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Impact studies of the gluon PDF using exclusive J/ψ photoproduction data in xFitter

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Exclusive quarkonium production

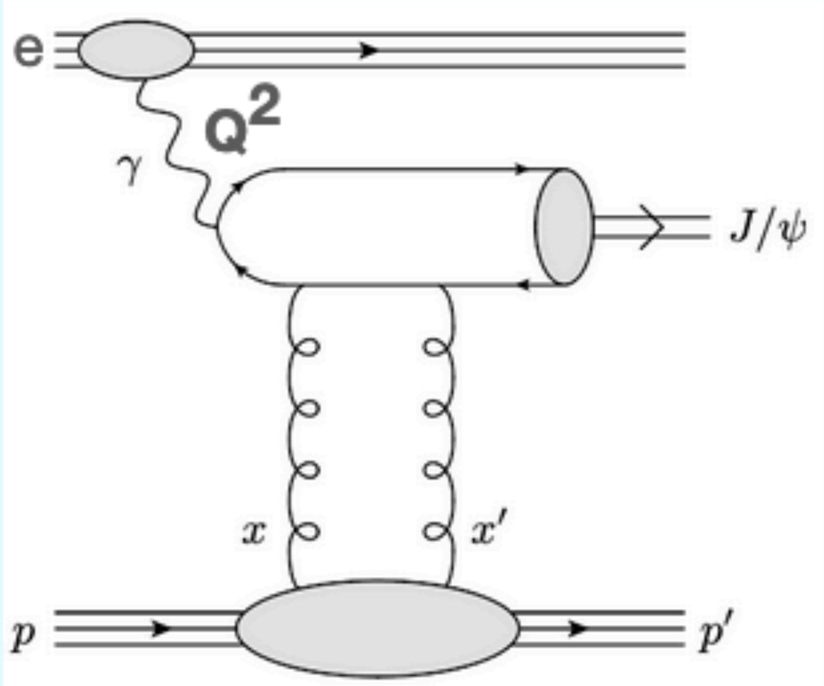
Exclusive quarkonium production at colliders:

< - - - .... - - - >

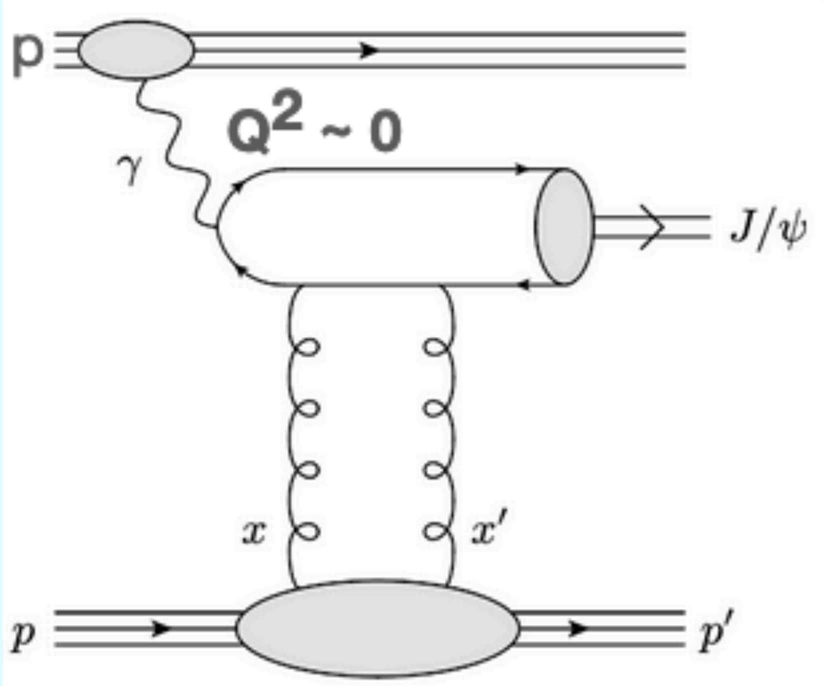
EIC (ep/eA) & HERA

Tagged e -> Lever arm in the virtuality Q^2 at **moderate-to-low(ish) x** reach on target

photo- (Q^2<1GeV^2) **and** electroproduction(Q^2>1GeV^2)



LHC (pp, pA, AA)



UPCs at the LHC -> flux of on-shell Q^2 ~ **0** photons and **low-x** reach on target

photoproduction

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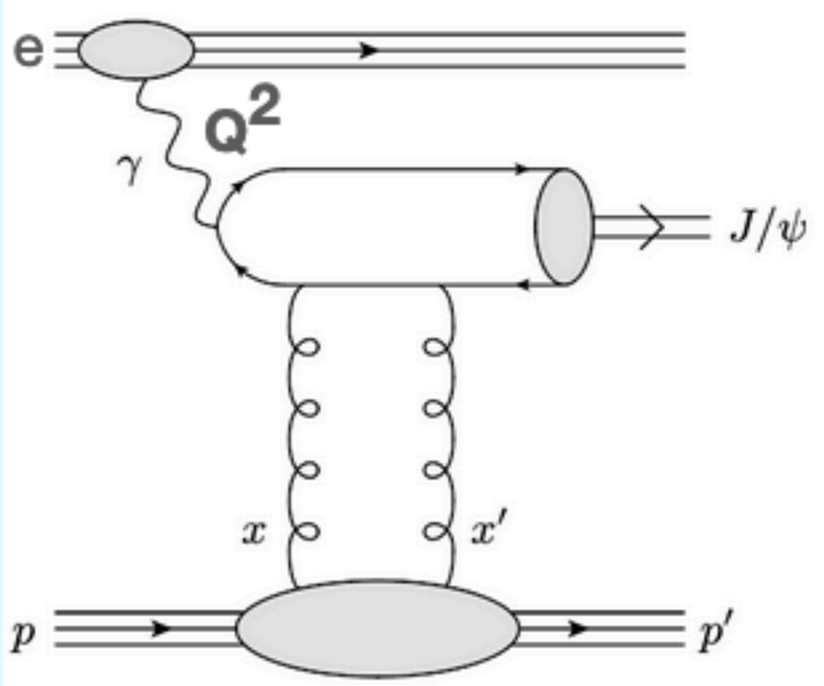

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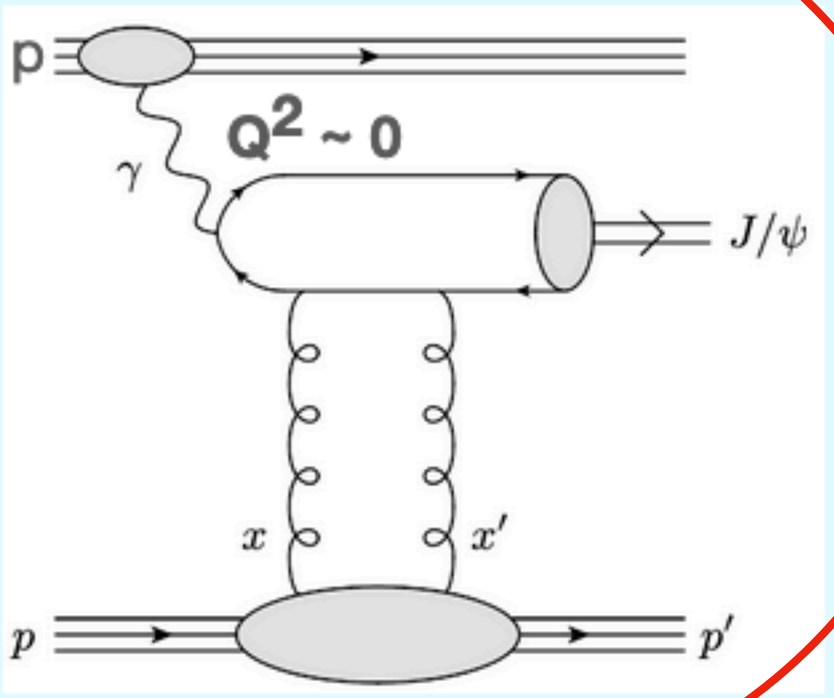

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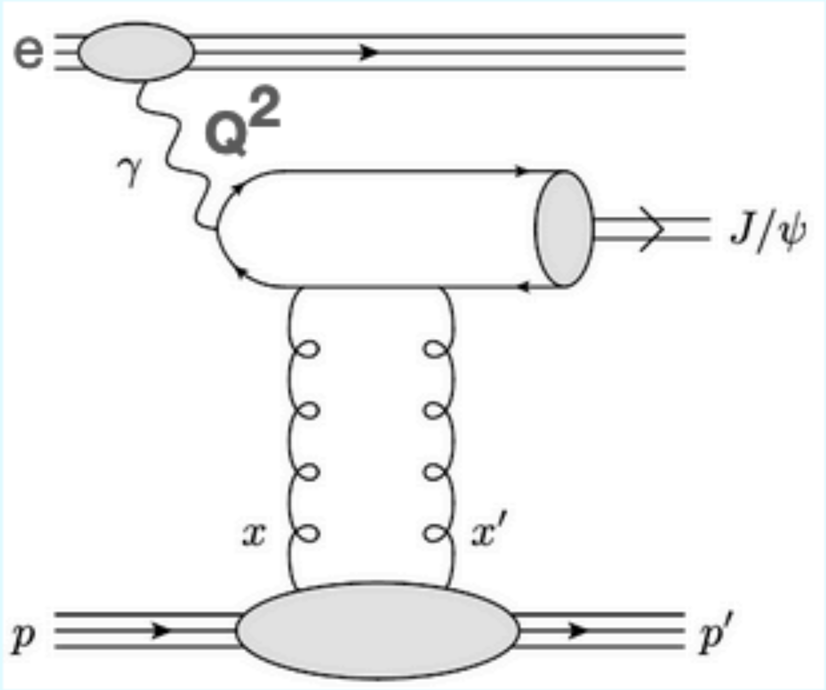

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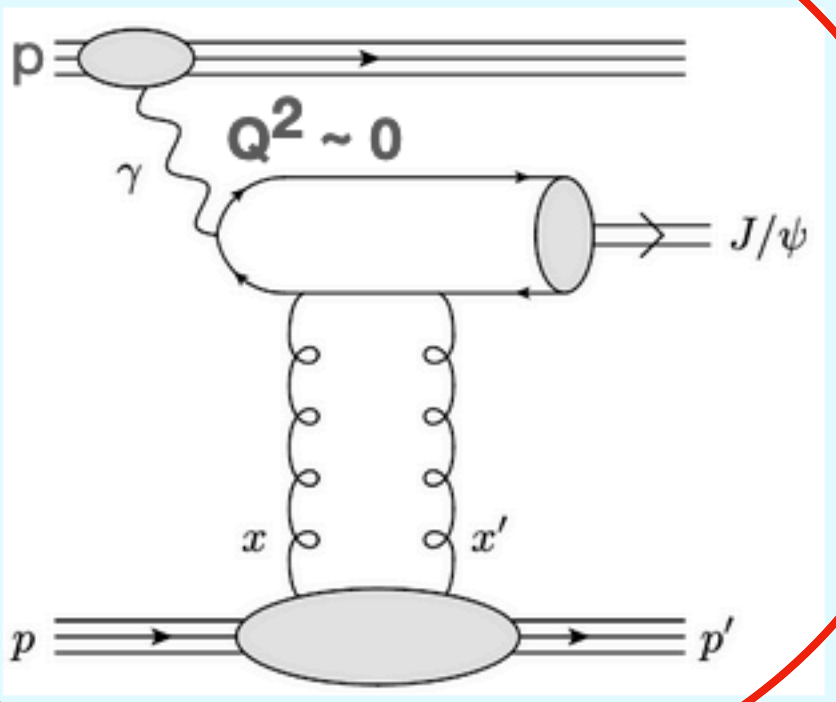

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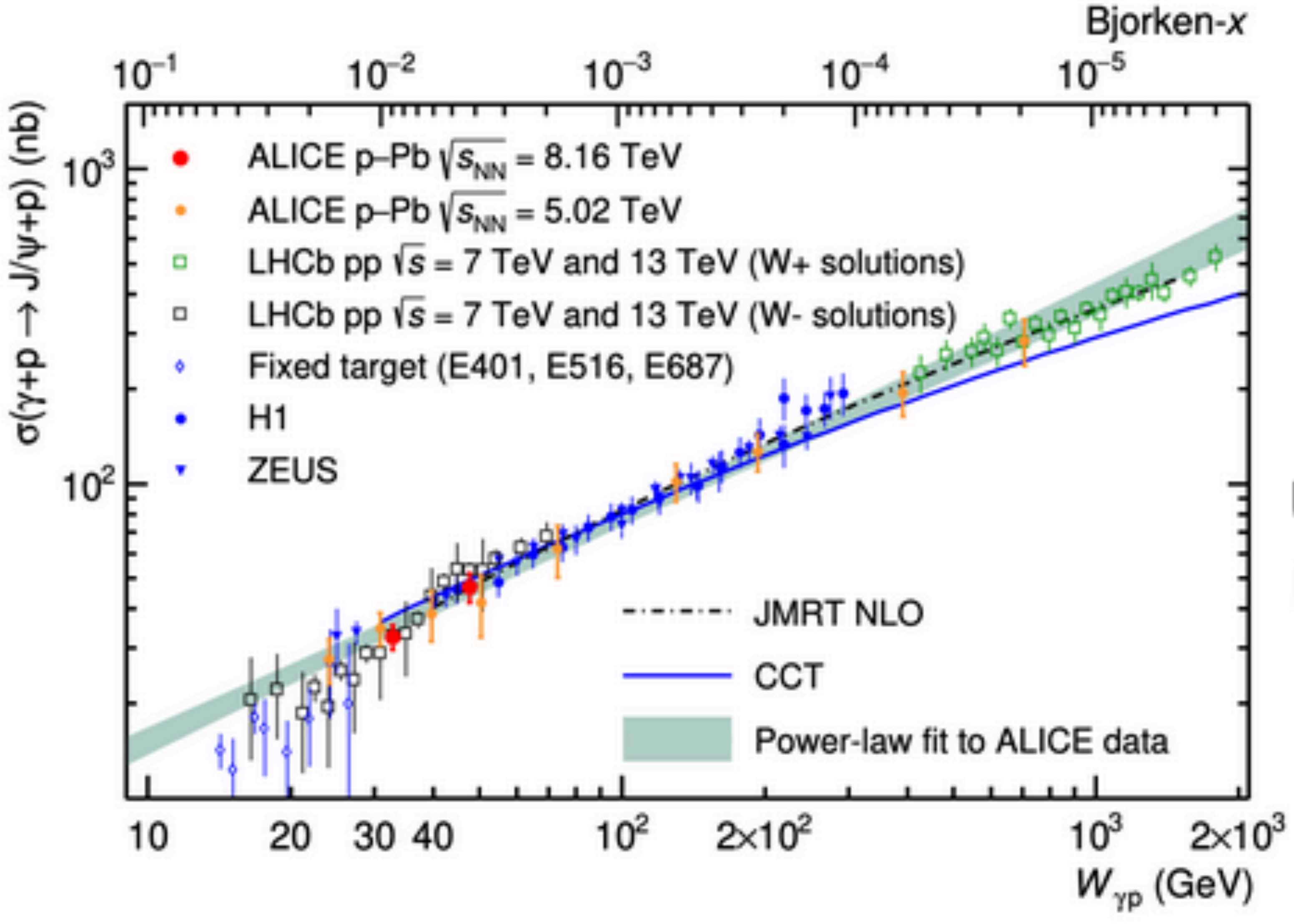
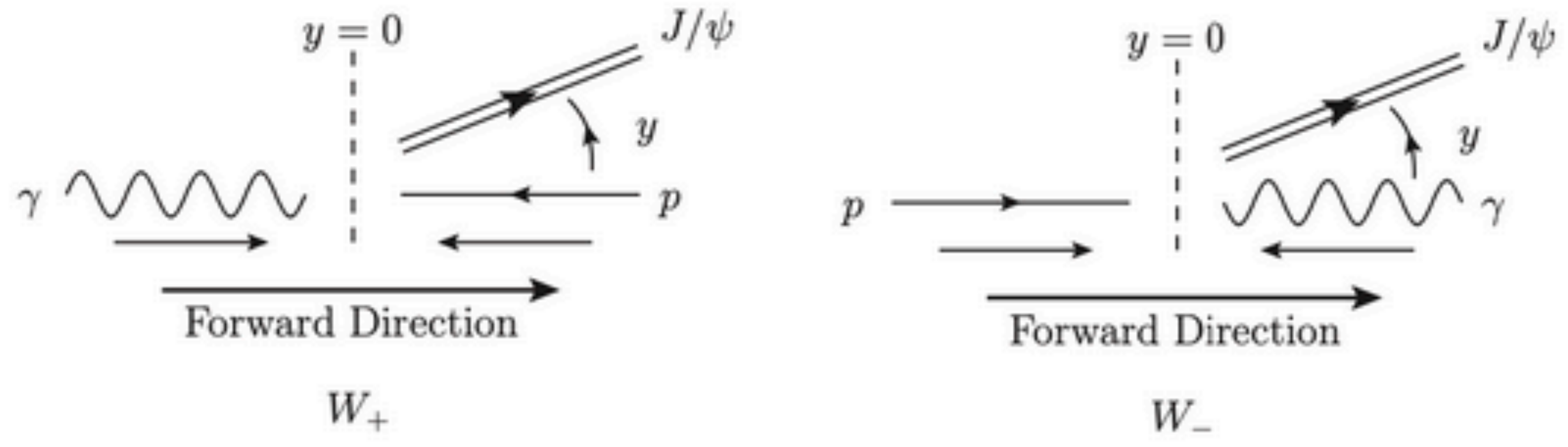
photoproduction

Q: Can we use the exclusive J/psi photoproduction data from LHC in such collision systems to constrain the low x and low scale gluon PDF?

eA vs. hadron-hadron

Exclusive J/psi photoproduction to date (fixed target+ ep, **pp**, pPb)





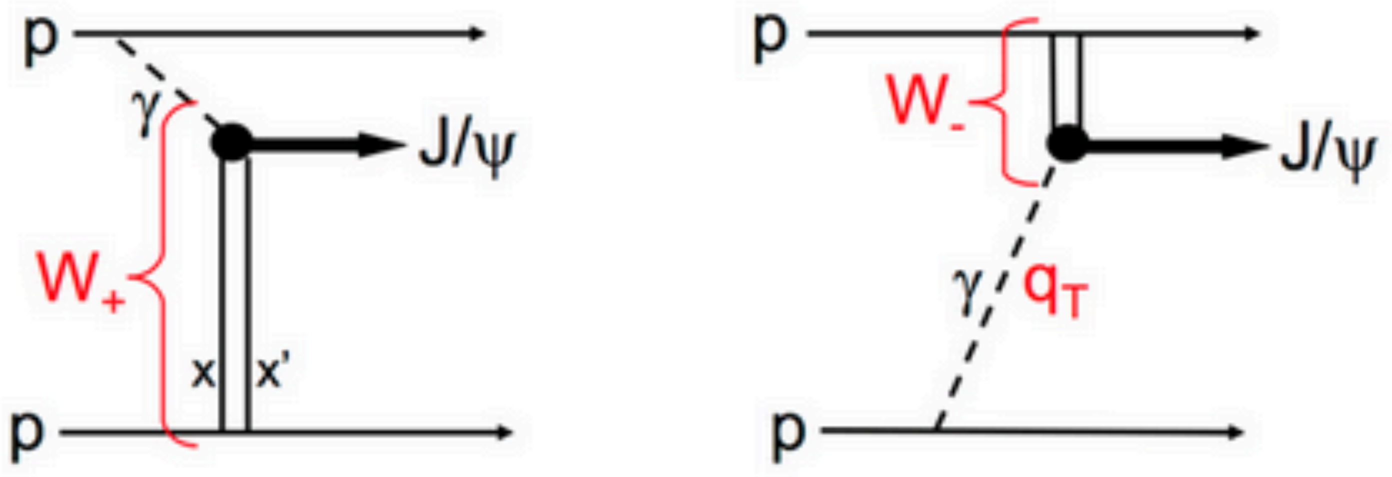
Unfolding at LHCb:

LHCb data

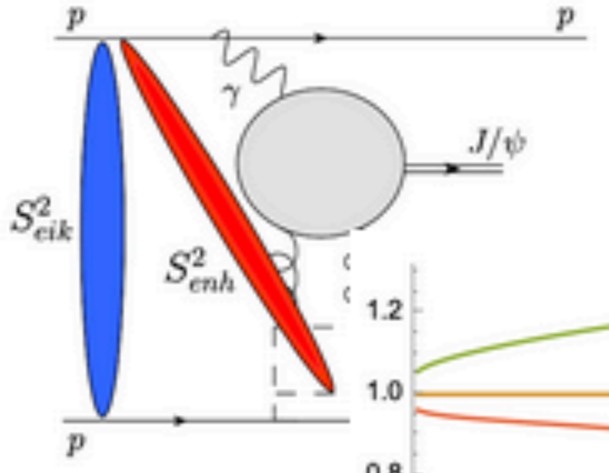
$$\frac{d\sigma(pp)}{dy} = S^2(W_+)\left(k_+\frac{dn}{dk_+}\right)\sigma_+(\gamma p) + S^2(W_-)\left(k_-\frac{dn}{dk_-}\right)\sigma_-(\gamma p)$$

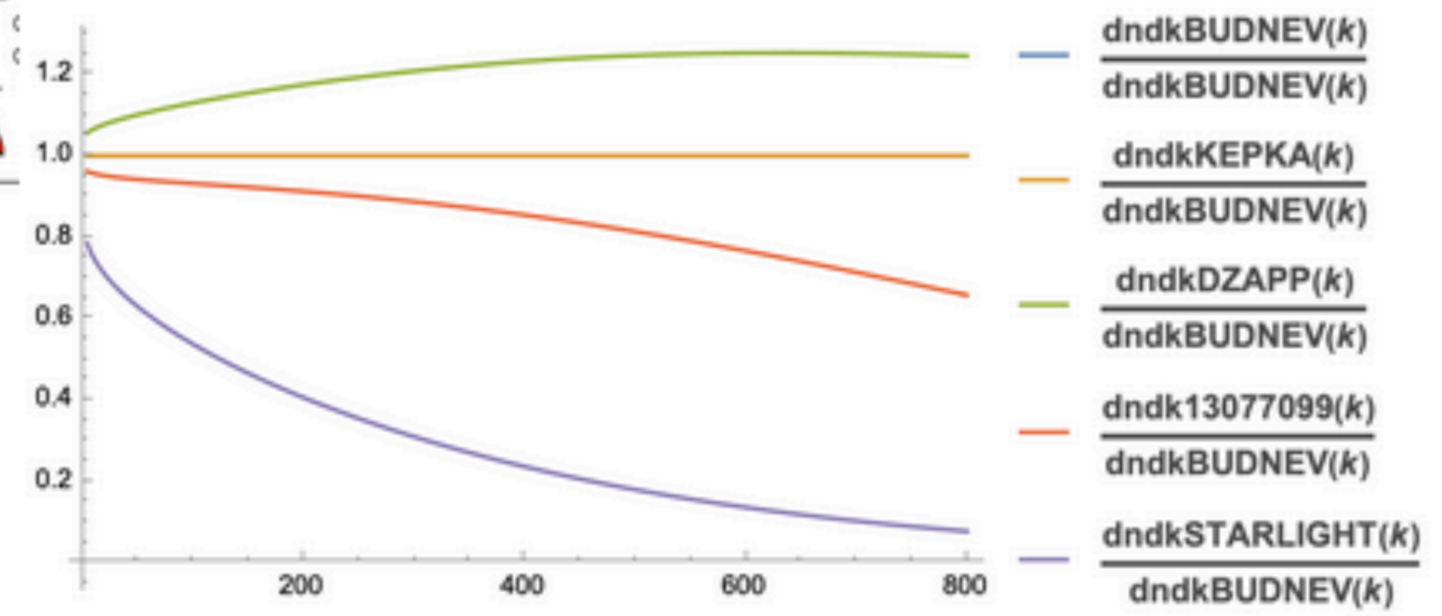
survival probability factors — LHCb 'data' — photon flux — HERA gives W-

pp@LHCb: 1401.3288, 1806.04079



W+/W- ambiguity: $W_\pm^2 = M_{J/\psi}\sqrt{s}e^{\pm|y|}$





Probe of nucleon gluon PDF

Probe of nucleon gluon PDF

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi p)\bigg|_{t=0} = \frac{\Gamma_{ee}^{J/\psi} M_{J/\psi}^3 \pi^3}{48\alpha_{em}} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} R_g xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

Sensitive to GPD not PDF! but can relate PDF & GPD at low x reliably via the so-called Shuvaev transform CAF, Jones, Martin, Ryskin, Teubner 1908.08398 & 2006.13857

(1) UPC -> large W photoproduction **(2)** -> constraints on gluon PDF

-For pp, have more lumi. but more pileup than pPb

-For pp, have W+/W- ambiguity, **very much less so** for pPb

-For pp, more model dependence in survival factor/photon flux combination

-For pp, more contamination from Odderon-pomeron due to relatively smaller impact parameter

- In pPb, survival factor close to unity and there is less modelling dependence in (1) as compared to pp
- There will be data from EIC in eA where such modelling does not play a role but then the energy range is limited.
- In pp/pPb at the LHC we can access larger W, in pPb we can push the **precision** of (2), i.e. that of low x and low scale exclusive quarkonium data as constraints on the gluon PDF

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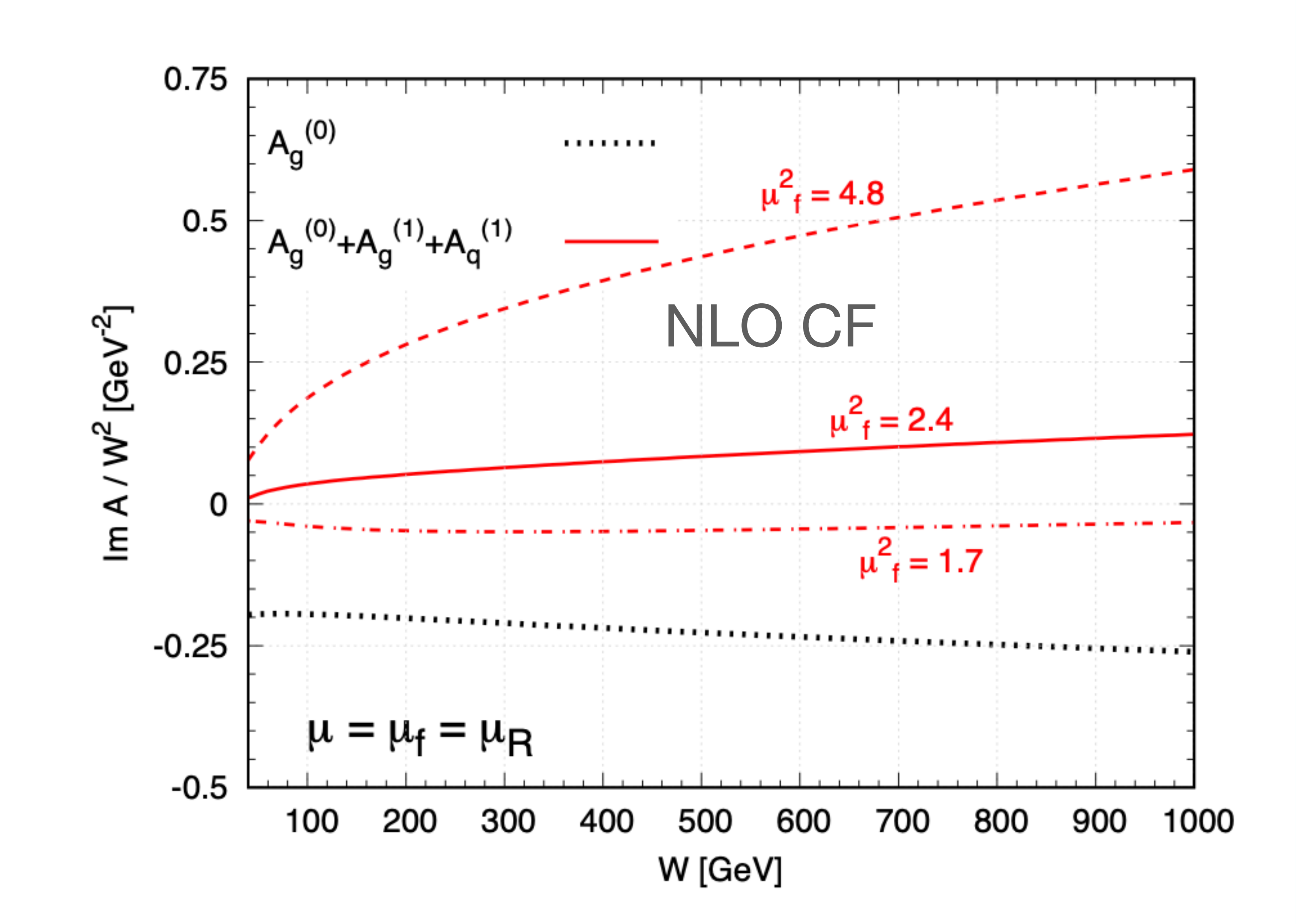
Framework: NLO collinear factorisation (CF) with Shuvaev



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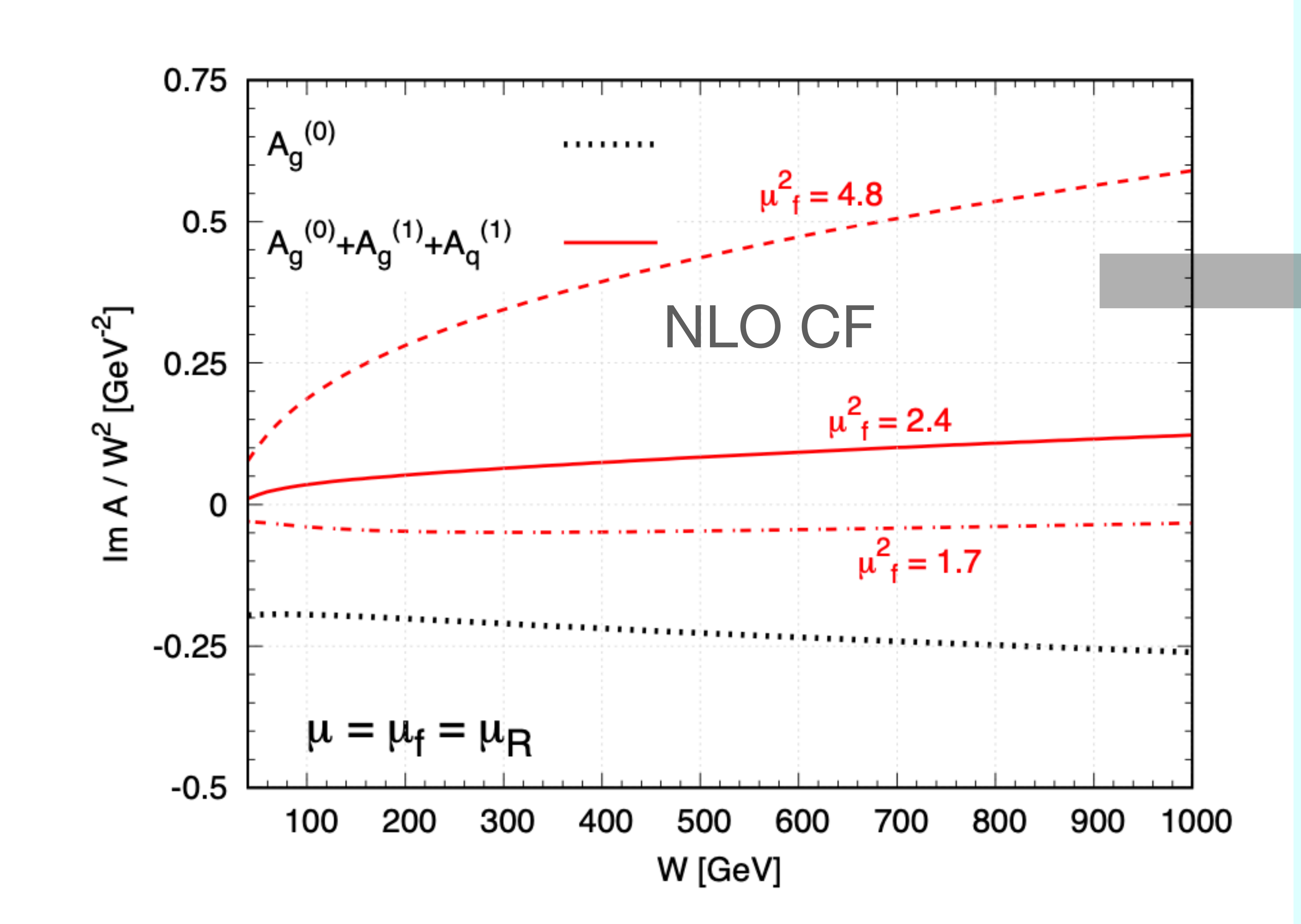
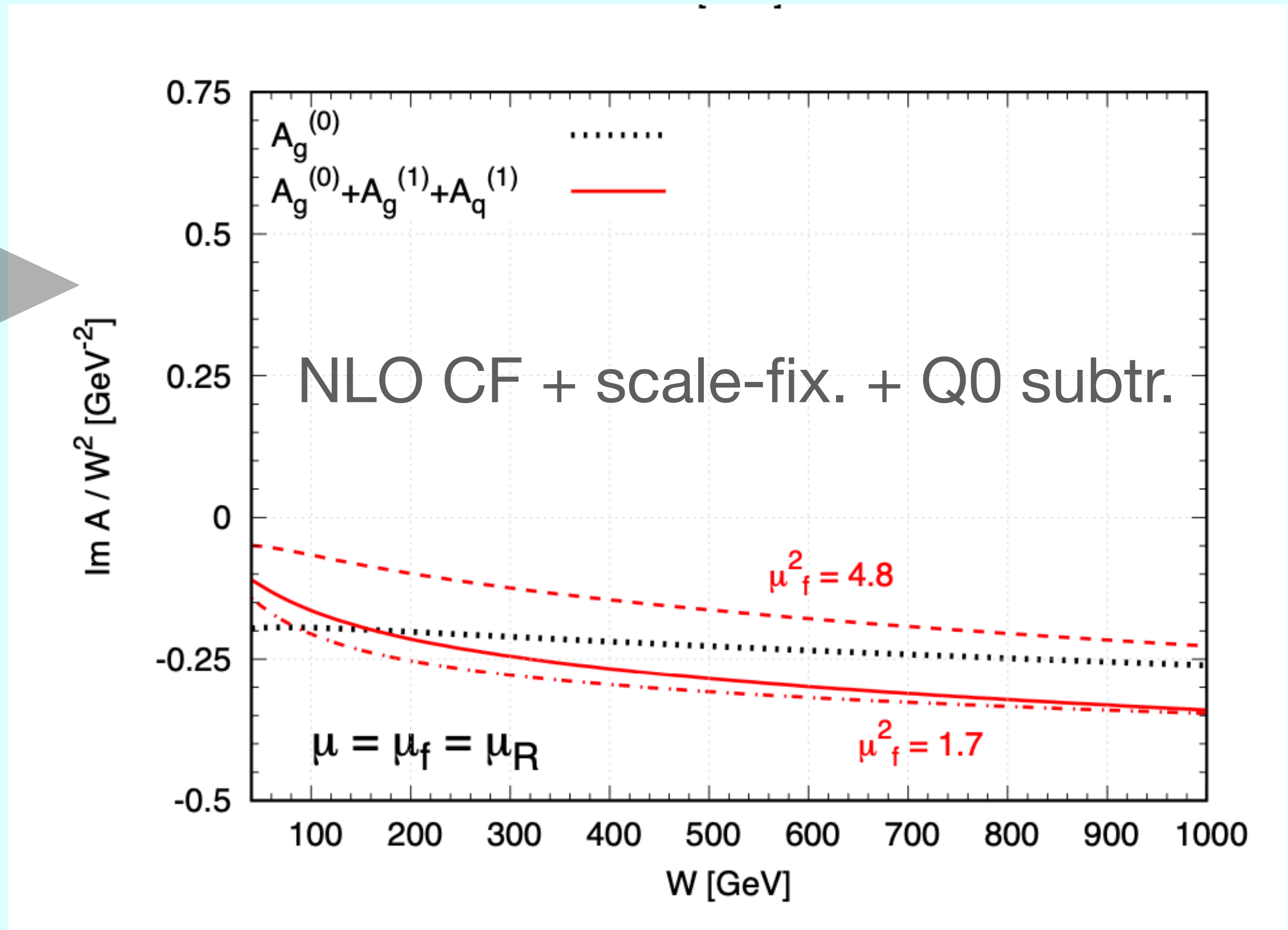
Framework: NLO collinear factorisation (CF) with Shuvaev + scale-fixing + Q0 subtr. 1908.08398 & 2006.13857





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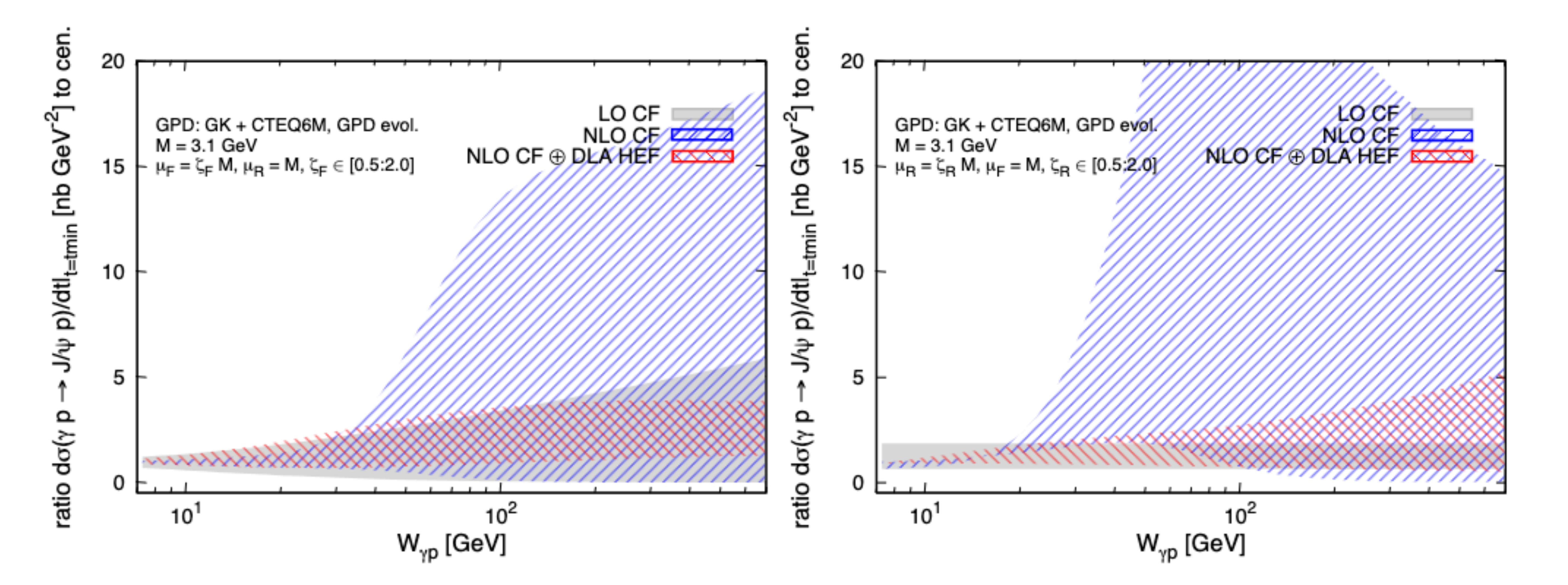
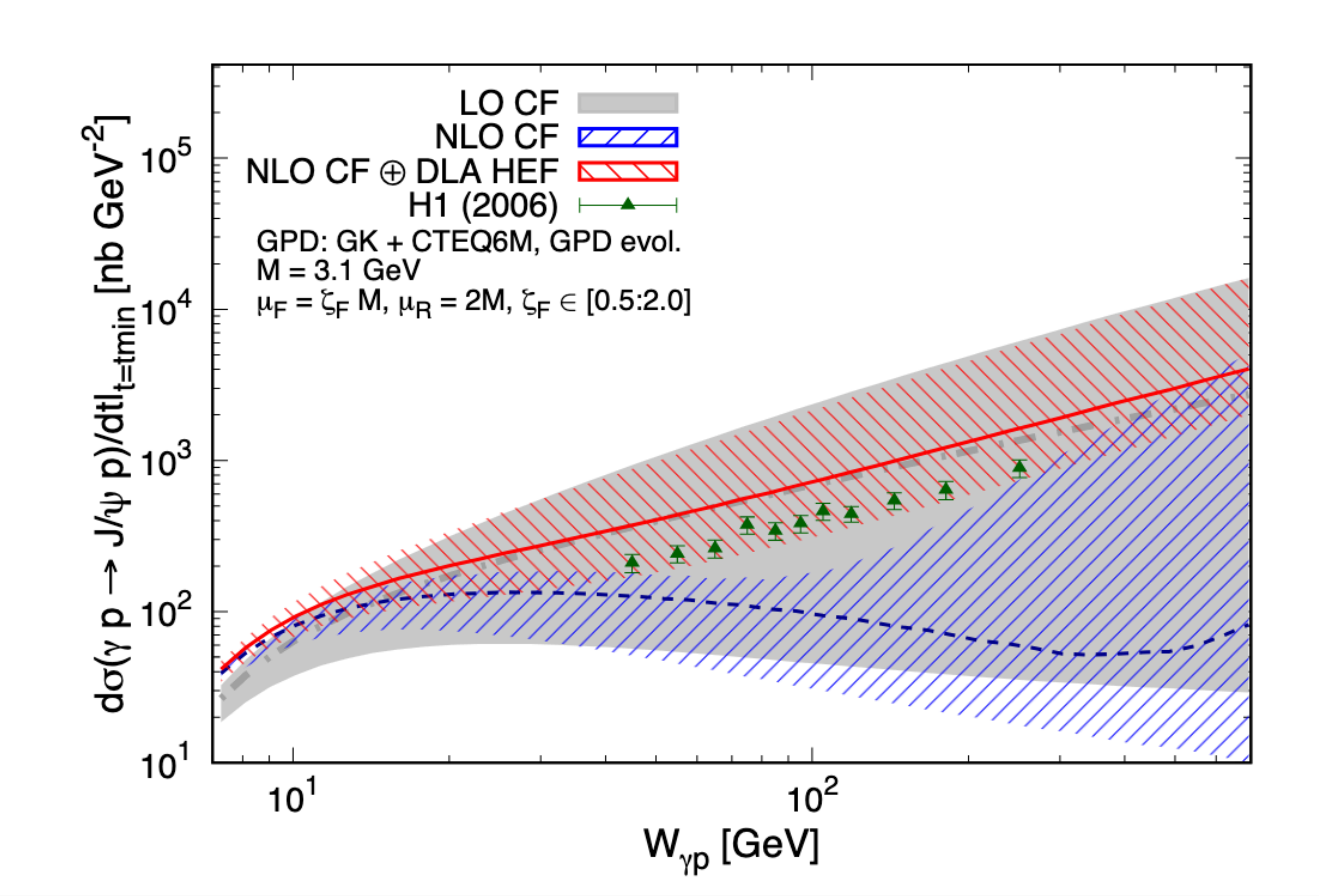
Framework: NLO collinear factorisation (CF) with High-energy factorisation + GPD evolution





See CAF, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, to appear

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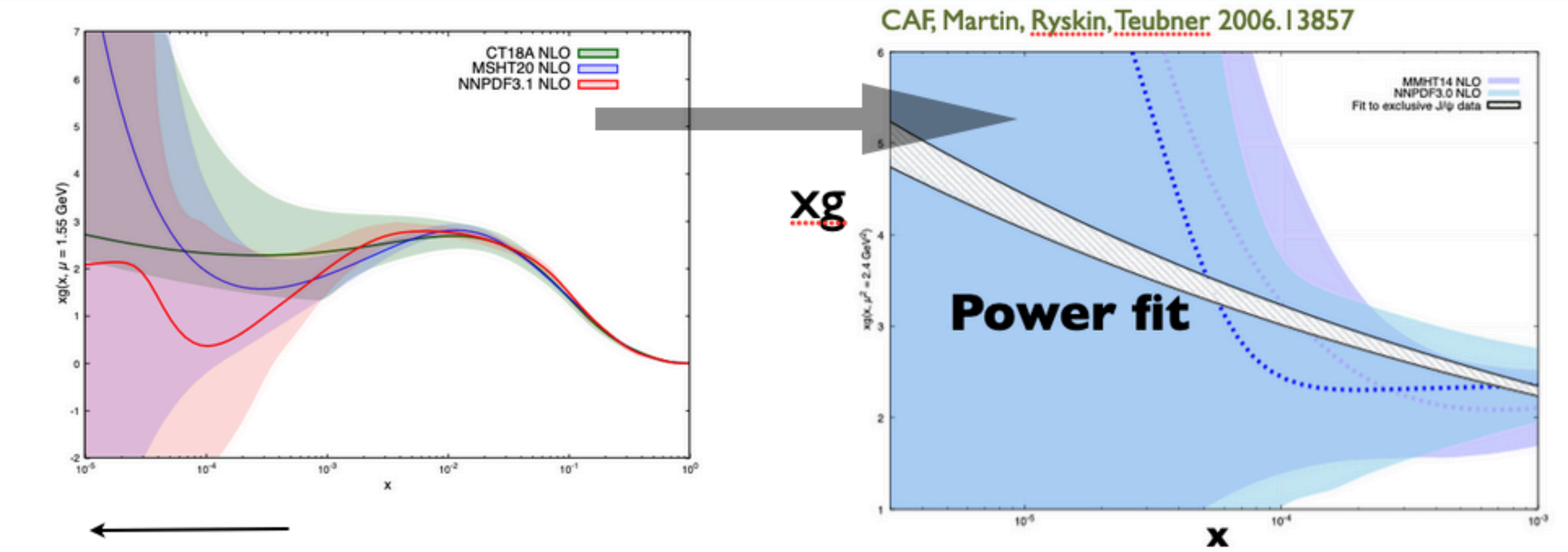


pp@LHCb excl. J/psi UPCs currently probes down to $x{\sim}3\times10^{-6}$ ...unconstrained domain in PDF fits!

Standalone fits + reweighting studies using pp data, but not yet considered in a larger fitting framework......

xFitter implementation

1410.4412

Public PDF fitting tool to perform a variety of tasks:
a_S extraction, PDF reweightings, fits...

- QCDNUM/APFEL for QCD evolution
- MINUIT/CERES for minimisation in various mutually consistent approaches
- interfaces to independent codes
- various output formats (e.g. LHAPDF6,..)
- Default config. based on set-up of HERAPDF2.0

- Incorporate new 'JPSI' reaction via xFitter's ReactionTheory class

...to perform various PDF profiling and fitting studies using the exclusive J/psi production data

(i) PDF profiling:

NNPDF30_nlo_as_0118

N_{rep} = **1000**

profiled with LHCb 13 TeV excl. J/psi data
1806.04079

$$N_{\text{eff}} = \exp\left(\frac{1}{N_{\text{rep}}}\sum_{k=1}^{N_{\text{rep}}} w_k \ln(N_{\text{rep}}/w_k)\right)$$

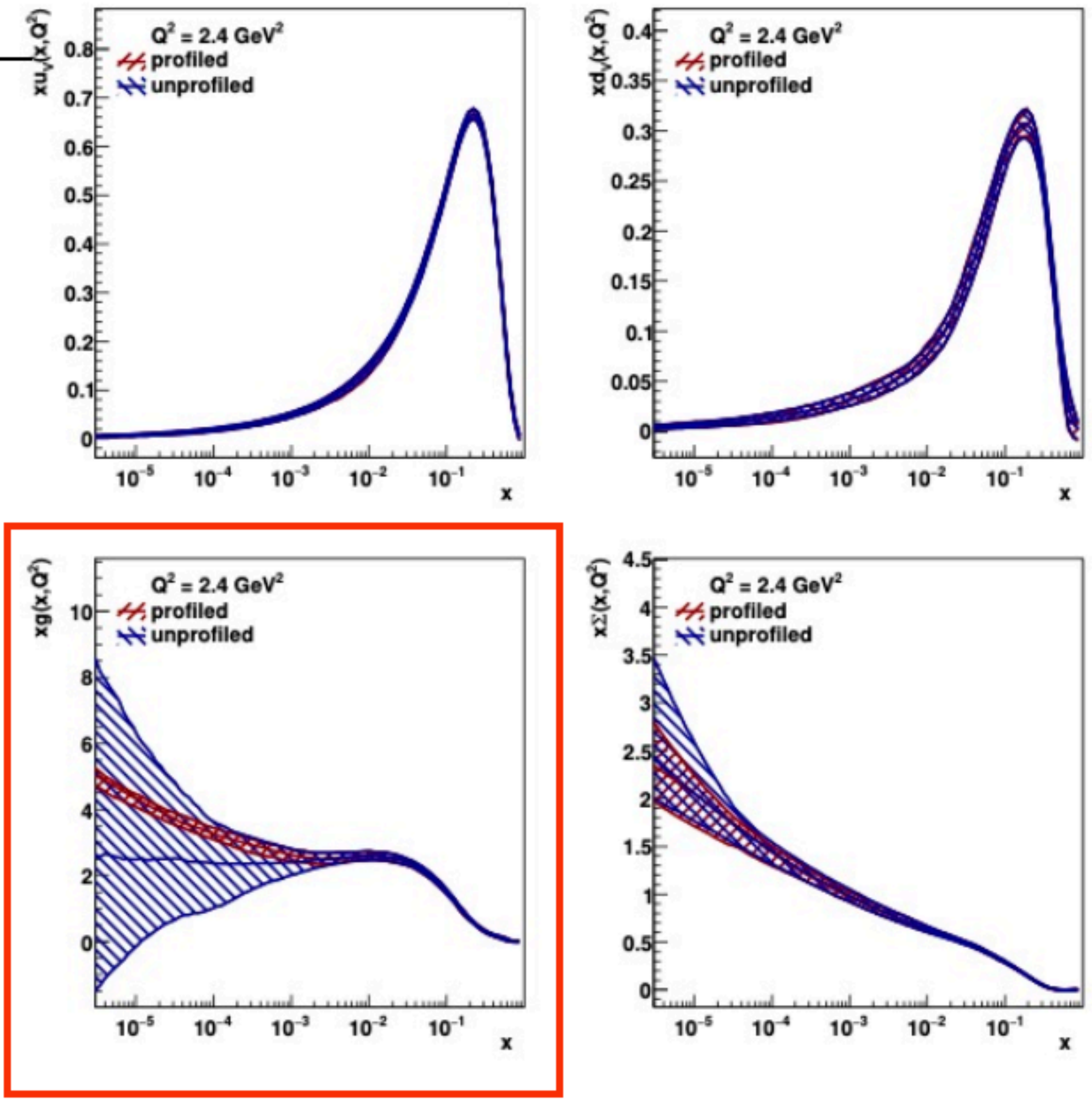
= 63 << N_{rep}

Condition N_{eff} << N_{rep} expected here

Precursor to full fit

$$\langle O\rangle = \frac{1}{N_{\text{rep}}}\sum_{k=1}^{N_{\text{rep}}} O(f_k),$$

$$\langle O^{\text{new}}\rangle = \frac{1}{N_{\text{rep}}}\sum_{k=1}^{N_{\text{rep}}} w_k O(f_k)$$



(ii) Fitting: approach 1: gluon pseudodata

- Generate effective gluon PDF pseudodata from experimental data:

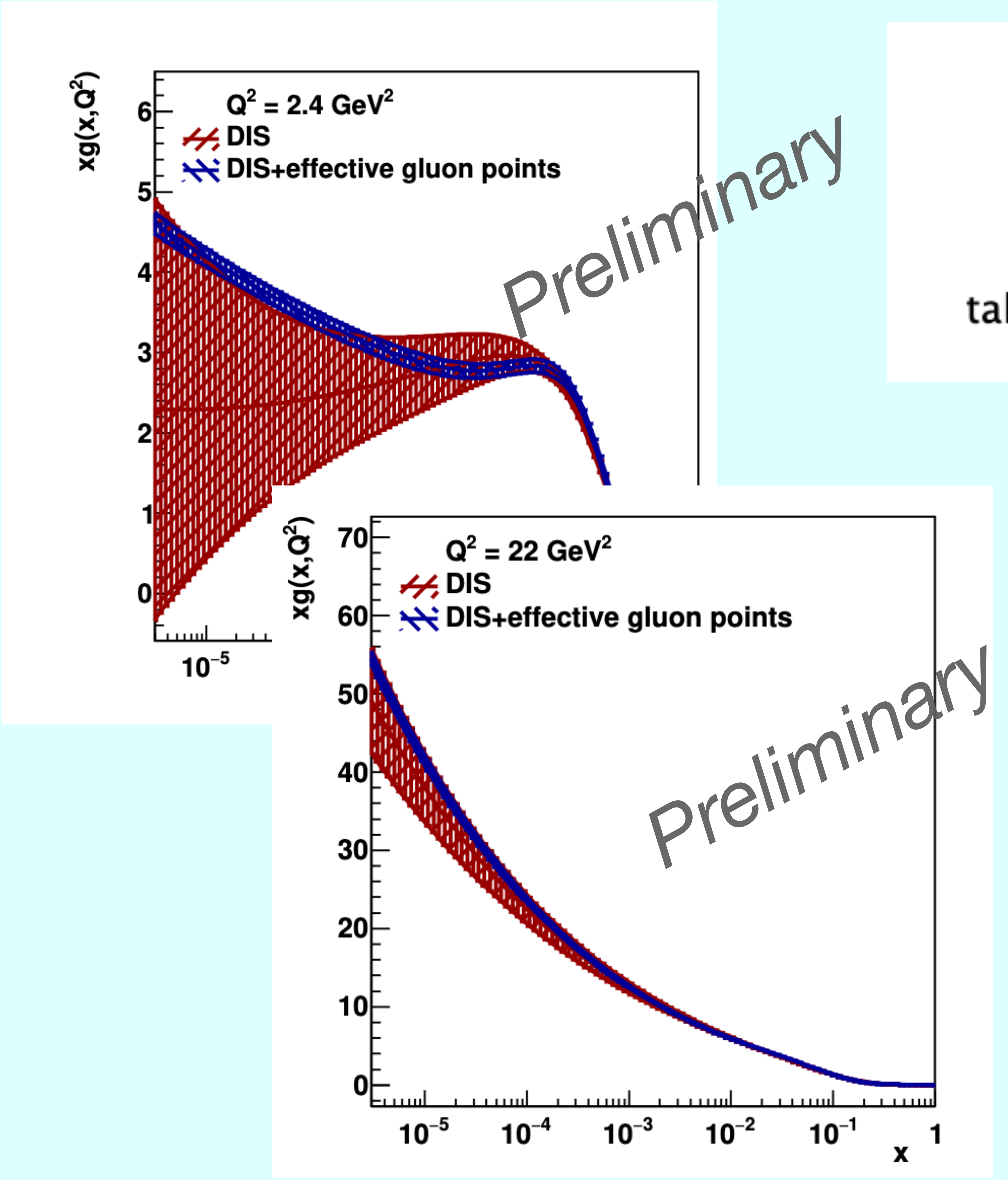
$$g_{\rm eff}(x_i,\mu_{\rm opt}) \;=\; g_{\rm fit}(x_i,\mu_{\rm opt})\,\sqrt{\frac{\sigma_+({\rm data})_i}{\sigma_+({\rm fit})_i}}$$

taken from 2006.13857

$$\delta g_{\rm eff}(x_i) = \frac{1}{2}\, g_{\rm eff}(x_i)\,\frac{\delta\sigma_+({\rm data})_i}{\sigma_+({\rm data})_i}$$

(ii) Fitting: approach 1: gluon pseudodata: **Results**

- Default xFitter set up supplemented with generated effective gluon PDF data



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Dataset	χ^2_{min}/d.o.f (DIS)	χ^2_{min}/d.o.f (DIS+eff. gluon pts.)
HERA1+2 NCep 820	80/73	79/73
HERA1+2 NCep 460	220/207	220/207
HERA1+2 CCep	43/39	44/39
HERA1+2 NCem	221/159	220/159
HERA1+2 CCem	54/42	56/42
HERA1+2 NCep 575	223/257	227/257
HERA1+2 NCep 920	465/391	470/391
LHC excl. J/ψ pp 7 TeV	N/A	8.95/10
LHC excl. J/ψ pp 13 TeV	N/A	3.51/10
LHC excl. Υ pp 7,8 TeV	N/A	3.23/3
Total χ^2_{min}/d.o.f	$1412/1154 \sim 1.22$	$1444/1177 \sim 1.23$

(ii) Fitting: approach 2: cross section

- Integration of theoretical framework into xFitter to perform fits using cross section and JPSI datasets from HERA and LHC

Can reduce computationally intensive Shuvaev transform routine to **simpler** 1D numerical integration at the the point **x=xi:**

$$H_g(x/2, x/2) = \frac{4x}{\pi}\int_{x/4}^{1} dy y^{1/2}(1-y)^{1/2} g\left(\frac{x}{4y}\right)$$

→ For given input gluon distribution, this gives the result of the full Shuvaev transform at the point **x=xi**

For **(x-xi)>0.1(x+xi),** this is already a 10% deviation from the full result

Example: further assuming **pure-power behaviour** of gluon PDF gives famous **Rg** formula commonly used

$$R_g \approx \frac{2^{2\lambda_g+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda_g+5/2)}{\Gamma(\lambda_g+4)}$$

Computing this on the fly a more tractable exercise than

Full Transform:

$$\mathcal{H}_q(x,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds}{y(s)\sqrt{1-y(s)x'}}\right]\frac{d}{dx'}\left(\frac{q(x')}{|x'|}\right),$$

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$$y(s) = \frac{4s(1-s)}{x+\xi(1-2s)}.$$

[Shuvaev et. al 1999]

In progress...

Summary

Exclusive quarkonium **photo**production from LHC

Integration of NLO framework into xFitter to analyse exclusive heavy vector-meson data constraints in a global analysis **for the first time**

Proof of concept with first numerical insights

Exclusive quarkonium production studies in global analyses

Propagate what we learn from pp / pPb data on **free** gluon PDF to PbPb on **nuclear** gluon PDF

All such data will increase our understanding of the underlying theoretical mechanisms at play in these interactions and, importantly, lead to an improved understanding of the behaviour of the gluon distribution at small x.

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Profiling: **precomputed** GPD grids for each LHAPDF member set

Fitting: Generate JPSI theory prediction using an input GPD grid $\mathbf{G}^{(0)}$ constructed from a given LHAPDF member set $\mathbf{S}^{(0)}$

After each fit iteration i,

1. xFitter outputs an updated member set $\mathbf{S}^{(i)}$ in LHAPDF format

↓

2. which is interfaced to an independent GPD routine to produce a corresponding updated GPD grid $\mathbf{G}^{(i)}$

↓

3. which can be used for the JPSI theory prediction in iteration $i+1$

↓

4. perform iteration $i+1$

↓

5. repeat steps 1)–4) until convergence of fit

⟶ feasible?

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   ↓ → adaptation of xFitter code needed...doable

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   ↓ → time costly, could optimise required GPD grid output, granularity of LHAPDF x-grid...

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   ↓

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→ Observation: amplitude highly peaked at x~xi => 2D ->1D numerical integration

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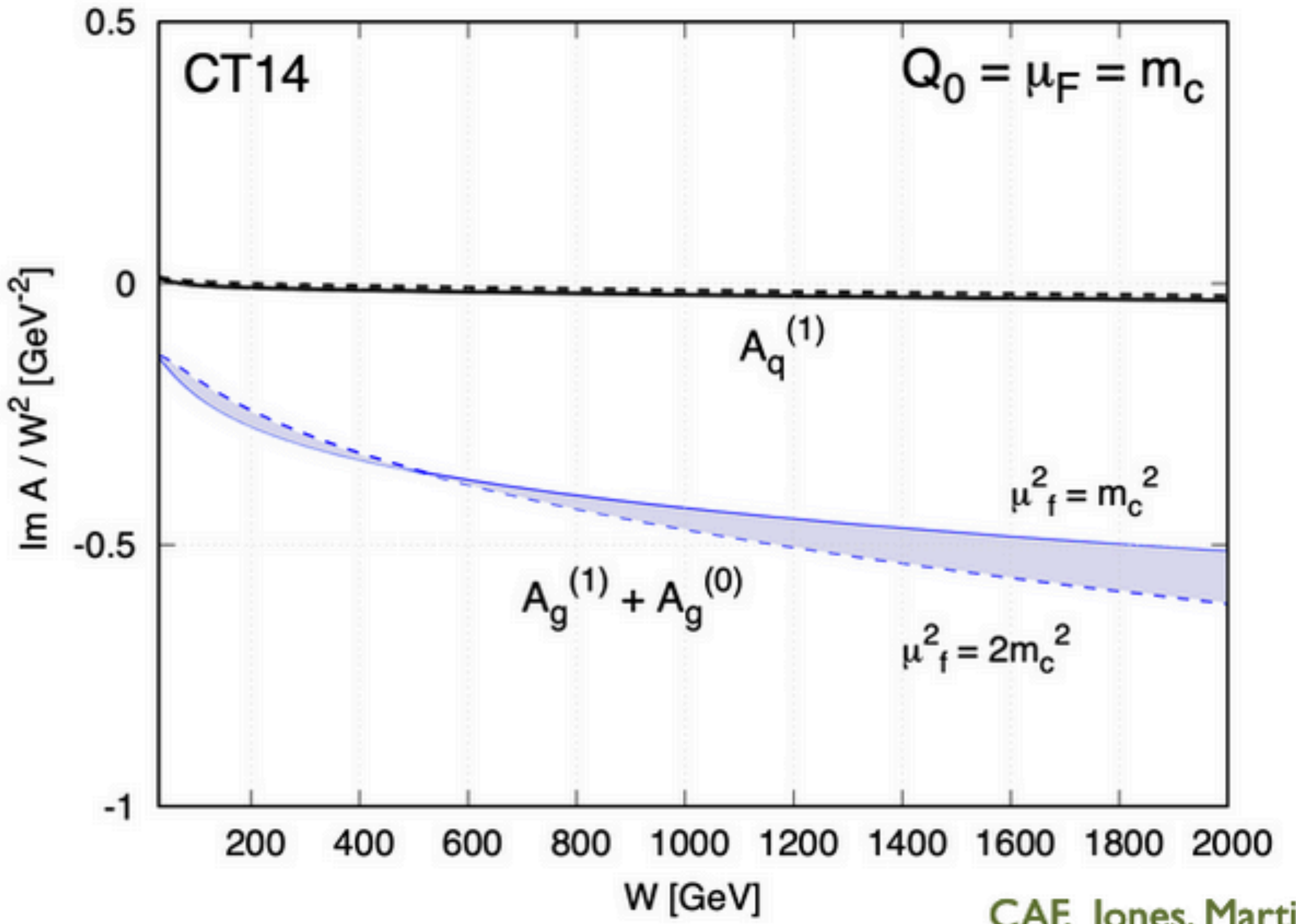
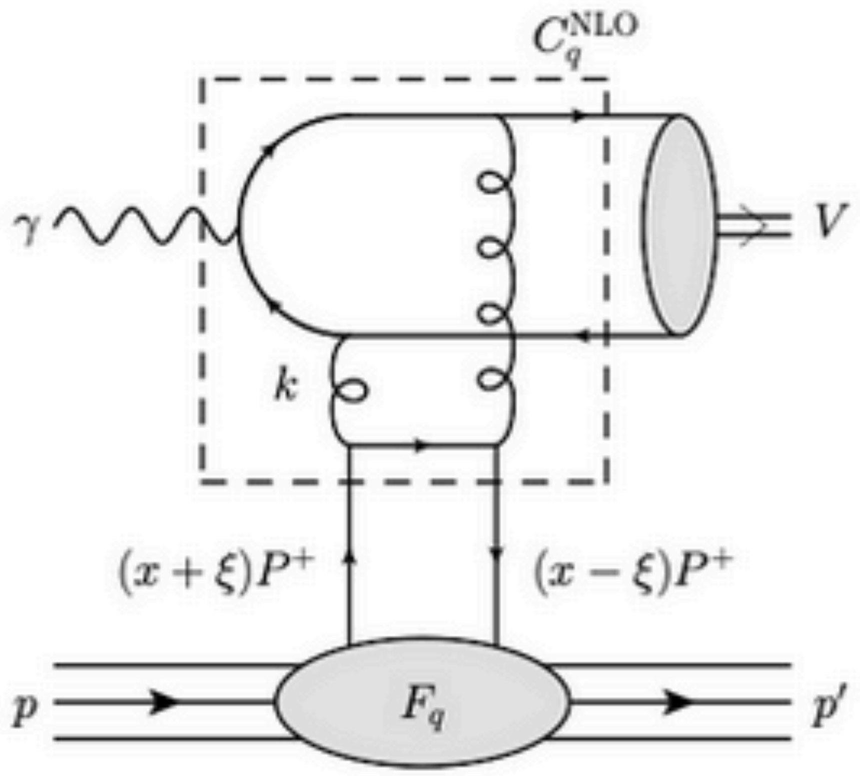
[Shuvaev et. al 1999]

In progress...

Interplay of quark and gluons at NLO

After Q_0 subtraction:





CAF, Jones, Martin, Ryskin, Teubner, 1908.08398

Quark contribution separated from hard scattering by at least *one* step of DGLAP evolution and is therefore removed after imposition of Q_0 subtraction (as reflected in the numerics)

⟶ Gluon driven like at LO

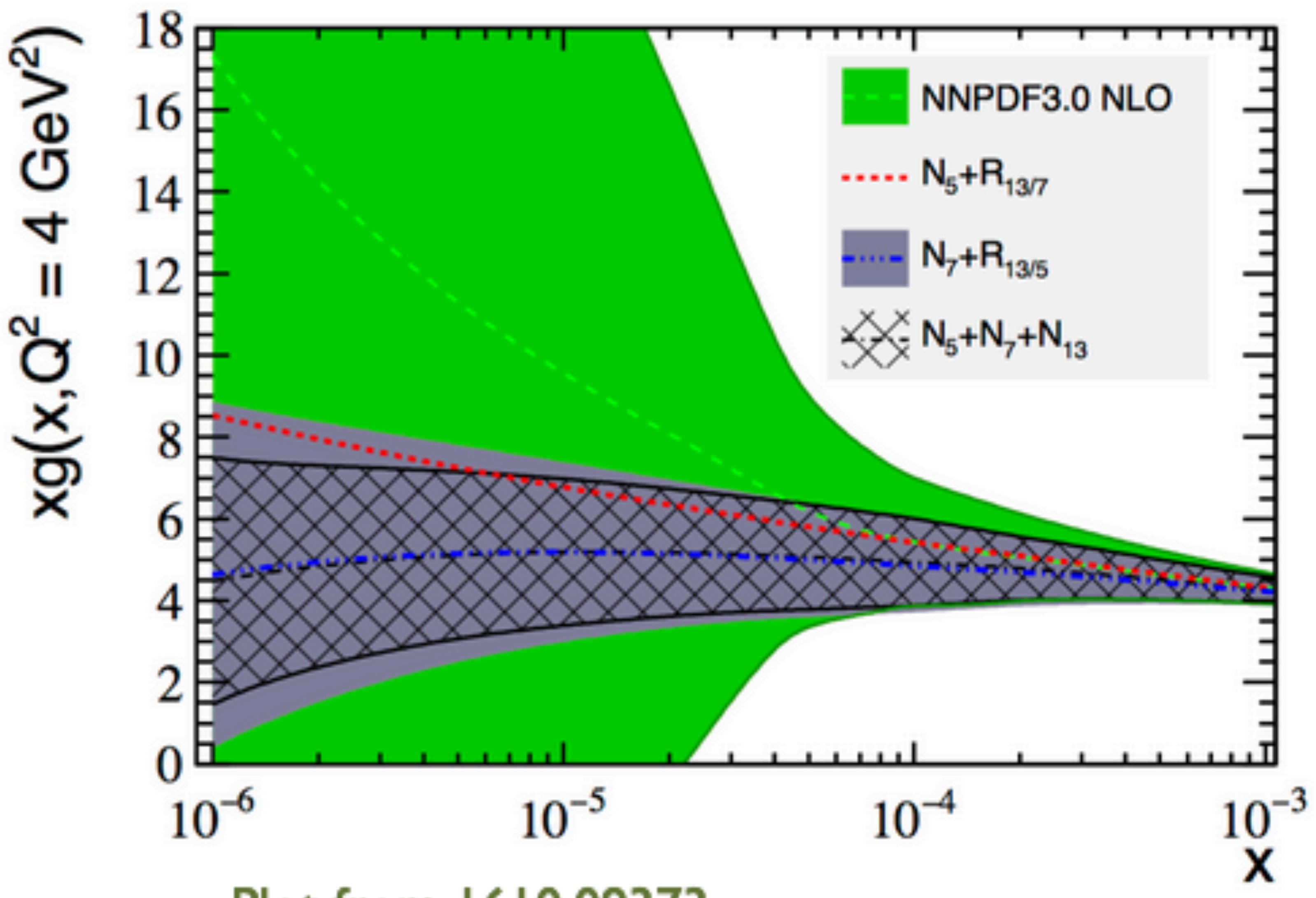
Constraints from inclusive D meson production data

Idea: Construct ratios of observables in y and p_t bins to combat various uncertainties

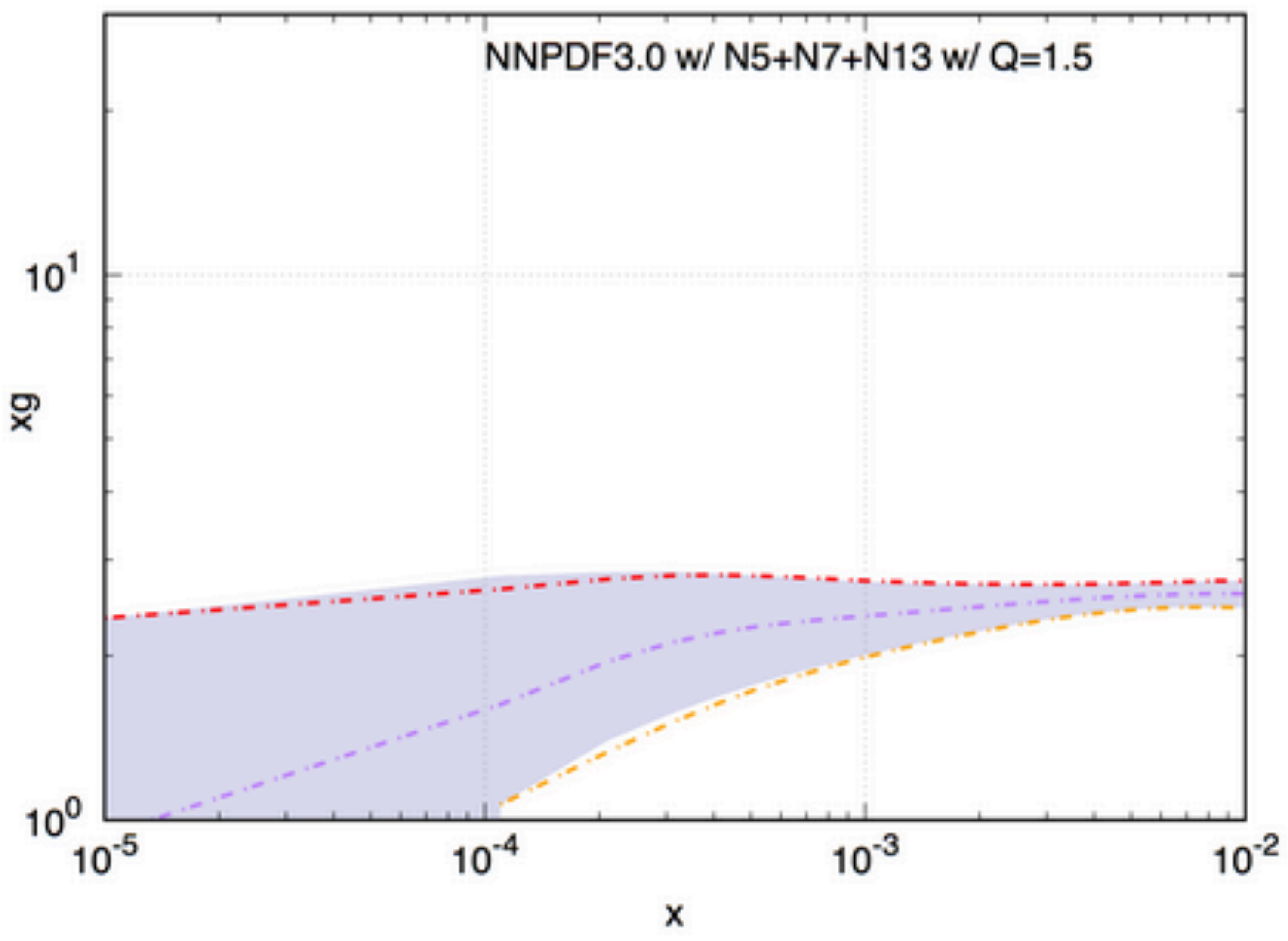
$$N_X^{ij} = \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j} \bigg/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{ref}}^D d(p_T^D)_j}$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(13\text{ TeV})}{dy_i^D d(p_T^D)_j} \bigg/ \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j}$$

→ find decreasing gluon at the lowest x they may probe



Plot from 1610.09373



Sensitivity to the MSbar gluon PDF

- Remain in MSbar scheme with Q0 subtracted coefficient functions to NLO accuracy
- Subtraction does not affect IR or UV divergence renormalisation procedures
- Soft singularity at l=0 is removed after subtracting off the LO part of the NLO coefficient function before integral over loop momentum from 0 to Q0 is performed

$$\Delta \mathrm{Im}\mathcal{M}^q = \frac{\alpha_s^2}{2\pi}\int_\xi^1 dx\,(F_q(x,\xi,m_c) - F_q(-x,\xi,m_c))\left(\int_0^{Q_0^2}(M_a^q + M_b^q)\frac{2\pi m_c^4}{\hat{s}^2}dl^2\right)$$

- Precisely this FINITE contribution that is subtracted from full MSbar coefficient functions to avoid double counting inherent within MSbar scheme (subtraction fundamentally ubiquitous but numerically relevant for low scale processes only*)

---

*see 1912.09304 for procedure applied to inclusive DIS and Drell-Yan production

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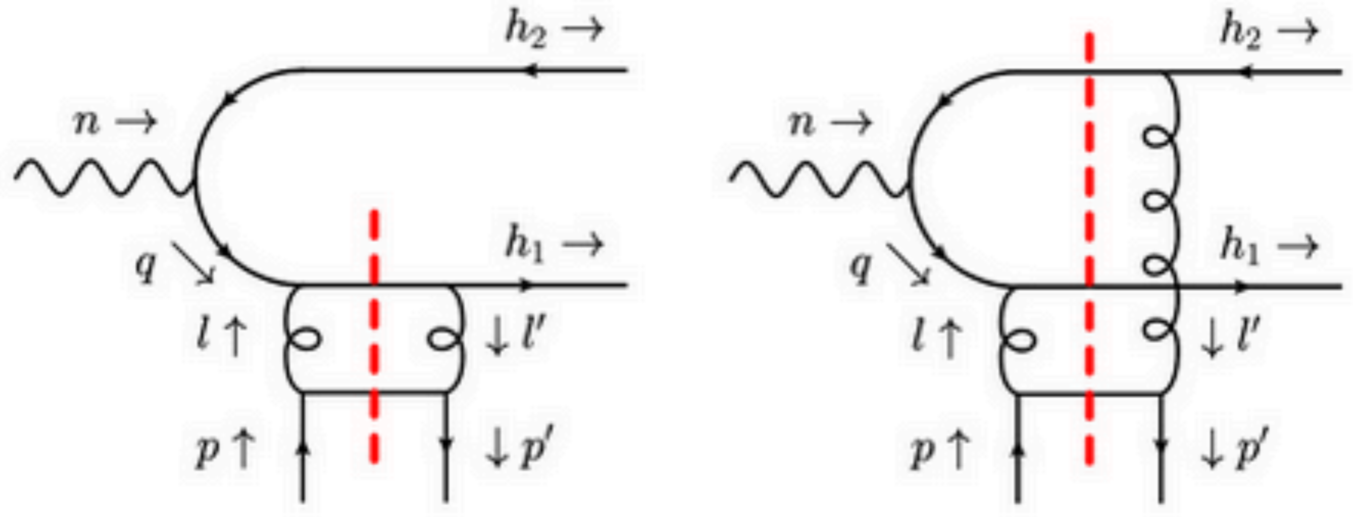
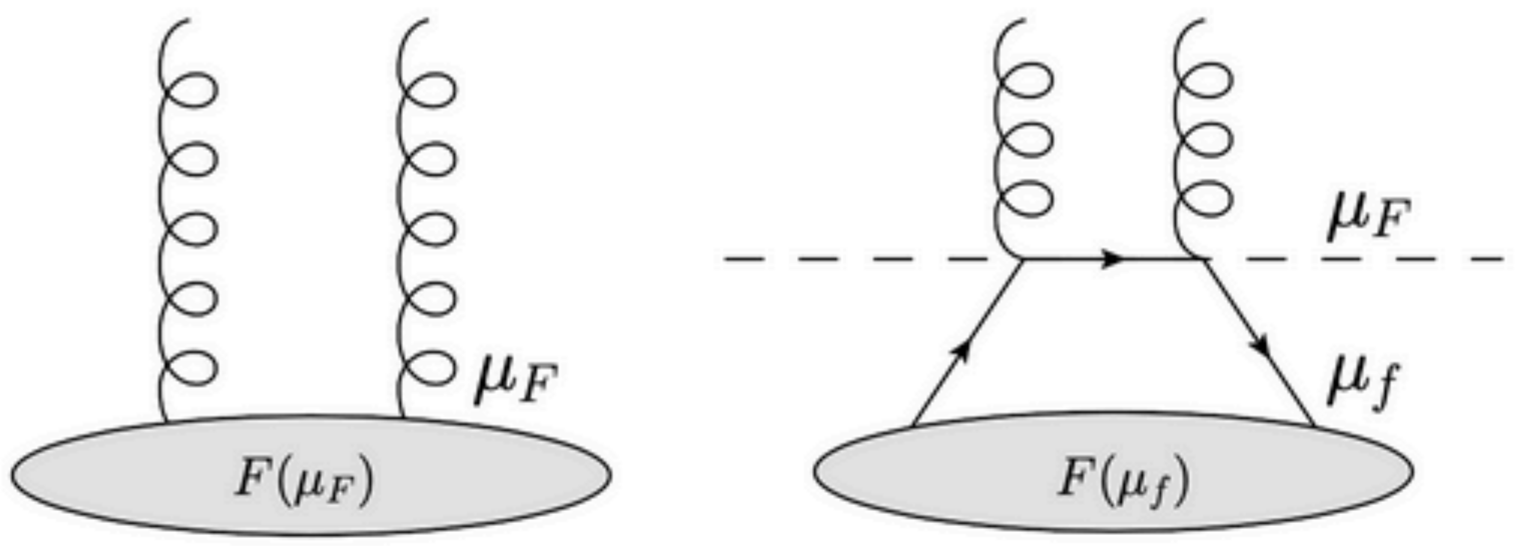


- NLO diagrams for quark and gluon channel considered. Contain both LO and NLO contributions. Subtract off LO contribution (part given by LO (generalised) DGLAP evolution P_LO x C^0, see previous) before integration over l is performed, cancelling soft singularity dl^2/l^2.

Treatment of double logarithmic contribution



Ideology: Use scale shifting to find optimal scale that removes the largest contribution from the NLO correction *

At fact. scale. μ_f , quark contribution is part of NLO hard matrix element

At fact. scale μ_F, absorbed quark contribution into LO result

Effect of scale change driven by (generalised, skewed) DGLAP evolution:

$$A^{(0)}(\mu_f) = \left(C^{(0)} + \frac{\alpha_s}{2\pi} \ln\left(\frac{\mu_f^2}{\mu_F^2}\right) C^{(0)} \otimes V \right) \otimes F(\mu_F)$$

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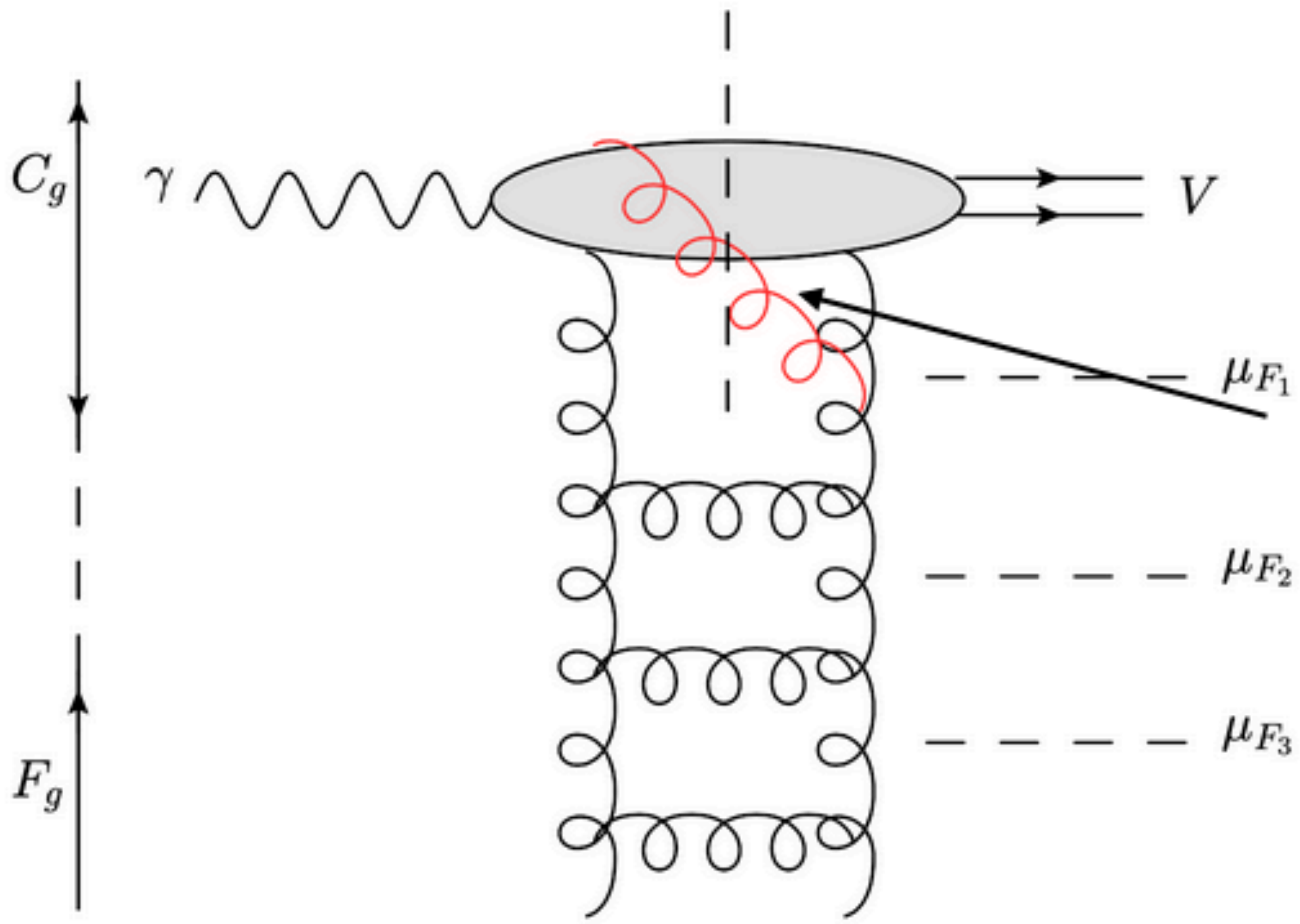
* At small xi, this is the double logarithmic contribution ~ln(1/xi) ln(muF^2/mc^2)

Treatment of double logarithmic contribution



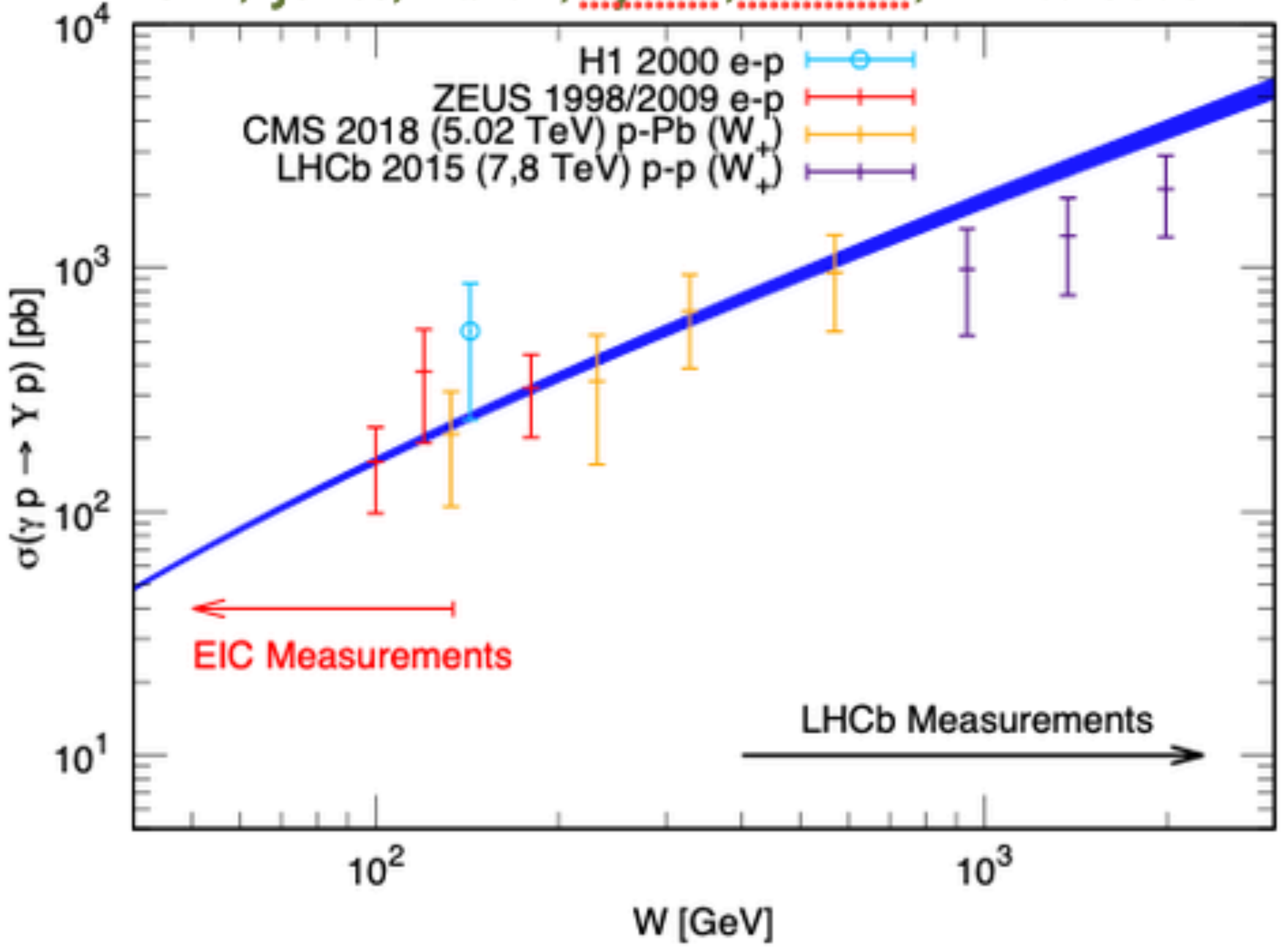
The red gluon cannot be resummed in this scale shifting approach and so will always be treated as part of the higher order correction

Choice muF = mc ‘resums’ the gluon ladder contributions, enhanced by this double logarithmic contribution. They are intrinsically resummed within the kt factorisation framework* and here by judicious choice of factorisation scale

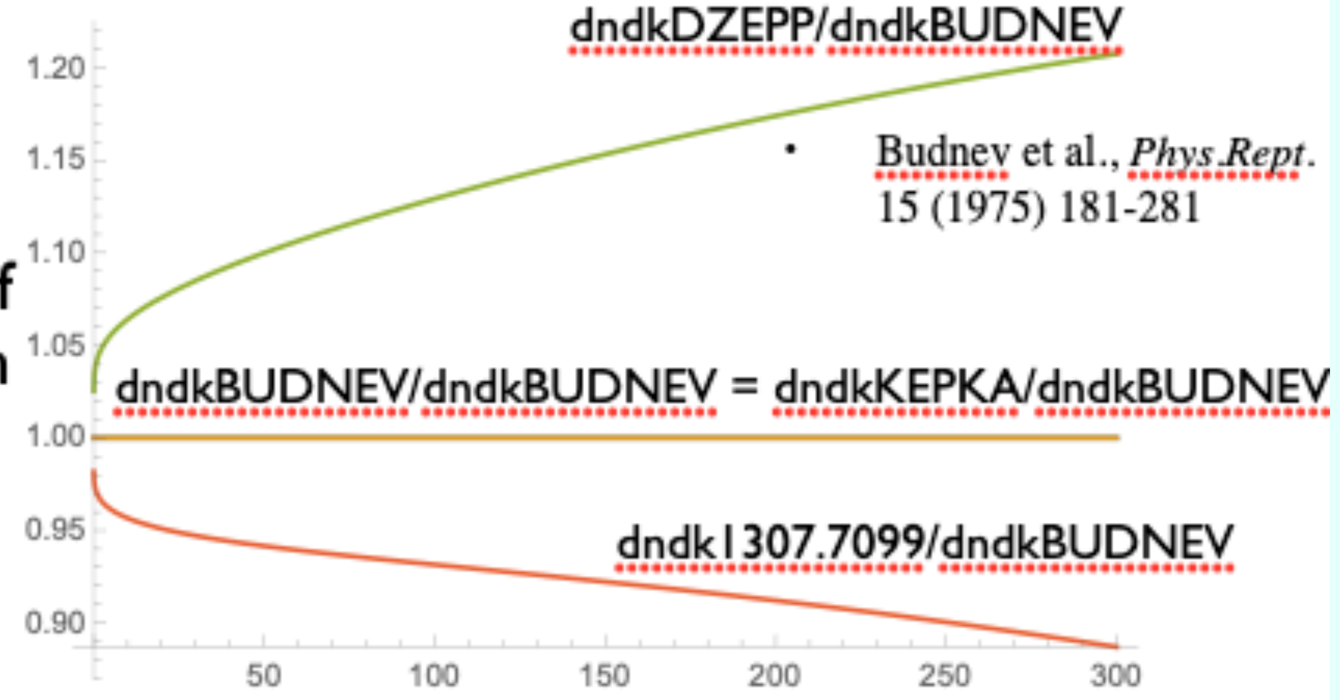
* But kt fact. framework treats only a *subset* of NLO corrections, those belonging to equivalence class of gluon-ladder diagrams

Other results in UPC: Photon flux in Upsilon photoprod. in pp

CAF, Jones, Martin, Ryskin, Teubner, 2110.15575



-DGLAP evolve gluon PDF obtained from fit to J/psi data to scale of Upsilon photoproduction and use as input to make cross-section prediction (blue band)



For J/psi rapidity at border of LHCb acceptance (y \sim 4.3675) and sqrts = 7 TeV, find

(ss1307.7099*flux1307.7099)/(ssBudnev*fluxBudnev)= 0.94901

~ 5% effect

For J/psi rapidity *outside* border of LHCb acceptance (y \sim 5.125) and sqrts = 7 TeV, find

(ss1307.7099*flux1307.7099)/(ssBudnev*fluxBudnev)= 1.24832

~ 25% effect

Upsilon photoproduction photon energies will be larger so discrepancy between fluxes (and survival factors) will be larger and we enter the region where the approximation of 1307.7099 flux breaks down at much lower rapidities and, importantly, within the acceptance of LHCb

=> use Budnev flux (without negligence of O(x) terms)

=> large W unfolded photoproduction LHCb data should be shifted upwards