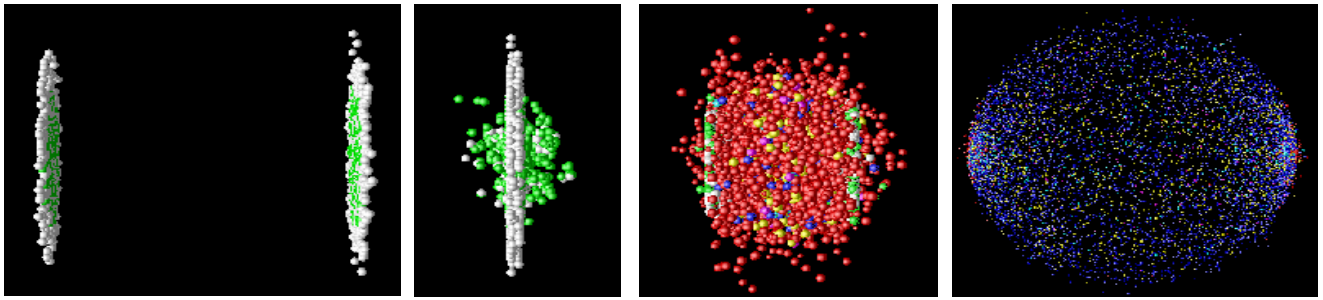
ALICE @ LHC
STATUS AND HIGHLIGHTS

Alberica Toia
Goethe University Frankfurt & GSI
on behalf of the ALICE Collaboration

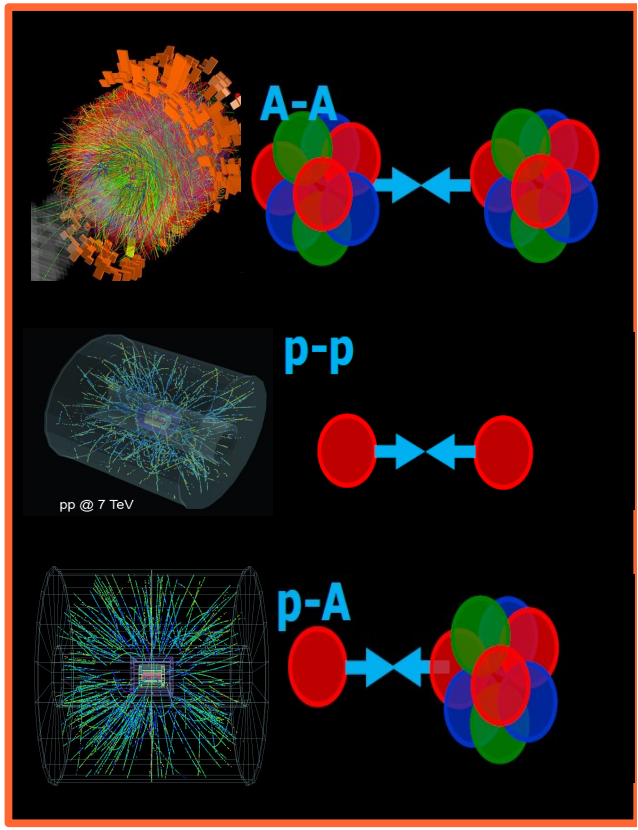
QCD @ Work
International Workshop on Quantum Chromodynamics
Theory and Experiment
Martina Franca (Italy), June 27 – 30, 2016

Martina Franca arch. detail - ph: Rosa Guarini - courtesy Accademia di Belle Arti / Academy of Fine Arts, Bari

THE ALICE PHYSICS PROGRAM



- **Pb-Pb**
  - **Study the properties of strongly interacting matter under extreme conditions of temperature and density.**
    - Confinement → deconfined QGP
      analogous to the early Universe evolution
- **pp**
  - **collect 'comparison data' for heavy ion program**
  - **comprehensive study of MB@LHC** (MC tuning)
    soft & semi-hard QCD
  - **very high multiplicity pp events** → mini-QGP?
- **p-Pb**
  - **Control experiment for Pb-Pb**
  - **Important measurements in their own right**
    nucleus structure in low-x (gluon saturation, shadowing…)
- **Run II: new higher energy pp@13 TeV, PbPb@5TeV**
  - New frontiers in physics
    → study the evolution of the basic event properties

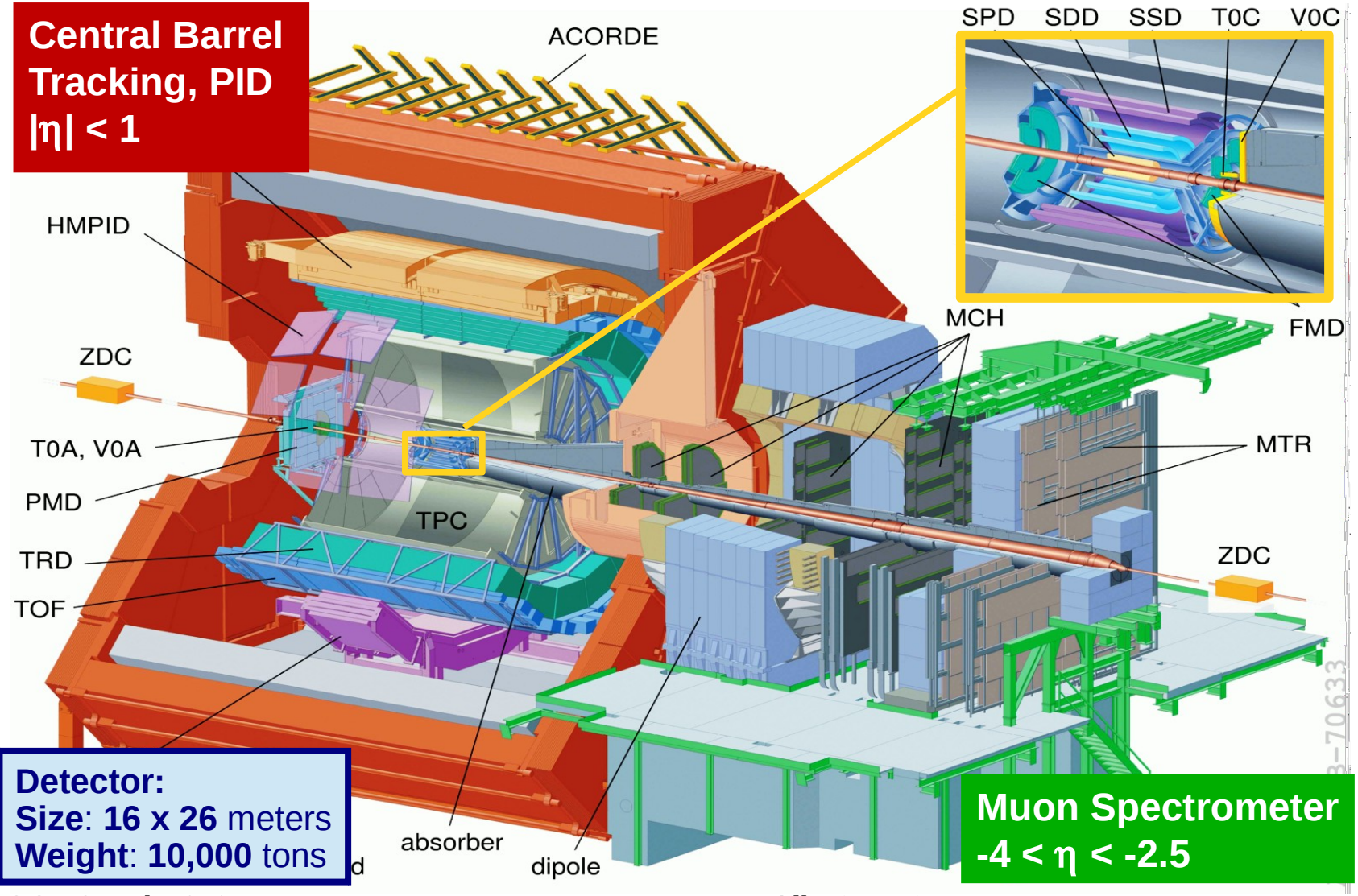


THE ALICE EXPERIMENT

Experiment designed for Heavy Ion collision
→ comprehensive, cover all relevant observables

VERY robust tracking (0.1 - 100 GeV/*c*)
high-granularity 3D detectors
(TPC: up to **560 million** → 180 space points/track)
very low material budget (**< 10%X_0** in r < 2.5 m)

Central Barrel Tracking, PID
|η| < 1



Secondary vertexing

PID large p_T range
TOF, dE/dx, RICH,
TRD, topology, EM cal

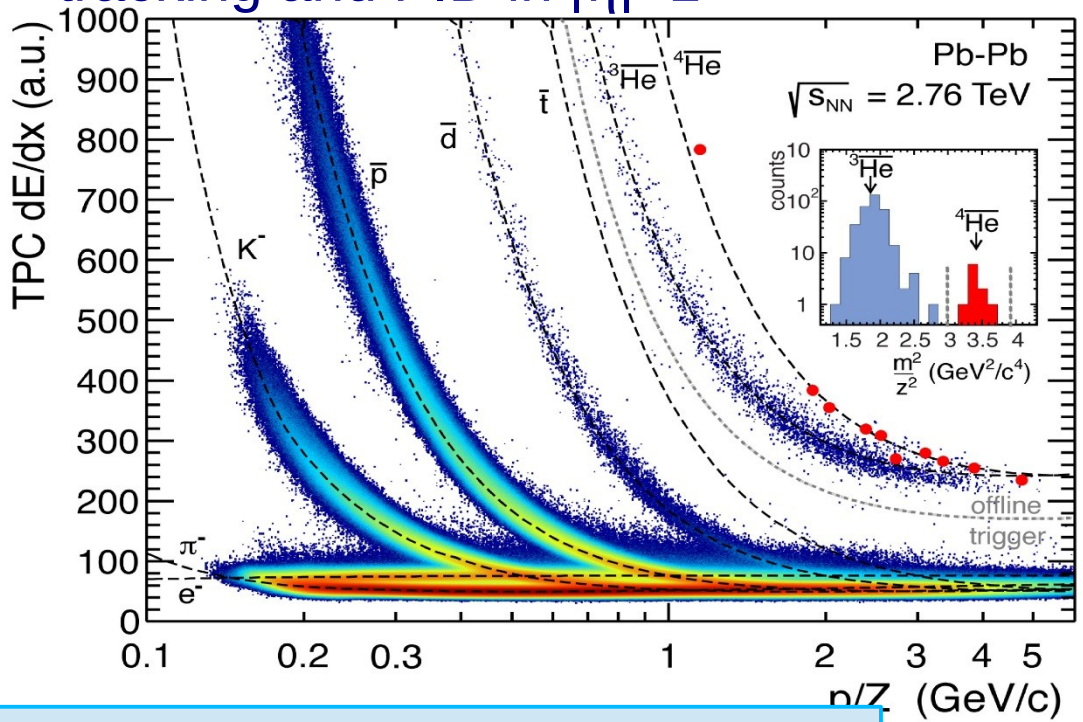
-Hadrons
-leptons
-photons
-muon

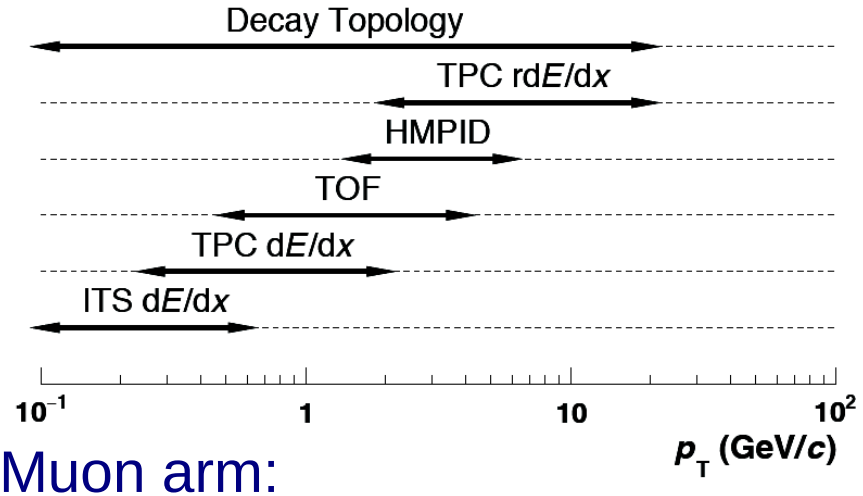
Detector:
Size: **16 x 26** meters
Weight: **10,000** tons

Muon Spectrometer
-4 < η < -2.5

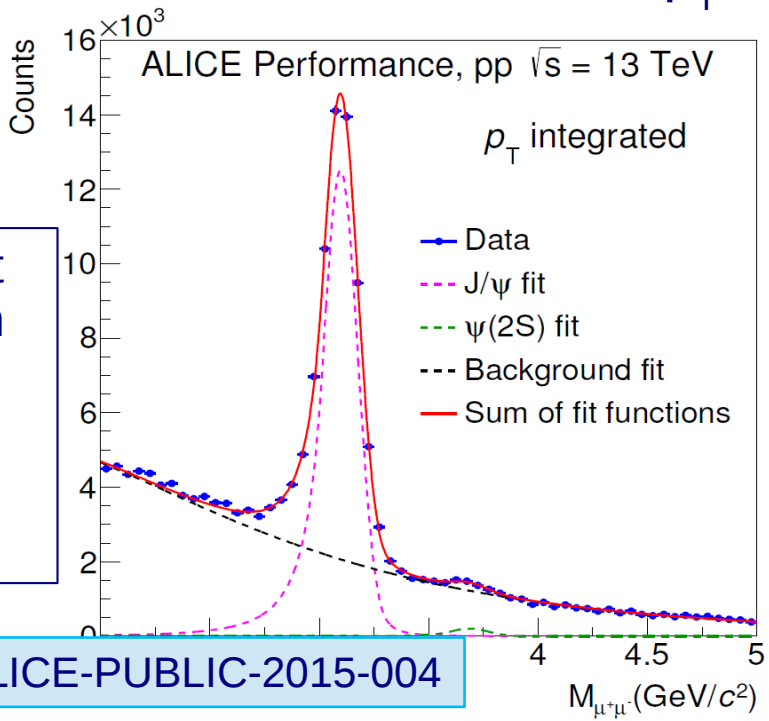
ALICE PERFORMANCE

- Central Barrel:
  tracking and PID in |η|<1





- Muon arm:
  reconstruction in -4<η<-2.5
  ψ and Υ measurements down to p_T=0



ALICE, Int.J.Mod.Phys. A29 (2014) 1430044

Specific energy loss dE/dx versus particle momentum in the TPC
→ anti 4He observed directly
Combined dE/dx and TOF methods offer π/K/p separation up to high momenta

Dimuon invariant mass distribution reconstructed in the muon spectrometer, p_T-integrated

ALICE-PUBLIC-2015-004

DATA COLLECTED

Run1 (2010-13)

year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 0.01 nb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

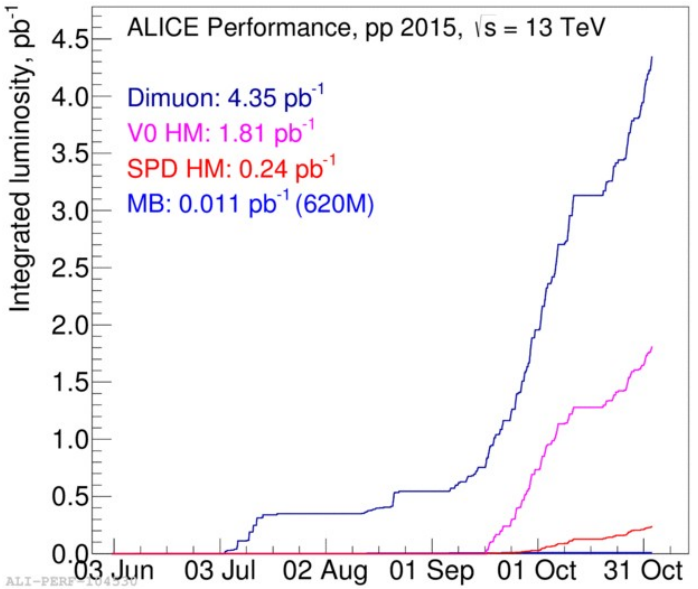
Run2 (2015-18)

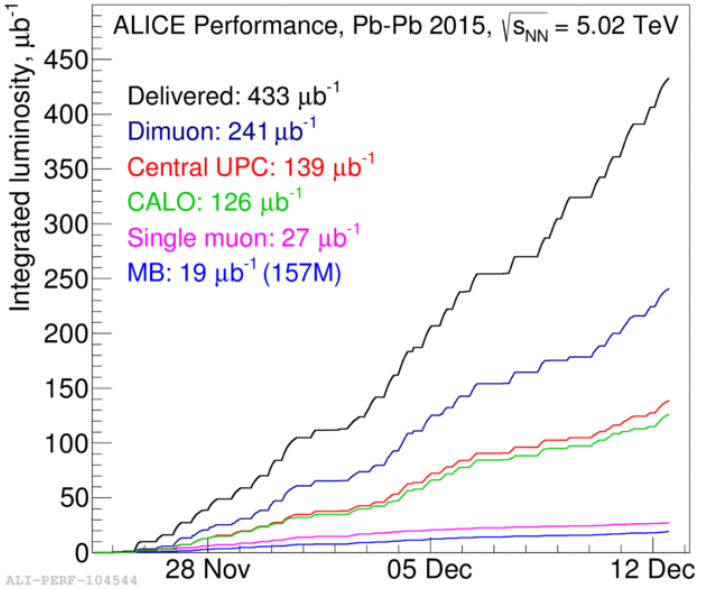
Pb-Pb @ 5 TeV: up to 1nb^{-1}

p-Pb @ 5 TeV: 10 x more statistics than Run1

pp @ 13 TeV and 4 days @ 5 TeV (109 nb^{-1})

reference for p-Pb and Pb-Pb measurements



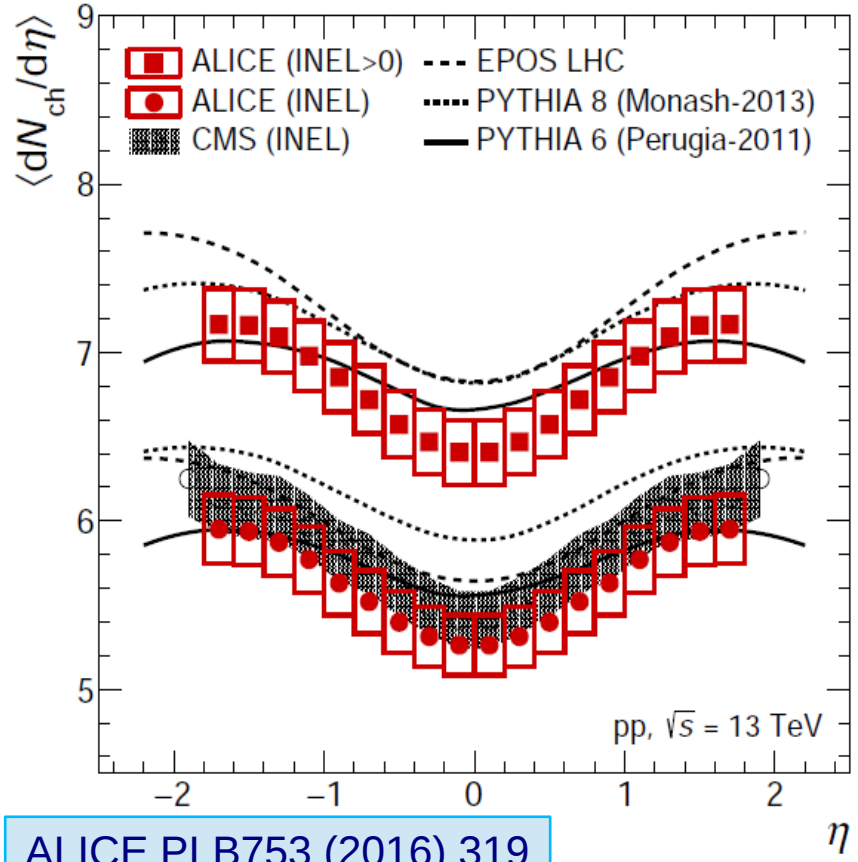


MULTIPLICITY: PP

Global properties of the system
Multiplicity ~ energy density

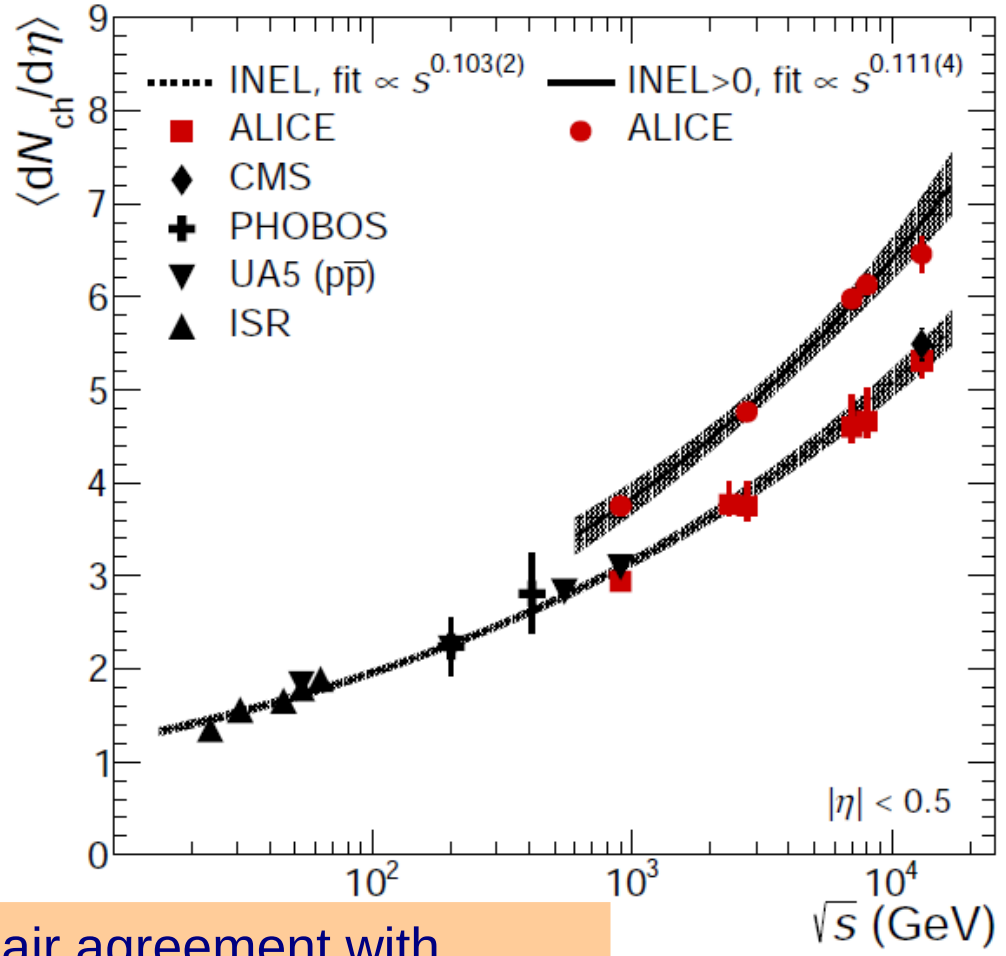
- Minimum bias trigger → 96.6% of σ_{INEL}
- $dN_{ch}/d\eta$ measured for:

INEL: inelastic events
INEL>0: at least one charged particle in $|\eta|<1$



ALICE PLB753 (2016) 319
CMS PLB751 (2015) 143

- Energy dependence fitted with power-law function as^b:
- INEL: $b = 0.103(2)$
- INEL>0: $b = 0.111(4)$



Fair agreement with
Monte Carlo and expectations
from low energy extrapolations

… AND PB-PB

Global properties of the system
Multiplicity ~ energy density

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- $dN_{ch}/d\eta$ measured for:

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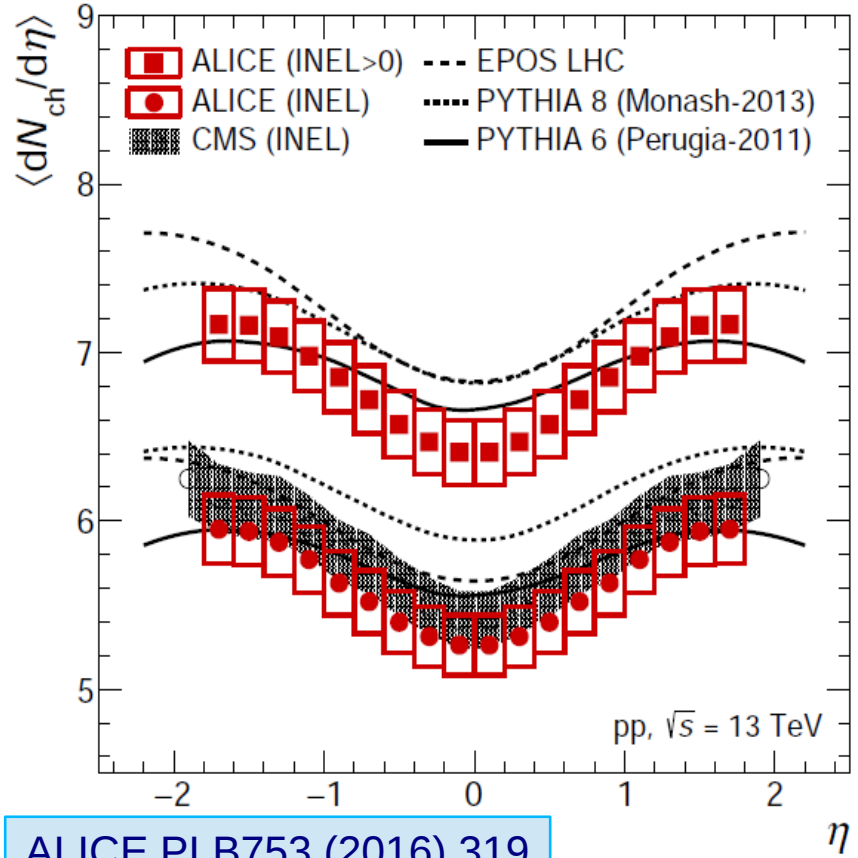
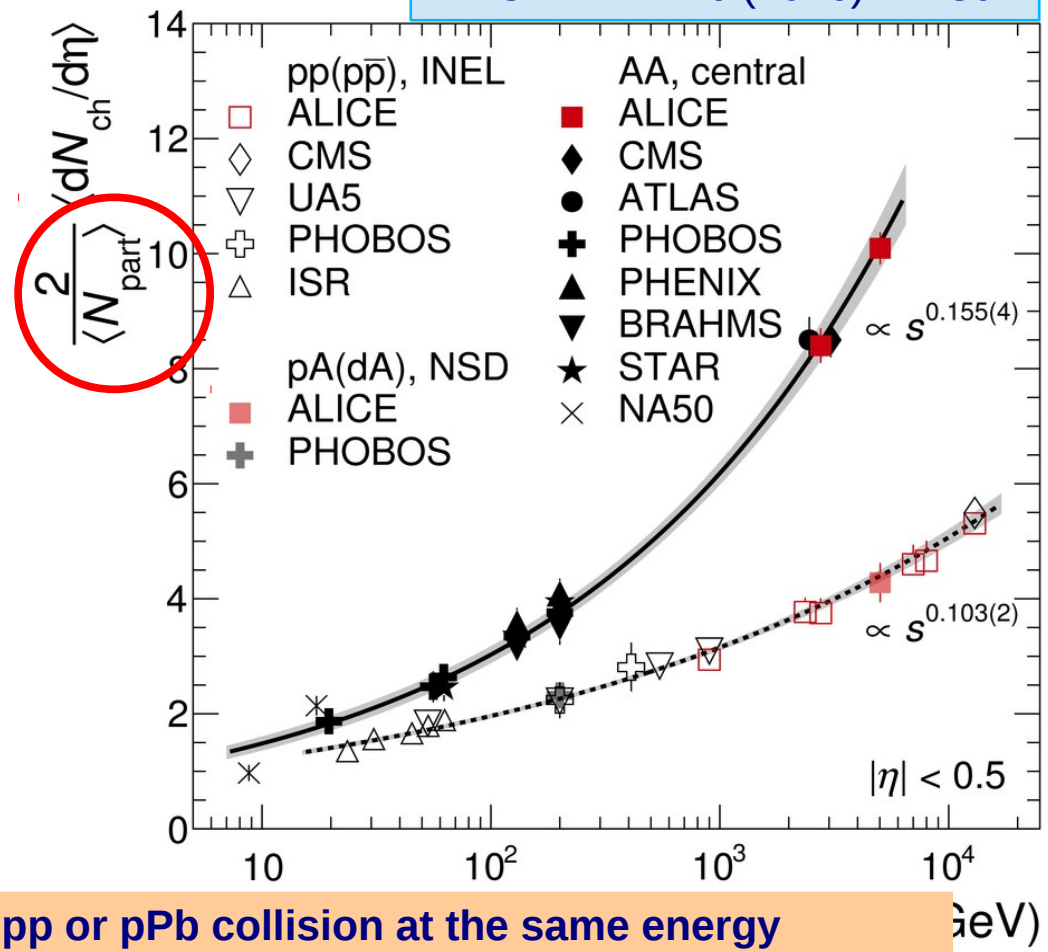


ALICE PLB753 (2016) 319
CMS PLB751 (2015) 143

- Energy dependence fitted with power-law function as^b:
- Pb-Pb: $b = 0.155(4)$

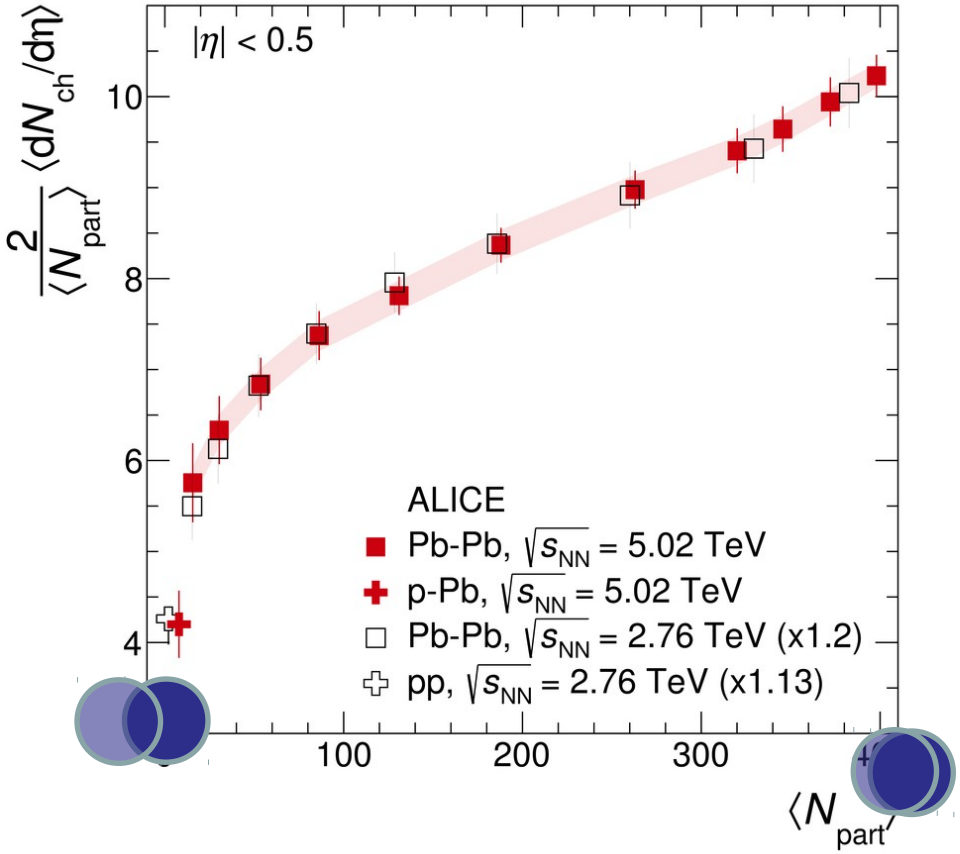
ALICE PRL 116 (2016) 222302

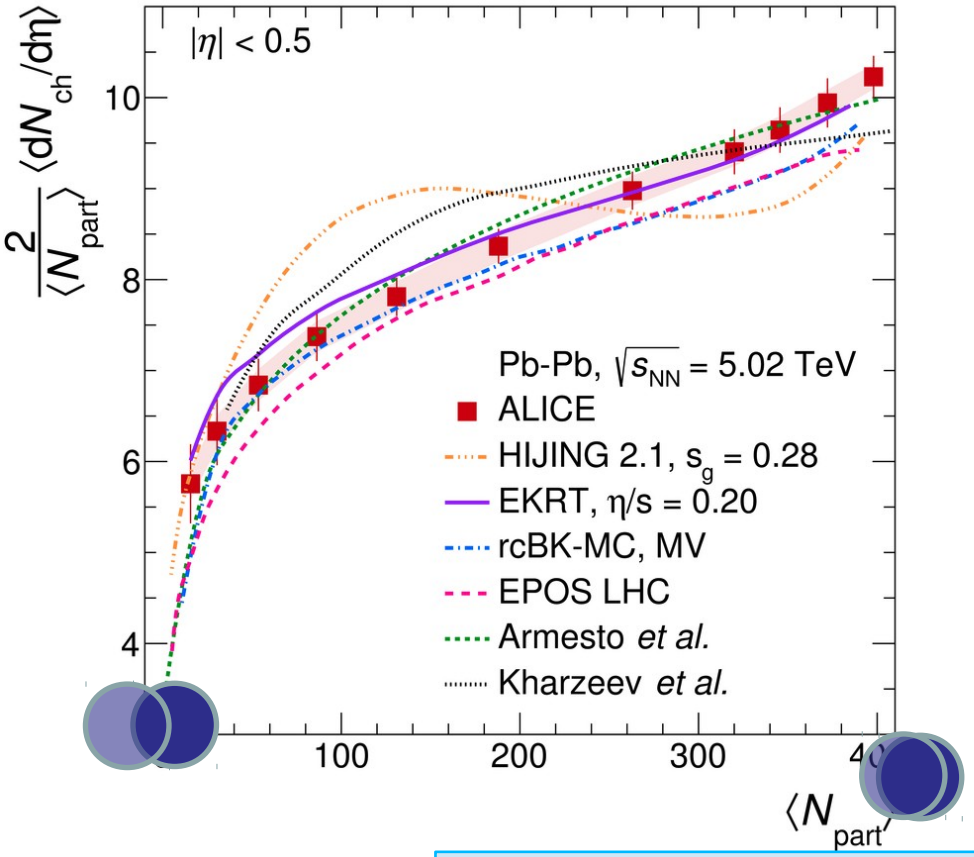


- **x 2.5 pp or pPb collision at the same energy**
- Much stronger energy dependence
- not solely related to the multiple collisions undergone by the participants (e.g. proton in pA collisions).

MULTIPLICITY: CENTRALITY DEPENDENCE

Evolution with energy and system size?





ALICE PRL 116 (2016) 222302

The average yield per participant pair is strongly dependent on collision centrality

- Similar trend seen at $\sqrt{s_{NN}}$=2.76 TeV

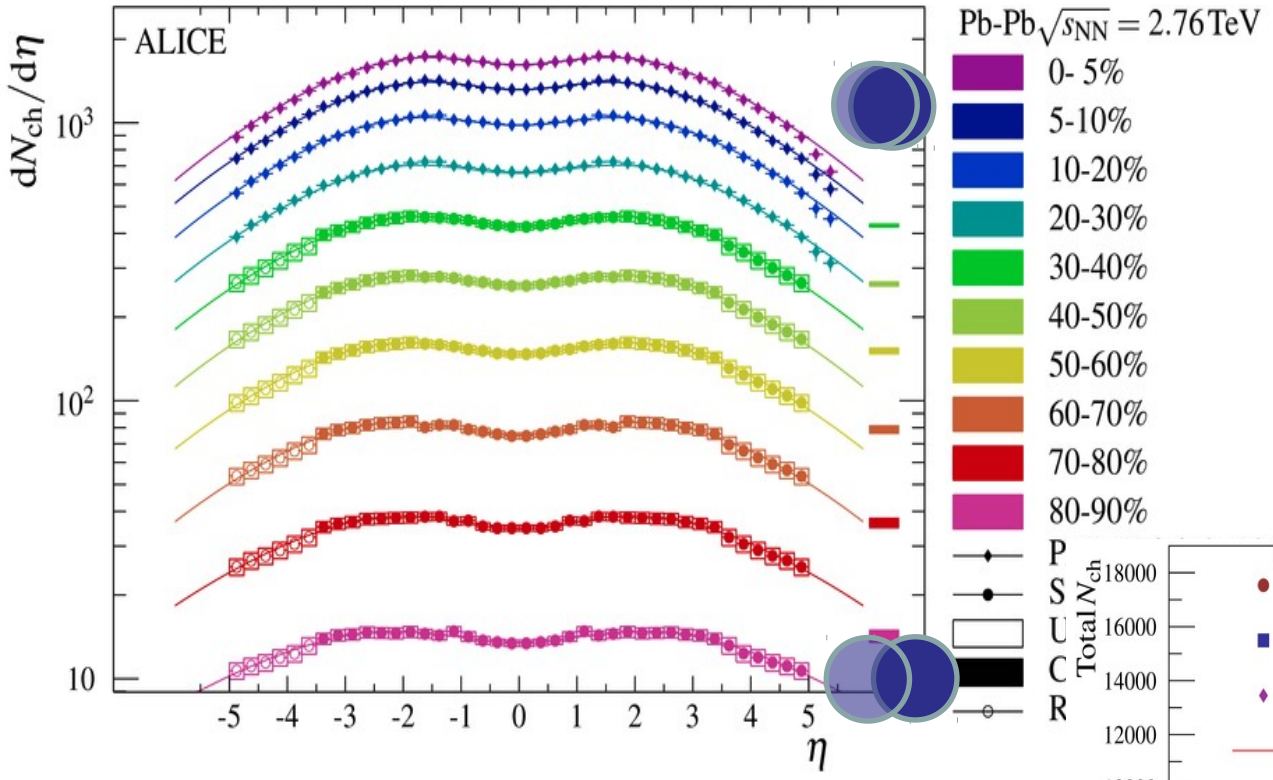
→ Energy- (and system-) scaling

- Yield in peripheral collisions close to the one measured in p-Pb and pp collisions
- Most of the models fairly describe the data (except HIJING).

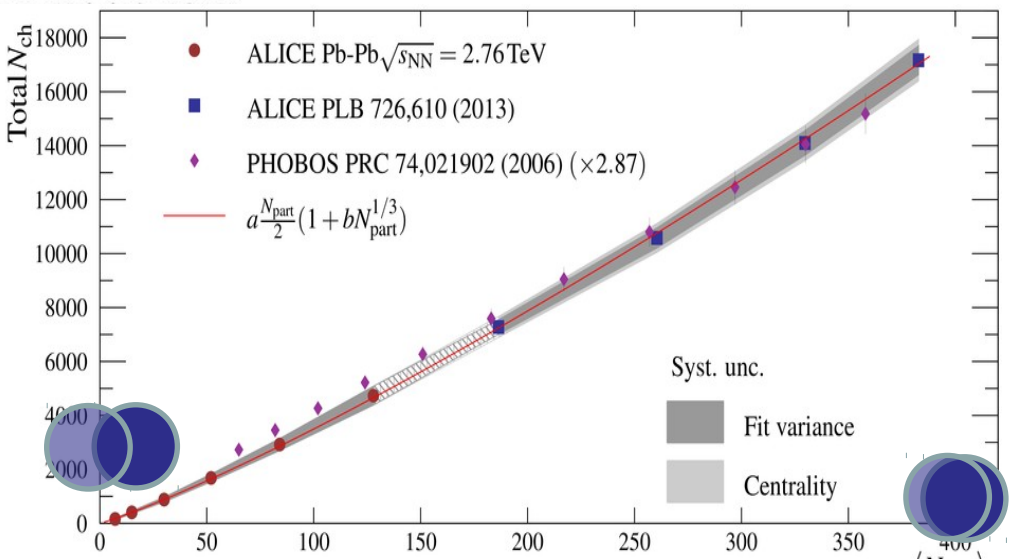
MULTIPLICITY IN WIDE RAPIDITY RANGE

Central Barrel: multiplicity in |η|<5

$dN_{ch}/d\eta$ vs η measurement over 10 rapidity units using forward detectors in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



ALICE PLB754 (2016) 373



allows for an estimate of the total number of charged particles produced

→ Total multiplicity scales approximately with N_{part}

→ hard contributions small

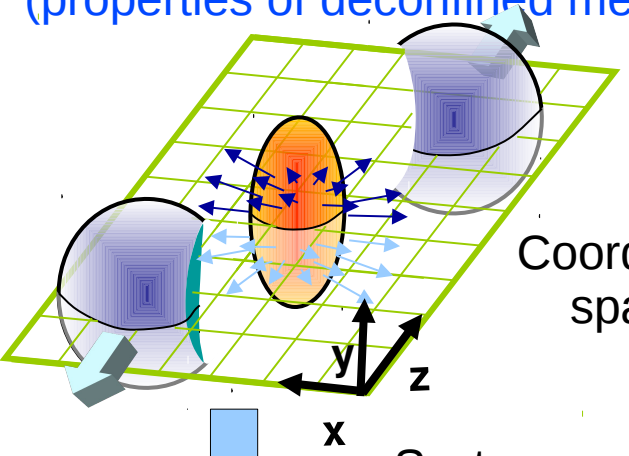
ANISOTROPIC FLOW

Collectivity of the system?

Initial spatial anisotropy of the overlap region of colliding nuclei
→ anisotropy in momentum space via interactions of produced particles.

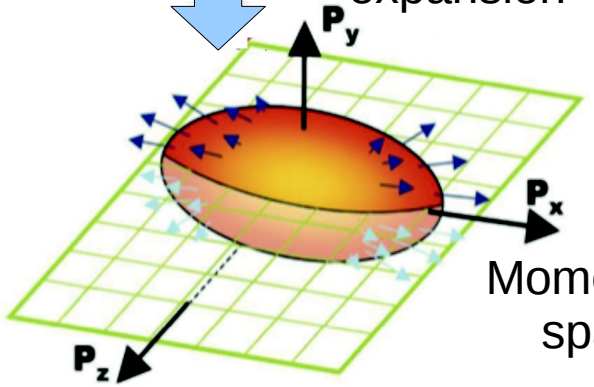
Sensitive to:
- initial collision geometry
- transport mechanism

→ provides a measurement of collectivity (properties of deconfined medium)



Coordinate space

System expansion



Momentum space

Quantified by the Fourier decomposition

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

v1: directed flow
v2: elliptic flow
v3: triangular flow
...

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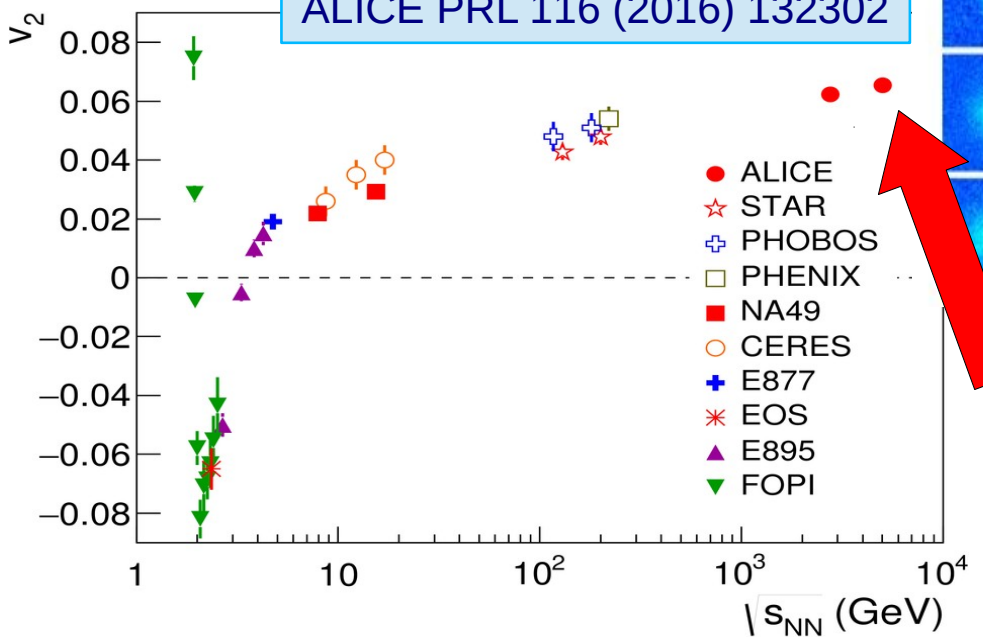
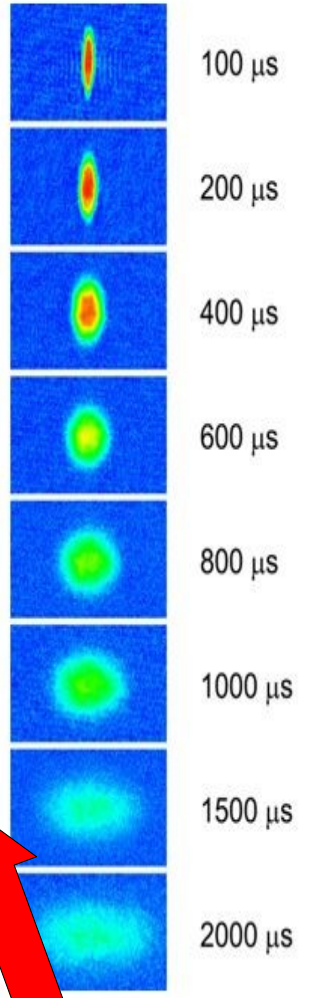


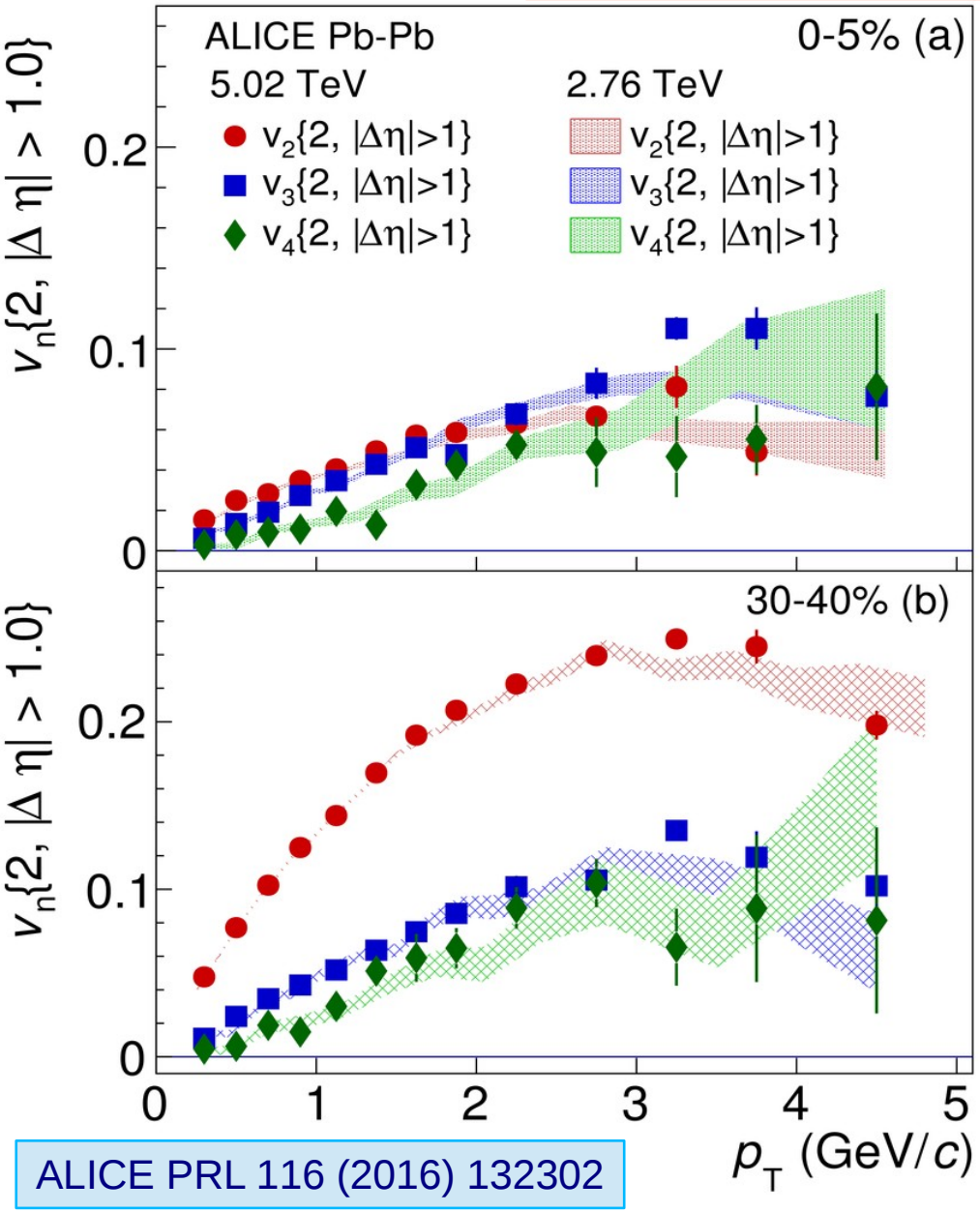


SCIENCE
Vol: 298
2179 (2002)

Ultra-cold Li explode into vacuum

ANISOTROPIC FLOW

Collectivity of the system?



ALICE PRL 116 (2016) 132302

Anisotropic flow measurements using two- and multi-particle cumulants

- Elliptic flow results show very similar values to the ones seen at $\sqrt{s_{NN}}$=2.76 TeV

- Higher harmonics (v3,v4) are also unchanged with energy
- v3 becomes larger than v2 at p_T>2GeV/c in central collisions

ANISOTROPIC FLOW

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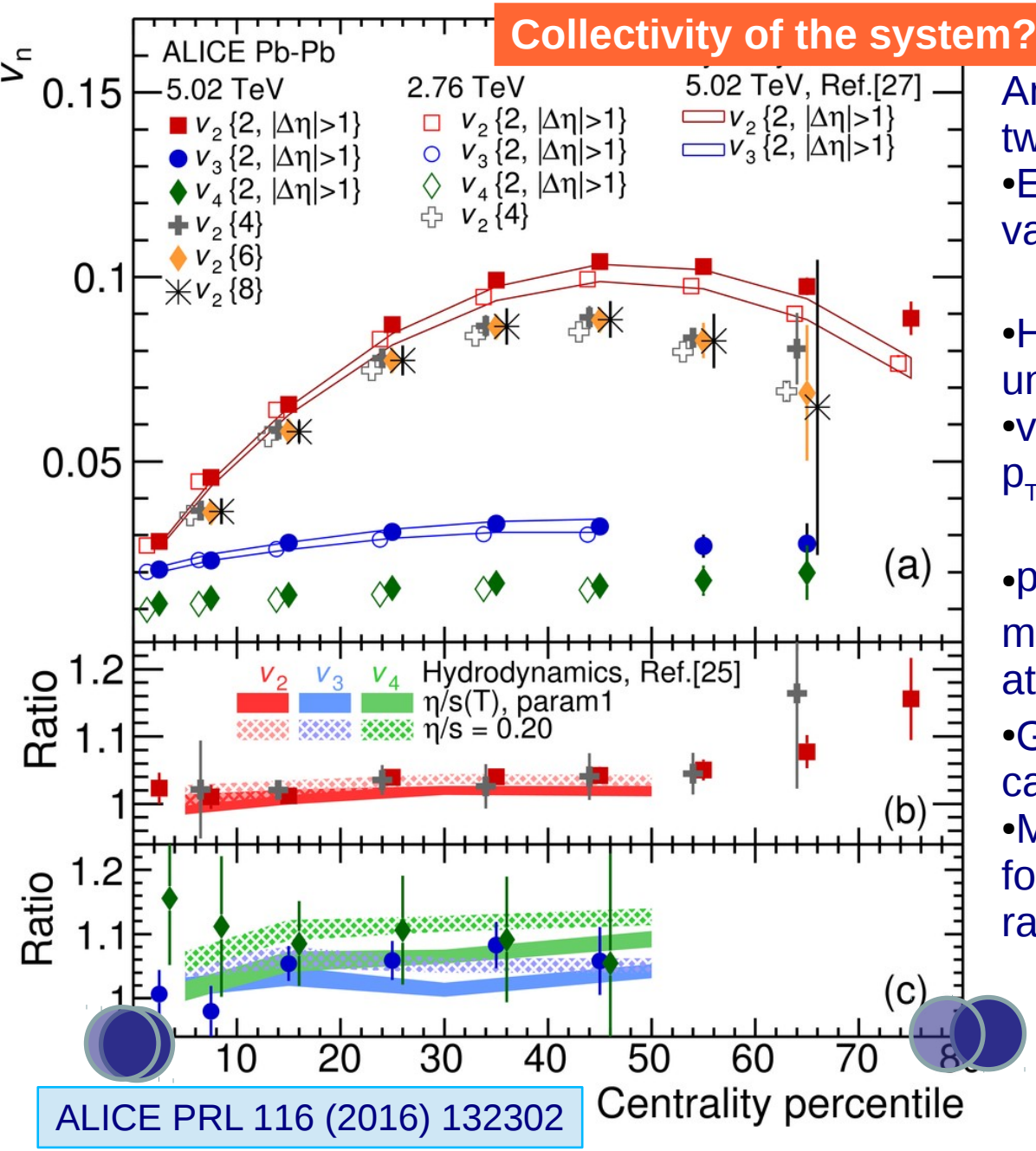

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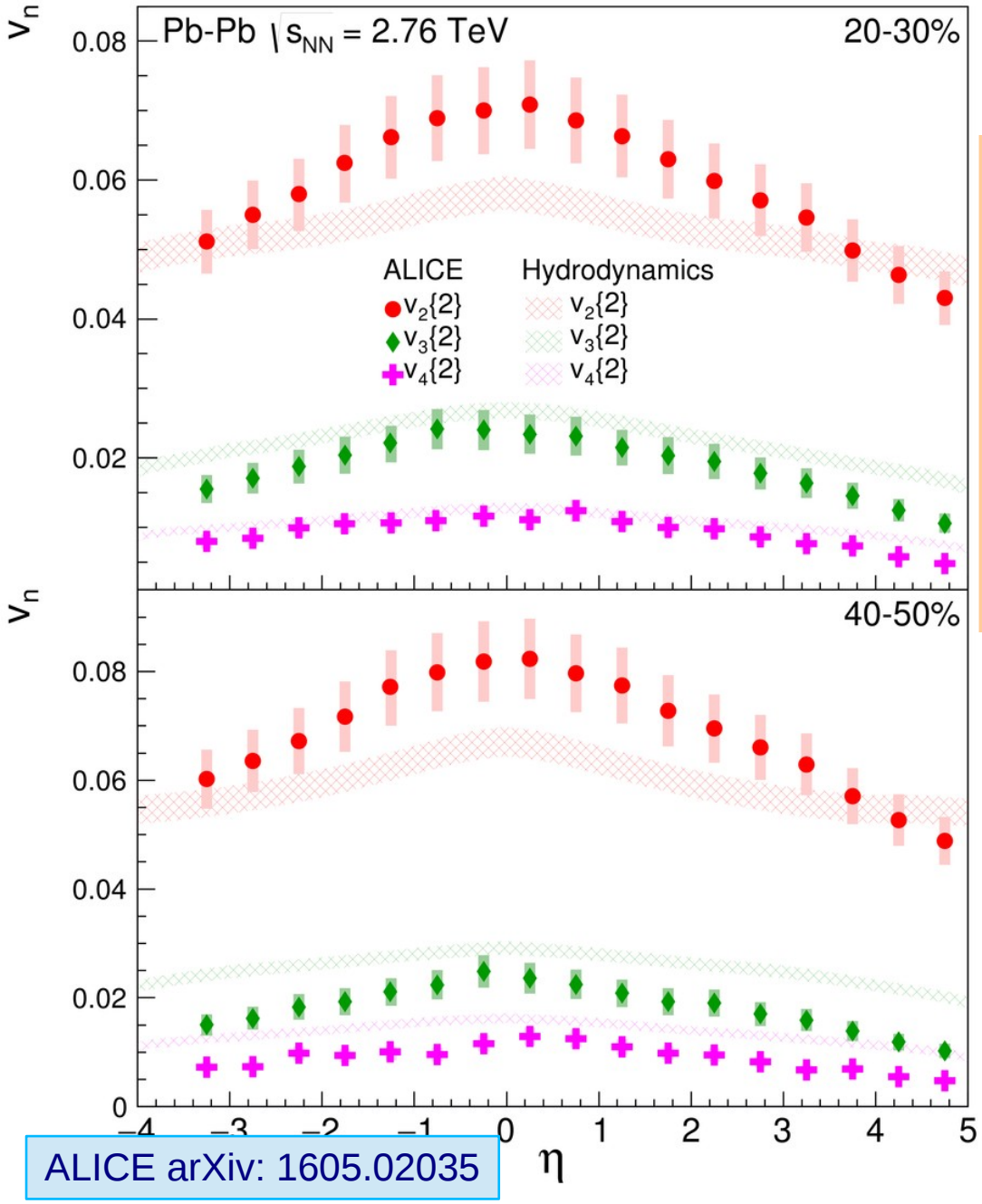
- v3 becomes larger than v2 at p_T>2GeV/c in central collisions

- p_T-integrated v2, v3 and v4 indicate a mild increase with collisions energy attributed to the increase in $\langle p_T \rangle$
- Good agreement with hydrodynamical calculations
- Measurements support a low value for the shear viscosity to entropy ratio (η/s)

FLOW IN WIDE RAPIDITY RANGE



ALICE arXiv: 1605.02035

Longitudinal scaling?

Temperature dependence of η/s
At forward rapidities T drops
→ η/s change
→ the system spend less time in QGP phase

At RHIC it was found that in the rest frame of one of the colliding nuclei (η-y_{beam}) **particle production** (multiplicity, v_1, v_2) is **energy-independent** → longitudinal scaling

- Shape of $v_n(\eta)$ largely independent of centrality for the flow harmonics n = 2, 3 and 4
- The higher harmonics fall off more steeply with increasing |η|.

- Results are not well reproduced by hydro, new challenge to the theory community

JET FLOW

Collectivity of the system?

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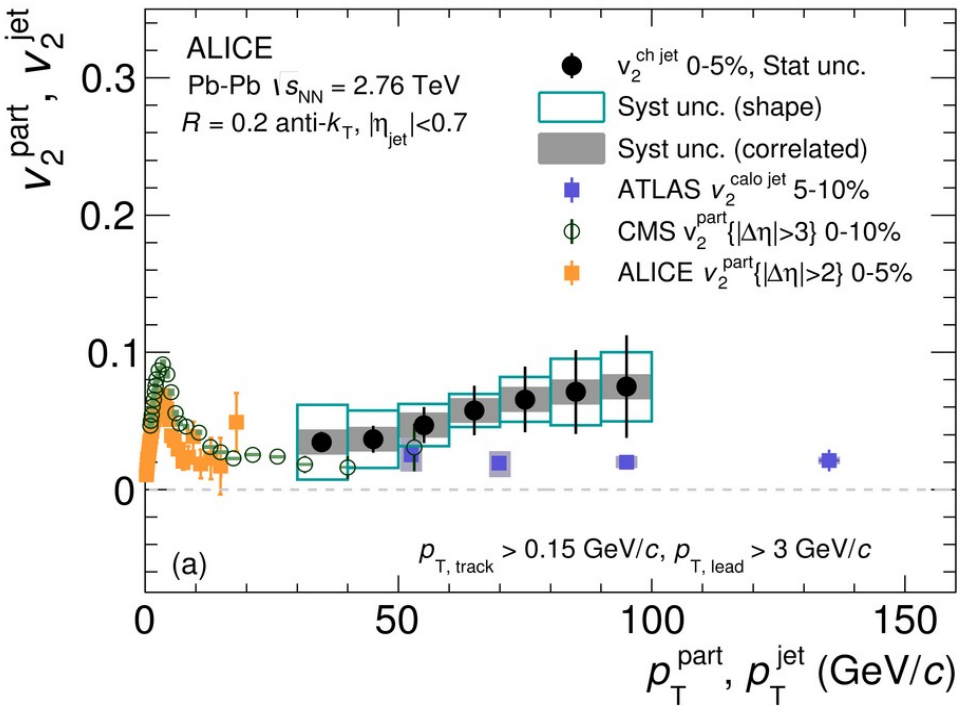
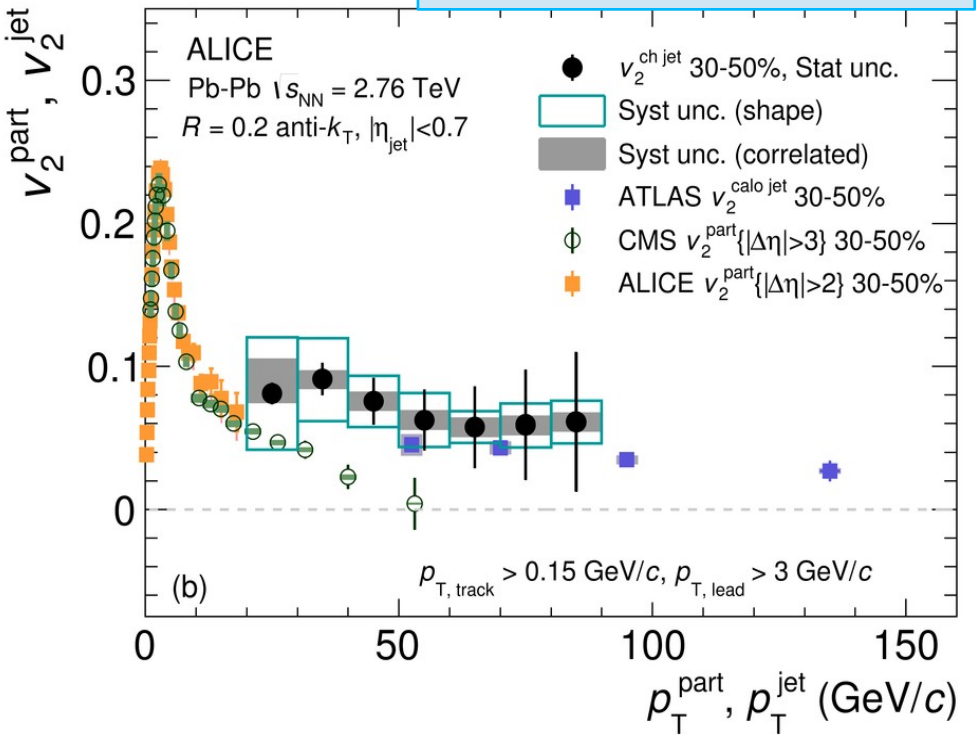




- Non-zero $v_2^{ch.jet}$ in semi-central Pb-Pb collisions (significance >3σ).
- v_2 of calo jet (ATLAS/CMS) (charged+neutral) → qualitative agreement
  - – different energy scale of ALICE $v_2^{ch.jet}$ (no neutral) and ATLAS v_2^{jet}
    → the difference in the central values of the measurement is not significant
- v_2 of single charged particles → Different energy scale but qualitative agreement

→ weak p_T dependence

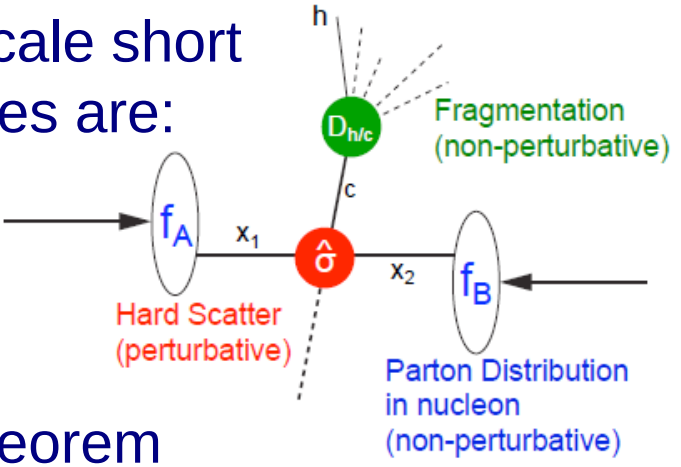
→ Indication of path-length dependence of parton energy loss.

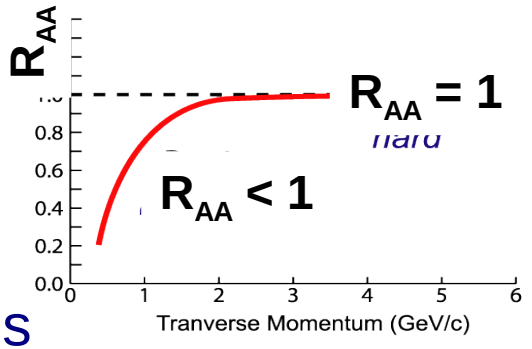
- Large parton energy loss and sensitivity to the collision geometry persist up to high p_T.

HARD PROBES

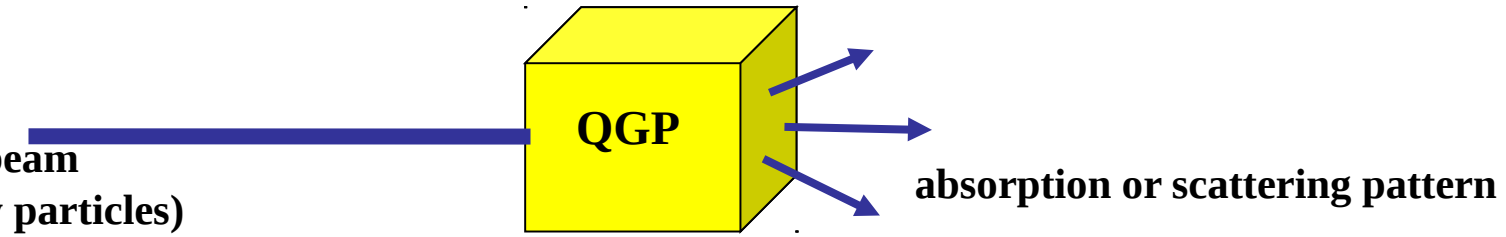
- Hard processes are those processes with high momentum transfer → short distances → Time Scale short
- Experimental observables connected to hard processes are:
  - Hadrons with high p_T → Jets
  - Hadrons from open heavy flavour (charm and beauty)
  - Quarkonia (J/Ψ, Ψ', ϒ, ϒ', ϒ")
- In pp collisions calculable with pQCD techniques using universality (of PDF and FF) and factorization theorem
- In AA collisions hard processes are expected to **scale with the number of** elementary nucleon-nucleon **collisions**
- The nuclear modification factor is defined as:

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$





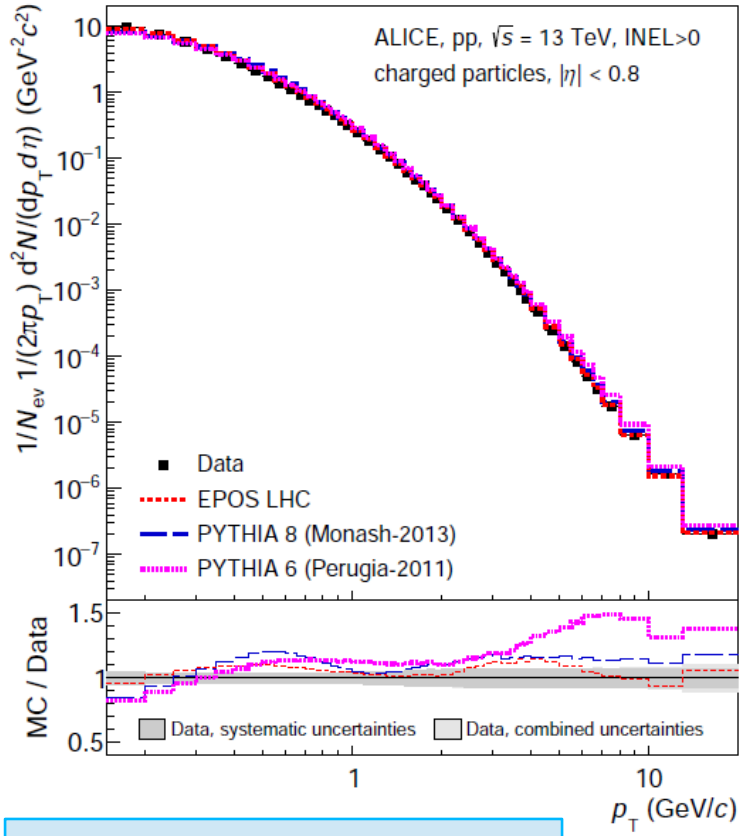
- Rutherford experiment α → atom discovery of nucleus
- SLAC electron scattering e → proton discovery of quarks

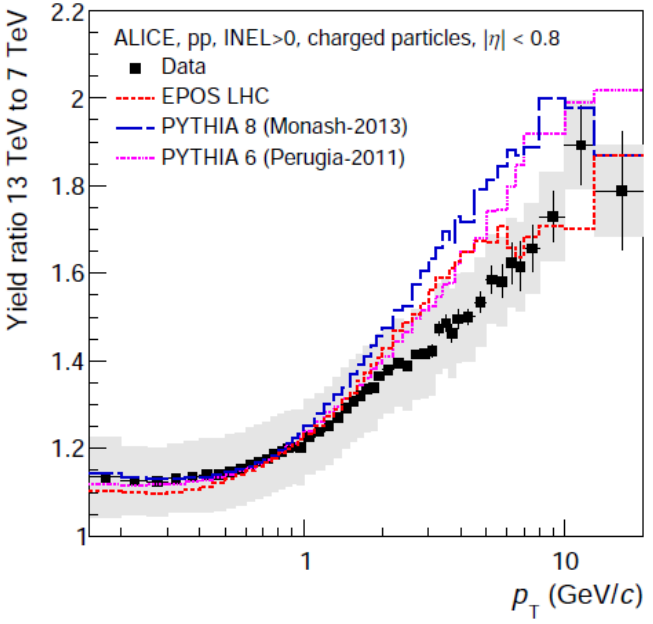


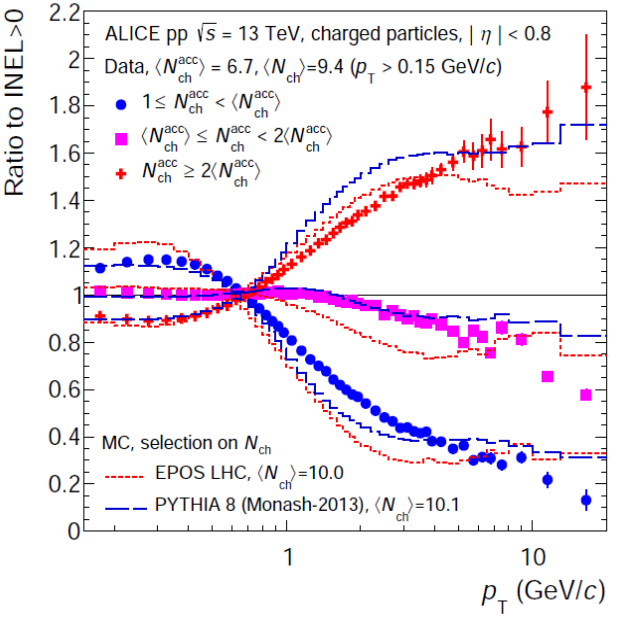
HIGH p_T PARTICLES: PP

- p_T distribution measured in $0.15 < p_T < 20$ GeV/c and $|\eta|<0.8$
- Comparison with Monte Carlo
  - EPOS LHC
    → collective (flow-like) effects
  - PYTHIA 8 (Monash-2013)
    PYTHIA 6 (Perugia 2011)
    → color reconnection

- The general features seen in the data are reproduced well by the models, but not all details
- Evolution with energy and multiplicity







- p_T spectrum harder at 13 TeV than at 7 TeV.
- models reproduce the trend in the data but exhibit a more pronounced hardening
- The correlation of the spectrum with multiplicity (same kinematic region) is prominent for the whole p_T range and in particular it is stronger at high p_T, then it saturates

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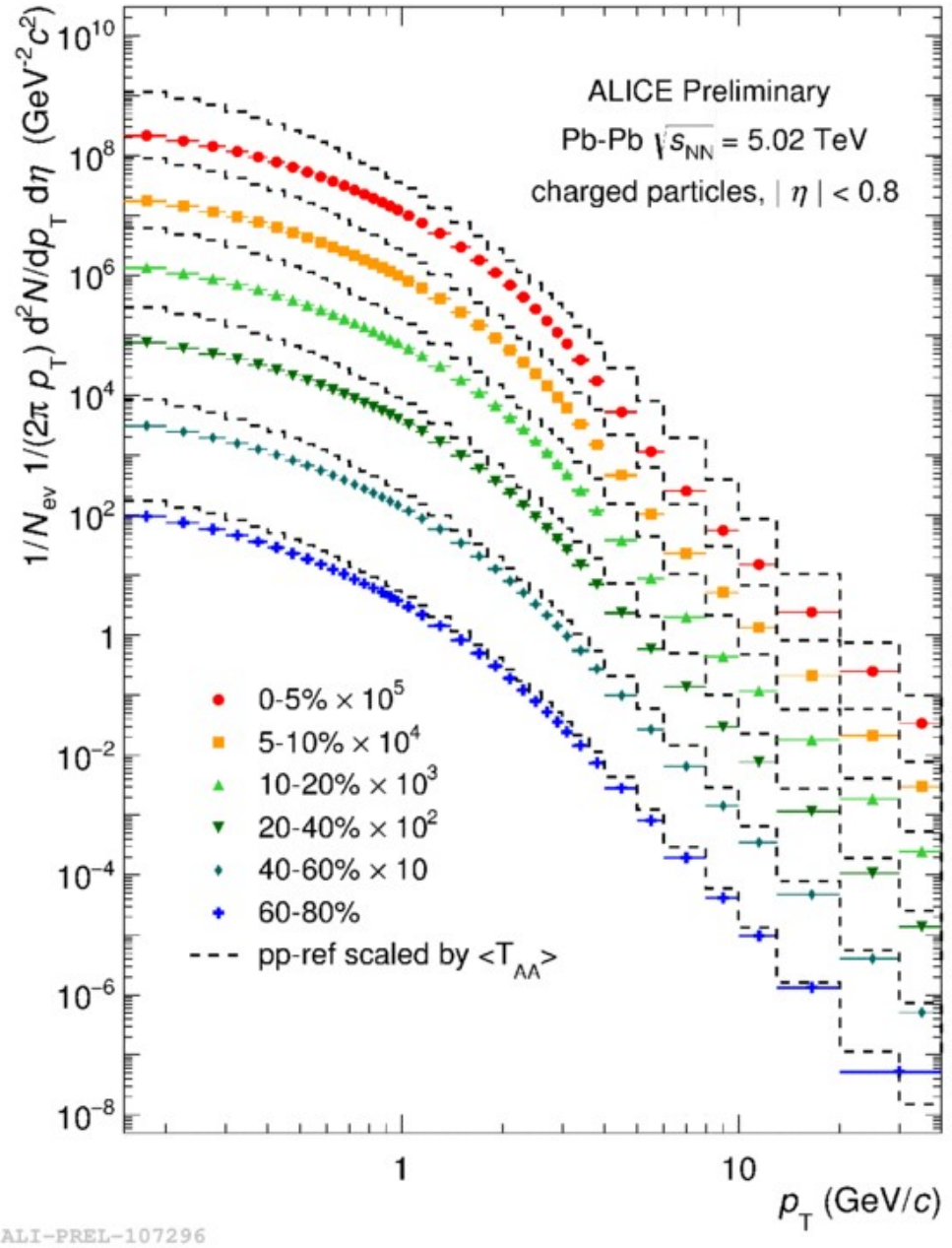
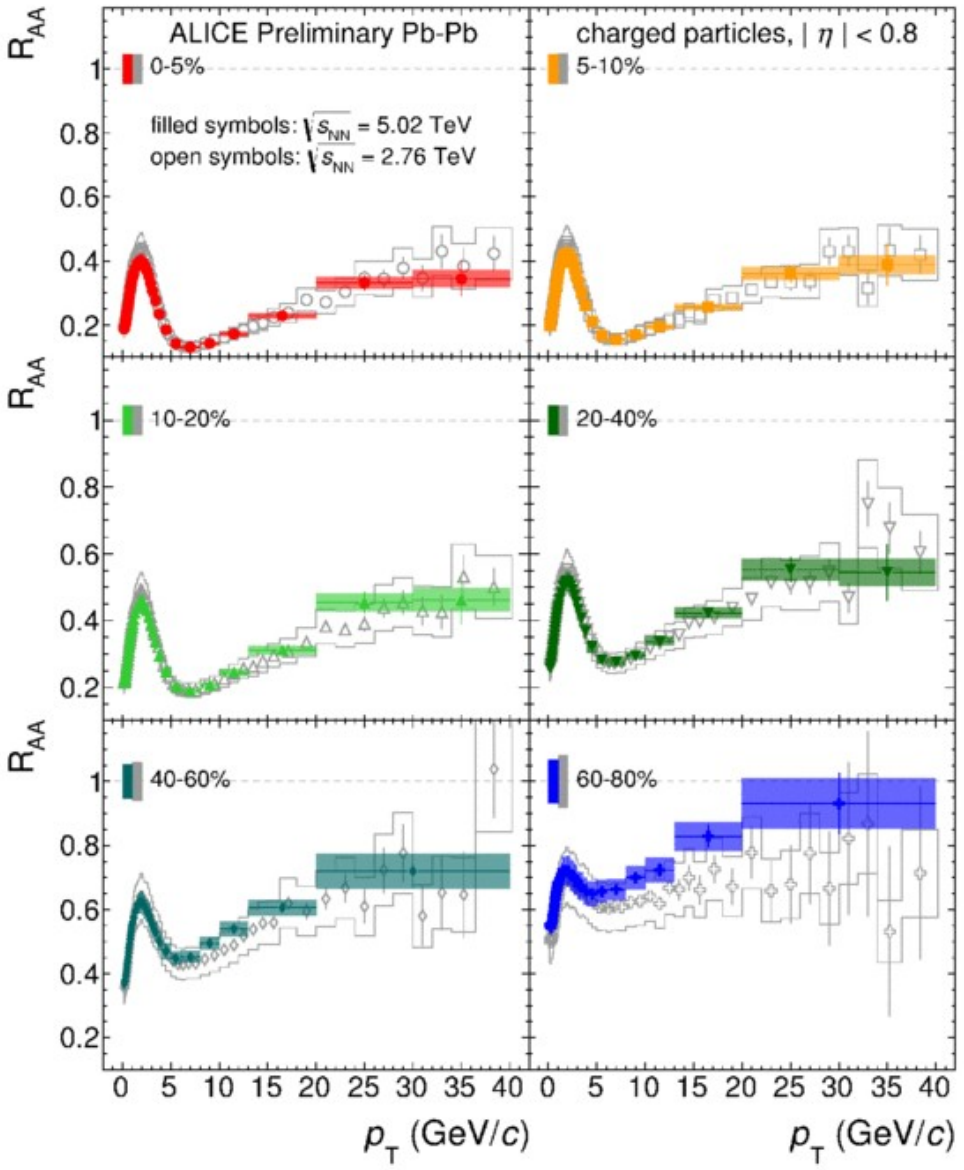
HIGH P_T PARTICLES: PB-PB

- Spectra measured for 0.15 GeV/c < p_T < 40 GeV/c
- Compared to pp-reference (measurement!) scaled by T_{AA}
- Reconstruction and track selection improved wrt. Run 1 → Reduced systematic uncertainties.
- Larger statistics recorded for Pb–Pb and pp. Currently under reconstruction

Centrality	<T_{AA}>	Sys (T_{AA})	N_{coll}
0-5%	26.27	0.93	1840
5-10%	20.48	0.74	1430
10-20%	14.30	0.46	1001
20-40%	6.76	0.27	473
40-60%	1.95	0.10	136
60-80%	0.40	0.032	28



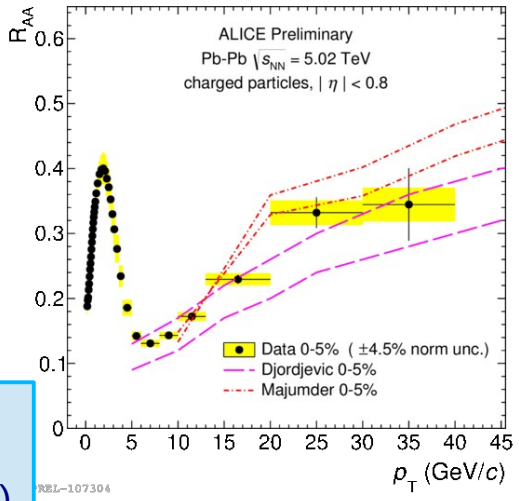
HIGH p_T PARTICLES: PB-PB

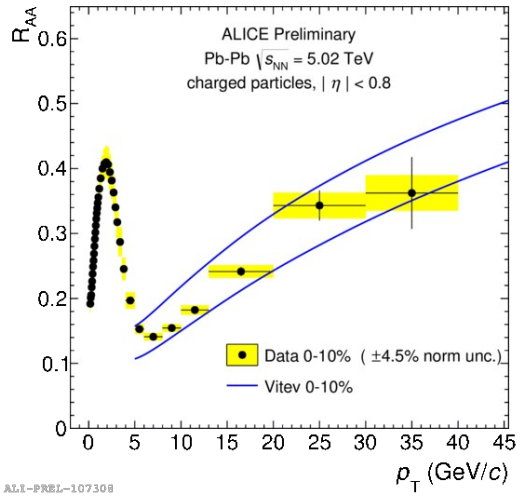


Strong modification of the spectra shape
- minimum at $p_T \approx$ 6-7 GeV/c
- strong rise in 6 < p_T < 50 GeV/c
- strong centrality dependence for p_T<40 GeV/c

Comparison 5.02 – 2.76 TeV
- R_{AA} in 5.02 TeV similar to 2.76 TeV
- Hotter / denser medium?

Model predictions seem to describe R_{AA} well
→ Further constraint on medium properties

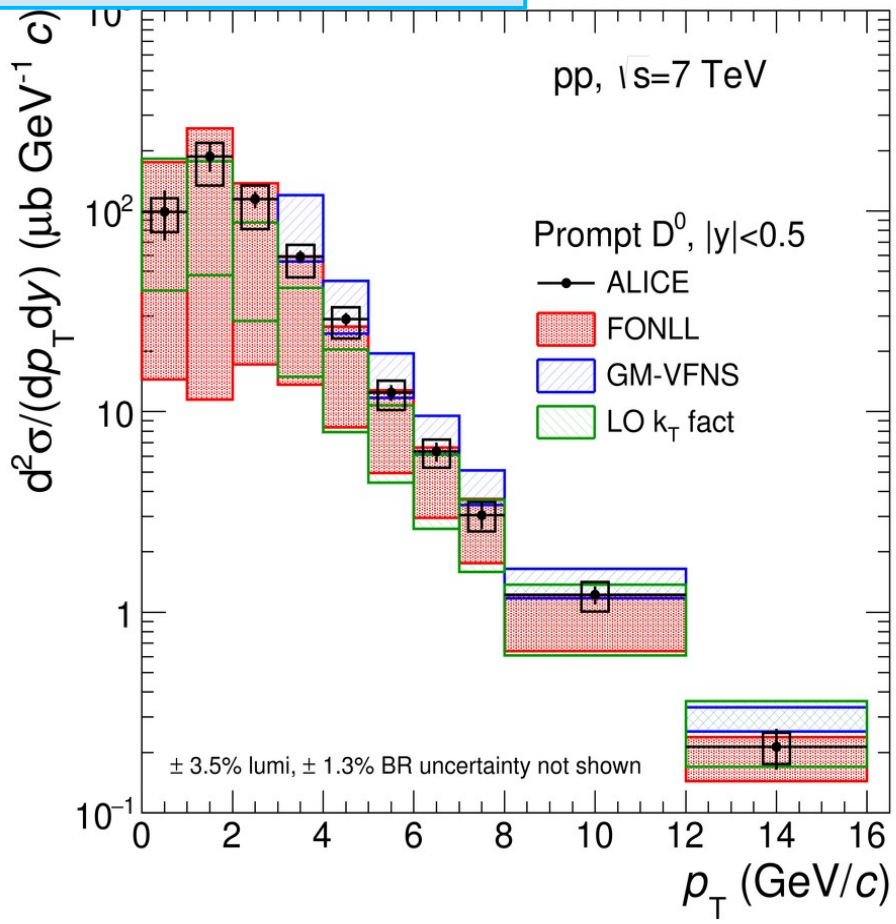




Vitev et al., Phys. Rev. D 93 (2016) no.7
Djordjevic et al., arXiv:1601.07852
Majumder et al., Phys. Rev. Lett. 109 (2012)

HEAVY FLAVOR: pp

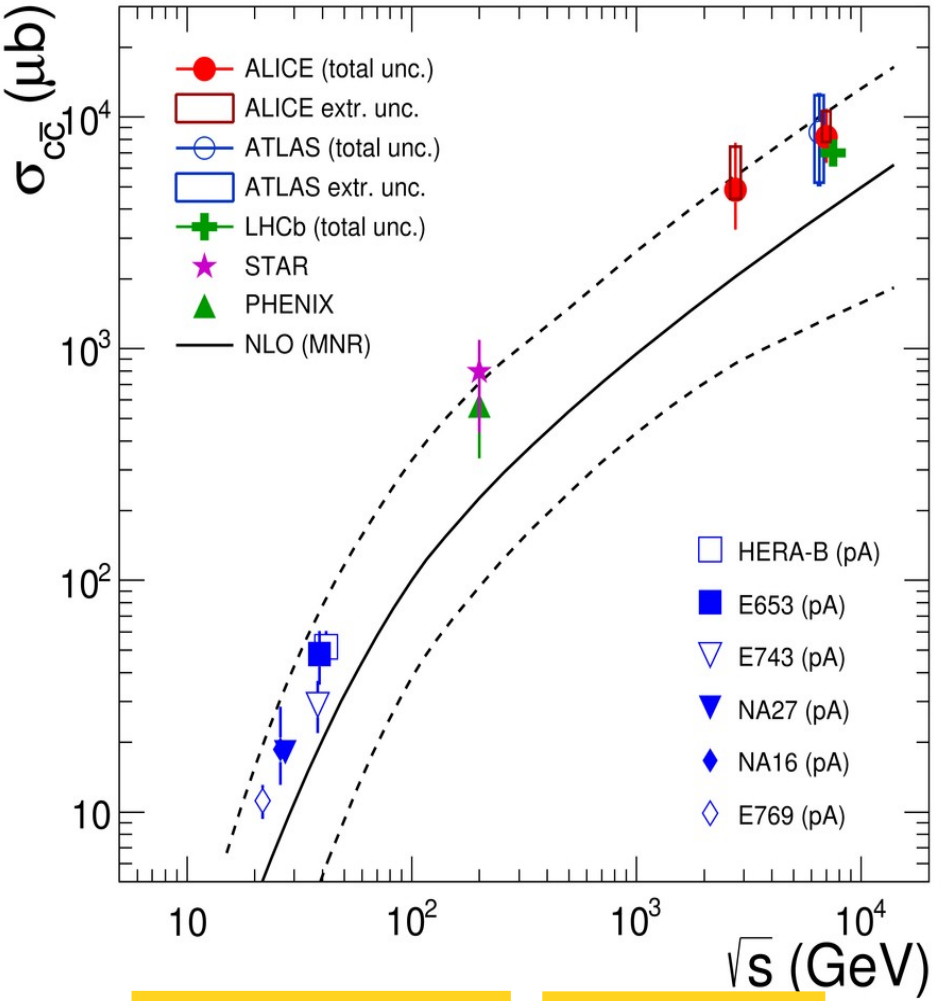
ALICE, arXiv: 1605.07569



D⁰ measurements at mid-rapidity in pp collisions at 7 TeV, **down to p_T=0** (no vertexing)

- Data and theory calculations in agreement, but theoretical uncertainties are currently larger than the ones of the measurements

• Updated total charm production cross-section dσ/dy (prompt D⁰) = $518 \pm 43(\text{stat.})^{+57}_{-102}(\text{syst.}) \pm 18(\text{lumi.}) \pm 7(\text{BR})$ μb



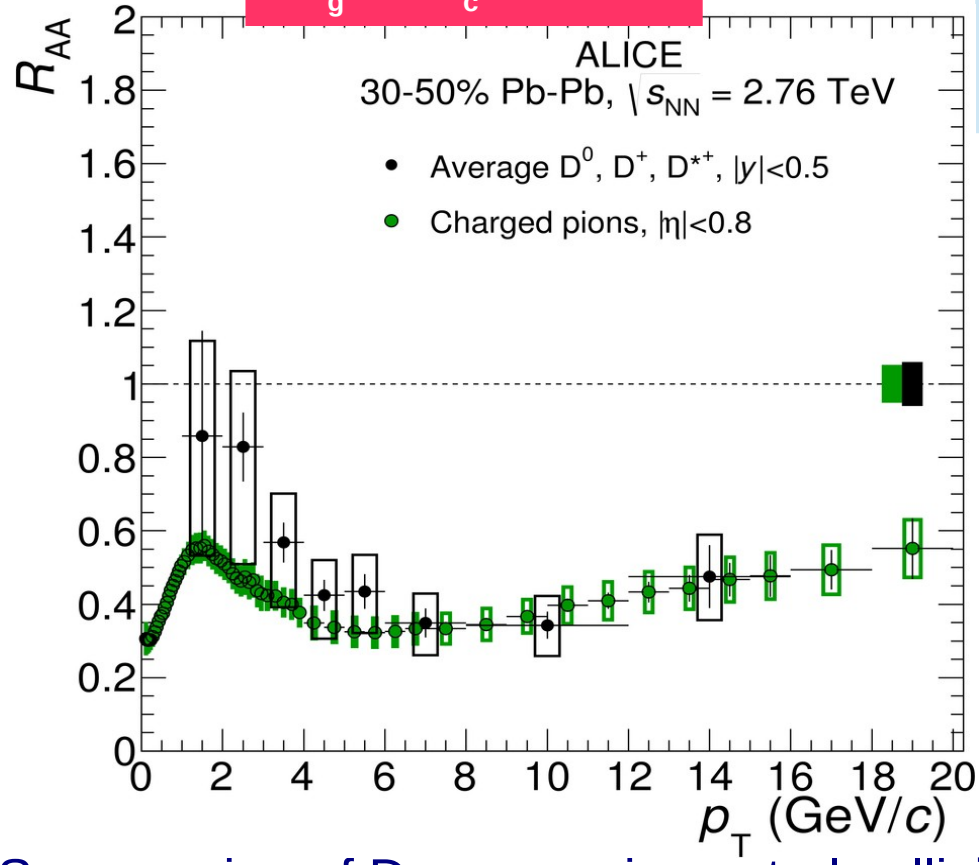
See talk/poster E. Mennino

See poster M. Mazzilli

HEAVY FLAVOR: PB-PB

ALICE JHEP 03 (2016) 081

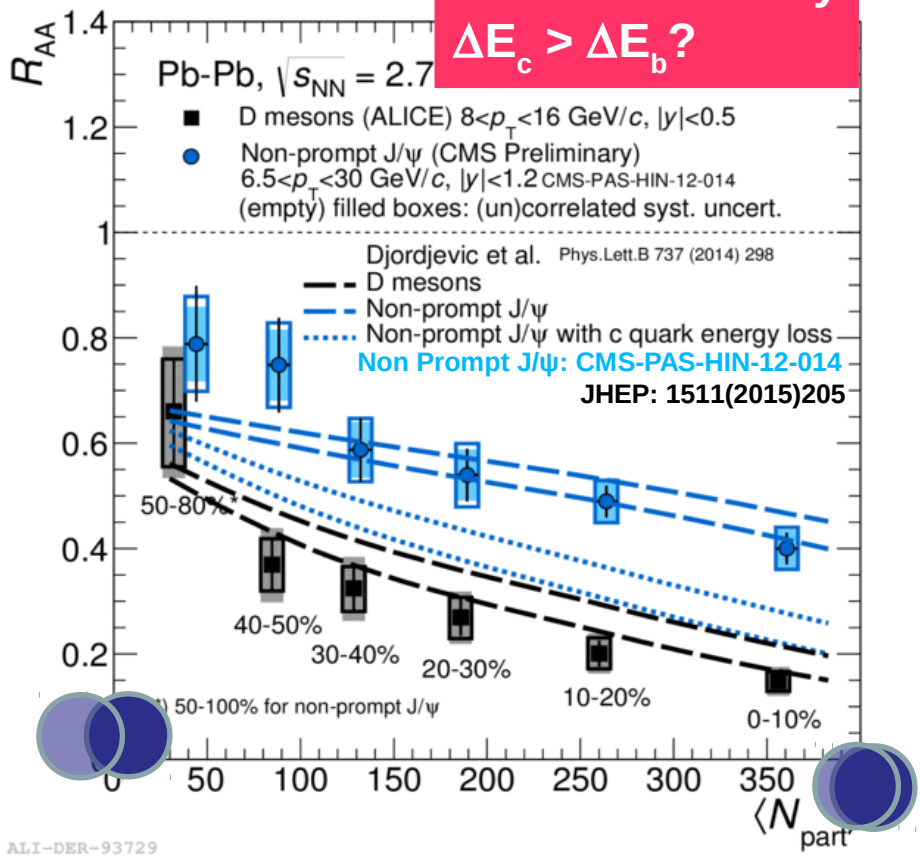
D vs light hadrons
$\Delta E_g > \Delta E_c$?



Expectations of **Hierarchy**
Radiative Energy loss decreases wrt light quarks (Casimir factor and dead cone effect)
$\Delta E^{rad}_{g} > \Delta E^{rad}_{charm} > \Delta E^{rad}_{beauty}$
→ R_{AA} (U,D) < R_{AA} (D) < R_{AA} (B)

- Comparison between D and secondary J/ψ (from B decays) for central collisions
- $R_{AA}^{charm} < R_{AA}^{beauty}$ → **expected hierarchy**

Charm vs beauty
$\Delta E_c > \Delta E_b$?

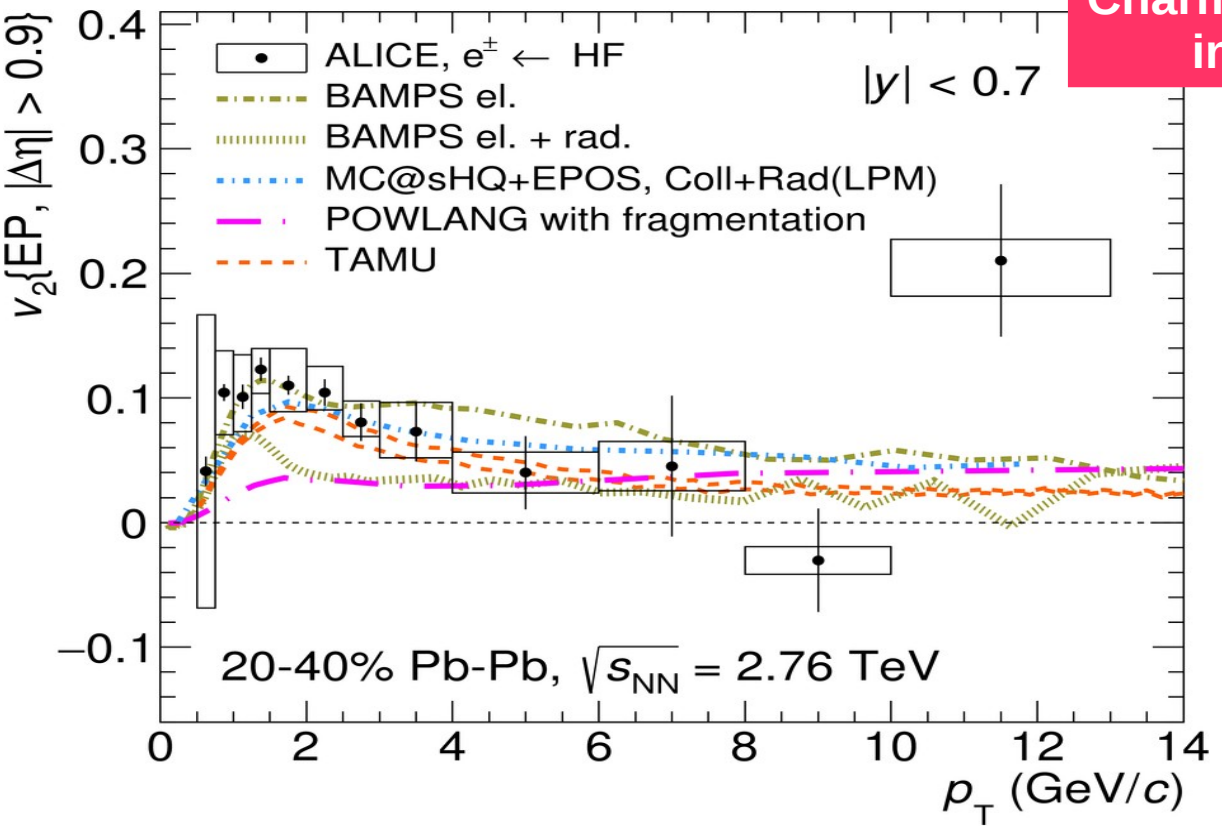


- Suppression of D mesons in central collisions
  - High p_T: the suppression for D and π is similar → explained by softer fragmentation and p_T spectrum of gluons w.r.t. c-quarks
  - Low p_T: indications of $R_{AA}^{D} > R_{AA}^{\pi}$

HEAVY FLAVOR IN PB-PB: v_2

Does heavy flavour thermalize in the QGP and consequently flows ?
-Heavy flavour elliptic flow sensitive to transport properties of QGP
Due to the large mass, b and c quarks should take longer time to be influenced by the collective expansion of the medium

Charm thermalize in QGP?



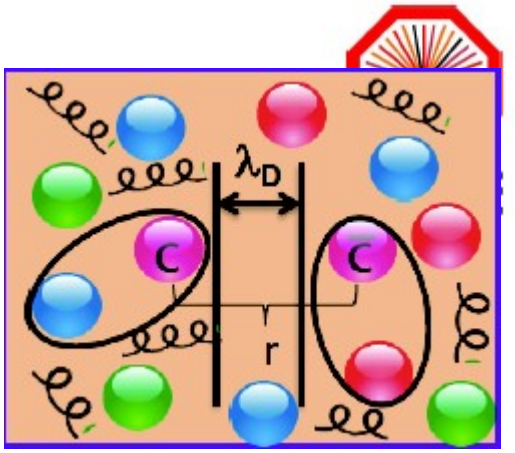
ALICE arXiv: 1606.00321

-Significant non-zero elliptic flow observed, **v_2(D) ~ v_2 (charged particles)**

-Models which implement strong collisional energy loss and hadronisation via coalescence agree with the data

See poster
G. Trombetta

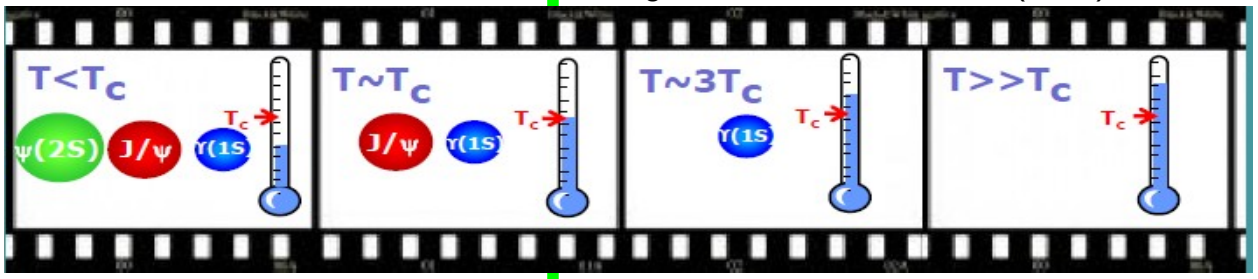
QUARKONIA



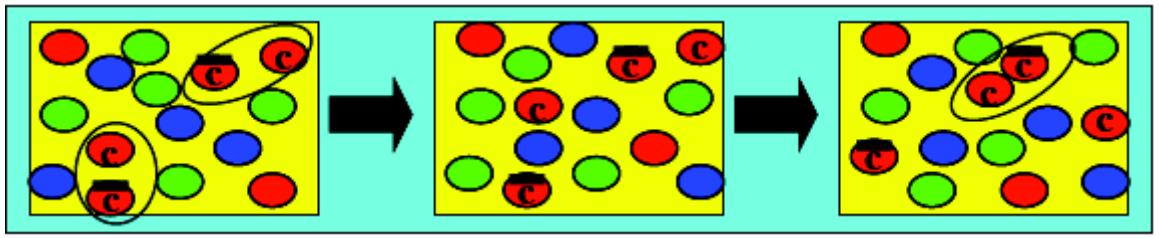
Digal,Petrecki,Satz PRD 64(2001) 0940150

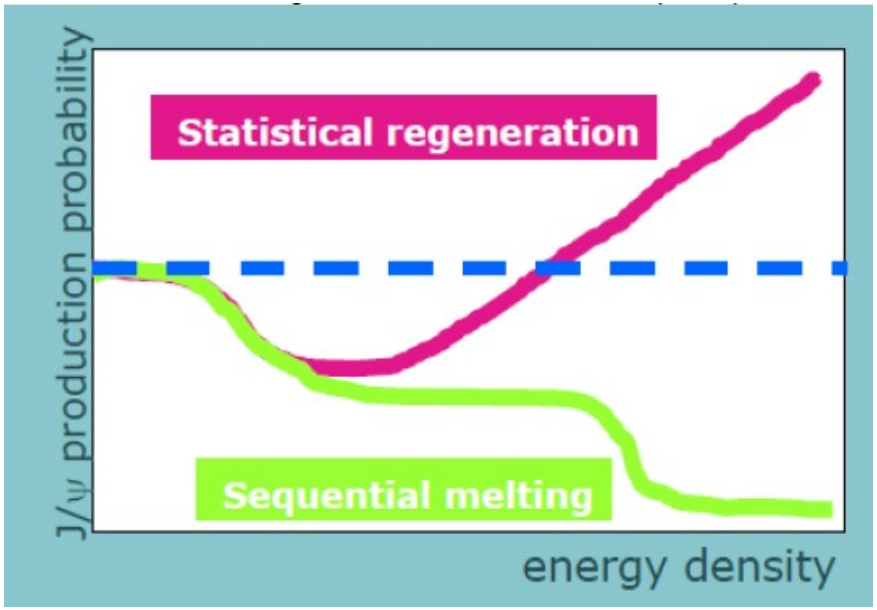
Bound states of charm or beauty quark and its anti-quark
Heavy and tightly bound
Heavy quark pairs produced in the initial hard partonic collisions.

Suppression (Debye screening) → Sequential melting
Color charge of one quark masked by surrounding quarks.
Prevents qq binding in the QGP.
Debye screening radius (λ_D) vs quarkonium radius (r).
λ_D < r the quarks are effectively masked from each other.
→ depending on the binding energies of the quarkonium states



Recombination
Increasing the collision energy the cc pair multiplicity increases (RHIC: ~10; LHC: ~100).
Regeneration of J/ψ pairs from independently cc.
Leads to an enhancement of J/ψ (or less suppression).
No/small regeneration is expected for bottomonia.

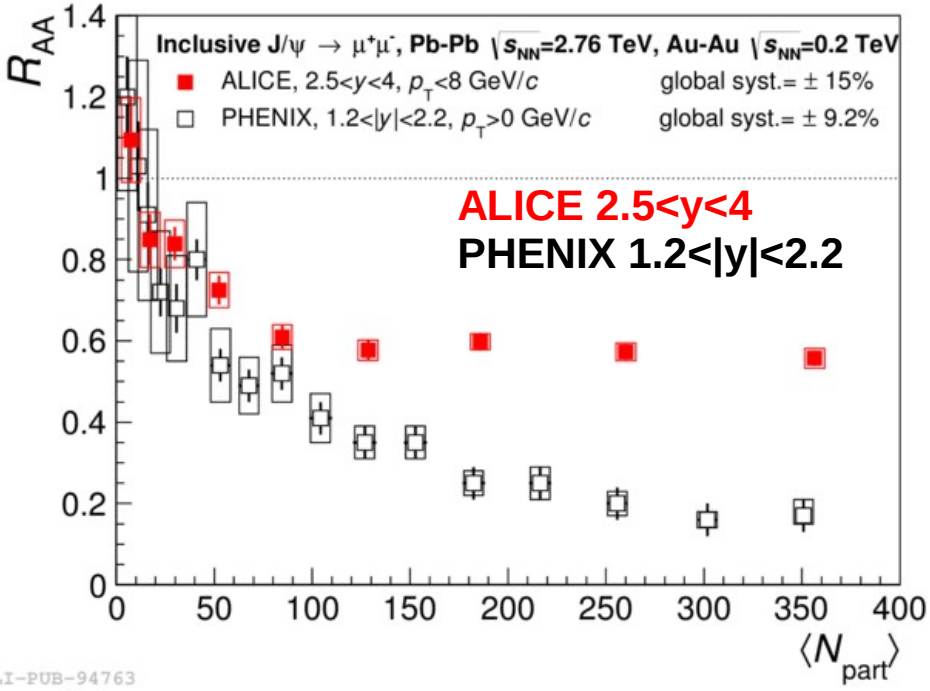


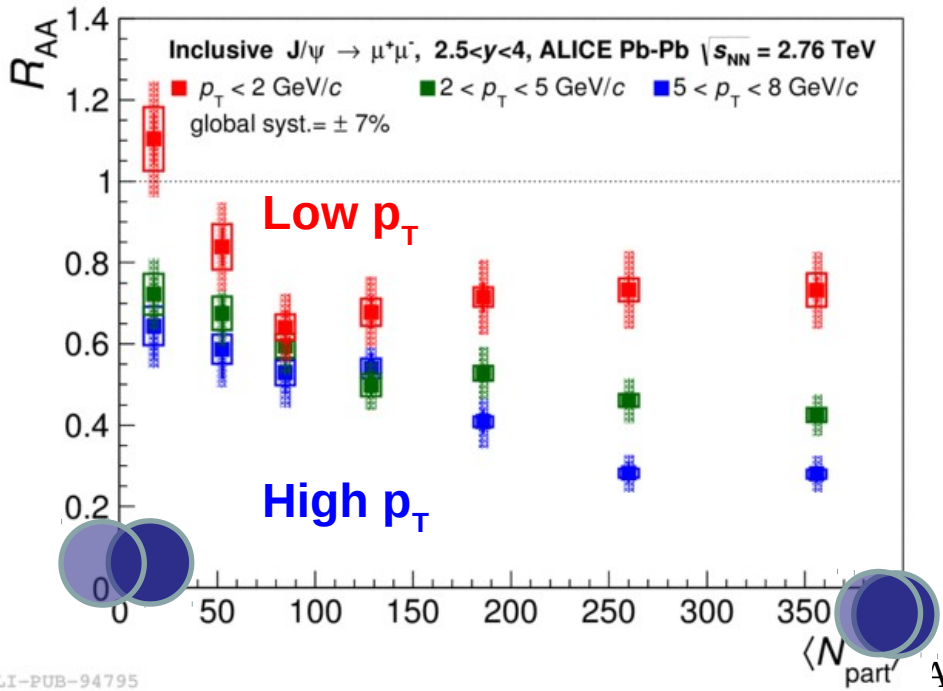


P. Braun-Munzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)

QUARKONIA R_{AA}

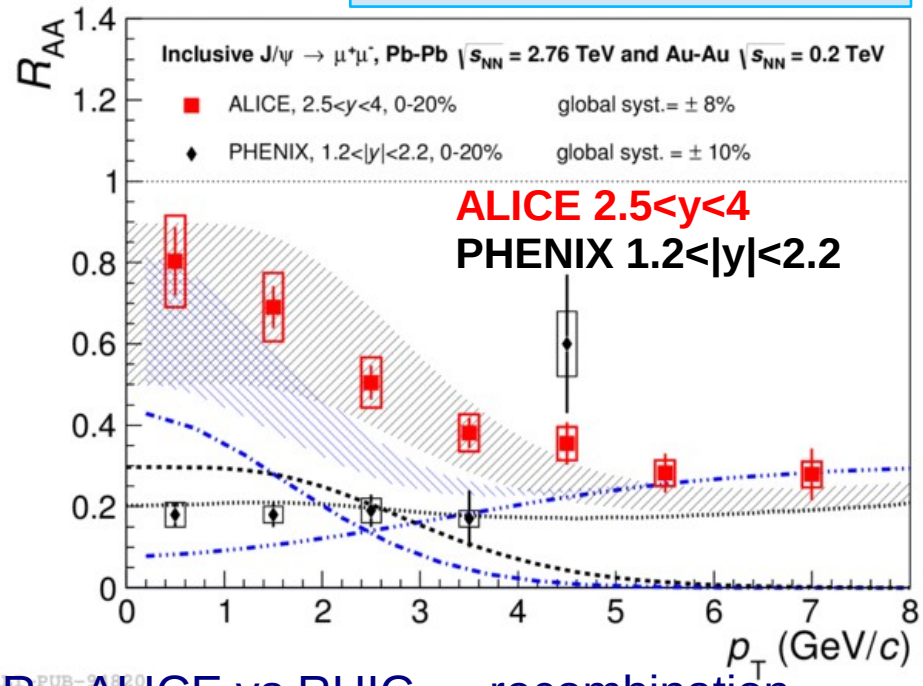
ALICE PLB 734 (2014) 314





Suppression and/or recombination?

ALICE JHEP 05 (2016) 179



Different R_{AA} ALICE vs RHIC → recombination

- Weaker centrality dependence
- Smaller suppression than at RHIC

Regeneration is higher at higher $\sqrt{s_{NN}}$

- High-p_T J/ψ are suppressed more than low p_T

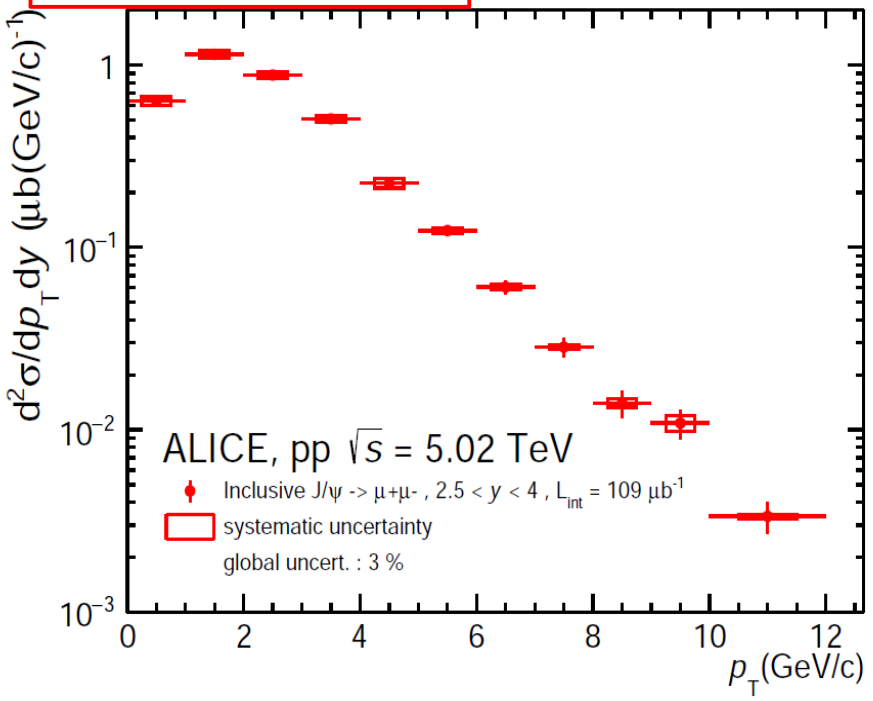
Regeneration is higher at low p_T.(bulk of cc production

Expected in Run2: 2.76 → 5.02 TeV

- higher color screening → more suppression
- higher cc cross section → more regeneration

QUARKONIA IN RUN2

pp at 5.02 TeV



Integrated cross section (p_T<12 GeV/c)

5.46 ± 0.08 ± 0.30 μb (syst. 5.5%)

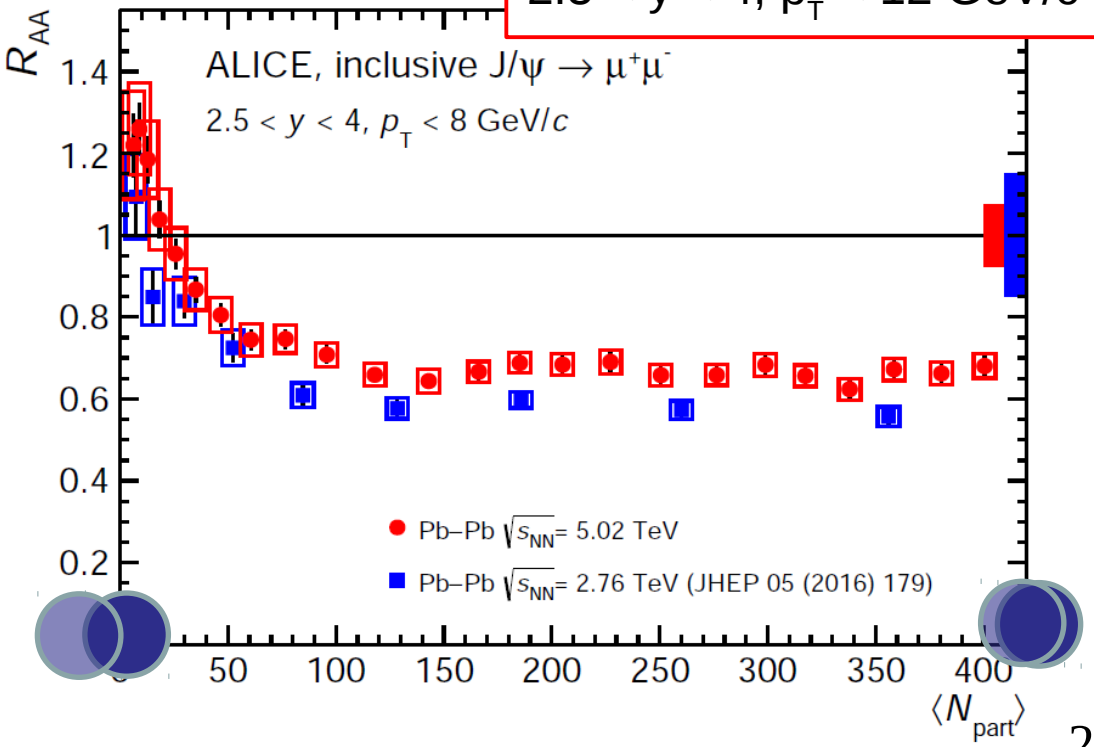
→ The integrated and differential cross sections are in very good agreement with the interpolation values used for p-Pb results for 5.02 TeV

ALICE arXiv: 1606.08197

Suppression and/or recombination?

- High statistics collected in 2015 allows the R_{AA} study in narrow centrality
- Clear J/ψ suppression with almost no centrality dependence above N_{part} ~100.
- Systematic difference ~ 20% wrt 2.76 TeV within the total uncertainty of the measurements
- Excess at low-p_T in peripheral events: photoproduction?

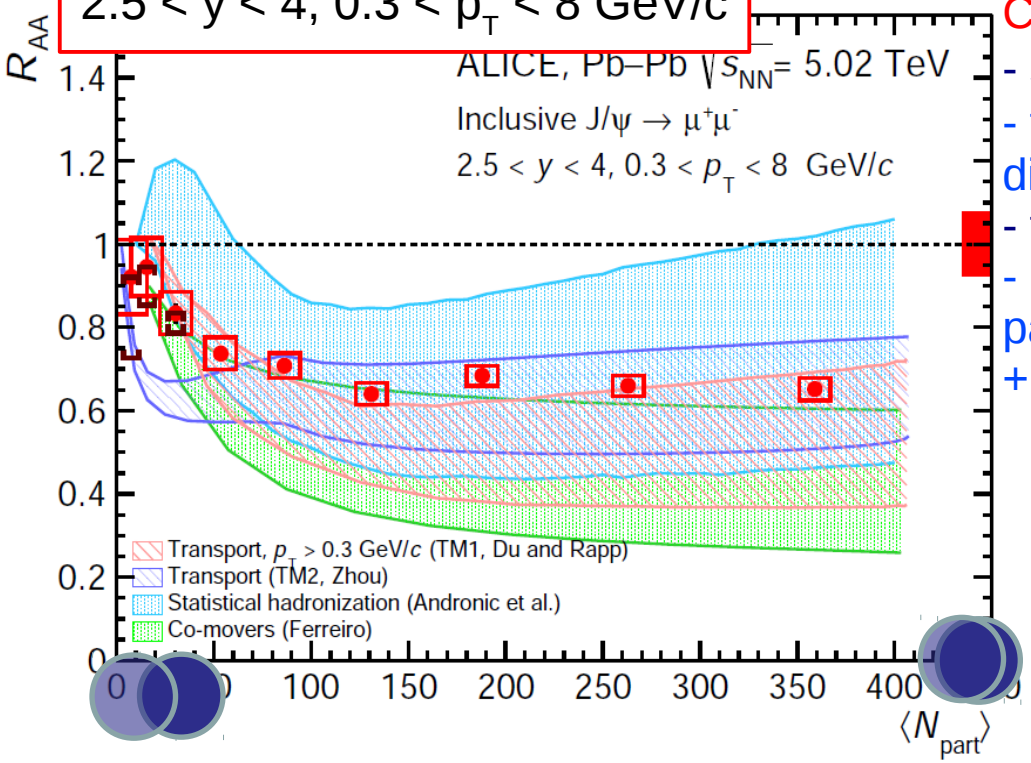
PbPb at 5.02 TeV
2.5 < y < 4, p_T < 12 GeV/c



QUARKONIA IN RUN2

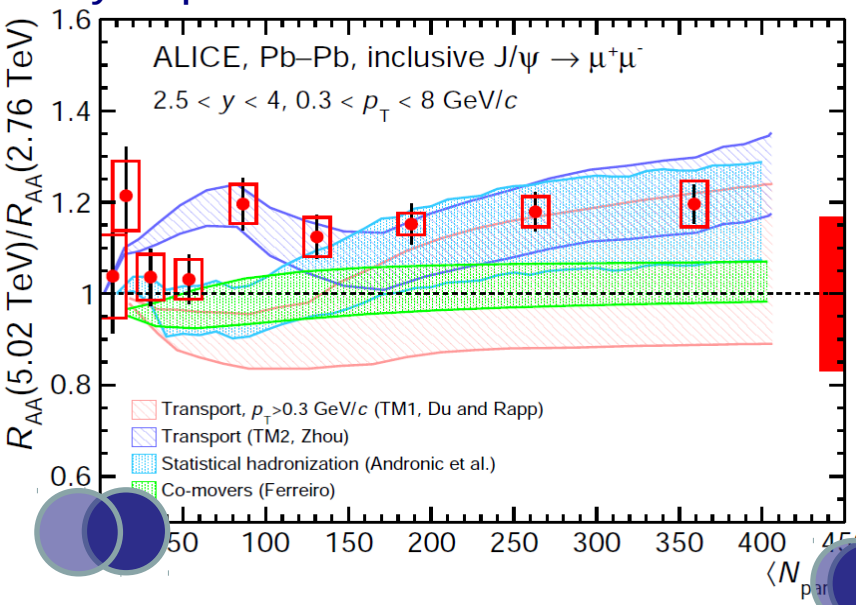
PbPb at 5.02 TeV
$2.5 < y < 4,\ 0.3 < p_T < 8$ GeV/c

Suppression and/or recombination?



Comparison with models
- statistical model: J/ψ created at chemical freeze-out
- transport model (TM1): thermal rate equation + dissociation/ regeneration in QGP/ hadronic phase.
- transport model (TM2): hydro for medium evolution
- 'co-mover' model: dissociation via interactions with partons/hadrons in the same y-range + regeneration + shadowing

Double Ratio → (some) error cancellation
Data are, within uncertainties, compatible with the theoretical models, and show no clear centrality dependence

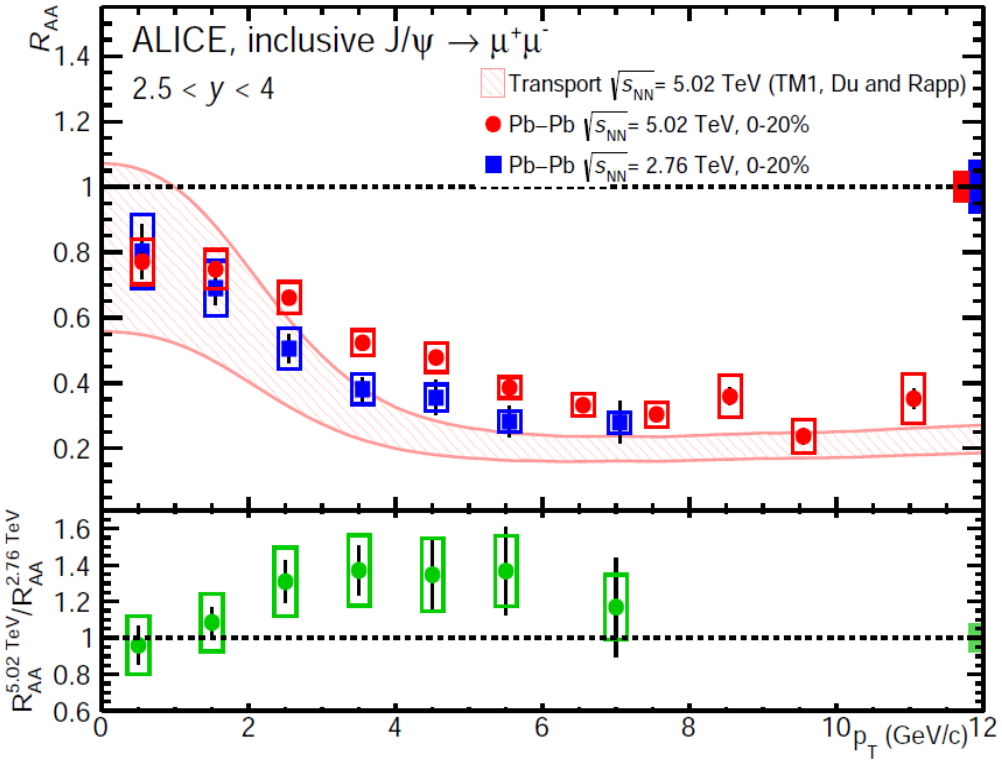


- Large uncertainties due to the choice of input parameters in particular cc cross-section
- For most calculations a better agreement is found when considering their upper limit.
- For transport models this corresponds to the absence of nuclear shadowing, which can be clearly considered as an extreme assumption

ALICE arXiv: 1606.08197

QUARKONIA IN RUN2

Suppression and/or recombination?



- R_{AA} measurement now extended up to 12 GeV/c

- Less suppression at low with respect to high pT, with stronger pT dependence for central events as expected from models with strong regeneration component.

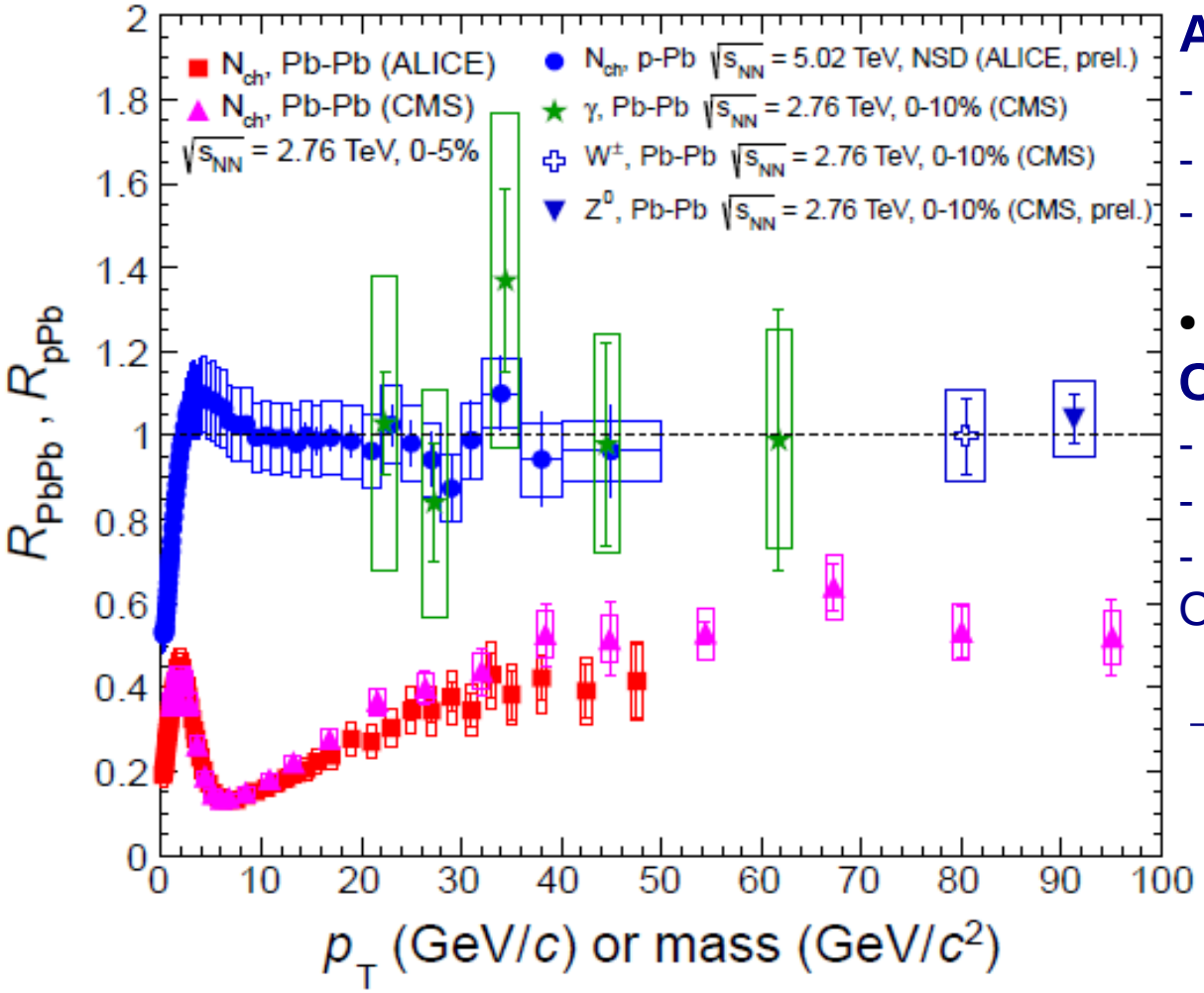
- Hint for an increase of R_{AA} with $\sqrt{s_{NN}}$ is visible in $2<p_T<6$ GeV/c, while they are consistent elsewhere

- TM1 describes the data at low p_T, but the overall shape of the p_T dependence is steeper in the model, which tends to underestimate the data at high p_T.

ALICE arXiv: 1606.08197

CONTROL EXPERIMENT

Is suppression of hard probes an effect of QGP?



• various observables measured in **"cold" nuclei (p–Pb):**

ALICE

- N_{ch}, EPJC 74 (2014) 3054
- heavy flavor, PRL 113 (2014) 232301
- Jets, EPJC 76 (2016) 5, 271

• **Electroweak probes**

CMS

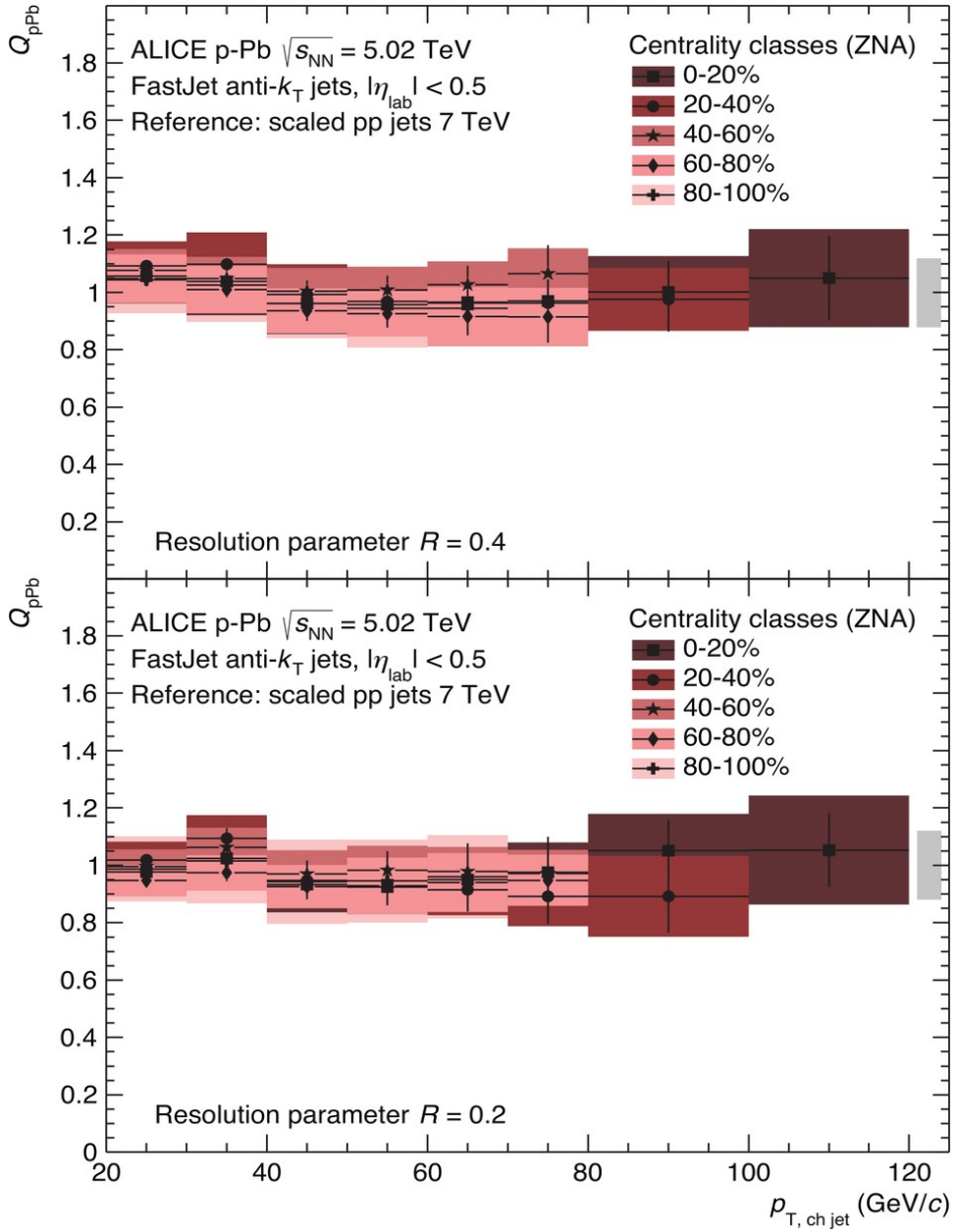
- γ, PLB 710 (2012) 256
- W±, PLB 715 (2012) 66
- Z^0, PRL 106 (2011) 212301, CMS-PAS-HIN-13-004

→ **N_{coll} binary scaling**

...provide experimental demonstration
that suppression in Pb-Pb is due to parton energy loss in a hot QGP

JETS R_{PA}

Do hard probes scale with N_{coll} in p-Pb?



Charged jets production in p-Pb collisions measured as a function of centrality

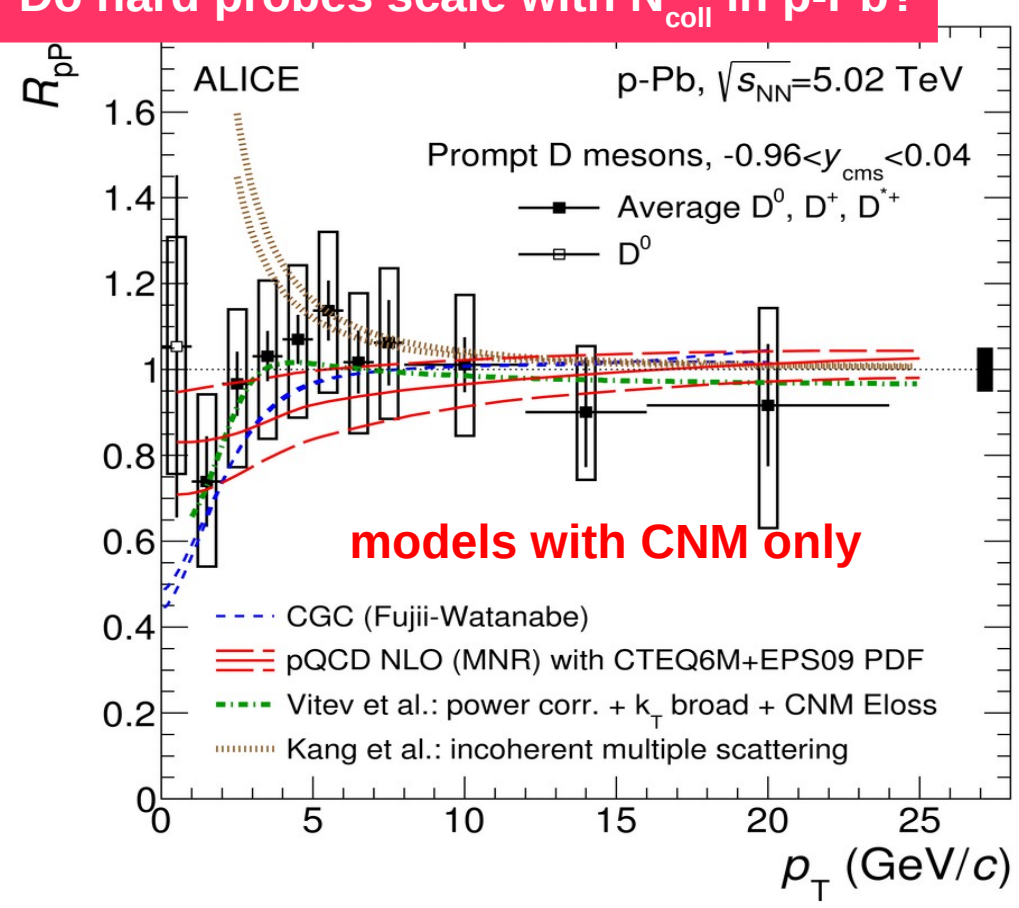
- Q_{pPb}~1 for all centrality classes and independent on the resolution parameter R and jet pT
- No or very small CNM effects in this kinematic range

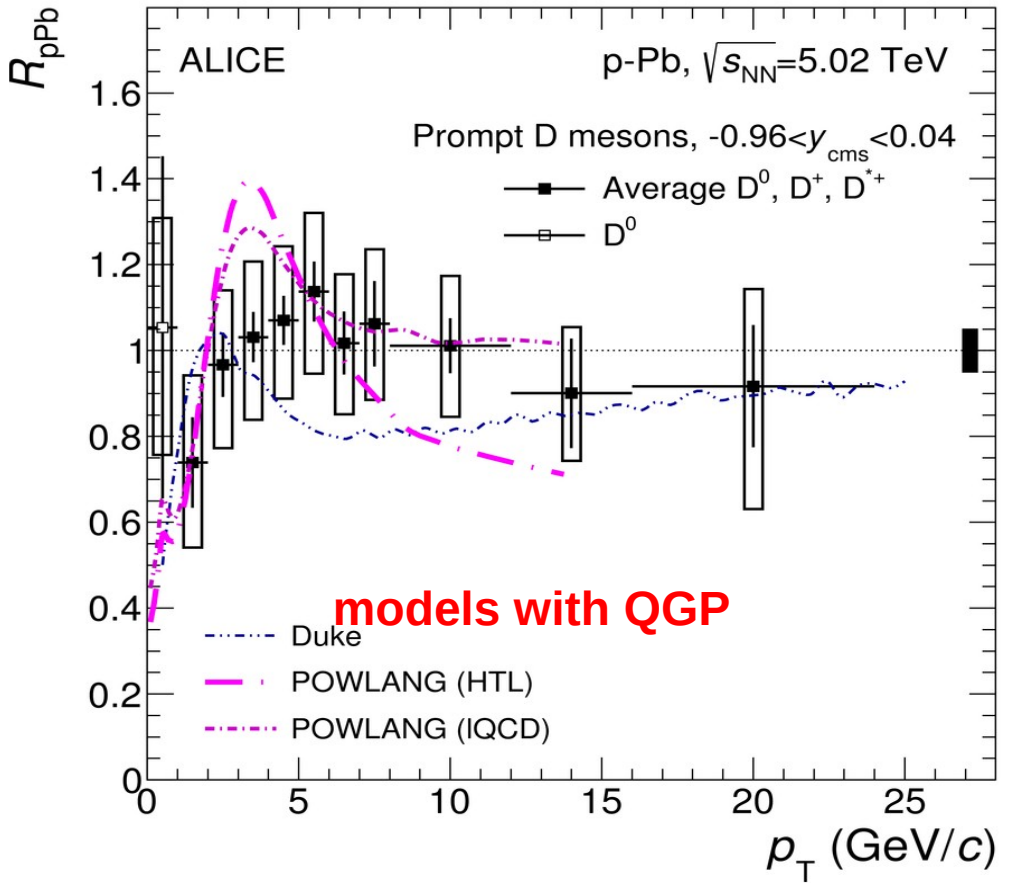
ALICE EPJC 76 (2016) 5, 271

HEAVY FLAVOR R_{pA}

ALICE arXiv: 1605.07569

Do hard probes scale with N_{coll} in p-Pb?





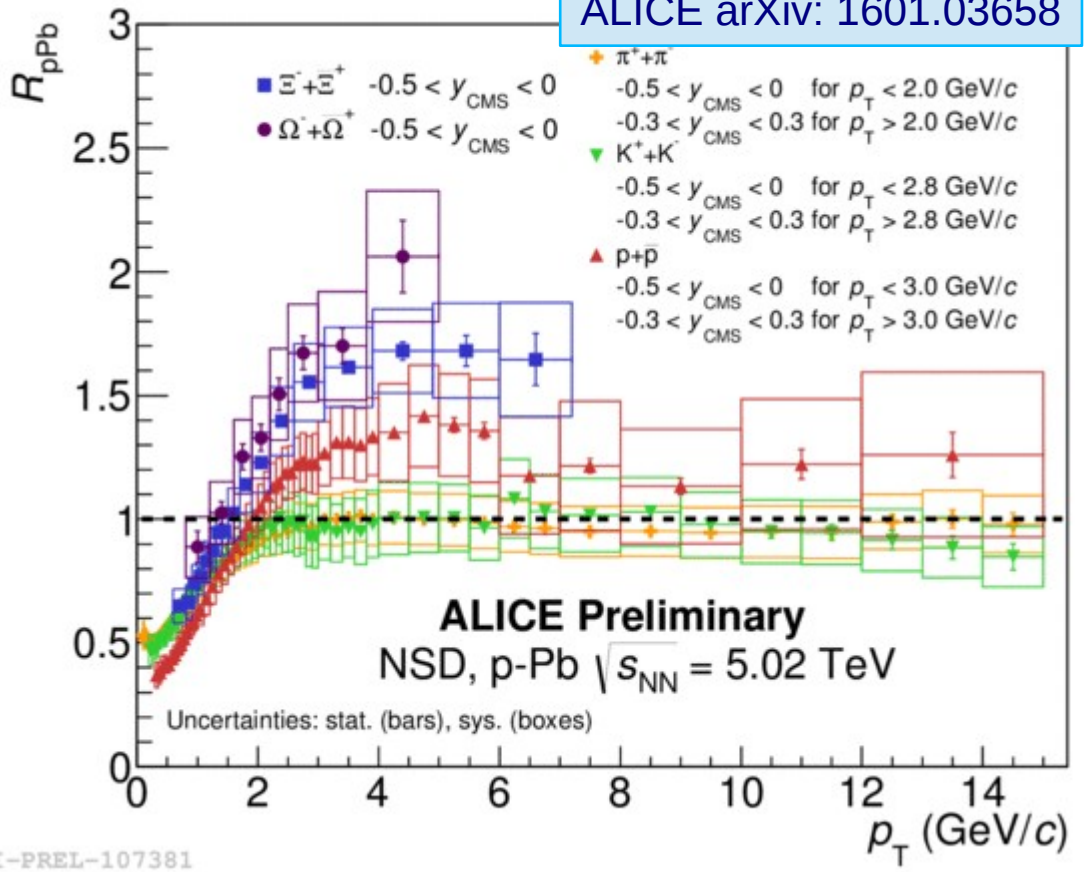
R_{pPb} consistent with unity → no suppression at intermediate/high-p_T

- Measurement compatible with no CNM effects
- Measurement compatible with models including initial or final state effects
- Experimental uncertainties are still too large to distinguish between the existing models
- Much larger sample of p-Pb collisions to be collected in 2016 → Constrain models

IDENTIFIED PARTICLES R_{pA}

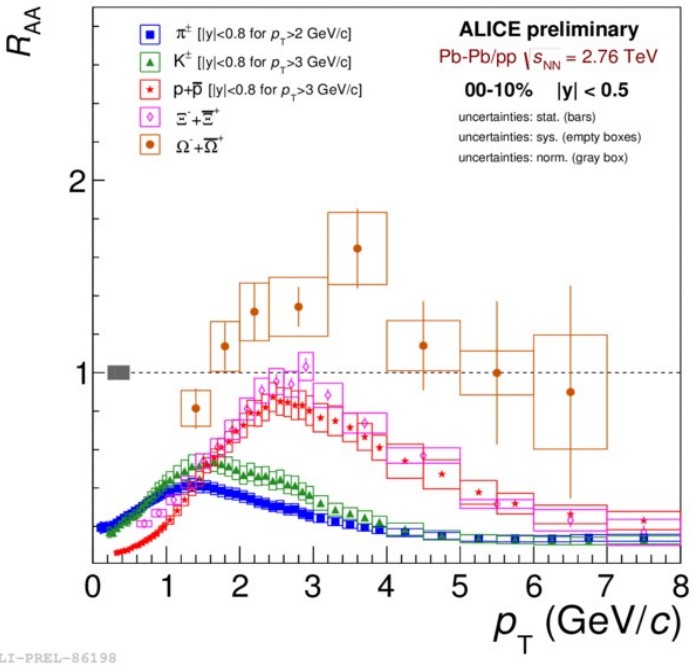
Do hard probes scale with N_{coll} in p-Pb?

ALICE arXiv: 1601.03658



Nuclear modification factor R_{pA} of primary charged π, K, p and multi-strange baryons Ξ and Ω at mid-rapidity

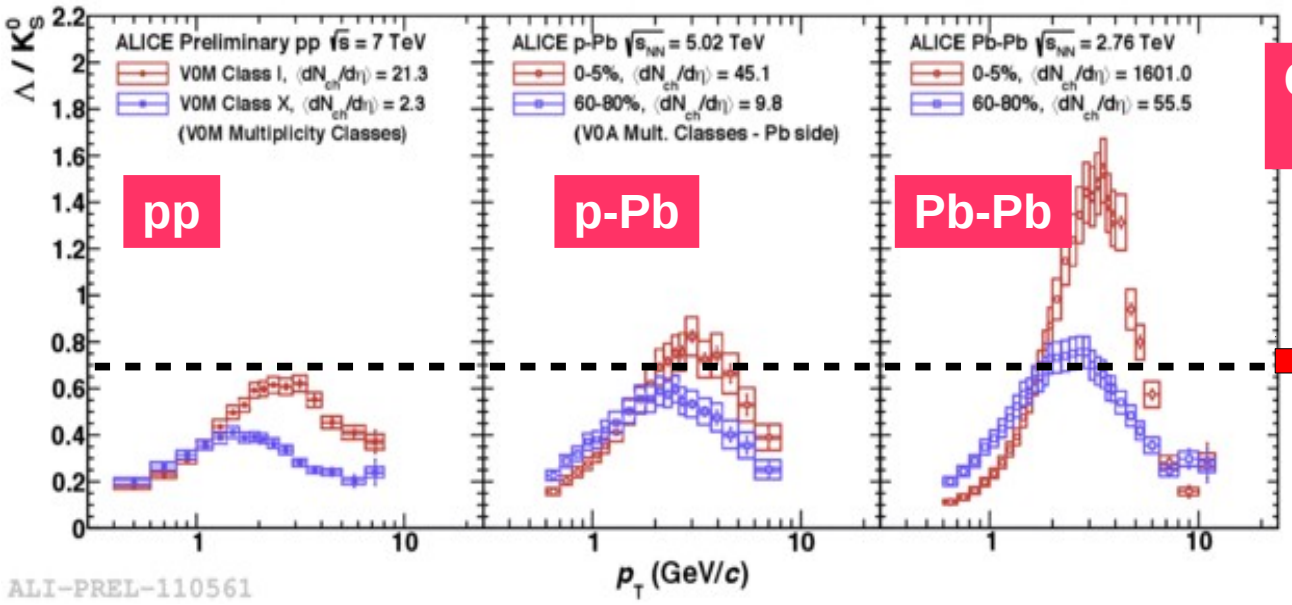
R_{AA} in Pb-Pb



- R_{pPb} is consistent with 1 at high p_T for all species.
- Mass ordering at intermediate p_T (Cronin region)
  - **Strong enhancement for p, Ξ and Ω**
  - Similar enhancement observed at RHIC.
  - Similar enhancement observed in Pb-Pb.

→ **signs of collectivity or change in paradigm?**

BARYON- OVER-MESON ENHANCEMENT

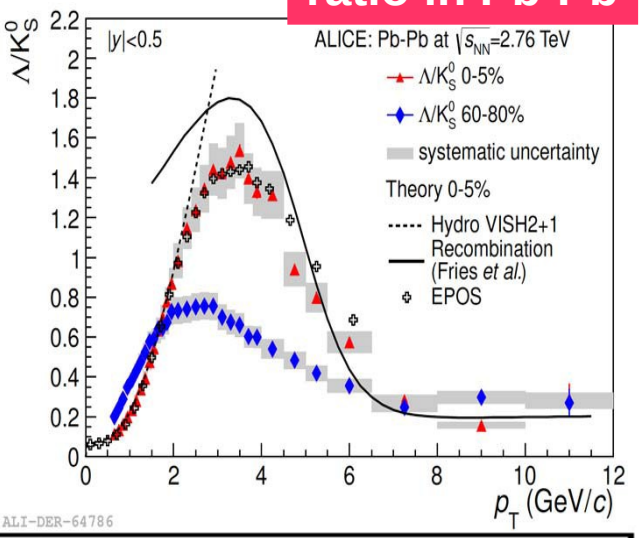


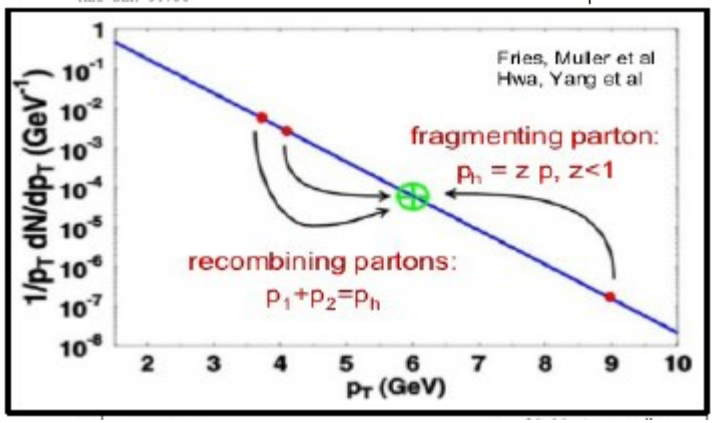
Collective flow or recombination in small systems?

pp: 0-1%
pA: 60-80%
AA: 80-90%

where $10<dN_{ch}/d\eta<20$

ratio in Pb-Pb





Clear evolution with multiplicity

Mid-p_T: ratio increases

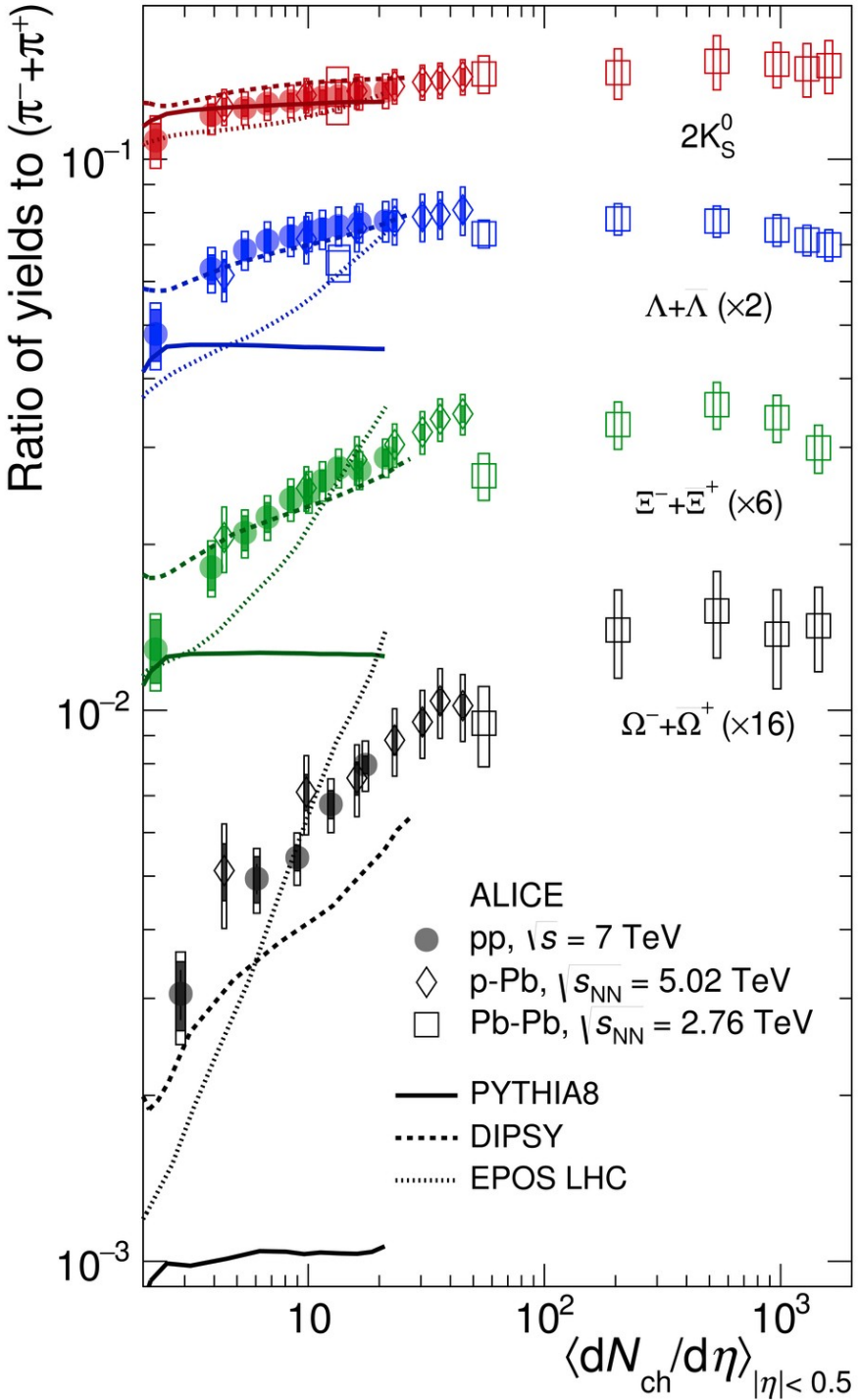
Low-p_T: corresponding depletion

Reminiscent of Pb-Pb phenomenology

...generally understood in terms of
- collective flow
- recombination

Quantitatively similar when comparing event classes with similar N_{ch}

STRANGENESS ENHANCEMENT

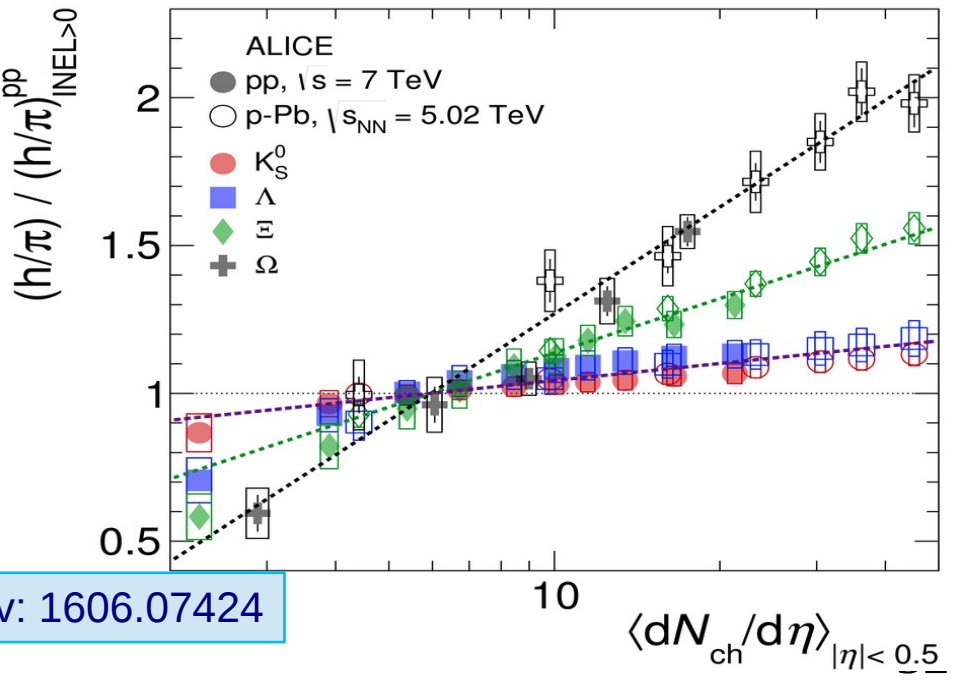


Which scaling for strangeness enhancement?

Study Yields Ratios evolution across systems

- For the **first time in pp collisions**: Significant **enhancement of strange** to non-strange hadron production is observed
- The observed enhancement follows a hierarchy with the number of strange valence quarks
- MC model predictions do not describe satisfactorily the behavior of the data
  - Λ/π and Ξ/π comparable to central Pb-Pb
  - Ω/π close to results from peripheral Pb-Pb

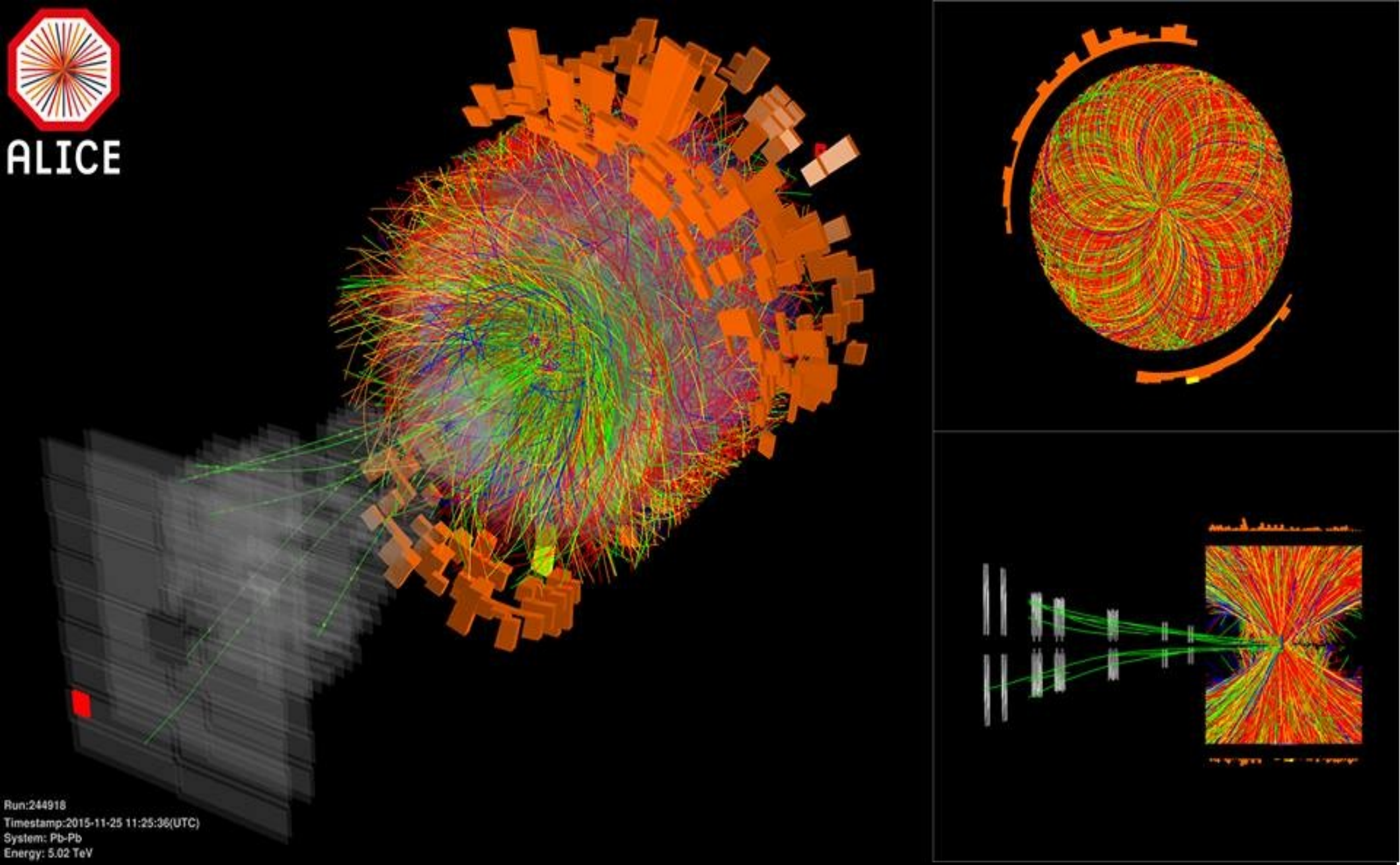
→ Ω/π do not reach the equilibrium limits?



ALICE arXiv: 1606.07424

SUMMARY

- Heavy ion collisions produce the most extreme state of matter ever created in lab
  - **Highest energy density, temperature, flow, suppression**
    → The AA physics program is rich but full of open questions
    - Different probes (soft, hard) allow to access medium properties
    - Significant progress in precision: v2, heavy-flavour, quarkonium…
  - Quantitative understanding requires:
    - Firm baseline from pp
    - Constrains of cold nuclear matter effects from pA
      - As control experiment: baseline measurements provide clear proof that effects in Pb–Pb collisions are genuine hot deconfined QCD matter effects related to parton energy loss
      - Many surprises: existence of collective effects at high multiplicities also in small systems
  - ALICE has collected an excellent set of data for pp, p-Pb and Pb-Pb collisions in Run1 and Run2
    → precision measurements of QGP properties



NIGHT WRAPS THE SKY IN TRIBUTE FROM THE STARS.
(VLADIMIR MAYAKOVSKY, 1930)