Beyond the Standard Proton

for 'Parton Distributions and Nucleon Structure, 2022' ,
at the Institute for Nuclear Theory, Seattle

James Moore, University of Cambridge
(on behalf of the 'Physics Beyond the Standard Proton' group)

PBSP

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PBSP: Physics Beyond the Standard Proton

- The **PBSP group** is based at the **University of Cambridge**, and is headed by **Maria Ubiali**; the project is **ERC-funded.**
- The aim is to **investigate interplay between BSM physics and proton structure** - the subject of the rest of this talk!
- The team members are:
  - *Postdocs:* Zahari Kassabov, Maeve Madigan, Luca Mantani
  - *PhD students:* Shayan Iranipour (*former*), Elie Hammou, **James Moore**, Manuel Morales, Cameron Voisey (*former*)

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Talk overview

1. Introduction: Joint fits of PDFs and BSM parameters

2. Simultaneous fits of PDFs and SMEFT Wilson coefficients

3. The dark side of the proton

4. Conclusions

1. - Introduction: Joint fits of PDFs and BSM parameters

Fitting PDFs and physical parameters

- **Theory predictions** for collider experiments are obtained from the standard **factorisation formula**; schematically, we have:

$$T(c, \theta) = \mathrm{FK}(c) \otimes \mathrm{PDF}(\theta)$$

observable

PDF evolution kernel + partonic cross-section

initial-scale PDF contribution

- Predictions are functions of:

(i) **'physics' parameters** c, e.g. $\alpha_S(m_Z)$, m_W, **Wilson coefficients** if we use the **SMEFT**, masses and couplings of new particles in specific **BSM models**;

(ii) **PDF parameters** θ, e.g. the weights of a neural network parametrising the initial-scale PDFs (in the NNPDF framework).

Fitting PDFs and physical parameters

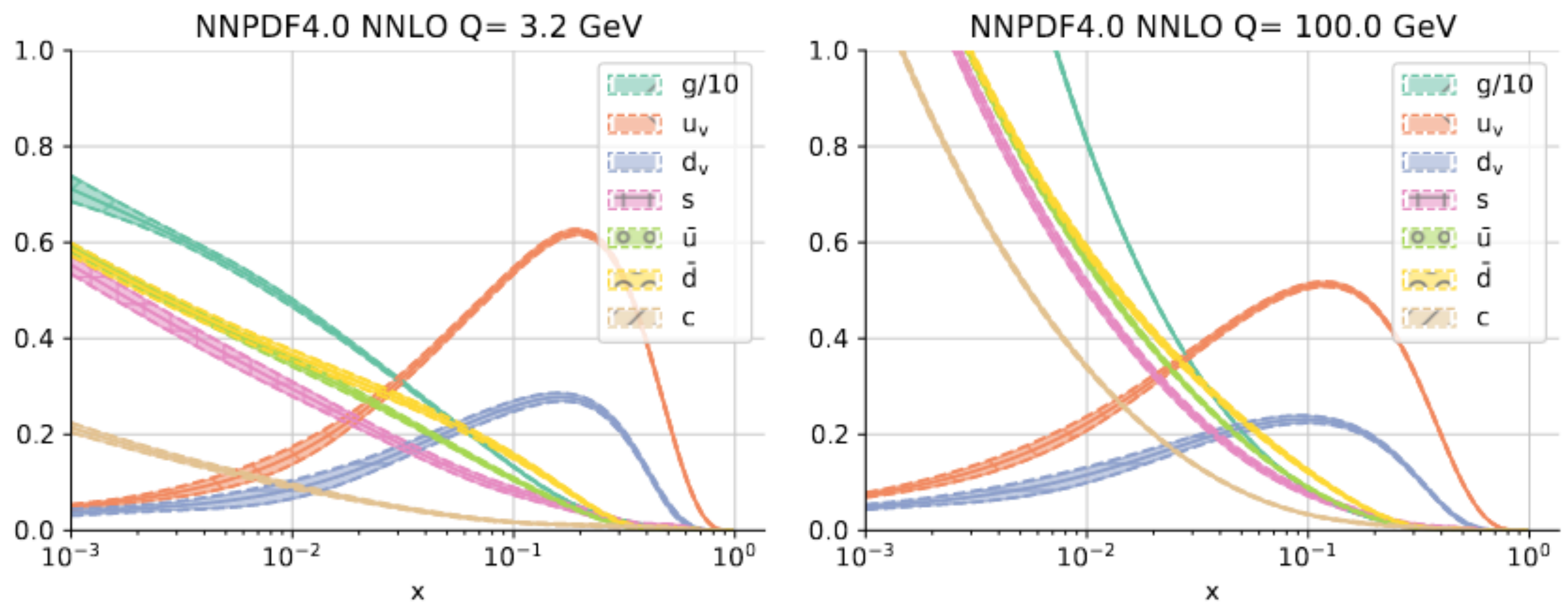
- Typically, the ‘physics’ parameter fits and PDF parameter fits **don’t talk.**

PDF parameter fits

- Fix physics parameters $c = \bar{c}$:

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

- Optimal PDF parameters θ^* then have an **implicit dependence** on initial physics parameter choice: $\text{PDF}(\theta^*) \equiv \text{PDF}(\theta^*(\bar{c}))$.
- E.g. NNPDF4.0 fit, Ball et al., 2109.02653.

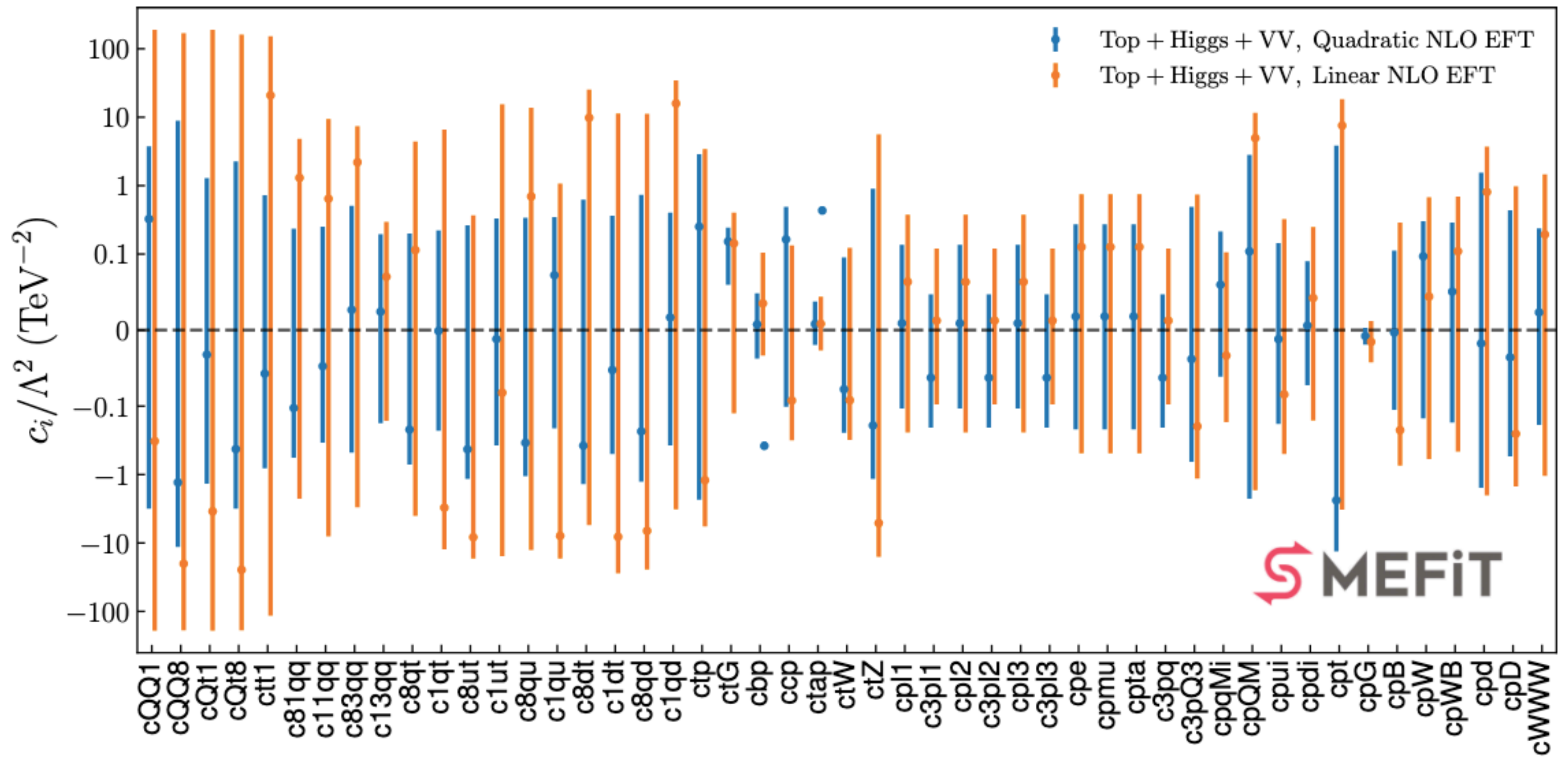


‘Physics’ parameter fits

- Fix PDF parameters $\theta = \bar{\theta}$:

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

- Optimal ‘physics’ parameters c^* then have an **implicit dependence** on PDF choice: $c^* = c^*(\bar{\theta})$.
- E.g. SMEFiT, Ethier et al., 2105.00006.



Fitting PDFs and physical parameters

- **This could lead to inconsistencies.**

PDF parameter fits

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

- Fitted PDFs can depend implicitly on fixed physical parameters used in the fit.

'Physics' parameter fits

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

- Bounds on physical parameters can depend implicitly on the fixed PDF set used in the fit.

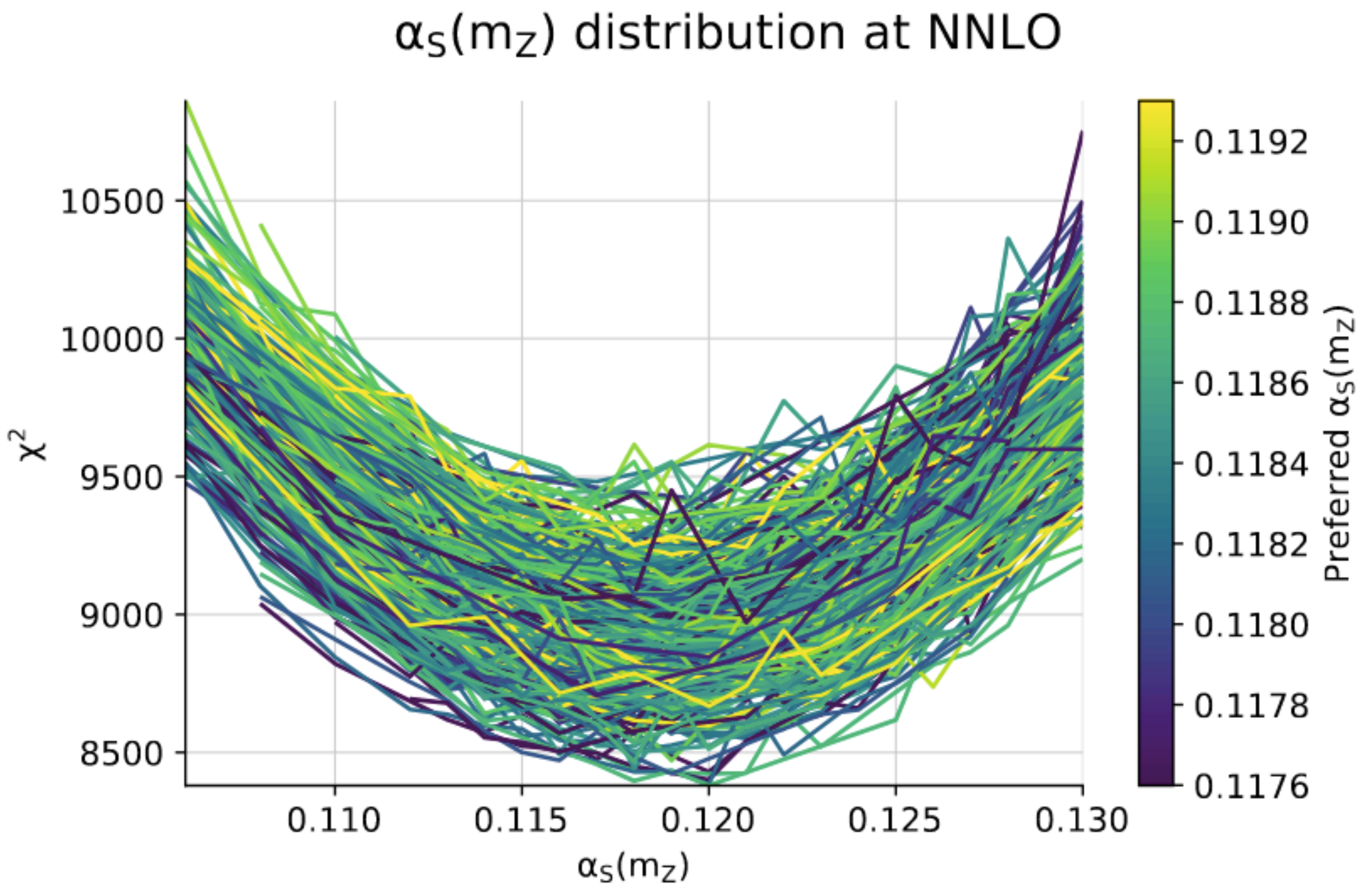
- For example, if we fit PDFs **assuming all Wilson coefficients in the SMEFT are zero**, but then **use those PDFs in a fit of SMEFT Wilson coefficients**, our resulting bounds **might be misleading**. The same applies to SM parameters.
- In the case of BSM models, we could even **miss New Physics**, or **see New Physics that isn't really there**!

Key question for this talk:

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

2. - Simultaneous fits of PDFs and SMEFT Wilson coefficients

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 value of $\alpha_S(m_Z)$ (see e.g. Forte, Kassabov, 2001.04986).

- The standard method for simultaneous extraction of $\alpha_S(m_Z)$ and PDFs is the **correlated replica method**, 1802.03398. In a nutshell:

  1. A grid of benchmark $\alpha_S(m_Z)$ points is selected.
  2. A **PDF fit** is performed at each benchmark point, with $\alpha_S(m_Z)$ set to the appropriate value for both **PDF evolution** and **convolution with the partonic cross-section**. The PDF replicas are correlated appropriately so as to be comparable for different values of $\alpha_S(m_Z)$.
  3. χ^2 parabolas for each set of correlated replicas are produced, and hence bounds on $\alpha_S(m_Z)$ are found.

Simultaneous SMEFT fits

- More recently, however, it has been shown that there can be a **non-negligible** interplay between **PDFs** and **Wilson coefficients in the SMEFT**.
- There are **four main works** in this direction:

1. **Carrazza et al., 1905.05215**. *Can New Physics Hide Inside the Proton?*

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

2. **Liu, Sun, Gao, 2201.06586**. *Machine learning of log-likelihood functions in global analysis of parton distributions.*

   A methodological study; simultaneous SMEFT/PDF extraction is noted as a possible application, and one SMEFT four-fermion operator is fitted using DIS-only data.

3. **PBSP team + Greljo and Rojo, 2104.02723**. *Parton distributions in the SMEFT from high-energy Drell-Yan tails.*

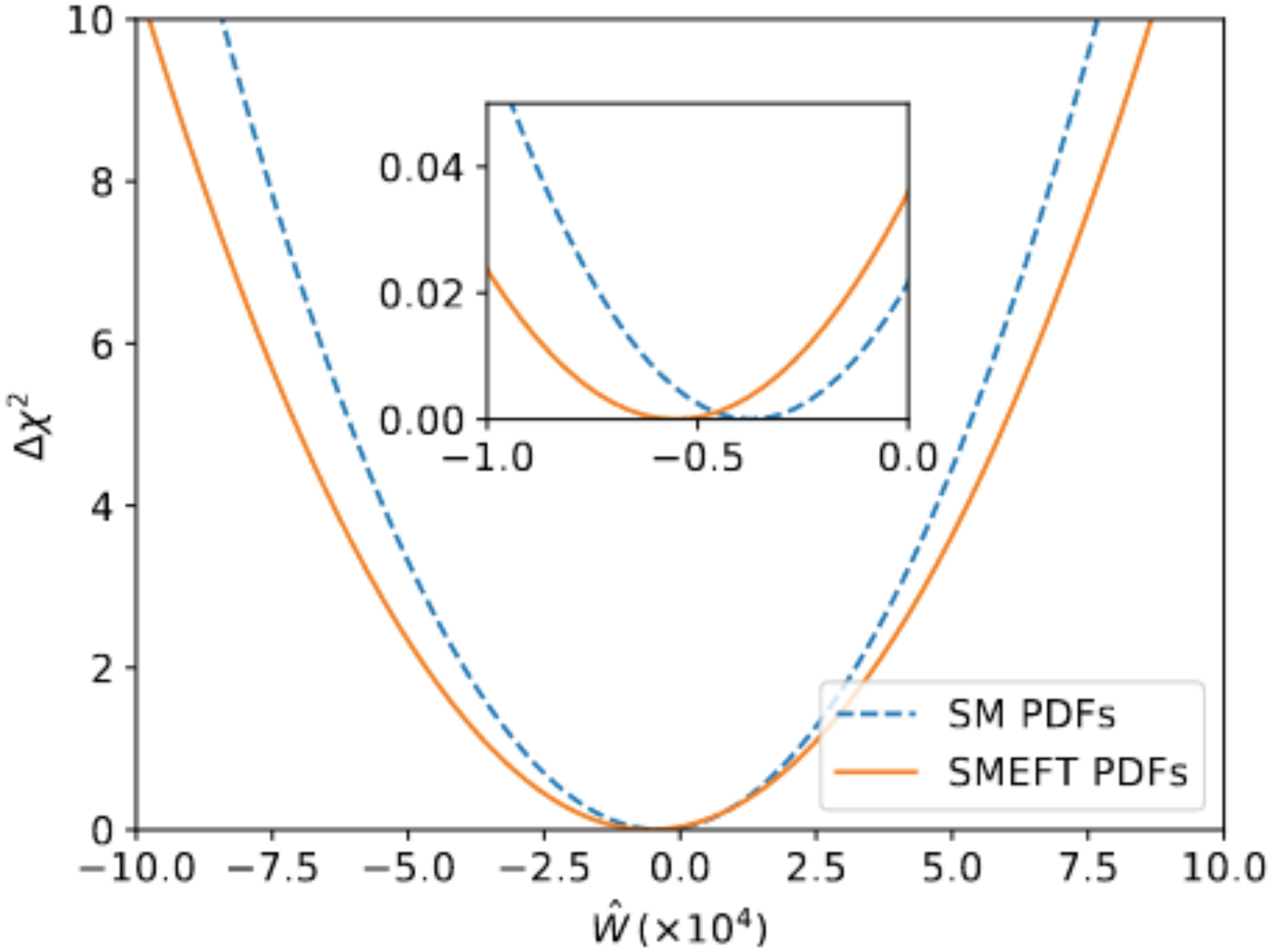
   A phenomenological study, demonstrating the impact of a simultaneous SMEFT/PDF fit in the context of the oblique W, Y parameters using current and projected Drell-Yan data.

4. **CMS, 2111.10431**. *Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV.*

   A proof-of-concept study in the SMEFT case, involving a simultaneous extraction of PDFs, $\alpha_S(m_Z)$, the top pole mass and one SMEFT Wilson coefficient.

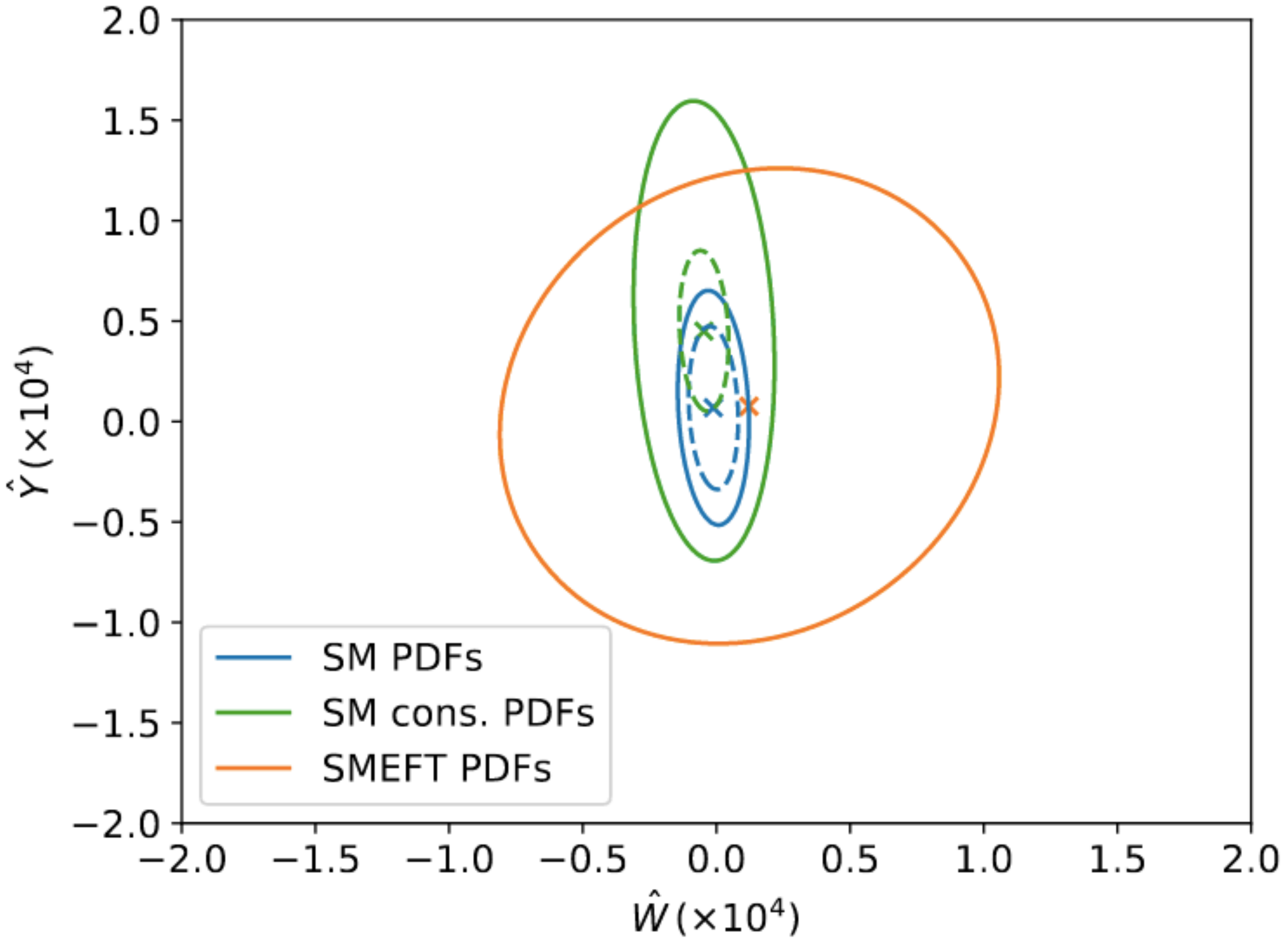
Parton distributions in the SMEFT from high-energy Drell-Yan tails

- 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 data** has a **small impact on the bounds**.
- 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**.



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**.



New simultaneous SMEFT fits in the top sector

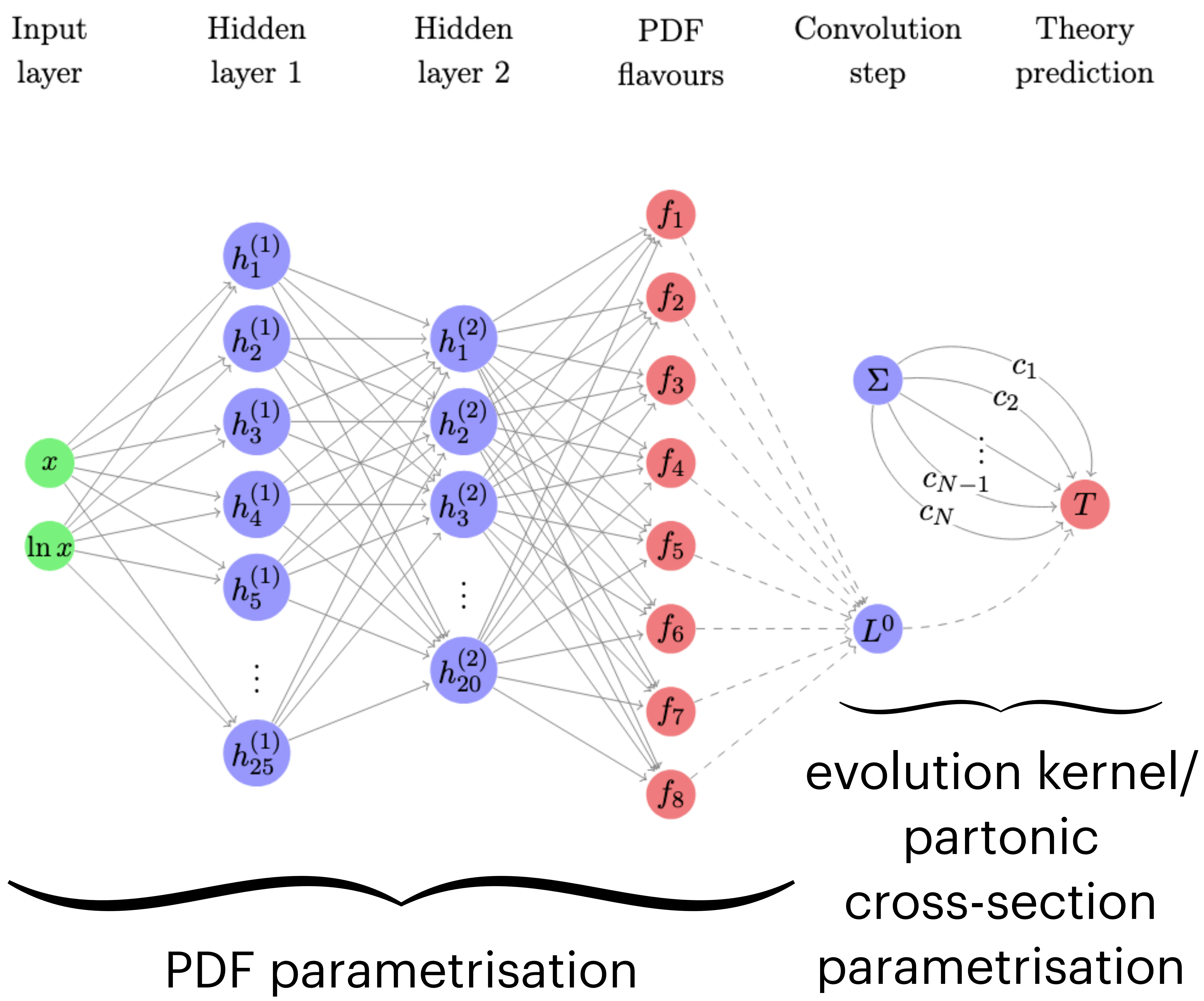
- Our DY study motivates more serious studies of PDF-SMEFT interplay; our next target is the **top sector.** The top sector provides a great playground in the search for New Physics, and has been used in multiple EFT analyses, including **SMEFiT** (2105.00006) and **FitMaker** (2012.02779), for example.

- Unfortunately, in a serious top fit, we need to include many more SMEFT operators: a total of **16 SMEFT operators** contribute to the observables of interest. The ‘scan’ methodology scales terribly though...

- Therefore, in our top study, we use a **new, efficient methodology** proposed in Iranipour, Ubiali, 2201.07240.

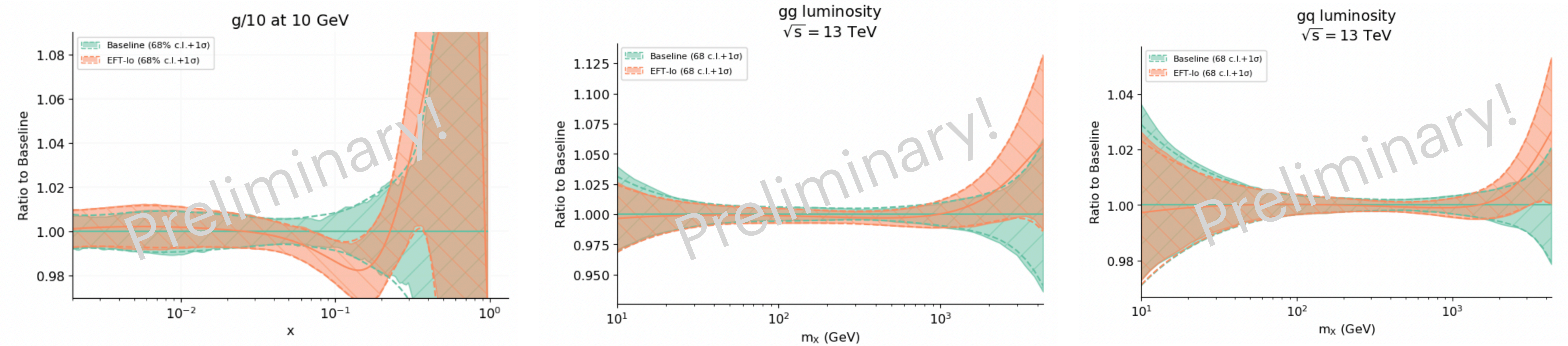
New simultaneous SMEFT fits in the top sector

- In the NNPDF4.0 framework, PDFs are modelled by **neural networks**. The neural network PDFs are convolved with the **PDF evolution kernel** and the **partonic cross-section** to produce theory predictions, which are compared to data.
- In brief, the idea of the new method is to **add the convolution step** to the neural network itself, with the physical parameters added as **weights** of **neural network edges**.
- In principle any **polynomial** dependence on physical parameters can be captured through the use of **non-trainable edges**.
- An **arbitrary number** of physical parameters can be fitted at basically **no extra cost**!



New simultaneous SMEFT fits in the top sector

- **Preliminary results** show that a simultaneous top fit versus a fixed PDF top fit can have significant impact on the **gluon PDF**, and in turn the gg and gq **luminosities** - **watch this space for more results**!



3. - The dark side of the proton

Light new physics and PDFs

- So far, we've focussed on **joint PDF-SMEFT determinations**. However, whilst the SMEFT is a great tool in searching for New Physics, it does not capture **new weakly-coupled, light particles**. Proton structure could also be affected by these new degrees of freedom!
- 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.

Light new physics and PDFs

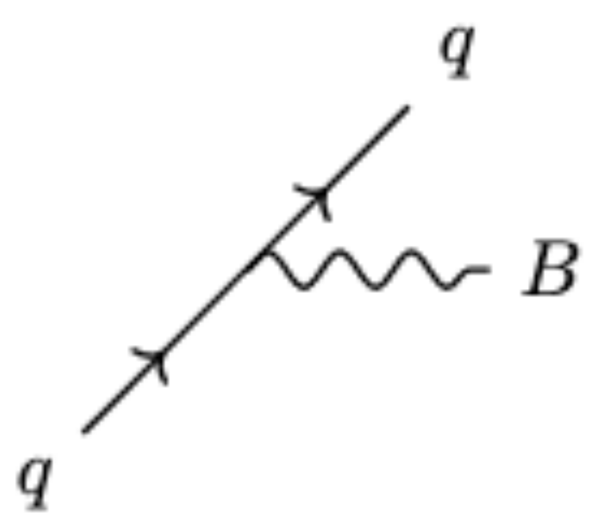
- *Idea:* now PDFs are known **very precisely**, and their uncertainties **will continue to reduce in the near future with the HL-LHC**, could we do the same for a **colourless** particle too?
- In McCullough, **Moore**, Ubiali, 2203.12628, we studied the impact of using a **toy dark matter candidate**, namely a **light leptophobic dark photon** B which couples to quarks via the effective interaction Lagrangian:

$$\mathscr{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \gamma^\mu B_\mu q$$

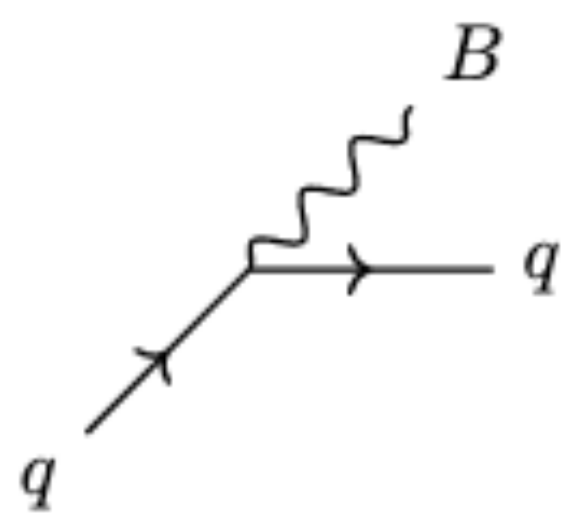
- Low-energy experimental probes already strongly constrain $m_B < 2$ GeV.
- We also treat this as an effective theory, valid up to the mass of the Z, where **kinetic mixing** effects become important; so for us: $m_B \in [2,80]$ GeV.

DGLAP in the presence of dark photons

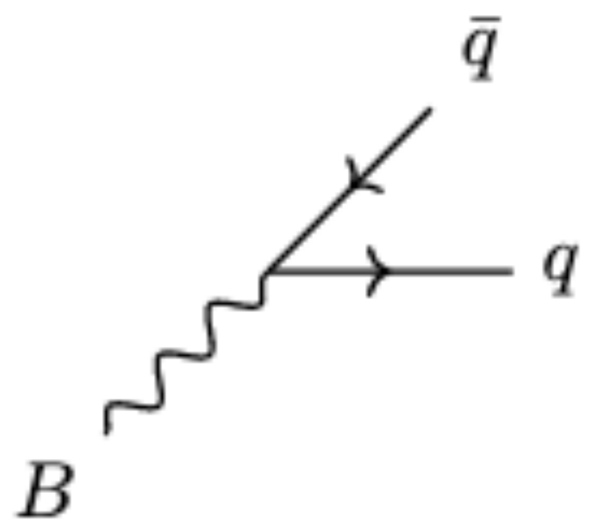
- Now, to include the dark photon as a constituent of the proton, we mimic the earliest studies into **photon PDFs** (namely MRST 0411040, from 2004), using the following procedure:
  1. Compute the **dark photon splitting functions**, and add them to **DGLAP evolution**.
  2. Starting from an **appropriate initial-scale ansatz**, and a **reference PDF set**, evolve using the **modified DGLAP equations**. Since we assume $m_B > 2$ GeV, greater than the standard initial scale 1.65 GeV, we **always generate the dark photon from zero** similar to a **heavy quark**. We choose the **state-of-the-art NNPDF3.1 LUXQED set** as our reference set (this will soon be replaced by NNPDF4.0 LUXQED).
  3. Compare resulting PDF set predictions with reference SM predictions to see **impact of inclusion of a dark photon**.



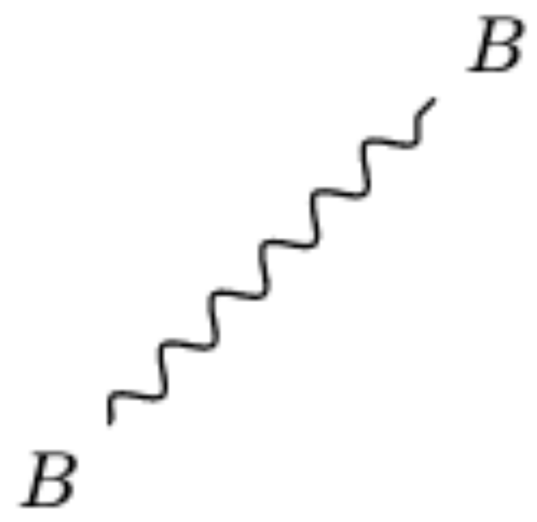
$$P_{qq}(x) = \frac{1+x^2}{9(1-x)_+} + \frac{1}{6}\delta(1-x)$$



$$P_{Bq}(x) = \frac{1}{9}\left(\frac{1+(1-x)^2}{x}\right)$$



$$P_{qB}(x) = \frac{x^2+(1-x)^2}{9}$$



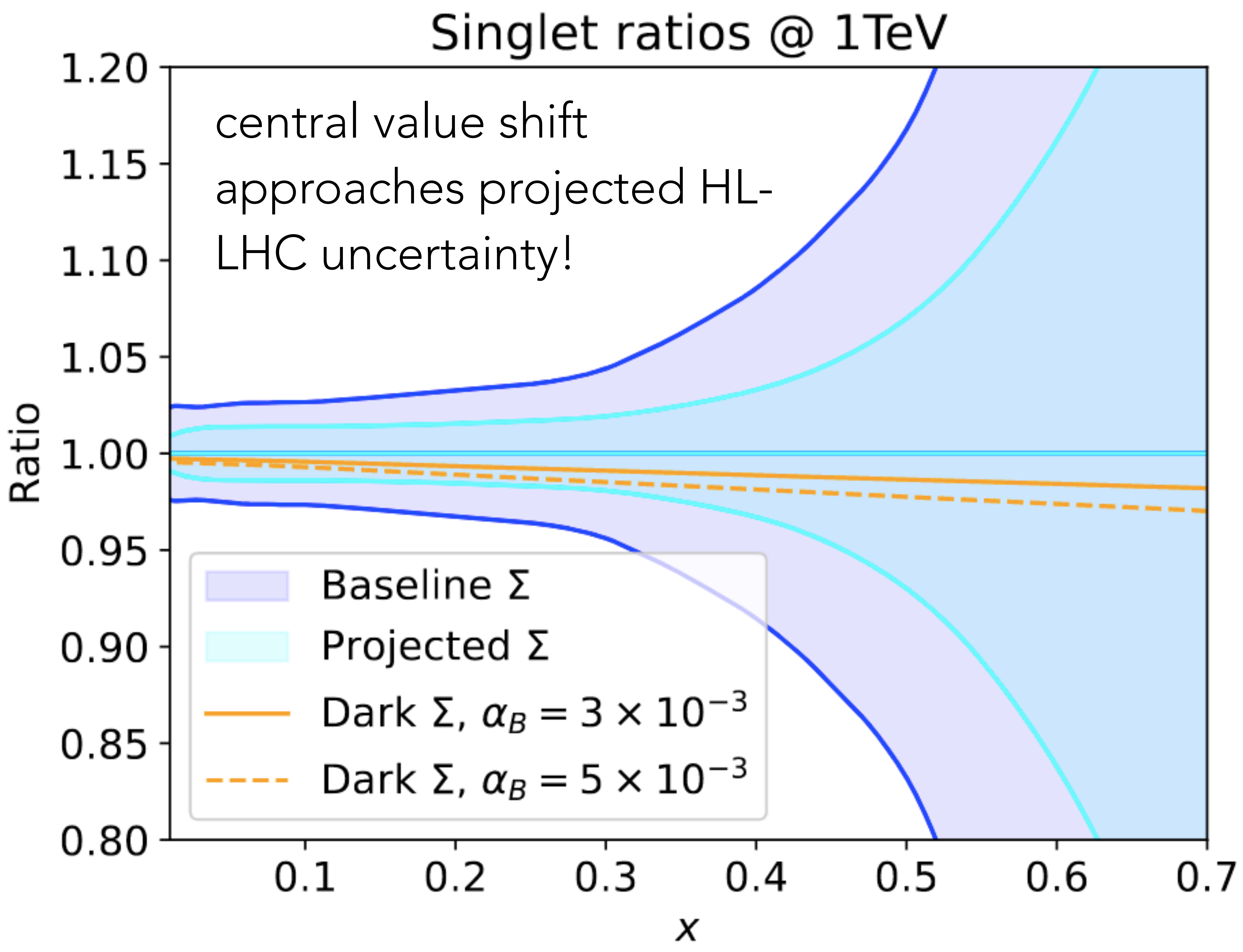
$$P_{BB}(x) = -\frac{2}{27}\delta(1-x)$$

DGLAP in the presence of dark photons

- All four splitting functions are multiplied by $\alpha_B = g_B^2/4\pi$ in the DGLAP equations. Assuming a dark coupling of order $\alpha_B \sim 0.001$ (reasonable in the literature for this model), we see that we must also include:
  - NNLO QCD effects, $\alpha_S^3 \sim 0.001$
  - LO QED effects, $\alpha \sim 0.01$ (this implies that we must use a **photon PDF**; we use the LUXQED PDF from the NNPDF3.1 QED baseline)
  - QED-QCD mixing, $\alpha\alpha_S \sim 0.001$
- These contributions are well-known and already implemented in the **APFEL public evolution code**, which we modify in our work.

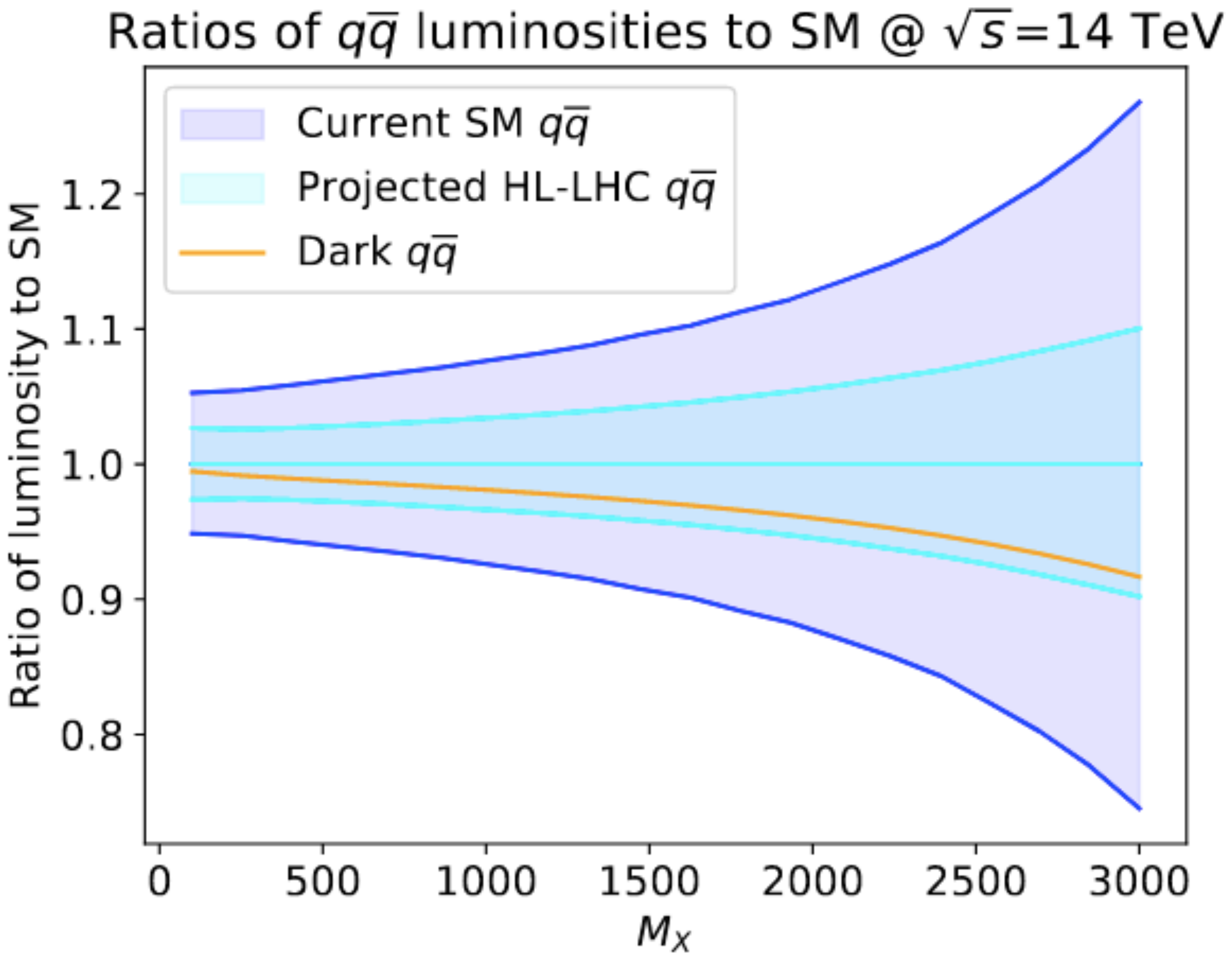
Impact on PDFs and parton luminosities

- We can now study the impact of including a dark photon in DGLAP evolution on **PDFs** and **parton luminosities**, and hence on **theoretical predictions for collider processes**.
- E.g. including a dark photon modifies the **singlet PDF**, as shown on the right. Light blue bands correspond to **projected PDF** uncertainty at the **HL-LHC** (see 1810.03639).
- 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.

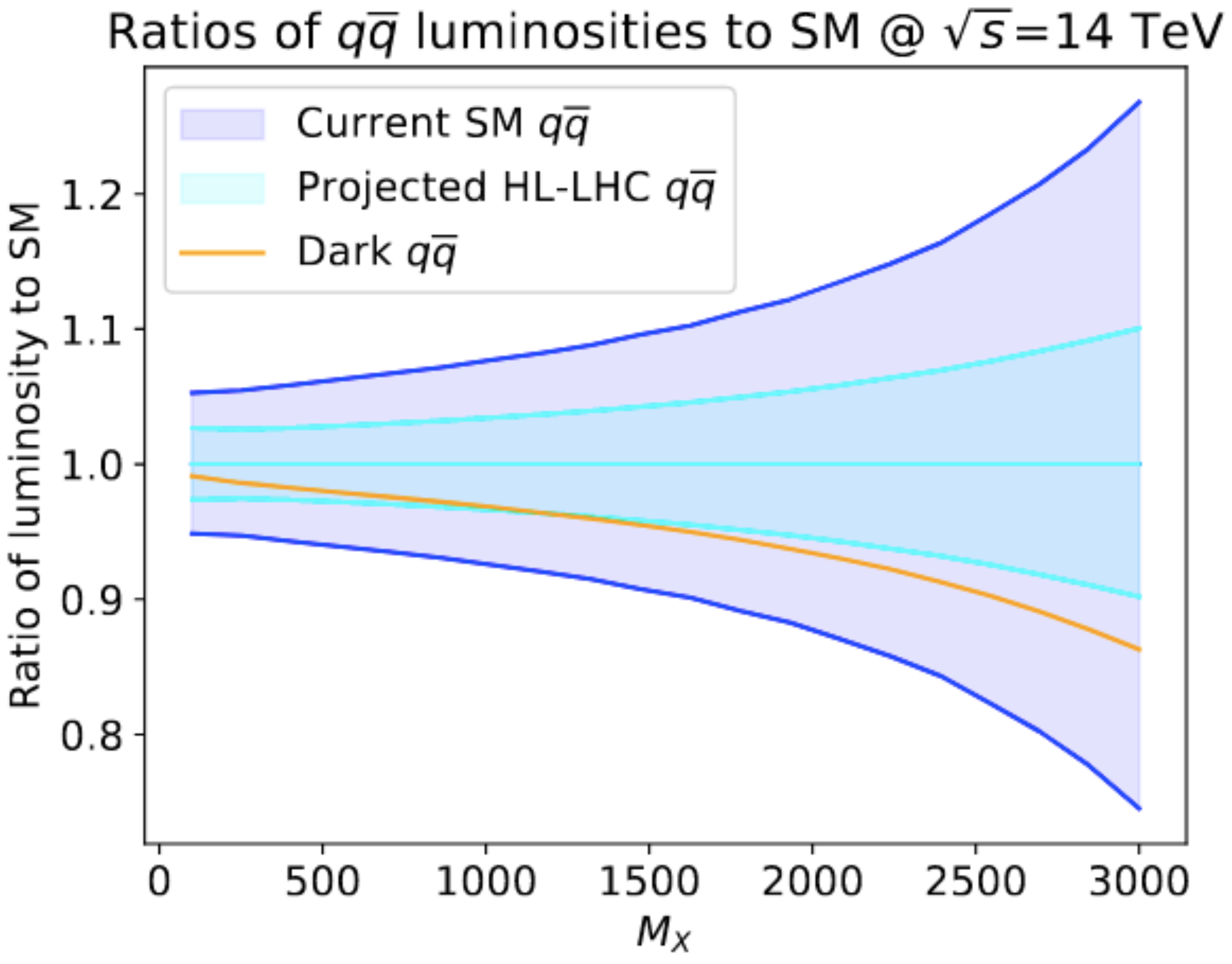


Impact on PDFs and parton luminosities

- 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, $\alpha_B = 3 \times 10^{-3}$



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

Impact on PDFs and parton luminosities

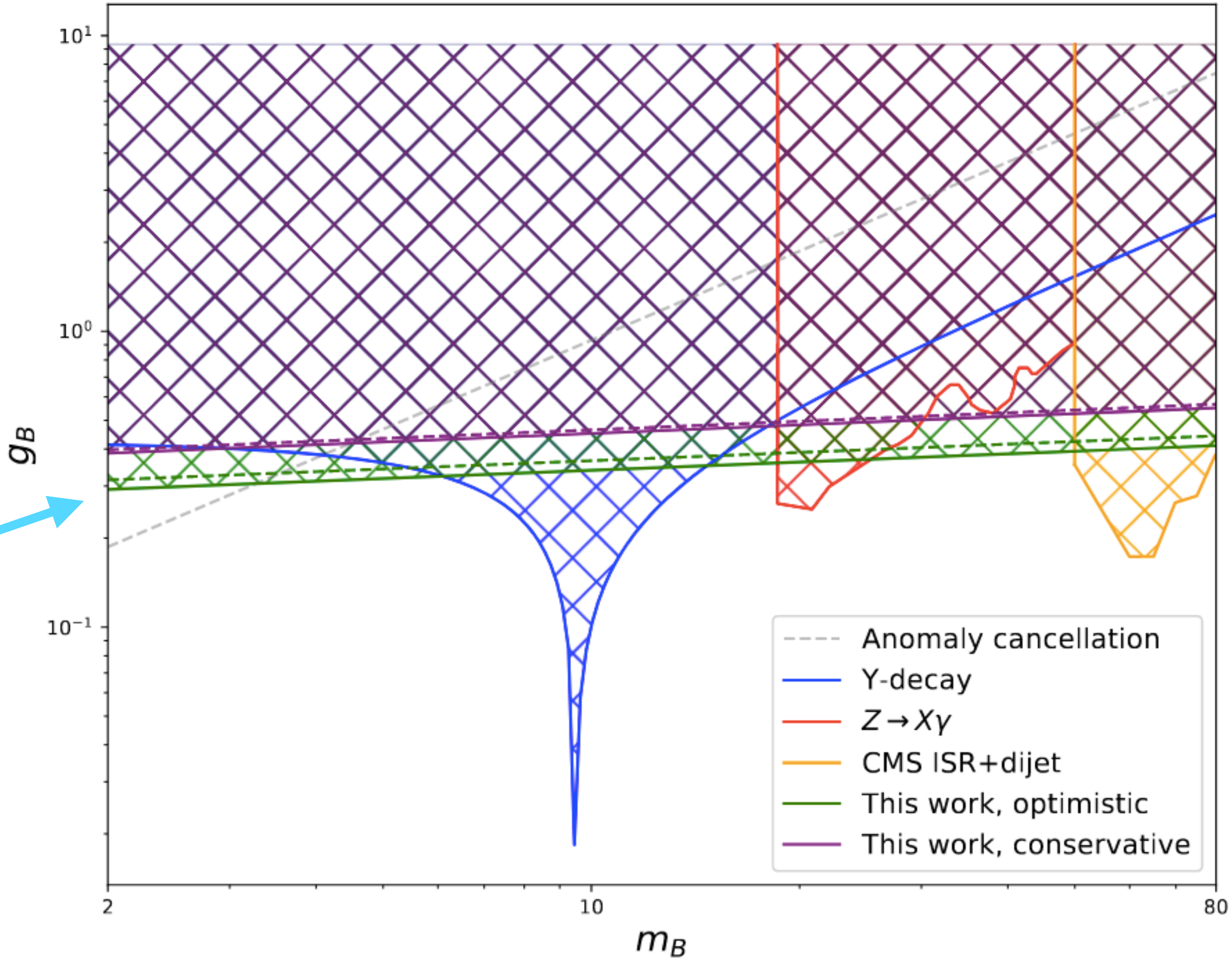
- Results we have seen so far suggest that we can definitely hope to constrain the dark photon's mass and coupling using DY data, **provided** we work with **HL-LHC projections** and **assume that PDF uncertainties will shrink as predicted**.
- We obtain **projected bounds** as follows:

1. Construct a large ensemble of 'dark' PDF sets, one for each point for a grid in dark parameter space (we use 32 points, so 32 PDF sets).
2. Construct predictions for a specific DY observable for each PDF set and compute the χ^2-statistic.
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.
- Two sets of projected data are used, corresponding to the following two scenarios:
  - *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

4. - Conclusions

Conclusions

- **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!
Quick questions before discussion?