Diffraction 2014
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Primošten 10.9-15.9.2014

Vector meson photoproduction in ultra-peripheral p-Pb and Pb-Pb collisions at the LHC with ALICE

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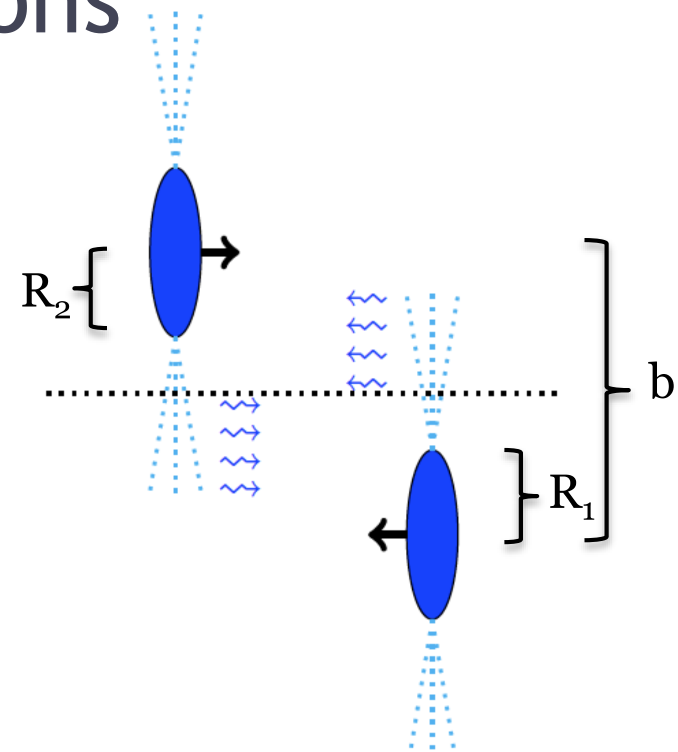
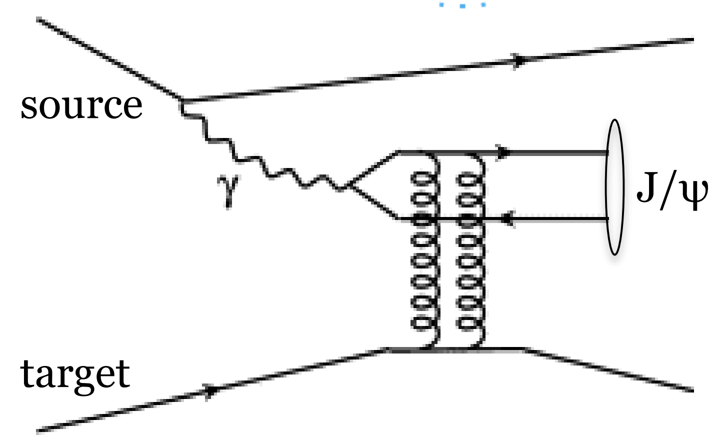
On behalf of the ALICE Collaboration

Ultra-peripheral collisions

- Ultra-peripheral collision = Impact parameter larger then sum of nuclear radii
- The EM field of protons and ions can be viewed as a beam of quasi real photons (intensity ≈ Z^2)
- Using Pb-Pb and p-Pb data at the LHC it is possible to study γ-Pb, γp and γγ collisions at higher center of mass energies than ever before
- ALICE is using LHC as a photon-hadron collider!





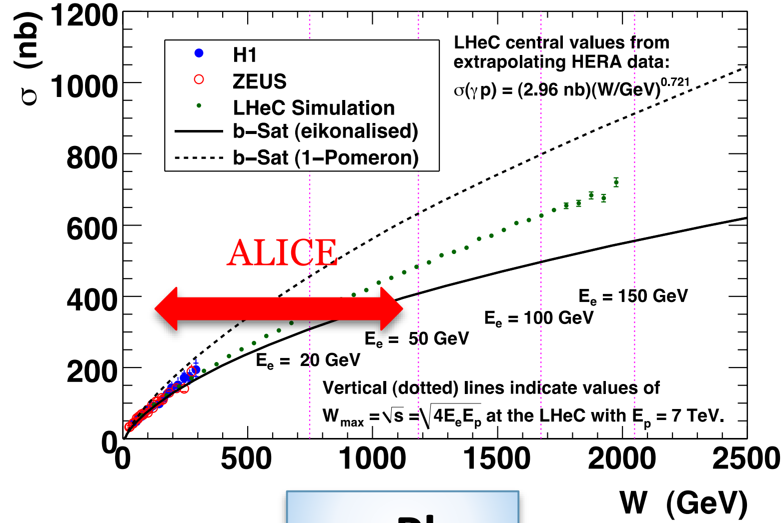
ALICE

Ultra-peripheral collisions

- Charmonium photo-production cross section is proportional to square of gluon structure function (at LO) of the target (Pb, proton)
- Charmonium rapidity maps the photon-target center of mass energy
- Charmonium photo-production permits us to study perturbatively non linear effects at low x in the gluon distribution of the target (key words: shadowing, saturation)

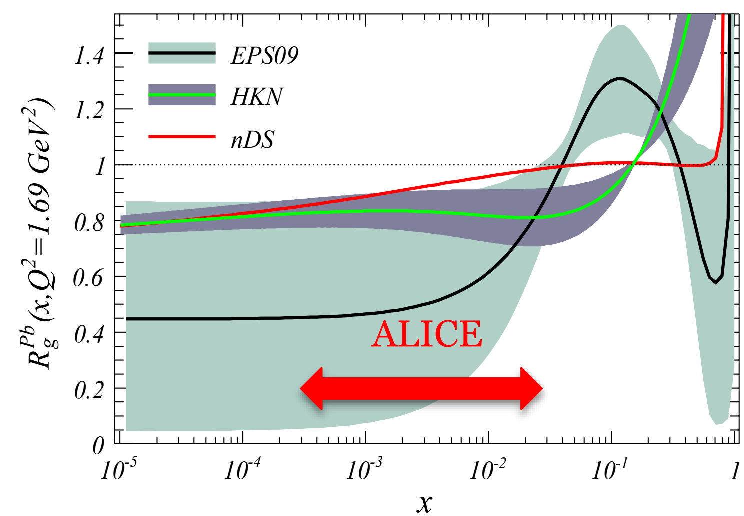
γp

LHeC Study group, ArXiv: 1211.4831



γ-Pb

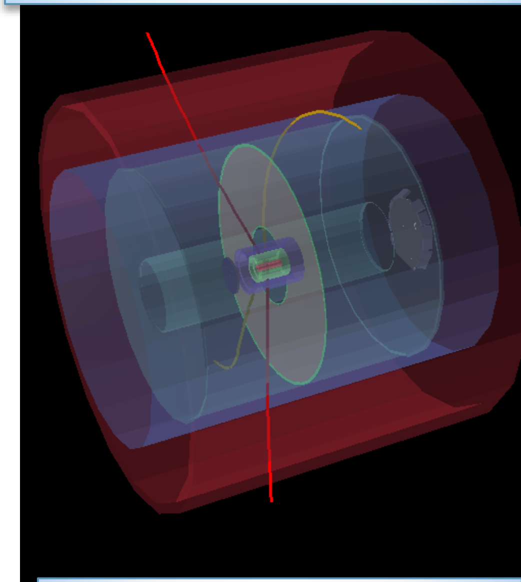
C. A. Salgado *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* 39 015010



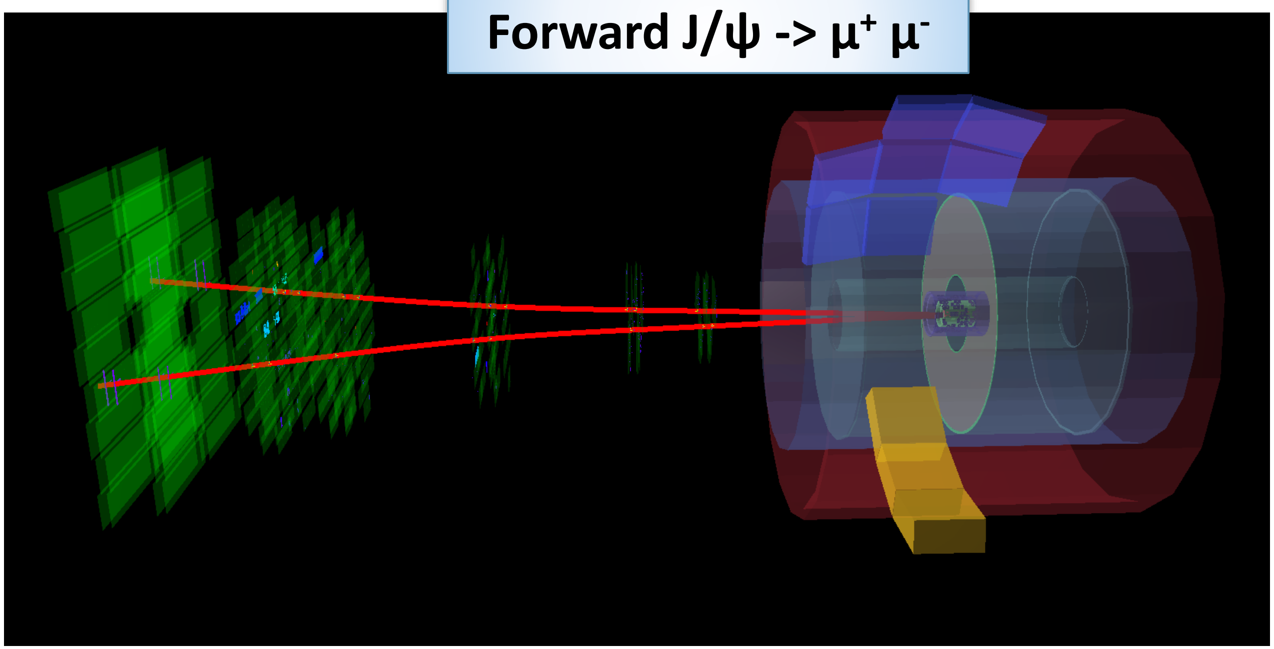
Ultra-peripheral collisions

- Have a very clean signature - two or four tracks in an otherwise empty detector
- Studied decay channels:
  - $\rho^0 \to \pi^+ \pi^-$
  - $J/\psi \to l^+ l^-$
  - $\psi(2S) \to l^+ l^-$
  - $\psi(2S) \to J/\psi\ \pi^+ \pi^-$

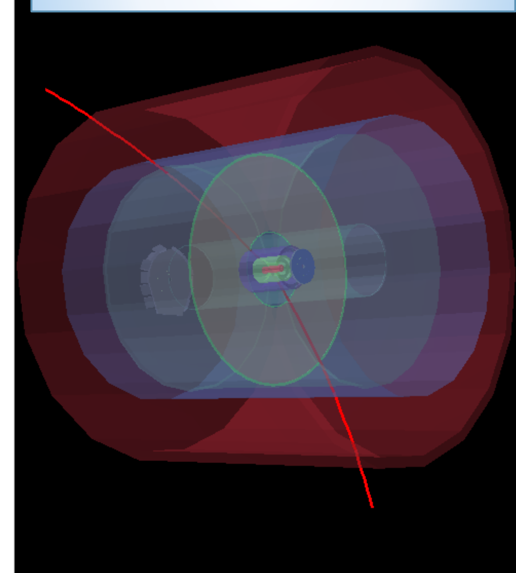
$\psi(2s) \to e^+ e^- + \pi^+ \pi^-$



Forward $J/\psi \to \mu^+ \mu^-$



Central $J/\psi \to \mu^+ \mu^-$



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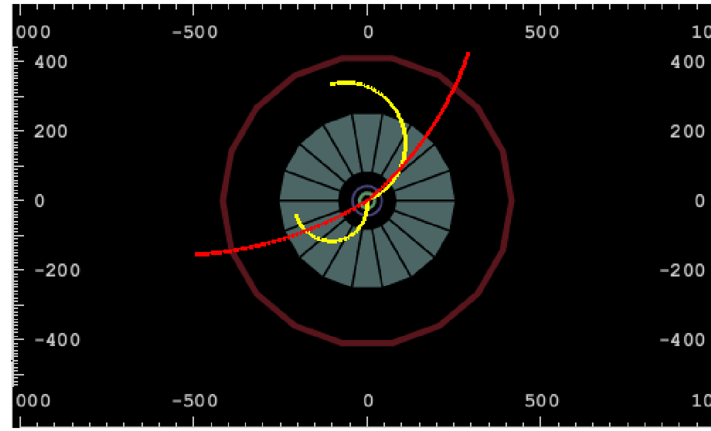
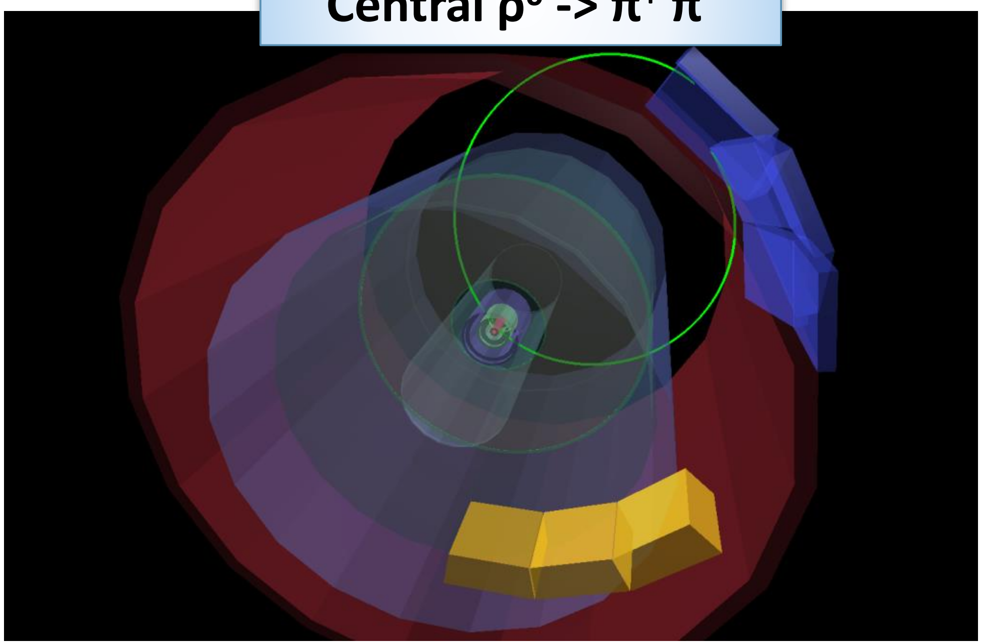
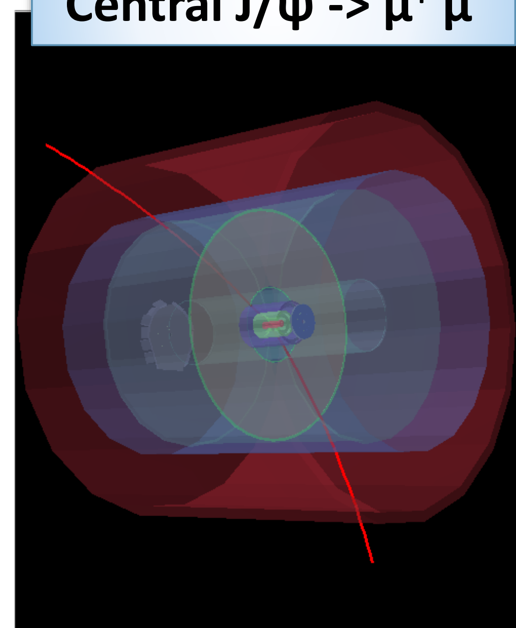


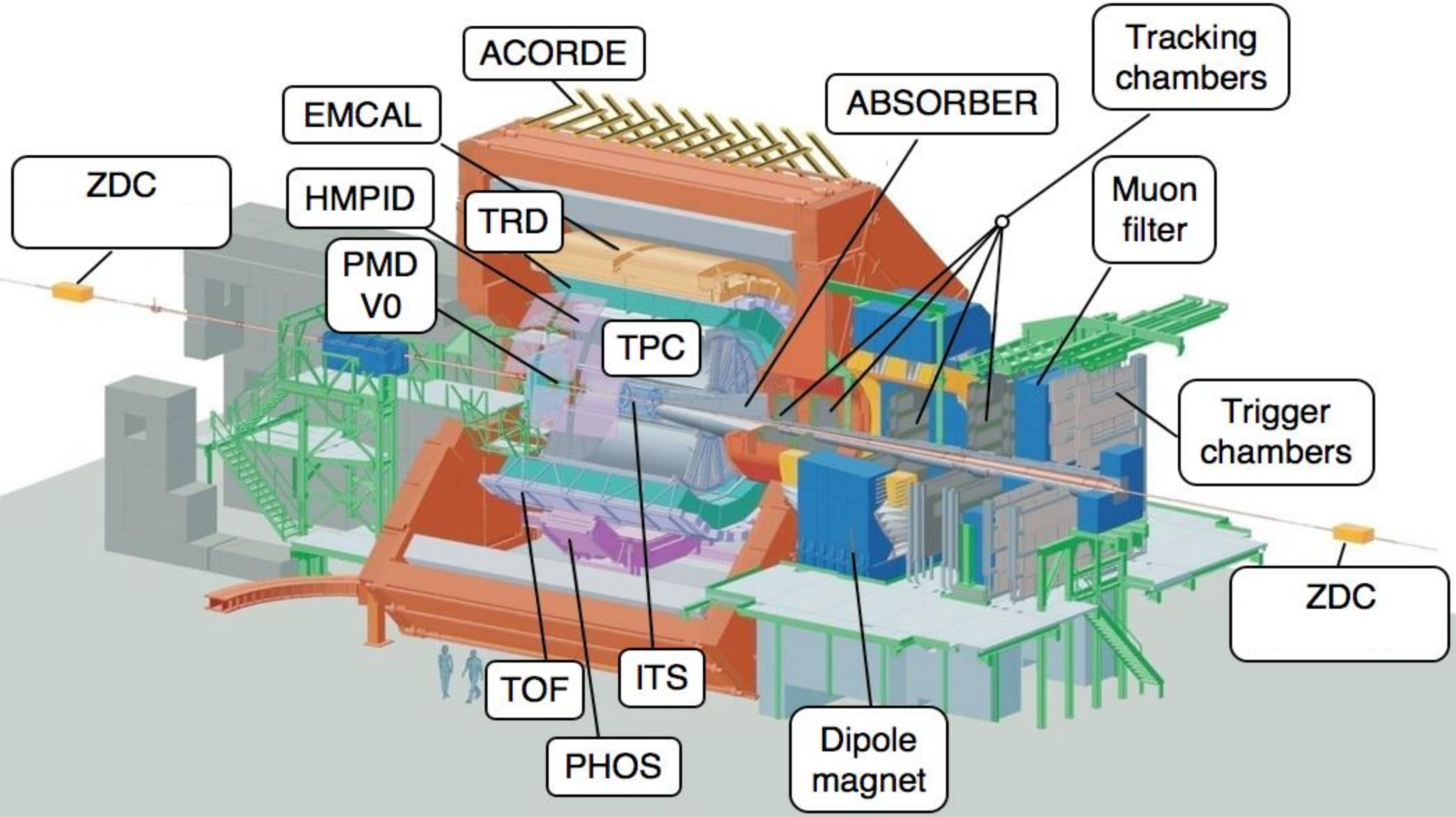
Central $\rho^0 \to \pi^+ \pi^-$



Central $J/\psi \to \mu^+ \mu^-$



ALICE detector



ρ^0 in Pb-Pb

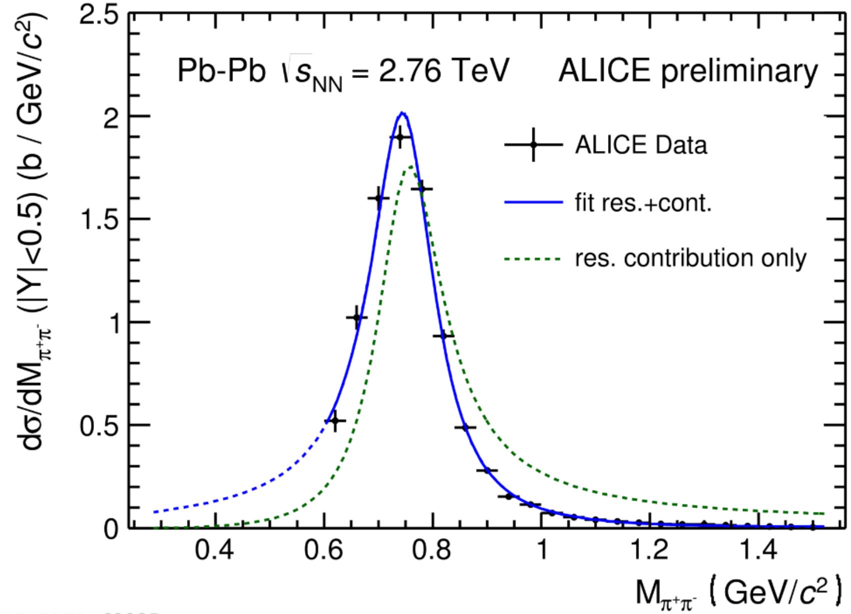
ρ^0 in Pb-Pb central rapidity

- 2010 Pb-Pb data
- Pions are identified by TPC dE/dx
- Coherent events selected by p_T < 0.15 GeV/c and corrected for incoherent contamination
- Invariant mass fitted by Breit-Wigner resonance + continuum term (Söding)

$$\frac{d\sigma}{dm_{\pi\pi}} = \left| A \frac{\sqrt{m_{\pi\pi} M_{\rho^0} \Gamma(m_{\pi\pi})}}{m_{\pi\pi}^2 - M_{\rho^0}^2 + i M_{\rho^0} \Gamma(m_{\pi\pi})} + B \right|^2$$

$$\Gamma(m_{\pi\pi}) = \Gamma_{\rho^0} \frac{M_{\rho^0}}{m_{\pi\pi}} \left(\frac{m_{\pi\pi}^2 - 4m_\pi^2}{M_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2}$$

- M = 761.6 ± 2.3 (stat.) $^{+6.1}_{-3.0}$(syst.) MeV/c²
  - PDG = 769 – 775 MeV/c²
- Γ = 150.2 ± 5.5 (stat.) $^{+12.0}_{-5.6}$(syst.) MeV/c²
  - PDG = 148 – 152 MeV/c²
- |B/A| = 0.5 ± 0.04 (stat.) $^{+0.10}_{-0.04}$(syst.)



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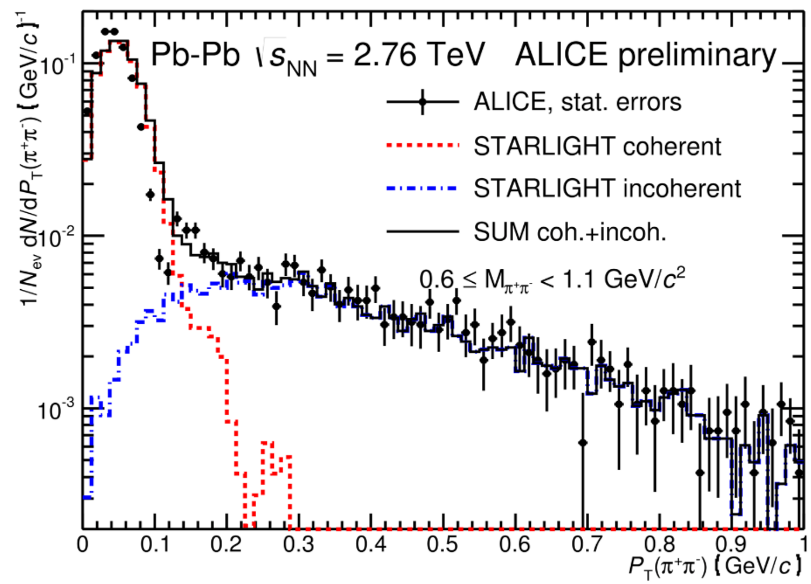

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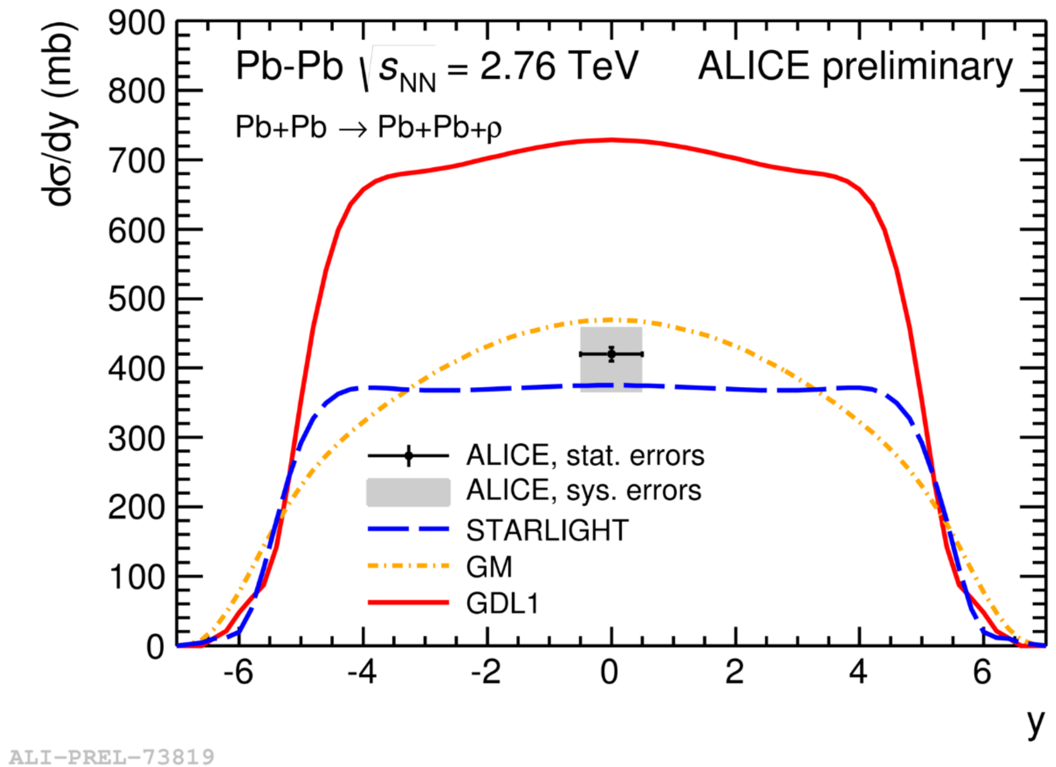
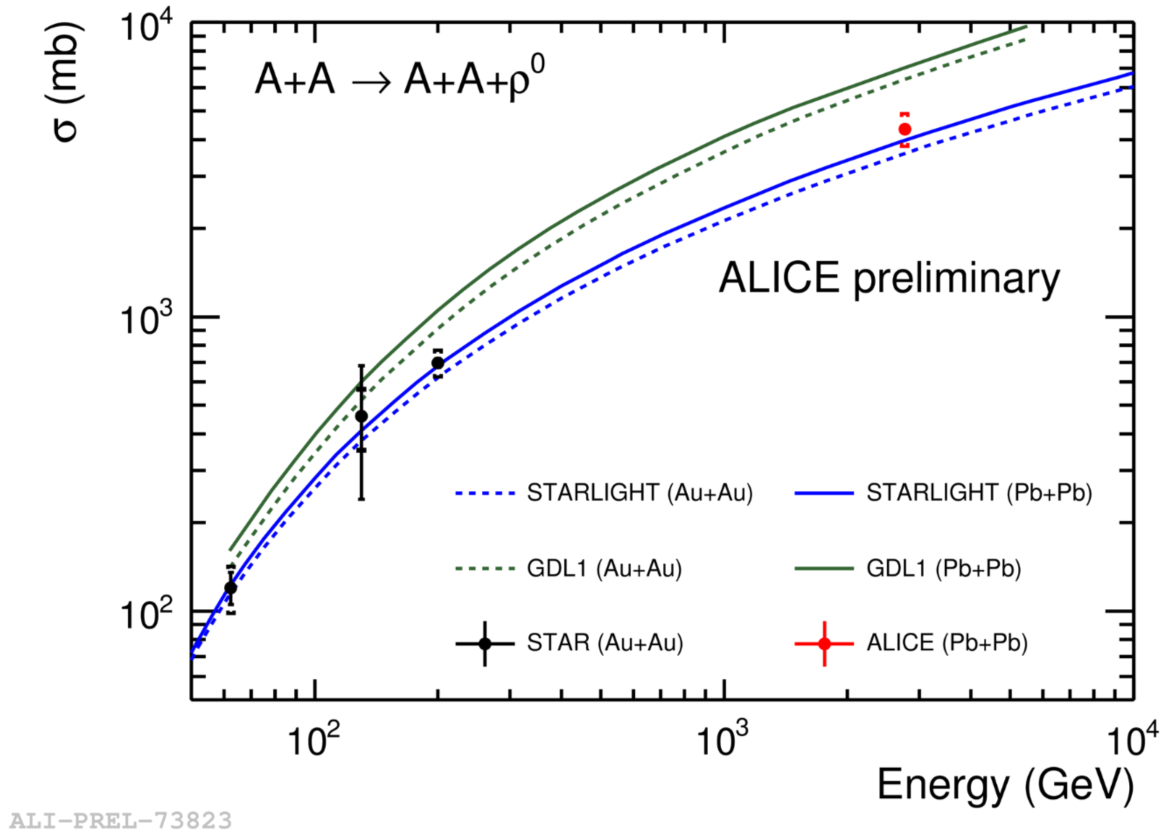
Differential cross section

- Cross section obtained by integrating the resonance contribution over $[2m_\pi, M_\rho + 5\Gamma]$
  - Same range in M_{inv} as used by STAR and ZEUS
- GDL(RSZ): Proper QM Glauber calculation for scaling $\sigma(\gamma p) \Rightarrow \sigma(\gamma A)$
- GM: Based on the color dipole model with saturation implemented by the Color Glass Condensate formalism
- STARLIGHT: Scales the experimentally measured γp cross section using a Glauber model, neglecting the elastic nuclear cross section



Total cross section

- Obtained by integrating over all rapidities
- Enables comparison with STAR results
- Additional systematic uncertainty on the shape of dσ/dy from the difference between GM and STARLIGHT models



Nuclear break-up

- One or both nuclei may get excited due to additional exchange of photons
- In the cascade decay channel we measured number of events with various types of neutron emission using ZDC detector
- As expected for photo-production, most of the events have no neutrons emitted on either side

- 0N0N – no neutrons emitted on either side
- XN – with at least one neutron emitted on either side
  - 0NXN – no neutron on one side and at least one neutron on the other one
  - XNXN – at least one neutron on both sides

All events	7293		STARLIGHT	RSZ
0N0N	6175	$\left(84.7 \pm 0.4(\mathrm{stat})\ ^{+0.4}_{-1.9}(\mathrm{sys})\right)\%$	$79\%\ (-2.9\sigma)$	$84\%\ (-0.4\sigma)$
XN	1174	$\left(16.1 \pm 0.4(\mathrm{stat})\ ^{+2.2}_{-0.5}(\mathrm{sys})\right)\%$	$21\%\ (+2.2\sigma)$	$16\%\ (-0.2\sigma)$
0NXN	958	$\left(13.1 \pm 0.4(\mathrm{stat})\ ^{+0.9}_{-0.3}(\mathrm{sys})\right)\%$	$16\%\ (+2.9\sigma)$	$12\%\ (-2.2\sigma)$
XNXN	231	$\left(3.2 \pm 0.2(\mathrm{stat})\ ^{+0.4}_{-0.1}(\mathrm{sys})\right))\%$	$5.2\%\ (+4.5\sigma)$	$3.7\%\ (+1.1\sigma)$

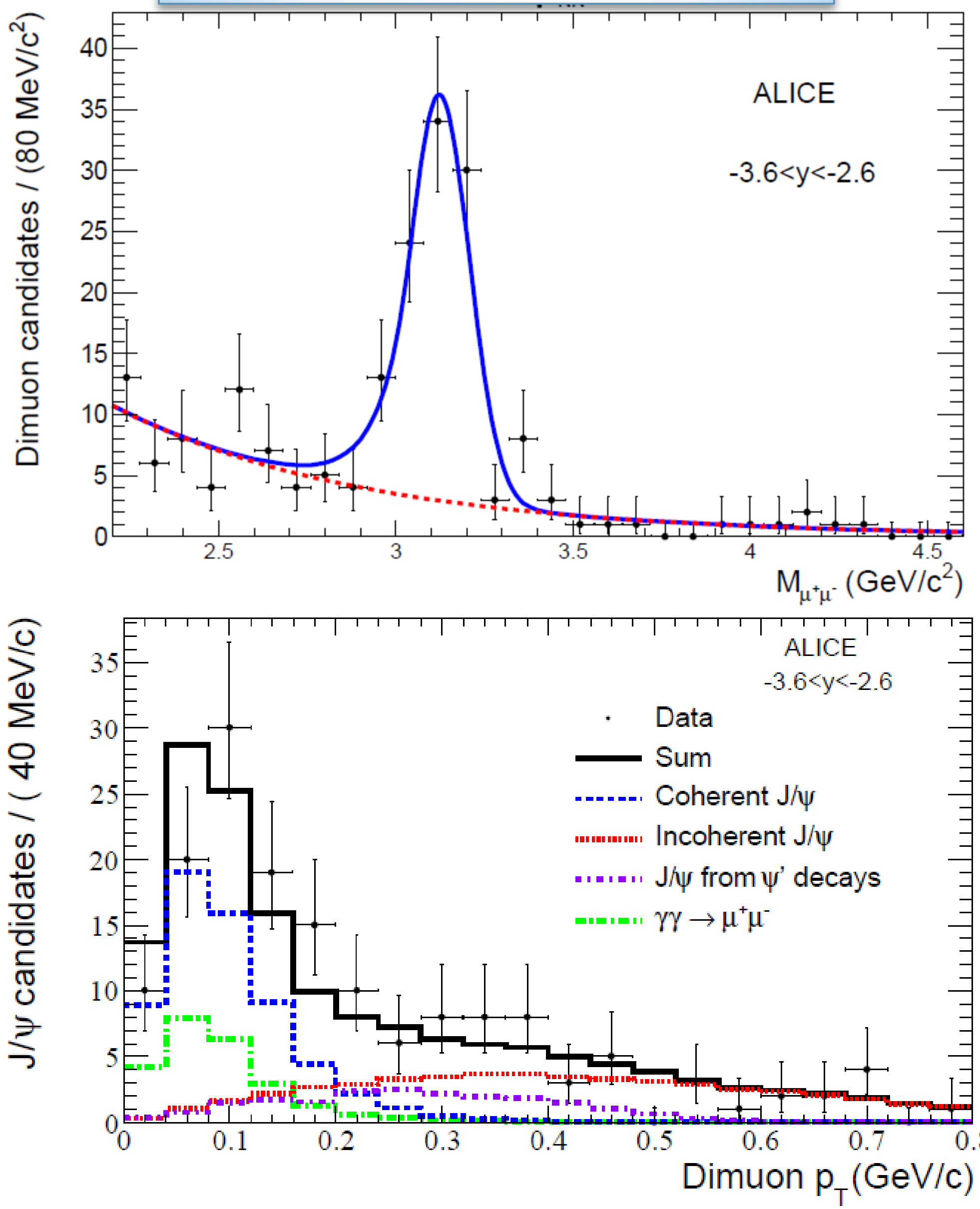
J/ψ in Pb-Pb

J/ψ in Pb-Pb forward rapidity

ALICE, Phys. Lett. B718, 1273 (2013)

- 2011 Pb-Pb data
- γ-Pb interaction can be
  - Coherent – coupling to whole nucleus
    $\langle p_T \rangle \approx 60$ MeV/c
  - Incoherent – coupling to single nucleon
    $\langle p_T \rangle \approx 500$ MeV/c
- Cut on p_T for coherent (incoherent) enriched sample
  - J/ψ -> $\mu^+ \mu^-$, $p_T = 0.2$ GeV/c
  - J/ψ -> $e^+ e^-$, $p_T = 0.3$ GeV/c
- Measured at forward rapidity
  - coherent, J/ψ -> $\mu^+ \mu^-$

Coherent J/ψ -> $\mu^+ \mu^-$

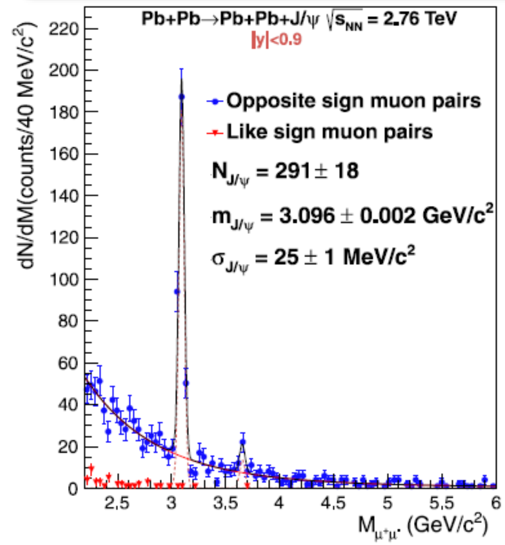


J/ψ in Pb-Pb central rapidity

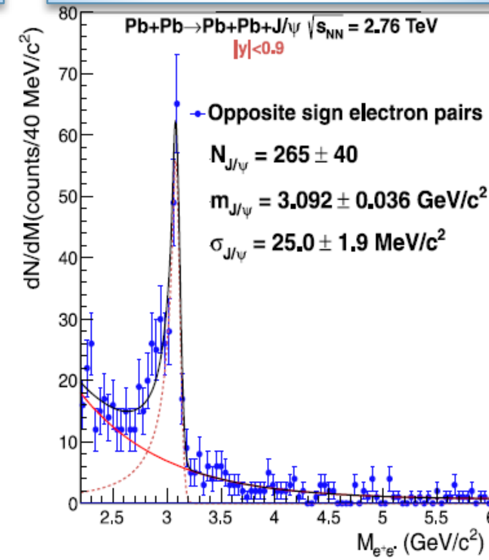
ALICE, EPJ C73, 2617 (2013)

- 2011 Pb-Pb data
- γ-Pb interaction can be
  - Coherent – coupling to whole nucleus
    $\langle p_T \rangle \approx 60$ MeV/c
  - Incoherent – coupling to single nucleon
    $\langle p_T \rangle \approx 500$ MeV/c
- Measured at central rapidity
  - coherent,
  - incoherent
  - $J/\psi \to \mu^+ \mu^-$
  - $J/\psi \to e^+ e^-$
  - Leptons identified using dE/dx in TPC

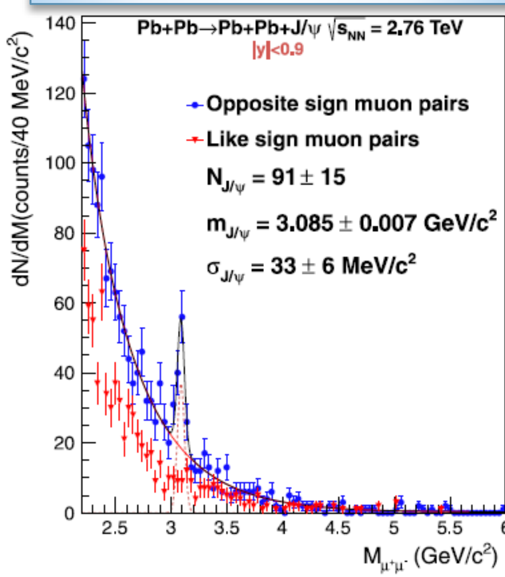
Coherent $J/\psi \to \mu^+ \mu^-$



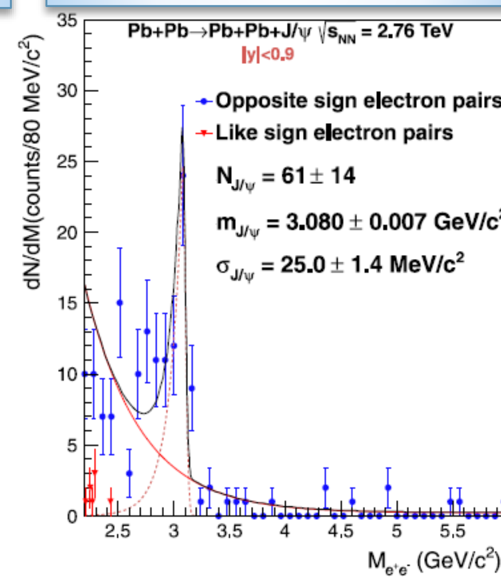
Coherent $J/\psi \to e^+ e^-$



Incoherent $J/\psi \to \mu^+ \mu^-$

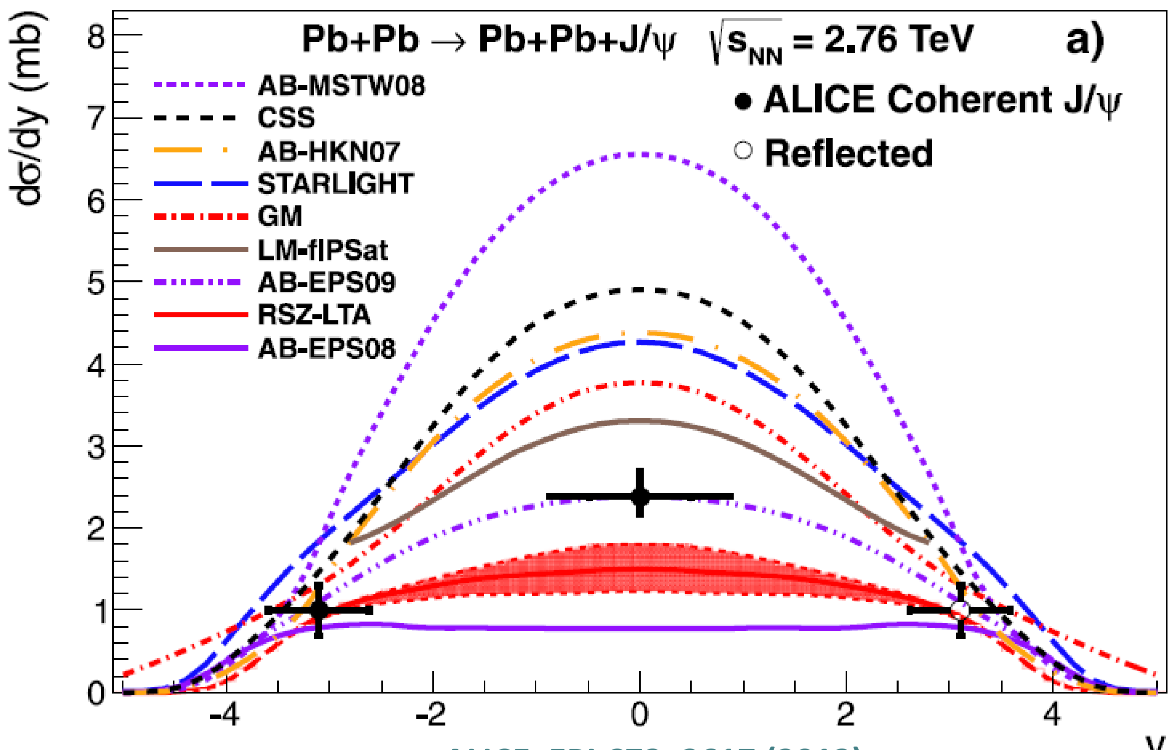


Incoherent $J/\psi \to e^+ e^-$



Cross section for **coherent** J/ψ in Pb-Pb

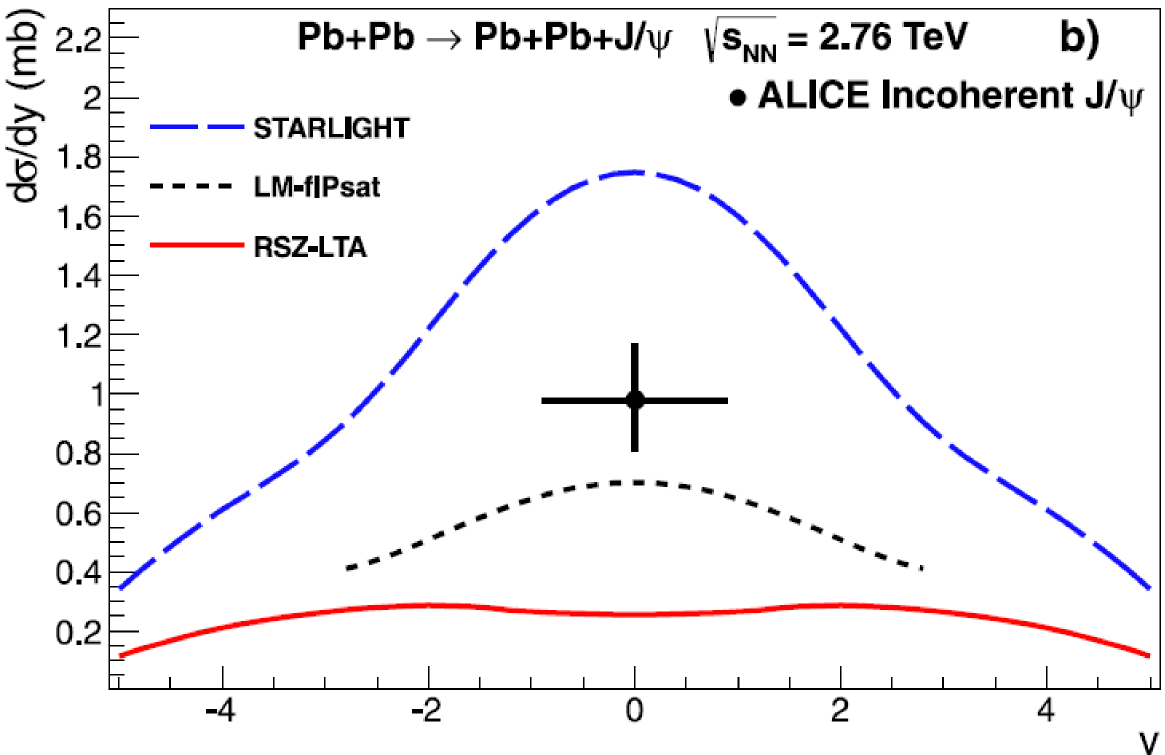
- ALICE results are able to distinguish between the different models
- No nuclear effects: AB-MSTW08
- Glauber approach: STARLIGHT, GM, CSS, LM
- Partonic models: RSZ-LTA, AB-EPS08,09, AB-HKN07
- Models with moderate nuclear gluon shadowing (EPS09) are favored



ALICE, EPJ C73, 2617 (2013)

Cross section for **incoherent** J/ψ in Pb-Pb

- ALICE sets strong constraints on models
- Glauber approach: STARLIGHT, LM
- Partonic models: RSZ-LTA
- STARLIGHT overestimated both cross sections, but got the ratio incoherent/coherent right (≈0.41)



ALICE, EPJ C73, 2617 (2013)

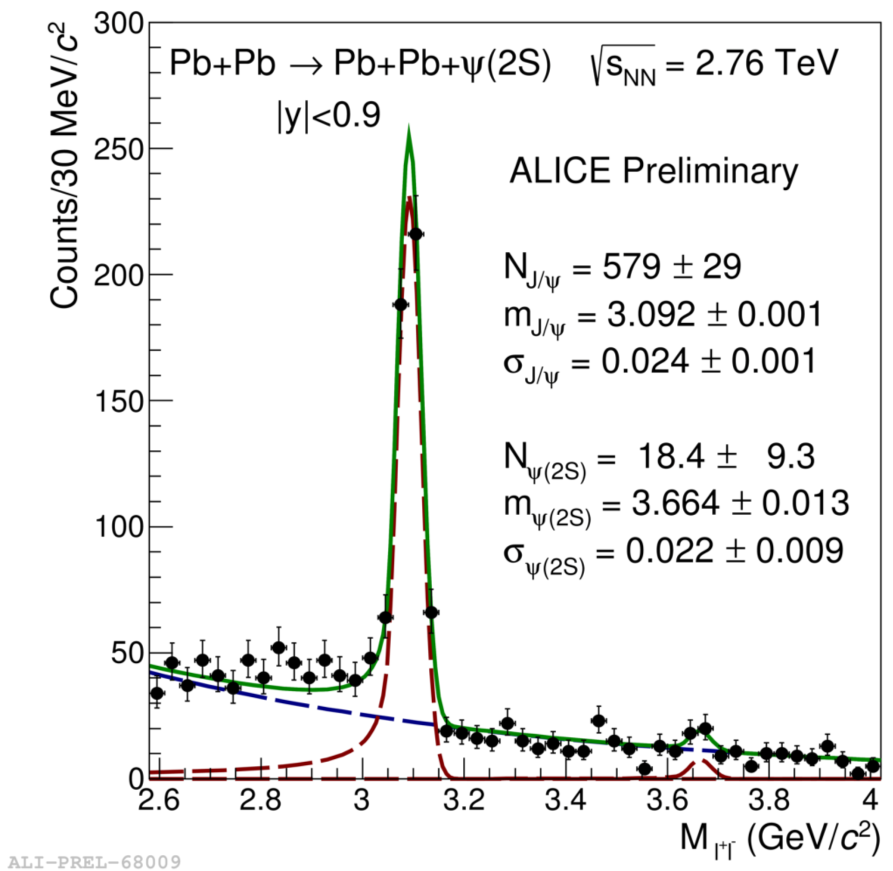
ψ(2S) in Pb-Pb

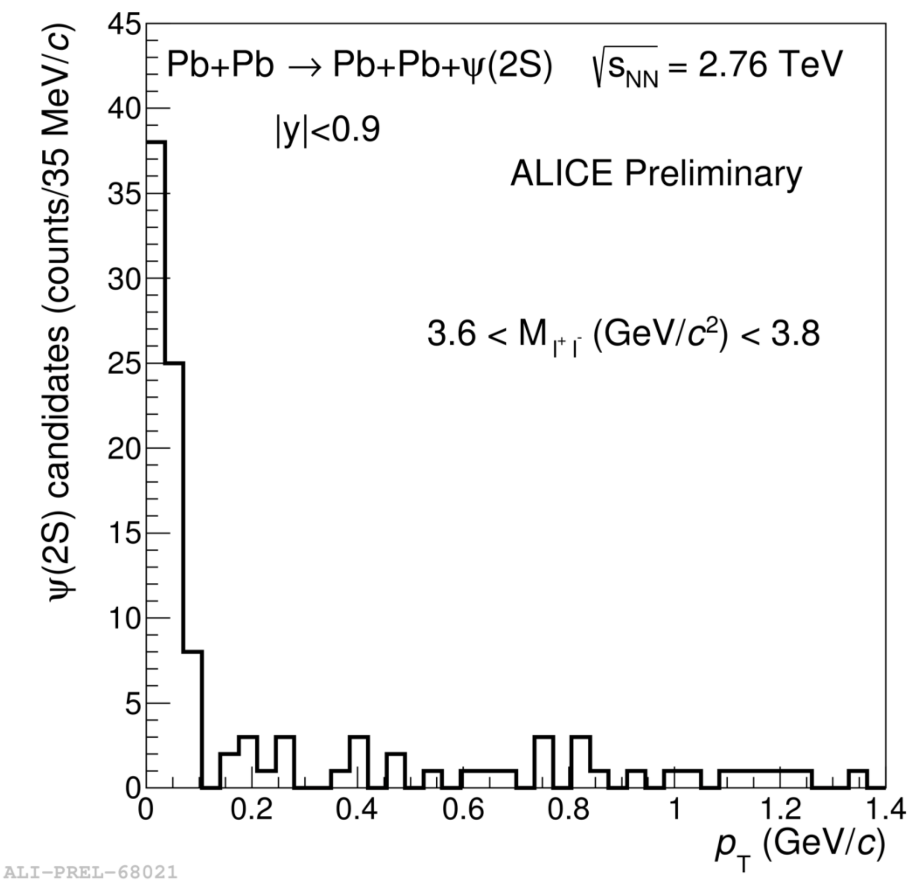
ALICE

Invariant mass and p_T of ψ(2S) candidates

- Clear coherent contribution at very low p_T

ψ(2s) -> $l^+ l^-$

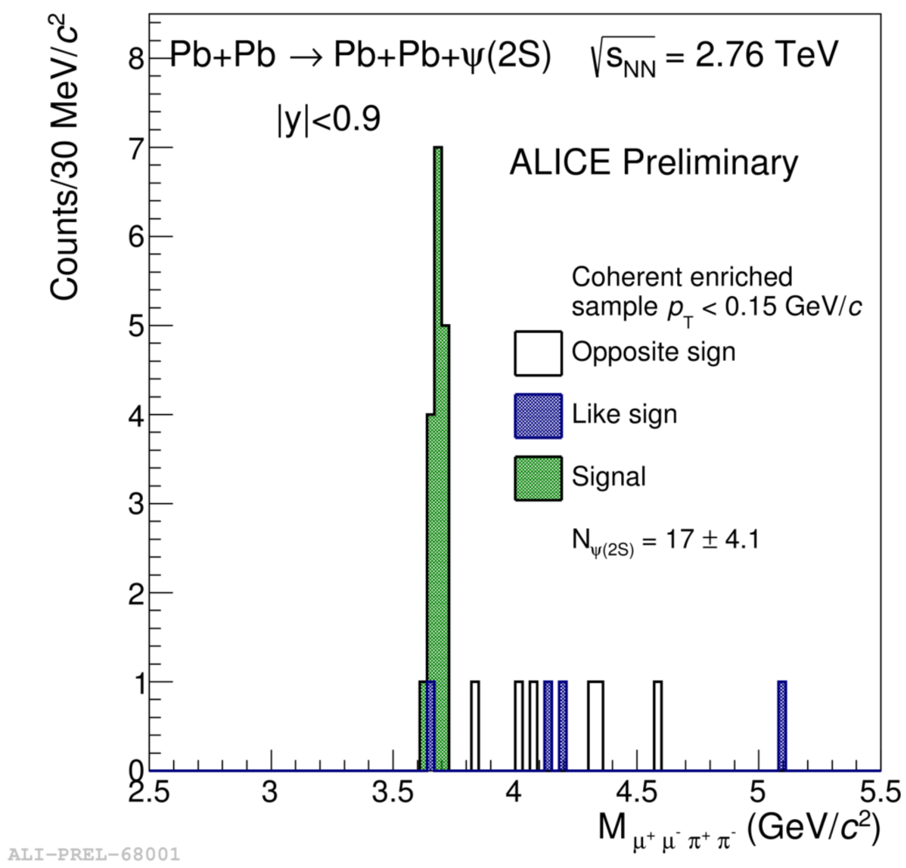


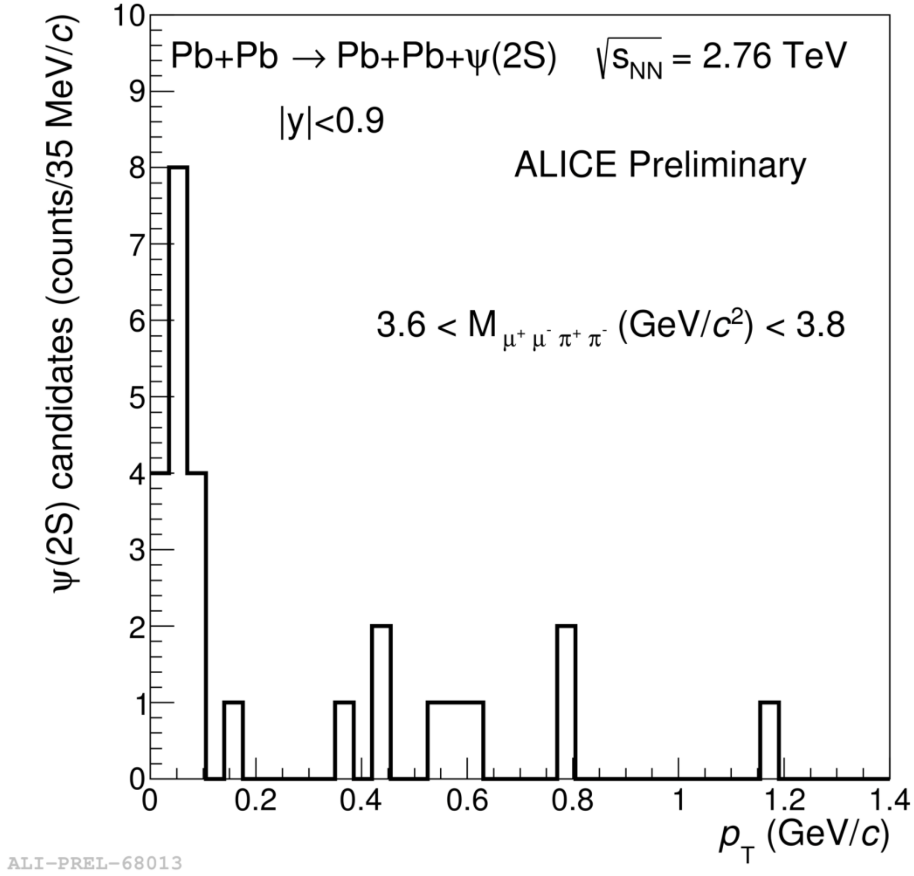


Invariant mass and p_T of ψ(2S) candidates

- Clear coherent contribution at very low p_T
- Moderate number of candidates, but very clean signal

ψ(2s) -> $\mu^+ \mu^- + \pi^+ \pi^-$





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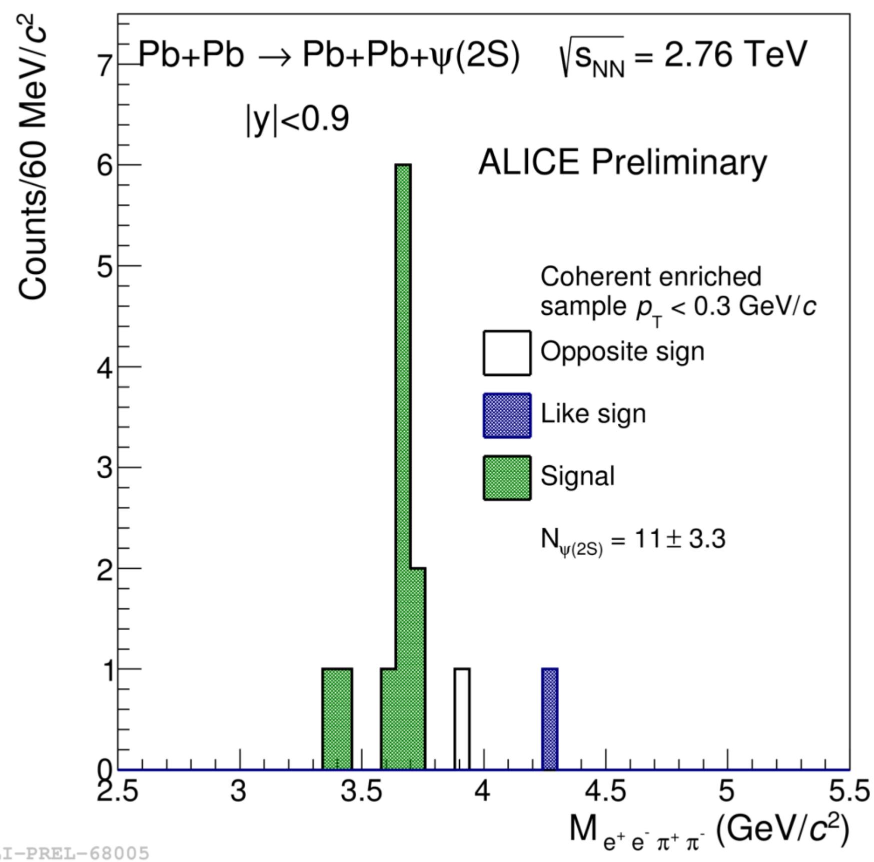
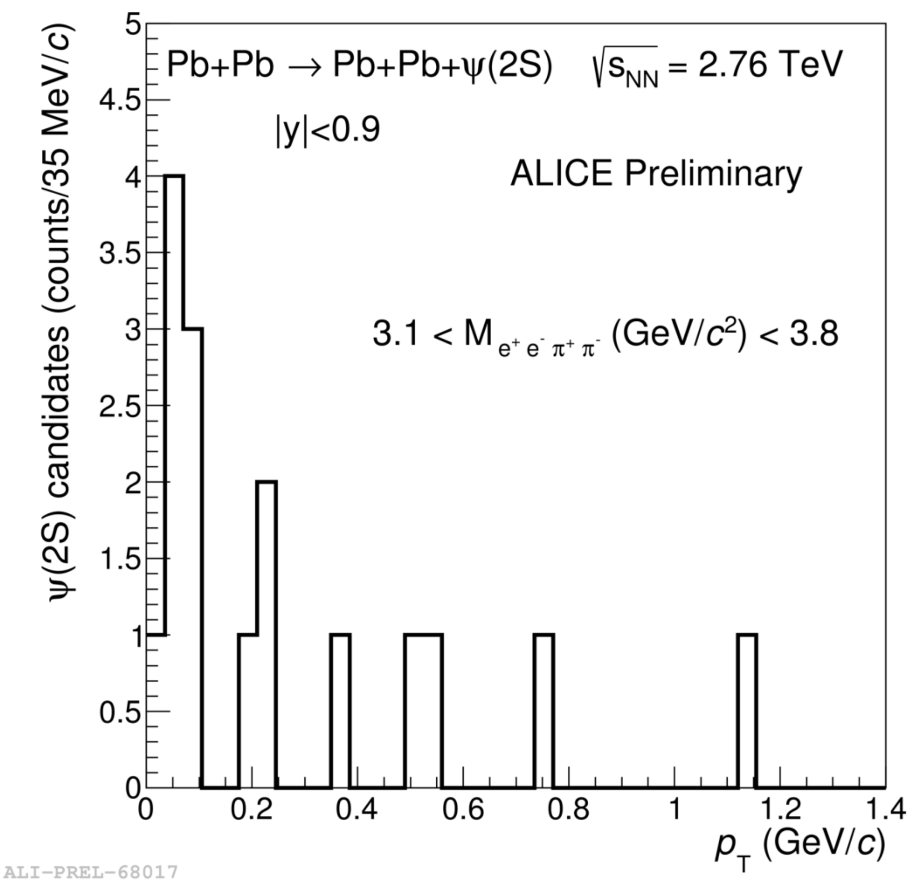
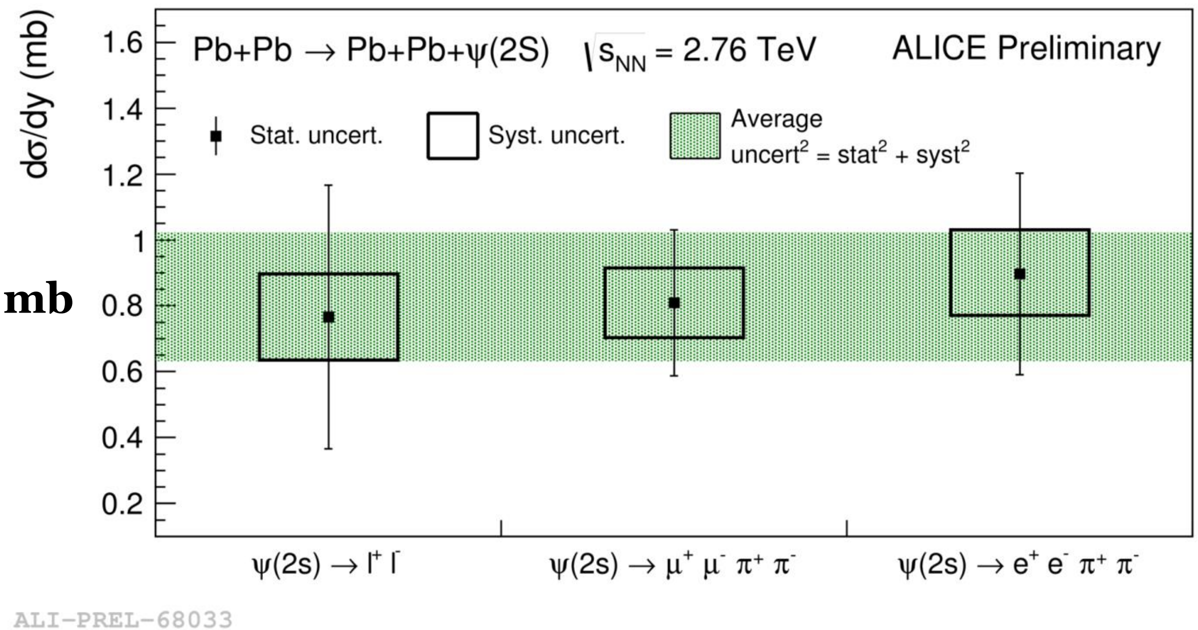




Coherent ψ(2s) cross section

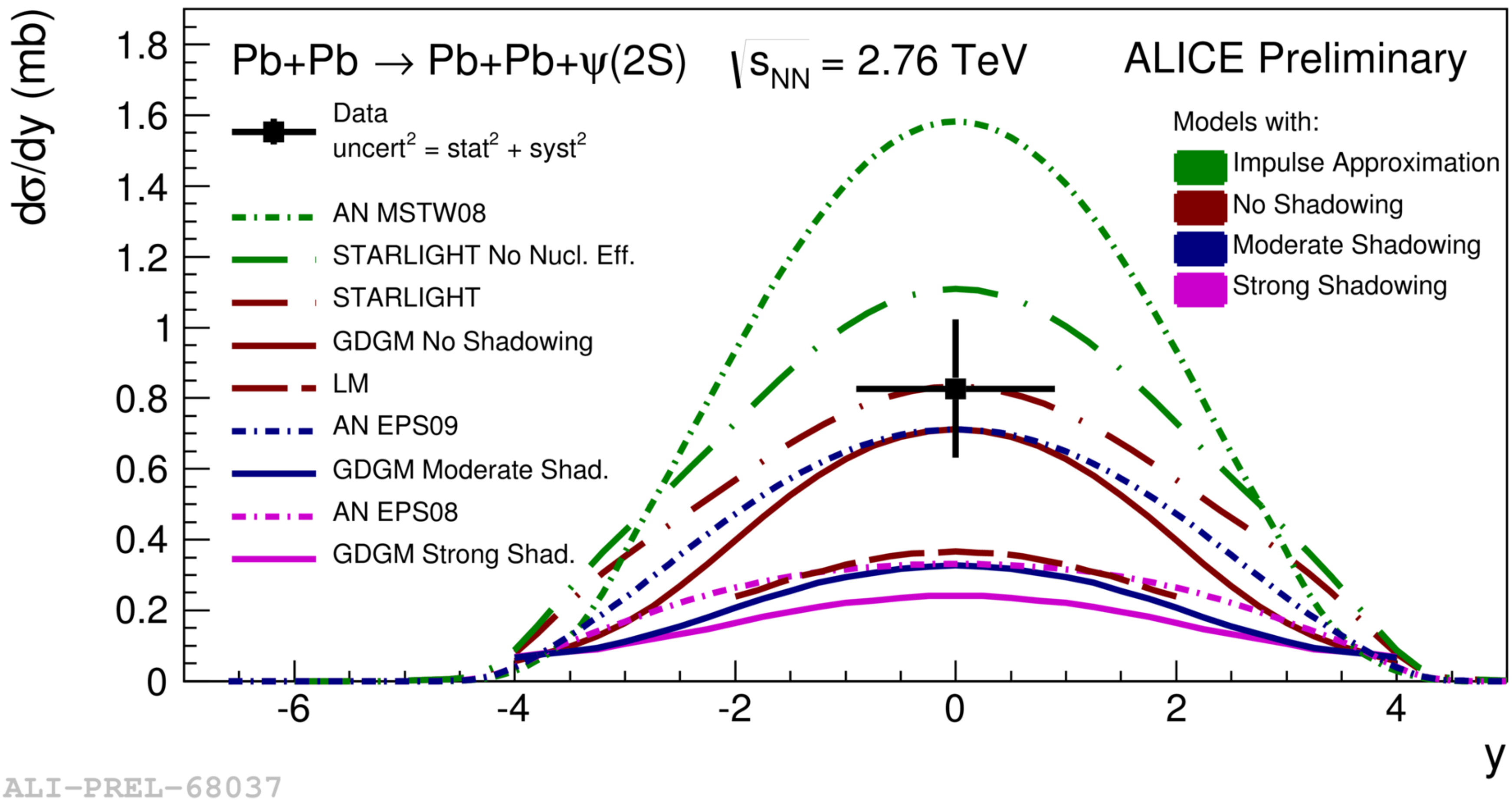
$$\frac{d\sigma}{dy} = 0.83 \pm 0.19\ \text{(stat+syst) mb}$$



	ψ(2s) -> $l^+ l^-$	ψ(2s) -> $\mu^+ \mu^-$ + $\pi^+ \pi^-$	ψ(2s) -> $e^+ e^-$ + $\pi^+ \pi^-$
Yield	18.4 ±9.3	16 ±4.2	11 ±3.3
Incoherent fraction	5.6% ±1.8%	3.4% ±1.1%	13.2% ±4.3%
Efficiency	3.7%	2.4%	1.3%
Luminosity	22.4 μb^{-1}	22.4 μb^{-1}	22.4 μb^{-1}
Branching ratio	2*0.78%	2.02%	2.02%
Δy	1.8	1.8	1.8
Cross section (mb)	0.76±0.40(stat)±0.13(syst)	0.81±0.22(stat)±0.10(syst)	0.89±0.31(stat) $^{+0.14}_{-0.12}$ (syst)

Coherent ψ(2s) cross section – Model comparison

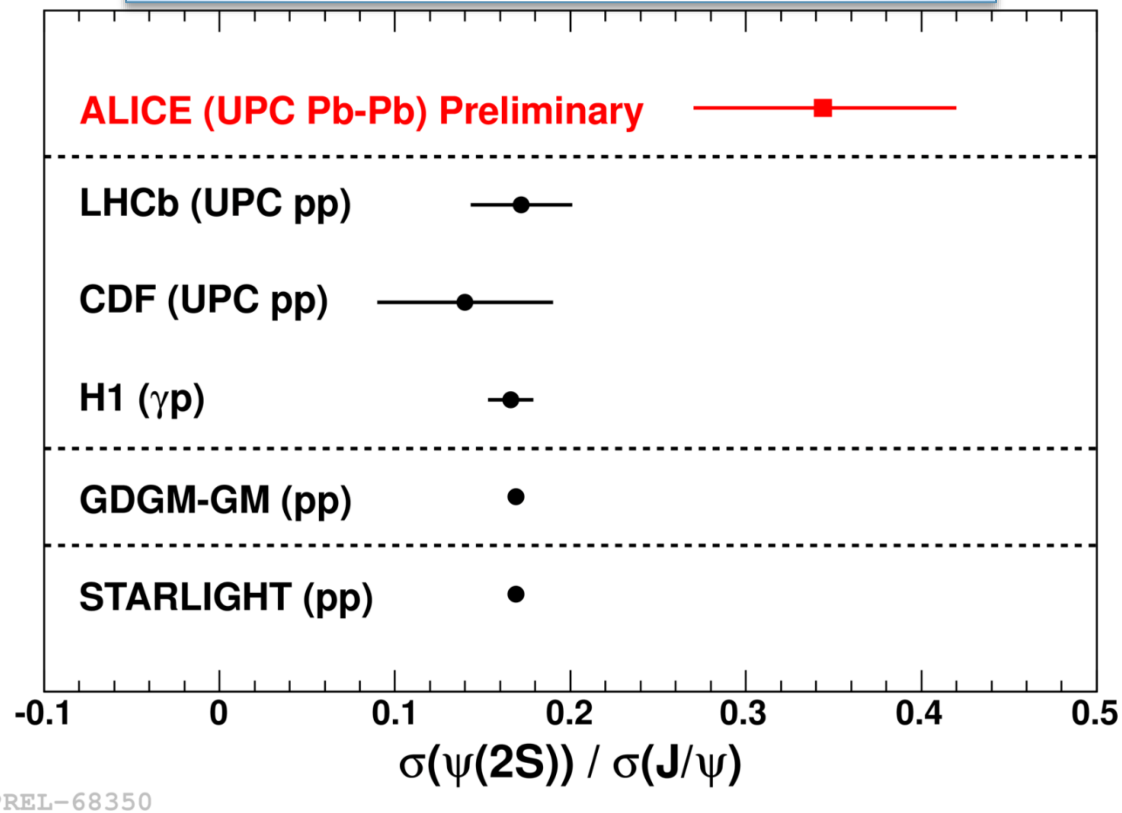
- Data disfavor models using impulse approximation and strong nuclear shadowing
- Difficult to give a preference between models with mild shadowing (EPS09) or Glauber nuclear treatment (STARLIGHT, GDGM, LM)



Ratio to J/ψ cross section

- Many sources of systematic uncertainties will cancel in the measured ratio
- **R [σ(ψ(2S))/σ(J/ψ)] = 0.34 $^{+0.08}_{-0.07}$ (stat+syst)**
- *Change of the ratio from pp to Pb-Pb may indicate that nuclear effects affect 1S and 2S states differently*
- Models predict the ratio for pp correctly

Comparison to pp data and models



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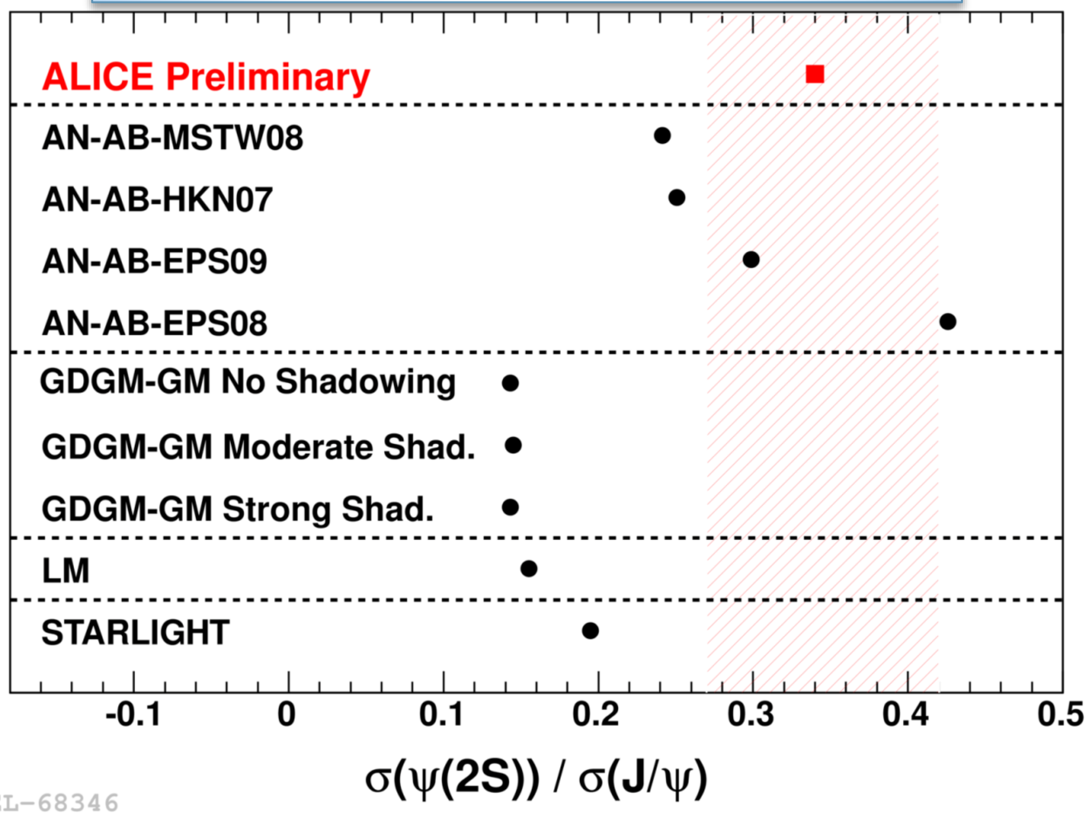
- **R [σ(ψ(2S))/σ(J/ψ)] = 0.34 $^{+0.08}_{-0.07}$ (stat+syst)**
- The same models that reproduced correctly the pp ratio, fail in describing the Pb-Pb ratio
- The AN EPS09 model, although it assumes a ψ(2S) wave function identical to the J/ψ one, describes in a satisfactory way this ratio

Comparison to Pb-Pb models

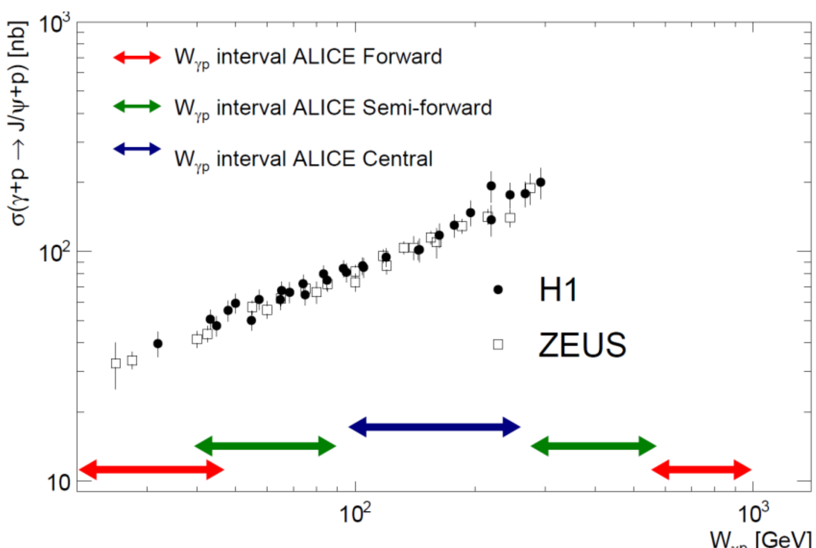


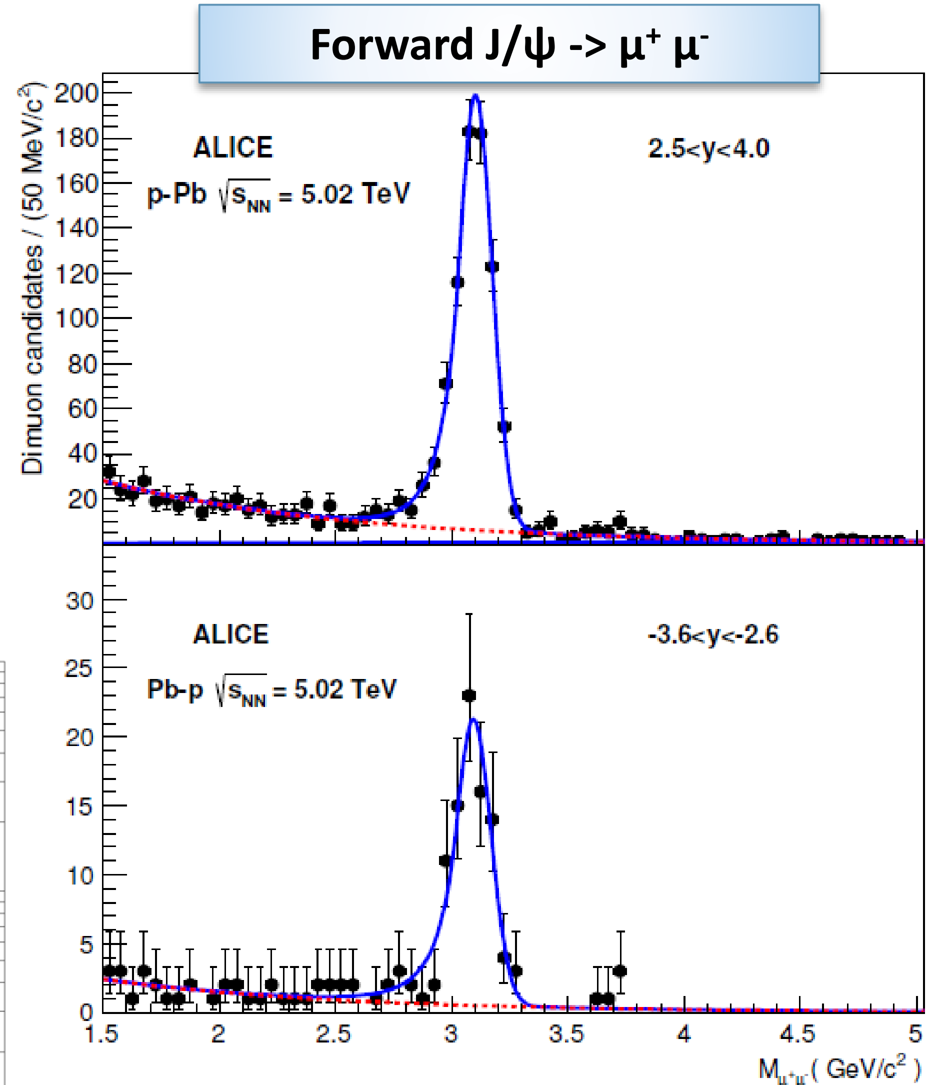
J/ψ in p-Pb

J/ψ in p-Pb and Pb-p

ALICE, arXiv:1406.7819

- 2013 p-Pb data
- Measuring the charmonium rapidity w.r.t. the direction of the target the energy in the photon target system can be determined
- Unique to p-Pb (Pb-p) is that the source of the photon is known (big advantage w.r.t. pp and Pb-Pb)
- **Central**: Both leptons in central barrel
- **Semi-forward**: One muon in MUON, the other in central barrel
- **Forward**: Both muons in MUON

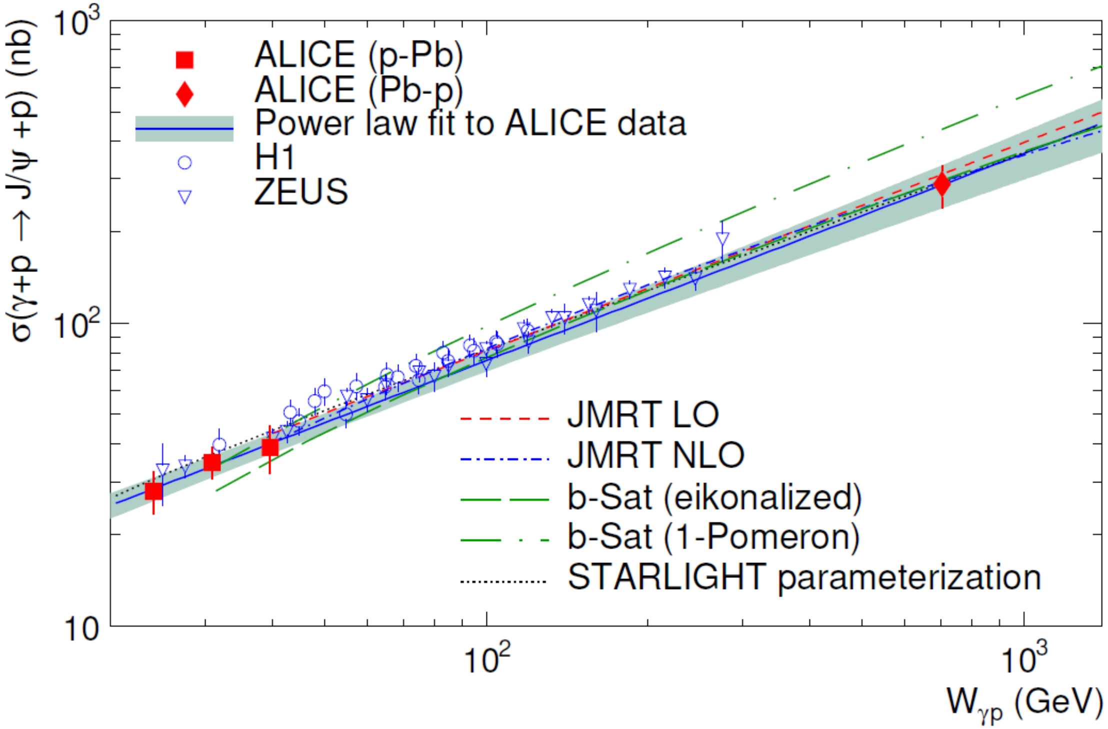




Cross section for J/ψ in γp

ALICE, arXiv:1406.7819

- First direct γp measurement at the LHC
- ALICE data are compatible with a power law with exponent 0.67±0.06
- Exponent is compatible with those from H1 (0.67±0.03) and ZEUS (0.69±0.02±0.03)
- LHCb solutions consistent with the power-law fit obtained from ALICE results



- HERA and ALICE cross section points stay on the same power law
- The most straightforward interpretation is that no change in the behavior of the gluon PDF in the proton manifests itself between HERA and LHC

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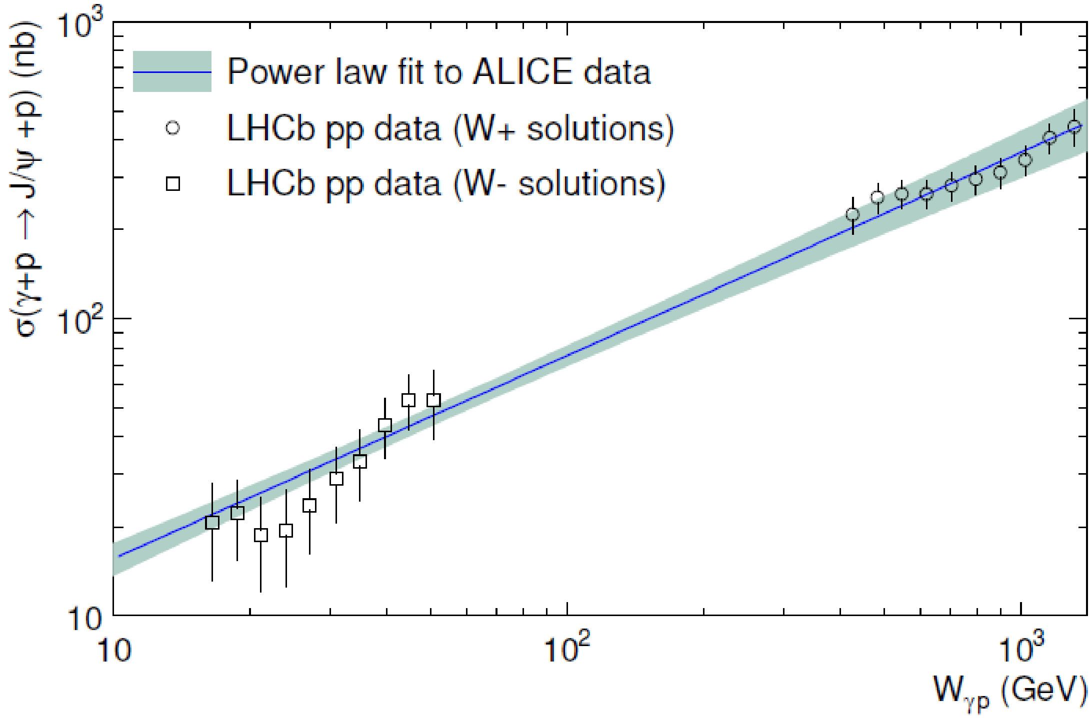

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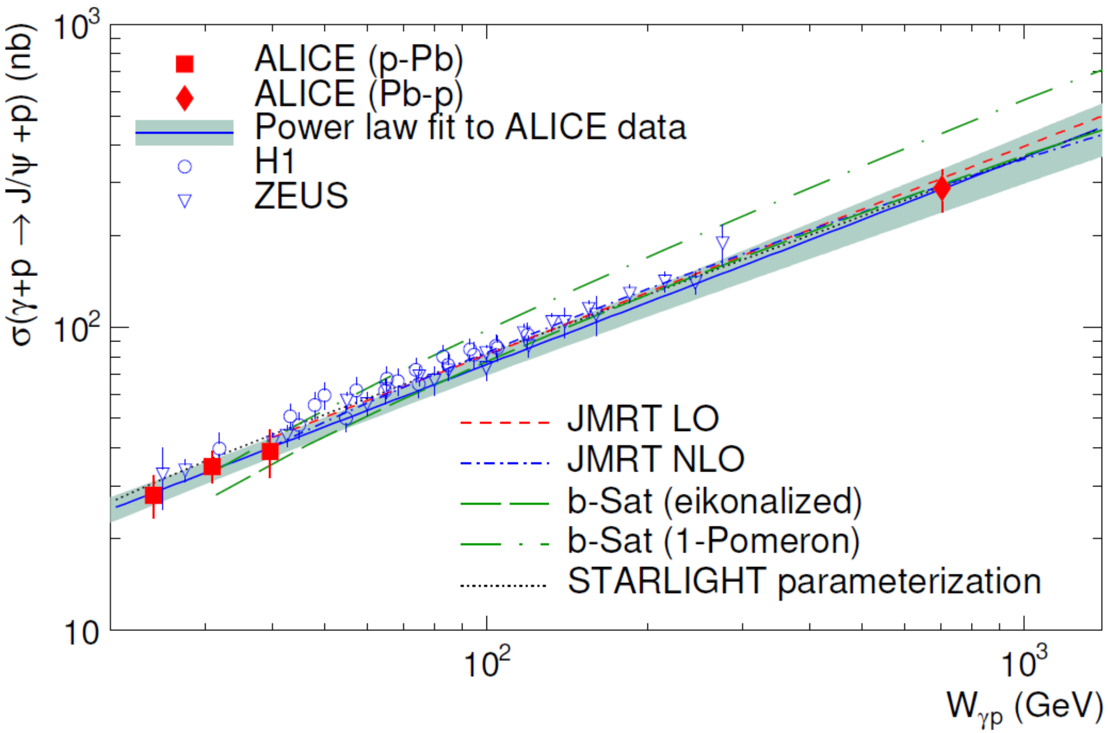
Cross section for J/ψ in γp

ALICE, arXiv:1406.7819

- JMRT: LO model based on a power law. NLO model includes the expected main NLO contributions
- b-Sat (eikonalised) includes b-dependent saturation effects based on a CGC inspired model
- STARLIGHT parameterization is based on a power law fit using only fixed-target and HERA data



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ALICE

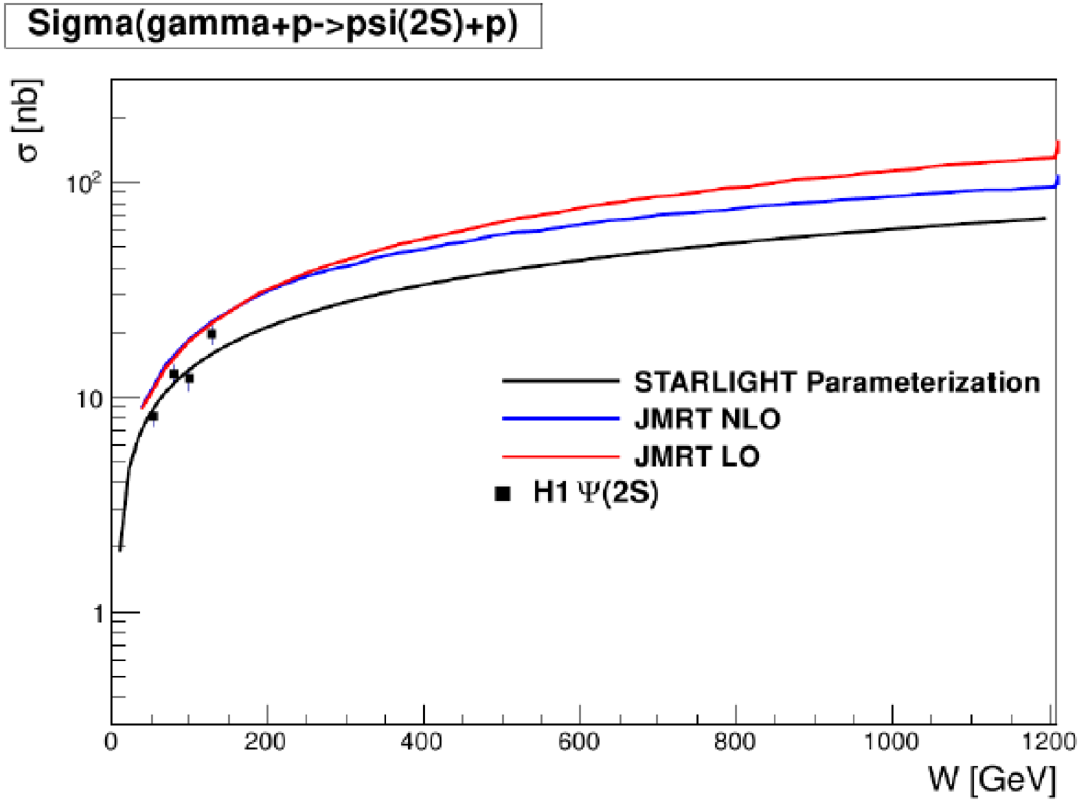
Summary and outlook

- ALICE has measured:
  - coherent and incoherent photo-production of J/ψ in Pb-Pb collisions
  - directly, exclusive J/ψ photo-production in γp collisions
  - the exclusive photo-nuclear production of ψ(2s)
  - coherent photo-production of ρ^0 in Pb-Pb collisions
- Cross section for the J/ψ found to be in agreement with models with moderate nuclear gluon shadowing (EPS09)
- The measured cross section for the ψ(2S) disfavors models with no nuclear effects and models with strong gluon shadowing.
- No change in the behavior of the gluon PDF in the proton between HERA and LHC
- Cross section for the ρ^0 consistent with STARLIGHT
- ALICE is preparing for new data in the Run2 of the LHC: increase in luminosity and center of mass energy of the photon-target system, new detectors for extended coverage in rapidity to veto non-exclusive reactions – **Stay tuned!**

Backup

γp cross section for ψ(2S)

- Photonuclear ψ(2S) production may probe nuclear gluon shadowing.
- However, to correctly interpret the nuclear effects, one has to understand the underlying γ+p -> ψ(2S)+p baseline.
- Here the uncertainties are much larger for ψ(2S) than for J/ ψ.



ALICE

Cross section models in Pb-Pb

- **AB**: Adeluyi and Bertulani, PRC85 (2012) 044904 - LO pQCD scaled by an effective constant to correct for missing contributions. MSTW08 assumes no nuclear effects, the other three incorporate nuclear effects according to different PDFs
- **CSS**: Cisek, Szczurek, Schäfer PRC86 (2012) 014905 - Color dipole model based on unintegrated gluon distribution of the proton
- **STARLIGHT**: Klein, Nystrand PRC60 (1999) 01493 - GVDM coupled to a Glauber approach and using HERA data to fix the γp cross section
- **GM**: Goncalves, Machado, PRC84 (2011) 011902 - Color dipole model, where the dipole nucleon cross section is from the IIM saturation model
- **RSZ**: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252 - LO pQCD amplitude for two gluon exchange where the gluon density incorporates shadowing computed in leading twist approximation
- **LM**: Lappi, Mantysaari, PRC87 (2013) 032201 - Color dipole model based with Glauber approach and a saturation prescription

J/ψ in Pb-Pb central rapidity

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- 2011 Pb-Pb data
- γPb interaction can be
  - Coherent – coupling to whole nucleus
    $\langle p_T \rangle \approx 60$ MeV/c
  - Incoherent – coupling to single nucleon
    $\langle p_T \rangle \approx 500$ MeV/c
- Measured at central rapidity
  - coherent ($p_T < 0.2$ GeV/c) incoherent ($p_T > 0.2$ GeV/c)
  - J/ψ -> $\mu^+ \mu^-$
  - J/ψ -> $e^+ e^-$
  - Leptons identified using dE/dx in TPC