Exclusive quarkonium photoproduction in pPb collisions at the HL-LHC

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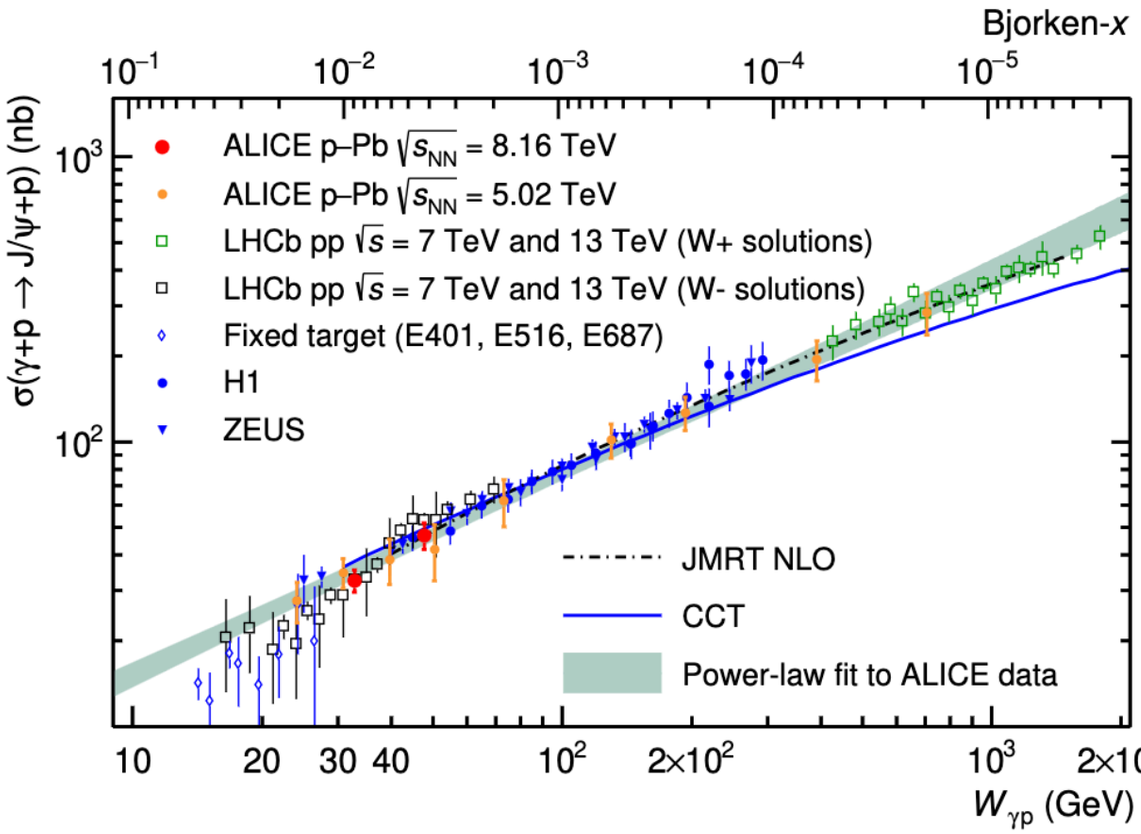
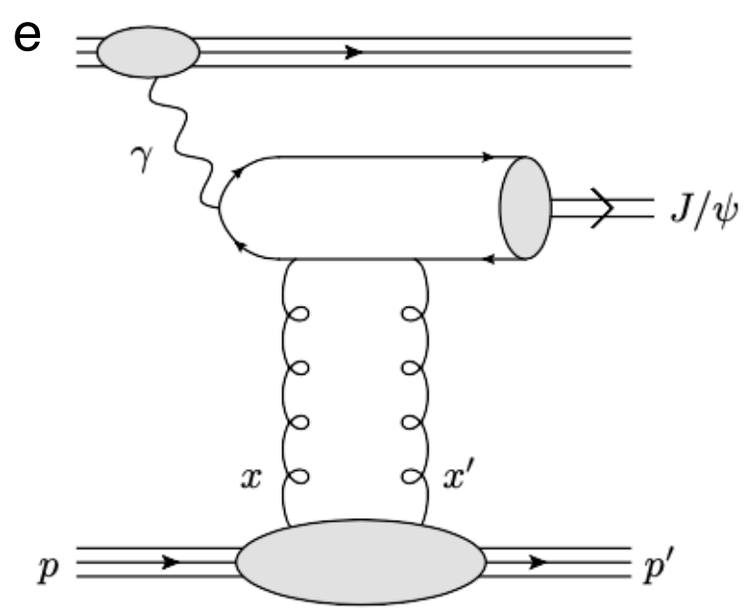
State of the art

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



ep@HERA: hep-ex/0201043, hep-ex/0404008, hep-ex/0510016, hep-ex/0404008



Tagged electron => measure photon virtuality. Here, discuss photoproduction (quasi-real photons)

Photon fluctuation into heavy-quark pair, producing J/psi via two-parton colour-singlet exchange

State of the art

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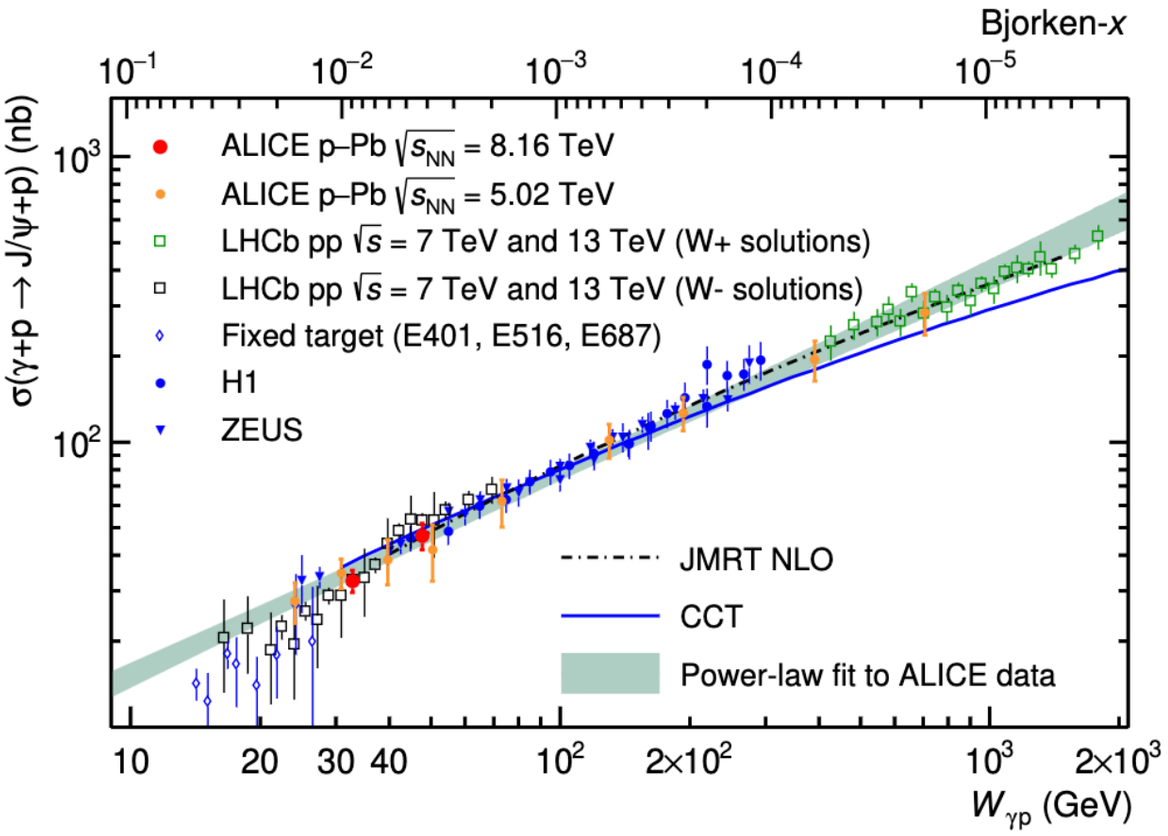
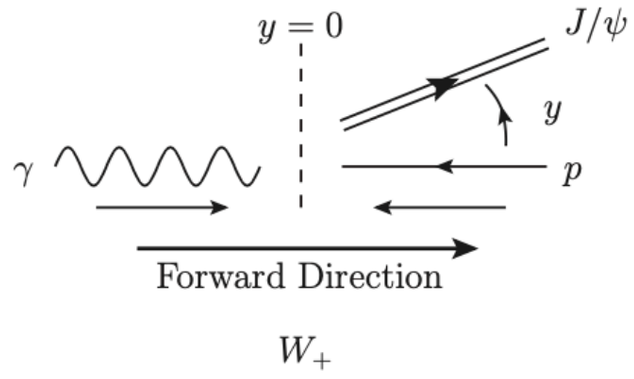
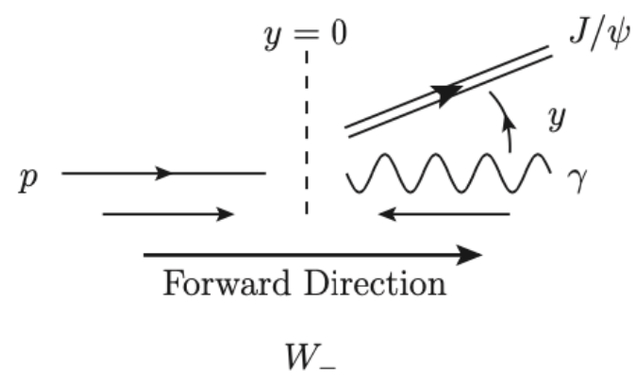
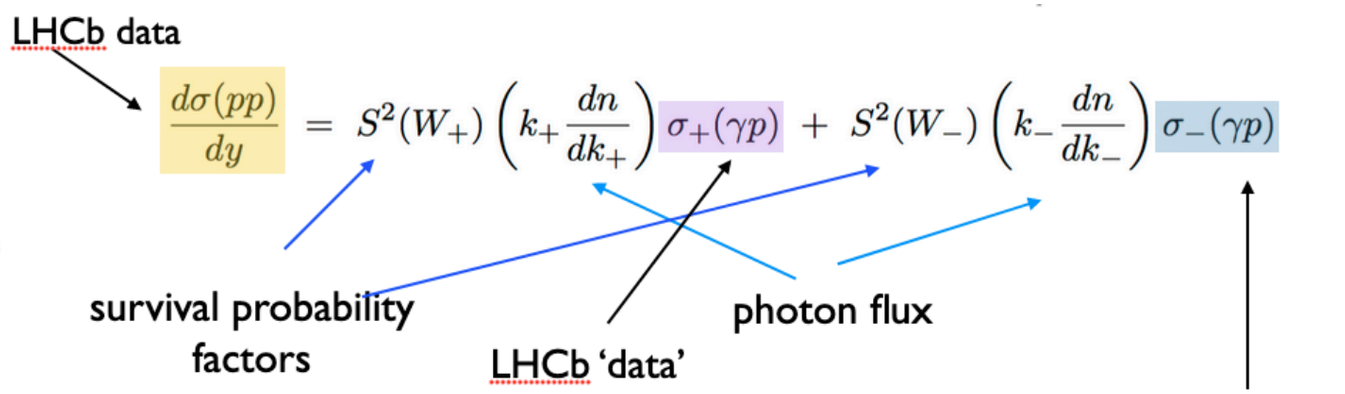


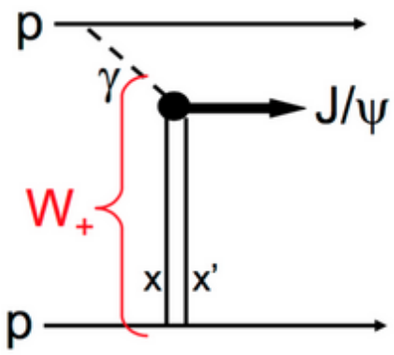


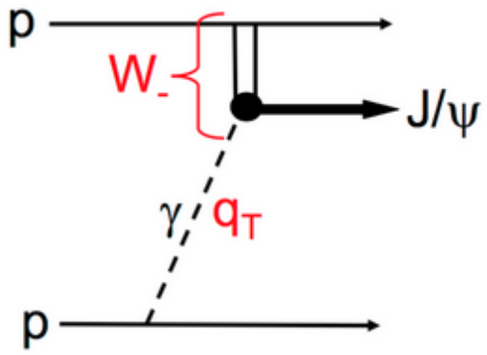


Unfolding at LHCb:

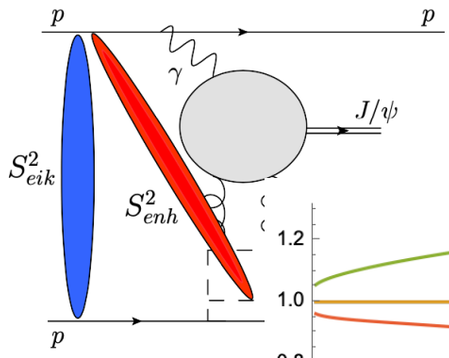


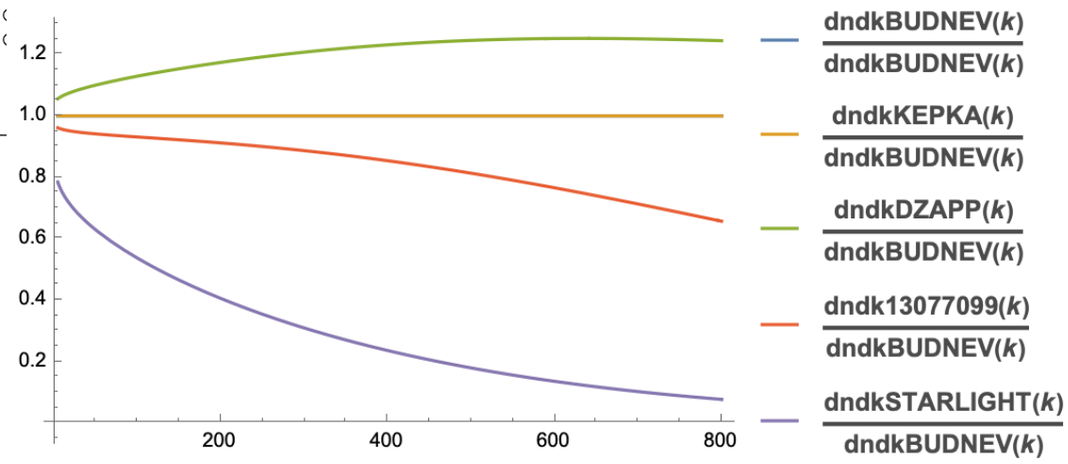
pp@LHCb: 1401.3288, 1806.04079





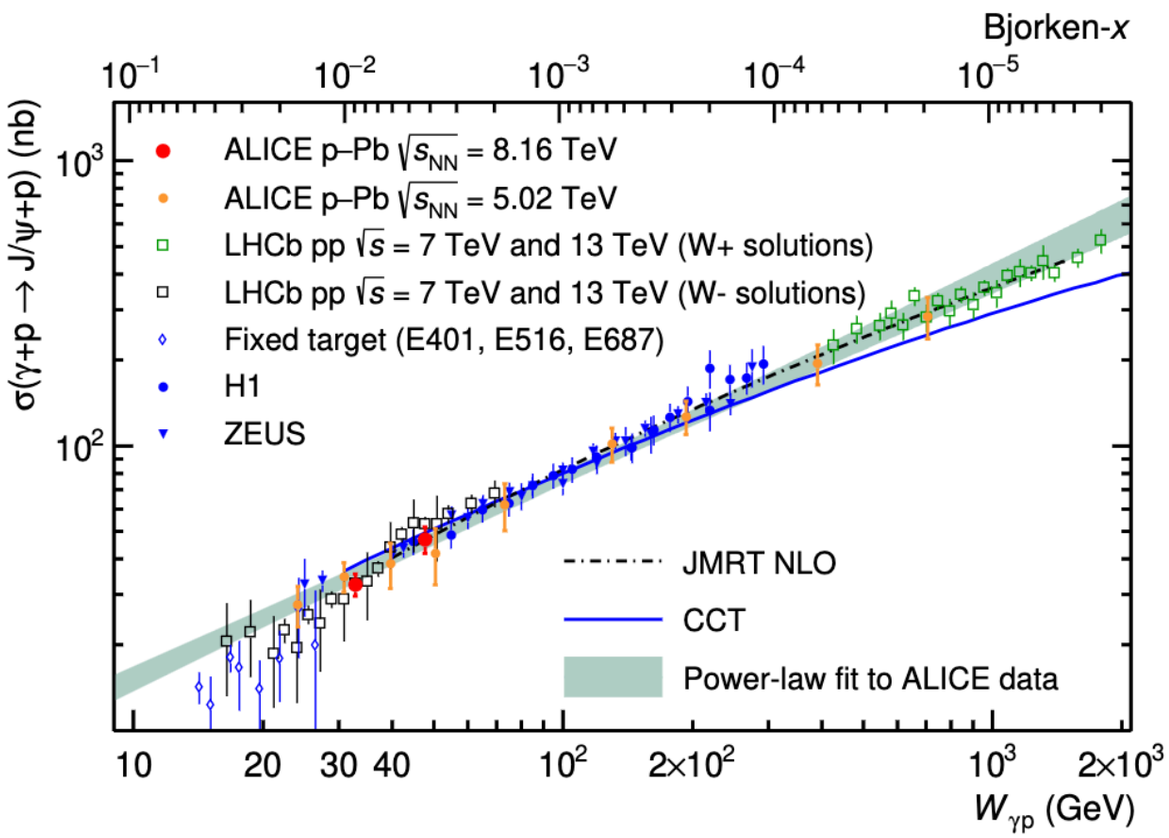
W+/W- ambiguity: $W_{\pm}^2 = M_{J/\psi}\sqrt{s}e^{\pm|y|}$





State of the art

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



ALICE: Exclusive J/psi photoproduction in pPb at 5.02 & 8.16 TeV [no Ups, psi']

5.02TeV at both **semi-forward, forward & mid-rapidity (wrt to p directn)**

pPb ($2.5 < y < 4$)
Pbp ($-3.6 < y < -2.6$)
} yield ~70-400 depend. on rapidity and lumi

Lint: 4-8 nb^{-1}

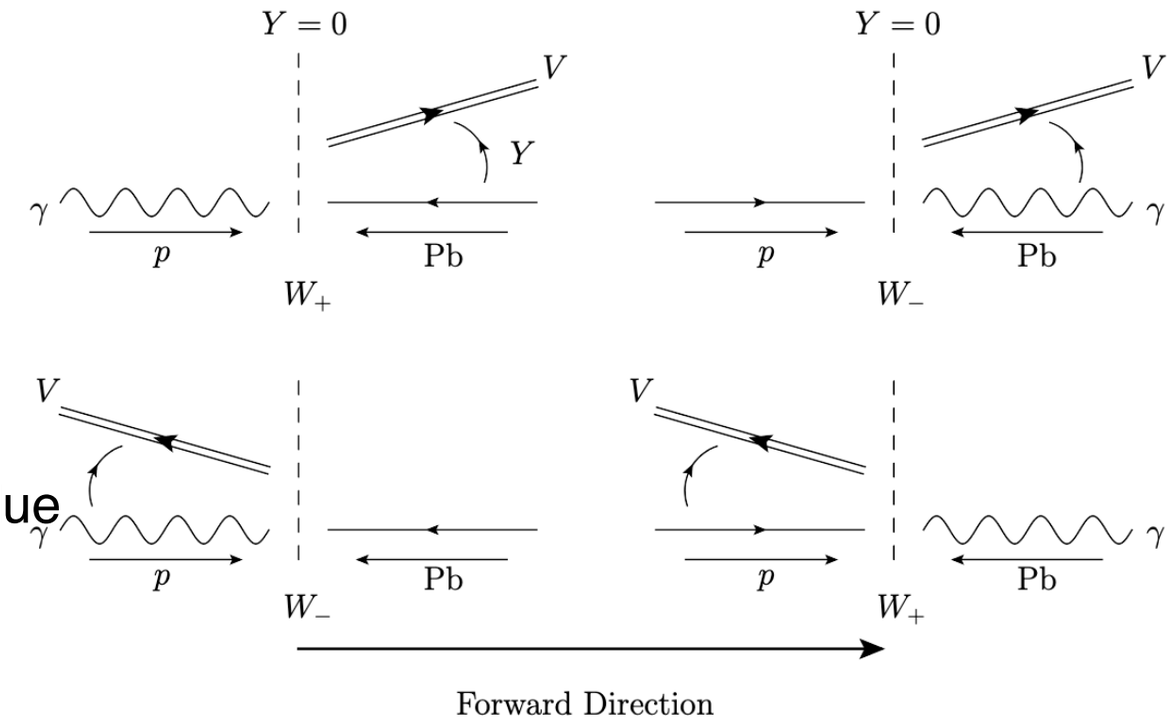
8.16 TeV **forward** only **(wrt to p directn)**

pPb ($2.5 < y < 4$) } yield ~1180

CMS: Exclusive Ups photoproduction in pPb at 5.02 TeV 1809.11080

yield ~24, Lint: 33 nb^{-1}

DAE Symp. Nucl. Phys., 63:958–959, 2018



pPb@LHC: 1406.7819, 1809.03235 , 2304.12403

-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

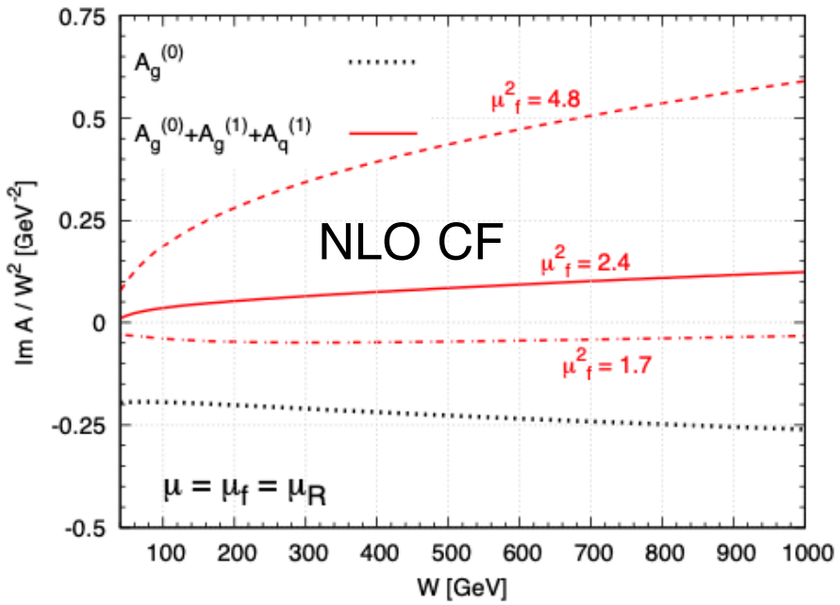
-For pp, more contamination from Odderon-pomeron due to relatively smaller impact parameter

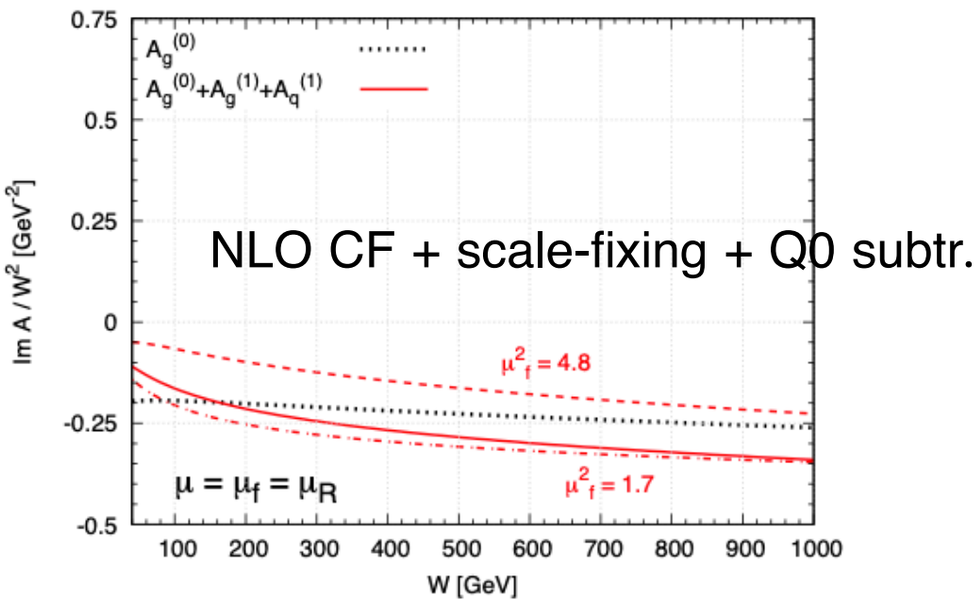
Theory developments

Predictions from variety of approaches: kt fact., colour dip., CGC, **pQCD**.

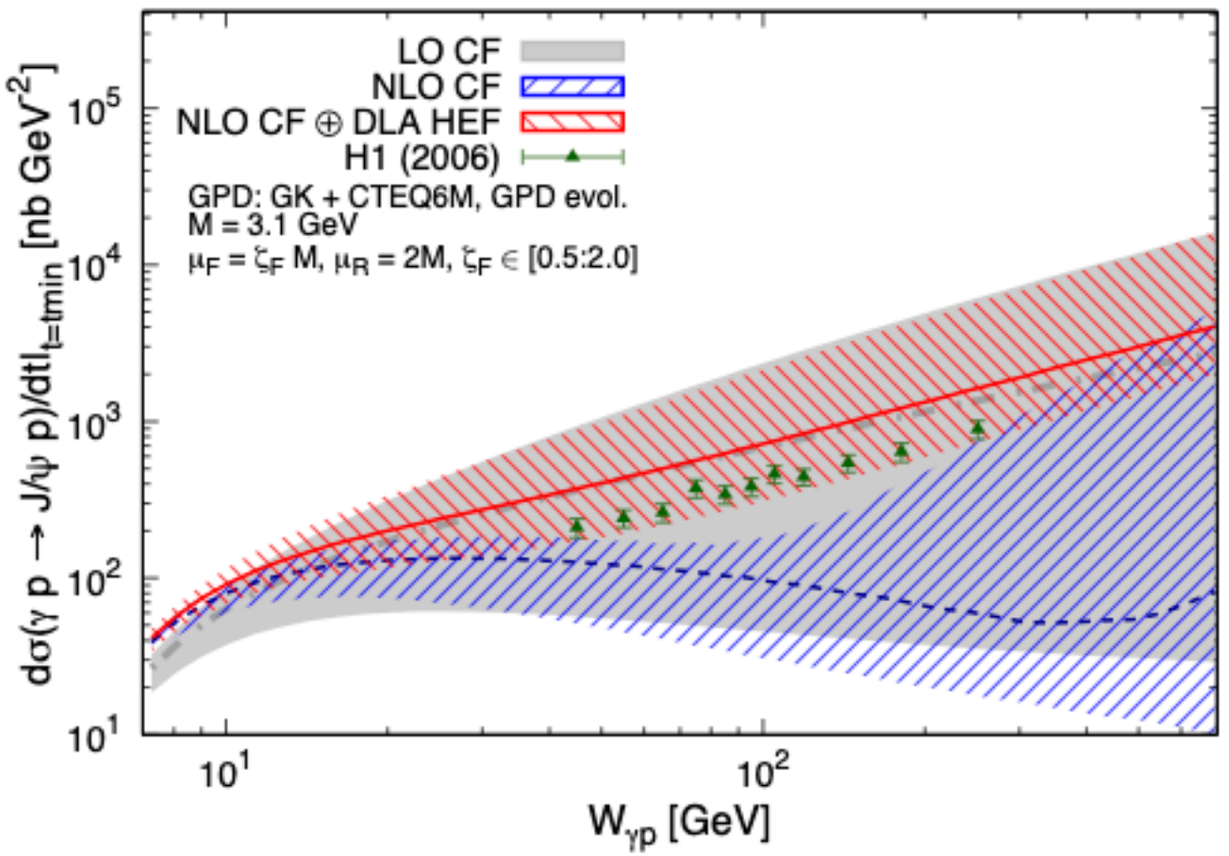
Current pQCD:

Two approaches to cure the infamously large scale dependence of the gamma p -> J/psi p NLO amplitude in coll. fact. (CF) driving the ep and pp/pPb collisions





CAF, Jones, Martin, Ryskin, Teubner 1908.08398, 2006.13857



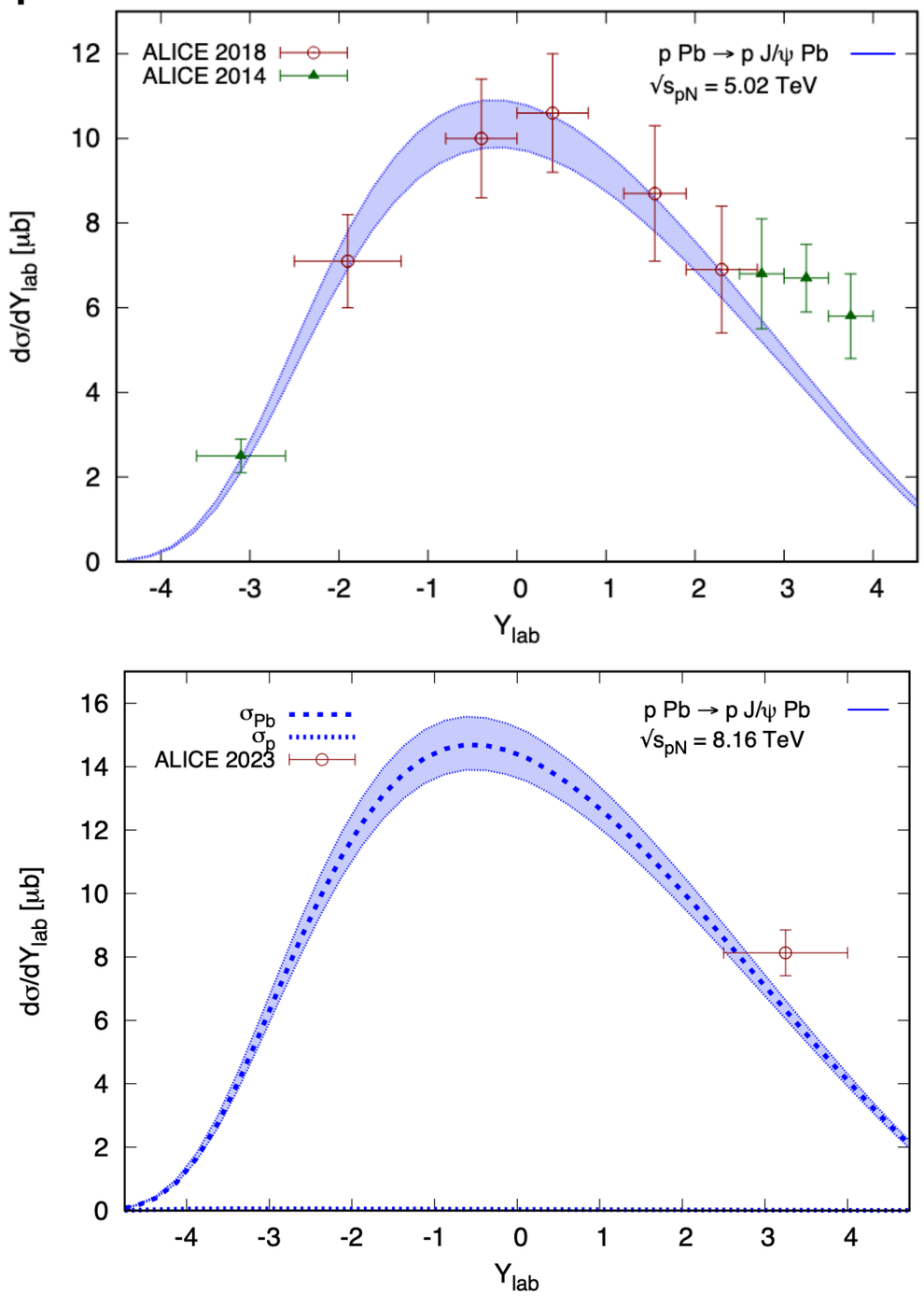
CAF, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, to appear

NLO CF + resummation in the double-leading-logarithmic approximation (DLA) within High-energy factorisation (HEF)

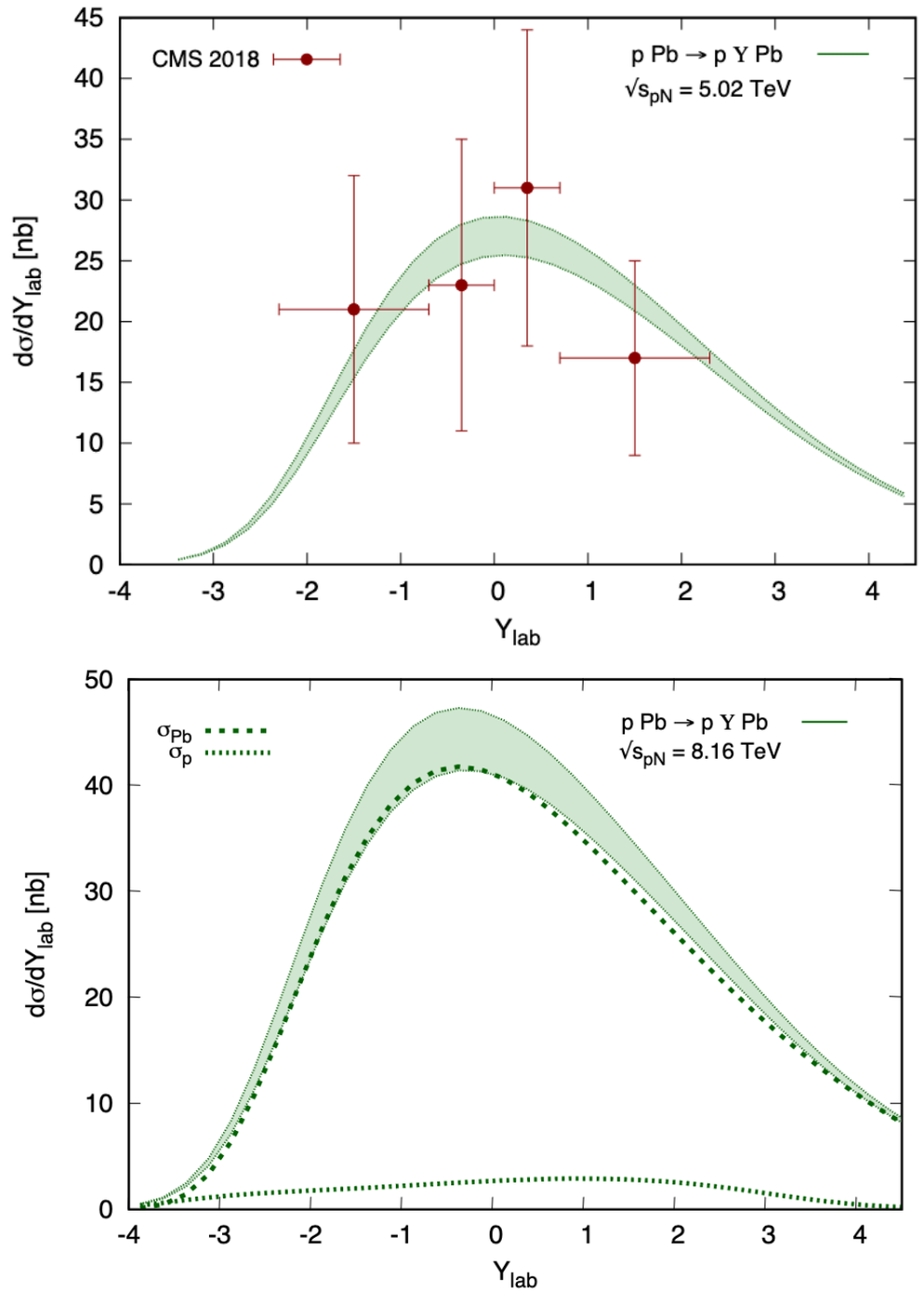
Theory developments

Current pQCD: From NLO CF + scale-fixing + Q0 subtr. approach, obtained pre- and postdictions for rapidity-differential pPb distributions + quantified size of photoproduction on Pb contribution

J/psi:



Ups:

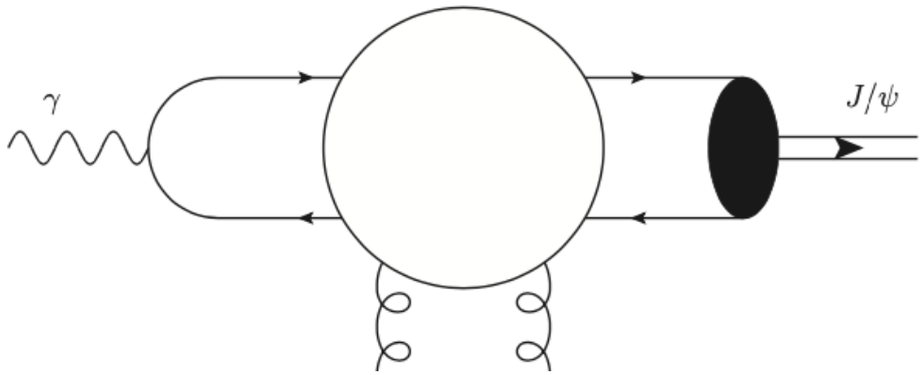


CAF, Jones, Martin, Ryskin, Teubner 2206.10161

Desirable measurements and Outlook

Polarisation

Leading-twist collinear factorisation (CF) =>
transversely polarised J/psi



=> Validate these assumptions via explicit polarisation studies

Polarisation measurements of J/psi photoproduction in ep at HERA confirmed transverse J/psi polarisation, i.e. s-channel helicity conservation
hep-ex/0510016, hep-ex/0404008

→ Vector-meson photoproduction analyses at the LHC always assumed transverse J/psi polarisation

↓

Pb+Pb analysis 2304.10928 constitutes the first measurement of the J/psi polarisation in UPCs where they find value consistent with unity

← If the conservation is seen and no helicity flip then can put constraints on higher twist

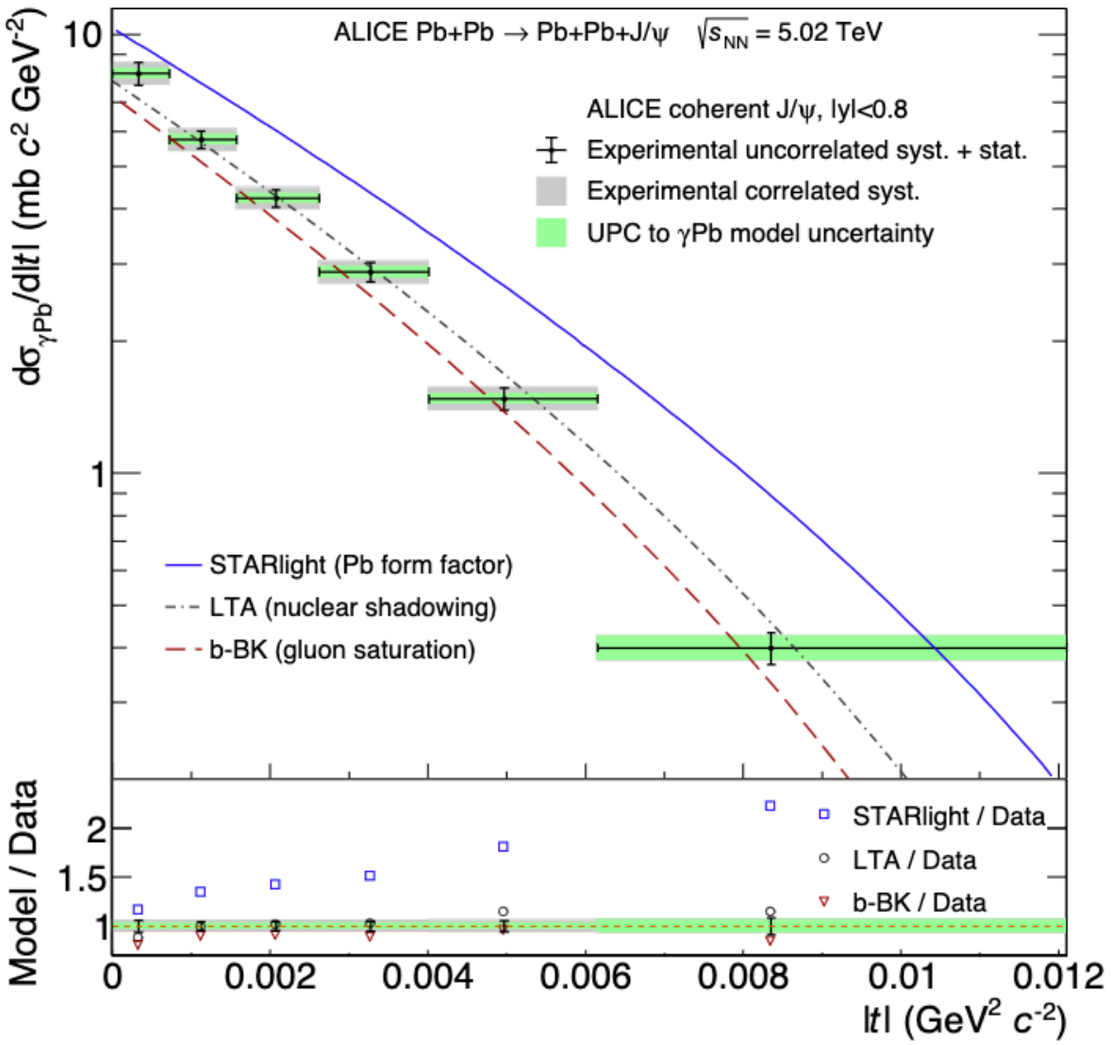
On-going analysis in peripheral PbPb puts 2sig deviation from unity.

=> $\Delta\lambda_\theta = 0.5$ with 1700 events. To reach $\Delta\lambda'_\theta = 0.1$ need 42,500 events

→ HL-LHC and complement with pPb measurement $(\Delta\lambda_\theta/\Delta\lambda'_\theta = \sqrt{N'/N})$

Desirable measurements and Outlook

t dependence



2101.04623

Complement first analysis by ALICE in PbPb where they measure t-differential cross section

In coherent PbPb, t dependence driven by Pb size. In pPb it is wrt. proton size as photoproduction on p largely dominates.

tmin practically the same in pp and pPb
low t: coherent-production dominated

⟶

such measurements can probe validity of t-dependence factorisation in GPD modellings widely adopted

RA

PbPb allows access to nuclear modification factor but then currently no robust understanding of GPDs in nuclear environment (and W+/W- ambiguity in PbPb)

Desirable measurements and Outlook

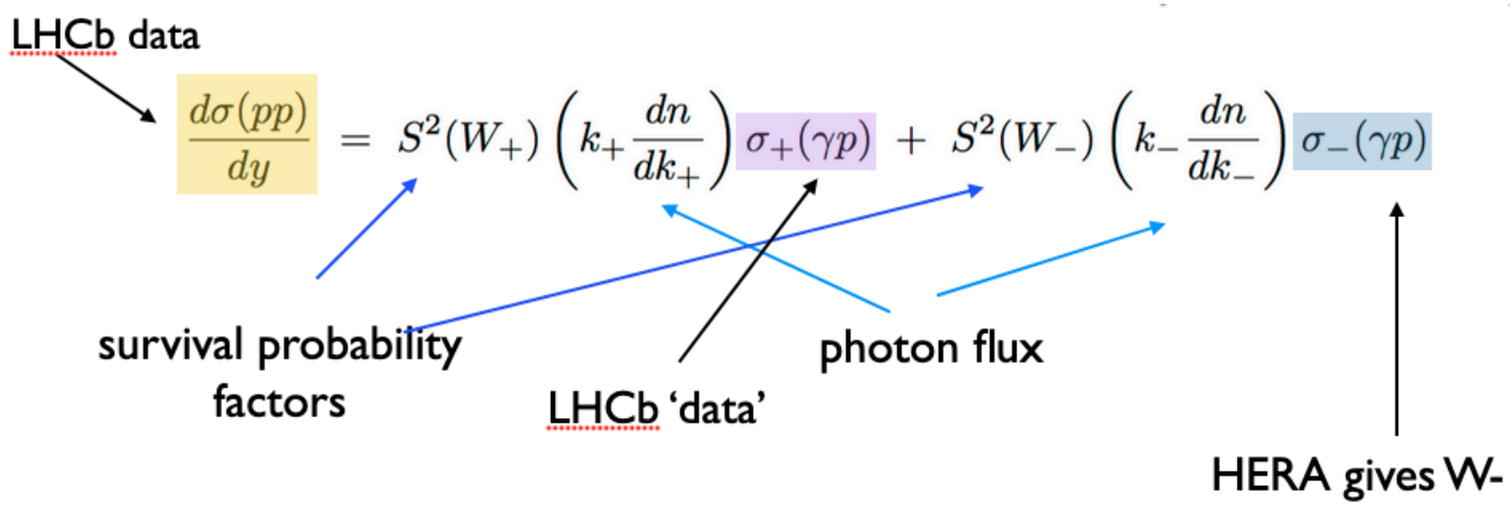
Probe of nucleon gluon PDF

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

Sensitive to GPD not PDF! but can relate PDF & GPD at low x reliably via the so-called Shuvaev transform 1908.08398 & 2006.13857

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

In pPb, survival factor close to unity/ 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. **Only** in pPb can we push the **precision** of (2), i.e. that of low x and low scale exclusive quarkonium data as constraints on the gluon PDF

Desirable measurements and Outlook

Probe of nucleon gluon PDF

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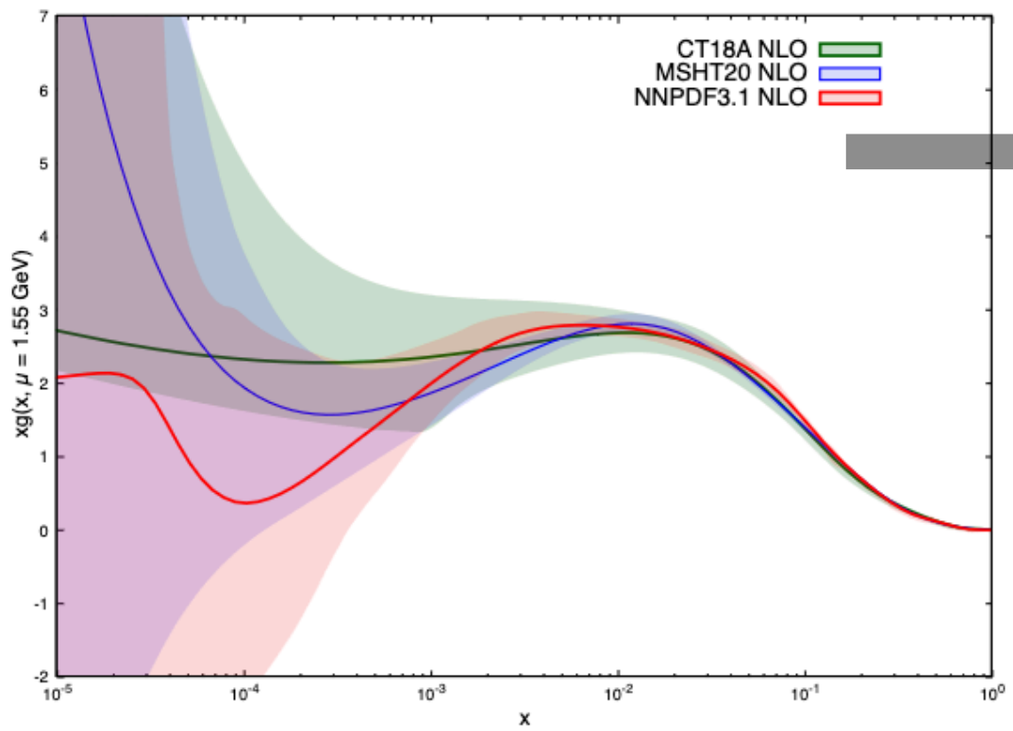
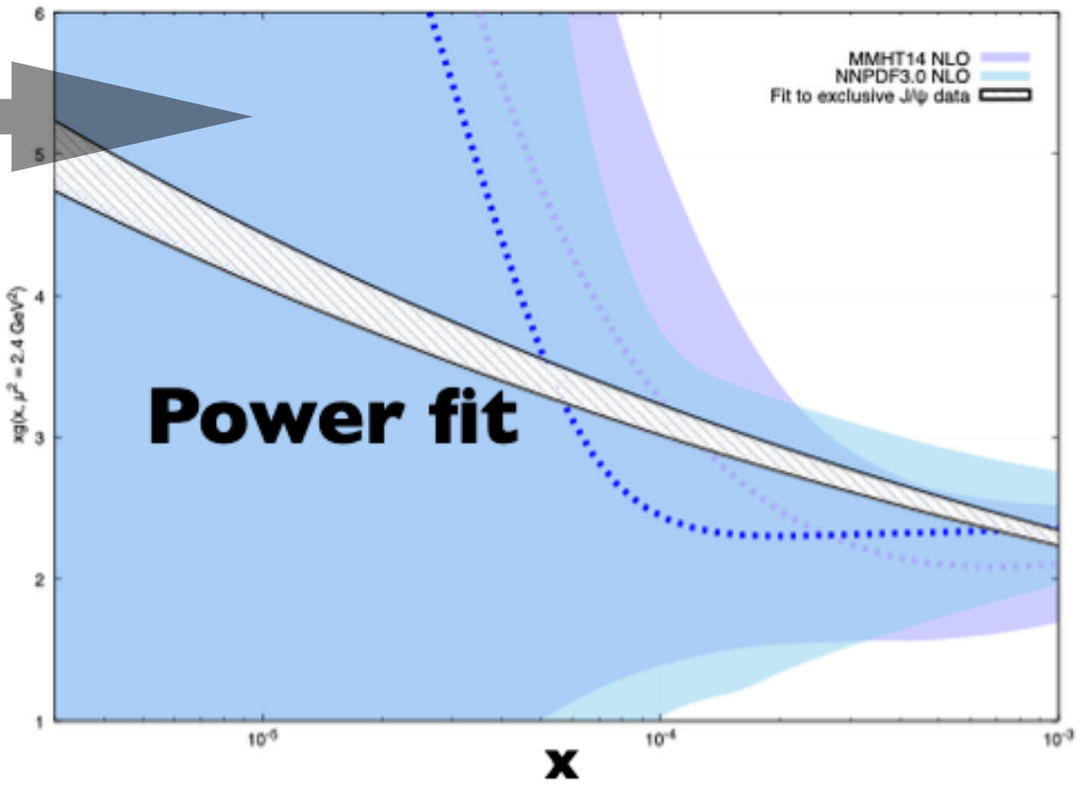


kinematics in pPb probe x~ 10^{-5}

...unconstrained domain in PDF fits!

CAF, Martin, Ryskin, Teubner 2006.13857

xg



Fits + reweighting exercises using the more plentiful pp data so far

Summary

Good variety of exclusive quarkonium-photoproduction measurements in small and large collision systems covering wide kinematic range

Current pp and pPb systems from LHC extend the coverage of HERA and upcoming EIC measurements

But generally, pPb@HL-LHC has the potential for **discovery** (i.e. probes at unprecedented x), **measure with high precision** (plentiful statistics anticipated) and be **less susceptible to model dependences**

A variety of observables can be measured to supplement existing data or ignite new discoveries (polarisation, t dep., gluon PDF probes)

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.

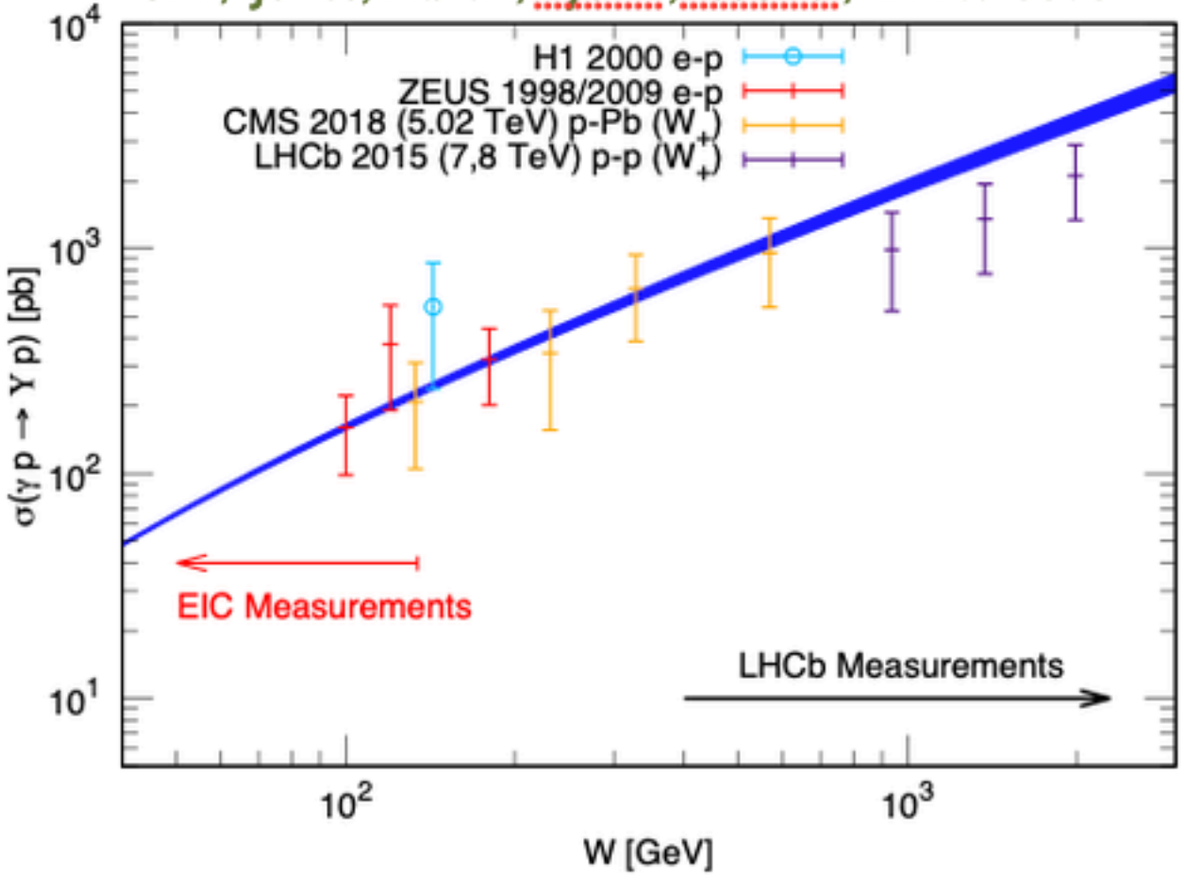
Thank you

with thanks to Jean-Philippe Lansberg & Laure Marie Massacrier for various inputs

backup

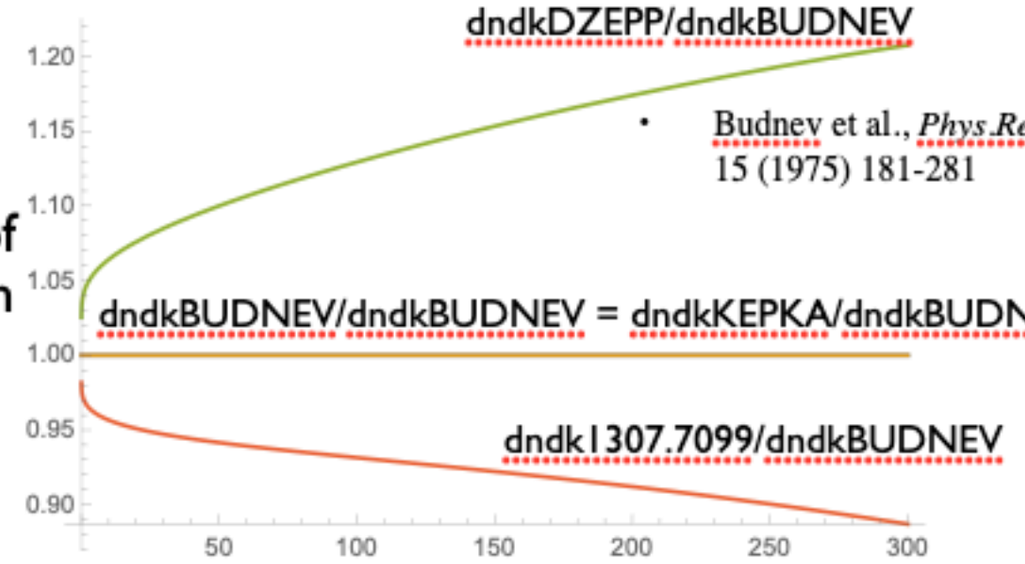
Other results in UPC: Photon flux in Upsilon photoprod. in pA

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)

ratio of photon fluxes



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

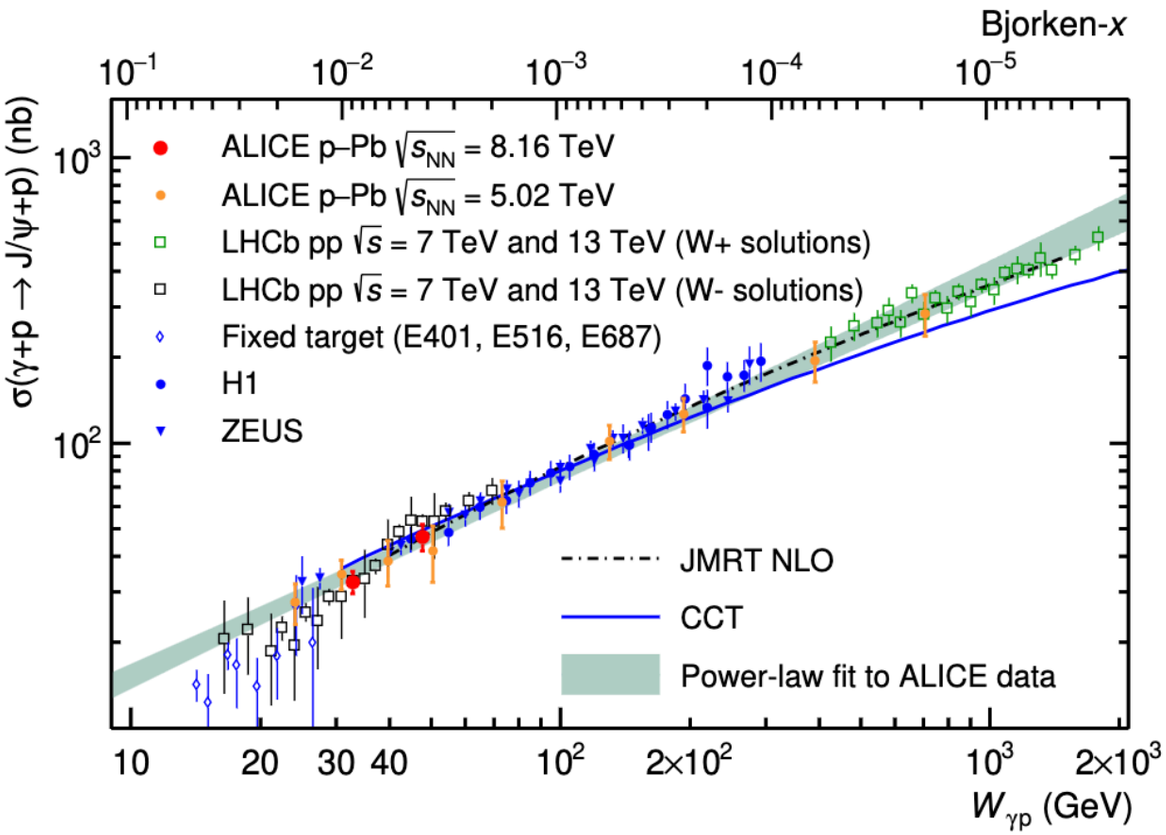
Upsilon photoproduction photon energies will be larger so discrepancy between fluxes (and survival factors) will be larger and we enter the region where the approximation of 1307.7099 flux breaks down at much lower rapidities and, importantly, within the acceptance of LHCb

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

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

State of the art

Exclusive J/psi photoproduction to date



LHC 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

LHC 'data'

photon flux

HERA gives W-

$$W_\pm^2 = M_{J/\psi}\sqrt{s}e^{\pm|y|}$$

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

ALICE: Exclusive J/psi photoproduction in pPb at 5.02 & 8.16 TeV [no ups, psi']

5.02TeV at both **semi-forward, forward & mid-rapidity (wrt to p directn)**

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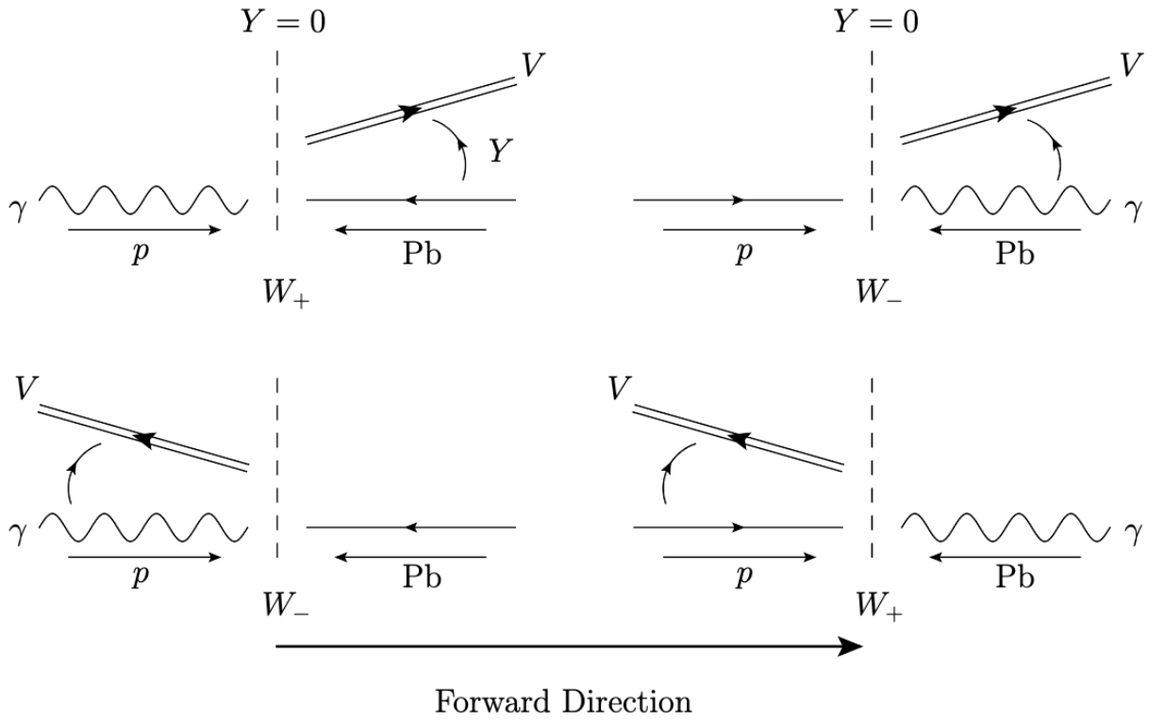
CMS: Exclusive Ups photoproduction in pPb at 5.02 TeV



Introduction

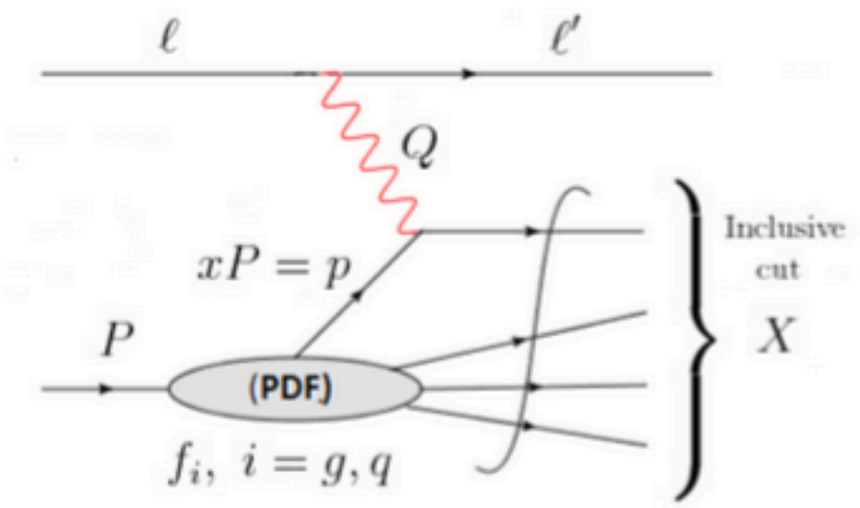
- Inclusive processes do not well constrain small x/Regge limit domain of PDFs
- Exclusive processes offer sensitive probe of this domain but as of yet not included in global analyses PDF determination – why?
    1. Off forward kinematics imply sensitivity to GPD over conventional PDFs
    2. Scale dependence and stability of theoretical predictions

- As higher CM energies are realised at LHC, pushed towards small x domain, W ~ 1/x

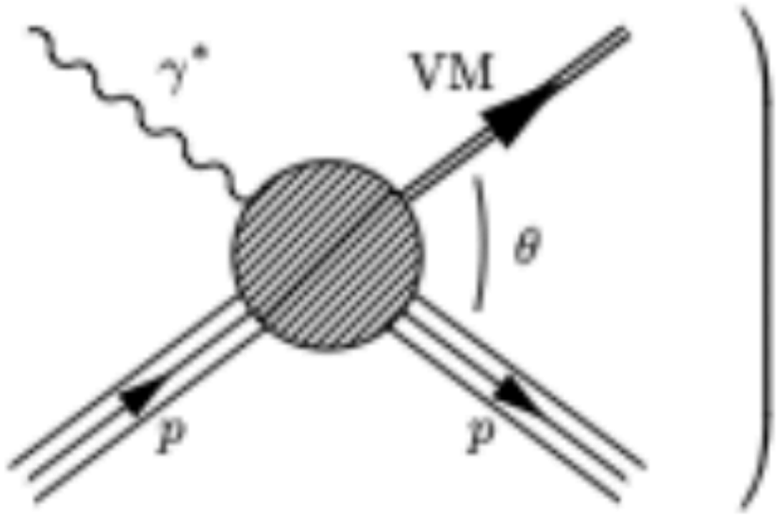
DLLA exclusive J/psi production:

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

Inclusive – e.g. DIS included in global parton analyses



Exclusive – can we use the data?



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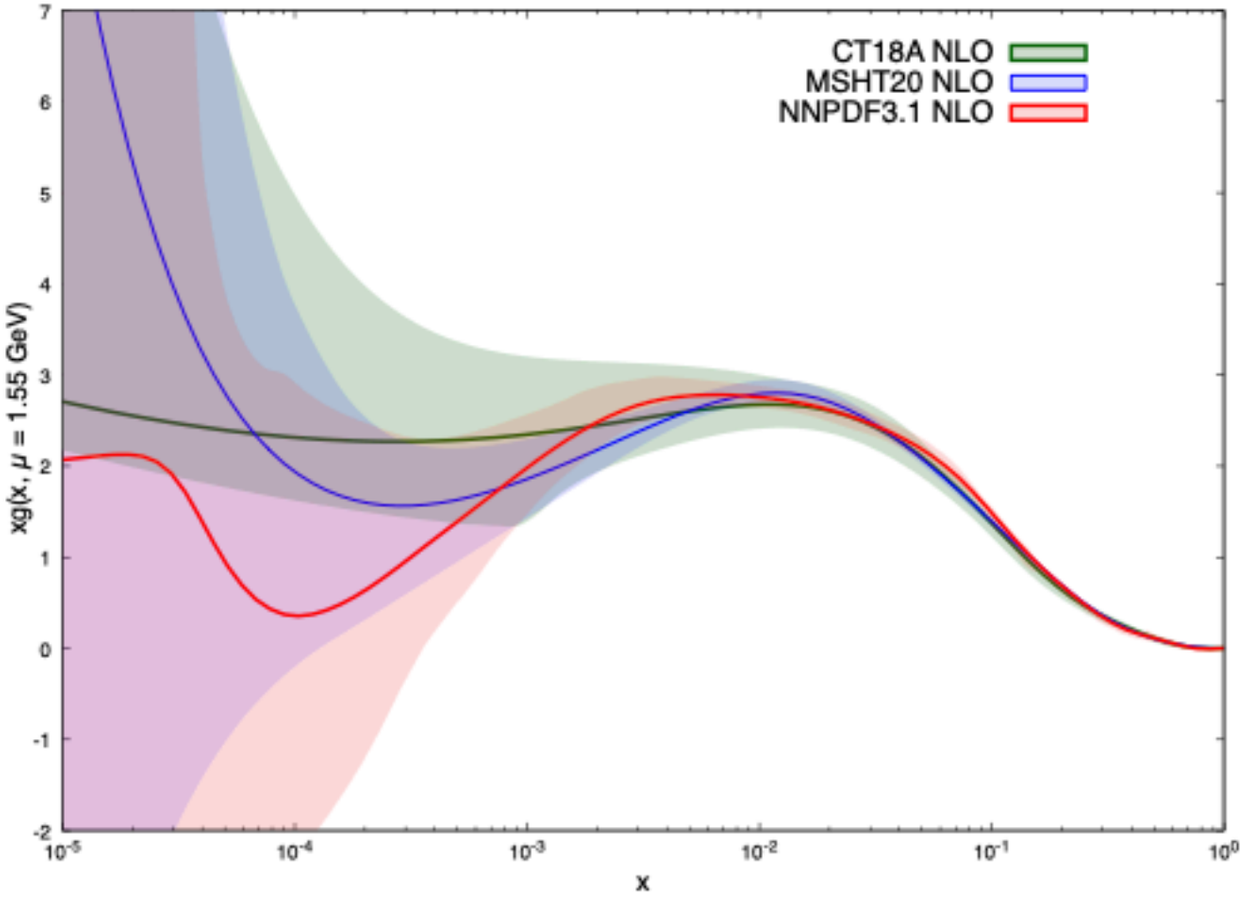
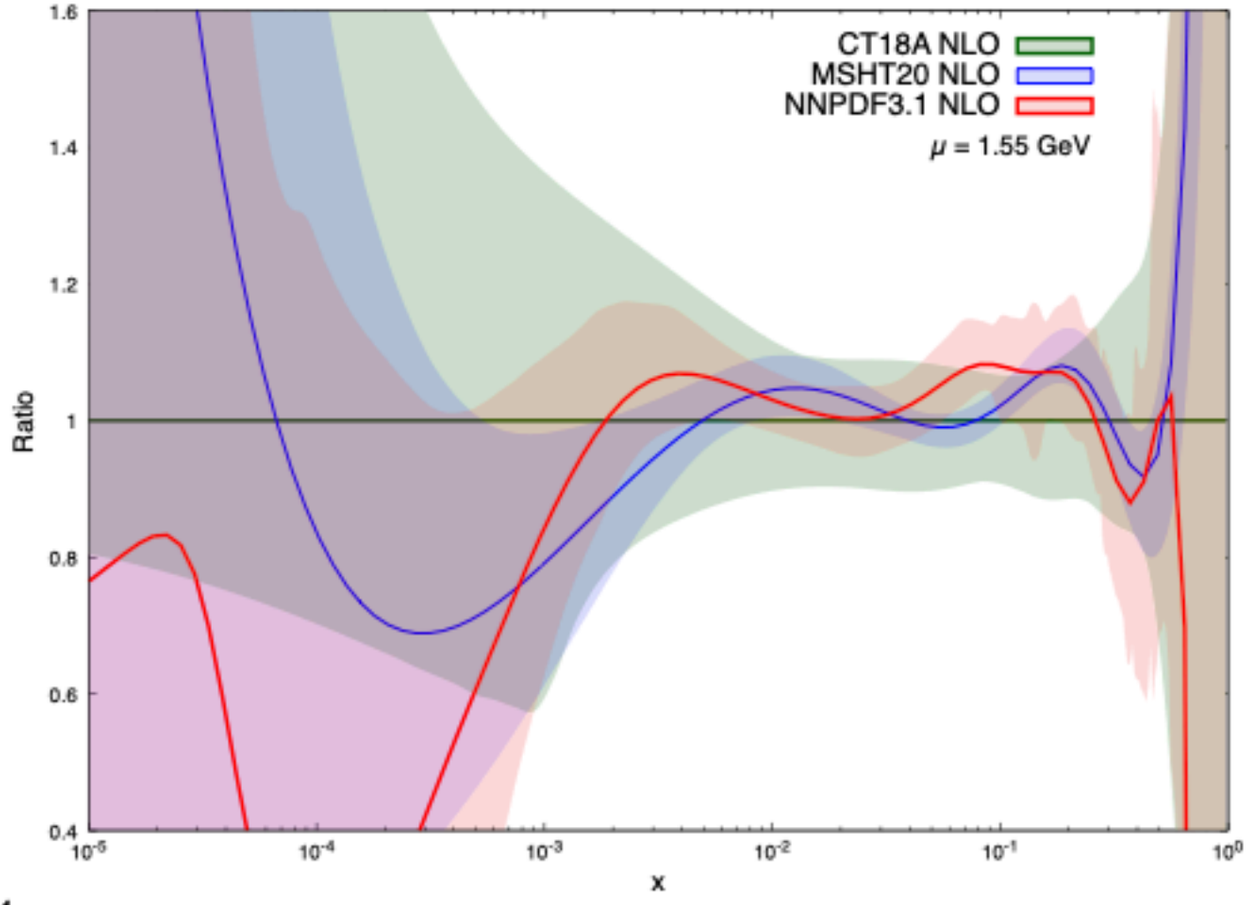
    1. Off forward kinematics imply sensitivity to GPD over conventional PDFs
    2. Scale dependence and stability of theoretical predictions

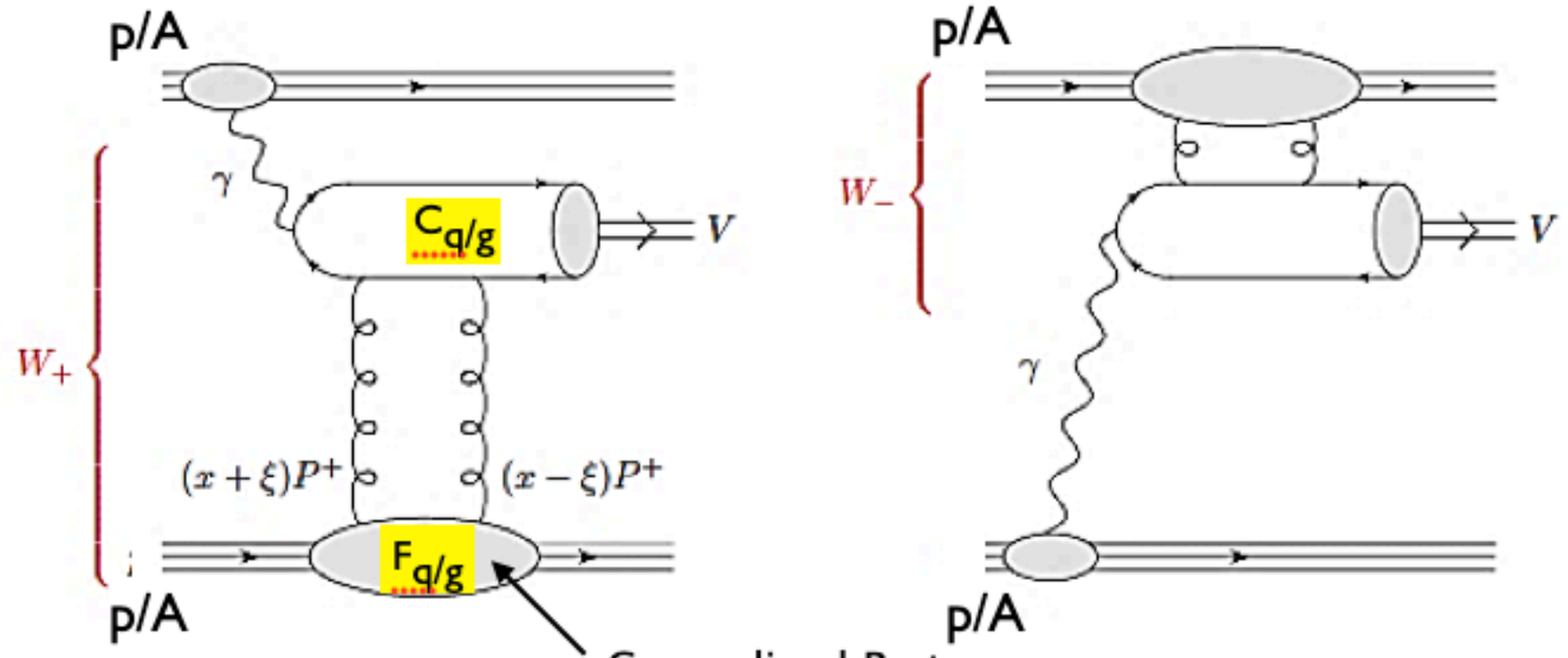
Scope: how to counteract these problems and so allow exclusive J/psi data to probe gluon PDF down to $x \sim 3 \times 10^{-6} \quad \& \quad \mu = O(M_{J/\psi}/2)$





General Set up and Framework

Exclusive J/psi photoproduction in p+p (A+A) UPC collisions in collinear factorisation



Setup for $\gamma p \to J/\psi p$ follows:
Ivanov, Schäfer, Szymanowski, Krasnikov, 04

- Factorisation: $F_{q/g} \otimes C_{q/g} \otimes \phi^V_{Q\bar{Q}}$
- Leading zeroth order term in rel. velocity (NRQCD)
- Colour singlet exchange between hard and soft sectors

$$A \propto \int_{-1}^{1} \mathrm{d}x \left[C_g(x,\xi) F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi) F_q(x,\xi) \right]$$

Photoproduction:
- hep-ph/0401131

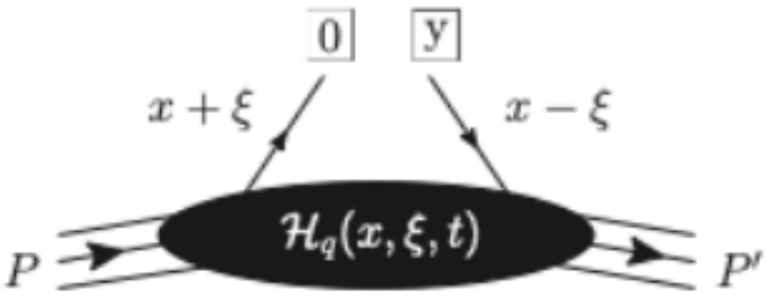
Ivanov, Schäfer, Szymanowski, Krasnikov, 04

Electroproduction:
- arXiv:1903.00171
- arXiv:2105.07657

Chen, Qiao, 19
CAF, Gracey, Jones, Teubner, 21

GPDs and the Shuvaev transform

GPDs generalise PDFs: outgoing/incoming partons carry different momentum fractions *Müller 94; Radyushkin 97; Ji 97*



$$\langle P'|\overline{\psi}_q(y)\mathcal{P}\{\}\psi_q(0)|P\rangle$$

Shuvaev: Relates GPDs to PDFs at small x under physically motivated assumptions c.f analyticity

Shuvaev 99 Martin et al. 09

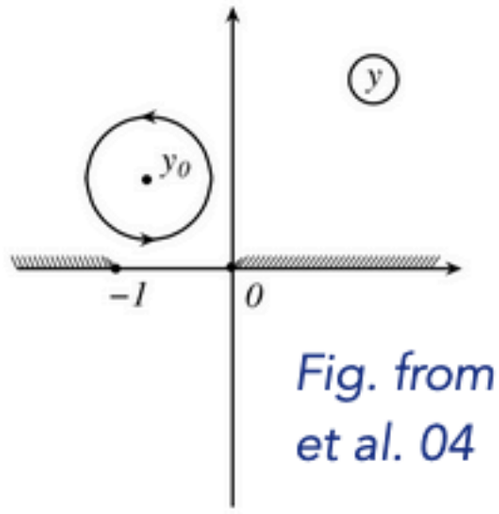


Fig. from Ivanov et al. 04

Idea: Conformal moments of GPDs = Mellin moments of PDFs
(up to corrections of O(xi^2) @ LO and O(xi) @ NLO)

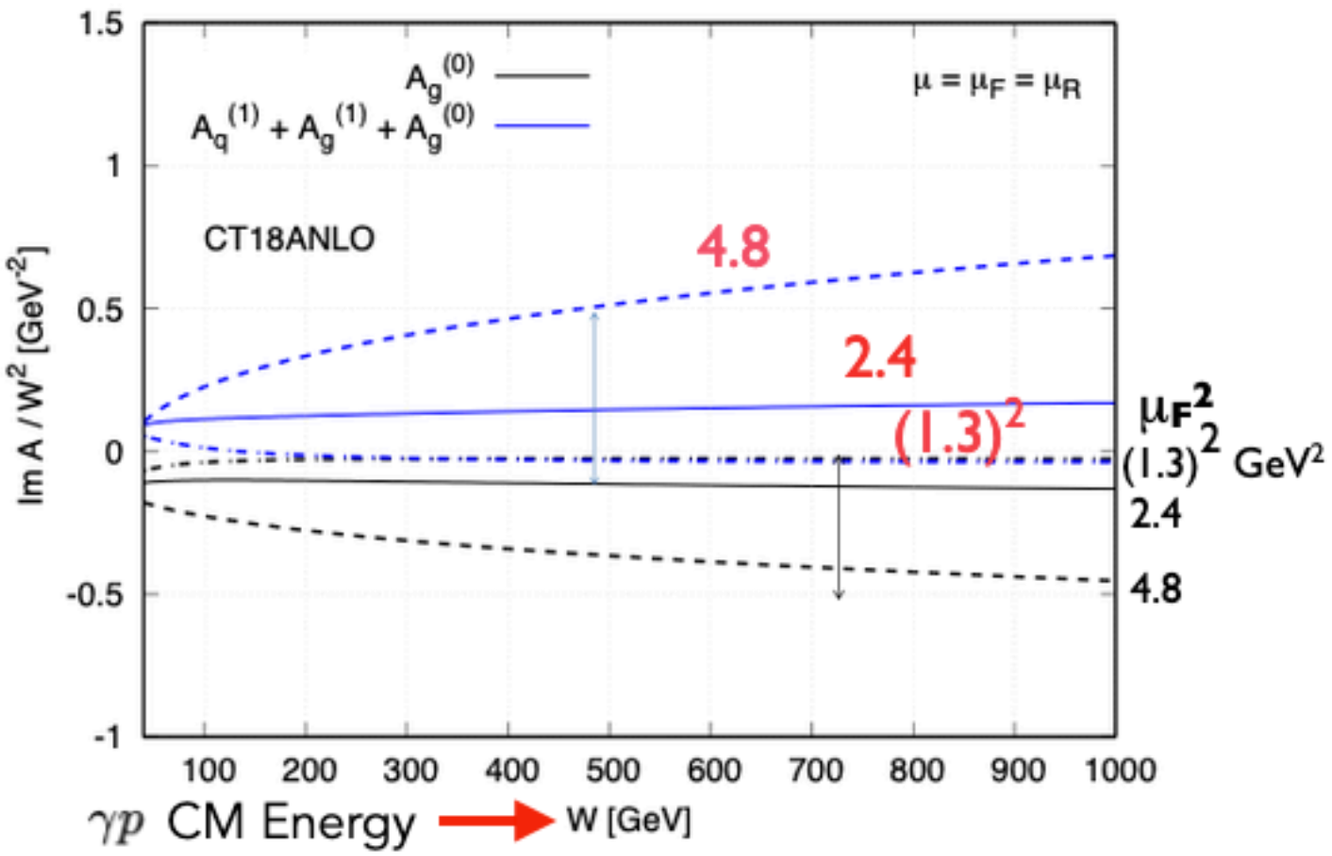
- Construct GPD grids in multidimensional parameter space x, xi/x, qsq with forward PDFs from LHAPDF
- Costly computationally due to slowly converging double integral transform
- Regge theory considerations => Shuvaev transform valid in space-like (DGLAP) region only. In time-like (ERBL) region imaginary part of coefficient function is zero

Framework in a nutshell: Stability of NLO prediction I+II

NLO in MSbar scheme

hep-ph/0401131

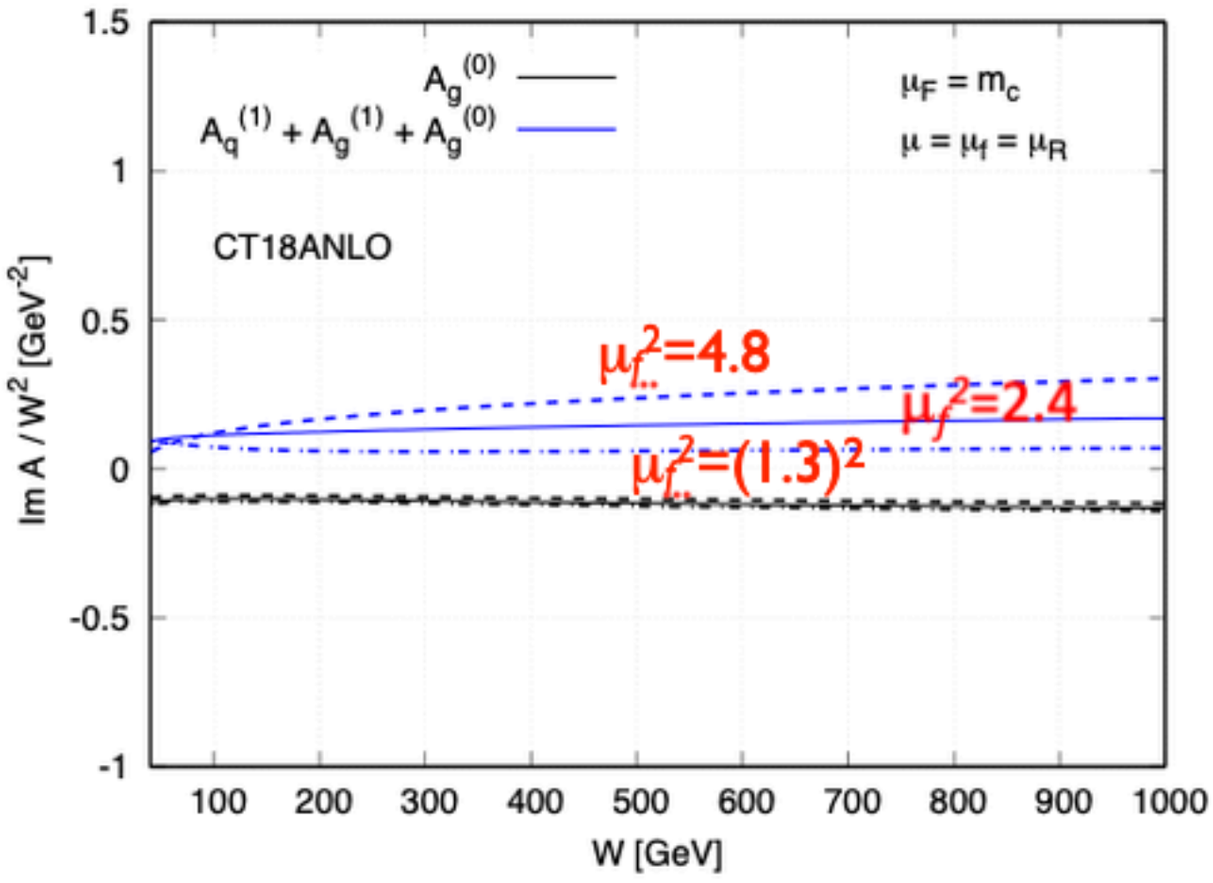
A. Bad perturbative convergence $|NLO_{correctn.}| > |LO|$ and
B. Strong dependence on scale μ_F opp. sign



'Effective' small-x resummation

1507.06942

Resummation of
$(\alpha_s \ln(1/\xi)\ \ln(\mu_{F/m}))^n$

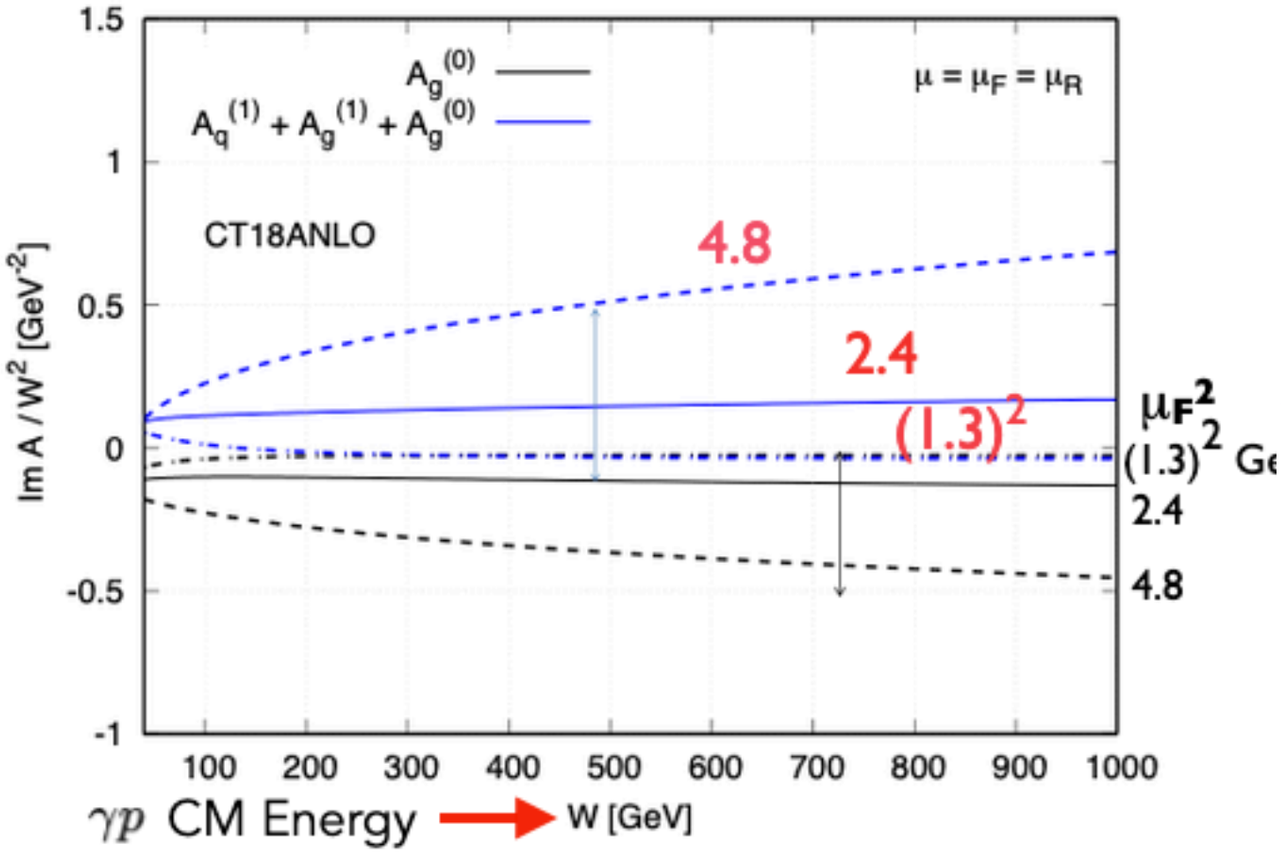


Framework in a nutshell: Stability of NLO prediction I+II

NLO in MSbar scheme

hep-ph/0401131

A. Bad perturbative convergence $|NLO_{correctn.}| > |LO|$ and
B. Strong dependence on scale μ_F opp. sign



'Effective' small-x resummation

1507.06942

Resummation of

$(\alpha_s \ln(1/\xi)\ \ln(\mu_{F/m}))^n$

NLO High-energy limit:

$$\mathcal{M} \approx \frac{-4\,i\,\pi^2\sqrt{4\pi\alpha}\,e_q(e_V^* e_\gamma)}{N_c\,\xi}\left(\frac{\langle O_1\rangle_V}{m^3}\right)^{1/2} \times$$

$$\times\left[\alpha_S(\mu_R)F^g(\xi,\xi,t) + \frac{\alpha_S^2(\mu_R)N_c}{\pi}\ln\left(\frac{m^2}{\mu_F^2}\right)\int_\xi^1 \frac{dx}{x}F^g(x,\xi,t)\right.$$

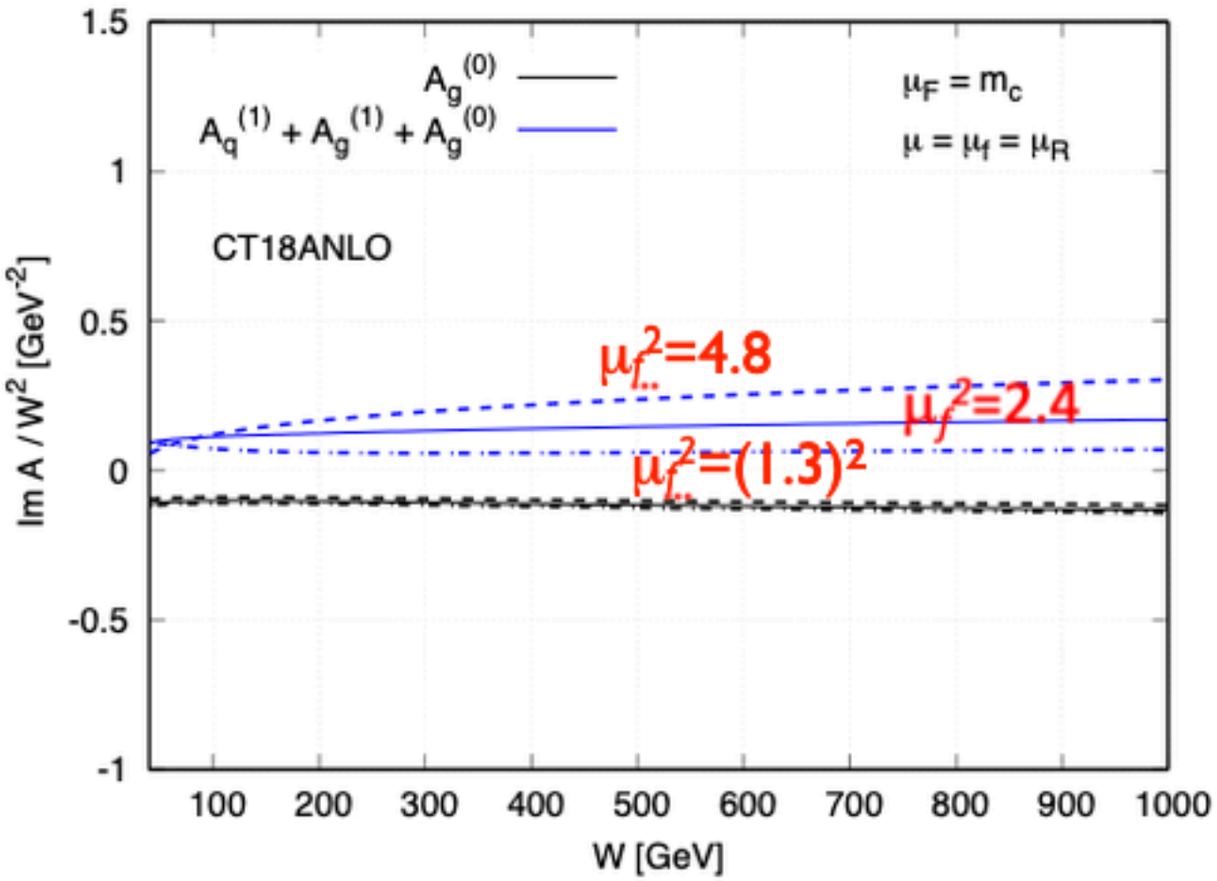
$$\left.+\frac{\alpha_S^2(\mu_R)C_F}{\pi}\ln\left(\frac{m^2}{\mu_F^2}\right)\int_\xi^1 dx\left(F^{q,S}(x,\xi,t) - F^{q,S}(-x,\xi,t)\right)\right]$$

Framework in a nutshell: Stability of NLO prediction II+III

'Effective' small-x resummation

1507.06942

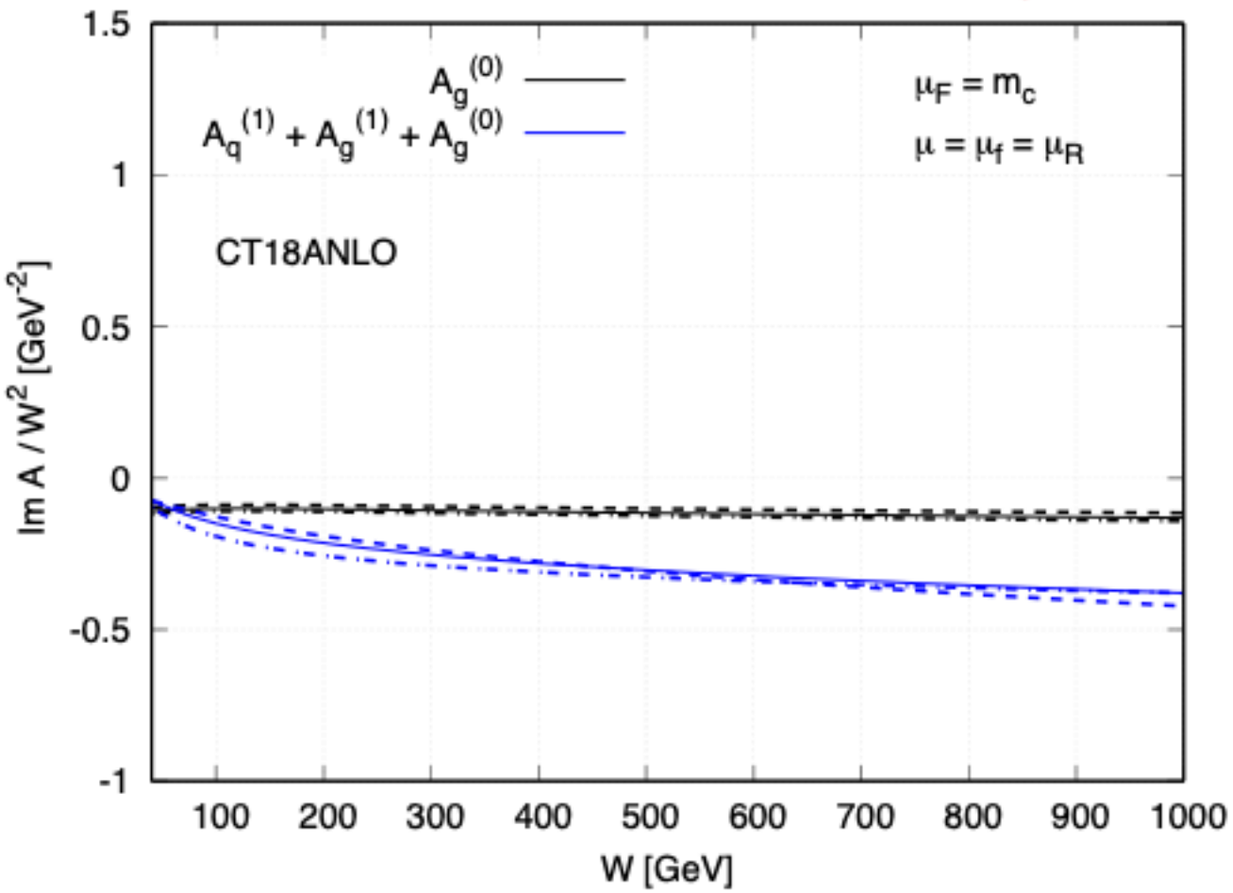
Resummation of $(\alpha_s \ln(1/\xi)\ \ln(\mu_F/m))^n$



Low $l_t < Q_0$ subtraction

1610.02272

Subtract DGLAP contribution NLO ($|\ell^2| < Q_0^2$) from known NLO MSbar coefficient function to avoid a double counting with input GPD at Q_0.



Predictions based on three global PDF analyses differ dramatically in large energy LHC region but are compatible in lower energy HERA region*

Extraction of low x gluon PDF via exclusive J/psi

Left

Approach 1: Fit a low x gluon PDF ansatz to the data

Right

Approach 2: Bayesian reweight current global PDF analyses

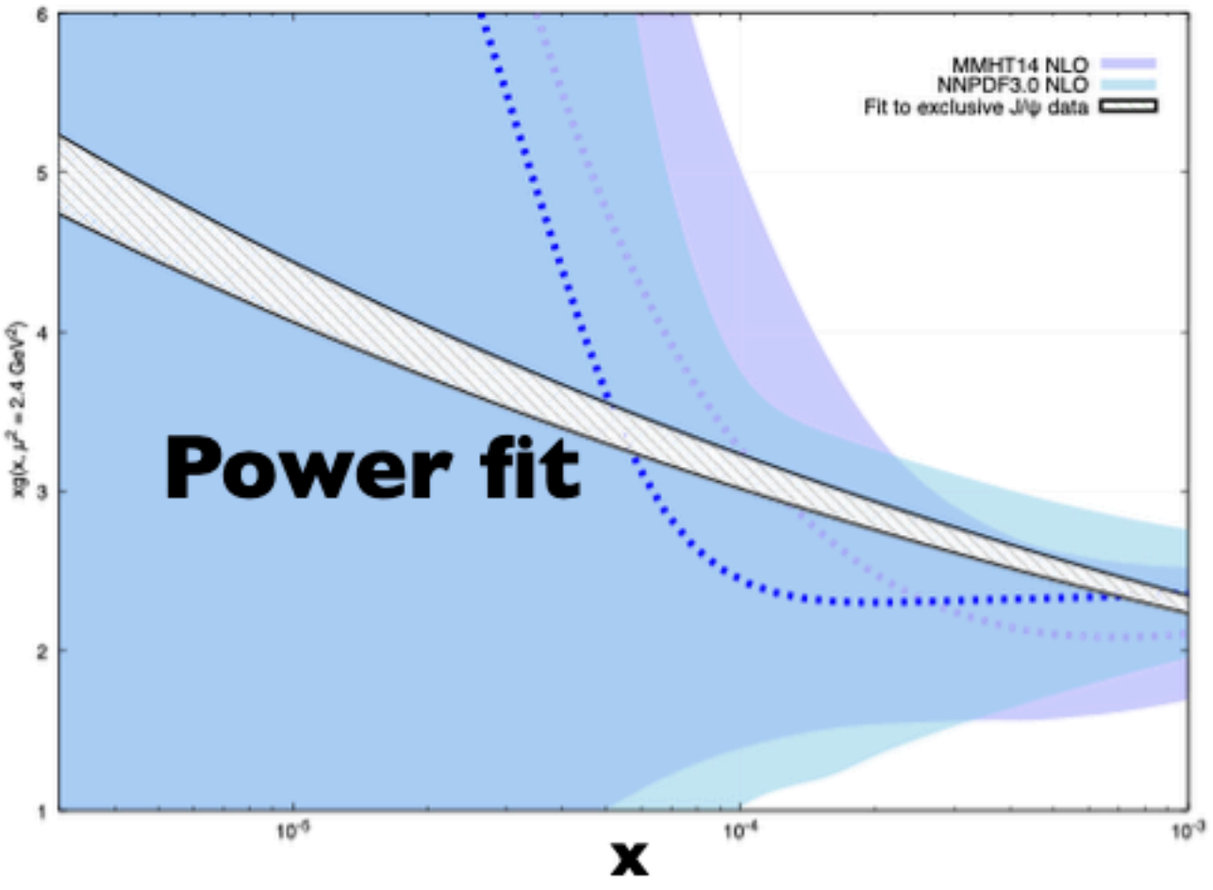
	λ	n	$\chi^2_{\rm min}$	$\chi^2_{\rm min}$/d.o.f
NNPDF3.0	0.136	0.966	44.51	1.04
MMHT14	0.136	1.082	47.00	1.09
CT14	0.132	0.946	48.25	1.12

$$xg^{\rm new}(x,\mu_0^2) \;=\; nN_0\,(1-x)\,x^{-\lambda}$$

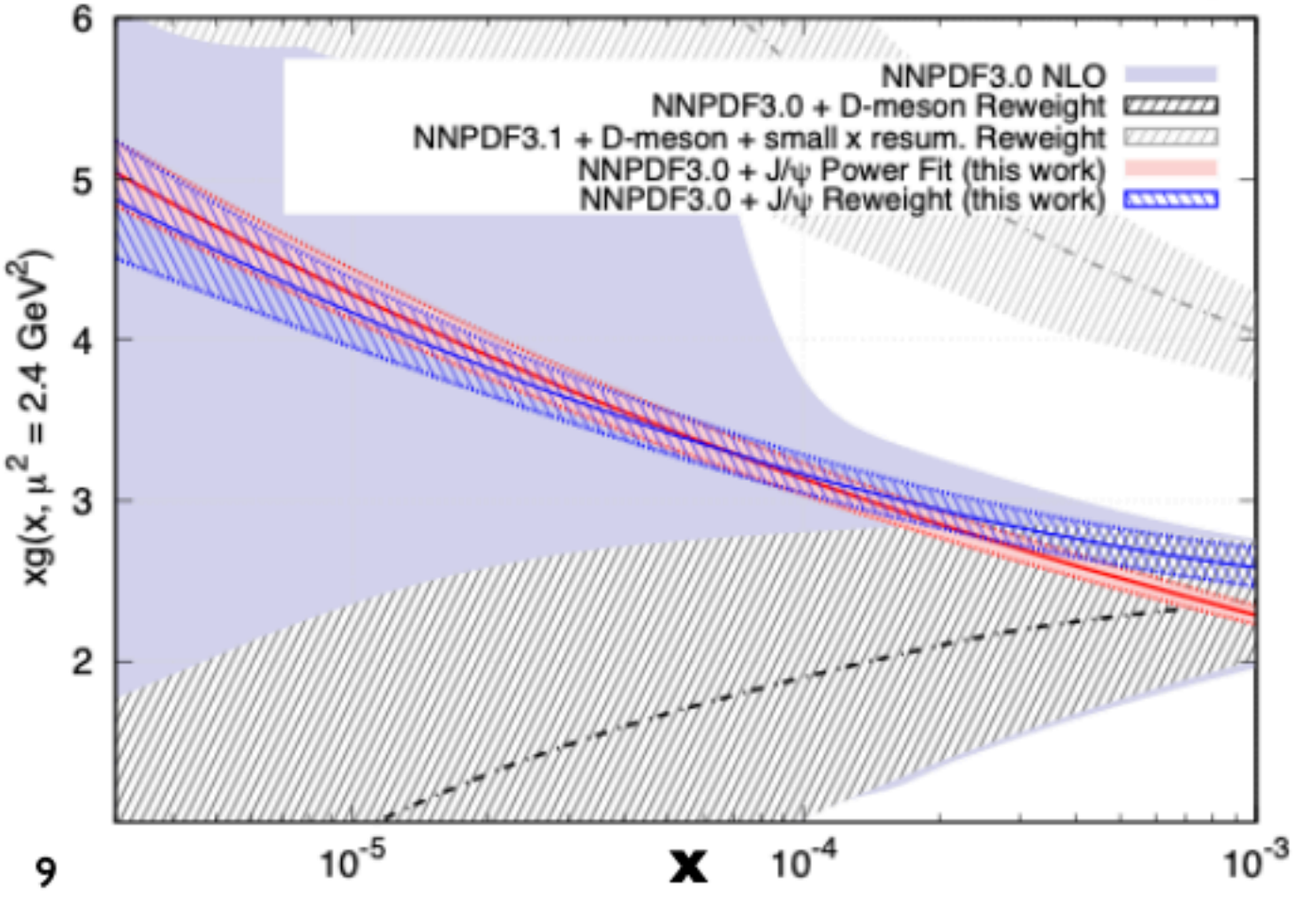
lambda = 0.136 +/- 0.006

n = 0.966 +/- 0.025

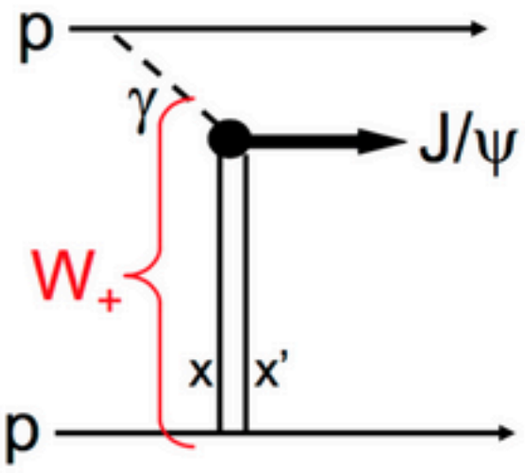
CAF, Martin, Ryskin, Teubner 2006.13857

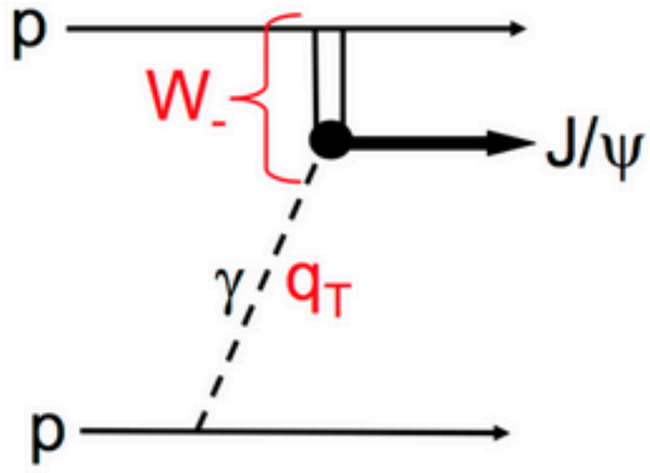


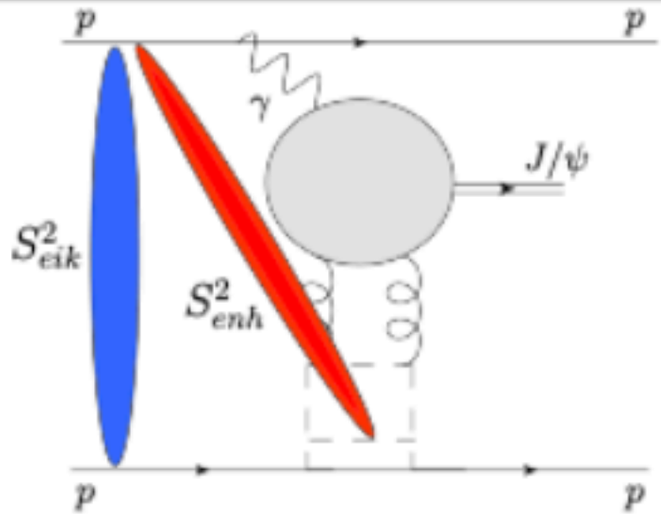
$N_{\rm eff} \ll N_{\rm rep}$



Unfolding photoproduction from UPC







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'

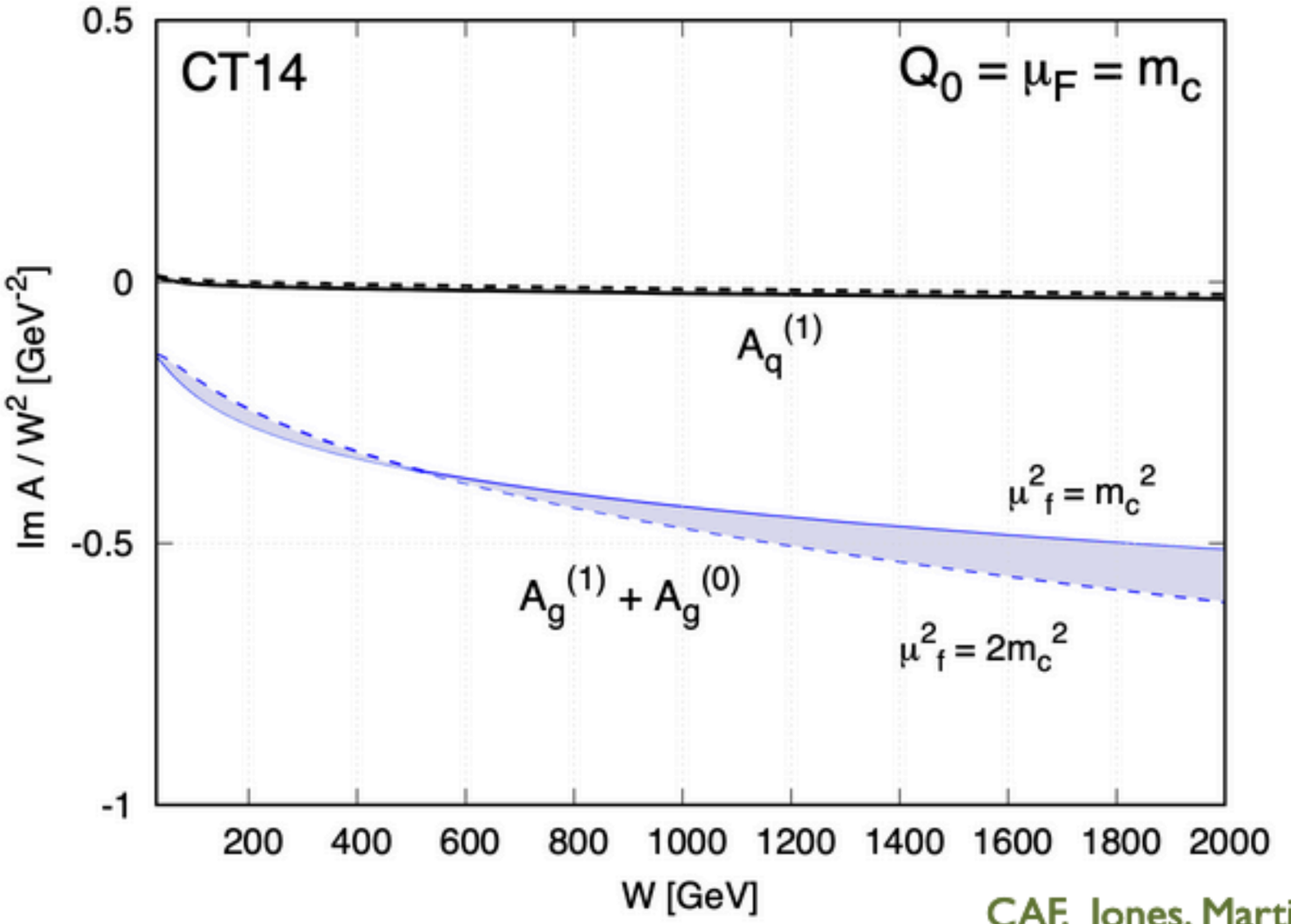
photon flux

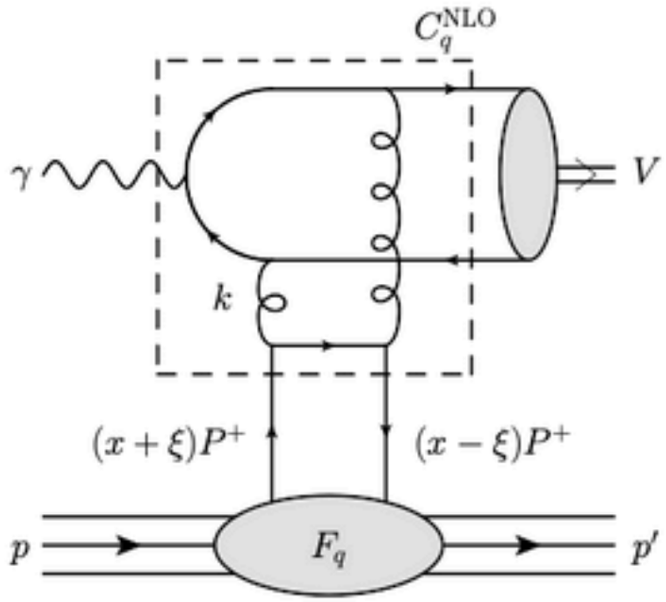
HERA gives W-

$$W^2_\pm = M_{J/\psi}\sqrt{s}e^{\pm|y|} \Rightarrow x_\pm = \begin{cases} 10^{-5} \\ 0.02 \end{cases} \quad \text{at } y = 4,\ \sqrt{s}{=}13\ \text{TeV}$$

Interplay of quark and gluons at NLO

After Q_o 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_o subtraction (as reflected in the numerics)

$\longrightarrow$ Gluon driven like at LO