ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Recent ALICE results on photon-lead interactions

Hard Probes 2023

Roman Lavička on behalf of the ALICE Collaboration

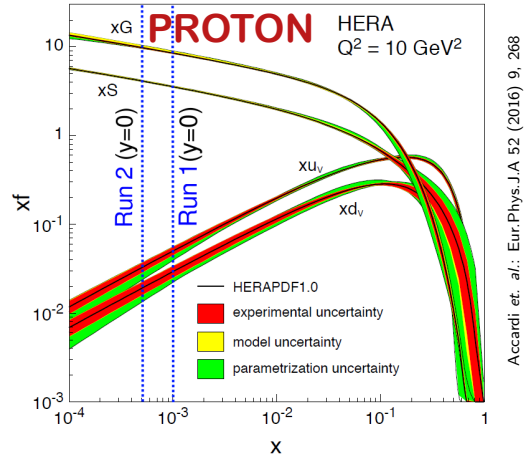
March 28, 2023, Aschaffenburg, Germany

ALICE

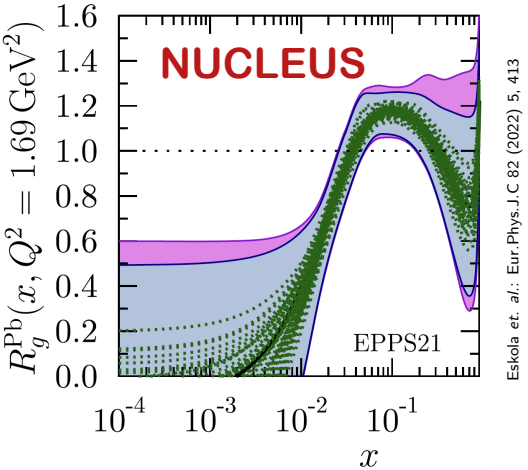
CERN

Where QCD is now

- The proton is dominated by gluons for Bjorken $x < 10^{-2}$ (HERA).
- The LHC gives the possibility to measure the gluonic structure of the nuclei to study saturation and shadowing at small Bjorken x.



Accardi *et. al.*: Eur.Phys.J.A 52 (2016) 9, 268



Eskola *et. al.*: Eur.Phys.J.C 82 (2022) 5, 413

Some important QCD questions

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What is the Bjorken-x evolution of the gluon structure?

Measure the dependence on the transferred energy.

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Measure the dependence on the transferred energy.

Can we learn more about structures inside nucleus?

Measure the dependence on the momentum transfer $|t|$.

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What is the Bjorken-x evolution of the gluon structure?
Measure the dependence on the transferred energy.

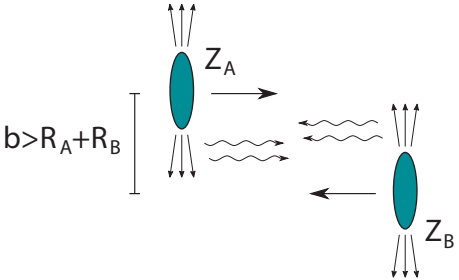
Can we learn more about structures inside nucleus?
Measure the dependence on the momentum transfer $|t|$.

ALICE has systematically studied this for years. New results at HP 2023!

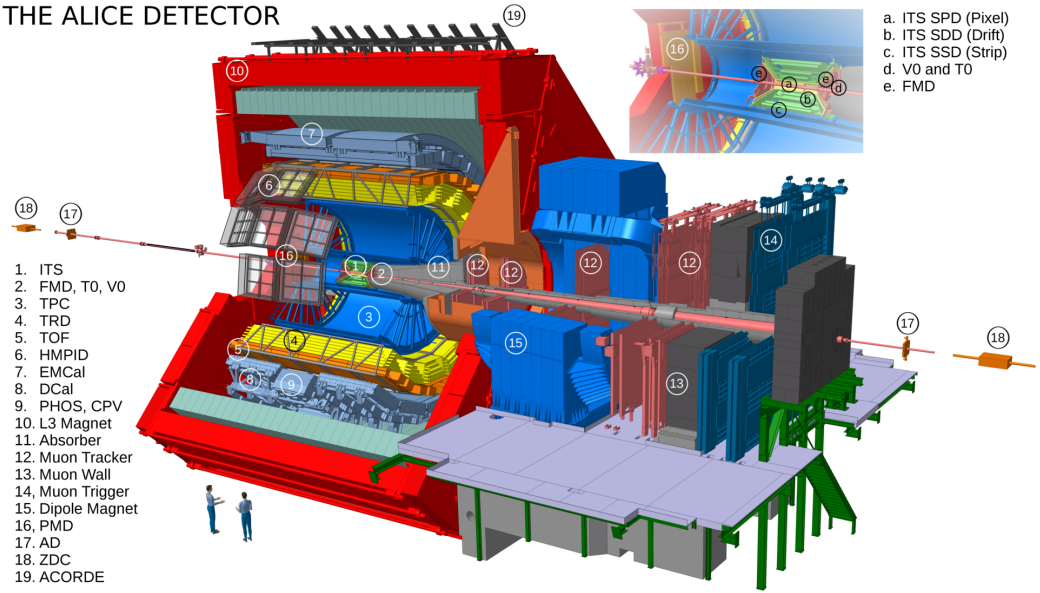
Ultra-peripheral collisions (UPCs)

- Collisions with impact parameter $b > R_A + R_B$.
  - Hadronic interactions suppressed.
  - EM induced interactions remain.

- EM field of ultrarelativistic electrically charged particle $\sim$ flux of photons.
  - Flux intensity increasing with Z^2.

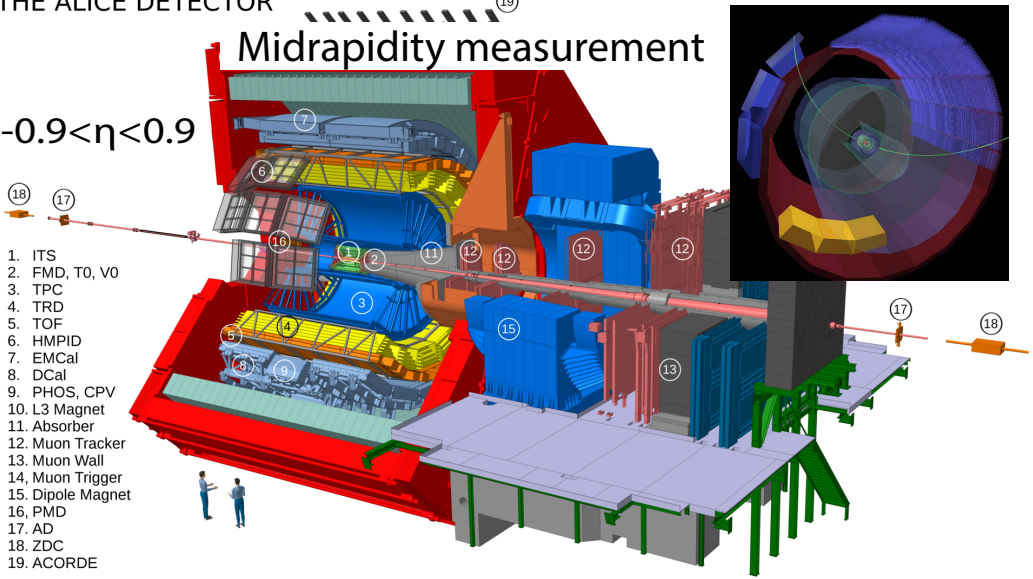


THE ALICE DETECTOR



Midrapidity measurement

$-0.9<\eta<0.9$



1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
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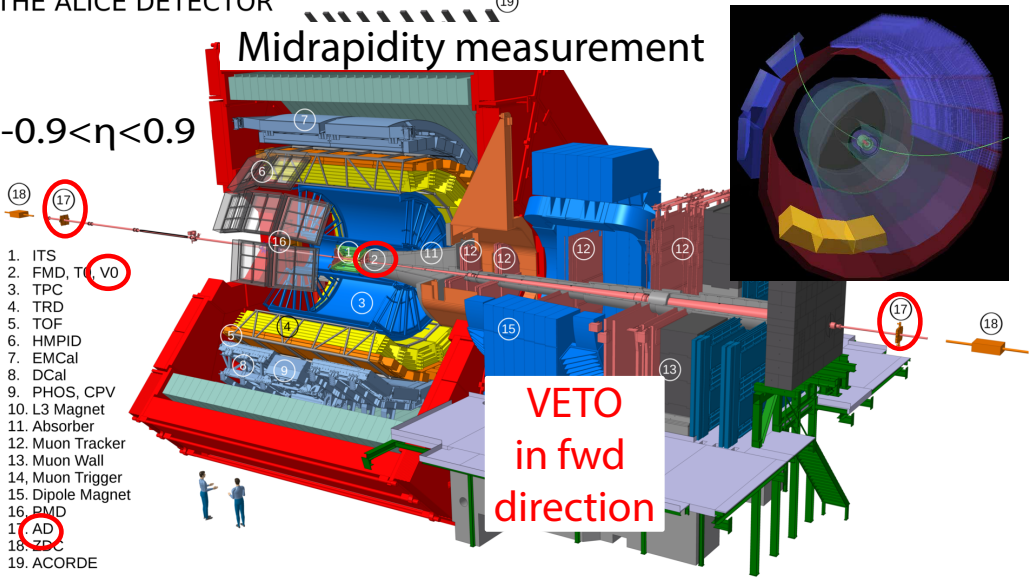

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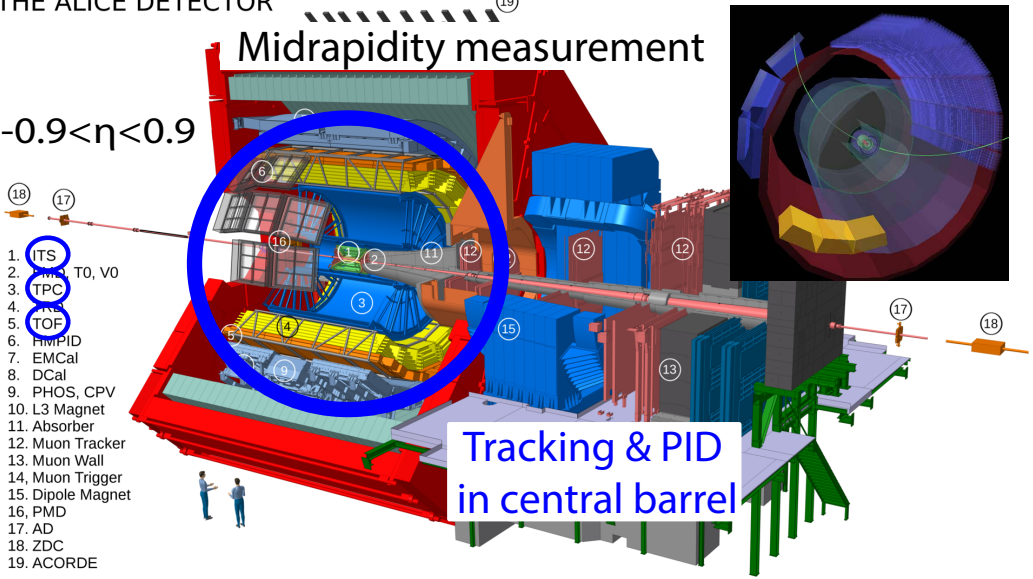

Forward rapidity measurement

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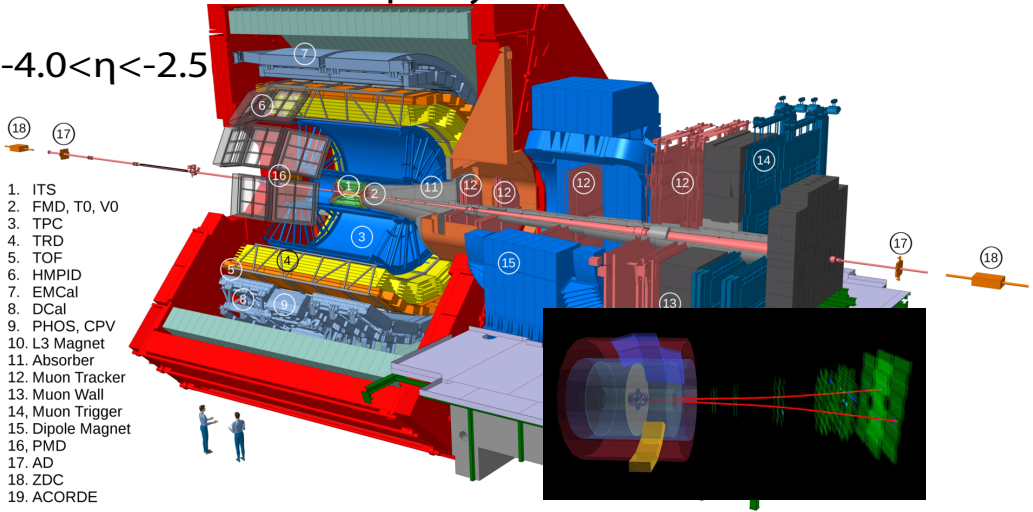

Forward rapidity measurement

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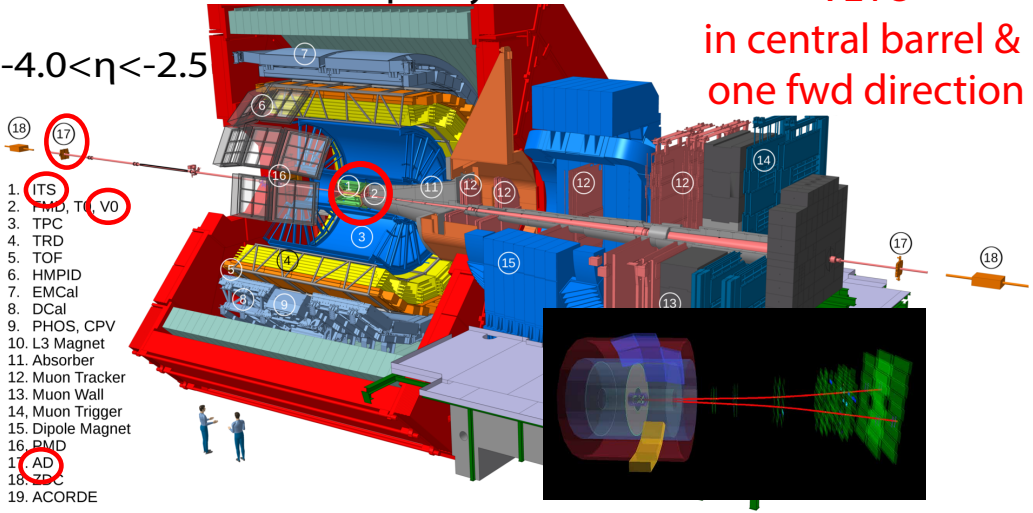
VETO
in central barrel &
one fwd direction



Forward rapidity measurement

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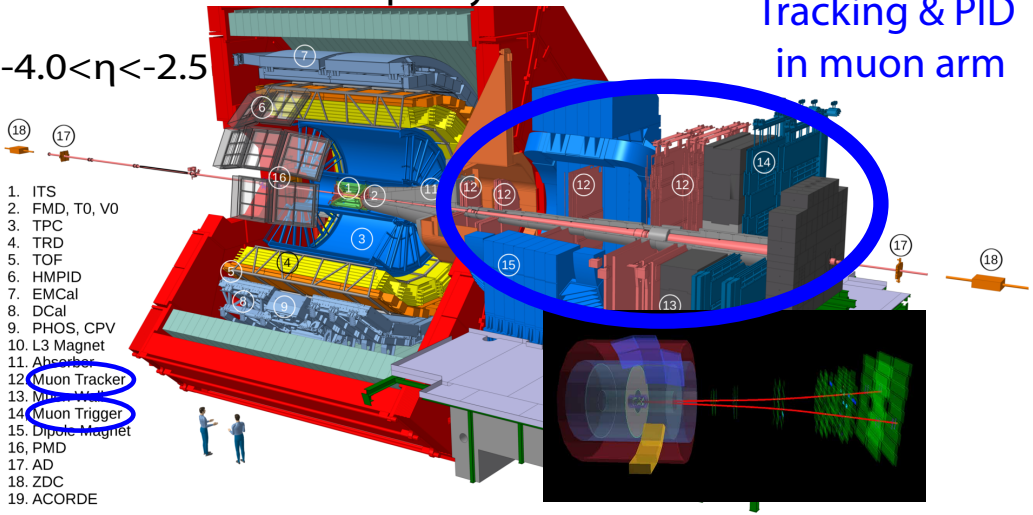
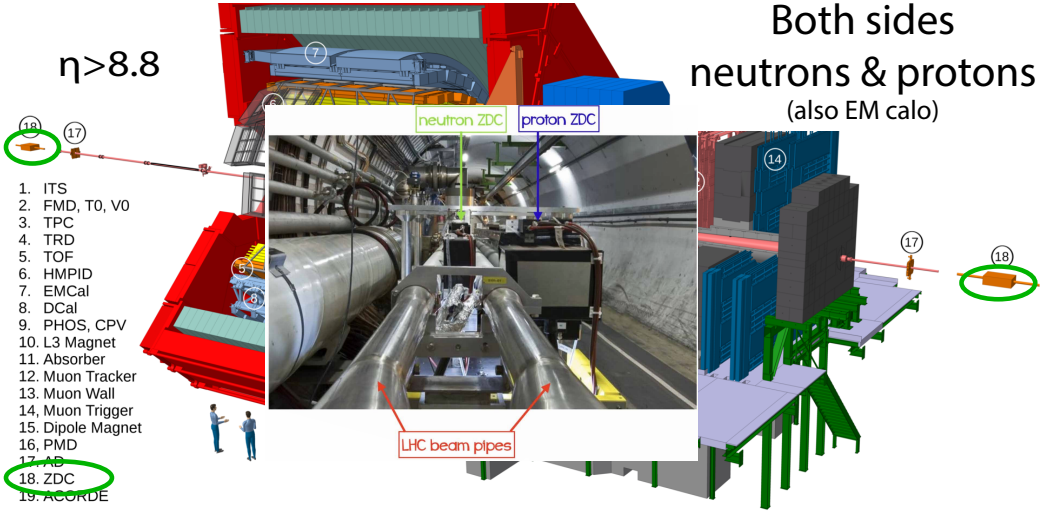
Tracking & PID in muon arm



ZERO DEGREE CALORIMETER

$\eta > 8.8$

Both sides
neutrons & protons
(also EM calo)



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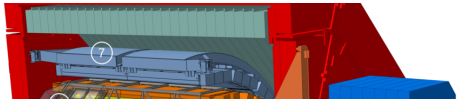
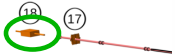


$\eta > 8.8$

Both sides neutrons



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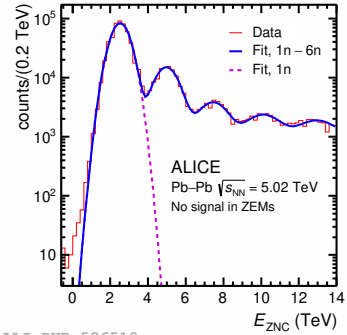
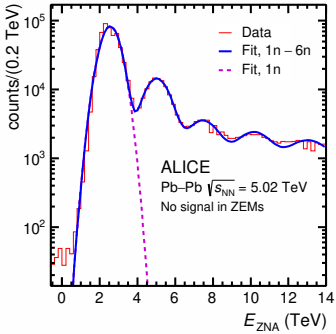
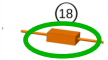
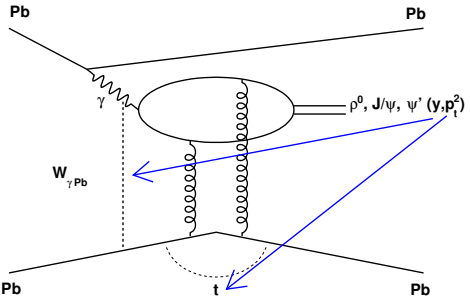






Overview of previous ALICE results

UPCs as a tool for vector meson photoproduction



$$W^2_{\gamma\mathrm{Pb}} = 2E_{\mathrm{Pb}} M_{\mathrm{J}/\Psi} e^{-\mathrm{y}}$$

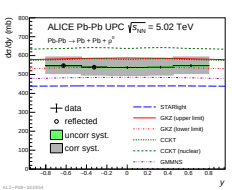
$$\mathrm{Bjorken}{-}x = \frac{M^2_{\mathrm{J}/\Psi}}{W^2_{\gamma\mathrm{Pb}}}$$

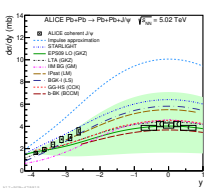
$$t = (p_{\mathrm{i,target}} - p_{\mathrm{f,target}})^2 c^2$$

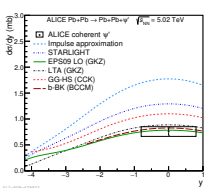
- Different mesons, rapidities, transversal momenta, targets $\rightarrow$ different transferred energies (Bjorken-x), transferred momenta.
- Provides information on gluon saturation and shadowing in nuclei.

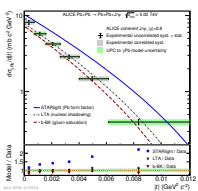
Published papers using Pb–Pb collisions in Run 2

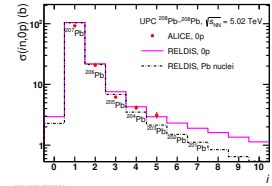
- Coherent J/Ψ photoproduction at forward rapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV
  Phys.Lett. B798 (2019) 134926
- Coherent photoproduction of ρ^0 vector mesons in ultra-peripheral Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV
  JHEP 06 (2020) 035
- Coherent J/Ψ and Ψ′ photoproduction at midrapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s} = 5.02$ TeV
  Eur. Phys. J. C 81 (2021) 712
- First measurement of the $|t|$dependence of coherent J/Ψ photonuclear production
  PLB 817 (2021) 136280
- Neutron emission in ultraperipheral Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV
  arXiv:2209.04250 (Accepted by PRC)





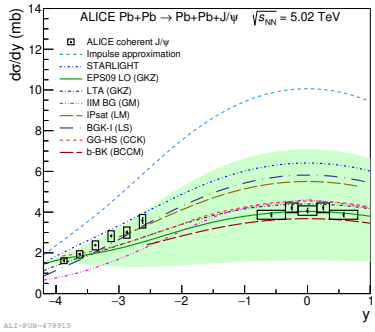


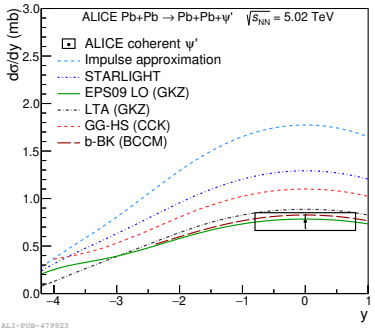


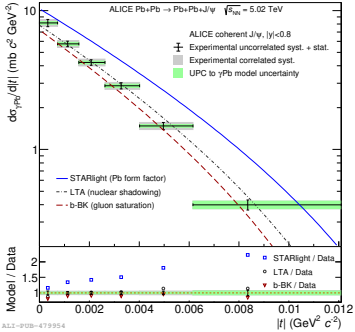


Very comprehensive programme. p–Pb: poster by M. Winn. 4-tracks events: poster by M. Kim.

What have we learnt





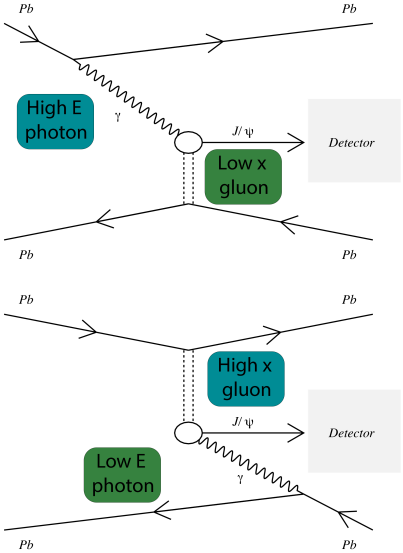


- Cross sections measured with precision below 10% → impacts numerous models.
- Nucleus scanned in 2D → sheds light on inner structure of nucleus.
- Clear evidence of shadowing in nucleus.

New (preliminary) results

Energy dependence of the photonuclear cross section

Source/target ambiguity



$$\frac{\mathrm{d}\sigma_{\mathrm{PbPb}}(y)}{\mathrm{d}y} = n_\gamma(y)\sigma_{\gamma\mathrm{Pb}}(y) + n_\gamma(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

- At midrapidity, contributions are equal.
- At forward rapidity, contributions are different.

$$1/x \sim W^2_{\gamma\mathrm{Pb}} = 2E_{\mathrm{Pb}}M_{\mathrm{J}/\Psi}e^{\pm y}$$

- 95% at $x \sim 10^{-2}$, 5% at $x \sim 10^{-5}$.

Broz *et. al.*: Comput.Phys.Commun. 253 (2020) 107181

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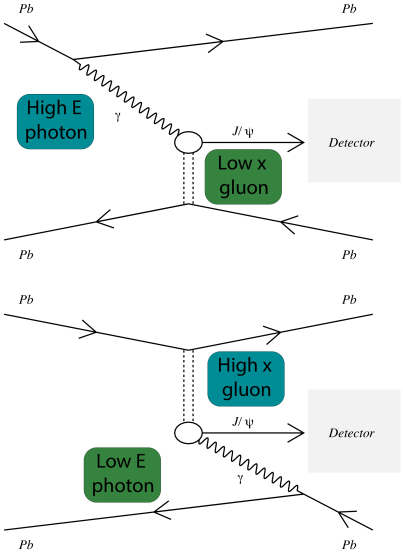

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- How to disentangle?

UPCs and peripheral collisions

- Photoproduction also found in peripheral events.
  - see talk by I. Arsene on Wed, 9:00.
- Different fluxes, same photonuclear cross sections.

$$\frac{\mathrm{d}\sigma^{\mathrm{UPC}}_{\mathrm{PbPb}}(y)}{\mathrm{dy}} = n^{\mathrm{UPC}}_{\gamma}(y)\sigma_{\gamma\mathrm{Pb}}(y) + n^{\mathrm{UPC}}_{\gamma}(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

$$\frac{\mathrm{d}\sigma^{\mathrm{Per}}_{\mathrm{PbPb}}(y)}{\mathrm{dy}} = n^{\mathrm{Per}}_{\gamma}(y)\sigma_{\gamma\mathrm{Pb}}(y) + n^{\mathrm{Per}}_{\gamma}(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

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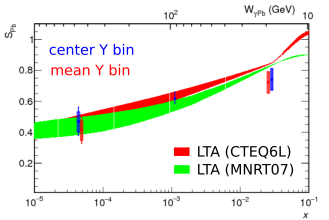
- The first calculation of low-x point using ALICE data $>$ 5 years ago by Contreras.

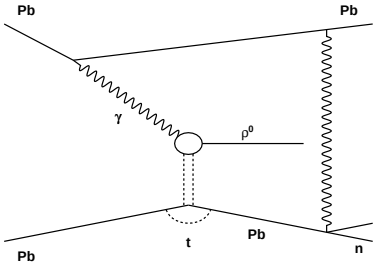


J.G. Contreras PRC 96 (2017) 015203

$$S_{\mathrm{Pb}} = \sqrt{\sigma_{\mathrm{data}}/\sigma_{\mathrm{IA}}}$$

- Impulse approximation = ignores nuclear effects except coherence.
- S_{Pb} is approximate measure of nuclear modification

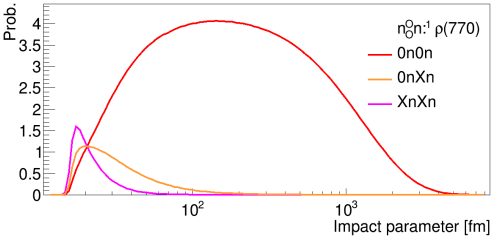
Electromagnetic Dissociation and neutron classes



- The different neutron classes allow you to access different impact parameters (b).

  Baltz *et. al.* PRL 89 (2002) 012301 && Guzey *et. al.* EPJC 74 (2014) 7

- XnXn = neutrons in both beam sides ('small' b),
- 0nXn = neutrons in one beam side ('medium' b),
- 0n0n = no neutrons are detected ('large' b).



$$\frac{\mathrm{d}\sigma^{0n0n}_{PbPb}(y)}{\mathrm{dy}} = n^{0n0n}_{\gamma}(y)\sigma_{\gamma Pb}(y) + n^{0n0n}_{\gamma}(-y)\sigma_{\gamma Pb}(-y)$$

$$\frac{\mathrm{d}\sigma^{0nXn}_{PbPb}(y)}{\mathrm{dy}} = n^{0nXn}_{\gamma}(y)\sigma_{\gamma Pb}(y) + n^{0nXn}_{\gamma}(-y)\sigma_{\gamma Pb}(-y)$$

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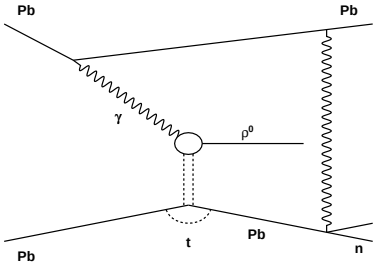

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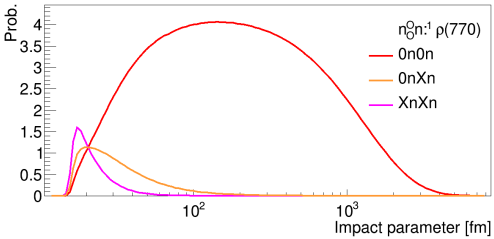

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- The different neutron classes allow you to disentangle low- and high-energy photon interactions!

Broz *et. al.*: Comput.Phys.Commun. 253 (2020) 107181

Classification in neutron classes is not a trivial task

$$\frac{\mathrm{d}\sigma^{0\mathrm{n}0\mathrm{n}}_{\mathrm{PbPb}}(y)}{\mathrm{d}y} = n_{\gamma}^{0\mathrm{n}0\mathrm{n}}(y)\sigma_{\gamma\mathrm{Pb}}(y) + n_{\gamma}^{0\mathrm{n}0\mathrm{n}}(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

$$\frac{\mathrm{d}\sigma^{0\mathrm{n}\mathrm{X}\mathrm{n}}_{\mathrm{PbPb}}(y)}{\mathrm{d}y} = n_{\gamma}^{0\mathrm{n}\mathrm{X}\mathrm{n}}(y)\sigma_{\gamma\mathrm{Pb}}(y) + n_{\gamma}^{0\mathrm{n}\mathrm{X}\mathrm{n}}(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

- Migrations due to missed neutron.
- Correction on pile-up.
- Correction on charged particles from nuclei dissociation at beam rapidities.
- Photon flux uncertainty from two models.
- Parameterization using several datasets.

χ^2 approach used to obtain the photonuclear cross sections.

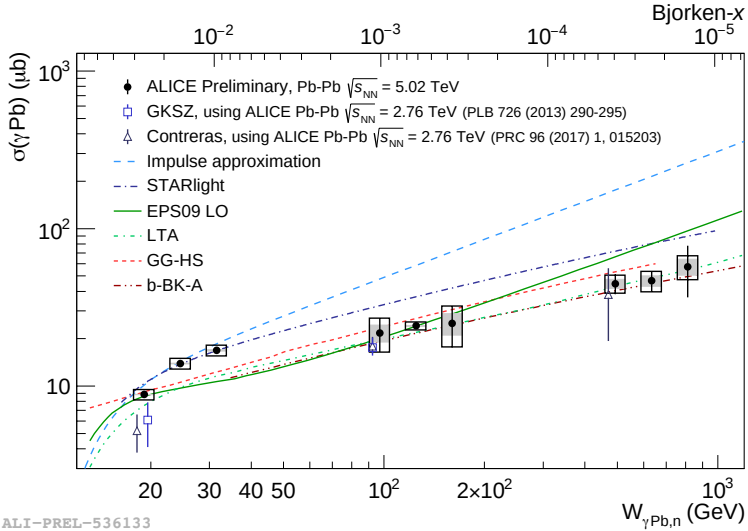
F. D. Aaron *et al.*, *Eur. Phys. J. C 63 (2009) 625–678*

Methods to measure energy dependence of coherent J/Ψ photoproduction

1. UPCs at midrapidity $\rightarrow$ symmetric contributions at $x \sim 10^{-3}$.
2. UPCs at forward rapidity $\rightarrow$ high-x contribution dominates ($x \sim 10^{-2}$).
3. Peripheral collisions $\rightarrow$ unlocks low-x contribution ($x = 4.4 \times 10^{-5}$, Run 1 data).
4. NEW!: UPCs in neutron classes $\rightarrow$ even lower x reached ($x = 1.1 \times 10^{-5}$, Run 2).

$W_{\gamma\mathrm{Pb}}$-dependence of coherent J/Ψ photonuclear cross section

- Measurement in a single experiment in range (20,800) GeV (x from 10^{-2} to 10^{-5}).



- No model describes well all data.

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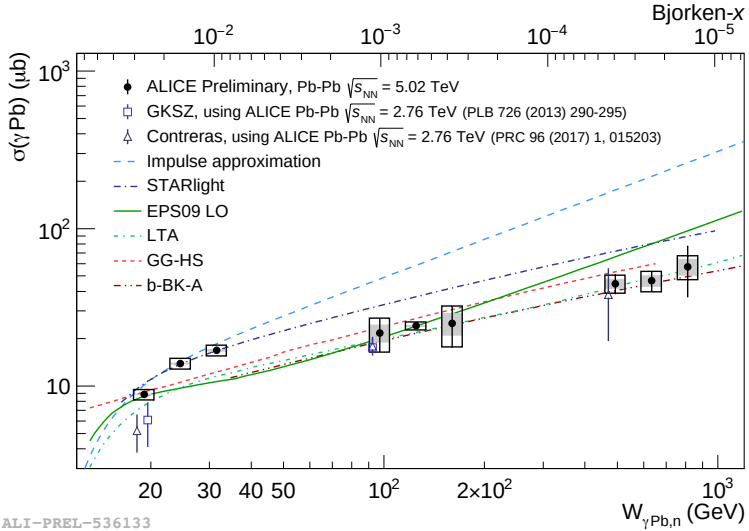

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- Models with saturation or shadowing undershoot high-x points, but describe well low-x points.
  - Sign of weaker shadowing at high-x?

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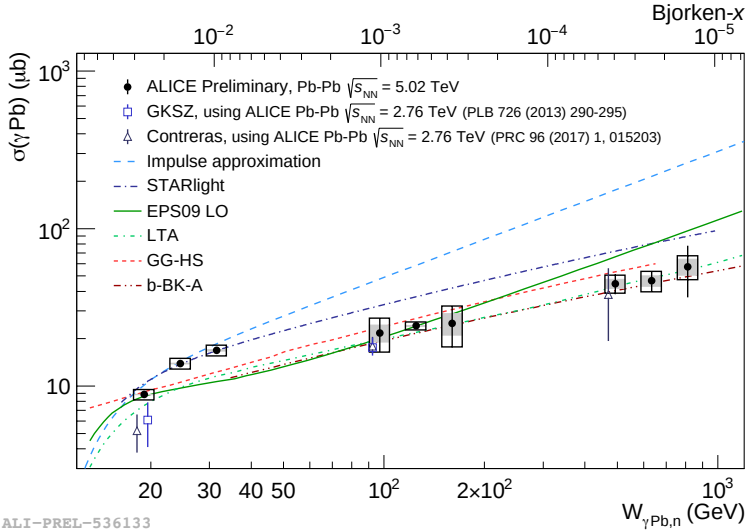

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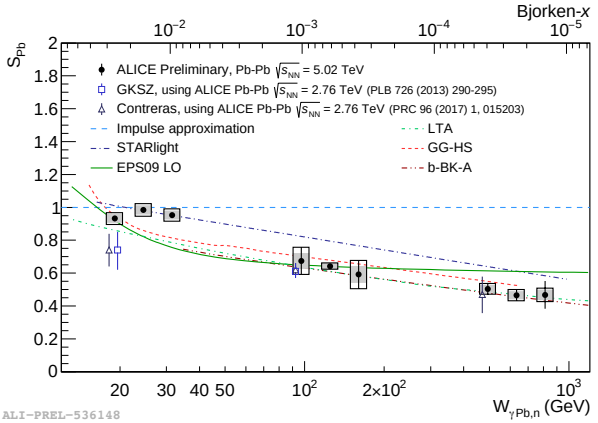
- Models with saturation or shadowing undershoot high-x points, but describe well low-x points.
  - Sign of weaker shadowing at high-x?
- Data described by both saturation, shadowing and EPS09 LO.
  - Interplay between saturation and shadowing?

$W_{\gamma\mathrm{Pb}}$-dependence of nuclear suppression factor



- Impulse approximation = ignores nuclear effects except coherence.

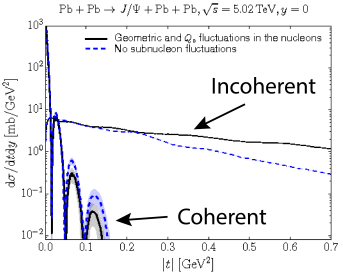
$$S_{\mathrm{Pb}} = \sqrt{\sigma_{\mathrm{data}}/\sigma_{\mathrm{IA}}}$$

- Approximate measure of nuclear effects.
- S_{Pb} strengthen with $W_{\gamma\mathrm{Pb}}$

$|t|$-dependence of the photonuclear cross section

Coherent vs incoherent photonuclear production

Type of process	γ interacts with	Target final state	$\sigma_{\gamma\mathrm{Pb}}$ sensitive to	$\langle p_{\mathrm{T}} \rangle$ of J/Ψ
Coherent	whole nucleus	intact	**average** target configuration	∼60 MeV
Incoherent elastic Incoherent dissociative	single nucleon	breaks up	**variance** over target configuration	∼300 MeV ∼500 MeV



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- Variations → quantum fluctuations.
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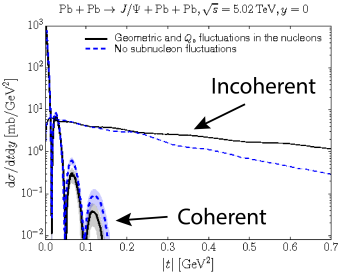

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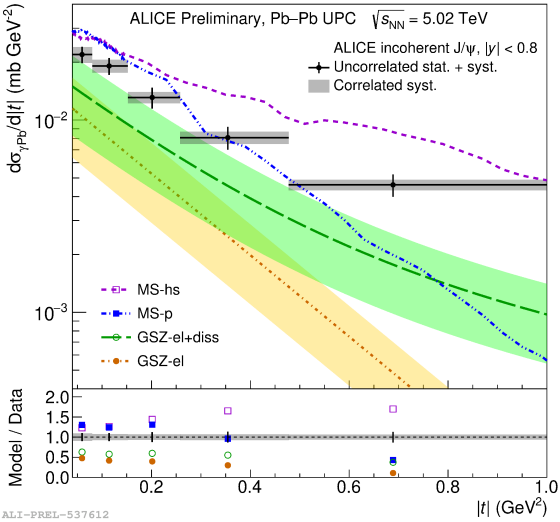
- Q:Are subnucleon dof. significant?

$|t|$-dependence of incoherent J/Ψ photonuclear cross section



- Two groups, each offering two options:
  - Nucleon has no internal structure: **MS-p**, **GSZ-el**.
  - Nucleon has subnucleon dof: **MS-hs**, **GSZ-el+diss**.
- No model fully describes data, but...

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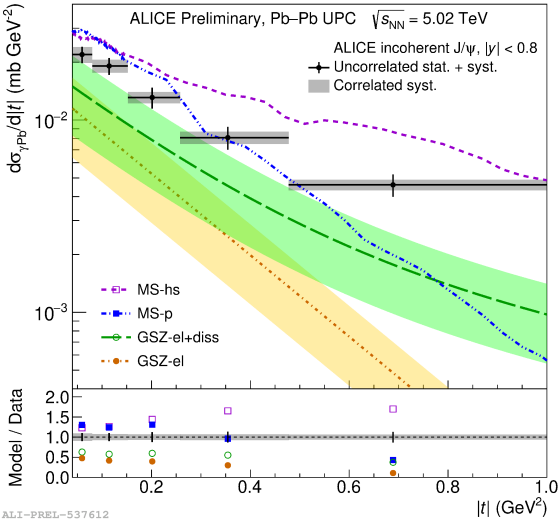

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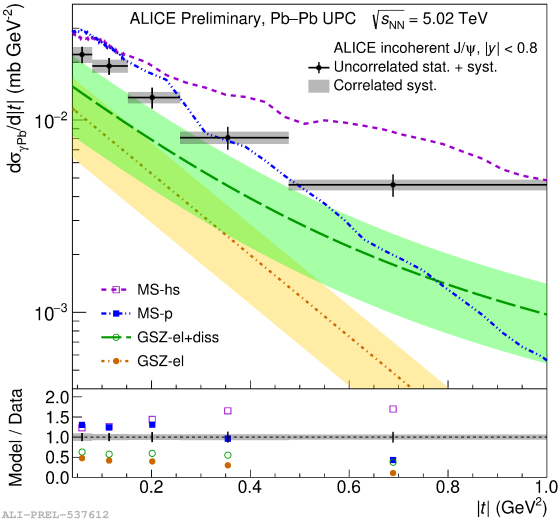

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- Normalization linked to the scaling from proton to nuclear targets.
- Probing for gluonic "hot spots" in Pb for the first time!

(partial) answers to QCD questions

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Bjorken-x dependence of shadowing in Pb $\rightarrow$ suppression factor is stronger with smaller x.

Still not possible to attribute role of saturation in nuclear shadowing.

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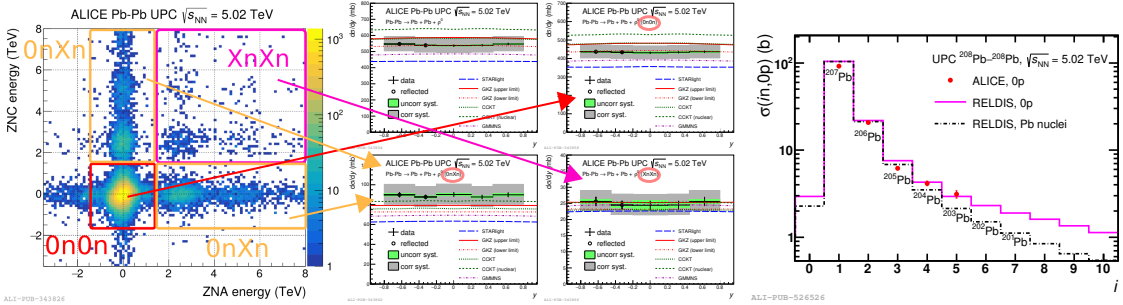
Time for your questions, please.

BACK UP

References to various models from plots

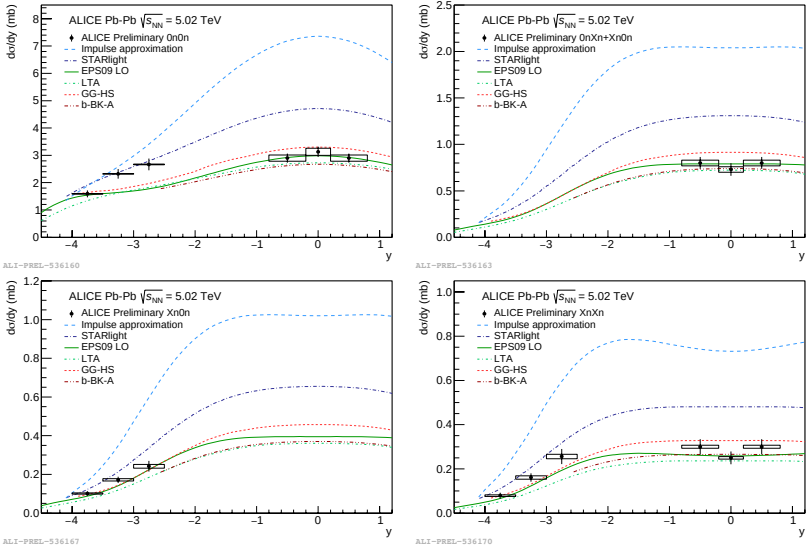
- Energy dependence of coherent J/Ψ photonuclear cross section:
  - Impulse approximation: G. F. Chew and G. C. Wick, Phys. Rev. 85 (1952) 636
  - STARlight: S. R. Klein and J. Nystrand, Phys. Rev. C60 (1999) 014903
  - EPS09 LO:K. 710 J. Eskola, H. Paukkunen, and C. A. Salgado, JHEP 04 (2009) 065
  - LTA: L. Frankfurt, V. Guzey, and M. Strikman, Phys. Rept. 512 (2012) 255–393
  - GG-HS: J. Cepila, J. G. Contreras, and M. Krelina, Phys. Rev. C 97 (2018) 024901
  - b-BK-A: D. Bendova, J. Cepila, J. G. Contreras, and M. Matas, Phys. Lett. B 817 (2021) 136306
- $|t|$-dependence of incoherent J/Ψ photonuclear cross section:
  - MS-hs: H. Mäntysaari and B. Schenke, Phys. Lett. B 772 (2017) 832–838
  - MS-p: H. Mäntysaari and B. Schenke, Phys. Lett. B 772 (2017) 832–838
  - GSZ-el+diss: V. Guzey, M. Strikman, and M. Zhalov, Phys. Rev. C 99, 015201
  - GSZ-el: V. Guzey, M. Strikman, and M. Zhalov, Phys. Rev. C 99, 015201

What have we learnt - nuclear breakup and neutron emission

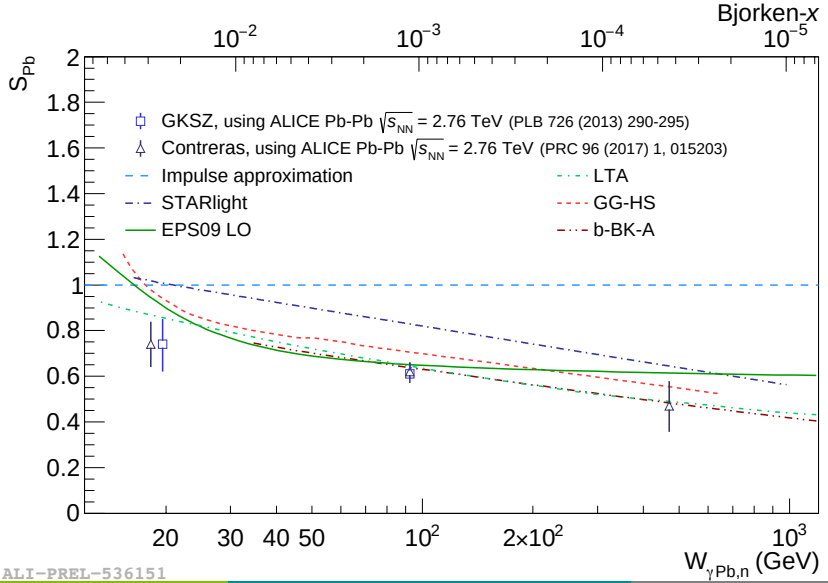


- Different nuclear-breakup classes at midrapidity:
  - Models describe data very well → possibility of γPb disentanglement proved.
  - Measurements at different impact parameters (still UPCs).
- Emission of forward neutrons understood very well.

Coherent J/Ψ photonuclear cross section in neutron classes



$W_{\gamma\mathrm{Pb}}$-dependence of nuclear suppression factor - Run 1



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Coherent J/Ψ photonuclear cross section - typical inv. mass and p_T