Relativistic Heavy Ions II
Studying the QGP

2016 Hadron Collider Physics Summer School

Fermi Lab

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Outline:

Defining a Calibrated Probe

High p_T Phenomena

News from the LHC

Recap of yesterday's lecture

We create a QGP in the laboratory in HI collisions
it is

fantastically hot

and has an

incredible energy density.

It

exists for only an instant

yet shows

many signs of being in equilibrium.

It flows like a

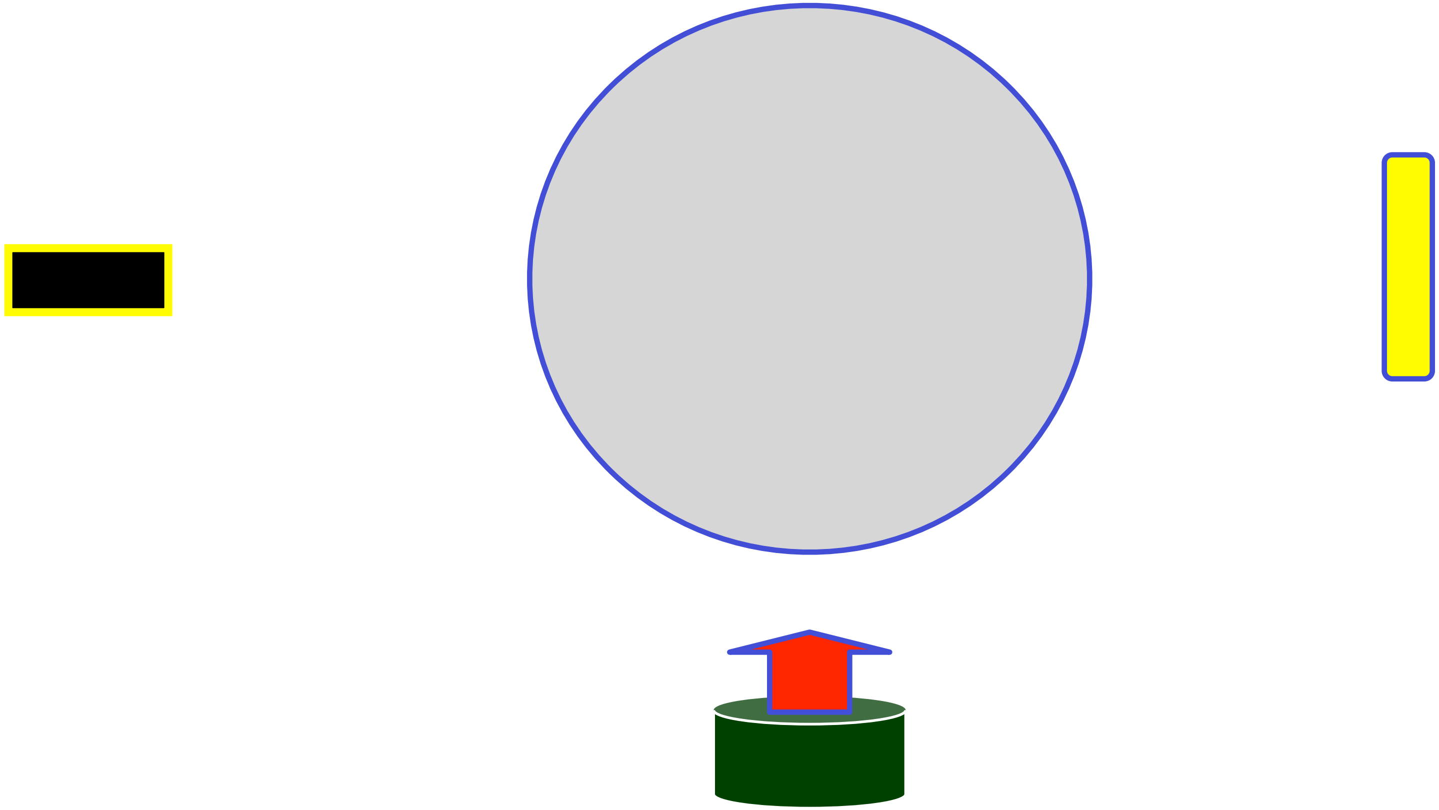
nearly "perfect" fluid

and appears to have

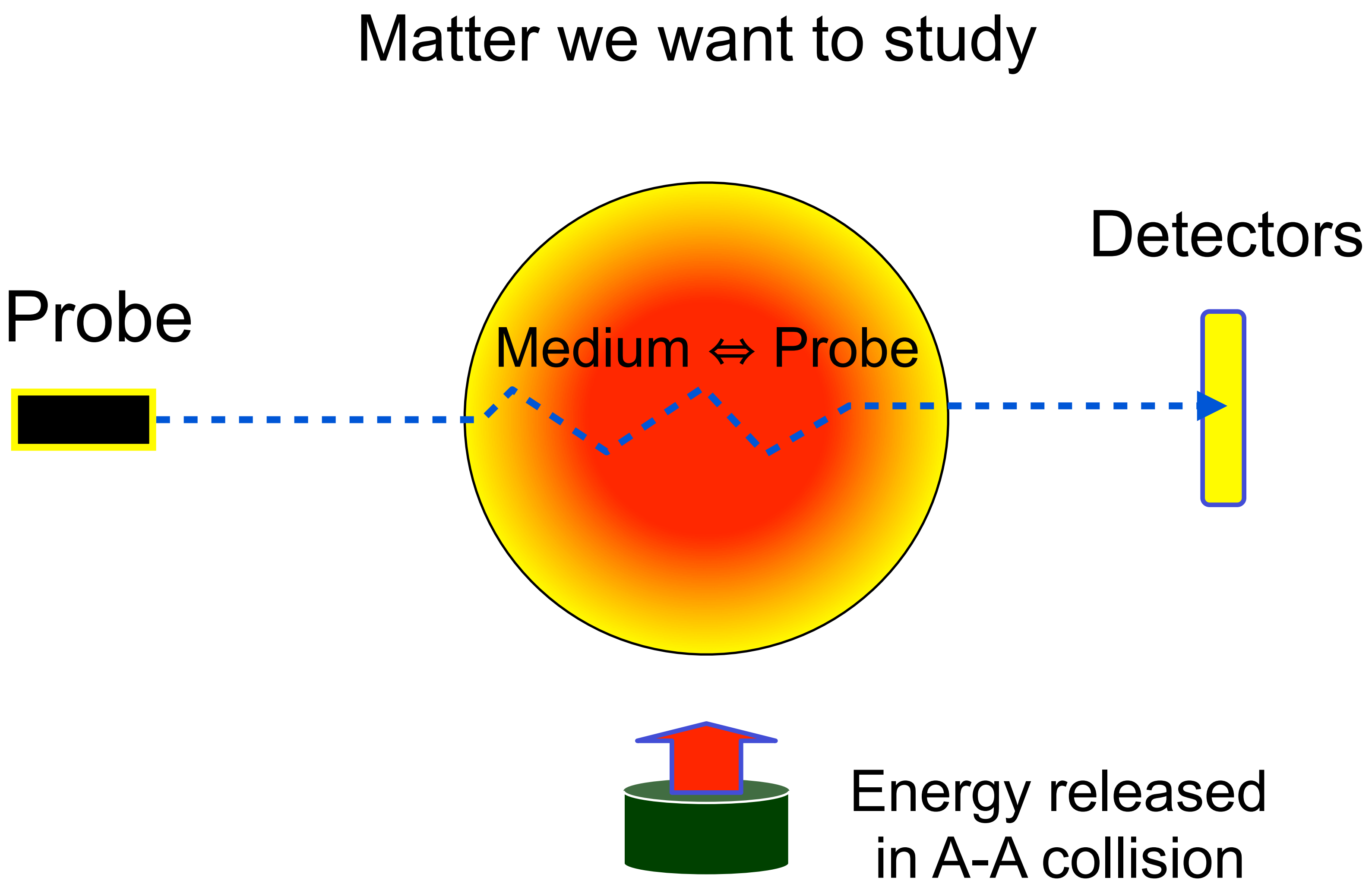
quark and gluon degrees of freedom

Defining a probe - Hard processes

Matter we want to study



Defining a probe - Hard processes



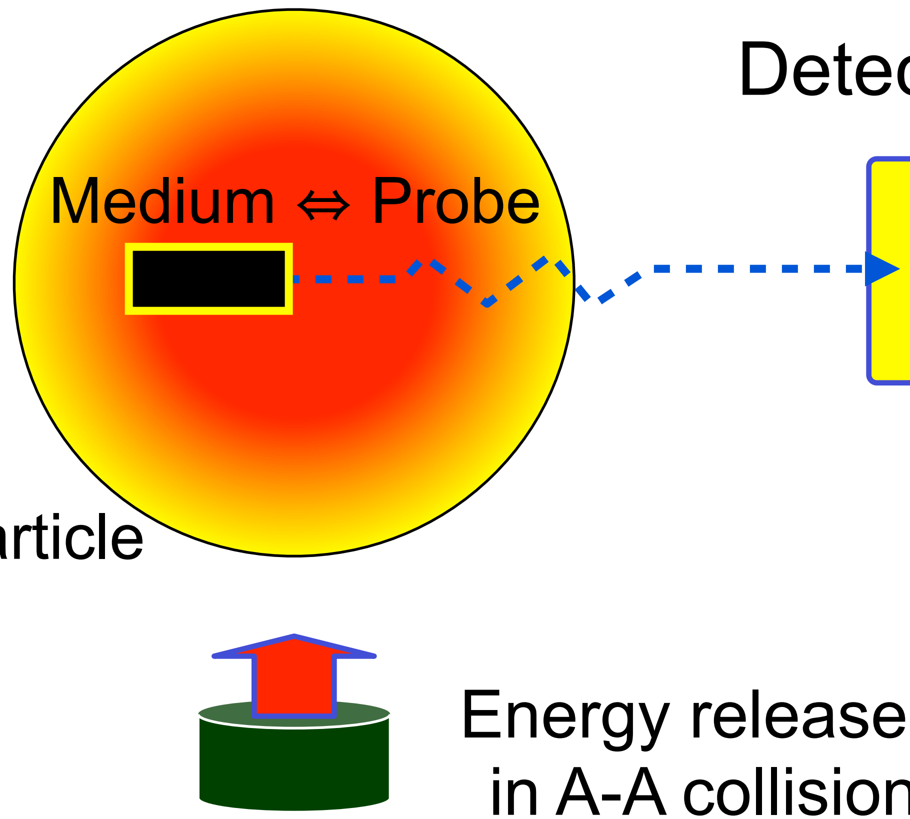
Defining a probe - Hard processes

Matter we want to study

Self-generated &
calibrated probes

- Photons
- Partons (q, g)
- High momentum particle

Detectors



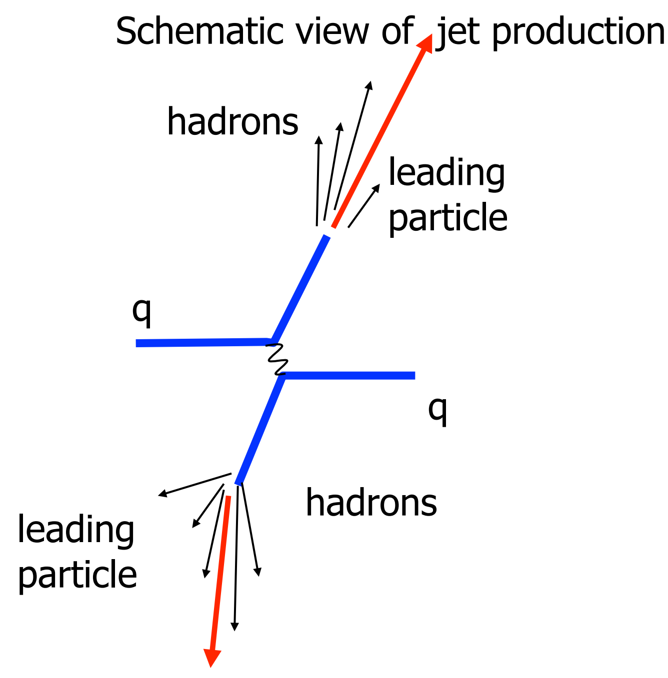
Energy released
in A-A collision

Using "hard" particles as probes

'Hard' processes have a large scale in calculation $\rightarrow$ pQCD applicable:

- high momentum transfer Q^2
- high transverse momentum p_T
- high 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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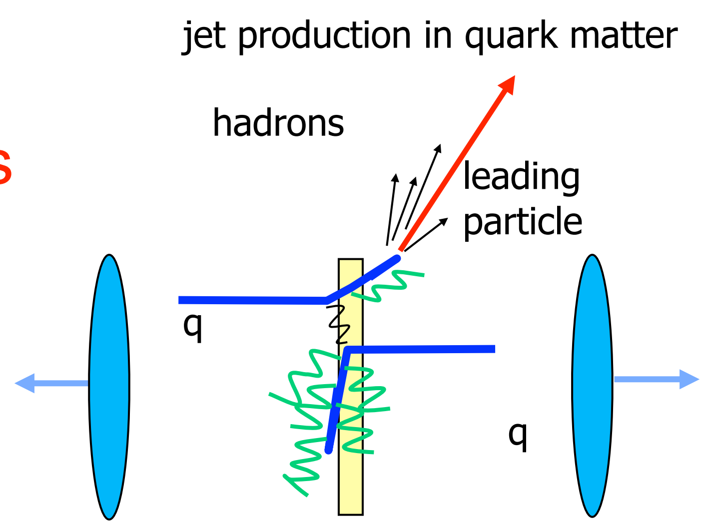
Early production in parton-parton scatterings with large Q^2

Direct interaction with partonic phases of the reaction

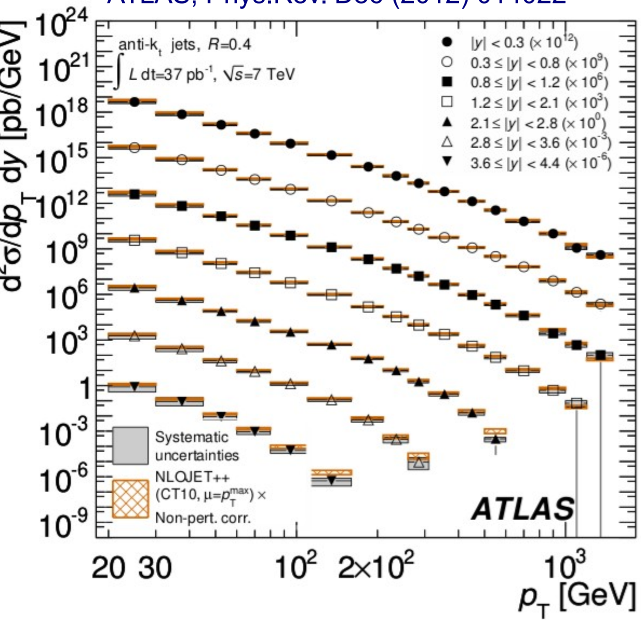
i.e. a calibrated probe

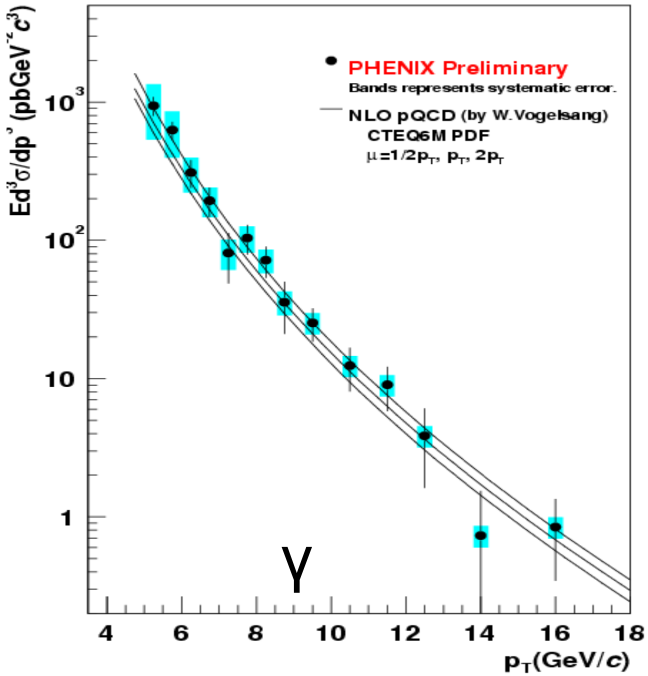


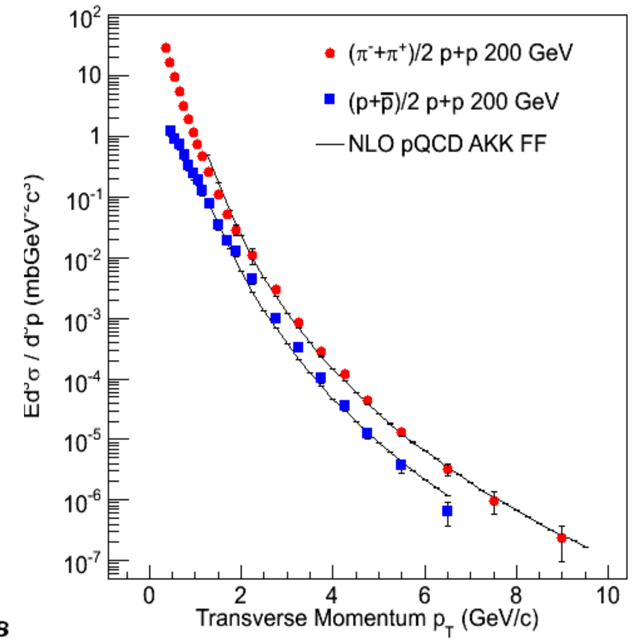
Look for attenuation/absorption of probe

High p_T production – a calibrated probe

ATLAS, Phys.Rev. D86 (2012) 014022







STAR : PLB 637 (2006) 161

S. Albino et al, NPB 725 (2005) 181

- Jet cross-section in p-p is well described by NLO pQCD calculations over many orders of magnitude at RHIC and LHC
- Minimum bias γ production in p-p well modeled
- Minimum bias particle production in p-p also well modeled.

Jet and particle spectra well calculated by pQCD

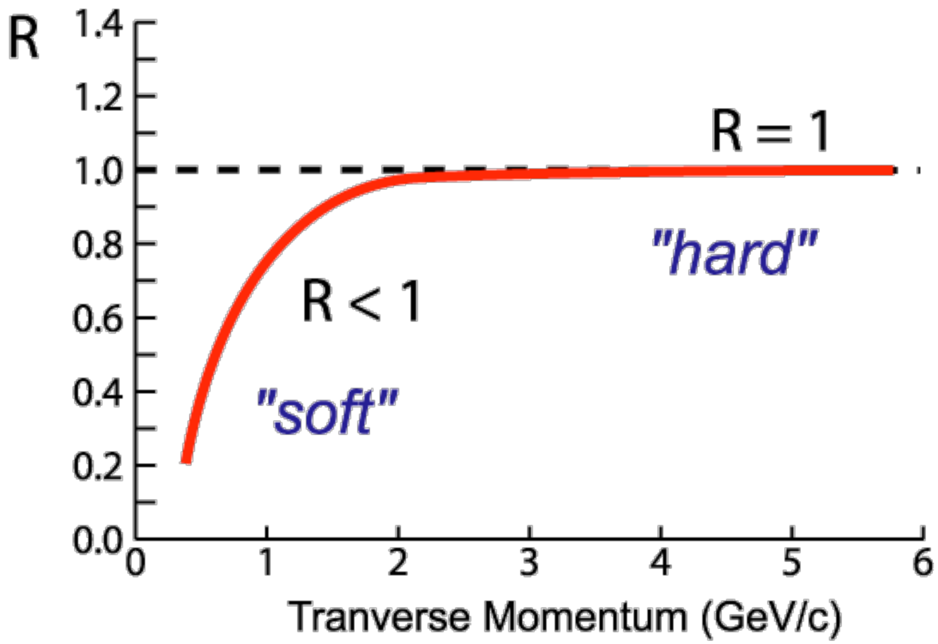
Looking for attenuation/absorption

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

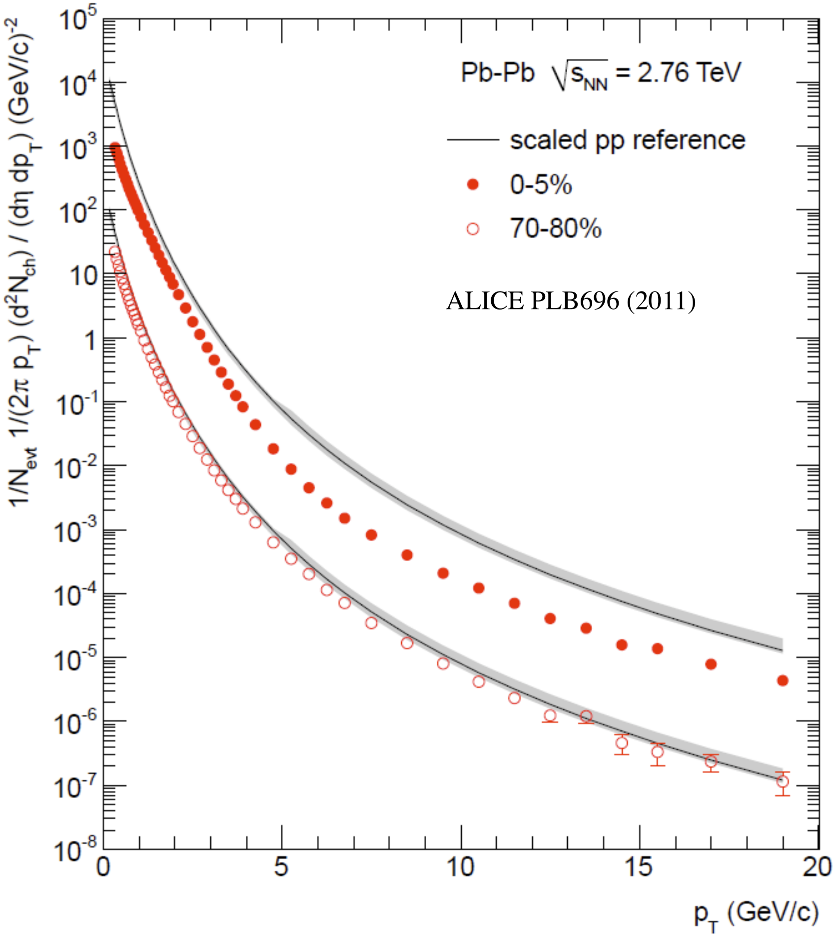


No "Effect":

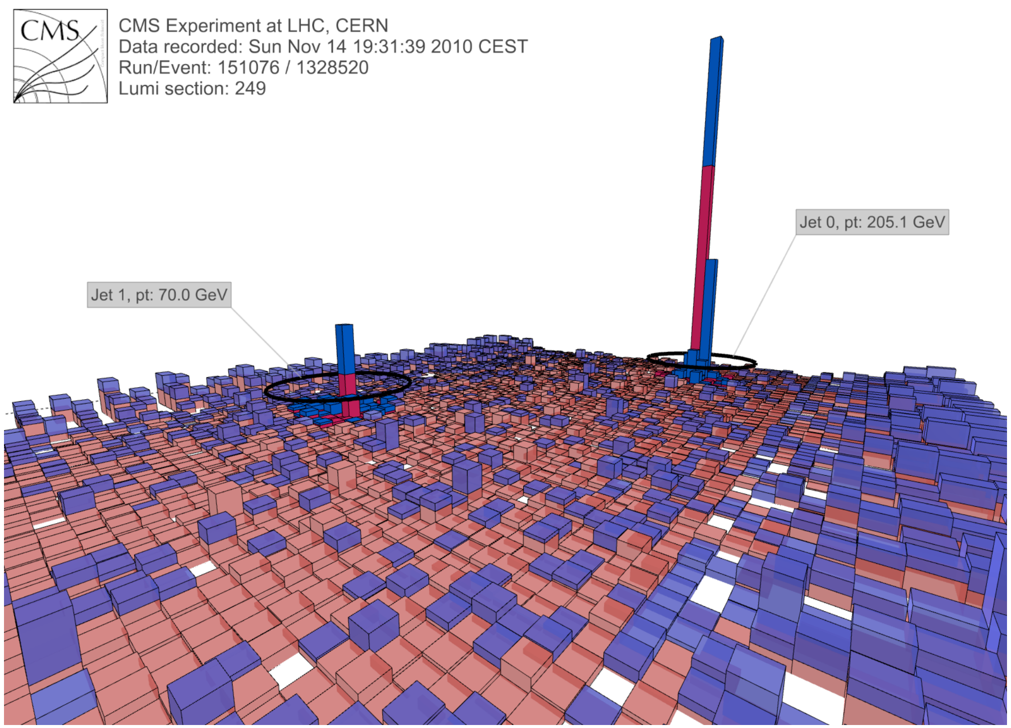
- R < 1 at small momenta - production from thermal bath
- R = 1 at higher momenta where hard processes dominate

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

Hard process - high p_T



Clear shape change at high p_T for central collisions



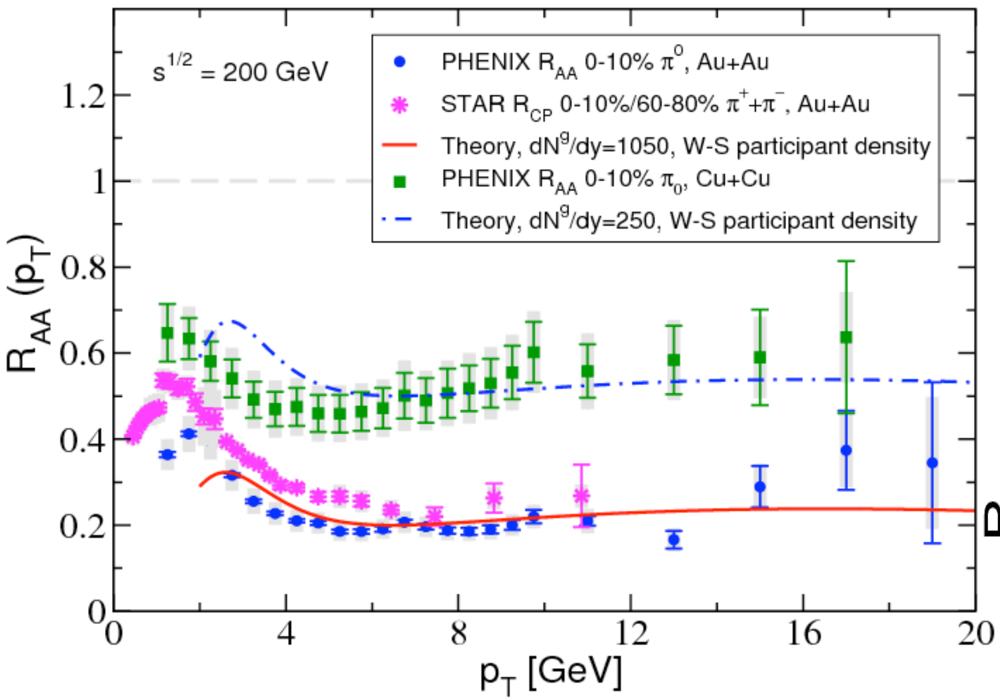
Even visible by eye in event displays at LHC

p-p reference:

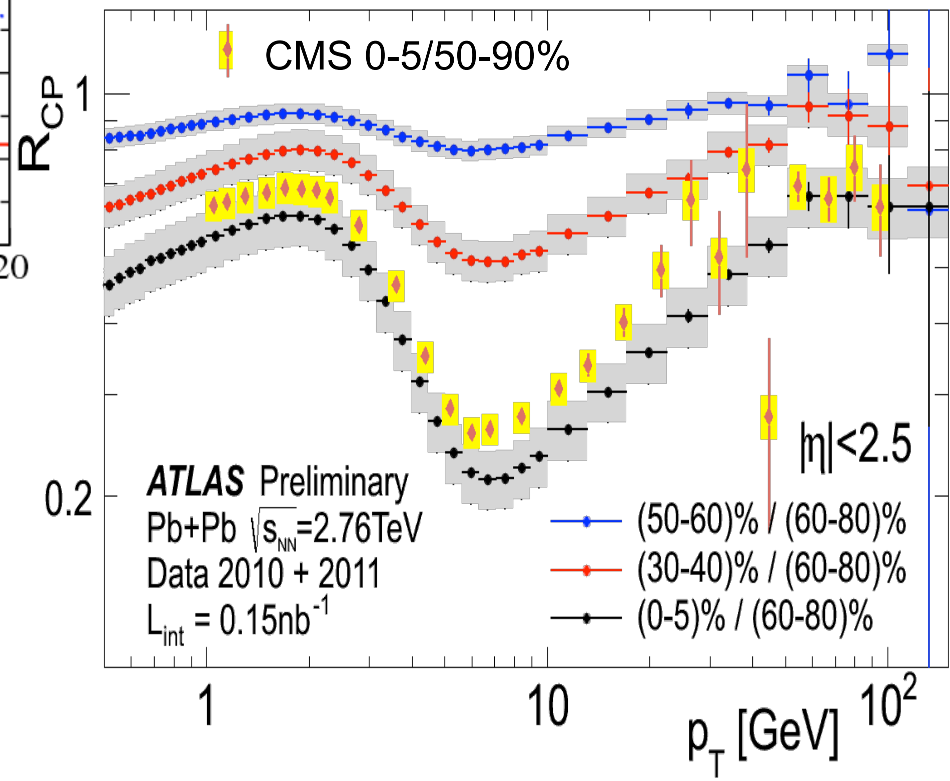
Interpolation of 0.9 and 7 TeV data

7 TeV data scaled by NLO QCD calc.

Strong suppression of high p_T particles



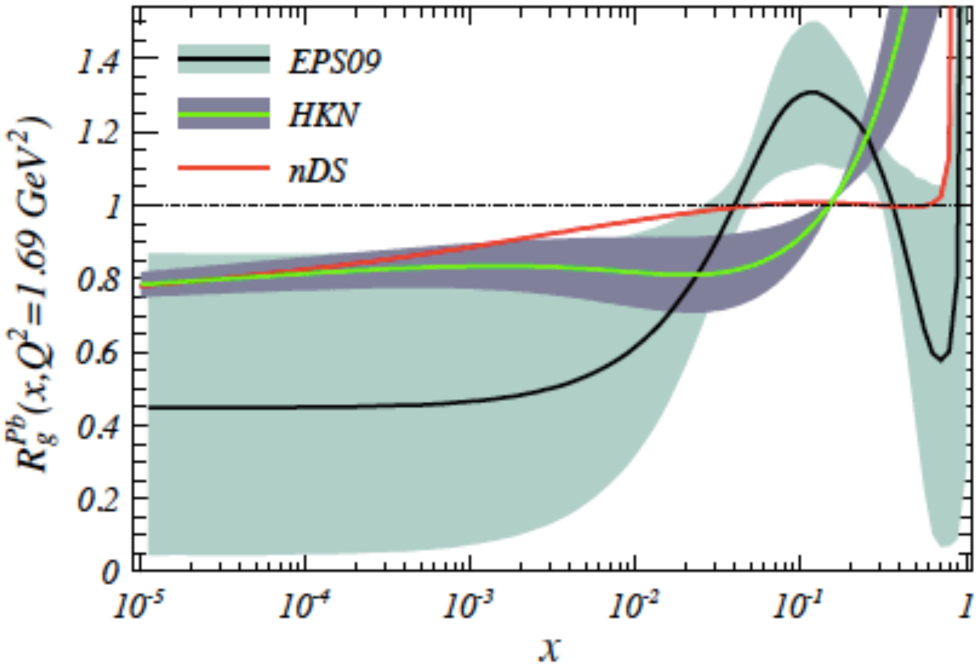
Both quarks and gluons strongly coupled to the medium



High p_T hadrons hadronize
at RHIC: from quarks
at LHC: from gluons
(larger color charge!)

From p-p to A-A: what changed?

$$\sigma_{AA\to jet} \propto f_{a/\mathrm{p}}(x_a,Q^2)\otimes f_{b/\mathrm{p}}(x_b,Q^2)\otimes\sigma^{ab\to c}\otimes D_{c\to c'\to jet+X}$$



Nuclear PDF (nPDF)
- different from free nucleon
  - (anti)Shadowing
  - Large uncertainty at small and large x
- Check effect using pA collisions (CNM) take it into account when interpreting the HI results

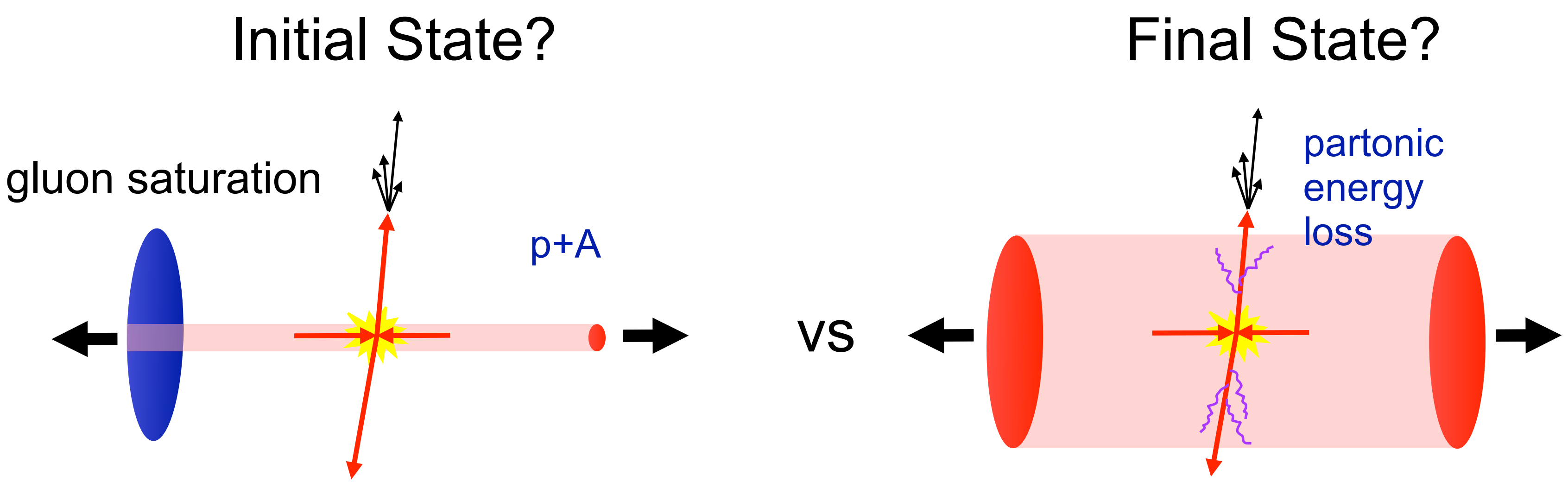
Hard scattering: unchanged since it happens before the medium is formed
- Factorization: immune from the changes in PDF

Fragmentation function

Initial or final state effects?

- A clear difference between p-p and A-A observed:

  Caused by initial state (quark/gluon shadowing) or final state (energy loss in plasma) effects?



- To test need collisions where no final state effects due to plasma but initial nuclear state effects present:

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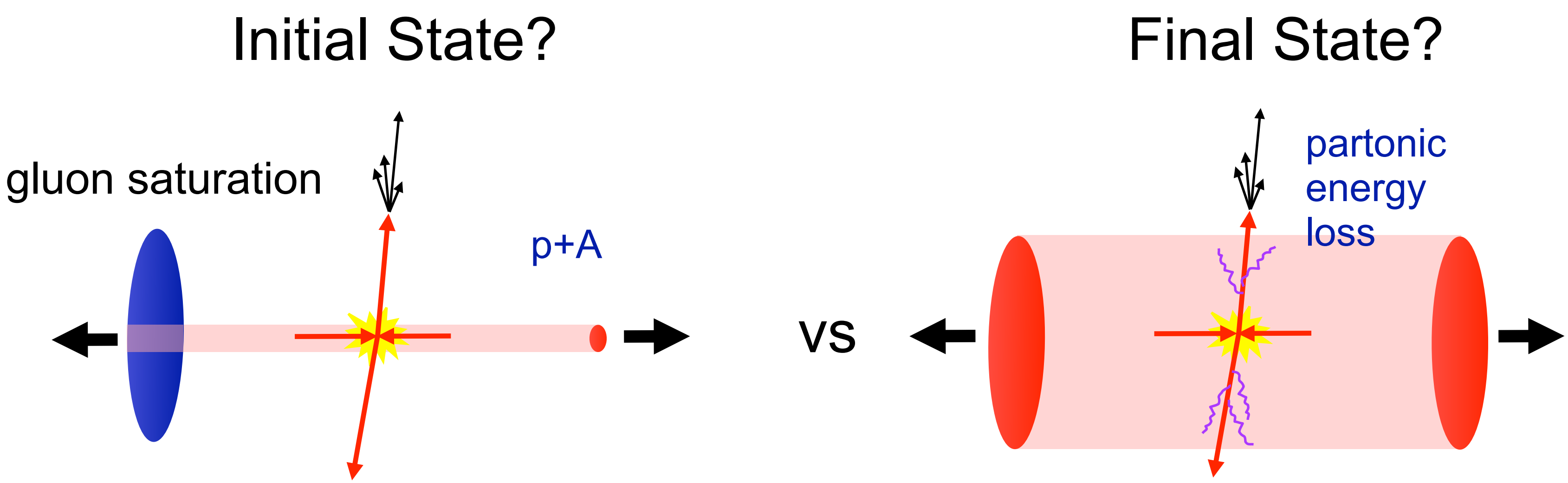

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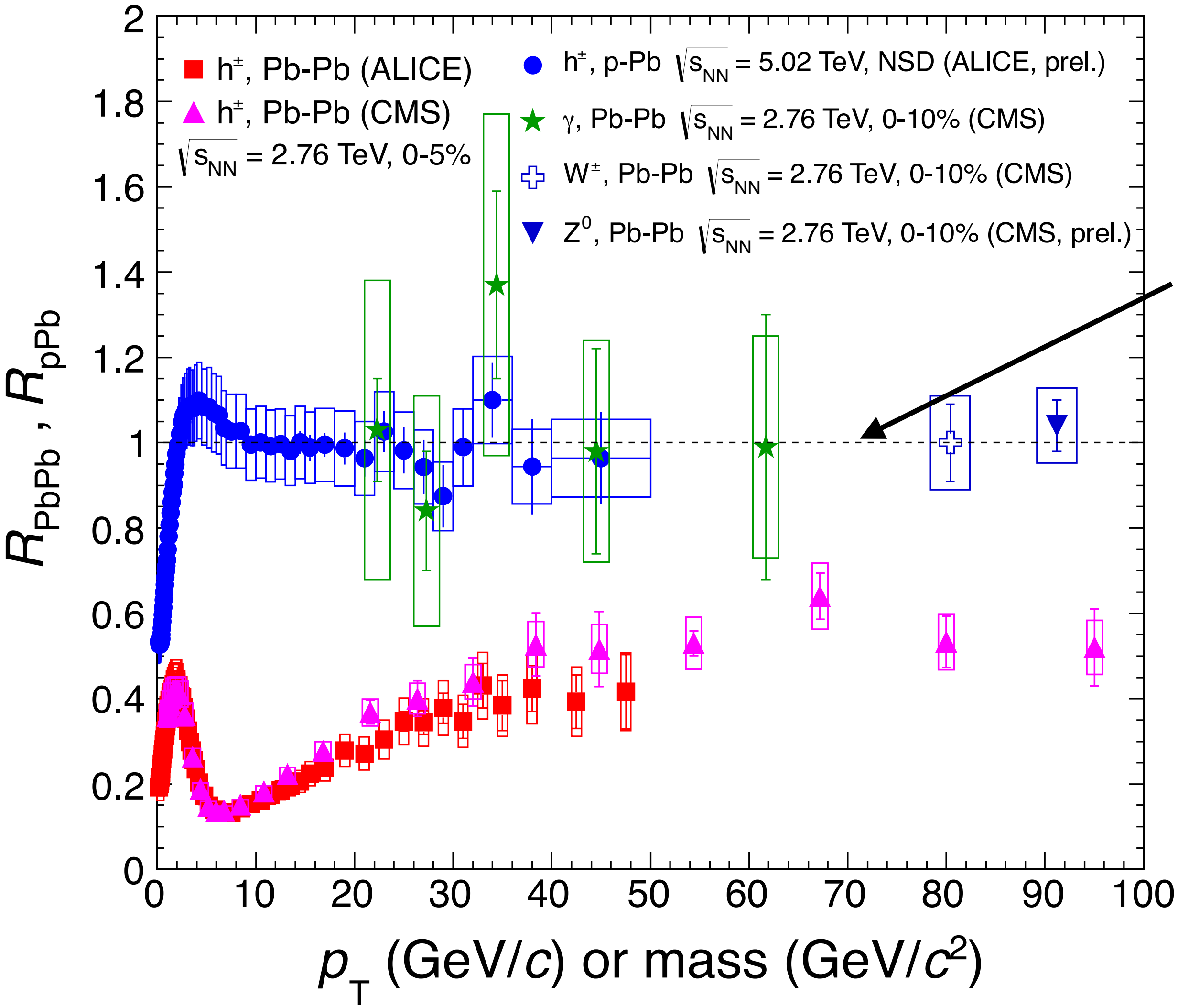
Use p-A (d-A)

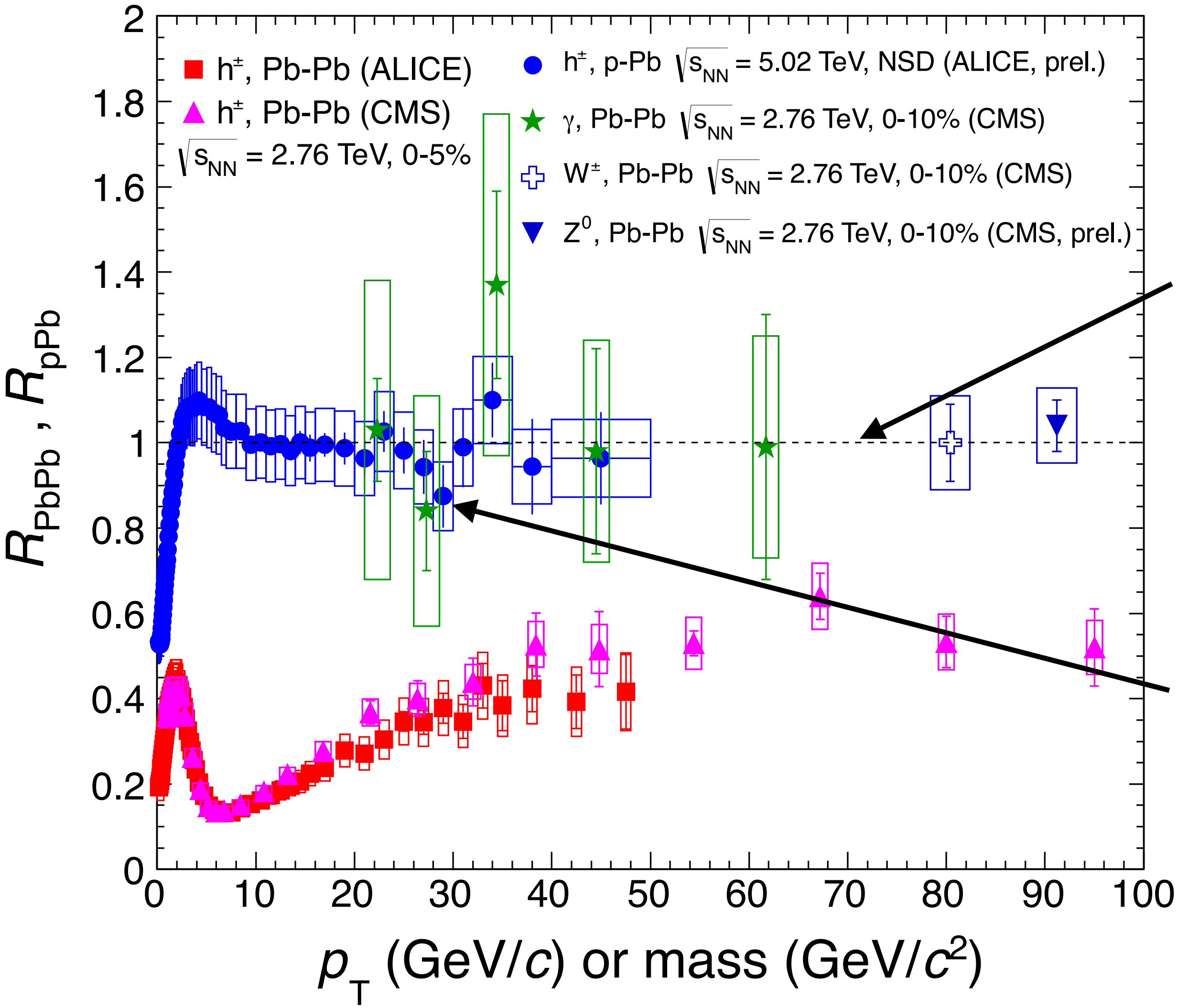
Sanity checks



Colorless objects should not interact with colored QGP

show no suppression

Sanity checks



Colorless objects should not interact with colored QGP

show no suppression

Minimum p-Pb collisions don't form QGP

R_{pPb} shows no suppression

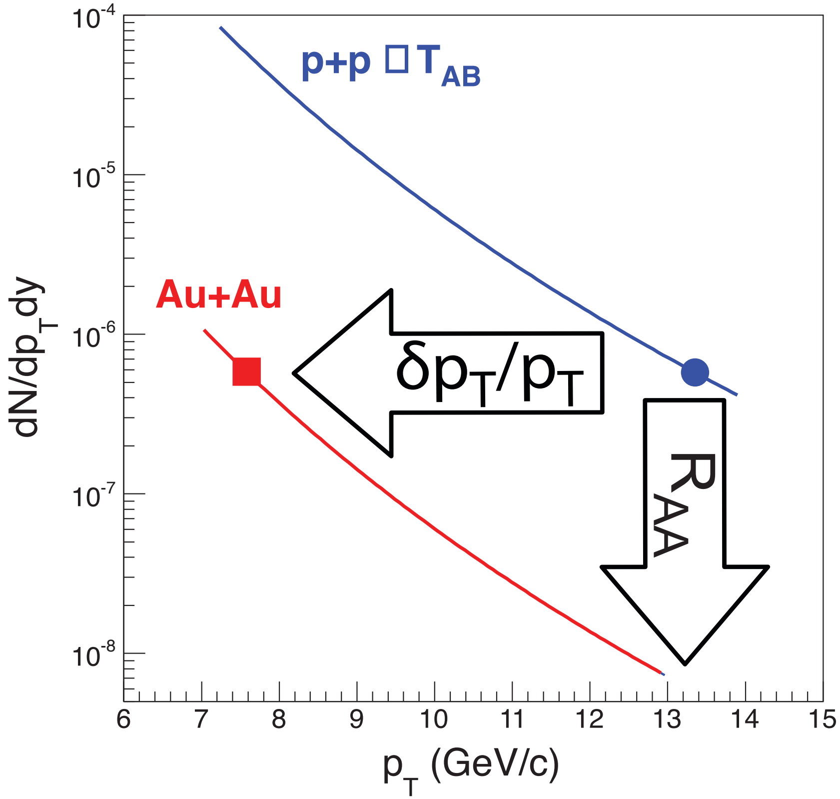
Suppression not seen where suppression shouldn't occur

Is it E_{loss} or absorption?

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)

Is it E_{loss} or absorption?

Measure fractional momentum loss

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

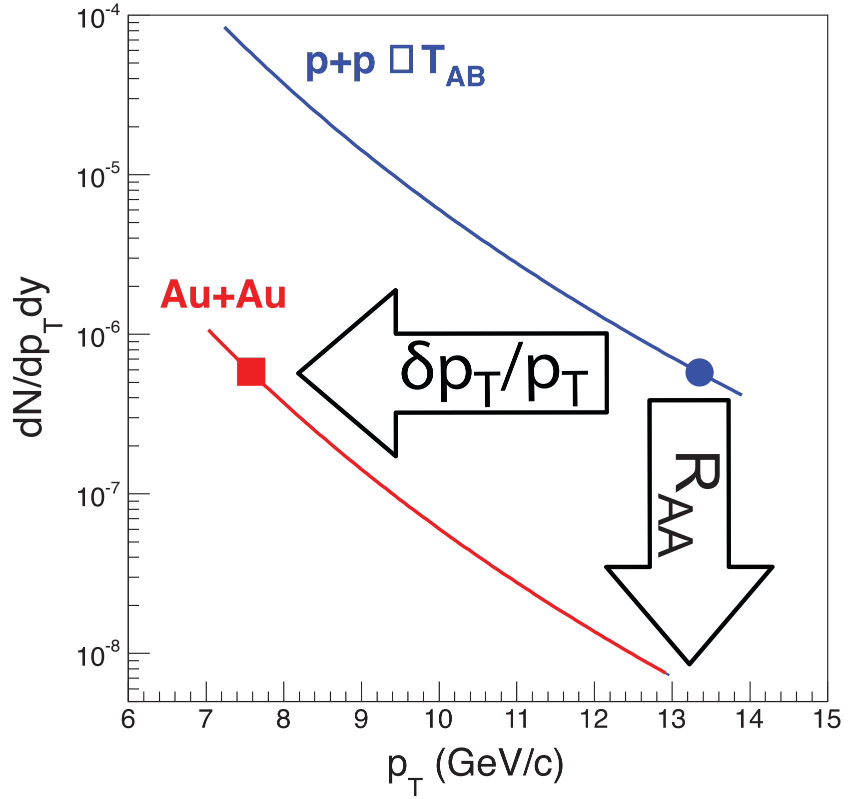
$R_{AA,0.200} \sim R_{AA,2.76}$

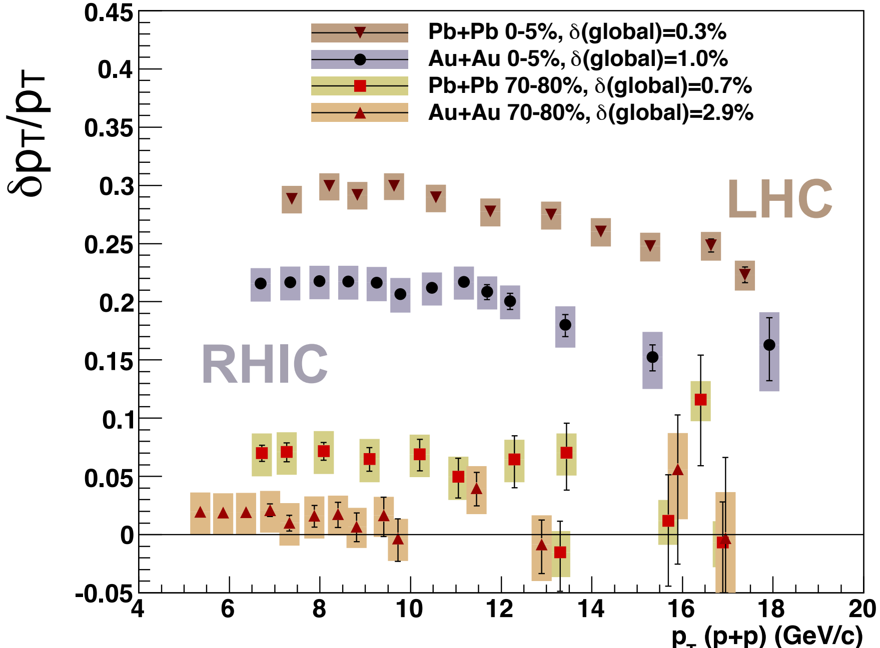
but

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

and

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





PRC 87, 034911 (2013)

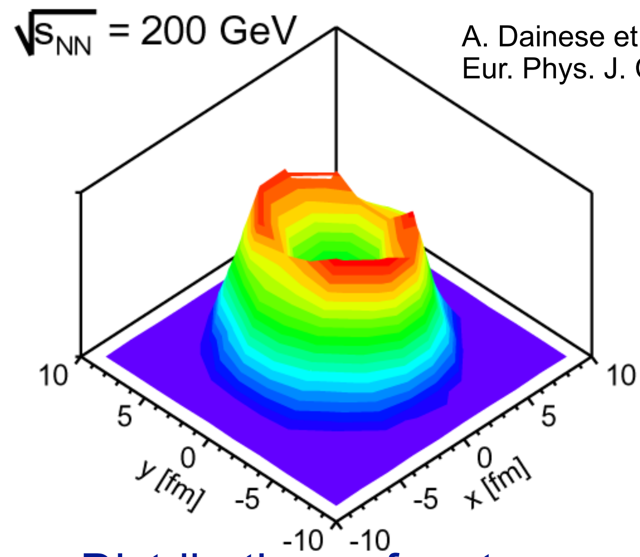
QGP at LHC and RHIC acts differently on hard partons

Smaller coupling at LHC?

Need to look in more detail

The limitations of R_{AA}

Insensitivity due to surface emission:



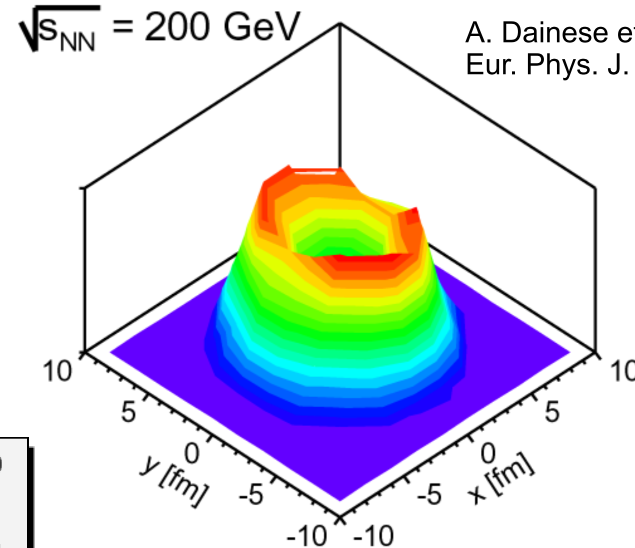
A. Dainese et al., Eur. Phys. J. C38(2005) 461

Distributions of parton production points in the transverse plane

The limitations of R_{AA}

Insensitivity due to surface emission:

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



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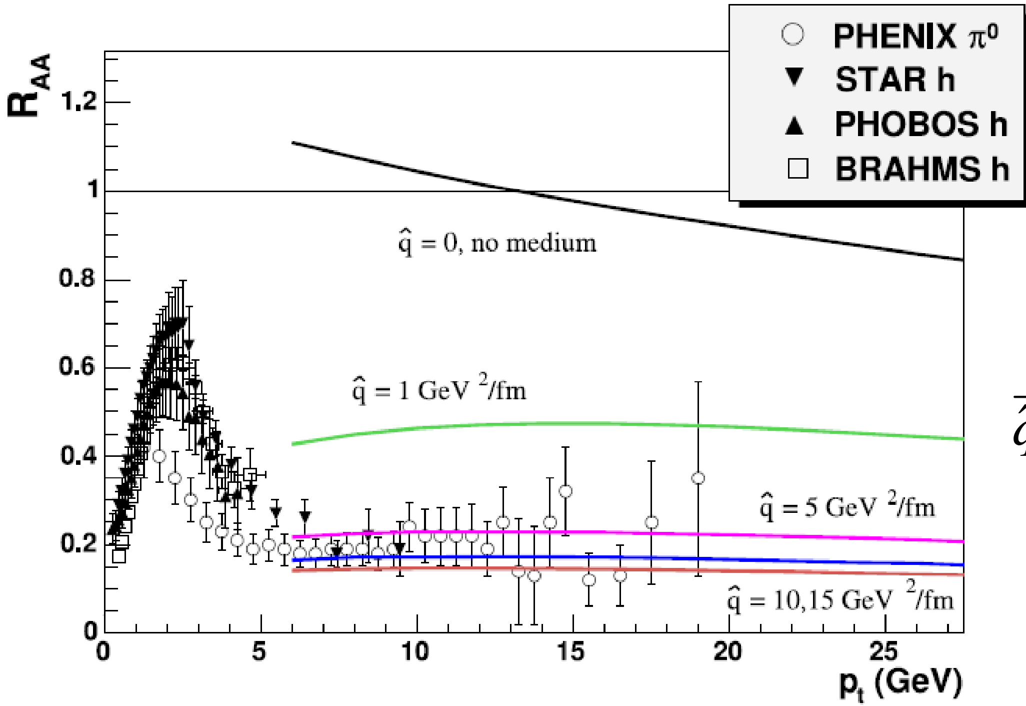

[Eskola, Honkanen, Salgado, Wiedemann (2004)]

Rough correspondence:

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

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

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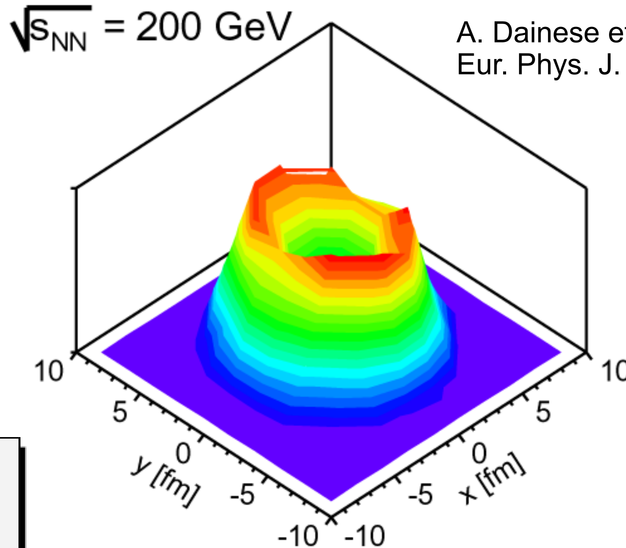

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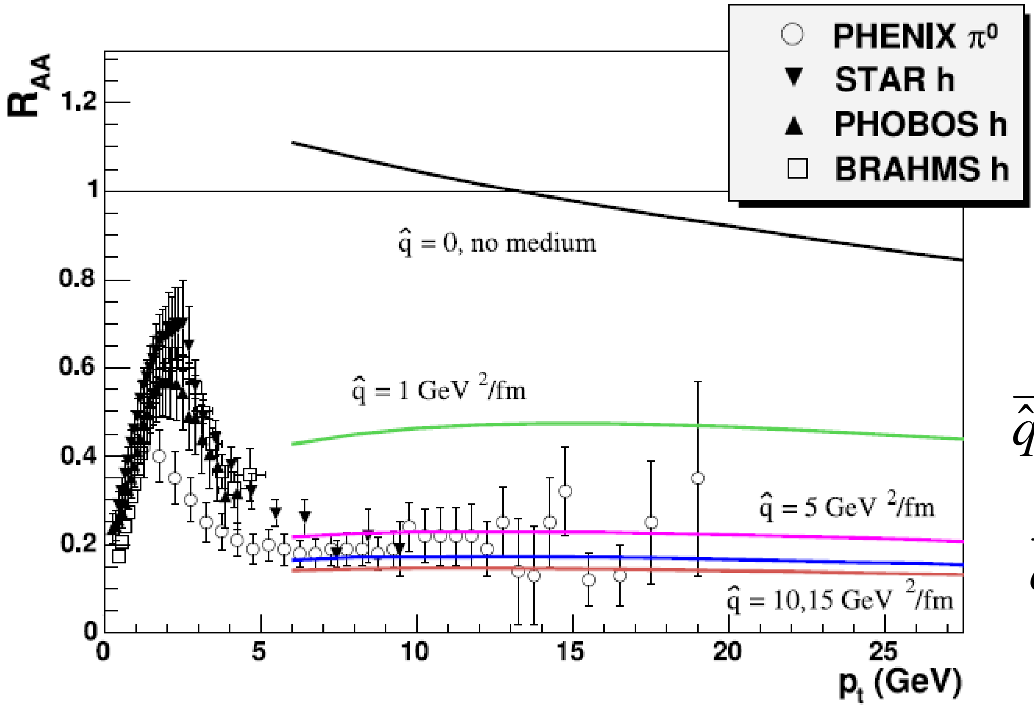

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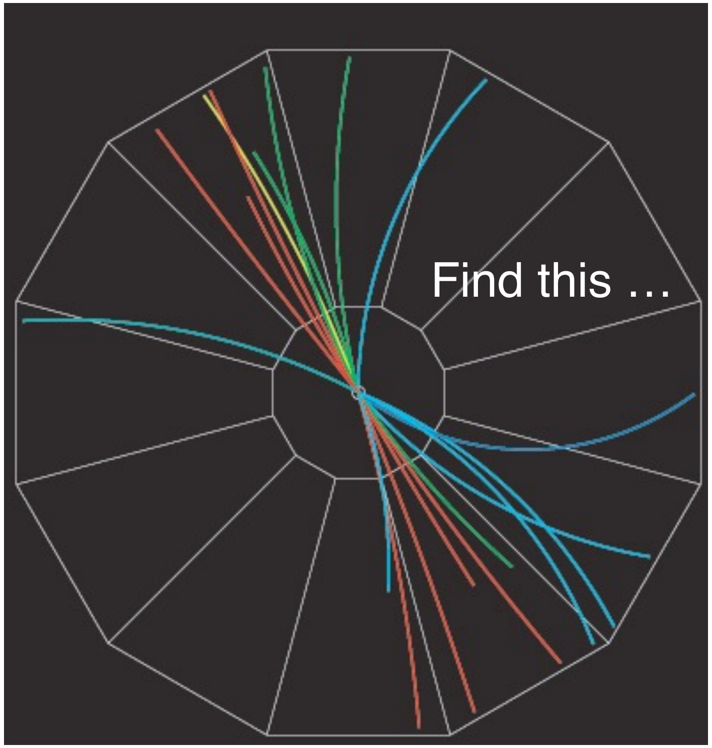
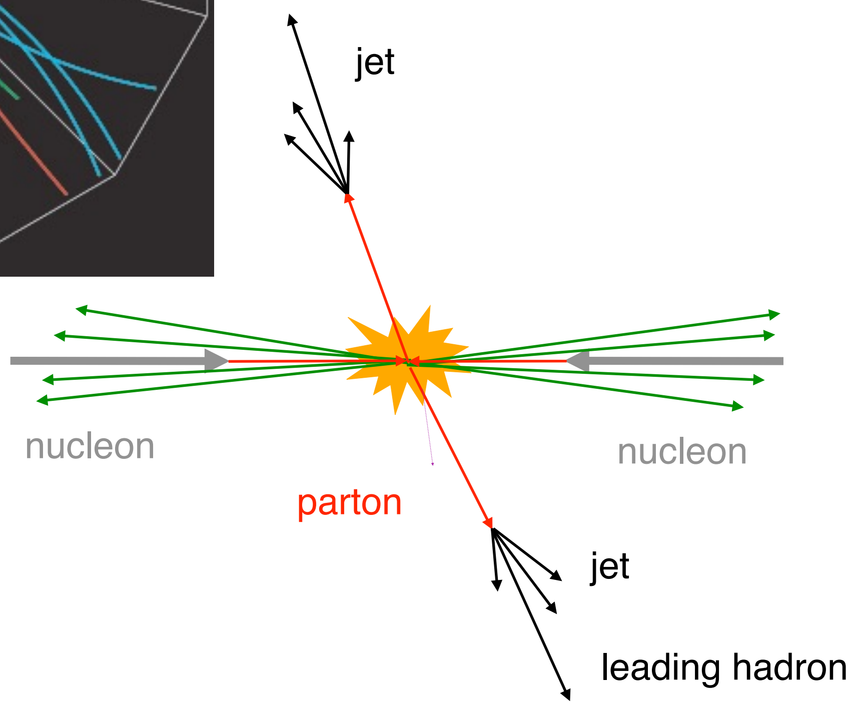
Need better tool

Finding a jet in a A-A event



p-p →jet+jet
(STAR@RHIC)



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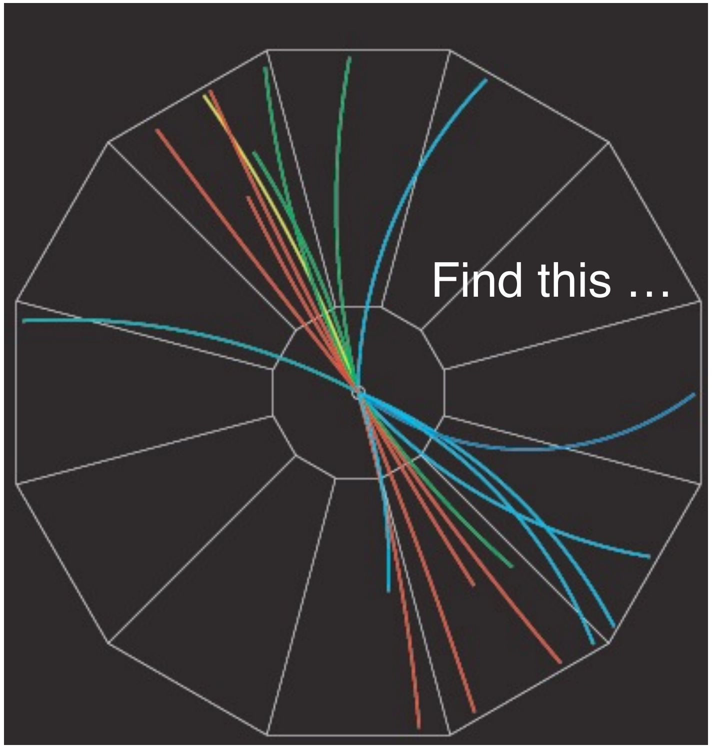

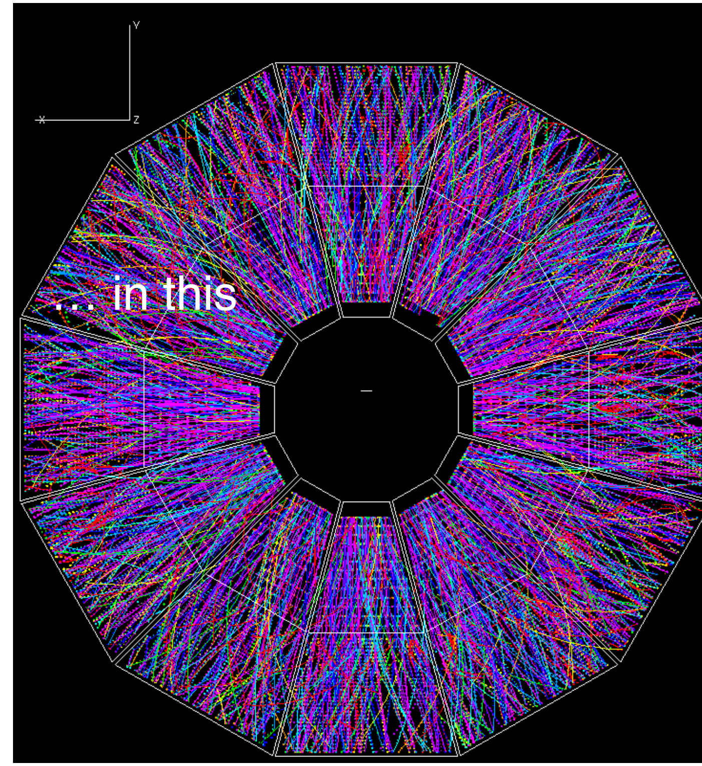

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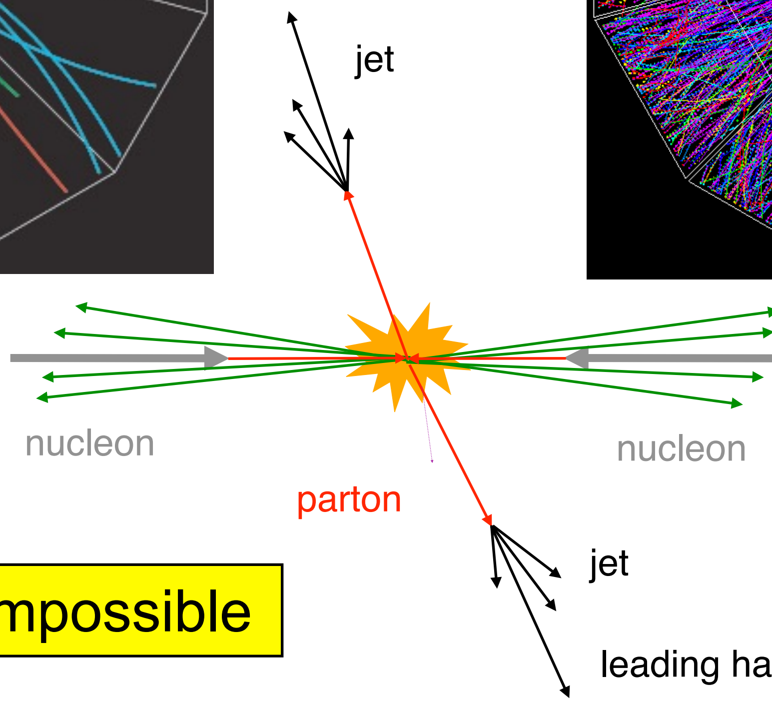
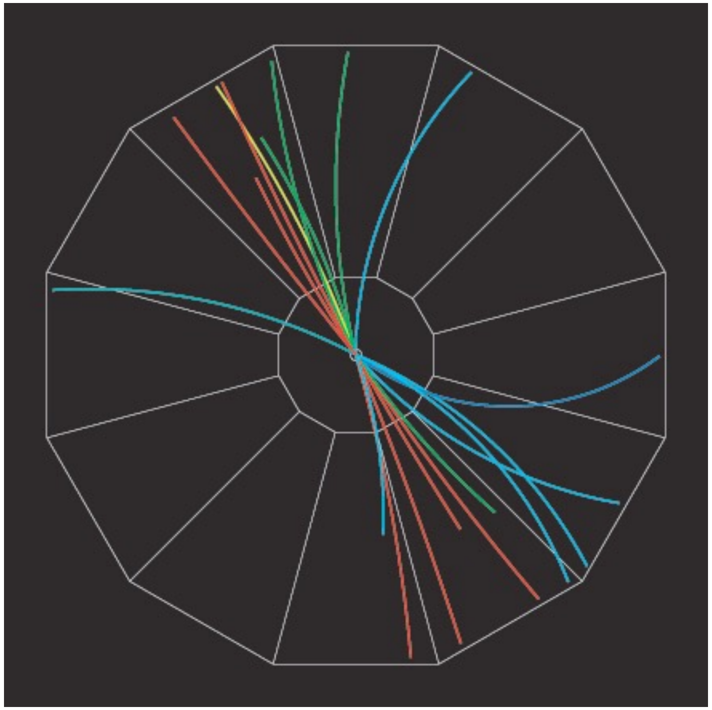


Au-Au →???
(STAR@RHIC)

Seems almost impossible

Start small: di-hadron collisions

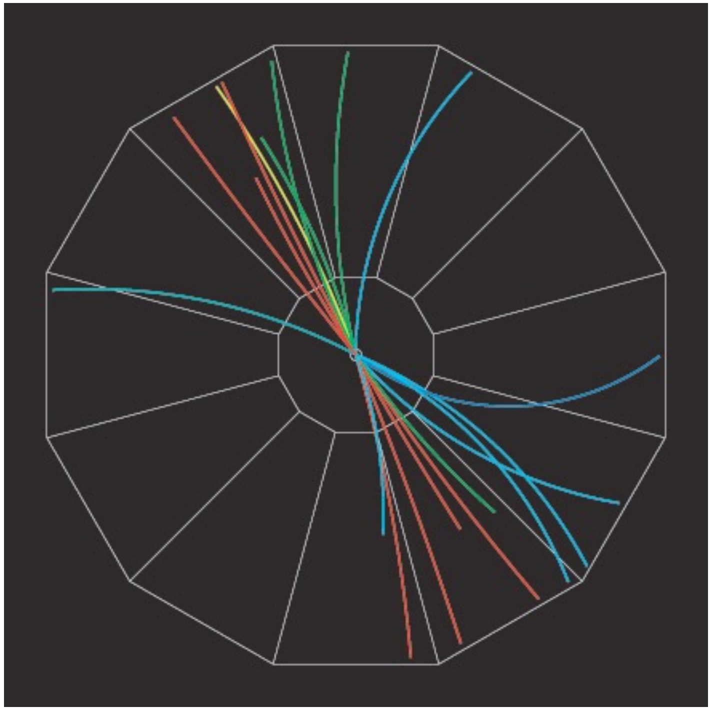
p-p → dijet



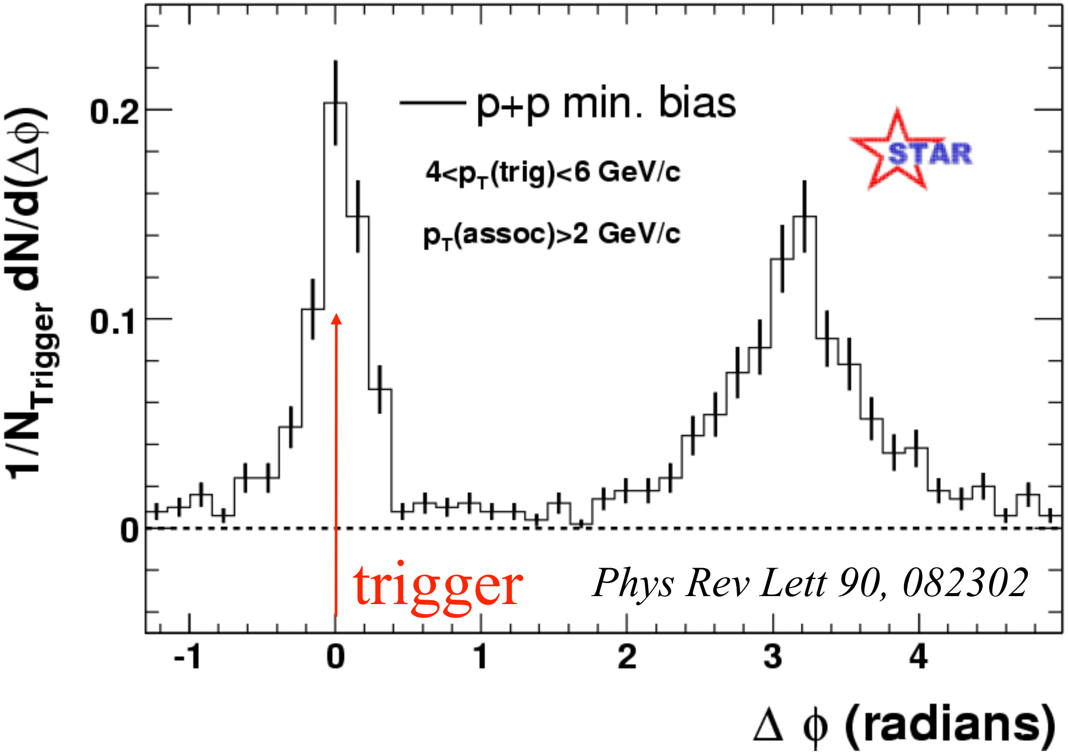
- Trigger: highest p_T track
- Δφ distribution:

Start small: di-hadron collisions

p-p → dijet



min. bias p-p collisions



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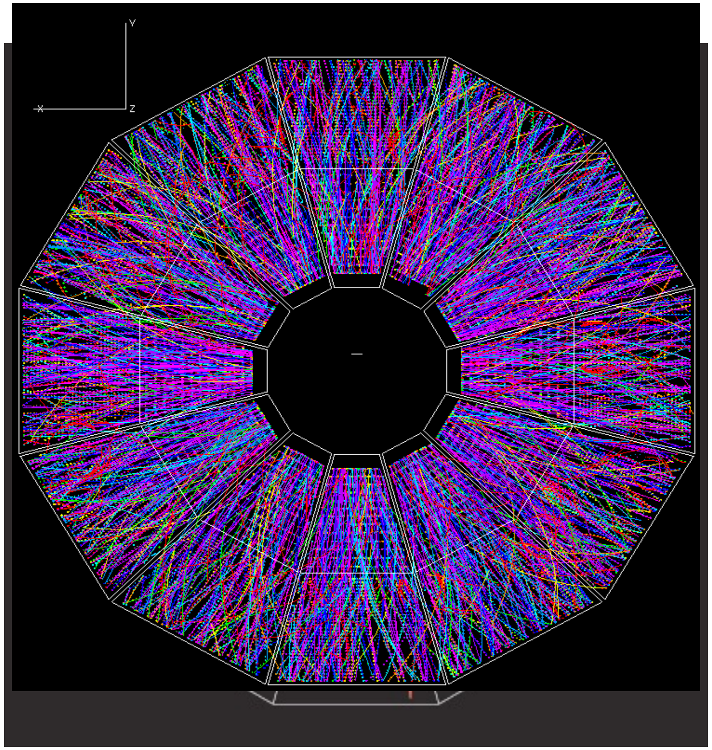
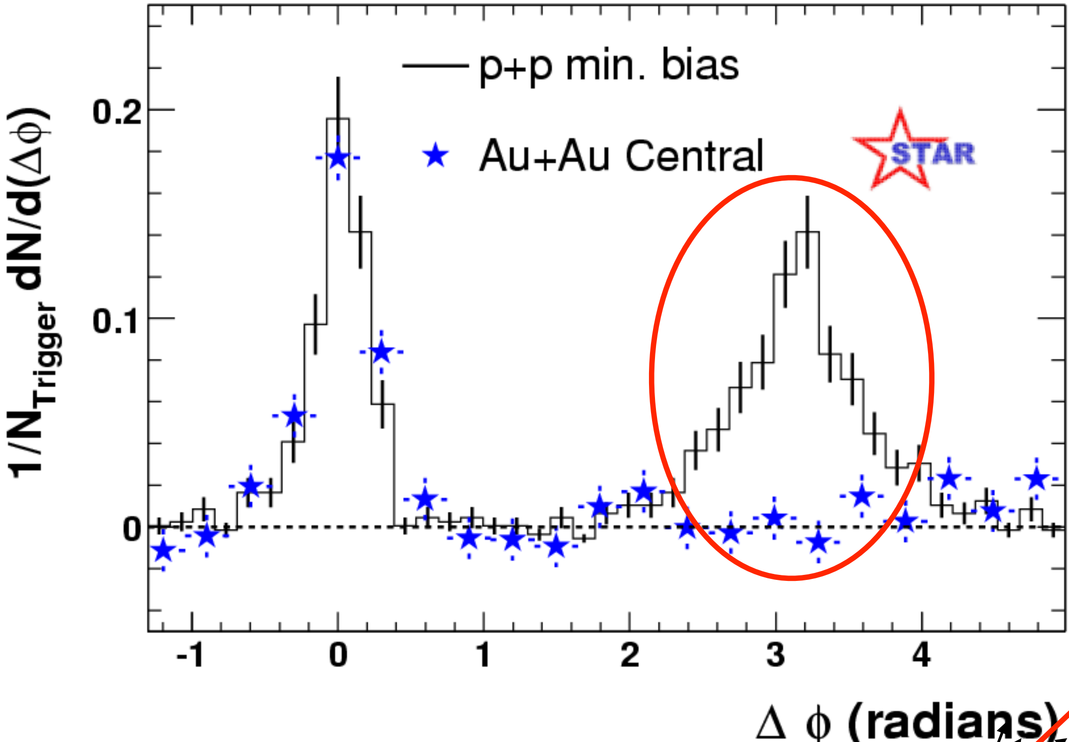
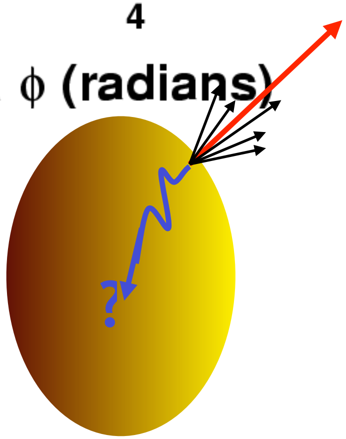


central Au-Au collisions





Δφ ≈ 0: central Au-Au similar to p-p

Δφ ≈ π: strong suppression of back-to-back correlations in central Au-Au

Start small: di-hadron collisions

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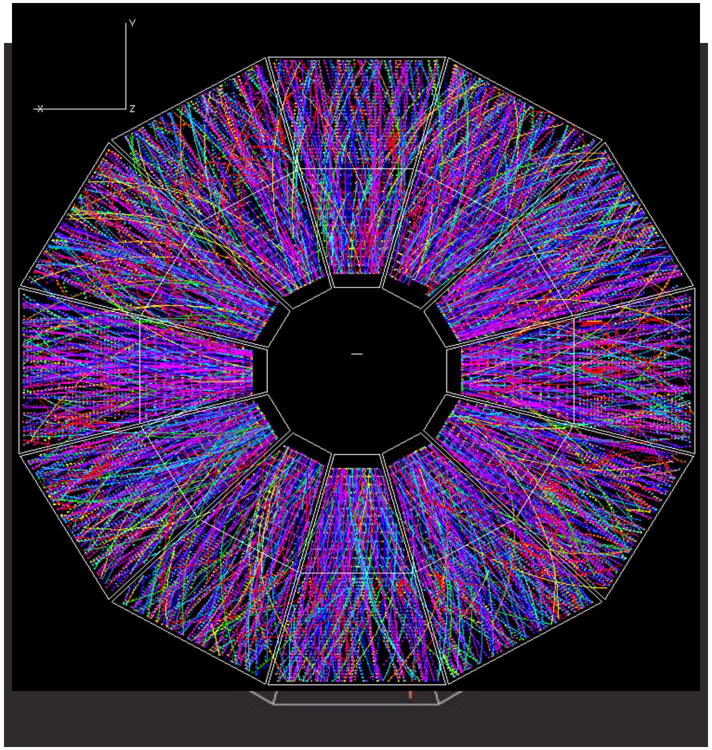

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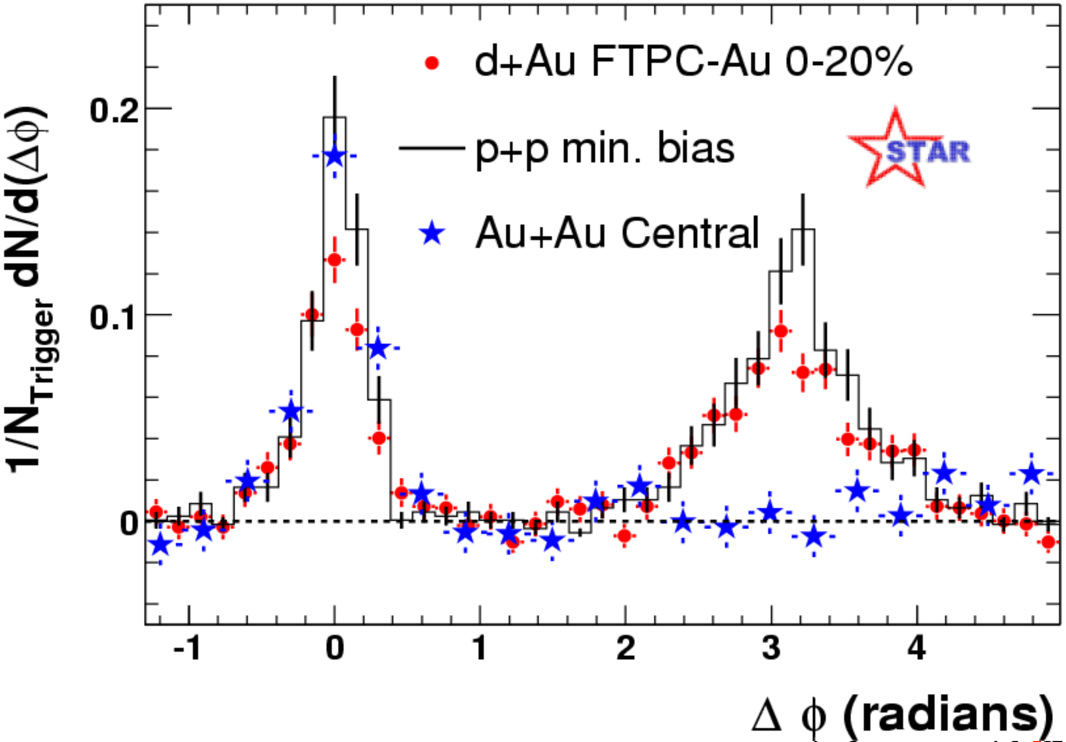

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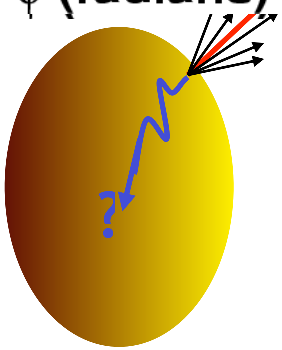
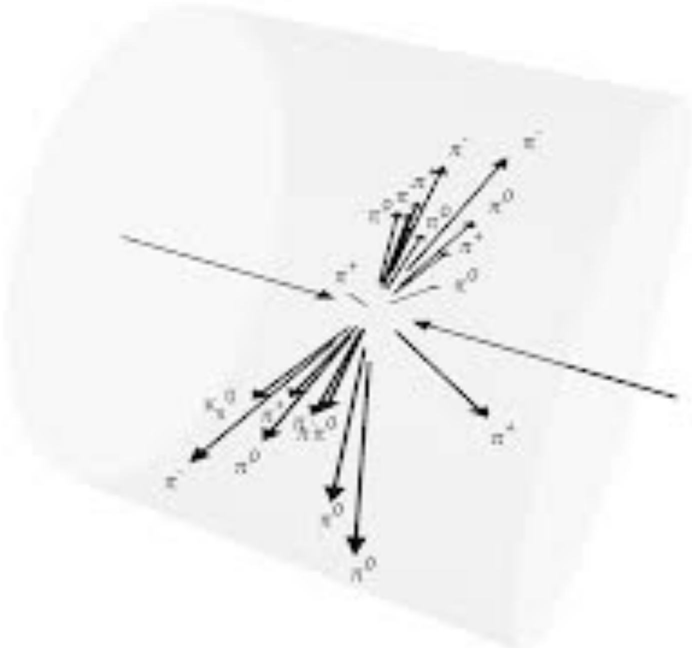


Di-jet energy (im)balance: A_J

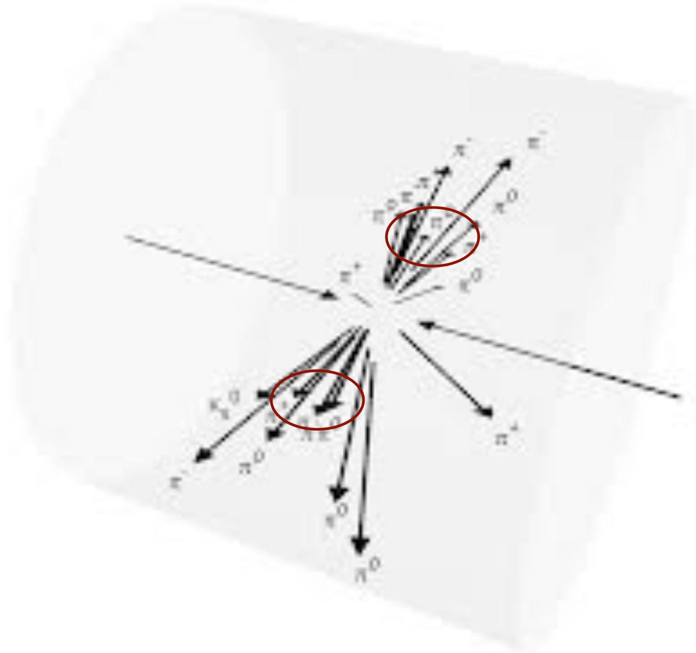


Energy and momentum conserved

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

Ideally A_J = 1

Di-jet energy (im)balance: A_J



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Using jet finder some energy missed

Even for p-p $A_J \neq 1$

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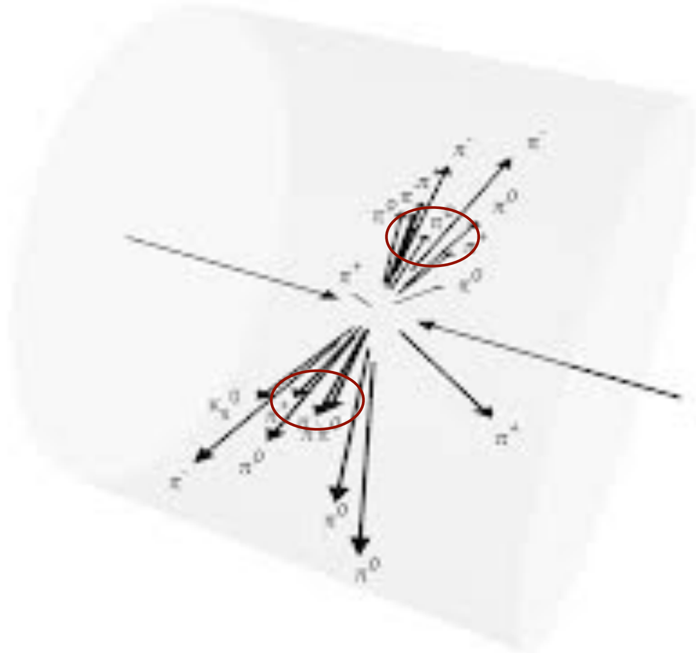

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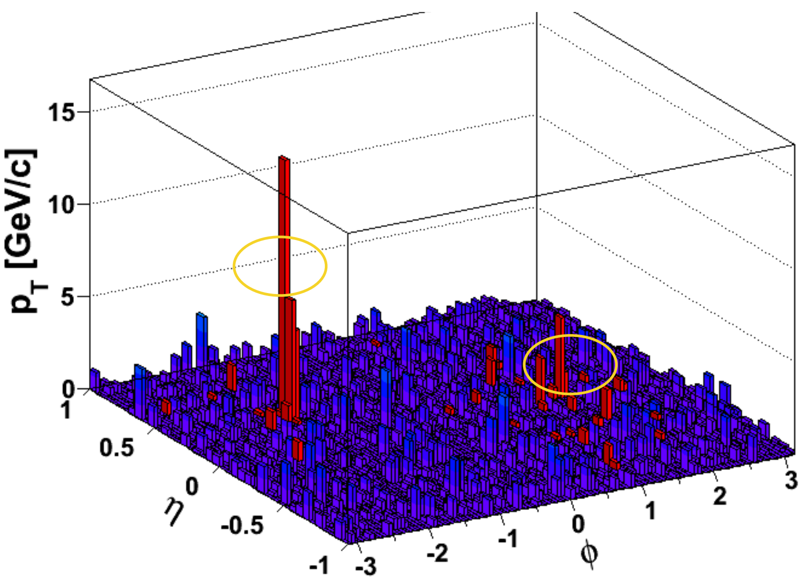


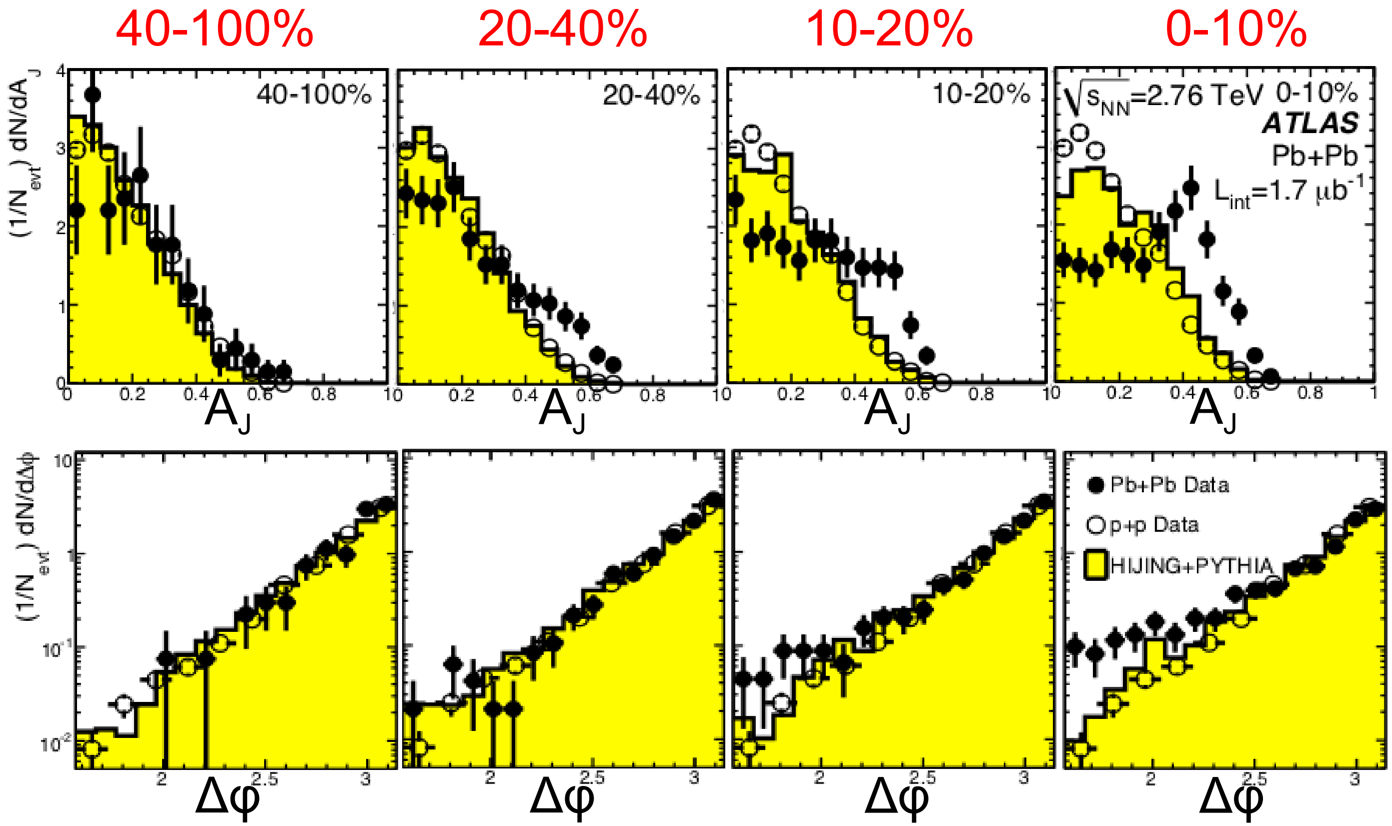
Even for p-p $A_J \neq 1$

In A-A collisions energy loss to QGP will also affect A_J

Compare A_J in p-p and A-A for different thresholds and radii

Di-jet momentum imbalance

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$



Little to no azimuthal decorrelation

Significant increase in momentum imbalance
  increases with centrality

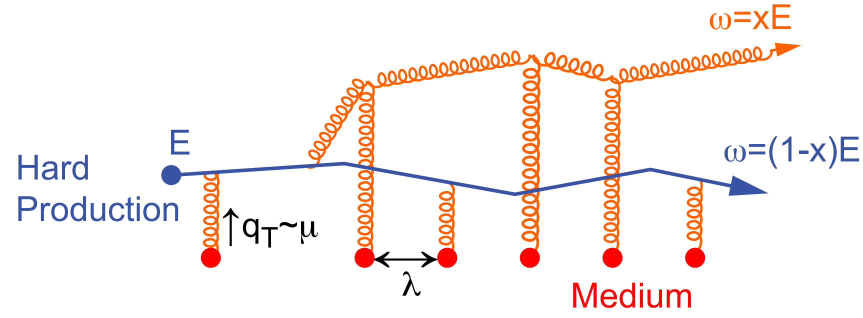
Energy not restored within cone of R=0.4

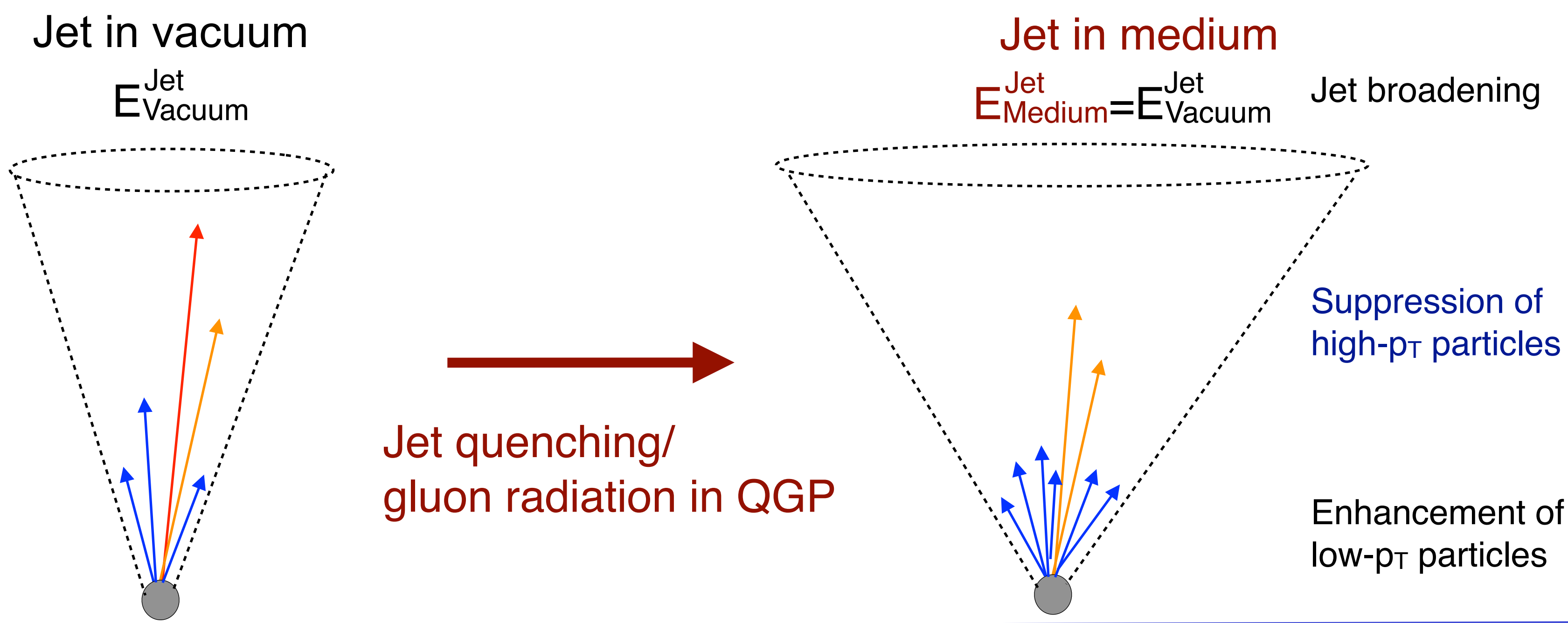
ATLAS, PRL 105 (2010) 252303
CMS, PRC 84 (2011) 024906

So what's happening

Jet quenching = Gluon radiation:

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





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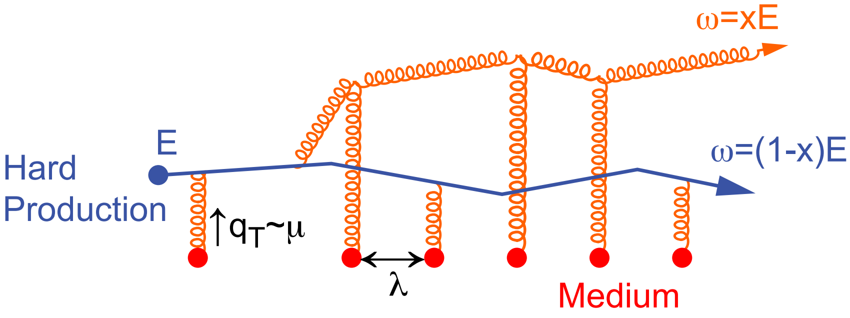
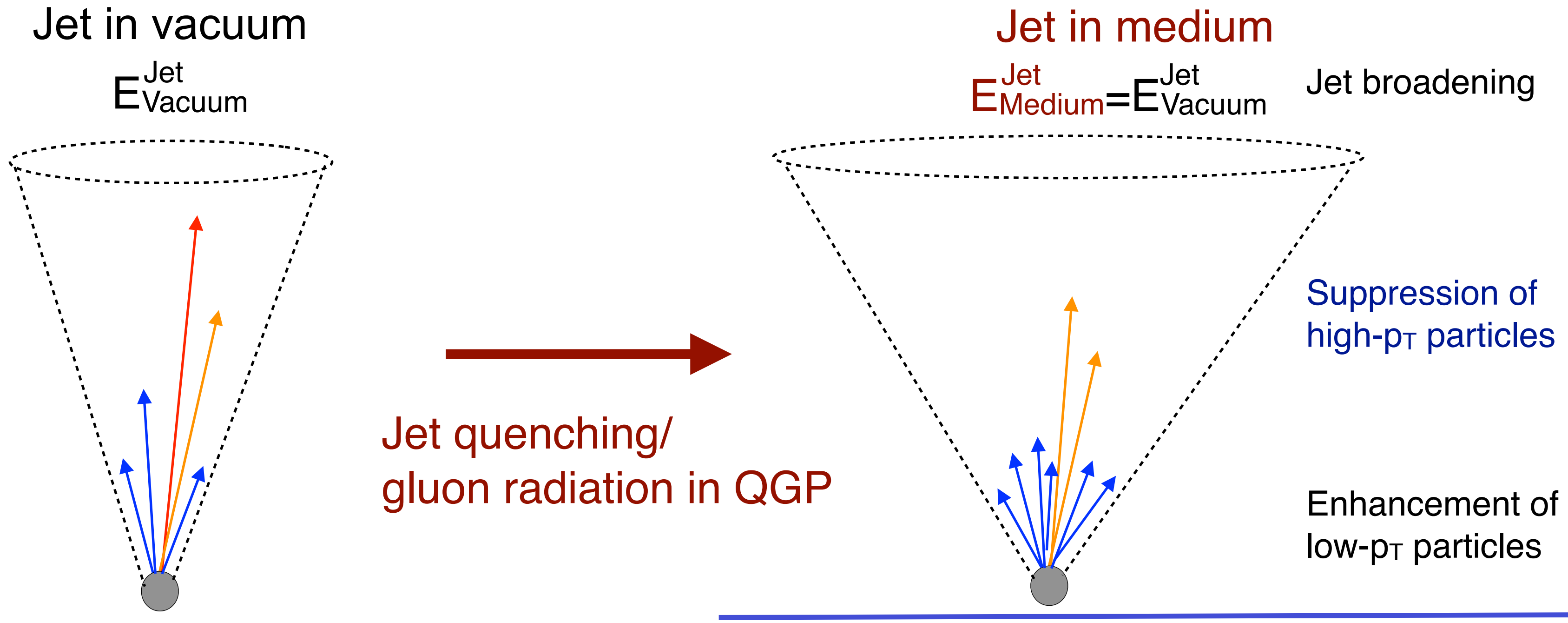


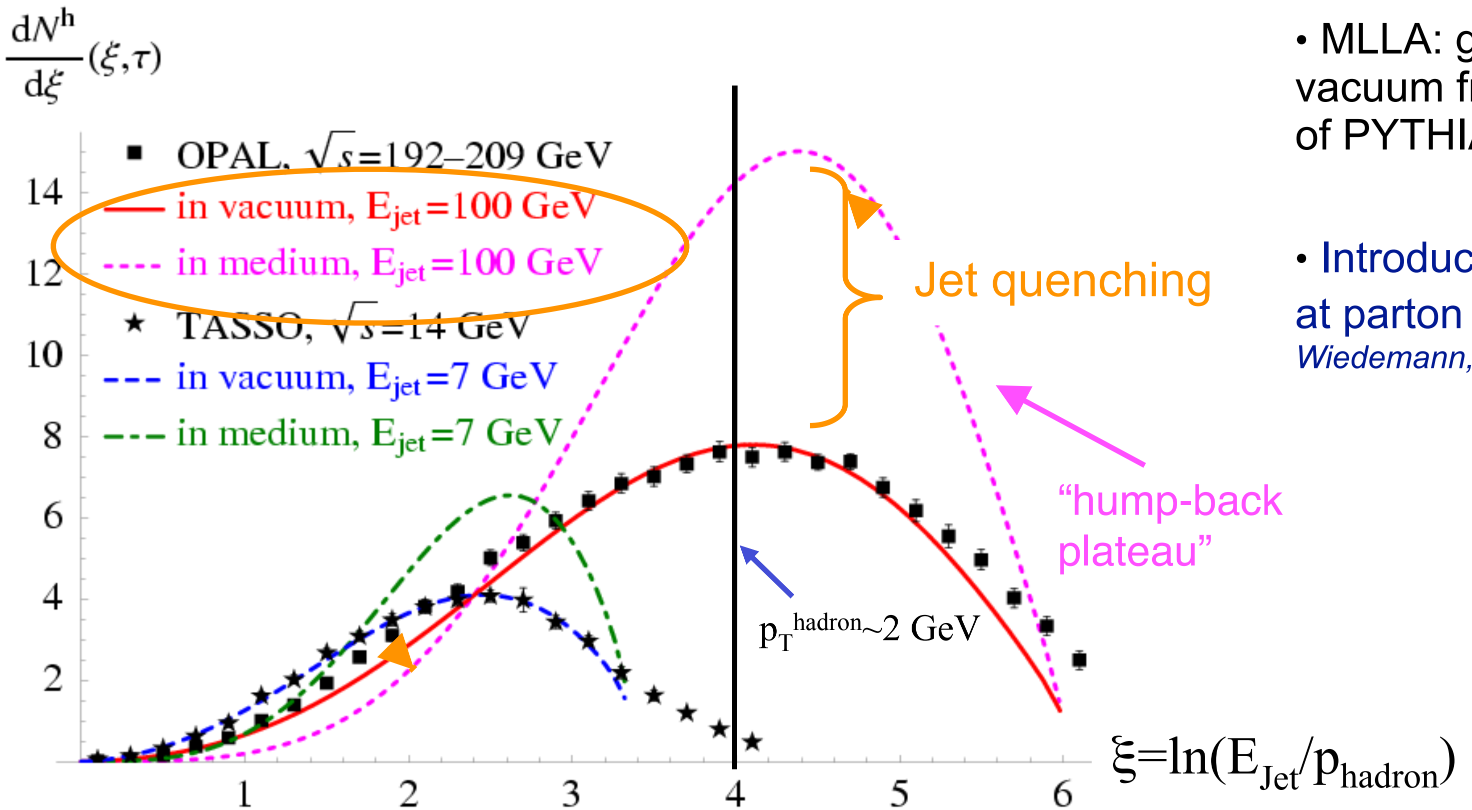
Modification of the Jet Structure



Modification of the fragmentation

p and E must be conserved so quenched energy must appear somewhere

Prediction that the fragmentation function is modified in the presence of a QGP - more and softer particles produced



- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

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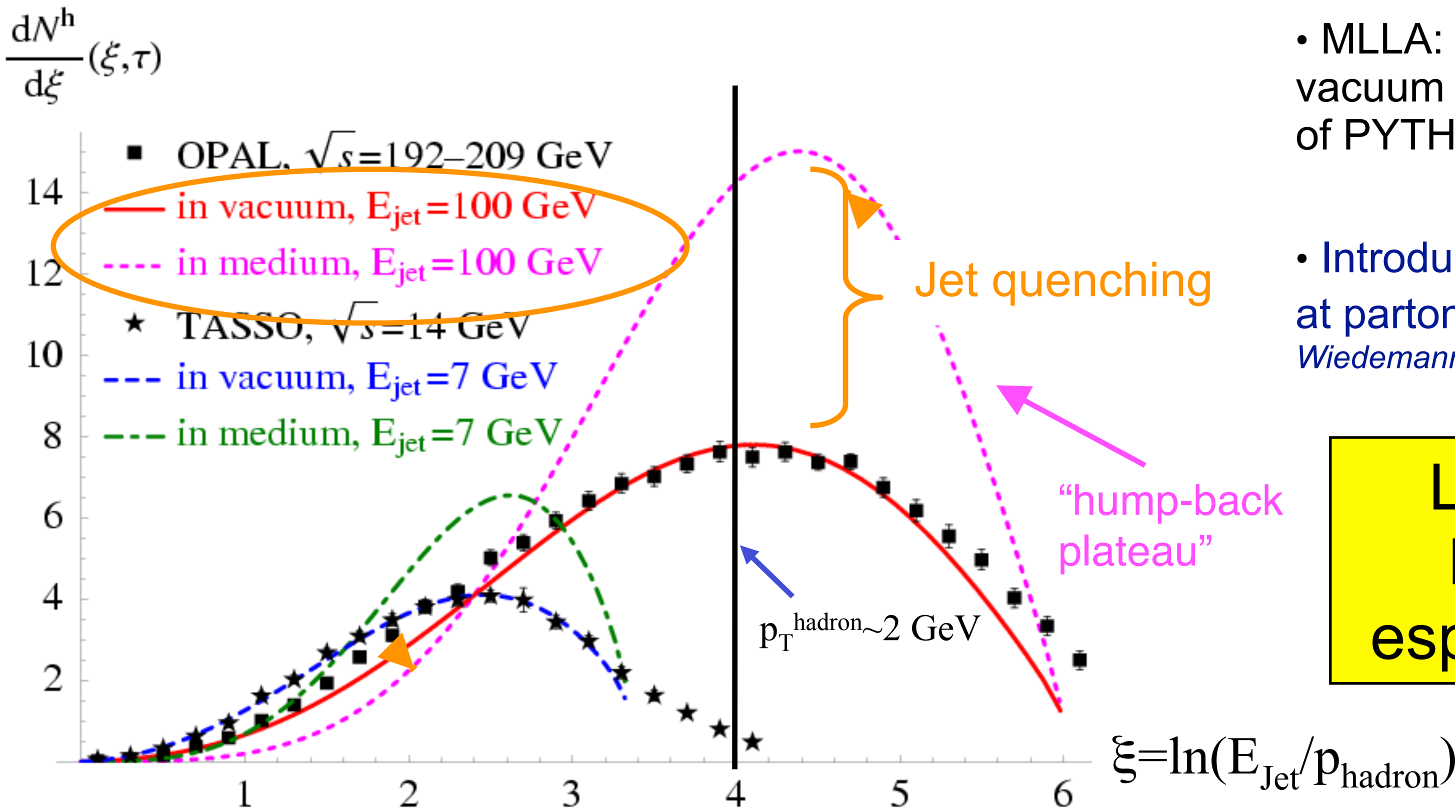

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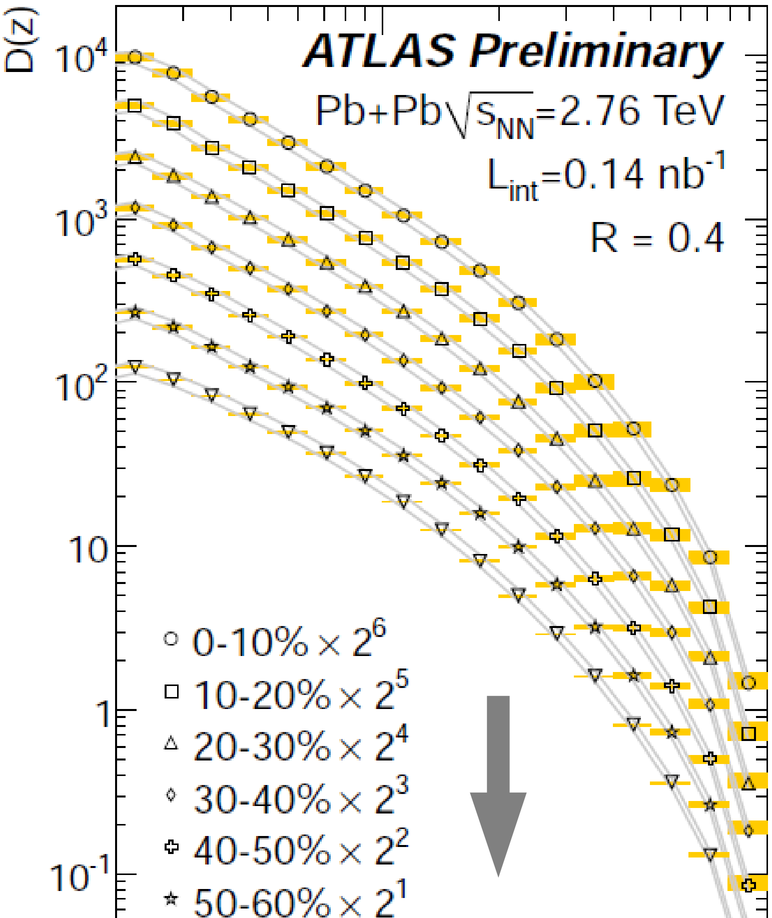
Look at A-A Frag. Fnc. especially low z

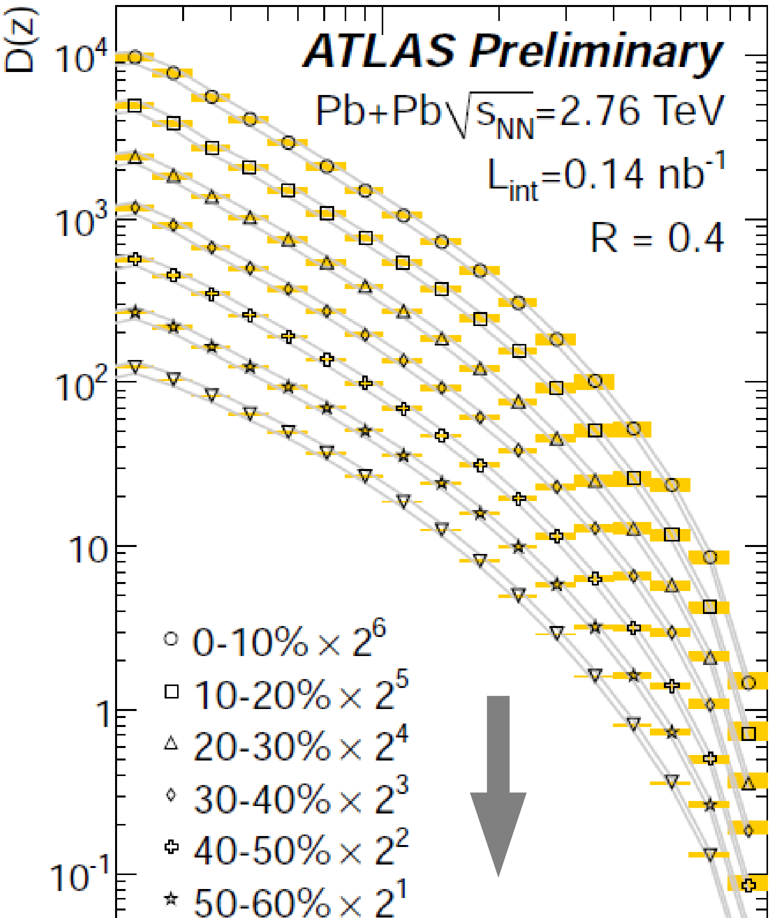
Where does the energy go?



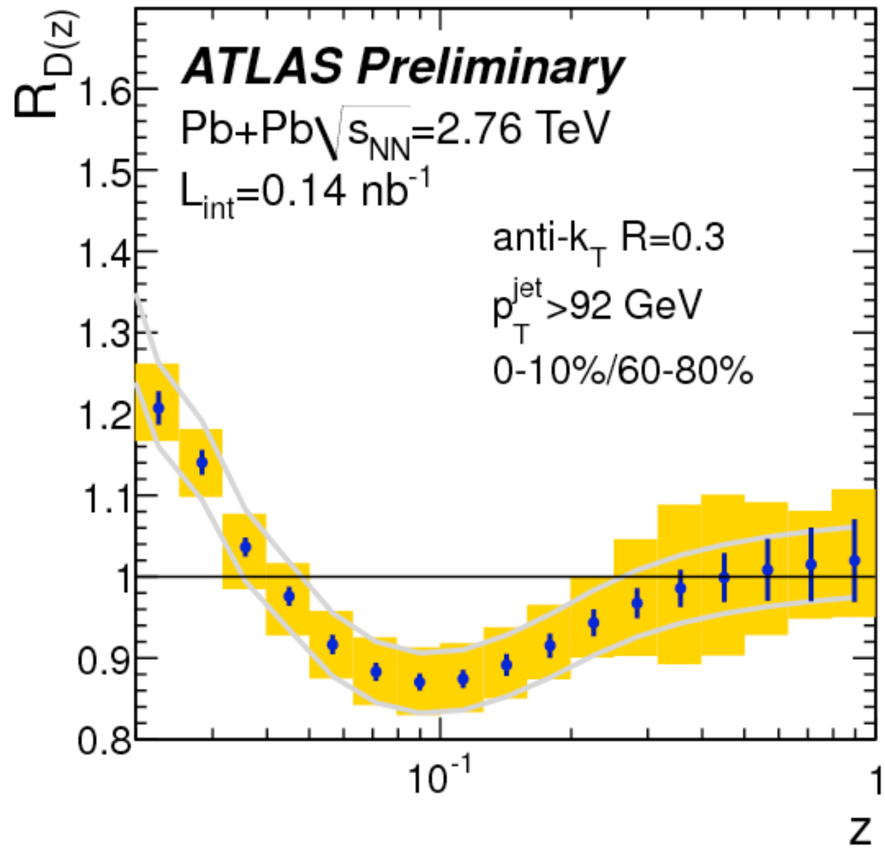
$$R_{\mathrm{D(z)}} = \frac{\mathrm{D}(z)|_{\mathrm{cent}}}{\mathrm{D}(z)|_{60-80\%}}$$

ATLAS-CONF-2012-115

Where does the energy go?



$$R_{D(z)} = \frac{D(z)|_{cent}}{D(z)|_{60-80\%}}$$



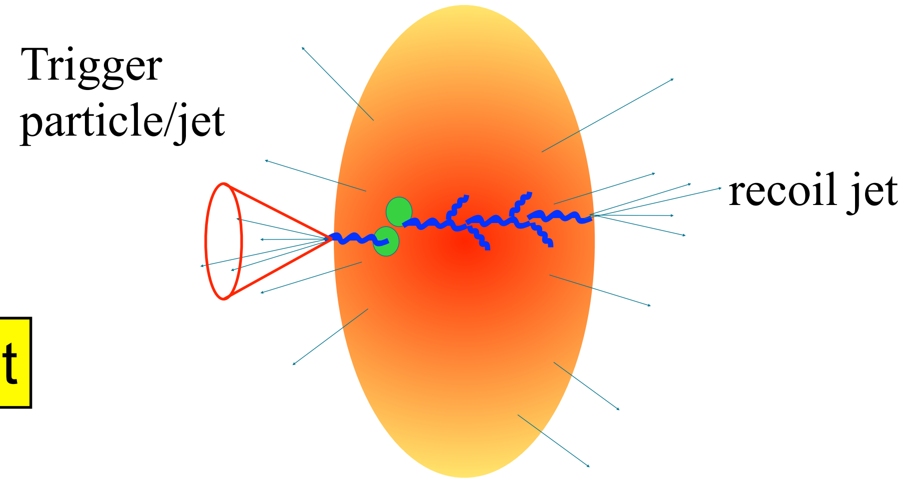
"Lost" hard particles emerge as multiple soft particles

- many remain correlated to jet axis

ATLAS-CONF-2012-115

Applying a path-length bias

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



More energy loss of recoil jet

T. Renk, Phys.Rev. C87 (2013) 024905

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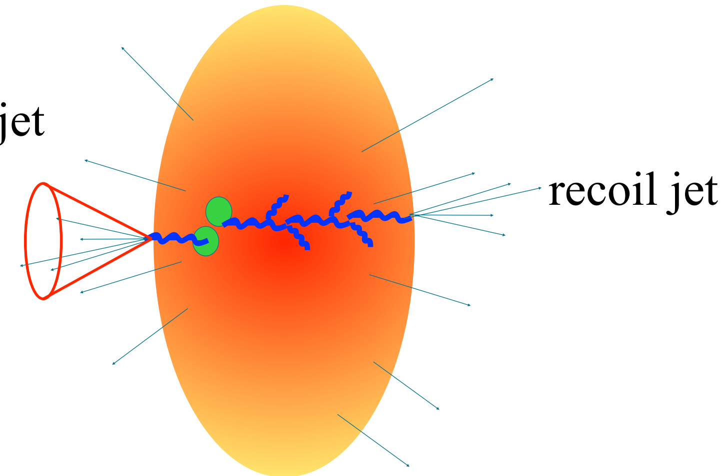

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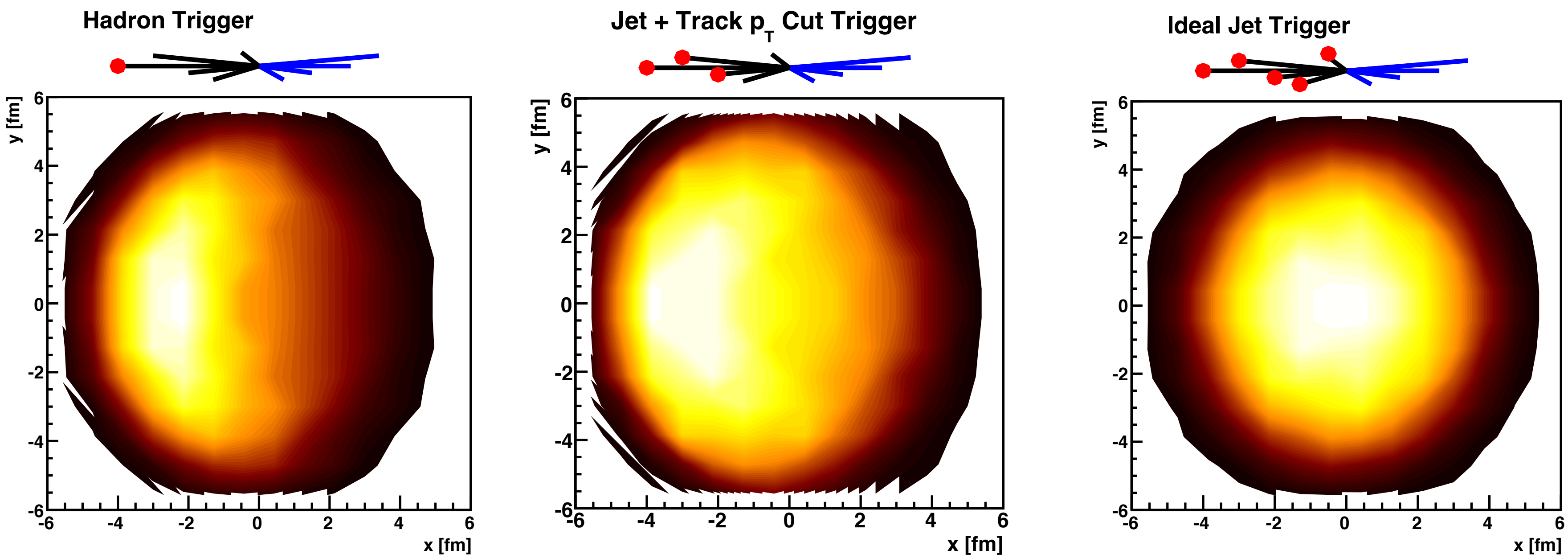
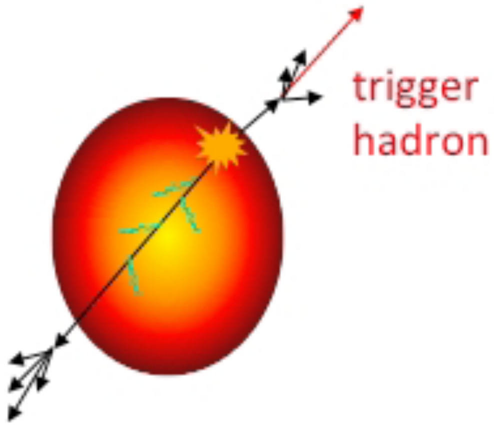


T. Renk, Phys.Rev. C87 (2013) 024905

Probe recoil jets - large path length



Trigger: Charged hadron $9 < p_T < 19$ GeV/c

Recoil: Charged particle jet:

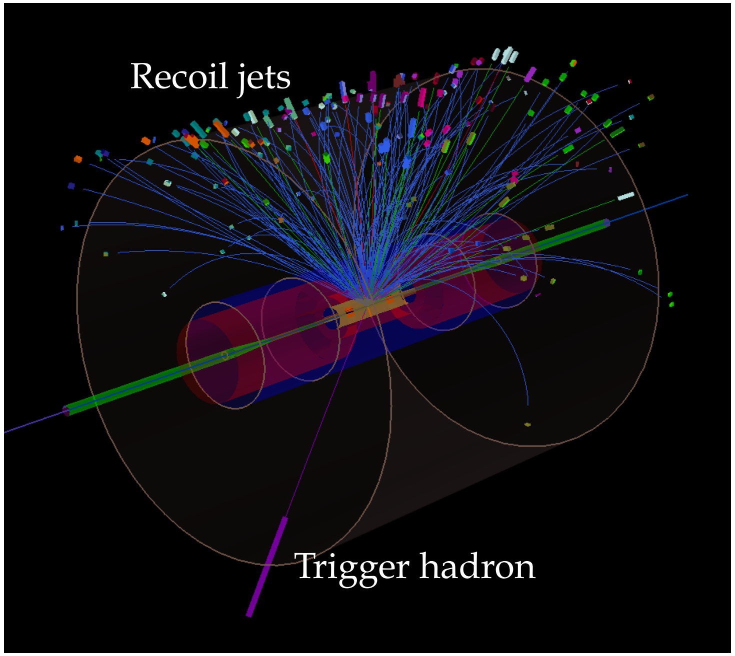
Anti-k_T R=0.3

Constituent tracks: $p_T > 0.2$ GeV/c

Recoil jet azimuth: $|\varphi - \pi| < \pi/4$

Semi-inclusive Observable:

Recoil jets per trigger



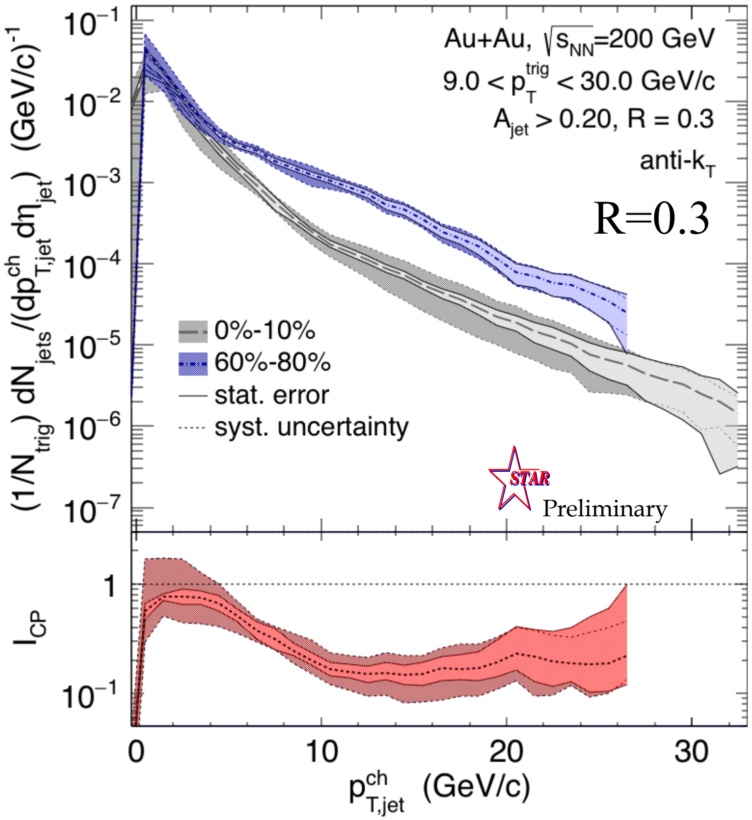
Ensemble-averaged analysis:

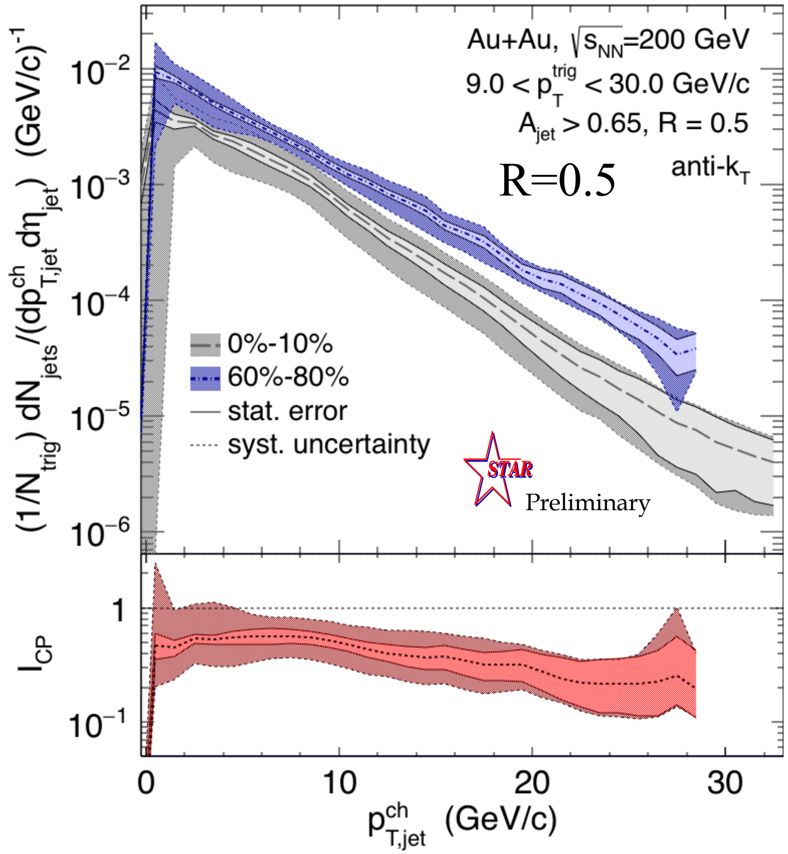
No rejection of jet candidates on jet-by-jet basis

No bias on recoil jet

Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)

Recoil jets are missing





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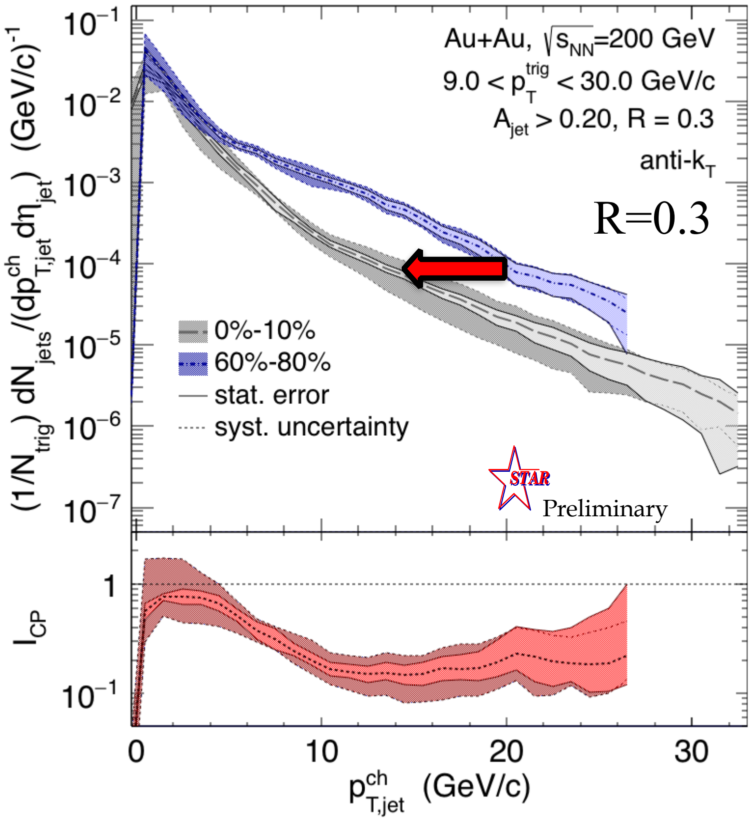
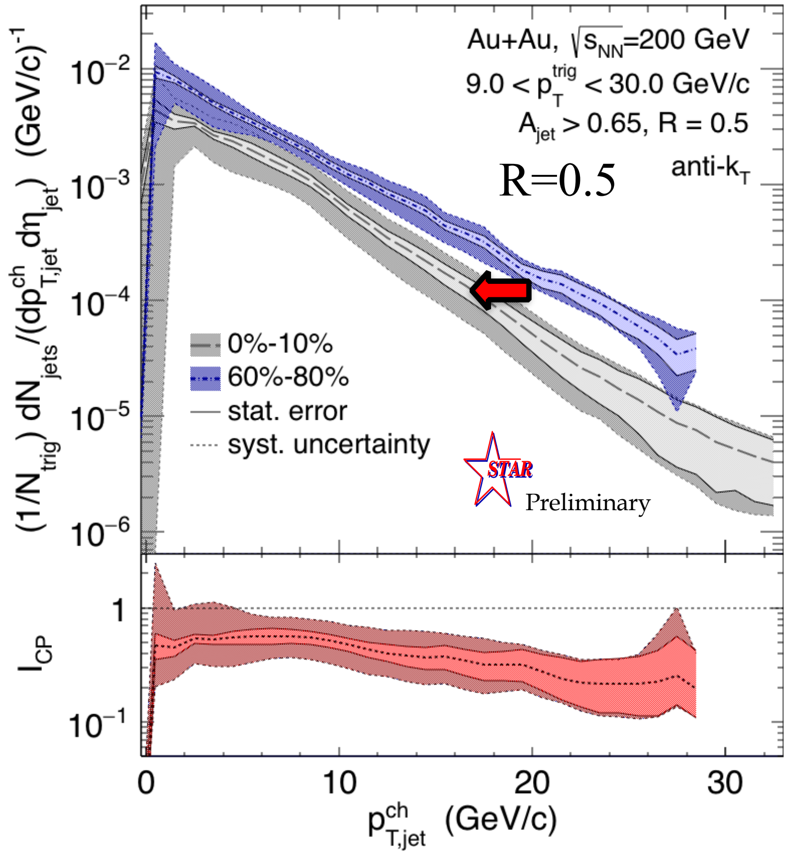




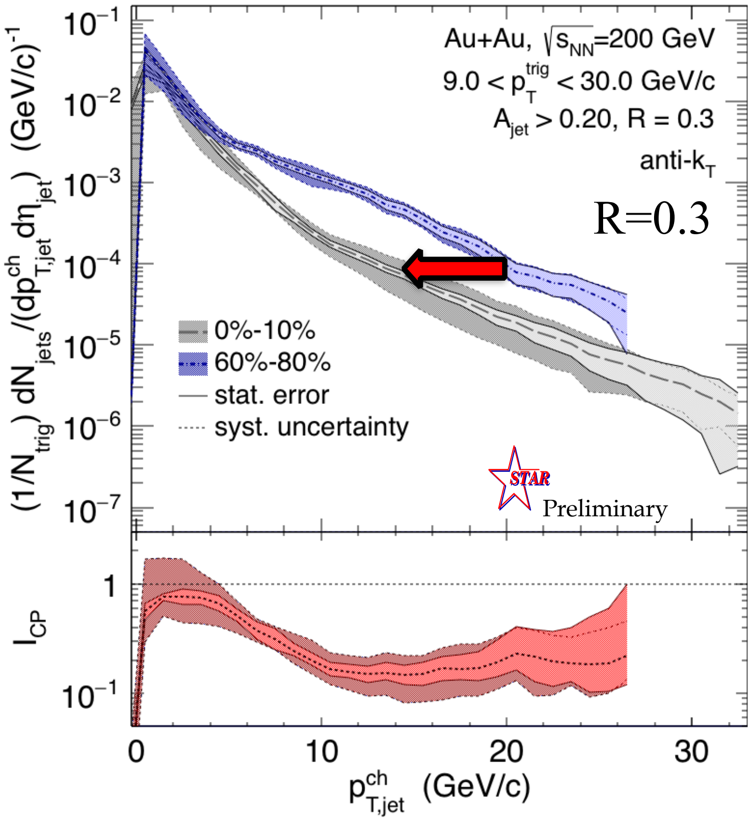
RHIC: Jet p_T =10-20 GeV

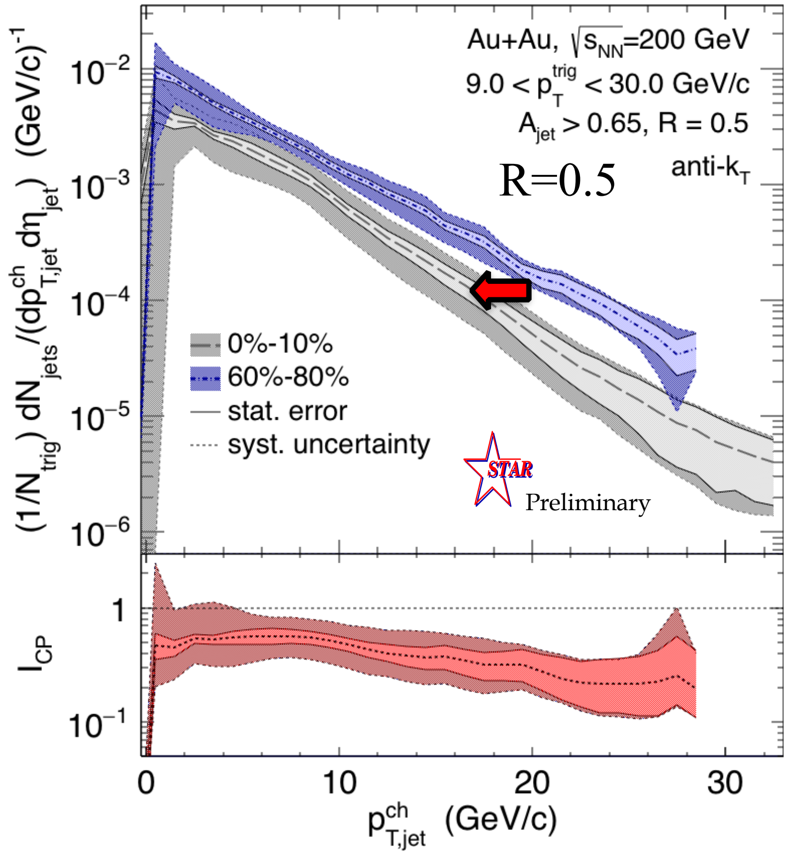
R=0.3: $p_{T,Shift}$ ~ -6 GeV

R=0.5: $p_{T,Shift}$ ~ -4 GeV

Energy recovered at larger angles

Recoil jets are missing





RHIC: Jet p_T =10-20 GeV

R=0.3: $p_{T,Shift}$ ~ -6 GeV

R=0.5: $p_{T,Shift}$ ~ -4 GeV

Energy recovered at larger angles

LHC: Jet p_T =60-100 GeV

R=0.5: $p_{T,Shift}$ ~ -8 GeV

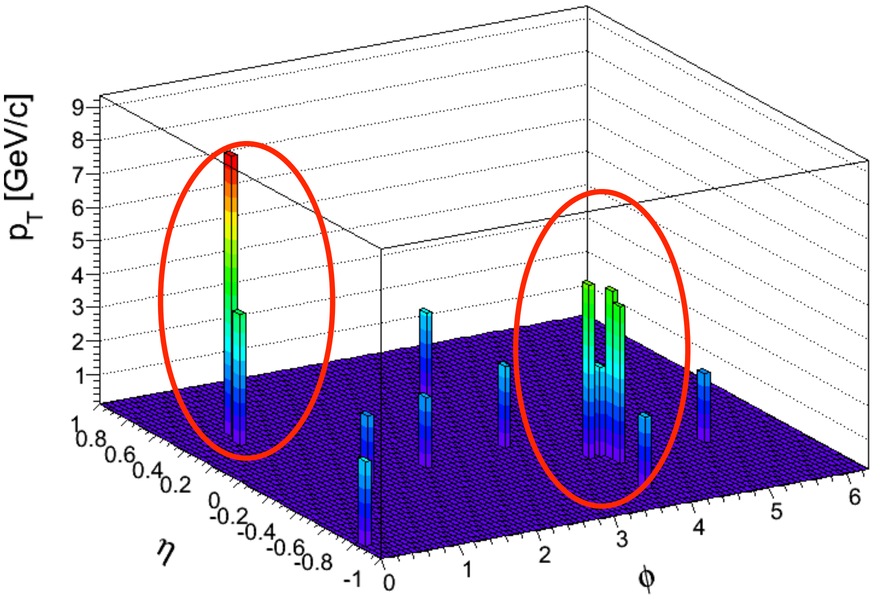
More energy loss at LHC

"Hard Core" jets - large path length

$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV
$p_T^{SubLead}$>10 GeV
$\Delta\Phi_{Lead,SubLead}$ > 2/3 π

$$p_T = p_T^{rec} - \rho \times A$$

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



To allow access to low p_T jets

First apply constituent $p_{T,cut}$>2 GeV/c

"Hard Core" jets - large path length

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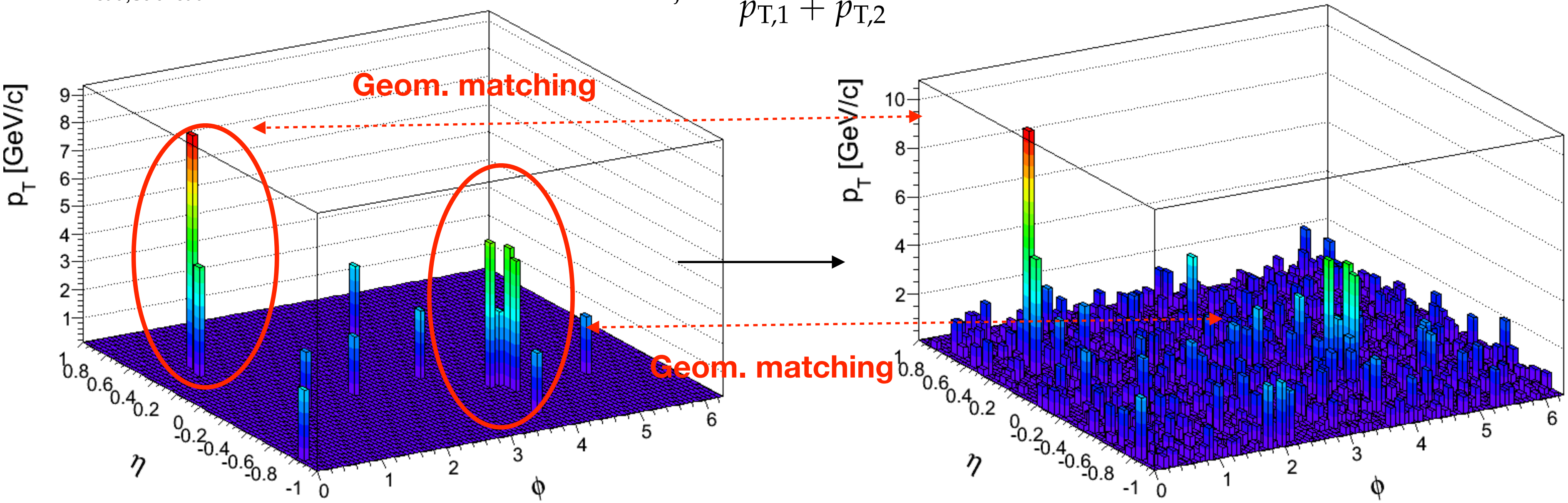
$p_{T,cut}$=0.2 GeV/c
p_T^{Lead}>20 GeV ($p_{T,cut}$=2 GeV/c)
$p_T^{SubLead}$>10 GeV ($p_{T,cut}$=2 GeV/c)



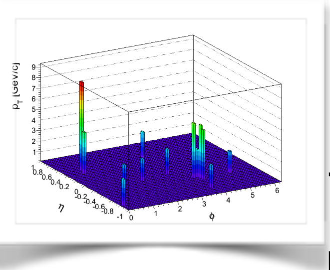
To allow access to low p_T jets

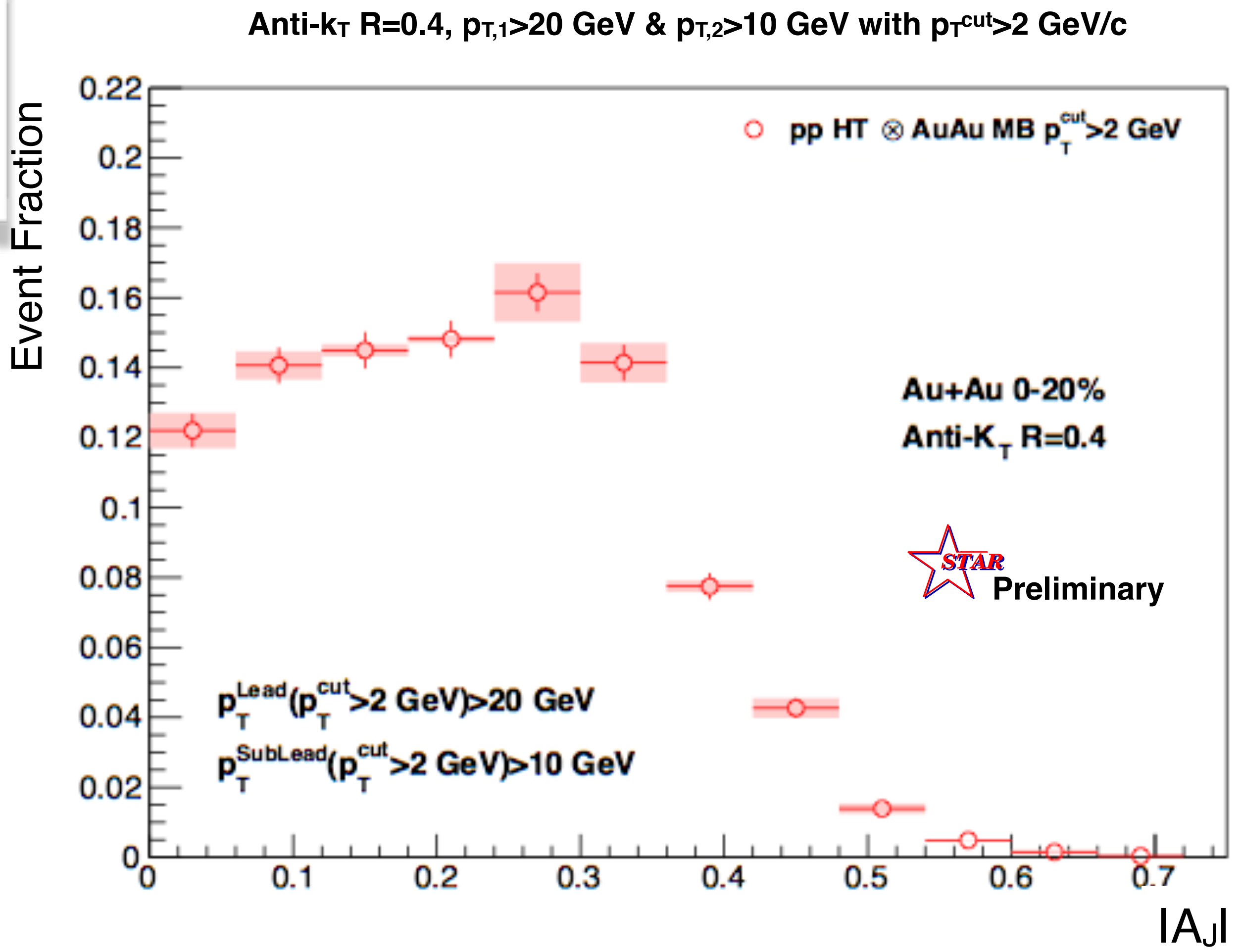
First apply constituent $p_{T,cut}$>2 GeV/c

Relax constituent cut
Rerun anti-k_T algorithm
match via geom. positions

Calculate $|A_j|$ twice with/without low p_T constituent cut

Di-jet imbalance A_J Au-Au 0-20% R=0.4

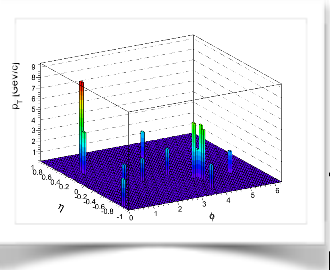


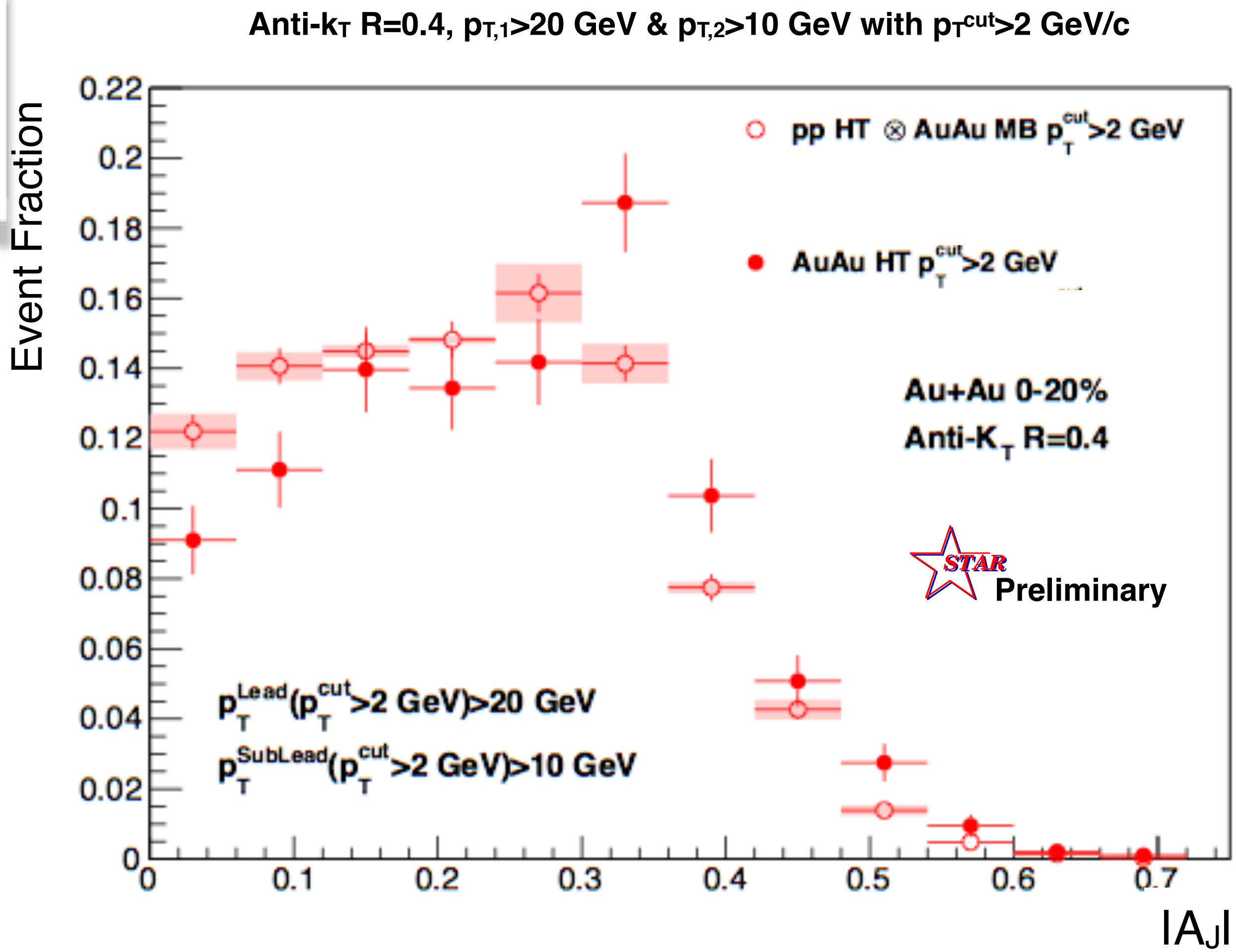


Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

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

Di-jet imbalance A_J Au-Au 0-20% R=0.4





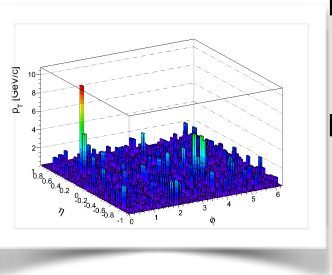
p-value<10^{-5}
(stat. error only)

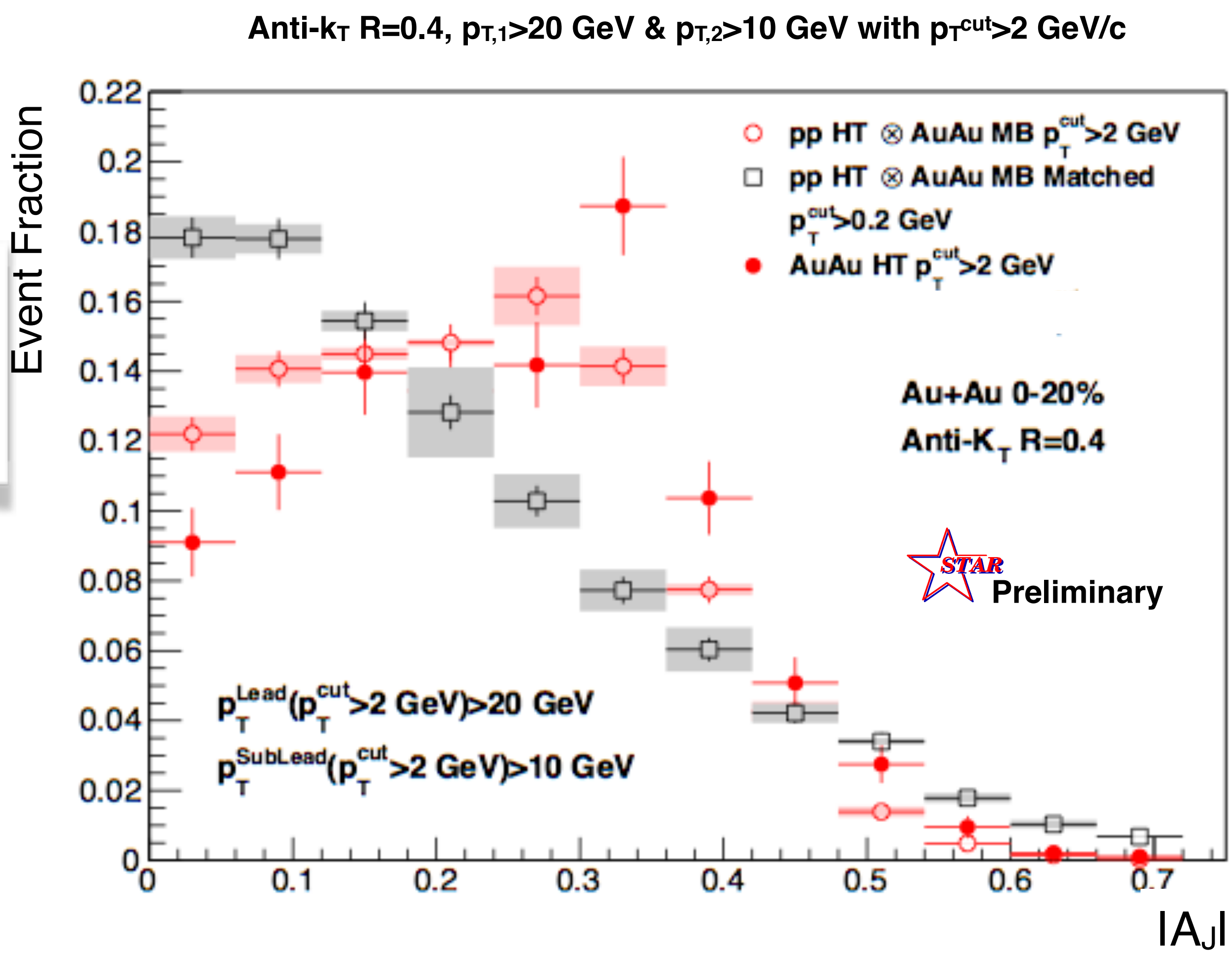
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Au-Au di-jets more imbalanced than p-p for p_T^{cut}>2 GeV/c

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

Di-jet imbalance A_J Au-Au 0-20% R=0.4





p-value<10^{-5}
(stat. error only)

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Au-Au di-jets more imbalanced than p-p for p_T^{cut}>2 GeV/c

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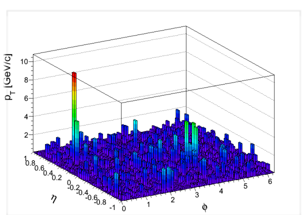
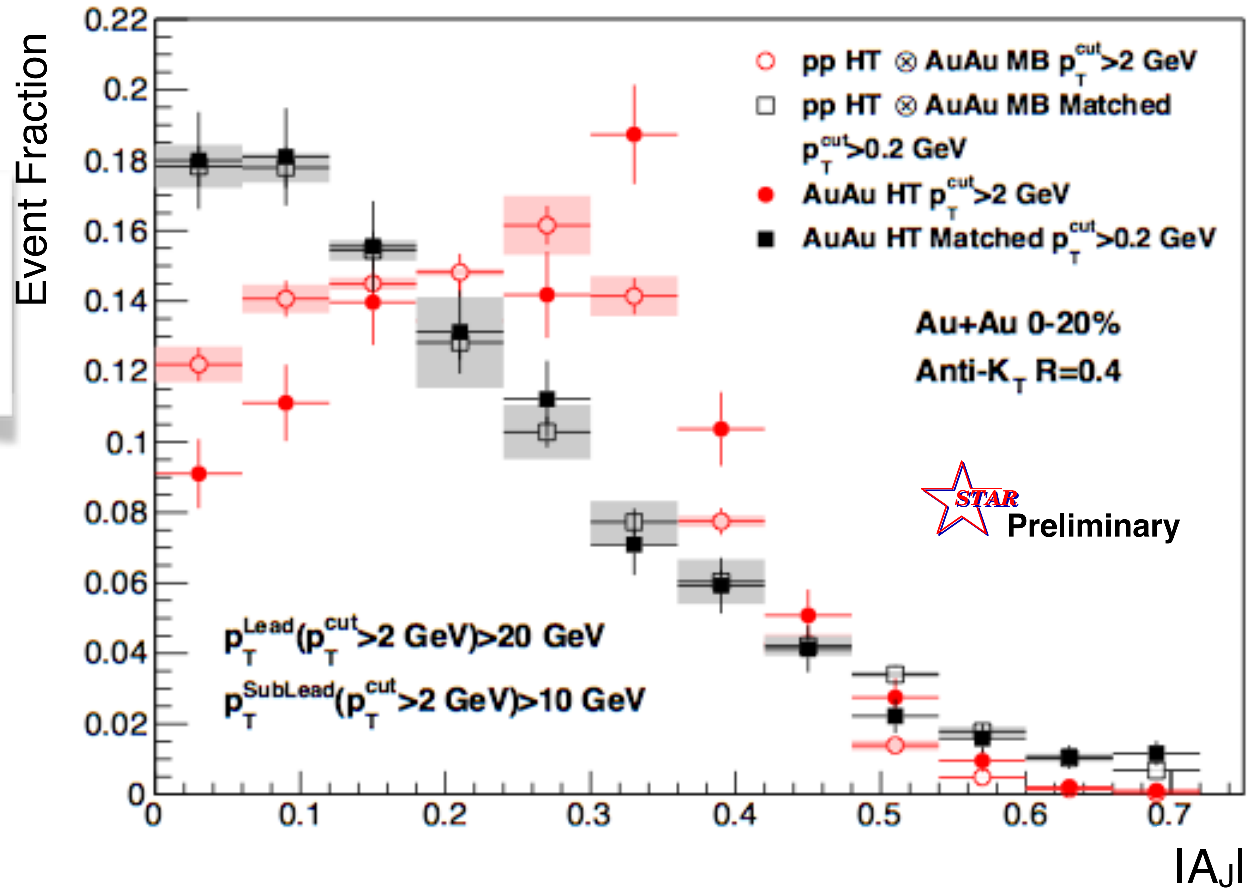
Di-jet imbalance A_J Au-Au 0-20% R=0.4



Anti-k_T R=0.4, $p_{T,1}$>20 GeV & $p_{T,2}$>10 GeV with p_T^{cut}>2 GeV/c



p-value<10^{-5}
(stat. error only)

p-value~0.8
(stat. error only)

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Au-Au di-jets more imbalanced than p-p for p_T^{cut}>2 GeV/c

Au-Au A_J ~ p-p A_J for matched di-jets (R=0.4)

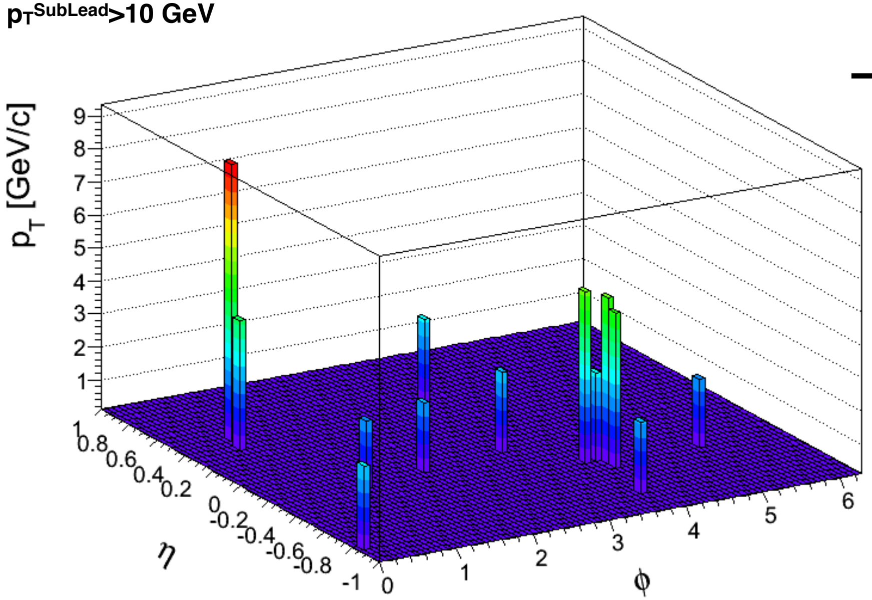
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Is this random luck?

Assumption: balancing for jets with low p_T constituents **only** due to background fluctuations, **not** correlated signal yield!

Method 1: Random Cone (RC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)



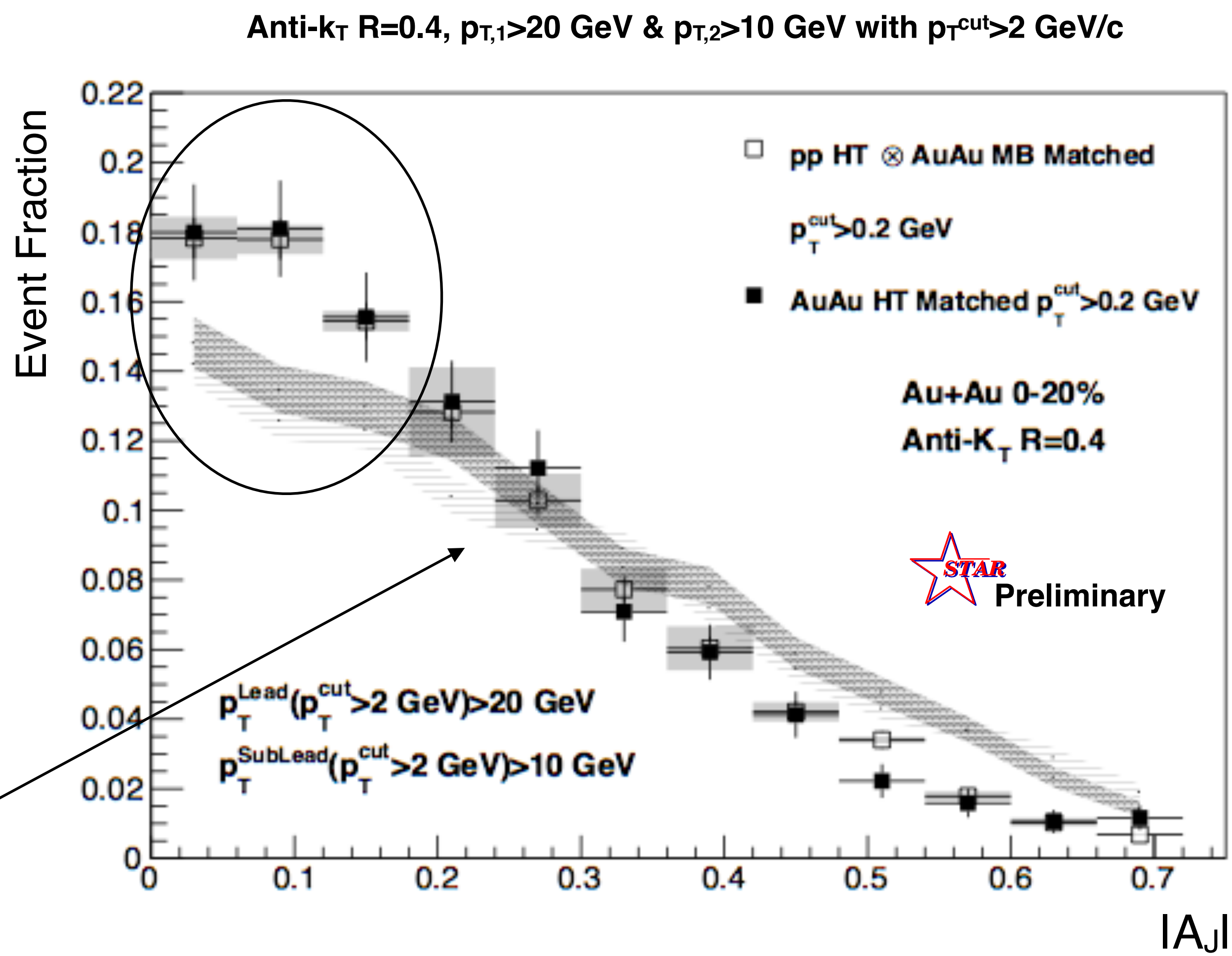
Embed randomly the 2 Jet vectors into a Au+Au 0-20% Minimum Bias event

Calculate $|A_J|$ with p_T^{Cut}>0.2 GeV/c using cone of R

If balance due to random noise
$|A_J|_{random} = |A_J|_{pp}$

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

Balancing is NOT due to random noise



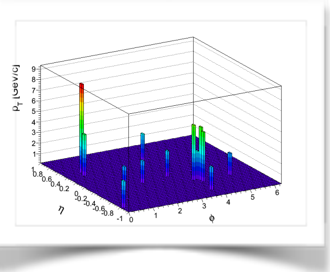
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

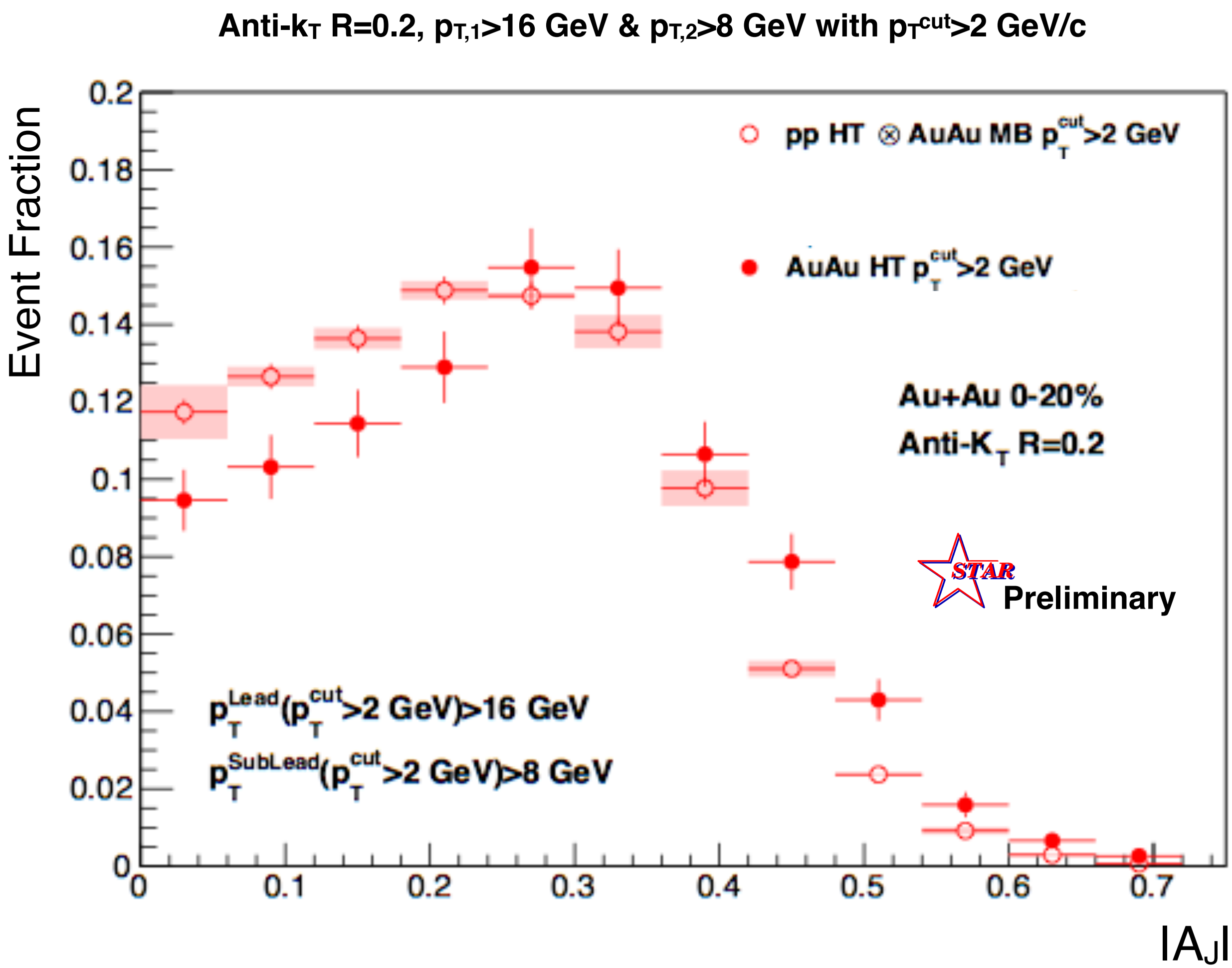
Method 1 (RC)

Balancing of Au-Au matched di-jets due to correlated signal yield in a cone of R=0.4

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

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





p-value<10^{-10}
(stat. error only)

Sys. Uncertainties:
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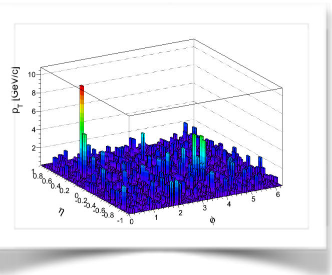
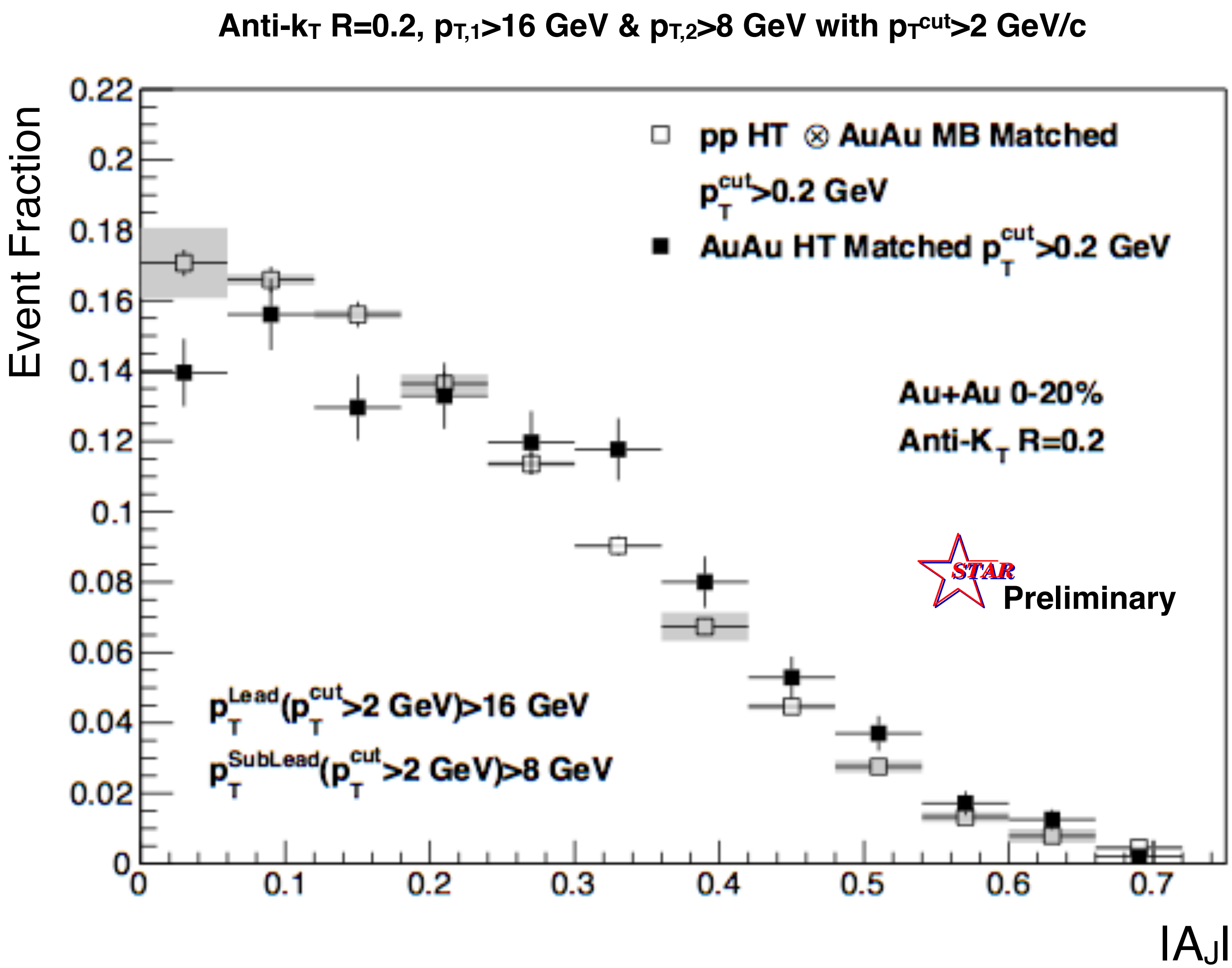
Di-jet imbalance A_J Au-Au 0-20% R=0.2





p-value<10^{-10}
(stat. error only)

p-value<10^{-4}
(stat. error only)

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Matched Au-Au $A_J \neq$ p-p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

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

Quick summary of A_J measurements

	R=0.4	R=0.2
Au+Au vs. p+p p_T^{Cut}>2 GeV/c	X	X
Matched Au+Au vs. p+p (p_T^{Cut}>0.2 GeV/c)	O	X

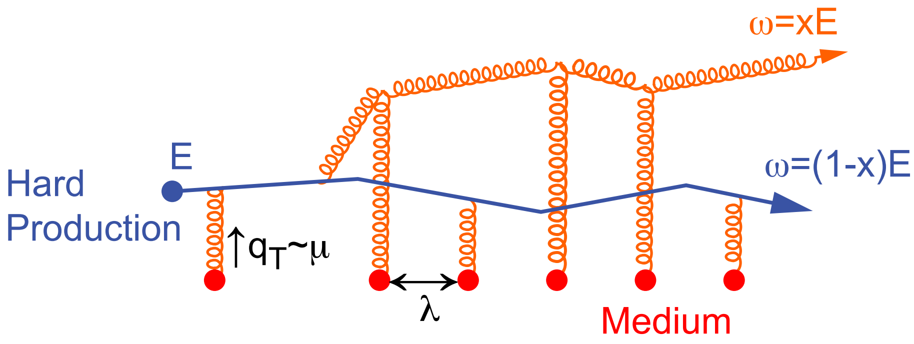
X = "*Non-identical*" A_J distribution (Au-Au vs. p-p)

O = "*Identical*" A_J distribution (Au-Au vs. p-p)

Jet geometry engineering underway

Interpretation

Gluon radiation: Multiple final-state gluon radiation off of the produced hard parton induced by the traversed dense colored medium



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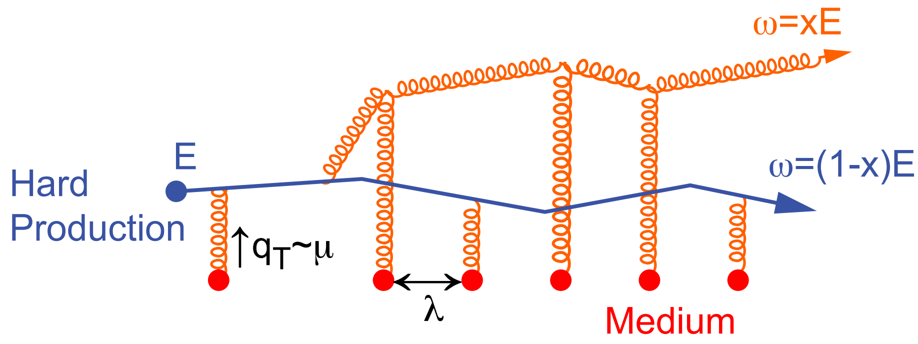
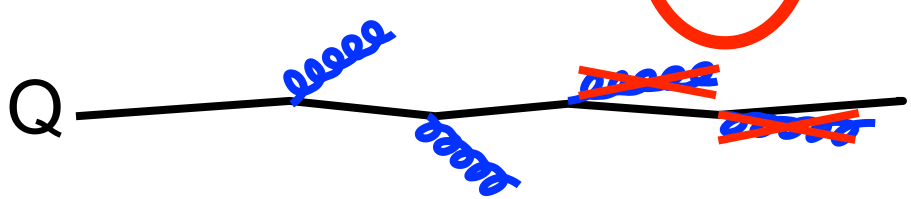


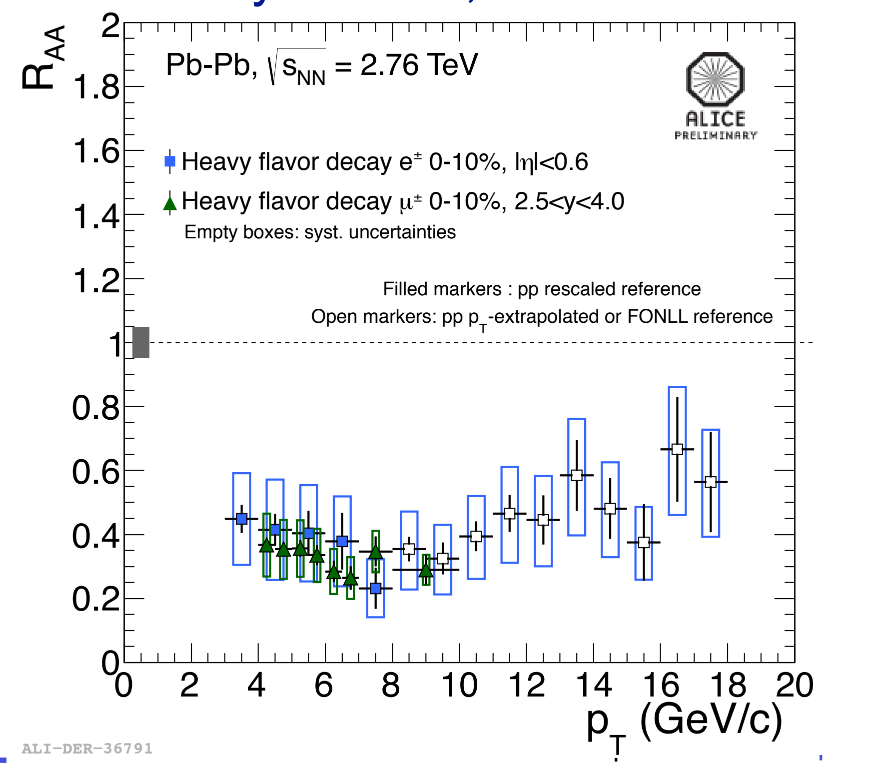
Dead cone effect implies less heavy quark energy loss in matter:

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

$$\omega \frac{dI}{dw}\Big|_{\mathrm{HEAVY}} = \frac{\omega \frac{dI}{dw}\Big|_{\mathrm{LIGHT}}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2\frac{1}{\theta^2}\right)^2}$$



Heavy flavor c,b → e K ν

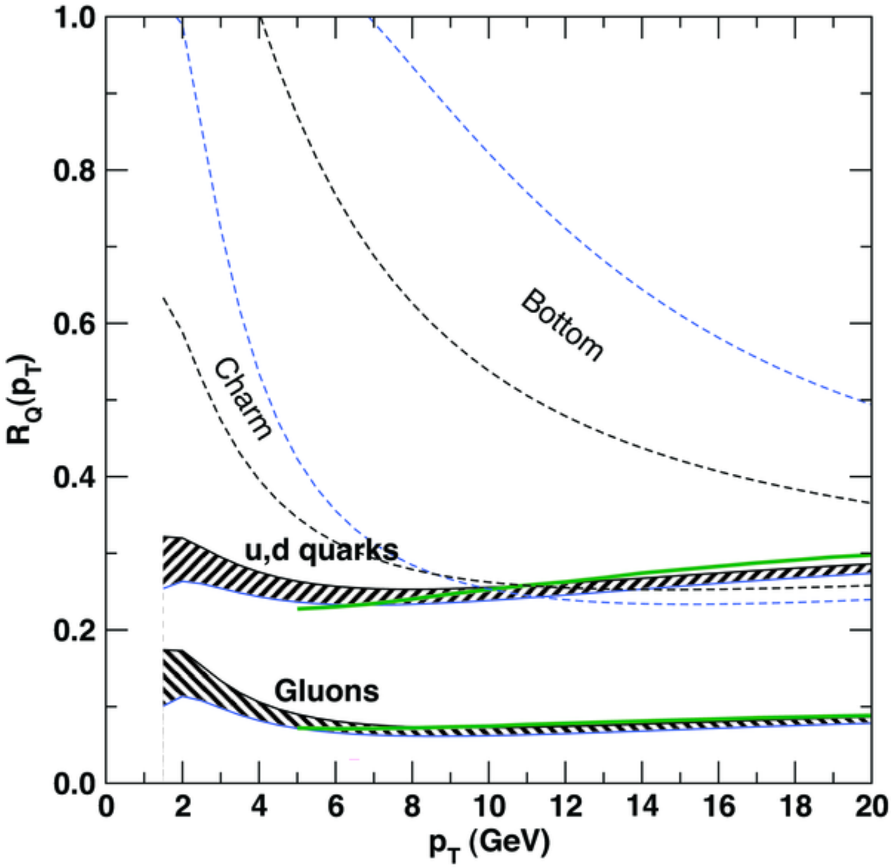


Heavy flavor JUST as suppressed

Identified charm R_{AA}

Need to disentangle charm and bottom contributions

Precision vertexing at LHC key



Wicks et al, Nucl. Phys. A784 (2007) 426

Identified charm R_{AA}

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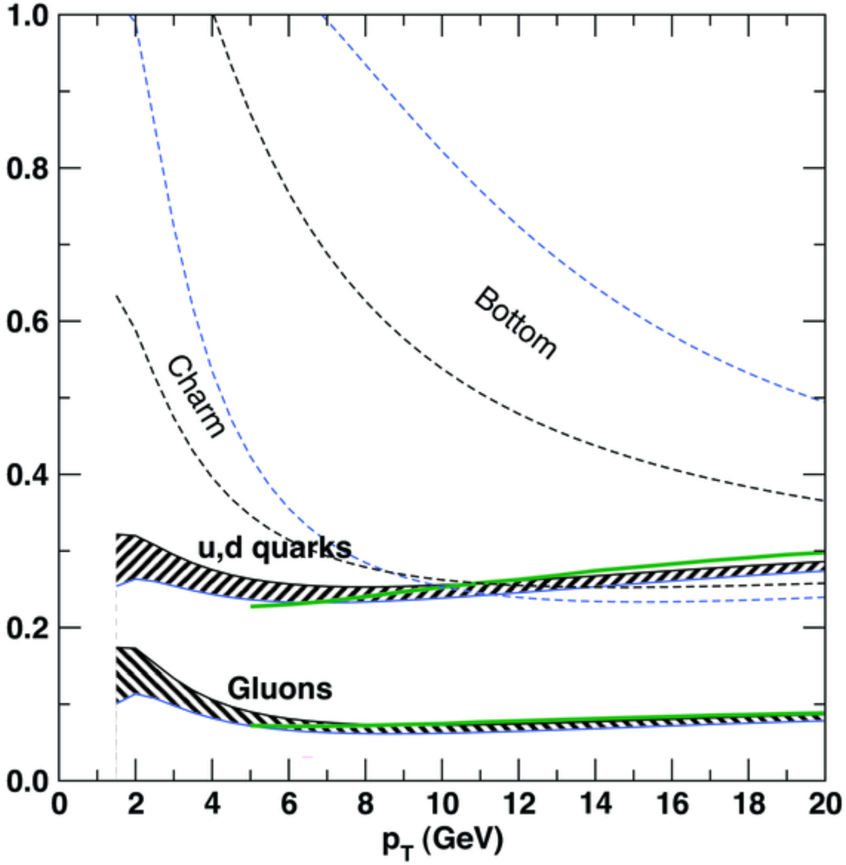
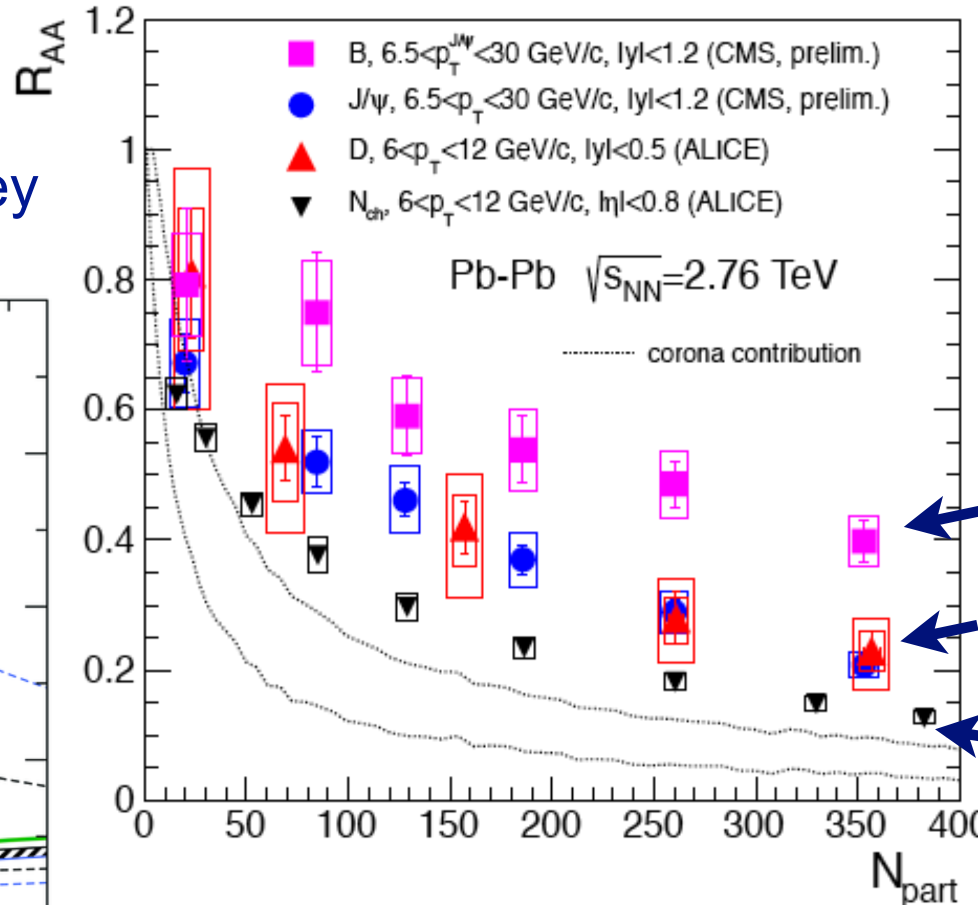
Precision vertexing at LHC key





$\Delta E_b < \Delta E_c \sim \Delta E_g$
c and g similar energy loss!

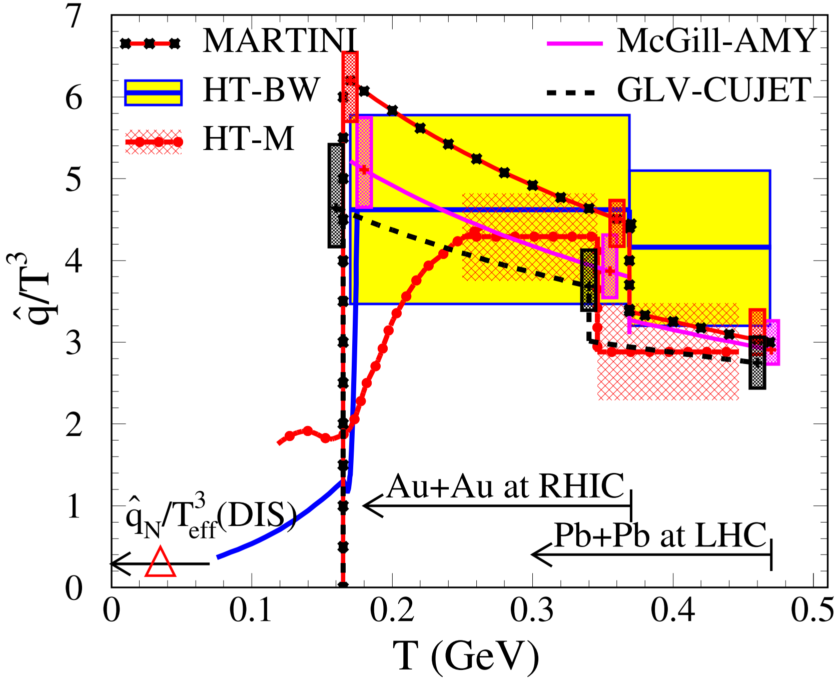
Wicks et al, Nucl. Phys. A784 (2007) 426

What has all this taught us?

Different initial conditions and evolutionary paths:

$\hat{q}$ ~ 1.2 ± 0.3 GeV^2/fm T=370 MeV
1.9 ± 0.7 GeV^2/fm T=470 MeV

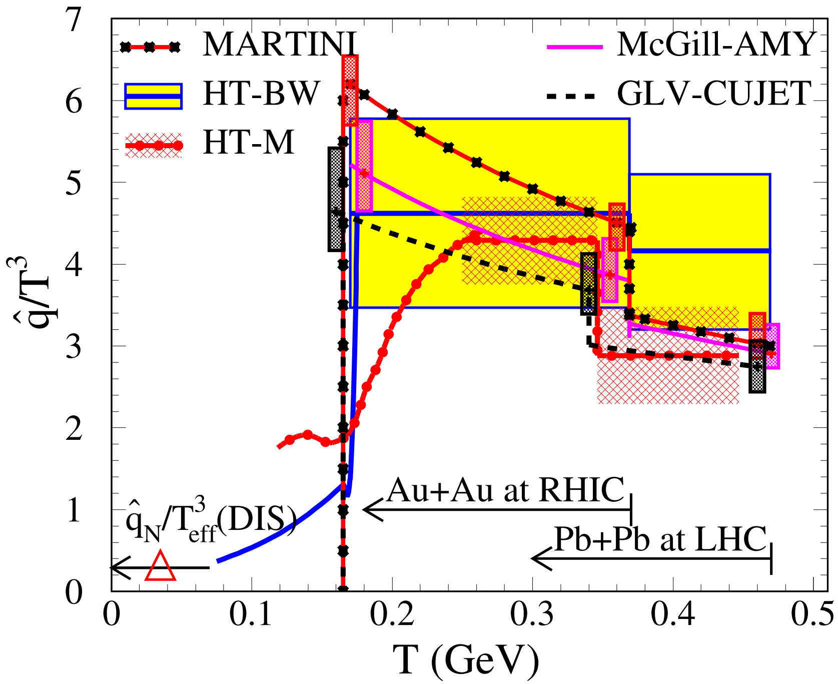
RHIC probes behave differently to LHC probes



What has all this taught us?

Different initial conditions and evolutionary paths:

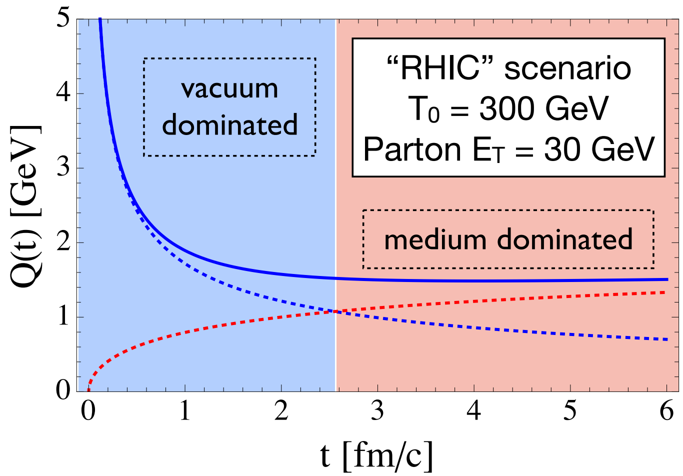
$\hat{q} \sim$ 1.2 ± 0.3 GeV^2/fm T=370 MeV
1.9 ± 0.7 GeV^2/fm T=470 MeV

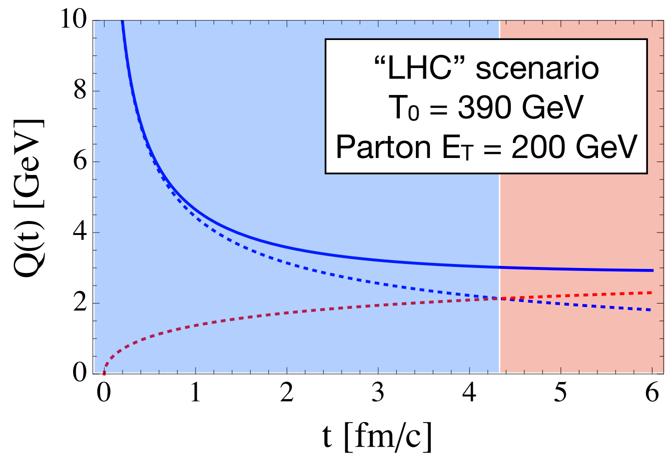


RHIC probes behave differently to LHC probes

Different virtuality evolutions:

How/when does parton become "aware" of medium





Summary

Experiments and the LHC operating wonderfully

As expected larger, denser, longer lived and more opaque source created at the LHC than at RHIC

Strong high p_T suppression for all observed particles including charm and bottom

- Highly opaque medium
- Path length dependence evident

Lost energy re-emerges as multiple low p_T particles

- Modification of fragmentation functions

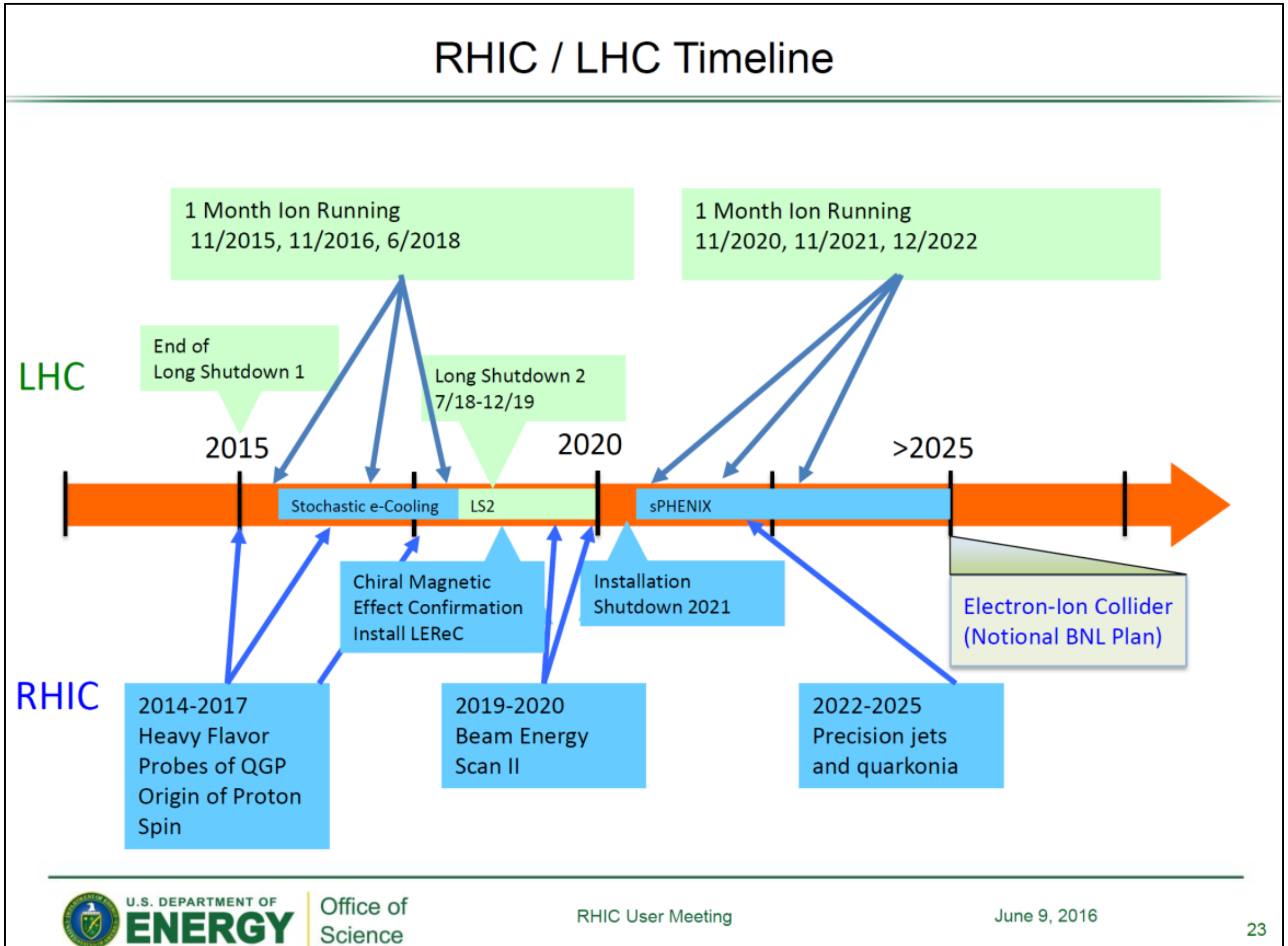
But there are still many open questions

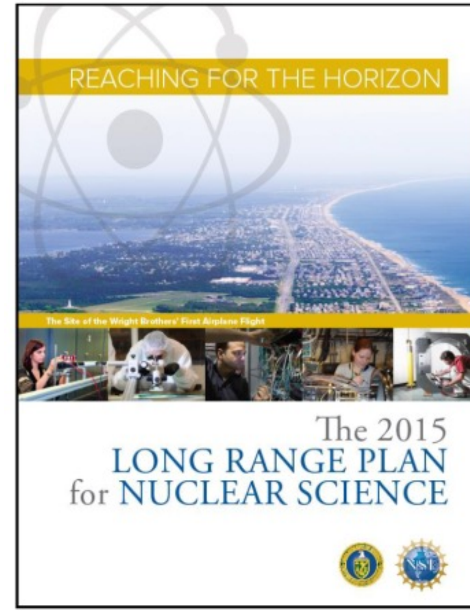
Just prying open the door to jet geometry engineering and jet shape studies

Our Long Range Plan

Lots left to do!!!!

DoE and internal support for our plan

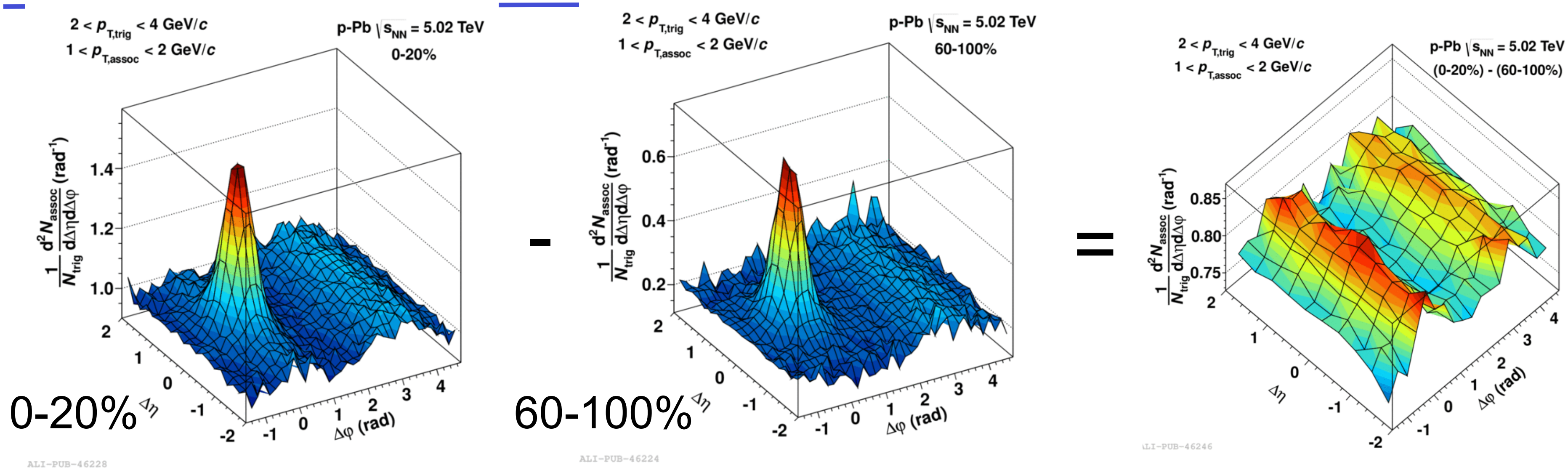




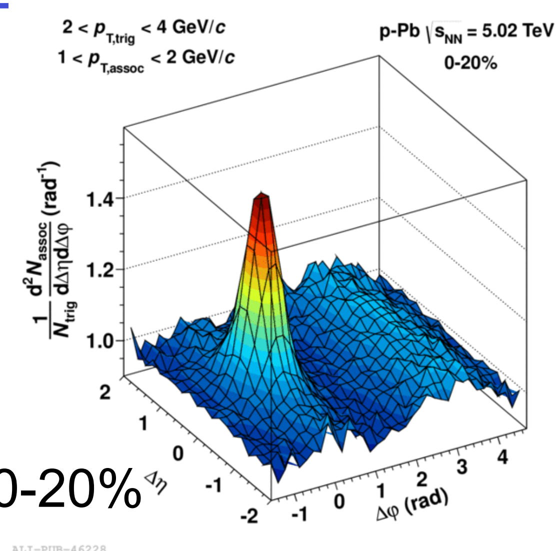
New detectors being designed and built NOW!

New accelerator being designed NOW!

Ridges in p-Pb

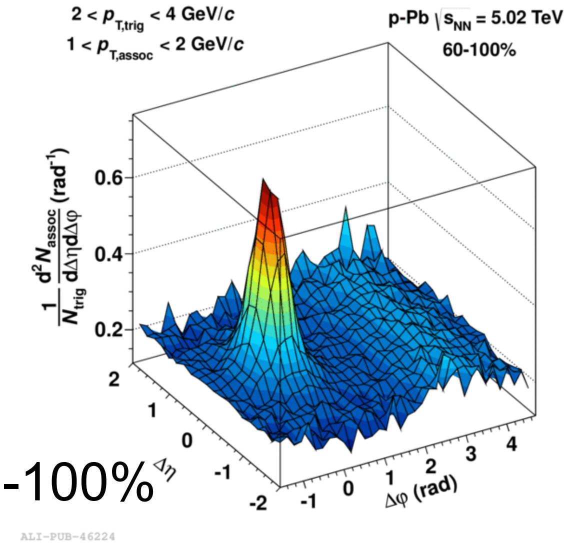


Ridges in p-Pb



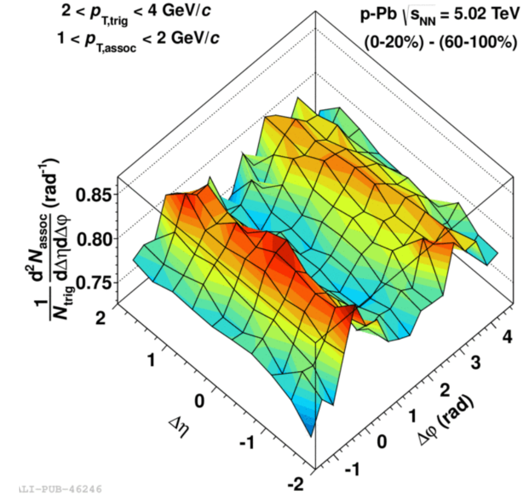
0-20%

\-

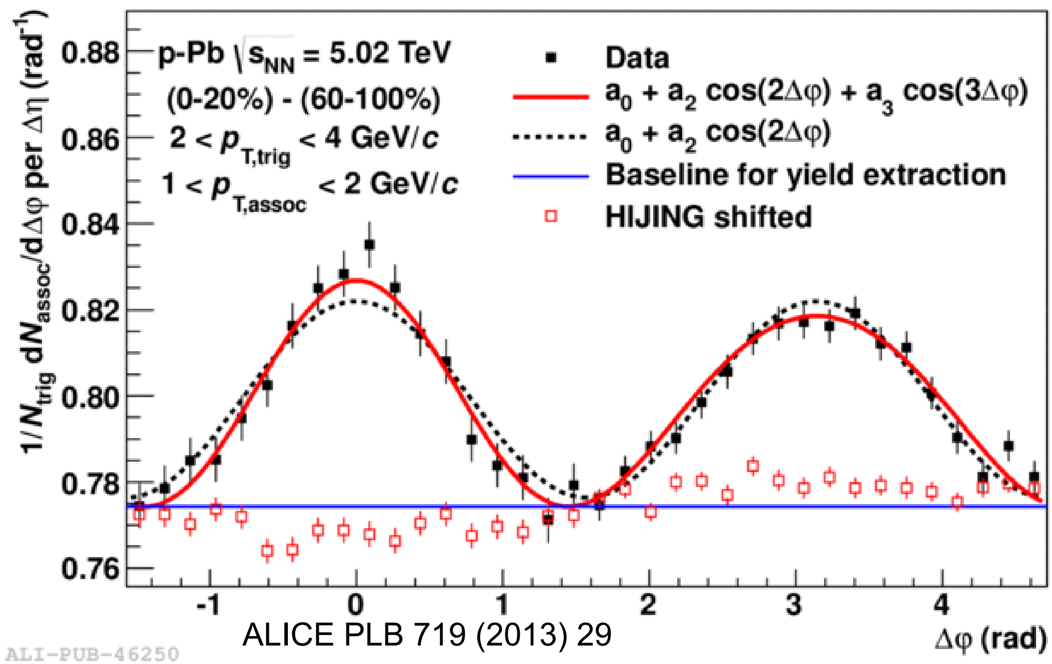


60-100%

=

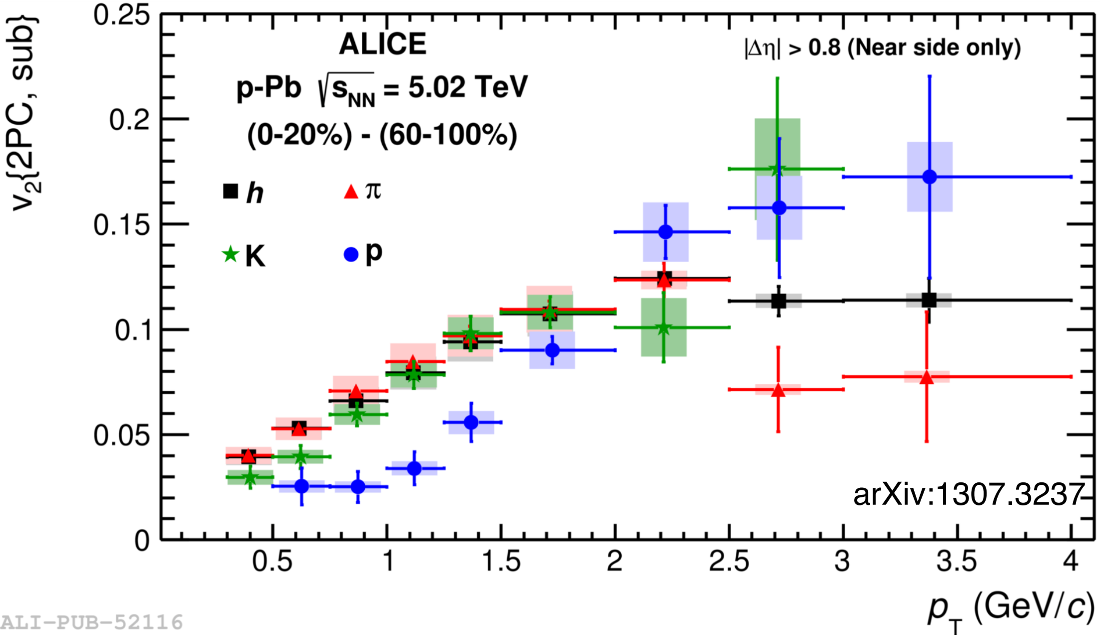


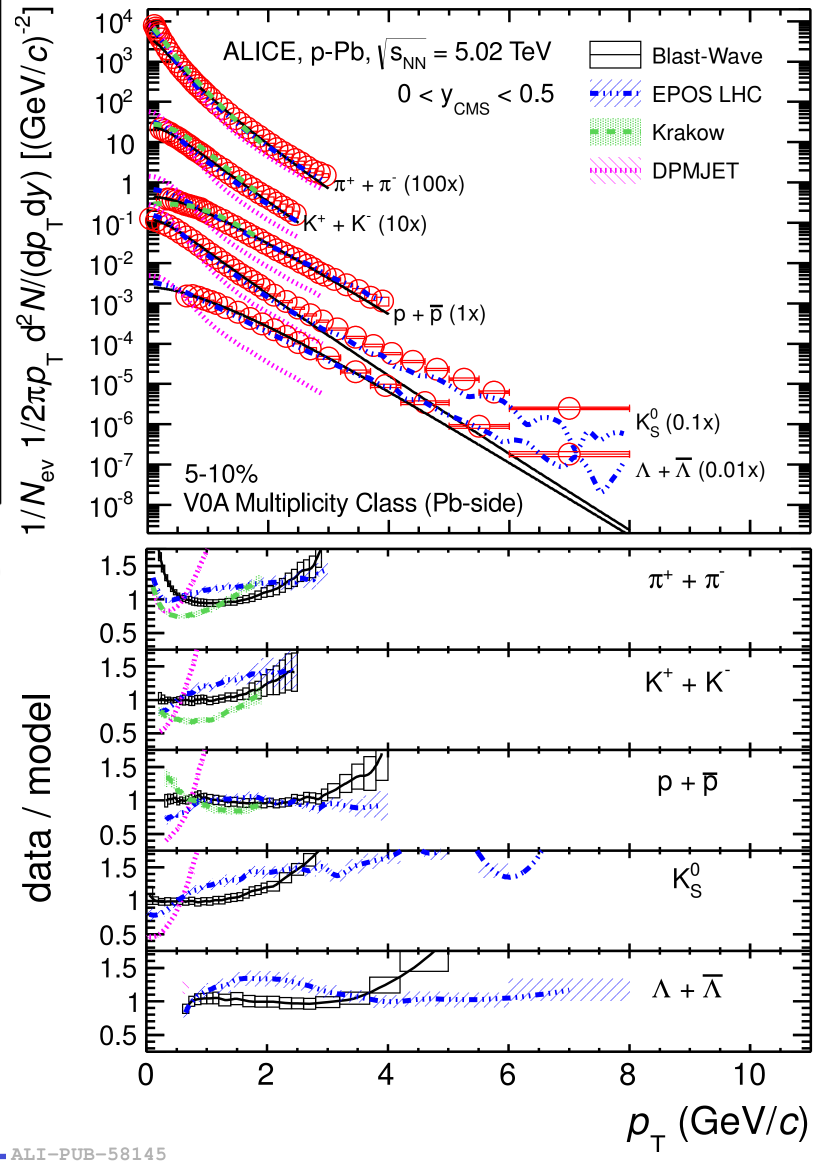
Flow in pPb or CGC?



ALICE PLB 719 (2013) 29

p-Pb v_2





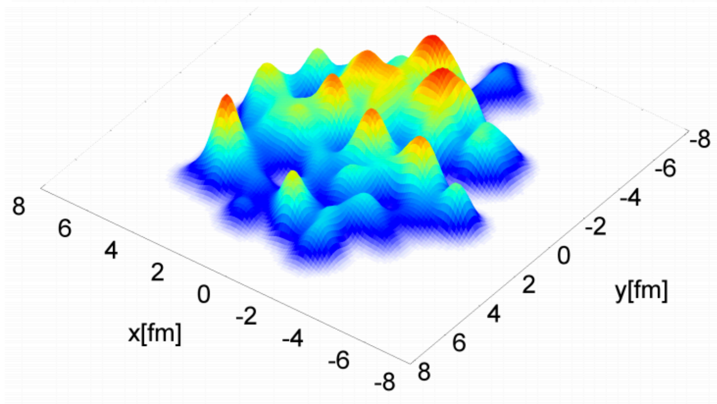
Mass dependence of v_2 and p_T spectra in p-Pb very similar to that in Pb-Pb

Collective motion in p-Pb systems?

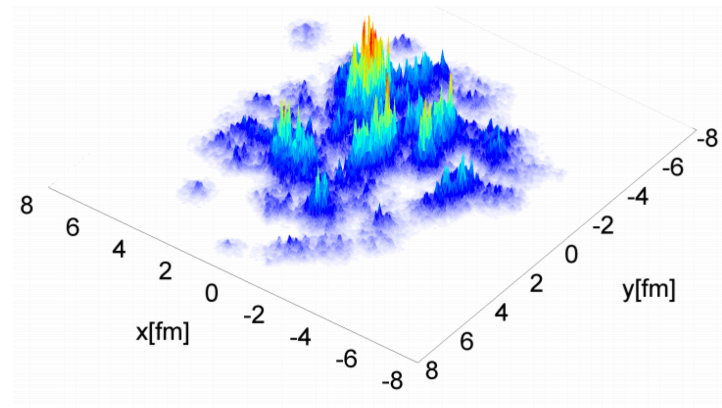
Our "simple" system is proving very complex!

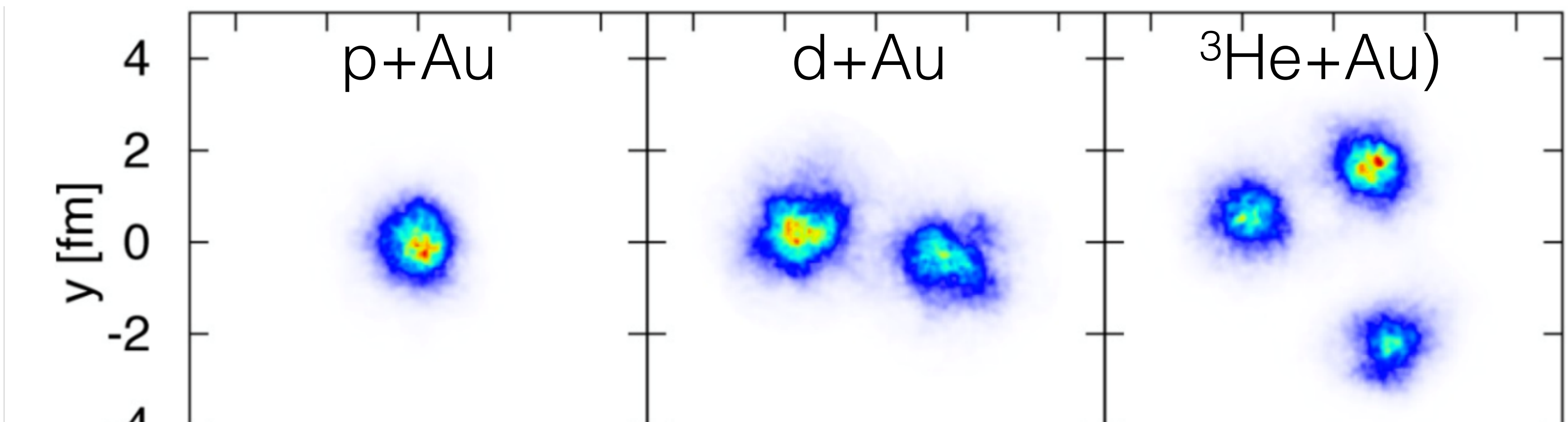
Testing geometry at RHIC

MC Glauber



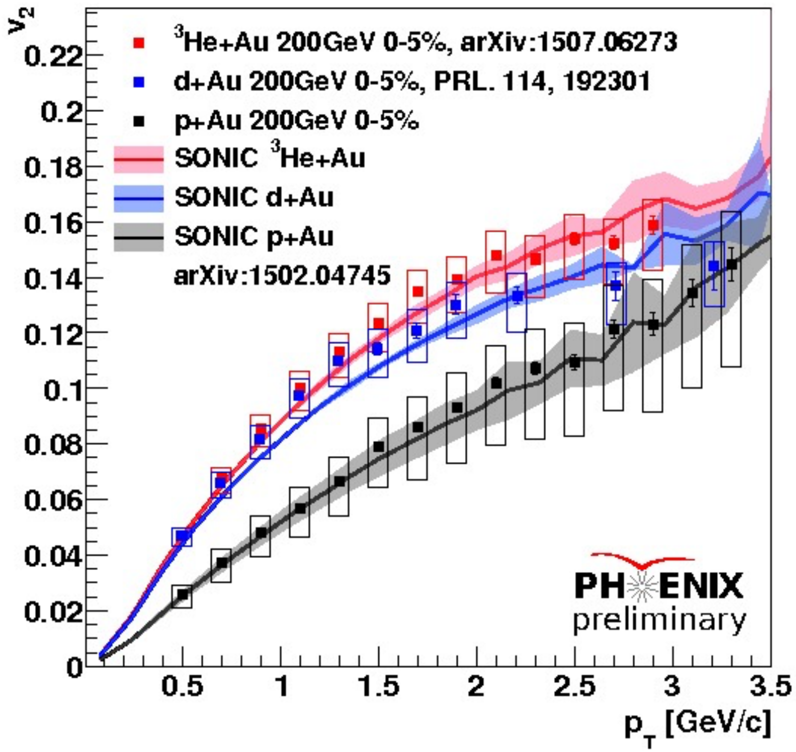
IPGlasma

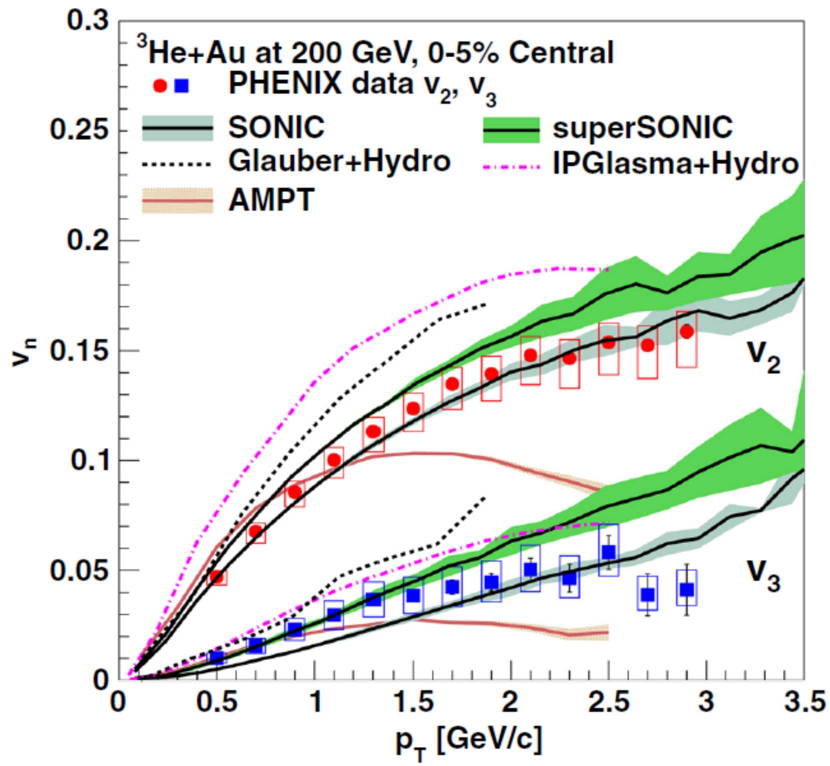




p+Au	d+Au	^{3}He+Au
$\varepsilon_2^{IPGlasma} = 0.10$	$\varepsilon_2^{IPGlasma} = 0.59$	$\varepsilon_2^{IPGlasma} = 0.55$
$\varepsilon_2^{Glauber} = 0.23$	$\varepsilon_2^{Glauber} = 0.54$	$\varepsilon_2^{Glauber} = 0.50$

Small systems scan





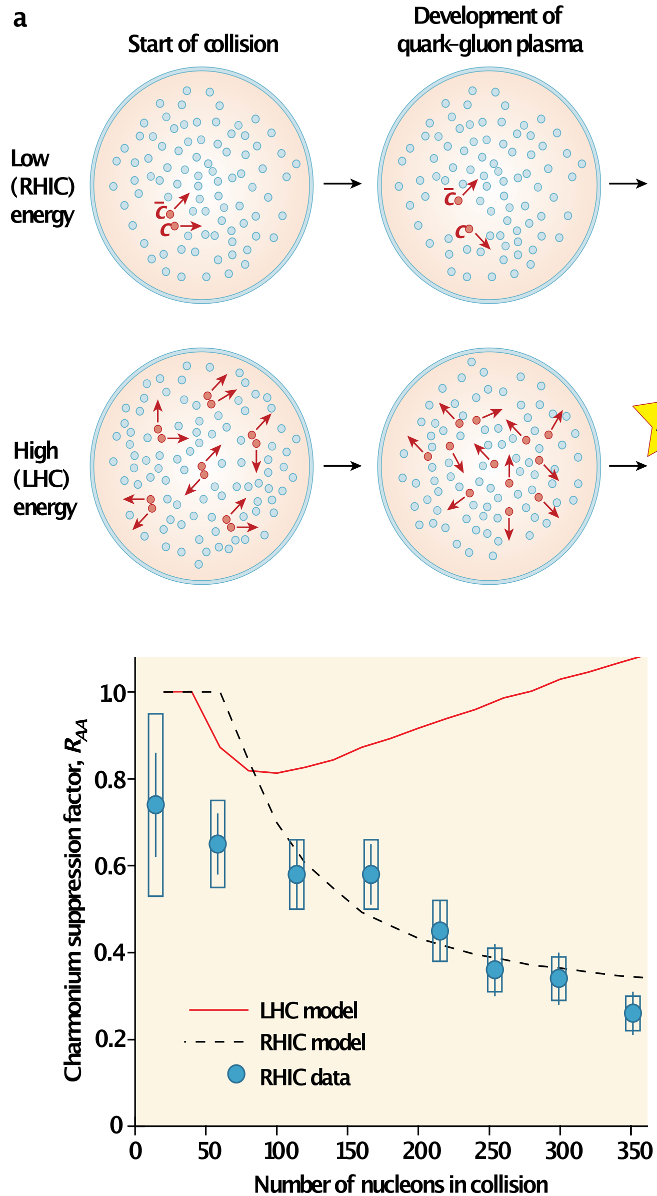
Elliptic flow seen in all systems!

v_3 only in He^3-Au as expected

Agreement with hydrodynamical calculations suggests systems really are flowing

Results under serious discussion with theorists

Sufficient charm for regeneration?



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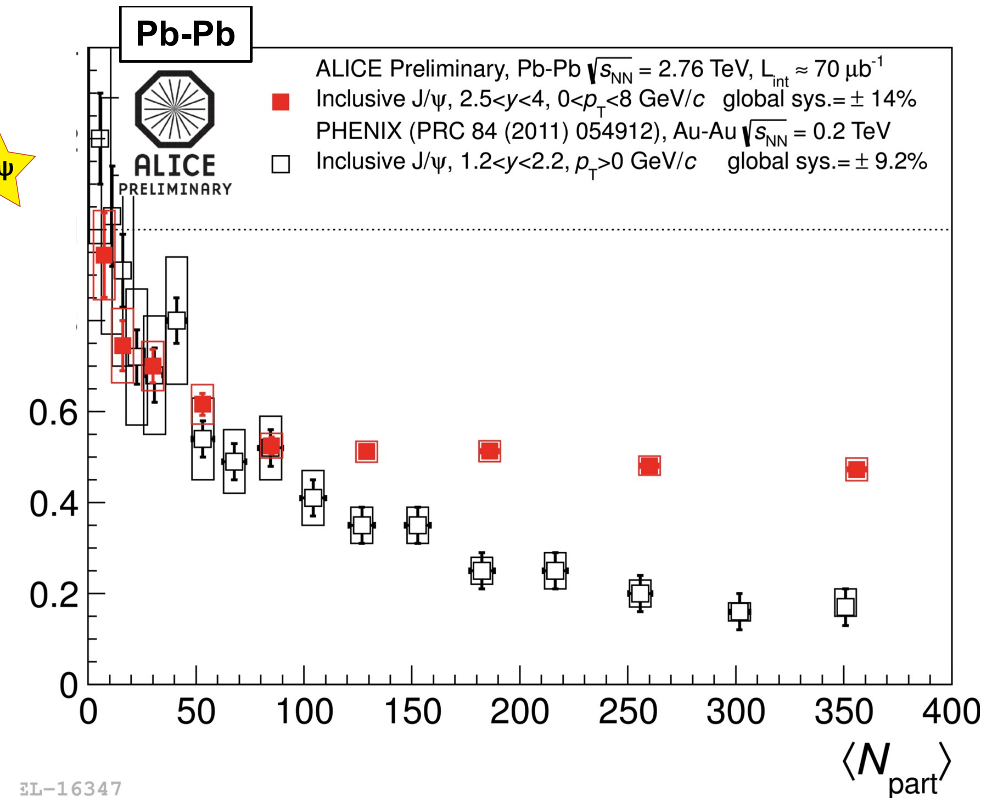
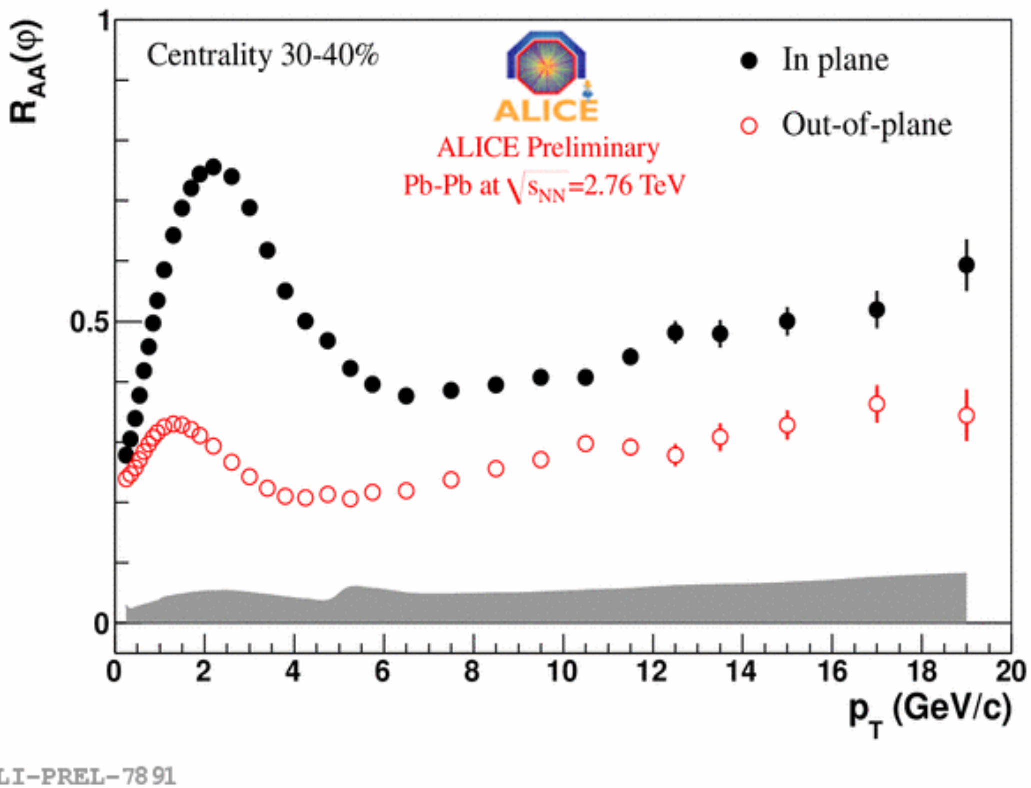
Braun-Munzinger & Stachel, Nature Vol. 448 (2007)

Regeneration of J/Ψ at the LHC?



Suppression vs. event plane



More suppression for charged hadrons exiting out-of-plane

- longer average path length in the medium

R_{AA}, jet measurements (and correlations) are providing lots of data on partonic E_{loss}