Incoherent production of J/ψ at midrapidities

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6. miniworkshop difrakce a ultraperiferních srážek
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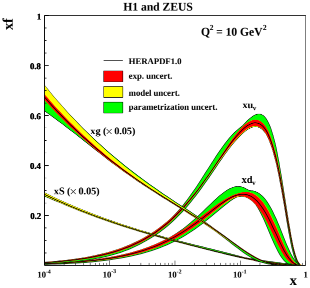
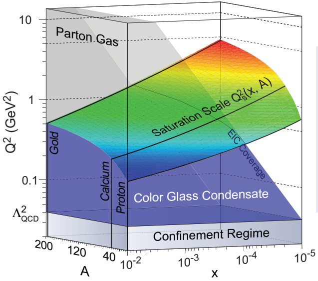
Physical motivation

- What do we know about the nuclear structure at high energies (low Bjorken-x)?
  - **Gluon contribution** is dominant and raising
  - At some point, gluon production should be balanced by annihilation $\Rightarrow$ **saturation**
  - For heavy nuclei, saturation expected at lower energies (than for nucleons)
- Various aspects of the target structure can be studied to determine the onset of saturation:
  - The average gluon density
  - Event-by-event fluctuations
- Ideal probes? **Photons**!



JHEP 01 (2010), p.109



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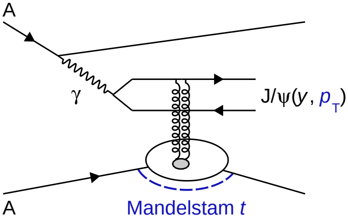
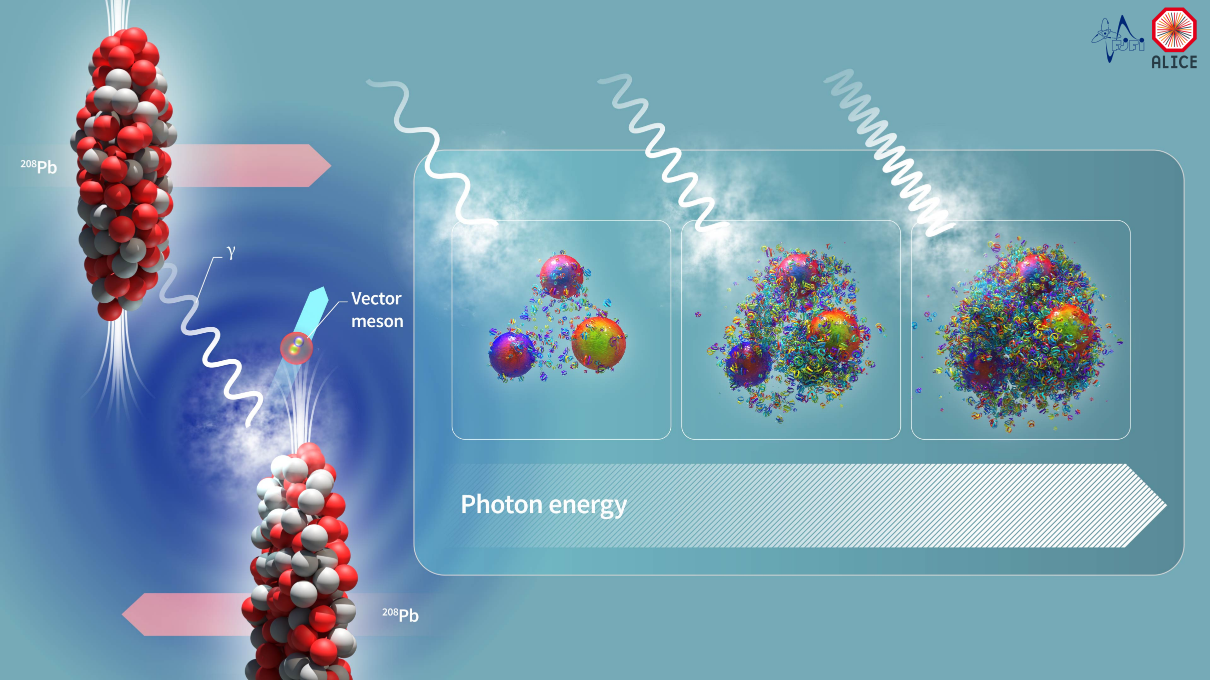
Photoproduction

- At hadron colliders, the tool at hand are **ultra-peripheral collisions** (UPCs):
  - $b > 2R \Rightarrow$ pure hadronic interactions suppressed
- The emitted photon fluctuates into a **color dipole**
- Exchange of gluons $\Rightarrow$ photonuclear interaction
- γPb at the LHC
  - E.g. **diffractive J/ψ photoproduction**:



For incoherent J/ψ: $|t| = p_T^2$

Process	γ interacts with	$\sigma_{\gamma\text{Pb}}$ sensitive to (Good-Walker) [1]	$\langle\|t\|\rangle$ [GeV^2]
Coherent	The whole nucleus	The average	$\lesssim 0.01$
Incoherent	A single nucleon	The variance	~ 0.1
Dissociative	Sub-nucleon structure		~ 1



^{208}Pb
γ
Vector meson
Photon energy
^{208}Pb

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2023-080
04 May 2023

First measurement of the $|t|$-dependence of incoherent J/ψ photonuclear production

ALICE Collaboration*

Abstract

The first measurement of the cross section for incoherent photonuclear production of J/ψ vector mesons as a function of the Mandelstam $|t|$ variable is presented. The measurement was carried out with the ALICE detector at midrapidity, $|y| < 0.8$, using ultra-peripheral collisions of Pb nuclei at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. This rapidity interval corresponds to a Bjorken-x range $(0.3–1.4) \times 10^{-3}$. Cross sections are given in five $|t|$ intervals in the range $0.04 < |t| < 1$ GeV^2 and compared to the predictions by different models. Models that ignore quantum fluctuations of the gluon density in the colliding hadron predict a $|t|$-dependence of the cross section much steeper than in data. The inclusion of such fluctuations in the same models provides a better description of the data.

Analysis overview

First measurement of the $|t|$-dependence of incoherent J/ψ photonuclear production

- Paper **approved by ALICE**: arXiv:2305.06169
- Submitted to Physical Review Letters (PRL)
  - Now waiting for the second round of comments from the referees

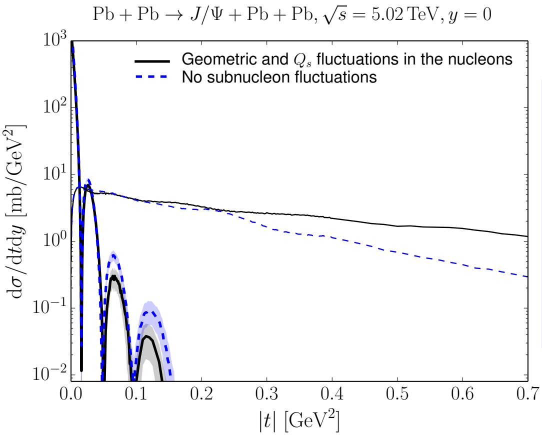
- The analysis carried out with ALICE using Pb–Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
- J/ψ reconstructed at midrapidity, $|y| < 0.8$, from the decay into $\mu^+\mu^-$
  - Sensitive to $x \in (0.3, 1.4) \times 10^{-3}$
- Five $|t|$ intervals in the range $0.04 < |t| < 1$ GeV^2

$$x = \frac{M_{\mathrm{J}/\psi}}{\sqrt{s_{\mathrm{NN}}}} e^{-y}$$

Analysis motivation

Mandelstam t $\xleftrightarrow{\text{Fourier tr.}}$ matter distribution in the transverse plane

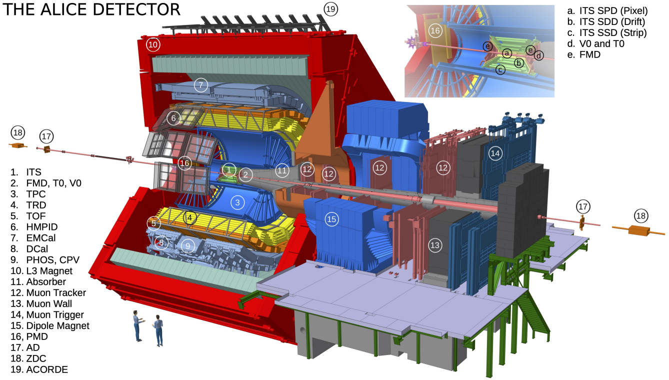
- Incoherent photonuclear cross section $\rightarrow$ **geometrical fluctuations of the target gluon density**
- Fluctuations at sub-nucleon scale would enhance the cross section at $|t| \sim 1$ GeV^2



Phys. Lett. B 772 (2017) 832-838

Participating ALICE detectors

- Event selection: **central UPC trigger** → inputs from the SPD, TOF, AD and V0
- Forward scintillation detectors AD and V0 operated as **vetoes** against hadronic activity
- **Tracking**: the ITS and TPC in a large solenoid magnet (0.5 T)
- **Particle ID**: ionization energy loss measured in the TPC compared to the muon hypothesis



Looking at events with two oppositely-charged tracks, $|\eta| < 0.8$

Photonuclear cross section

$$\frac{\mathrm{d}\sigma_{\gamma\mathrm{Pb}}}{\mathrm{d}|t|} = \frac{1}{2n_{\gamma\mathrm{Pb}}} \frac{N^{\mathrm{inc}}_{\mathrm{J}/\psi}}{(\mathrm{Acc}\times\varepsilon)^{\mathrm{inc}}_{\mathrm{J}/\psi} \times \mathrm{BR}(\mathrm{J}/\psi \to \mu^+\mu^-) \times \mathcal{L} \times \Delta y \times \Delta|t|}$$

Photonuclear cross section

Number of incoherent J/ψ

$$\frac{\mathrm{d}\sigma_{\gamma\mathrm{Pb}}}{\mathrm{d}|t|} = \frac{1}{2n_{\gamma\mathrm{Pb}}} \frac{N^{\mathrm{inc}}_{\mathrm{J}/\psi}}{(\mathrm{Acc}\times\varepsilon)^{\mathrm{inc}}_{\mathrm{J}/\psi} \times \mathrm{BR}(\mathrm{J}/\psi \to \mu^+\mu^-) \times \mathcal{L} \times \Delta y \times \Delta|t|}$$

Photonuclear cross section

Number of incoherent J/ψ

$$N_{J/\psi} = N^{\text{inc}}_{J/\psi} + N^{\text{coh}}_{J/\psi} + N^{\text{f-d}} = N^{\text{inc}}_{J/\psi}(1 + f_C + f_D) \Rightarrow N^{\text{inc}}_{J/\psi} = \frac{N_{J/\psi}}{1 + f_C + f_D}$$

$$\frac{d\sigma_{\gamma\text{Pb}}}{d|t|} = \frac{1}{2n_{\gamma\text{Pb}}} \frac{N^{\text{inc}}_{J/\psi}}{(\text{Acc} \times \varepsilon)^{\text{inc}}_{J/\psi} \times \text{BR}(J/\psi \to \mu^+\mu^-) \times \mathcal{L} \times \Delta y \times \Delta|t|}$$

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Coherent contamination

$$\frac{d\sigma_{\gamma Pb}}{d|t|} = \frac{1}{2n_{\gamma Pb}} \frac{N^{inc}_{J/\psi}}{(Acc \times \varepsilon)^{inc}_{J/\psi} \times BR(J/\psi \to \mu^+\mu^-) \times \mathcal{L} \times \Delta y \times \Delta|t|}$$

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Coherent contamination

Feed-down contamination

$$\frac{d\sigma_{\gamma \text{Pb}}}{d|t|} = \frac{1}{2n_{\gamma \text{Pb}}} \frac{N^{\text{inc}}_{J/\psi}}{(\text{Acc} \times \varepsilon)^{\text{inc}}_{J/\psi} \times \text{BR}(J/\psi \to \mu^+\mu^-) \times \mathcal{L} \times \Delta y \times \Delta|t|}$$

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Photon flux: 84.9 ± 1.7

Photonuclear cross section

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Acceptance & efficiency:

- STARlight MC [2]
- Control datasets for veto efficiencies

Photonuclear cross section

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Branching ratio ($J/\psi \to \mu\mu$) $\sim 6\%$ (PDG)

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Photon flux: 84.9 ± 1.7

Acceptance & efficiency:

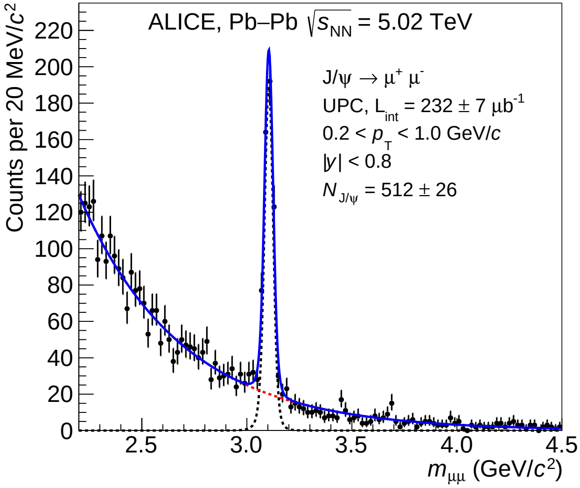
- STARlight MC [2]
- Control datasets for veto efficiencies

Integrated luminosity $\mathcal{L} = (232 \pm 7)\ \mu b^{-1}$

Branching ratio (J/$\psi \to \mu\mu$) $\sim 6\%$ (PDG)

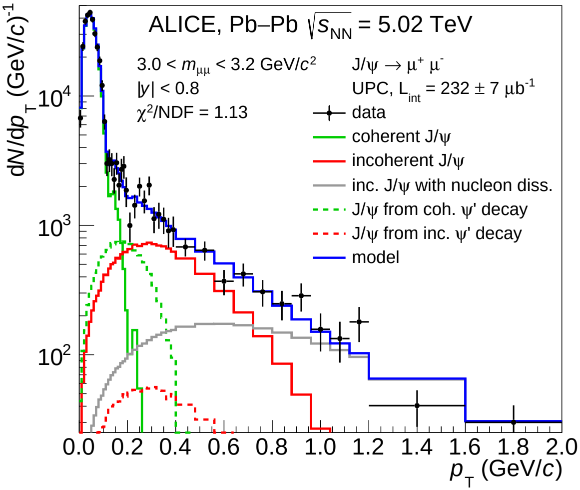
Signal extraction

- J/ψ yields: extended likelihood fits to unbinned invariant-mass distribution of muon pairs (Crystal Ball + exponential)
- Total yield ($0.04 < |t| < 1$ GeV^2): 521 ± 26, about 100 per a $|t|$ interval



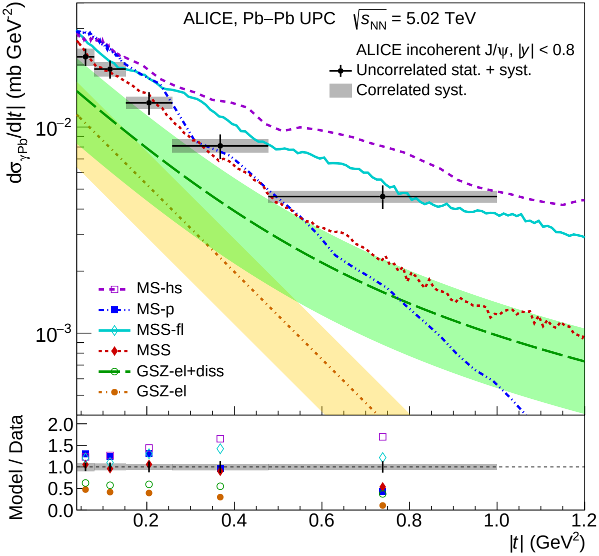
Coherent and feed-down contamination

- Contamination from coherent J/ψ production + feed-down from ψ' ($\psi' \rightarrow J/\psi + X$)
- Extended likelihood fit to transverse momentum ditribution of muon pairs with $3.0 < m_{\mu\mu} < 3.2$ GeV$/c^2$
- Templates obtained with the STARlight MC generator: reweighted to reproduce the peak at low p_{T} dominated by coherent J/ψ
- Nucleon dissociation: H1 parametrization [3]



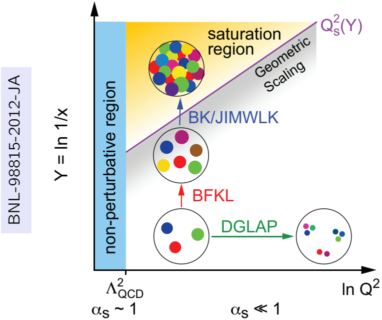
MS [4]: "The IPsat model":

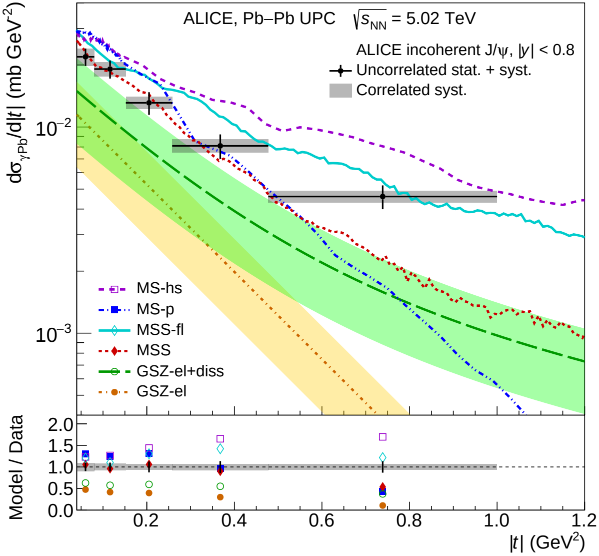
- **MS-p**: elastic interaction with a full nucleon
- **MS-hs**: event-by-event changes of the transverse proton structure (three *hot spots*) + fluctuating saturation scale



MSS [5]: CGC based, solving the JIMWLK equation

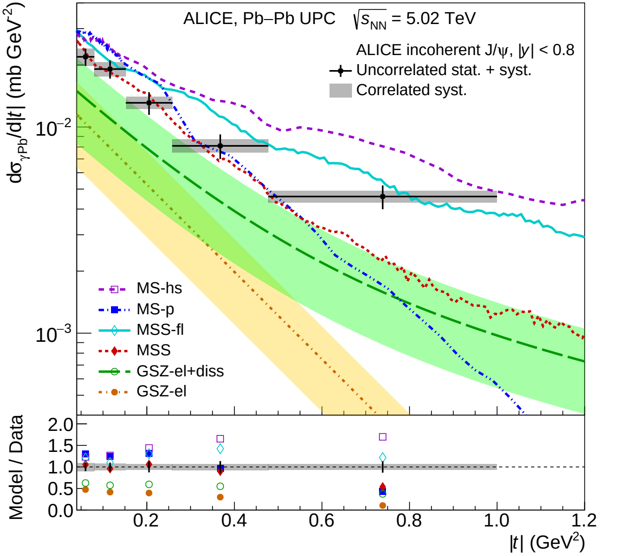
- **MSS**: full nucleon
- **MSS-fl**: hot spots included





GSZ [6]: HERA data + Glauber-Gribov and shadowing

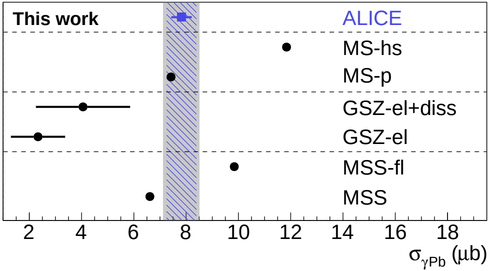
- **GSZ-el**: full nucleon
- **GSZ-el+diss**: extra dissociative component (sub-nucleon d.o.f.)



Discussion of the results

Two aspects of the data-model comparison:

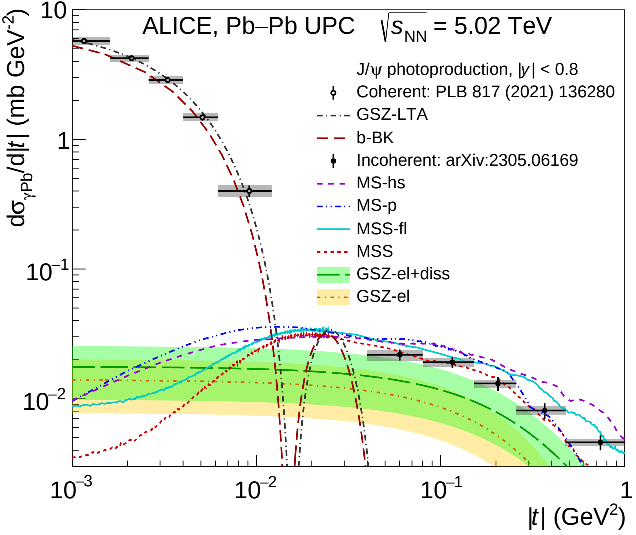
1. **The normalization**: mainly linked to the scaling from proton to nuclear targets
2. **The $|t|$-slope**: driven by the size of the scattering object



- Models ignoring quantum fluctuations at sub-nucleon scale predict a $|t|$-dependence **much steeper** than in the data
- Inclusion of such fluctuations in the same models provides a better description of the data

Complementary measurement of coherent production

- This analysis complements the ALICE measurement of coherent J/ψ photoproduction at $|t| < 0.012$ GeV^2 [7]:
  - @Roman Lavička, 2021
- Together, three orders of magnitude in $|t|$ covered
- HERA-like accuracy



Conclusions

- The first measurement of the $|t|$-dependence of incoherent J/ψ photoproduction is presented
- Analysis performed at midrapidity using Pb–Pb UPCs measured with ALICE
- From the comparison with phenomenological models, the data favor sub-nucleon fluctuations!

Thank you for listening!

References

1. M. L. Good and W. D. Walker. "Diffraction disssociation of beam particles". In: *Phys. Rev.* 120 (1960), pp. 1857–1860.
2. S. R. Klein et al. "STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions". In: *Comput. Phys. Commun.* 212 (2017), pp. 258–268.
3. C. Alexa et al. "Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA". In: *Eur. Phys. J. C* 73.6 (2013), p. 2466.
4. H. Mäntysaari and B. Schenke. "Probing subnucleon scale fluctuations in ultraperipheral heavy ion collisions". In: *Phys. Lett. B* 772 (2017), pp. 832–838.
5. H. Mäntysaari, F. Salazar, and B. Schenke. "Nuclear geometry at high energy from exclusive vector meson production". In: *Phys. Rev. D* 106 (2022) 7, 074019.
6. V. Guzey, M. Strikman, and M. Zhalov. "Nucleon dissociation and incoherent J/ψ photoproduction on nuclei in ion ultraperipheral collisions at the Large Hadron Collider". In: *Phys. Rev. C* 99.1 (2019), p. 015201.
7. S. Acharya et al. "First measurement of the $|t|$-dependence of coherent J/ψ photonuclear production". In: *Phys. Lett. B* 817 (2021), p. 136280.

Back-up slides

Numerical results

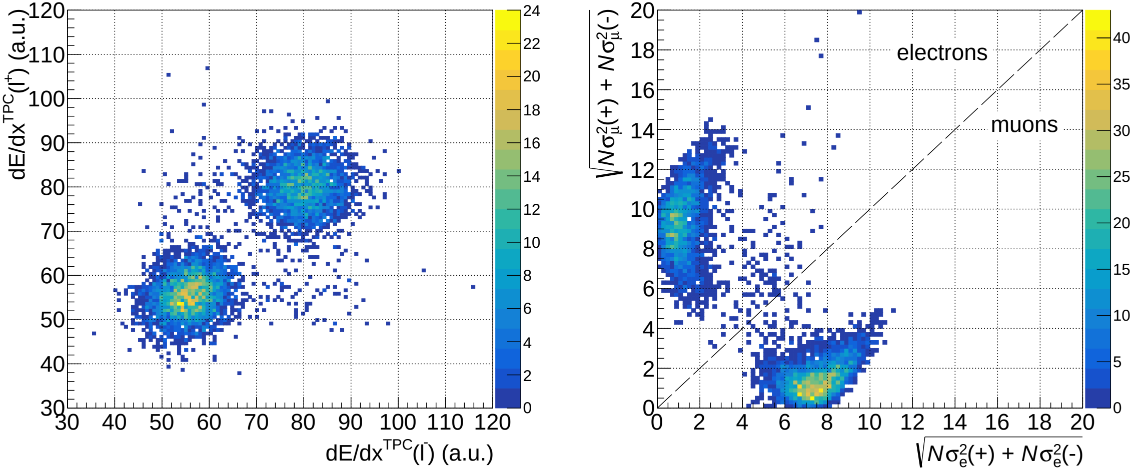
$\|t\|$ (GeV^2)	$N_{J/\psi}$	f_C (%)	f_D (%)	$(\mathrm{Acc} \times \varepsilon)_{\mathrm{MC}}$ (%)	$\frac{d\sigma_{\gamma\mathrm{Pb}}}{d\|t\|}$ (μb/GeV^2)
(0.040, 0.080)	128 ± 12	9.4 ± 0.8	81.9 ± 11.7	3.39 ± 0.03	$21.8 \pm 2.1 \pm 0.3 \pm 2.1$
(0.080, 0.152)	127 ± 12	0.024 ± 0.002	36.0 ± 4.9	3.03 ± 0.02	$19.1 \pm 1.9 \pm 0.3 \pm 1.5$
(0.152, 0.258)	85 ± 10	0	9.3 ± 1.0	2.49 ± 0.02	$13.1 \pm 1.6 \pm 0.4 \pm 0.9$
(0.258, 0.477)	86 ± 11	0	4.9 ± 0.4	2.04 ± 0.02	$8.1 \pm 1.1 \pm 0.1 \pm 0.6$
(0.477, 1.000)	86 ± 11	0	2.7 ± 0.2	1.57 ± 0.02	$4.6 \pm 0.6 \pm 0.1 \pm 0.3$

The uncertainties on the cross section are (in this order): statistical, uncorrelated systematic, and correlated systematic

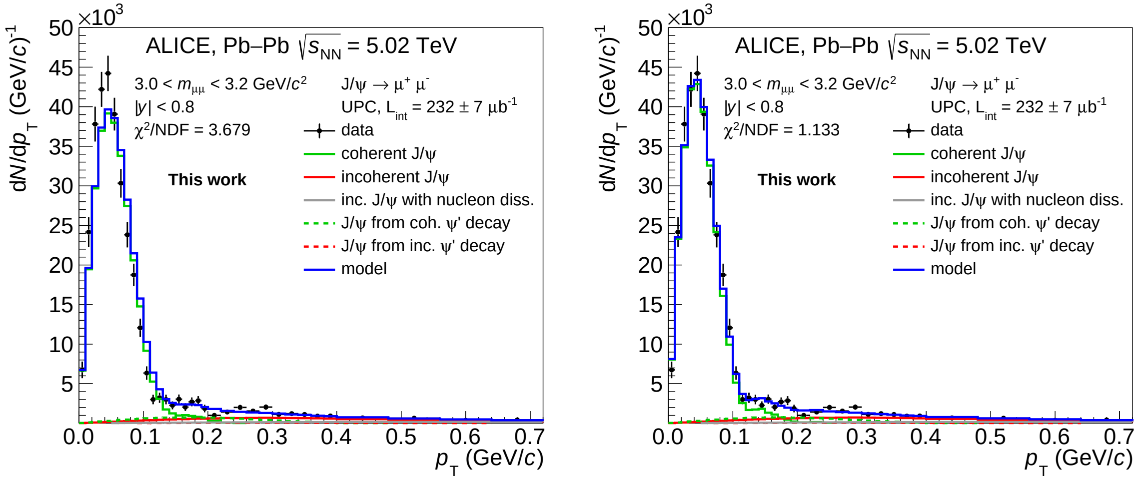
Systematic uncertainties

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

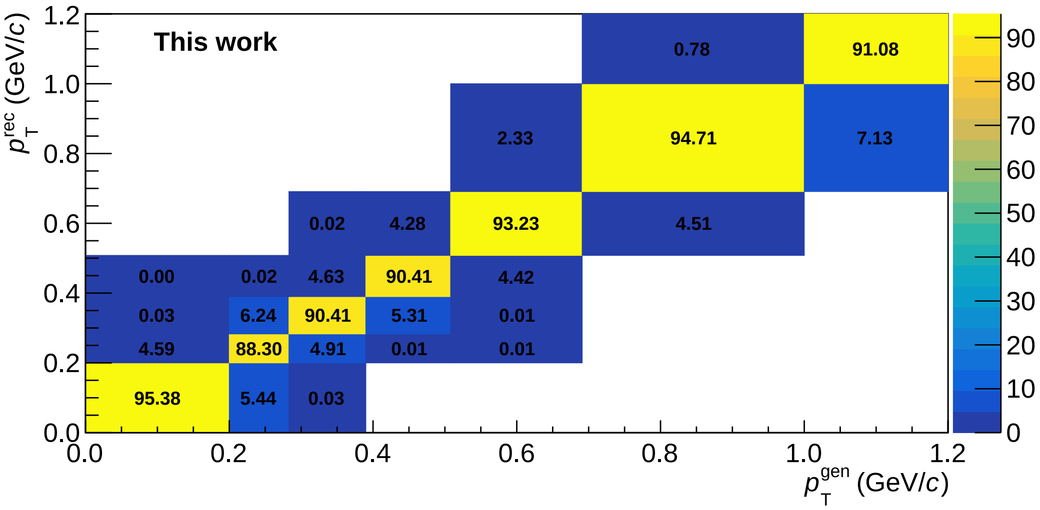
PID: complete rejection of electrons



Reweighted STARlight templates



Need for unfolding?



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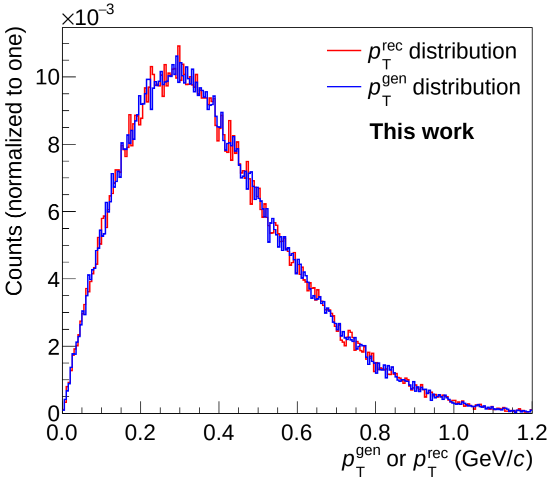

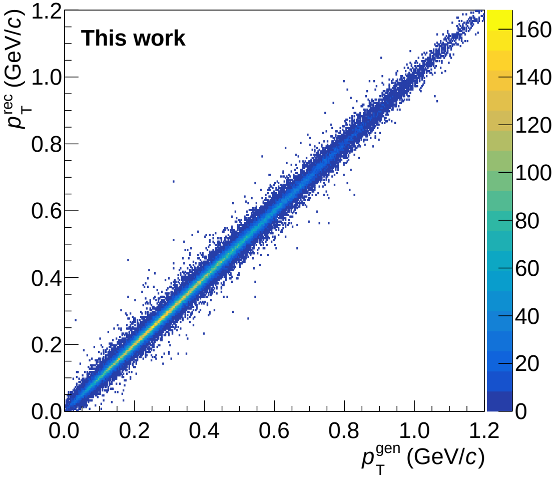

$|t|$ vs p_T^2: photon transverse momentum