Beyond the Standard Proton

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Jefferson Lab

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PBSP

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Talk overview

1. PDFs: a lightning introduction

2. PDF fitting

3. Joint PDF-SMEFT fits

4. The dark side of the proton

1. - PDFs: a lightning introduction

Hadron structure through PDFs

- Hadrons are **QCD bound states** - they are **strongly-coupled, non-perturbative** objects.

$$\mathscr{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \sum_q \bar{q}(i\gamma_\mu D^\mu - m_q) q \longrightarrow$$ **hadrons?**

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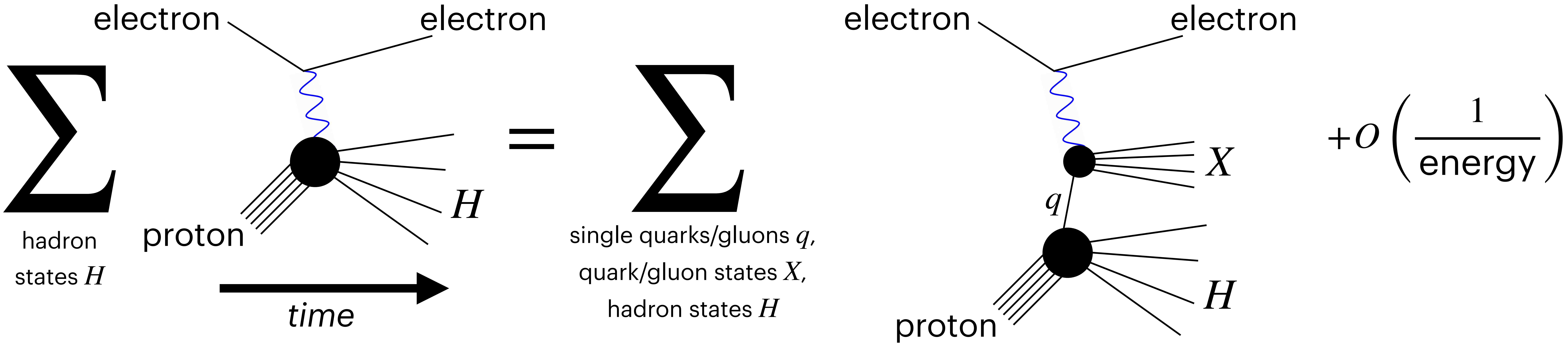
- But we still want to make predictions for experiments involving hadrons!
- **Solution:** package all non-perturbative elements into unknown functions, called **parton distribution functions (PDFs)**.

Factorisation theorems

- This is formalised through **factorisation theorems.**
- Model case: **deep inelastic scattering**, $e^- + \text{proton} \rightarrow e^- + \text{any hadron}$.



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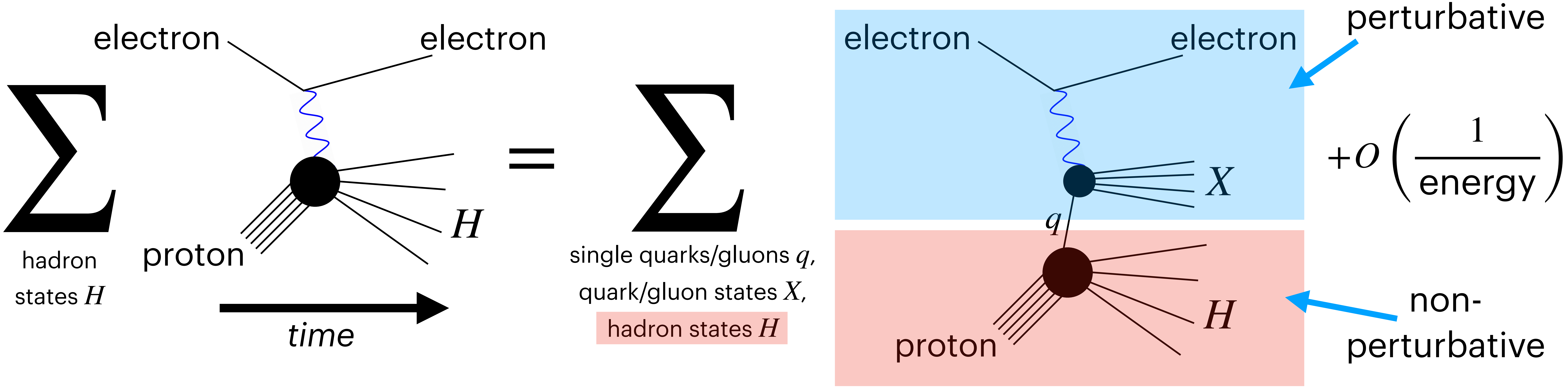

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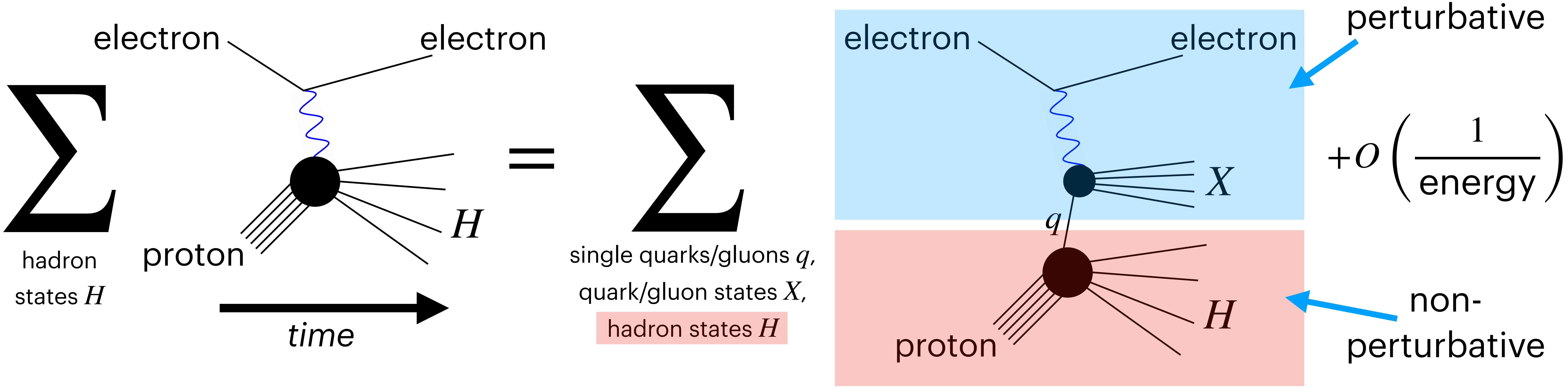
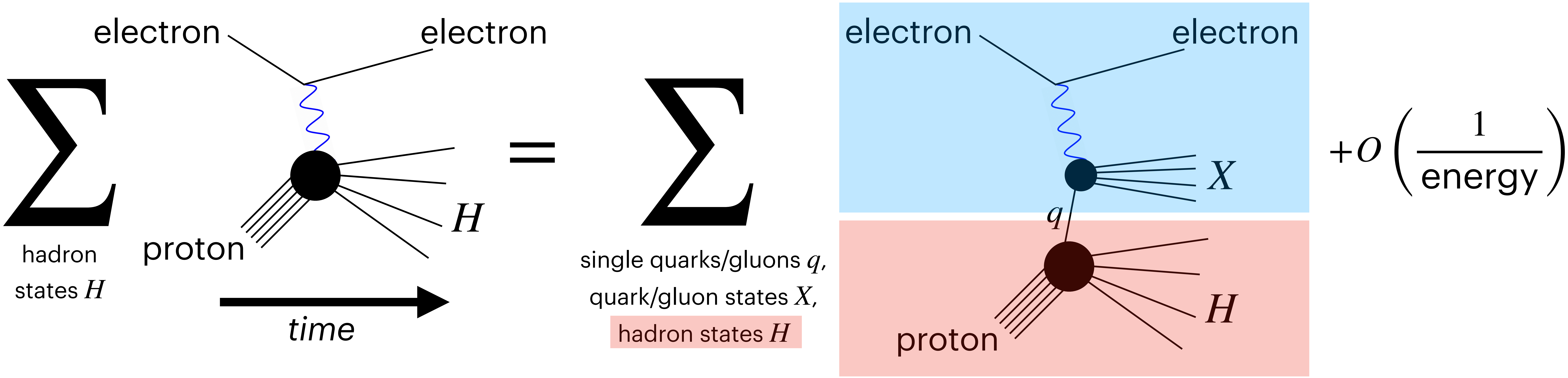


- The calculation is split into a **perturbative process-dependent part,** and a **non-perturbative, BUT universal, parton distribution function**.

Factorisation theorems



In maths… $$\sigma(x, Q^2) = \sum_{\text{single quarks/gluons } q,\ \text{quark/gluon states } X} \int_x^1 \frac{dy}{y} \hat{\sigma}_{eq\to eX}\left(\frac{x}{y}, Q^2\right) f_q(y, Q^2) + O\left(\frac{1}{\text{energy}}\right)$$

Mellin convolution

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  - An **energy scale** Q^2 (comes from **absorbing collinear divergences**)
  - The fact we are colliding **protons** - if we started with a neutron, we would need different PDFs

Universality of PDFs

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Scaling of PDFs

- Whilst the PDFs are non-perturbative, we can still say something about their Q^2-dependence, which enters the PDFs when we **absorb collinear IR divergences**.

- Just as in **standard UV renormalisation theory**, this leads to a Callan-Symanzik equation for the PDFs called the **DGLAP equation**:

$$Q^2 \frac{\partial f_q(x, Q^2)}{\partial Q^2} = \sum_{\text{quarks/gluons } q'} \int_x^1 \frac{dy}{y} P_{qq'}\left(\frac{x}{y}\right) f_{q'}(x, Q^2)$$

- The functions (technically distributions) $P_{qq'}$ are called **splitting functions** and can be determined perturbatively.

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- This means if we know the PDFs at some **initial energy scale** Q_0, we can compute them at some energy scale $Q > Q_0$ by solving DGLAP.
- In particular, only the x-dependence of the PDFs is truly **unknown**.
- We can obtain this x-dependence by **fits to collider data**, as we shall now describe...

Summary of PDFs

- The **non-perturbative structure** of hadrons can be parametrised by **parton distribution functions** $f_q(x, Q^2)$, which depend only on the **type of hadron** being collided, **not** on the process.

- The PDFs have **known** Q^2**-dependence**, described by a linear system of **integro-differential equations** called the **DGLAP equations**.

- The PDFs have **unknown** x**-dependence**, which must be obtained through fits to experimental data.

2. - PDF fitting

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- Example functional form:

$$f(x, Q_0^2) = Ax^{\alpha}(1-x)^{\beta}\left(1 + ax^{1/2} + bx + cx^{3/2}\right)$$

large and small x behaviour motivated by **Regge theory**

polynomial in $\sqrt{x}$

How to make PDFs...

- The best-fit parameters are found by **minimising the χ^2-statistic**, which measures the **goodness of fit** of our model:

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- *General idea*: we want **theory to be close to data**, but if the data is **more uncertain**, we don't require such precise agreement.

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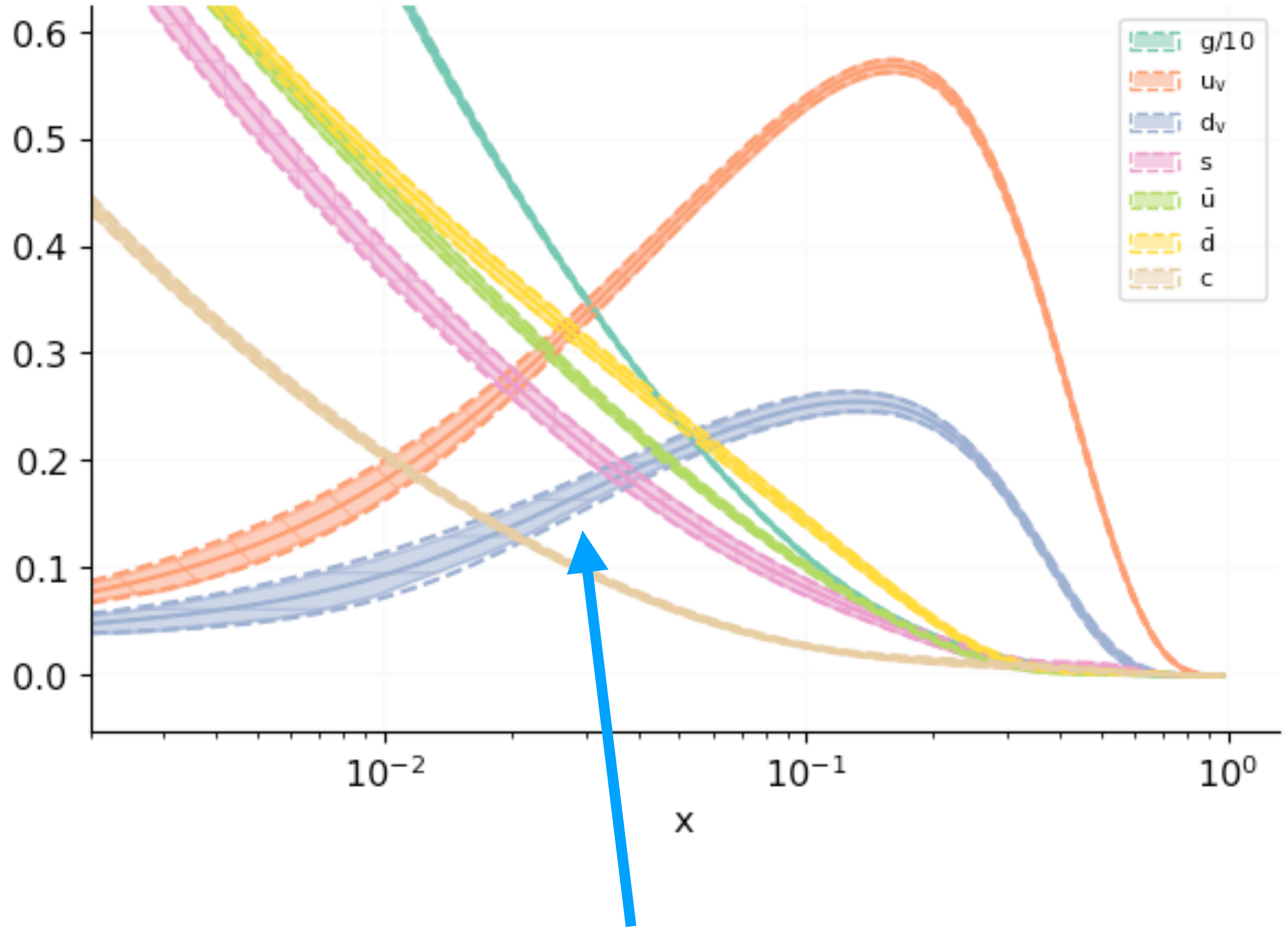

PDFs with error bands

The choice of functional form

- The choice of functional form that we have suggested so far is:

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- This seems a bit arbitrary though! To try to remove as much **bias** as possible, another possible choice is to parametrise the PDFs using a **neural network** instead:

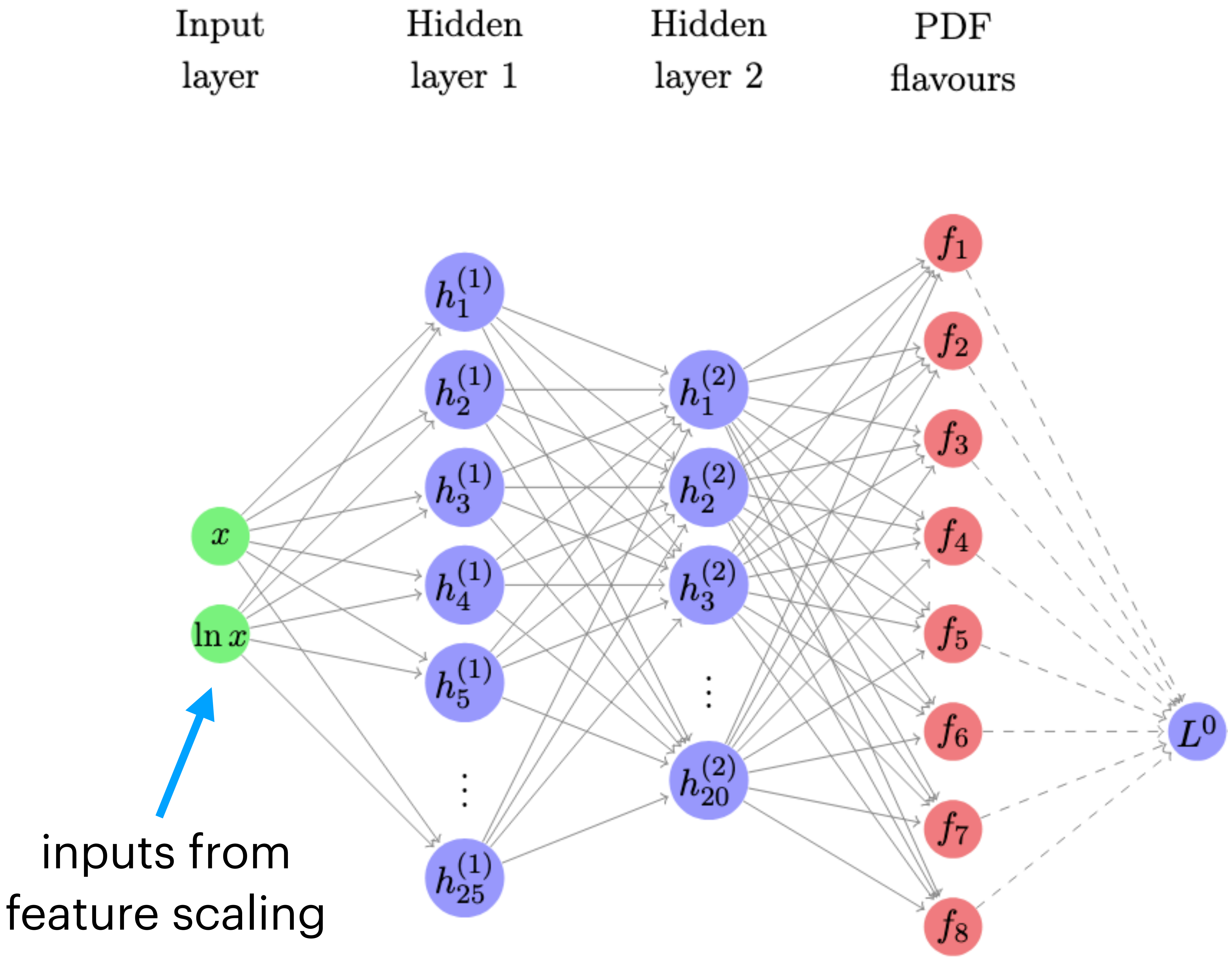
$$f(x, Q_0^2) = Ax^{\alpha}(1-x)^{\beta}\mathrm{NN}(x, \omega)$$

- Here, $\mathrm{NN}(x, \omega)$ is a **neural network** which takes in x as an argument, and has network parameters ω.

The choice of functional form

$$f(x, Q_0^2) = Ax^{\alpha}(1-x)^{\beta}\mathrm{NN}(x, \omega)$$

- The neural network parametrisation is used by the **NNPDF collaboration**, whose fitting code is **publicly available**.
- *See 2109.02653 and 2109.02671 for details.*



3. - Joint PDF-SMEFT fits

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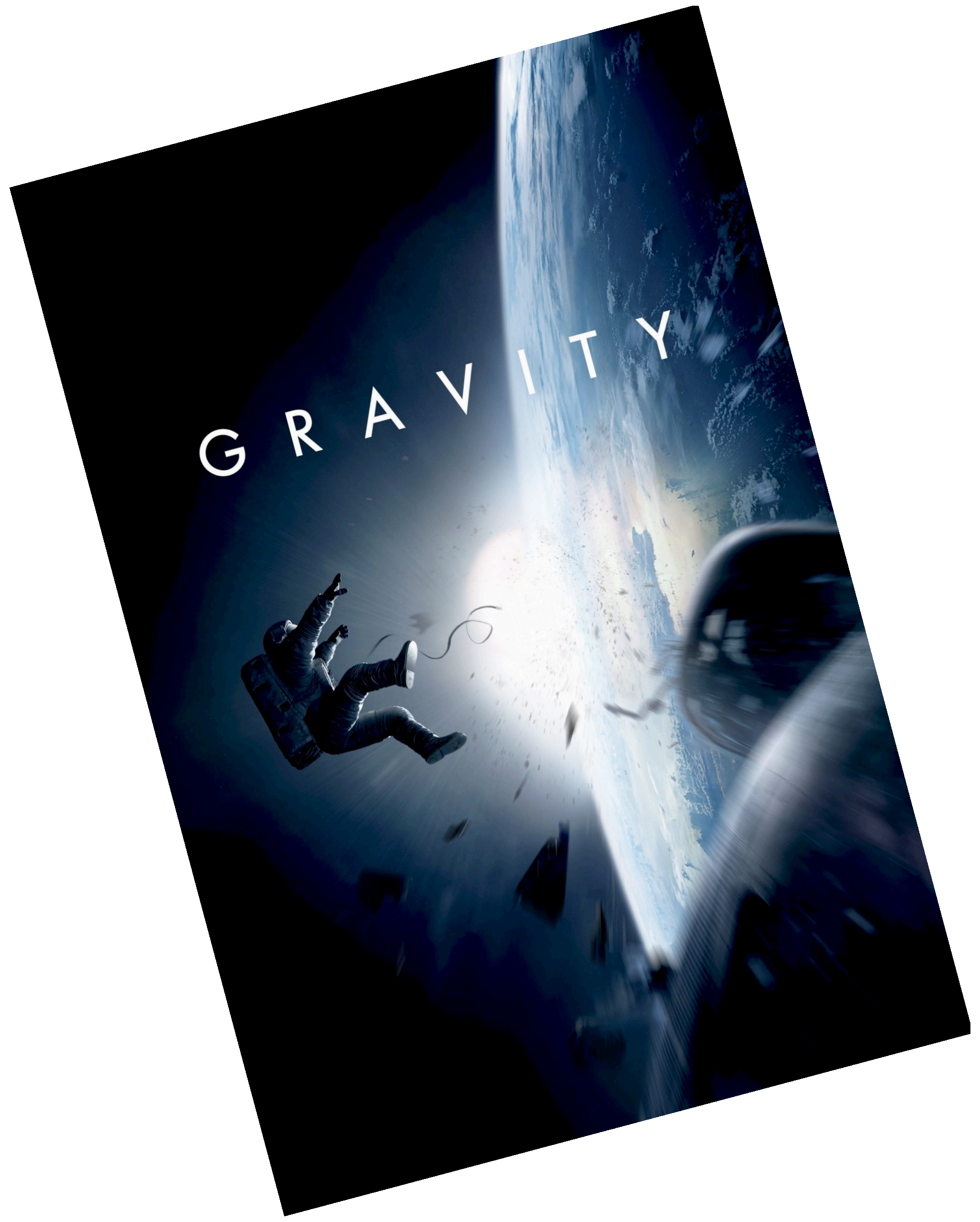

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  - *many more...*

So how do we fix the Standard Model?

- For example, to **include dark matter** in the Standard Model, we might **hypothesise new particles** and add them in. The Standard Model Lagrangian density is augmented to:

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- However, there are **thousands** of possibilities, so just guessing particles seems a bit like **stabbing in the dark**!
- Some models are **more motivated** than others, but it would be nice to have a more general approach...

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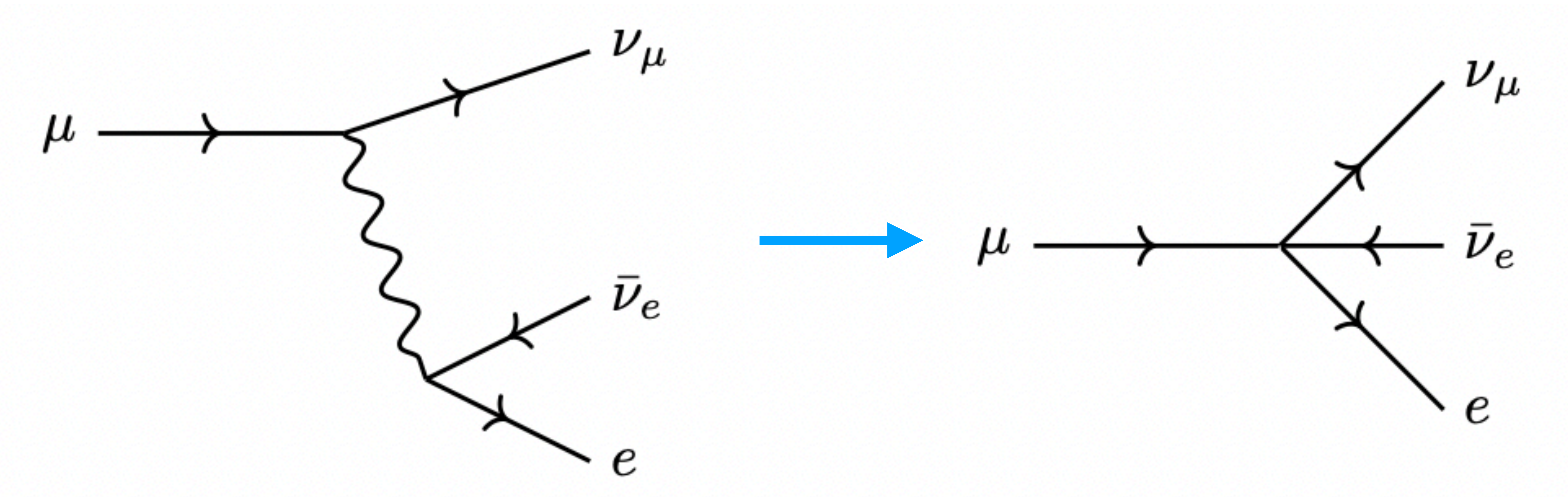
- *Idea*: at **low energies** we can **integrate out heavy particles from a theory**, giving **effective non-renormalisable interactions**:



- Integrating out particles can also yield **shifts in SM couplings**.

Enter the SMEFT…

- Since **any*** heavy particle manifests at low energies as non-renormalisable interactions, if we are hunting for **extensions of the SM**, we can simply **add on all non-renormalisable operators built from the SM fields** (and respecting the SM symmetries):

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- We can organise the additional non-renormalisable operators by their **mass dimension**, with higher-dimensional operators being **suppressed** by **powers of** $1/\Lambda$, where Λ is a characteristic scale of the New Physics.

SMEFT fits

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- However, the number of operators **decreases significantly** if we **assume additional symmetries**, e.g. **no baryon number violation**. There are only **59 operators** if we assume **flavour universality**.
- The main sectors studied so far are: **top**, **Higgs** and **electroweak** physics.

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- Finally, note that various fitting groups **just fit** the SMEFT couplings, for example the **SMEFiT collaboration**, and the **FitMaker collaboration**.
- In particular, SMEFiT and FitMaker both assume a **SM PDF input**. This could be **problematic** because the PDFs were fitted **assuming no New Physics**...

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- Fix SMEFT parameters (usually to zero), $c = \bar{c}$:

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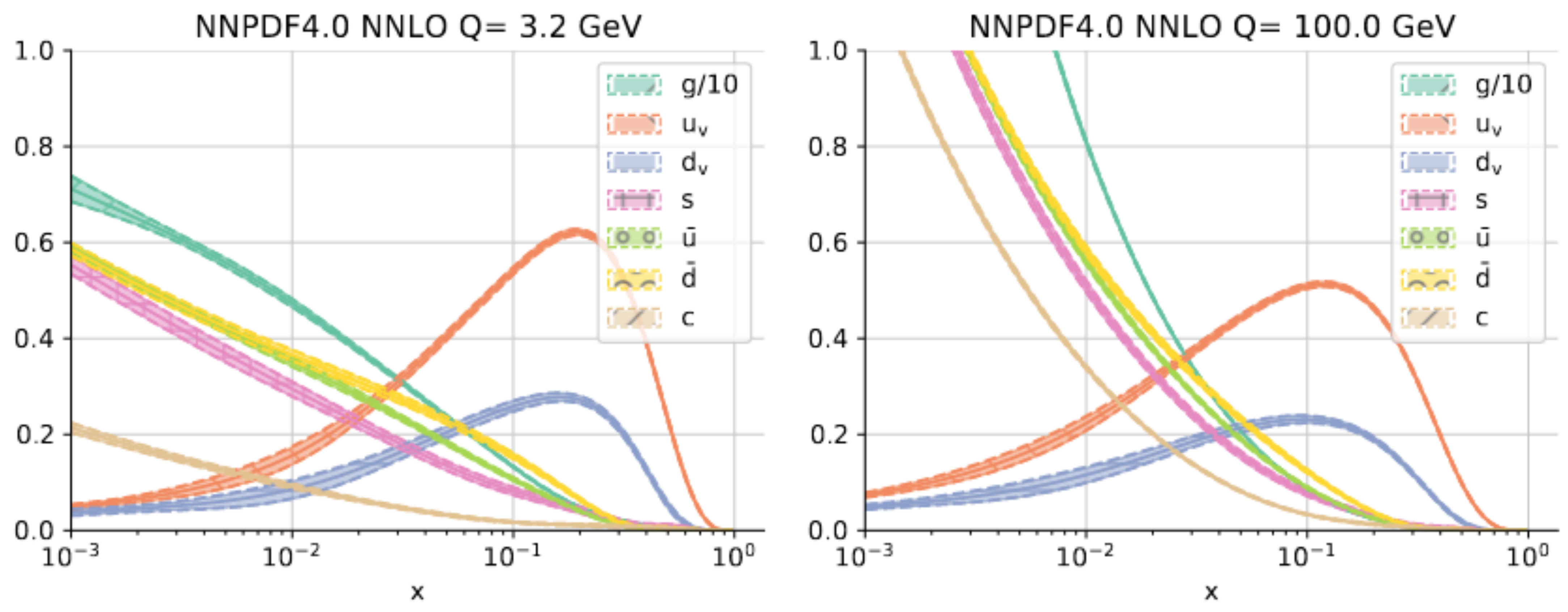

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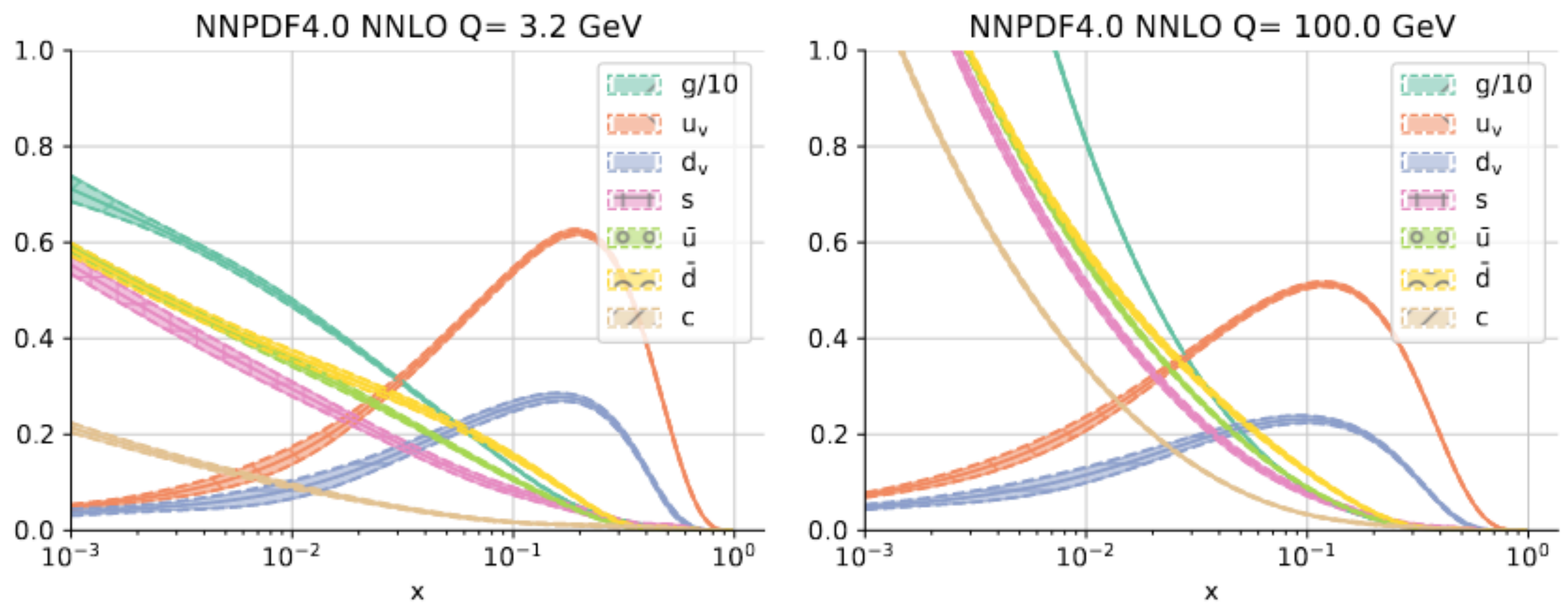

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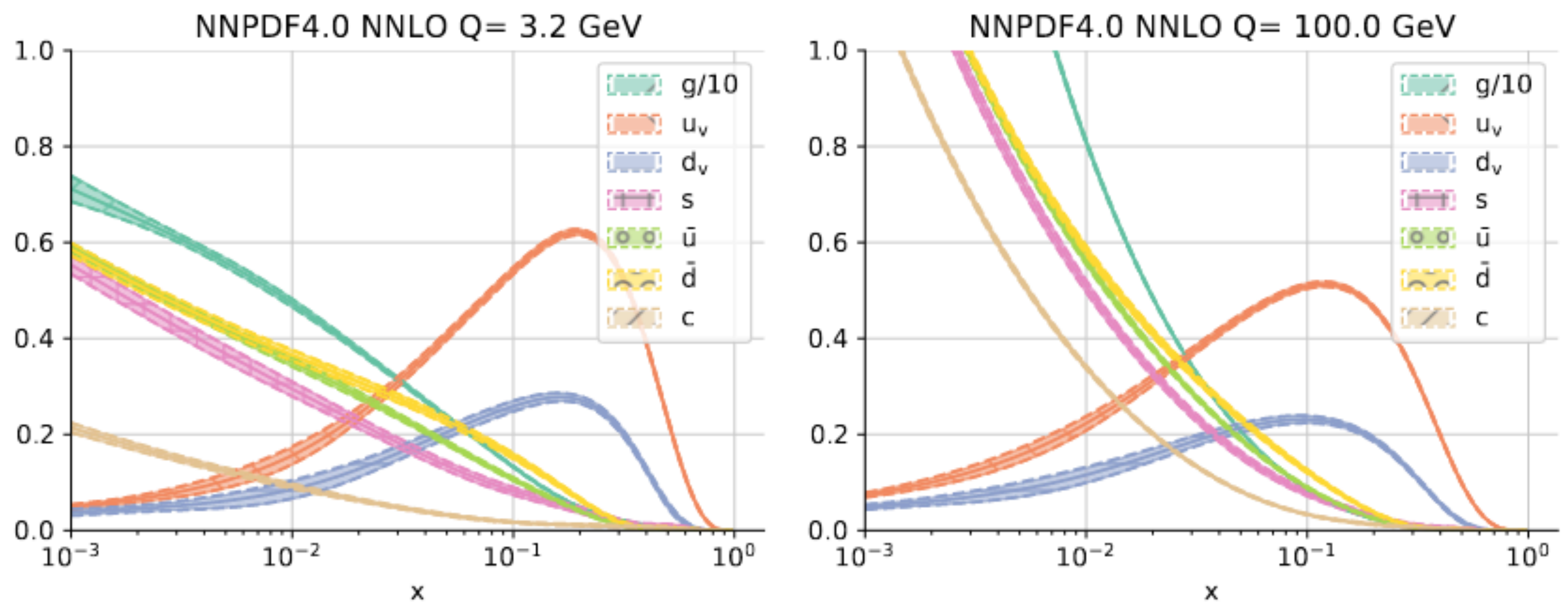

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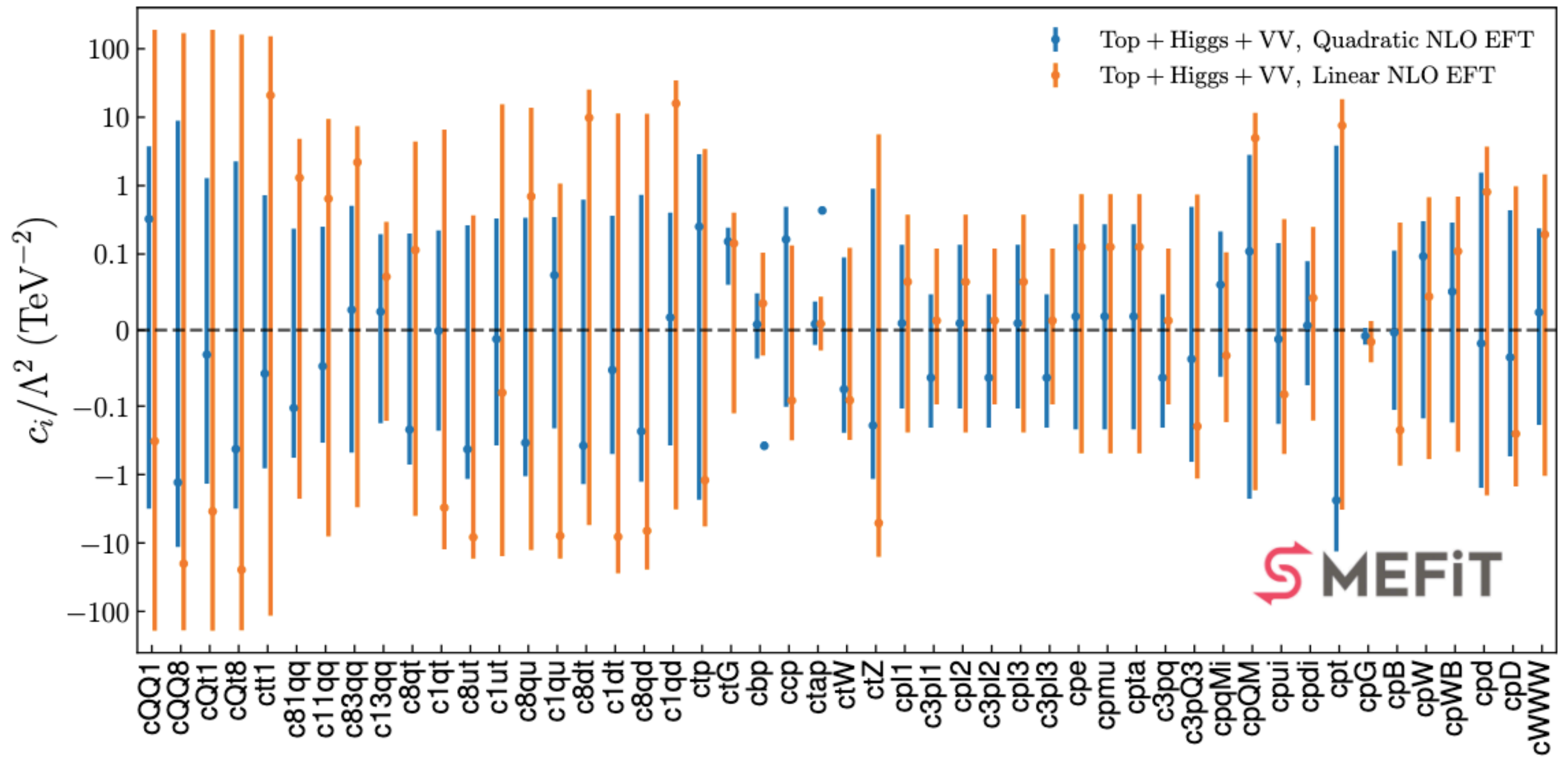

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- **This could lead to inconsistencies.**

PDF parameter fits

$$\text{PDF}(\theta^*) \equiv \text{PDF}(\theta^*(\bar{c}))$$

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- We could even **miss New Physics**, or **see New Physics that isn't really there**!

Key question for remainder of section:

To what extent do bounds on SMEFT parameters change if they are fitted simultaneously with PDF parameters? Is a consistent treatment important?

Simultaneous SM fits

- **This is not a new problem!** It's been known for a while that **simultaneous fits** of **SM parameters** alongside PDFs can be **important** in many cases. In particular, PDF parameters have a **strong correlation** with the **strong coupling** $\alpha_S(m_Z)$ (see e.g. Forte, Kassabov, 2001.04986).

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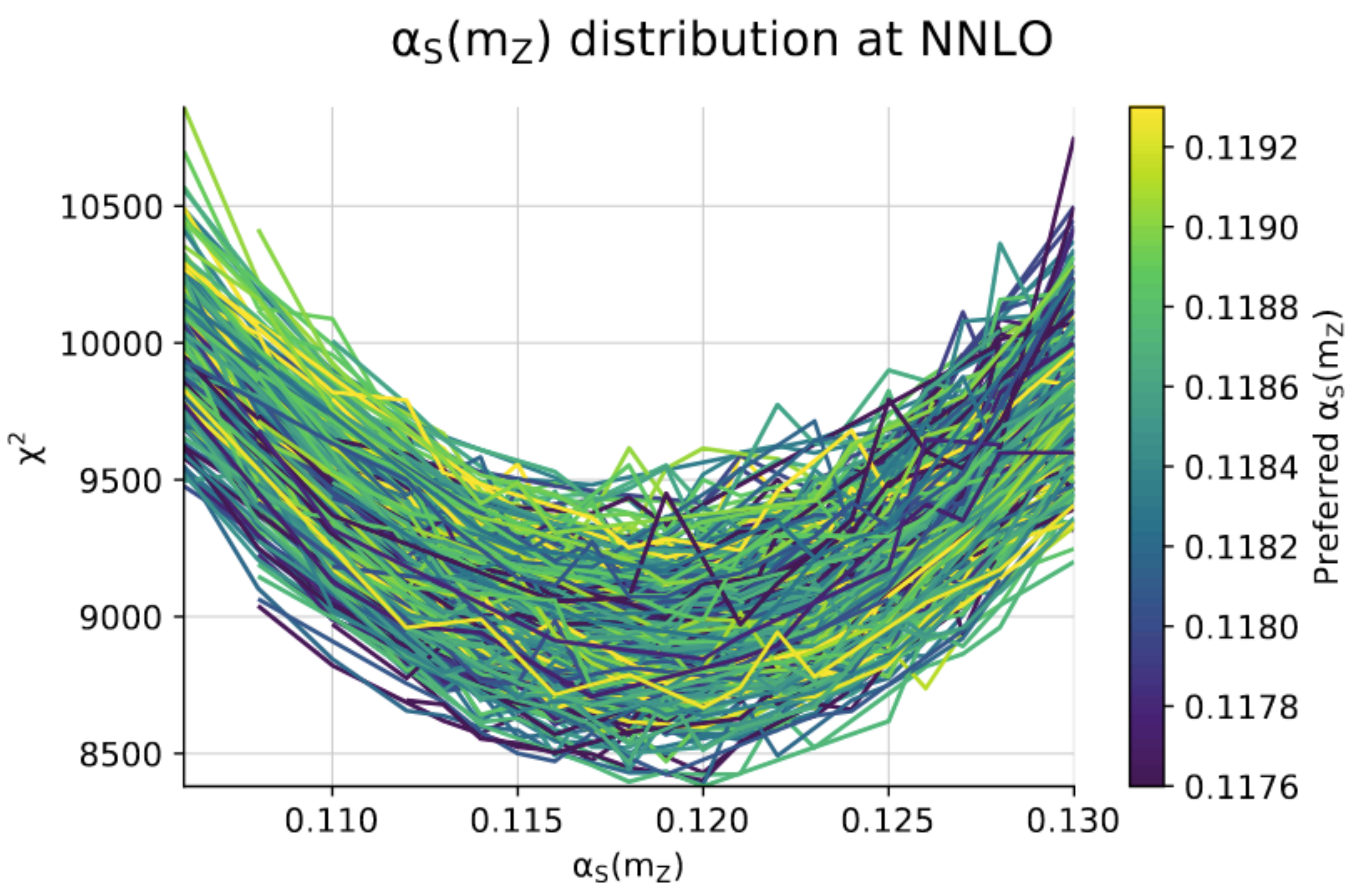

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  3. χ^2 parabolas for each set of correlated replicas are produced, and hence bounds on $\alpha_S(m_Z)$ are found.

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   A proof-of-concept study, performing a simultaneous extraction of 4 four-fermion SMEFT operators together with PDFs, using DIS-only data.

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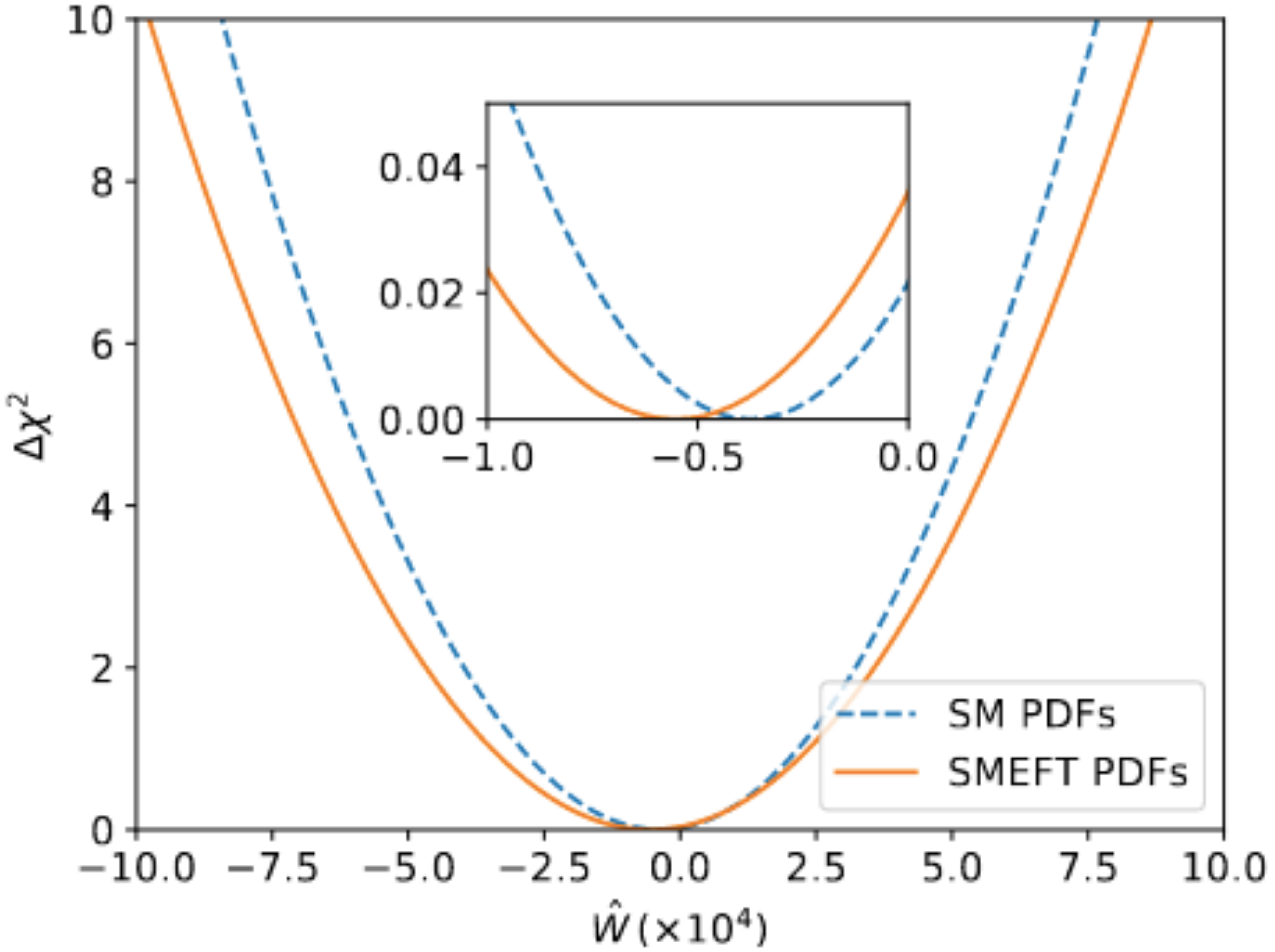
- In particular, in the paper 2104.02723 from the PBSP team (+ Greljo, Rojo), we find that in the context of the **oblique** W, Y **parameters**, a simultaneous fit of PDFs and the SMEFT parameters using **current high-mass DY data** has a **small impact on the bounds**.



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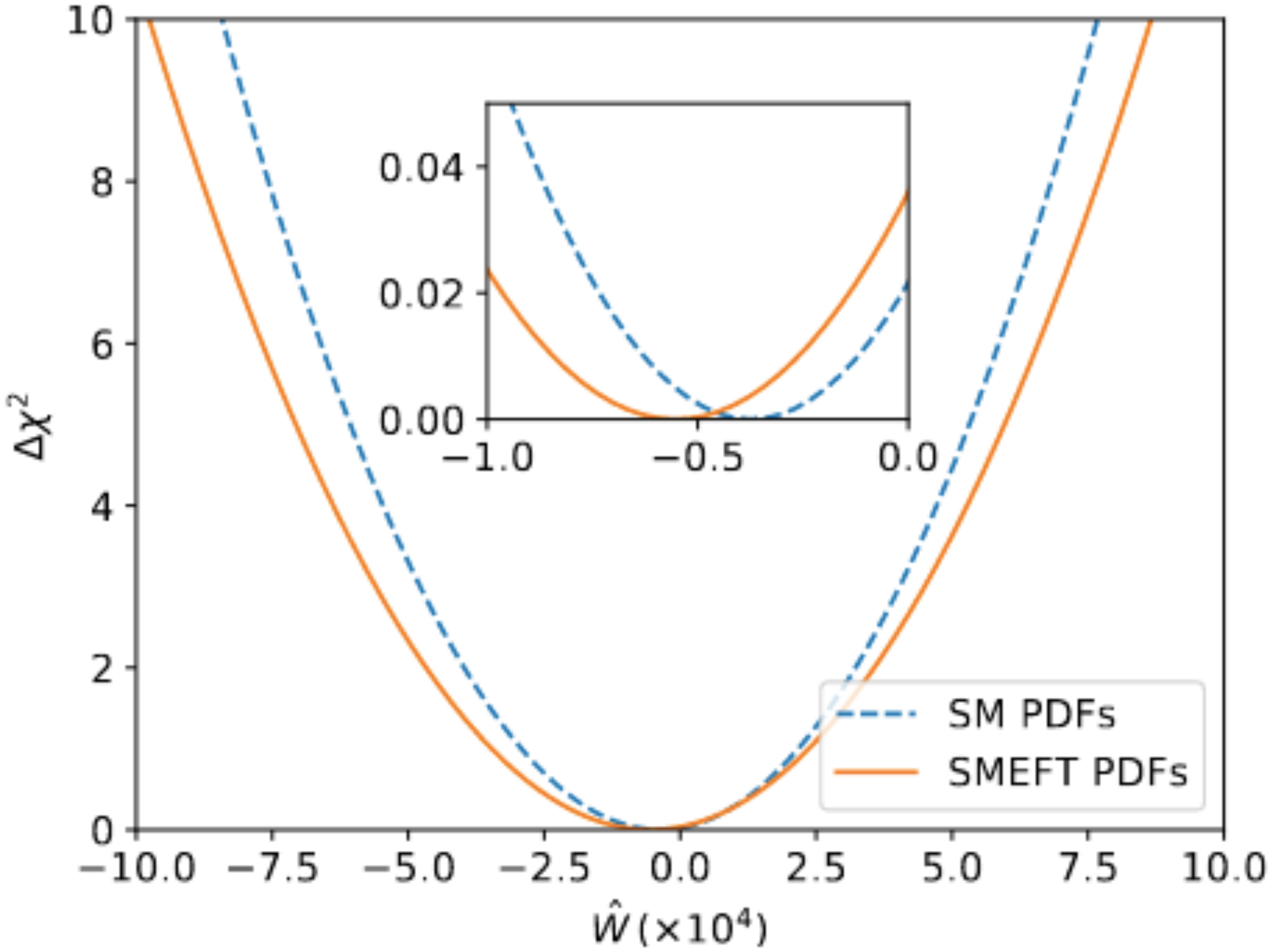
- The methodology used is similar to the **'scan' methodology** described for the $\alpha_S(m_Z)$ fit, but replicas are not correlated, we simply take the χ^2 of a PDF fit at each **benchmark point** in Wilson coefficient space to **construct bounds**.



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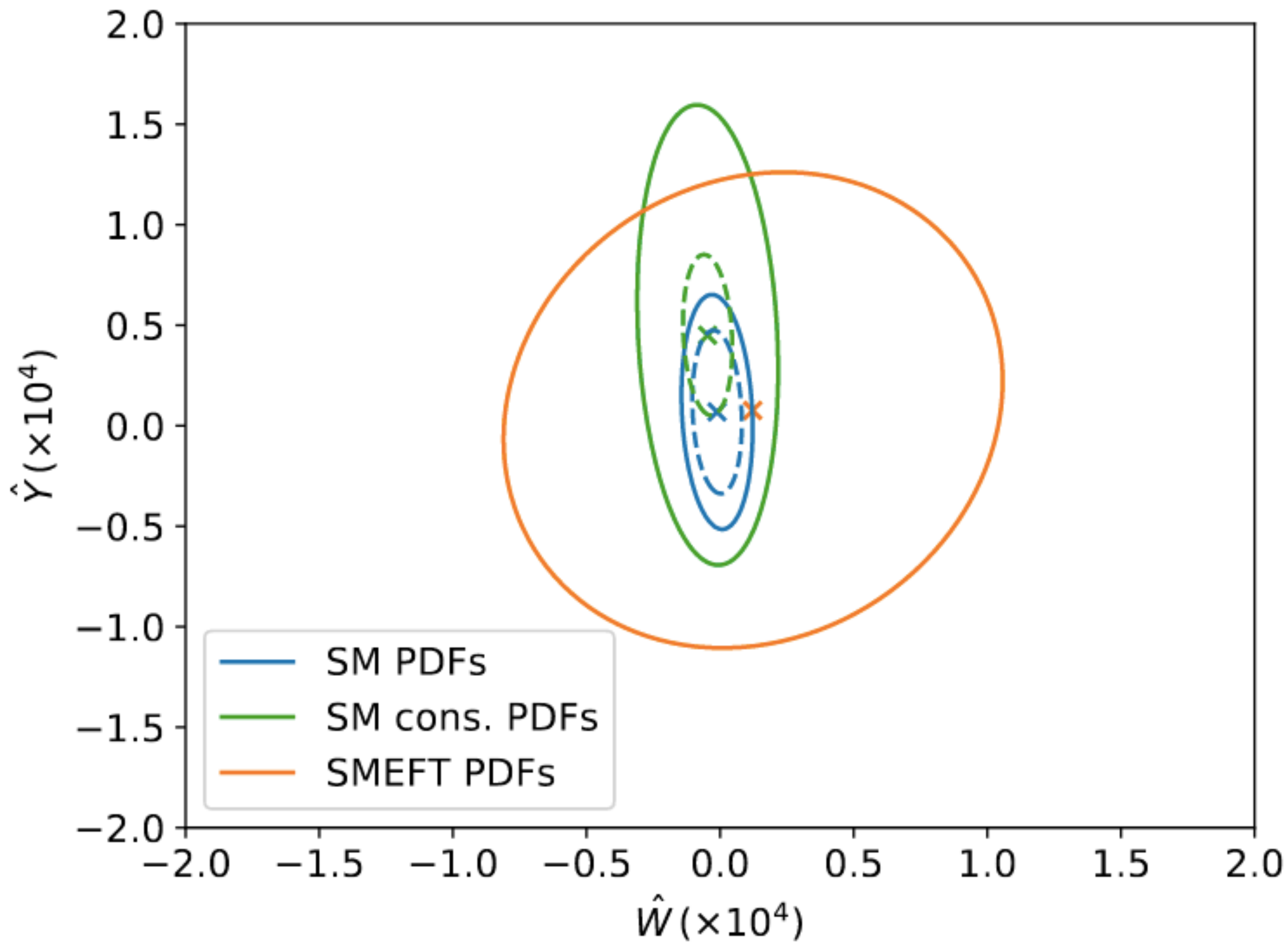
Parton distributions in the SMEFT from high-energy Drell-Yan tails

- On the other hand, when we use **projected HL-LHC data**, the impact of a simultaneous fit versus a fixed PDF fit becomes **enormous**!
- Without a simultaneous fit, we find that the size of the bounds is **significantly underestimated** - this could lead to claims of discovering New Physics when it **isn't necessarily there**.



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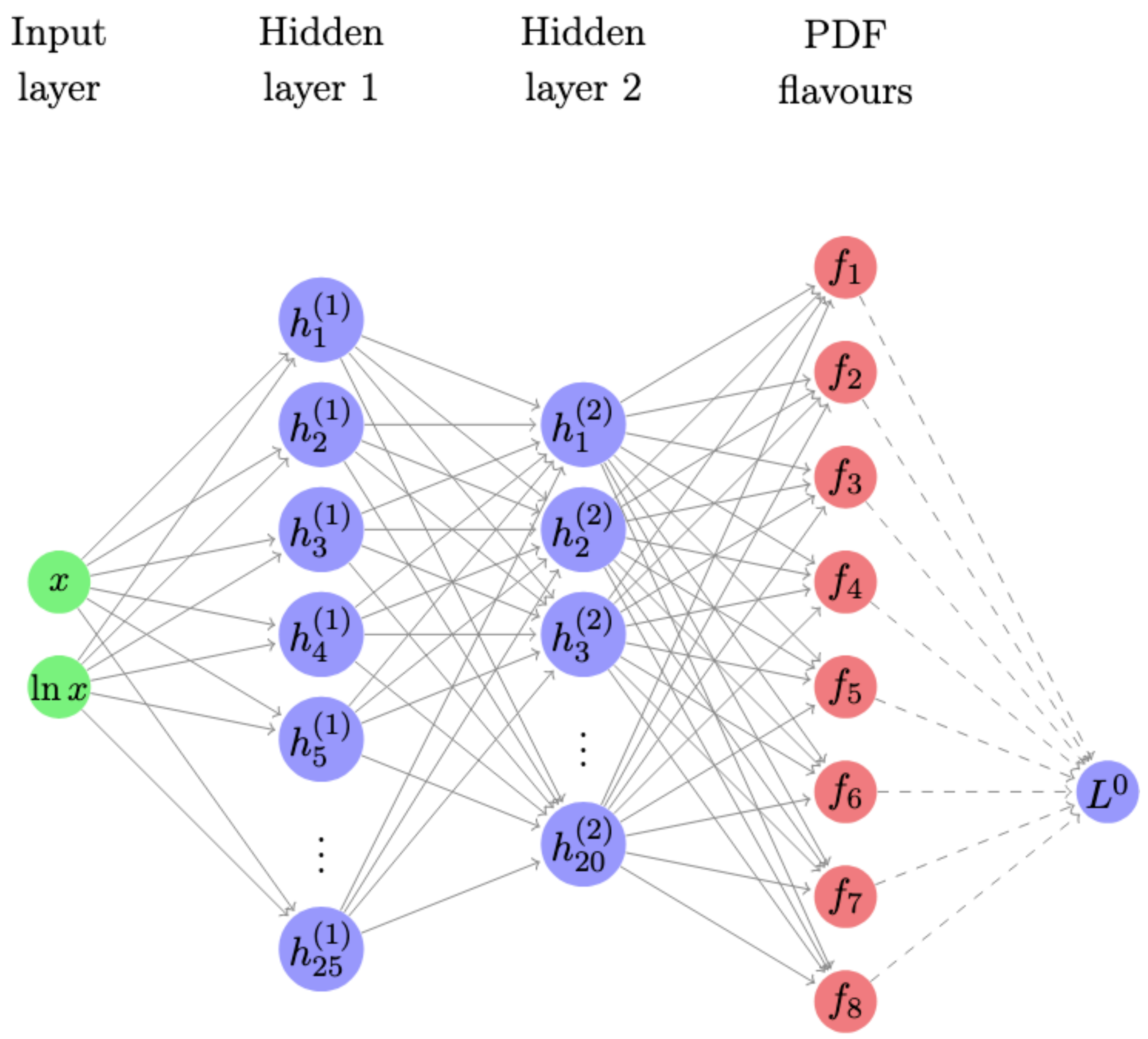
- Hence, we need a **new method** which will **scale well**. One suggestion is given in Liu, Sun, Gao, 2201.06586.
- Two members of the PBSP group have developed another approach based directly on the NNPDF4.0 PDF-fitting framework, which we call the **SimuNET methodology**, presented in Iranipour, Ubiali, 2201.07240.

The SimuNET methodology

- The SimuNET methodology **extends the existing NNPDF neural network** with an additional **convolution layer**.



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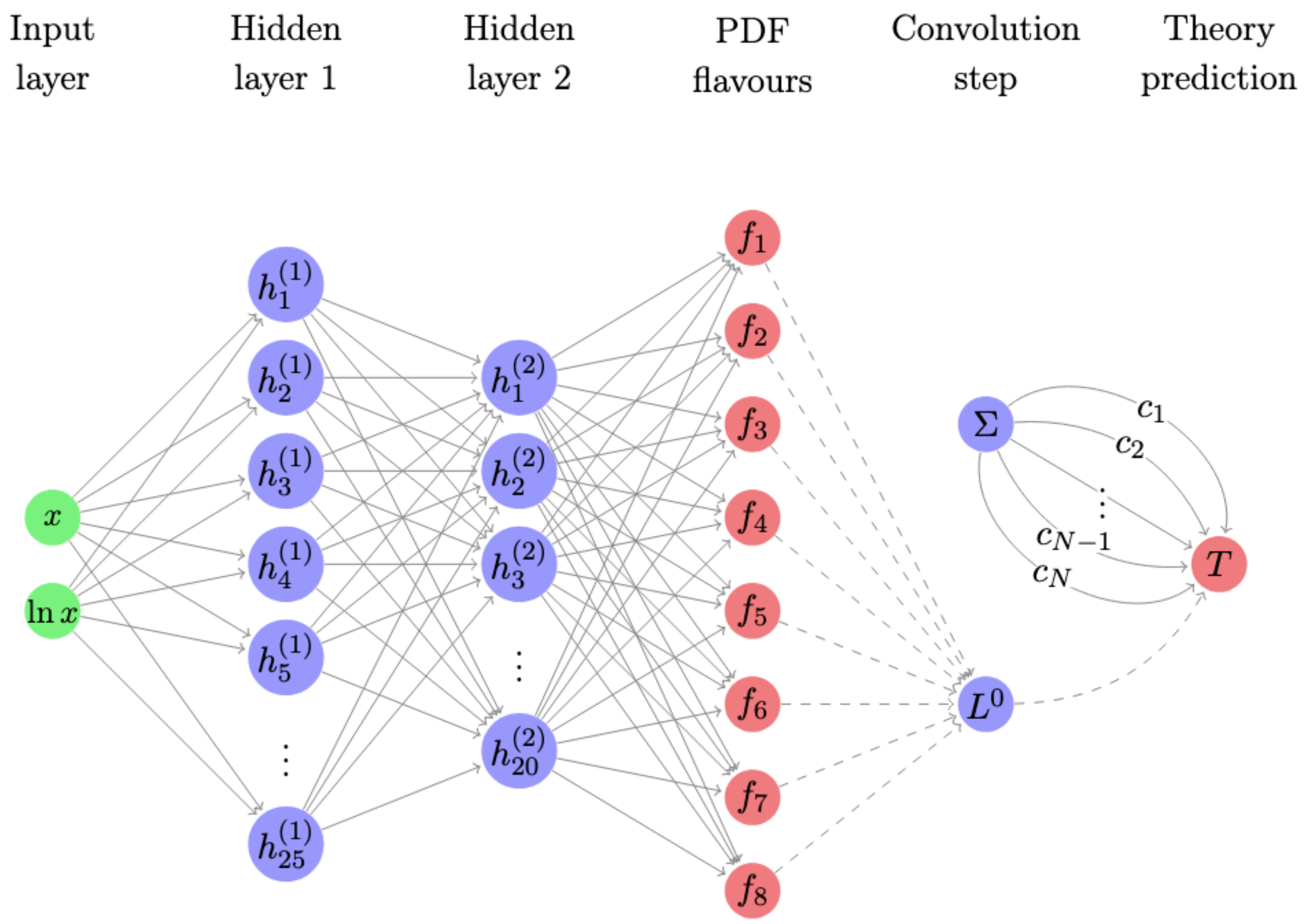
- The SimuNET methodology **extends the existing NNPDF neural network** with an additional **convolution layer**.
- The SMEFT couplings are added as **weights of neural network edges**, and are **trained alongside the PDFs**.



Benchmark of results

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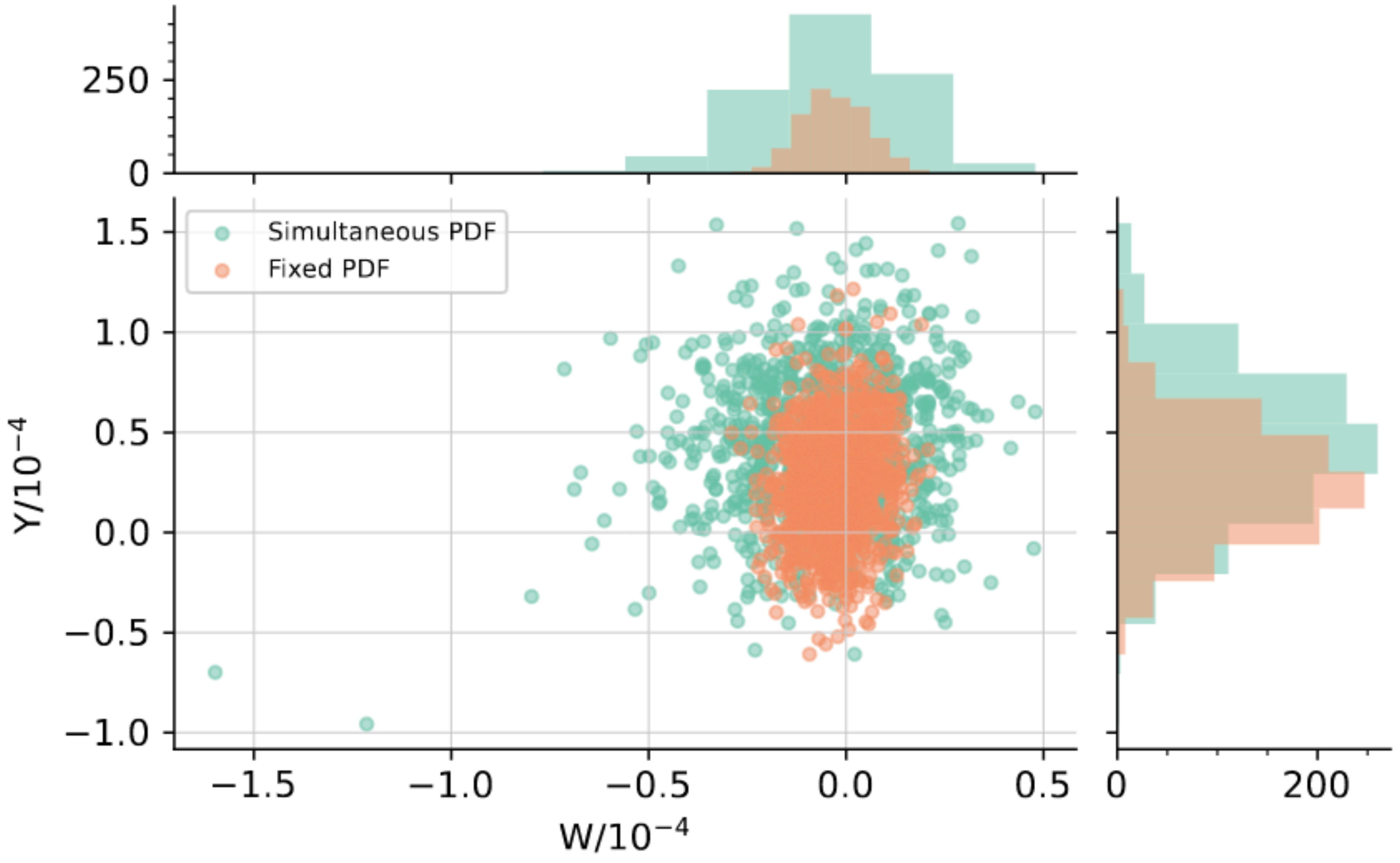
- In Iranipour, Ubiali, 2201.07240, the authors repeat the 'scan' study of Greljo et al, 2104.02723, now using the new **SimuNET methodology**.
- **Compatible bounds** in all cases are obtained, with **similar broadenings of the bounds** on the SMEFT couplings compared with **fixed PDFs** in the **projected HL-LHC fit**.

	SM PDFs	SMEFT PDFs	best-fit shift	broadening
$W \times 10^5$ (this work)	$[-2.0, 1.4]$	$[-4.3, 3.4]$	-0.2	$+126\%$
$W \times 10^5$ [17]	$[-1.4, 1.2]$	$[-8.1, 10.6]$	-1.4	$+620\%$
$Y \times 10^5$(this work)	$[-3.2, 8.1]$	$[-3.1, 11.7]$	$+1.9$	$+31\%$
$Y \times 10^5$[17]	$[-5.3, 6.3]$	$[-11.1, 12.6]$	$+0.3$	$+110\%$

Benchmark of bounds from SimuNET paper against
Greljo et al., 2104.02723 ([17] in above)



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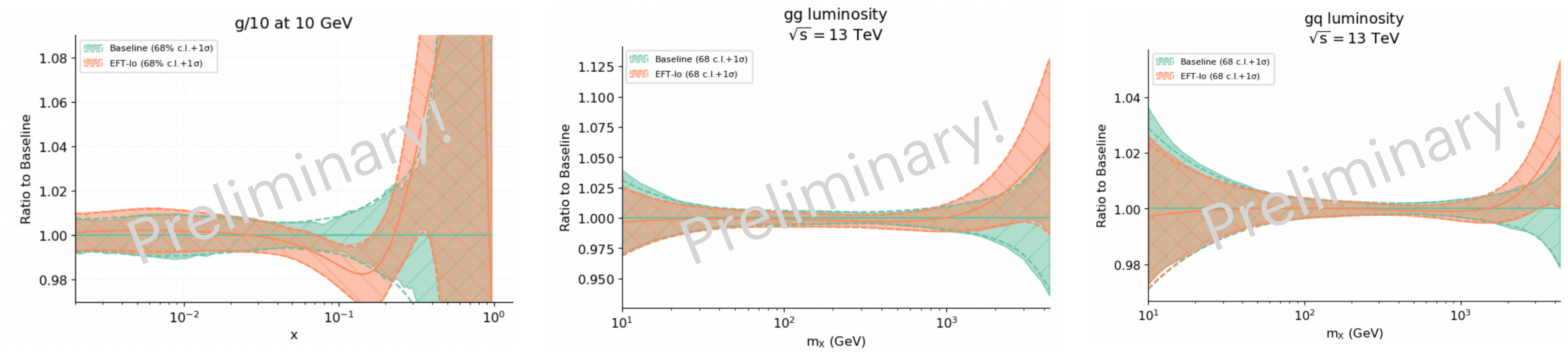
- For PDFs, top data mainly impacts the **gluon PDF** at large x.
- Preliminary results show that simultaneously fitting SMEFT alongside PDFs can result in an **enhancement in the gluon shift**:



4. - The dark side of the proton

Light new physics and PDFs

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- In this case, we could **still see the impact on proton structure** by including the new particles as **constituents of the proton**.
- The idea is not too far-fetched! The inclusion of new **coloured** particles, e.g. **gluinos**, has already been studied by Berger et al. in 0406143 (from 2005) and 1010.4315 (from 2010). **Strong constraints** can be derived assuming that new coloured particles alter our SM view of proton structure.

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- We also treat this as an effective theory, valid up to the mass of the Z, where **kinetic mixing** effects become important; so for us: $m_B \in [2,80]$ GeV.

DGLAP in the presence of dark photons

- Now, to include the dark photon as a constituent of the proton, we mimic the earliest studies into **photon PDFs** (namely MRST 0411040, from 2004), using the following procedure:

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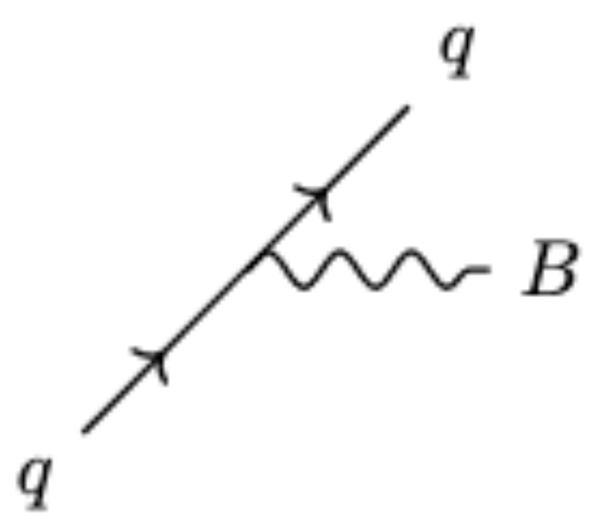

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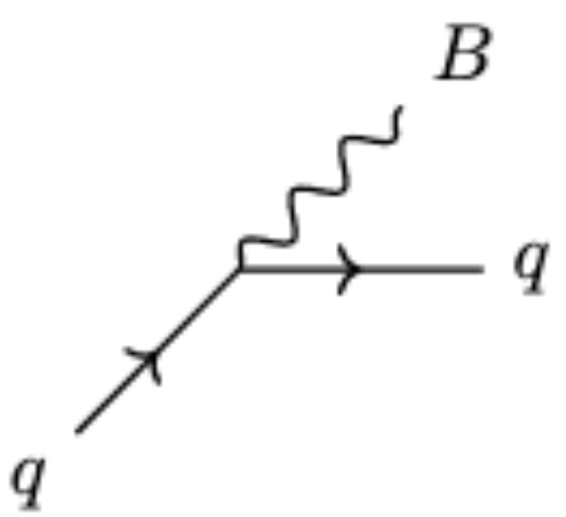

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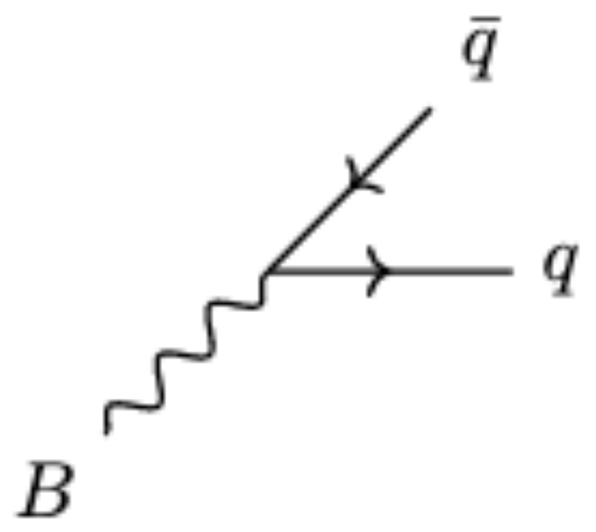

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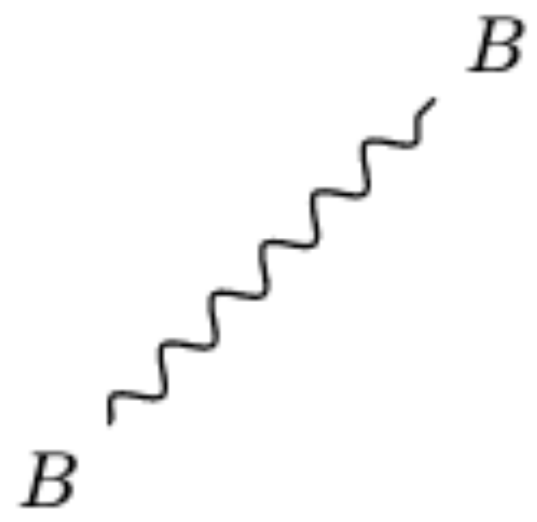

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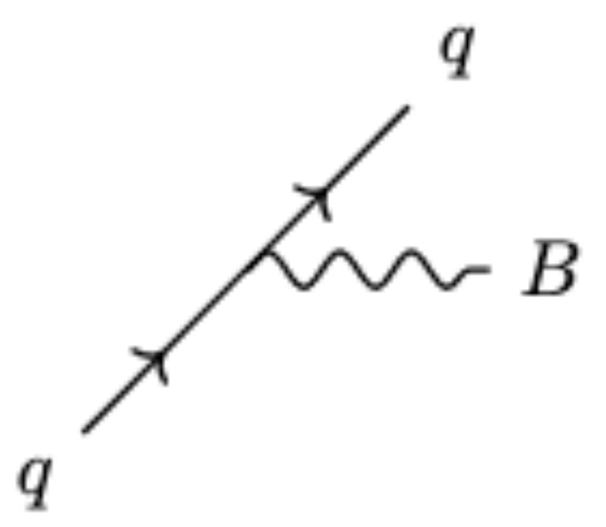

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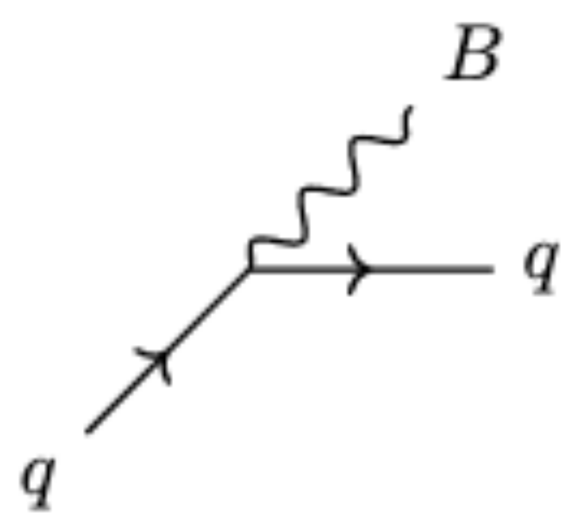

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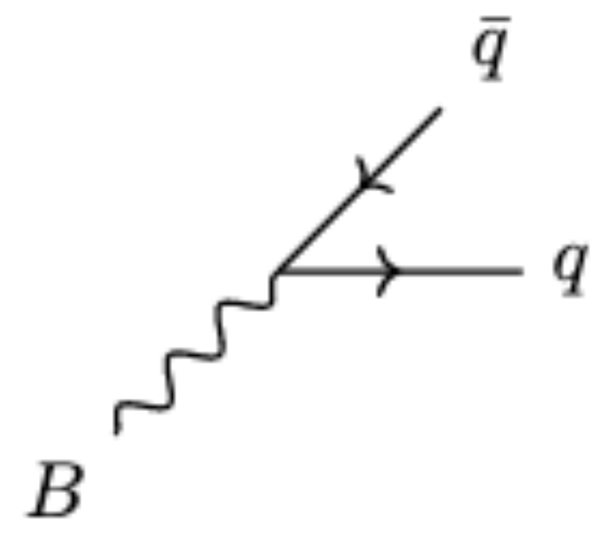

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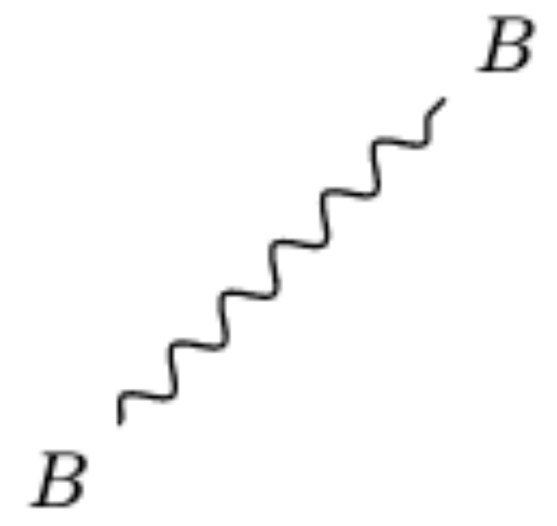

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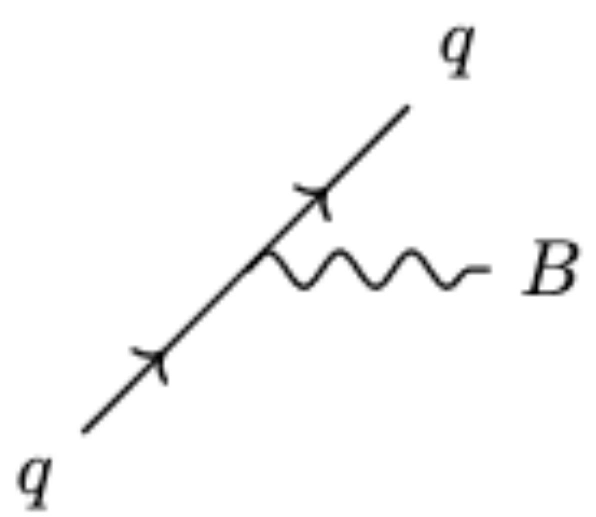
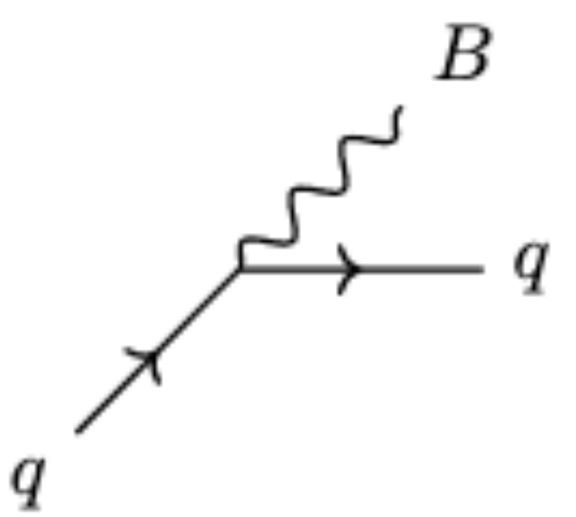
  3. Compare resulting PDF set predictions with reference SM predictions to see **impact of inclusion of a dark photon**.





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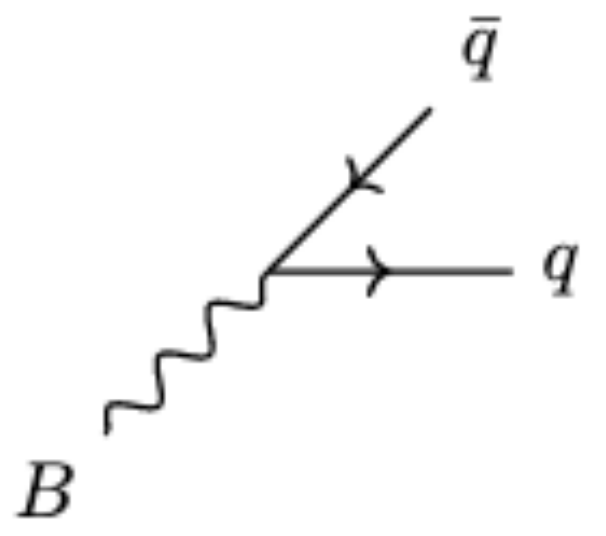

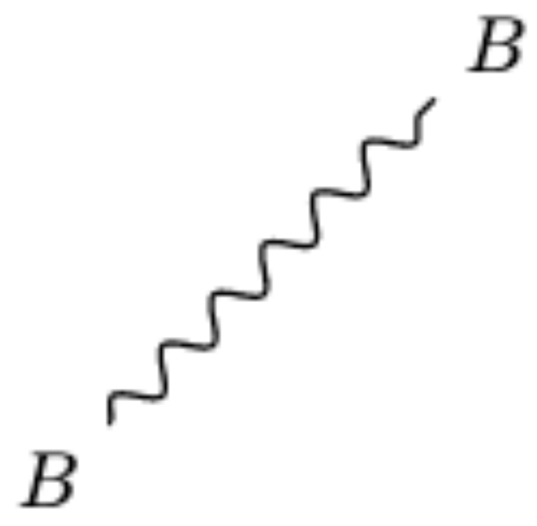

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- These contributions are well-known and already implemented in the **APFEL public evolution code**, which we modify in our work.

Impact on PDFs and parton luminosities

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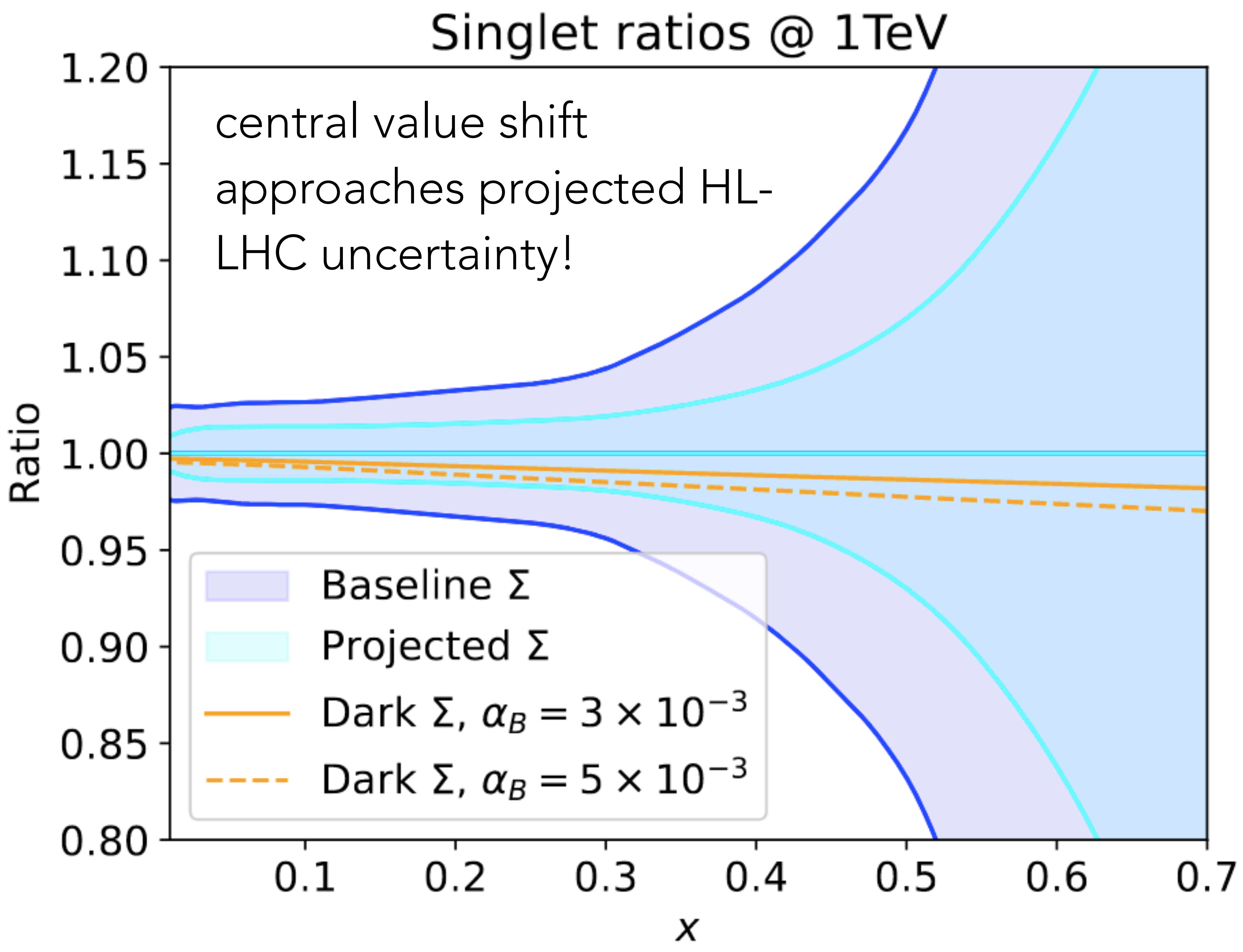

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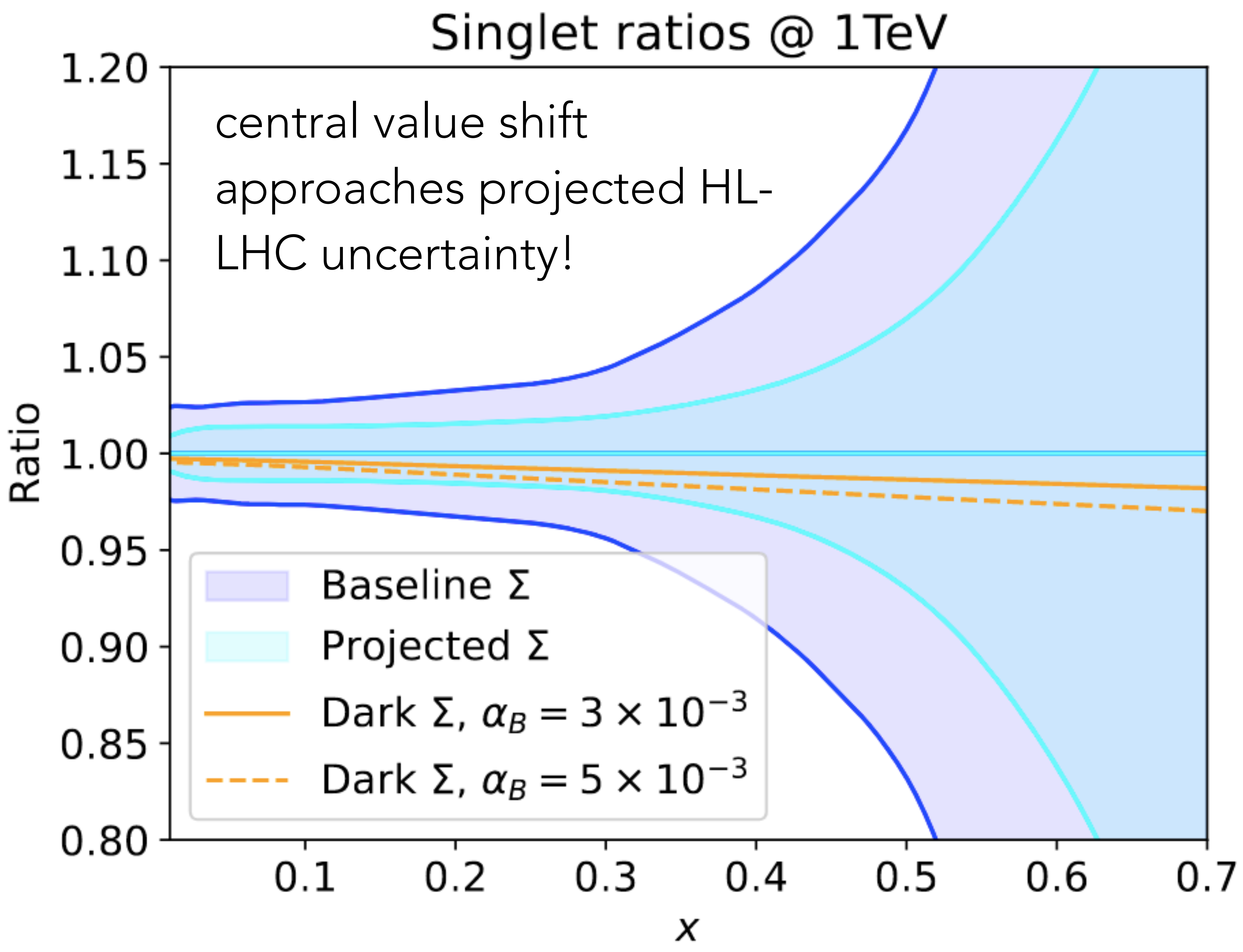
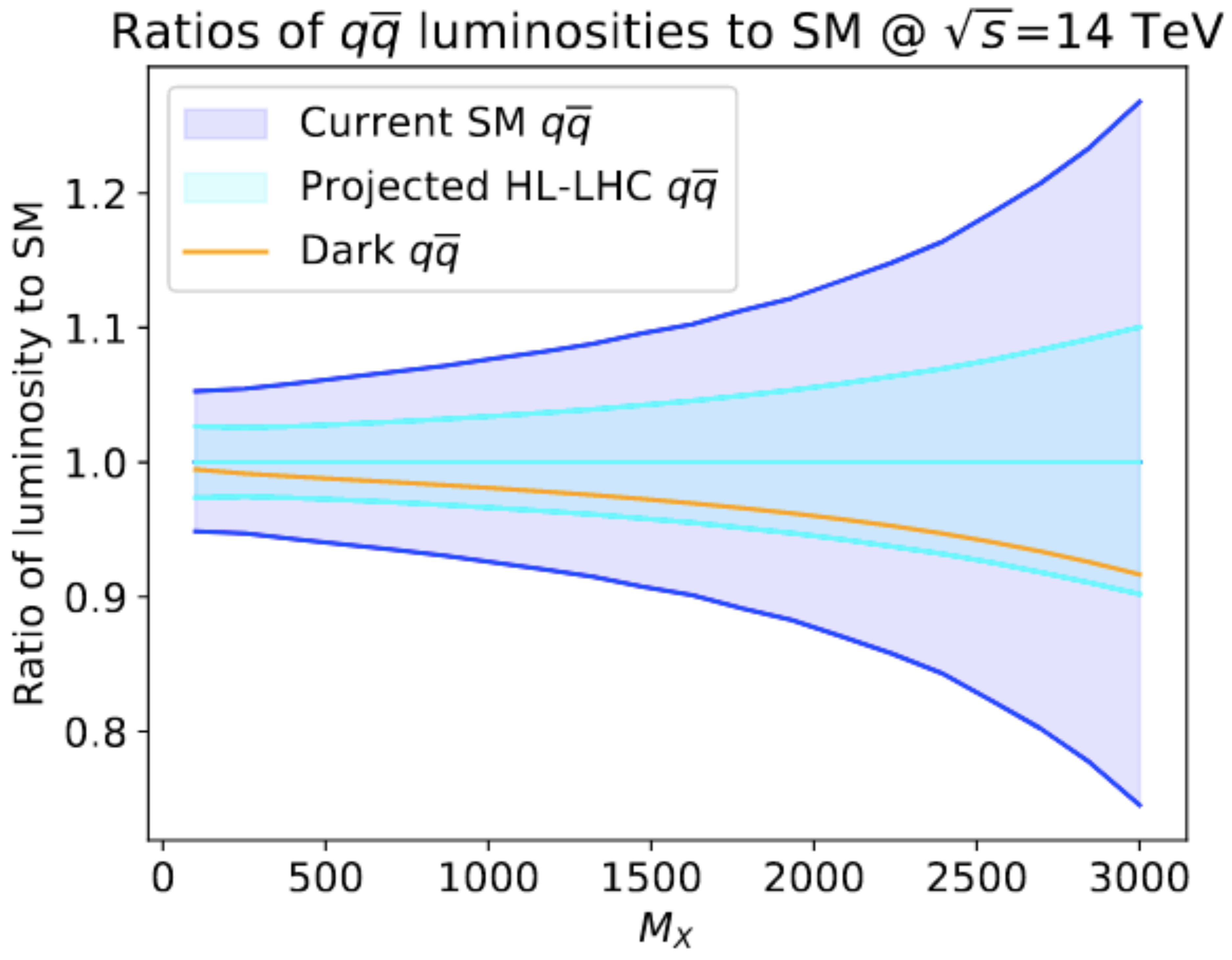
- The region that is most modified suggests that some values of the dark mass and coupling might lead to PDF sets which **perform too poorly** on **Drell-Yan sets**, relative to the baseline.

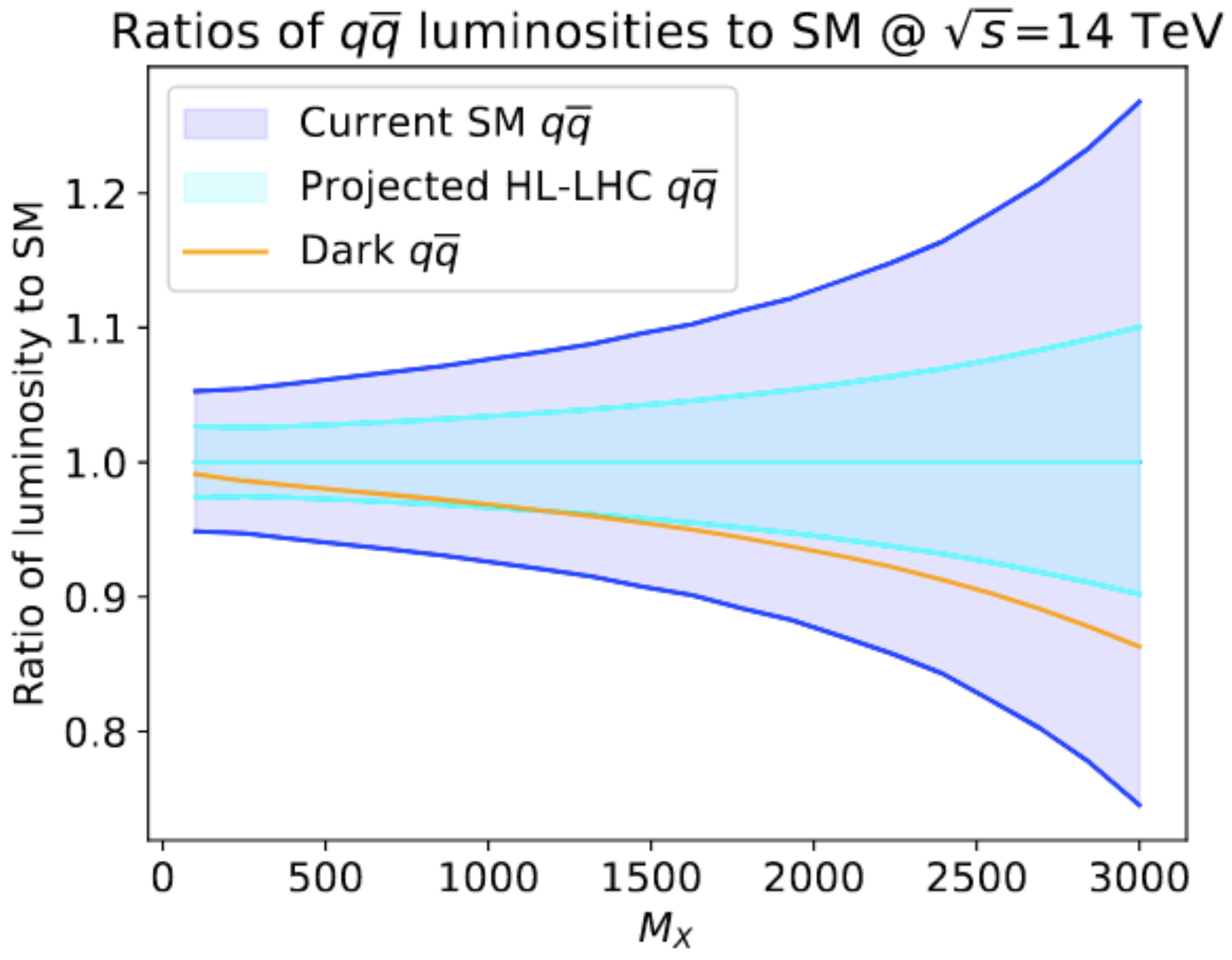


Impact on PDFs and parton luminosities

- The most important luminosity channel for DY is $q\bar{q}$; here, there is **tension with projected HL-LHC uncertainties** for some values of the mass and couplings!



(c) $m_B = 5$ GeV, $\alpha_B = 3 \times 10^{-3}$



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3. Compare to the reference fit's χ^2-statistic, and hence obtain projected bounds.

Impact on PDFs and parton luminosities

- The specific HL-LHC observable we choose to use is **neutral current Drell-Yan** at a centre-of-mass-energy $\sqrt{s} = 14$ TeV, in 12 bins of lepton invariant pair-mass. The projected data we use is a small modification of that produced for **Parton Distributions in the SMEFT from High-Energy Drell-Yan Tails**, 2104.02723.

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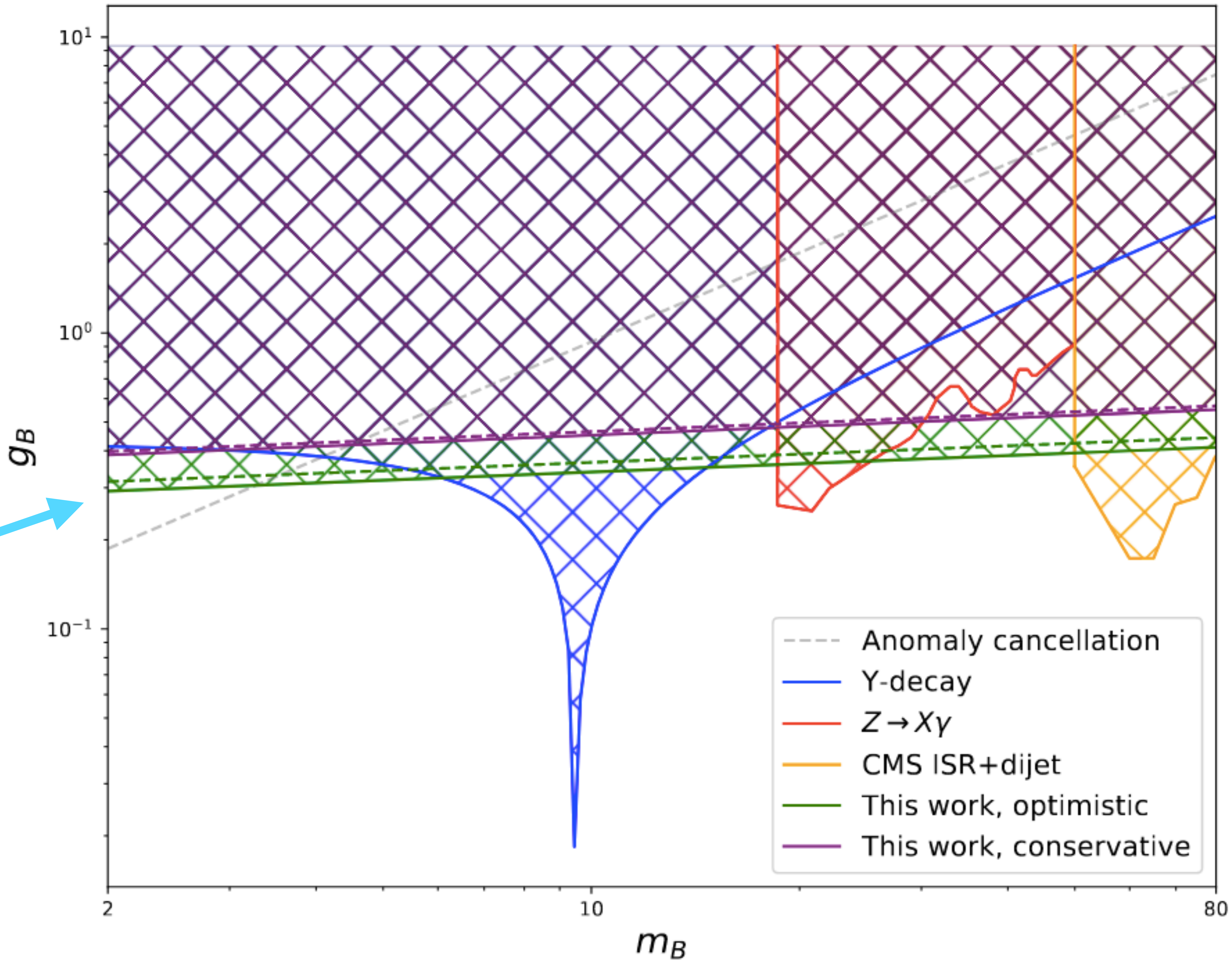
  - *Optimistic*: Total integrated luminosity 6 ab^{-1} (both CMS and ATLAS available), with five-fold reduction in systematics.
  - *Conservative*: Total integrated luminosity 3 ab^{-1} (only CMS or ATLAS is available), with two-fold reduction in systematics.

Comparison of (projected) bounds



dashed lines: including projected HL-LHC PDF uncertainty

Conclusions

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- **Simultaneous determination of PDFs and BSM parameters**, will be **very important in future analyses** (especially as we enter Run III).

- Members of the **PBSP team** have already produced two works in the direction of simultaneous PDF-SMEFT fits: (i) a **phenomenological study** 2104.02723 showing the need for simultaneous extraction; (ii) a **methodology** (SimuNET, 2201.07240) capable of **fast simultaneous fitting**. We aim to continue with a more ambitious **top-sector fit**.

- There are interesting directions outside the SMEFT, e.g. studying **light, weakly-coupled particles** inside the proton, like our **dark photon** study.

Thanks for listening!
Questions?