PHOTON INDUCED CHARMONIUM PRODUCTION FROM ULTRA- TO SEMI-PERIPHERAL NUCLEUS-NUCLEUS COLLISIONS

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OUTLINE

- Photonuclear reactions in Ultra-Peripheral collisions (UPC)
- Charmonium photoproduction at RHIC in UPC (Au-Au)
- Charmonium photoproduction at ALICE in UPC (Pb-Pb)
- Charmonium photoproduction at ALICE in peripheral and semi-peripheral Pb-Pb collisions
- Prospects for charmonium photoproduction measurements in LHCb
- Discussion

PHOTONUCLEAR REACTIONS IN ULTRA-PERIPHERAL A-A COLLISIONS

- Ultra-Peripheral collisions: impact parameter (b) is larger than the sum of radii of colliding nuclei

→ Hadronic interaction are strongly suppressed

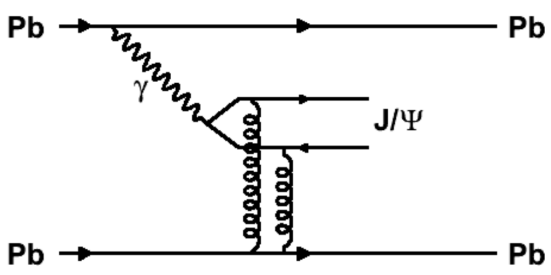
- The strong electromagnetic field of ultra-relativistic heavy nuclei can be represented by a spectrum of equivalent photons

Weizsäcker-Williams (EPA) formula

$$\frac{dN_\gamma}{d\xi}(b > b_{\min}) = \frac{\alpha_{em} Z^2}{\pi} \frac{1}{\xi}\left[2xK_0(x)K_1(x) - x^2\left(K_1^2(x) - K_0^2(x)\right)\right]; \ \xi = \frac{E_\gamma}{E_A} \ \& \ x = \xi m_A b_{\min}$$

Nucleus Form factor dependence is included in modified Bessel functions K_1 and K_0

- Exclusive vector meson photoproduction:



Coherent production: γ couples coherently to all nucleons
<p_T> ~ 60 MeV/c
Target nucleus normally doesn't break up

Incoherent production: γ couples to a single nucleon
<p_T> ~ 500 MeV/c
Nucleus normally breaks up

- I won't discuss J/ψ photoproduction in A-A UPC as a tool to provide information on gluon shadowing in the nuclei at low x

J/Ψ PHOTOPRODUCTION AT RHIC IN UPC Au-Au ($\sqrt{s_{NN}}$ = 200 GeV)

- **Results from PHENIX**

→ **2004 Run, mid-rapidity: -0.35 < η < 0.35, Au + Au → Au + Au + e^+e^-**

→ Published in: *S. Afanasiev et al., PHENIX Collaboration, Phys. Lett. B 321(2009)*

→ The first measurement of heavy final states in ultra-peripheral nucleus-nucleus collisions

→ L_{int} = 141 ± 12 μb^{-1}

→ Maximum photon energy in c.o.m system: ω_{max}~ 3 GeV

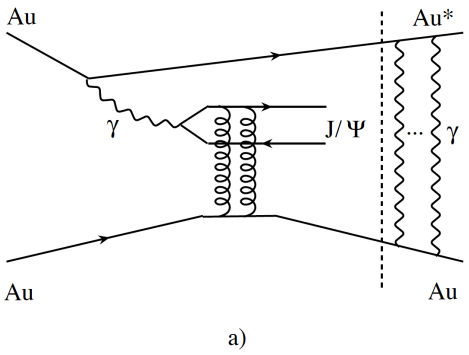
→ Maximum photon-nucleon & two-photon c.o.m energies: $W_{\gamma n}$ ~ 34 GeV, $W_{\gamma\gamma}$ ~ 6 GeV

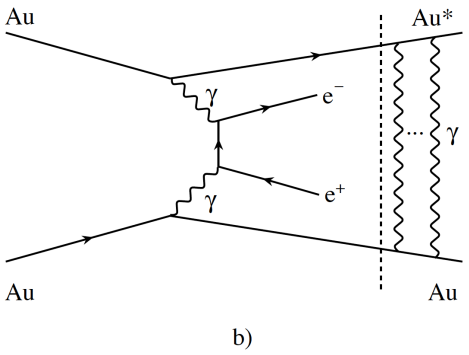
→ Exchange of soft photons can lead to excitation of the interaction nuclei (GDR)

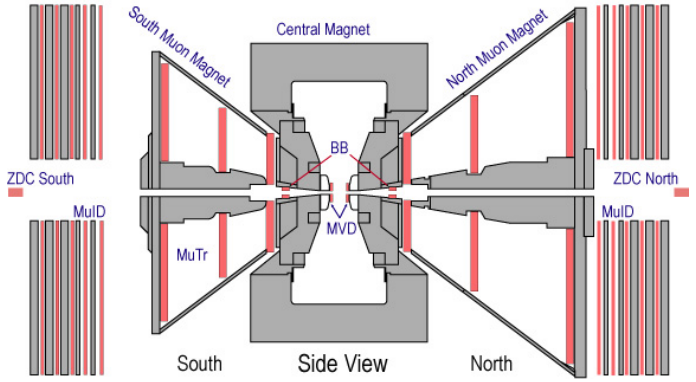
→ Emission of neutrons at very forward rapidities

→ Emission of neutrons in coincidence with coherent J/ψ production (P ~ 55%)

→ Permits to trigger on UPC with Zero Degree Calorimeters







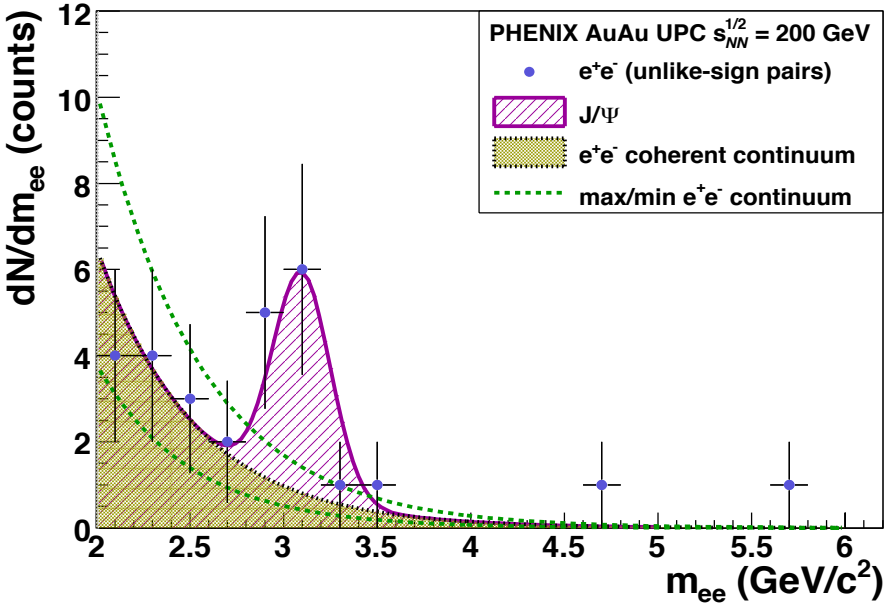
J/Ψ PHOTOPRODUCTION AT RHIC IN UPC Au-Au ($\sqrt{s_{NN}}$ = 200 GeV)

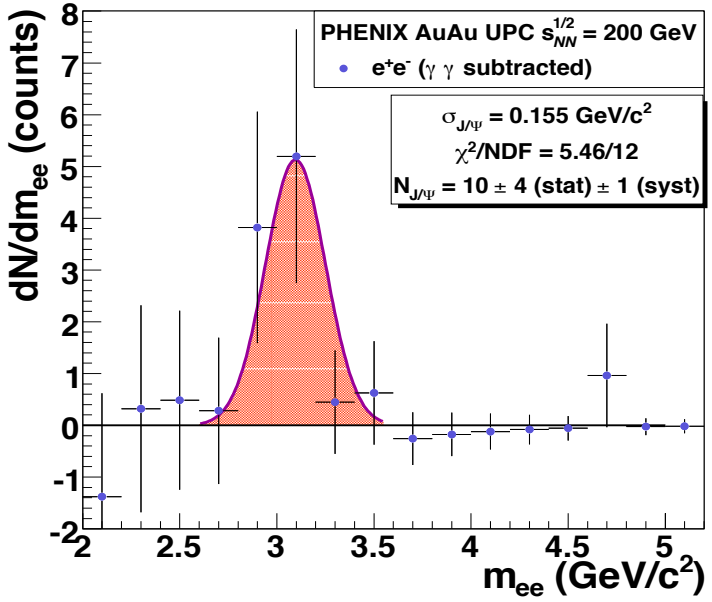
- **Results from PHENIX**

→ **2004 Run, mid-rapidity: -0.35 < η < 0.35, Au + Au → Au + Au + e^+e^-**

Dedicated UPC trigger:

- Veto on coincident signals in both Beam-Beam counters (3.0 < |η| < 3.9)
  - → Selection of exclusive events with large rapidity gaps on either side of the central arm
- Mimimum energy deposition in electromagnetic calorimeter
- At least 30 GeV energy deposit in one or both of the ZDCs



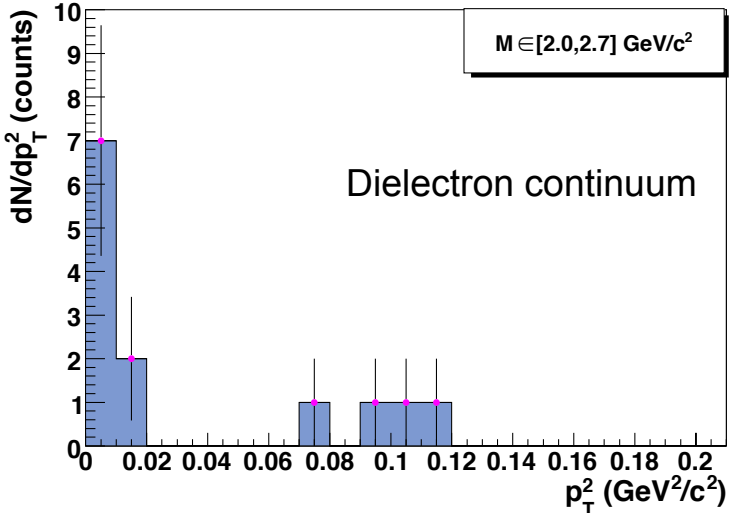


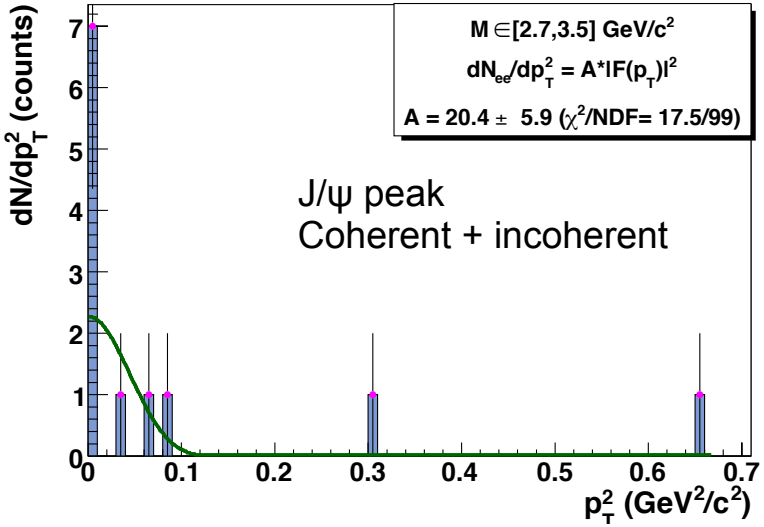
~ 10 J/ψ after γγ background subtraction

J/Ψ PHOTOPRODUCTION AT RHIC IN UPC Au-Au ($\sqrt{s_{NN}}$ = 200 GeV)

- **Results from PHENIX**

→ **2004 Run, mid-rapidity: -0.35 < η < 0.35, Au + Au → Au + Au + e^+e^-**

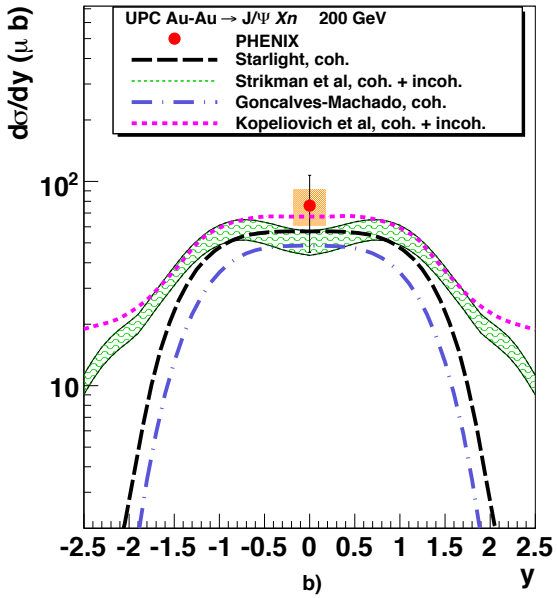




→ No separation of coherent and incoherent J/ψ photoproduction components

→ Estimation of 40 (60%) of the total J/ψ production from incoherent photoproduction

→ No strong conclusion from the comparison of theoretical models with the measured J/ψ y-differential photoproduction cross section



Starlight, Phys. Rev Lett. 89 (2002) 220-226
Strikman et al., Phys. Lett. B 626 (2005) 72-79
Goncalves-Machado, arXiv:0706.2810
Kopeliovich et al, arXiv:0706.1532

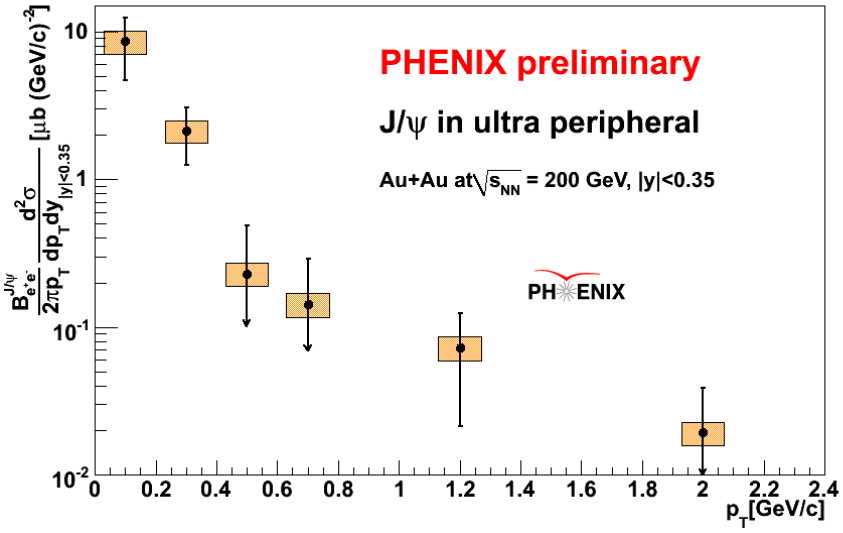
J/Ψ PHOTOPRODUCTION AT RHIC IN UPC Au-Au ($\sqrt{s_{NN}}$ = 200 GeV)

- **Results from PHENIX (preliminary)**

→ **2007 Run, mid-rapidity: -0.35 < η < 0.35, Au + Au → Au + Au + e^+e^-**

→ From the presentation of: *Akihisa Takahara, JPS 2011*

→ Lint ~ 530 μb^{-1}



p_T-differential cross section for UPC J/ψ photoproduction with forward neutron emission

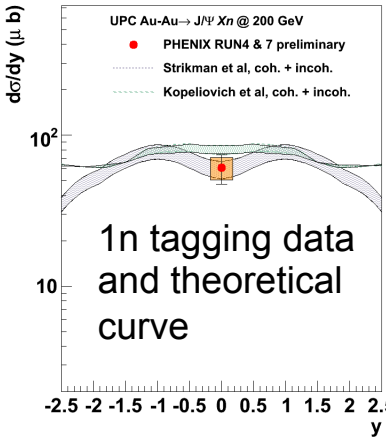
Coherent photoproduction is dominant (low p_T peak)

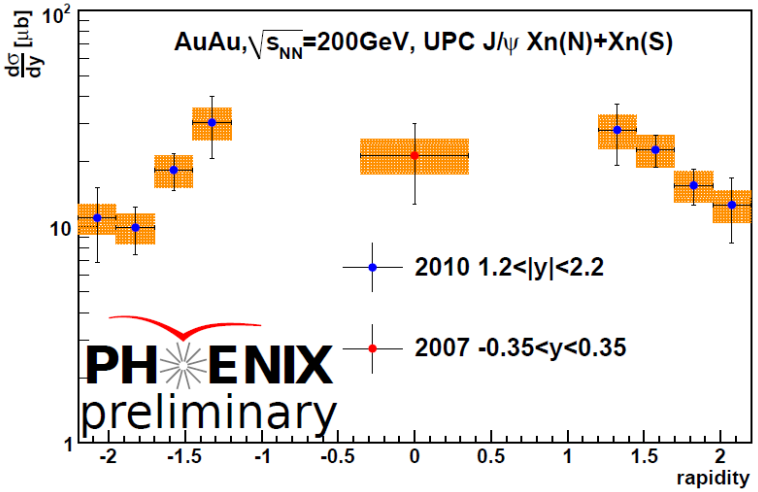
→ **2010 Run, forward rapidity: 1.2 < |η| < 2.2**

→ Lint ~ 1400 μb^{-1}

→ Neutron tagging in **both** ZDC

→ Rapidity shape similar to theory expectations



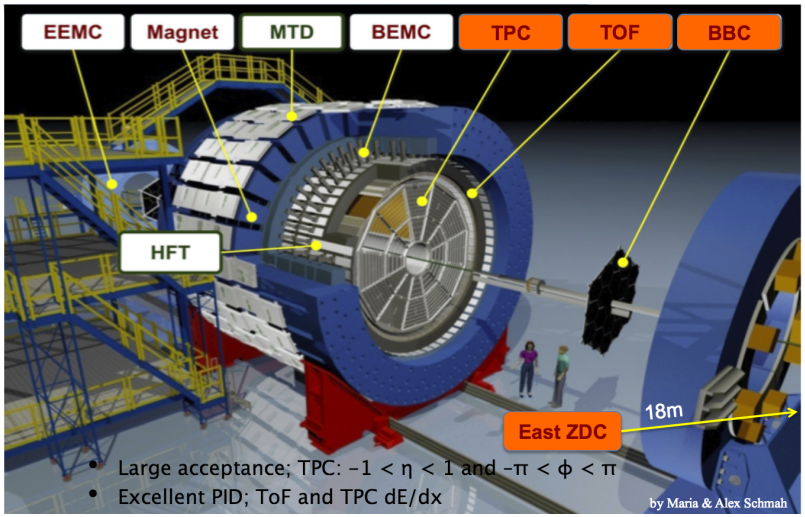


J/Ψ PHOTOPRODUCTION AT RHIC IN UPC Au-Au ($\sqrt{s_{NN}}$ = 200 GeV)

- **Results from STAR (Preliminary)**

→ **2010 Run, mid-rapidity measurement**

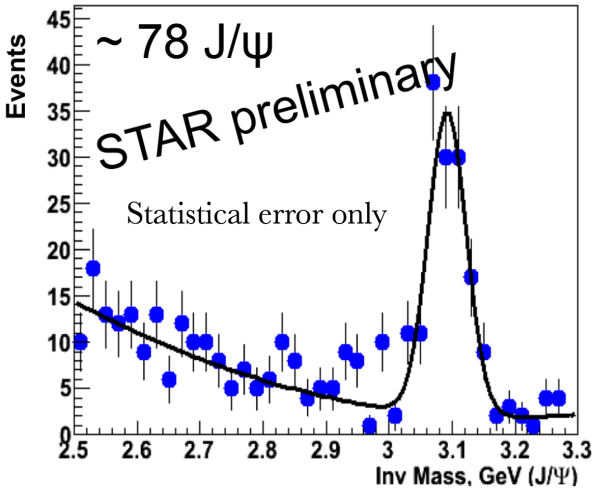
→ From the presentation of: *L. Chanaka de Silva, APS Prairie Section Meeting 2015*



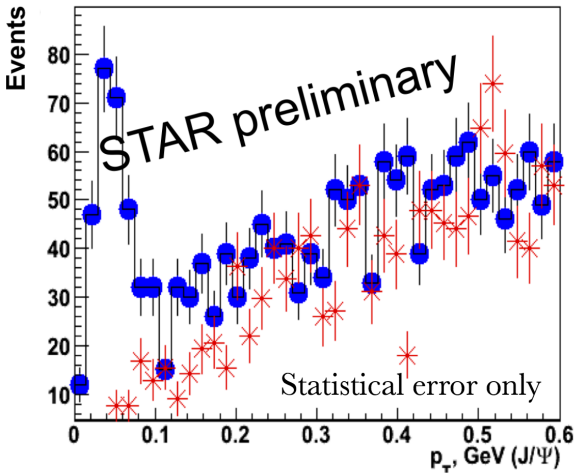
STAR UPC trigger:
2 ≤ TOF hits ≤ 6
Veto on BBC (2 < |η| < 5)
1 ≤ neutrons ≤ 5 in both ZDC

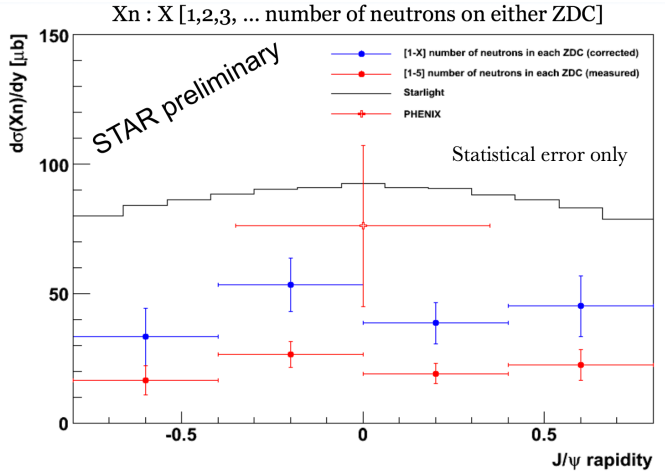
Lint ~ 1075 μb^{-1}

Blue: unlike sign pairs
Red: background estimated with like sign pairs



After LS background subtraction

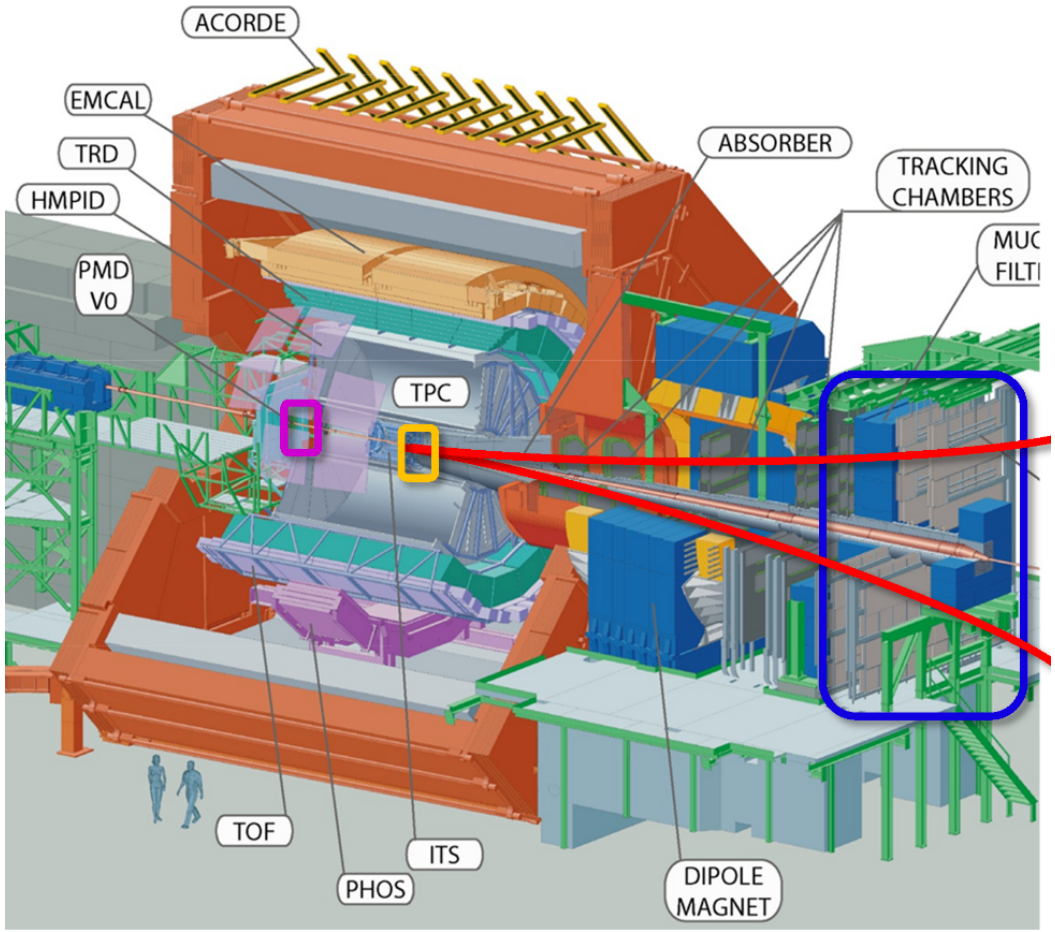


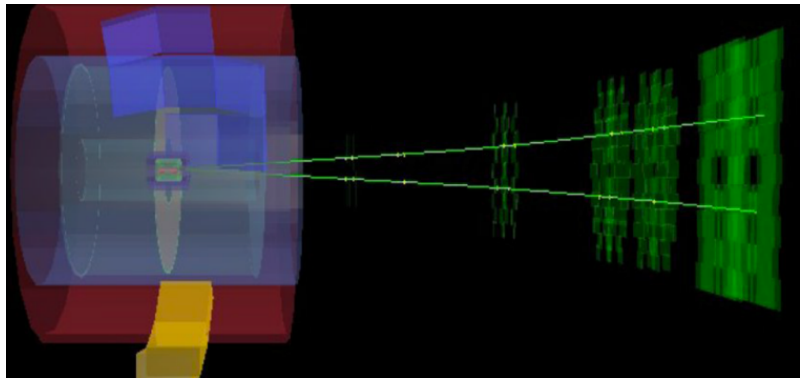


Coherent J/ψ (p_T < 0.15 GeV/c)

J/Ψ PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

- **Results from ALICE**
- **2011 Run, forward rapidity: - 3.6 < η < - 2.6 , Pb + Pb → Pb + Pb + J/ψ (→$\mu^+\mu^-$)**
- Published in: *Phys. Lett. B718 (2013) 1273*
- Lint ~ 55 μb^{-1}

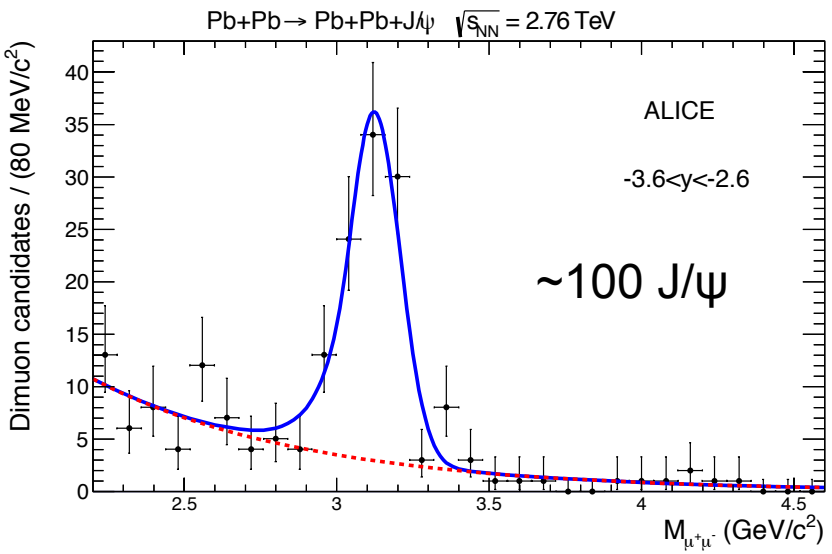


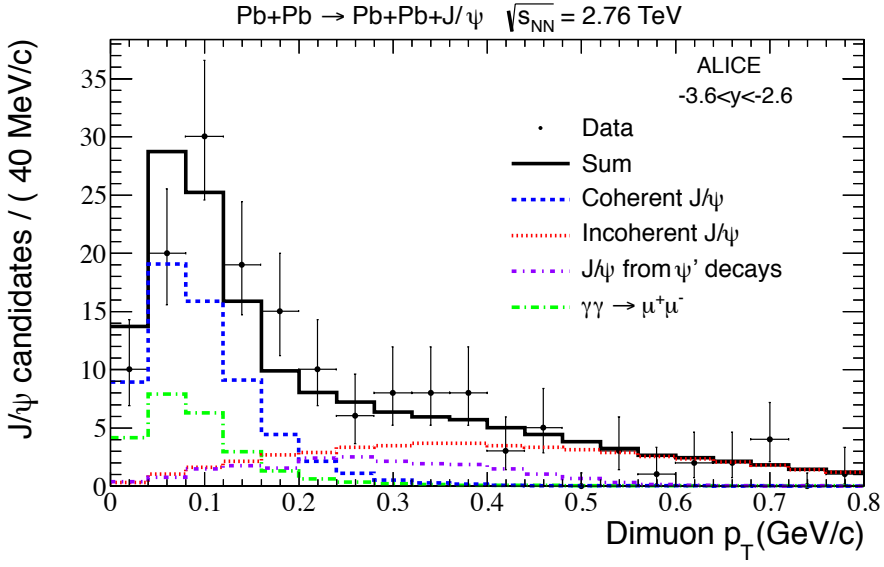


ALICE UPC forward trigger:
Single muon trigger
with p_T > 1 GeV/c
Hit in VZERO-C (-3.7 < η < -1.7)
No hits in VZERO-A
(2.8 < η < 5.1)

J/Ψ PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

- **Results from ALICE**
- **2011 Run, forward rapidity: - 3.6 < η < - 2.6 , Pb + Pb → Pb + Pb + J/ψ (→$\mu^+\mu^-$)**



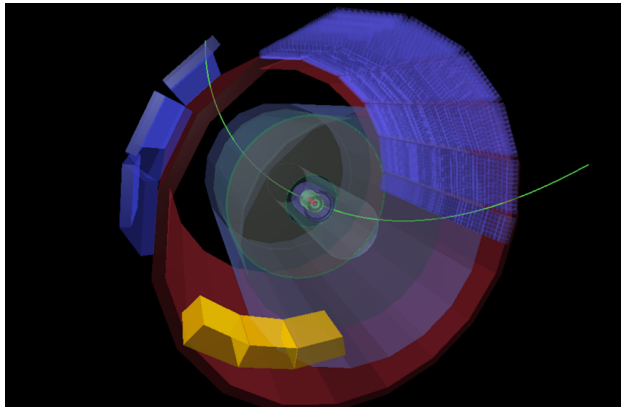


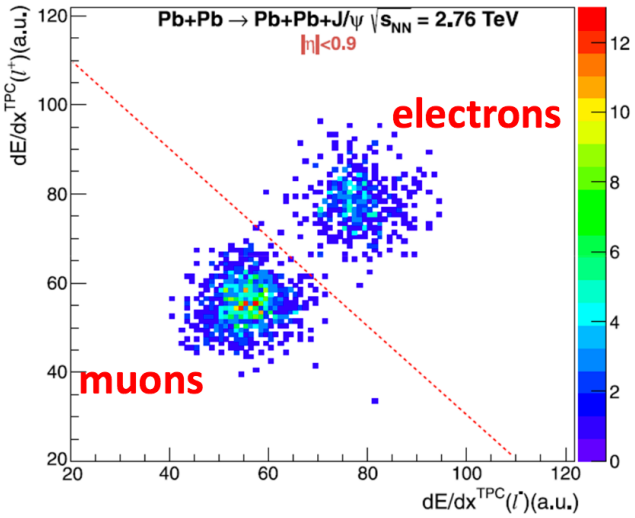
Invariant mass distribution:
Dimuon p_T < 0.3 GeV/c
Signal fitted with Crystal Ball shape
Background well describes by exponential shape compatible with expectations from γγ → $\mu^+\mu^-$

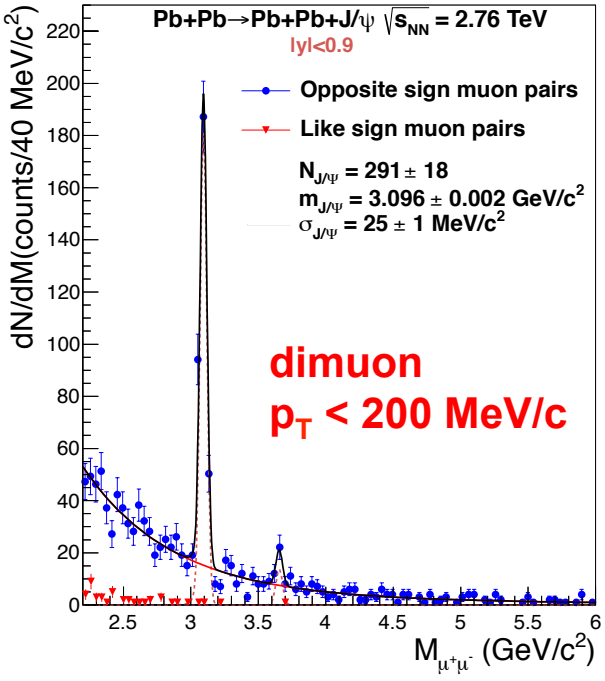
Coherent J/ψ
Incoherent J/ψ
J/ψ from ψ' decays
γγ → $\mu^+\mu^-$

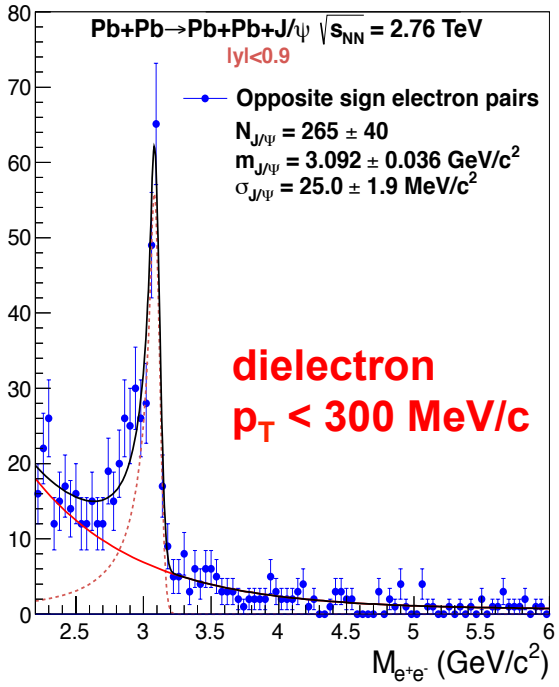
J/Ψ PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

- **Results from ALICE**
- **2011 Run, mid-rapidity: - 0.9 < η < 0.9 , Pb + Pb → Pb + Pb + J/ψ (→$\mu^+\mu^-$ or e^+e^-)**
- Published in: *Eur. Phys. J. C73 (2013) 2617*
- Lint ~ 23 μb^{-1}





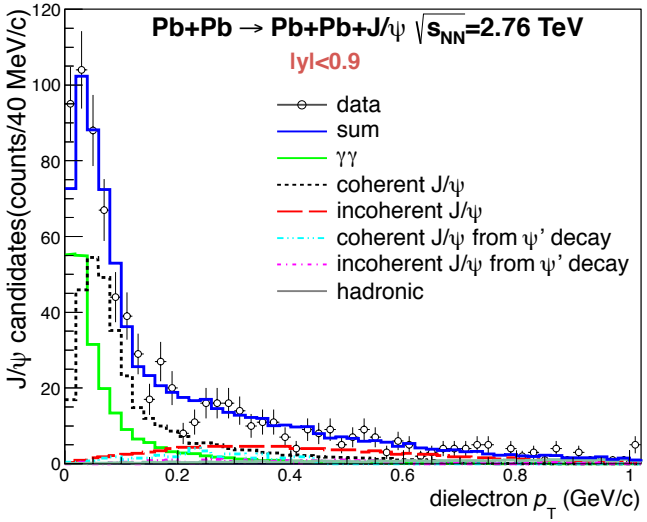


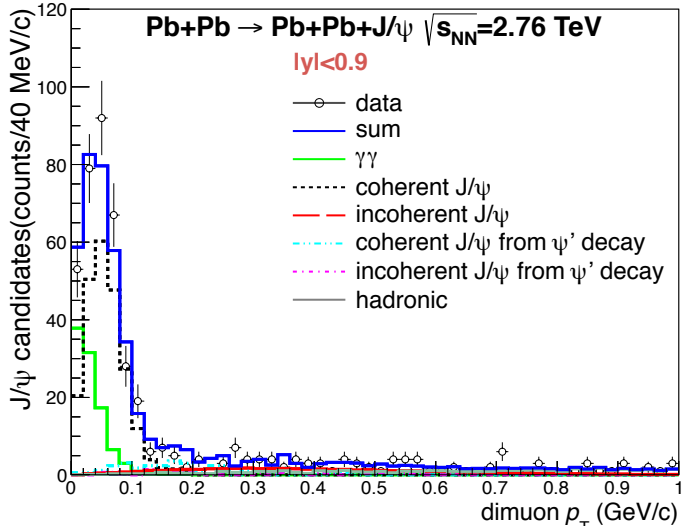


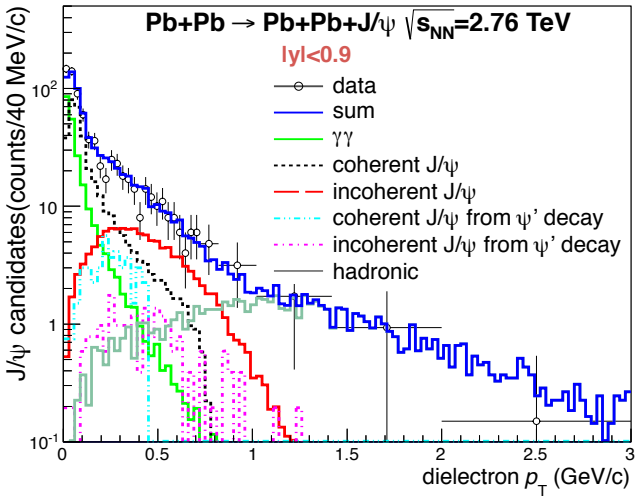
ALICE central barrel trigger:
2 ≤ TOF hits ≤ 6
+ back-to-back topology
≥ 2 hits in SPD
No hits in VZERO

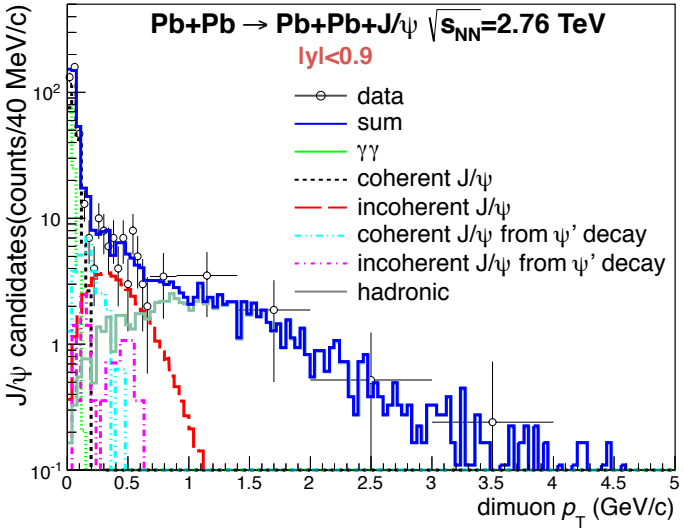
J/Ψ PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

- **Results from ALICE**
- **2011 Run, mid-rapidity: - 0.9 < η < 0.9 , Pb + Pb → Pb + Pb + J/ψ (→$\mu^+\mu^-$ or e^+e^-)**







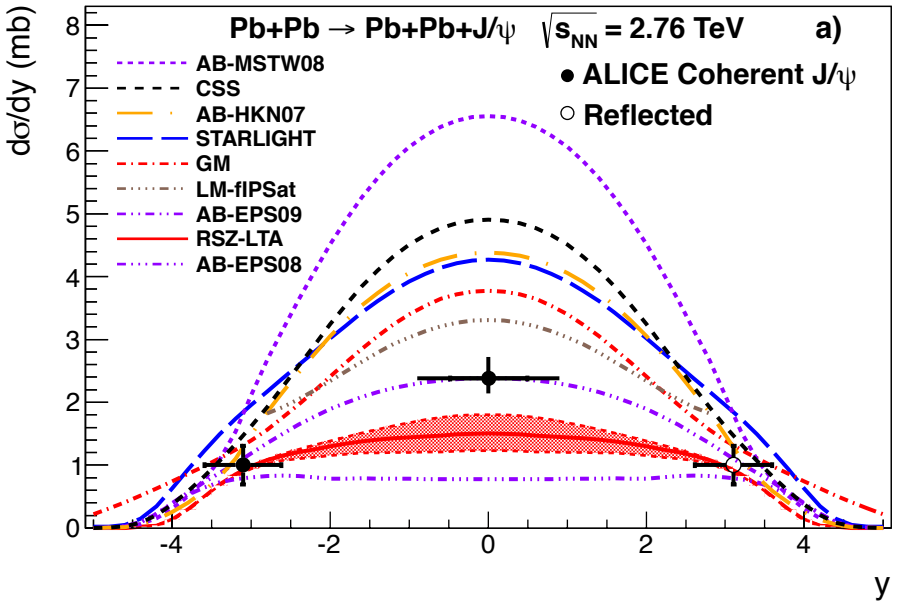


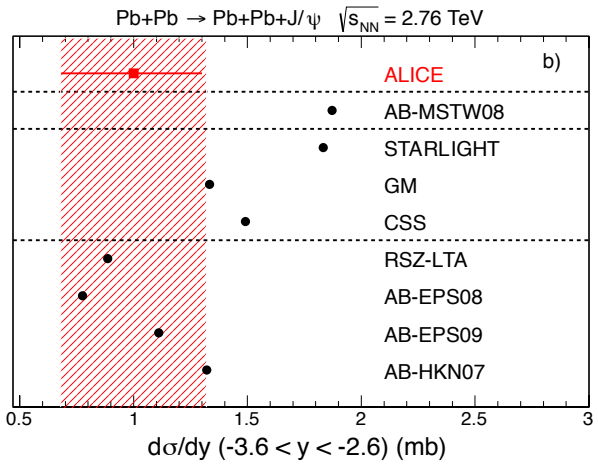
Clear coherent peak from J/ψ and continuum γγ→l^+l^-

Full spectrum explained by, in addition:
Incoherent J/ψ
J/ψ from ψ' feed down
Hadronic contribution at high p_T

J/Ψ PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

- **Results from ALICE**
- **2011 Run, results from mid- and forward rapidity**





Model assuming no nuclear effects

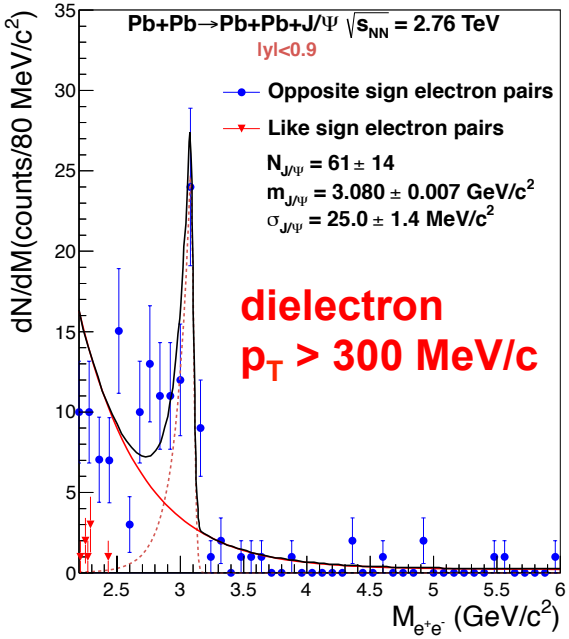
Model using a Glauber Approach

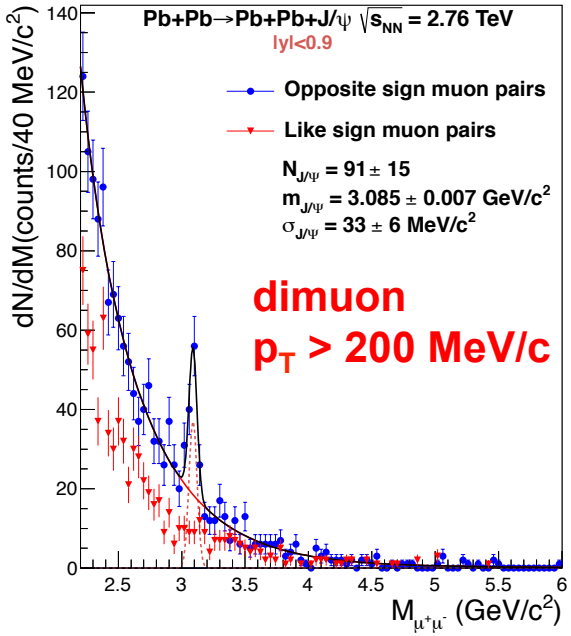
Models based on pQCD

- **STARLIGHT: Klein, Nystrand, PRC60 (1999) 014903** VDM + Glauber approach where J/ψ+p cross section is obtained from a parameterization of HERA data
- **GM: Gonçalves, Machado, PRC84 (2011) 011902** color dipole model, dipole nucleon cross section taken from the IIM saturation model
- **AB: Adeluyi and Bertulani, PRC85 (2012) 044904** LO pQCD calculations: AB-MSTW08 assumes no nuclear effects for the gluon distribution, other AB models incorporate gluon shadowing effects according to the EPS08, EPS09 or HKN07 parameterizations
- **CSS: Cisek, Szczurek, Schäfer, PRC86 (2012) 014905** Glauber approach accounting $c\bar{c}g$ intermediate states
- **RSZ: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252** LO pQCD calculations with nuclear gluon shadowing computed in the leading twist approximation
- **Lappi, Mäntysaari, PRC87 (2013) 032201**: color dipole model + saturation

J/Ψ PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

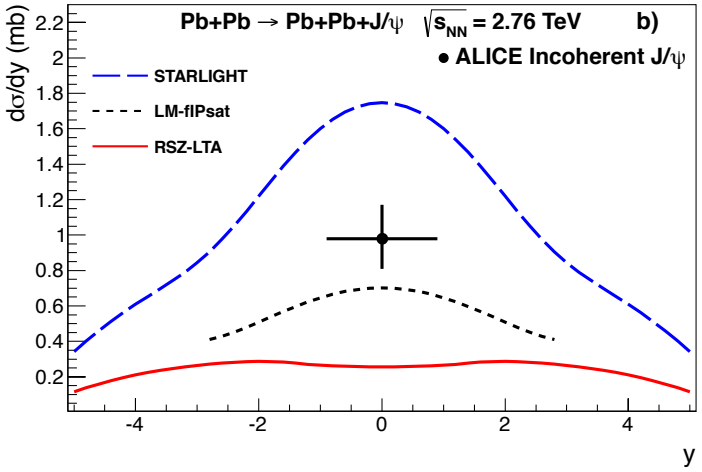
- **Results from ALICE**
- **2011 Run, incoherent J/ψ production at mid-rapidity**





$N_{J/\psi}$ ~ 61 for dielectron channel

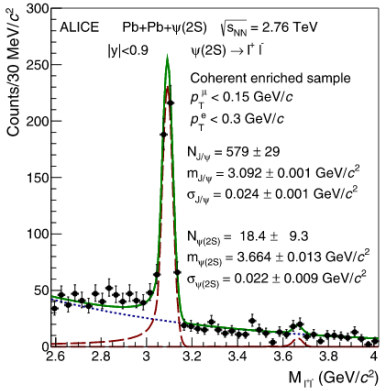
$N_{J/\psi}$ ~ 91 for dimuon channel

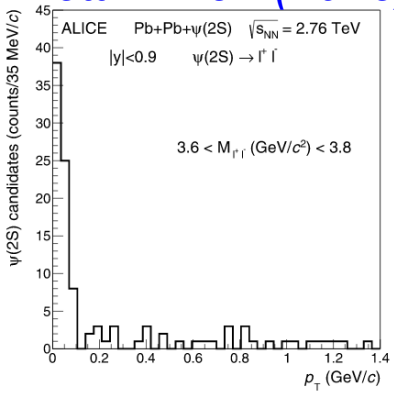


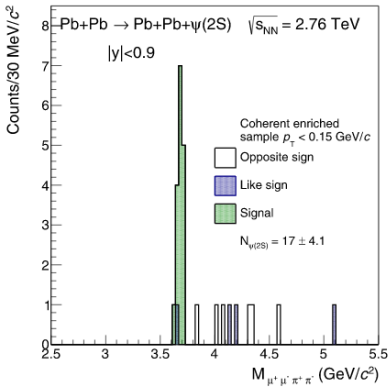
Models under-estimate or over-estimate the measured cross sections

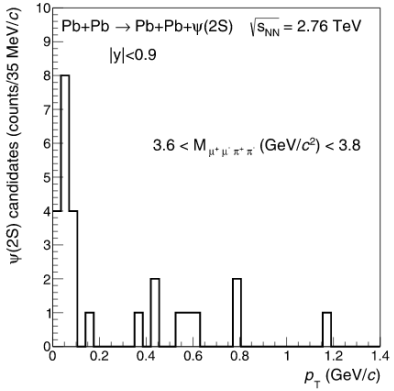
Ψ' PHOTOPRODUCTION AT ALICE IN UPC Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

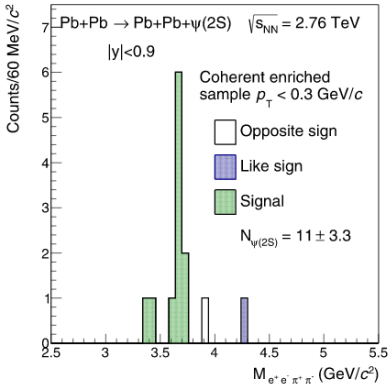
- **Results from ALICE**
- **2011 Run, ψ' photoproduction at mid-rapidity, in 3 different channels**
- Published in: *Phys. Lett. B 751 (2015) 358-370*

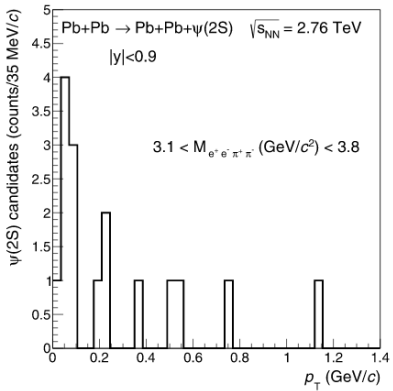




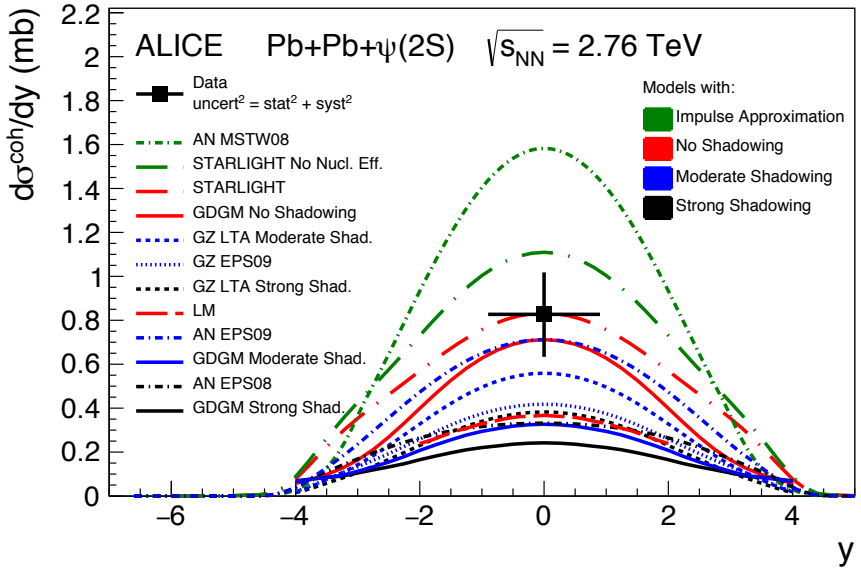






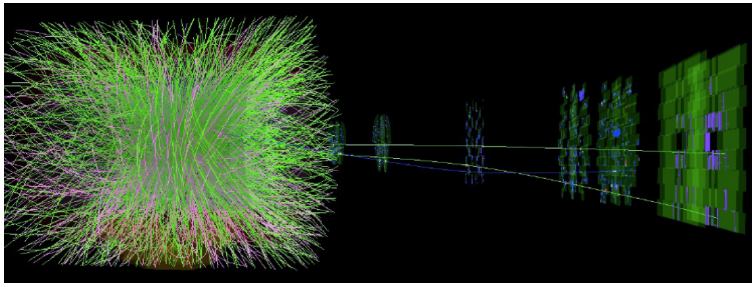


p_T distributions clearly show a coherent peak at low p_T
Negligeable hadronic contamination

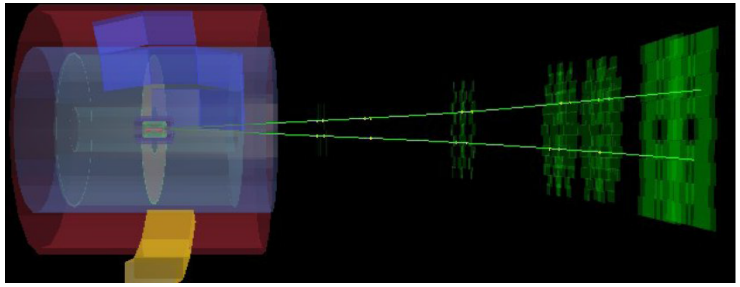


$d\sigma^{coh}/dy$ (ψ(2S)) << $d\sigma^{coh}/dy$ (J/ψ)
Nuclear effetcs and/or gluon shadowing modify the J/ψ and ψ(2S) production in a different way?

CHARMONIUM PHOTOPRODUCTION AT ALICE IN PERIPHERAL AND SEMI-CENTRAL Pb-Pb COLLISIONS ?

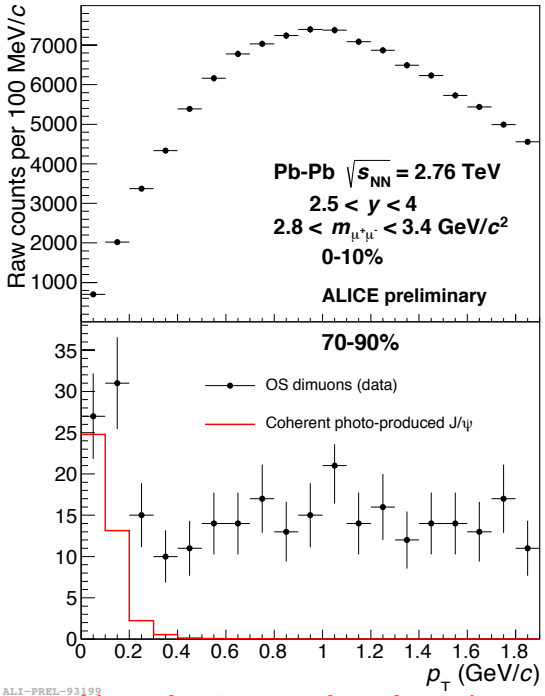


Hadronic Pb-Pb collisions (b < 2R)

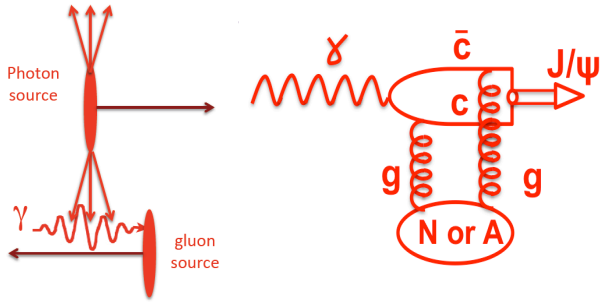


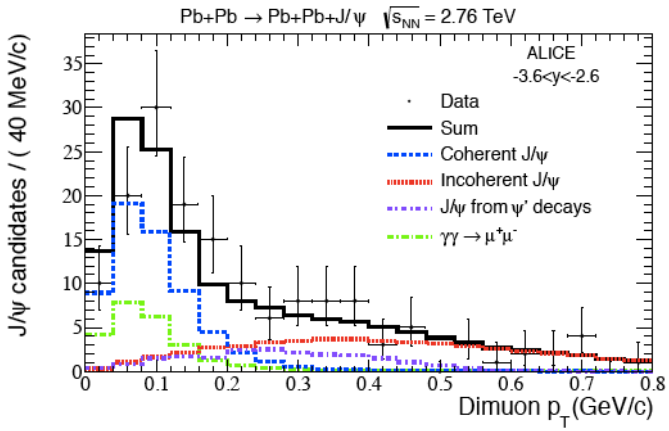
UPC Pb-Pb collisions (b > 2R) with J/ψ candidate

Observation for the first time of an excess at low-p_T in the opposite sign dimuon distribution in peripheral Pb-Pb collisions



J/ψ photoproduction in γ + A

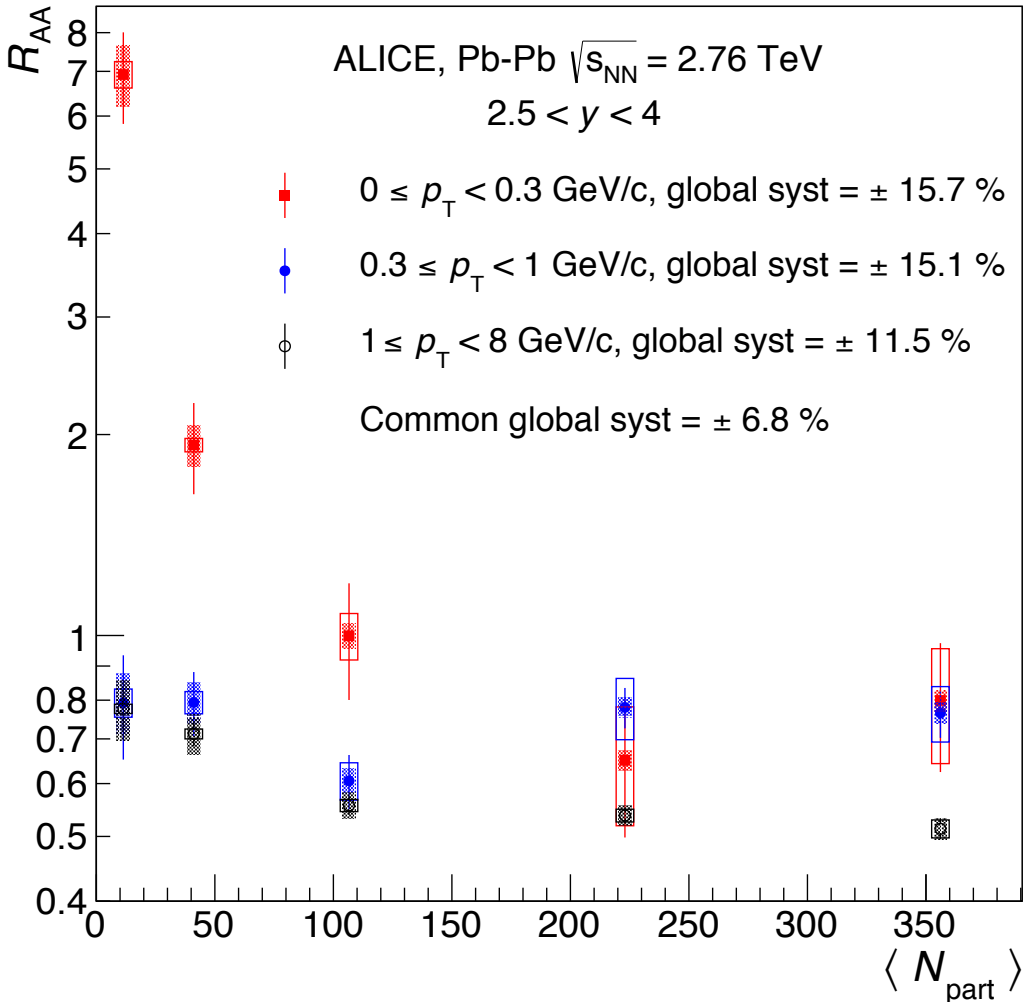




Coherent J/ψ photoproduction (occuring at b < 2R) is proposed as the underlying physics mechanism at the origin of the J/ψ low p_T yield excess observed in hadronic Pb-Pb collisions

CHARMONIUM PHOTOPRODUCTION AT ALICE IN PERIPHERAL AND SEMI-CENTRAL Pb-Pb COLLISIONS ?

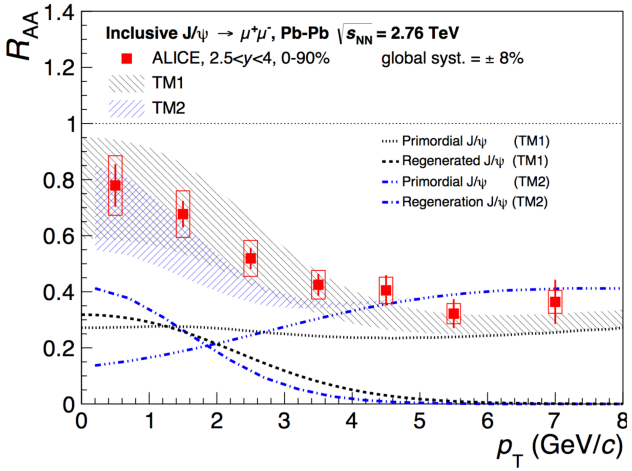
- **J/ψ Nuclear modification factor R_{AA} as a function of centrality at very low p_T**



arXiv:1509.08802

Strong increase of the J/ψ R_{AA} (~7) in most peripheral collisions at low p_T
None of the regeneration models (transport models), which describe well the previous J/ψ R_{AA} measurements predicts such a pattern at LHC energies

arXiv:1506.08804
Nucl. Phys. A859 (2011) 114-125
Phys. Lett. B678 (2009) 72-76



CHARMONIUM PHOTOPRODUCTION AT ALICE IN PERIPHERAL AND SEMI-CENTRAL Pb-Pb COLLISIONS ?

- ✓ We observed an excess in the yield of J/ψ at low p_T but an excess with respect to what?
- ✓ The expected J/ψ yield from hadroproduction in Pb-Pb is calculated from the evolution of the J/ψ yield versus p_T in pp collisions, assuming a smooth evolution of the R_{AA} at low p_T (in a « data driven » way)

$$\int_{p1}^{p2}\left[\frac{dN_{AA}^{J/\Psi}}{dp_T}(p_T)\right]^{\text{uncorrected, no excess}} = N \times \int_{p1}^{p2}\left[\frac{dN_{pp}^{J/\Psi}}{dp_T}(p_T)\right]^{corrected} \times R_{AA}^{J/\Psi}(p_T) \times (A\times\varepsilon)^{J/\Psi}(p_T)$$

$\left[\frac{dN_{pp}^{J/\Psi}}{dp_T}(p_T)\right]^{corrected}$ — Fit of the 2.76 TeV pp data with the same expression as the one used to extract the reference pp cross section

$R_{AA}^{J/\Psi}(p_T)$ — Fit of the $R_{AA}(p_T)$ data in the centrality bins 0-20%, 20-40% and 40-90% with several functions.

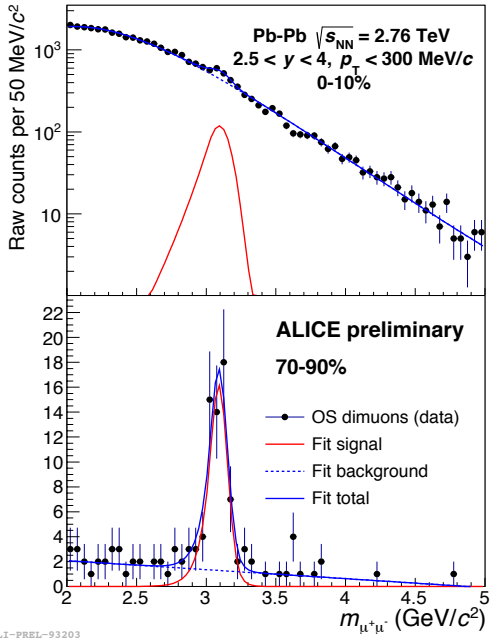
$(A\times\varepsilon)^{J/\Psi}(p_T)$ — Fit of the A x ε (p_T) simulations in the centrality bins 0-20%, 20-40%, 40-90%

N — Normalization factor (measured raw yield in the p_T range 1-8 GeV/c in which hadroproduced J/ψ are dominant).

CHARMONIUM PHOTOPRODUCTION AT ALICE IN PERIPHERAL AND SEMI-CENTRAL Pb-Pb COLLISIONS ?

- Measured number of J/ψ at very low p_T

Centrality class	0-10%	10-30%	30-50%	50-70%	70-90%
$N_{J/\psi\ measured}$ (0-0.3 GeV/c)	339 ± 85 ± 78	373 ± 87 ± 75	187 ± 37 ± 15	89 ± 13 ± 2	59 ± 9 ± 3



- Number of J/ψ expected from hadroproduction at very low p_T

Centrality class	0-10%	10-30%	30-50%	50-70%	70-90%
$N_{J/\psi\ hadronic}$ (0-0.3 GeV/c)	406 ± 14 ± 55	397 ± 10 ± 61	126 ± 4 ± 15	39 ± 2 ± 5	8 ± 1 ± 1

arXiv:1509.08802

- Excess in the yield of J/ψ at very low p_T

Centrality class	0-10%	10-30%	30-50%	50-70%	70-90%
$N_{J/\psi\ excess}$ (0-0.3 GeV/c)	< 251	< 237	62 ± 37 ± 21	50 ± 14 ± 5	51 ± 9 ± 3

Significance of the excess: **5.4σ significance for the bin 70-90%, 3.4σ in bin 50-70%, 1.4σ in 30-50%**

CHARMONIUM PHOTOPRODUCTION AT ALICE IN PERIPHERAL AND SEMI-CENTRAL Pb-Pb COLLISIONS ?

- Assuming that coherent photoproduction is the mechanism at the origin of the excess the corresponding cross section is obtained (*Phys. Lett. B 718 (2013) 1273-1283*)

$$\frac{d\sigma^{\mathrm{coh}}_{\mathrm{J/\Psi}}}{dy} = \frac{\mathrm{N}^{\mathrm{coh}}_{\mathrm{J/\Psi}}}{(A\times\varepsilon)^{coh}_{J/\psi}\times \mathrm{BR}(\mathrm{J/\Psi}\rightarrow\mu^{+}\mu^{-})\times \mathrm{L}_{\mathrm{int}}\times\Delta\mathrm{y}} \quad \text{with} \quad \mathrm{N}^{\mathrm{coh}}_{\mathrm{J/\Psi}} = \frac{\mathrm{N}^{\mathrm{J/\Psi}}_{\mathrm{excess\ yield}}}{1+f_{\mathrm{I}}+f_{\mathrm{D}}}$$

- f_I: fraction of incoherently photoproduced J/ψ over coherently photoproduced J/ψ
- f_D: fraction of J/ψ mesons coming from the decay of coherently photoproduced ψ(2S)
- $(A \times \varepsilon)^{coh}$ is the acceptance times efficiency obtained from STARLIGHT simulations
  → J/ψ are simulated transversaly polarized

Centrality class	0-10%	10-30%	30-50%	50-70%	70-90%
dσ /dy (μb)	< 318	< 290	$73 \pm 44^{+26}_{-27}$	$58 \pm 16^{+8}_{-10}$	$59 \pm 11^{+7}_{-10}$

- Correlated systematic uncertainties: + 13.7% - 14.3%

CHARMONIUM PHOTOPRODUCTION AT ALICE IN PERIPHERAL AND SEMI-CENTRAL Pb-Pb COLLISIONS ?

→ No theoretical calculations on the market for b < 2R at the time of the measurement

→ **Photon flux integrated in the impact parameter range of the measurement**

→ **2 different approaches were used to get an estimate of the cross section:**

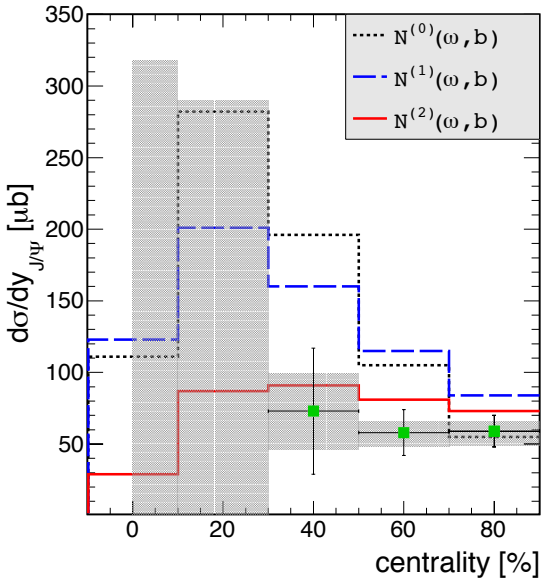
*** Vector dominance model[1] normalized to the measured UPC data[2]**

*** pQCD[3] model using the parametrisation in [4]**

1. Phys. Rev. C60 (1999) 014903
2. Phys. Lett. B718 (2013) 1273-1283, Eur. Phys. J. C73 (2013) 2617
3. Phys. Rept. 364 (2002) 359-450
4. Phys. Lett. B726 (2013) 290-295

→ In both cases, dσ /dy (μb) ~ 40 μb for centrality range 70-90%

2015: Model from M. Klusek-Gawenda & A. Szczurek (arXiv:1509.03173v1)

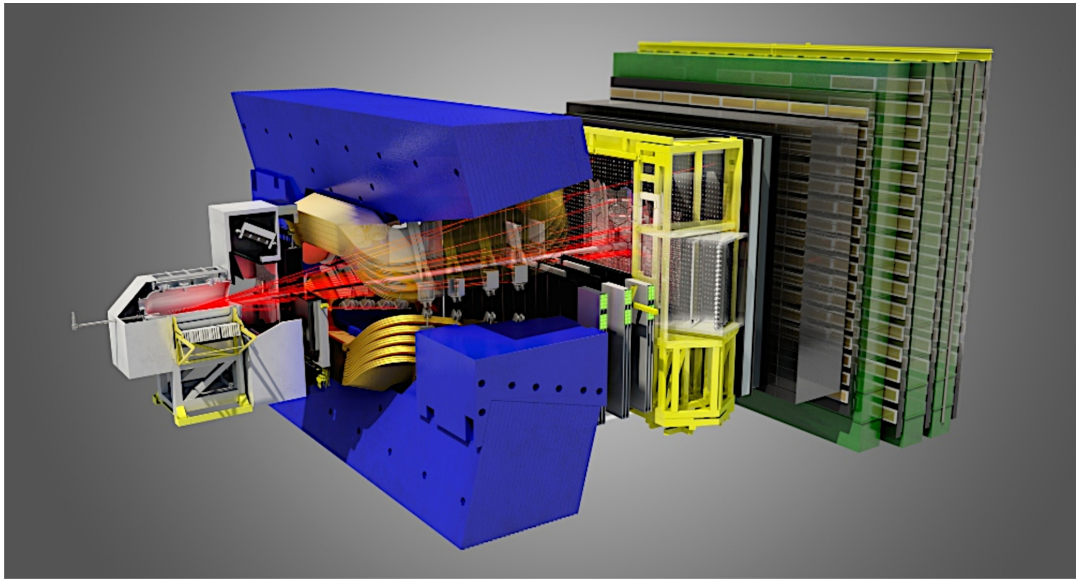


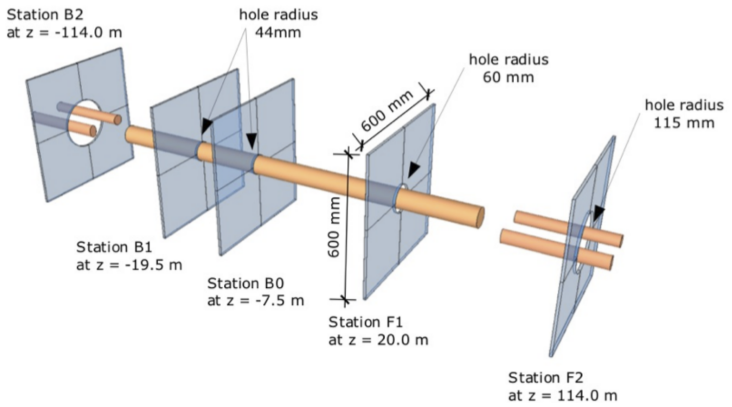
(0) UPC γ flux approximation.
(1) γ flux in the whole nuclear target.
(2) γ flux in the spectator nuclear target.

Different ways to treat the overlap region
Reasonable agreement with data
Experimental data seem to favour the scenario where only the spectator region contributes to the coherent photoproduction

PROSPECTS FOR CHARMONIUM PHOTOPRODUCTION MEASUREMENTS IN LHCb

- LHCb is a newcomer in the field of heavy ion physics thanks to its new approved heavy ion program (fixed target data taking and p-Pb/Pb-Pb data taking)





New HERSHEL forward detector: $5 < |\eta| < 8$

- LHCb can measure up to ~ semi-central Pb-Pb collisions and can participe to the study of charmonium photoproduction
- LHCb has no ZDC and no dedicated UPC trigger was set up for the 2015 Pb-Pb data taking but:
  - Minimum bias trigger was very loose
  - The new HERSHEL detector should permit to define rapidity gaps
  - The VELO has also a backward coverage (possibility to VETO)
- LHCb will be able to measure the J/ψ low p_T excess seen in peripheral and semi-central events seen by ALICE

For the discussion session

- What did we learn from Nucleus-Nucleus UPC measurement?
  → Any constraint on nuclear gluon distribution at low x?

- Low p_T J/ψ excess in peripheral hadronic collisions

→ Is coherent photoproduction of J/ψ the mechanism at the origin of the excess?
What to look at ?
  → Expect to see also incoherent photoproduction and γγ contribution
  → Coherently photoproduced J/ψ should be transversaly polarized
  → Should also see some photoproduced ψ(2S) and (no excess of χ_c?)

Other ideas : - Varying the type of nucleus?
  → since photon flux scales with Z^2
  - Photoproduction of Υ in CMS ?
  - Having a look to RHIC data in smaller p_T intervals?
  → Photoproduction cross section might be too small but we might have simply missed it by not looking at it

→ Can this observable become a new probe of charmonium color screening in the QGP?
  → Need theoretical « reference »
  → Need to measure it in most central collisions