Beyond the Standard (Model) proton

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European Research Council
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UNIVERSITY OF CAMBRIDGE

PBSP

Introduction

PDF extraction

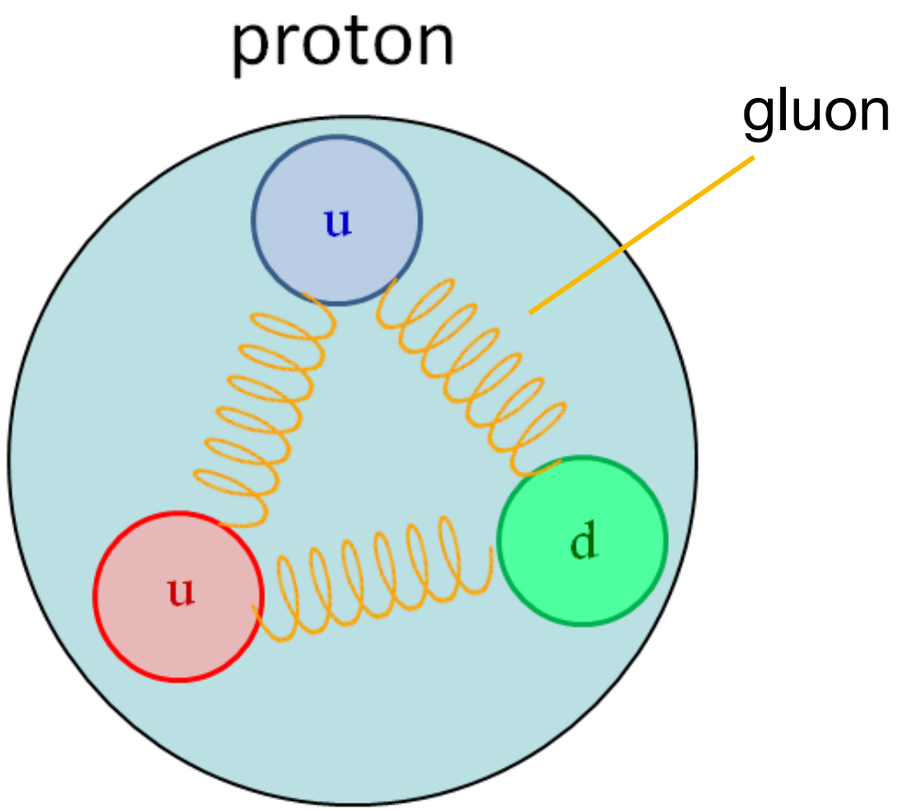
SMEFT

SIMUnet

Simultaneous fit of PDFs and SMEFT: top quark sector

Outlook and conclusions

Proton structure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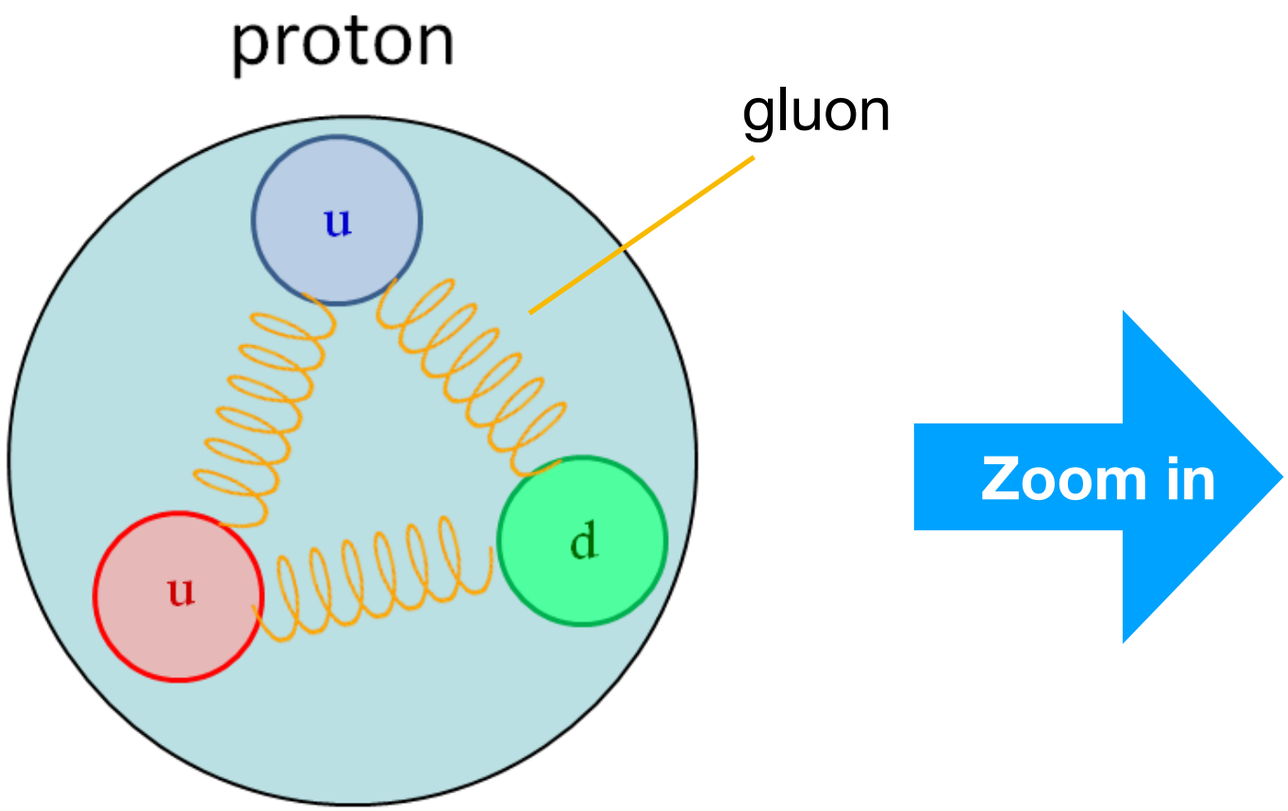
proton
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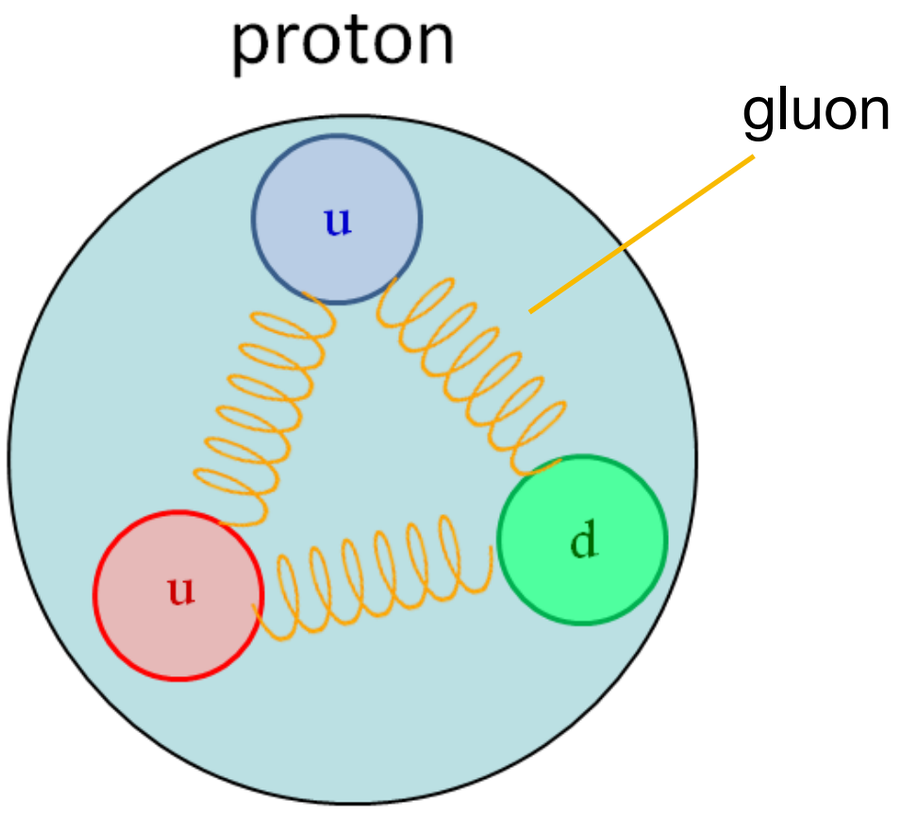
Zoom in



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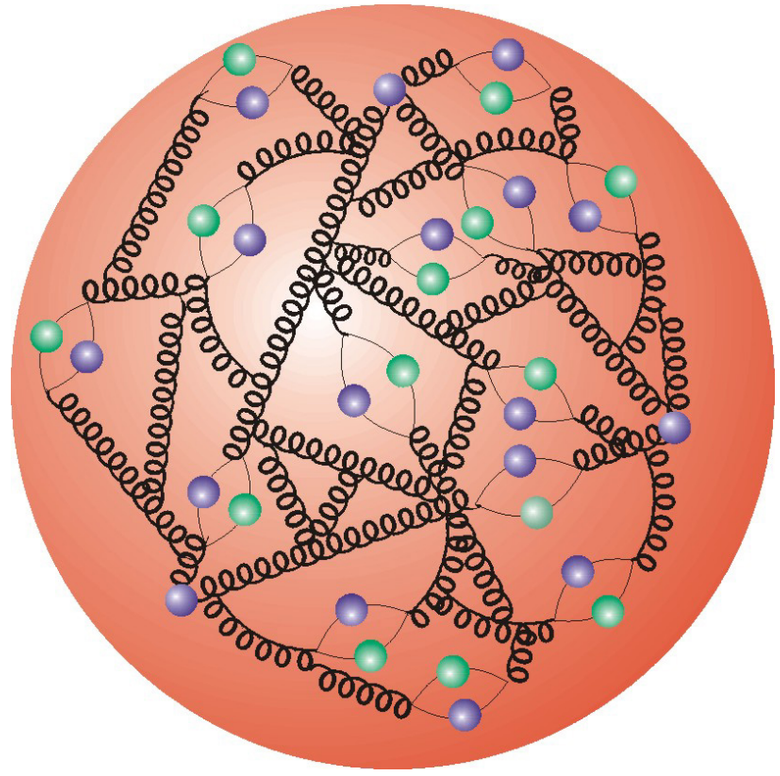

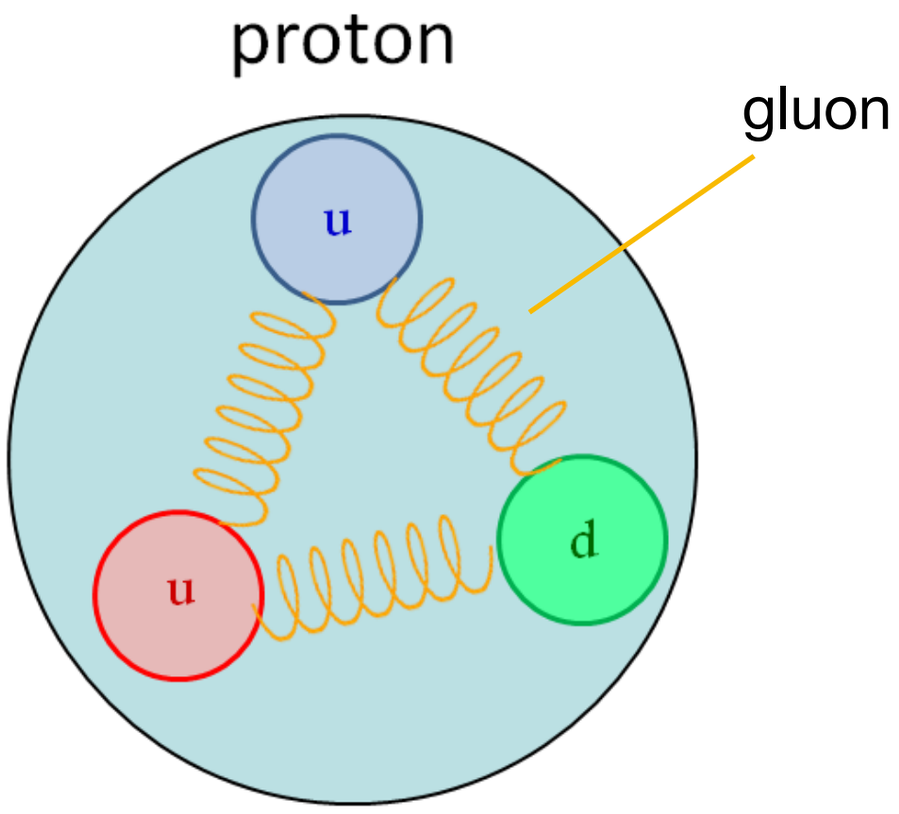

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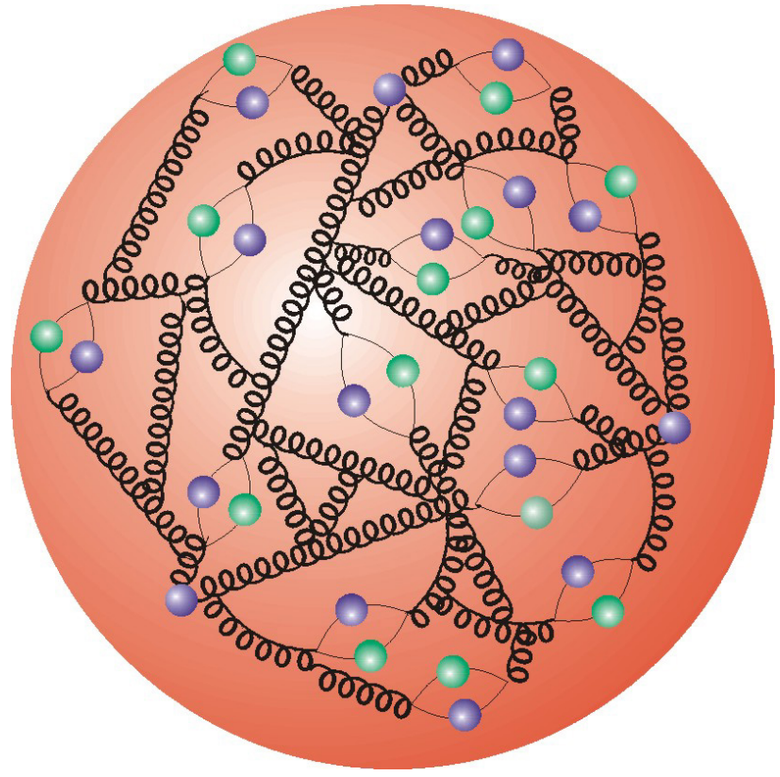

There is A LOT of dynamics inside a proton!

At the LHC we smash protons

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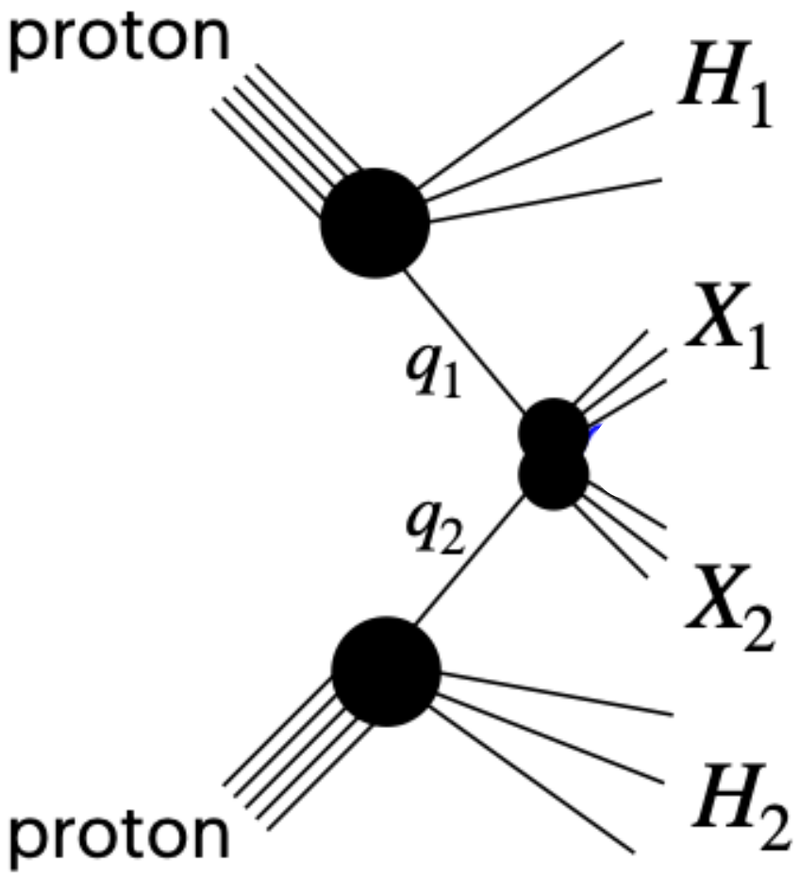

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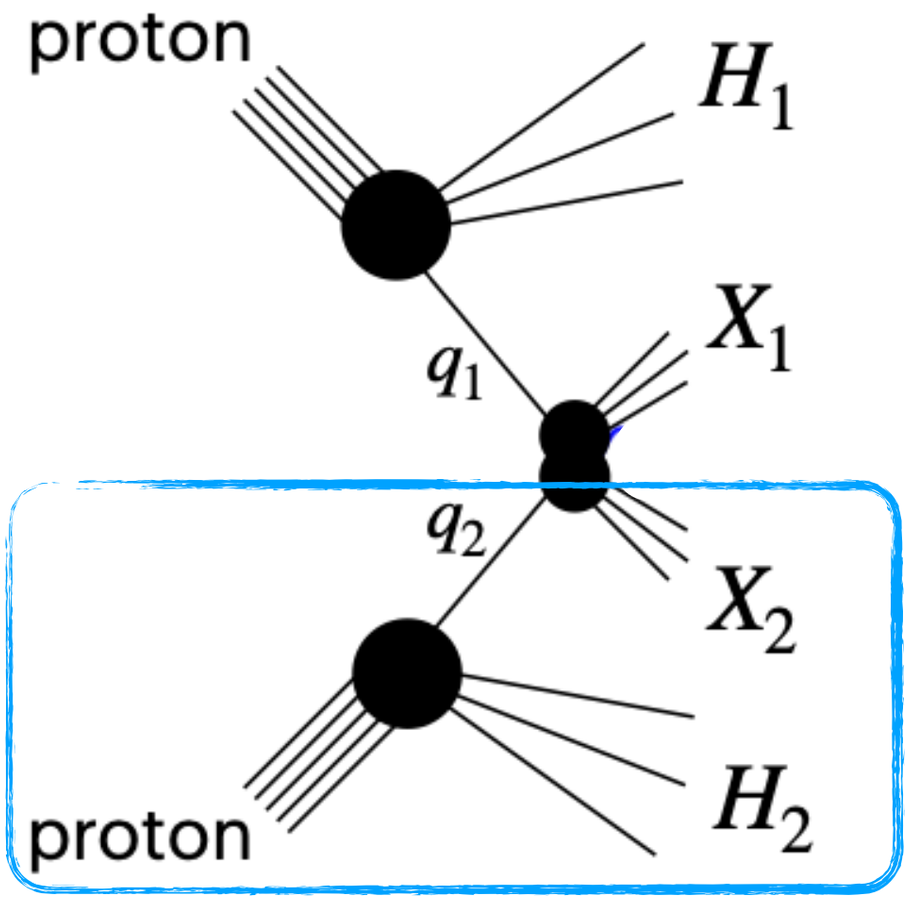

parton distribution function (PDF)

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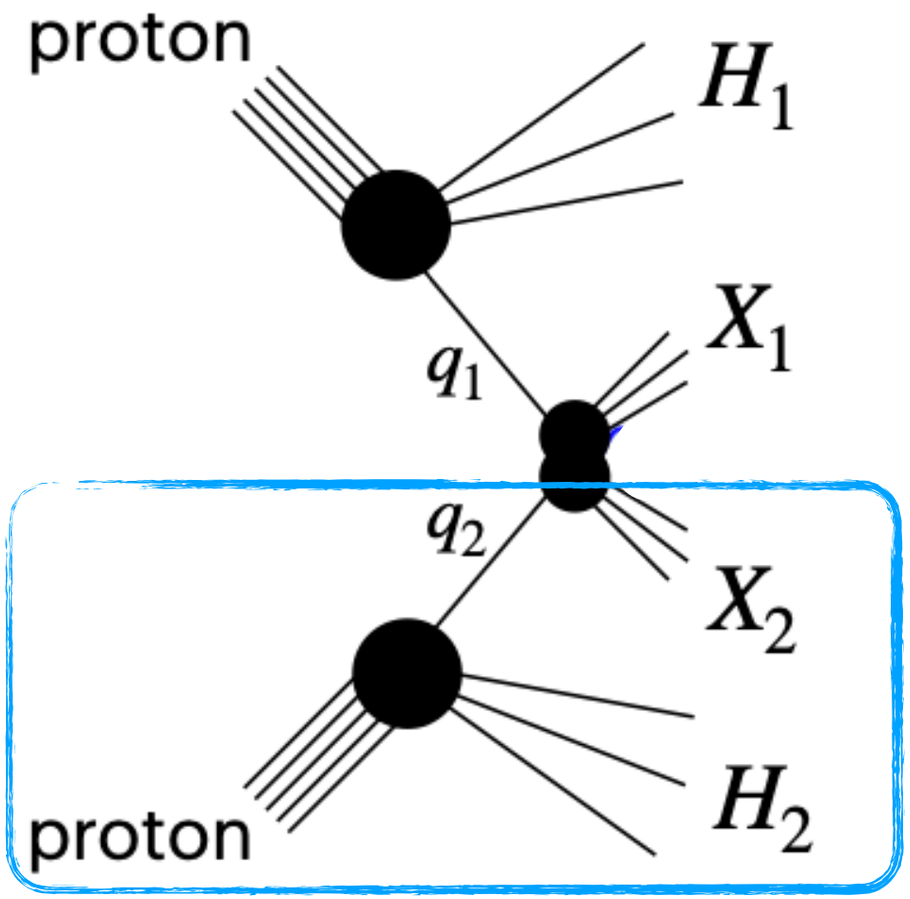

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Difficult to determine
on theoretical basis (lattice QCD)

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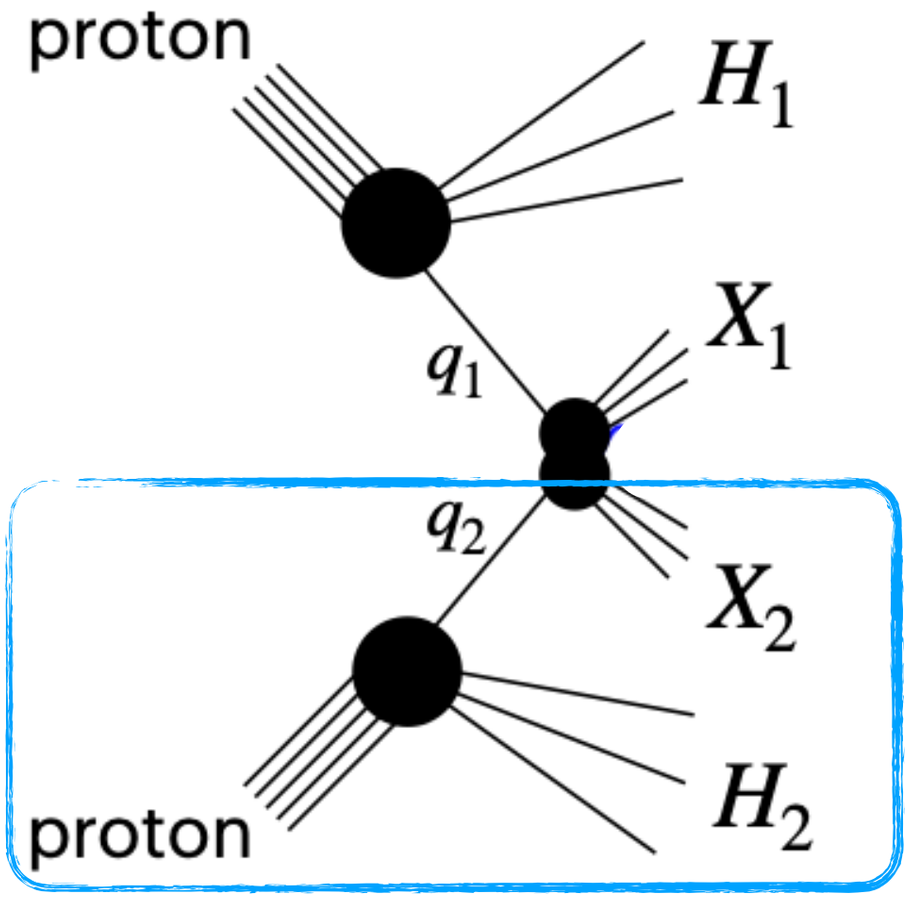

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$$\sigma = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{q_1,q_2} f_{q_1}(x_1) f_{q_2}(x_2) \hat{\sigma}(x_1, x_2)$$

Idea: use data to infer the structure of the proton

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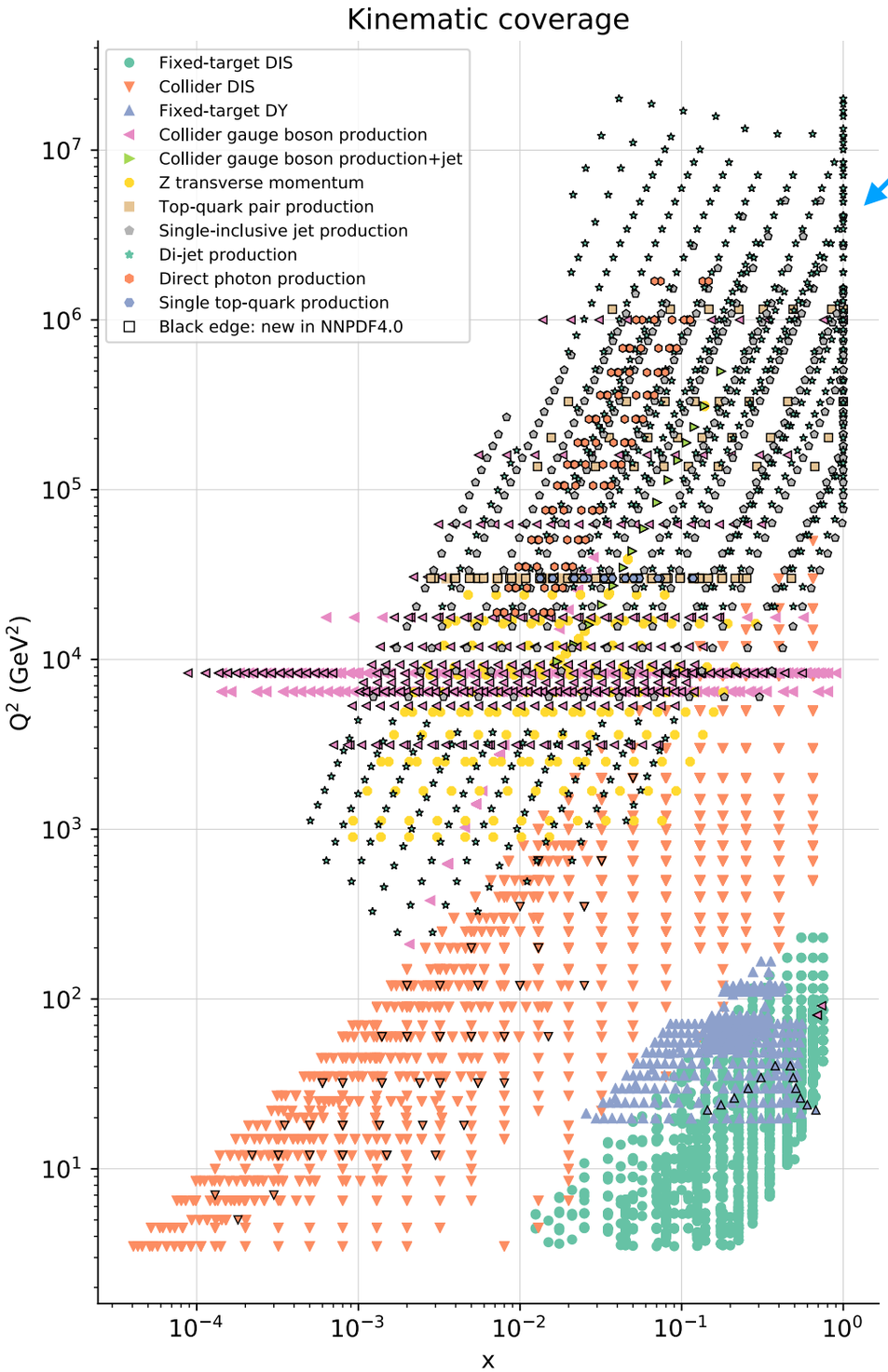
$$f(x, \mu^2)$$



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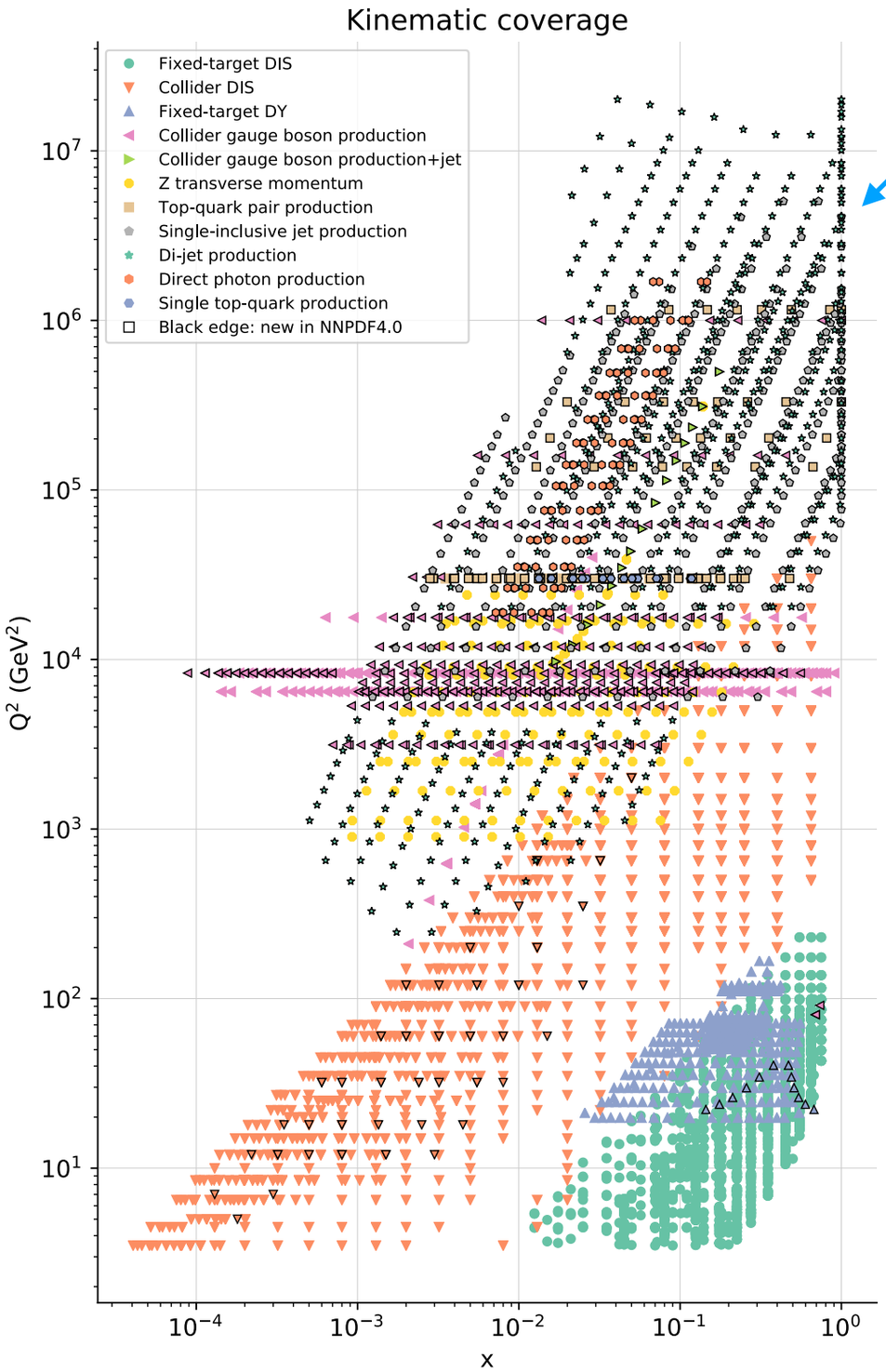

DGLAP equations

$$\frac{\partial}{\partial \log(\mu^2)} \begin{pmatrix} q(x,\mu^2) \\ g(x,\mu^2) \end{pmatrix} = \frac{\alpha_S(\mu^2)}{2\pi} \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{qq}(z) & P_{qg}(z) \\ P_{gq}(z) & P_{gg}(z) \end{pmatrix} \begin{pmatrix} q(x/z,\mu^2) \\ g(x/z,\mu^2) \end{pmatrix}$$

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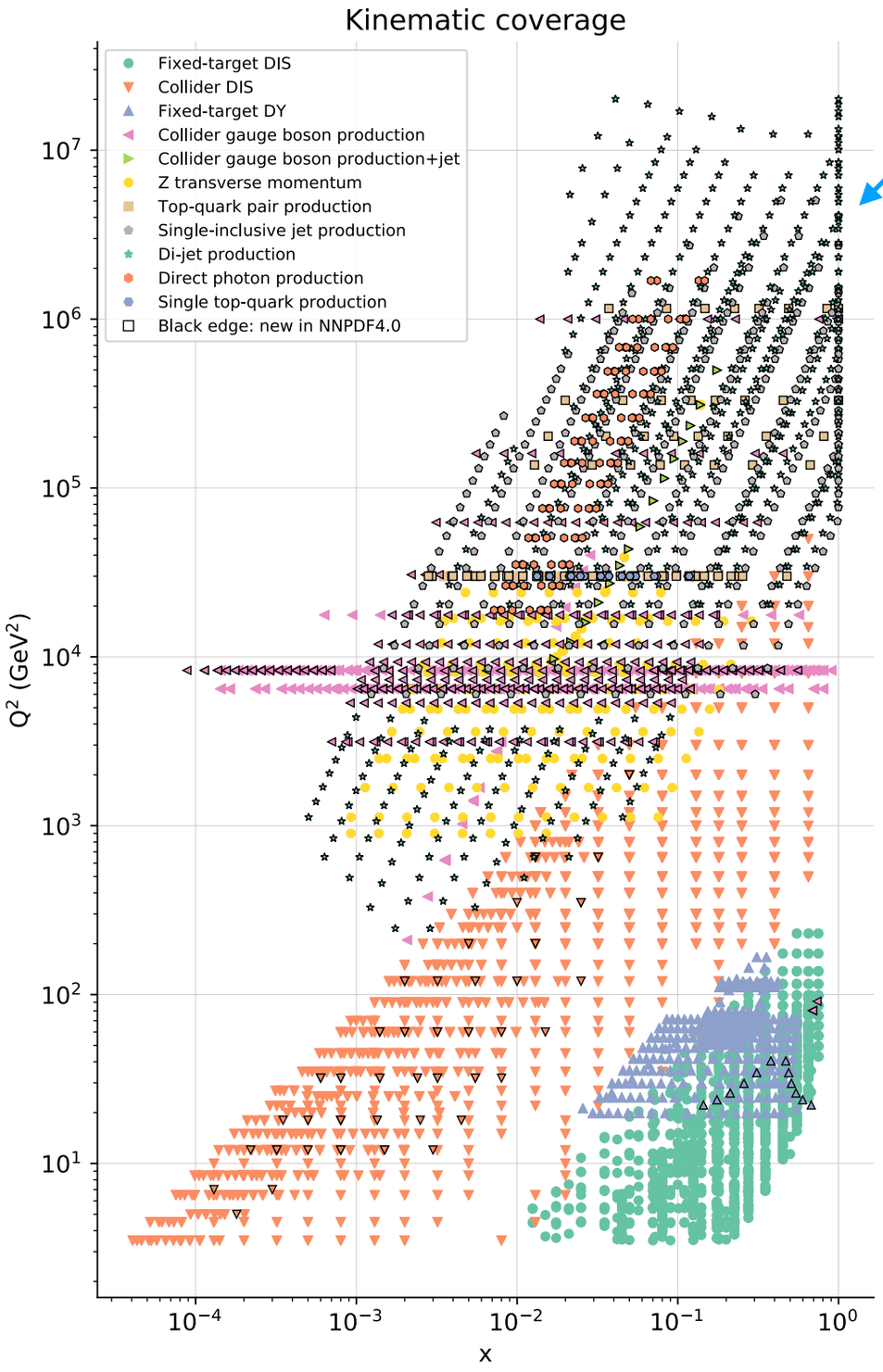

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We just need a functional form for the PDFs

Theory assumptions

Data driven determination

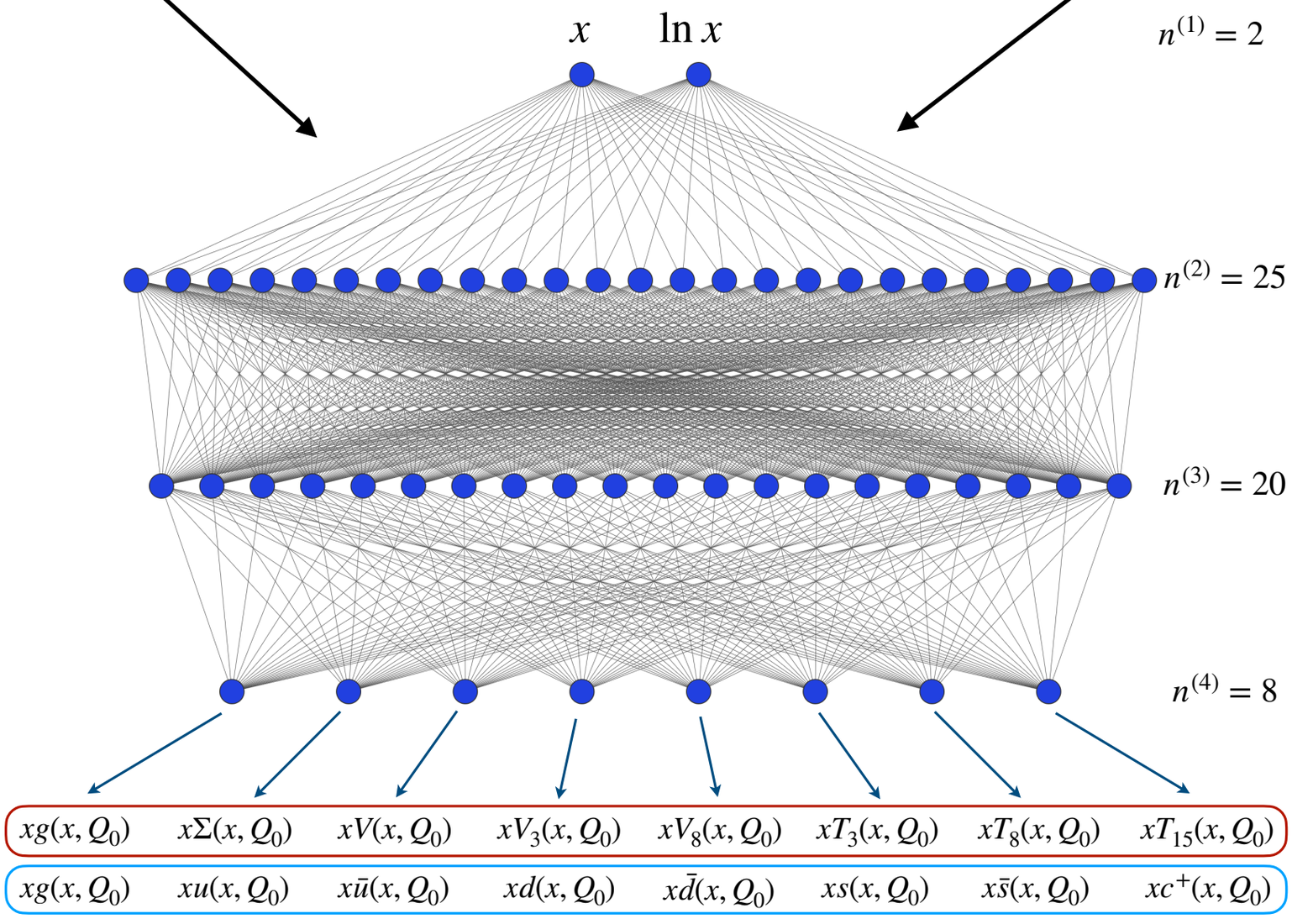
Measurements

Data driven determination

Theory assumptions

Measurements

Neural network



Experimental uncertainties are propagated to the PDFs via Monte Carlo

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$$p(x_i) = e^{-\frac{1}{2}(x_i-\bar{x}_i)^T C^{-1}(x_i-\bar{x}_i)}$$

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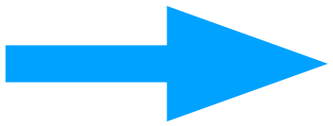

N pseudodata samples $\{x_i\}$

$N \sim 1000$

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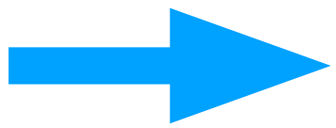

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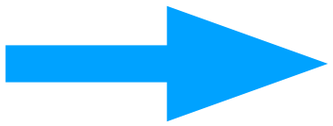

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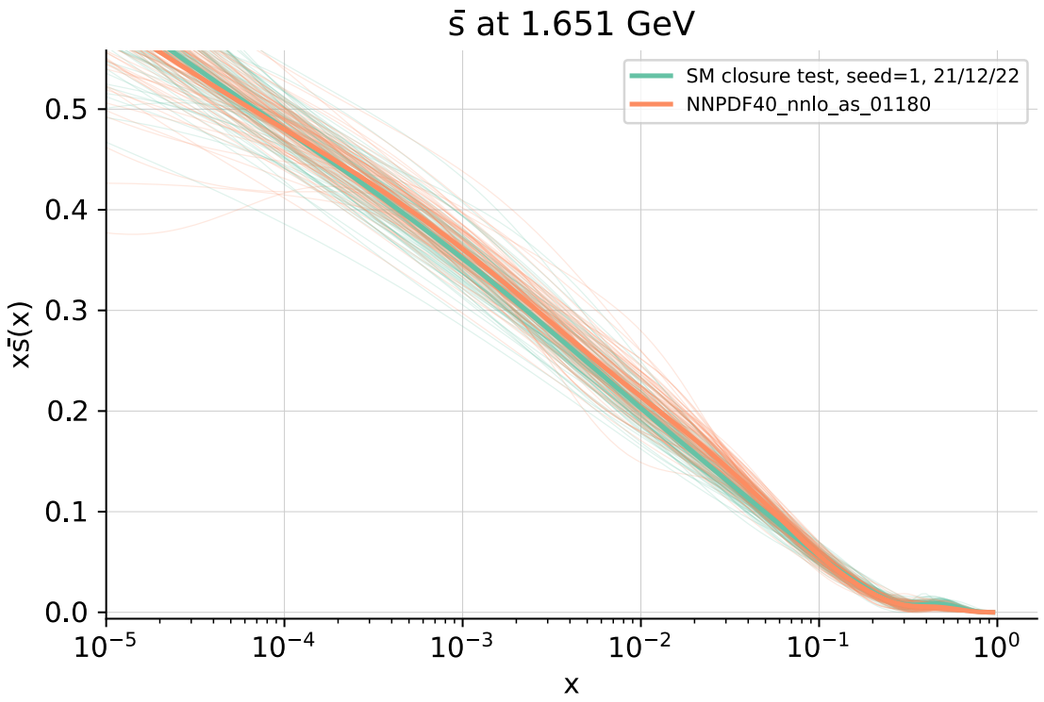

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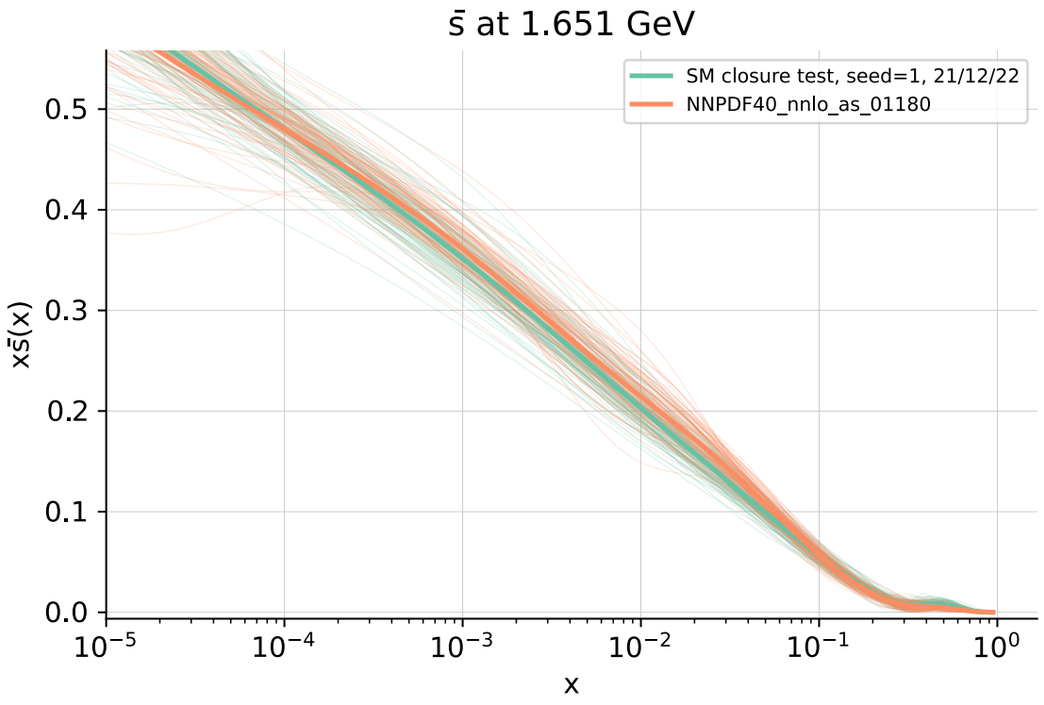
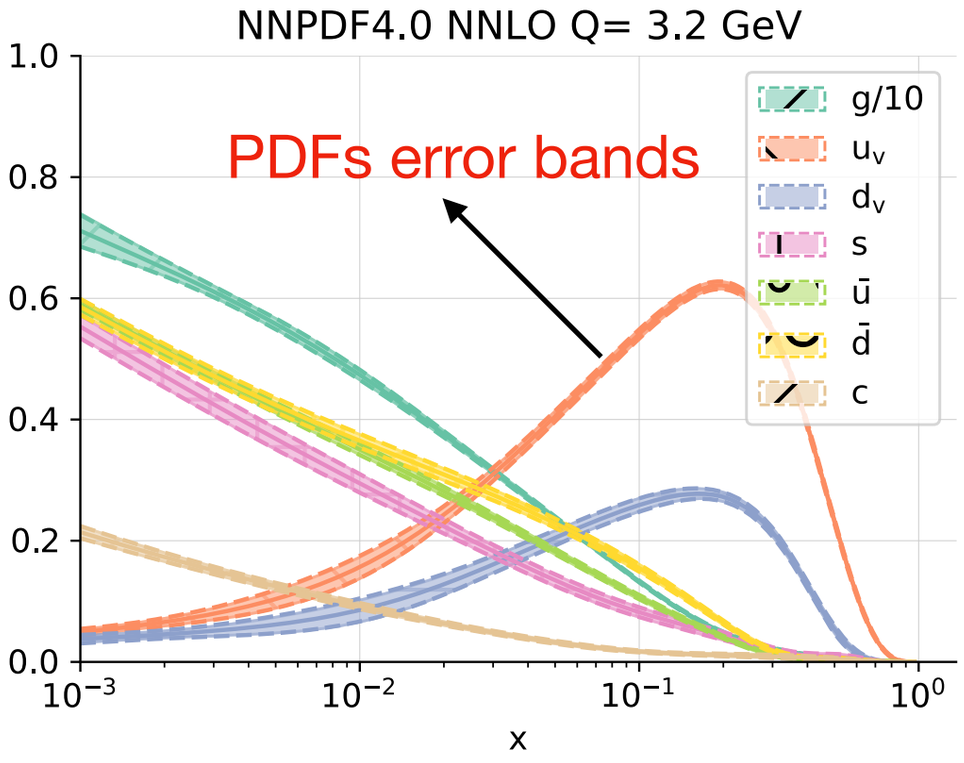
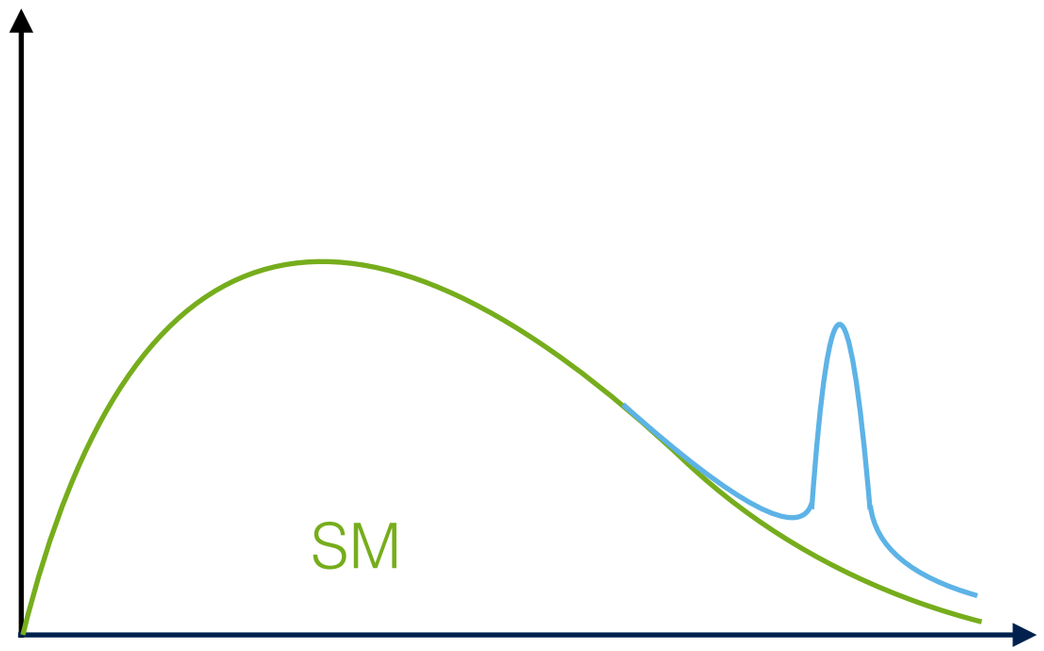




Ball et. al, NNPDF4.0, 2109.02653

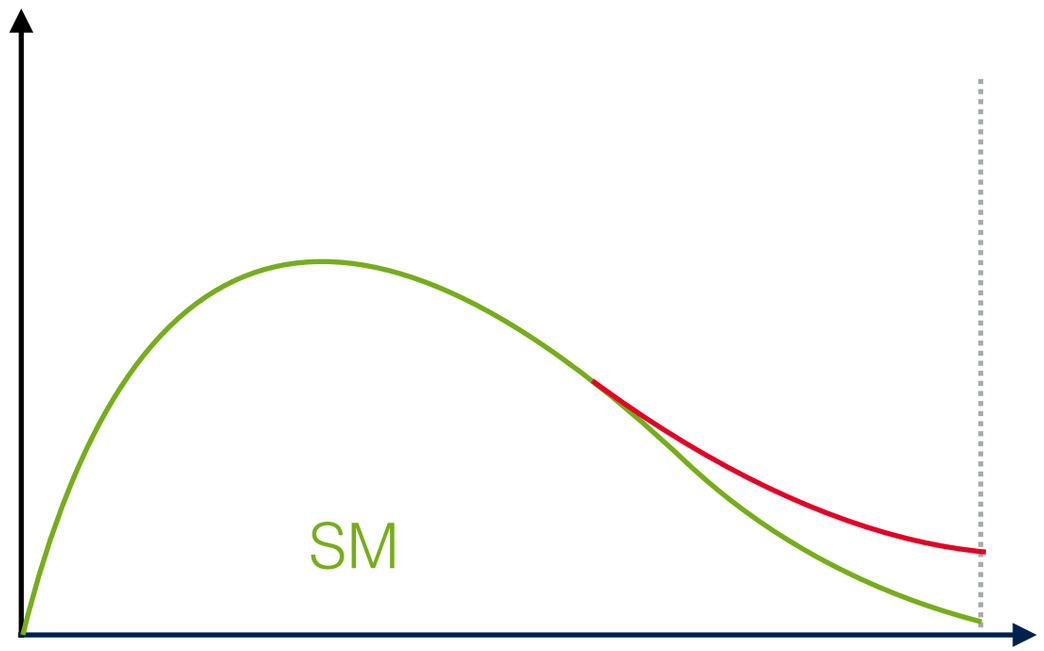
The Standard Model Effective Field Theory

Direct search (Bumps)



Direct search (Bumps)

Indirect (scouting tails)



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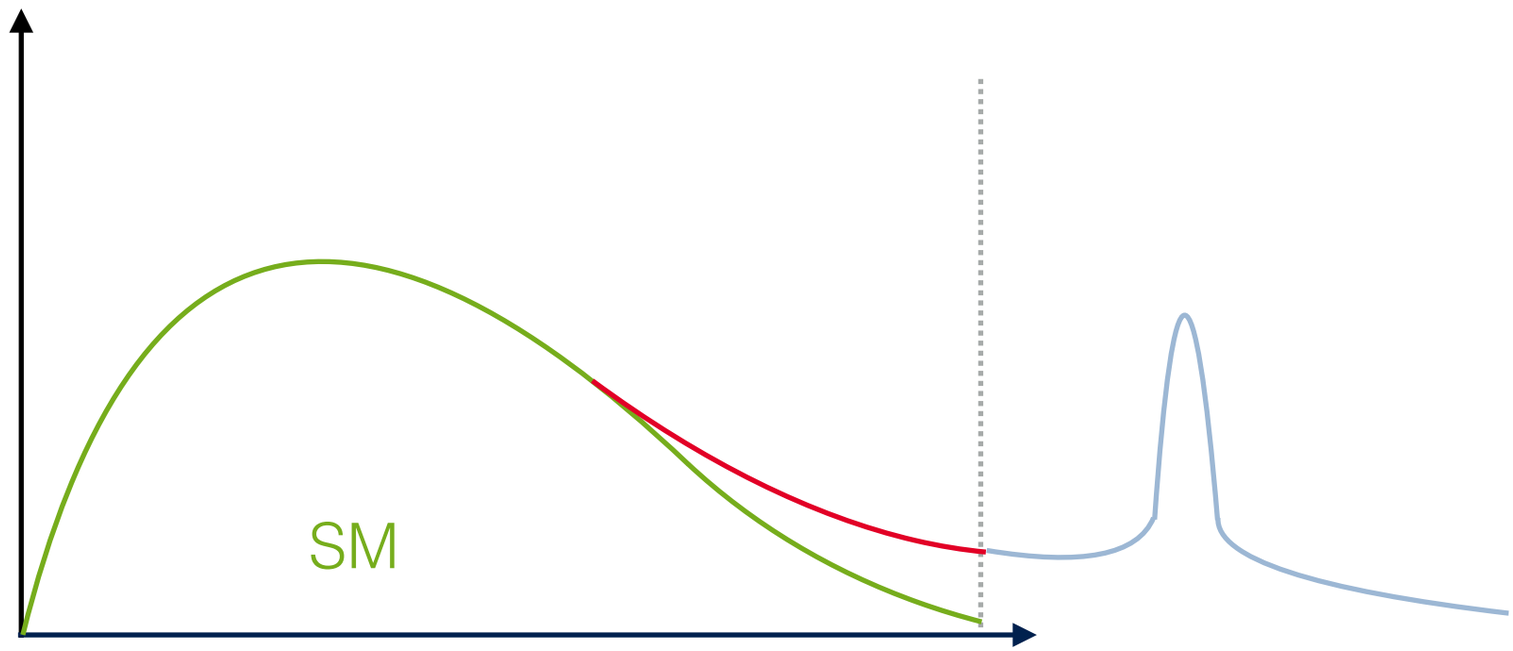
⇒ New physics is heavy



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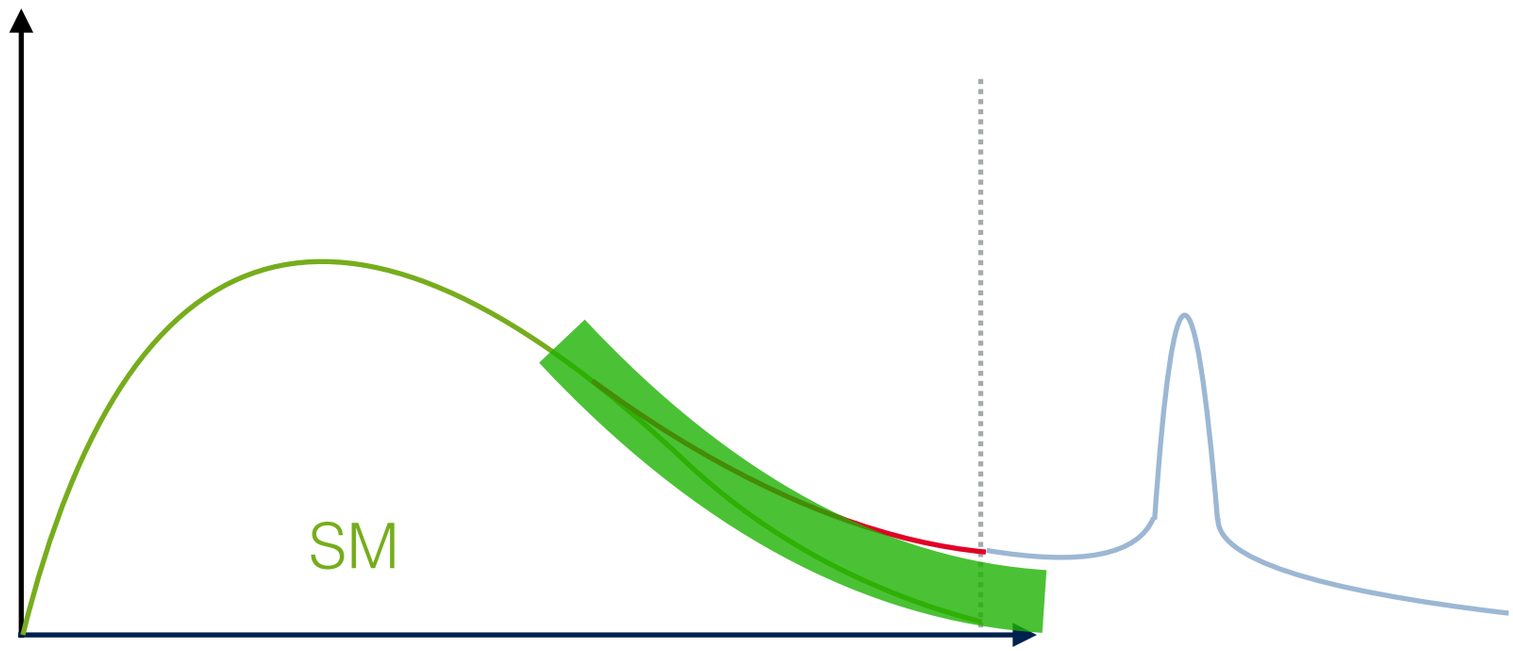

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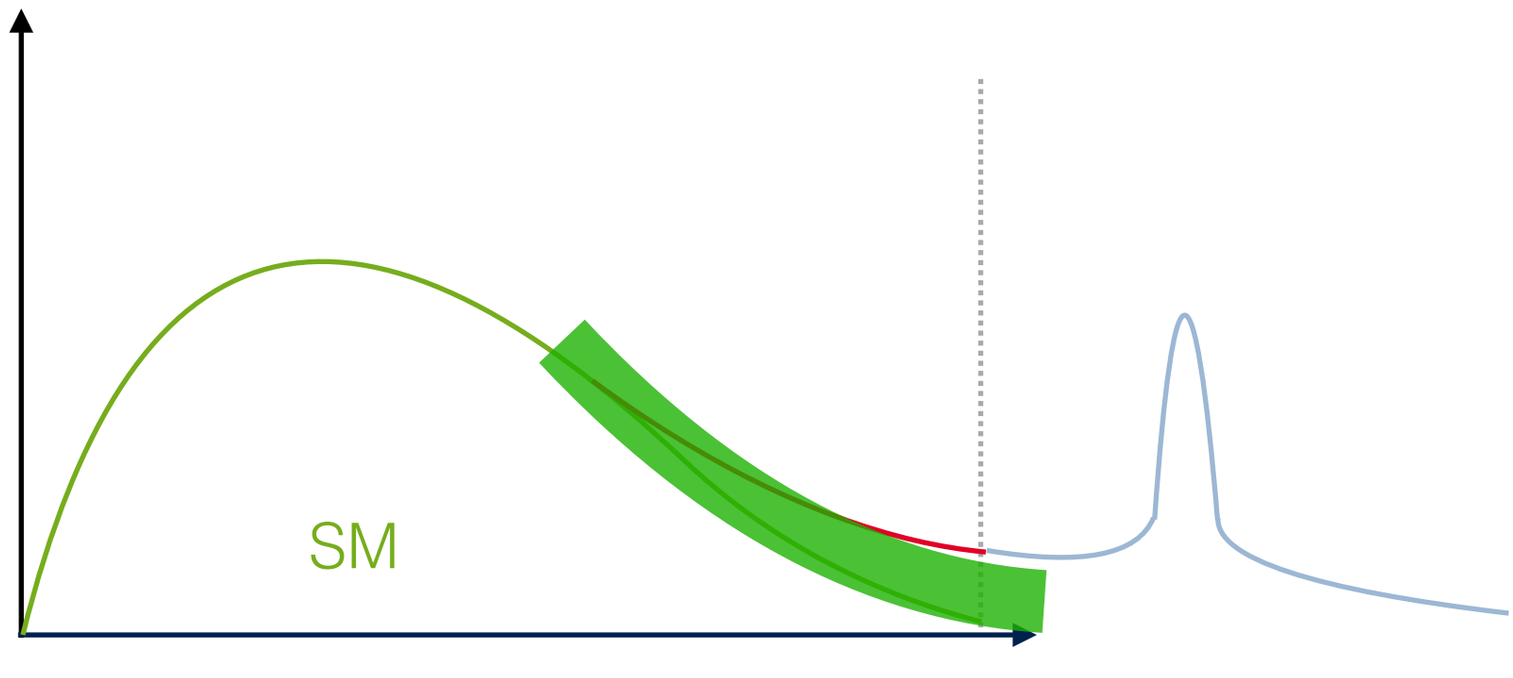

Framework to describe both precision physics and Heavy New Physics.

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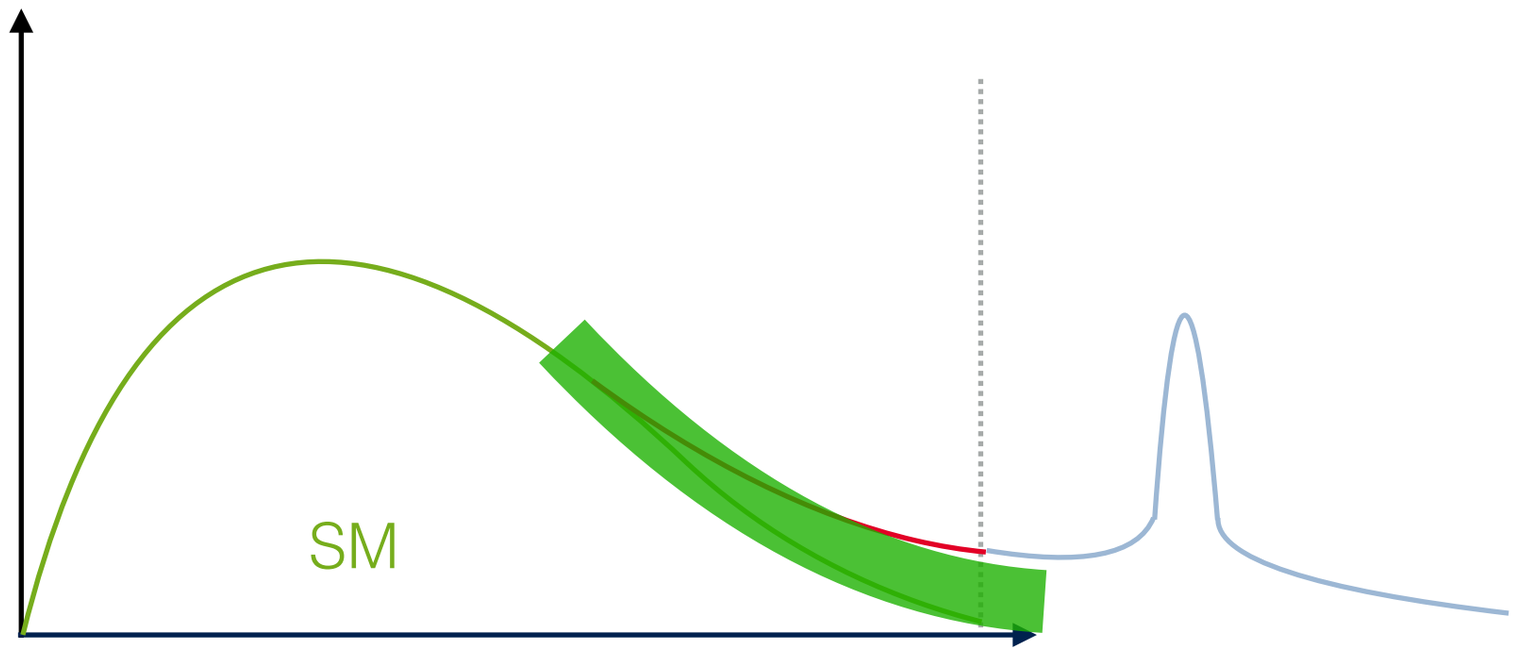

Framework to describe both precision physics and Heavy New Physics.

Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i^6 + \dots$$

- **Modified interactions among SM particles**
- **Higher dimensional operators preserve SM symmetries.**
- **Mappable to a large class of BSM models.**
- **Truncate at dim 6: leading corrections**

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Scale of NP

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EFT to-do list

- **Define target operators: e.g. top-philic EFT** [arXiv:1802.07237]
- **Find optimal observables to probe them**
- **Compute with precision theoretical predictions (both SM and EFT)**
- **Make accurate measurements**

59 operators flavour universal

2499 operators flavour general

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
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$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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Dim 6: Large number of operators and therefore degrees of freedom

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Many observables and final states

Break degeneracies in parameter space

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$$\mathcal{O} = \mathcal{O}_{SM} + \frac{C_i}{\Lambda^2}\,\mathcal{O}_i^{INT} + \frac{C_i\,C_j}{\Lambda^4}\,\mathcal{O}_{ij}^{SQ}$$

NLO-QCD with SMEFT@NLO

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Dim 6: Large number of operators and therefore degrees of freedom

Many observables and final states → **Break degeneracies in parameter space**

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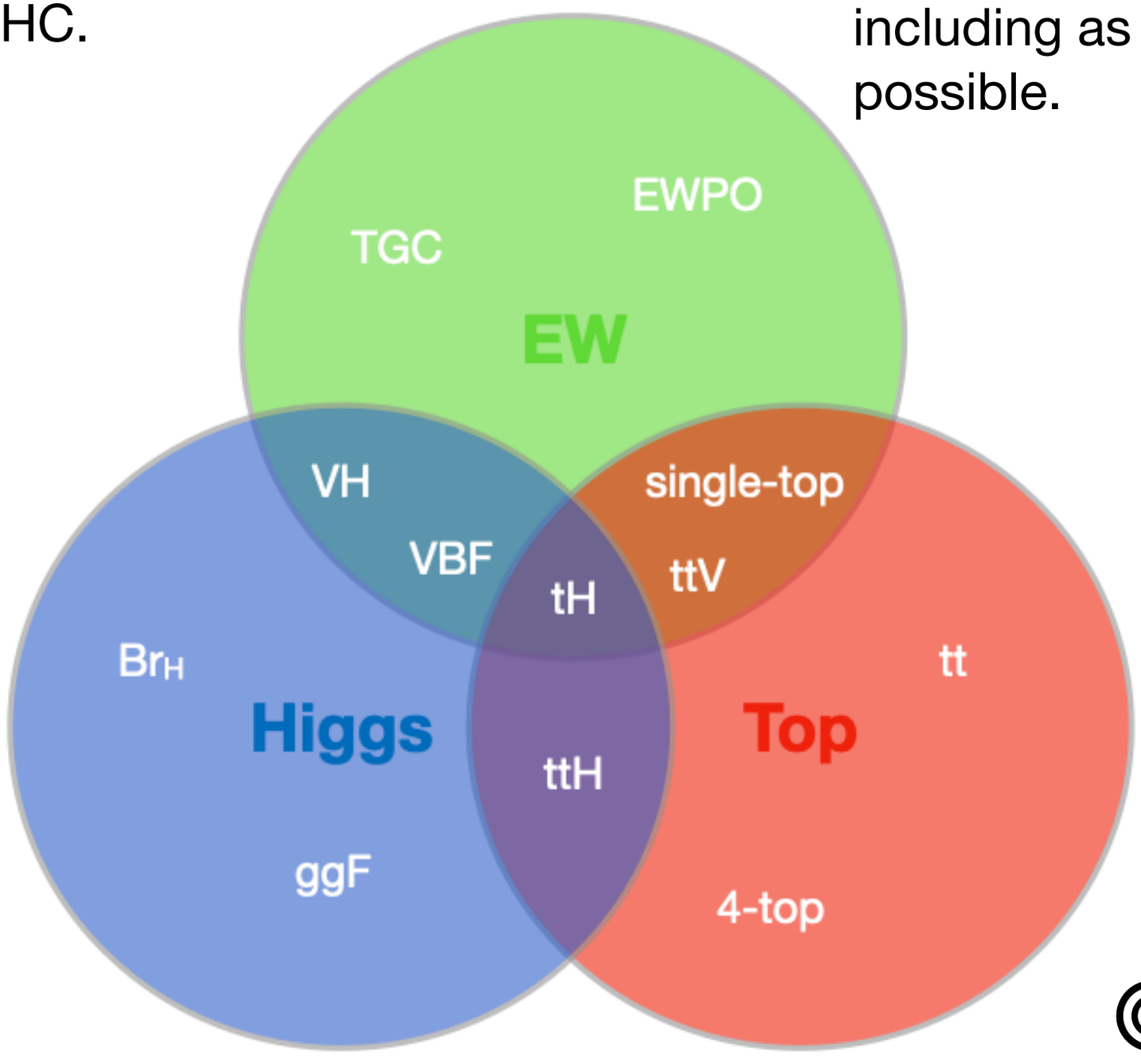
Quadratic contribution: useful information in many instances

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

We can probe the SMEFT by taking a **global approach,** including as many datasets as possible.



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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

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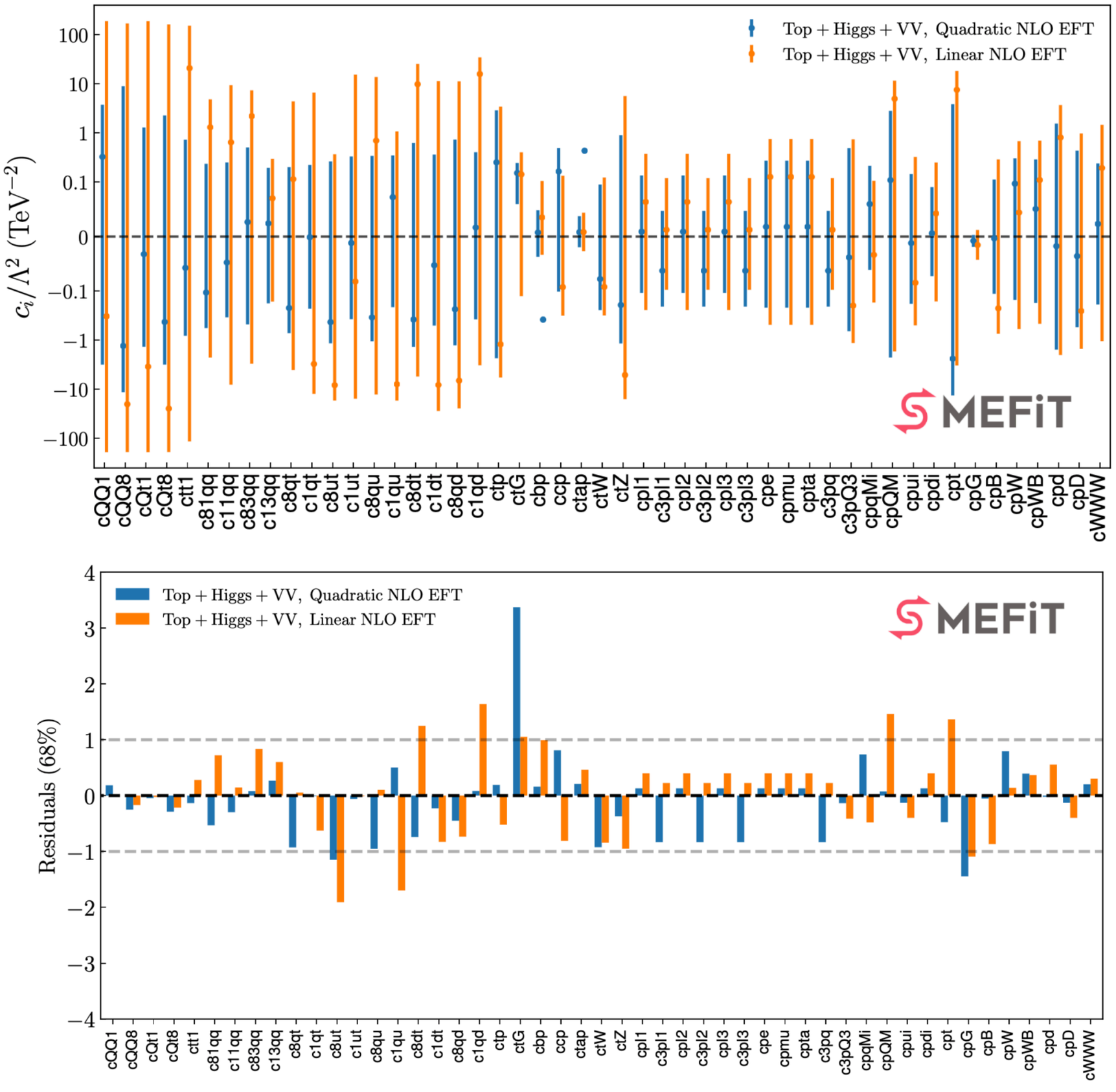
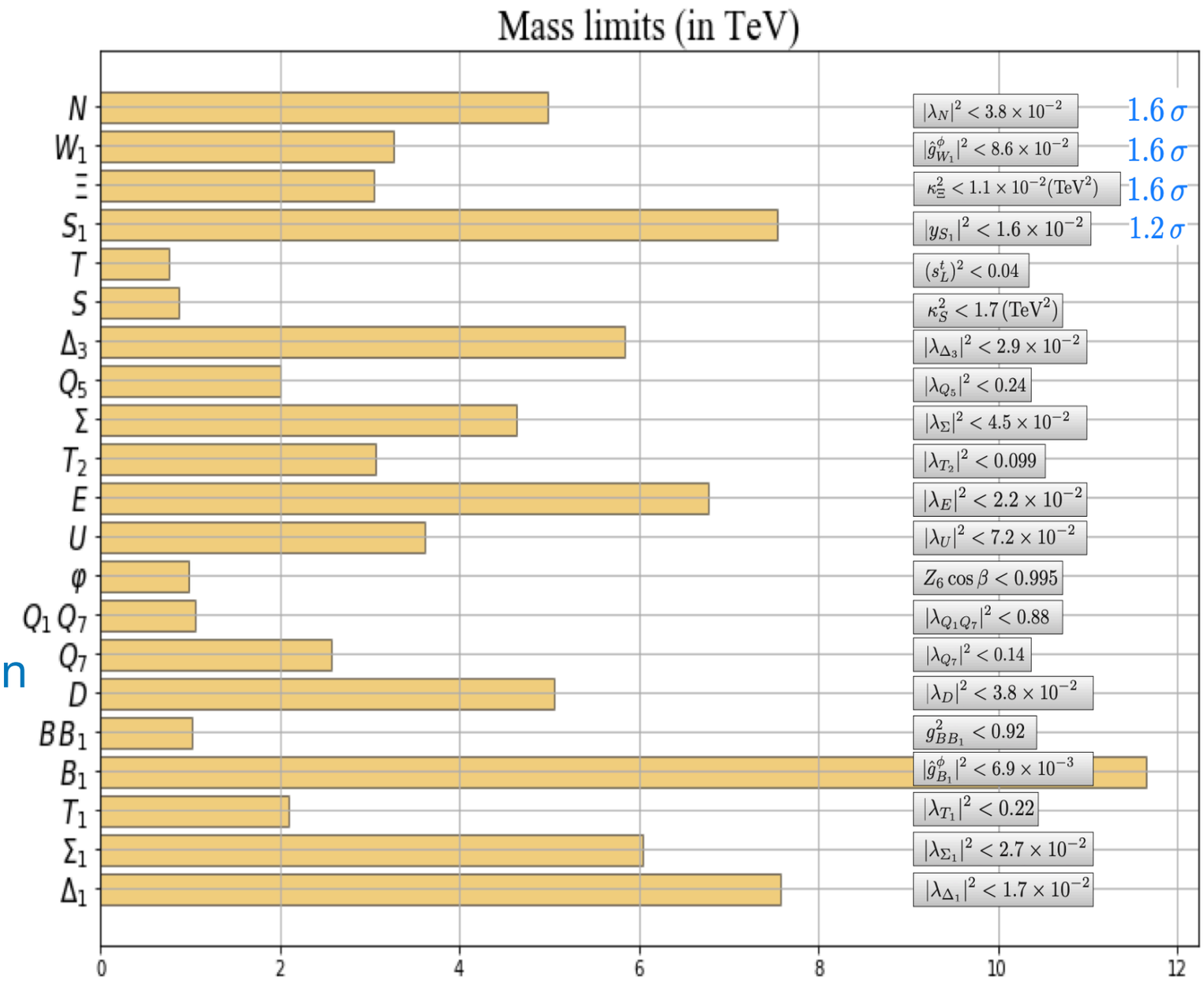
Top + Higgs + VV, Quadratic NLO EFT
Top + Higgs + VV, Linear NLO EFT
c_i/Λ^2 (TeV^{-2})
100
10
1
0.1
0
−0.1
−1
−10
−100
MEFiT
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ cpl1 c3pl1 cpl2 c3pl2 cpl3 c3pl3 cpe cpmu cpta c3pq c3pQ3 cpqMi cpQM cpui cpdi cpt cpG cpB cpW cpWB cpd cpD cWWW

Global fit result

Luca Mantani



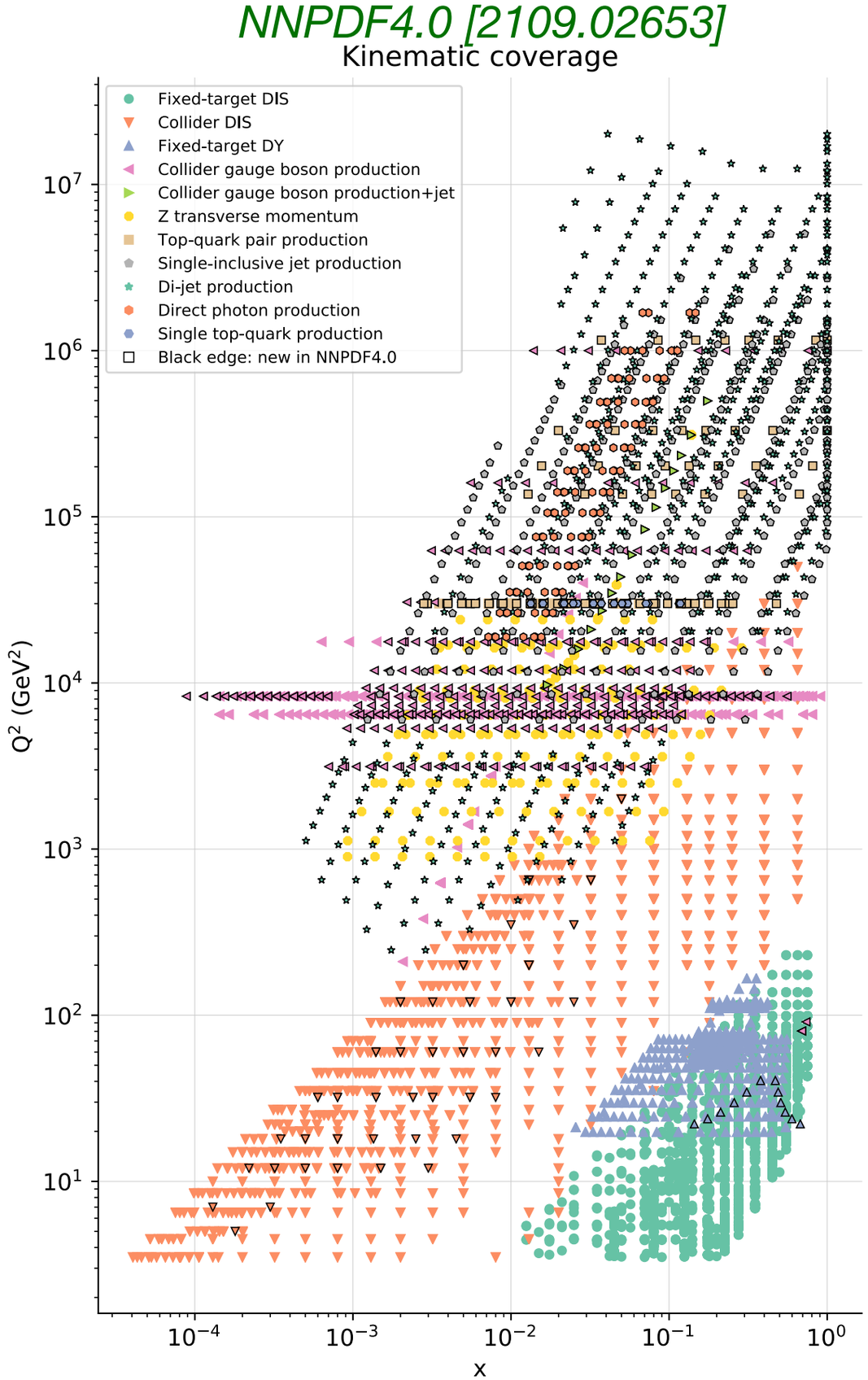
- Fits can be interpreted in UV completion models
- Bounds on coefficient translate on bounds on mass or couplings
- Simple case: single field extension



Ellis et al: arXiv:2012.02779

The SMEFT proton

Often data used in SMEFT interpretations and PDF extraction coincide



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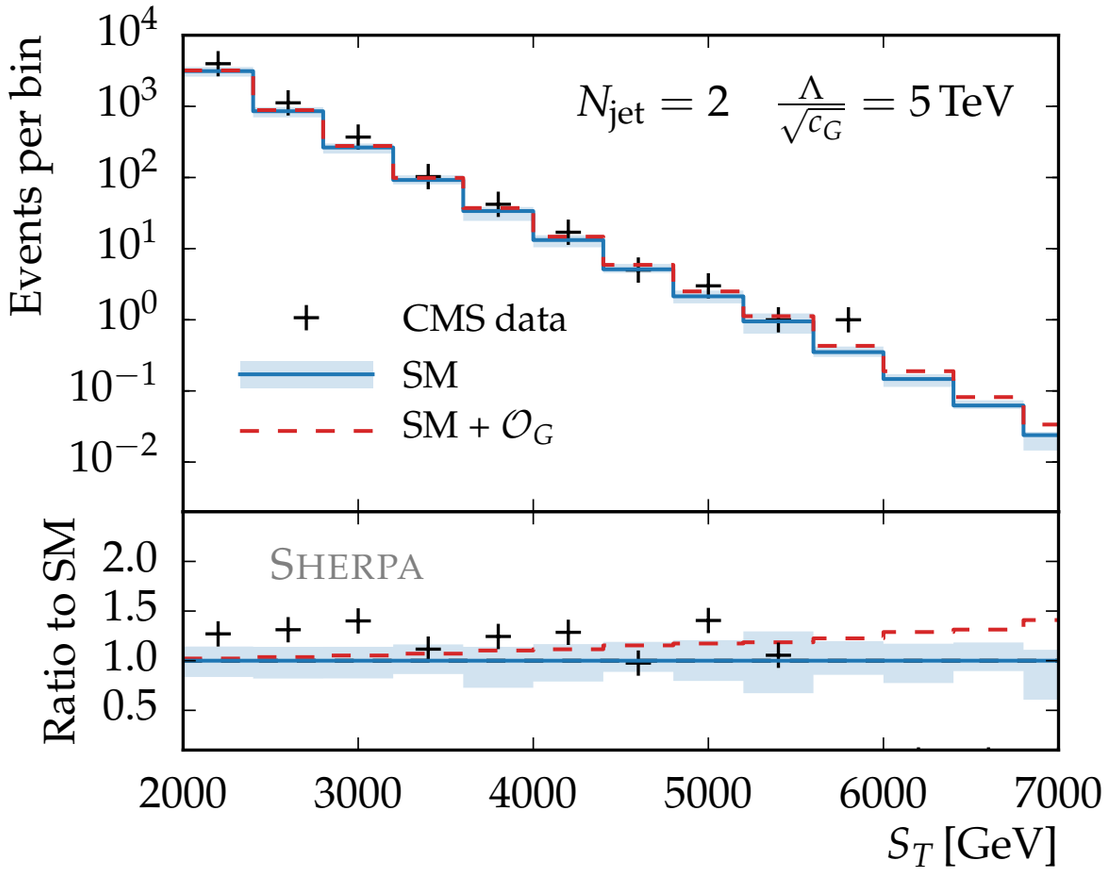
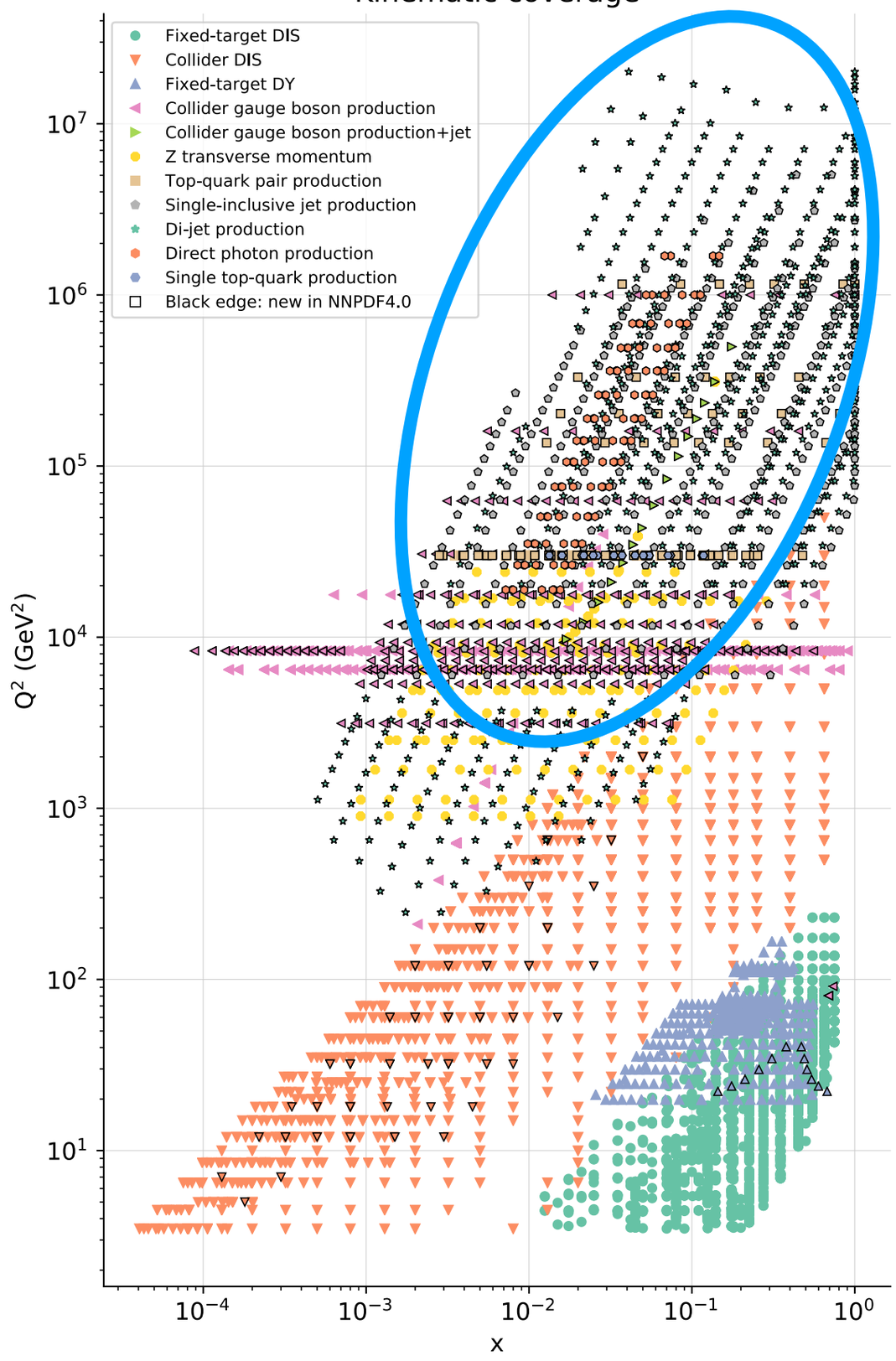
e.g. Dijet data used to fit the SMEFT operator in *F. Krauss et. al, 1611.00767*



NNPDF4.0 [2109.02653]



Typically fits of physics parameters and PDFs do not talk

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

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PDFs extraction

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

We extract the PDFs from data,
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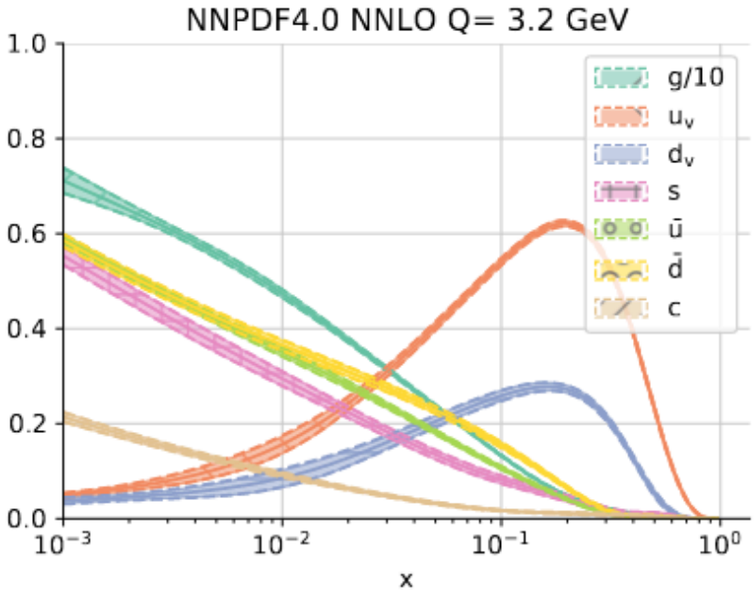

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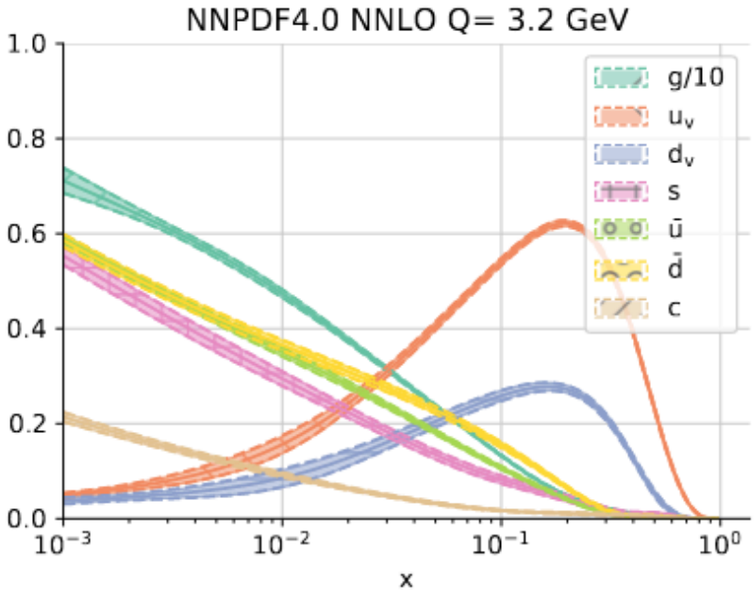

Physics parameters

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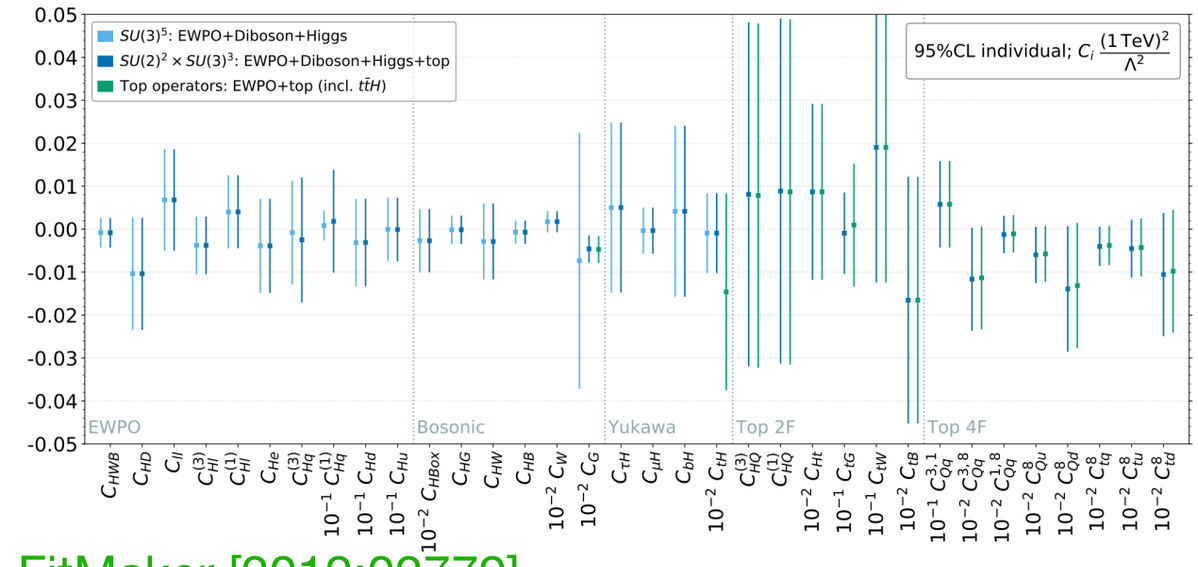

FitMaker [2012:02779]

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

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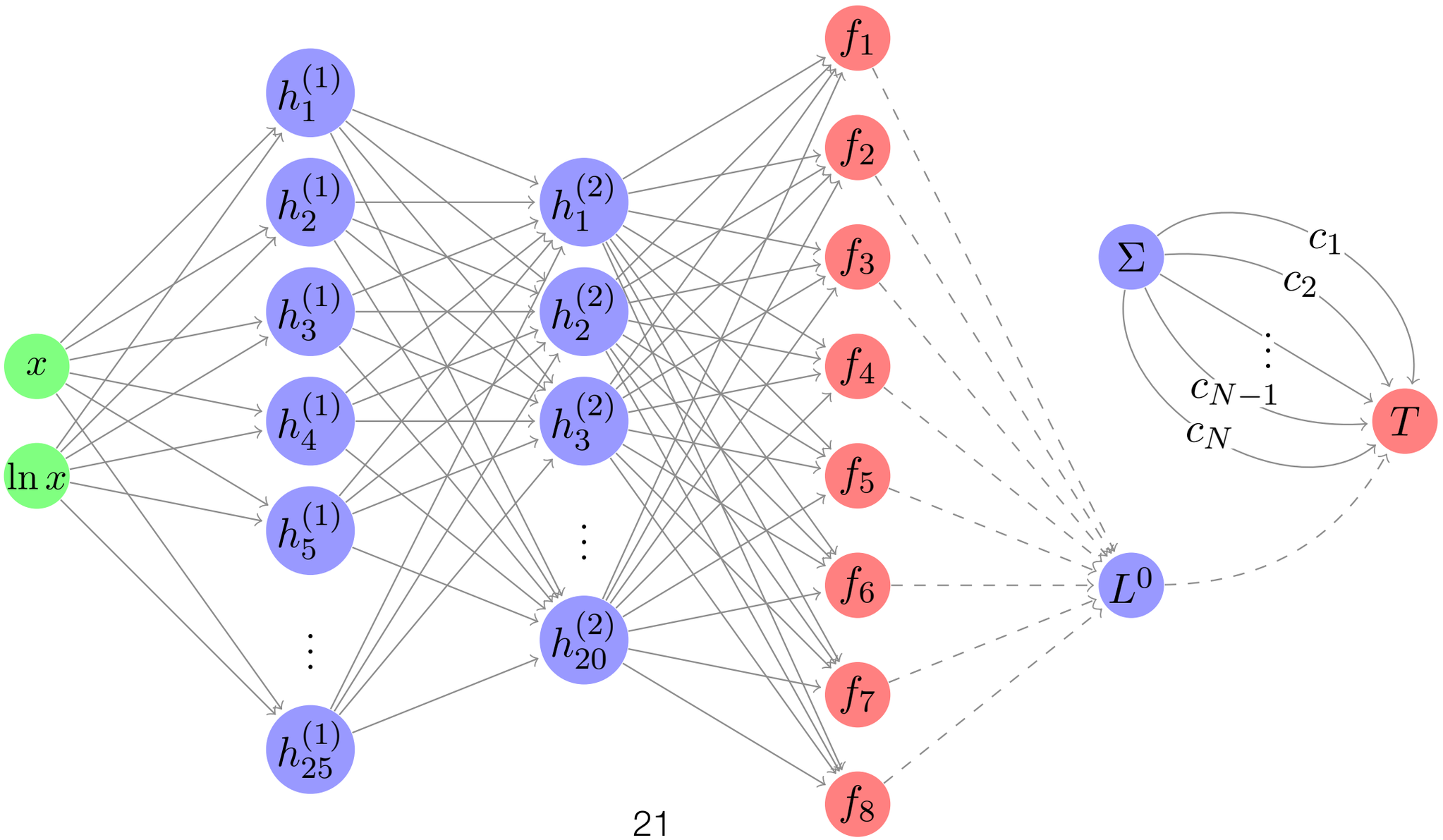
Could we be absorbing signs of new physics into the PDFs?

SIMUnet S. Iranipour, M. Ubiali, [2201.07240]

"A new methodology that is able to yield a simultaneous determination of the PDFs alongside **any set of parameters that determine the theory predictions**"



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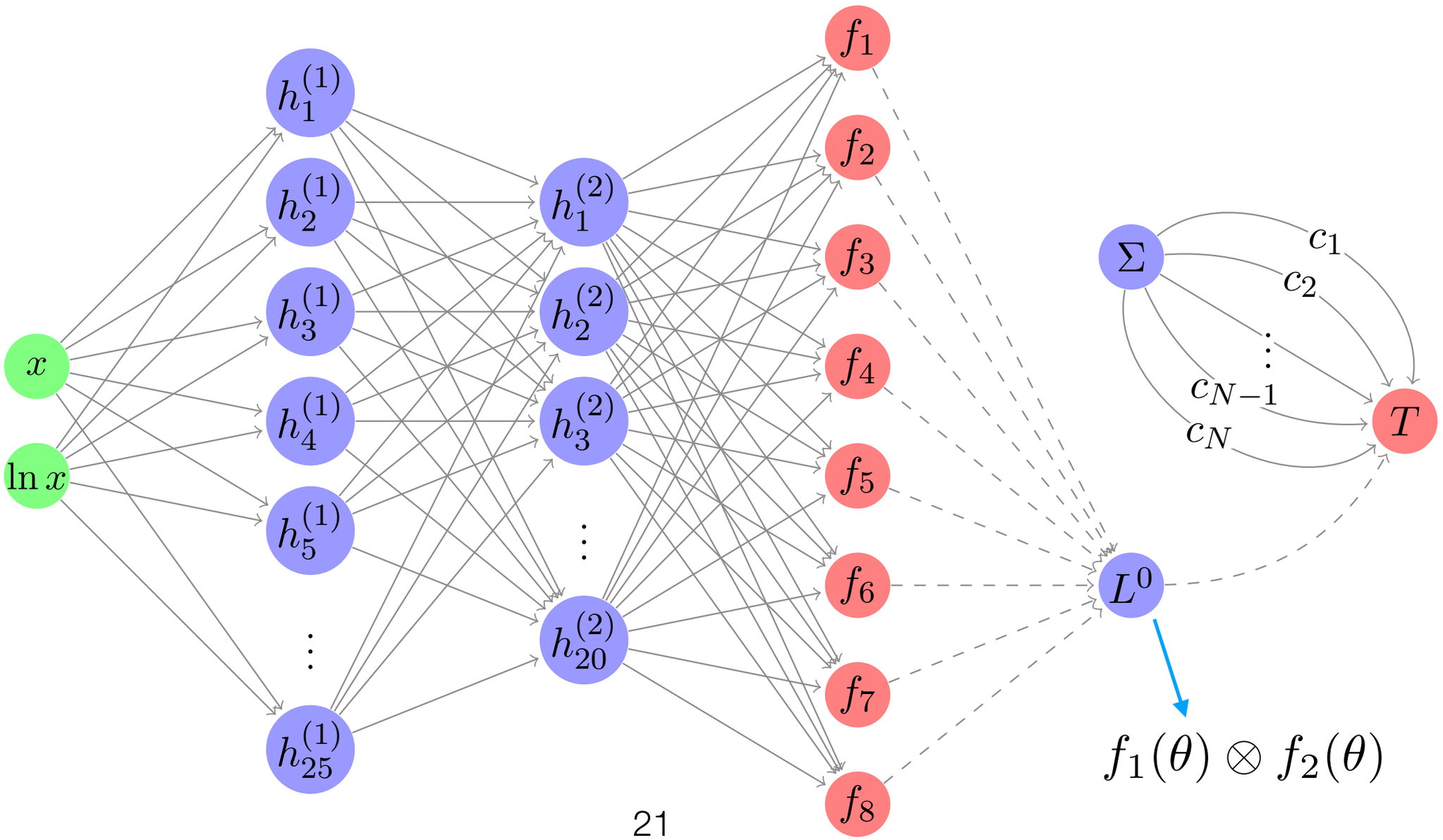

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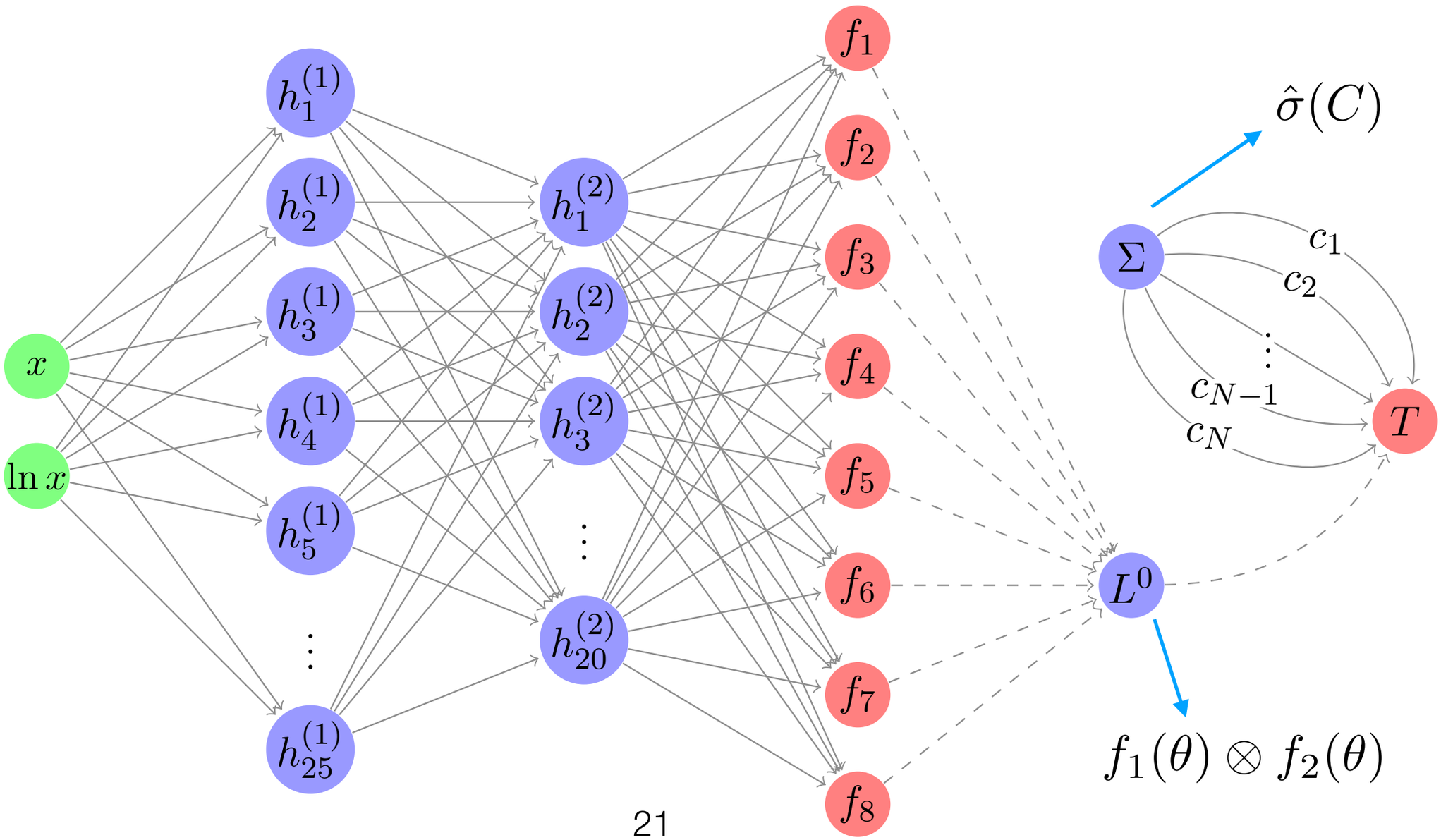


SMEFT-PDF interplay in top

work in progress

The **top sector** has been used in multiple EFT analyses, including **SMEFiT** (2105.00006) and **FitMaker** (2012.02779).

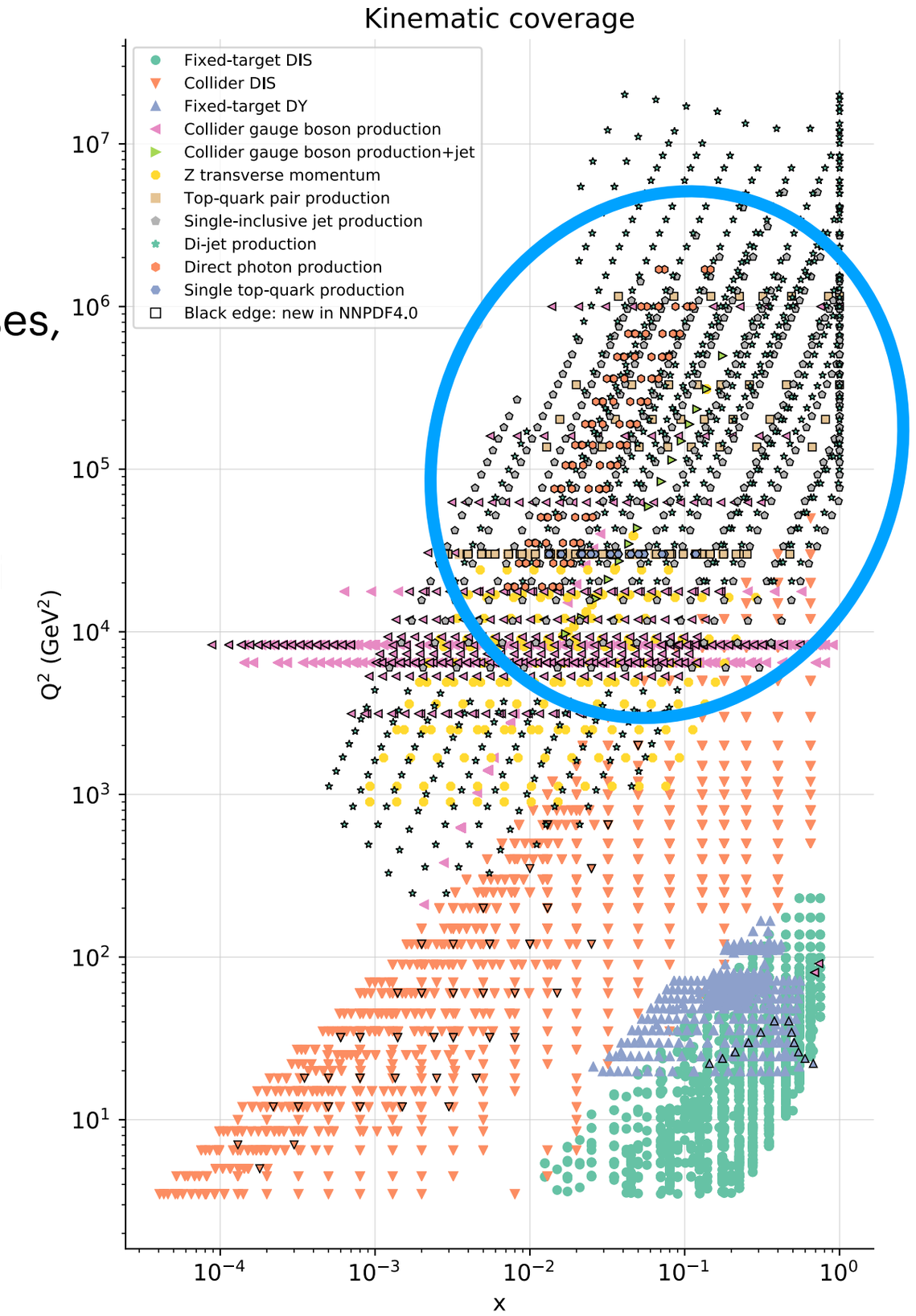
PDFs: the top sector is relevant for **high-x** $\bar{q}q$ lumi + **gluon** lumi

EFT: ~ 20 operators affect top processes

Dataset superset of SMEFiT & FitMaker

$$t\bar{t}\ (\text{incl. } A_C), \qquad t\bar{t}+X,$$

$$\text{single } t, \qquad tZ, tW, \ldots$$

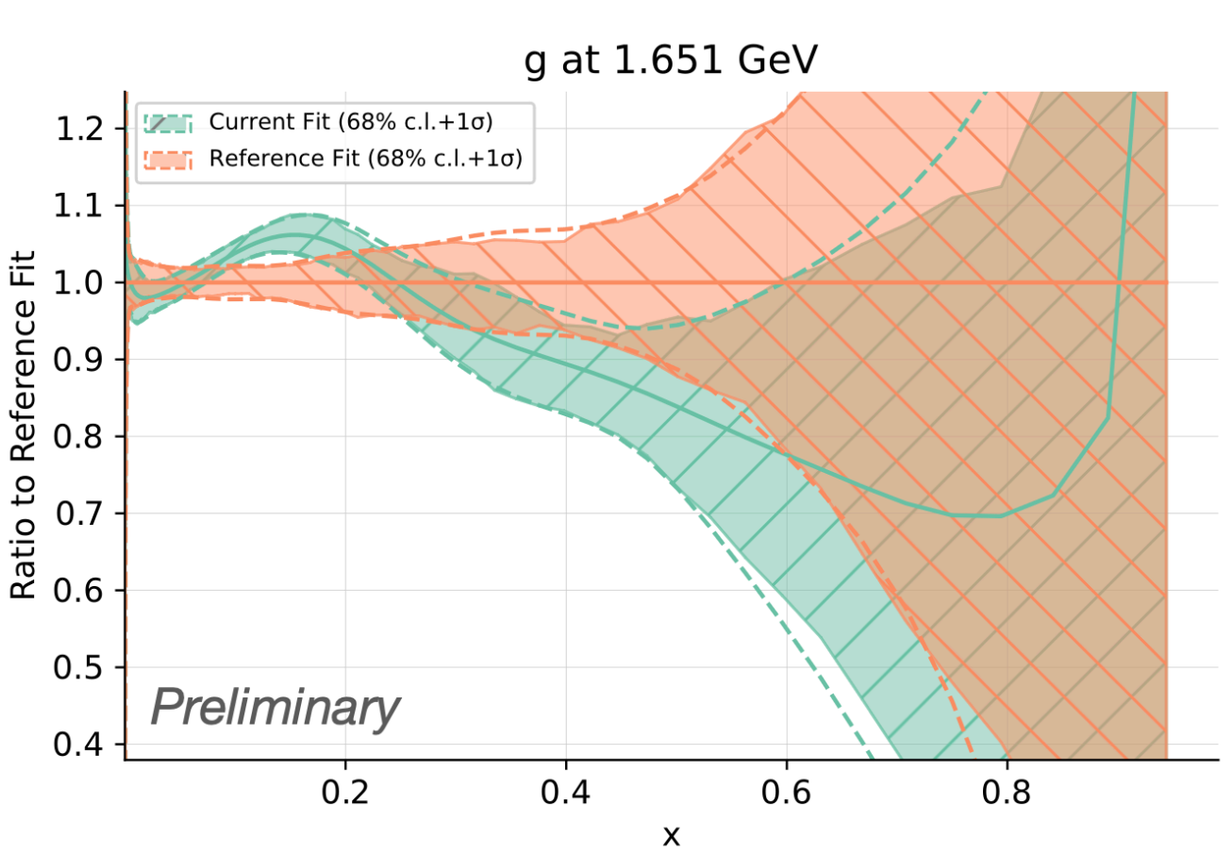


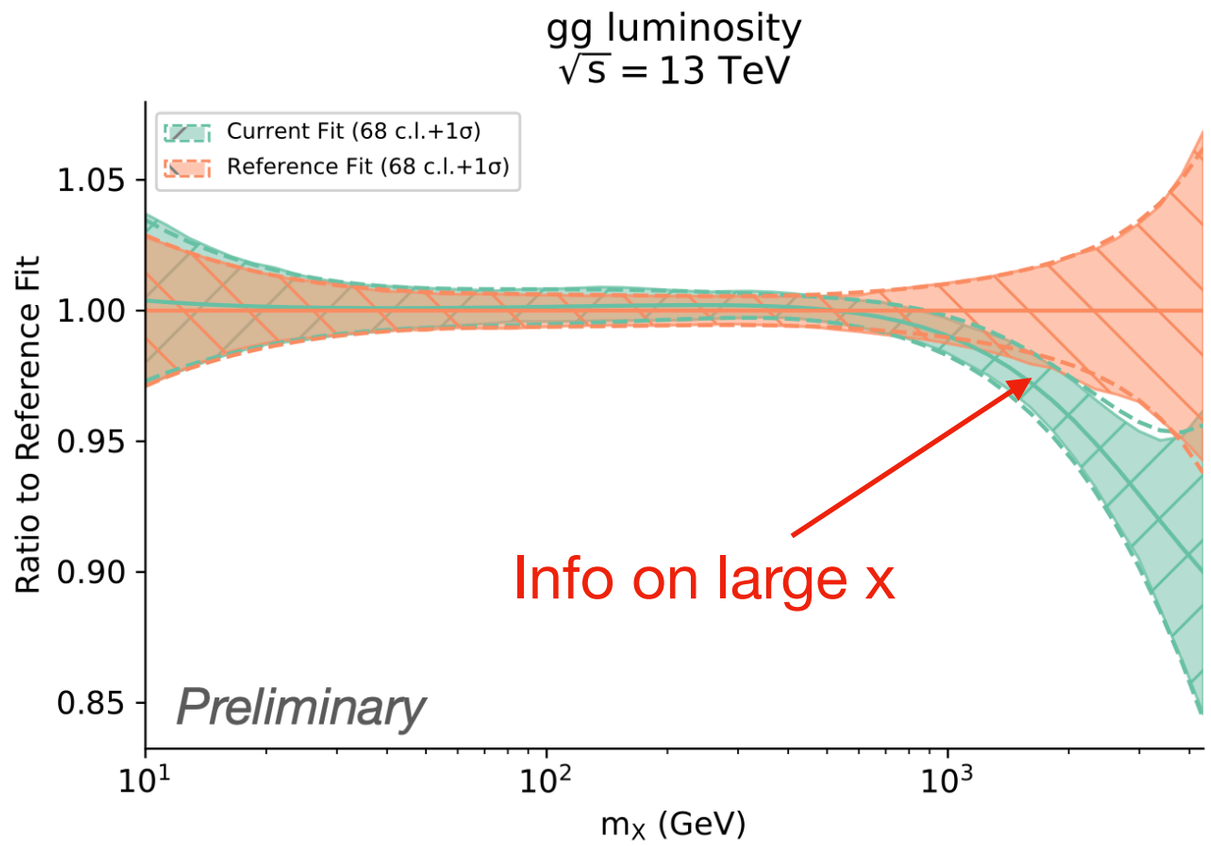
Top data is important especially for the gluon PDF

PDF fit, no top data

PDF fit with top data

Additional data include: DIS, DY, jets, V + jets





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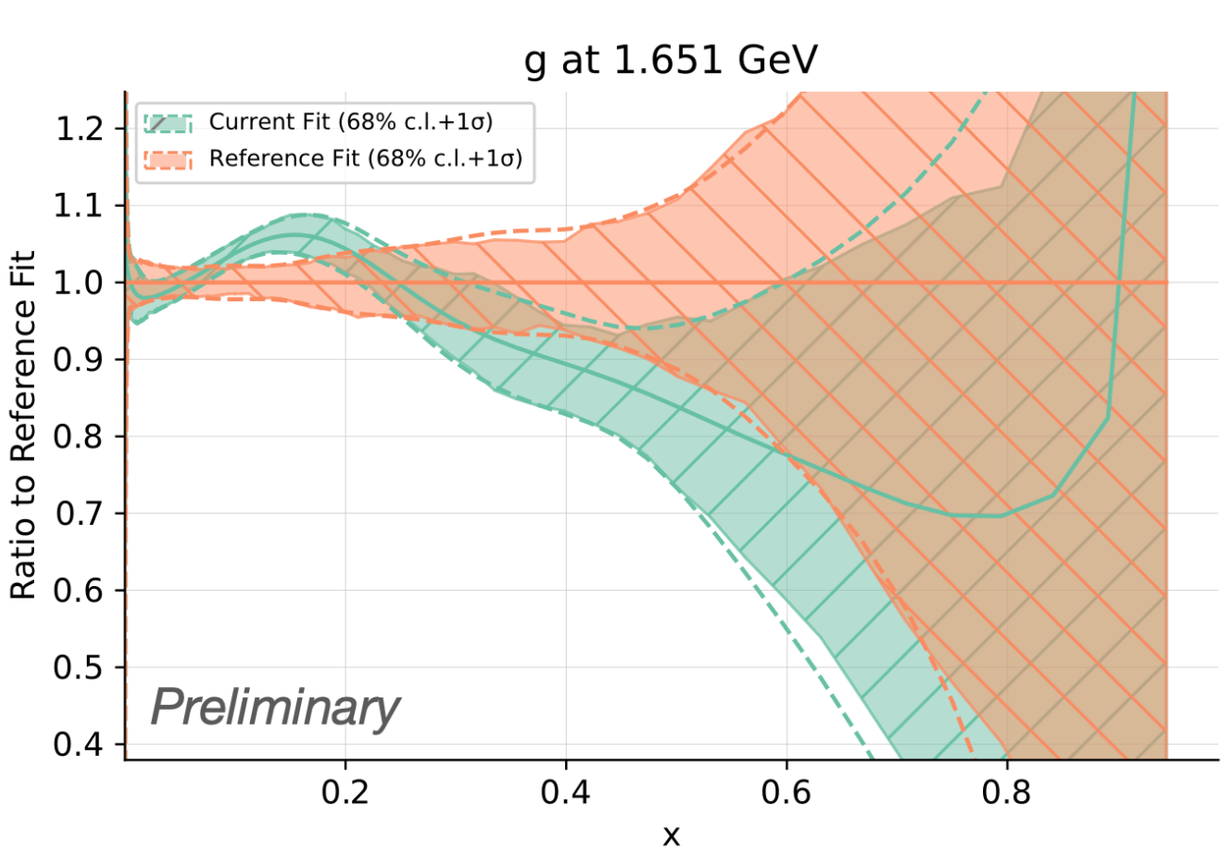

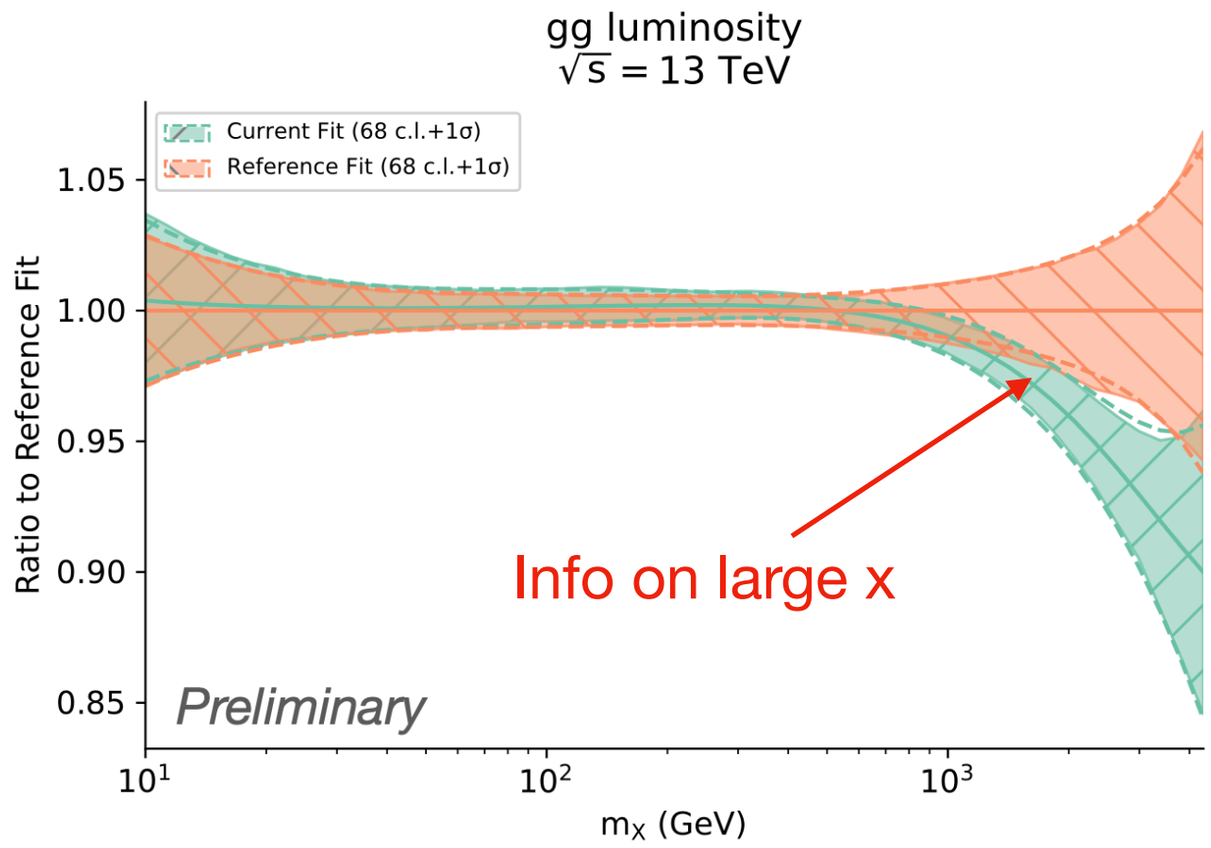

Impact mostly from ttbar data

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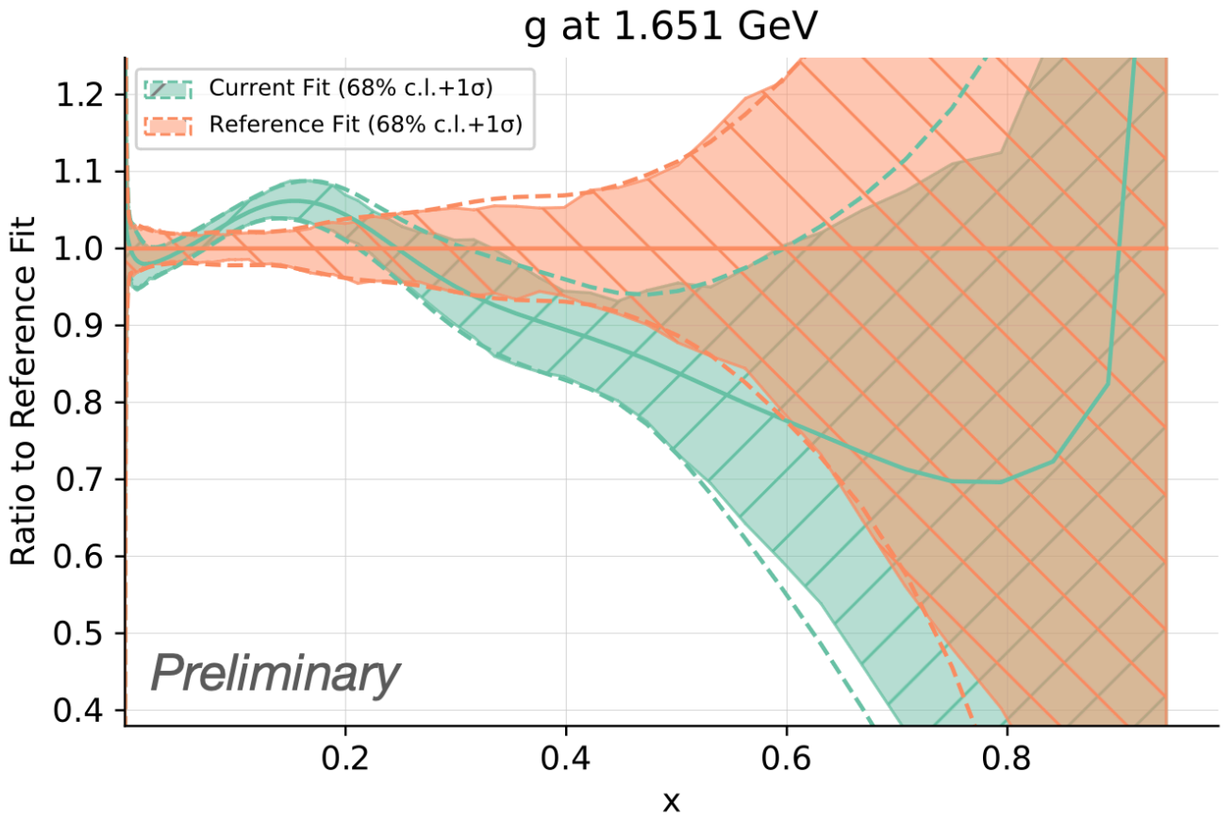
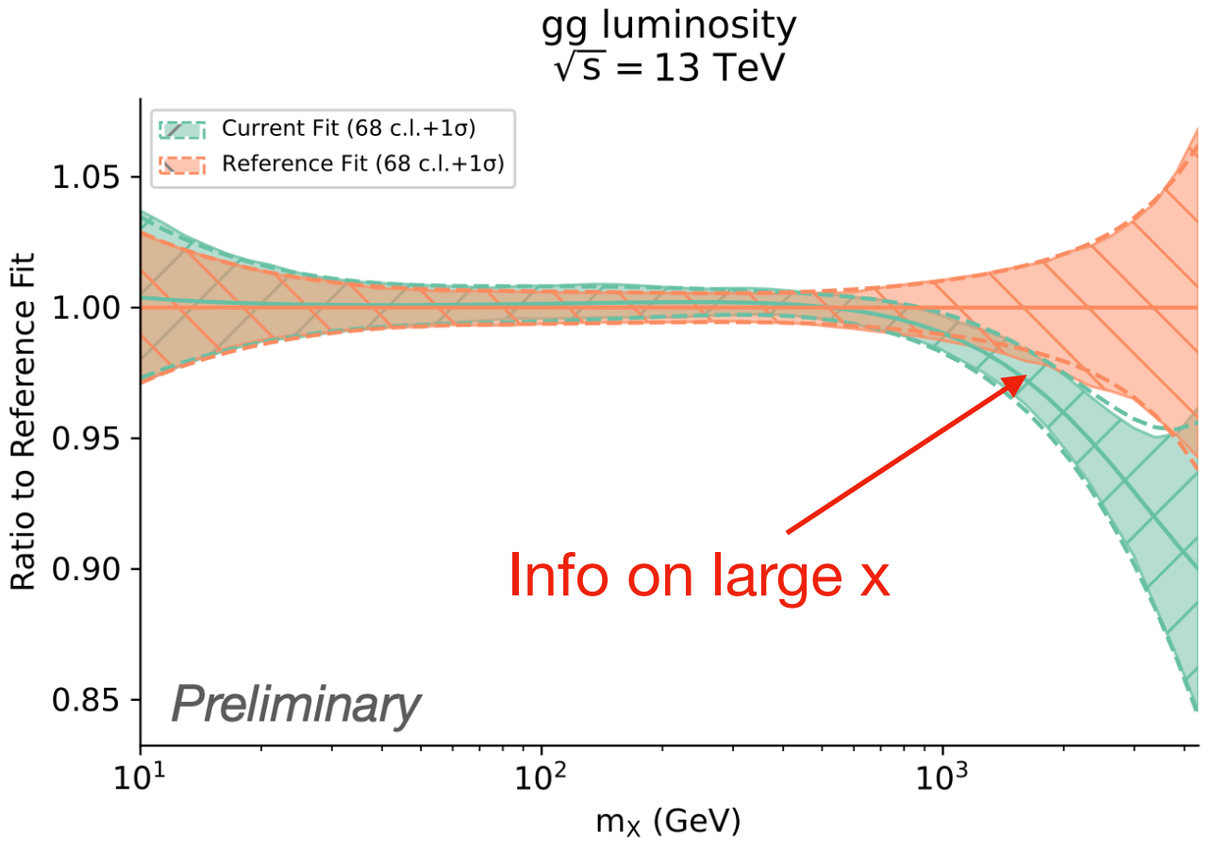


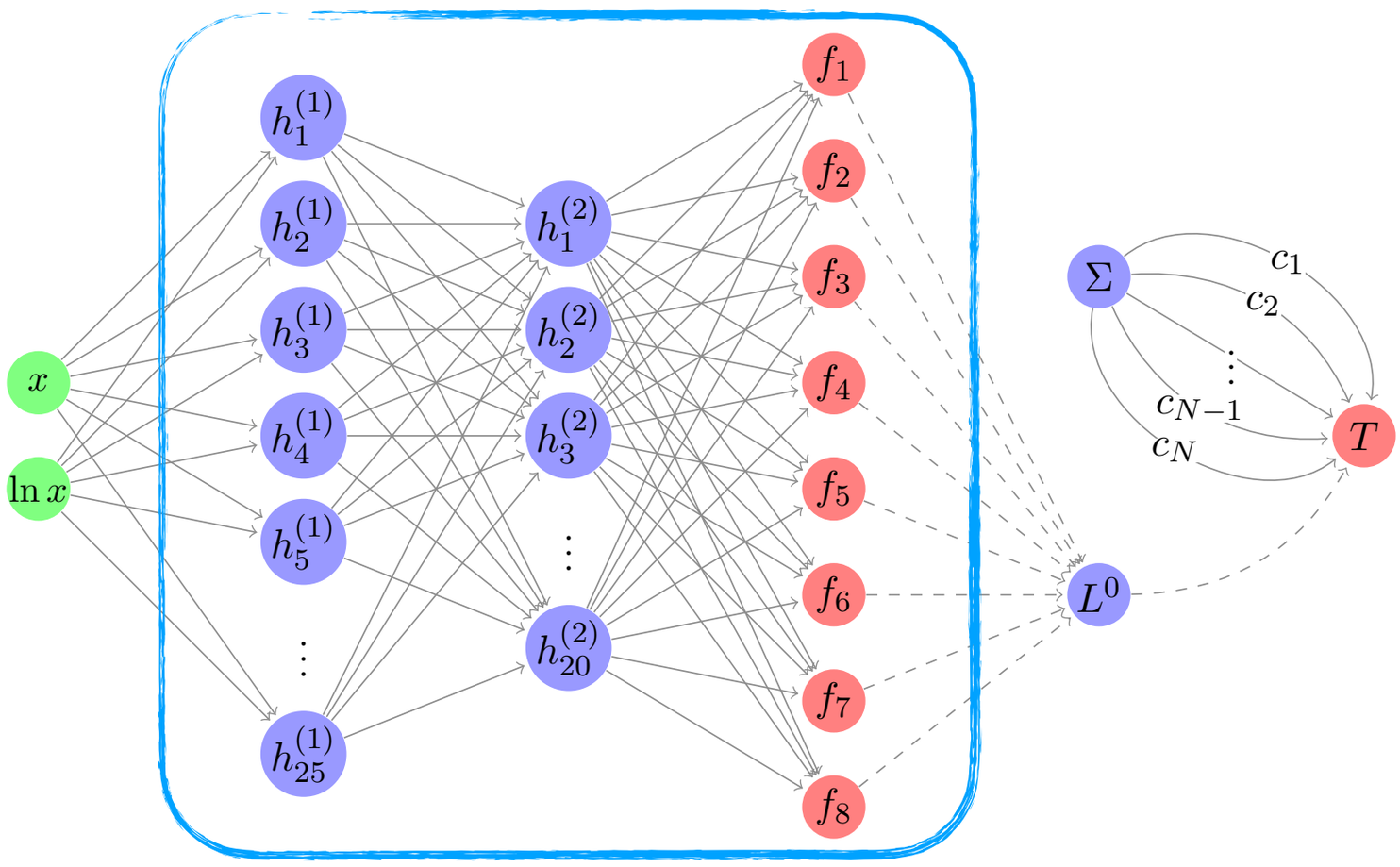


Impact mostly from ttbar data

Likely interplay
gluon PDF - EFT operators

Conservative fixed PDF fit

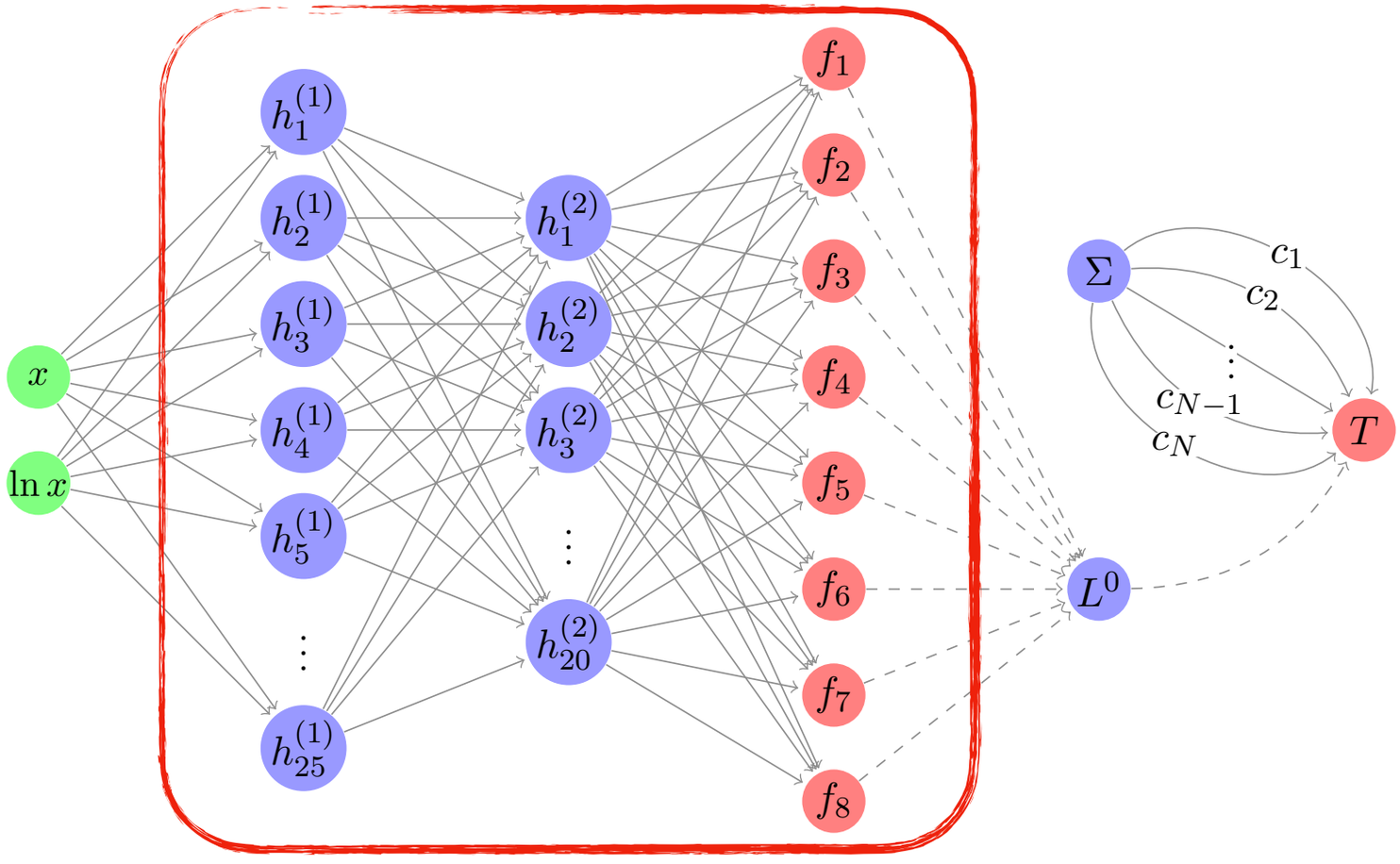
NN weights fixed,
no top PDF



Conservative fixed PDF fit

Improper fixed PDF fit

NN weights fixed, all top PDF

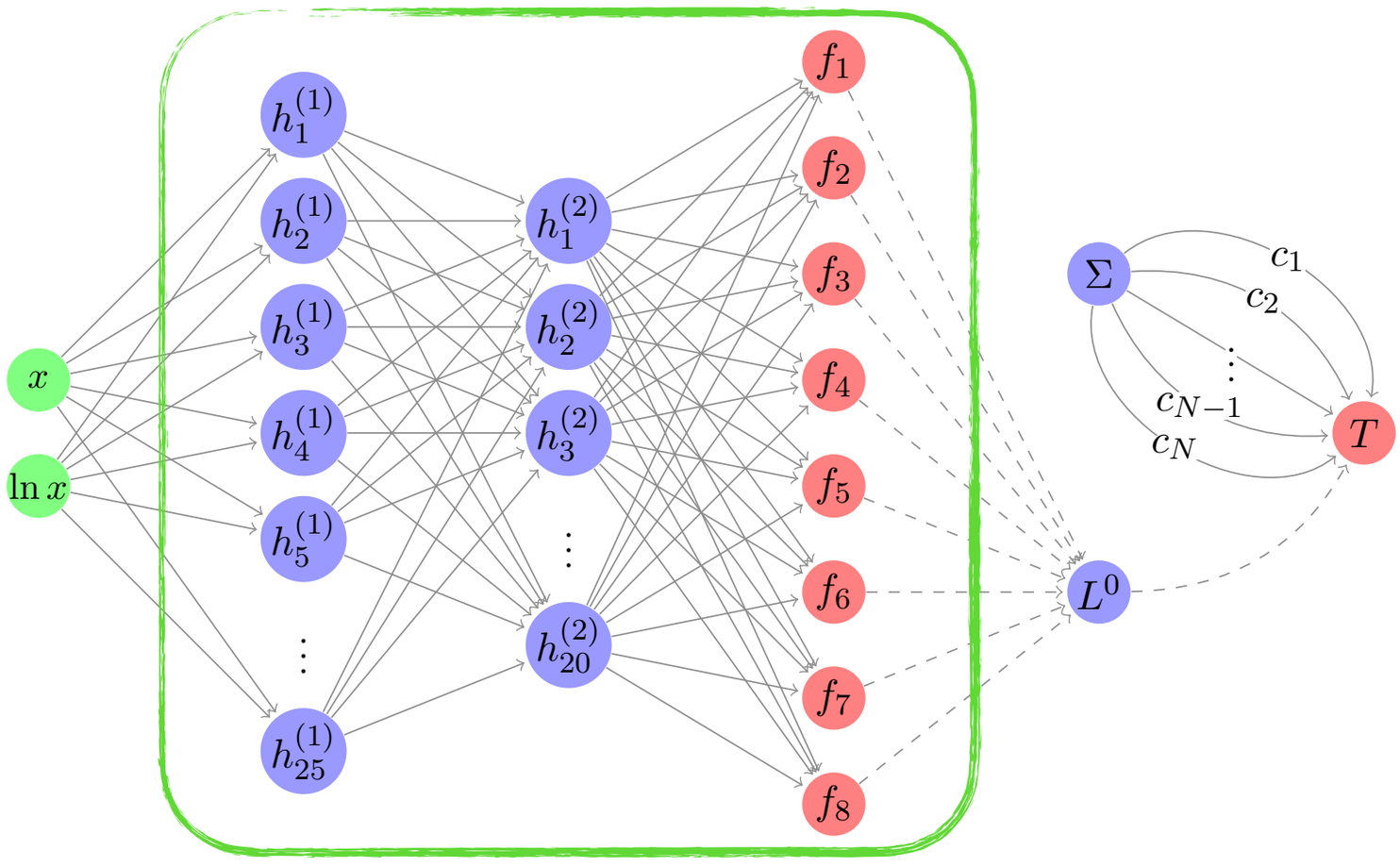


Conservative fixed PDF fit

Improper fixed PDF fit

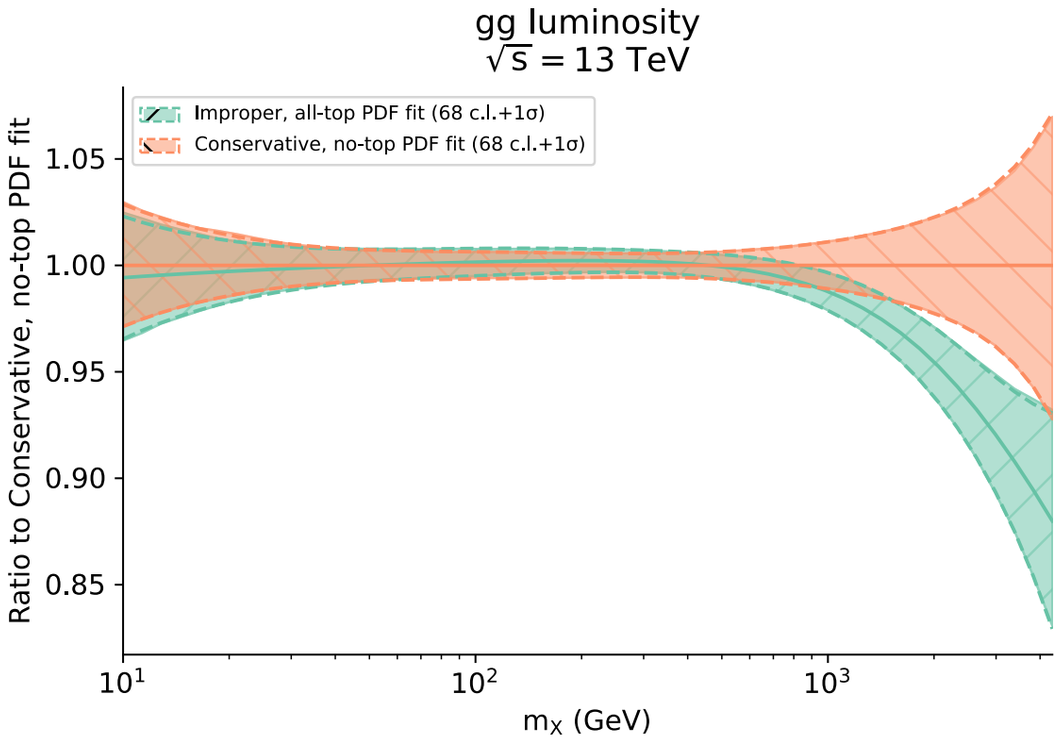
Simultaneous PDF-EFT fit

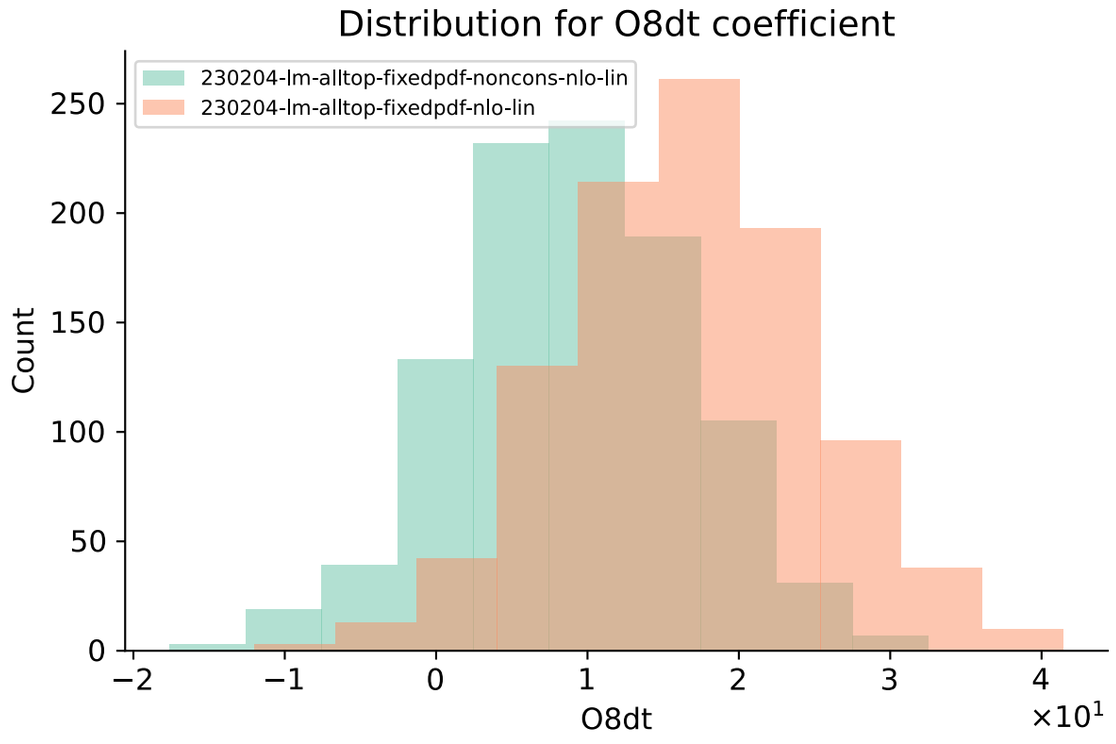
NN weights trainable



Conservative vs improper

Luca Mantani





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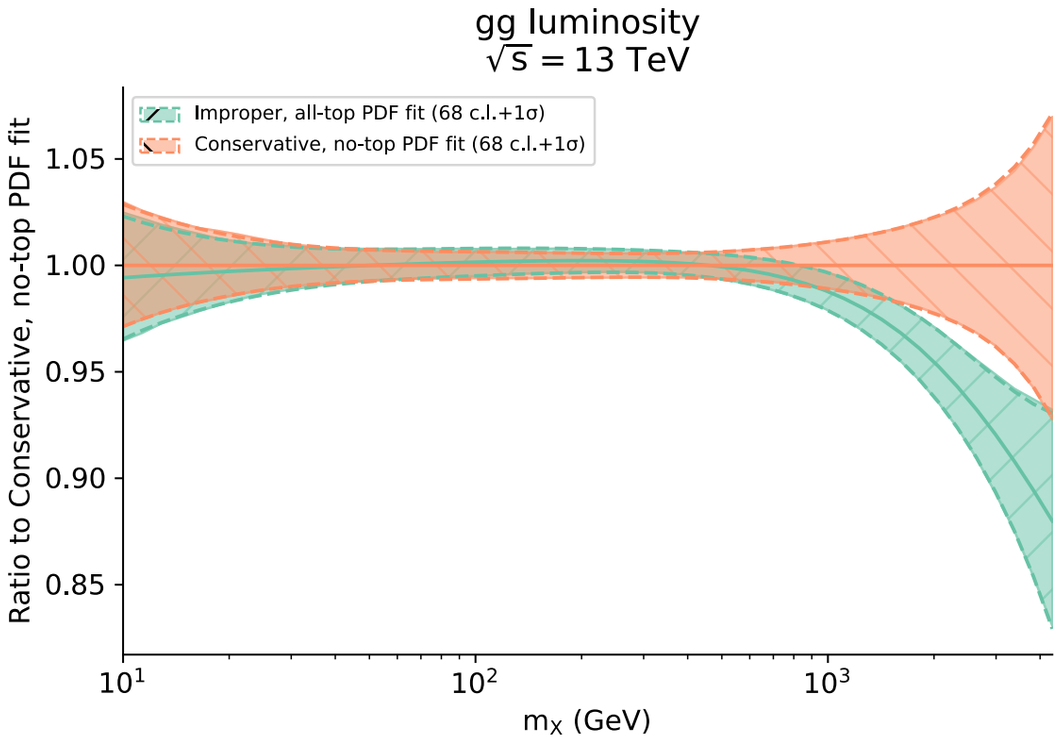

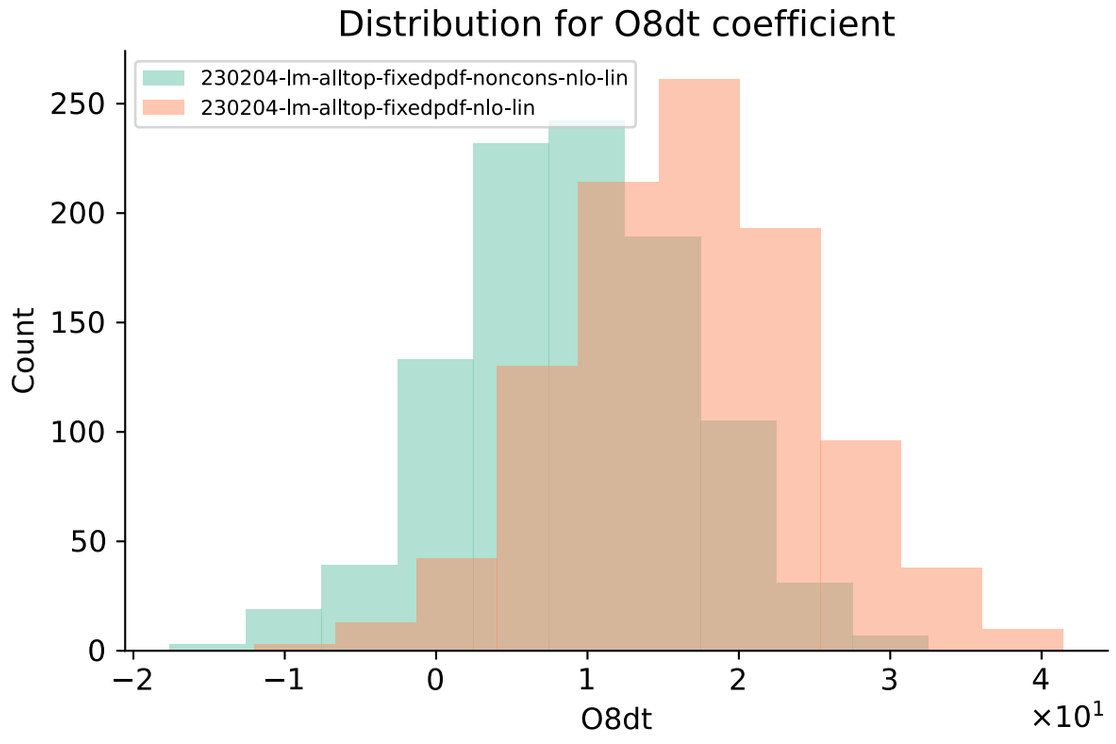

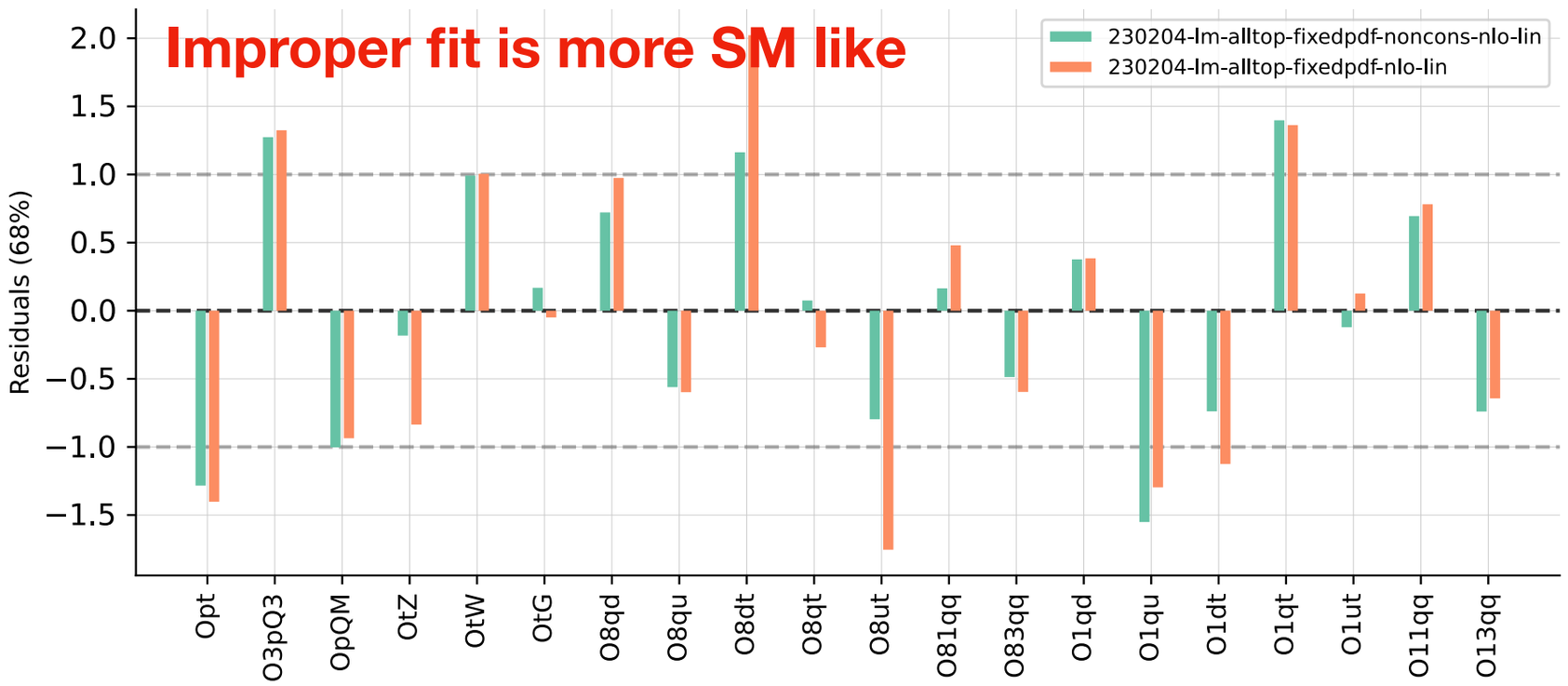

Why not simply use a conservative PDF fit?

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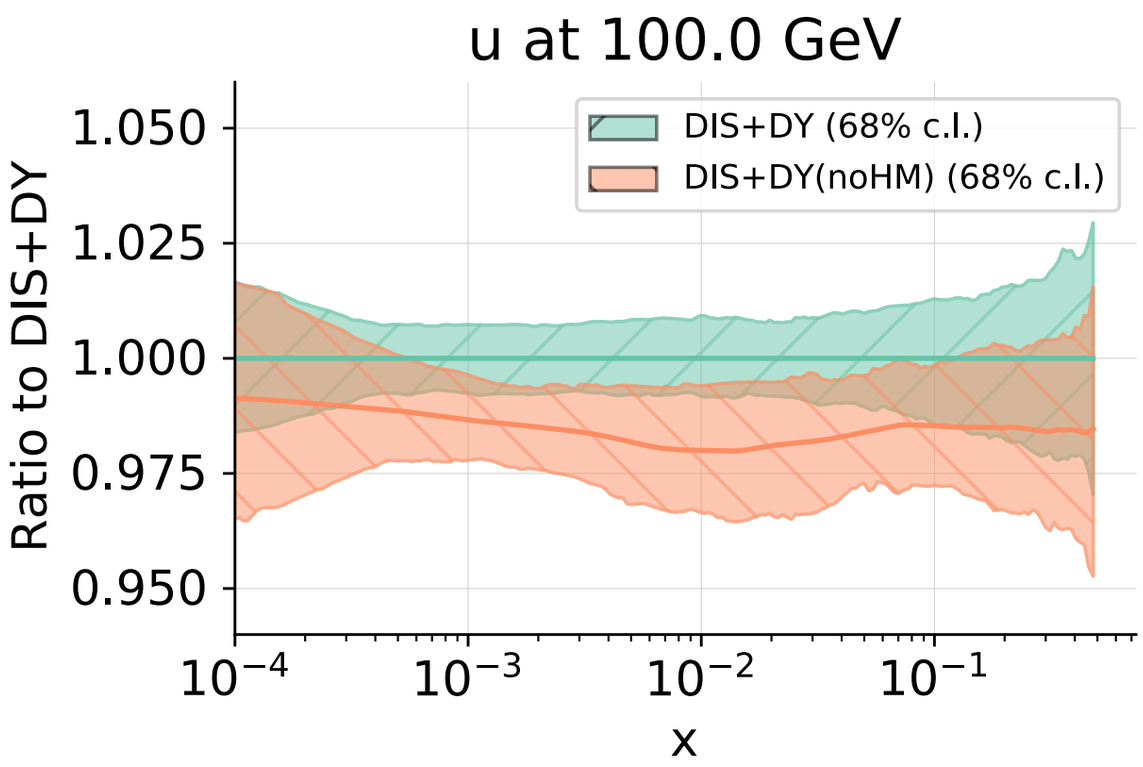

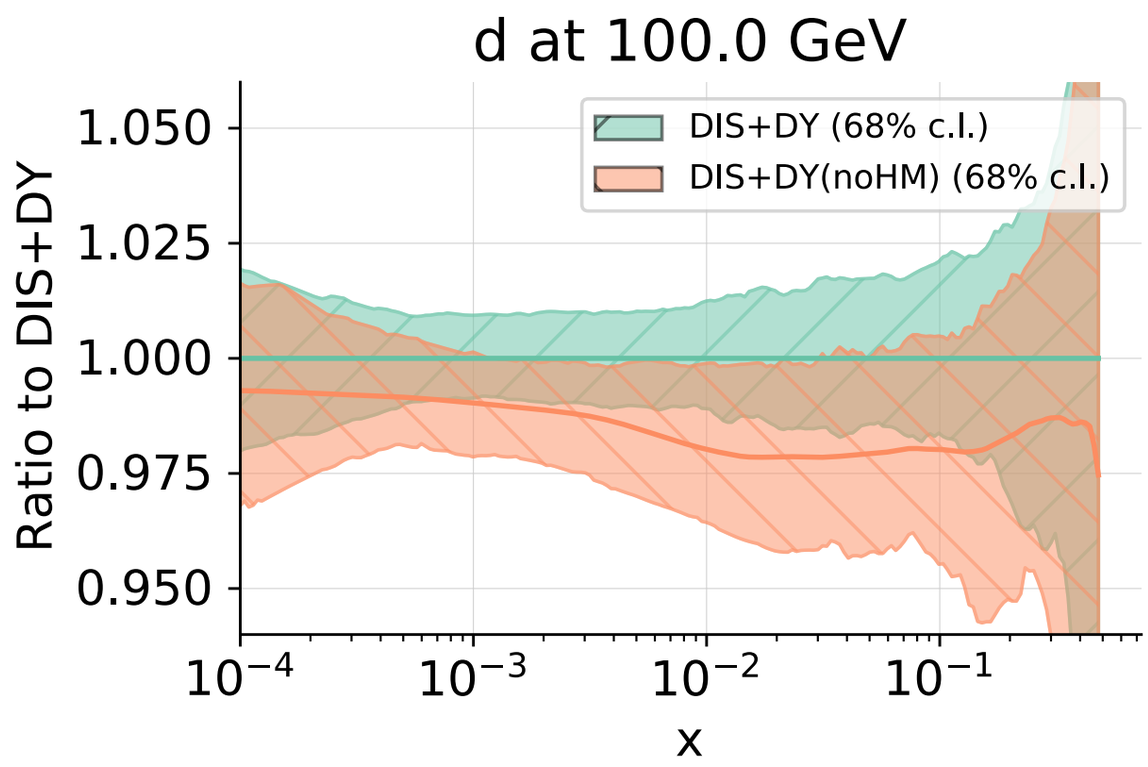

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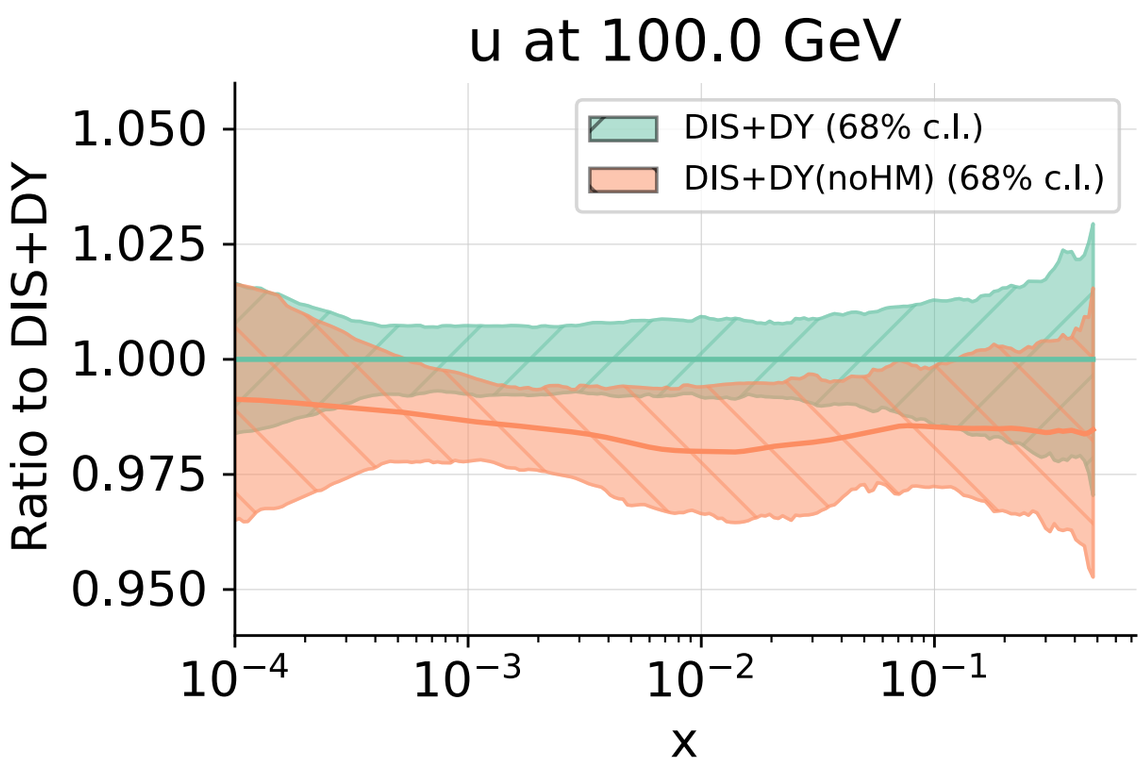

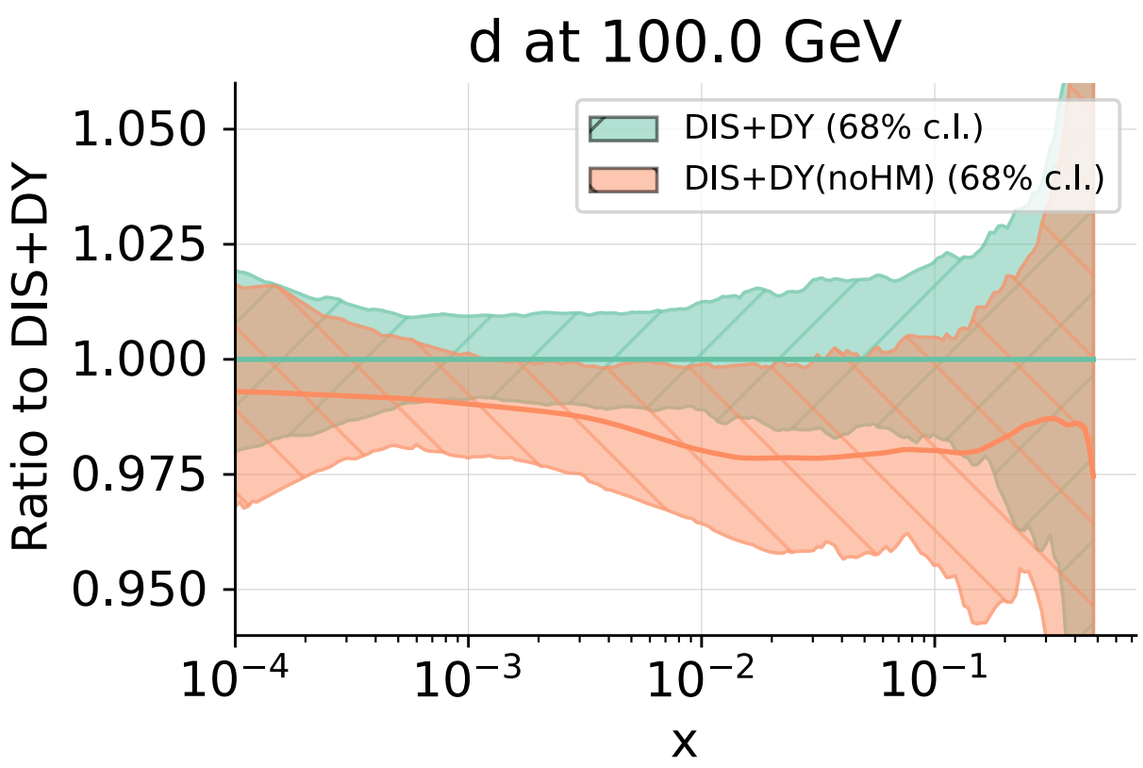

Increased PDF uncertainties in high-x region for several processes interesting for NP:

- diboson
- VBF
- high mass ttbar
- high mass jets
- etc..

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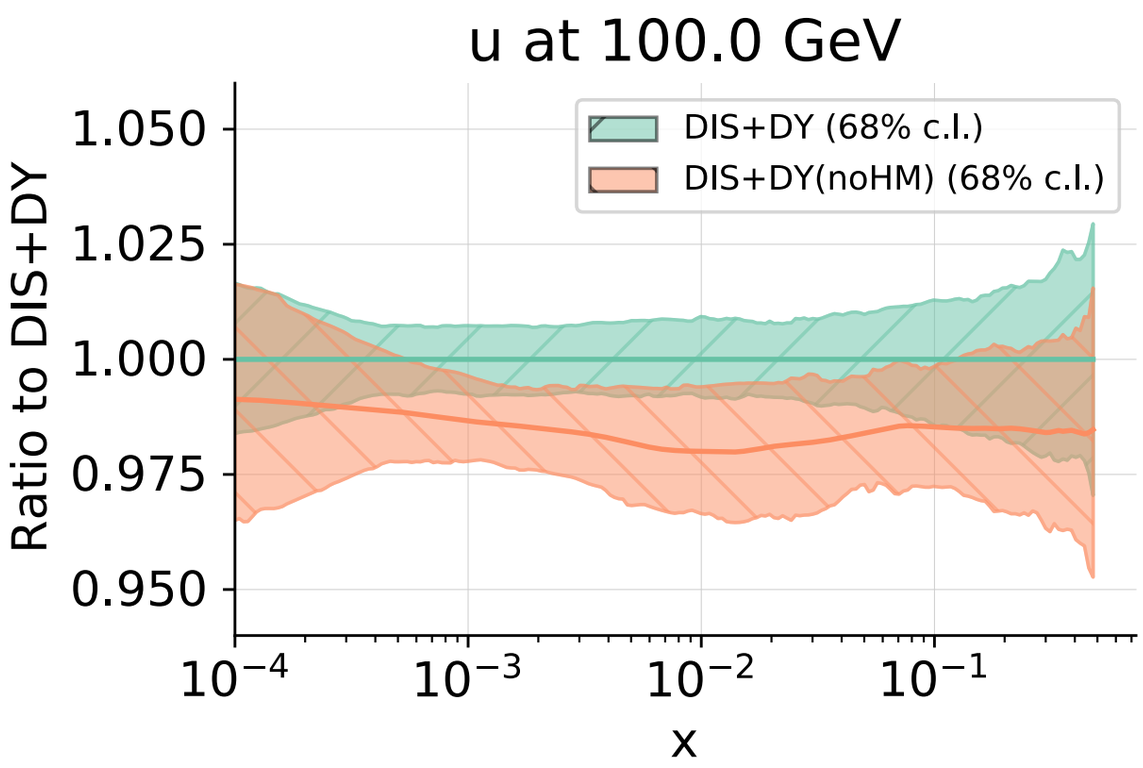

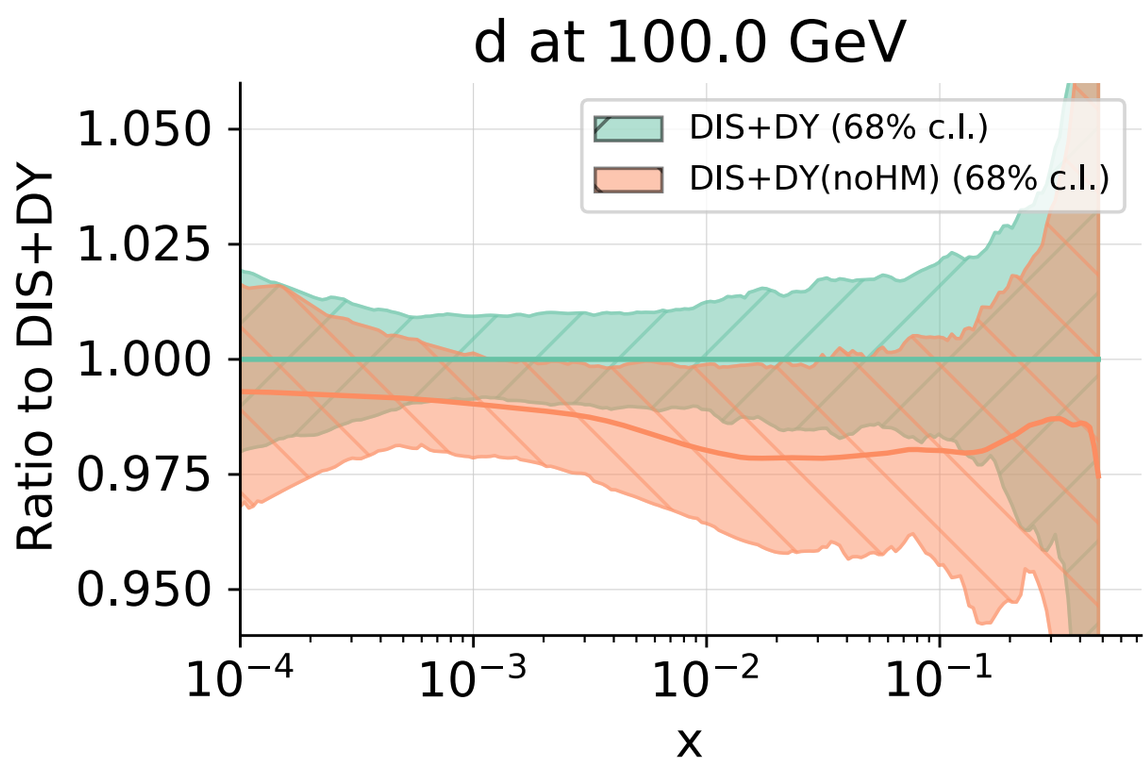

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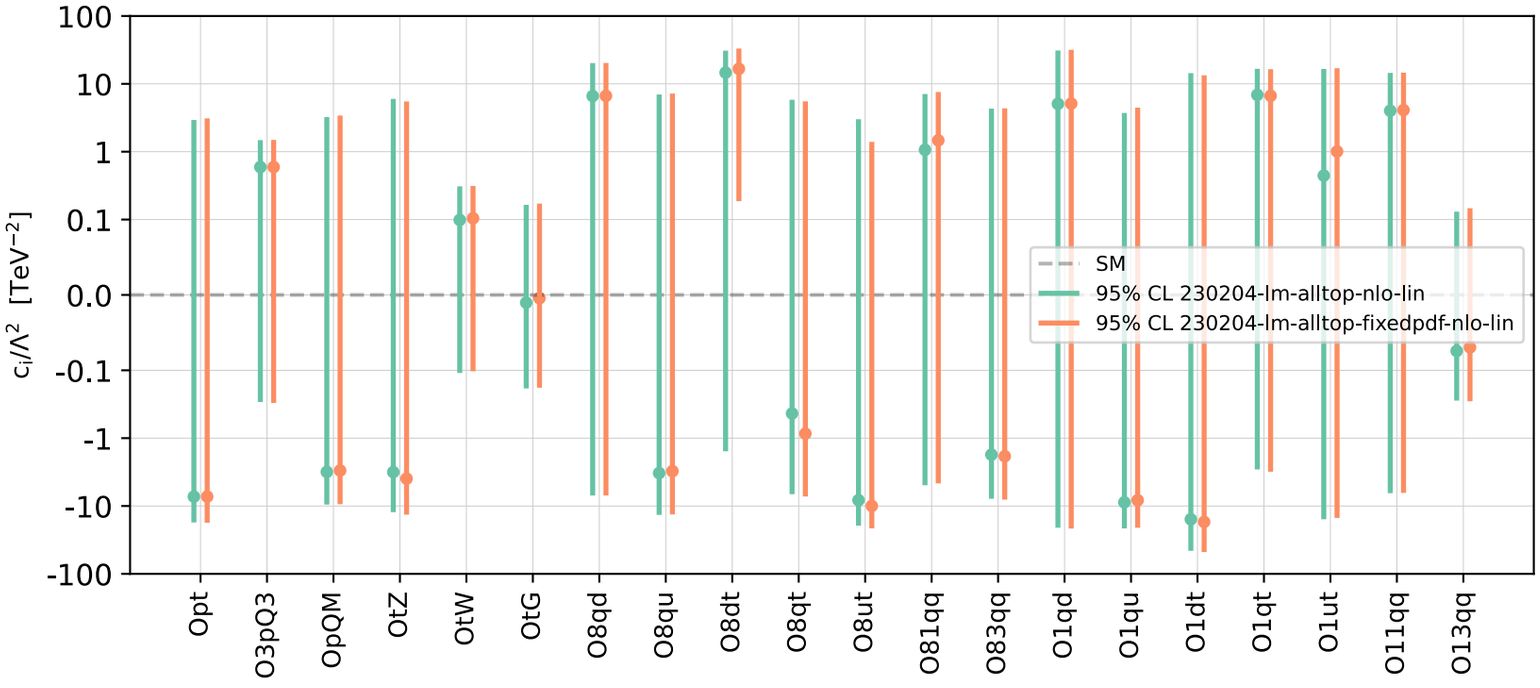
- etc..

Also: NN good at interpolating, bad in extrapolation

Conservative fit

Simultaneous fit

Moderate effect on WC, ~ 5-10%



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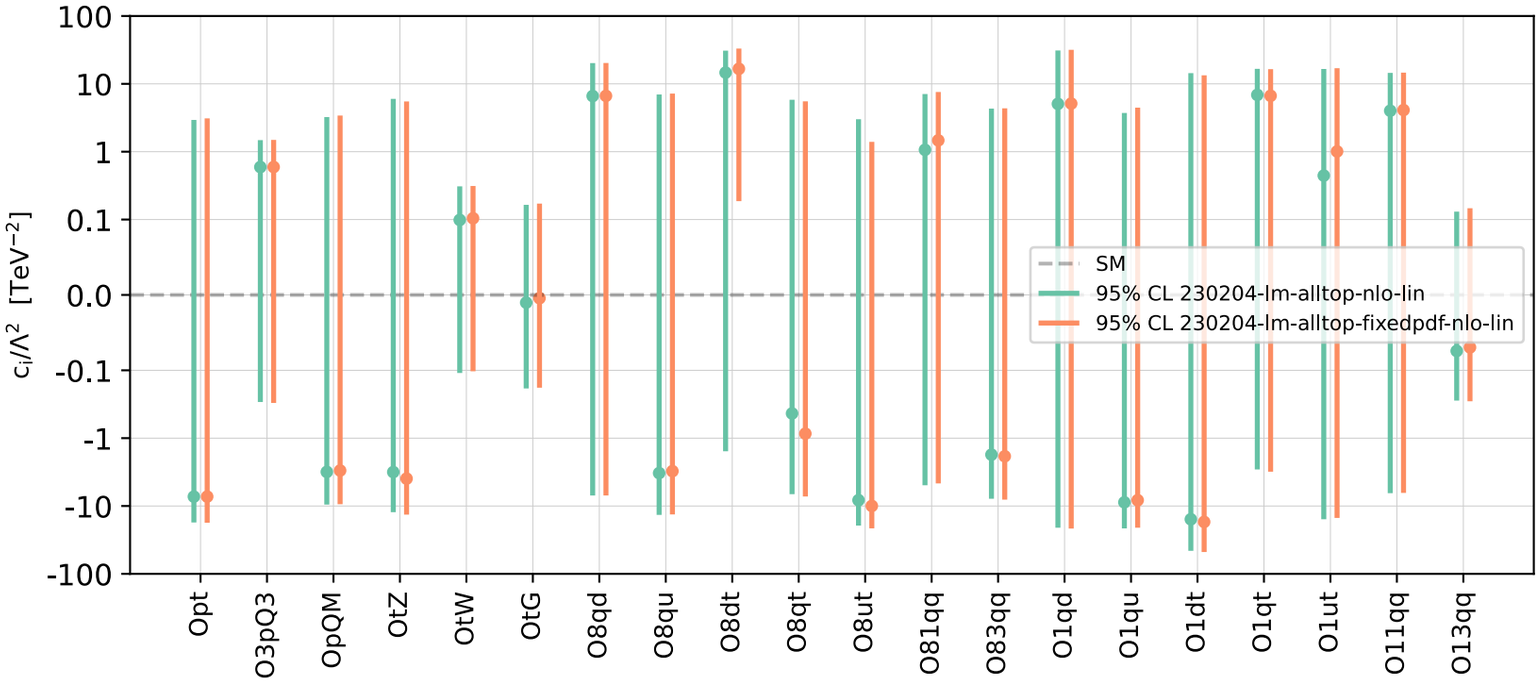
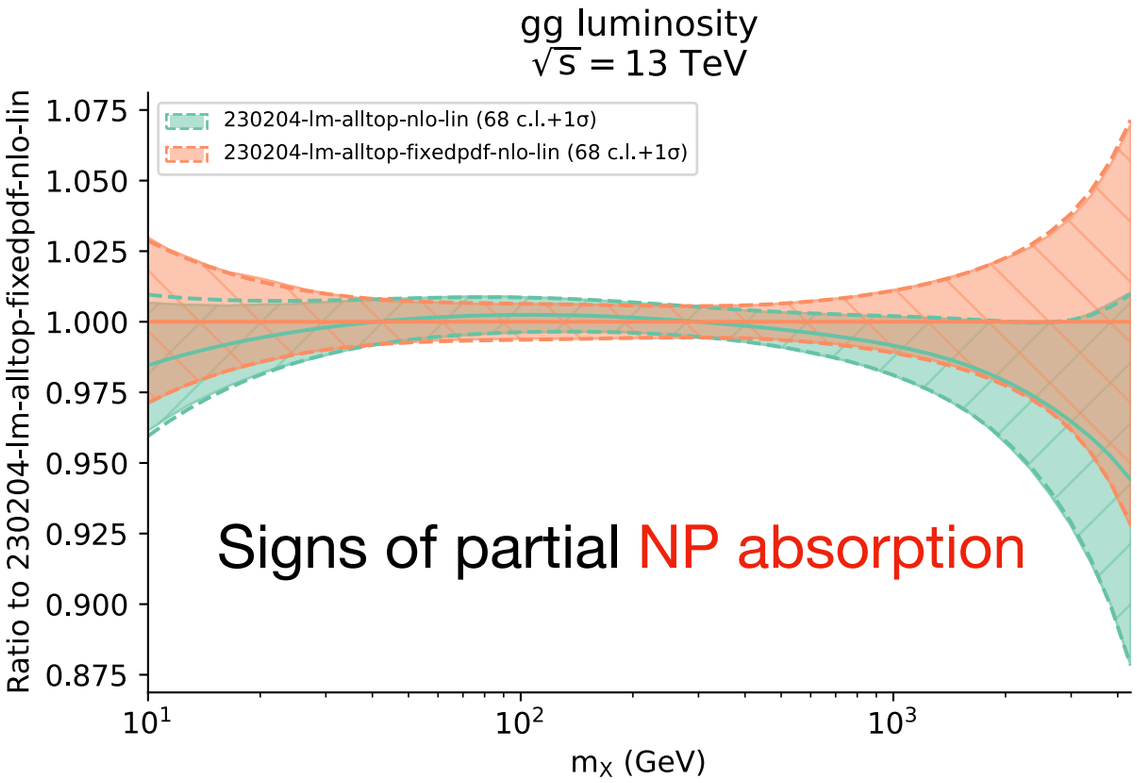


Shift in PDF not as dramatic as SM



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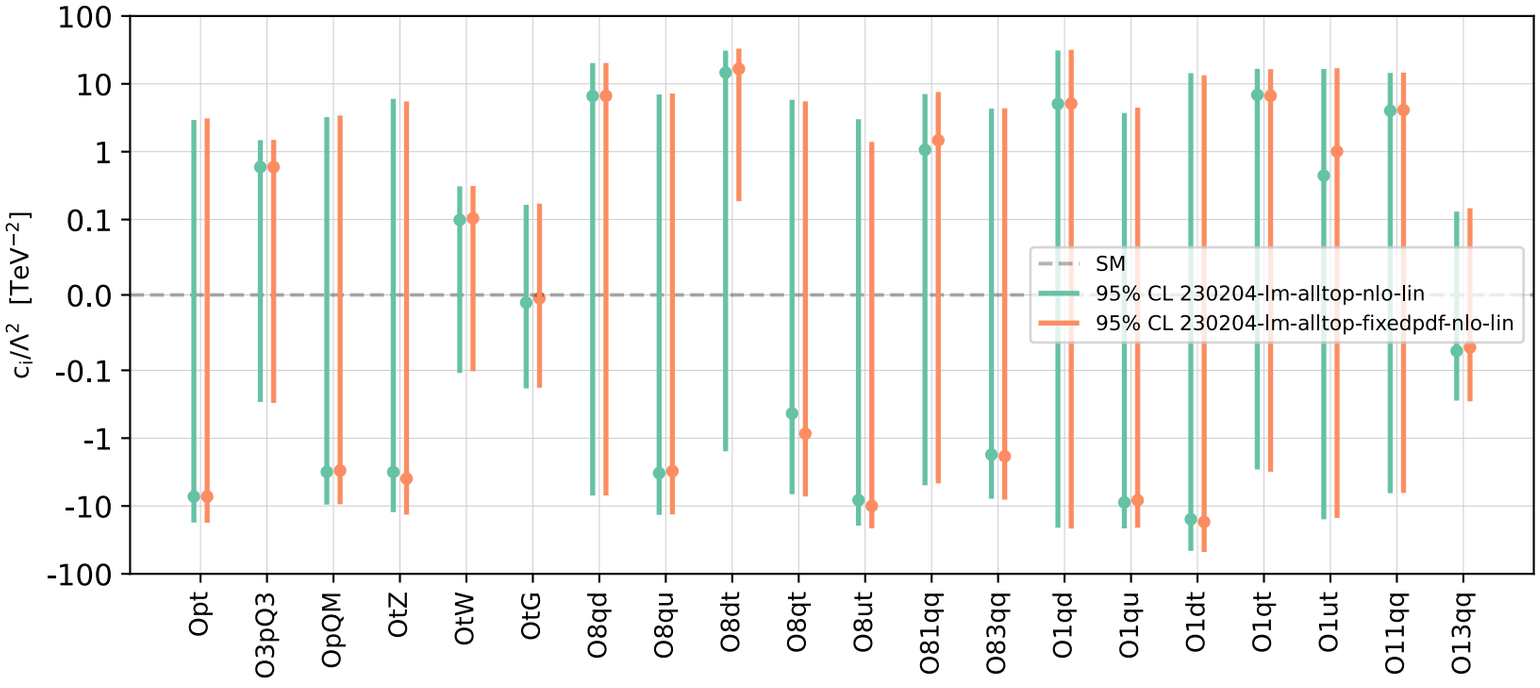

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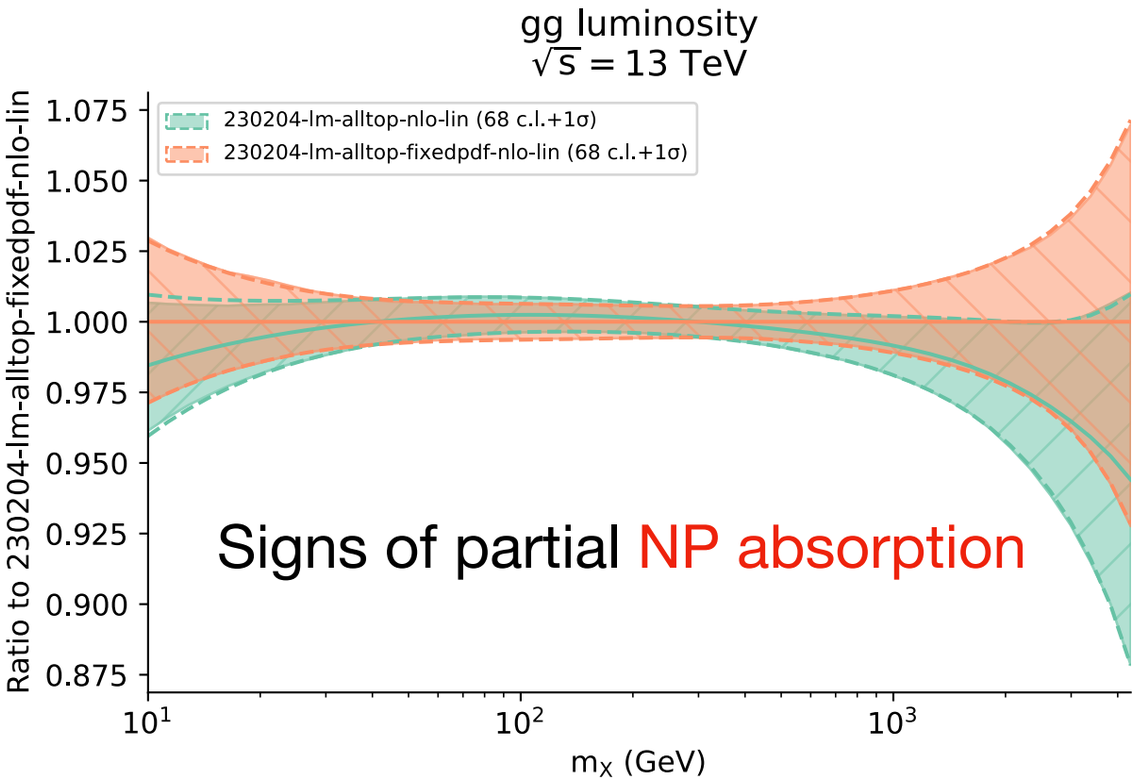
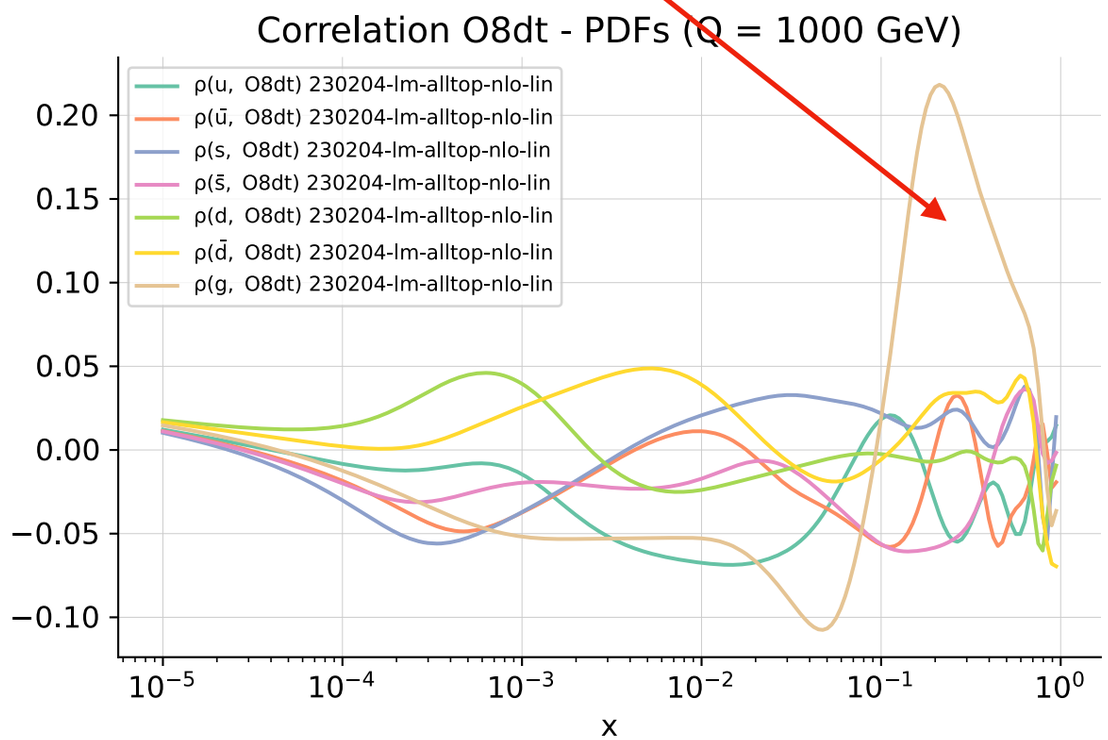


Signs of partial NP absorption

Correlation gluon-EFT



We now have a 4th option to perform a SMEFT fit

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From the simultaneous fits we now have a SMEFT PDF

We now have a 4th option to perform a SMEFT fit

From the simultaneous fits we now have a SMEFT PDF

EFT degrees of freedom → **Enhanced PDF uncertainties**

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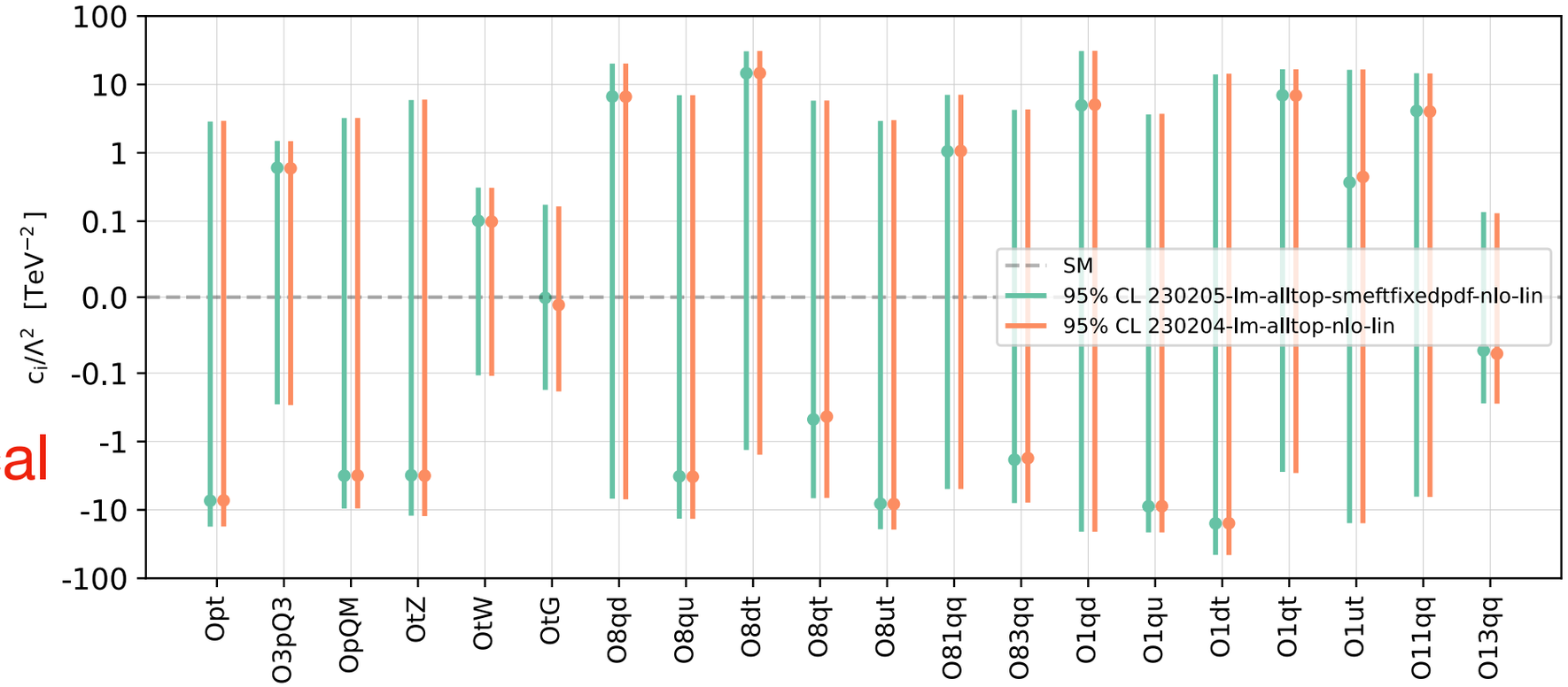
From the simultaneous fits we now have a SMEFT PDF

EFT degrees of freedom → **Enhanced PDF uncertainties**

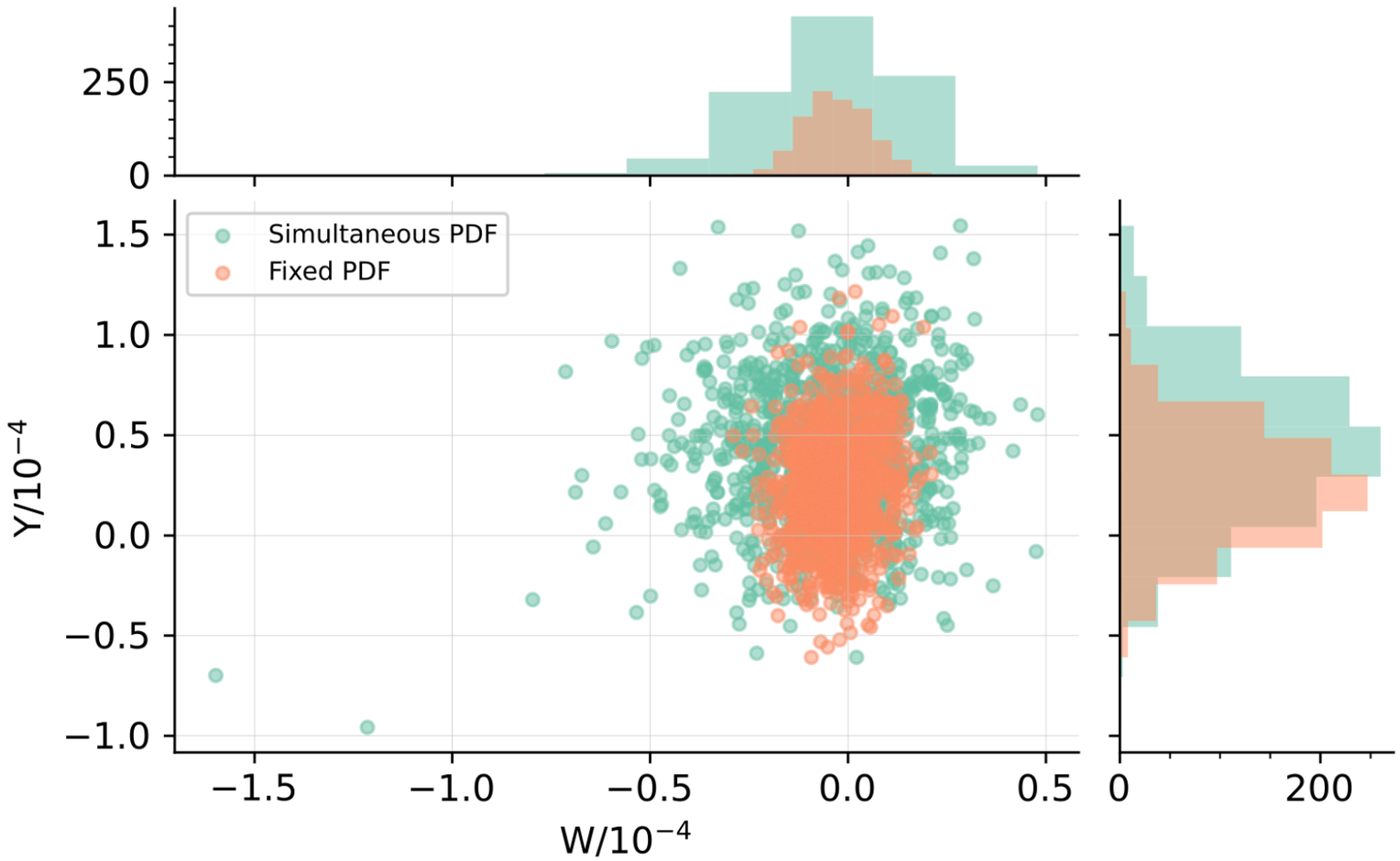
Simultaneous fit

SMEFT PDF fit

Results almost identical



Things become more relevant at HL-LHC



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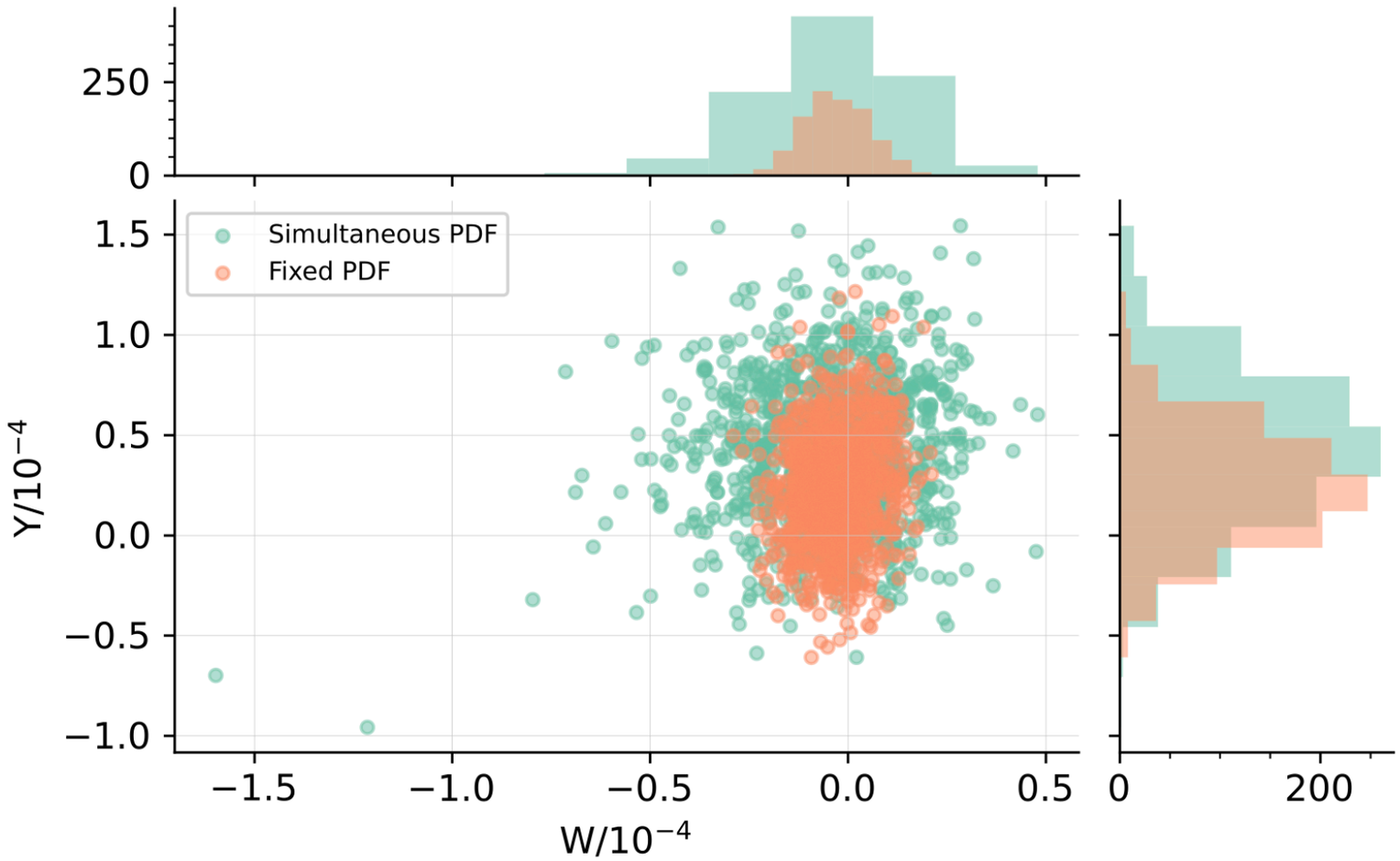
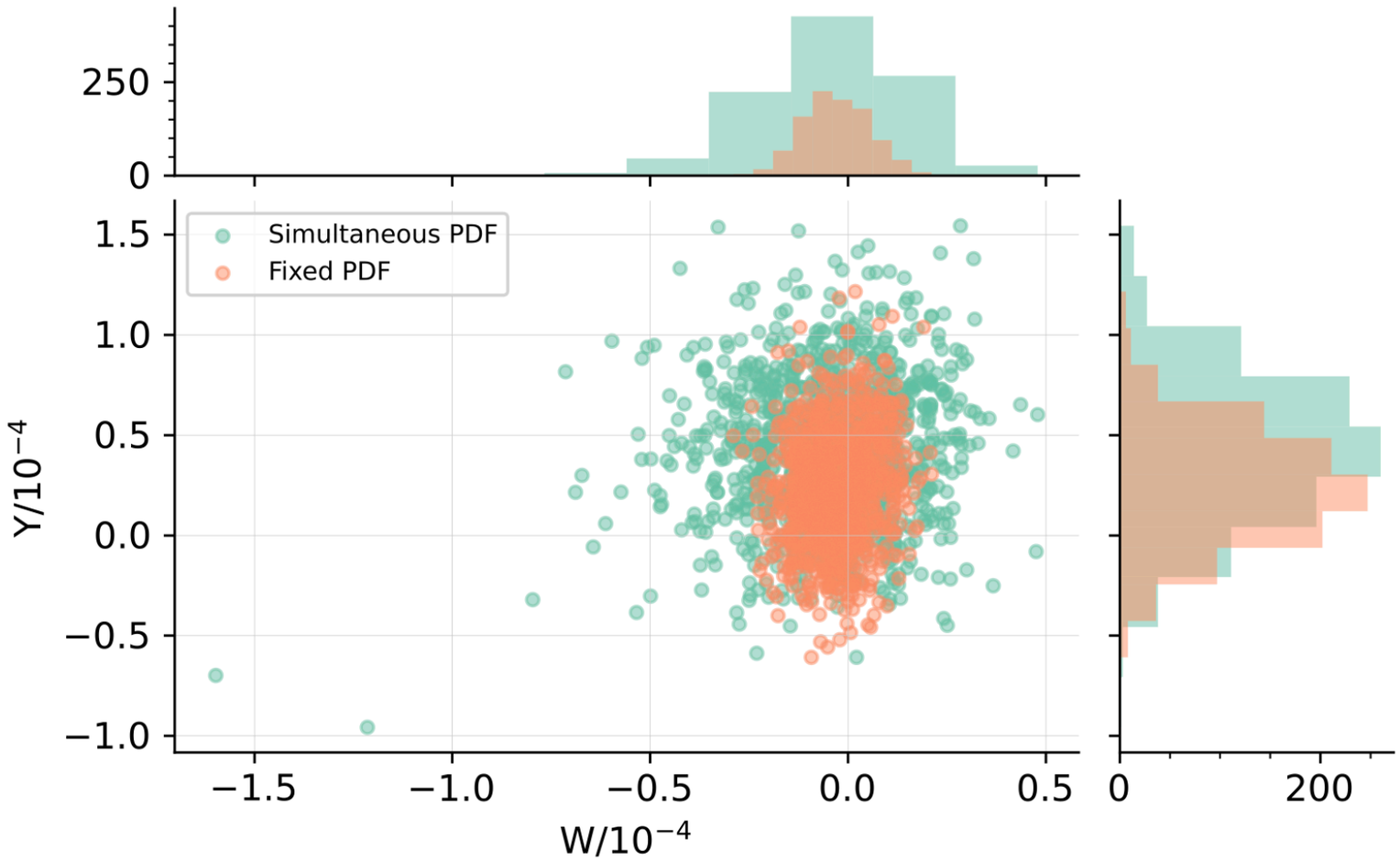


	SM PDFs	SMEFT PDFs	best-fit shift	broadening
$W \times 10^5$ (68% CL)	$[-1.1, 0.5]$	$[-2.4, 1.5]$	-0.2	$+144\%$
$W \times 10^5$ (95% CL)	$[-2.0, 1.4]$	$[-4.3, 3.4]$	-0.2	$+126\%$
$Y \times 10^5$ (68% CL)	$[-0.4, 5.2]$	$[0.6, 8.0]$	$+1.9$	$+32\%$
$Y \times 10^5$ (95% CL)	$[-3.2, 8.1]$	$[-3.1, 11.7]$	$+1.9$	$+31\%$

Things become more relevant at HL-LHC



	SM PDFs	SMEFT PDFs	best-fit shift	broadening
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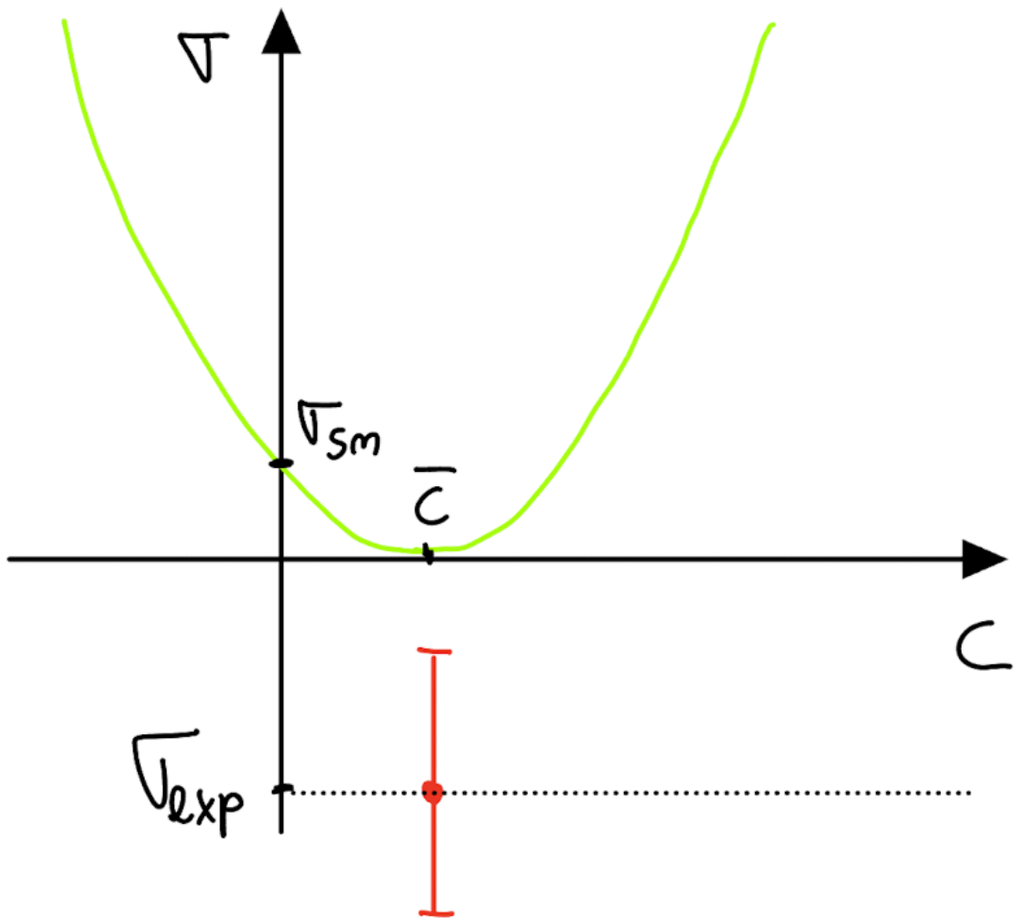

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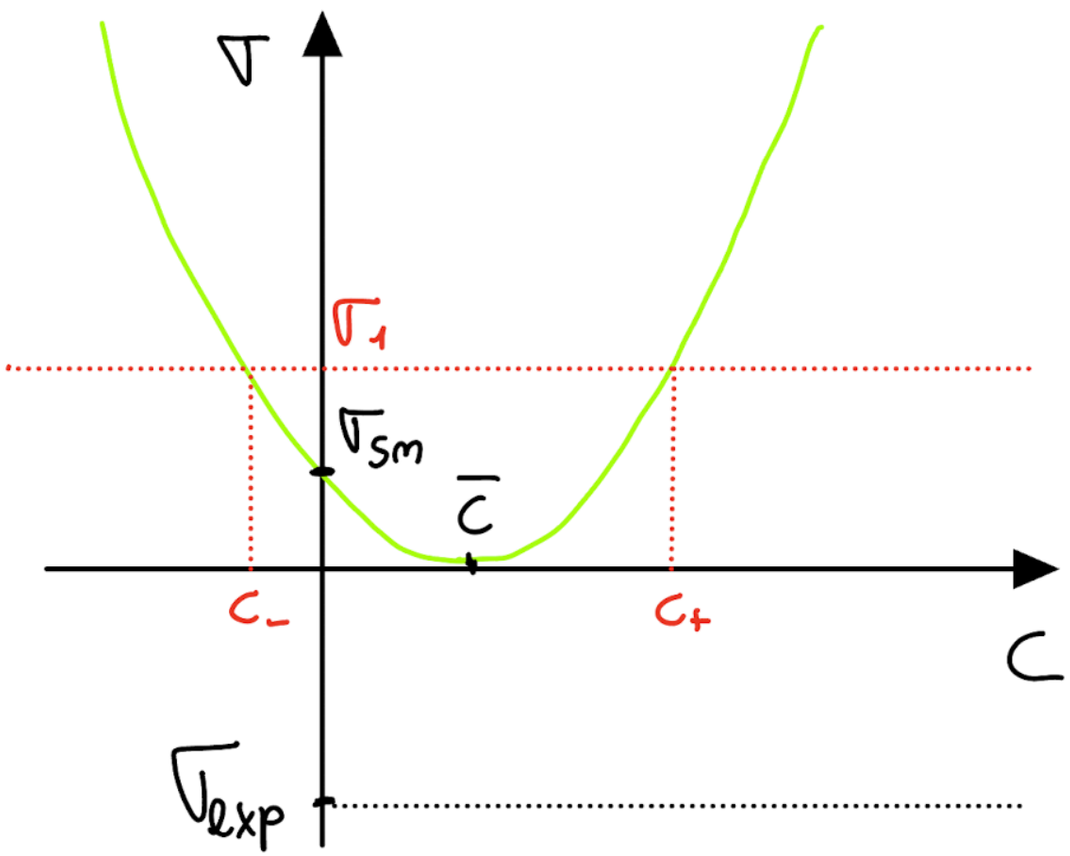
Monte Carlo replica 1



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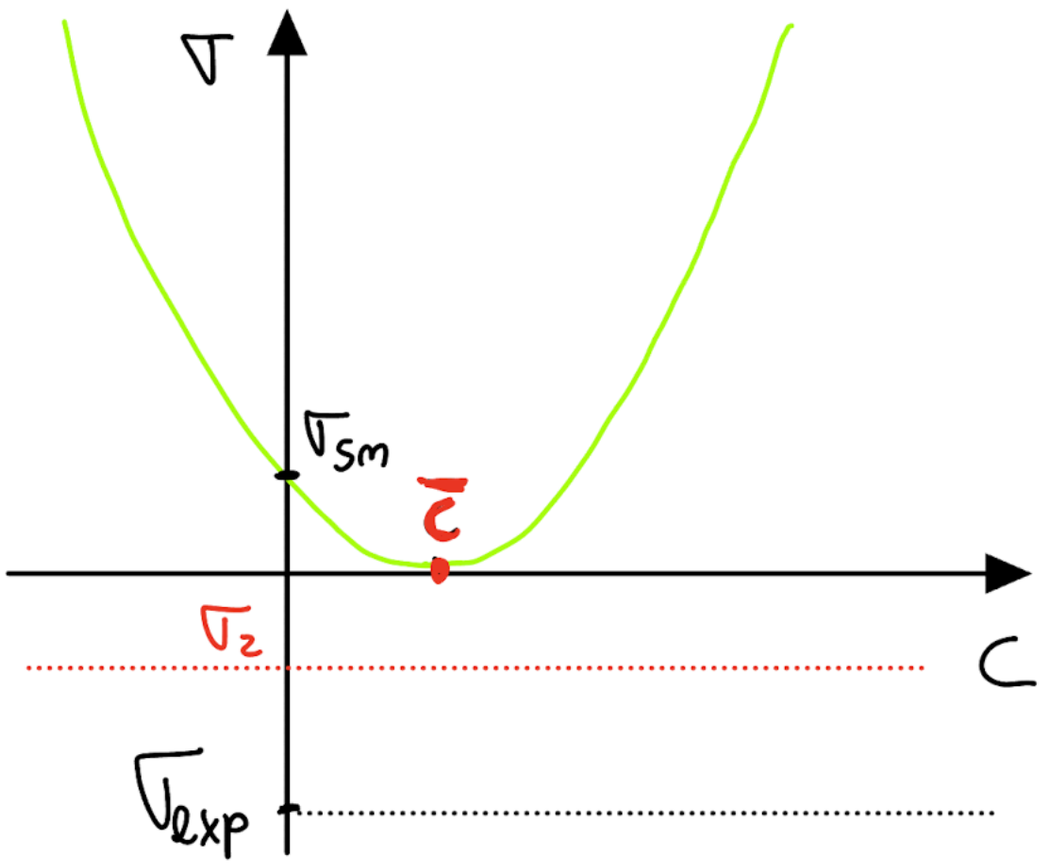
Monte Carlo replica 2



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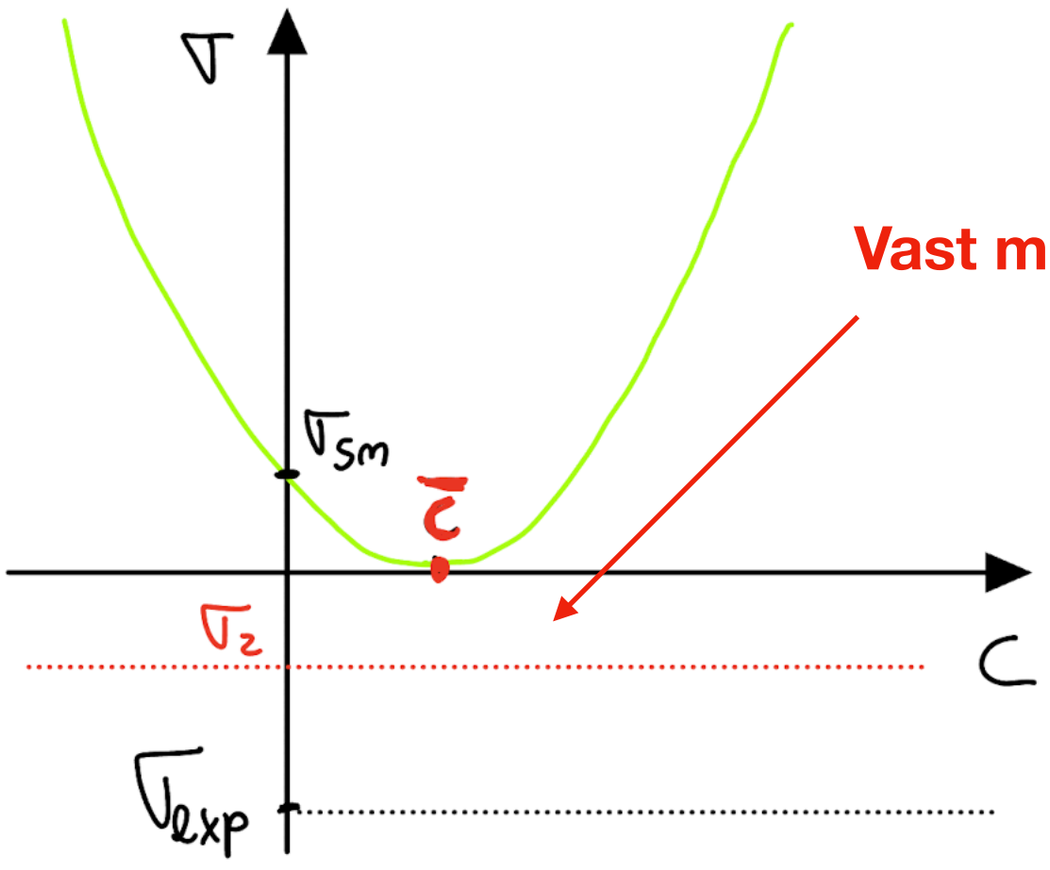

Vast majority

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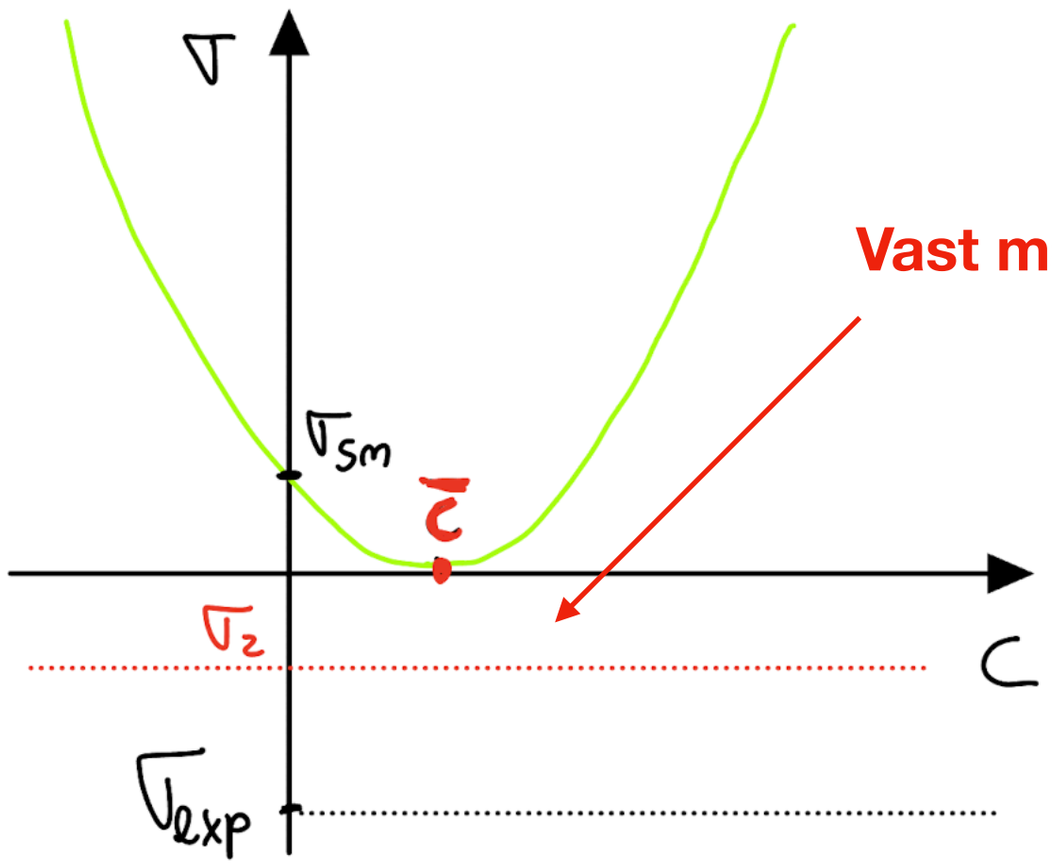
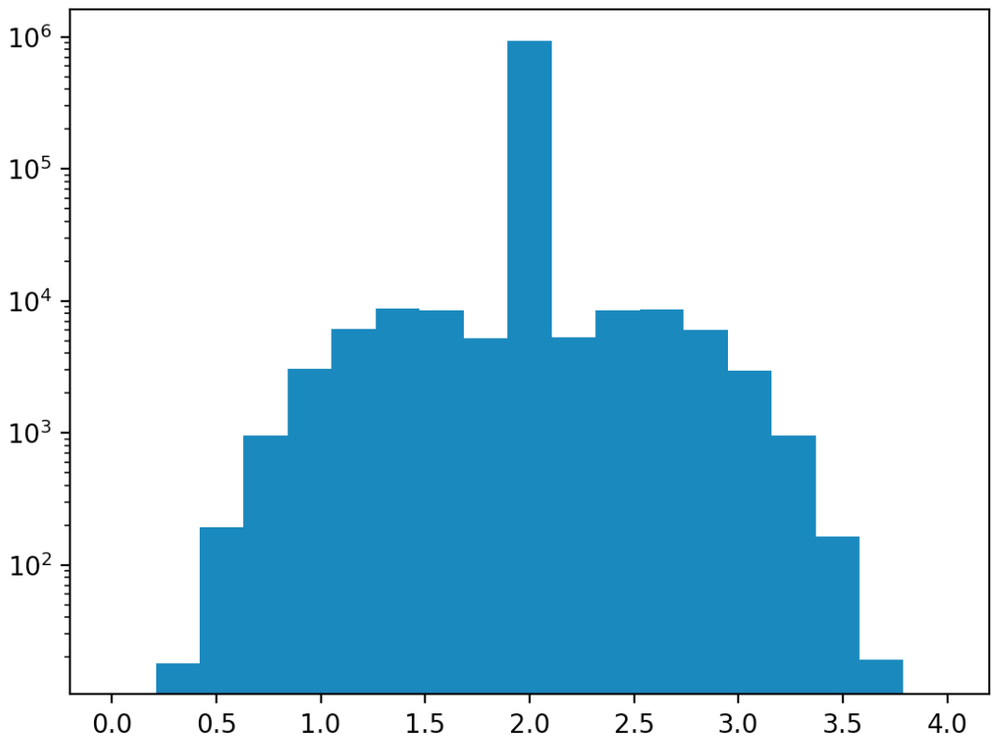


Vast majority

Computed bounds completely wrong:
the spike dominates



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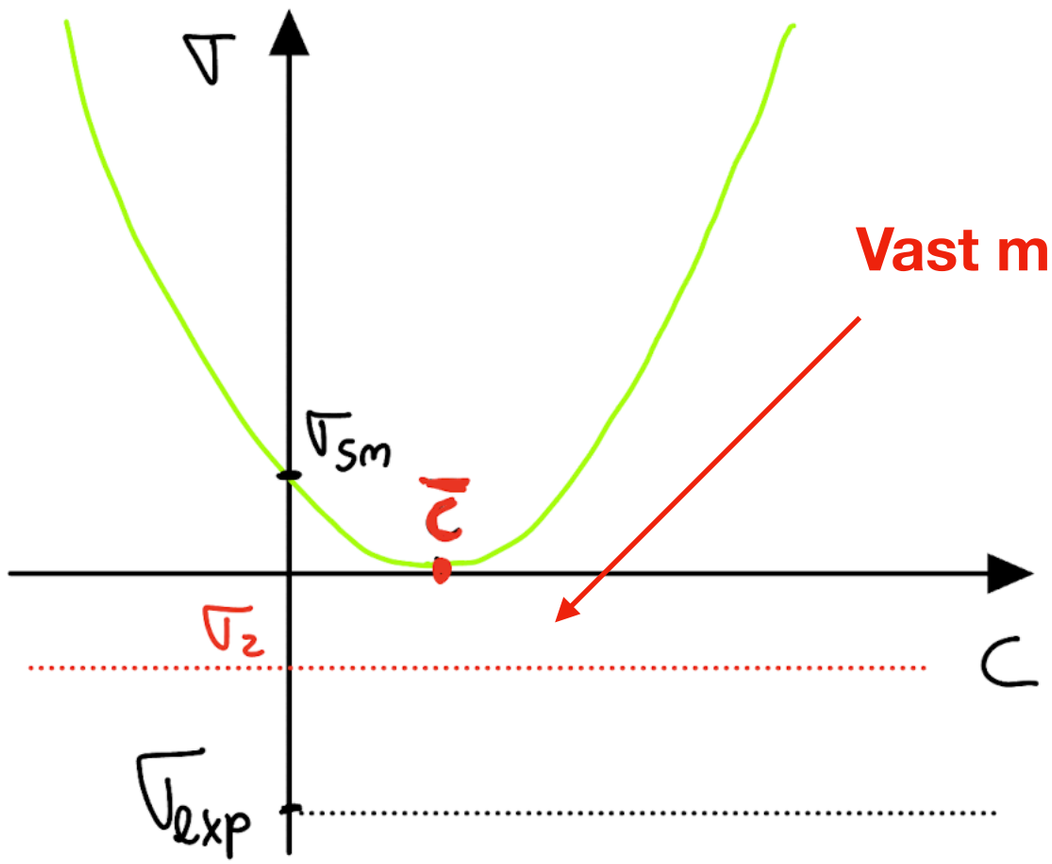

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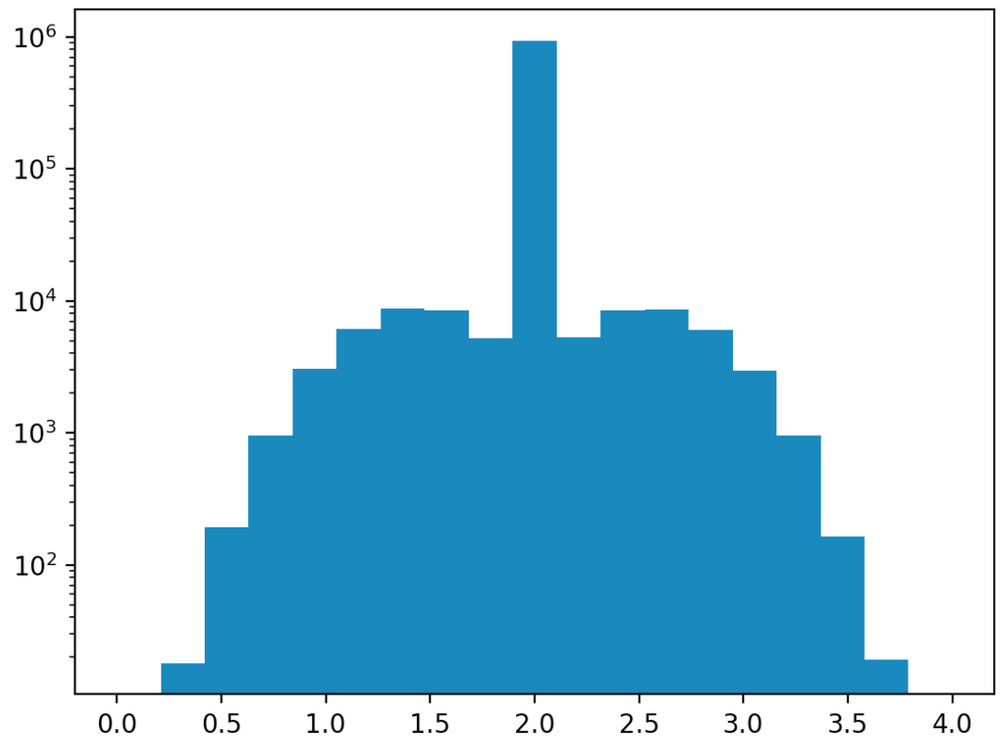

Different approach is needed

- ❖ PDF fitting is currently done by assuming the SM. This could lead to problems in estimation of NP parameters.
- ❖ The **SMEFT** is a powerful framework to parametrise NP, but global studies are necessary.
- ❖ Interplay PDFs-EFT needs to be understood, could be crucial in HL-LHC.
  - NP effects can be at least partially absorbed during PDF fits
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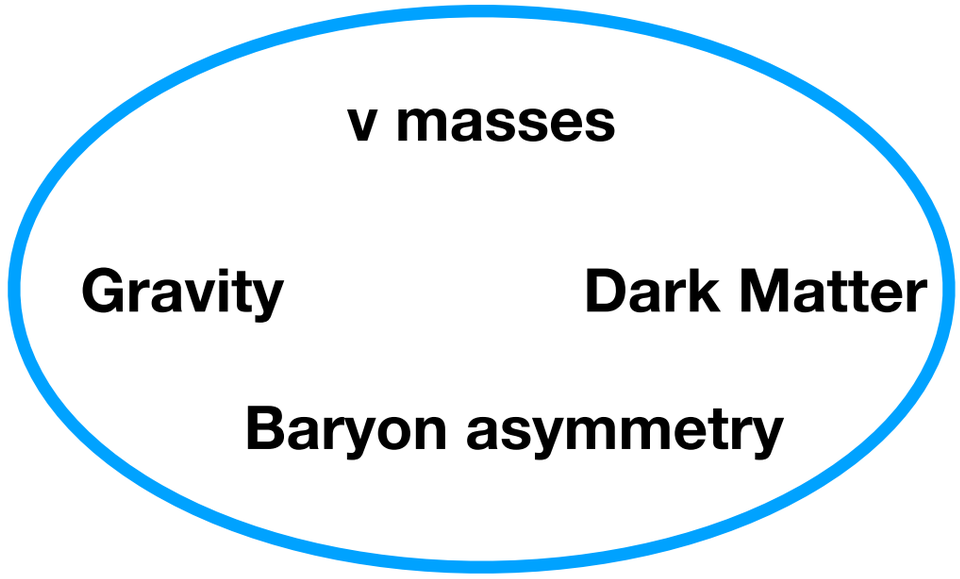
Thanks!

Backup

The SM does not explain everything.



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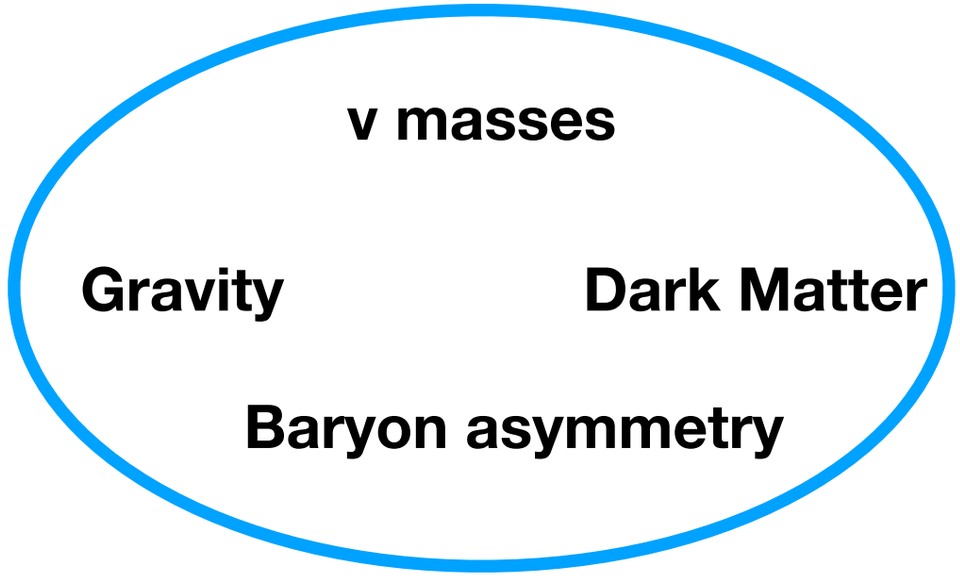

We look for New Physics or BSM to explain the deficiencies.

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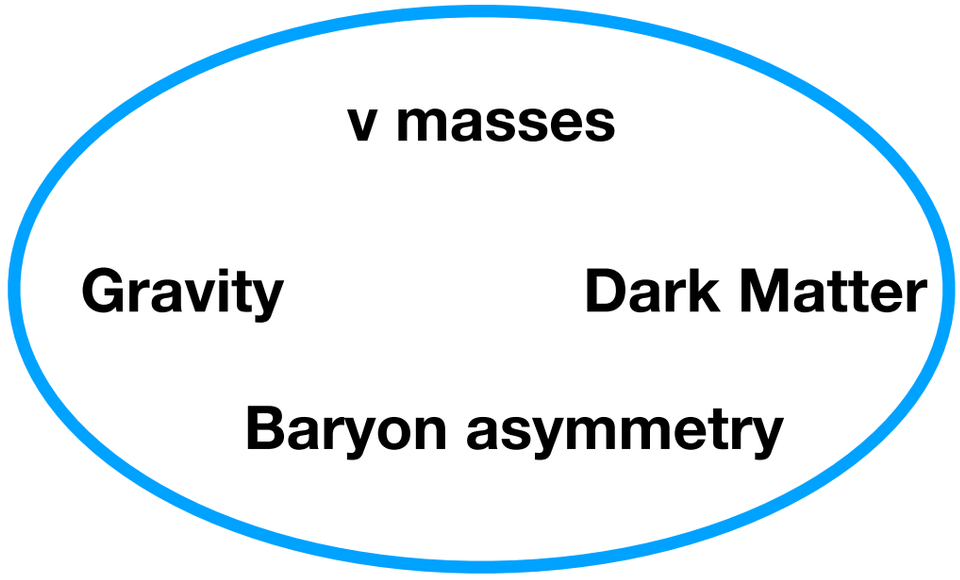

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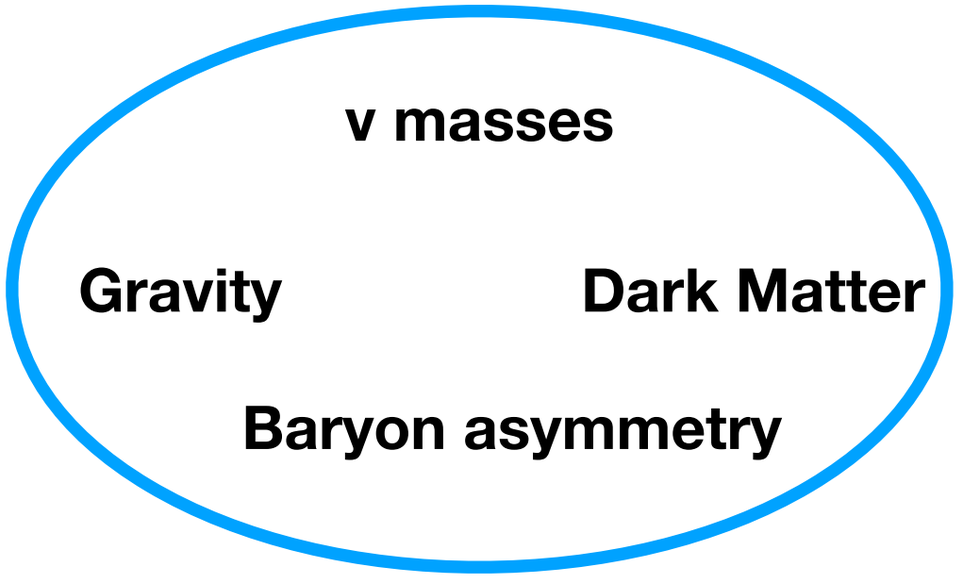

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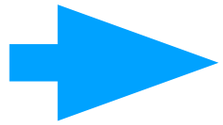
Where do we go from here?

LHC operations started around 2010



(16 zeros)
1000000000000000 proton collisions!!

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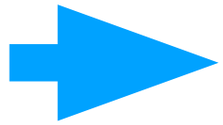

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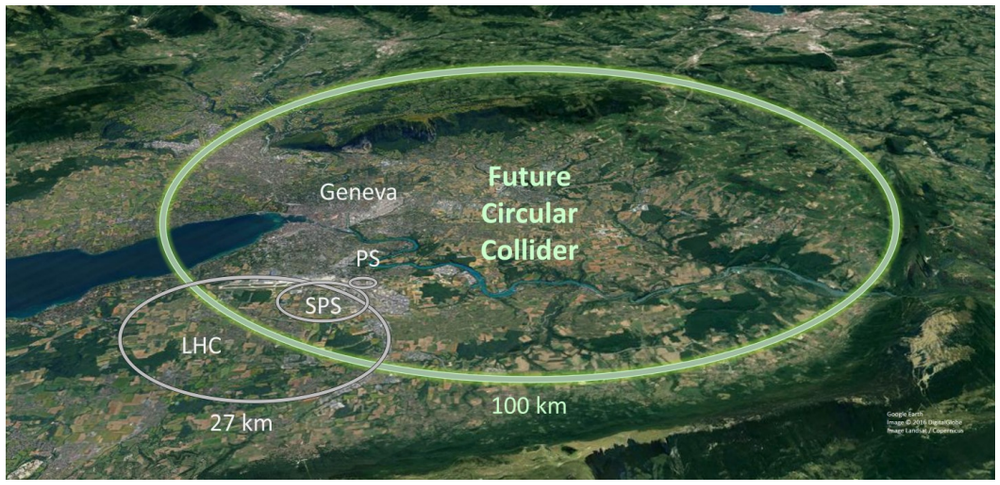

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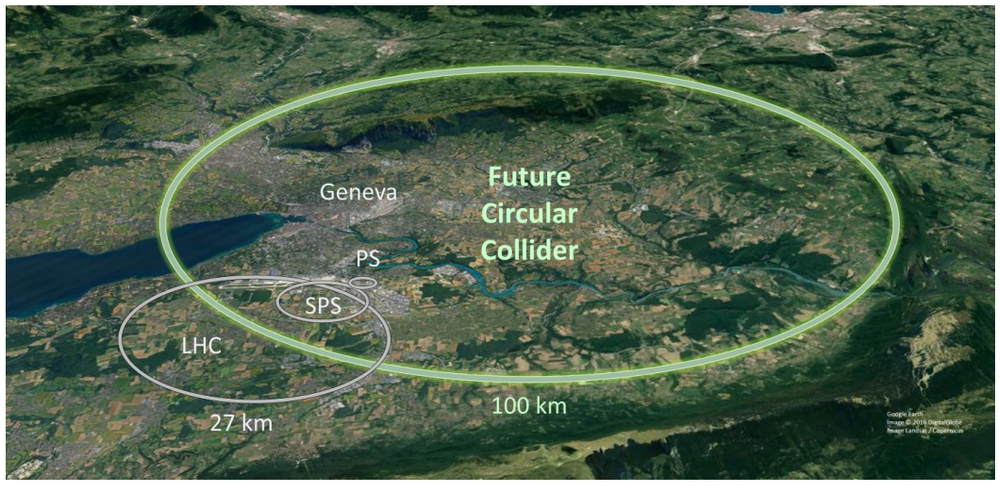

Many years to wait…
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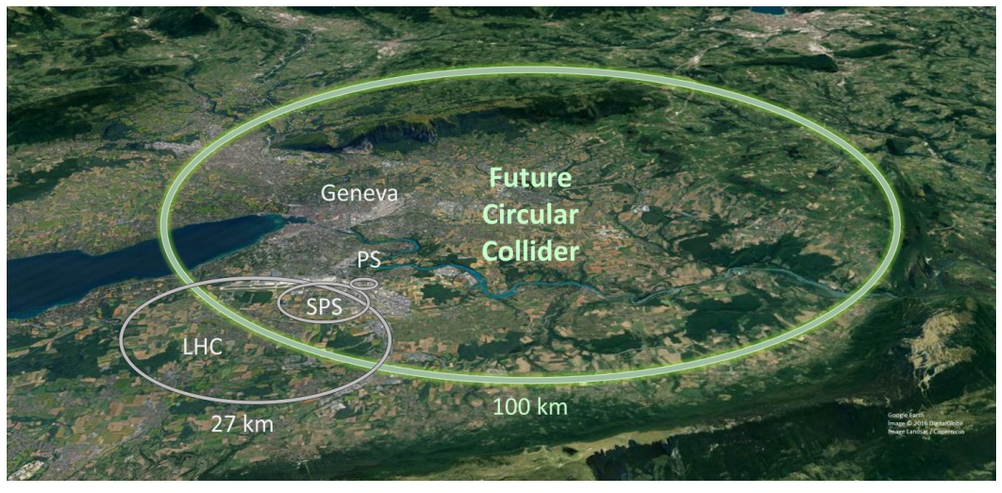

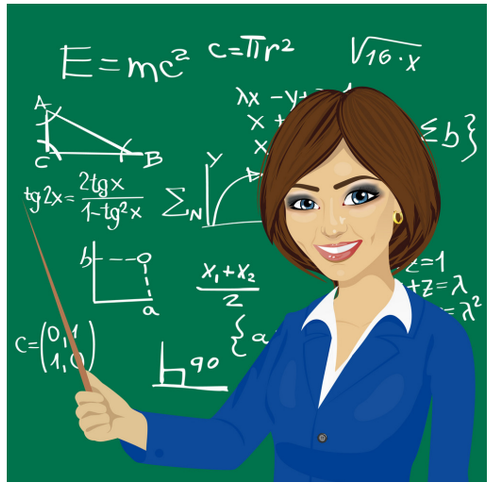

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Precise measurements

Accurate calculations

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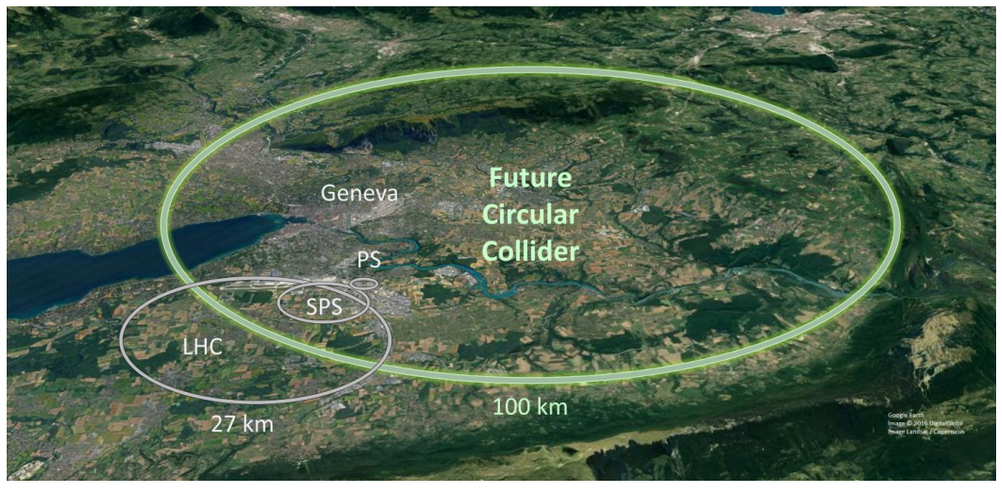

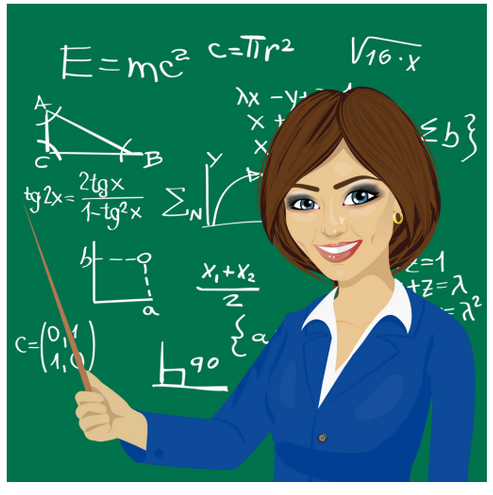

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Indirect discovery!

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New particles being exchanged in collisions

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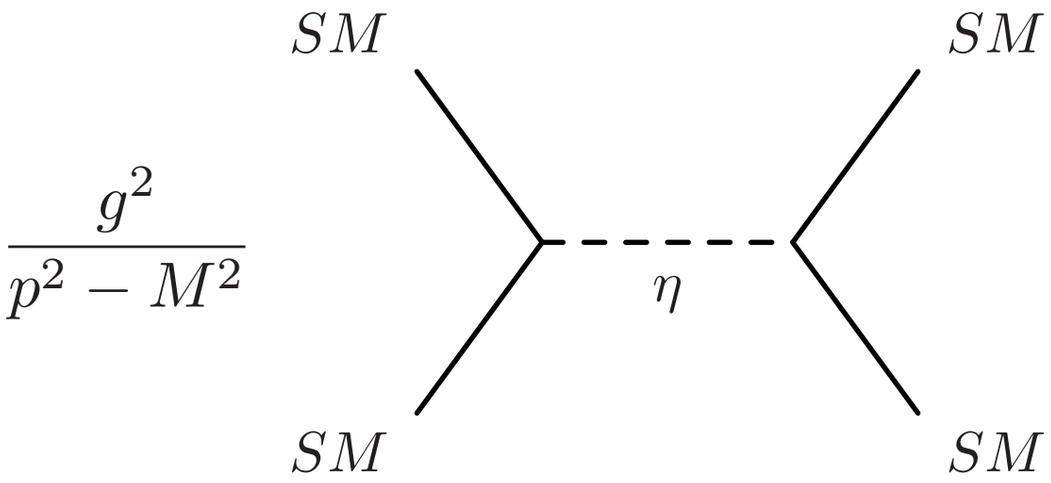

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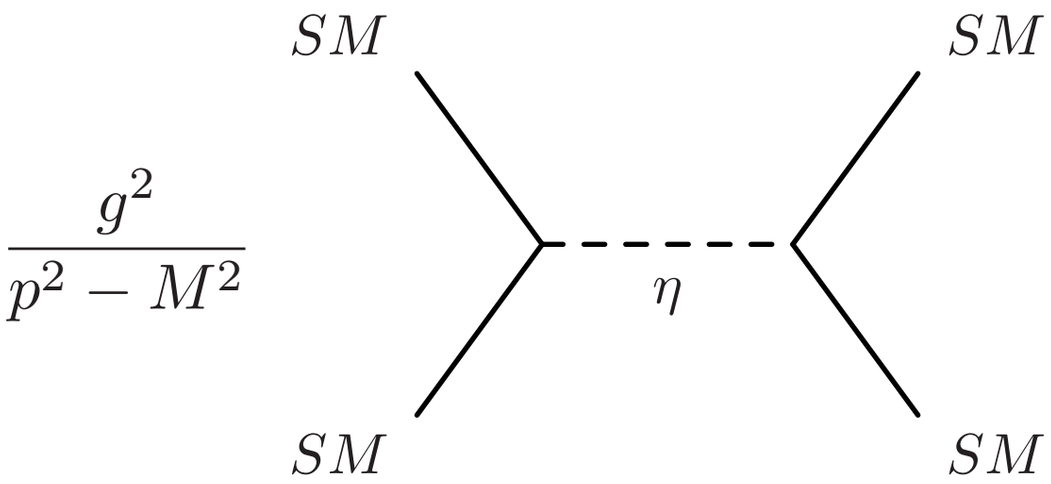

$$\frac{g^2}{p^2 - M^2}$$

$$M \equiv \Lambda$$
$$p^2 \ll \Lambda^2$$

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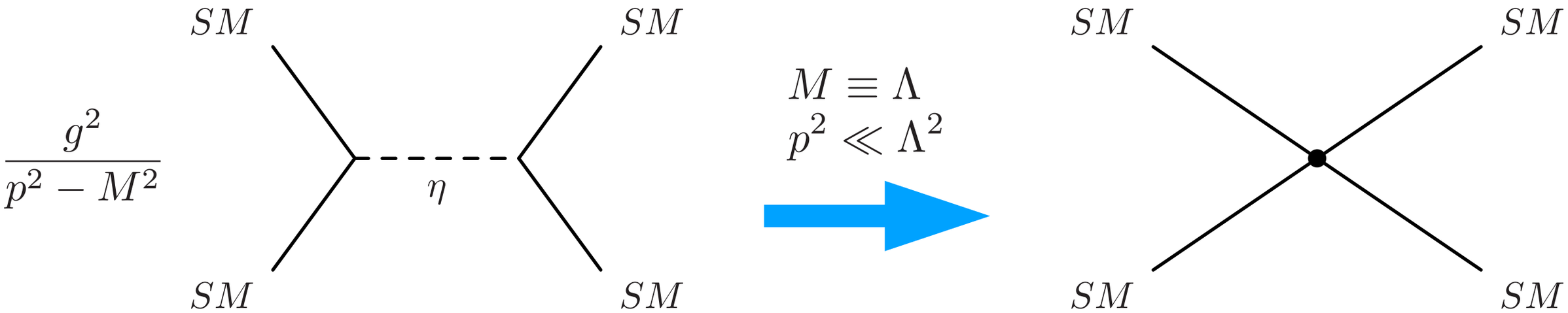

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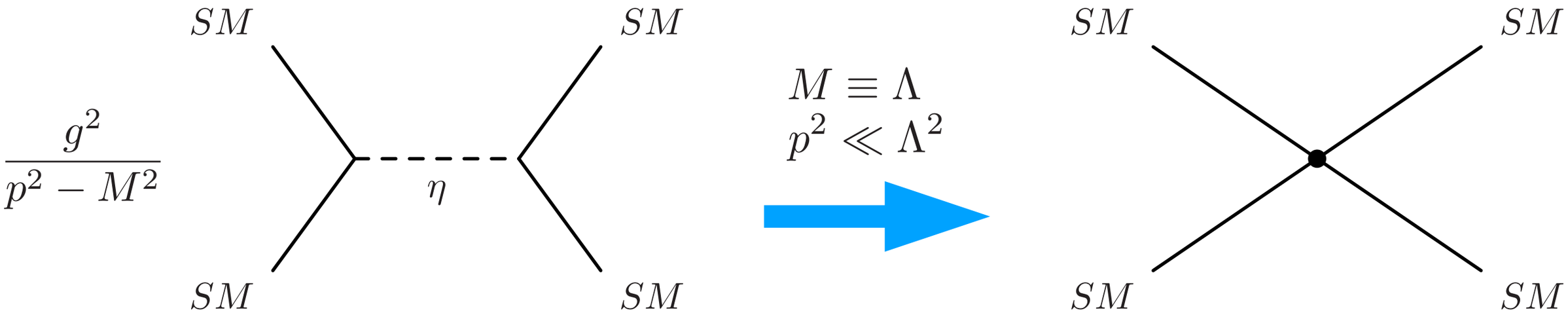

Interaction can be described without explicit presence of new states!

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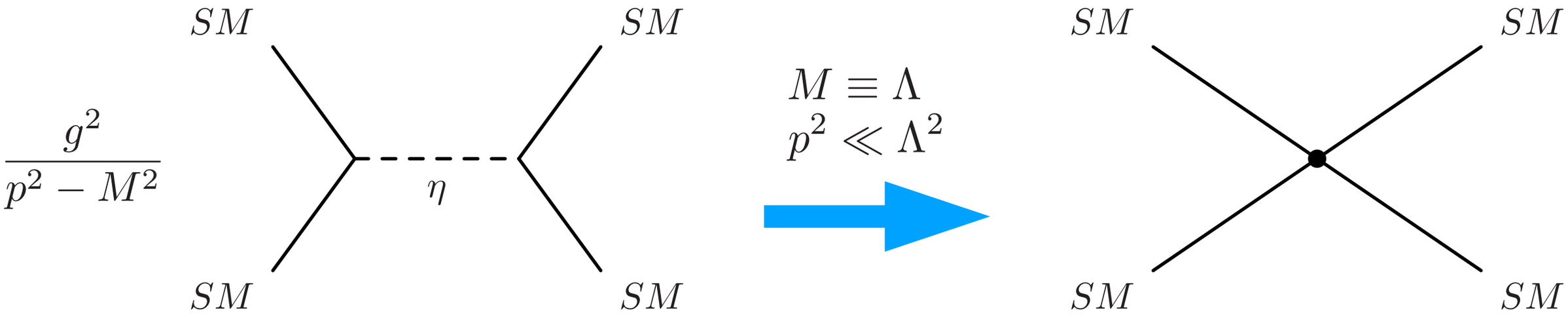

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New framework → **Effective Field Theory**

SMEFT fits are highly dependent on several input assumptions

Flavour assumptions

EW input scheme

EFT truncation

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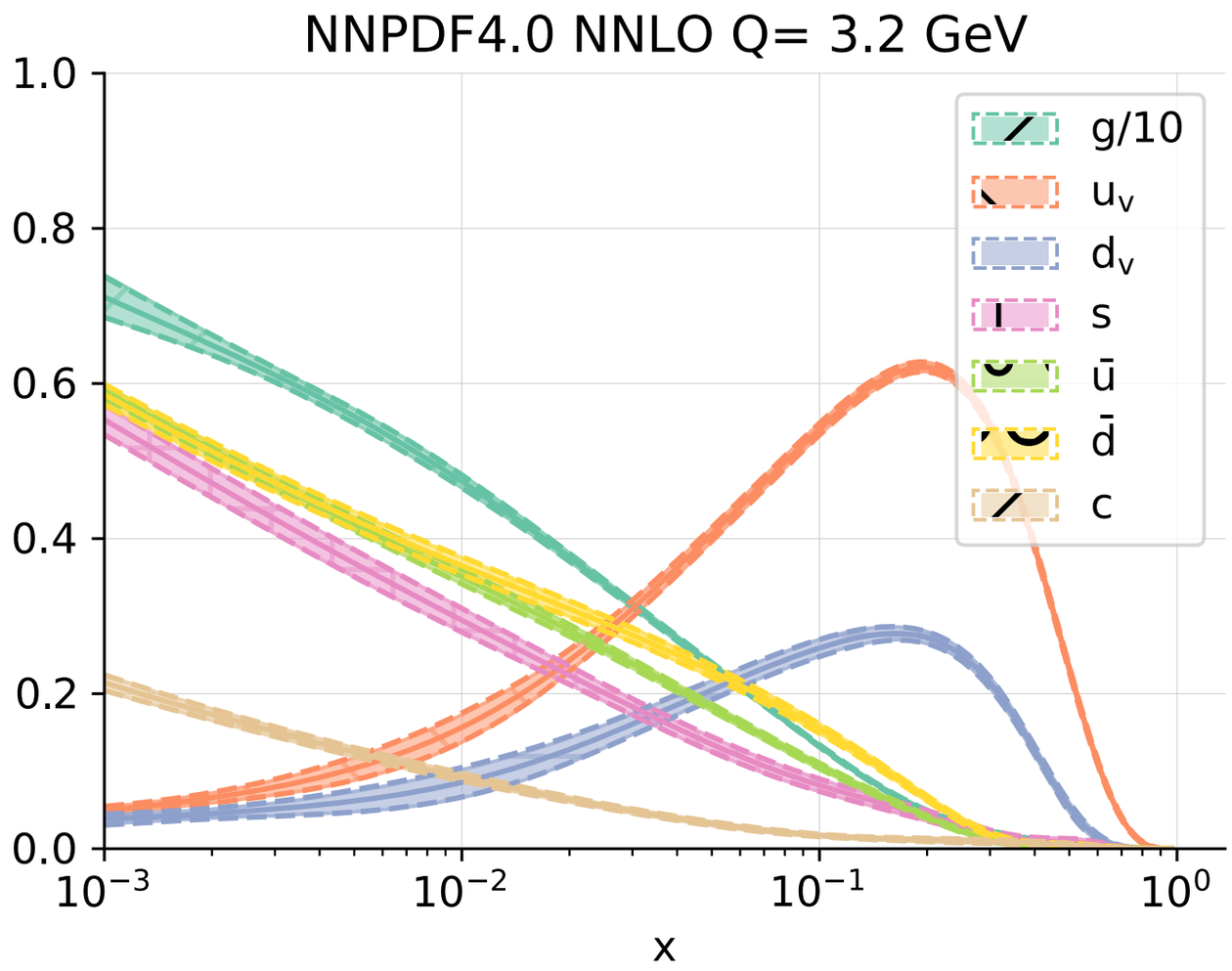
Parton distribution functions



Ball et. al, NNPDF4.0, 2109.02653

Particularly interesting sector: **Drell-Yan**

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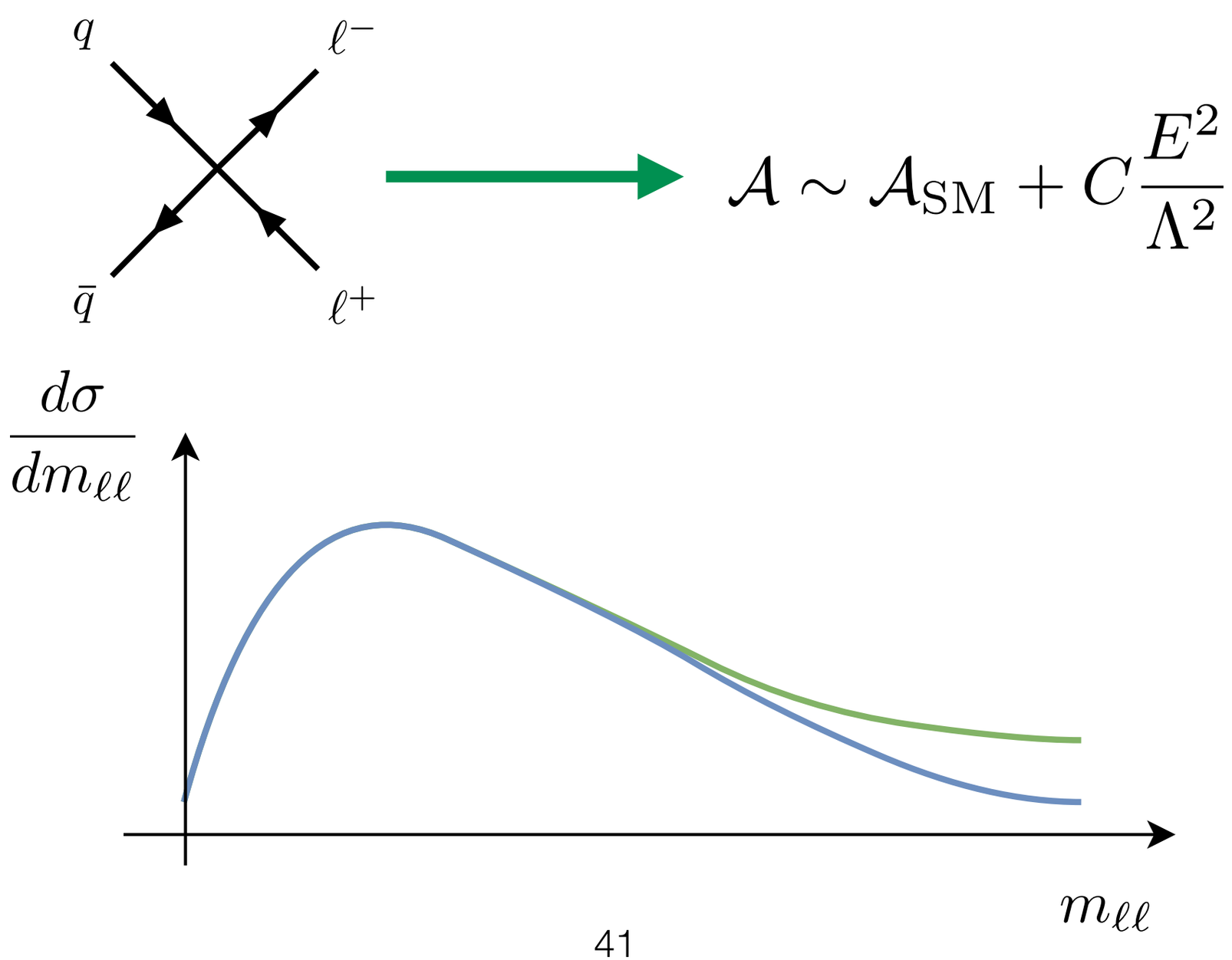

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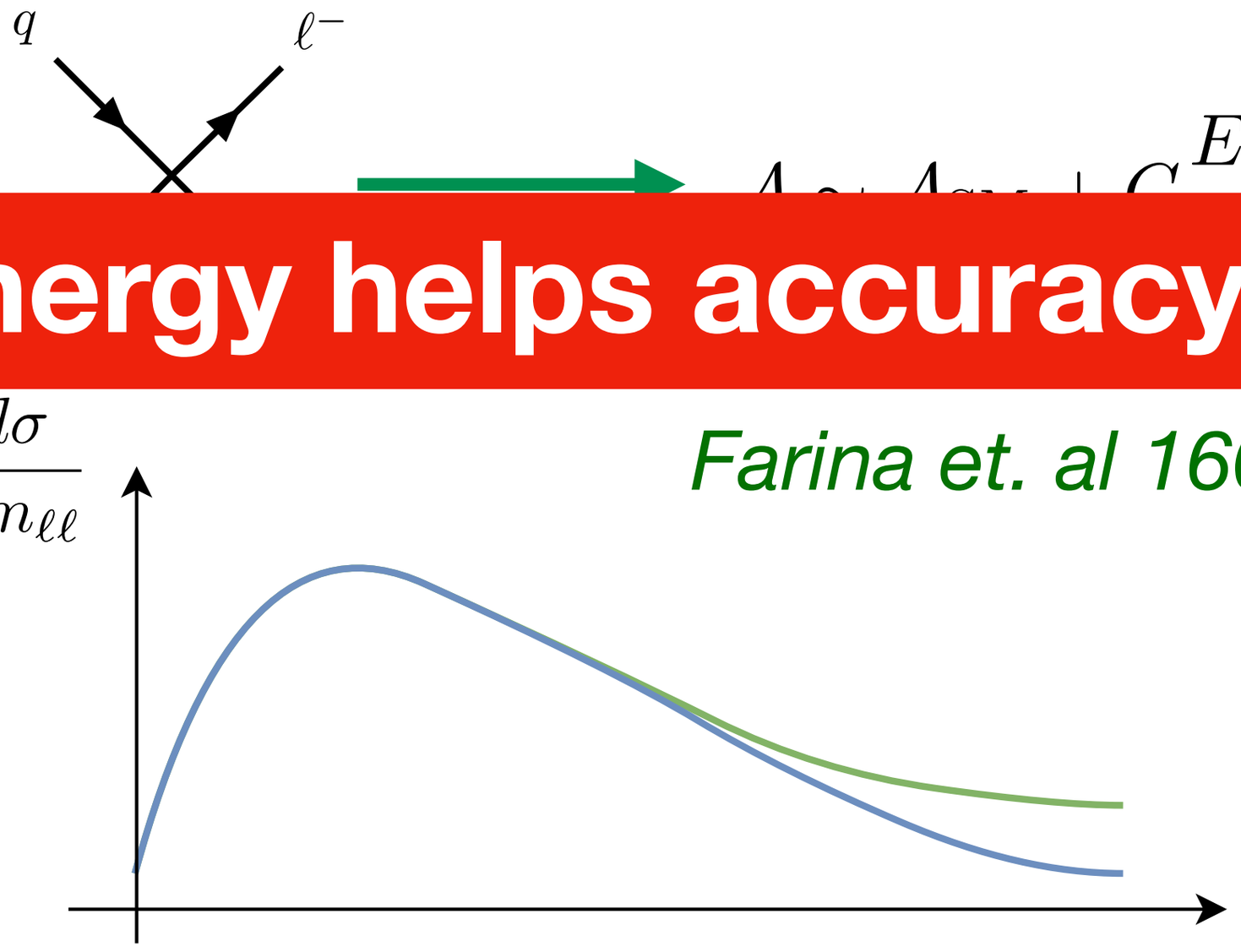

Energy helps accuracy

Farina et. al 1609.08157