Recent results from ALICE at the LHC

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ALICE

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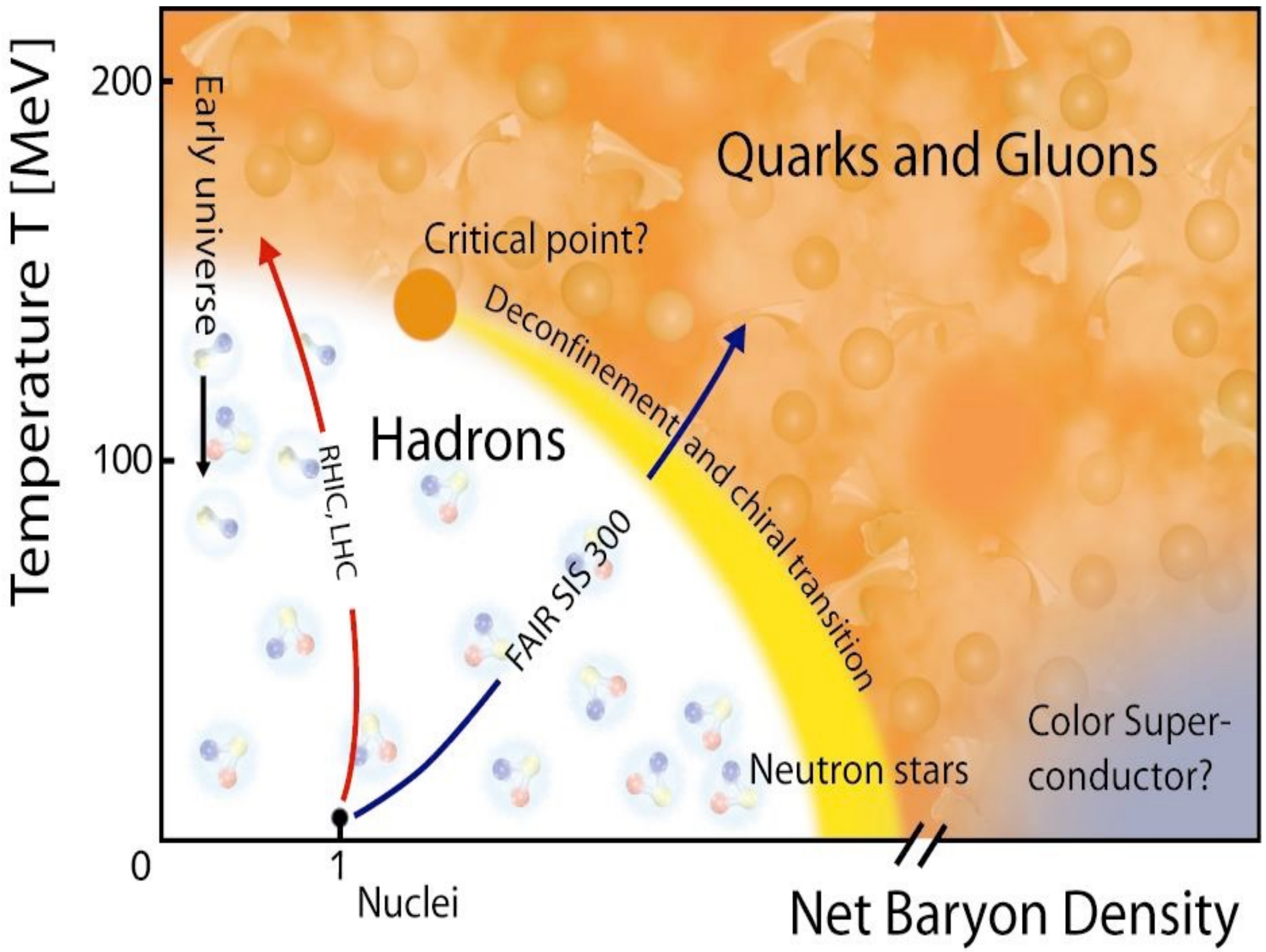
- Ultra-relativistic heavy-ion collisions and Quark Gluon Plasma at the LHC with A Large Ion Collider Experiment (ALICE)
- Soft probes: measuring low-p_T particles for studying the bulk and the collective properties of the medium produced in heavy-ion collisions
- Hard probes: hard QCD processes, such as high-pt particles, open heavy flavour and quarkonia, that cross the produced medium and allow to quantify its characteristics

Why heavy-ions at the LHC?

QCD phase diagram



Nuclear matter at high temperature and high density = Quark Gluon Plasma (QGP)

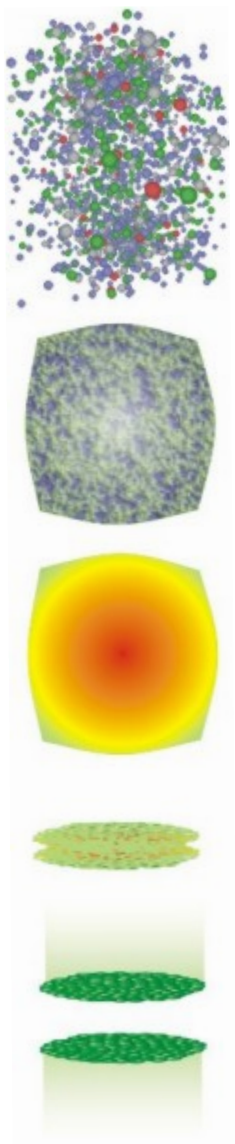
- Partons are deconfined (not bound into composite object)
- Chiral symmetry is restored (partons are massless)
- Behaves as a perfect fluid (well described by ideal hydrodynamics)

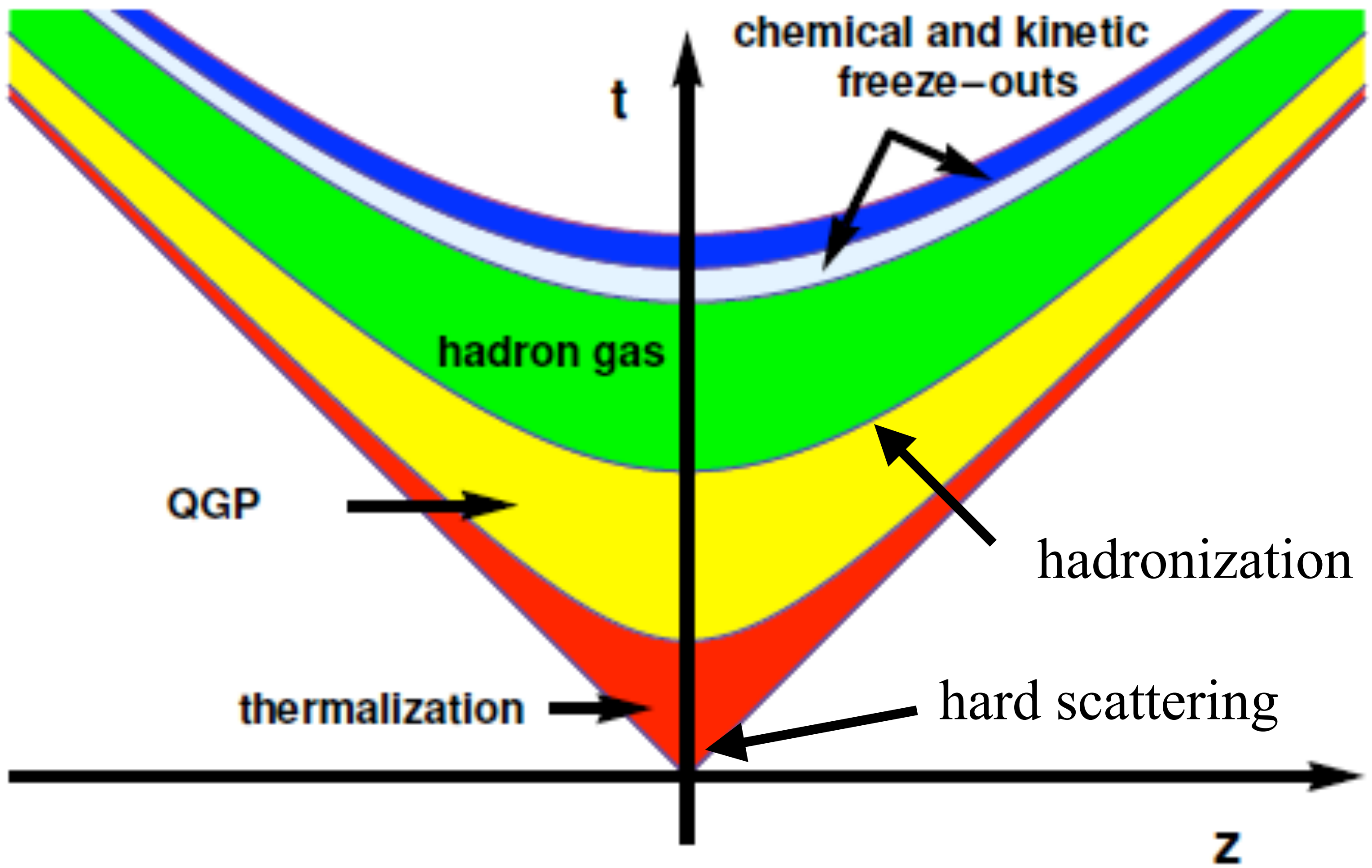
From lattice QCD: phase transition near T_c = 170 MeV (ε_c = 1 GeV/fm^3)

At LHC energies: most particles produced during the collisions → very low net baryon density

Heavy ion collision experiments: search for the QGP phase and characterize it

Space-time evolution of the collision





τ ≃ 20 fm/c
Kinetical freeze-out
Chemical freeze-out

τ ≃ 10 fm/c $T < T_c$
Hadron gas

τ ≃ 1 fm/c $T > T_c$
Thermalized QGP

τ ≃ 0
Heavy-ion collision

LHC size and time numbers
1 fm/c ~ 3 10^{-24} s

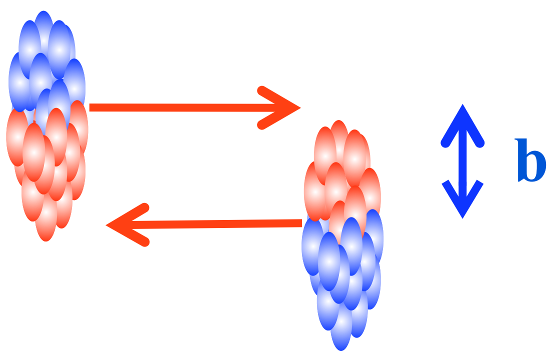
QGP volume ≃ 300 fm^3

At large energy: large, hot, dense, long life-time plasma

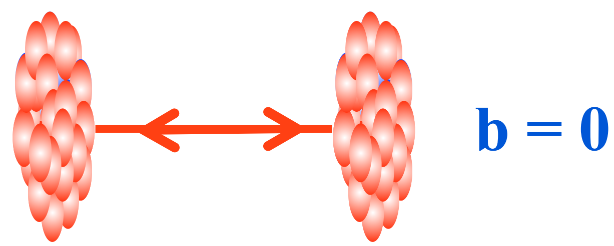
Collision geometry: few definitions

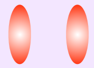
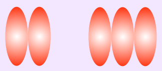
Centrality of the collisions: overlap of two nuclei

semi-central collision



central collision



	N_{part} = 2	N_{coll} = 1
	N_{part} = 5	N_{coll} = 6
Pb-Pb cent.	N_{part} = 360	N_{coll} = 1500
p-Pb cent.	N_{part} = 16	N_{coll} = 15

Impact parameter of the collision: b
Number of participants nucleons: N_{part}
Number of binary collisions: N_{coll}

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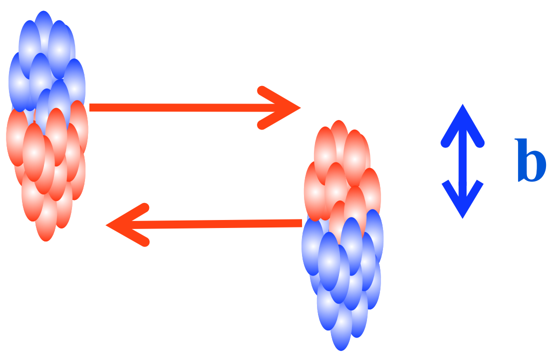
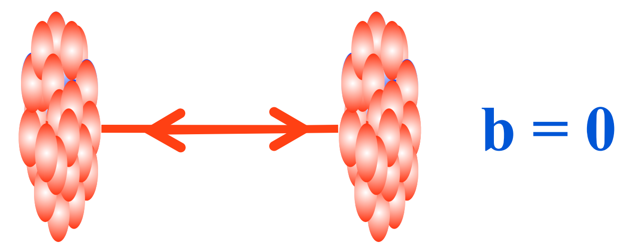
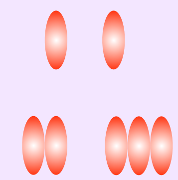


central collision





	$N_{part} = 2$	$N_{coll} = 1$
	$N_{part} = 5$	$N_{coll} = 6$
Pb-Pb cent.	$N_{part} = 360$	$N_{coll} = 1500$
p-Pb cent.	$N_{part} = 16$	$N_{coll} = 15$

Impact parameter of the collision: b
Number of participants nucleons: N_{part}
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Event centrality determination

- Cannot measure b, N_{part}, N_{coll} directly
- Multiplicity measurements with forward or central detectors (charged particles multiplicity - π, K, p… -, spectator neutrons, …)
- Use Glauber model to map the measured multiplicities in A-A collisions to b, N_{part} and N_{coll}

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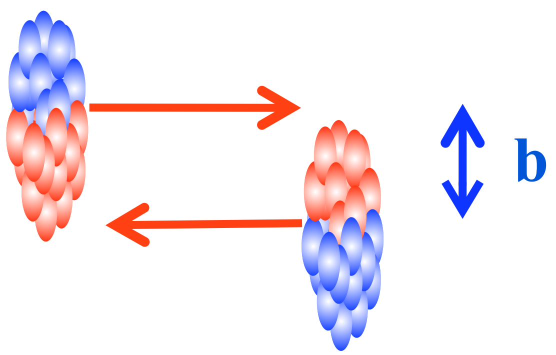
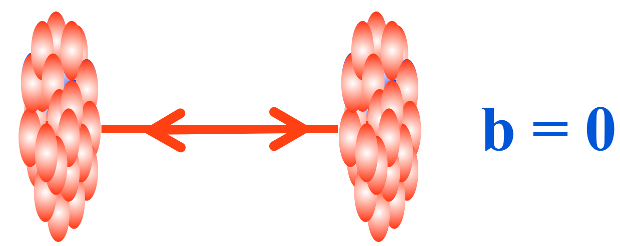


central collision



(2 nucleons)	N_{part} = 2	N_{coll} = 1
(2 + 3 nucleons)	N_{part} = 5	N_{coll} = 6
Pb-Pb cent.	N_{part} = 360	N_{coll} = 1500
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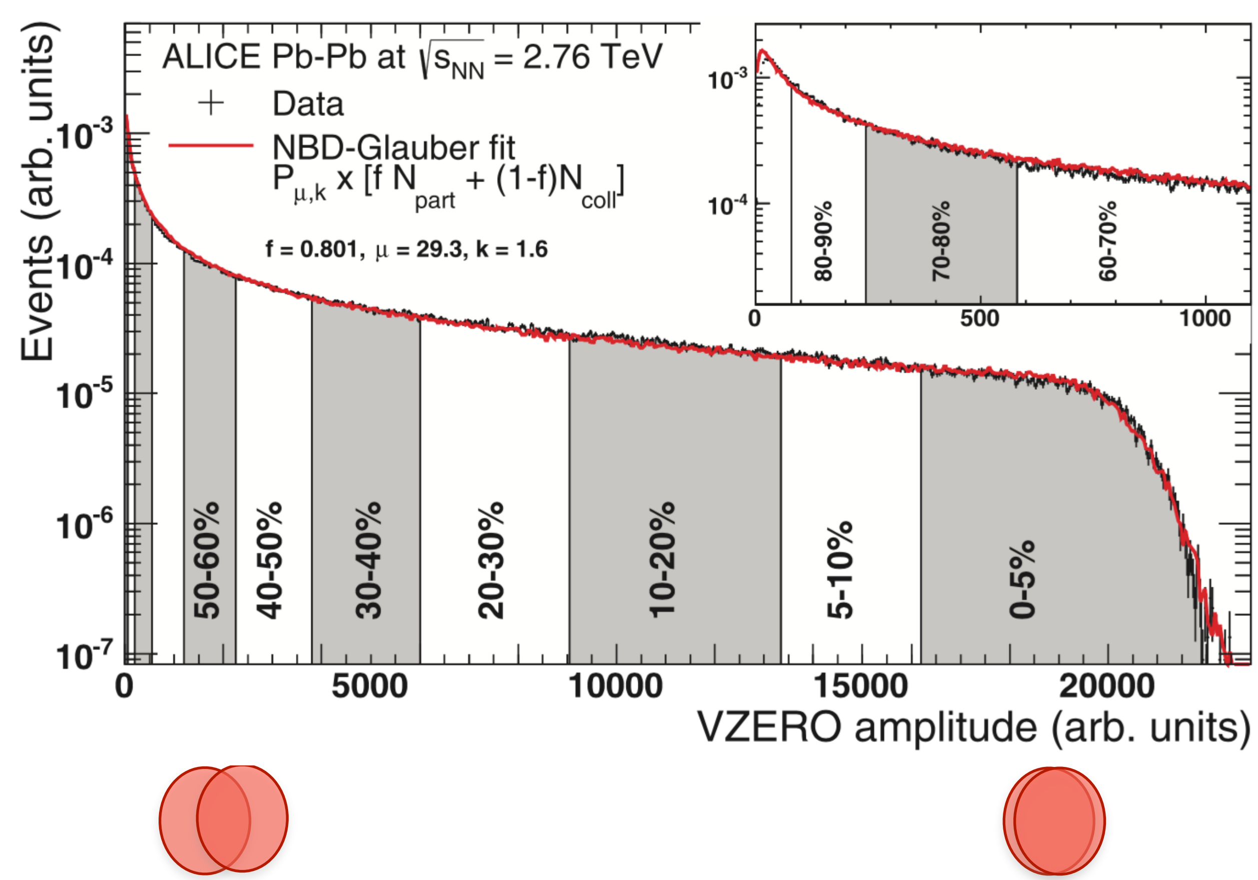
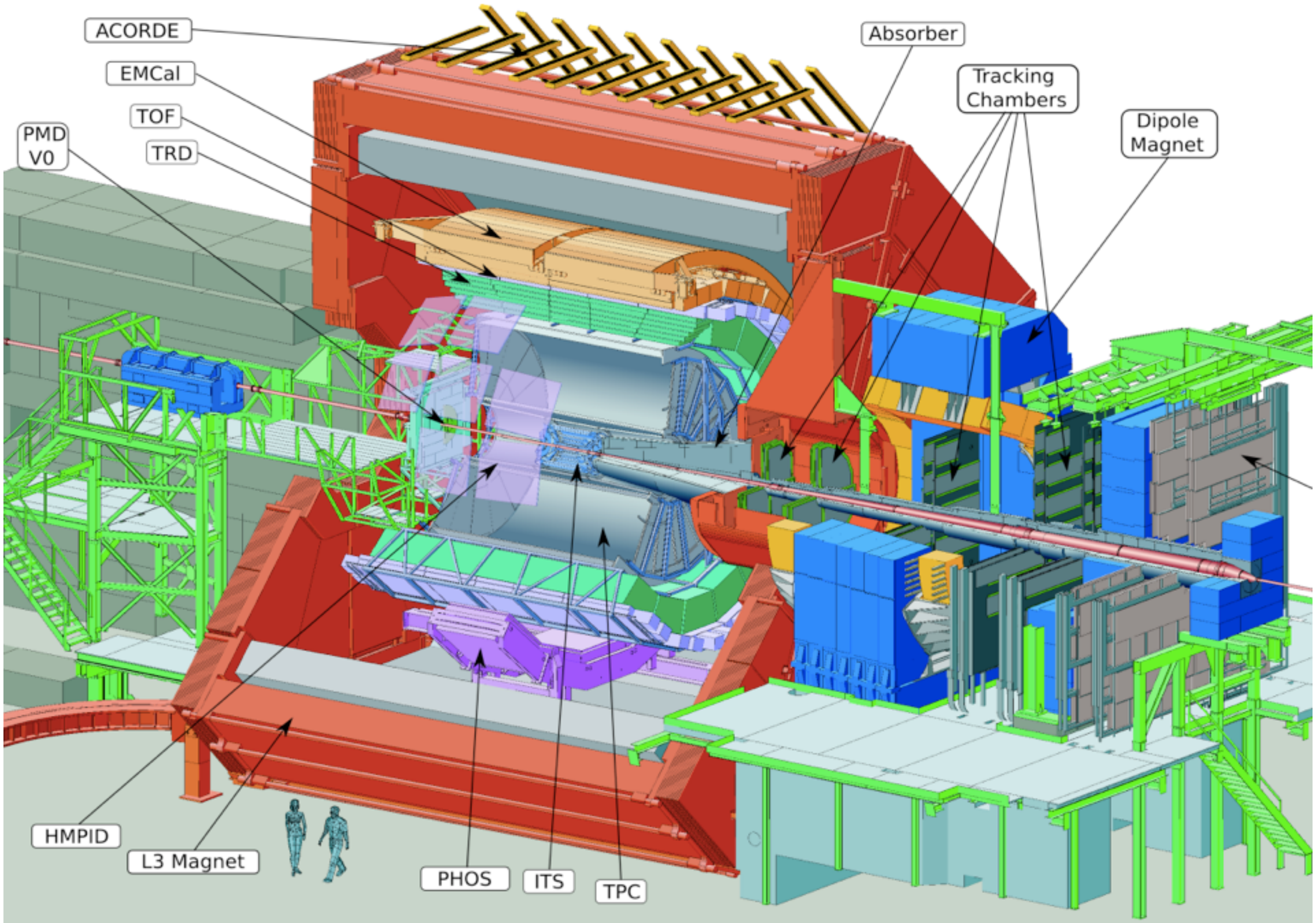
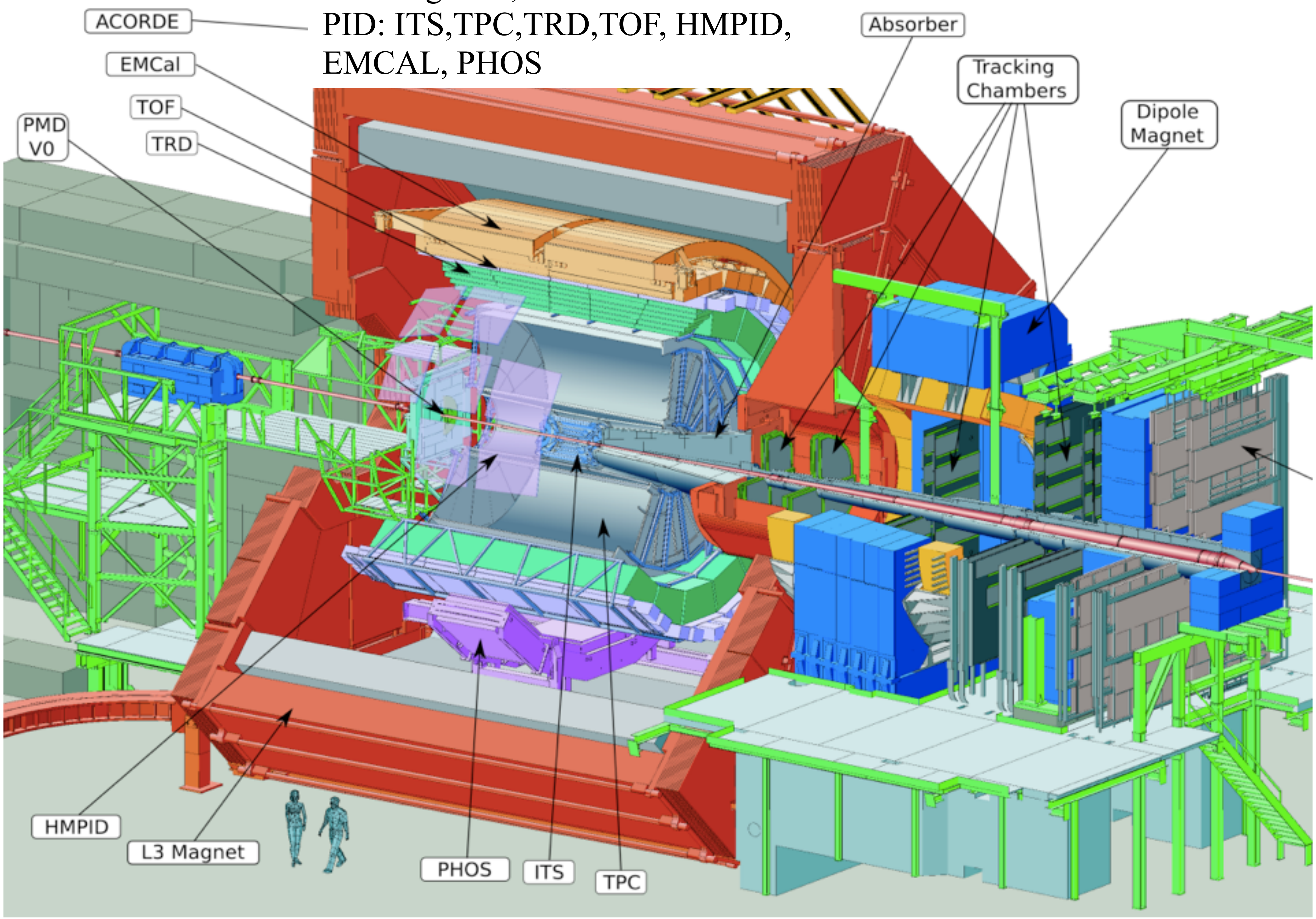


A Large Ion Collider Experiment (ALICE)



A Large Ion Collider Experiment (ALICE)

Central barrel: |η| < 0.9
0.5 T solenoidal magnet
Vertexing: ITS
Tracking: ITS,TPC
PID: ITS,TPC,TRD,TOF, HMPID, EMCAL, PHOS



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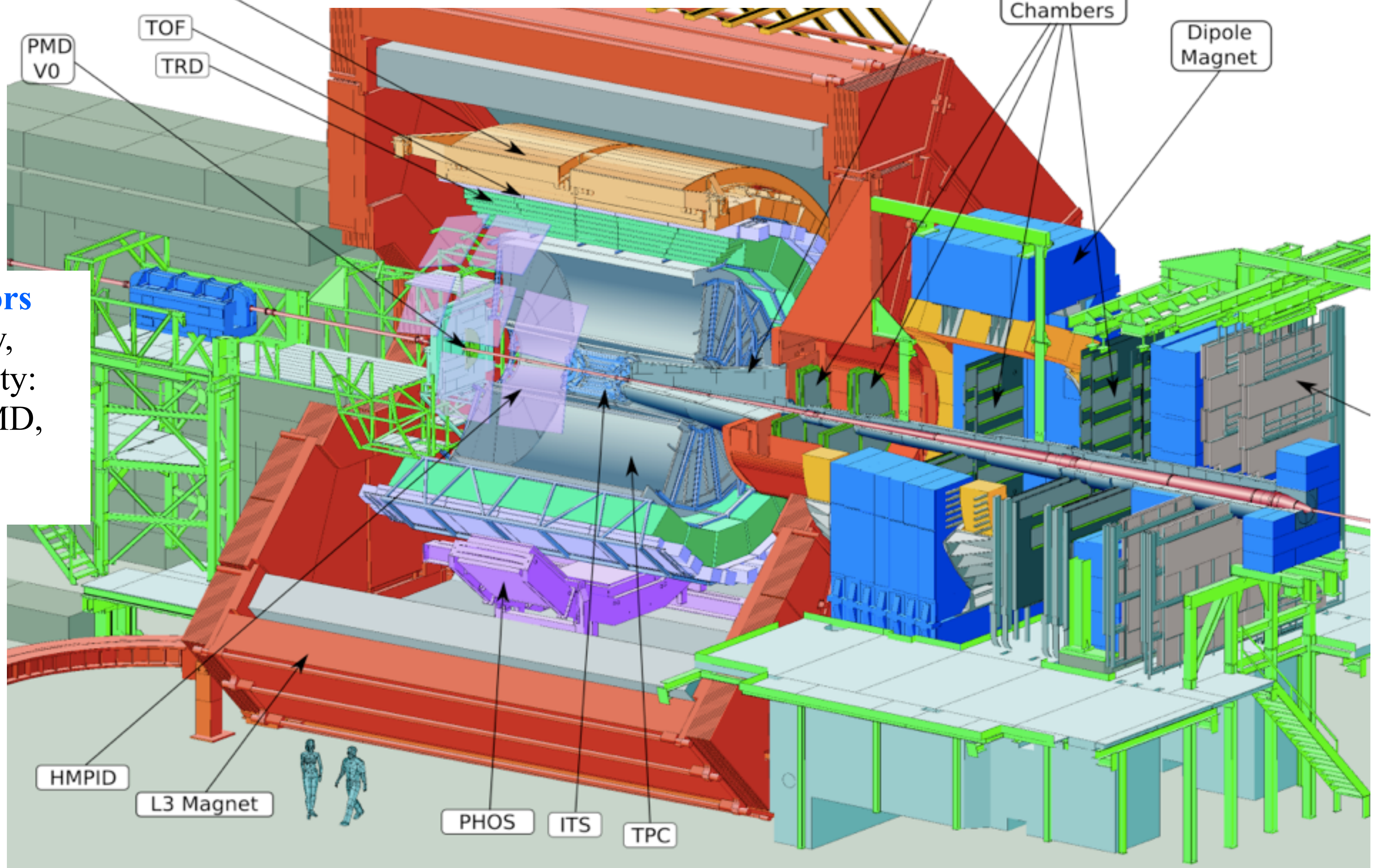

Forward detectors
Trigger, centrality,
timing, multiplicity:
V0, T0, ZDC, PMD,
FMD, AD

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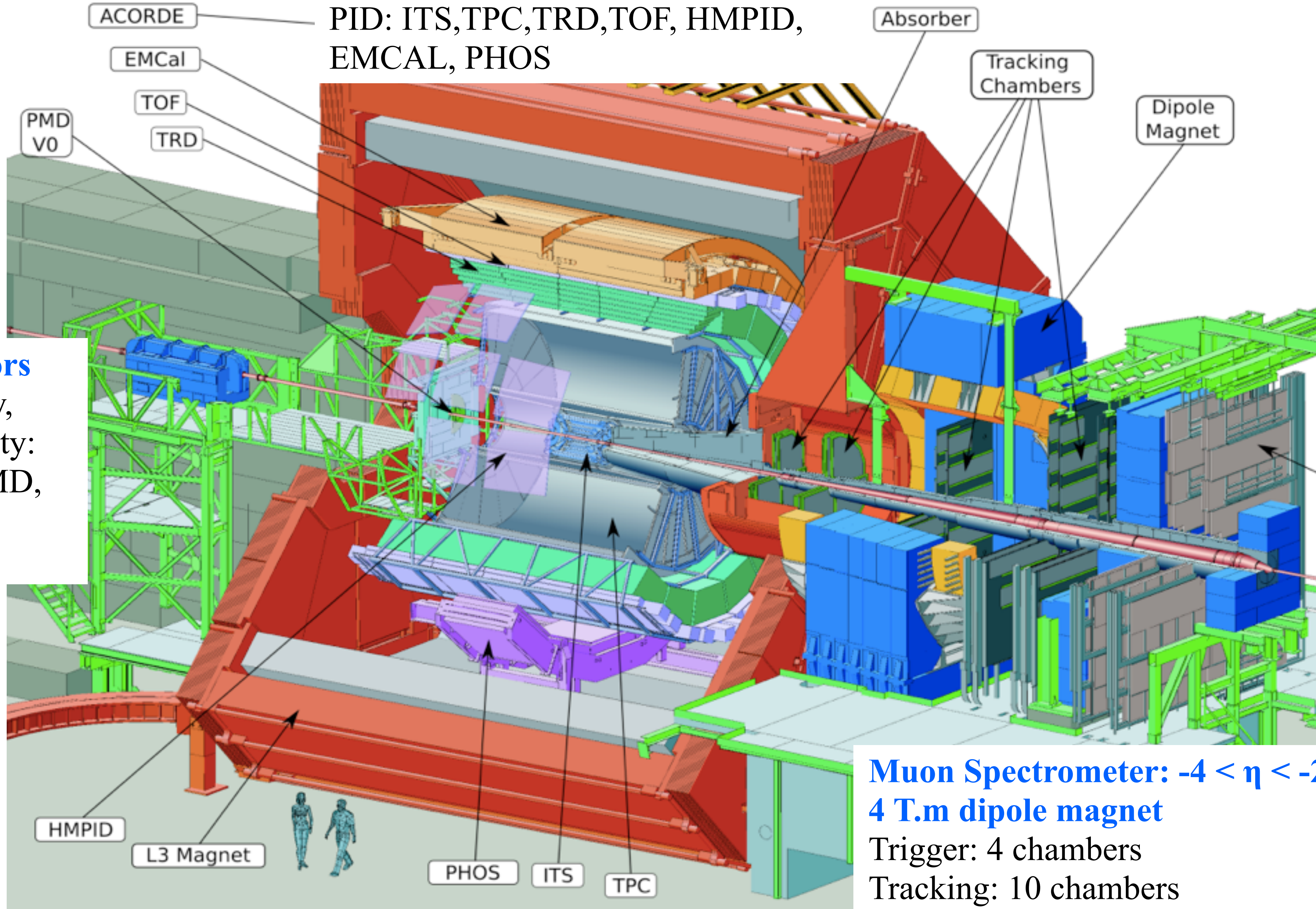


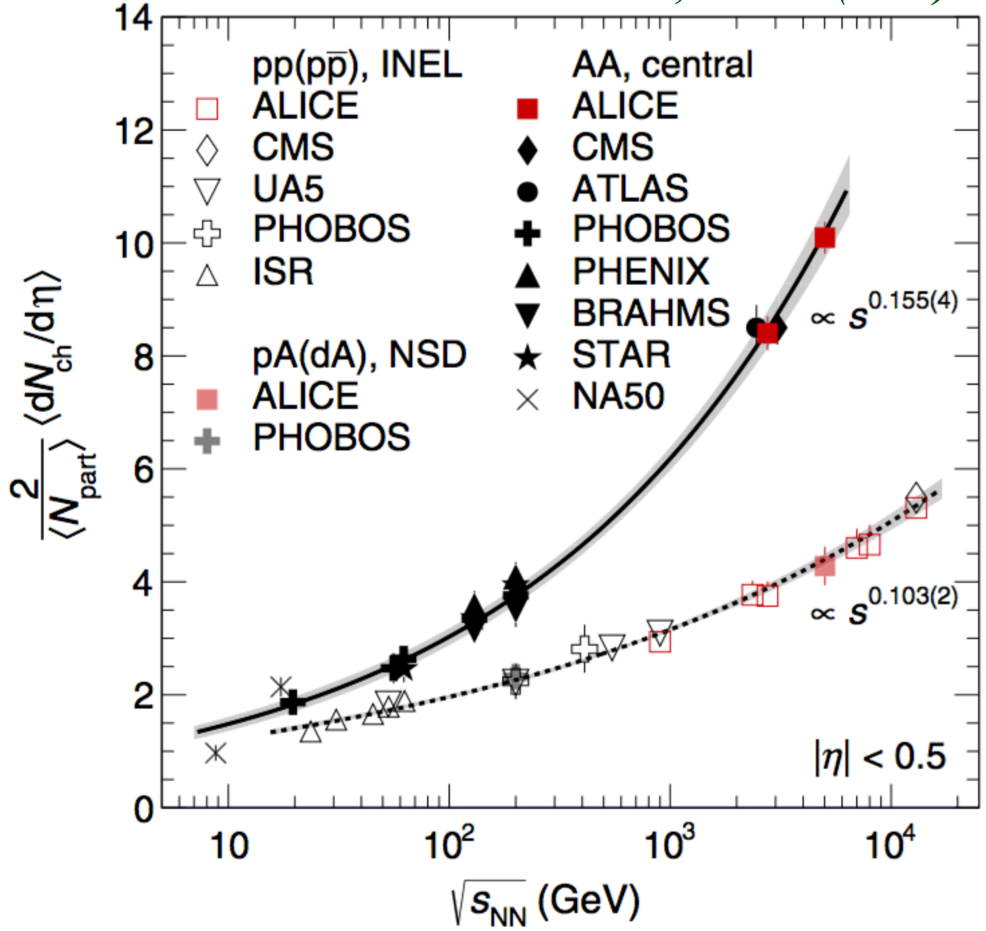
Forward detectors
Trigger, centrality, timing, multiplicity: V0, T0, ZDC, PMD, FMD, AD

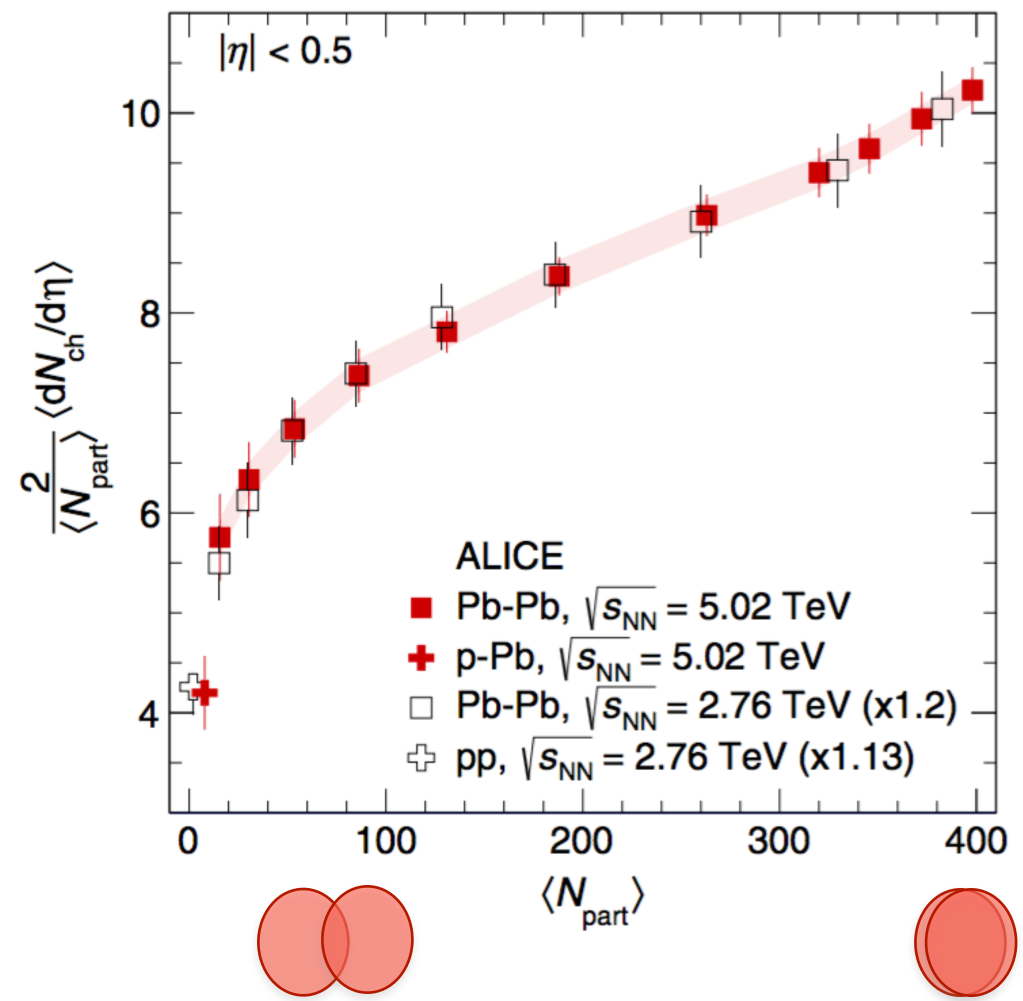
Muon Spectrometer: -4 < η < -2.5
4 T.m dipole magnet
Trigger: 4 chambers
Tracking: 10 chambers
Hadron rejection: absorbers

Soft probes

Charged particle multiplicity at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

PRL 116, 222302 (2016)

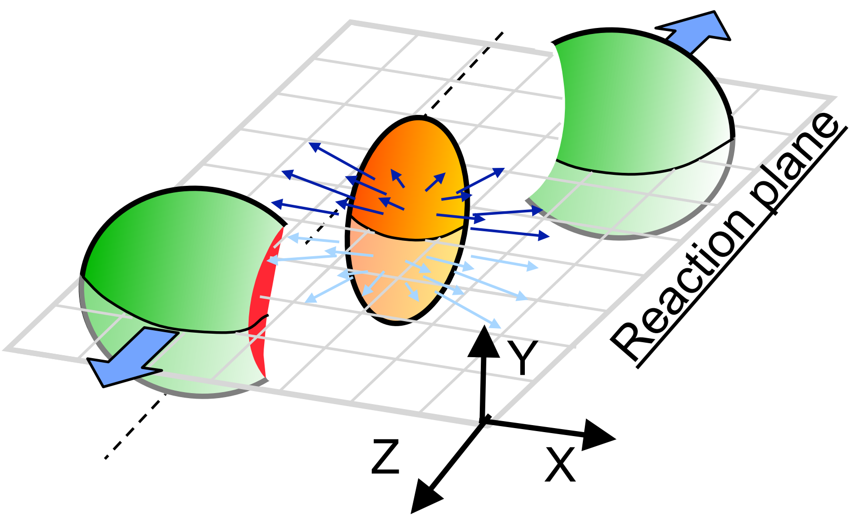




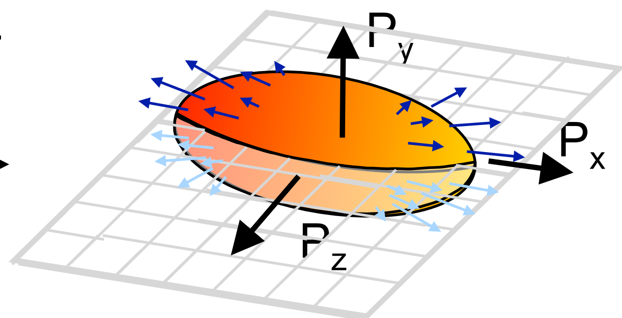
- Last November: highest energy achieved experimentally in heavy-ion collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- $\langle dN_{ch}/d\eta \rangle$ (0-5%) = 1943 ± 54 → x 2.5 the average multiplicity per participating nucleon pair, $\langle N_{part} \rangle$/2, in pp and p-Pb collisions at the same energy
- The dependence of $\langle dN_{ch}/d\eta \rangle$ with energy is steeper in A-A than in pp and p-A collisions: 20% increase in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV wrt 2.76 TeV
- The average yield per participant pair depends strongly on collision centrality: same dependence observed at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

Azimuthal asymmetry

Overlap region in noncentral heavy-ion collisions is asymmetric, in « almond » shape



For interacting matter, spatial asymmetry leads to a momentum anisotropy of final-state particles

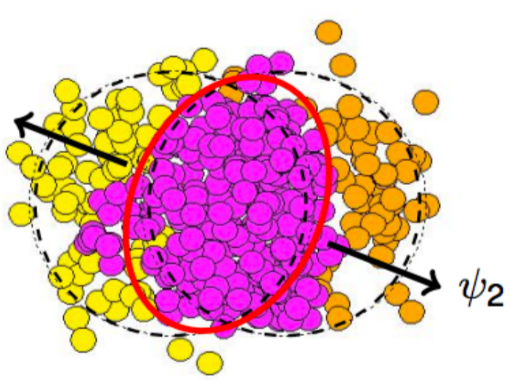


Azimuthal dependence of the particle yield:

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

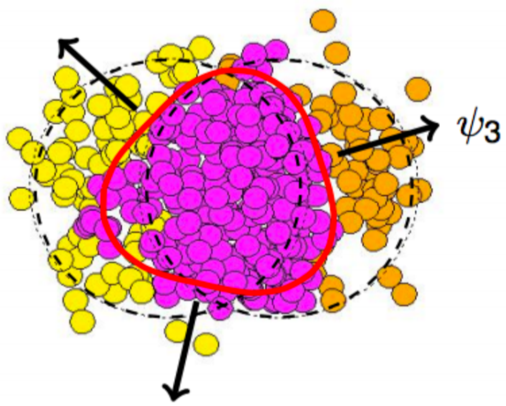
Ψ_n: symmetry planes

n = 2: elliptic flow



+

n = 3: triangular flow

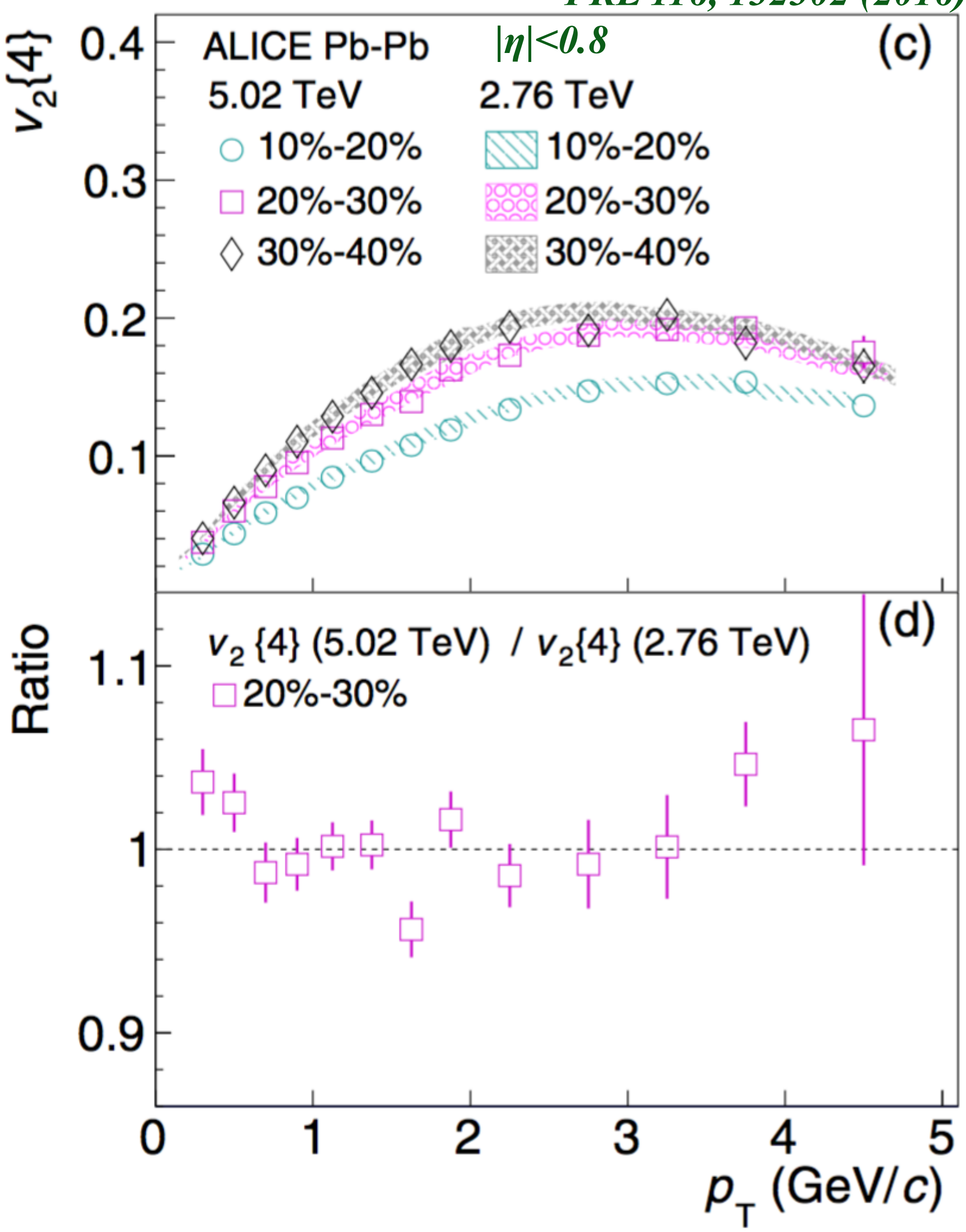


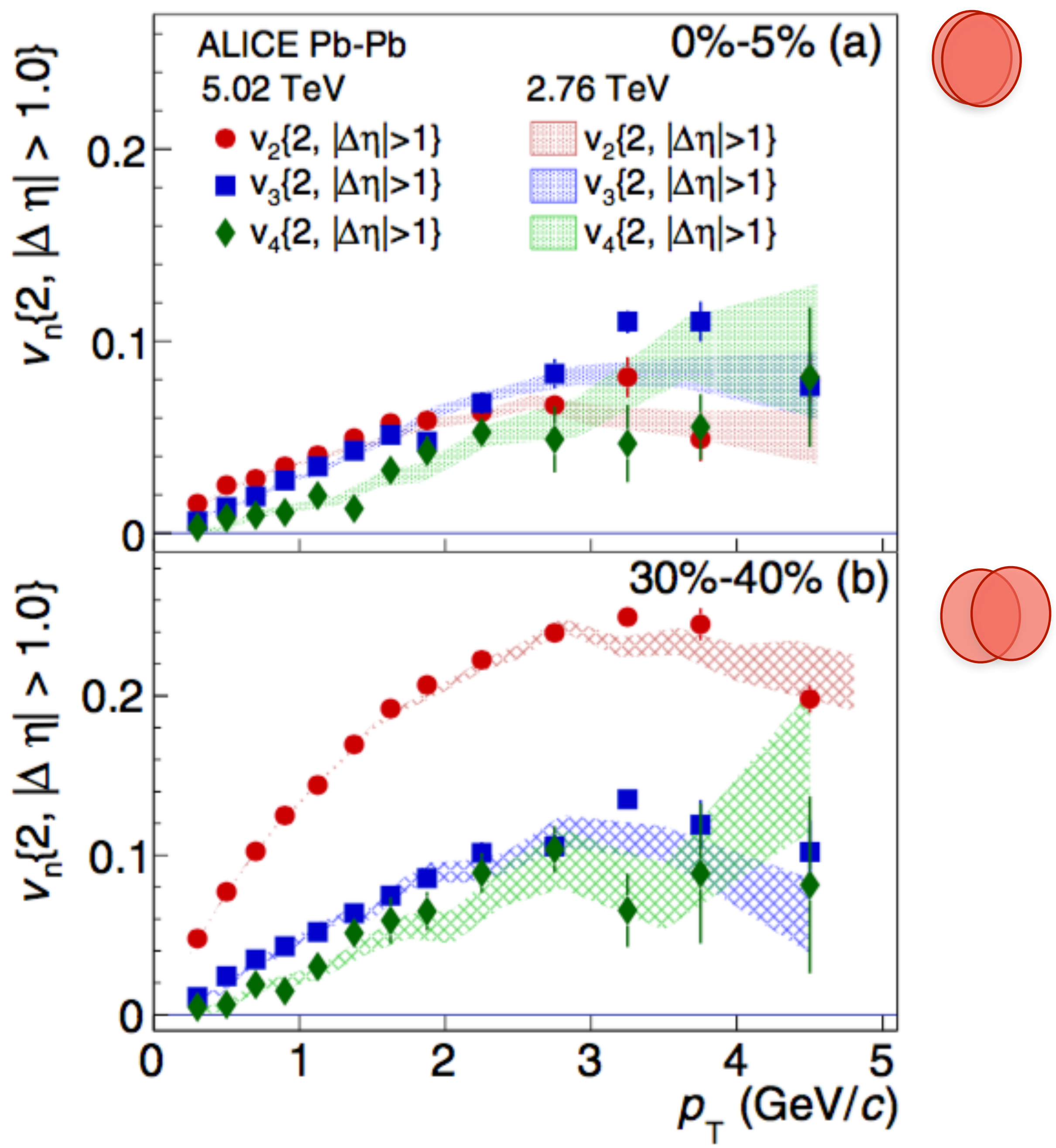
+ …

Anisotropic flow is sensitive to the initial geometry and properties of the produced medium

Anisotropic flow at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

PRL 116, 132302 (2016)





– Anisotropic flow measurements using multi-particle cumulant method and two-particle correlations with $|\Delta\eta|>1$
– Elliptic flow $v_2(p_T)$ very similar at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV
– Comparable values also for the higher harmonics (v3, v4) vs p_T at both energies

Anisotropic flow at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

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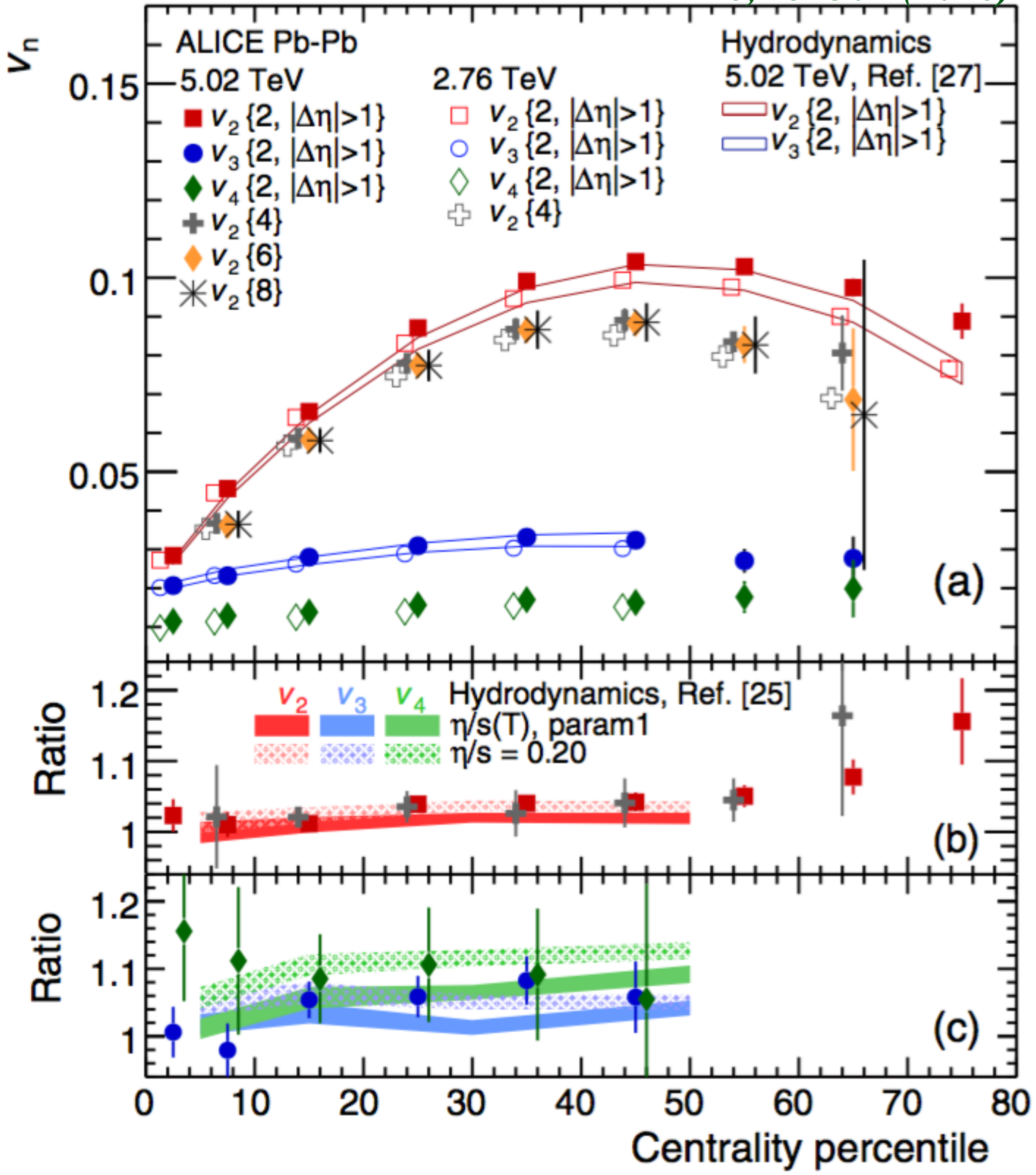
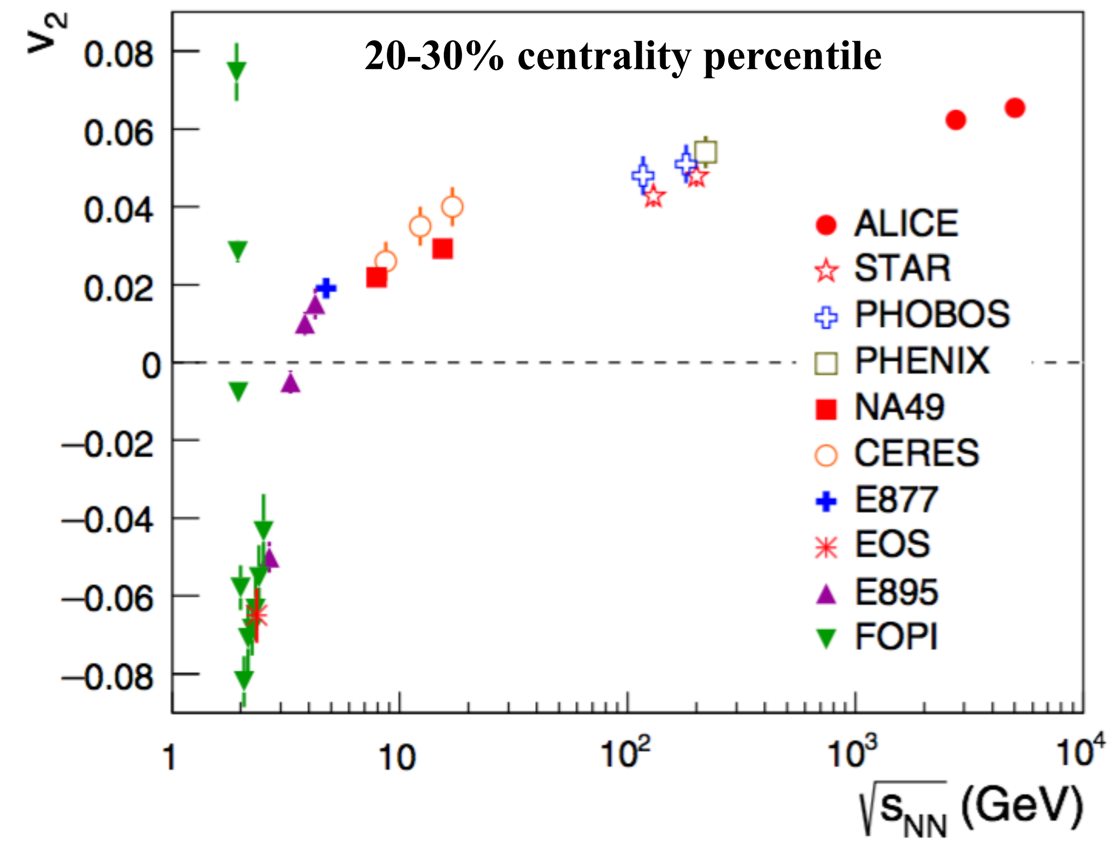
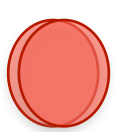
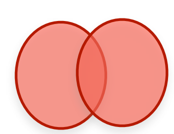




Ref. [25] H. Niemi et al. Phys. Rev. C 93, 014912 (2016).
Ref. [27] J. Noronha-Hostler et al. Phys. Rev. C 93, 034912 (2016).





- p_T-integrated results show an increase of 3.0±0.6% (v_2), 4.3±1.4% (v_3) and 10.2±3.8% (v_4) from $\sqrt{s_{NN}}$ = 2.76 to 5.02 TeV → this can be attributed to an increase in $\langle p_T \rangle$
- Measurements in good agreement with hydrodynamical calculations → the data support a low value for the shear viscosity to entropy density ratio (η/s) of the QGP
- Continuous increase of p_T-integrated v_2 from SPS to LHC

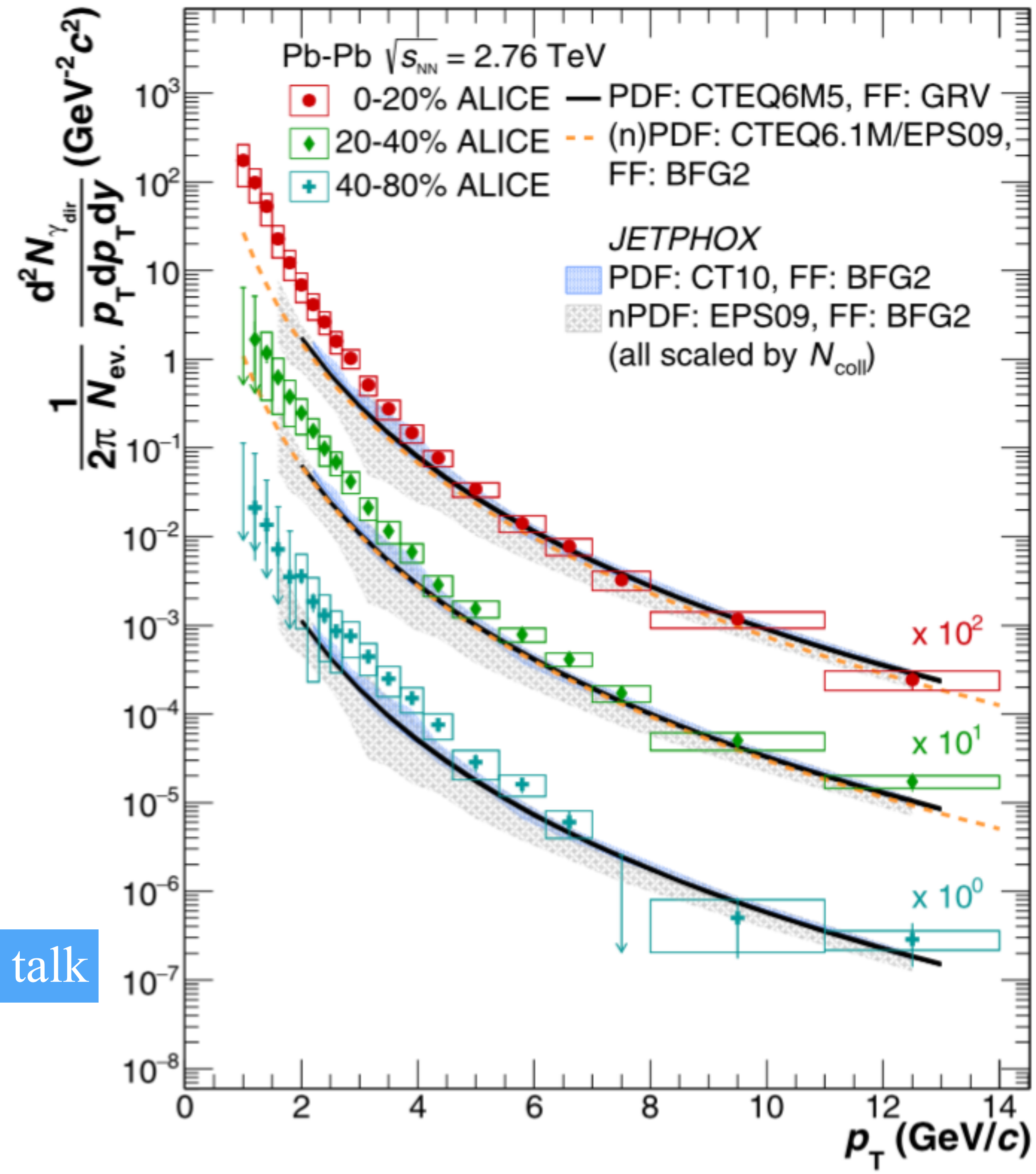
more in You Zhou's talk

Direct photons

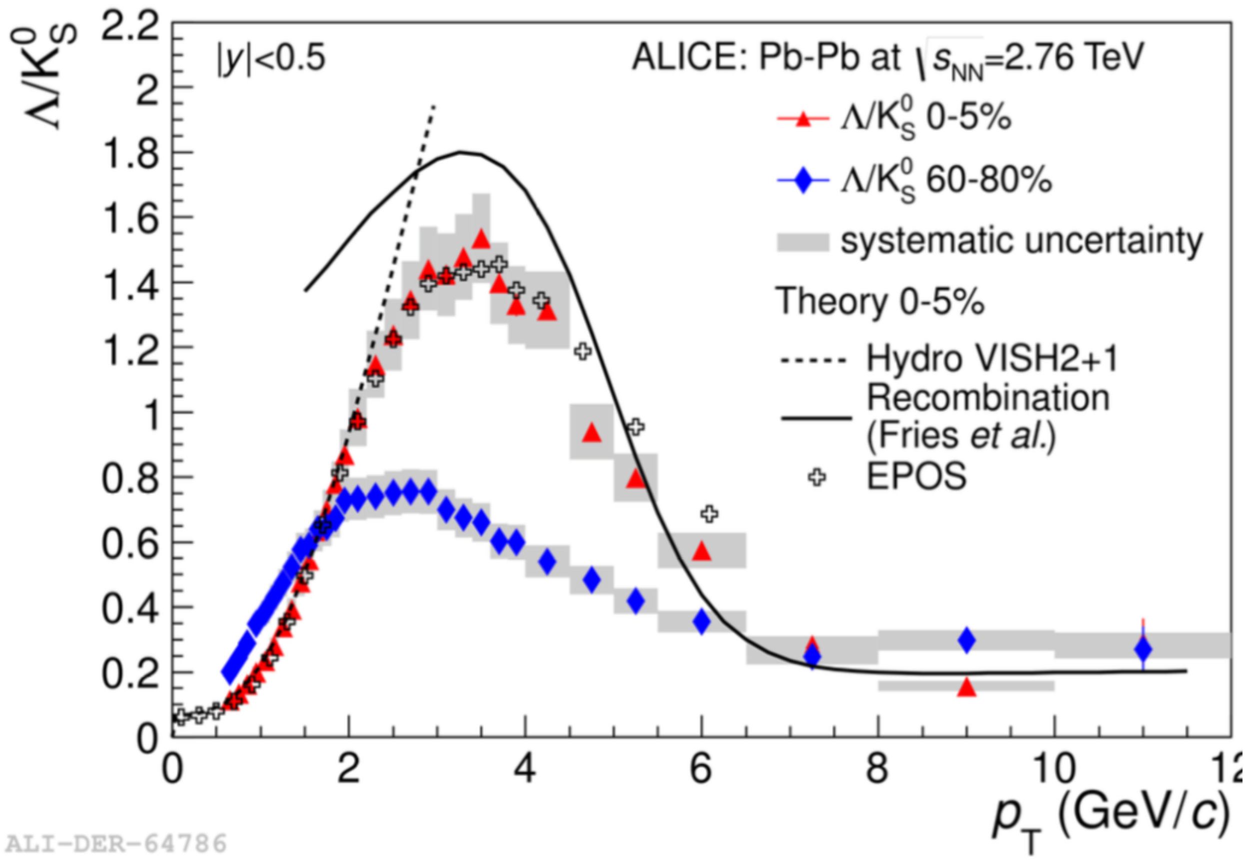
- Direct photons at low p_T give access to thermal photons emitted by QGP and hadronic matter
- Good agreement with NLO pQCD calculations scaled by N_{coll} for $p_T > 5$ GeV/c → data supports N_{coll} scaling at large p_T
- In 0-20% and 20-40%: excess of low p_T direct photons wrt pQCD calculations
- p_T-spectrum described at $p_T < 2.1$ GeV/c by an exponential with an inverse slope parameter: $T_{eff} = (297 \pm 12 \pm 41)$ MeV in central collisions → 30% higher than at RHIC

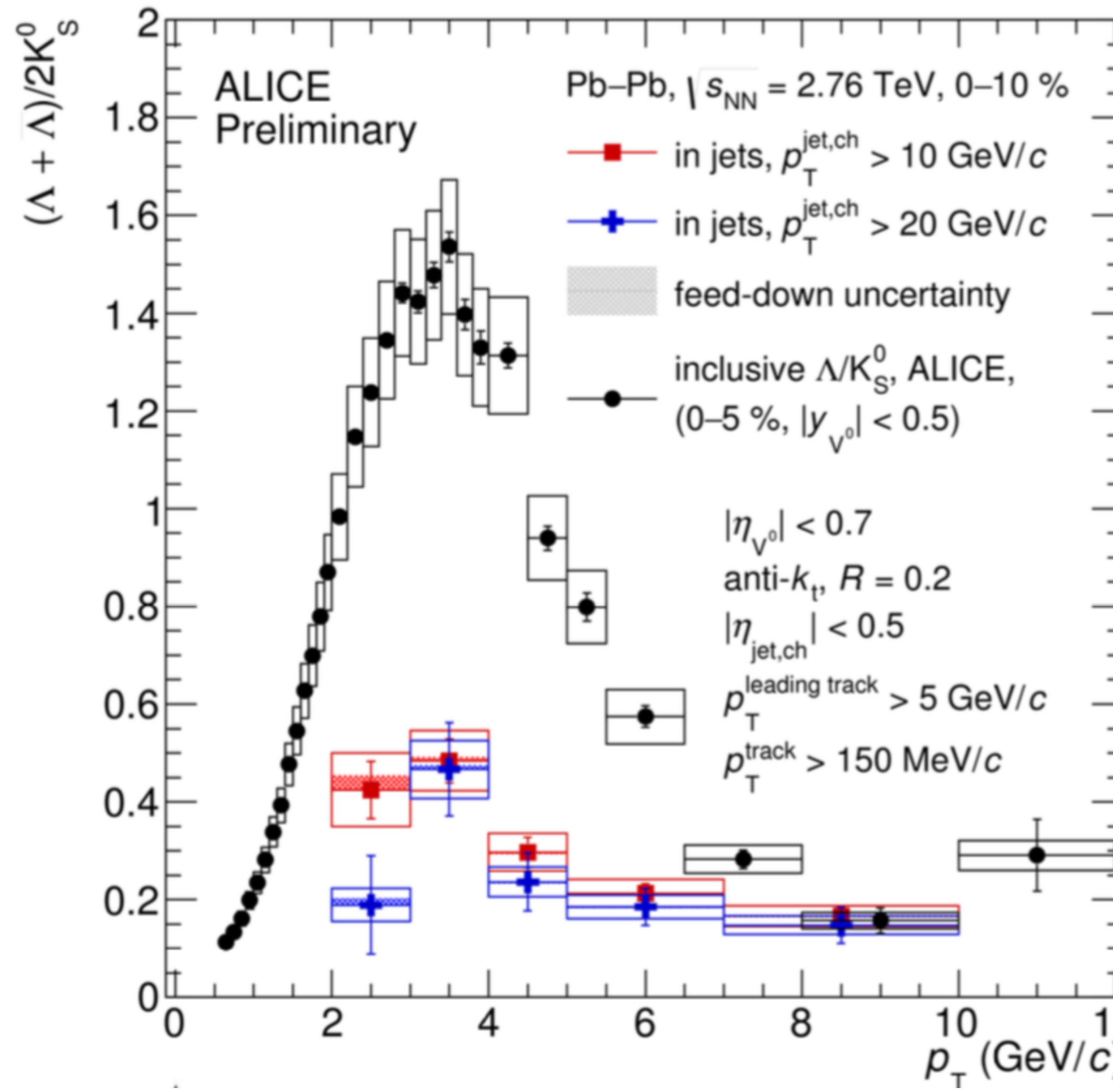
more in Lucile Ronflette's talk

PLB 754 (2016) 235-248



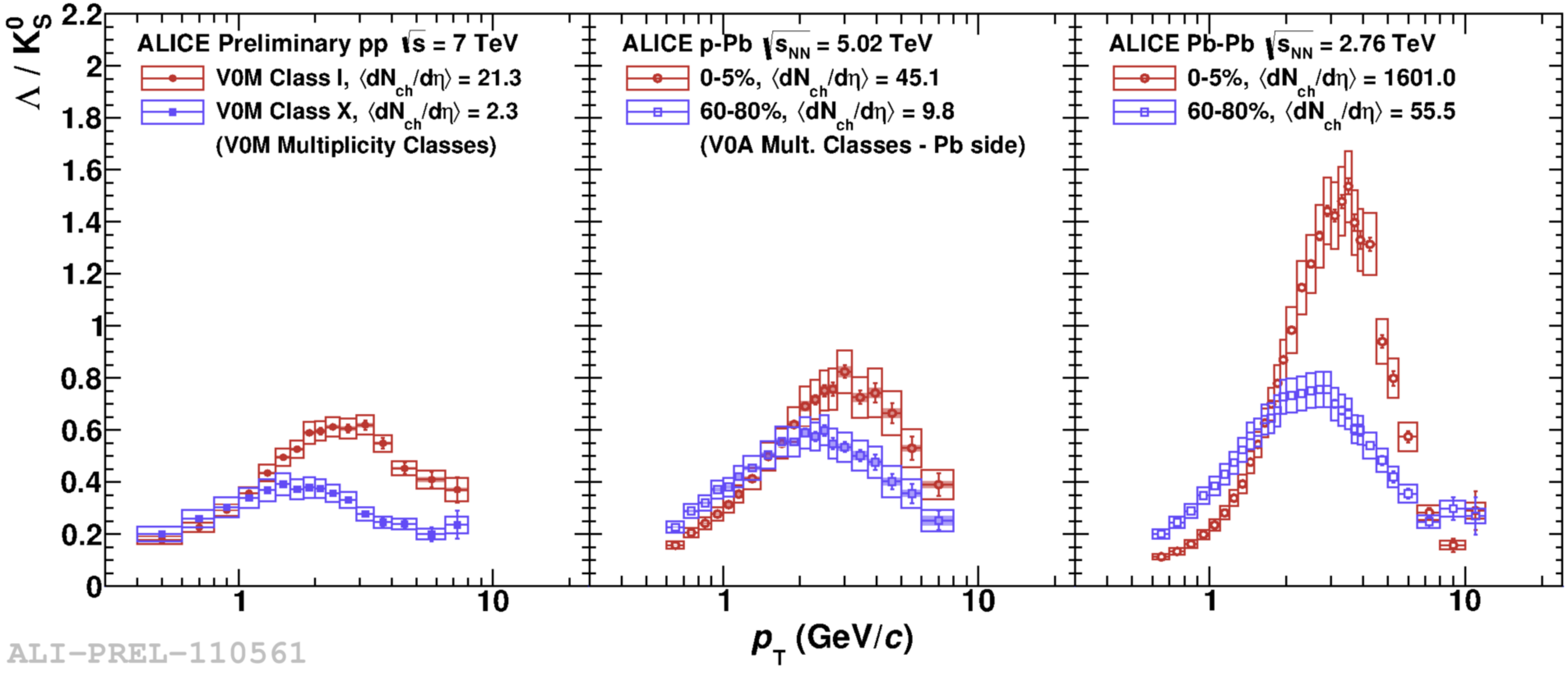
Baryon-to-meson ratio





- Enhancement of baryon-to-meson ratio at intermediate p_T in Pb-Pb: understood in terms of collective flow or recombination
- B/M ratio significantly lower in jets than for the inclusive measurements and consistent with PYTHIA expectations (vacuum fragmentation) → baryon enhancement seen in Pb-Pb does not originate in jets but arises from the bulk

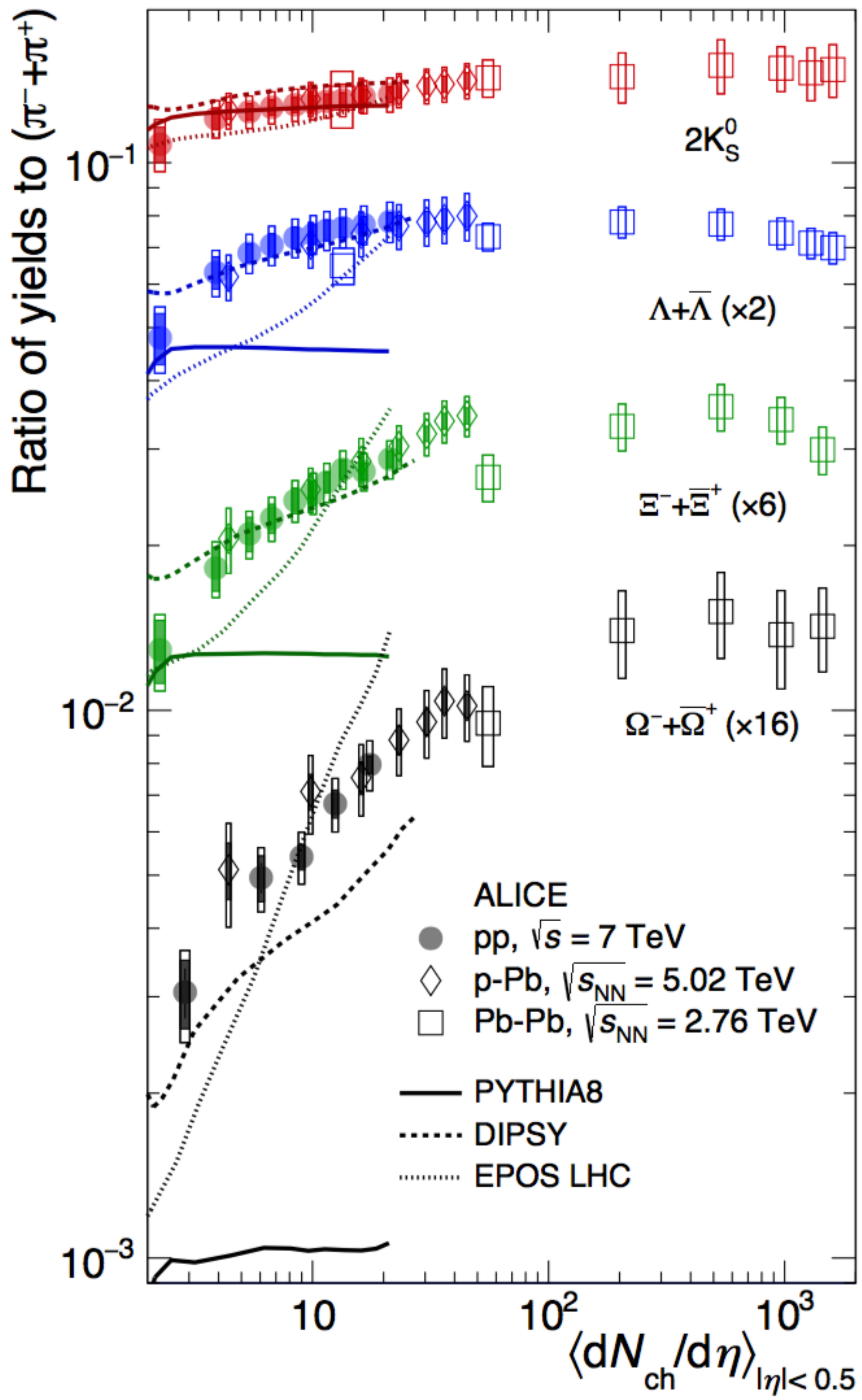
Baryon-to-meson ratio in pp and p-Pb



– Clear evolution of B/M ratios with event multiplicity also in pp and p-Pb!

Strangeness enhancement in pp, p-Pb and Pb-Pb

ALICE, *arXiv:1606.07424*



- Strangeness production in AA: first QGP signature proposed ***Rafelski PRL48(1982)1066***
- Strange to non-strange particle ratios increase with event multiplicity in Pb-Pb but also in pp and p-Pb!
- Saturation at large mult. in Pb-Pb in agreement with grand canonical thermal models (not shown) ***Andronic et al, PLB 673 (2009) 142, Cleymans et al, PRC 74 (2006) 034903***

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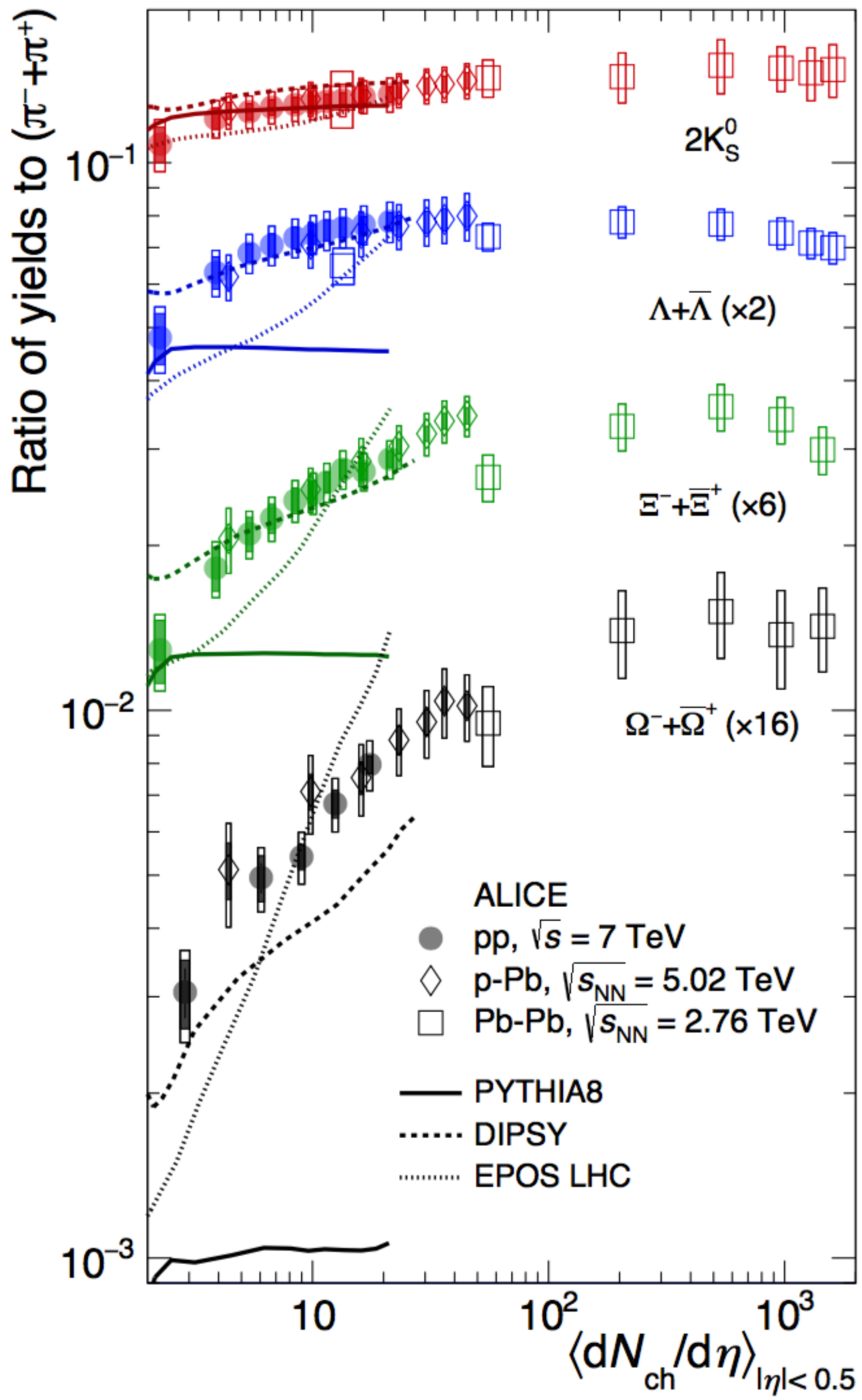

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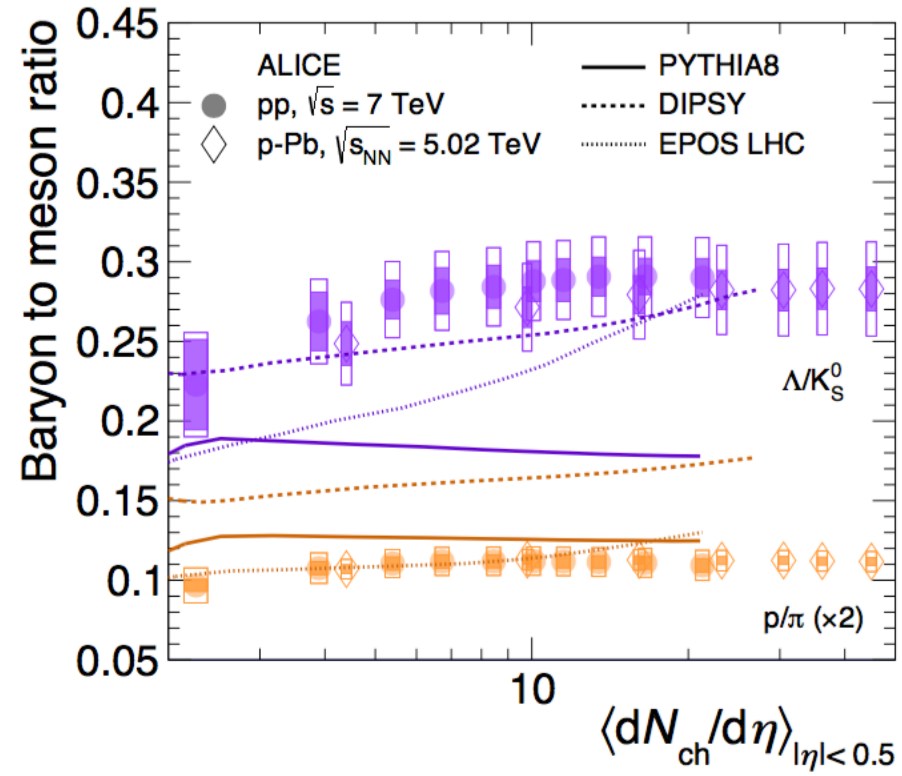

– Baryon-to-meson ratios Λ/K^0_s and p/π do not increase significantly → increase is not mass but strangeness related

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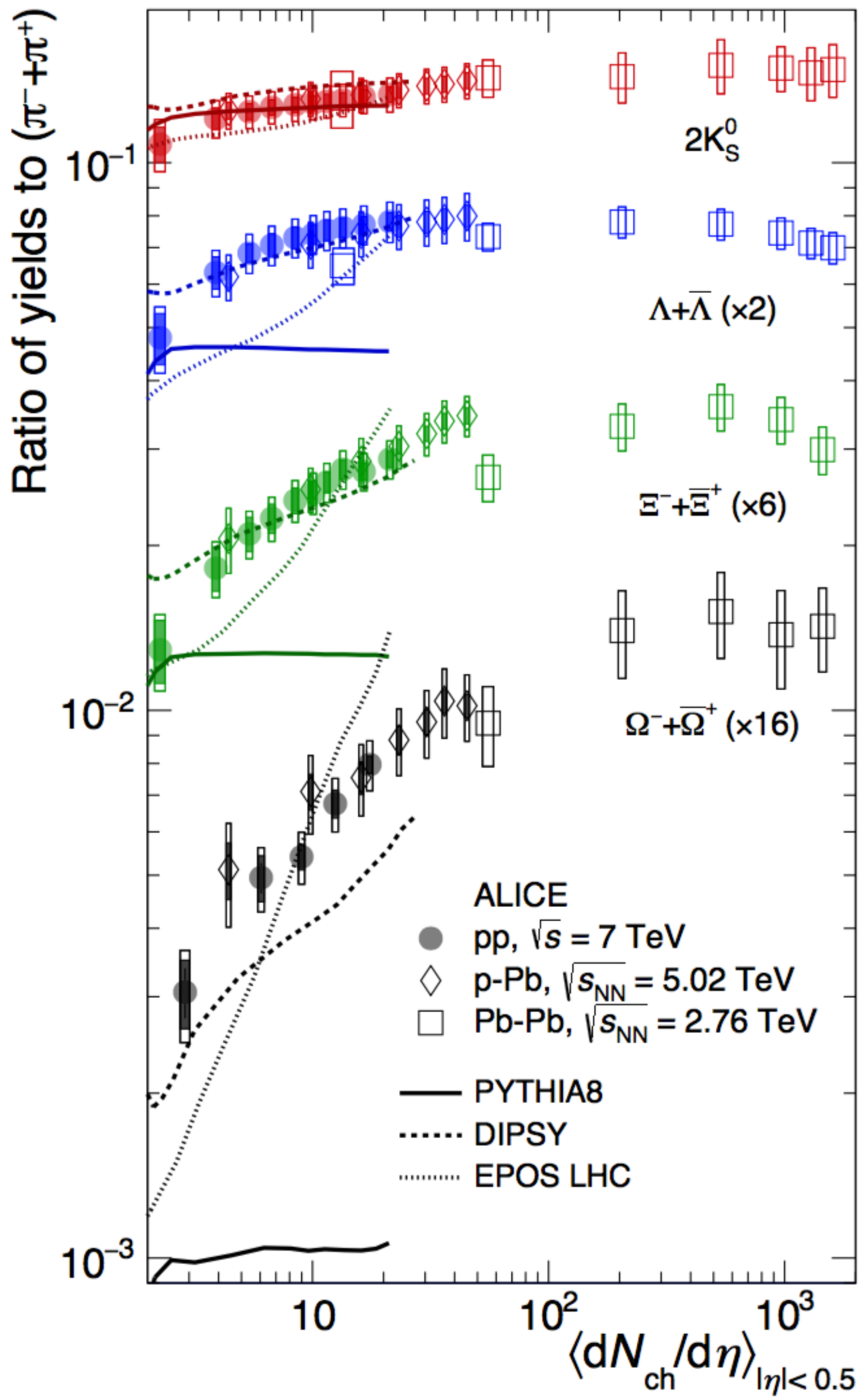

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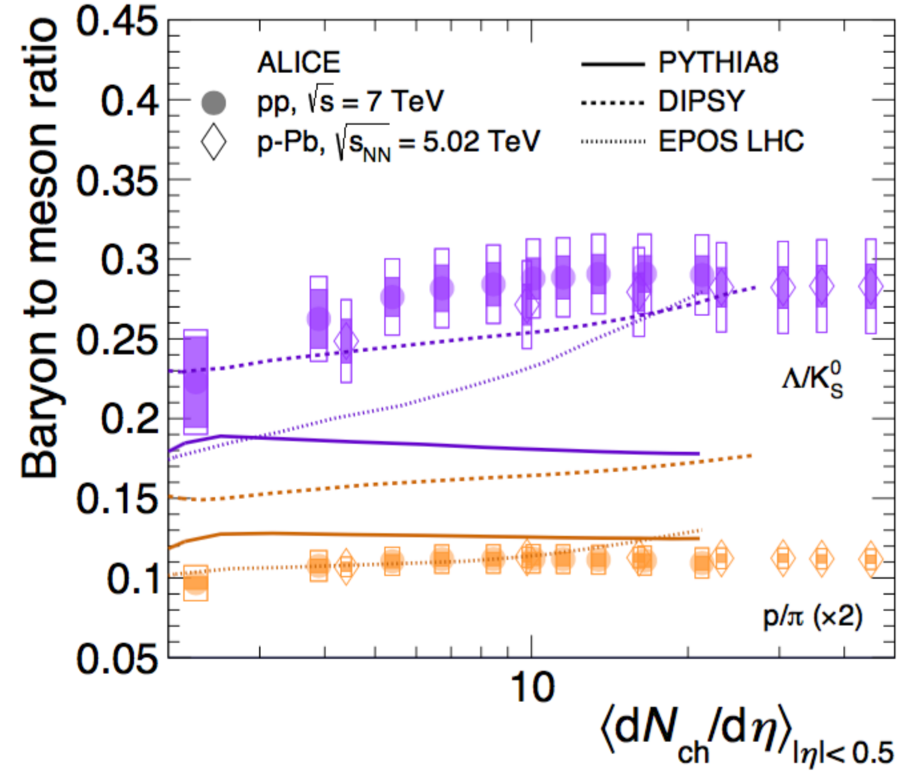


– Baryon-to-meson ratios $\Lambda/K^0{}_s$ and p/π do not increase significantly → increase is not mass but strangeness related

– Hierarchy of increase with strangeness content observed

– MC models with color ropes - interactions between produced strings - (DIPSY) and radial expansion (EPOS) qualitatively reproduce the measured trend with multiplicity

Hard probes

Hard processes

Hard probes

- Hard scattering in pp collisions described by pQCD calculations using universal non-perturbative functions such as (n)PDF and Fragmentation Function
- Produced in the initial hard partonic collisions in the early stage of the collisions ($\tau \simeq 1/m$)
- In A-A, hard probes cross the formed medium

Nuclear modification factor

- In A-A (and p-A), if there is no interaction with the medium (high-p_T photons, electroweak bosons), hard processes are expected to be a superposition of independent nucleon-nucleon collisions and to scale with N_{coll}

$$R_{AA} = \frac{dN^{AA}/dp_T\,dy}{\langle N_{coll}\rangle\, dN^{pp}/dp_T\,dy}$$

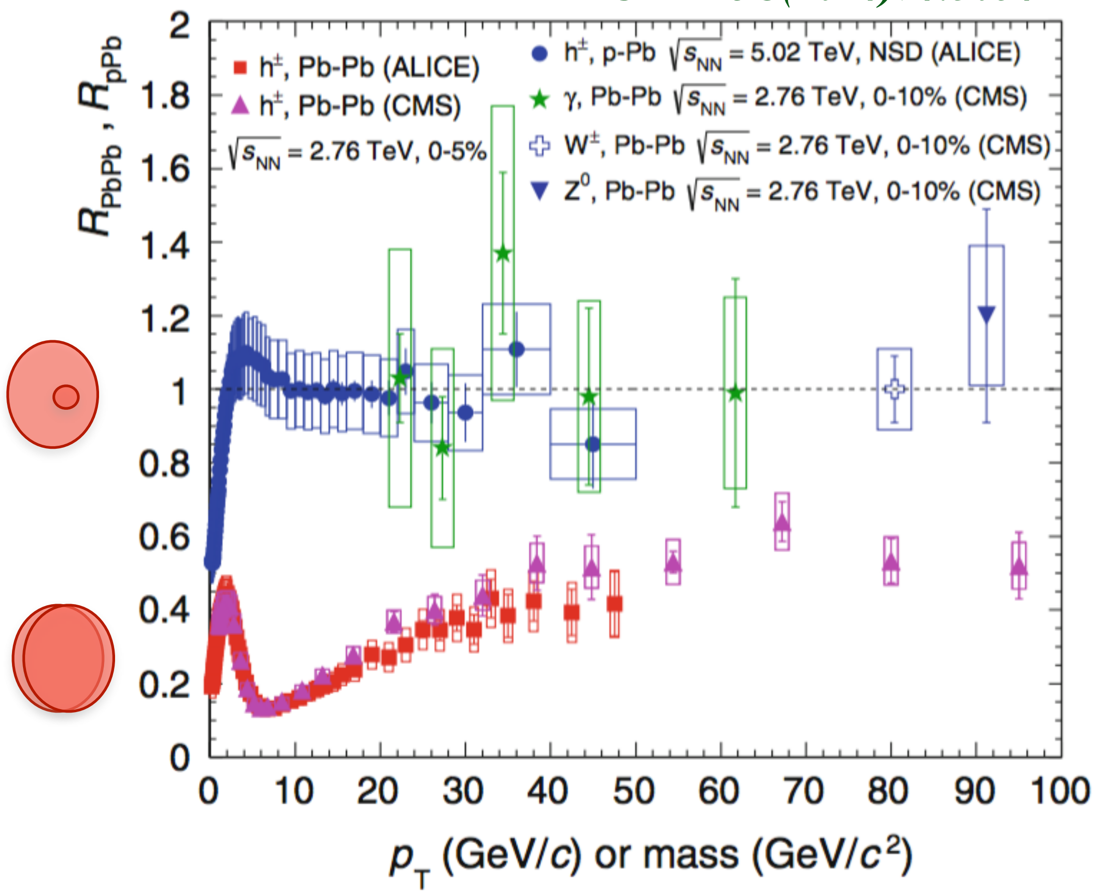
- $R_{AA} = 1$: no modification
- $R_{AA} > 1$: enhancement
- $R_{AA} < 1$: suppression

References

- pp collisions: test of production models and reference for A-A and p-A
- p-A collisions: initial/final state effects in « cold » nuclear environment (cold nuclear matter effects) such as shadowing or gluon saturation, multiple interaction of partons in the initial state (Cronin effect), energy loss, …

Suppression of high-p_T charged particles

ALICE *EPJC(2014)74:3054*



- R_{AA} = 1 for probes that do not interact with QGP (electroweak bosons, high-p_T photons) → essential verification of N_{coll} scaling
- R_{AA} < 1: strong suppression of high-p_T charged particles (→ jets), minimum at p_T = 6-7 GeV/c and slow increase at larger p_T → strong parton energy loss in nuclear matter that decreases with increasing p_T
- R_{pPb} consistent with unity at p_T > 2 GeV/c → suppression observed in Pb-Pb is a final-state effect

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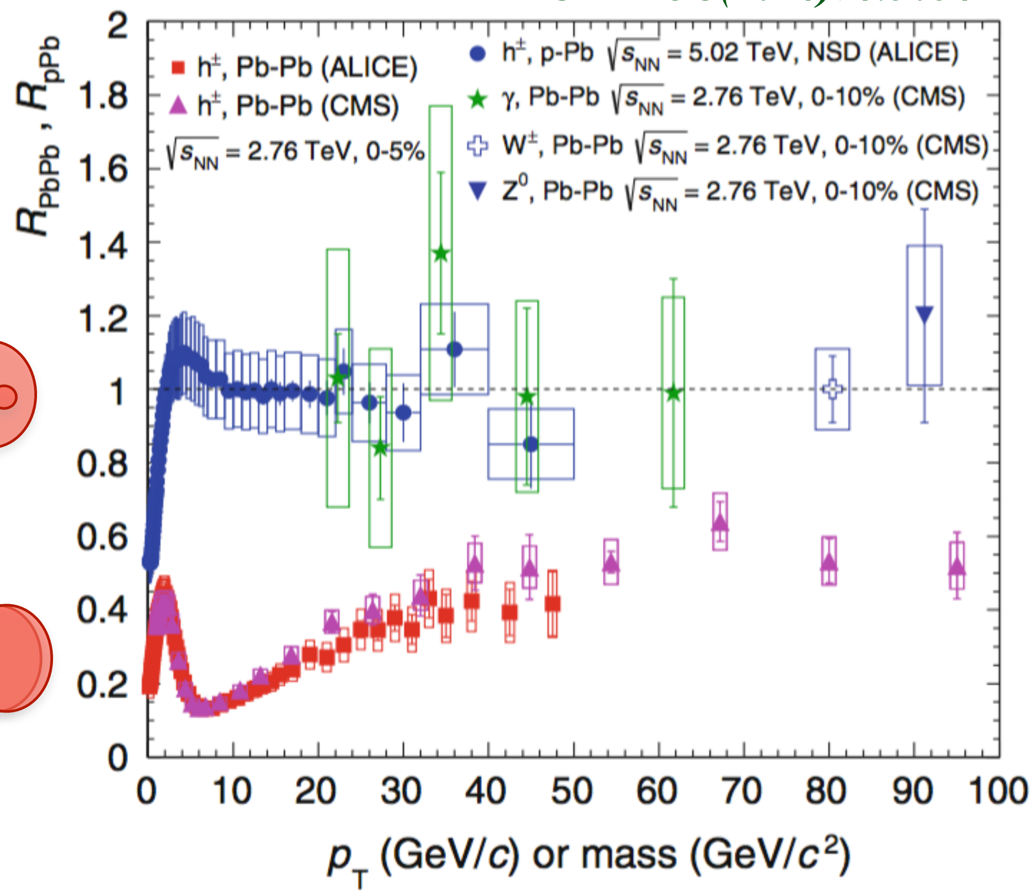

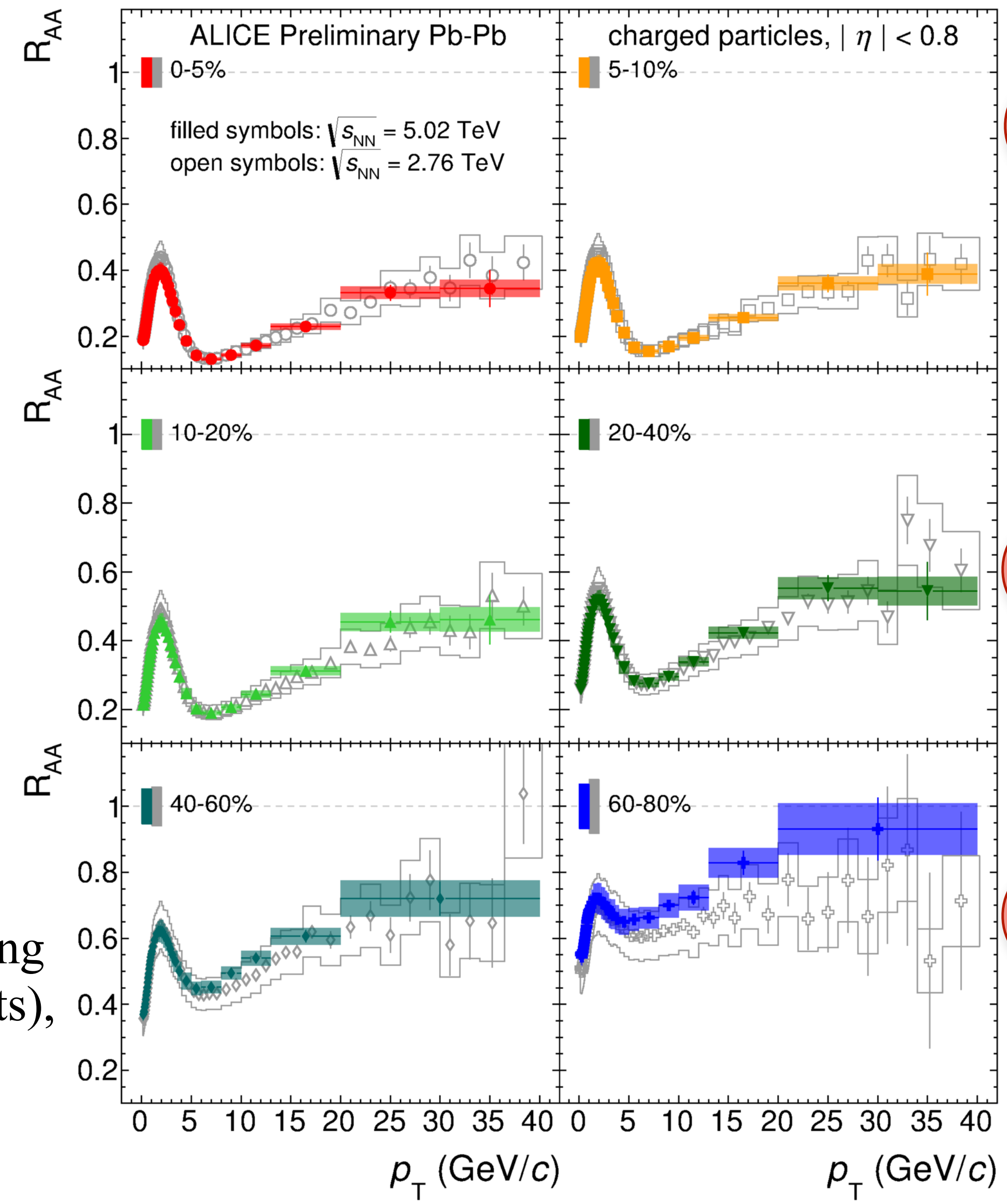

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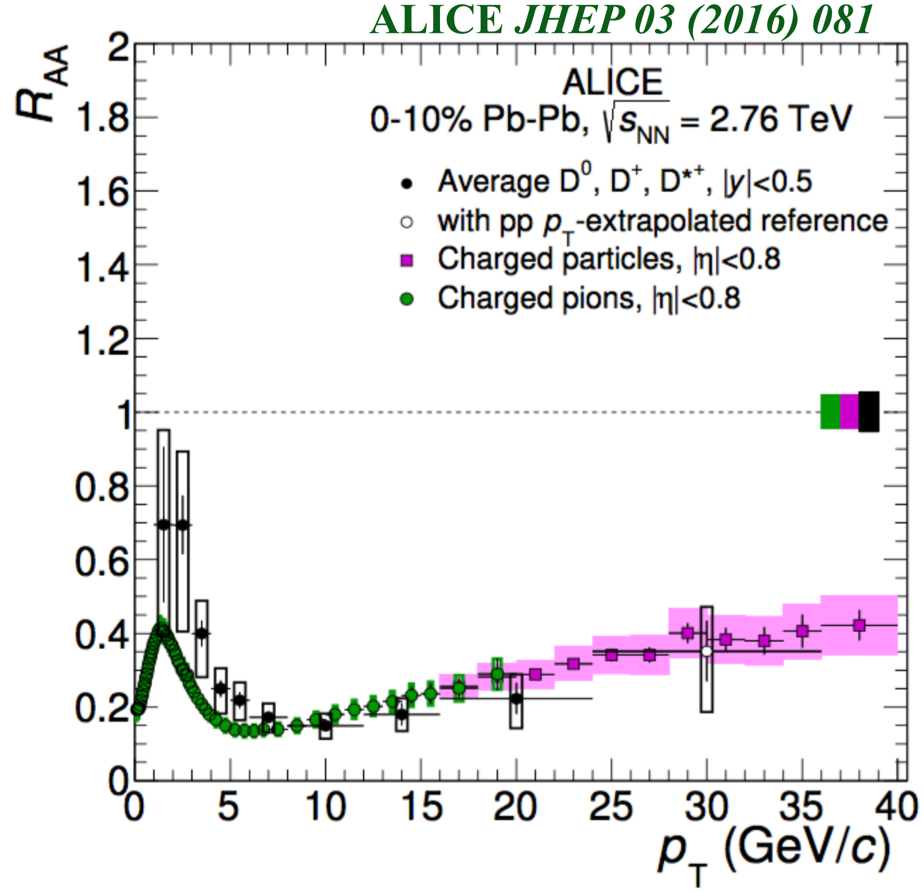
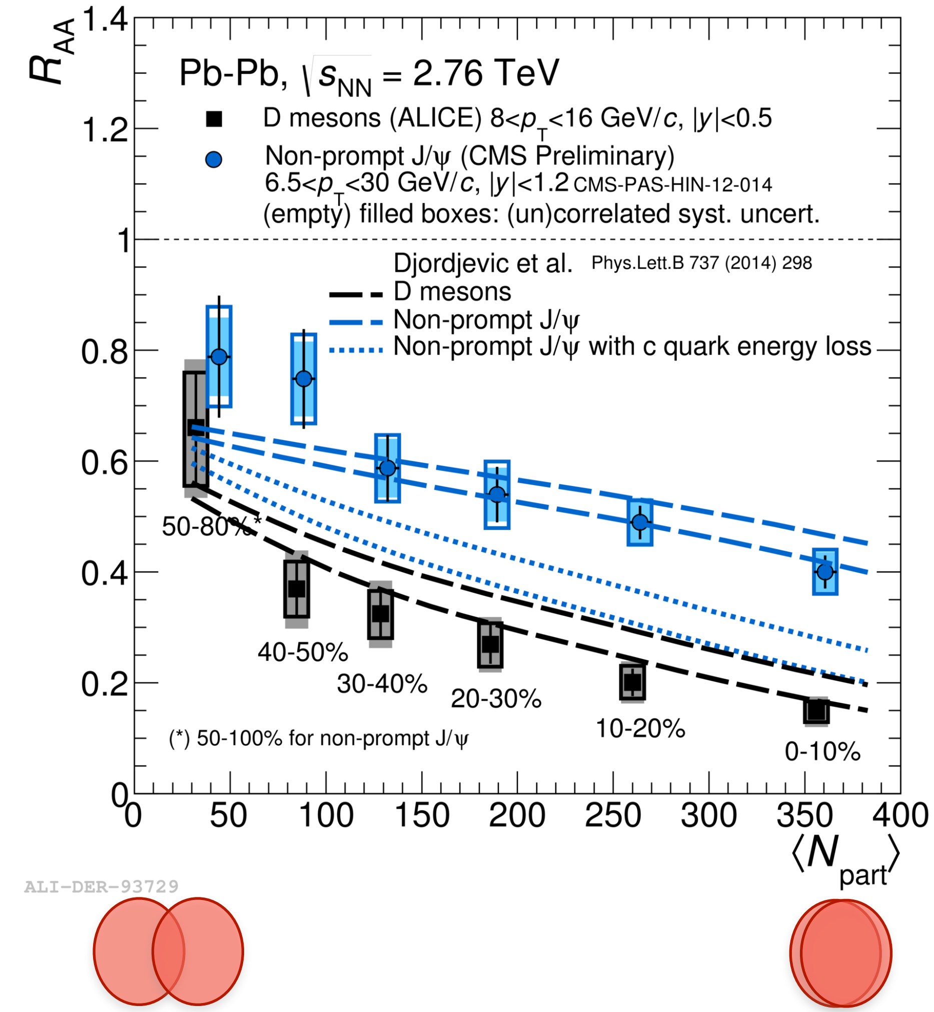
- R_{pPb} consistent with unity at $p_T > 2$ GeV/c → suppression observed in Pb-Pb is a final-state effect
- Results at $\sqrt{s_{NN}} = 5.02$ TeV with improved systematics → very similar results wrt $\sqrt{s_{NN}} = 2.76$ TeV

Open heavy-flavor R_{AA}

Radiative energy loss decreases for heavy quarks (Casimir factor and dead cone effect):
$\Delta E_g > \Delta E_c > \Delta E_b \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

ALICE *JHEP 03 (2016) 081*



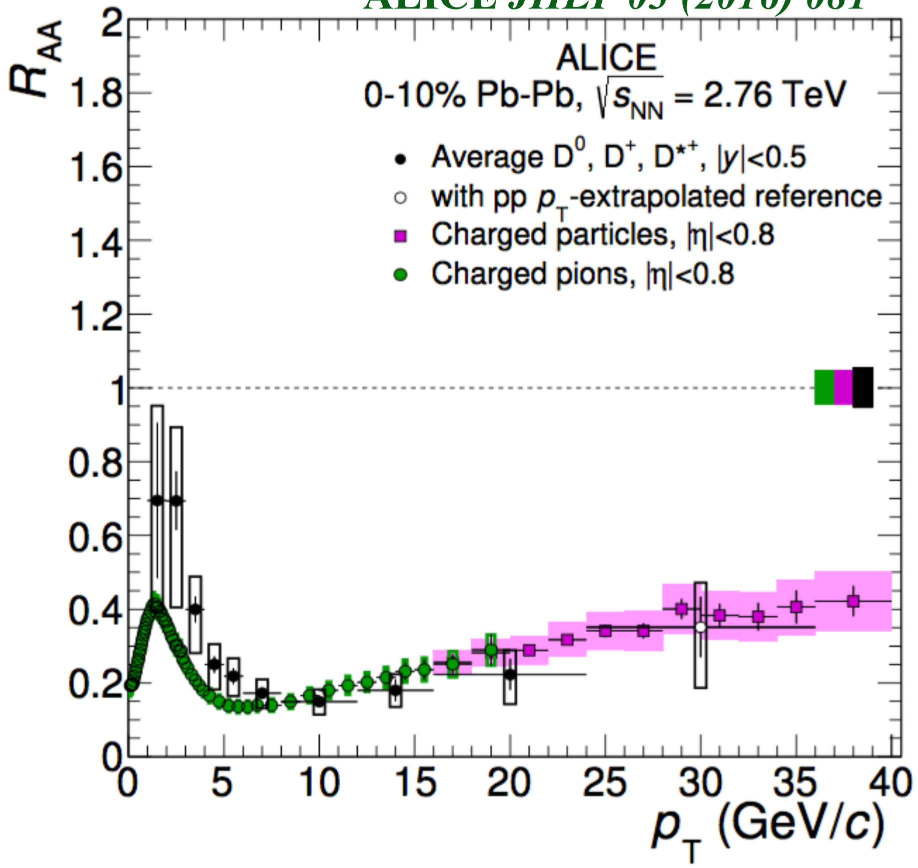


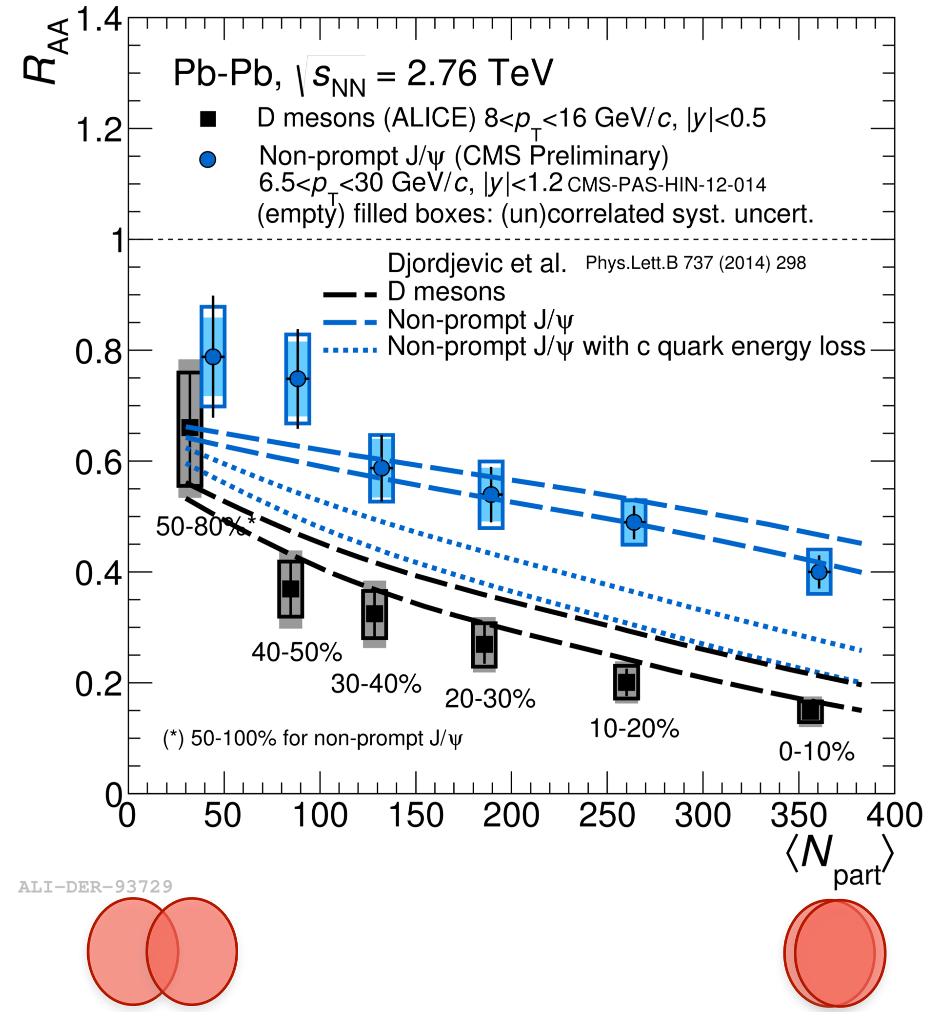
- At high p_T the suppression for D mesons and π and/or charged hadrons is similar: can be explained by harder fragmentation and p_T spectrum for charm wrt gluon
- Indications of $R_{AA}(\pi) < R_{AA}(D)$ at low p_T, $p_T < 6$ GeV/c
- $R_{AA}(D) < R_{AA}(B \leftarrow J/\psi)$ measured at large p_T: expected from $\Delta E_c > \Delta E_b$

Open heavy-flavor R_{AA}

Radiative energy loss decreases for heavy quarks (Casimir factor and dead cone effect):
$\Delta E_g > \Delta E_c > \Delta E_b \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

ALICE *JHEP 03 (2016) 081*





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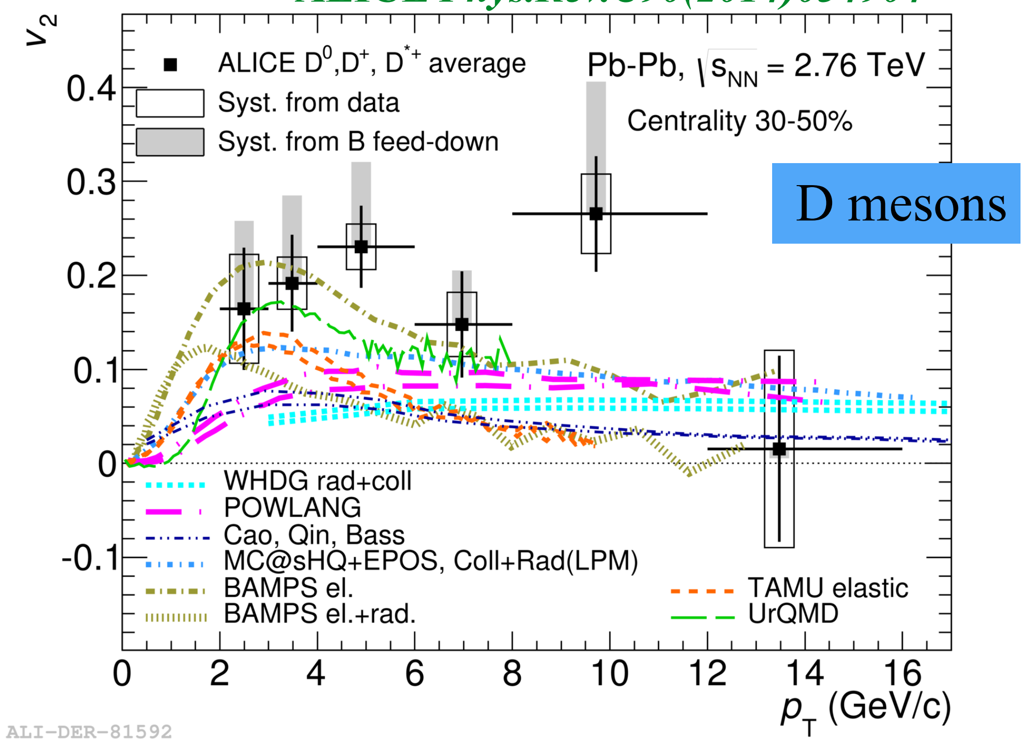
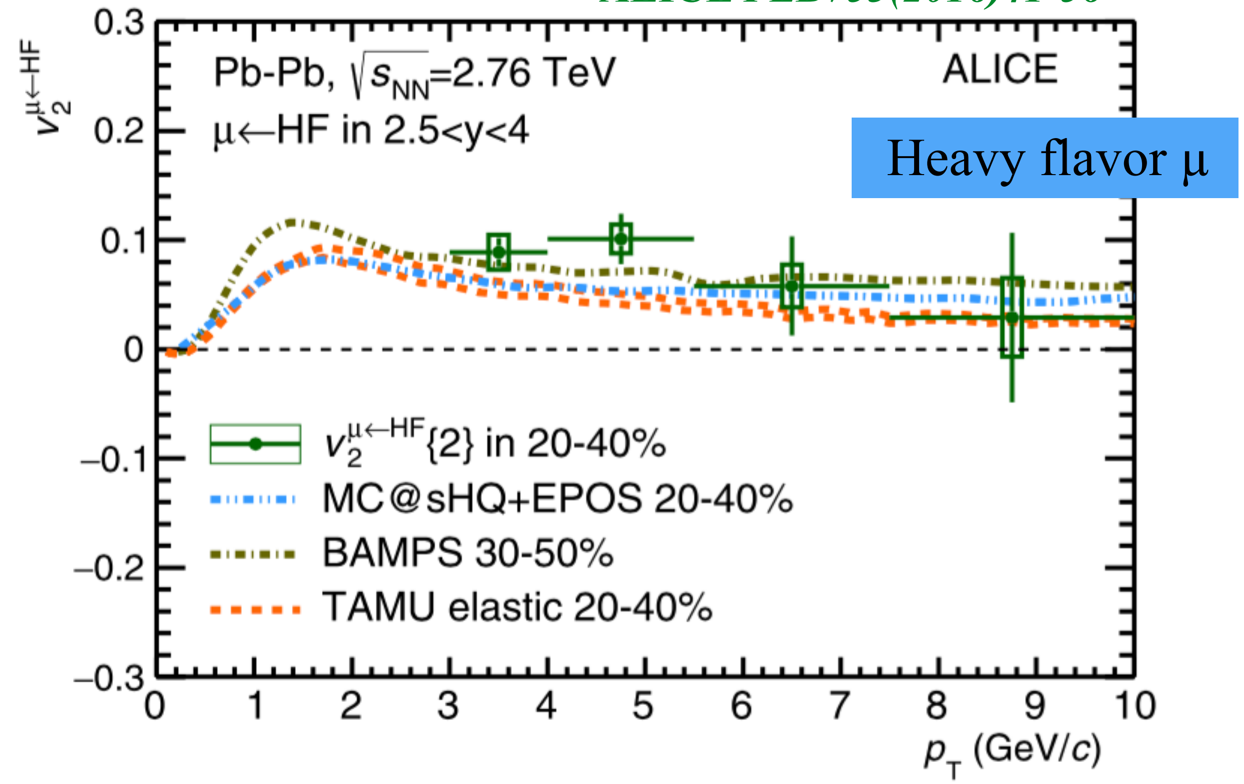
more in Renu Bala, Lehas Fatiha and Kim Mijung's talks

Heavy flavor v_2

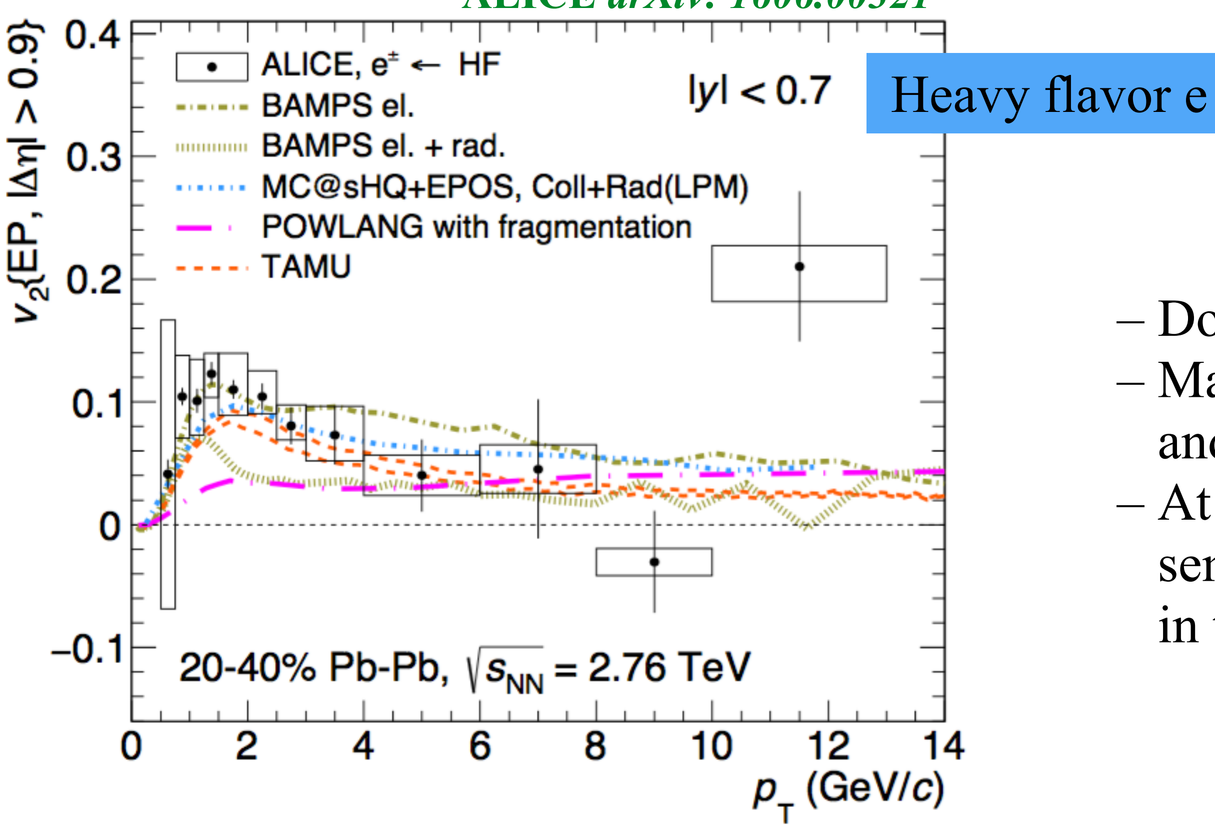
ALICE *Phys.Rev.C90(2014)034904*



ALICE *PLB753(2016)41-56*



ALICE *arXiv: 1606.00321*

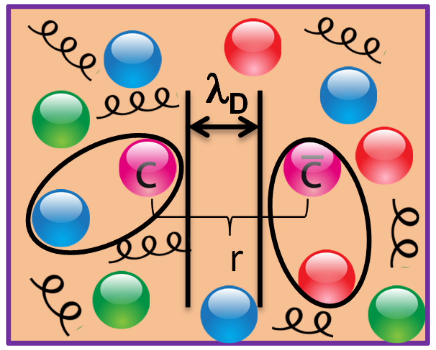


- Does heavy flavor thermalize and flow in the QGP?
- Many HF v_2 results in Pb-Pb collisions with a broad p_T and rapidity range: D mesons, HF e and HF μ
- At low and mid p_T: significant non-zero v_2 measured in semi-central collisions → participation of heavy-quarks in the collective expansion of the system

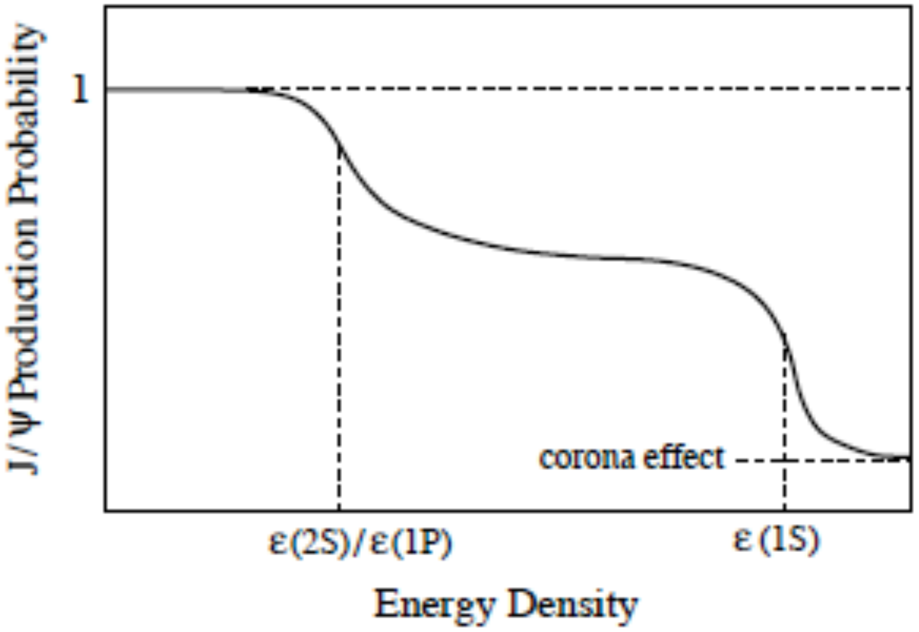
Quarkonia in AA

From sequential suppression...

- At $T >> 0$, high density of colour charge in the medium induces Debye screening
- At $T > T_D$, melting of quarkonia *Matsui, Satz PLB178(1986)*
- Since quarkonia (J/ψ, ψ(2S), Υ(nS),…) have different binding energy
  → sequential suppression of quarkonium states *Karsch, Satz Z.Phys.C51 (1991) 209*



prompt J/ψ in pp ≃ 10% ψ(2S) + 30% χ_C + 60% direct J/ψ



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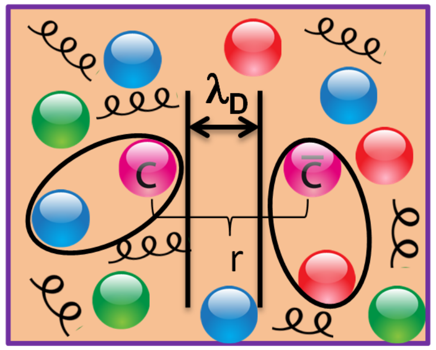

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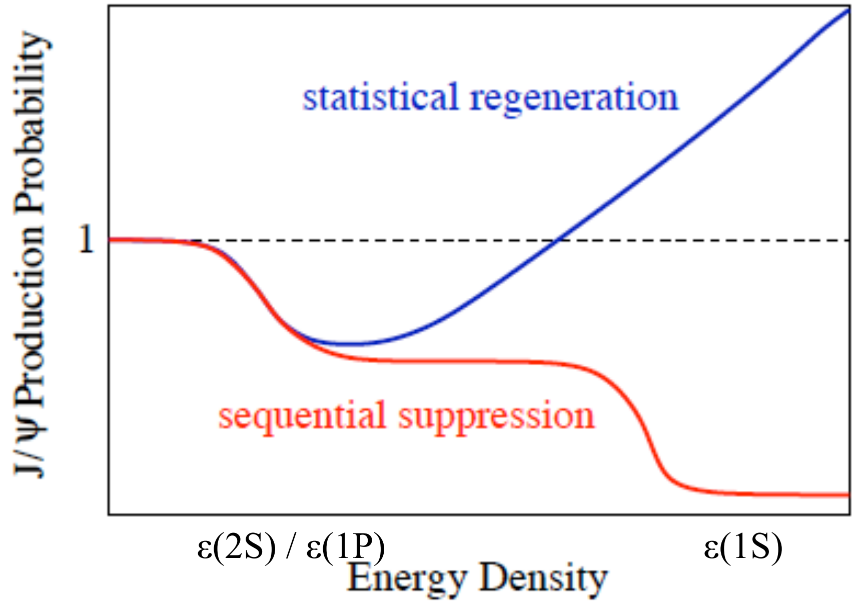


... to regeneration

- Total charm cross-section increases with energy
- c and $\bar{c}$ combination in the QGP or at the phase boundary
  → regeneration of J/ψ
  Braun-Munzinger, Stachel PLB490(2000) *Thews et al. PRC62(2000)*
  ➡ enhancement (depending on open charm cross-section) of J/ψ
  ➡ evidence of thermalization of charm quarks
- Small regeneration expected for bottomonia

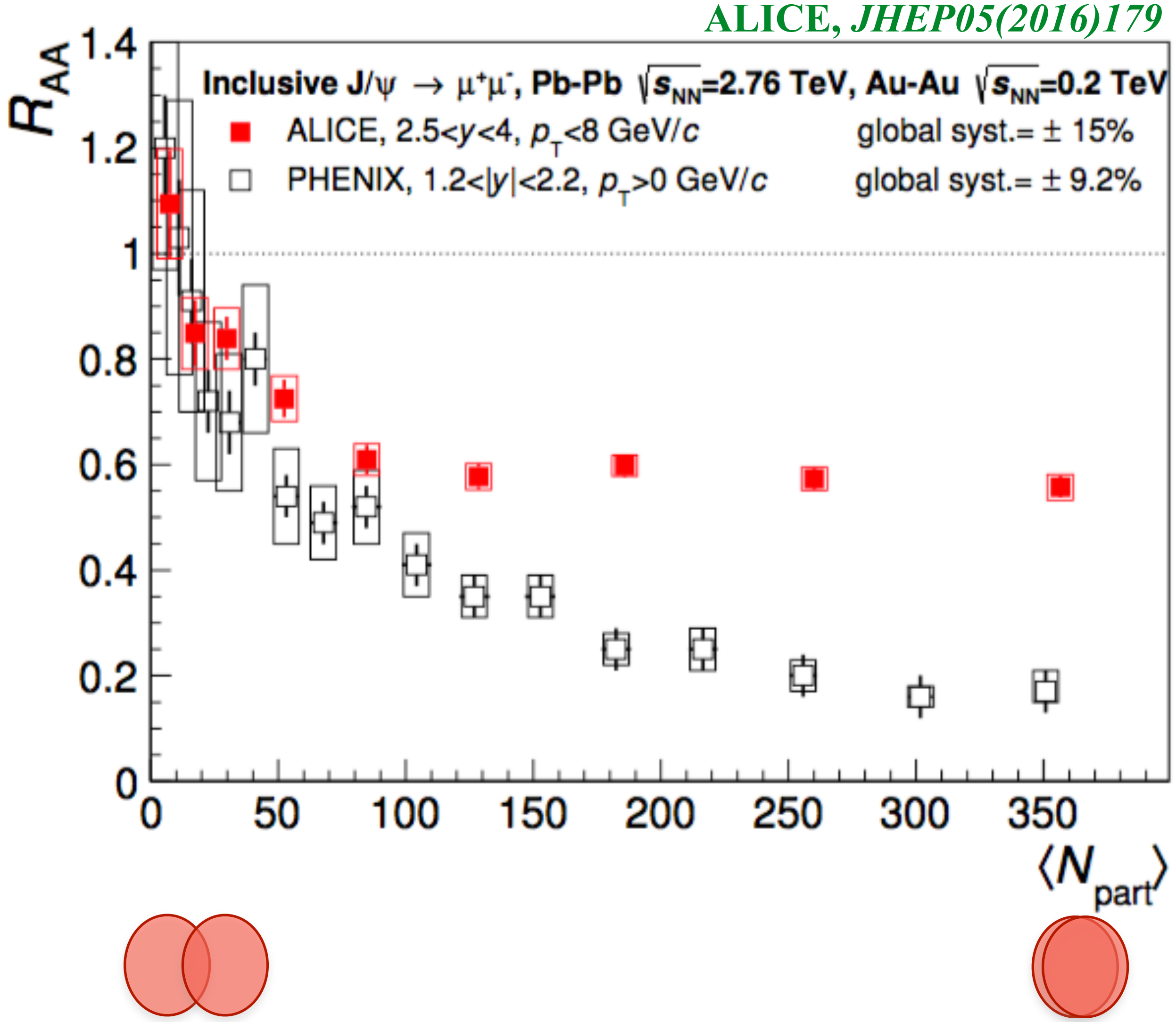
$$\frac{N_{q\bar{q}}}{event} = \frac{\sigma^{pp}_{q\bar{q}}}{\sigma^{pp}_{inel}} \times N_{coll}$$

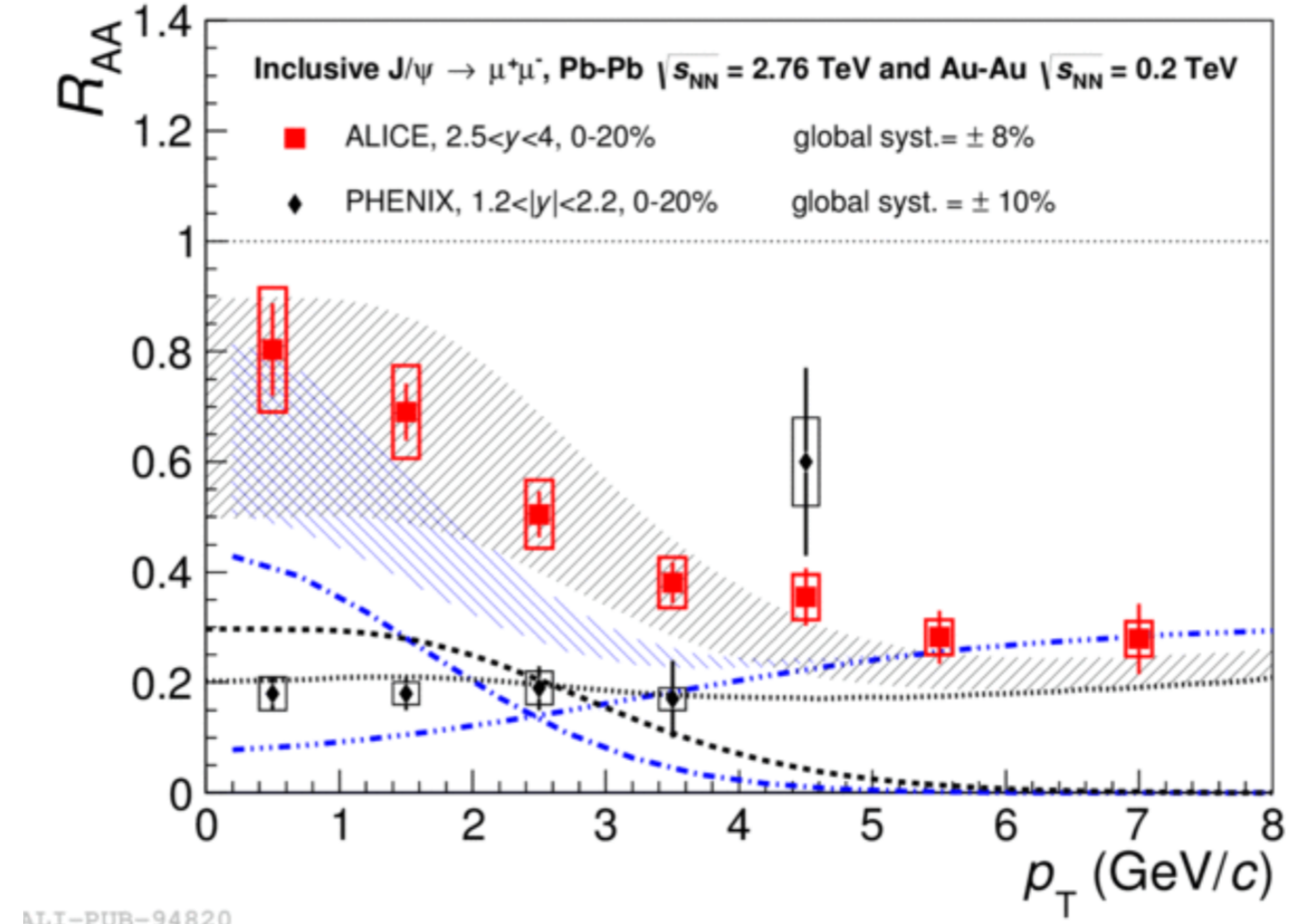
ALICE, JHEP 1207 (2012) 191

In most central collisions [0-10%]	RHIC 200 GeV	LHC 2.76 TeV
N_{cc}/event	13	115
N_{bb}/event	0.1	3

J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 2.76 TeV

ALICE, *JHEP05(2016)179*

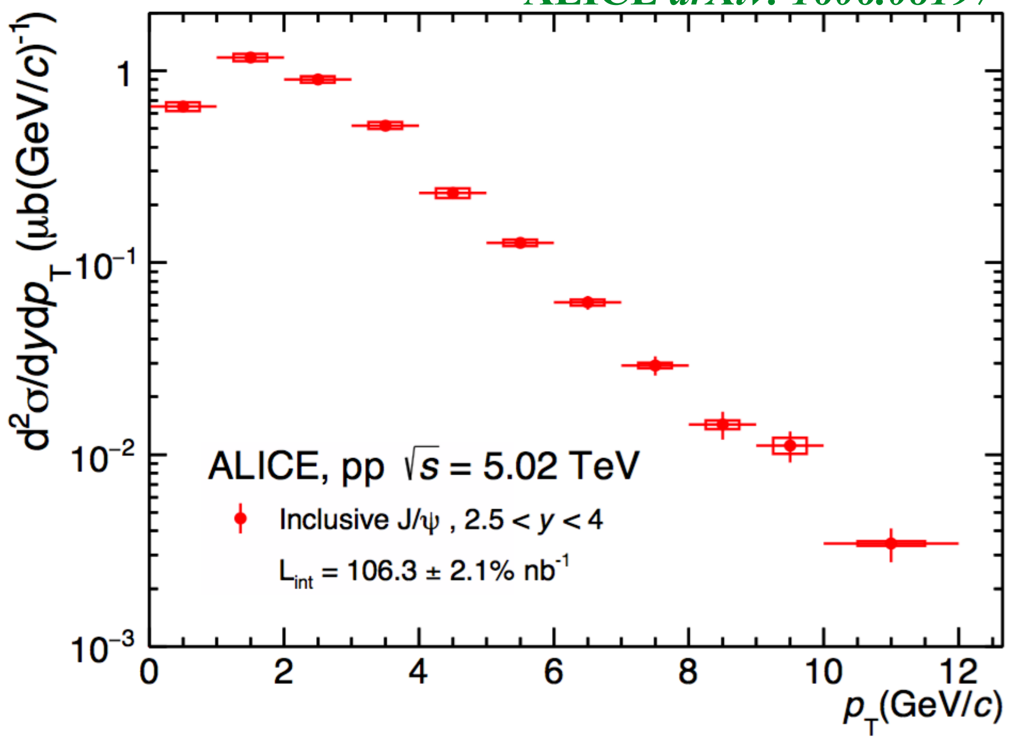




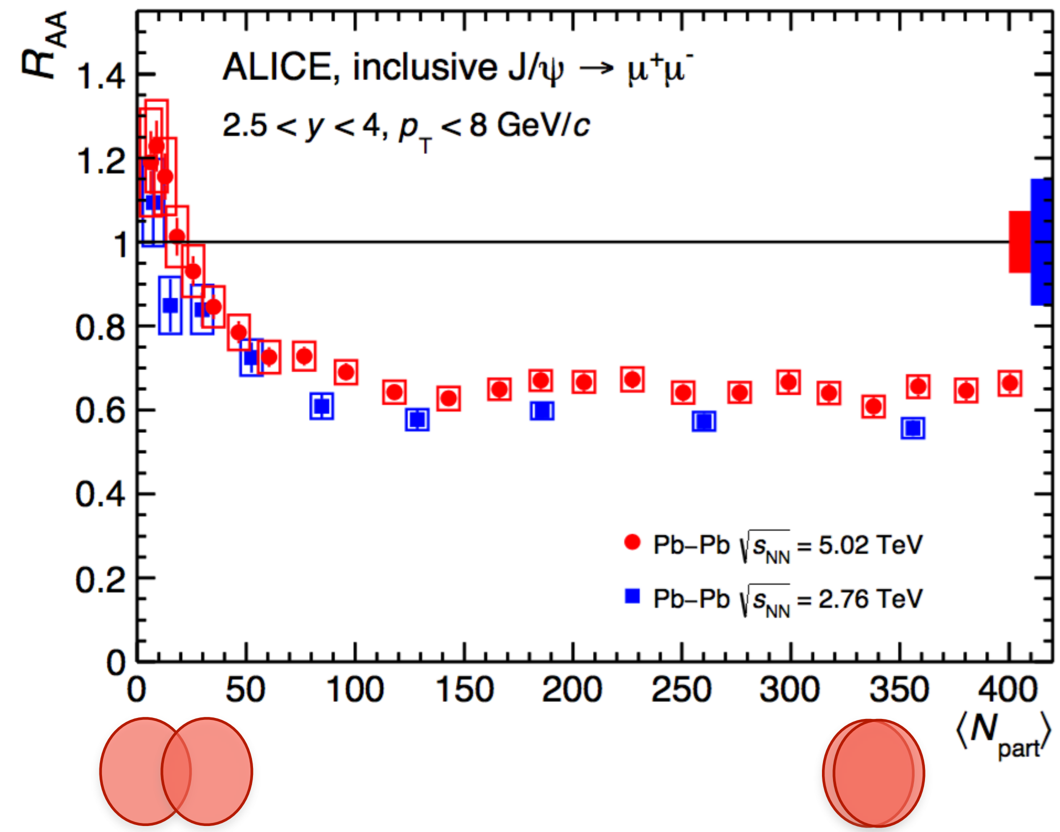
- Higher J/ψ R_{AA} at LHC than at RHIC
- R_{AA} vs N_{part} flat from N_{part} > 70 and R_{AA} increases with decreasing p_T → different behavior at RHIC
- Only models including J/ψ regeneration can describe the data
- How does the J/ψ suppression evolve at higher energy, $\sqrt{s_{NN}}$ = 5.02 TeV?

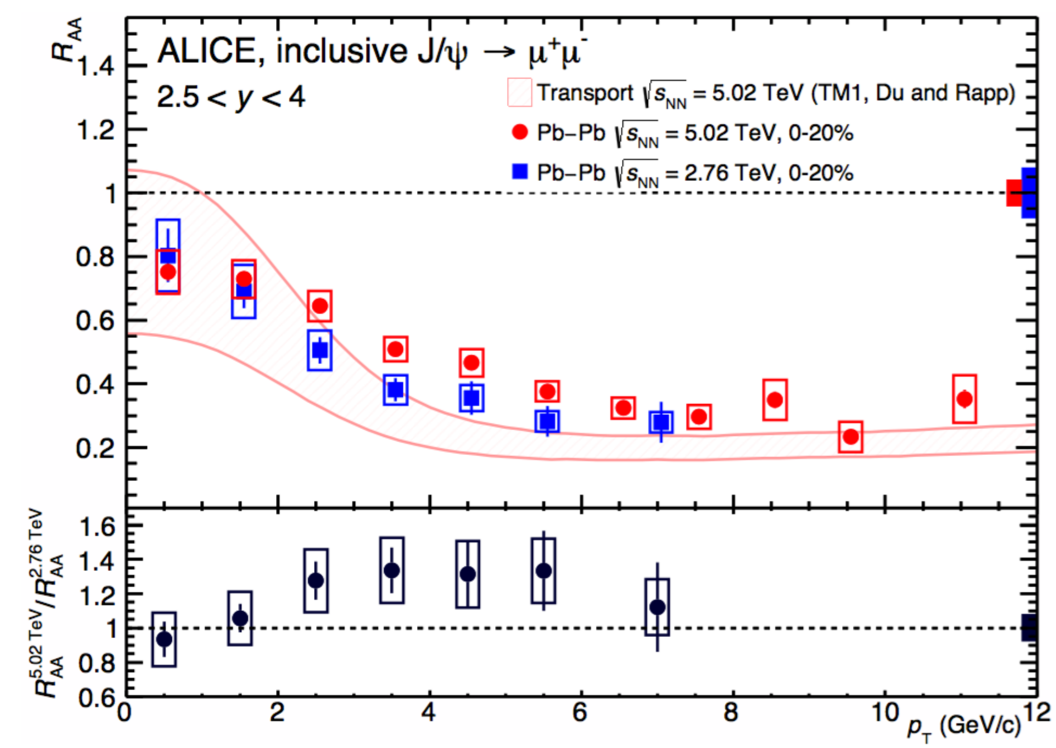
J/ψ production at $\sqrt{s_{(NN)}}$ = 5.02 TeV

ALICE *arXiv: 1606.08197*



ALICE *arXiv: 1606.08197*





- Inclusive J/ψ cross-sections measured in pp collisions at √s = 5.02 TeV
- More precise R_{AA} measurements at $\sqrt{s_{NN}}$ = 5.02 TeV wrt 2.76 TeV!
- R_{AA}(5.02 TeV) / R_{AA}(2.76 TeV) = 1.13 ± 0.02 (stat) ± 0.18 (syst) → results compatible
- Hint for an increase at $\sqrt{s_{NN}}$=5.02 TeV for p_T = 2-5 GeV/c

Charmonium production in p-Pb

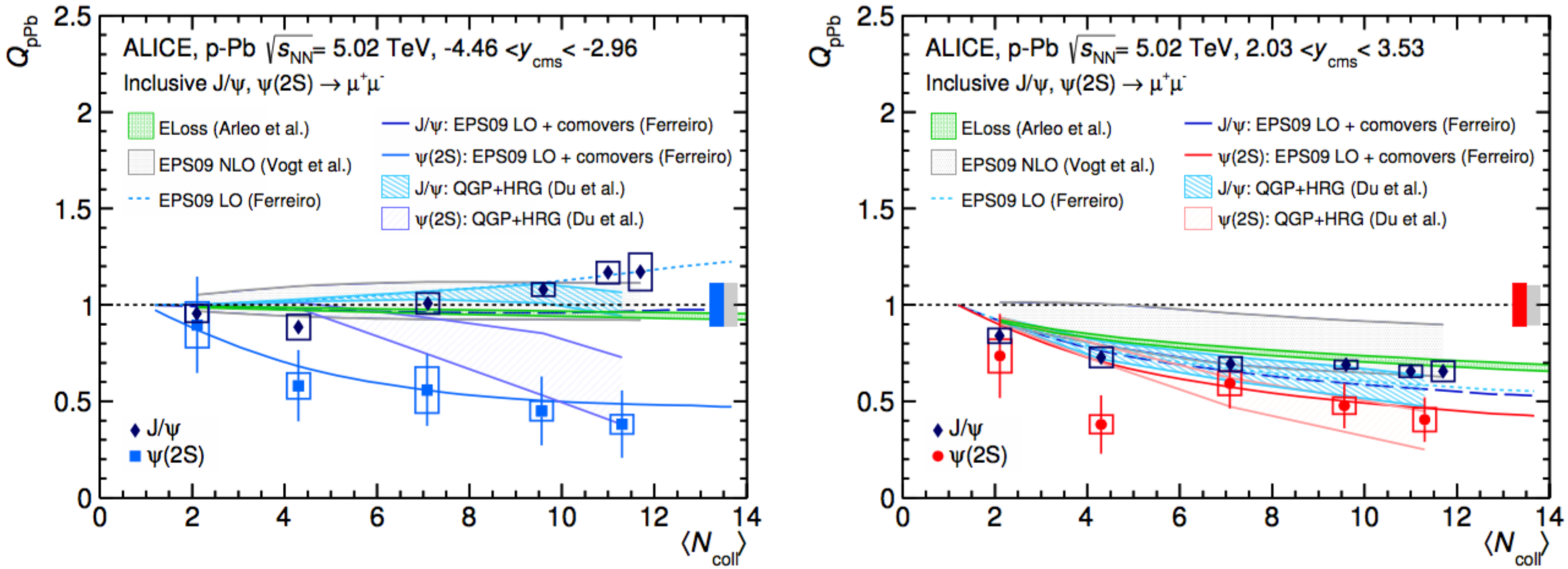
Nuclear modification factor as a function of ZN (forward neutron detector) centrality class: possible bias in the $<N_{coll}>$ evaluation in ZN class, hence the Q_{pPb} notation

backward-*y*
Pb-going

p → ← **Pb**

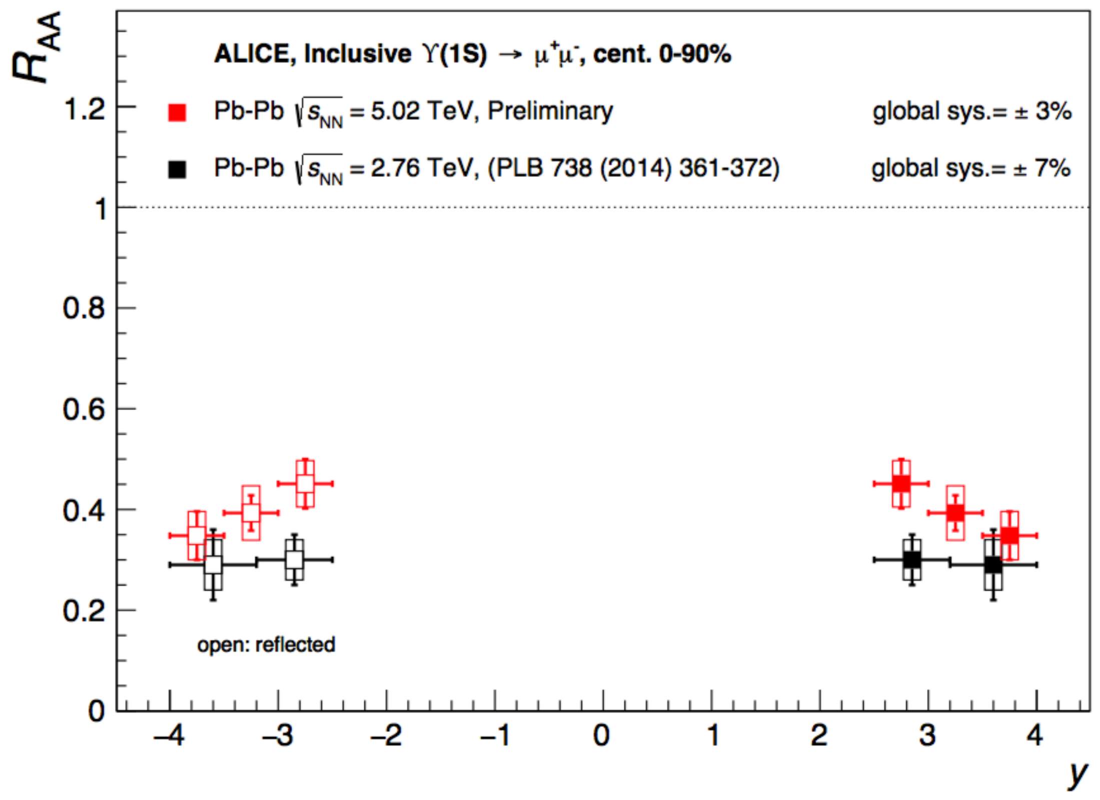
forward-*y*
p-going

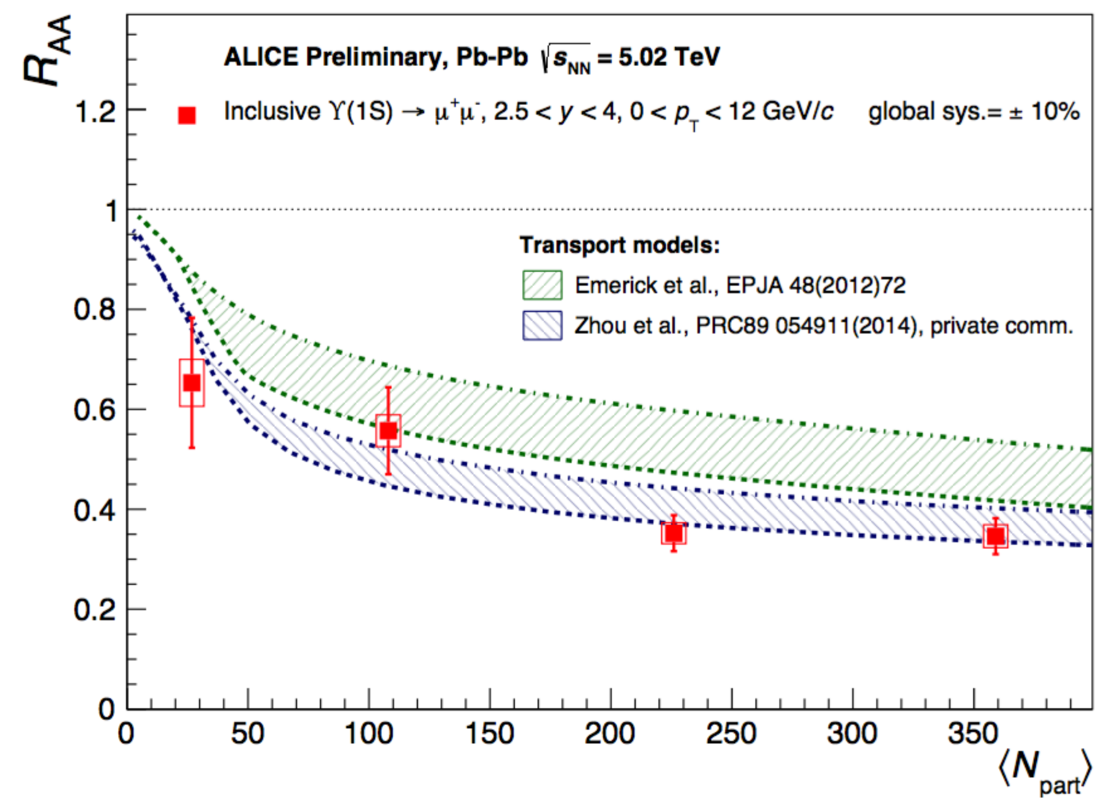
ALICE *JHEP1511(2015)127, JHEP1606(2016)050*



– Nuclear matter effect important for the J/ψ in the p-going direction and in most central events: well reproduced by models that include shadowing, gluon saturation (not shown) or coherent energy loss
– Additional mechanisms are needed to describe the ψ(2S): only models that include final-state interaction with a comoving medium are able to describe the data

Υ(1S) in Pb-Pb and p-Pb





– Decreasing trend of R_{AA} with rapidity and N_{part} at $\sqrt{s_{NN}} = 5.02$ TeV
– Energy comparison: R_{AA}(5.02 TeV) / R_{AA} (2.76 TeV) = 1.3 ± 0.2 ± 0.2 → results compatible
– Transport models reproduce the centrality dependence

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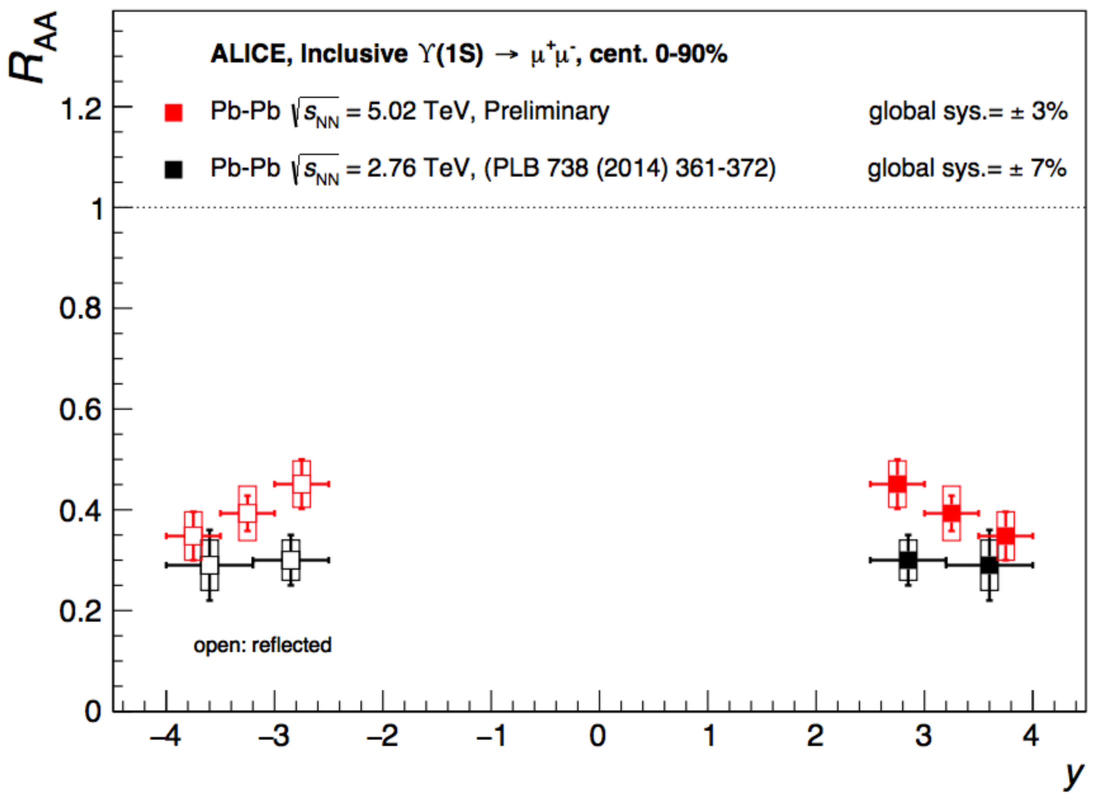

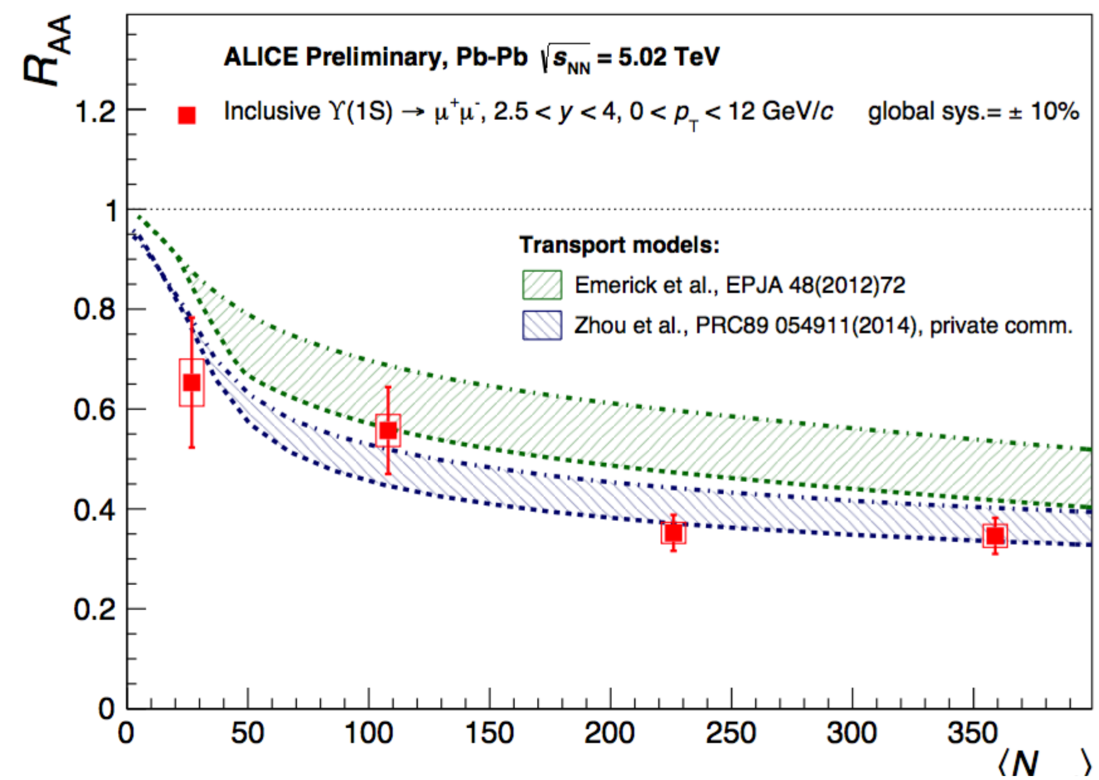

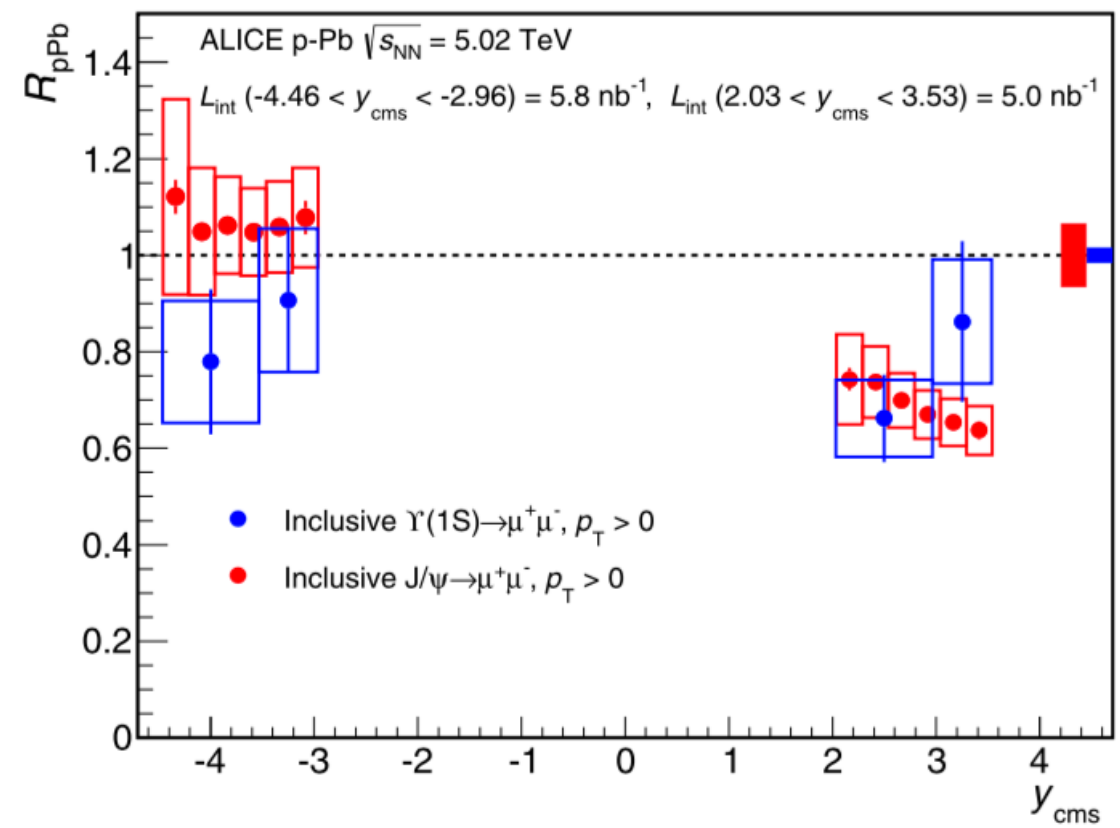

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–In p-Pb: Υ(1S) suppression in the p-going direction

Summary

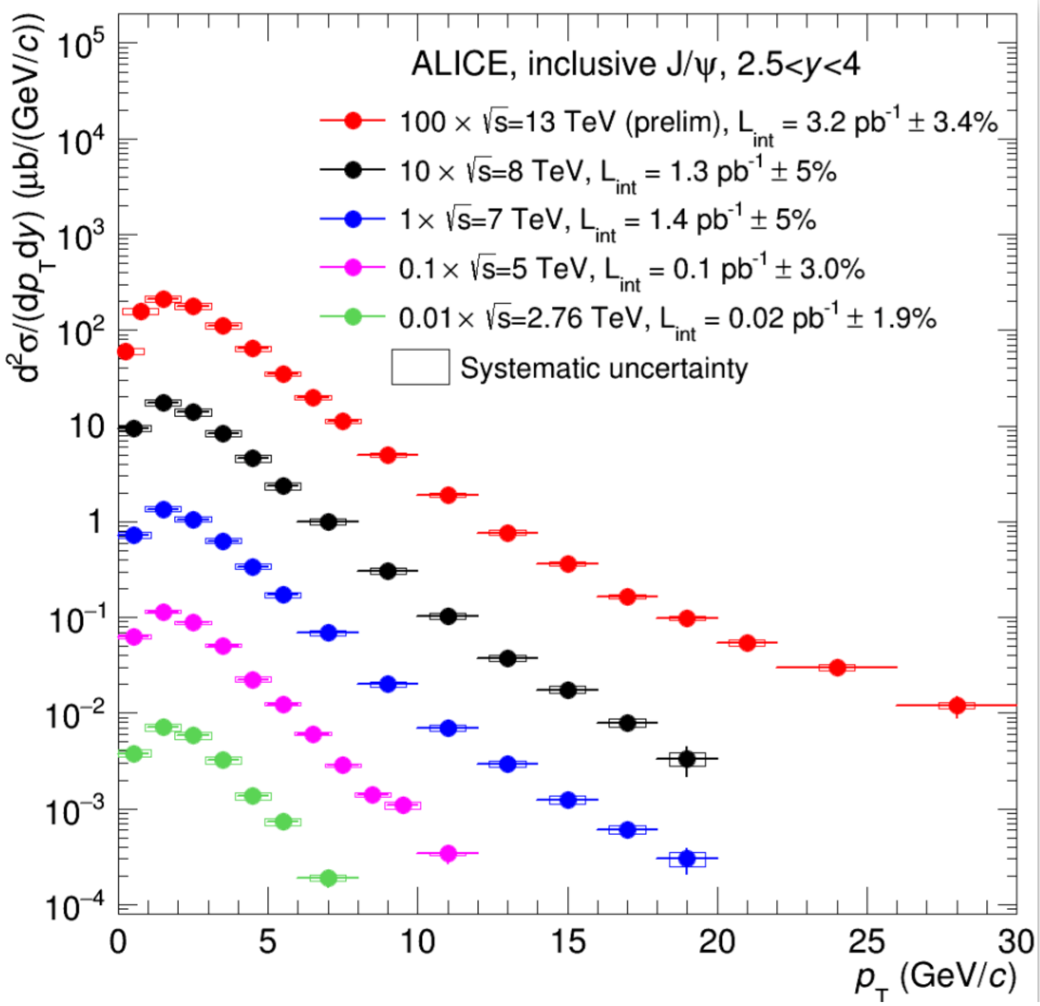
- ALICE studies the quark gluon plasma created in the ultra-relativistic heavy-ion collisions of the LHC
- The measurements of various probes, soft or hard, allow to characterize the created medium
- Energy dependence is studied in Pb-Pb collisions thanks to the results obtained at $\sqrt{s_{NN}} = 2.76$ TeV (Run I) and the new ones at $\sqrt{s_{NN}} = 5.02$ TeV (Run II):
  - Average multiplicity of charged particle increases by 20%
  - Increase of charged particle anisotropic flow that can be attributed to an increase of $\langle p_T \rangle$
  - J/ψ and ϒ(1S) measurements in Pb-Pb wrt pp are compatible at both energies
- High precision measurements in pp collisions at various energies and p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV provide a quantitative understanding of the features observed in Pb-Pb but many surprises found in these small systems at high event multiplicities
- Many more results to come from Run I and II, stay tuned!

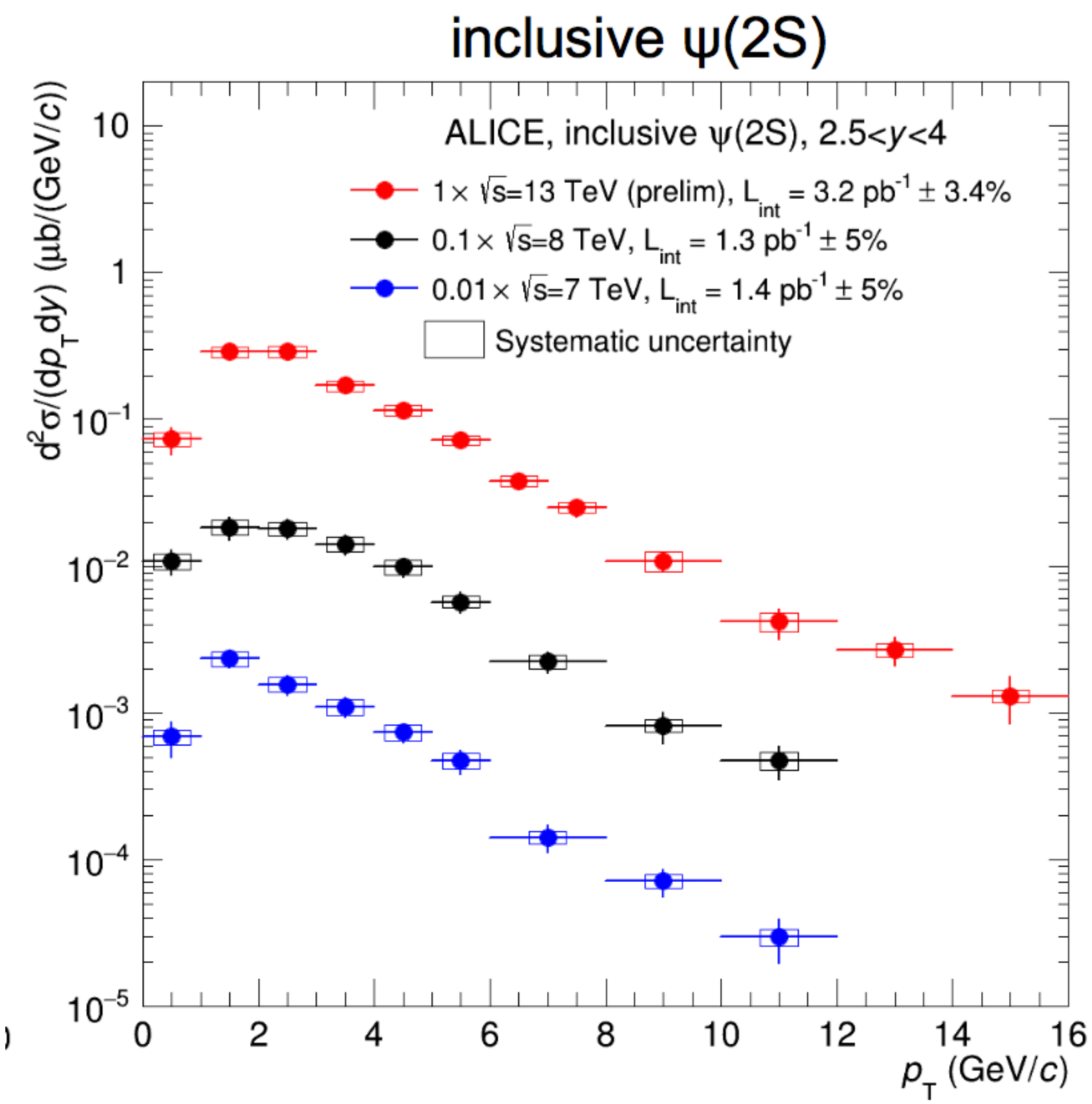
ALICE talks in ICNFP 2016

- You Zhou: Overview of recent azimuthal correlation measurements
- Renu Bala: Open charm production in pp, p-Pb and Pb-Pb collisions
- Minjung Kim: Beauty production measurements
- Lehas Fatiha: Azimuthal angular correlations of D mesons and charged particles in pp collisions at 7 TeV and p-Pb collisions at 5.02 TeV
- Lucile Ronflette: Neutral meson and direct photon measurements
- Thomas Humanic: $K^0_S K^{\pm}$ femtoscopy in Pb-Pb collisions

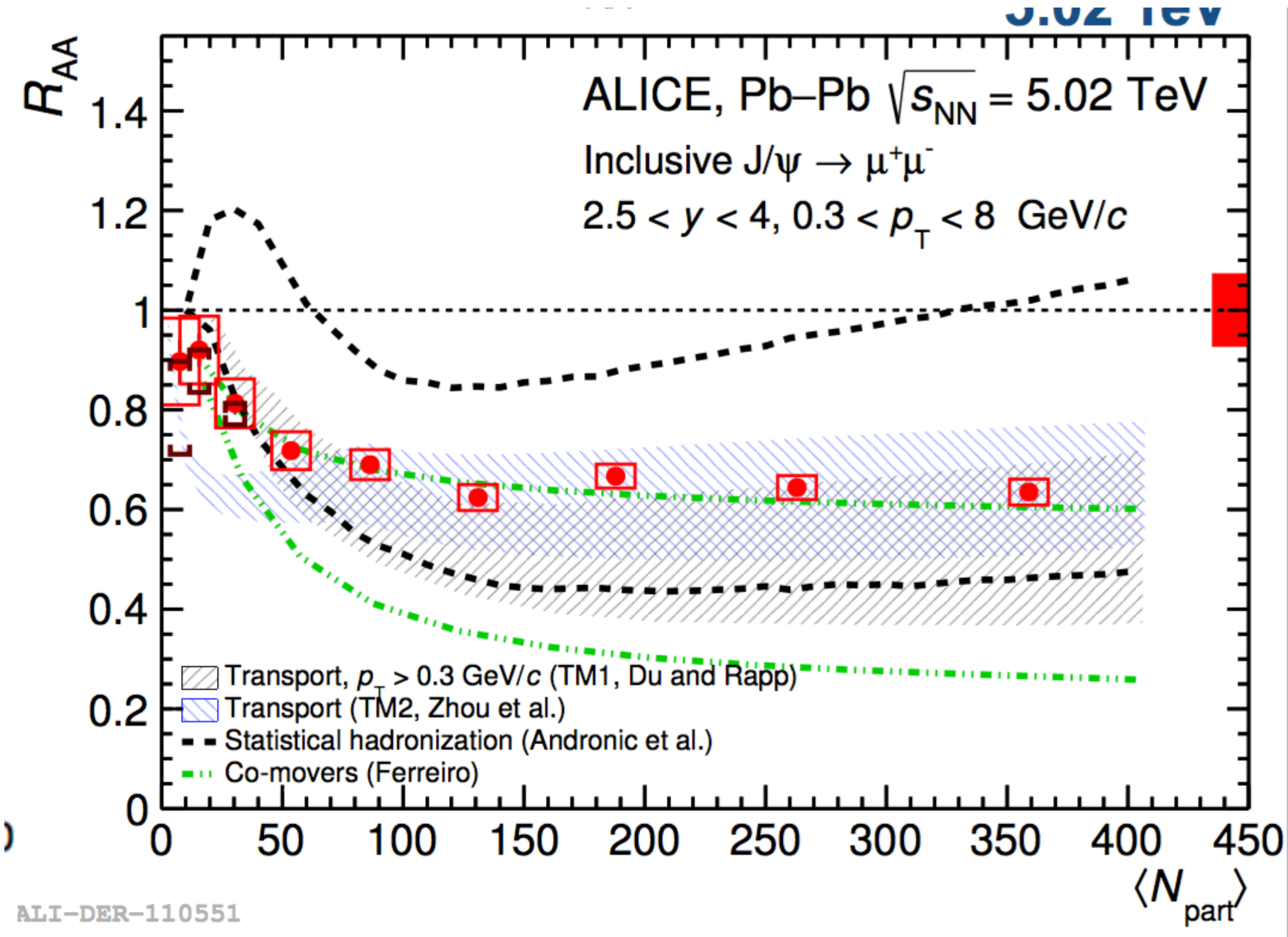
back-up slides

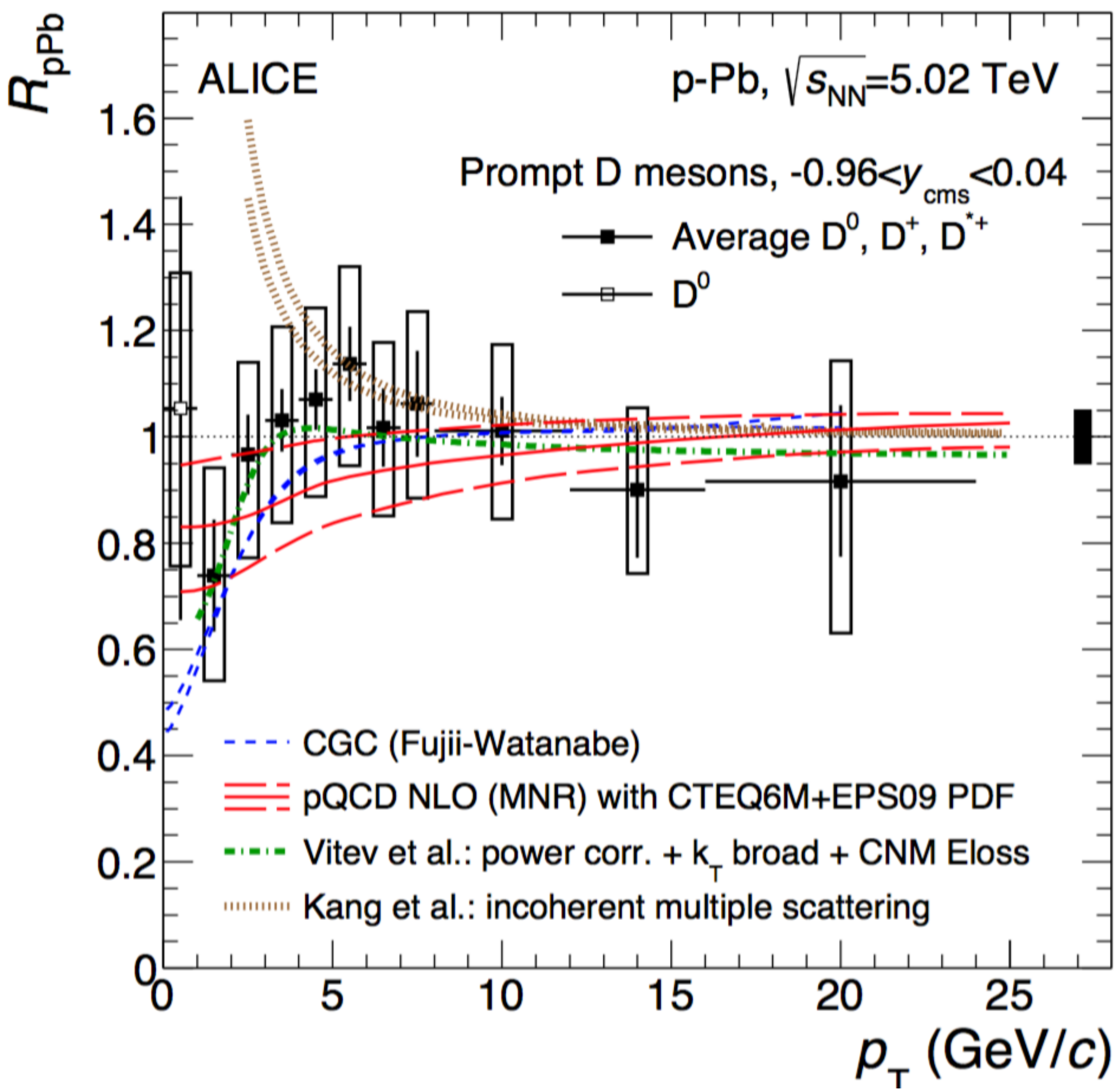
Charmonium production: pp





J/ψ production at $\sqrt{s_{(NN)}}$ = 5.02 TeV

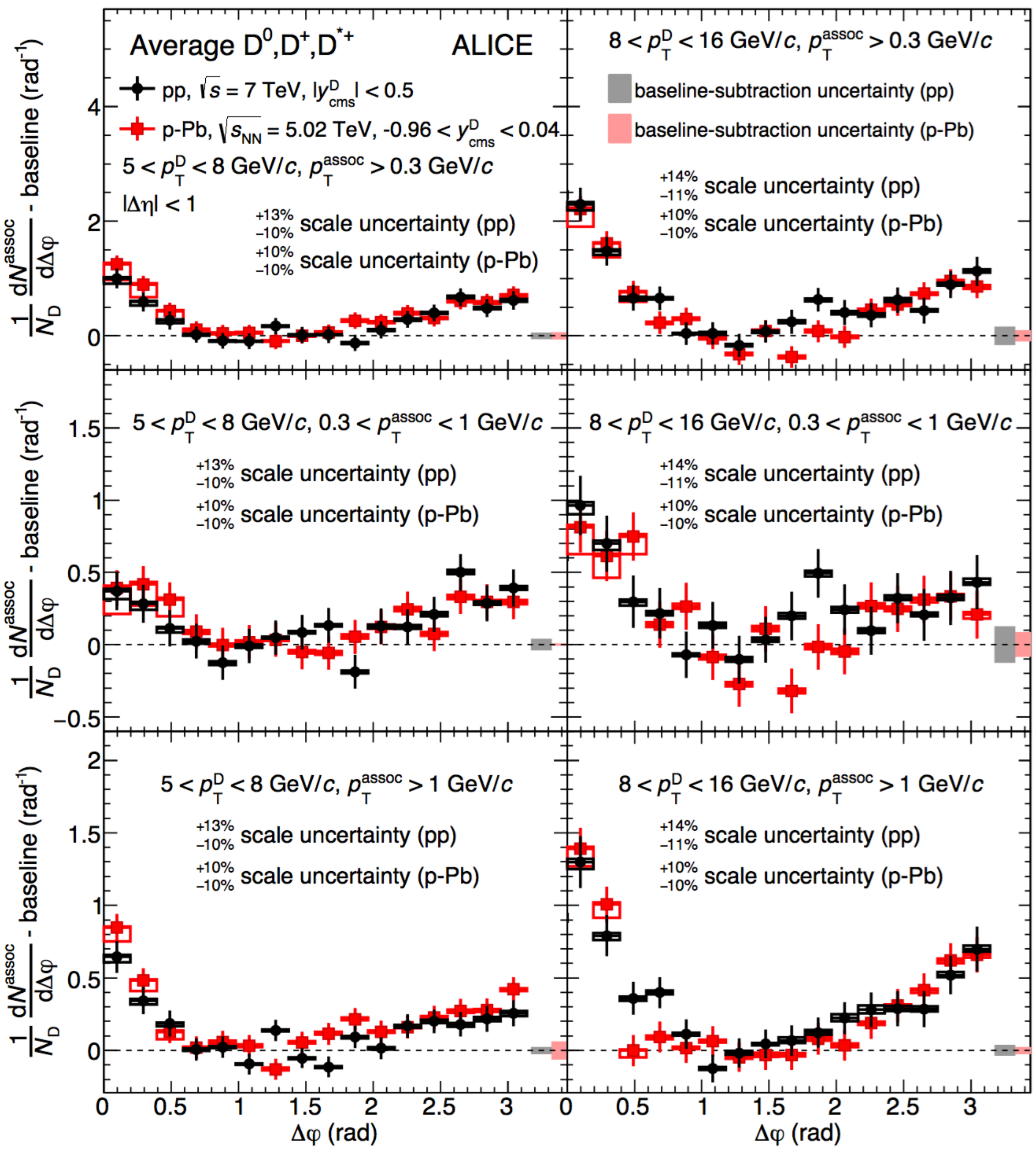




– R_{pPb} is compatible with unity at large p_T: the large suppression measured in Pb-Pb is due to a final-state effect

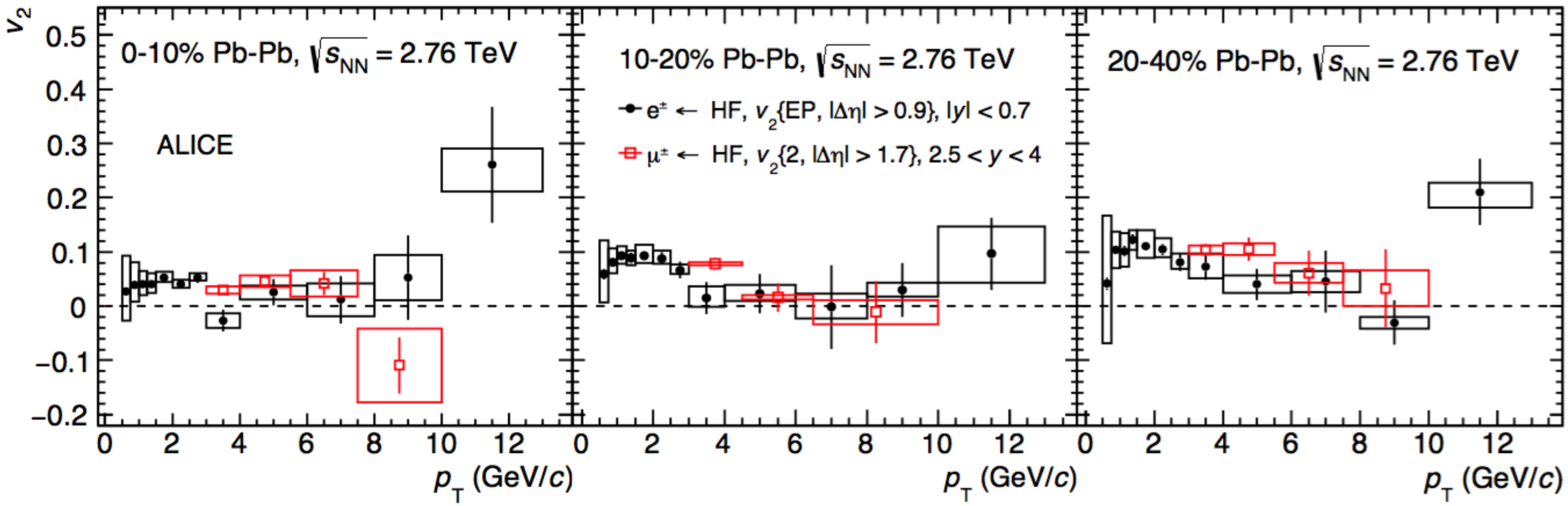
D-hadron correlations in pp and p-Pb

arXiv:1605.06963

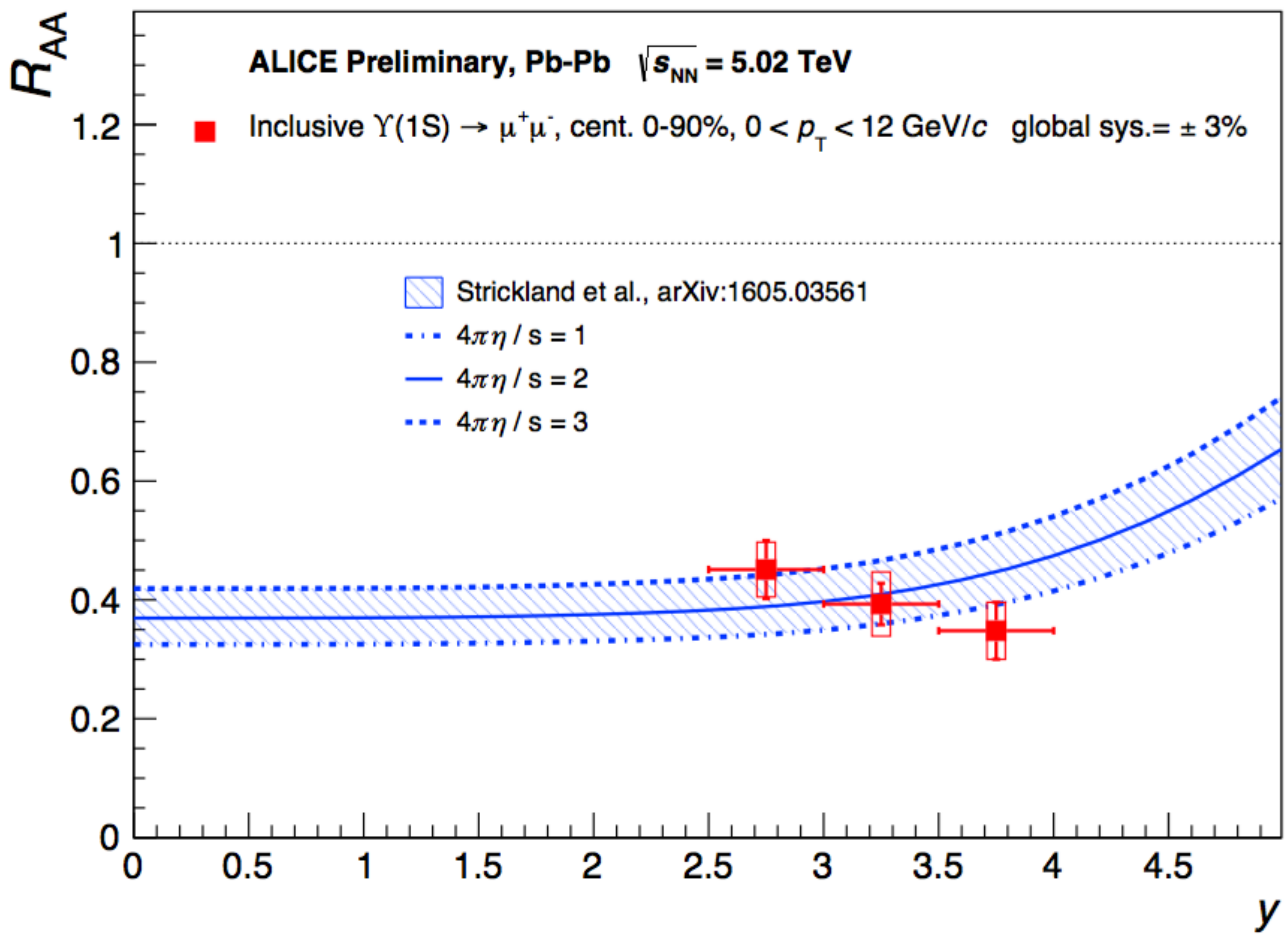


- Measure hadronic activity near and away from the direction of D-meson
- Near-side correlation peak sensitive to the characteristics of the jet containing the D meson
- Very similar correlation functions obtained in pp and p-Pb pointing out to unmodified charm-quark fragmentation processes in p-Pb
- Next: measurement of the azimuthal correlation of D mesons and charged particles in Pb–Pb: information on the charm-quark energy-loss mechanisms

v_2 of leptons from HF decays

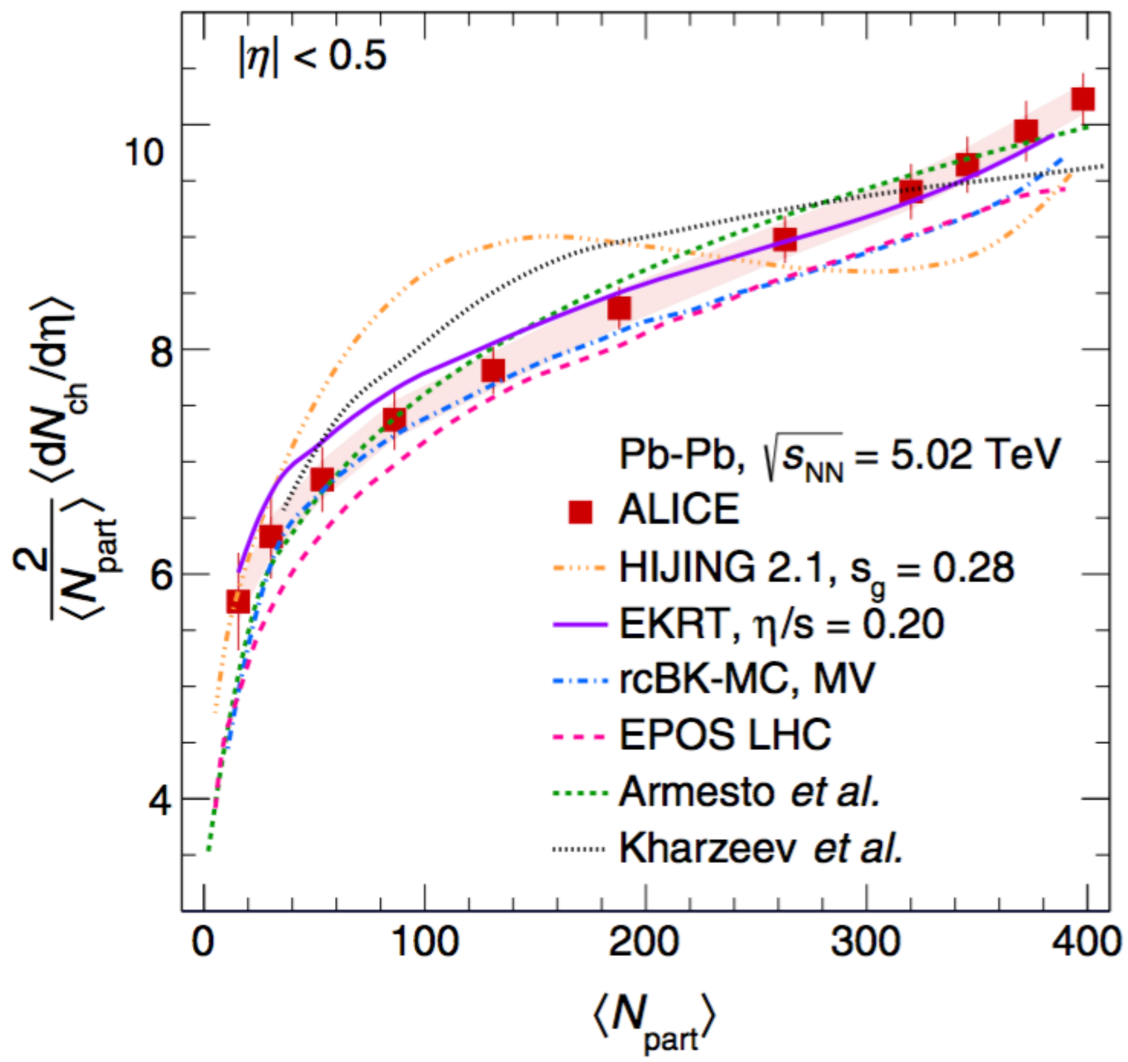


Υ(1S) production

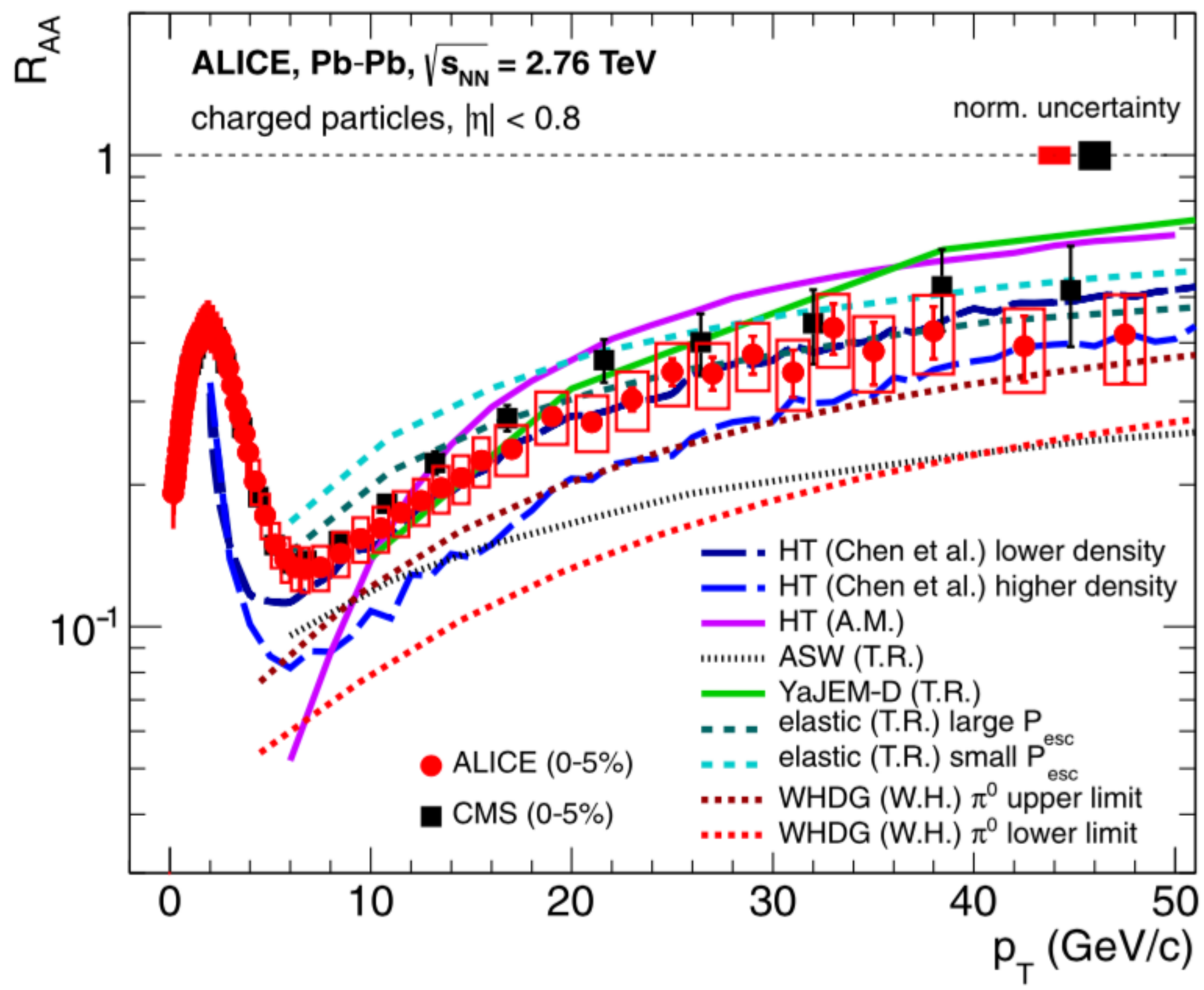


Charged particles production in Pb-Pb

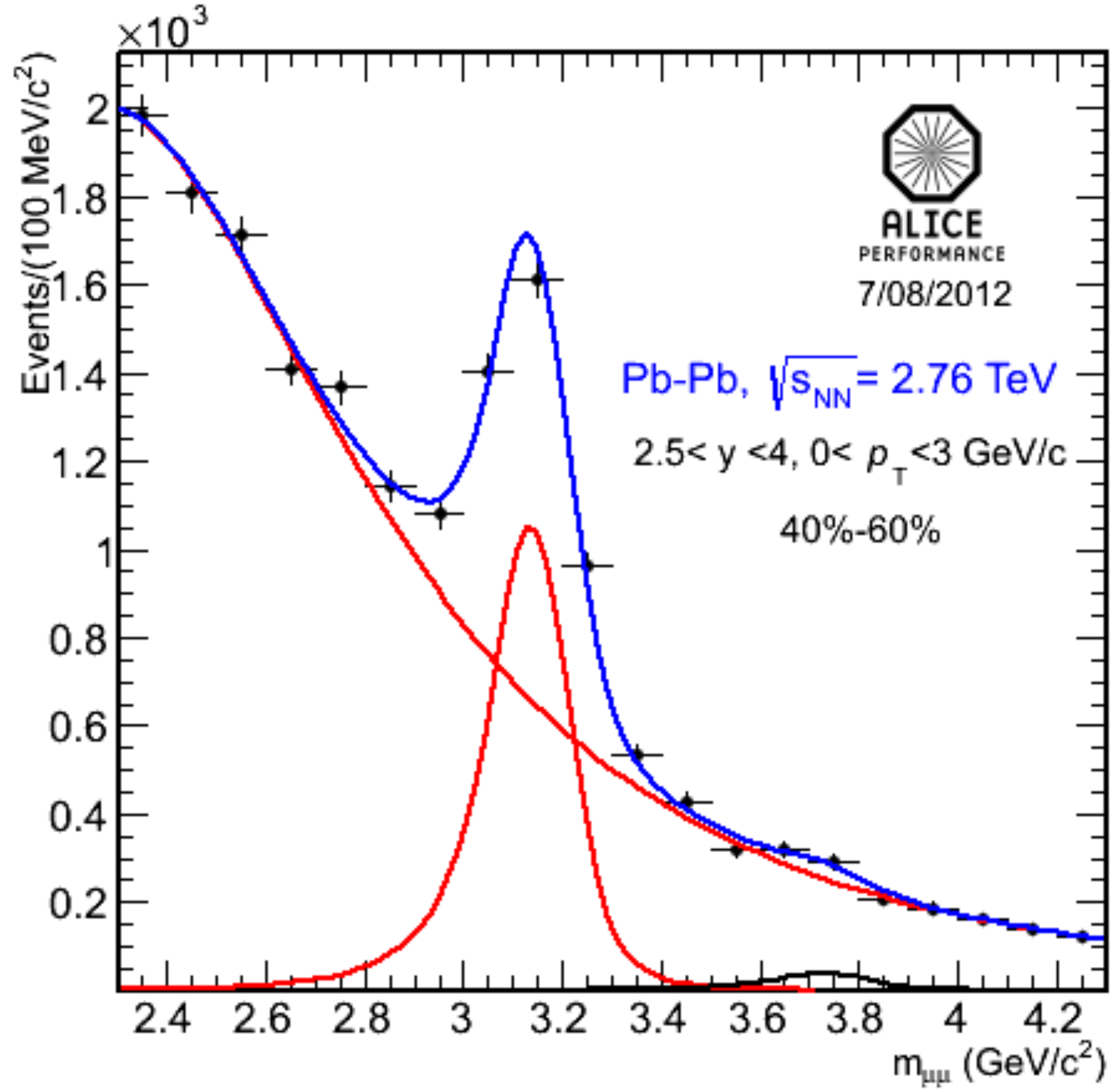
ALICE *PRL 116, 222302 (2016)*

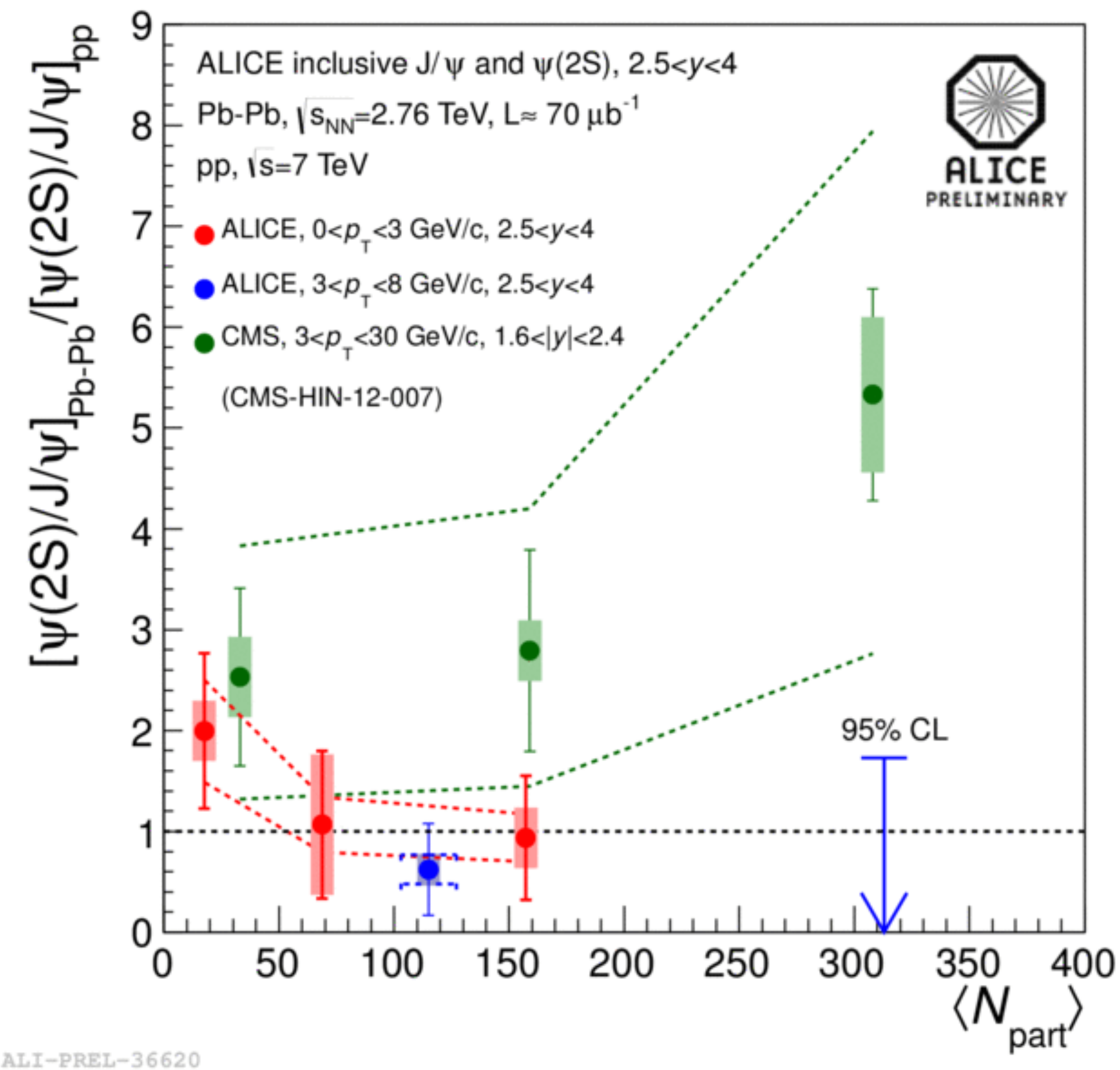


ALICE *PLB720(2013)52-62*



Ψ(2S) measurements at forward rapidity



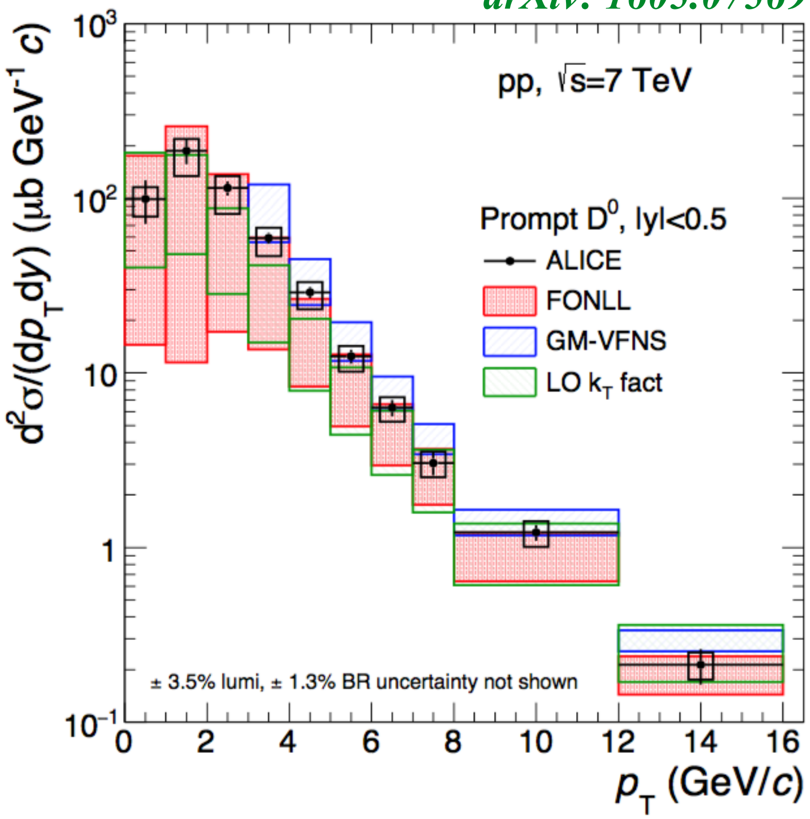


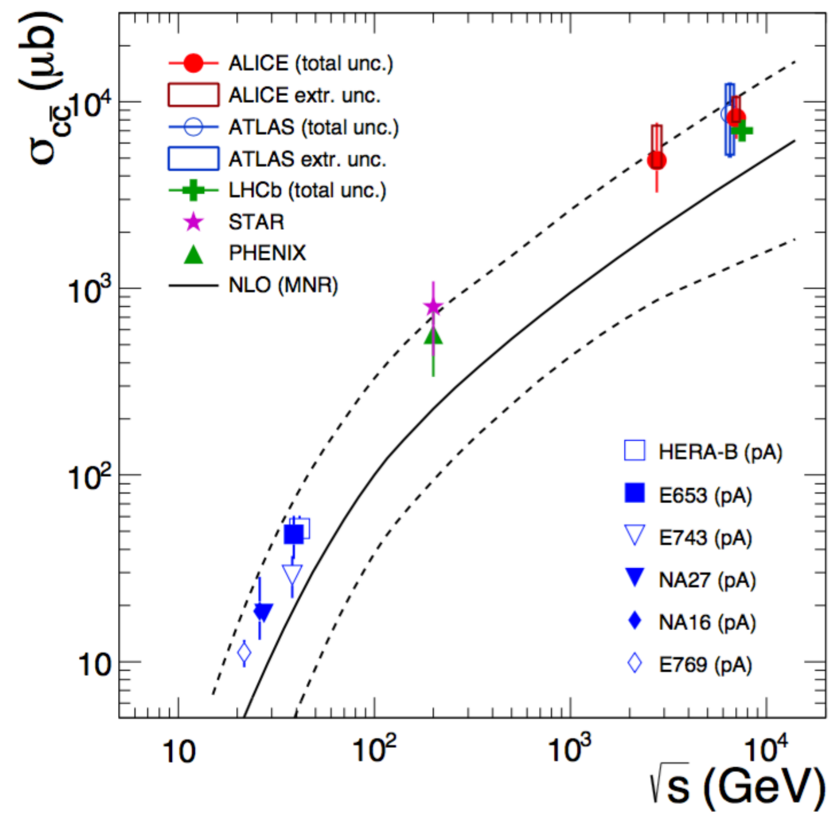
Double ratio measurement: Ψ(2S)/ J/Ψ in Pb-Pb over pp
pp reference from 7 TeV data but ratio is not expected to vary much with energy (dashed line uncertainty)

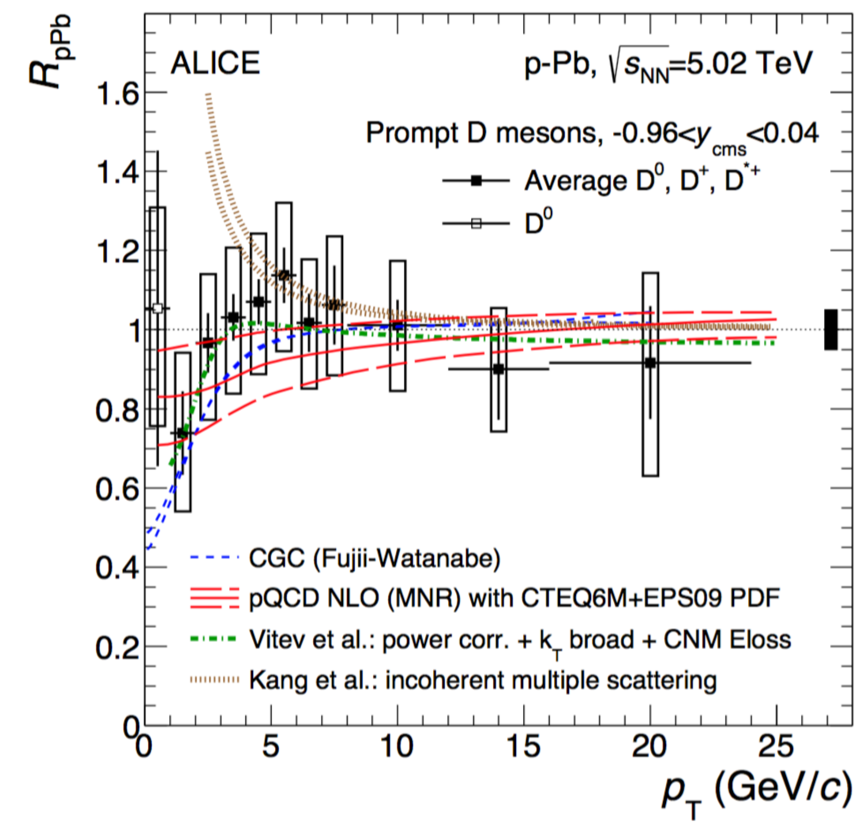
ALICE measurements has large uncertainties but there is not indication of a large Ψ(2S) enhancement in most central collisions

Open heavy flavour: D mesons in pp and p-Pb collisions

arXiv: 1605.07569







–D^0 measurement without reconstruction of the decay vertex in pp and p-Pb collisions: D mesons reconstructed down to $p_T = 0$

–Reduced uncertainty on total charm cross-section

–R_{pPb} (p_T>0, -0.96<y<0.04) = $0.89 \pm 0.11(stat)^{+0.13}_{-0.18}(syst)$: no sensitivity yet to distinguish between the existing models → much large sample in pp and p-Pb collisions to be collected soon

–R_{pPb} is compatible with unity at large p_T: the large suppression measured in Pb-Pb is due to a final-state effect

p-Pb measurements at $\sqrt{s_{NN}} = 5.02$ TeV

Crucial measurements to determine the cold nuclear matter effects in heavy-ion collisions

2013 Jan.-Feb. data taking running conditions:
- 2 beam configurations: p-Pb and Pb-p
- Shift in rapidity in the proton beam direction $\Delta y = 0.465$

p-Pb measurements at $\sqrt{s_{NN}} = 5.02$ TeV

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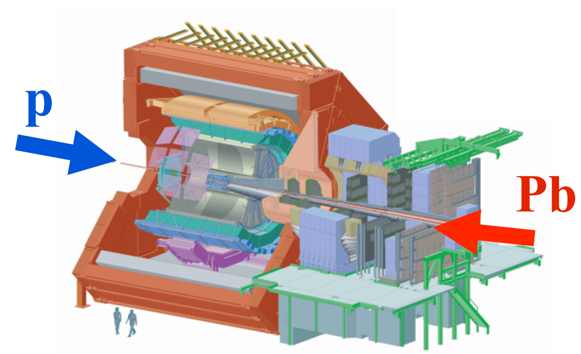
→ two rapidity ranges with the ALICE Muon Spectrometer

1


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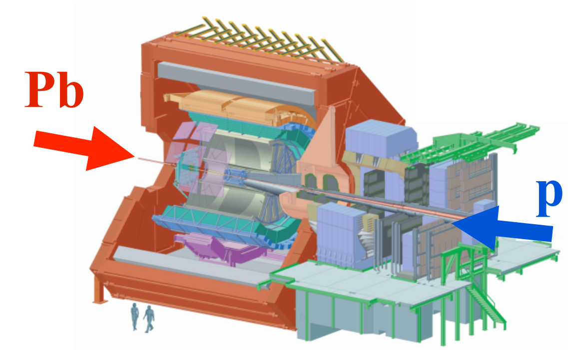
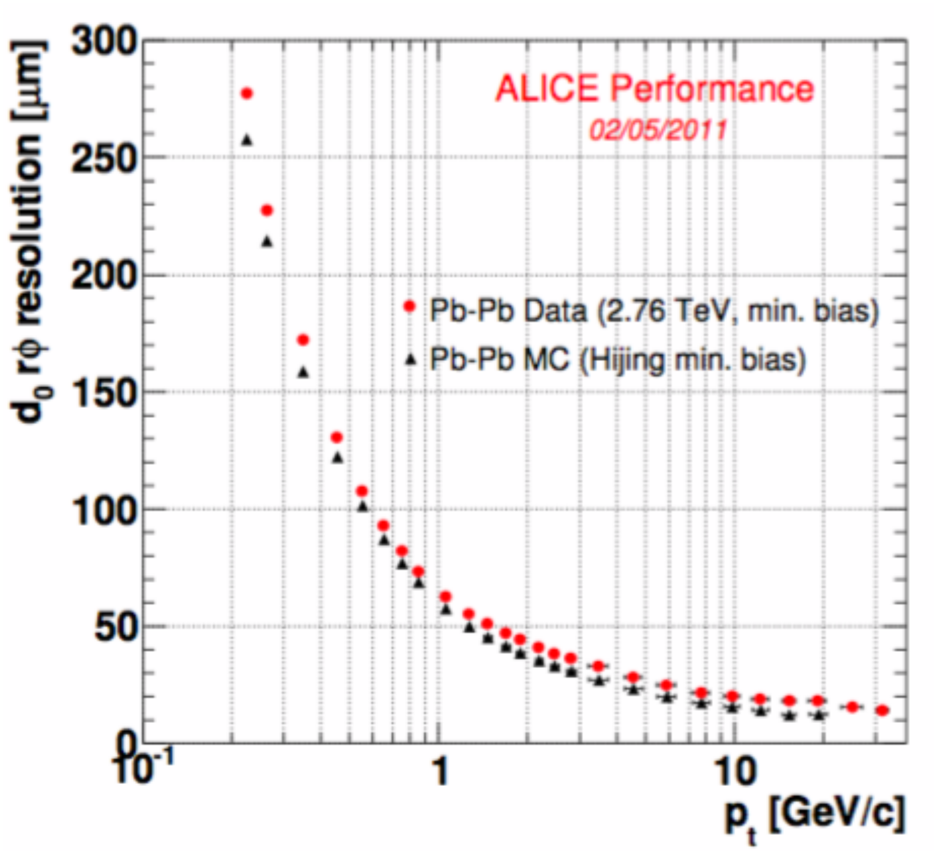
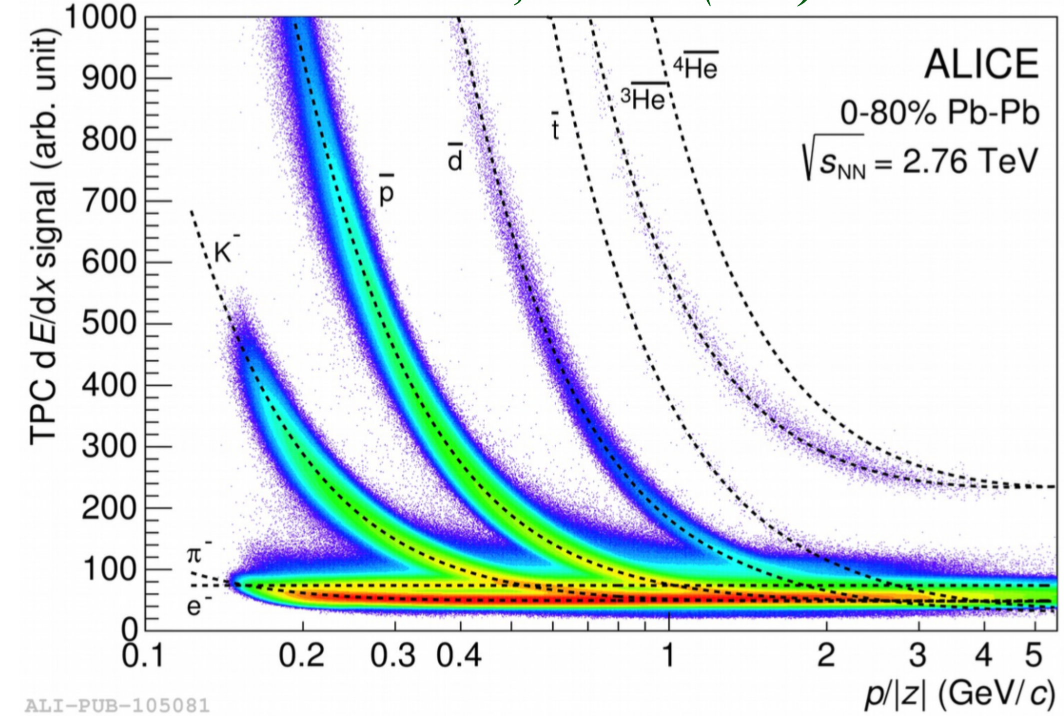


1	p-Pb	$2.5 < y_{lab} < 4$	$2.03 < y_{cms} < 3.53$
2	Pb-p	$-4 < y_{lab} < -2.5$	$-4.46 < y_{cms} < -2.96$

ALICE performance



ALICE, PLB 752 (2016) 267



– Tracking/vertexing: excellent track and reconstruction capabilities in a high multiplicity environment over a wide p_T range (and down to low p_T~100 MeV in the central barrel)

– Particle identification: strong capabilities by using energy loss dE/dx, time-of-flight, Cherenkov radiation, transition radiation, calorimetry…

– Muon arm: Quarkonium measurements down to low p_T