Recent experimental resuls in UPC collisions on incoherent and dissociative production with ALICE

Michael Winn

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

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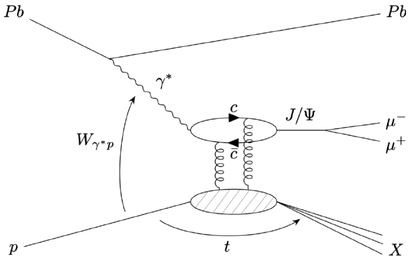
Outline

- Motivation
- proton-lead (pPb): proof-of-principle for proton dissociation at the LHC
  arxiv:2304.12403, submitted to PRD
- lead-lead (PbPb): illustration of coherent and incoherent separation with t-dependent measurements
- Discussion of limitations
- Perspectives, conclusions
  $\rightarrow$ focus on motivation and on current methods

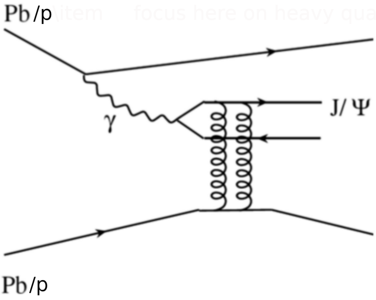
Motivation



- background for exclusive vector-meson production, see presentation by Ronan
- Motivation on its own for incoherent/dissociative production

Focus on heavy quarkonium: hard scale via mass;
focus on $\gamma(^*)p$,
short recap on γ^*Pb$\rightarrow J/\psi X$
focus on ALICE, STAR preliminary results discussed by Daniel yesterday

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
- see presentations of Ronan, Mallick, Daniel

Coherent production: measuring the ´average´ size

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

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
  $\rightarrow$ GPDs single-particle distributions, see in Z. Panjsheeri

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 :

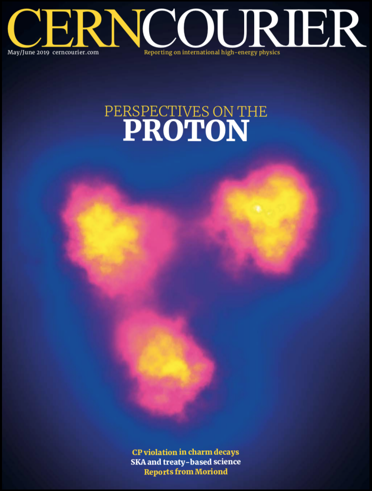
$$\frac{d\sigma^{\gamma^* p \rightarrow p^* \; J/\psi}}{dt} = \frac{1}{16\pi}\left(\langle|\mathcal{A}^{\gamma^* p \rightarrow pJ/\psi}|^2\rangle - |\langle\mathcal{A}^{\gamma^* p \rightarrow pJ/\psi}\rangle|^2\right)$$

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 $< x >^2$

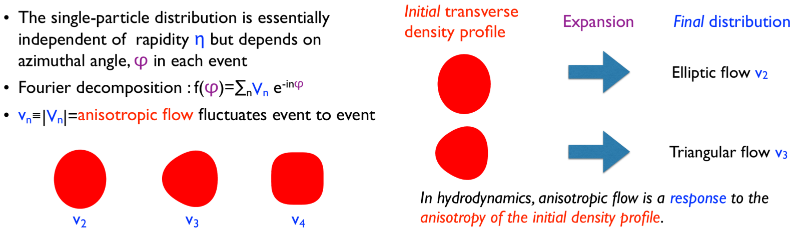
- γp: dissociative production $\rightarrow$ fluctuations of the proton
- HERA data does not reach full kinematics accessible at the LHC due to higher energies
  $\rightarrow$ measure at the LHC interesting, in particular for lowest x
- can apply same formalism also to nuclear target

Hadron-hadron-collision motivation for incoherent production



- shape fluctuations $\rightarrow$ understand azimuthal anisotropies

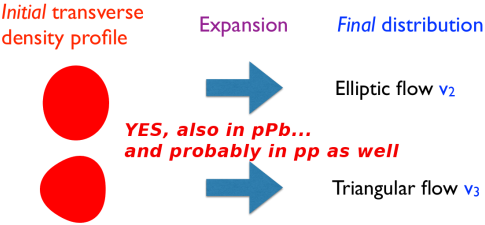
Initial state shape and hydrodynamic response

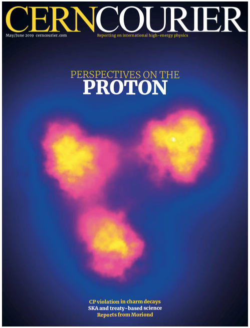


taken from from J.-Y. Olltrault's talk at Epiphany conference '19

- 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

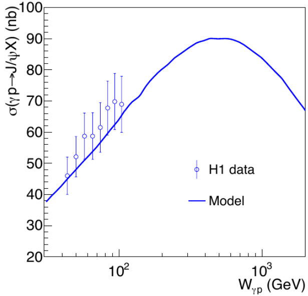
Proton ´geometry´ in proton-nucleus collisions

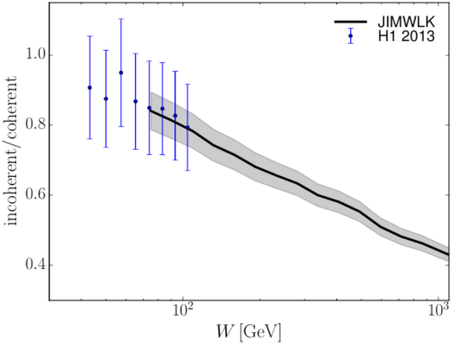




- geometry response observed in proton-nucleus collisions
  Zaijc, Nagle Ann.Rev.Nucl.Part.Sci. 68 (2018) 211
- require sub-nucleonic geometry fluctuations with $n > 1$ hot-spots
  $\rightarrow$ "the proton snapshot with multi-parton interactions is not round"
  e.g. discussed in PLB 774 (2017) PLB 772 (2017)
- naïve remark: if theory connection solid & modeling controllable, hadron correlations useful to learn about hadron fluctuations, not only nuclear structure

Saturation physics motivation

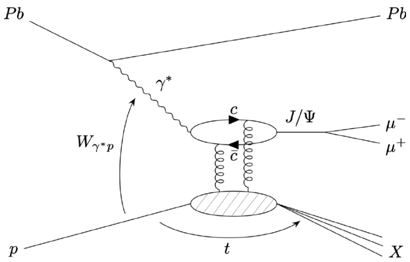




Left: Cepila, Contreras, Takaki PLB766 (2017) 186, right: Schenke, Mäntisaary PRD 98 (2018) 3, 034013

- at asymptotically large energies: system becomes black disk
  $\rightarrow$ fluctuations vanish and hence dissociative production
- seen in model calculations, see Renaud´s talk later today

Measurement in pPb collisions



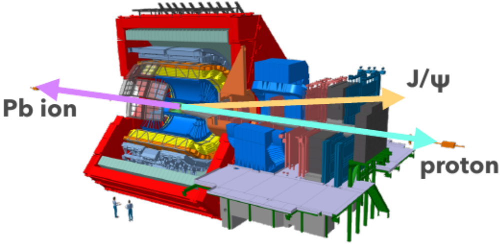
- 6.5 TeV proton-beam, $6.5 \cdot Z^{Pb} (= 82)$ TeV lead beam
- only J/ψ measurement in spectrometer with momentum information
- $W_{\gamma * p} = 2 E_p M_{J/\psi} e^{-y}$, y rapidity of J/ψ w.r.t. proton beam
- $t \approx -p^2_{T,jpsi}$, (photon-$k_T \approx 1/R_{Pb}$) $\rightarrow$ t hence in principle accessible, however, muon-arm resolution modest
  $\rightarrow$ measurement not differential in t
- pPb luminosity: 7.62 nb^{-1}

pPb Kinematics in ALICE

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

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

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

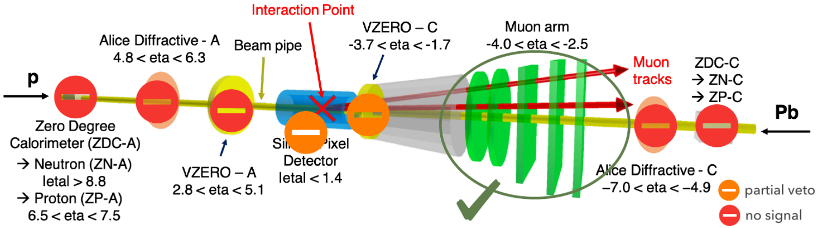


Courtesy by A. Glaenzer

Analysis strategy

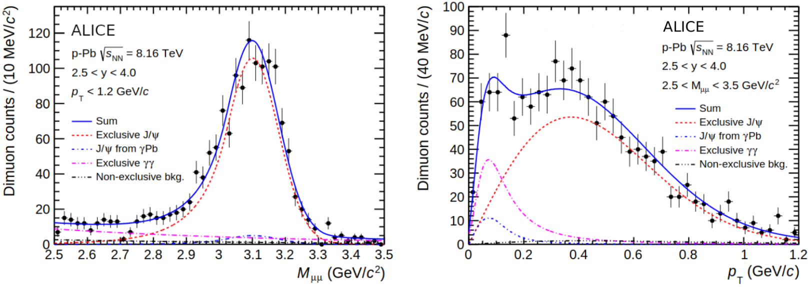
- standard selection and methods for muon analyses in ALICE and UPC
- new features:
  $\rightarrow$ exclusive selection to fix exclusive contribution shape
  $\rightarrow$ more open selection including dissociative and exclusive to do fit
  $\rightarrow$ 2-D loglikelihood fit of mass and p_T to extract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



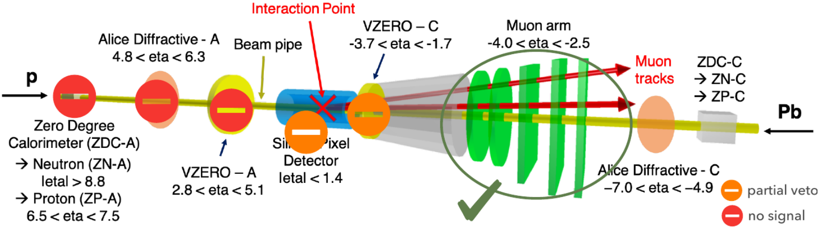
- selection used to derive p_T distribution of exclusive production
- also used as cross check

Exclusive selection



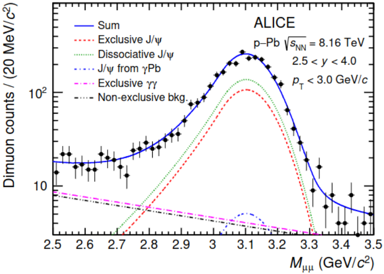
- tight selection used for exclusive shape determination

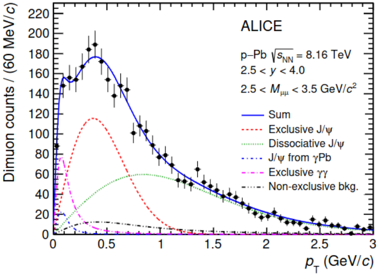
Key aspect: exclusive selection vetos



- 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

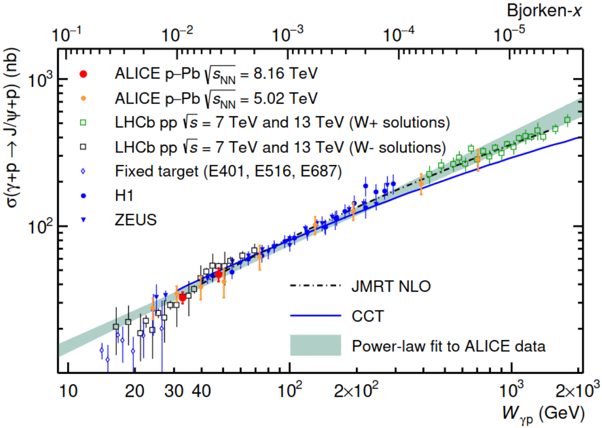
From UPC cross section to photoproduction cross section

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

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

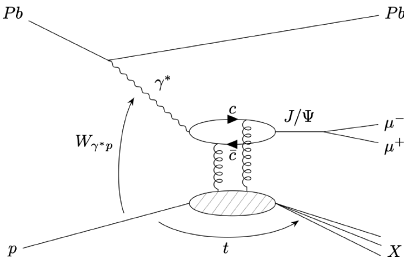
- to get from measured cross section to photoproduction, need photon-flux from Pb nucleus as input
- extracted from Starlight event generator
- exclusive production still statistically limited, dissociative systematically limited

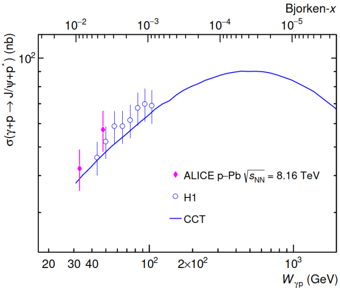
Exclusive analysis results



- results of this analysis well in line with previous results

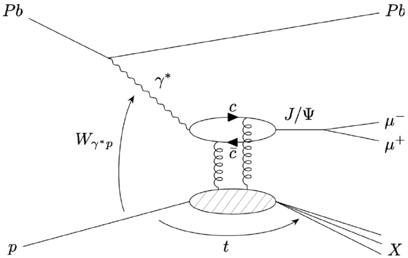
Dissociative results compared with H1 results and models

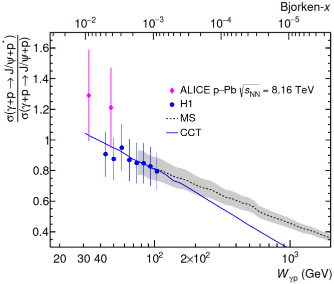




- measured dissociative production in $\gamma - p \rightarrow$ consistent with H1

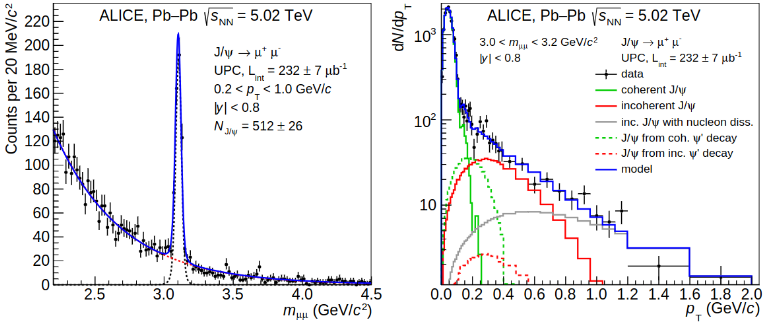
Dissociative results compared with H1 results and models





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

Incoherent production in PbPb collisions: t-dependence



arXiv:2305.06169, submitted to PRL

- most recent result: t-dependence ($t \approx -p_T^2$)
- measurement in ALICE central barrel $y \approx 0$: better p_T resolution, no photon emitter ambiguity
- separation based on p_T-templates
- measurement performed where good S/B for incoherent production: $p_T > 0.2$ GeV/c

Incoherent ant coherent t-ranges in UPC

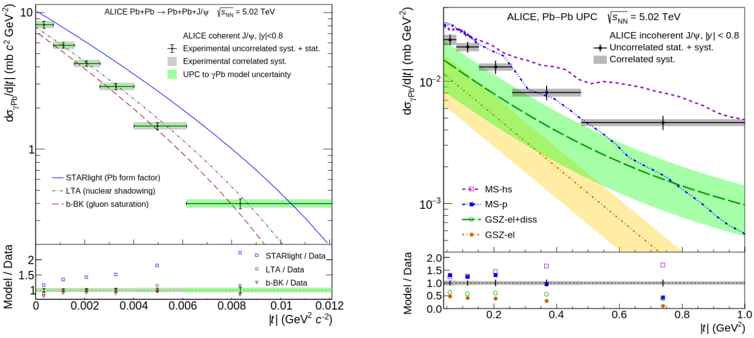
$\|t\|$ (GeV^2)	$N_{J/\psi}$	f_C (%)	f_D (%)	$(\mathrm{Acc}\times\varepsilon)_{MC}$ (%)	$\frac{d\sigma_{\gamma Pb}}{d\|t\|}$ (μb/GeV^2)
(0.040, 0.080)	128 ± 12	9.4 ± 0.8	81.9 ± 11.7	3.39 ± 0.03	$21.8\pm2.1\pm0.3\pm2.1$
(0.080, 0.152)	127 ± 12	0.024 ± 0.002	36.0 ± 4.9	3.03 ± 0.02	$19.1\pm1.9\pm0.3\pm1.5$
(0.152, 0.258)	85 ± 10	0	9.3 ± 1.0	2.49 ± 0.02	$13.1\pm1.6\pm0.4\pm0.9$
(0.258, 0.477)	86 ± 11	0	4.9 ± 0.4	2.04 ± 0.02	$8.1\pm1.1\pm0.1\pm0.6$
(0.477, 1.000)	86 ± 11	0	2.7 ± 0.2	1.57 ± 0.02	$4.6\pm0.6\pm0.1\pm0.3$

p_T^2 interval (GeV$^2/c^2$)	f_I	f_D	$(\mathrm{Acc}\times\varepsilon)^{coh}_{J/\psi}$
(0, 0.00072)	0.0045	0.0039	0.0348
(0.00072, 0.0016)	0.0047	0.0046	0.0352
(0.0016, 0.0026)	0.0047	0.0058	0.0358
(0.0026, 0.004)	0.0072	0.0072	0.0365
(0.004, 0.0062)	0.0120	0.011	0.0379
(0.0062, 0.0121)	0.0300	0.028	0.0412

incoherent production arXiv:2305.06169(top), coherent production PLB 817 (2021) 136280(bottom)

- extraction done in two distinct regions

t-dependent results in PbPb collisions



left: coherent production, right: incoherent production (MS: Mäntisaary-Schenke) GSZ: Guzey, Strikman, Zhalov)

- t-dependent coherent production well modeled by leading twist shadowing and b-BK model
- t-incoherent production not well reproduced by any model, but slope better described when fluctuations subnucleonic scales

Limitations

- not yet ultimate LHC luminosity, see HL-LHC Yellow Report CERN Yellow Rep.Monogr. 7 (2019) 1159
  $\rightarrow$ pPb: need to push for high luminosity
- 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 as benchmark
  $\rightarrow$ UPCs can profit from EIC theory developments with minor additional effort

Longer term 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:
  $\rightarrow$ forward instrumentation
  nuclear case: challenging to go beyond good S/B range as at the LHC

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?

pPb 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

PbPb uncertainties t-dependence incoherent

Source	Uncertainty (%)
Signal extraction	$(1.0, 2.9)$
Selection on $\lvert z_{\mathrm{vtx}} \rvert$	$(0.0, 2.9)$
f_{C}	$(0.0, 0.4)$
f_{D}	$(0.2, 6.5)$
Integrated luminosity	2.9
Veto inefficiency due to pile-up	3.0
Veto inefficiency due to dissociation	3.8
ITS-TPC tracking	2.8
Trigger efficiency	1.3
Branching ratio	0.6
Photon flux	2.0