Energy dependence of J/ψ production in ultra-peripheral collisions at the LHC

Michael Winn

Department of Nuclear Physics IRFU/CEA, university Paris-Saclay

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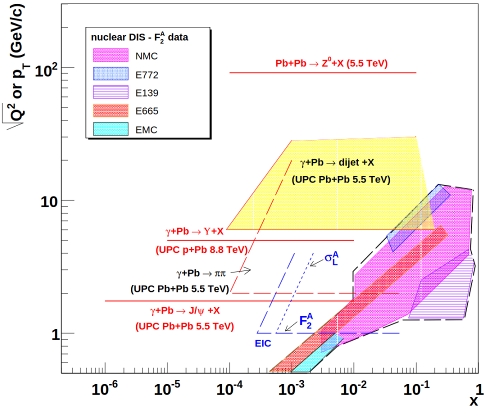
Outline

- Motivation & experimental set-ups
- γ-proton methods and measurements
- γ-Pb methods and measurements
- Conclusions and outlook

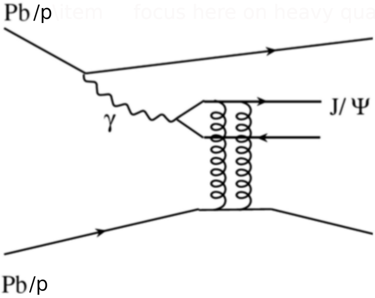
Motivation



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

- UPC at the LHC:
  → use hadron collider as photon-hadron collider
- low-x/high-W:
  → kinematics beyond the reach of past & future lepton-hadron colliders

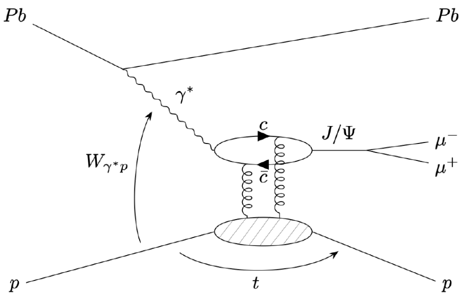
Motivation: coherent quarkonium production in UPC



- ultra-peripheral collisions:
  instrumentation and rate limitations, restriction to photo-production

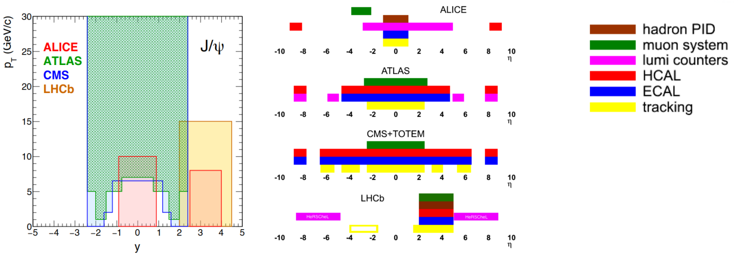
- quarkonium coherent photoproduction:
  most prominent accessible observables with hard scale provided by heavy quark mass
  $\rightarrow$ amenable to perturbative QCD calculations

From UPC to γ-hadron cross section



- incoming hadron energy known, hadron-hadron luminosity measured
- photon fluxes: QED calculation & nuclear form factors
- quantify γ-hadron process: determine W and Mandelstam-t
  $\rightarrow$ first t-dependent γPb J/ψ measurements in talk by David Grund
  $\rightarrow W^2 = 2 \cdot E_p M_{jpsi} exp^{\pm y_{jpsi}}$, $t \approx -p^2_{T,J/\psi}$
- a priori unknown photon emitter: two contributions $\pm y$
  $\rightarrow$ topic of this talk

Experimental set-ups



Acceptance of *pp* inclusive charmonium measurements by T. Dahms link.

- bulk of coherent/incoherent J/ψ photoproduction: $p_{T,jpsi} << m_{jpsi}$
  $\rightarrow$ complementary acceptance of LHC experiments
- different forward instrumentation, luminosities, triggers and resolution
- ALICE, CMS and LHCb:
  $\rightarrow$ important contributions to quarkonium measurements in UPC
  $\rightarrow$ partial redundancy to check for consistency

γ-proton collisions

γ-proton collisions: extract W-dependence using *pp* & HERA

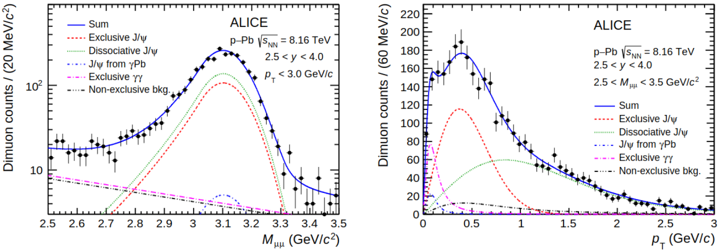
- measure at midrapidity, where it does not matter (not done)
  $\rightarrow$ limited to 1 W-point per centre-of-mass energy

- LHCb: deconvolute assuming power-law dependence for low-W component based on HERA measurements: $\sigma_{\gamma p \rightarrow \psi p} = a(W/90\text{GeV})^{\delta}$
  $\rightarrow$ 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

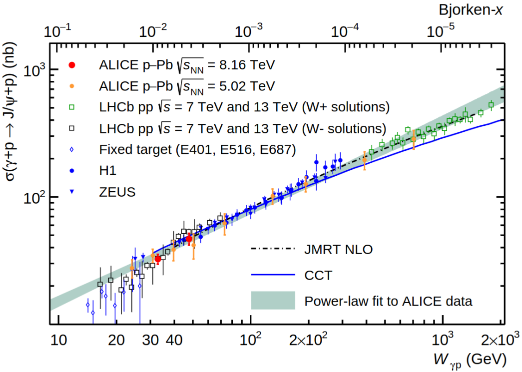


arXiv:2304.12403, accepted by PRD

- 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
  $\rightarrow$ ´subtract´ γ-Pb
  $\rightarrow$ ALICE measurements for J/ψ at $\sqrt{s}_{NN} = 5, 8.16$ TeV
  $\rightarrow$ 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, accepted by PRD

- 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)

Motivation for dissociative production: measure 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 :

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

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.

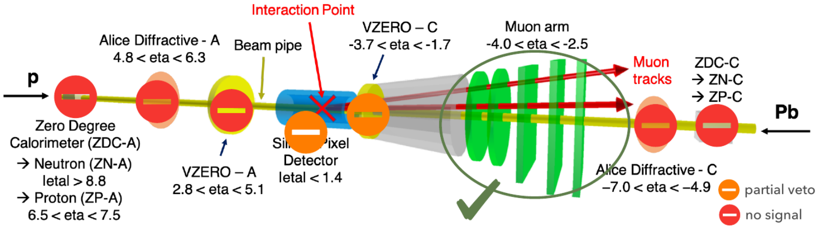
$\rightarrow$ dissociative (´incoherent´): variance $< x^2 > - < x >^2$, not average $< x >^2$

- 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 strategy for dissociative production

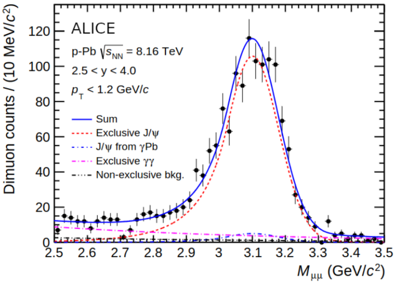
- standard selection and methods for muon analyses in ALICE and UPC
- specifically here:
  $\rightarrow$ exclusive selection to fix exclusive contribution shape
  $\rightarrow$ more open selection including dissociative and exclusive to do fit
  $\rightarrow$ 2-D loglikelihood fit of mass and p_T to 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

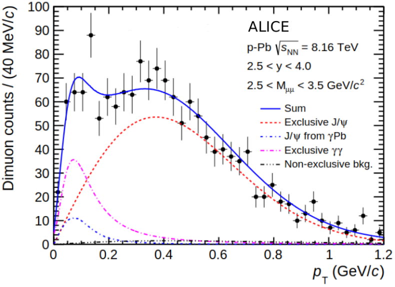
Dissociative production: exclusive selection vetos



- selection used to derive p_T distribution of exclusive production
- also used as cross check

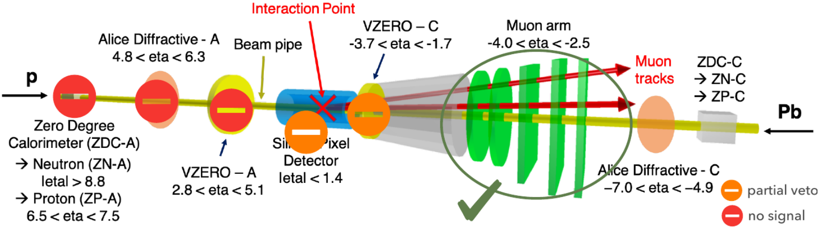
Dissociative production: exclusive selection





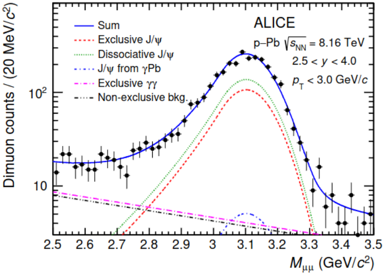
- tight selection used for exclusive shape determination

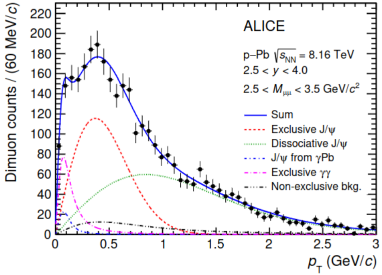
Dissociative production: Open selection



- selection used for cross section determination
- verified via RapGap simulation that V0C vetoes do not introduce inefficiency for dissociative process
- largest systematic uncertainties for dissociative:
  V0C veto & exclusive shape

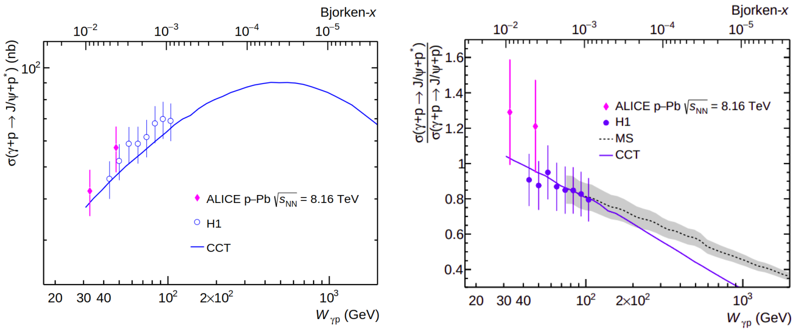
Analysis key aspect: signal extraction





- 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, accepted by PRD

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

γ-lead collisions

γ-lead:
extract W-dependence directly

Direct approaches:

- measure at midrapidity, where W the same for both emitters
  $\rightarrow$ ALICE measurements at 2.76 TeV and 5 TeV
- measure in pPb collisions, where only one lead
  $\rightarrow$ need to isolate w.r.t. dominating γ-p, not done so far

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

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

If:

- several independent measurements with different sampled impact parameters b
- capacity to calculate $n_{\gamma}(y, \{b\})$ precisely

$\rightarrow$ system of equations to extract $\sigma_{\gamma Pb}$ from $d\sigma/dy$

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

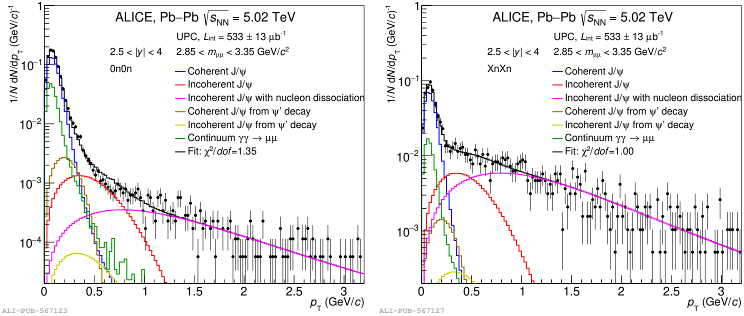
Two approaches realised:

- measure in neutron emission classes via zero degree calorimeters
  $\rightarrow$ proposed by Baltz et al. PRL 89 (2002) 012301 and by Guzey et al. EPJC 74 (2014) 2942
- measure in peripheral and ultraperipheral collisions
  $\rightarrow$ proposed by J. G. Contreras PRC 96 (2017) 015203

1st method:
modeling of photon fluxes associated to neutron emission
$\rightarrow$ done with $n_0^0 n$ model in ALICE, CMS with Starlight
see discussion and reference in ALICE publication for differences JHEP 10 (2023) 119, relevant difference for most forward bins

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 signal extraction for different classes



JHEP 10 (2023) 119

- signal extraction at forward rapidity in 0n0n:
  $\rightarrow$ no neutron detected in both fragmentation regions
- signal extraction at forward rapidity in XnXn:
  $\rightarrow$ at least 1 neutron detected on both sides
- measurements need to be corrected for efficiency and migration between neutron emission classes

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

γ-lead: W-dependence results compilation

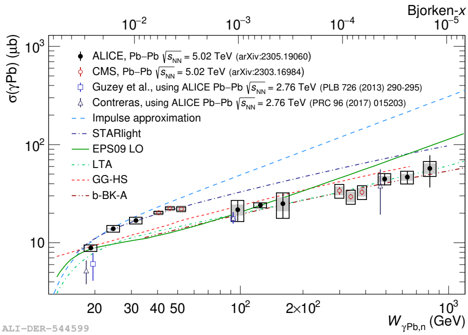


Figure from ALICE JHEP 10 (2023) 119 including CMS data arXiv:2303.16984(accepted by PRL)

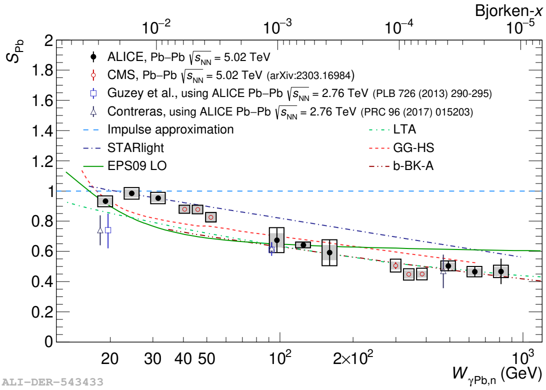
- both methods agree, compatibility between experiments
- strong nuclear suppression based on impulse approximation (IA) comparison
  $\rightarrow$ consistent with findings based on inclusive heavy-quark *pPb* data
- model spread much larger than experimental uncertainties
  no model curve describes all measurement points

γ-lead: nuclear suppression factor

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

- observable to quantify nuclear effects 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
  $\sigma^{IA}_{\gamma Pb} = \frac{d\sigma}{dy}_{\gamma p \to J/\psi p}(t=0) \cdot \int_{|t_{min}|}^{\infty} dt |F_A(t)|^2$
- assuming: gluon dominance, cross section proportional to gluon-PDF^2
  $\rightarrow$ measure of gluon PDF suppression in nucleus
- analogue to inclusive observables $R_{pPb} = \sigma_{pPb}/(208 \cdot \sigma_{pp})$
- personal remark:
  preference to take experimental γ-p and not its parameterisation
  $\rightarrow$ better separation of theory & experiment when going to fit things

γ-lead: W-dependence of nuclear suppression factor



- strong nuclear suppression:
  major finding of the LHC QCD programme!
- no discrimination: saturation vs. collinear factorisation-based

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

Summary

- LHC data allows to deconvolute experimentally W-dependence of quarkonium production: demonstrated with J/ψ
- LHC results from 3 experiments
  $\rightarrow$ partial redundancy, different methods and overlap with HERA
  $\rightarrow$ emergence of an overall coherent picture

- comprehensive set of γp and γPb measurements for J/ψ
- γ-p W-data far beyond HERA:
  $\rightarrow$ constraining gluons in the proton at low-x
- strong nuclear suppression in γ-Pb collisions:
  $\rightarrow$ consistent with inclusive charm and beauty pPb data
  $\rightarrow$ **strong nuclear suppression of gluons**
- collinear factorisation & saturation-based calculations compatible with data
  $\rightarrow$ nuclear: all data points not described by any model

Outlook

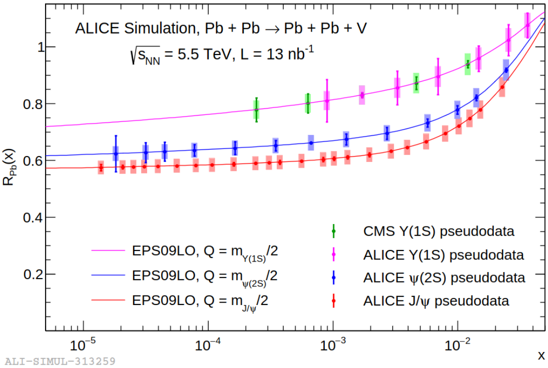
Feasible missing pieces with existing and/or Run 3 data:

- W-dependence of incoherent production
  $\rightarrow$ one data point only in γ-p and one in γ-Pb so far
- t-dependent measurements for different W (coherent/incoherent)
  $\rightarrow$ done for γ-Pb measurement at midrapidity, see talk by D. Grund
- Measurement of cross section for different mass quarkonium states
  $\rightarrow$ first measurements available, often statistically limited

Open, but worthwhile challenges:

- inclusive $q\bar{q}$ photoproduction, K. Lynch at Orsay workshop ´23 link
- how far in t can we go in γ- and γ-Pb at the LHC with high statistics data with current and future instrumentation and better modeling?

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!