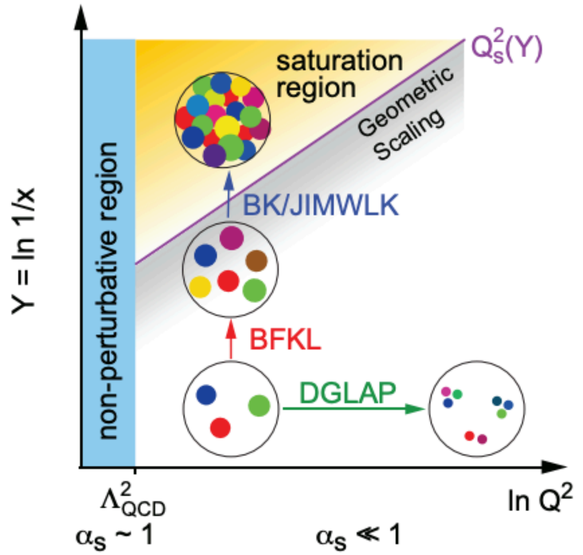
Advancements in photonuclear J/ψ production in ultra-peripheral Pb–Pb collisions from Run 2 and early results from Run 3 in ALICE

Diana Krupová for the ALICE Collaboration
Czech Technical University in Prague & Université Paris-Saclay

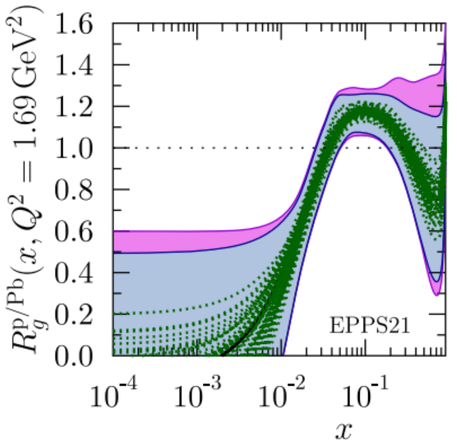
Triggering Discoveries in High Energy Physics III, High Tatras
December 10, 2024

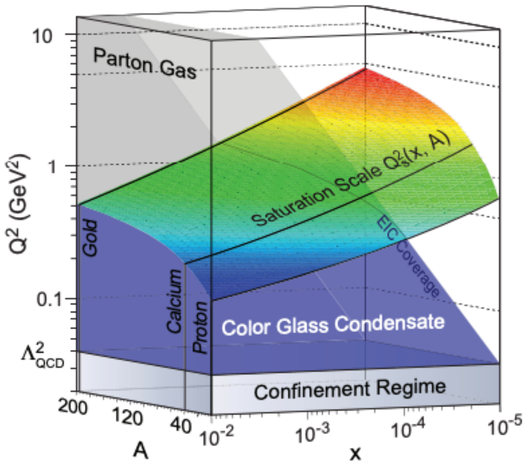
Introduction to photonuclear J/ψ production in UPCs

- goals:
  - search for gluon saturation at low x
  - study of nuclear effects (shadowing, gluon PDFs)
    - nuclear shadowing effects on gluon PDFs
      - $R_g^A(x,Q^2) = \dfrac{g_A(x,Q^2)}{A g_p(x,Q^2)} < 1$
    - saturation may contribute to nuclear shadowing
- tools:
  - measurement of energy dependence
  - measurement of t-dependence



Accardi, A., et al., "Electron Ion Collider: The Next QCD Frontier," Eur. Phys. J. A 52 (2016) 268

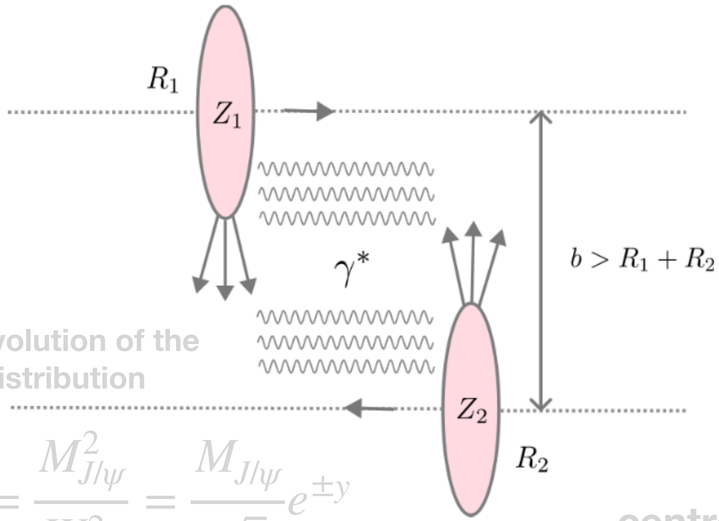




Eskola, K. J., Paakkinen, P., Paukkunen, H., and Salgado, C. A., "EPPS21: a global QCD analysis of nuclear PDFs," Eur. Phys. J. C 82 (2022) 413

Introduction to photonuclear J/ψ production in UPCs

- UPCs: collisions at $b > 2R$
  - hadronic interaction suppressed
- at the LHC, photon-induced reactions probe gluon densities in a wide range of x
- J/ψ production in UPC:
  - clear experimental signature
    - $J/\psi \rightarrow l^+l^-$: two lepton tracks in an otherwise empty detector
    - large lepton branching ratios
    - small decay width
  - energy evolution can be observed through the rapidity of the vector meson

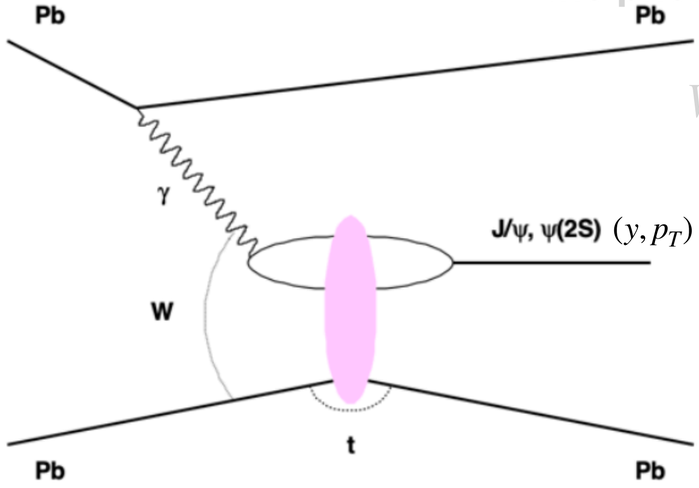


Bjorken-x evolution of the parton distribution

$$x = \frac{M_{J/\psi}^2}{W_{\gamma A}^2} = \frac{M_{J/\psi}}{\sqrt{s}} e^{\pm y}$$

centre-of-mass energy of the photon-target system

$$W_{\gamma A}^2 = \sqrt{s} M_{J/\psi} e^{\pm y}$$



transverse plane distribution of the partons: 2D Fourier transforms to the $t \approx -p_T^2$ dependence

Introduction to photonuclear J/ψ production in UPCs

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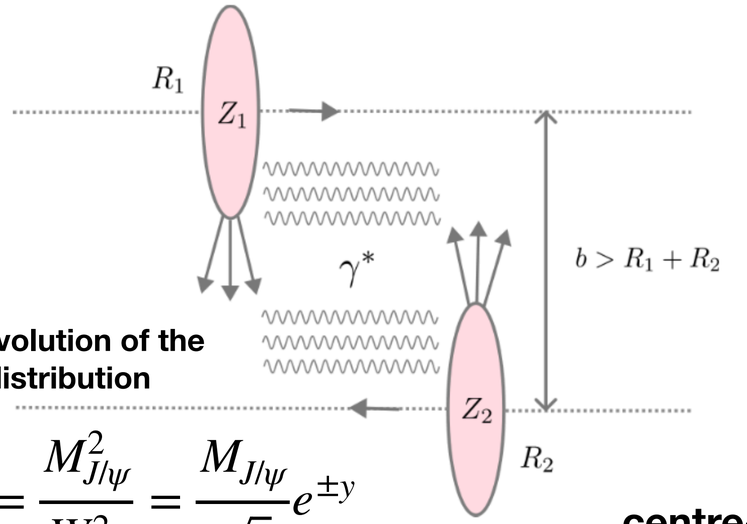

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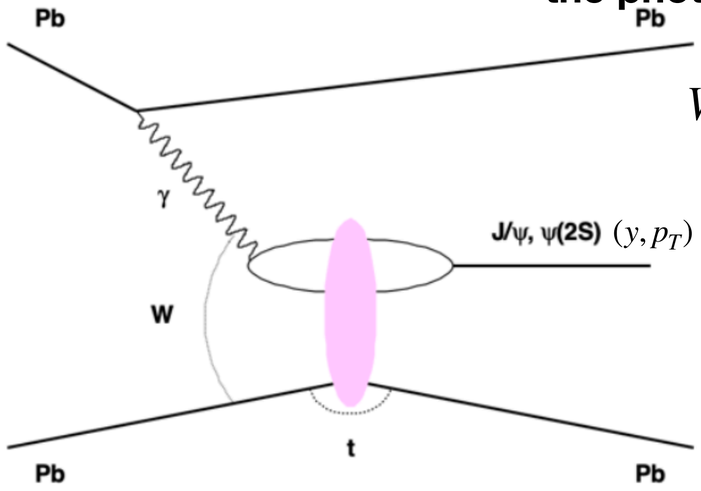

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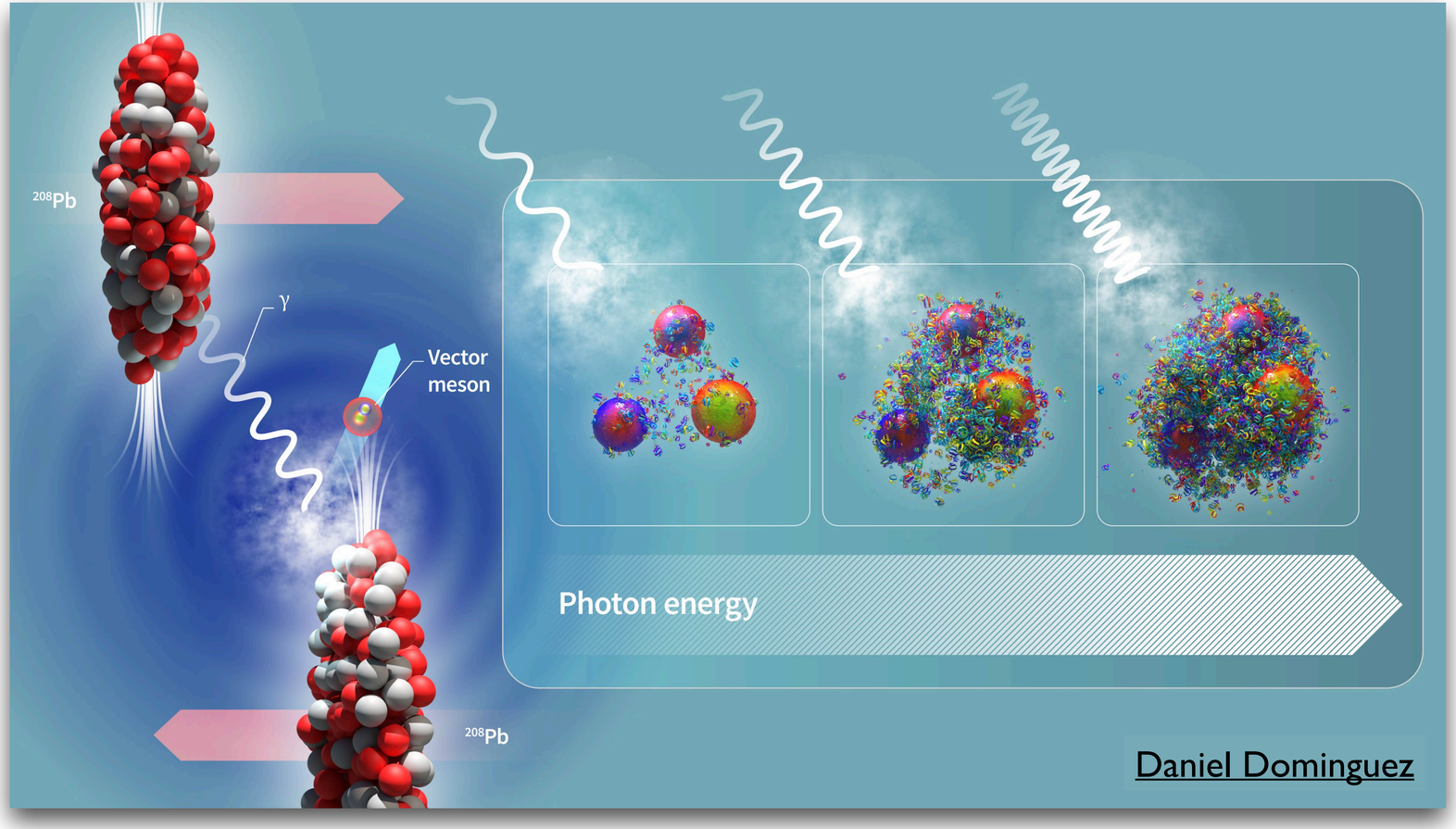
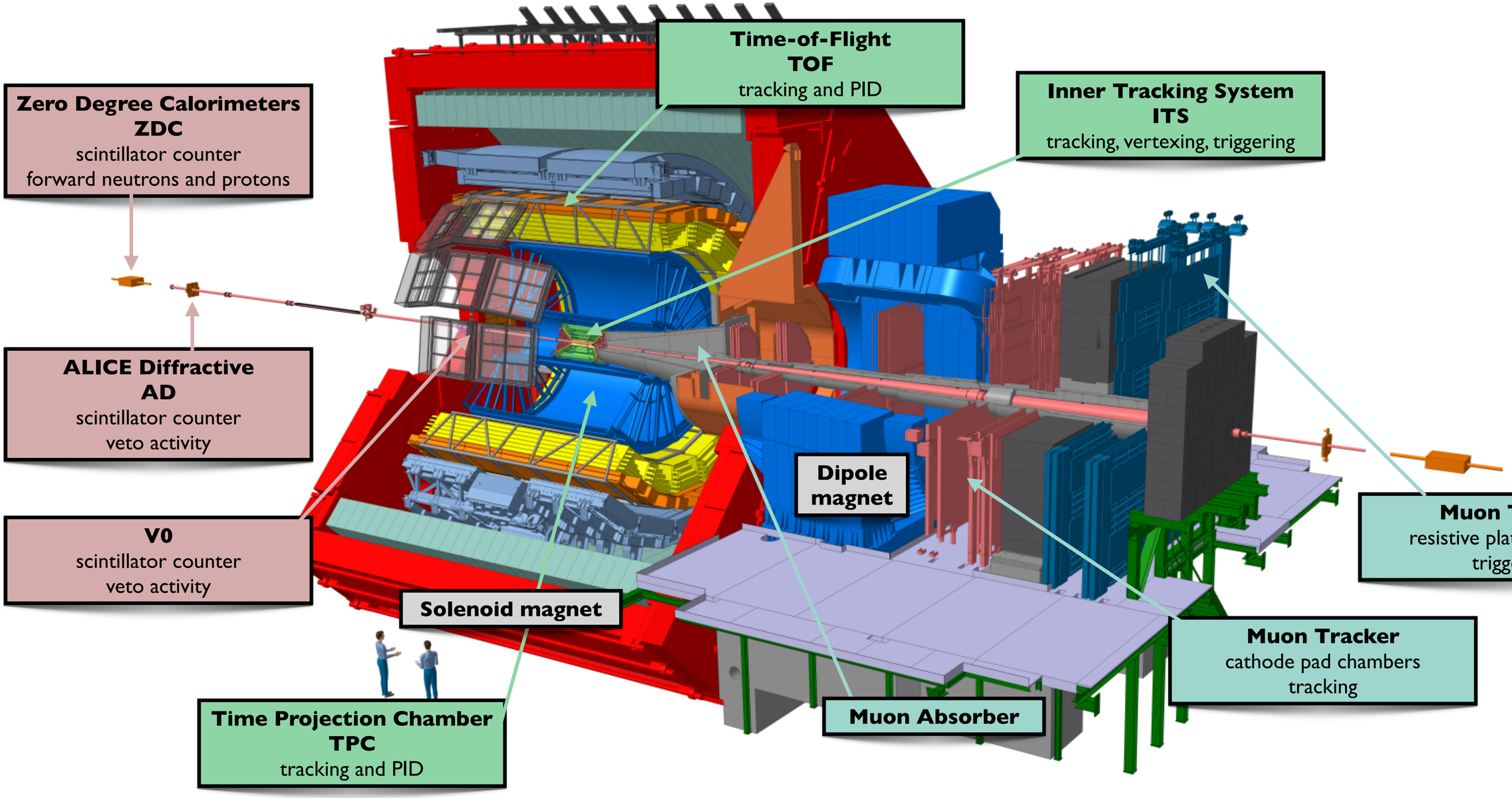
Introduction to photonuclear J/ψ production in UPCs

- **photoproduction p_T signatures**
- in Pb-Pb collisions
  - coherent: target ion stays intact,
    $< p_T > \sim$ 60 MeV $\sim 1/R_{\mathrm{Pb}}$
  - incoherent, two components:
    - elastic: target ion breaks,
      nucleon stays intact
      $< p_T > \sim$ 300 MeV/c $\sim 1/R_{\mathrm{N}}$
    - dissociative: both ion
      and the target nucleon break
      $< p_T > \sim$ 1 GeV/c



ALICE detector in Run 2

Key components of ALICE for UPC measurements



J/ψ in UPCs: measurements at midrapidity ($|y| < 0.8$) and forward rapidity ($-4 < y < -2.5$)

Run 2 results: Energy dependence

Energy dependence of coherent photonuclear production of J/ψ mesons in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$*=5.02 TeV*

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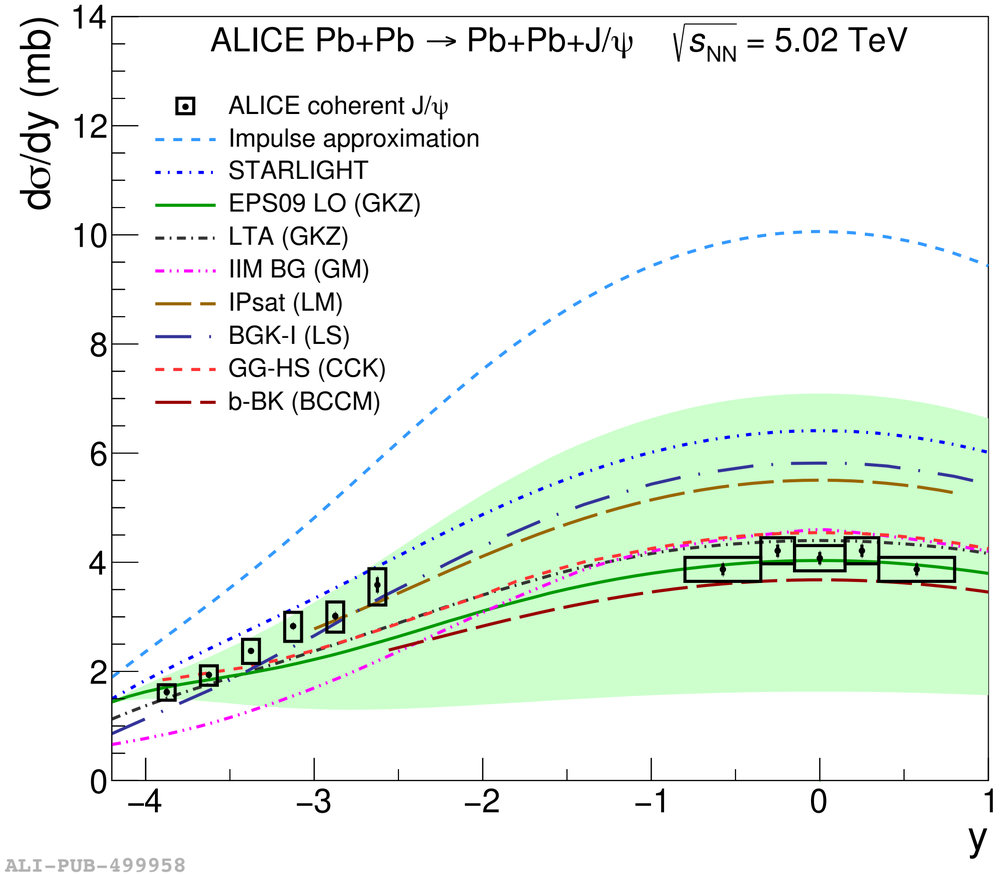
Coherent J/ψ photoproduction - Energy dependence

- difference between the impulse approximation and data
  - nucleus is not just a collection of nucleons
  - the difference depends on the rapidity
- no model describes data
  - some models describe data well at low rapidities, some at midrapidities
- GKZ models are shadowing based
- GM, LM, LS, CCK and BCCM are saturation based
  - predictions from saturation-based models span from 3.5 mb to 5.5 mb at midrapidity

⇒ data can constrain the different approaches



ALI-PUB-499958

Eur. Phys. J. C 81 (2021) 712

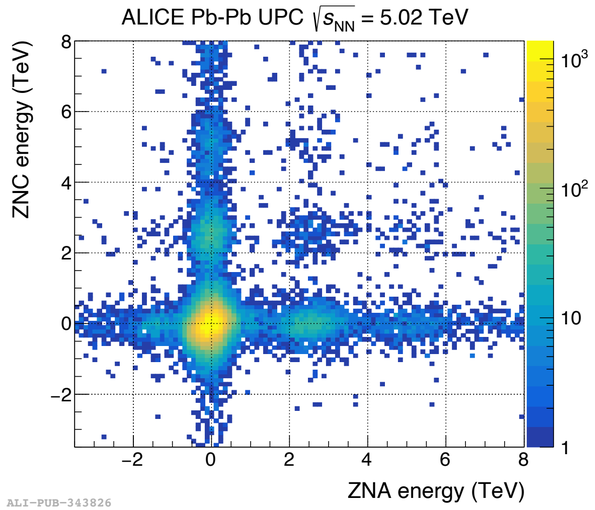
* references to the models can be found in the backup

Coherent J/ψ photoproduction - Energy dependence

photon flux

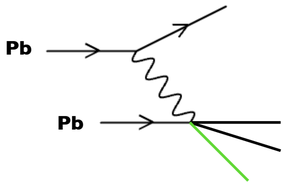
$$\frac{d\sigma_{\mathrm{PbPb}}(y)}{dy} = N_\gamma(y)\sigma_{\gamma\mathrm{Pb}}(y) + N_\gamma(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

photon-target cross section



JHEP 06 (2020) 035

- both contributions equal at midrapidity
- at forward rapidity, the contributions are different
- using neutron tagging (ZDC information), we are able to solve the equation above
  - photon exchange may lead to electromagnetic dissociation (EMD) of a nucleus



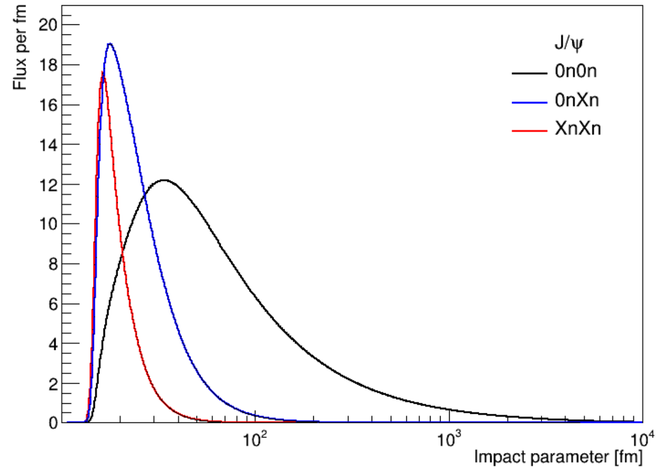
nucleons at beam rapidities

0n0n: no neutrons on either side → large impact parameters

0nXn, Xn0n: neutrons on one side → smaller impact parameters

XnXn: neutrons on both sides

at forward rapidity: low photon energy

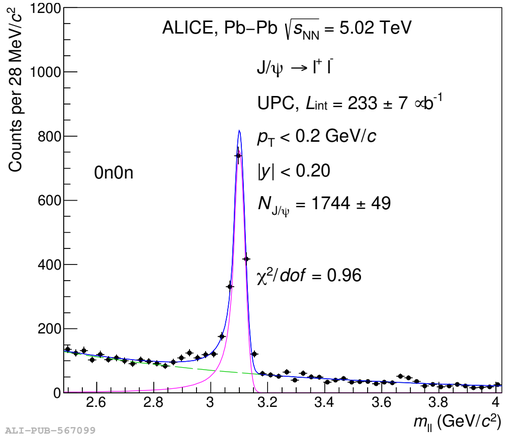


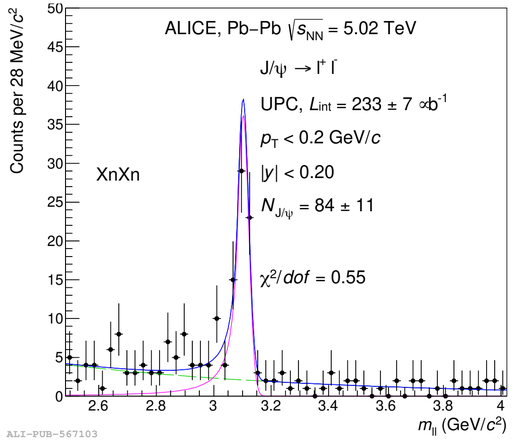
Comput.Phys.Commun. 253 (2020) 107181

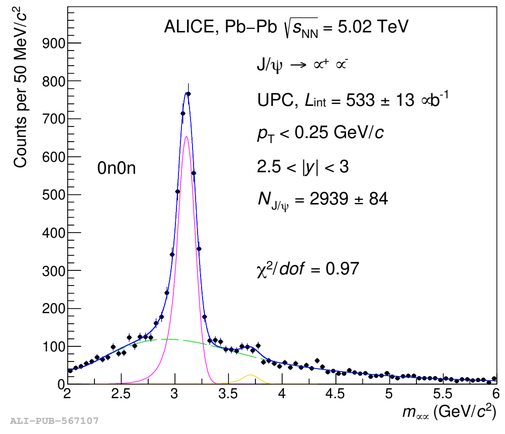
Coherent J/ψ photoproduction - Energy dependence

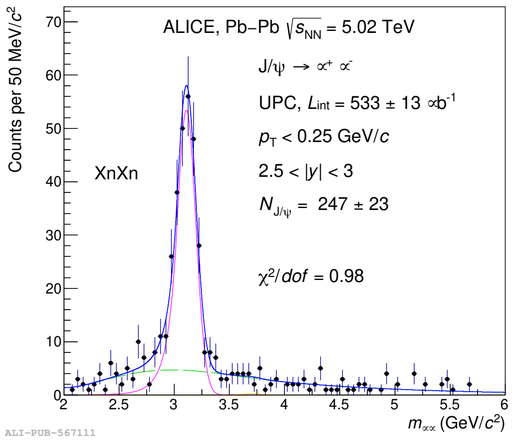
- midrapidity and forward rapidity analysis

- 0n0n (left column), XnXn (right column)

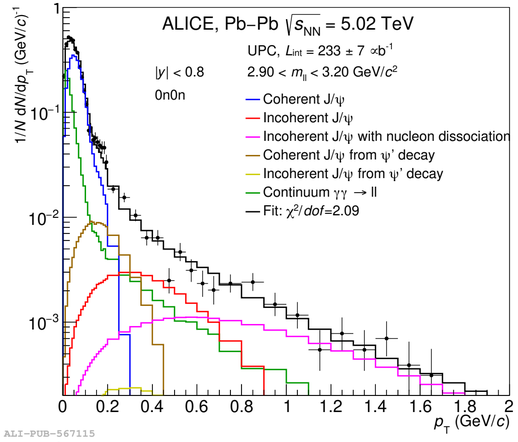


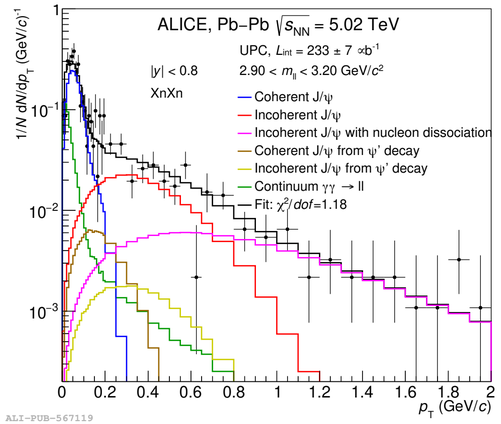


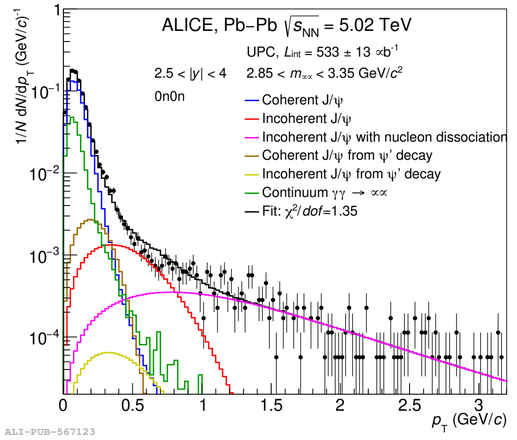


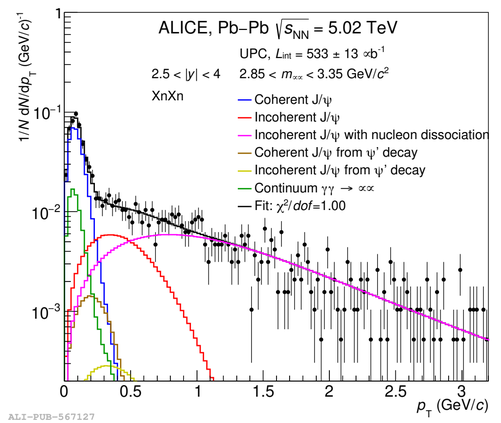


- 0n0n (left column), XnXn (right column)





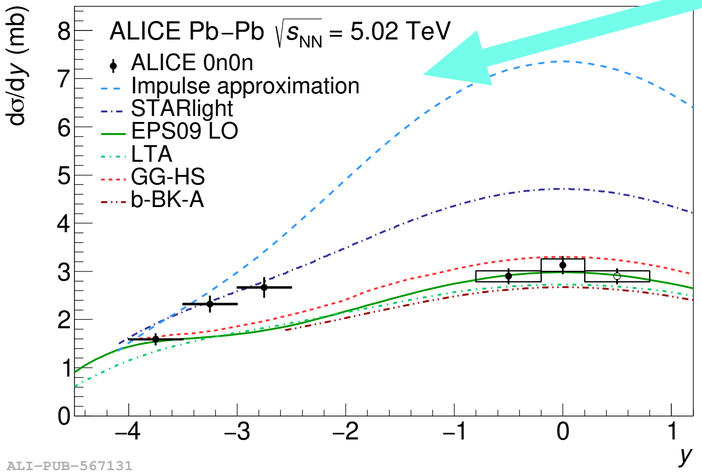


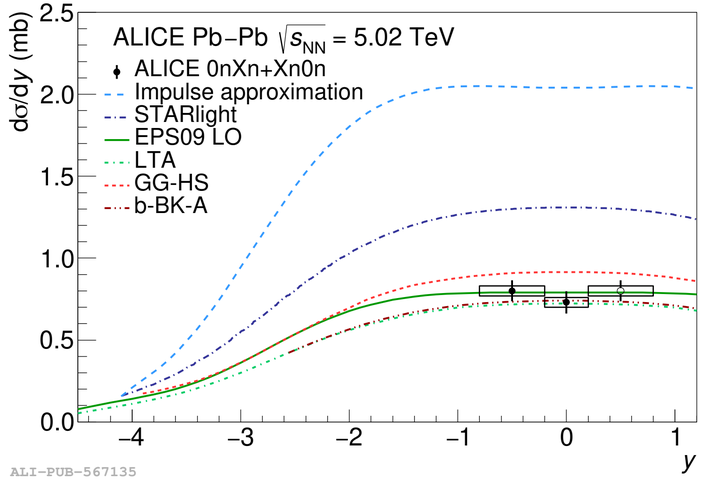


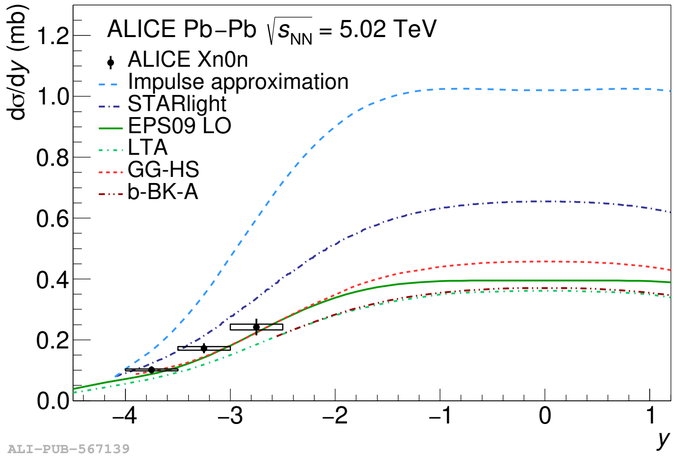
Coherent J/ψ photoproduction - Energy dependence

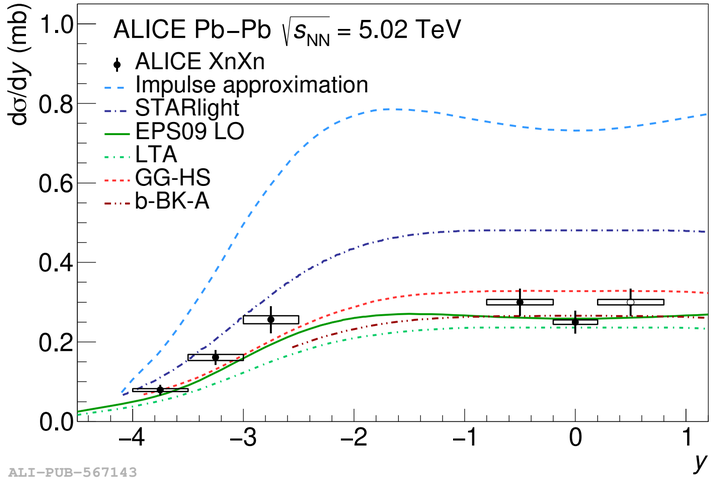
- measured cross sections:

the main discrepancy between data and saturation/shadowing models comes from 0n0n (large impact parameters)









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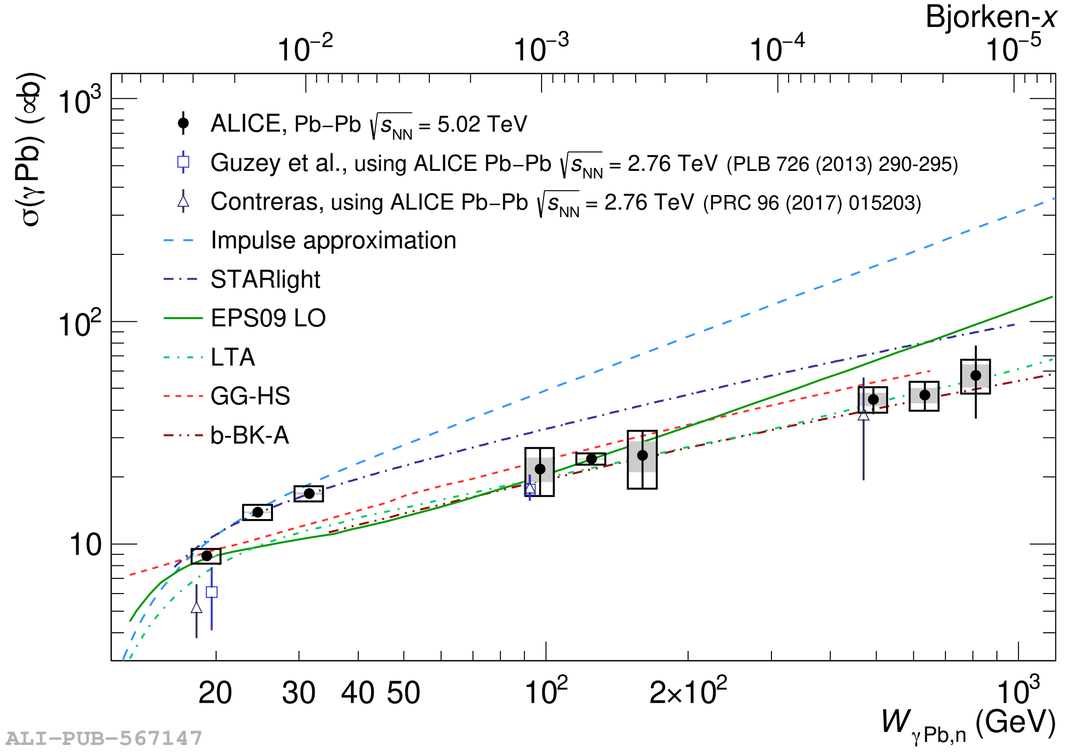
Coherent J/ψ photoproduction - Energy dependence

- agreement with Run 1 results
- LTA (shadowing), GG-HS and b-BK-a (saturation) describe high energy data
- impulse approximation and STARlight describe low energy data



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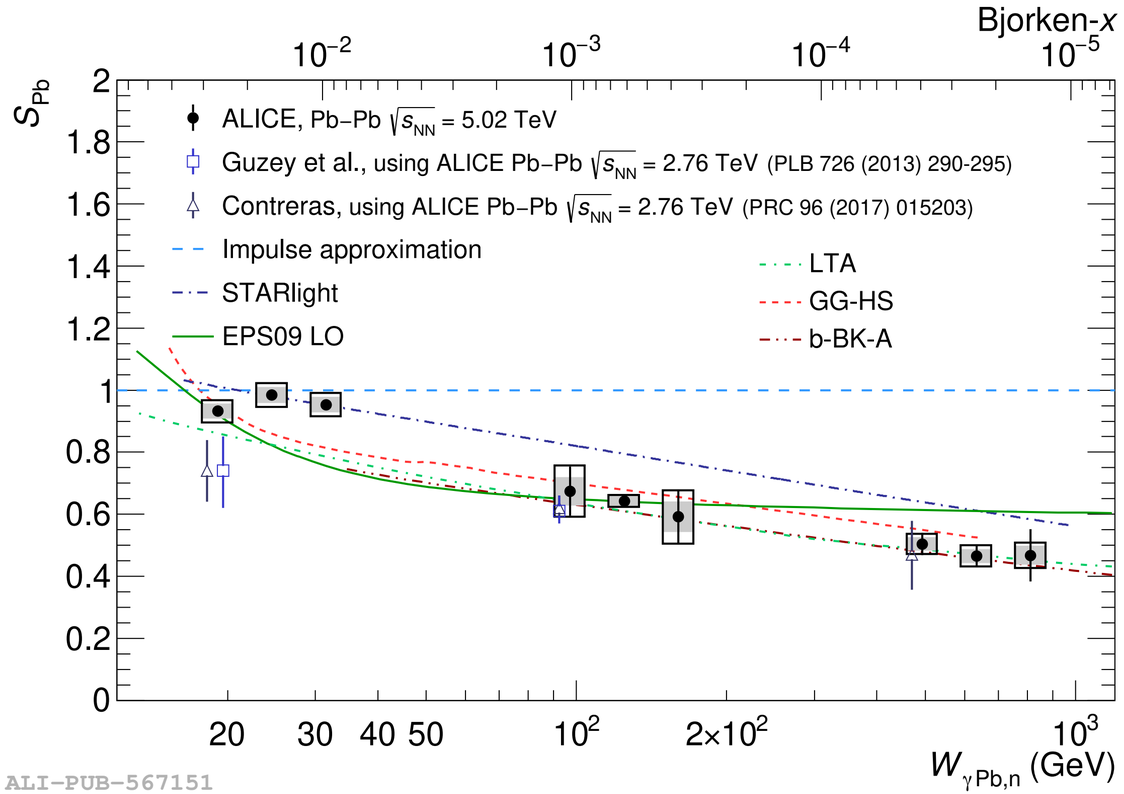
Coherent J/ψ photoproduction - Energy dependence

- nuclear suppression factor:
  - approximate measure of nuclear shadowing

$$S_{\mathrm{Pb}} = \sqrt{\frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{data}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{IA}}}}$$

- flattening trend observed at high energies:
  - 0.94 at low energies,
  - ~0.64 at intermediate energies,
  - 0.47 at the highest measured energies.



ALI-PUB-567151

JHEP 10 (2023) 119

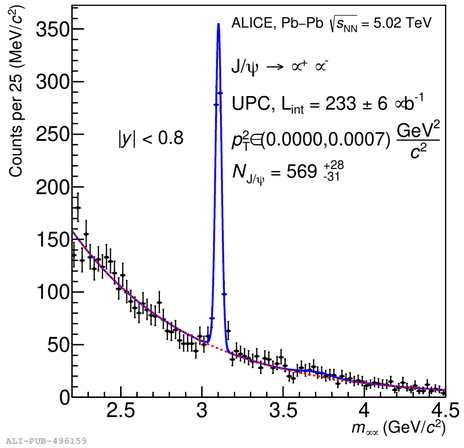
Run 2 results: t-dependence

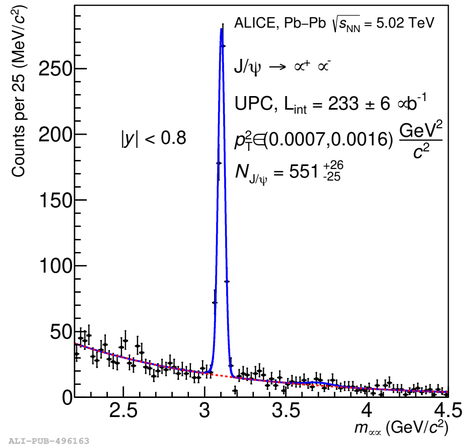
First measurement of the $|t|$-dependence of coherent J/ψ photonuclear production
Phys.Lett.B 817 (2021) 136280

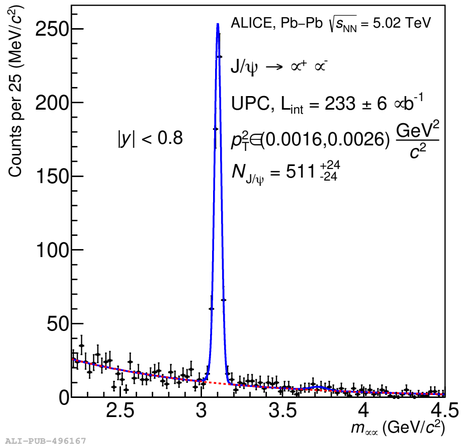
First measurement of the $|t|$-dependence of incoherent J/ψ photonuclear production
Phys.Rev.Lett. 132 (2024) 162302

Coherent J/ψ - t-dependence

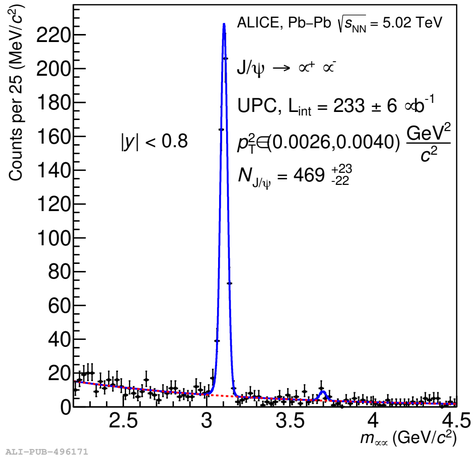
- J/$\psi \to \mu^+\mu^-$ at midrapidity
- unfolding performed to account for p_T migrations
- $p_T^2 \to |t|$ unfolding

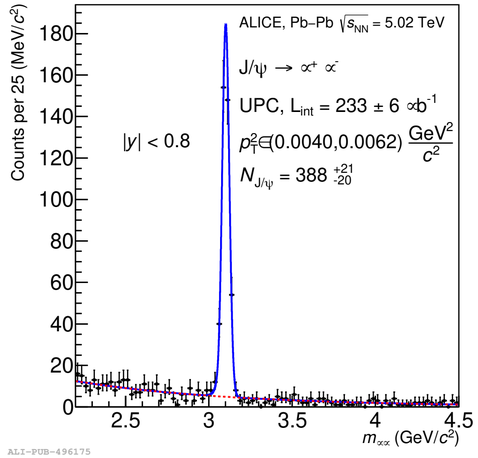


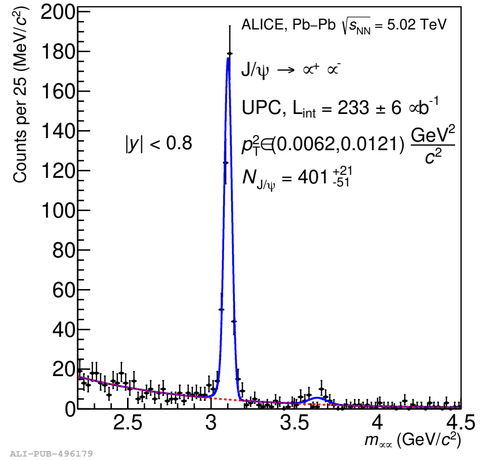




Phys.Lett.B 817 (2021) 136280



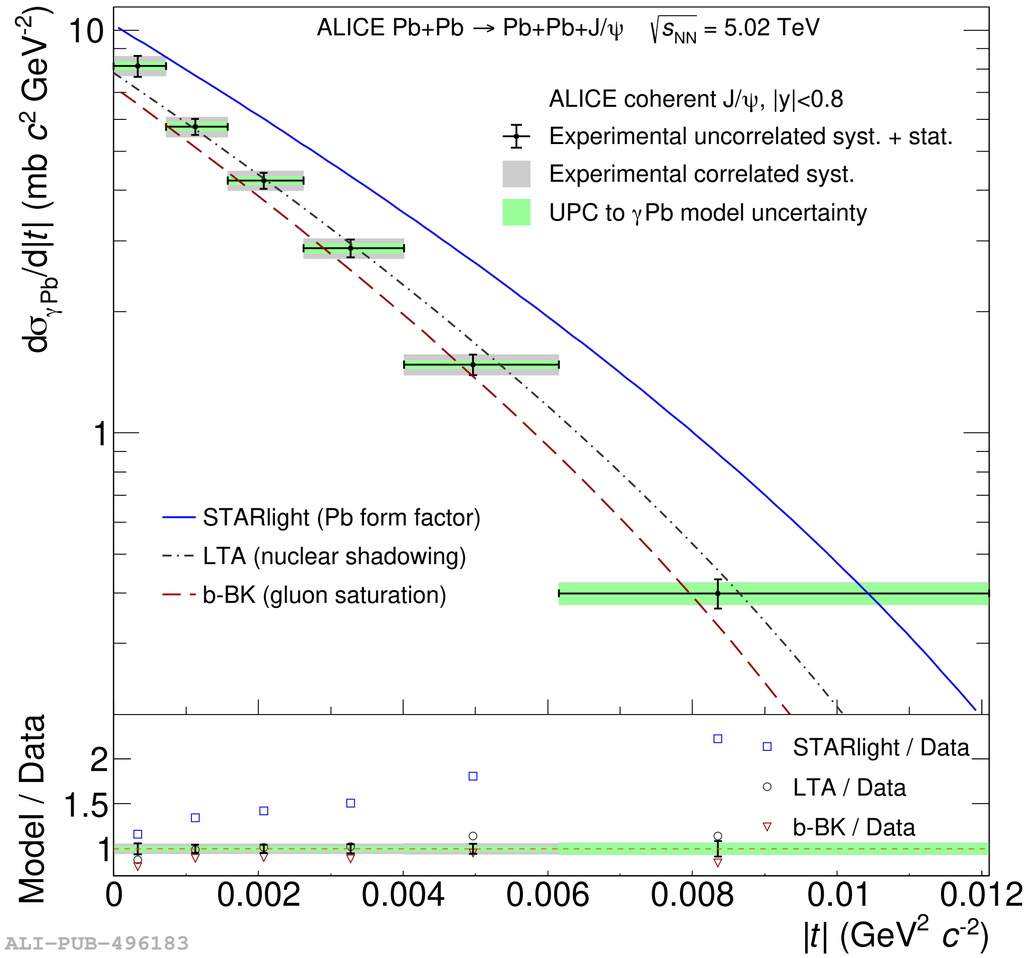




Coherent J/ψ - t-dependence

- sensitive to average transverse spatial distribution of the nucleus
- comparison with models:
  - nuclear shadowing (LTA) and gluon saturation (b-BK) match within uncertainties
  - STARlight overpredicts data
- agreement of data with saturation and shadowing models, disagreement with STARlight that does not include such QCD-dynamic ingredients

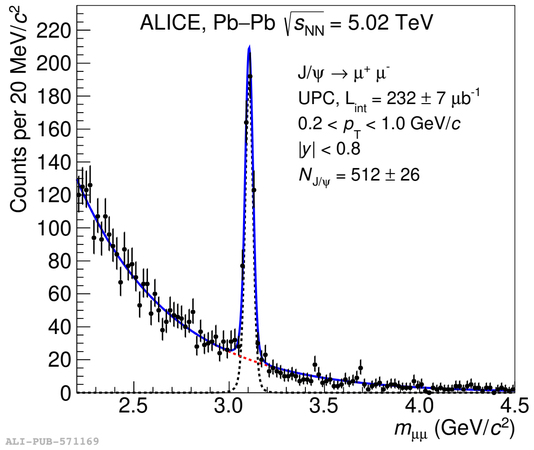
  $\Longrightarrow$ highlights the importance of these QCD effects for this measurement



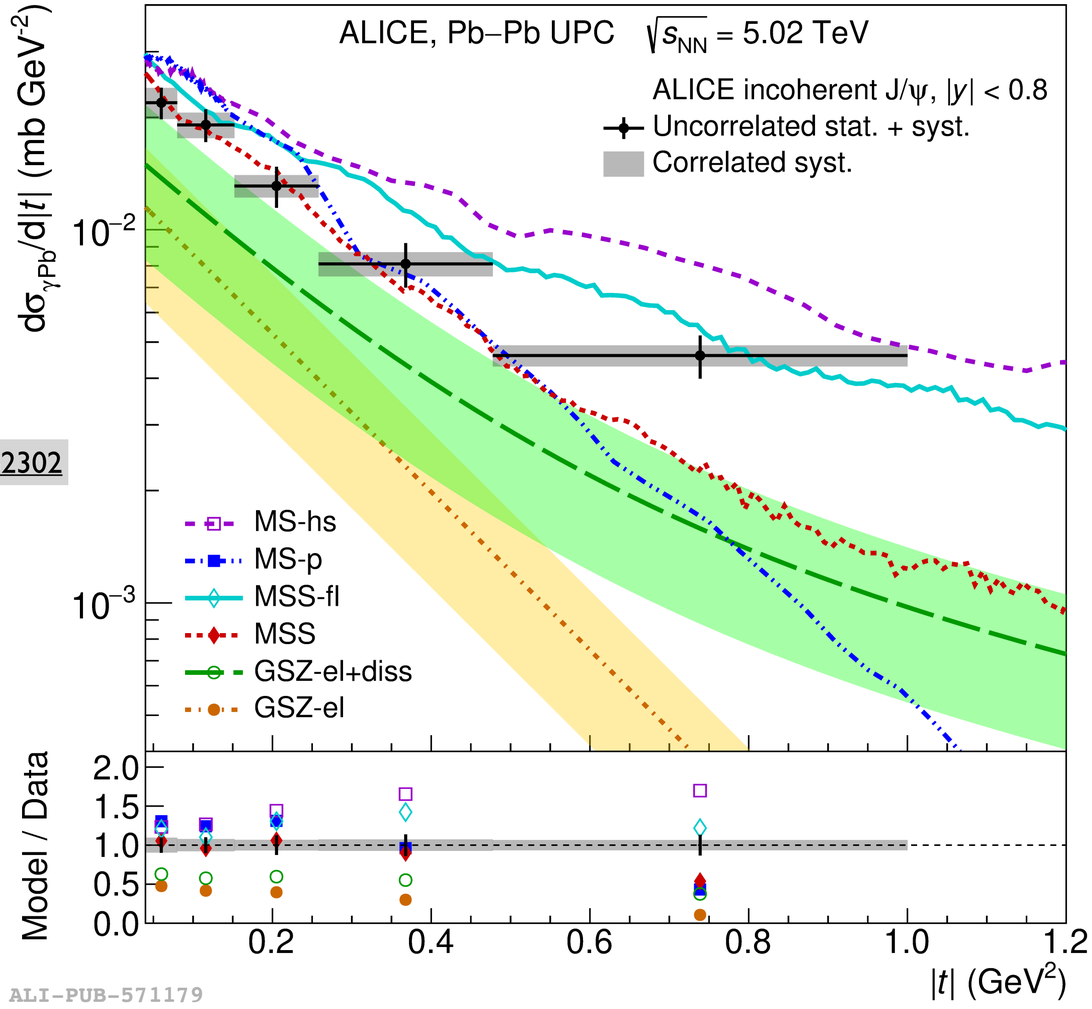
Phys.Lett.B 817 (2021) 136280

Incoherent J/ψ - t-dependence

- J/$\psi \to \mu^+\mu^-$ at midrapidity
- $p_T^2 = |t|$ large momentum transfer



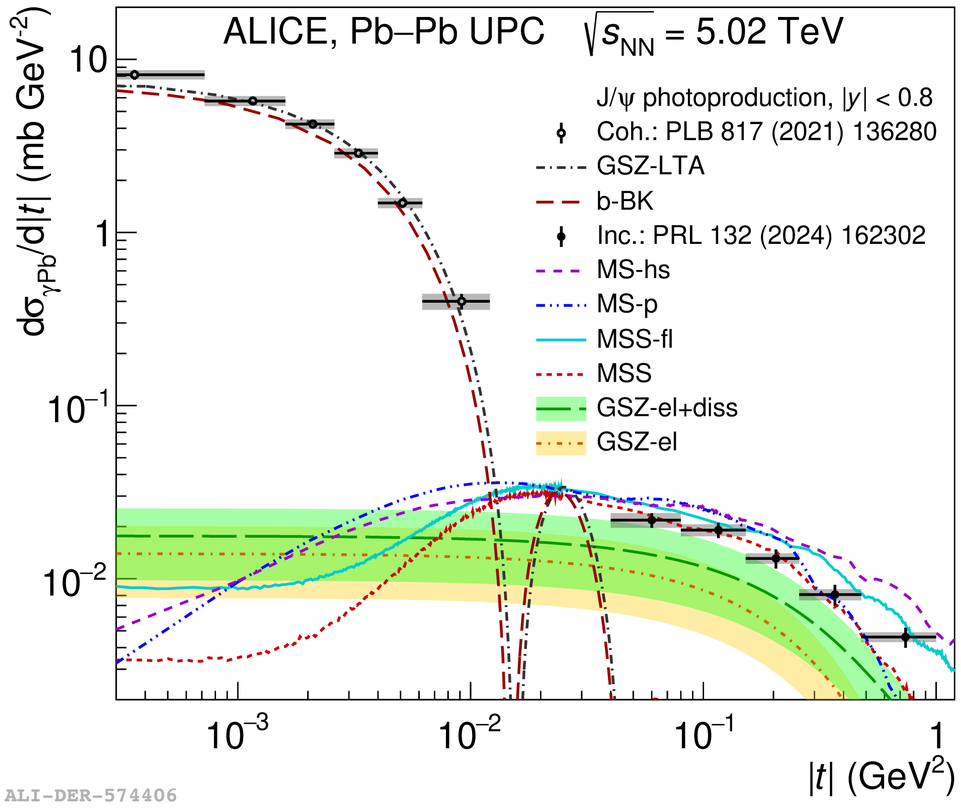
- probes fluctuations in gluon distribution [Phys.Rev.Lett. 132 (2024) 162302]
- data suggests sub-nucleon structure (hot spots)
  - models that ignore quantum fluctuations of the gluon density in the colliding hadron predict a $|t|$-dependence of the cross section much steeper than in data
    - the inclusion of such fluctuations in the same models provides a better description of the data



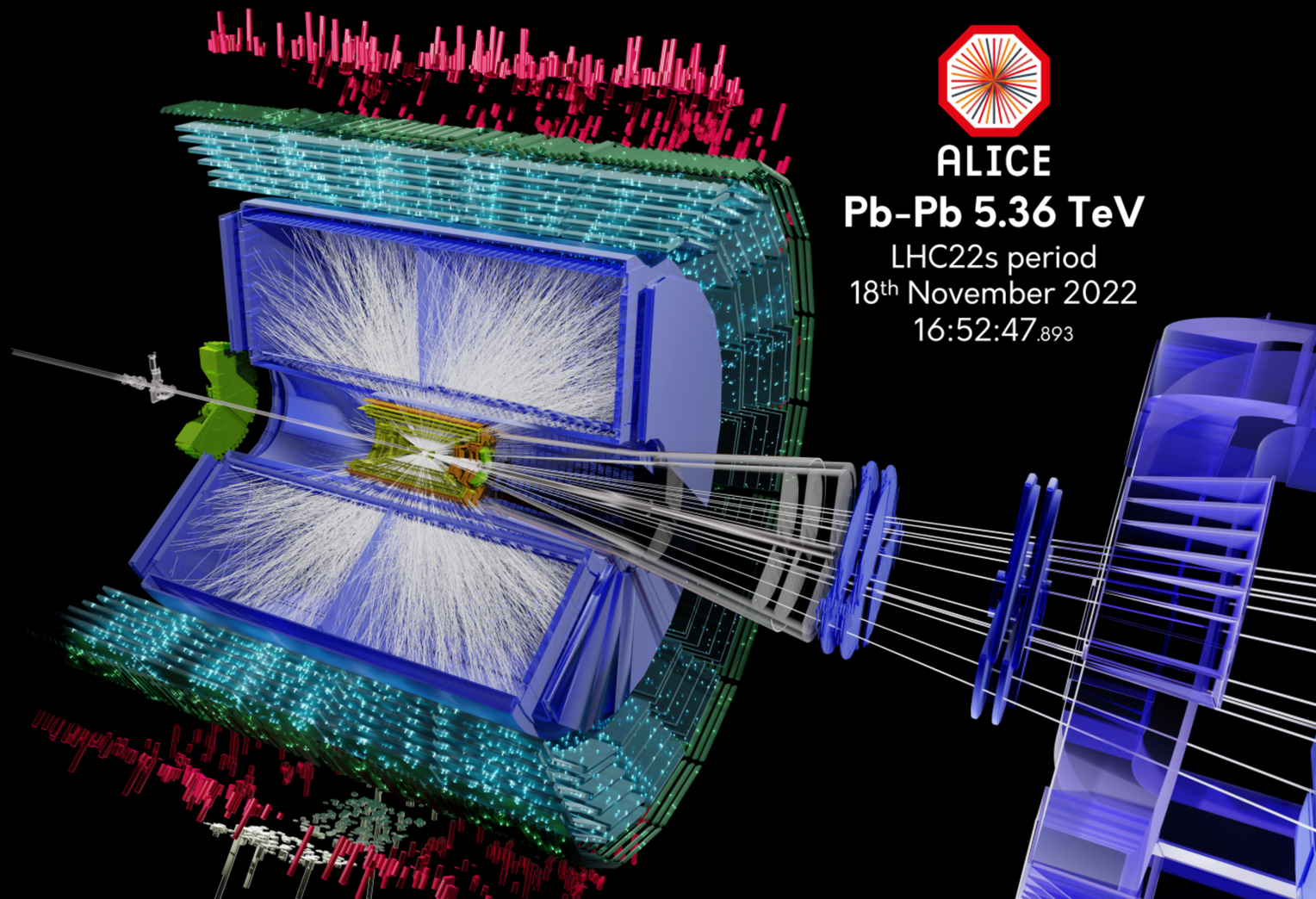
[Phys.Rev.Lett. 132 (2024) 162302]

Combined t-dependence results

- results span three orders of magnitude in t with high precision

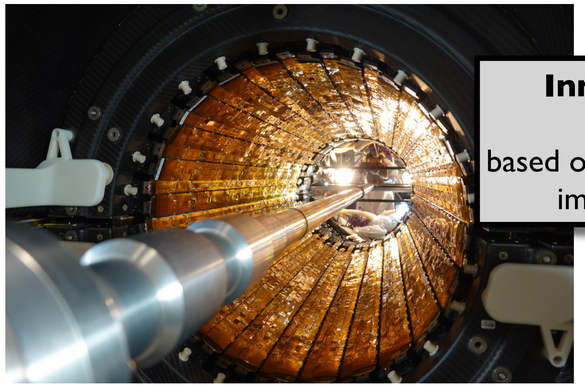


Run 3

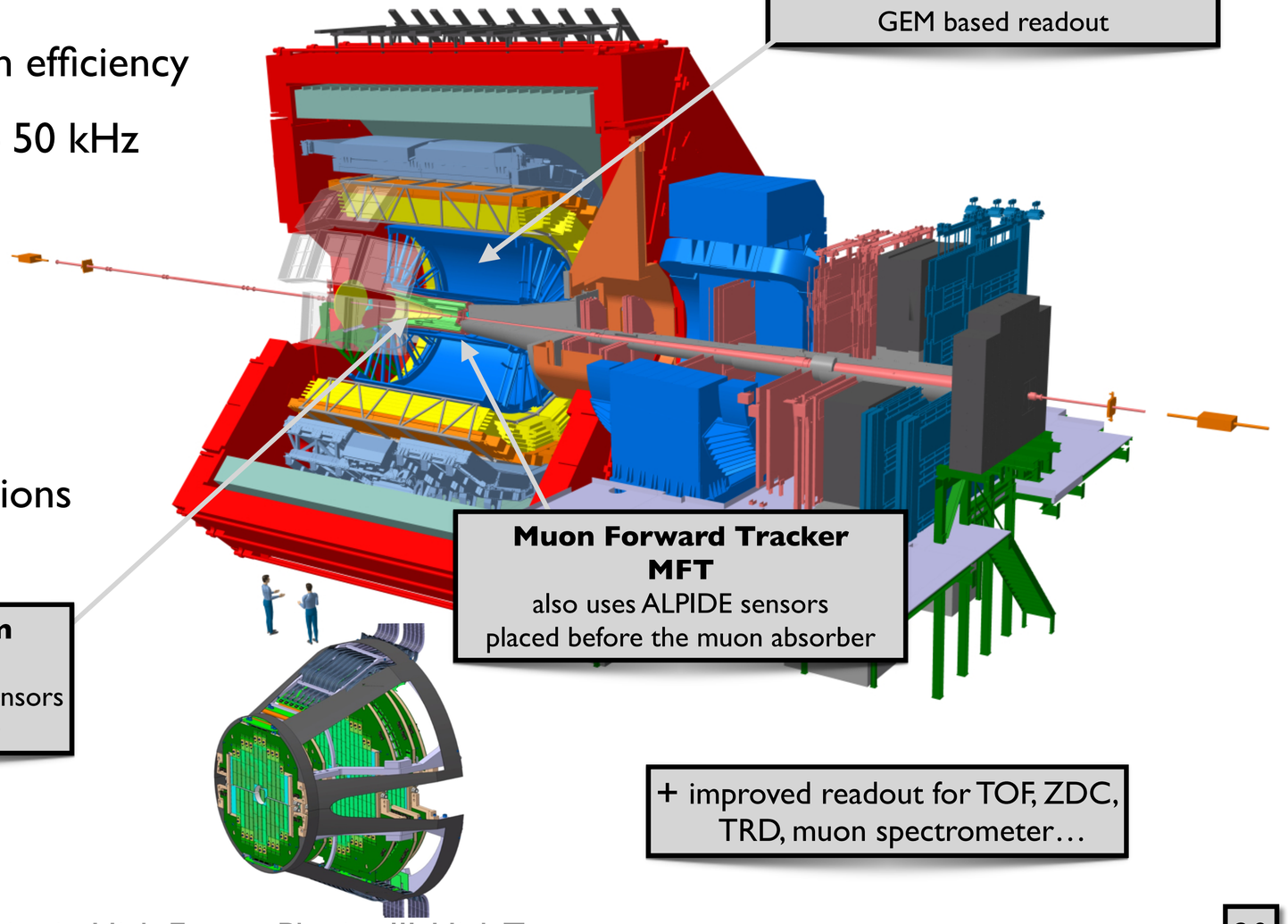

ALICE
Pb-Pb 5.36 TeV
LHC22s period
18th November 2022
16:52:47.893

Upgrades to ALICE in Run 3

- key upgrades for Run 3:
  - continuous readout for higher data acquisition efficiency
    - to handle increased interaction rate, up to 50 kHz for Pb-Pb and 1 MHz for pp collisions
  - increased luminosity
  - improved tracking and PID
  - new capabilities for exclusive event tagging
- possibility to study pp, pPb, Pb-Pb, O-O, pO collisions



Inner Tracking System
ITS
based on MAPS, new ALPIDE sensors
improved space resolution



Time Projection Chamber
TPC
GEM based readout

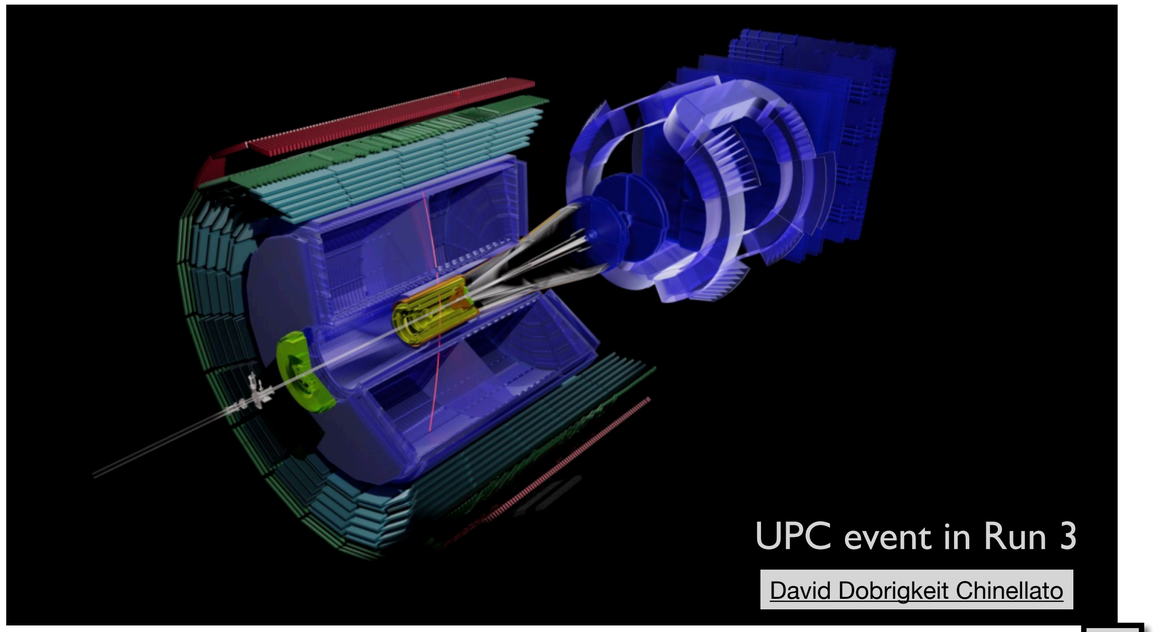
Muon Forward Tracker
MFT
also uses ALPIDE sensors
placed before the muon absorber

+ improved readout for TOF, ZDC, TRD, muon spectrometer…

UPC performance in Run 3

- improved tracking allows more detailed studies of coherent and incoherent processes
- continuous readout
  - efficient data taking without inefficiencies related to trigger
- higher luminosity (0.75 nb^{-1} in Run 2 to 13 nb^{-1} in Runs 3+4)

- first Pb-Pb data taking in September 2023
  - interaction rate up to 45 kHz
  - integrated luminosity ~ 1.5 nb^{-1}
- Pb-Pb data taking in 2024
  - interaction rate regularly at 50 kHz
  - total delivered luminosity ~ 1.98 nb^{-1}



UPC event in Run 3

David Dobrigkeit Chinellato

Run 3: Performance plots

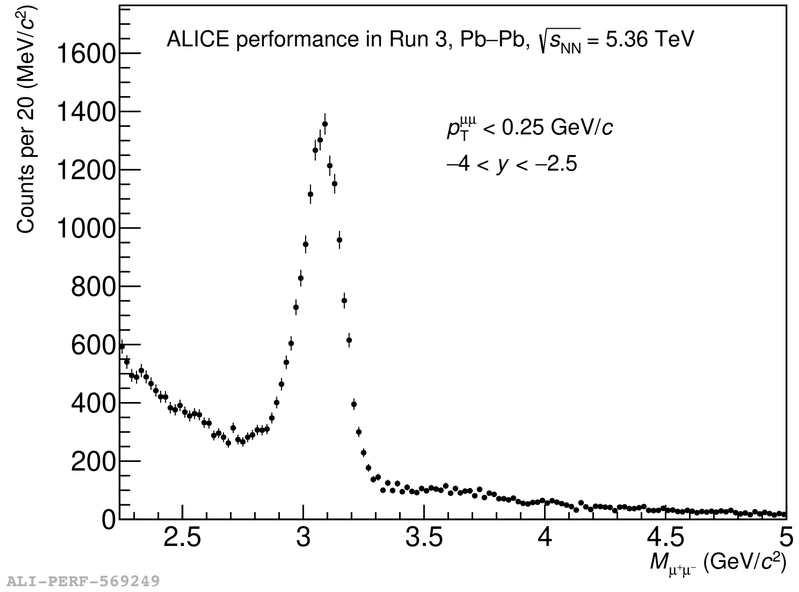
- higher luminosity and improved detector allow for more differential measurements

Z. Citron et al. Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams. 2018.

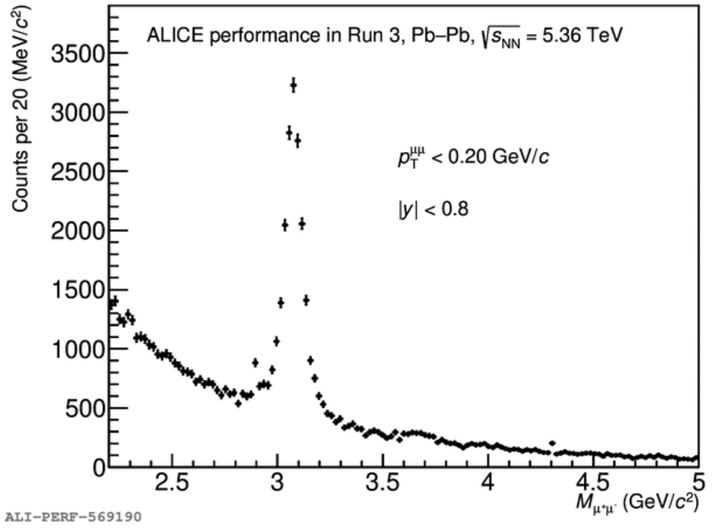
		PbPb				
meson	σ	all	$\|y\| < 0.9$	$\|y\| < 2.4$	$2.5 < y < 4.0$	$2 < y < 5$
		#events	#events	#events	#events	#events
$\rho \to \pi^+\pi^-$	5.2 b	58B	5.5B	21B	4.9B	13B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5B	210M	2.1B	190M	1.2B
$\phi \to K^+K^-$	0.22 b	2.9B	82M	490M	15M	330M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14M	1.1M	5.7M	600K	1.6M
$\psi(2\,S) \to \mu^+\mu^-$	30 μb	400K	35K	130K	19K	47K
$\Upsilon(1\,S) \to \mu^+\mu^-$	2.0 μb	26K	2.8K	14K	880	2.0K

Cross sections and numbers of events in 13 nb^{-1} integrated luminosity corresponding to the expectations of Run 3 and Run 4 for vector mesons in Pb–Pb collisions.

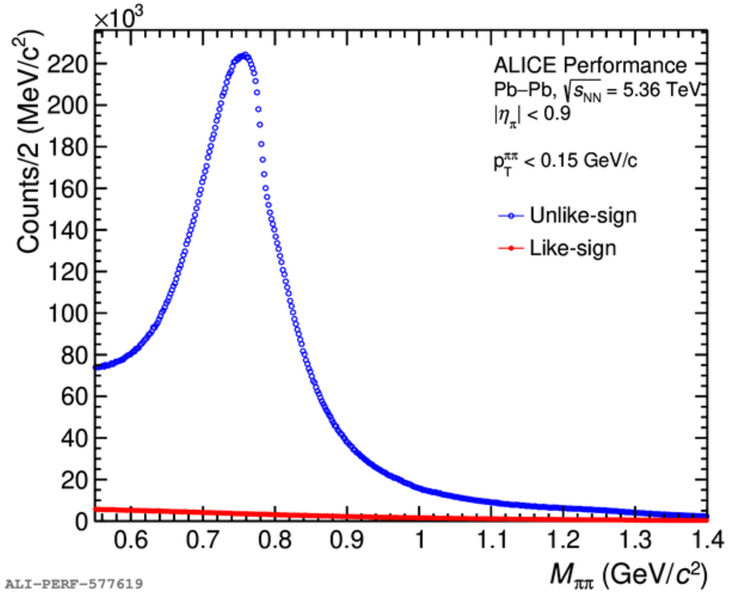
forward rapidity J/ψ candidates



midrapidity J/ψ candidates



midrapidity ρ candidates



Summary

- Run 2 advancements:
  - energy dependence of coherent J/ψ production, dependence of coherent and incoherent J/ψ production on $|t|$
  - insights into high-energy QCD:
    - probing gluon saturation and nuclear shadowing
    - studying fluctuations at sub-nucleon scales
    - models with shadowing or saturation describe the coherent $|t|$ dependence
    - sub-nucleon structure models favored for the incoherent $|t|$ dependence
- Run 3: increased precision, more differential measurements and new measurements

Backup

Models - Energy dependence
References

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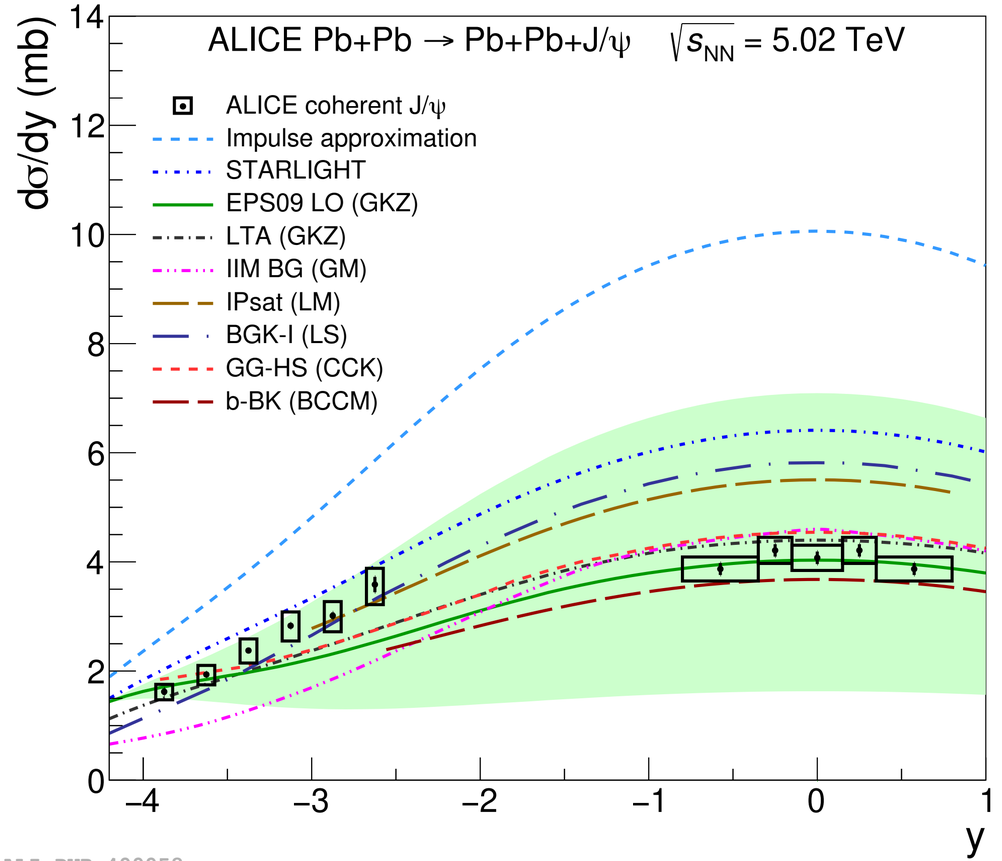

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