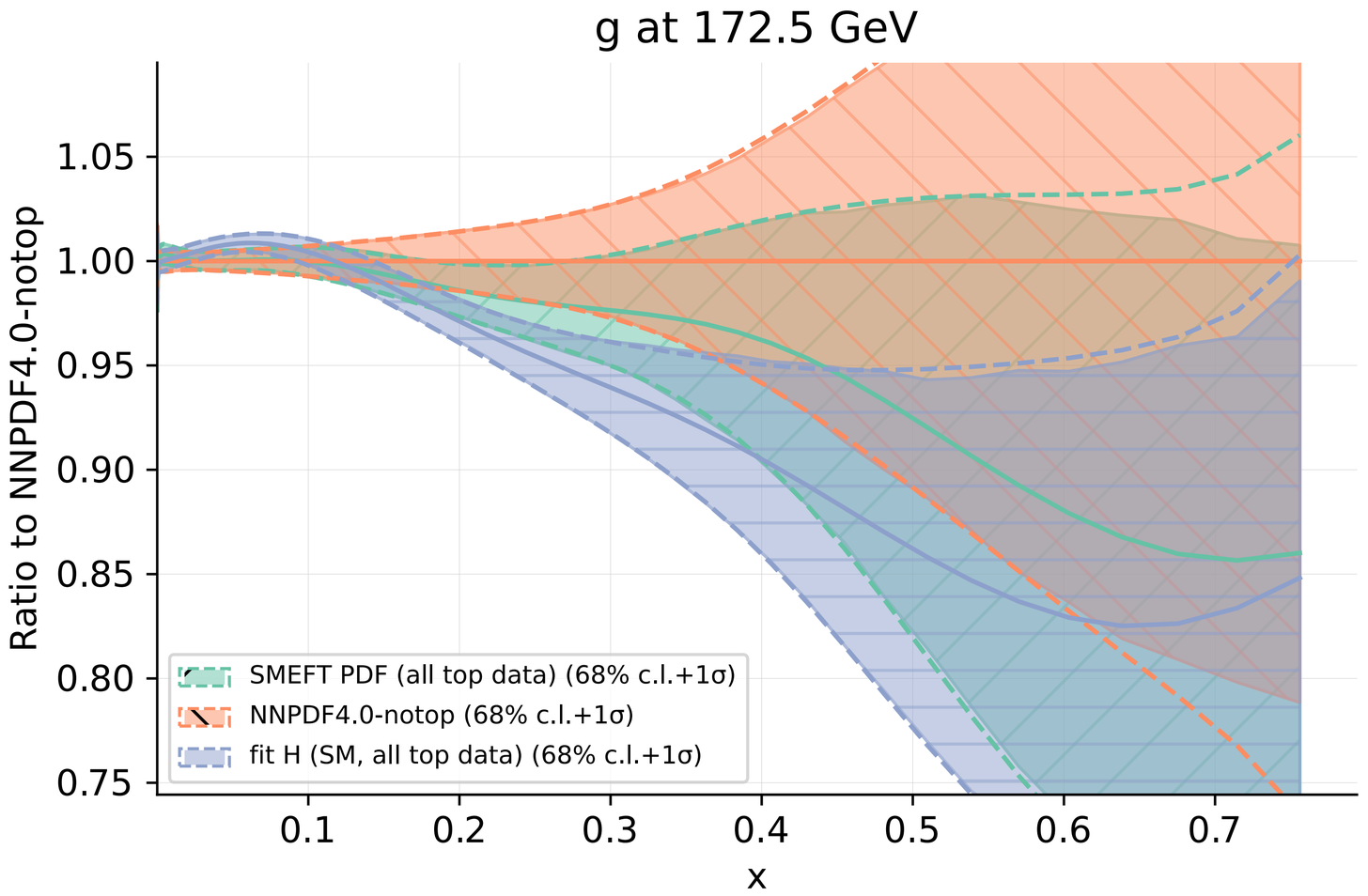
Uncertainties increase relative to the *SM, all top data* PDF fit

- reflecting the increase in number of fitted parameters



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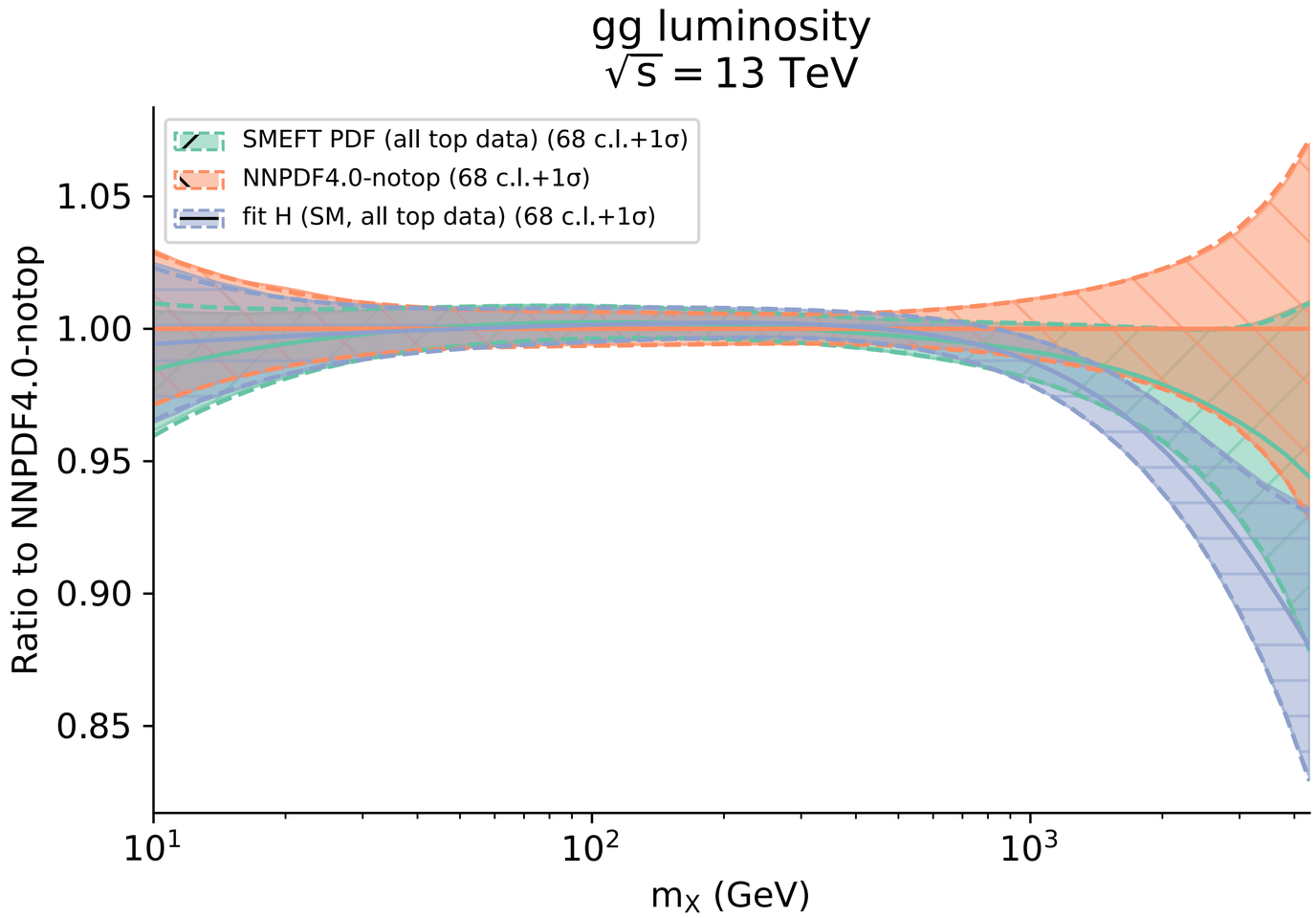

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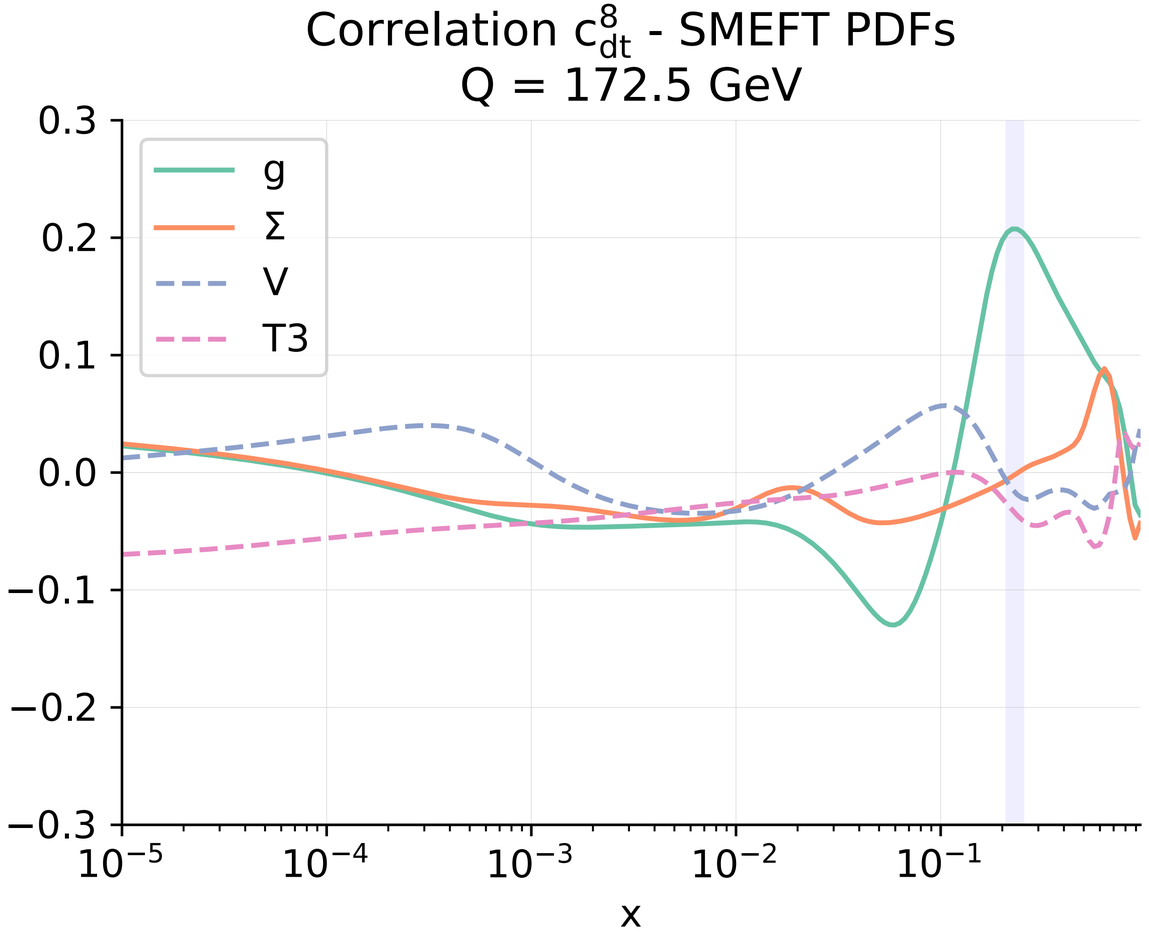
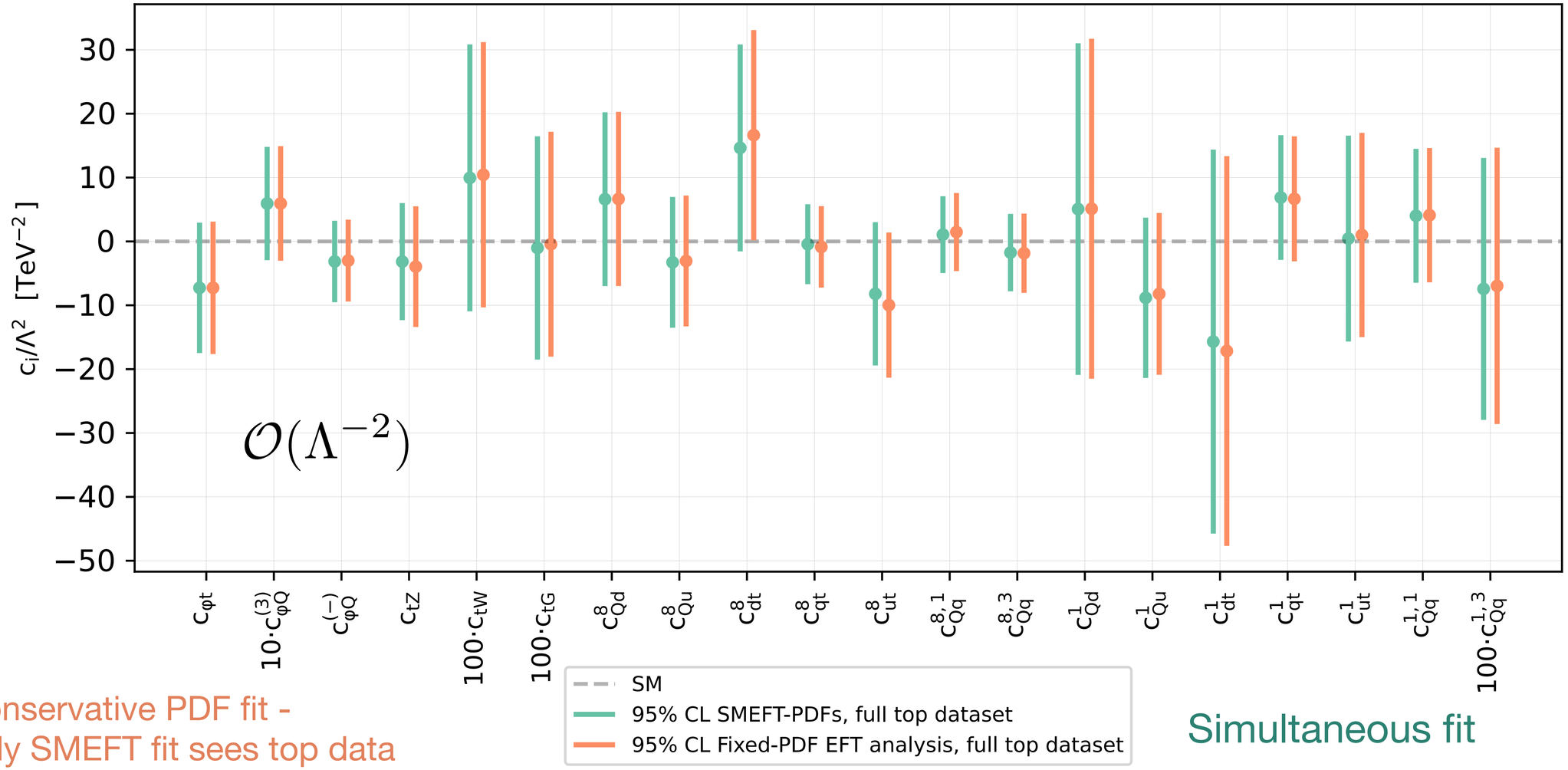


Significant correlation between large-*x* gluon PDF and SMEFT coefficients

Simultaneous fit

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



Conservative PDF fit -
only SMEFT fit sees top data

Simultaneous fit

SMEFT PDFs

Simultaneous PDF-EFT determination outputs a **SMEFT PDF**

Use this as an input to future SMEFT determinations as an approximation for a full PDF-SMEFT fit

Captures the increase in PDF uncertainties due to the inclusion of SMEFT parameters in the fit

Neglects PDF-SMEFT correlations captured by a full simultaneous determination

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Simultaneous PDF-EFT determination outputs a **SMEFT PDF**

Use this as an input to future SMEFT determinations as an approximation for a full PDF-SMEFT fit

$$R_n = \frac{c_n^*}{\sigma_n}$$

SMEFT PDFs are a good approximation - small PDF-EFT correlation in the top sector

Conclusions

Global SMEFT fits of LHC Run II data provide precise constraints on the top sector of the SMEFT

Studies of PDF-EFT interplay are necessary, particularly as we move towards the HL-LHC:

- signals of new physics may be absorbed by the PDF fit *E. Hammou et. al, 2307.10370*
- HL-LHC projections show a significant potential to over-constrain the SMEFT and PDFs *Greljo et. al 2104.02723*

In top data, moderate interplay is observed between the PDFs and SMEFT.

See *2303.06159* and https://www.pbsp.org.uk/topproject/ for more details and results

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Thank you for listening!

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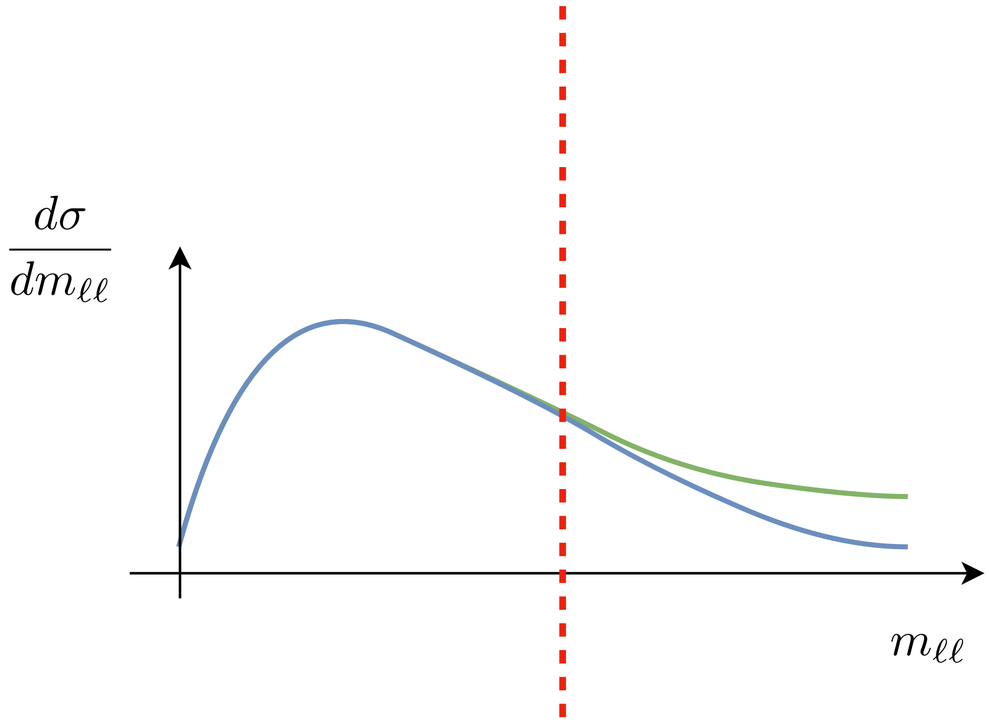
Backup

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



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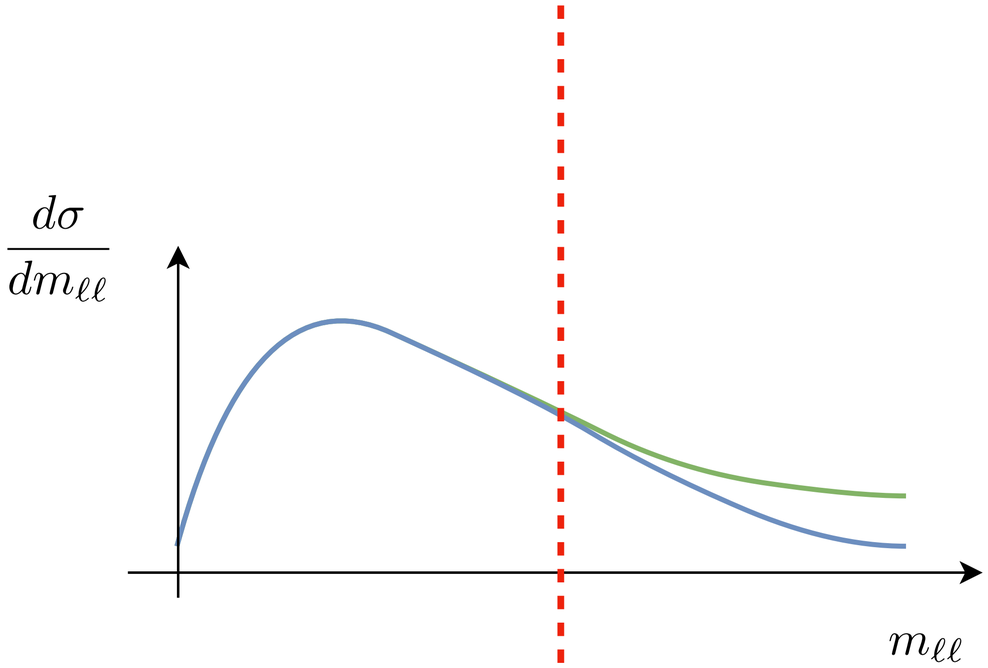
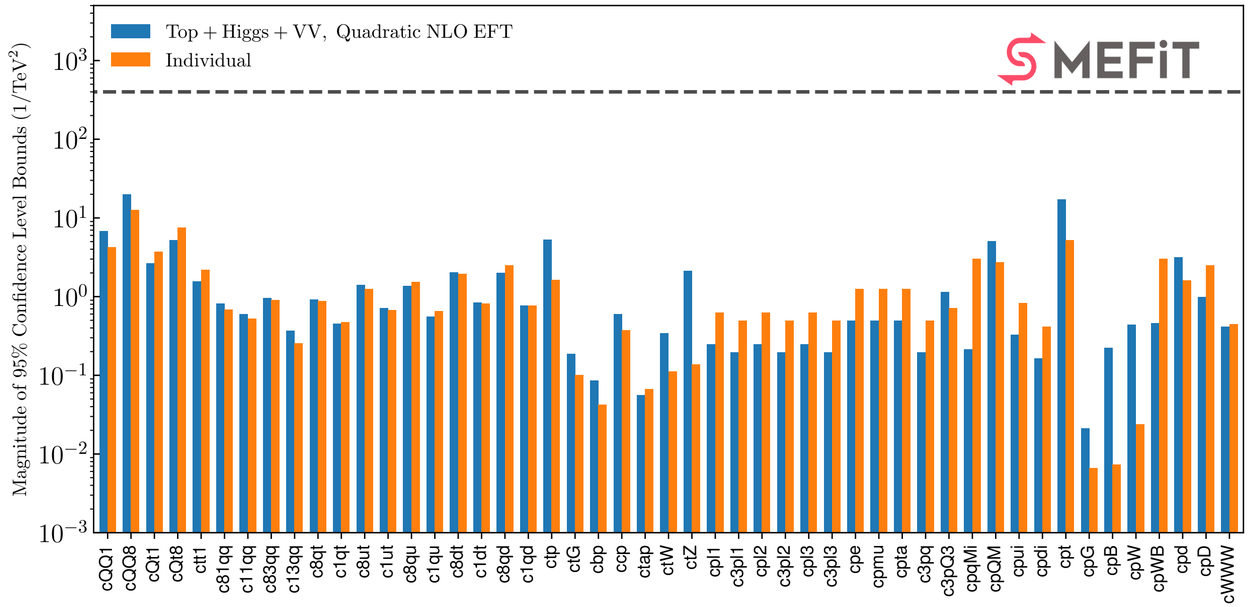
See *J. Ethier et. al, 2105.00006* for the use of conservative PDFs in a global SMEFT fit





Conservative PDFs for high-mass Drell-Yan

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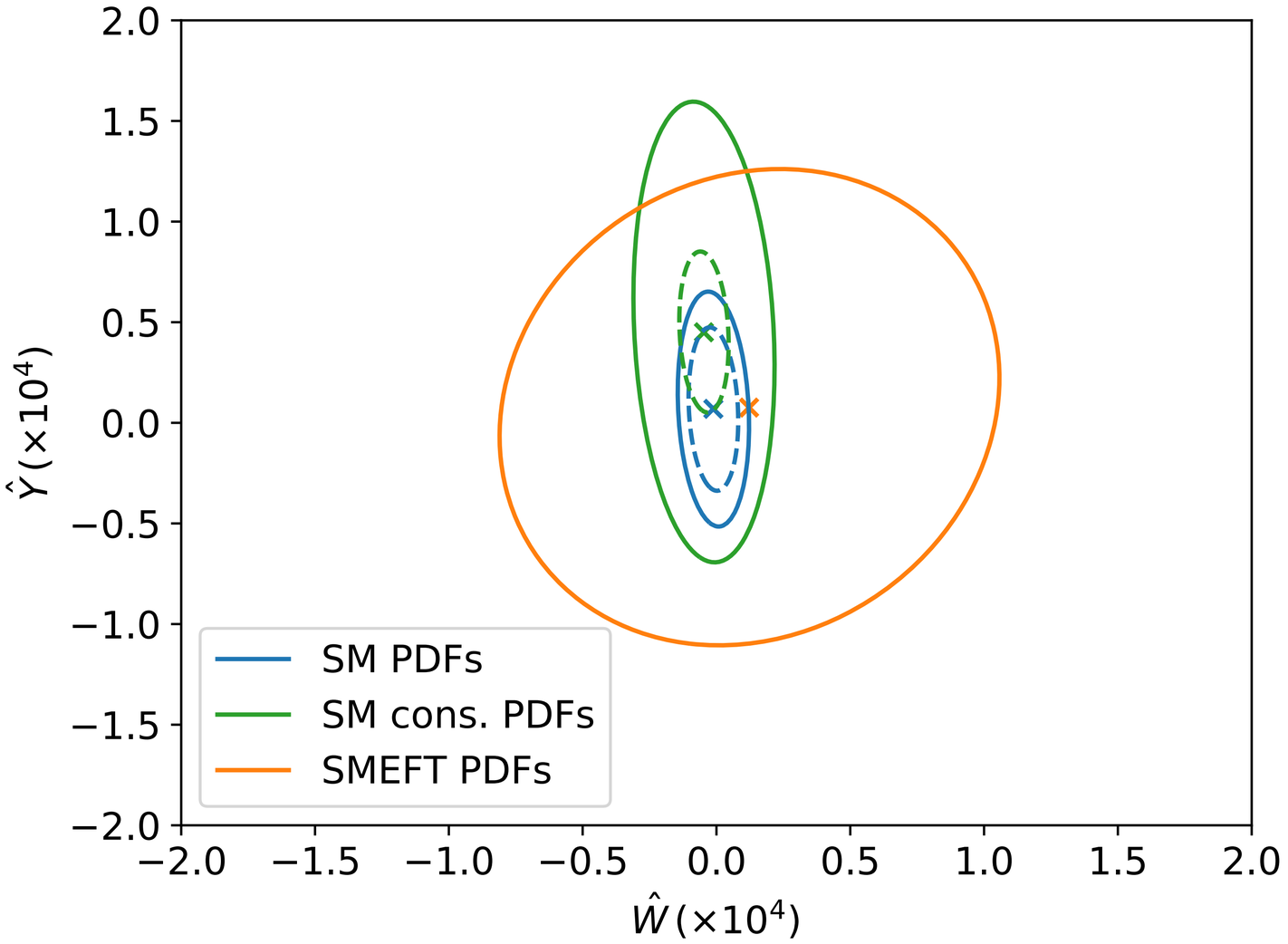
dashed: not including PDF uncertainties



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Comparing green to orange:

- the constraints using SM conservative PDFs are closer to those using SMEFT PDFs
- still overestimating the constraints, especially in the $\hat{W}$ direction

dashed: not including PDF uncertainties