Ultra-Relativistic Heavy Ion Collision Results

John Harris (Yale), September 17, 2016

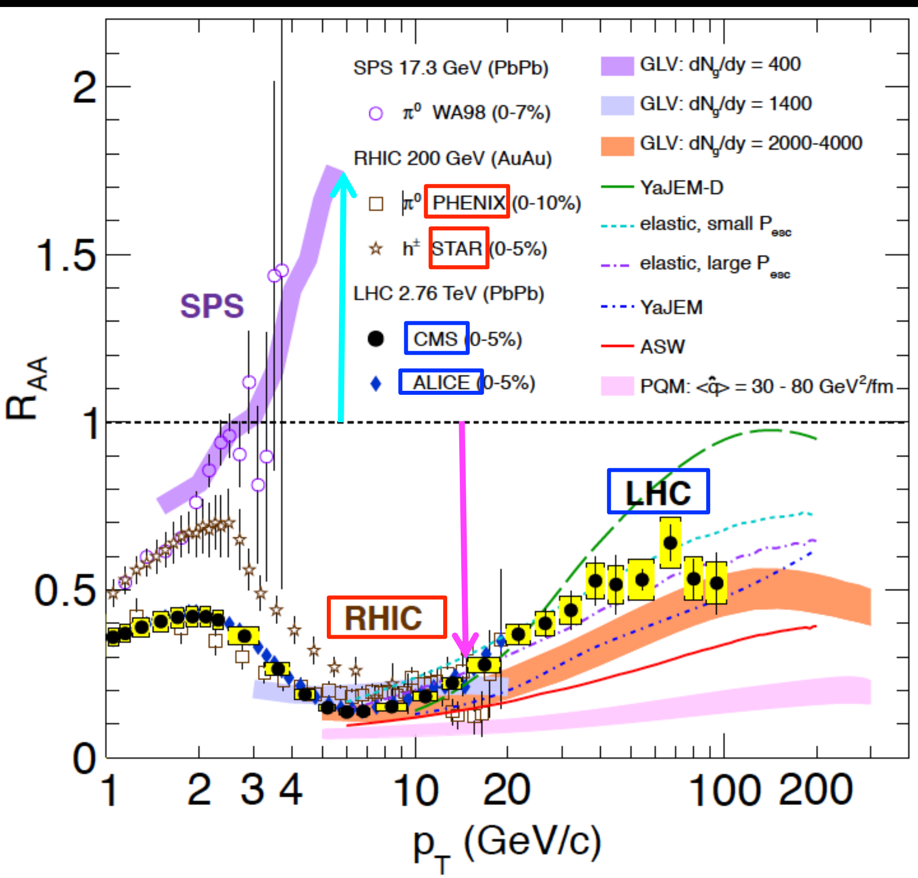
Nuclear Matter under Extreme Conditions, Erice-Sicily, Italy

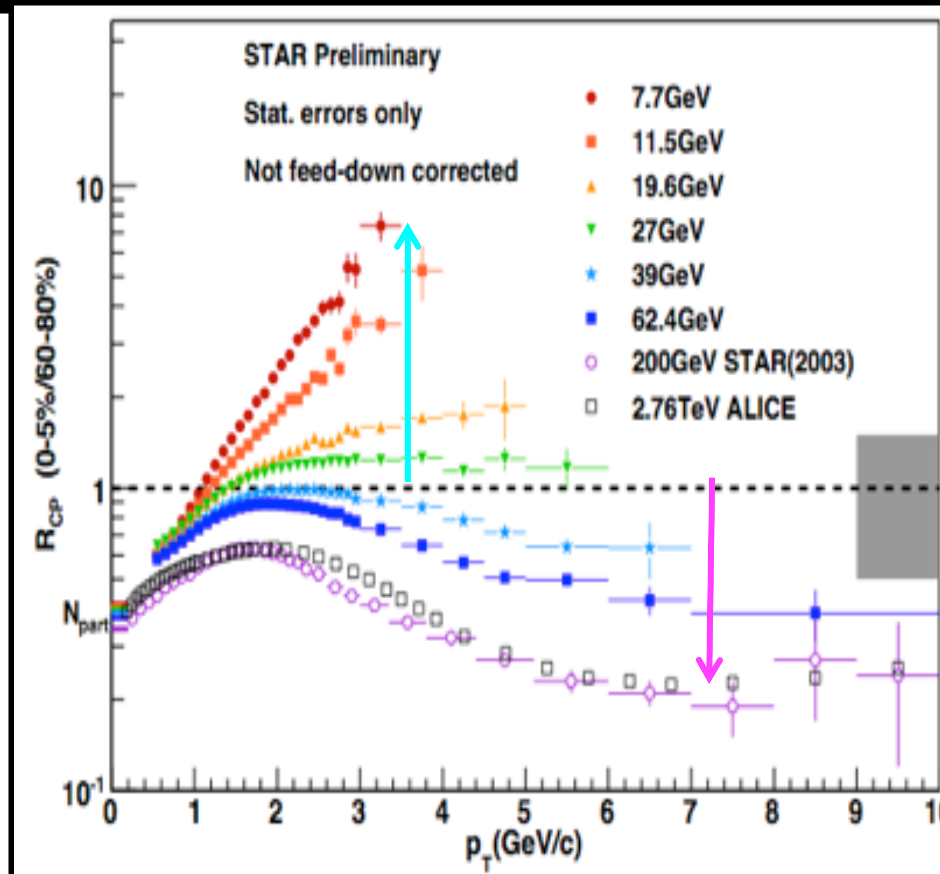
I. Overview of Effects Observed in Large Nucleus-Nucleus Collision Systems (Au+Au, Pb+Pb)

High p_T Hadrons Are Suppressed at LHC & RHIC

Central Pb-Pb and Au-Au Collisions

Suppression → parton energy loss in hot QCD medium





$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

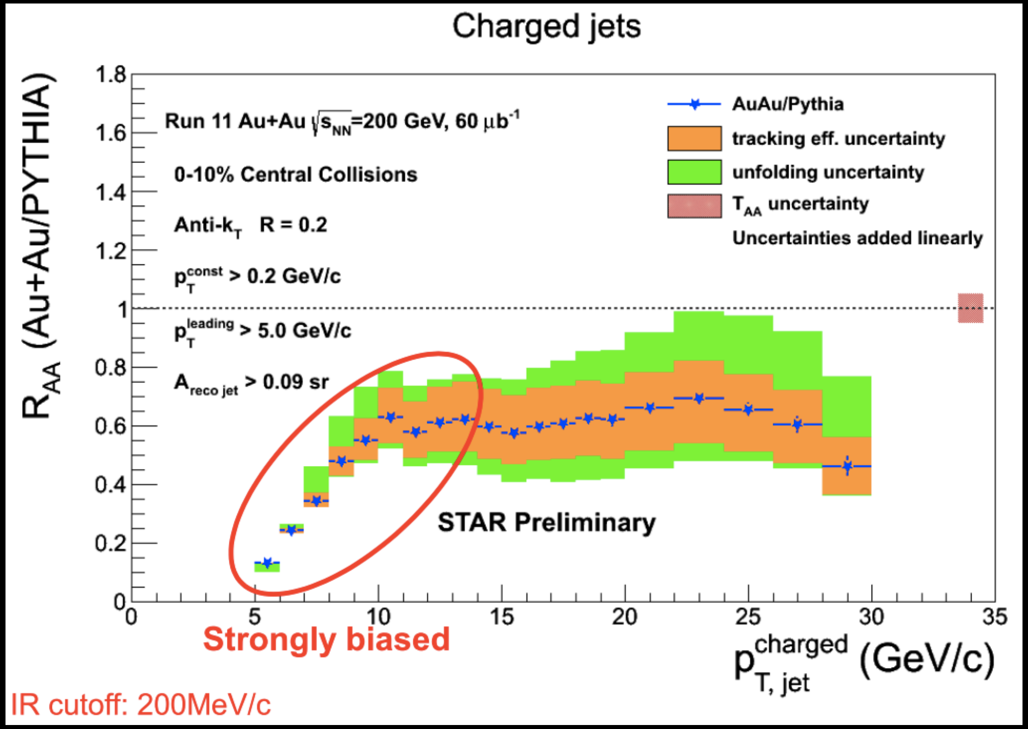
Also enhancement at lower energies
→ initial state effects
(Cronin enhancement)

$$R_{CP} = N_{central} / N_{peripheral}$$

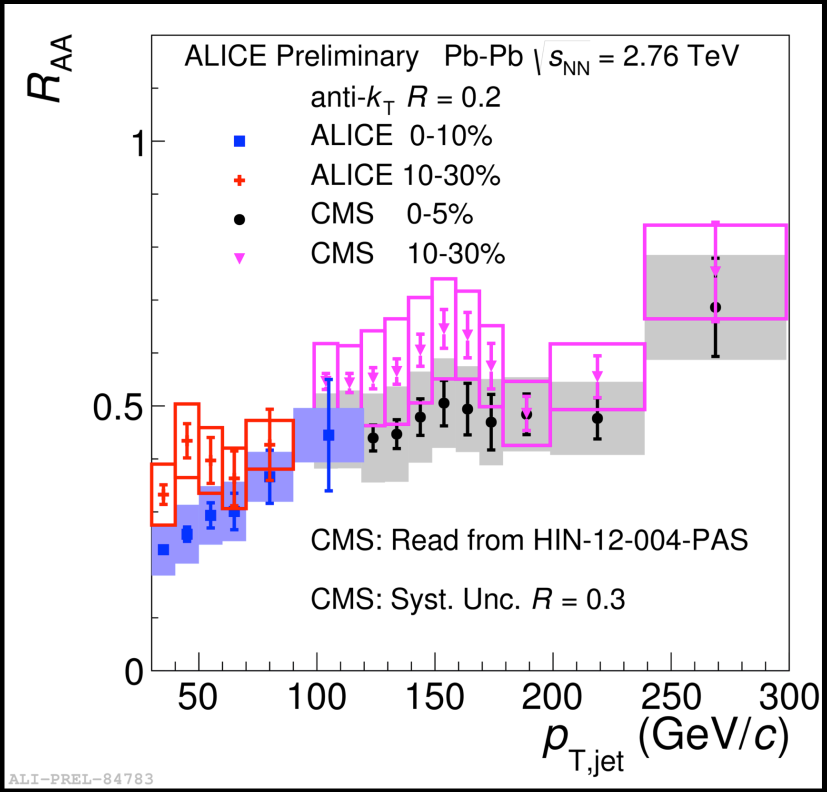
$$\sim R_{AA}$$

Jets Are Quenched at RHIC & LHC

RHIC



LHC



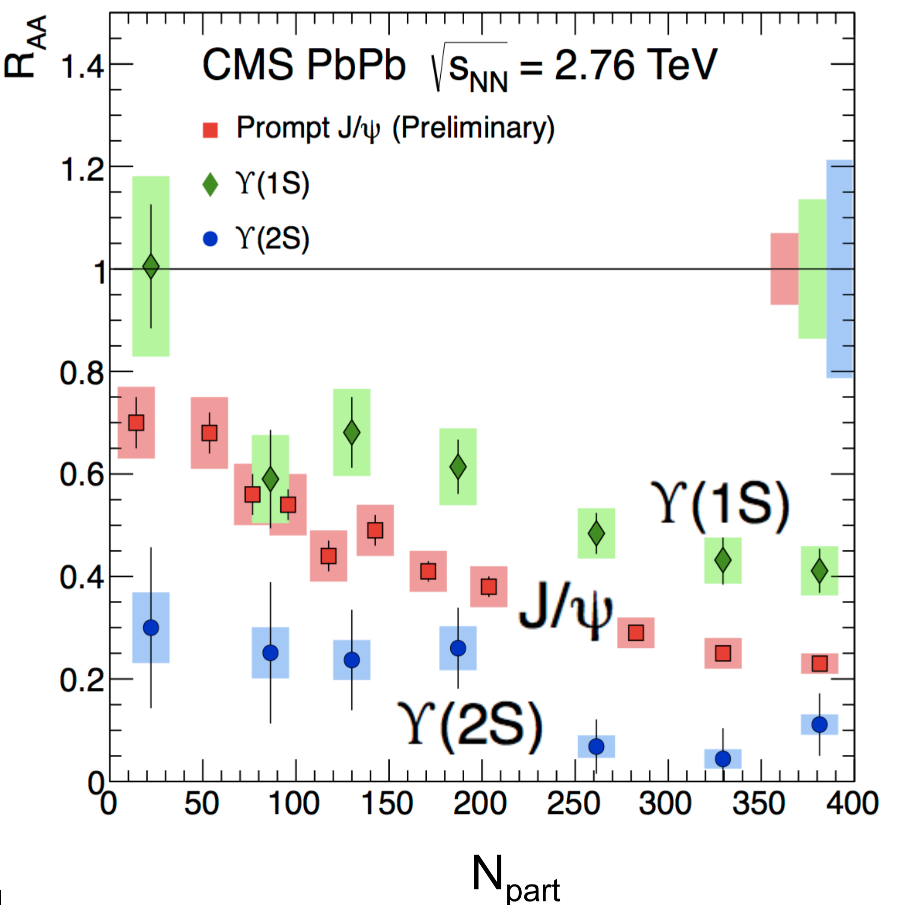
RHIC Jets less suppressed than LHC Jets
at low jet momentum

PLB 715 (2012) 66
PLB 710 (2012) 256

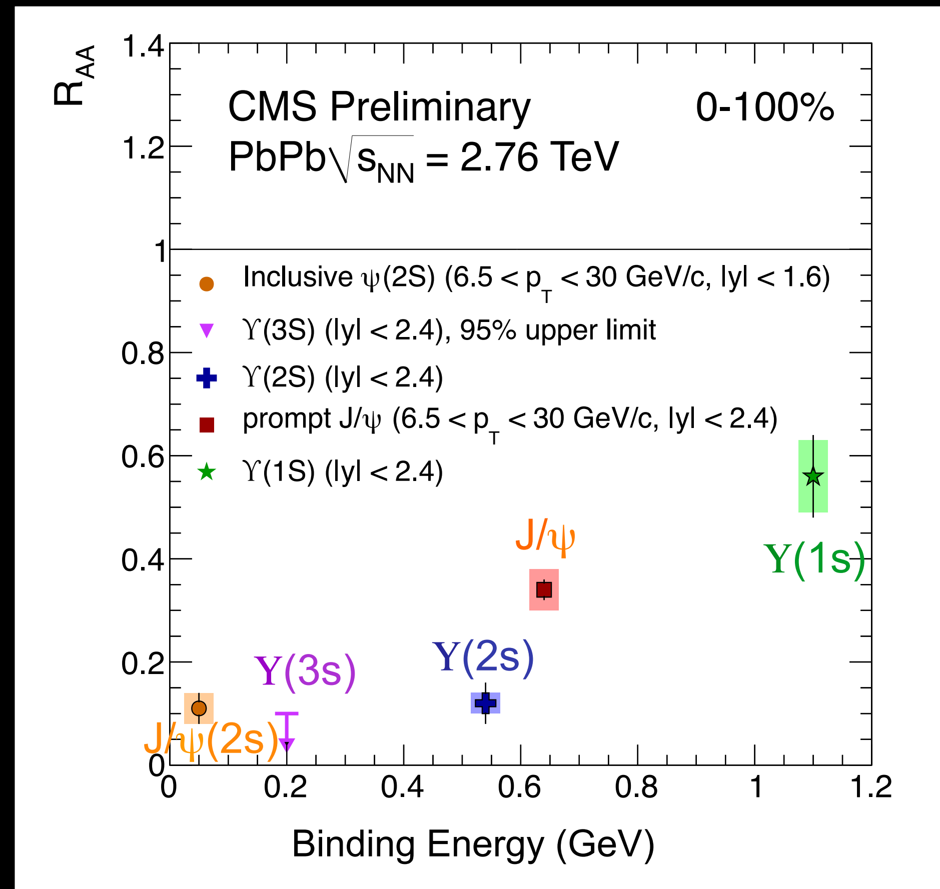
QM 2014

J/Ψ and Υ Suppressed at the LHC
(also at RHIC)

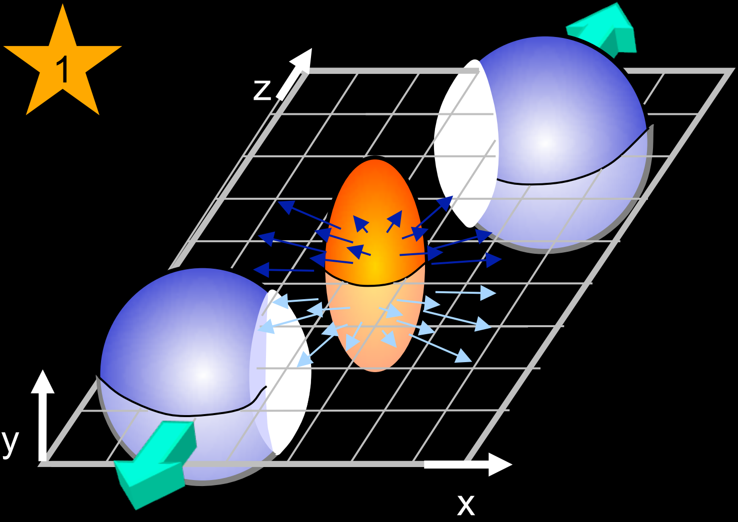
CMS-PAS HIN-11-011



CMS, PRL 107 (2011) 052302



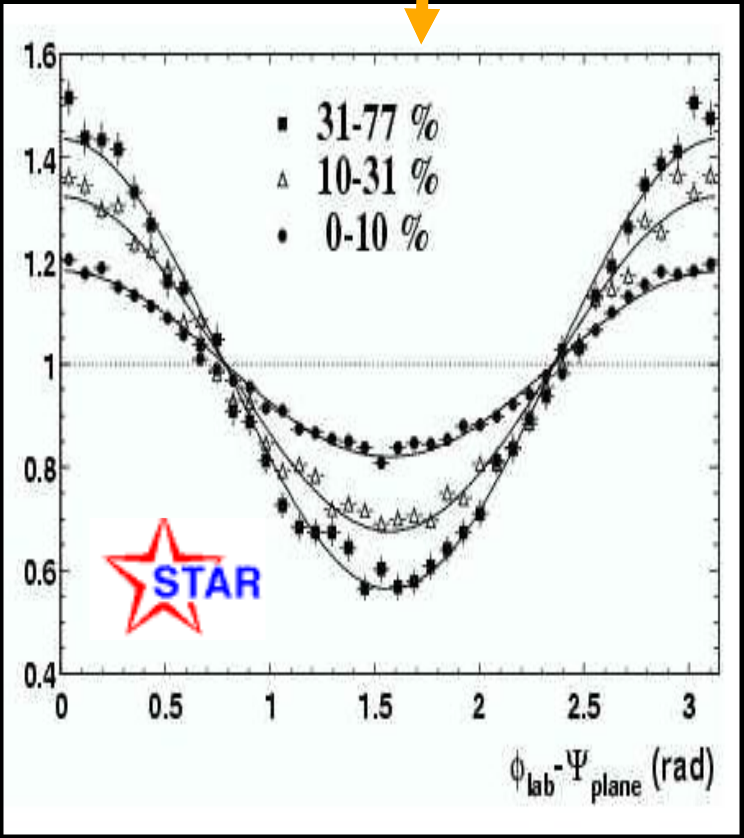
Suppression of Quarkonium States expected in a hot QCD Medium!

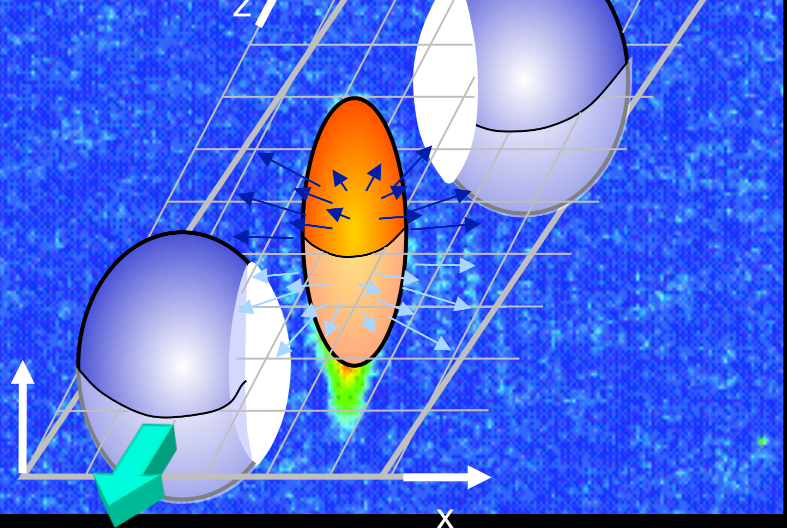


Elliptic Flow Saturates Hydrodynamic Limit

- **Azimuthal asymmetry of charged particles:**

  $dn/d\phi \sim 1 + 2\ v_2(p_T)\ \cos(2\ \phi) + \ldots$





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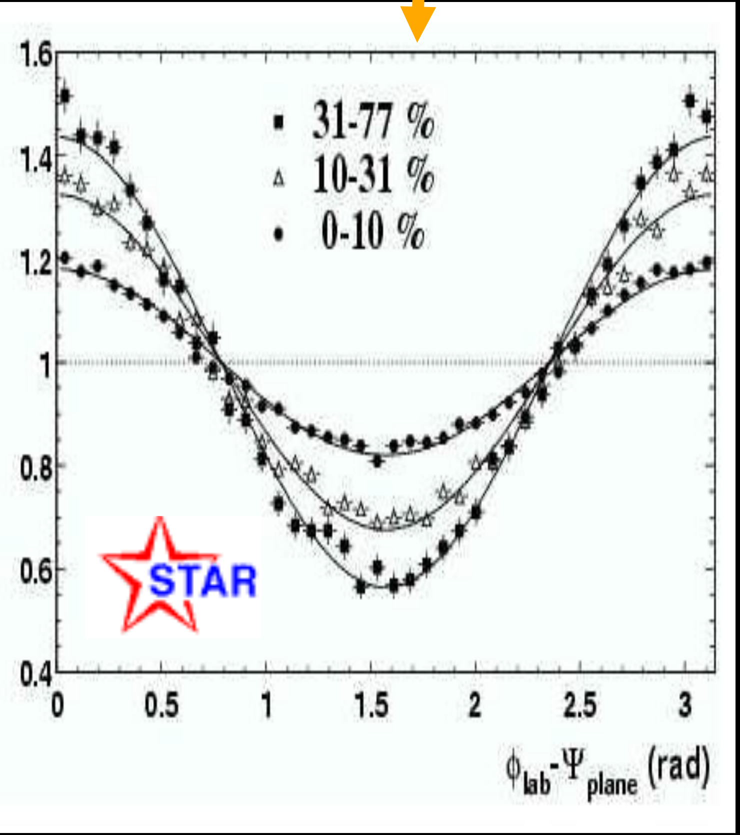

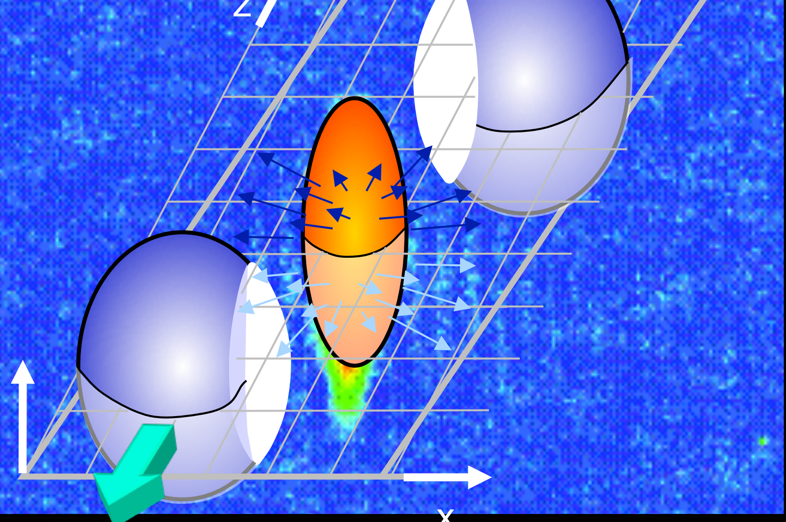

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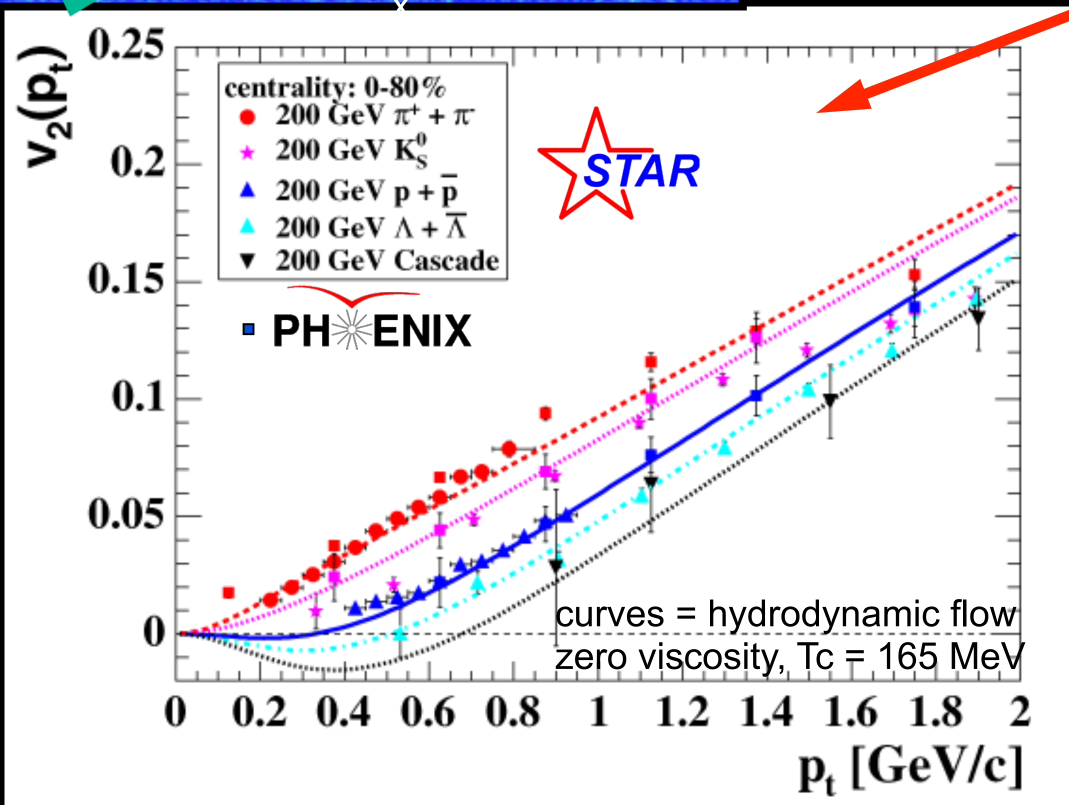

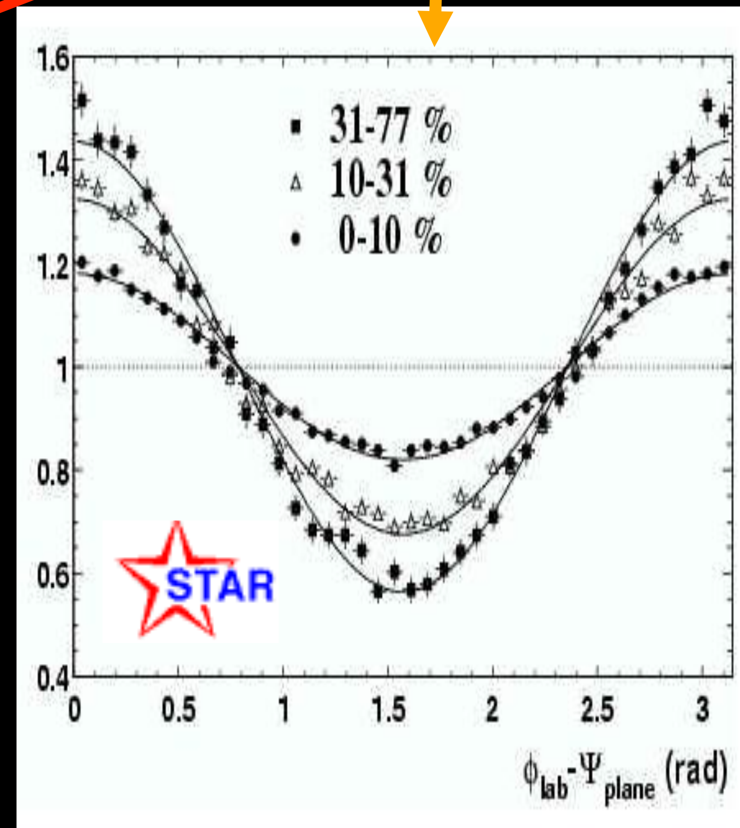

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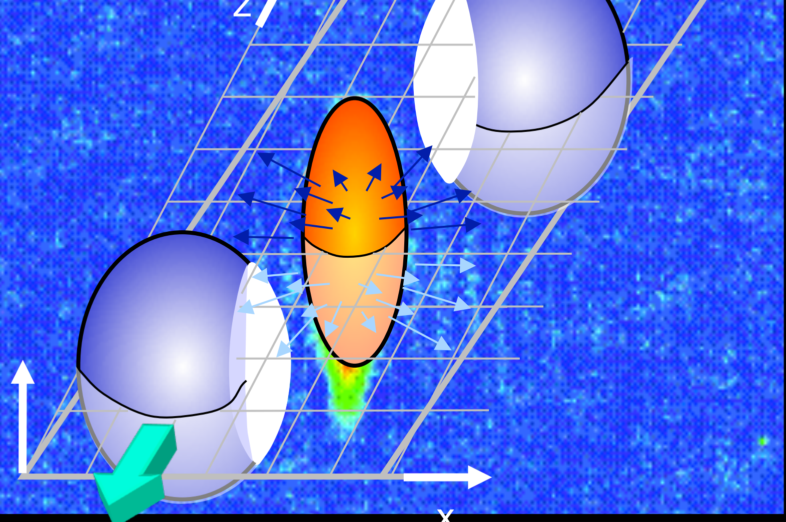
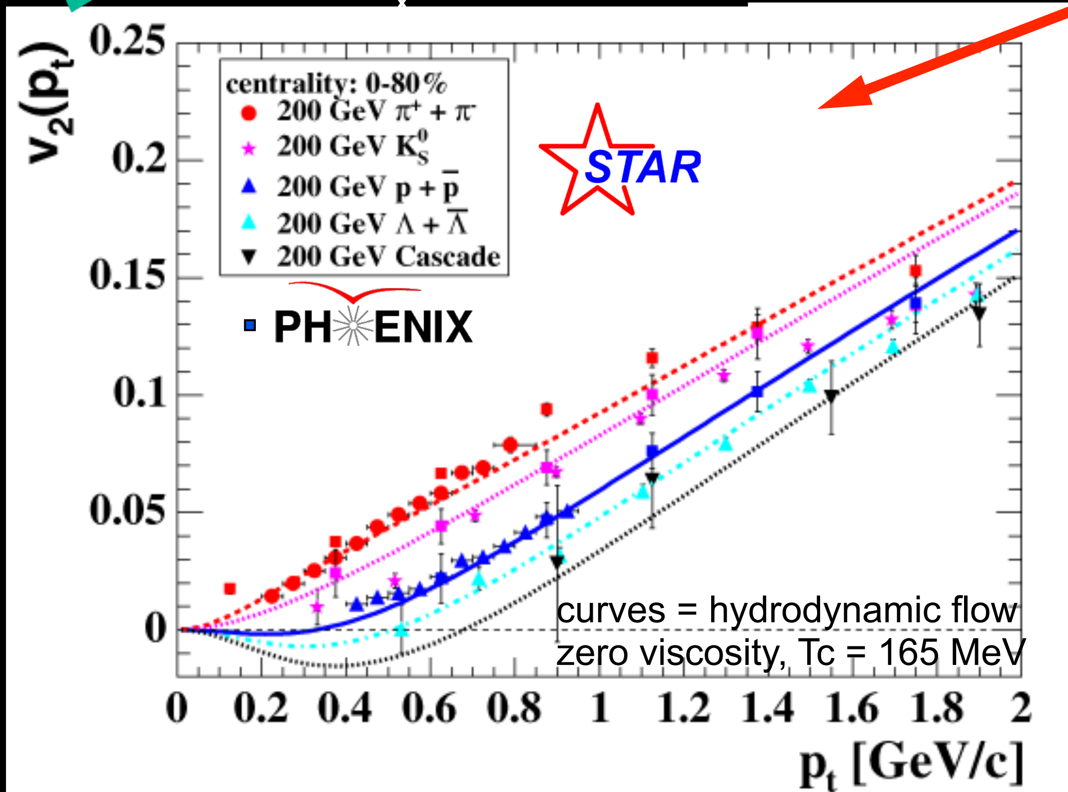


Azimuthal asymmetry of charged particles:

$$dn/d\phi \sim 1 + 2\, v_2(p_T)\, \cos(2\phi) + \ldots$$

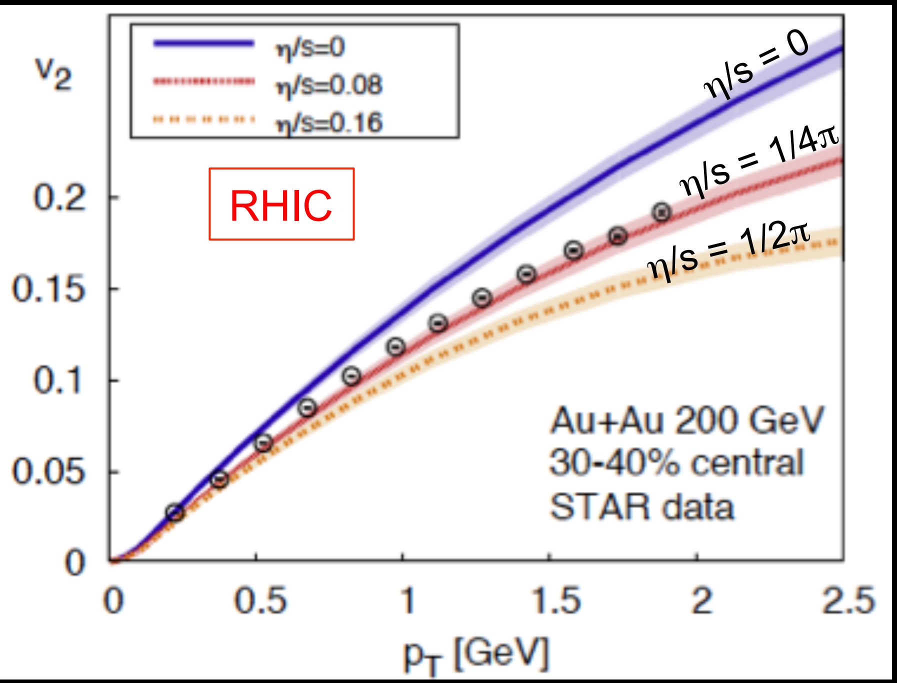


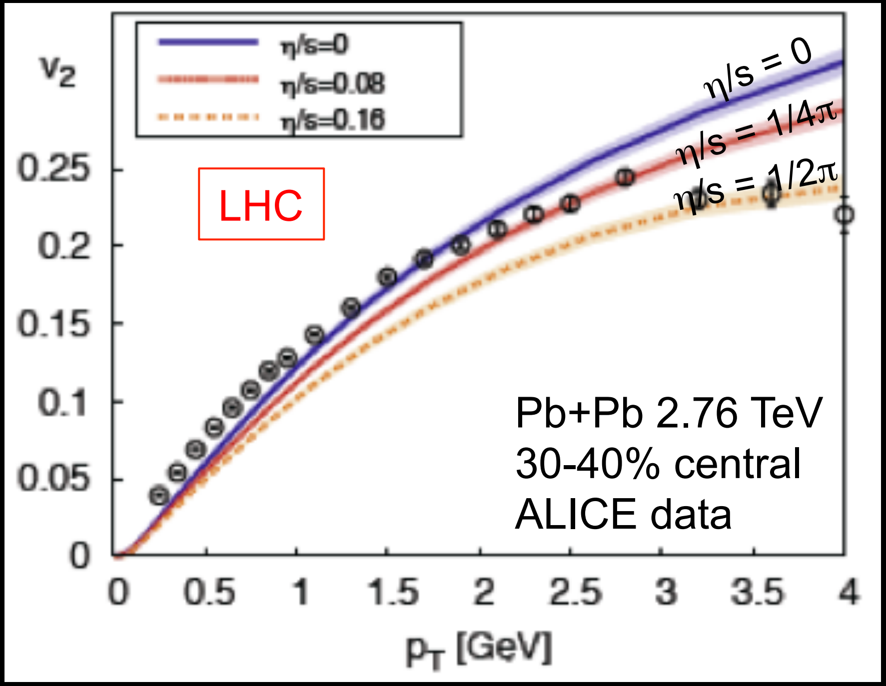
Mass dependence of v_2

Requires -

- **Early thermalization (0.6 fm/c)**
- **Near-ideal hydrodynamics (near-zero viscosity)**
  → **"nearly perfect liquid"**
- **$\varepsilon \sim 25$ GeV/fm^3 ($>> \varepsilon_{critical}$)**
- **Quark-Gluon Equ. of State**

Flow Consequences → a Strongly-Coupled Medium with Ultra-low η/s (shear viscosity / entropy)





Viscous hydrodynamics calculations: Schenke, et al. PRL 106 (2011) 042301

→ $1/4\pi < \eta/s < 1/2\pi$

The strong-coupling limit of non-Abelian gauge theories with a gravity dual (ref: Kovtun, Son, Starinets, PRL 94, 111601 (2005))

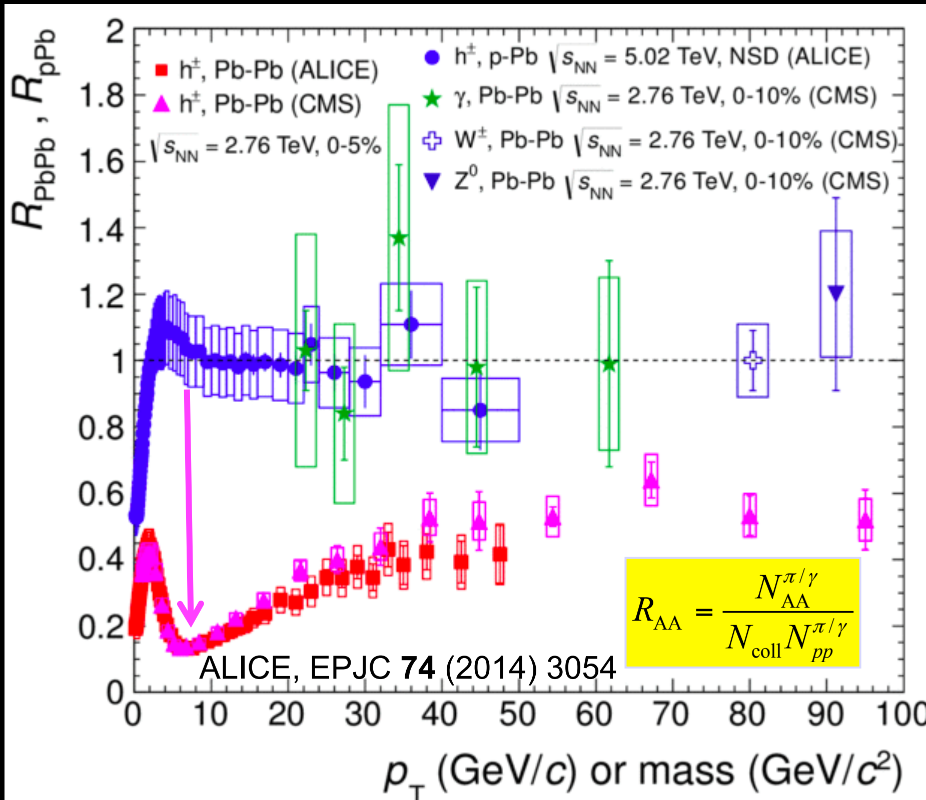
Universal lower bound on shear viscosity / entropy ratio (η/s)

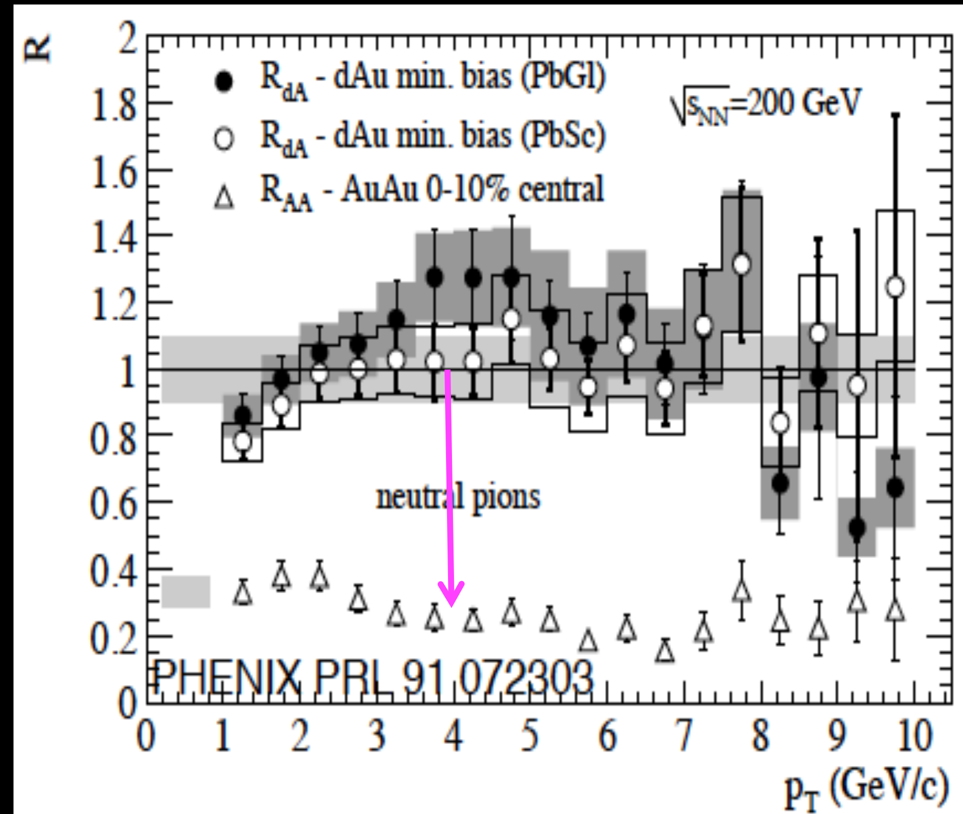
→ $\eta/s = 1/4\pi$ for a "perfect liquid"

II. Effects in p(d) + A compared to A + A

High p_T Particles & Jets

High p_T Hadrons $R_{p(d)A}$ & R_{AA} at LHC and RHIC





LHC p-Pb & RHIC d-Au (p_T > 2 GeV/c)

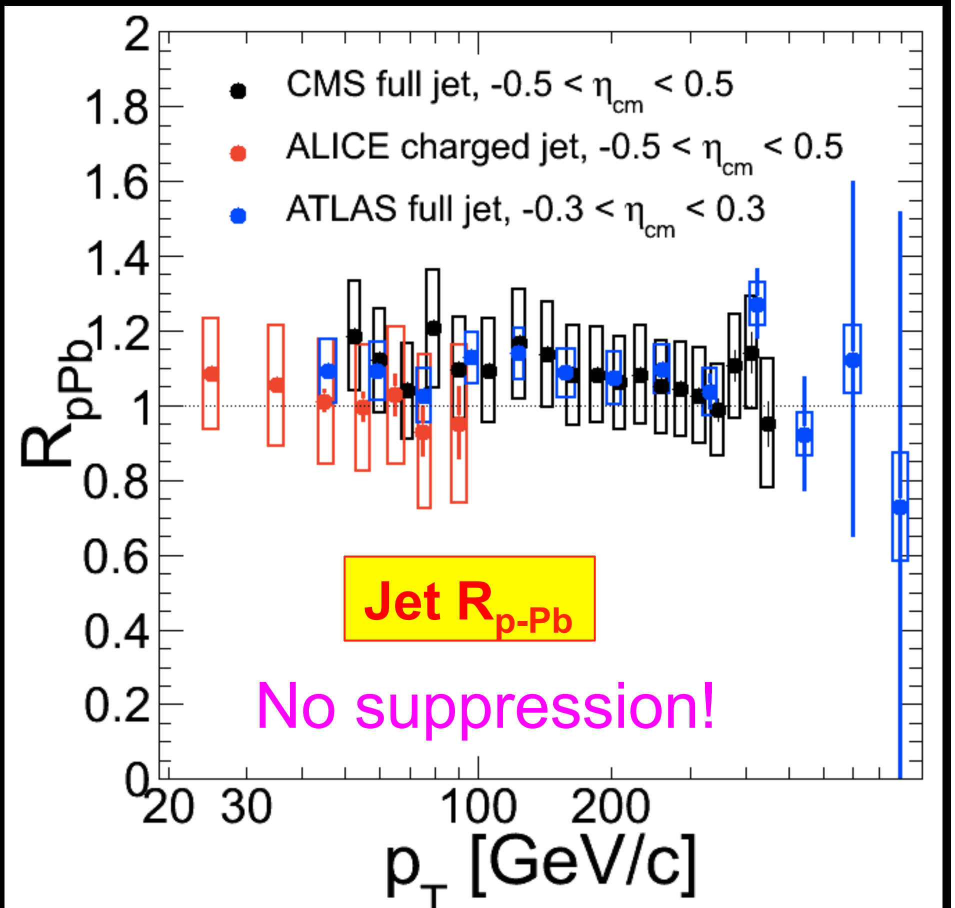
- Binary scaling (R_{dAu} ~ R_{pPb} ~ 1), except "bump" at ~ 4 GeV/c
- Absence of Nuclear Modification → Initial state effects small

RHIC Au-Au and LHC Pb-Pb

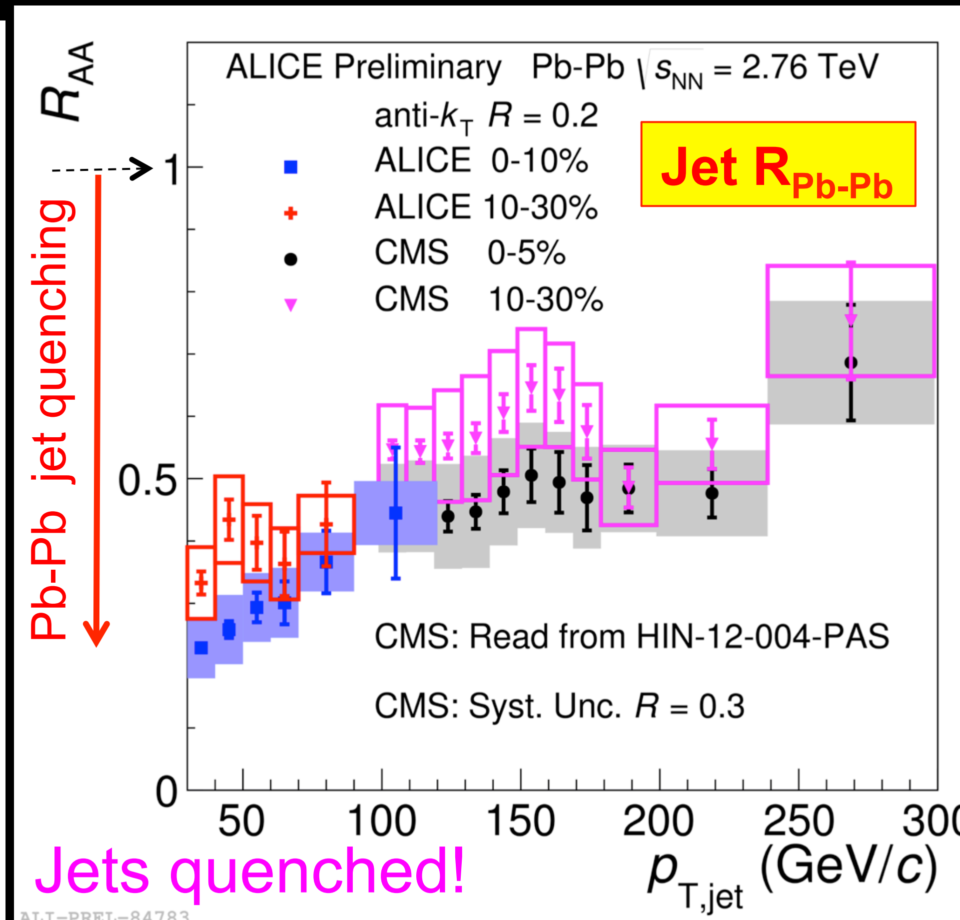
- Suppression (R_{PbPb} << 1, R_{AuAu} << 1) → Final state effects (hot QCD matter)

Jets in p-Pb & Pb-Pb at LHC

QM2014: ALICE ATLAS CMS (black)



ALICE QM 2014

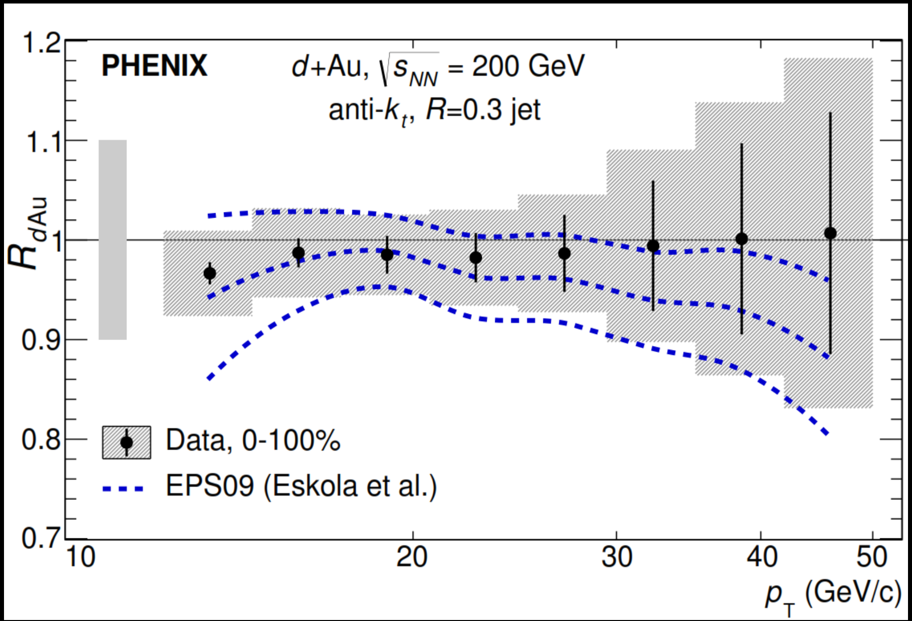


ALICE ≈ ATLAS ≈ CMS: $R_{p\text{-}Pb}$ (jet) ≈ 1
Binary scaling, no initial state effects!

ALICE ≈ ATLAS ≈ CMS: $R_{Pb\text{-}Pb}$ (jet)<<1
Jets quenched in Pb-Pb collisions

Jets in d-Au at RHIC

PHENIX arXiv:1509.04657v2



Jets reconstructed in p+p and d+Au

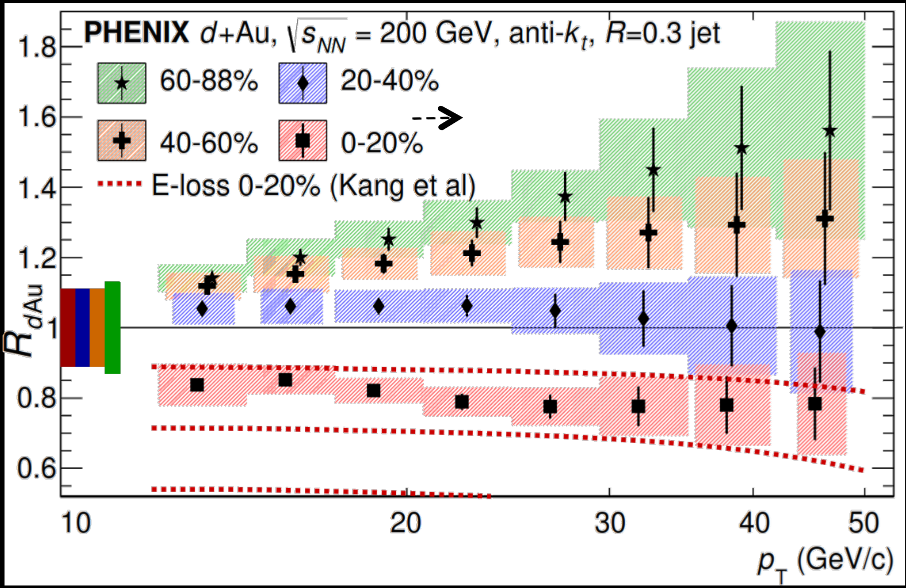
$12 < p_T < 50$ GeV/c

R_{dAu} ~ 1 for min.bias d+Au

R_{dAu} exhibits strong centrality dependence

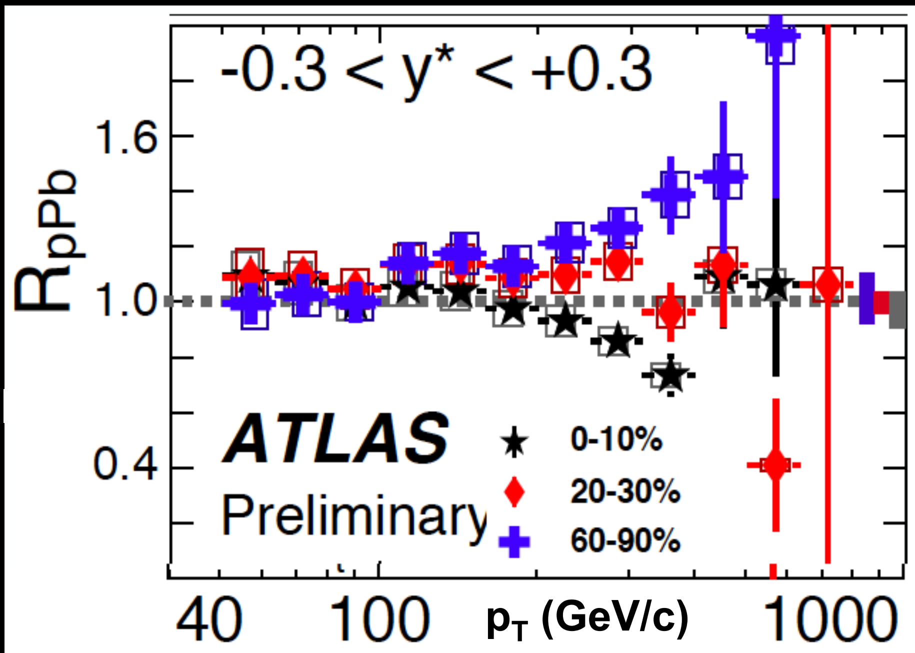
Peripheral collisions: jets enhanced

Central collisions: jets suppressed



Centrality Dependence of Jets in p (d) + A

ATLAS, PLB 748 (2015) 392



R_{pPb} jets → strong centrality dependence

Peripheral collisions: jets enhanced

Central collisions: jets suppressed

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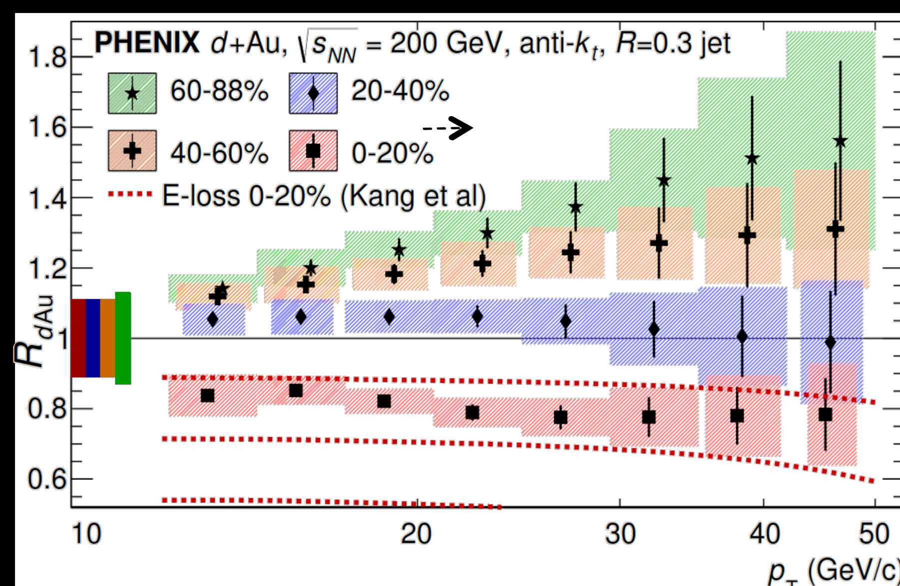


R_{dAu} jets → strong centrality dependence

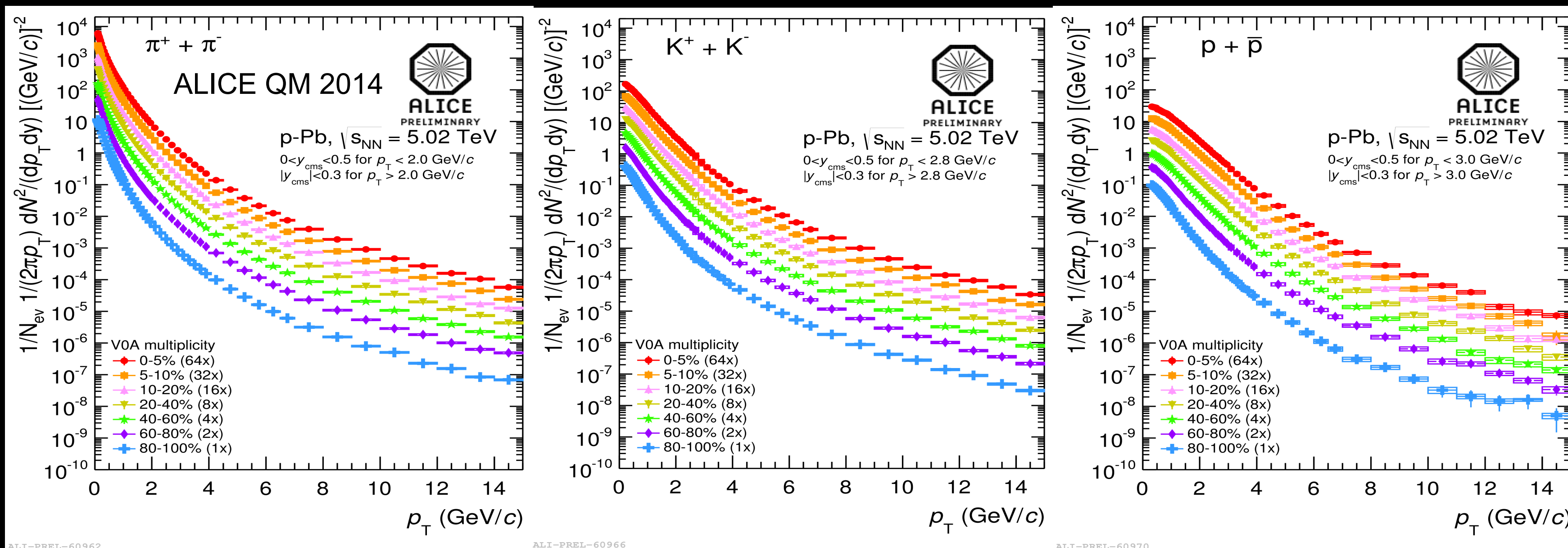
Peripheral collisions: jets enhanced

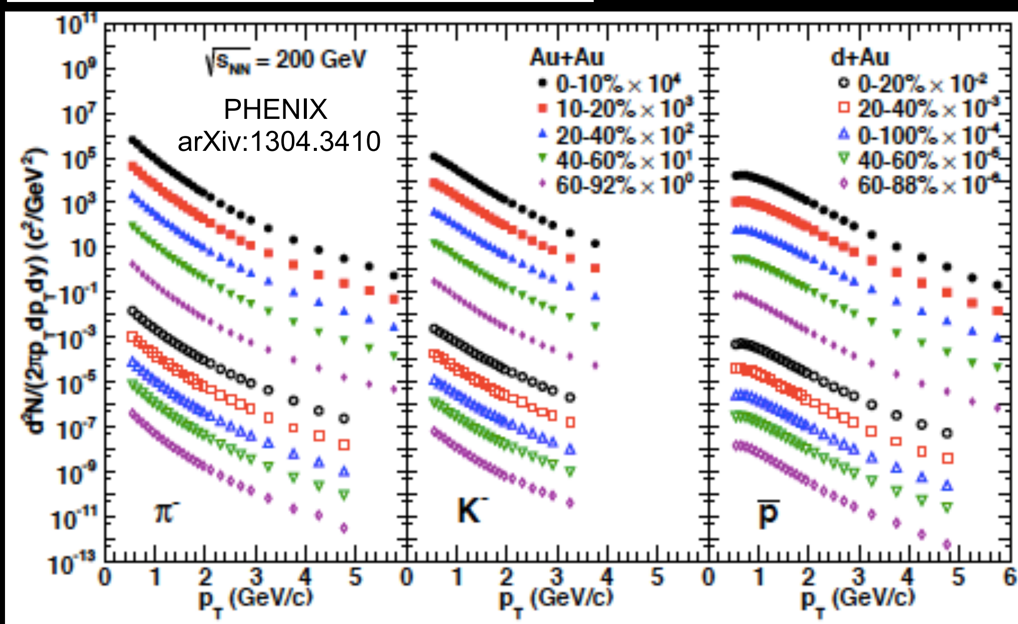
Central collisions: jets suppressed

Challenge to factorization in hard-scattering?

Identified Particles

Identified Particle Spectra in p-Pb





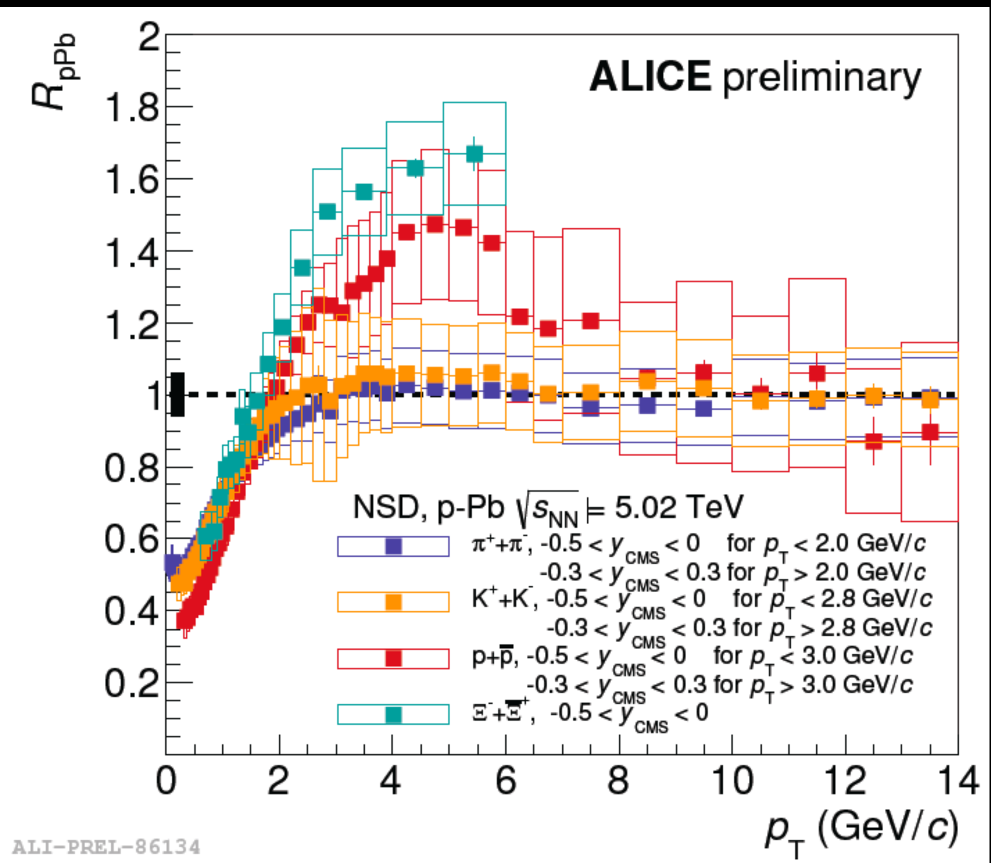
Hardening with multiplicity and particle mass indicative of collective effects in A-A!

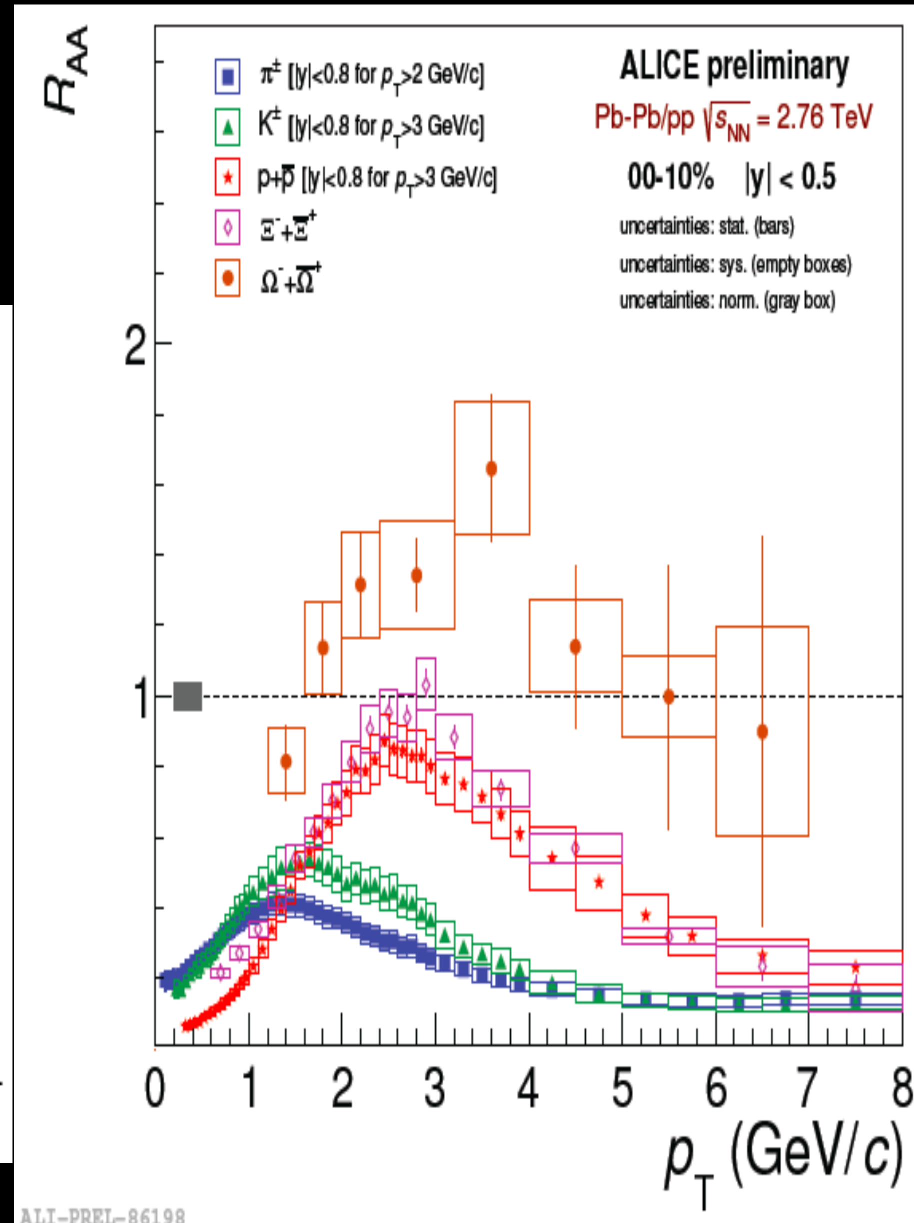
Similar to effects observed in A-A → has been attributed to radial flow

R_{pPb} for Identified Hadrons

Suppression in Pb-Pb

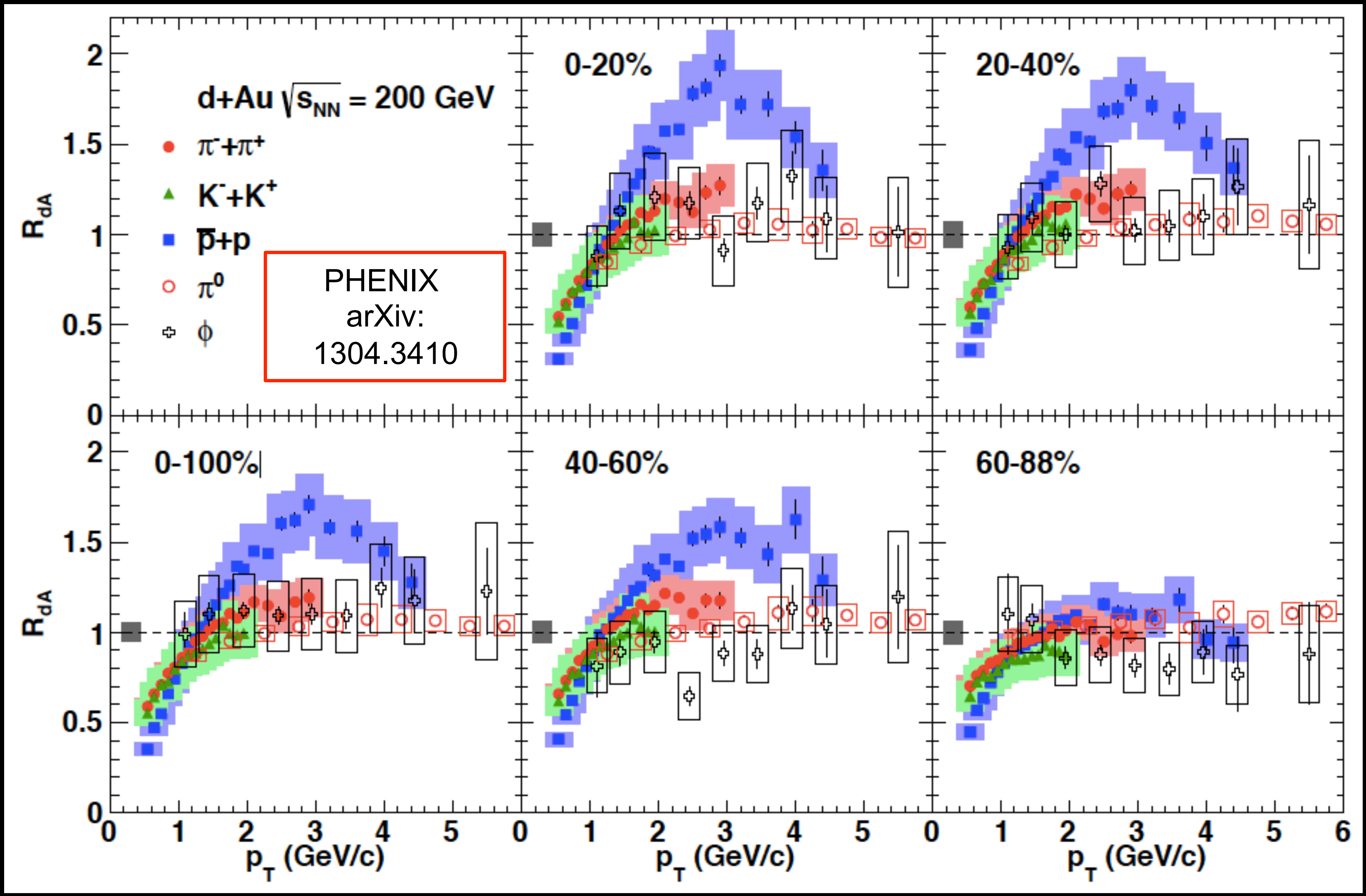
R_{pPb} mass dependence
→ Protons peak at intermediate p_T
→ π and K flat over measured p_T range





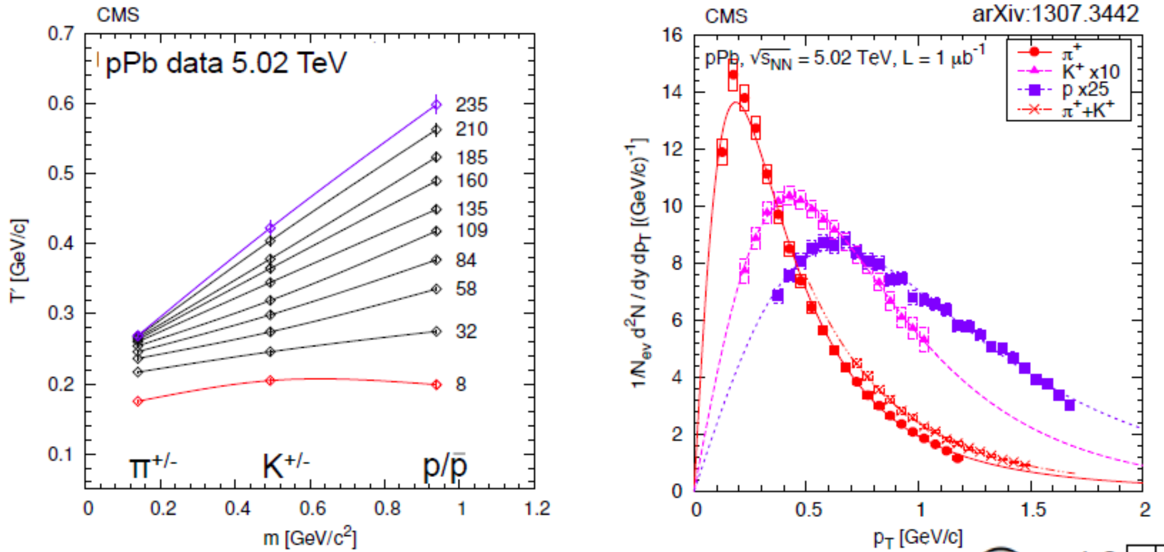
pp reference interpolated from 2.76 and 7.0 TeV

Similar Effects at RHIC in d+Au



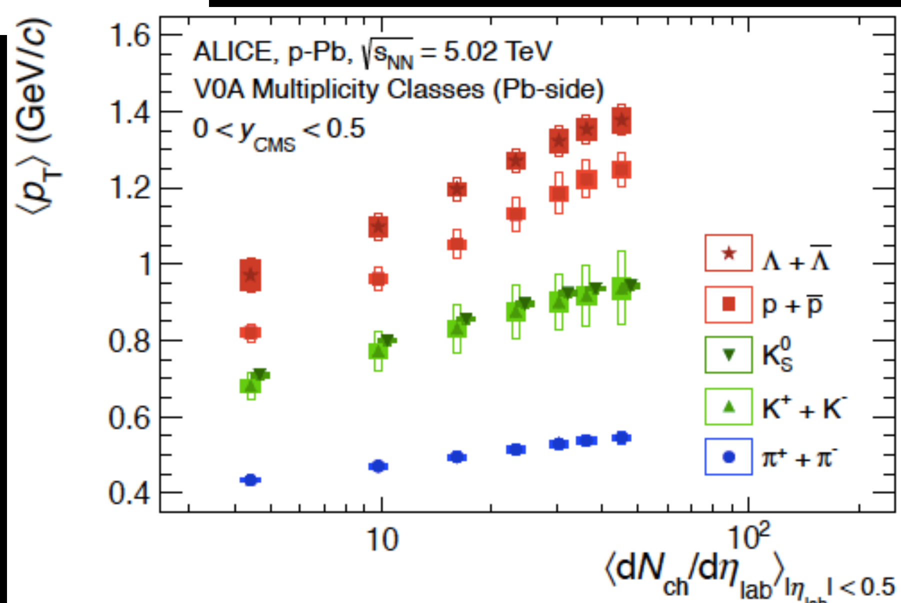
Indications of Collective Flow of Identified Particles in p-Pb

Inverse slope of m_T distributions, T_{slope}: $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp(-\frac{m_T}{T_{slope}})$



Identified π, K, p

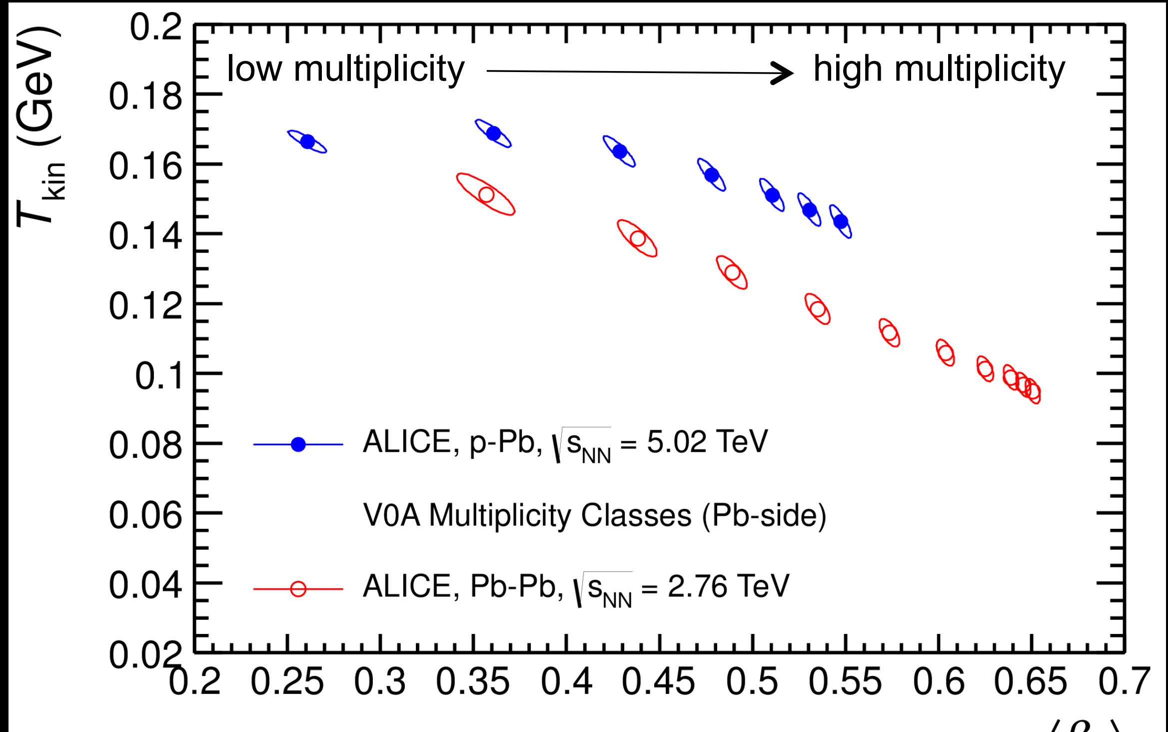
Strong mass ordering in pPb



π, K, p – Blast Wave pPb & PbPb

Blast wave model
(Schnedermann, PRC 48 (1993) 2462)

Hydro-inspired
- Particle source at T
- Radial flow β
  - $\beta(r) = \beta_s (r/R)^n$
- Fit particle spectra simultaneously
  - $\langle\beta_T\rangle$ from $2\beta_s / (2+n)$
  - T_{kin}
  - n



ALICE, PLB 728 (2014) 25

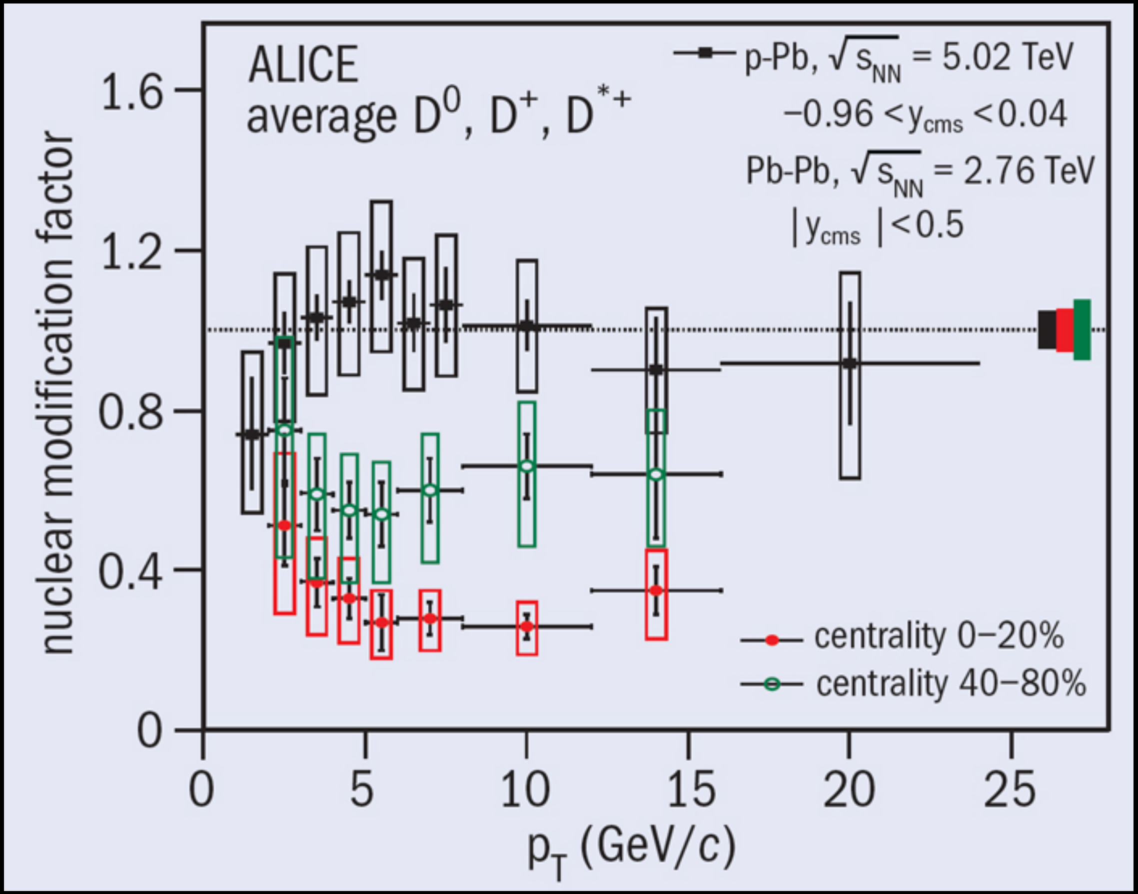
Similar trends → indicative of radial flow in p-Pb and Pb-Pb
- T_{kin} similar in Pb-Pb and p-Pb for same multiplicities
- $\langle\beta_T\rangle$ larger in p-Pb for similar multiplicities

→ stronger collective flow for smaller system size…?

See Shuryak, arXiv:1301.4470 [hep-ph]

Heavy Flavor – D-Mesons: R_{pPb} & R_{PbPb}

ALICE Collaboration, *Phys. Rev. Lett.* **113** (2014) 232301



D-meson NOT suppressed in p-Pb
R_{pPb} consistent with ≈1
Initial state effects small!

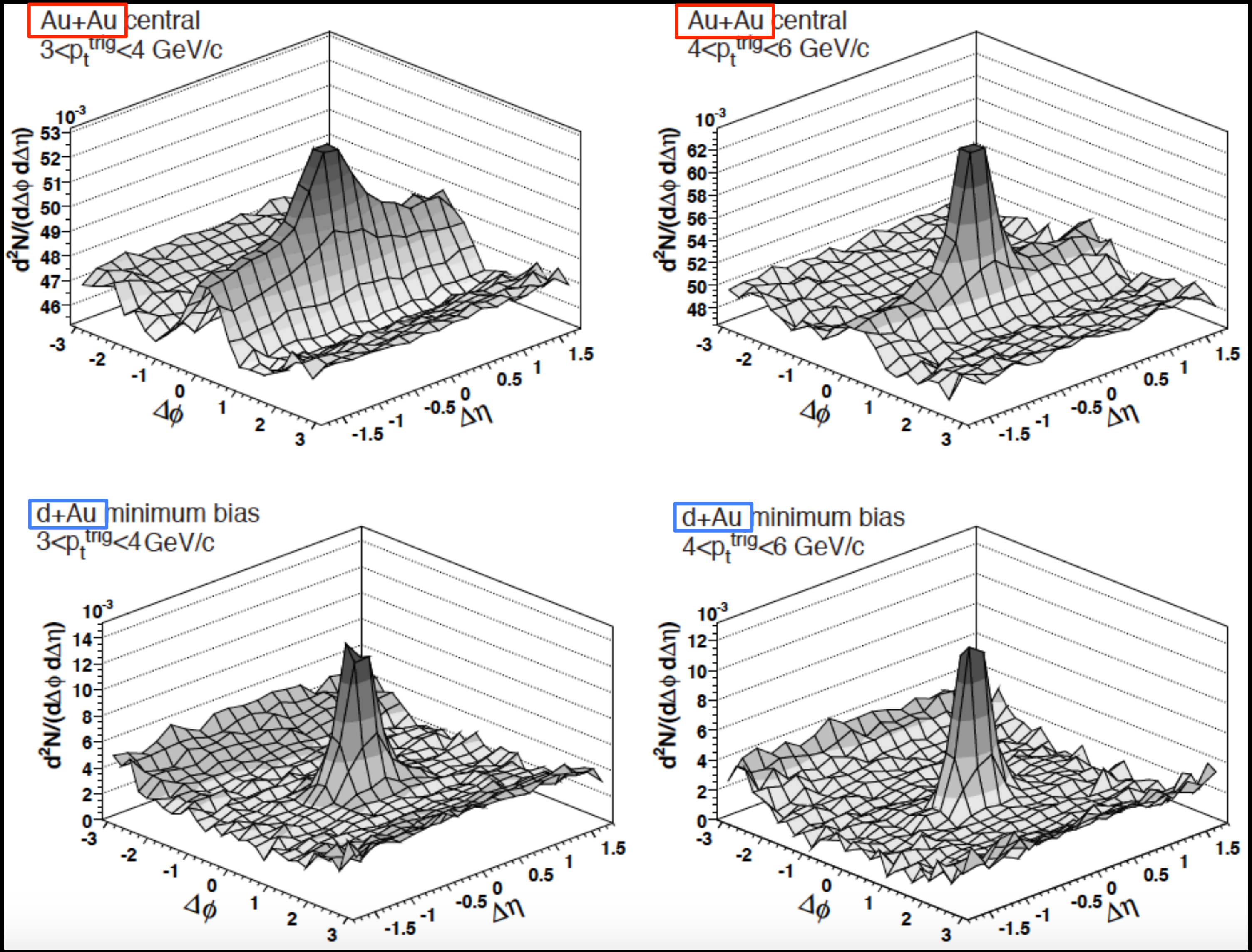
D-meson central R_{PbPb} suppressed!
Centrality dependence
Not initial state effect!

Particle Correlations:

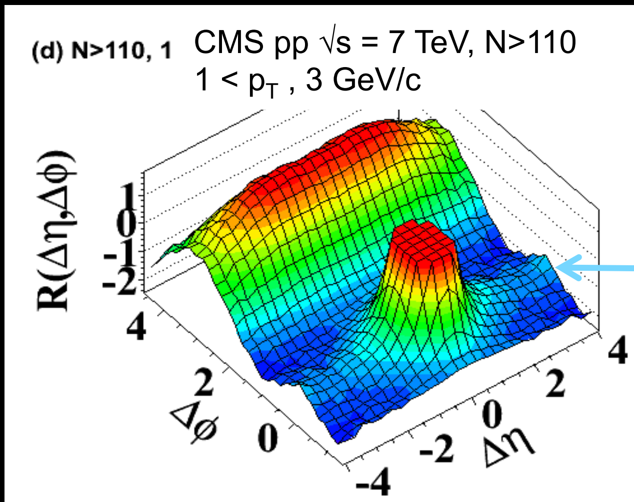
Flow Harmonics of Lighter Systems

Initial (Historical) STAR Discovery of the AA Ridge

Phys. Rev. C 80 (2009) 64912



Long-range Di-hadron Correlations in pp, p-A

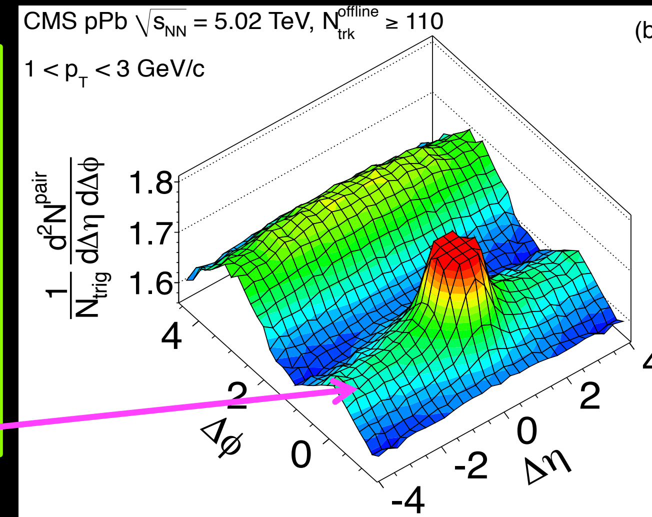


CMS, JHEP 09 (2010) 091

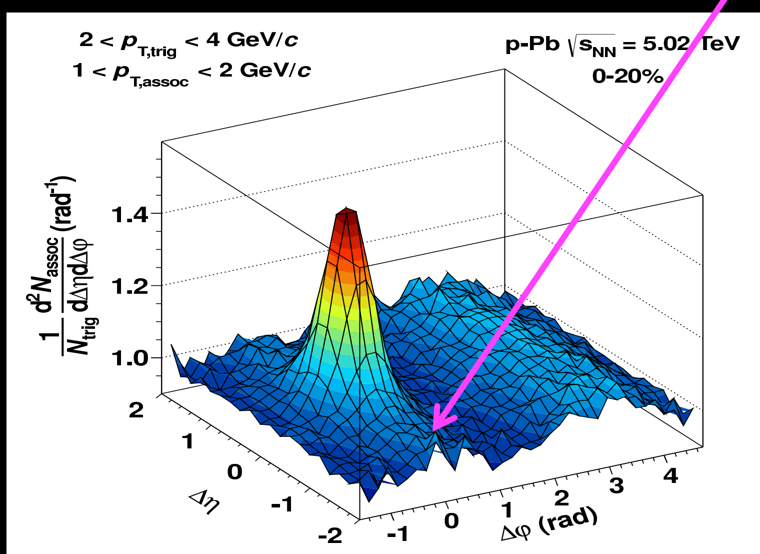
LHC near-side ridge for $\sqrt{s_{NN}}$ =

7 TeV pp

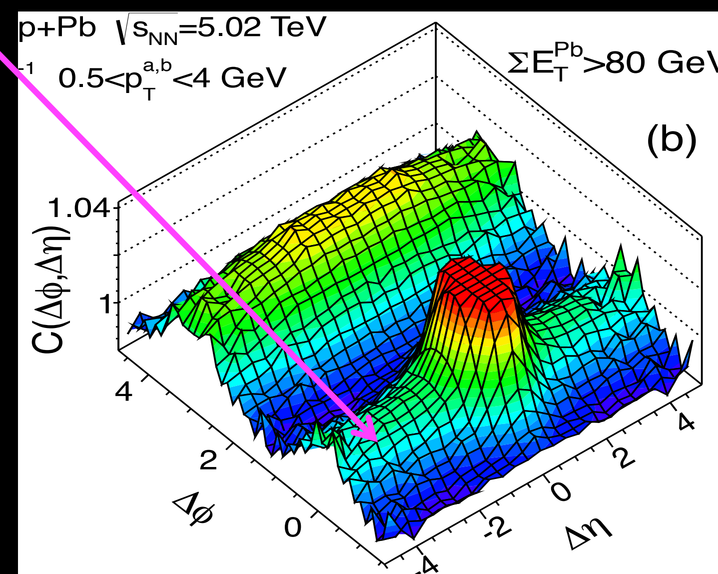
5.02 TeV p-Pb



CMS, PLB 718 (2013) 795



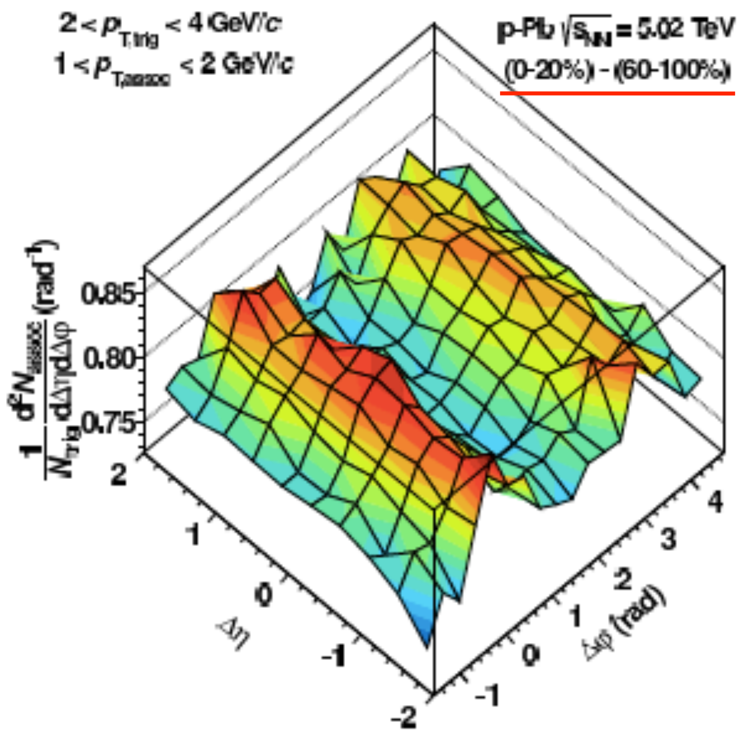
ALICE, PLB 719 (2013) 29



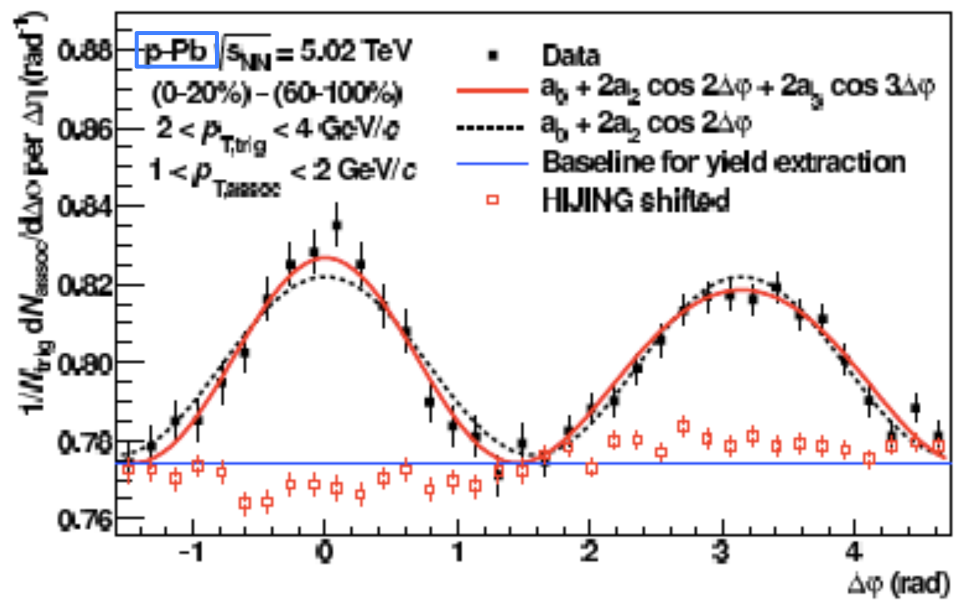
ATLAS, Phys. Rev. Lett. 110, 182302 (2013)

Potential interpretations include CGC, long-range color correlations……, hydro??

Observation of p-Pb Double Ridge



ALICE, Phys. Lett. B 719 (2013) 29

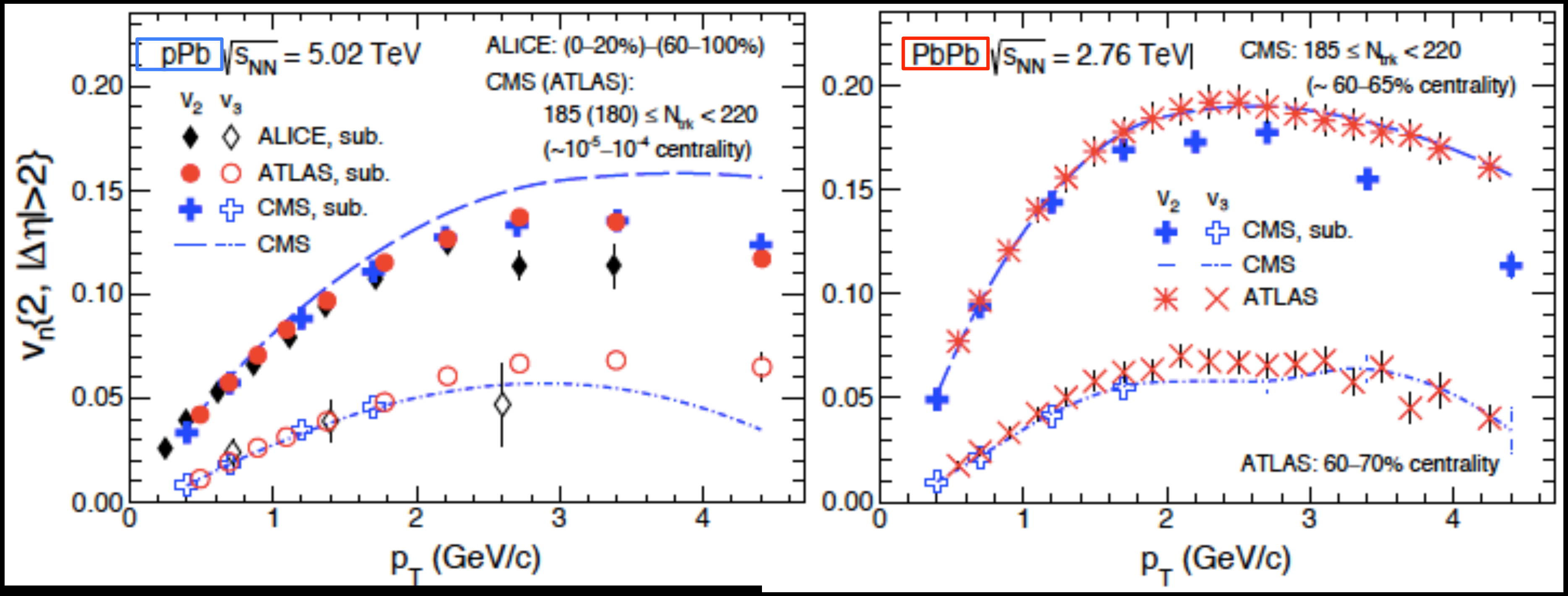


After subtraction of low multiplicity from high multiplicity events:
Fourier decomposition seen as curves

ALICE, arXiv:1307.3237

Comparing v_2 and v_3 from Long-range Correlations

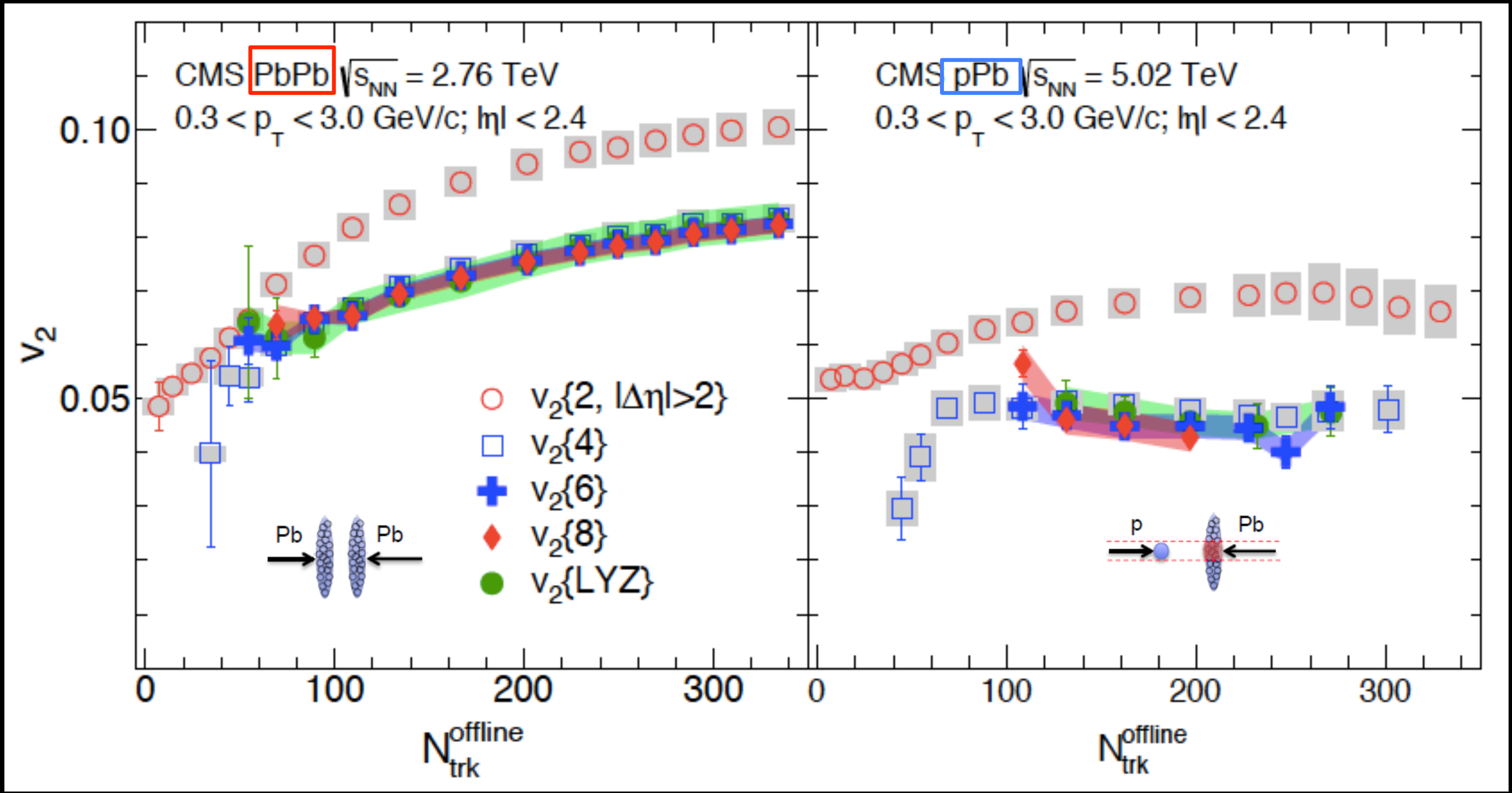
$V_n\{2, |\Delta\eta|>2\}$ data
from ALICE arXiv:1212.2001, CMS arXiv:1305.0609,
ATLAS arXiv:1409.1792 & arXiv:1203.3087.



Symbols are (back-to-back jet) subtracted data.
Curves are before subtraction.
Notice v_2 trends and v_3 almost identical (p-Pb and Pb-Pb)

Collective Flow $v_2(n)$ in Pb-Pb & p-Pb

CMS, Phys. Rev. Lett. 115 (2015) 012301arXiv:1502.05382

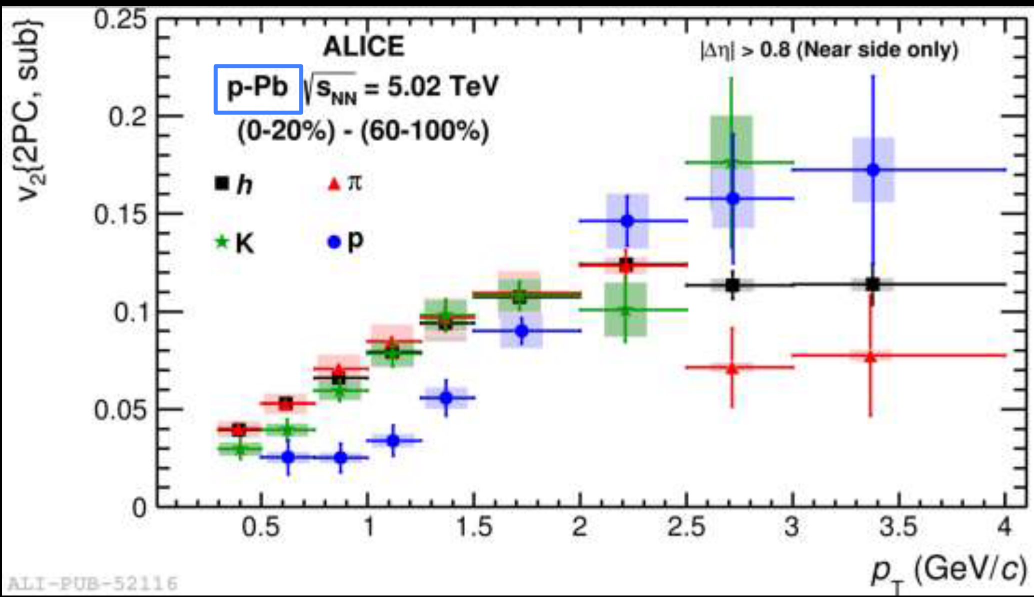


For PbPb and pPb – Collective effects!

v_2 (n) remains large when using more (n) particles

v_2 (4) = v_2 (6) = v_2 (8) = v_2 (LYZ) within 10%

Fourier Decomposition of p-Pb Double Ridge



After subtraction Fourier coefficient v_2 (2PC, sub)

Observe ordering in mass!

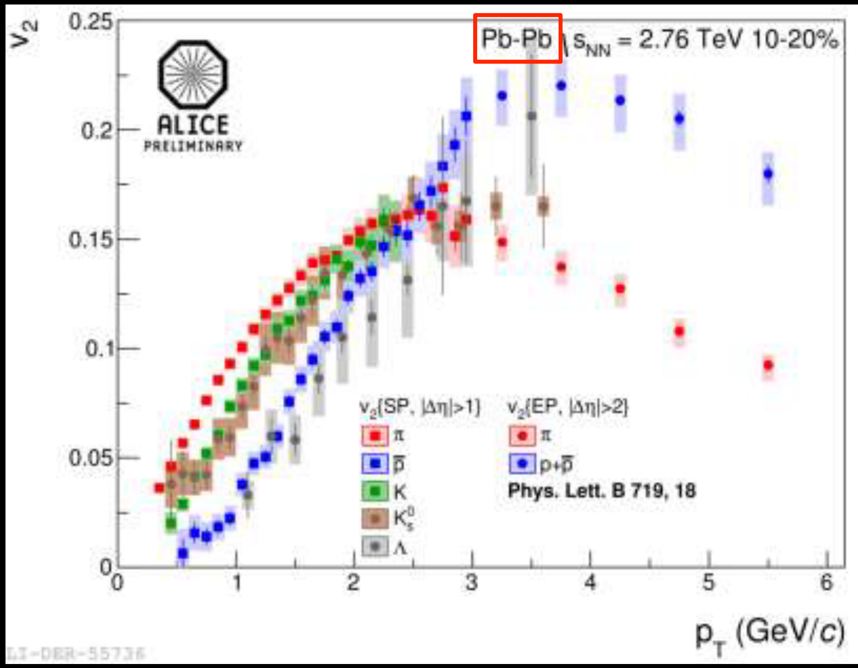
p-Pb ordering similar to Pb-Pb

v_2 (2PC, sub) mass hierarchy

~ described by

Hydro with Glauber initial conditions

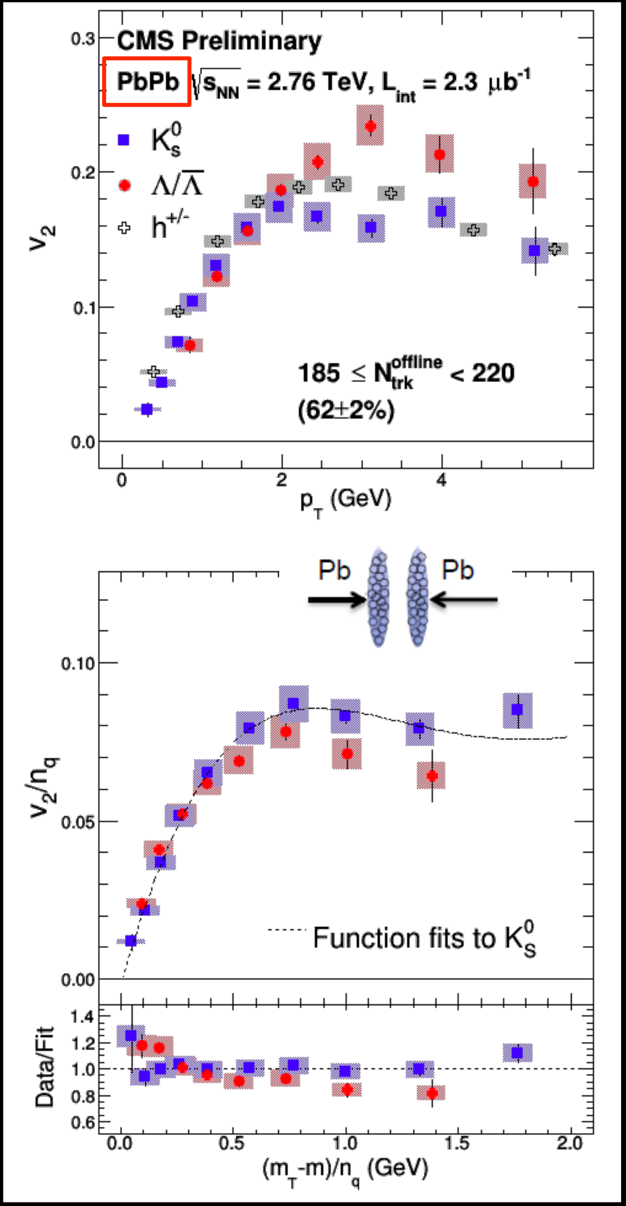
ref: Bozek, Broniowski, Torrieri, arXiv:1307.5060

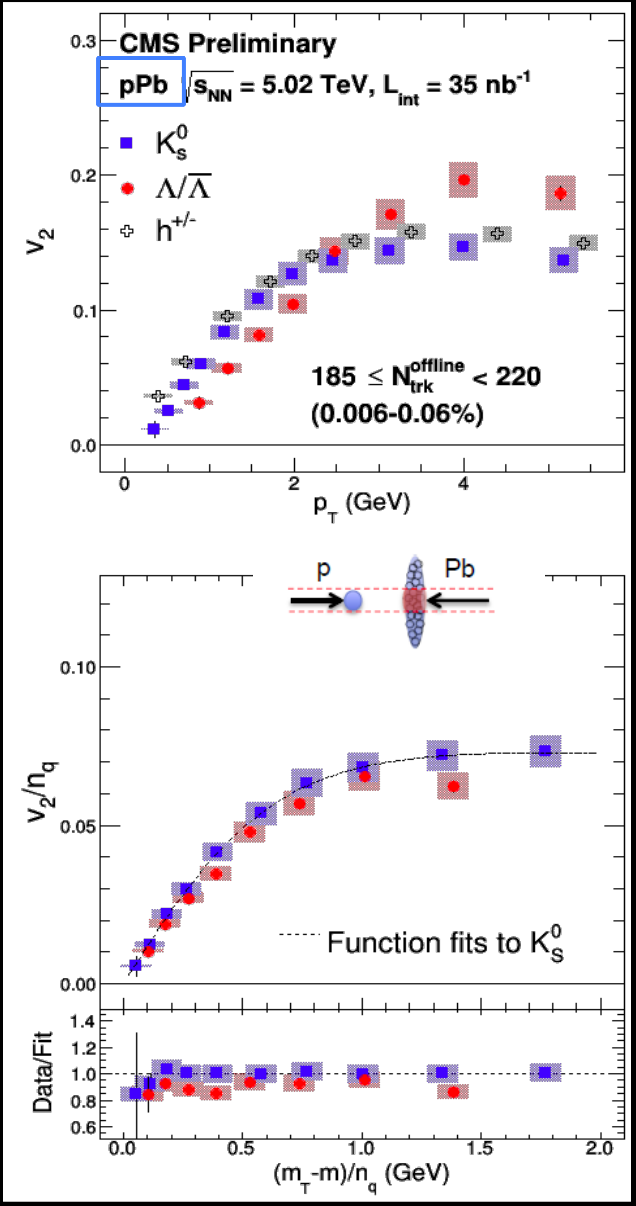


ALICE, arXiv:1307.3237

Collective Flow of Identified Particles in p-Pb!

CMS, arxiv:1409.3392





Identified Ks , Λ & charged hadrons

v_2 from 2-particle correlations

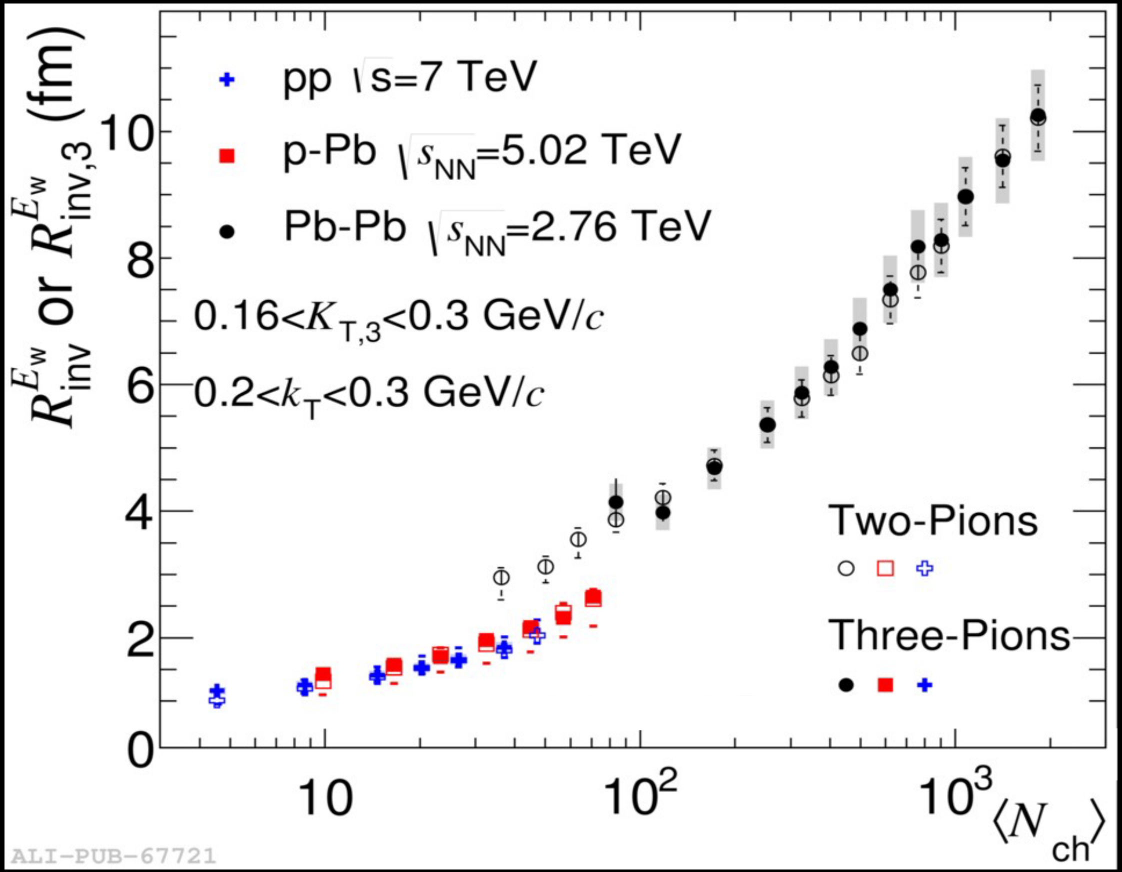
Exhibit mass ordering in pPb and PbPb

NCQ scaling better in pPb

Particle Correlations:

System Size from Freeze-out Radii

System Size in pp, p-Pb and Pb-Pb



ALICE, PLB 739 (2014) 139

Invariant radii vs <N_{ch}>

– pp similar to pPb

– pPb smaller than PbPb

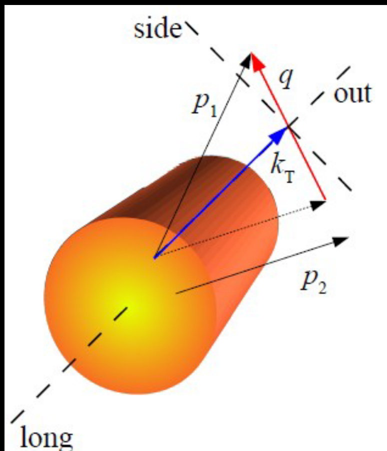
Invariant Source Radii from HBT fits of 2 & 3 Pion Correlation Measurements:

R_{inv} (p-Pb) ~ 1.05-1.15 R_{inv} (pp)

R_{inv} (Pb-Pb) ~ 1.35-1.55 R_{inv} (p-Pb)

Perhaps only small hydrodynamic expansion in pPb beyond that in pp at same Nch

Evolution of p-Pb System



3d radii (Rout, Rside, Rlong)

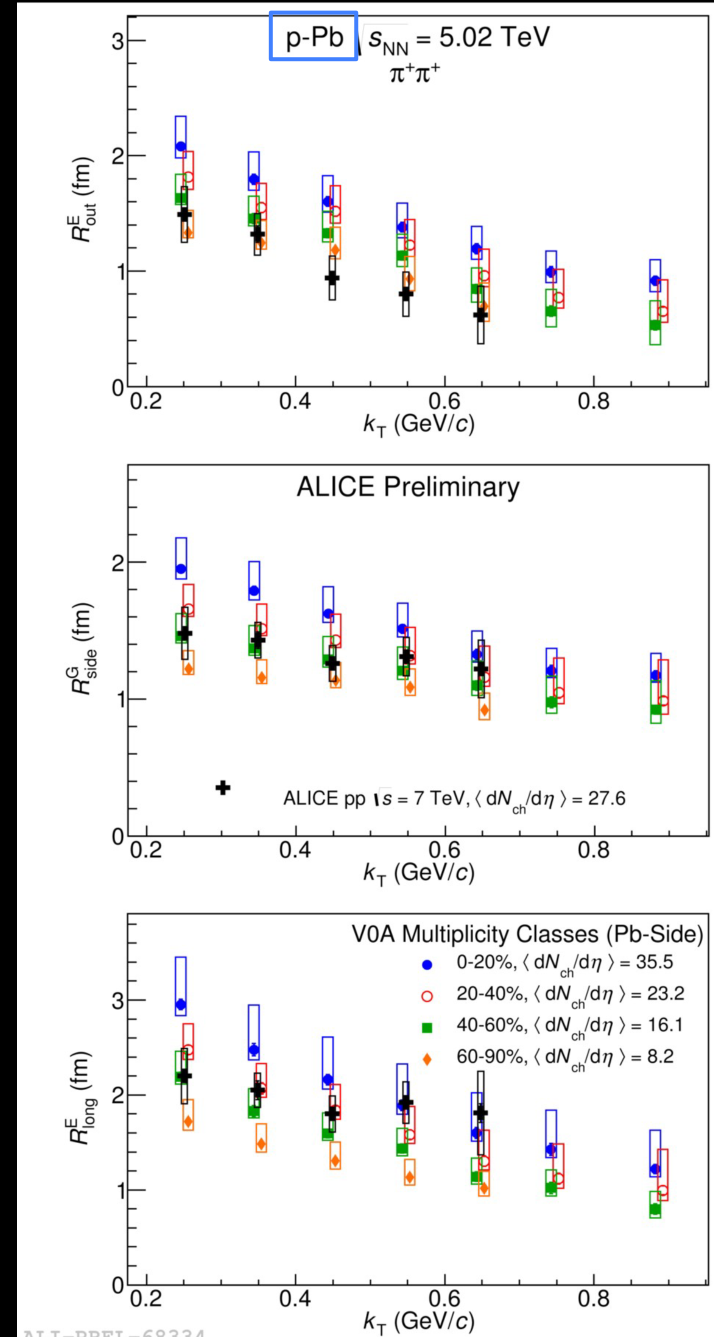
in LCMS

from two-pion correlations

Radii decrease with increasing k_T

as in AA (and in hydro)

Similarity between pPb and high multiplicity pp



ALICE, PLB 739 (2014) 139

What are the Freezeout Radii Telling Us?

ALICE, Physics Letters B739 (2014) 139–151:

Invariant Source Radii from HBT 2 & 3 Pion Correlation Measurements

R_{inv} (p-Pb) ~ 1.05-1.15 R_{inv} (pp)

R_{inv} (Pb-Pb) ~ 1.35-1.55 R_{inv} (p-Pb)

- This disfavors models incorporating significantly larger flow in p-Pb than in pp at same multiplicity!
- Consistent with CGC initial conditions without a hydro-dynamical phase!
- See also (Shuryak interpretation)
  arxiv:1404.1888 – "collective implosion"

Demonstrates importance of initial conditions on the final-state – and/or – indicates significant collective expansion in peripheral Pb–Pb collisions.

What Have We Learned from p(d)A + A?

- p(d)+A studies confirm quenching/suppression in A+A is final state effect

- p(d)+A hard probes described by pQCD-inspired models

  Exceptions – High p_T hadrons (enhancement?)

  High p_T jets (peripheral enhanced? Central suppressed?)

- Many aspects of p(d)+A (at lower p_T) exhibit effects attributed to collective behavior – e.g. strong mass ordering, radial flow, $v_2(4) = v_2(6) = v_2(8)$

- Size of system much smaller in p(d)+A than in A+A

  p+A close to p+p at similar multiplicity – important to understand theoretically

- Need more theoretical guidance, direct model comparisons, more precise data!

A Final Comment

- We seek to investigate high density QCD phenomena in collisions of various (large and small) systems!
- Can we separate the initial state from the final state (even in theory) to compare p+p, p+A , A+A results and extract vital answers on:
  - → The initial state: CGC, Glauber, pdf's, etc?
  - → The effect of cold nuclear matter on final state observables?
  - → The basic parton energy loss mechanisms?
  - → The dependence on multiplicity and energy in p+p, p+A & A+A?
  - → The basic mechanisms of equilibration, transport and production?
- What are the key measurements to discriminate models or better yet theories?

We are investigating collective phenomena in a variety of nuclear systems to learn how the many-body system emerges from the fundamental interactions!

Thanks for your attention!