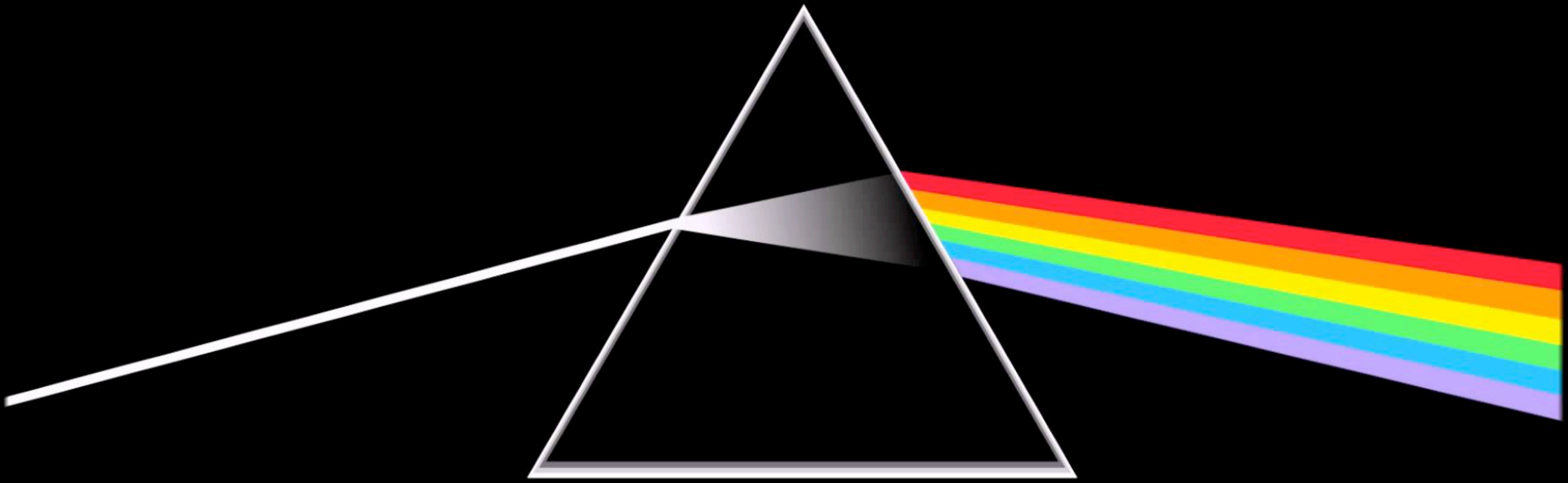
THE DARK SIDE OF THE PROTON



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BASED ON 2203.12628, WITH MATTHEW MCCULLOUGH & MARIA UBIALI

PBSP

BSM-PDF INTERPLAY

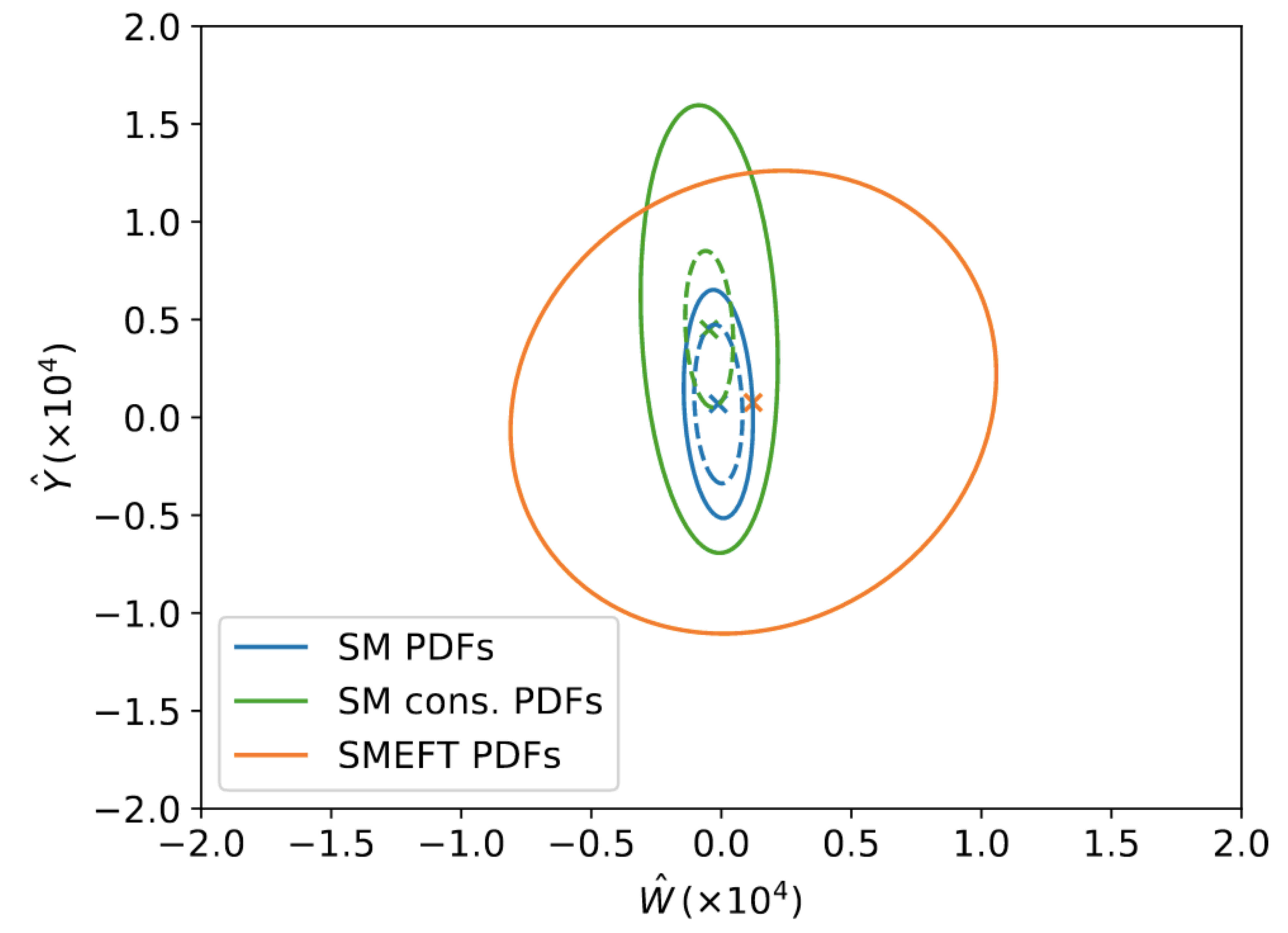
- Predictions made for **BSM studies** often use PDFs determined using the **SM**. This can cause **inconsistencies**, especially if the datasets used for PDF determination **overlap** with those used for the BSM fit.

- Already studied in the case of the SMEFT in:

  - **Can New Physics Hide Inside the Proton?** Stefano Carrazza, Celine Degrande, Shayan Iranipour, Juan Rojo, Maria Ubiali, 1905.05215.

  - **Parton Distributions in the SMEFT from High-Energy Drell-Yan Tails.** Admir Greljo, Shayan Iranipour, Zahari Kassabov, Maeve Madigan, JM, Juan Rojo, Maria Ubiali, Cameron Voisey, 2104.02723.

- **More on the way** from Maria's PBSP team in a **top sector** study!



BSM-PDF INTERPLAY

- This work (2203.12628) focusses instead on **low-mass**, **weakly-coupled** new physics, where the SMEFT is less appropriate.

- In this case, we could **still see the impact on proton structure** by including the new particles as **constituents of the proton**.

- **Key question:**

Is there enough space inside the proton for **new PDF flavours** corresponding to **BSM particles**?

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 our SM view of proton structure.
- *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?
- E.g. a **dark matter candidate**: **neutral** and **colourless.**

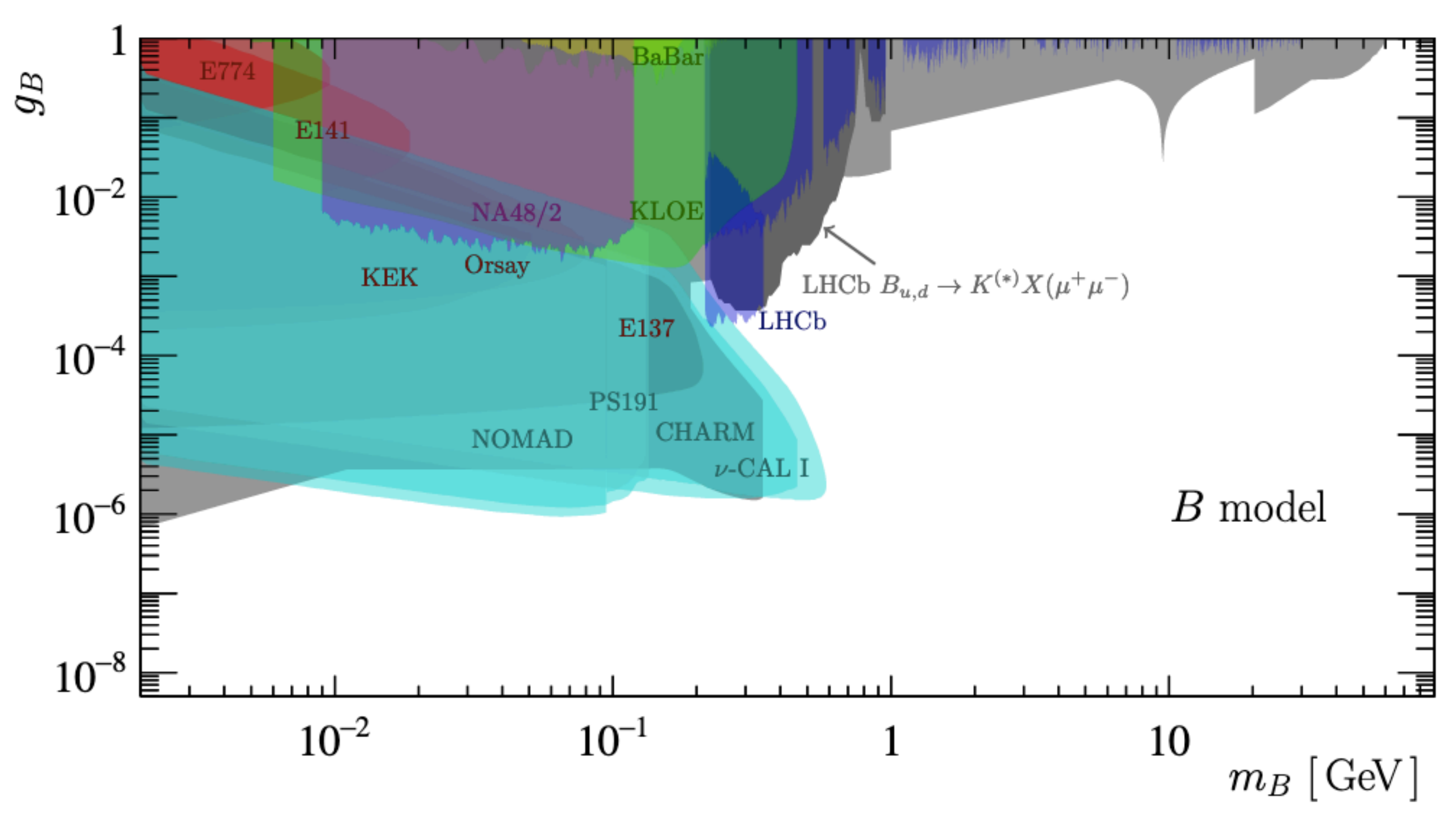
DARK MATTER IN THE PROTON

- 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:

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

- 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**.



Existing constraints summary from Ilten et al., 1803.06347

DARK MATTER IN THE PROTON

- **Refined key question:**

Is there enough space inside the proton for a new PDF corresponding to a **leptophobic 'dark' photon**, with mass $m_B \in [2,80]$ GeV?

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 make progress, we mimic the method of the first studies of the inclusion of the **photon PDF** and the **lepton PDFs**.

CLASSIC PHOTON PDFS

- The first study of **photon PDFs** (MRST 0411040, from 2004) avoided **determination** altogether. Instead:

1. At the initial PDF evolution scale Q_0 they assumed a **phenomenological model** for the photon PDF, based on the assumption that photons in the proton are generated solely from **quark splitting.** Other initial-scale PDFs are drawn from some **reference set.**

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

2. The initial-scale PDFs are evolved using the DGLAP equations, but now including new **photon splitting functions**, which are computed in standard QED perturbation theory.

$$P_{\gamma\gamma}(x) = -\frac{4}{3}\delta(1-x)$$

$$P_{q\gamma}(x) = 2(x^2 + (1-x)^2)$$

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

3. The other flavours' evolution is **distorted** due to the presence of the photon, allowing its **inclusion in the proton** to be assessed.

DARK PDF SETS

- We can **mimic this procedure** to additionally include **our dark photon** inside the proton. In summary, we:

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

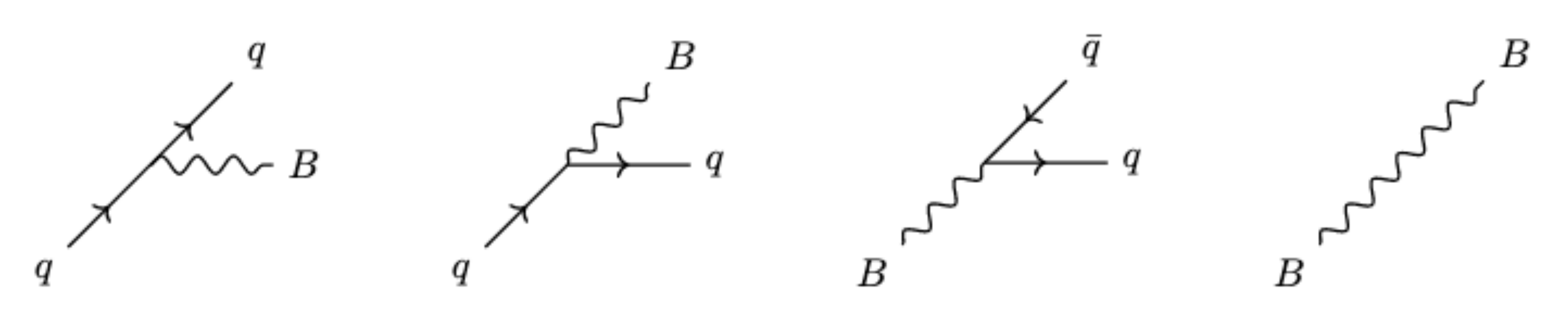
2. Starting from an **appropriate initial-scale ansatz**, and a **reference PDF set**, evolve using the **modified DGLAP equations**.

   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**.

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:

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

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

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

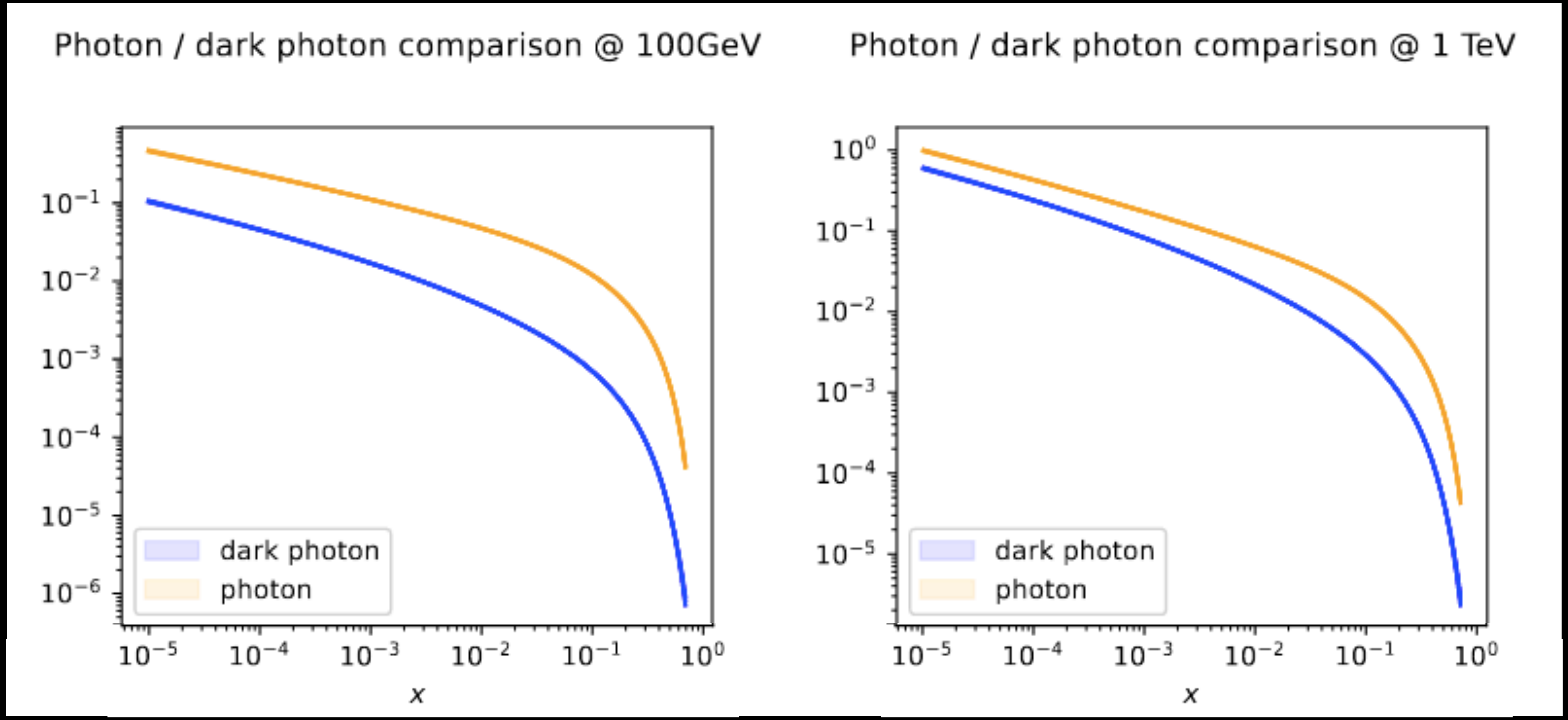
$$P_{Bq}(x) = \frac{1}{9}\left(\frac{1+(1-x)^2}{x}\right)$$

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.

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 two 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:

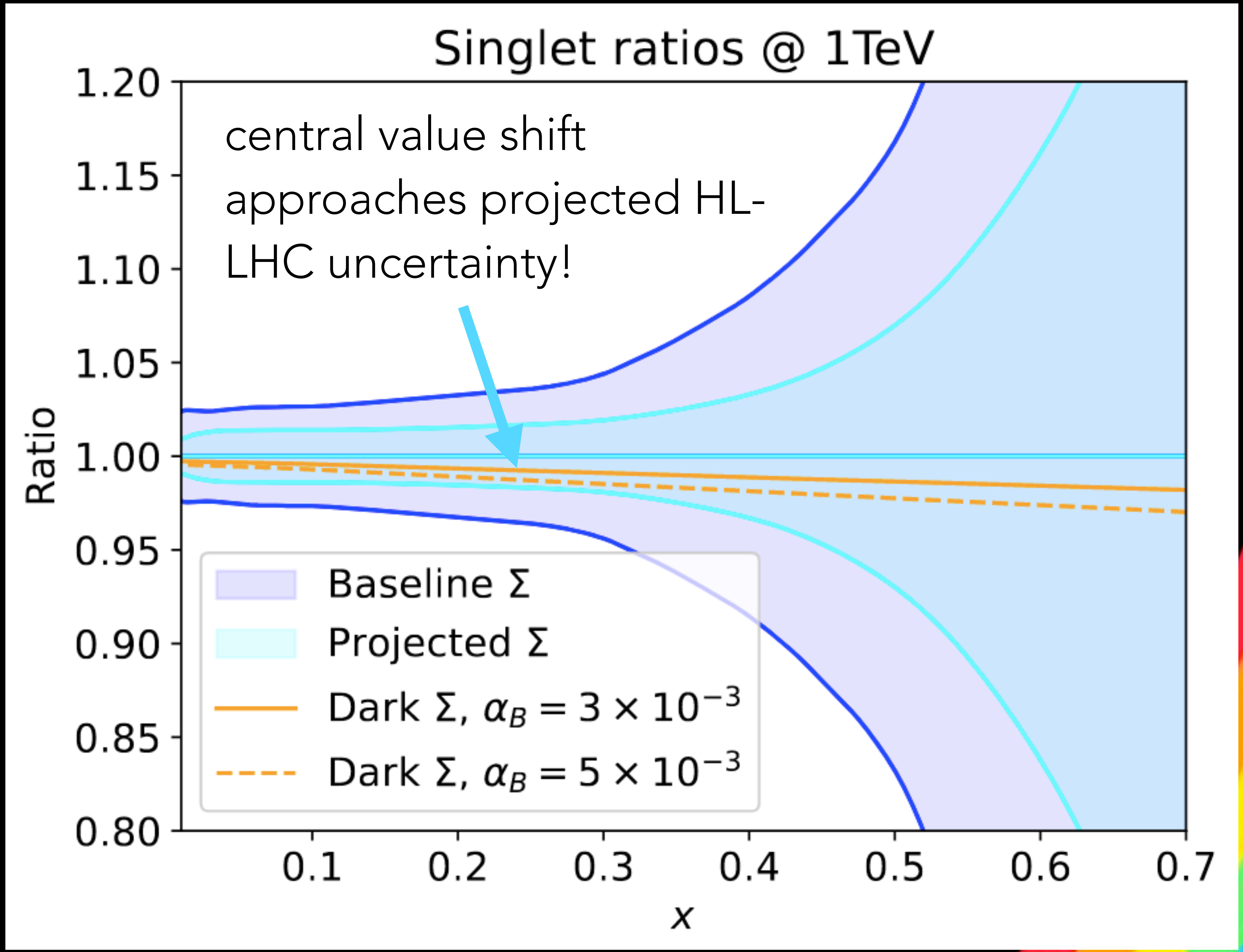
$$\langle x \rangle_q(Q) = \int_0^1 dx \; x f_q(x, Q^2) \, .$$

- 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%

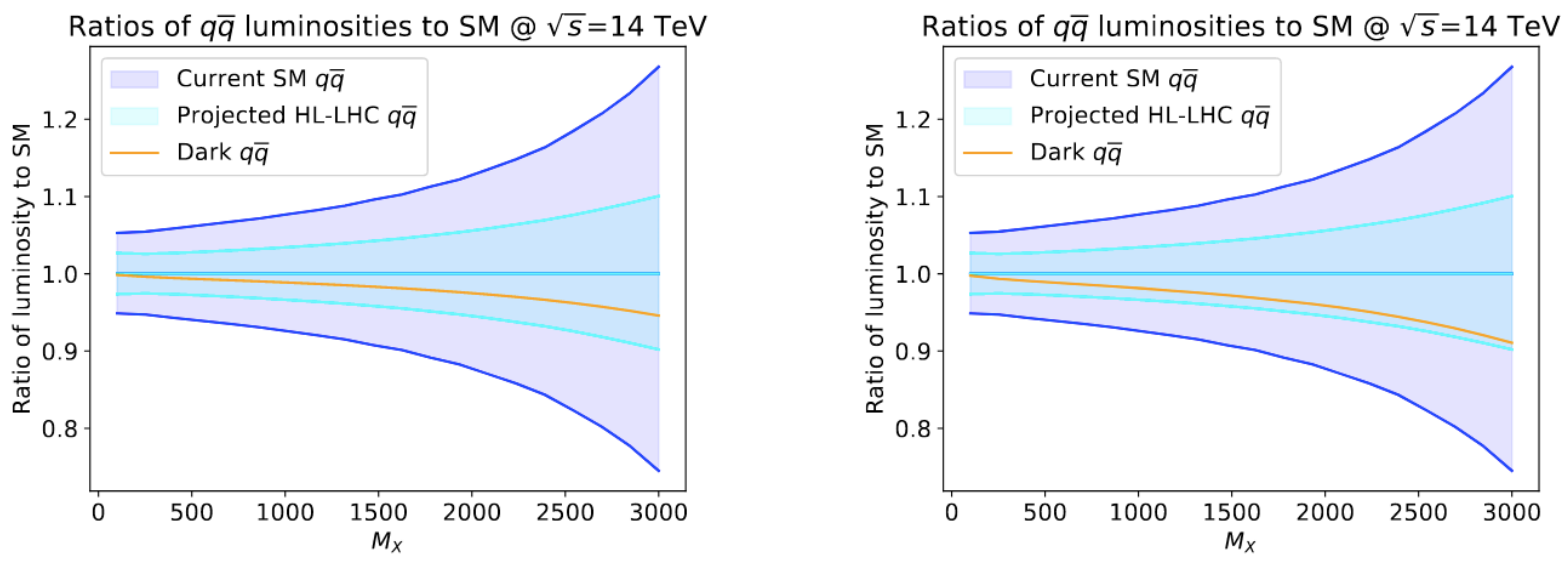
EXAMPLE 'DARK' PDF SETS

- 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,** we have the comparison on the right.
- Light blue bands correspond to **projected PDF** uncertainty at the **HL-LHC** (see 1810.03639).
- 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.



'DARK' PDF LUMINOSITIES

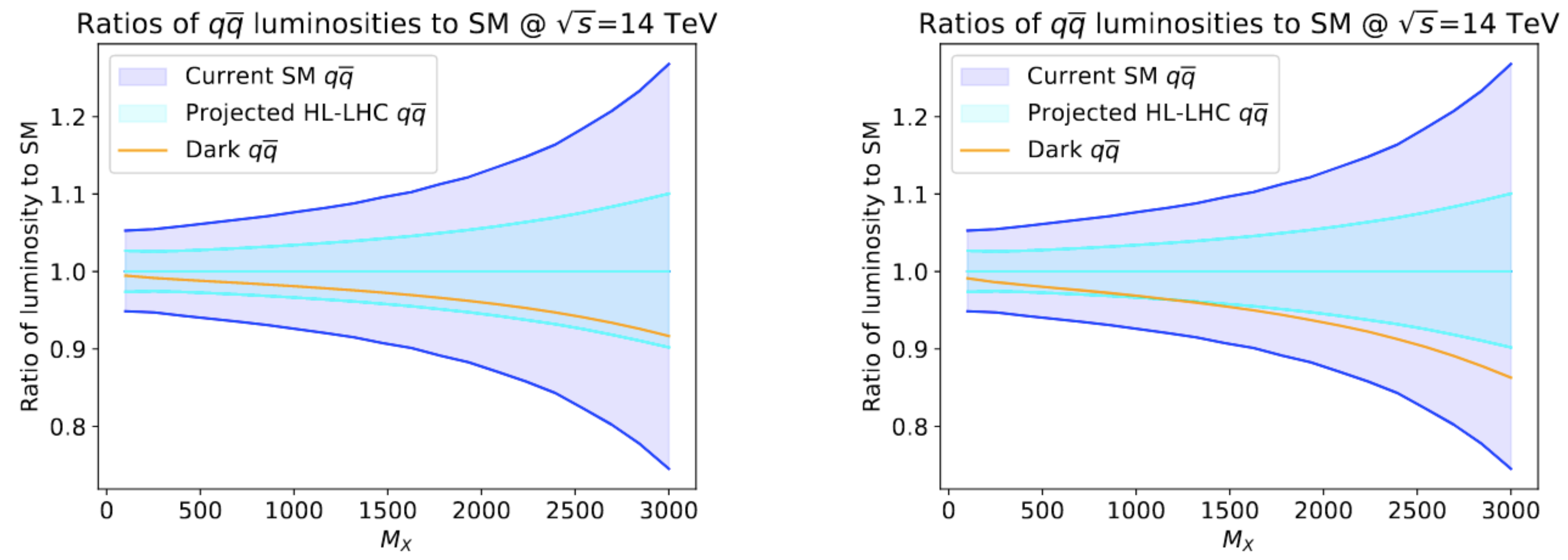
- With this view, we look at the most important channel for DY, $q\bar{q}$. Comparing the **'dark' luminosities** for different values of the coupling and mass to the reference set luminosities, we get the following:



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

(b) $m_B = 50$ 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 **Parton Distributions in the SMEFT from High-Energy Drell-Yan Tails**, 2104.02723.

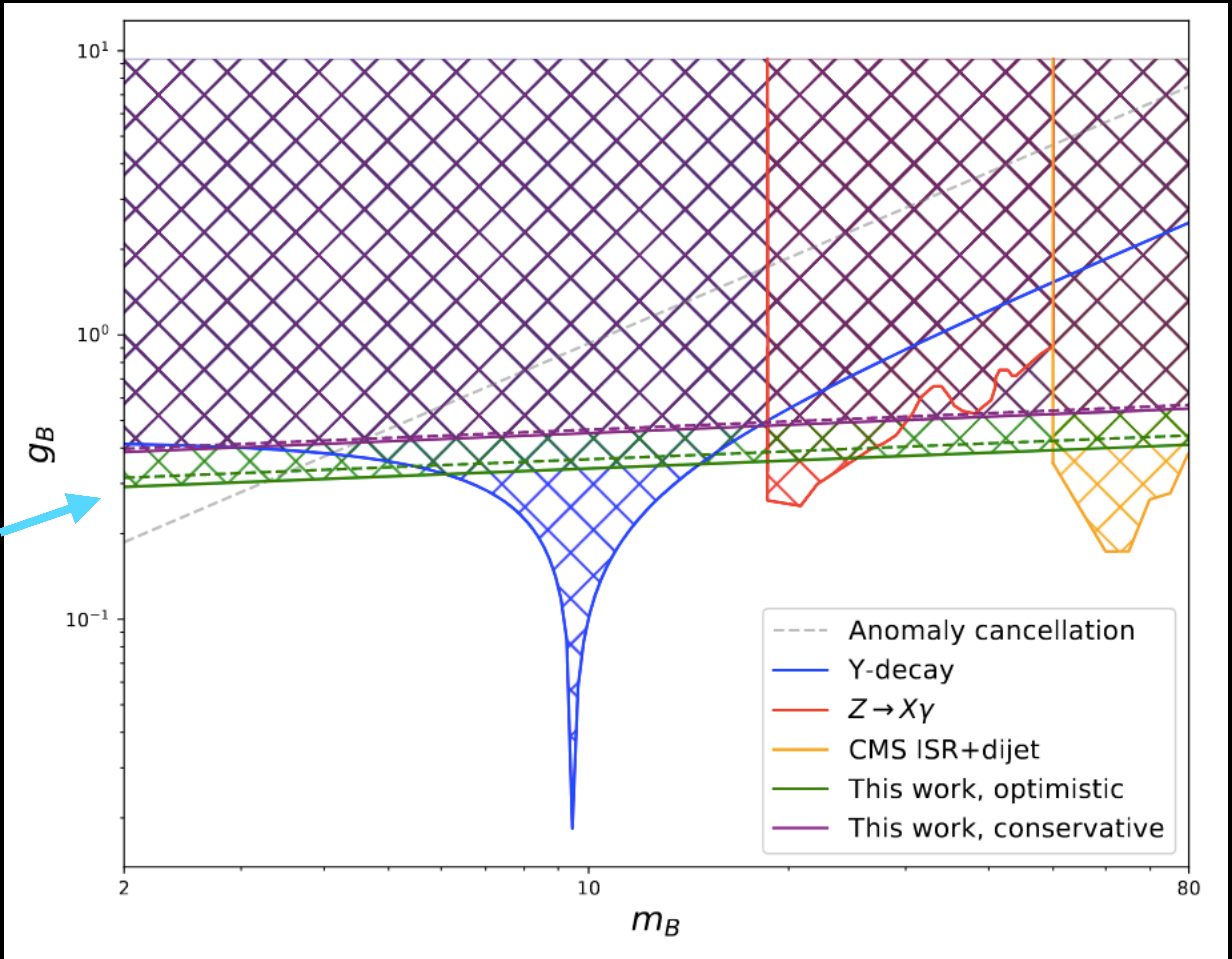
- Two sets of projected data are used, corresponding to the following two scenarios:

  - *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



CONCLUSIONS

- **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.**