Relativistic Heavy Ions II - Studying the QGP

2010 Hadron Collider Physics Summer School

Fermi Lab - August 2010

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Yale University

Outline:

Defining a Calibrated Prob

High p_T Phenomena

News from the LHC

Recap of yesterday's lecture

The matter we create in the laboratory at RHIC is the **sQGP**
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

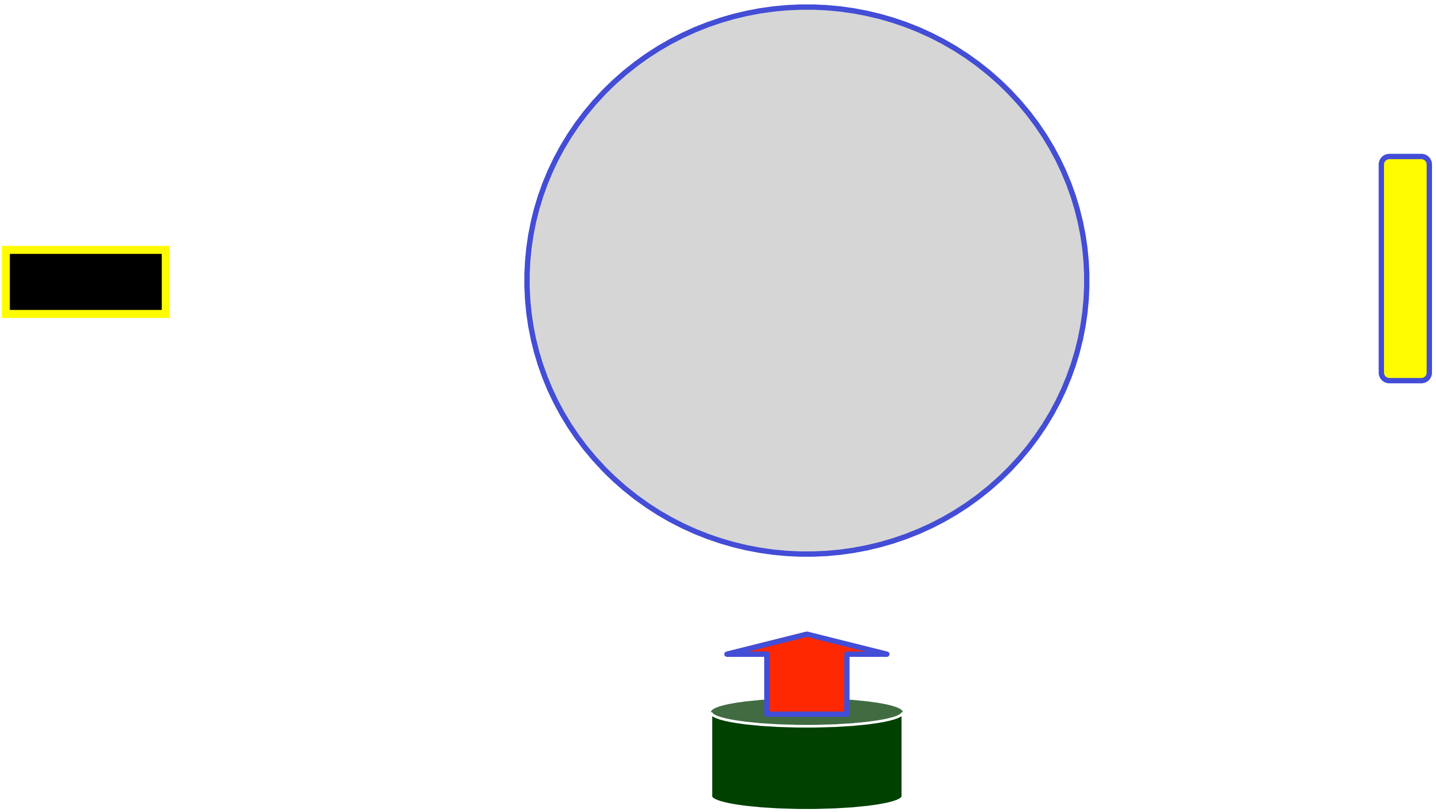
nearly "perfect" fluid

and appears to have

quark and gluon degrees of freedom

Defining a probe - Hard processes

Matter we want to study



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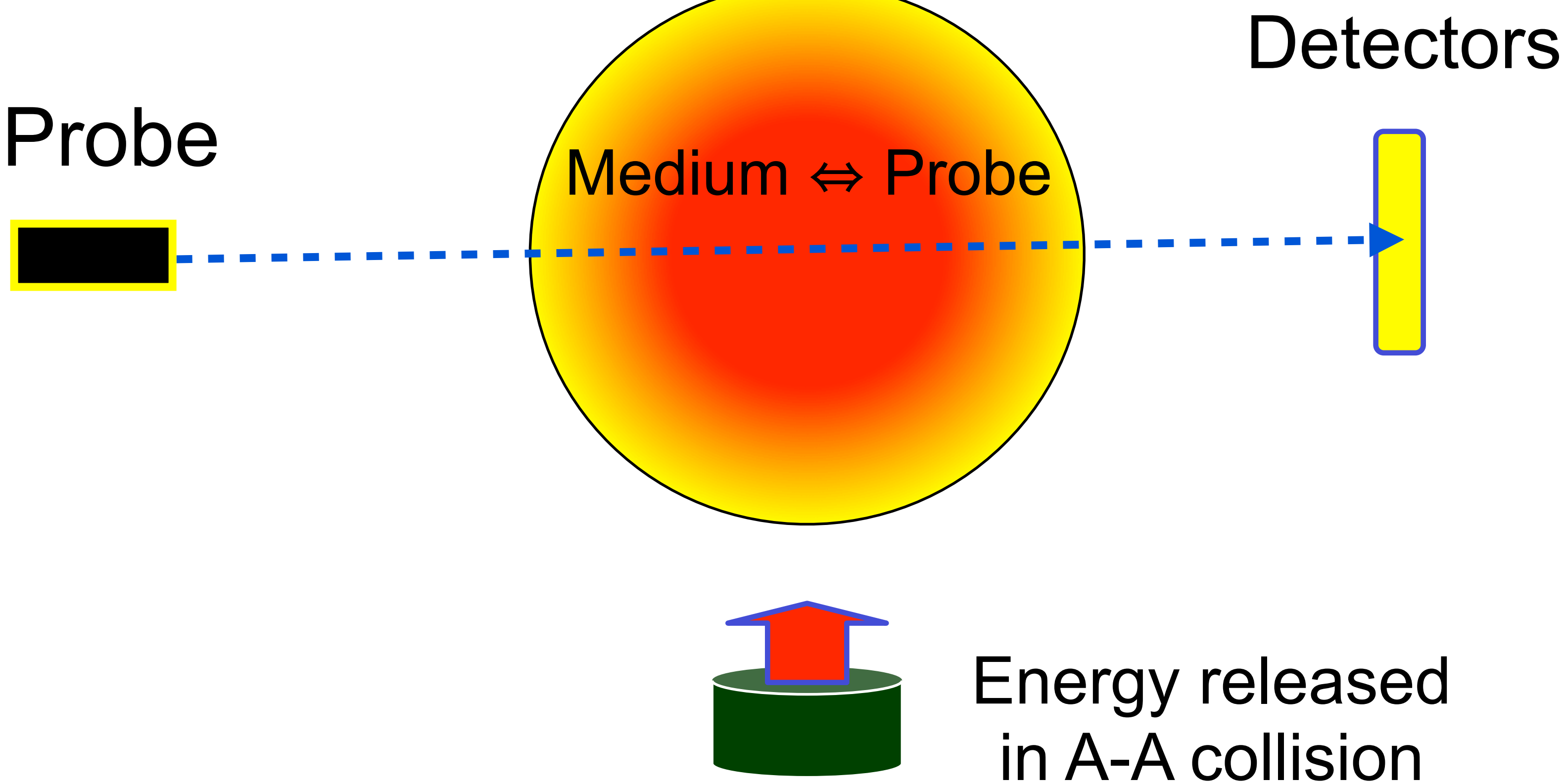
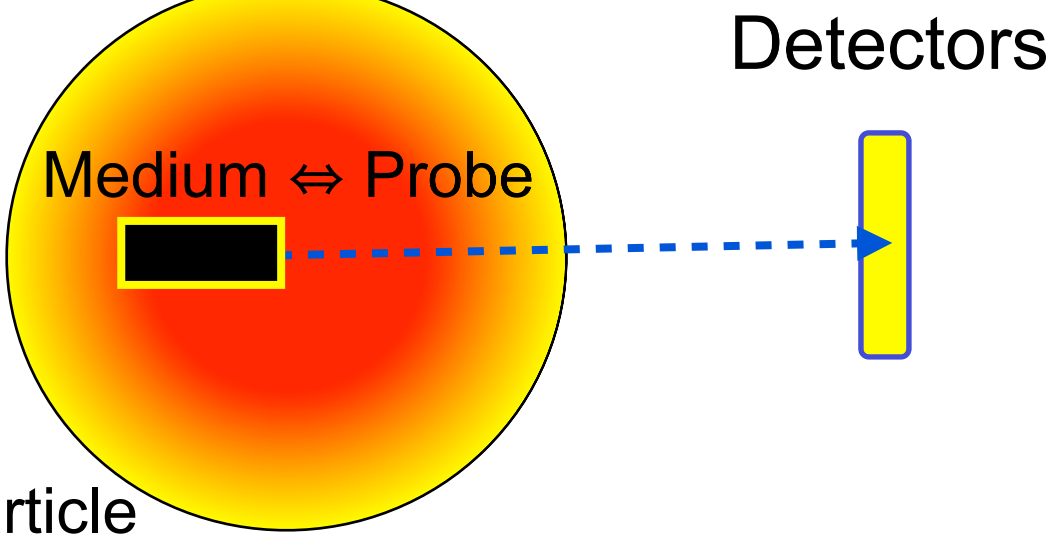


Energy released
in A-A collision
(27 TeV for Au-Au at RHIC)

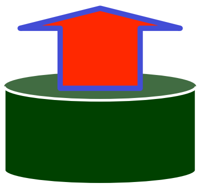
Defining a probe - Hard processes

Matter we want to study

Self-generated &
calibrated probes



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



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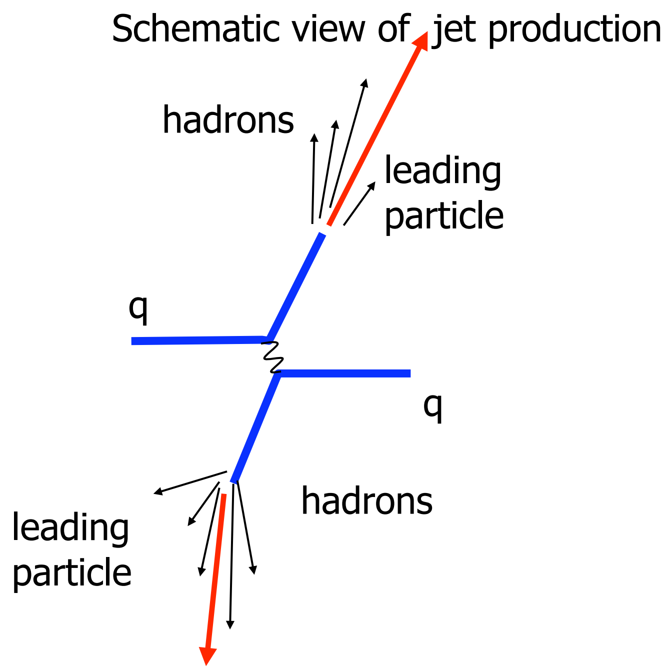
Using "hard" particles as probes

'Hard' processes have a large scale in calculation → 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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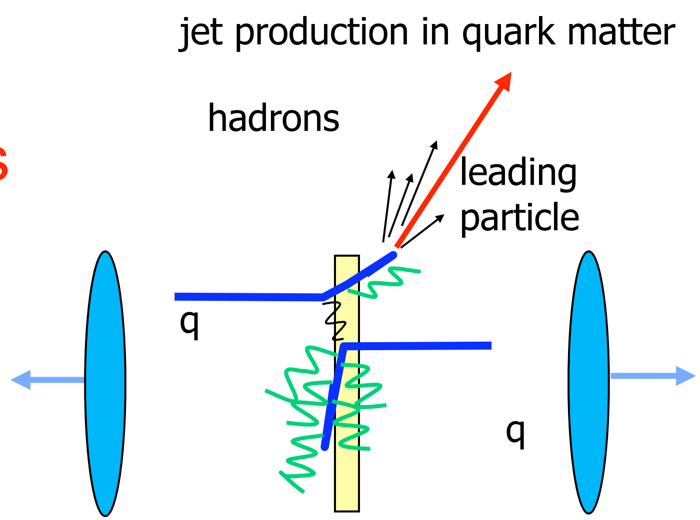
Direct interaction with partonic phases of the reaction

i.e. a calibrated probe



Look for attenuation/absorption of probe

Hard probes of dense matter (Bricks)

quark (color triplets)

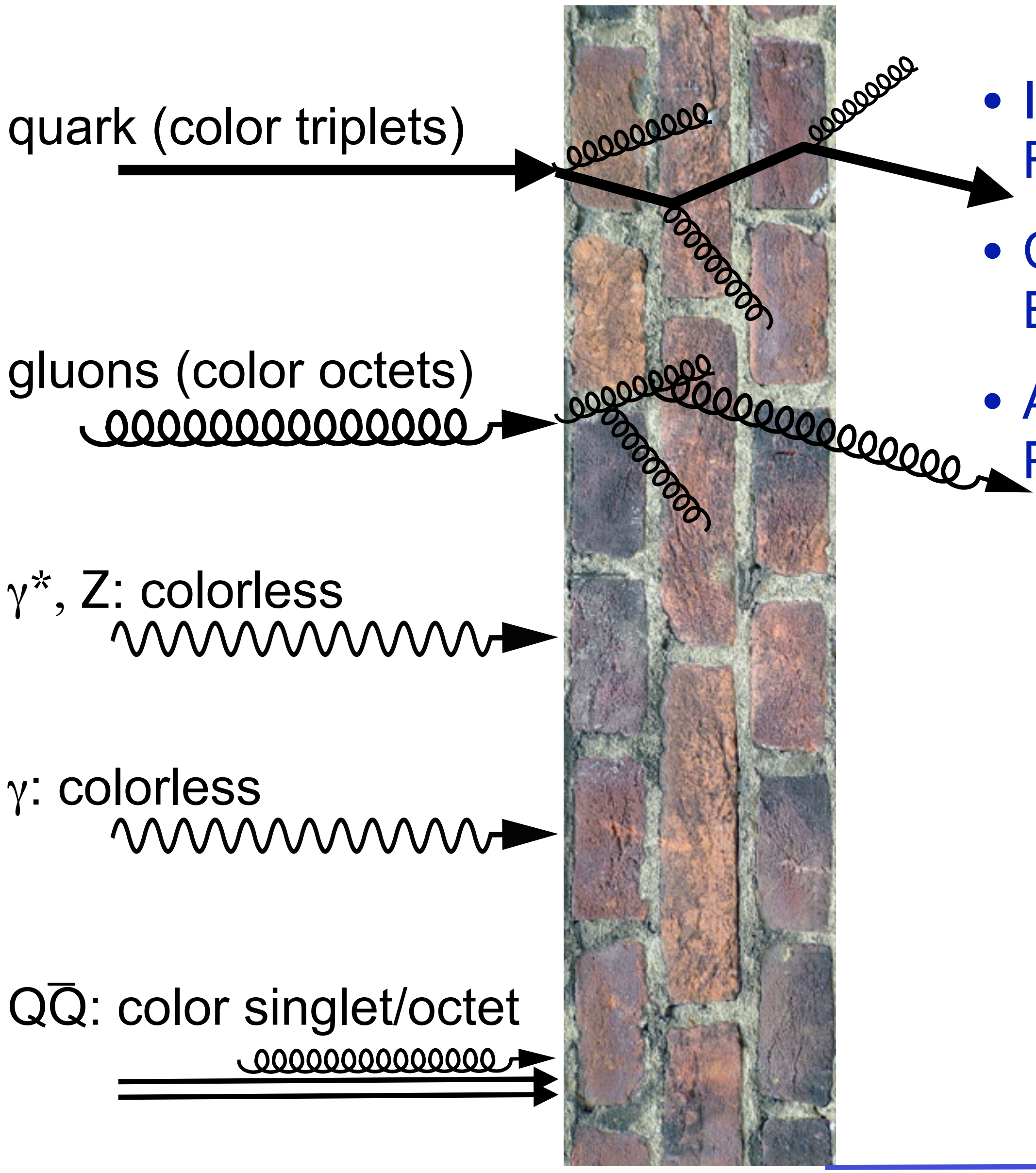
gluons (color octets)

γ^*, Z: colorless

γ: colorless

$Q\bar{Q}$: color singlet/octet

Hard probes of dense matter (Bricks)



- Induced Gluon Radiation
- Collisional Energy Loss
- Absorption as Pre-Hadrons

Yields:

- transport coefficient
- Gluon Density
- Energy Density

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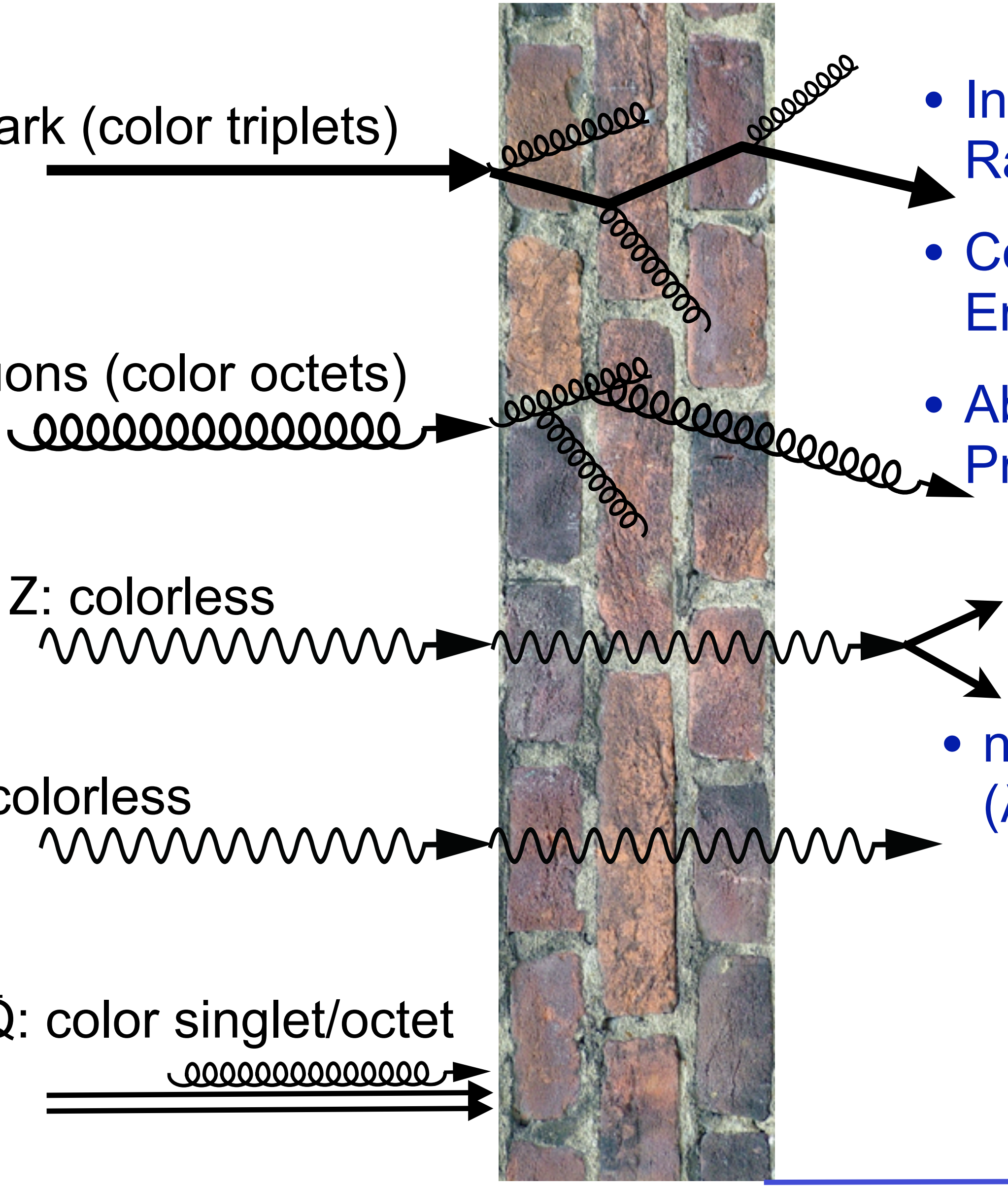

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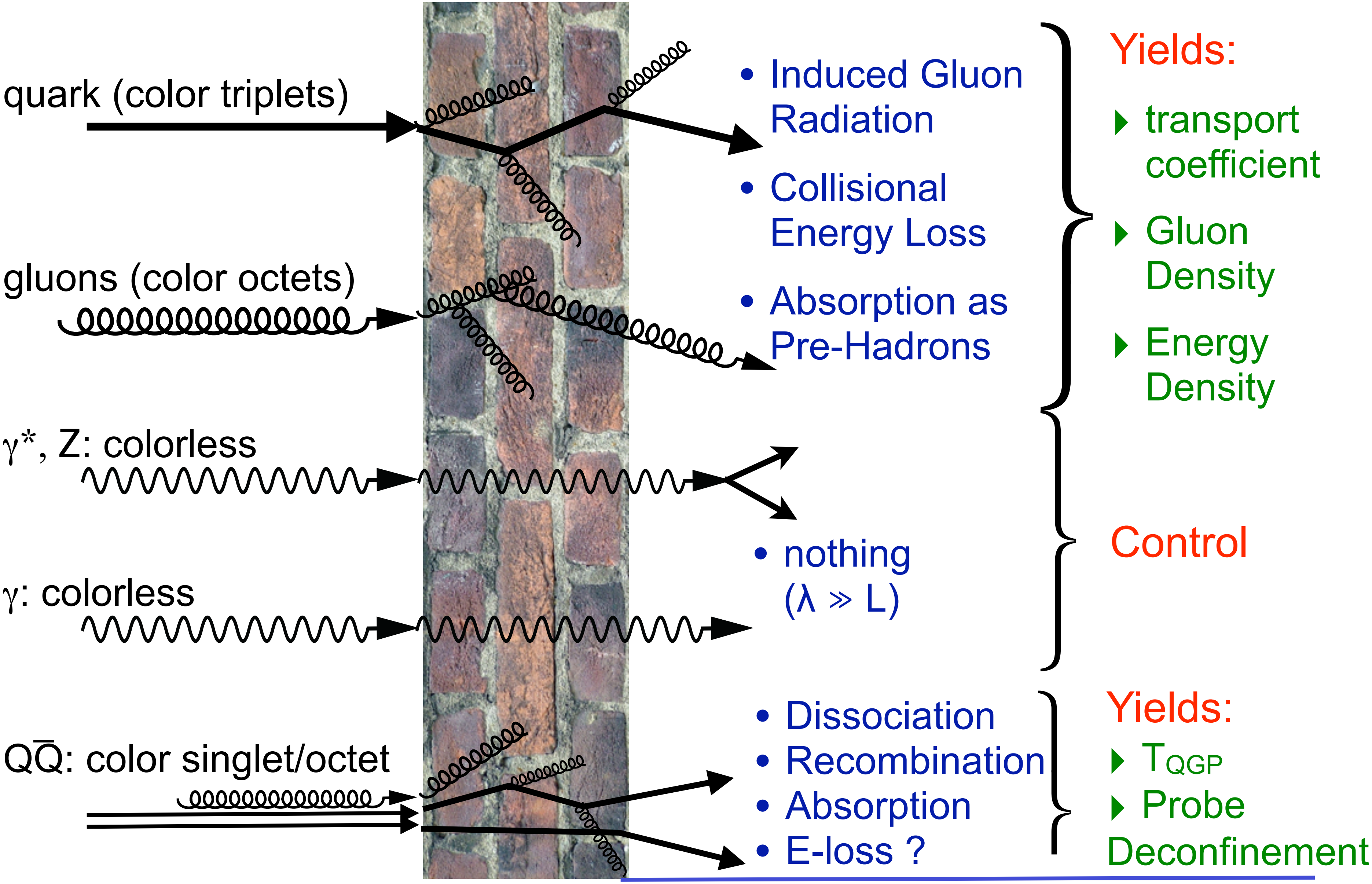
- nothing ($\lambda \gg L$)

Control

Hard probes of dense matter (Bricks)



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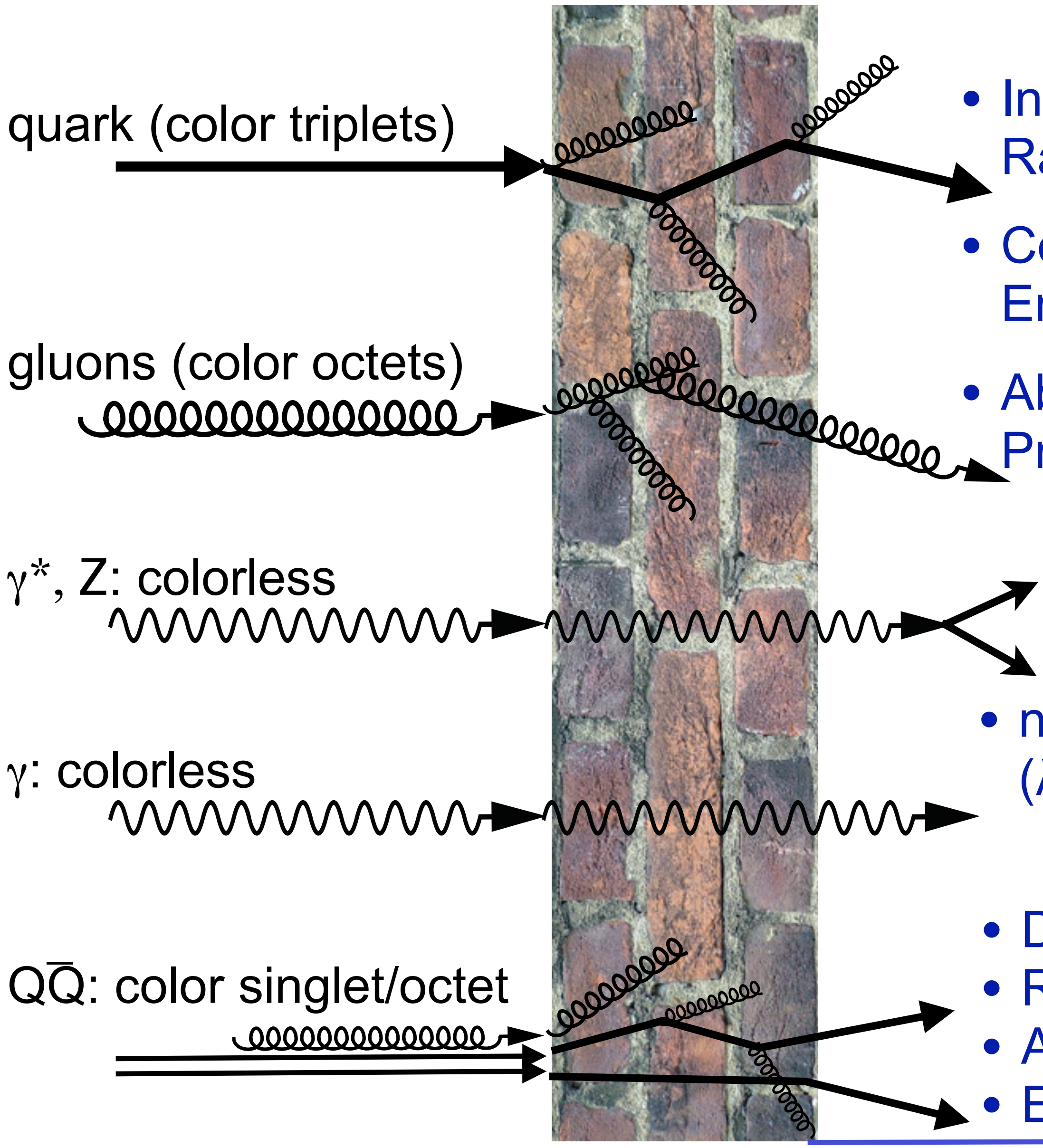

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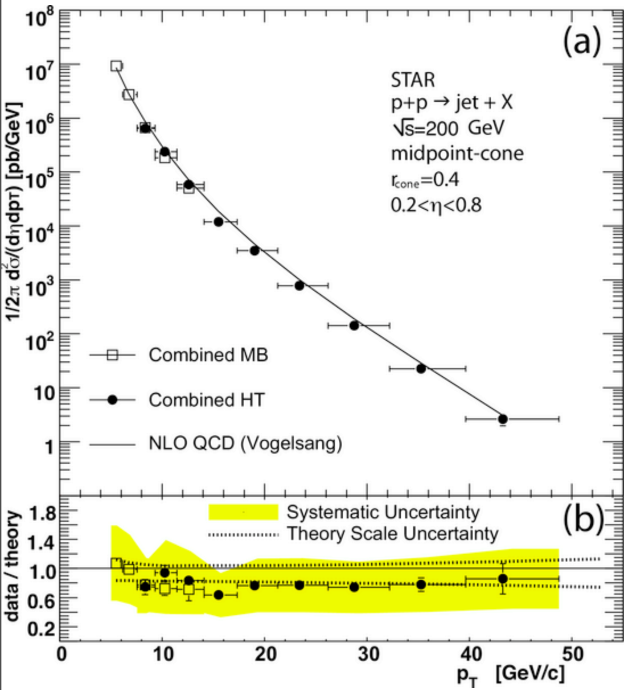
Control

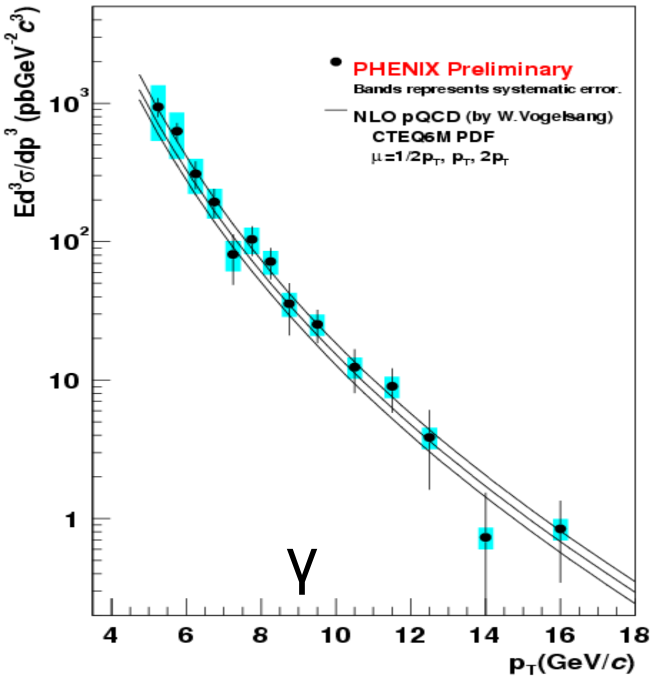
- Dissociation
- Recombination
- Absorption
- E-loss ?

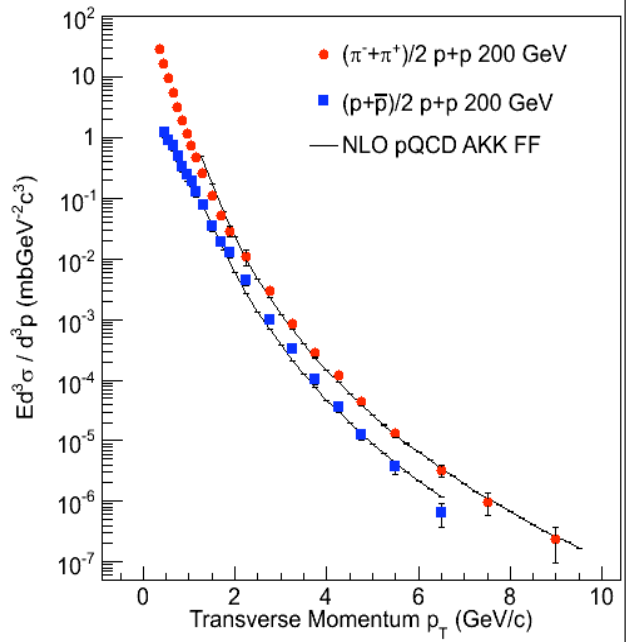
~~Yields:~~
- T_{QGP}
- Probe Deconfinement

High p_T production – a calibrated probe



STAR : PRL 97 (2006) 252001





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 7 orders of magnitude.
- 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

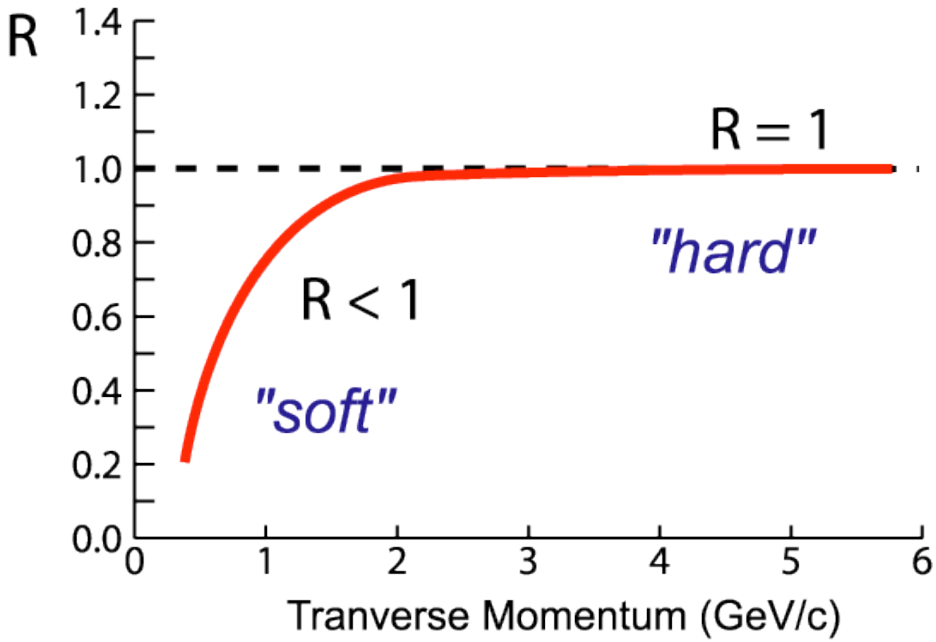
Looking for attenuation/absorption

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 collision in A-A collision

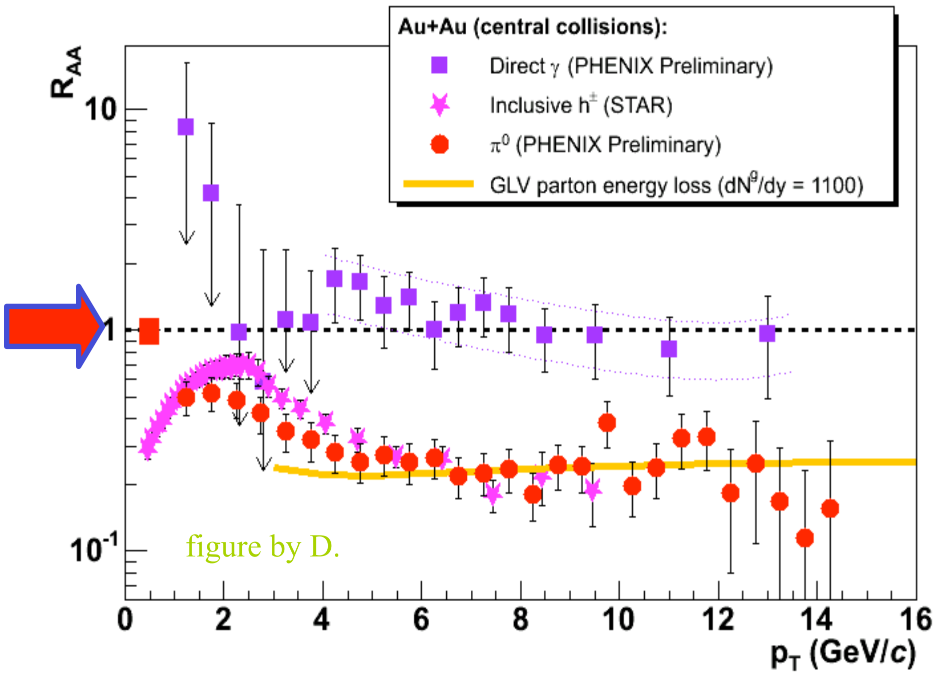


No "Effect":

- 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

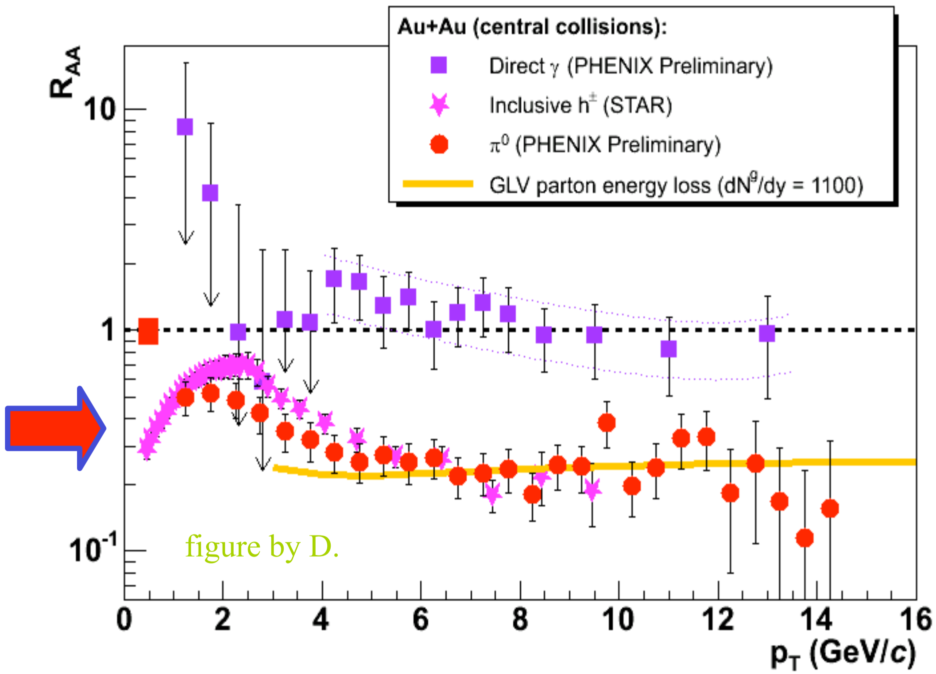
High-p_T suppression



Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works

High-p_T suppression



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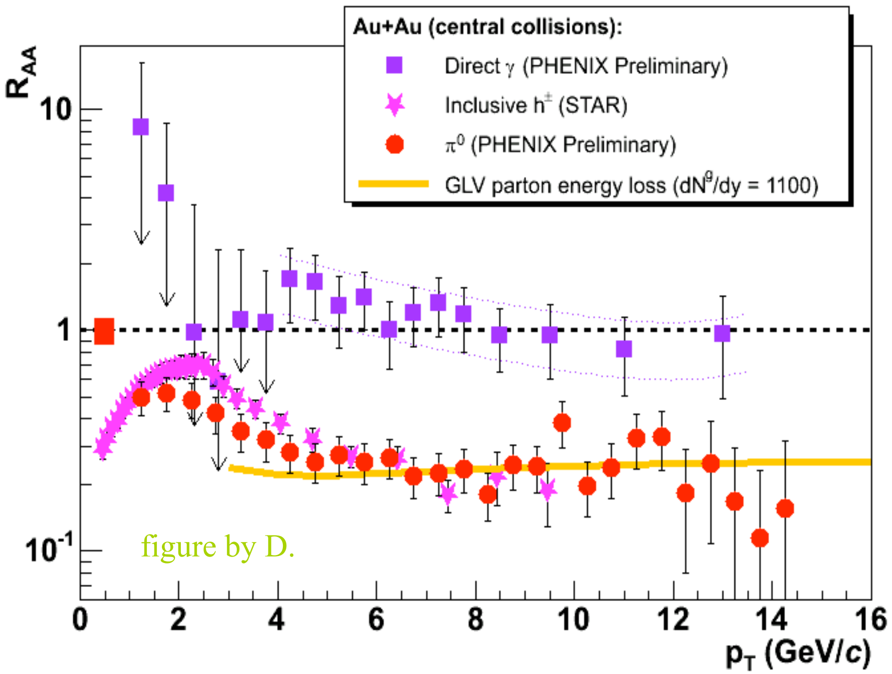

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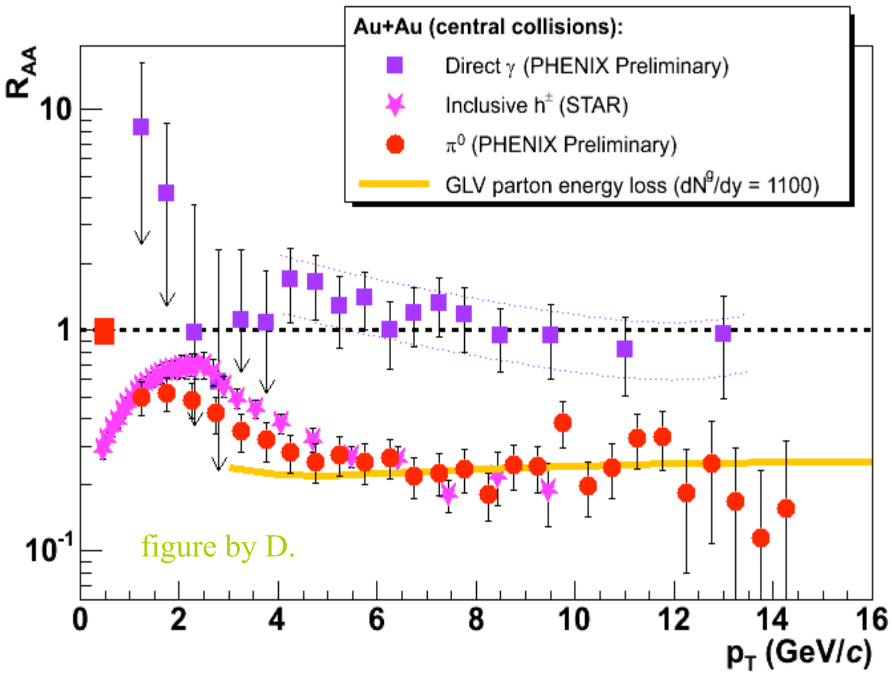

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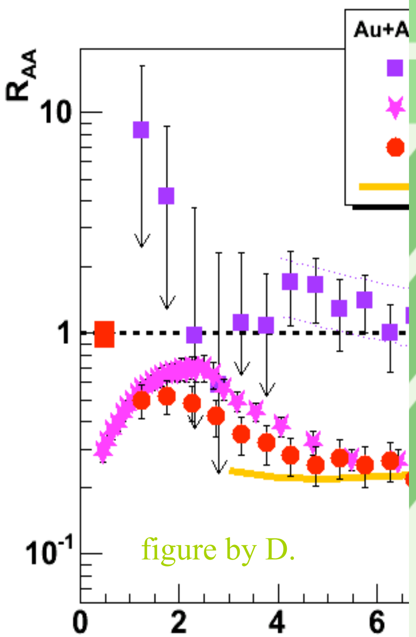
sQGP - strongly coupled - colored objects suffer large energy loss

High-p_T suppression



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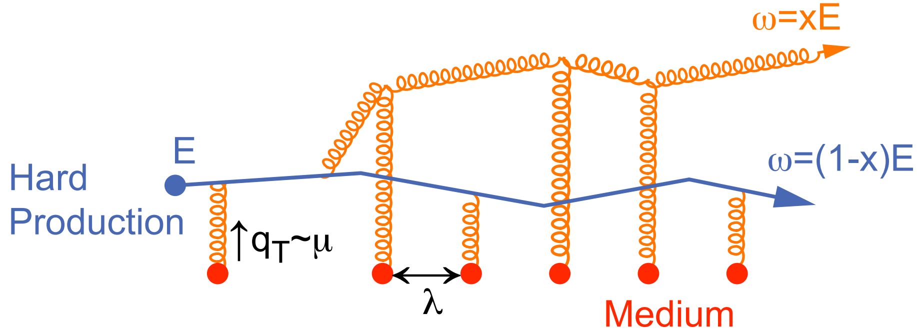
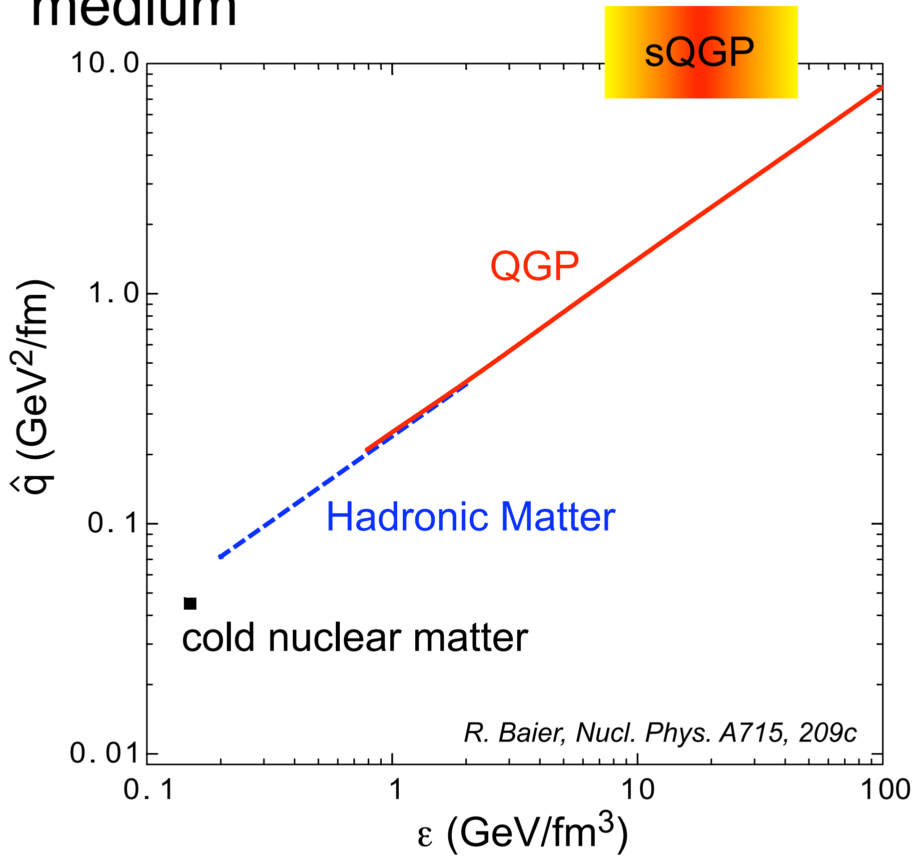
Interpretation



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



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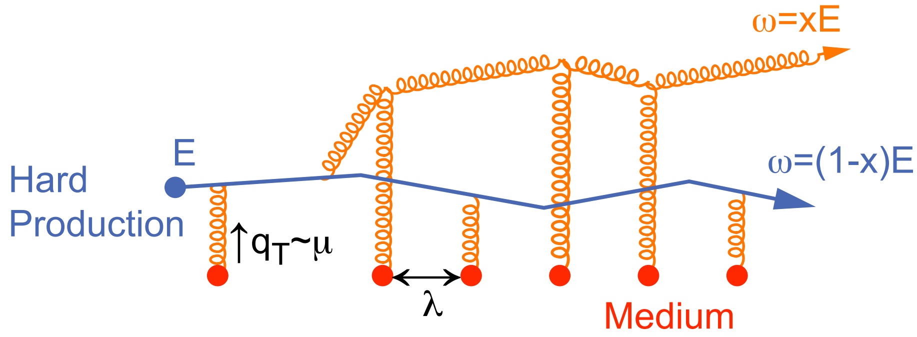
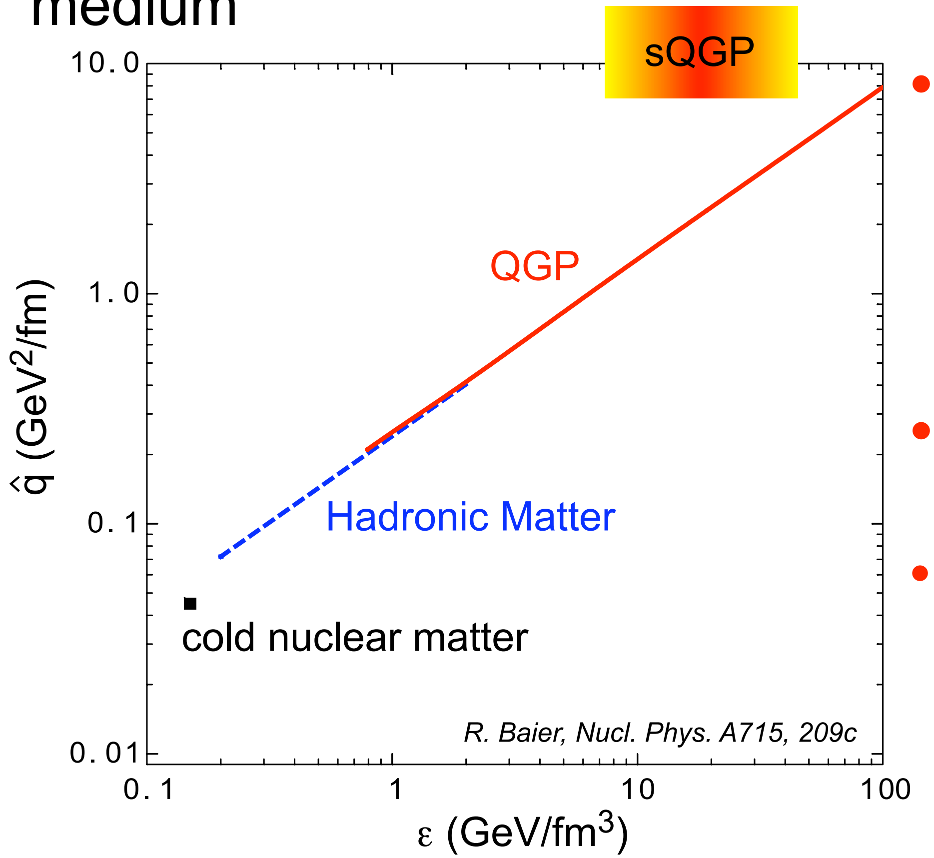




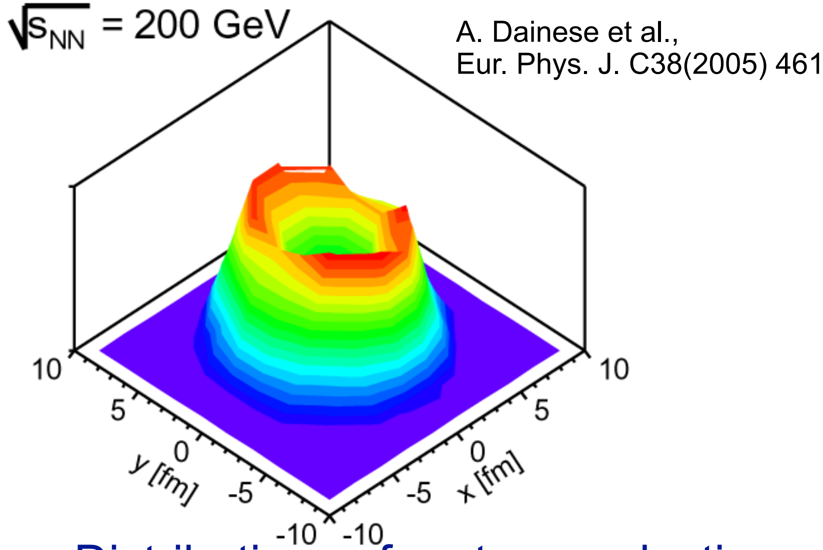
- Mean parton energy loss $\propto$ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim \Delta L^2$ (medium length)

    $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$
- is $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length

$\hat{q}$ ~5-10 GeV/fm

The limitations of R_{AA}

Insensitivity due to surface emission:

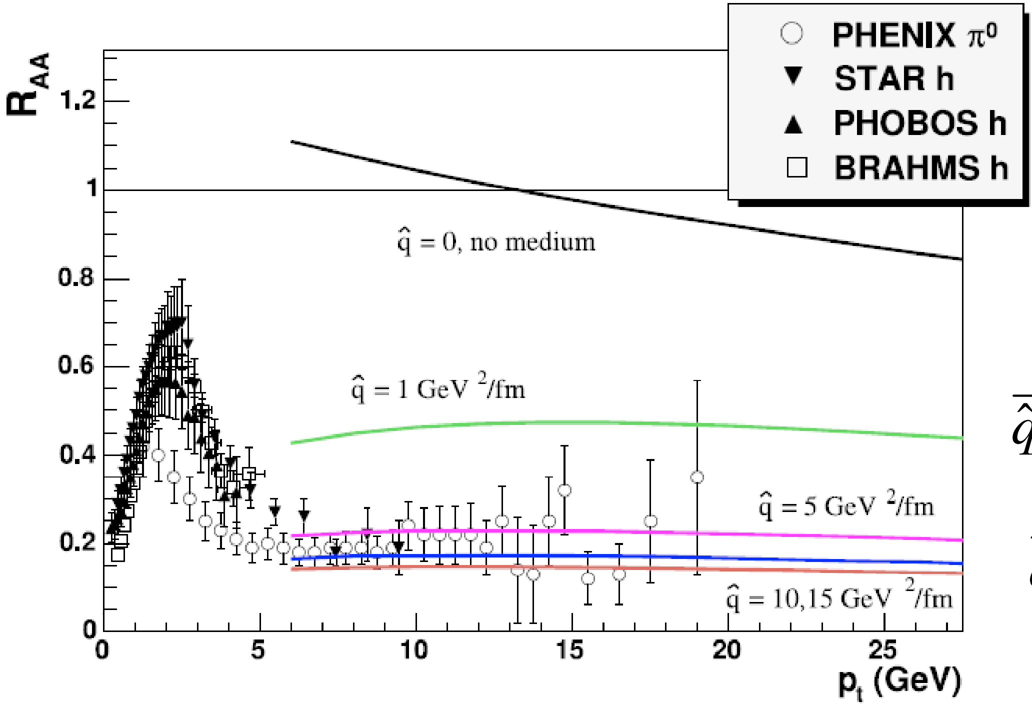


Distributions of parton production points in the transverse plane

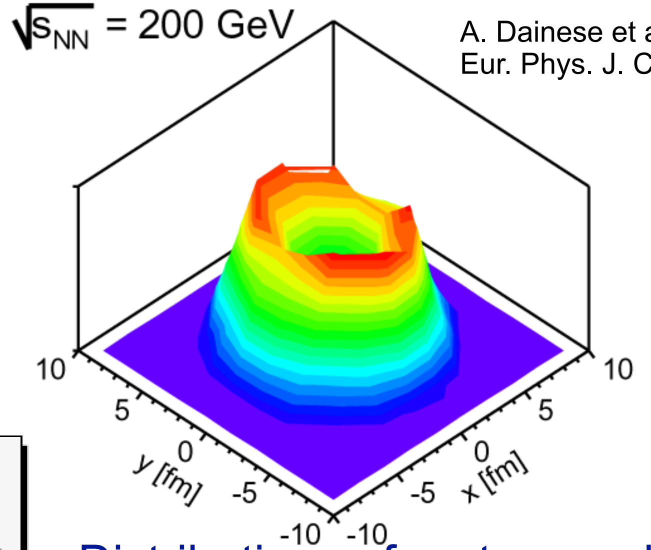
The limitations of R_{AA}

Insensitivity due to surface emission:

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



[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:

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

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

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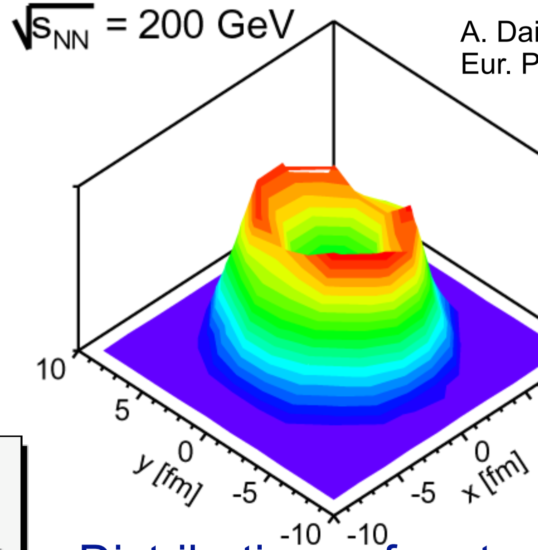

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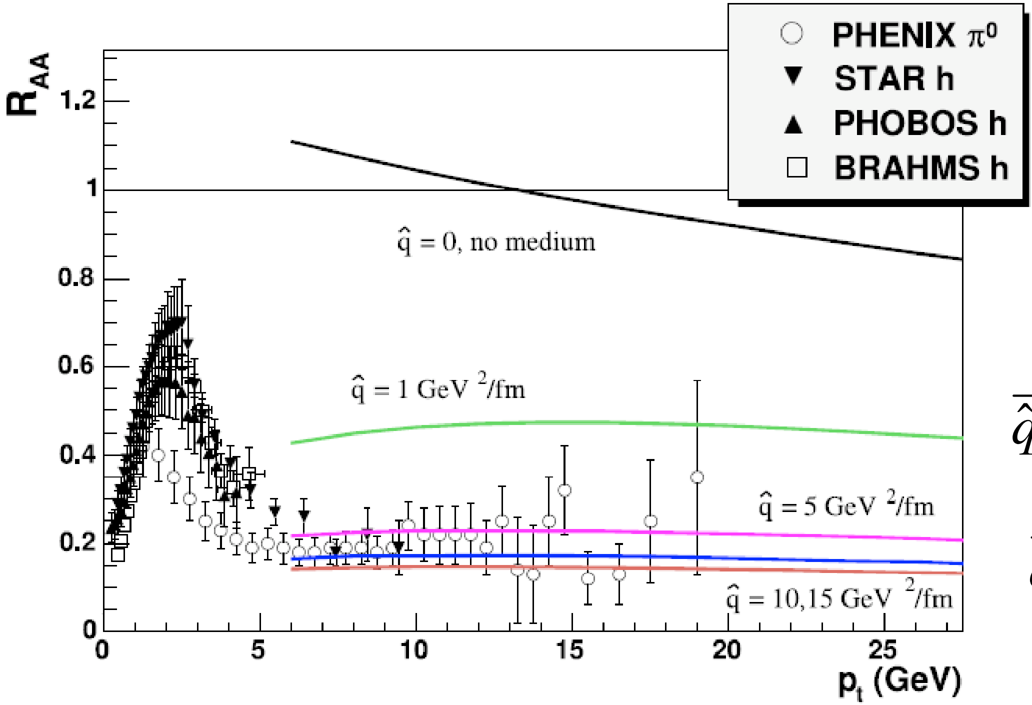

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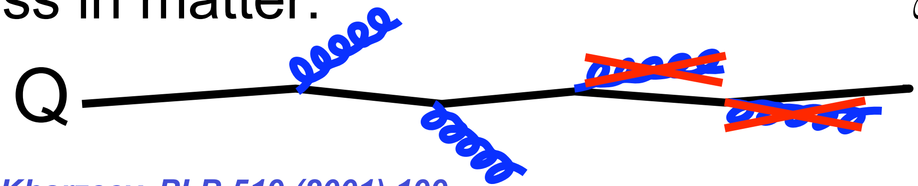
Need better tool

Heavy quarks are gray probes

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



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

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

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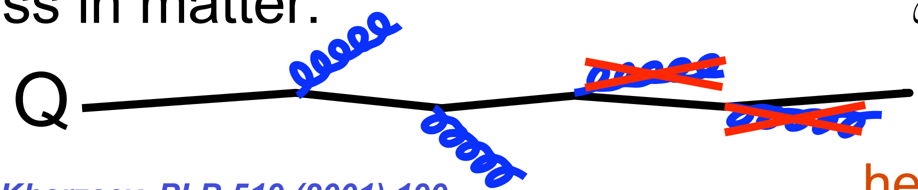

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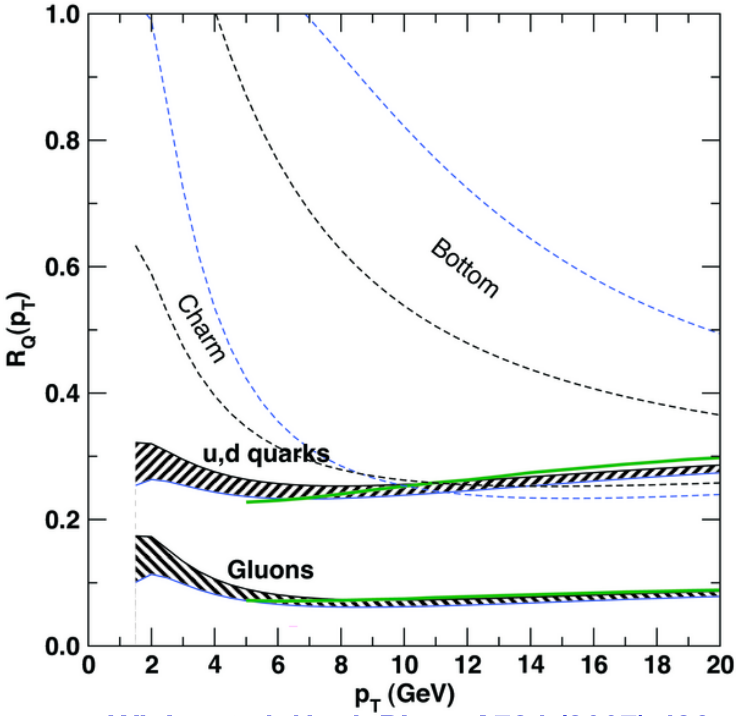
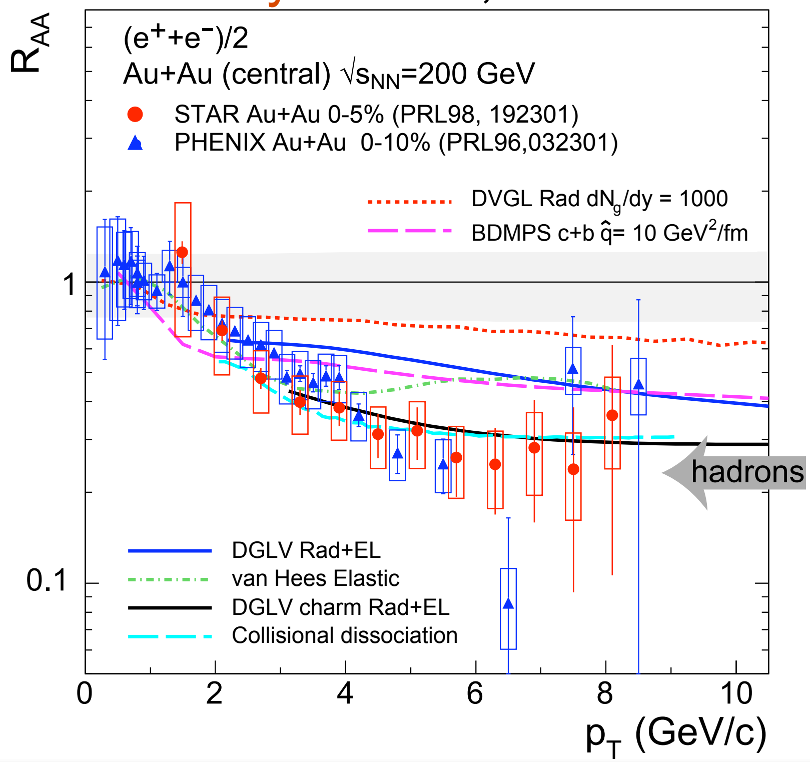


Wicks et al, Nucl. Phys. A784 (2007) 426

heavy flavor c,b → e K ν



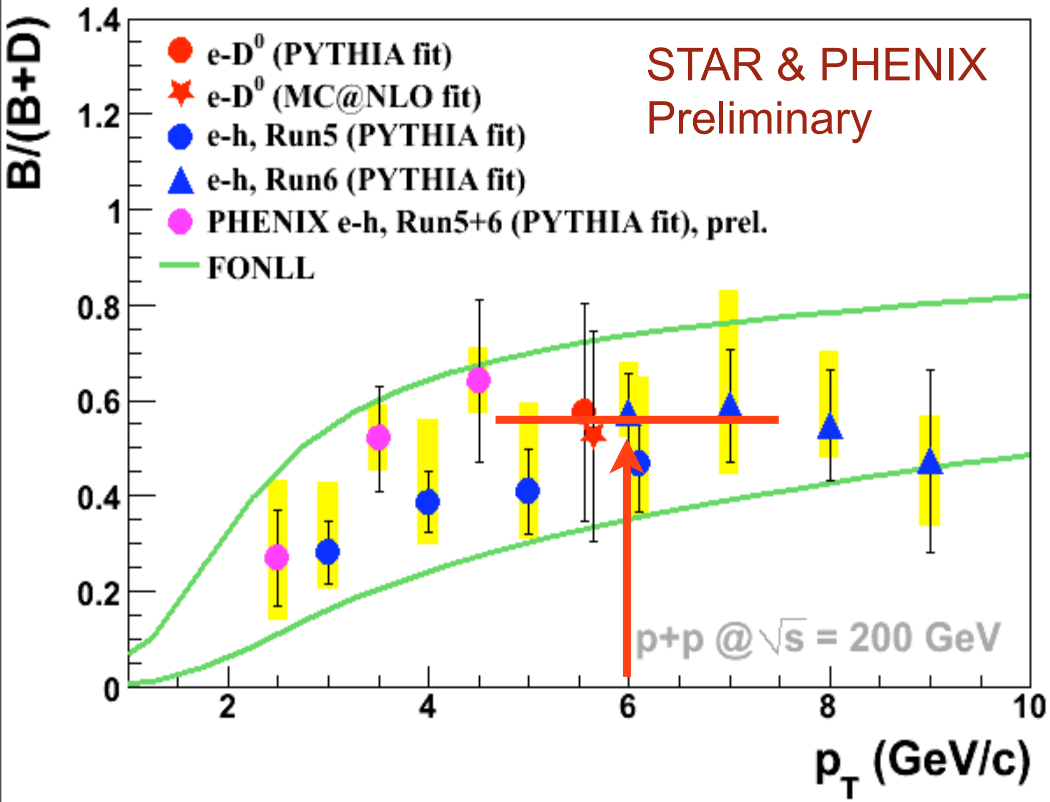
Heavy flavor JUST as suppressed

It gets worse ... bottom not gray either

Can get R_{AA} only if:

include radiation and elastic collisional energy loss

assume **all** non-photonic energy loss comes from c



BUT STAR and PHENIX show b contribution in p+p collisions

⇒ ~55% at p_T^e = 6 GeV/c

Beauty appears equally suppressed

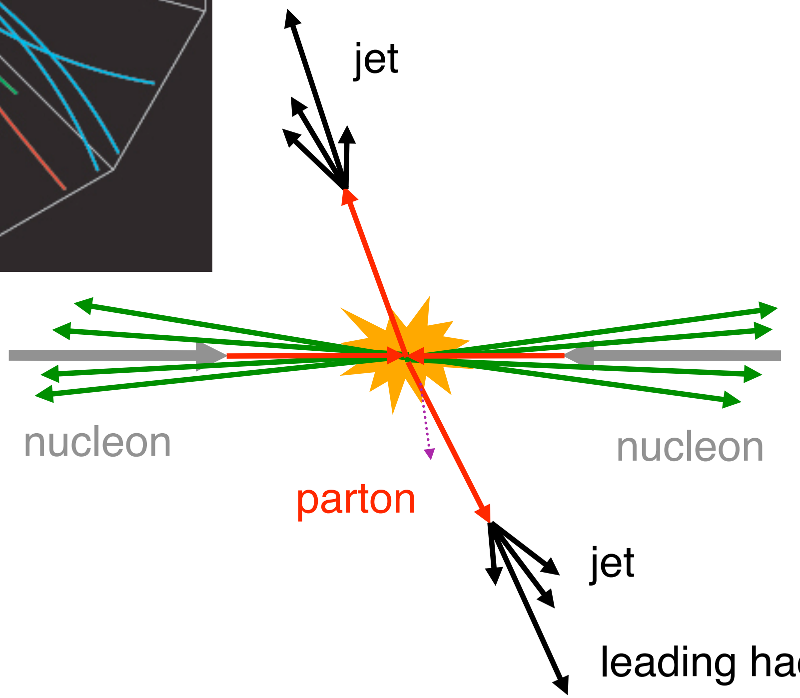
We still don't fully understand energy loss

Needed to measure b and c R_{AA} independently AND accurately

A key measurement at the LHC

Look for jets in Au-Au events

p-p →jet+jet
(STAR@RHIC)



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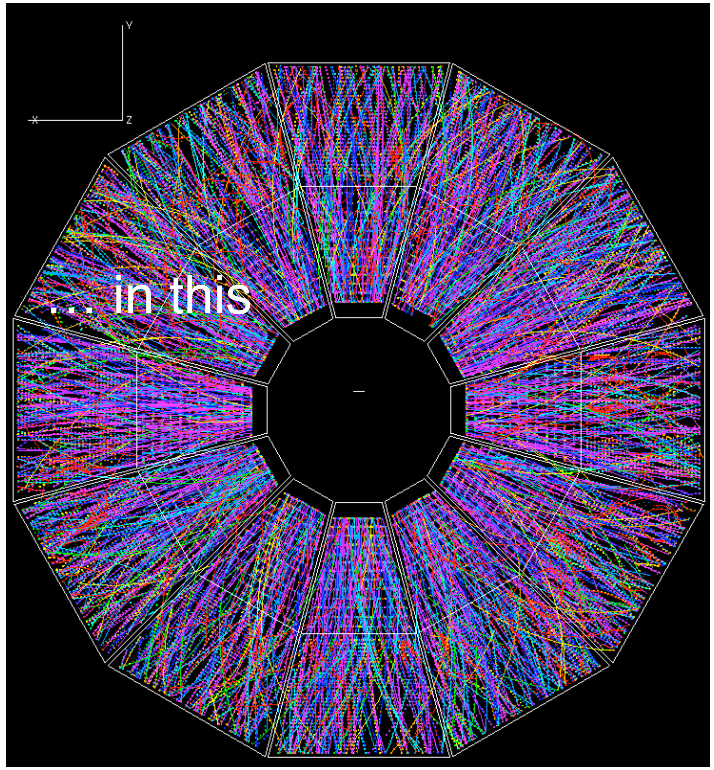
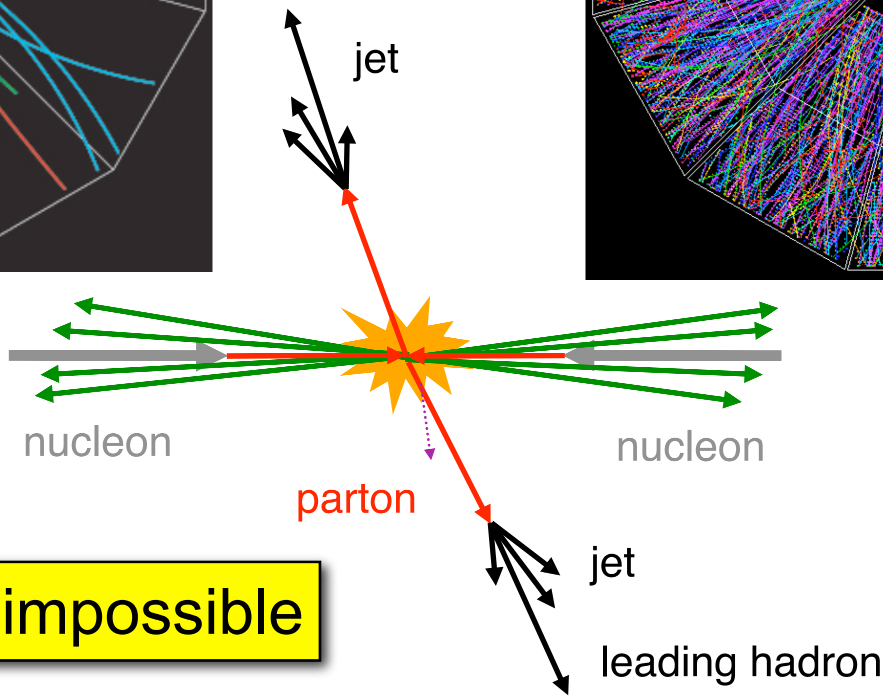


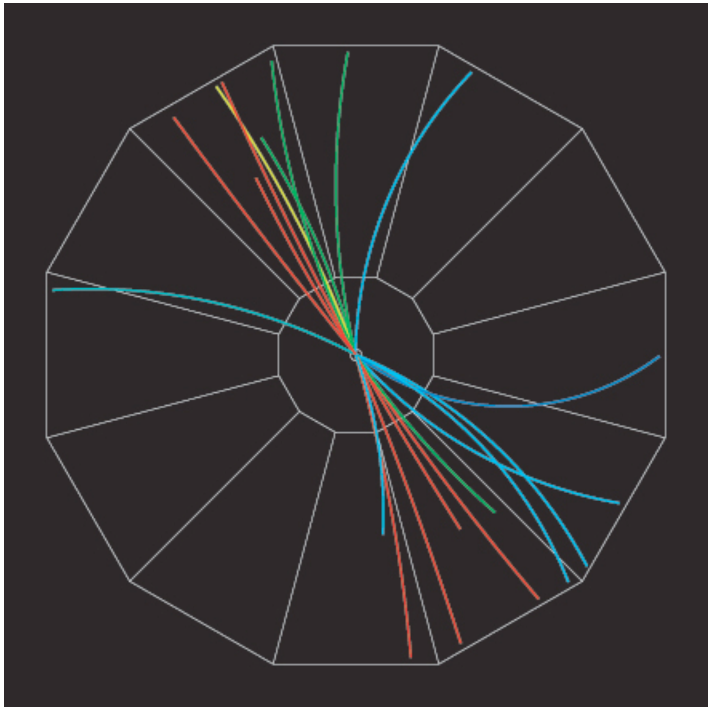
Au-Au →???
(STAR@RHIC)



Seems almost impossible

Jets in Au-Au collisions!

p-p → dijet

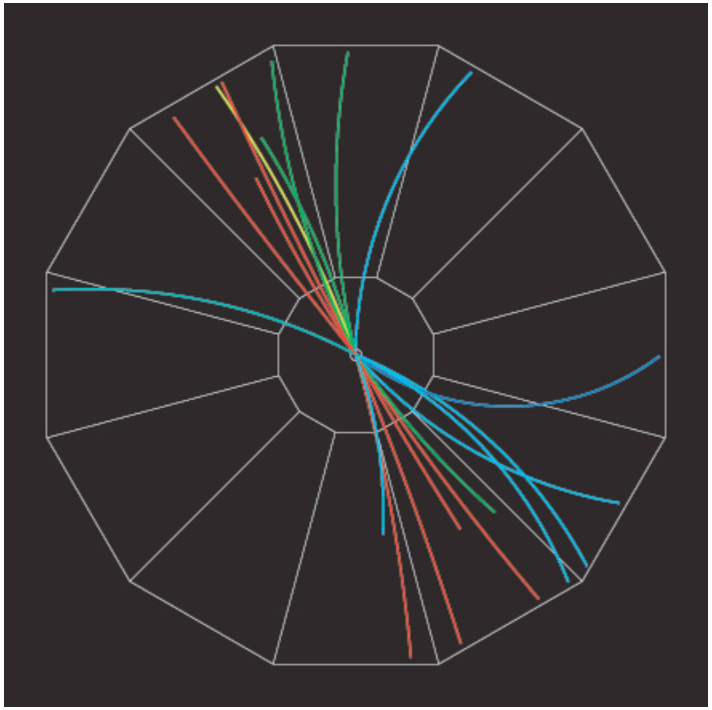


- Trigger: highest p_T track

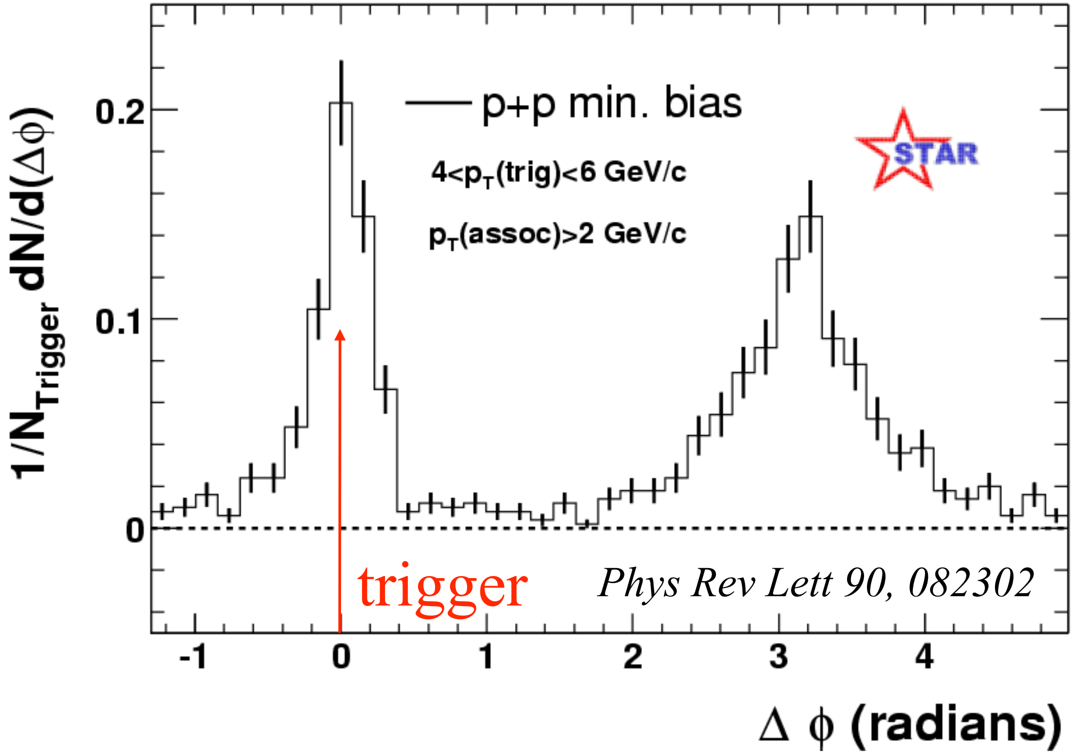
- Δφ distribution:

Jets in Au-Au collisions!

p-p → dijet



min. bias p-p collisions



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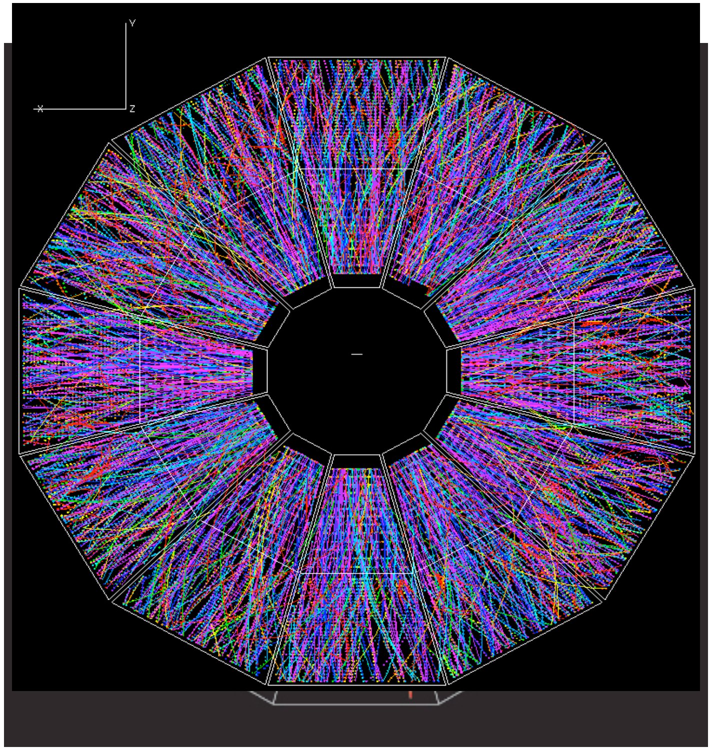
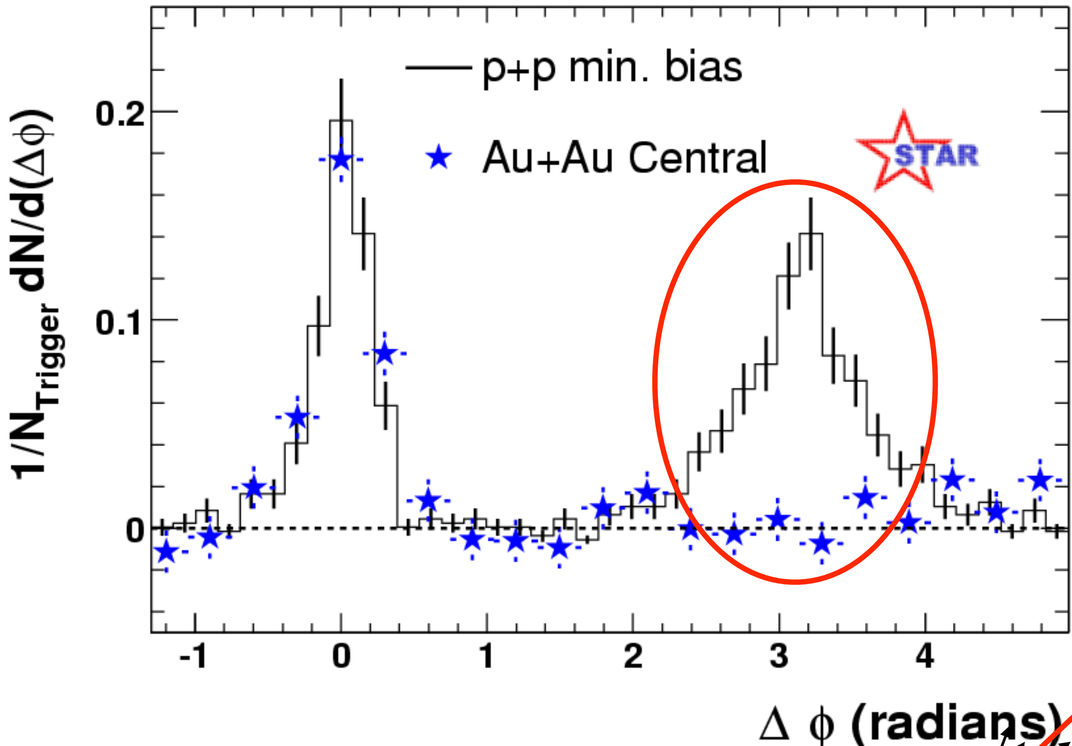
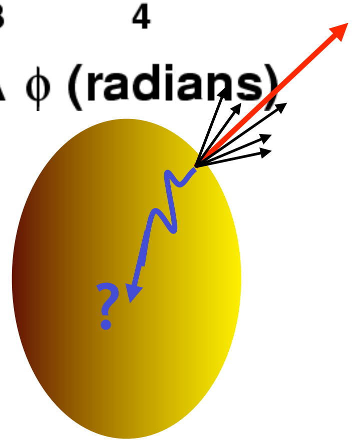


central Au-Au collisions



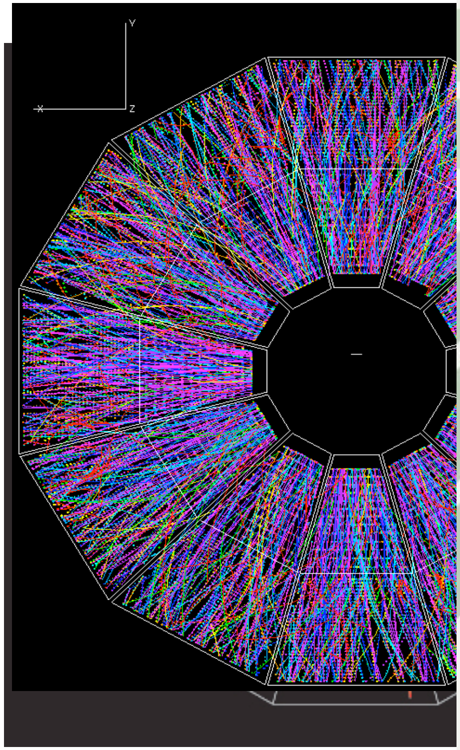


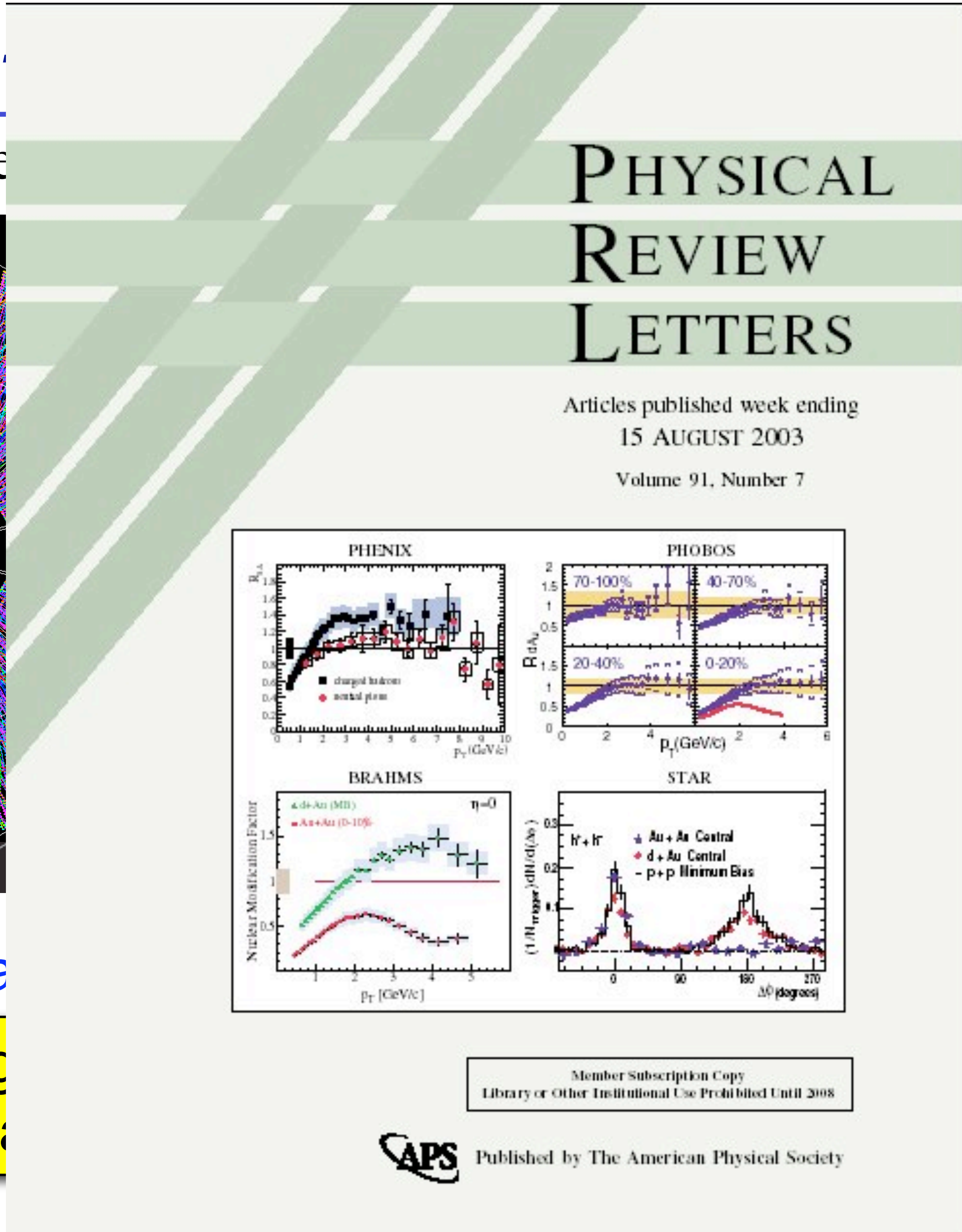
Δφ ≈ 0: central Au-Au similar to p-p

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

Jets in Au-

p-p → dije … llisions

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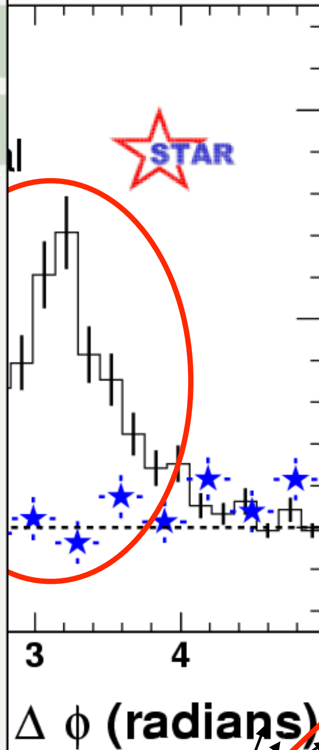
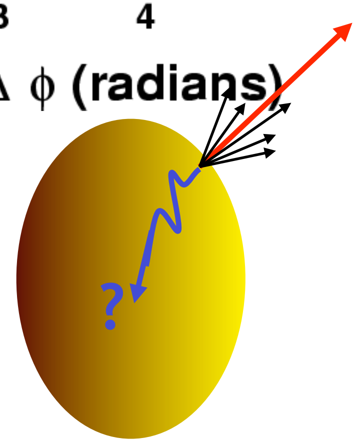




Δφ ≈ 0: centra

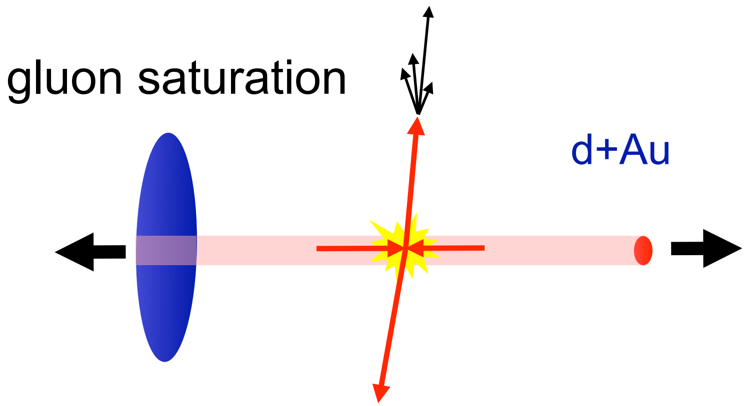
Δφ ≈ π: strong
correla

Initial or final state effects?

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

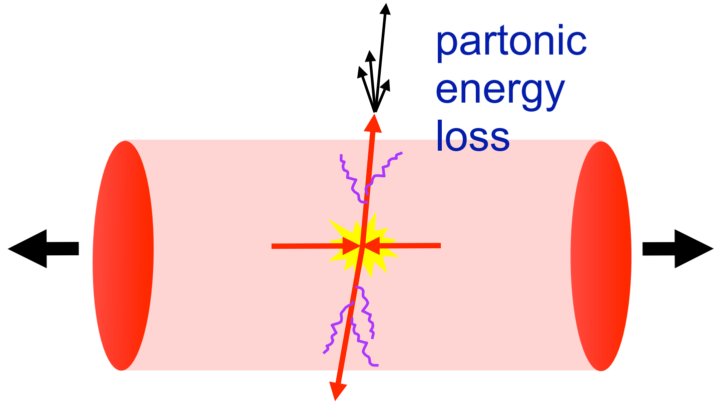
  Caused by initial state (quark/gluon shadowing) or final state (energy loss in plasma) effects?

Initial State?



vs

Final State?



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

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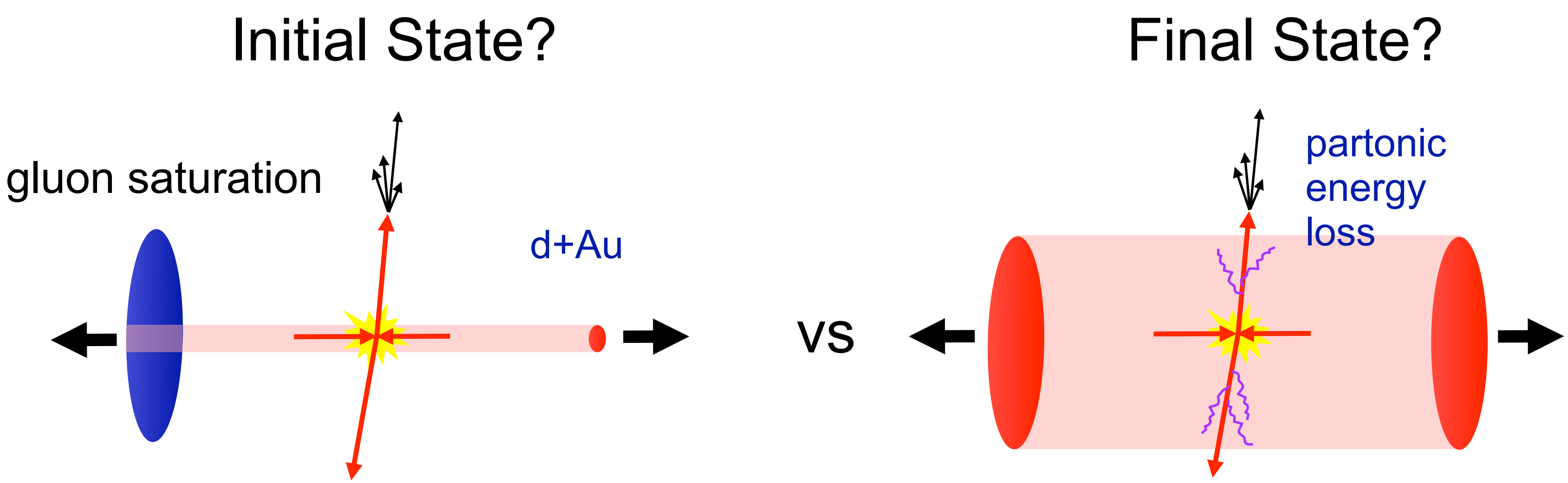

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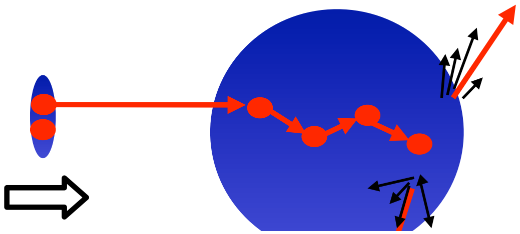
Use d-Au

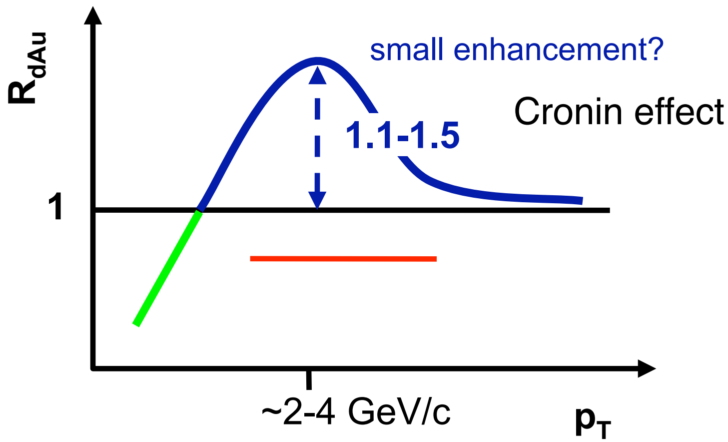
Expectations for d-Au

RAA

Final state effect, R_{dAu} >1.



Initial state effect, R_{dAu} < 1.



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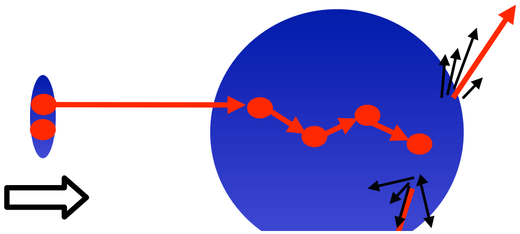
Expectations for d-Au

R_{AA}

Final state effect, $R_{dAu} > 1$.



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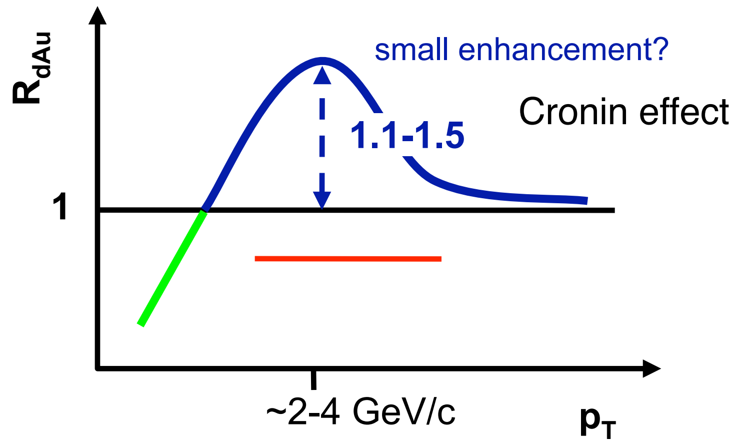
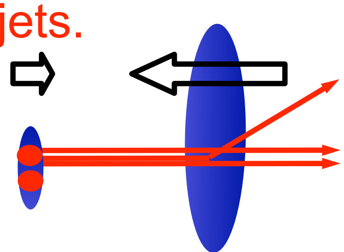
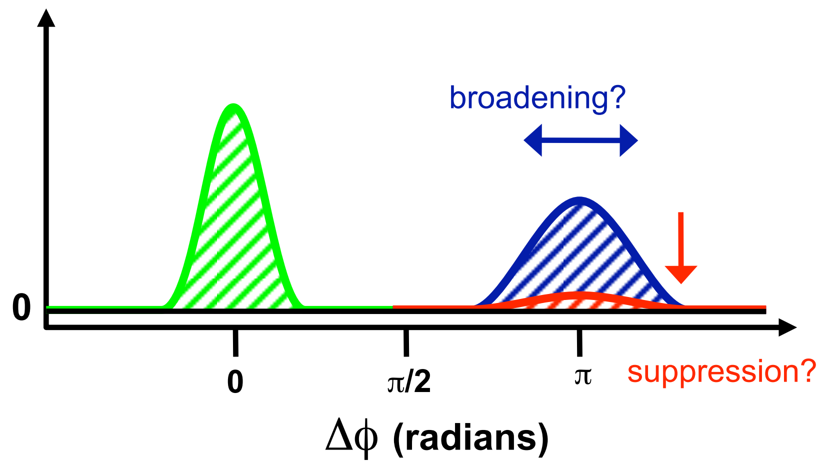


di-hadron

Final state effect: pQCD: no suppression, small broadening due to Cronin effect.

Saturation models: suppression persists due to mono-jets.





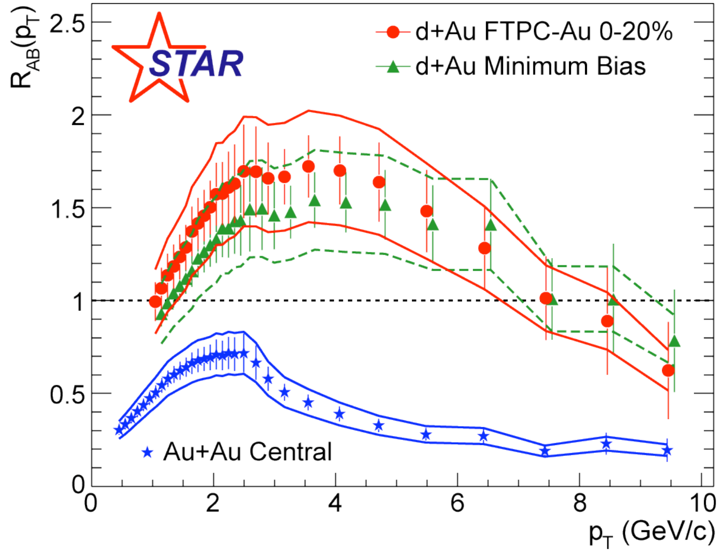
(Deuteron valence quark scatters of gluon condensate.)

The results

R$_{AA}$

- Au-Au highly suppressed
- d-Au enhanced in same p_T range
- Suppression is a final state effect

$$R_{dAu}(p_T) = \frac{dN^{dAu}/dp_T d\eta}{T_{dAu} d\sigma^{pp}/dp_T d\eta}$$



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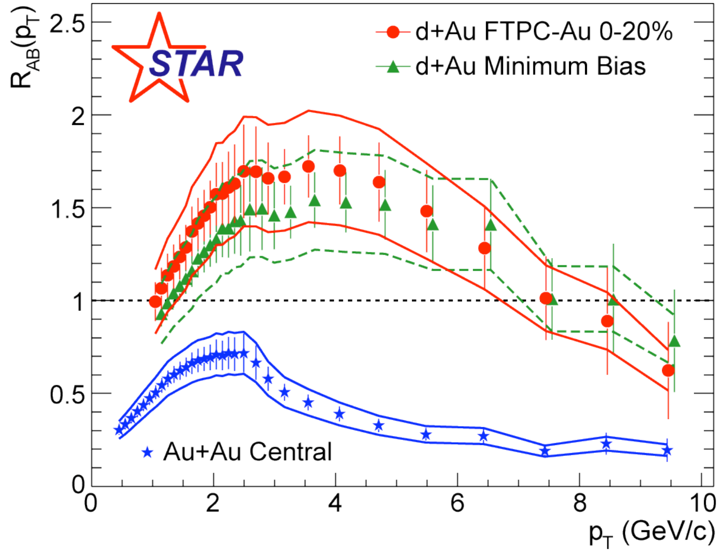
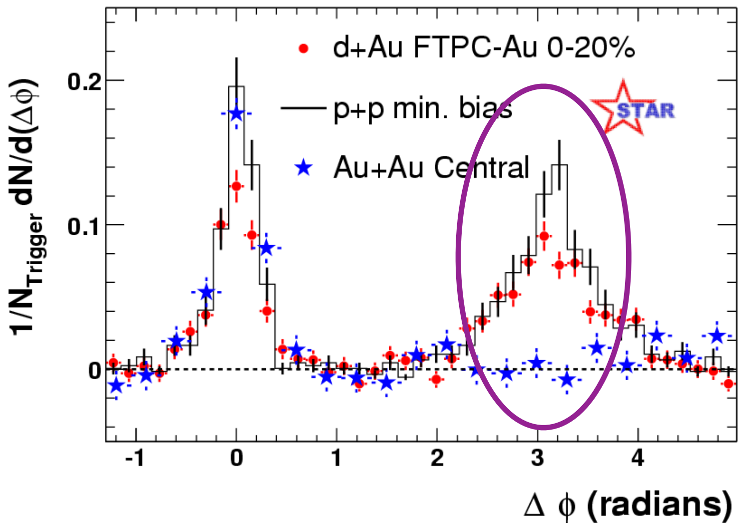


di-hadrons

- Au-Au Back-to-back jets suppressed
- d-Au similar to p-p



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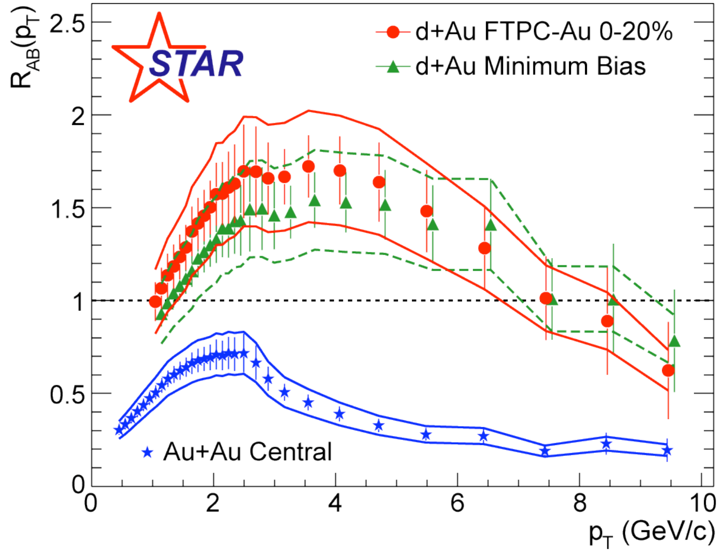

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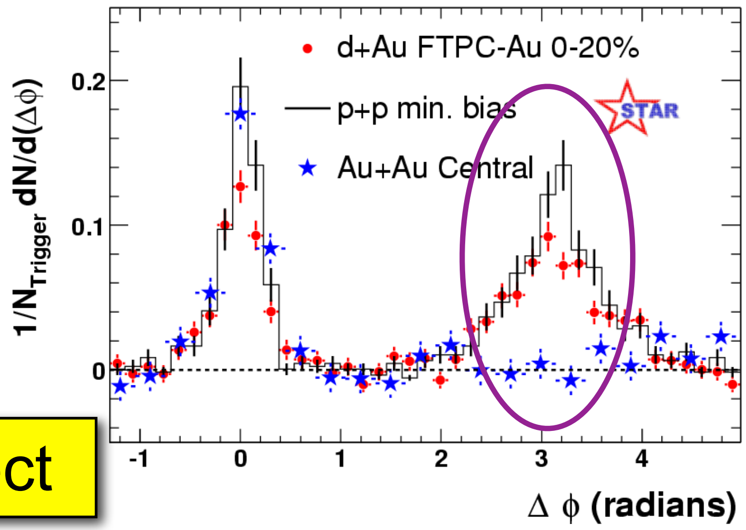
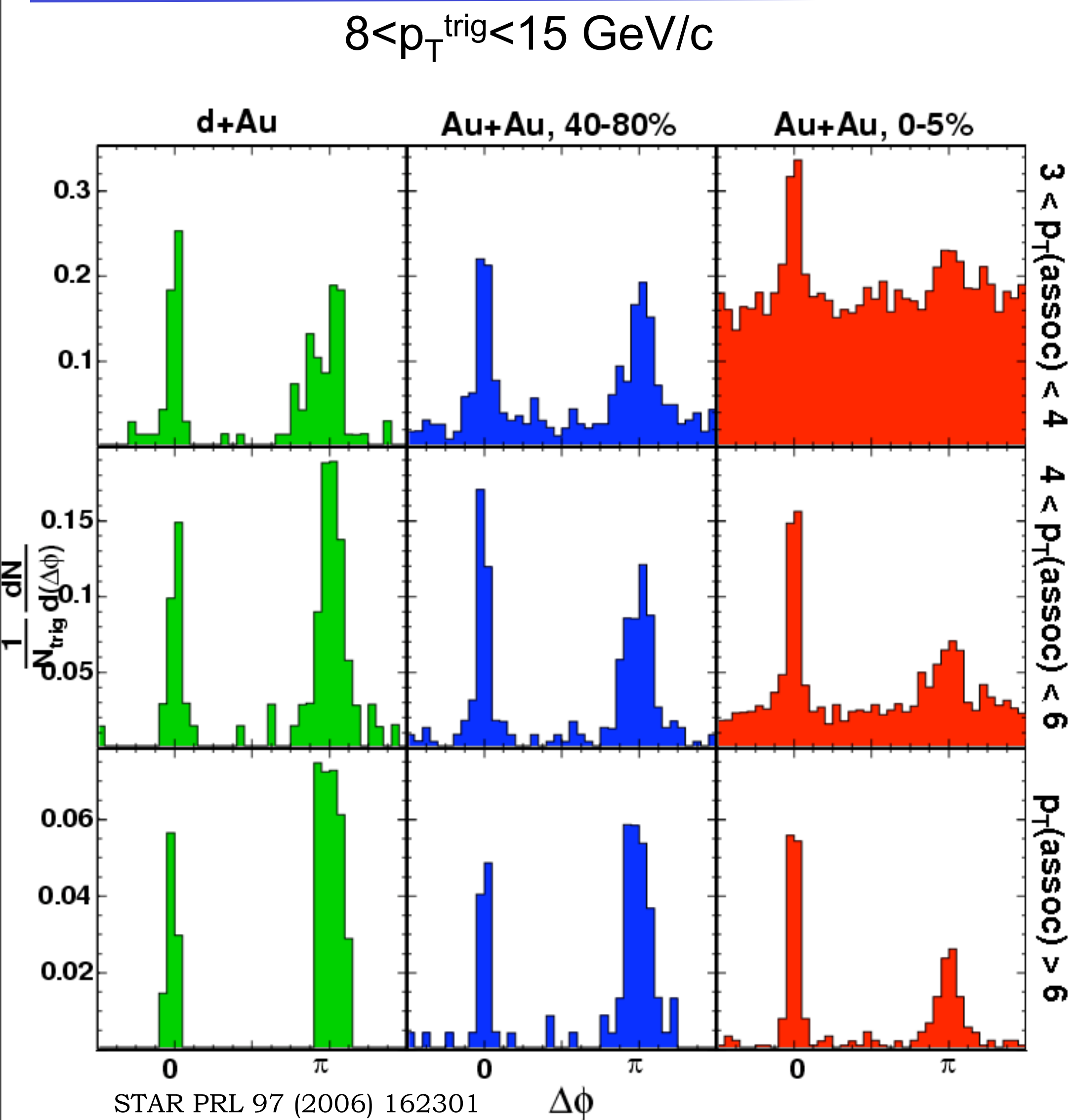


Quenching is a final state effect

Observation of "Punch through"

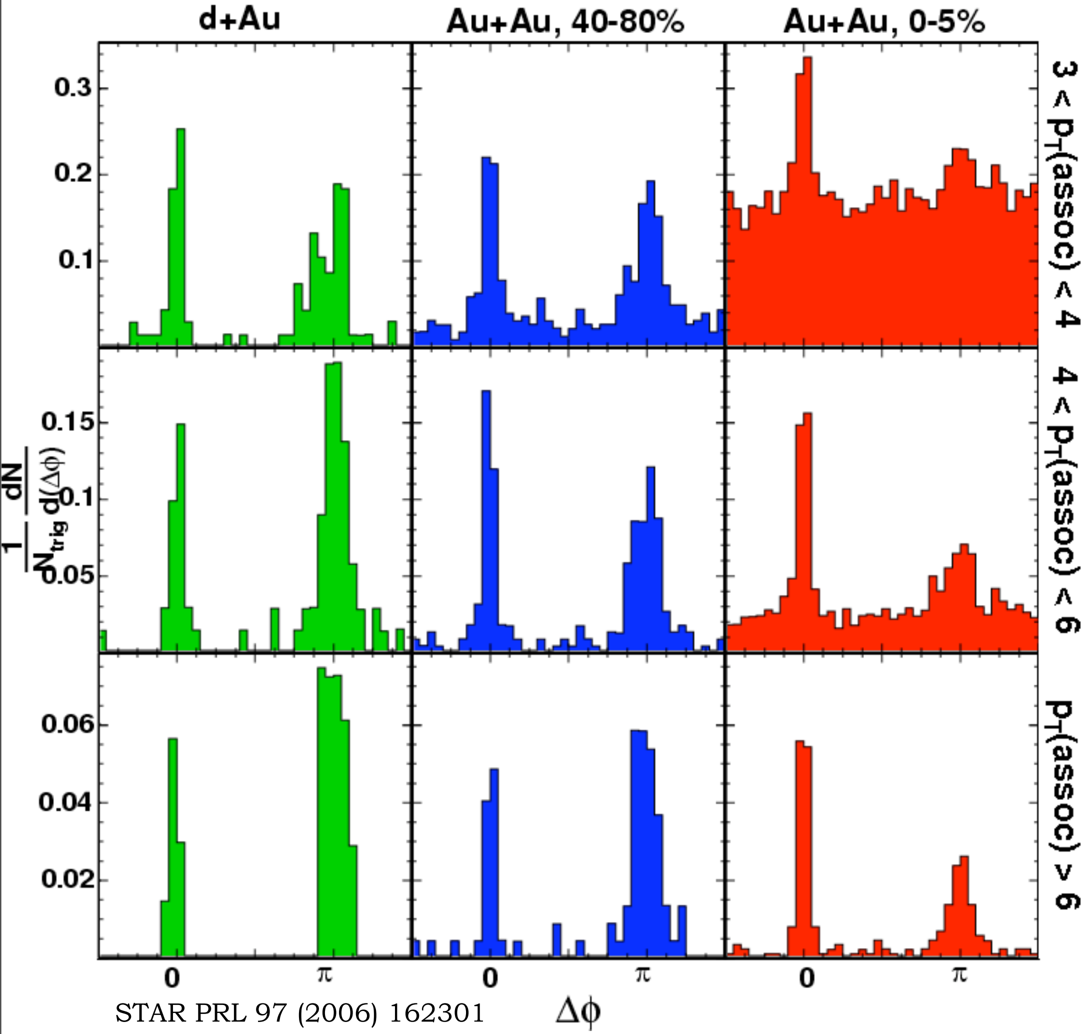


If use high-p_T triggers:

- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background

Observation of "Punch through"

$8 < p_T^{trig} < 15$ GeV/c



STAR PRL 97 (2006) 162301

If use high-p_T triggers:

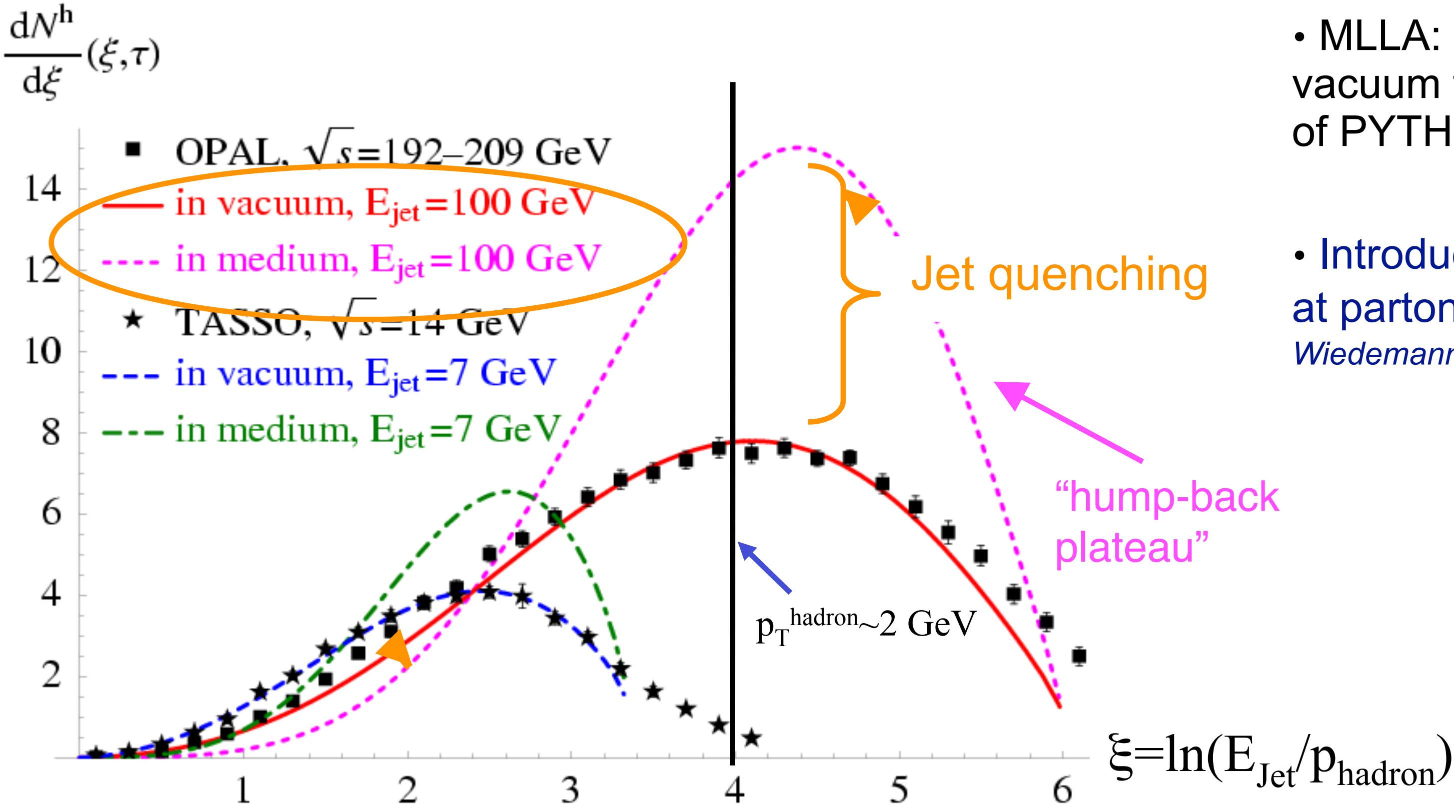
- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background

High energy jets *"punch through"* the medium.

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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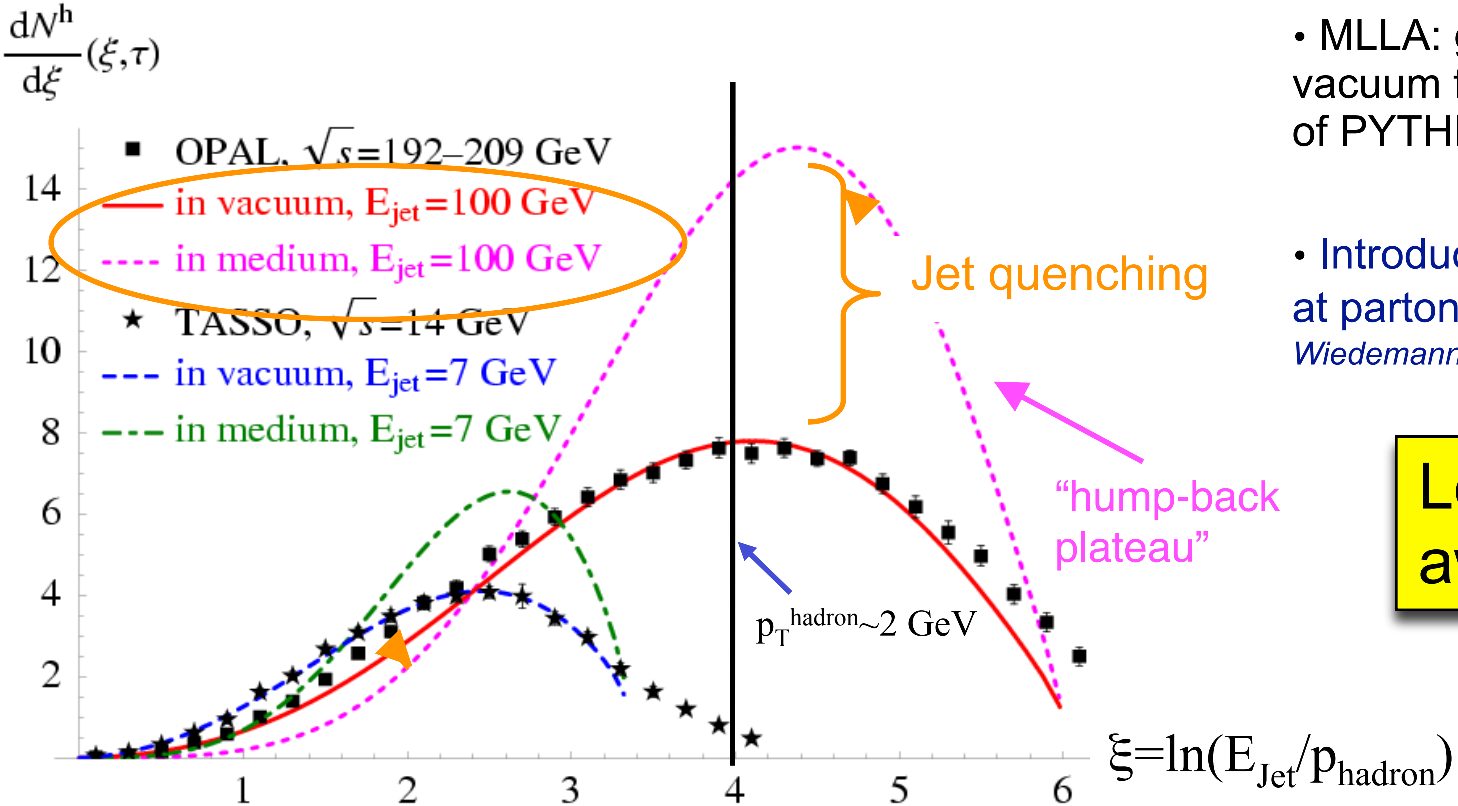


- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

Look at away-side FF

Away-side di-hadron fragmentation functions

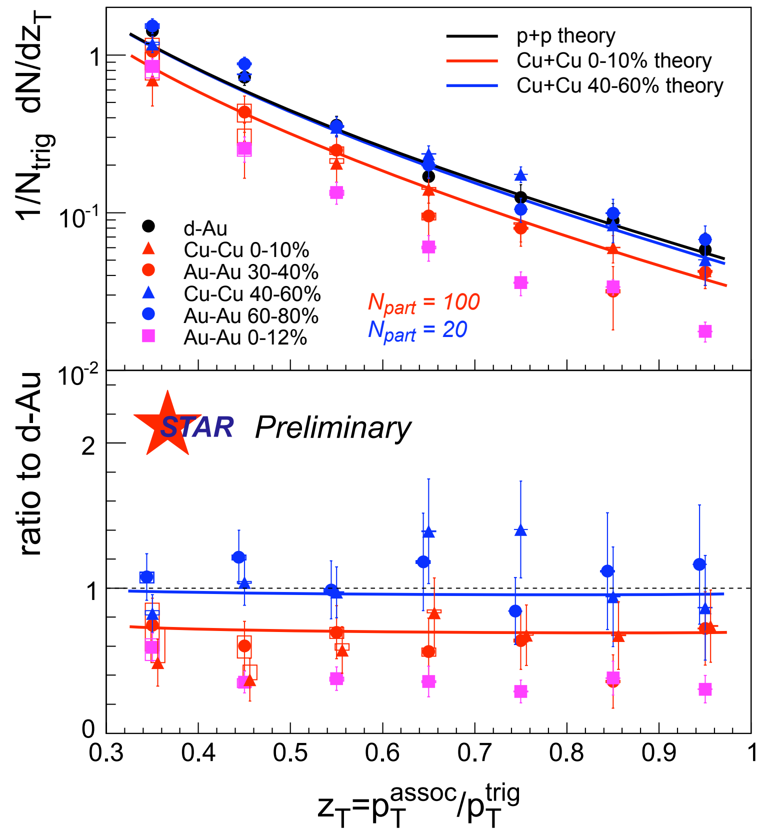
- Measure fraction of parton energy each hadron carries

  $z = p_{hadron}/p_{parton}$

- Without full jet reconstruction, parton energy not measurable

- Instead measure approximation

  $z_T = p_{Tassoc}/p_{Ttrig}$



Denser medium in central Au-Au than central Cu-Cu

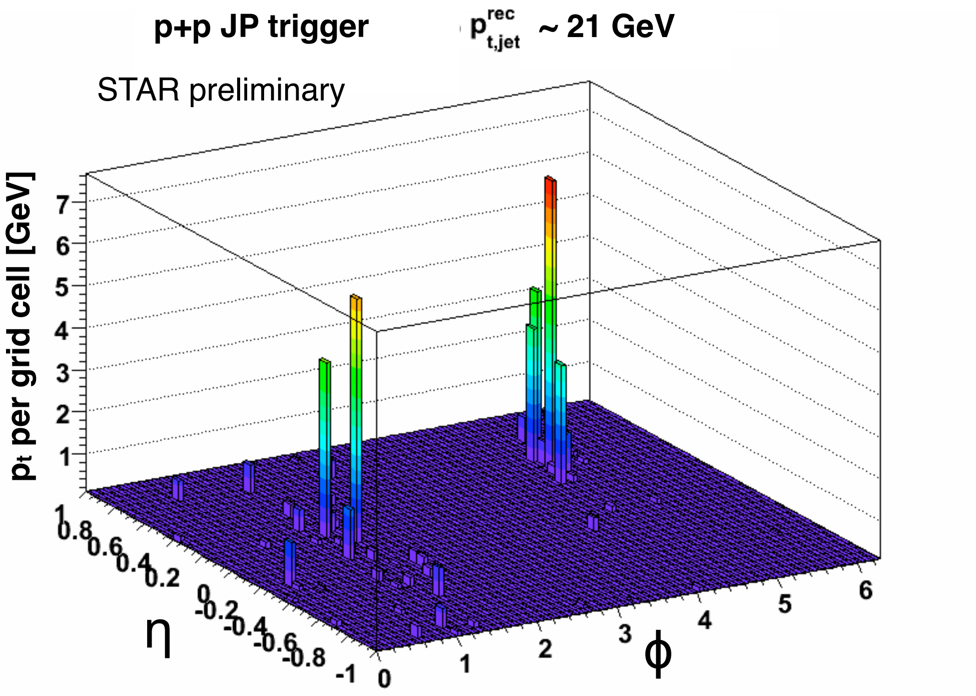
Similar medium for similar N_{part}

Vacuum fragmentation after parton E_{loss} in the medium

Full-jet reconstruction in HI collisions

Di-hadrons *indirect* measurements of jet quenching !

- Full jet reconstruction needed



In p-p jet clearly visible

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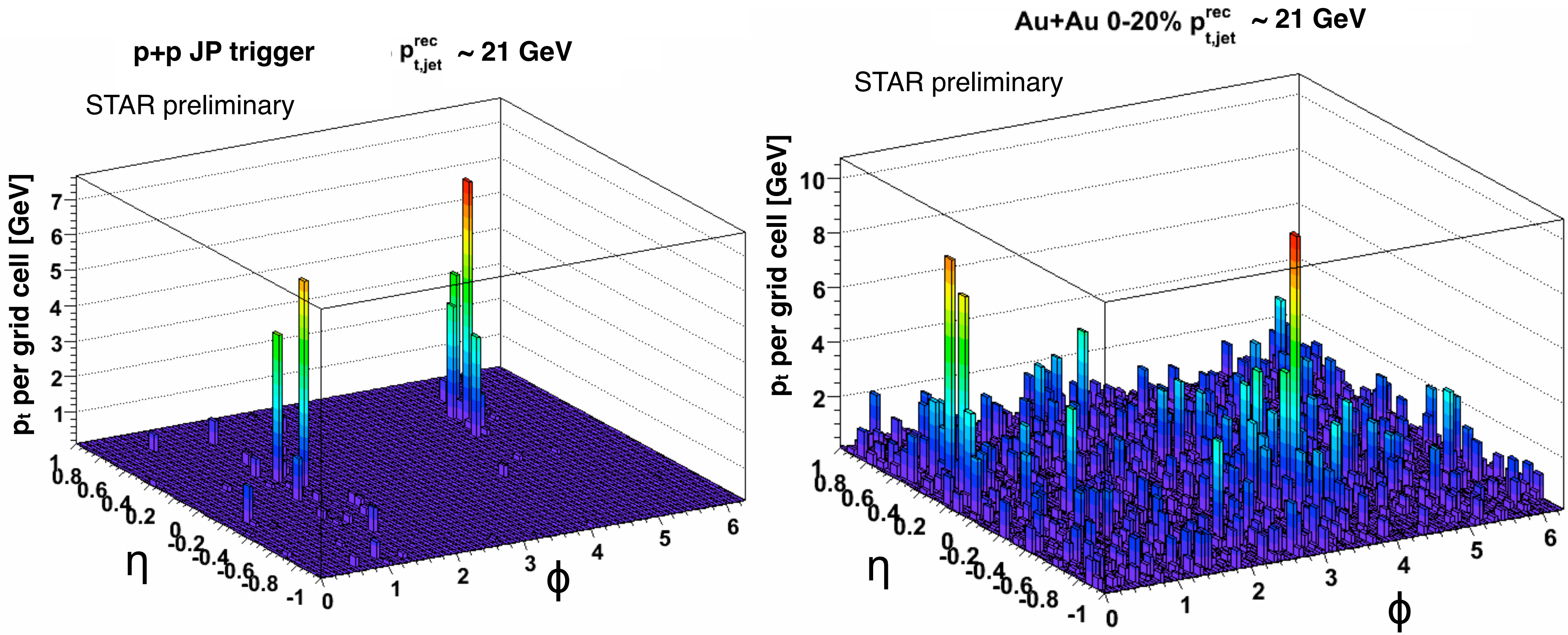


In p-p jet clearly visible

In Au-Au more challenging

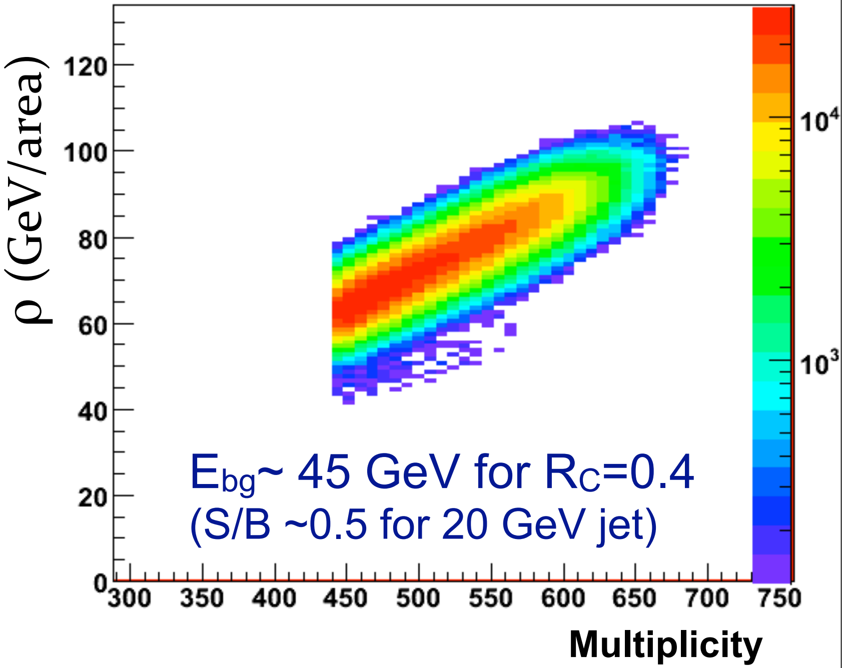
Underlying event background a significant challenge - magnitude and fluctuations

Background - central Au-Au collisions

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + ρ A ± $\sigma \sqrt{A}$

ρ - background energy per unit area
A - jet area



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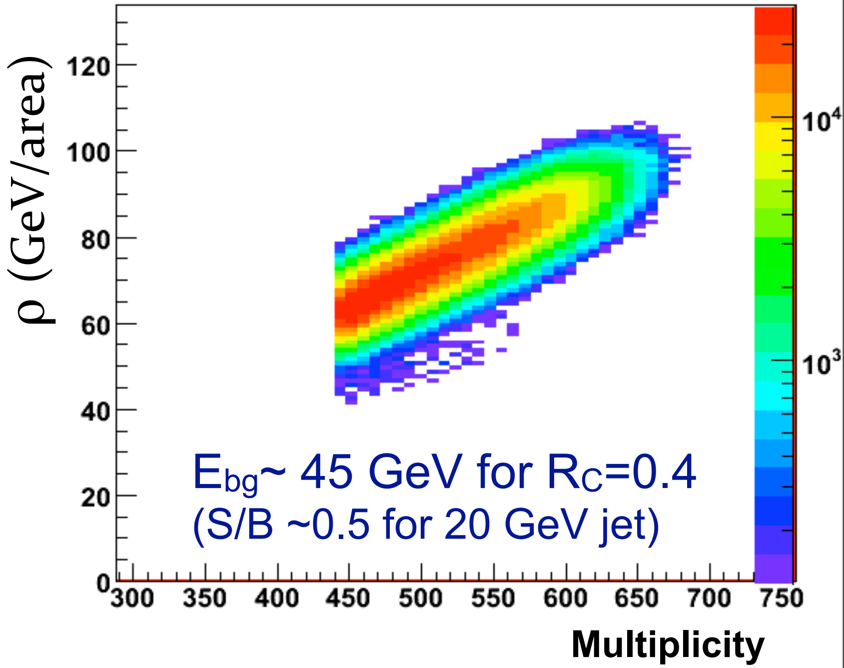
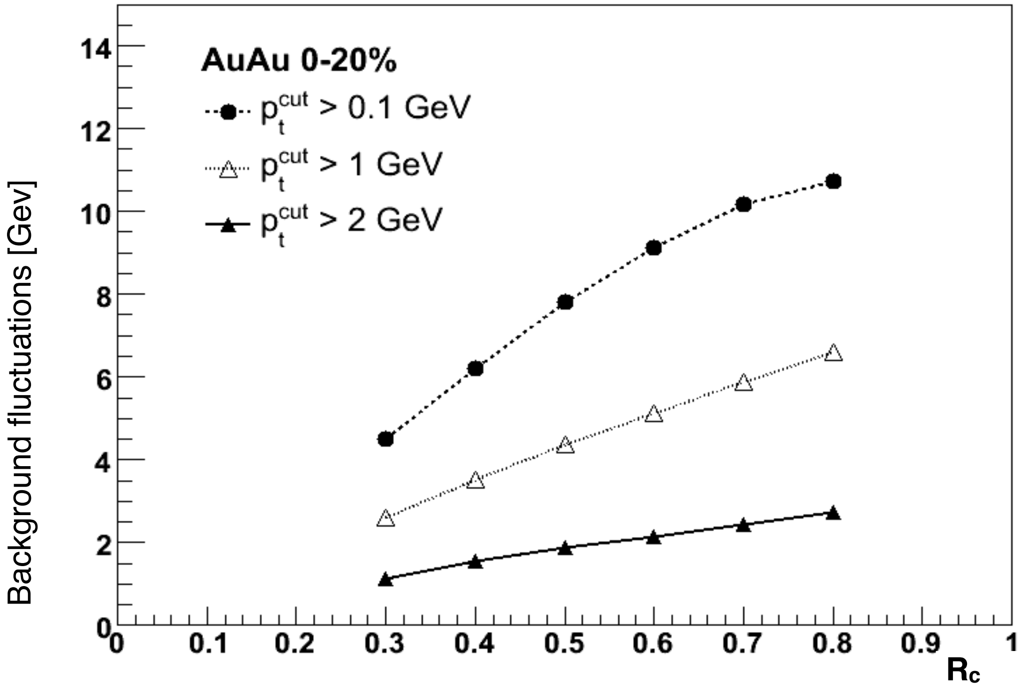


E_{bg}~ 45 GeV for R_C=0.4
(S/B ~0.5 for 20 GeV jet)



Substantial region-to-region background fluctuations

σ - comparable magnitude from FastJet and naïve random cones

Both reduced significantly by increasing p_T^{cut}

What's expected from Au-Au jet spectrum

p and E MUST be conserved even with quenched jets

- Study nuclear modification factor (R_{AA}) of jets

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

Average number of p-p collision in A-A collision

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

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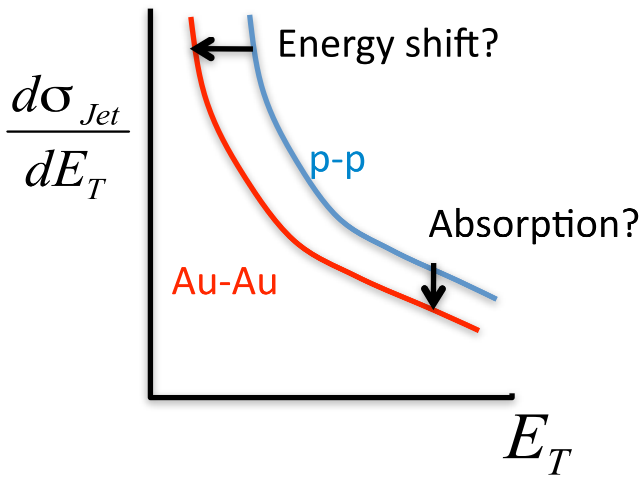
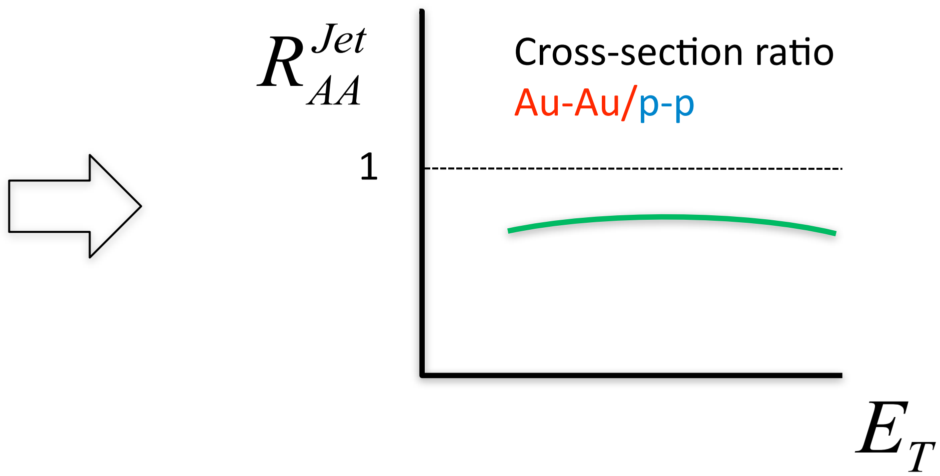
Average number of p-p collision in A-A collision

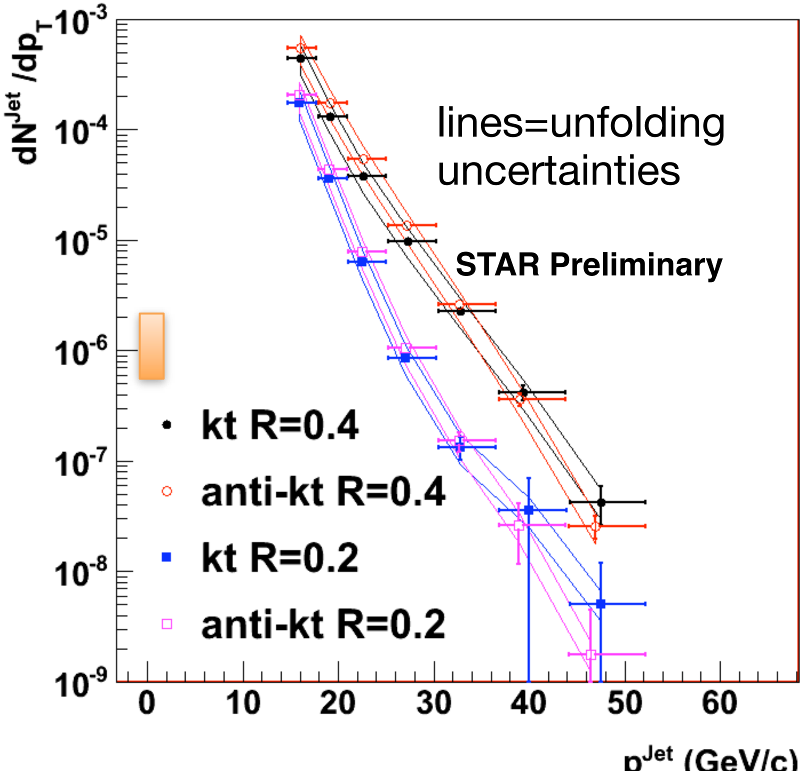
- If jet reconstruction complete and unbiased R_{AA}==1
- If some jets absorbed and/or not all energy recovered R_{AA}<1



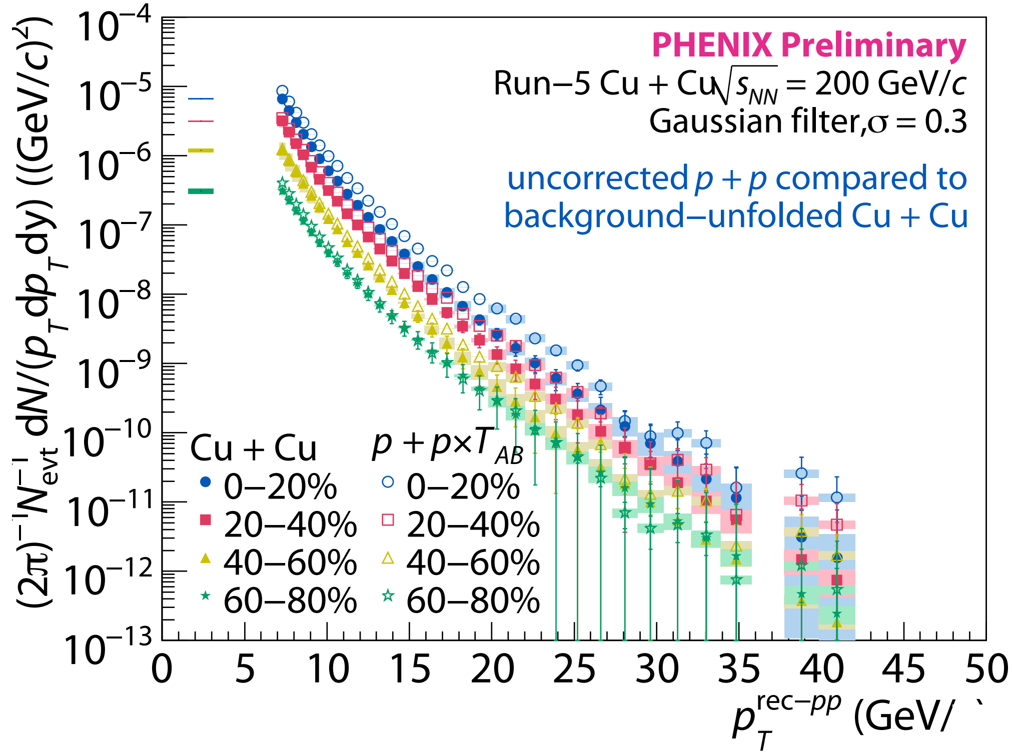


Inclusive jet x-section in Au-Au and Cu-Cu

Au-Au collisions 0-10%



M.Ploskon QM2009

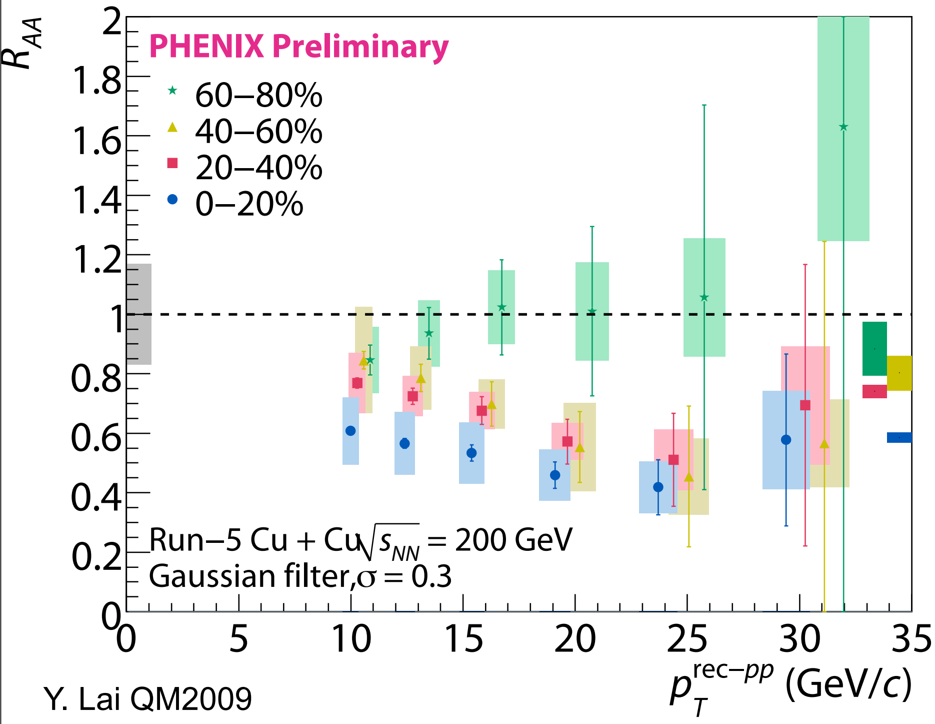


Y. Lai QM2009

Inclusive jet spectrum measured in A-A collisions for first time

Extends reach of jet quenching studies to p_T > 40 GeV

Jet R_{AA} in Cu-Cu using Gaussian Filter



Y. Lai QM2009

Gaussian Filter: designed to find vacuum like fragmentation

- Reconstructed jets highly suppressed in central collisions

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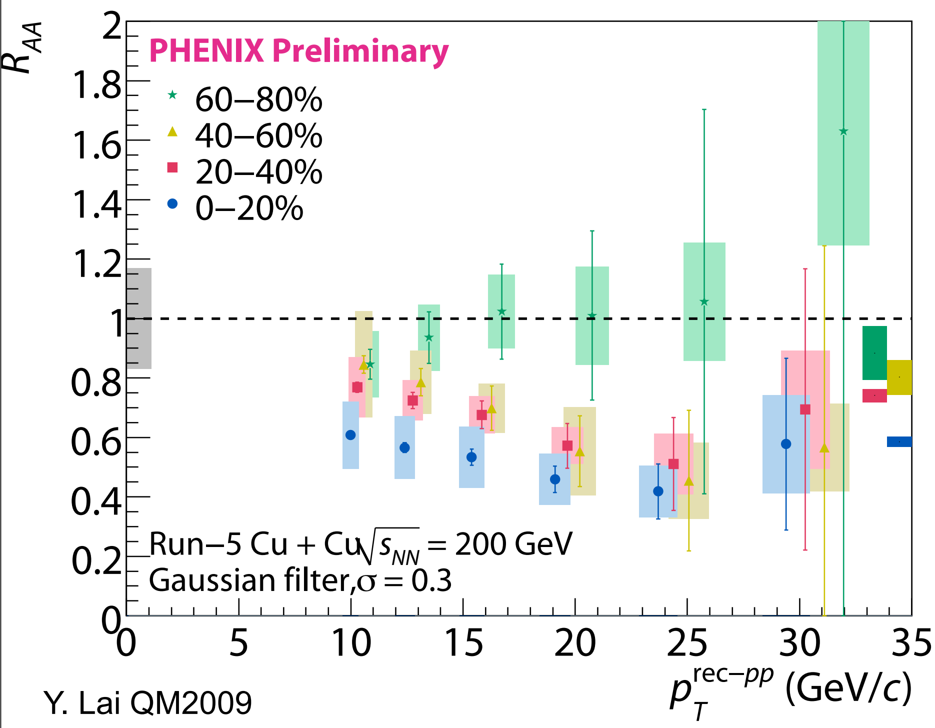
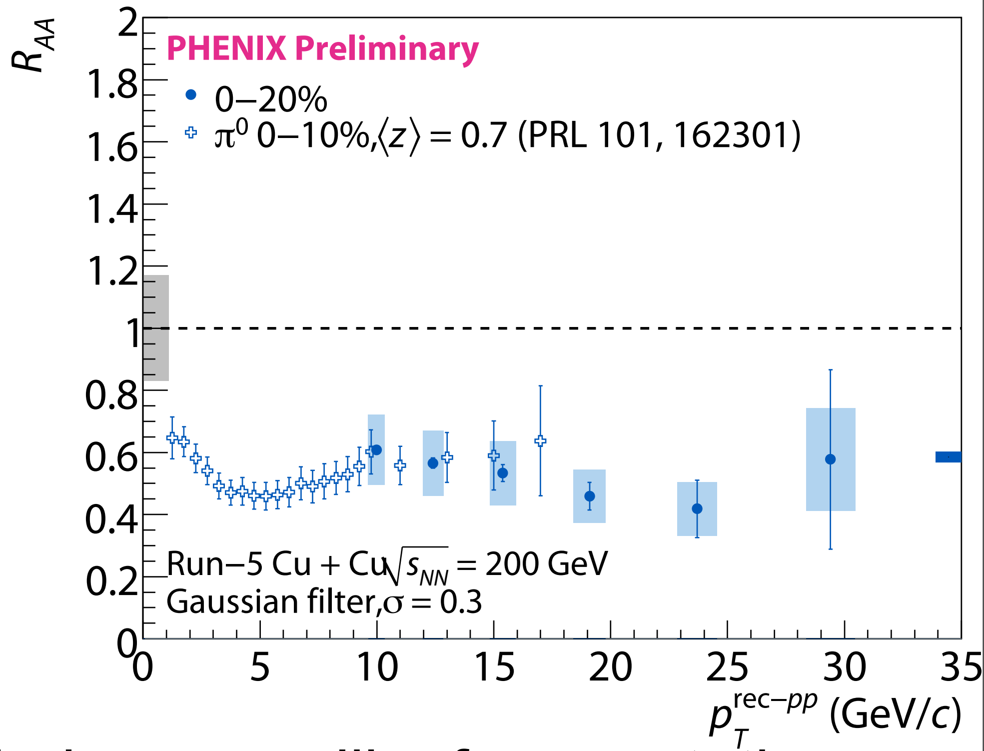


Y. Lai QM2009



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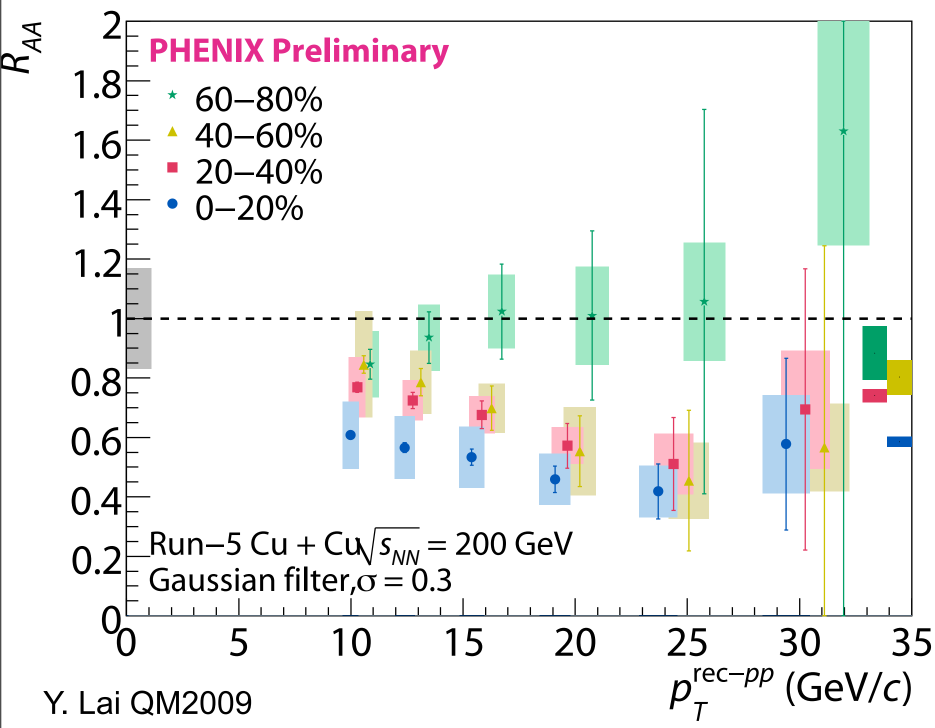

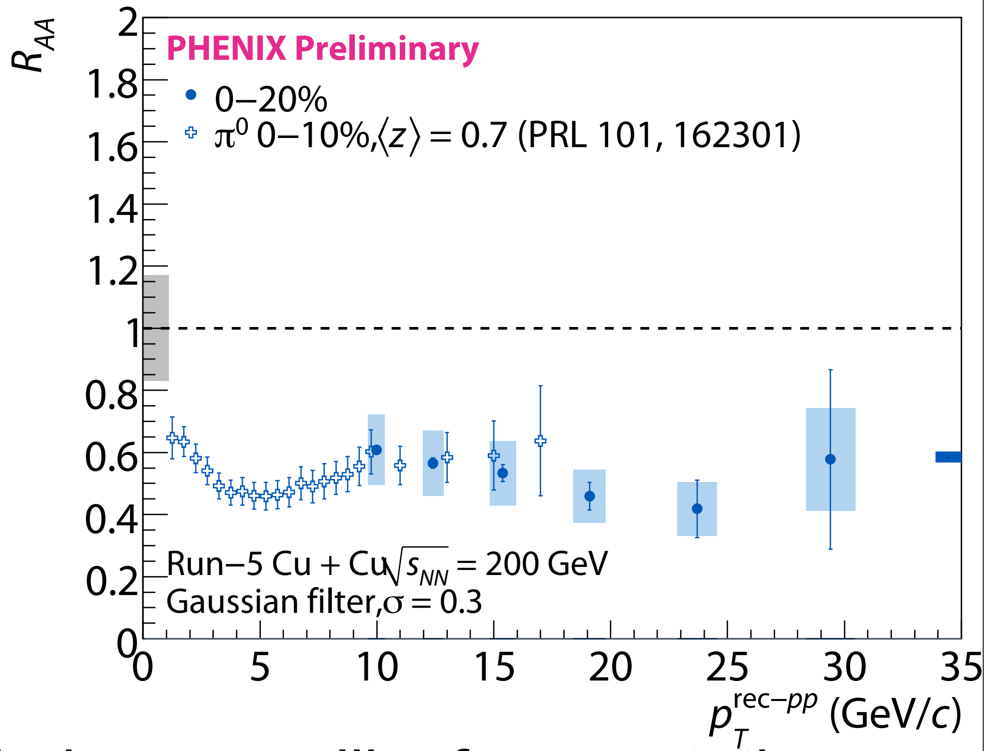

Y. Lai QM2009

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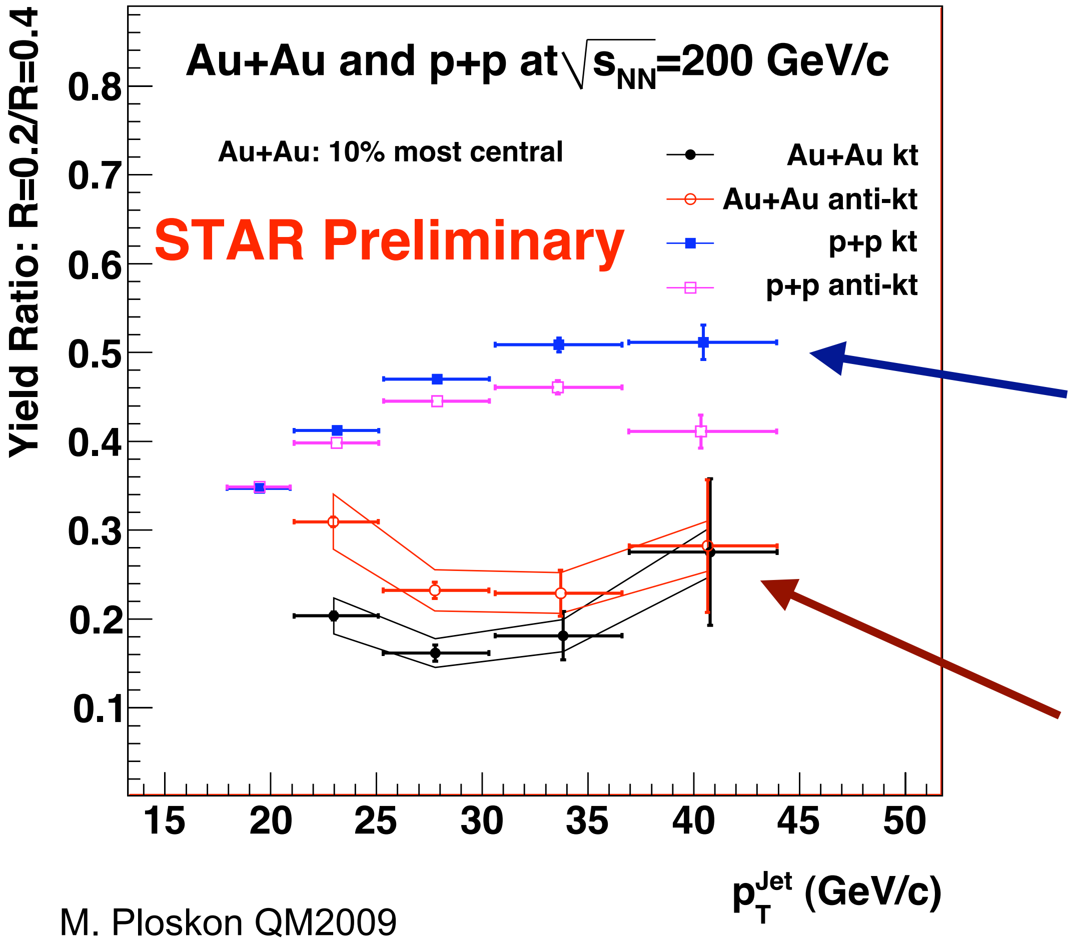
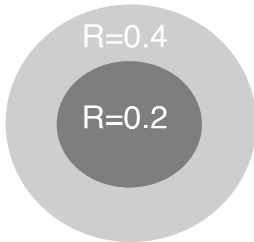
Energy shift or jet not reconstructed?

Look at the jet energy profile



M. Ploskon QM2009

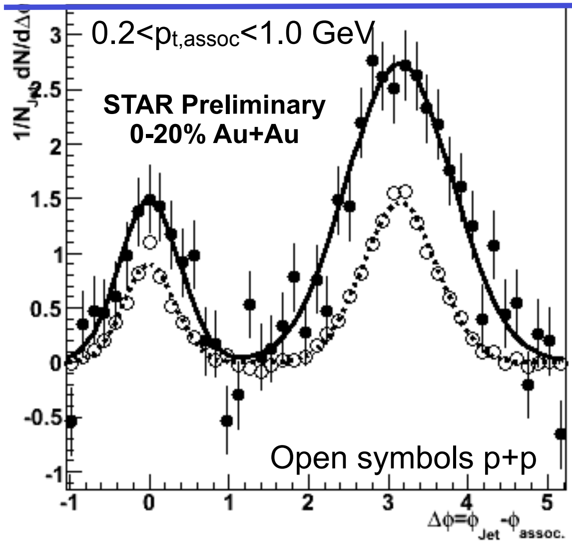


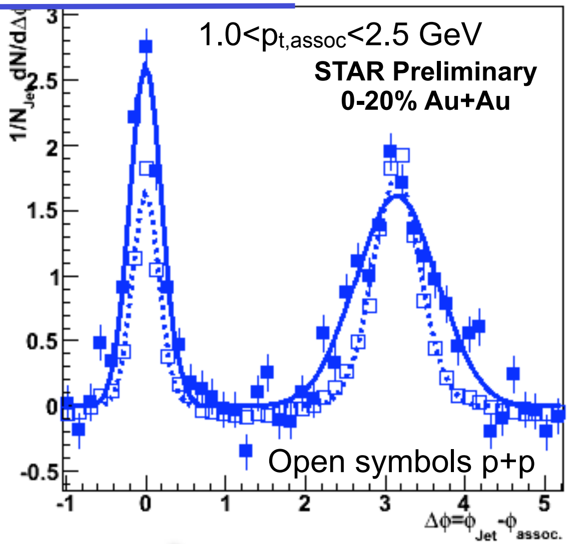
p-p:
"Focussing" of jet fragmentation with increasing jet energy

Au-Au:
"Broadening" of jet fragmentation with increasing jet energy

De-focussing of energy profile when jet passes through sQGP

Jet-hadron correlations Au-Au vs. p-p



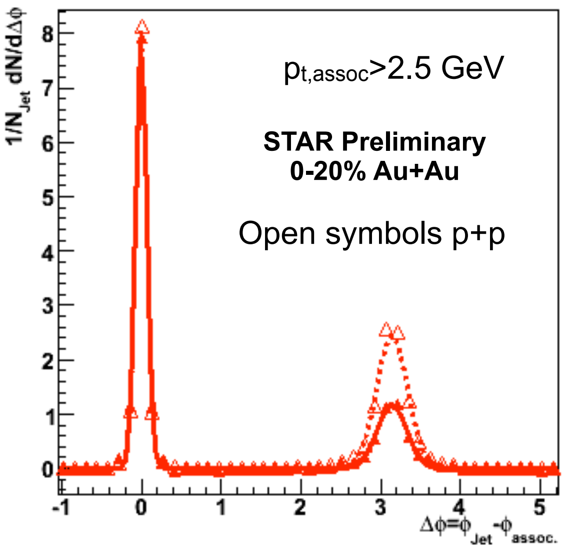


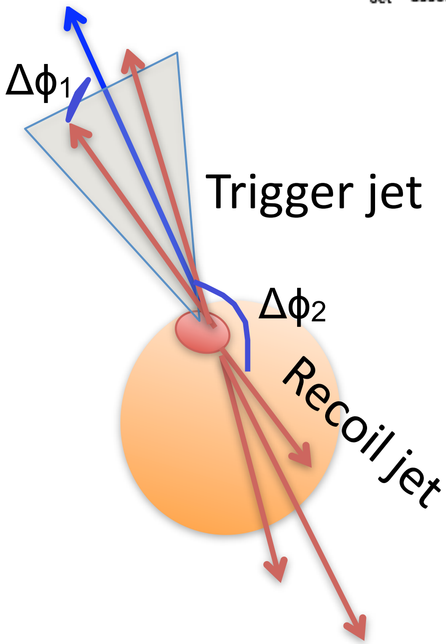
High Tower Trigger (HT):
tower 0.05x0.05 (ηxϕ)
with E_t> 5.4 GeV

$\Delta\phi=\phi_{Jet}-\phi_{Assoc.}$

ϕ_{Jet} = jet-axis found by Anti-k_T, R=0.4, $p_{t,cut}$>2 GeV and $p_{t,rec}(jet)$>20 GeV

J.Putschke RHIC/AGS 2009





Thursday, August 26, 2010

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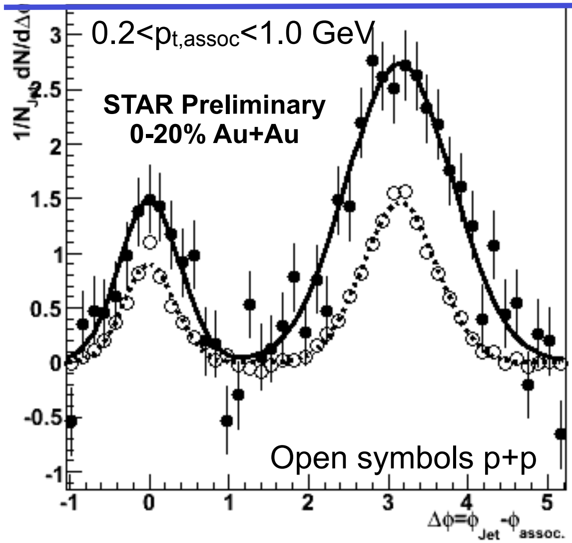

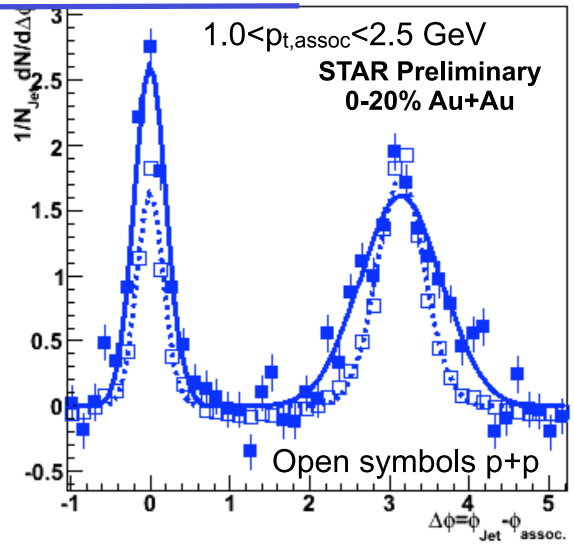

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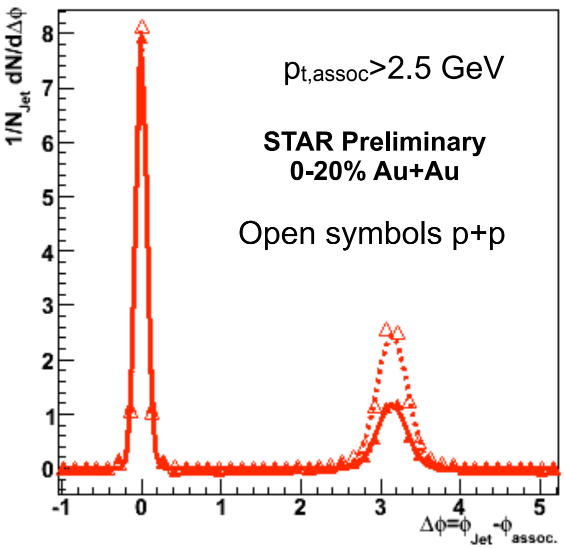


- Broadening of recoil-side
- Softening of recoil-side

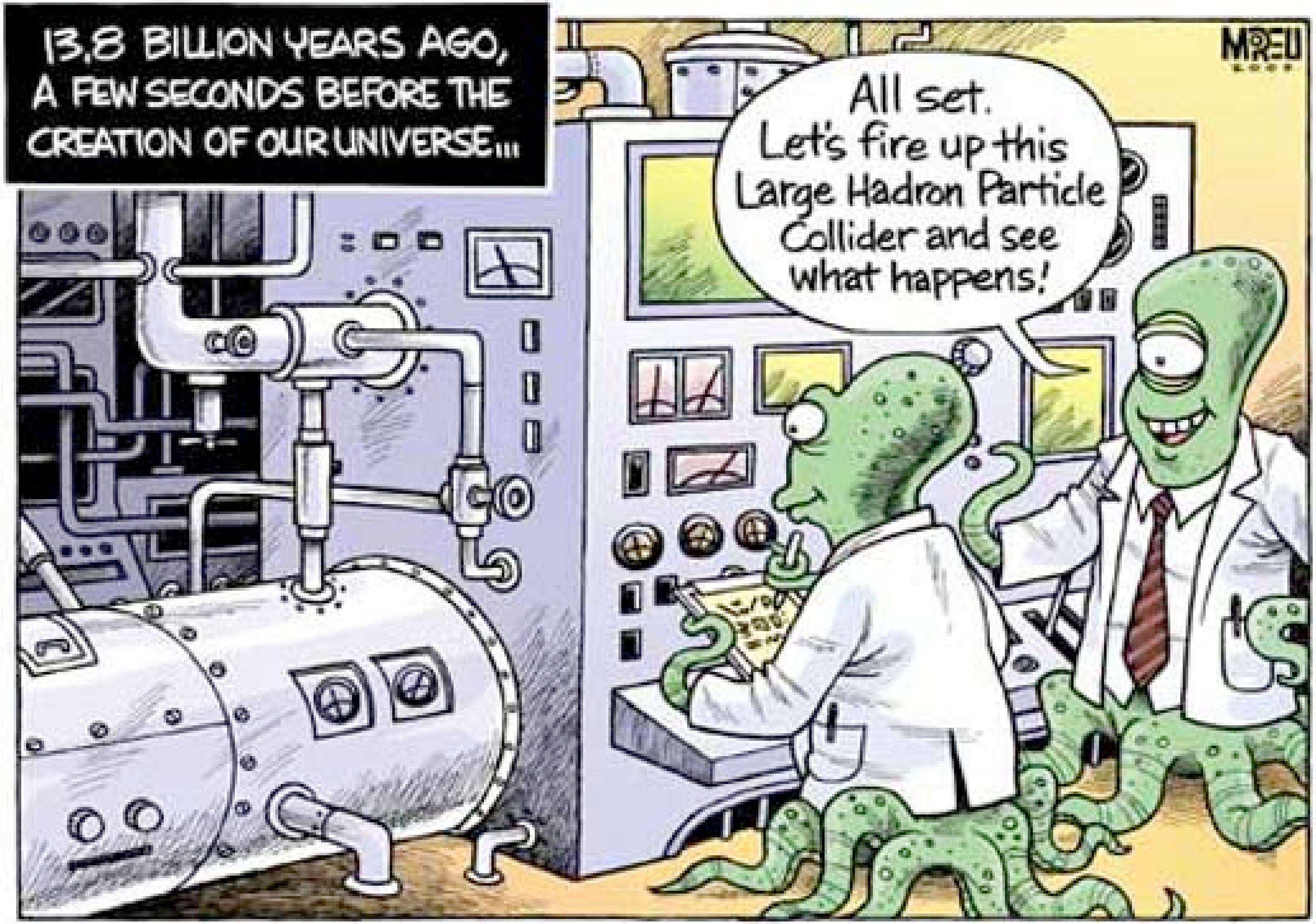
First direct measurement of Modified Fragmentation due to presence of sQGP

Summary of high p_T studies

- p-p jet reference measurements are well understood - we have a calibrated probe
- Cold nuclear matter effects on jets are small (d-Au compared to p-p)
- Large suppression of high p_T hadrons in the presence of a sQGP
- Once parton escapes medium fragments as in vacuum
- Jets reconstructed in A-A assuming vacuum frag. show same suppression as for single hadrons (Gaussian filter studies)
- Strong evidence of broadening and softening of the jet energy profile (R=0.2/R=0.4, jet-hadron)

Results can be explained as due to significant partonic energy loss in the sQGP before fragmentation - numerous details left to be understood

The LHC continues the investigation...



RHIC vs LHC

RHIC	LHC
Beams: p to U	Beams: p to Pb
$\sqrt{s}$: 5-200 (p-p 500) GeV	$\sqrt{s}$: 5.5 (p-p 14) TeV
Central Events:	
$T \sim 2T_C$	$T \sim 4T_C$
ε (GeV/fm^3) = 5	ε (GeV/fm^3) = 15-60
τ(fm/c) = 2-4	τ(fm/c) >10
HI Running:	
12 weeks/year	4 weeks/year
Ave. A+A Luminosity	
5×10^{27}cm^{-1}s^{-1}	5×10^{26}cm^{-1}s^{-1}
20nb^{-1}/year (50% up time)	500μb^{-1}/year (50% up time)

RHICs higher luminosity and longer running time keep it competitive

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RHICs higher luminosity and longer running time keep it competitive

The expectation:

LHC plasma hotter, denser, longer lived

Open questions:

same sQGP? different evolution?

The LHC is a hard probes machine

An LHC Pb-Pb year:

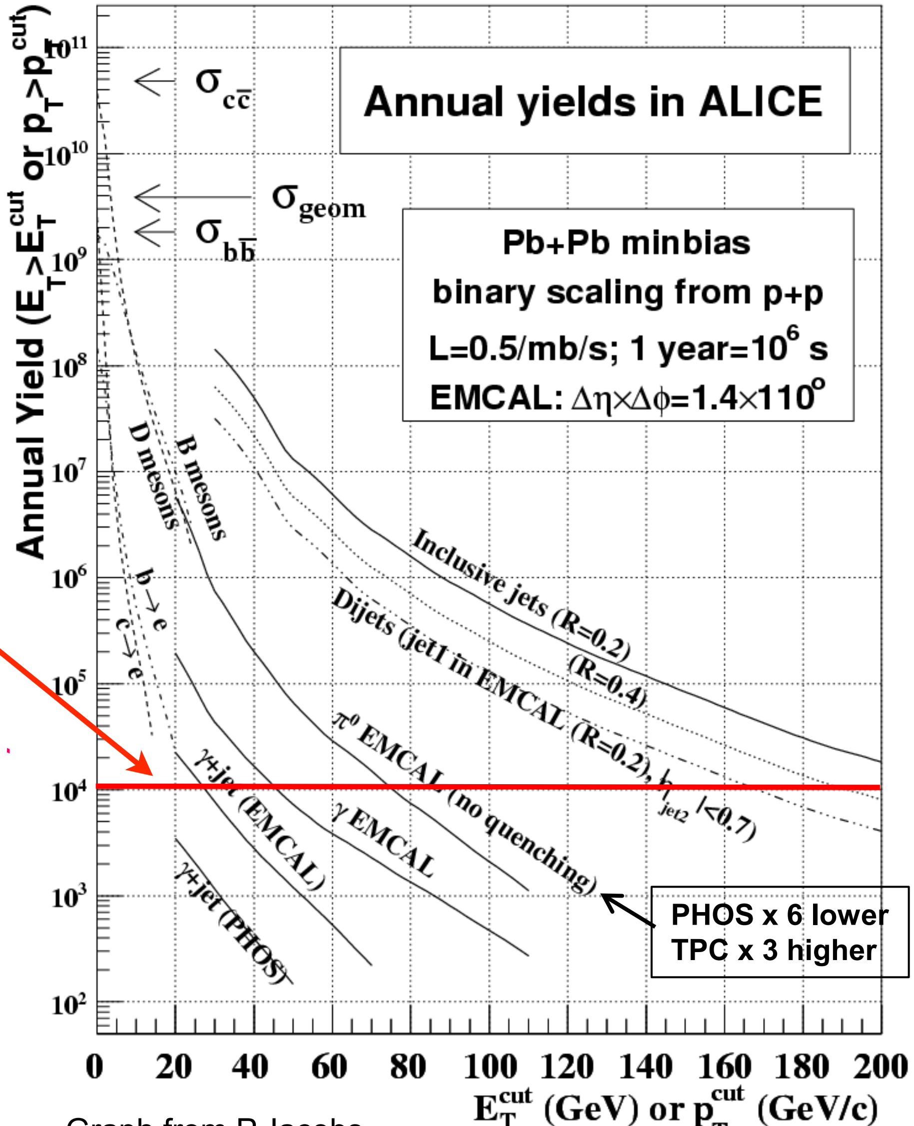
1 month ~ 10^6 seconds

Need 10^4 "events" in a year to make a measurement:

- inclusive jets E_T < 200 GeV
- di-jets E_T < 170 GeV
- π^0 p_T <75 GeV
- inclusive γ p_T<45 GeV
- inclusive e p_T<30 GeV

- σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)
- σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)

Hard probes are no longer rare probes



Graph from P.Jacobs

Heavy ions at the LHC

What are the initial conditions

Is gluon saturation seen?

What is the measured T_{ch} from particle ratios?

$T_{ch} \sim T_c$ as at RHIC or higher - thermal models interpretation?

Is $v_{2LHC} < v_{2RHIC}$?

Time evolution of the medium

Is QGP still strongly coupled?

Behaving like a perfect liquid or more gas like?

Energy loss similar to at RHIC?

What is the mass/flavor dependence of the Eloss

Heavy flavor copiously produced at LHC

Pb-Pb "First Physics"

First 10^5 Pb-Pb events: global properties, unidentified mult, rapidity distribution, p_T spectra, elliptic flow

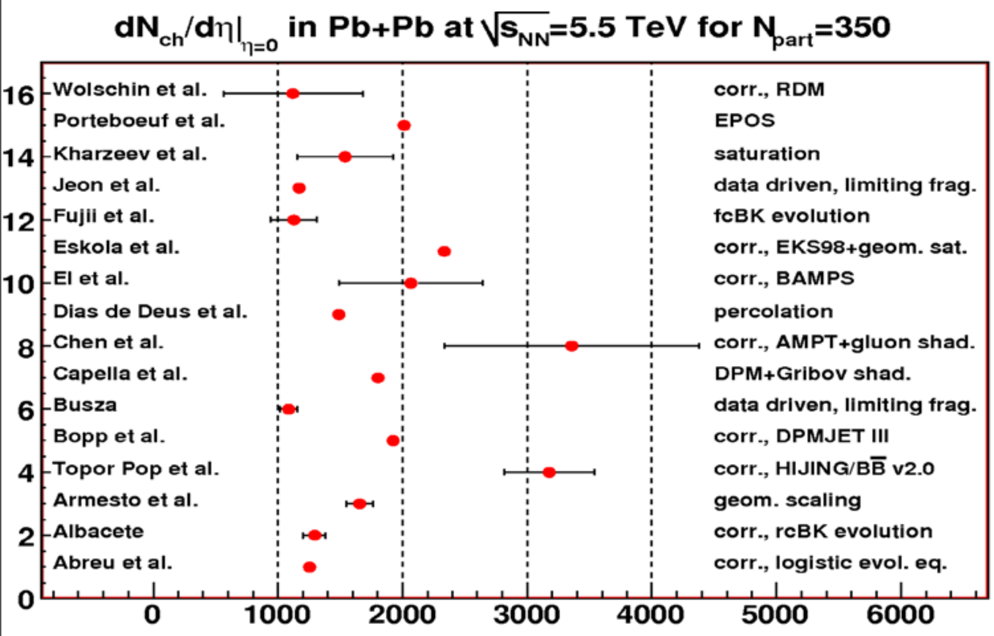
First 10^6 Pb-Pb events: PID spectra, resonances, differential flow analyses, particle correlations

First 10^7 Pb-Pb events: jet quenching and heavy flavor (charm) production and energy loss

Ultimate analyses: energy density, temperature, pressure, entropy, viscosity, energy loss mechanisms

And of course p-p as the baseline, and new basic understanding: mult, baryon transport, PID spectra and cross-sections (including c and b)

First question: how many particles?

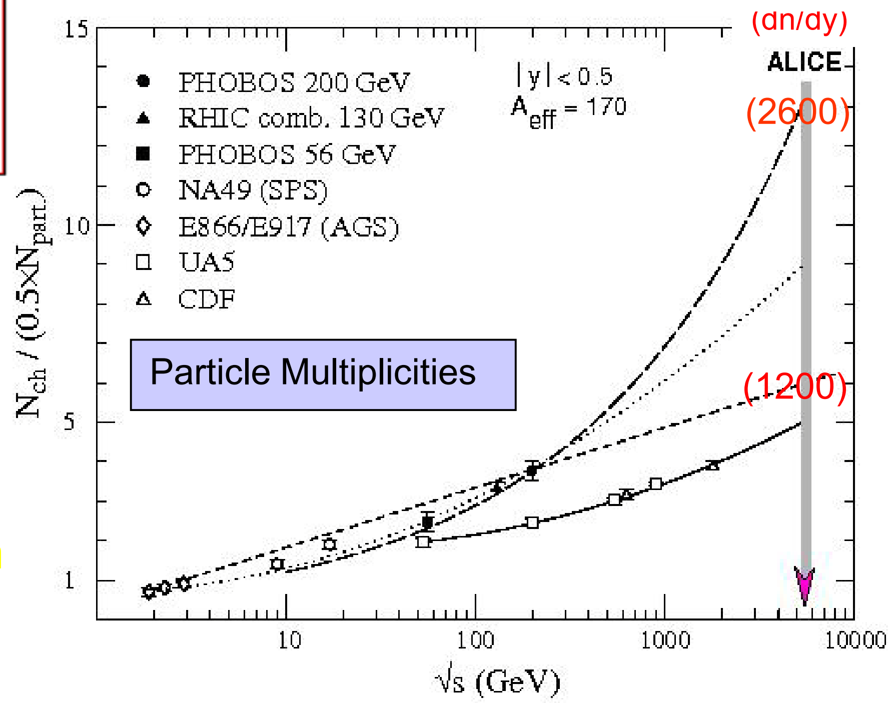


N. Armesto arXiv:084.4158

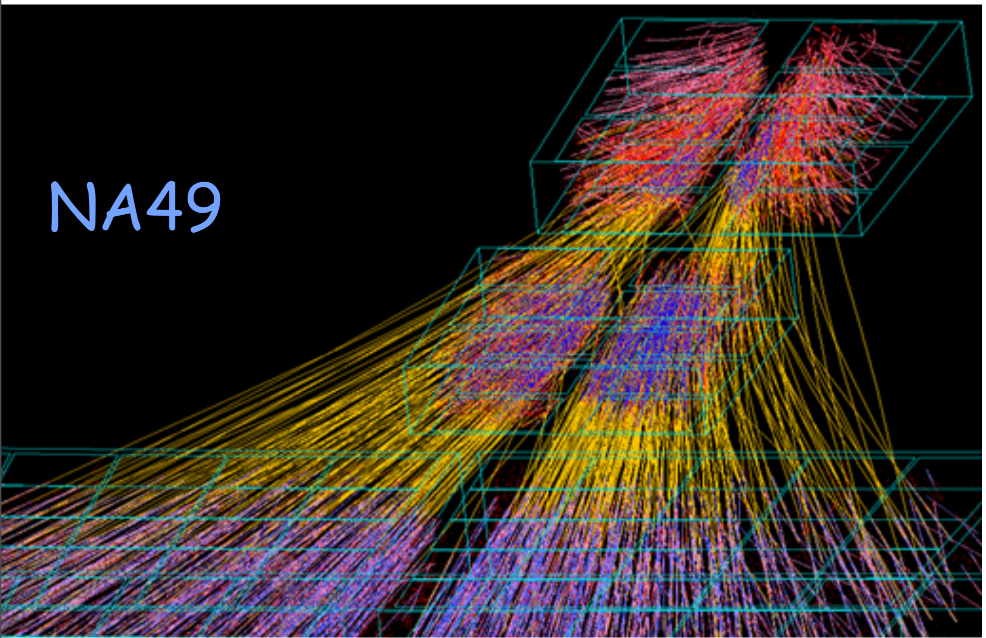
Saturation models N_{ch} <2000

Largest values from models without collective motion

First few events will "kill" many models

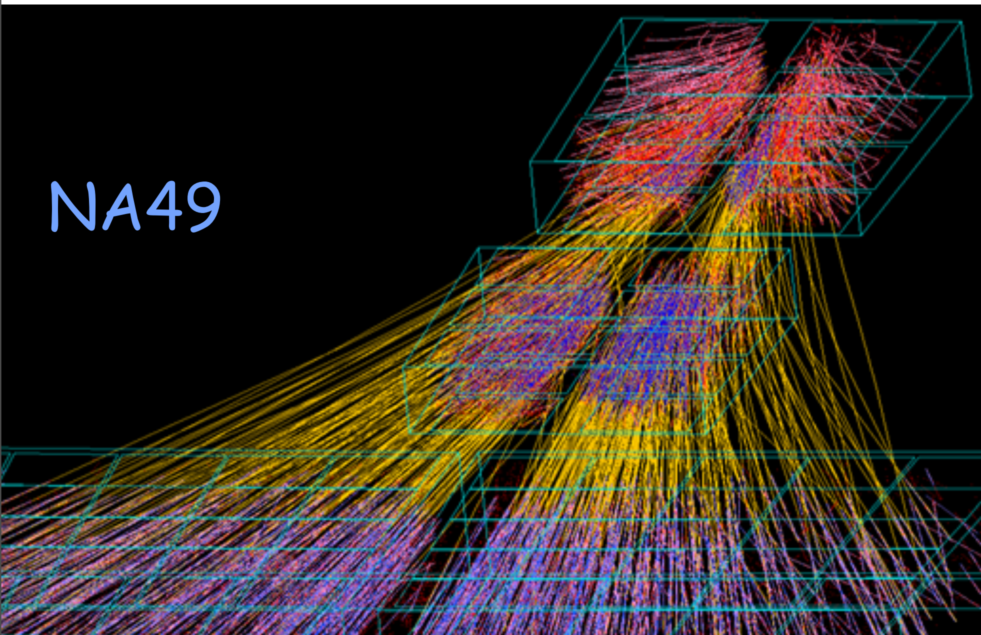


Each generation: new extreme of tracking

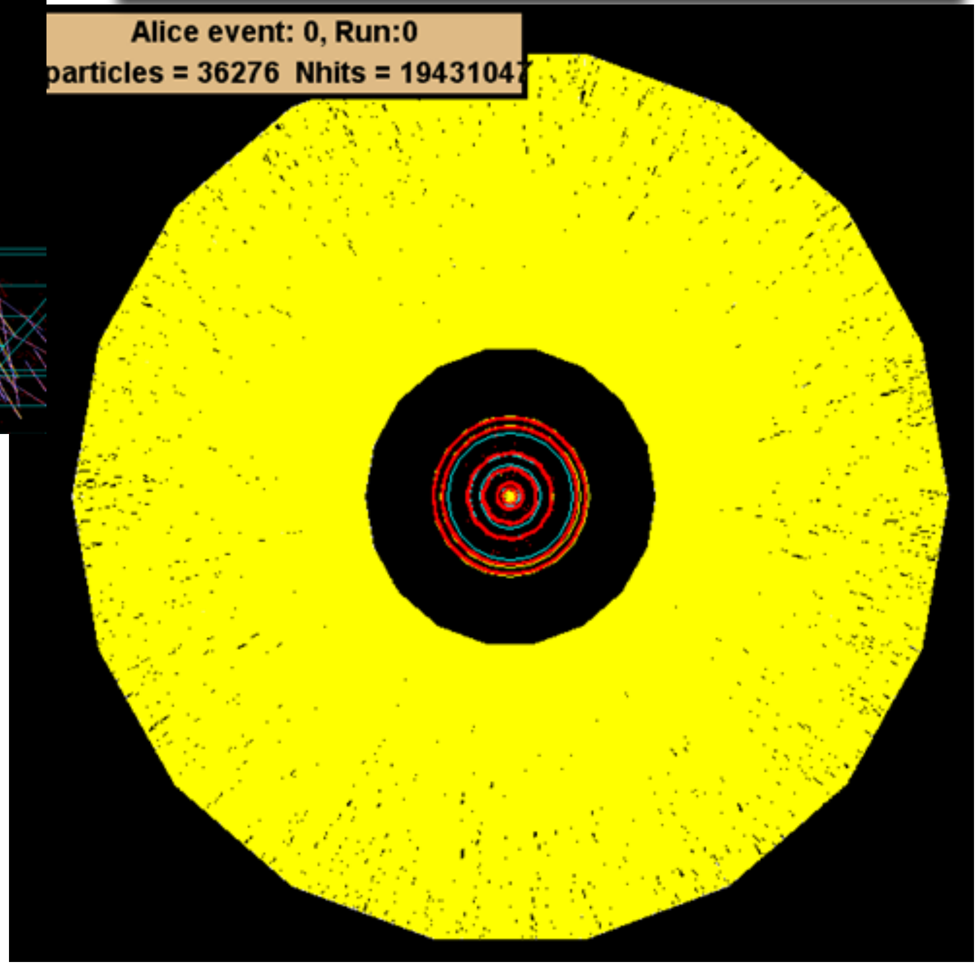


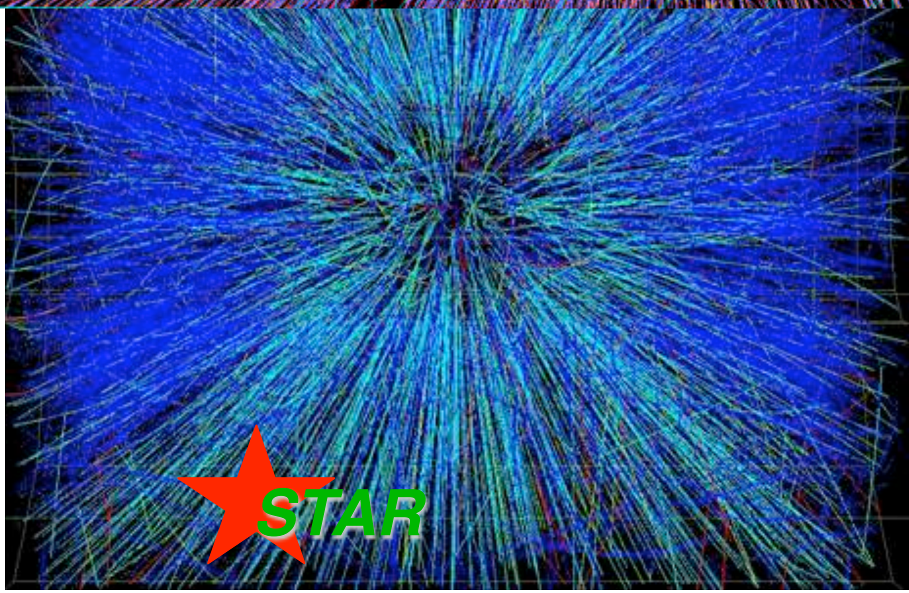
STAR

Each generation: new extreme of tracking

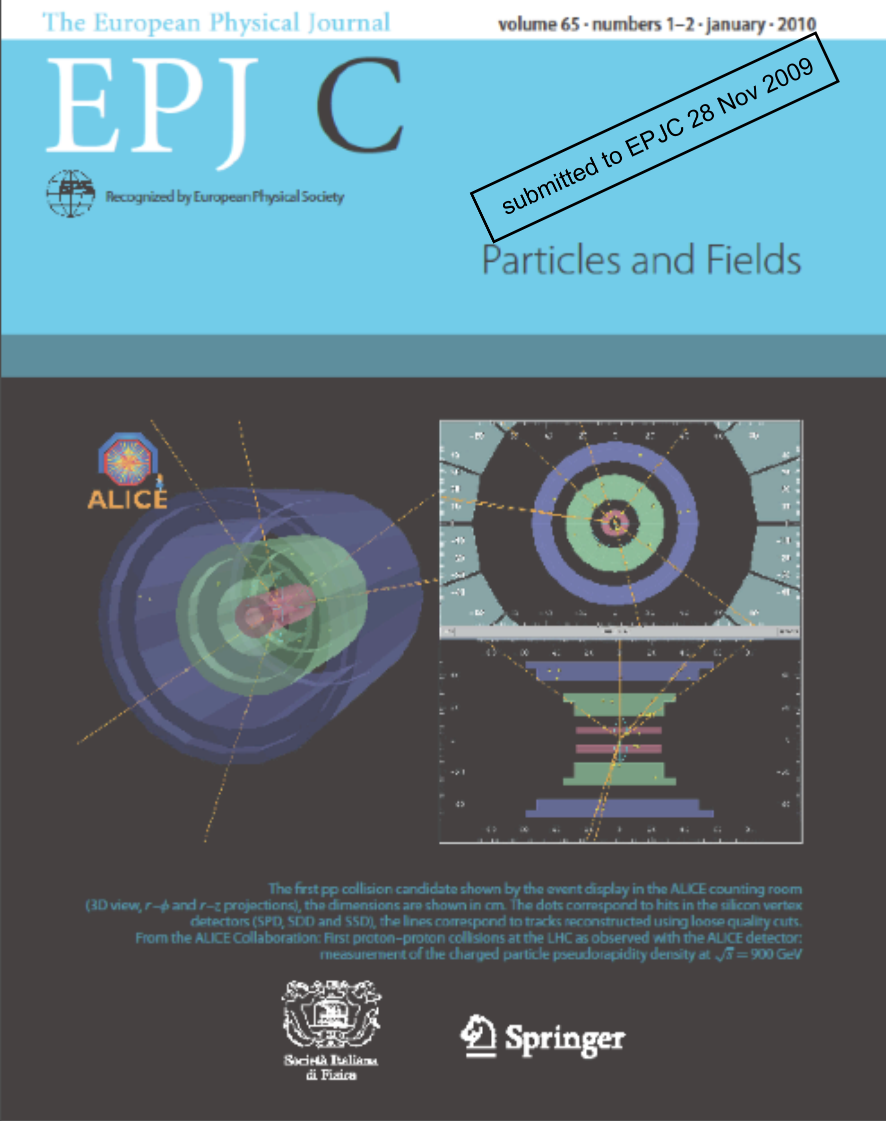


ALICE 'worst case' scenario:
dN/dy_{ch} = 8000





First publication



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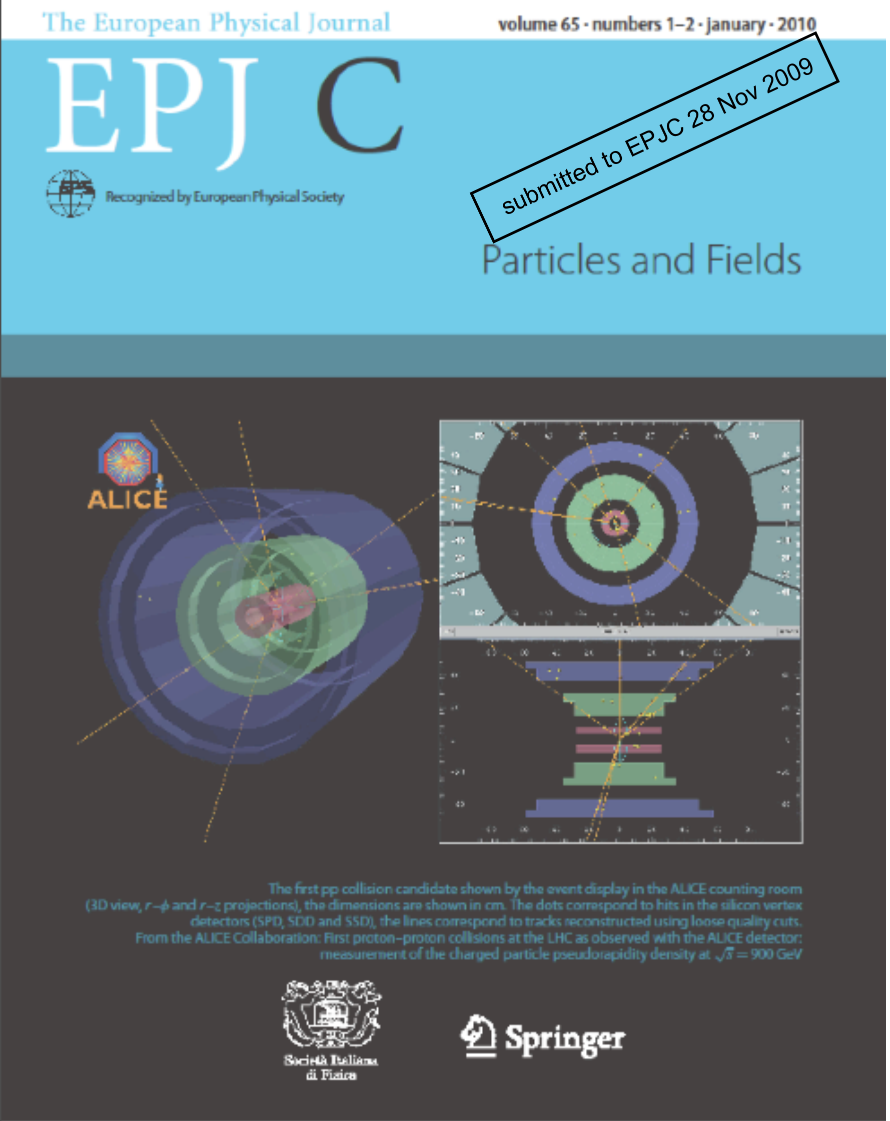

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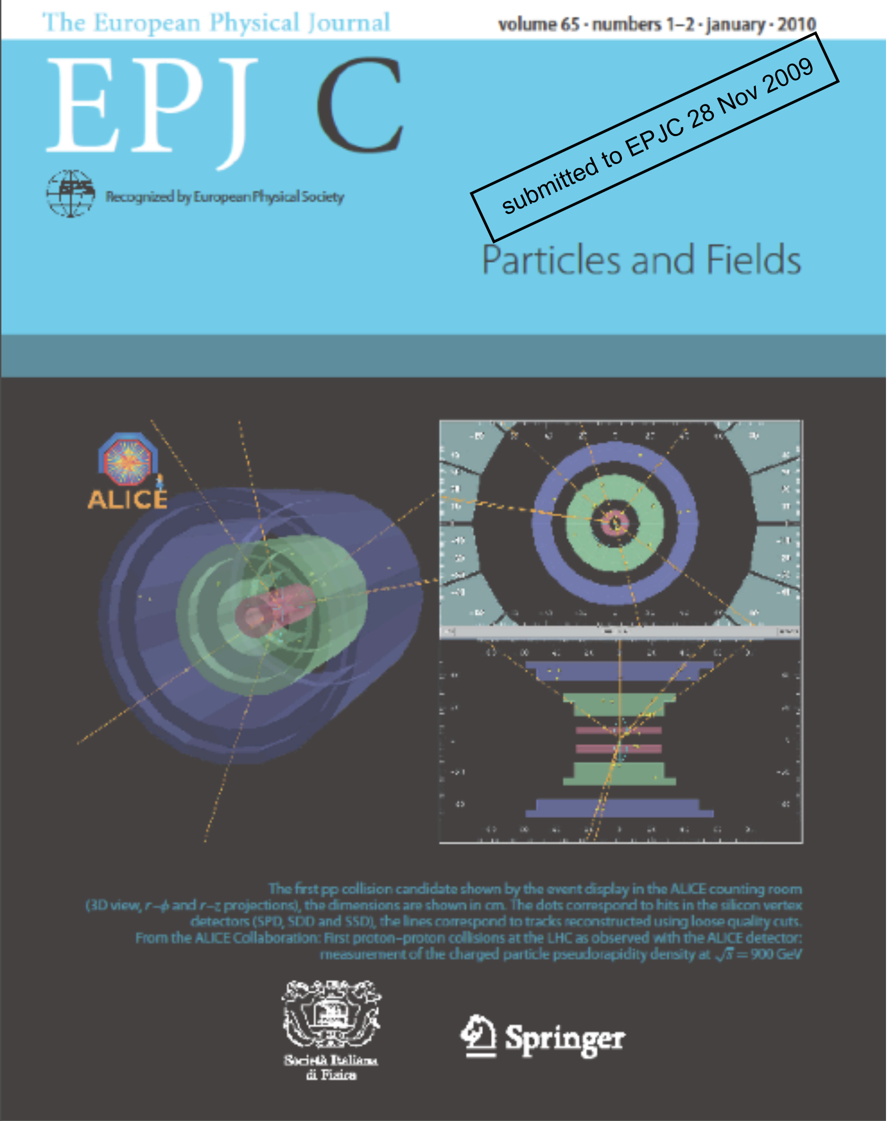

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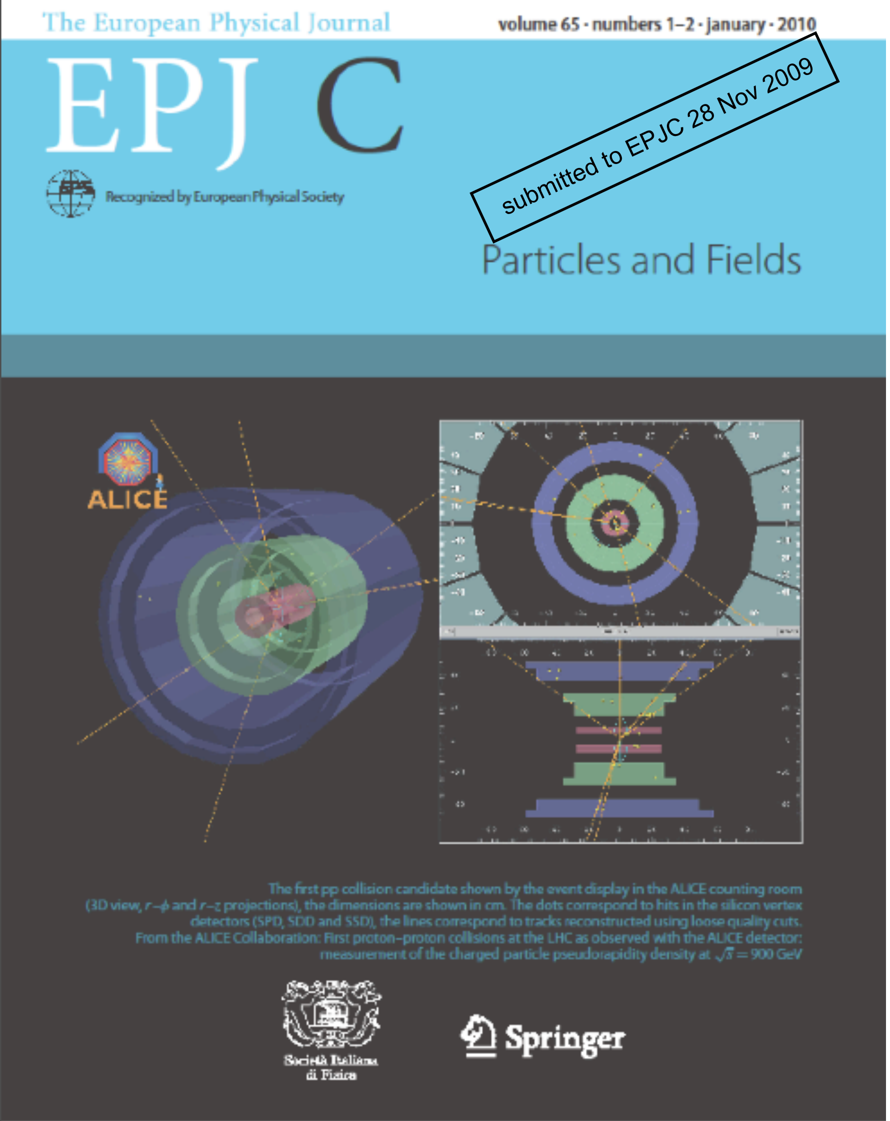

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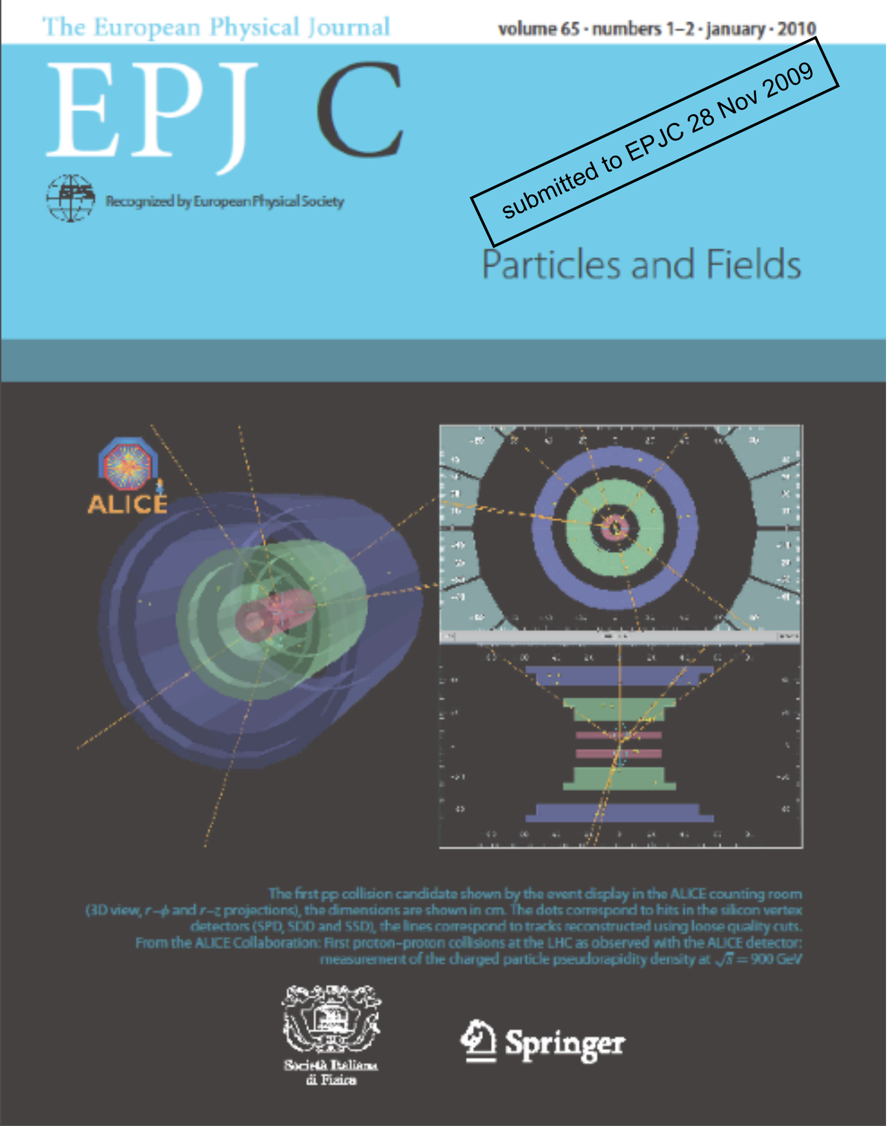

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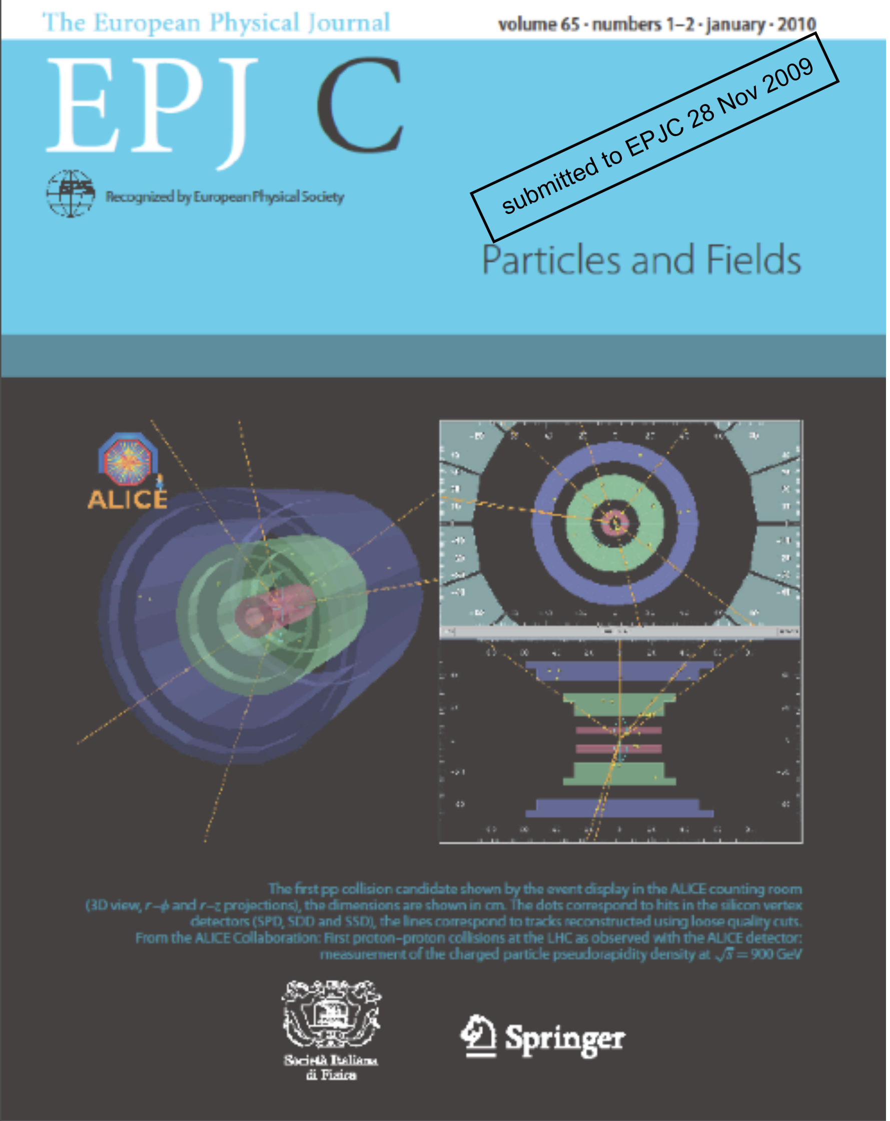

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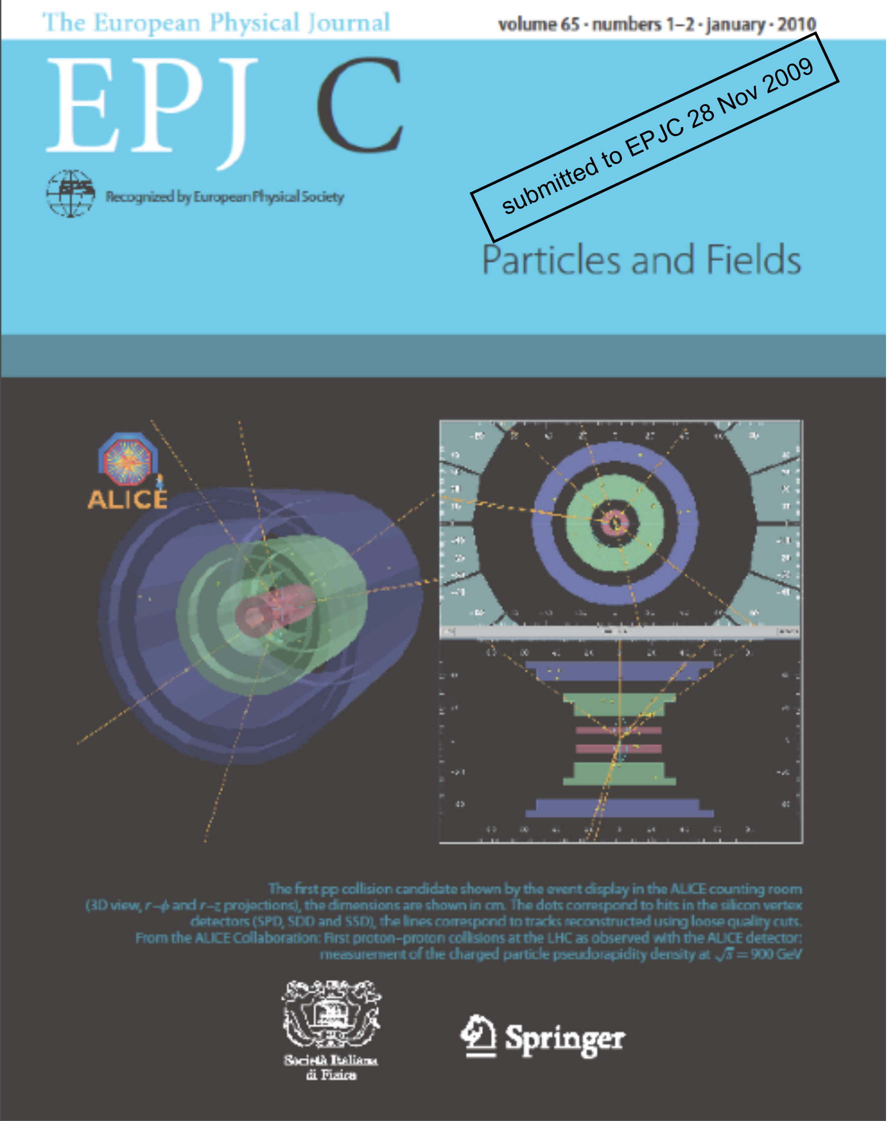

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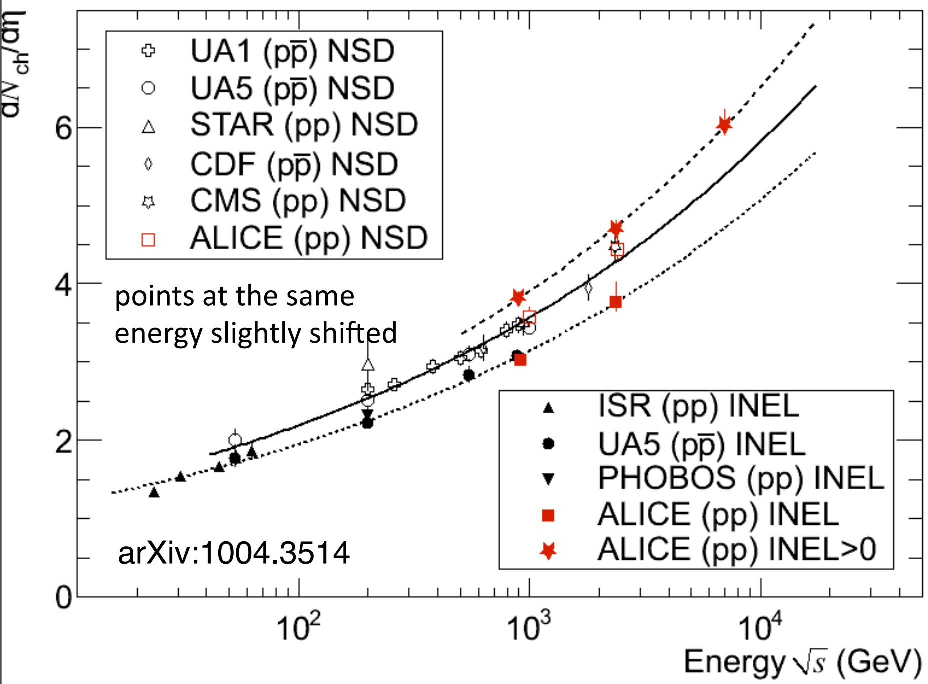
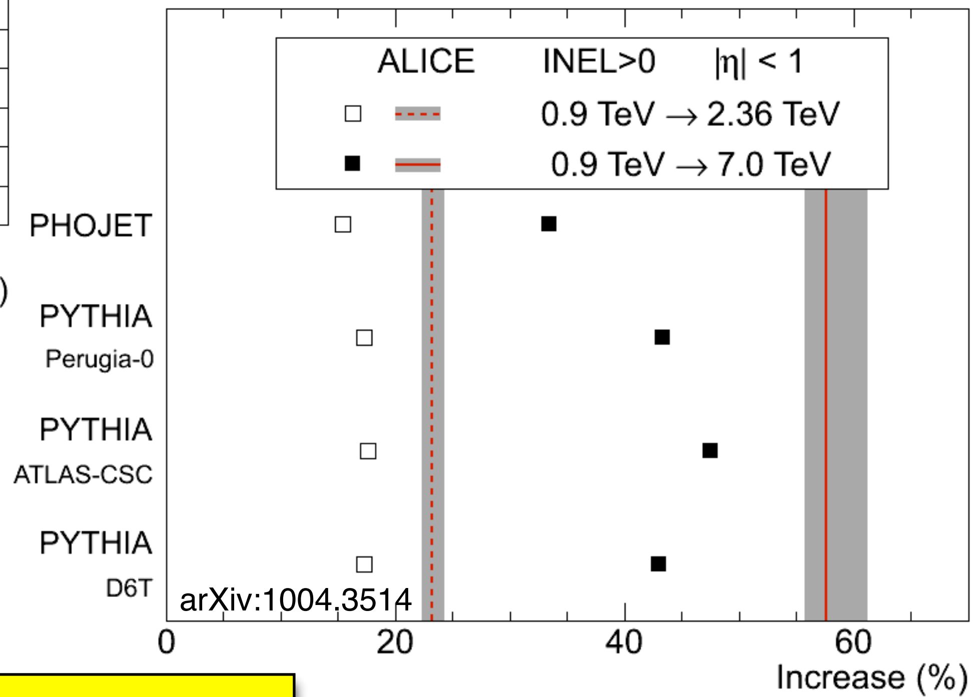
- ⇨ and **3 days** to agree on the Authorlist

A closer look at the √s dependence



Data appears to have a power law dependence but as yet no real physics motivation for this

Even PYTHIA "ATLAS-CSC" doesn't get the % increase as function of collision energy correct



Some physics missing from all models

Summary

The LHC is up and running successfully

The p-p data is being analyzed and already reveals surprises

The models of p-p collisions need some serious tuning

First Pb-Pb data is scheduled for November 2010

The QGP at the LHC is expected to be longer-lived and hotter than at RHIC

With the LHC and RHIC programs running in parallel the 2010's promise an exciting decade for Relativistic Heavy-Ion Collision Research