Photon induced processes in Pb–Pb collisions with nuclear overlap

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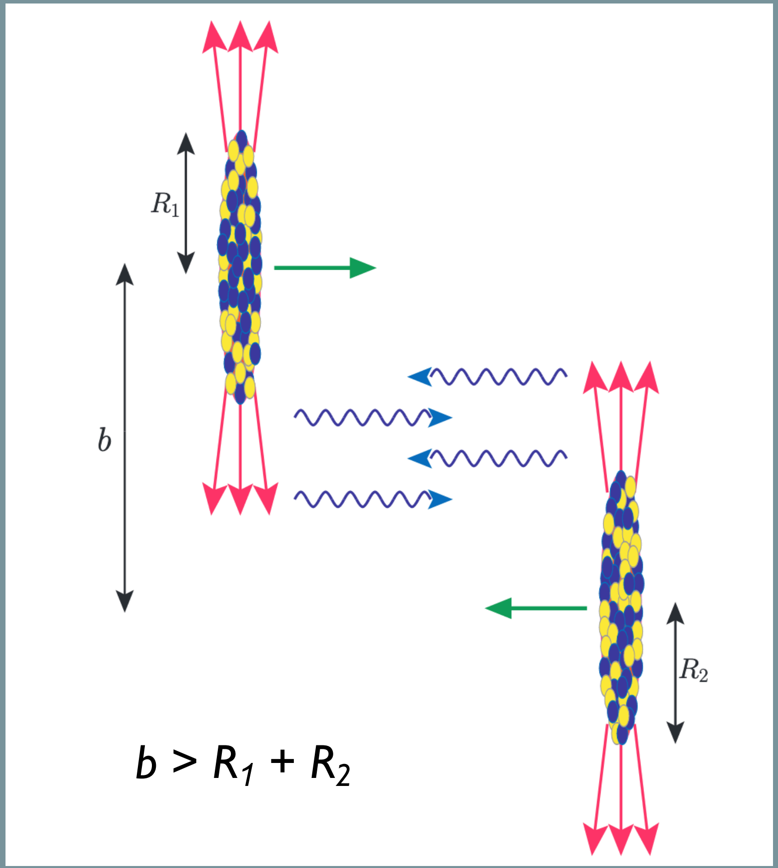
Quarkonia as tools, 9-13th January 2023, Aussois, France

Photon induced processes and ultra-peripheral Pb–Pb collisions (UPC)



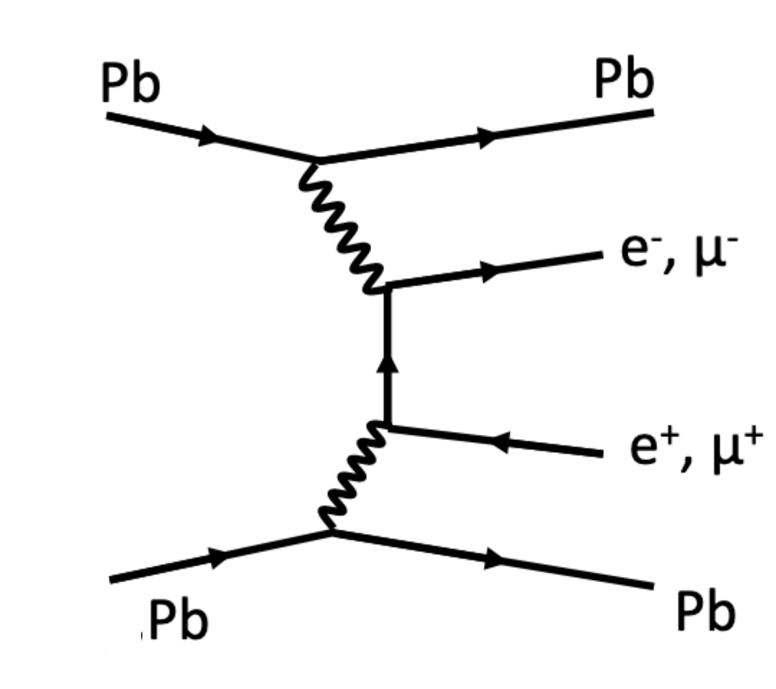
- ❑ The EM field of Pb nuclei can be described as beam of quasi-real photons (number of photons proportional to Z^2)

→ Use LHC as photon-photon or photon-hadron collider

- ❑ UPC: interactions with b larger than the sum radii of the incoming nuclei. Involve at least one photon.
  - ❖ Hadronic interaction strongly suppressed
  - ❖ Electromagnetic interactions dominant
  - ❖ Clean experimental signature: few tracks in an otherwise empty detector

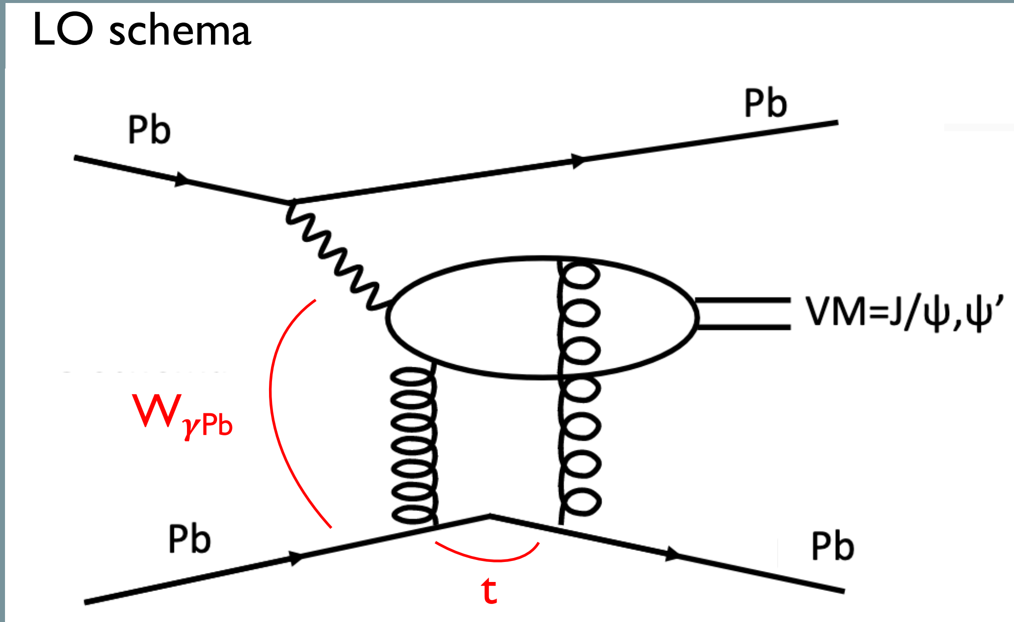
- ❑ Photon induced reactions well studied in UPC

Dilepton production in two-photon interactions



- Breit Wheeler mechanism (G. Breit, Phys. Rev. 46 (1934) 1087):
  - Production of very low p_T lepton pair
- Test QED (at LO + possibly higher order corrections)
  - ~ 15% effect for the reduction of the cross section at LHC energies A. J. Baltz, Phys. Rev. C 80, 034901
- Map the EM field produced in heavy-ion collisions
  - Larger Lorentz-boost factor w.r.t RHIC
  - Maximum electric field reached 30 times larger than at RHIC

Vector meson (VM) photoproduction

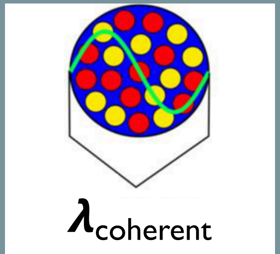


- ❑ Photon fluctuates into a quark-antiquark pair
- ❑ Production of a very low p_T vector meson (for coherent process)
- ❑ Gives access to gluon distributions in nuclei at low Bjorken-x

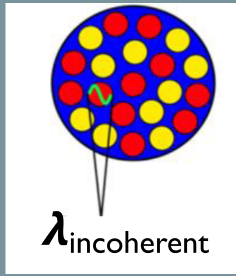
$$x_{\pm} = \frac{m_{J/\Psi}}{\sqrt{s_{NN}}} e^{(\pm y)}$$

$10^{-5} < x < 10^{-2}$ at LHC energies

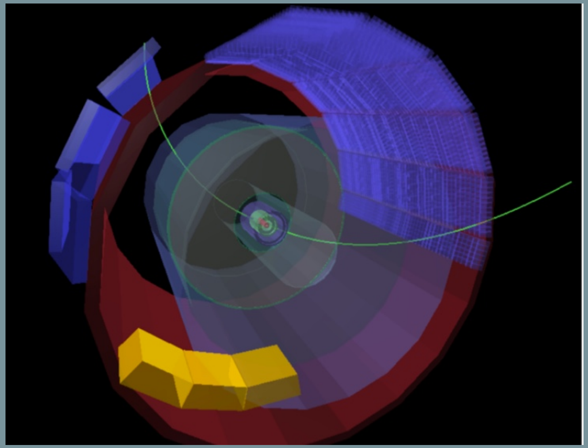
- ❑ Coherent photoproduction of VM
  - ɣ couples coherently to all nucleons
  - $<p_T>^{J/\Psi} \sim 60$ MeV
  - Usually no breaking of target nucleus



- ❑ Incoherent photoproduction of VM
  - ɣ couples to a nucleon
  - $<p_T>^{J/\Psi} \sim 500$ MeV
  - Usually target nucleus breaks

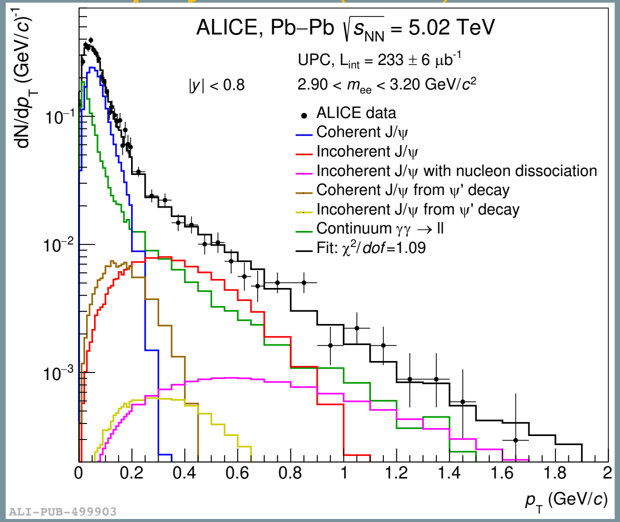


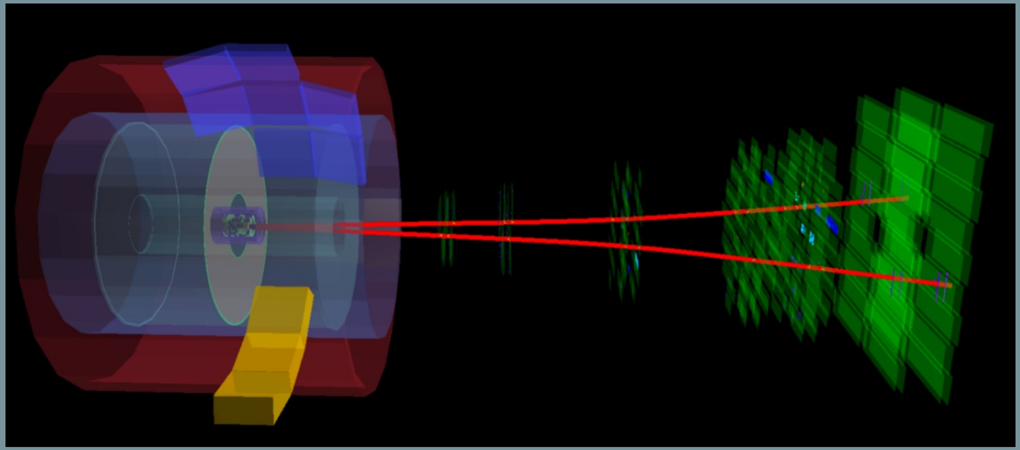
ALICE Event display: UPC events versus hadronic events



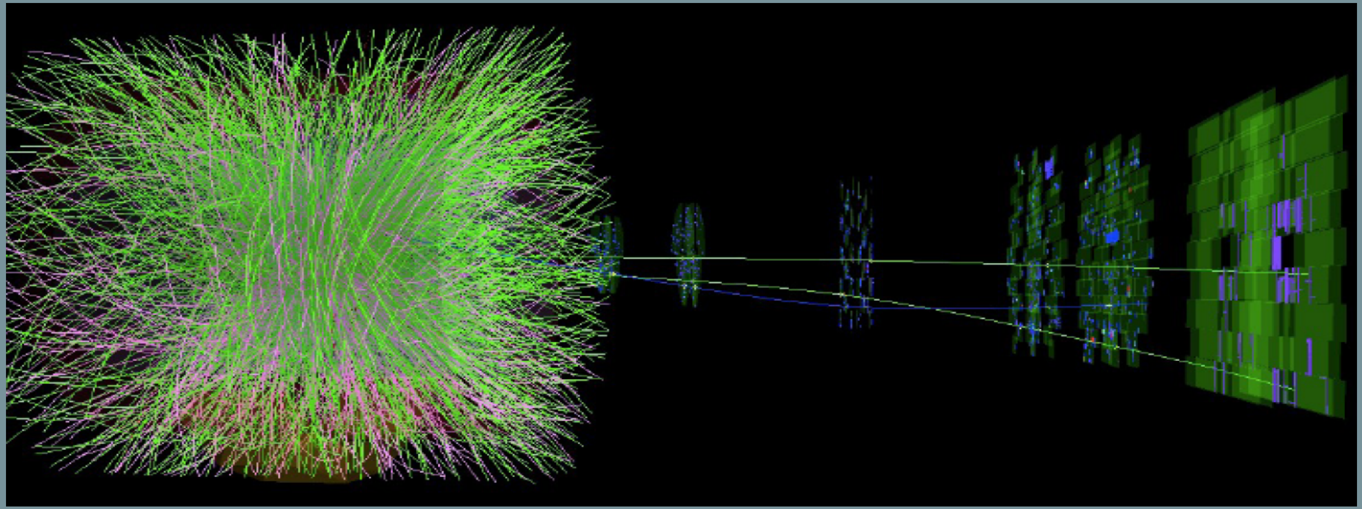
UPC event in the central barrel

Eur. Phys. J. C 81 (2021) 712





UPC event in the muon spectrometer

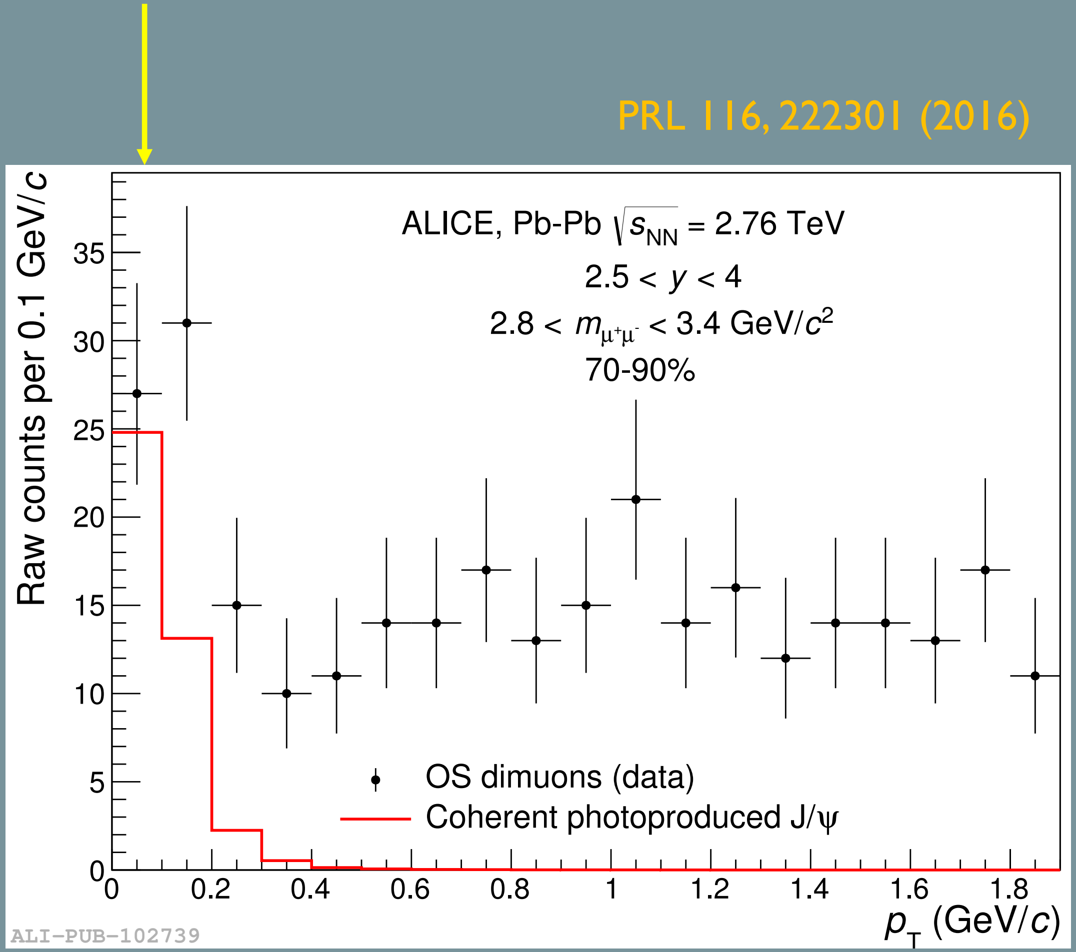


Pb–Pb hadronic event

First observation of VM photoproduction in Pb–Pb collisions with nuclear overlap

- Very low-p_T J/ψ excess in peripheral Pb–Pb collisions first measured in ALICE at forward y and $\sqrt{s_{NN}}$ = 2.76 TeV
  - Interpreted as coherent photoproduction
  - Significance: 5.4σ (70-90%), 3.4σ (50-70%), 1.4σ (30-50%)

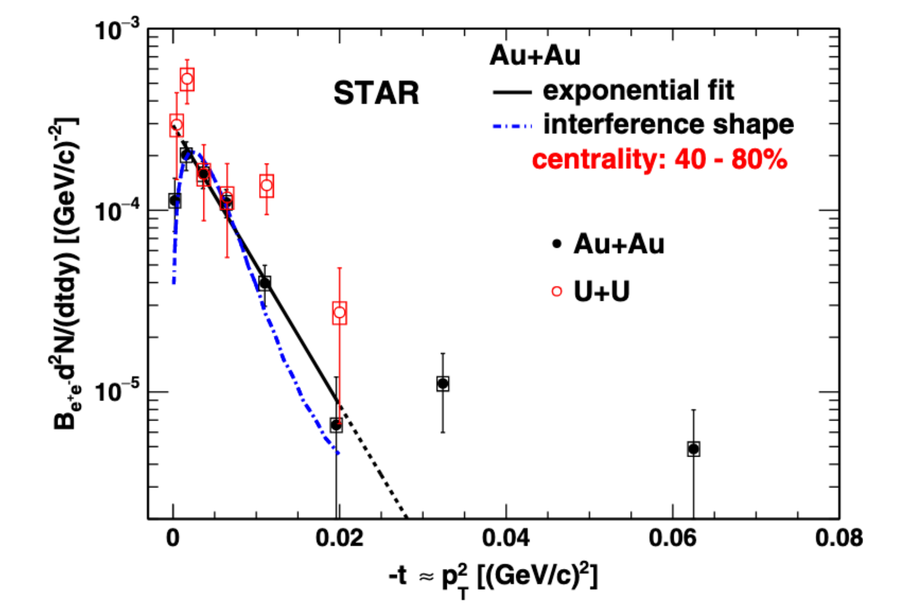
PRL 116, 222301 (2016)

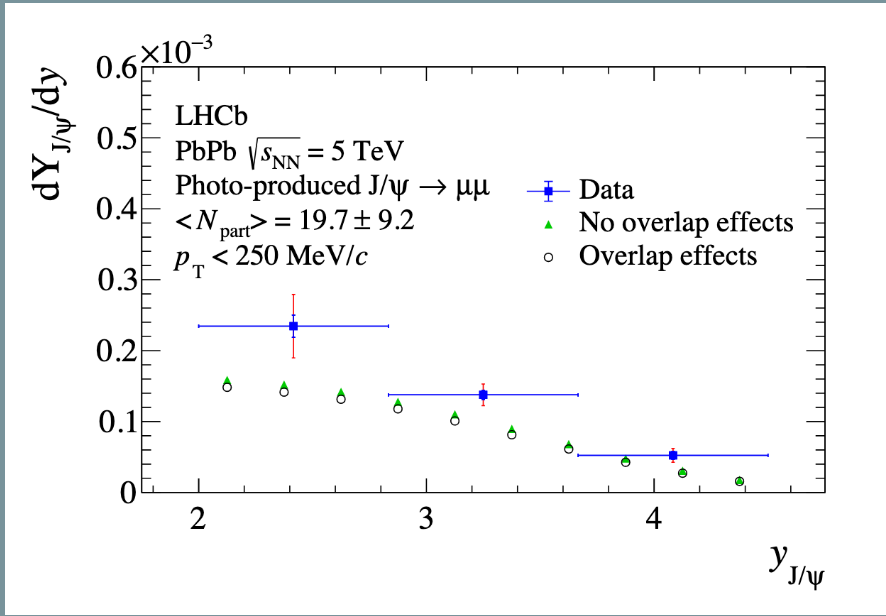


First observation of VM photoproduction in A–A collisions with nuclear overlap

- Similar observation by STAR Collaboration at lower energy in U–U and Au–Au collisions (PRL 123, 132302 (2019))
  - First measurement of the *t*-dependence of the J/ψ excess
  - Supports also photoproduction origin

- Observation confirmed in Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV by LHCb (PRC 105 (2022) L032201)
  - p_T and *y*-differential J/ψ excess yield measurement



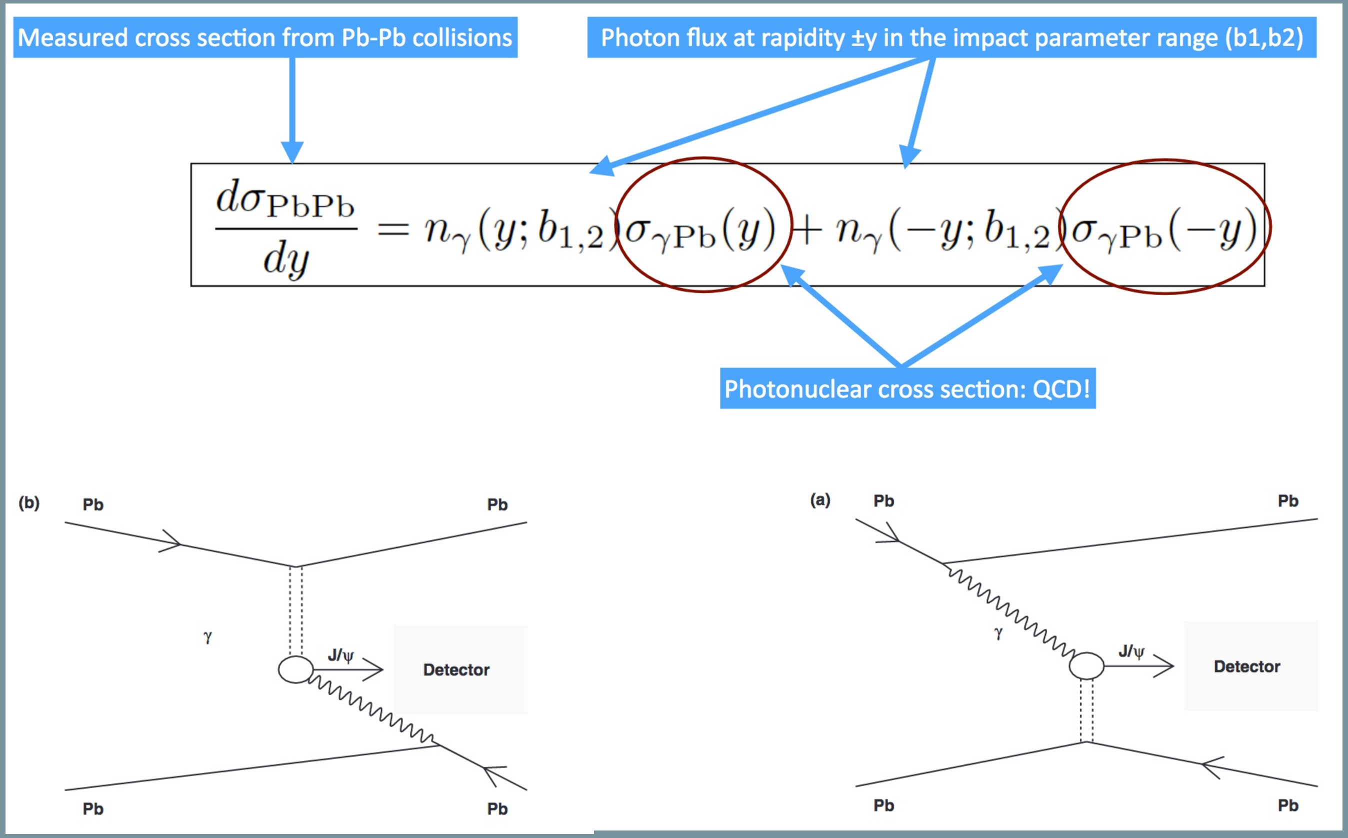


VM photoproduction in heavy-ion collisions with nuclear overlap

- Theoretical challenges:
  - Survival of coherence condition for a broken nucleus? Only spectator nucleons participating to coherence?

- A potential new probe of charmonium color screening in the QGP?

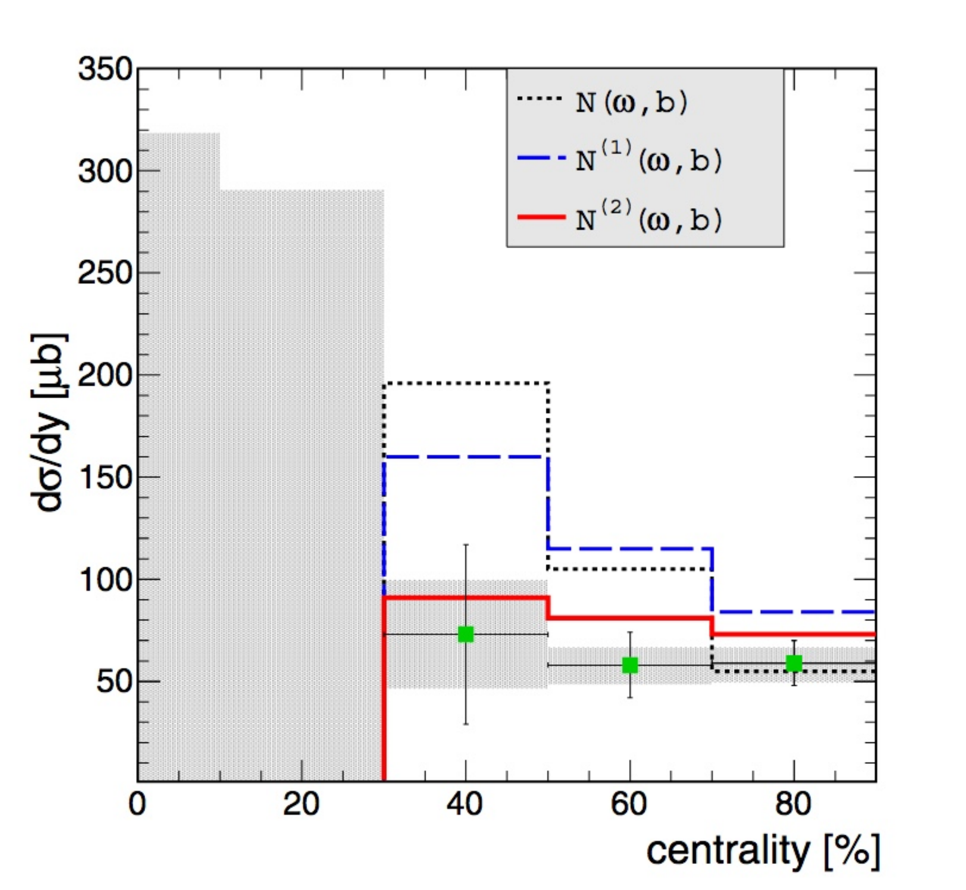
- A novel way to access $\sigma_{\gamma Pb}$ when combined to UPC measurement? (see J.G. Contreras, Phys. Rev. C 96, 015203 (2017))
  → Need to understand time ordering of the interaction and theoretical open questions related to the treatment of the nuclear overlap



- First theoretical approches developed since 2016 based on UPC-like models with modified photon flux and/or modified photonuclear cross section to account for overlap

First theoretical developments to describe VM photoproduction in Pb–Pb collisions with nuclear overlap

M. Klusek-Gawenda, PRC 93, 044912 (2016)



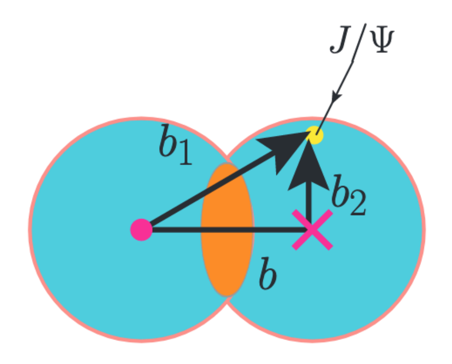
Equivalent photon approximation + vector dominance model

- Standard photon flux (UPC)
- Effective photon flux (considering geometrical constraints for the photon to reach the nucleus medium)

$$N^{(1)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - b_2)}{\pi R_A^2} \mathrm{d}^2 b_1$$

- Effective photon flux (considering photons reaching the spectator nucleon region only)

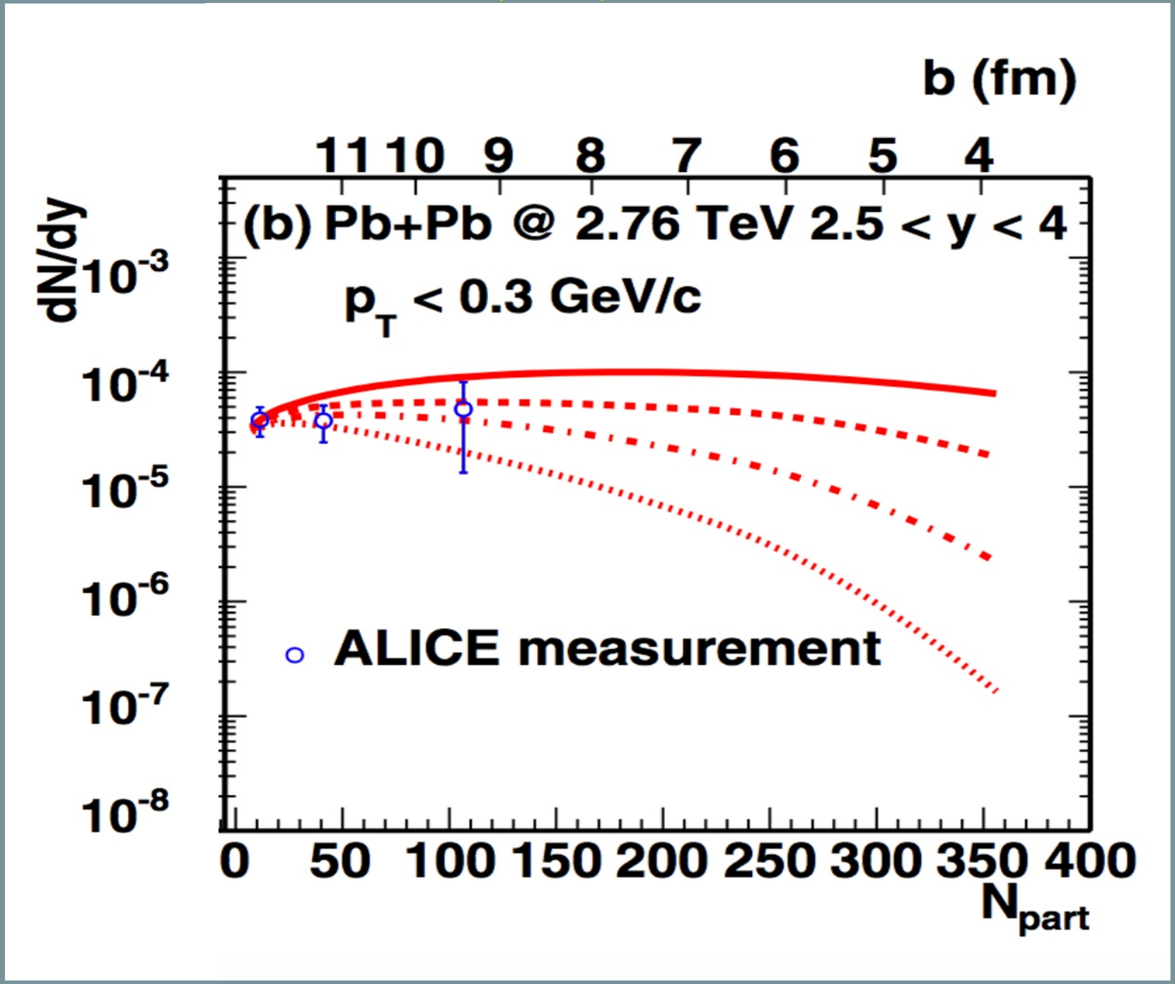
$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - b_2) \times \theta(b_1 - R_A)}{\pi R_A^2} \mathrm{d}^2 b_1$$



- ALICE data (Pb–Pb, $\sqrt{s_{NN}}$ = 2.76 TeV)
- ALICE syst. uncertainties

First theoretical developments to describe VM photoproduction in Pb–Pb collisions with nuclear overlap

W. Zha, PRC 97, 044910 (2016)



- ❑ Strong interactions in the overlapping region of incoming nuclei may disturb the coherent production, leaving room for different coupling assumptions between photon and pomeron:

N + N	Nucleus (γ emitter) – Nucleus (pomeron emitter)
N + S	Nucleus (γ emitter) – Spectator (pomeron emitter)
S + N	Spectator (γ emitter) – Nucleus (pomeron emitter)
S + S	Spectator (γ emitter) – Spectator (pomeron emitter)

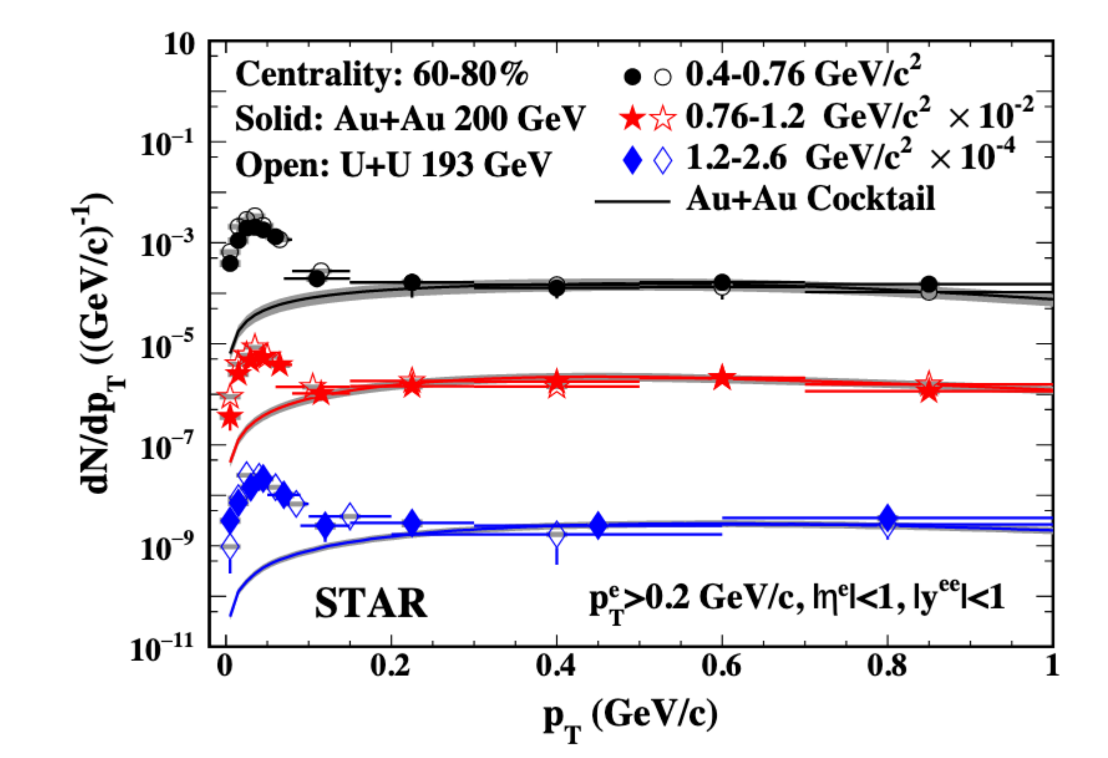
- ❑ ALICE Run 1 data consistent with all 4 scenarios within uncertainties

- ❑ Need more precise data and measurement towards most central collisions (challenging!) to constrain theoretical models

Dilepton production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

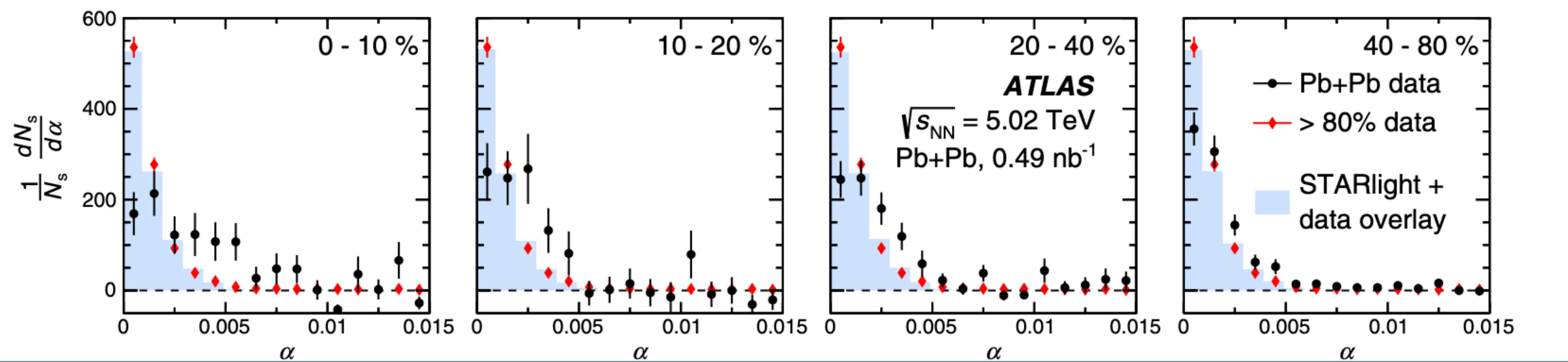
STAR Collaboration, PRL 121, 132301 (2018)

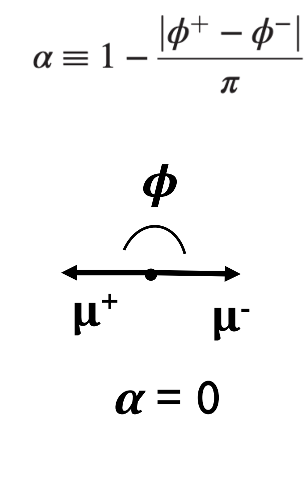
- Very low-p_T dielectron excess observed by STAR, at mid-rapidity for $0.4 < m_{e+e-} < 2.6$ GeV/c^2 in Au–Au and U–U collisions (centrality 60-80%)
  - Excess compatible with expectations from photon-photon interaction processes, but p_T^2 distribution not reproduced
  - p_T broadening may indicate the possible existence of a strong magnetic field trapped in a conducting QGP



Dilepton production via $\gamma\gamma$ interaction in heavy-ion collisions with nuclear overlap

- Observation by ATLAS of centrality-dependent acoplanarity for muon pairs produced via $\gamma\gamma$ scattering in hadronic Pb–Pb collisions (PRL 121, 212301 (2018)), for $4 < m_{\mu+\mu-} < 45$ GeV/c^2

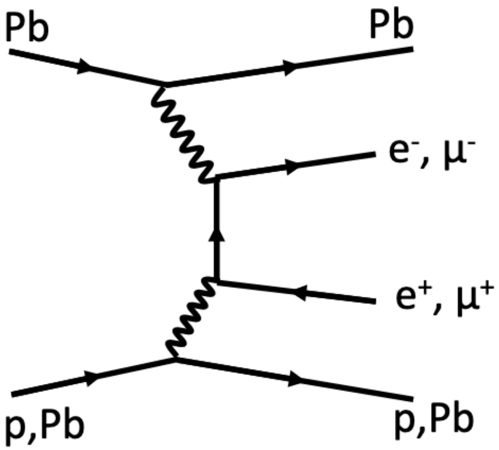




- Originally interpreted as a sign of em. scattering of the muons with a hot and dense medium
- Inclusion of a *b*-dependence of photon-k_T distribution in QED calculations permits now to reproduce both STAR and ATLAS data (without need for medium induced or final state effects)

M. Klusek-Gawenda, J. Phys. Lett. B 814 (2021) 136114

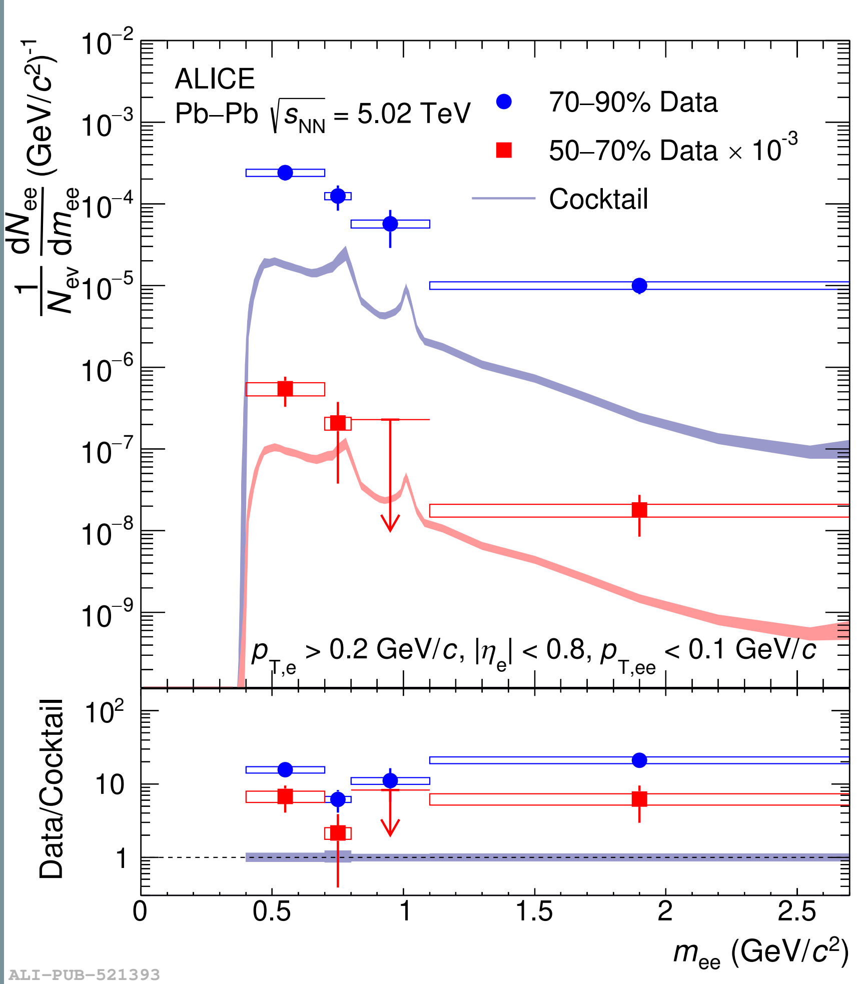
First measurement of a very low-p_T dielectron excess at low invariant mass in hadronic Pb–Pb collisions



ALICE

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

arXiv:2204.11732



- First measurement at LHC of a dilepton excess at very low-p_T (< 0.1 GeV/c) for 0.4 < m_{e+e-} < 2.6 GeV/c^2 in peripheral Pb–Pb collisions
- Corrected dielectron invariant mass distribution in centrality 50-70% and 70-90%, for $|\eta_e|$ < 0.8 and $p_{T,ee}$ < 0.1 GeV/c
  - Data cannot be described by cocktail of e^+e^- expected hadronic sources
  - Significance of the excess larger in most peripheral events

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

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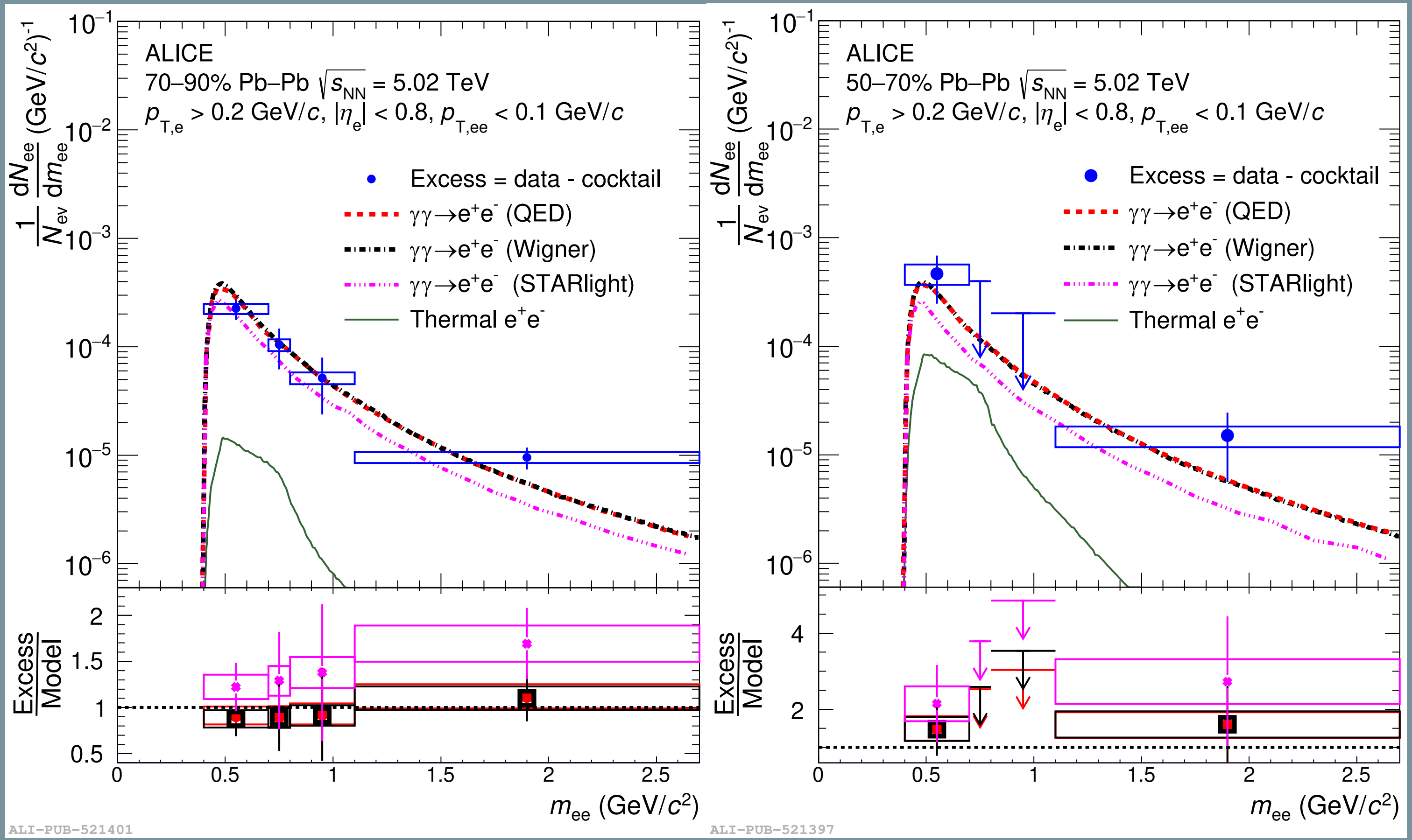

- ❑ Mass distribution of the e^+e^- excess (p_T < 0.1 GeV/c) after background subtraction from known hadronic sources
- ❑ No significant centrality dependence
- ❑ At $p_{T,ee}$ < 0.1 GeV/c, thermal radiation from medium is expected to be one order of magnitude smaller than the observed excess. Also different p_T shape and centrality dependence
- ❑ Ratio excess/model compatible with unity within total uncertainties (although STARlight predictions further away from data)

QED: W. Zha *et al.*, Phys. Lett. B 800 (2020) 135089, J. D. Brandenburg *et al.*, Eur. Phys. J. A 57 (2021) 299
Wigner: M. Klusek-Gawenda *et al.*, Phys. Lett. B. 814 (2021) 136114
STARlight: S.R. Klein *et al.*, Comput. Phys. Commun. 212 (2017) 258, S.R. Klein, Phys. Rev. C. 97 (2018) 054903

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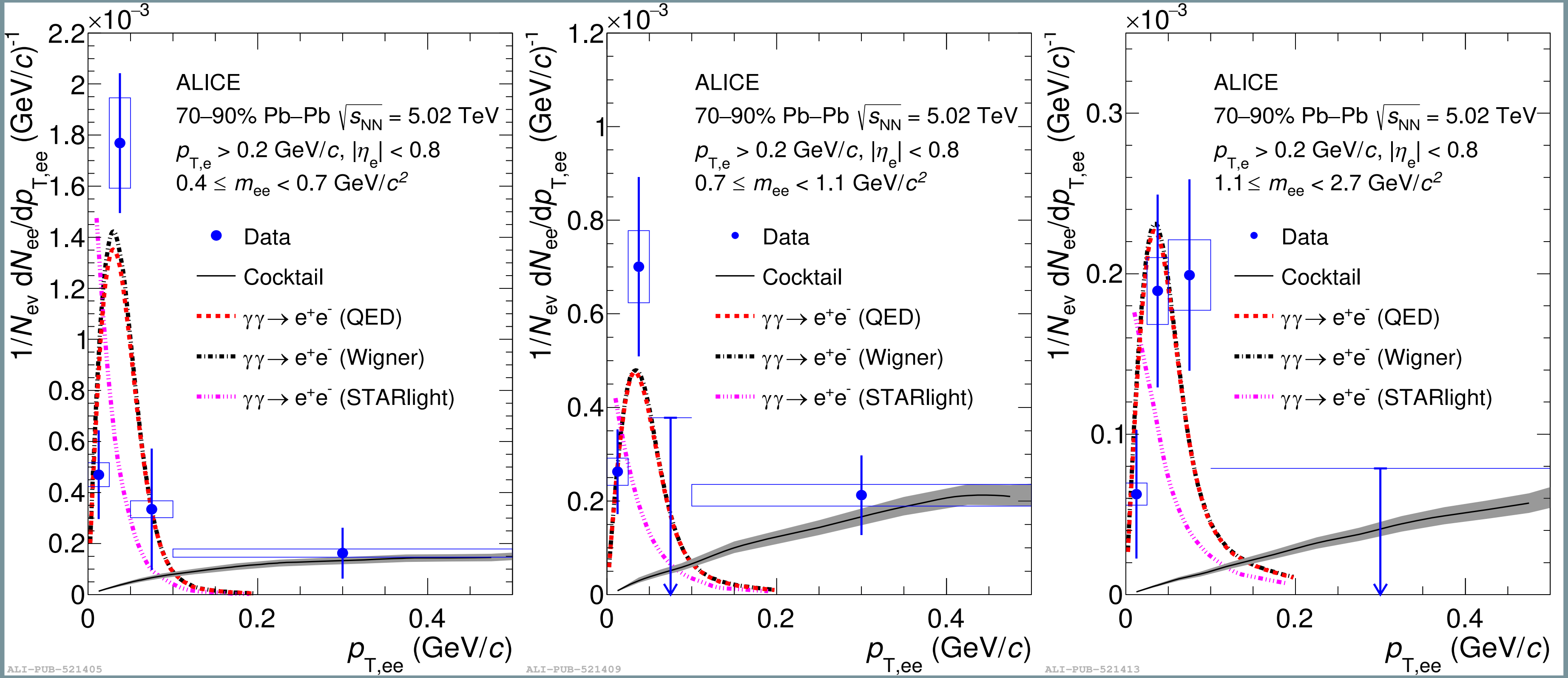

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W. Zha *et al.*, Phys. Lett. B 800 (2020) 135089
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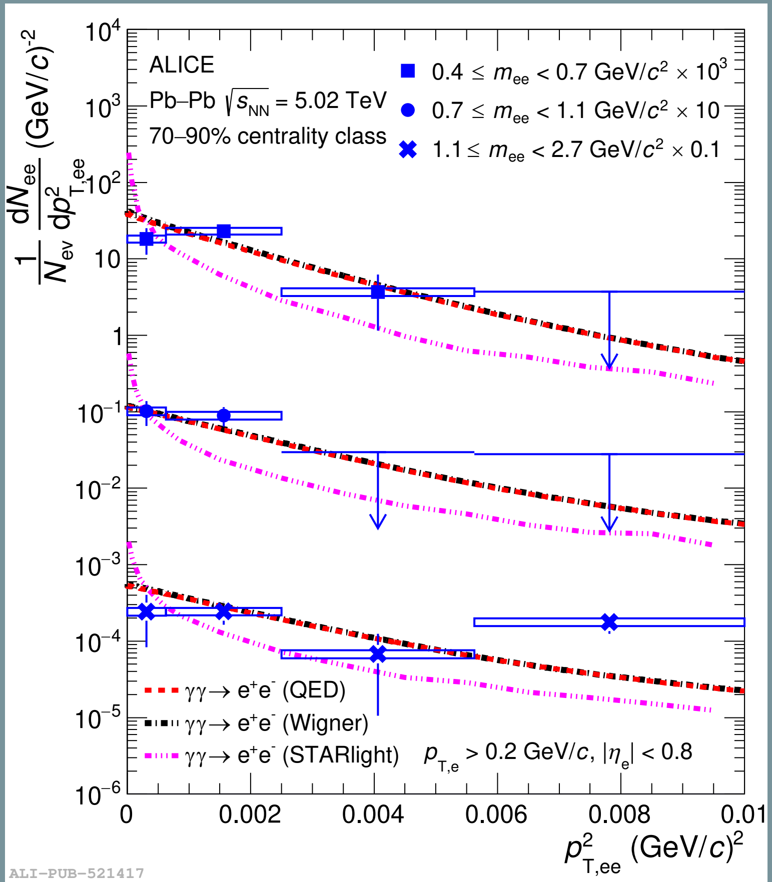
S.R. Klein, Phys. Rev. C. 97 (2018) 054903

- ❑ Clear peak observed at low p_{Tee} in 70-90%, for three invariant mass ranges
- ❑ Data described by $\gamma\gamma$ interaction models including the b-dependence of the photon-k_T distribution (QED, Wigner)
- ❑ STARlight disfavored by data

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

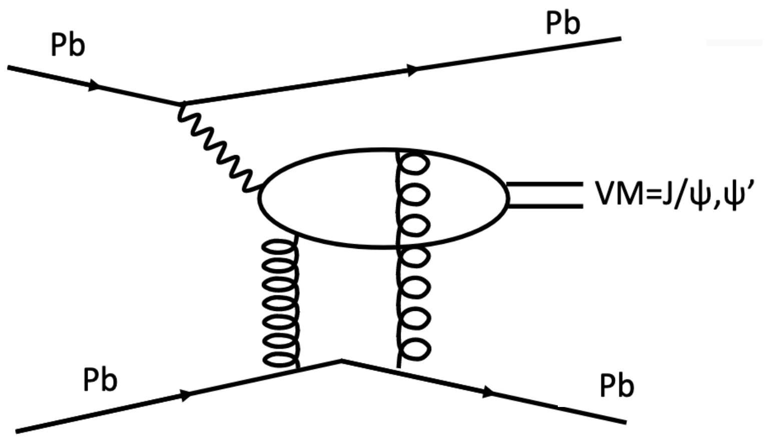
arXiv:2204.11732



- ❑ p_T^2 distribution of the excess after subtracting the hadronic cocktail
- ❑ From comparison with models: p_T broadening observed in HIC originates predominantly from initial EM field strength which varies significantly with b

QED: W. Zha *et al.*, Phys. Lett. B 800 (2020) 135089, J. D. Brandenburg *et al.*, Eur. Phys. J. A 57 (2021) 299
Wigner: M. Klusek-Gawenda *et al.*, Phys. Lett. B. 814 (2021) 136114
STARlight: S.R. Klein *et al.*, Comput. Phys. Commun. 212 (2017) 258, S.R. Klein, Phys. Rev. C. 97 (2018) 054903

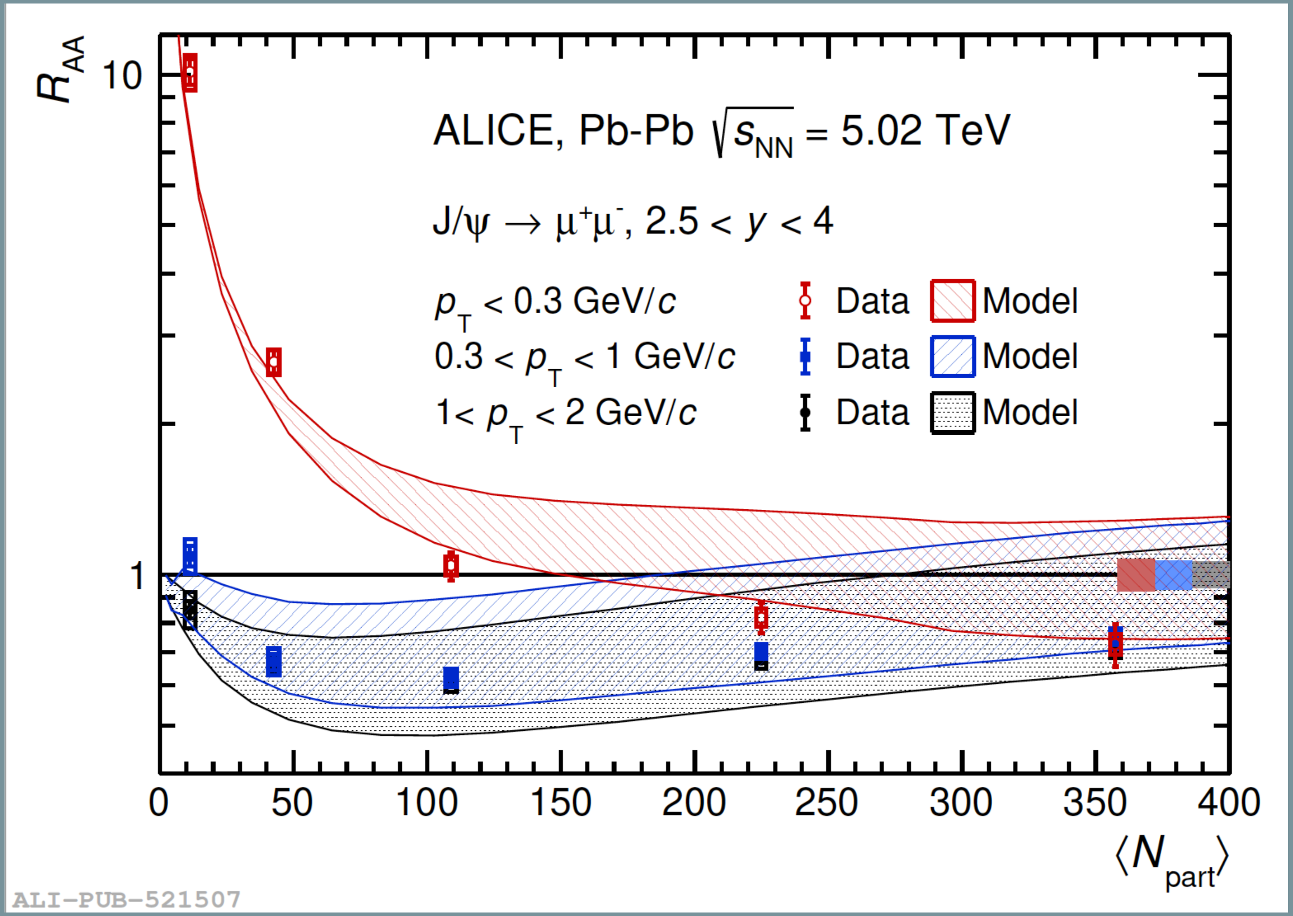
Coherent J/ψ photoproduction cross section measured towards most central Pb–Pb collisions ($\sqrt{s_{NN}}$ = 5.02 TeV) at forward rapidity



ALICE

J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (forward-y)

arXiv:2204.10684



W. Shi et al., Phys. Lett. B 777 (2018) 399-405

$$R_{AA} = \frac{Y_{J/\psi}^{Pb-Pb}}{<T_{AA}> \sigma_{J/\psi}^{pp}}$$

- J/ψ R_{AA} for p_T < 0.3 GeV/c significantly larger than in 1 < p_T < 2 GeV/c where hadroproduction dominates (except in most central events)
- Hint for incoherent photoproduction in 70-90% for 0.3 < p_T < 1 GeV/c (~2σ deviation w.r.t 1 < p_T < 2 GeV/c)
- Data well described by a model including hot medium effects on J/ψ production (primordial J/ψ survival, regeneration)+ J/ψ photoproduction (p_T < 0.3 GeV/c). QGP effects on photoproduced J/ψ are also considered.

J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (forward-y)

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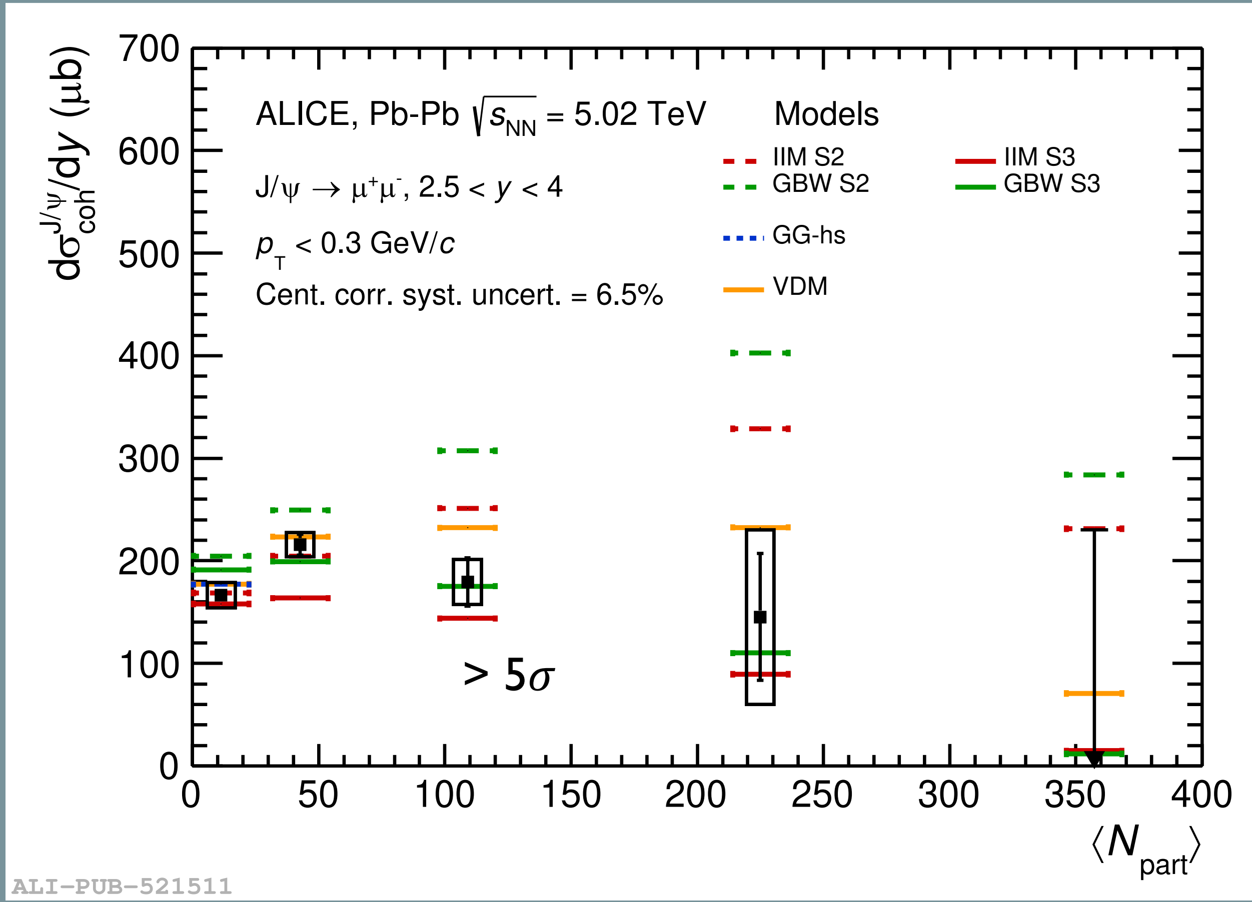


Centrality (70-90%) (50-70%) (30-50%) (10-30%) (0-10%)

Caveat: No normalization to the centrality interval width!

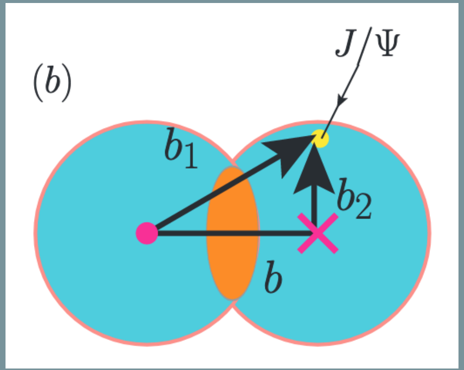
- No centrality dependence of the coherent J/ψ photoproduction cross section within uncertainties

GG-hs: J. Cepila et al., Phys. Rev. C. 97 (2018) 024901
- γ flux with constraints on impact parameter range

VDM: M. Klusek-Gawenda et al., Phys. Lett. B. 790 (2019) 339
- γ flux: only photons reaching the spectator region are considered [fixed area]
- photonuclear cross section unmodified

IIM/GBW: M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013
- γ flux: only photons reaching the spectator region are considered [b-dependent area]

- S2: photonuclear cross section unmodified
- S3: photonuclear cross section modified (exclusion of overlap region)



J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (forward-y)

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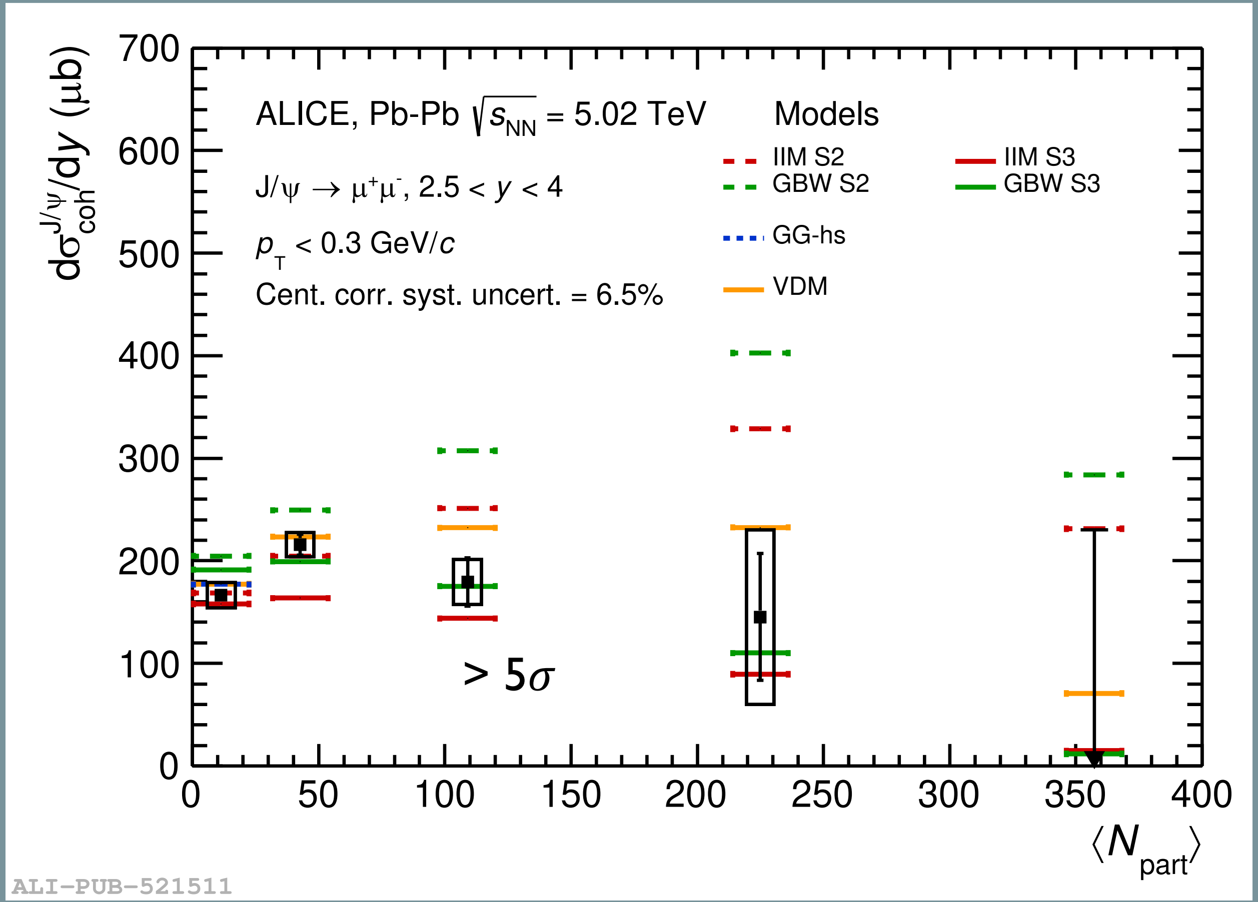
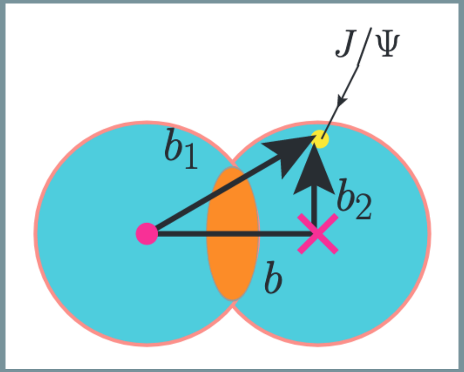


Centrality (70-90%) (50-70%) (30-50%) (10-30%) (0-10%)

Caveat: No normalization to the centrality interval width!

- No centrality dependence of the coherent J/ψ photoproduction cross section within uncertainties
- Models with either a modification of the γ flux (VDM) or a modification of the γ flux + photonuclear cross section (IIM/GBW S3) describe semicentral data



J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (forward-y)

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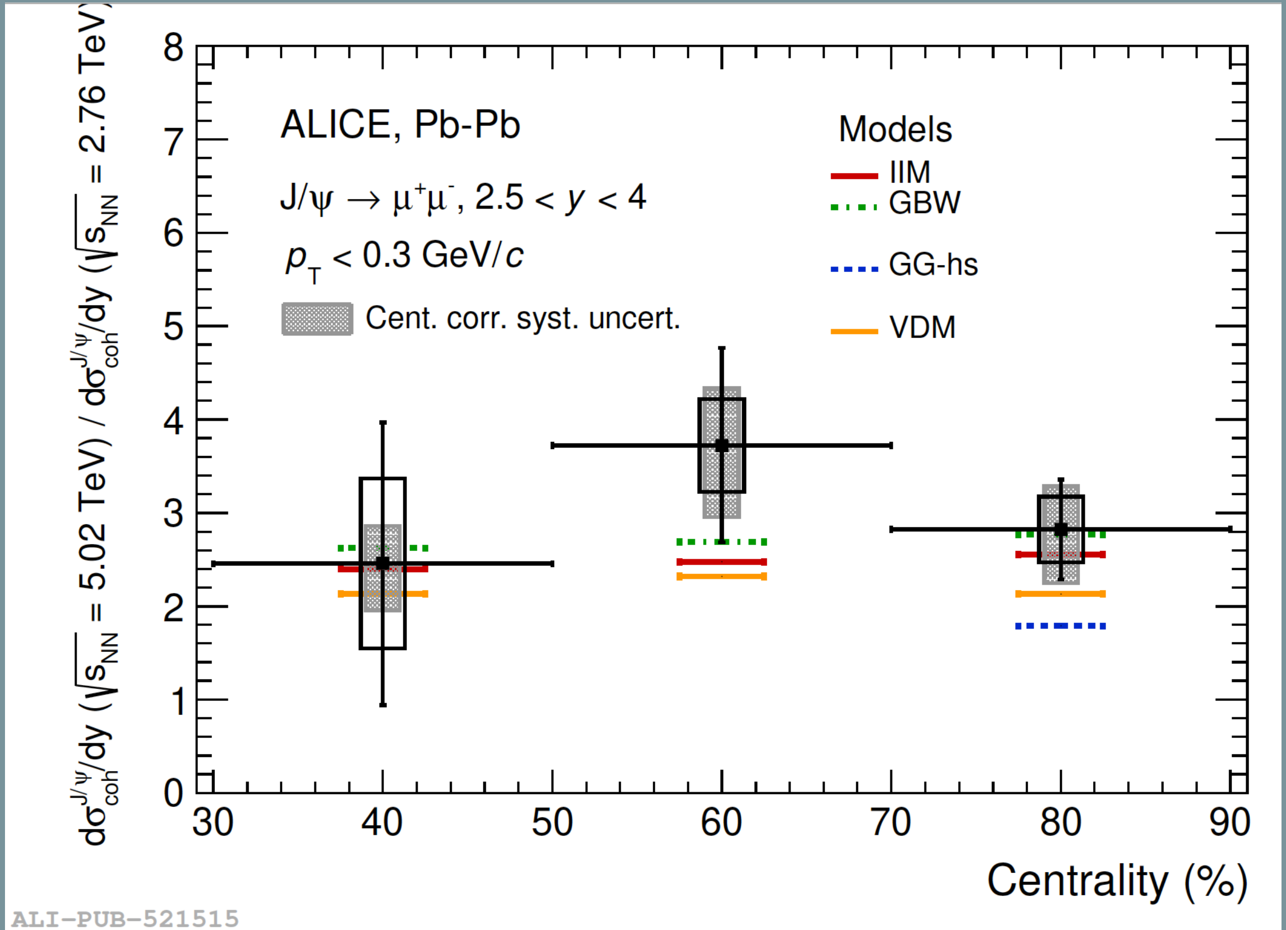
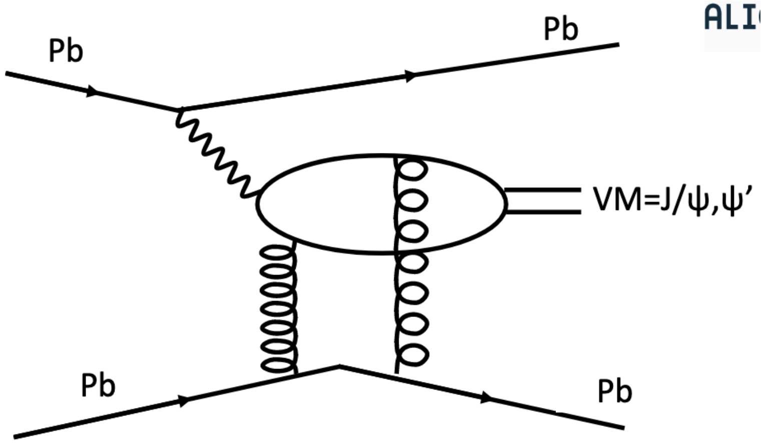
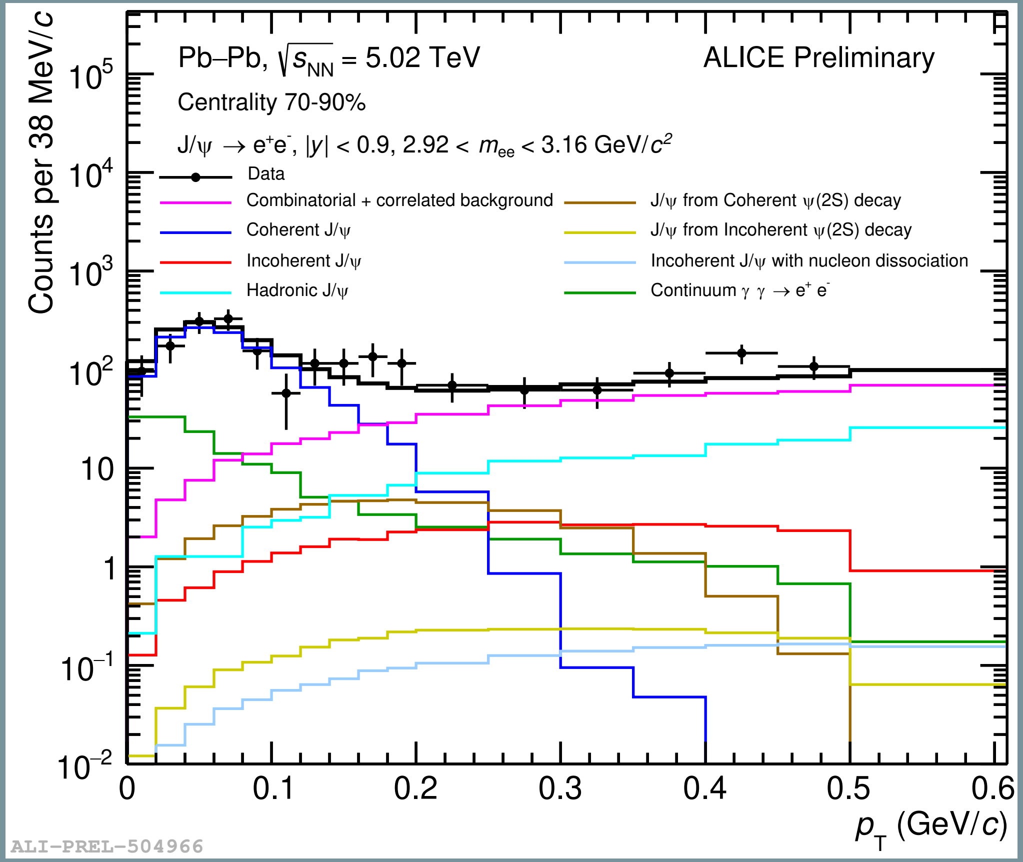


- J/ψ photoproduction cross section increases with the c.m.s energy and doesn't depend on the centrality
- VDM and IIM/GBW models reproduce fairly well the cross section ratio in the three centrality intervals

First p_T-differential measurement of the coherent J/ψ photoproduction cross section in peripheral Pb–Pb collisions at midrapidity and $\sqrt{s_{NN}}$ = 5.02 TeV

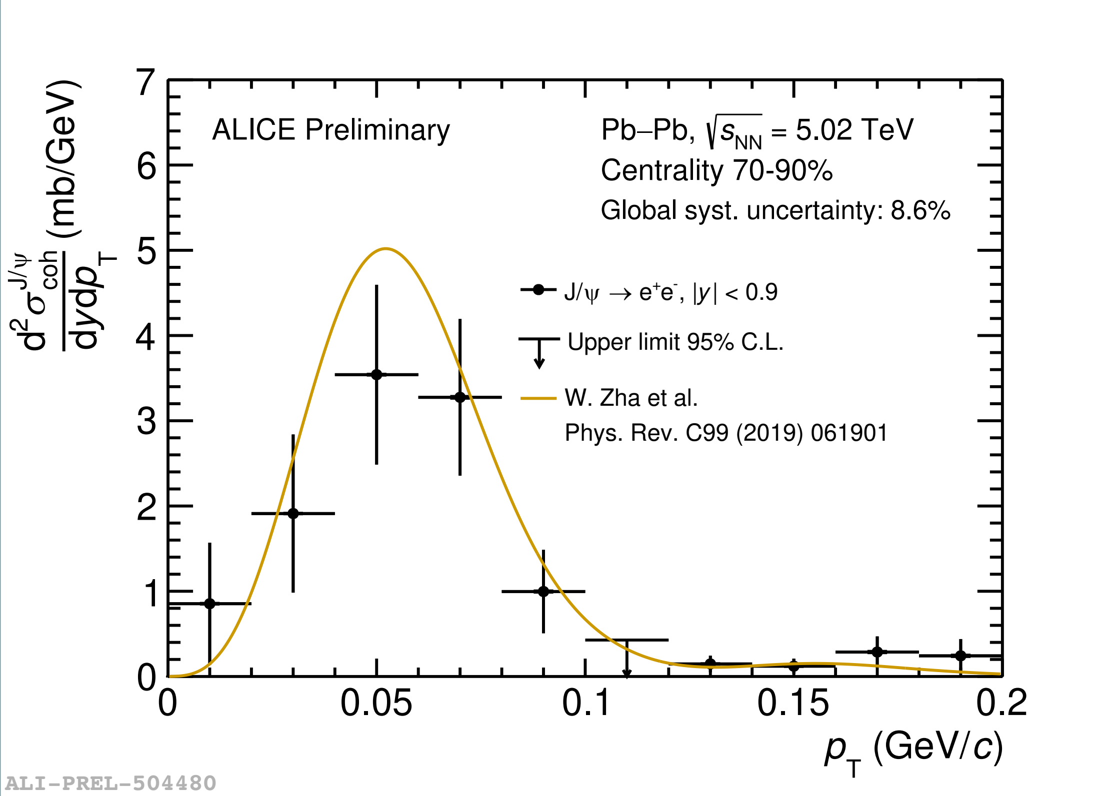


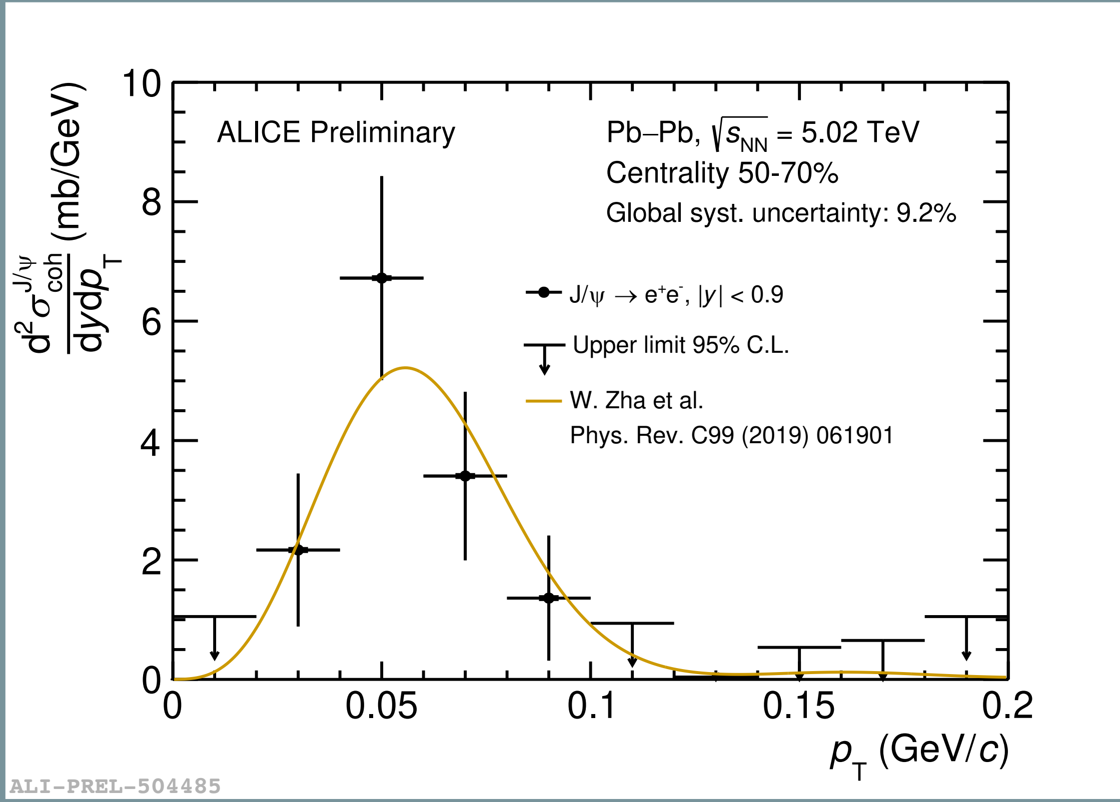
J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (mid-y)



- Coherent J/ψ yield measured using an unbinned (m_{ee}, p_T) likelihood fit
- Photoproduced J/ψ components obtained from STARlight

J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (mid-y)

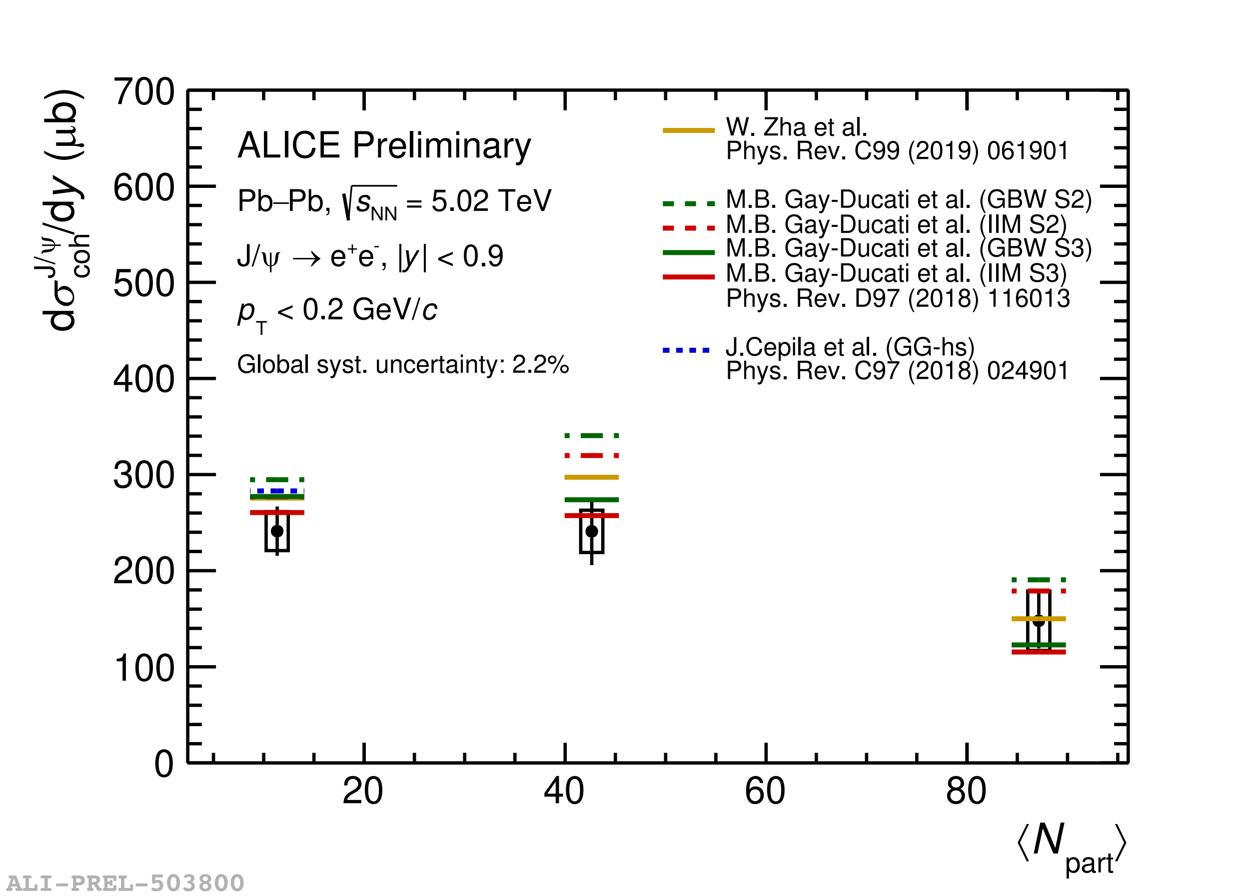




- p_T-differential J/ψ photoproduction cross section measured in 50-70% and 70-90% at mid-y
- p_T shape reproduced by model including modified photon flux and photonuclear cross section to account for the overlap (impact from overlap however limited in peripheral event). N+S scenario (with shadowing inc.)

W. Zha et al., Phys. Rev. C99 (2019) 061901

J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (mid-*y*)



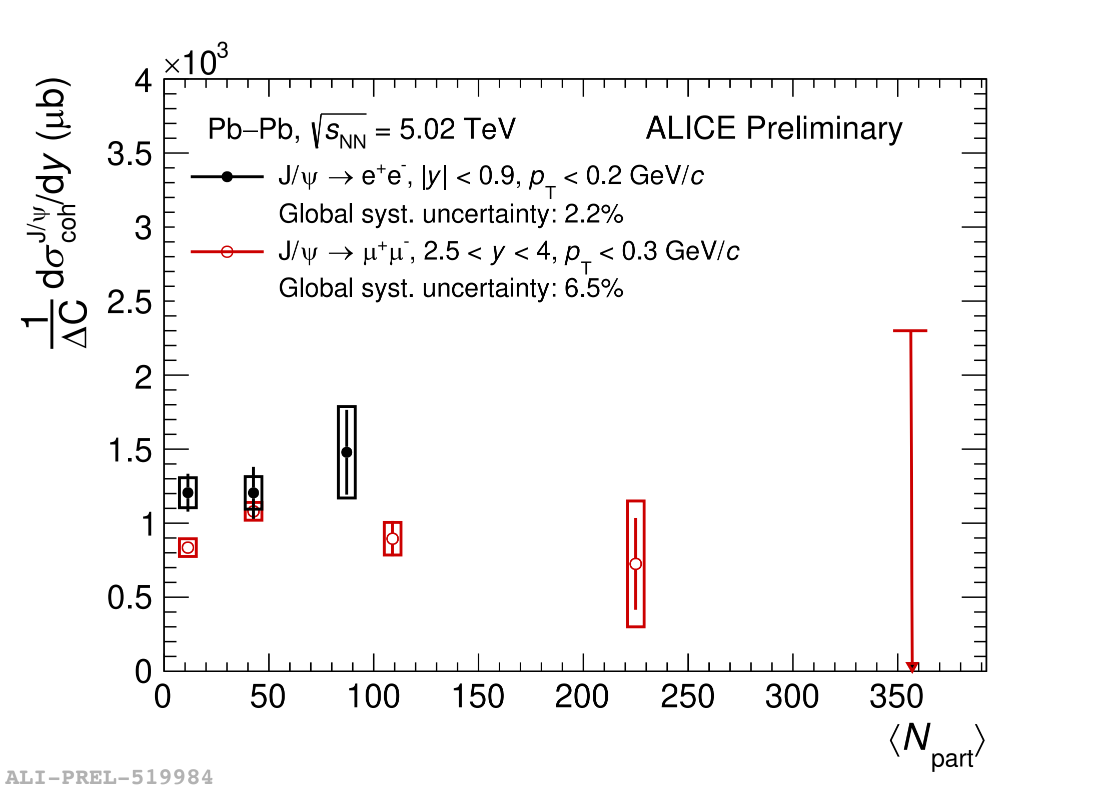
Centrality (70-90%) (50-70%) (40-50%)

Caveat: No normalization to the centrality interval width!

- No centrality dependence of the coherent J/ψ photoproduction cross section within uncertainties
- Same models (GG-hs, GBW/IIM) reproduce at the same time the order of magnitude of the cross section at midrapidity and forward rapidity
- Current precision in semicentral collisions do not permit to distinguish between models with modifications of γ flux only, or models with modification of γ flux + photonuclear cross section

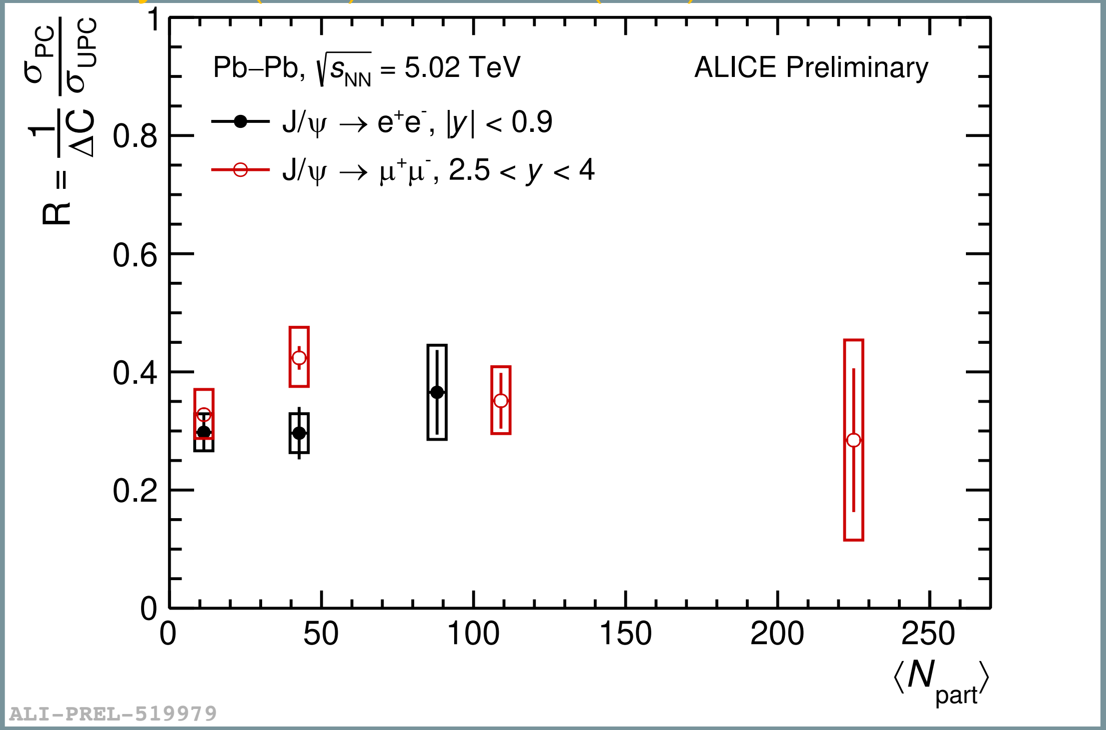
J/ψ photoproduction in Pb–Pb collisions with nuclear overlap (mid-y and forward-y comparison + comparison to UPC)

ΔC: width of centrality interval



PC: arXiv:2204.10684

UPC: EPJC 81 (2021) 712, PLB 98 (2019) 134926



- ❑ Larger J/ψ photoproduction cross section at mid-y than at forward-y (as expected from models). No strong centrality dependence at both rapidities.
- ❑ J/ψ photoproduction ratio in Pb–Pb to UPC (in the same rapidity window) → similar ratio for mid-y and forward-y.
  - ➢ Ratio flat with centrality → no evidence for a decrease of σ_{PC} because of the overlap or medium effects

Conclusion

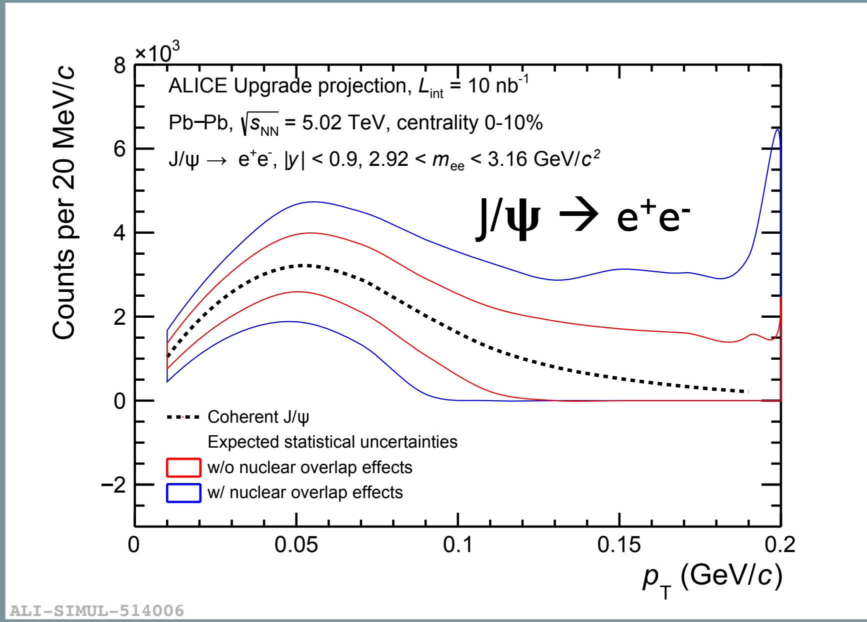
- First measurement of photoproduced dielectron pair at LHC for low m_{e+e-} in peripheral Pb–Pb collisions
  - Reproduced by $\gamma\gamma$ interaction models including the *b*-dependence of the photon-k_T distribution
  - Very little room left so far for medium induced effects (!)

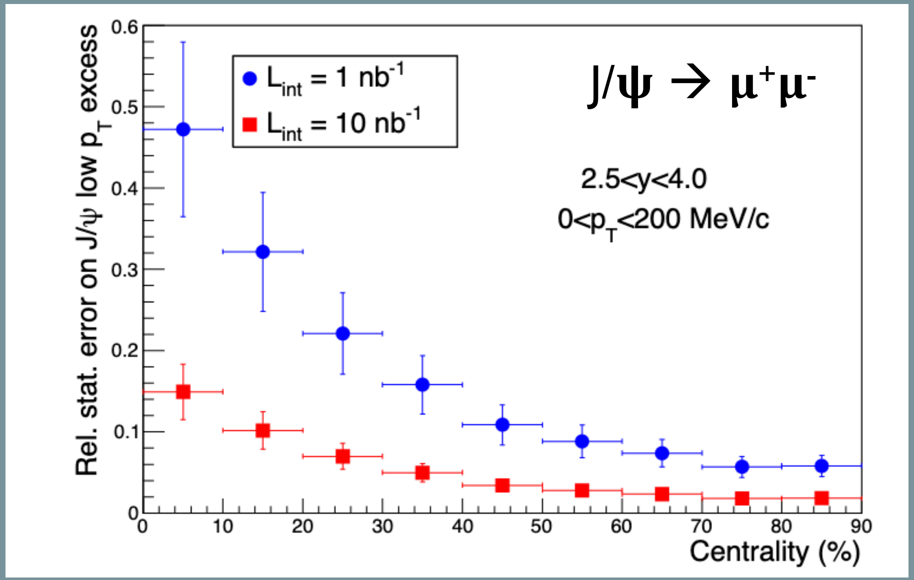
- J/ψ photoproduction cross section measured towards most central Pb–Pb collisions at forward-*y* and towards semicentral collisions at mid-*y*.
  - First p_T -differential measurement at mid-*y*
  - UPC-like models including either a modification of the **γ** flux or a modification of the **γ** flux + photonuclear cross section to account for the nuclear overlap can describe the semicentral data

Outlook

- Perspectives for Run 3 + 4: L_{int} ~ 10 nb^{-1} (increase of the stat. by ~ factor 10 at forward-*y* and few 100 (MB events) at mid-*y*
  - Photoproduced J/ψ:
    - Significant signal at both mid- and forward-*y* in 0-10% centrality range can be expected
    - Opportunity to look to other observables: polarization, flow, *y*-differential σ + other quarkonium states
    - Precise measurement of the p_T-differential cross section at mid-*y* for centrality > 10%

J. Phys. G 41 (2014) 087001



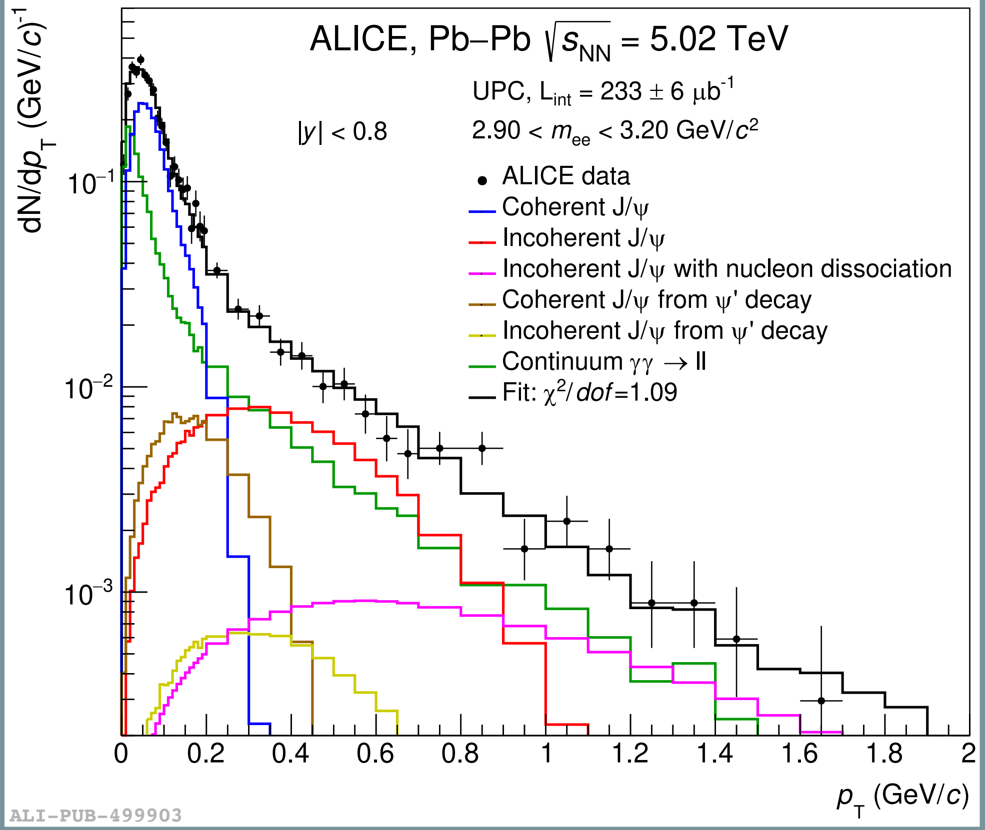


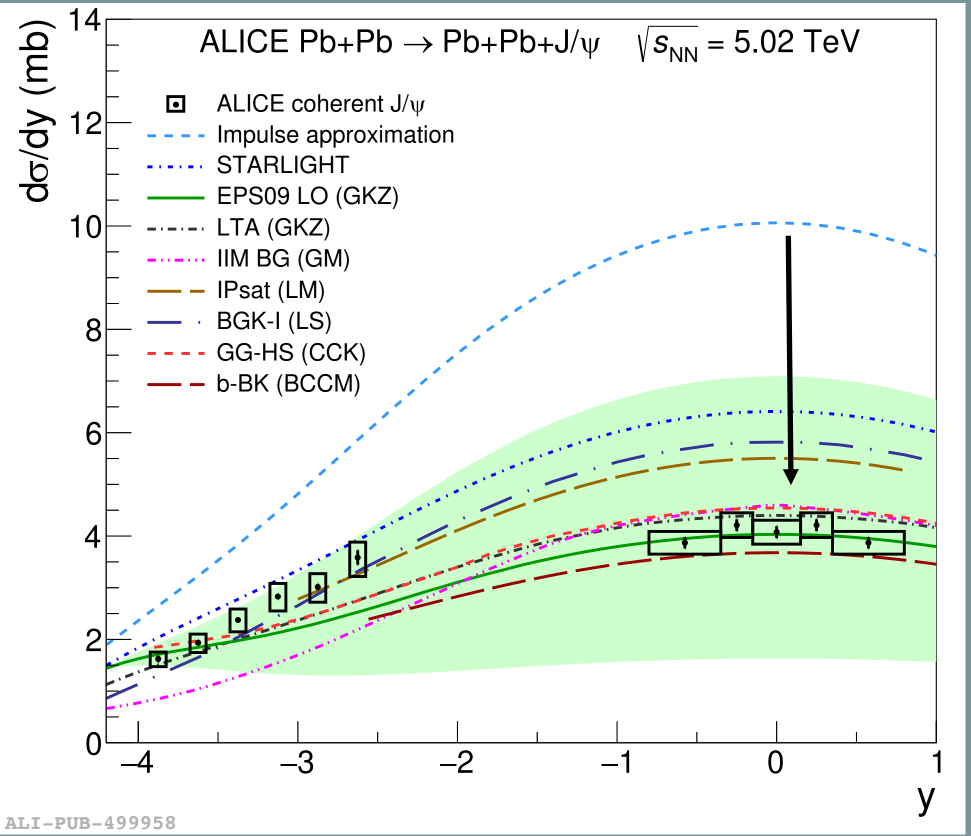
- Dileptons from photon-photon interaction:
  - High precision measurement of $p_{T,ee}$
  - Acoplanarity measurement, differential measurement as a function of EP or rapidity gap between e^+ and e^-

Back up

Results from photon induced processes in UPC

Eur. Phys. J. C 81 (2021) 712





- ❑ Nuclear gluon shadowing of S_{Pb} = 0.64 ± 0.04 for Bjorken-x ~ 10^{-3}
- ❑ Provides important constraints to initial state of HIC

New investigations from ALICE of photon induced processes in Pb–Pb collisions with nuclear overlap

new First measurement of a very low-p_T dielectron excess at low invariant mass ($0.4 < m_{e+e-} < 2.7$ GeV/c^2) at the LHC in hadronic Pb–Pb collisions

new Coherent J/ψ photoproduction cross section measured towards most central Pb–Pb collisions ($\sqrt{s_{NN}}$ = 5.02 TeV) at forward-y (5σ significance in 30-50%!)

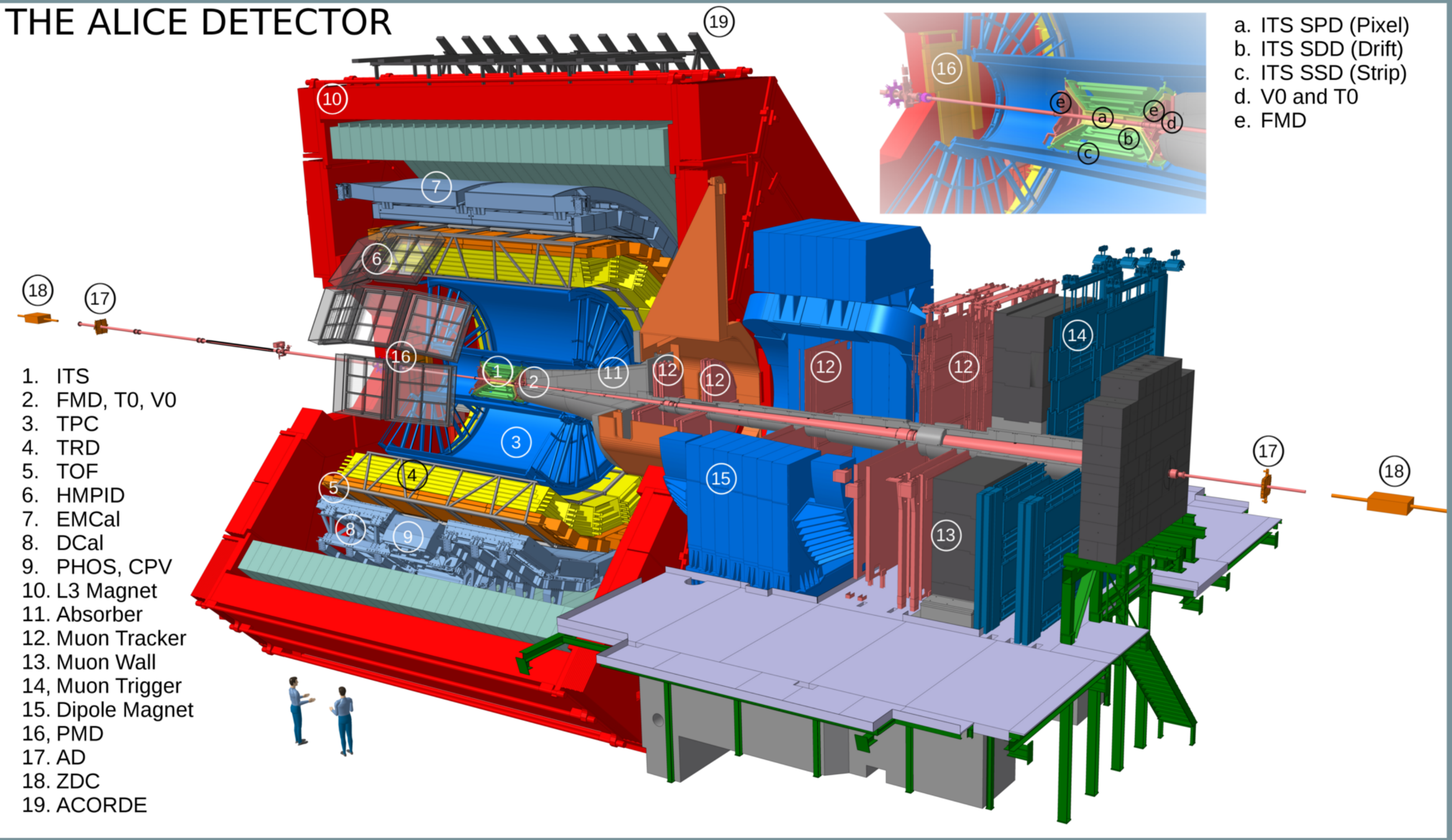
new First p_T-differential measurement of the coherent J/ψ photoproduction cross section in peripheral Pb–Pb collisions at mid-y and $\sqrt{s_{NN}}$ = 5.02 TeV

The ALICE apparatus(Run 2)

Data sample: 2015+2018 Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (full Run 2 stat.)

Central barrel:
|y| < 0.9
low mass dielectrons
J/Ψ → e^+e^-

ITS: tracking
TPC: tracking, PID
TOF: PID

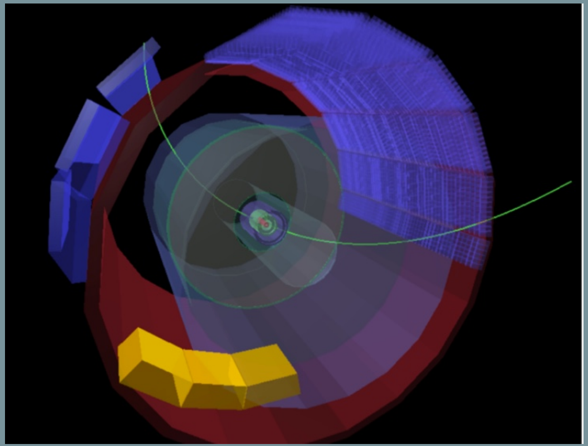


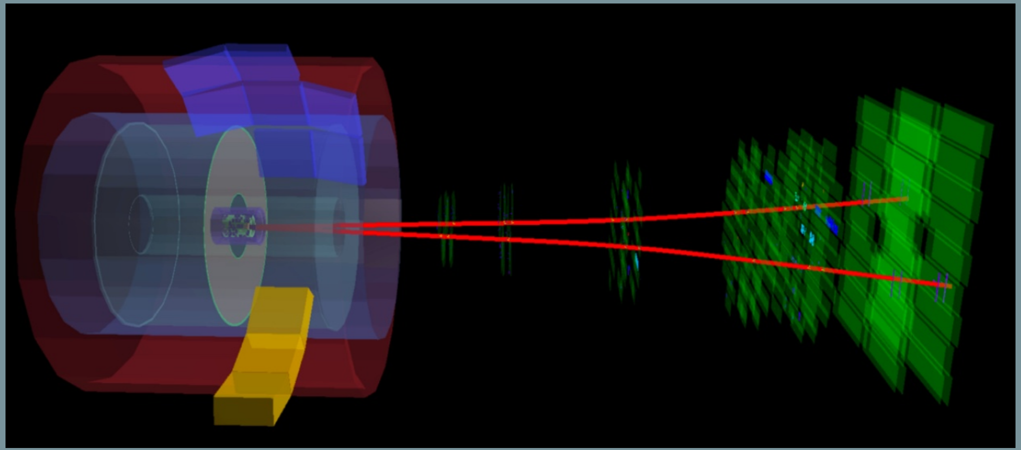
Muon spectrometer:
2.5 < y < 4
J/Ψ → $\mu^+\mu^-$

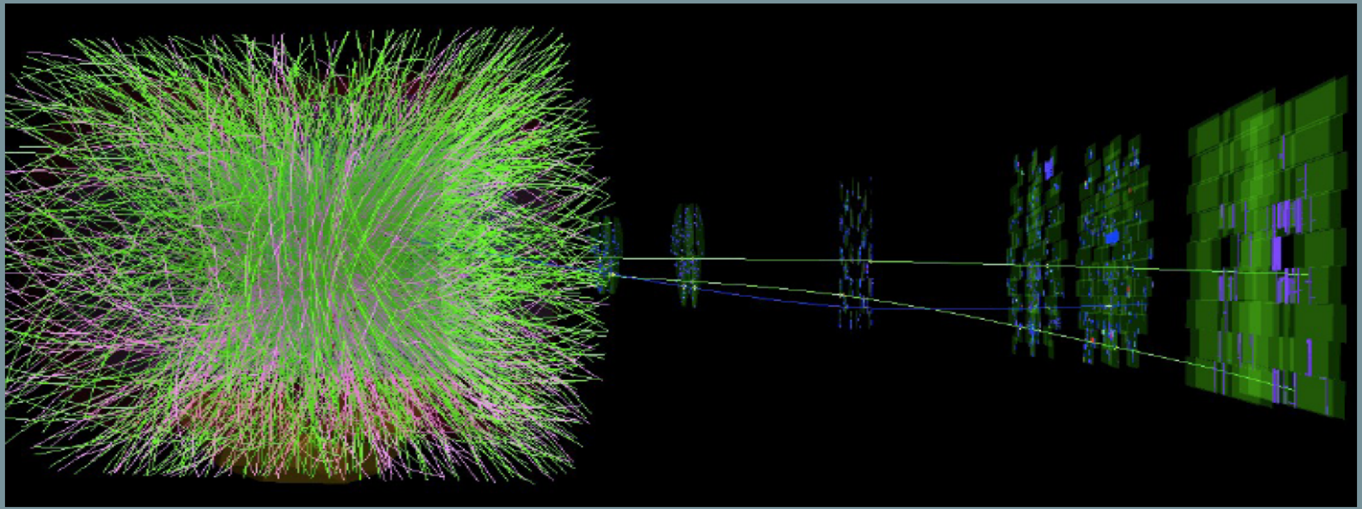
Muon tracker: tracking
Muon trigger: triggering

ITS: vertex reconstruction, ZDC: background rejection
V0 scintillators: triggering, centrality determination, background rejection

Event display: UPC events versus hadronic events

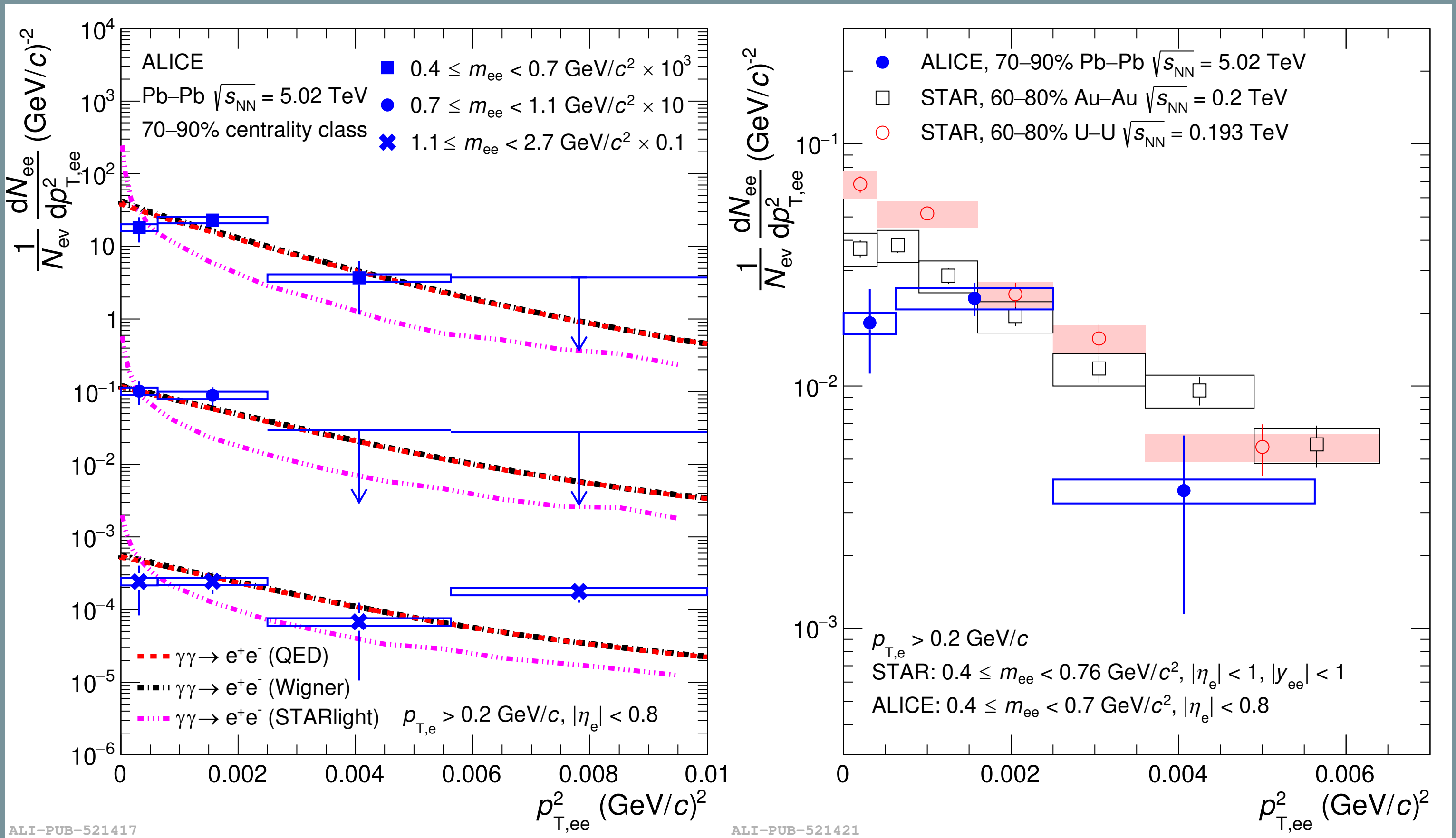

UPC event in the central barrel


UPC event in the muon spectrometer


Pb–Pb hadronic event

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

arXiv:2204.11732



- p_T^2 distribution of the excess after subtracting the hadronic cocktail
- From comparison with models: p_T broadening observed in HIC originates predominantly from initial EM field strength which varies significantly with b
- Similar p_T^2 spectrum for ALICE and STAR peripheral events despite different c.m.s energies, Z of nuclei

QED: W. Zha *et al.*, Phys. Lett. B 800 (2020) 135089, J. D. Brandenburg *et al.*, Eur. Phys. J. A 57 (2021) 299
Wigner: M. Klusek-Gawenda *et al.*, Phys. Lett. B. 814 (2021) 136114
STARlight: S.R. Klein *et al.*, Comput. Phys. Commun. 212 (2017) 258, S.R. Klein, Phys. Rev. C. 97 (2018) 054903

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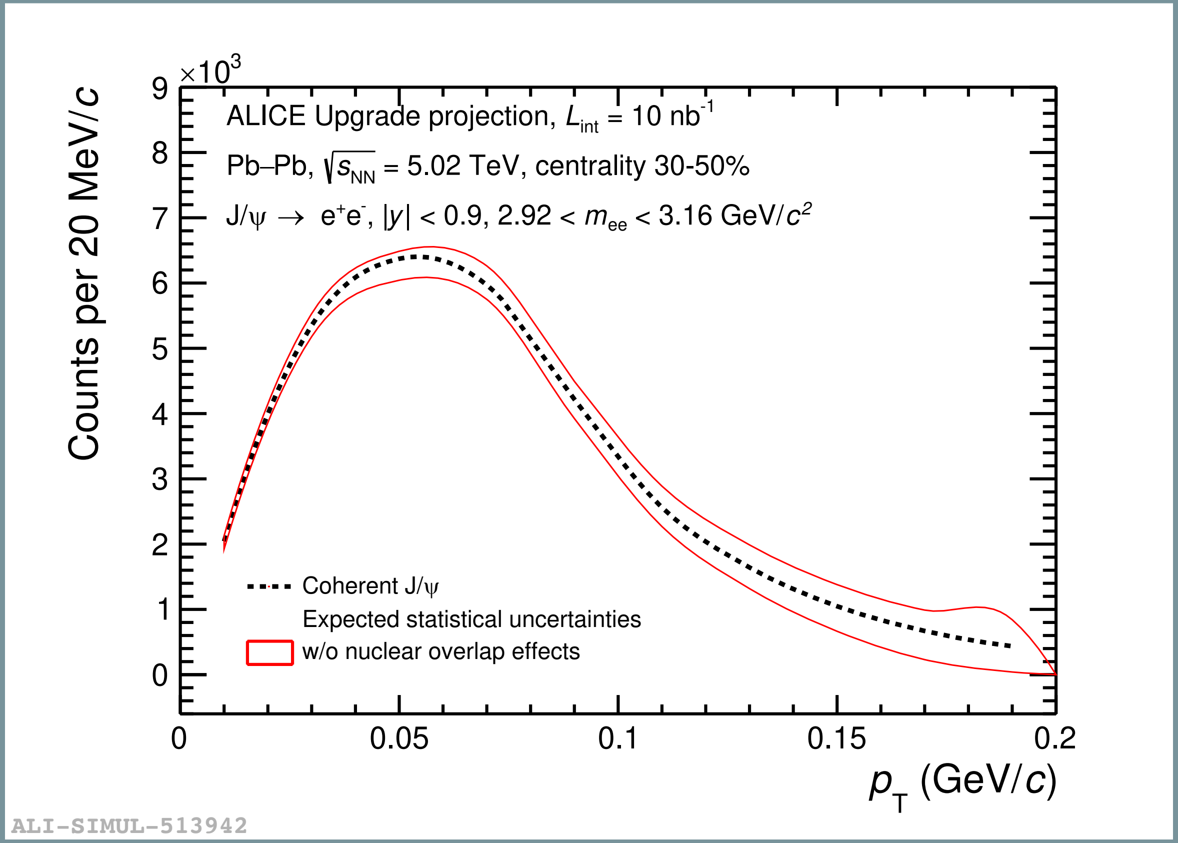

×10^3
ALICE Upgrade projection, L_{int} = 10 nb^{-1}
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, centrality 30-50%
J/ψ → e$^+$e$^-$, |y| < 0.9, 2.92 < m_{ee} < 3.16 GeV/c^2
Coherent J/ψ
Expected statistical uncertainties
w/o nuclear overlap effects
Counts per 20 MeV/c
p_T (GeV/c)
0
0.05
0.1
0.15
0.2
0
1
2
3
4
5
6
7
8
9
ALI-SIMUL-513942

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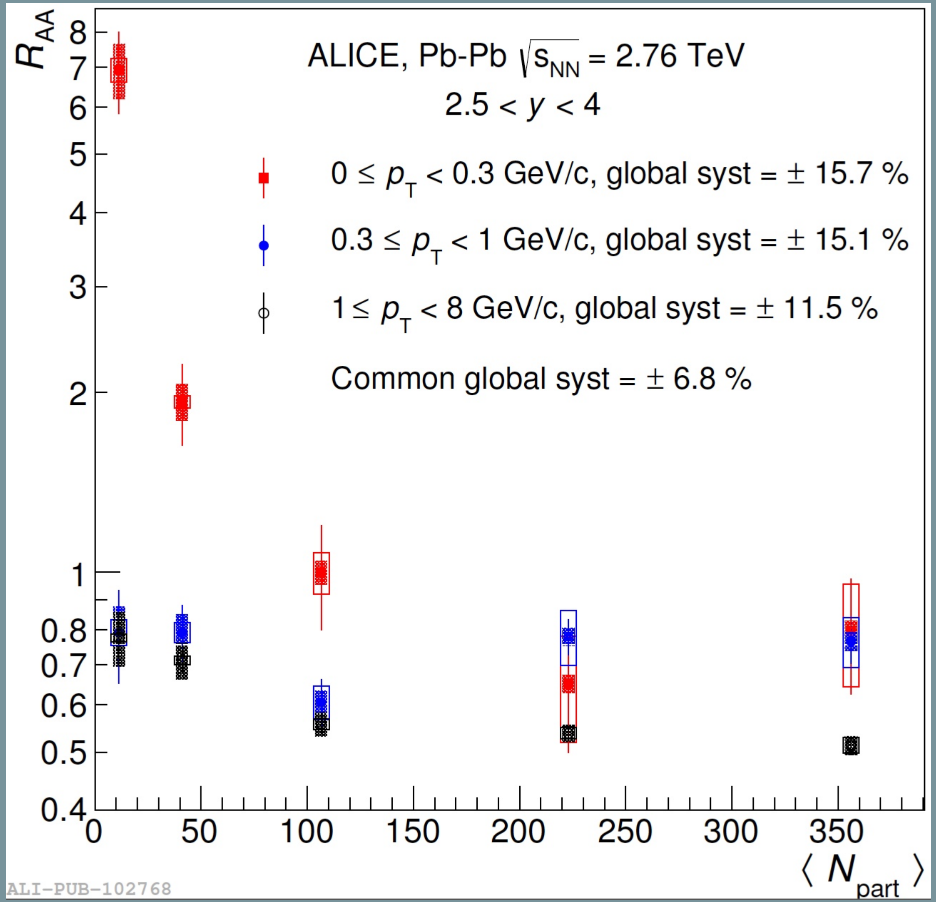
PRL 116, 222301 (2016)



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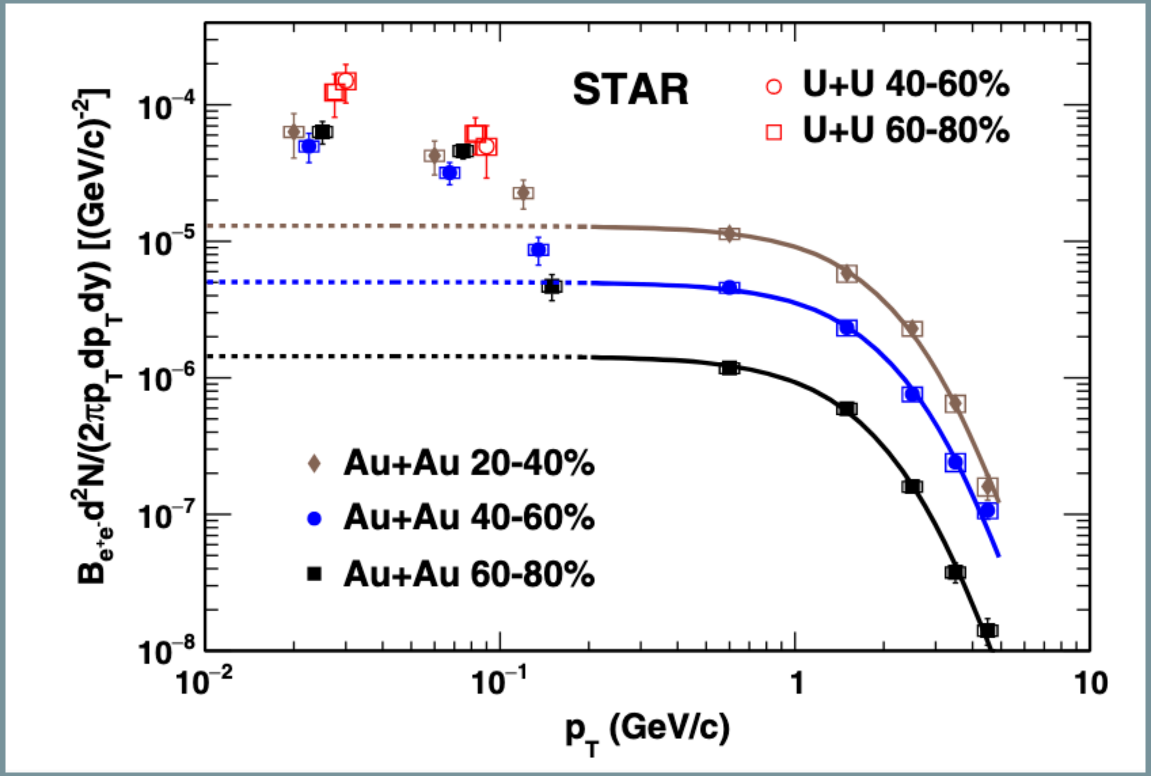
STAR Collaboration, PRL 123, 132302 (2019)



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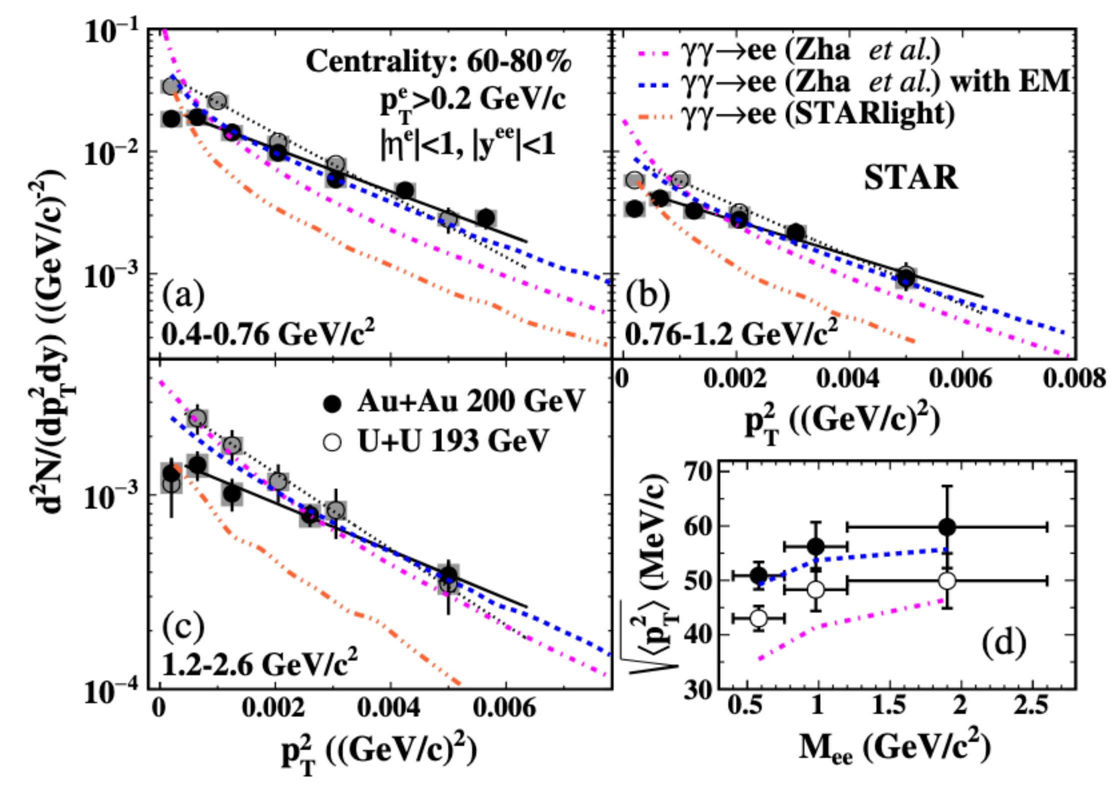
STAR Collaboration, PRL 121, 132301 (2018)



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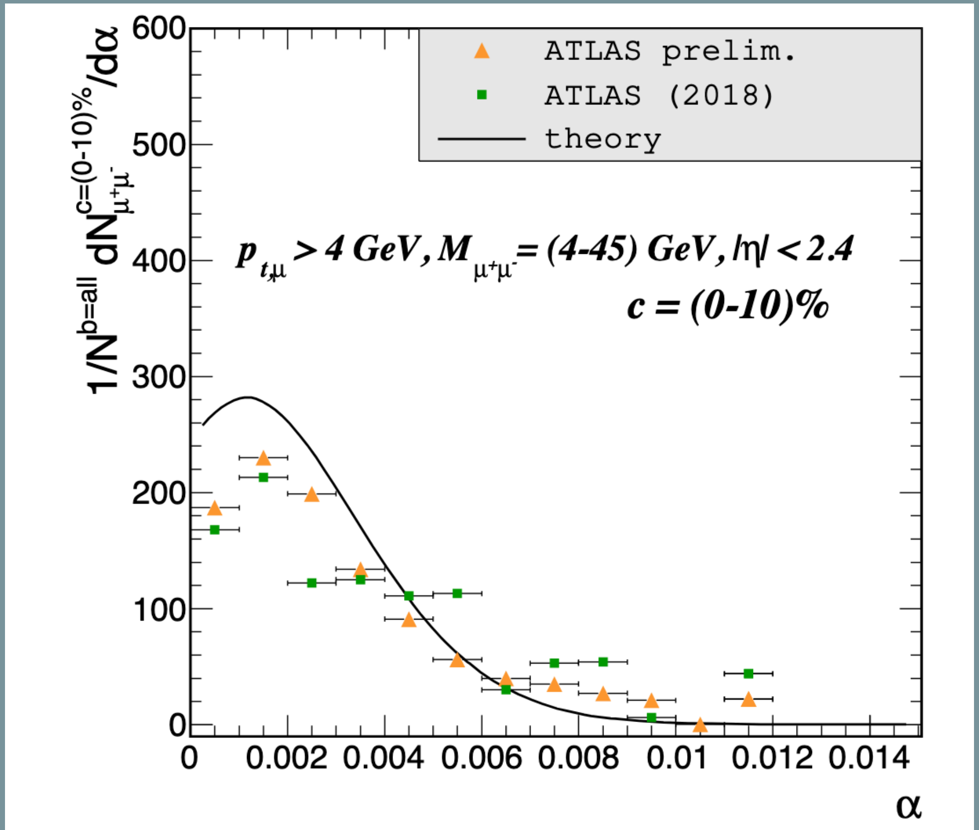
M. Klusek-Gawenda, J. Phys. Lett. B 814 (2021) 136114



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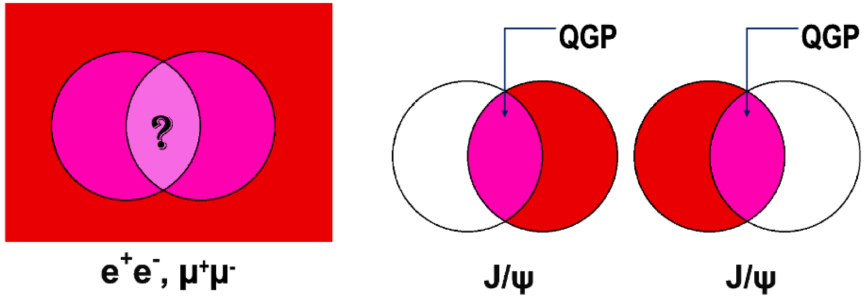
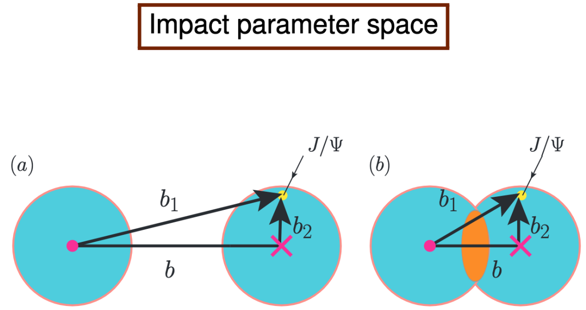
M. Klusek-Gawenda, PRC 93, 044912 (2016), from presentation of M. Klusek-Gawenda at HF2022 workshop





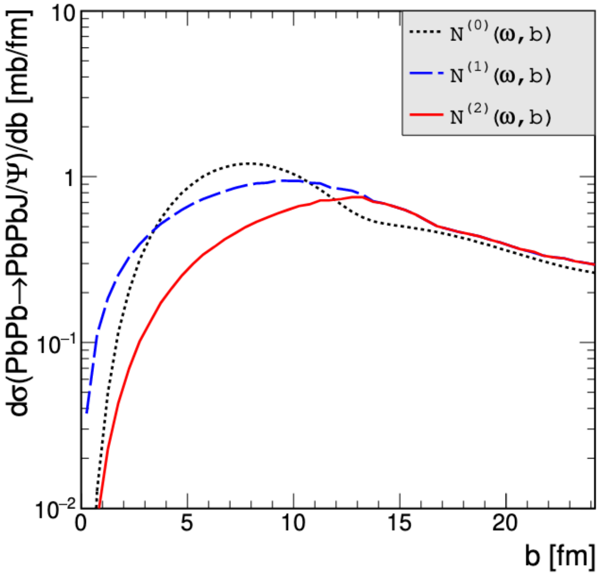
J/ψ photoproduction for (a) ultraperipheral and (b) central heavy ion collisions.

The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

$$N^{(1)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))}{\pi R_A^2} \mathrm{d}^2 b_1$$

$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))(b_1 - R_A)}{\pi R_A^2} \mathrm{d}^2 b_1$$

$$\sigma(N^{(0)}, UPC) = \sigma(N^{(1)}, UPC) = \sigma(N^{(2)}, UPC)$$



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M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013

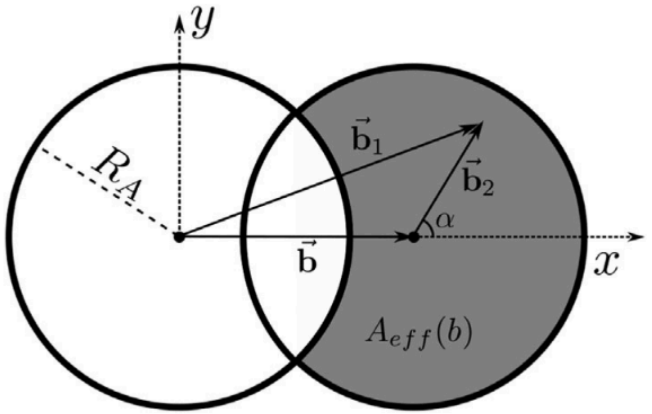

FIG. 2. Schematic drawing used in the construction of the effective photon flux.

$$N^{\text{eff}}(\omega,b) = \frac{1}{A_{\text{eff}}(b)}\int d^2b_1 N(\omega,b_1)\theta(R_A - b_2)\theta(b_1 - R_A), \quad (12)$$

where

$$A_{\text{eff}}(b) = R_A^2\left[\pi - 2\cos^{-1}\left(\frac{b}{2R_A}\right)\right] + \frac{b}{2}\sqrt{4R_A^2 - b^2}.$$