Hadron structure at the LHC with an emphasis on UPC

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Hadron Workshop

Outline

Hadron collider hadroproduction data for parton distributions

Motivation for photoproduction at hadron colliders

3 different types of measurements in ultra-peripheral collisions

Conclusion

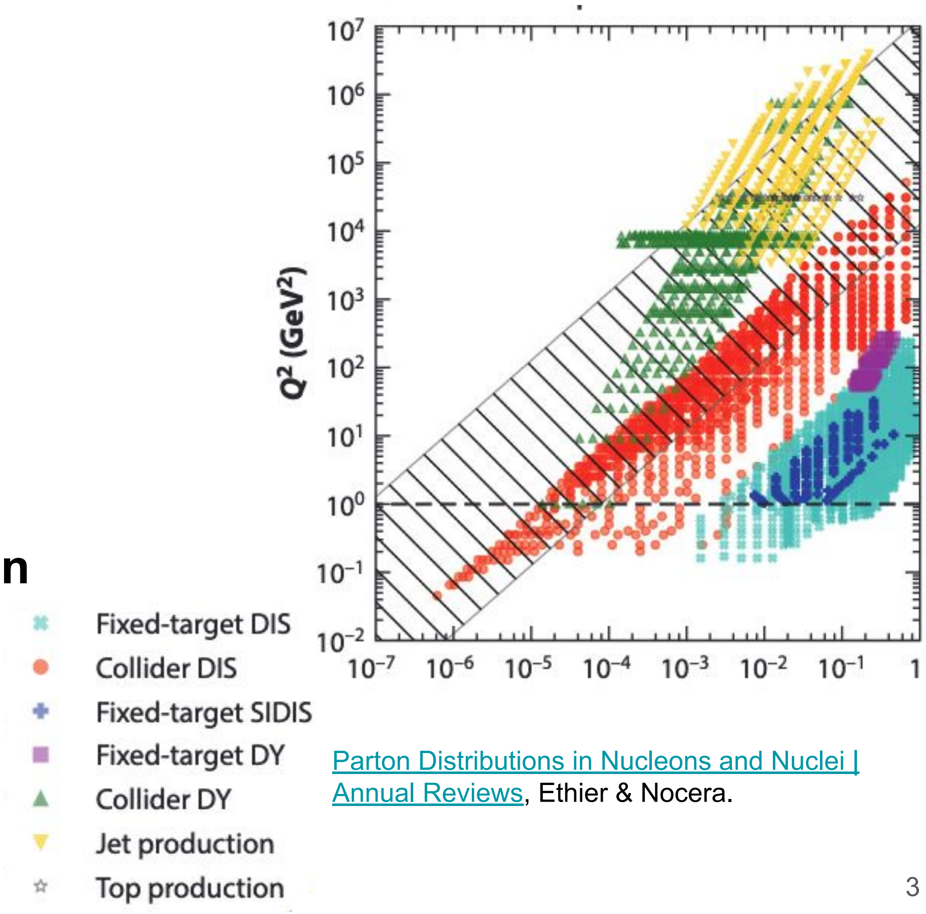
Hard processes in inclusive hadronic collisions

Hadron collider data

- Large kinematic reach
- Complementary sensitivity to different partons w.r.t. DIS

Proton PDF: important contribution

- High-mass/high-p_T very precise



Parton Distributions in Nucleons and Nuclei | Annual Reviews, Ethier & Nocera.

Hard processes in inclusive hadronic collisions

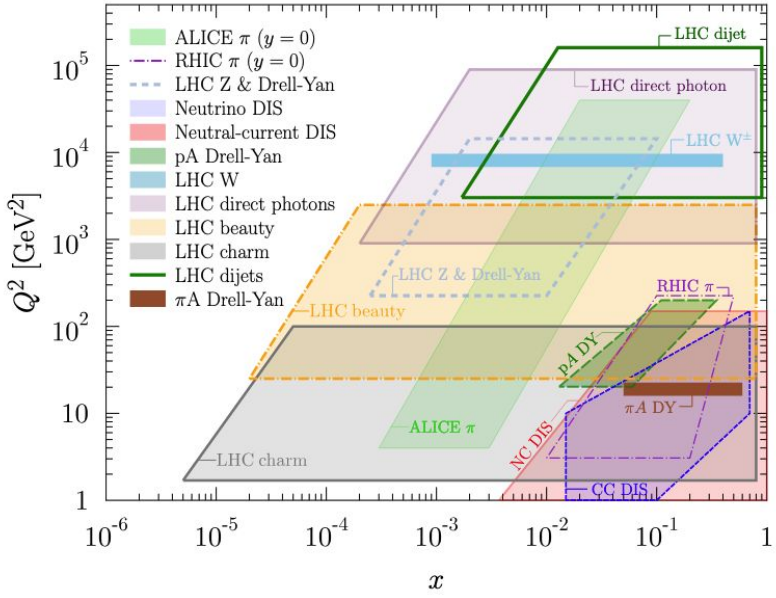
Hadron collider data

Large kinematic reach

Complementary sensitivity to different partons w.r.t. DIS

Nuclear PDFs: no HERA

RHIC/LHC 'backbone' at intermediate/low-x



https://www.annualreviews.org/content/journals/10.1146/annurev-nucl-102122-022747 Klasen & Paukkunen

Hard processes in inclusive hadronic collisions

Hadron collider data

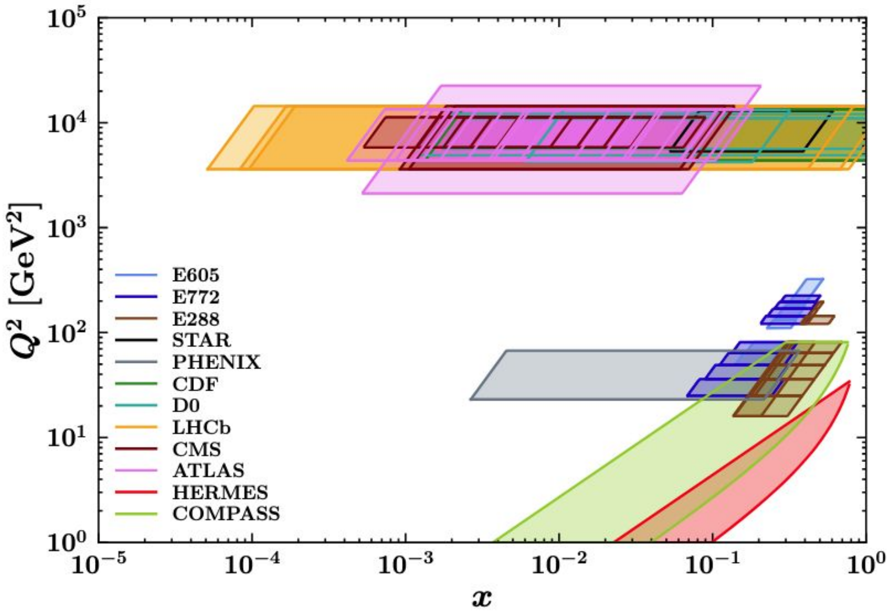
Large kinematic reach

Complementary sensitivity to

ifferent partons w.r.t. DIS

Proton TMD:

Z/ɣ Drell-Yan backbone with fixed-target Drell-Yan + SIDIS



Example MAP-publication: 10.1007/JHEP10(2022)127

About 250 out of about 2000 data points from collider DY

Why photoproduction at a hadron collider?

What might think at first sight:

detectors not focused on this topic

too rare for precision

too ‘dirty’ environment

Partially wrong: depends on detector, collision system, specific observable

Photoproduction at the LHC important for hadron structure

UPC interesting for other reasons: QED phenomena, Beyond the standard model searches, interference

Why photoproduction at a hadron collider?

Proton structure

For PDF/TMD-LHC-standards low scales: lower x -> complement HERA & High-mass/p_T data

Going exclusive: Generalized Parton Distributions access

Why not sticking to hadroproduction?

'**Theoretically clean**' photon/Drell-Yan hadroproduction at low scales suffer from **large backgrounds**

Not yet measured in most extreme kinematics

'**Experimentally clean'** charm/beauty hadroproduction plagued by **theoretical caveats**

higher-twist effects, hadronisation universality violation: typically not used in global proton fits proton, used in nuclear case nonetheless, see discussion in Apolinario et al. https://arxiv.org/abs/2203.16352 PPNP 103990 (2022)

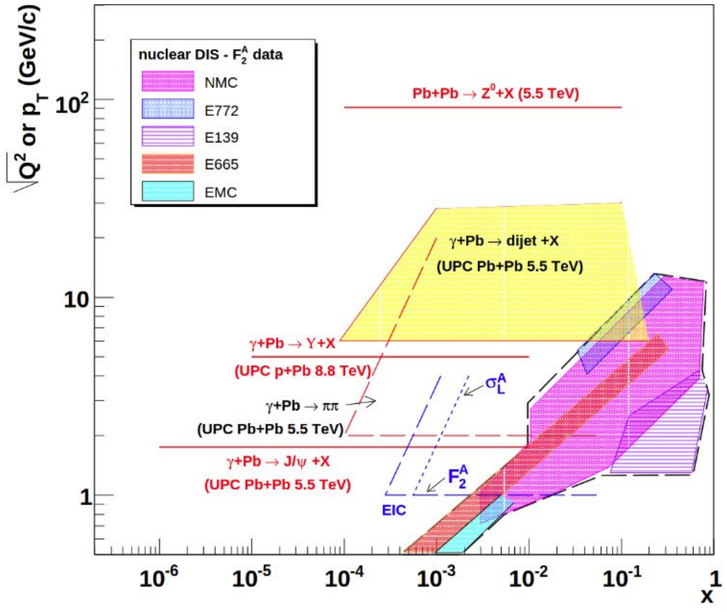
Hence: LHC photoproduction central for low-x frontier beyond EIC-reach

Why photoproduction at a hadron collider?

Nuclear structure

same reasons as for proton

+ there is no HERA!



Baltz et al. Phys.Rept.458:1-171,2008.

There is no luminosity for precision at

High-mass in hadroproduction

as in proton-case at the LHC

Hence: LHC photoproduction central for low-x frontier beyond EIC reach

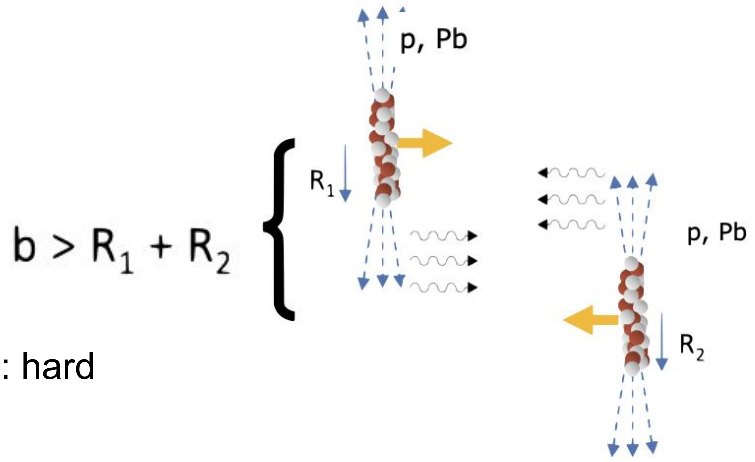
Photon-induced reactions at hadron colliders

UPC: ultra-peripheral collisions

Large impact parameter ($b>R_1+R_2$)

See discussion on overlap in Harlang-Lang et al.

https://arxiv.org/pdf/1810.06567v3



Induced by photons with small virtuality (tens of MeV^2): hard scale for pQCD must be provided by final state mass/transverse momentum

Photon flux intensity $\propto Z^2$

pPb & PbPb collisions at the LHC: probability of hadronic pile-up < 10 %,

very clean environment with sizeable effective gamma-hadron luminosities

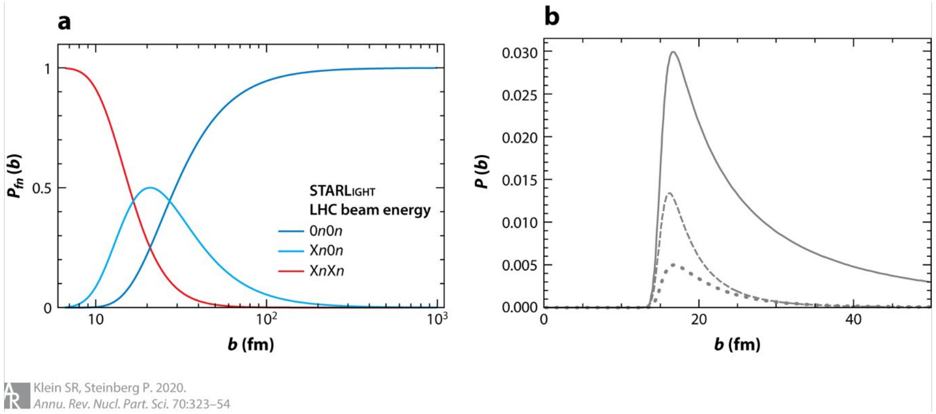
Photon-induced reactions at hadron colliders

UPC: ultra-peripheral collisions

Nuclear collisions: Z*α ≅ 0.6 large probability of nuclear excitation by additional photon

- **Neutron emission**

Can be used to 'dial in' impact



impact parameter dependence of Probabilities for different neutron emissions

taken from Starlight generator

Impact parameter dependence of Probabilities for different neutron emissions for coherent ρ production

taken from Starlight generator

Exemplary UPC measurements

Three types of measurements exemplified with recent examples

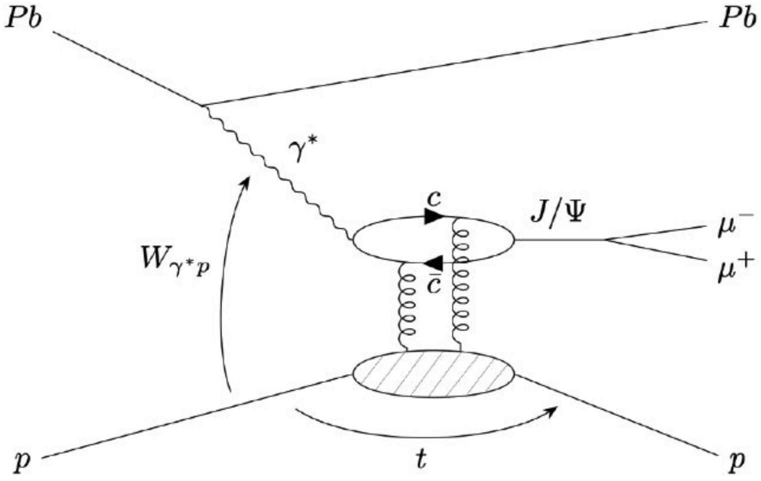
Energy dependence of coherent J/ψ production in ɣ-Pb collisions & t-dependence

Exclusive and dissociative J/ψ production in ɣ-p collisions

Inclusive photoproduction of dijets

First international UPC conference 2023:
https://indico.cern.ch/event/1263865
2nd edition in Finland June 2025:
https://inspirehep.net/conferences/2804738

From UPC to γ-hadron cross section



Incoming hadron energy known, hadron-hadron luminosity measured

Photon fluxes: QED calculation & nuclear form factors

Quantify ɣ-hadron process: determine W and Mandelstam-t

First t-dependent ɣ-Pb J/psi measurements in UPC

$W^2 = 2\, E_p\, M_{jpsi}\, \exp(\pm y_{jpsi})$, $t \cong -\, p_{T,jpsi}^2$

- A priori unknown photon emitter: two contributions $\pm y_{jpsi}$

γ-lead: W-dependence via impact-parameter dependent photon fluxes

$$\frac{d\sigma_{PbPb}}{dy} = n_\gamma(y,\{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\})\sigma_{\gamma Pb}(-y)$$

Several independent measurements with different samples impact parameters b

Capacity to calculate photon flux corresponding to event classes

System of equations to extract $\sigma_{\gamma Pb}$ from dσ/dy

γ-lead: W-dependence via impact-parameter dependent photon fluxes

Two approaches

Measure in neutron emission classes via zero degree calorimeters

Baltz et al. PRL 89 (2002) 012301, Guzey et al. EPJC 74 (2014) 2492

Measure in peripheral and ultraperipheral collisions

J.G. Contreras PRC 96 (2017) 015203

1st method: Modeling of photon fluxes associated to neutron emission

Done with nOO model in ALICE, CMS with Starlight

See discussion and reference in ALICE publication for differences JHEP10 (2023) 119

2nd method: Neglect difference (or model difference in future) in peripheral collisions

Take impact parameter from centrality determination in hadronic collisions

γ-lead: W-dependence results compilation

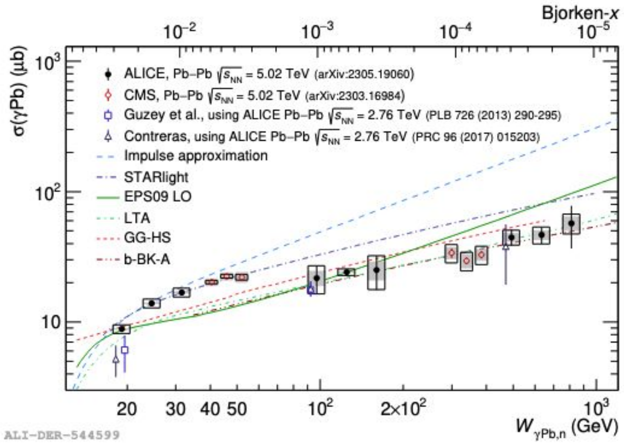


Figure from ALICE JHEP 10 (2023) 119 including CMS data arXiv:2303.16984(accepted by PRL)

Both methods agree, compatibility between experiments

Strong nuclear suppression based on impulse approximation (IA) comparison

Consistent with findings based on inclusive heavy-quark pPb data

Model spread much larger than experimental uncertainties

No model cursive describes all measurement points

No GPD-based calculation on nuclear targets yet available

γ-lead: nuclear suppression factor

$$S = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma^{IA}_{\gamma Pb}}}$$

$$\sigma^{IA}_{\gamma Pb} = \frac{d\sigma}{dy}_{\gamma p \to J/\psi p}(t=0) \cdot \int_{|t_{min}|}^{\infty} dt |F_A(t)|^2$$

introduced by Guzey et al. EPJC 74 (2014) 2942

ALICE and CMS use calculation from Guzey et al.

5% uncertainty assumed by authors based on parameterisation/experimental inputs of

Assuming: gluon dominance, cross section proportional to gluon-PDF^2

Measure of gluon PDF suppression in nucleus

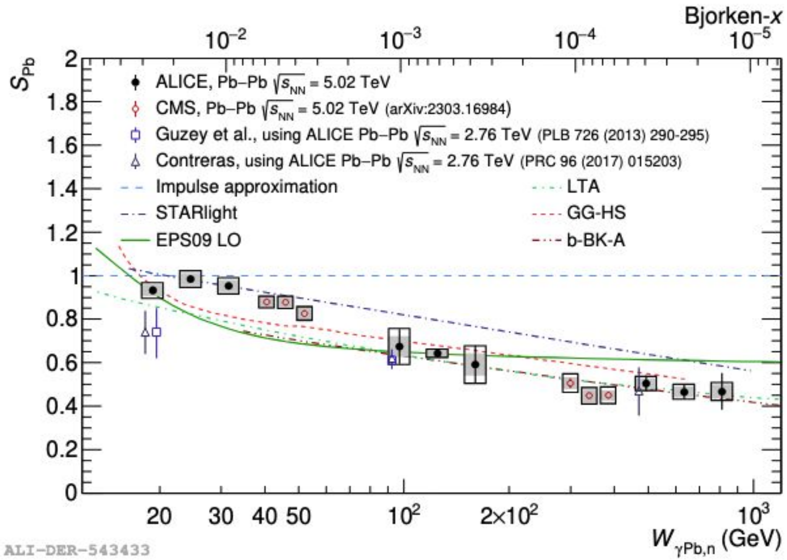
- Analogue to inclusive observables RpPb = $\sigma_{pPb}/(208\ \sigma_{pp})$

Personal remark:

Preference to take experimental ɣ-p and not its parameterisation

- separation of theory & experiment when going to fit

γ-lead: W-dependence of nuclear suppression factor



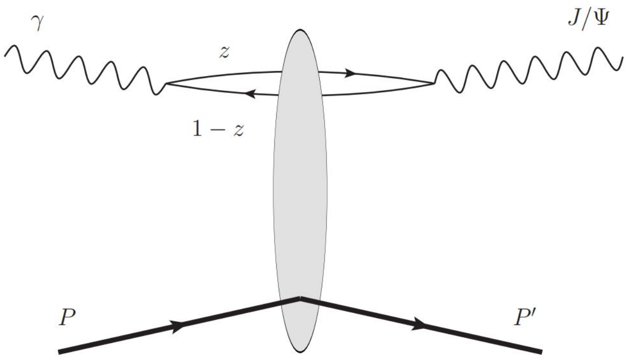
Strong nuclear suppression

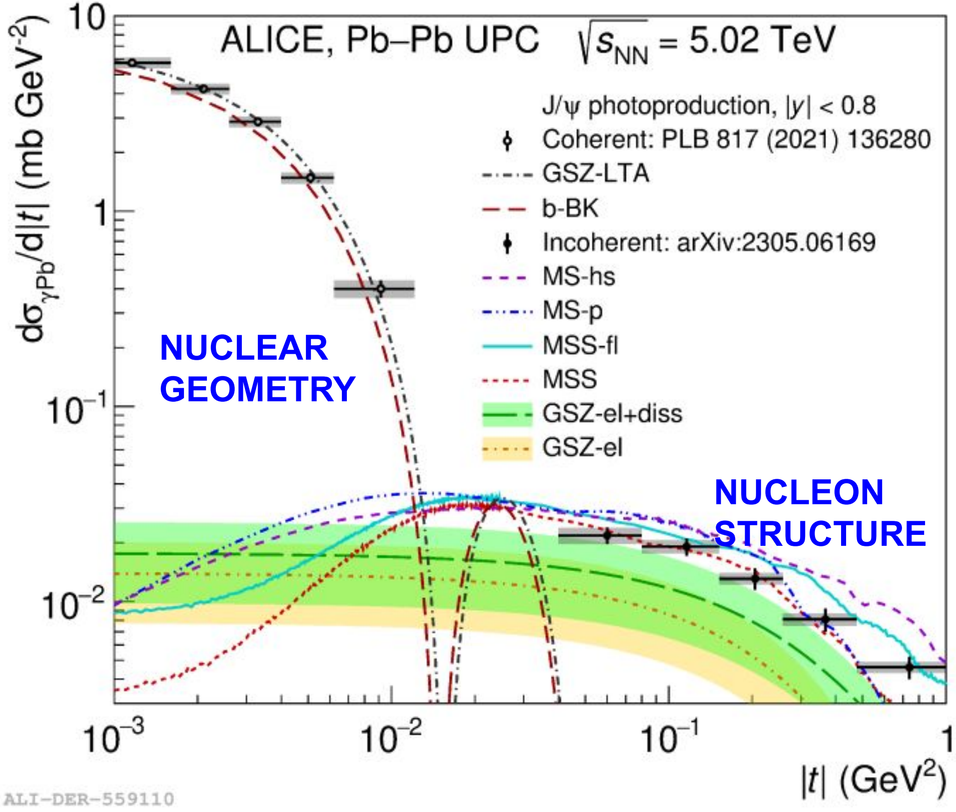
Major finding of the LHC QCD programme !

Confirmation of finding with inclusive observables, see back-up

No discrimination: saturation vs. collinear factorization-based calculations

t-dependent coherent and incoherent data from ALICE





Inferring parameters for ^{208}Pb and nucleon shape/fluctuations within nucleus

Incoherent data: https://arxiv.org/abs/2305.06169, coherent https://arxiv.org/abs/2101.04623

γ-proton collisions: Extract W-dependence using pp & HERA cross sections

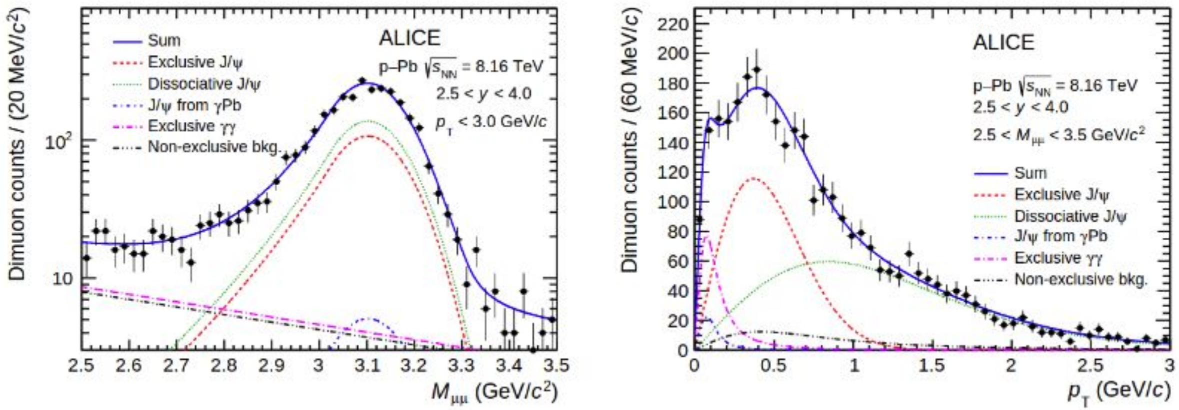
- measure at midrapidity, where it does not matter (not done)
  $\rightarrow$ limited to 1 W-point per centre-of-mass energy

- LHCb: deconvolute assuming power-law dependence for low-W component based on HERA measurements: $\sigma_{\gamma p \rightarrow \psi p} = a(W/90\mathrm{GeV})^{\delta}$
  $\rightarrow$ LHCb dimuon forward rapidity in pp at $\sqrt{s}_{pp} = 7, 13$ TeV
  $\rightarrow$ profit from large luminosity at still relatively low pile-up μ about 1
  W-range for J/ψ up to almost 2 TeV

$$\sigma_{pp \rightarrow p\psi p} = r(W^{+})k_{+}\frac{dn}{dk_{+}}\sigma_{\gamma p \rightarrow \psi p}(W_{+}) + r(W^{-})k_{-}\frac{dn}{dk_{-}}\sigma_{\gamma p \rightarrow \psi p}(W_{-})$$

$k_{\pm} = M_{\psi}/2e^{\pm y}$ r: survial factor (taken from calculation), $\frac{dn}{dk}$: photon flux, see JHEP 10 (2018) 167 J/ψ 13 TeV: LHCb-PAPER-2018-011, JHEP 10 (2018) 167; Υ 7,8 TeV: JHEP 1509 (2015) 084, LHCb-PAPER-2015-011; J/ψ/ψ(2S) 7 TeV: J. Phys. G41 (2014) 055002, LHCb-PAPER-2013-059; J/ψ/ψ(2S) 7 TeV: J. Phys. G40 (2013) 045001, LHCb-PAPER-2012-044

γ-proton collisions: extract W-dependence using pPb

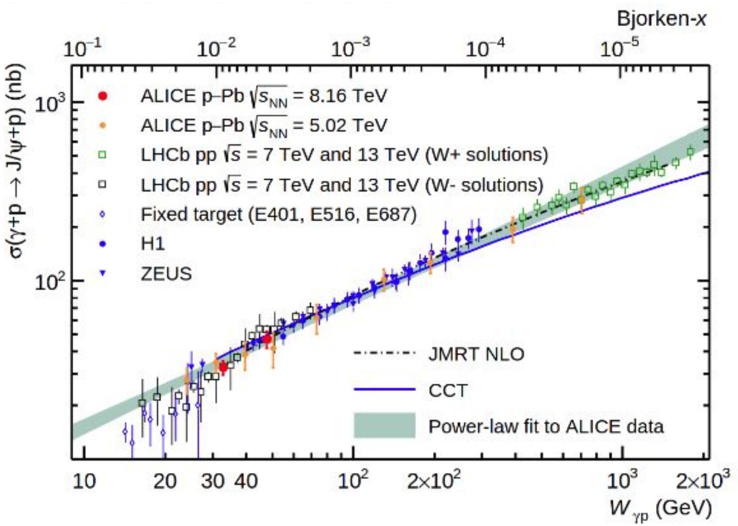


arXiv:2304.12403, accepted by PRD

- pPb collider: Pb in 95% of the cases photon emitter
- typical t of γ-p and γ-Pb very different due to different digluon p_T
  → ´subtract´ γ-Pb
  → ALICE measurements for J/ψ at $\sqrt{s_{NN}} = 5, 8.16$ TeV
  → cover broad W-range from 20 up to 700 GeV

J/ψ 8.16 TeV (fwd rapidity): arXiv:2304.12403(accepted by PRD), J/ψ 5 TeV with both tracks barrel and barrel muon+ forward muon pair: EPJC (2019) 79: 402 J/ψ 5 TeV (fwd rapidity): PRL 113 (2014) 232504, CMS ϒ at 5 TeV: EPJC 79 (2019) 277; Erratum: EPJC 82 (2022) 343

Results on exclusive production



compilation from arXiv:2304.12403 Phys. Rev. D 108 (2023) 112004

- good agreement between experiments within uncertainties
- need precise high-W from pPb: confirm LHCb high-energy solution
- strong sensitivity to constrain gluons at low-x
  → first steps towards PDF-fit-inclusion
  e.g. sensitivity proton Flett et al.PRD 102 (2020) 114021, NLO calc. for Pb Eskola et al. PRC 106 (2022)
- however exclusive process: generalized parton distributions, not PDFs
  → develop theory uncertainty for ´PDF´-extraction Dutrieux et al. PRD 107 (2023)

New developments on low-x resummation with GPDs taming scale dependence encouraging https://arxiv.org/abs/2409.05738

Motivation for dissociative production: fluctuations

incoming ($|i\rangle$) and outgoing state ($|f\rangle$) different

$$use: \sum_{f\neq i} |\langle f|A|i\rangle|^2 = \sum_f \langle i|A^*|f\rangle\langle f|A|i\rangle - \langle i|A|i\rangle\langle i|A^*|i\rangle$$

$$= \langle i|A^*A|i\rangle - |\langle i|A|i\rangle|^2$$

average over i :

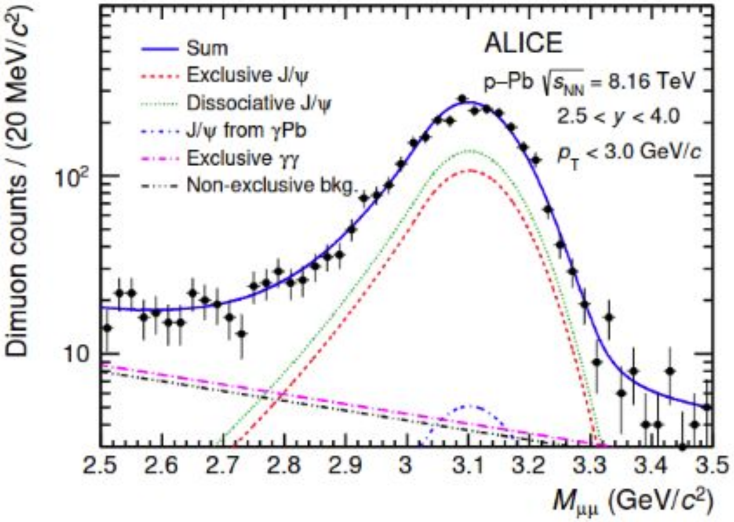
$$\frac{d\sigma^{\gamma^* p\to p^*\, J/\psi}}{dt} = \frac{1}{16\pi}\left(\langle|\mathcal{A}^{\gamma^* p\to pJ/\psi}|^2\rangle - |\langle\mathcal{A}^{\gamma^* p\to pJ/\psi}\rangle|^2\right)$$

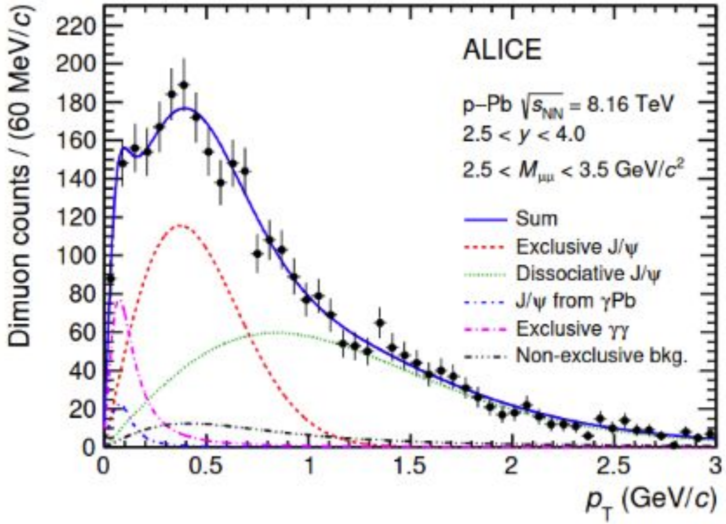
p: proton (also valid for nuclei), p^* proton excited, J/ψ could be any vector, recent review in H. Mäntisaary Rep. Prog. Phys. 83 (2020), ´Good-Walker´ formalism, also in Frankfurt, Strikman, Treleani, WeissPRL 101 (2008) 202003.

$\rightarrow$ dissociative (´incoherent´): variance $< x^2 > - < x >^2$, not average $< x >^2$

- γp: dissociative production $\rightarrow$ fluctuations of the proton
- HERA data does not reach full kinematics accessible at the LHC due to higher energies
  $\rightarrow$ measure at the LHC!

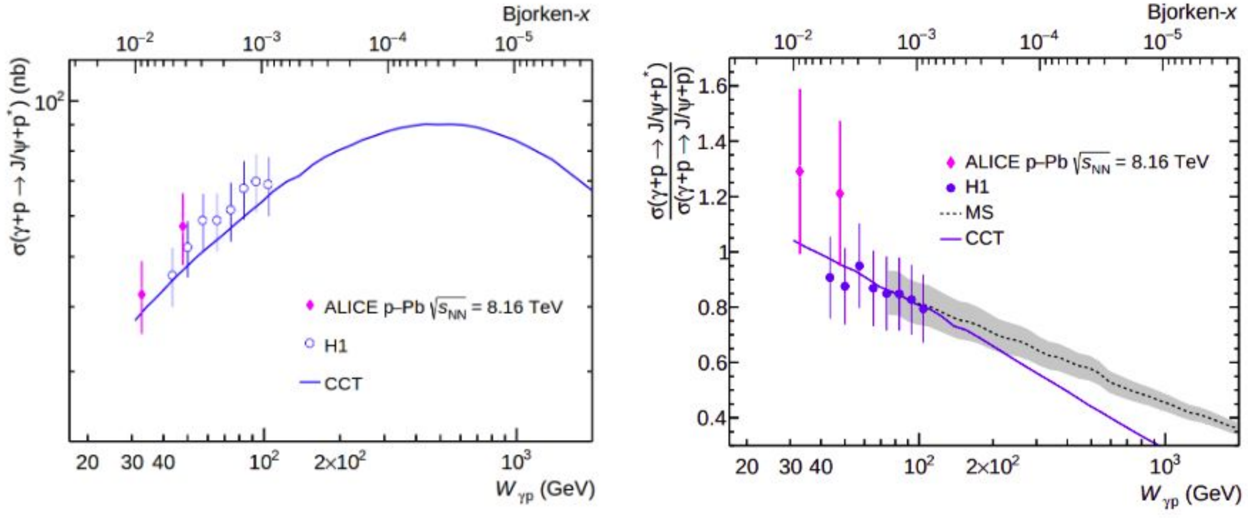
Analysis key aspect: signal extraction





- Exclusive: shape fixed with pure exclusive sample
- Dissociative J/ψ parameterisation following H1
- γ-Pb production fixed from PbPb measurement

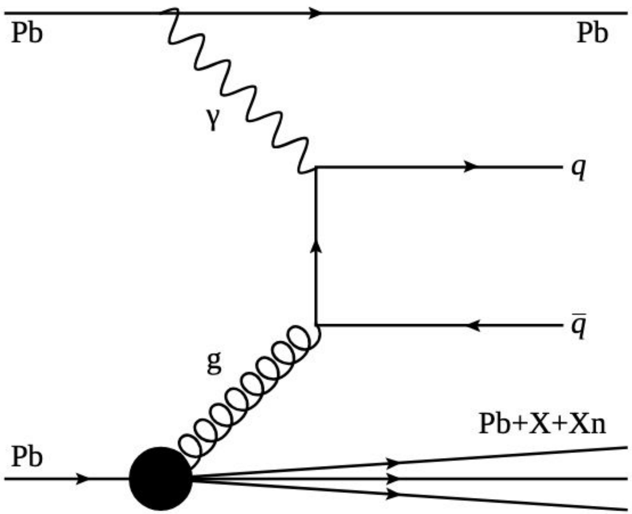
Results on dissociative production



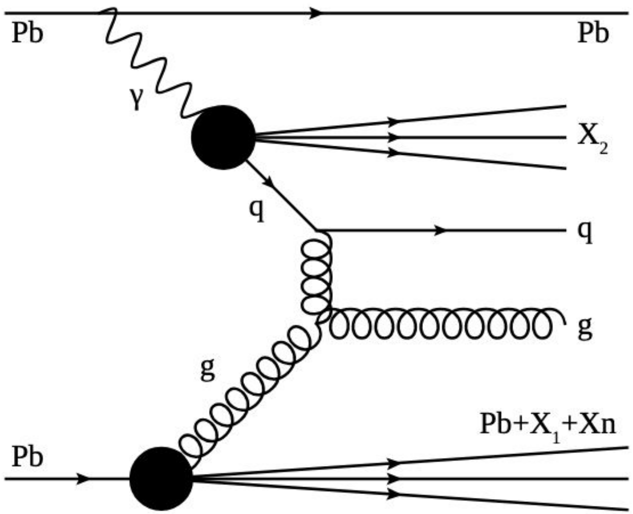
arXiv:2304.12403, Phys. Rev. D 108 (2023) 112004

- measurement compatible with H1 results, similar precision for absolute cross section
- larger uncertainty on ratio
  anticorrelation of statistical and signal extraction uncertainties
  $\to$ **proof-of-principle**
- in future: cover full available kinematics at the LHC!

γ-lead inclusive dijets



direct



resolved

First cross section measurement in inclusive photoproduction in UPC

https://arxiv.org/abs/2409.05738

Feasibility demonstration of quarkonium production

https://arxiv.org/abs/2409.01756

γ-lead Inclusive dijets: kinematic variables

$$H_{\mathrm{T}} \equiv \sum_i p_{\mathrm{T}\,i}$$

$$z_\gamma \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{+y_{\mathrm{jets}}}$$

$$x_{\mathrm{A}} \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_{\mathrm{jets}}}$$

$$m_{\mathrm{jets}} \equiv \left[\left(\sum_i E_i \right)^2 - \left| \sum_i \vec{p}_i \right|^2 \right]^{1/2}$$

$$y_{\mathrm{jets}} \equiv \frac{1}{2} \ln \left(\frac{\sum_i E_i + \sum_i p^*_{z\,i}}{\sum_i E_i - \sum_i p^*_{z\,i}} \right).$$

no photon-emitter ambiguity resolved by hadronic activity from break-up of target

‘Full’ reconstruction of kinematics

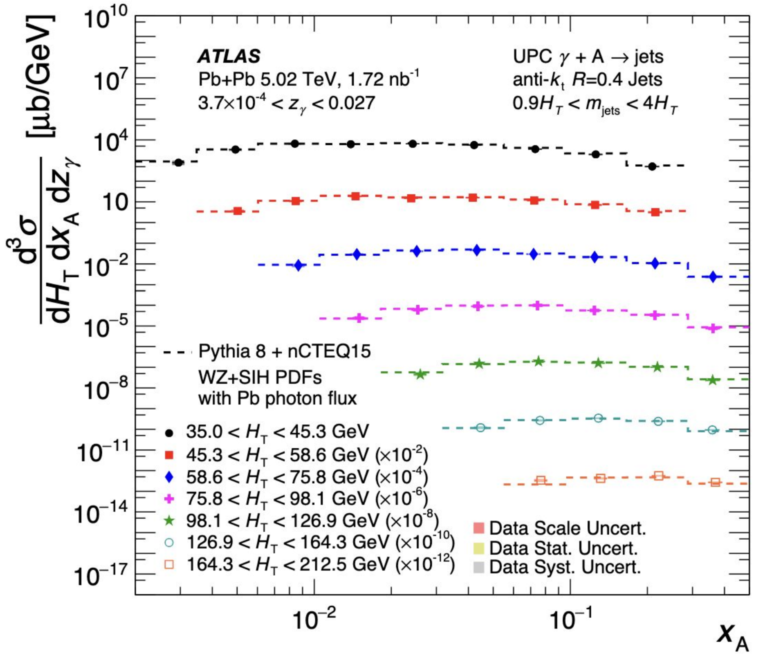
γ-lead inclusive dijets

Large kinematic domain covered thanks to decent statistical precision

Based on full 2015+2018 PbPb data set

Clean environment allows to access low jet-transverse momentum

- Large adaptation effort to go from hadro to photoproduction



https://arxiv.org/pdf/2409.11060

ATLAS measurement on inclusive dijets

sizeable spread of nuclear PDFs predictions

point-to-point uncertainty larger than typical nPDF uncertainty (10%)

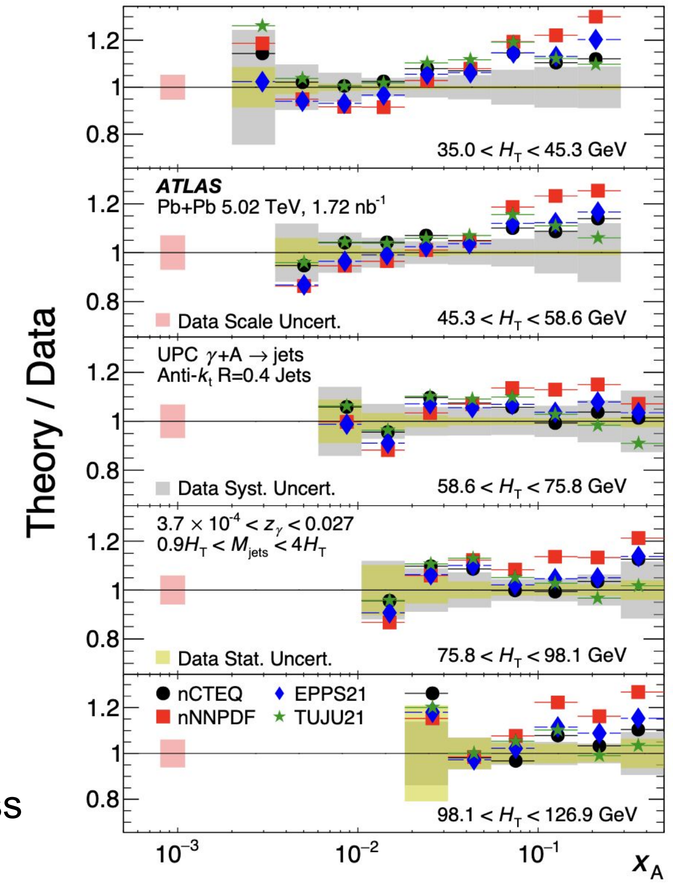
However: nPDF more assumptions than proton-case: nuclear mass-dependence, hadroproduction caveats mentioned earlier

A first measurement - starting point

include in nuclear PDF fits

other measurements based on jets in inclusive photoproduction:

N.B.: Most constraining dijet measurement in pPb hadro production double-ratio, not a cross section



Conclusions

UPC as close as you can get to a DIS experiment at a hadron collider
A large number of 'exclusive' & first inclusive photoproduction measurements

- much more feasible
- luminosity to be increased by a factor 10 & more in future

Interest for hadron structure:

- Wider kinematics than past and future DIS
  - lowest x reach
  - nuclear targets

GPDs not yet used for exclusive charmonium data

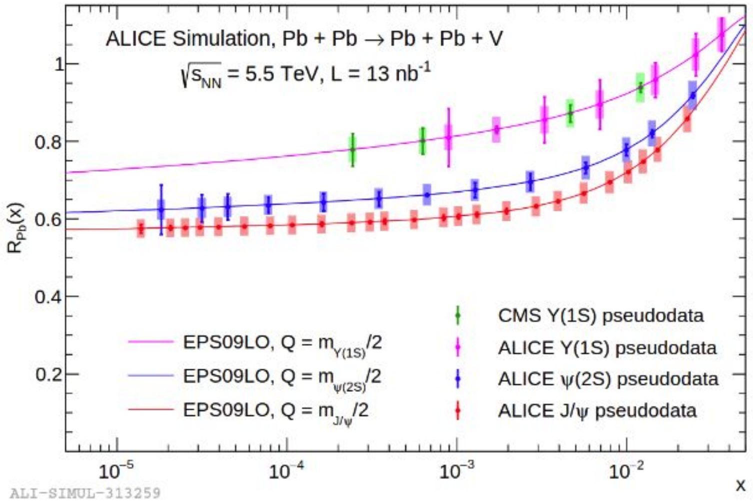
Recent theory progress:

GPD-PDF connection, impact of non-zero skewness at low-x: https://arxiv.org/pdf/2302.07861
Resummation to reduce scale uncertainties: https://arxiv.org/pdf/2409.05738

Full potential far from being exploited : unclear how far one can go

LHC data:
empower & anticipate quests in EIC program

Outlook



HL-LHC Yellow Report WG5, arXiv:1812.06772

- proven that this type of measurement used for Run 3 projection already feasible with Run 2 data
- ...and that we can go beyond
  → t-dependence, incoherent measurements
- the future is full of opportunities!

Taken from:
https://indico.cern.ch/event/1263865/contributions/5586082/attachments/2769169/4825401/UPC_2023_2.pdf

BACKUP

γ-lead: W-dependence time-line

- 2013:
  first midrapidity data by ALICE EPJC 73 (2012) used in Guzey et al. with ALICE fwd rapidity data using only dominant contribution PLB 718 (2013)

- 2016:
  first extraction with peripheral and ultraperipheral collisions by J.C. Contreras with ALICE data forward rapidity data PRC 96 (2017)
  $\rightarrow$ see talk by Nicolas Bizé for more precise recent final and preliminary results at 5 TeV

- 2023:
  first publications by ALICE and CMS based on neutron emission classes

Nuclear suppression of gluons at low-x: UPC quarkonia data vs. inclusive heavy-quark pPb

- Charm/beauty inclusive pPb data already included in nuclear PDF fits since directly sensitive to PDFs
- constraining power of LHCb forward results

  see e.g. in EPP21 EPJC 82 (2022) 5, 413 and nNNPDF3.0 EPJC 82 (2022) 6, 507

  → uncertainties related to hadronisation difference pp vs. pPb & possible presence of coherent energy loss
- UPC coherent quarkonium production data:

  → uncertainties related to transfer from GPD to PDF, see Vadim Guzey´s talk at HP23 for references link

Both type of data suffer from large scale uncertainties
→ future observables: reduce/remove part of the theory uncertainties

Analysis strategy for dissociative production

- standard selection and methods for muon analyses in ALICE and UPC

- specifically here:
  $\rightarrow$ exclusive selection to fix exclusive contribution shape
  $\rightarrow$ more open selection including dissociative and exclusive to do fit
  $\rightarrow$ 2-D loglikelihood fit of mass and p_T to extract signals

- analysis of $\gamma\gamma \rightarrow \mu^+\mu^-$ as test of QED part & photon fluxes as bonus, ingredient for time-like-compton scattering feasibility

Scale uncertainties in NLO FC with DLA HEF

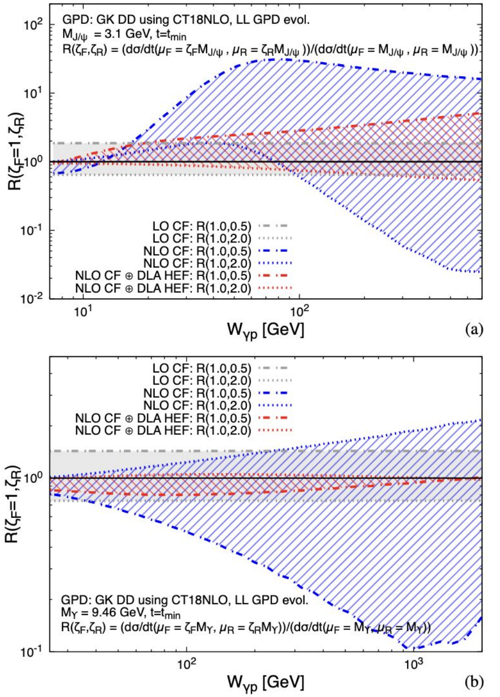


Figure 4: μ_R scale uncertainty of the LO CF, NLO CF and NLO CF $\oplus$ DLA HEF (a) J/ψ and (b) Υ t-differential cross sections.

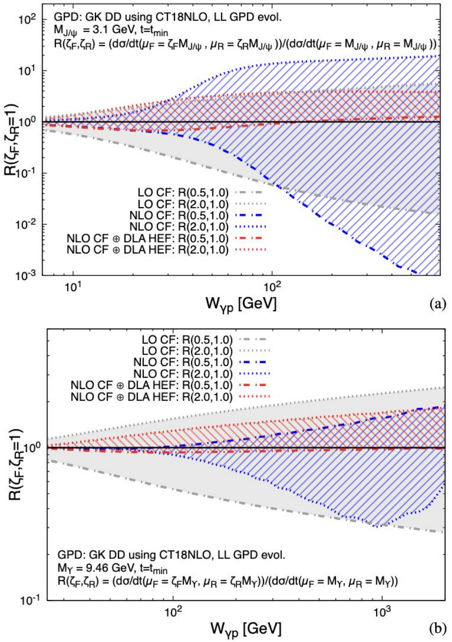


Figure 2: μ_F scale uncertainty of the LO CF, NLO CF and NLO CF $\oplus$ DLA HEF (a) J/ψ and (b) Υ t-differential cross sections at $t_{\min}$.

Taken from: https://arxiv.org/pdf/2409.05738