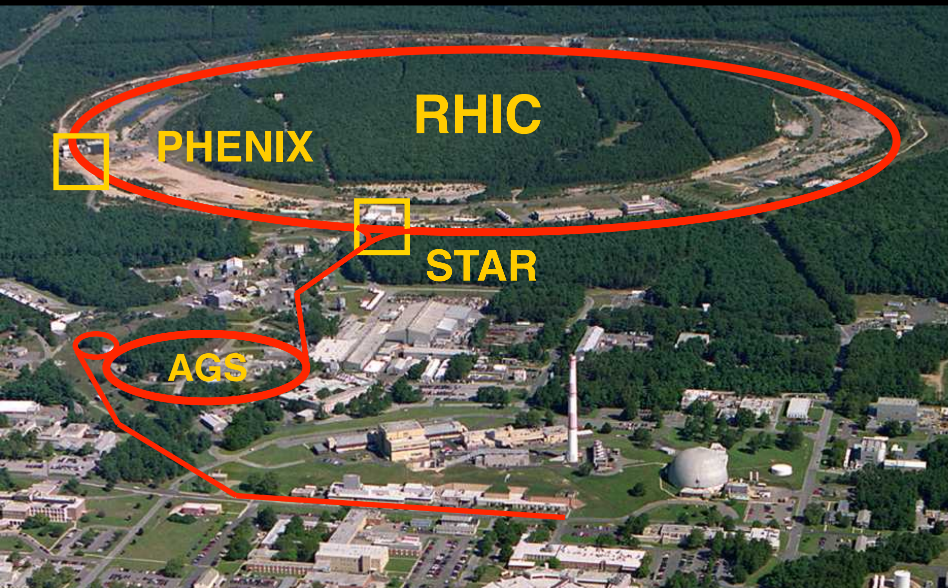
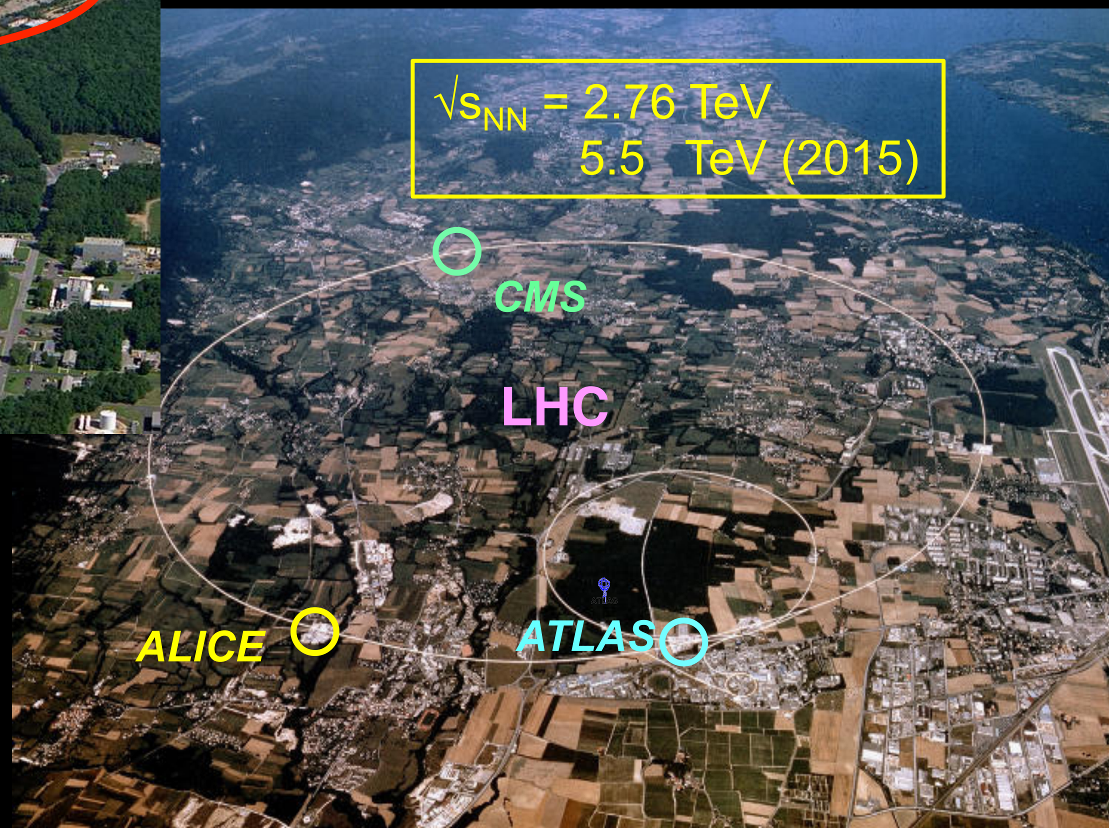
Results with "Hard Probes" – High p_T Particle & Jet Suppression from RHIC to LHC



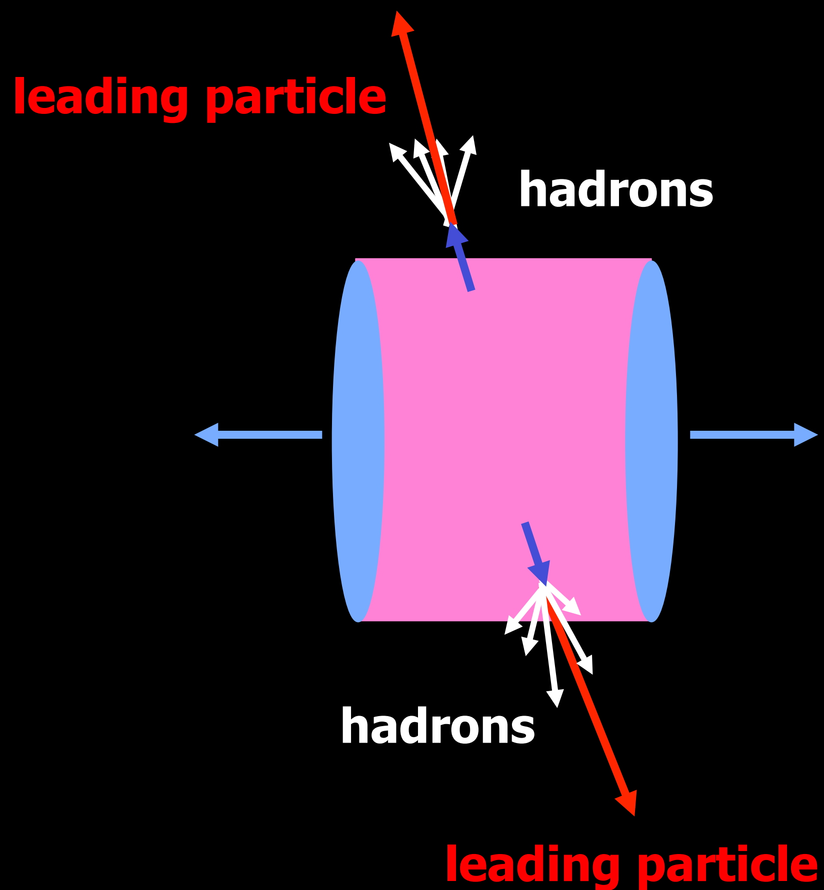
$\sqrt{s_{NN}}$ = 5 - 200 GeV

Cover 3 decades of energy in center-of-mass



Investigate properties of **hot QCD matter** at T ~ 150 – 1000 MeV!

Probing Hot QCD Matter with "Hard-Probes"

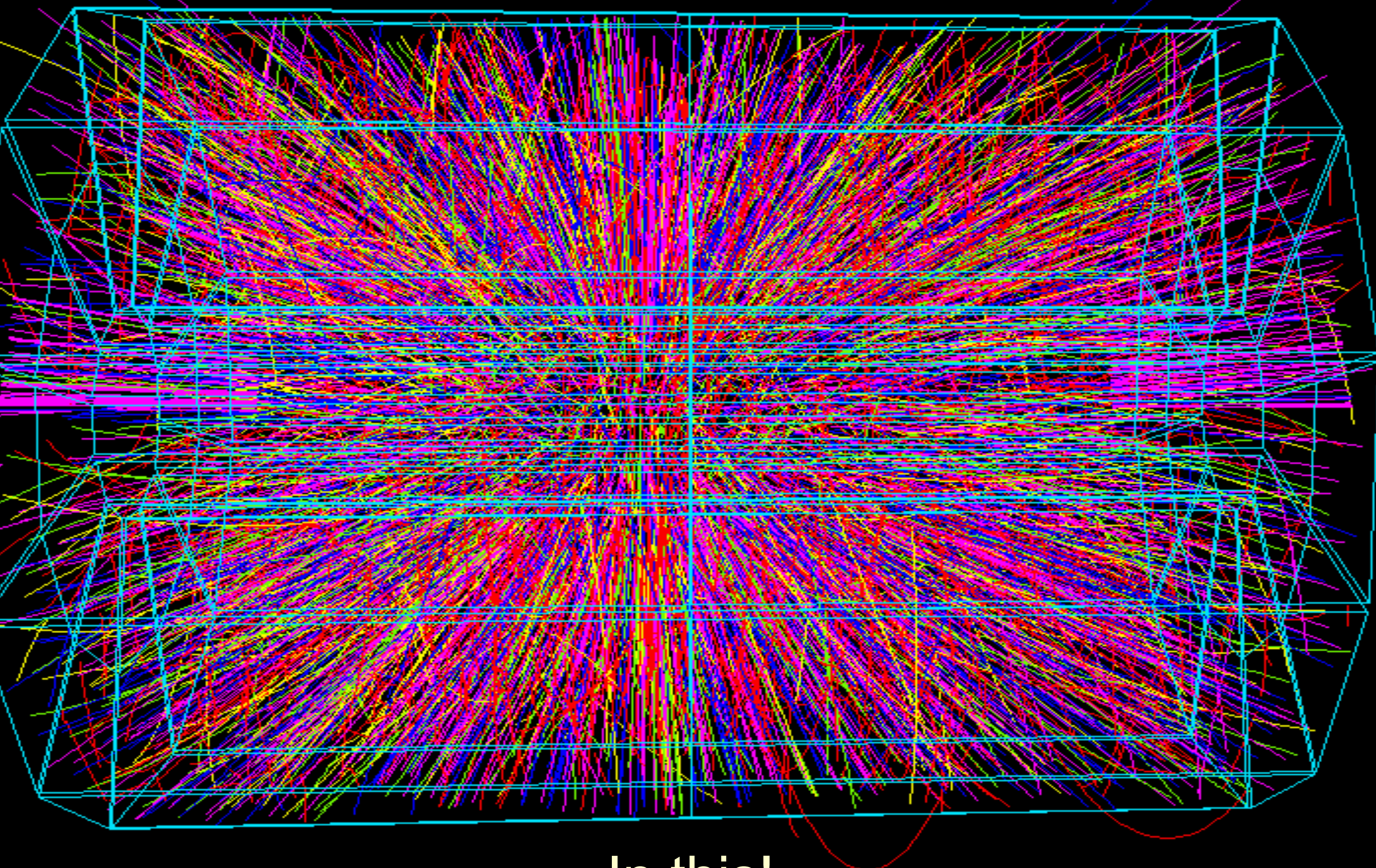


Initial Hard Parton Scattering
- gluon-gluon
- gluon-quark
- quark-quark

→ **Hard Probes**
- Large "p_T" partons
- Heavy quark – anti-quark

This is what we wish to "see" and investigate!

Probing Hot QCD Matter with "Hard-Probes"

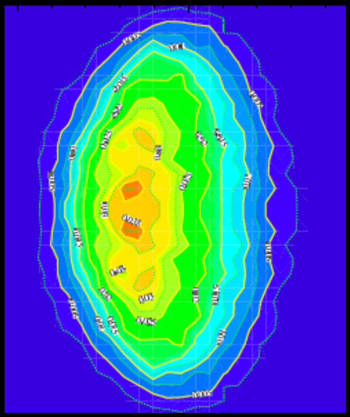


ng

ark

In this!

Hard Processes



In QCD:

Highly penetrating probes originate from hard processes.

In QCD hard processes are those where perturbative QCD is applicable and are characterized either by:

- large momentum transfer Q^2
  (→ 4-momentum transfer squared)
- large transverse momentum p_T
- large mass m scale
  (e.g. heavy quark production also at low p_T)

Why Study pp, pA (dA) & A-A Collisions?

Can pp, pA (or dA) and A-A all be understood in a consistent framework?

- Can we separate the initial state from final state? (Is it even possible?)
  Is the initial state composed of gluon fields?
  Is it saturated? Is it a CGC?

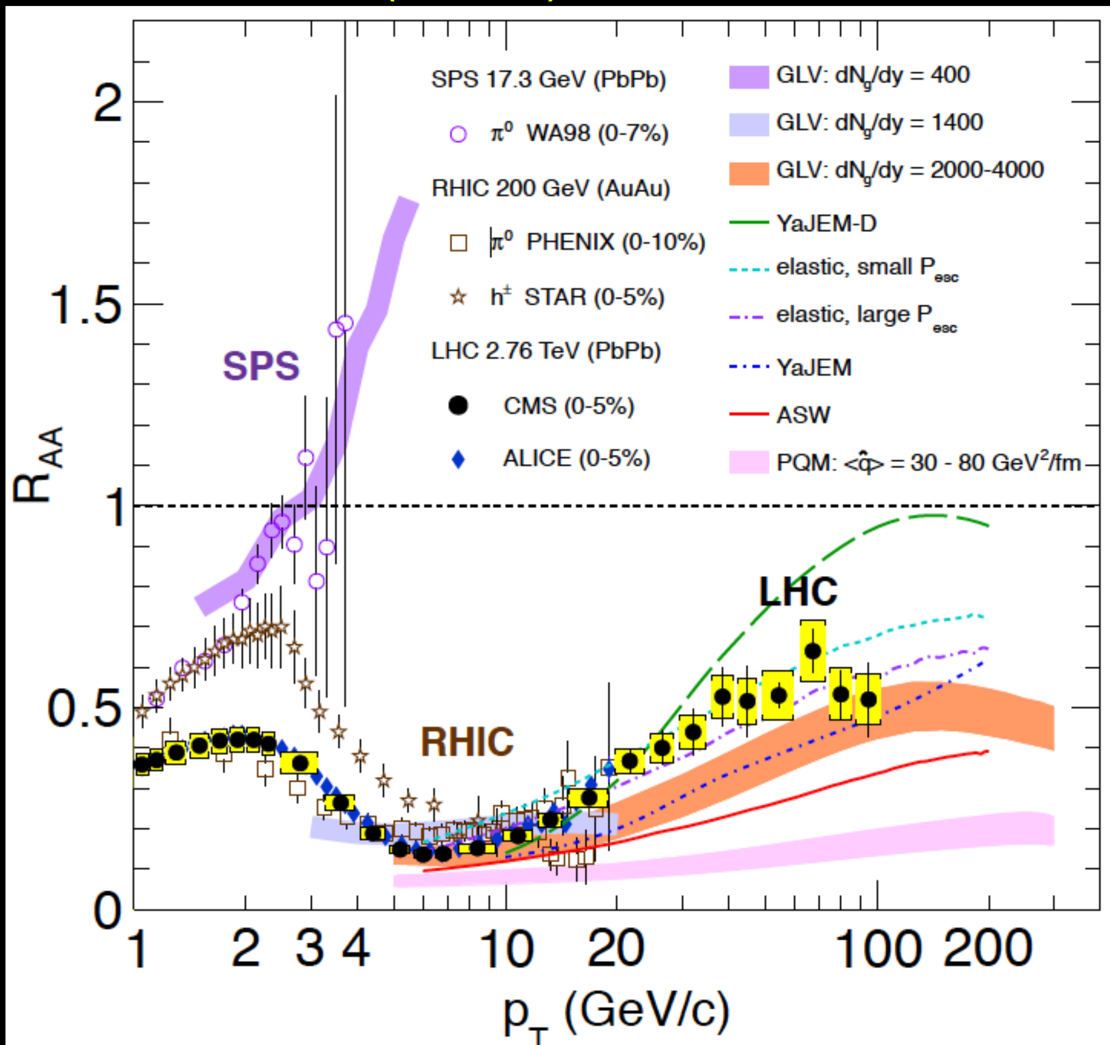
- What is the effect of cold nuclear matter (on final state observables)?

- Can we understand multiplicity and energy dependence of pA & AA?
  e.g. compare high mult pA at LHC & same mult AA at LHC & RHIC

- Can we extract information on parton energy loss mechanisms?

RHIC and LHC Suppression of Charged Particles

Pb-Pb (Au-Au) Central Collisions



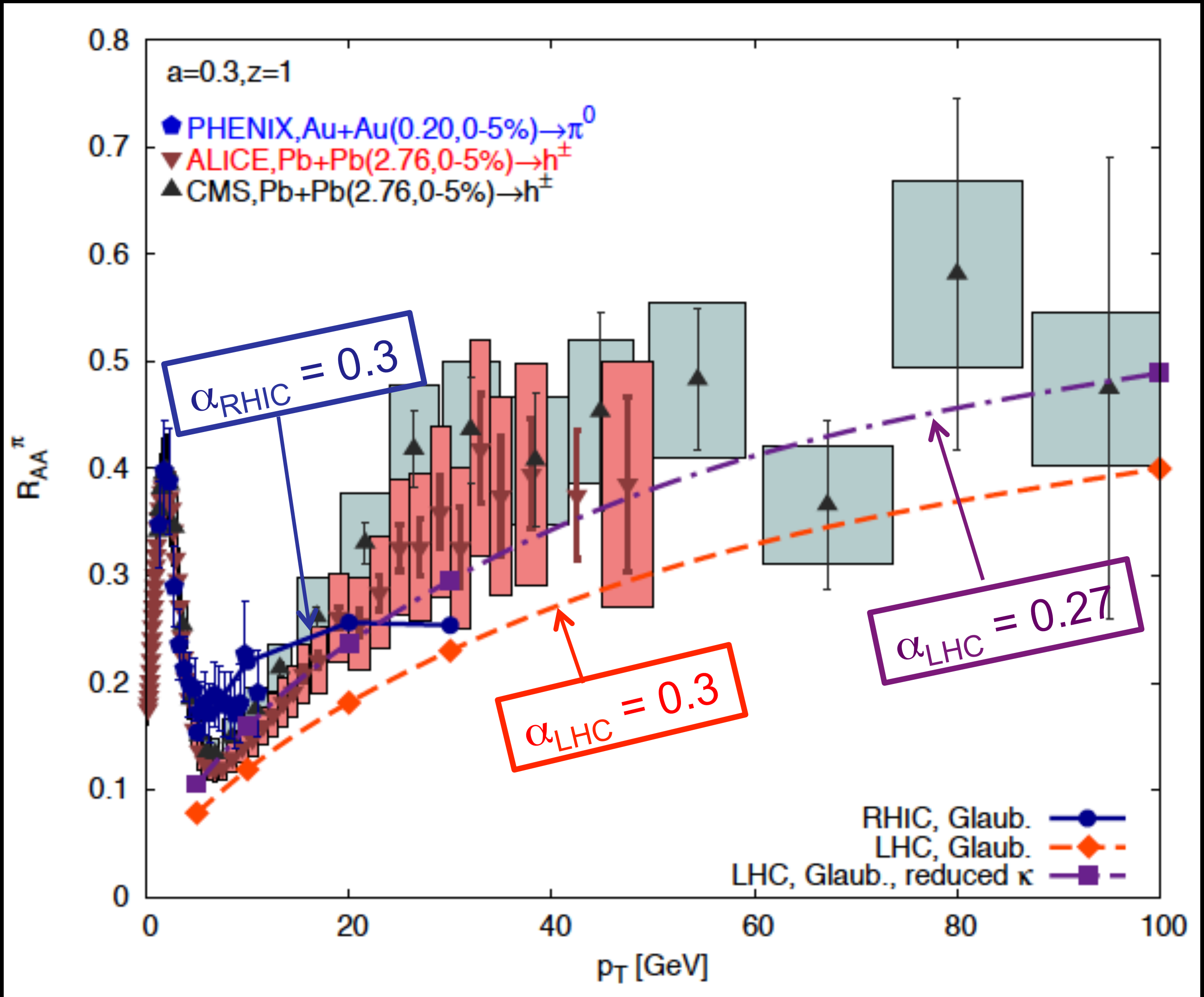
CMS, arXiv:1202.2554v1

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

$R_{AA} = 1$

Suppression

Reduced α_s Describes LHC Trend



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

R_{AA} at LHC in pQCD:

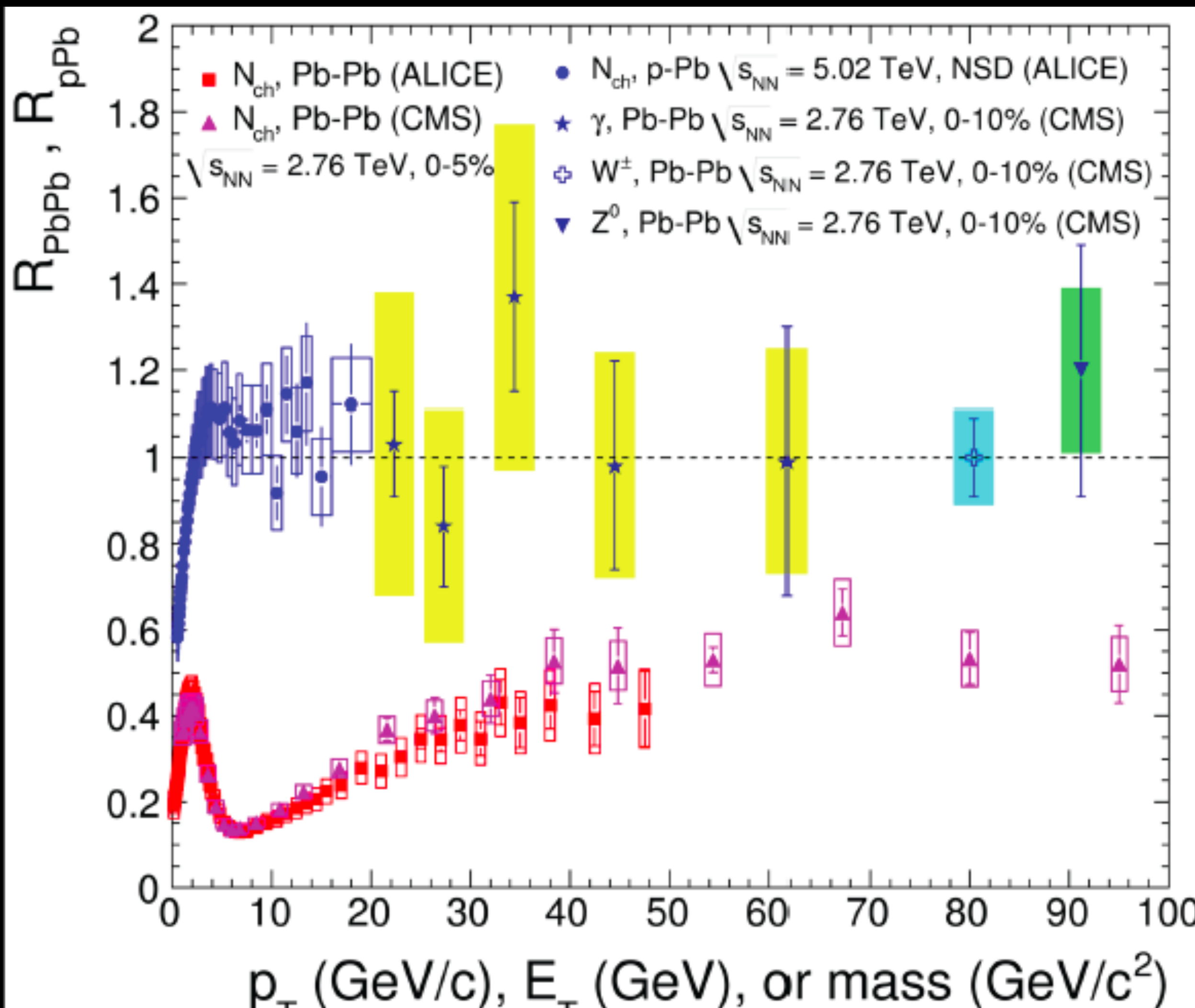
Suppression described with reduced α_s!

Some details remain.

B. Betz & M. Gyulassy, arXiv:1201.0281

At LHC – Hadrons at Very Large p_T Suppressed, Photons, W, Z Are NOT!!!

Deviations from binary scaling of hard collisions:

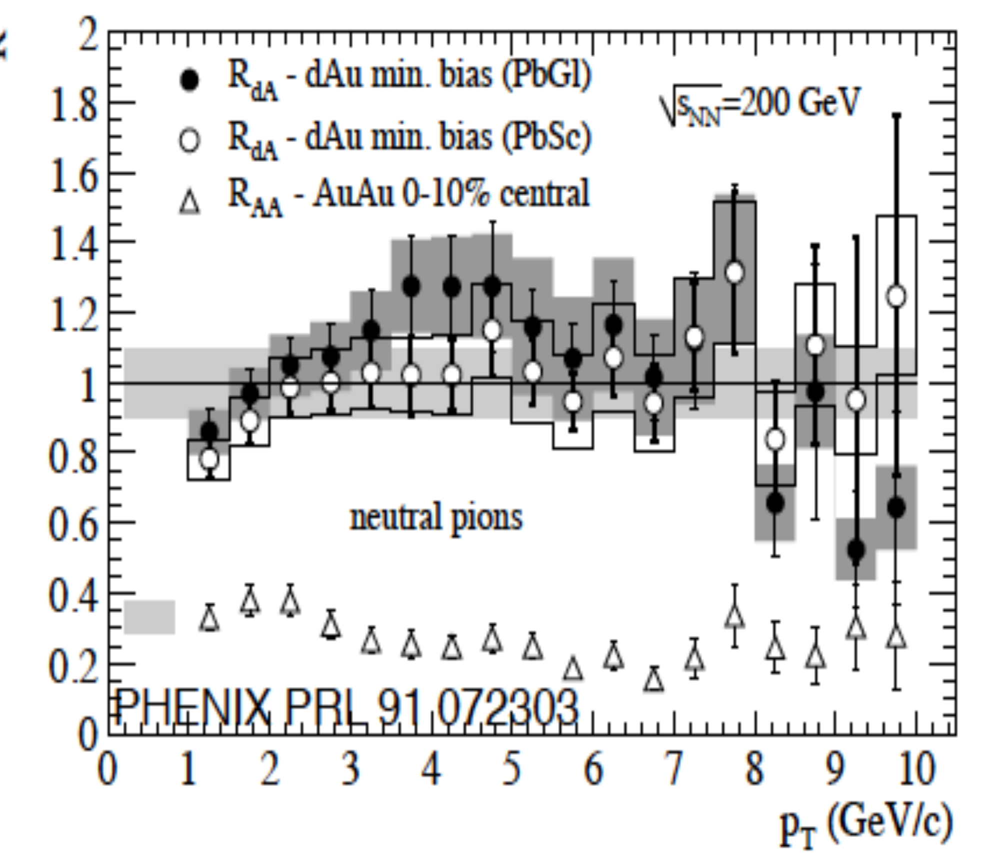


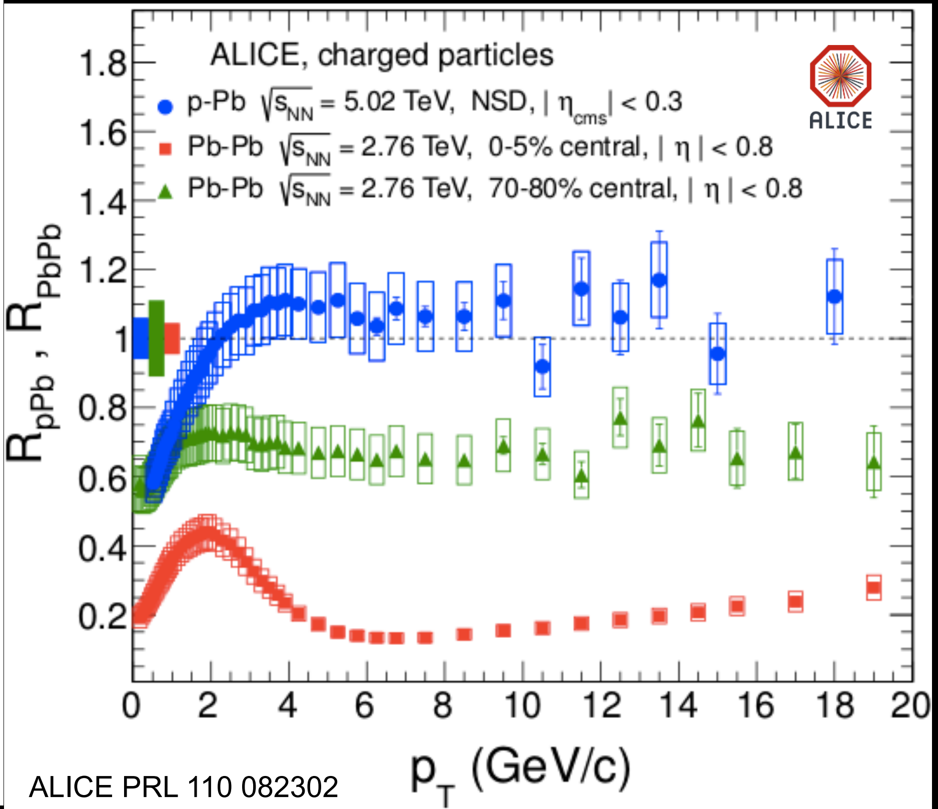
$$R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$$

Pb-Pb → Photons, W, Z
(p-Pb → charged)

Pb-Pb → charged (factor 2 – 5 suppression)

$R_{p(d)A}$ and R_{AA} Comparison RHIC and LHC





ALICE PRL 110 082302

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

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

RHIC Au-Au and LHC Pb-Pb

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

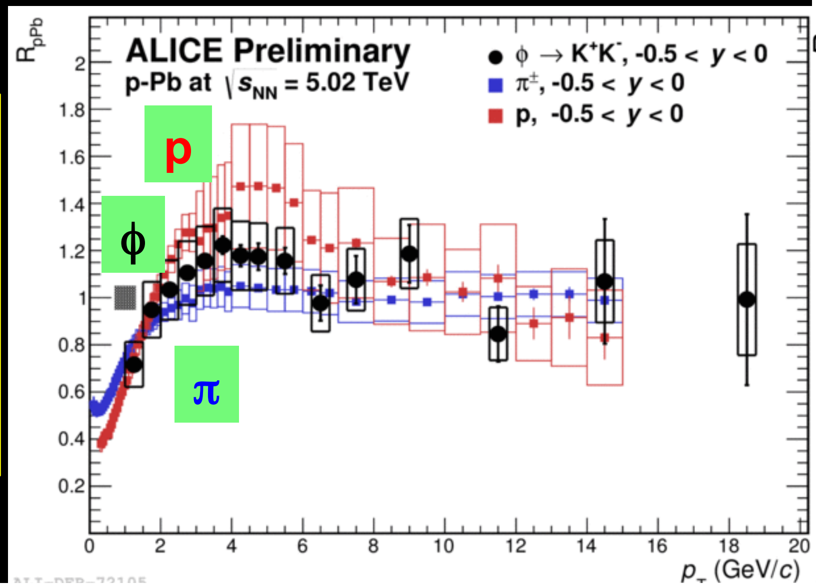
R_{pPb} for Different Particles at LHC

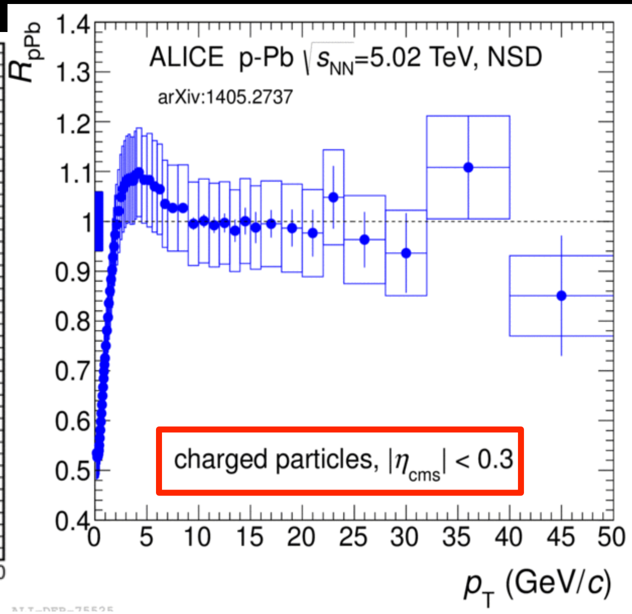
$R_{pPb} \rightarrow$ charged particles
proton enhancement

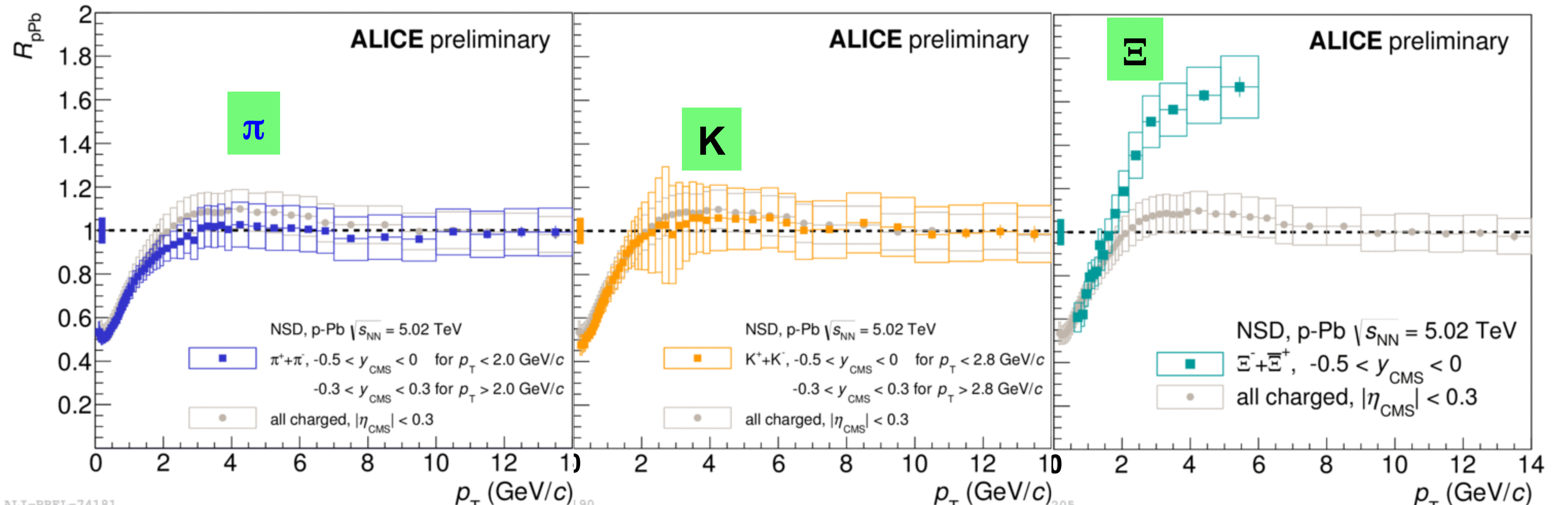
R_{pPb}
π & K is ~ flat ~ 1

R_{pPb}
ϕ slight enhancement

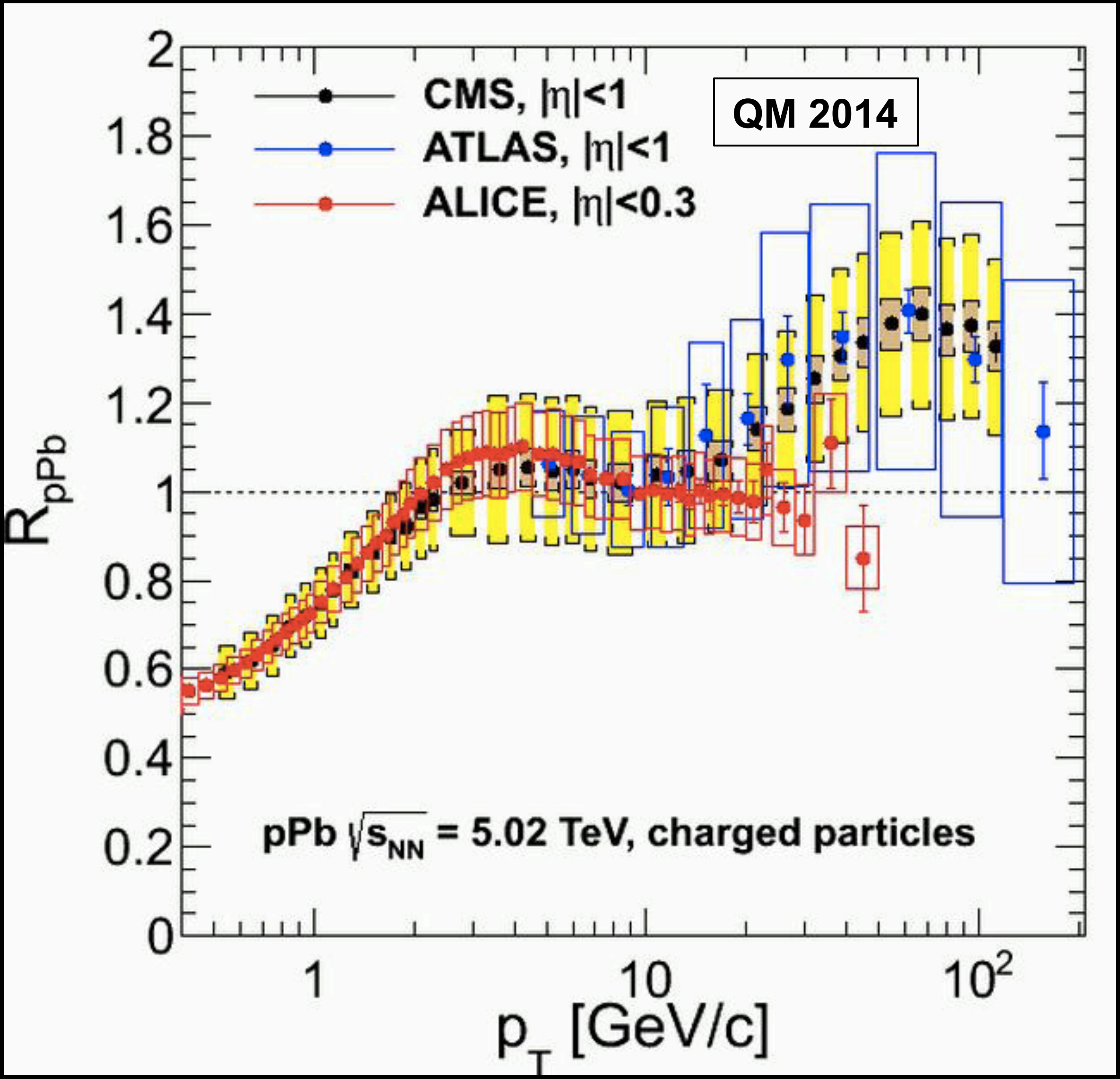
M. Knickel, ALICE QM14







p-Pb → Hadrons at Higher p_T at LHC???



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

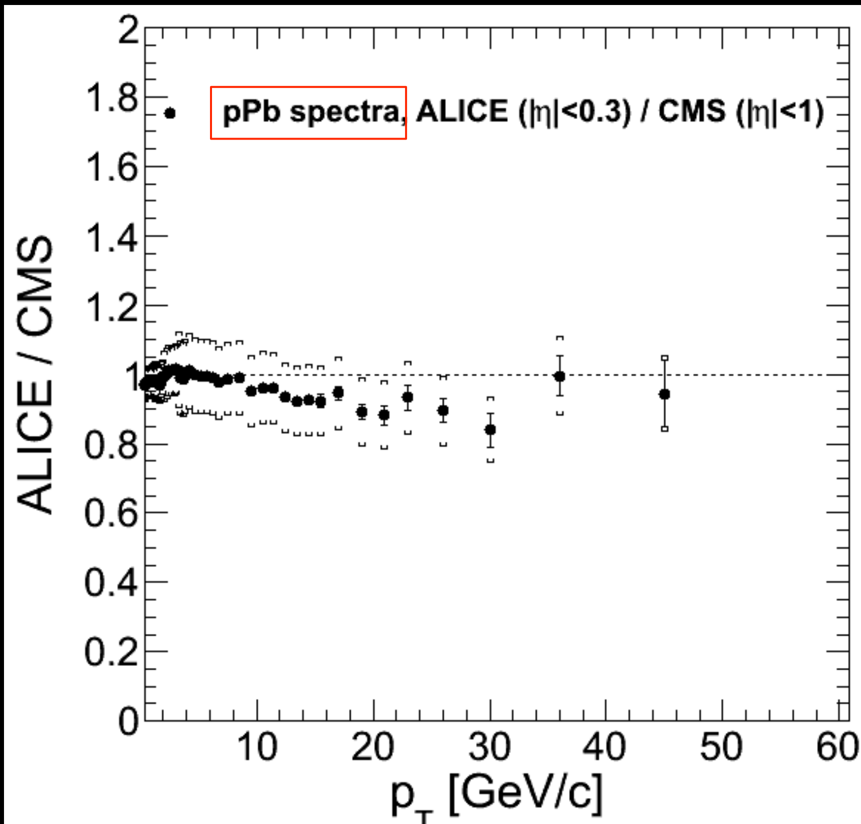
p-Pb $2 < p_T < 20$ GeV/c

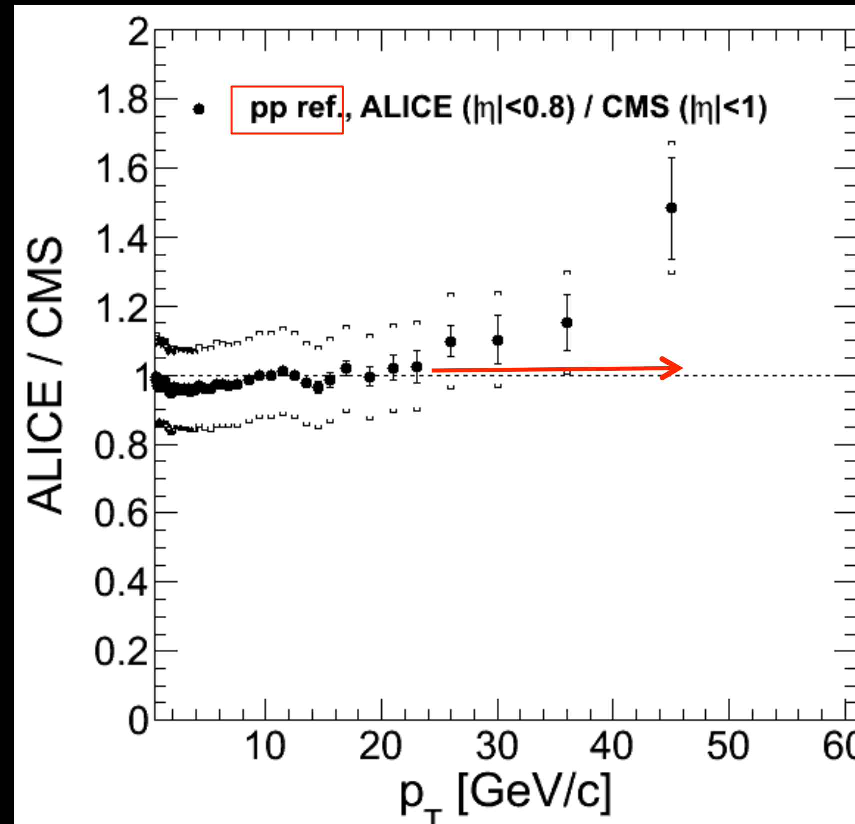
- Binary scaling ($R_{pPb} \sim 1$)
- Absence of Nuclear Modification

p-Pb $20 < p_T < 150$ GeV/c

- CMS/ATLAS enhancement?
- ALICE data disagree

Comparison p-Pb, pp → Hadrons at LHC???



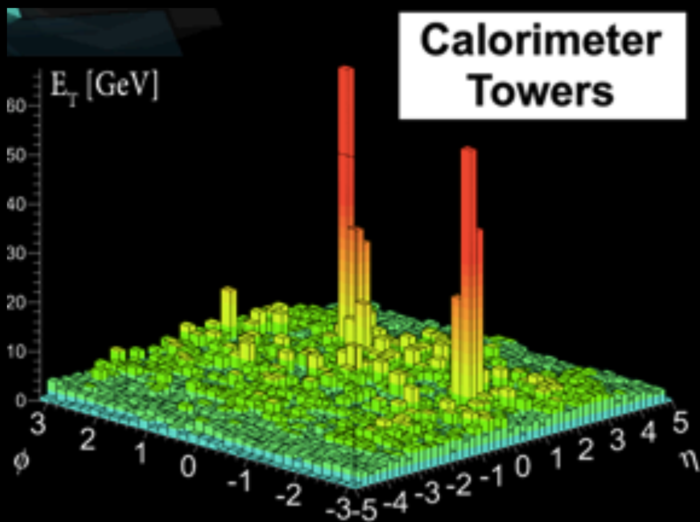


p-Pb → spectra $2 < p_T < 50$ GeV/c
- ALICE/CMS agree

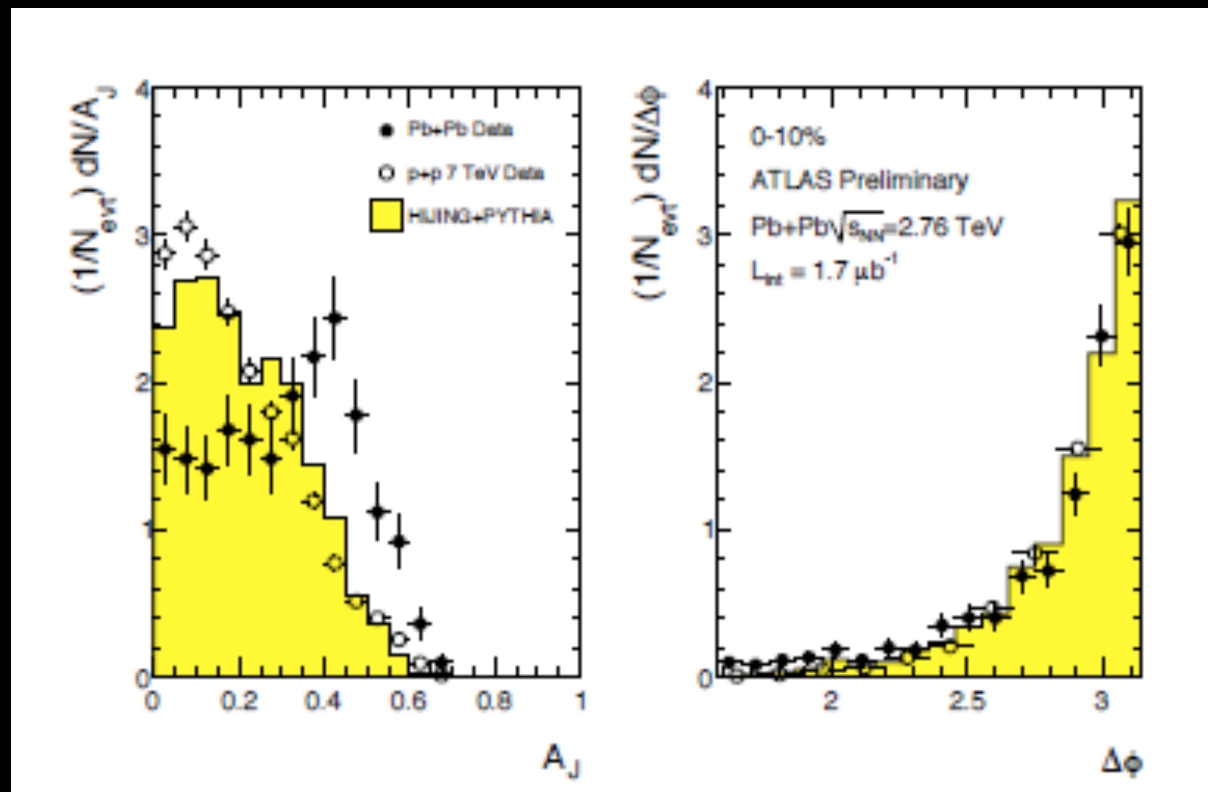
pp → spectra $2 < p_T < 50$ GeV/c
- pp reference differences $p_T > 25$ GeV/c
- Need pp reference at 5.02 TeV

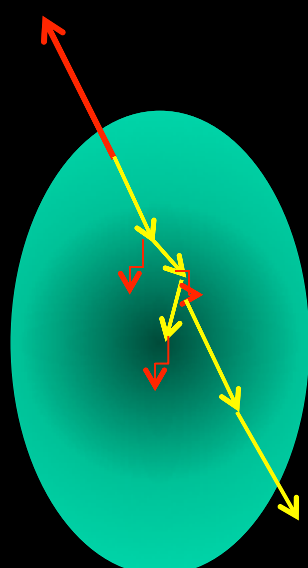
Y-J Lee, QM 2014

Jets at the LHC – Di-Jet Energy Imbalance!



ATLAS, Phys. Rev. Lett. 105 (2010) 252303





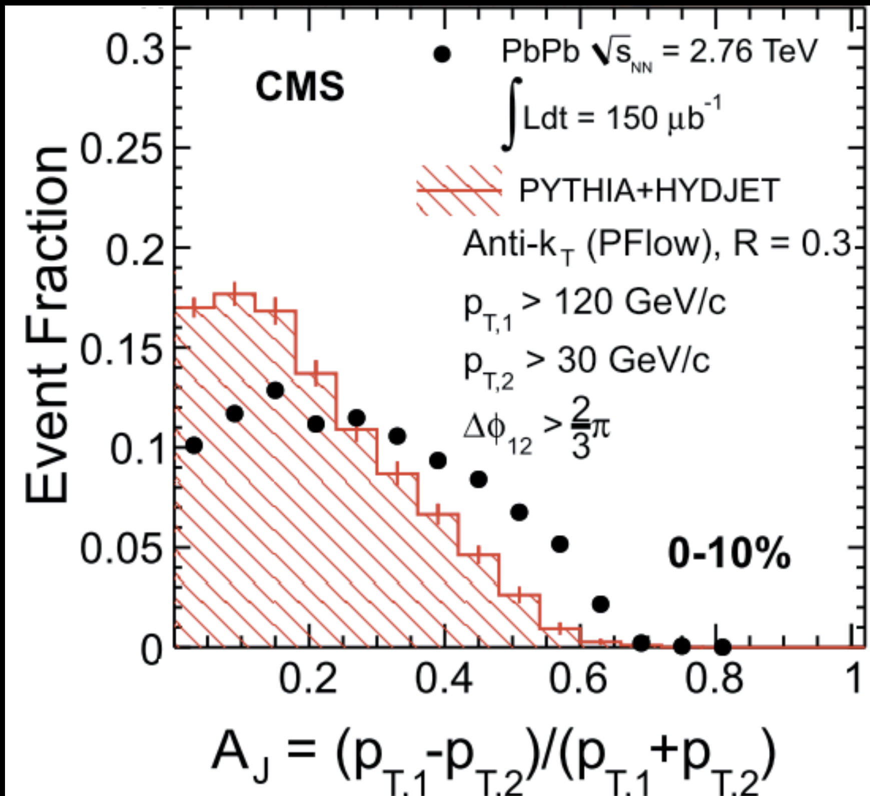
Energy Asymmetry: $A_J = E_{T1} - E_{T2}\ /\ E_{T1} + E_{T2}$

for $\Delta\phi > \pi/2$

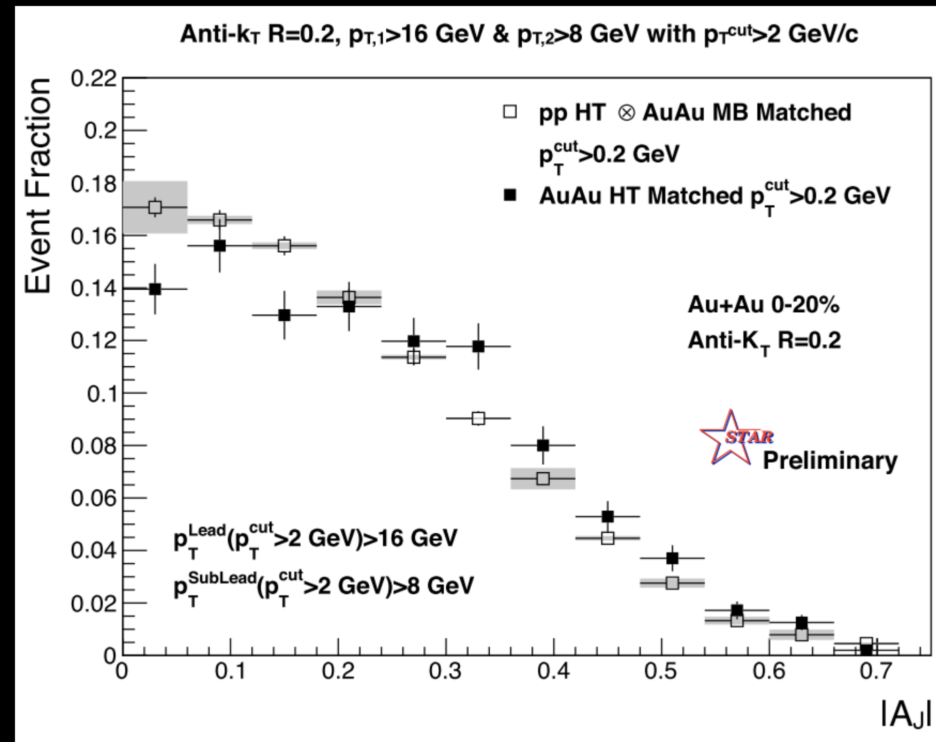
(E_{T1} > 100 GeV, E_{T2} > 25 GeV)

Jets at LHC & RHIC – Di-Jet Imbalance!

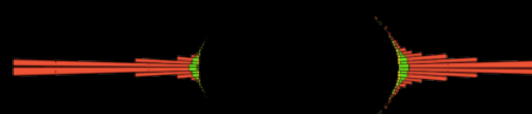
LHC CMS, Phys. Rev. C84 (2011) 024906
QM 2014

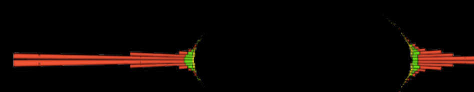


RHIC STAR, QM 2014



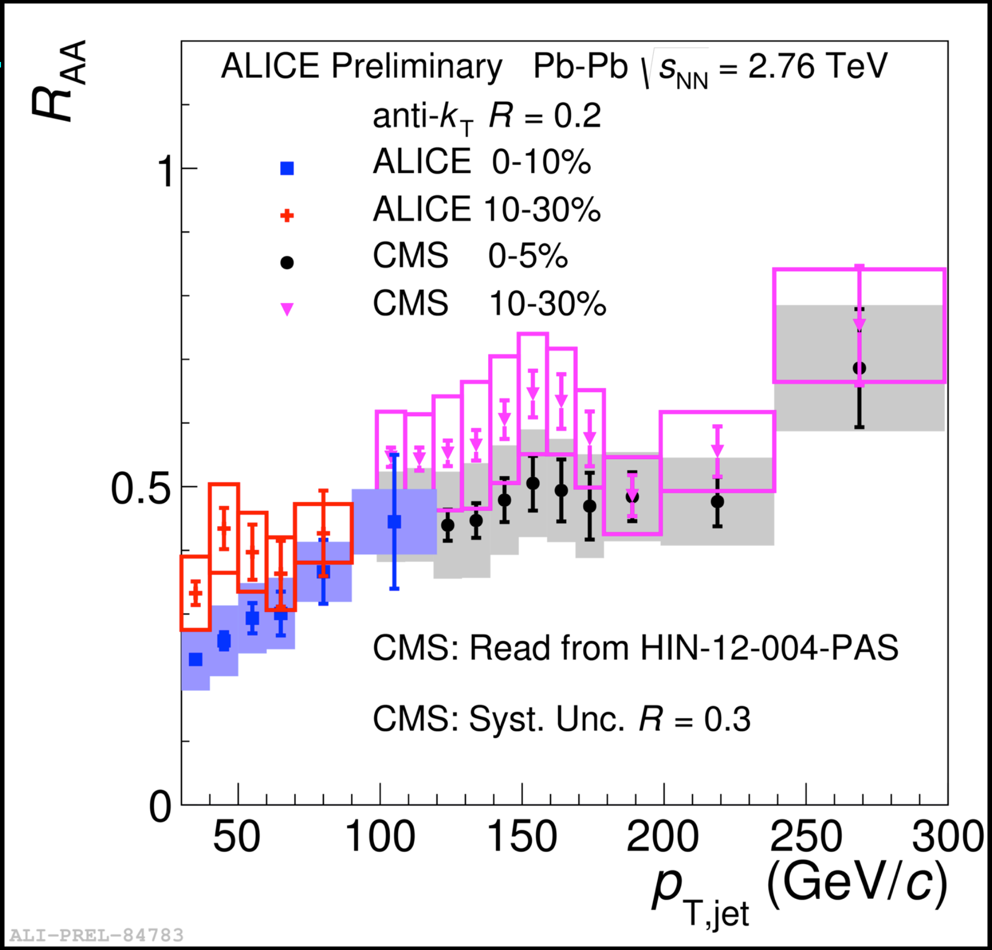
Asymmetry: $A_J = p_{T1} - p_{T2}$ / $p_{T1} + p_{T2}$ for $\Delta\phi > \pi/2$

$A_J \rightarrow 0$  balanced

$A_J \rightarrow 1$  imbalance

Momentum and Centrality Dependence of Jet Quenching

LHC   ALICE, CMS QM 2014



p_T-dependence of jet quenching

Lower p_T jets more strongly quenched

centrality-dependence

jets in more central collisions more strongly quenched

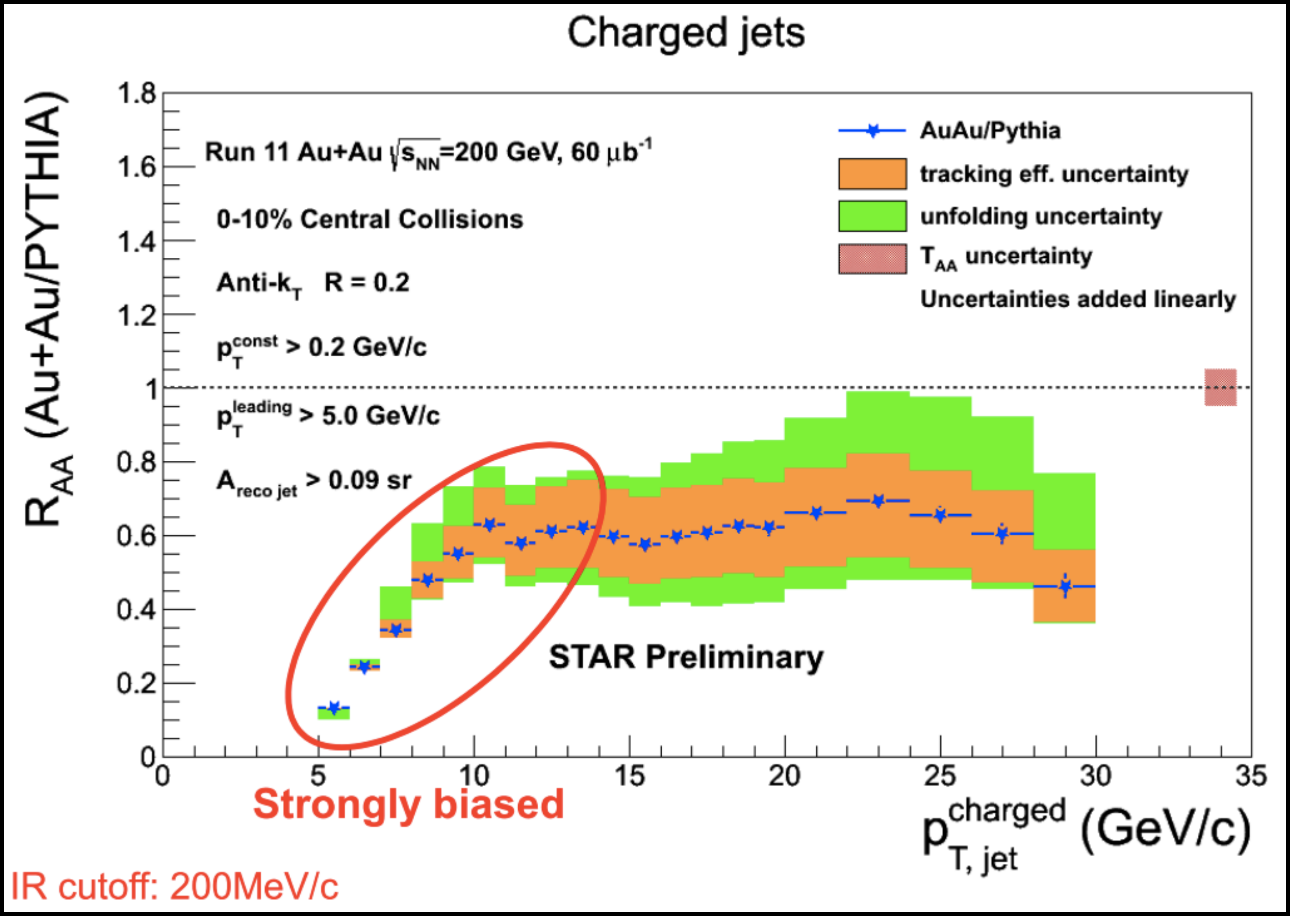
ALICE R_{AA}(jet) ~ CMS R_{AA}(jet)

at overlap

Jet Quenching at RHIC

RHIC

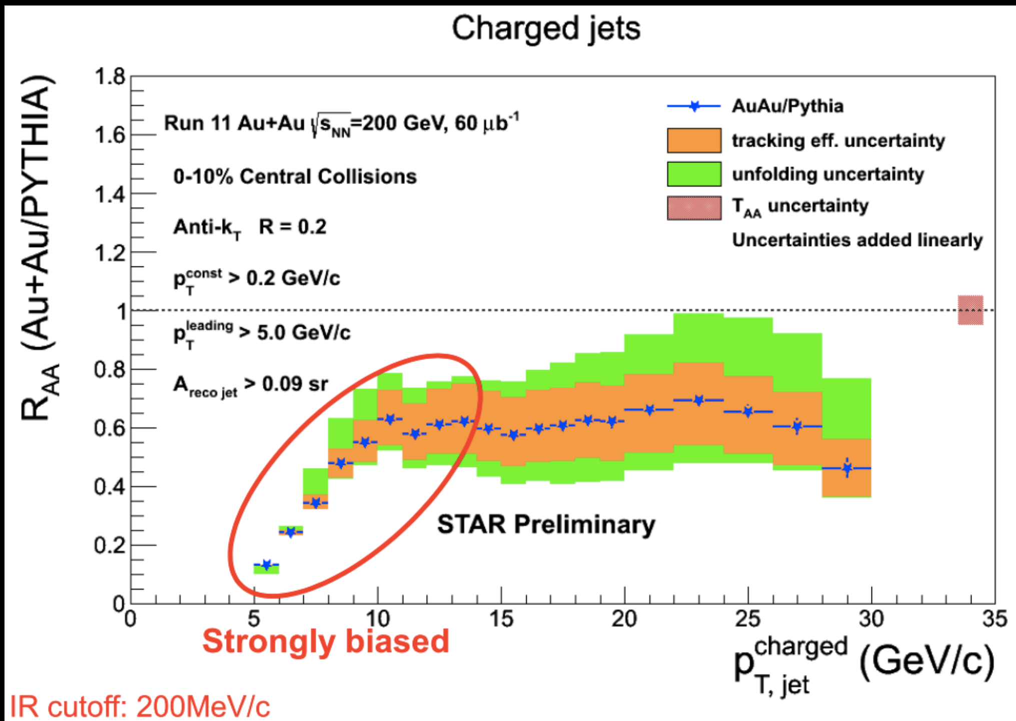
J. Rusnak, STAR
HP 2013

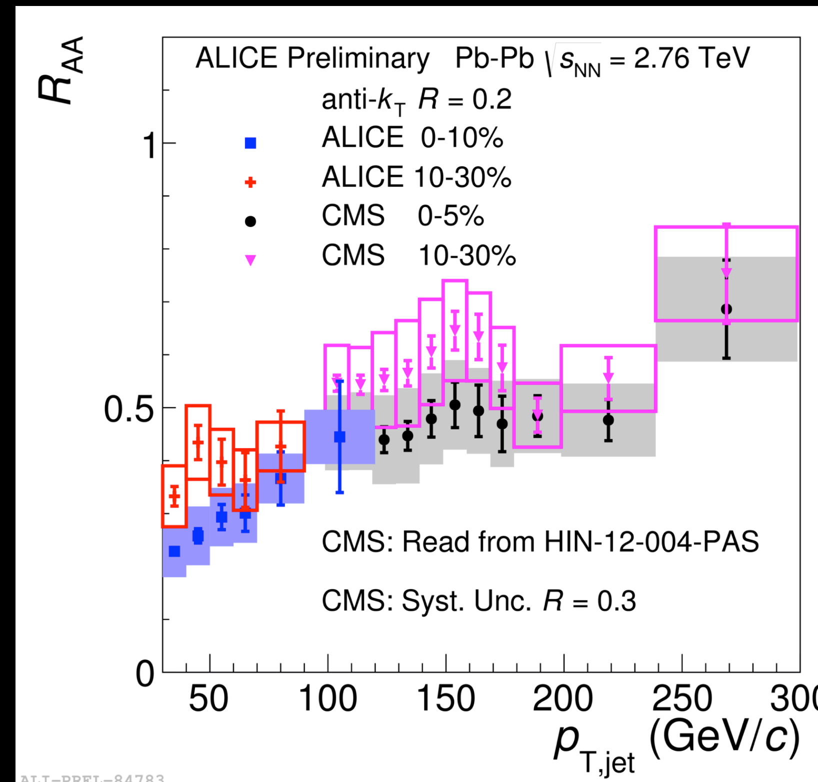


At RHIC: Jets are less suppressed than high p_T particles
$R_{AuAu}(\pi)$ ~ 0.2 – 0.3 for p_T = 4 – 20 GeV/c
→ suggests modification of fragmentation function!

Jet Quenching at RHIC vs LHC

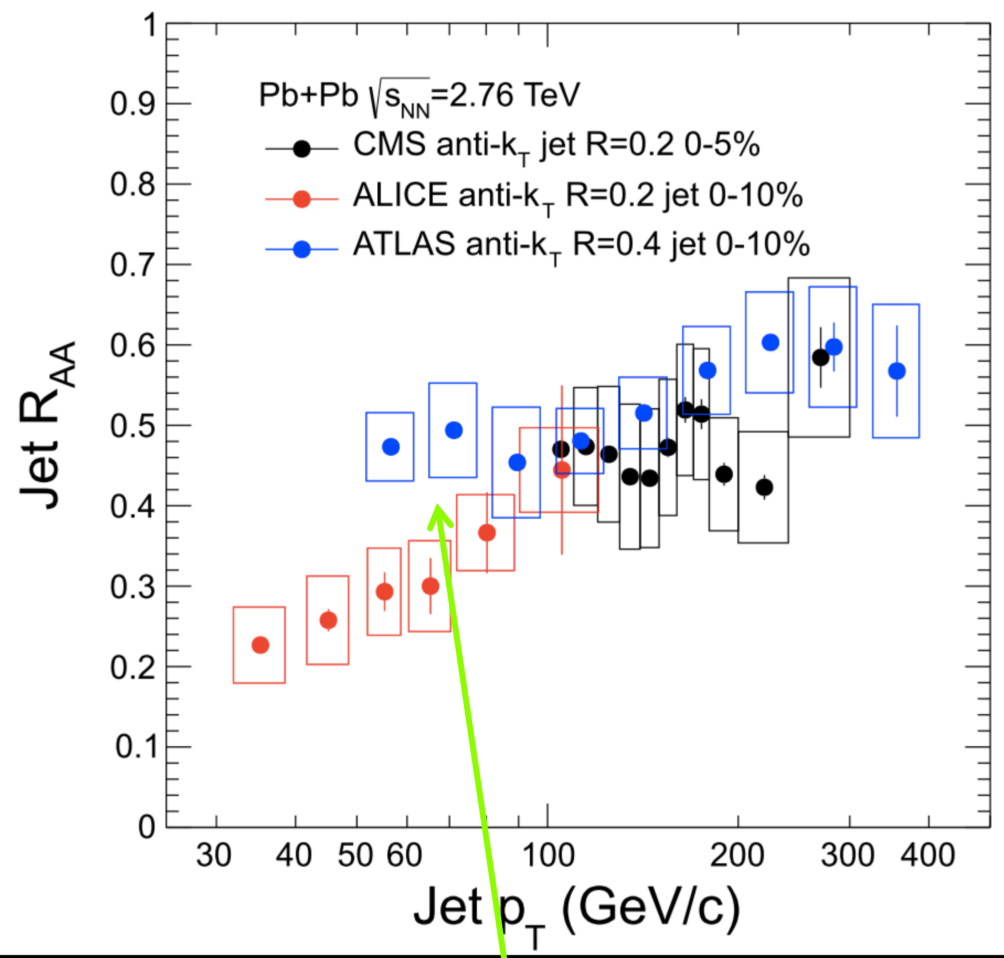
RHIC





RHIC Jets less suppressed than LHC Jets
at low jet momentum

Momentum Dependence of Jet Quenching



ALICE

ATLAS QM 2014

CMS (black)

ALICE R_{AA}(jet) ≠ ATLAS R_{AA}(jet)

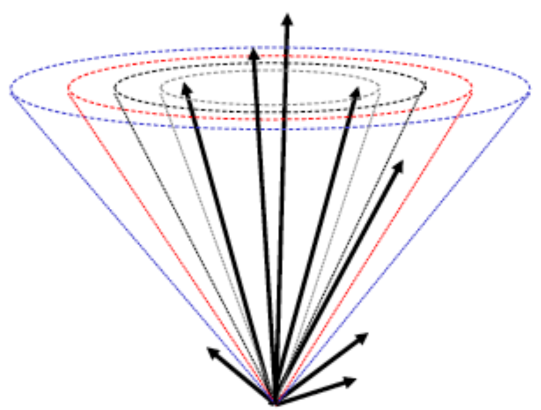
at lower jet p_T

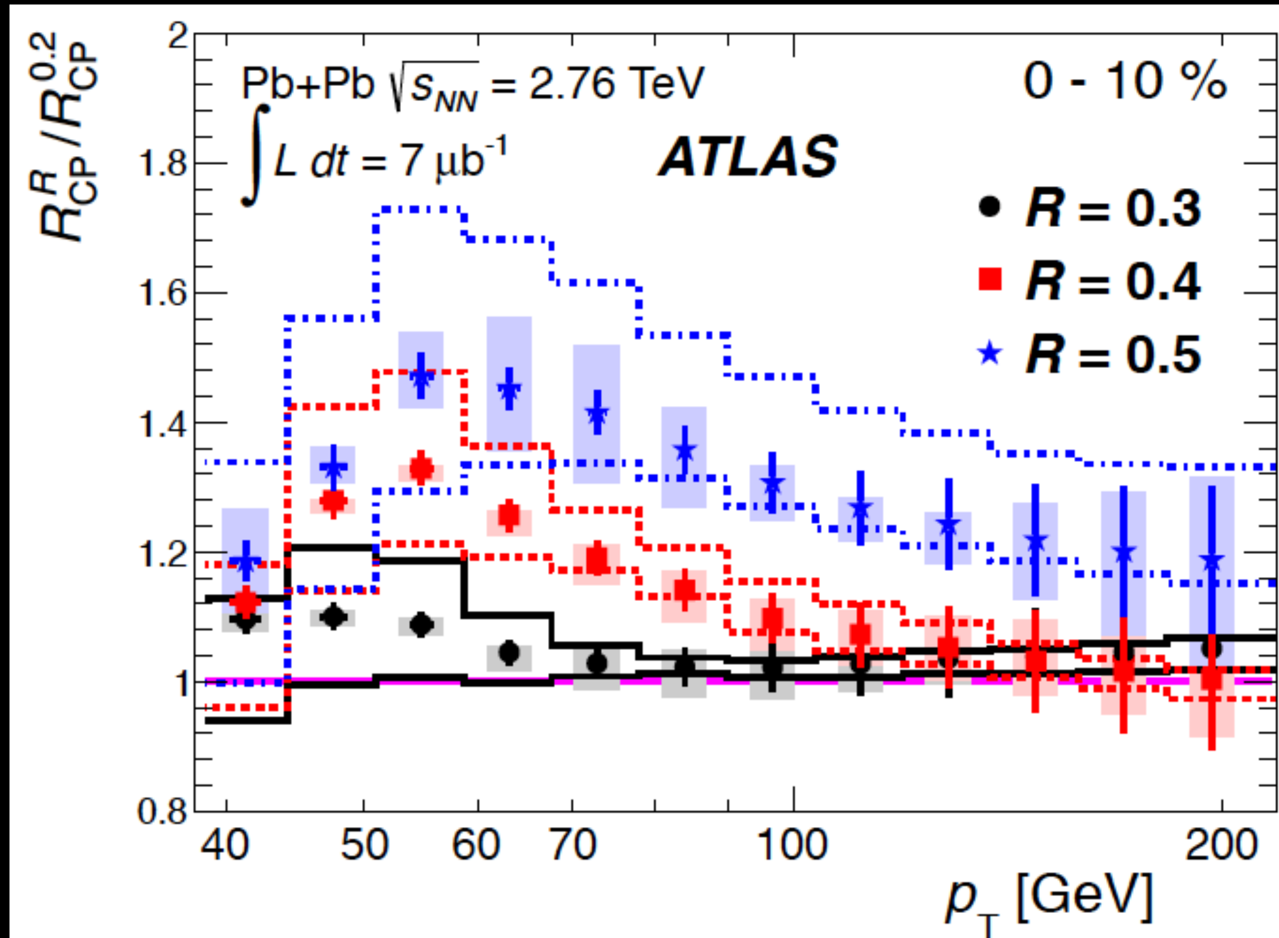
But: ALICE R=0.2 vs ATLAS R=0.4

R – "cone size" Dependence of Jet Quenching

ATLAS HP 2013

Anti-k_T jet "cone sizes":
R = 0.2, 0.3, 0.4, 0.5



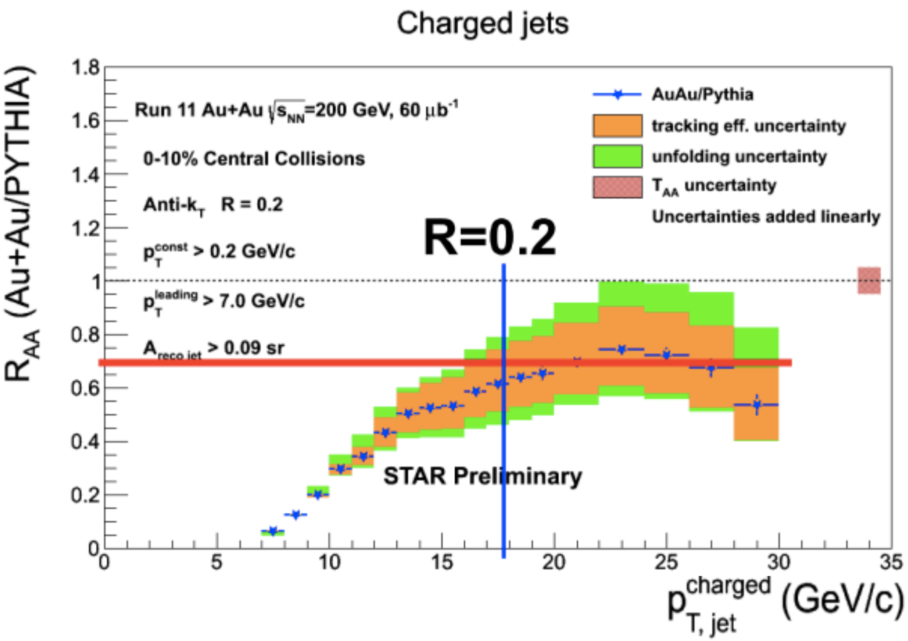


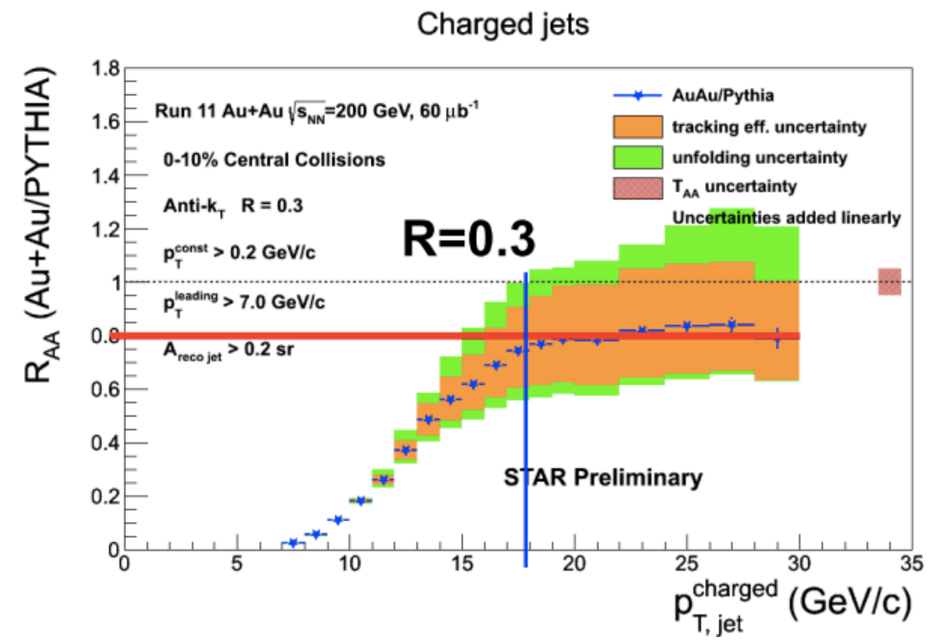
R^R_{CP} / $R^{0.2}_{CP}$ increases for larger R

→ more jet energy in larger cones, especially below 100 GeV

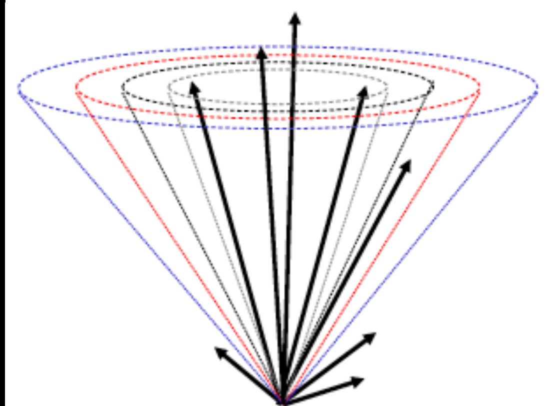
→ thus, jet shape changes in central Pb-Pb compared to pp

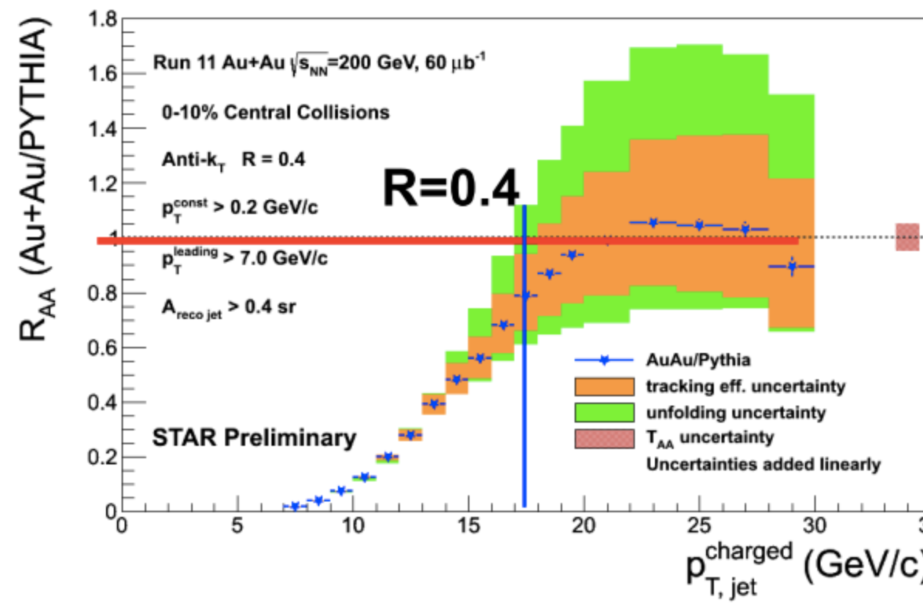
R – “cone size” Dependence of Jet Quenching





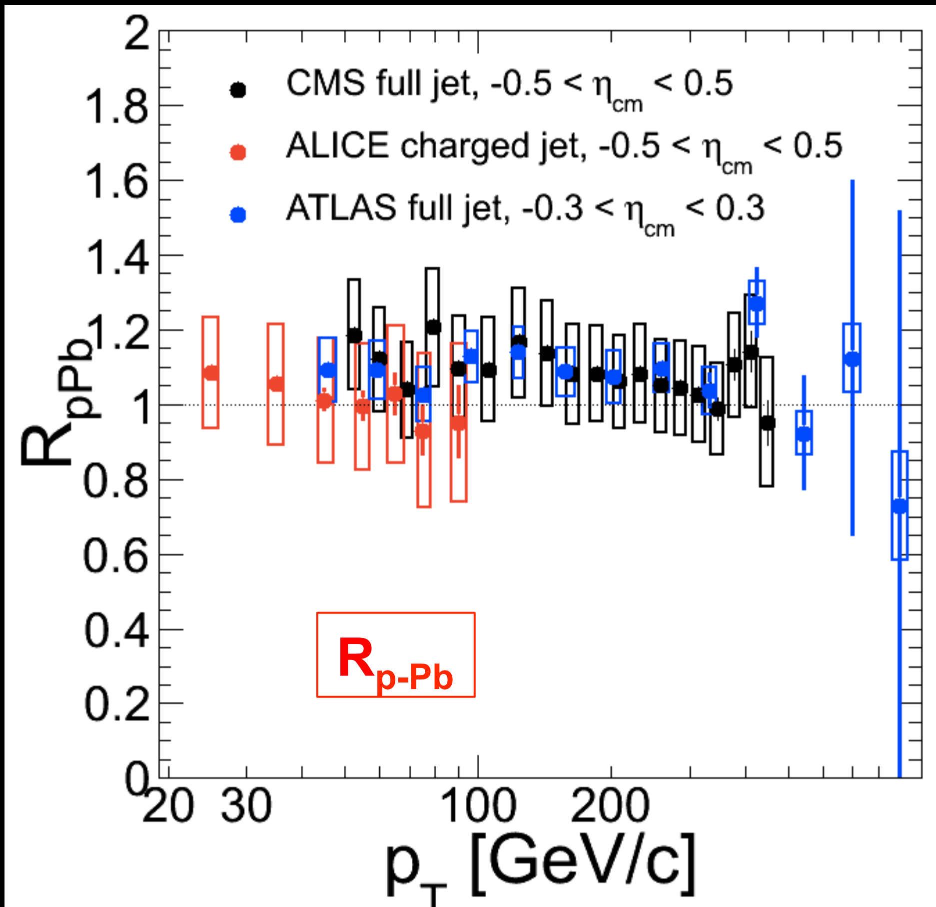
STAR
Au+Au

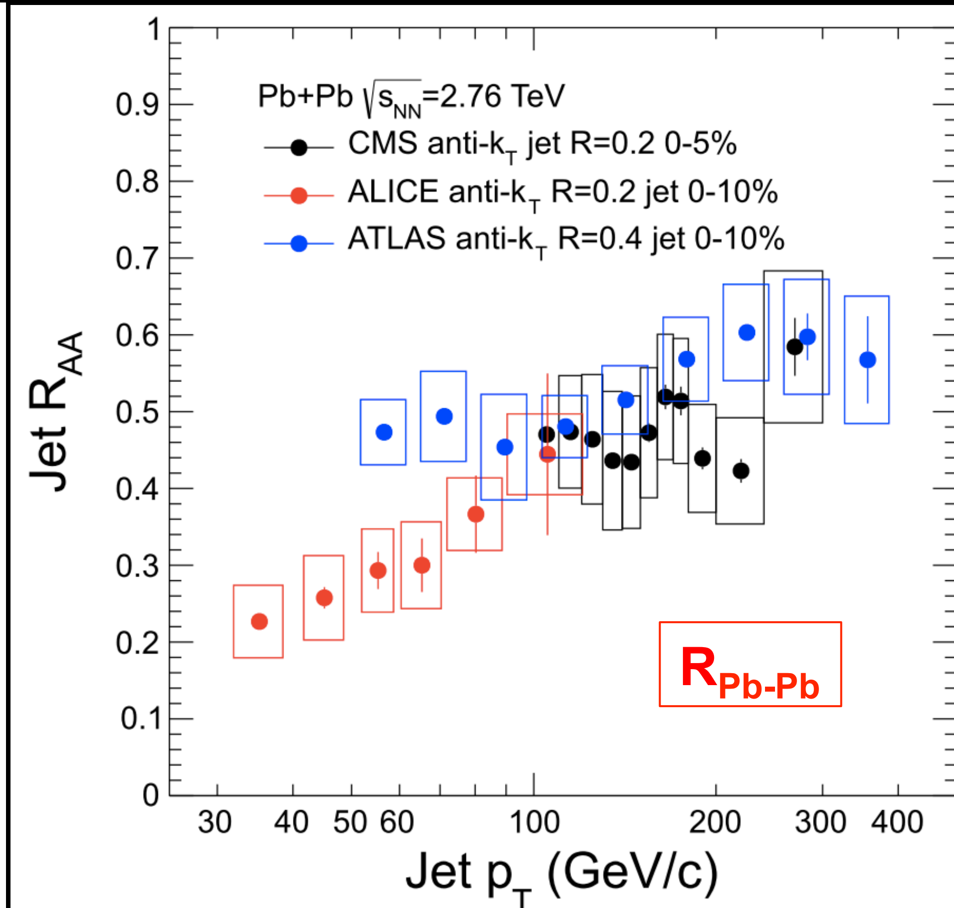




ALICE
ATLAS QM 2014
CMS (black)

Jet R_{p-Pb} & R_{Pb-Pb}



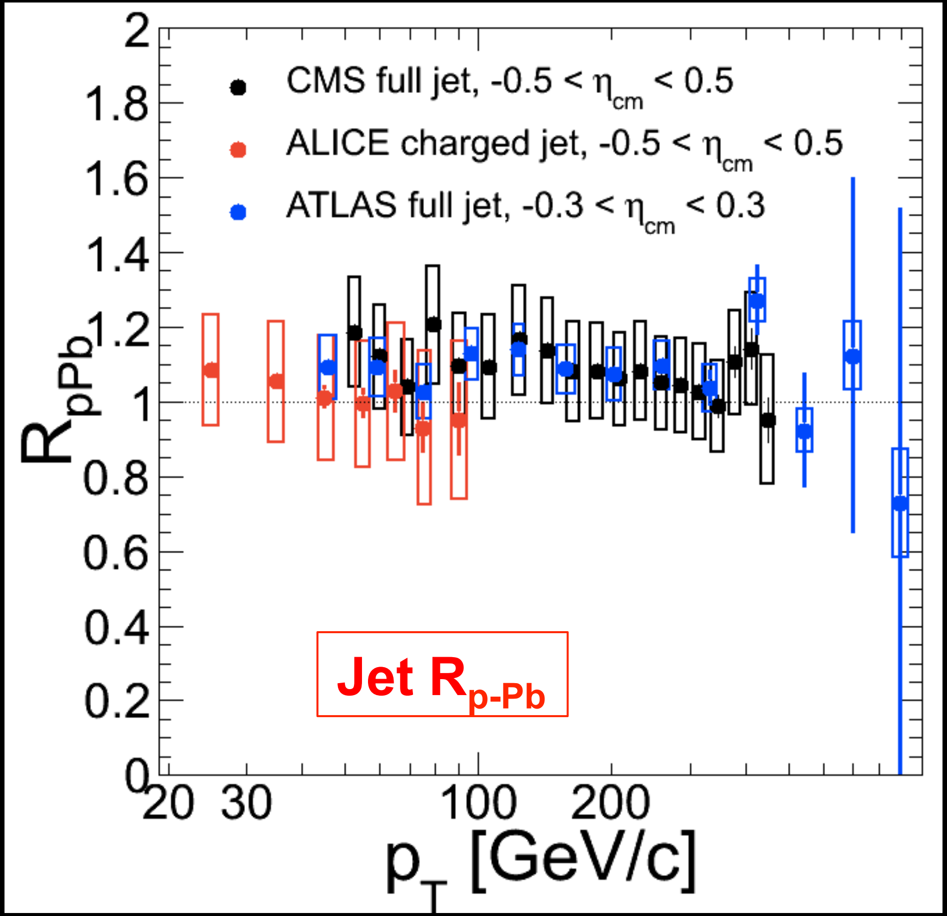


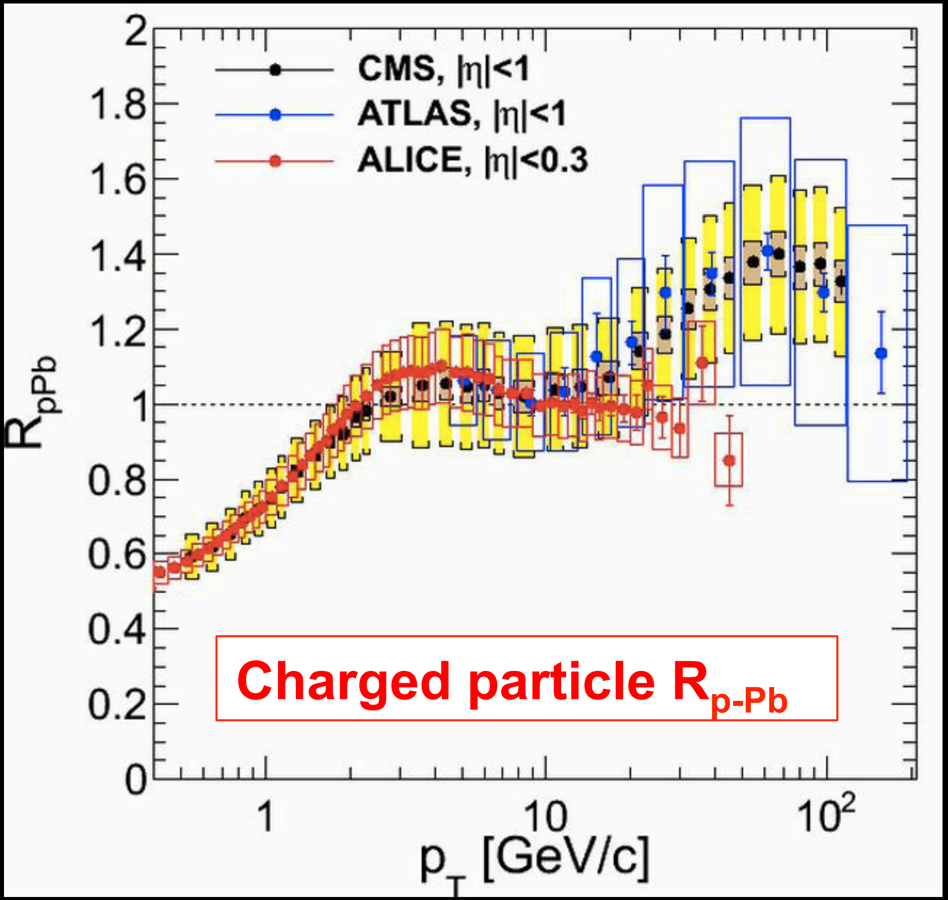
ALICE R_{p-Pb} (jet) ~
ATLAS R_{p-Pb} (jet) ~
CMS R_{p-Pb} (jet)

Note: ALICE, CMS R=0.2
ATLAS R=0.4

ALICE
ATLAS QM 2014
CMS (black)

$R_{p\text{-}Pb}$ Jets vs Charged Particles





If correct: fragmentation function must be altered or …. what?

Need jet fragmentation function in p-Pb

& measurements in pp at $\sqrt{s}$ = 5 TeV for comparison!

Fragmentation Function in Pb-Pb at LHC

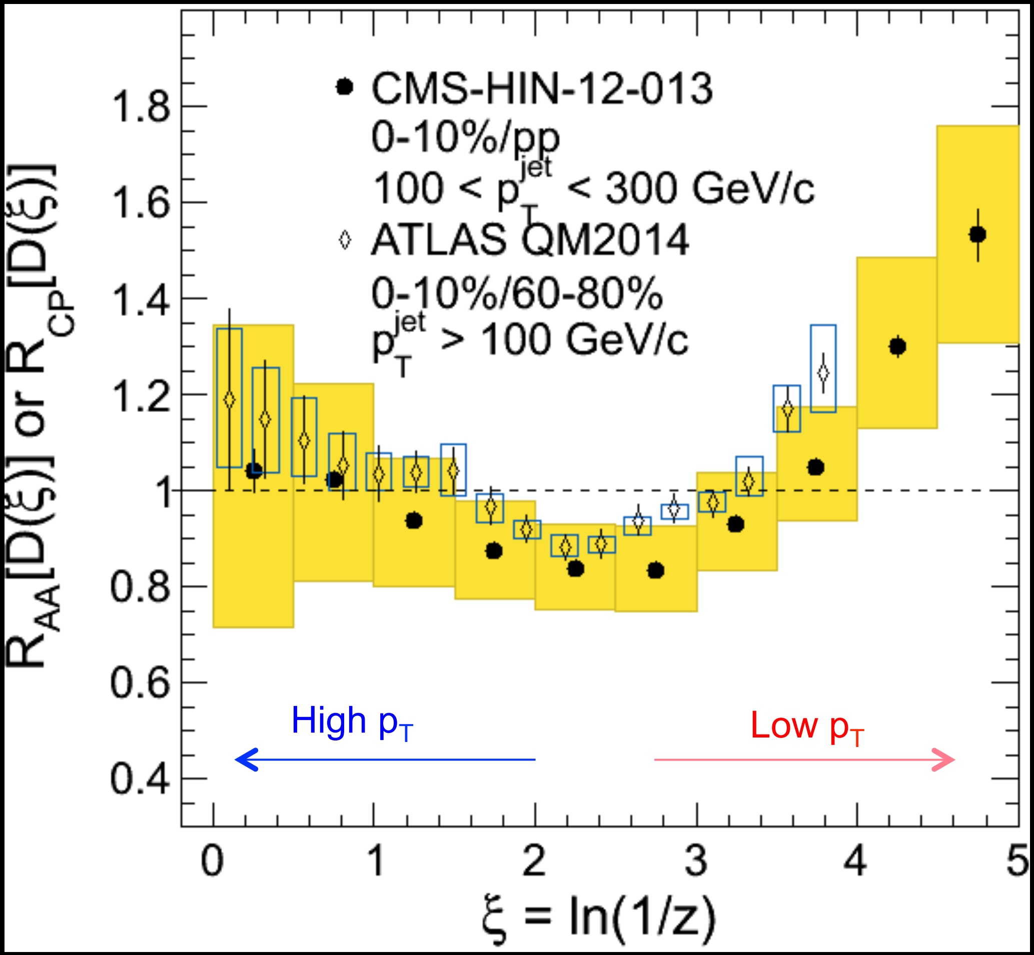
QM 2014

ATLAS R_{CP} [D(ξ)]

CMS R_{Pb-Pb} [D(ξ)]

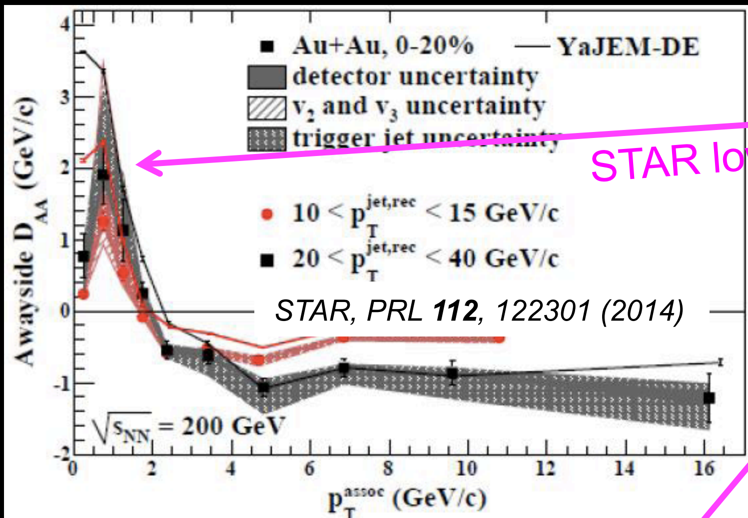
Results consistent

$z = p_T^{track} / p_T^{jet}$



Fragmentation Function in Pb-Pb modified compared to pp and central Pb-Pb compared to peripheral Pb-Pb!!

Excess of Low p_T Particles in Jet Cone



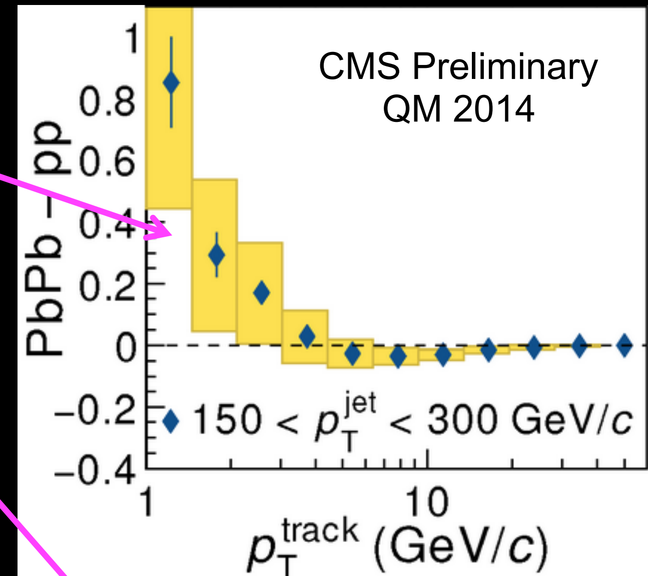
Track Excess

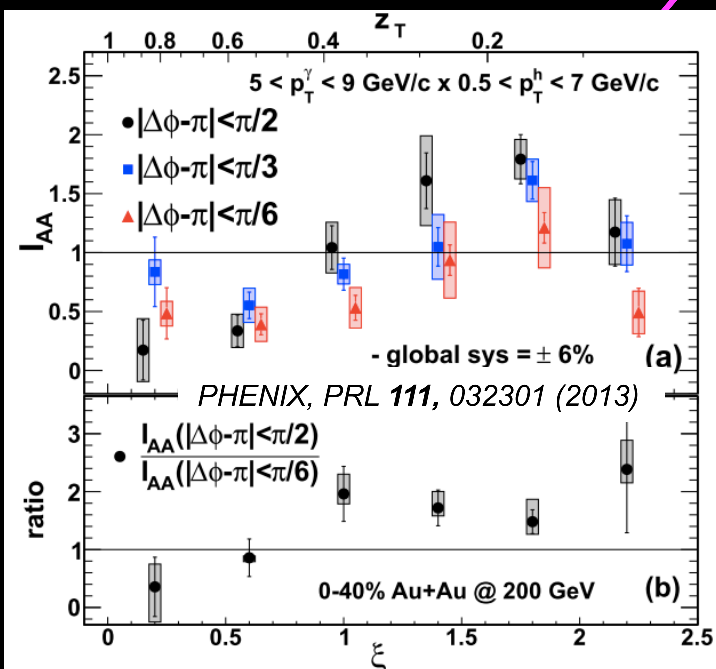
STAR low p_T

CMS low p_T

PHENIX high ξ

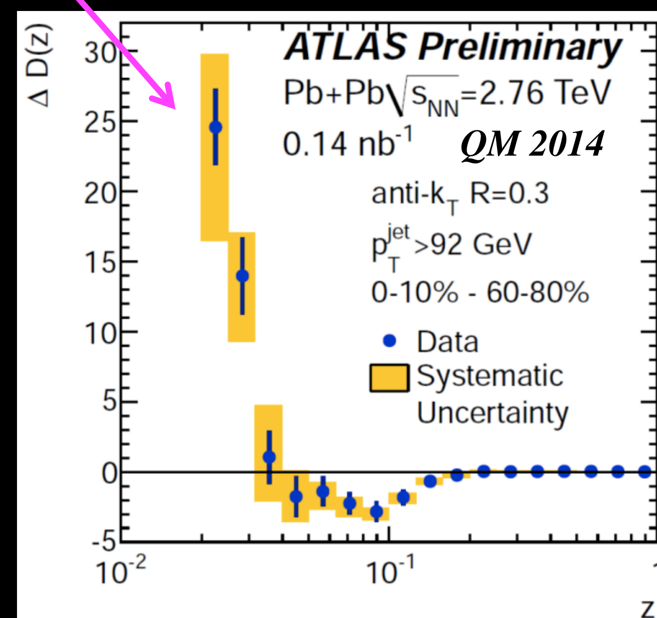
ATLAS low z



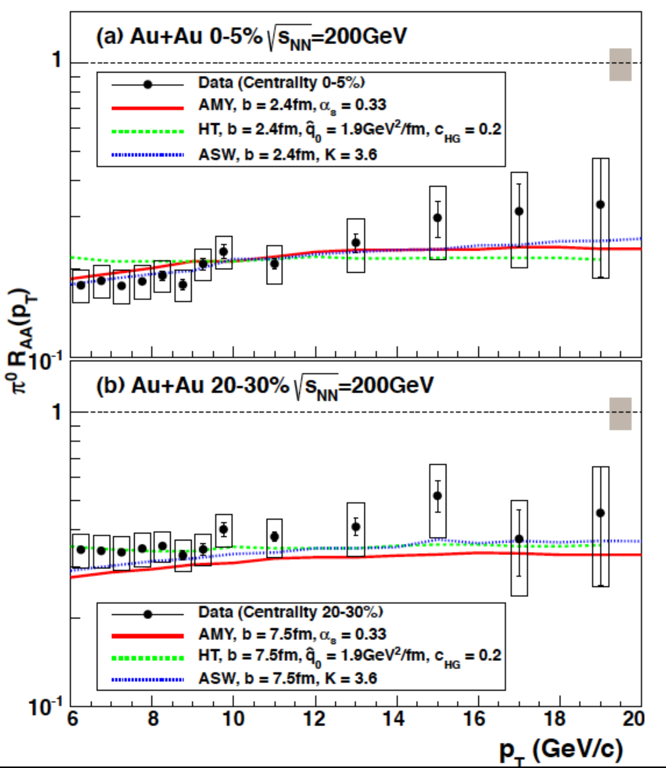


$z = p_T^{track} / p_T^{jet}$

$\xi = \ln(1/z)$

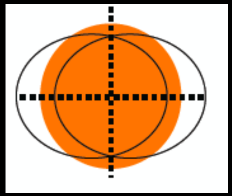


Path-length Dependent R_{AA}

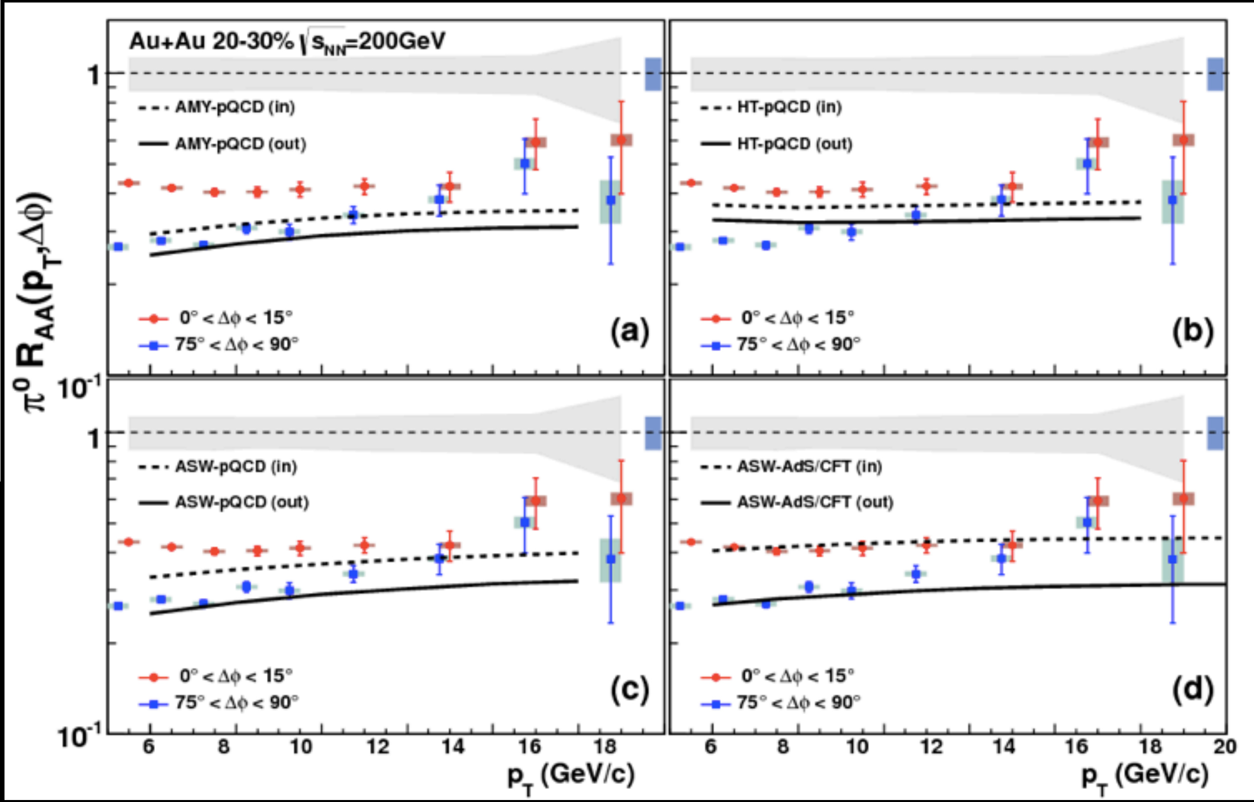


PHENIX, arXiv:1208.2254

Out-of-plane

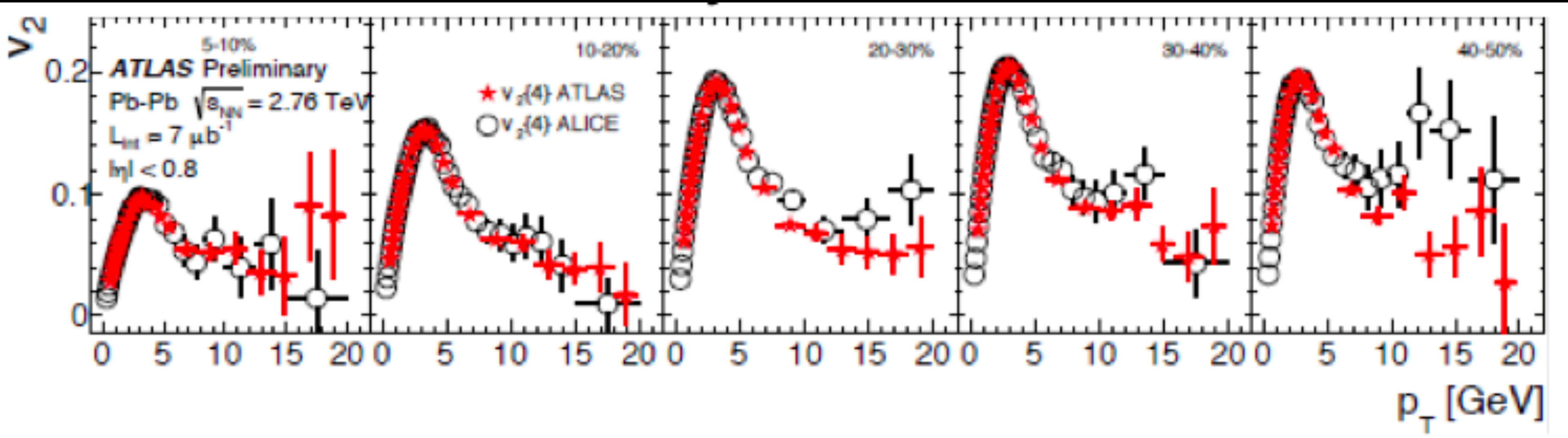


In-plane



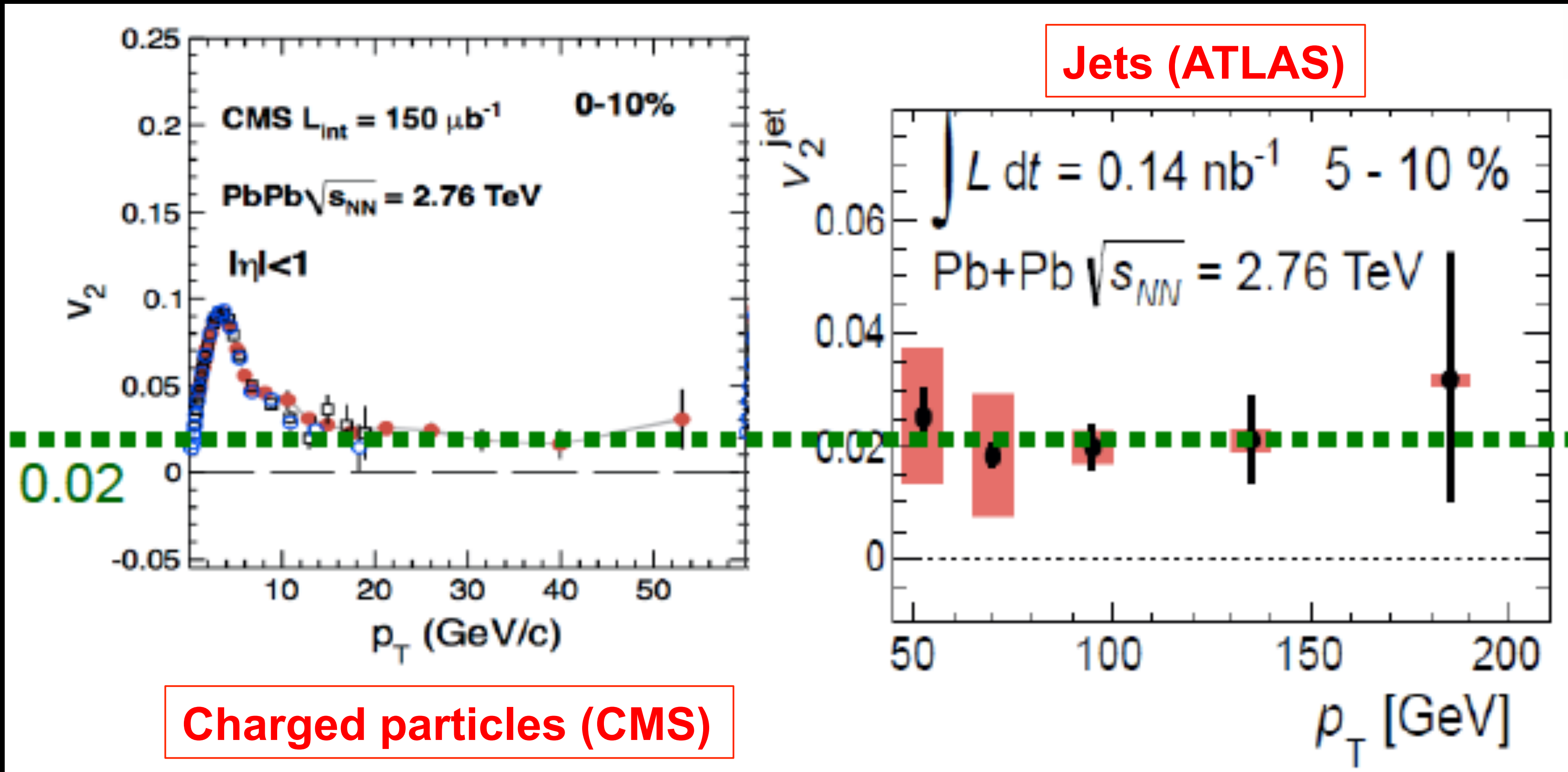
Centrality and angle relative to plane differences!

Significant v_2 Observed at High p_T



Significant charged particle v_2 (4) observed up to 100 GeV/c

v_2 Observed for High p_T Particles & Jets!

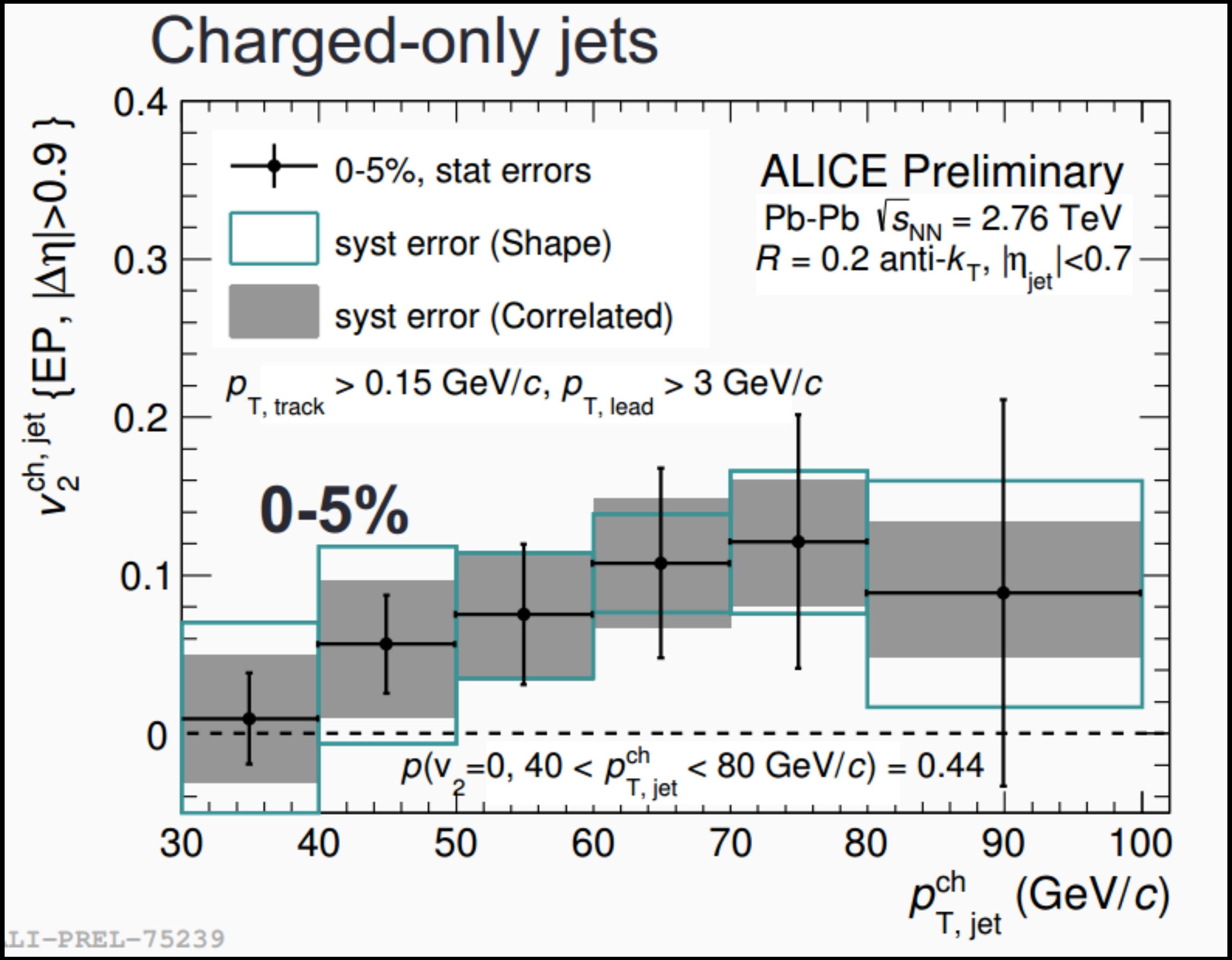


QM 2014

High p_T jet & particle v_2 observed by all three LHC experiments

Significant v_2 Observed for Charged Jets

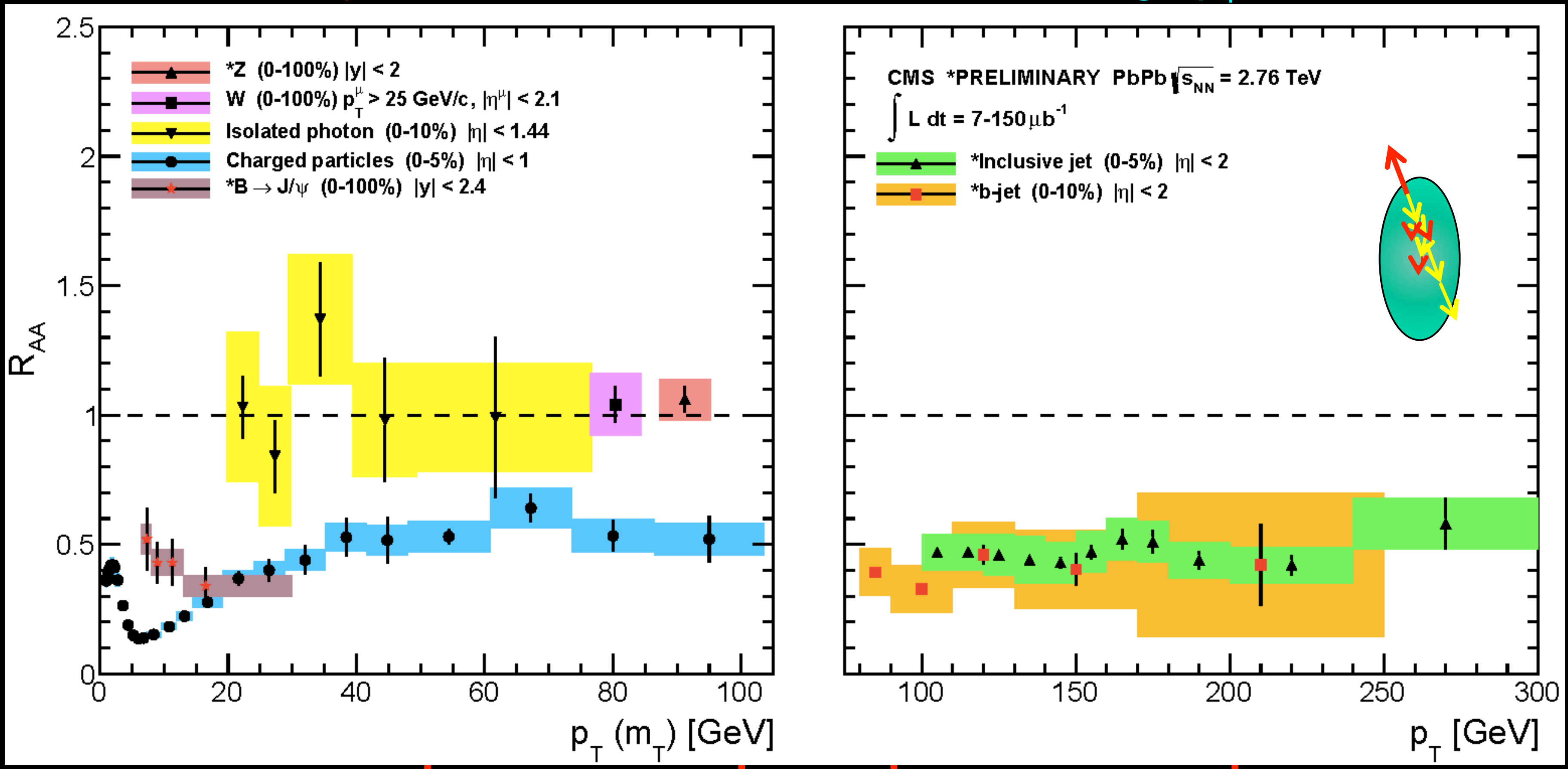
ALICE
QM 2014



Charged Jet v_2 Observed up to 100 GeV/c

Flavor Dependence of Jet Quenching at the LHC!

High p_T Particles High p_T Jets



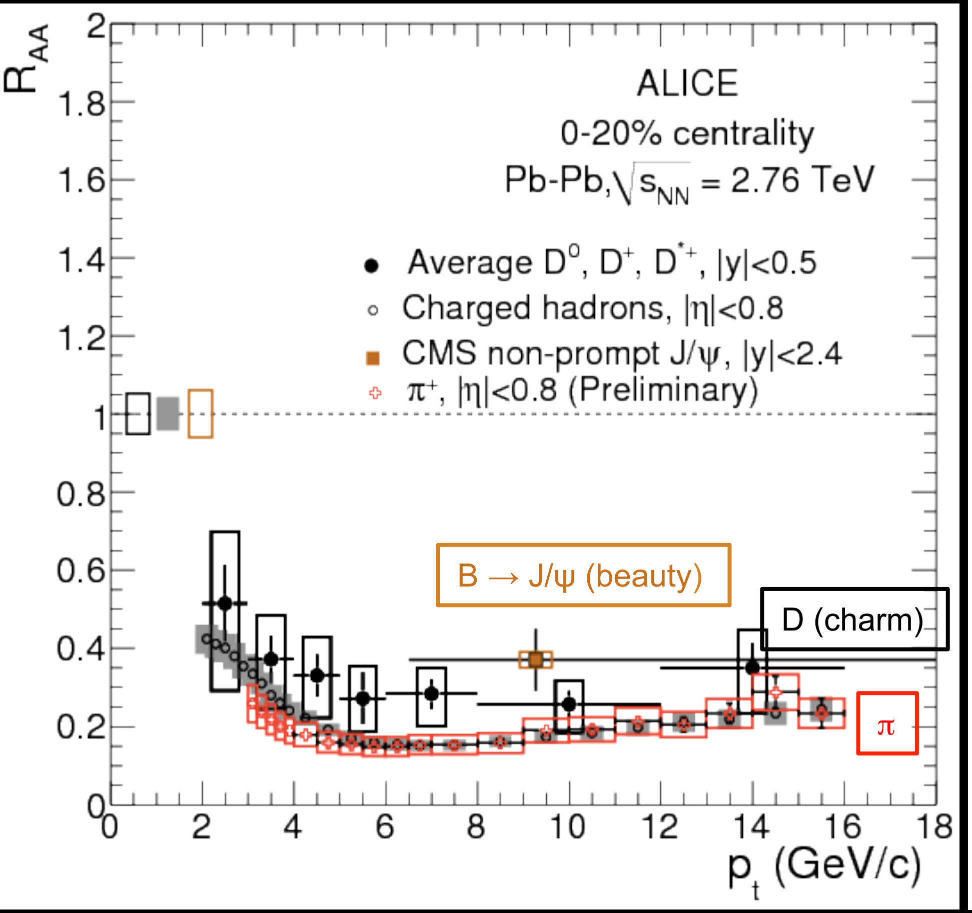
J. Velkovska (CMS) HP 2013

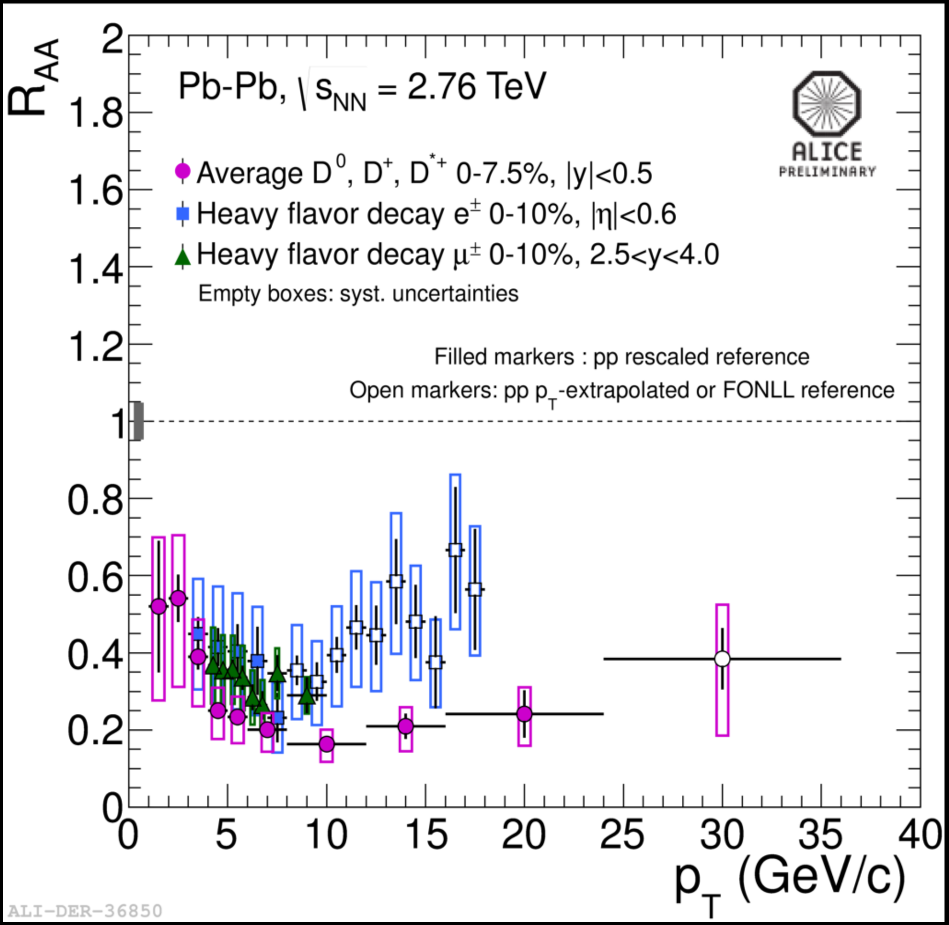
Same range of parton p_T

EPJC 72 (2012) 1945
PLB 715 (2012) 66
PLB 710 (2012) 256

Jets quenched – even at largest jet p_T (250 GeV/c)

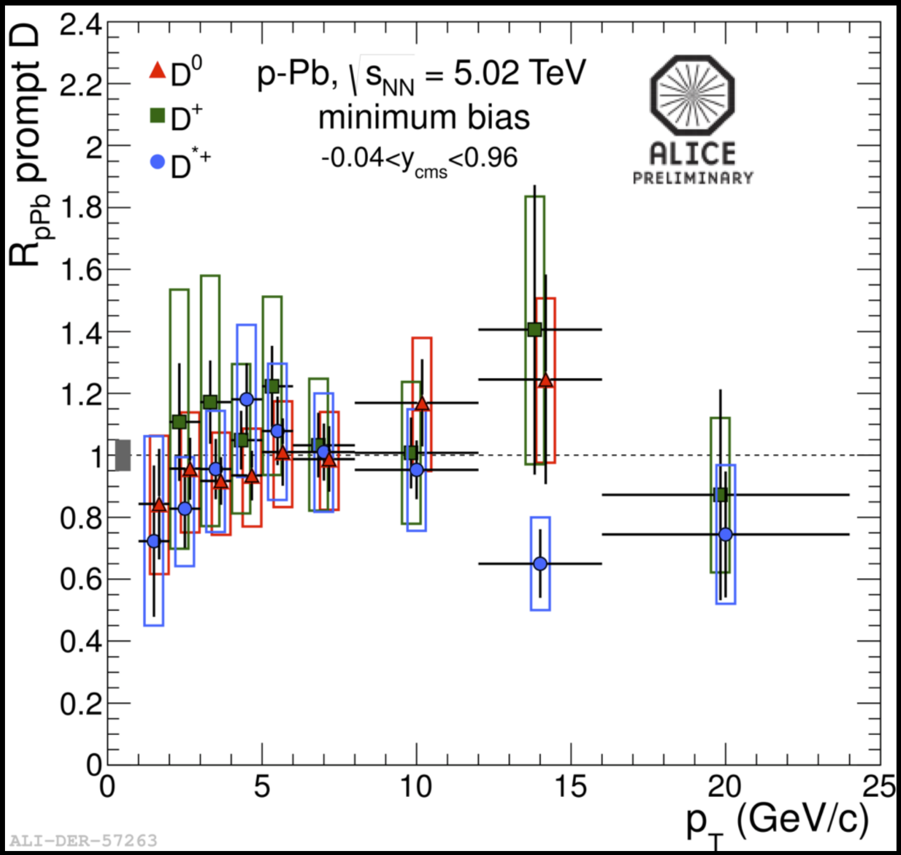
LHC Suppression of Heavy Flavors

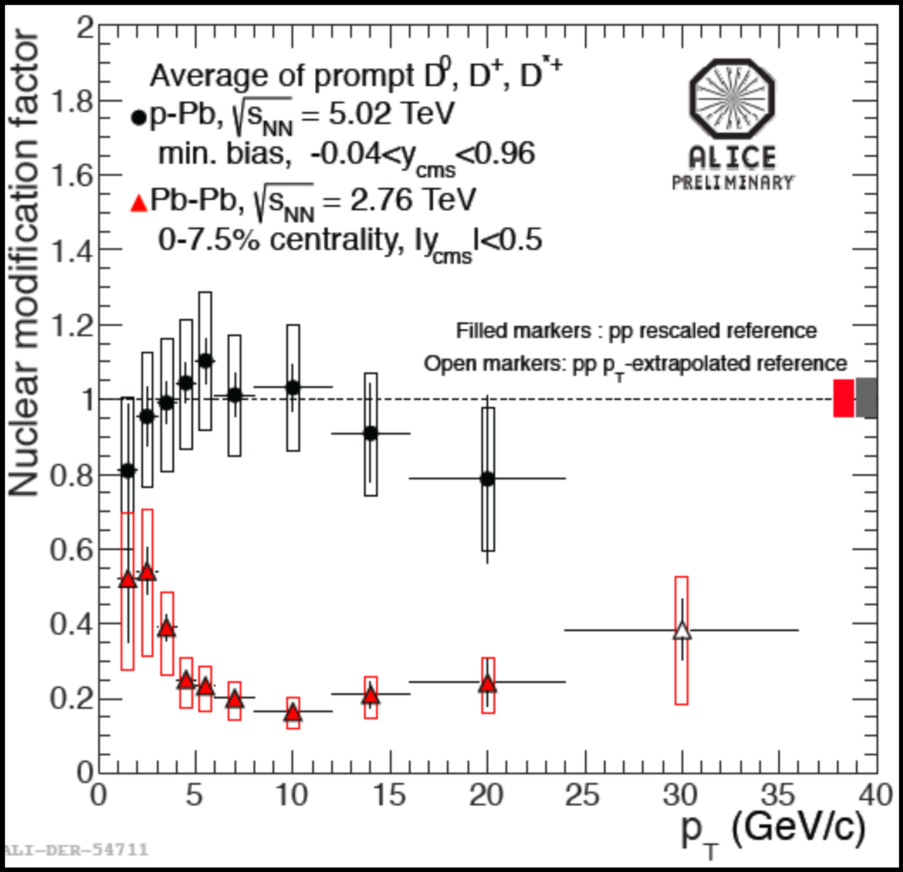




Pions, charm and beauty - Suggestion of a hierarchy!

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

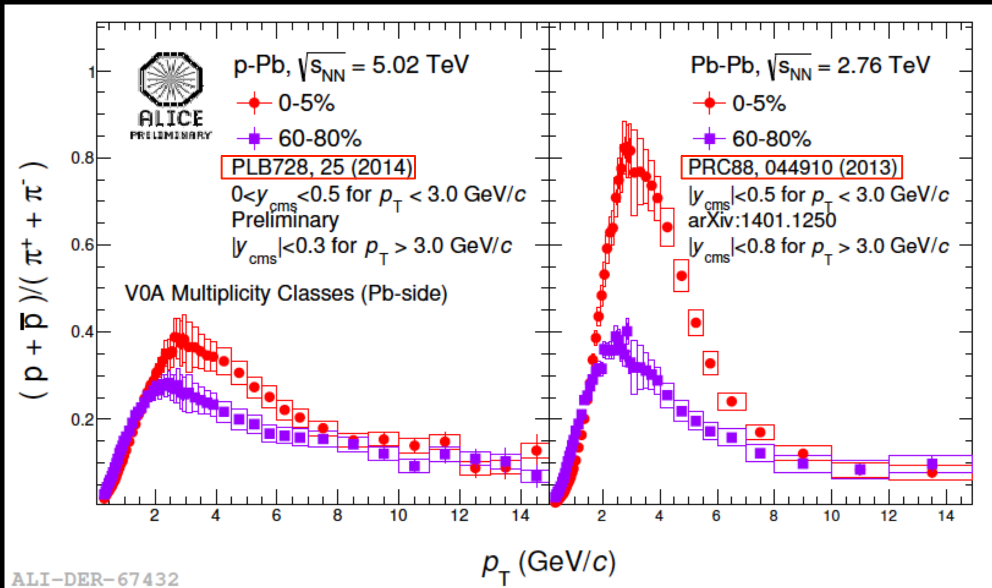


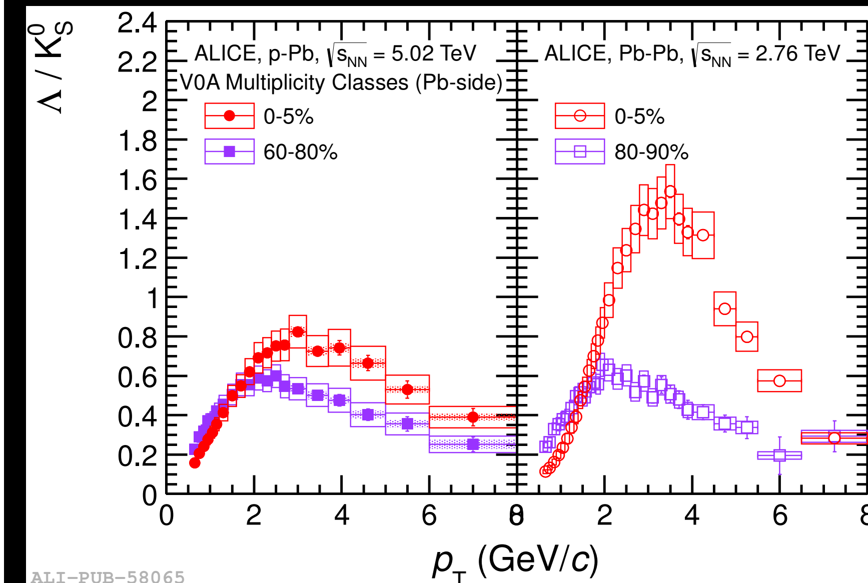


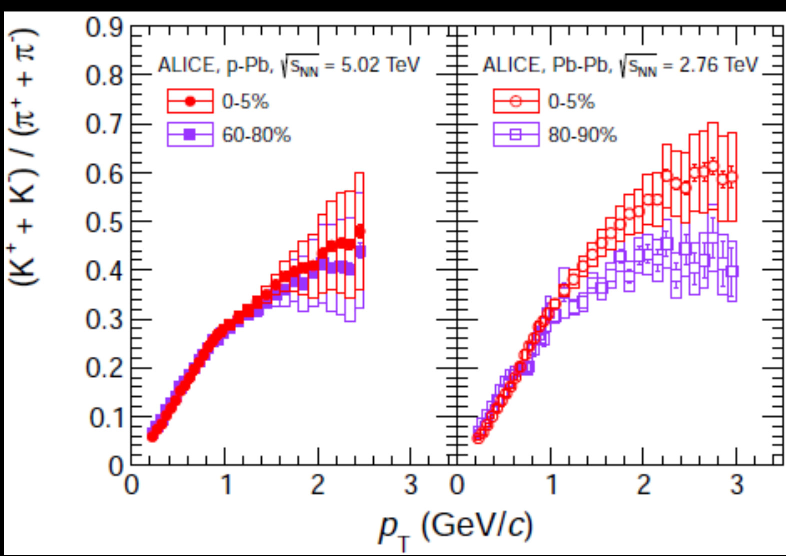
D-meson R_{pPb} consistent with ≈1
Initial state effects small!

D-meson central R_{PbPb} suppressed!
($p_T \gtrsim$ 4 GeV/c)
Not initial state effect!

Identified Particle Ratios vs p_T in pPb & PbPb







Baryon anomaly:

p-Pb similar behavior & pattern to Pb-Pb

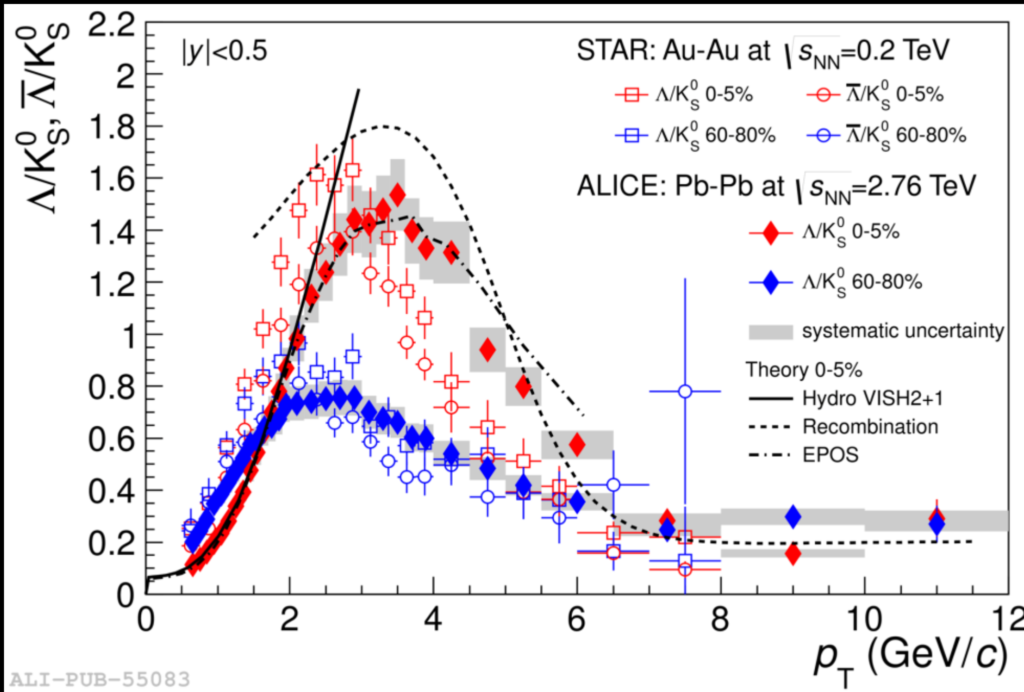
- increase with p_T, peak near p_T = 3 GeV/c
- increased enhancement: Λ/K > p/π > K/π

p-Pb ratios increase not as strongly as in Pb-Pb

ALICE, arXiv:1307.6796

Λ/K Ratios in AA vs p_T at RHIC & LHC

ALICE



RHIC and LHC:
- Ratios similar for peripheral events.
- Ratios differ for central events

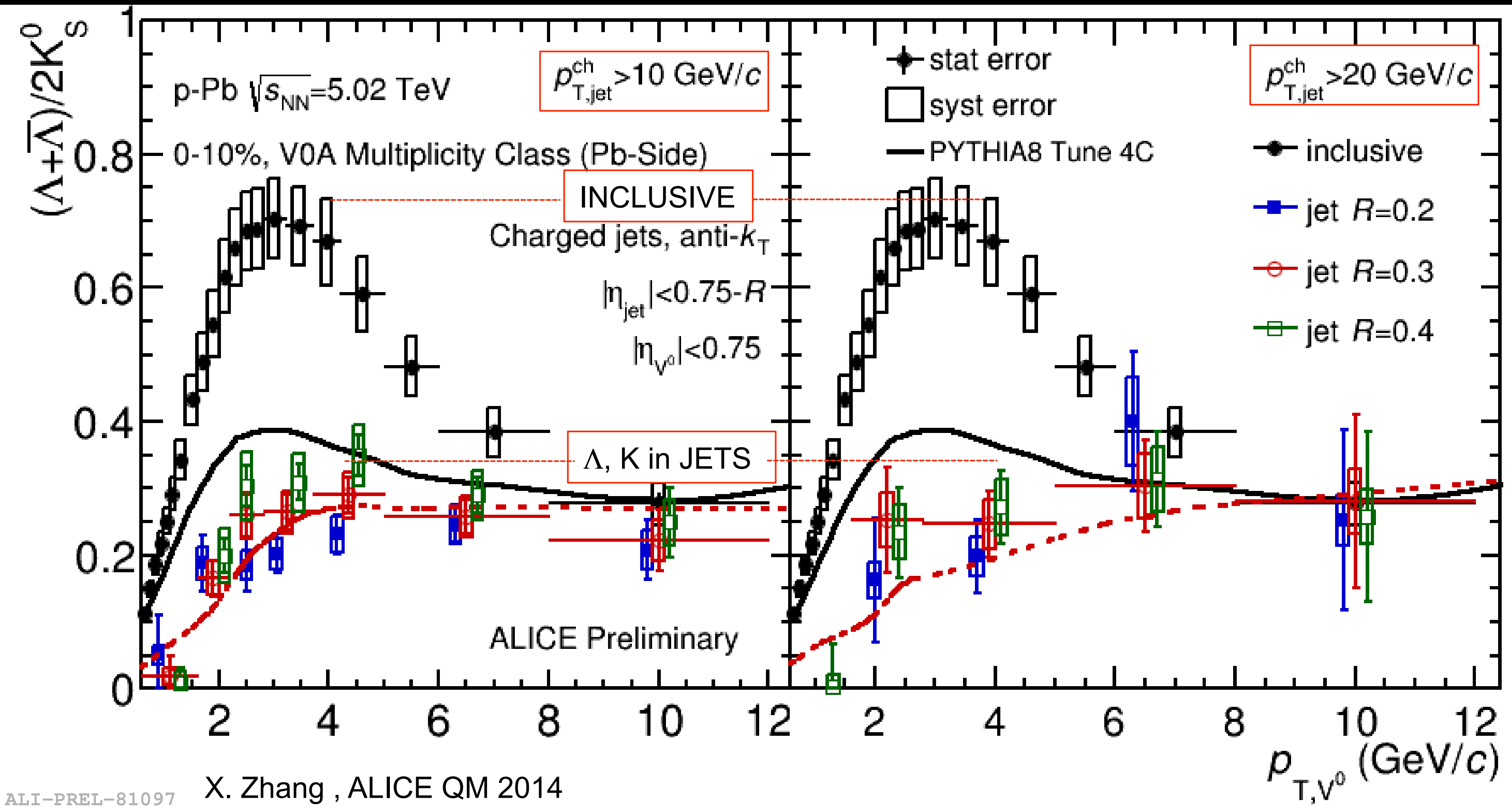
(Peak in most central collisions at slightly higher p_T at LHC)

- Since μ_B << T, RHIC & LHC ratios should be similar.

Can this centrality dependence of ratios at RHIC and LHC be explained by hydro?

ALICE, arXiv:1307.5530

Λ/K Ratio in Charged Jets in p-Pb

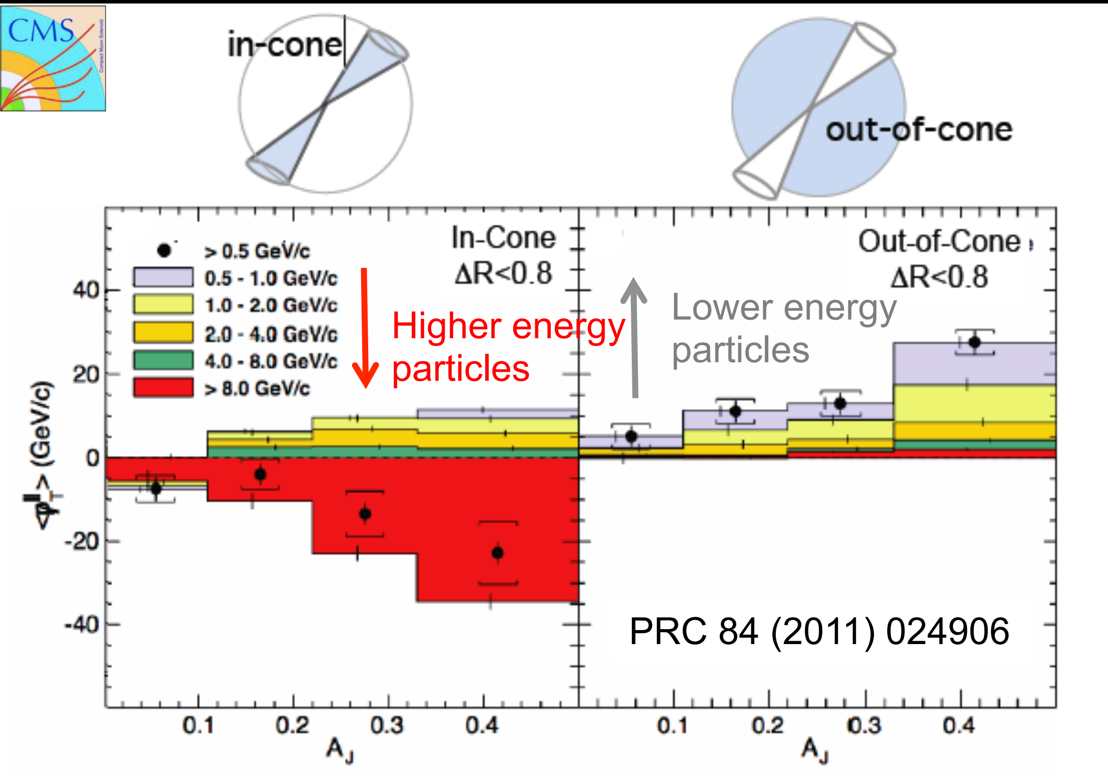


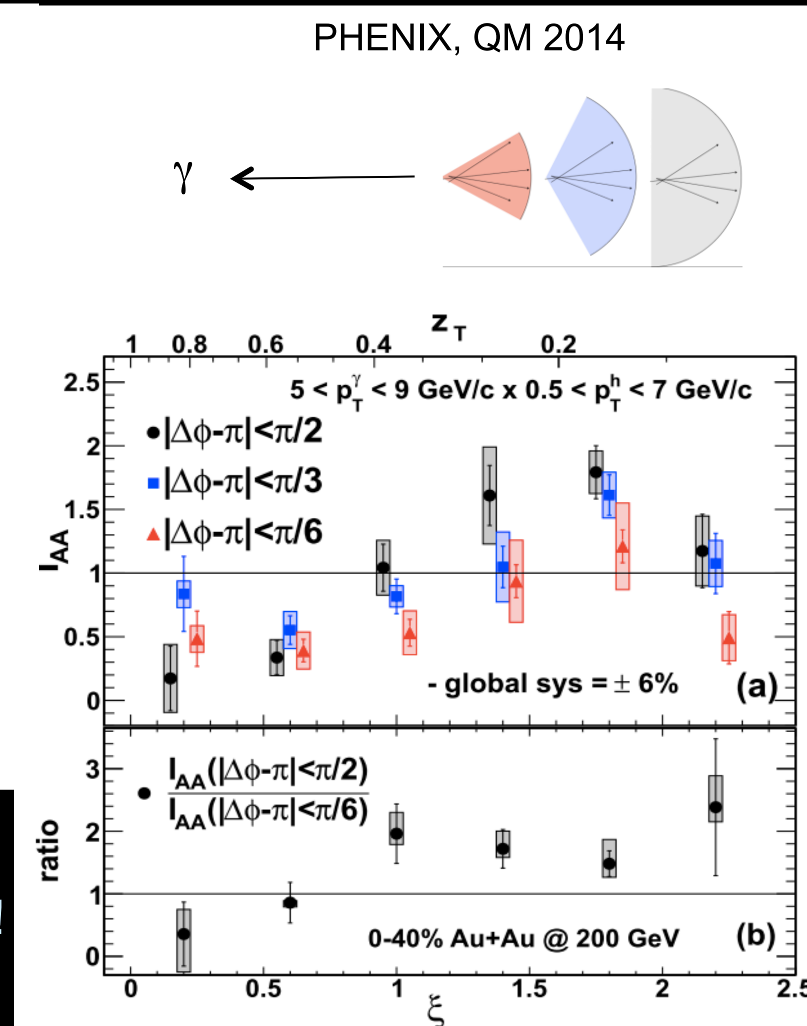
X. Zhang , ALICE QM 2014

No baryon/meson enhancement observed in Λ/K^0 within jets

Background Λ and K^0 estimated outside jet cone in events w.o. jets

Where does the Energy Go? – LHC & RHIC





Energy/momentum balance in event carried by low momentum particles at large angles to jets!

Energy appears at large R, wider angles to jet.

pQCD, vacuum fragmentation, thermalization of lost energy?

R_{AA} Summary & Conclusions

$\sqrt{s_{NN}}$ = 5.02 TeV p-Pb, 0.2 TeV d-Au   Results $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb, 0.2 TeV Au-Au

- $R_{p(d)A}^{\text{charged particles}}$ ~ 1 for p_T > 2 GeV/c, consistent with binary scaling
  Absence of nuclear modification → small initial state effects
  Described by Saturation (CGC) models, EPS09 with shadowing
  $R_{pPb}^{\text{D-mesons}}$ ~ 1 for p_T = 1.5 - 20 GeV/c, consistent with binary scaling
  Described by various models, does not distinguish models
  $R_{p(d)A}^{\text{charged particles}}$ ~ 1 but 10(20)% enhancement "bump" ~ 4 – 6 GeV/c
  Primarily in proton (baryon?) channel, associated with baryon anomaly?
  $R_{pPb}^{\text{charged particles}}$ ~ 1.3 – 1.4 for p_T ~ 30 – 100 GeV/c, reference data needed or ?
- $R_{AA}^{\text{charged particles}}$ ~ 0.2 – 0.4 for p_T = 4 - 100 GeV/c (smallest for most central)
  $R_{pPb}^{\text{D-mesons}} \gtrsim R_{AA}^{\text{charged particles}}$ for p_T = 2 - 30 GeV/c
  $R_{AA}^{\text{single particles}}$ → high p_T particle suppression → a final state effect
- R_{pPb}^{jets} ~ 1 for p_T = 20 - 800 GeV/c
  Absence of nuclear modification → small initial state effects
- R_{PbPb}^{jets} ~ 0.2 – 0.5 for p_T = 35 - 300 GeV/c (smallest at lowest p_T & for most central)
  Fragmentation functions modified → jet quenching
  R_{AuAu}^{jets} ~ 0.5 – 0.6 for p_T = 15 - 30 GeV/c (~ flat in p_T & smallest for most central)
  $R_{AuAu}^{\text{jets}} \lesssim R_{PbPb}^{\text{jets}}$, smaller R_{AA} for RHIC energy jets thus far
  R_{AA}^{jets} → jet quenching → parton energy loss in QCD medium

Particle Ratios: Summary & Conclusions

$\sqrt{s_{NN}}$ = 5.02 TeV p-Pb, 0.2 TeV d-Au Results $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb, 0.2 TeV Au-Au

- Ratios of identified particles (π, K, p, Λ)

  p-Pb ratios similar behavior & pattern to Pb-Pb, do not increase as strongly as Pb-Pb

  Baryon/meson (B/M) ratios increase with p_T, peak near p_T = 3 GeV/c

  Enhancement increases as Λ/K > p/π > K/π

  Baryon/meson ratio peak at slightly higher p_T at LHC

- Λ/K Ratios in jets

  No baryon/meson (Λ/K) enhancement in jets in p-Pb

“What Have We Learned” from RHIC & LHC

It’s opaque to the most energetic probes:

Light & heavy quarks are suppressed at large p_T

Slight flavor dependence observed in particle suppression

High p_T B-jets quenched similarly to inclusive jets

Away-side jets quenched and jet energy imbalance

Lost energy redistributed to lower p_T particles at larger angles

Frag. functions and jet shapes modified (low p_T excess in cone)

Angular correlations of di-jets and γ-jet not modified

Suppression differences vs centrality and angle wrt event plane

Non-zero high p_T jet track v_2 (path-length dependence?)

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

Need theoretical guidance and direct model comparisons!

Thanks for your Attention!