A new take on PDFs - Resolved-Photon PDFs w/ Errors

PDF fitting and UE tuning via a chain of event modelling machinery

All silly things I say are my own words!

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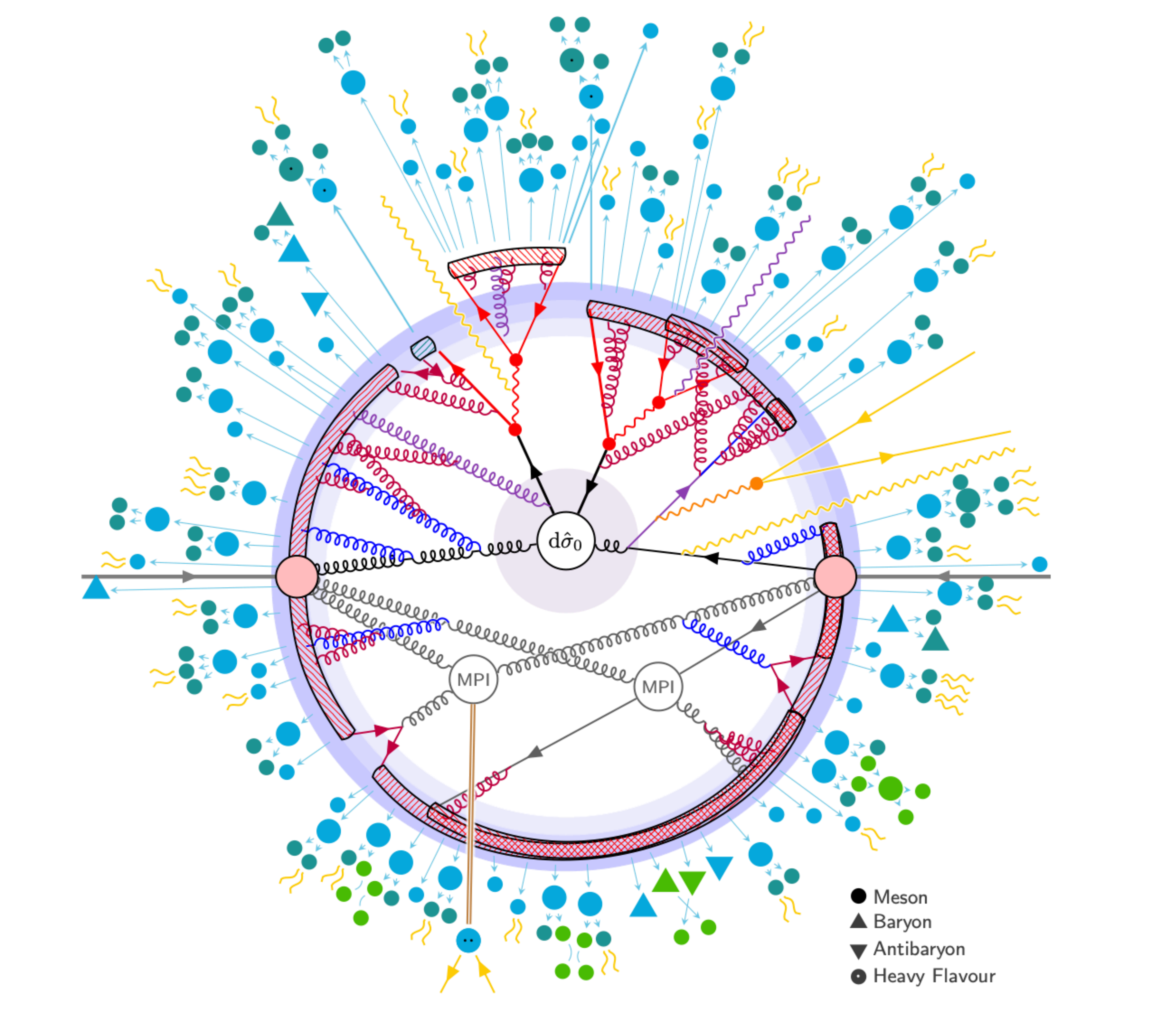
with Peter Meinzinger (Universität Zürich) and Frank Krauss and (IPPP Durham)

EIC Physics School, Spain, 24/06/2025

Before I start…

PDFs



[C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, P. Ilten et al., A comprehensive guide to the physics and usage of pythia 8.3, 2020]

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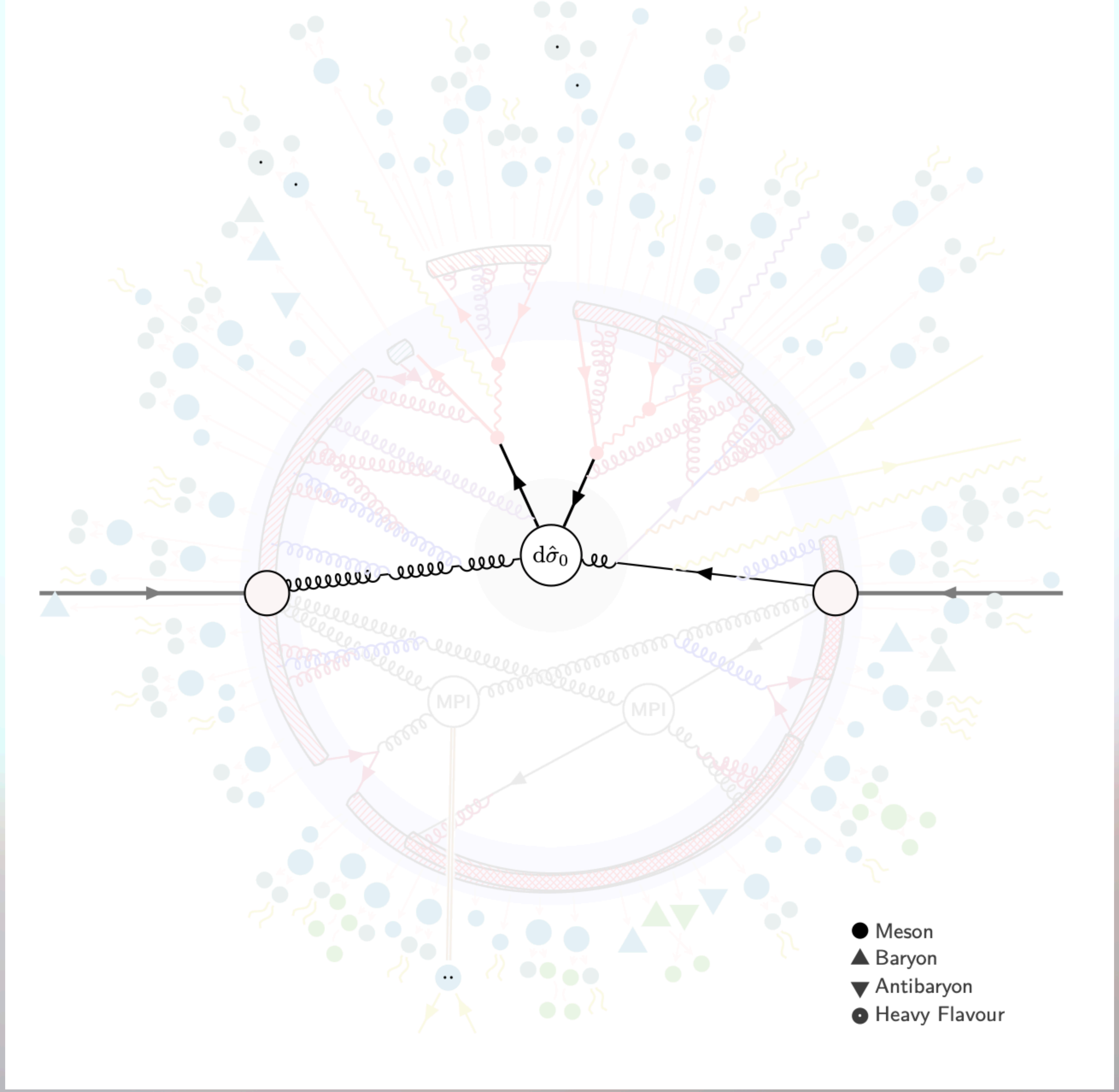

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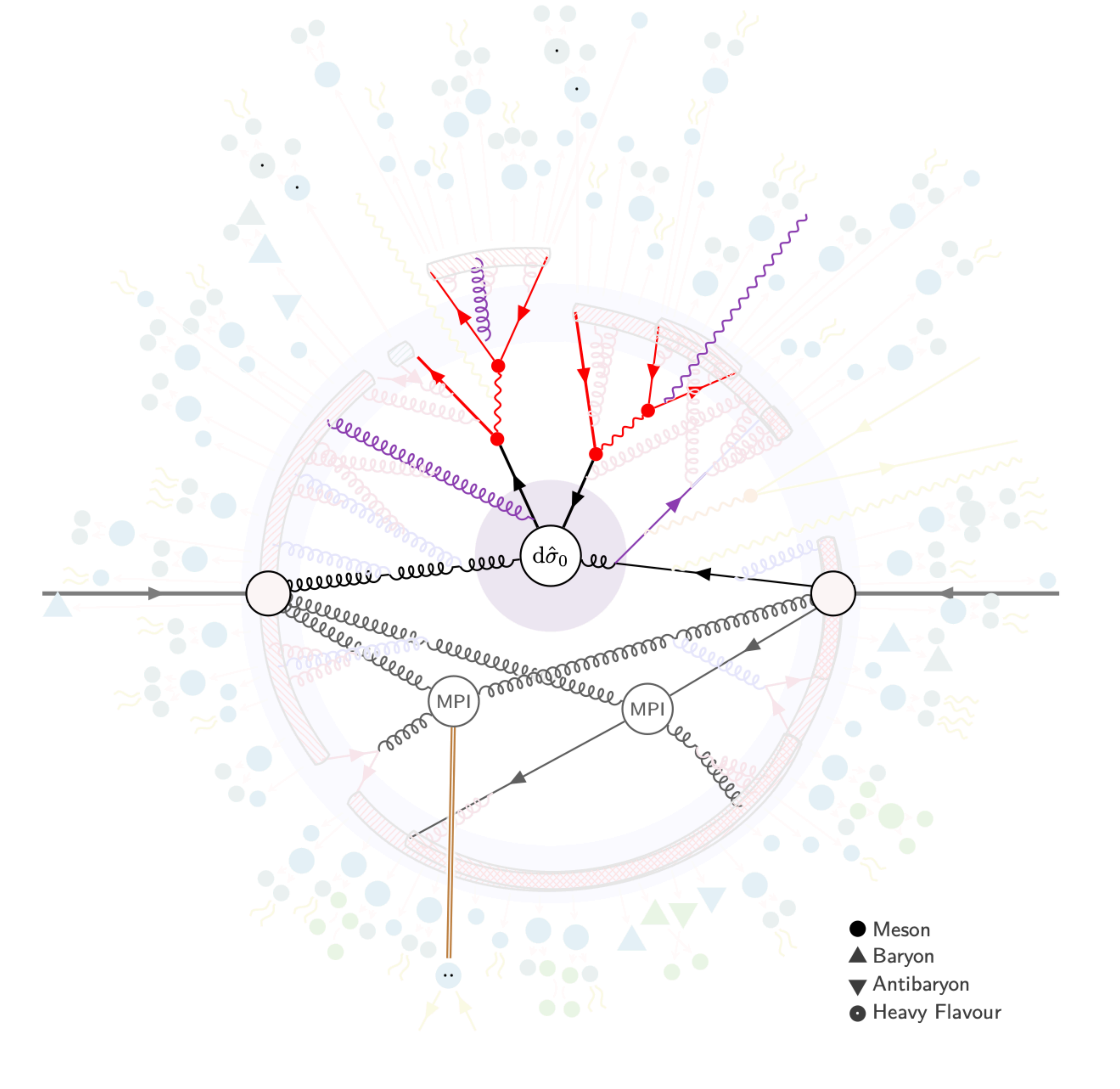
PDFs and Underlying Event



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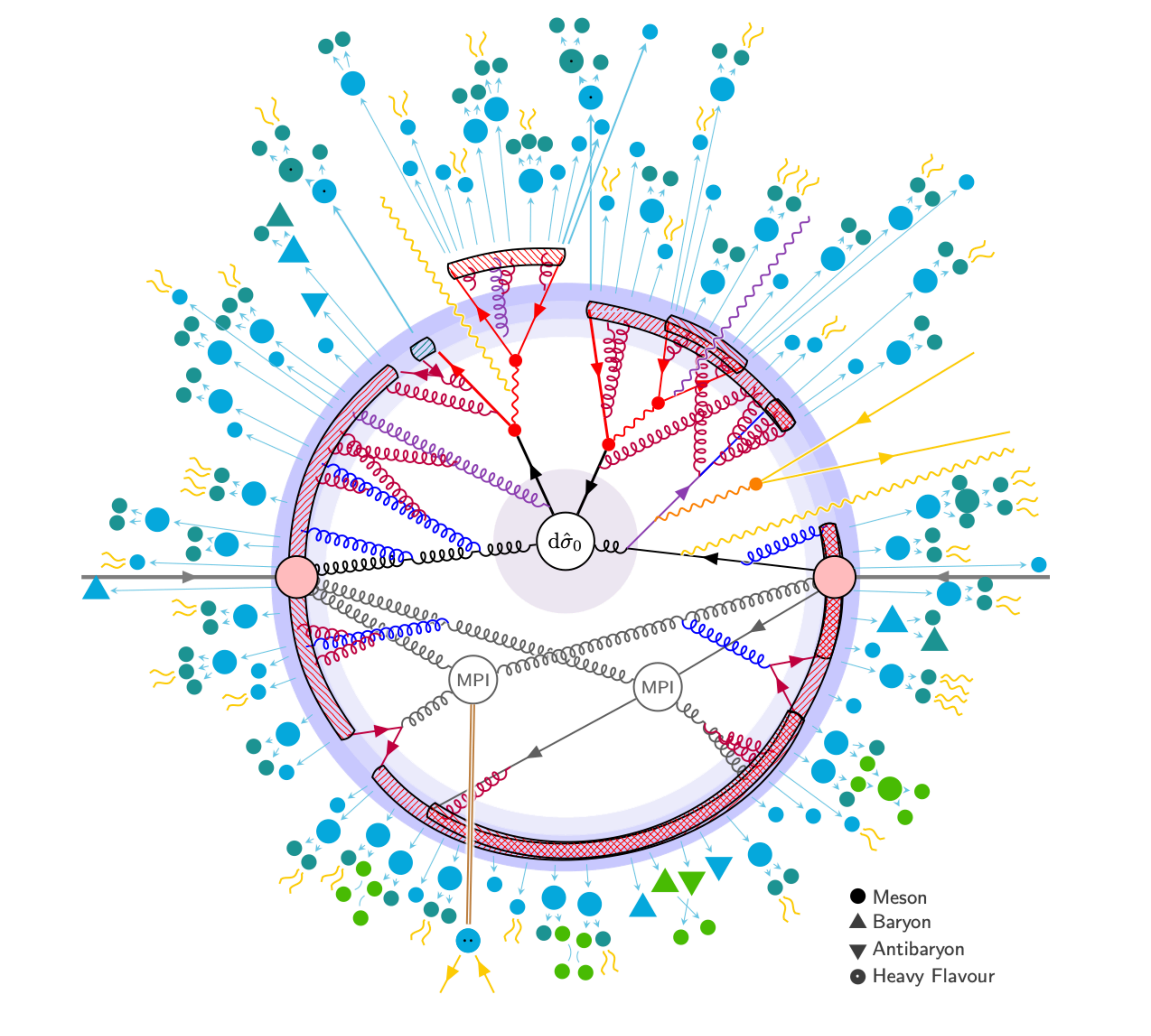

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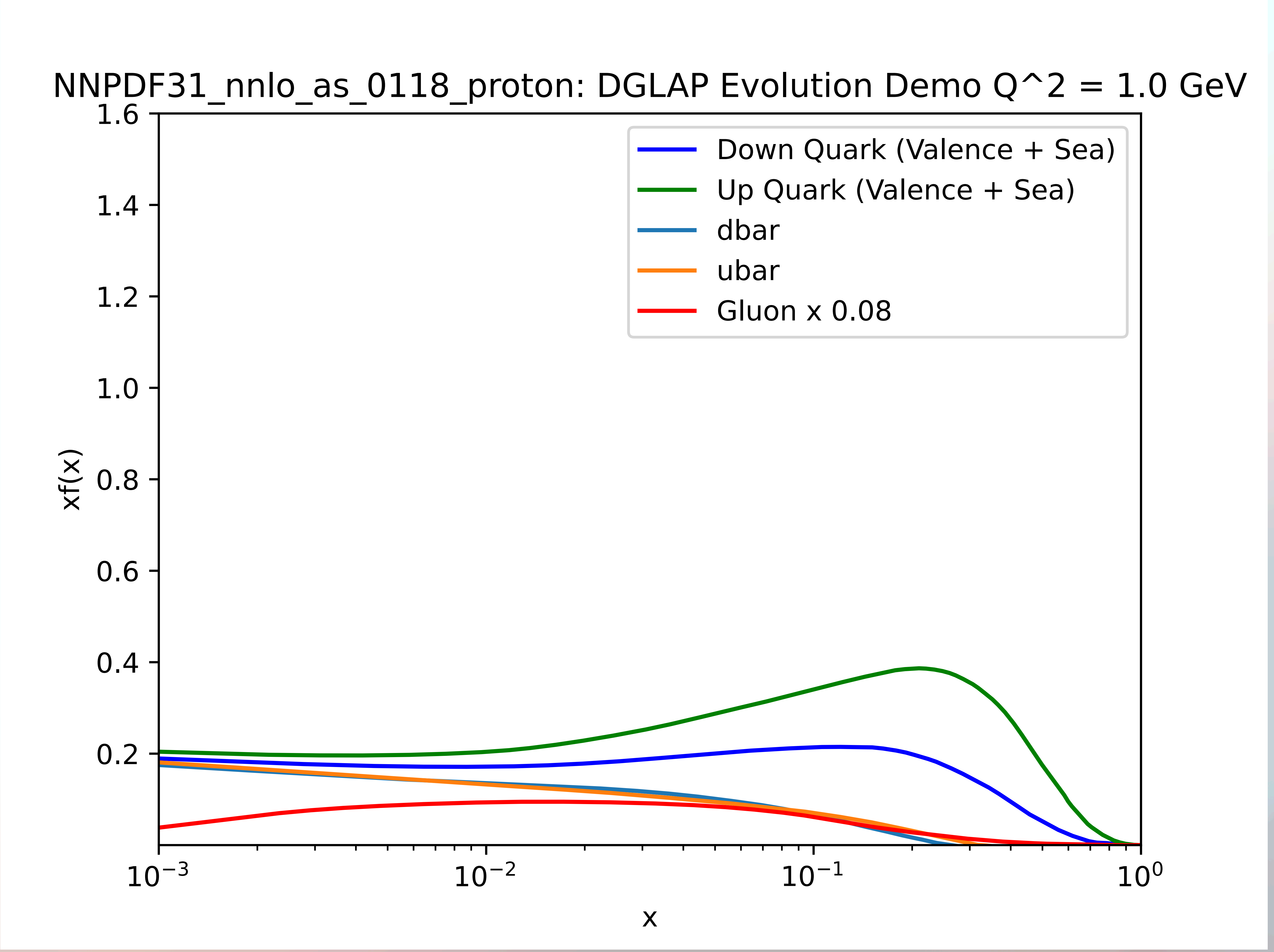
Extracting PDFs

Guess initial PDF shape

↓ DGLAP Evolution

Full PDF set



[Y. L. Dokshitzer, Calculation of the Structure Functions for Deep Inelastic Scattering and e+ e- Annihilation by Perturbation Theory in Quantum Chromodynamics., Sov. Phys. JETP 46 (1977) 641.]
[V. N. Gribov and L. N. Lipatov, Deep inelastic e p scattering in perturbation theory, Sov. J. Nucl. Phys. 15 (1972) 438.]
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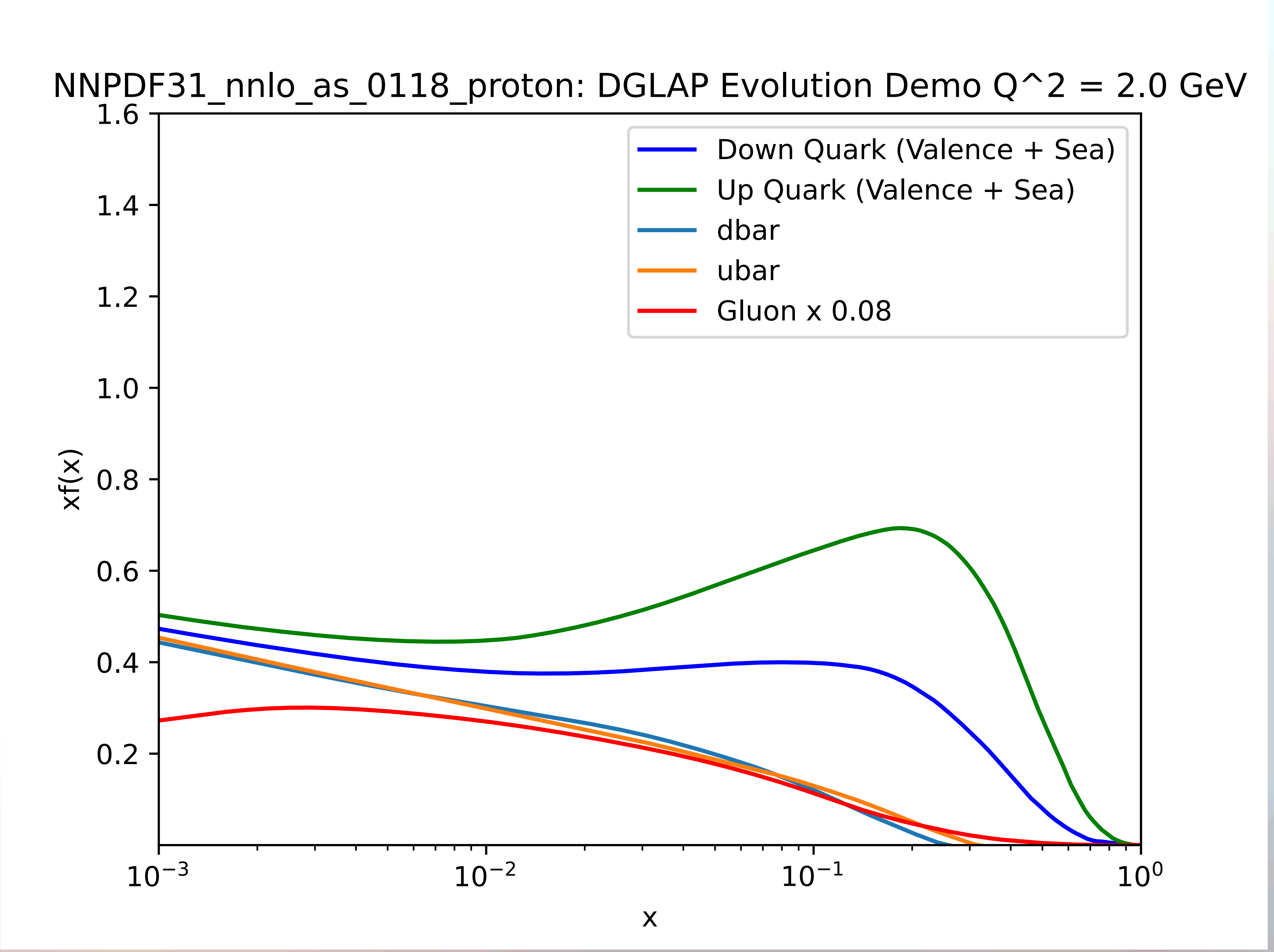

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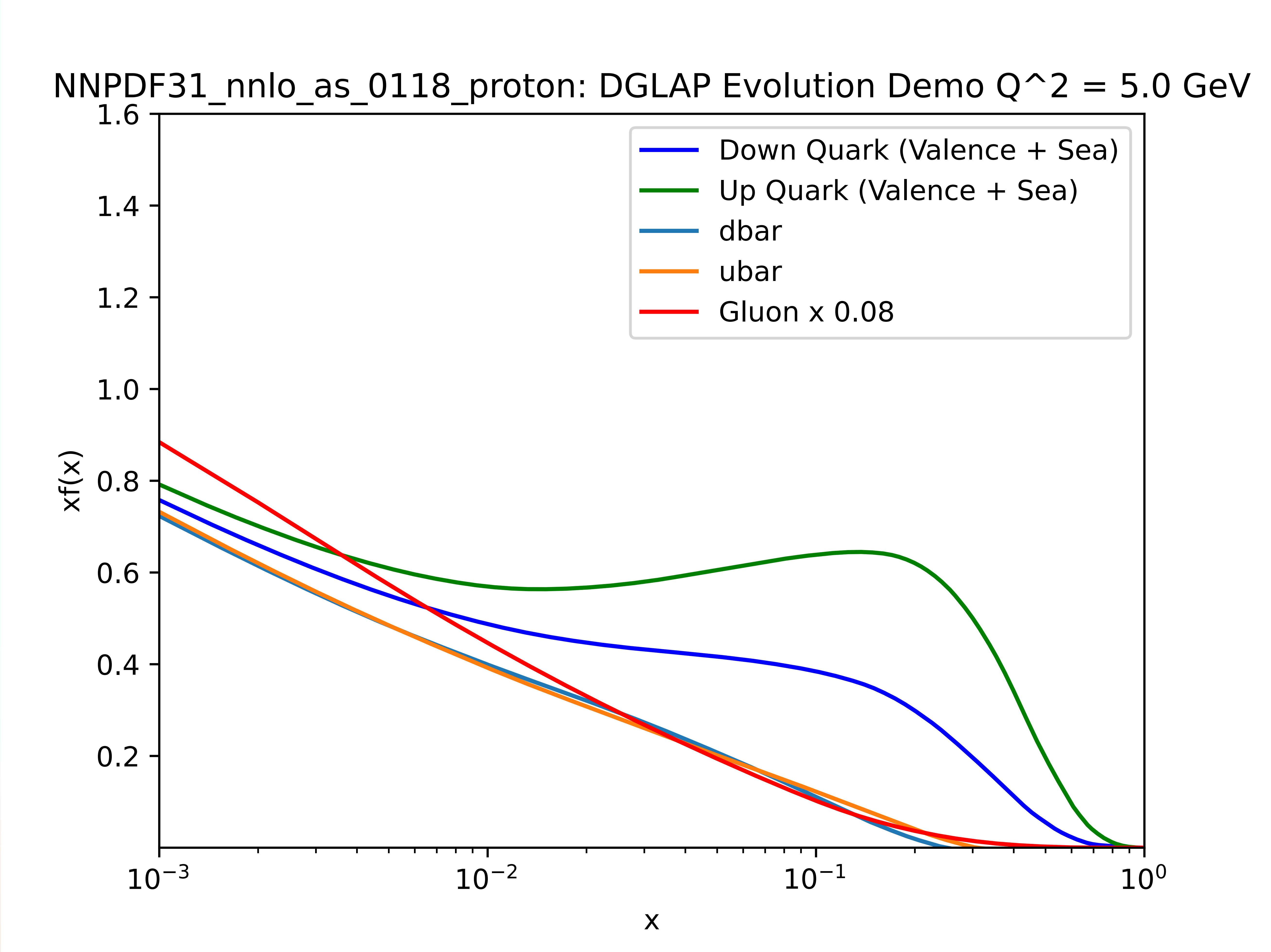

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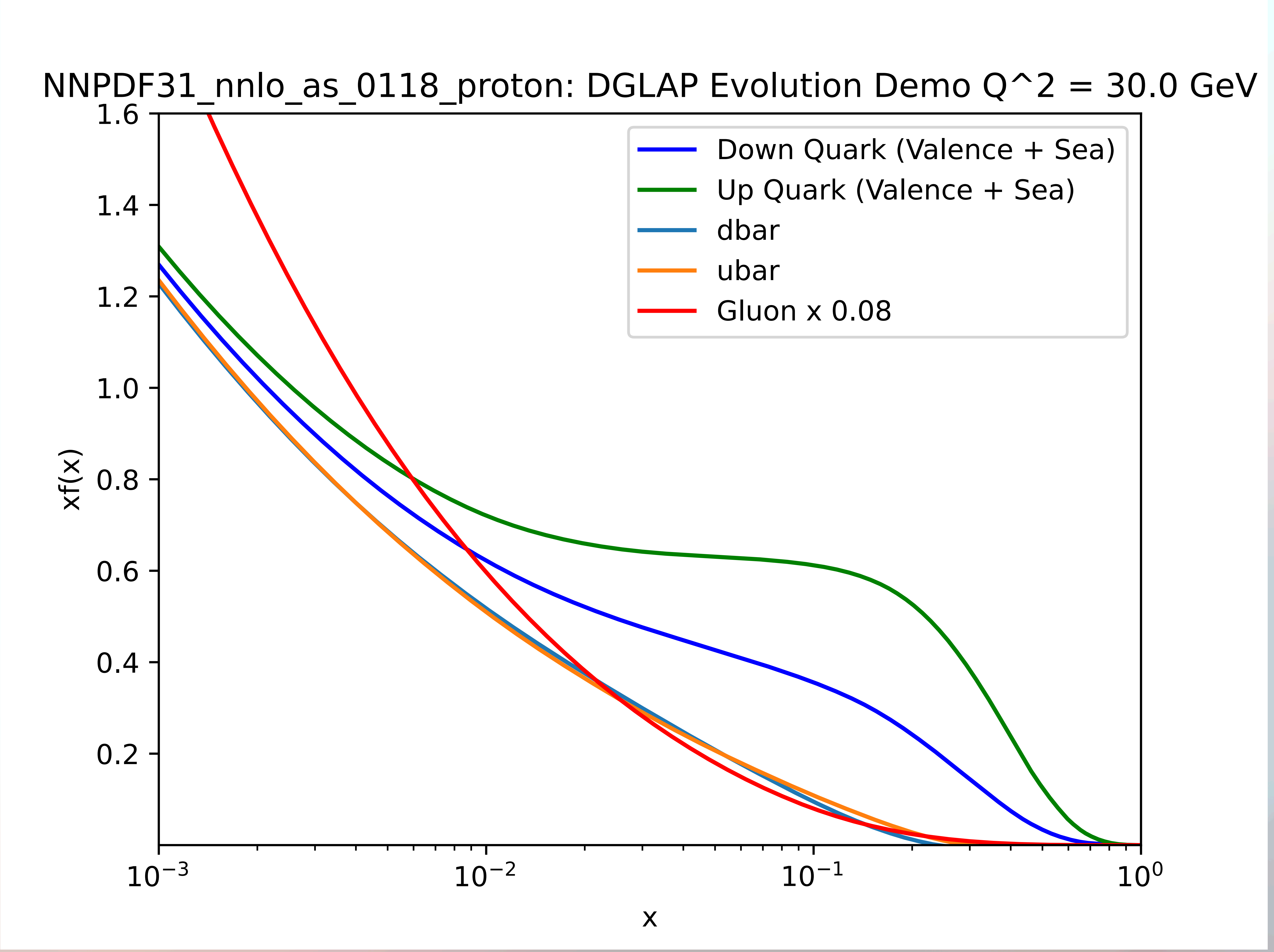

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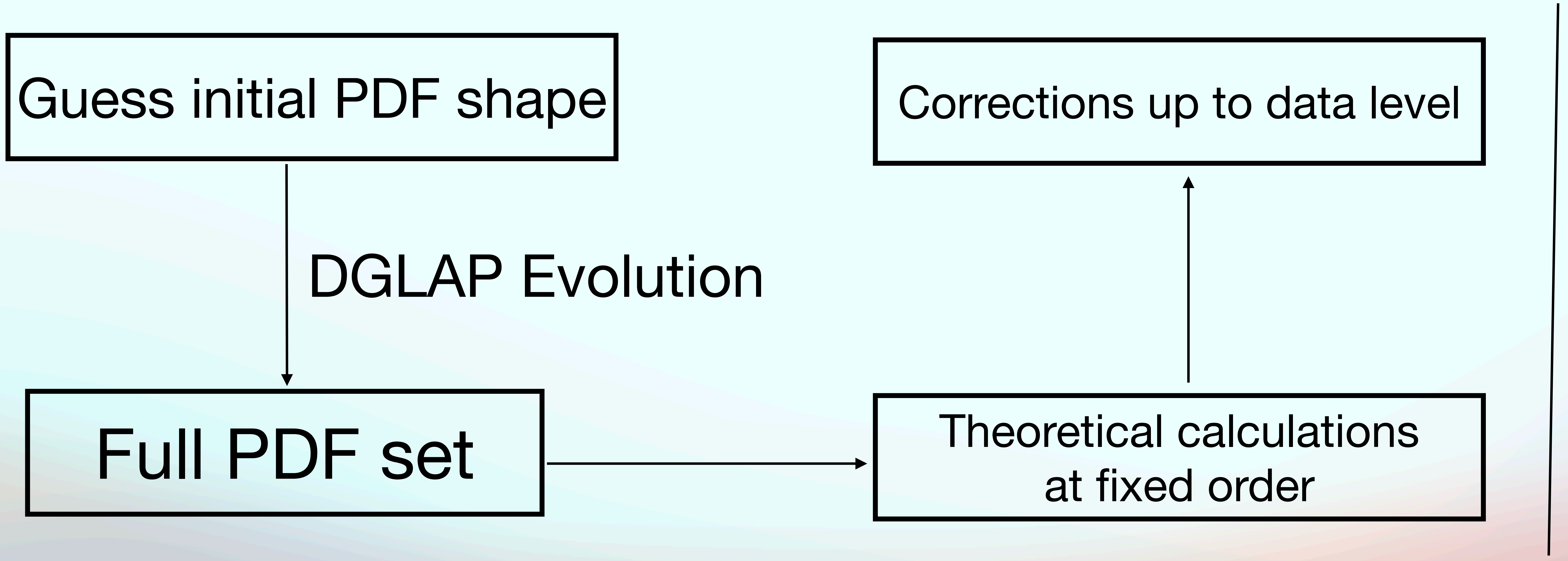


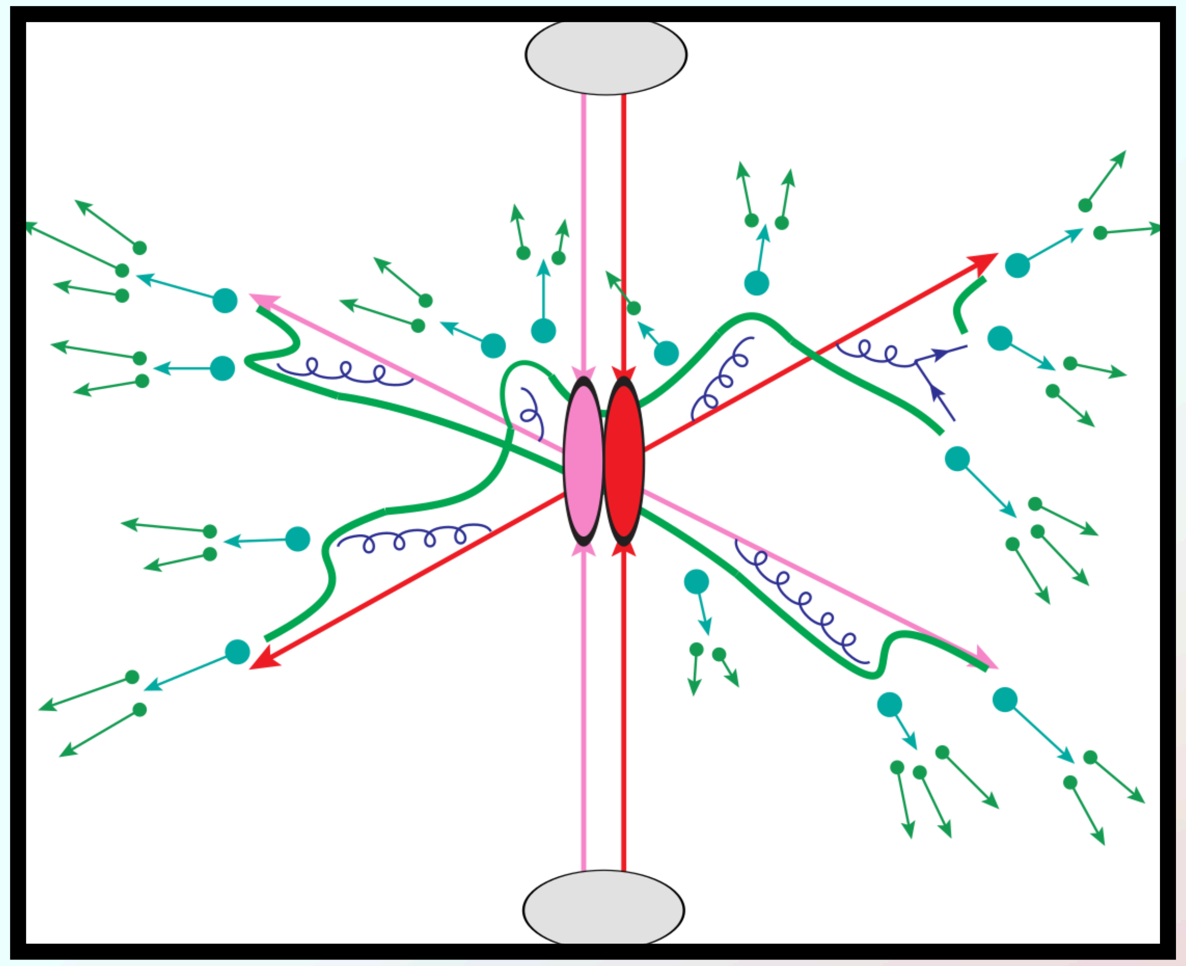
Extracting PDFs

Extracting PDFs

MC-tuning, and can you MC-tune a PDF?

Why?

Two ways of doing PDFs



- Typically, fit PDFs via minimisation of the **(PDF x ME) - data** difference, step by step. This is already difficult - adding shower/hadronization models on top of this makes it all the more difficult.
- Several potential advantages to including shower & hadronisation in a PDF fit - more datasets, PDFs being directly useful to MC generation.
- We can do this by matching PDFs to particle level MC generators.
- While this would have been historically difficult, it may no longer be the case! We can now use PDF-weight-variation mechanisms in generators to get MC predictions from randomly sampled PDFs. Can look at 1000s of random PDFs in one MC run.

PDF fitting with ME+PS MC

Our Procedure

Sample
A set of N, low Q, PDF parameters

Evolve
To the full Q range and export as lhapdf PDF set members

MC Generator (no UE)
Run MC events with PDF weight vectors to produce N sets of histograms

Parametrise
The response of each bin to the PDF starting parameters

Tune
Find the best fit parameters and make first PDFs

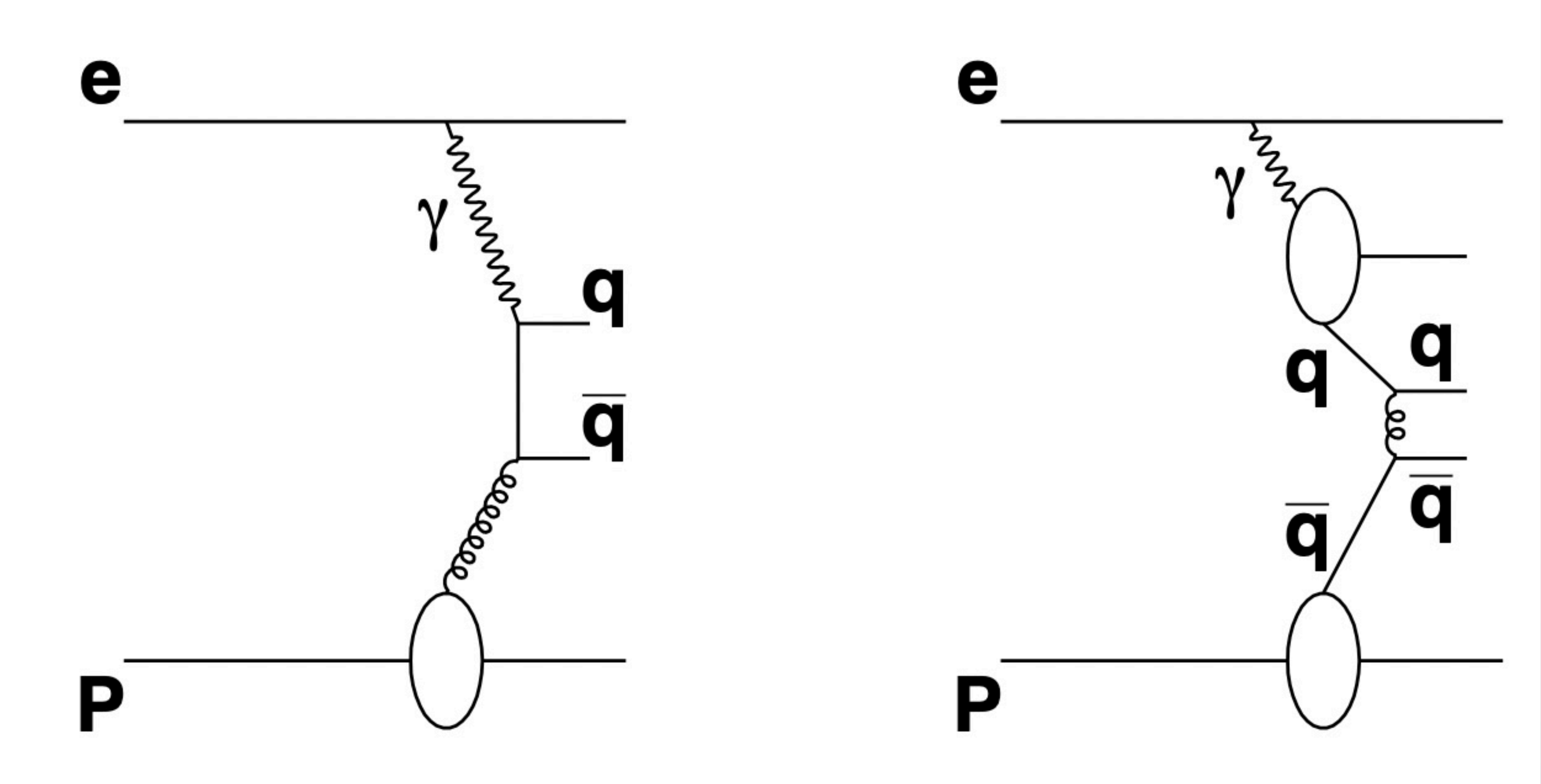
MC Gen (w/ MPIs)
Feed first PDFs in, vary MPI parameters

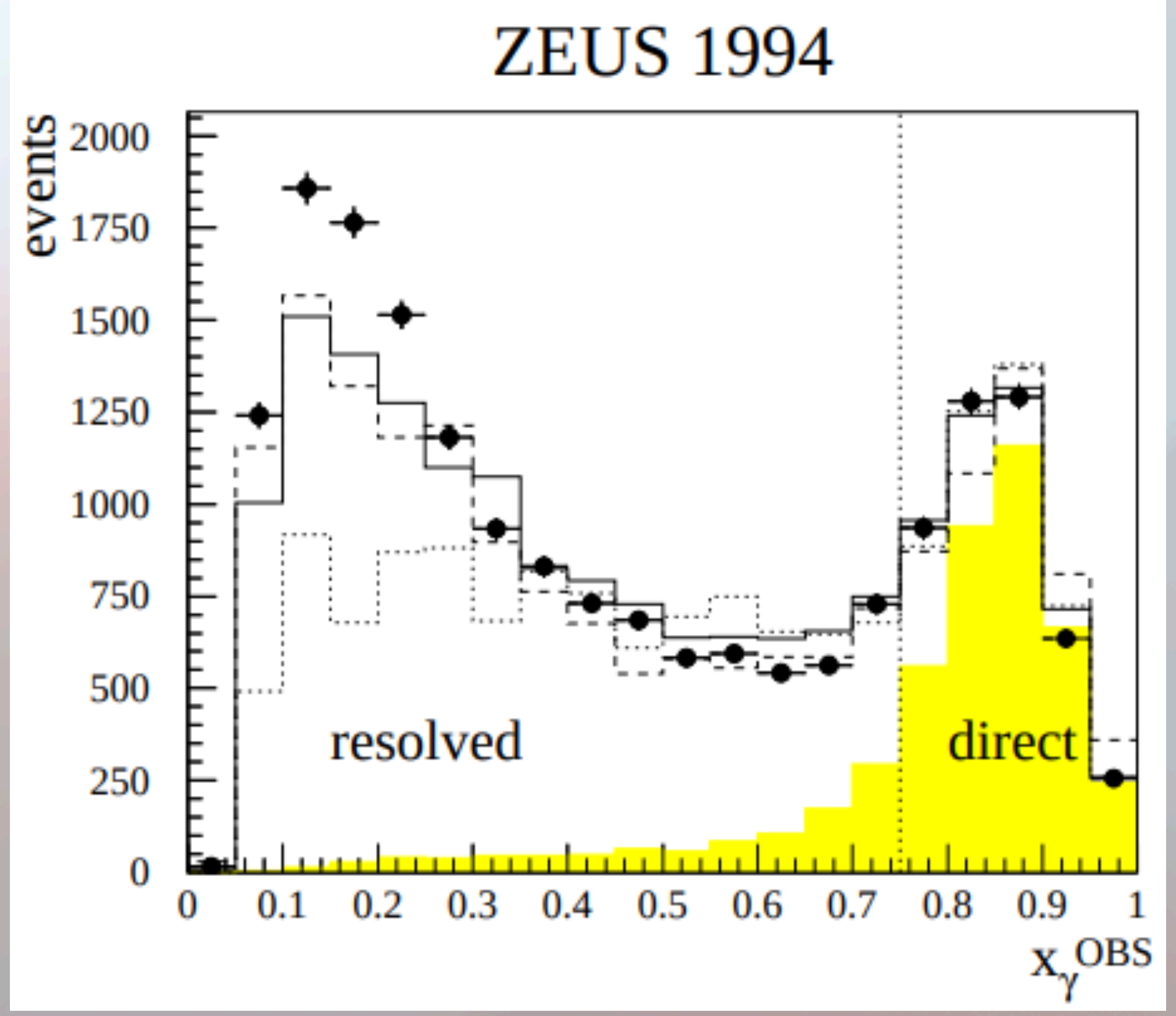
Tune MPIs
Feed first PDFs in, vary MPI parameters

Repeat for final PDFs
Repeat process with MPI tune for final PDFs

The Resolved Photon

- $\gamma \to q\bar{q}$ allows for virtual photon to acquire QCD structure (with hadronic features)
- There are no valence quarks, as the initial structure is from the EM charge. i.e. $e \to \gamma$ via the Weizacker-Williams approximation
- Can access this in ee, ep, eA, AA → Relevant to the EIC!





[arXiv:hep-ex/9710018]

Why Resolved Photon?

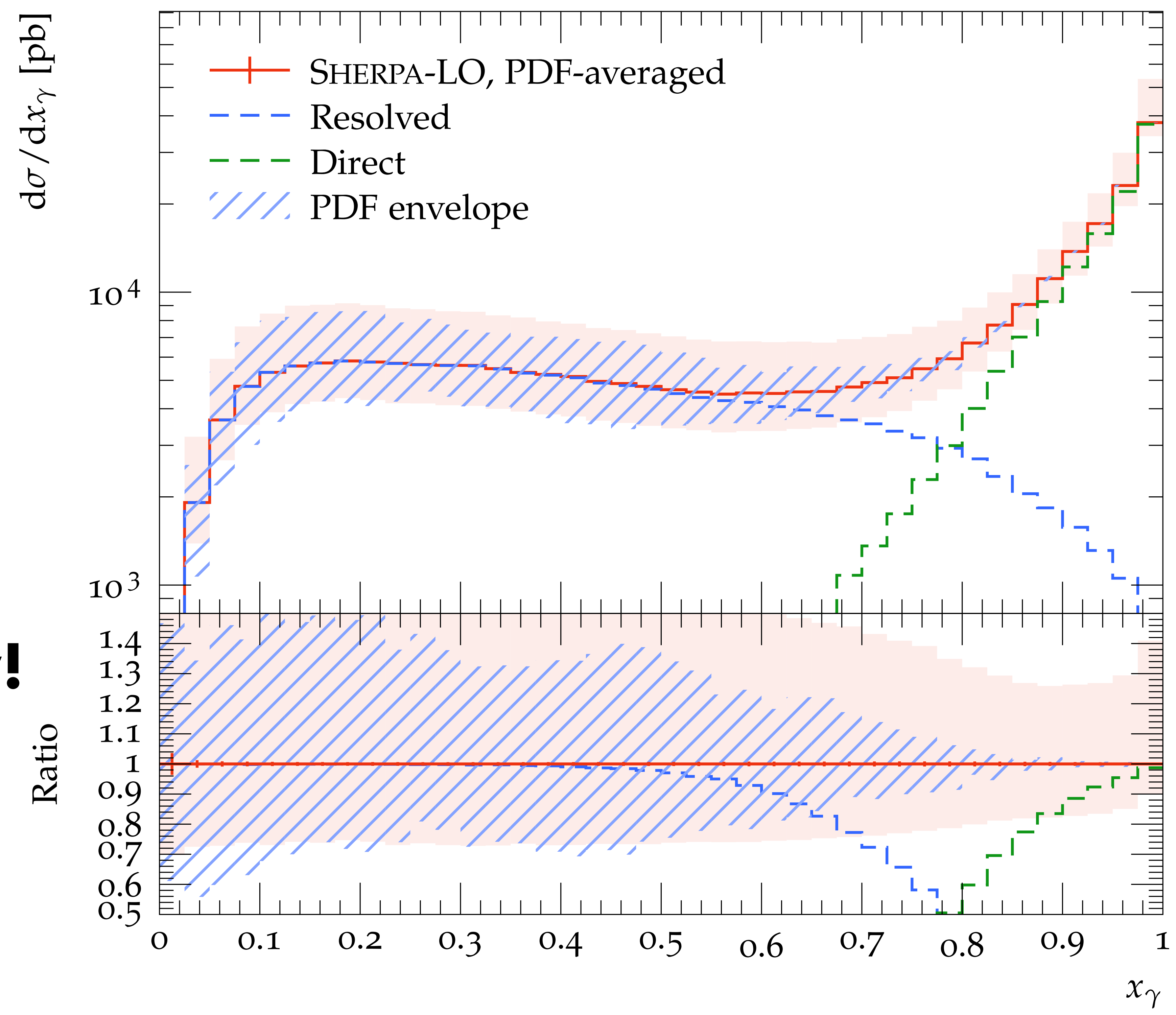
Our testbed

- Major activity at HERA since the last public photon PDFs ~ 2004 CJK fit. No photon PDFs on lhapdf since 1996 Schuler & Sjöstrand.
- Existing photon PDFs in lhapdf don’t have errors.
- More ep data available.
- Modern Proton PDF sets ⇒ coupled extraction of better Photon PDFs (in theory)
- New photon PDFs (with error sets) with HERA and LEP datasets becomes immediately useful to the EIC.

Photon PDFs

Bottleneck for precision calculations

- interfaced 11 photon PDF sets to SHERPA
- Leading Order, scale and PDF varied independently



PDF variation as large as LO scale uncertainty!

Last fit from 2004!

[Peter Meinzinger, EIC Workshop, INT, Seattle, 2025]

Parametrization and Evolution of PDFs

SAL Parametrisation [hep-ph/0507091, DIS05]

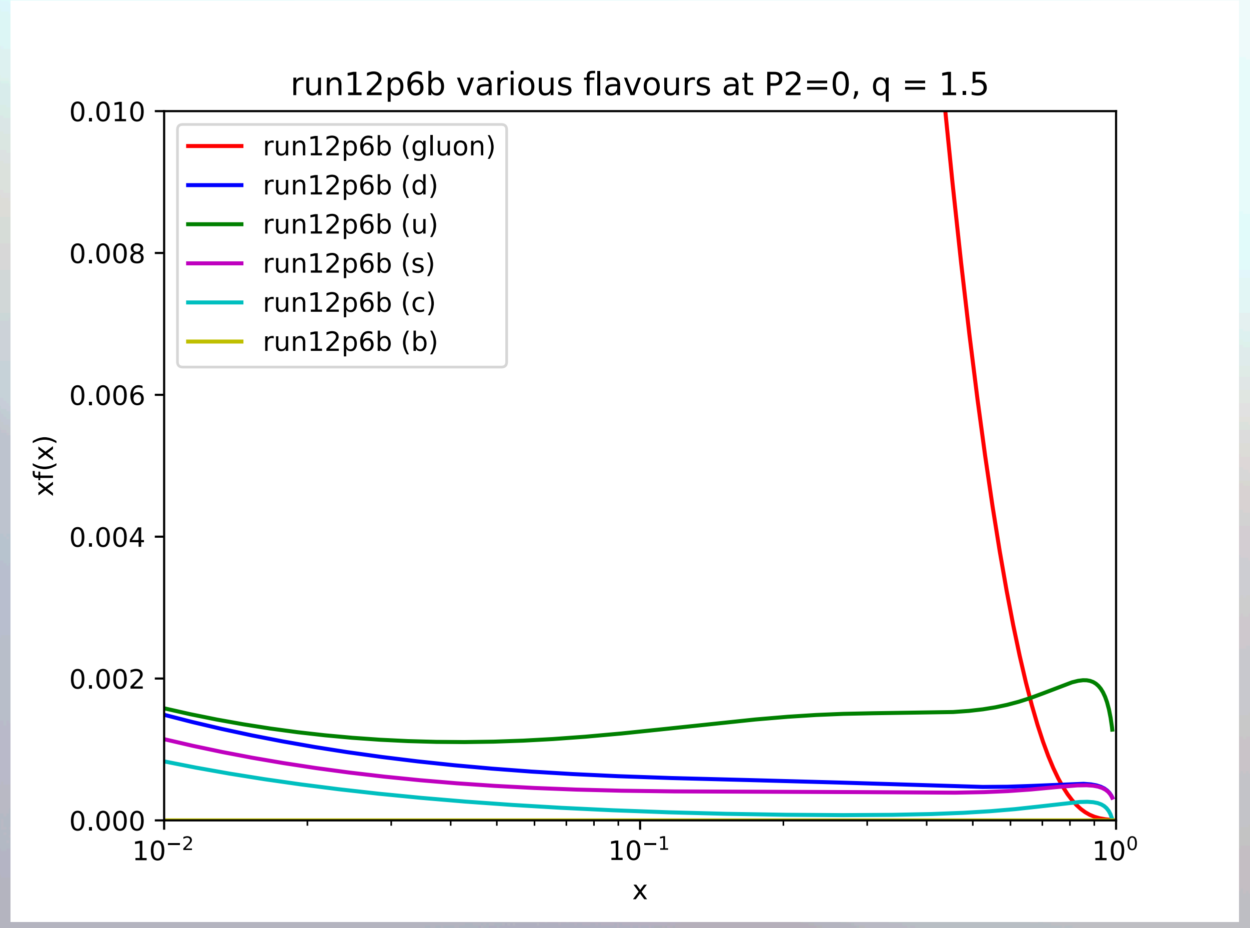
- We begin with a parametrisation from SAL, consisting of point-like and hadronic terms.
- No c,b components. These are turned on later in the evolution at the appropriate scales.
- Using APFEL++ (QED test branch) for DGLAP evolution of PDFs, starting from Q^2= 2GeV.

$$f_q(x) = f_{\bar{q}}(x) = e_q^2 A^{\mathrm{PL}} \frac{x^2 + (1-x)^2}{1 - B^{\mathrm{PL}} \ln(1-x)} + f_q^{\mathrm{HAD}}(x)$$

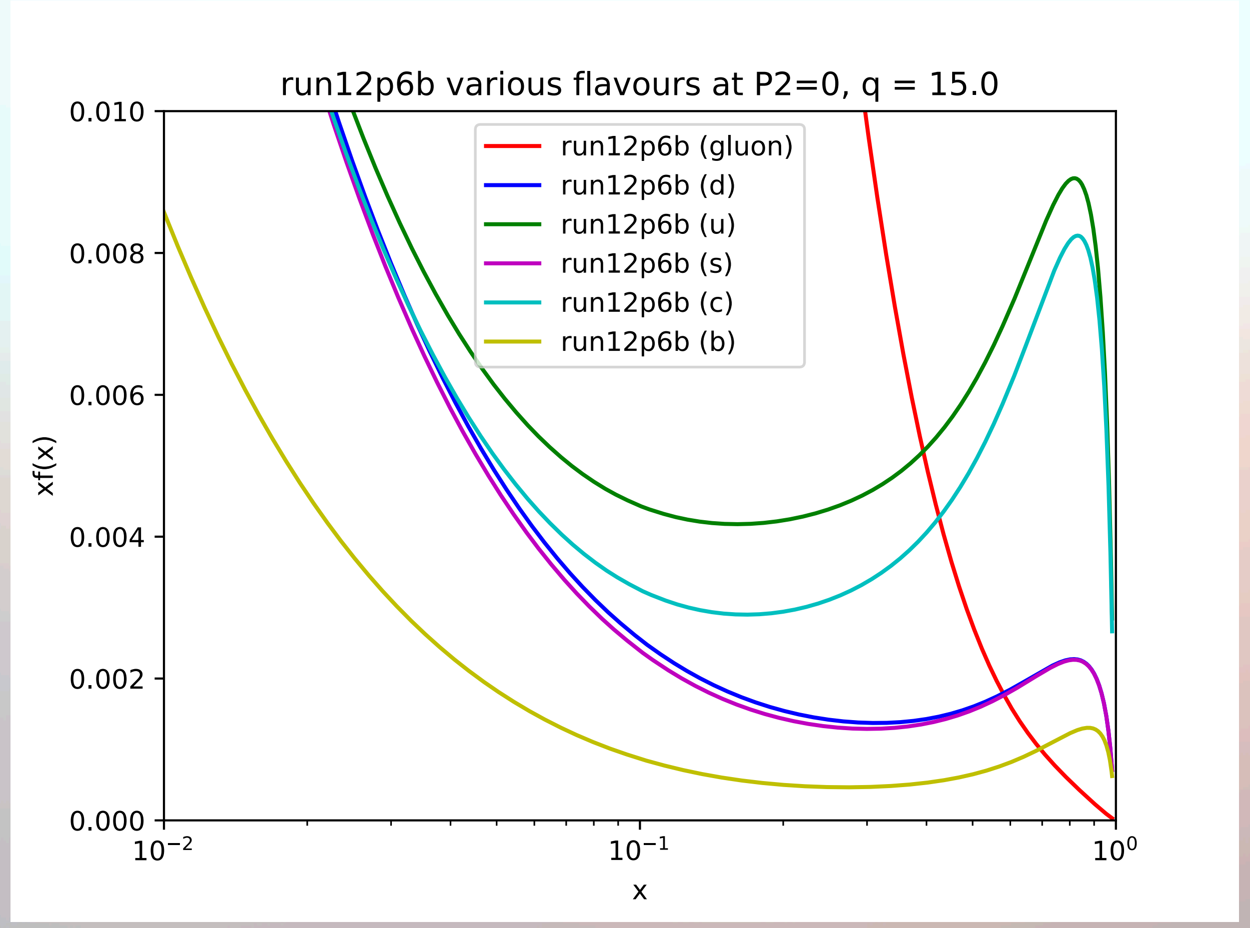
$$f_u^{\mathrm{HAD}}(x) = f_d^{\mathrm{HAD}}(x) = A^{\mathrm{HAD}} x^{B^{\mathrm{HAD}}} (1-x)^{C^{\mathrm{HAD}}}$$

$$f_s^{\mathrm{HAD}}(x) = 0.3 f_d^{\mathrm{HAD}}(x)$$

$$f_G^{\mathrm{HAD}}(x) = A_G^{\mathrm{HAD}} x^{B_G^{\mathrm{HAD}}} (1-x)^{C_G^{\mathrm{HAD}}}$$



PDFs before DGLAP evolution

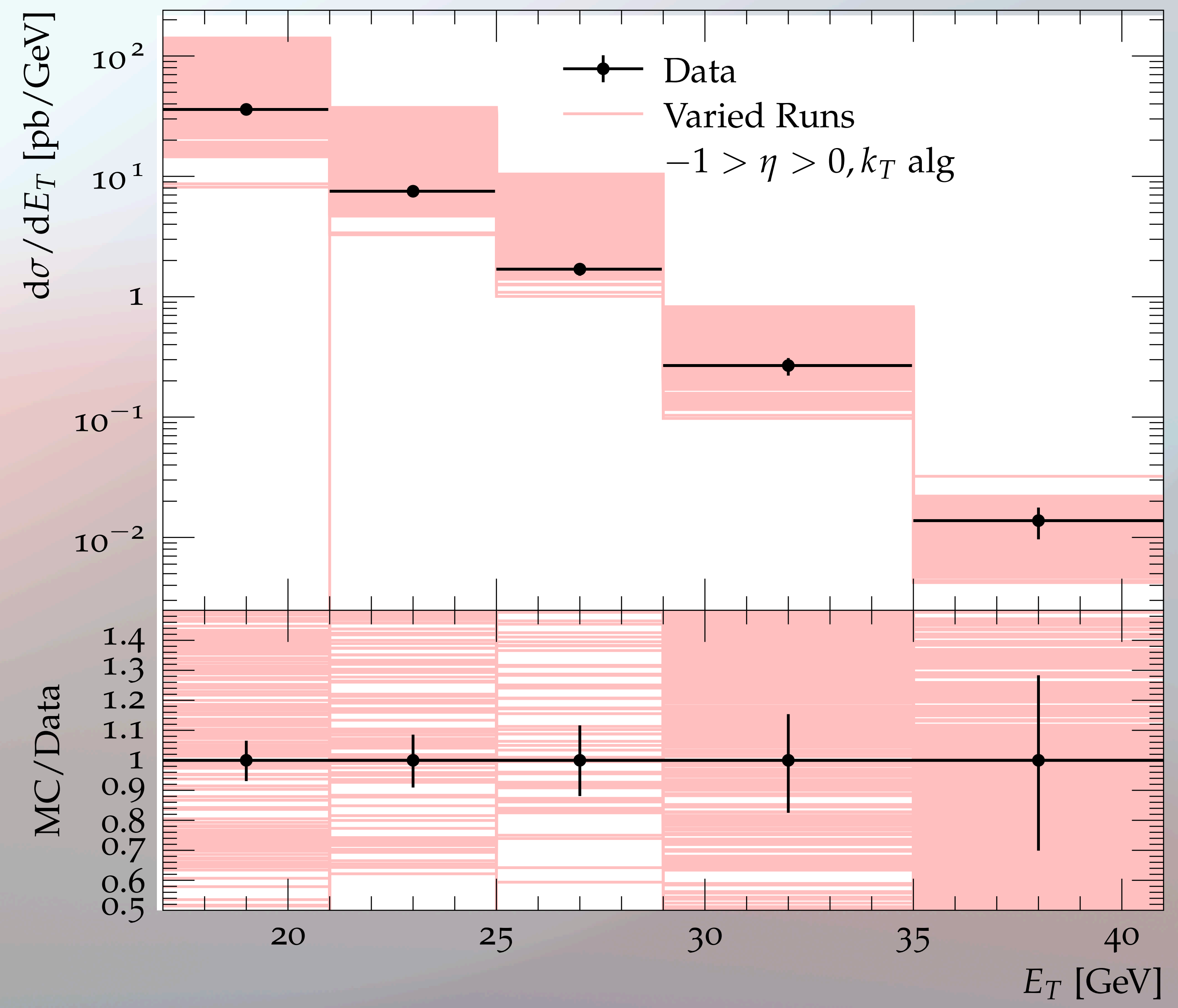


PDFs evolved up to Q= 15GeV

Sherpa MC and Analysis in Rivet

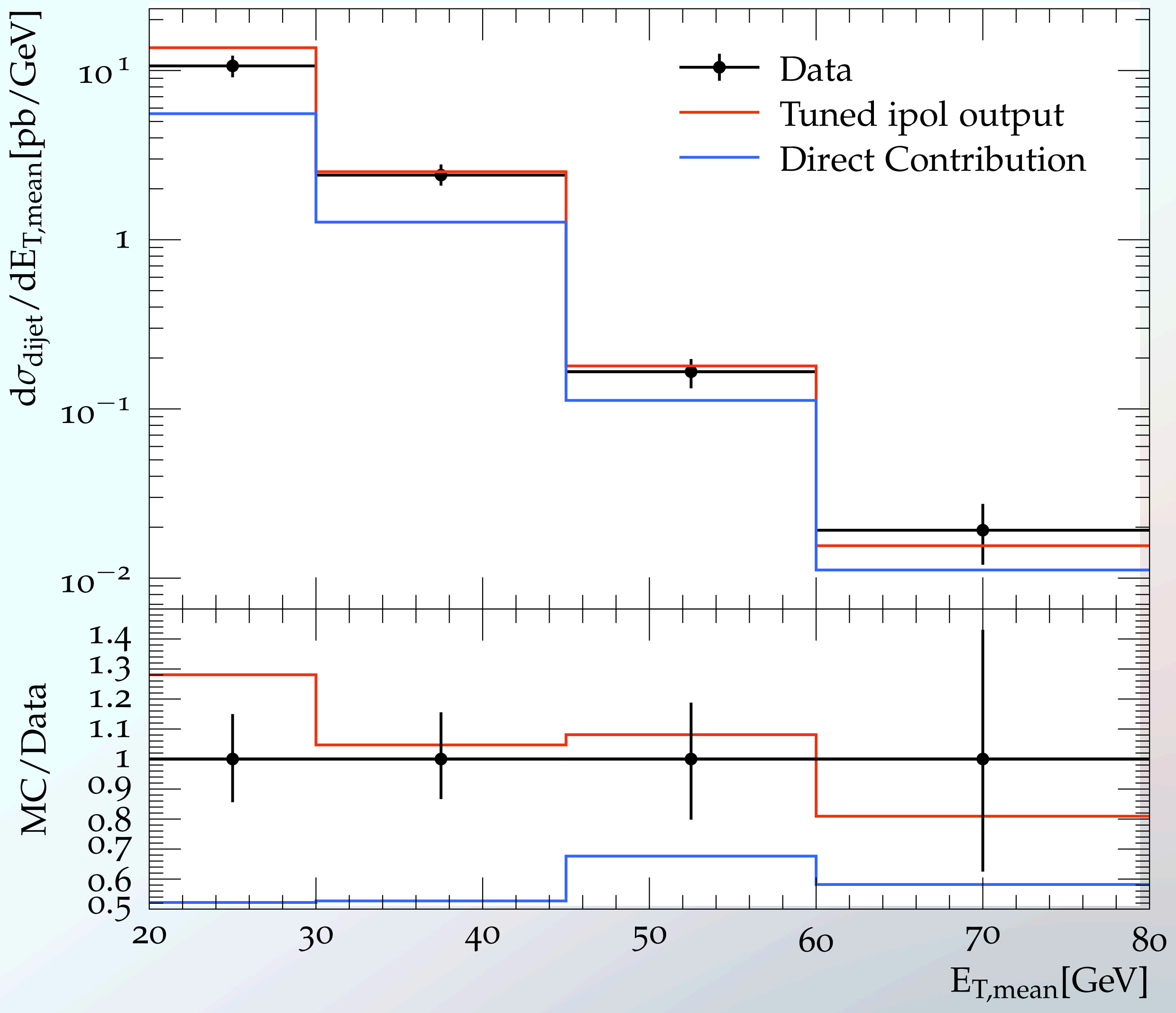
- Using Sherpa 3 - with photon variations branch now in master!
- NLO ME (2->2) + LO ME (2->3-5) + PS
- Sherpa e-p - one run of O(1B) events in direct mode (parallelised and rivet-merged)
- Sherpa e-p O(100)s resolved results (from varied PDFs) in one run - using the PDF_VARIATIONS mode in Sherpa.

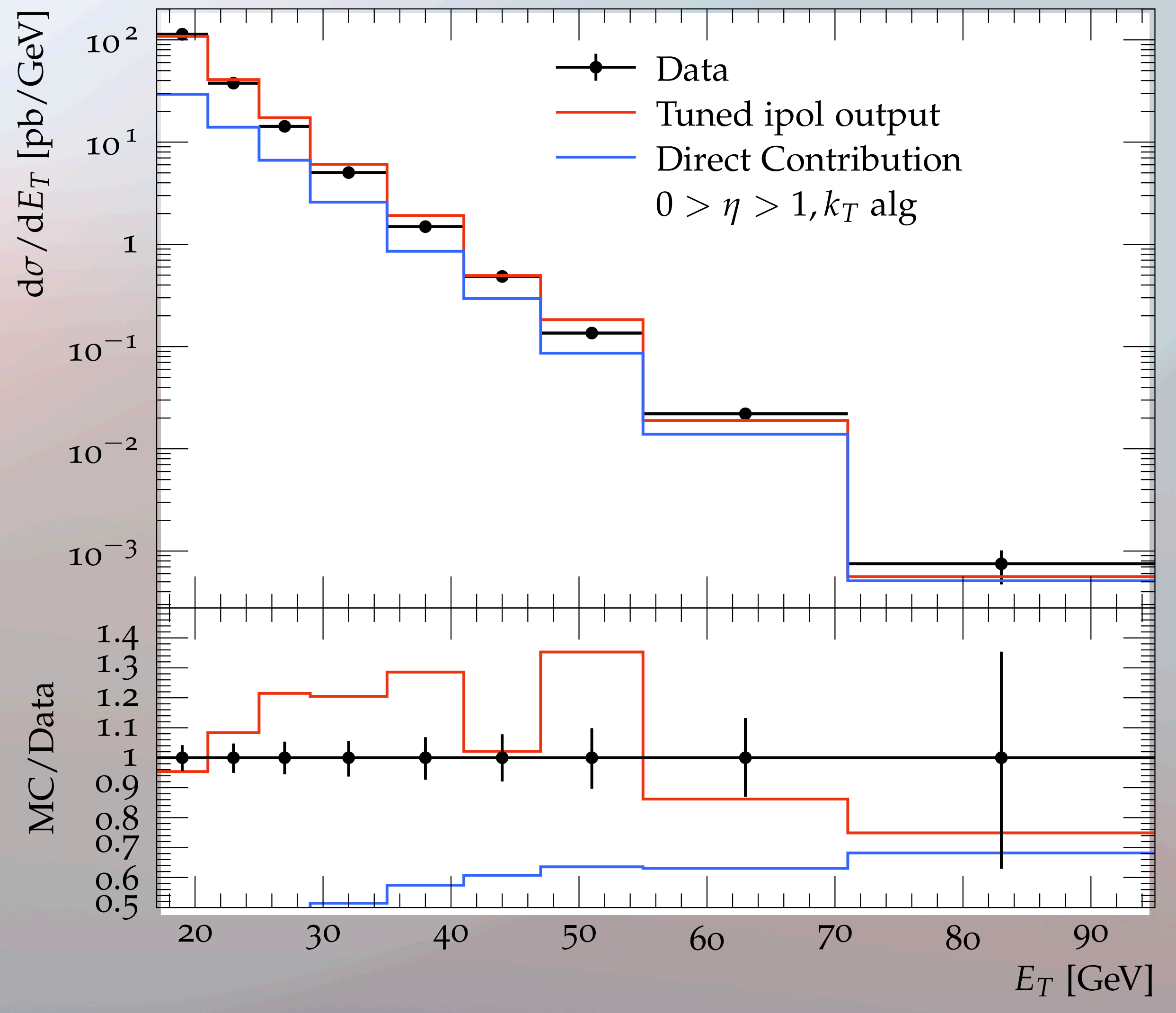
- H1_2002_I581409 - New! Dijet cross sections in photo production
- ZEUS_2012_I1116258 - Inclusive Jet photo production
- ZEUS_1997_I450085 - Dijet cross sections in photo production
- ZEUS_2007_I756660 - New! - 3/4 jets FS in photoproduciton
- ZEUS_2003_I613625 - New! - Dijet angular distribution in photo production of charm
- OPAL_2003_I611415 - Dijet Photoproduction



Tuning with Professor

- 6 free parameters
- Weights primarily on resolved part of the distributions
- Adding new shape-fitting, where the histograms are normalised to area before fitting - useful where clear there are scaling issues - or where cross sections/ direct-process modelling is problematic.
- Last time we floated all the norms using meta-params in the fit. Now, Professor's norm-mode ⇒ allow most histos to be fitted regularly, constraining the normalisation.
- Weight on UE-insensitive bins

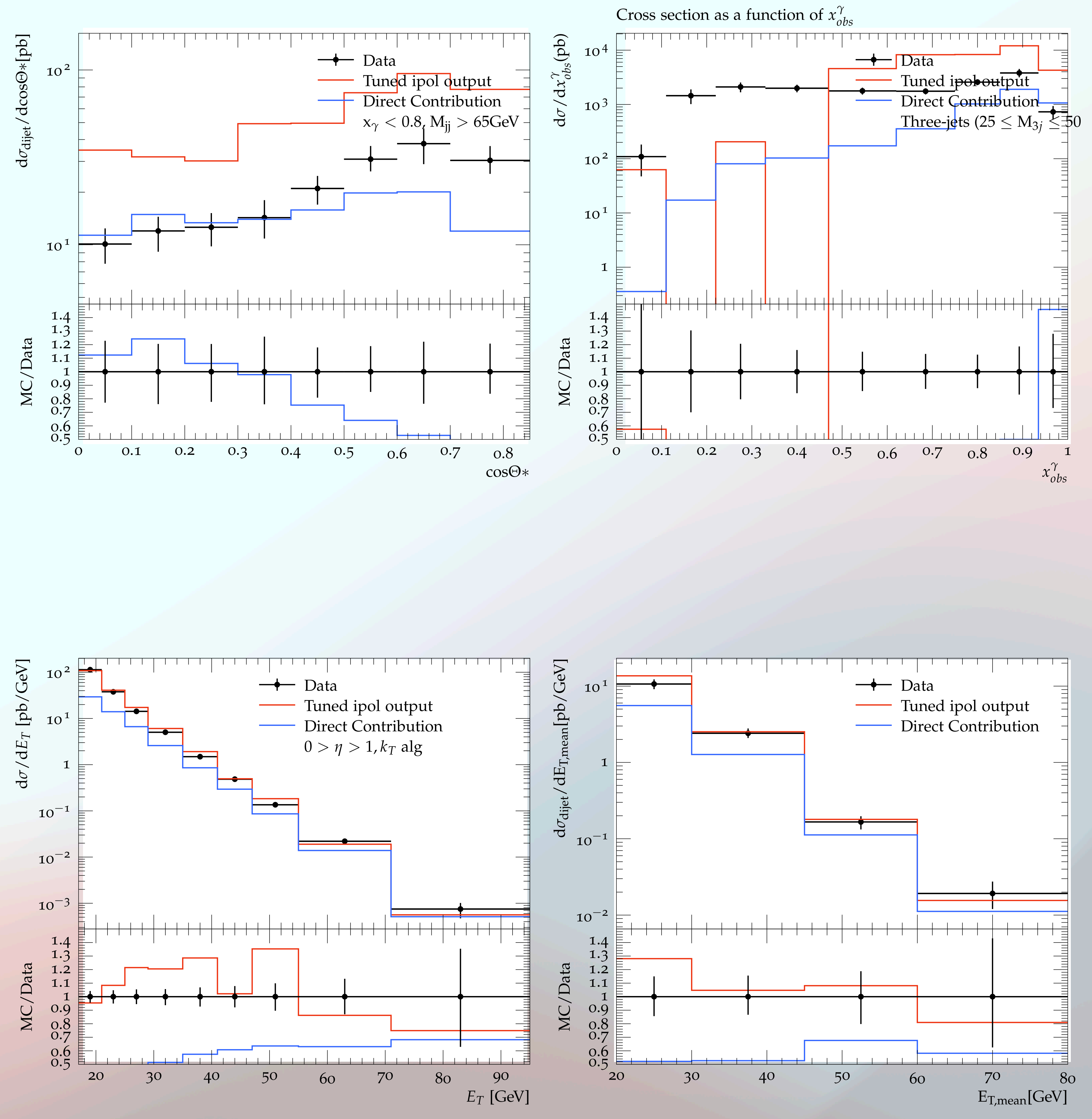




PDF Results & Errors

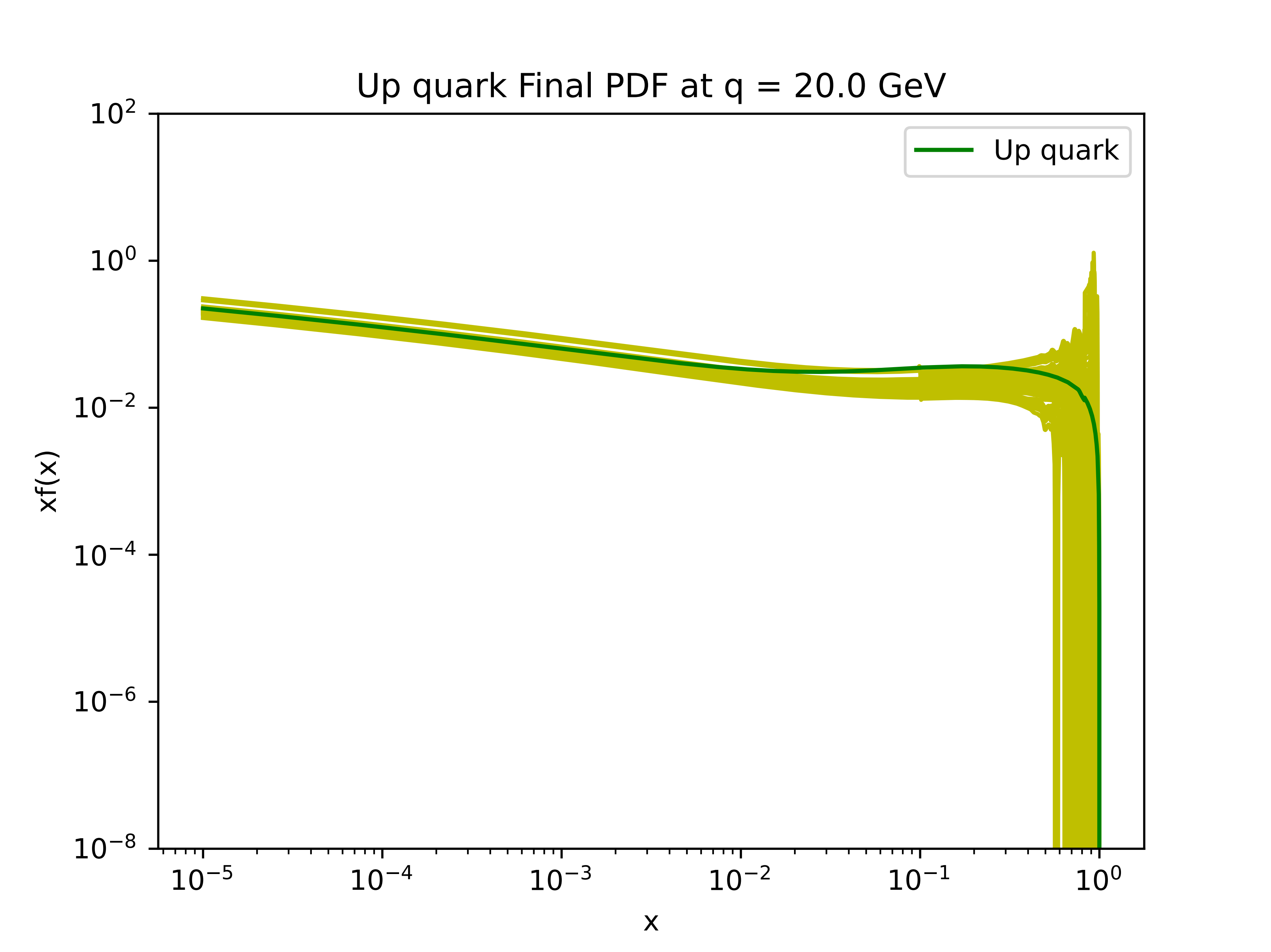
IPOL and Tuning

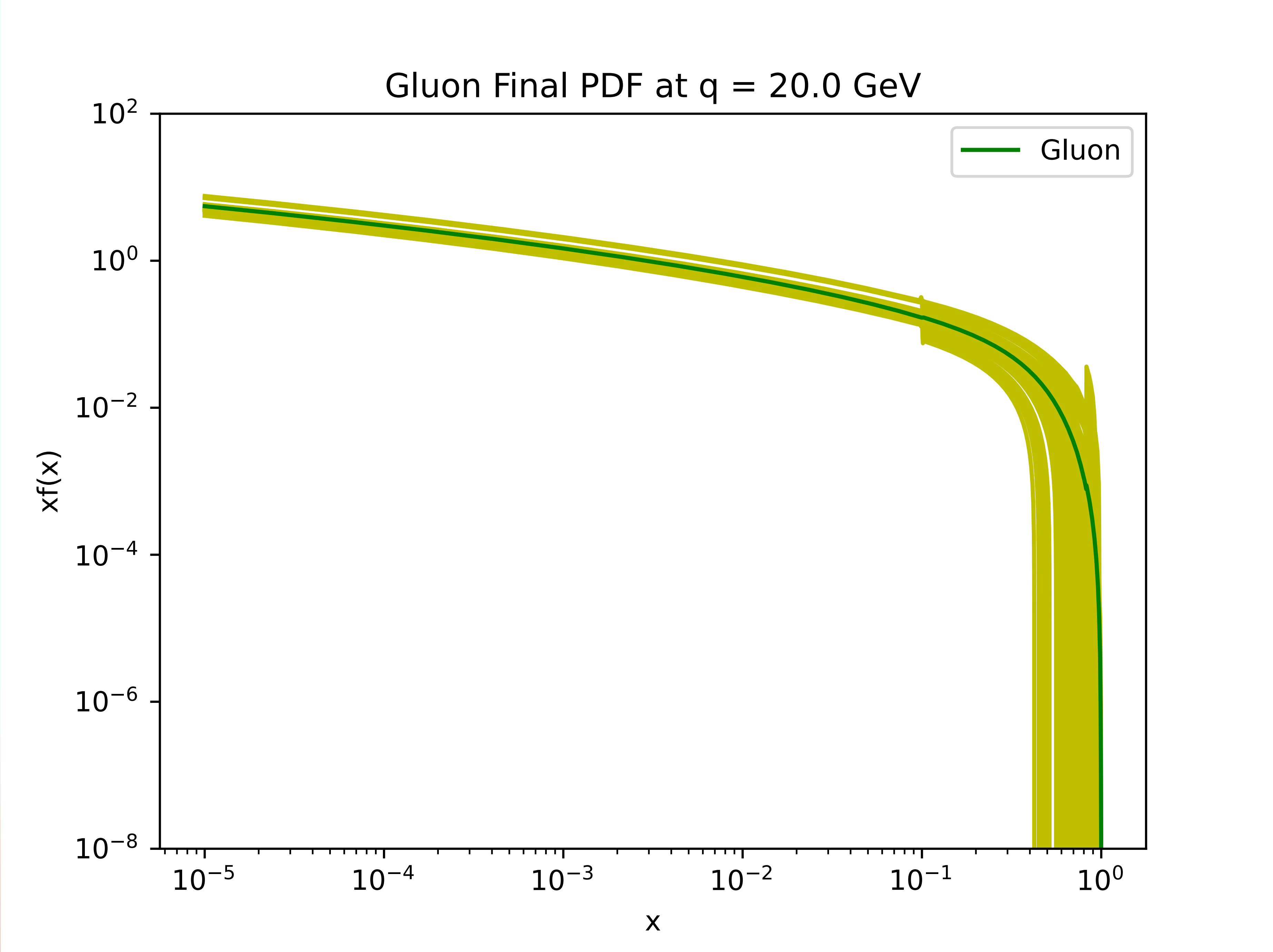
- Predominantly weighting on resolved areas
- Weights on “high momentum/ high invariant mass” bins.
- Remove areas with weird ipol-issues & direct mis-modelling.



PDF Error Demo w/ bootstrapping

PRELIM!!



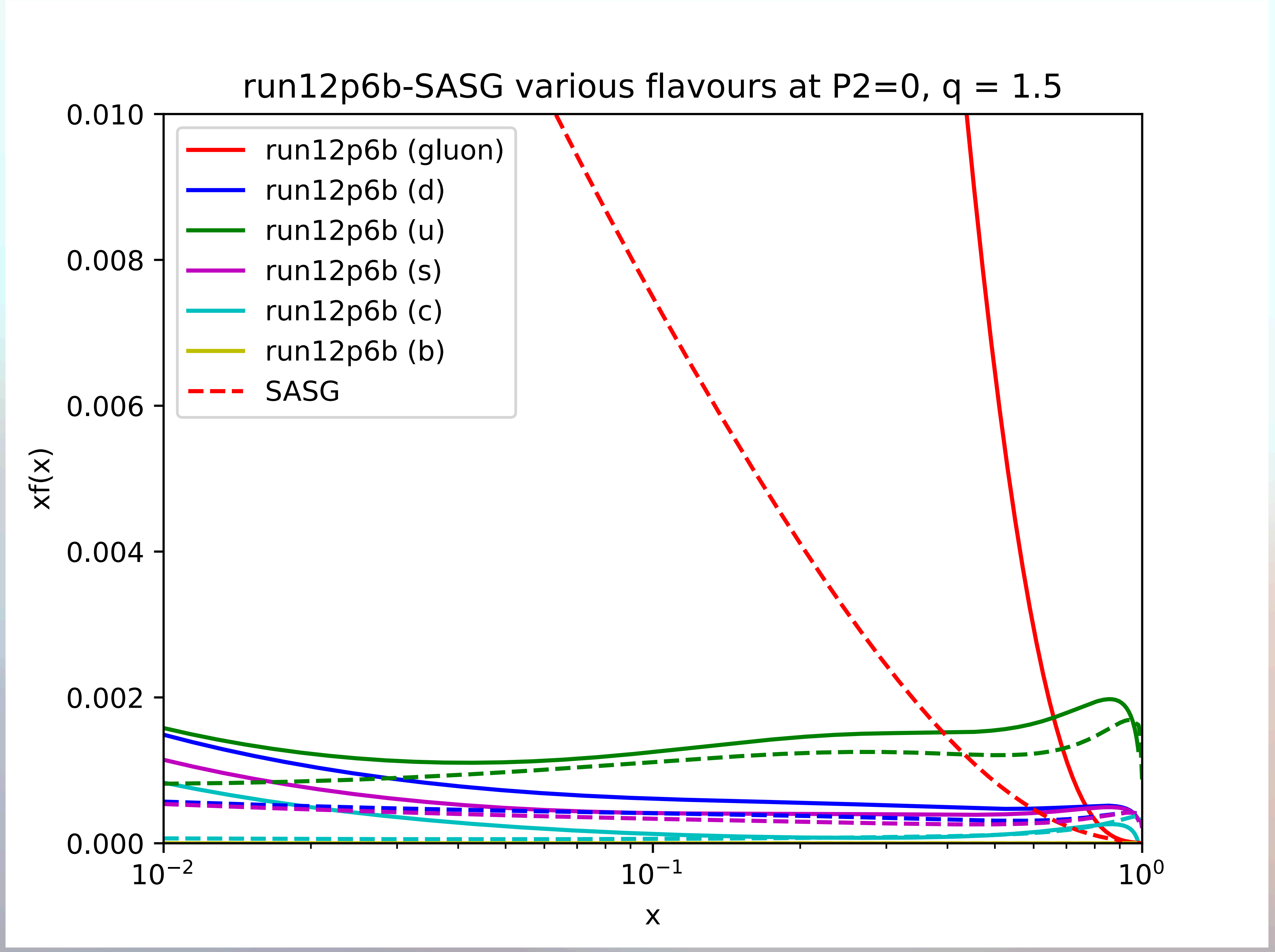


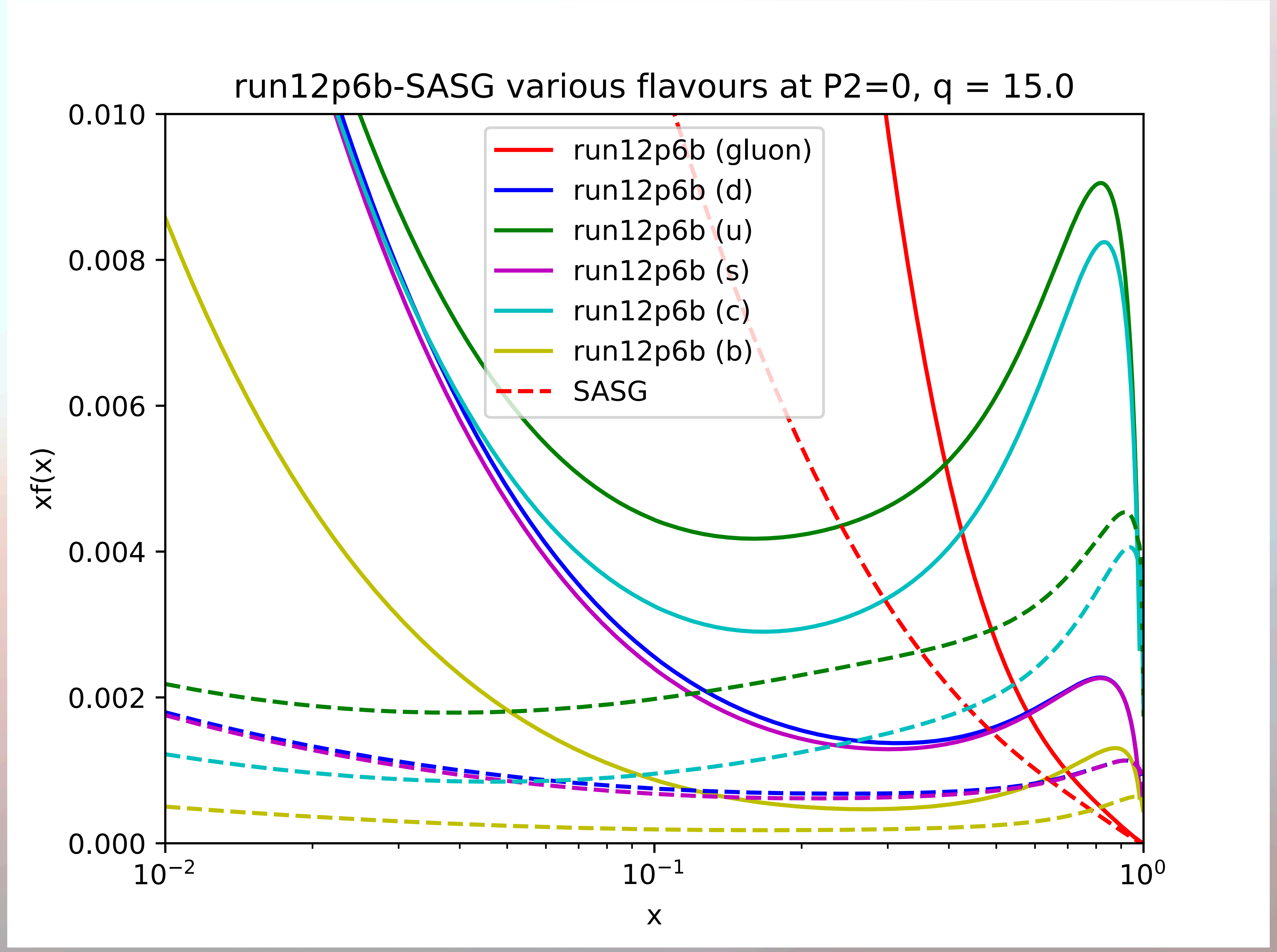
Prelim PDF Results & Errors

Prelim - DGLAP broken

- Using replica sets for errors - resample reference data from error bars -> refit the ipols to each smeared reference data set to obtain multiple tunes - supply as (non 0000) member PDFs.

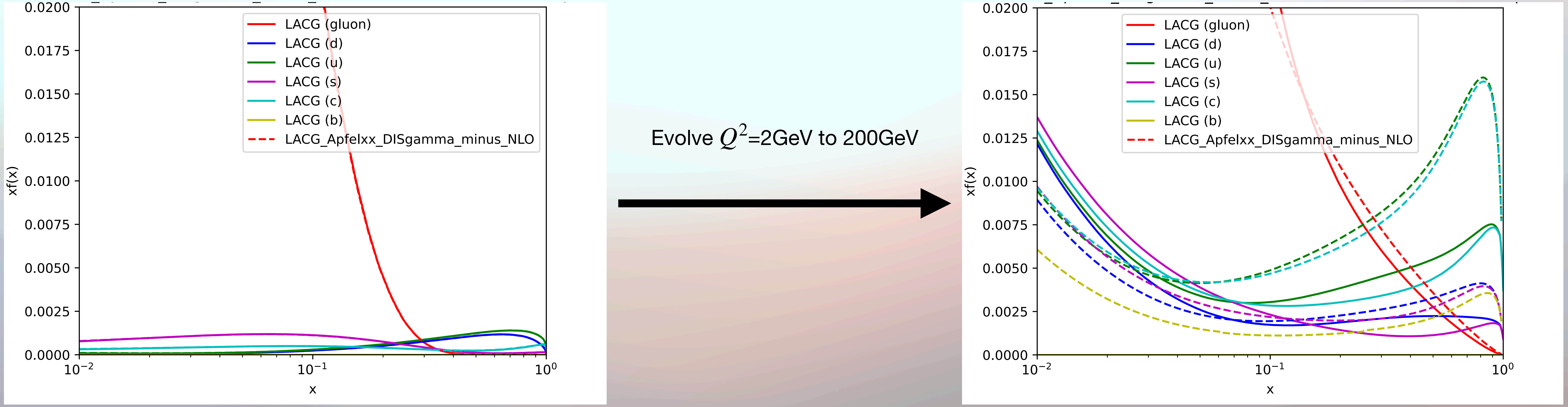
- Clear charge separation of u and d. Mass suppression of c and b also works (these are not parametrised, just switched on in APFEL++ at the appropriate Q^2.





The DGLAP evolution…

- Huge thanks to Valerio Bertone of APFEL++ for implementation of the evolution.
- Validation, and more testing currently underway for the implementation of the photon evolution into APFEL++
- Validating against 11 different photon PDF sets - something is not quite right, yet…



MPI tuning as part of the PDF fitting

Why?

- There are MPIs in doubly resolved e-e and resolved e-p processes.
- We can't simply use p-p MPI tunes for resolved processes in e-p, and similarly for double resolved in e-e. So we need different MPI tunes.
- The data we are using can also constrain this - and we can use the LEP data here without issue.
- And more importantly, we don't want our PDFs to absorb MPI effects!

Conclusions

What we have so far, and what we need to do!

- MC tuning with PS + ME generators can give us PDF fits - allows us to produce error sets as well - all @ particle level.
- We can also tune MPIs along the way - and supply as part of a Sherpa MPI+PDF setup for the EIC. Tuned to a large selection of HERA and LEP data available via (old and new) Rivet analyses.
- With PDF errors, we can finally make use of the NLO MEs in Sherpa.
- We still need to figure out the final parts of the DGLAP evolution - we are close!

Questions!

Extras

Sherpa’s MPI

The parameters we are looking at

- PT_0 and PT_min - IR regulator and cut-off
- $p_{\mathrm{T},0} = p_{\mathrm{T},0}^{(\mathrm{ref})} \left(\frac{E_{\mathrm{cms}}}{E_{\mathrm{cms}}^{(\mathrm{ref})}} \right)^{2\eta}$
- Sigma_ND_norm - a scale factor
- BeamRemnants:MatterForm (for each particle)
- BeamRemnants:MatterRadii (for each particle)
- BeamRemnants:MatterFraction (for each particle)