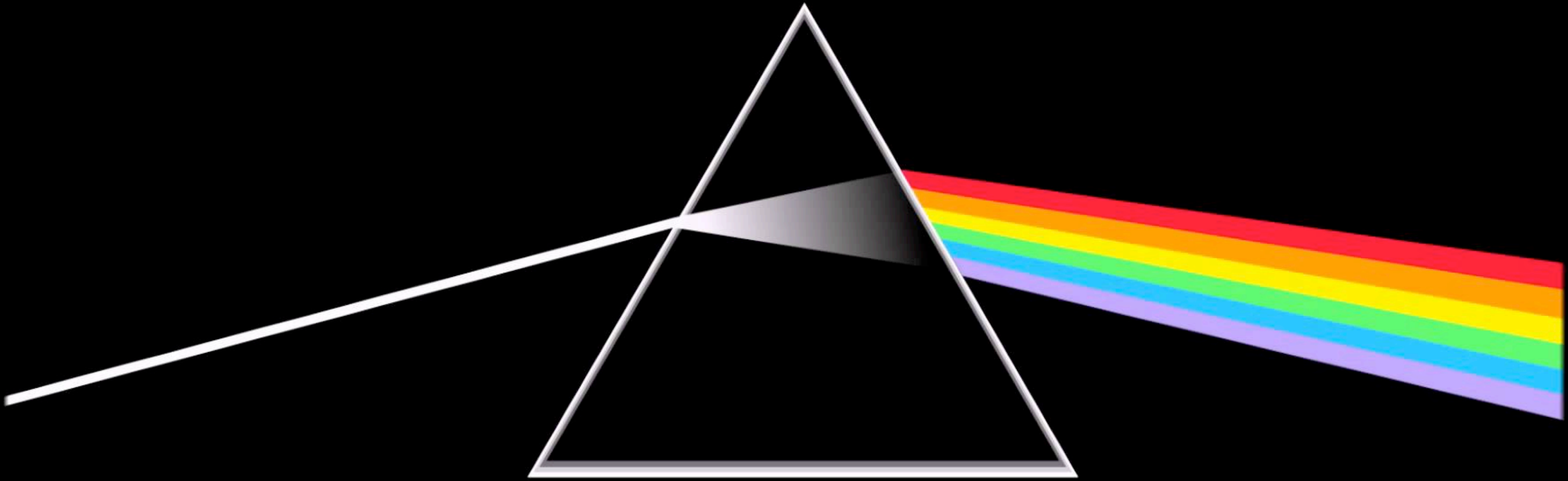
THE DARK SIDE OF THE PROTON



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PBSP

TALK OUTLINE

1. **Background: PDFs and dark matter**
2. **PDFs for colourless partons**
3. **‘Dark’ PDF sets**
4. **Phenomenology of the ‘dark’ PDF sets**

1. BACKGROUND: PARTON DISTRIBUTIONS AND DARK MATTER

HADRON STRUCTURE THROUGH PDFS

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

$$\mathscr{L} = -\frac{1}{4}G^{a}_{\mu\nu}G^{a,\mu\nu} + \sum_{q} \overline{q}(i\gamma^{\mu}D_{\mu} - m_{q})q \quad \longrightarrow \quad \text{hadrons?}$$

- 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).**

HADRON STRUCTURE THROUGH PDFS

- In more detail, PDFs describe the **number density** of different constituents of a hadron carrying different fractions of the hadron's total momentum*.
- The number of partons of type q inside a hadron H with momentum in the (infinitesimal) interval $[x, x + dx]$ is given by:

$$\underbrace{f_{q/H}}_{\text{parton flavour}}\underbrace{(x)}_{\text{momentum fraction}}\ dx$$

HADRON STRUCTURE THROUGH PDFS

- Theory predictions are then obtained from the **QCD factorisation theorems**, e.g. for processes with two hadrons in the initial state:

$$\sigma_{H_1H_2}(s) = \sum_{X,q_1,q_2} \int_0^1 \int_0^1 dx_1 dx_2 \; f_{q_1/H_1}(x_1) f_{q_2/H_2}(x_2) \hat{\sigma}_{q_1q_2 \to X}(s x_1 x_2)$$

partonic cross-section,
from QCD perturbation theory

- Formula valid provided we work at **sufficiently high energies.**

PDF EVOLUTION

- **Infrared divergences** in the partonic cross-section require that we **regulate** and **renormalise** the theory, similar to the way ultraviolet divergences are handled in basic QFT.
- In particular, **collinear infrared divergences** are absorbed into the PDFs, so that they acquire a dependence on an arbitrary **factorisation scale** μ_F:

$$f_{q/H}(\underset{\substack{\nearrow \\ \text{momentum fraction}}}{x}, \underset{\substack{\nwarrow \\ \text{factorisation scale}}}{\mu_F^2})$$

PDF EVOLUTION

- **Invariance of observables** under changing the factorisation scale implies a Callan-Symanzik equation for the PDFs, called the **DGLAP equation:**

$$\mu_F^2 \frac{\partial f_{q_i/H}}{\partial \mu_F^2} = \sum_{q_j} \int_x^1 \frac{dy}{y}\, P_{q_i q_j}\left(\frac{x}{y}\right) f_{q_j/H}(y, \mu_F^2)$$

‘splitting function’

- Factorisation scale is usually identified with a characteristic energy scale for a process under consideration, $\mu_F^2 = Q^2$, so PDF evolution corresponds to **increasing resolution** of a hadron’s structure.

PDF EVOLUTION

$$\mu_F^2 \frac{\partial f_{q_i/H}}{\partial \mu_F^2} = \sum_{q_j} \int_x^1 \frac{dy}{y}\; P_{q_i q_j}\left(\frac{x}{y}\right) f_{q_j/H}(y, \mu_F^2)$$

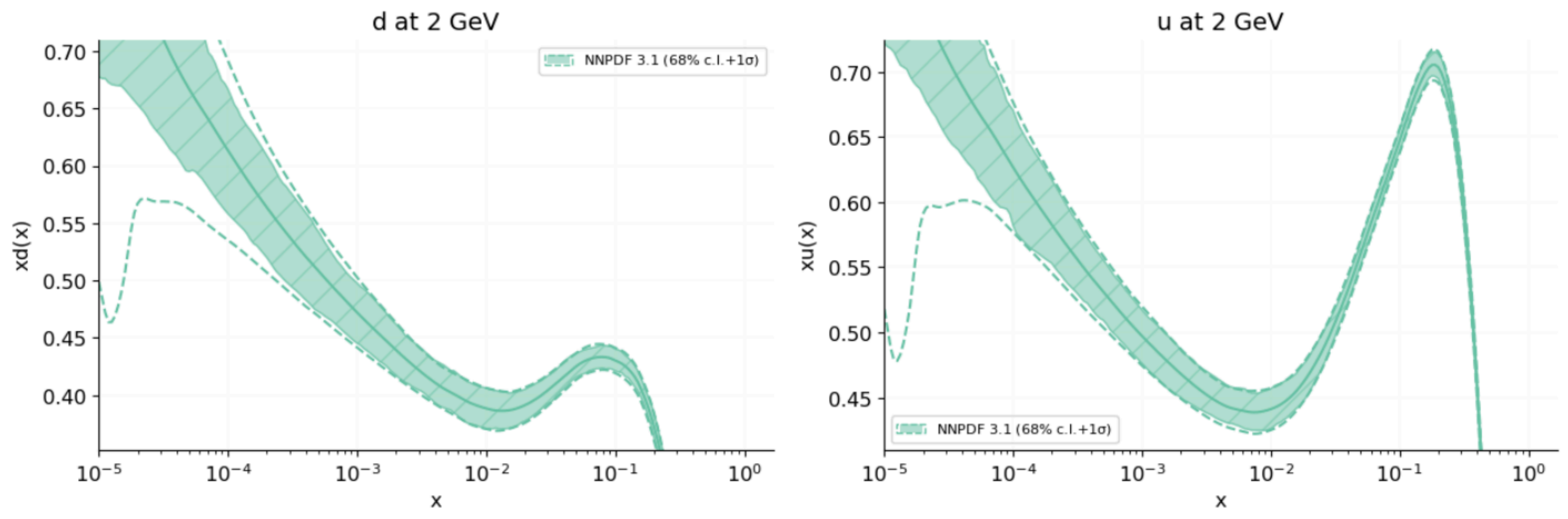
- **Splitting functions** $P_{q_i q_j}$ roughly correspond to the ‘probability of radiating one parton flavour from another’.

- They can be computed in **perturbation theory**, in particular by looking at the most **collinearly divergent** part of certain partonic cross-sections.

$$P_{ij} = \left(\frac{\alpha_S}{2\pi}\right) P_{ij}^{(1,0)} + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ij}^{(2,0)} + \left(\frac{\alpha_S}{2\pi}\right)\left(\frac{\alpha}{2\pi}\right) P_{ij}^{(1,1)} + \cdots$$

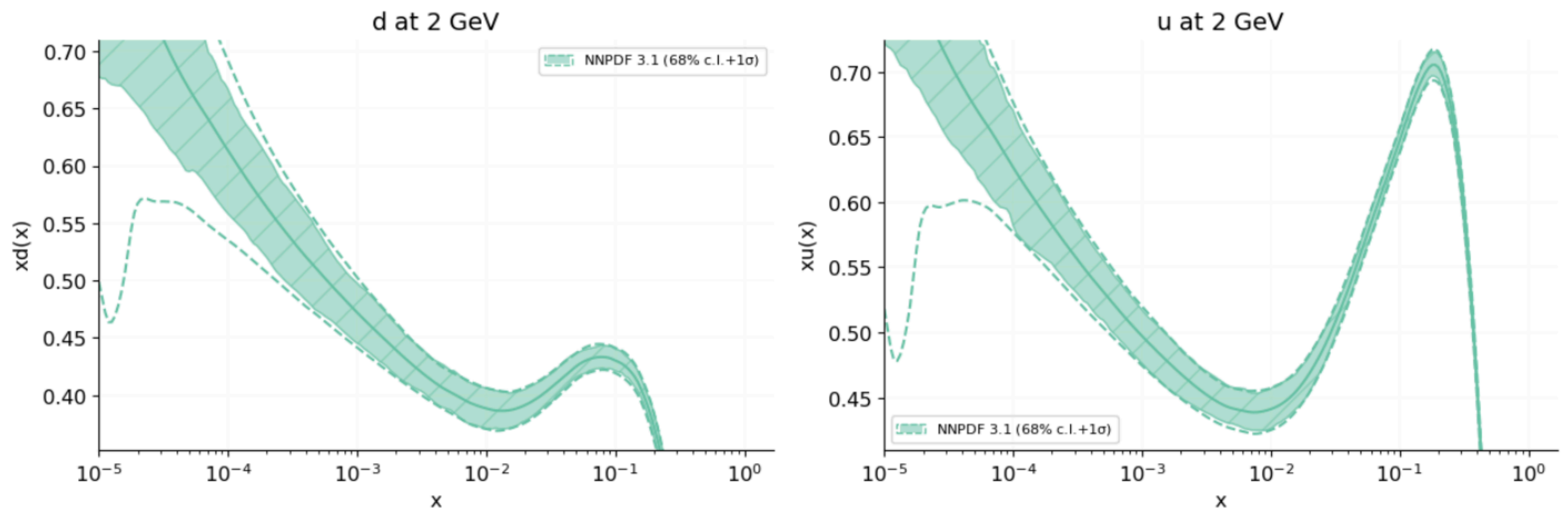
DETAILED EXAMPLE: PROTON PDFS

- In the proton (naively thought of as **'2 up quarks and 1 down quark'**) the (NNPDF 3.1) PDFs for the **up** and **down** quarks are shown below at the factorisation scale 2 GeV.



DETAILED EXAMPLE: PROTON PDFS

- Naively expect distributions to be **peaked at 1/3**, but quantum fluctuations produce additional **virtual long-lived partons** with **small momentum fractions**, pushing up the distributions at smaller values of x.



DETAILED EXAMPLE: PROTON PDFS

- **Quantum fluctuations** don't just push up the distributions of the **valence quarks** u and d; they also result in non-zero PDFs for **other flavours too.**
- In particular, we also obtain **gluon PDFs** which account for almost **a half of the momentum** carried by the proton.
- Similarly, we have PDFs for other **coloured** particles (**strange**, etc.), but also **colourless** particles, e.g. the **photon.**

KEY QUESTION:

Is there enough space inside the proton for **new, hypothetical particles** (e.g. dark matter)?

NEW 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 proton structure.

- *Idea:* now PDFs are known **very precisely**, and their uncertainties **will continue to reduce in the near future**, could we do the same for a **colourless** particle too?

- E.g. a **dark matter candidate**: **neutral** and **colourless.**

DARK MATTER IN THE PROTON

- The best chance we have to see a significant change in proton structure is to choose a dark matter candidate coupling primarily to **quarks** instead of **leptons**.

- We choose to introduce a **leptophobic dark photon** B, which simply augments the SM Lagrangian by an **effective** interaction term:

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

DARK MATTER IN THE PROTON

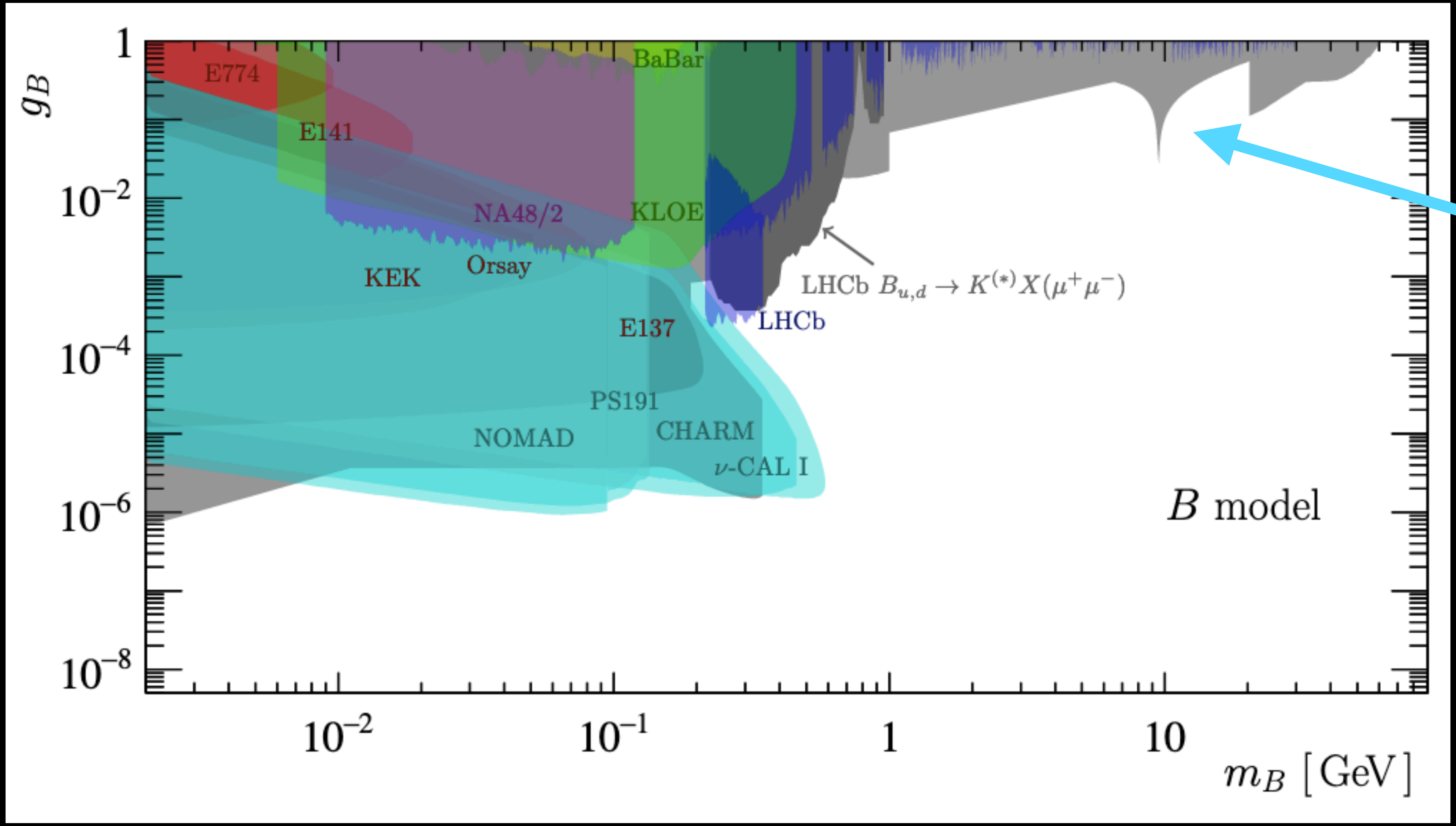
$$\mathscr{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \gamma^\mu B_\mu q$$

- As long as we treat this as an **effective theory**, valid up to the **mass of the Z-boson** where **kinetic mixing** effects become important, we can **remain agnostic** about any specific **UV-completion**.

- In particular, we don't commit to any model-dependent features, e.g. the requirement of certain **anomaly-cancelling fermions**.

DARK MATTER IN THE PROTON

- The model is already constrained by lots of experimental and theoretical methods; a summary is given in Ilten et al., 1803.06347.



grey: collider/
anomaly
constraints

- We hence focus on the region $m_B \in [2,80]$ GeV.

(MORE SPECIFIC) KEY QUESTION:

Is there enough space inside the proton for an **additional leptophobic 'dark' photon**, described by the model above, with mass $m_B \in [2,80]$ GeV?

2. PDFS FOR COLOURLESS PARTONS

COLOURLESS PARTONS

- How can we include a new dark photon PDF? In general, this is **more subtle** because the dark photon is **colourless**.
- In particular, PDFs for colourless partons are **very small** compared to coloured flavours, so they can be **challenging to determine**.
- To introduce the main ideas, let’s see how the (SM) **photon PDF** has been treated historically.

PHOTON PDFS: METHOD 1

- There are three main routes one can take in introducing a photon PDF, organised chronologically:

1. Avoid **determination** altogether. Instead, use a **phenomenologically-motivated model**, as in MRST 0411040 (from 2004).

   MRST assume a photon PDF at some **initial scale** Q_0^2 of the form:

$$\gamma(x, Q_0^2) = \frac{\alpha}{2\pi} \sum_q e_q^2 \log\left(\frac{Q_0^2}{m_q^2}\right) P_{\gamma q} \otimes q(Q_0^2)$$

PHOTON PDFS: METHOD 1

initial quark distributions from some reference set

$$\gamma(x, Q_0^2) = \frac{\alpha}{2\pi}\sum_q e_q^2 \log\left(\frac{Q_0^2}{m_q^2}\right) P_{\gamma q} \otimes q(Q_0^2)$$

QED coupling

'probability' of quark radiating photon

- Essentially, this is a leading-order solution to the DGLAP equations assuming the quarks PDFs are 'frozen' beneath the initial scale Q_0^2.
- Physically we imagine that **photons in the proton are generated only by quark splitting** at this scale.

PHOTON PDFS: METHOD 1

- Choosing this functional form for the photon PDF at the initial scale, we then **evolve** using the **QED-modified DGLAP equations:**

$$Q^2 \frac{\partial f_{q_i}}{\partial Q^2} = \sum_{q_j} \int_x^1 \frac{dy}{y} \, P_{q_i q_j}\left(\frac{x}{y}\right) f_{q_j}(y, Q^2)$$

sum now includes photons

extra splitting functions

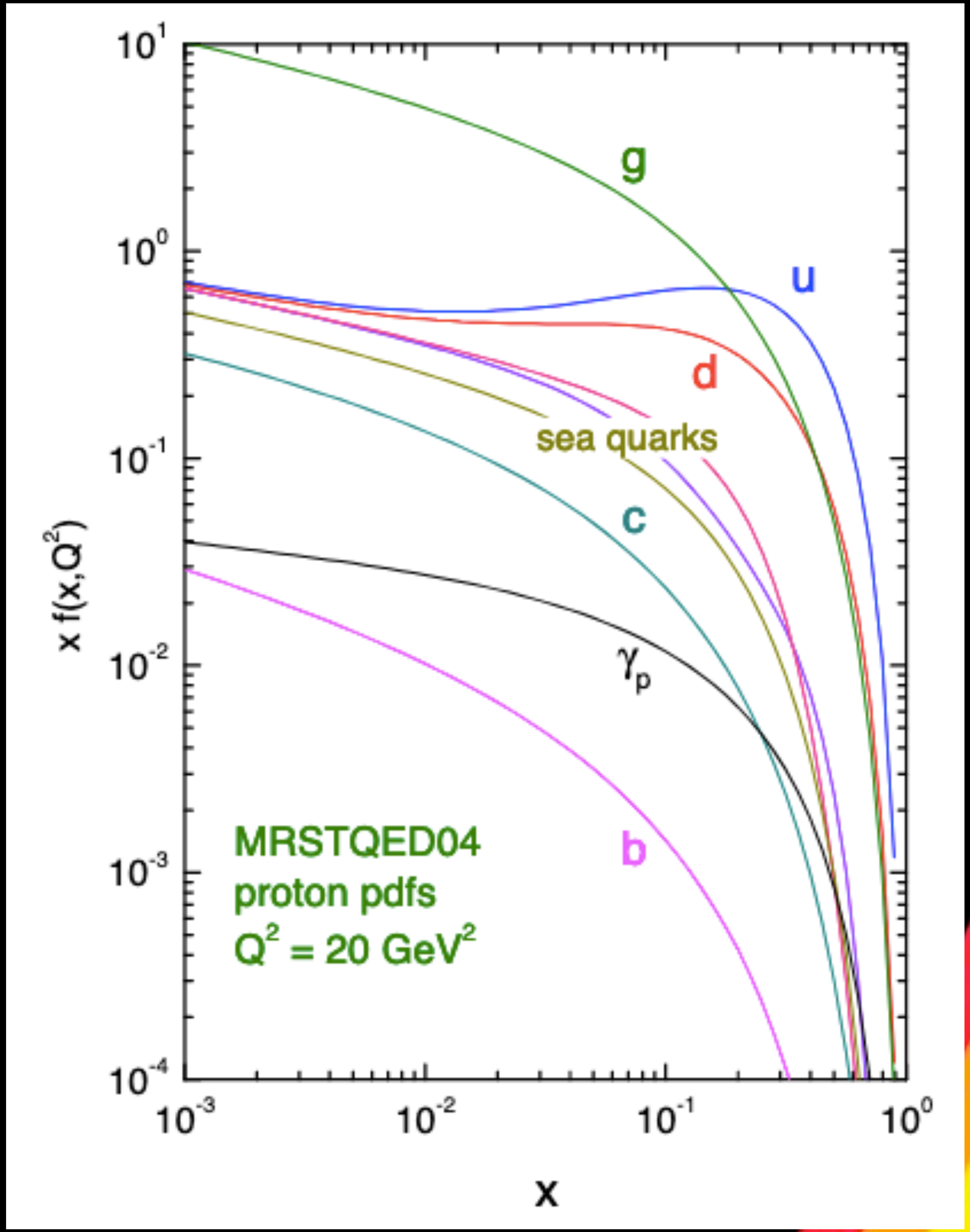
$$P_{q\gamma}(x) = 2(x^2 + (1-x)^2) \qquad P_{\gamma q}(x) = 2\left[\frac{1+(1-x)^2}{x}\right] \qquad P_{\gamma\gamma}(x) = -\frac{4}{3}\delta(1-x)$$

PHOTON PDFS: METHOD 1

- The quark and gluon PDFs are now **modified relative to the original reference set**, because of the inclusion of the photon PDF in the PDF evolution (the gluon effect is second-order, though).

- This **modifies predictions** for **observables**, allowing us to assess the impact of including a photon PDF in the proton structure, versus ignoring its contribution.

- Same idea holds completely analogously for a **dark photon PDF.**



PDFs from MRST 0411040

PHOTON PDFS: METHOD 2

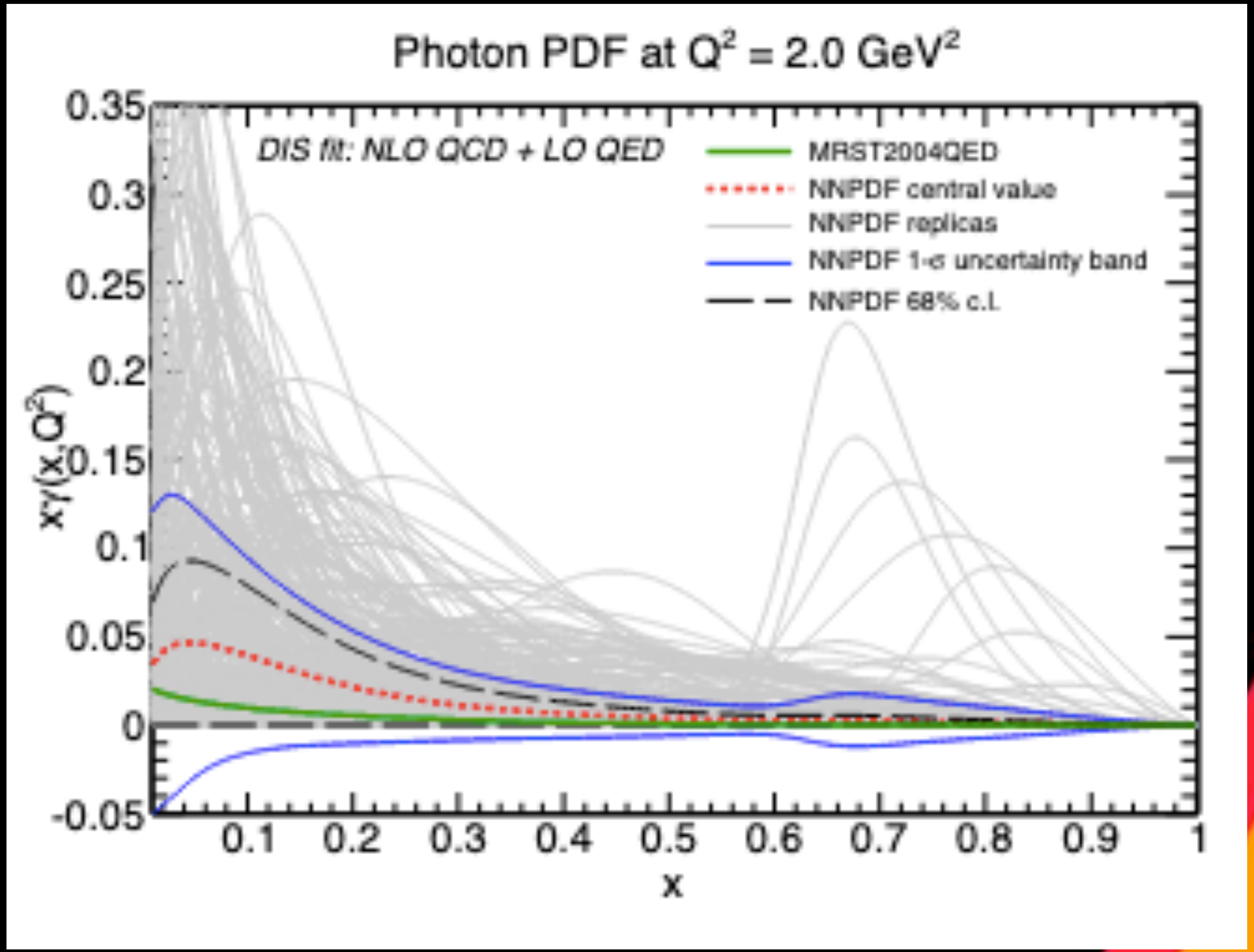
- However, **improved methods** do exist for photon PDF determination. The second chronologically is:

  2. **Fitting** the photon PDF to data. Instead of just modifying PDF evolution by including extra splitting functions and an extra PDF, we also modify the **partonic cross-section** in the factorisation formula.

     This allows us to **fit the photon PDF** like any other flavour. But this is much more **labour-intensive:** need to compute photon contributions to many observables.

PHOTON PDFS: METHOD 2

- This method was adopted by members of the **NNPDF collaboration** in 1308.0598.
- **Deep-inelastic scattering** data, along with **W/Z production** data from the LHC, was used to provide the first **fitted** photon PDF, **including uncertainties**.
- The photon PDF uncertainties were initially **relatively large**.



Photon PDF from 1308.0598

PHOTON PDFS: METHOD 3

- The final approach is the most surprising! It played an essential role in **reducing PDF uncertainty** on the photon distributions.

  3. Amazingly, the photon PDF can be described **perturbatively** in terms of DIS **structure functions**; this is the cutting-edge **LUXQED method**. It was introduced by Manohar et al. in 1607.04266.

     The 'bare bones' description is: the photon can be treated either as a **mediator** of DIS or as a **constituent of the proton**; the requirement that both approaches agree gives an **analytic formula** for the photon PDF at **all scales**.

PHOTON PDFS: METHOD 3

$$\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \int_{x^2 m_P^2/(1-z)}^{\mu^2/(1-z)} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(zP_{\gamma q}(z) + \frac{2x^2 m_P^2}{Q^2} \right) F_2^\gamma\left(\frac{x}{z}, Q^2\right) - z^2 F_L^\gamma\left(\frac{x}{z}, Q^2\right) \right]$$

$$-\alpha^2(\mu^2) z^2 F_2^\gamma\left(\frac{x}{z}, Q^2\right)$$

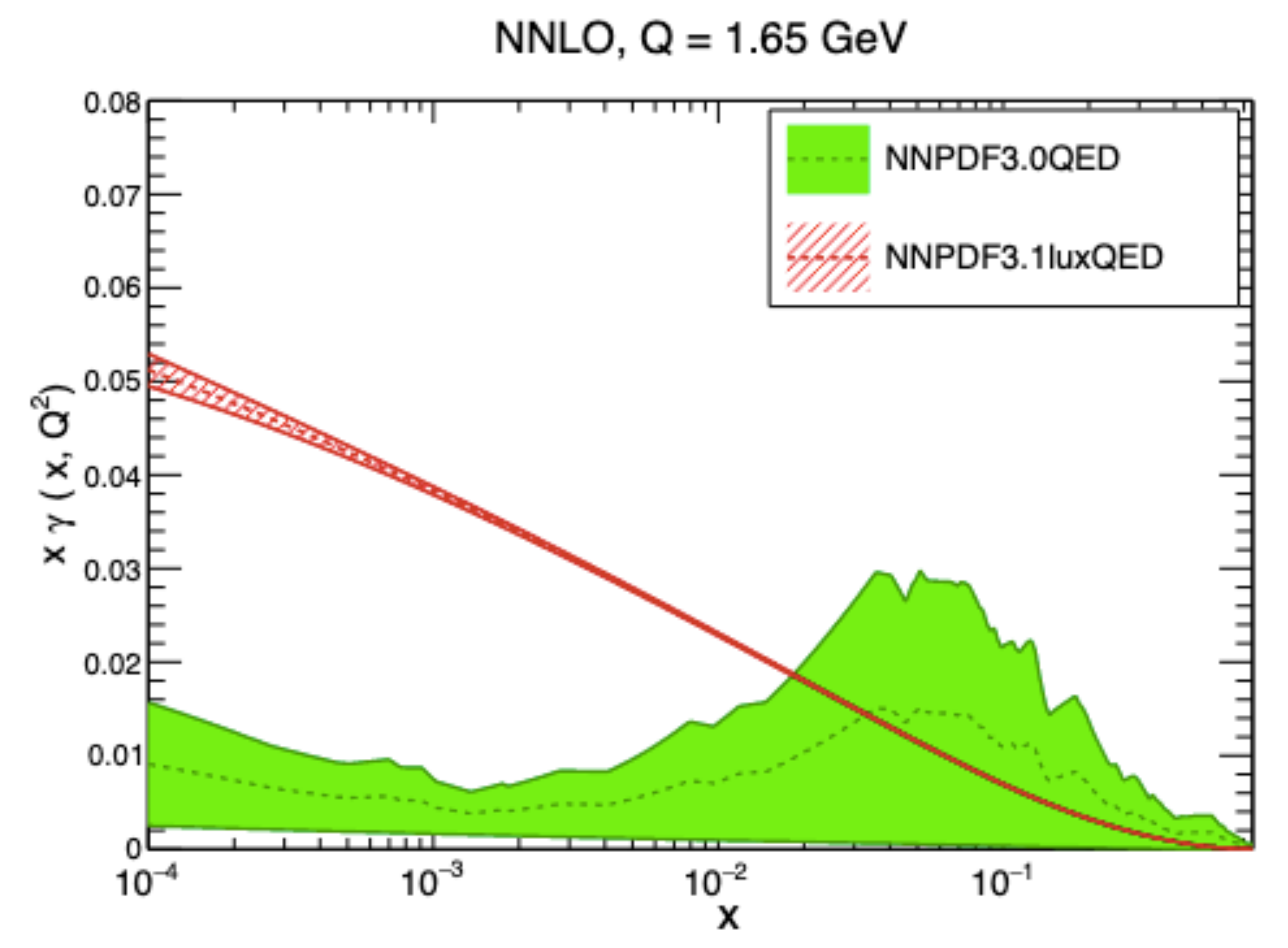
structure function
for **photon-induced** DIS

- The formula is **perturbative**, and can be improved **order by order in QED.**

- Since structure functions are (essentially) observable, can just do **integration** to get the photon PDF!

PHOTON PDFS: METHOD 3

- The method was eventually included in the **NNPDF framework**, in 1712.07053, allowing for the production of the precise **NNPDF3.1 LUXQED set**.
- Not only were uncertainties **drastically reduced** compared to the previous NNPDF determinations, but additionally the central value shifted by up to 40% in regions with less data in the former fit!



Photon PDF from 1712.07053

3. ‘DARK’ PDF SETS

DARK PDF SETS

- In order to include a **dark photon** then, we can try to follow one of the three approaches outlined above:
  - **Method 1:** Compute dark photon splitting functions, and use an ansatz for the dark photon PDF at the initial scale. Evolve using modified DGLAP and see how other PDFs change. *Possible!*
  - **Method 2:** Fit to data. *Not possible without new, very* ***labour-intensive*** *technology (would need to generalise the fast-convolution grids - APPLgrids - produced by MadGraph5 to include dark photons).*

DARK PDF SETS

- **Method 3:** Use the LUXQED method for the dark photon PDF. This is possible (and an analytic formula can be derived), but there are some technical subtleties. In particular:

  - We would need to split the experimental structure functions into ‘photon induced’ and ‘dark-photon induced’, which would involve some novel fitting machinery.

  - **More concerning**: interference between photon-mediated and dark-photon mediated DIS implies the need to introduce an additional **photon-dark photon interference PDF**. This is described in an analysis of Z-boson PDFs in Manohar et al., 1803.06347.

DARK PDF SETS

- In short: **Method 1** is only viable option for a first study. The steps are:

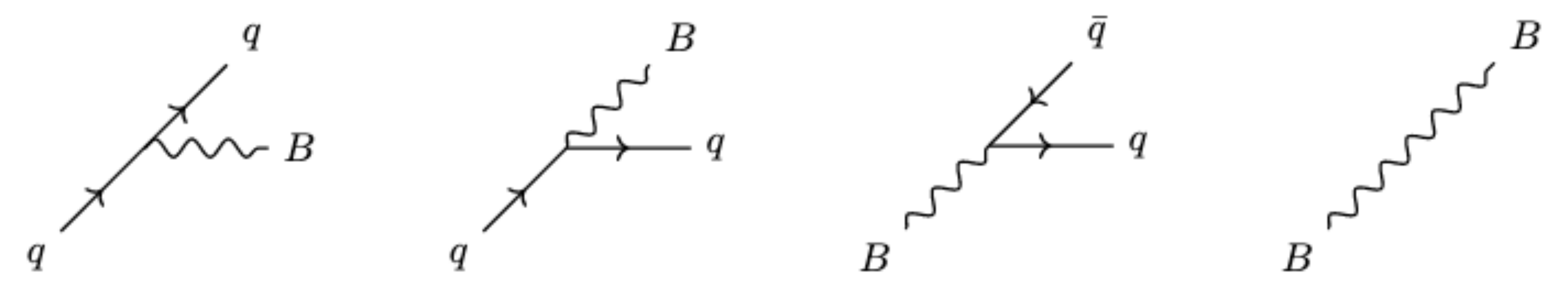
  1. Compute the dark photon splitting functions, and add them to the DGLAP evolution.

  2. Starting from an appropriate initial-scale ansatz, and a reference PDF set, evolve using the modified DGLAP equations.

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

DARK SPLITTING FUNCTIONS

- The first step is **straightforward**: the splitting function calculation is completely analogous to that of the **photon** splitting function calculation.



- Splitting occurs in four channels, giving four splitting functions:

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

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

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

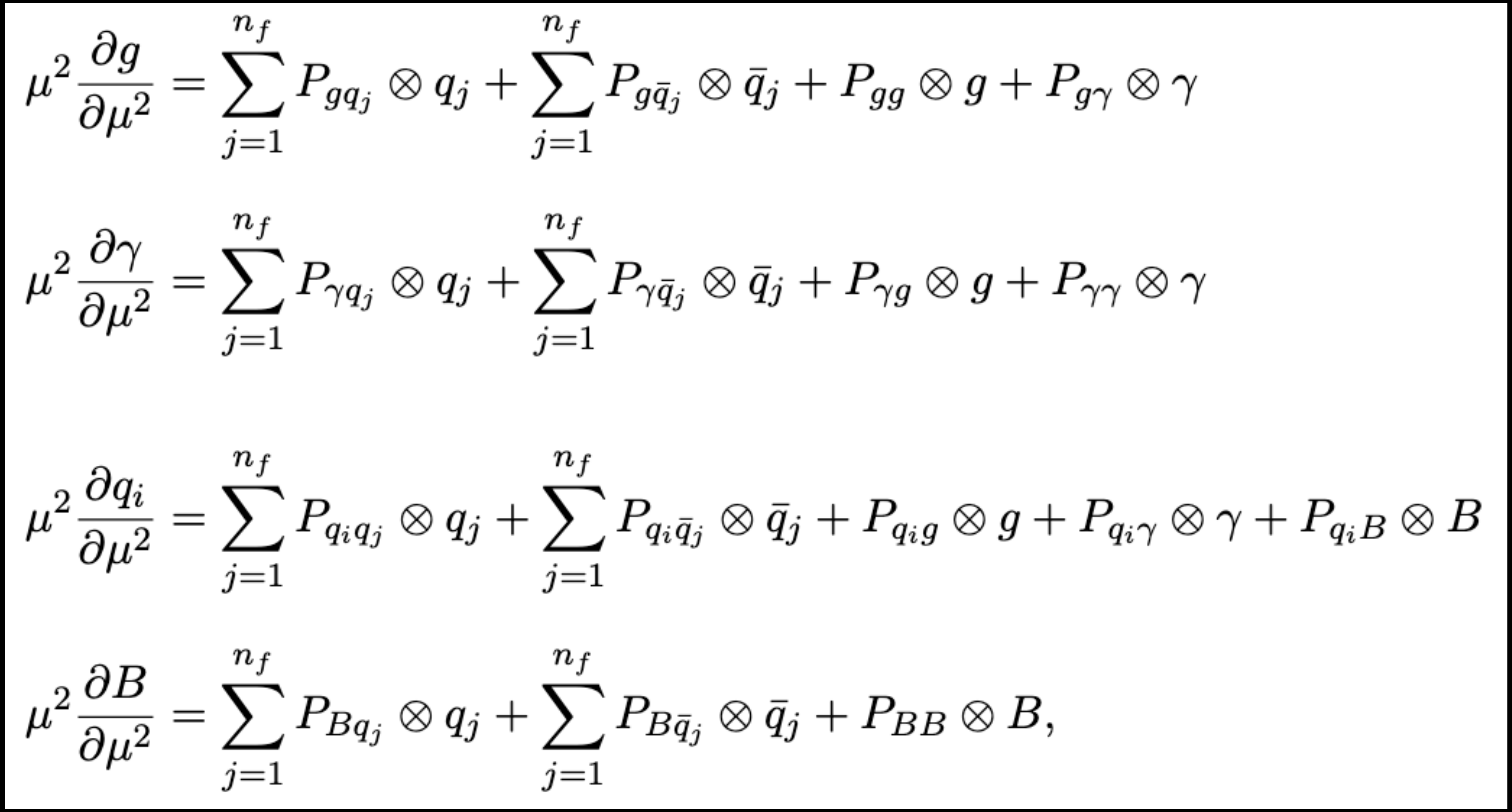
$$P_{Bq}(x) = \frac{1}{9}\left(\frac{1+(1-x)^2}{x}\right)$$

DARK SPLITTING FUNCTIONS

- 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)
  - 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.

DARK SPLITTING FUNCTIONS

- Overall, the DGLAP equations are modified to:



$$\mu^2 \frac{\partial g}{\partial \mu^2} = \sum_{j=1}^{n_f} P_{g q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{g \bar{q}_j} \otimes \bar{q}_j + P_{gg} \otimes g + P_{g\gamma} \otimes \gamma$$

$$\mu^2 \frac{\partial \gamma}{\partial \mu^2} = \sum_{j=1}^{n_f} P_{\gamma q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{\gamma \bar{q}_j} \otimes \bar{q}_j + P_{\gamma g} \otimes g + P_{\gamma\gamma} \otimes \gamma$$

$$\mu^2 \frac{\partial q_i}{\partial \mu^2} = \sum_{j=1}^{n_f} P_{q_i q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{q_i \bar{q}_j} \otimes \bar{q}_j + P_{q_i g} \otimes g + P_{q_i \gamma} \otimes \gamma + P_{q_i B} \otimes B$$

$$\mu^2 \frac{\partial B}{\partial \mu^2} = \sum_{j=1}^{n_f} P_{B q_j} \otimes q_j + \sum_{j=1}^{n_f} P_{B \bar{q}_j} \otimes \bar{q}_j + P_{BB} \otimes B,$$

INITIAL DARK PDFS

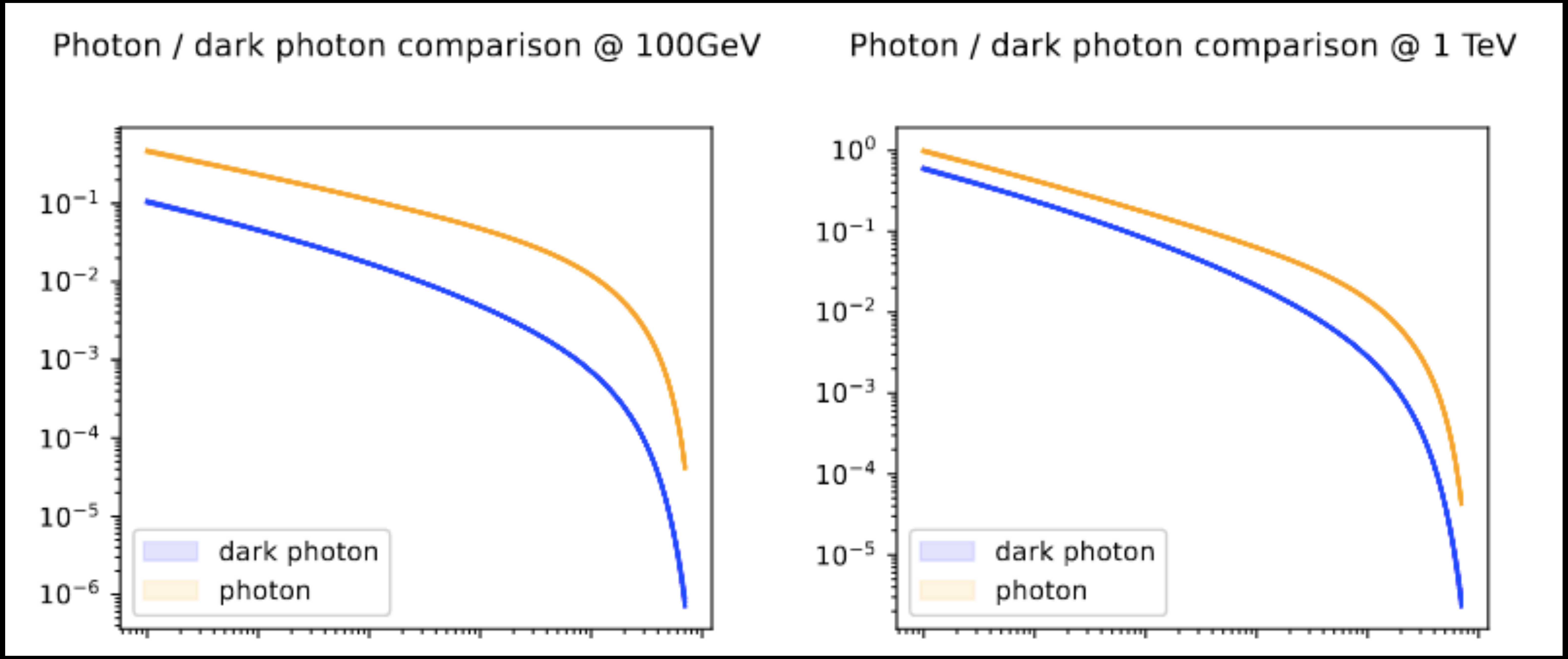
- Still need to specify **initial conditions** to solve these equations.
- Modern PDF fits use the standard initial scale $Q_0^2 = 1.65$ GeV. Since we assume $m_B \geq 2$ GeV, for the purposes of initial conditions we should treat the **dark photon** in the same way as **heavy quarks** (otherwise, we could use a **quark-splitting ansatz** like the photon one we saw earlier).
- In particular, we **freeze** the dark photon PDF to **zero** throughout the evolution from 1.65 to 2 GeV, then 'turn on' its inclusion above this scale.

INITIAL DARK PDFS

- For the other PDFs, we choose to set their initial values to the initial values of some fixed **reference set** which we will compare against.
- We choose to take the **NNPDF3.1 NNLO LUXQED** set, which is the state-of-the-art set including a photon. It will be replaced in the near future by the updated **NNPDF4.0 LUXQED** set.

EXAMPLE 'DARK' PDF SETS

- With everything specified, we can see an example! We look at a 'dark' PDF set made with $\alpha_B = 3 \times 10^{-3}$, $m_B = 50$ GeV in the next few slides.



- In the 'dark' set, the dark photon PDF takes the same functional form as the photon, but has smaller abundance.

EXAMPLE 'DARK' PDF SETS

- Quantitavely, we can look at the **momentum** carried by each flavour in the 'dark' proton. The momentum fraction carried by flavour q at scale Q^2 is defined to be:

$$\langle x\rangle_q(Q) = \int_0^1 dx \; x f_q(x, Q^2)\,.$$

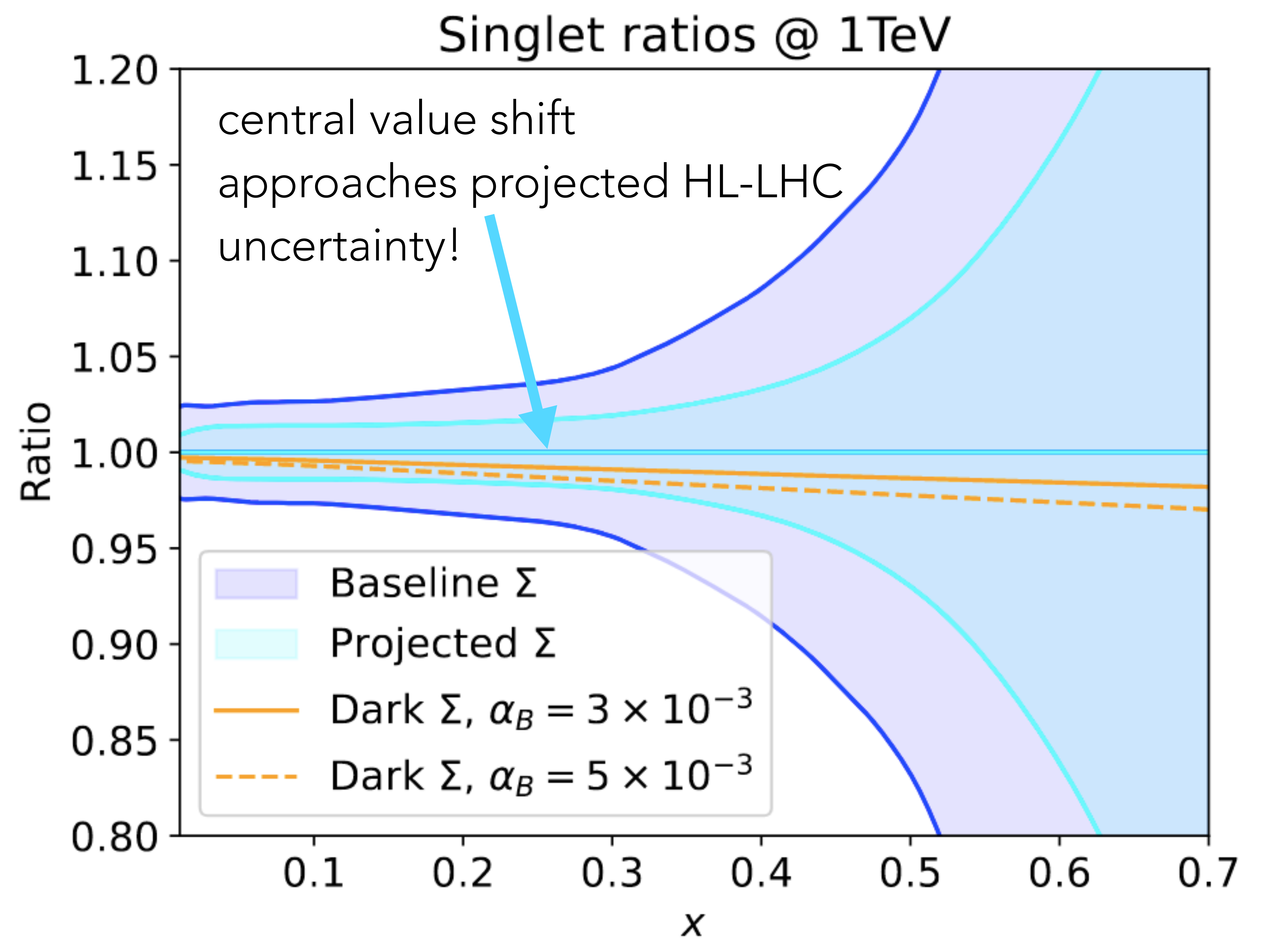
- Tabulating momentum fractions at 1 TeV, we have:

$\langle x\rangle_f(Q = 1\ \text{TeV})$	$f = \Sigma$	$f = \gamma$	$f = B$
Baseline	48.36%	0.5279%	0%
Dark set	48.12%	0.5275%	0.1357%

EXAMPLE 'DARK' PDF SETS

- We can also assess the impact of the inclusion of a dark photon on the other flavour's evolution. E.g. for the **singlet PDF** (the sum of all quark flavours' PDFs), we have the comparison on the right.

- Light blue bands correspond to **projected PDF** uncertainty at the **HL-LHC** (see 1810.03639.)

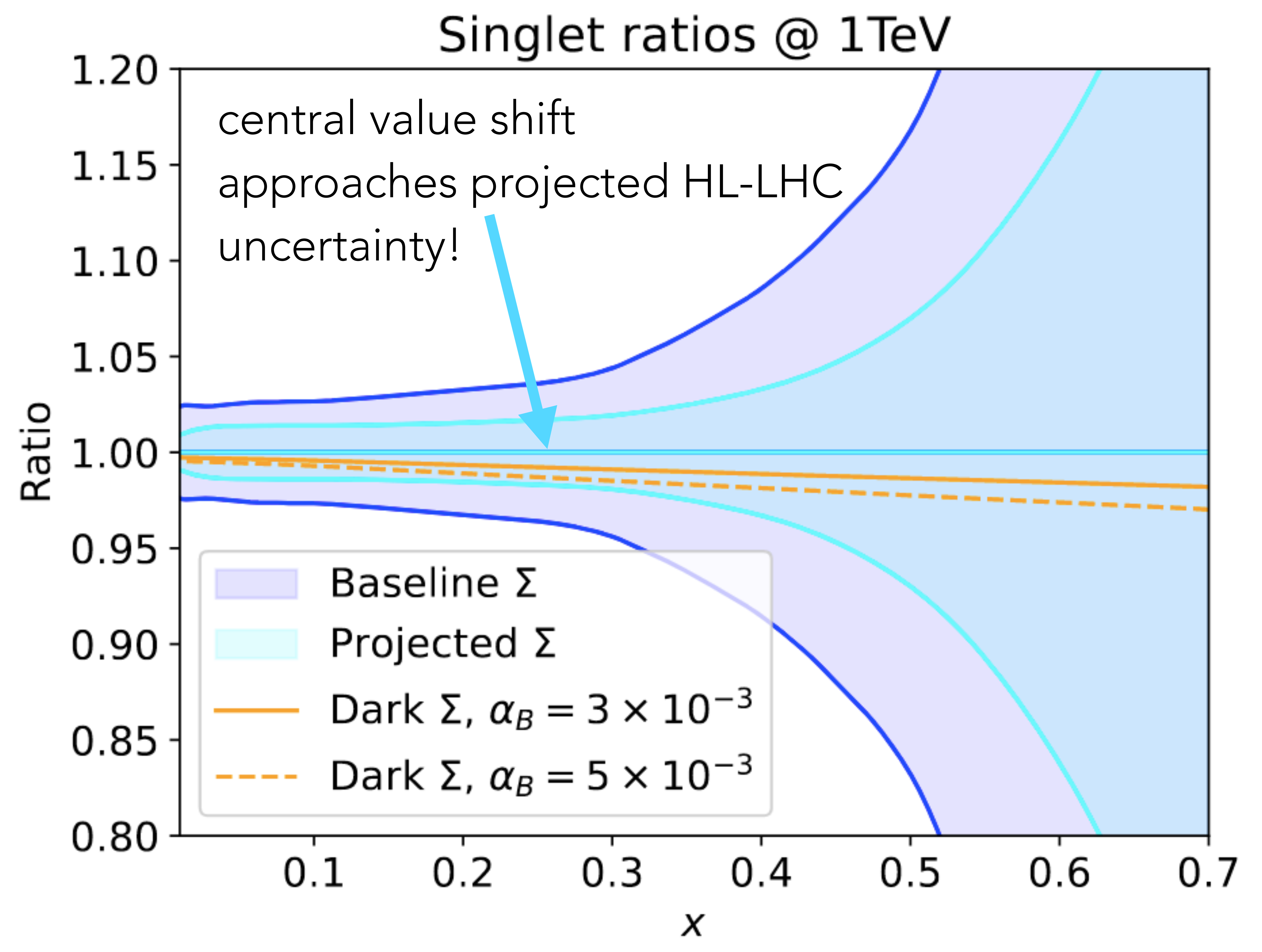


central value shift approaches projected HL-LHC uncertainty!

EXAMPLE 'DARK' PDF SETS

- Significant modification in this region is phenomenologically interesting because it's mainly constrained by **Drell-Yan data** in PDF fits.

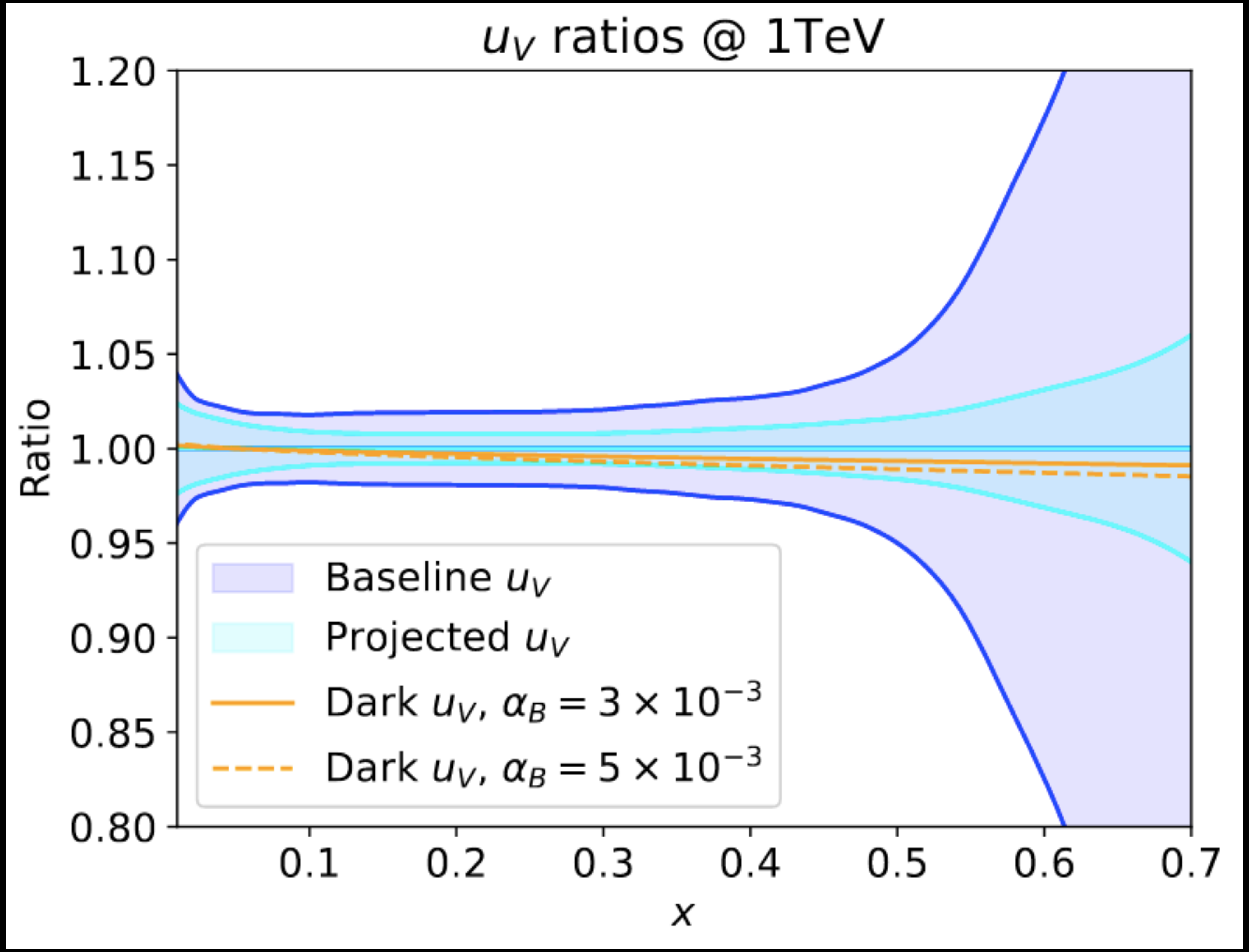
- Some values of the dark mass and coupling might lead to PDF sets which **perform too poorly** on Drell-Yan sets, relative to the baseline.



central value shift approaches projected HL-LHC uncertainty!

EXAMPLE 'DARK' PDF SETS

- Similar behaviour is seen in the u_V valence distribution, the difference between the up and anti-up PDFs.



4. PHENOMENOLOGY OF THE ‘DARK’ PDF SETS

‘DARK’ PDF LUMINOSITIES

- We have seen that including dark photons of sufficiently high coupling (or sufficiently low mass) can distort other PDF flavours considerably. In particular, we expect to be able to obtain **constraints** from **Drell-Yan data.**

- In hadron-hadron collisions like DY, PDFs contribute through **parton luminosities**, which are double-differential quantities defined by:

$$\frac{d\mathscr{L}_{ij}}{dy\,d\tau} = f_i(x_1, Q^2) f_j(x_2, Q^2), \quad x_{1,2} = \sqrt{\tau}\exp(\pm y), \quad \tau = m_X^2/s$$

invariant mass of partonic final state

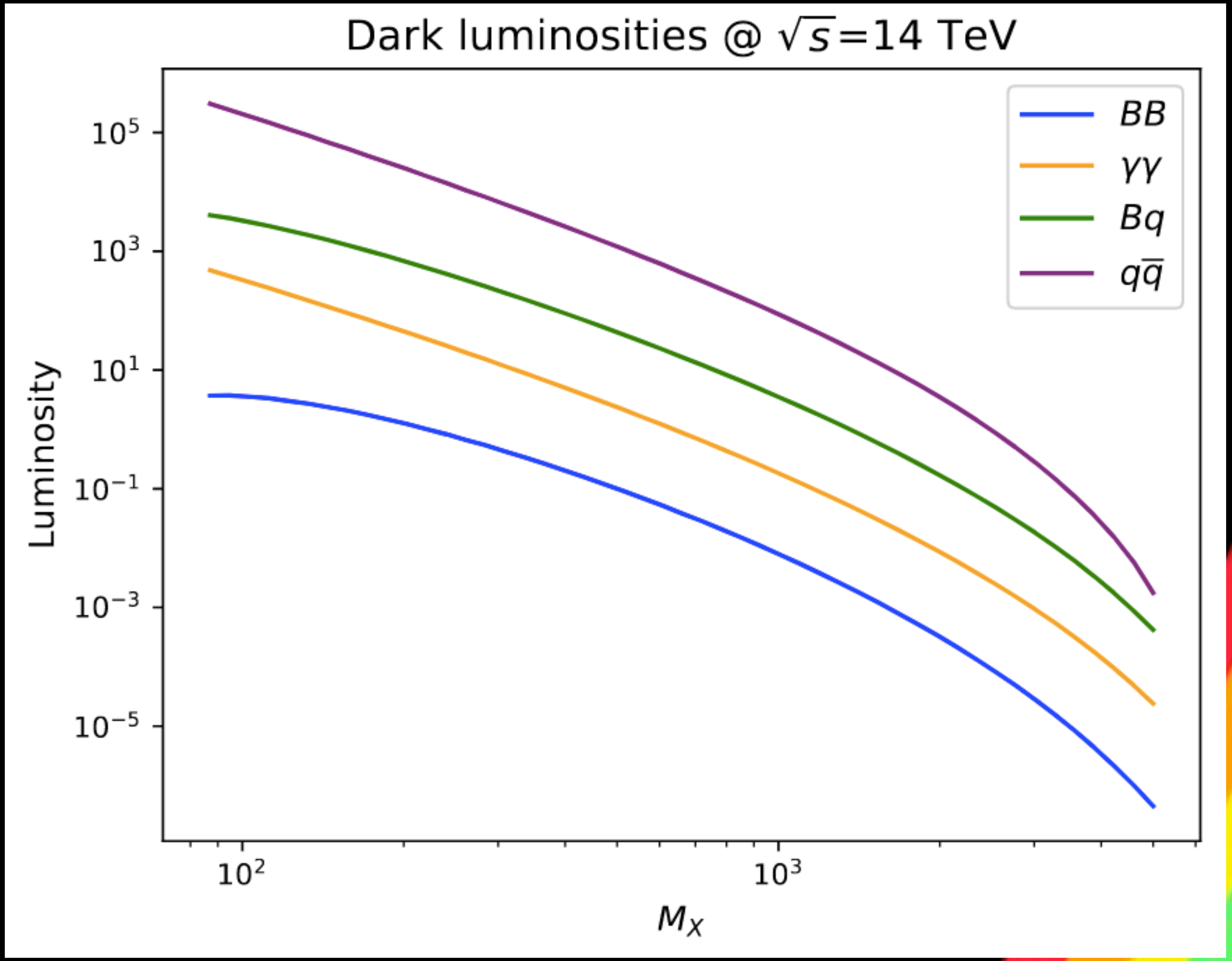
centre of mass energy

‘DARK’ PDF LUMINOSITIES

- To assess the impact of including a dark photon on dark luminosities, we look at integrated single-variable versions of the parton luminosities instead:

$$\Phi_{ij}(M_X^2) = \frac{1}{s}\int_{M_X^2/s}^{1} \frac{dx}{x}\, f_i(x, M_X^2)\, f_j\left(\frac{M_X^2}{xs}, M_X^2\right).$$

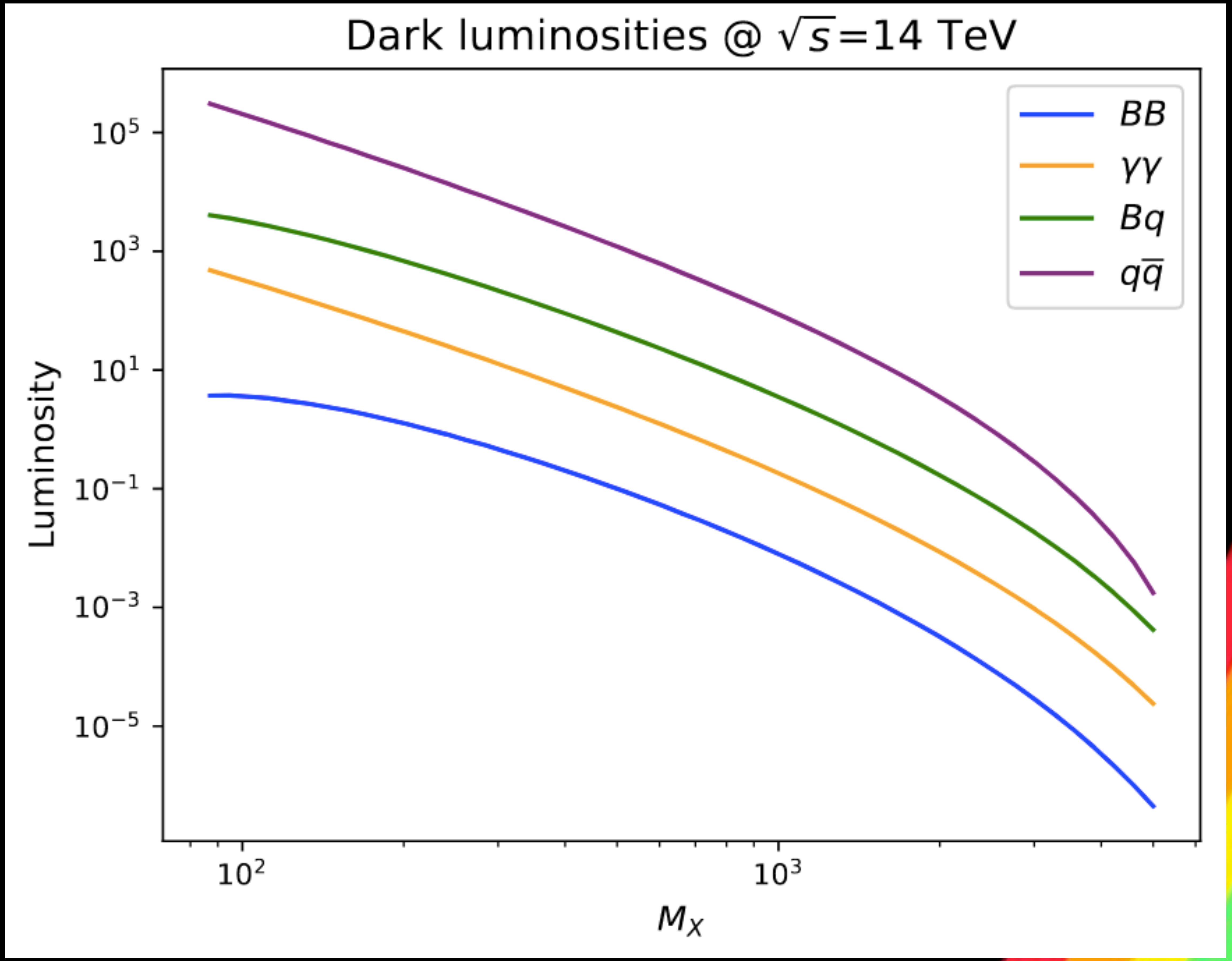
- Right, we show the luminosities for $\alpha_B = 3 \times 10^{-3}$, $m_B = 50$ GeV.



‘DARK’ PDF LUMINOSITIES

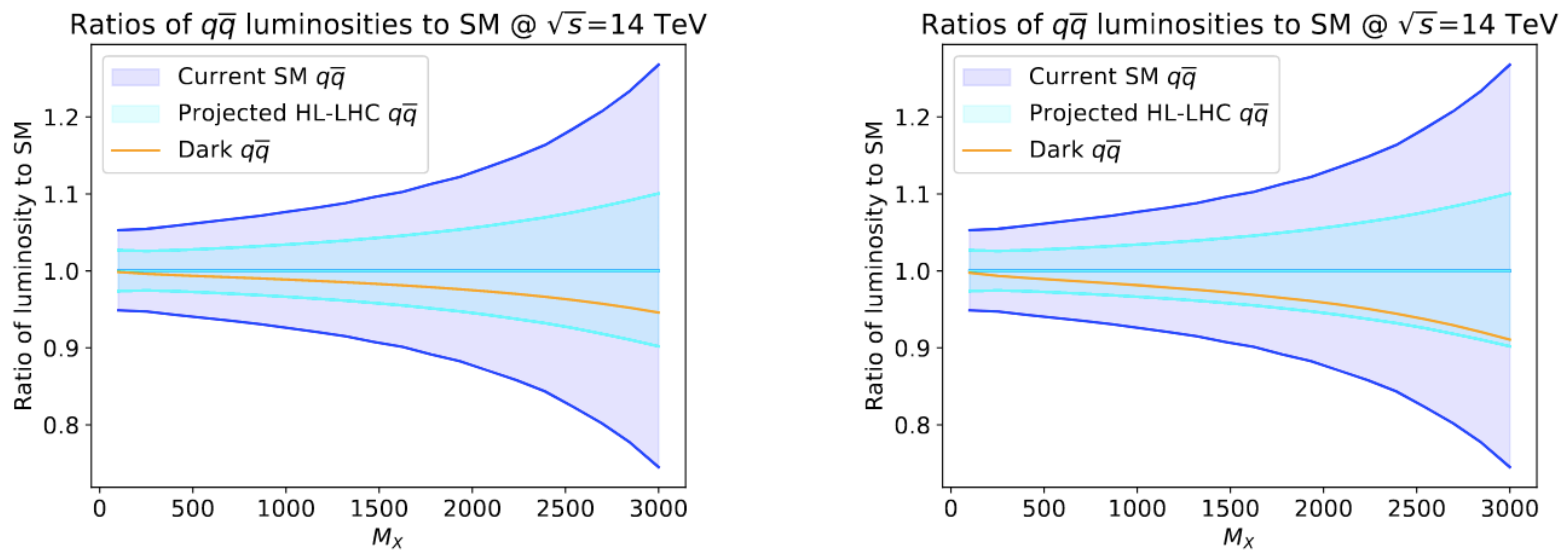
- The BB luminosity is very small relative to the $q\bar{q}$ channel, since it is suppressed by two powers of the dark coupling.

- On the other hand, the Bq channel becomes more important than the $\gamma\gamma$ luminosity, suggesting that the dark photon starts to have an impact on some phenomenology at this mass and coupling.



‘DARK’ PDF LUMINOSITIES

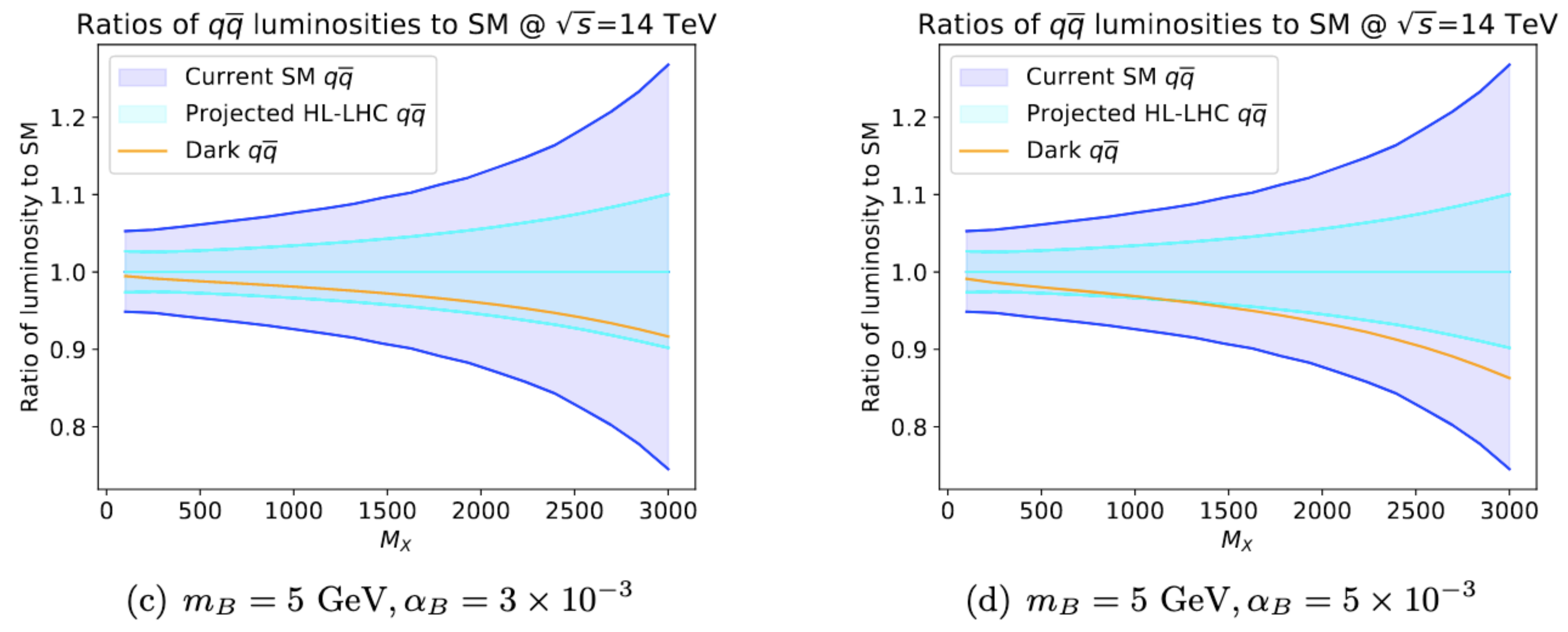
- The relevant channel in the case of DY is the $q\bar{q}$ luminosity. Comparing the ‘dark’ luminosities for different values of the coupling and mass to the reference set luminosities, we get the following:



(a) $m_B = 50 \text{ GeV}, \alpha_B = 3 \times 10^{-3}$

(b) $m_B = 50 \text{ GeV}, \alpha_B = 5 \times 10^{-3}$

'DARK' PDF LUMINOSITIES



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

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

- Indications of incompatibility at the level of projected HL-LHC uncertainties!

HL-LHC DRELL-YAN CONSTRAINTS

- 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.

HL-LHC DRELL-YAN CONSTRAINTS

- 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 by **Maeve Madigan** for the PBSP group's study of the simultaneous determination of PDFs and Wilson coefficients, 2104.02723.

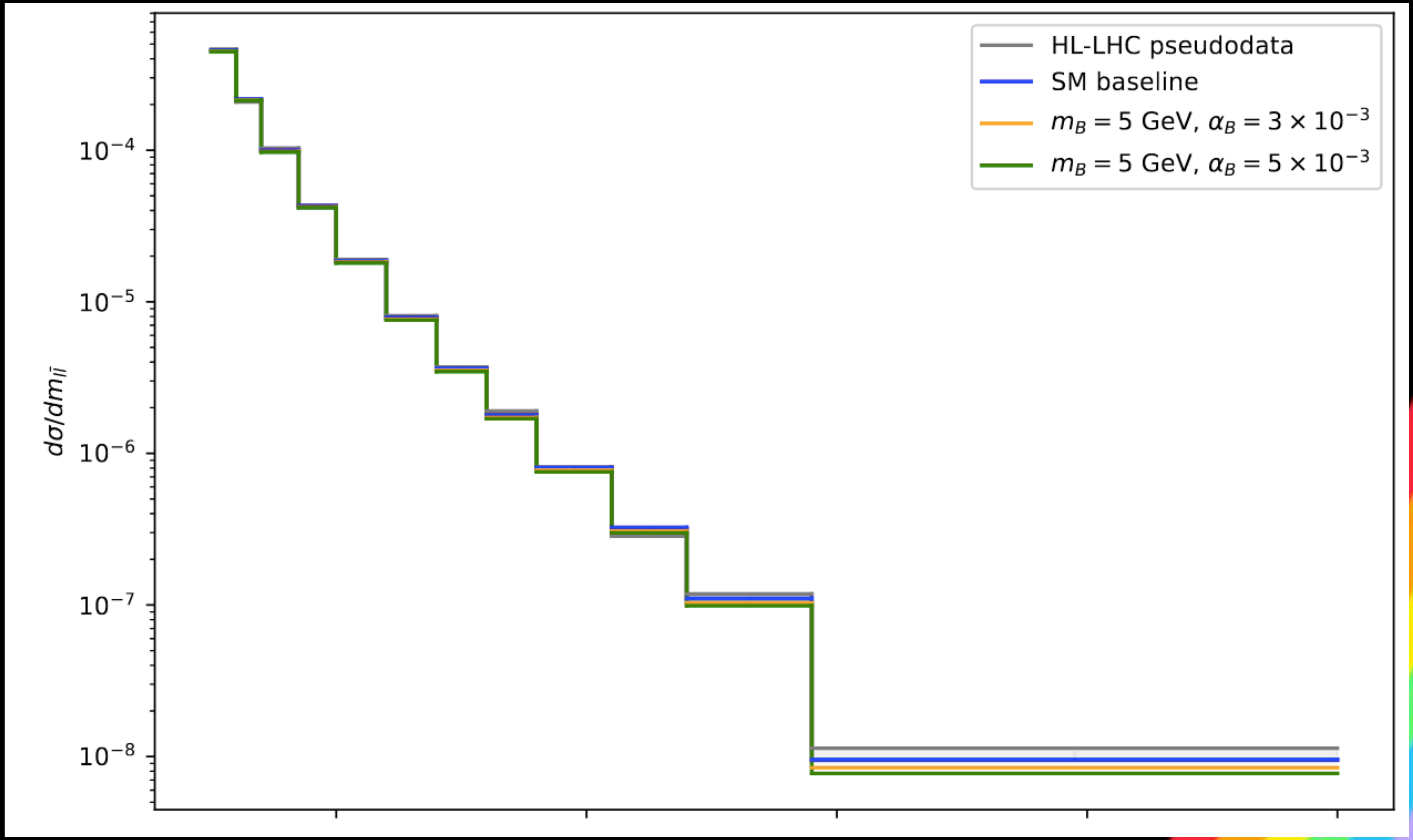
- Two sets of projected data are used, corresponding to the following two scenarios:

    - *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.

HL-LHC DRELL-YAN CONSTRAINTS

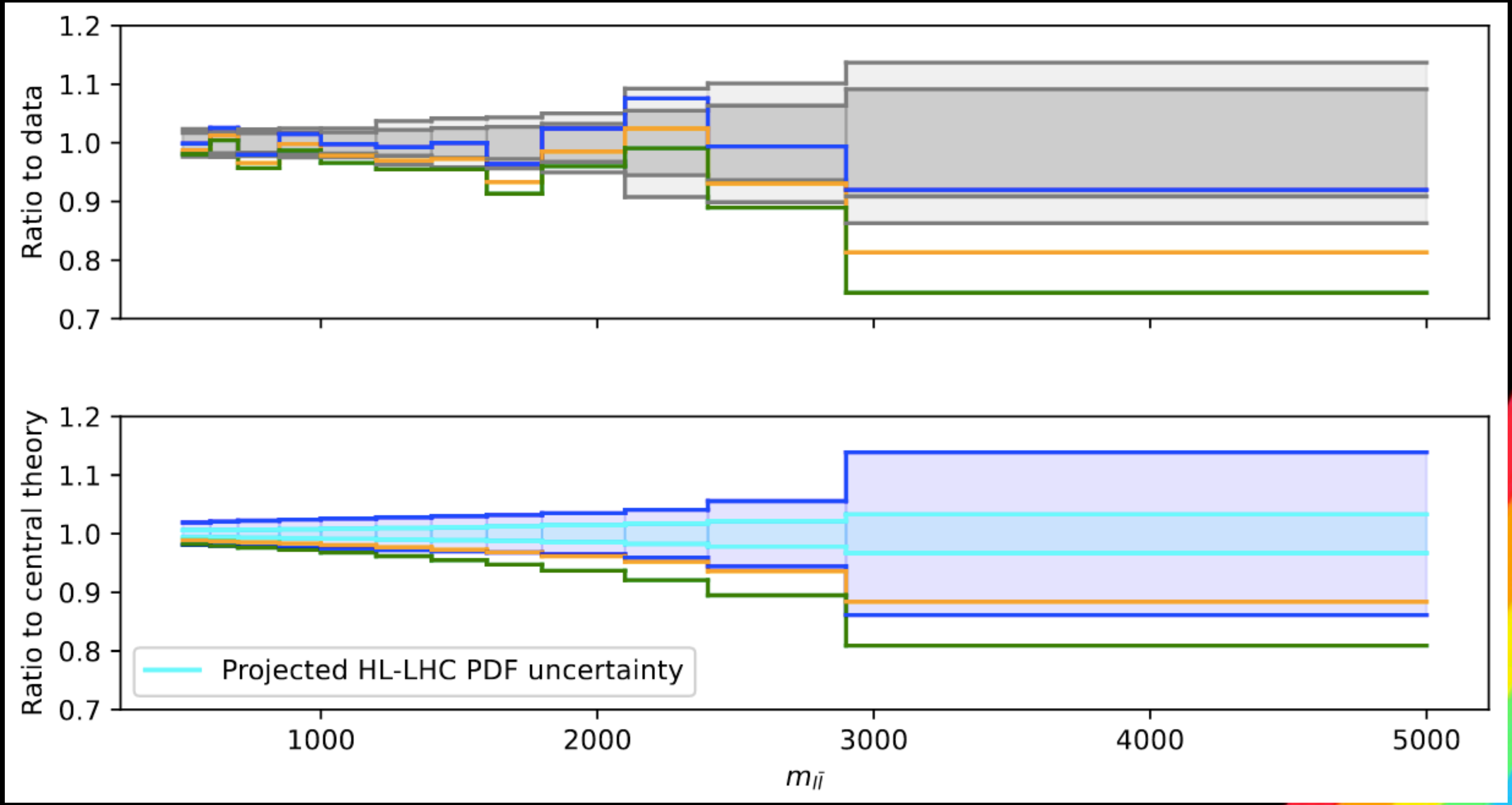
- *Right:* a comparison of the **projected data** (shown in grey) with the **SM baseline** (NNPDF3.1 LUXQED) and two 'dark' PDF sets used in the grid scan.



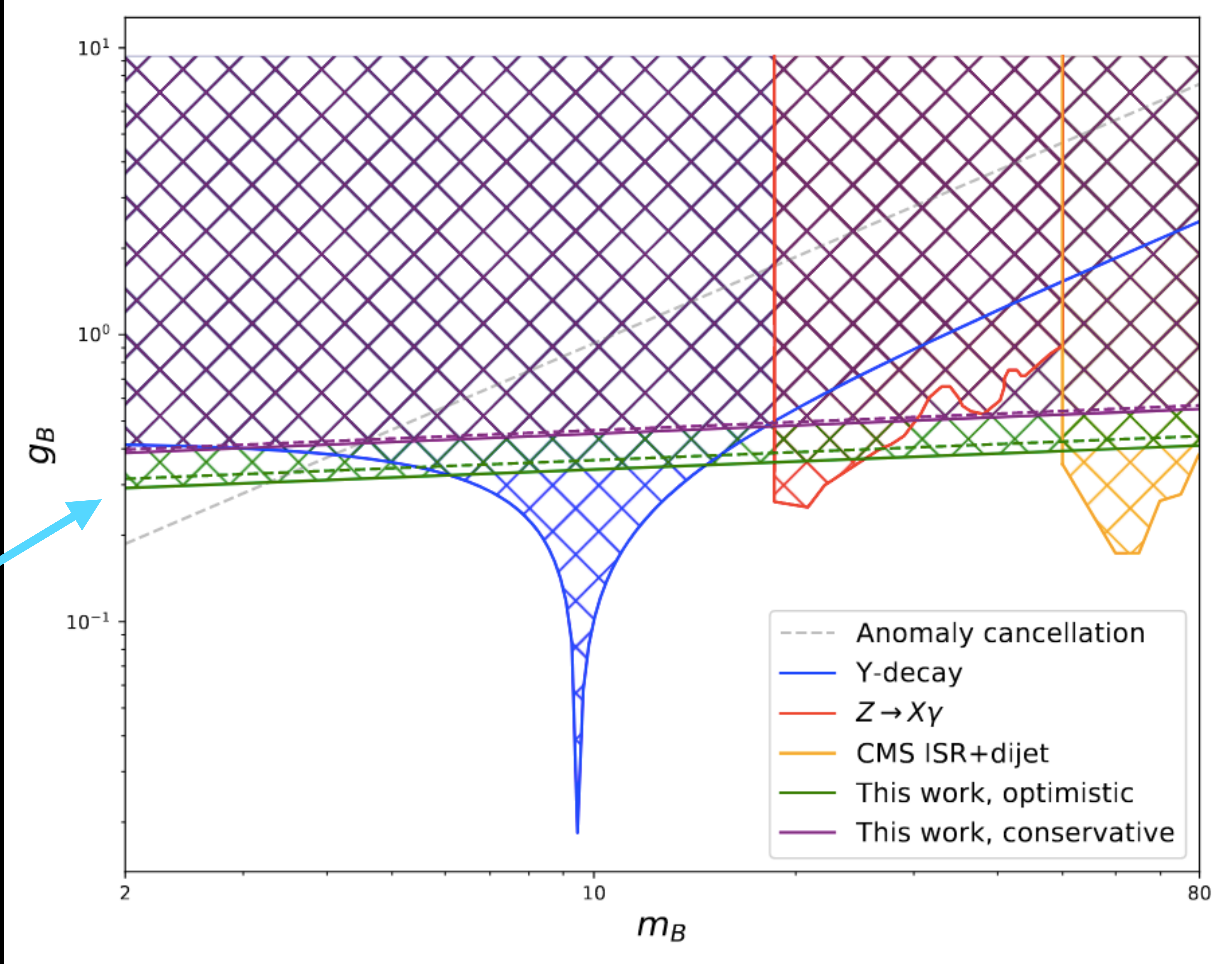
HL-LHC DRELL-YAN CONSTRAINTS

- *Right top:* The previous plot as a ratio to the central data values. Dark grey is 'optimistic', light is 'conservative'.

- *Right bottom:* The previous plot, as a ratio to central theory, with (projected) PDF uncertainties displayed.



COMPARISON OF (PROJECTED) BOUNDS



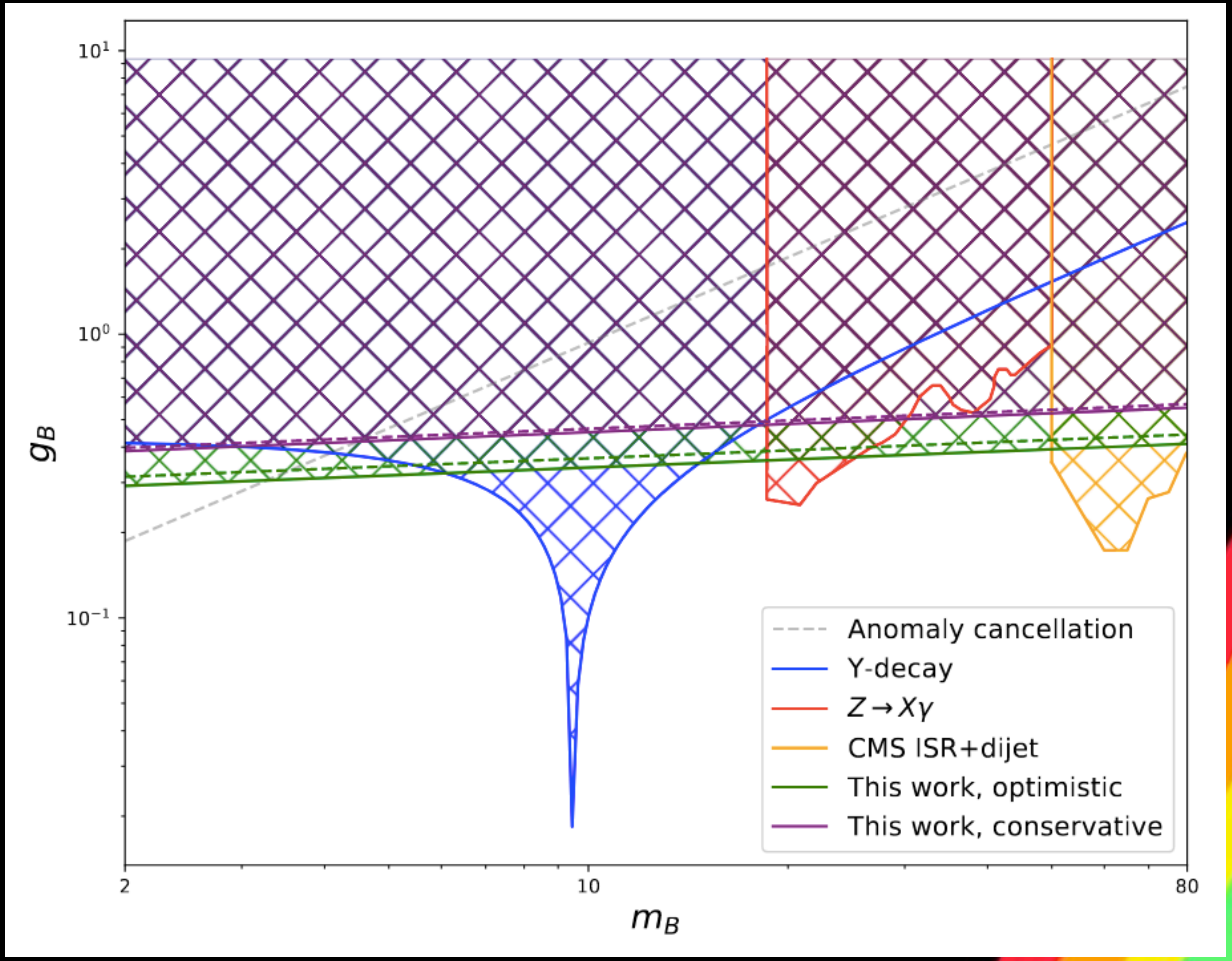
dashed lines: including PDF uncertainty

COMPARISON OF (PROJECTED) BOUNDS

- *Dashed:* From 1404.3947. **UV-completing** our theory requires the introduction of **anomaly-cancelling fermions**, which acquire masses from $U(1)_B$-breaking, mediated by some Higgs-like scalar.

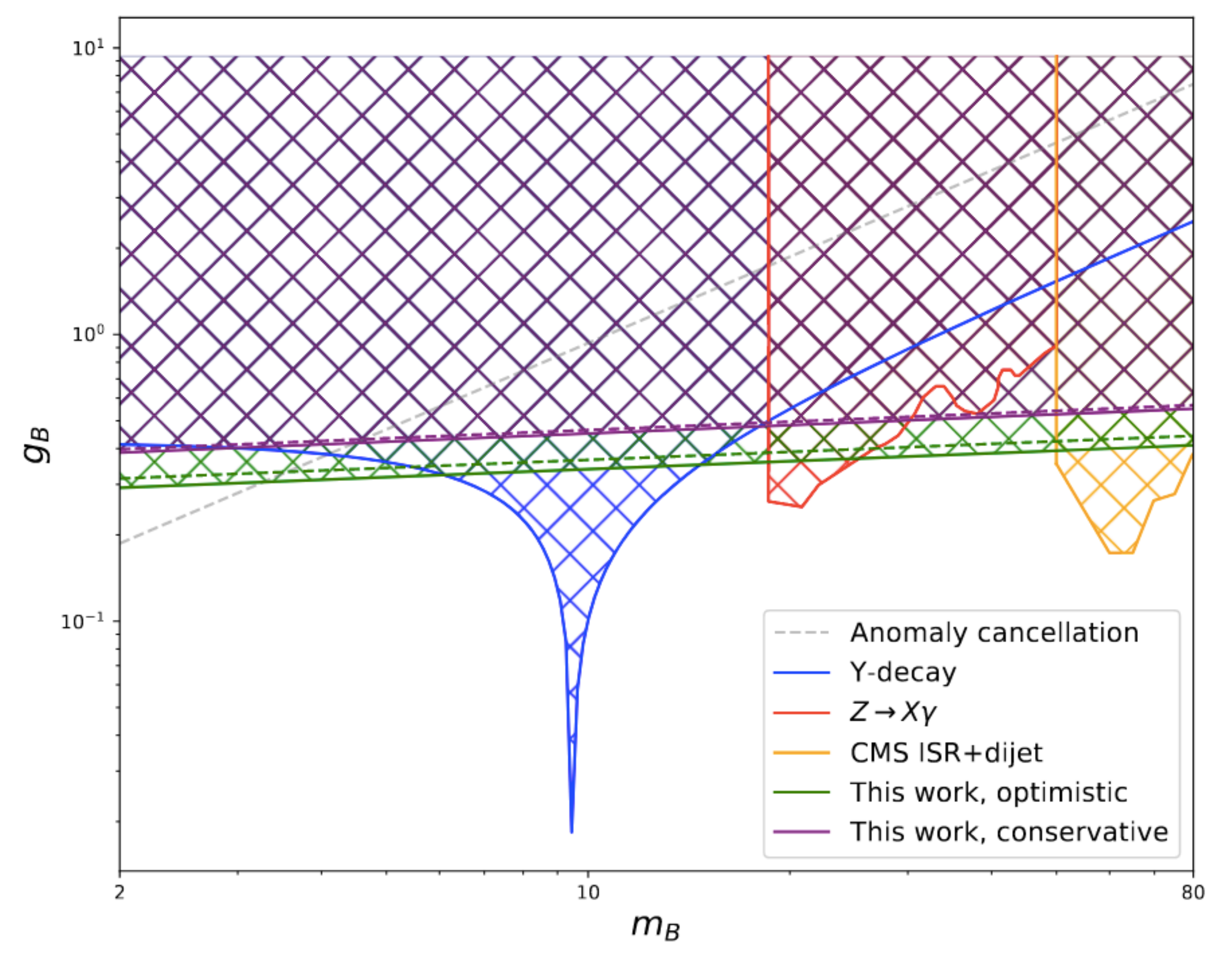
- The resulting Yukawa Higgs-fermion coupling then looks like $\lambda \sim m_F/v_B$, whilst our coupling looks like $g_B \sim m_B/v_B$. So: $g_B \sim \lambda m_B/m_F$.

- Assuming perturbativity, $\lambda \leq 4\pi$, and $m_F = 90$ GeV gives the bound.



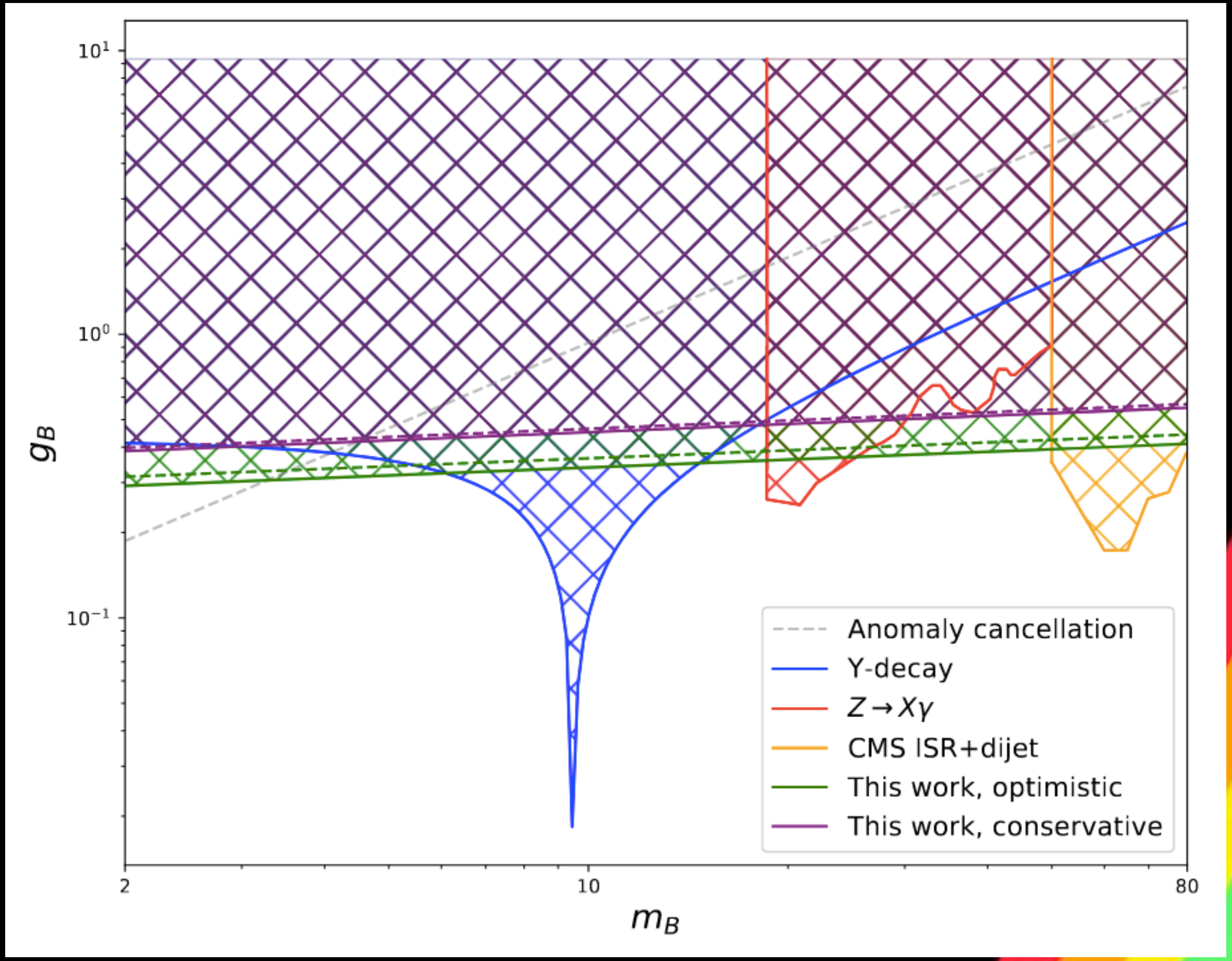
COMPARISON OF (PROJECTED) BOUNDS

- All remaining constraints are experimental.
- *Blue:* From 9411256, 9809522 and ARGUS 1986. Bound from **upsilon-decays**, which are enhanced by the presence of a dark photon.
- *Red:* From 1705.06726 and the 1996 LEP study of $Z \to H\gamma, H \to$ hadrons. Bound from $Z \to B\gamma$ decays (called X there), and subsequent SM decay of B.

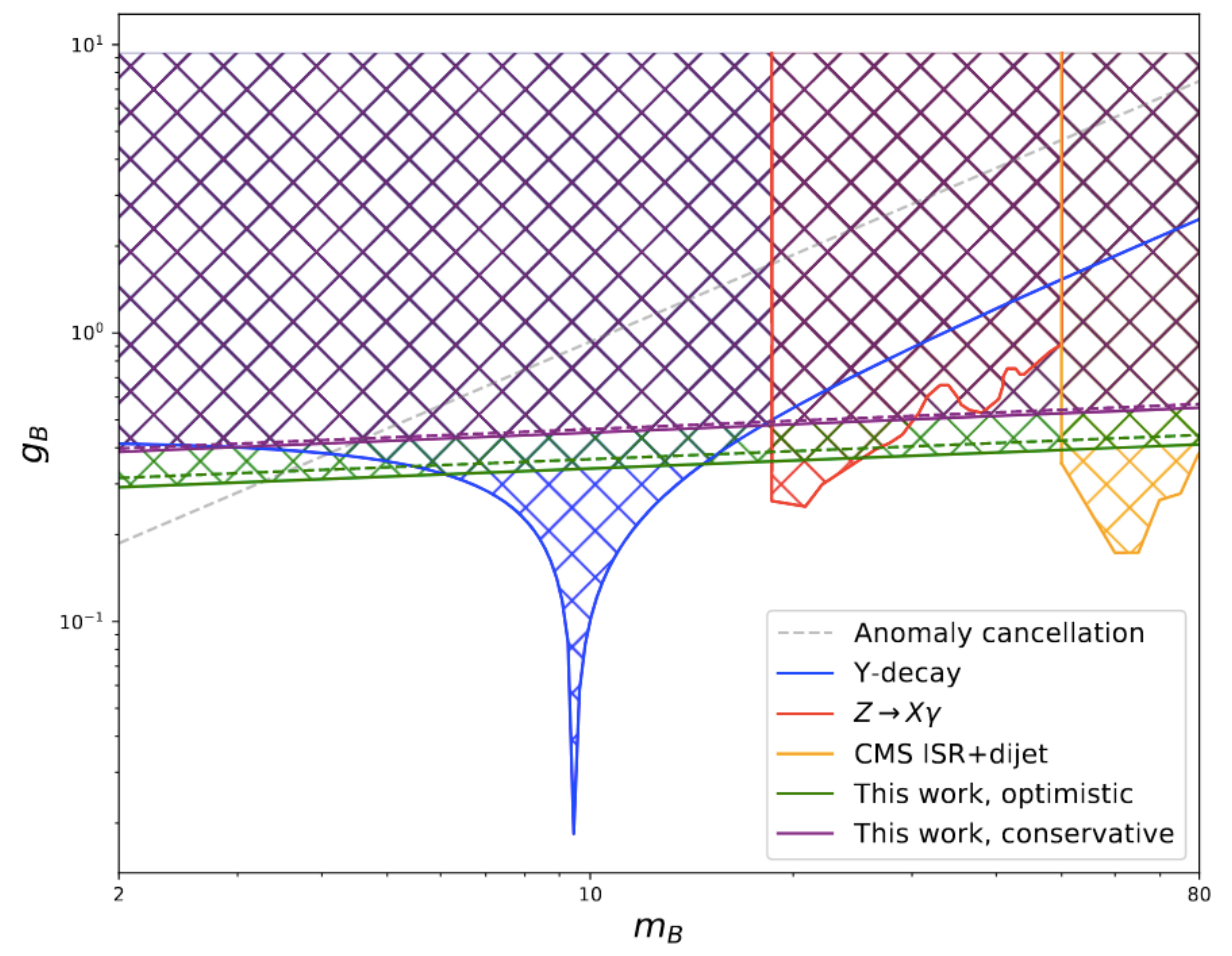


COMPARISON OF (PROJECTED) BOUNDS

- *Yellow:* From CMS studies 1905.10331 and 1909.04114. Bounds from **resonances decaying into $q\bar{q}$ pairs** - dark photon signal would enhance **dijet invariant mass spectrum**.
- *Purple and green:* This work.



COMPARISON OF (PROJECTED) BOUNDS



CONCLUSIONS

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- **New BSM particles** can be included in DGLAP evolution by computing their **splitting functions**; this distorts the DGLAP evolution of **SM PDFs**.

- Even for **colourless BSM particles**, which have very small abundance in the proton, inclusion in proton structure will significantly affect predictions in the near future of the LHC.

- Projected sensitivity of this method is **competitive with current, lower-energy, experimental probes** and **theoretical bounds from assumptions on the UV-completion.**