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

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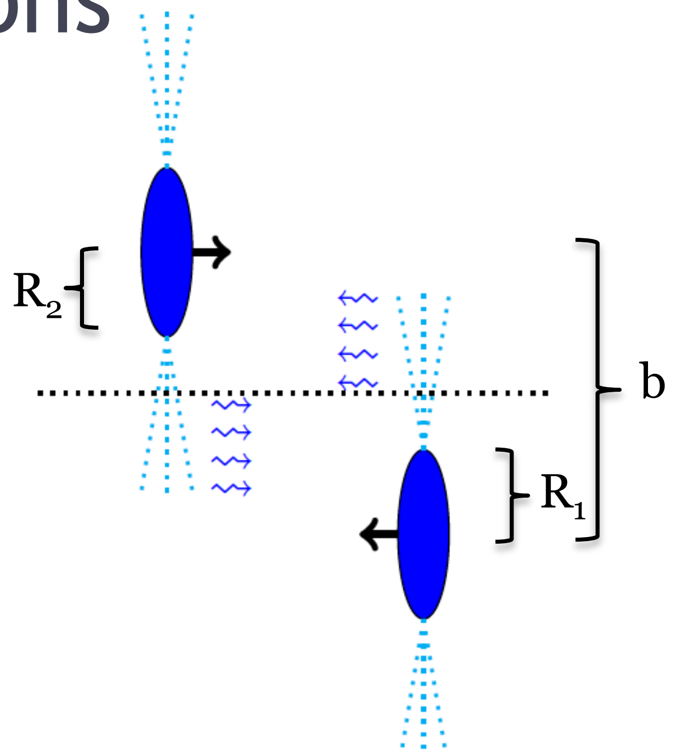
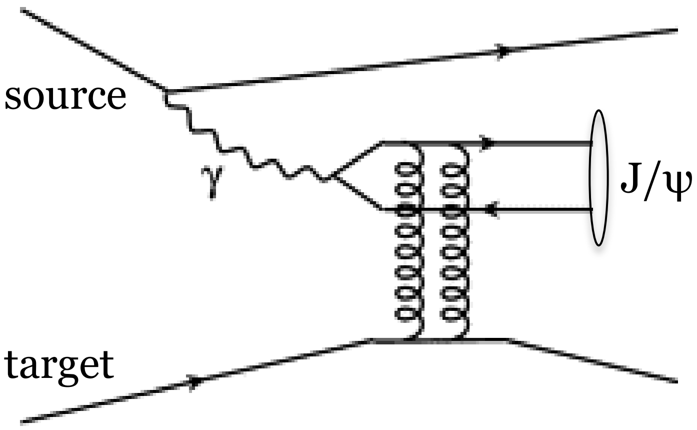
On behalf of the ALICE Collaboration

Ultra-peripheral collisions

- Ultra-peripheral collision = Impact parameter larger than 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!



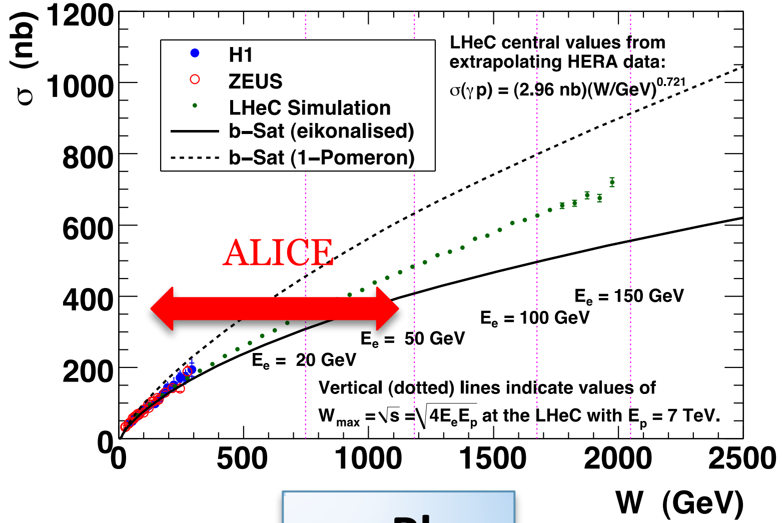


Ultra-peripheral collisions

- Charmonium photo-production cross section is proportional to square of gluon structure function (at LO) of the target (Pb, proton)
- Charmonium rapidity measures energy of the photon-target(p,Pb) interaction
- 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)

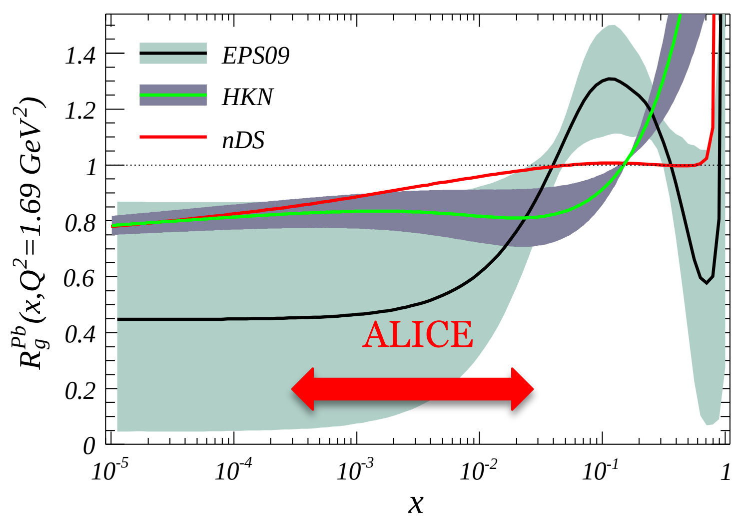
γp

LHeC Study group, ArXiv: 1211.4831



γ-Pb

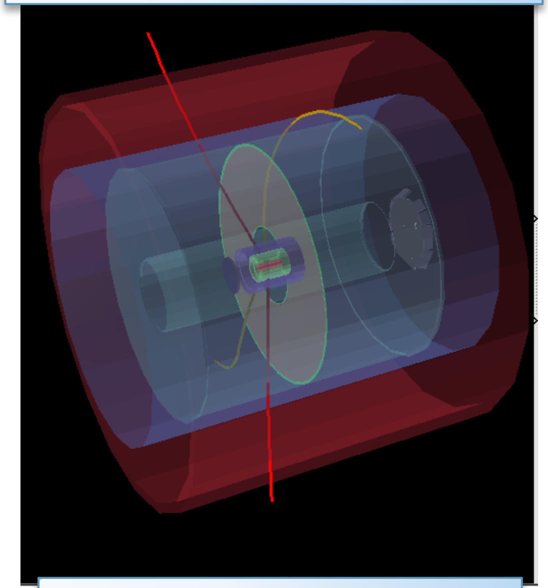
C. A. Salgado *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* 39 015010



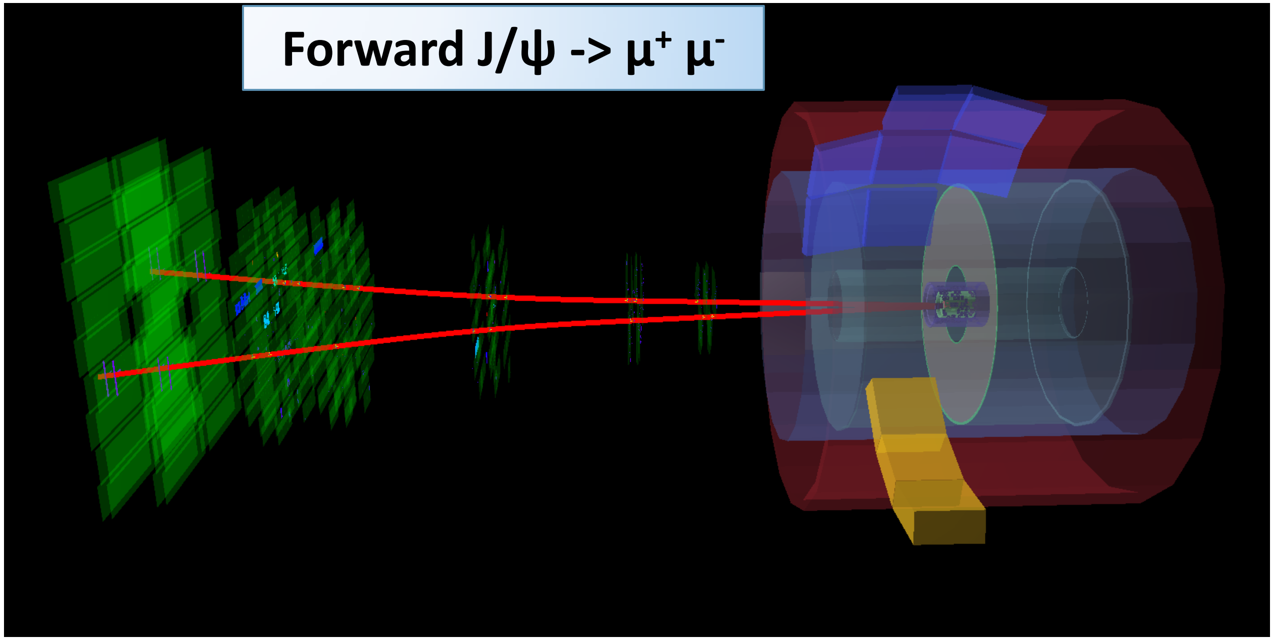
Ultra-peripheral collisions

- Very clean signature - two or four tracks in an otherwise empty detector
- Decay channels:
  - $\rho^0 \to \pi^+ \pi^-$
  - $J/\psi \to l^+ l^-$
  - $\psi(2S) \to l^+ l^-$
  - $\psi(2S) \to J/\psi\, \pi^+ \pi^-$

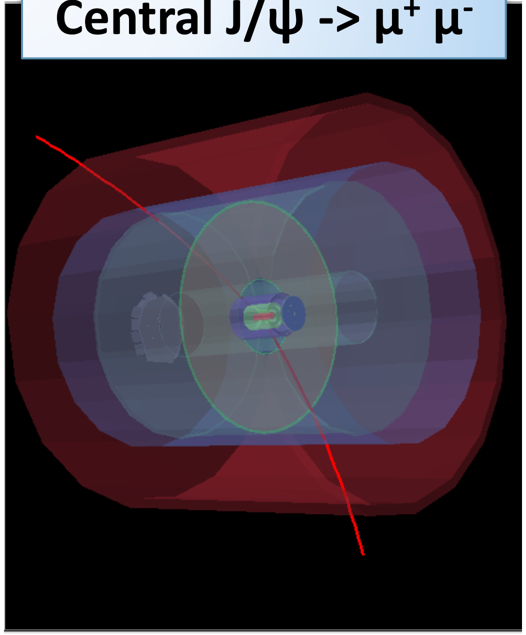
$\psi(2s) \to e^+ e^- + \pi^+ \pi^-$



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



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



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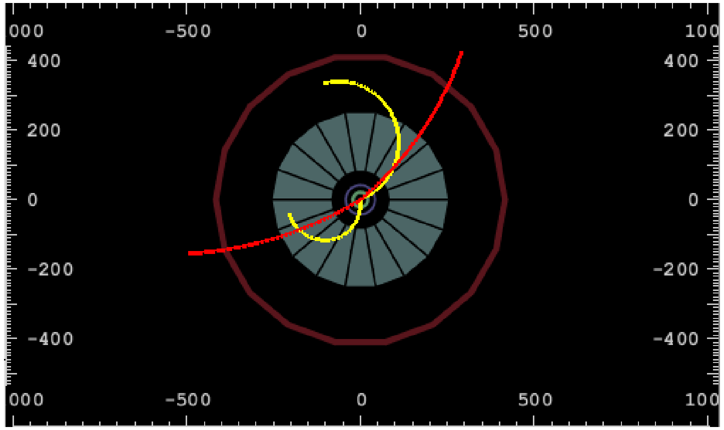

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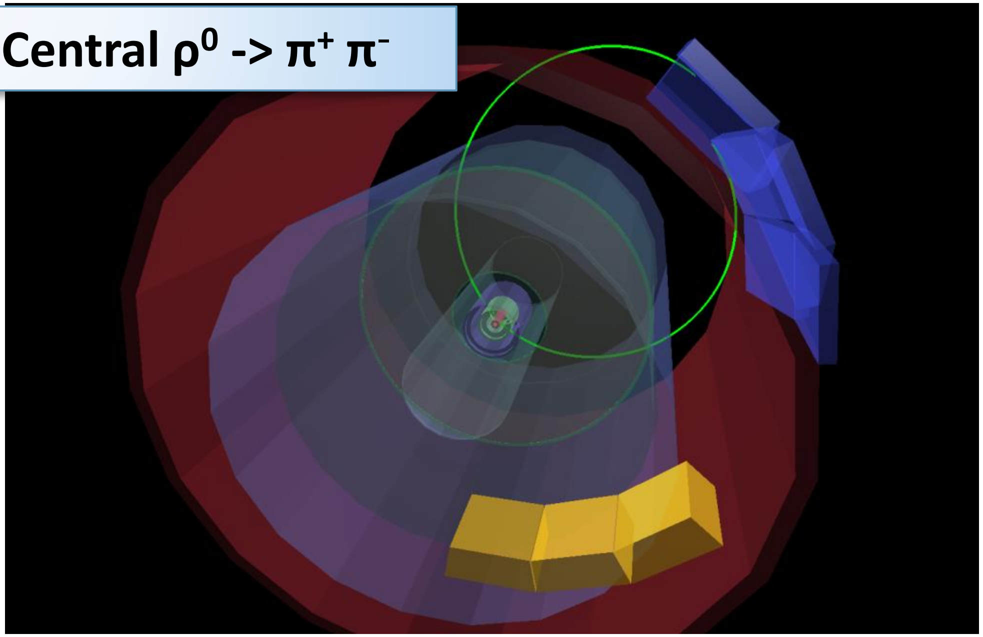

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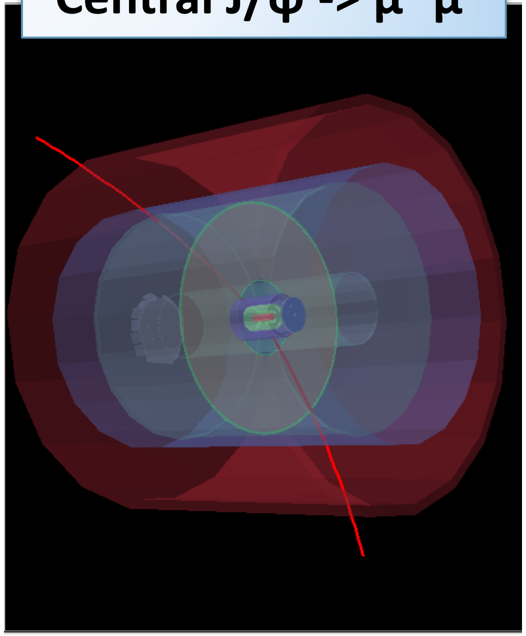
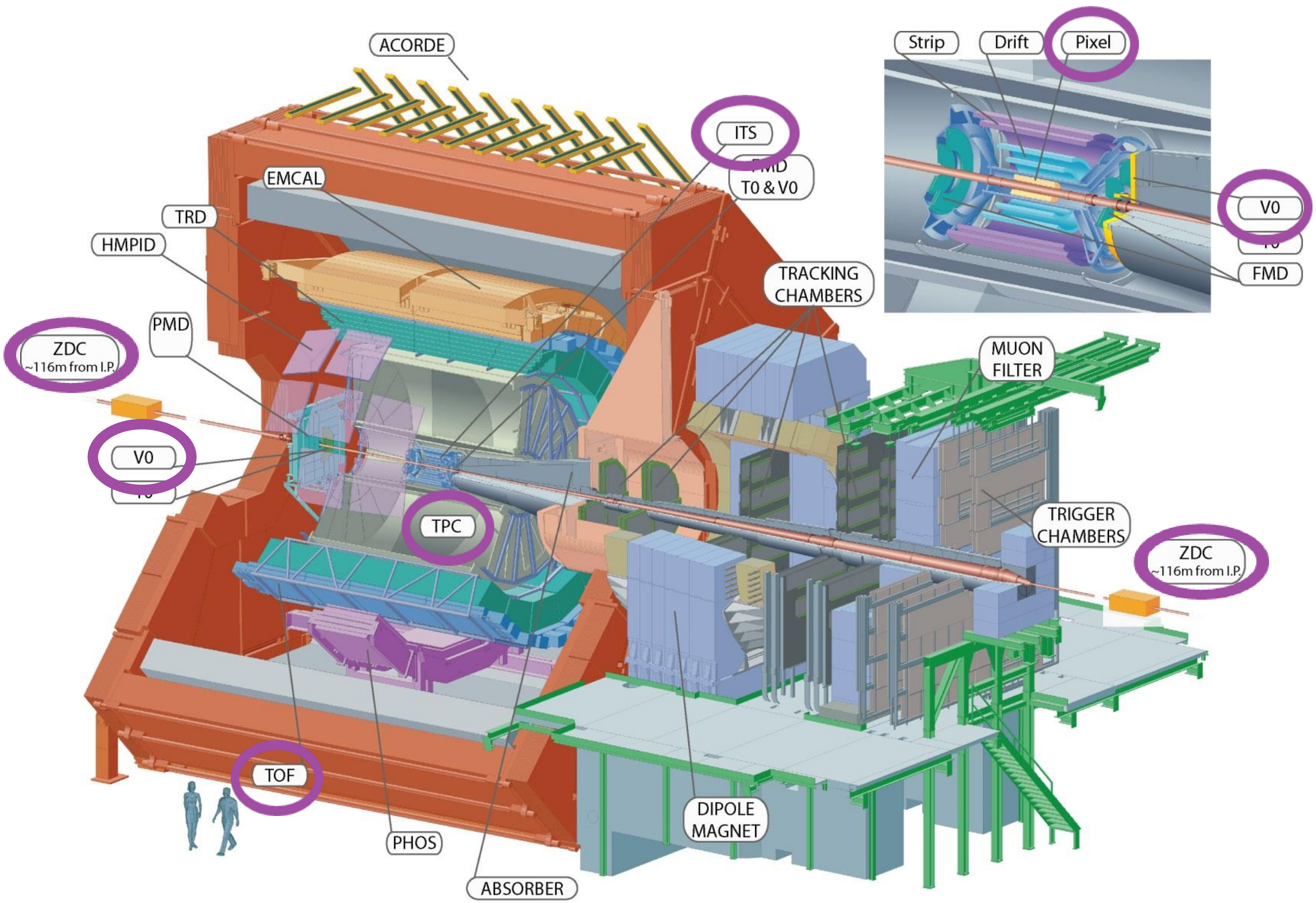


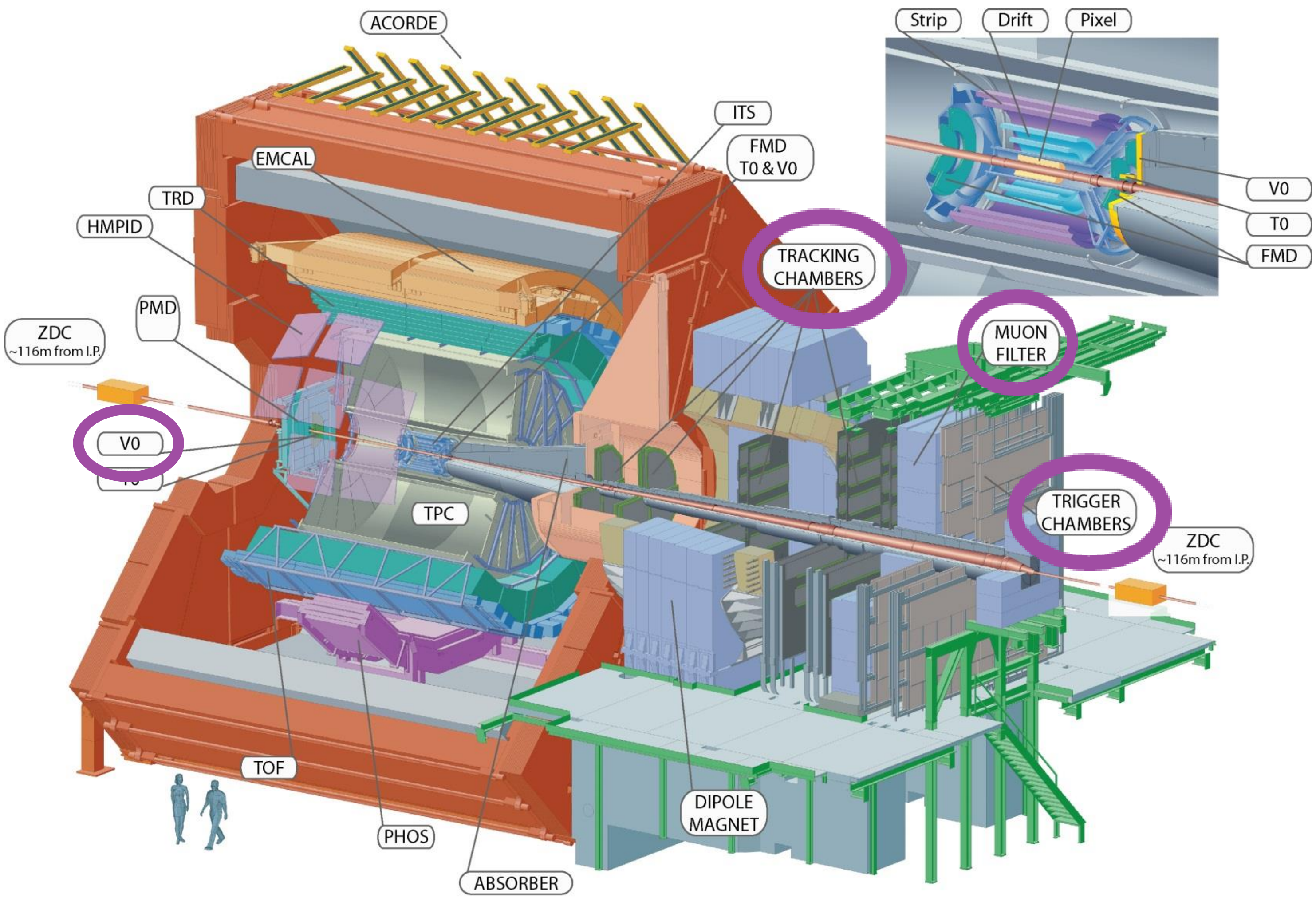
ALICE and UPC trigger

- Central barrel trigger on UPC
  - 2010: veto on V0, hits in SPD ≥ 2 , TOF hits ≥ 2
  - 2011: veto on V0, hits in SPD ≥ 2 , 2 ≤ TOF hits ≤ 6 with back-to-back topology
  - 2015: veto on V0, veto on AD, hits in SPD ≥ 4 with back-to-back topology / TOF hits ≤ 6 with back-to-back topology



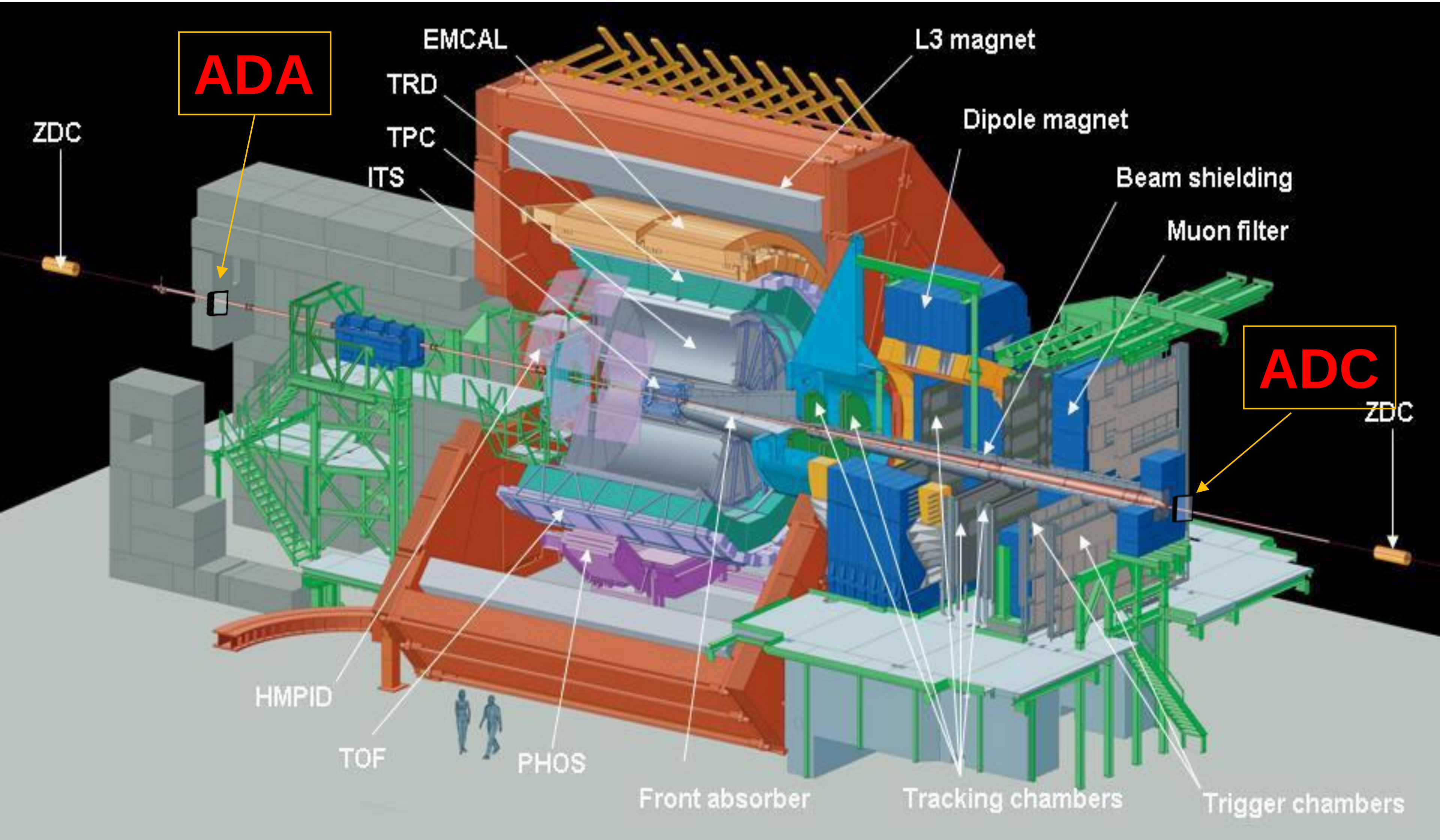
ALICE and UPC trigger

- Forward rapidity trigger on UPC
  - 2011: veto on V0-A , hits in V0-C , single muon with $p_T > 1$ GeV/c
  - 2013: veto on V0-A , hits in V0-C , di-muon, each with $p_T > 0.5$ GeV/c
  - 2015: veto on V0-A, veto on AD, di-muon, each with $p_T > 1$ GeV/c



New ALICE detector for diffractive physics

ALICE Diffractive (AD) detector



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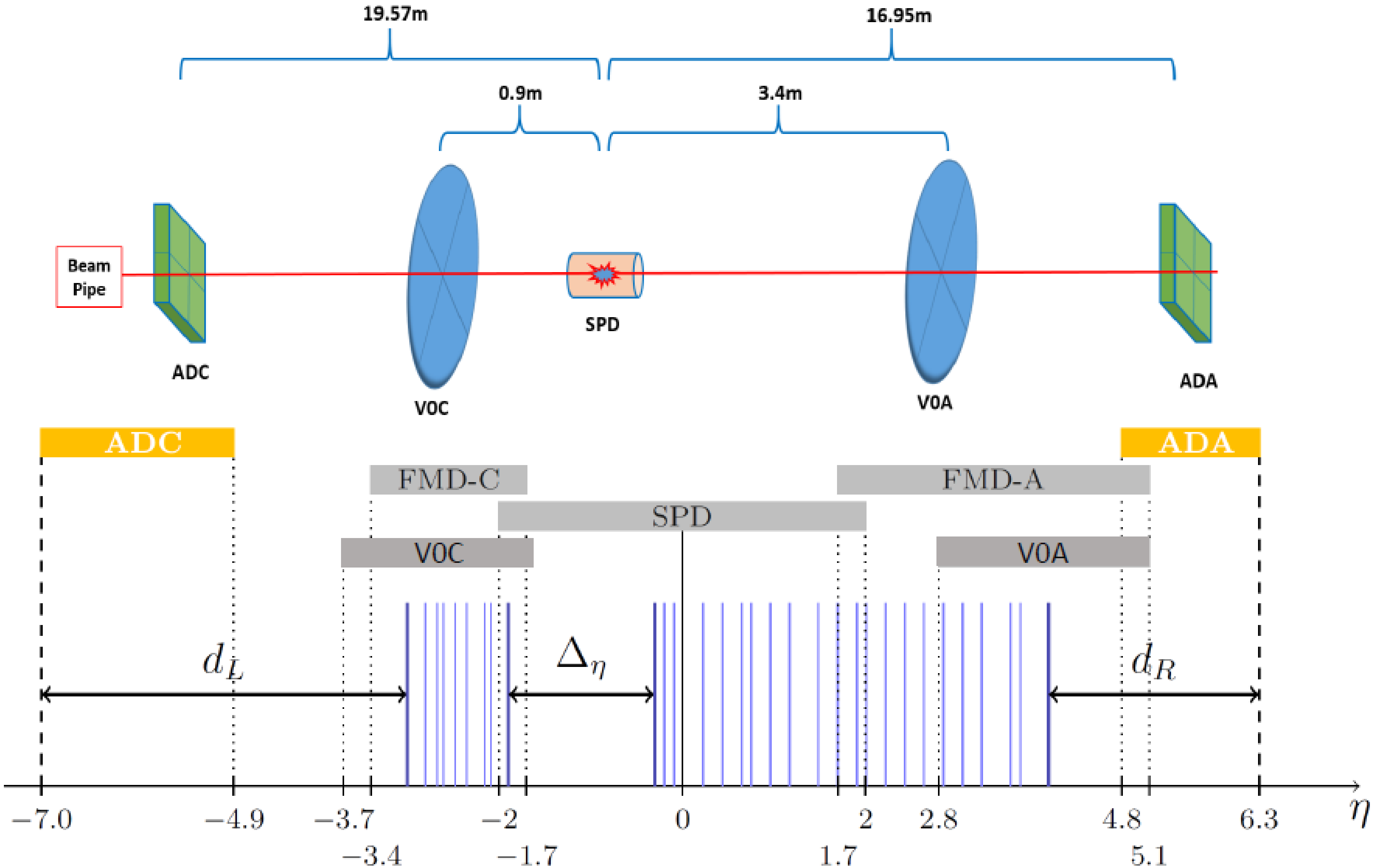
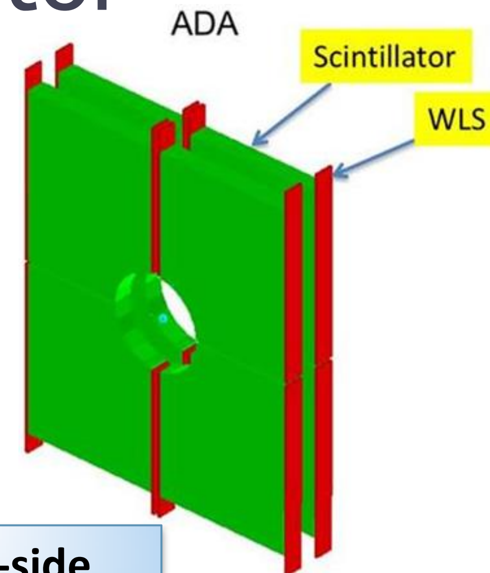
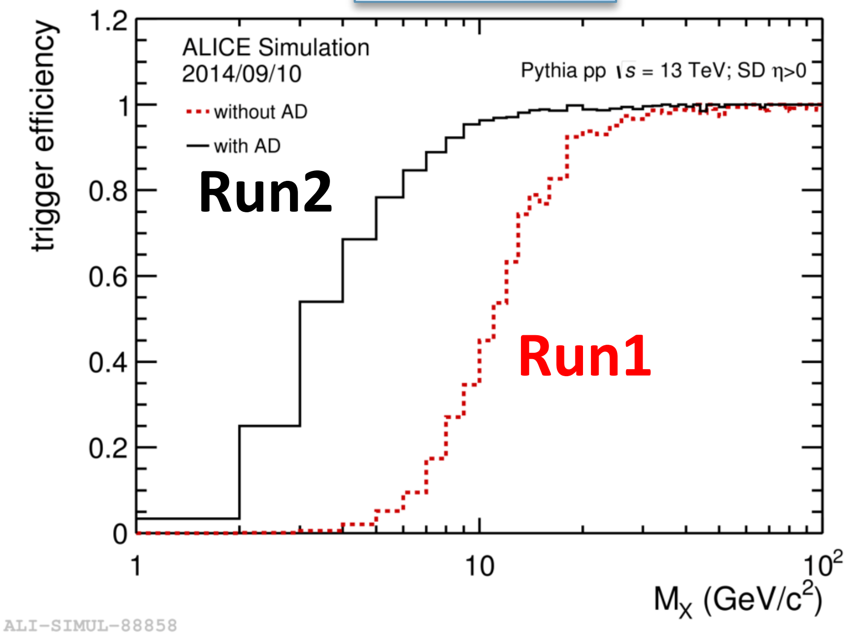


ALICE Diffractive (AD) detector

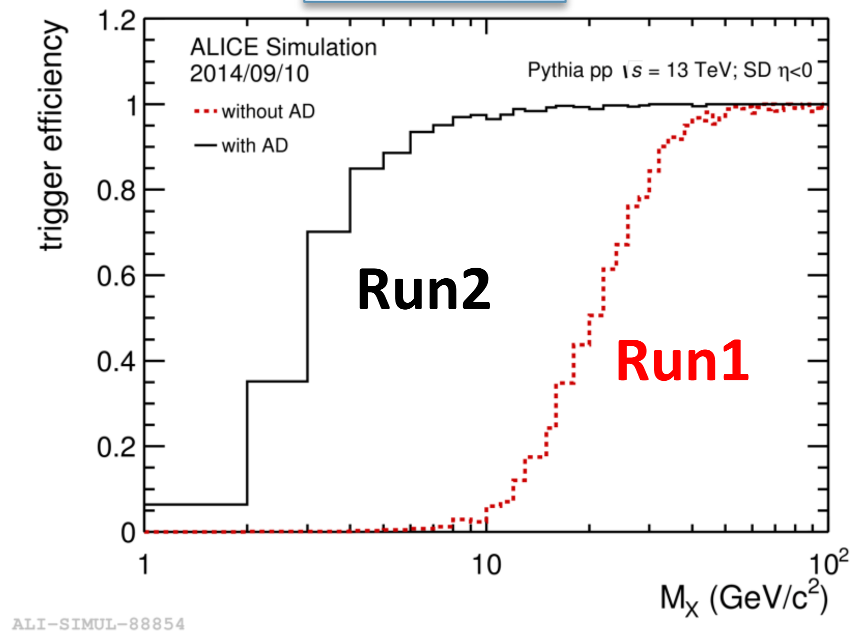
- Double layers of scintillator counters
- ADA: z = 17.0 m, $4.9 < \eta < 6.3$
- ADC: z= −19.5 m, $-7.0 < \eta < -4.8$
- Increase pseudo-rapidity coverage from 8.8 to 13.2
- Enhanced trigger efficiency at low diffractive masses
- Increased capability to impose veto for exclusive processes in UPC



A-side



C-side



ρ^0 in Pb-Pb

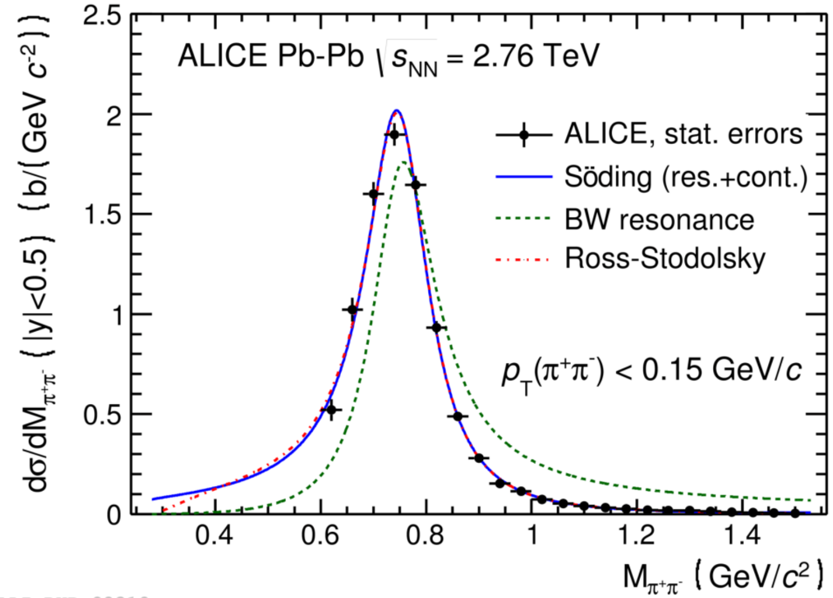
JHEP 09, 095 (2015)

Preliminary 2017

ρ^0 in Pb-Pb central rapidity

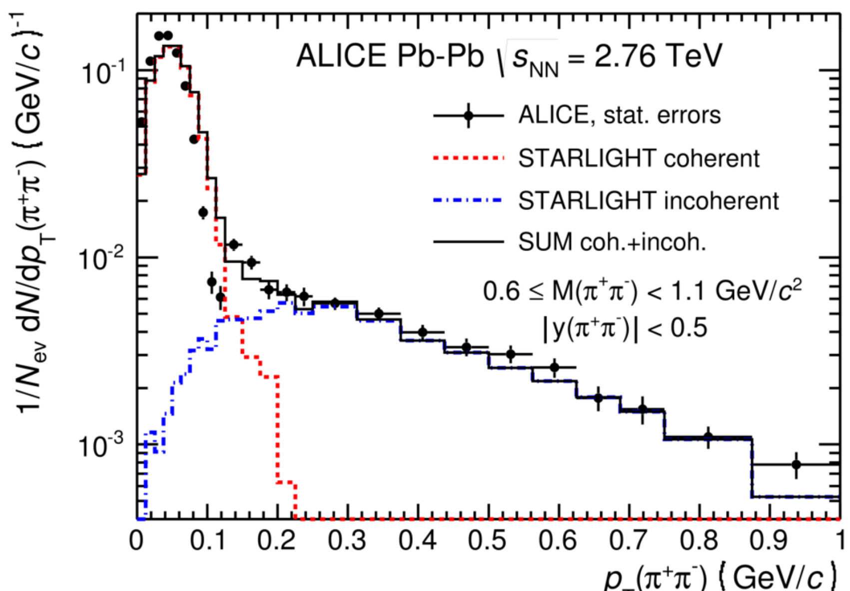
- **2011 Pb-Pb data**
- Pions are identified by TPC dE/dx
- Coherent events selected by $p_T < 0.15$ GeV/c and corrected for incoherent contamination
- Invariant mass fitted by Breit-Wigner resonance + continuum term (Söding)

JHEP 09, 095 (2015)



ALI-PUB-92319

- 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.)

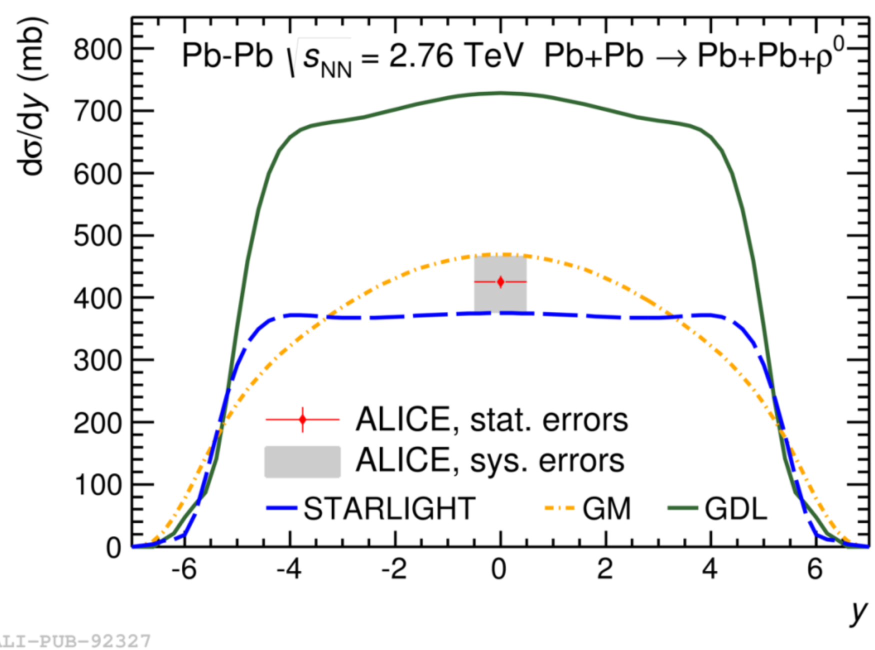


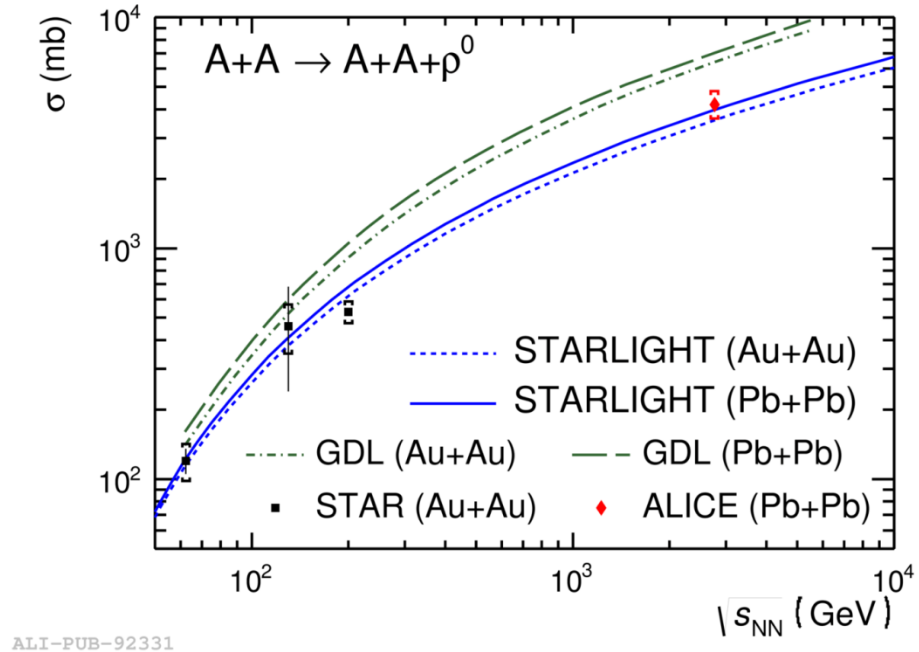
ALI-PUB-92315

Cross section

- Cross section obtained by integrating the resonance contribution over $[2m_\pi, M_\rho + 5\Gamma]$
- GDL: 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

JHEP 09, 095 (2015)

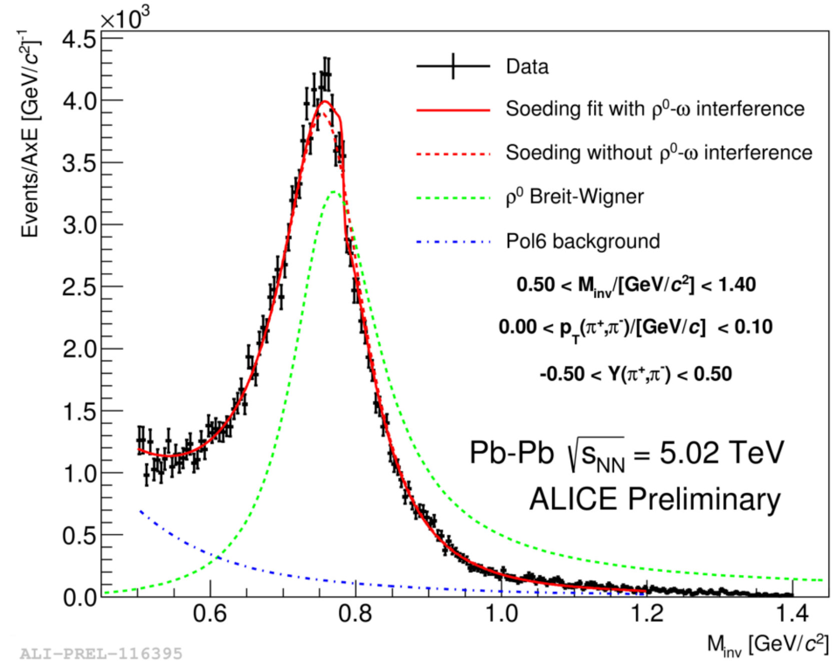


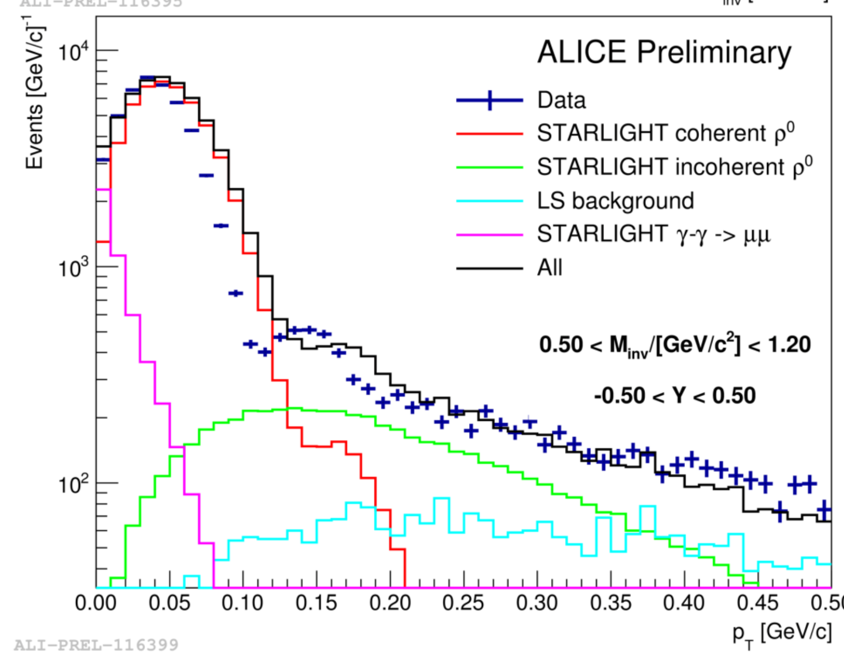


ρ^0 in Pb-Pb central rapidity

- **2015 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)
- $\rho^0 - \omega$ interference term can improve the description of invariant mass shape

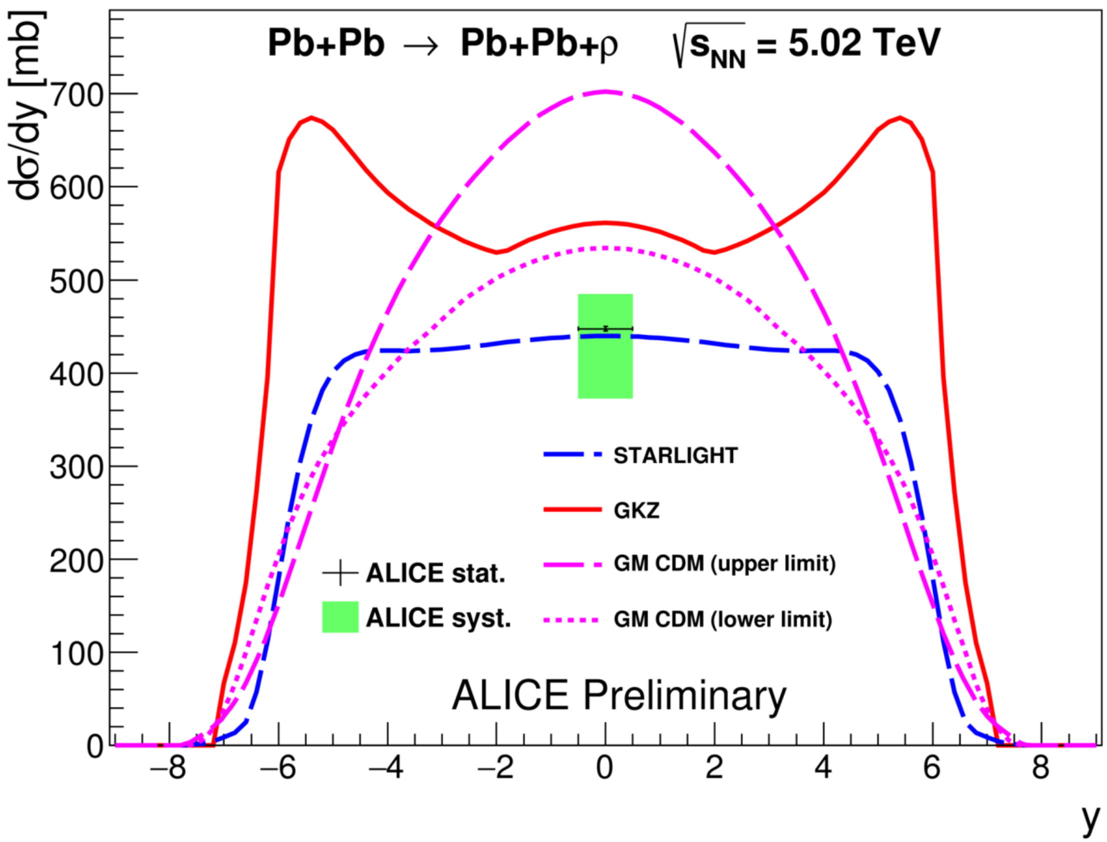
- Second diffractive peak clearly visible
- Coherent p_T distribution from STARLIGHT significantly wider than data





Cross section

- GKZ: Gribov -Glauber shadowing
- 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



ALI-PREL-116391

J/ψ in Pb-Pb

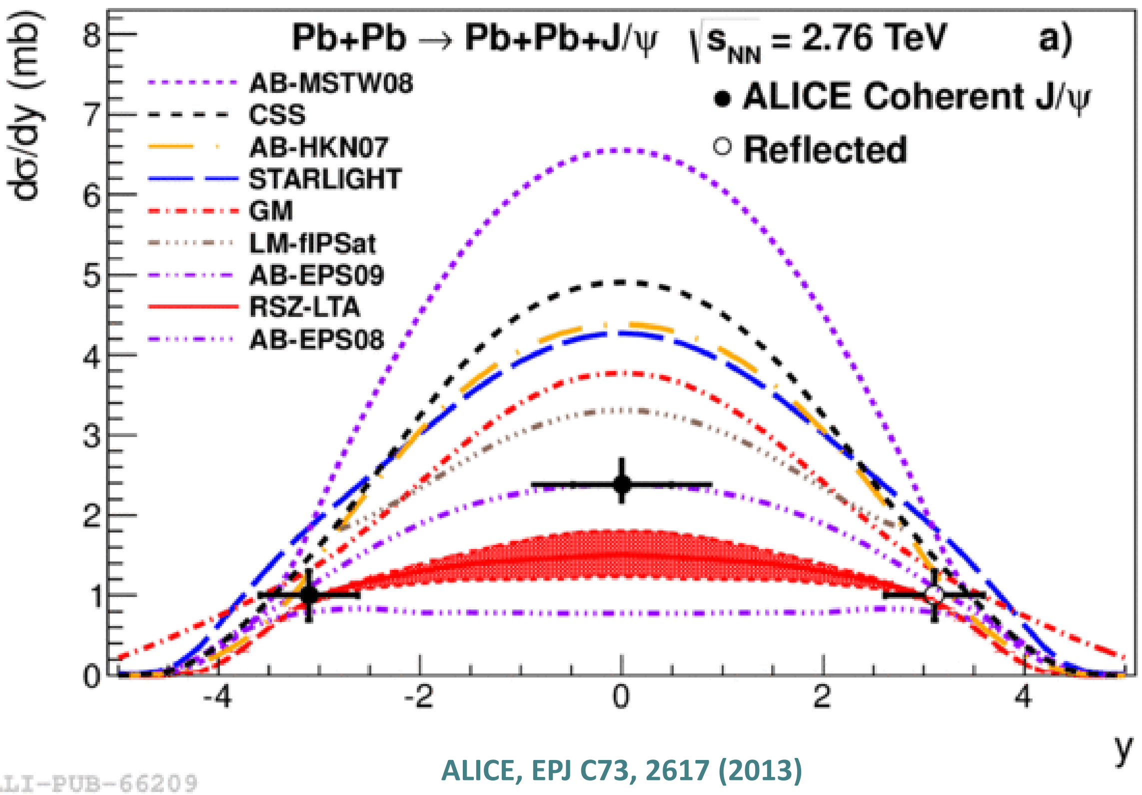
ALICE, Phys. Lett. B718, 1273 (2013)

ALICE, EPJ C73, 2617 (2013)

Preliminary (2017)

Coherent cross section from 2011 data

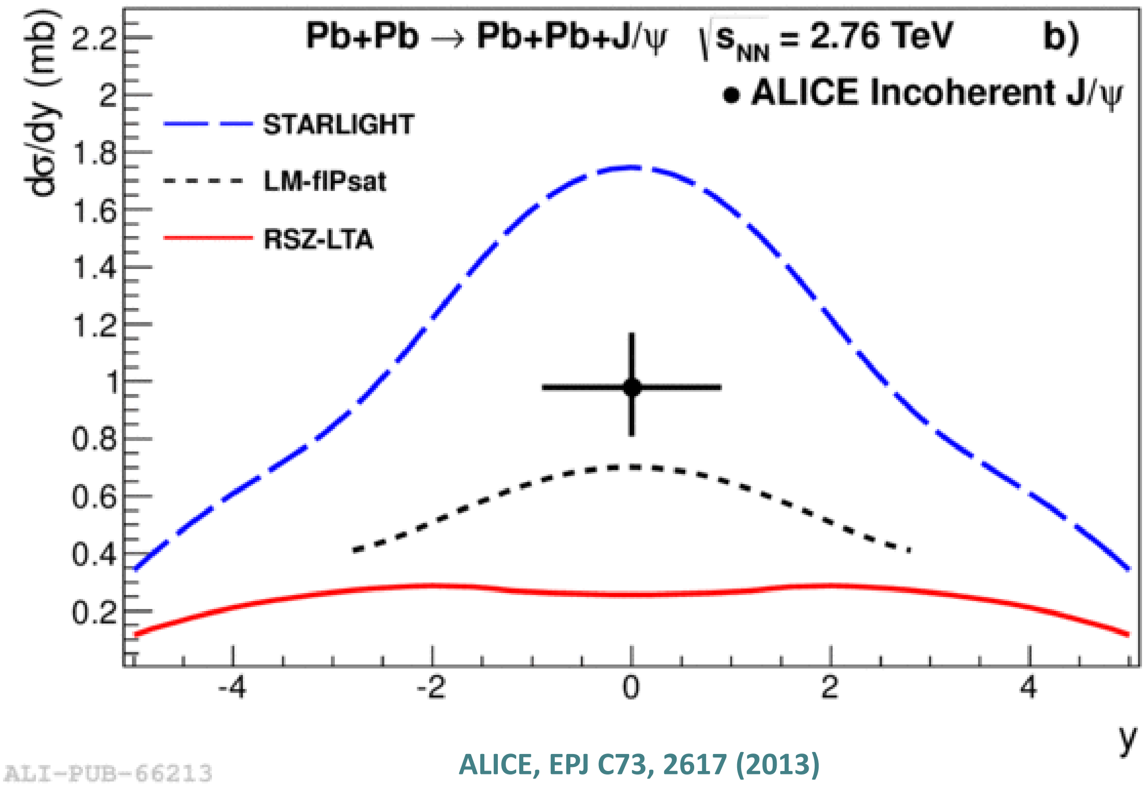
- ALICE results are able to distinguish between the different models
- No nuclear effects: AB-MSTW08
- Glauber approach: STARLIGHT, GM, CSS, LM
- Partonic models: RSZ-LTA, AB-EPS08,09, AB-HKN07
- Models with moderate nuclear gluon shadowing (EPS09) are favored



ALICE, EPJ C73, 2617 (2013)

Incoherent cross section from 2011 data

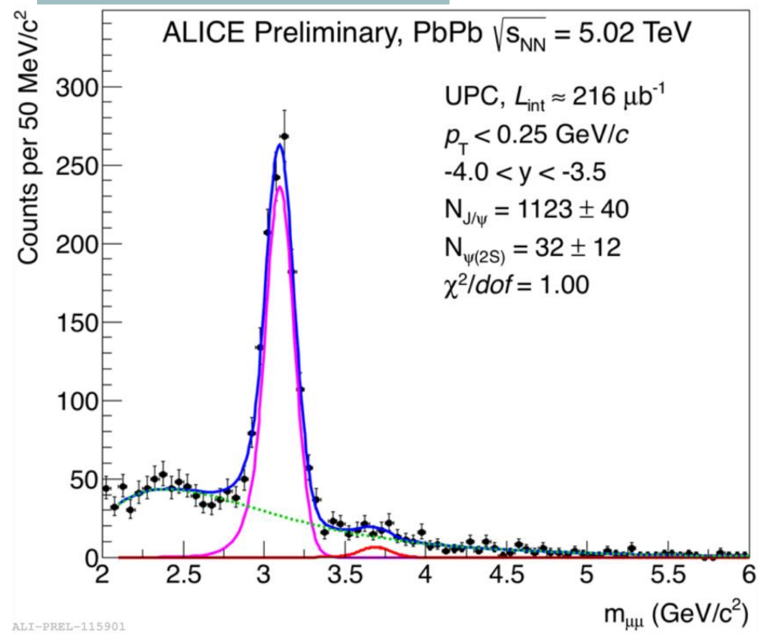
- ALICE sets strong constraints on models
- Glauber approach: STARLIGHT, LM
- Partonic models: RSZ-LTA
- STARLIGHT overestimated both cross sections, but got the ratio incoherent/coherent right (≈0.41)

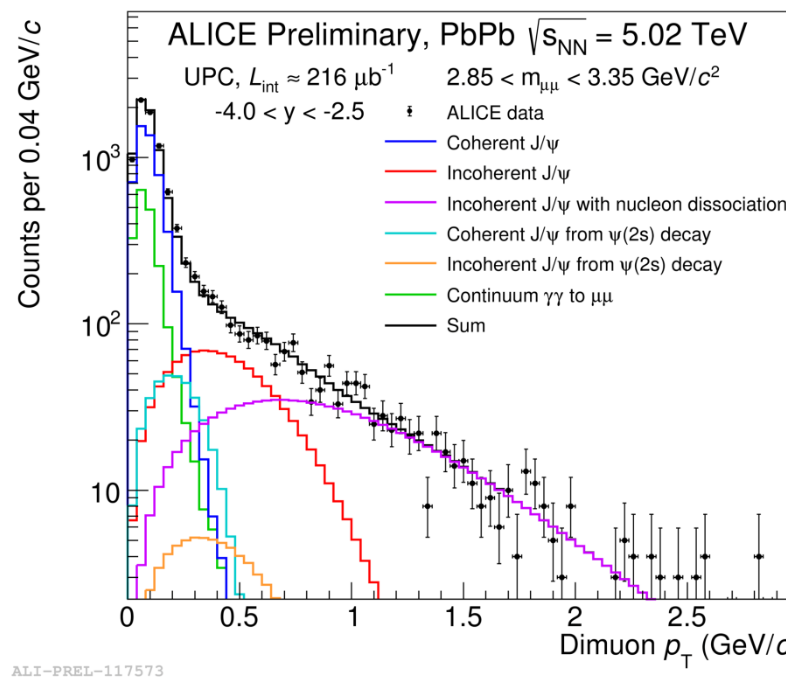


ALICE, EPJ C73, 2617 (2013)

Forward J/ψ in 2015 data

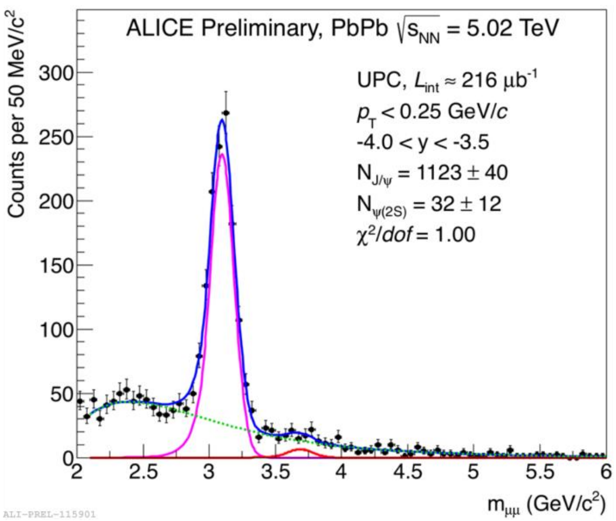
- J/ψ -> $\mu^+ \mu^-$ measured in the muon arm
- J/ψ and ψ(2S) fitted by crystal ball
- ψ(2S) at 3σ significance σ(ψ(2S))/σ(J/ψ) ratio close to HERA γp results
- Background, dominated by γγ->μμ process, is essentially exponential with low-mass decrease due to trigger condition which is fitted by fourth-order polynomial

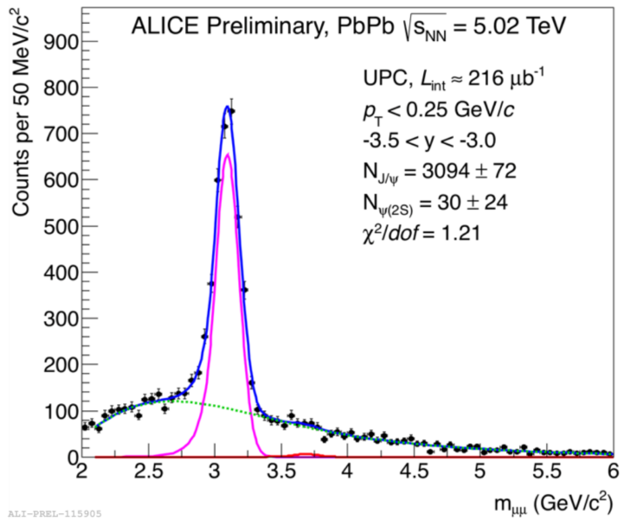


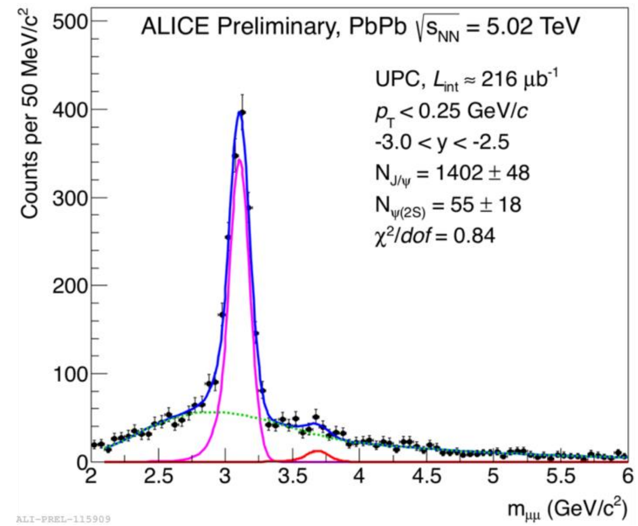


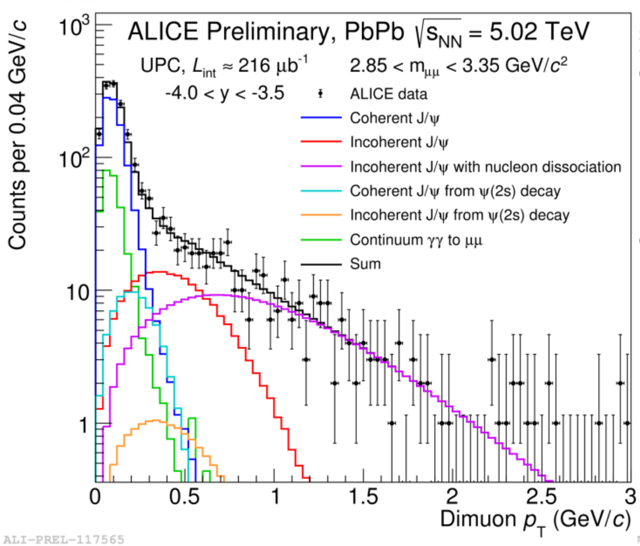
Forward J/ψ in 2015 data

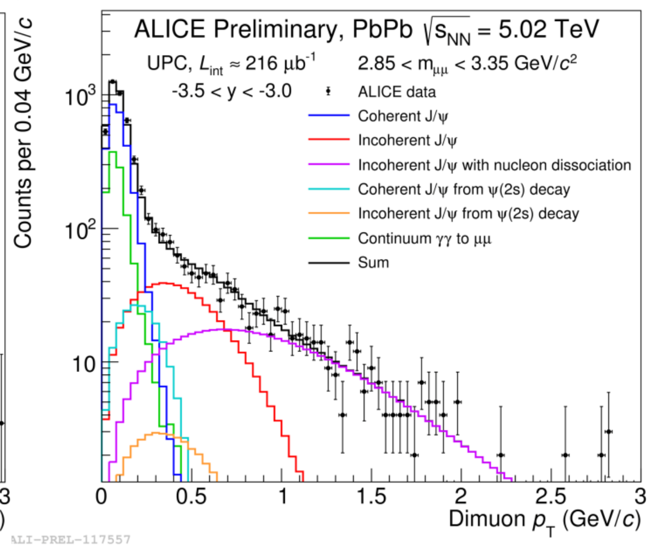
- Analysis performed in 3 rapidity bins

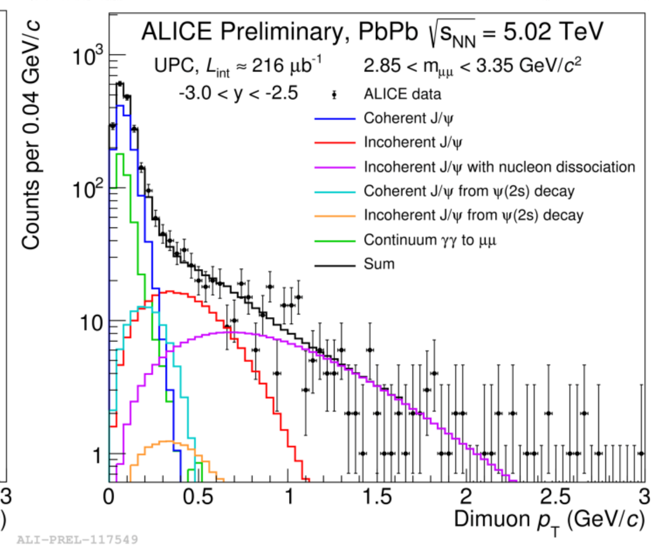






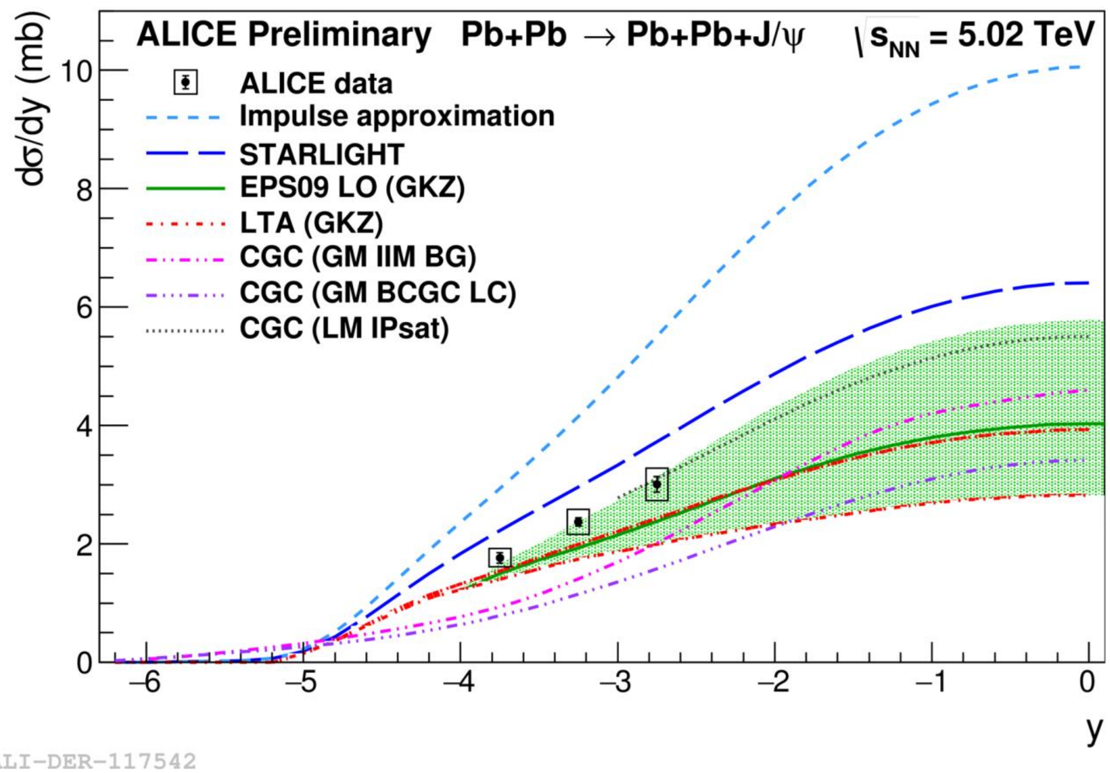






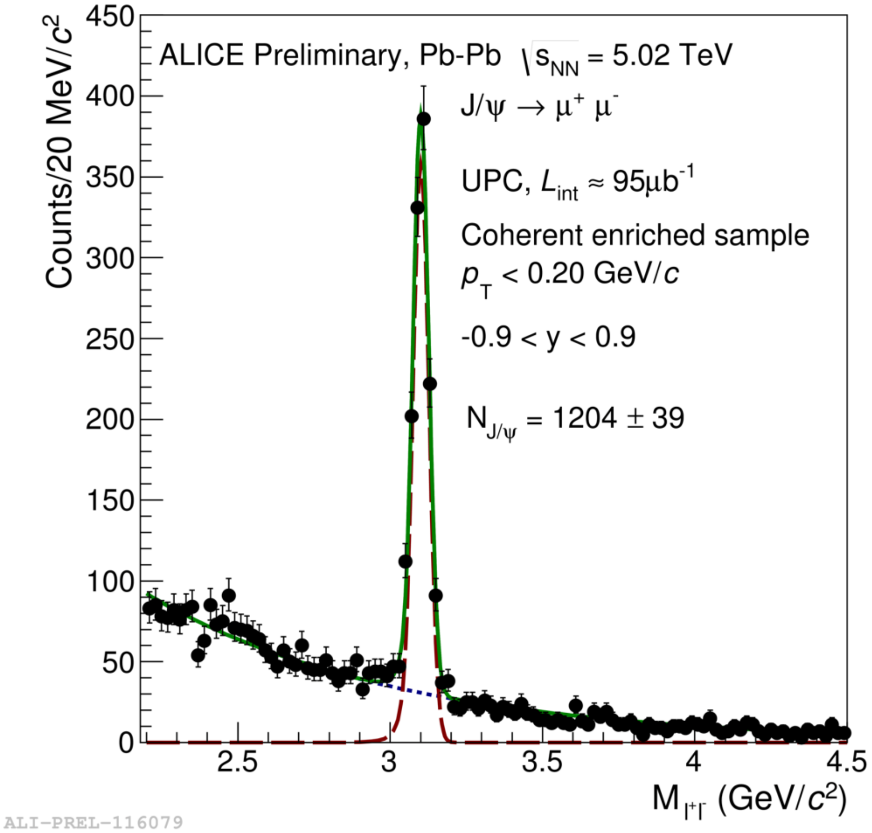
Forward J/ψ in 2015 data

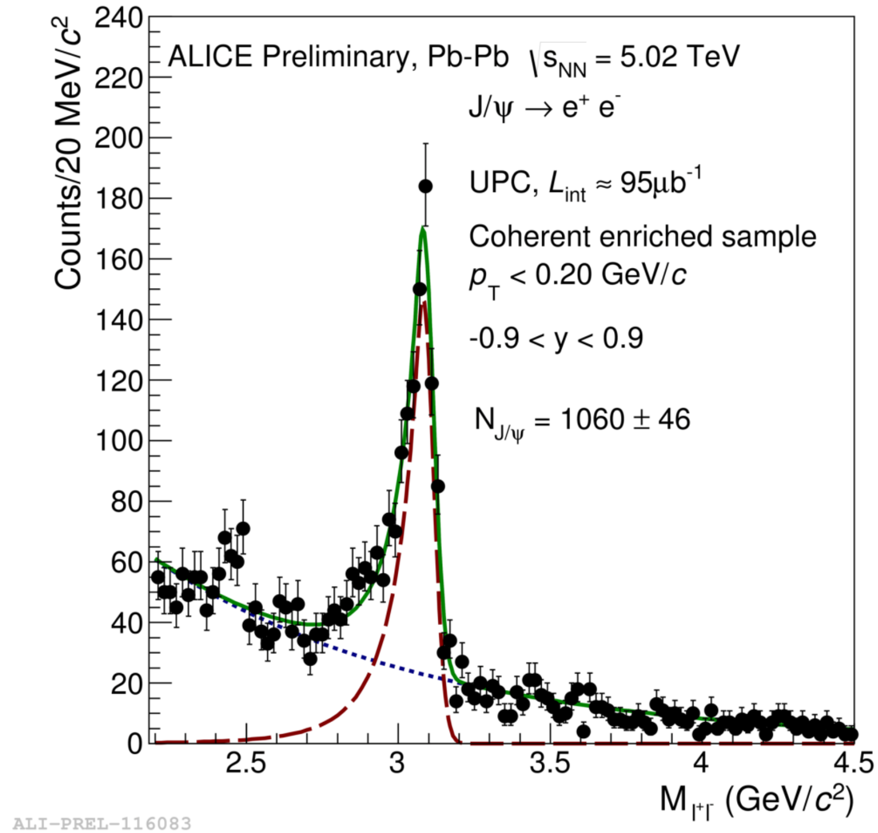
- No nuclear effects: Impulse approximation
- STARLIGHT: VDM + Glauber
- EPS09 LO: EPS09 shadowing
- LTA: Leading twist approximation
- GM, LM: Color dipole model
- Models with moderate nuclear gluon shadowing (EPS09) are favored



Mid-rapidity J/ψ in 2015 data

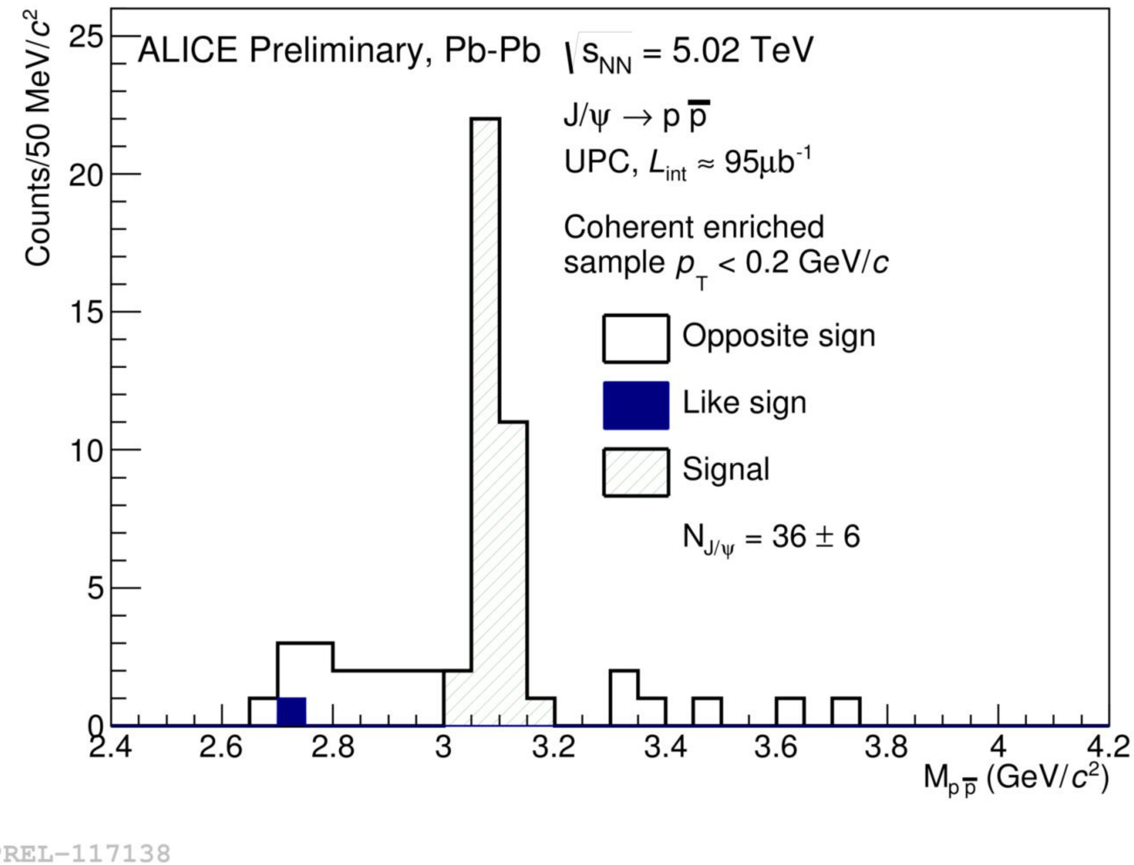
- New data with 4x more statistics
- J/ψ photoproduction accompanied by neutron emission (measured with Zero Degree Calorimeters)
- Incoherent cross section





Mid-rapidity J/ψ in 2015 data

- New data with 4x more statistics
- **First observation of J/ψ->pp in UPC**
- Protons identified by Time-Of-Flight
- Moderate number of candidates, but very clean signal



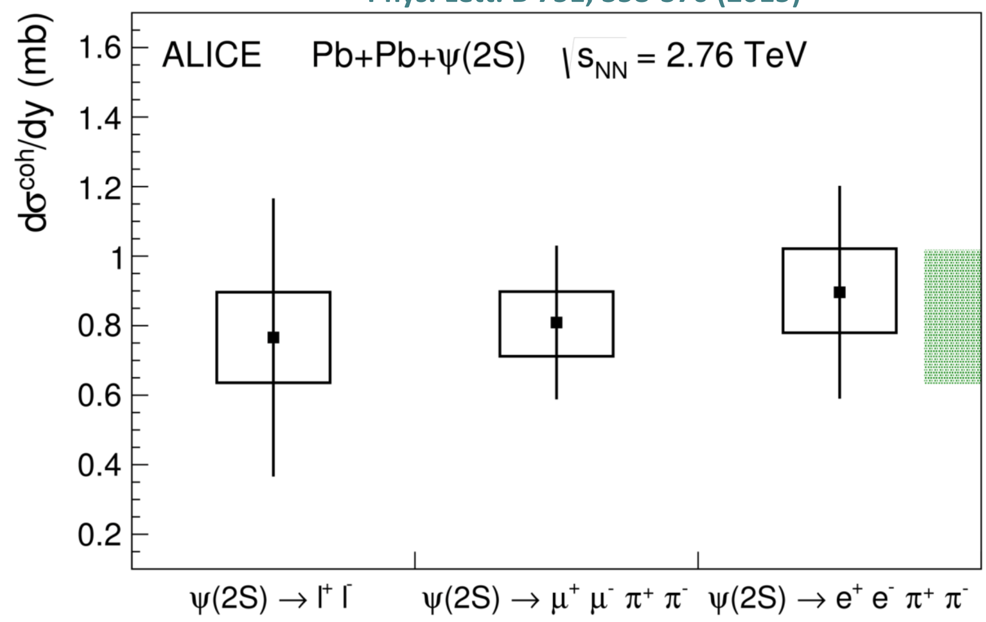
ψ(2S) in Pb-Pb

Phys. Lett. B 751, 358-370 (2015)

Coherent ψ(2s) cross section

- Measured via 3 decay channels
- Moderate number of candidates, but very clean signal in cascade decay via J/ψ

Phys. Lett. B 751, 358-370 (2015)



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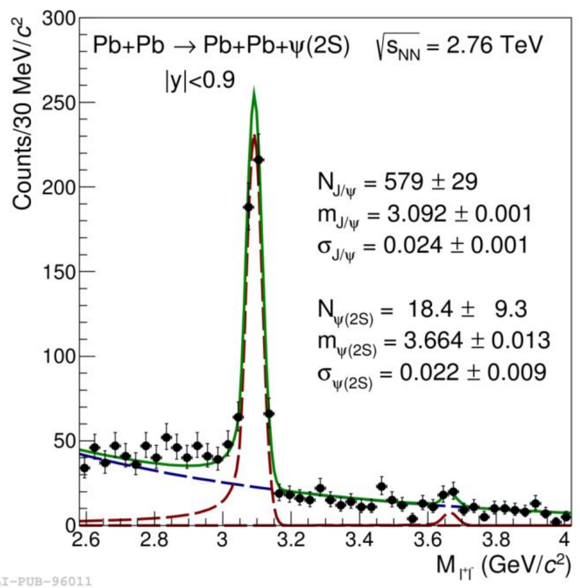
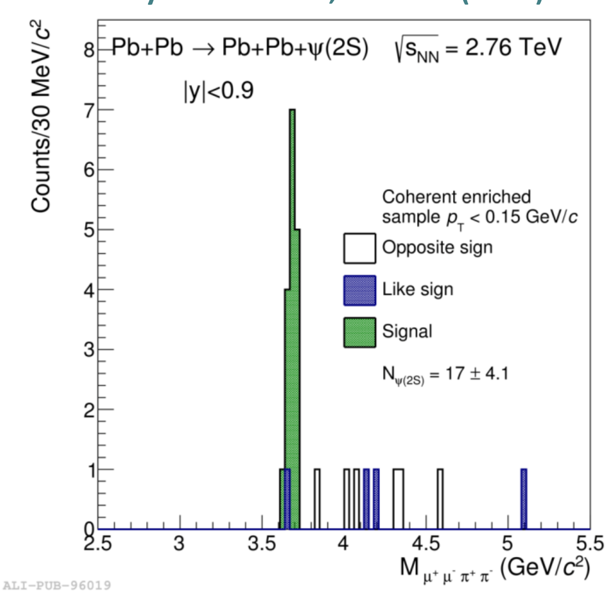
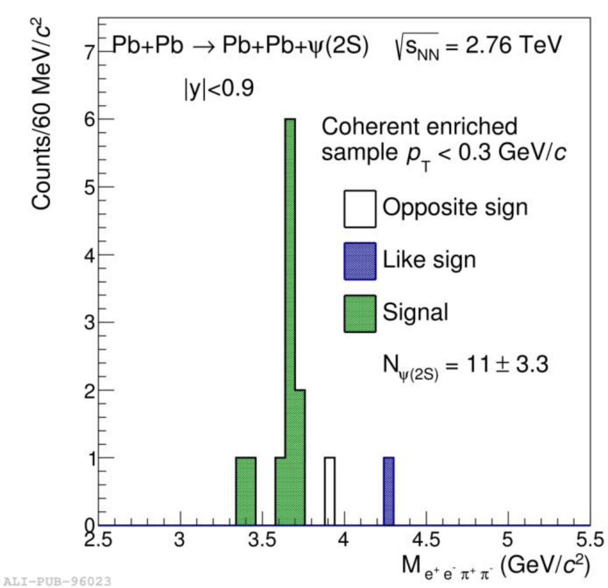
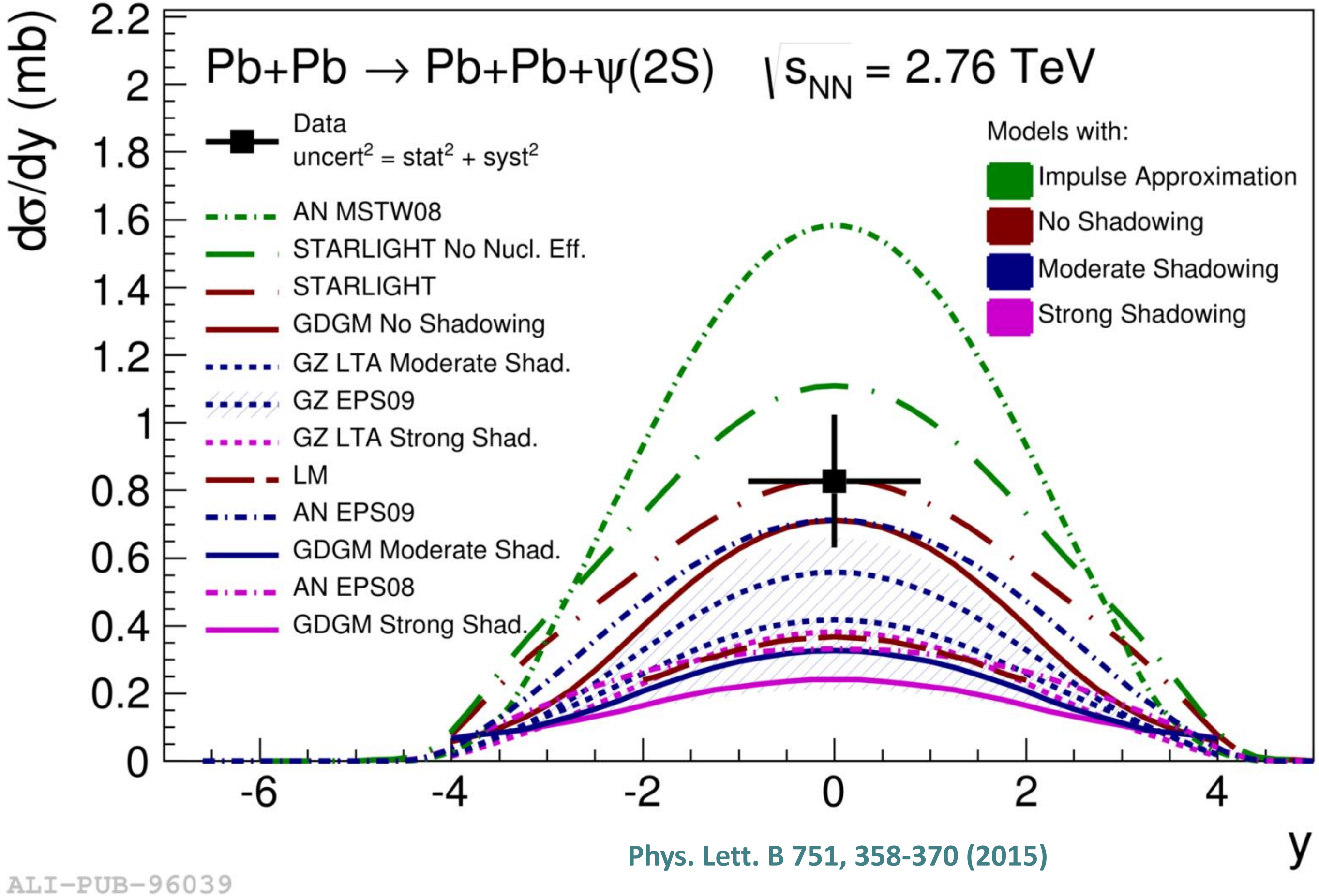






Coherent ψ(2s) cross section – Model comparison

- 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)

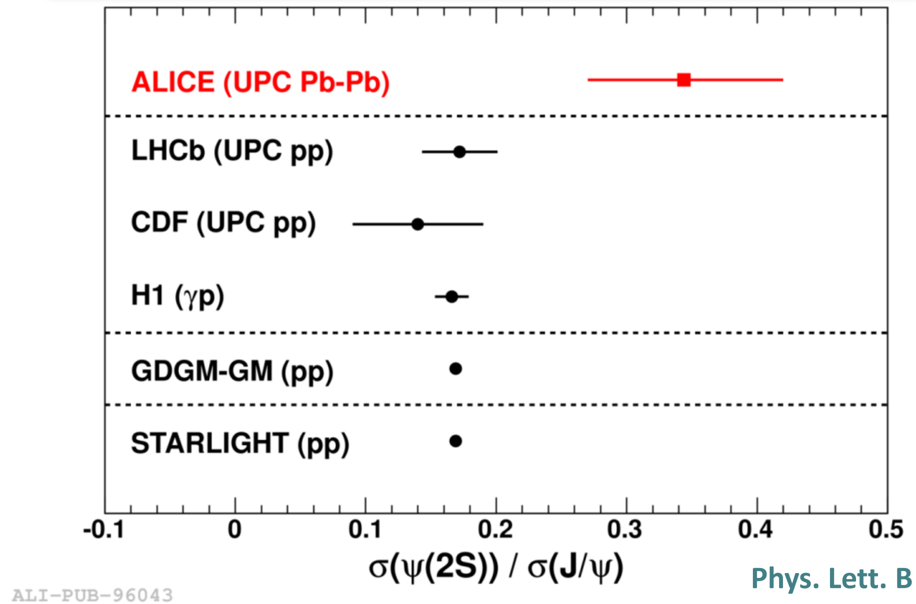


Phys. Lett. B 751, 358-370 (2015)

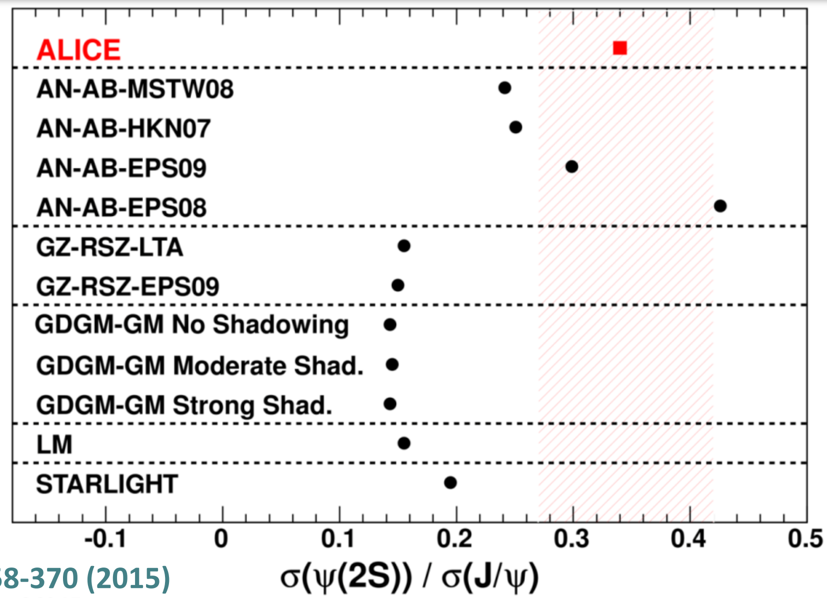
Ratio to J/ψ cross section

- Many sources of systematic uncertainties 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
- The same models that reproduced correctly the pp ratio, fail 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 pp data and models



Comparison to Pb-Pb models



Phys. Lett. B 751, 358-370 (2015)

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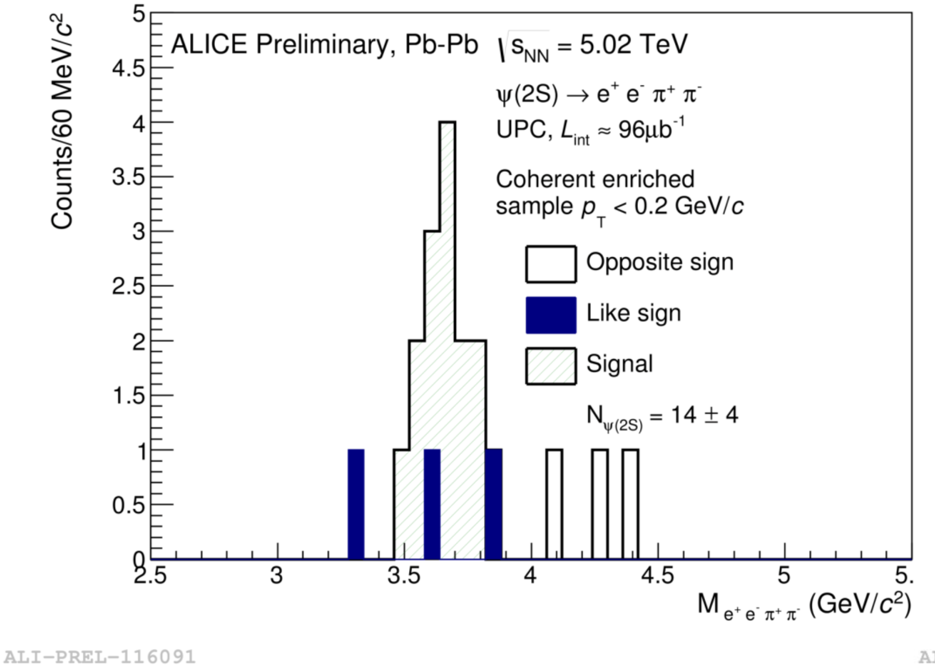
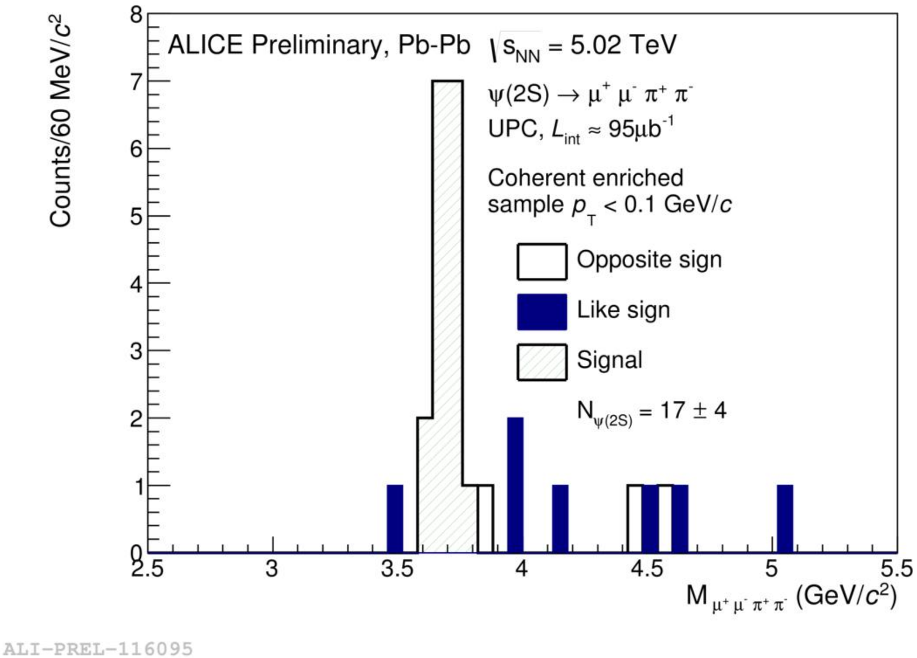




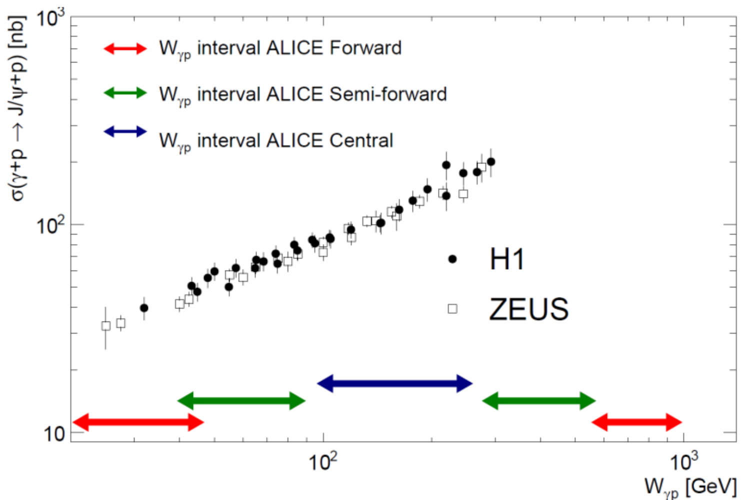
J/ψ in p-Pb

ALICE, Phys. Rev. Lett. 113, 232504 (2014)

Preliminary (2017)

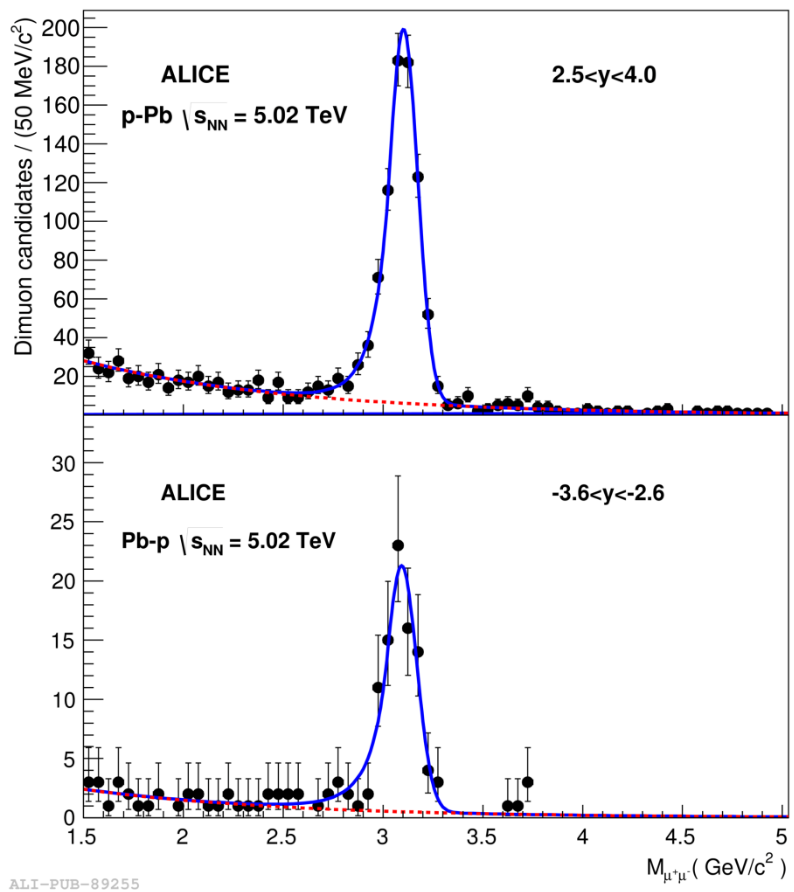
J/ψ in p-Pb and Pb-p

- 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



Forward J/ψ -> $\mu^+ \mu^-$

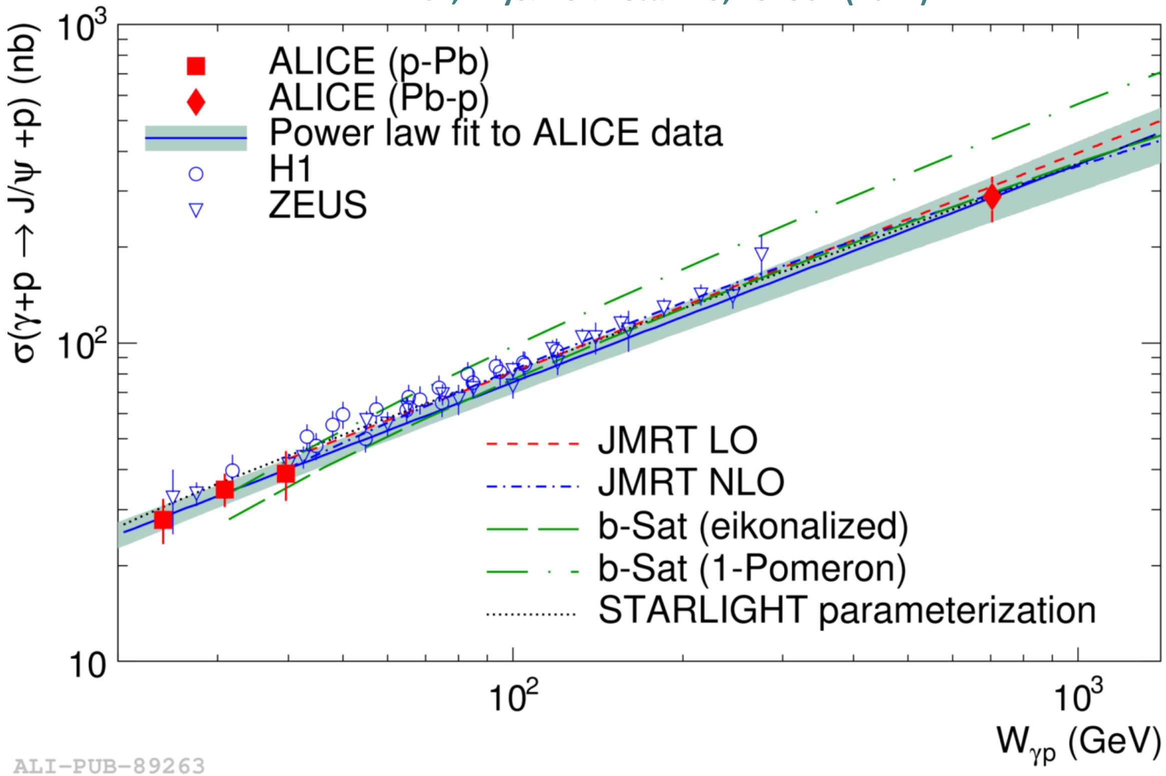
ALICE, Phys. Rev. Lett. 113, 232504 (2014)



Cross section for J/ψ in γp

- 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

ALICE, Phys. Rev. Lett. 113, 232504 (2014)

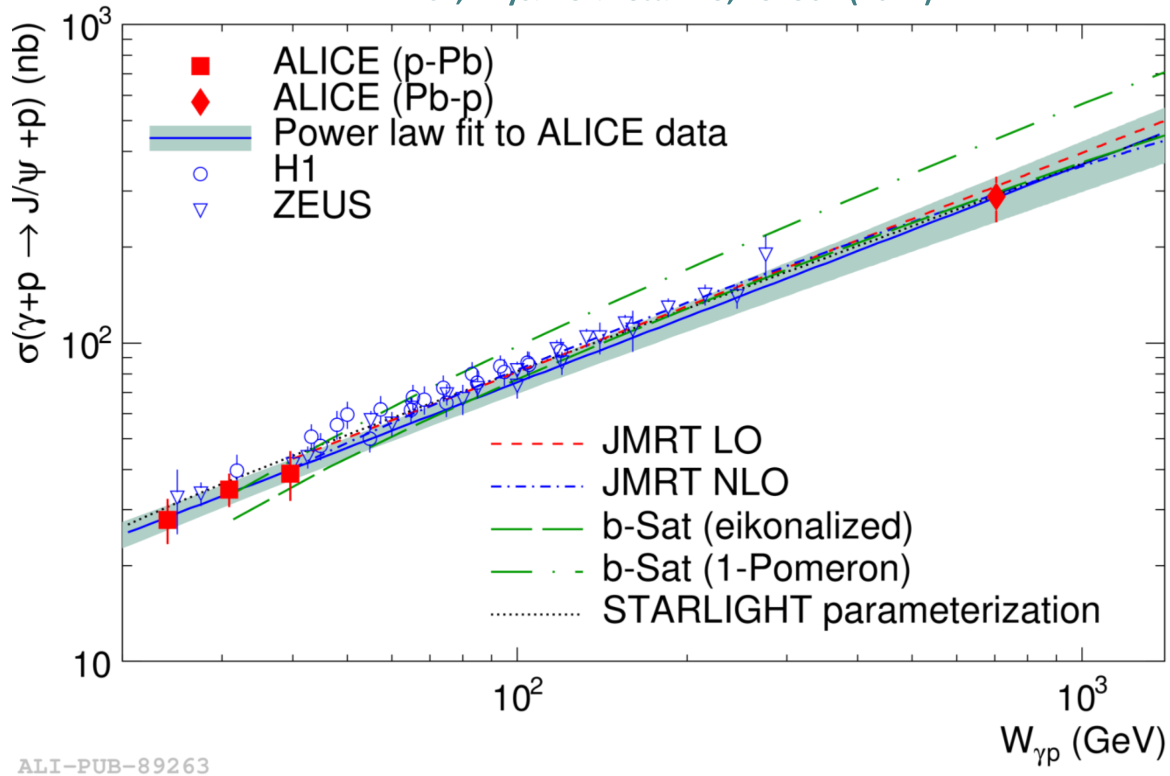


- HERA and ALICE cross section points stay on the same power law
- The most straightforward interpretation is that no change in the behavior of the gluon PDF in the proton manifests itself between HERA and LHC

Cross section for J/ψ in γp

ALICE, Phys. Rev. Lett. 113, 232504 (2014)

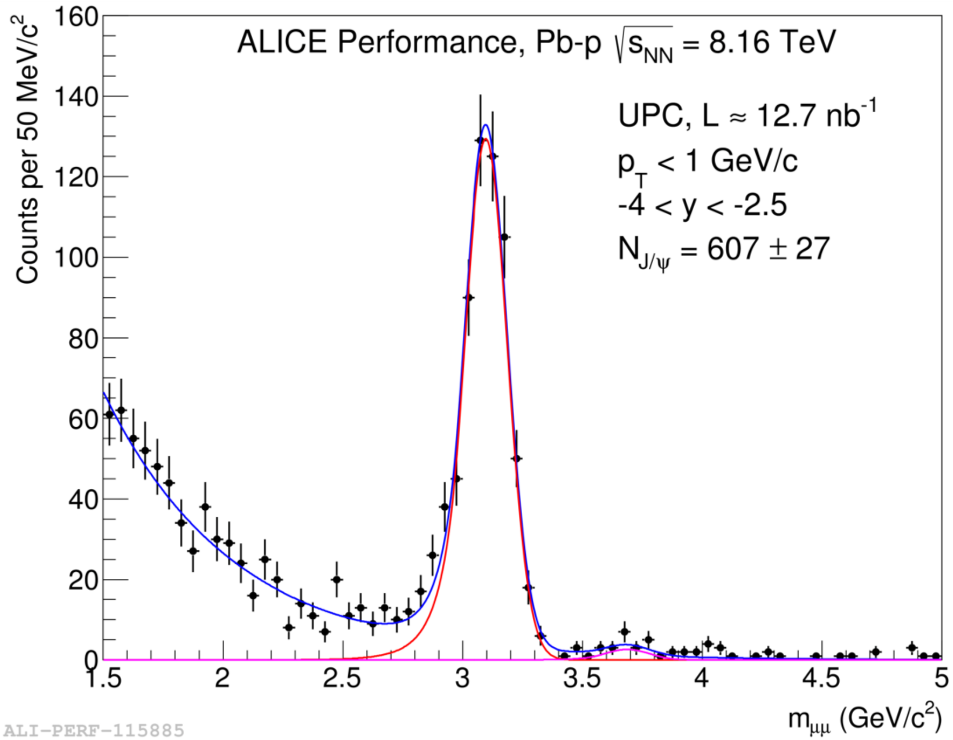
- JMRT: LO model based on a power law. NLO model includes the expected main NLO contributions
- b-Sat (eikonalised) includes b-dependent saturation effects based on a CGC inspired model
- STARLIGHT parameterization is based on a power law fit using only fixed-target and HERA data

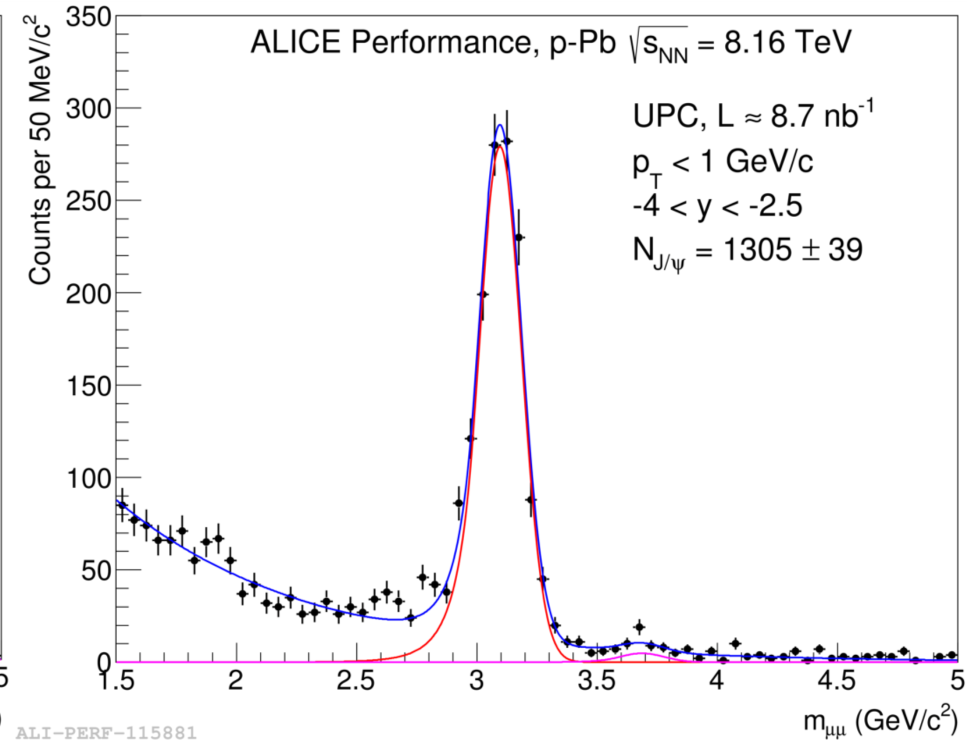


- HERA and ALICE cross section points stay on the same power law
- The most straightforward interpretation is that no change in the behavior of the gluon PDF in the proton manifests itself between HERA and LHC

p-Pb at 8 TeV

- Data at 5 Tev and 8 TeV p-Pb and Pb-p were recorded in 2016
- 10x more stats at high $W_{\gamma p}$ ~0.7 - 1.4 TeV
- Search for gluon saturation effects in p at low x
- Study proton-dissociative cross section at high $W_{\gamma p}$ using AD and ZDC





J/ψ in peripheral Pb-Pb

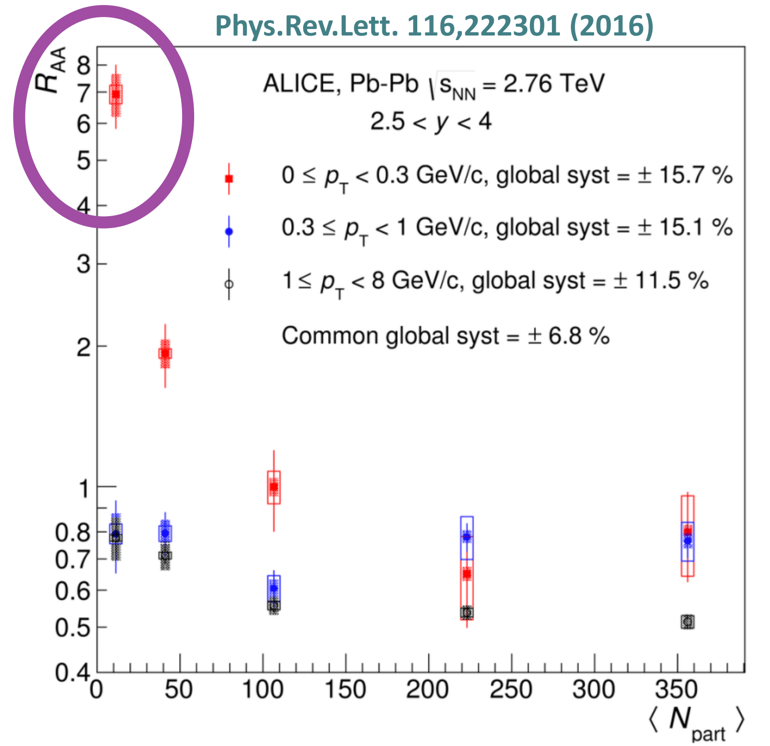
Phys.Rev.Lett. 116,222301 (2016)

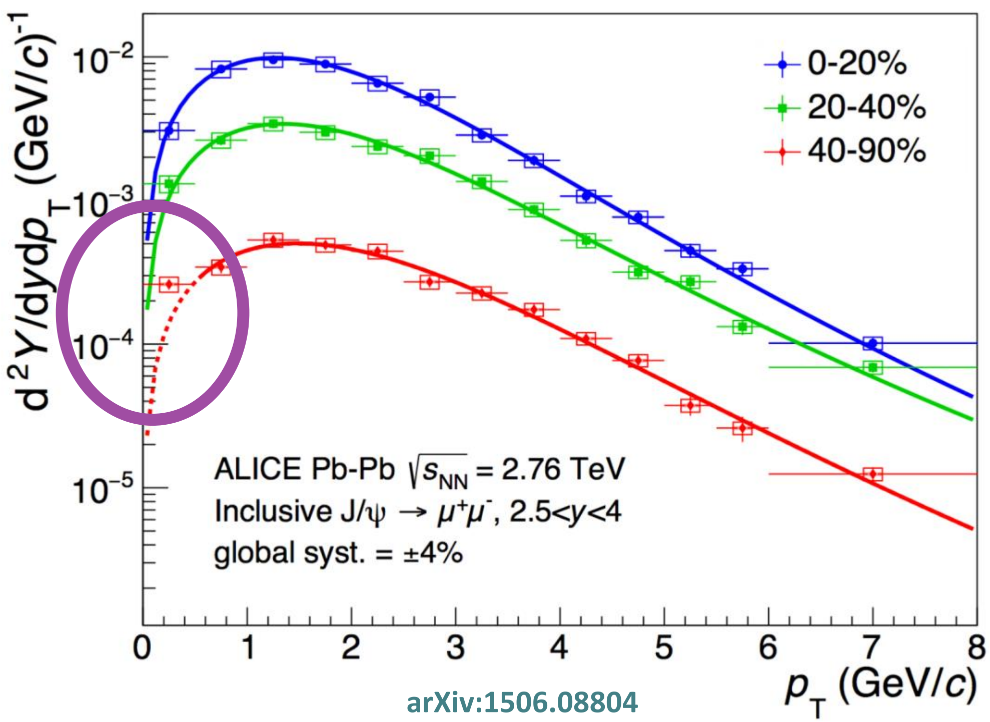
Preliminary (2017)

Excess of very low-p_T J/ψ in peripheral Pb-Pb

- Clear excess at very low p_T in peripheral Pb-Pb collisions with respect to expected hadronic production
- Enhancement of J/ψ R_{AA} in most peripheral collisions for p_T < 0.3 GeV/c

Phys.Rev.Lett. 116,222301 (2016)





arXiv:1506.08804

$$R_{AA} = \frac{N_{AA}^{J/\psi}}{\langle N_{coll} \rangle \, N_{pp}^{J/\psi}}$$

$= 1 \rightarrow$ No medium effect

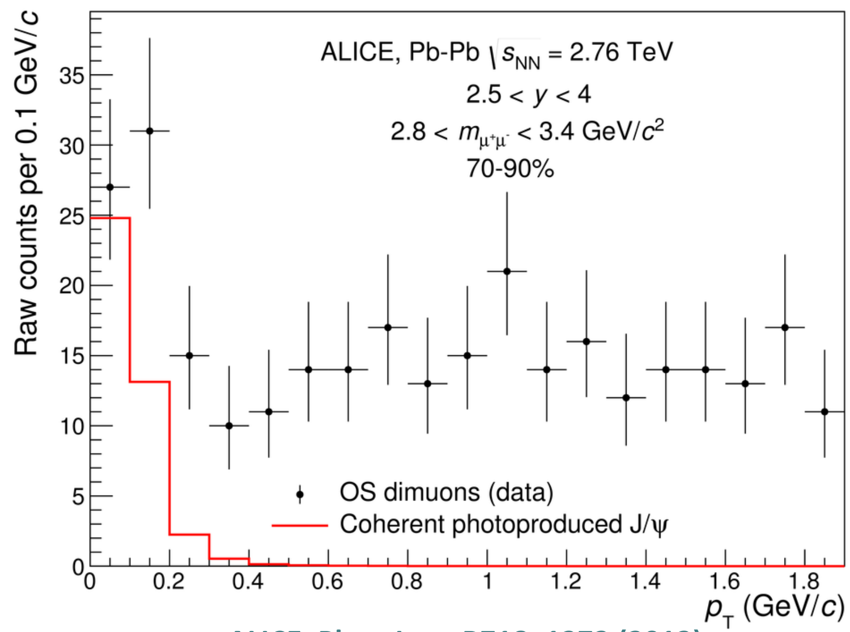
$< 1 \rightarrow$ Suppression

$> 1 \rightarrow$ Enhancement

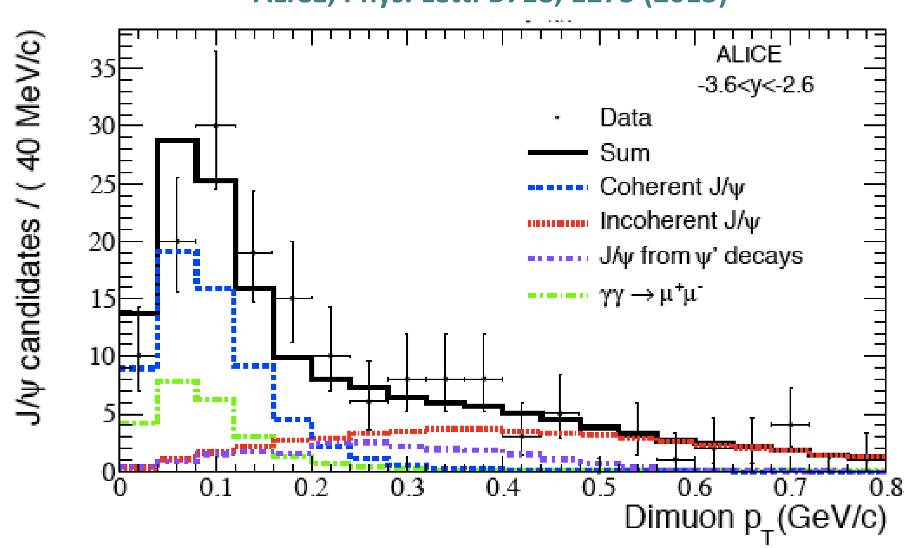
Excess of very low-p_T J/ψ in peripheral Pb-Pb

- Clear excess at very low p_T in peripheral Pb-Pb collisions with respect to expected hadronic production
- Enhancement of J/ψ R_{AA} in most peripheral collisions for $p_T < 0.3$ GeV/c
- Remarkably similar to J/ψ photo-production in ultra-peripheral collisions
- No theory prediction yet
- It is not clear how to include at the same time the coherence condition and the fact that there was a hadronic collision that broke the colliding particles

Phys.Rev.Lett. 116,222301 (2016)



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



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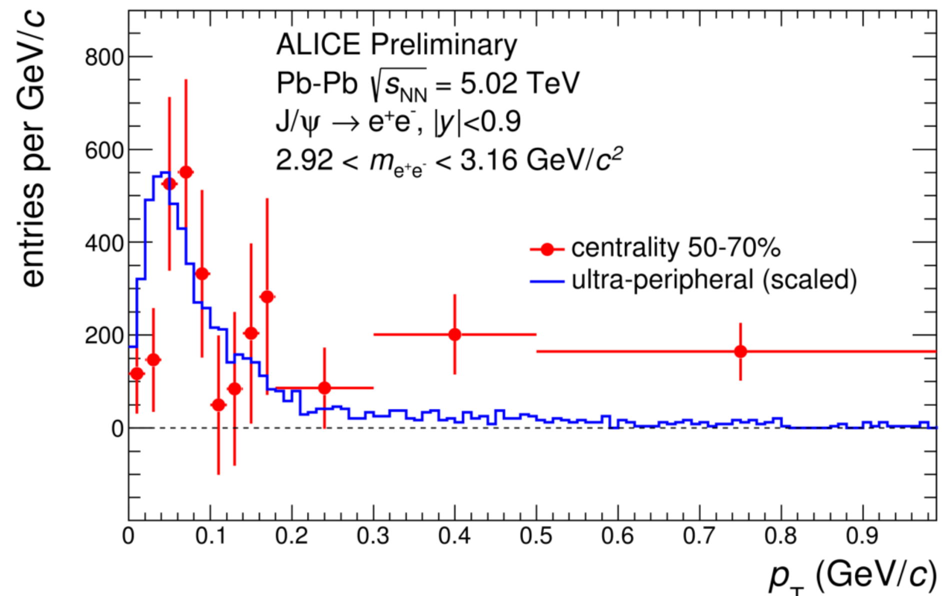
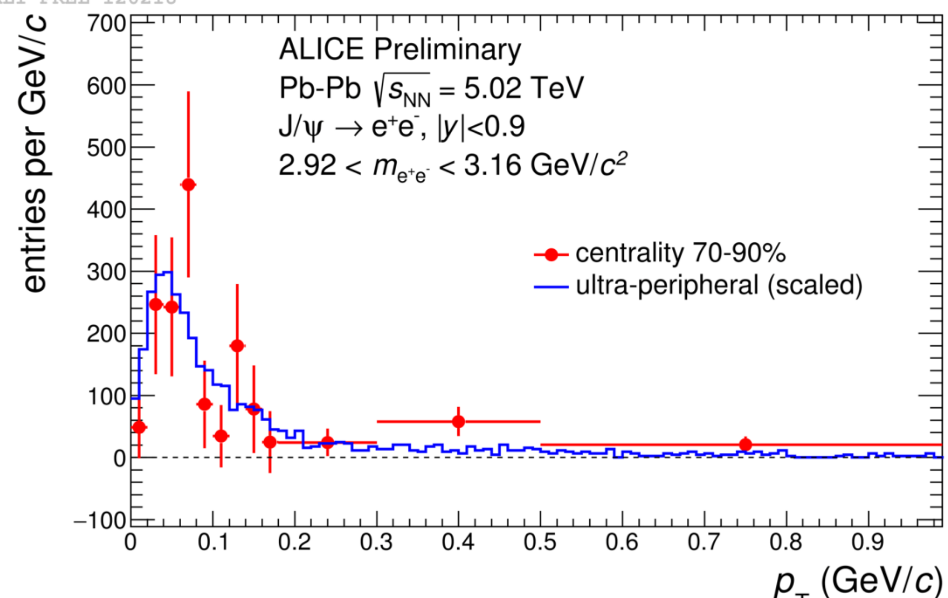


ALI-PREL-120218



ALI-PREL-120222

ALICE

Summary and outlook

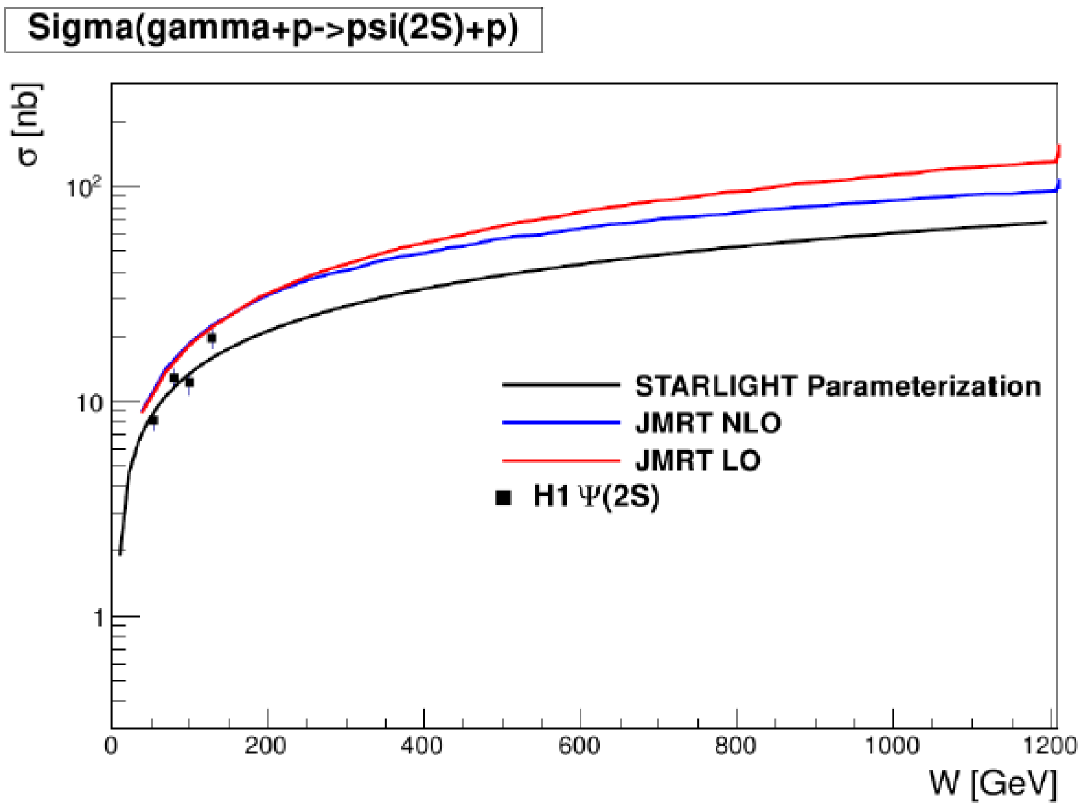
- ALICE has measured:
  - coherent and incoherent photo-production of J/ψ in Pb-Pb collisions
  - directly, exclusive J/ψ photo-production in γp collisions
  - the exclusive photo-nuclear production of ψ(2s)
- The cross section for the J/ψ found to be in agreement with models with moderate nuclear gluon 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
- An excess at very low p_T in peripheral Pb-Pb collisions was observed which may point to coherent-like production in peripheral Pb-Pb collisions
- ALICE is analyzing new data from 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 and to study dissociation – **Stay tuned!**

ALICE

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

ALICE, EPJ C73, 2617 (2013)

- 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