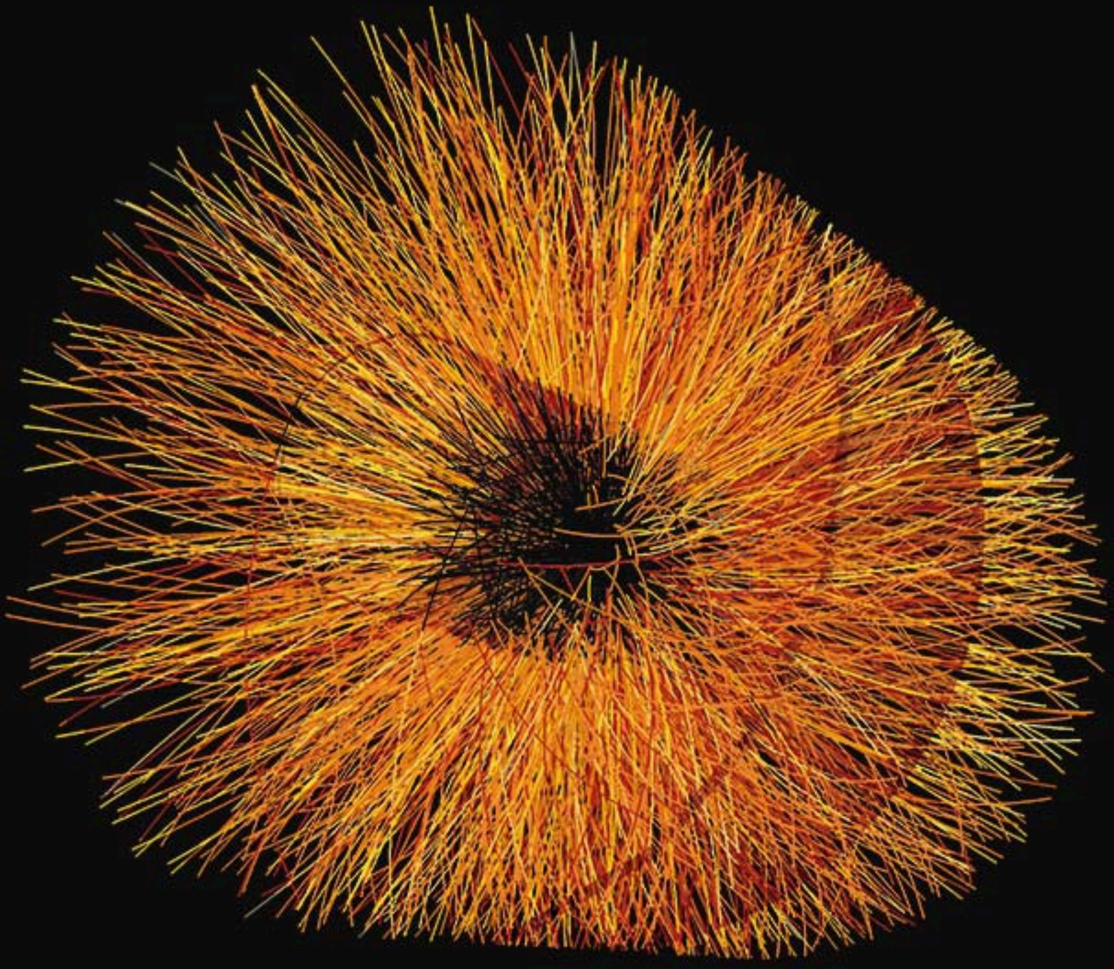
The Proton-Nucleus Enigma



The Proton-Nucleus Enigma

Collective effects are observed in collisions of large nuclear systems.

- Collective phenomena occur in many different & disparate systems.

  e.g.) Ultra-cold atomic systems to cosmological scales (galaxy formation)

→ These are associated with emergent phenomena of a complex many-body system where the basic interaction (e.g. two-body) may be understood!

- In simple everyday terms, for the field of relativistic heavy ion physics:

Can we determine the smallest QCD system that exhibits collective effects & has the properties of the quark-gluon liquid?

The Proton-Nucleus Enigma

Can we determine the smallest QCD system that exhibits collective effects & has the properties of the quark-gluon liquid?

- We seek to investigate high density QCD phenomena in collisions of small systems!
- Can we separate the initial state from the final state (even in theory) to compare pp, pA , AA 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 dependences on multiplicity and energy in pp, pA & AA?
  - → The basic mechanisms of equilibration, transport and production?

We thus investigate collective phenomena in nuclear systems to learn how the many-body system emerges from its fundamental interactions!

The Proton-Nucleus Enigma

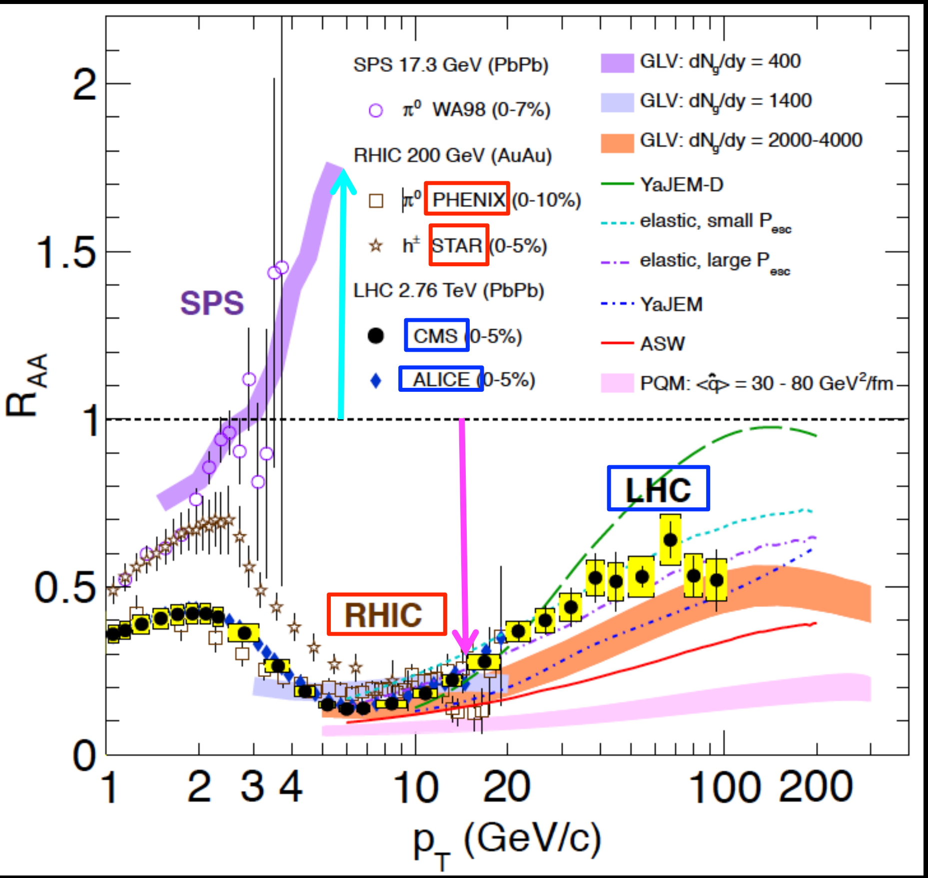
A Play in Four Acts

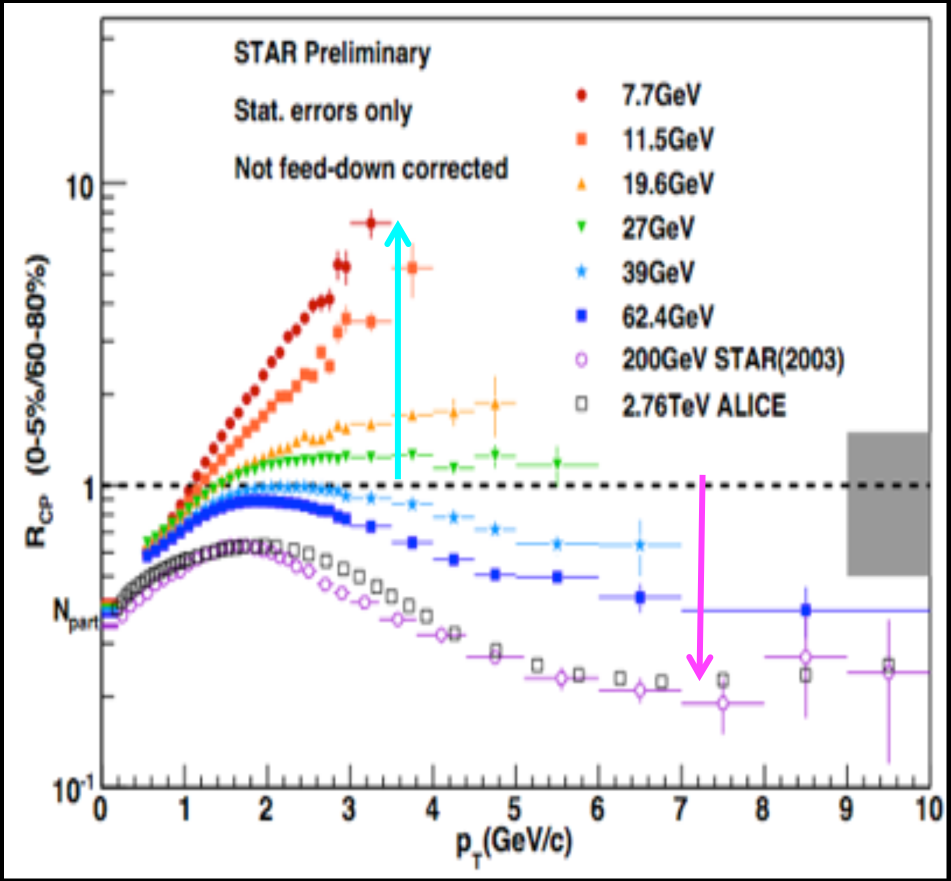
Prologue – Brief Reminder of Key Effects Observed in Large Nucleus-Nucleus Collision Systems

High p_T Hadrons Are Suppressed at LHC & RHIC

Central Pb-Pb and Au-Au Collisions

Suppression → parton energy loss in hot QCD medium





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

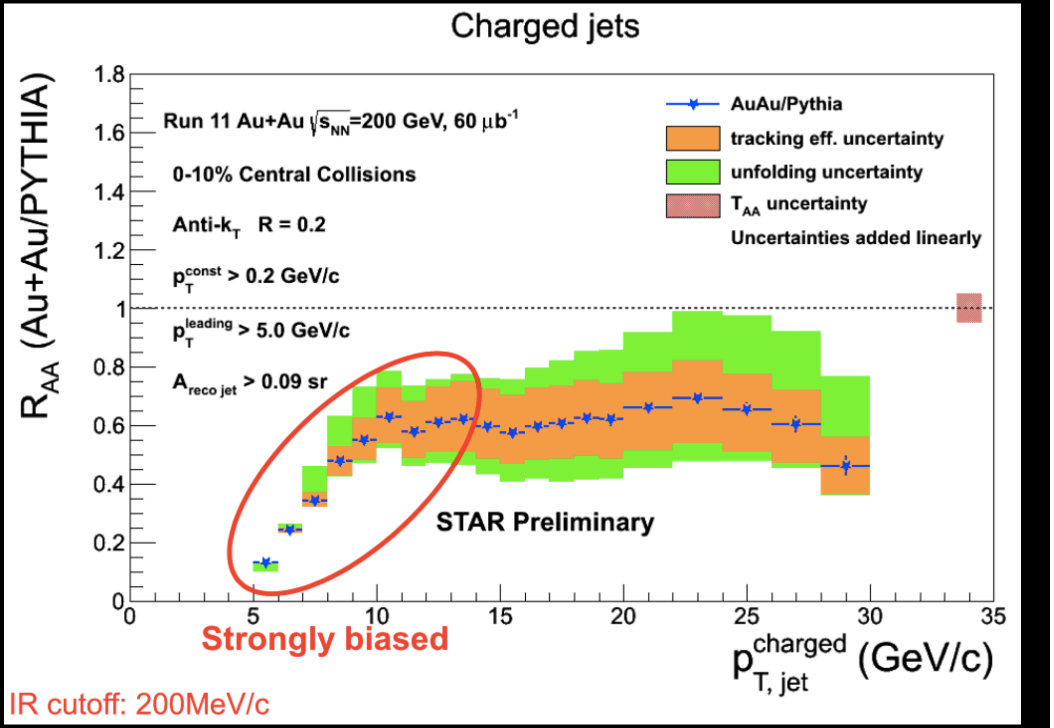
Also enhancement at lower energies
→ initial state effects
(Cronin enhancement)

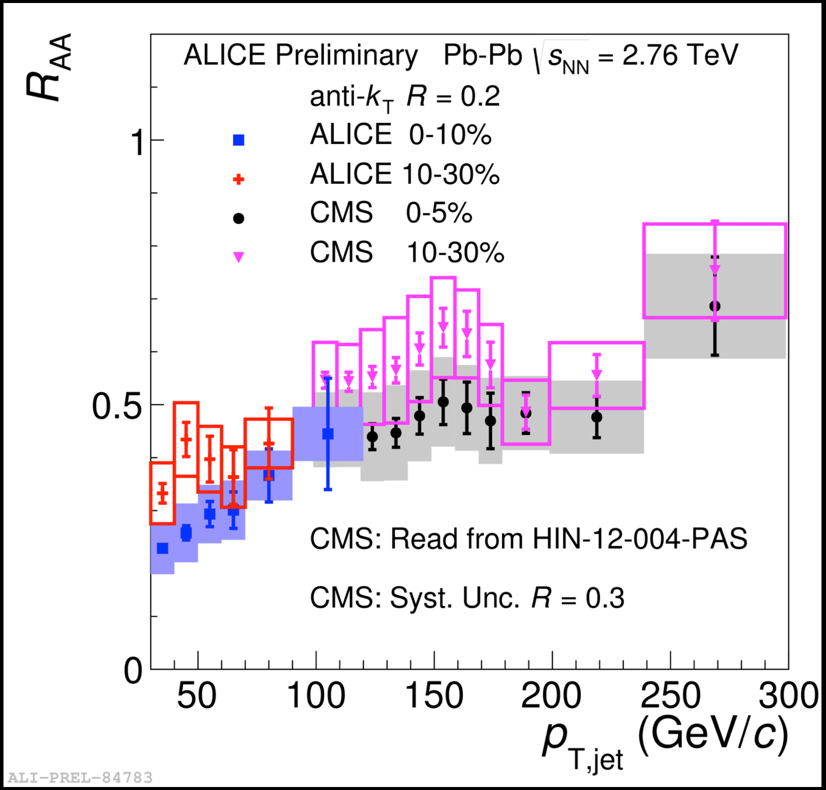
$$R_{CP} = N_{central} / N_{peripheral}$$

$$\rightsquigarrow R_{AA}$$

Jets Are Quenched at RHIC & LHC

RHIC





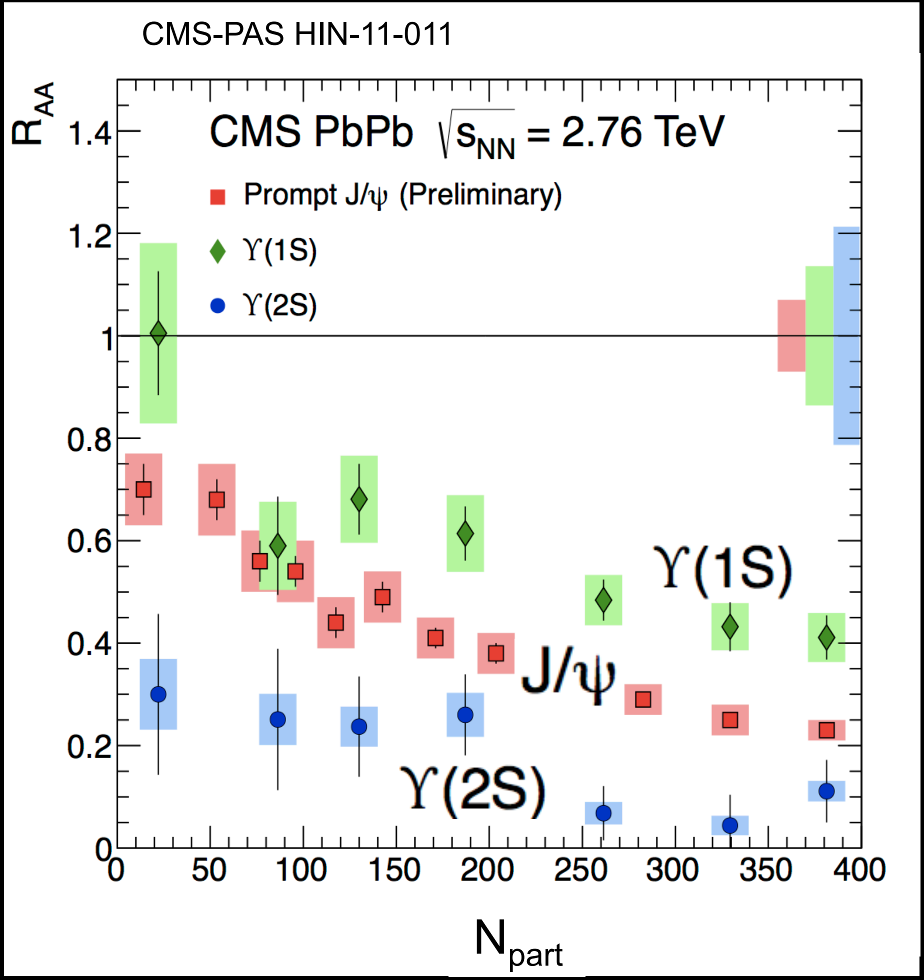
RHIC Jets less suppressed than LHC Jets
at low jet momentum

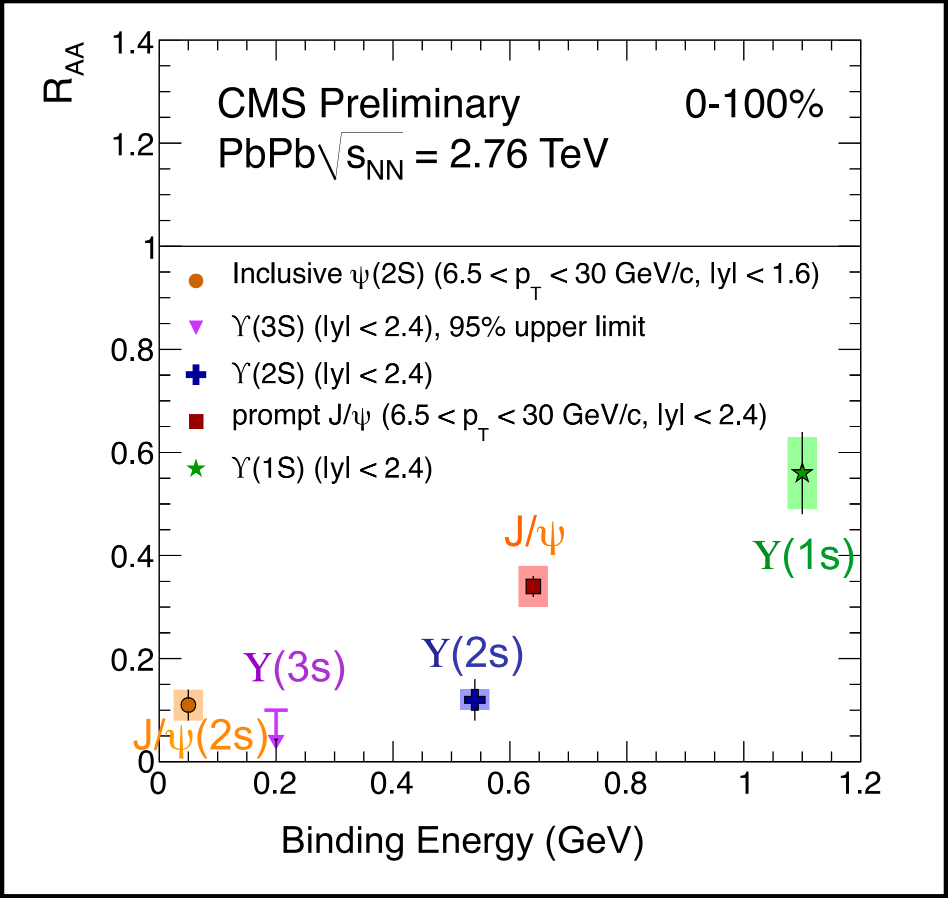
PLB 715 (2012) 66
PLB 710 (2012) 256

QM 2014

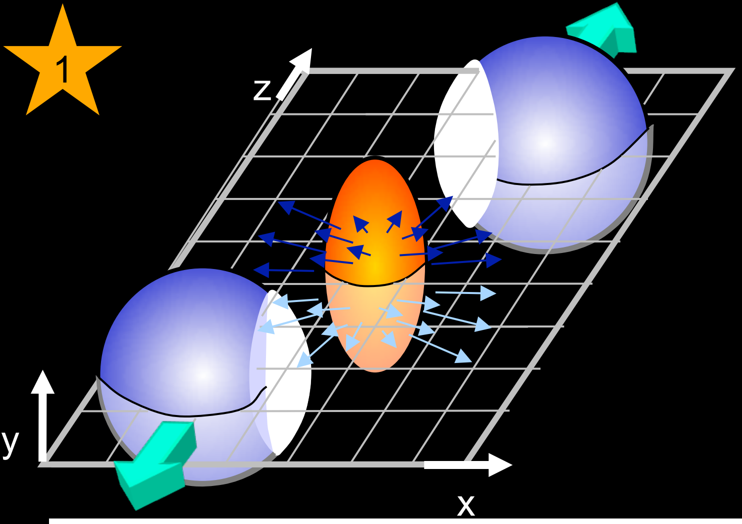
J/Ψ and Υ Suppressed at the LHC

CMS, PRL 107 (2011) 052302





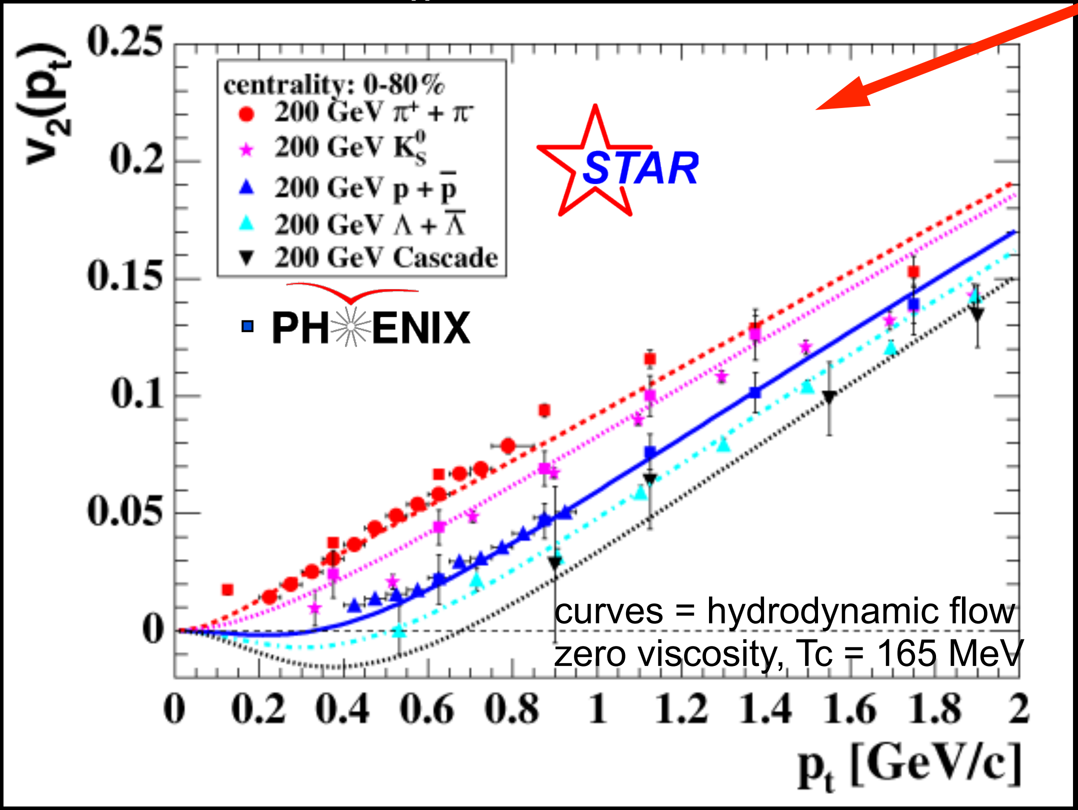
Suppression of Quarkonium States expected in a hot QCD Medium!



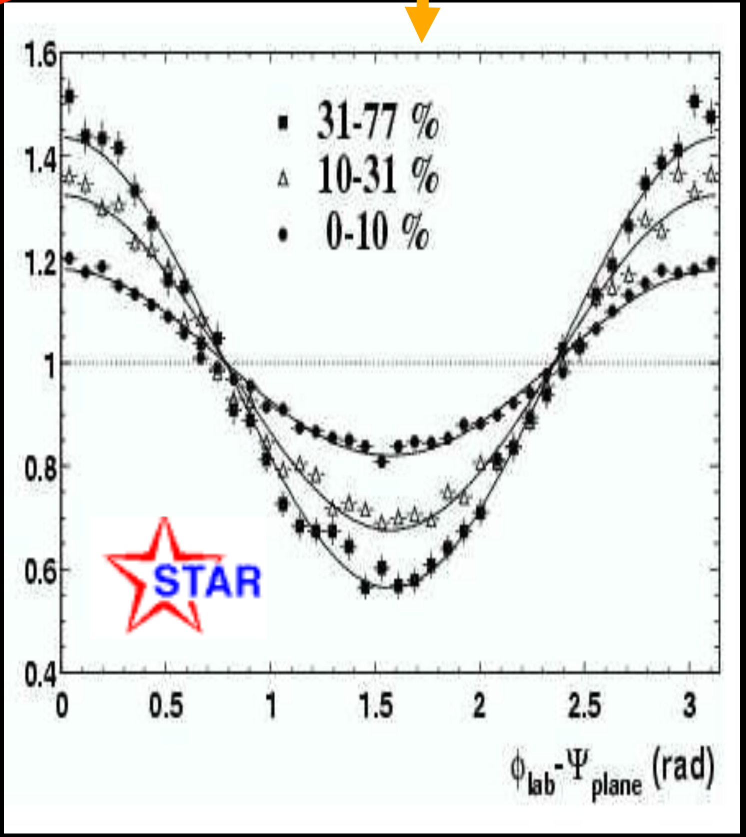
Elliptic Flow Saturates Hydrodynamic Limit

- **Azimuthal asymmetry of charged particles:**

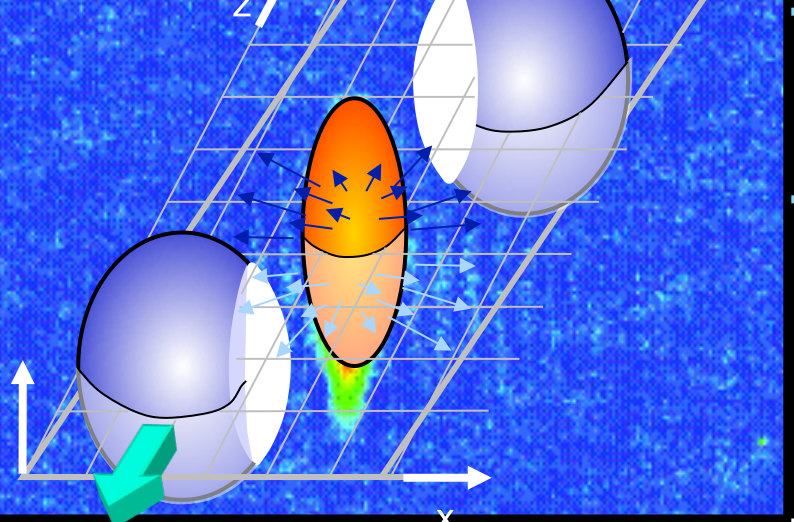
  $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



curves = hydrodynamic flow
zero viscosity, Tc = 165 MeV



Elliptic Flow Saturates Hydrodynamic Limit



Azimuthal asymmetry of charged particles:

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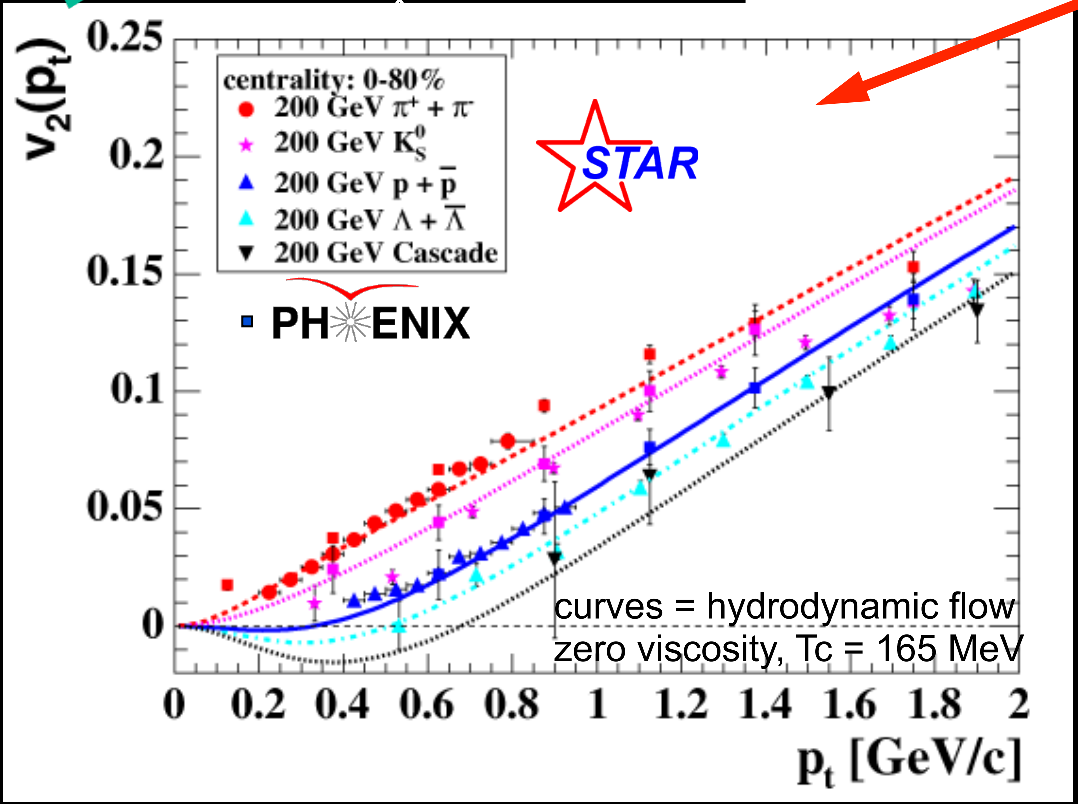


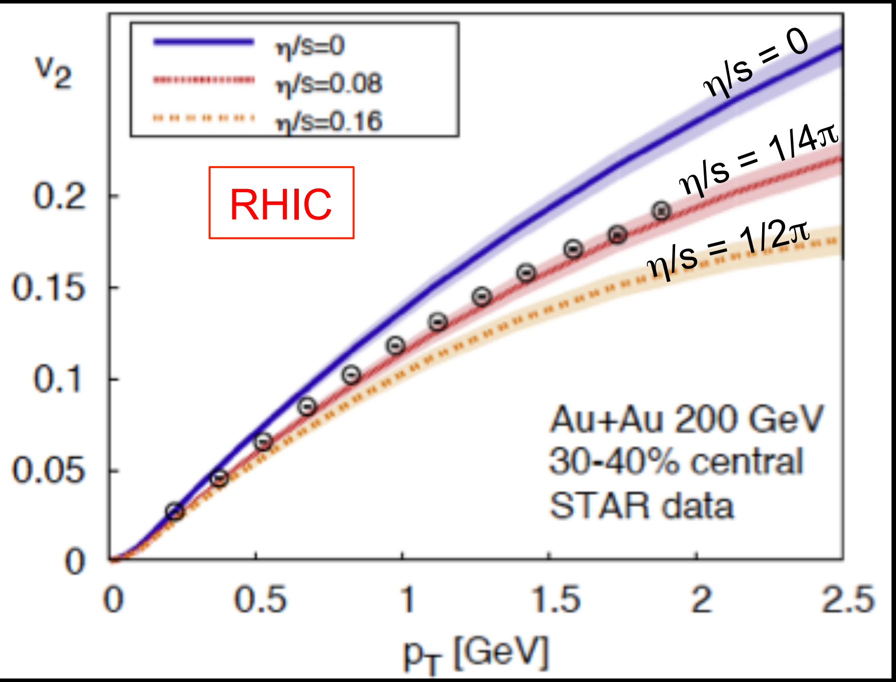
curves = hydrodynamic flow
zero viscosity, Tc = 165 MeV

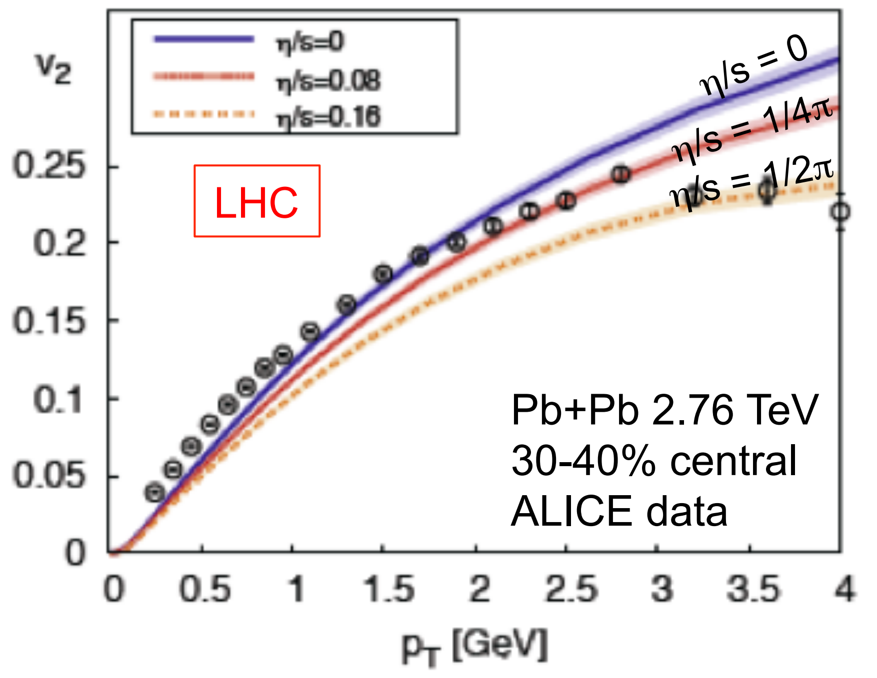
Mass dependence of v_2

Requires -

- **Early thermalization (0.6 fm/c)**
- **Near-ideal hydrodynamics (near-zero viscosity)**
  → **“nearly perfect liquid”**
- **$\varepsilon \sim 25$ GeV/fm^3 ($\gg \varepsilon_{critical}$)**
- **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))

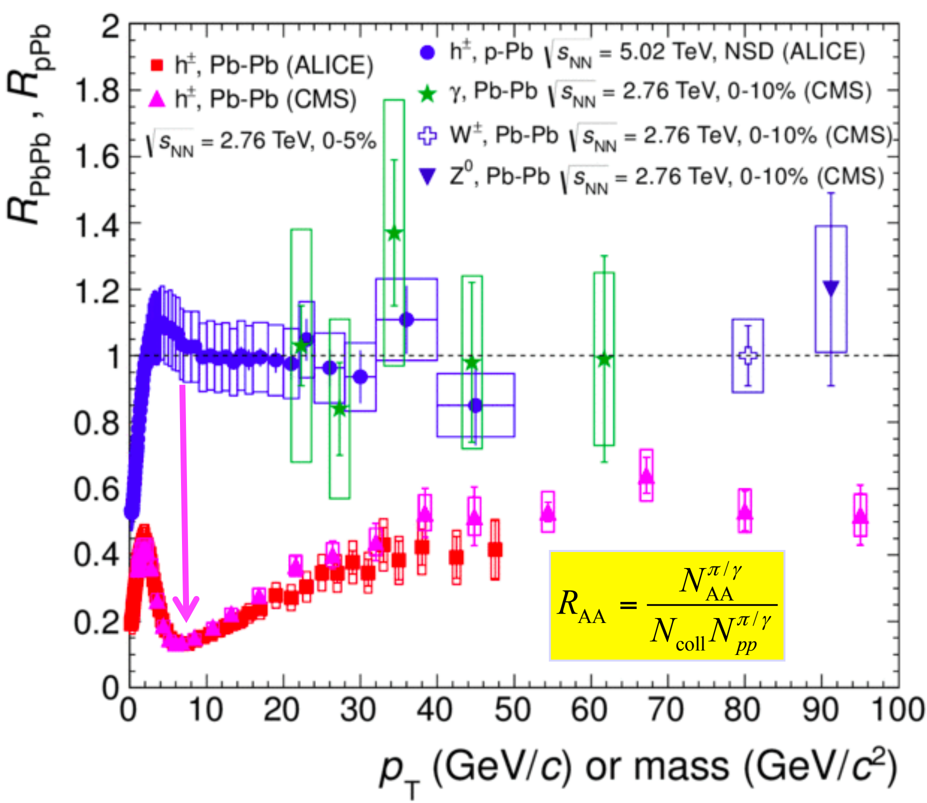
Universal lower bound on shear viscosity / entropy ratio (η/s)
→ $\eta/s = 1/4\pi$ for a "perfect liquid"

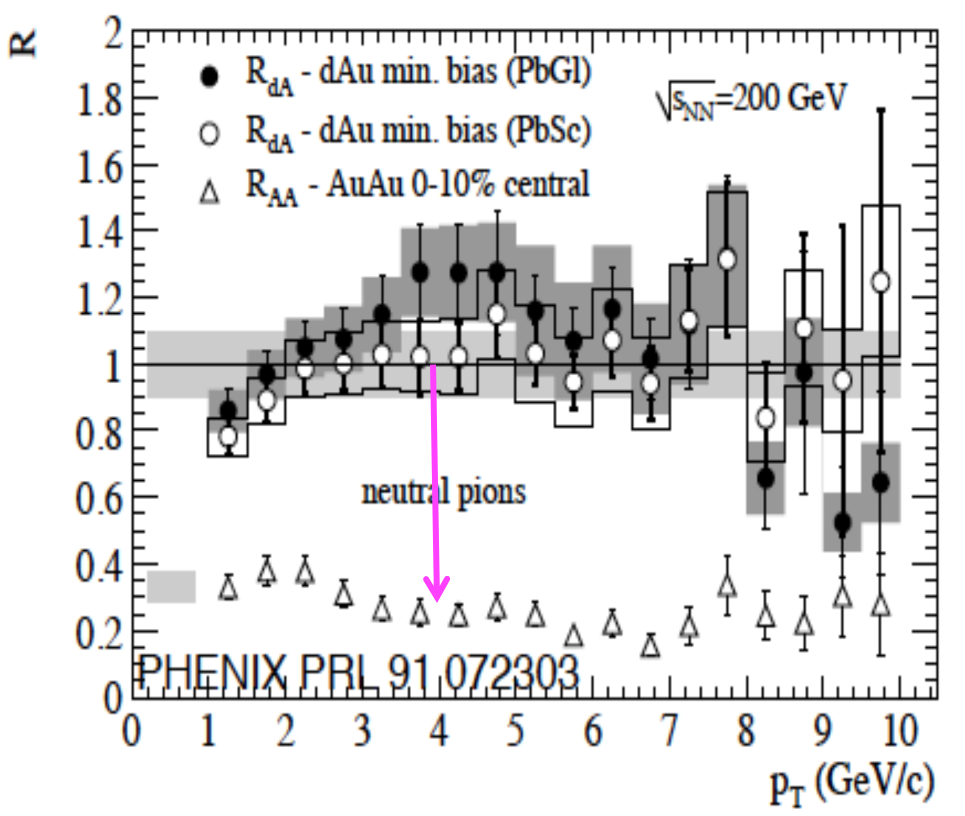
The Proton-Nucleus Enigma

A Play in Four Acts

Act 1 – "High p_T Particles & Jets"

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





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

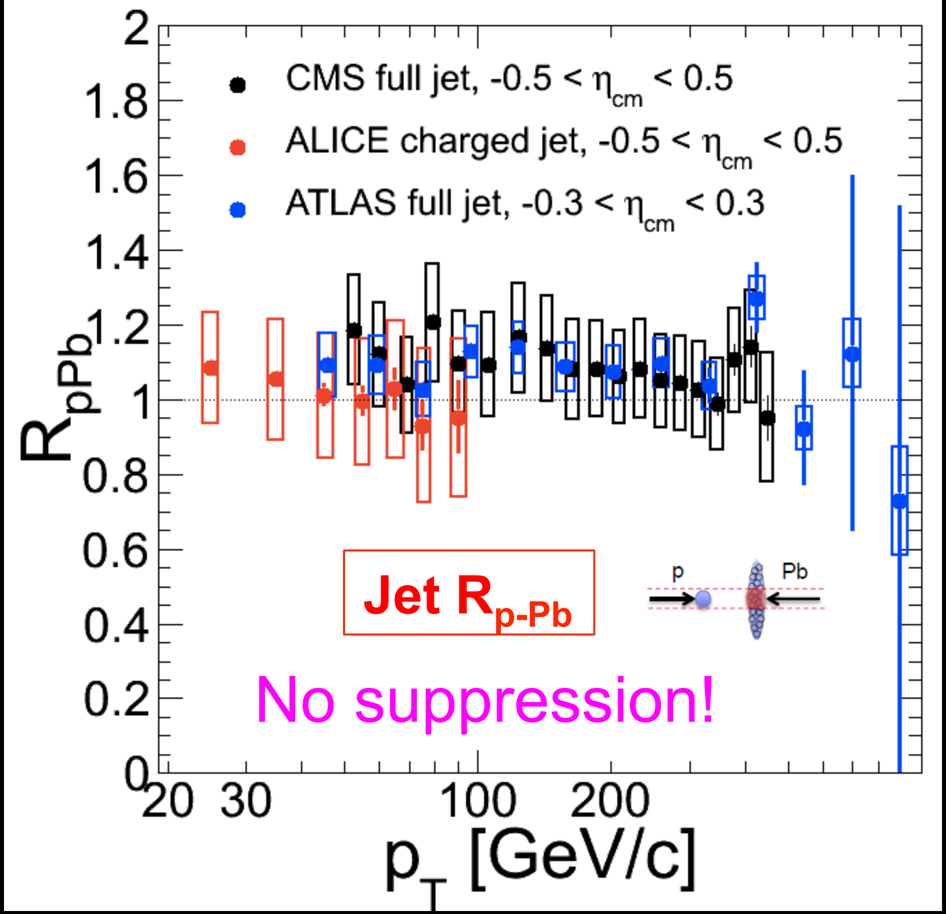
- Binary scaling (R_{dAu} ~ R_{pPb} ~ 1), except "bump" at ~ 4 GeV/c
- Absence of Nuclear Modification → Initial state effects small

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

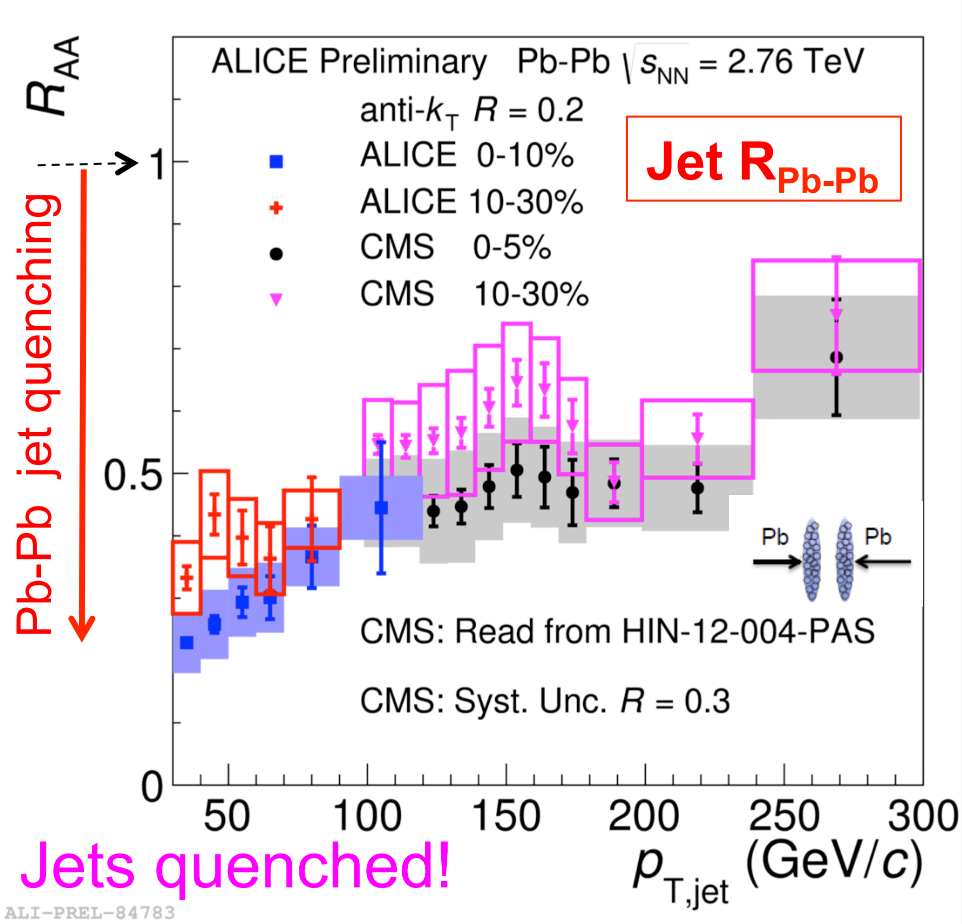
QM2014: ALICE ATLAS CMS (black)



Jet $R_{p\text{-}Pb}$

No suppression!

ALICE QM 2014



Jet $R_{Pb\text{-}Pb}$

CMS: Read from HIN-12-004-PAS

CMS: Syst. Unc. R = 0.3

Jets quenched!

ALICE ≈ ATLAS ≈ CMS: $R_{p\text{-}Pb}$ (jet) ≈ 1

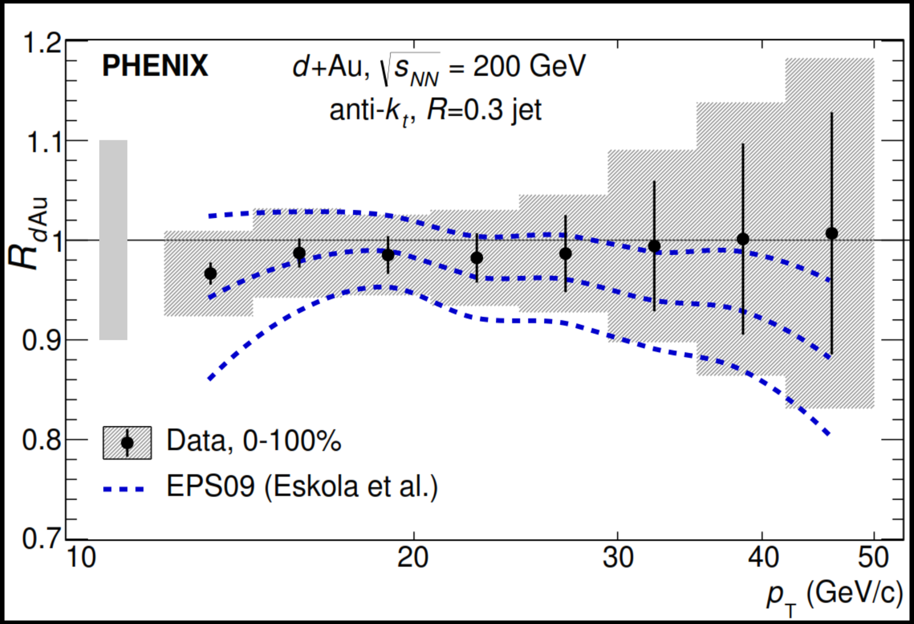
Binary scaling, no initial state effects!

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

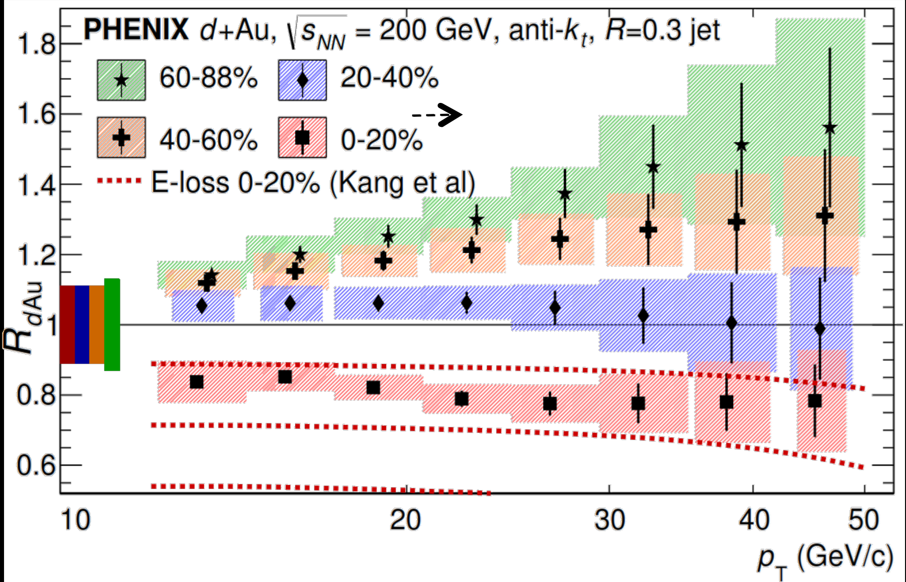
→ binary scaling

R_{dAu} exhibits strong centrality dependence

Peripheral collisions: jets enhanced

Central collisions: jets somewhat suppressed

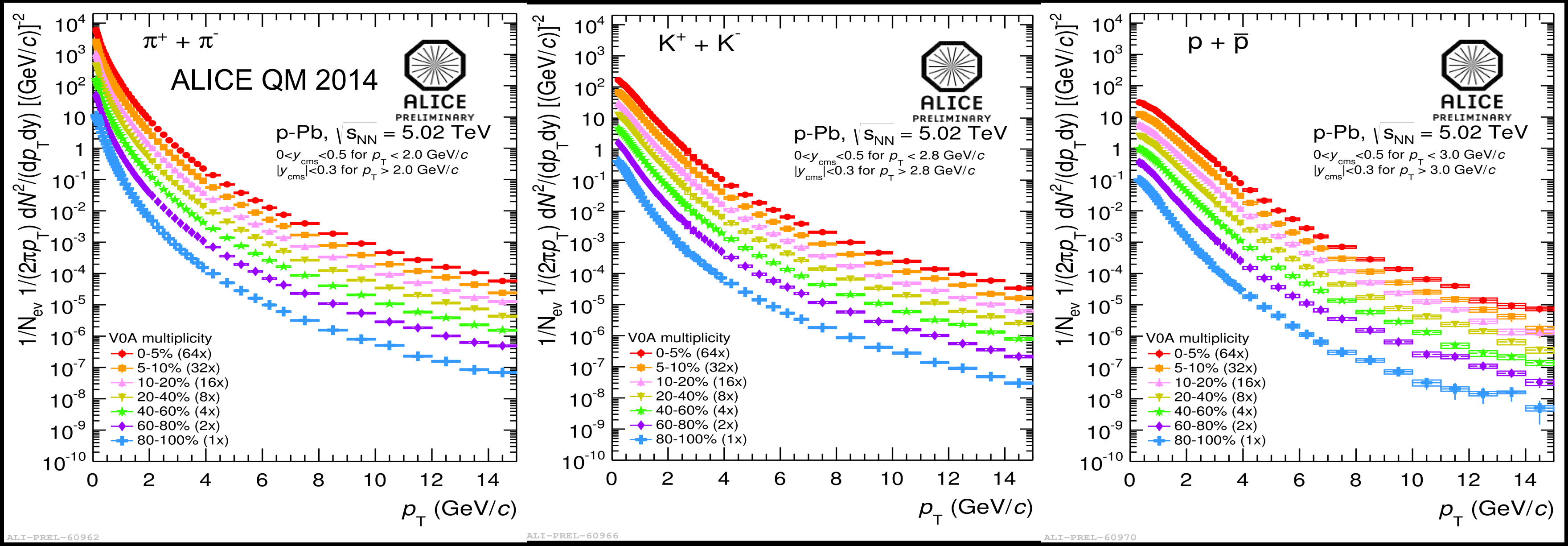
R_{pPb} exhibits same effect (ATLAS)

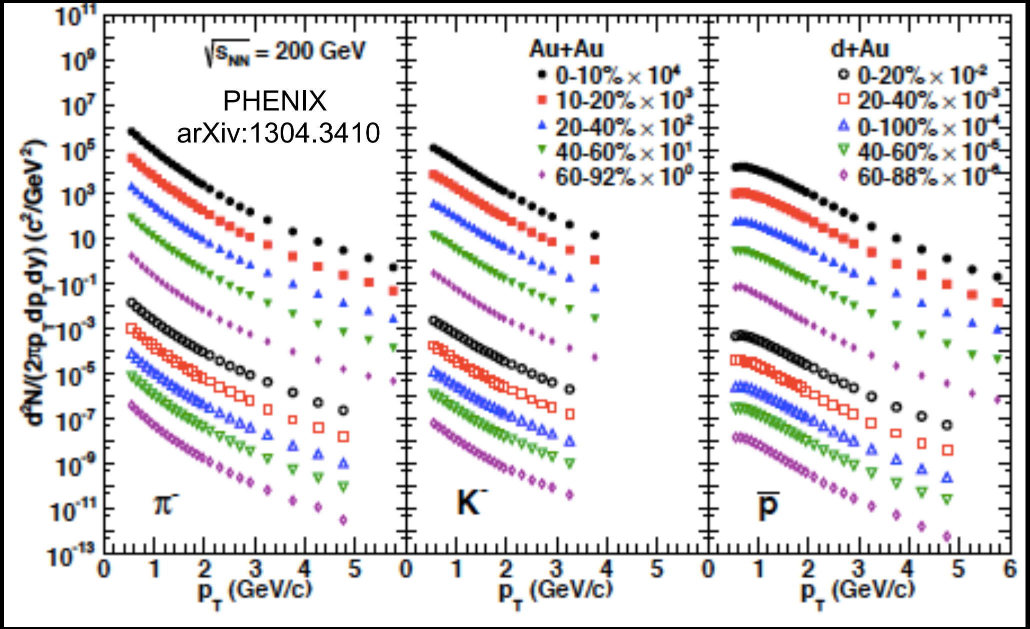


The Proton-Nucleus Enigma – Act 2

“Identified Particles”

Identified Particle Spectra in p-Pb



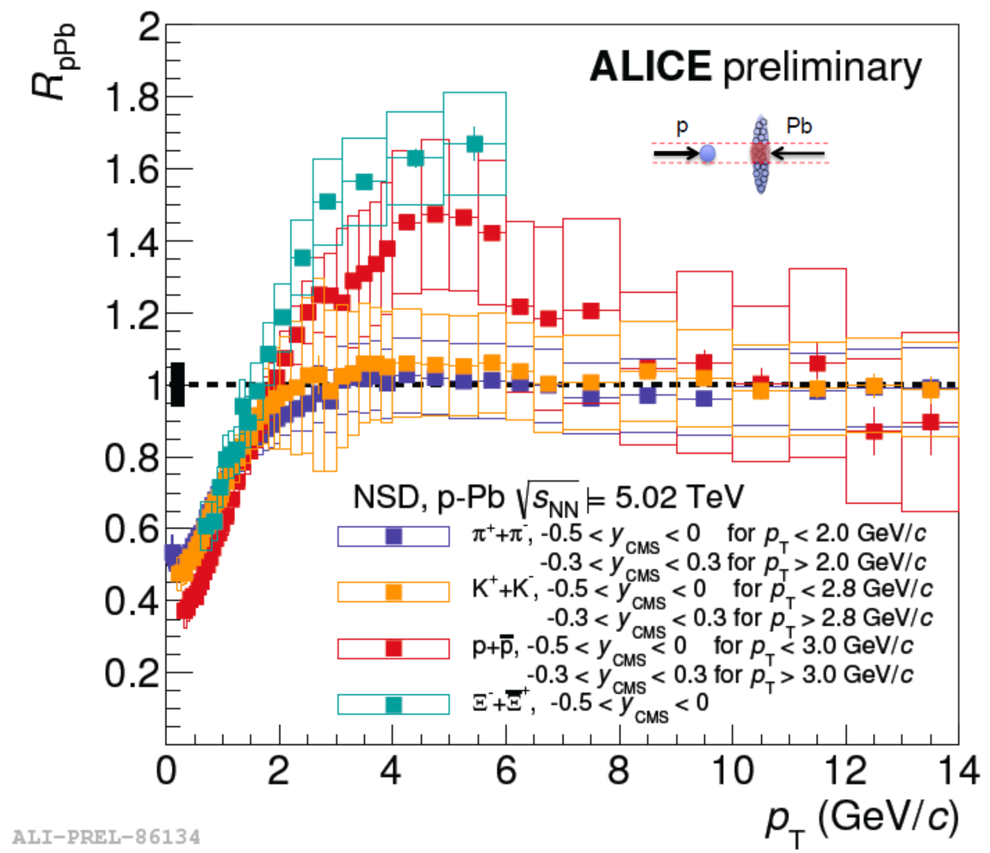


Hardening with multiplicity and particle mass indicative of collective effects in A-A!

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

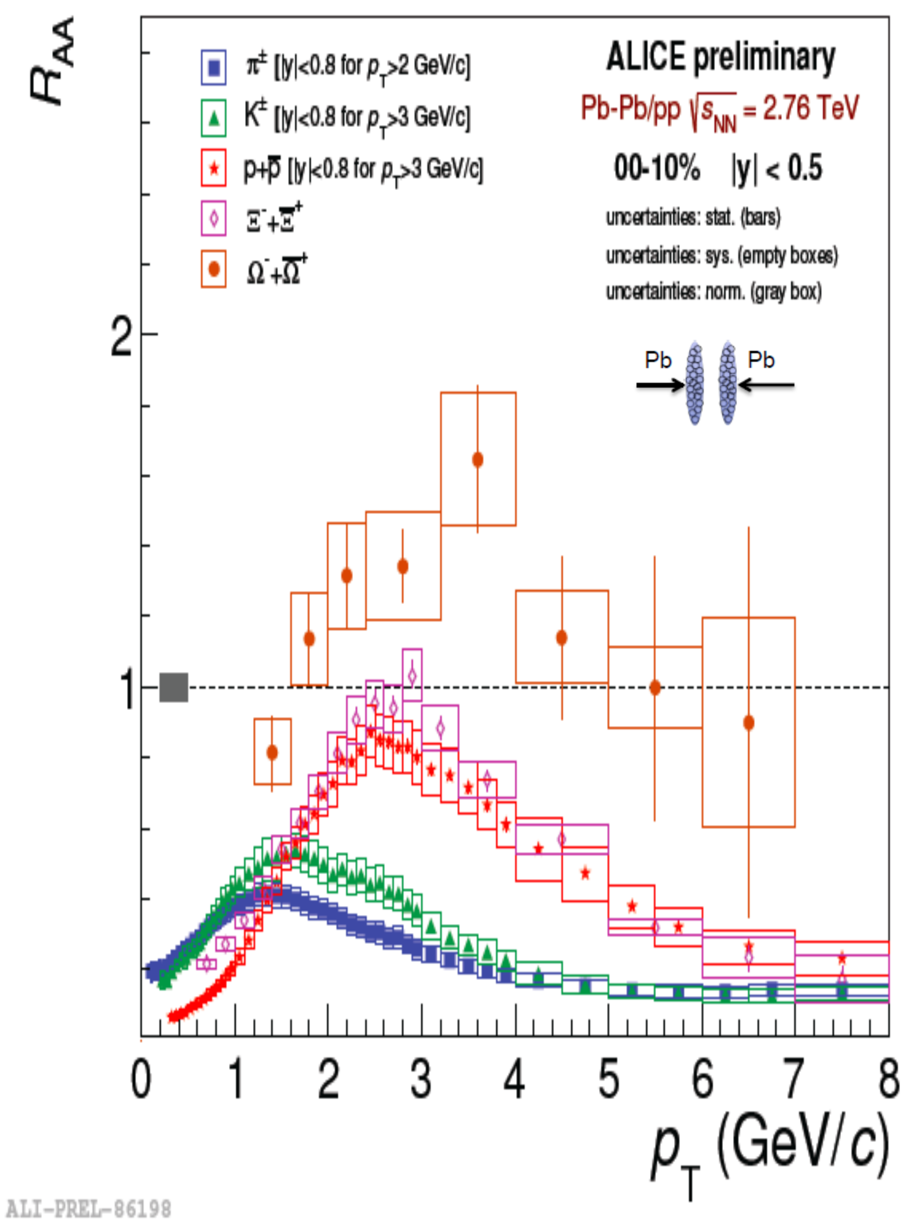
R_{pPb} for Identified Hadrons

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

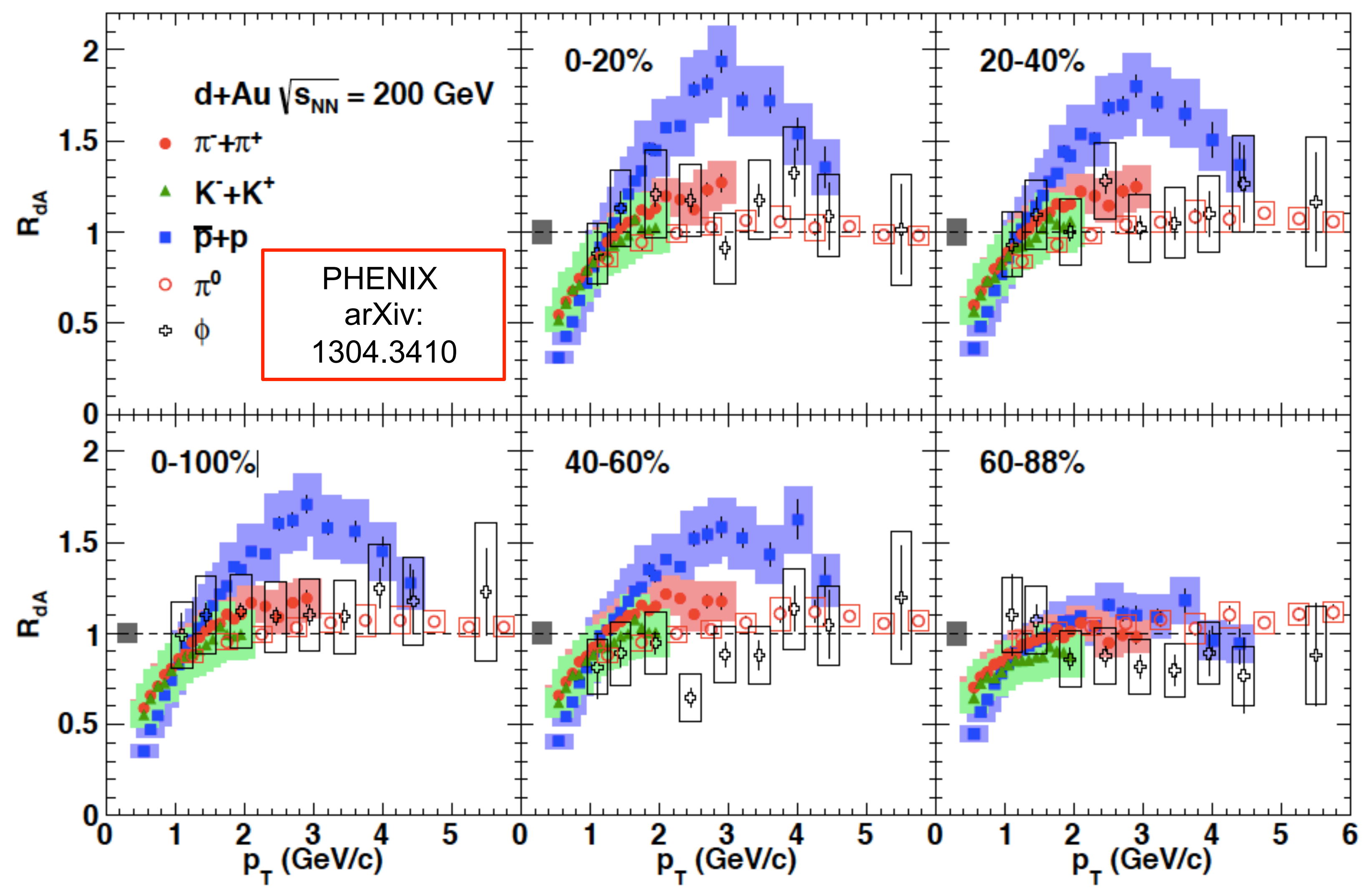


pp reference interpolated from 2.76 and 7.0 TeV

Suppression in Pb-Pb



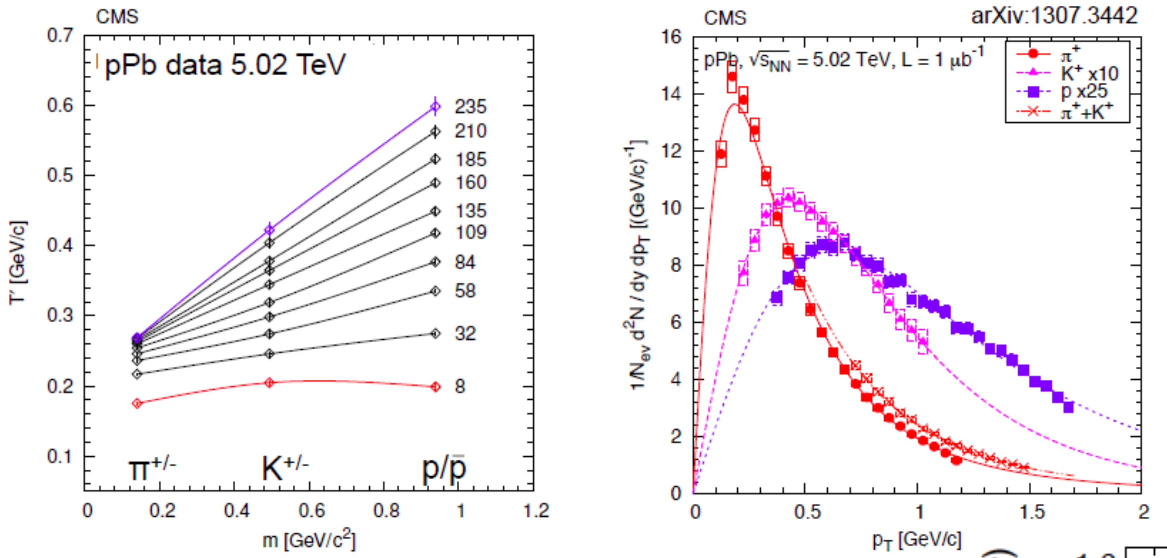
Similar Effects at RHIC in d+Au



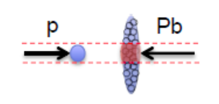
PHENIX
arXiv:
1304.3410

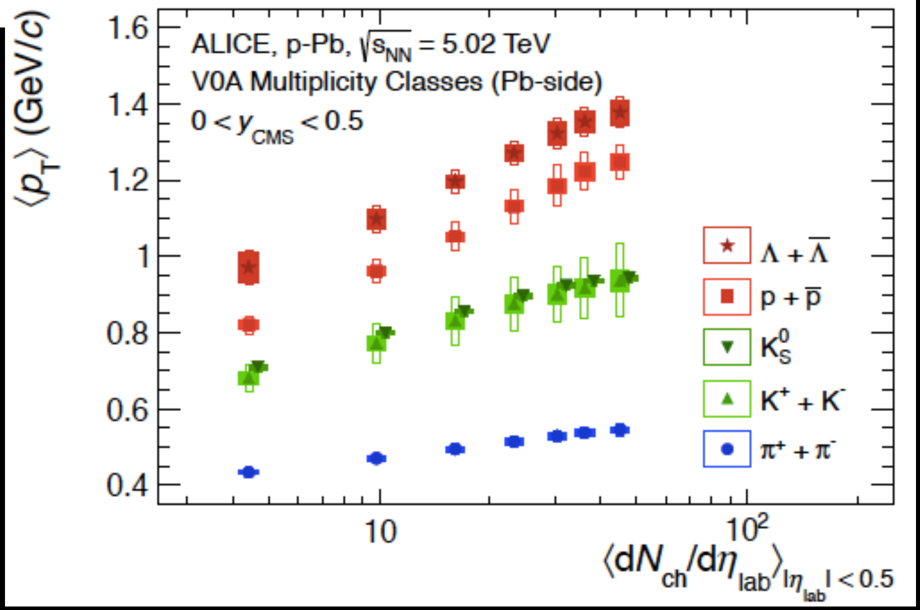
Indications of Collective Flow of Identified Particles in p-Pb

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



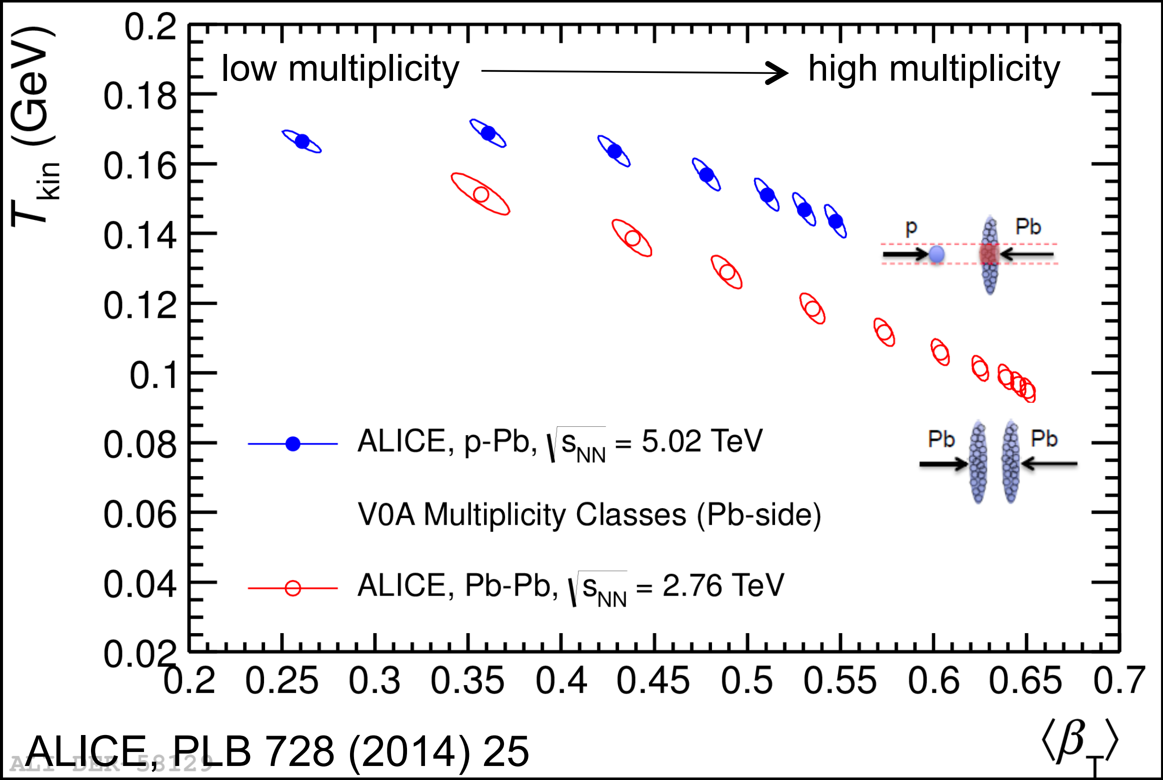


Strong mass ordering in pPb

π, K, p – Blast Wave p-Pb & Pb-Pb

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

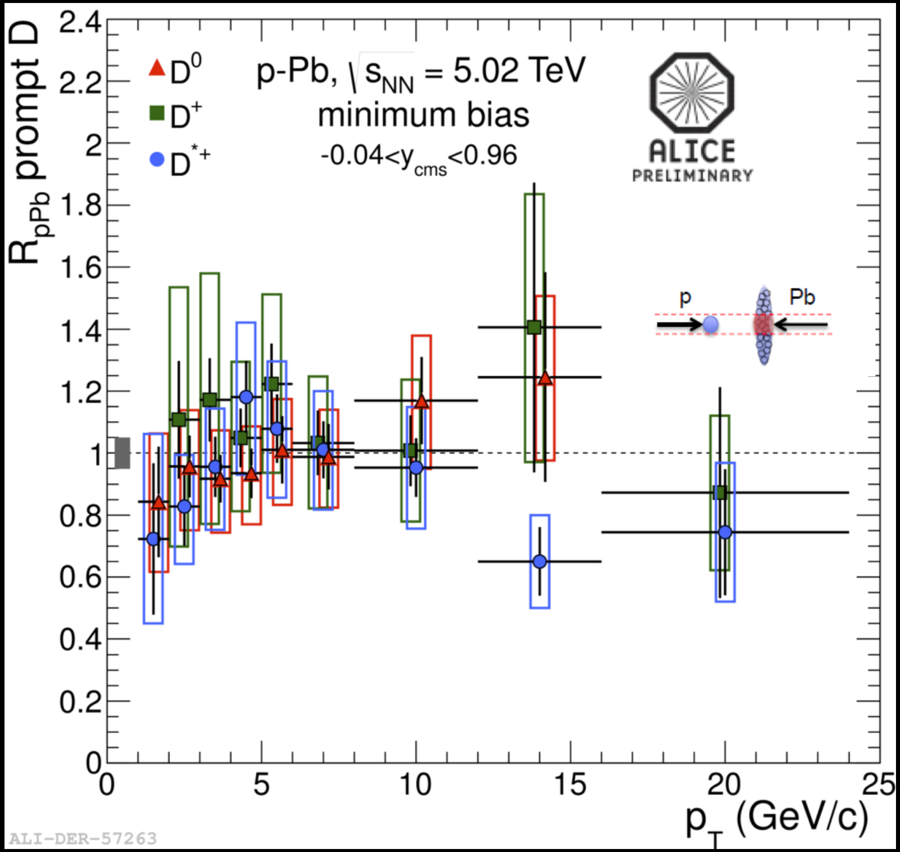
Similar trends → indicative of radial flow in p-Pb and Pb-Pb

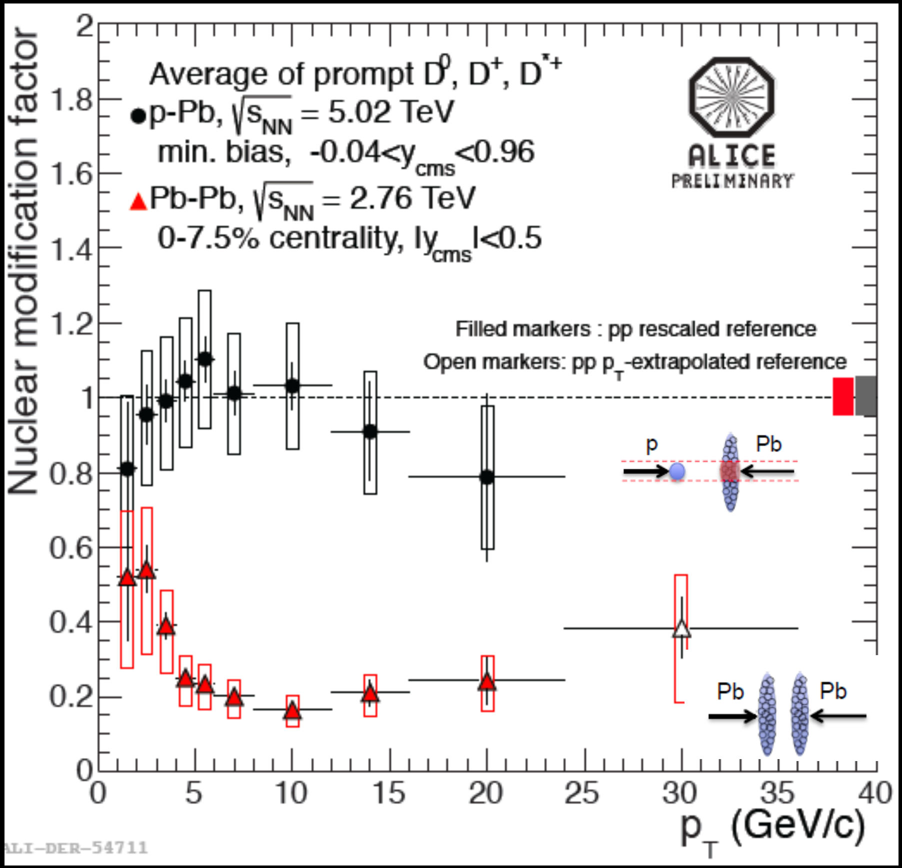
- T_{kin} similar in Pb-Pb and p-Pb for same multiplicities
- $\langle\beta_T\rangle$ larger in p-Pb for similar multiplicities

→ stronger collective flow for smaller system size…?

See Shuryak, arXiv:1301.4470 [hep-ph]

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





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

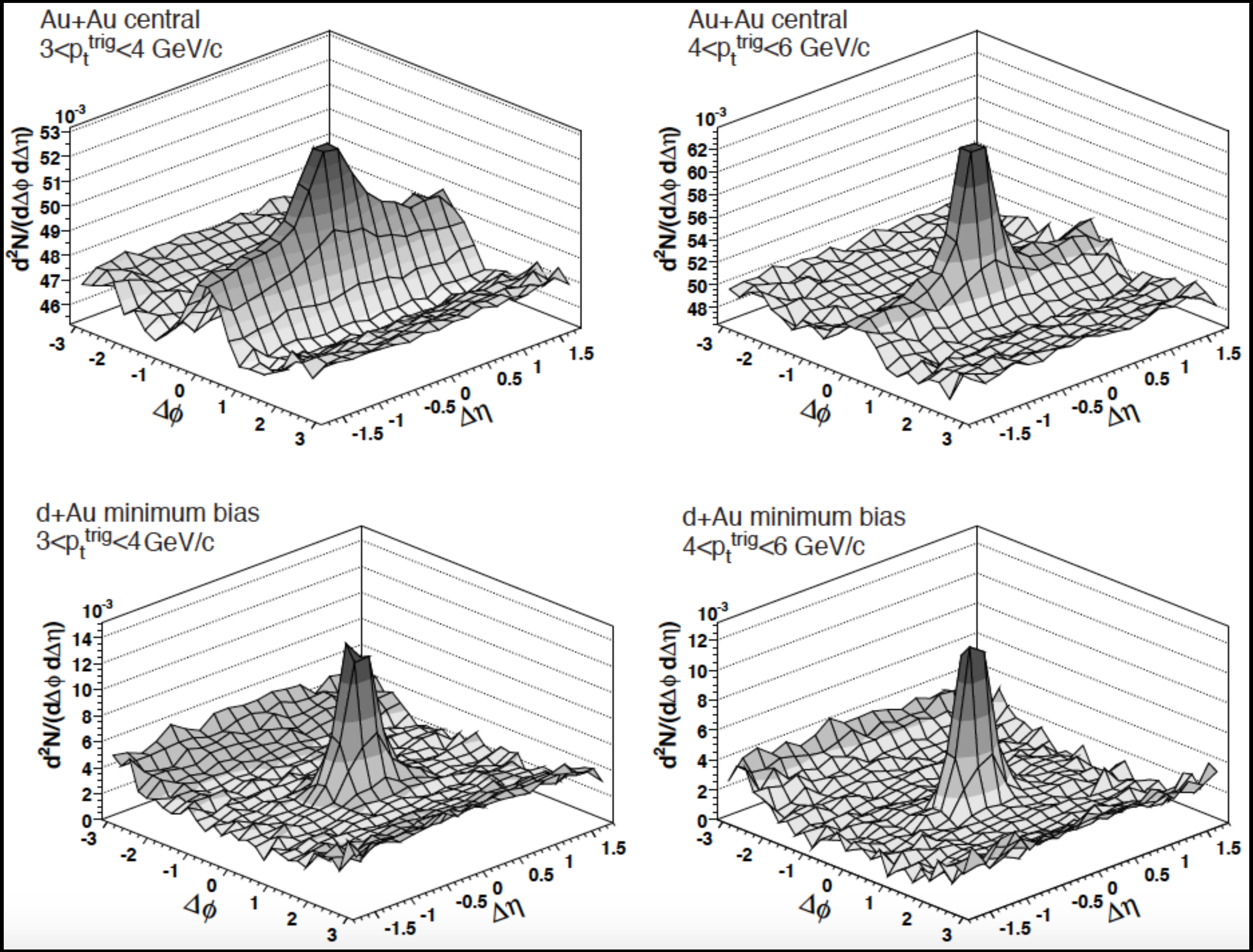
D-meson central R_{PbPb} suppressed!
($p_T \gtrsim 4$ GeV/c)
Again verifies it's not an initial state effect!

The Proton-Nucleus Enigma – Act 3

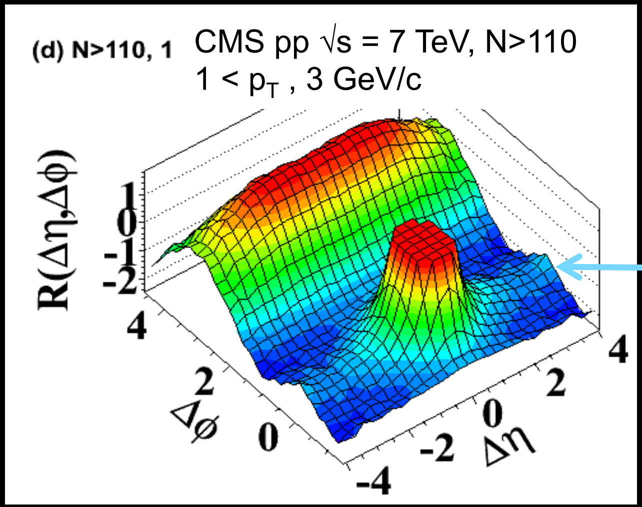
“Particle Correlations”

Initial (Historical) STAR Result on the Ridge

Phys. Rev. C 80 (2009) 64912



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

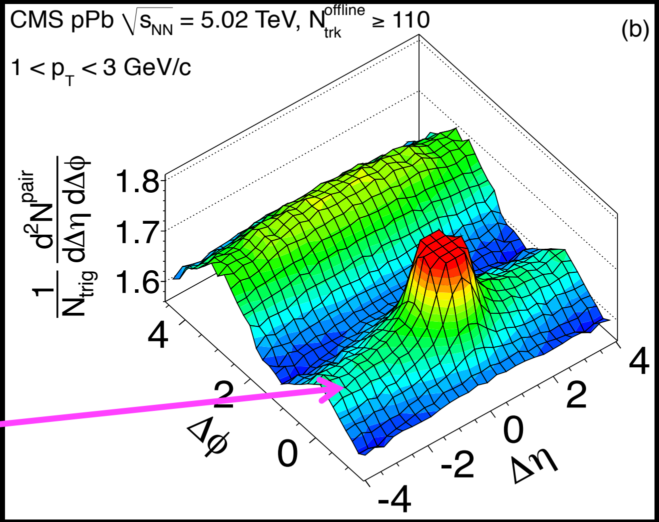


CMS, JHEP 09 (2010) 091

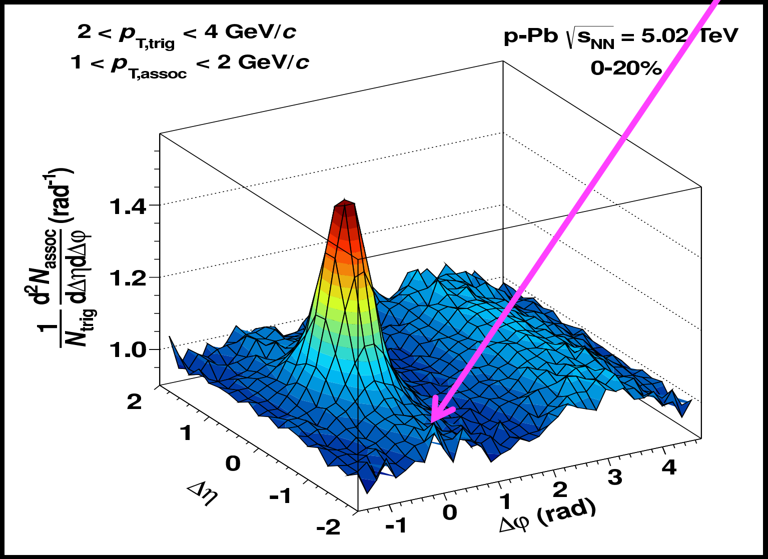
LHC near-side ridge for $\sqrt{s_{NN}}$ =

7 TeV pp

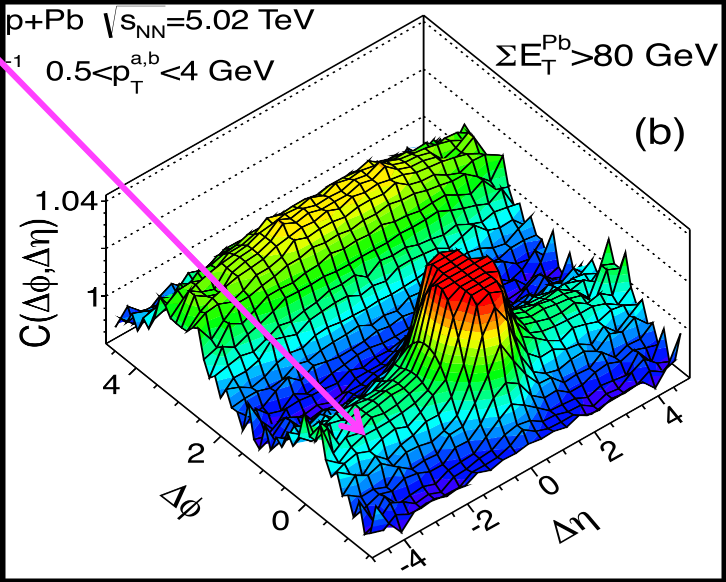
5.02 TeV p-Pb



CMS, PLB 718 (2013) 795



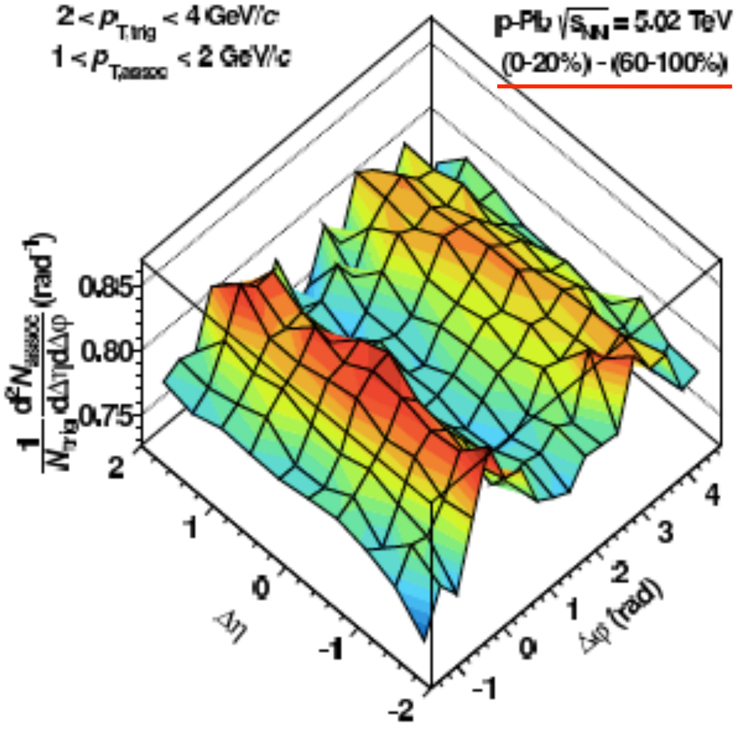
ALICE, PLB 719 (2013) 29



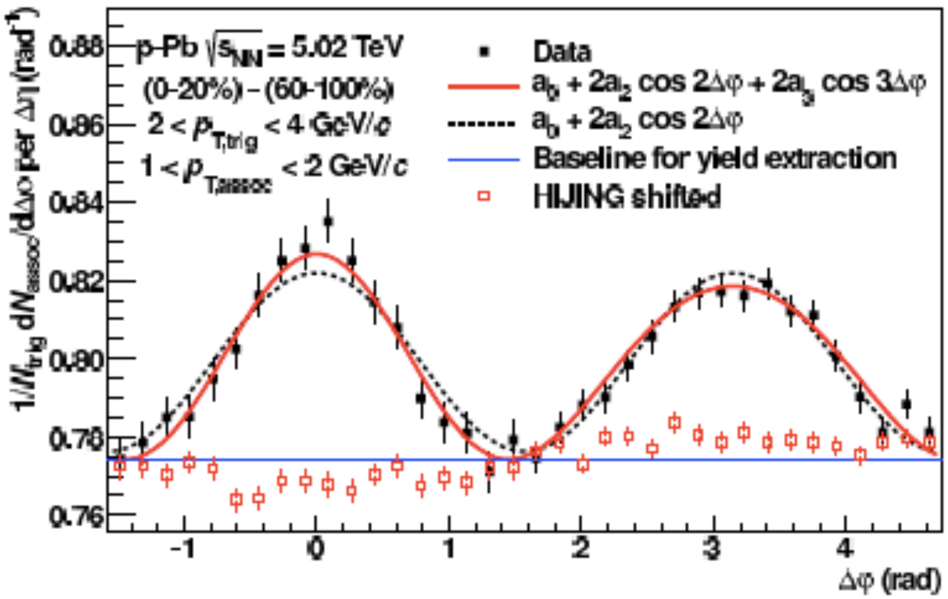
ATLAS, Phys. Rev. Lett. 110, 182302 (2013)

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

Investigate p-Pb Double Ridge



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

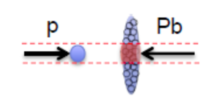


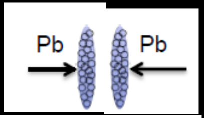
After subtraction of low multiplicity from high multiplicity events:
Fourier decomposition seen as curves

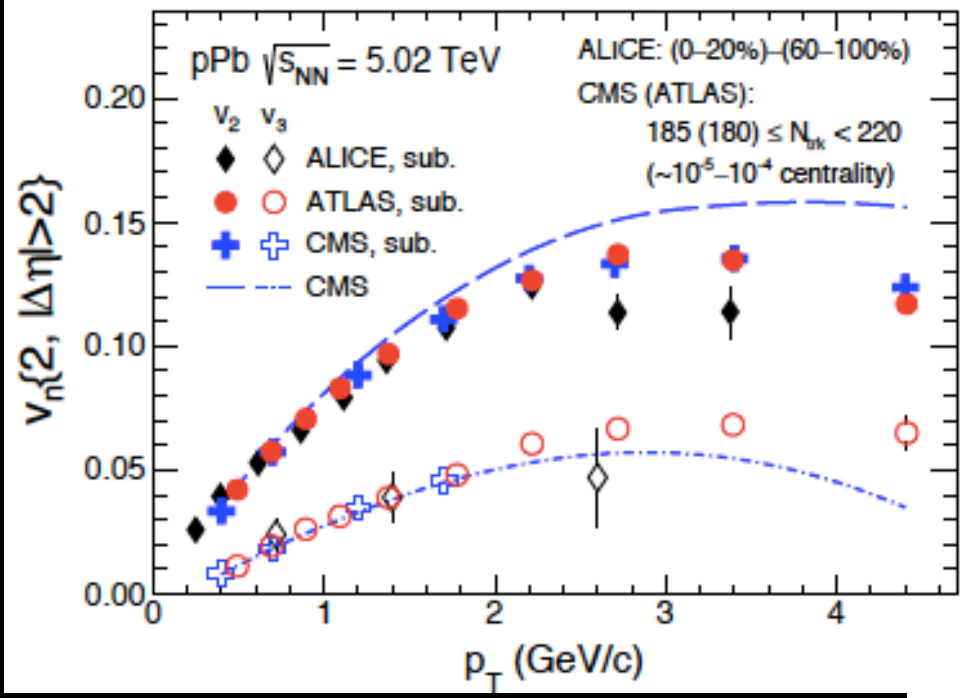
ALICE, arXiv:1307.3237

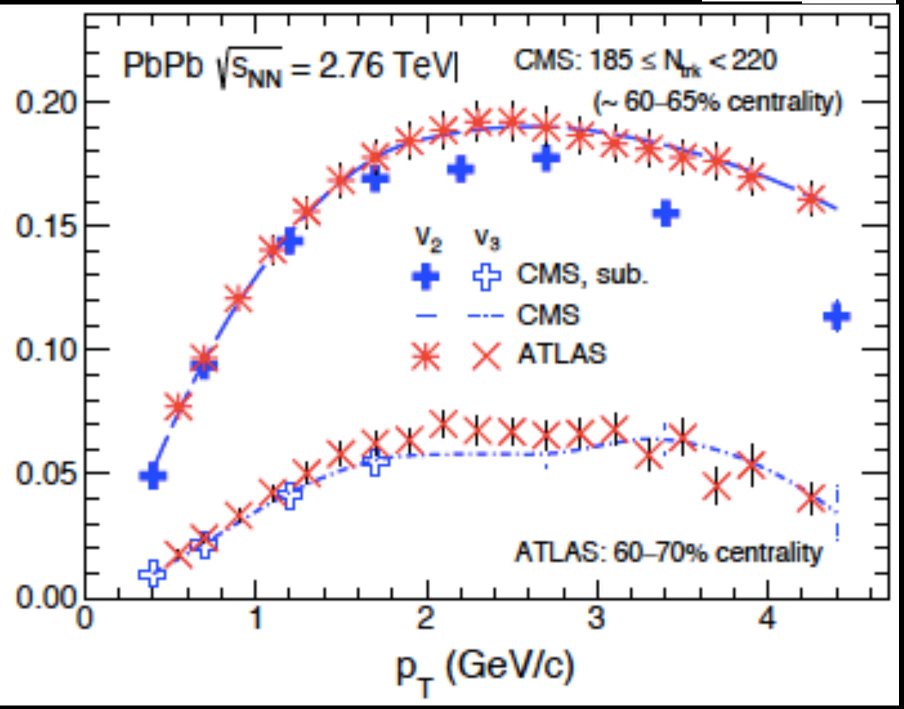
Comparing v_2 and v_3 from Long-range Correlations

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



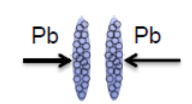




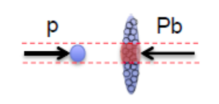


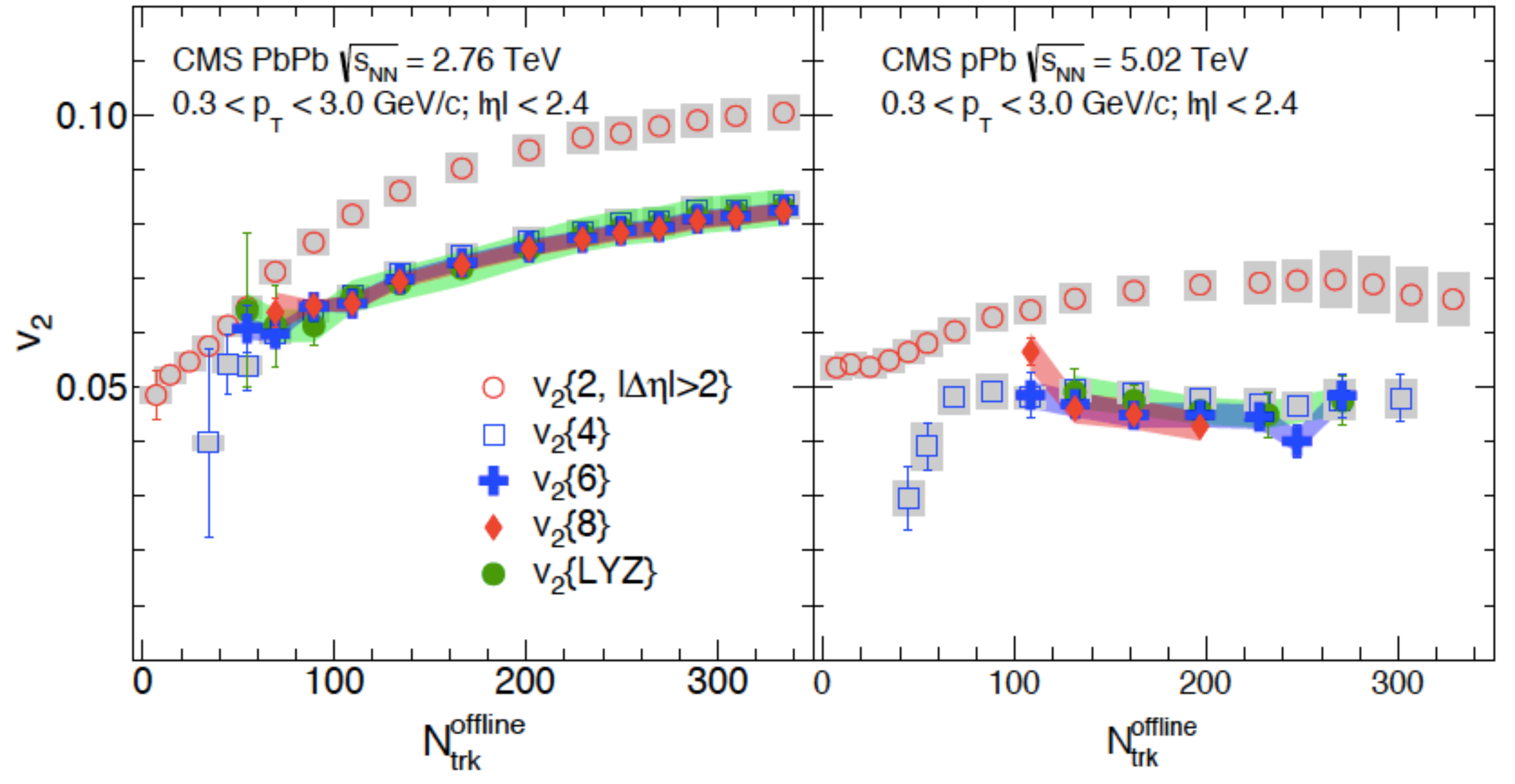
Symbols are (back-to-back jet) subtracted data.
Curves are before subtraction.
Notice v_2 trends and v_3 almost identical (p-Pb and Pb-Pb)

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



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



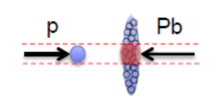


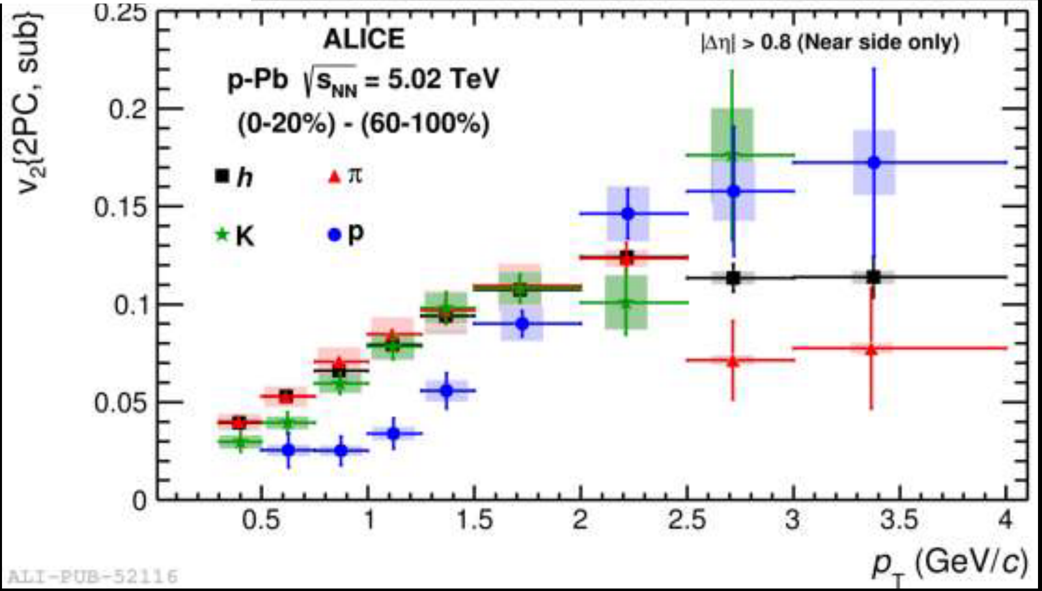
For PbPb and pPb – Collective effects!

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





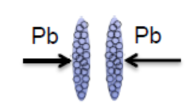
After subtraction Fourier coefficient v_2 (2PC, sub)

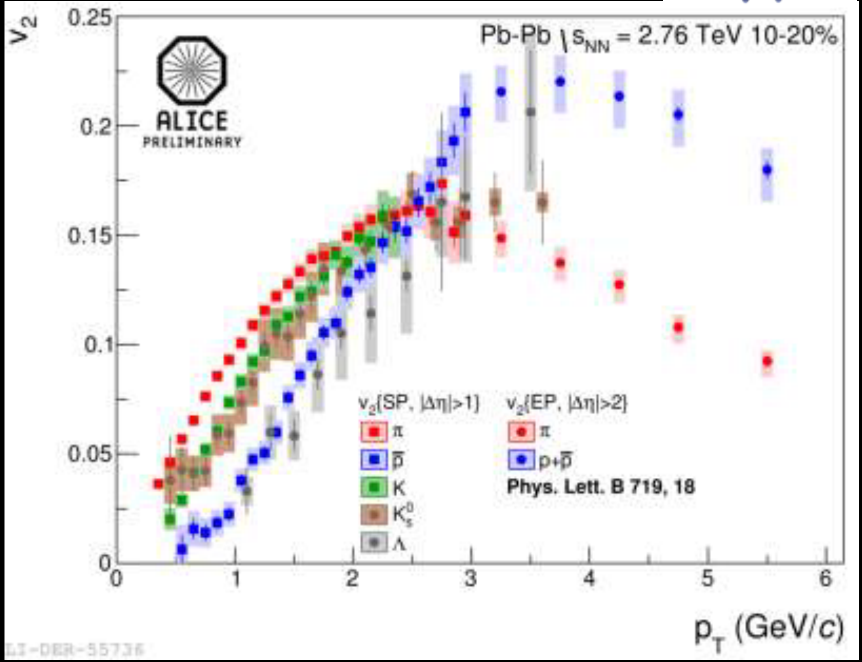
Observe ordering in mass!

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!

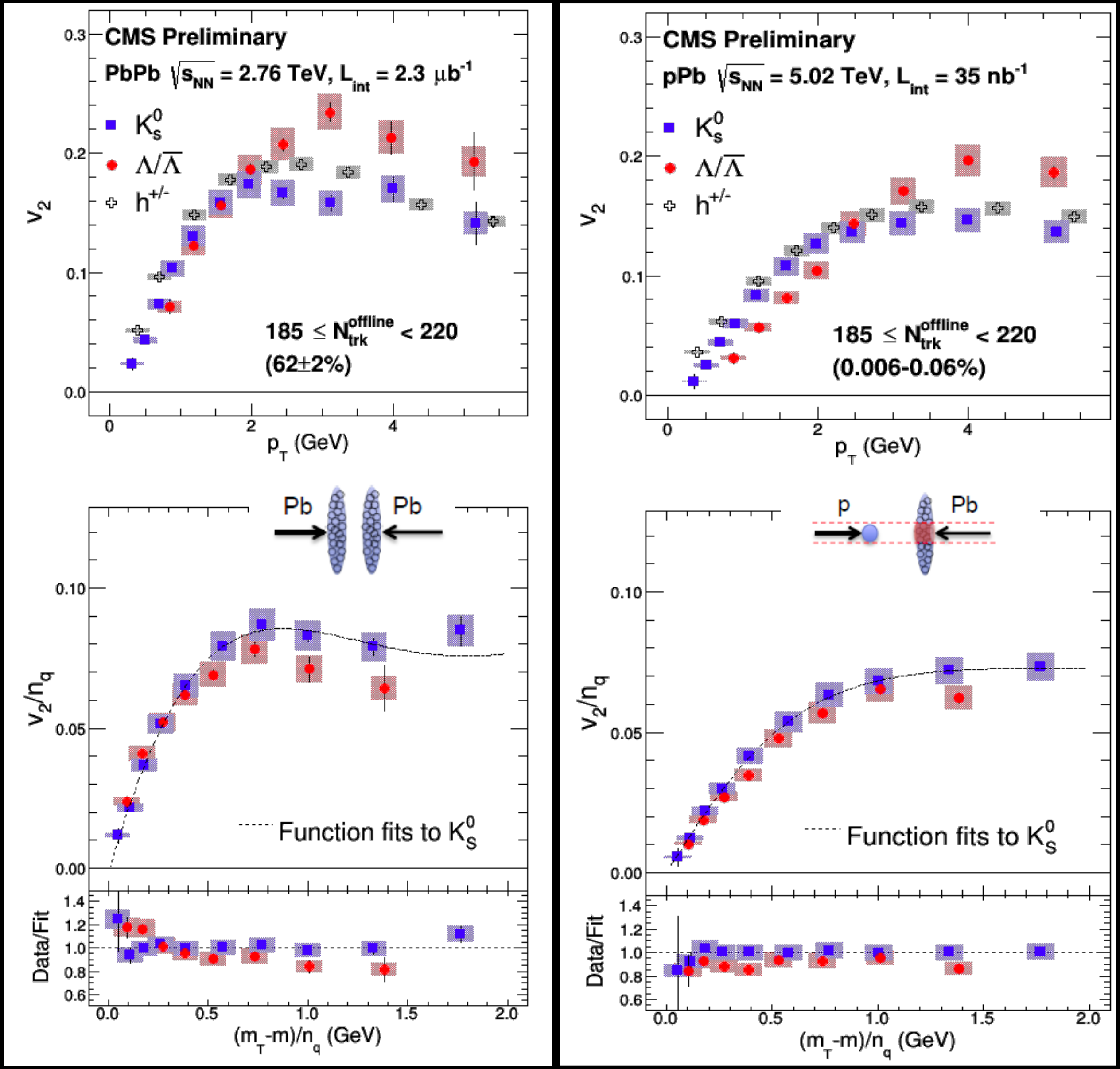
CMS, arxiv:1409.3392

Identified K_s , Λ & charged hadrons

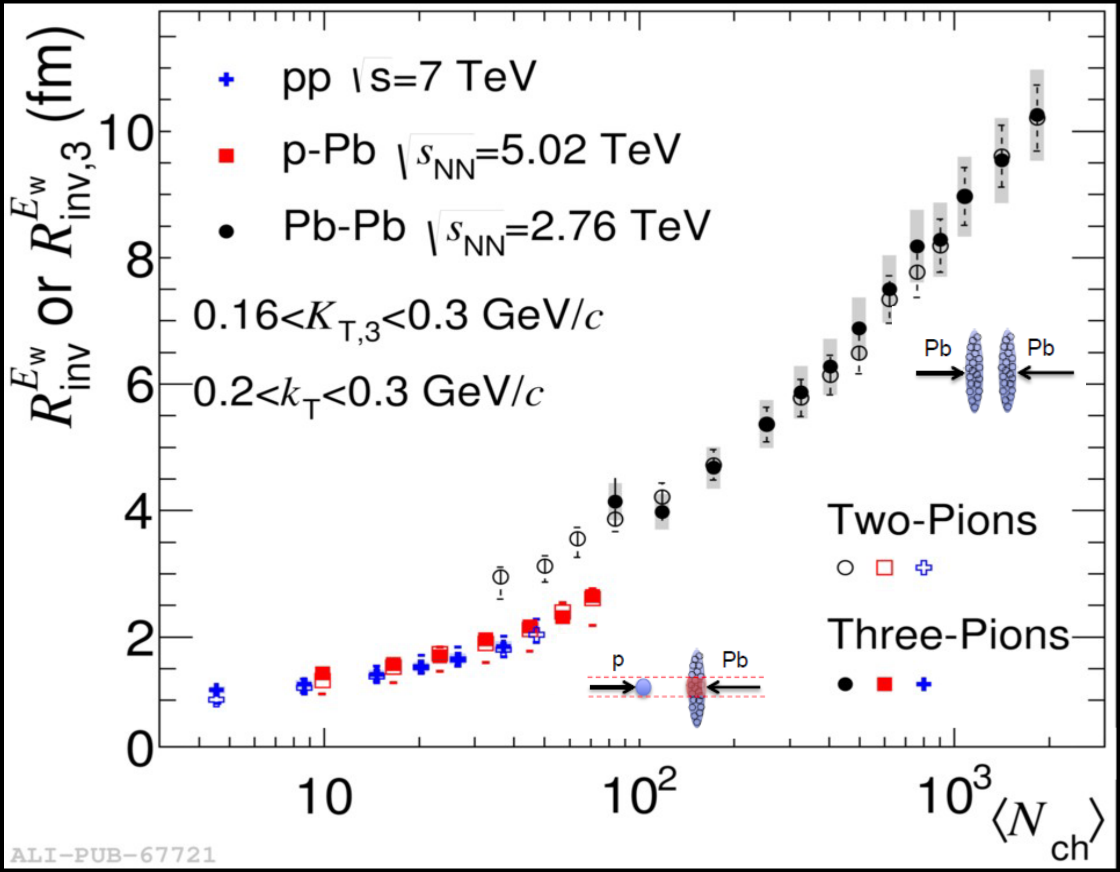
v_2 from 2-particle correlations

Exhibit mass ordering in pPb and PbPb

NCQ scaling better in pPb



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



ALICE, PLB 739 (2014) 139

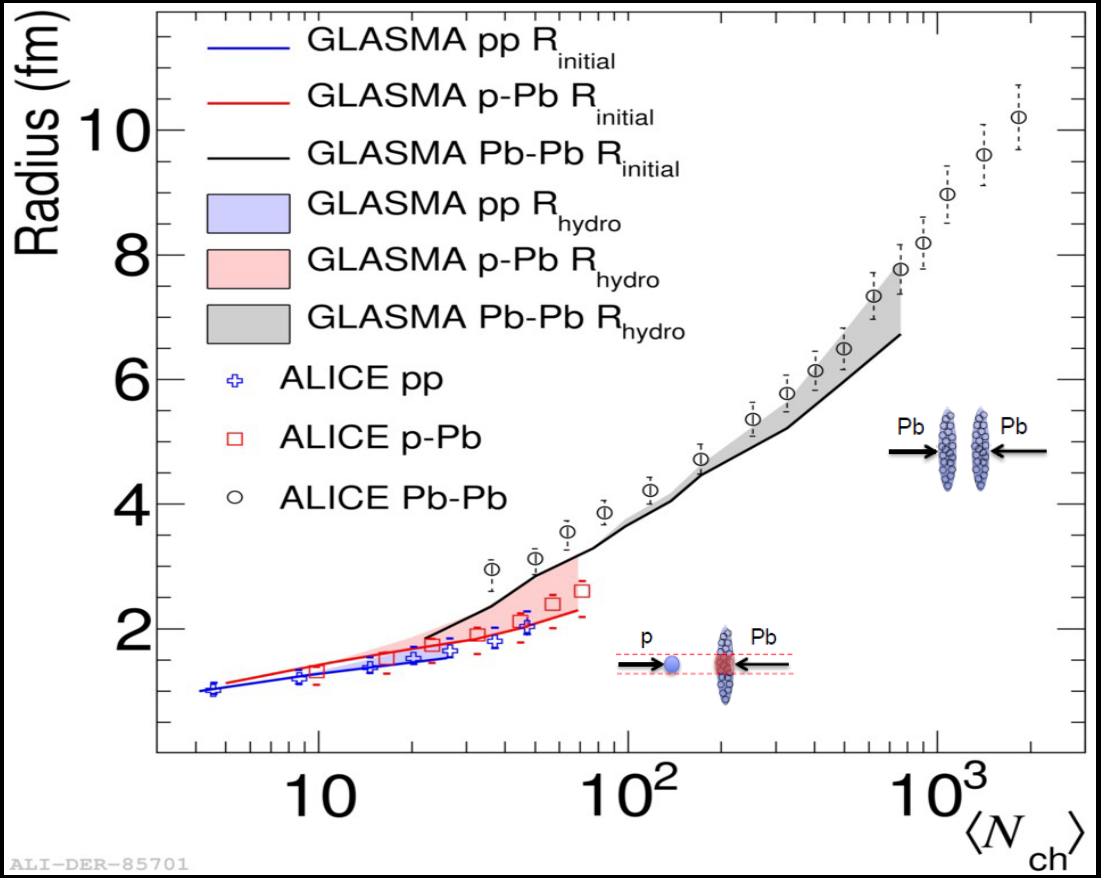
Invariant radii vs $<N_{ch}>$

– pp similar to pPb

– pPb smaller than PbPb

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

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



Schenke & Venugopalan,
PRL 113 (2014) 102301

Radii in pp and pPb can be reproduced by IPGLASMA Initial conditions alone

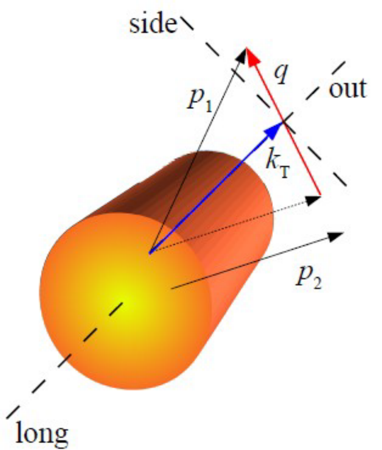
Radii in pPb can also be described by adding a hydrodynamic phase

* GLASMA result is scaled by 1.15 such that calculations match the pp ALICE data.

* Calculation has uncertainty due to infra-red cutoff (m=0.1 GeV).

Yang-Mills evolution in IPGLASMA reproduces difference

Evolution of p-Pb System

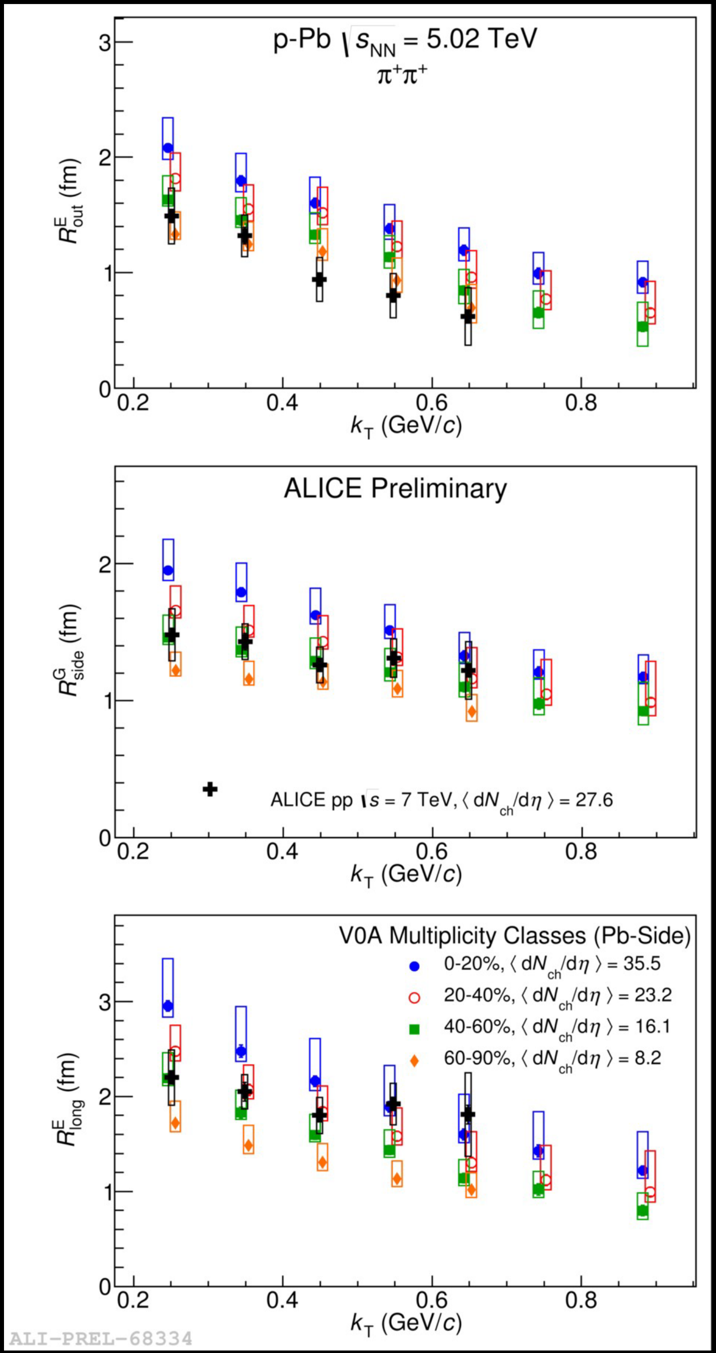


3d radii (Rout, Rside, Rlong)
in LCMS
from two-pion correlations

Radii decrease with increasing k_T
as in AA (and in hydro)

Similarity between pPb & high multiplicity pp

ALICE, PLB 739 (2014) 139



Summary from ALICE Freezeout Radii

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)

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 of spaghetti strings"

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

The Proton-Nucleus Enigma – Act 4

“Epilogue”

"What Have We Learned" from p-Pb at LHC

- p-Pb studies confirm quenching/suppression in Pb-Pb is final state effect

- p-Pb hard probes described by pQCD-inspired models

  Exception – High p_T jets (peripheral enhanced! Central suppressed!)

- Many aspects of p-Pb (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-Pb than in Pb-Pb

  p-Pb close to pp at similar multiplicity – important to understand theoretically

- Need more theoretical guidance, direct model comparisons, more precise data (and similar multiplcities)!

Thanks for your attention!