ALICE results on ultra-peripheral p-Pb and Pb-Pb collisions

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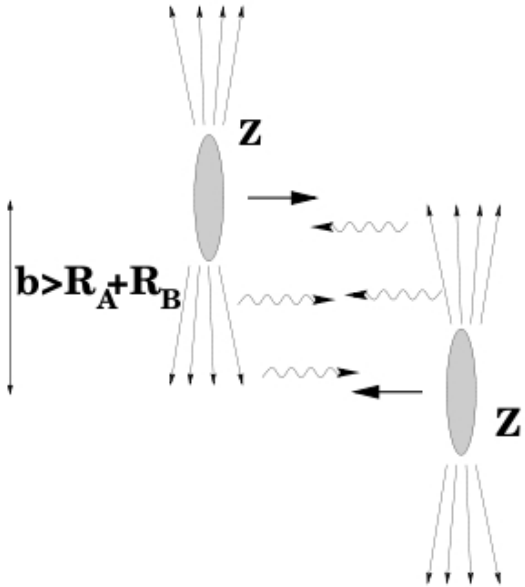
Ultra-peripheral collisions (UPC)

- Impact parameter b is larger than sum of nuclear radii
- Hadronic interactions are suppressed, only interactions mediated by the strong electromagnetic field behaving as a flux of virtual photons possible
- Field intensity is proportional to Z^2
- LHC is used as a photon collider
- Study of saturation phenomena and nuclear gluon shadowing in γp and γPb interactions



ALICE results on p-Pb J/ψ photoproduction

- PRL 113 (2014) 232504

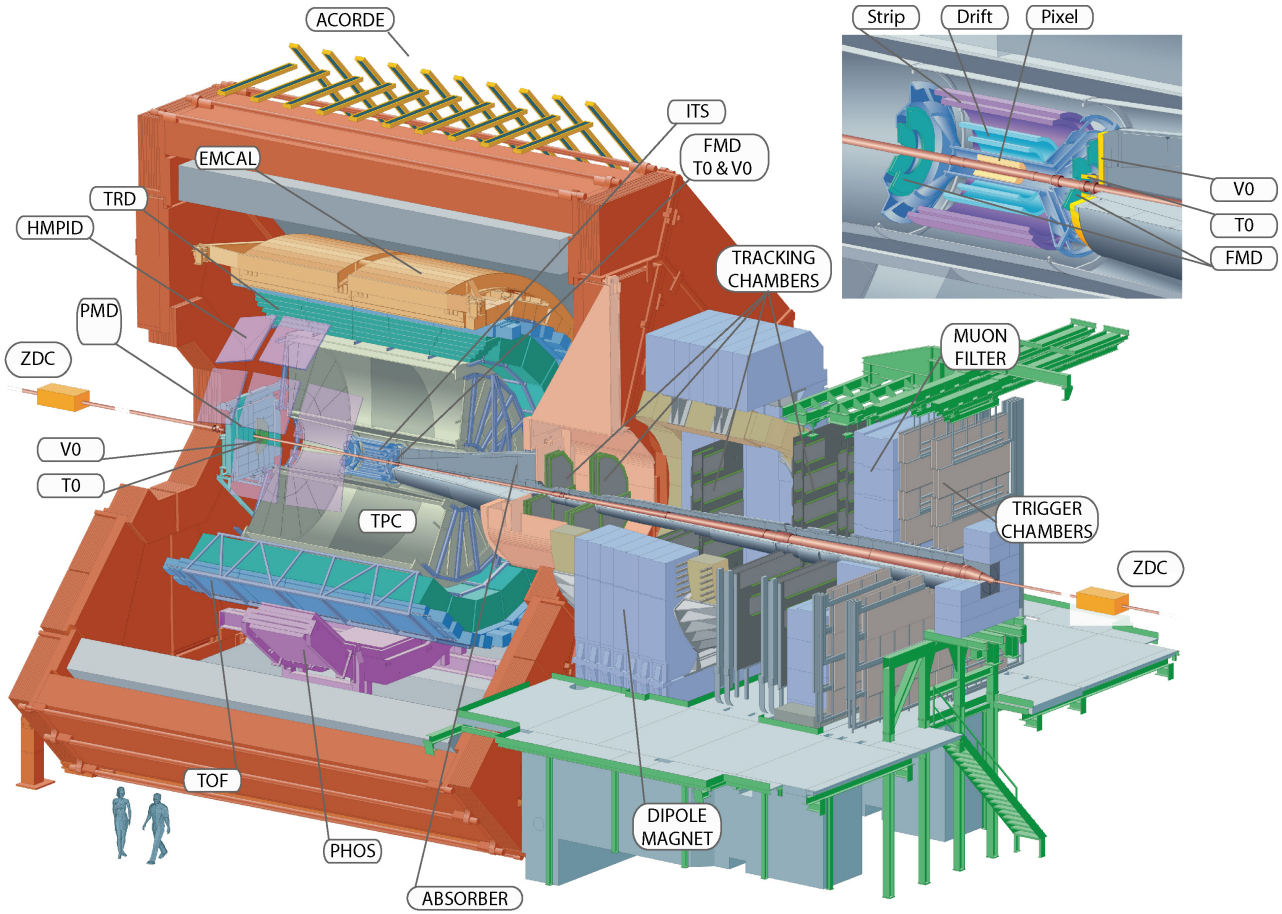
ALICE results on Pb-Pb J/ψ photoproduction

- Phys. Lett. B718, 1273 - 1283 (2013), forward rapidities
- Eur. Phys. J. C73, 2617 (2013) central rapidities, also $\gamma\gamma \to l^+l^-$ cross section

ALICE results on Pb-Pb ρ^0 photoproduction

- arXiv:1503.09177 [nucl-ex], submitted to JHEP

The ALICE experiment (A Large Ion Collider Experiment)



- Central detectors
  - Tracking in ITS+TPC
  - Acceptance $|\eta| < 0.9$
  - Trigger from SPD and TOF
- Muon spectrometer
  - $-4.0 < \eta < -2.5$
  - Tracking (MWPC), trigger (RPC)

- VZERO scintillator arrays: VZERO-C ($-3.7 < \eta < -1.7$) on the muon arm side and VZERO-A ($2.8 < \eta < 5.1$) opposite to the muon arm
- Zero Degree Calorimeters (ZDC): detection of very forward neutrons ($|\eta| > 8.8$) and protons ($6.5 < |\eta| < 7.5$ and $-9.7° < \phi < 9.7°$)

J/ψ in ultra-peripheral p-Pb collisions

J/ψ photoproduction on a proton target

- Photoproduction cross section is a probe to gluon distribution in the proton at low-x with scale q^2, allows to search for saturation effects

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p \to J/\psi p)|_{t=0} \propto [xg(x, q^2)]^2$$

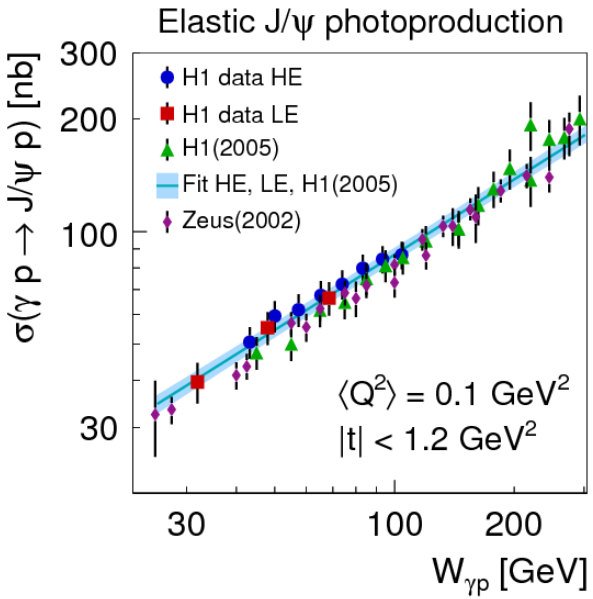
- Smaller x probed by higher photon-proton energy $W_{\gamma p}$

$$x = (M_{J/\psi}/W_{\gamma p})^2$$

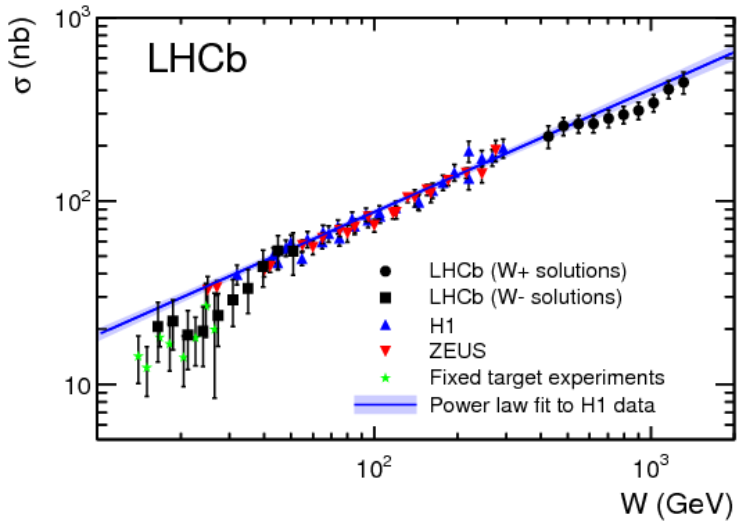
- Cross section of $\gamma p \to J/\psi p$ parametrized as power law of energy

$$\sigma \propto W_{\gamma p}^{\delta}$$

- Empirical parametrization found at HERA (ep)
- Solutions of photon-proton cross section by LHCb (pp), power law had to be assumed due to ambiguity on photon source



Eur.Phys.J. C73, 2466 (2013)



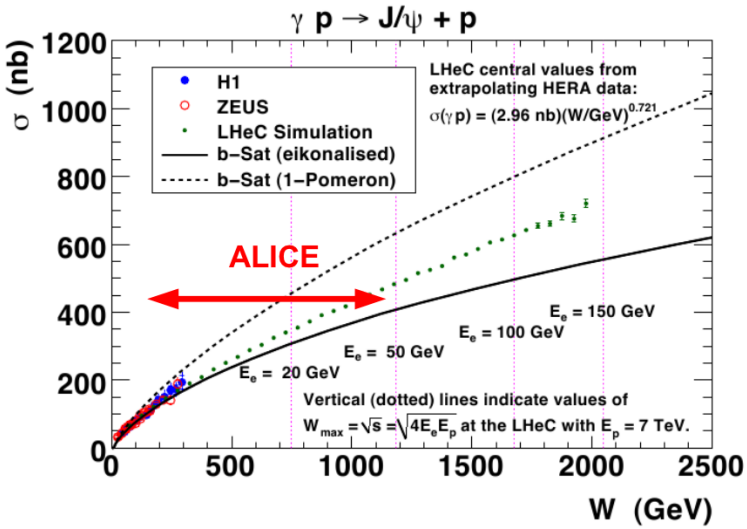
J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

ALICE measurement of J/ψ photoproduction on a proton target

- In p-Pb collisions the lead-ion is most likely ($\sim$95%) the photon source
- Power law proportionality, $\sigma \propto W_{\gamma p}^{\delta}$, implies more gluons at lower x
- Any change in gluon behavior starting at some $W_{\gamma p}$ may affect the proportionality law
- Energy $W_{\gamma p}$ is given by J/ψ rapidity y measured vs. direction of proton beam of energy E_p

$$W_{\gamma p}^2 = 2E_p M_{J/\psi} e^{-y}$$

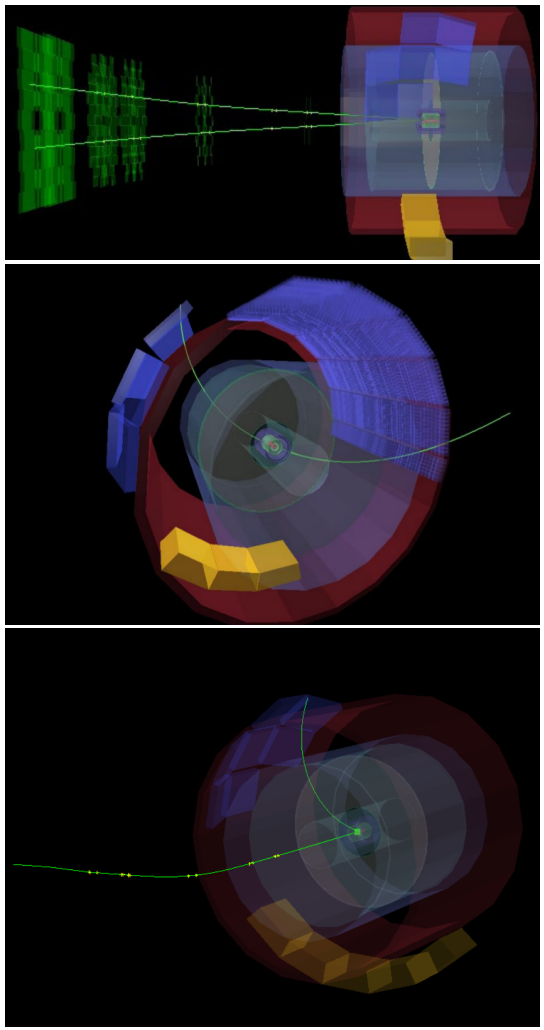
- LHC switched the direction of the beams: for the MUON spectrometer $y > 0$ ($y < 0$) in p-Pb (Pb-p), yielding lower (higher) $W_{\gamma \mathrm{p}}$
- Energy range of HERA extended by factor of $\sim$2, important connection between HERA and future facilities like LHeC



arXiv:1211.4831 (LHeC Study Group)

Possible ALICE configurations for $J/\psi \to l^+l^-$ in UPC

- Analysis criteria: *just two tracks in an otherwise empty detector*
- J/ψ at low-p_T; different laboratory rapidity intervals



Forward

- Both tracks in muon arm
- J/ψ rapidity $2.5 < |y| < 4.0$ GeV
- $W_{\gamma p} \in [21, 45]$ GeV (p-Pb) and [577, 952] (Pb-p)

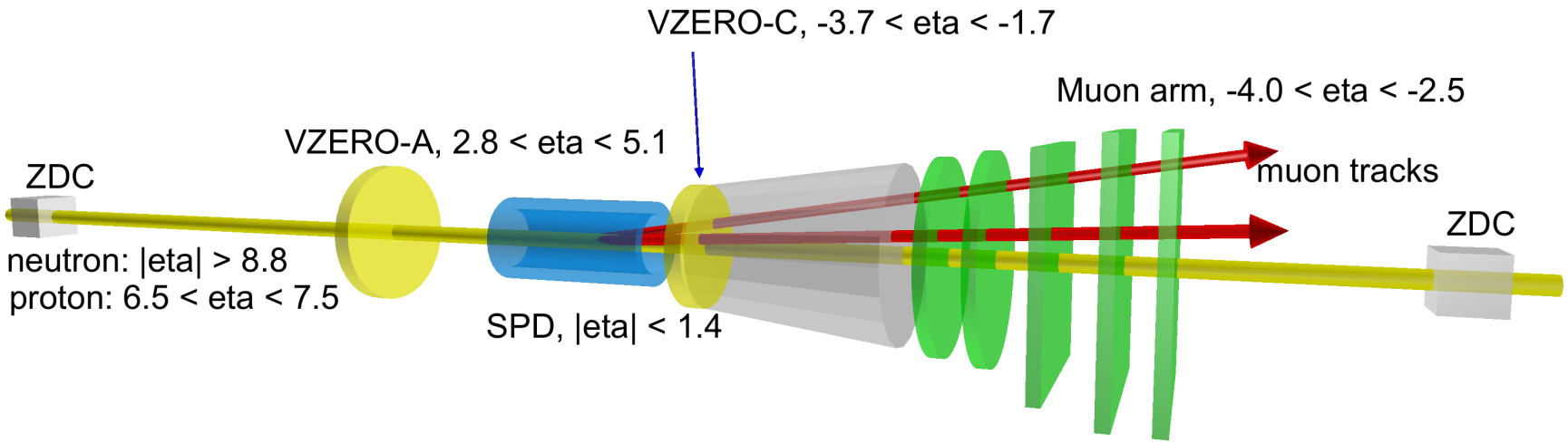
Mid-rapidity

- Both muons or electrons in central barrel
- J/ψ rapidity $|y| < 0.9$
- $W_{\gamma p} \in [100, 246]$ GeV (p-Pb and Pb-p)

Semi-forward

- One muon in muon arm, one in central barrel
- J/ψ rapidity $1.2 < |y| < 2.7$
- $W_{\gamma p} \in [41, 86]$ GeV (p-Pb) and [287, 549] (Pb-p)

Trigger and event selection for the forward p-Pb UPC

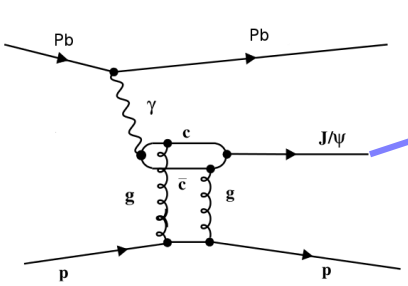


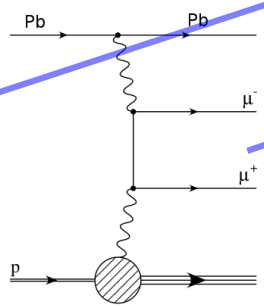
- Two unlike-sign tracks in the muon spectrometer, tracks quality selection
- Activity in VZERO-C compatible with expected muons from beam-beam interaction
- No activity in SPD, VZERO-A and ZDCs
- Trigger inputs from VZEROs and muon trigger
- Selection on dimuon rapidity for a specific $\langle W_{\gamma \mathrm{p}} \rangle$

Detectors not in scale in the illustration

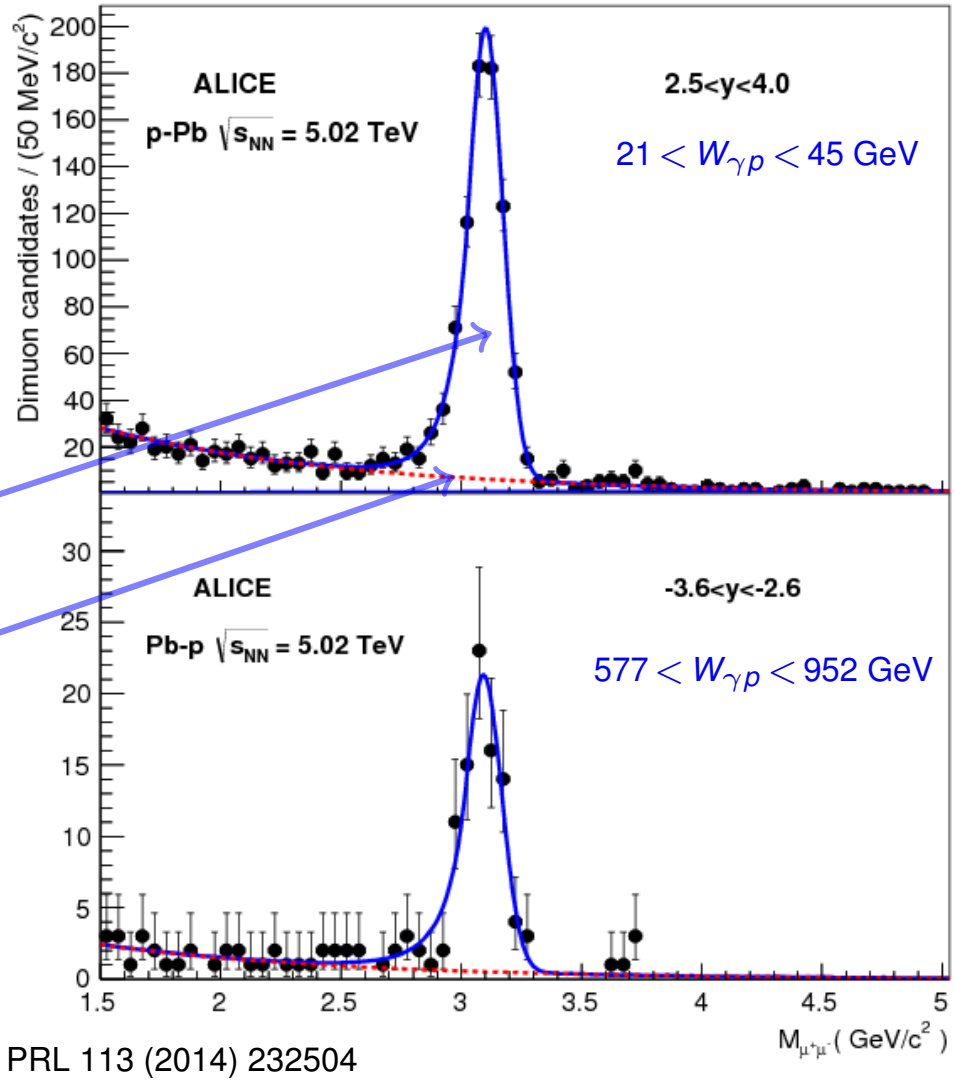
Invariant mass distribution of the forward dimuons

- Dimuons passing the selection criteria
- Fit by Crystal-Ball (J/ψ) and exponential function (dimuon continuum)
- Parameters of the fit compatible with MC simulations
- Events within the J/ψ mass peak are still a mixture of elastic or dissociative production of J/ψ or $\gamma\gamma \to \mu^+\mu^-$:





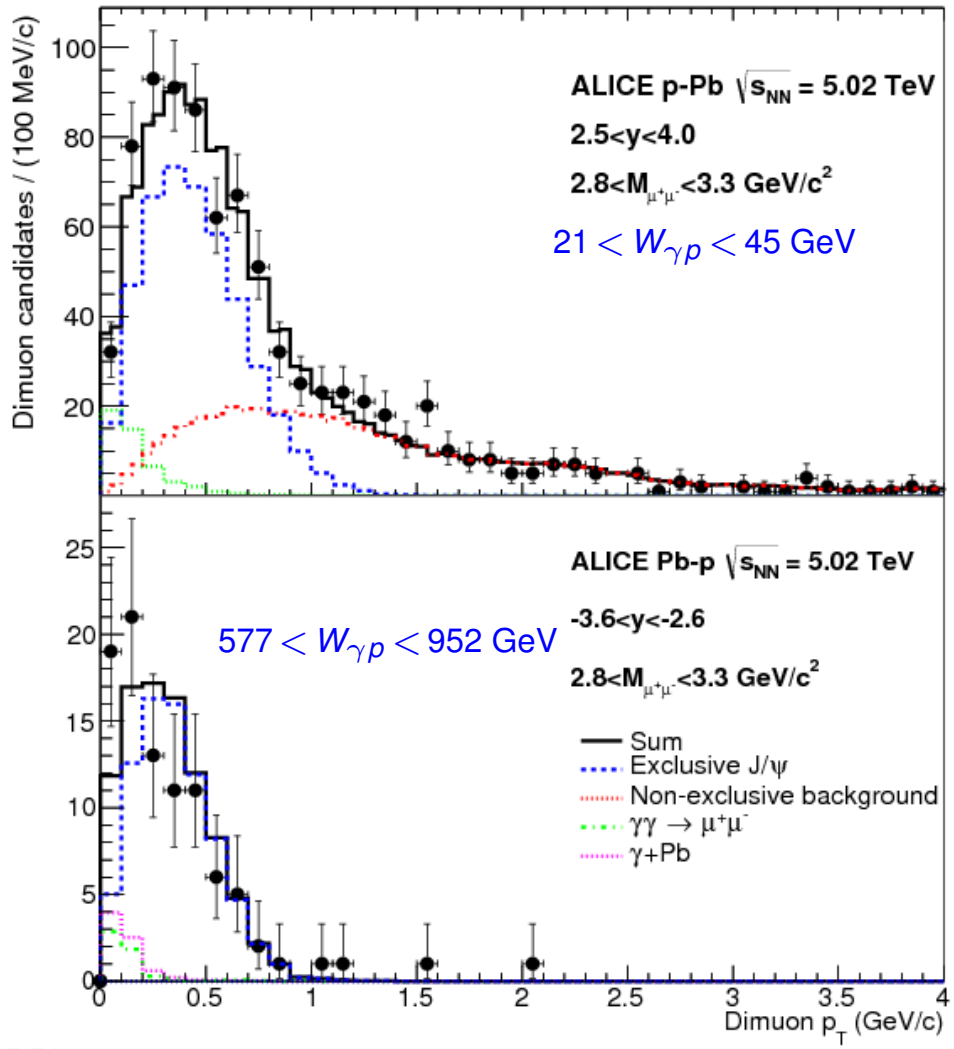
- The processes have different shapes of p_T, allowing one to separate the number of exclusive events from all J/ψ candidates



PRL 113 (2014) 232504

Fit to the p_T distribution

- Extraction of signal of exclusive J/ψ in p-Pb
- p_T of selected dimuons with inv. mass around the mass of J/ψ
- Spectrum of p_T described by templates of the processes
  - Exclusive J/ψ in γp
  - Elastic $\gamma\gamma \to \mu^+\mu^-$
  - Non-exclusive J/ψ and $\gamma\gamma \to \mu^+\mu^-$
- The shapes for exclusive J/ψ and $\gamma\gamma \to \mu^+\mu^-$ were generated using STARLIGHT* and folded by detector simulation
- Non-exclusive J/ψ and $\gamma\gamma \to \mu^+\mu^-$ contribution estimated from data, special sample of events with increased energy deposition in VZERO or in ZDC in the direction of proton beam



PRL 113 (2014) 232504

* Phys.Rev. C60, 014903 (1999), hep-ph/9902259

Cross section of exclusive J/ψ photoproduction in the forward p-Pb

- Differential cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}y}(\mathrm{p}+\mathrm{Pb})$ is measured to get the cross section of $\gamma\mathrm{p} \to \mathrm{J}/\psi\,\mathrm{p}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{N^{exc}_{J/\psi}}{(A\times\varepsilon)*BR*\mathcal{L}*\Delta y}$$

- $N^{exc}_{J/\psi}$ = yield of exclusive J/ψ
  - p-Pb: $N^{exc}_{J/\psi} = N_{J/\psi}/(1+f_D)$, where $N_{J/\psi}$ was obtained using the p_T fit and f_D is feed-down from ψ'
  - Pb-p: $N^{exc}_{J/\psi}$ taken by event counting followed by subtraction of the $\gamma\gamma$, γPb and f_D components
  - f_D: feed-down from ψ', estimated using STARLIGHT, based on ratio of efficiency of J/ψ from ψ' and efficiency of prompt J/ψ and corresponding cross sections and branching ratios. Numerical values are $f_D = 7.9^{+2.4}_{-1.9}$ % (p-Pb) and $11^{+3.6}_{-2.8}$ % (Pb-p)
- $A \times \varepsilon$ = detector acceptance and efficiency, calculated using MC
- BR = branching ratio of $J/\psi \to \mu^+\mu^-$
- $\mathcal{L}$ = luminosity for a given UPC trigger
- Δy = width of the rapidity bin

Relation of measured $\frac{\mathrm{d}\sigma}{\mathrm{d}y}(\mathrm{p}+\mathrm{Pb})$ and photon-proton cross section

- To get the cross section of $\gamma\mathrm{p} \to \mathrm{J}/\psi\,\mathrm{p}$, we need to extract the photon-proton cross section $\sigma(\gamma{+}\mathrm{p})$ from the measured differential cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}y}(\mathrm{p}+\mathrm{Pb})$
- The cross sections are related via the photon spectrum $\frac{dN_\gamma}{dk}$ (distribution of photons carrying a momentum k)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(\mathrm{p{+}Pb} \to \mathrm{p{+}Pb} + J/\psi) = k\frac{dN_\gamma}{dk}\sigma(\gamma{+}\mathrm{p} \to J/\psi{+}\mathrm{p})$$

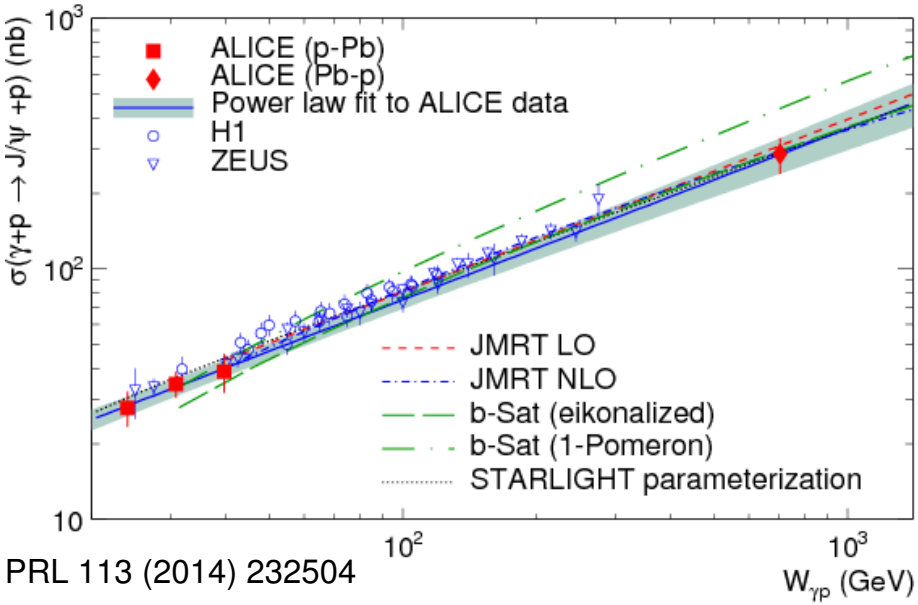
- The average photon flux has been calculated from STARLIGHT
- Procedure is based on Weizsäcker-Williams method and integration over impact parameter
- Corresponding energy $W_{\gamma p}$ given by rapidity of the J/ψ, the mean $\langle W_{\gamma p}\rangle$ for a given rapidity interval computed by weighting with photon flux and STARLIGHT cross section of $\gamma\mathrm{p} \to \mathrm{J}/\psi\,\mathrm{p}$

ALICE cross section of exclusive J/ψ photoproduction off protons

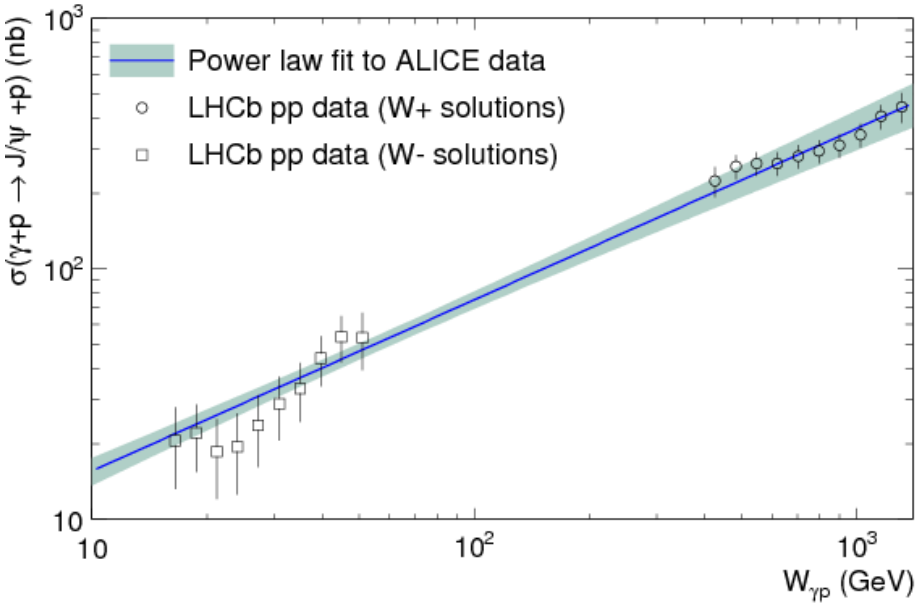
- A fit by power law $\sigma \propto W_{\gamma p}^{\delta}$ to the cross section as a function of energy $W_{\gamma p}$

	ZEUS	H1	ALICE
δ	0.69 ± 0.04	0.67 ± 0.03	0.68 ± 0.06

- Parameter of ALICE fit in agreement with HERA, errors are (stat + syst)
- Models based on VDM, standard pQCD (LO and NLO like) and including saturation describe ALICE data
- LHCb solutions consistent with the power-law fit obtained from ALICE results



PRL 113 (2014) 232504



b-Sat: arxiv:1206.2913, 1211.4831

JMRT: JHEP 1311, 085 (2013)

J/ψ and $\psi(2S)$ in ultra-peripheral Pb-Pb collisions

J/ψ photoproduction in Pb-Pb UPC

- Exclusive photoproduction of J/ψ on heavy-ion target probes the nuclear gluon distribution
- Momentum fraction carried by probed gluons varies with y the rapidity of J/ψ

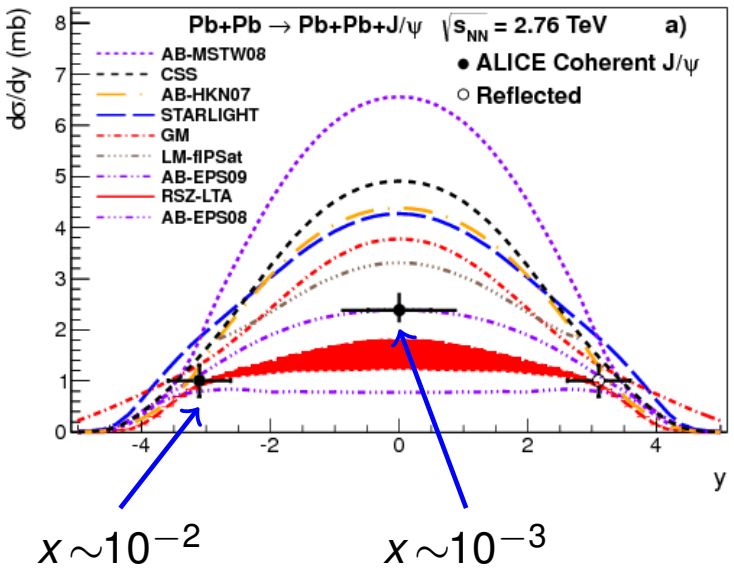
$$x = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} \exp(\pm y)$$

- Ambiguity in x by $\pm y$: each nucleus can act as photon source or target
- At first approximation the nuclear density would scale with number of nucleons

$$G^A(x, q^2) = A \cdot g(x, q^2)$$

- Coherent photon coupling to the nucleus leads to coherent photoproduction, coupling to a single nucleon described as incoherent photoproduction
- Coherently produced J/ψ mesons characterized by very low p_T
- Nuclear gluon shadowing: observed partial depletion of nuclear (w.r.t. nucleon) gluon density. Coherent production is sensitive to it

Coherent J/ψ results in Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV



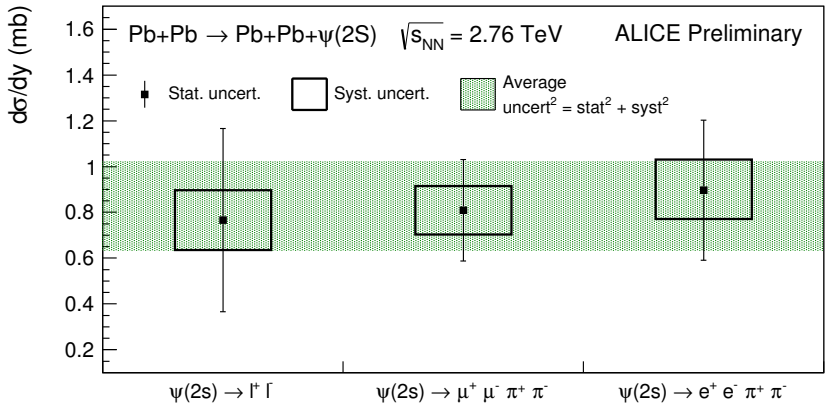
- Nuclear suppression in Pb at small x
- Best agreement with the model which incorporates nuclear gluon shadowing according to the EPS09 parameterization (AB-EPS09)

- **AB:** Adeluyi, Bertulani, PRC85 (2012) 044904
  LO pQCD scaled by an effective constant to correct for missing contributions. MSTW assumes no nuclear effects, the other incorporate nuclear effects according different nuclear PDFs
- **CSS:** Cisek, Szczurek, Schäfer, PRC86 (2012) 014905
  Color dipole model based on unintegrated gluon distribution of the proton
- **STARLIGHT:** Klein, Nystrand, PRC60 (1999) 014903
  VDM coupled to a Glauber approach and using Hera data to fix the γp cross section
- **GM:** Gonçalves, 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
  Based on LO pQCD amplitude for two gluon exchange where the gluon density incorporates shadowing computed in leading twist approximation
- **LM:** Lappi, Mäntysaari, PRC87 (2013) 032201
  color dipole model + saturation

Phys. Lett. B 718 (2013) 1273 - 1283, Eur. Phys. J. C73, 2617 (2013)

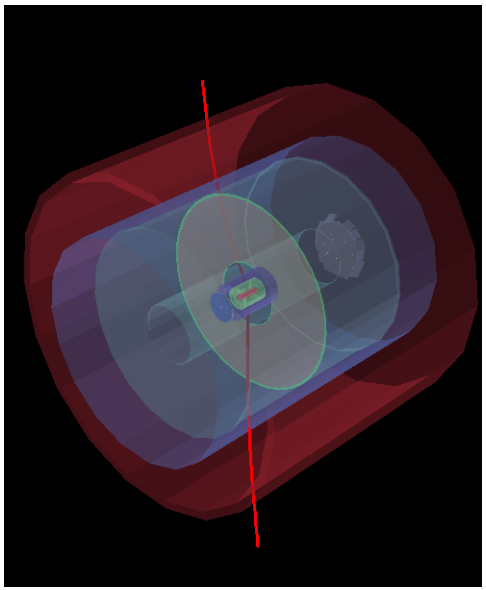
Coherent $\psi(2S)$ photoproduction in Pb-Pb

- First measurement of $\psi(2S)$ coherent photoproduction
- Tagging via decays (mid-rapidity)
  - $\psi(2S) \to l^+l^-$
  - $\psi(2S) \to J/\psi\pi^+\pi^-$ and $J/\psi \to l^+l^-$
- Clean signal despite moderate statistics

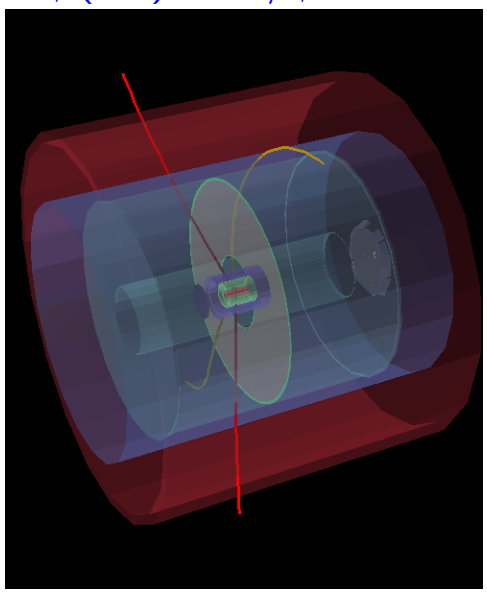


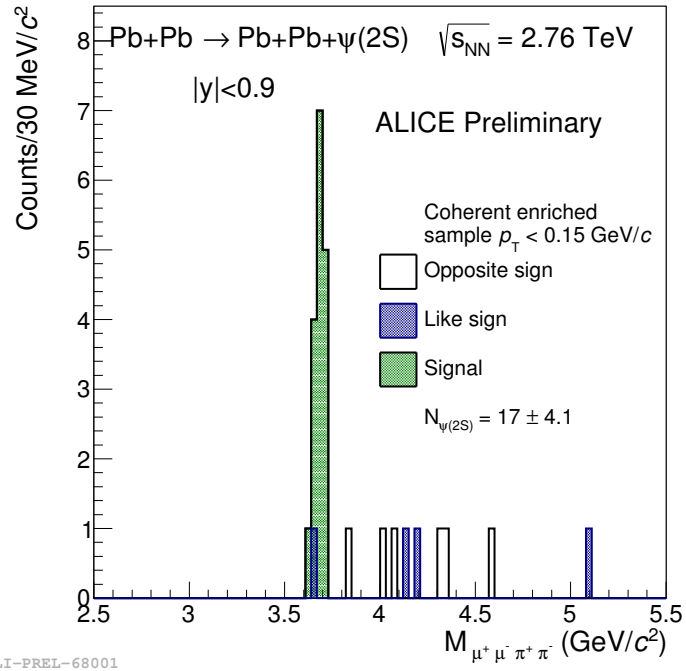
ALI-PREL-68033

$\psi(2S) \to l^+l^-$



$\psi(2S) \to J/\psi\pi^+\pi^-$





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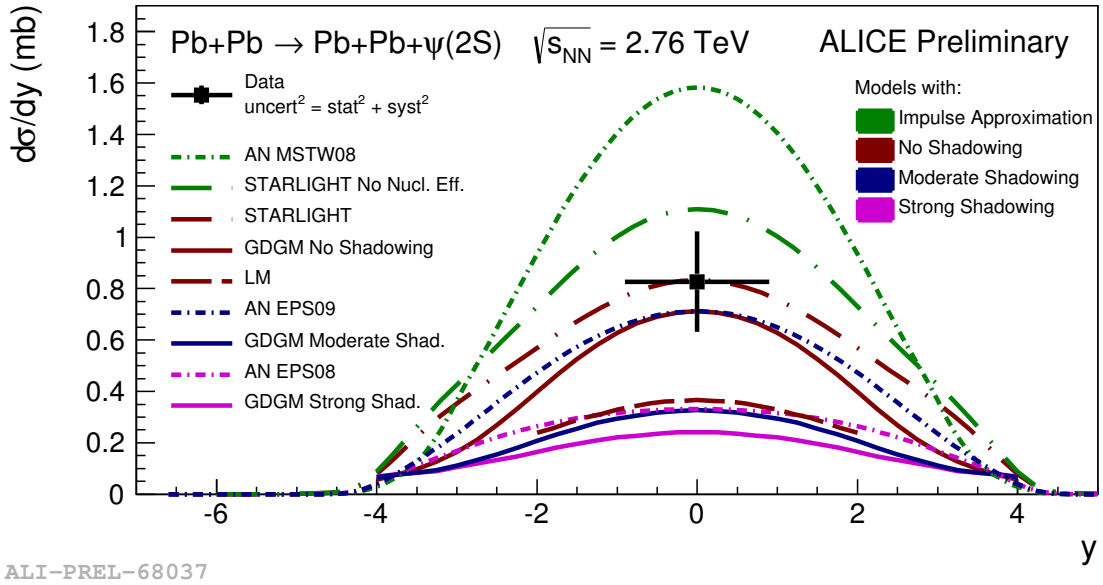
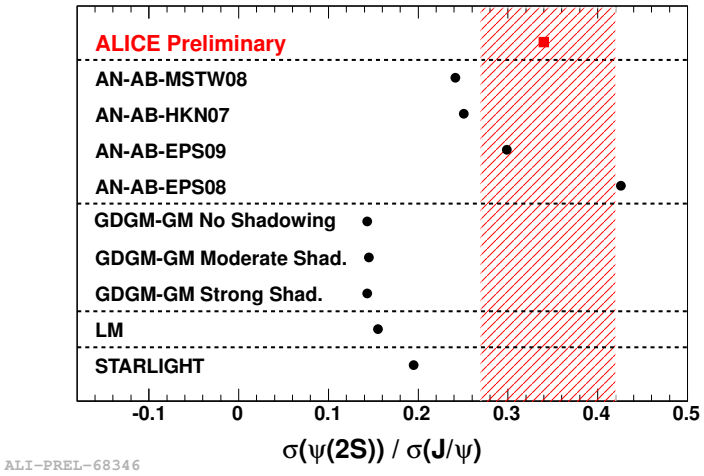
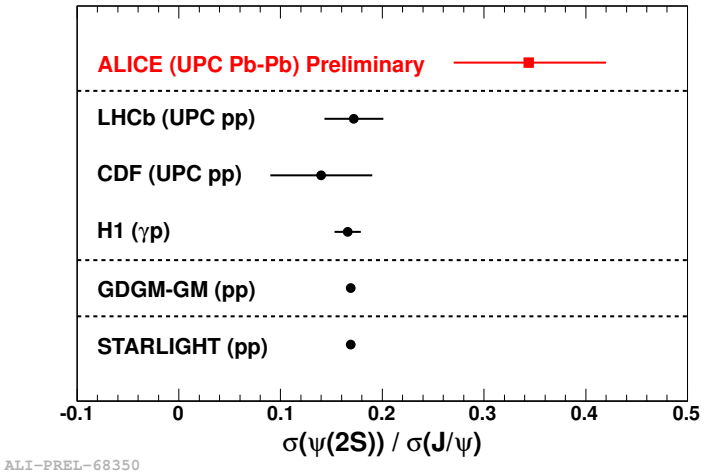
Cross section of coherent $\psi(2S)$ photoproduction in Pb-Pb





- Agreement with models that include nuclear gluon shadowing consistent with the EPS09 parameterization
- Ratio $\sigma(\psi(2S))/\sigma(J/\psi)$ convenient because many experimental systematic uncertainties cancel
- Possibility of different nuclear effects to the 1S and 2S charmonia states

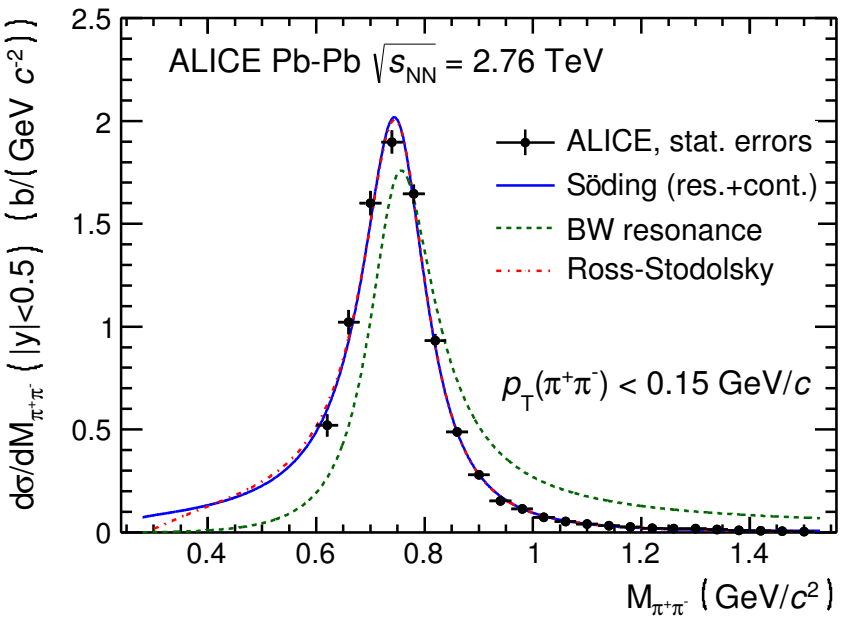


ρ^0 photoproduction in ultra-peripheral Pb-Pb collisions

ρ^0 photoproduction in ultra-peripheral Pb-Pb collisions

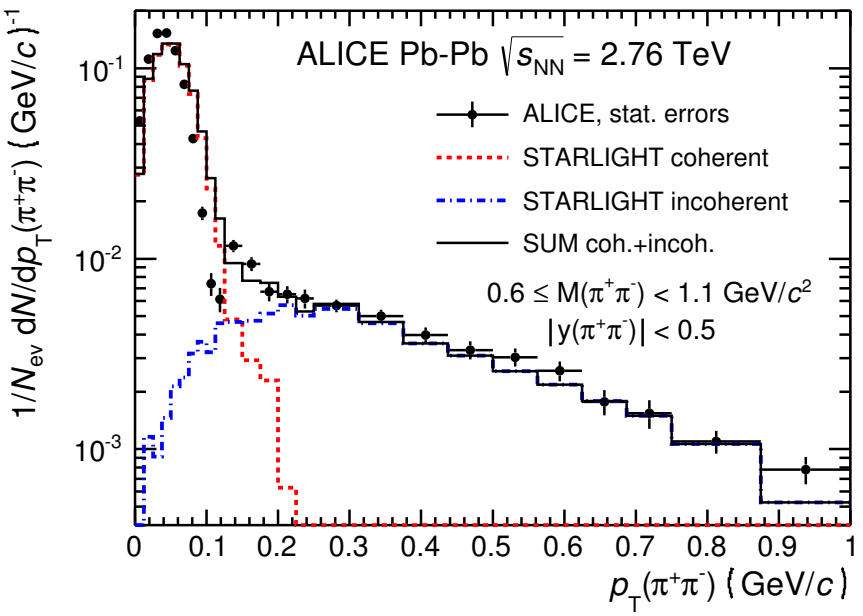
- Light vector meson photoproduction provides a probe to soft interactions at high energies
- ALICE measurement of mid-rapidity decays $\rho^0 \to \pi^+\pi^-$
- Pions and electrons separation by dE/dx in TPC
- Fit to the p_T distribution using coherent and incoherent templates, data narrower than MC (same observation by STAR at RHIC)

Invariant mass of $\pi^+\pi^-$ pairs

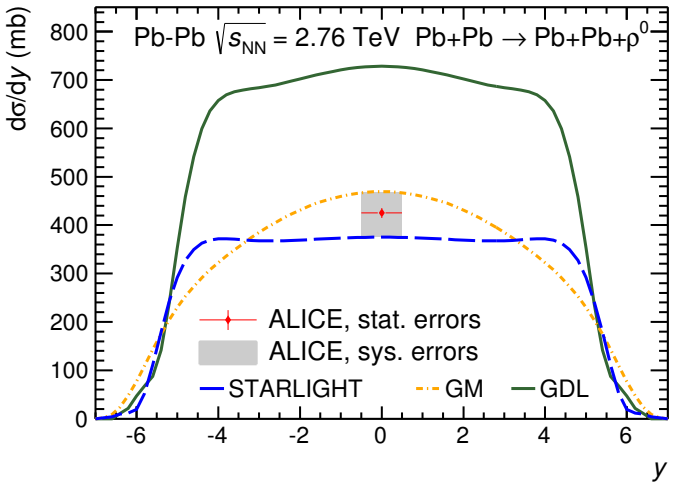


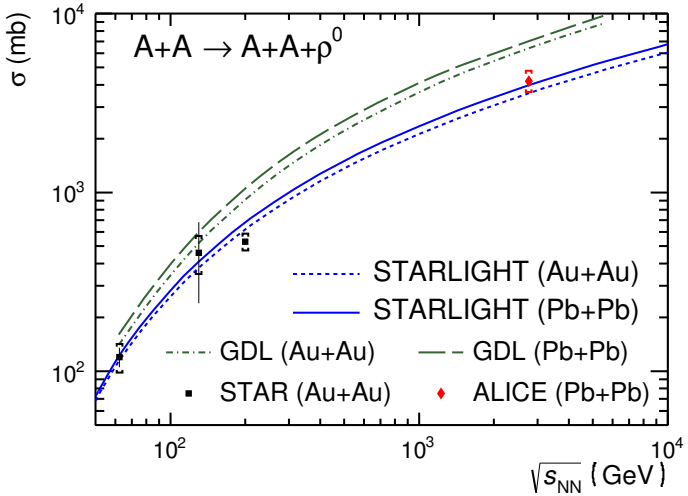
arXiv:1503.09177v1 [nucl-ex]

Fit to the p_T distribution of ρ_0 candidates



Cross section of ρ^0 photoproduction in ultra-peripheral Pb-Pb collisions





arXiv:1503.09177v1 [nucl-ex]

- **GDL:** Glauber-Donnachie-Landshoff
  - Vector Meson Dominance Model in the Gribov-Glauber approach
  - $\sigma_{\rho N}$ using Donnachie-Landshoff model
  - [Phys. Lett. B 537 (2002) 51 and Phys. Lett. B 710 (2012) 647]
- **GM:** Gonçalves, Machado
  - Based on the color dipole model in combination with saturation from a CGC-IIM model
  - [Phys. Rev. C 84 (2011) 011902]
- **STARLIGHT:** Klein, Nystrand
  - VDM coupled to a Glauber approach
  - HERA and fixed target data to fix the γp cross section
  - [PRC60 (1999) 014903, http://starlight.hepforge.org]

Prospects for Run 2

- Vector mesons in Run 1 Pb-Pb@2.76 TeV:

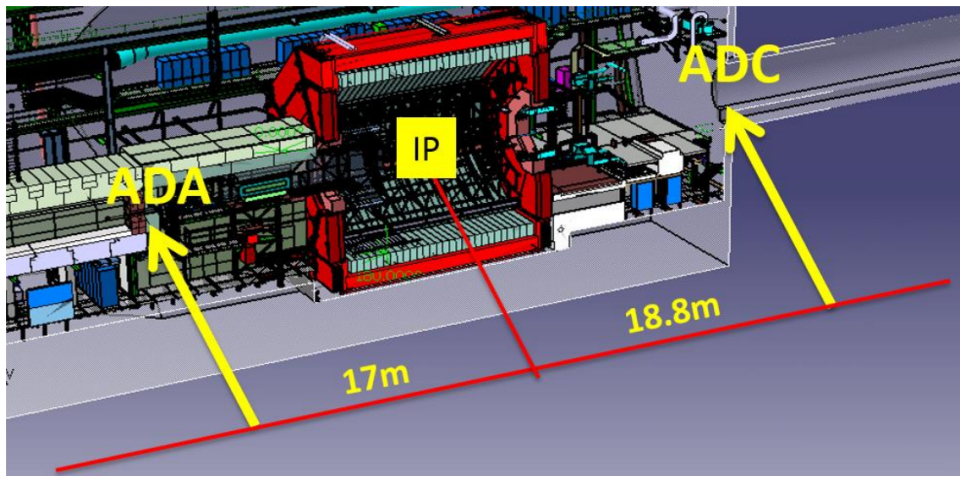
Meson	Yield	$\mathcal{L}_{int}$	Error sources
ρ_0	$\sim 10^4$	0.26 μb^{-1}	stat error $\ll$ sys err
J/ψ (mid-rapidity)	~ 500	23 μb^{-1}	stat error $<$ sys err
J/ψ (forward)	~ 100	55 μb^{-1}	
$\psi(2S)$	~ 50	23 μb^{-1}	stat error $\gg$ sys err

- Run 2 assumptions:

System	$\sqrt{s}$	$\mathcal{L}_{int}$	Increase factor in $\mathcal{L}_{int}$
Pb-Pb	5.1 TeV	1 nb^{-1}	$\sim$7
p-Pb	5.1 or 8 TeV	50 nb^{-1}	$\sim$2

- Precision measurements of J/ψ, study of Υ

- New forward scintillators
  - Two layers each, in coincidence
  - ADA: $5.5 < \eta < 7.5$
  - ADC: $-7.5 < \eta < -5.5$
  - Stronger veto to non-UPC events thanks to better coverage extending the range of existing VZEROs



Conclusions

- J/ψ photoproduction in p-Pb
  - No significant change in gluon density behavior going from HERA to LHC energy
- Coherent J/ψ in Pb-Pb
  - Models including nuclear gluon shadowing consistent with the EPS09 parametrization are favored
- Coherent $\psi(2S)$ in Pb-Pb
  - Models with no nuclear effects or with strong gluon shadowing disfavored
- ρ^0 photoproduction in Pb-Pb
  - Consistent with STARLIGHT and about a factor of 2 below the GDL Glauber calculation, similar to what was observed at lower energies by STAR
- Next LHC run
  - More luminosity
  - Higher CM energy of photon-target system
  - New forward detector for cleaner exclusive / coherent samples
  - Stay tuned!