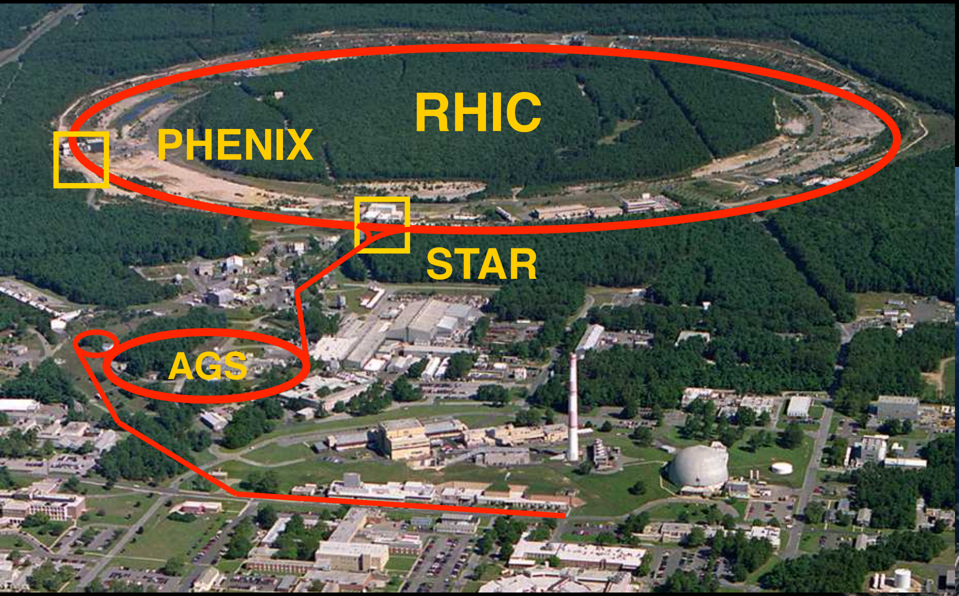
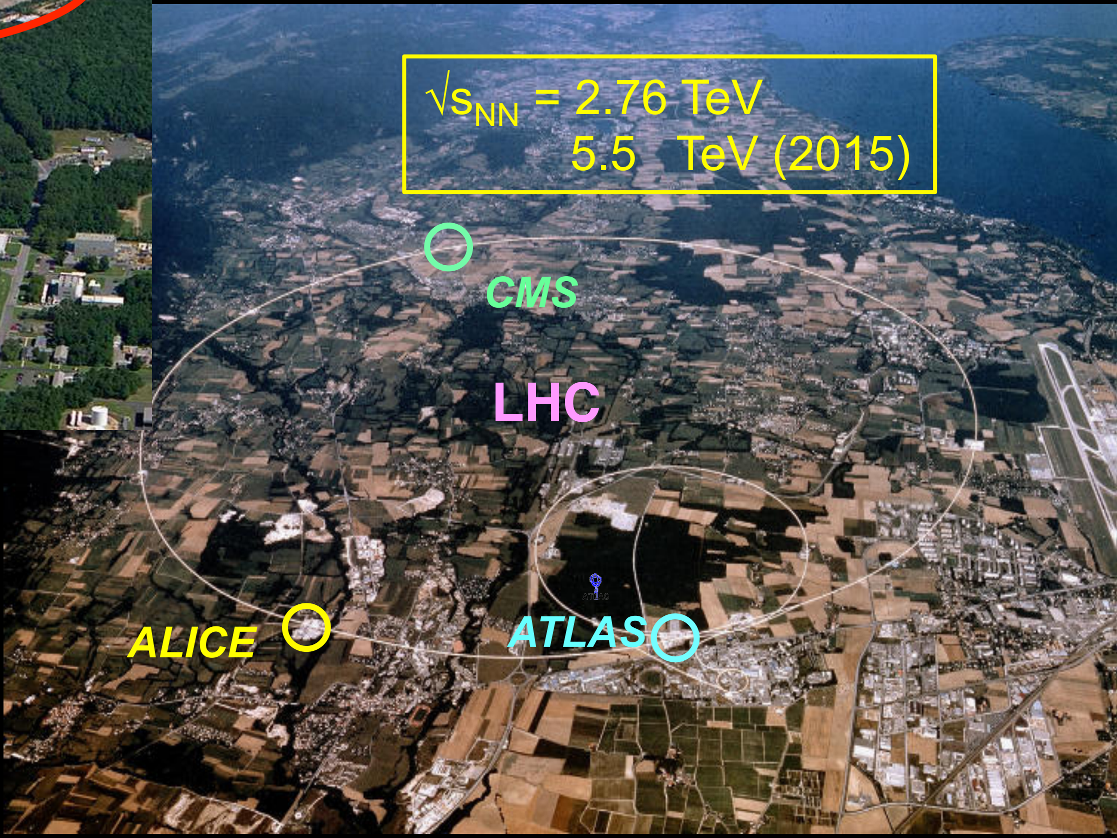
Using "Hard Probes" – High p_T Particle & Jet Suppression – to Study the QGP



Cover 3 decades of energy in center-of-mass



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

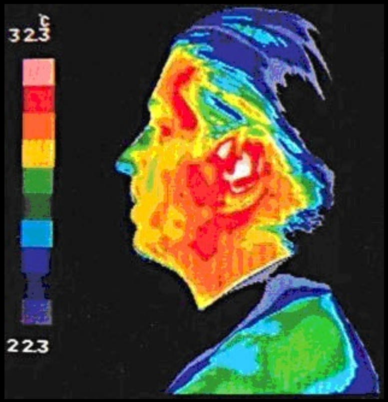
Investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!

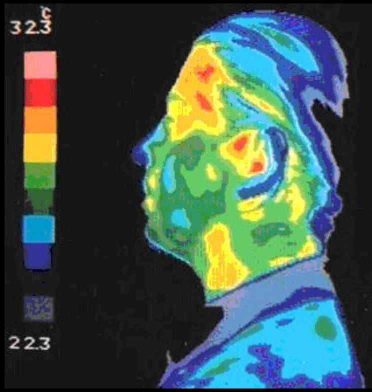
Definition of "Hard Probes"

Definition of "Hard" – "relating to radiation that is highly penetrating or energetic"

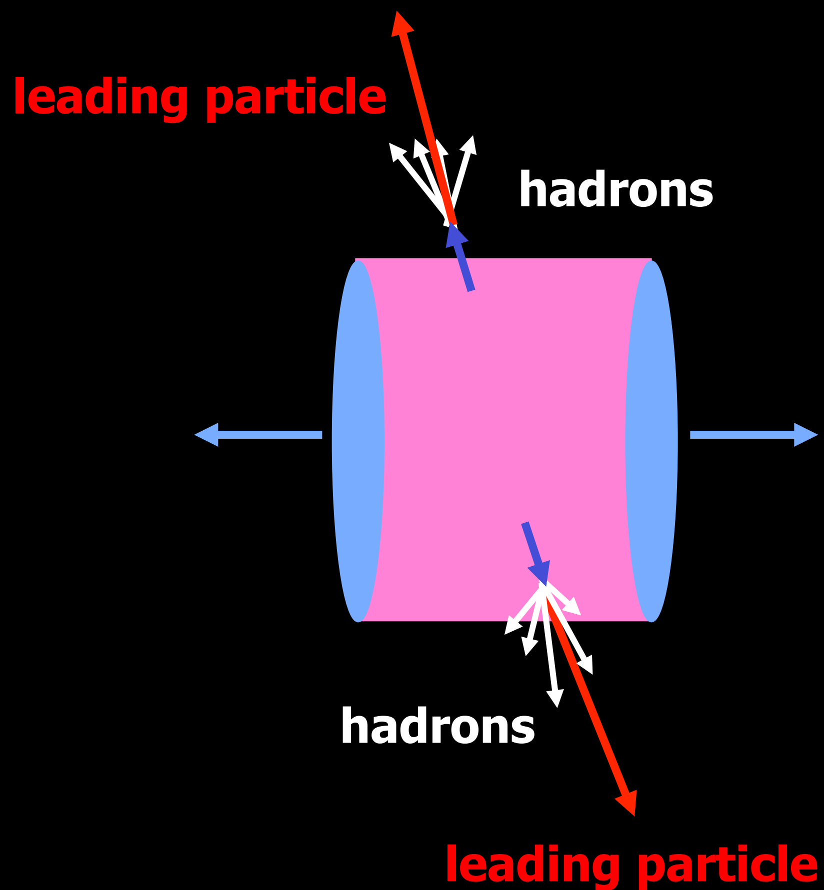
Definition of "Probe" – "device to explore properties of something that cannot be viewed directly"

"Hard Probes" –
"highly penetrating observables (particles, radiation) used to explore properties of matter that cannot be viewed directly!"





Probing Hot QCD Matter with "Hard-Probes"



Initial Hard Parton Scattering

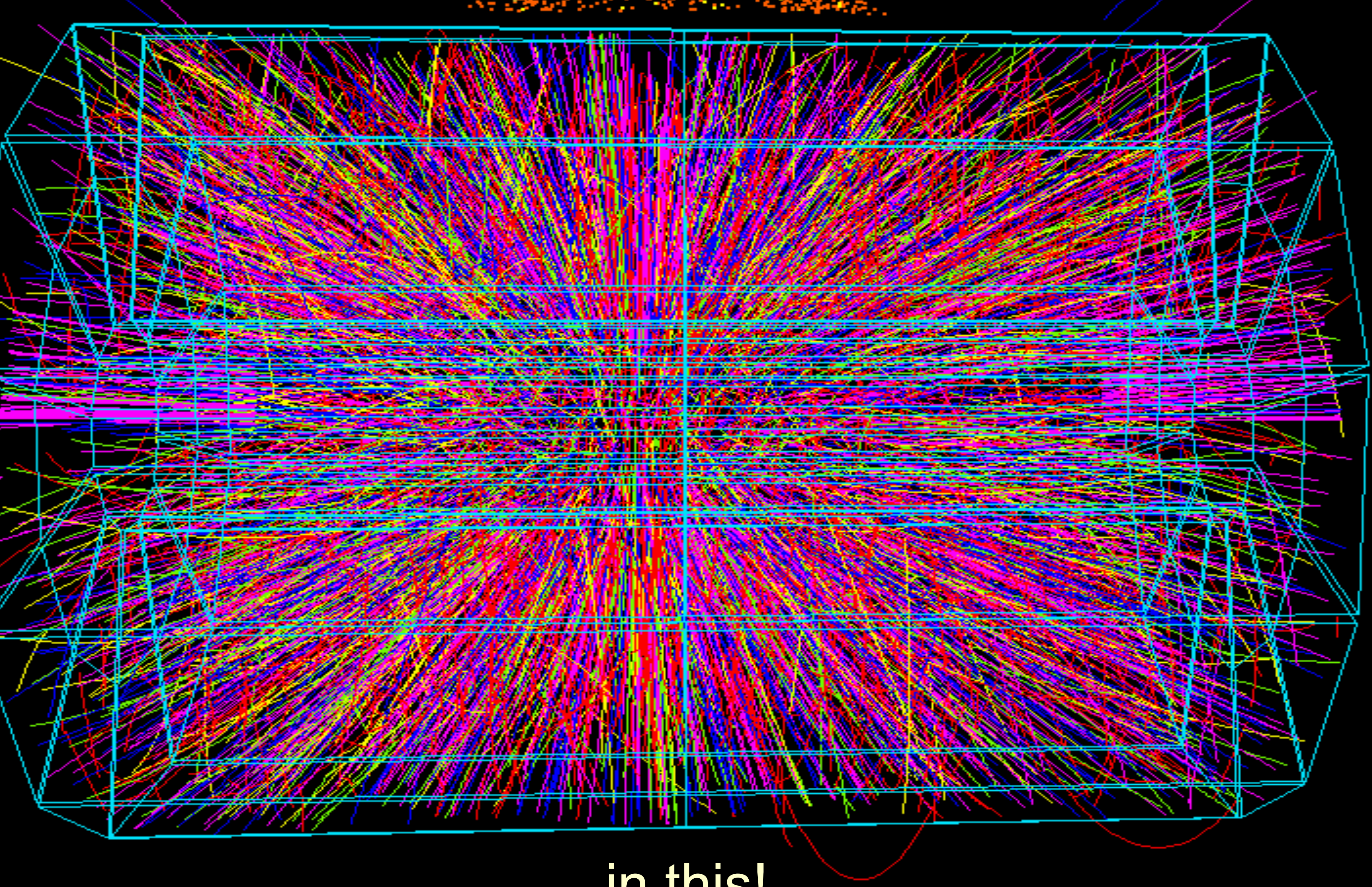
gluon-gluon
gluon-quark
quark-quark

→ **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"

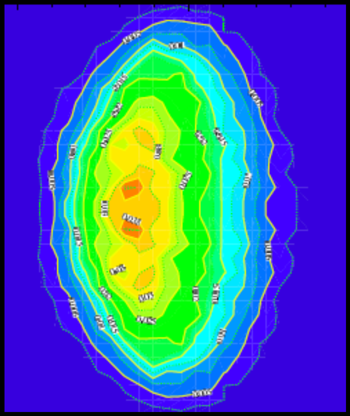


ng

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:

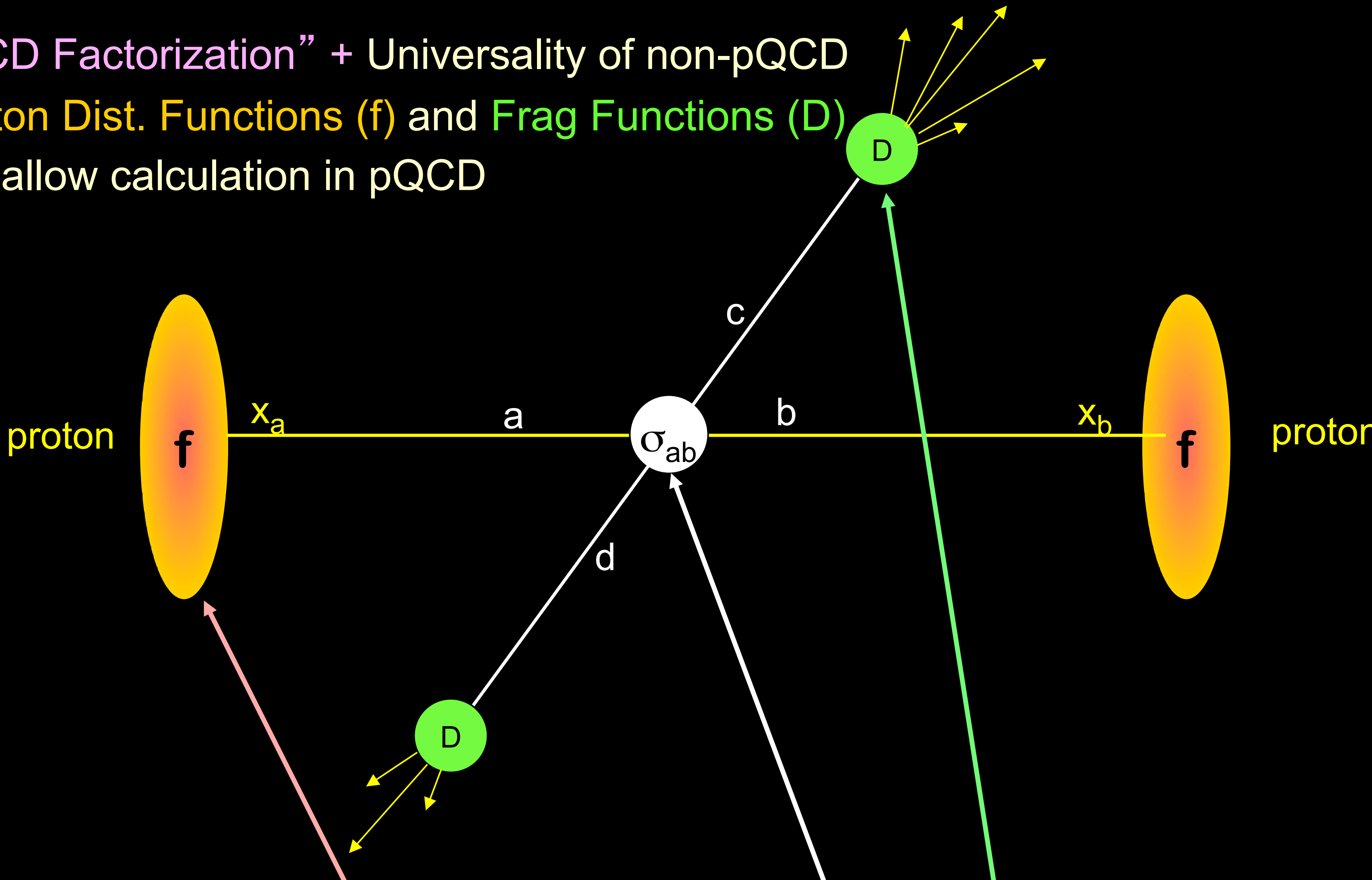
- large momentum transfer Q^2
  (→ 4-momentum transfer squared)
- large transverse momentum p_T
- large mass m scale
  (e.g. heavy quark production also at low p_T)

QCD – Factorization in Proton-Proton Collisions

"QCD Factorization" + Universality of non-pQCD

Parton Dist. Functions (f) and Frag Functions (D)

allow calculation in pQCD

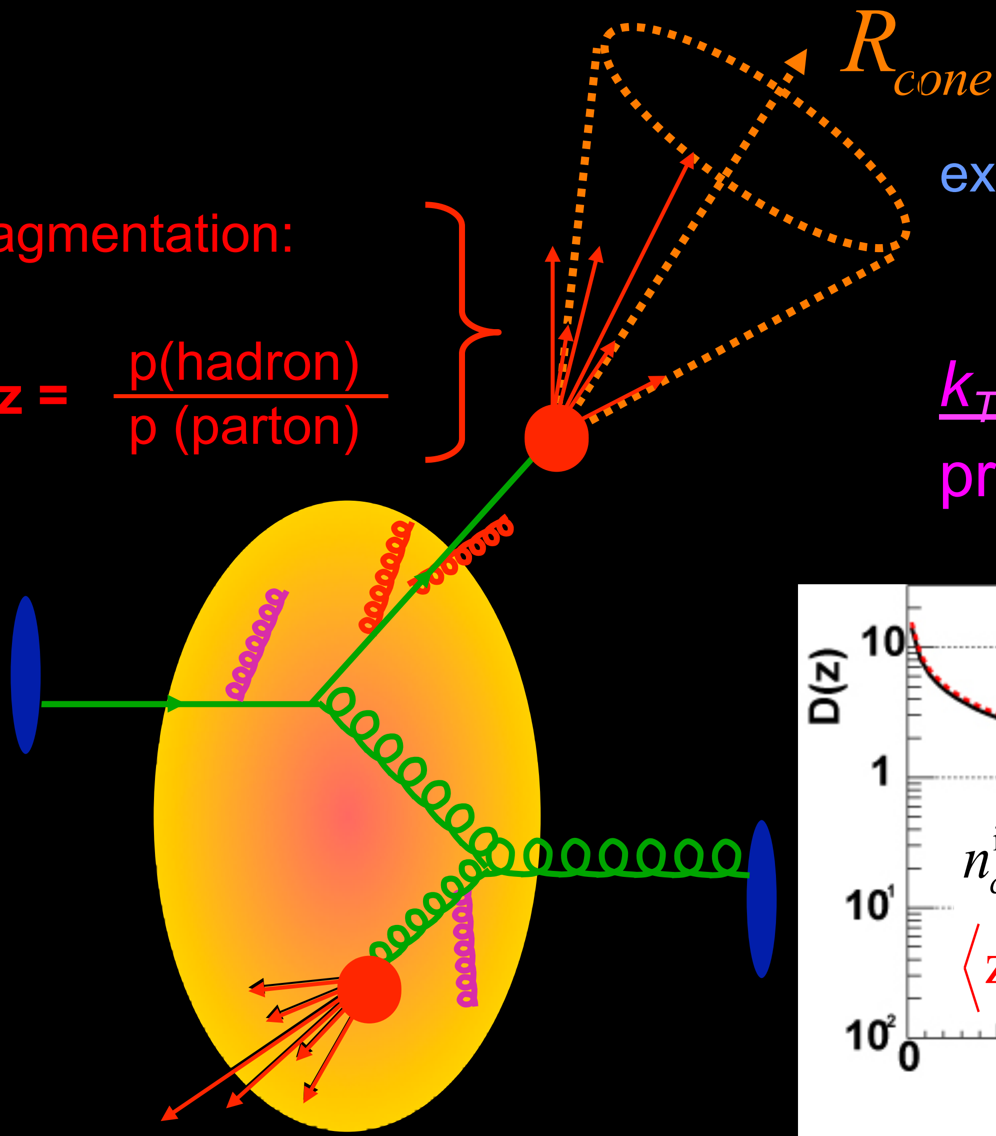


$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a, Q^2\right) \otimes f_{b/B}\left(x_b, Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\rightarrow cd}}{dt} \otimes D_{h/c}\left(z_c, Q^2\right)$$

Hard Scattering in Nucleus-Nucleus Collisions

Fragmentation:

$z = \frac{p(\text{hadron})}{p\ (\text{parton})}$

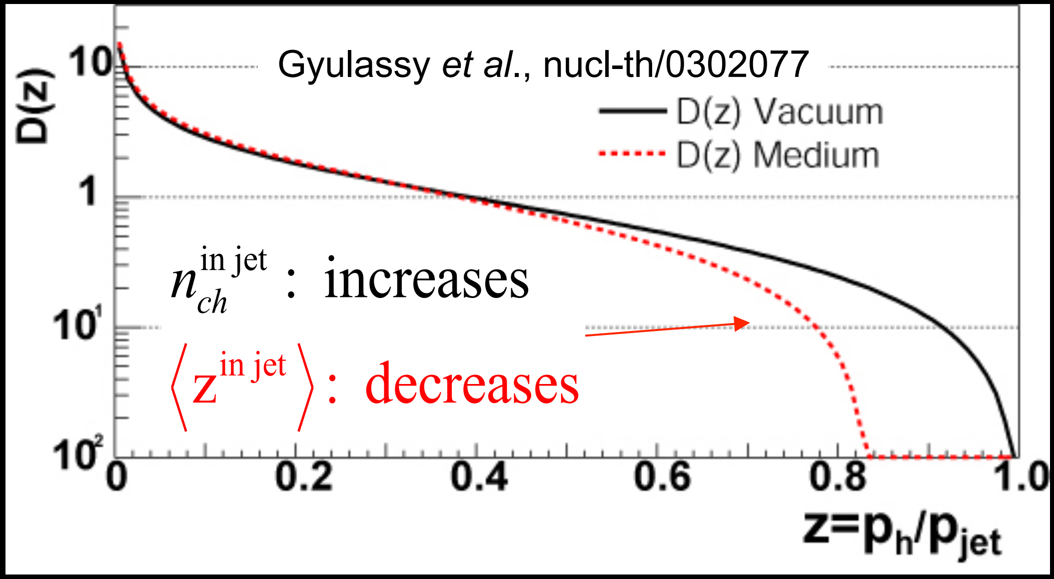


Same as pp case

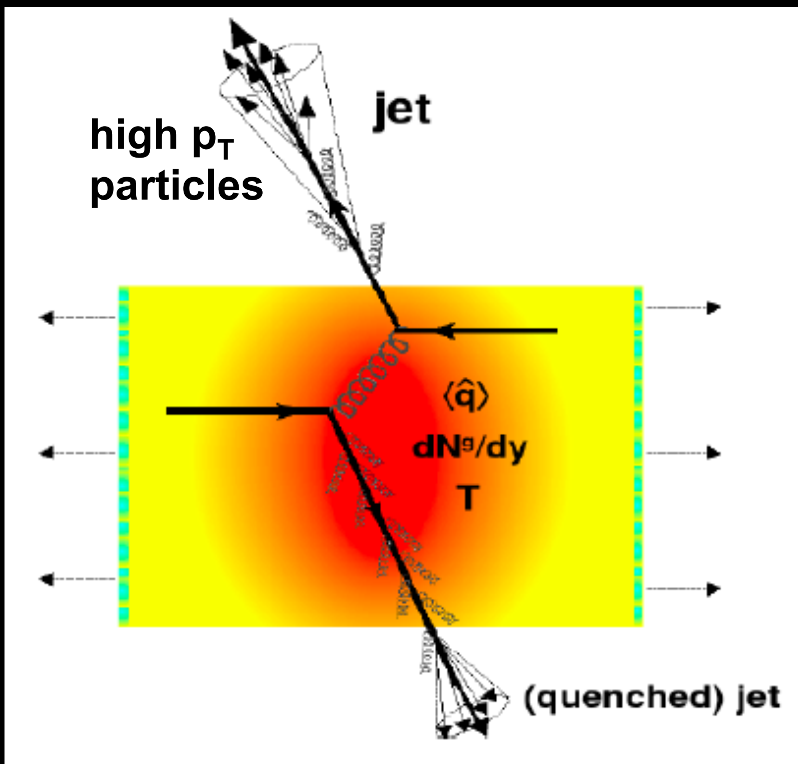
except: partons propagate in medium

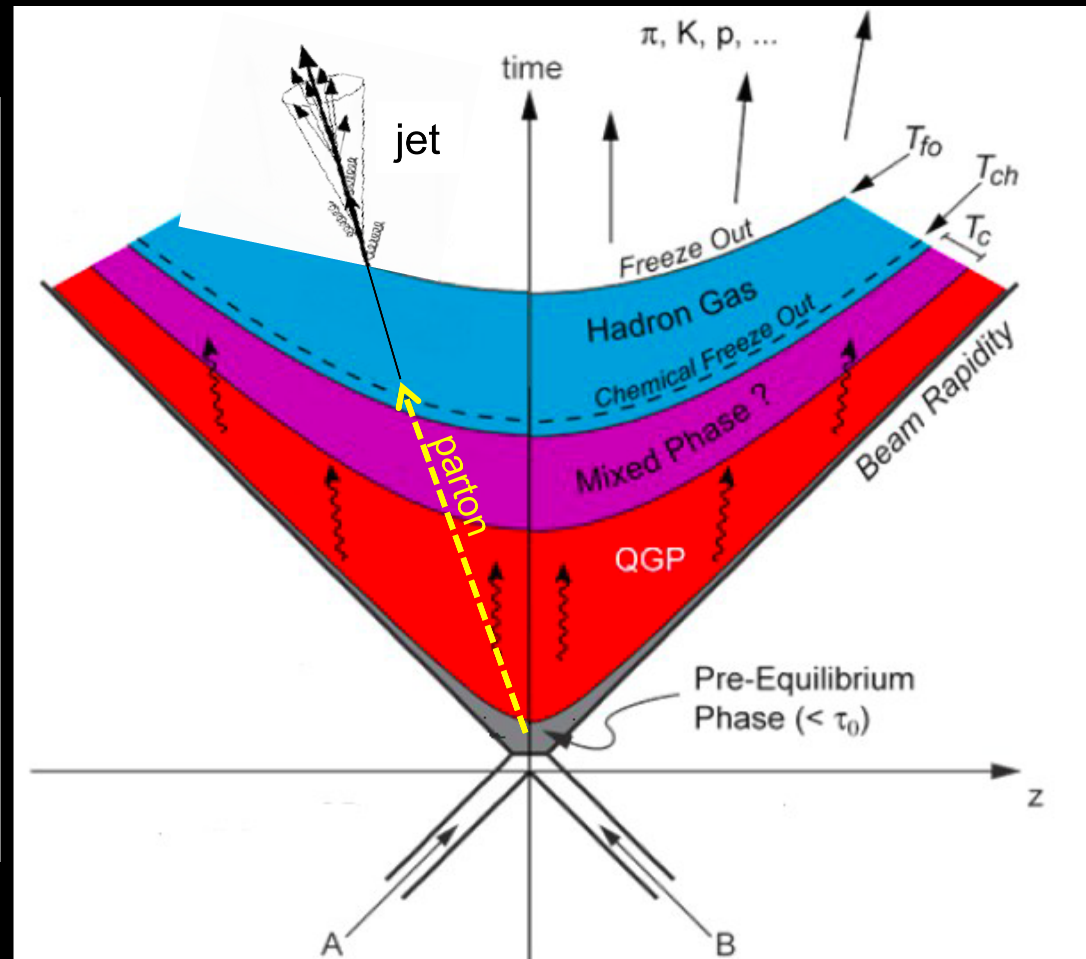
k_T "radiative corrections"

pre- and post-scattering



Probing Hot QCD Matter with Hard Probes



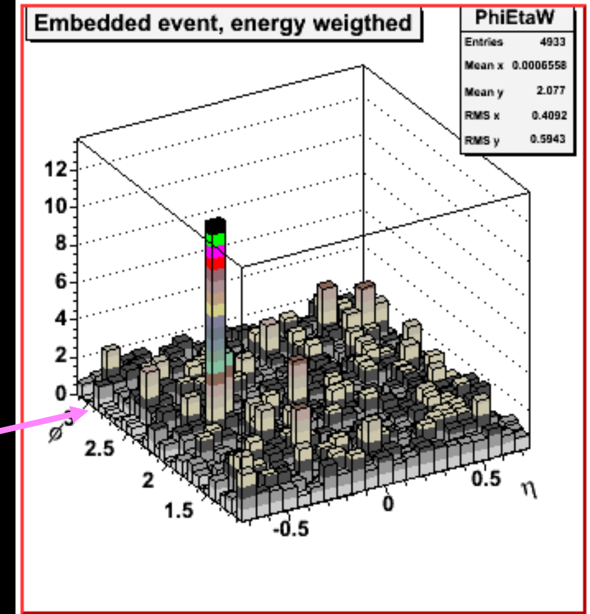


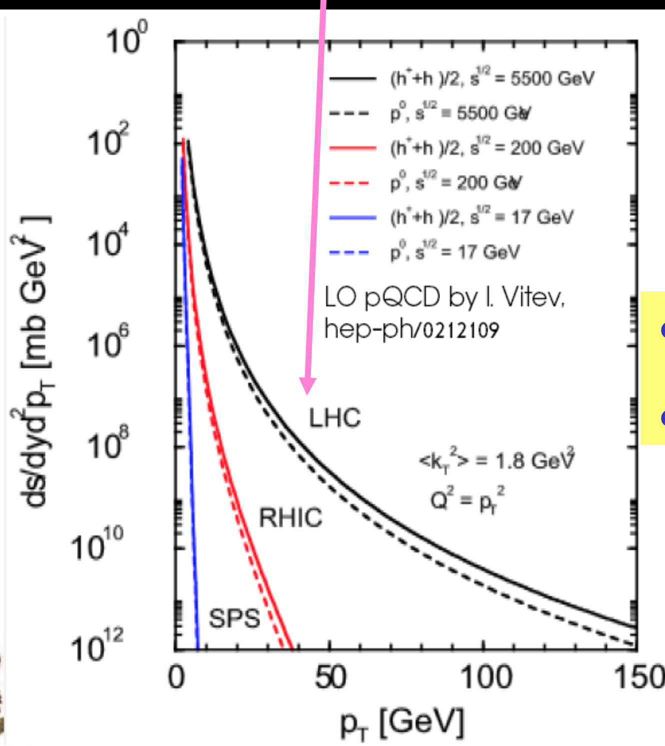
Hard Probes with Heavy Ions at LHC

Significant increase in hard cross sections (p_T or mass > 2 GeV/c) at LHC –

→ $\sigma_{\text{large pT}} / \sigma_{\text{total}}$ ~ 2% at SPS
50% at RHIC
98% at LHC

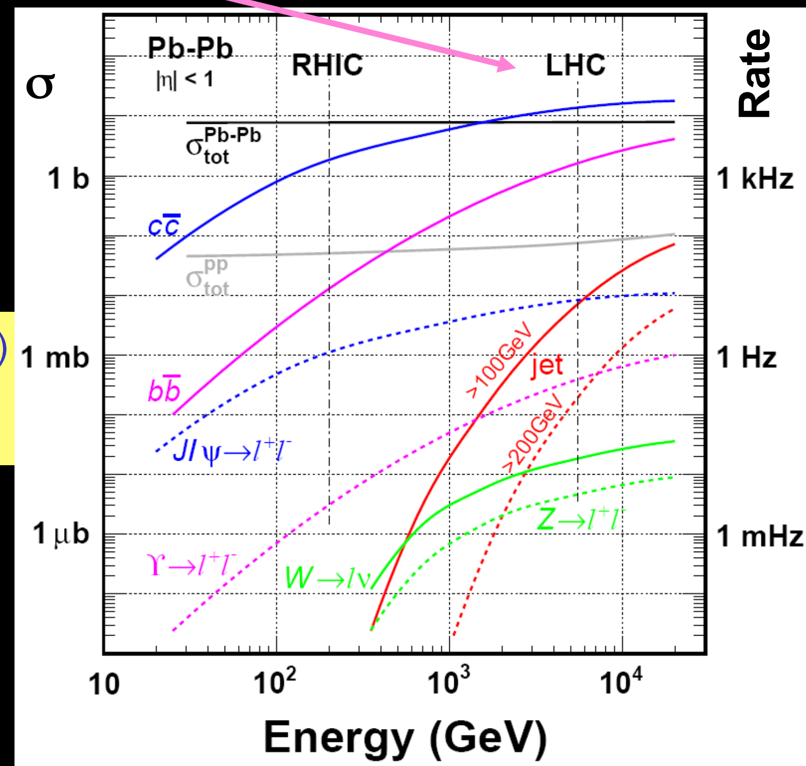
- “real” jets, large p_T processes
- abundance of heavy flavors
- probe early times, calculable





σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)

σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)



High p_T Particles and Jet Rates at LHC

Hard probe physics measurements:

- High p_T hadron (PID) suppression (R_{AA})
- Di-hadron $\Delta\phi$ correlations to ~100 GeV/c
- Jet spectra & shapes
- γ, Z, γ-jet (Z-jet) corr's (statistics?)

Hard Probe statistics with 0.5 nb^{-1} in ALICE/ATLAS/CMS:

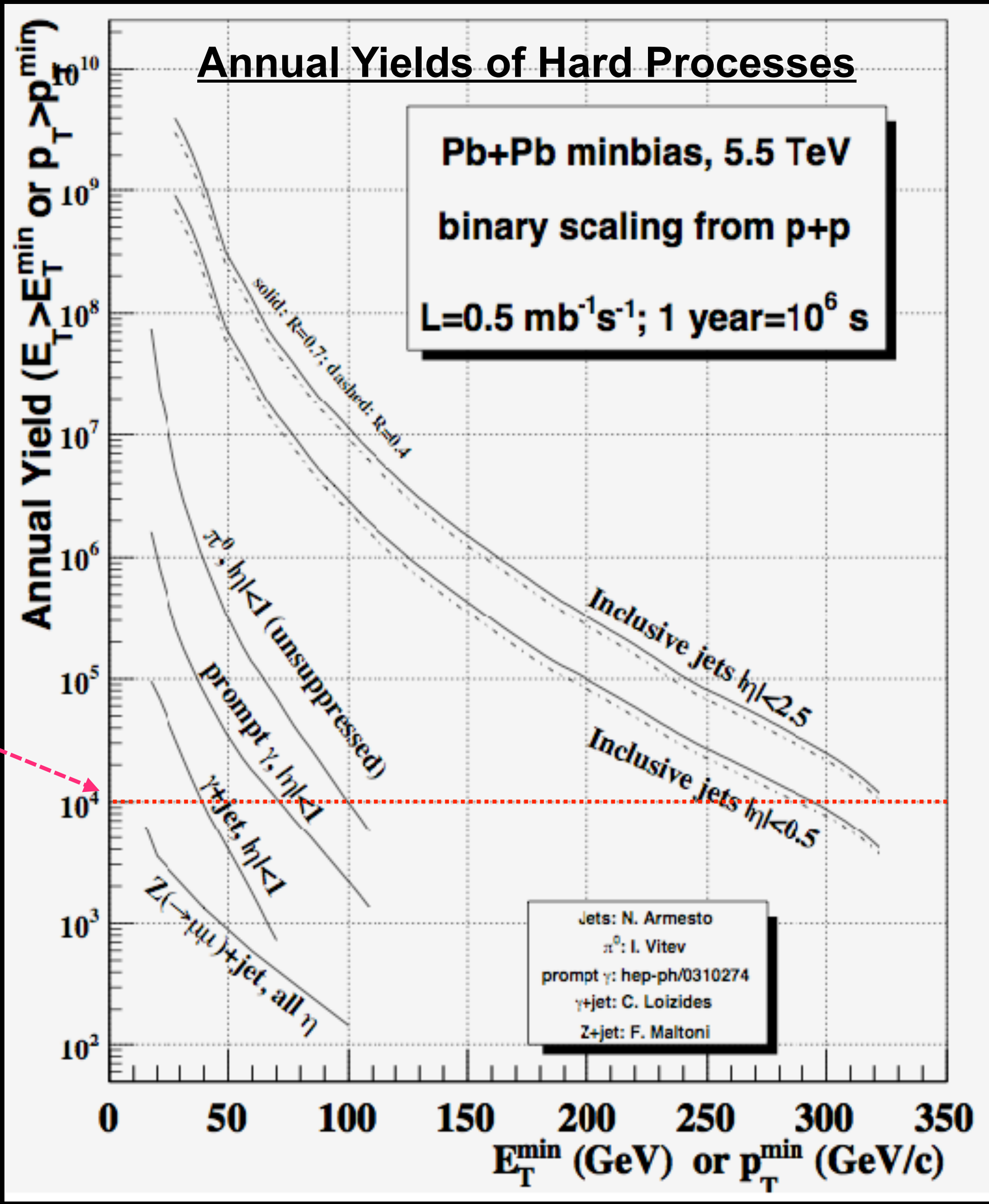
10^4/year

inclusive jets: E_T ~ 200-325 GeV

dijets: E_T ~ 170-250 GeV

π^0: p_T ~ 75-150 GeV/c

inclusive γ: p_T ~ 45-100 GeV



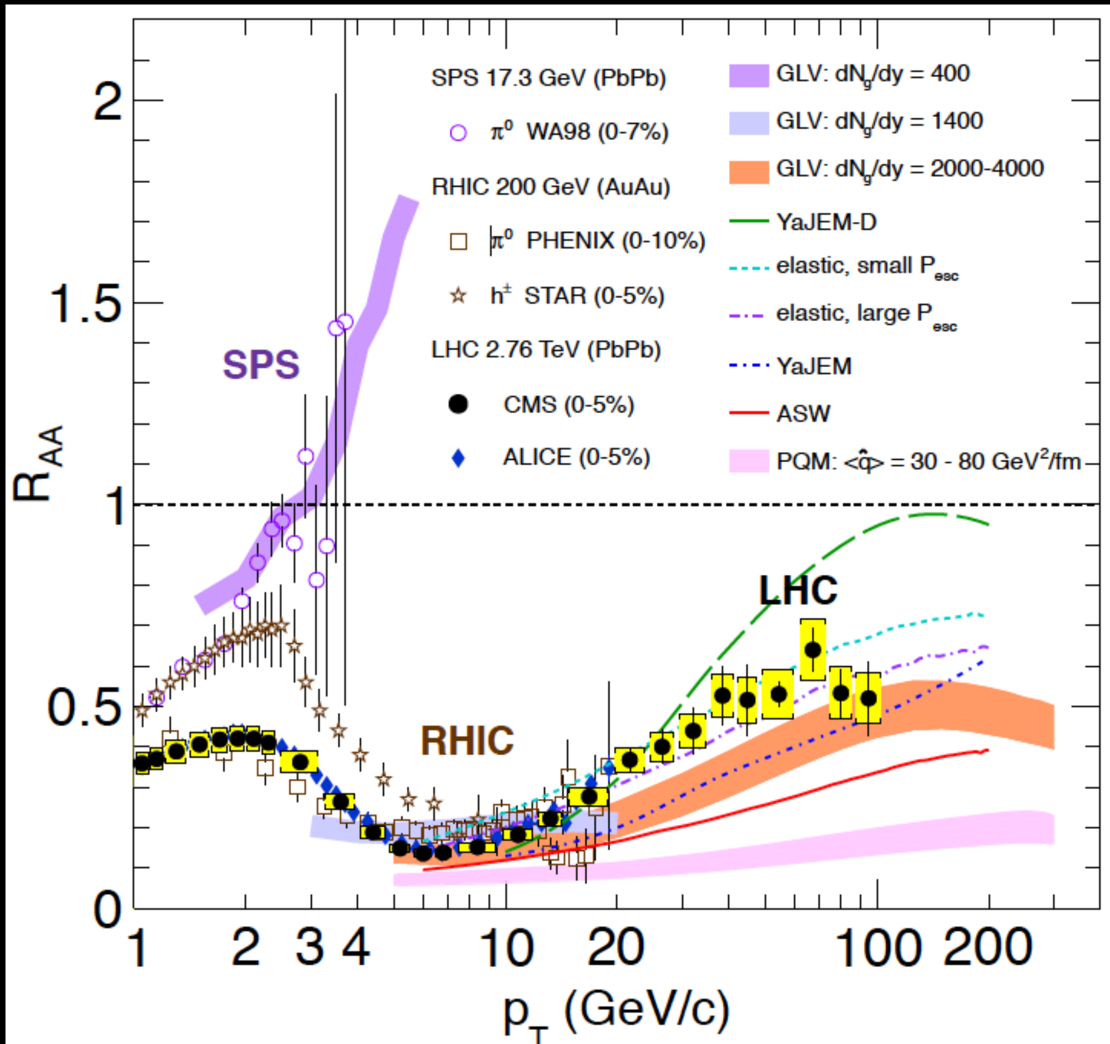
Why Study pp, pA (dA) & A-A Collisions?

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?
  - It has to be saturated? But, 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



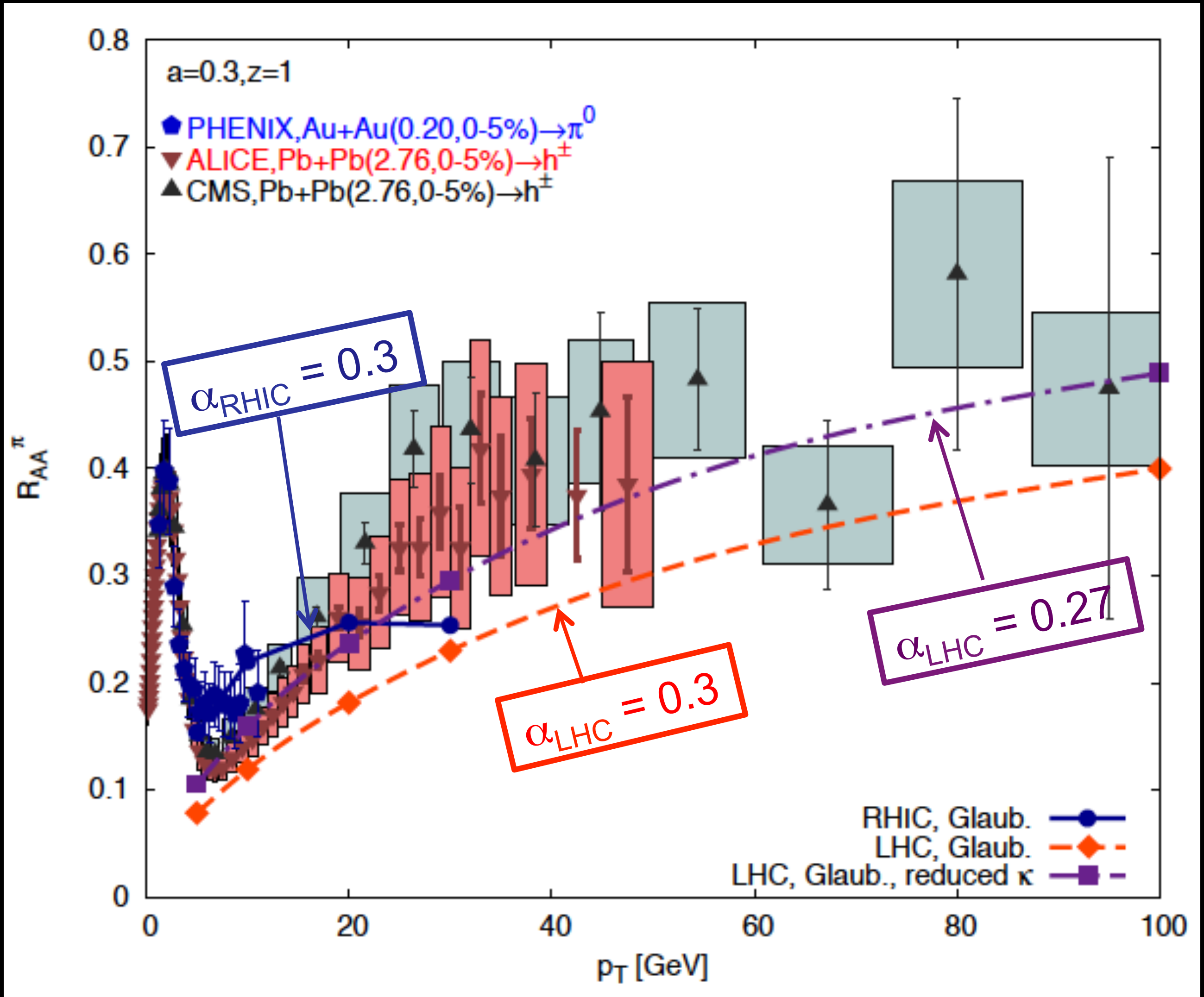
$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

$R_{AA} = 1$

Suppression

CMS, arXiv:1202.2554v1

Reduced α_s Describes LHC Trend



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

R_{AA} at LHC in pQCD:

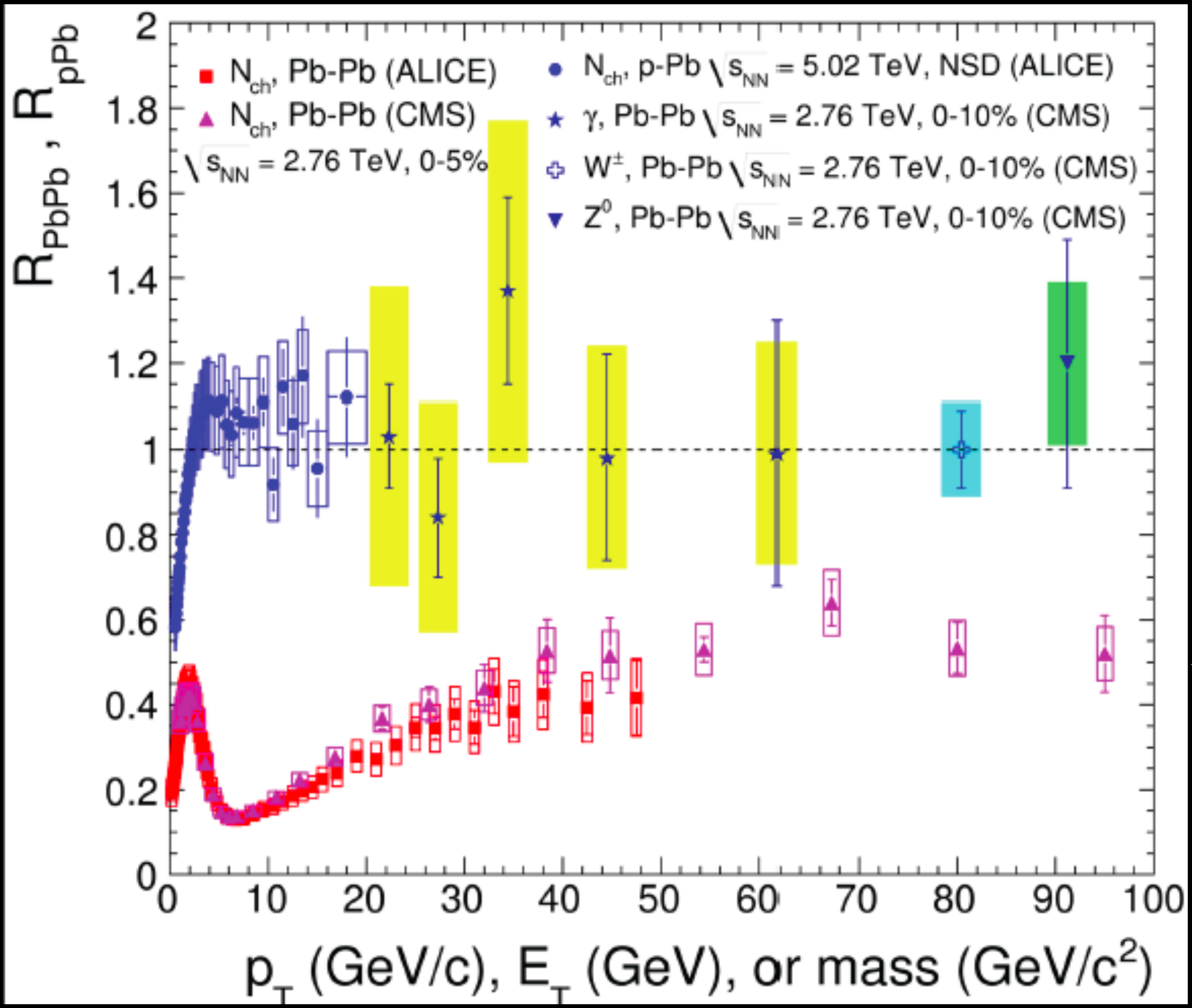
Suppression described with reduced α_s!

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

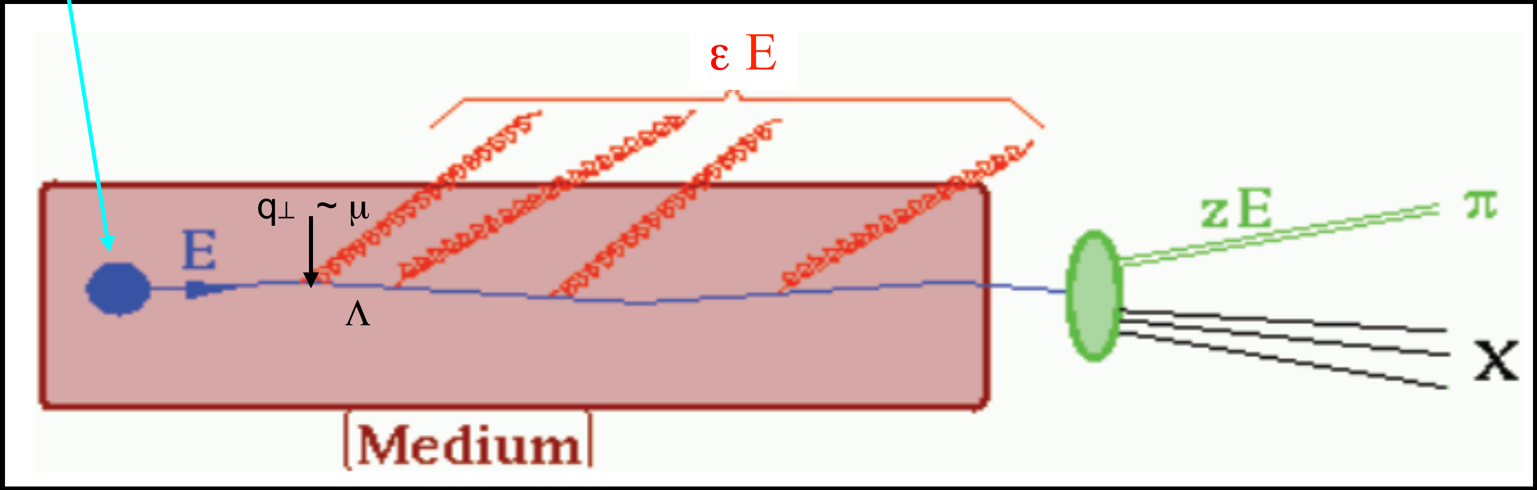
(p-Pb → charged)

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

Dynamical Origin of High p_T Hadron Suppression?

How does parton lose energy?

What happens to the radiation?



What is the dependence on the type of parton?

For collisional energy loss what about recoil energy?

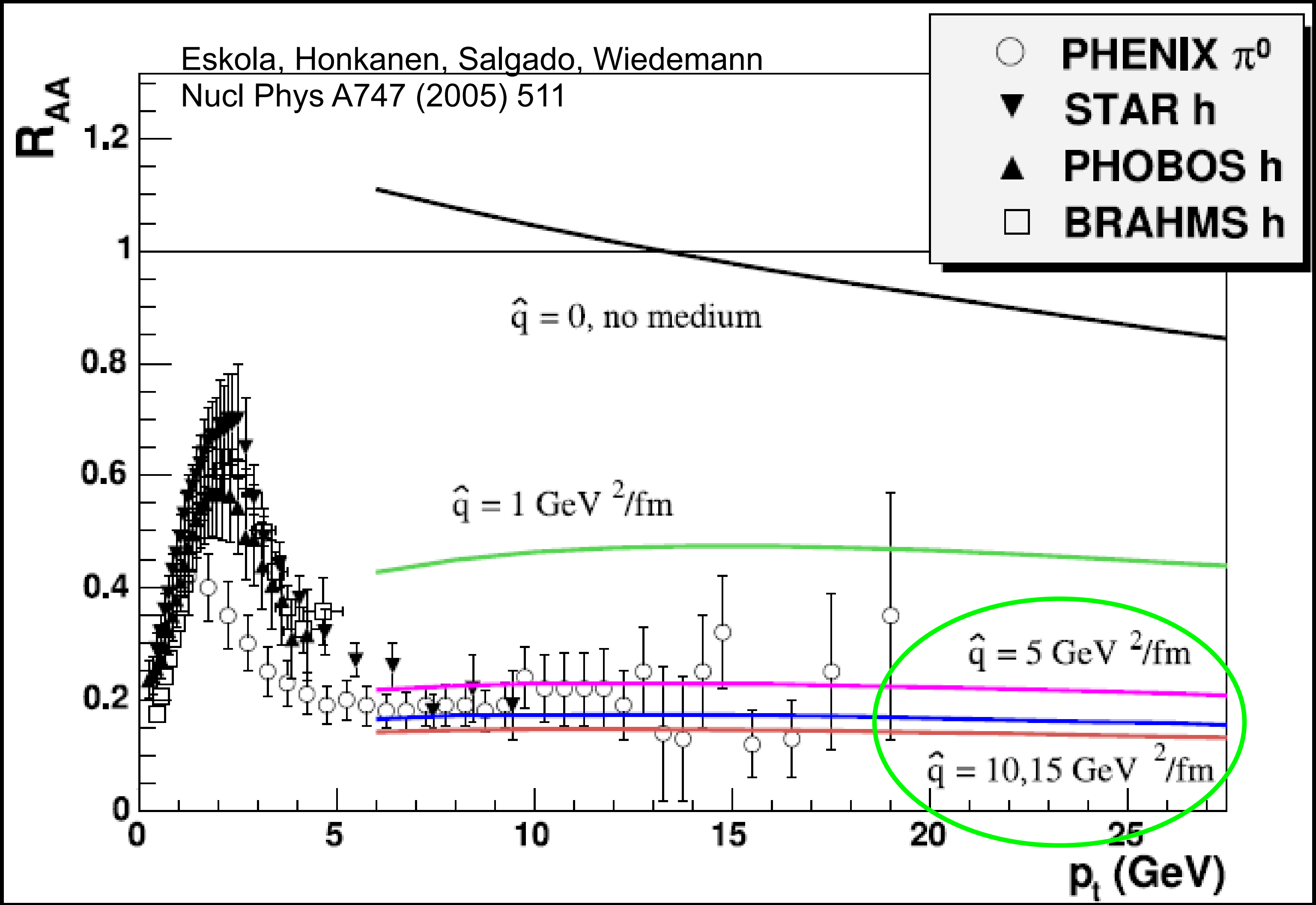
$$\Delta E_{gluon} > \Delta E_{quark,\ m=0} > \Delta E_{quark,\ m>0}$$

Important to measure ΔE of gluons → light → heavy quarks…

One parameterization of energy loss →

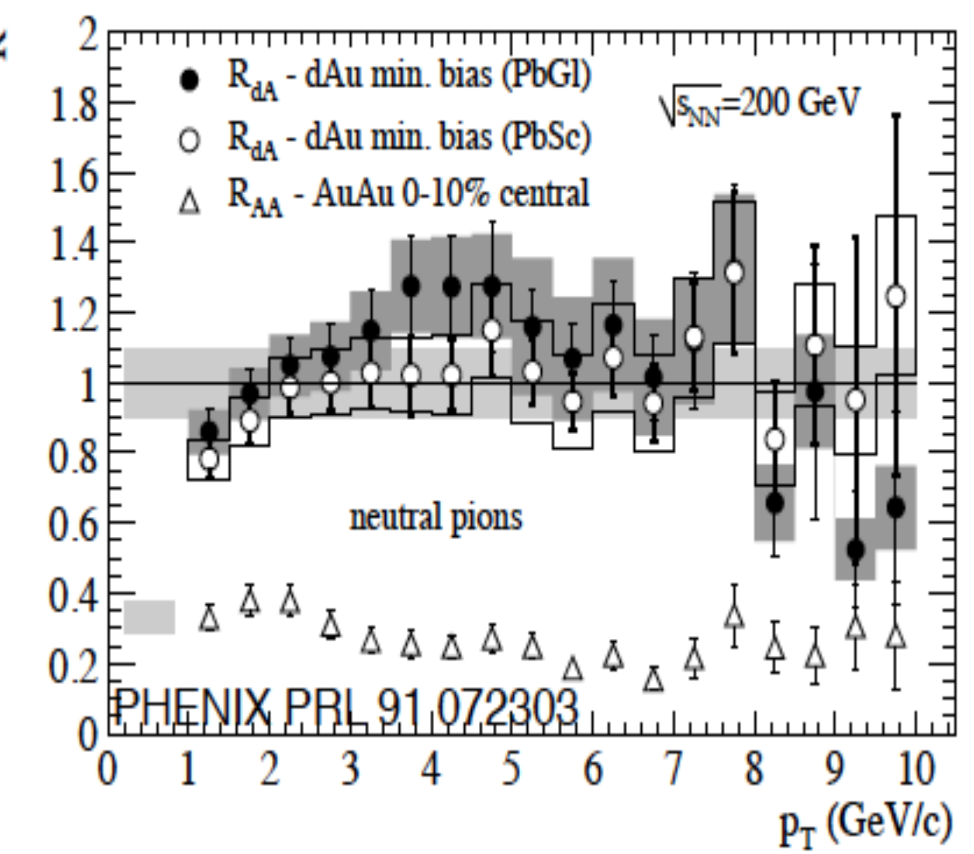
$$\hat{q} = \mu^2 / \Lambda$$

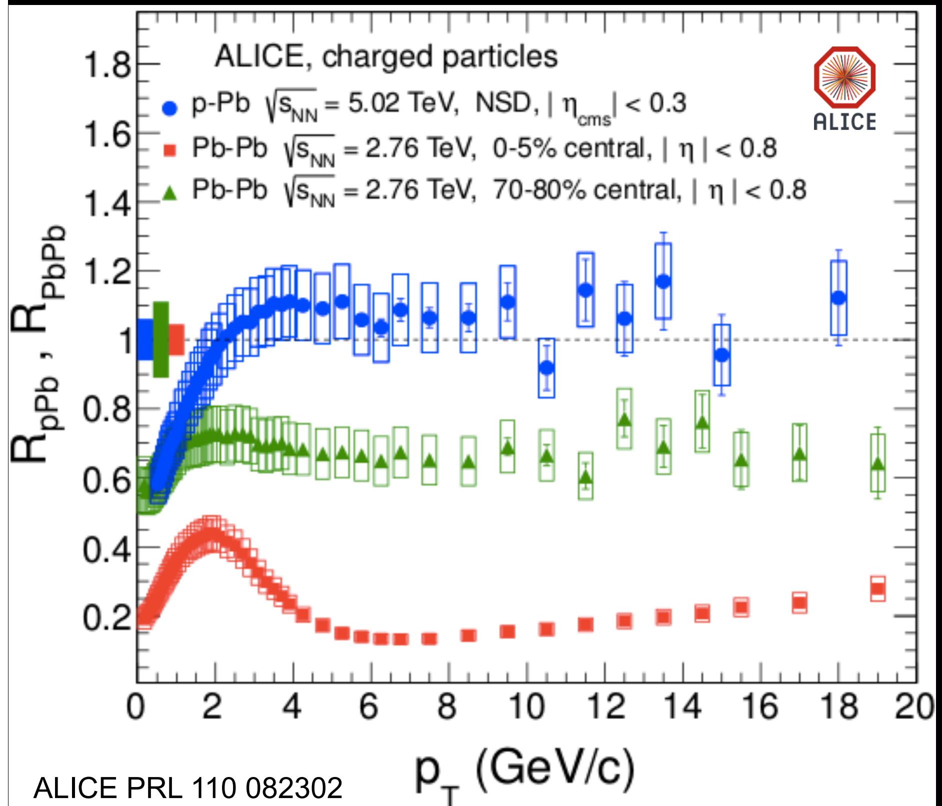
$\hat{q}$ Parameterization of Parton Energy Loss



$\hat{q}$ = 5 – 15 GeV^2 / fm from RHIC R_{AA} Data

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





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

- Binary scaling (R_{dAu} ~ R_{pPb} ~ 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)

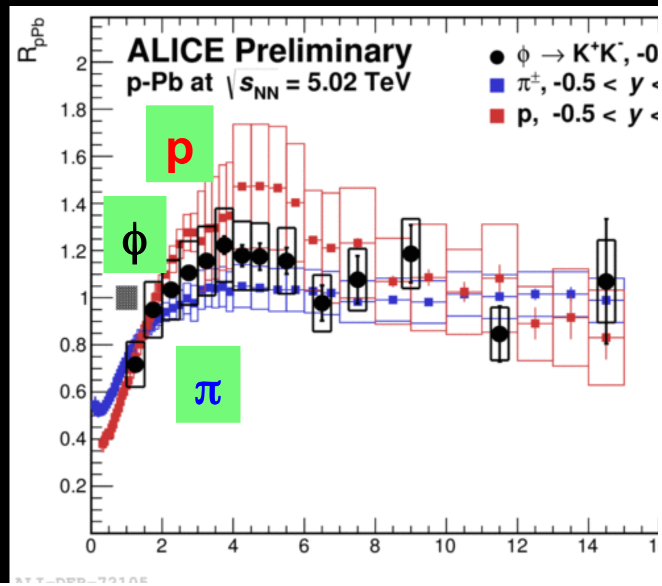
R_{pPb} for Different Particles at LHC

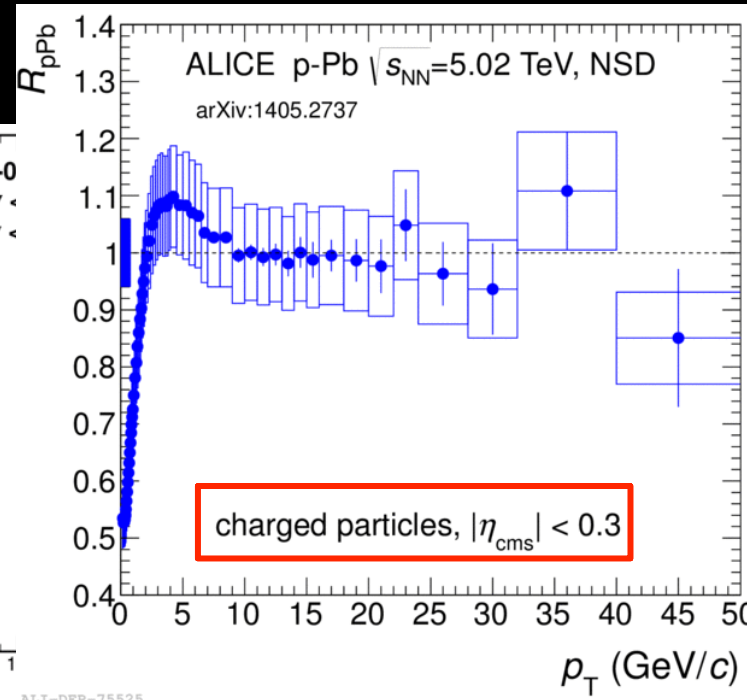
R_{pPb} → charged particles
proton enhancement

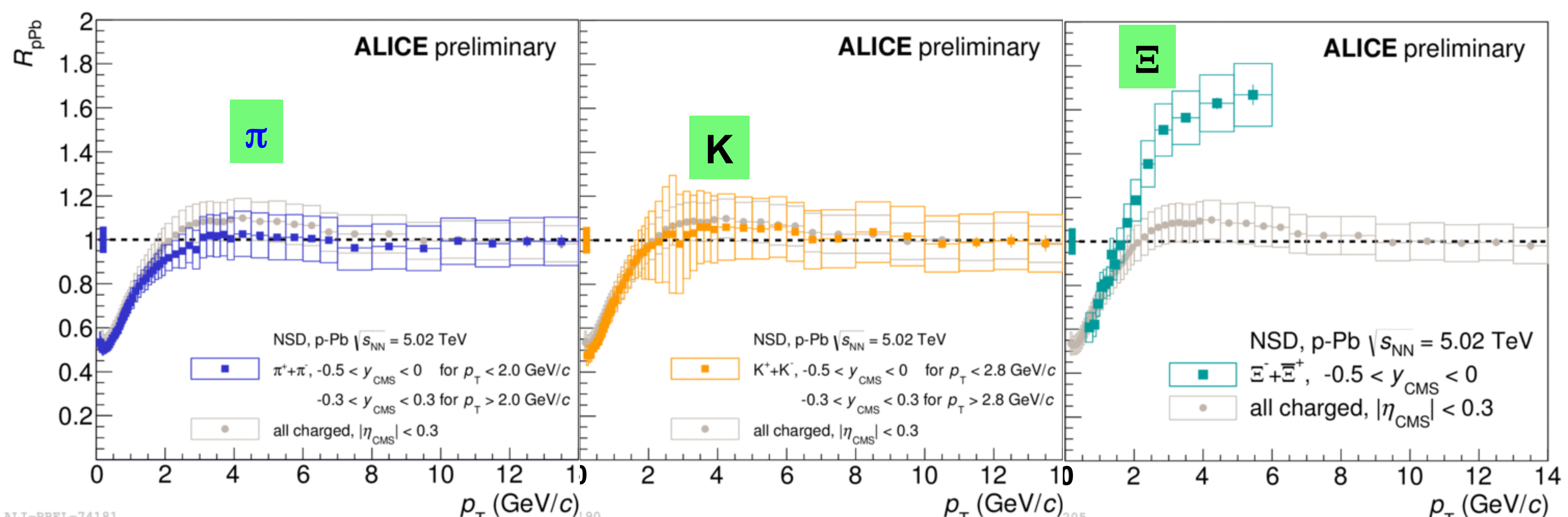
R_{pPb}
π & K is ~ flat ~ 1

R_{pPb}
ϕ slight enhancement

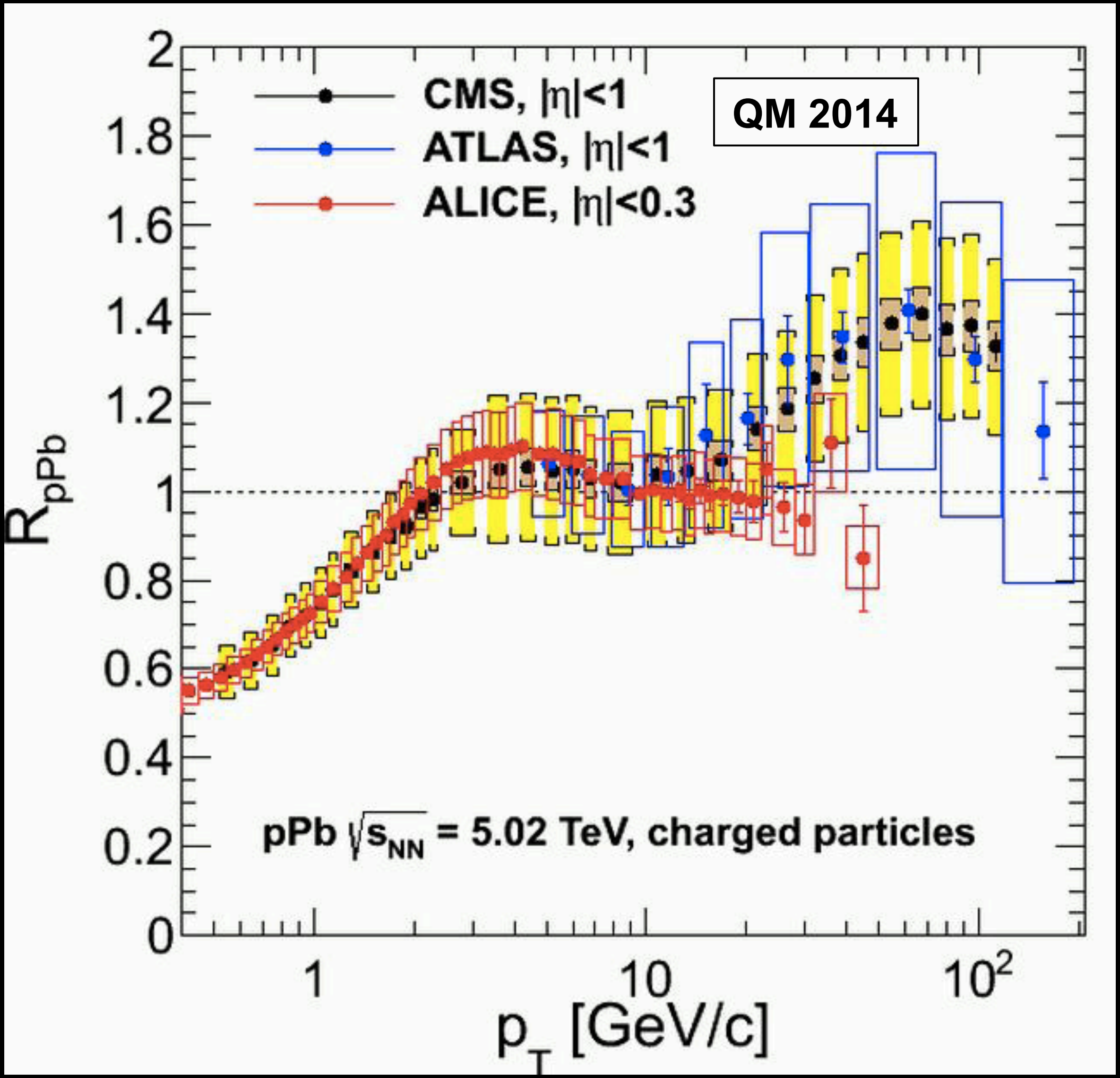
M. Knickel, ALICE QM14







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



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

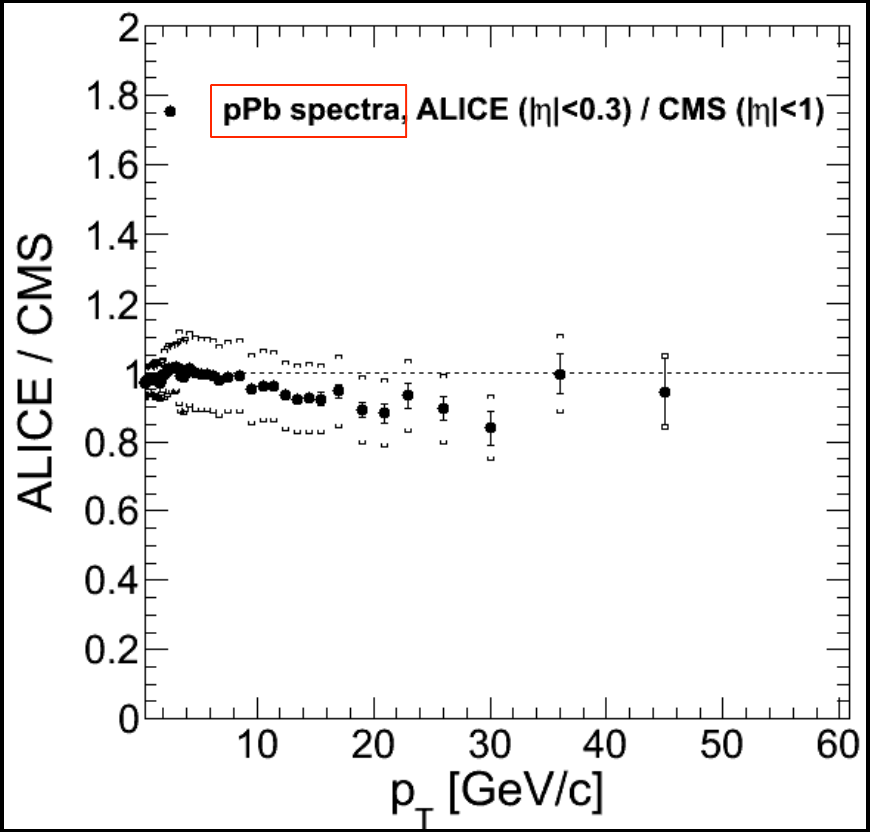
p-Pb 2 < p_T < 20 GeV/c

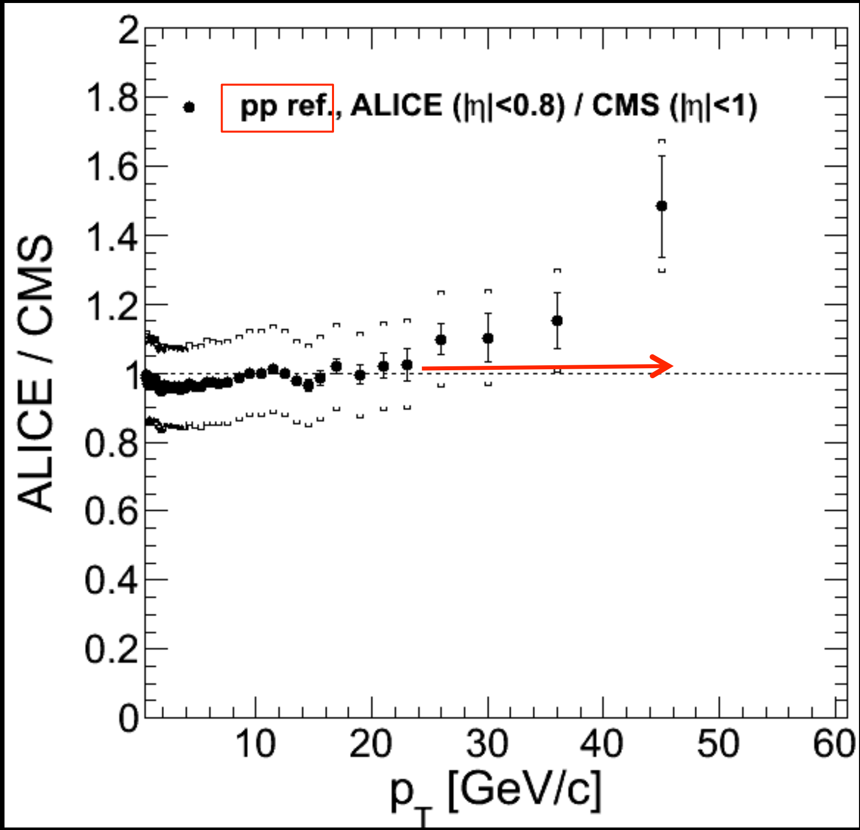
- Binary scaling (R_{pPb} ~ 1)
- Absence of Nuclear Modification

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

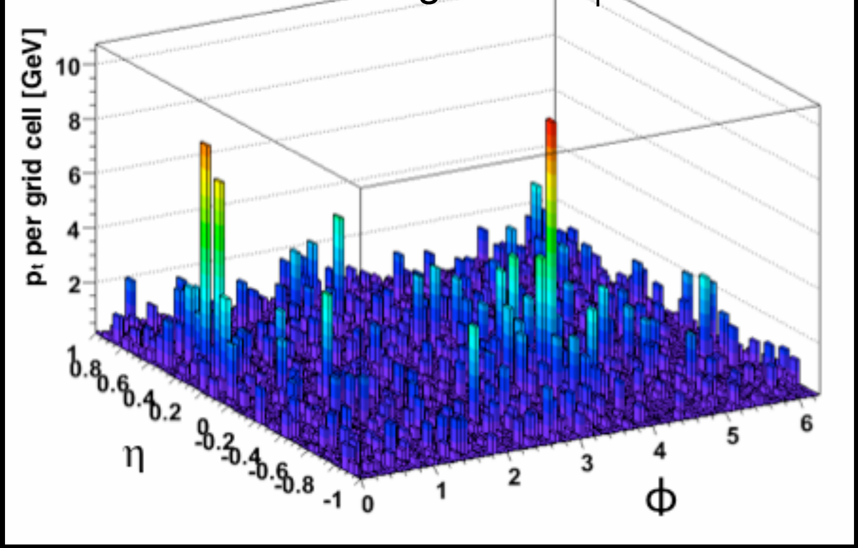
pp → spectra $2 < p_T < 50$ GeV/c

- pp reference differences $p_T > 25$ GeV/c
- Need pp reference at 5.02 TeV

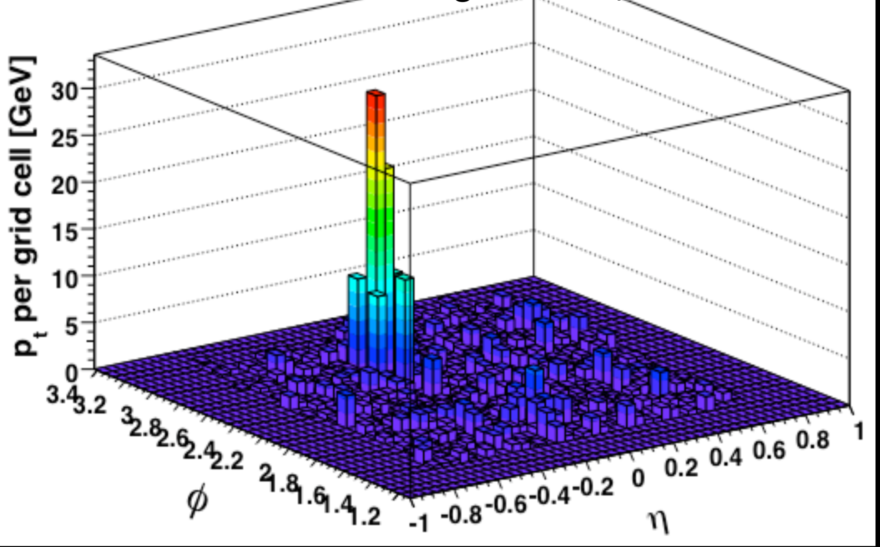
Y-J Lee, QM 2014

Jets in Heavy Ion Collisions at RHIC & LHC

Central Au+Au $\sqrt{s_{NN}}$=200 GeV



Central Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV



Why measure jets in heavy ion collisions? [inclusive, di-jets, hadron-jet, γ-jet,..]

- Determine the kinematics of the binary hard-scattering (parton-parton) interaction
- Characterize the parton energy loss in the hot QCD medium

  [Requires detailed measurements for theoretical comparison / understanding]

  Establish energy-loss mechanisms and modification of fragmentation

  – energy flow within jets, quark vs gluon jet differences

  – flavor and mass dependence
- Study medium response to parton energy loss – establish properties of the medium

Jet Reconstruction in Heavy Ion Collisions

Primary Jet Reconstruction Approaches

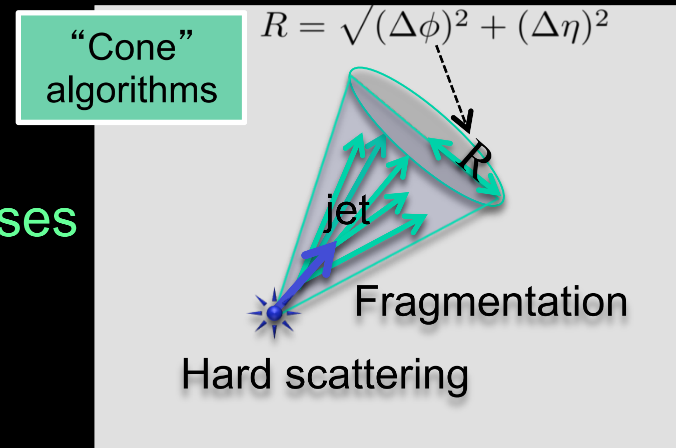
Cone-based algorithms

- Cone shape restriction
- Seeded-cone & strong trigger seed biases

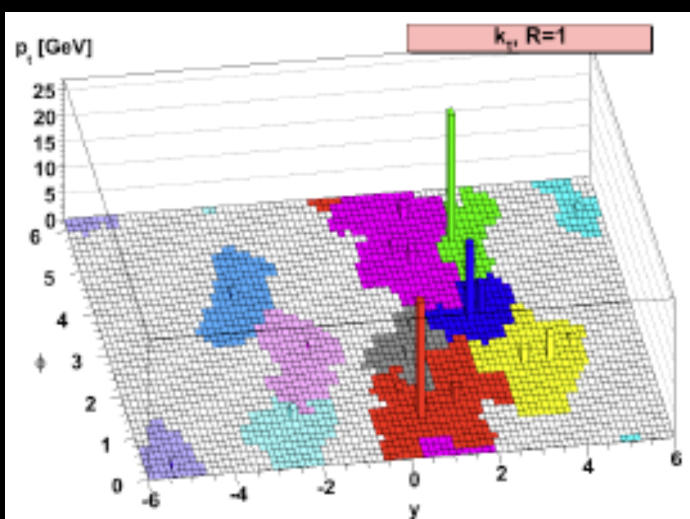
Recombination algorithms – kT (anti-kT)

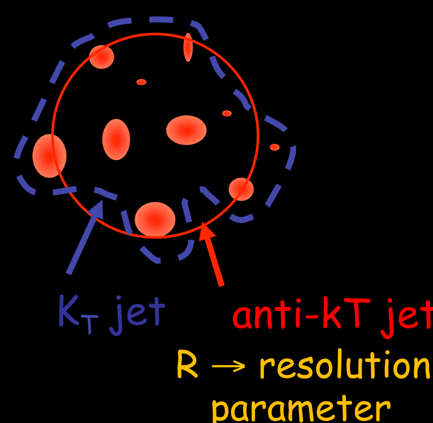
- starts from low (high) p_T
- merges weighted by $1/p_T$ (p_T)

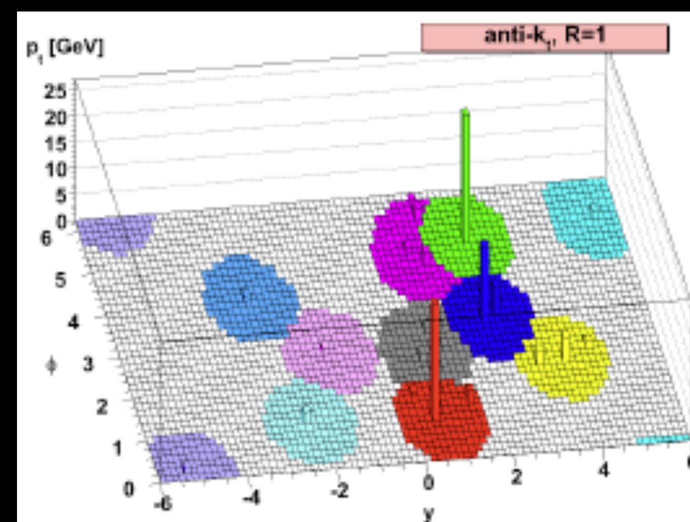
  → high (low) p_T disfavored



Recombination algorithms

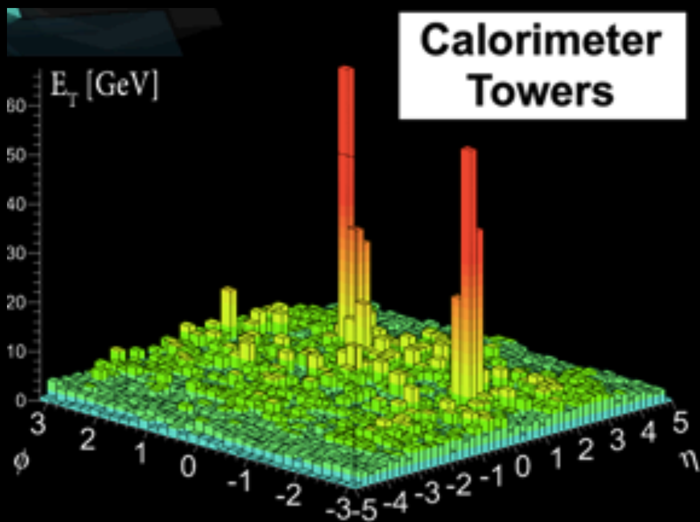




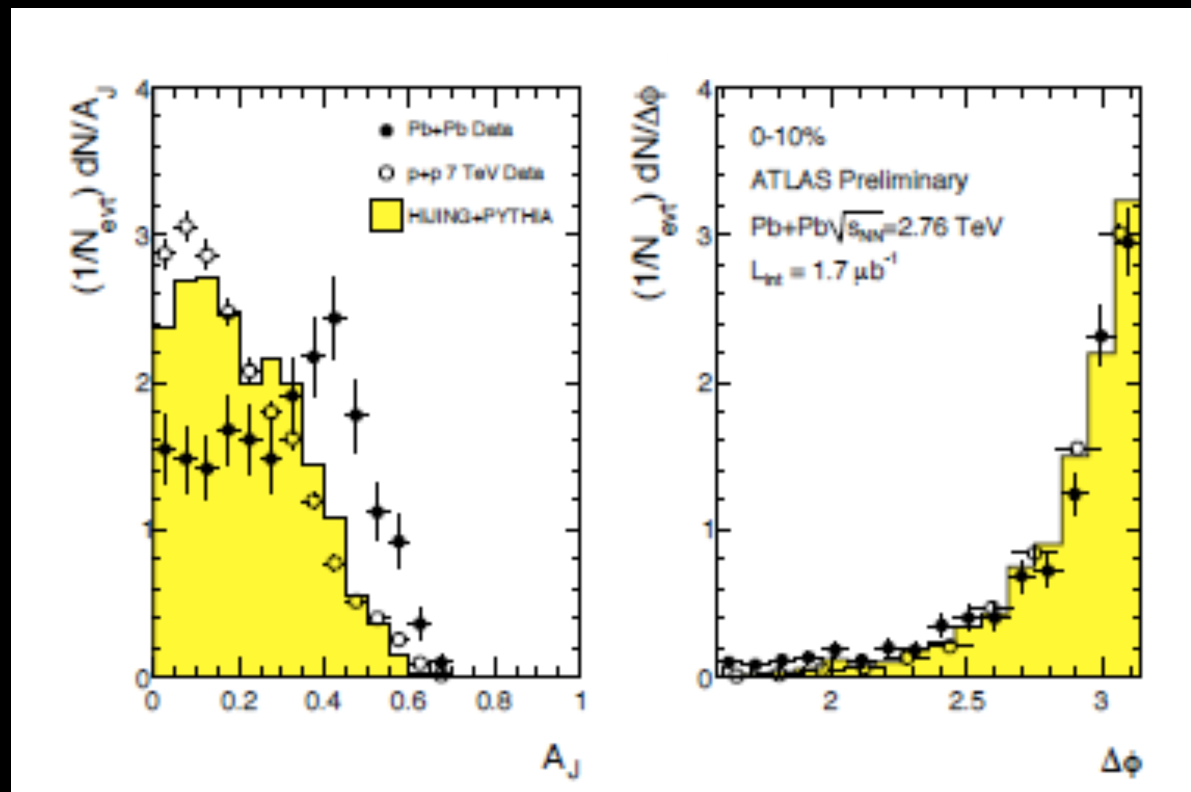


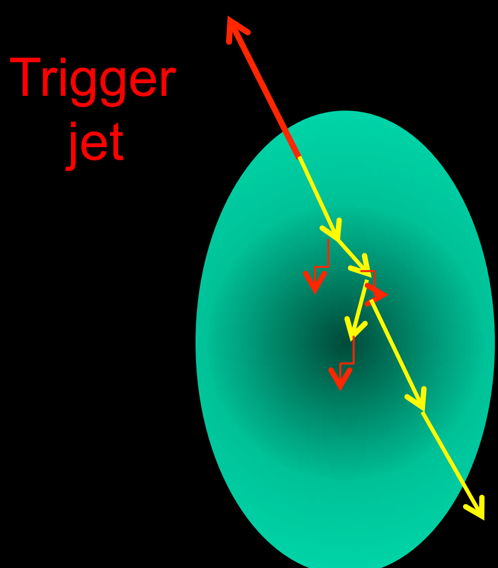
FastJet M. Cacciari, G. Salam, G. Soyez JHEP 0804:005 (2008)

Jets at the LHC – Di-Jet Energy Imbalance!



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





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

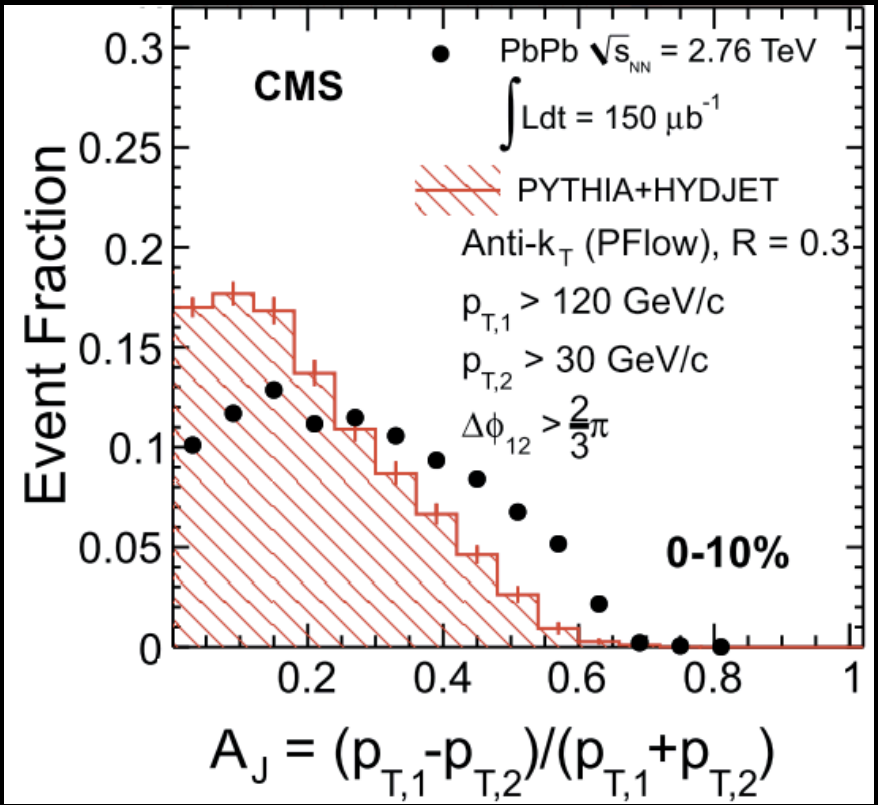
for $\Delta\phi > \pi/2$

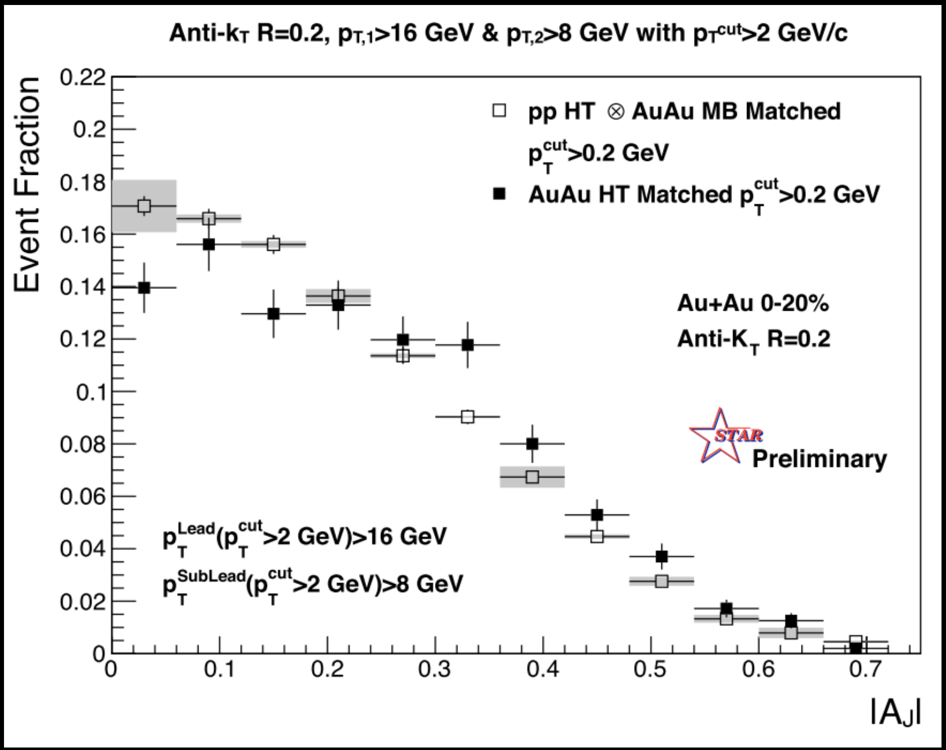
(E_{T1} > 100 GeV, E_{T2} > 25 GeV)

Jets at LHC & RHIC – Di-Jet Imbalance!

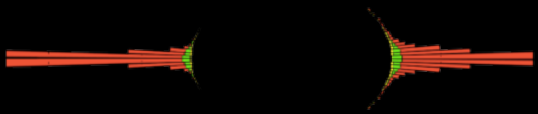
LHC   CMS, Phys. Rev. C84 (2011) 024906
QM 2014

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

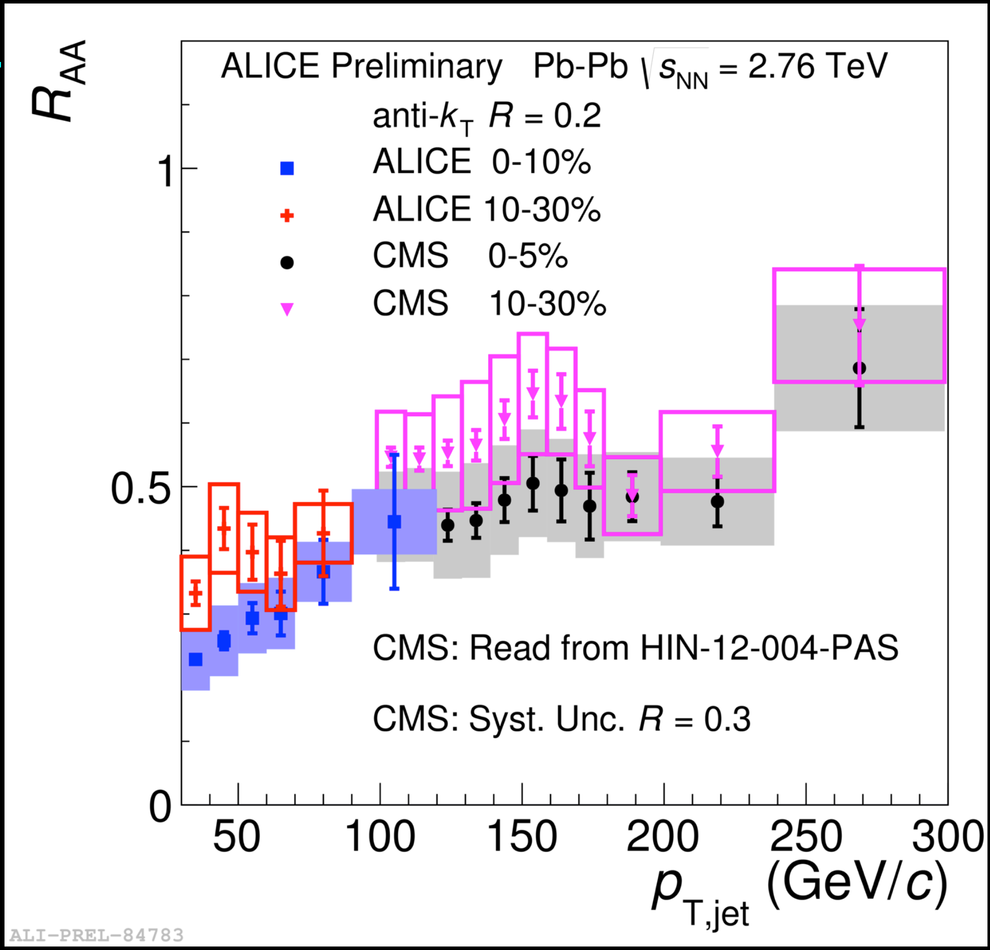
LHC ALICE, CMS QM 2014

p_T-dependence of jet quenching

Lower p_T jets more strongly quenched

centrality-dependence

jets in more central collisions more strongly quenched

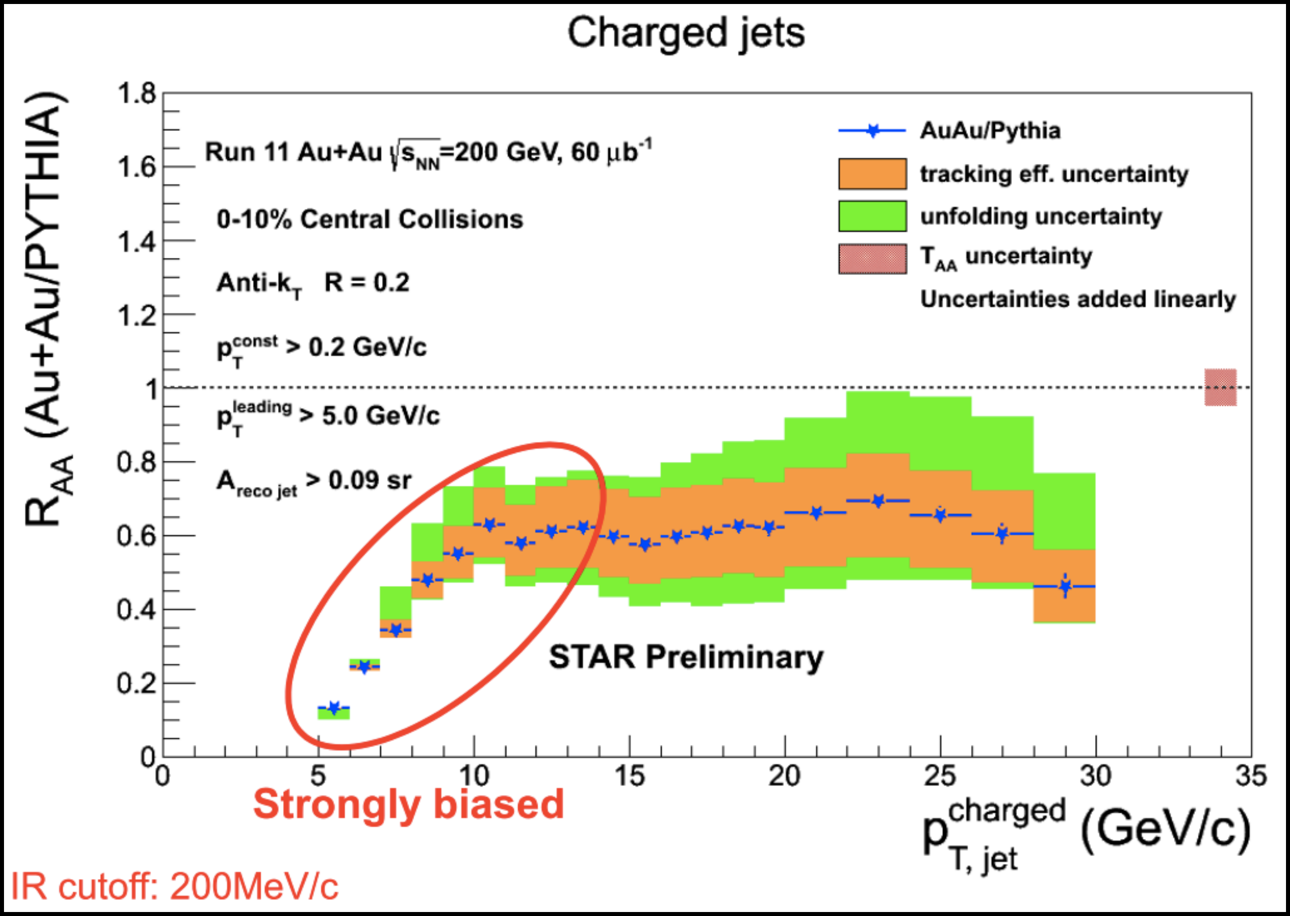


ALICE R_{AA}(jet) ~ CMS R_{AA}(jet) at overlap

Jet Quenching at RHIC

RHIC

J. Rusnak, STAR
HP 2013



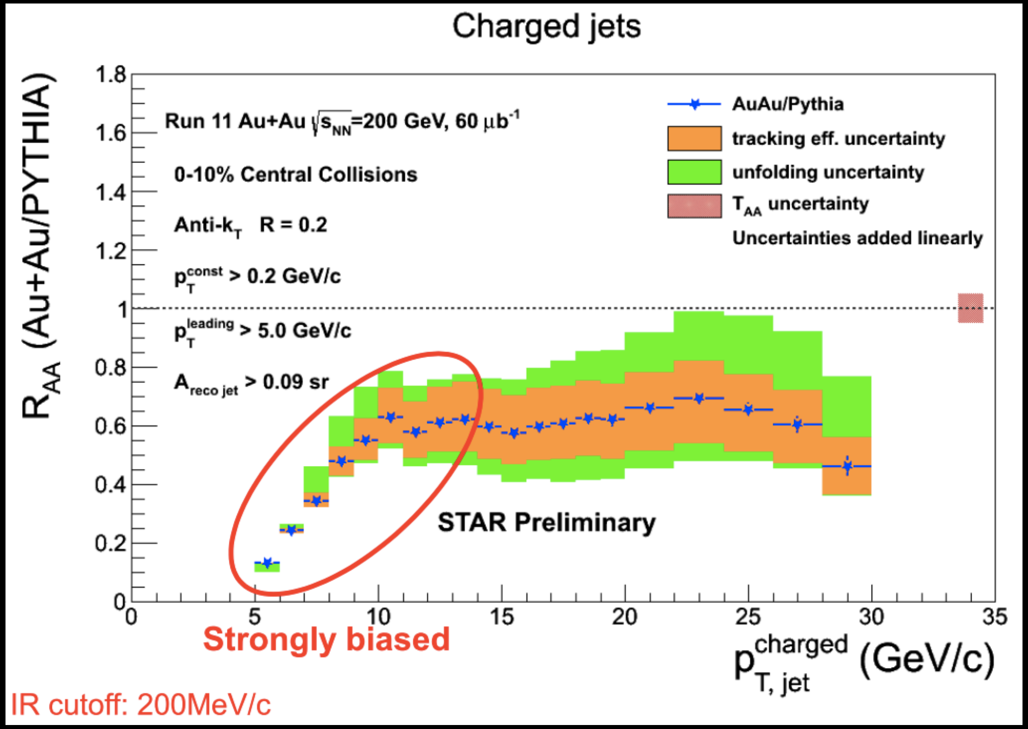
At RHIC: Jets are less suppressed than high p_T particles

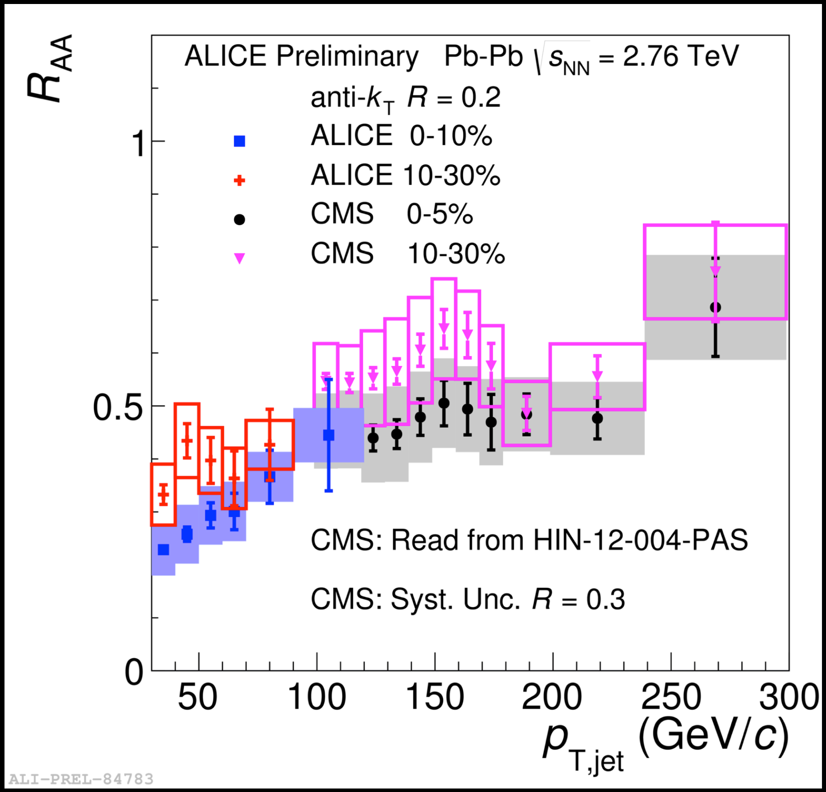
$R_{AuAu}(\pi) \sim 0.2 – 0.3$ for $p_T = 4 – 20$ GeV/c

→ suggests modification of fragmentation function!

Jet Quenching at RHIC vs LHC

RHIC





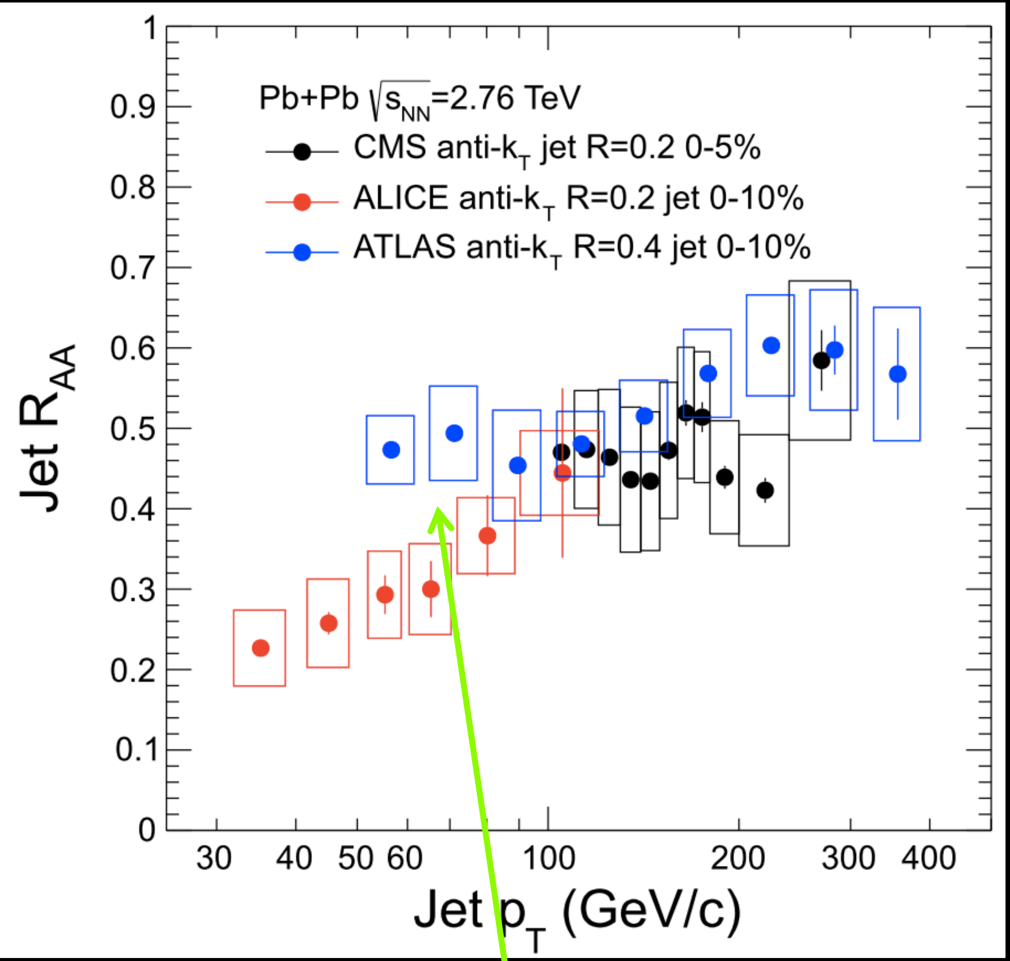
RHIC Jets less suppressed than LHC Jets
at low jet momentum

Momentum Dependence of Jet Quenching

ALICE

ATLAS QM 2014

CMS (black)



ALICE R_{AA}(jet) ≠ ATLAS R_{AA}(jet)

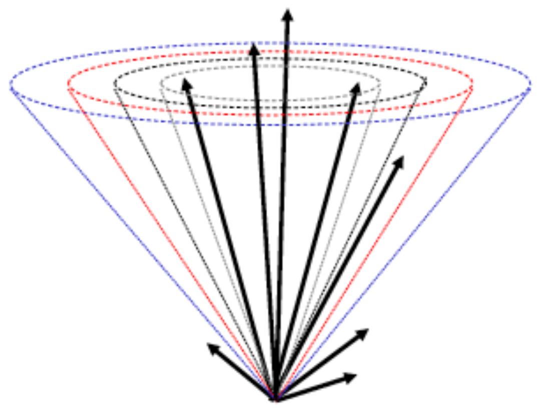
at lower jet p_T

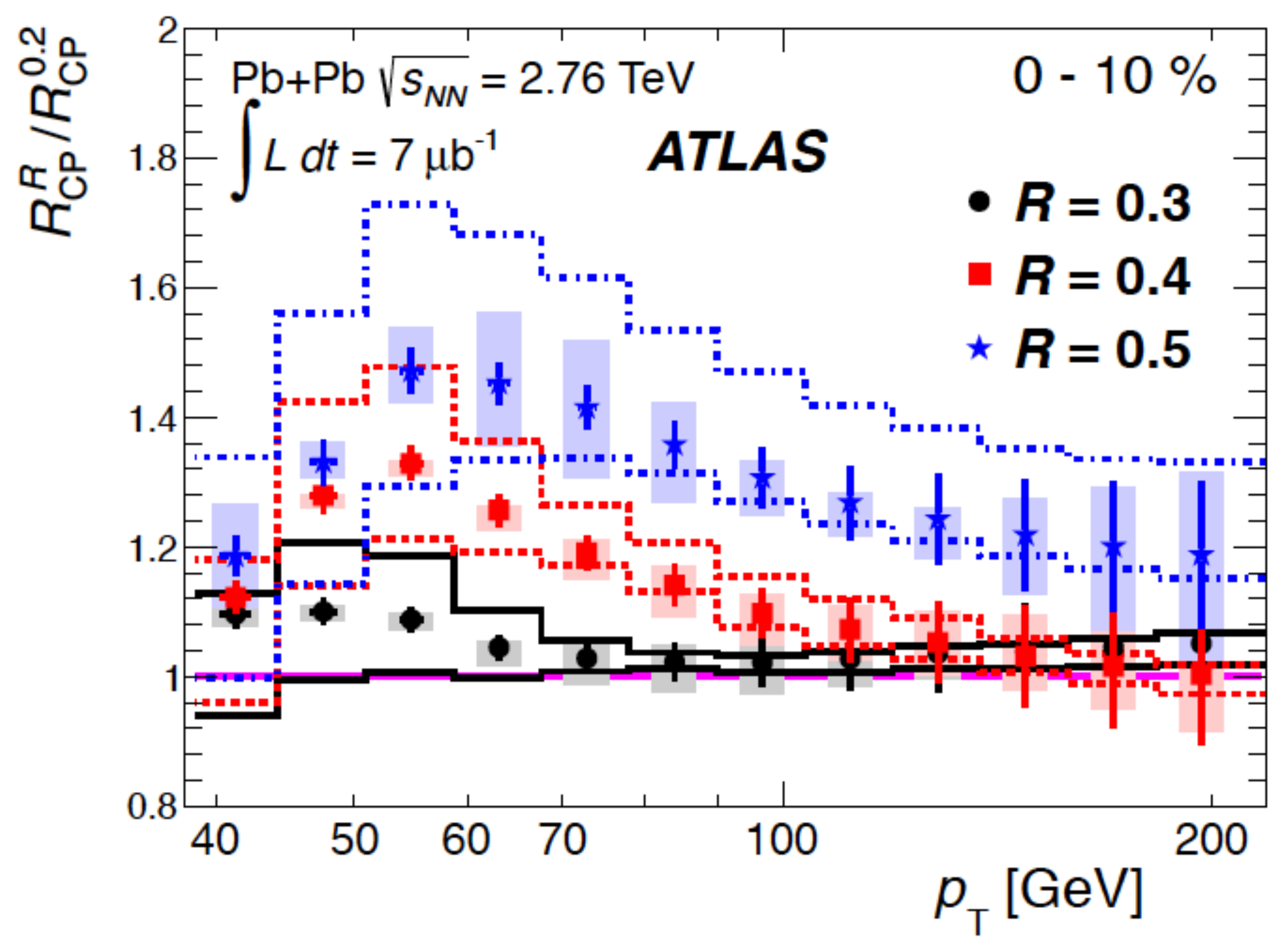
But: ALICE R=0.2 vs ATLAS R=0.4

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



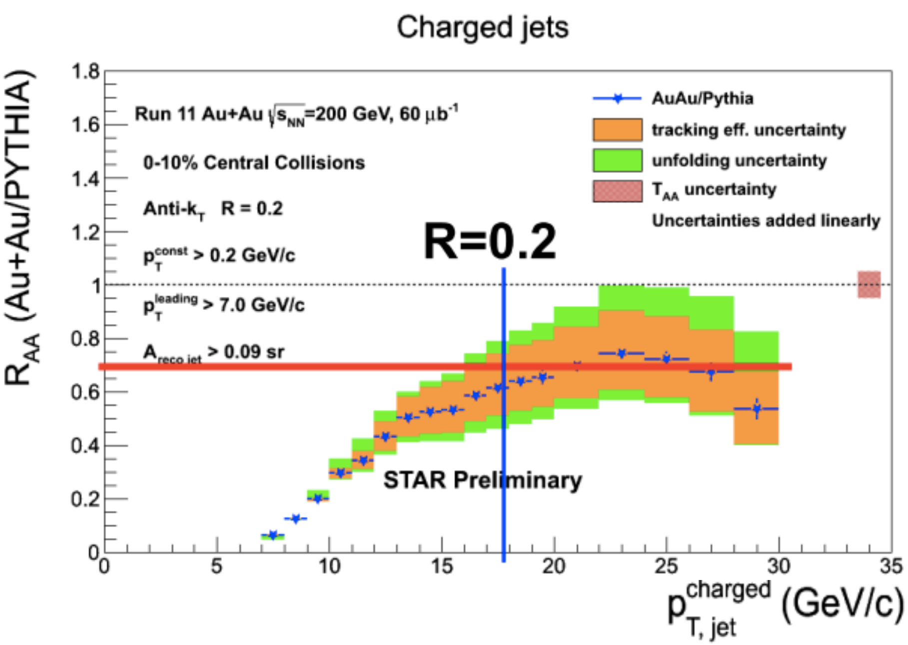


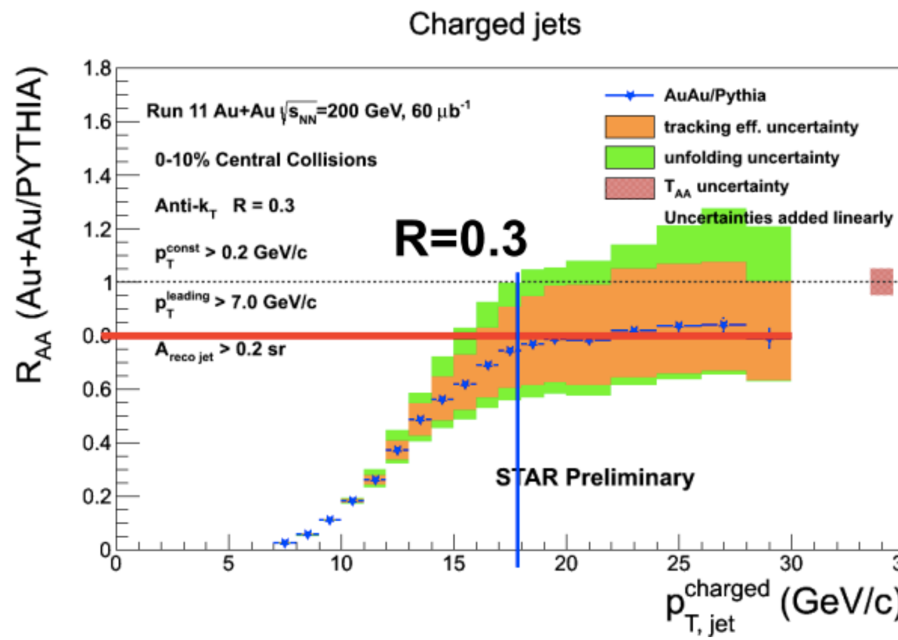
R^R_{CP} / $R^{0.2}_{CP}$ increases for larger R

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

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

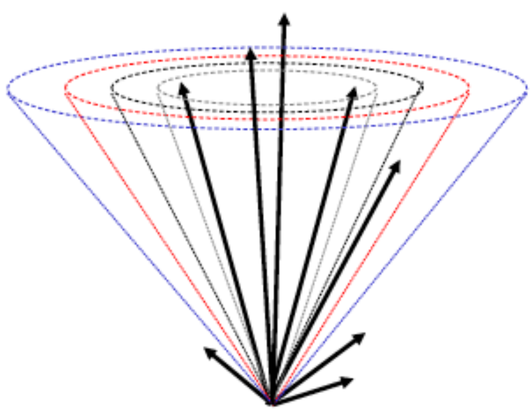
R – "cone size" Dependence of Jet Quenching

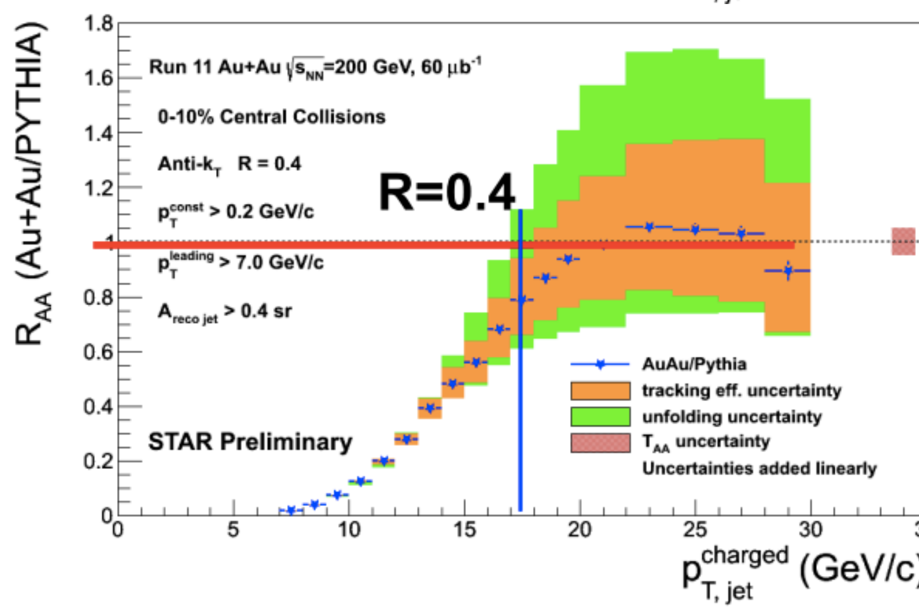




STAR
Au+Au

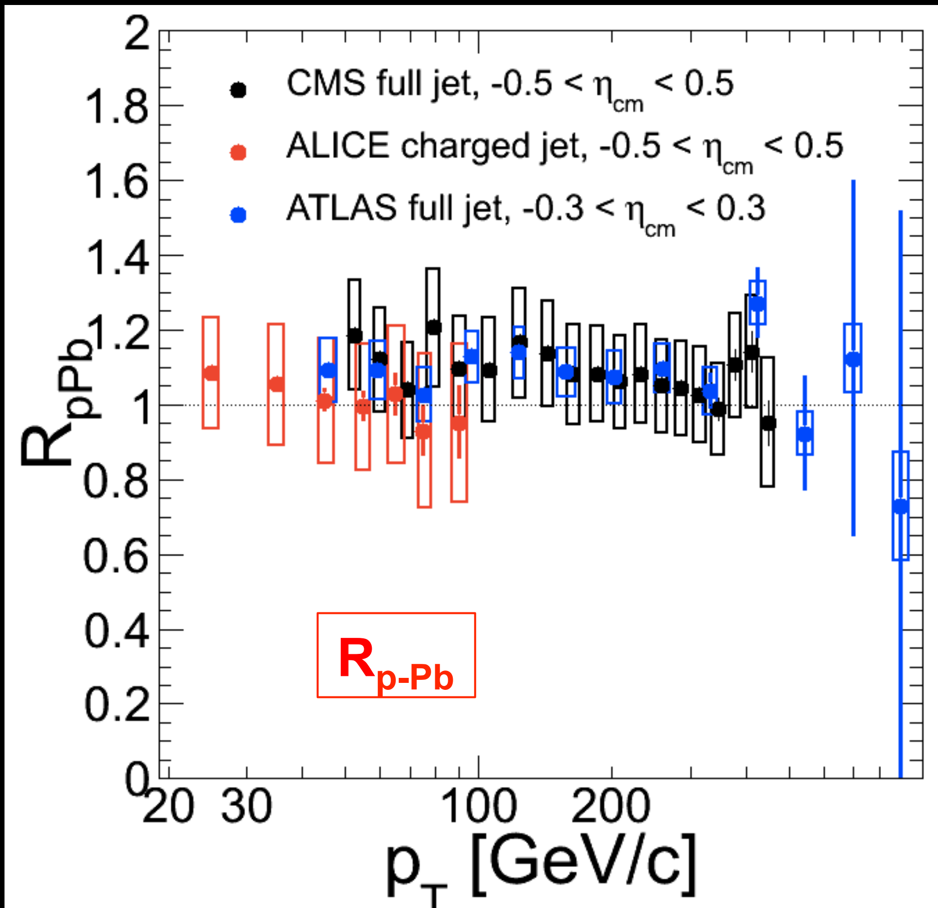
Anti-k_T jet "cone sizes":
R = 0.2, 0.3, 0.4

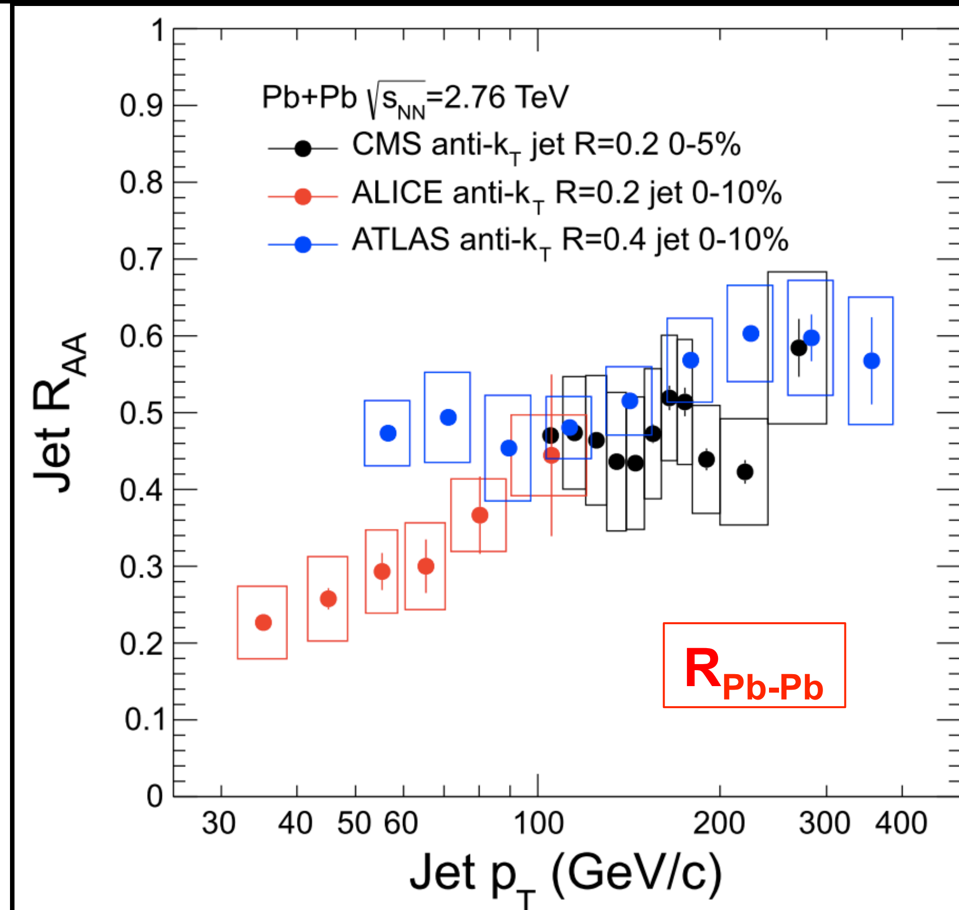




ALICE
ATLAS QM 2014
CMS (black)

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



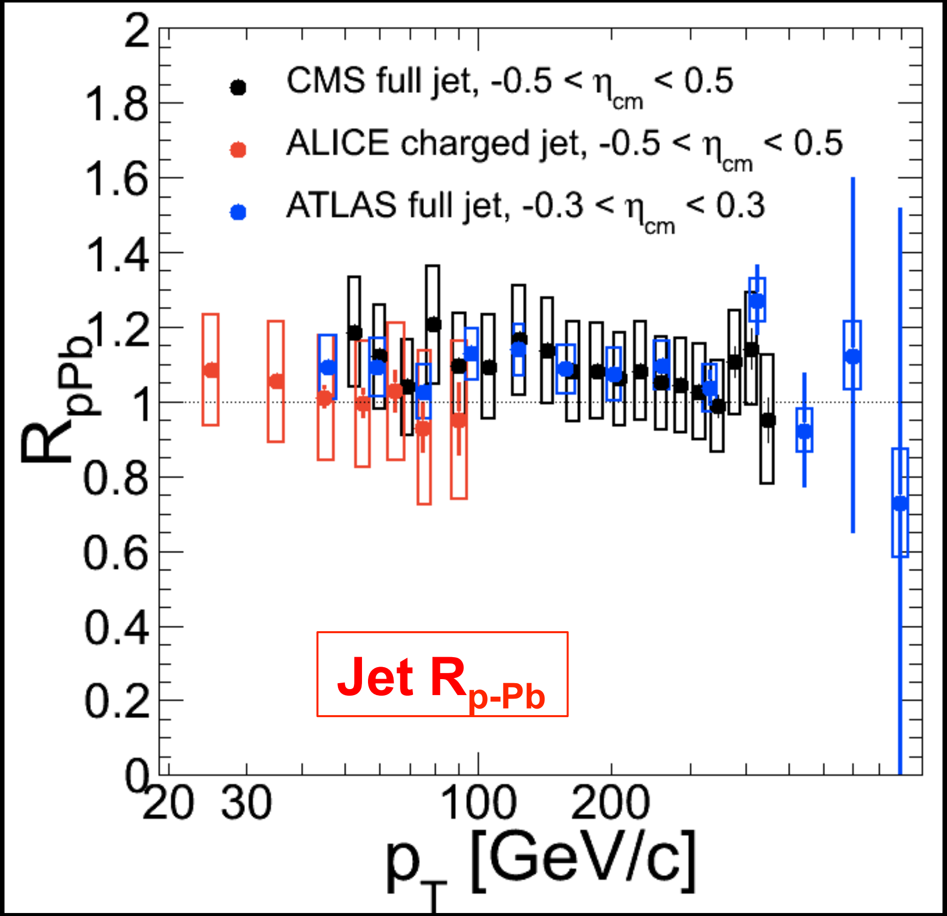


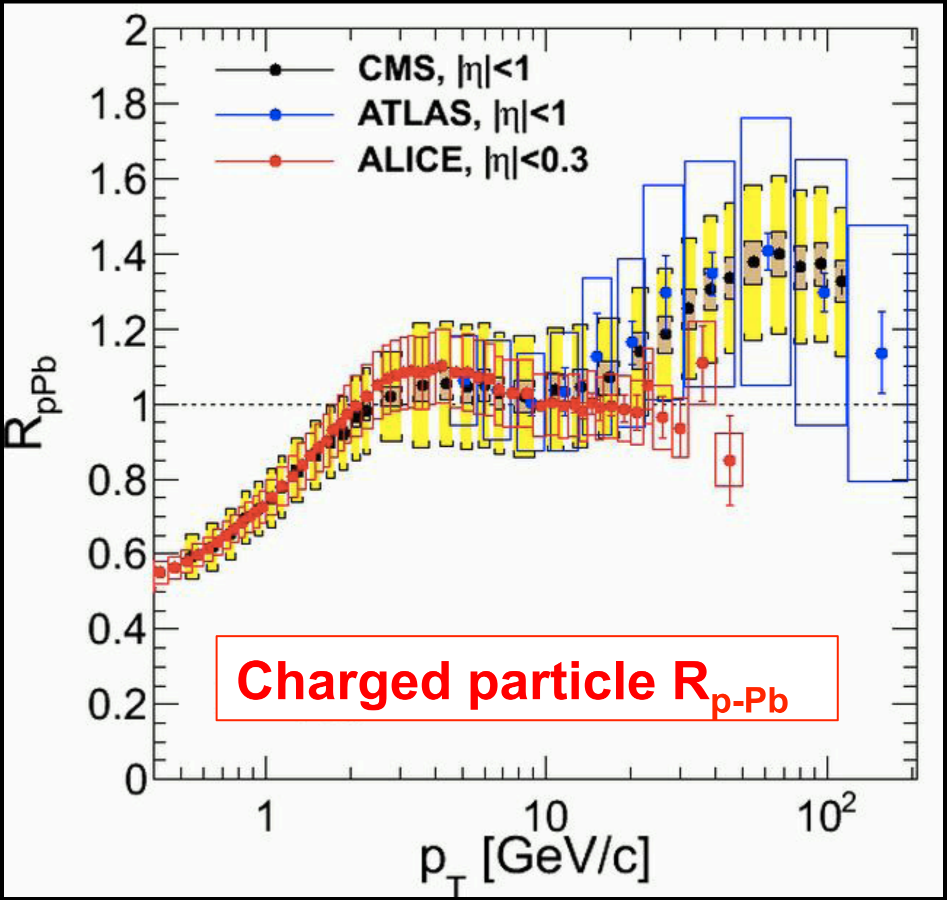
ALICE $R_{p\text{-}Pb}$ (jet) ~
ATLAS $R_{p\text{-}Pb}$ (jet) ~
CMS $R_{p\text{-}Pb}$ (jet)

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

ALICE
ATLAS QM 2014
CMS (black)

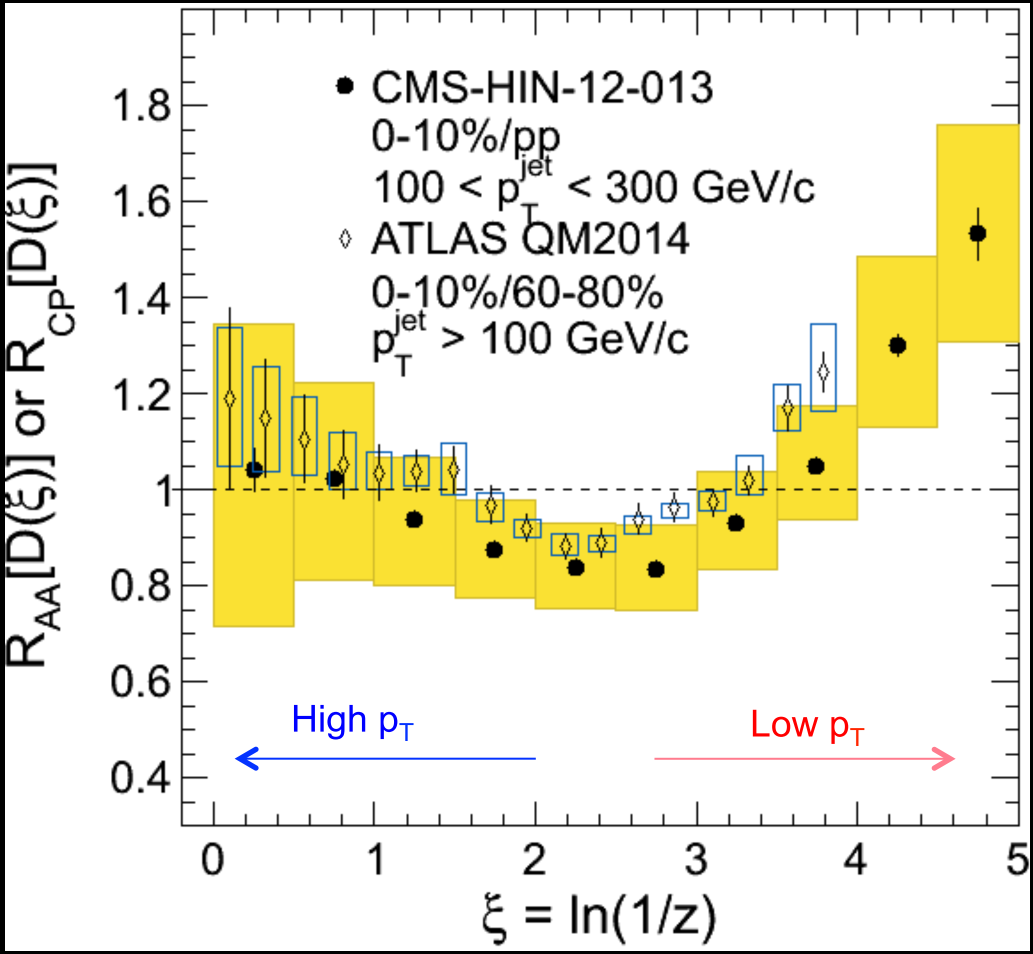
$R_{p\text{-}Pb}$ Jets vs Charged Particles





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)]

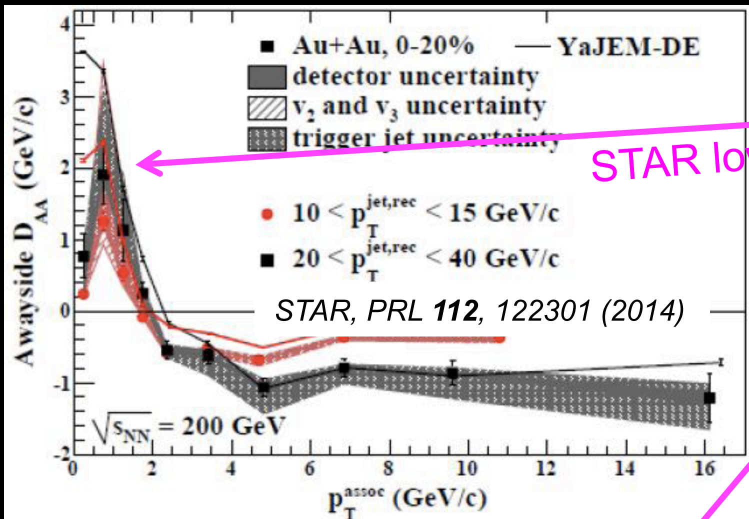
CMS $R_{Pb\text{-}Pb}$ [D(ξ)]

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



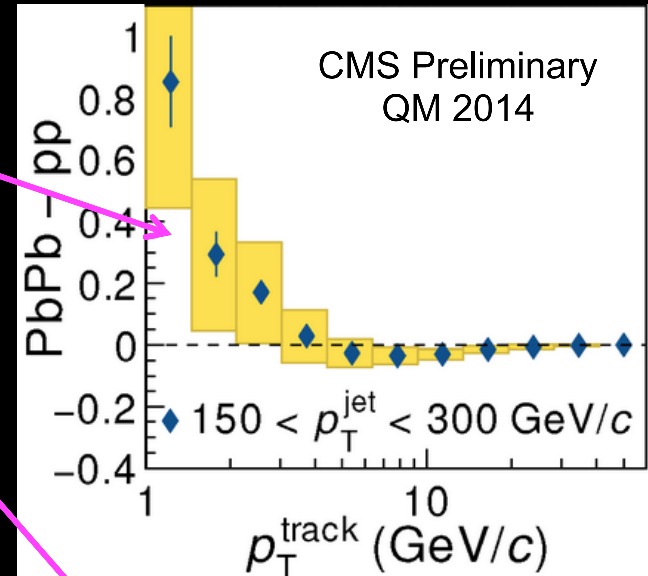
STAR low p_T

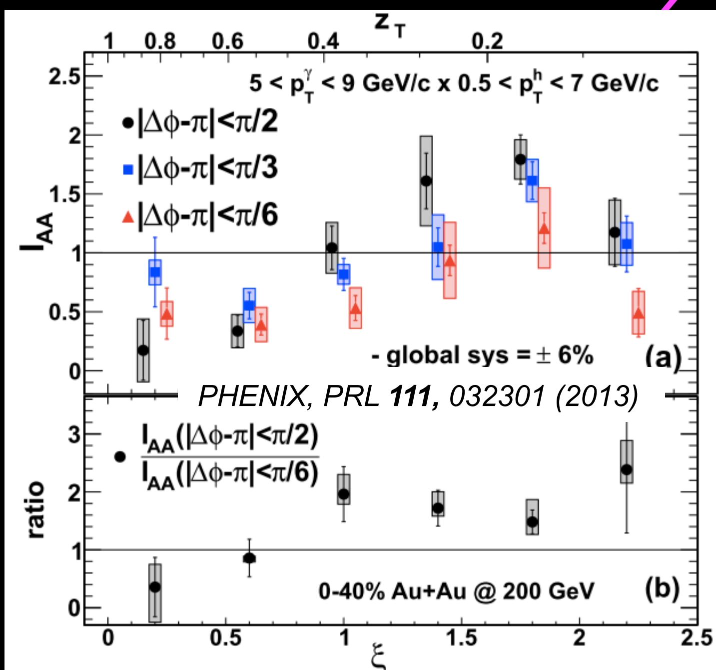
Track Excess

CMS low p_T

PHENIX high ξ

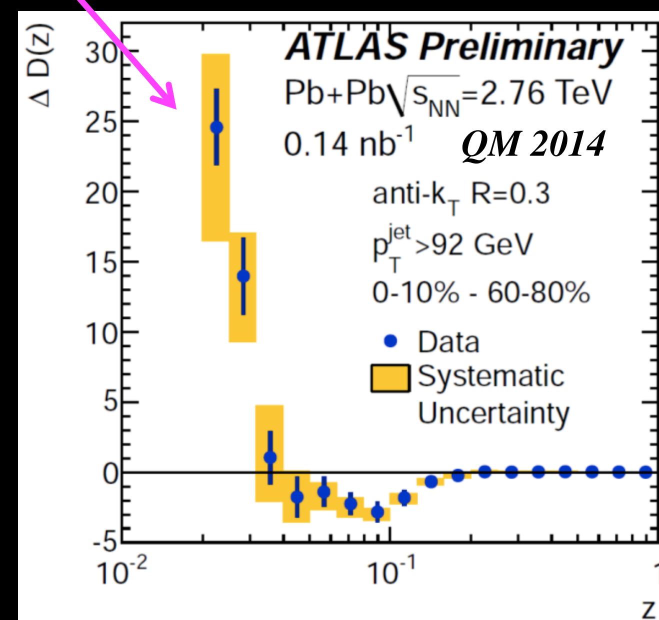
ATLAS low z



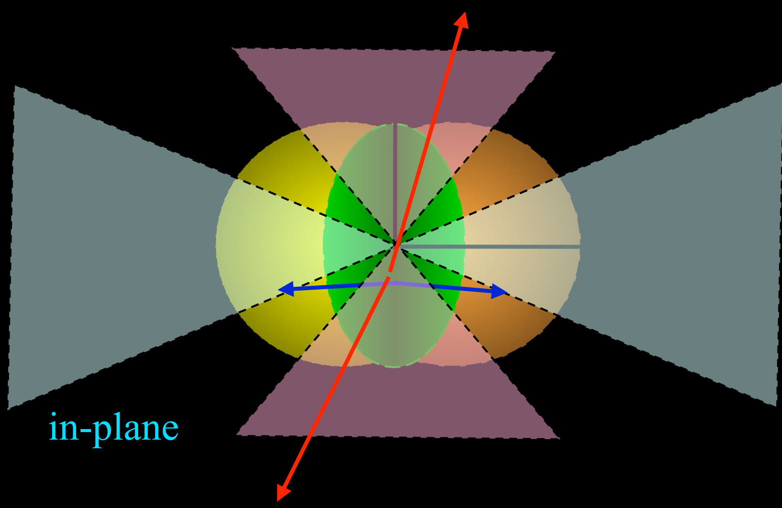


$z = p_T^{track} / p_T^{jet}$

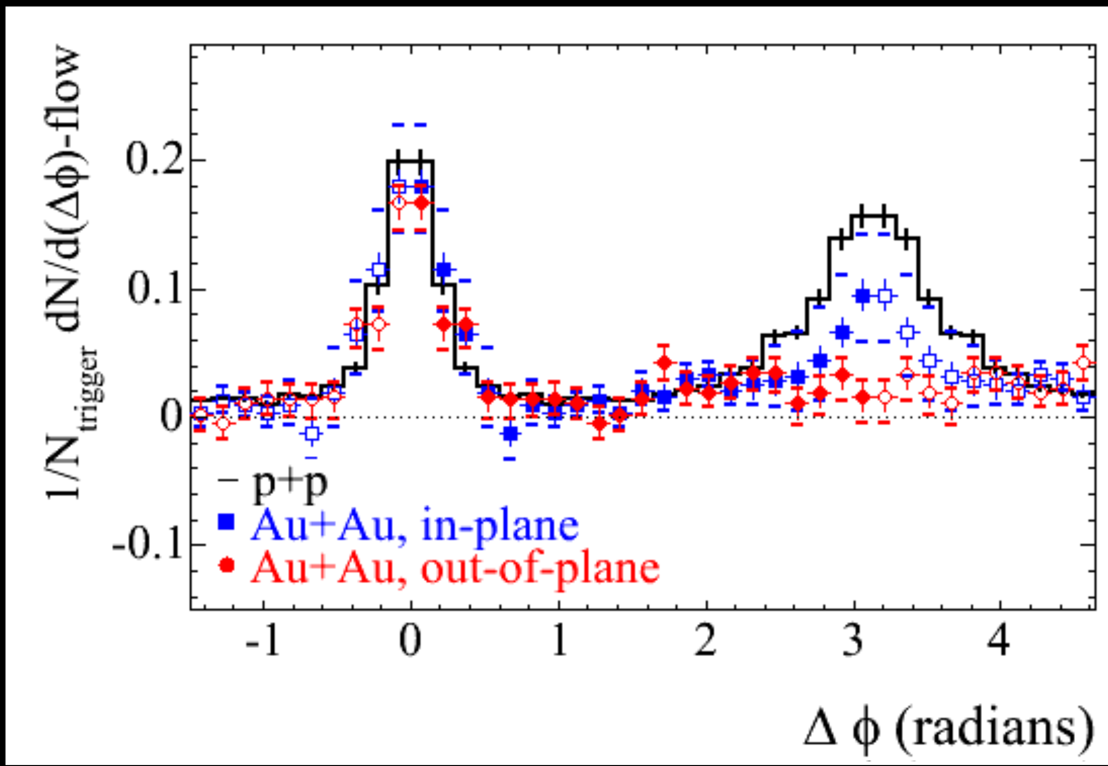
$\xi = \ln(1/z)$



Path Length Dependence of Di-jet Topologies



$p_T^{trigger}$=4-6 GeV/c, 2<$p_T^{associated}$<$p_T^{trigger}$, |η|<1

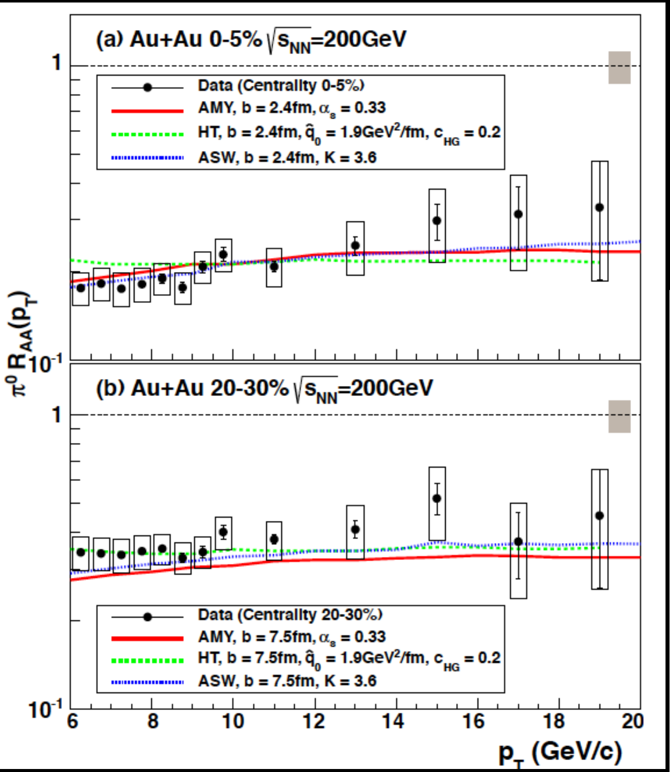


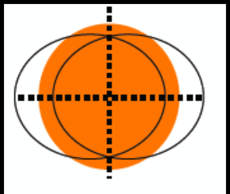
Back-to-back suppression out-of-plane stronger than in-plane

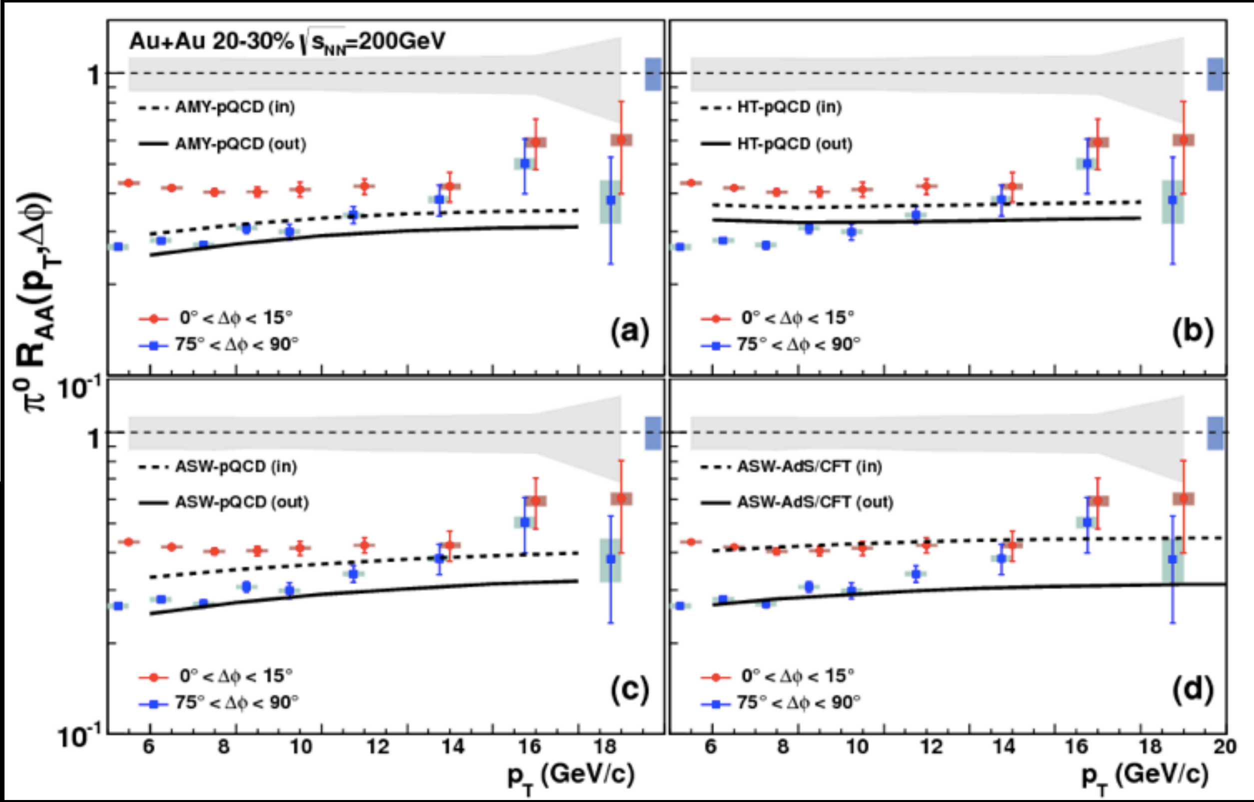
Effect of path length on suppression is experimentally accessible

Path-length Dependent R_{AA}

PHENIX, arXiv:1208.2254

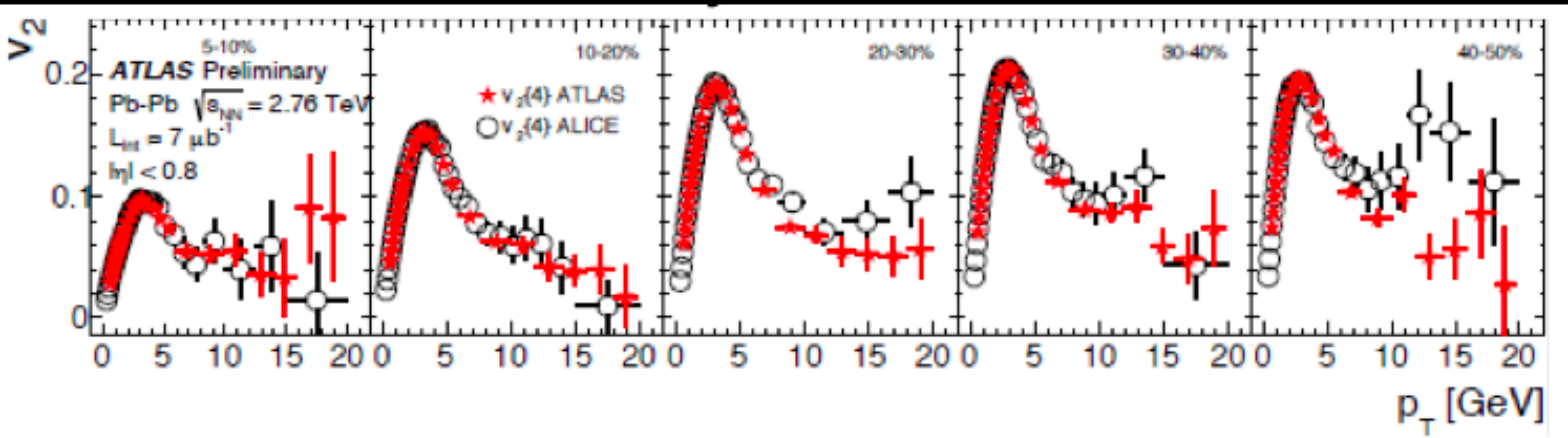






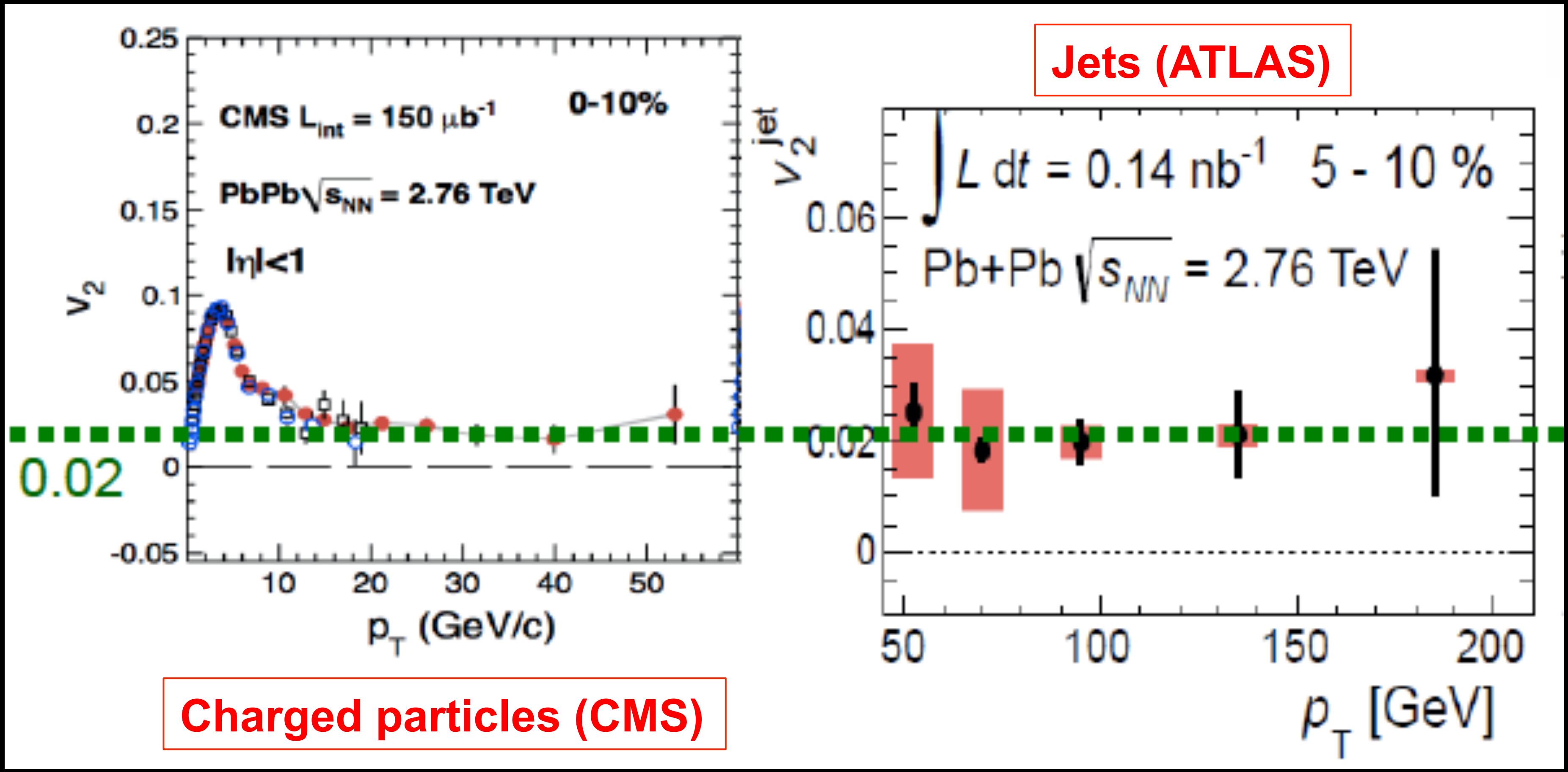
Centrality and angle relative to plane differences!

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!

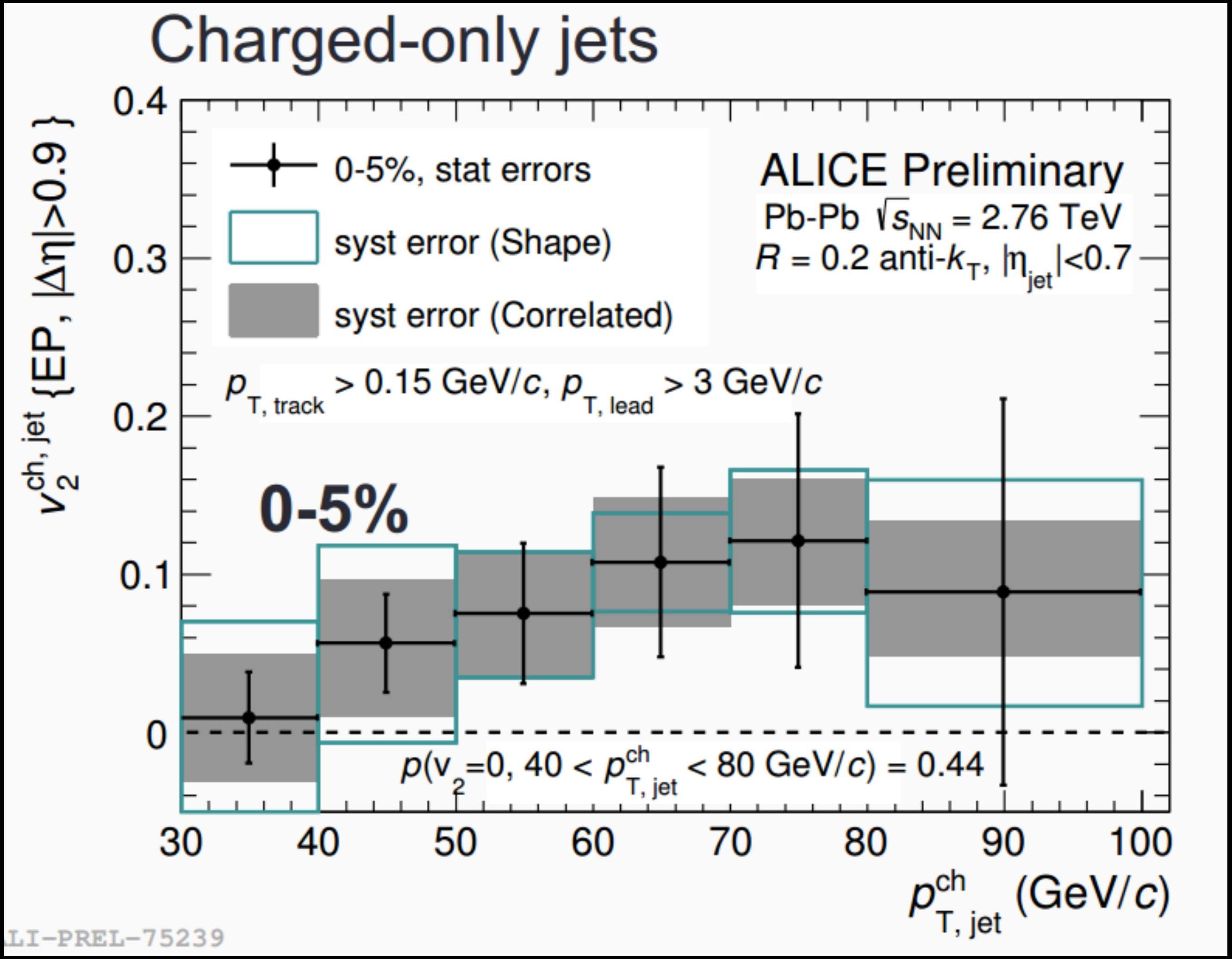


QM 2014

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

Significant v_2 Observed for Charged Jets

ALICE
QM 2014

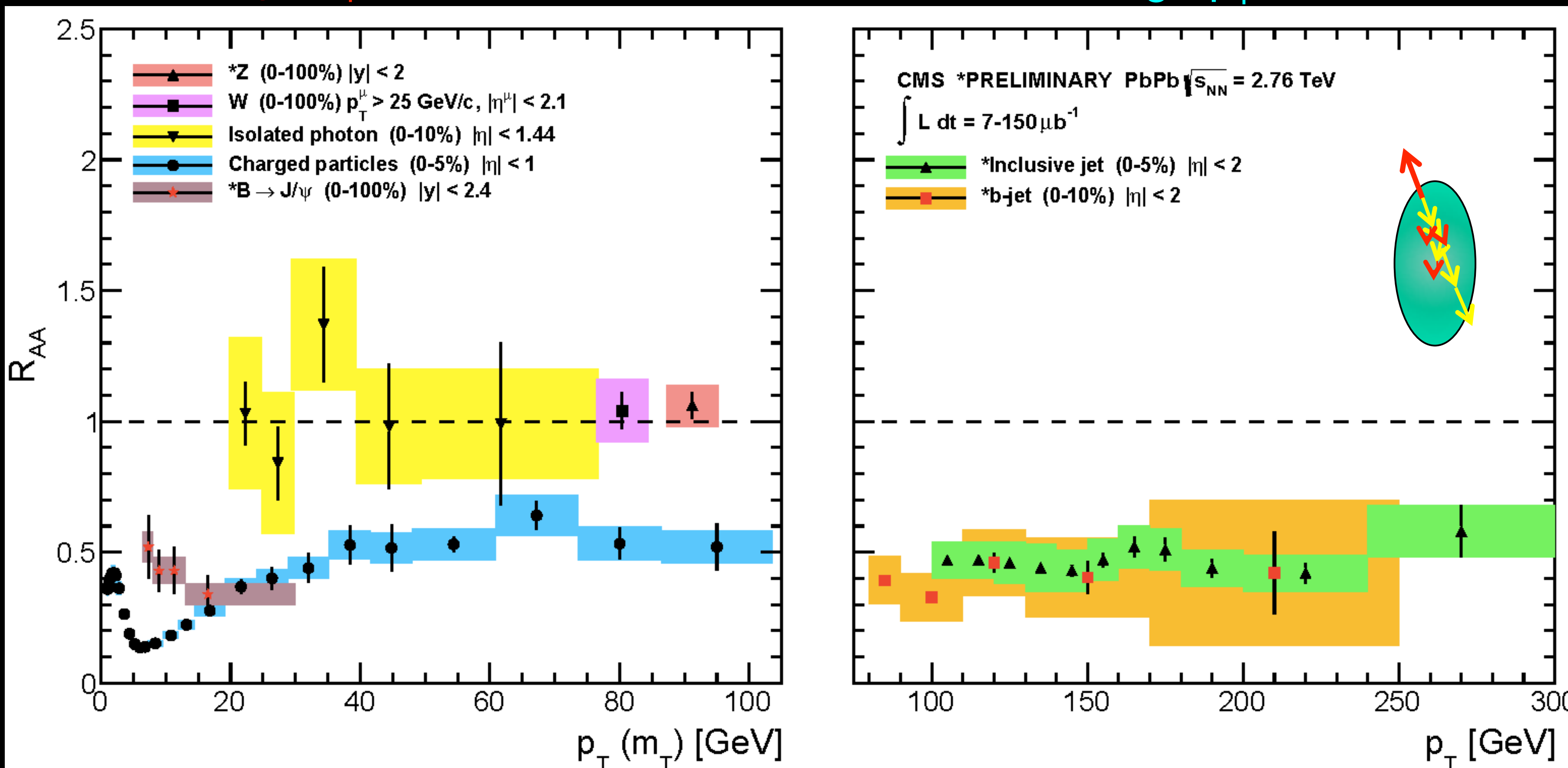


Charged Jet v_2 Observed up to 100 GeV/c

Flavor Dependence of Jet Quenching at the LHC!

High p_T Particles

High p_T Jets



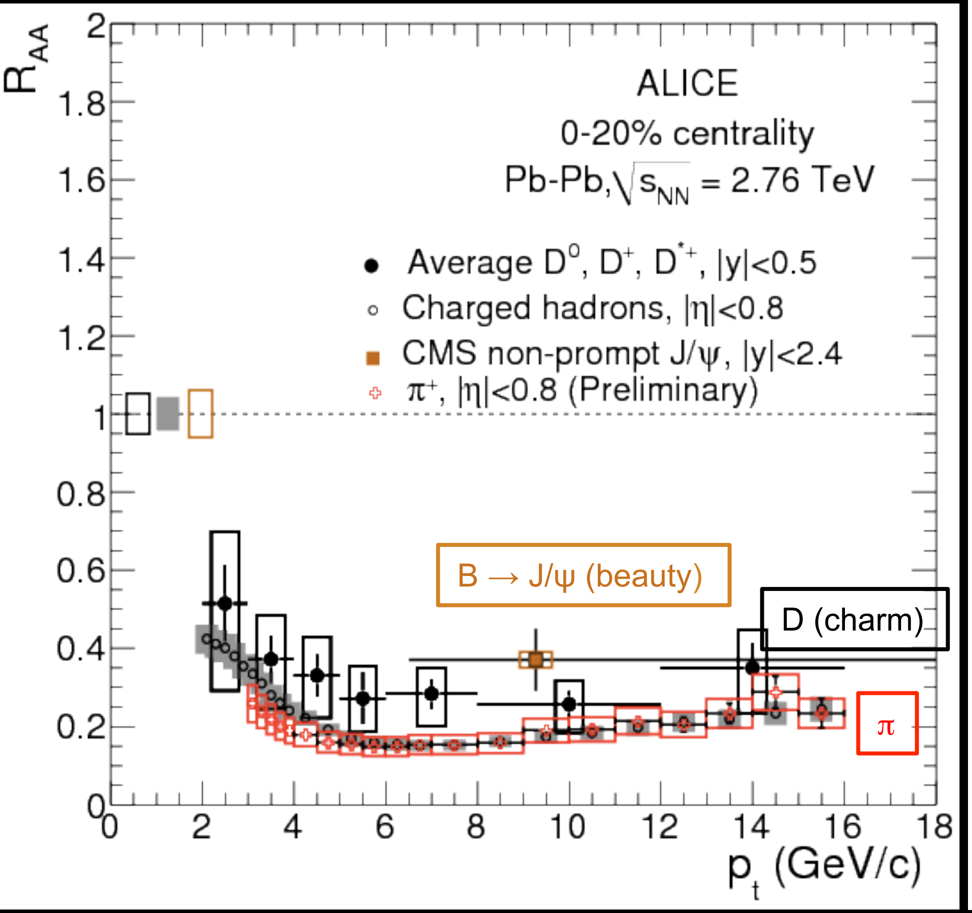
Same range of parton p_T

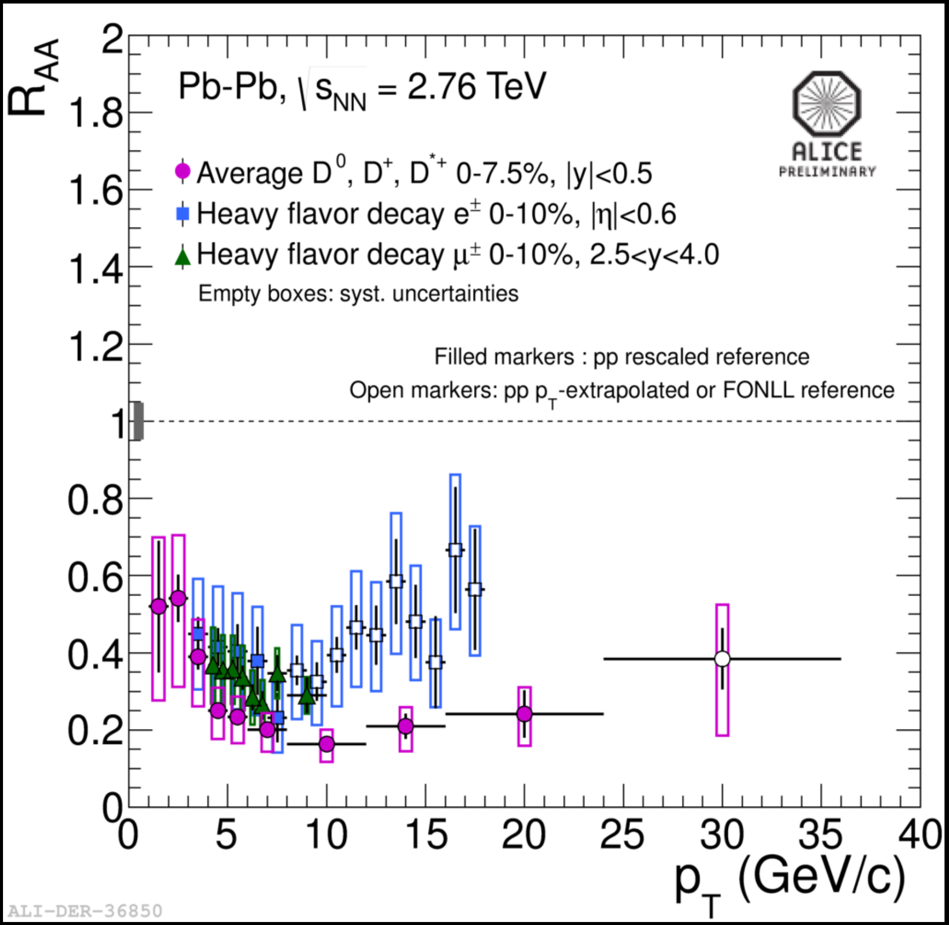
J. Velkovska (CMS) HP 2013

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

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

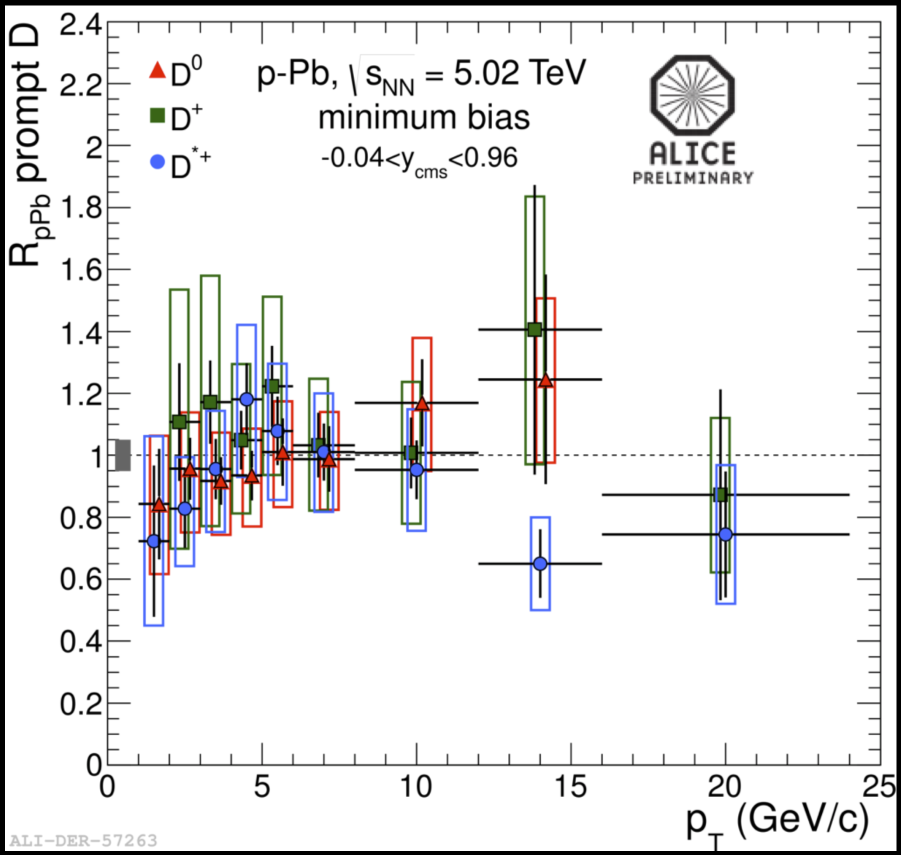
LHC Suppression of Heavy Flavors

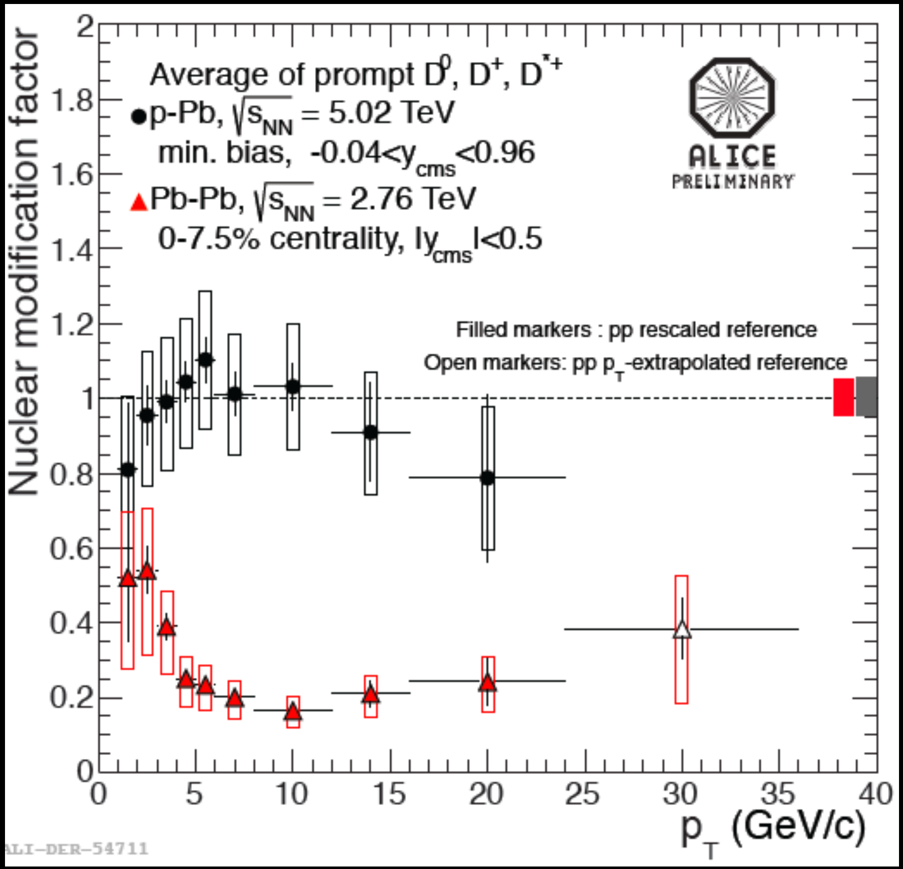




Pions, charm and beauty - Suggestion of a hierarchy!

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

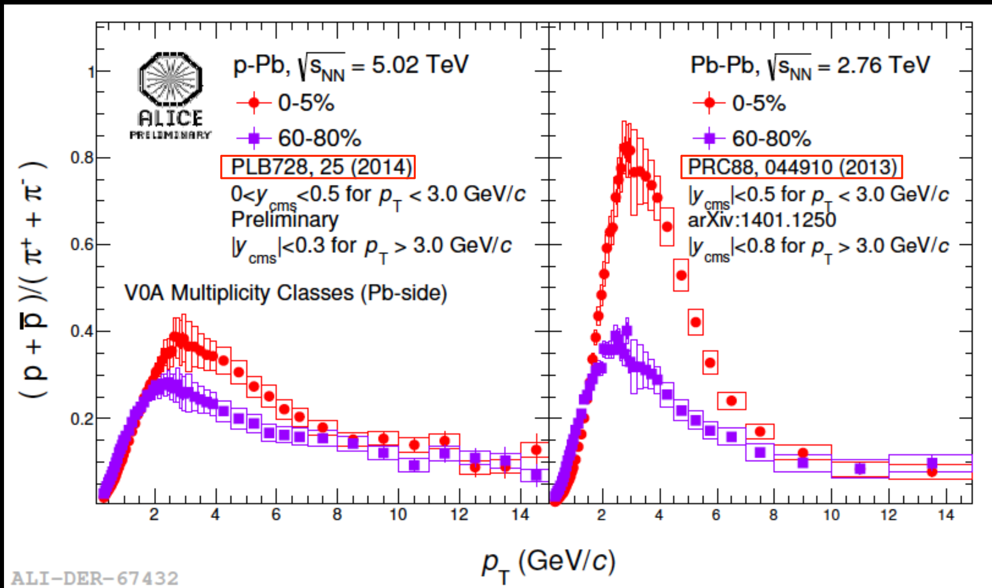


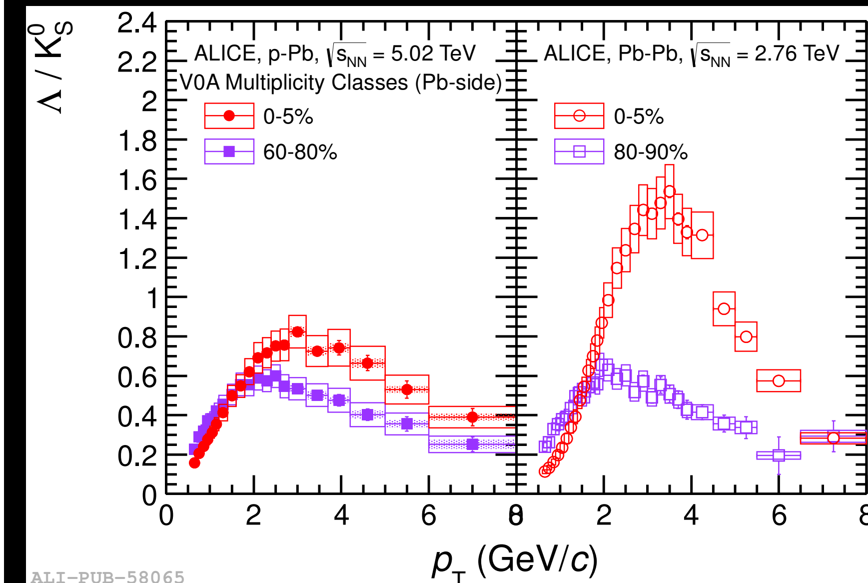


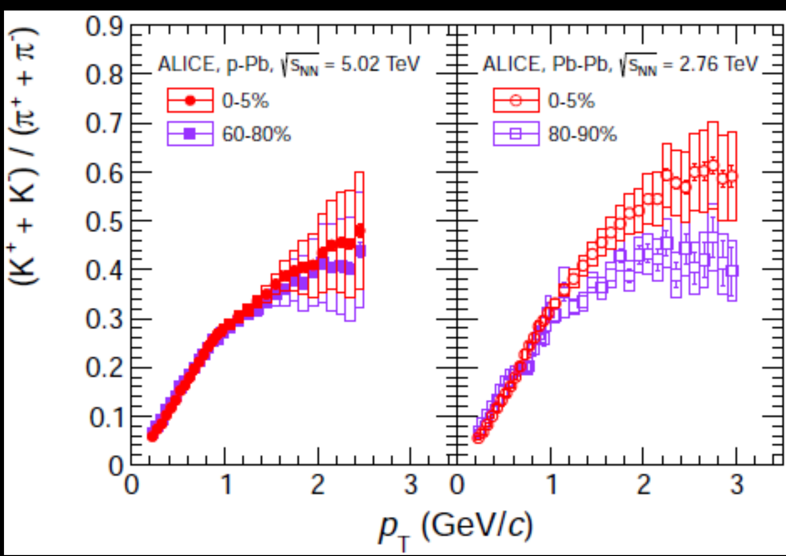
D-meson R_{pPb} consistent with ≈1
Initial state effects small!

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

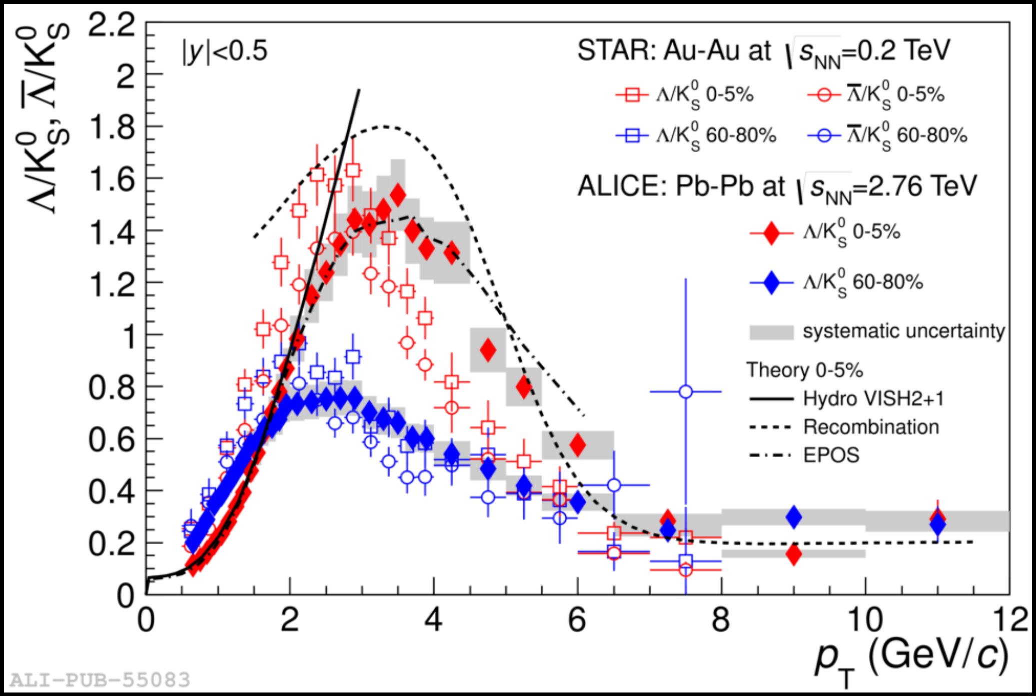
increase with p_T, peak near p_T = 3 GeV/c

increased enhancement: $\Lambda/K > p/\pi > K/\pi$

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



RHIC and LHC:

- Ratios similar for peripheral events.
- Ratios differ for central events

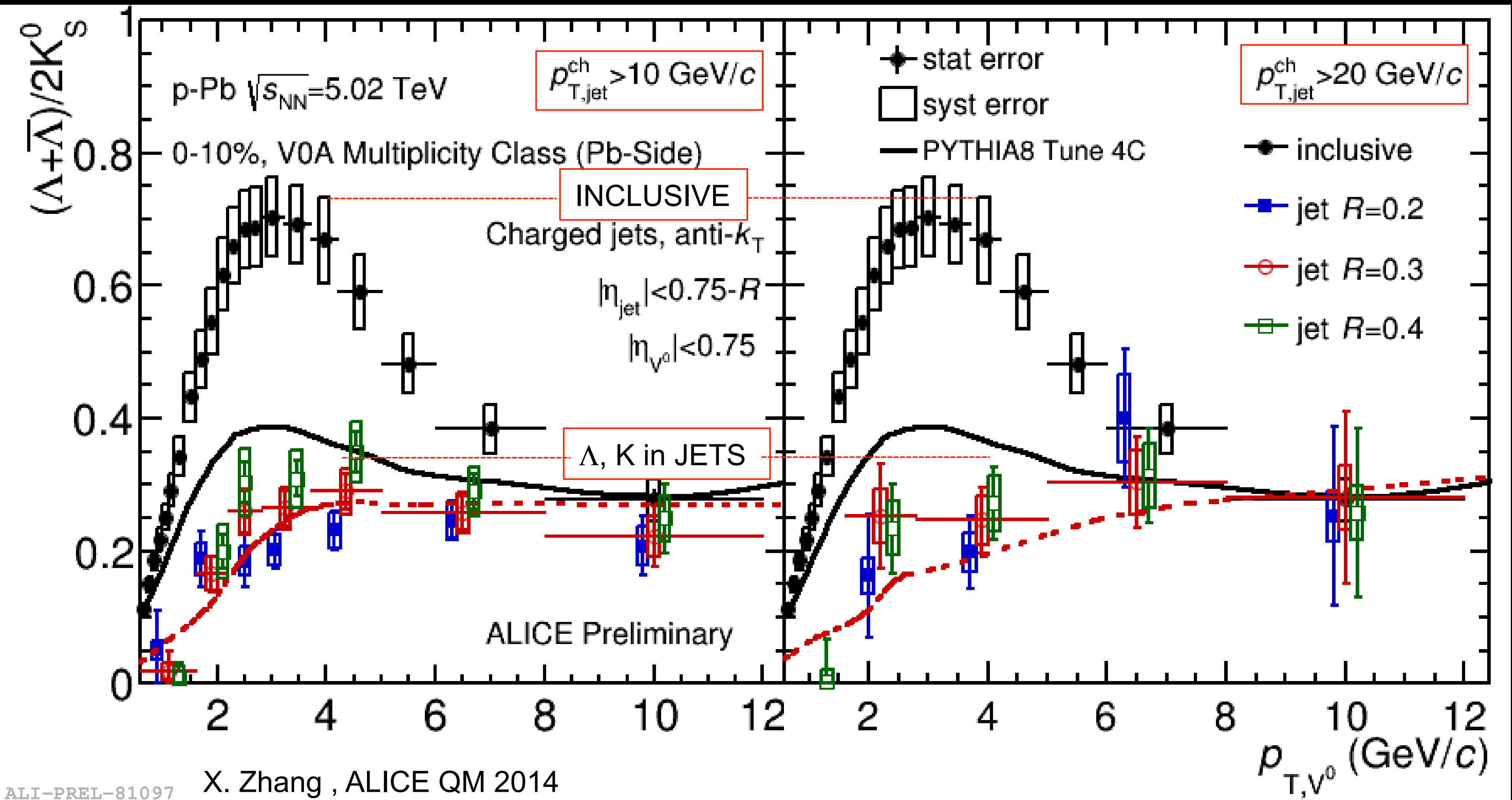
(Peak in most central collisions at slightly higher p_T at LHC)

- 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

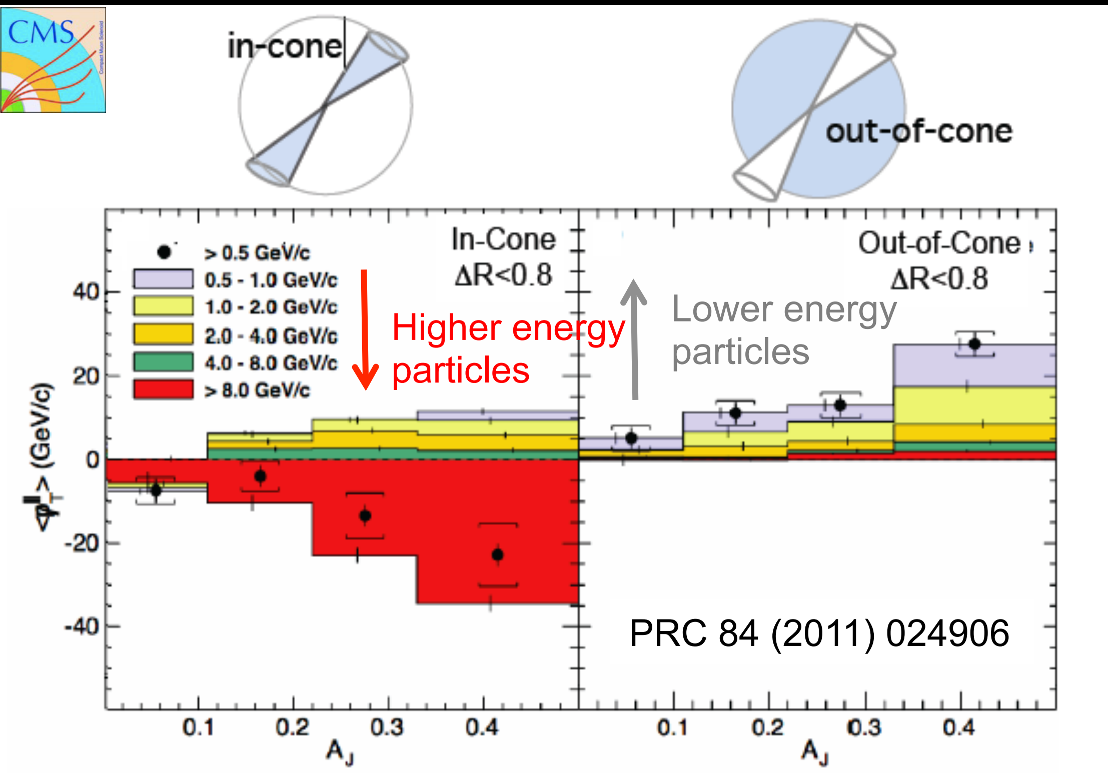


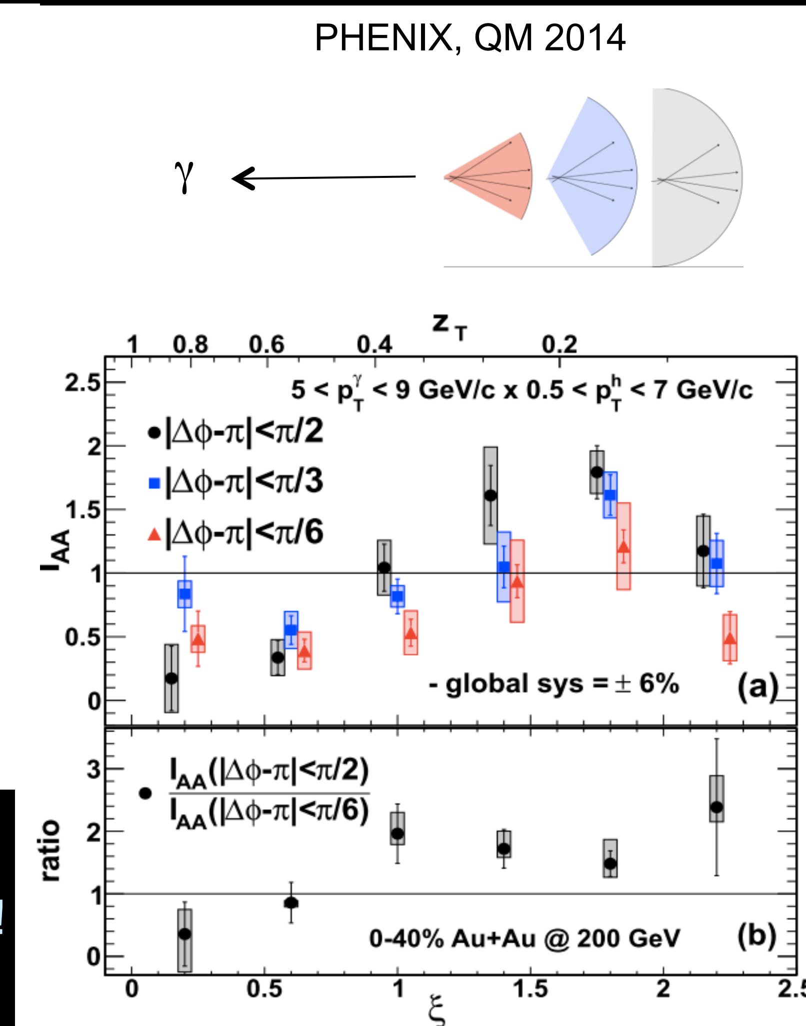
X. Zhang , ALICE QM 2014

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

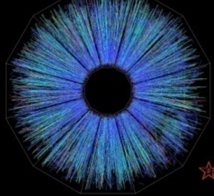




Energy/momentum balance in event carried by low momentum particles at large angles to jets!

Energy appears at large R, wider angles to jet.

pQCD, vacuum fragmentation, thermalization of lost energy?



"What Have We Learned" from RHIC & LHC

It's opaque to the most energetic ("hard") probes:

Light & heavy quarks (jets) are suppressed at large p_T

Away-side jets quenched and jet energy imbalance

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

"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!

Future LHC Heavy Ion Program

Year	Beams	Program
2013 2014	none	Long Shutdown 1
2015 2016	Pb-Pb Pb-Pb	Design luminosity ($\approx$250 μb^{-1}) Design luminosity ($\approx$250 μb^{-1})
2017	Pb-Pb p-Pb	If int. lumi. still insufficient, else at highest possible energy
2018	none	Long Shutdown 2, ALICE upgrade installation, DS collimators to protect magnets
2019	Pb-Pb	Operation beyond design luminosity
2020-21	p-Pb Ar-Ar	If still priority, else intensity to be seen from injector commissioning for SPS fixed target
2022	none	Long Shutdown 3, stochastic cooling?
$>$2022	ions	Lumi. production, other ions (U?)

Energy & Luminosity Increase!

Precision Jet, Heavy Flavor
& Large Statistics E-by-E

Upgraded detectors

Precision Jet, Heavy Flavor
& Large Statistics E-by-E

Ref: J.M. Jowett, LHC Chamonix Meeting 2012

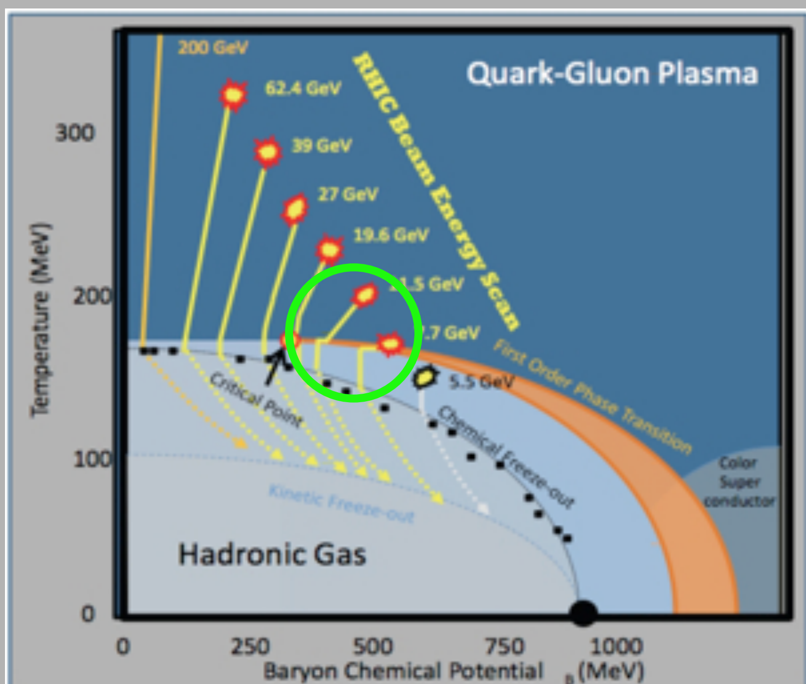
Future at RHIC

Probing the QCD Phase-Diagram

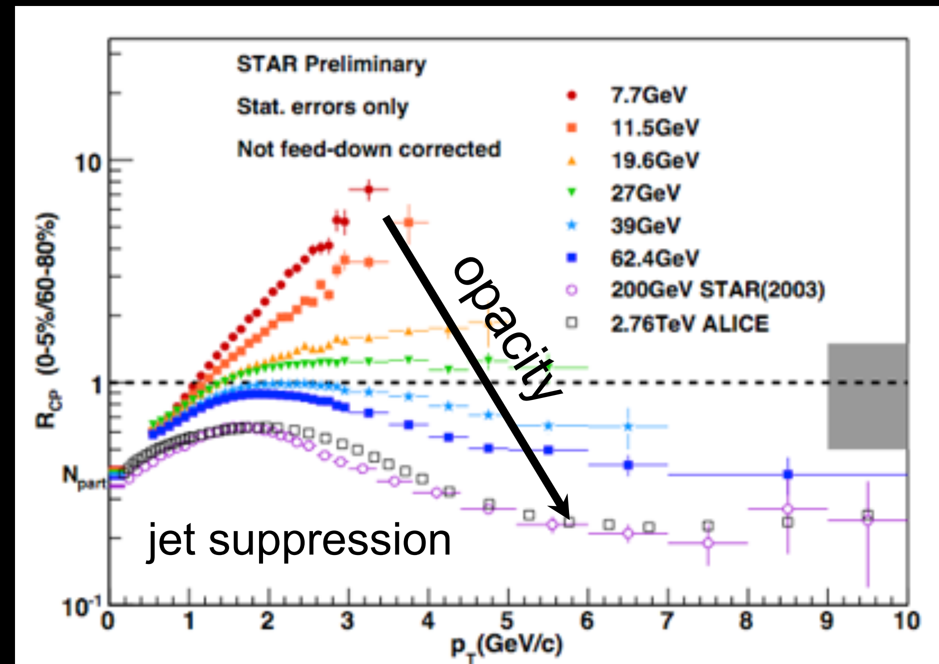
•RHIC Beam Energy Scan: use beam energy as control parameter to vary initial temperature and chemical potential

•Beam energy range in area of relevance is unique to RHIC!

•BES-II will deliver precision required to search for signatures of the CEP



1. Beam Energy Scan, Search for Critical Pt.



As energy reduced (above):
opacity increases and flow decreases

2. Investigate heavy flavors and jets
with new vertex detectors & calorimeters

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

- $R_{p(d)A}^{charged\ particles}$ ~ 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
  $R_{pPb}^{D\text{-}mesons}$ ~ 1 for p_T = 1.5 - 20 GeV/c, consistent with binary scaling
  Described by various models, does not distinguish models
  $R_{p(d)A}^{charged\ particles}$ ~ 1 but 10(20)% enhancement "bump" ~ 4 – 6 GeV/c
  Primarily in proton (baryon?) channel, associated with baryon anomaly?
  $R_{pPb}^{charged\ particles}$ ~ 1.3 – 1.4 for p_T ~ 30 – 100 GeV/c, reference data needed or ?
- $R_{AA}^{charged\ particles}$ ~ 0.2 – 0.4 for p_T = 4 - 100 GeV/c (smallest for most central)
  $R_{PbPb}^{D\text{-}mesons} \gtrsim R_{AA}^{charged\ particles}$ for p_T = 2 - 30 GeV/c
  $R_{AA}^{single\ particles}$ → 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)
  $R_{AuAu}^{jets} \lesssim R_{PbPb}^{jets}$, 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