Measurement of diffractive dissociative J/ψ production at ALICE

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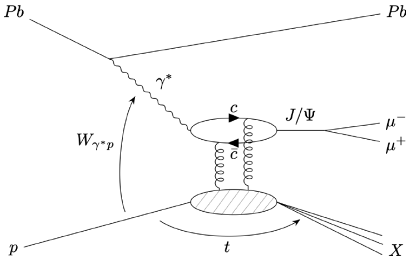
Outline

- Motivation
- pPb analysis: proof-of-principle for proton dissociation at the LHC
  arxiv:2304.12403, submitted to PRD
  thesis by A. Glaenzer for details link
- Discussion of limitations
- Perspectives, conclusions and questions

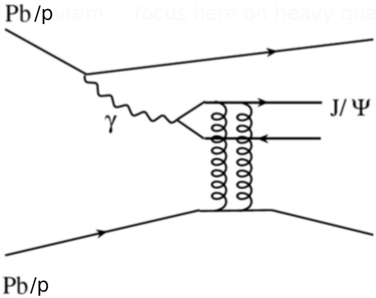
Motivation



- background for exclusive vector-meson production at the LHC measured by ALICE, CMS, LHCb, see presentation by Ronan
- similar size of exclusive and dissociative cross section at HERA, see e.g. H1 EPJC 73 (2013) 6, 2466
- Why should we be interested in dissociation?

Focus on heavy quarkonium: hard scale via produced mass; focus on $\gamma(^*)p$, also results on γ^*Pb$\rightarrow J/\psi X$

Ronan´s talk: exclusive vector meson production in ultra-peripheral collisions



- sensitive to generalised gluon distributions (GPD) for $x \in 10^{-2} - 10^{-6}$
- measurements for protons and nuclei
- exclusive photoproduction at small t $\approx$ interaction with full wavepackage of target hadron
  $\rightarrow$ coherent interaction

Coherent production: measuring the ´average´ size

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

p: proton (also valid for nuclei), J/ψ could be any vector, e.g. in H. Mäntisaary Rep. Prog. Phys. 83 (2020).

- Good-Walker formalism PRD 120 (1960)
- average over interactions of states that make up the incoming particle and diagonalise the interaction matrix
- high energy: Fock states of the incoming virtual photon with frozen number of partons and frozen configuration of the target
  $\rightarrow$ relates to the fact that GPDs are single-particle distributions, see discussion in Z. Panjsheeri, Luiti group

Incoherent production: measure fluctuations

incoherent case: 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 :

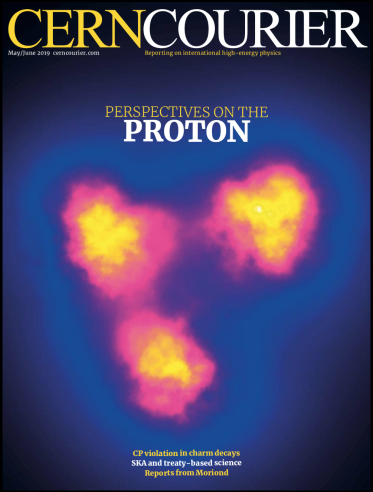
$$\frac{d\sigma^{\gamma^* p\rightarrow p^*\ J/\psi}}{dt} = \frac{1}{16\pi}\left(\langle|\mathcal{A}^{\gamma^* p\rightarrow pJ/\psi}|^2\rangle - |\langle\mathcal{A}^{\gamma^* p\rightarrow pJ/\psi}\rangle|^2\right)$$

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), so-called ´Good-Walker´ formalism, also in Frankfurt, Strikman, Treleani, WeissPRL 101 (2008) 202003.

$\rightarrow$ incoherent: variance $< x^2 > - < x >^2$, not average $< x >^2$

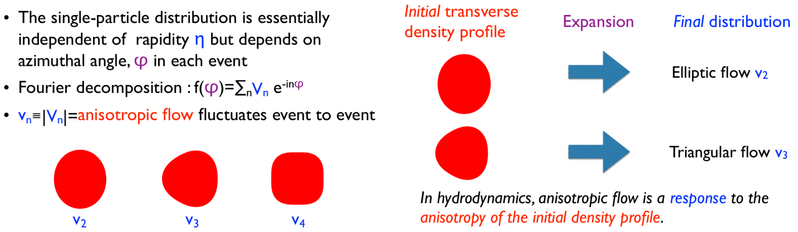
- γp: dissociative production $\rightarrow$ fluctuations of the proton
- HERA data does not reach full kinematics accessible at the LHC due to higher energies
  $\rightarrow$ measure at the LHC!

A QGP motivation to constrain hadrons beyond the average with dissociation



- shape fluctuations crucial to understand azimuthal anisotropies

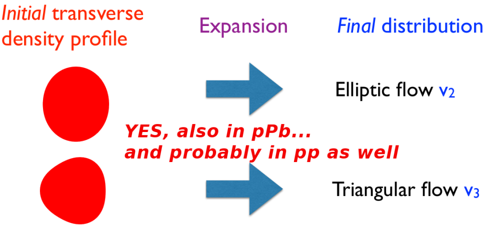
Initial state shape and hydrodynamic response

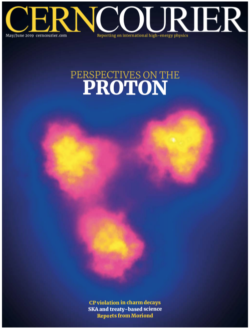


taken from from J.-Y. Olltrault's talk at Epiphany conference '19

- transverse collision-zone **geometry in coordinate space**: azimuthal particle **correlations in final state in momentum space**
- hydrodynamic properties (viscosities) measured as response of this shape
- constraining shape: central to QGP physics
  $\rightarrow$ mechanism exploited to constrain nuclear structure, see thesis of G. Giuliano

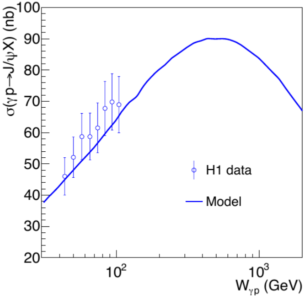
Proton ´geometry´ in proton-nucleus collisions

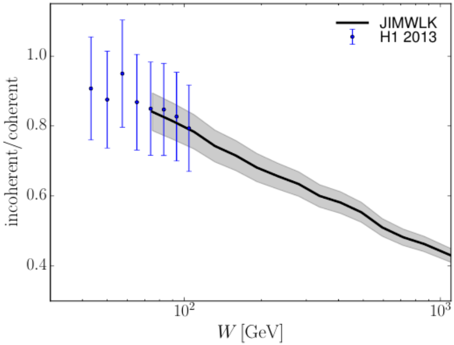




- geometry response observed in proton-nucleus collisions
  Zaijc, Nagle Ann.Rev.Nucl.Part.Sci. 68 (2018) 211
- require sub-nucleonic geometry fluctuations with $n > 1$ hot-spots
  $\rightarrow$ "the proton snapshot with multi-parton interactions is not round"
  e.g. discussed in PLB 774 (2017) PLB 772 (2017)
- Side remark (or naïve dreaming?): if theory connection, hadron correlation measurements may be used to learn about hadron fluctuations, not only nuclear structure
  $\rightarrow$ double-GPDs or double-PDFs distributions the best way?

Saturation physics motivation

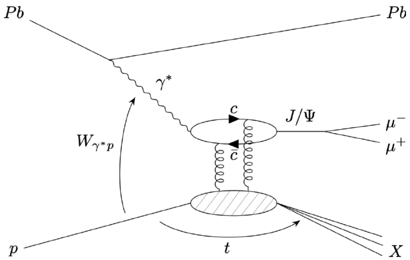




Left: Cepila, Contreras, Takaki PLB766 (2017) 186, right: Schenke, Mäntisaary PRD 98 (2018) 3, 034013

- at asymptotically large energies: system becomes black disk $\rightarrow$ fluctuations vanish and hence dissociative production
- seen in model calculations

Measurement in pPb collisions



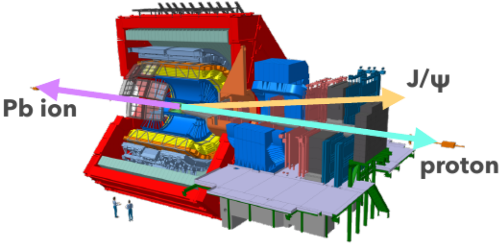
- 6.5 TeV proton-beam, 6.5$\cdot Z^{Pb}(= 82)$ TeV lead beam
- only J/ψ measurement in spectrometer with momentum information
- $W_{\gamma * p} = 2E_p M_{J/\psi} e^{-y}$, y rapidity of J/ψ w.r.t. proton beam
- $t \approx -p^2_{T,jpsi}$, (photon-$k_T \approx 1/R_{Pb}$) $\rightarrow$ t hence in principle accessible, however, muon-arm resolution modest
  $\rightarrow$ measurement not differential in t
  see PbPb t-differential measurements by ALICE at midrapidity, http://arxiv.org/abs/2305.06169 (incoherent), PLB 817 (2021) 136280 (coherent)
- pPb luminosity: 7.62 nb^{-1}

pPb Kinematics in ALICE

- The J/ψ goes in the direction of the proton, **y > 0**:

$$27 \text{ GeV} < W_{\gamma^* p} < 58 \text{ GeV}$$

$$5 \times 10^{-3} < x < 2 \times 10^{-2}$$



Courtesy by A. Glaenzer

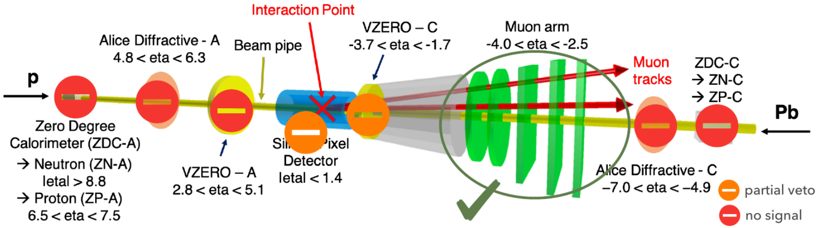
Analysis strategy

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

- new:
  $\rightarrow$ 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

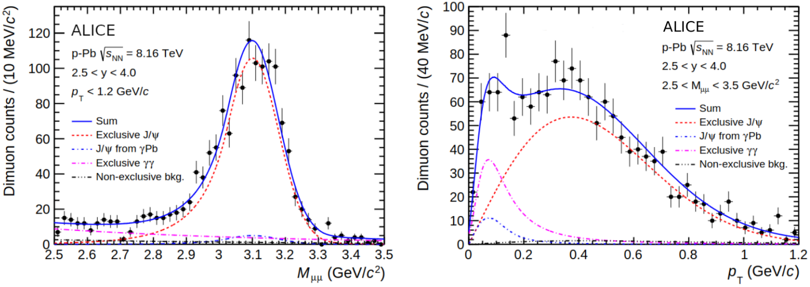
- analysis of $\gamma\gamma \rightarrow \mu^+\mu^-$ as test of QED part & photon fluxes as bonus (not covered here), ingredient for TCS feasibility

Key aspect: exclusive selection vetos



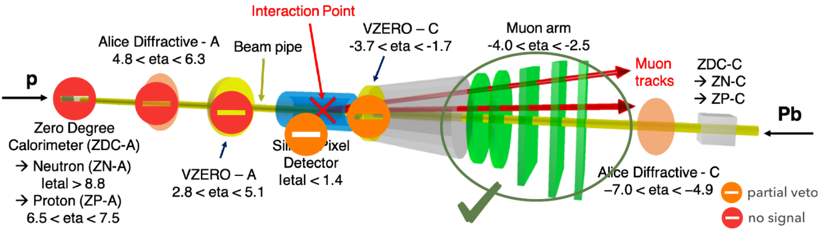
- selection used to derive p_T distribution of exclusive production
- also used as cross check

Exclusive selection



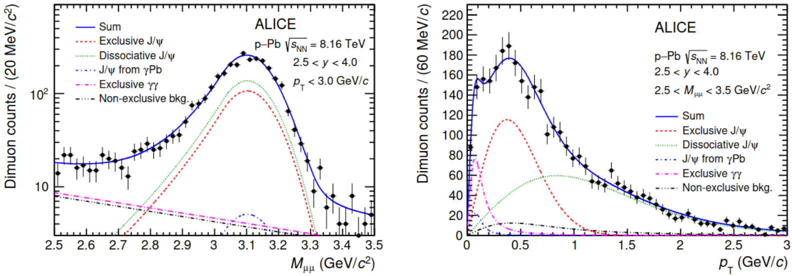
- tight selection used for exclusive shape determination

Key aspect: exclusive selection vetos



- 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

From UPC cross section to photoproduction cross section

$$\frac{d\sigma}{dy}(p+Pb \to p^{(*)}+Pb+J/\psi) = k\frac{dn}{dk}\sigma(\gamma+p \to J/\psi+p^{(*)}).$$

Rapidity range	$N^{exc}_{J/\psi}$, $N^{diss}_{J/\psi}$	$d\sigma^{exc}_{J/\psi}/dy$, $d\sigma^{diss}_{J/\psi}/dy$ (μb)	$k\,dn/dk$	$W_{\gamma p}$ (GeV)	$\langle W_{\gamma p}\rangle$ (GeV)	$\sigma(\gamma+p\to J/\psi+p)$ (nb), $\sigma(\gamma+p\to J/\psi+p^{(*)})$ (nb)
(2.5, 4)	1180 ± 84	$8.13\pm0.58\pm0.43$	209 ± 4	(27, 57)	39.9	$39.0\pm2.8\pm2.2$
	1515 ± 83	$10.43\pm0.57\pm1.39$				$50.0\pm2.7\pm6.7$
(3.25, 4)	564 ± 53	$7.16\pm0.67\pm0.48$	220 ± 4	(27, 39)	32.8	$32.51\pm3.0\pm2.3$
	733 ± 52	$9.31\pm0.66\pm1.28$				$42.3\pm3.0\pm5.9$
(2.5, 3.25)	629 ± 54	$9.21\pm0.80\pm0.51$	197 ± 4	(39, 57)	47.7	$46.8\pm4.1\pm2.8$
	768 ± 55	$11.26\pm0.80\pm1.53$				$57.2\pm4.1\pm7.8$

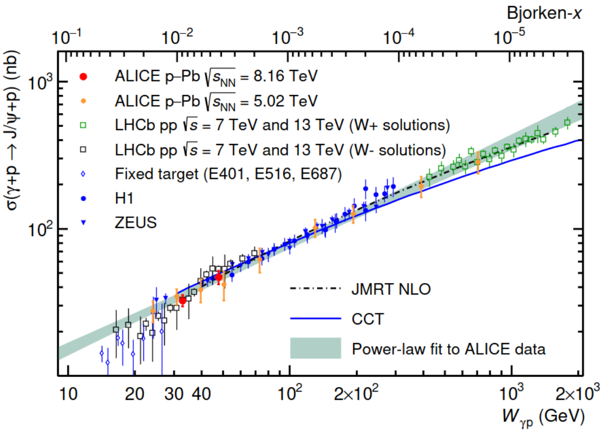
- to get from measured cross section to photoproduction, need photon-flux from Pb nucleus as input
- extracted from Starlight event generator

Uncertainties

Signal	Source	Mass range (GeV/c^2)	Value (%)
All	Luminosity		1.8%
	Tracking efficiency		1%
	Matching efficiency		1%
	Pile-up correction		0.2%
	Total common		**2.3%**
$\gamma\gamma$ only	Muon trigger efficiency	(1.0, 1.5)	from 2.1% to 3.4%
		(1.5, 2.0)	from 2.5% to 5.0%
		(2.0, 2.5)	from 1.6% to 3.3%
	$\phi \to \mu^+\mu^-$ contamination	(1.0, 1.5)	1.5%
	V0C veto	(1.0, 1.5)	1.2%
		(1.5, 2.0)	1.7%
		(2.0, 2.5)	0.5%
	Signal extraction	(1.0, 1.5)	from 3.2% to 3.9%
		(1.5, 2.0)	from 3.3% to 4.4%
		(2.0, 2.5)	from 4.9% to 7.6%
	Total	(1.0, 1.5)	**from 4.9% to 6.0%**
		(1.5, 2.0)	**from 5.5% to 7.1%**
		(2.0, 2.5)	**from 6.0% to 8.6%**
J/ψ only	Muon trigger efficiency		1.1%
	Branching ratio		0.55%
	Photon flux		2%
	$\delta(1+f_{\mathrm{D}})$		1.1%
	V0C veto		2.6% (excl.), 12.7% (diss.)
	Signal extraction	(2.5, 3.5)	from 3.6% to 5.5% (excl.), from 2.9% to 4.4% (diss.)
	Total		**from 5.6% to 7.0% (excl.), from 13.5% to 13.9% (diss.)**
$\frac{\sigma^{\mathrm{diss}}}{\sigma^{\mathrm{exc}}}$	V0C veto		12.7%
	Signal extraction		from 6.2% to 7.6%
	Total		**from 14.1% to 14.8%**

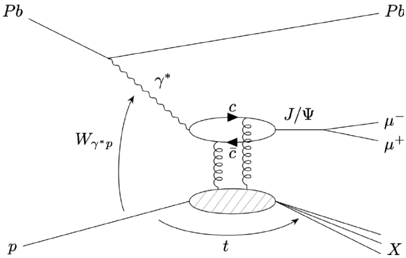
exclusive production still statistically limited, dissociative systematically limited

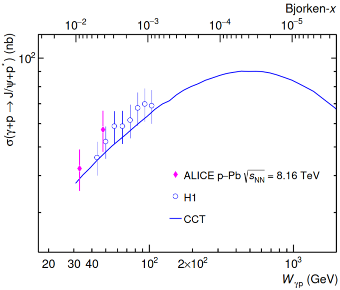
Exclusive analysis results



- results of this analysis well in line with previous results

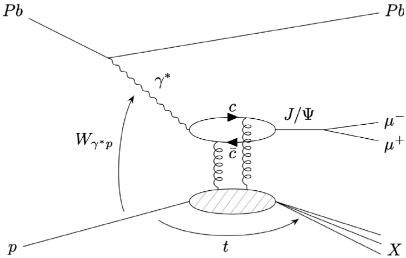
Dissociative results compared with H1 results and models

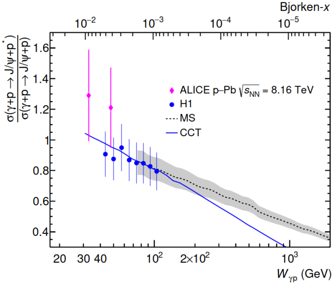




- measured dissociative production in $\gamma - p \to$ consistent with H1

Dissociative results compared with H1 results and models





- next steps:
  $\rightarrow$ future data sets up to $W_{\gamma p} \approx 1.5$ TeV at the LHC
  $\rightarrow$ transverse momentum dependence ($p_t^2 \approx -|t|$)
- input for hydrodynamic QGP simulations
- future studies parallel to electron-ion-collider at higher energy

Limitations

- not yet ultimate pPb LHC luminosity, see HL-LHC Yellow Report for discussion and projections CERN Yellow Rep.Monogr. 7 (2019) 1159
  $\rightarrow$ need to push for pPb run with high luminosity, many other topics to cover in this data set
- Main limitation: incomplete reconstruction of final state
  $\rightarrow$ limits accessible t-range, measure only where S/B is sufficiently good for given process & avalaible selections
  $\rightarrow$ control of veto efficiency limiting systematic uncertainty
  $\rightarrow$ not capable to reconstruct dissociative system
- improvement without new instrumentation for better quantification of uncertainties: better MC-generators
  $\rightarrow$ HERA data very good benchmark
  $\rightarrow$ UPCs can profit from EIC developments with minor additional effort

Perspectives

- Dream for LHC :
  roman pots for diffractive masses between 3 and 30 GeV
  $\rightarrow$ at the LHC not available for this mass-range (beam particle inelasticity and pt in ATLAS/CMS for BSM)
  Zero-degree-calorimeters for low-x high-resolution LHCb would be already a great gain
- Electron-ion-collider: $\rightarrow$ good forward instrumentation central, see talks by Alex Jentsch

Conclusions

- Dissociative quarkonium photoproduction interesting:
  $\rightarrow$ fluctuations of hadrons with connection to QGP physics
  $\rightarrow$ saturation physics
- LHC: higher energy as HERA & EIC, experimentally less clean
- first measurement at the LHC compatible with HERA results with good precision
- interesting future measurements at the LHC:
  $\rightarrow$ higher energy data points
  $\rightarrow$ t-dependence as in PbPb
- better event class/observable definition/conception & simulations:
  $\rightarrow$ reduce uncertainties in future & go further in experiment/theory exchange

Questions for discussion

- Can the relation between dissociation and fluctations be formalised in a way that it can be carried over to hadron-hadron collisions without reference to a model ansatz, i.e. at operator level?
  $\rightarrow$ via GPD formalism or other means? What are the limits of applicability/uncertainties of this connection?
- What do we learn from the dissociative system in this kinematic regime with fully reconstructed final state?
- In principle, the concepts carry over to nuclear collisions, very interesting for QGP physics & saturation
  $\rightarrow$ however: what do we treat nuclear excitation & coherence in inelastic collisions?
  see questions posed by Spencer Klein on caveats/problems arXiv:2301.01408
- What do we know about the quarkonium wave function that can also fluctuate and may not be very ´small´ w.r.t. the target, see Demirci, Lappi, Schlichting PRD 106 (2022) 7, 074025?