ALICE RESULTS RELEVANT TO EIC

L. Massacrier for the ALICE Collaboration,

Laboratoire Irène Joliot Curie (IJCLab), Orsay

Workshop on forward physics and QCD with LHC, EIC and cosmic rays, 20-23rd January, JLab (remote)

OUTLINE

- Quark-gluon plasma studies with HI collisions
- Strategies for quark-gluon plasma studies
- Physics goals identified for the HL-LHC era
- The ALICE apparatus: focus on forward detection (Run 2 and Run 3)
- A selection of p-Pb (and few high multiplicity pp) results relevant for EIC
- A selection of Pb-Pb results relevant for EIC
- Opportunities in ALICE after LS3 relevant for EIC
- Conclusions

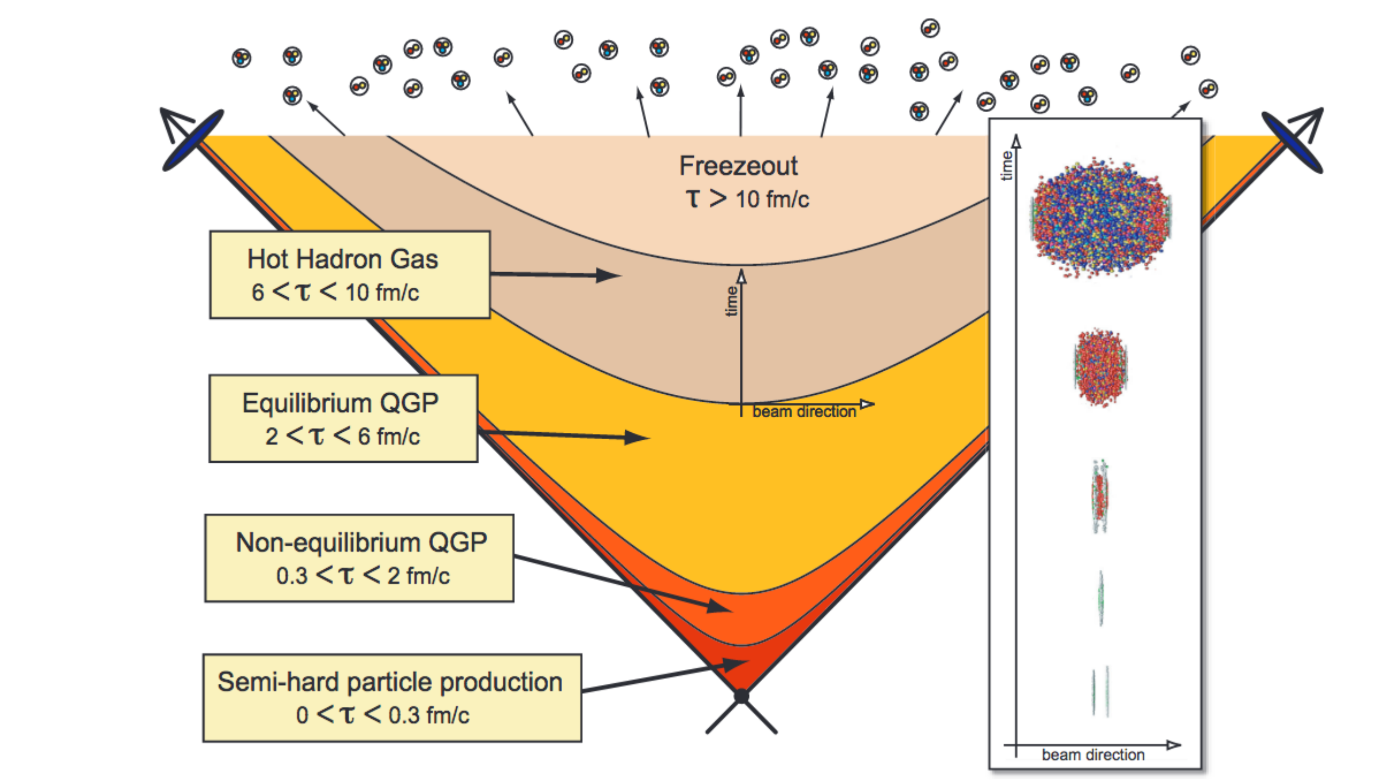
Quark-gluon plasma studies with HI collisions

- Quark-gluon plasma (QGP) is a deconfined state of quarks and gluons predicted by QCD and studied in ultra-relativistic HI collisions

HADRONIZATION
Soft particle production

QGP
Thermal photons and dileptons

INITIAL STATE INTERACTIONS
Production of high-momentum particles (heavy quarks, quarkonia, jets…) via hard scatterings
Hard probes can interact with the QGP



[M. Strickland, Acta Physica Polonica B 45, 2355 (2014)]

EIC can provide valuable inputs for the understanding of the initial stages of the HI collisions with eA collisions
EIC can also help understanding the dependence of hadronization on the underlying environment and the initial state

Strategies for quark-gluon plasma studies

- ❑ Minimum bias pp collisions: the vacuum reference
- ❑ Minimum bias p-A collisions: understanding of cold nuclear matter effects and initial stages of the collision

} but indication of collective effects in high multiplicity pp/p-Pb events

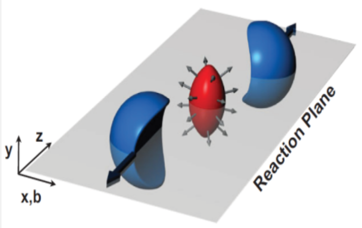
- ❑ A-A collisions: study the QGP by disentangling genuine QGP effects from other effects studied in reference systems

Main observables:

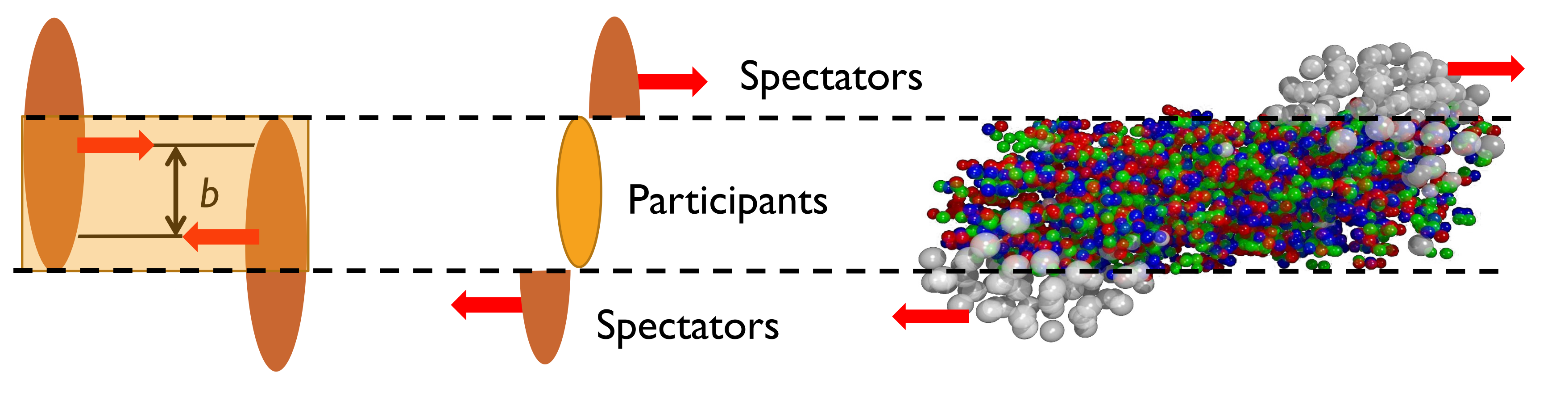
nuclear modification factor (R_{AA})

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

elliptic flow (v_2)



$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi n))$$



To probe the QGP properties:

- Multiple probes, observables
- Differential measurements
- As a function of the collision centrality
- For various system sizes (Pb-Pb, Xe-Xe, O-O?)

Physics goals identified for the HL-LHC era (already starting with Run 3 for ions)

ALICE

see Z. Citron et al., « Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams», arXiv:1902.10229

1 ***Characterize the macroscopic long-wavelength QGP properties (fluid dynamics) with unprecedented precision***

→ temperature, QCD phase transition at μ_B ~0, viscosity, heavy quark transport coefficients …

2 ***Access the microscopic parton dynamics underlying QGP properties***

→ color field strength of the medium, colour screening/regeneration, evolution of collective partonic system to hadronic phase

3 ***Developing a unified picture of particle production from small (pp) to larger (p-A and A-A) systems***

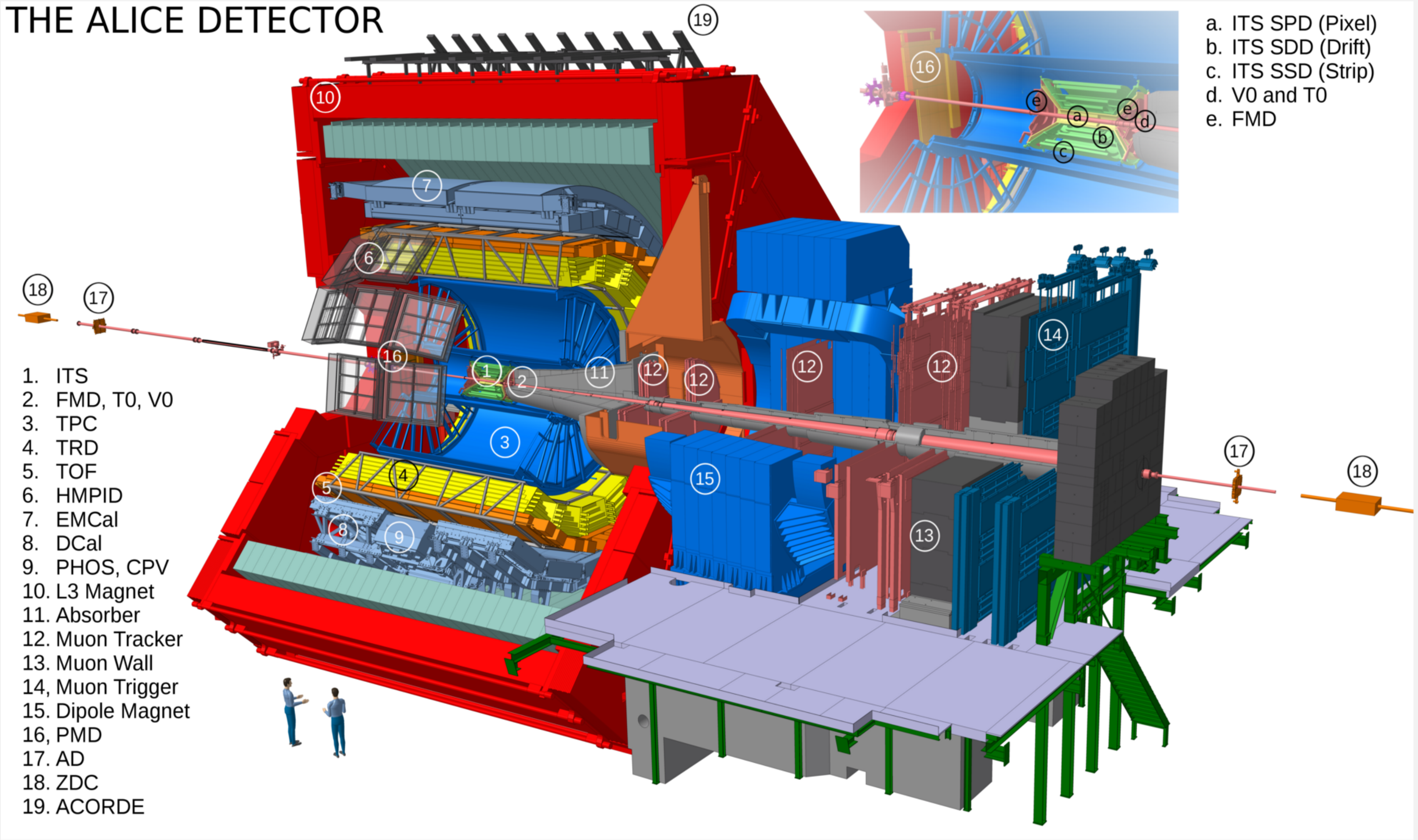
→ flow of heavy flavour and quarkonia, energy-loss, thermal radiation in small systems, strangeness production versus system size

4 ***Probing parton density in nuclei in a broad (x,Q^2) kinematic range and search for parton saturation***

→ constraining nuclear PDFs at high and low Q^2, test saturation effects at small x

→ ep, eA physics at the EIC can provide additional inputs for points 3 and 4

The ALICE apparatus : focus on few forward detectors (Run 2)



V0 counters (scintillators)

V0A: $2.8 < \eta < 5.1$

V0C: $-3.7 < \eta < -1.7$

T0 counters (quartz Cherenkov)

T0A: $4.6 < \eta < 4.9$

T0C: $-3.3 < \eta < -3.0$

Used as trigger, for luminosity determination, for beam-gas rejection

ZDC: ZN+ ZP (quarks fiber sampling calo)

+/- 112 m from IP

Rejection of EM events

AD (scintillators)

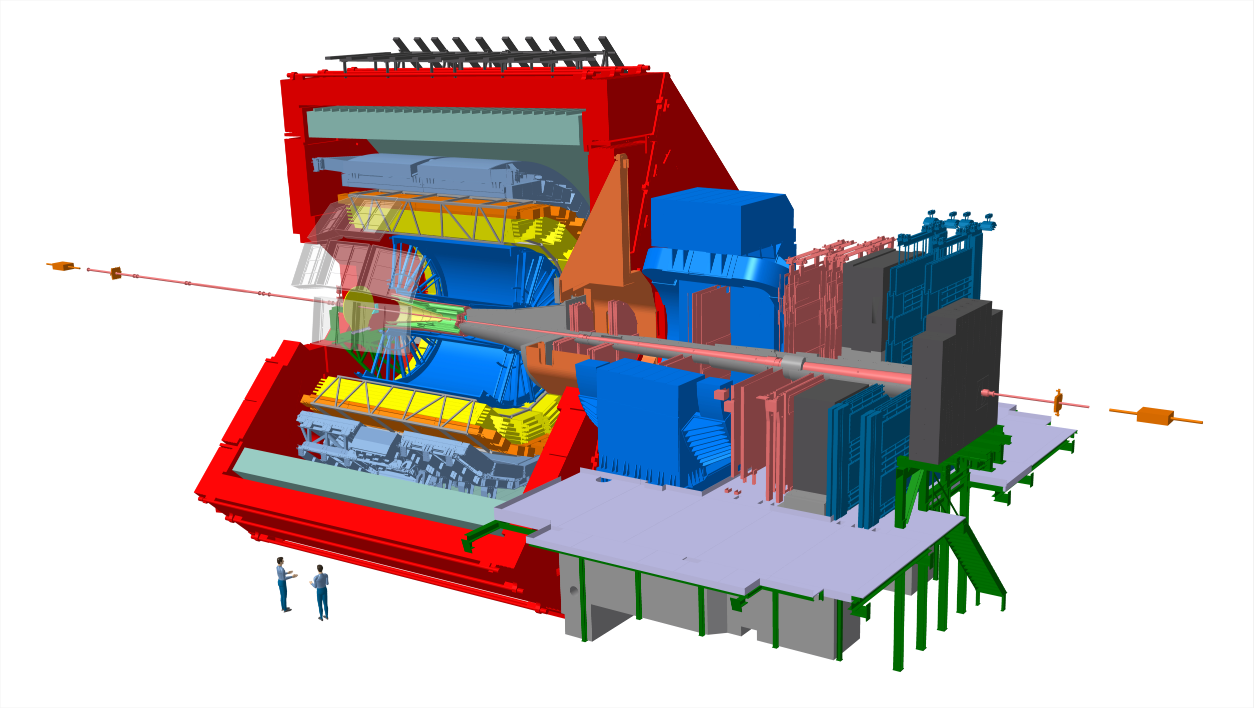
ADA: 16 m from IP, $4.8 < \eta < 6.3$

ADC: -19 m from IP, $-7 < \eta < -4.9$

Diffractive physics, VETO for UPC

Centrality estimators: SPD, TPC, V0, ZDC

The ALICE apparatus after LS2 (Run 3)



50 kHz interaction rate, continuous readout

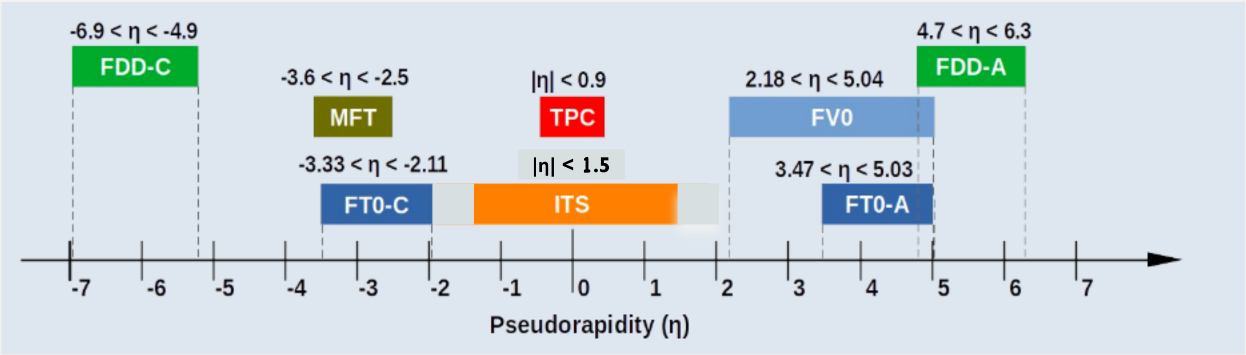
New Inner Tracking System
Improved vertex and tracking precision (closer to IP, smaller pixels, less material)

New TPC readout chambers (GEM)

Readout upgrade (TOF, TRD, MUON, ZDC, Calo)

Integrated Online-Offline system (O^2)

Forward detection



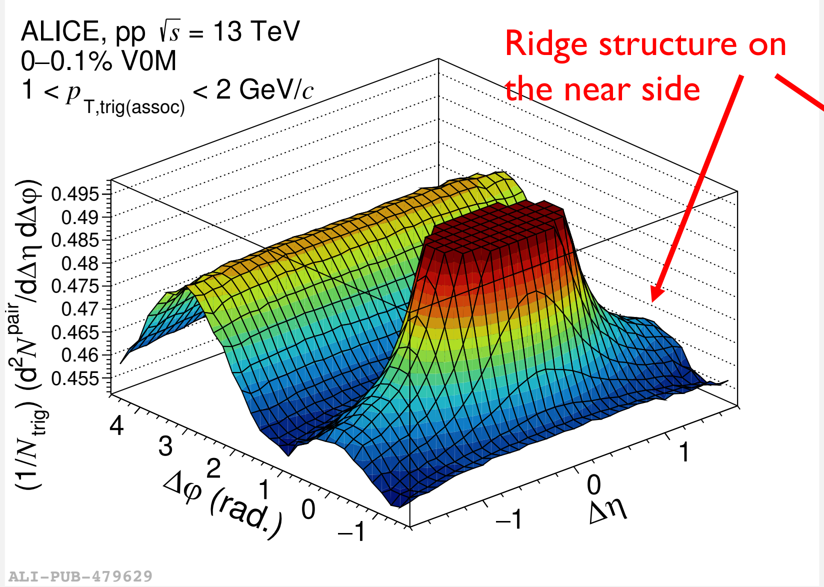
New Muon Forward Tracker (MFT)
CMOS pixels, vertex tracker at forward y

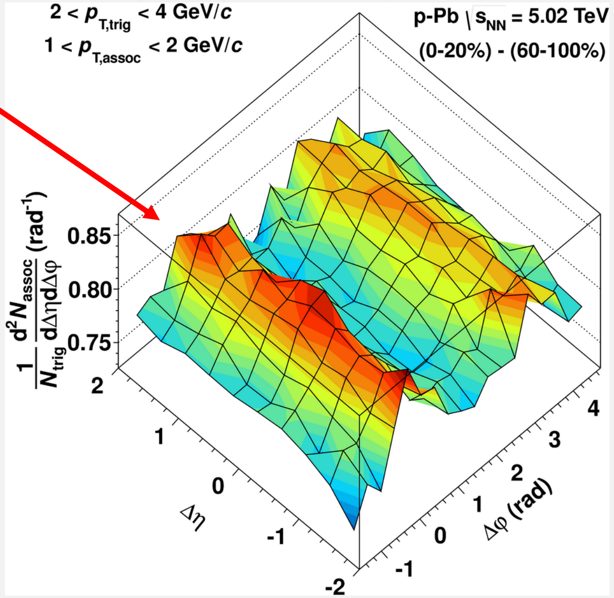
New Fast Interaction Trigger detector (FIT):
Luminosity monitor, fast interaction trigger (online vertex, MB trigger, centrality), Beam-gas rejection, VETO for UPC, diffractive processes

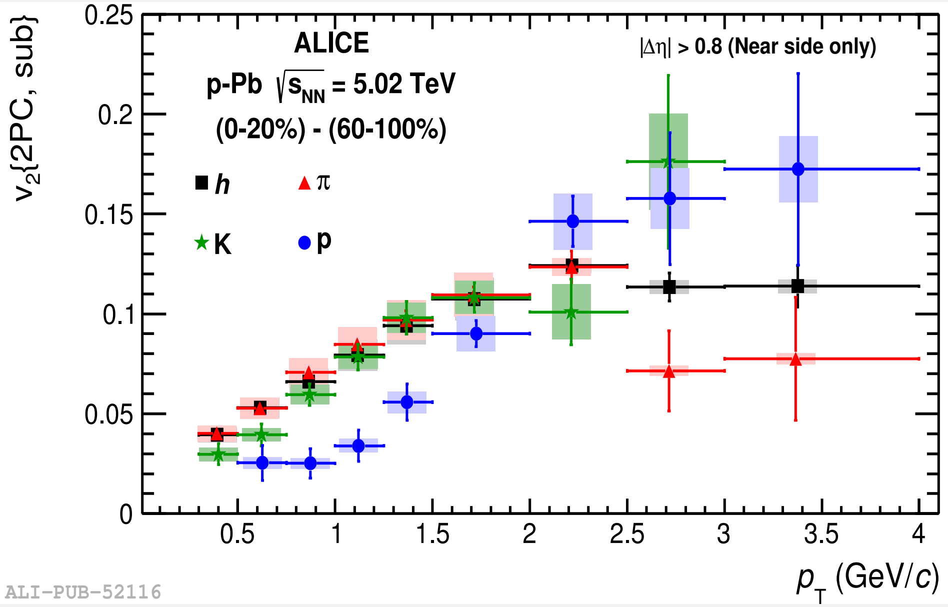
A selection of p-Pb (and few high multiplicity pp) results relevant for EIC

Long-range angular correlations and elliptic flow in small systems

arXiv:2101.03110 | Phys. Lett. B. 719 (2013) 29-41 | Phys. Lett. B. 726 (2013) 164-177



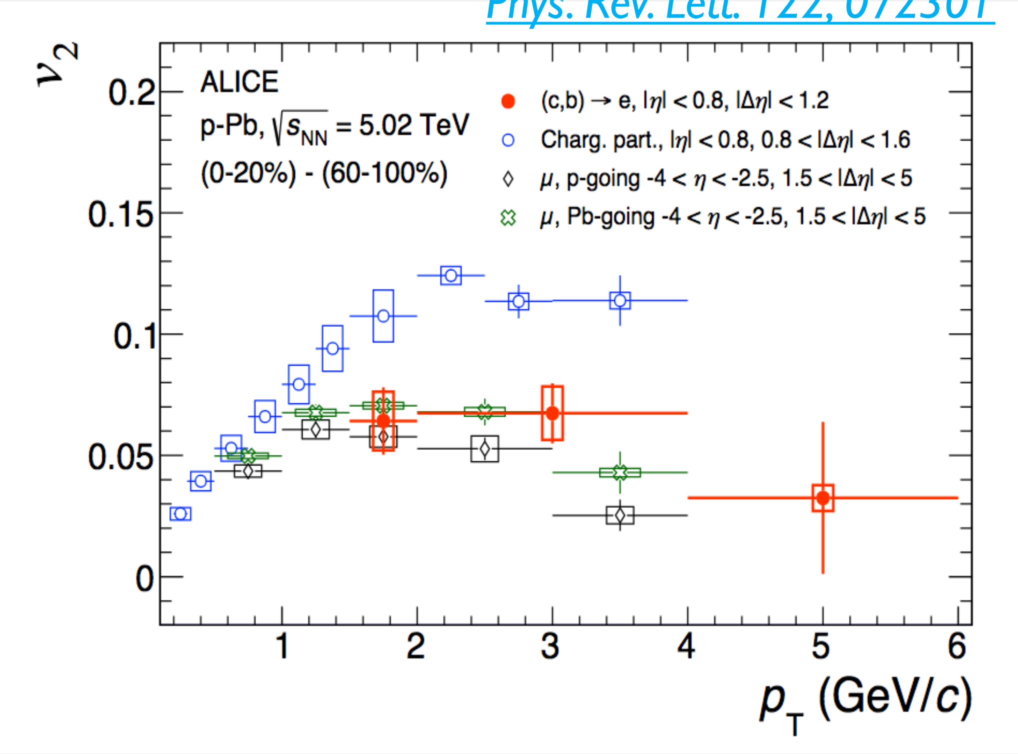




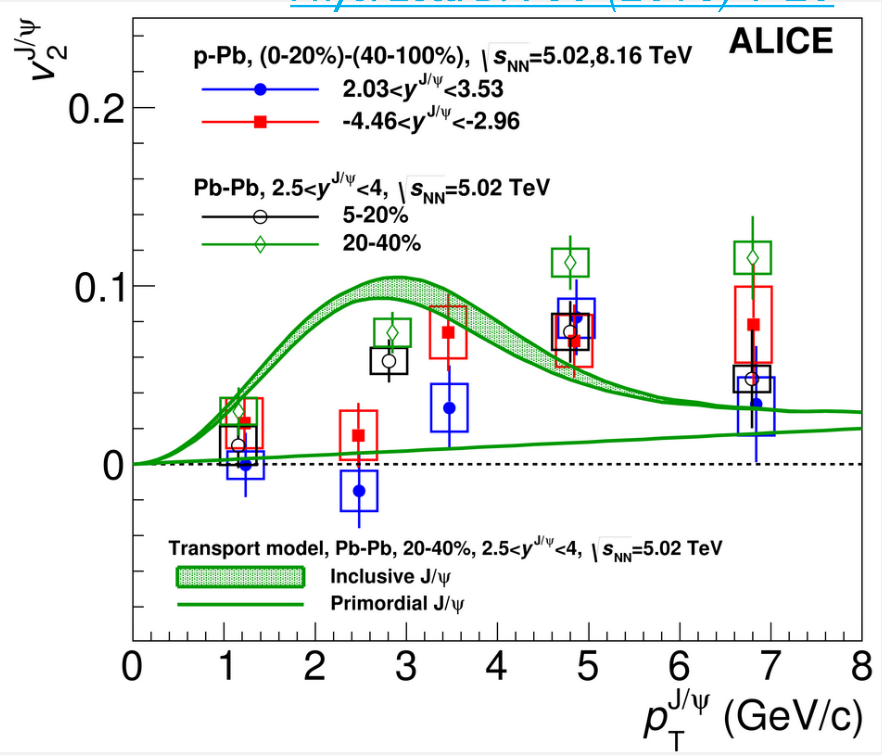
- A long-range angular correlation is observed in small systems (pp, p-A) in high multiplicity collisions. Initial state effect? Final state effect?
- In Pb-Pb it is interpreted as the sign of the collective expansion of the system (together with the hadron mass ordering of the v_2)
- Hadrons also flow in high multiplicity p-Pb events with a mass ordering pattern similar to Pb-Pb!

Elliptic flow of heavy quarks in p-Pb collisions

Phys. Rev. Lett. 122, 072301



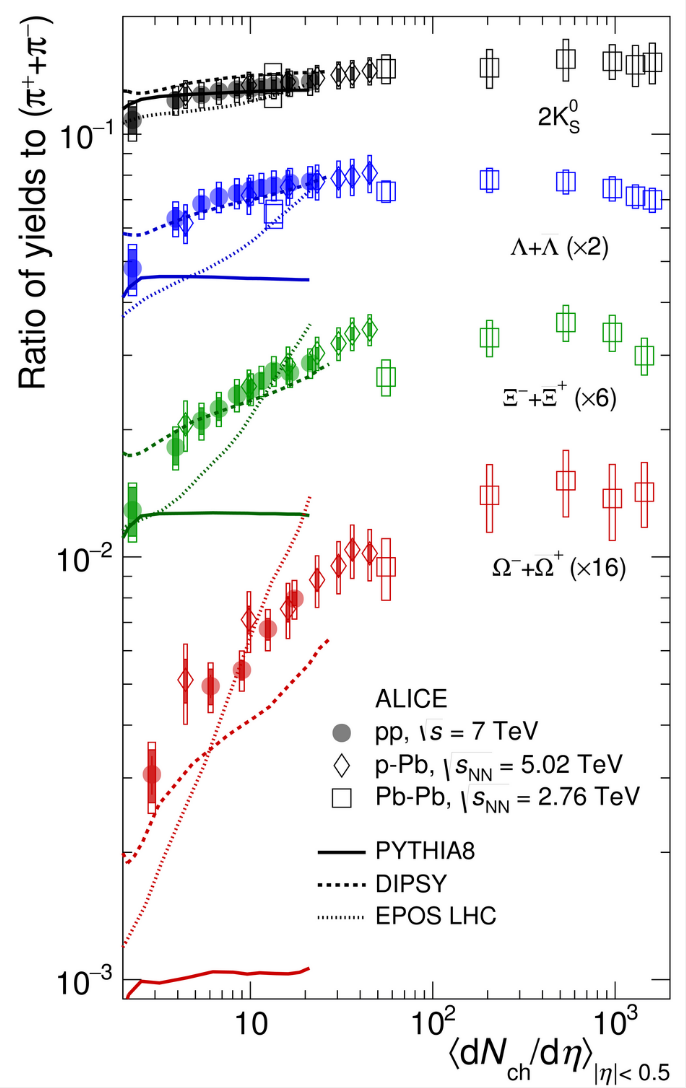
Phys. Lett. B. 780 (2018) 7-20



- Positive HF decay electron v_2 at midrapidity with a significance of 5σ for 1.5 < p_T^e < 4 GeV/c in high-multiplicity p-Pb events. Similar v_2 for inclusive muons at forward rapidity.
- Positive J/ψ v_2 at forward rapidity with a significance of ~5σ for 3 < $p_T^{J/\psi}$ < 6 GeV/c in high-multiplicity p-Pb events. Similar magnitude as in Pb-Pb at high p_T could indicate a similar mechanism at play in both systems
- Collective behavior of heavy quarks in high multiplicity p-Pb collisions?

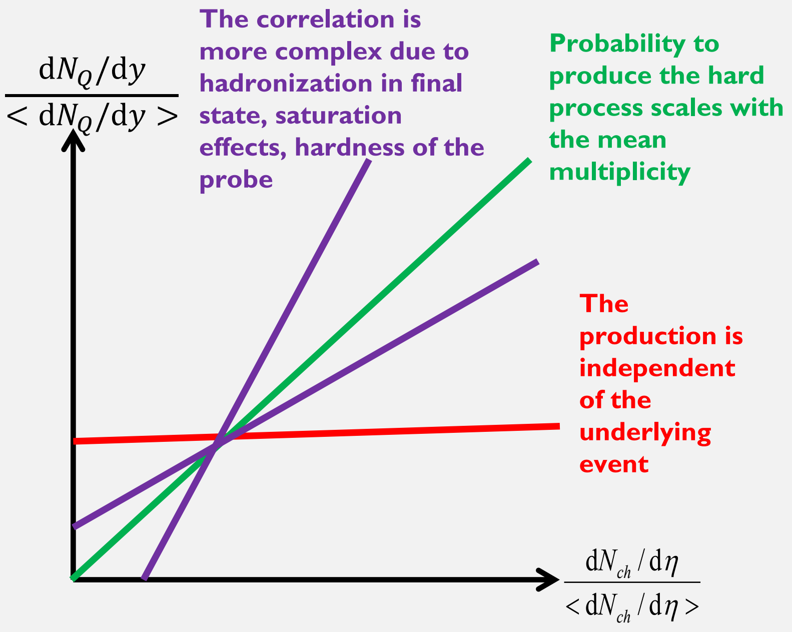
Enhanced production of multi-strange hadrons in small systems

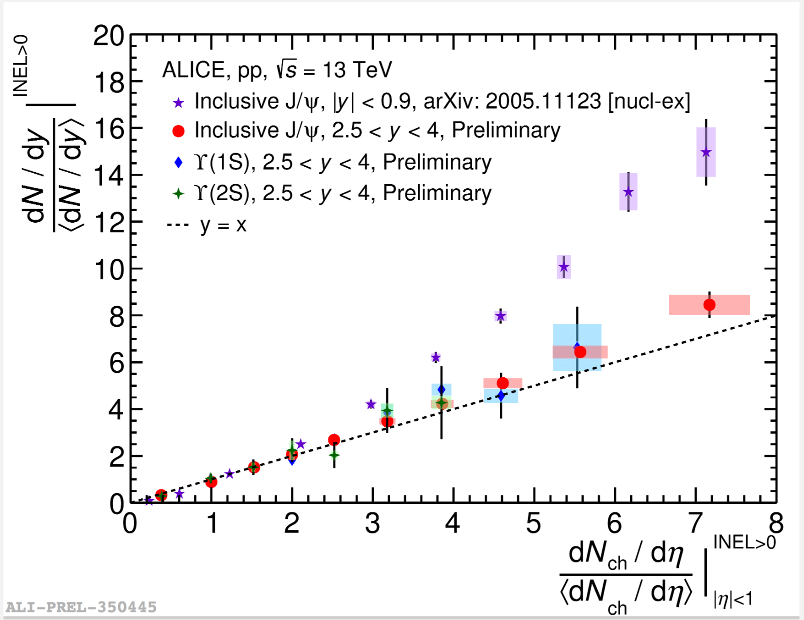
- Significant enhancement of strange to non-strange hadron production observed with increasing multiplicity in pp collisions. The trend is independent of √s from 5 to 13 TeV.
- The observed enhancement increases with the strangeness content rather than mass or baryon number of the hadron
- Similar behaviour as in p-Pb at lower energy in the same multiplicity intervals
- Similar yields reach in high multiplicity pp and in Pb-Pb collisions
- A common underlying physics mechanism?

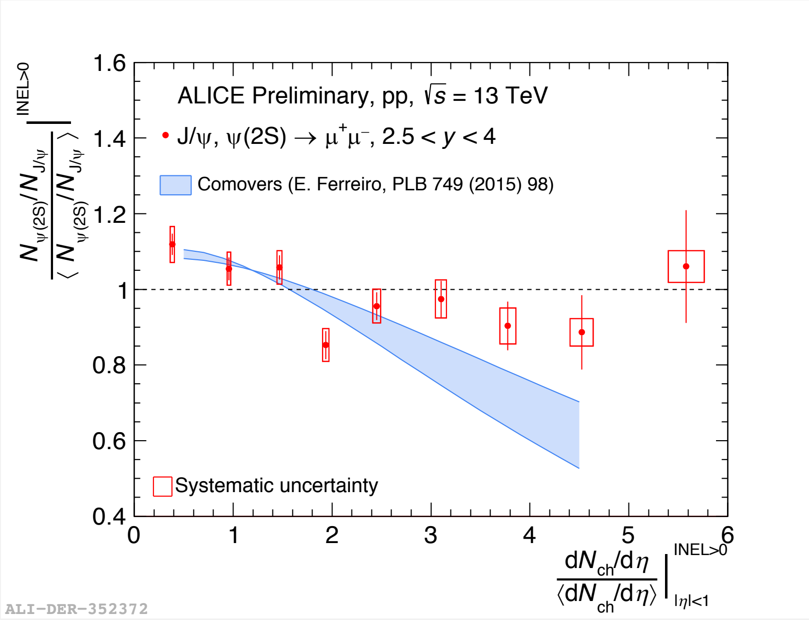


Nature Physics 13 (2017) 535-539

Charmonium and bottomonium production as a function of the charged particle multiplicity in pp collisions





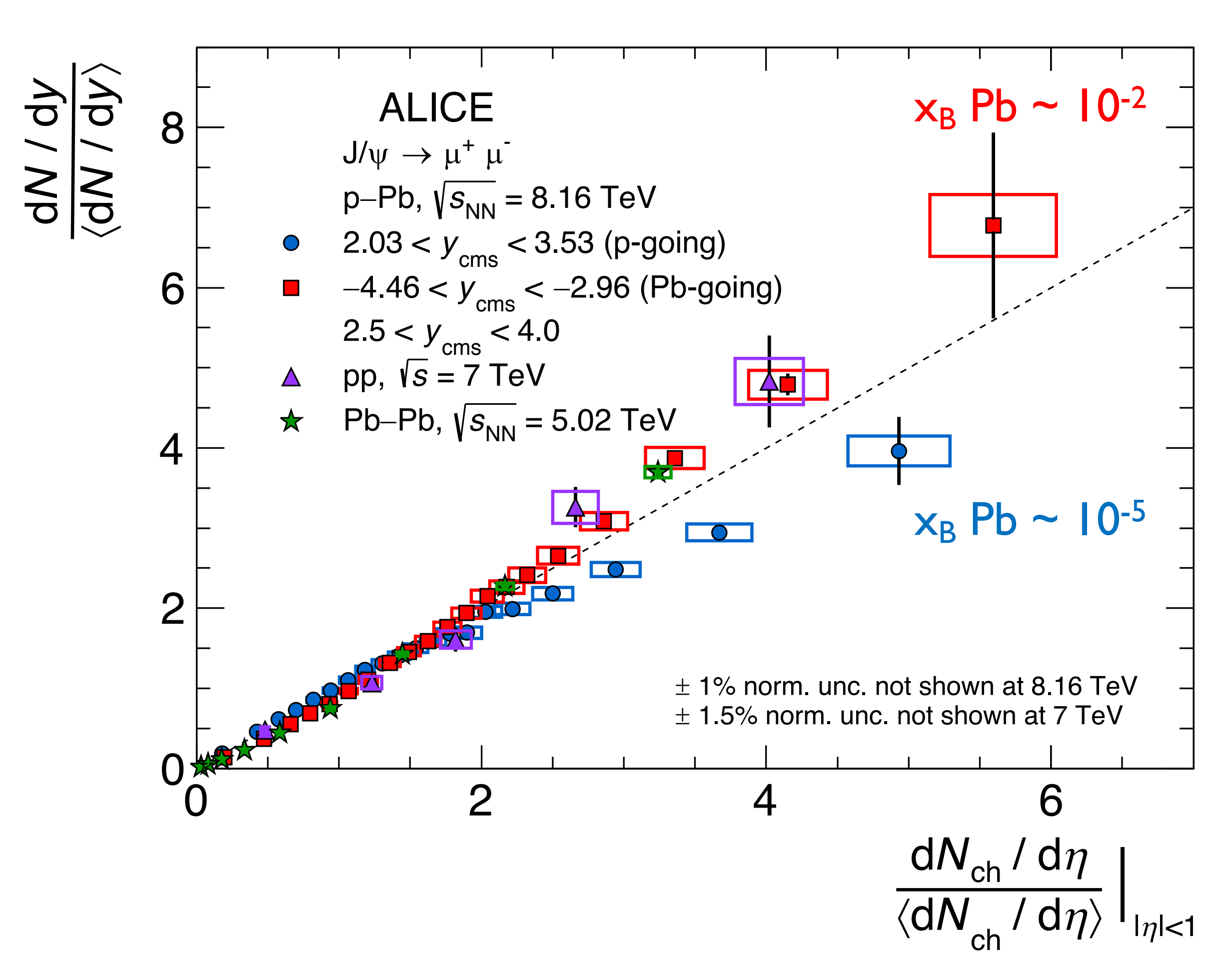


- ❑ Understand the inital state of hadronic collisions in terms of multiparton interactions and study the specific high-multiplicity regime. Correlation of soft and hard processes.
- ❑ At forward rapidity, linear increase of the J/ψ, Υ(1S), Υ(2S) self-normalized yields with the charged-particle mutliplicity.
- ❑ At midrapidity, stronger than linear increase for the J/ψ self-normalized yields with the multiplicity.
- ❑ ψ(2S) / J/ψ ratio no strong dependence with multiplicity. Suppression stronger in comover model (final state interactions).

Charmonium and bottomonium production as a function of charged particle multiplicity in p-Pb

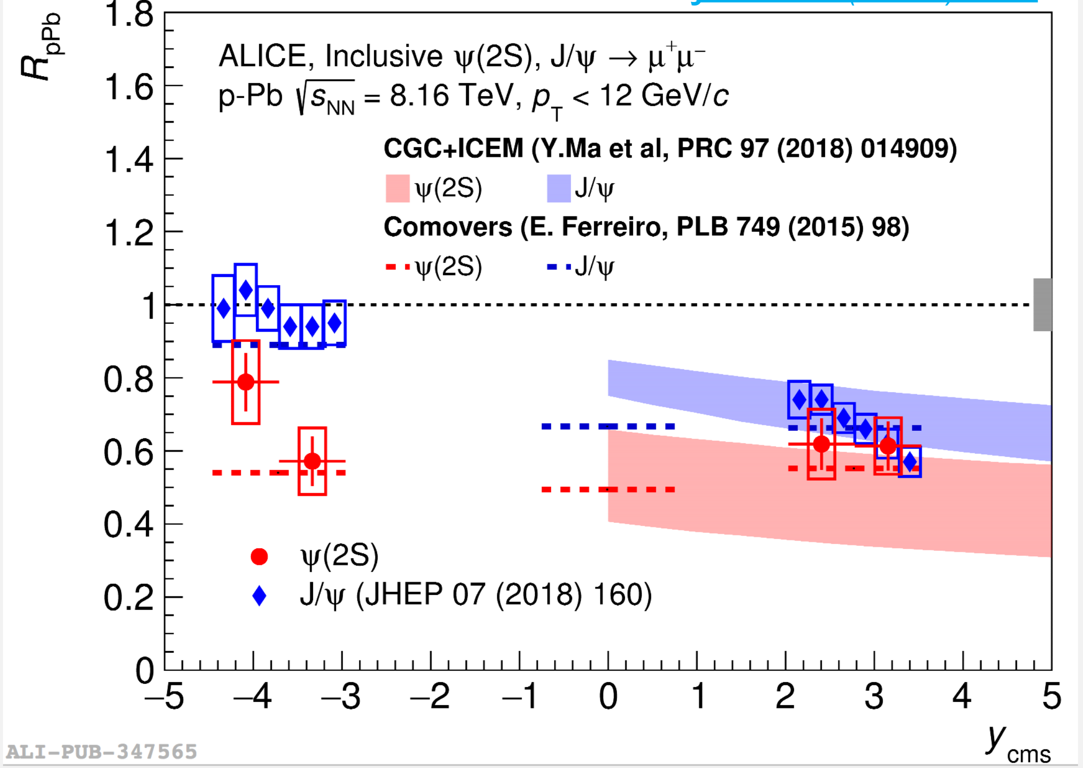
JHEP 2009 (2020) 162

- Yield at backward rapidity (Pb-going) increases faster than at forward rapidity (p-going)
- Slower than linear increase at forward rapidity. Stronger CNM effects at forward rapidity (shadowing/saturation)
- Underlying mechanism not clear. Comparison with models suggest a J/ψ production from an incoherent superposition of parton-parton interaction
- Similar evolution of the J/ψ self-normalized yield with multiplicity for pp, p-Pb (backward) and Pb-Pb systems

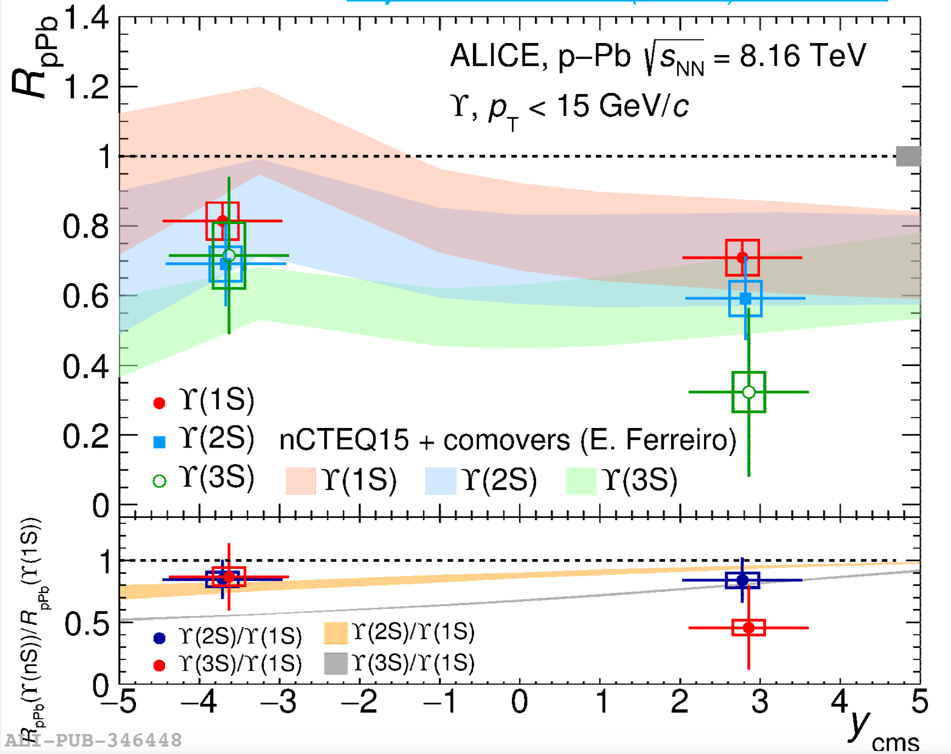


Suppression of quarkonium excited states in p-Pb collisions

JHEP 07 (2020) 237



Phys. Lett. B. 806 (2020) 135486

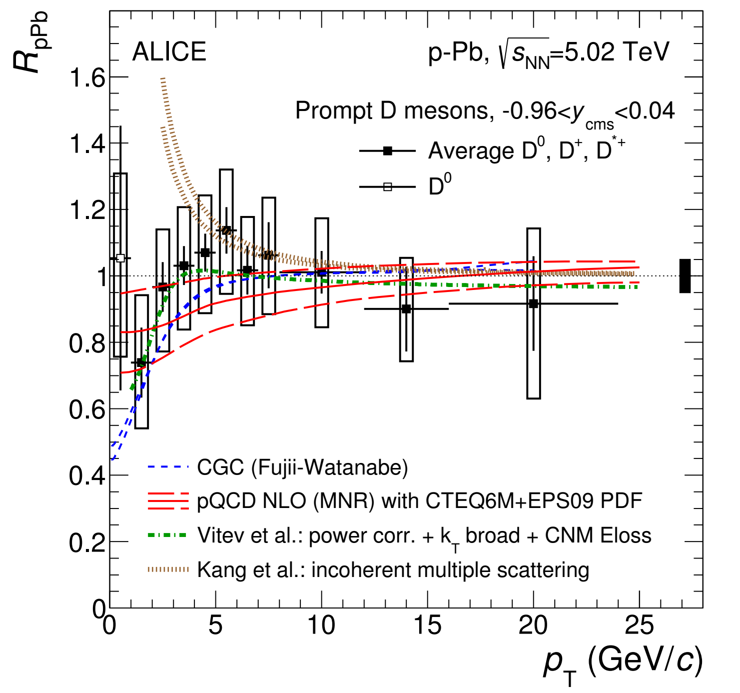


- ❑ Stronger suppression of the ψ(2S) w.r.t J/ψ at backward rapidity. Nuclear shadowing, energy loss cannot reproduce the backward rapidity ψ(2S). Need additional final state interactions (e.g comovers).
- ❑ Large experimental uncertainties on the measurement of the Υ excited states R_{pPb}. No firm conclusion yet on the role of final state interactions in the bottomonium sector.

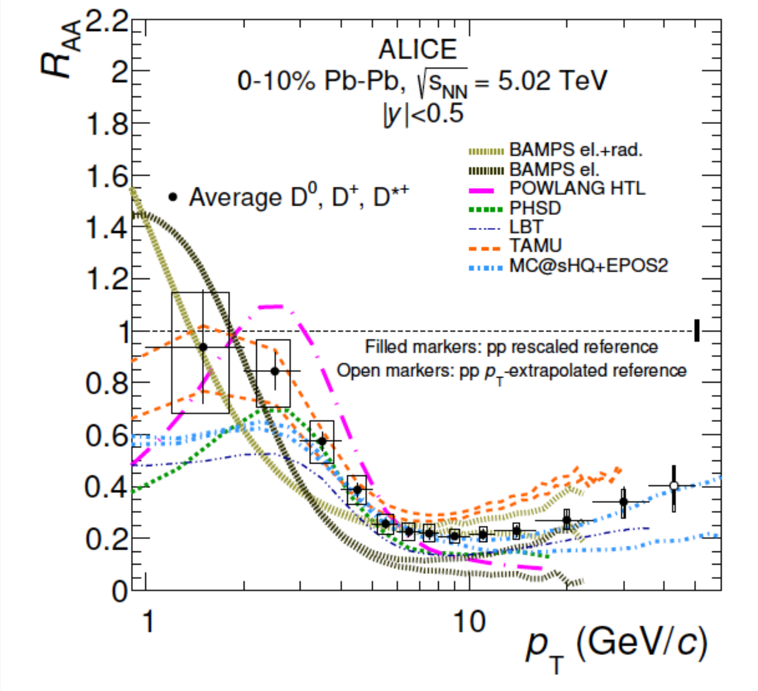
Heavy flavour nuclear modification factor (p-Pb vs Pb-Pb)

ALICE

Phys. Rev. C. 94.054908

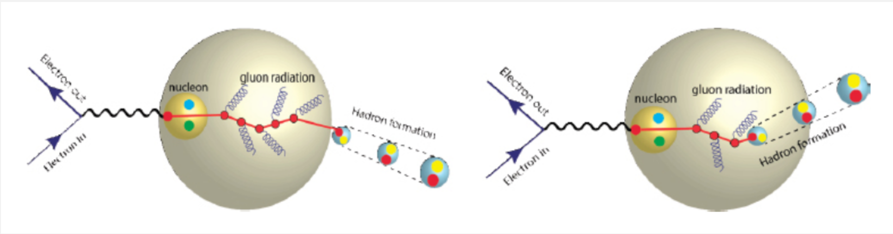


JHEP 10 (2018) 174



- D meson R_{pPb} compatible with unity within the large experimental uncertainties at low p_T
- At low p_T and midrapidity, mild sensitivity to shadowing regime
- R_{pPb} compatible with models including CNM effects (CGC, nPDF, eloss)
- Strong suppression of R_{AA} observed in Pb-Pb attributed to final state effects induced by the interaction of *c* quarks with the hot medium (in-medium energy loss)

eA collisions: clean tools to study hadronization in cold nuclear matter. Clean measurements of medium induced energy loss and study of hadronization outside the nucleus



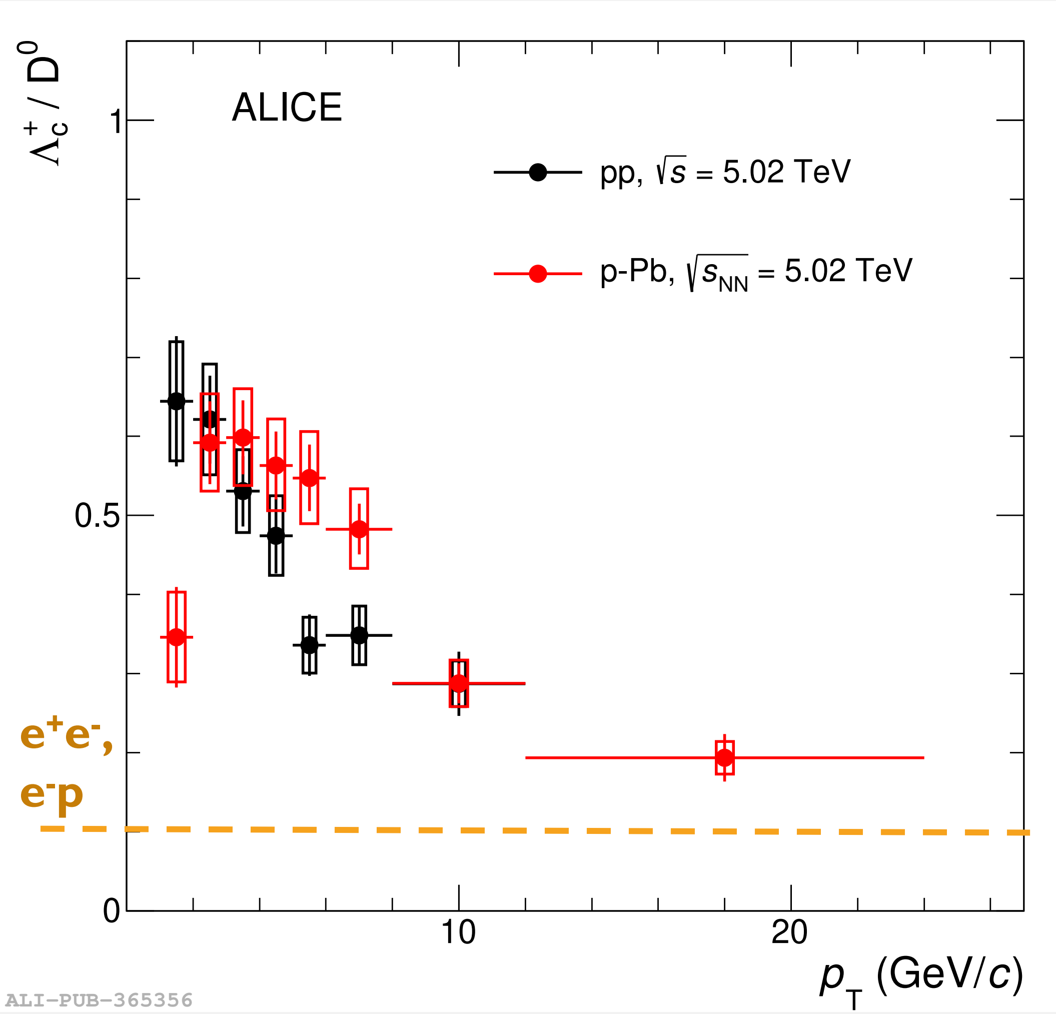
Baryon-to-meson ratio Λ^+_c/D^0 in pp and p-Pb

ALICE

arXiv:2011.06079

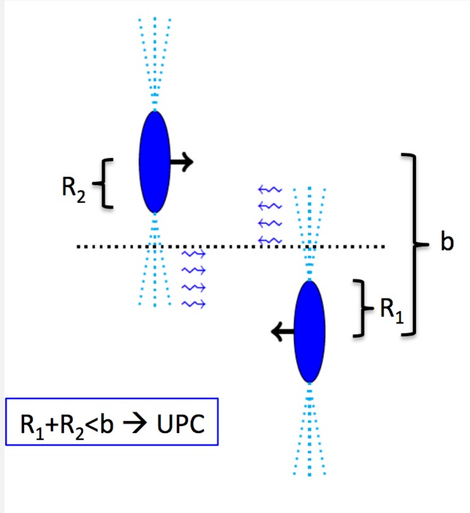
- Qualitatively similar p_T-dependent Λ^+_c/D^0 ratio in pp and p-Pb collisions
- Ratio significantly larger than previous measurements in e^+e^-, e^-p collisions
- Indication that the fragmentation fractions of charm quarks into baryons are not universal (collision system independent)

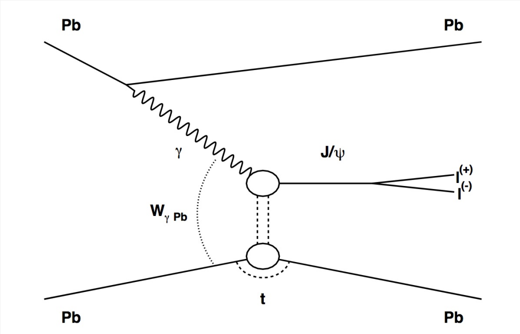
Interesting to study the ratio at EIC down to low p_T in ep and eA collisions



A selection of Pb-Pb results relevant for EIC

Vector meson photoproduction in ultra-peripheral collisions

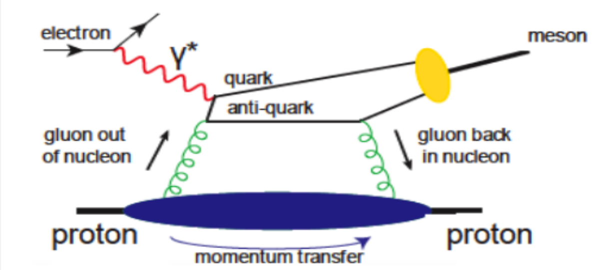




- The EM field of Pb nuclei described as beam of quasi-real photons ($N\gamma \propto Z^2$)
- In UPC, hadronic interaction strongly suppressed.
- Photoproduction of vector meson (VM) in UPC with clean experimental signature:
  - Very low p_T production, large rapidity gaps
- Provides information on gluon saturation in the proton and shadowing in nuclei at low x
- At LO in collinear approach

$$\left.\frac{d\sigma_{\gamma A \rightarrow J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

Ryskin: Z. Phys. C 57, 89 (1993)



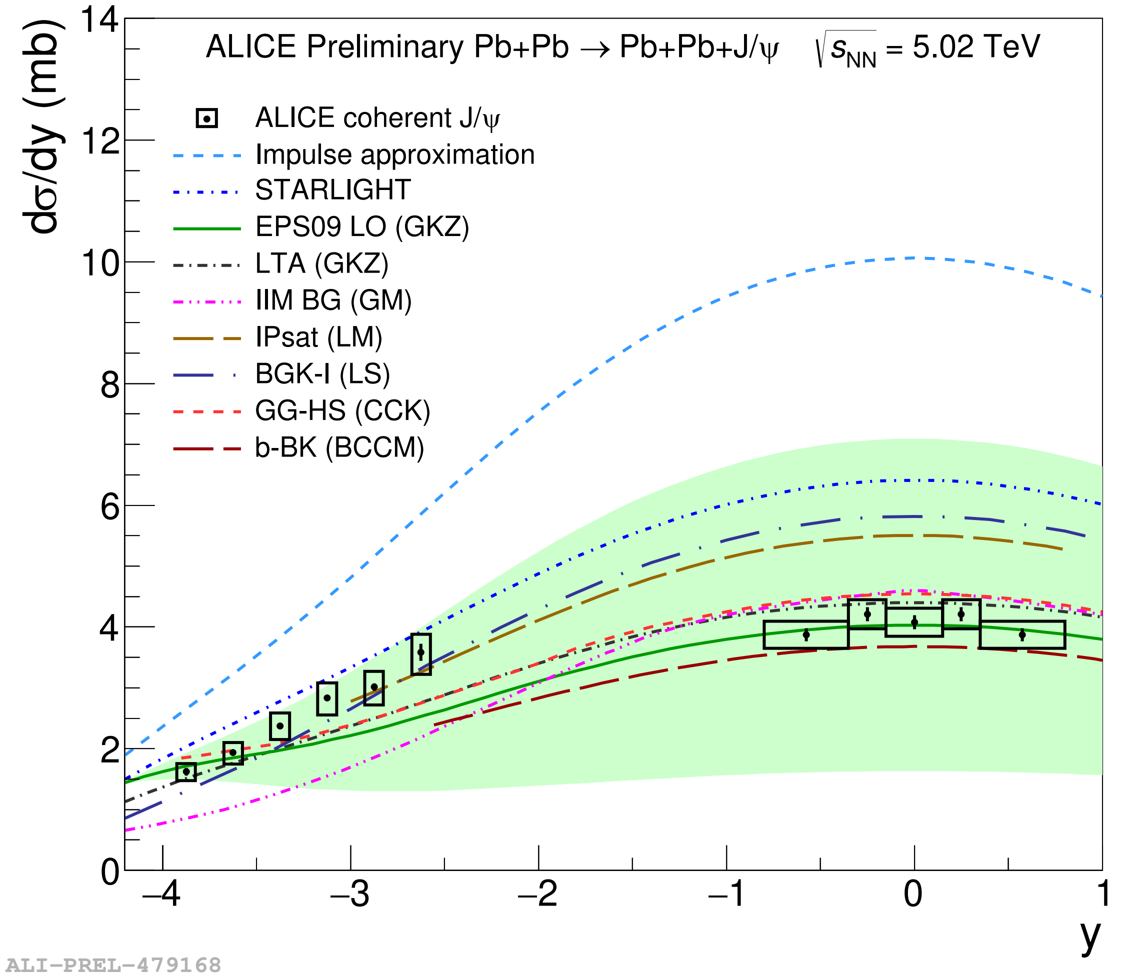
Complementarily diffractive/exclusive production of heavy quarkonia at EIC can probe the gluon distributions in proton and nuclei

Rapidity dependence of coherent J/ψ photoproduction in Pb-Pb

ALICE

arXiv:2101.04577

- Inclusion of new midrapidity data
- Comparison of data to impulse approximation (no nuclear effects) leads to a nuclear suppression factor $S_{Pb}(x \sim 10^{-3}) \sim 0.65 \pm 0.03$
- STARLIGHT model (no gluon shadowing) overpredicts the data
- GKZ with EPS09 shadowing and the GG-HS (colour-dipole model with hot spots and including saturation) agree with data at forward and midrapidity, but not at semi-forward rapidity (2.5 < y < 3.5). The data might be better explained with a model where shadowing has a smaller effect in this Bjorken-x region.

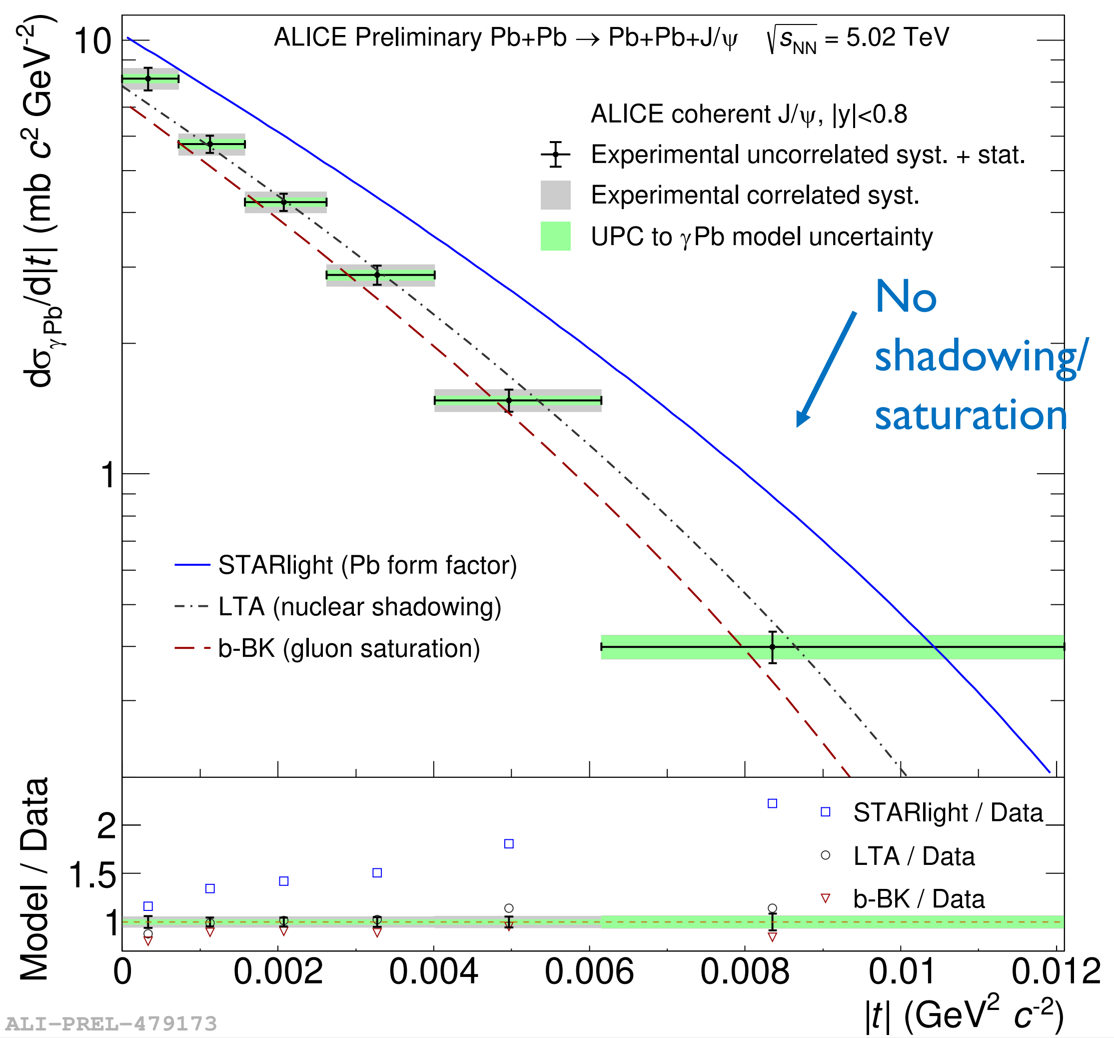


|t| dependence of coherent J/ψ photoproduction in Pb-Pb

ALICE

arXiv:2101.04623

- The first measurement ever of the |t|-dependence of the J/ψ photonuclear production cross section
- |t| obtained from J/ψ p_T^2 measurement + unfolding
- Access to the distribution of gluons in the impact-parameter plane
- STARLIGHT calculation (Pb form factor) without shadowing/saturation overpredicts the data → existence of QCD dynamical effects
- Models incorporating nuclear shadowing (LTA) or gluon saturation (b-BK) describe well the data



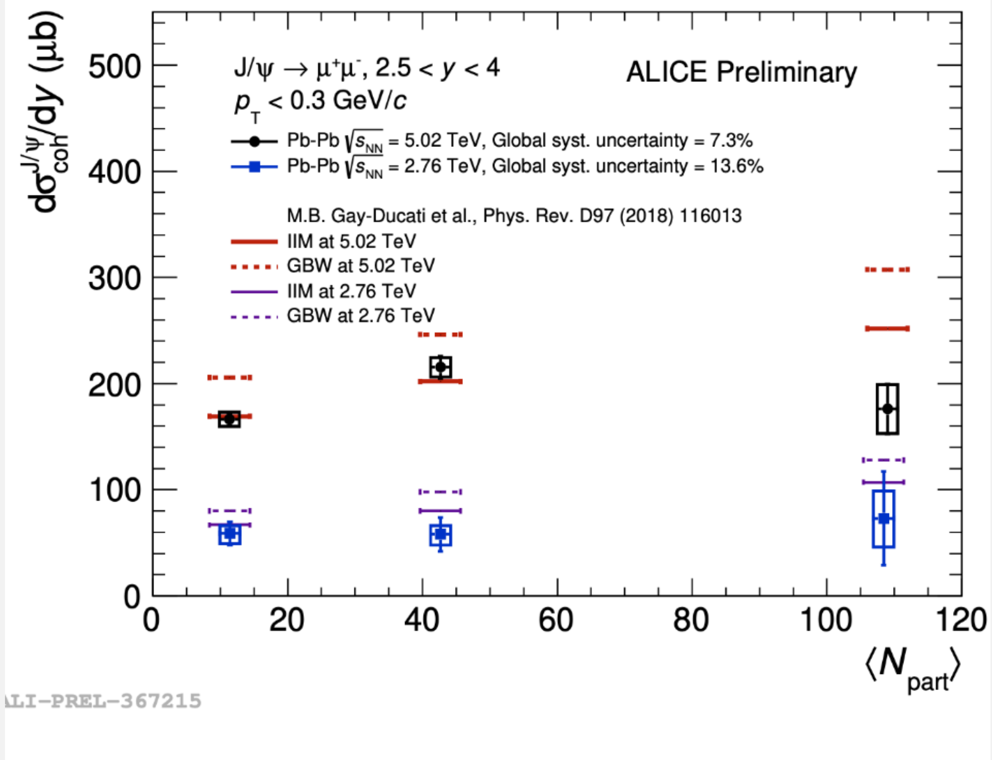
Coherent J/ψ photoproduction in Pb-Pb collision with nuclear overlap

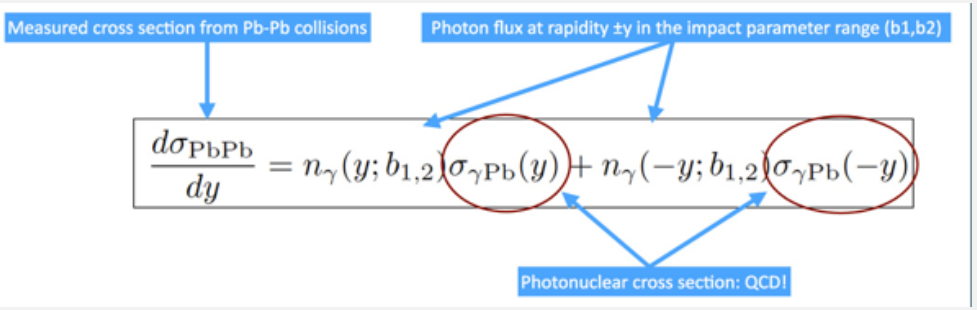
- An excess in the J/ψ yield attributed to coherent J/ψ photoproduction in peripheral and semicentral Pb-Pb collisions was also measured at $\sqrt{s_{NN}}$= 2.76 and 5 TeV

- Opens new theoretical challenges: how can the coherence survive when the nuclei is broken by the hadronic interaction? Do only spectator nucleons participate to the coherence?

- UPC-like models with modification of the photon flux can reproduce the peripheral data. In semicentral event need to account for the modification of the photonuclear cross section and various coupling scenarios (N+N, S+N, S+S)

- Coupled to UPC measurement, a potential novel way to measure $\sigma_{\gamma Pb}$
  J. G. Contreras, Phys. Rev. C96, 015203 (2017)





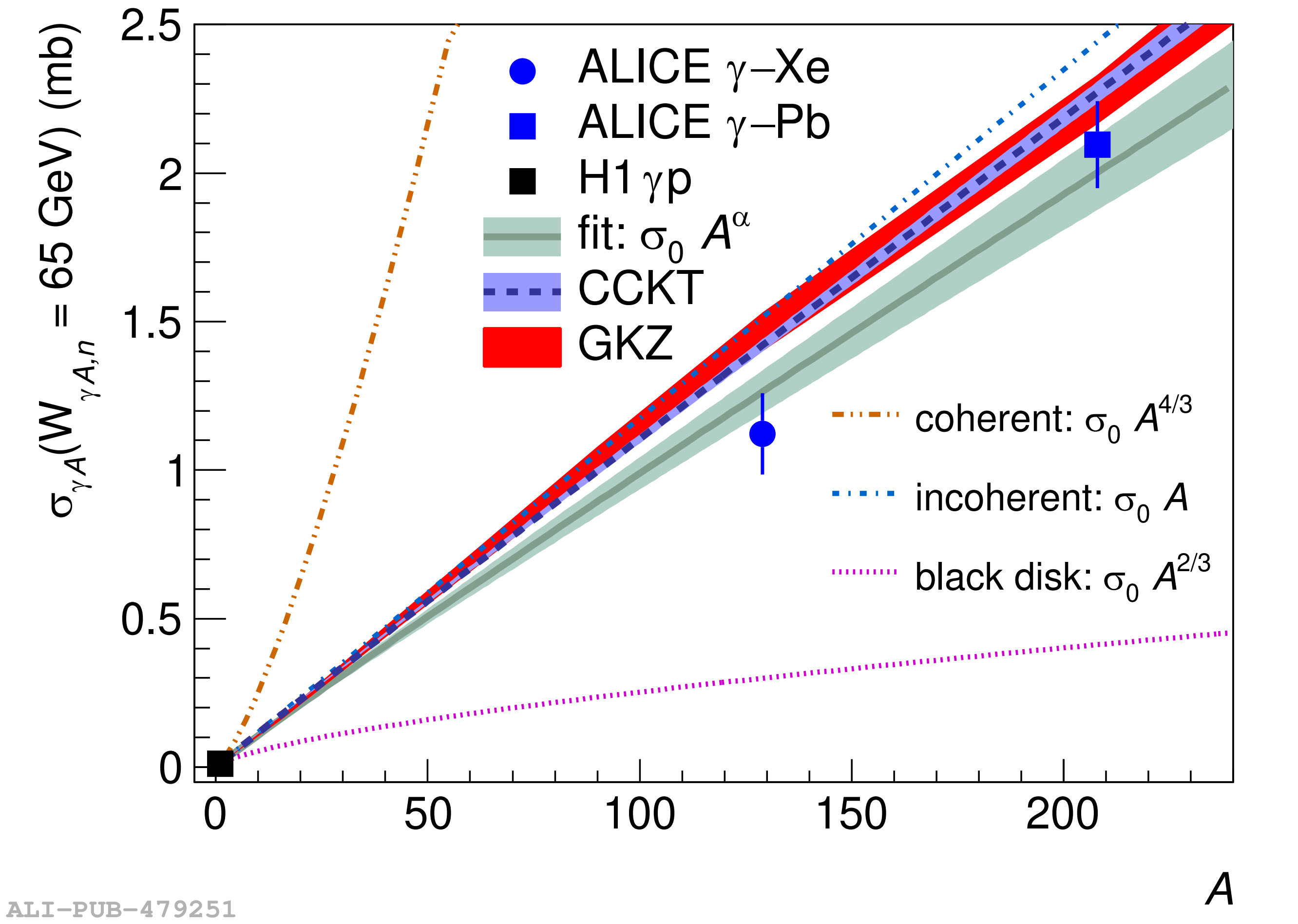
$$\frac{d\sigma_{\mathrm{PbPb}}}{dy} = n_\gamma(y;b_{1,2})\sigma_{\gamma\mathrm{Pb}}(y) + n_\gamma(-y;b_{1,2})\sigma_{\gamma\mathrm{Pb}}(-y)$$

A dependence of coherent ρ^0 photoproduction in Xe-Xe and Pb-Pb

- The A dependence of the ρ^0 photonuclear cross section is explored with two collision systems: Xe-Xe and Pb-Pb → study A dependence of CNM effects

- Measured slope of cross section with A:
  - Approximately linear
  - Close to model with strong nuclear effects (GKZ, CCKT)
  - Lower than expectations from coherent processes with no nuclear effects, but much larger than black-disk limit

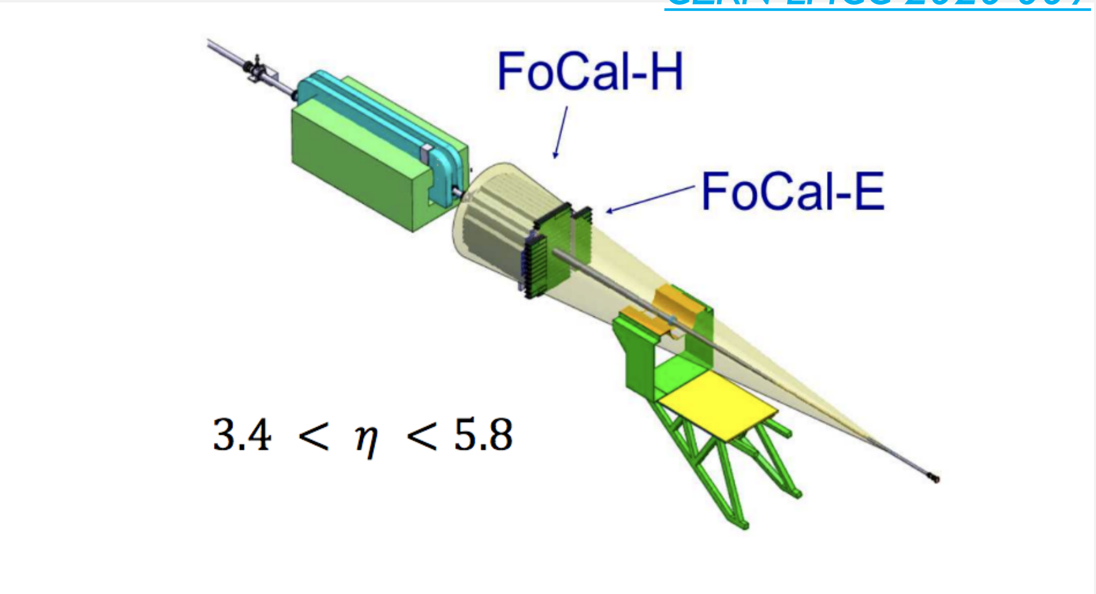
arXiv:2101.02581

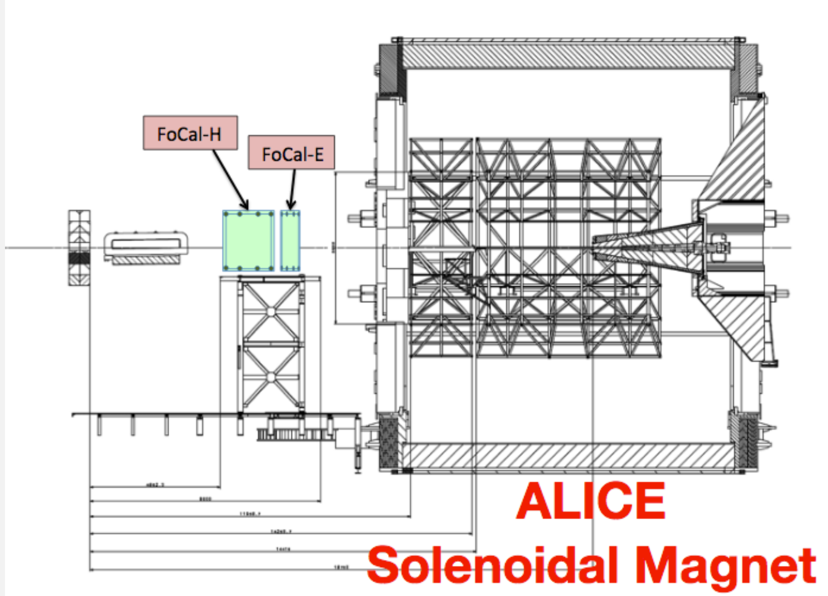


Opportunities in ALICE after LS3 (2024-2026) relevant for EIC

Forward physics after LS3: the FOCAL detector

CERN-LHCC-2020-009

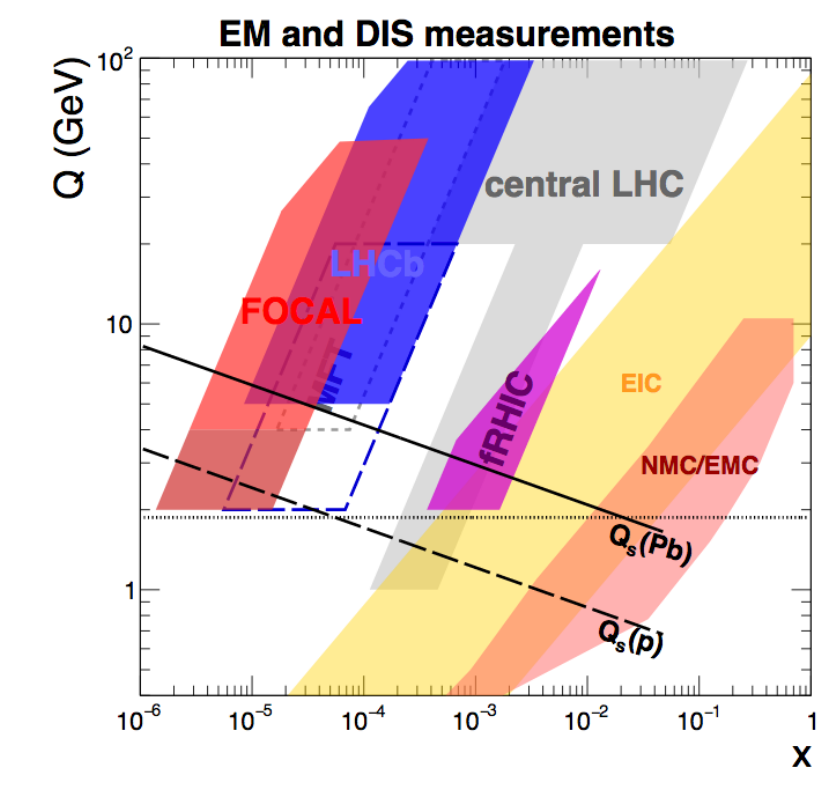




- ❑ FOCAL proposal: Forward high-granularity calorimeter:
  - Particular emphasis on study of gluon saturation and measurements to constrains nPDFs at small x
  - Location 7 m upstream of the IP (A-side), covering very forward rapidity to access the small x region
  - FOCAL-E, electromagnetic part: direct photon and π^0 measurements, good energy resolution 2-5%
  - FOCAL-H, hadronic calorimeter: isolation cut, jet measurement
  - Installation possibly during LS3 (2024-2026) to be used for Run 4
  - Ongoing R&D and TDR in preparation

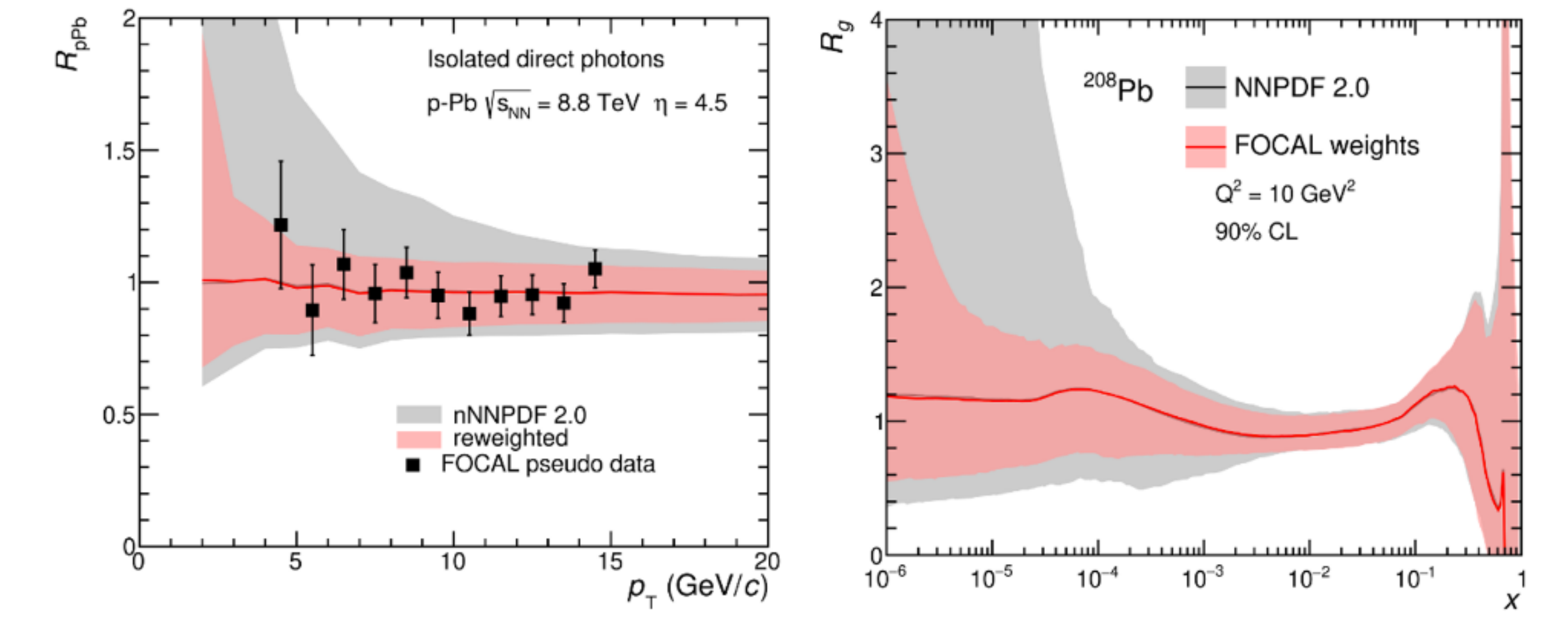
Forward physics after LS3: the FOCAL detector

CERN-LHCC-2020-009



Uncertainty of gluon nPDF for Pb from isolated forward photons in p-Pb

R. Khalek et al, JHEP 09 (2020) 183



- ❑ (x,Q) coverage complementarity between EIC and FOCAL. Access to saturation regime.
- ❑ Significant impact from FOCAL isolated photon measurements expected on gluon nPDFs down to x ~ 10^{-5}

A fixed target programme in ALICE after LS3?

- Fixed-target programme already running at the LHC in LHCb with the SMOG device
- Ongoing feasibility studies in ALICE to install a solid target at ~5 m upstream of the interaction point (A-side)
- Opportunities to study the large-x gluon, antiquark and heavy-quark content in the nucleon and nucleus, HI collisions at large rapidities between SPS and RHIC energies
- ALICE in FT-mode covers the mid (muon) to backward (central barrel) rapidity in the c.m frame

C. Hadjidakis et al, arXiv:1807.00603

Energy range

7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	

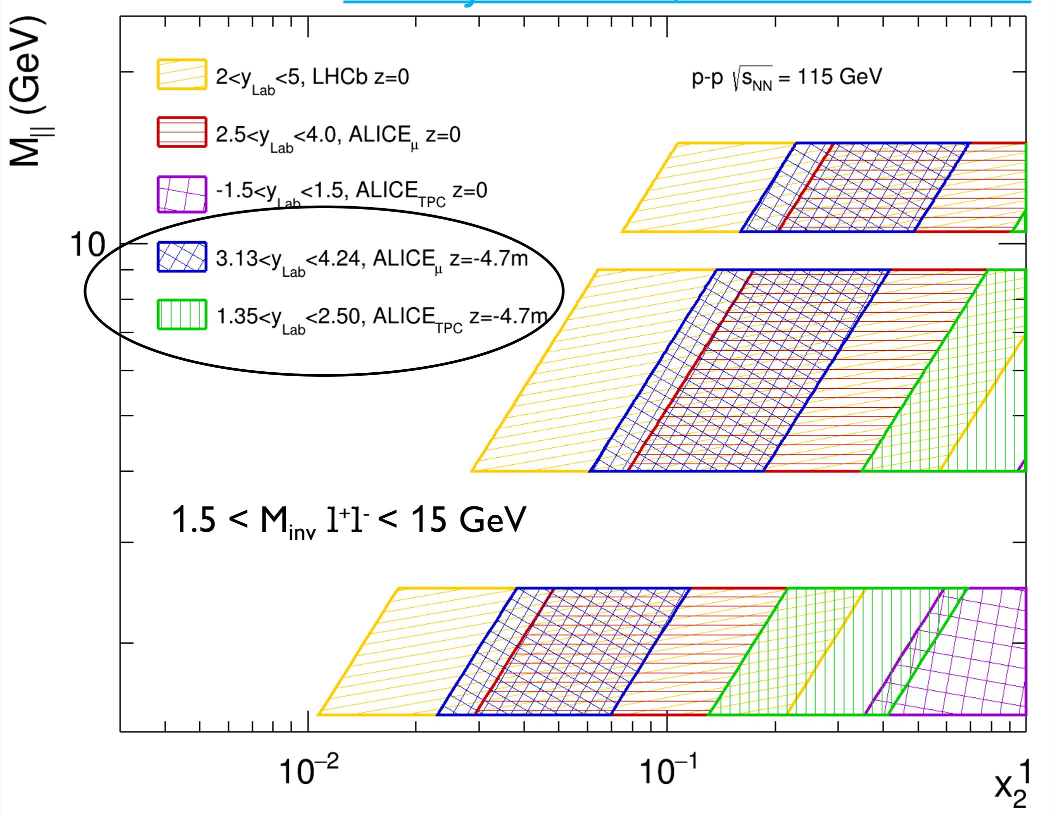
2.76 TeV Pb beam on a fixed target

c.m.s. energy:	$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	

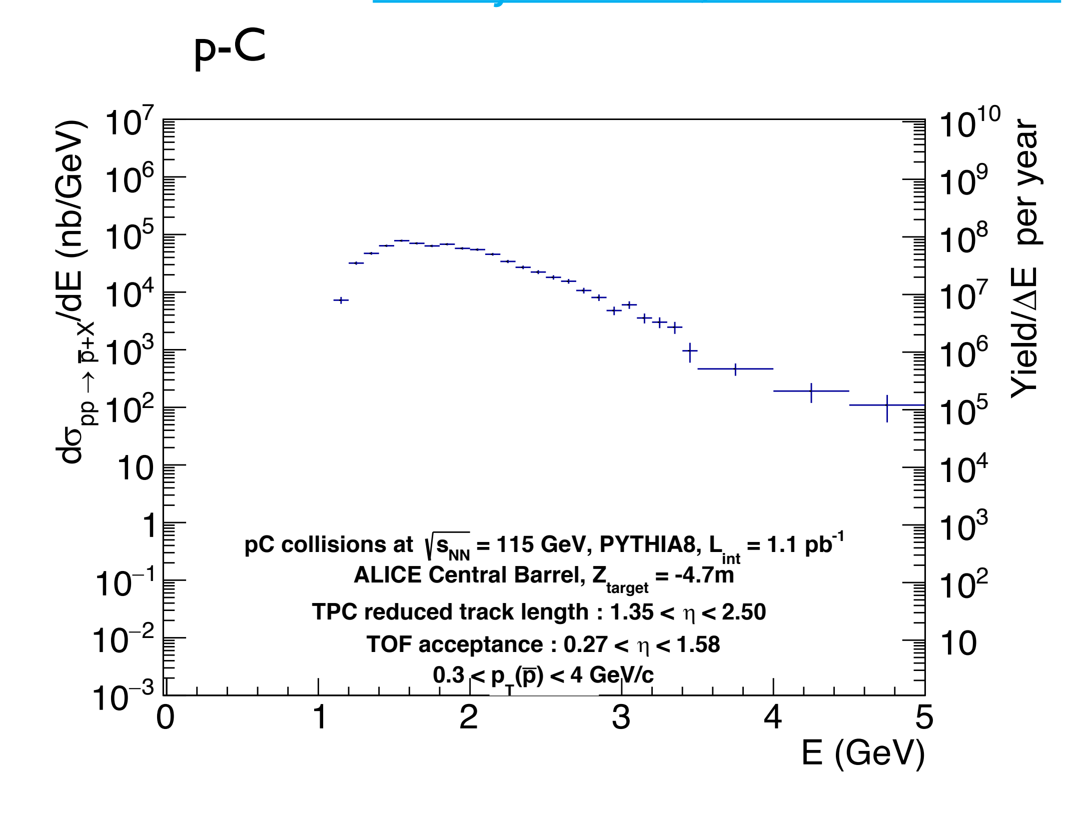
Target			ALICE proton beam ($\sqrt{s_{NN}} = 115$ GeV) $\mathcal{L}$ [cm^{-2} s^{-1}]	σ_{inel}	Inel rate [kHz]	$\int\mathcal{L}$	Pb beam ($\sqrt{s_{NN}} = 72$ GeV) $\mathcal{L}$ [cm^{-2} s^{-1}]	σ_{inel}	Inel rate [kHz]	$\int\mathcal{L}$
Beam splitting	Unpol-arised solid target	C (658 μm)	3.7×10^{30}	271 mb	1000	37 pb^{-1}	–	–	–	–
		C (5 mm)	–	–	–	–	5.6×10^{27}	3.3 b	18	5.6 nb^{-1}
		Ti (515 μm)	1.4×10^{30}	694 mb	1000	14 pb^{-1}	–	–	–	–
		Ti (5 mm)	–	–	–	–	2.8×10^{27}	4.7 b	13	2.8 nb^{-1}
		W(184 μm)	5.9×10^{29}	1.7b	1000	5.9 pb^{-1}	–	–	-	–
		W(5 mm)	–	–	–	–	3.1×10^{27}	6.9 b	21	3.1 nb^{-1}

A fixed target programme in ALICE after LS3?

C. Hadjidakis et al, arXiv:1807.00603



C. Hadjidakis et al, arXiv:1807.00603



- ❑ DY measurement can constrain the valence and light sea quark PDFs at large x. Measurement of DY pairs in the ALICE central barrel would allow measurement up to $x_2 \rightarrow 1$ for intermediate mass lepton pairs
- ❑ Antiproton production in pH, p-A collisions: important input for CR physics (Dark Matter searches). ALICE central barrel accesses the very low energy domain for antiproton production

Conclusion

- Surprising results in the LHC «HI» programme came from the small systems (high mutliplicity pp and p-Pb) which exhibit «QGP-like» signatures:
  - Small system physics can be interesting for the EIC physics case: is collectivity also observed?
  - In electron-hadron collisions, no MPI to build the charged-particle multiplicity. EIC data could be interesting for the interpretation and understanding of LHC data.

- Importance of disentangling CNM effects from hot medium effects to interpret A-A data:
  - EIC can have a significant contribution to understand the initial stages of the HI collision, especially by providing strong constrains on gluon nPDFs.
  - eA collisions are a clean tool to study hadronization mechanisms in CNM.