

Quarkonium and dilepton photoproduction with ALICE

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for the ALICE Collaboration

DIS2022

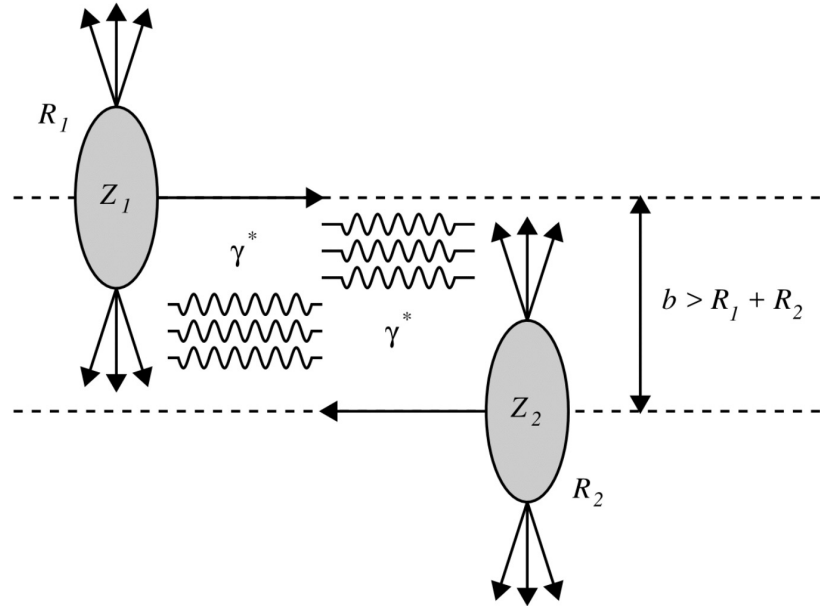
2-6 May 2022

Santiago de Compostela (Spain)



Ultra-peripheral collisions

- Ultra-relativistic moving nuclei are a powerful EM source
 - Quasi-real photon flux ($\propto Z^2$)



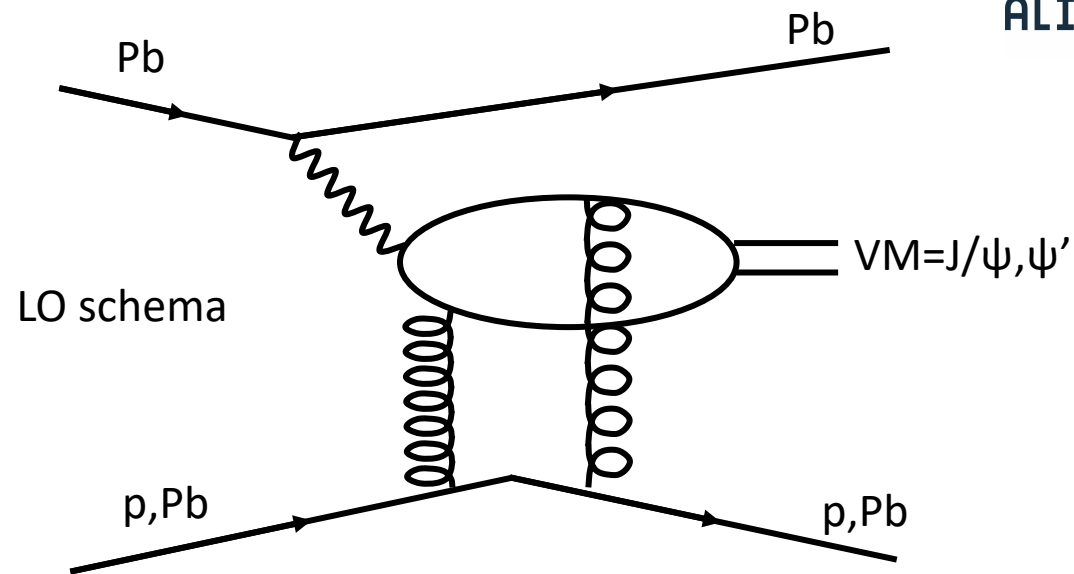
- Photon-induced interactions first studied in ultra-peripheral collisions, UPCs ($b > R_1 + R_2$)
 - Suppressed hadronic interactions

Vector meson photoproduction

- VM photoproduction cross section can be described as:

$$\frac{d\sigma_{AA}}{dy} = n_{\gamma,1}(y)\sigma_{\gamma A_2}(y) + n_{\gamma,2}(-y)\sigma_{\gamma A_1}(-y)$$

 Photon flux
  Photonuclear cross section

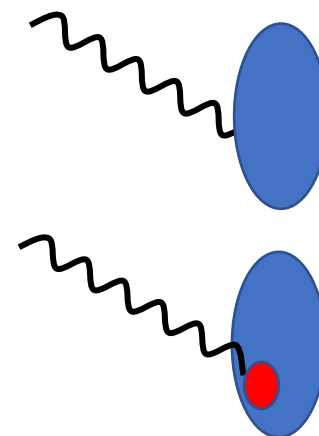


- Photonuclear cross section sensitive to gluon distribution at low- x

- Explored range at LHC: $x = \frac{M_{VM}}{\sqrt{s}} e^{\pm y} \Rightarrow 10^{-5} < x < 10^{-2}$

- VM $\langle p_T \rangle \propto 1/R_{\text{target}}$

- Coherent (target = ion): 60 MeV/c
 - Incoherent (target = proton): 500 MeV/c



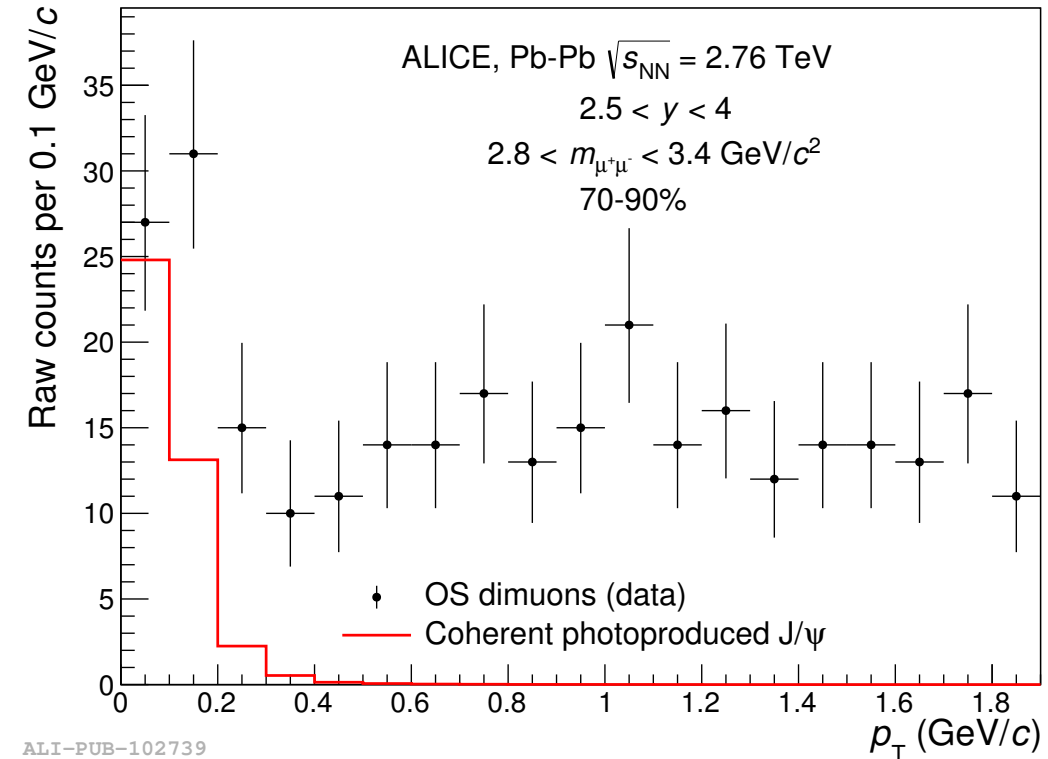
VM photoproduction in collisions with nuclear overlap

- J/ψ excess at very low p_T observed for the first time with ALICE in peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Compatible with coherent J/ψ photoproduction

Open questions:

- How can the coherence condition survive if the nucleus breaks up?
- Do only spectator nucleons participate?

ALICE, Phys. Rev. Lett. 116, 222301



$\gamma\gamma \rightarrow l^+l^-$ production



UPC:

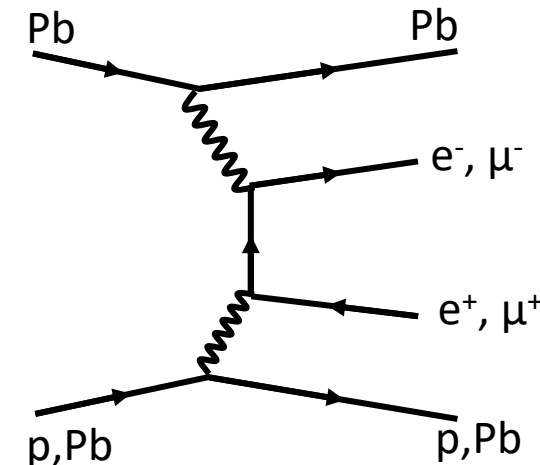
- Can be used to test pure EM calculations in UPC

Nuclear overlap:

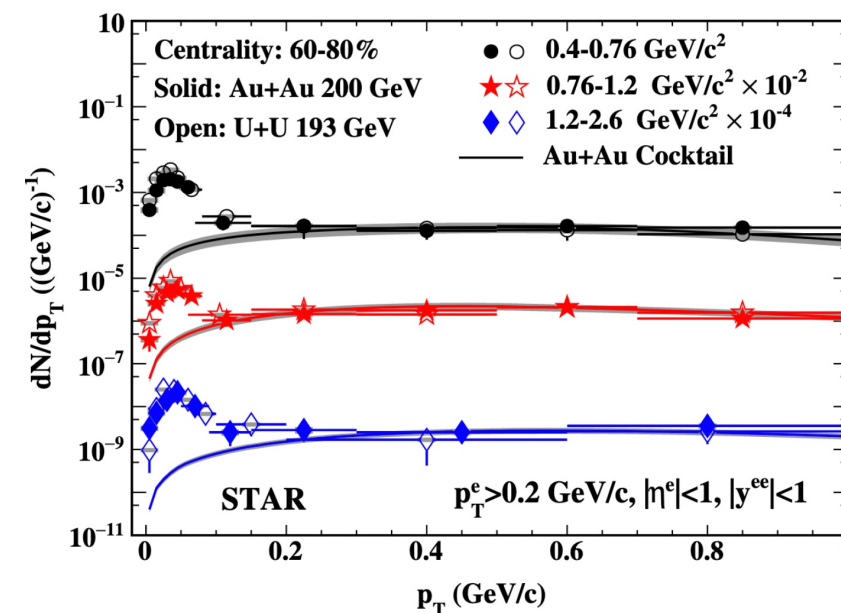
- Excess with respect to hadronic sources measured in non-central A–A collisions at RHIC and LHC
- Increase of acoplanarity of dimuon pairs measured toward central Pb–Pb collisions with ATLAS

ATLAS, Phys.Rev.Lett. 121 (2018), 212301

- Initially interpreted as potential electromagnetic scatterings of muons with fireball
- Recent inclusion of b dependence in QED calculations can describe data as well Phys.Rev.D 101 (2020), 034015



STAR, Phys.Rev.Lett. 121 (2018), 132301

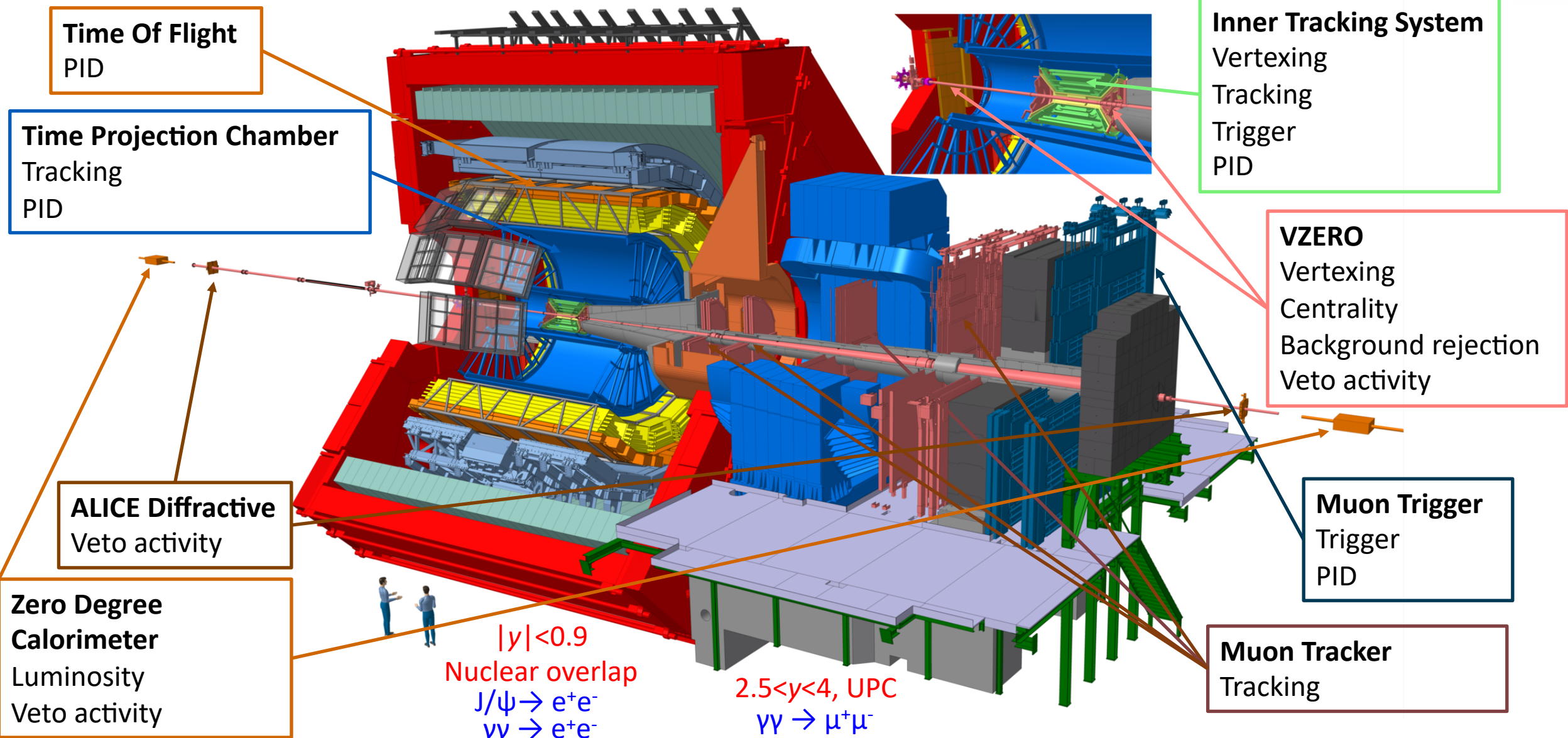


ALICE detector



$|y| < 0.9$, UPC
 $J/\psi \rightarrow e^+e^-, \mu^+\mu^-, p\bar{p}$
 $\psi' \rightarrow e^+e^-, \mu^+\mu^-, e^+e^-\pi^+\pi^-, \mu^+\mu^-\pi^+\pi^-$

$2.5 < y < 4$
 UPC, nuclear overlap
 $J/\psi \rightarrow \mu^+\mu^-$



Time Of Flight
PID

Time Projection Chamber
Tracking
PID

Inner Tracking System
Vertexing
Tracking
Trigger
PID

VZERO
Vertexing
Centrality
Background rejection
Veto activity

ALICE Diffractive
Veto activity

Muon Trigger
Trigger
PID

Zero Degree Calorimeter
Luminosity
Veto activity

Muon Tracker
Tracking

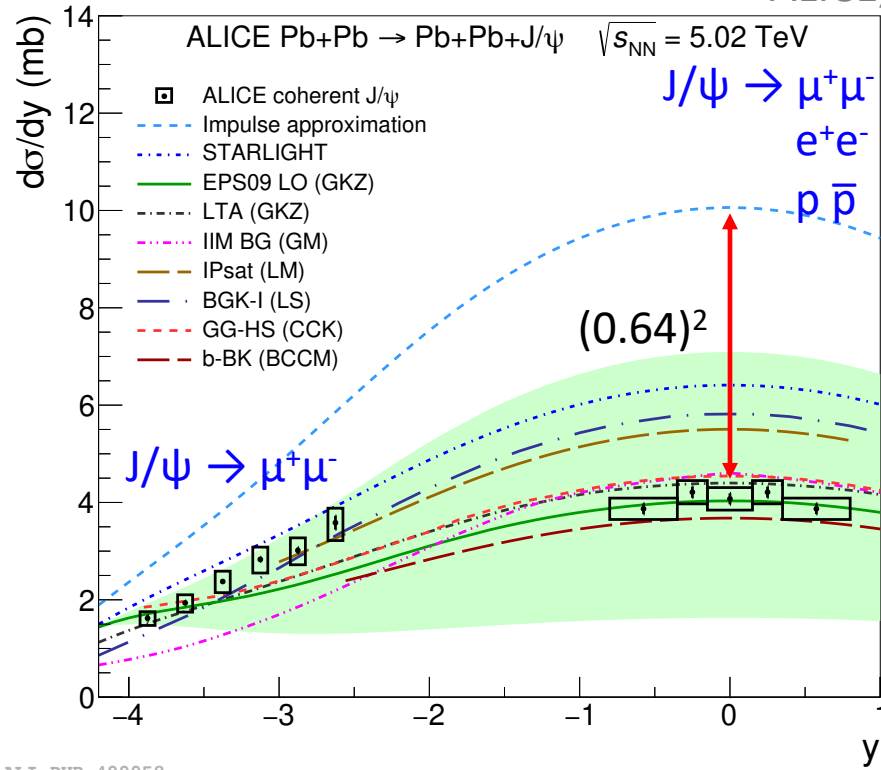
$|y| < 0.9$
Nuclear overlap
 $J/\psi \rightarrow e^+e^-$
 $\gamma\gamma \rightarrow e^+e^-$

$2.5 < y < 4$, UPC
 $\gamma\gamma \rightarrow \mu^+\mu^-$

Coherent J/ψ and ψ' photoproduction in Pb–Pb UPC

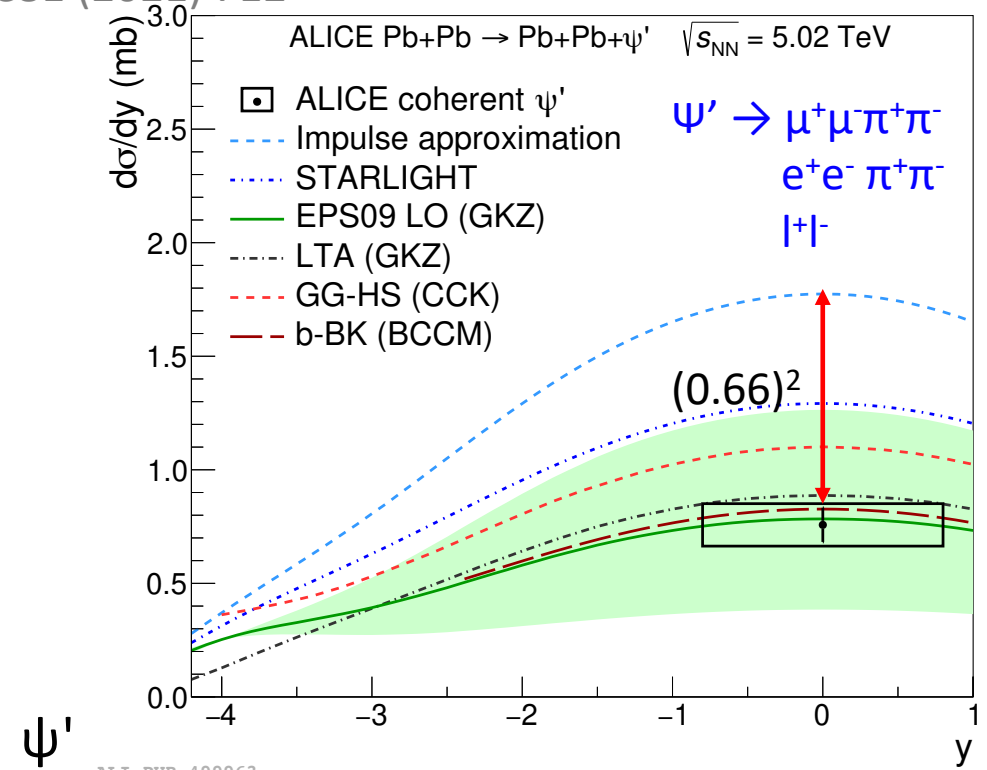


ALICE, Eur. Phys. J. C81 (2021) 712



J/ψ

ALI-PUB-499958



ψ'

ALI-PUB-499963

- Nuclear shadowing (for $x \sim 10^{-3}$): $S_{p_b} = 0.64 \pm 0.04$
- Models with shadowing (LTA) and saturation (**GG-HS**) describe mid and forward y but not semi-forward y ($2.5 < y < 3.5$)
- No model describes the full y range (except **EPS09** with large shadowing uncertainties)

- $S_{p_b} = 0.66 \pm 0.06$
- **EPS09**, LTA and **b-BK** (gluon saturation) describe data
- **GG-HS** overpredicts data

EPS09 LO, LTA (GKZ): Phys.Rev.C 93 (2016) 5, 055206

GG-HS: Phys.Rev.C 97 (2018), 024901, Phys.Lett.B 766 (2017) 186-191

B-BK: Phys.Lett.B 817 (2021) 136306

Coherent J/ψ photoproduction in Pb–Pb UPC: $|t|$ dependence



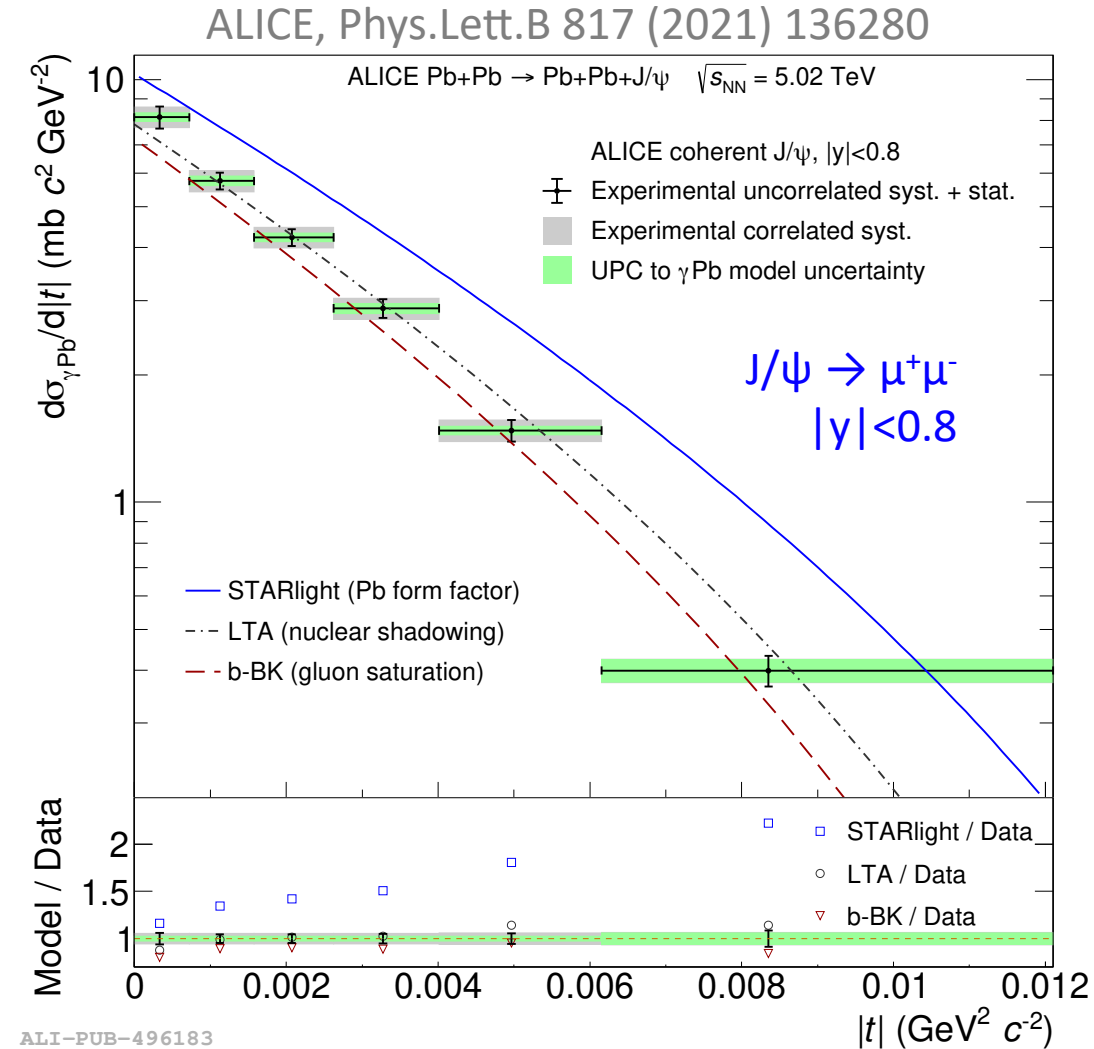
- $|t|$ = square of the momentum transferred between incoming and outgoing nucleus

$$\left. \frac{d\sigma_{J/\psi}^{coh}}{dy dp_T^2} \right|_{y=0} = 2n_{\gamma Pb}(y=0) \frac{d\sigma_{\gamma Pb}}{d|t|}$$

- Probes the transverse partonic structure of the nucleus

- Poor description by **STARlight** model (driven by nuclear form factor) Comput.Phys.Commun. 212 (2017) 258-268

- Agreement with models including nuclear shadowing (LTA) and gluon saturation (**b-BK**)



Exclusive J/ψ production in p–Pb collisions



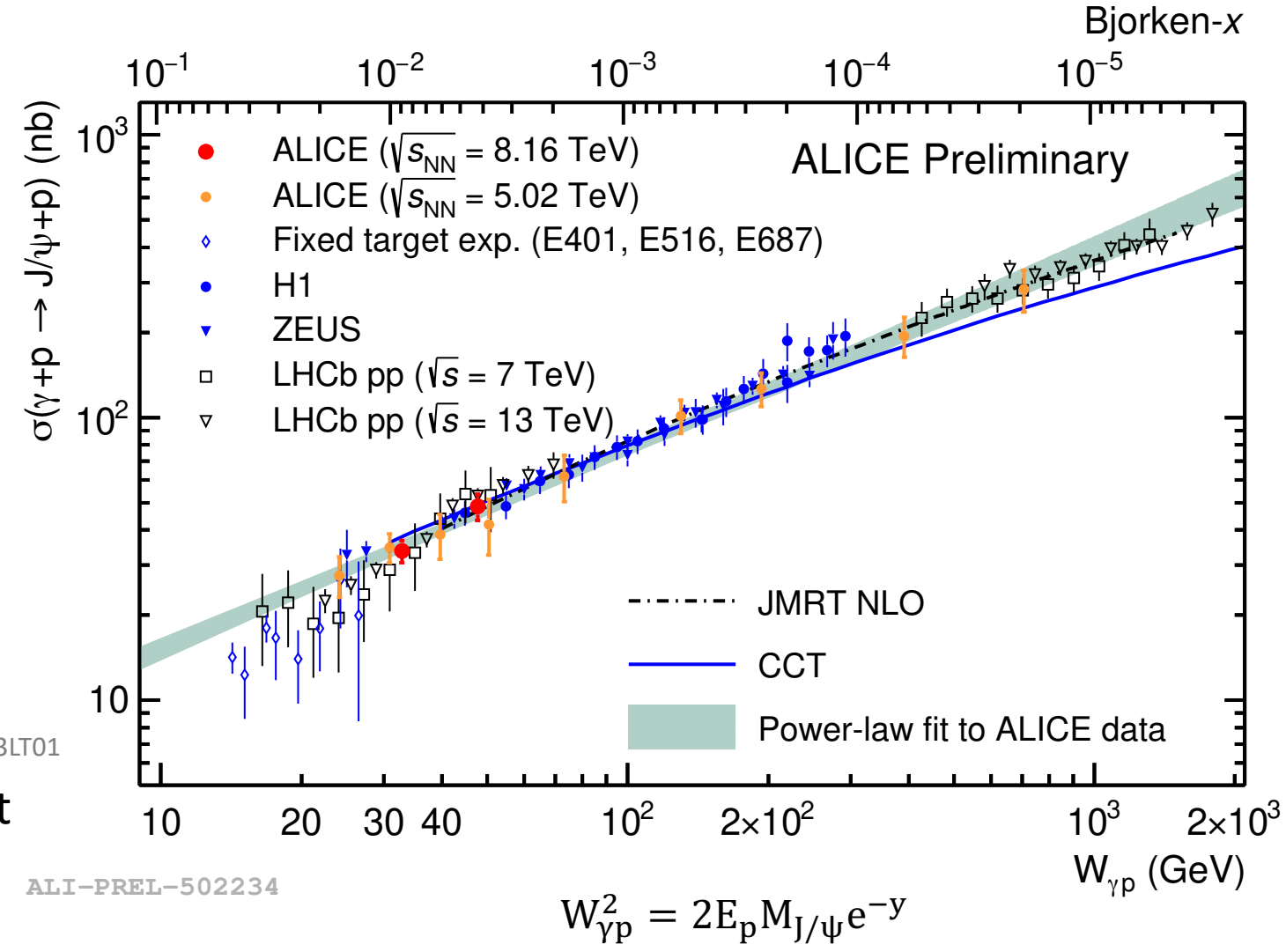
- Photon emitted most likely by Pb
=> no ambiguity

- No changes between HERA (e–p) and LHC

- Compatible with LHCb (pp)

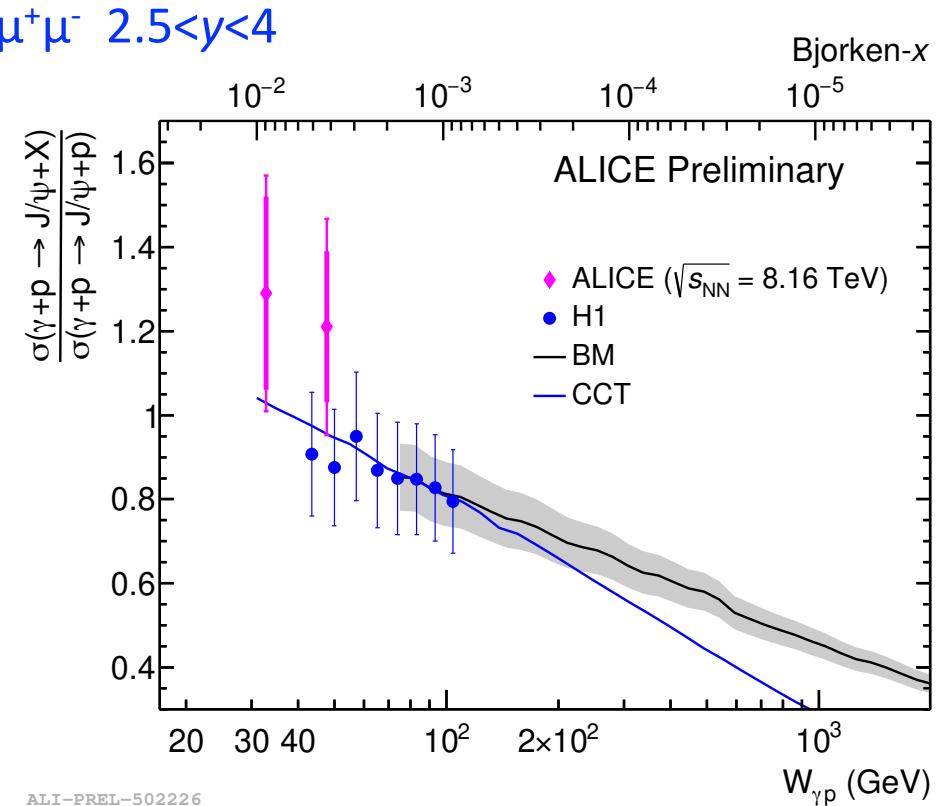
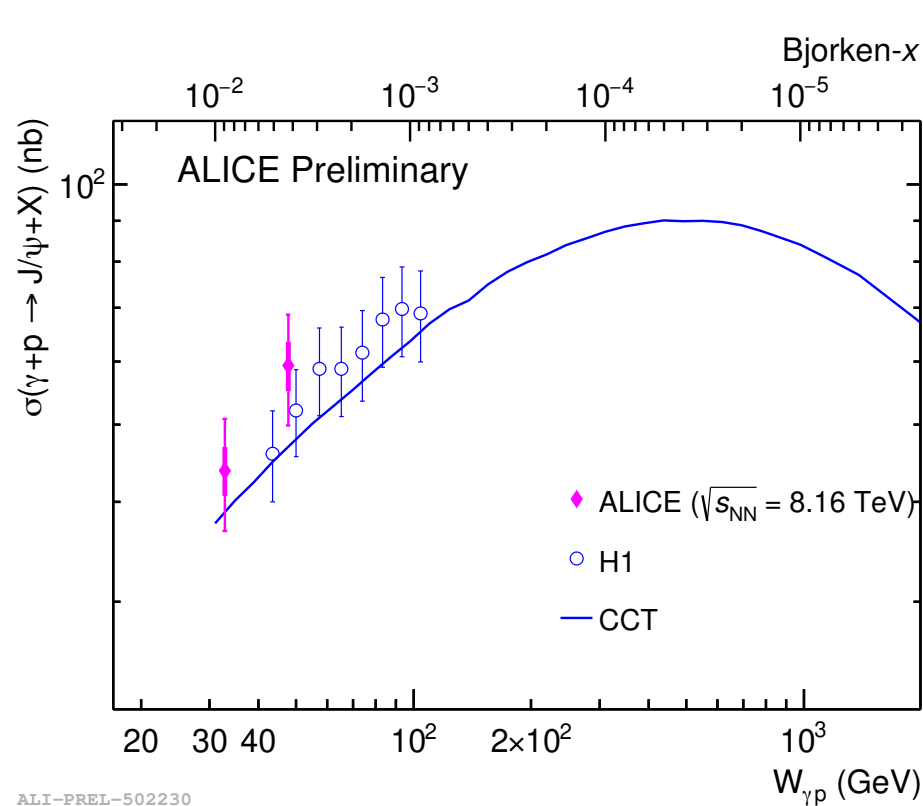
- In agreement with models:
 - JMRT NLO: DGLAP formalism with main NLO contributions J.Phys.G 44 (2017), 03LT01
 - CCT: saturation in energy-dependent hot-spot model Phys.Lett.B 766 (2017) 186-191

ALICE measurement: $J/\psi \rightarrow \mu^+\mu^-$ $2.5 < y < 4$



Dissociative J/ψ production in p–Pb collisions

- First measurement at the LHC

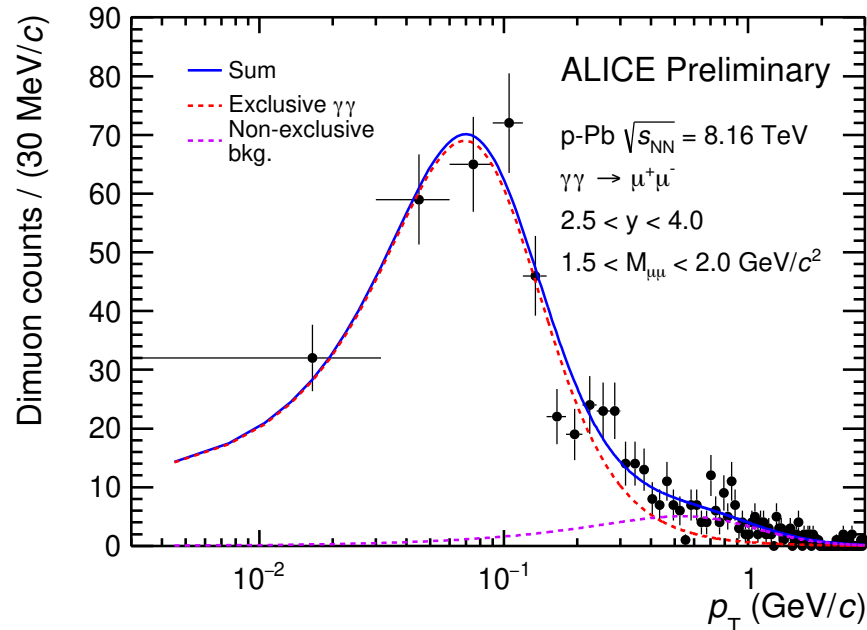


- Well described by CCT
- Compatible with HERA measurements

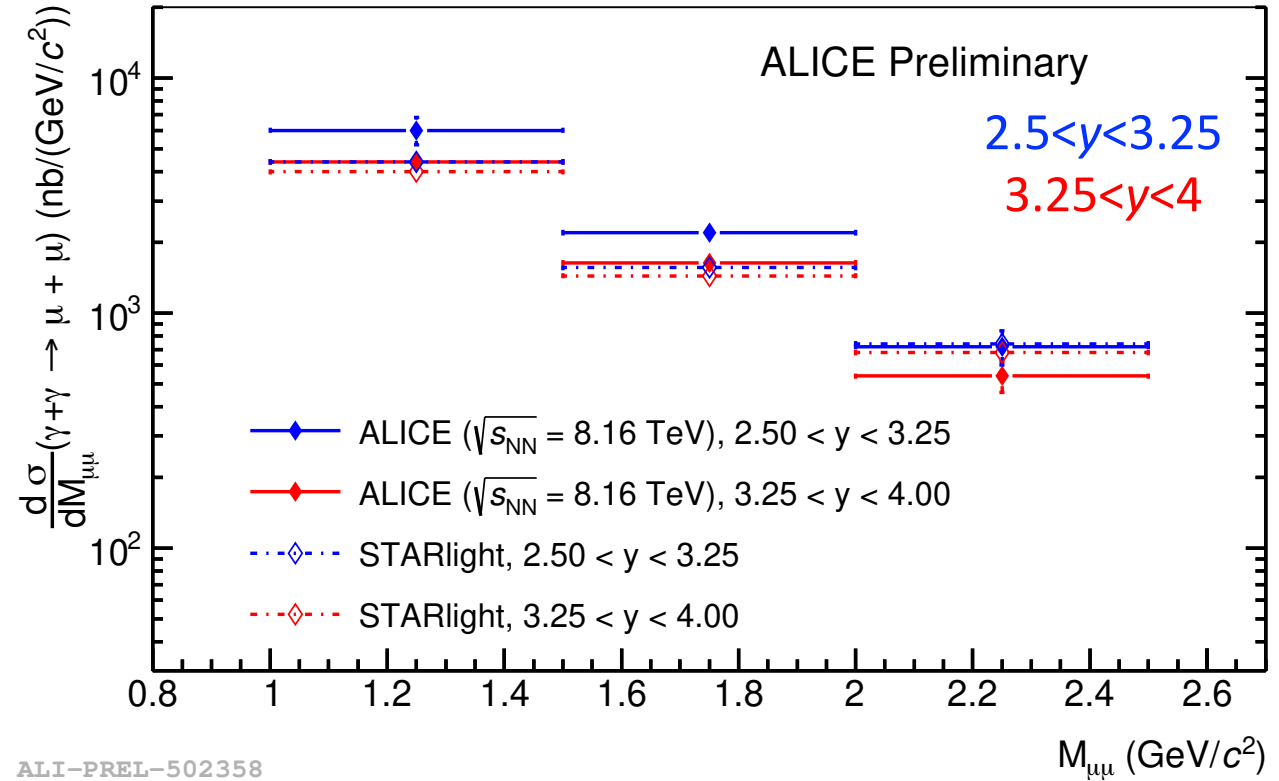
$\gamma\gamma \rightarrow \mu^+\mu^-$ production in p-Pb collisions

- Signal extracted from fit of the $\mu^+\mu^- p_T$

$J/\psi \rightarrow \mu^+\mu^-$



ALI-PREL-502222



ALI-PREL-502358

- Compared with STARlight (LO QED, no final-state interactions, no interactions within proton radius)

- Agreement found within 3σ

Coherent J/ψ photoproduction in Pb–Pb collisions: p_T

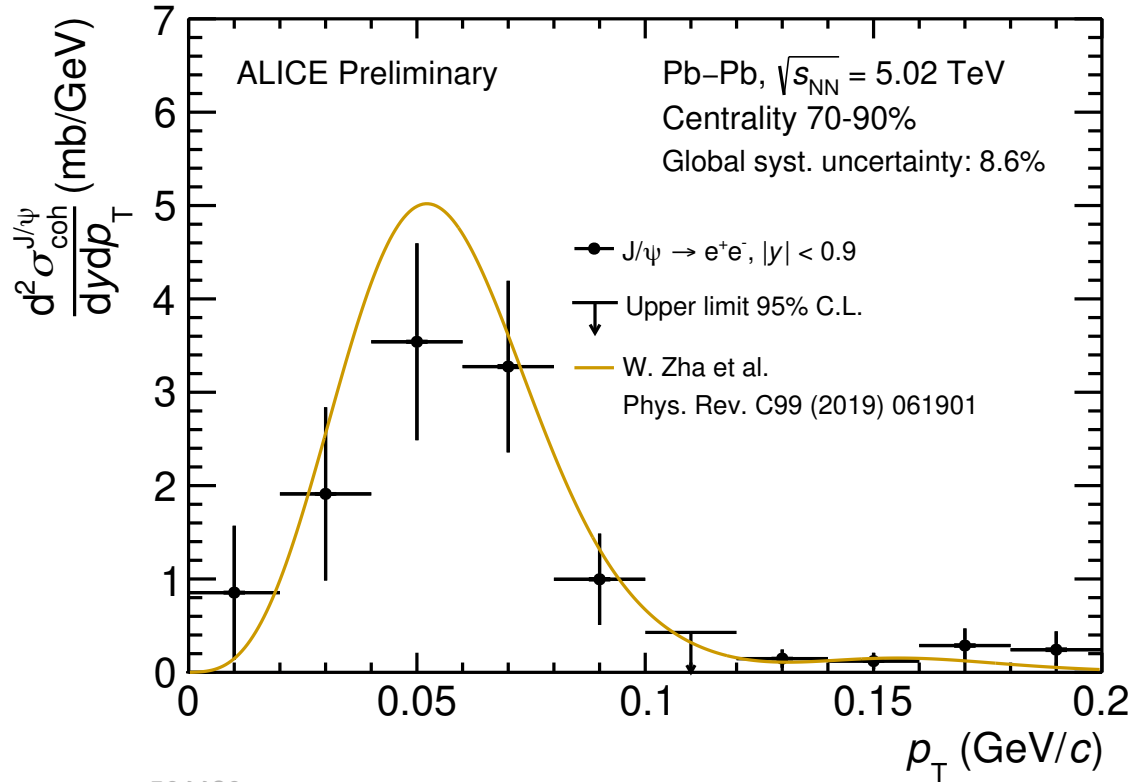


- p_T distribution measured in 2 centrality classes at mid rapidity

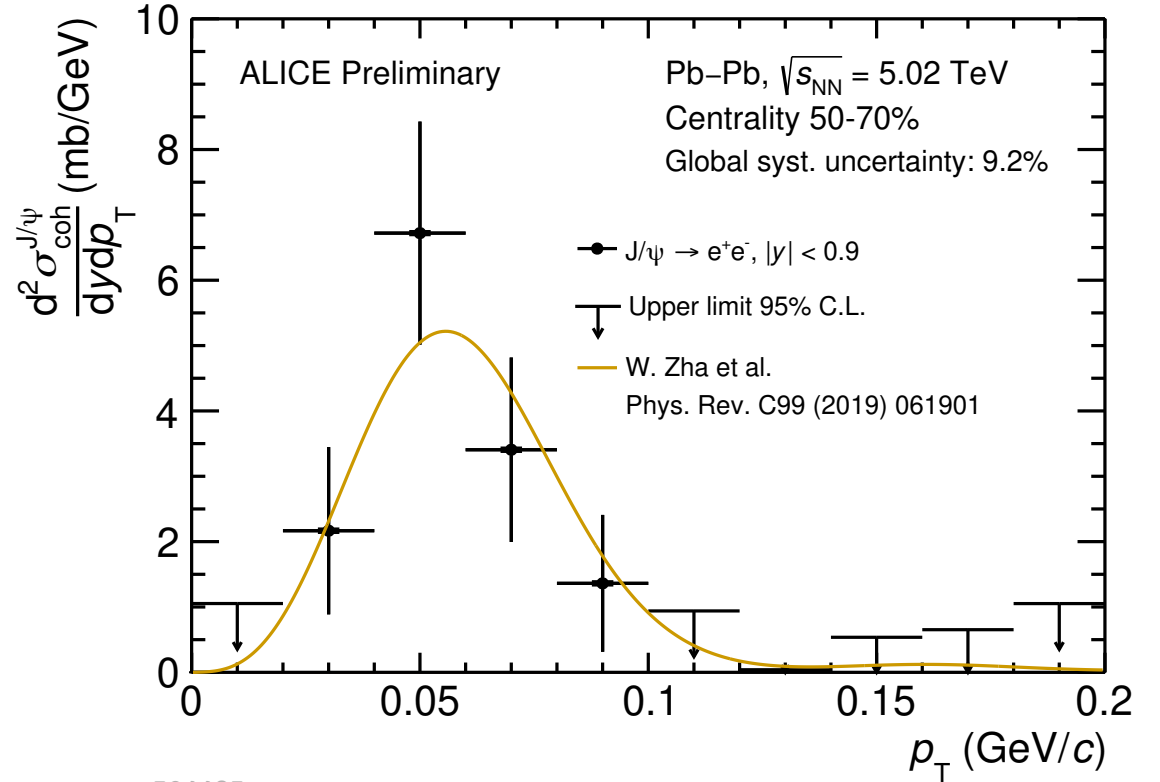
70-90%

$J/\psi \rightarrow e^+e^- \quad |y| < 0.9$

50-70%



ALI-PREL-504480



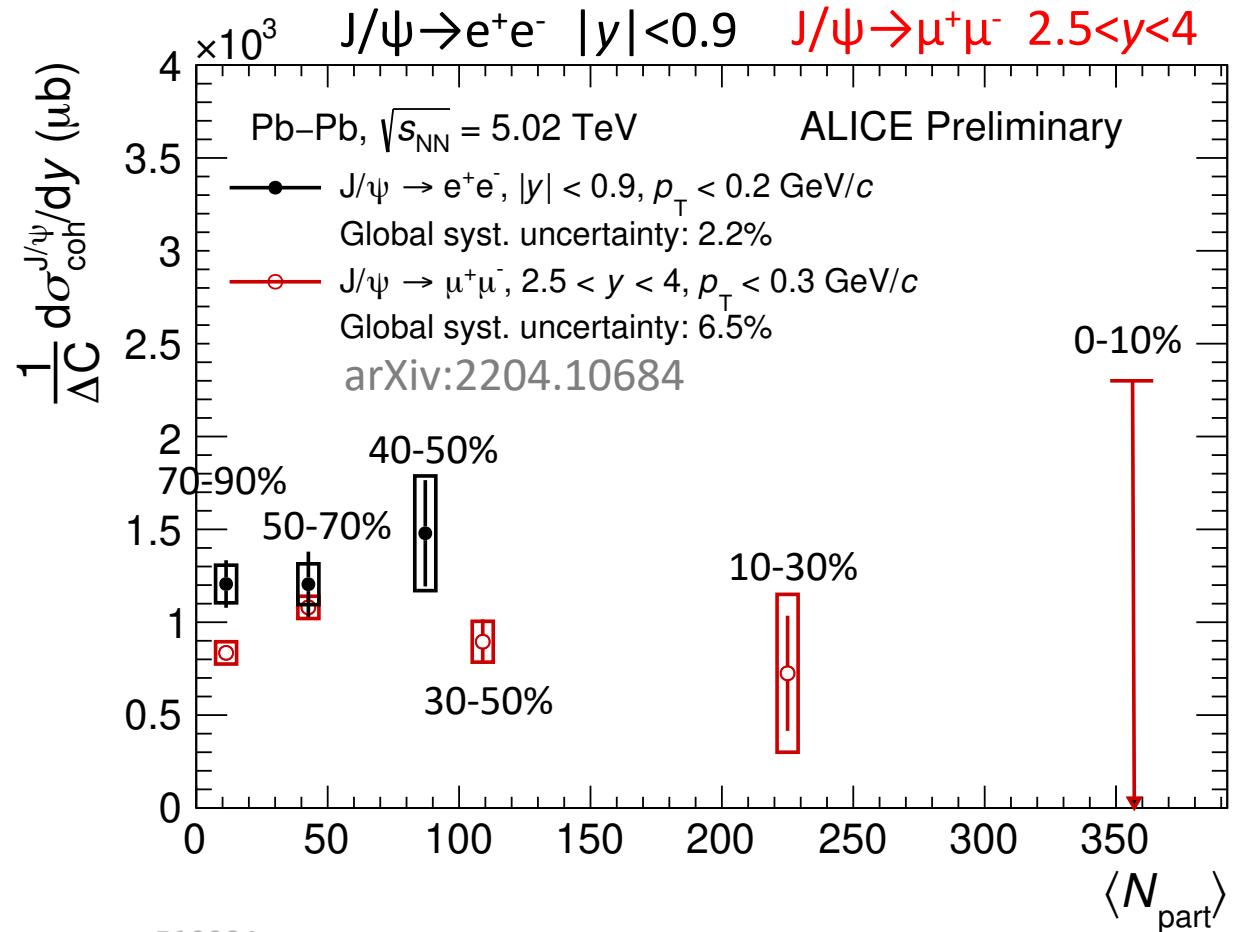
ALI-PREL-504485

- Compatible with theoretical models including nuclear overlap

Coherent J/ψ photoproduction in Pb–Pb collisions: centrality

- Measured at mid and **forward** rapidity

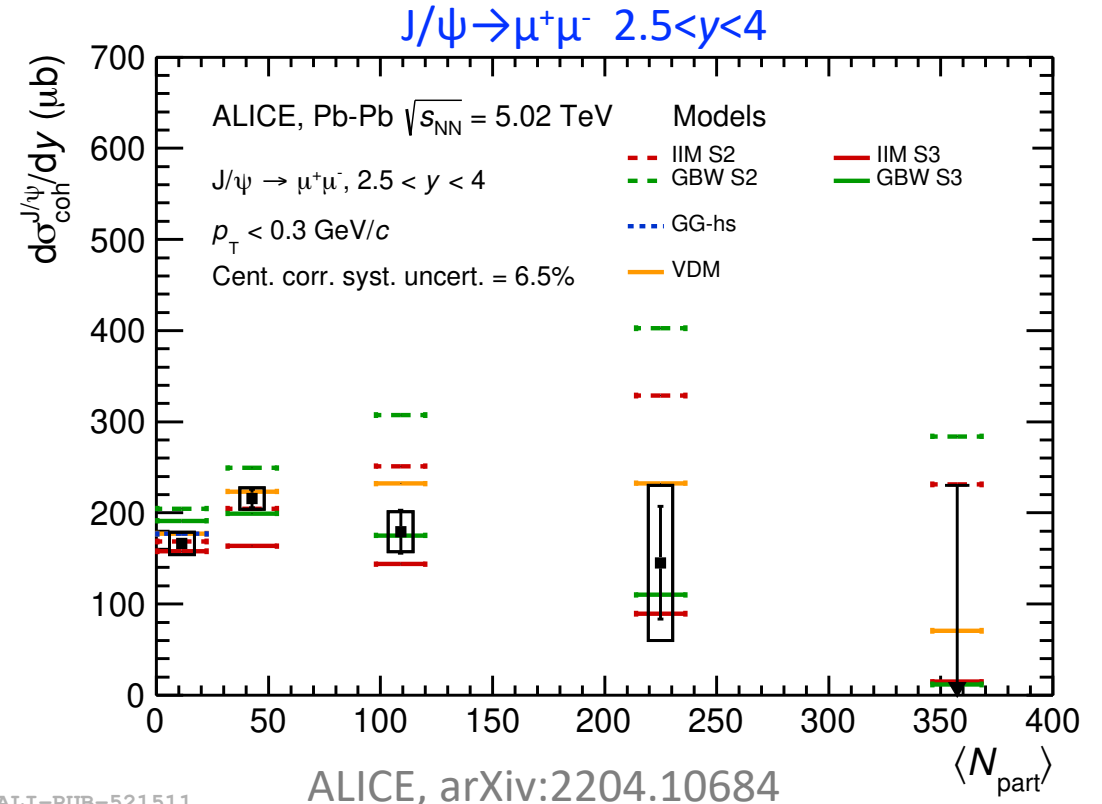
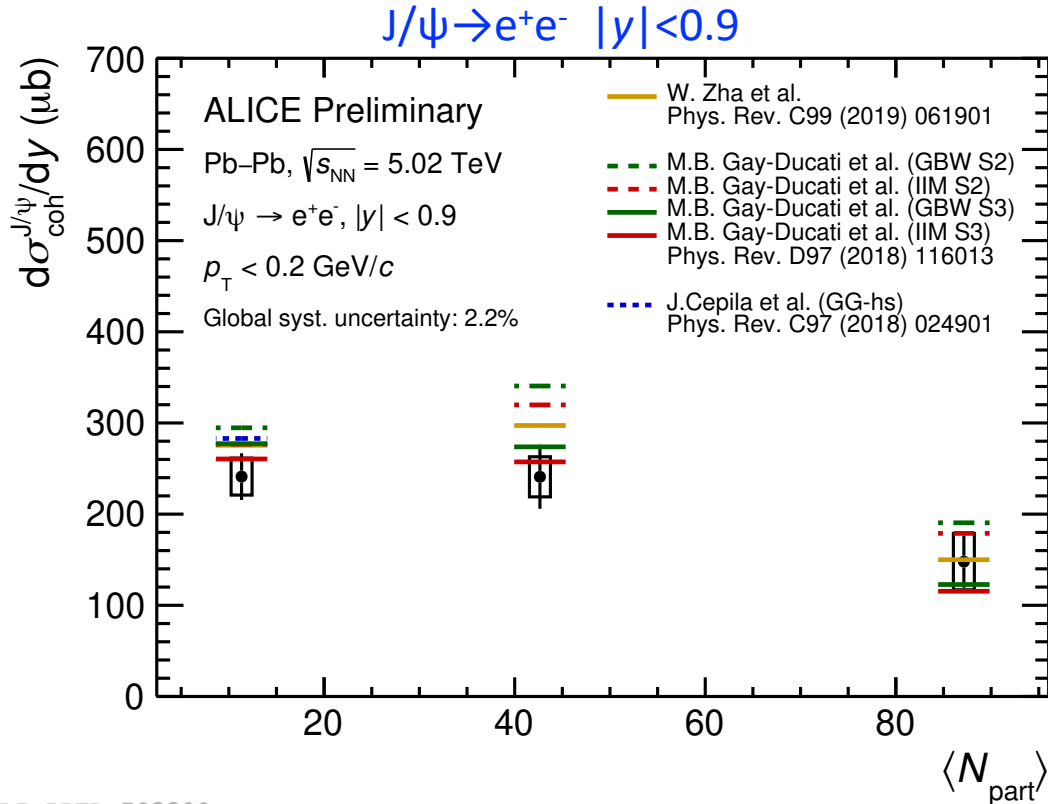
Normalized to centrality interval width ΔC (in percentile) to avoid trivial interval width dependence



ALI-PREL-519984

- Similar centrality dependence in the common intervals
- No reduction of the cross section observed towards more central collisions with current uncertainties

Coherent J/ψ photoproduction in Pb–Pb collisions: model comparison

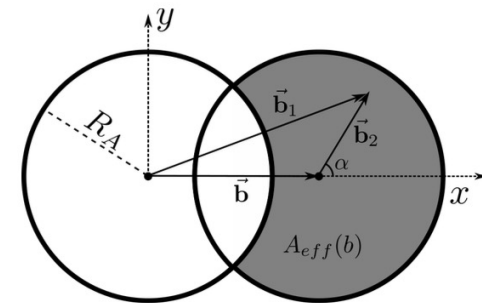


ALI-PREL-503800

ALI-PUB-521511

ALICE, arXiv:2204.10684

- Effective photon flux for **IIM** and **GBW S2** and **VDM**:
 - VDM fairly describes data over the full centrality range VDM: Phys.Lett.B 790 (2019) 339-344
 - Additional modification of the photonuclear cross section (S3) needed for IIM and GBW to describe semi-central to central events
- Effective photon flux and modification of the photonuclear cross section for **Zha**: describes mid-rapidity data
- **GG-hs** valid only for peripheral collisions



$\gamma\gamma \rightarrow e^+e^-$ in Pb–Pb collisions



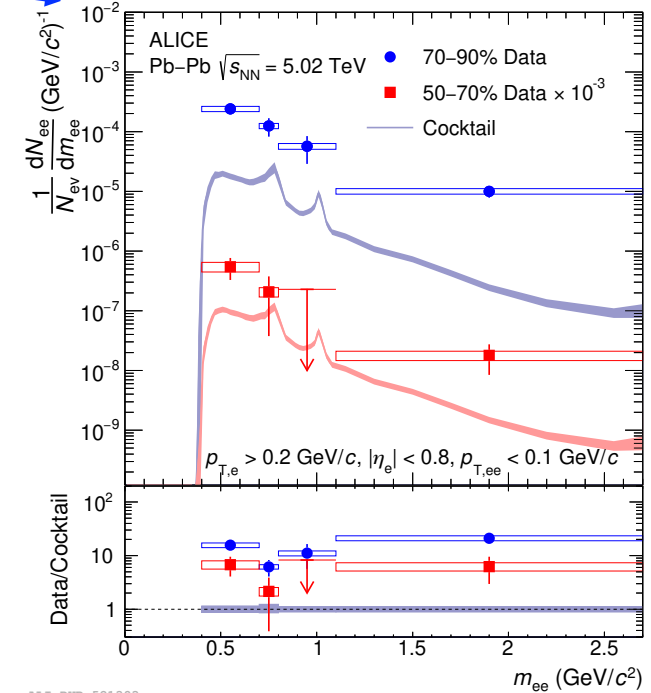
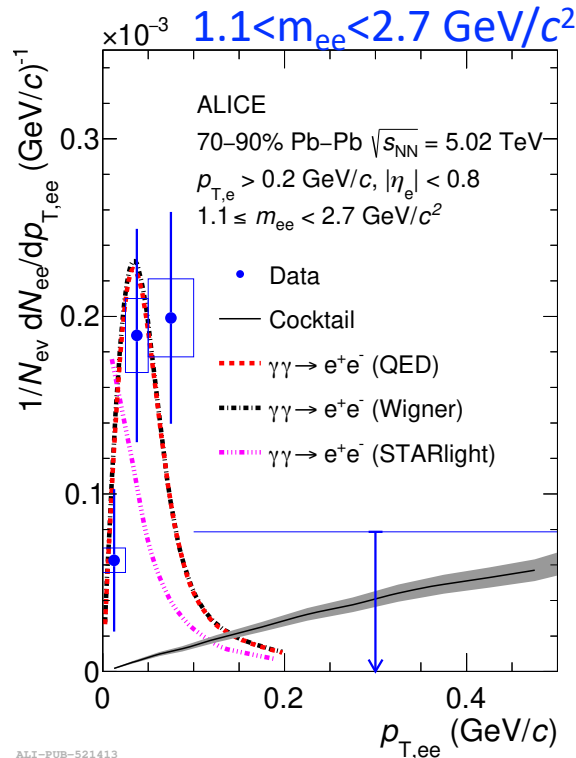
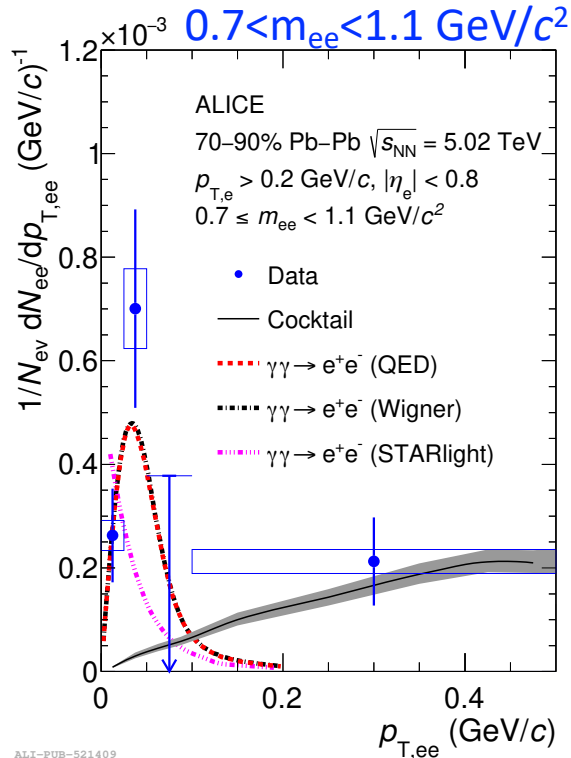
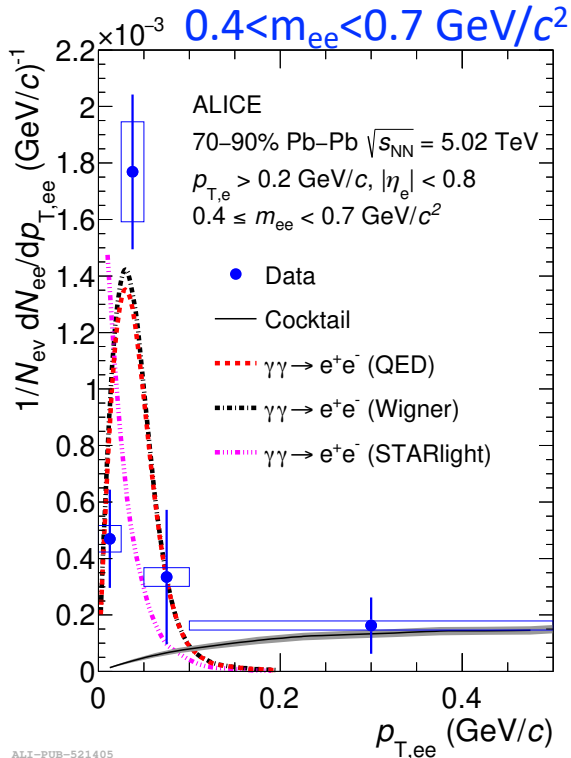
ALICE

- Excess observed over known hadronic e^+e^- sources

- Similar observation from STAR

- First measurement of $\gamma\gamma \rightarrow e^+e^-$ pairs with $m_{ee} < 2.7$ GeV/ c^2 in peripheral Pb–Pb collisions at the LHC

$J/\psi \rightarrow e^+e^-$ $|\eta_e| < 0.8$



ALICE, arXiv:2204.11732

- Data described by models including b dependence of the photon k_T distribution (**QED**, Wigner)

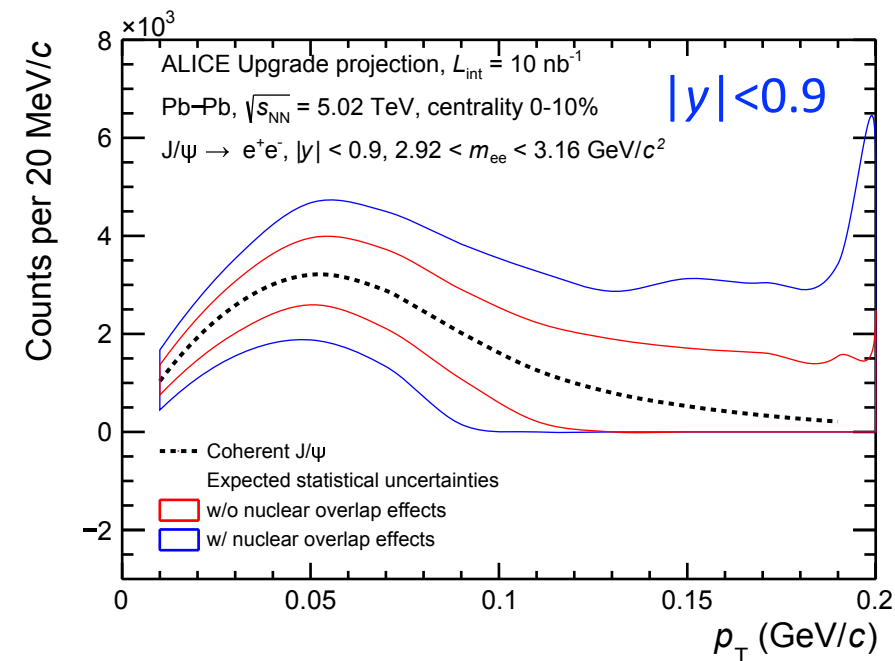
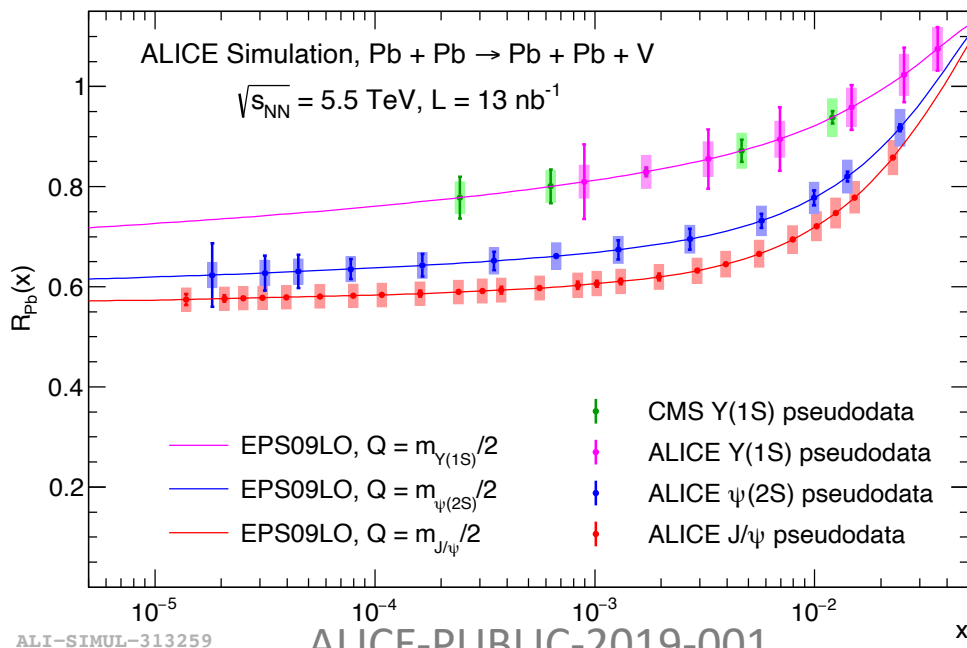
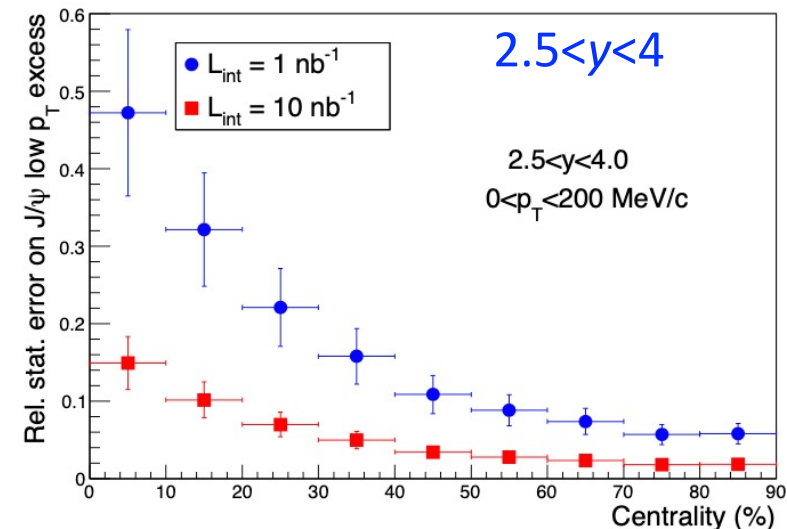
QED: Phys.Lett.B 800 (2020) 135089, Eur.Phys.J.A 57 (2021) 10, 299
Wigner: Phys.Lett.B 814 (2021) 136114

Outlook

- Run 3+4: features
 - Luminosity increase: $\sim 1 \text{ nb}^{-1}$ (Run 2) $\Rightarrow \sim 10 \text{ nb}^{-1}$ (Run 3+4)
 - Upgraded detectors: continuous readout
- Larger statistics
 - Several hundreds for (MB events) at mid rapidity
- New measurements possible (e.g. $\Upsilon(1S)$ in UPC)



ALICE, J.Phys.G 41 (2014) 087001



UPC

- **Coherent J/ψ** photoproduction cross section measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
 - Moderate **gluon shadowing** in nucleus (~ 0.64)
 - $|t|$ dependence sensitive to transverse parton distribution in nucleus
 - Described by models with **shadowing** or **saturation**
- **Exclusive J/ψ** photoproduction off proton measured in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV:
 - In agreement with previous results from HERA and LHCb
- **Dissociative J/ψ** photoproduction and **low mass $\gamma\gamma \rightarrow \mu^+\mu^-$** production measured in p–Pb collisions for the **first time at the LHC**

Pb-Pb collisions with nuclear overlap

- **Coherent J/ψ** photoproduction cross section measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV down to **40%** most central collisions at mid rapidity and **10%** most central collisions at forward rapidity
 - Described by models implementing **effective photon flux** and/or **modified photonuclear cross sections**
- **$\gamma\gamma \rightarrow e^+e^-$** measured for the first time at low invariant mass in **peripheral** Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

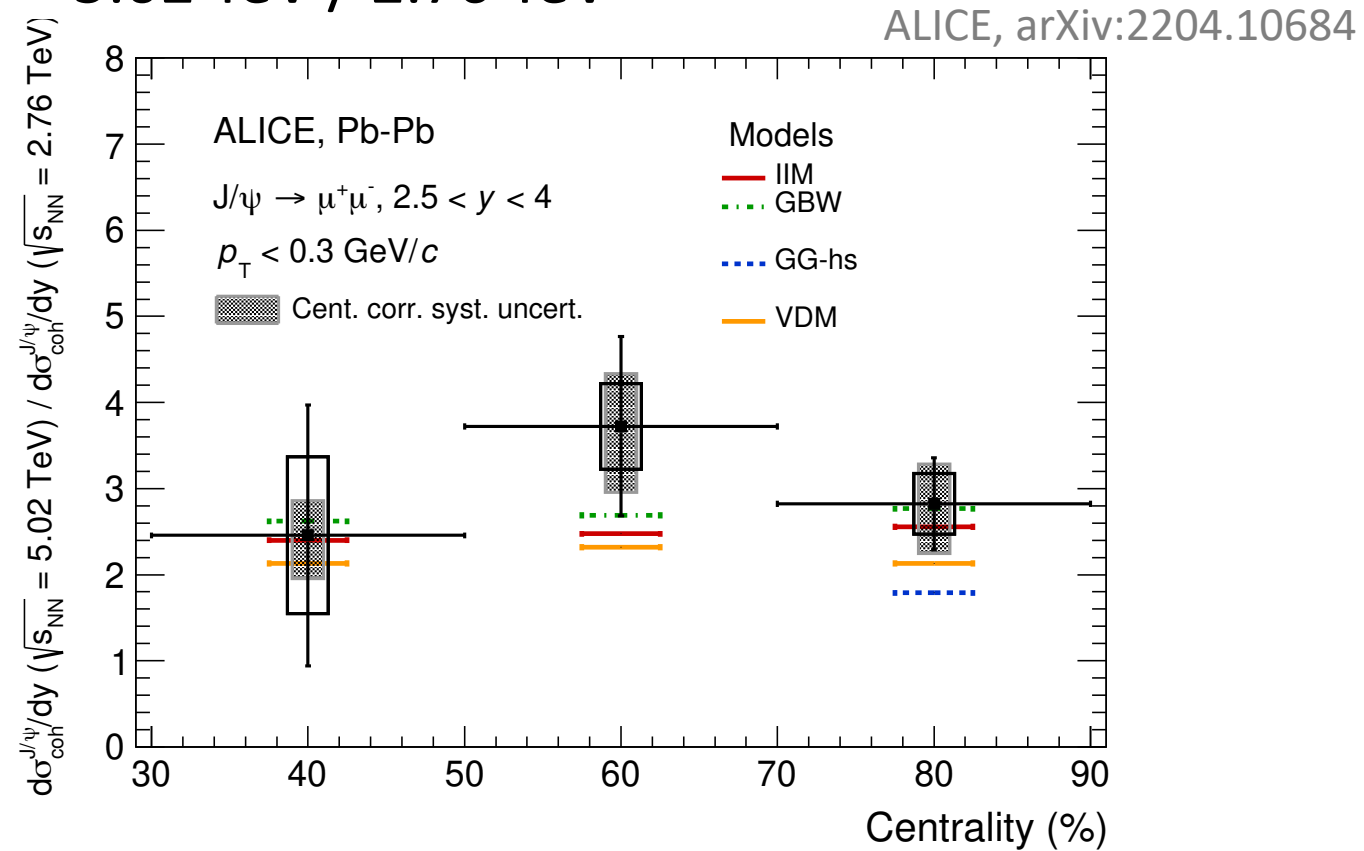
Outlook

- Significant increase in statistics expected for Run 3 and 4

Backup

Coherent J/ψ photoproduction in Pb–Pb collisions: energy dependence

- Ratio of results at $\sqrt{s_{NN}} = 5.02 \text{ TeV} / 2.76 \text{ TeV}$



ALI-PUB-521515

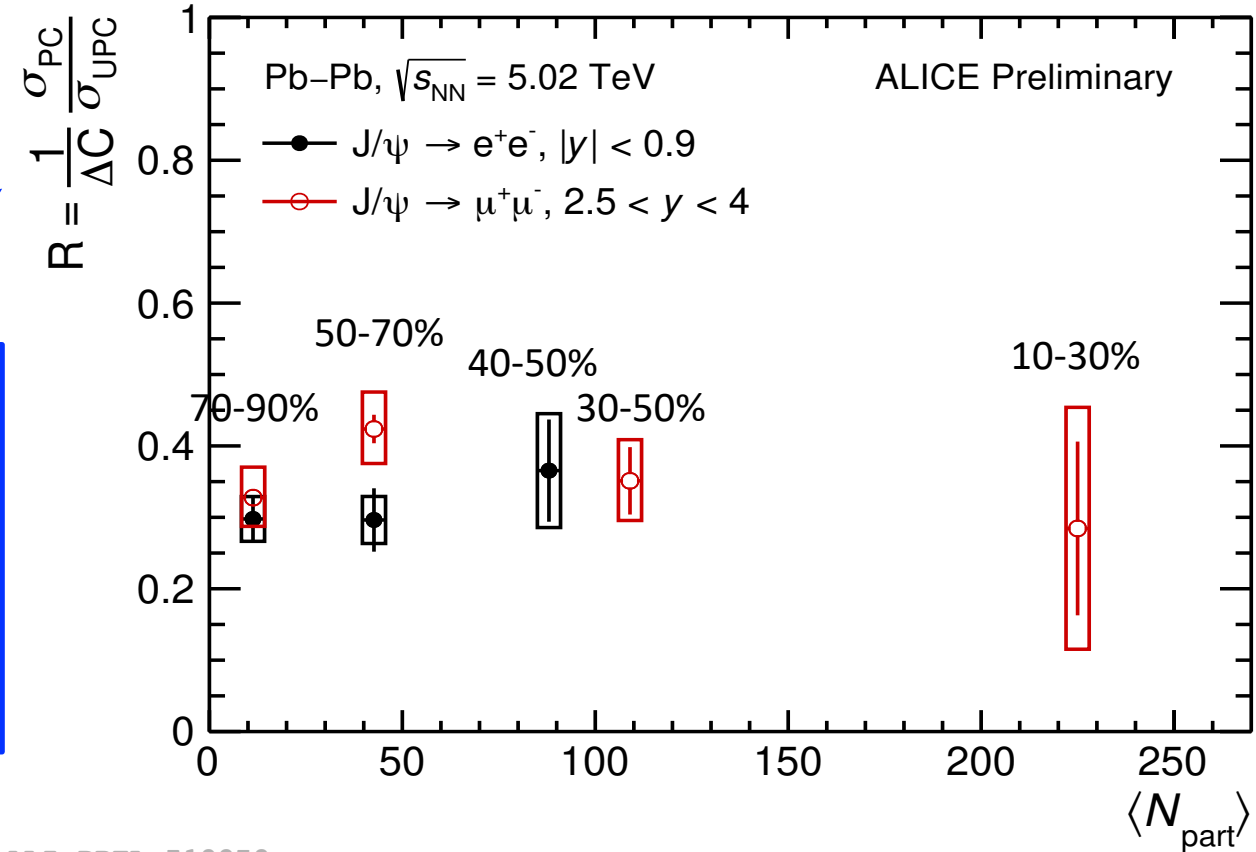
- No centrality dependence
- Models describe data within uncertainties

Coherent J/ψ photoproduction in Pb–Pb collisions vs UPC



- Ratio to UPC measurement:

Normalized to centrality interval width ΔC (in percentile) to avoid trivial interval width dependence



ALI-PREL-519979

ALICE, arXiv:2204.10684

ALICE, Phys.Lett.B 798 (2019) 134926

ALICE, Eur. Phys. J. C81 (2021) 712

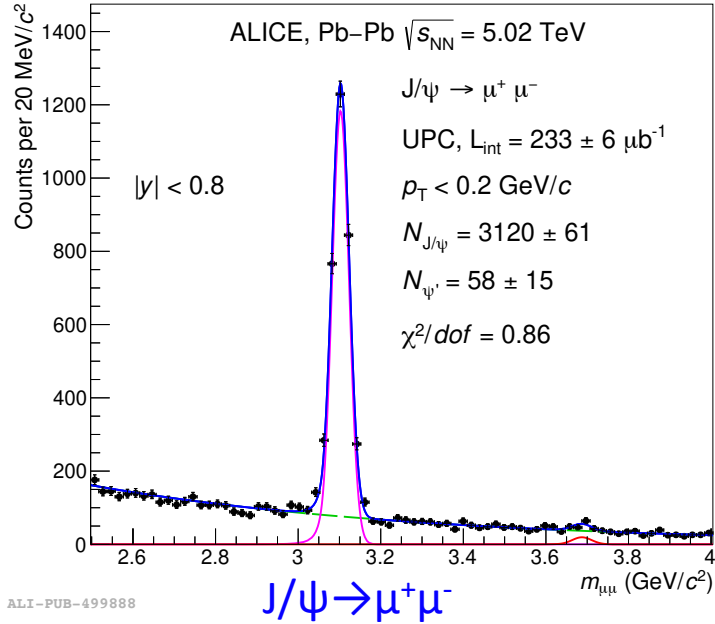
- Similar behavior at mid and **forward** rapidities
- No reduction of the cross section ratio observed towards more central collisions with current uncertainties

Coherent J/ψ photoproduction in Pb–Pb UPC: signal

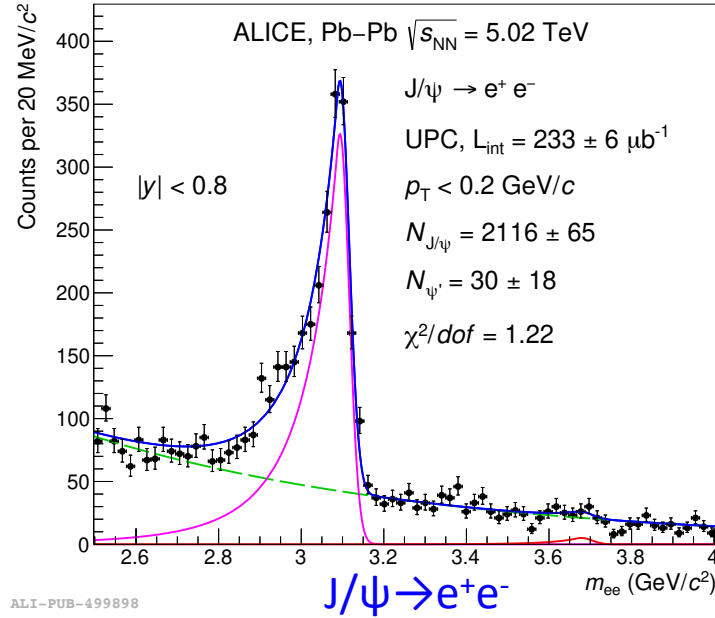


ALICE

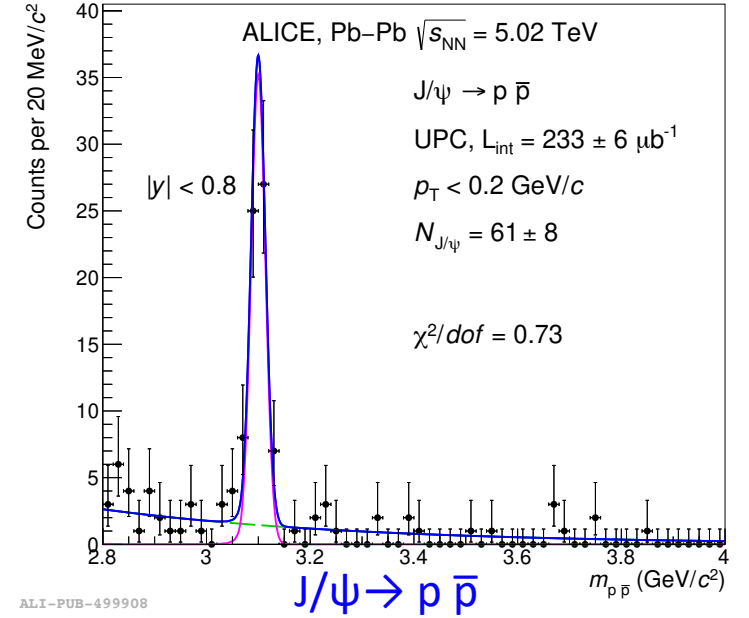
ALICE, Eur. Phys. J. C81 (2021) 712



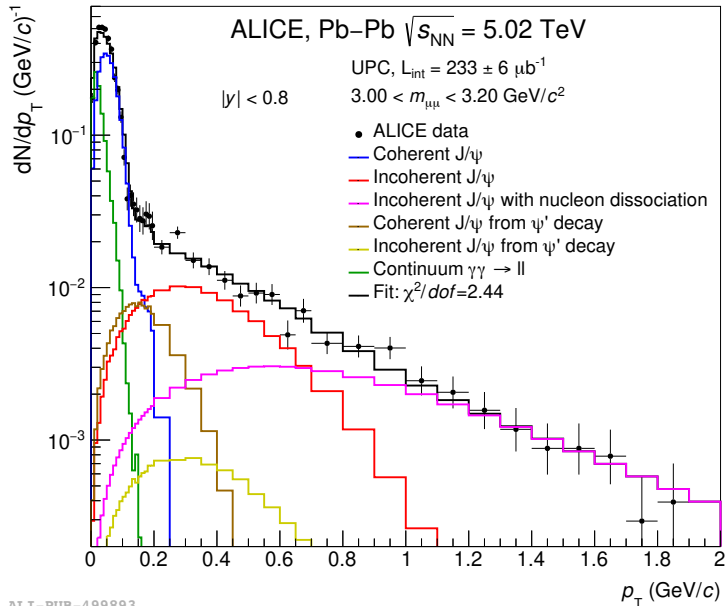
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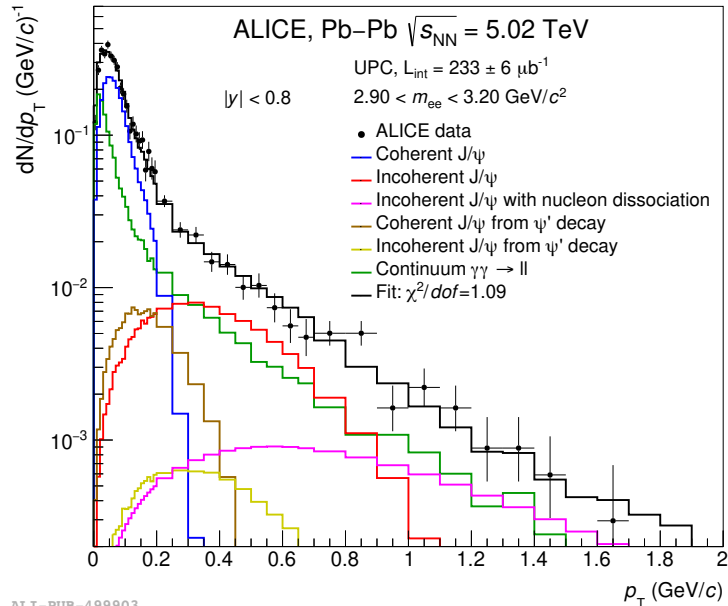
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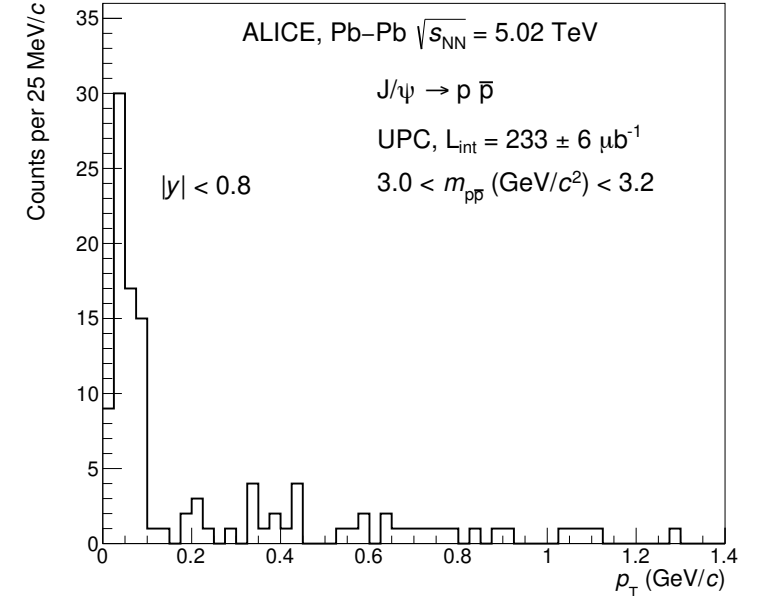
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ALI-PUB-499893



ALI-PUB-499903



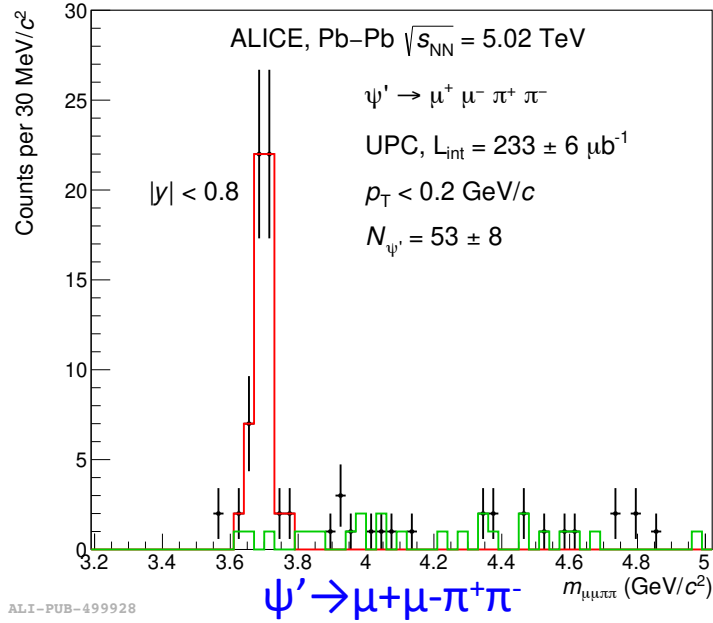
ALI-PUB-499913

Coherent ψ' photoproduction in Pb–Pb UPC: signal

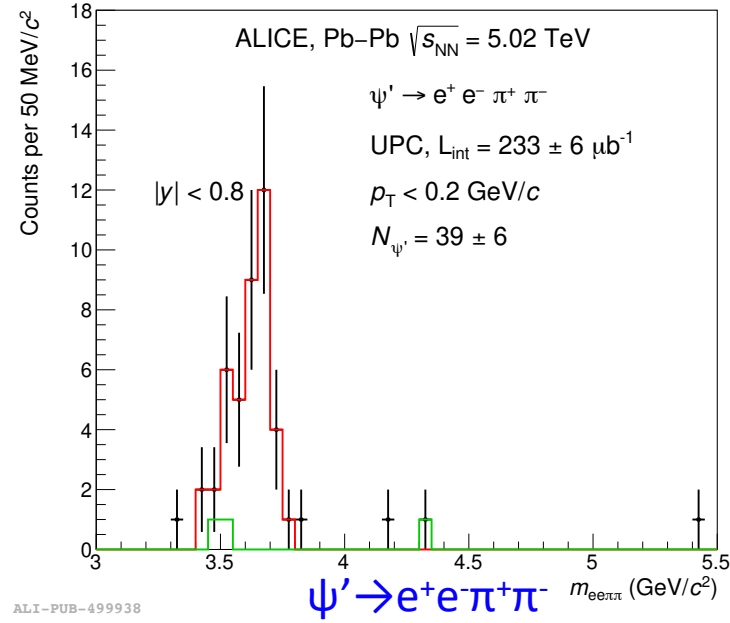


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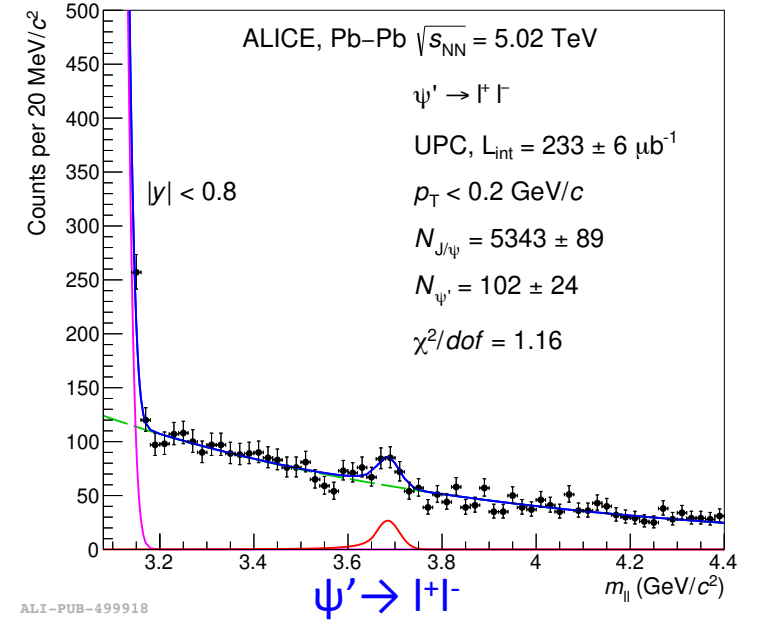
ALICE, Eur. Phys. J. C81 (2021) 712



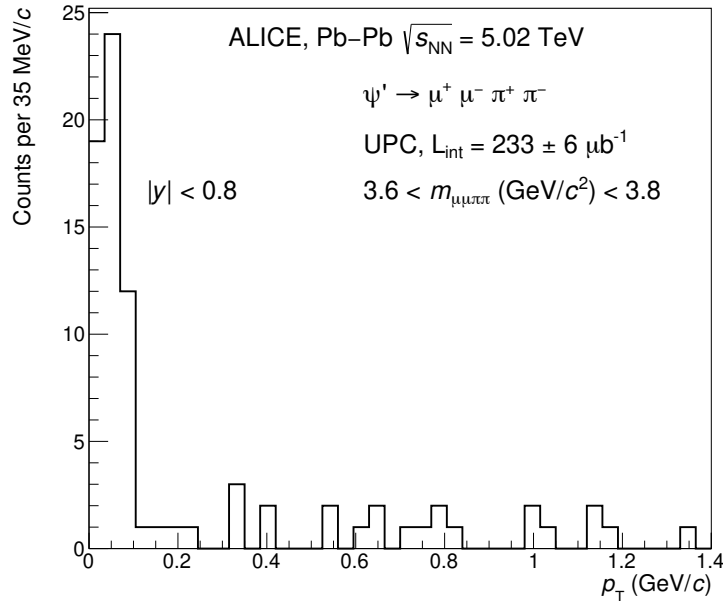
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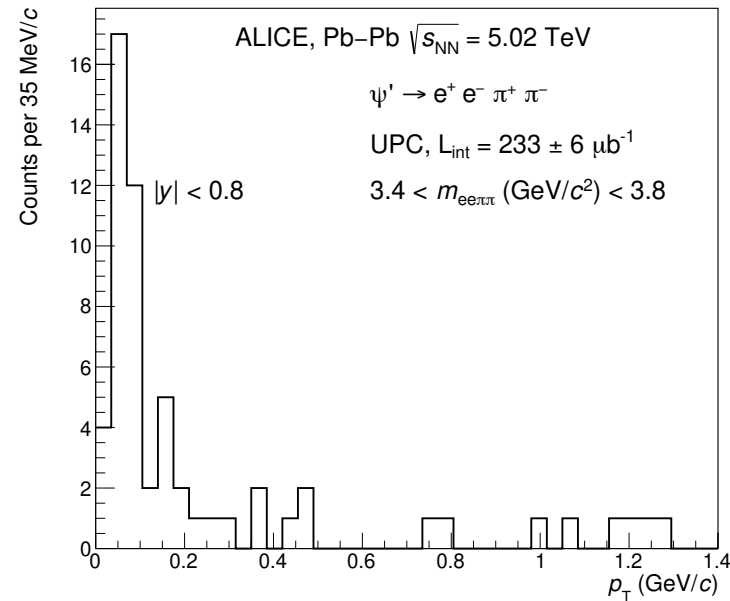
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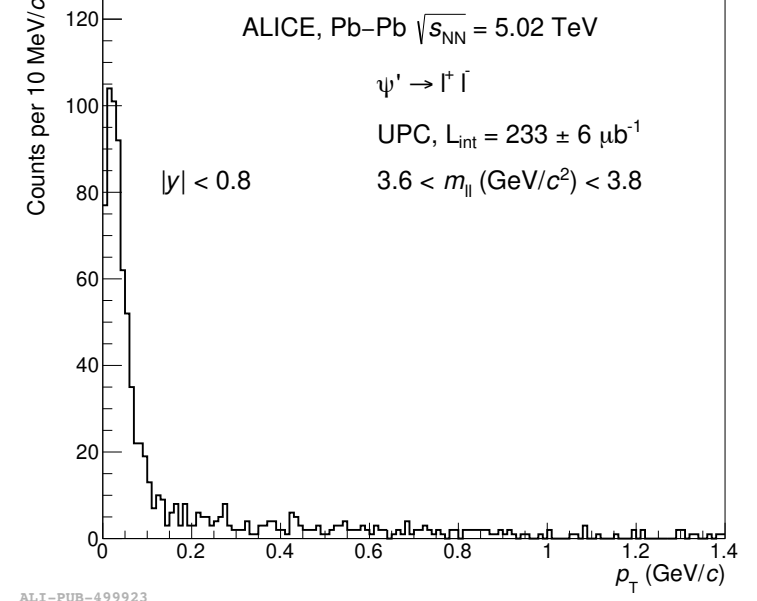
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ALI-PUB-499933



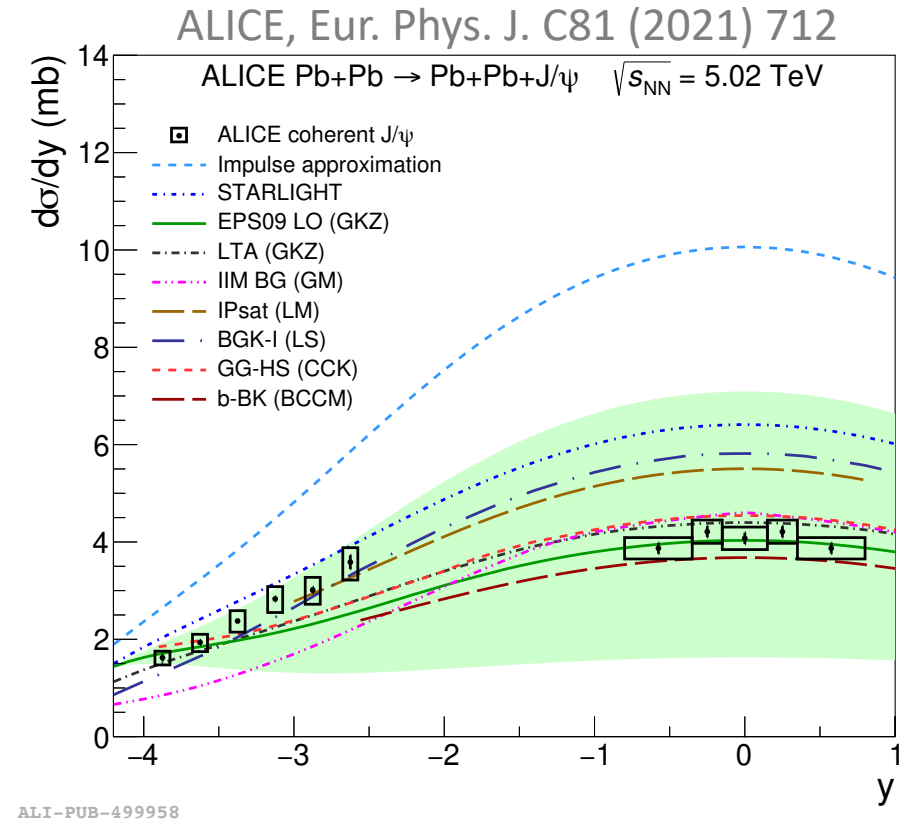
ALI-PUB-499943



ALI-PUB-499923

Coherent J/ψ photoproduction in Pb–Pb UPC: models

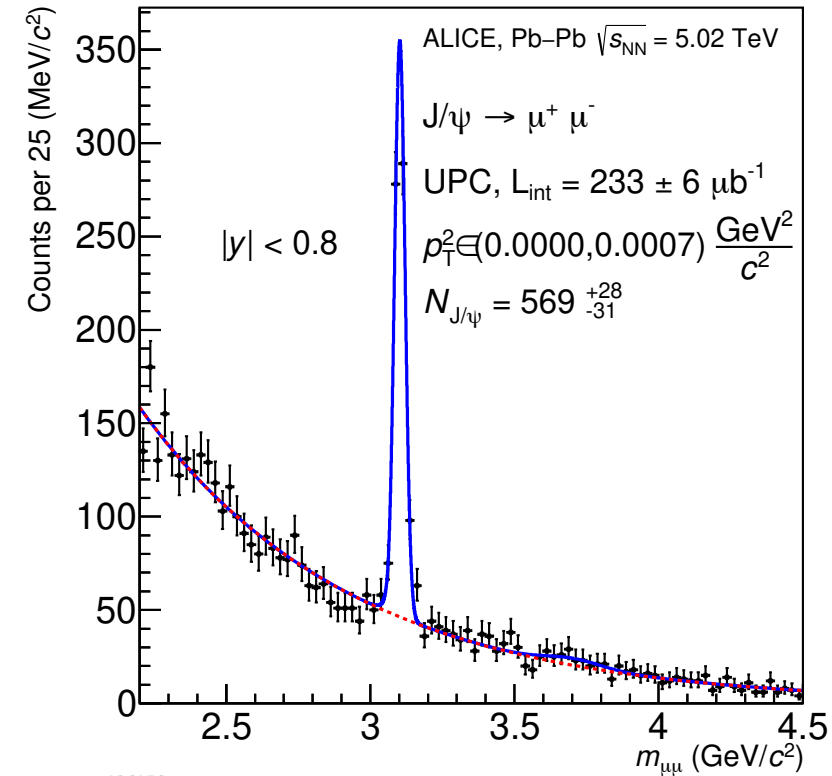
- **Impulse approximation**: no nuclear effect
- **STARlight**: VDM + Glauber Comput.Phys.Commun. 212 (2017) 258-268
- **EPS09 LO (GKZ)**: parameterization of nuclear shadowing data Phys.Rev.C 93 (2016), 055206
- **LTA**: Leading Twist Approximation of nuclear shadowing Phys.Rev.C 93 (2016), 055206
- **IIM BG, IPsat, BGK-I**: color dipole approach coupled to the Color Glass Condensate formalism with different assumptions on the dipole-proton scattering amplitude
Phys.Rev.C 90 (2014), 015203 Phys.Rev.C 83 (2011), 065202 Phys.Rev.C 99 (2019), 044905
 J.Phys.G 42 (2015), 105001 Phys.Rev.C 87 (2013), 032201
- **GG-HS**: color dipole model with hot-spots nucleon structure Phys.Rev.C 97 (2018), 024901 Phys.Lett.B 766 (2017) 186-191
- **b-BK**: Color dipole approach coupled with impact-parameter dependent Balitsky-Kovchegov equation Phys.Lett.B 817 (2021) 136306



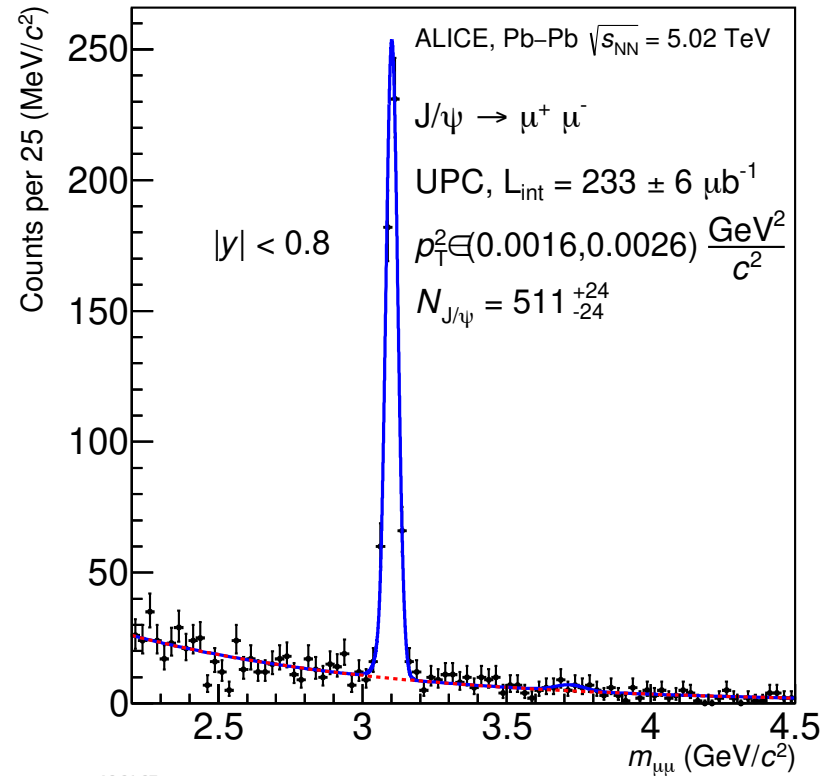
Coherent J/ψ photoproduction in Pb-Pb UPC: |t| dependence

- Signal extraction: fit with two CB functions (J/ψ, ψ′) and an exponential (**background**)

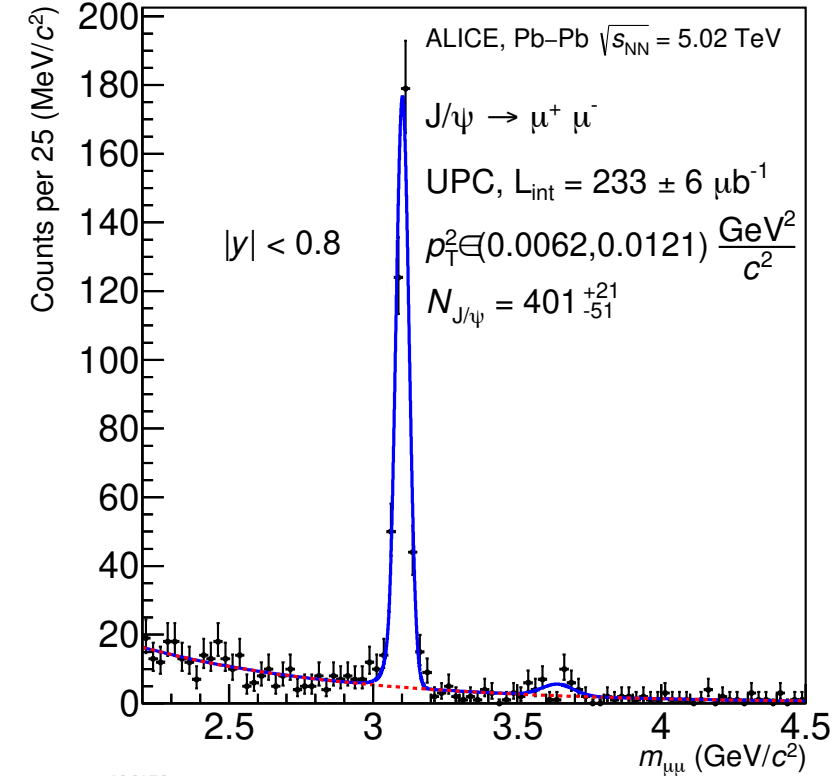
$0 < p_T^2 < 0.0007 \text{ GeV}^2/c^2$



$0.0016 < p_T^2 < 0.0026 \text{ GeV}^2/c^2$

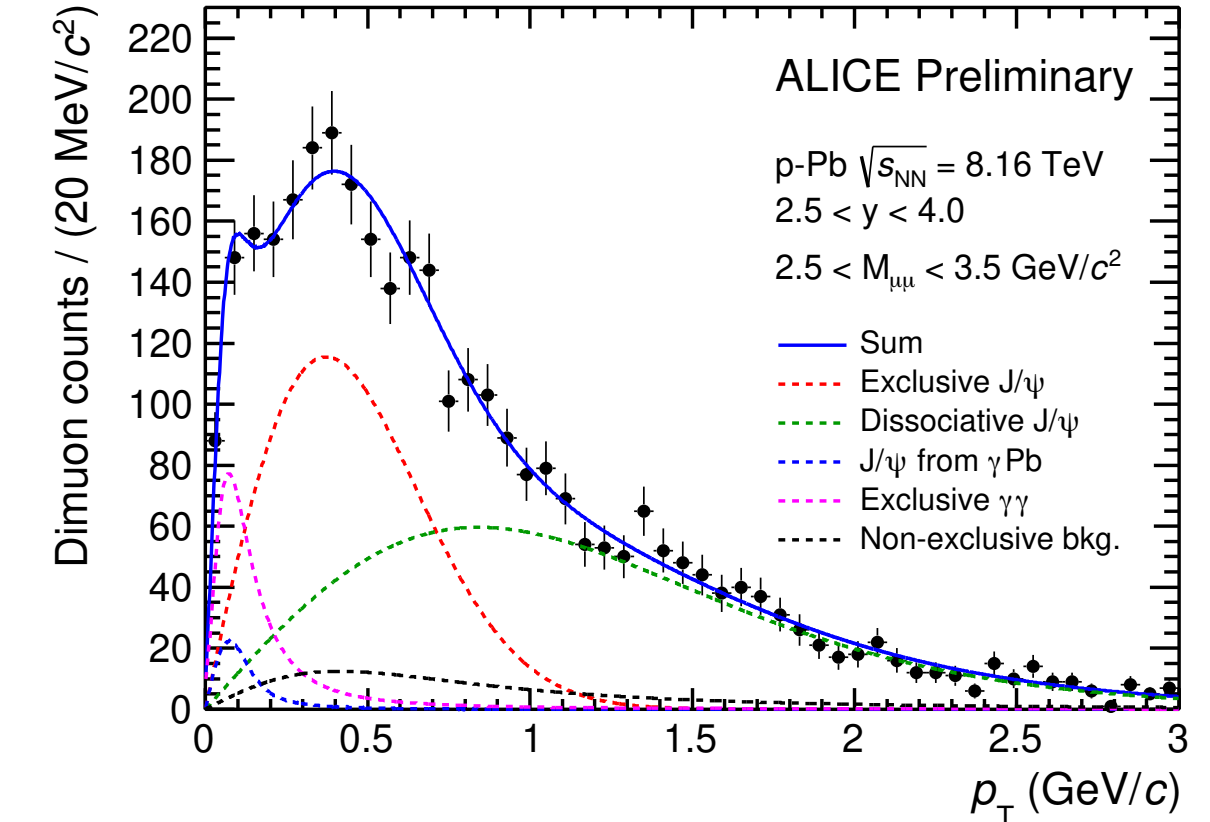
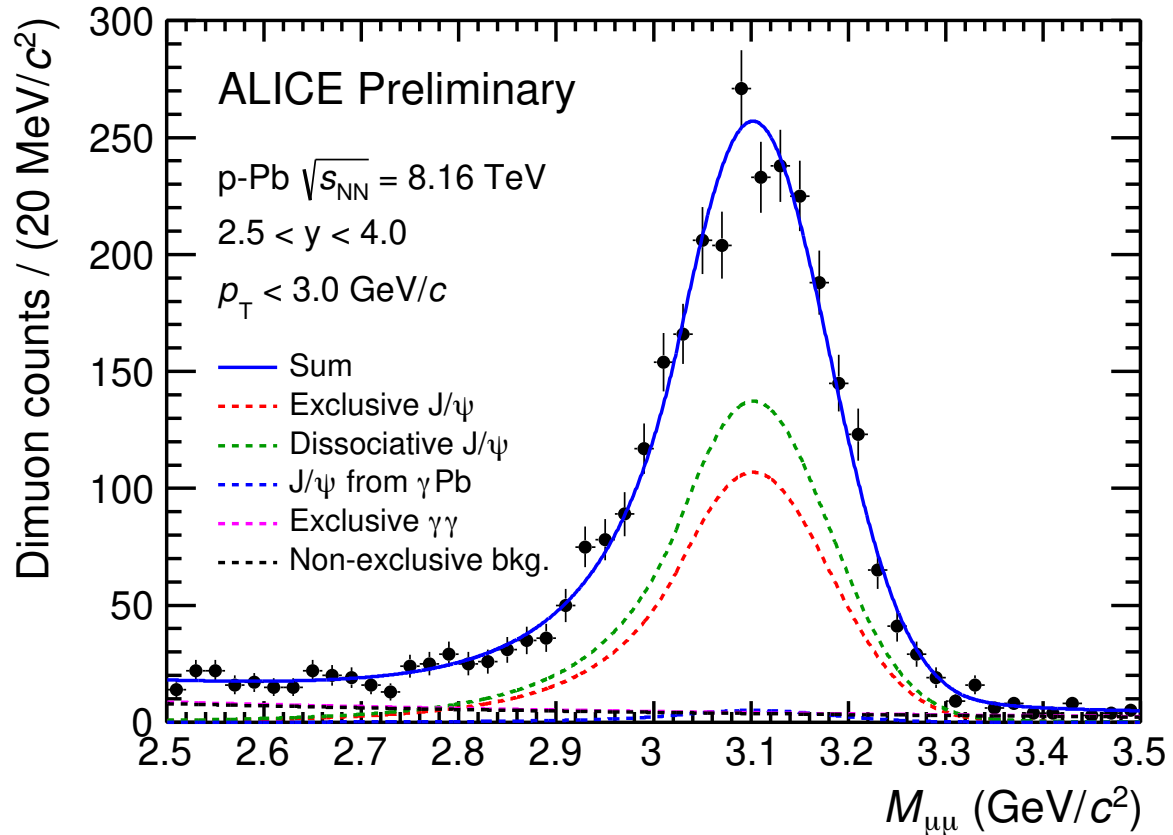


$0.0062 < p_T^2 < 0.0121 \text{ GeV}^2/c^2$



Exclusive and dissociative signal extraction

- Simultaneous unbinned fit of mass and p_T of $\mu^+\mu^-$ pairs



ALI-PREL-502210

ALI-PREL-502214

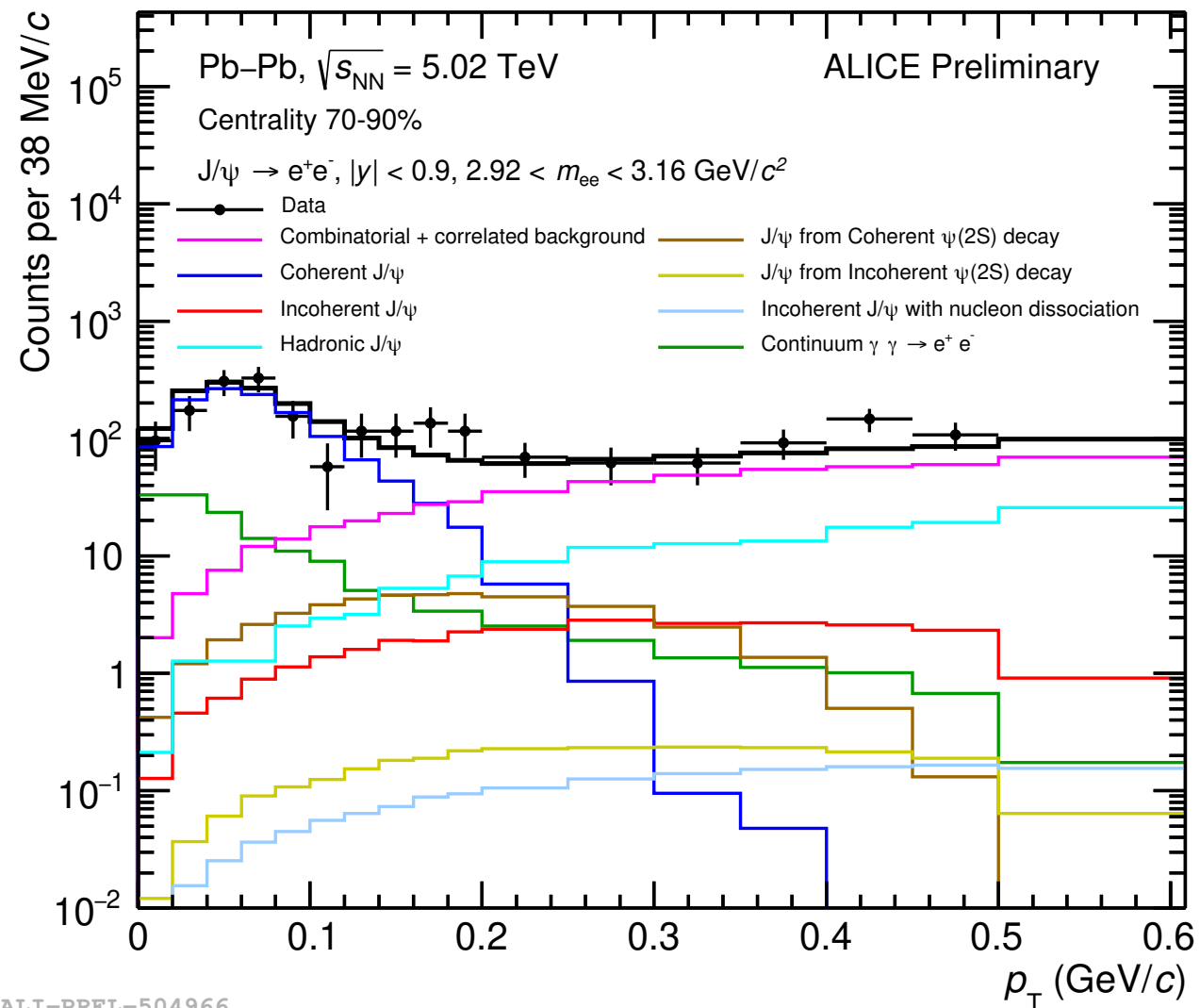
Coherent J/ψ photoproduction in Pb–Pb collisions



- Coherent J/ψ yield extracted through an unbinned 2D (m_{ee} , p_T) fit

Sources

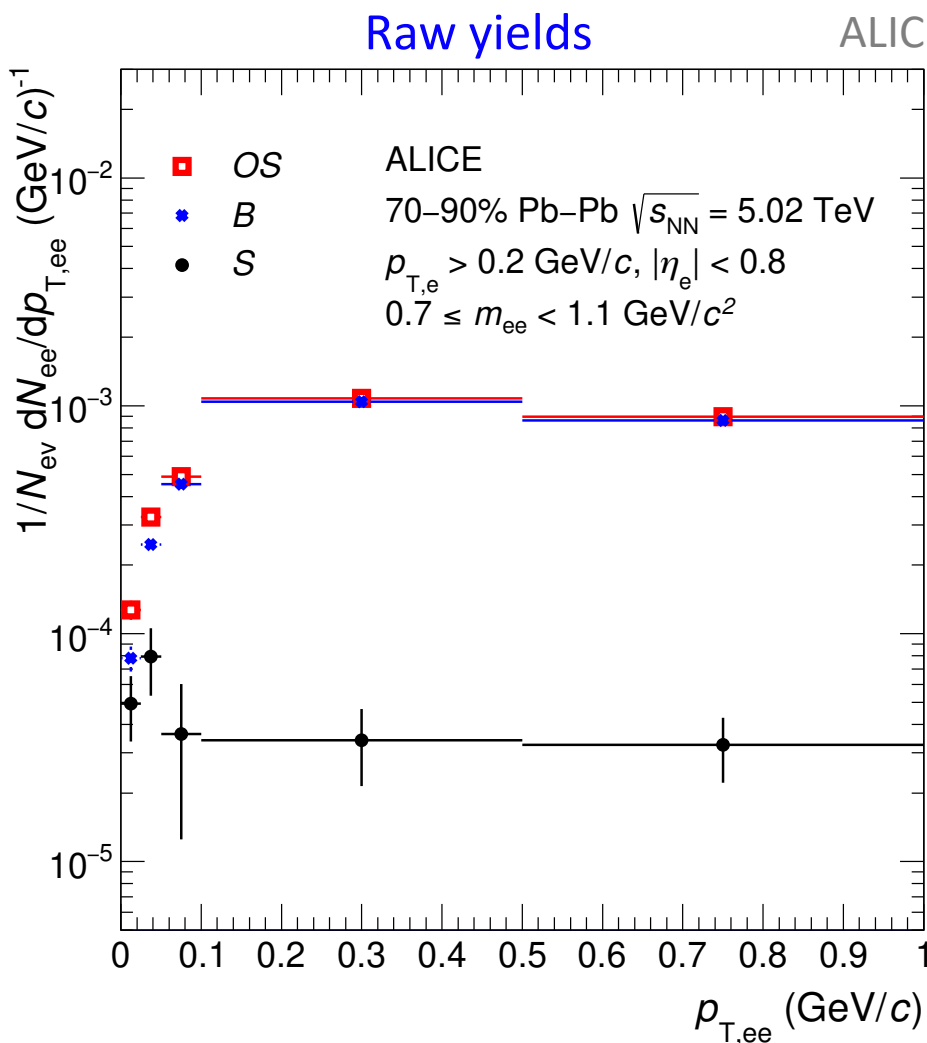
- Photoproduction:
 - Direct **coherent** J/ψ
 - Direct **incoherent** J/ψ
 - Feed-down from **coherent** and **incoherent** ψ'
 - Incoherent J/ψ with nuclear dissociation
 - $\gamma\gamma \rightarrow ee$ continuum
- Hadronic J/ψ
- Combinatorial + correlated background
- Photoproduced J/ψ component: STARlight + HIJING



ALI-PREL-504966

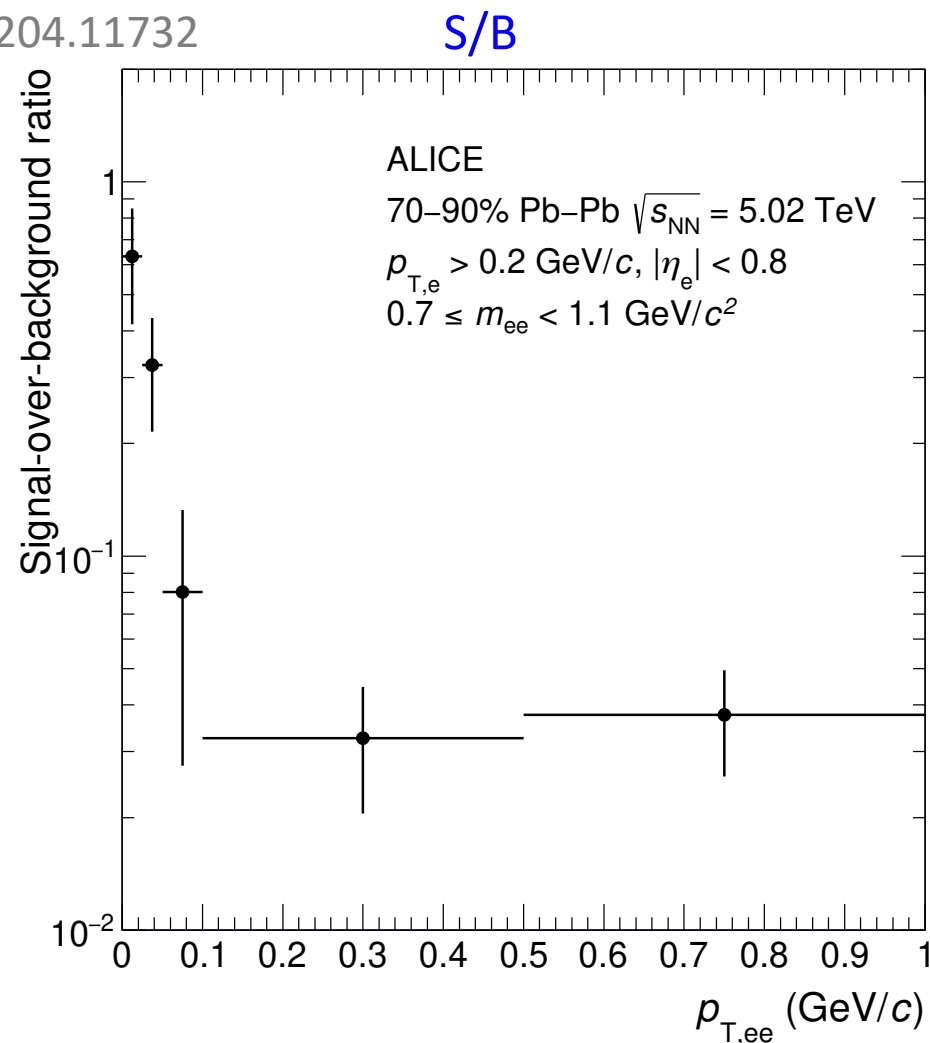
$\gamma\gamma \rightarrow e^+e^-$ in Pb–Pb collisions with nuclear overlap

- Relative signal and background contributions



ALI-PUB-521385

ALICE, arXiv:2204.11732



ALI-PUB-521389