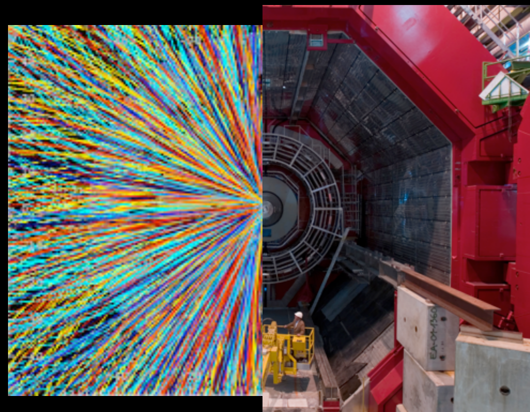
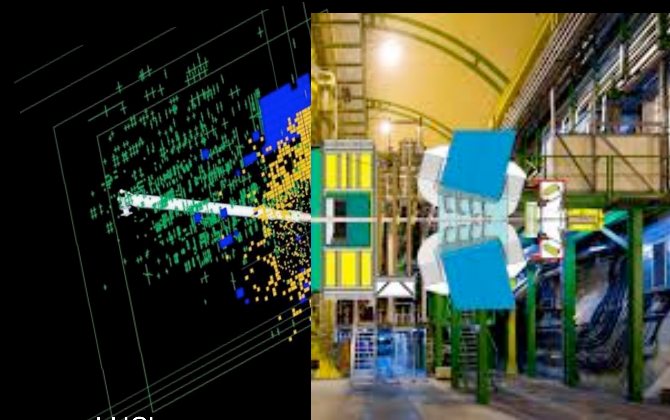
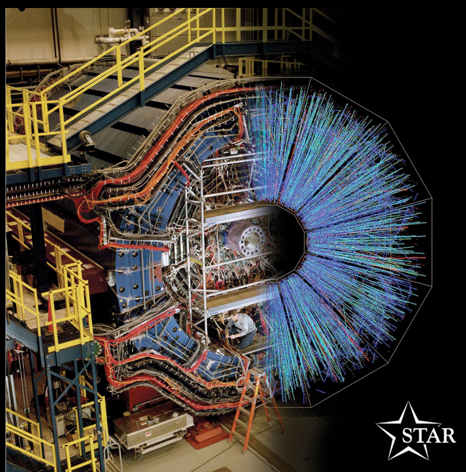
ALICE

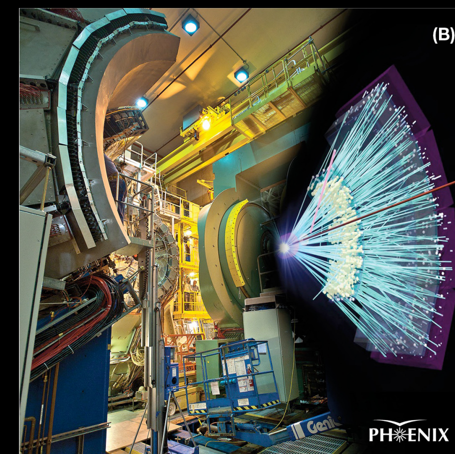




LHCb

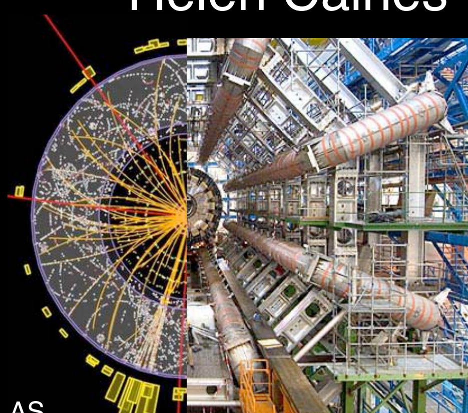
Using jets and high p_T particles to probe the QGP



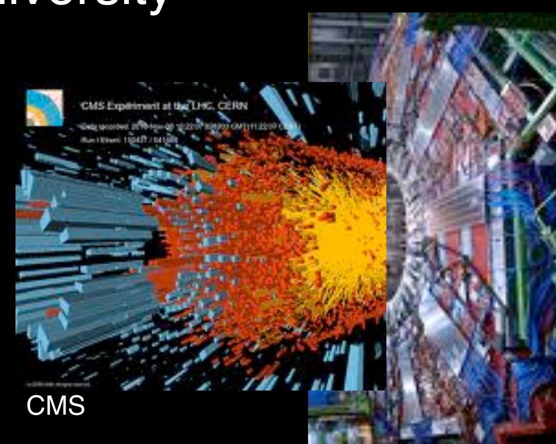


ANPC African Nuclear Physics Conference

Helen Caines - Yale University

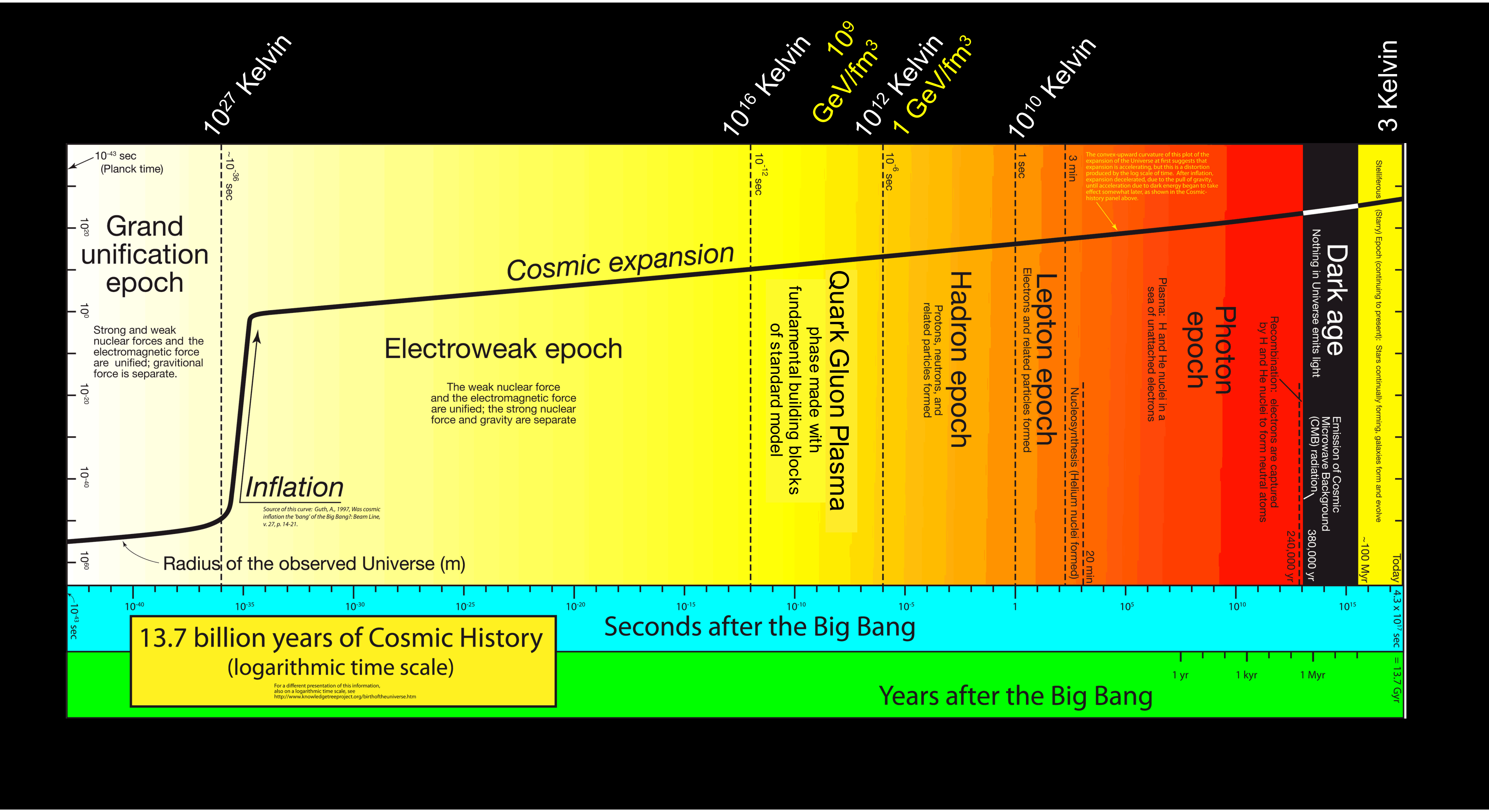


ATLAS



CMS

Our cosmic history



Many phases and phase transitions in the early universe

So far only QGP-hadron phase transition can be recreated and studied in lab

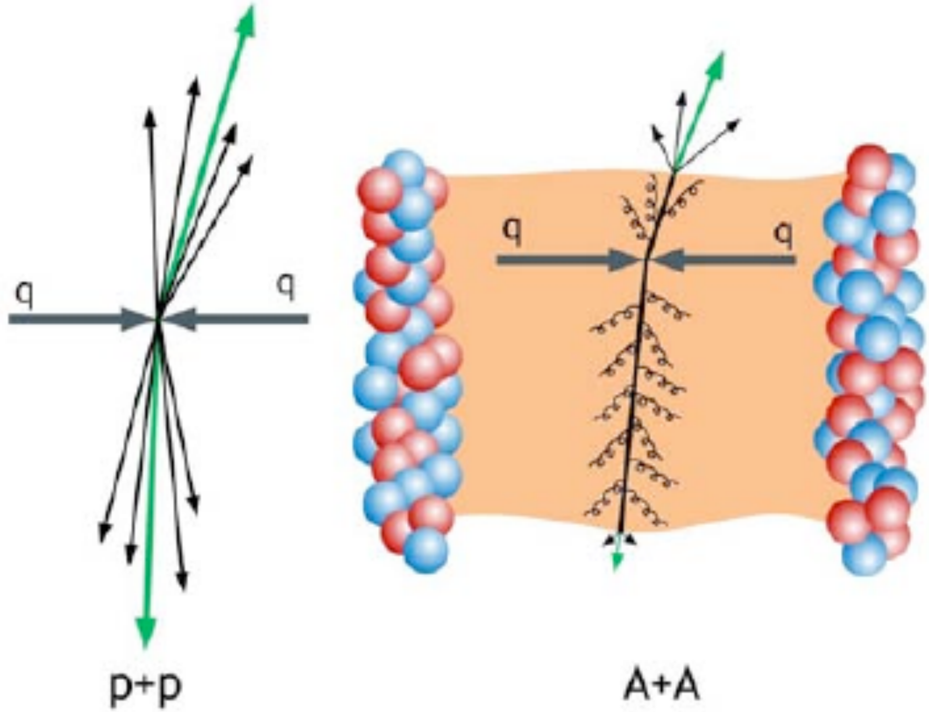
Image:P.Soresen

Using "hard" particles as probes

'Hard' processes have a large scale in calculation
→ pQCD applicable:

- <u>high</u> momentum transfer Q^2
- <u>high</u> transverse momentum p_T
- <u>high</u> mass m (N.B.: since m>>0 heavy quark production is 'hard' process even at low p_T)

Early production in parton-parton scatterings with large Q^2



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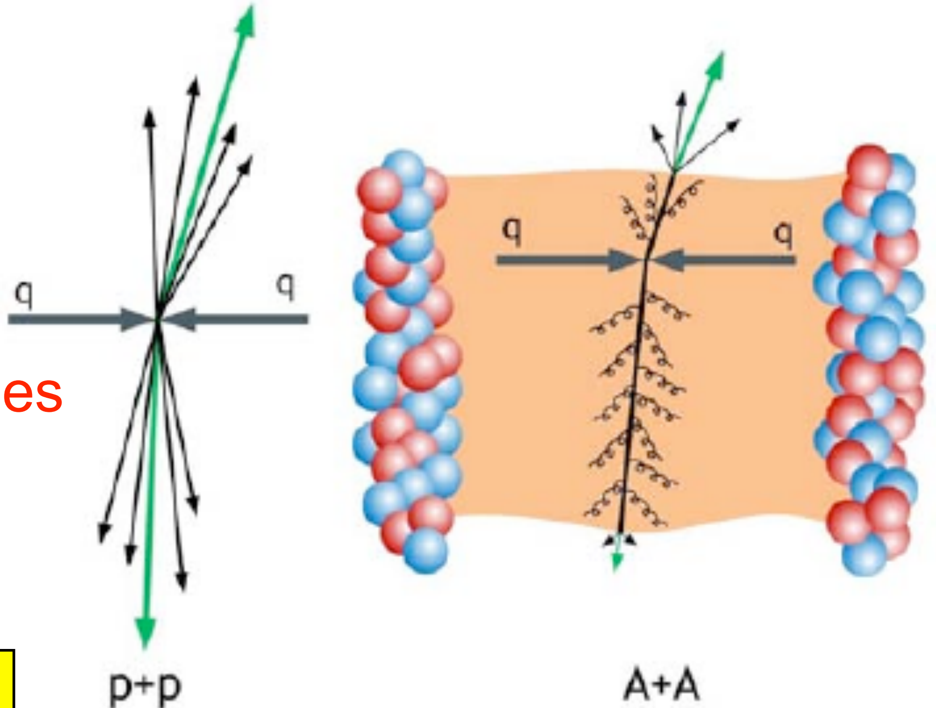
Early production in parton-parton scatterings with large Q^2

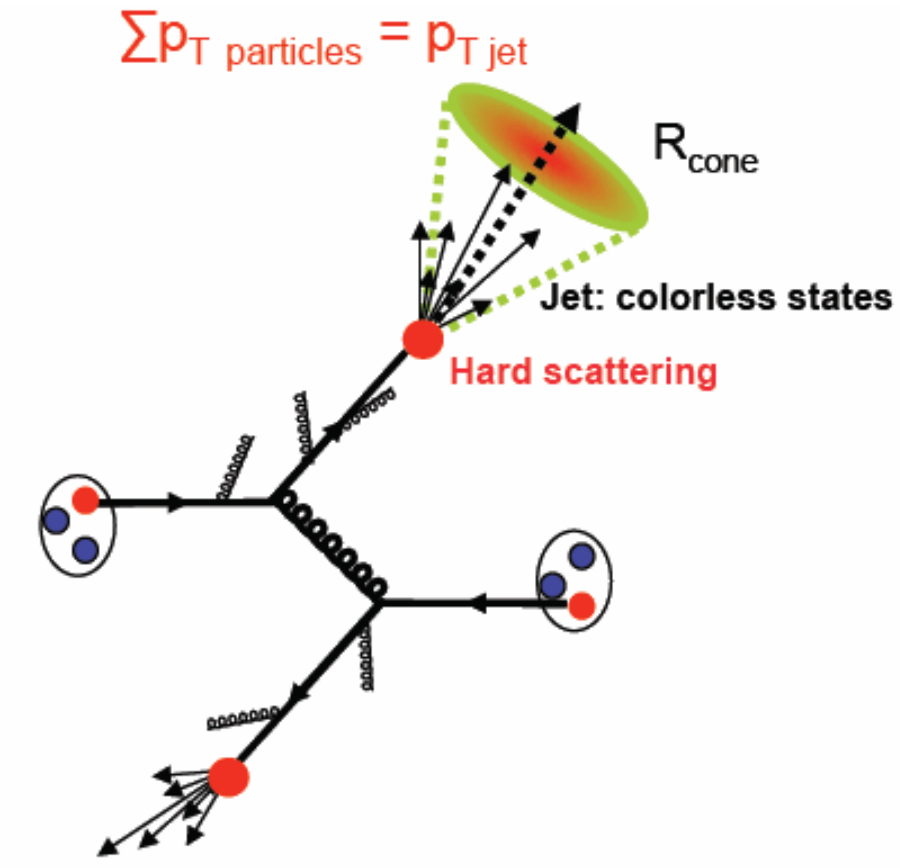
Direct interaction with partonic phases of reaction

i.e. a calibrated probe



Look for attenuation/absorption/ modification of probe

Jets - result of confinement in QCD



QCD confinement tells us that colored objects (quarks and gluons) cannot exist in free form

Partons involved in hard scatterings fragment into hadrons

Produces a highly collimated cone of particles pointing in direction of initial scattered parton

$E_{jet} = \sum E_{hadron} = E_{parton}$

Looking for attenuation/absorption

Compare to p+p at same collision energy

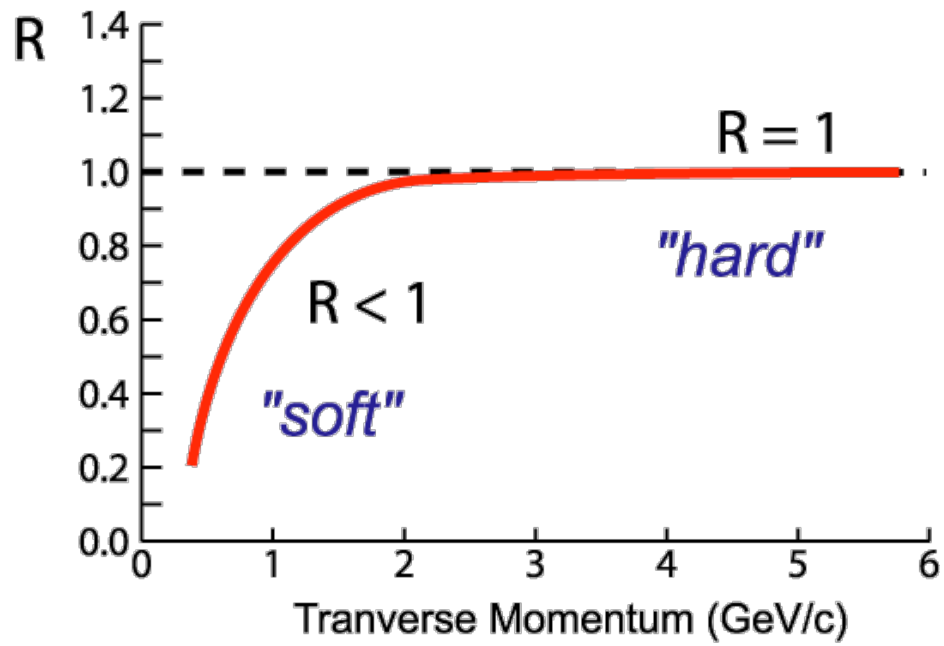
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Average number of p+p collisions in A+A collision

No “Effect”:

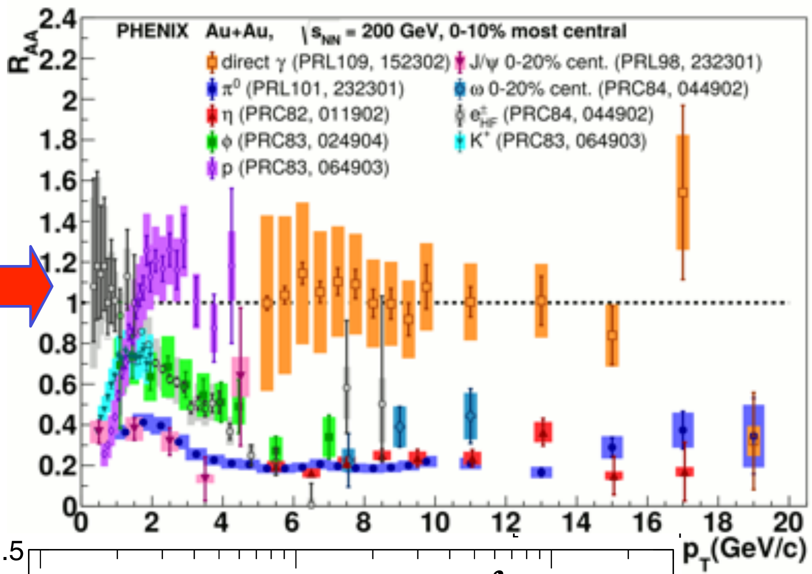
- R < 1 at small momenta - production from thermal bath
- R = 1 at higher momenta where hard processes dominate

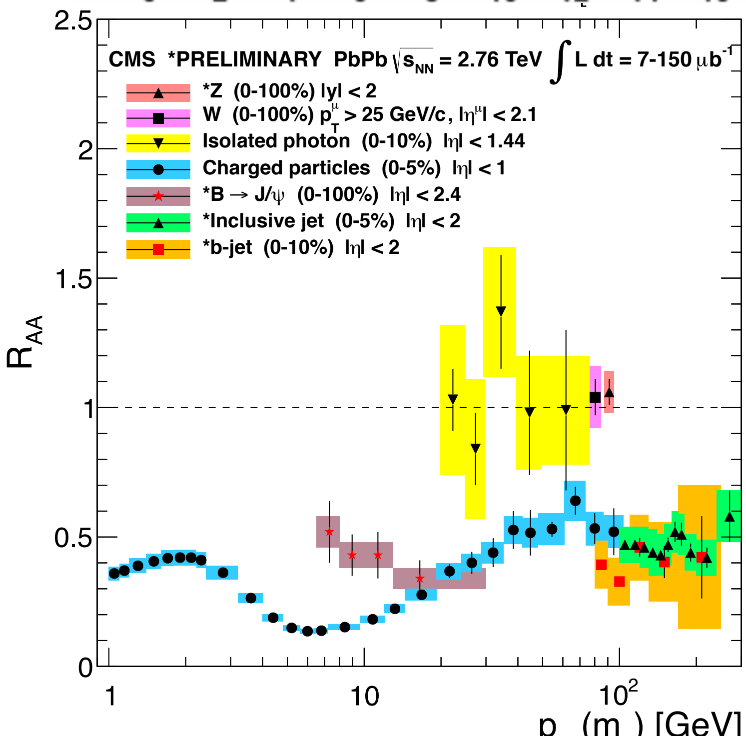


if QGP affecting parton’s propagation R<1 at high p_T

"Jet quenching" clearly at work

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\times\langle N_{coll}\rangle}$$





Observations:

1. Photons, W and Z not suppressed
   - Good! colorless objects should not interact with colored QGP
   - N_{coll} scaling works

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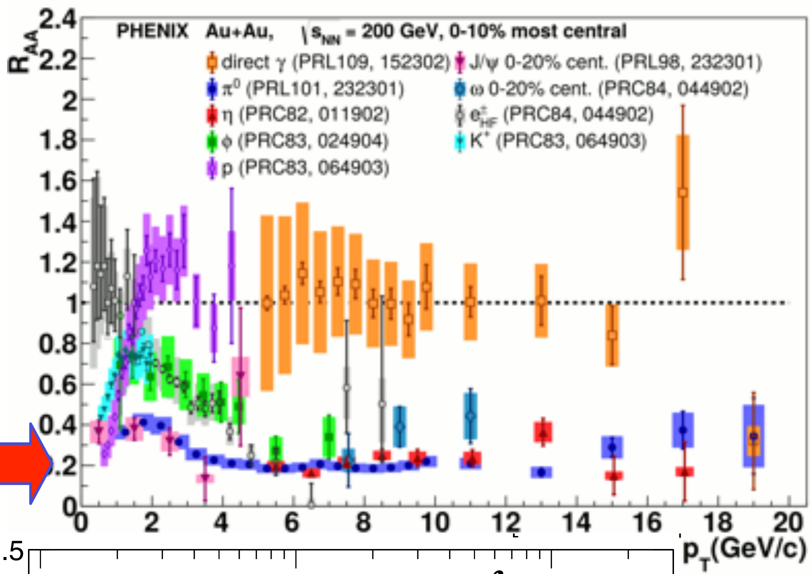

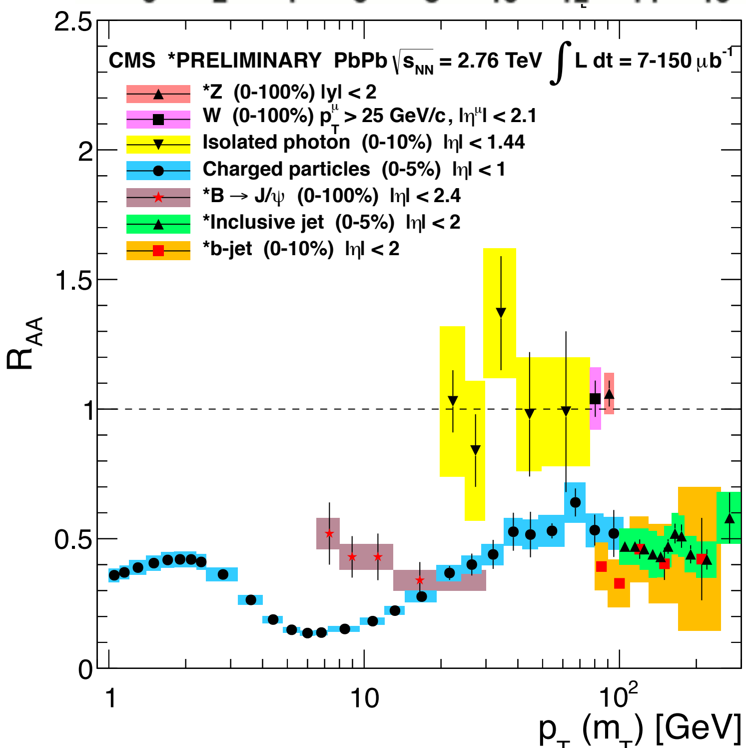

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   - R_{AA} - factor 5 suppression
   - Strong suppression up to p_T ~1 TeV
   - Similar values at RHIC and LHC
     Compensating effects of higher E_{loss}, flatter p_T spectrum, q/g differences

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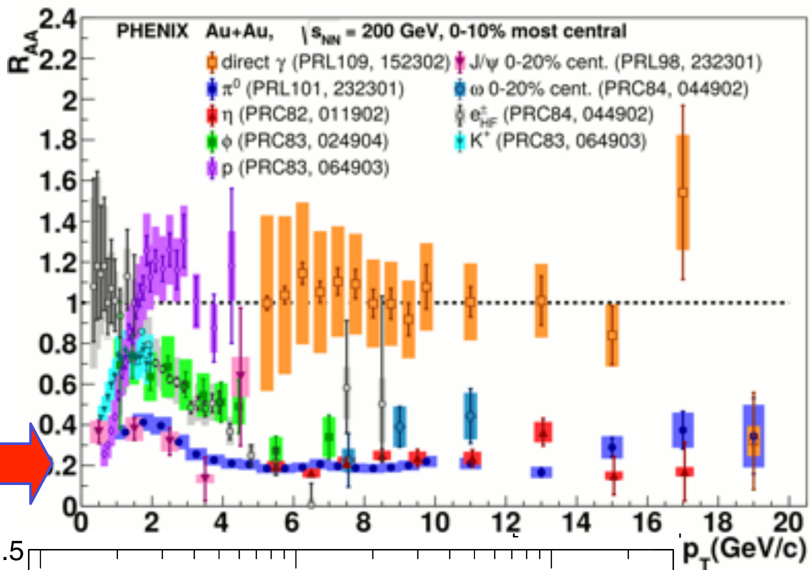

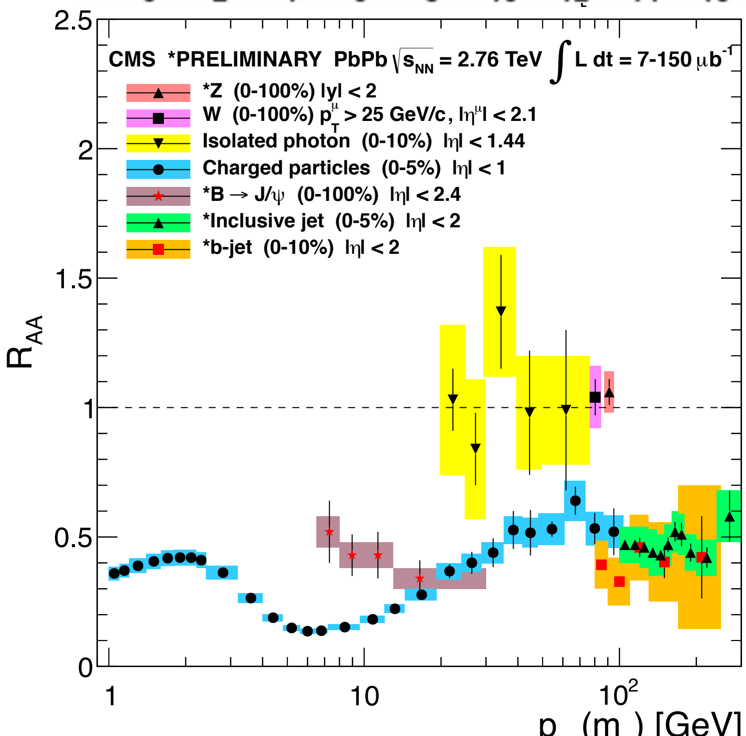

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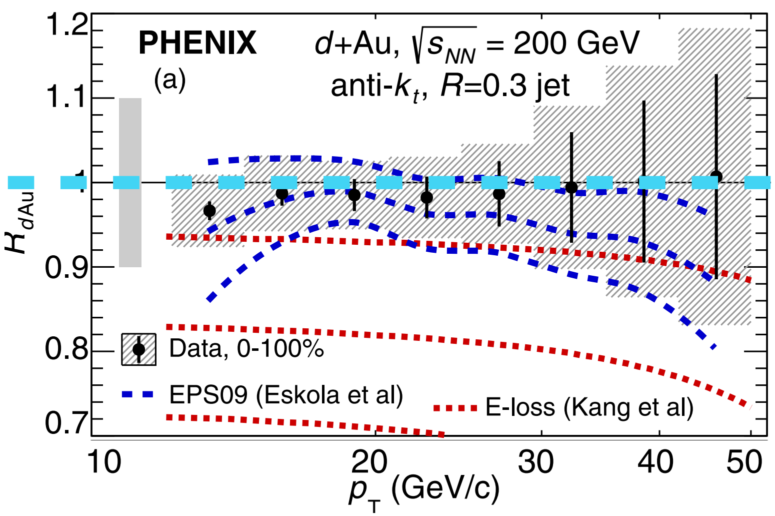
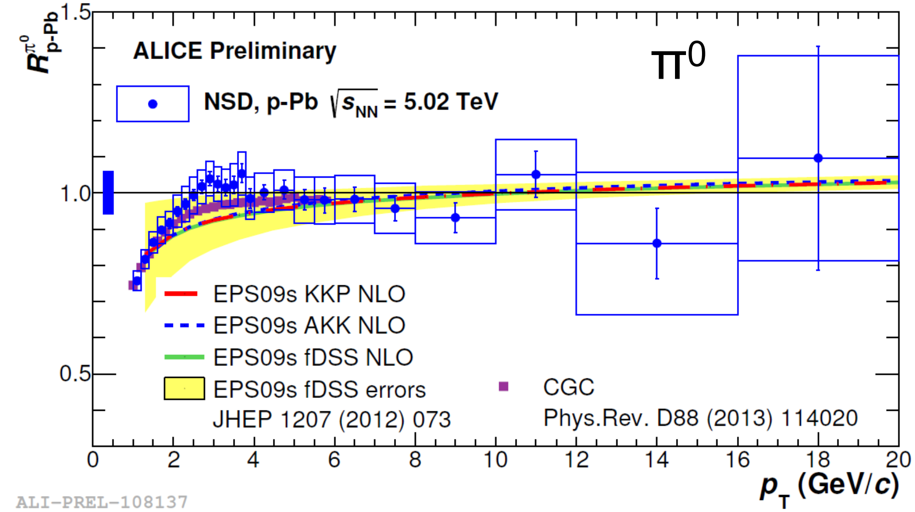
sQGP - strongly coupled: colored objects suffer large E loss

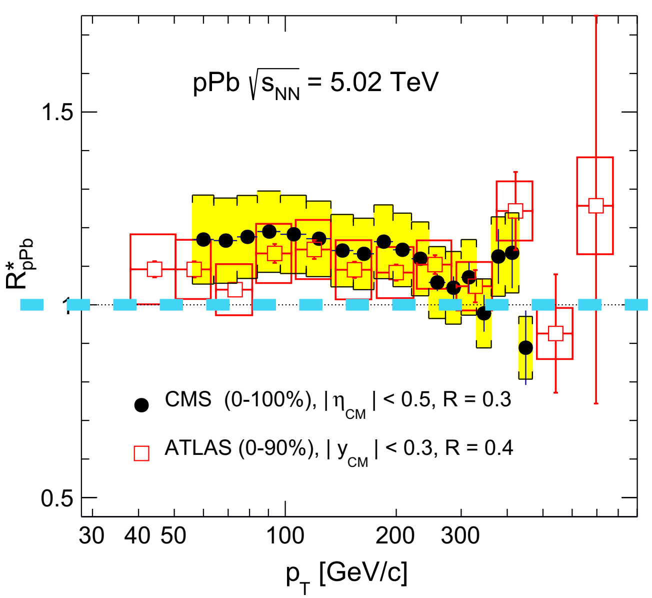
Cold QCD baseline - No suppression

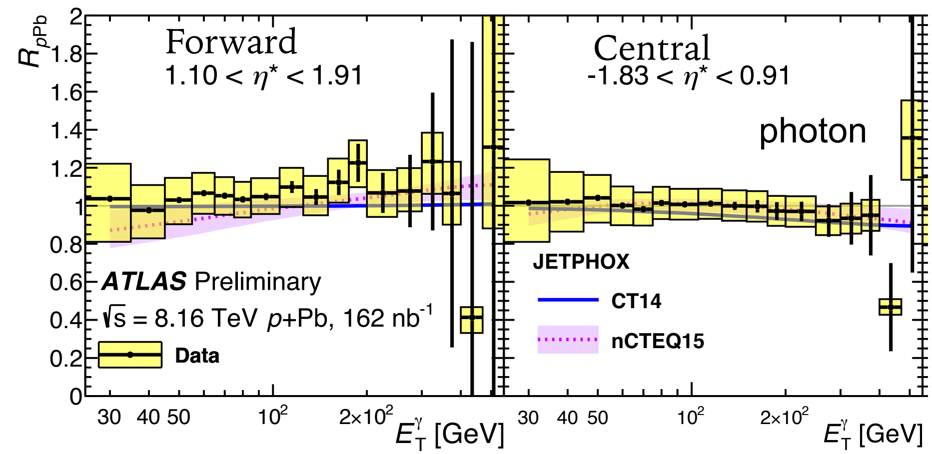




Consistent with nPDF expectations

Suppression due to A+A final state effects



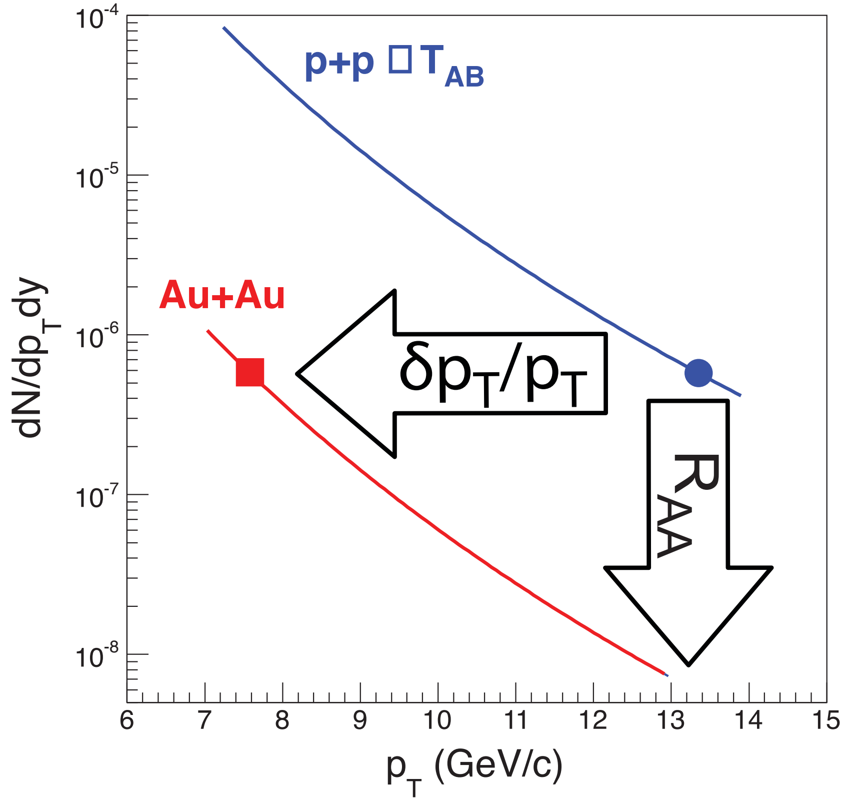


Opaqueness/stopping power of QGP

Measure fractional momentum loss

$\delta p_T/p_T$ instead of R_{AA}

$$R_{AA,0.200} \sim R_{AA,2.76}$$



PRC 87, 034911 (2013)

Opaqueness/stopping power of QGP

Measure fractional momentum loss

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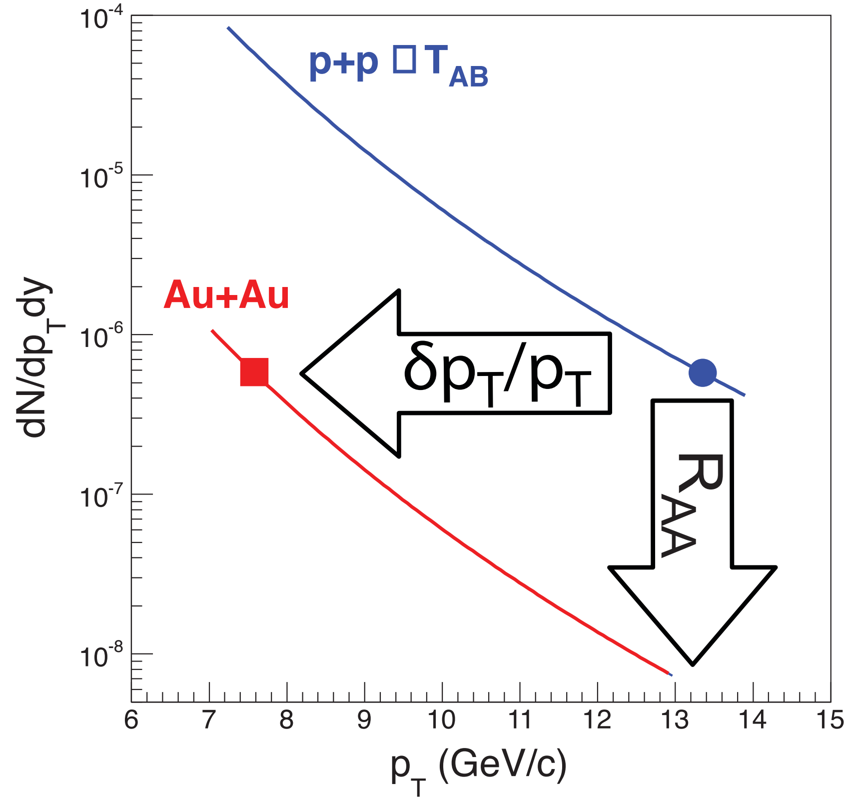
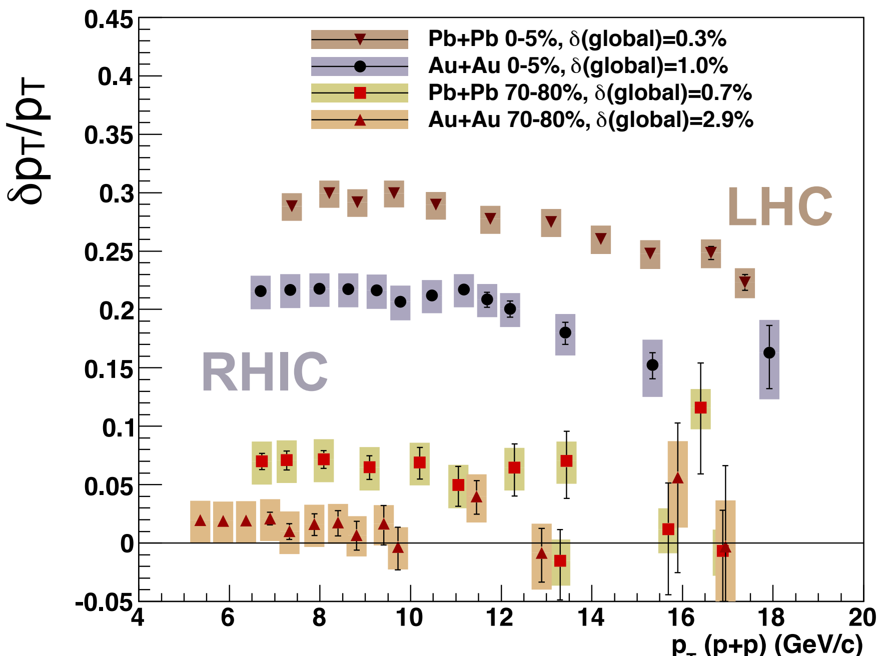
but

$$(\delta p_T)_{LHC} \approx 1.3\ (\delta p_T)_{RHIC}$$

and

$$(dN/dy)_{LHC} \approx 2.2\ (dN/dy)_{RHIC}$$





PRC 87, 034911 (2013)

QGP at LHC and RHIC acts differently on hard partons

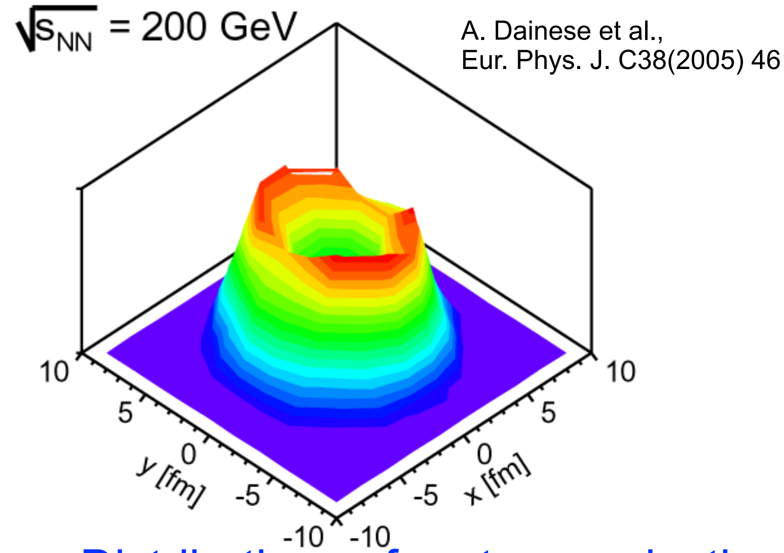
Smaller coupling at LHC?

Need to look in more detail

The limitations of R_{AA}

Insensitivity due to surface emission:

- R_{AA} can't go to zero even for the highest densities



Distributions of parton production points in the transverse plane

The limitations of R_{AA}

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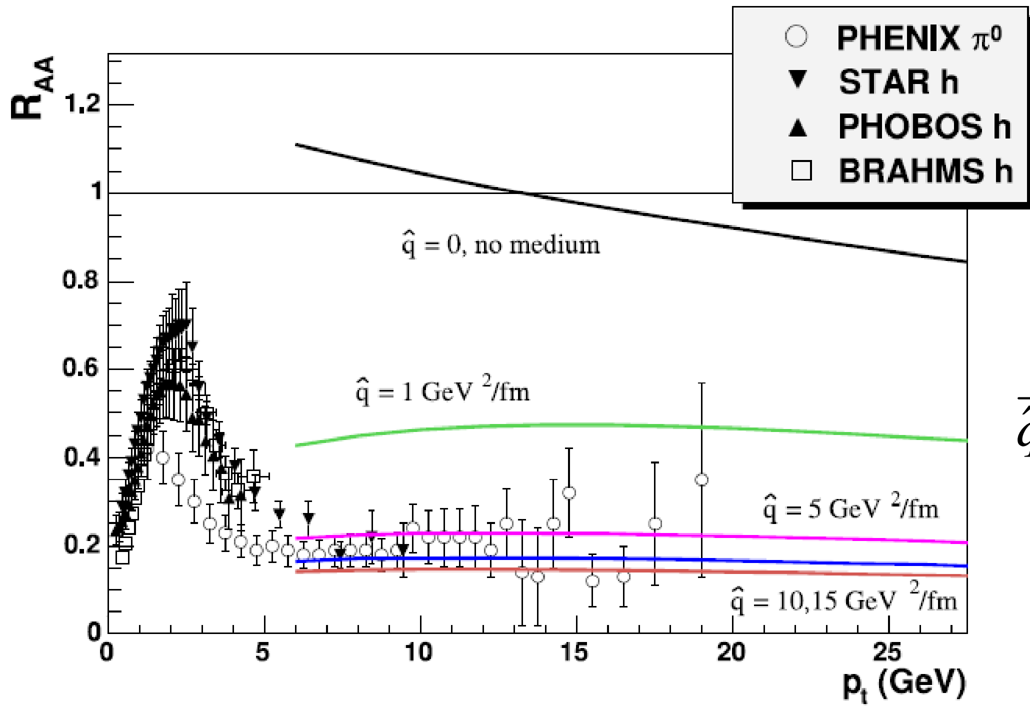
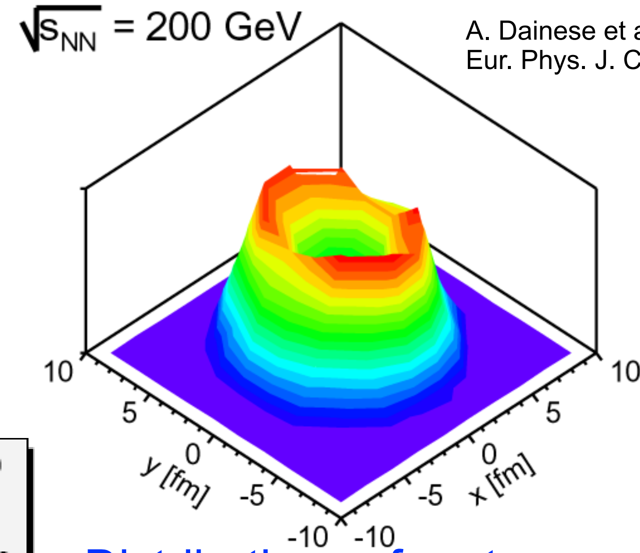


[Eskola, Honkanen, Salgado, Wiedemann (2004)]



A. Dainese et al., Eur. Phys. J. C38(2005) 461

Distributions of parton production points in the transverse plane

Rough correspondence:

$$\bar{\hat{q}} = 10 \frac{GeV^2}{fm} \Leftrightarrow \frac{dN^g}{dy} \approx 1800$$

$$\bar{\hat{q}} = 5 \frac{GeV^2}{fm} \Leftrightarrow \frac{dN^g}{dy} \approx 900$$

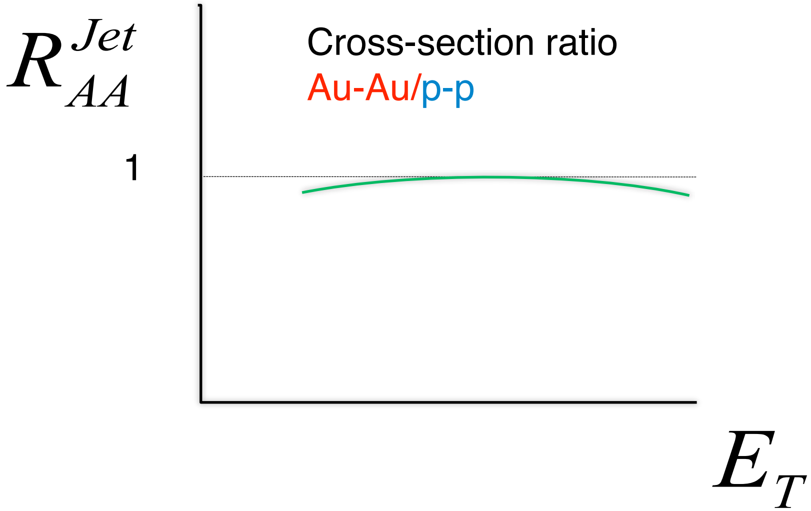
Need better tool

Got to bite the bullet and jet find

p and E MUST be conserved even with quenched jets

- Study nuclear modification factor of jets

If jet reconstruction complete and unbiased R_{AA}==1



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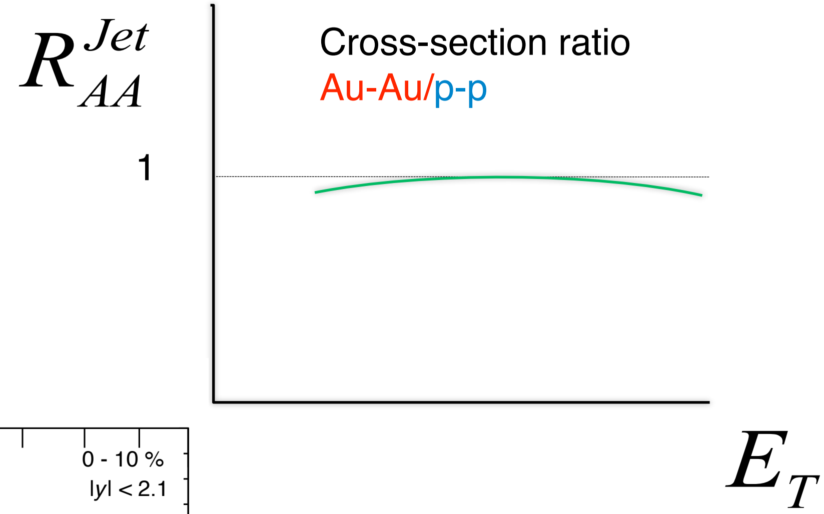
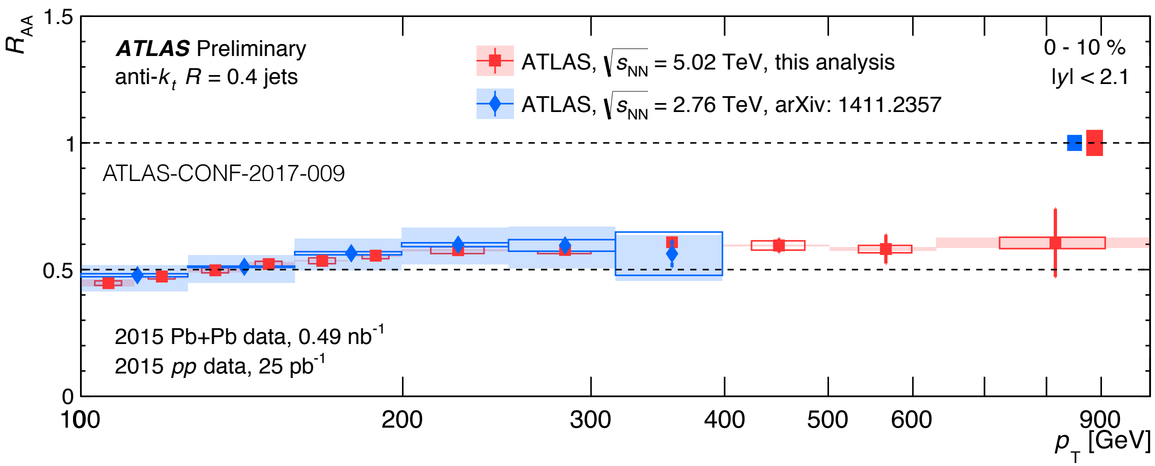


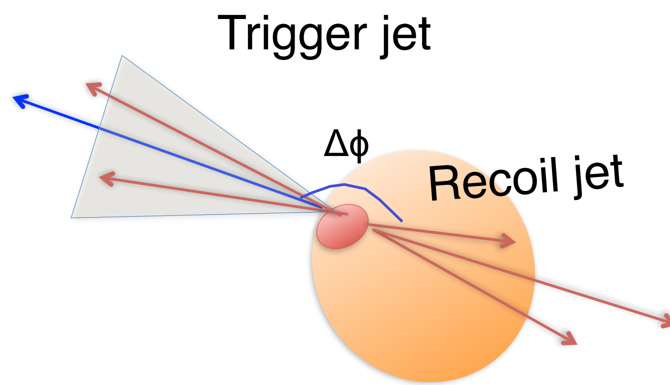
Jet R_{AA}



Jets: R_{AA} < 1 out to high p_T

Quenched energy not recovered even for jets with 900 GeV and R=0.4

Where does lost energy go?

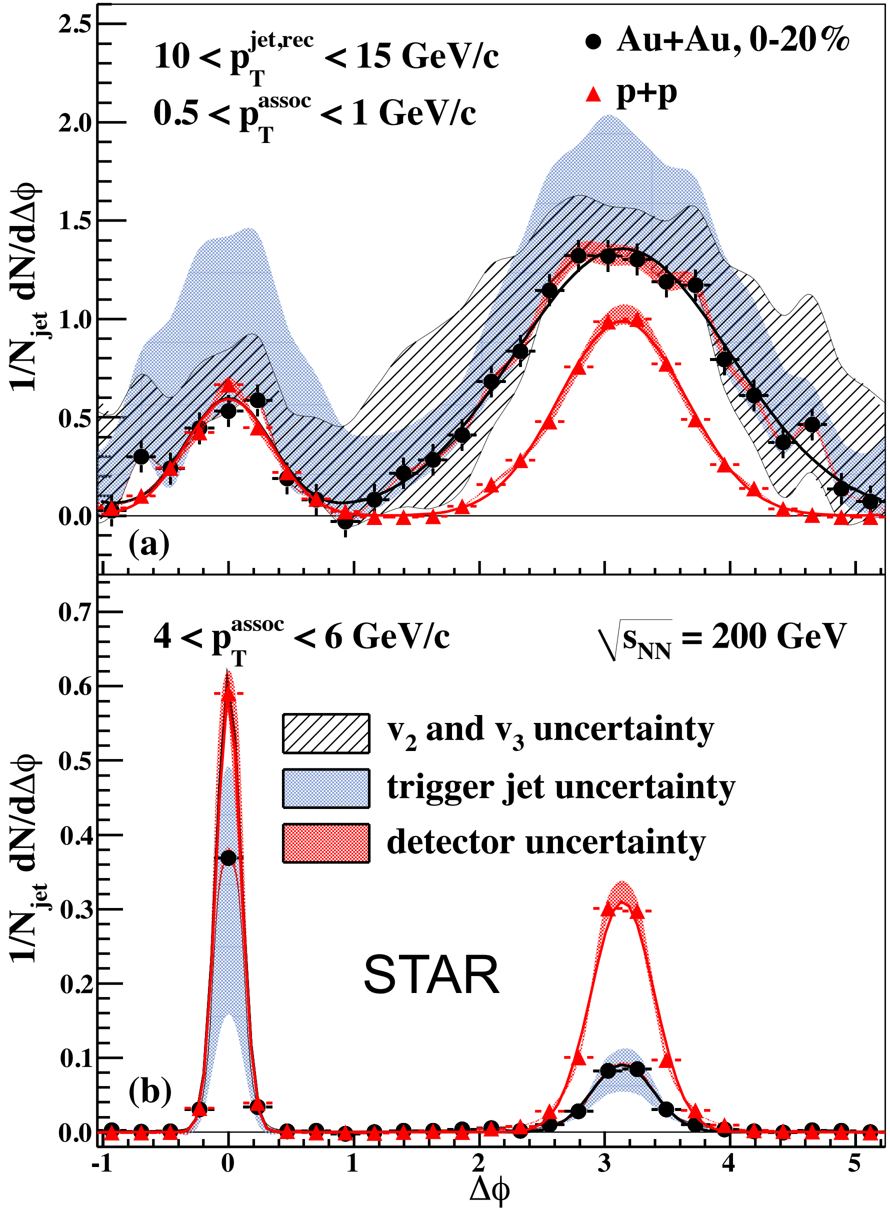


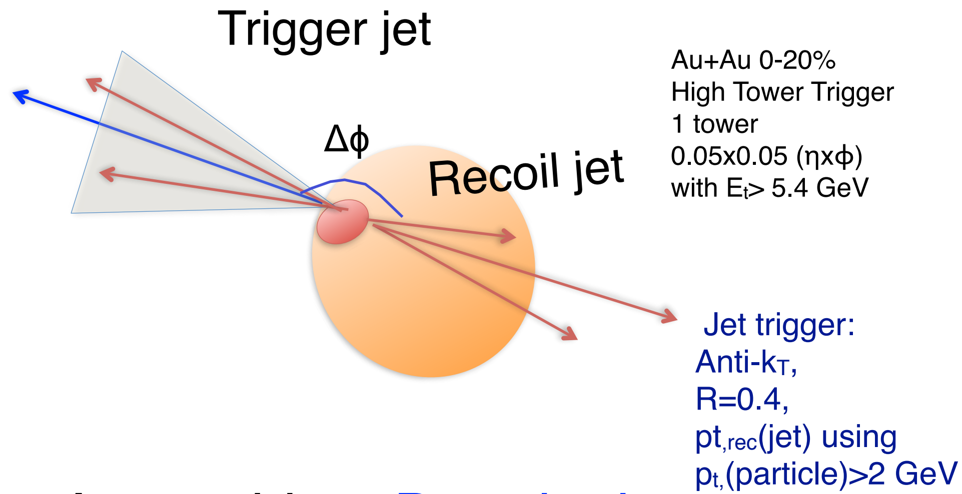
Au+Au 0-20%
High Tower Trigger
1 tower
0.05x0.05 ($\eta x \phi$)
with E_t> 5.4 GeV

Jet trigger:
Anti-k_T,
R=0.4,
$p_{t,rec}$(jet) using
$p_{t,}$(particle)>2 GeV

STAR:PRL 112 (2014) 122301

Where does lost energy go?





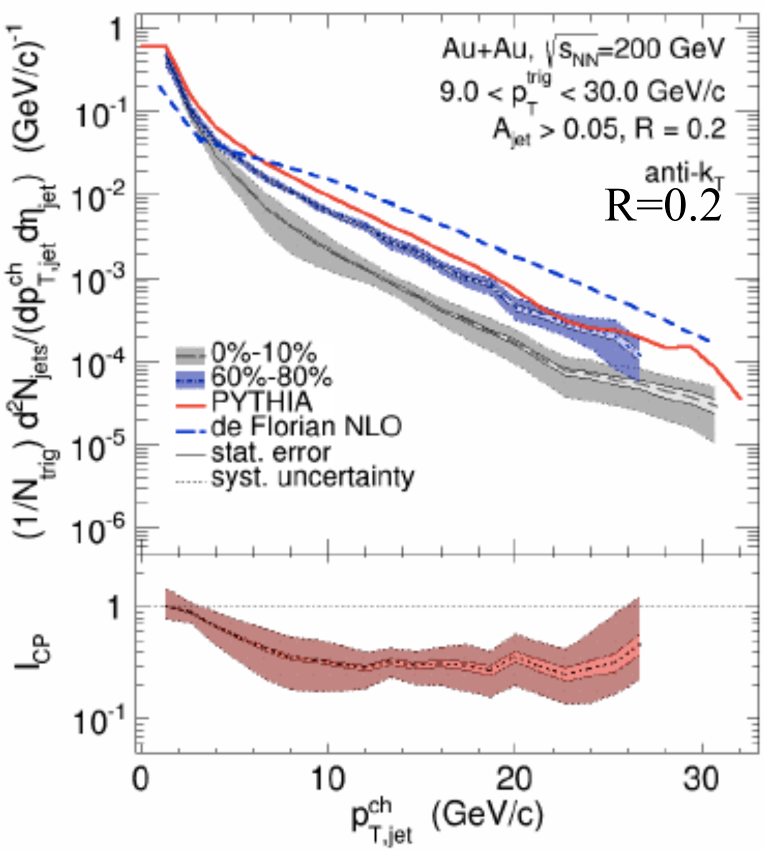
Away-side: Broadening
Softening

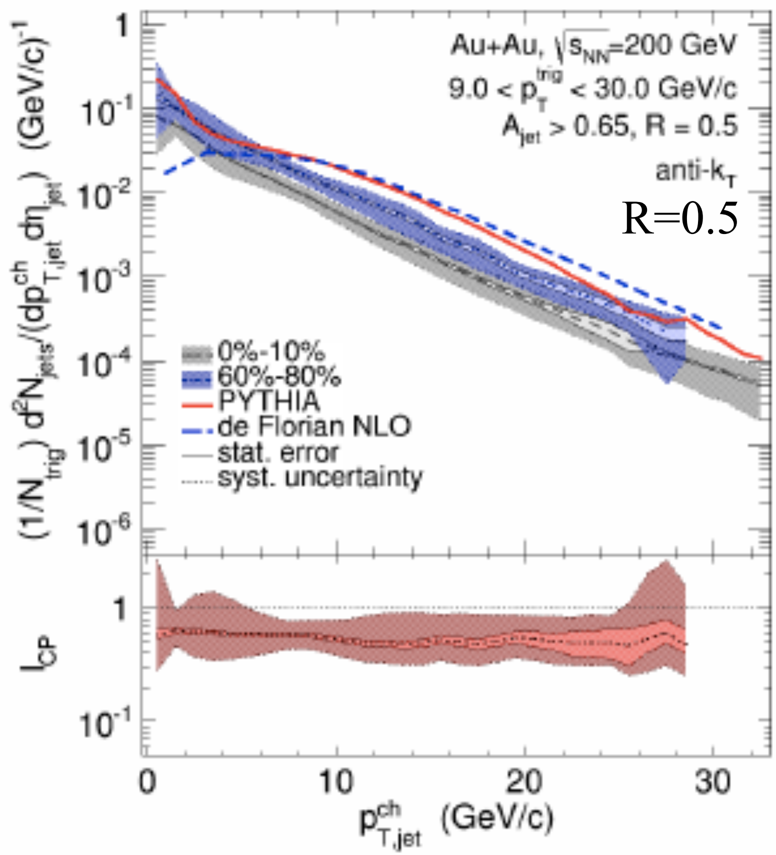
E remains correlated to jet axis but at large angles

Direct measurement of modified fragmentation due to presence of QGP

STAR:PRL 112 (2014) 122301

Lost energy of a recoil jet





ALICE: JHEP 09 (2015) 170
STAR: PRC 96, 024905 (2017)

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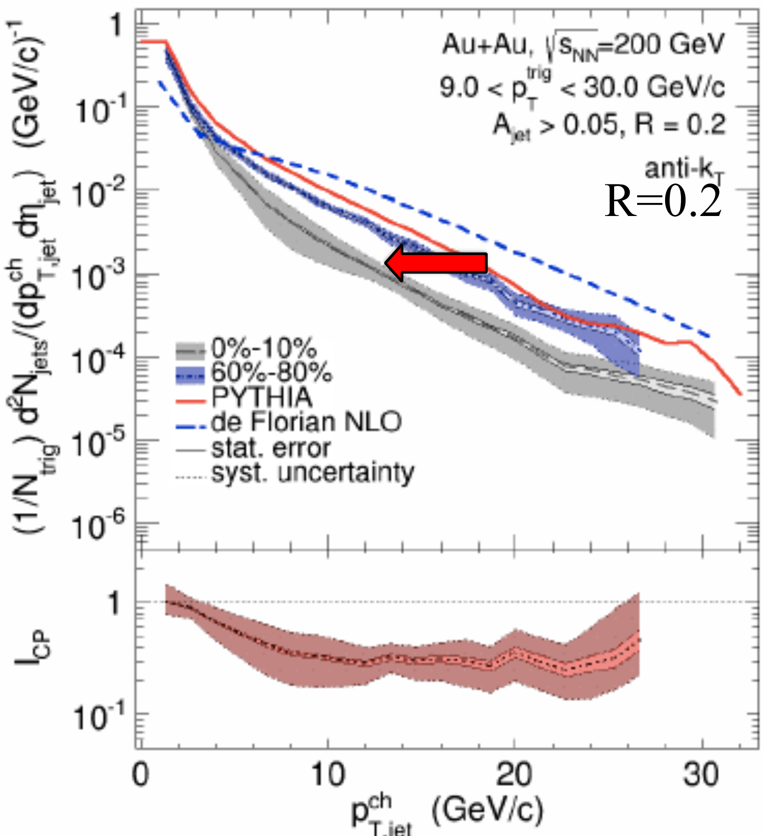

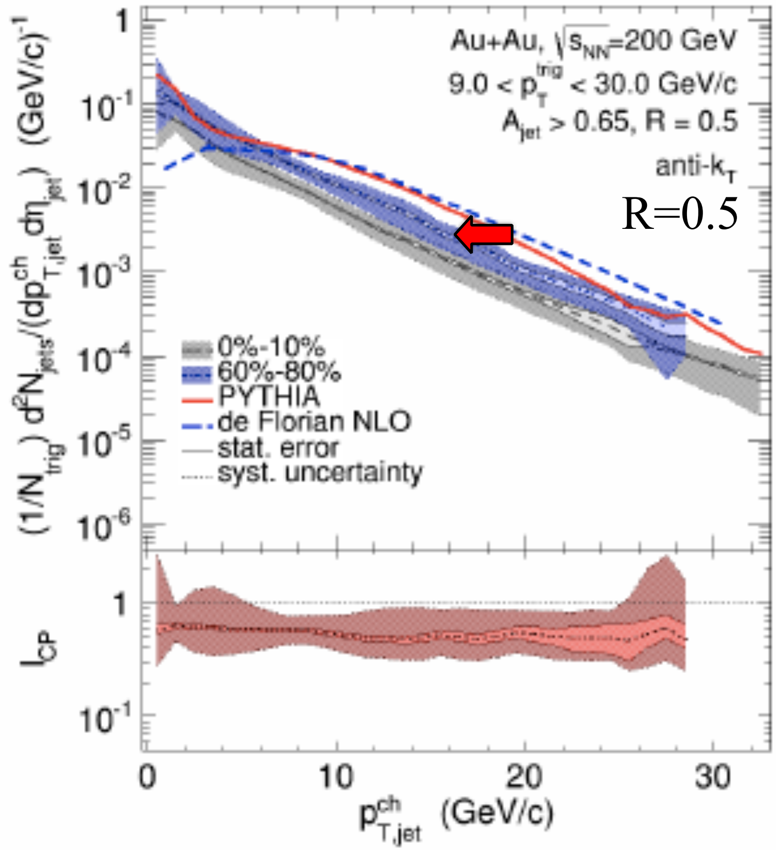

RHIC: Jet p_T =10-20 GeV

R=0.2: $p_{T,Shift}$ ~ -4.4 ± 0.2 ± 1.2 GeV

R=0.5: $p_{T,Shift}$ ~ -2.8 ± 0.5 ± 1.2 GeV

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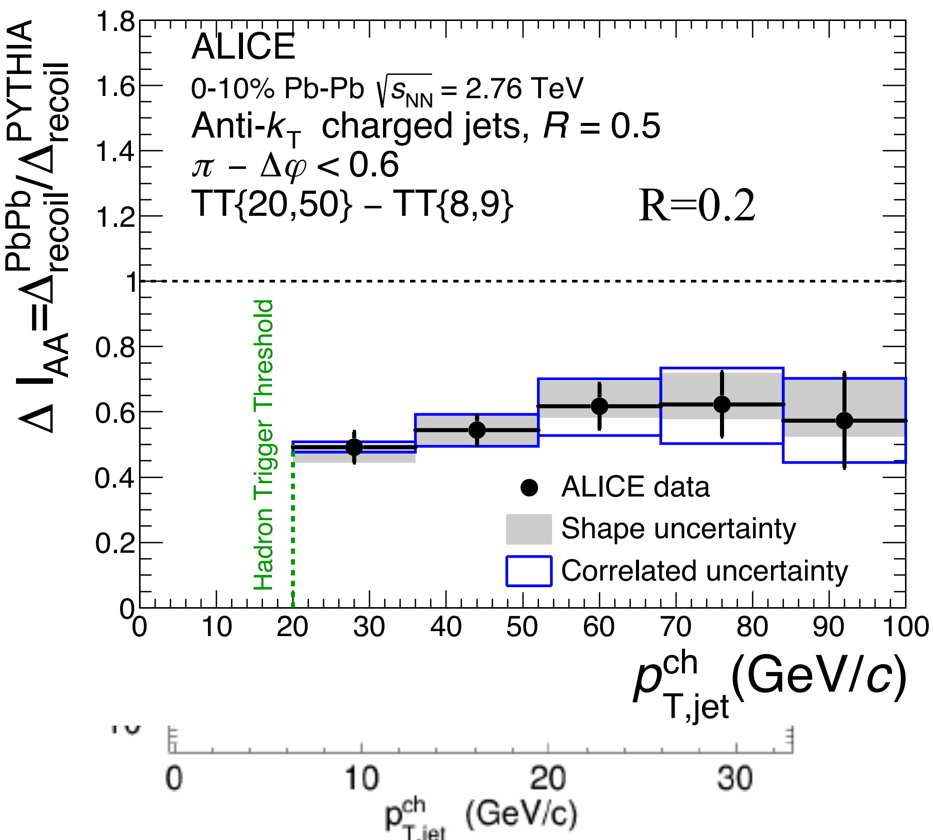

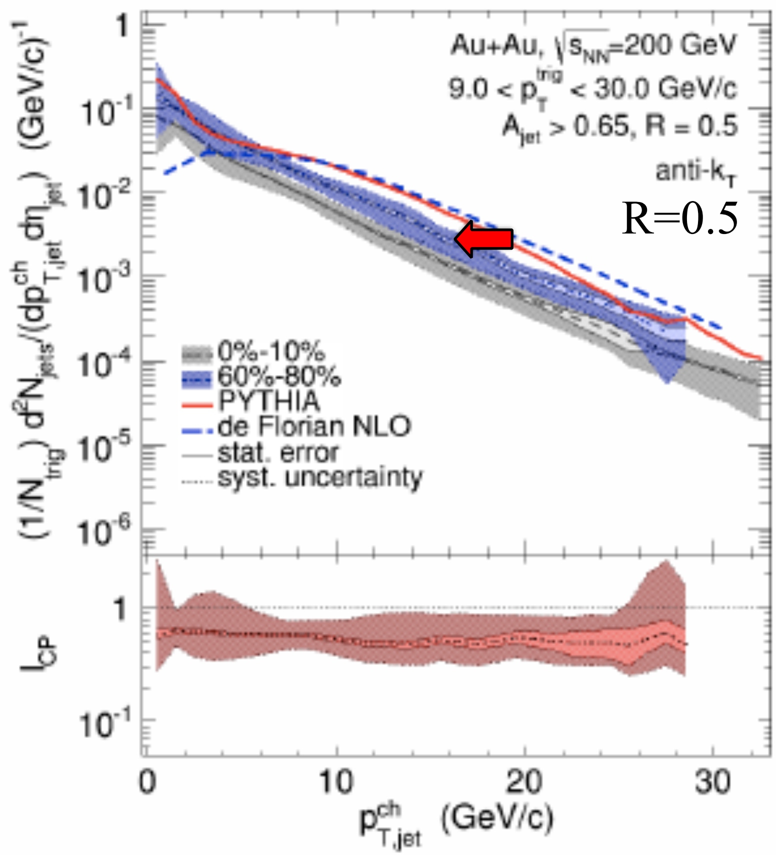

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LHC: Jet p_T =60-100 GeV

R=0.5: $p_{T,Shift}$ ~ -8 ± 2GeV

Energy almost recovered at moderate angles at RHIC but not at LHC

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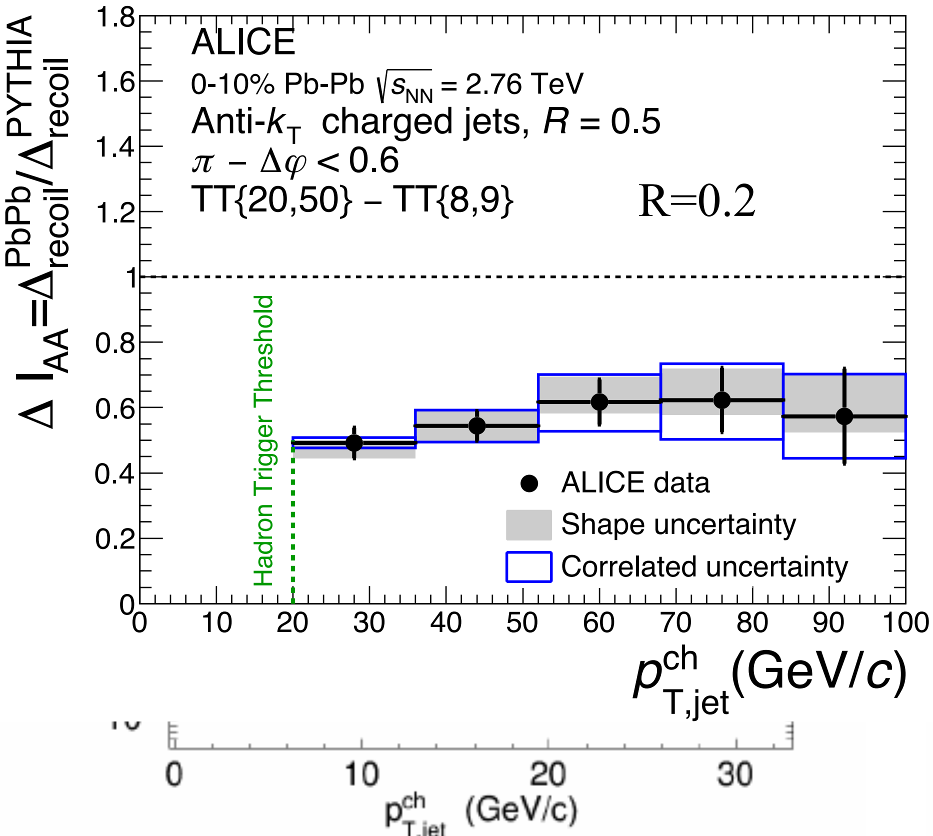
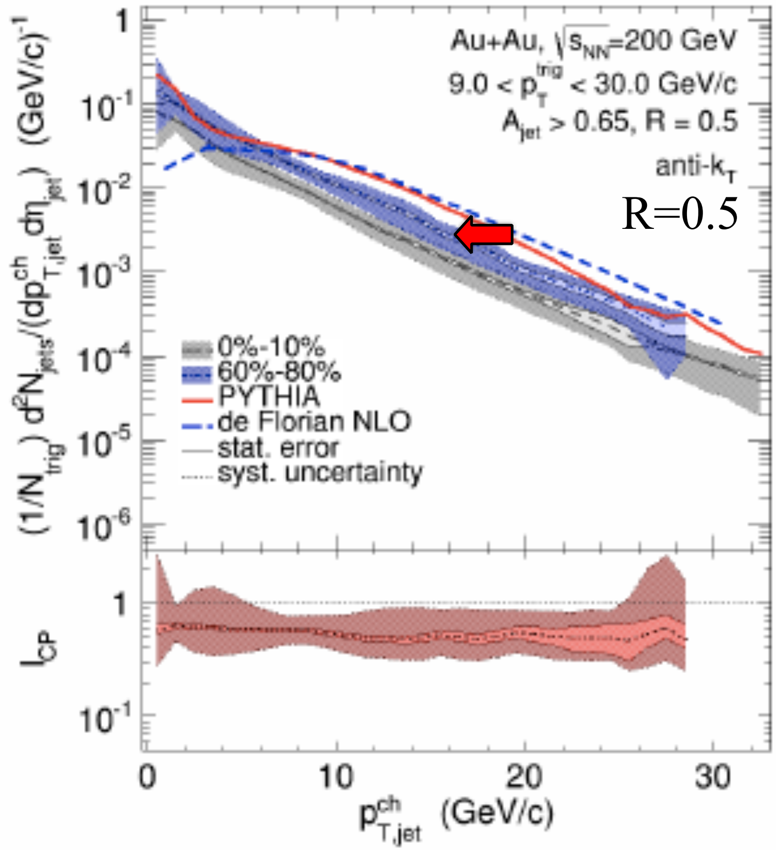
Lost energy of a recoil jet





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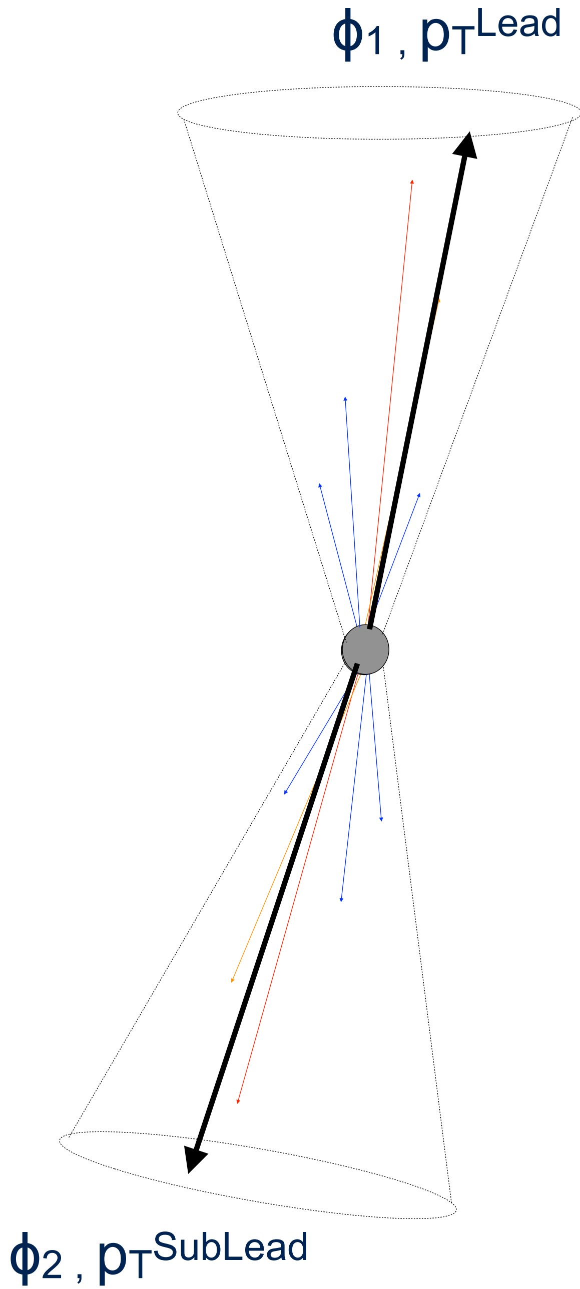
How to look event-by-event?

ALICE: JHEP 09 (2015) 170
STAR: PRC 96, 024905 (2017)

Dijet energy (im)balance: A_J or x_J



$$A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$$

$$x_J = \frac{p_T^{SubLead}}{p_T^{Lead}}$$

Ideally $A_J = 0$ or $x_J = 1$

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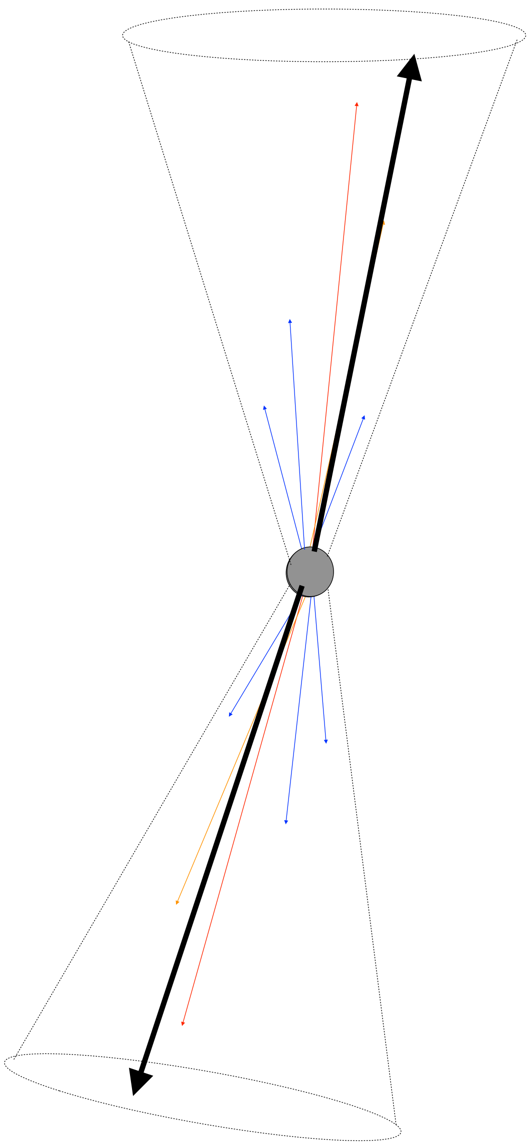

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Ideally $A_J = 0$ or $x_J = 1$

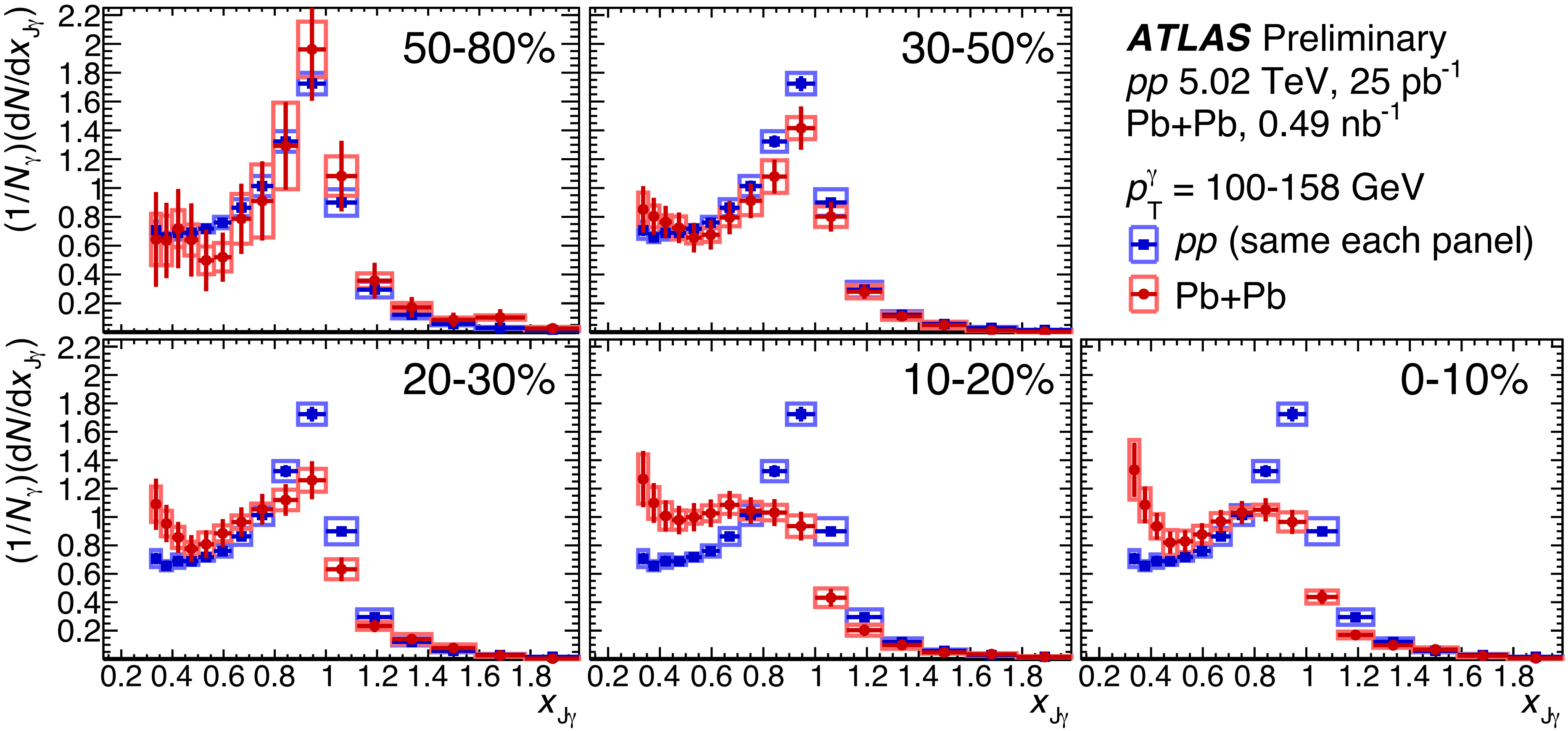
Using jet finder some energy missed

Even for p+p this is not observed

In A+A collisions energy loss to QGP will enhance imbalance

Compare imbalance in p+p and A+A for different thresholds, radii, partons

Individual dijets are imbalanced



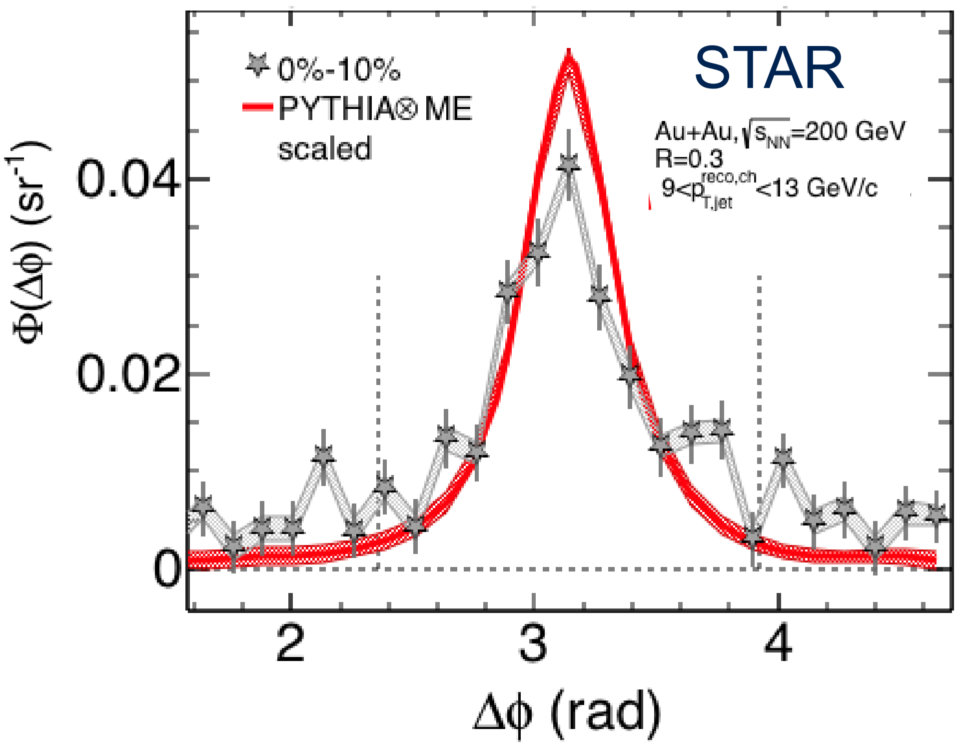
Fix trigger photon p_T = 100-158 GeV

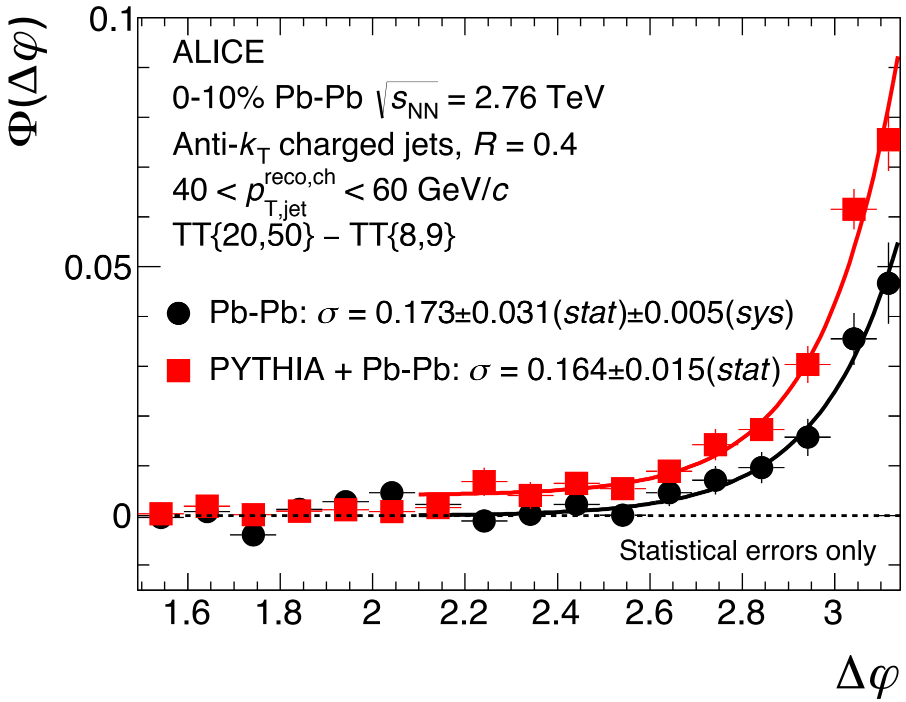
Imbalance clearly increases with centrality - more E_{loss} of recoil jet

Dijets are not deflected

Examine Δϕ - azimuthal angle between dijets

Leading order expectation: Δϕ ~π



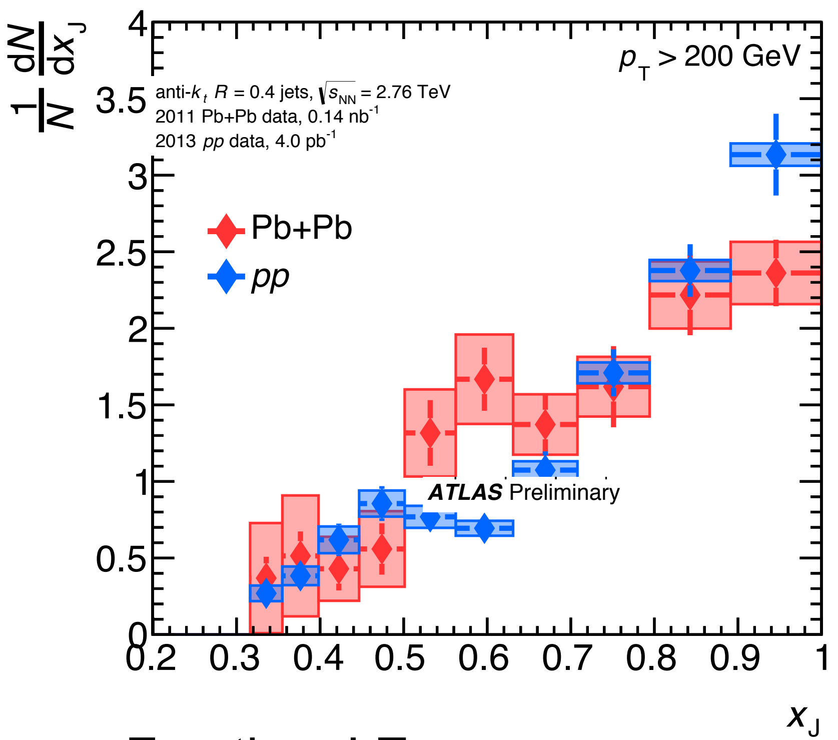


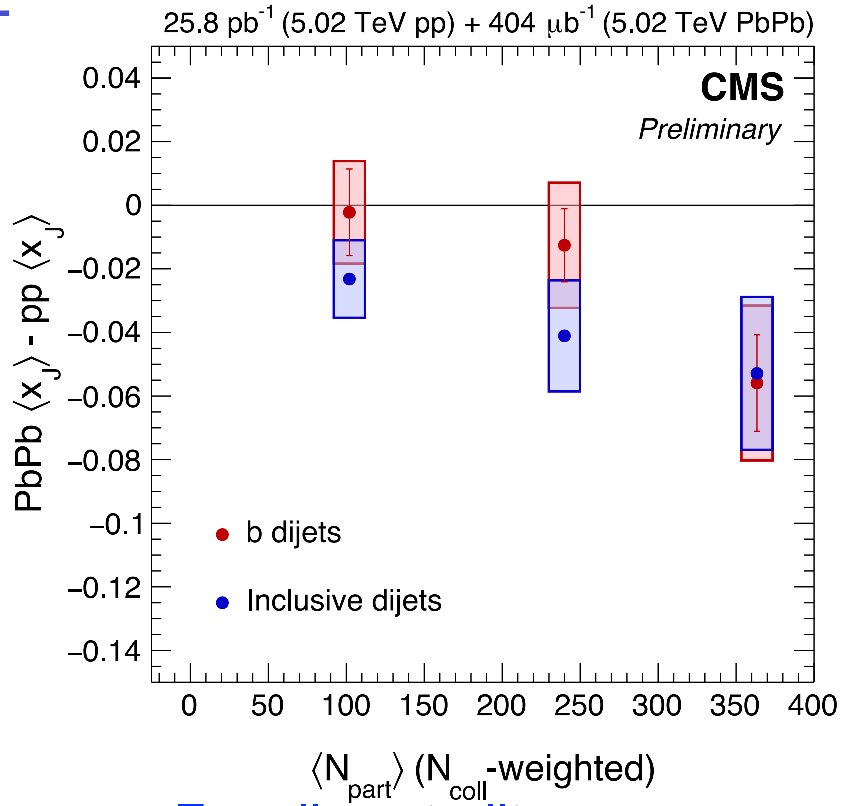
Little to no azimuthal de-correlation observed

Partons lose energy but are not deflected from original path

ALICE: JHEP 09 (2015) 170
STAR: PRC 96, 024905 (2017)

Which partons loose energy?





Fractional E_{loss} decreases with p_T

p_T> 200 GeV
Pb+Pb approaches p+p

For all centrality
inclusive ~ di-b

Inclusive: q and g
di-b: q

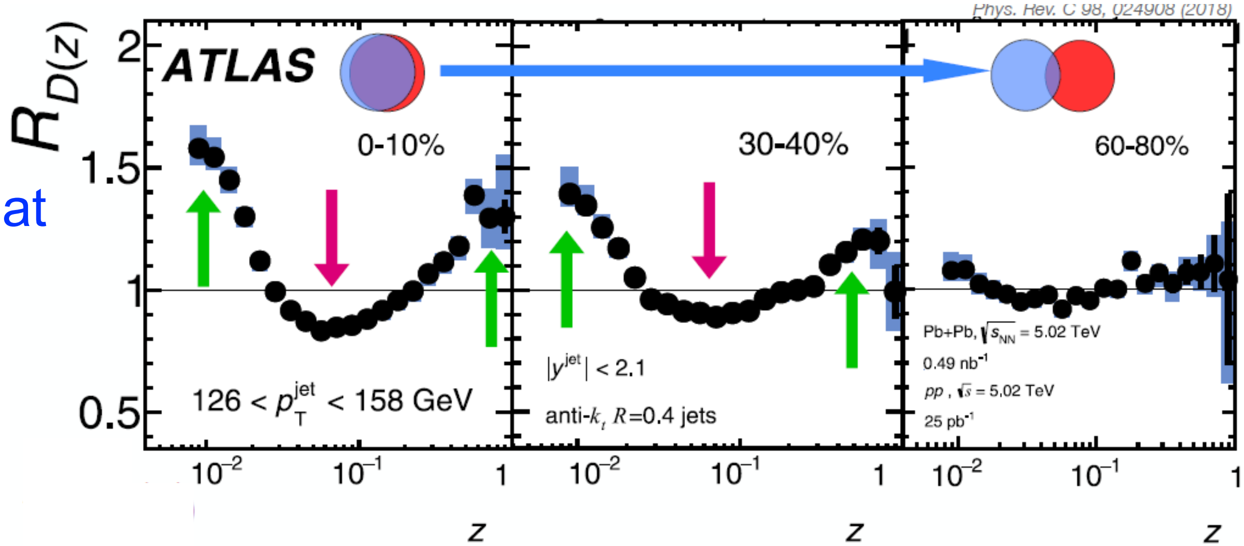
Probing parton flavor energy loss with ever enhancing precision

Changes in fragmentation functions

dijet:

Central - enhancement at high and low z

Peripheral - p+p like



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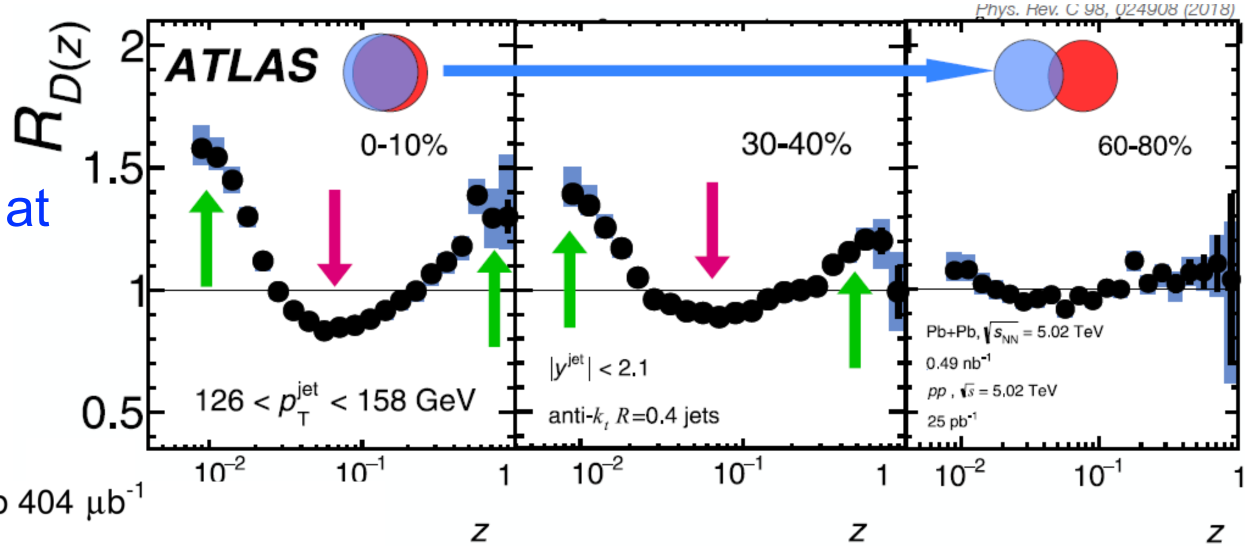
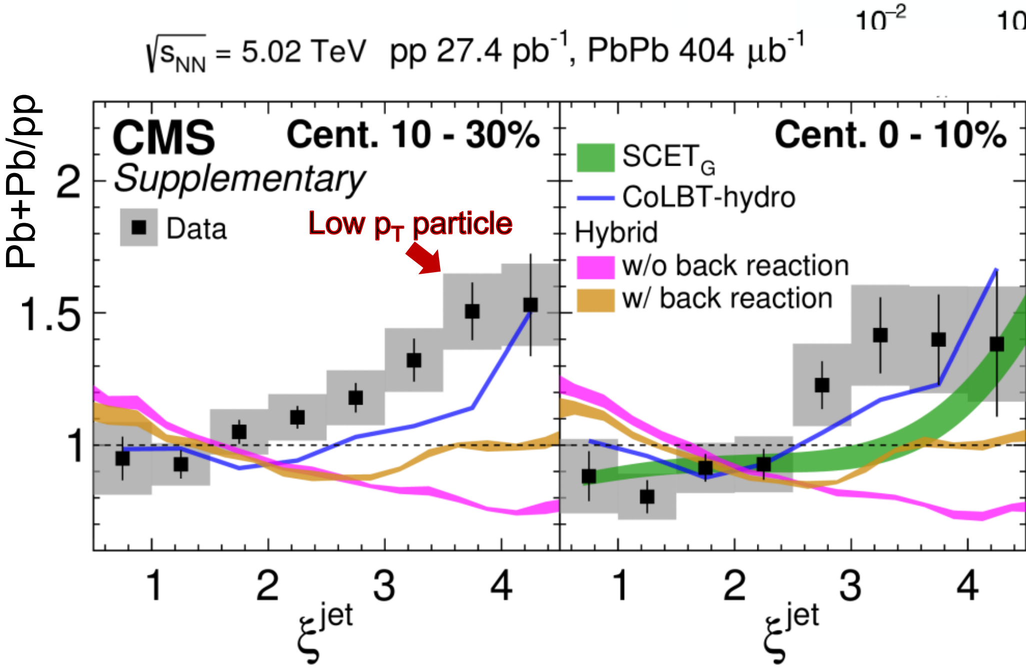




photon-jet:

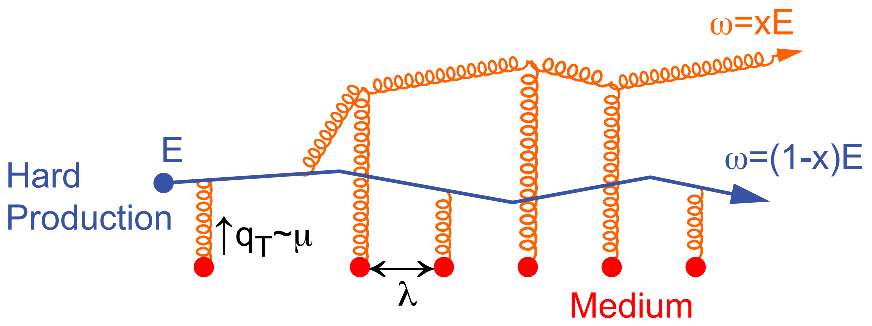
Peripheral - p+p like

Central - Enhancement at low z
No clear enhancement at high z

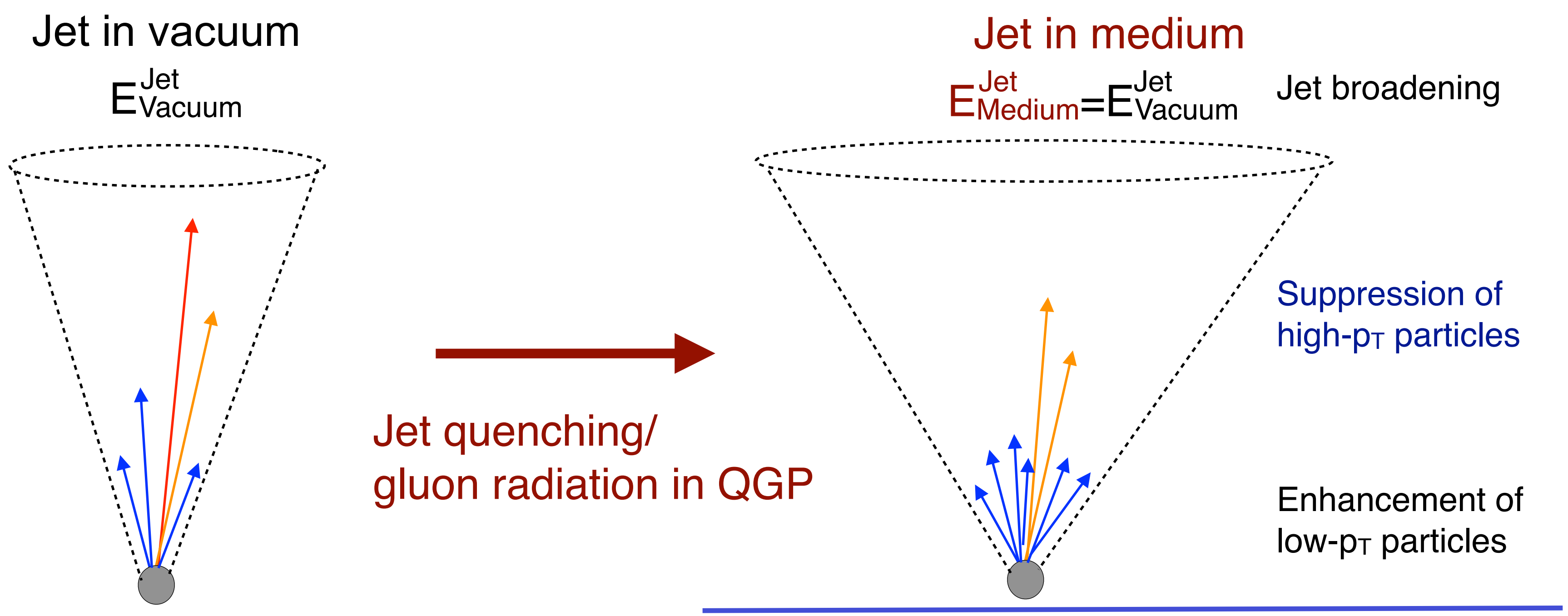
Different selection of quark vs gluon jets?
Flavor dependence of quenching?

So what's happening?

Jet quenching = Gluon radiation:
Multiple final-state gluon radiation off of produced hard parton induced by traversed dense colored medium ~ "Gluon Bremsstrahlung"



Modification of Jet Structure

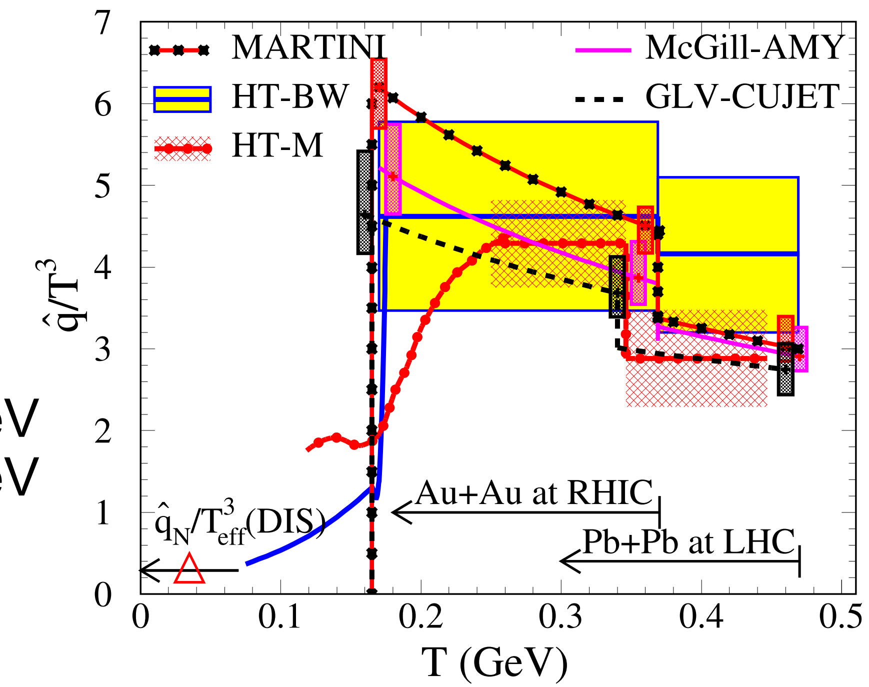


What has all this taught us?

Different initial conditions and evolutionary paths:

$\hat{q} = Q^2/L$ Q - mtm transfer to medium
L - path length

$\hat{q}$(t=0.6fm/c) ~ 1.2 ± 0.3 GeV²/fm T=370 MeV
1.9 ± 0.7 GeV²/fm T=470 MeV



Probes behave differently at RHIC and LHC

JET: PRC 90, 014909 (2014)

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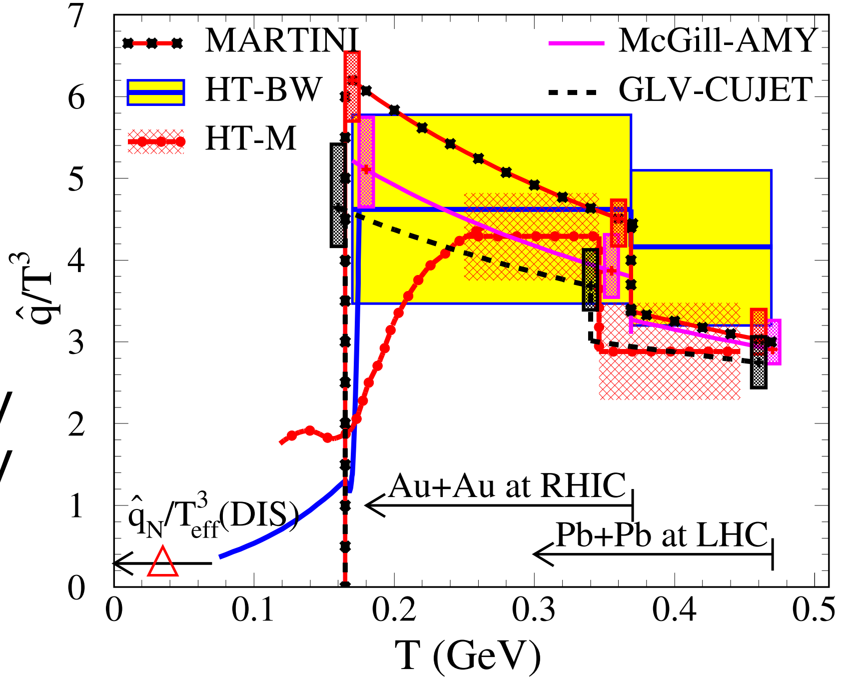
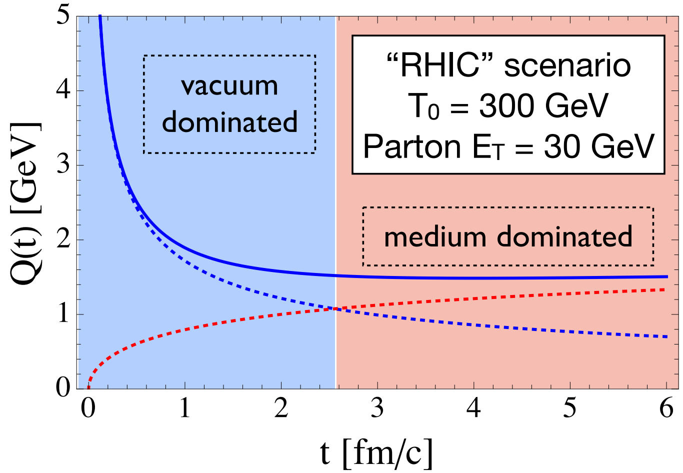


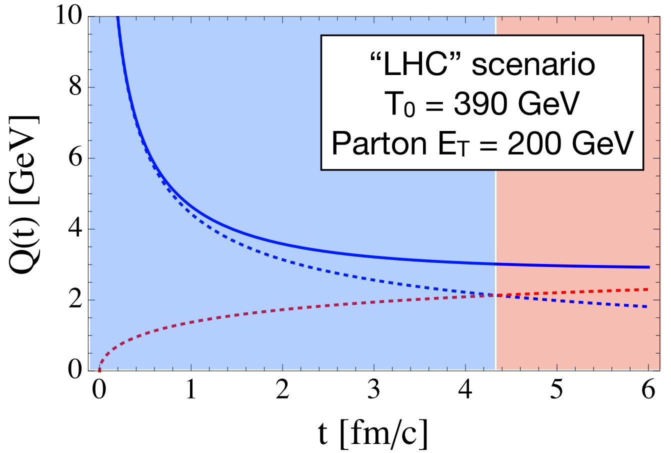
$\hat{q}(t=0.6\text{fm/c}) \sim$ 1.2 ± 0.3 GeV^2/fm T=370 MeV
1.9 ± 0.7 GeV^2/fm T=470 MeV

Probes behave differently at RHIC and LHC

Different virtuality evolutions:

How/when does parton become "aware" of medium





JET: PRC 90, 014909 (2014)

Summary

All "jet" results reveal consistent picture:

- Strong energy loss of hard scattered patrons
- Lost energy re-emerges as soft (low p_T) particles
- Lost energy re-emerges as large angles to initial parton direction
- Core of jet remains unmodified

For jet observables peripheral A-A collisions behave a lot like p-p collisions

- Small/no energy lost to medium in small systems

Differences between QGP properties at RHIC and LHC emerging

- Informing about QCD at high T

Qualitatively consistent picture of partonic energy loss emerging

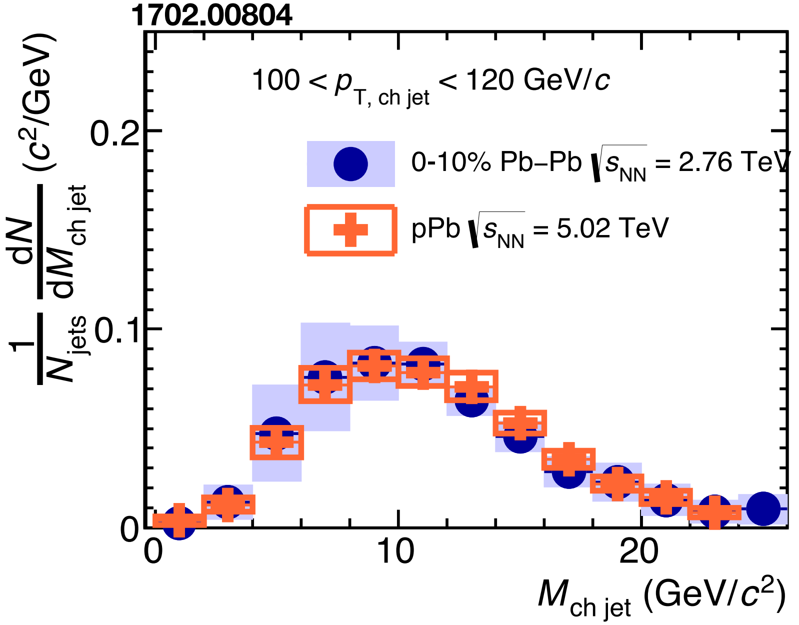
Starting to explore jet substructure and geometry engineering to learn more about how interactions with QGP modify fragmentation

New detectors, sPHENIX and STAR Forward at RHIC; ALICE streaming TPC readout at LHC come on line in next couple of years.

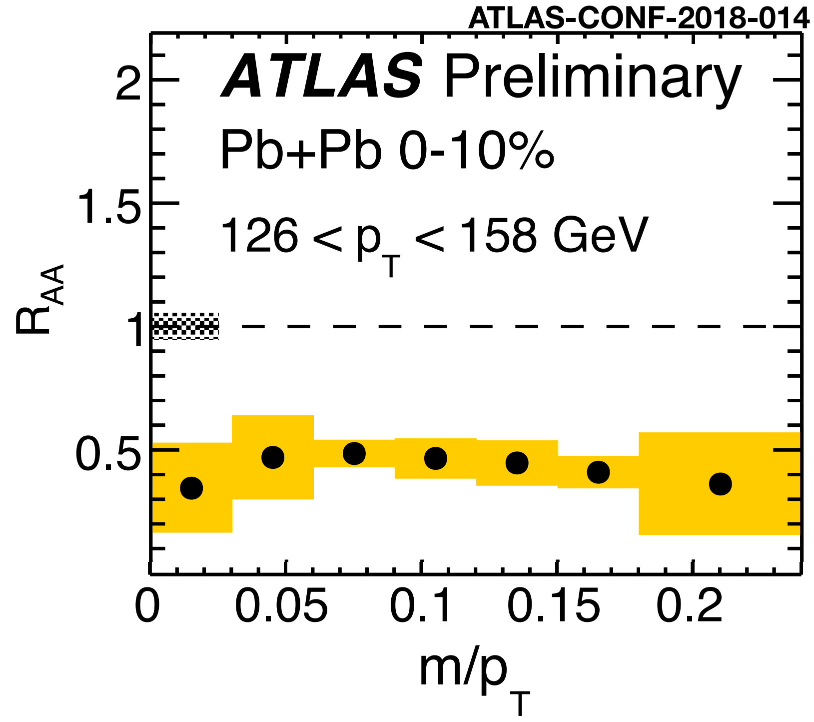
- High statistics measurements of rare probes coming soon

But jet mass does not change

ALICE: mass from charged particles

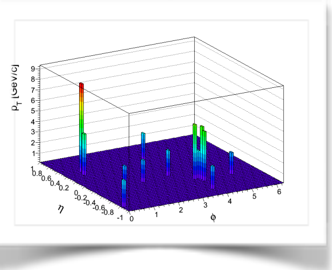


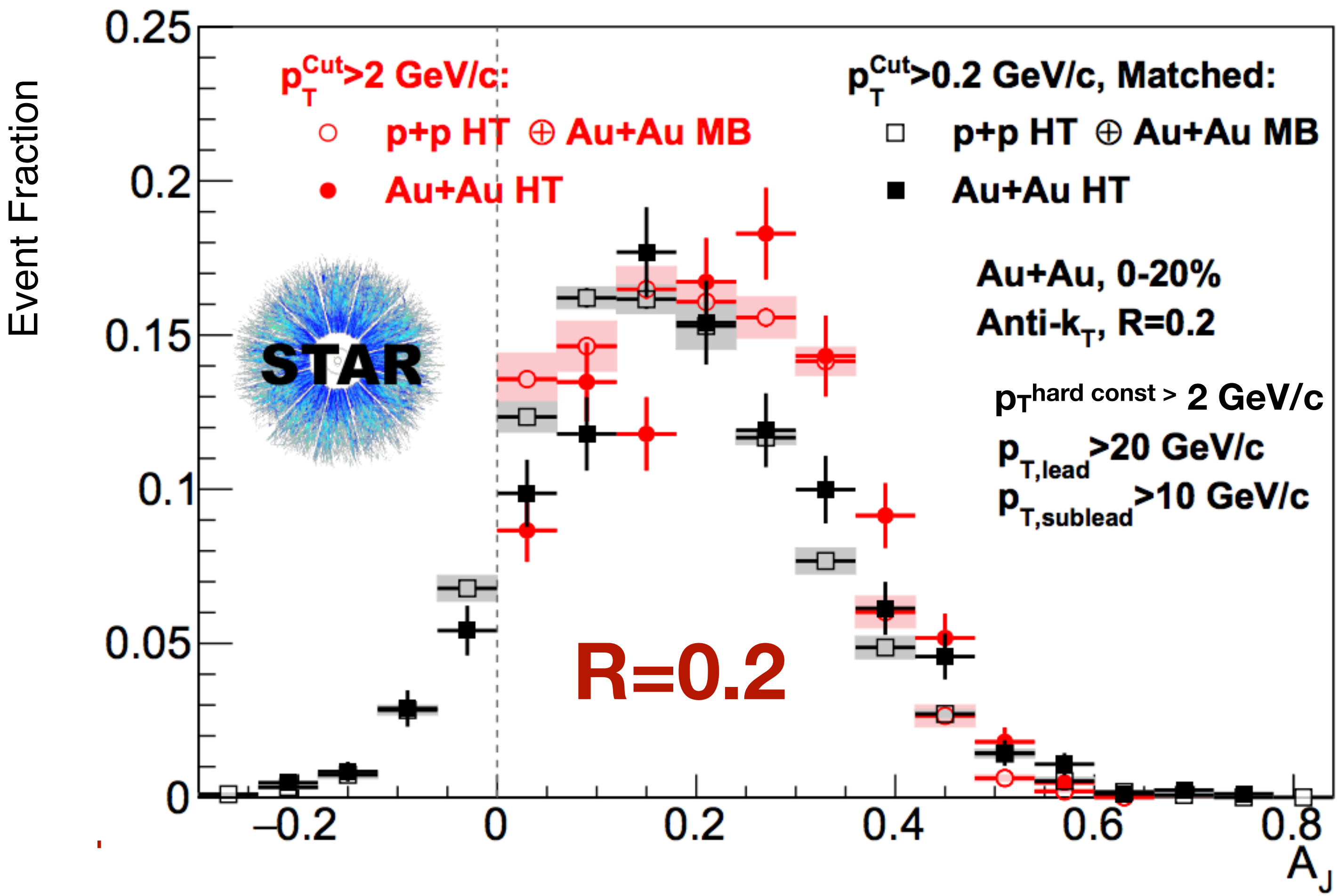
ATLAS: mass from calorimeter towers



no significant mass modification observed in PbPb within the uncertainties

Di-jet imbalance A_J Au+Au 0-20% R=0.2





$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

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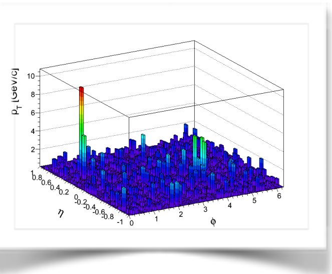
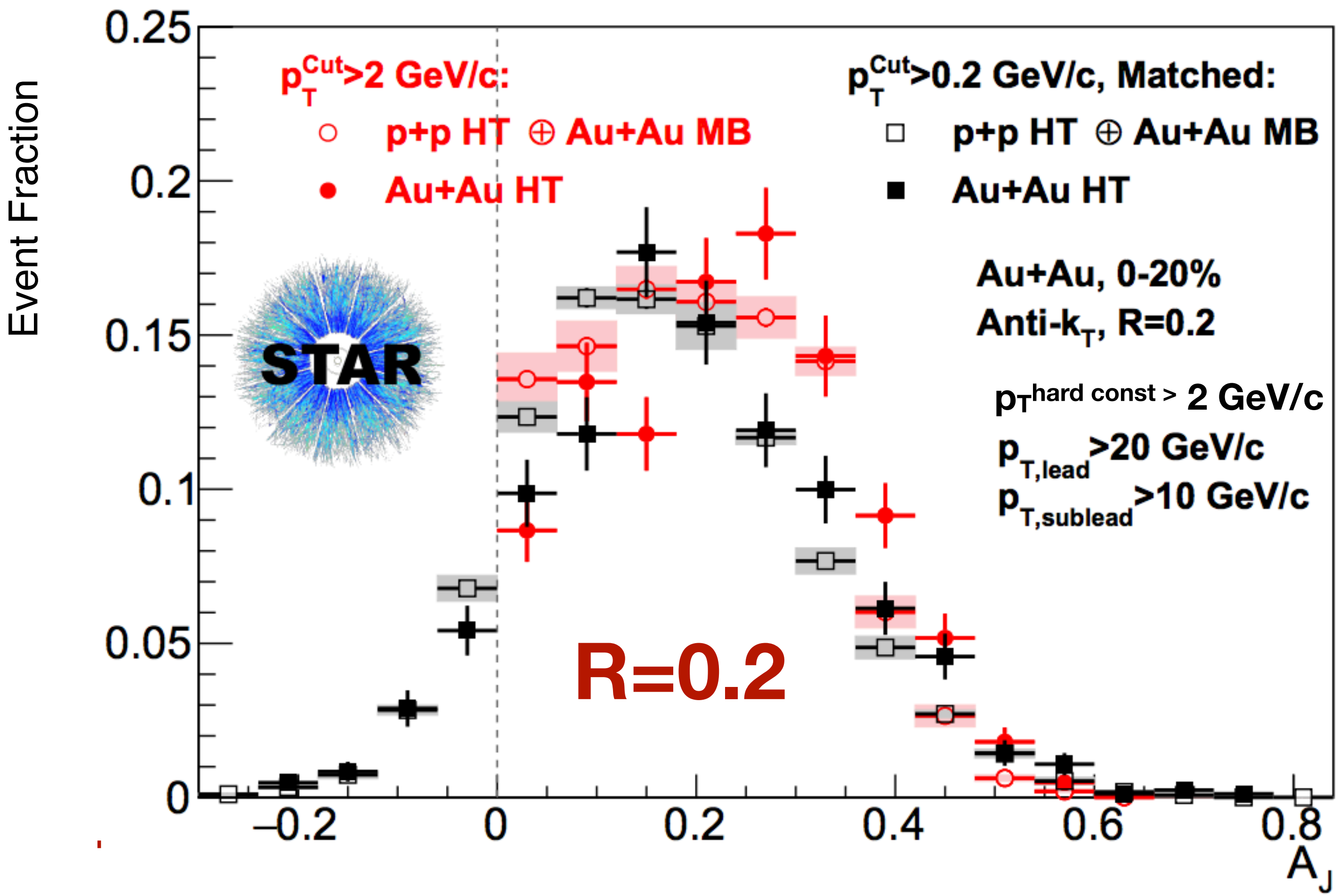


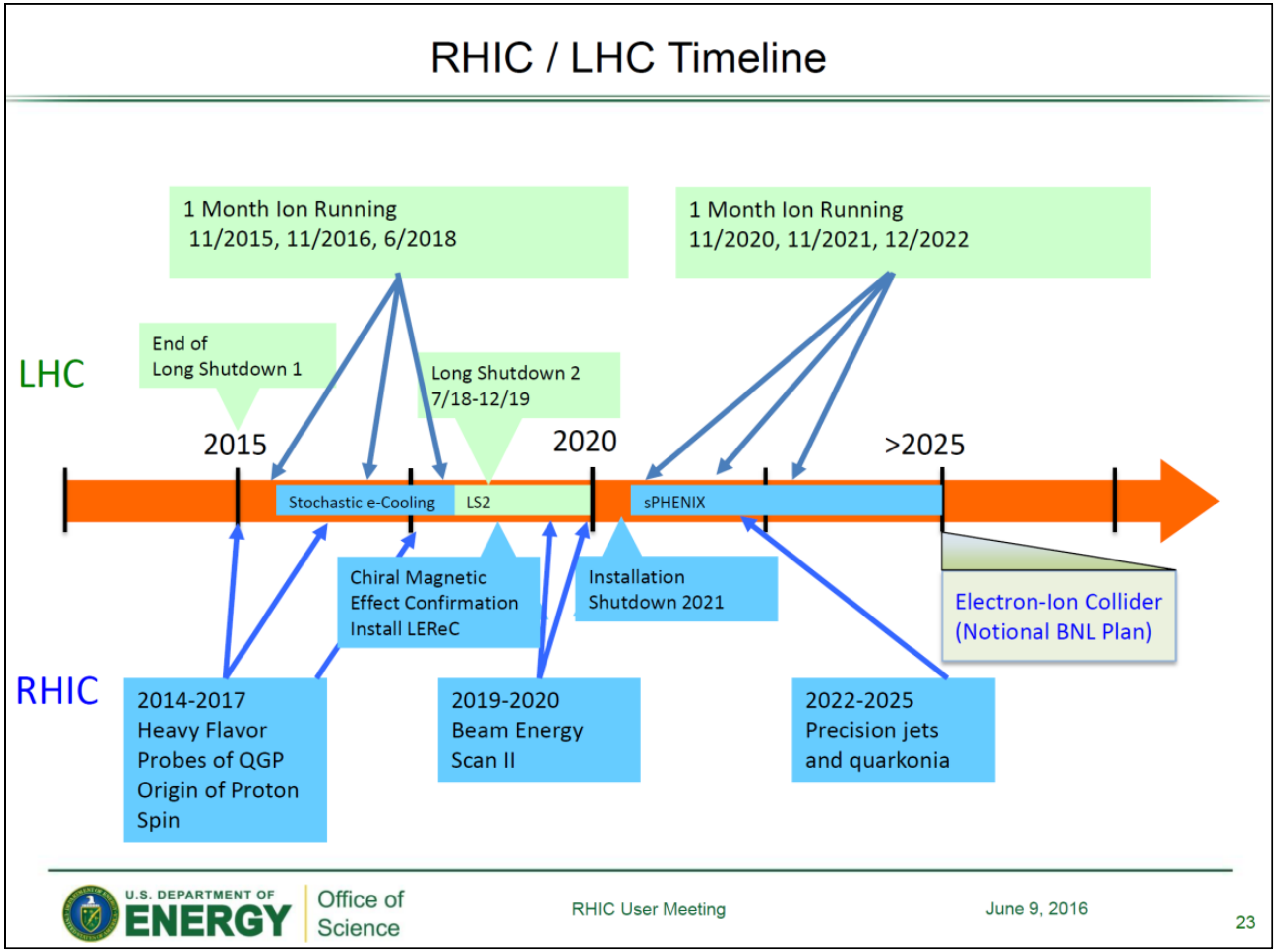


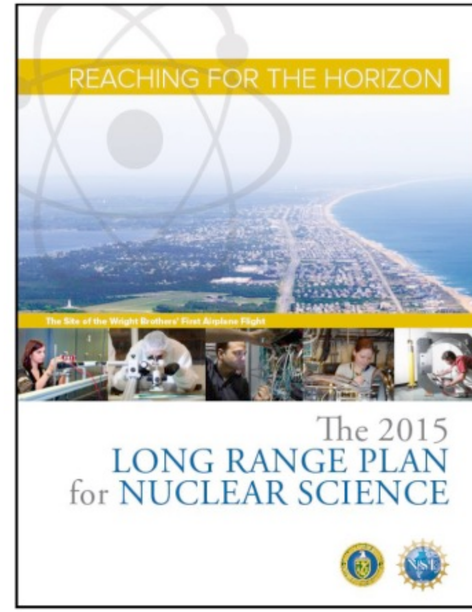
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Matched Au+Au A_J ≠ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

Our Long Range Plan

DoE and international support for our plan





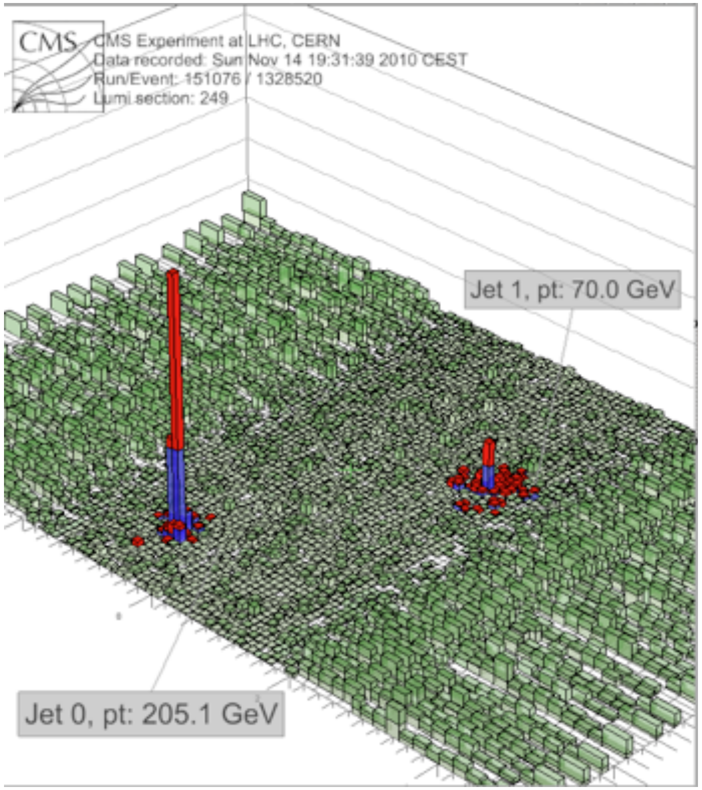
New detectors being designed and built NOW!

New accelerator being designed NOW!

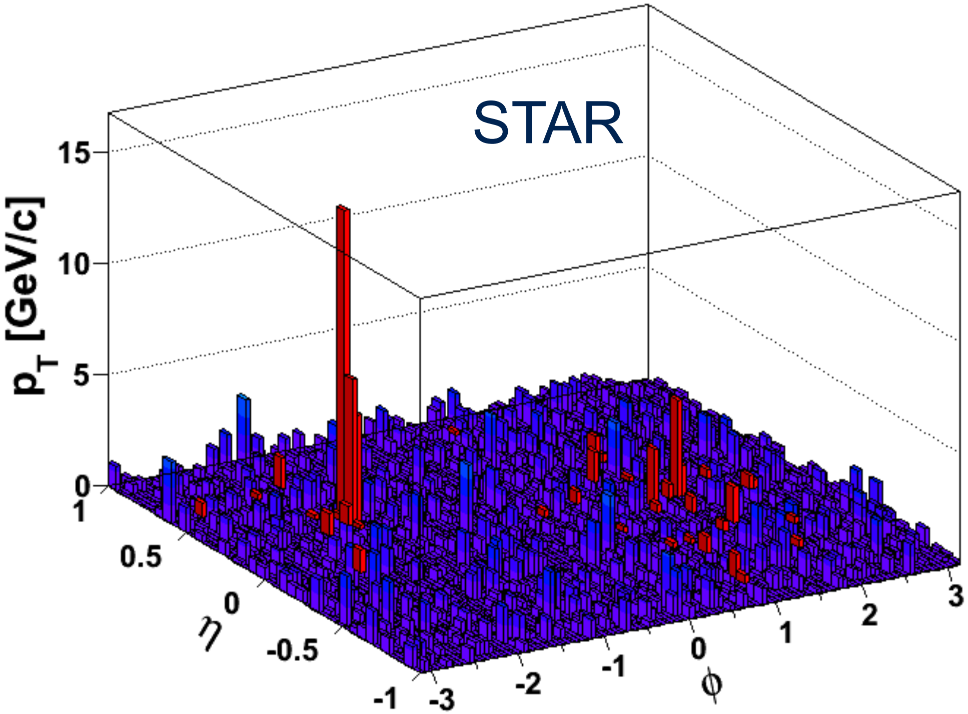
At RHIC BES-II, followed by forward physics followed by sPHENIX
At LHC upgrades being installed for high precision Run-3 in 2022

Backup

Got to bite the bullet and jet find



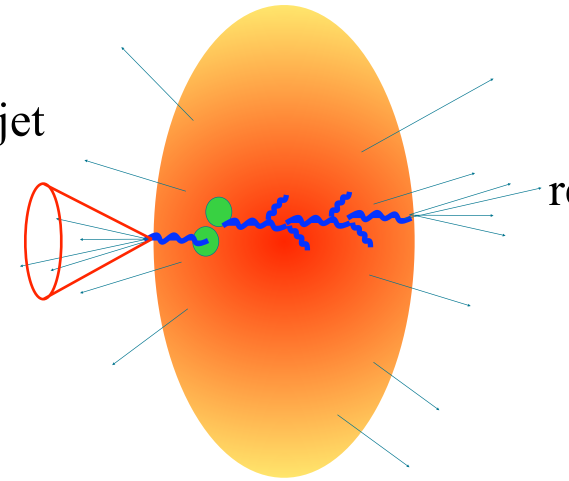
Even visible by eye in event displays



Can we select specific jet geometries?

Can we *affect path-length* of recoil jet?

More energy loss of recoil jet



T. Renk, PRC87 (2013) 024905

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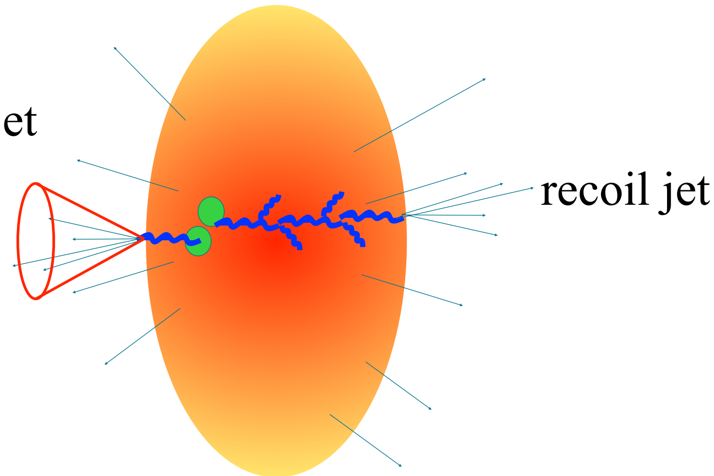
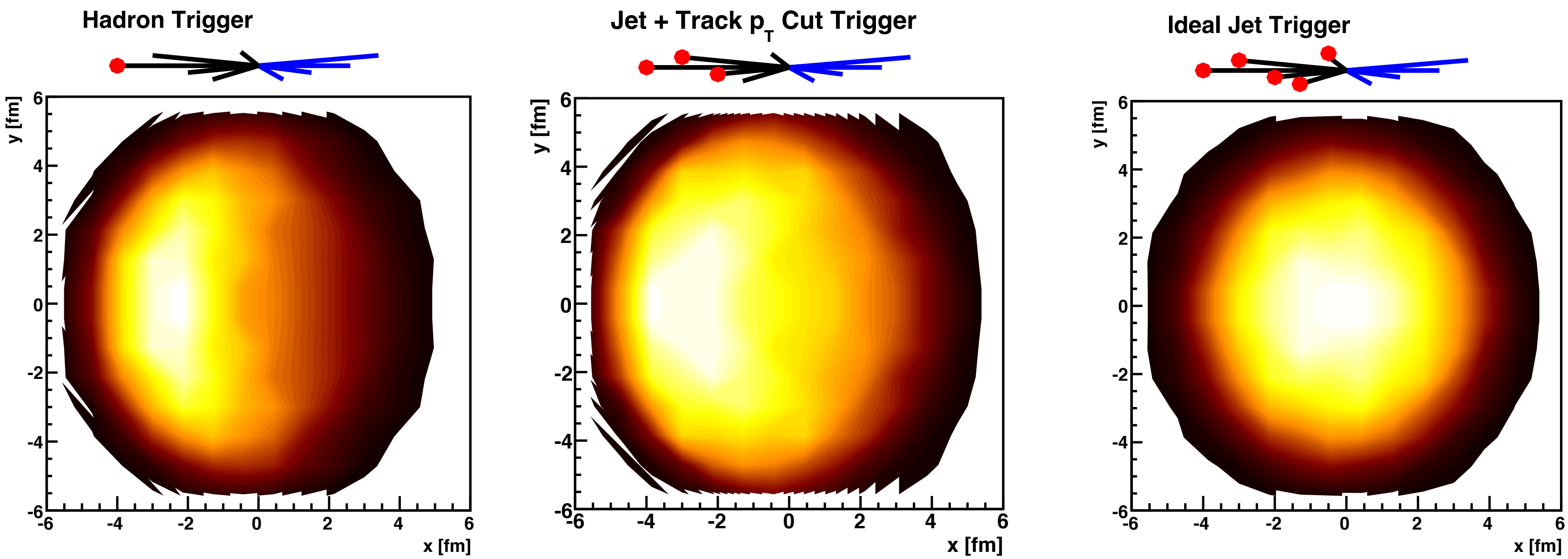




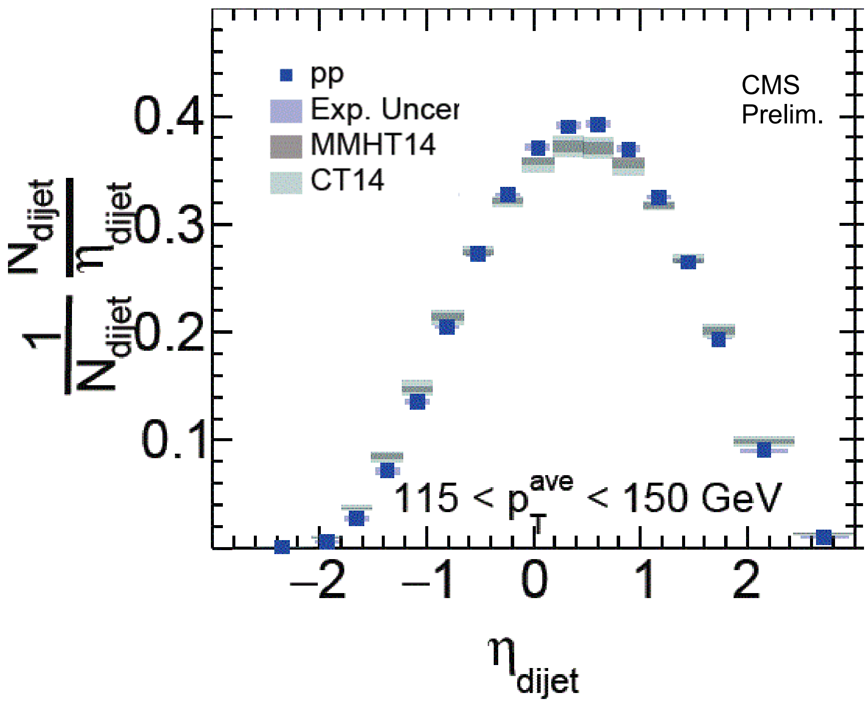
T. Renk, PRC87 (2013) 024905

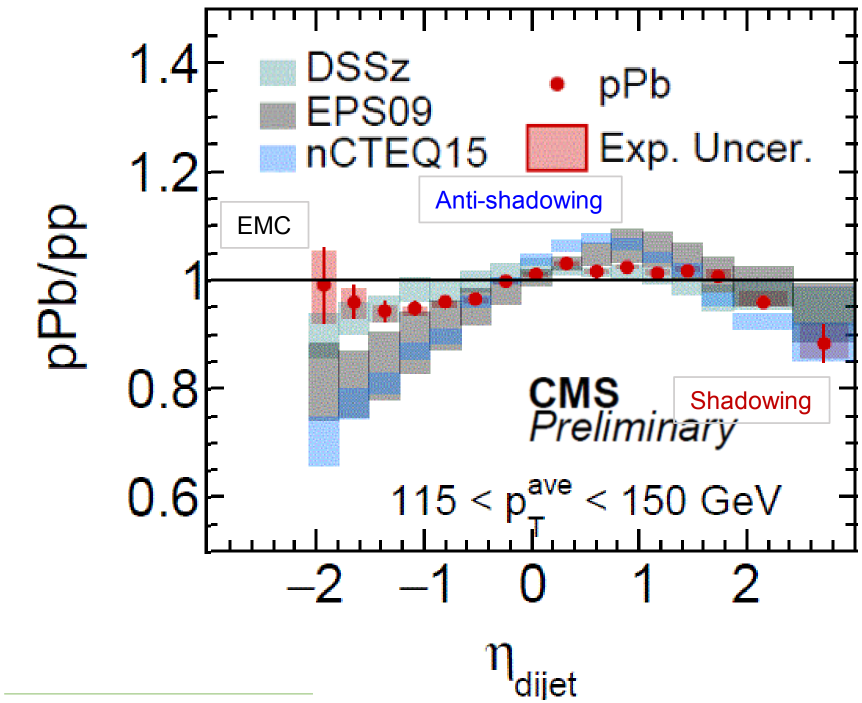
p-Pb : Constraining gluon (n)PDFs

Precision measurements of $\eta_{dijet} = (\eta_1+\eta_2)/2 \propto 0.5 \log(x_p/x_{pB}) + \eta_{CM}$

η_{dijet} Theoretically: can be calculated in pQCD
Experimentally: "avoid" fragmentation and hadronization effects

p_T^{ave} Access to Q^2

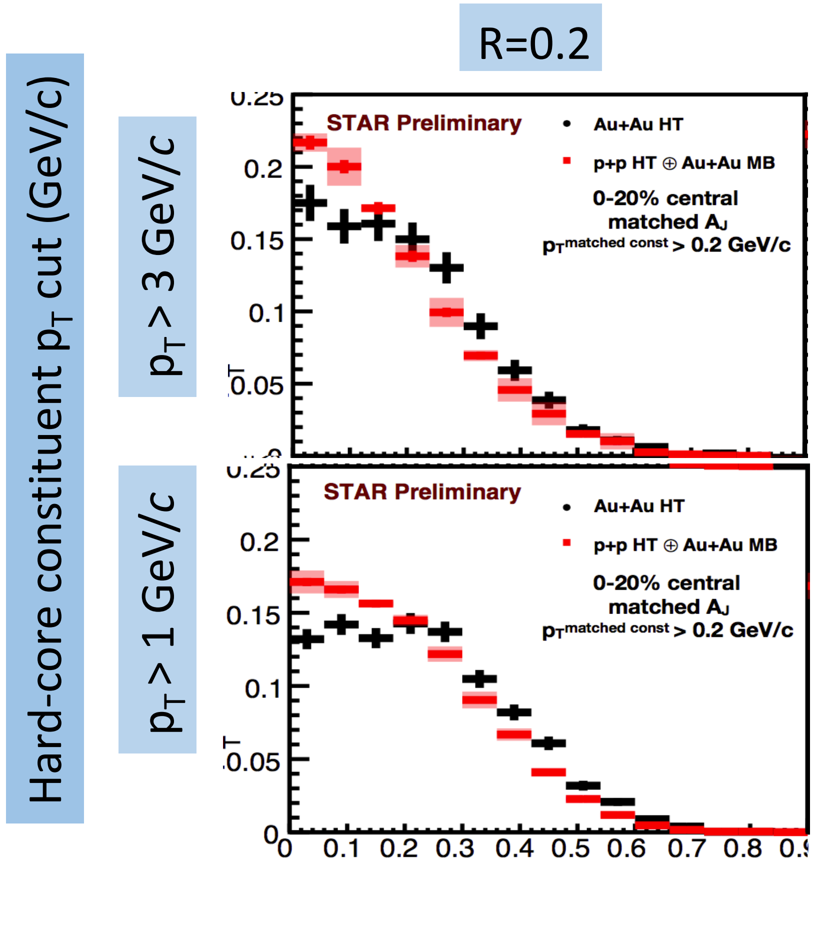




Neither PDFs nor nPDFs gives good fit across whole range

Evidence of gluon modification in EMC region x>0.3

Are all di-jets balancable?



Always imbalanced when low p_T constituents not included

Imbalance persists for small radii

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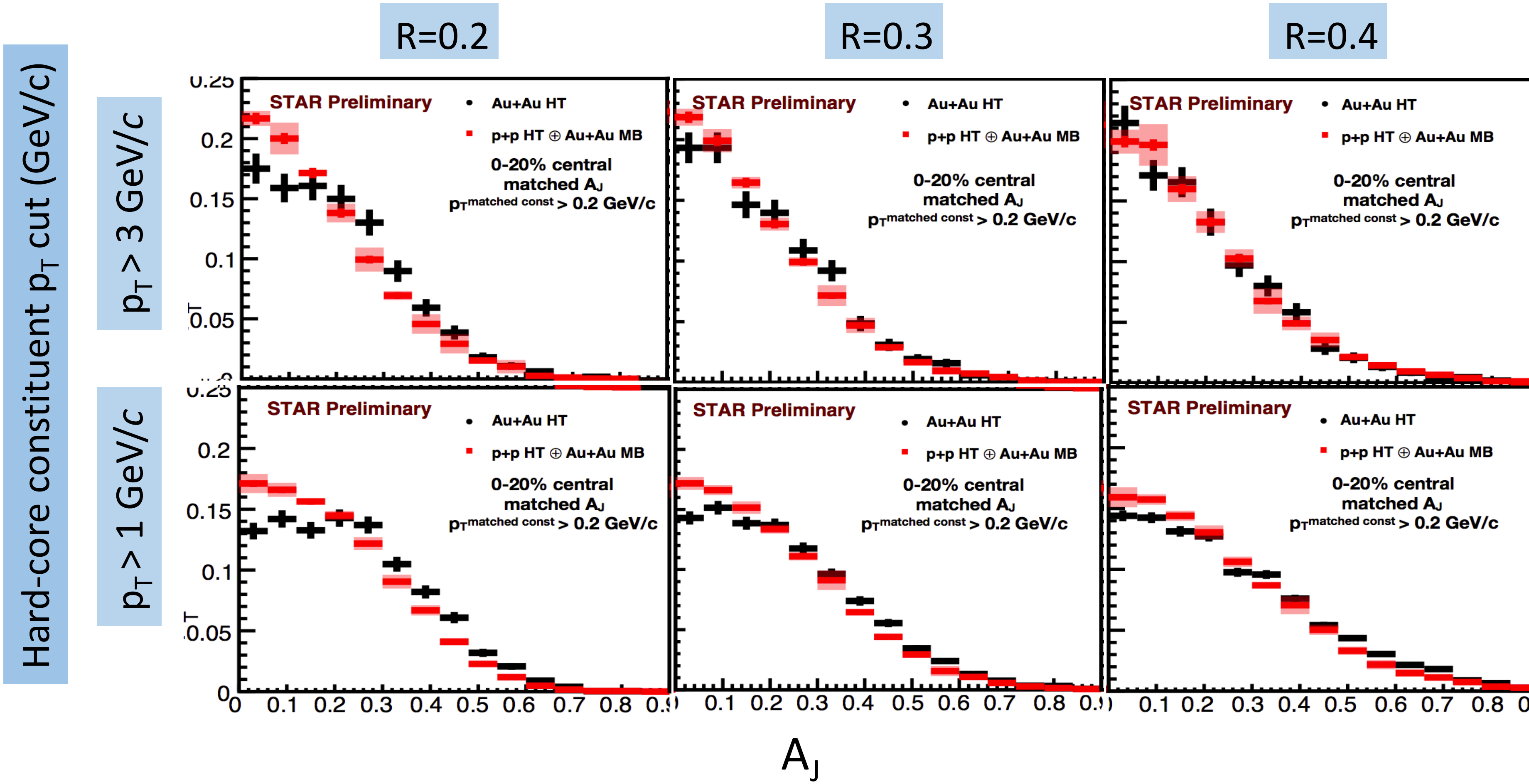


Always imbalanced when low p_T constituents not included

Imbalance persists for small radii

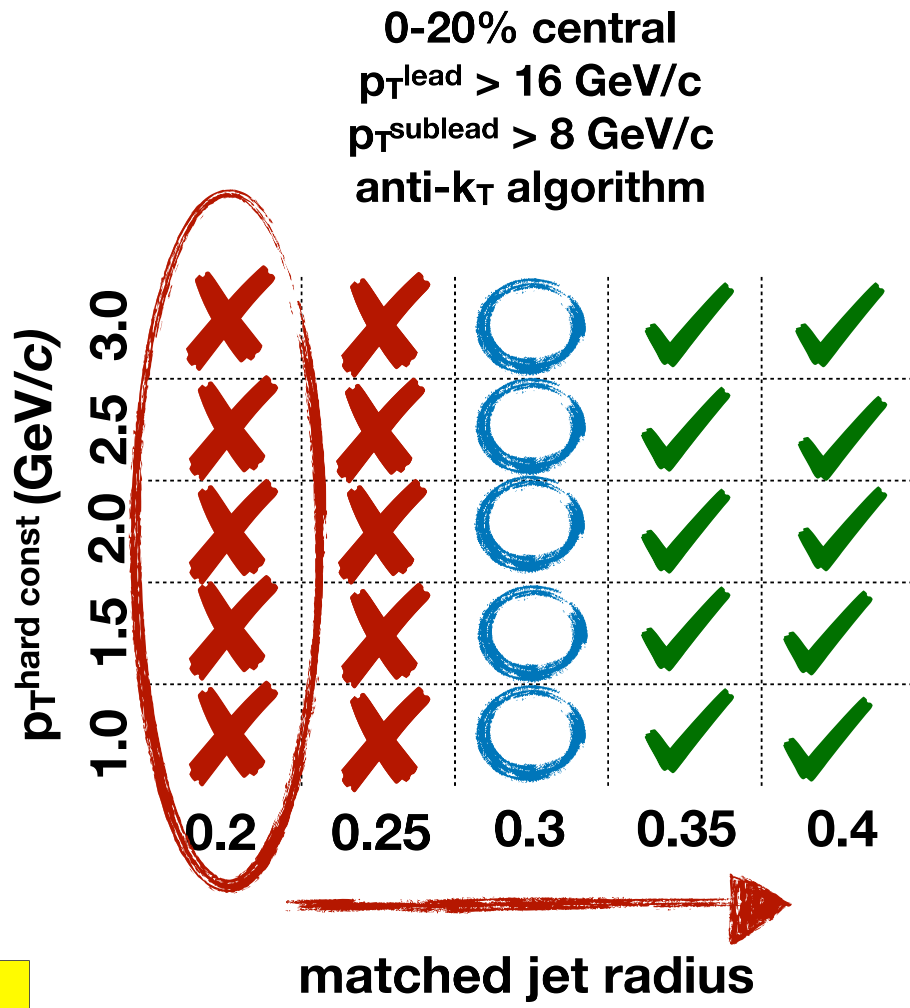
Balance identified for large jet R

Di-jet variation scorecard

Starting with imbalanced di-jets with R=0.2

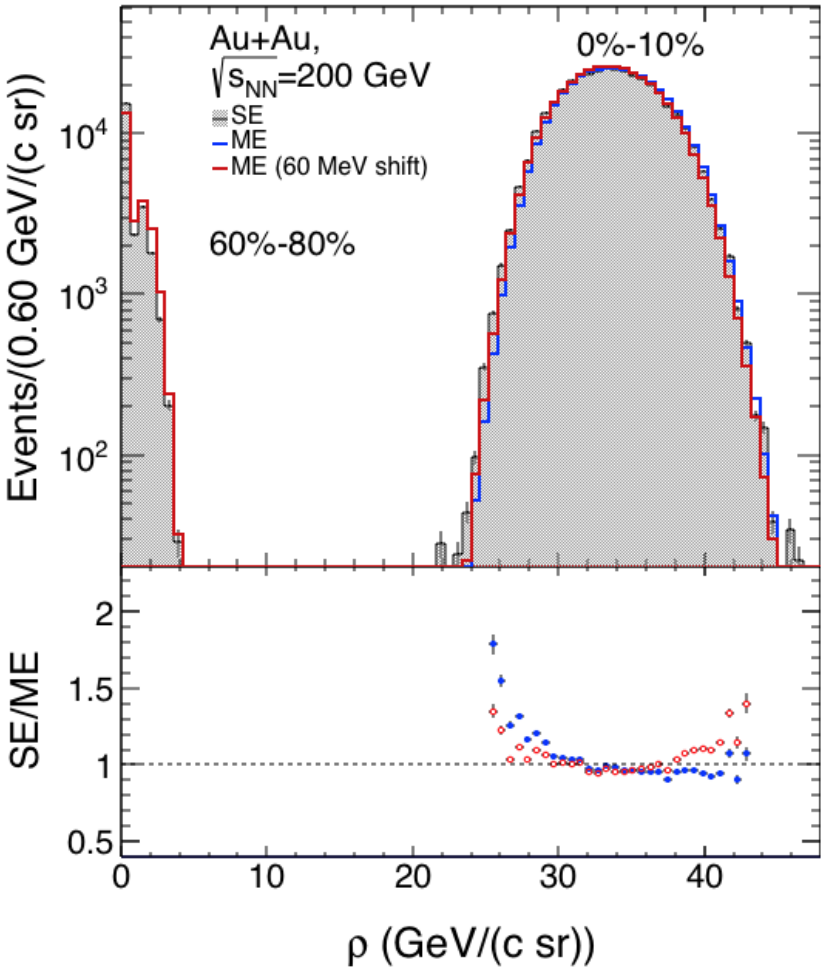
Radial modification is relatively independent of $p_T^{hard\ const}$

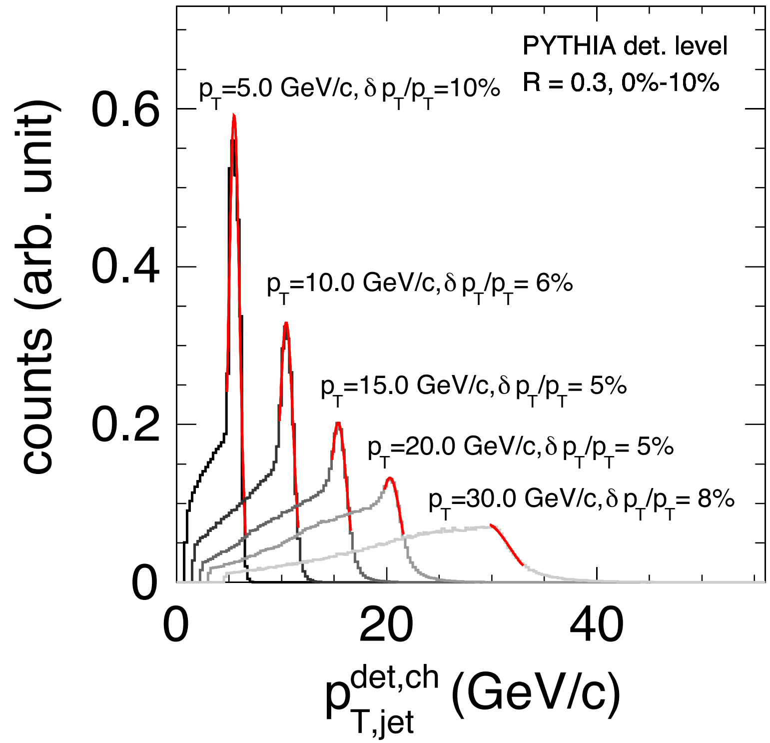
But can find combinations were lost energy recovered



Broadening of jet structure can be related to diffusion of medium-induced soft gluon radiation in QGP

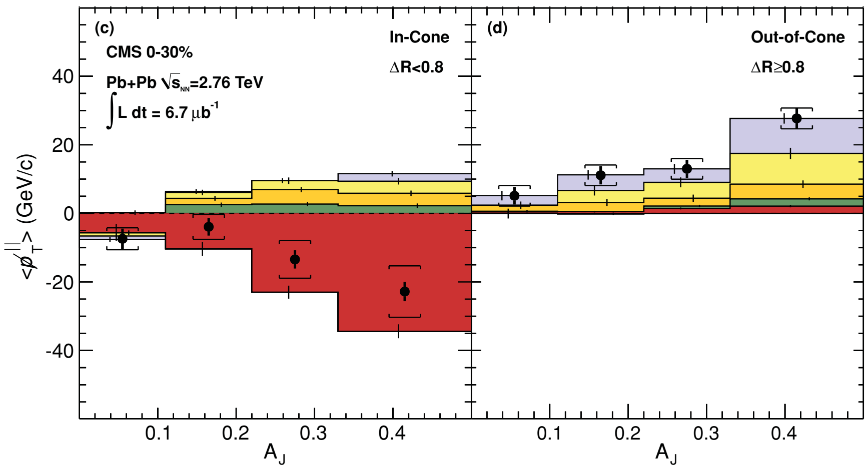
Rho and JES


Au+Au,
$\sqrt{s_{NN}}$=200 GeV
SE
ME
ME (60 MeV shift)
60%-80%
0%-10%
Events/(0.60 GeV/(c sr))
SE/ME
ρ (GeV/(c sr))


PYTHIA det. level
R = 0.3, 0%-10%
p_T=5.0 GeV/c, $\delta p_T/p_T$=10%
p_T=10.0 GeV/c, $\delta p_T/p_T$= 6%
p_T=15.0 GeV/c, $\delta p_T/p_T$= 5%
p_T=20.0 GeV/c, $\delta p_T/p_T$= 5%
p_T=30.0 GeV/c, $\delta p_T/p_T$= 8%
counts (arb. unit)
$p_{T,jet}^{det,ch}$ (GeV/c)

Discussion: RHIC vs LHC

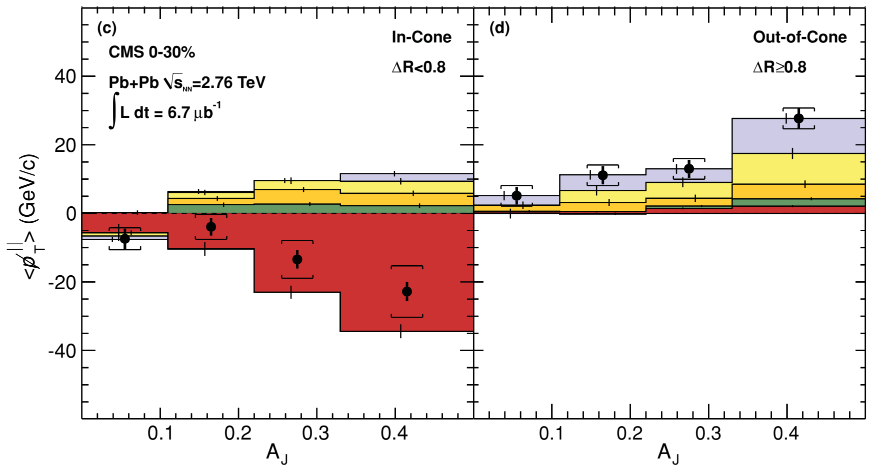
CMS, PRC ***84****, 024906 (2011)*



The momentum difference in the di-jets is balanced by low p_T particles at large angles relative to the away side jet axis

Discussion: RHIC vs LHC

*CMS, PRC **84**, 024906 (2011)*



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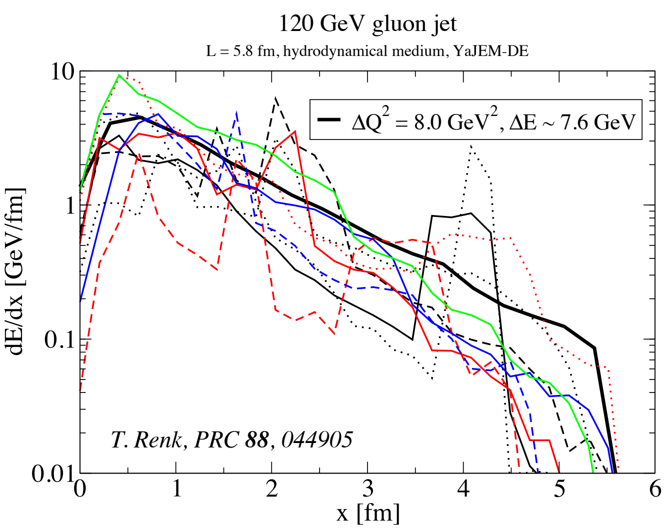
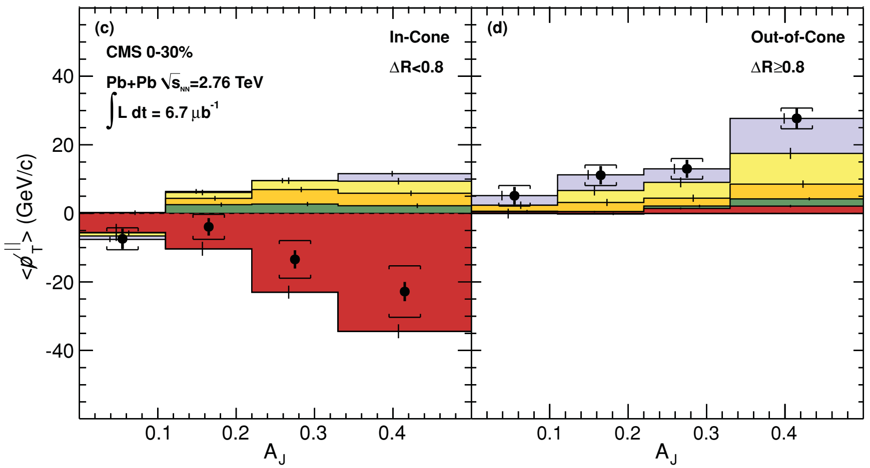


LHC:
Larger energy loss at early times
→ more diffusion in medium
→ larger angles

Discussion: RHIC vs LHC

CMS, PRC 84, 024906 (2011)



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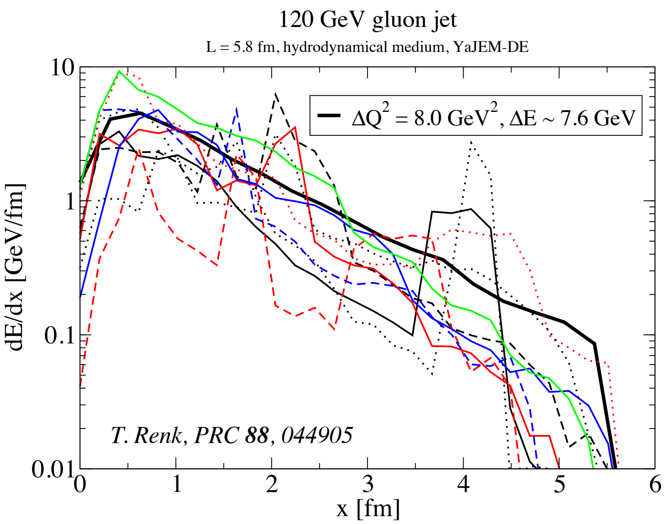
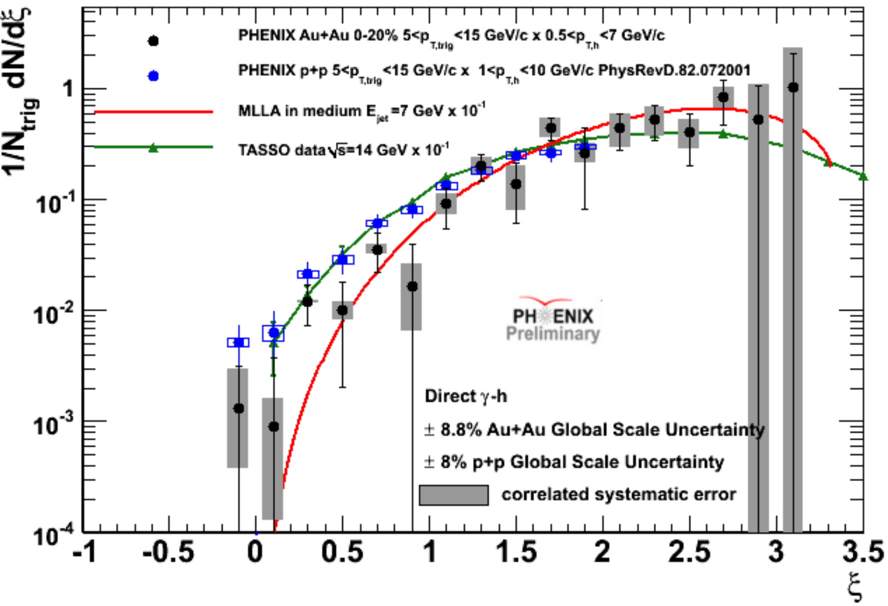


LHC:
Larger energy loss at early times
→ more diffusion in medium
→ larger angles

RHIC:
Quenched energy closer to initial parton/jet direction. Can utilize biases for systematic exploration.
→ (easier) to study soft gluon radiation

?γ-hadron

PRL ***111*****,** *032301 (2013)*

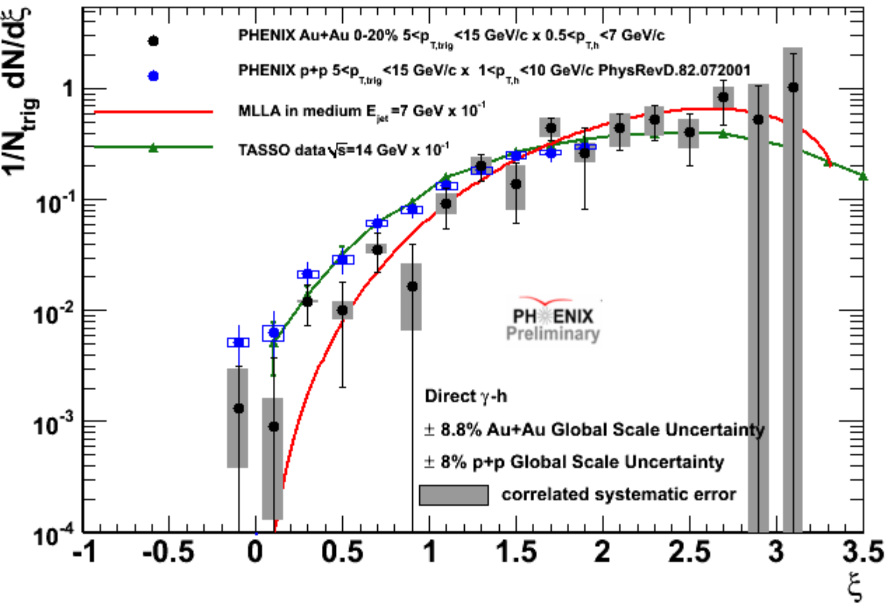


γ - Energy calibration

Unbiased recoil jet highly modified

γγ-hadron

*PRL **111**, 032301 (2013)*



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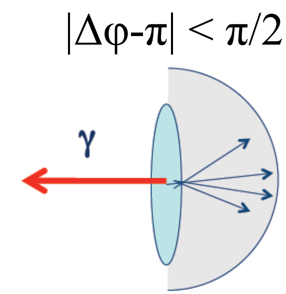
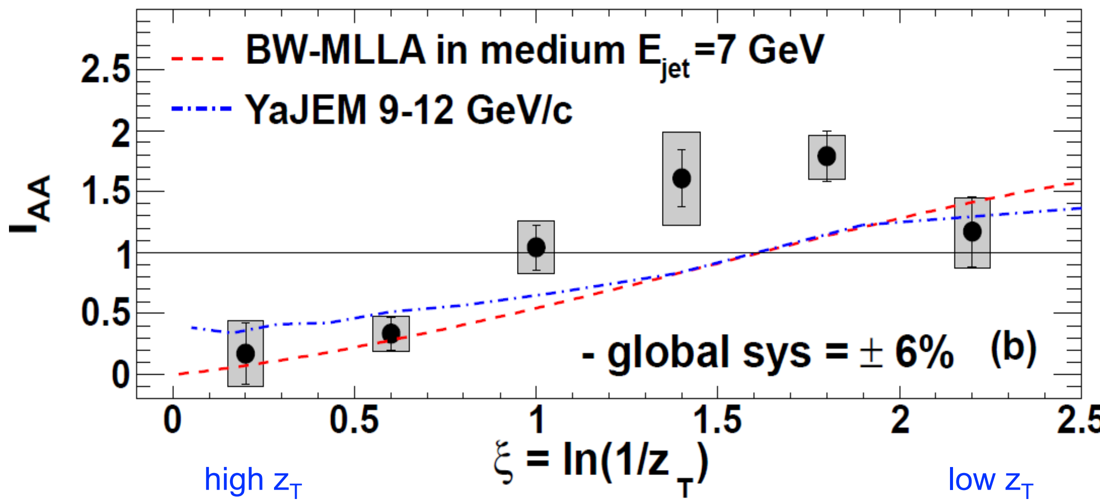


I_{AA} as function of "cone R"

E correlated to jet axis but at large angles and soft



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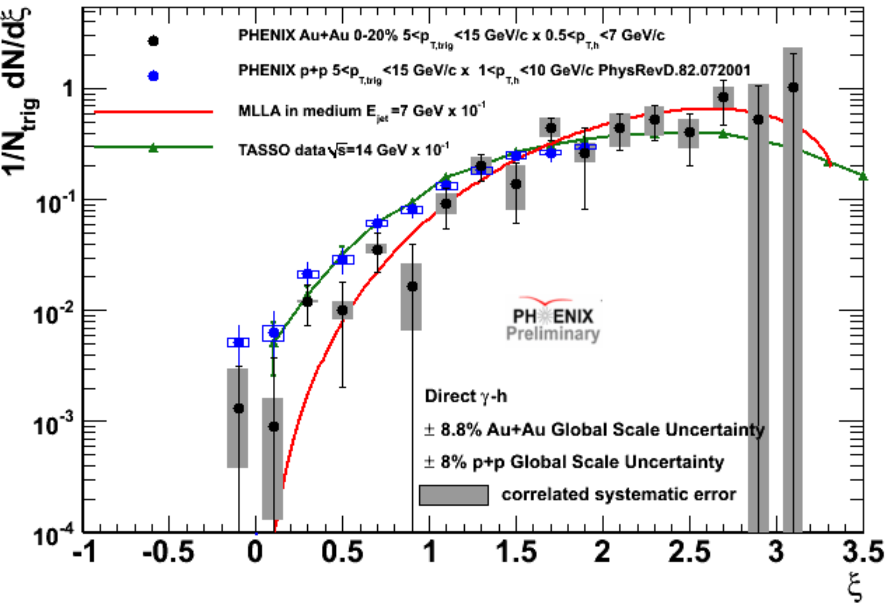

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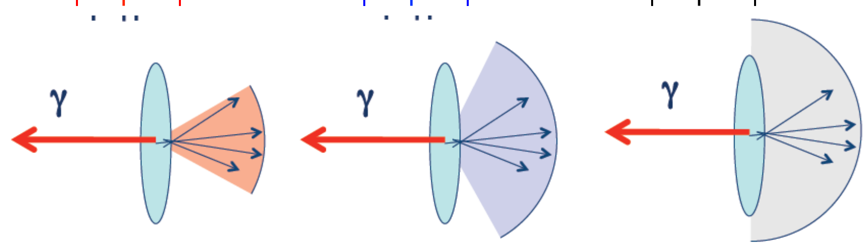

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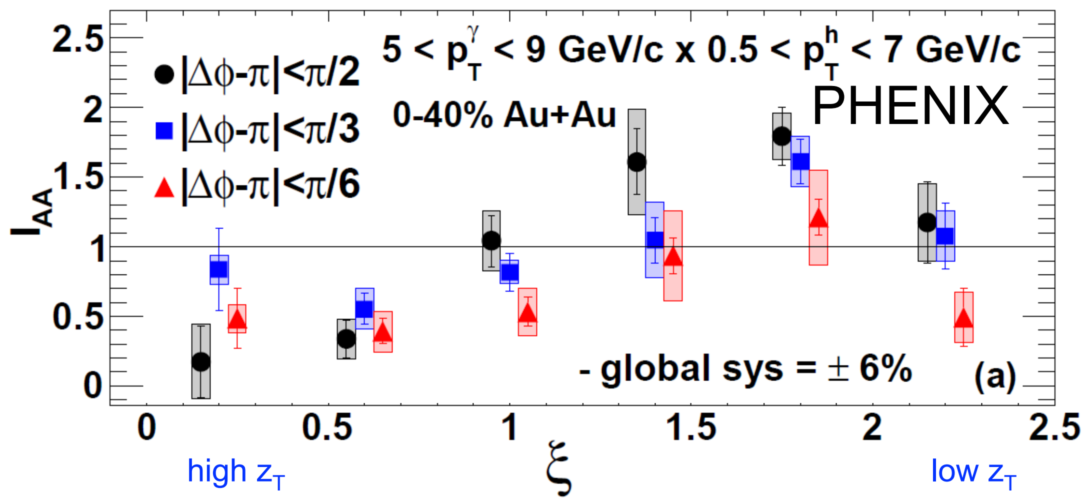
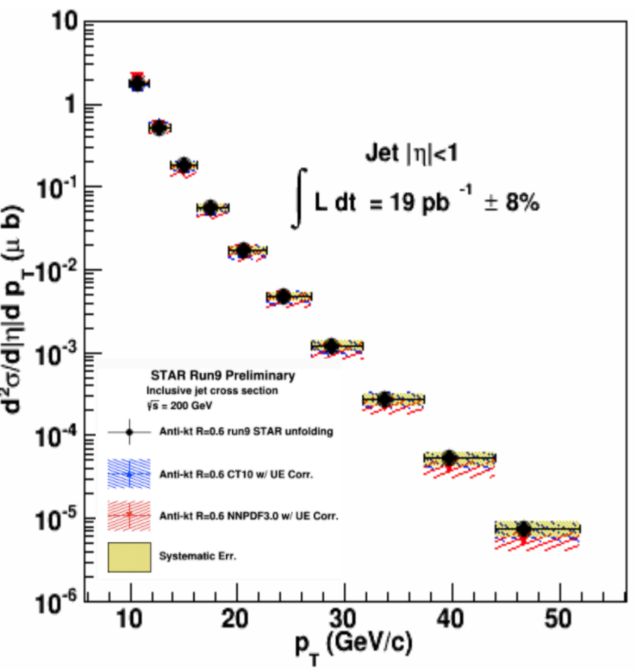


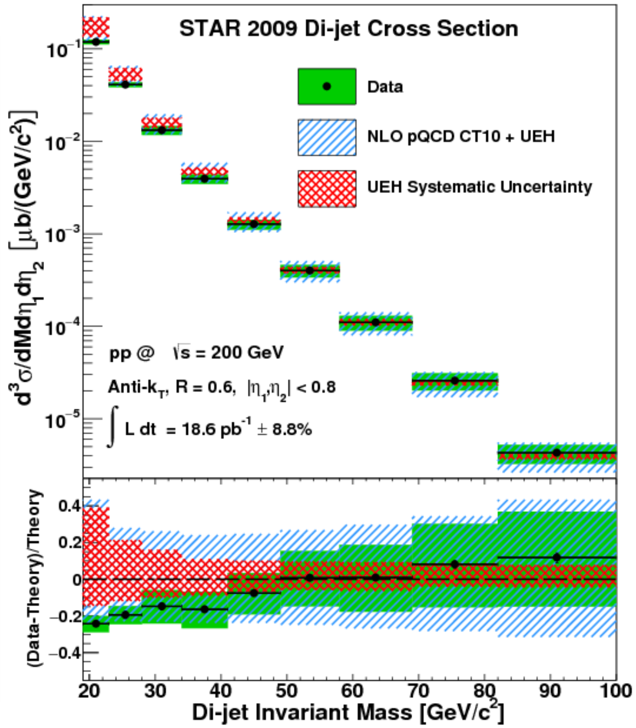
In narrow cone

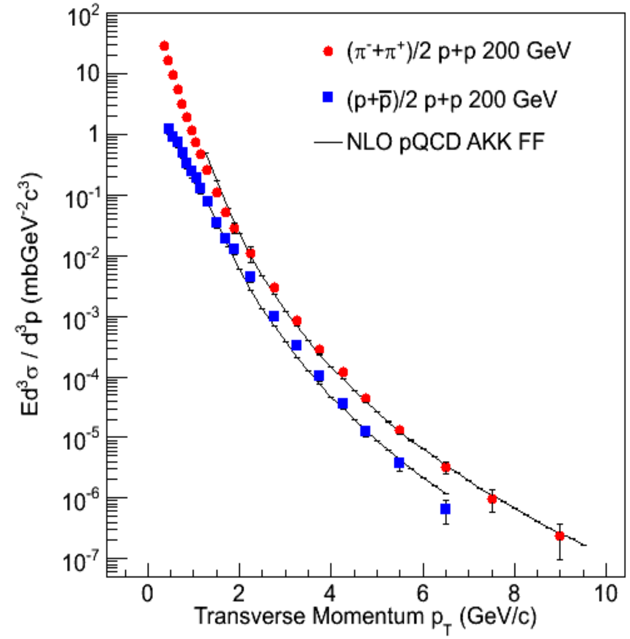
(|Δφ-π| < π/6 (R~0.5)):

high-z_T hadrons "lost", no corresponding "gain" at low z_T

High p_T at RHIC – a calibrated probe?







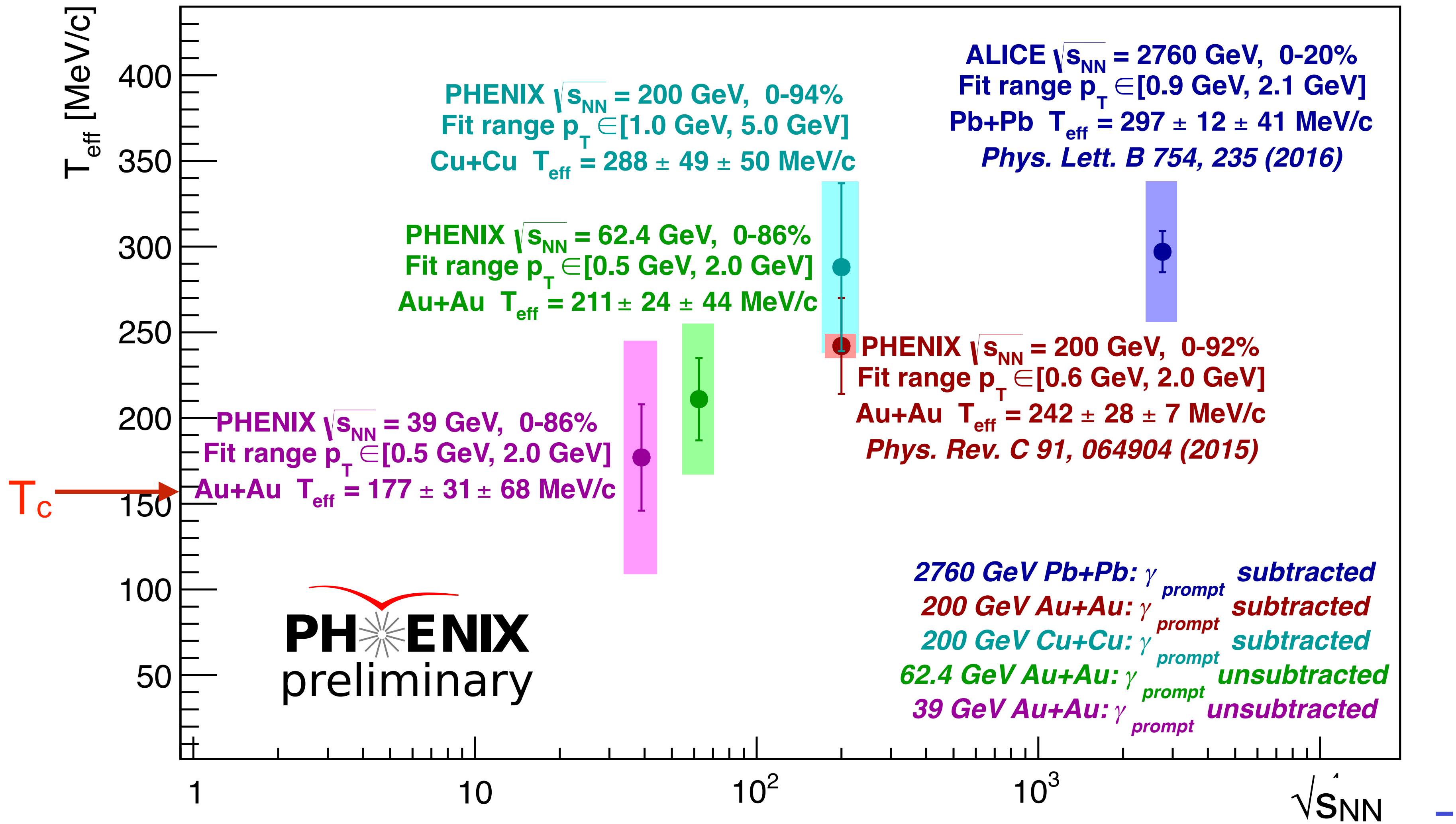
- Jet and di-jet cross-section in p+p is well described by NLO pQCD calculations over 6 orders of magnitude
- Minimum bias particle production in p+p also well modeled.

Jet and high p_T particle spectra well calculated by pQCD

STAR : PLB 637 (2006) 161, PRD 95 (2017) 7, 071103
S. Albino et al, NPB 725 (2005) 181

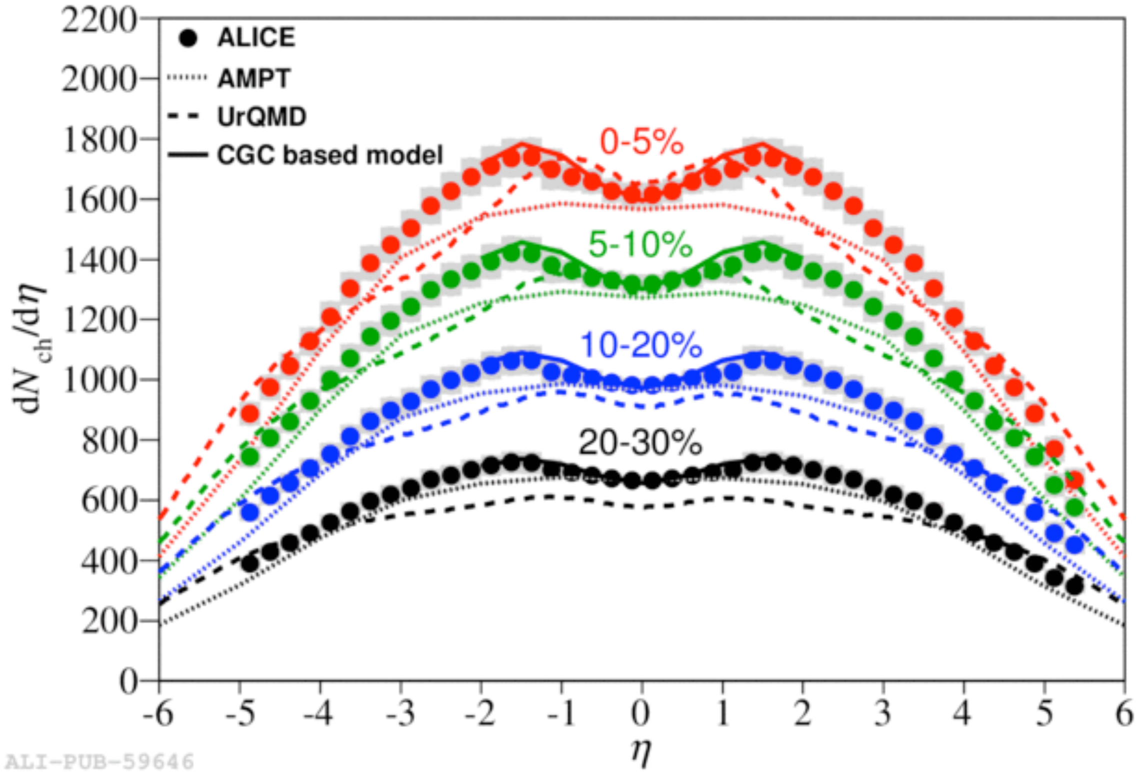
Early conditions: Temperature

Initial temperature well above T_c even at $\sqrt{s_{NN}}$ = 39 GeV



T from direct photon p_T spectra

Initial Conditions: Energy density



In central events:

$dN_{ch}/d\eta \sim 1600$

$\langle p_T \rangle \sim 650$ MeV

$R \sim 7$ fm

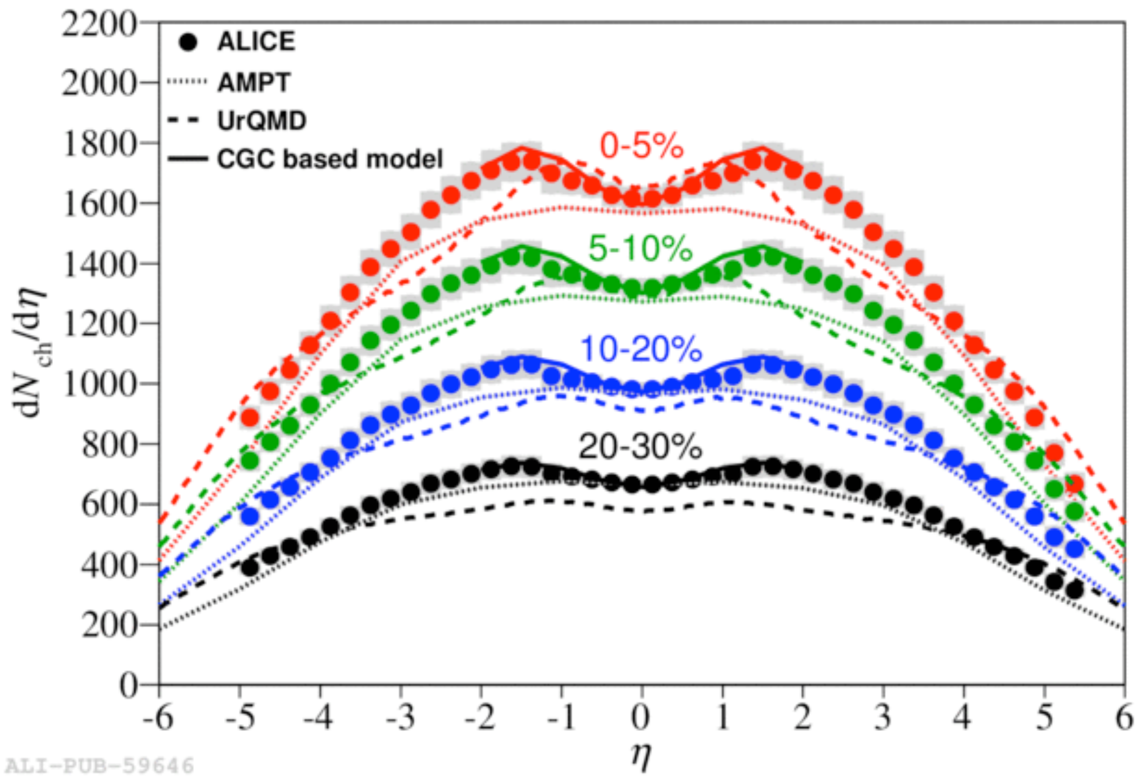
$\tau_0 \sim 1$fm

$$\epsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{3}{2} \frac{dN_{ch}}{d\eta} \langle p_T \rangle$$

Radius of medium

Time it takes to thermalize system

Initial Conditions: Energy density



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Radius of medium

Time it takes to thermalize system

$\varepsilon_{BJ} \approx 10$ GeV/fm^3
~75 times normal nuclear density
~ 15 times > $\varepsilon_{critical}$ (lattice QCD)

10 GeV/fm³. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy (1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060J}{BTU} \times \frac{1eV}{1.6 \times 10^{-19} J} = 6.6 \times 10^{38} eV$$

At 10 GeV/fm³, this would fit in a volume of:

$$\frac{6.6 \times 10^{38}}{10 \times 10^{9}} = 6.6 \times 10^{28} fm^{3}$$

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Or, in other words, in a box of the following dimensions:

$$\sqrt[3]{6.6 \times 10^{28} fm^3} = 4 \times 10^{9} fm = 4 \mu m$$

A human hair