Relativistic Heavy Ions III - Hard Probes and Jet Quenching

RHI Physics

The US National Nuclear Physics Summer School & TRIUMF Summer Institute

Vancouver, Canada

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Outline:

What is a jet?

Using a Calibrated Probe

How to Reconstruct a Jet

High p_T Phenomena

Recap of last lecture

- Clear evidence of a new state of matter → QGP

- Energy density of fireball higher than QCD predicts for phase transition

- Chemical freeze-out temperature higher than predicts for phase transition

- Strong evidence for collective motion - nearly perfect fluid created

- Strong evidence for partonic phase followed by brief hadronic phase

What is “Hard” physics?

‘Hard’ processes have a large scale in the calculation that makes perturbative QCD applicable:

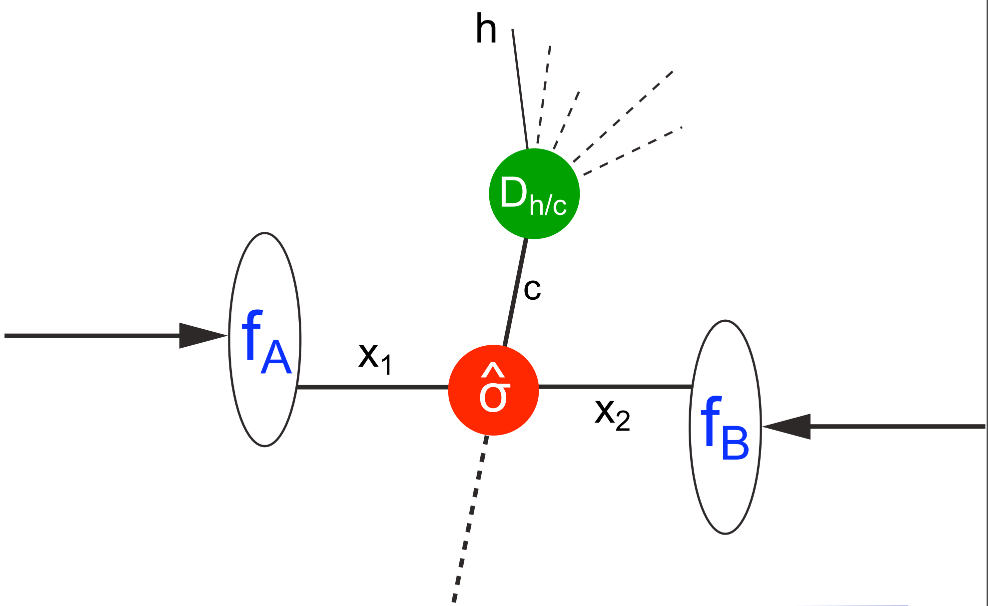
- high momentum transfer Q^2
- high mass m
- high transverse momentum p_T

N.B.: since m≠0 heavy quark production is ‘hard’ process even at low p_T

Assumptions:

Factorization assumed between the perturbative hard part and the universal, non-perturbative fragmentation (FF) and parton distribution functions (PDF)

Universal fragmentation and parton distribution functions (e.g. PDF from ep, FF from ee, use for p-p)



Hard = pQCD + factorization + universality

Hadron production cross-section in an AB collision where AB=pp,pA, AA is:

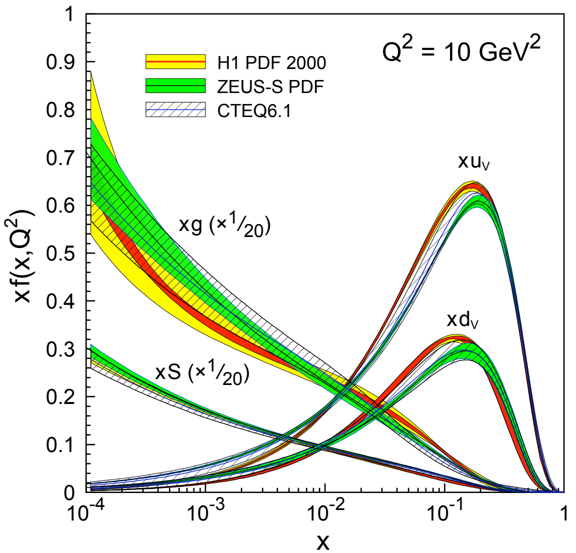
$$E\frac{d^3\sigma_h}{dp^3} \propto \sum_{a,b,c,d} \int dz_c dx_1 dx_2 \frac{s}{z_c^2} f_{i/A}(x_1,Q^2) f_{j/B}(x_2,Q^2)$$

Collins, Soper, Sterman, Nucl. Phys. B263 (1986) 37

$$D_{h/c}(z_c,Q^2)\frac{d\hat{\sigma}^{(ab\to cd)}}{dt}\delta(s+u+t) + \mathcal{O}\left(\frac{\Lambda}{m}\right)^p$$

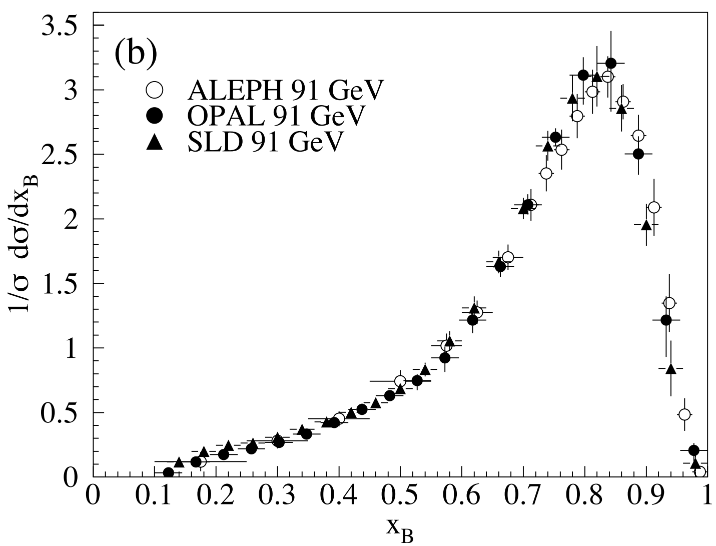
Parton Distribution Functions

Flux of incoming partons (structure functions) from Deep Inelastic Scattering



Fragmentation Functions

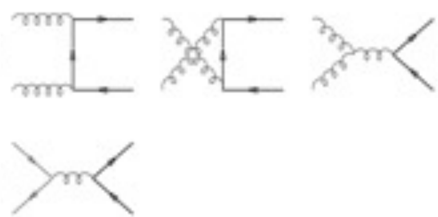
D(z) in order to relate jets to observed hadrons



Perturbative QCD

dσ/dt = hard partonic cross section calculable in QCD in powers of α_s^{2+n}

- n=0: leadings order (LO)
- n=1: next-to-leading order (NLO)



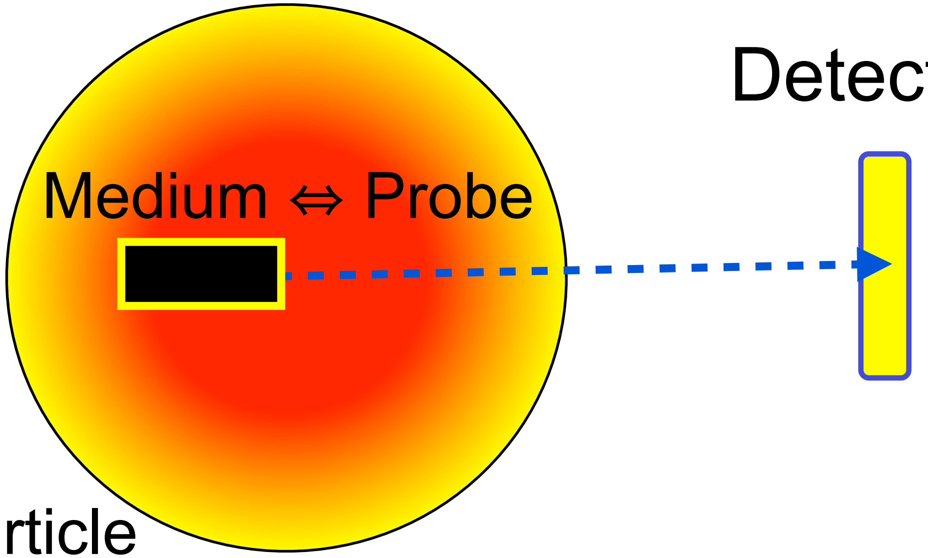
Why do we study "Hard" processes?

Matter we want to study

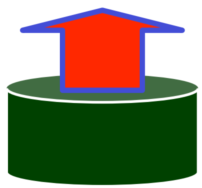
Hard Probes

Self-generated probes

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



Detectors



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

Hard probes of dense matter (Bricks)

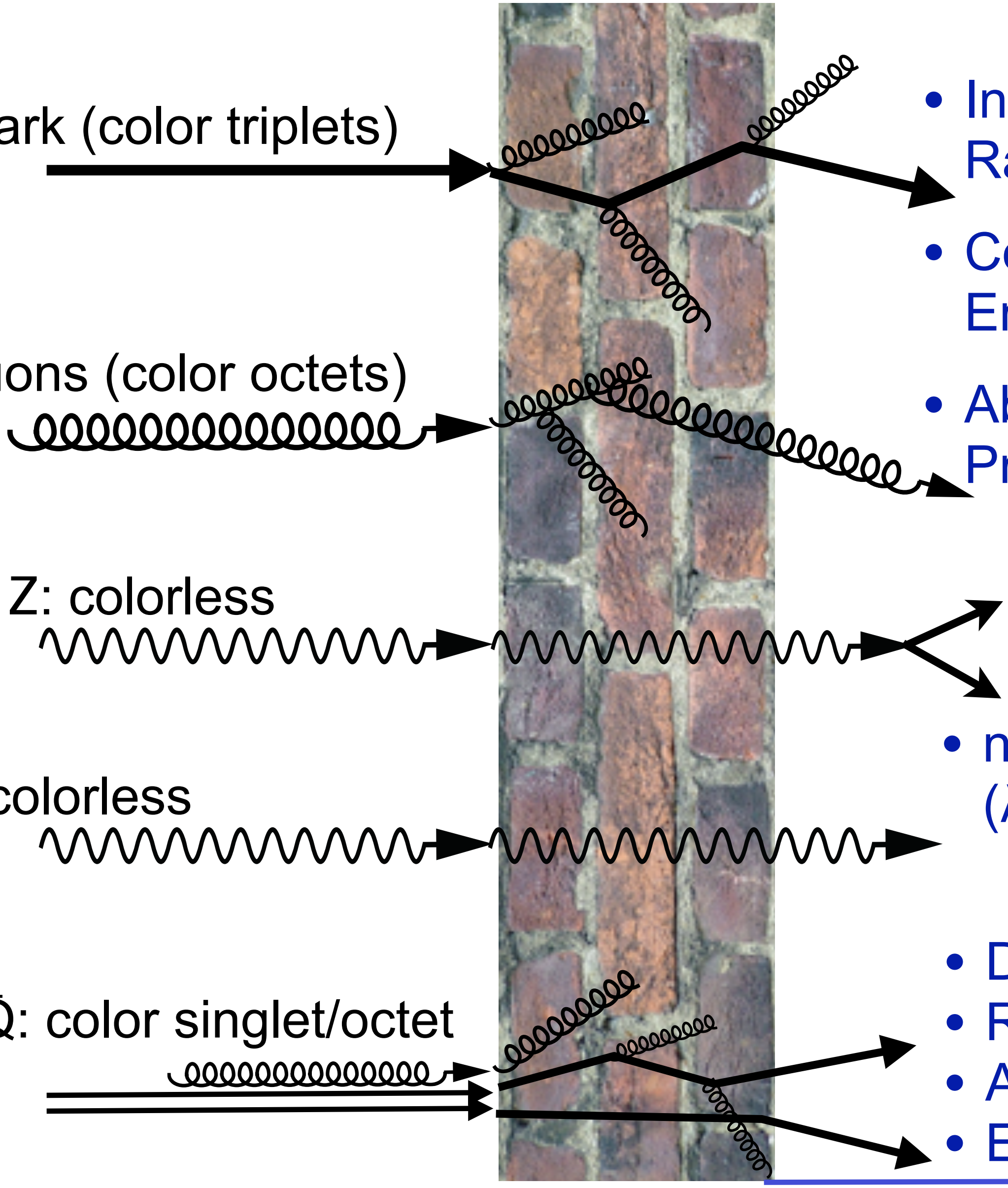
quark (color triplets)

gluons (color octets)

γ^*, Z: colorless

γ: colorless

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



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

- nothing ($\lambda \gg L$)

Yields:

- transport coefficient
- Gluon Density
- Energy Density

Control

- Dissociation
- Recombination
- Absorption
- E-loss ?

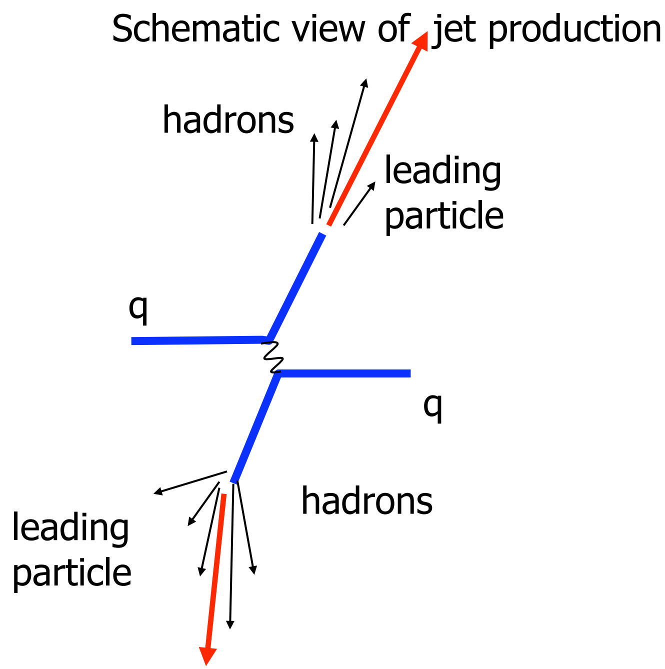
Yields:

- T_{QGP}
- Probe Deconfinement

Using high momentum particles as probes

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

Direct interaction with partonic phases of the reaction



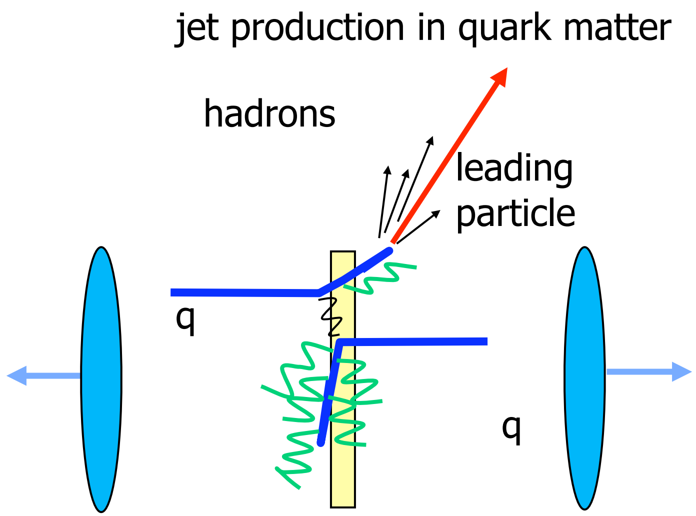
Using high momentum particles as probes

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

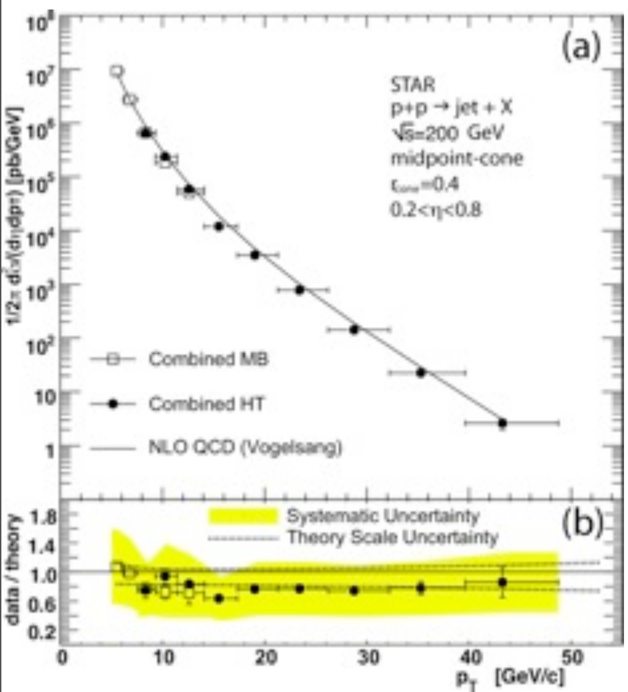
Direct interaction with partonic phases of the reaction

Therefore use these high momentum products as probes at RHIC

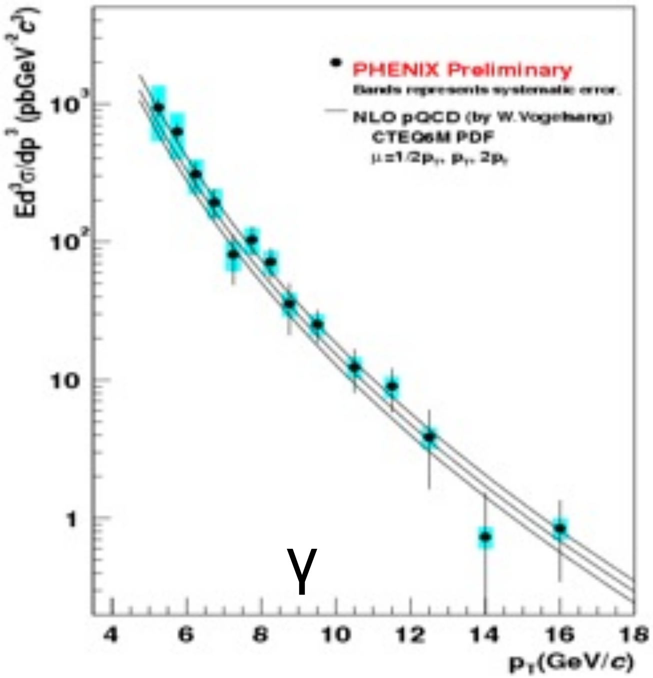
- attenuation or absorption of high p_T hadrons

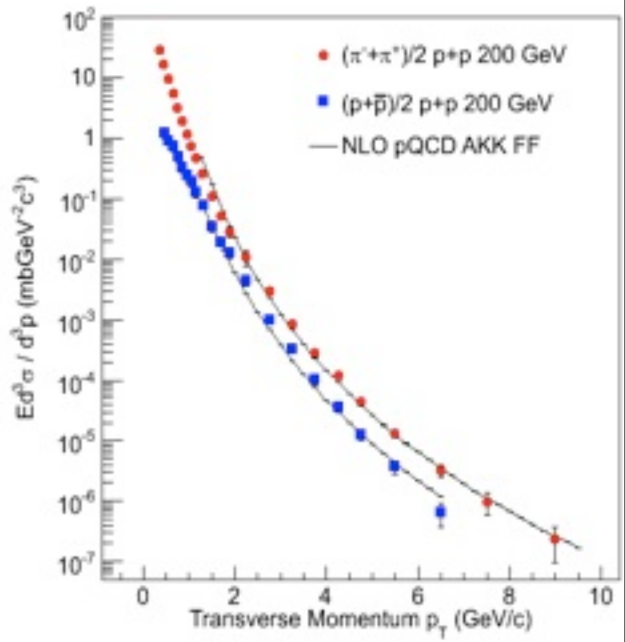


high p_T production – a calibrated probe



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

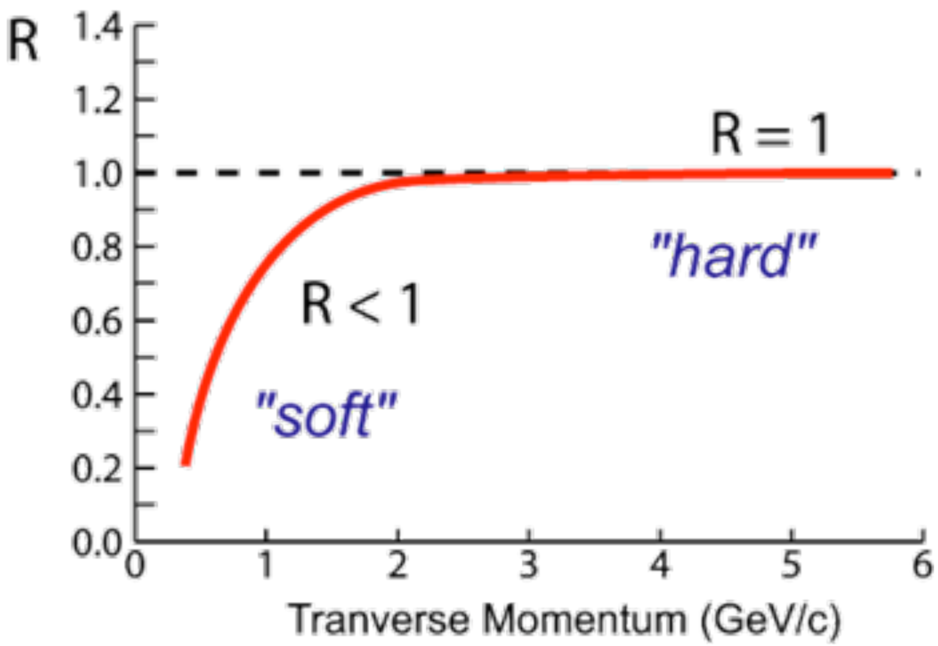
Looking for attenuation/absorption

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

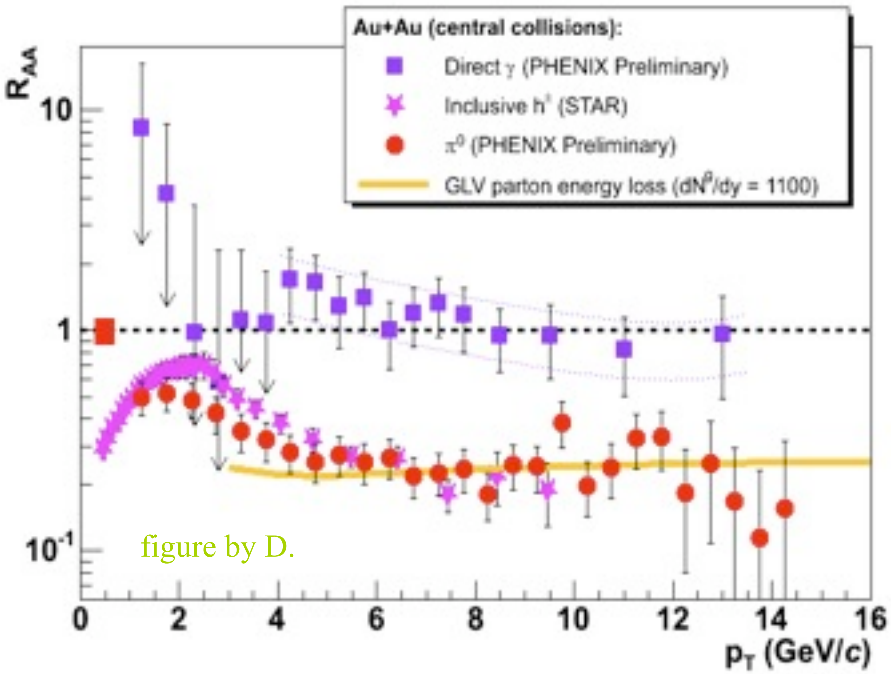


No "Effect":

- 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



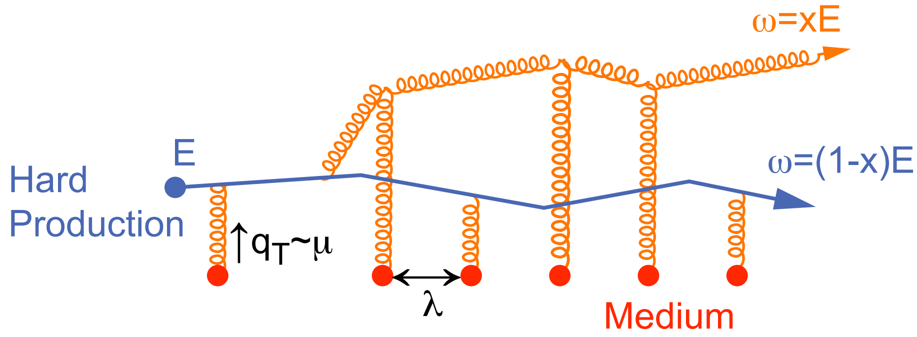
Observations at RHIC:

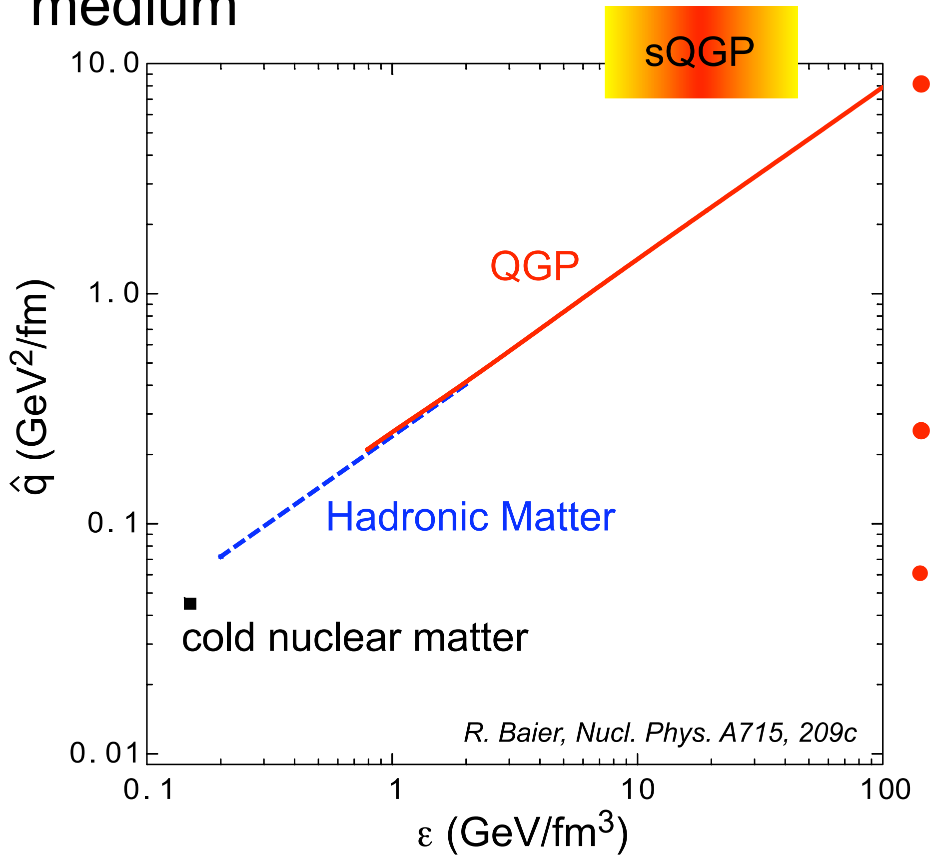
1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5
3. Hadrons are not suppressed in peripheral collisions
   - Good! medium less dense

sQGP - strongly coupled - colored objects suffer large energy loss

Interpretation

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





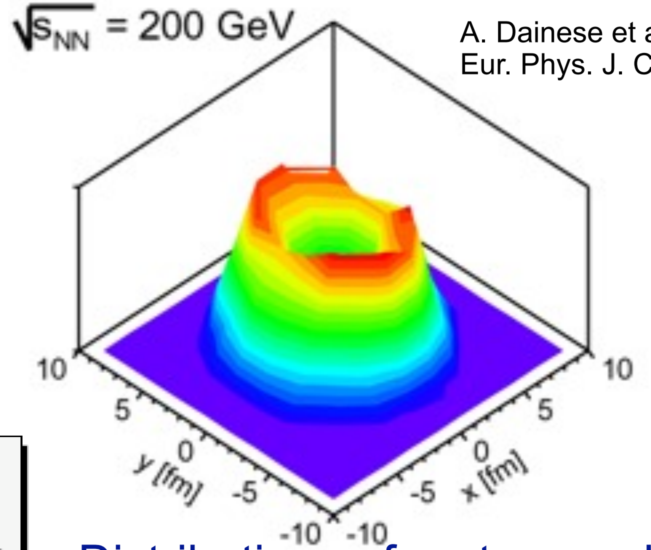
- Mean parton energy loss ∝ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim \Delta L^2$ (medium length)
    $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$
- is $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length

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

The limitations of R_{AA}

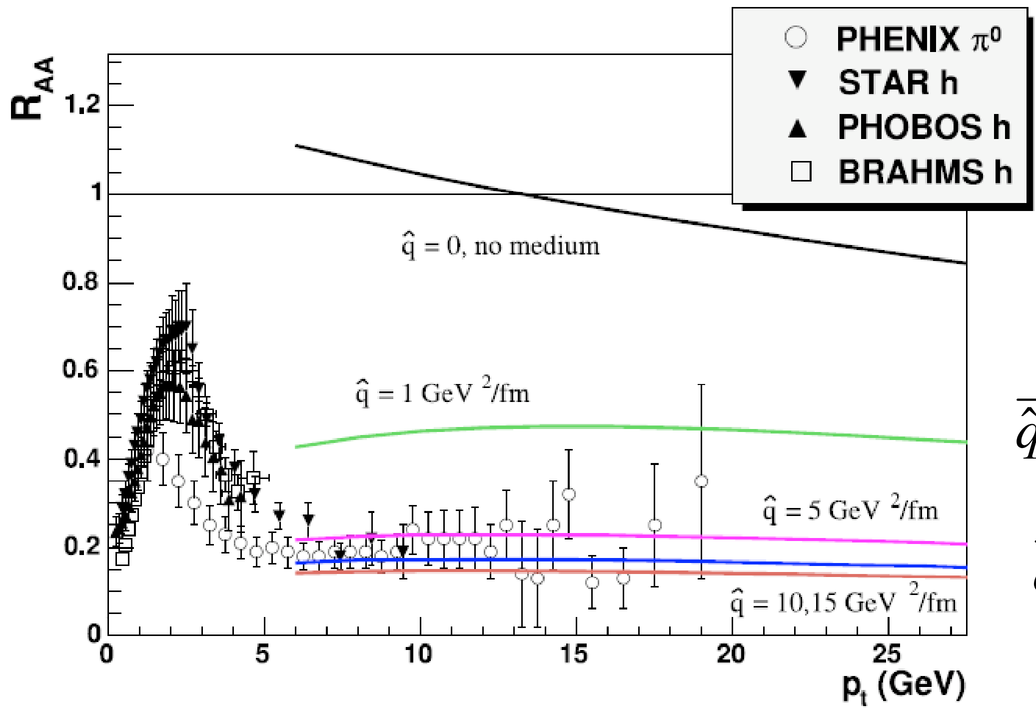
Insensitivity due to surface emission:

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



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

Distributions of parton production points in the transverse plane



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

Rough correspondence:

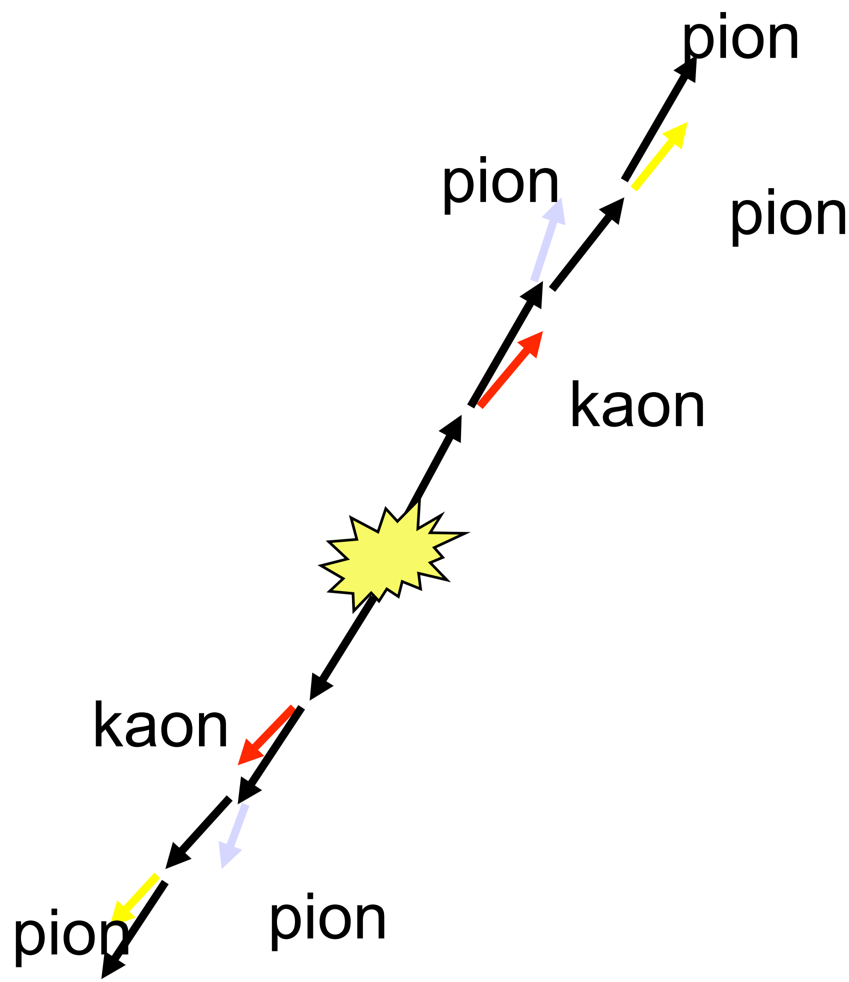
$$\bar{\hat{q}} = 10 \frac{GeV^2}{fm} \Leftrightarrow \frac{dN^g}{dy} \approx 1800$$

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

Need better tool

Jet studies

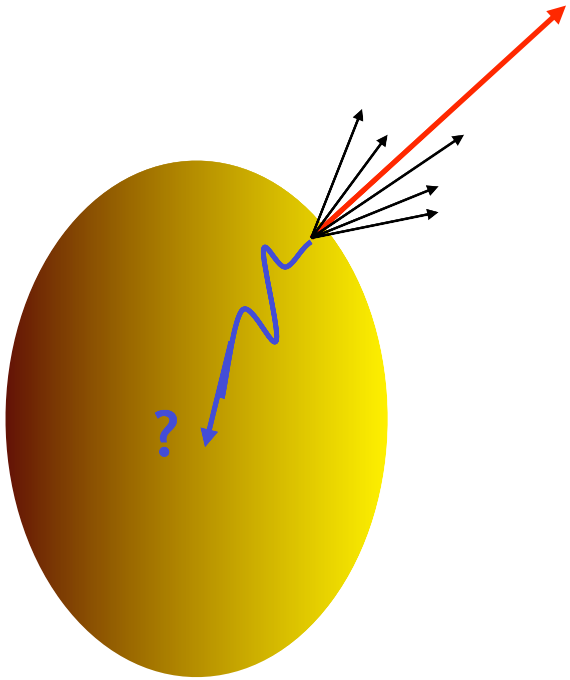
- Jets – the results of high Q^2 parton-parton collisions
- Partons fragment into collimated spray of hadrons (pions, kaons,etc) - the “jet”
- Seen in high-energy physics experiments since mid-1970’s



Jets commonly come in pairs

Using jets to study the QGP properties

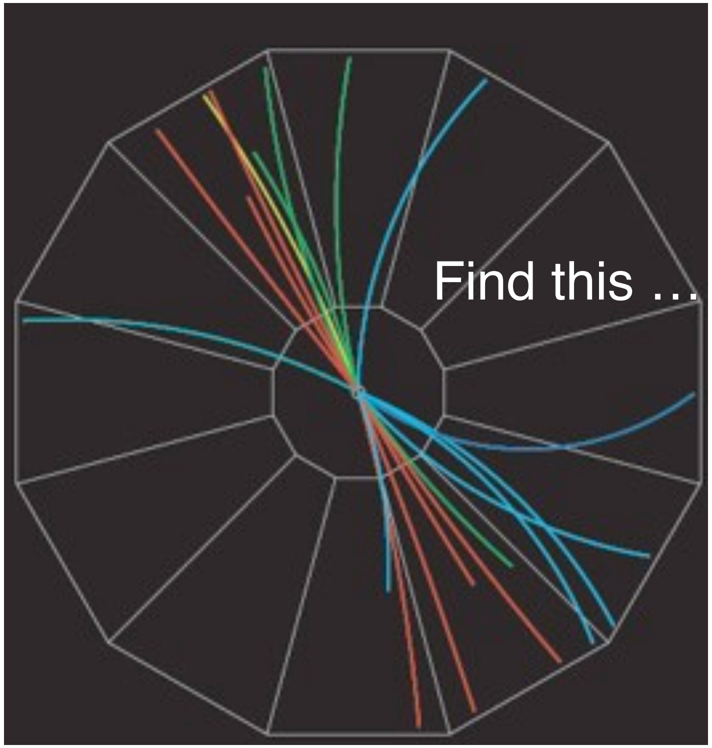
A case study: opacity of fog

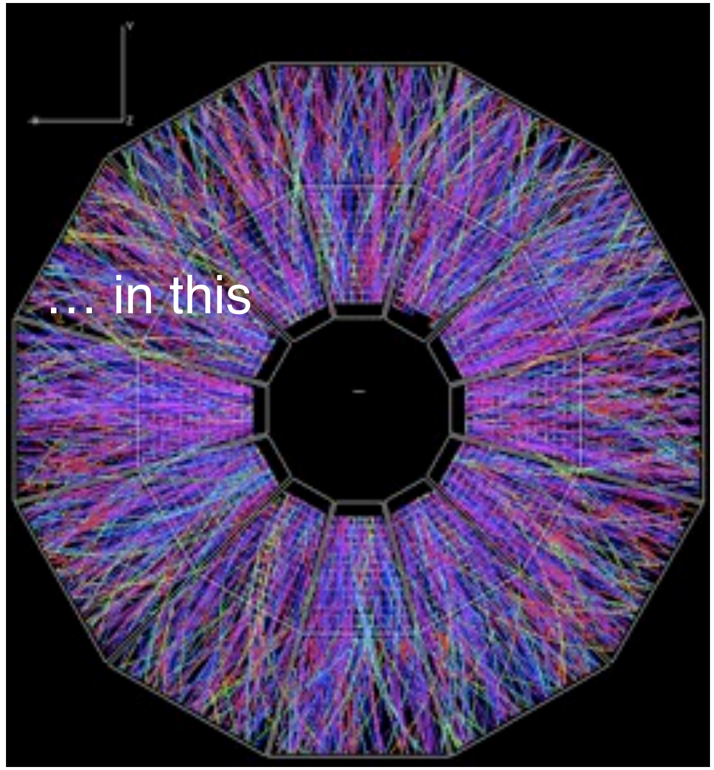


- First beam - least know the source is on.
- Second beam intensity tells you a lot about matter passed through

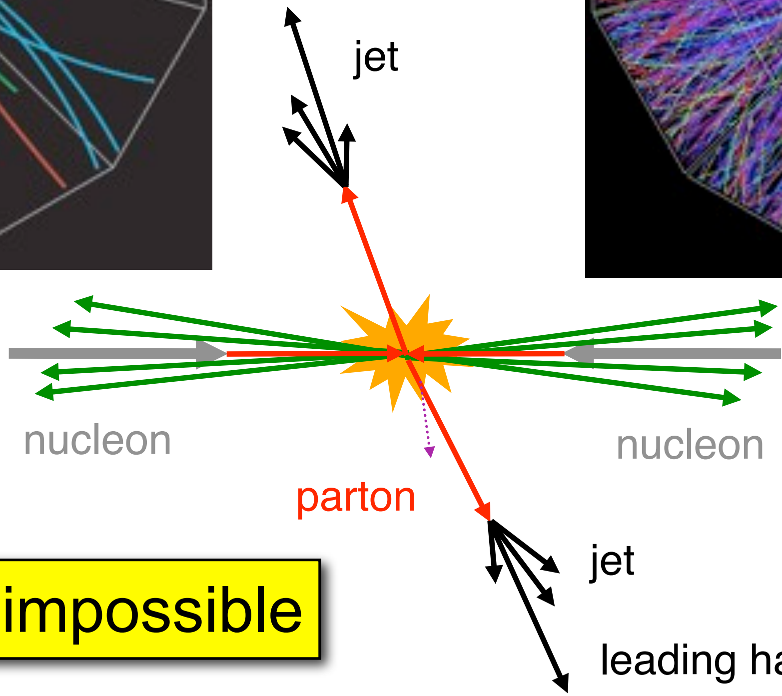
Predictions
QGP: “backwards” jet will be absorbed by medium
Hadron gas: “backwards” jet be less affected by medium

Finding a jet in a Au-Au event





p-p →jet+jet
(STAR@RHIC)

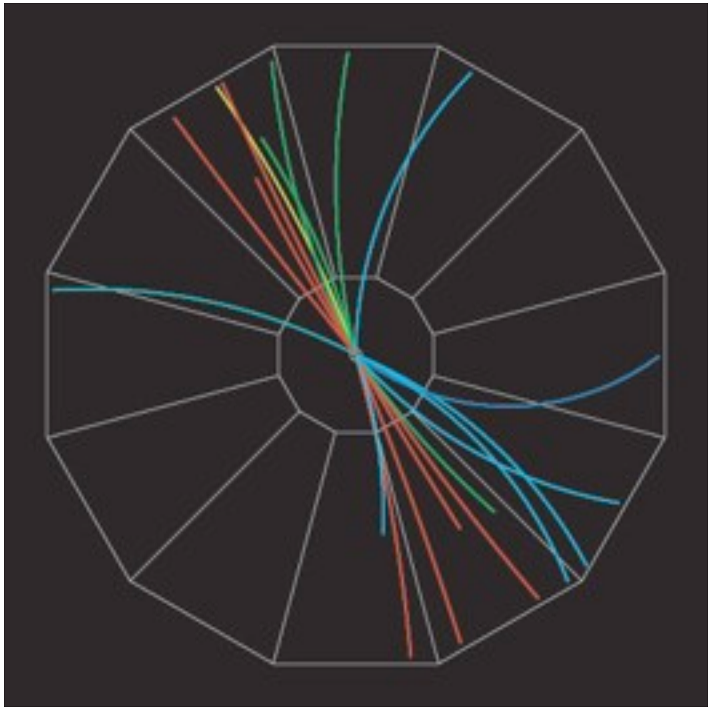


Au-Au →???
(STAR@RHIC)

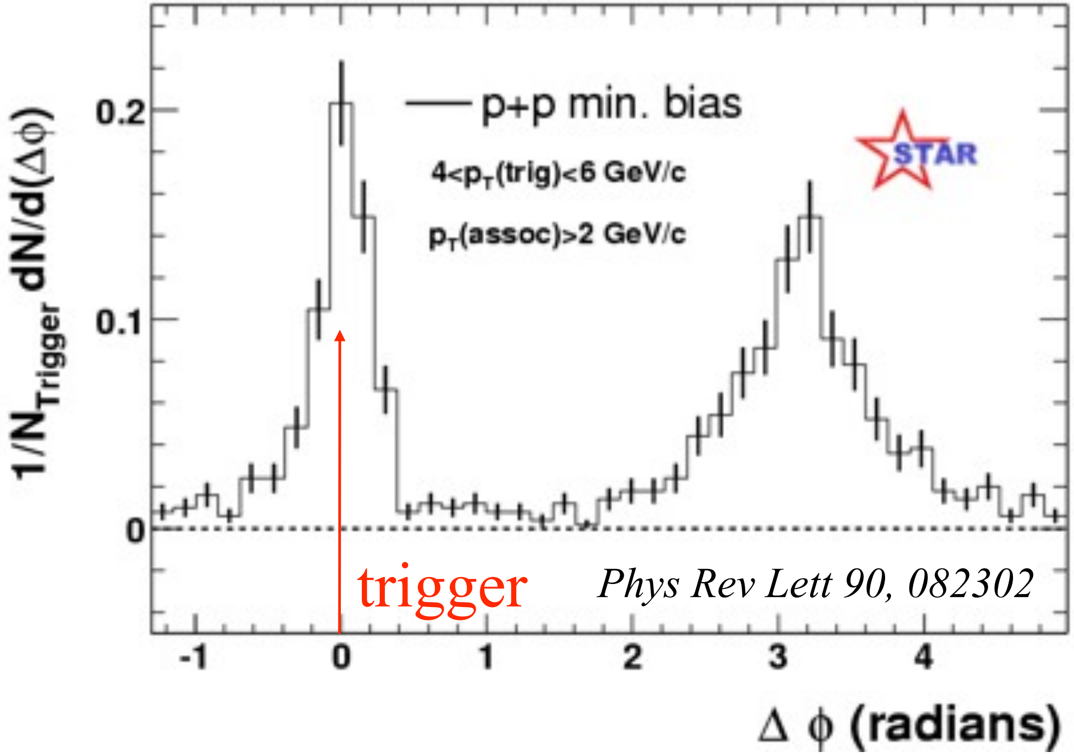
Seems almost impossible

Jets in Au-Au collisions!

p-p → dijet



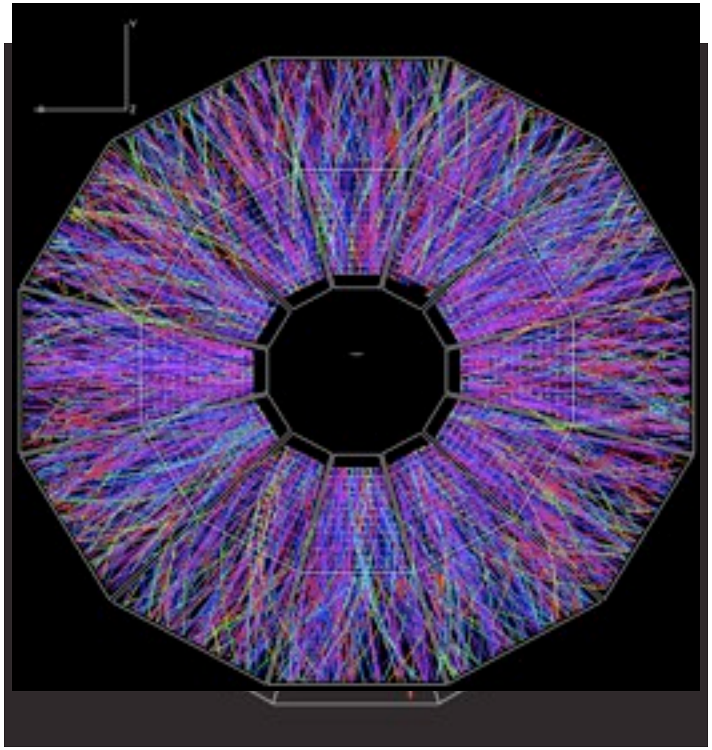
min. bias p-p collisions



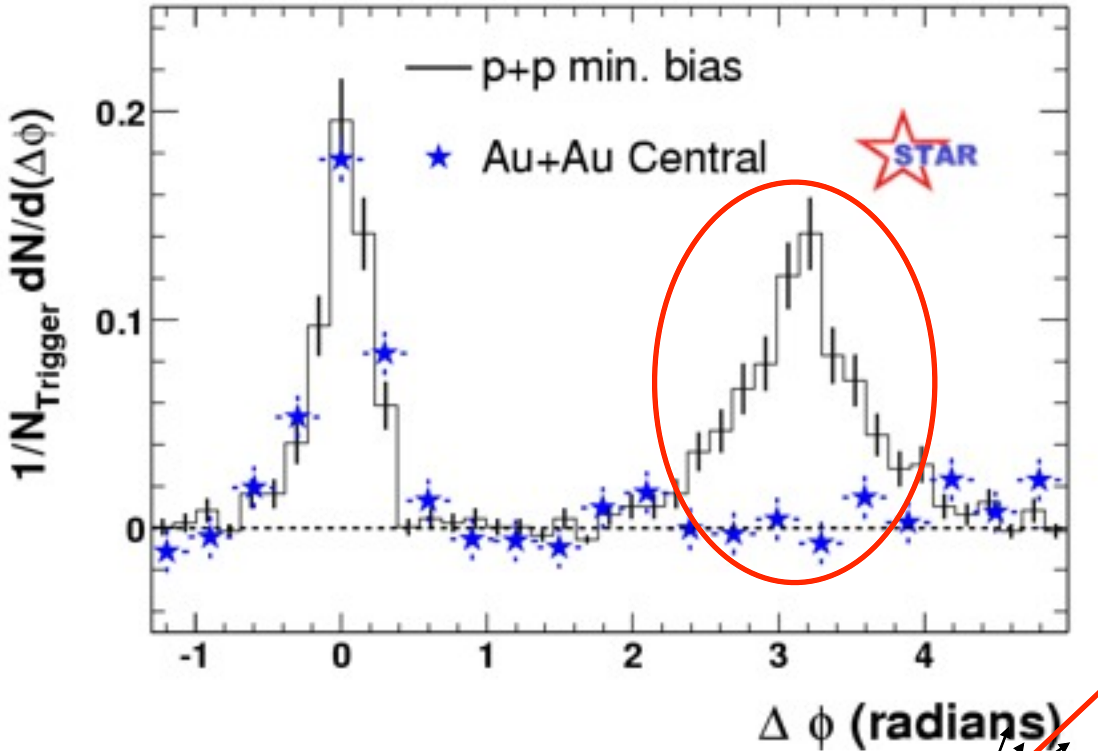
Phys Rev Lett 90, 082302

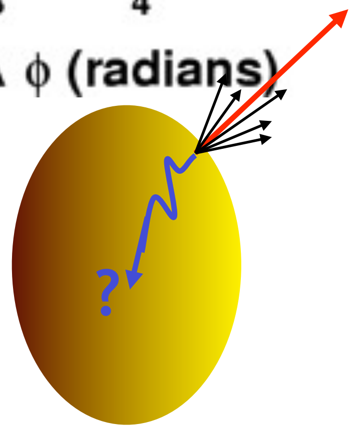
Jets in Au-Au collisions!

p-p → dijet



central Au-Au collisions





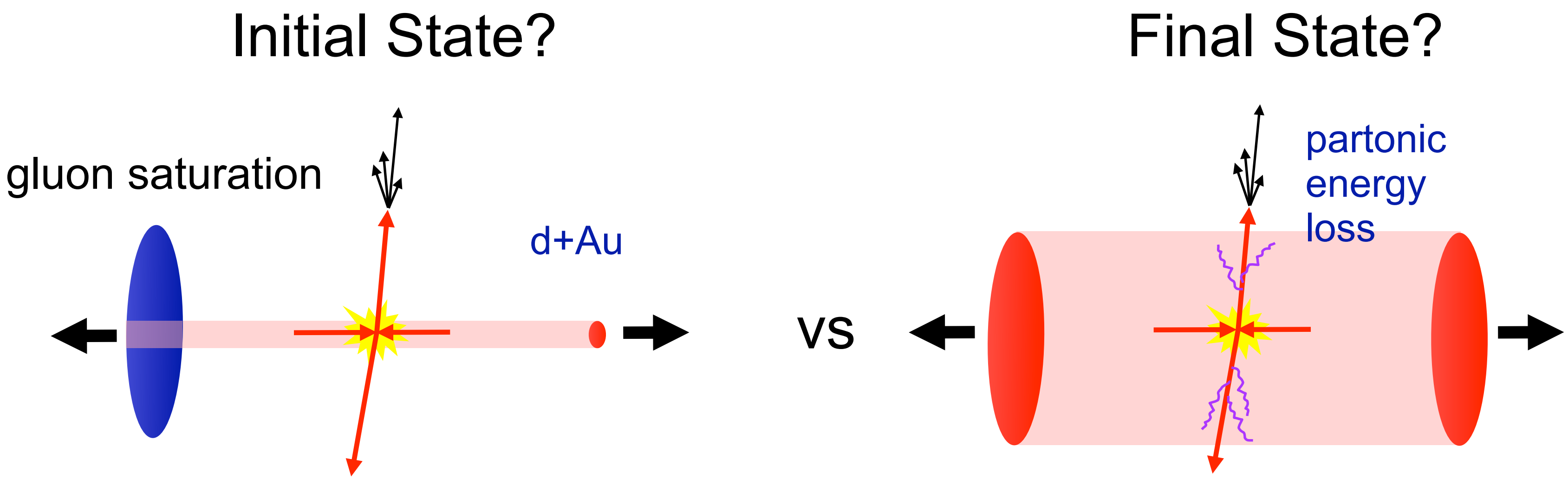
Δφ ≈ 0: central Au-Au similar to p-p

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

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?



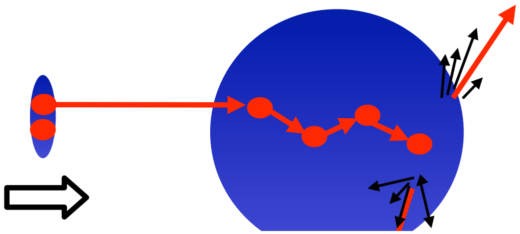
- To test need collisions where no final state effects due to plasma but initial nuclear state effects present:

Use d-Au

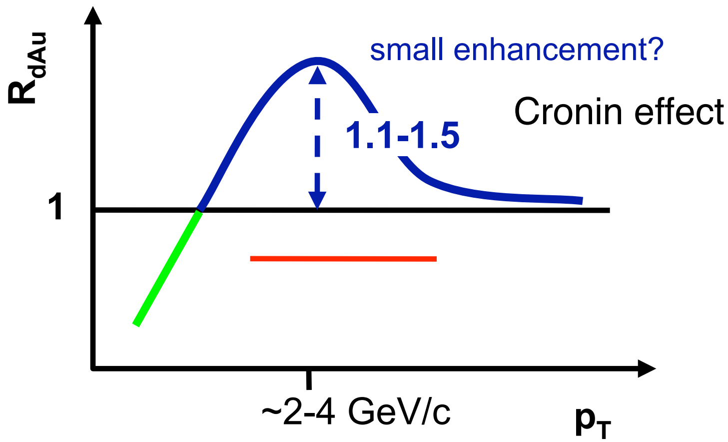
Expectations for d-Au

R_{AA}

Final state effect, R_{dAu} >1.



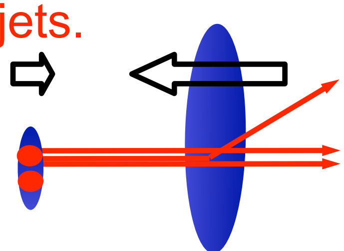
Initial state effect, R_{dAu} < 1.

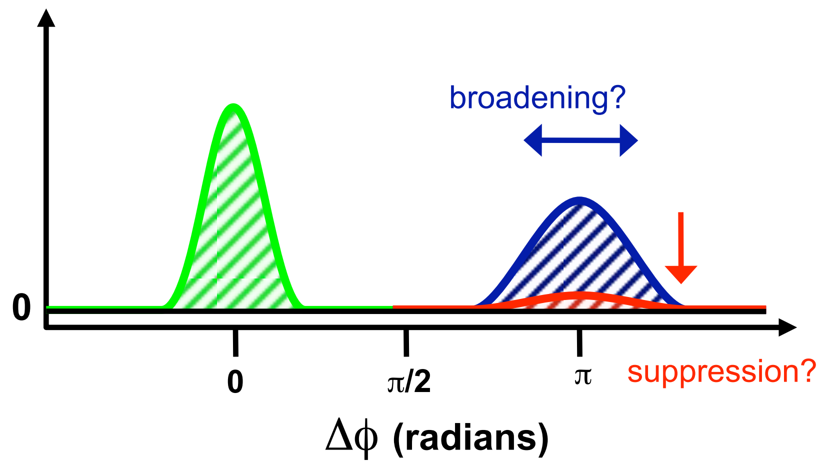


di-hadron

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

Saturation models: suppression persists due to mono-jets.





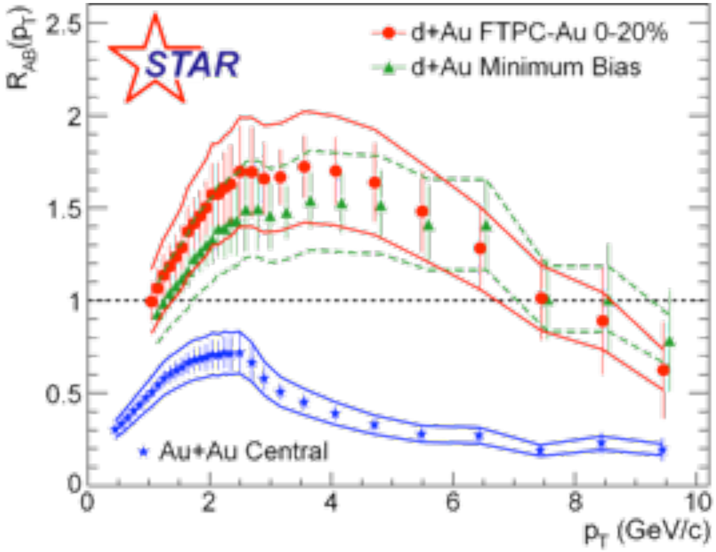
(Deuteron valence quark scatters of gluon condensate.)

The results

RAA

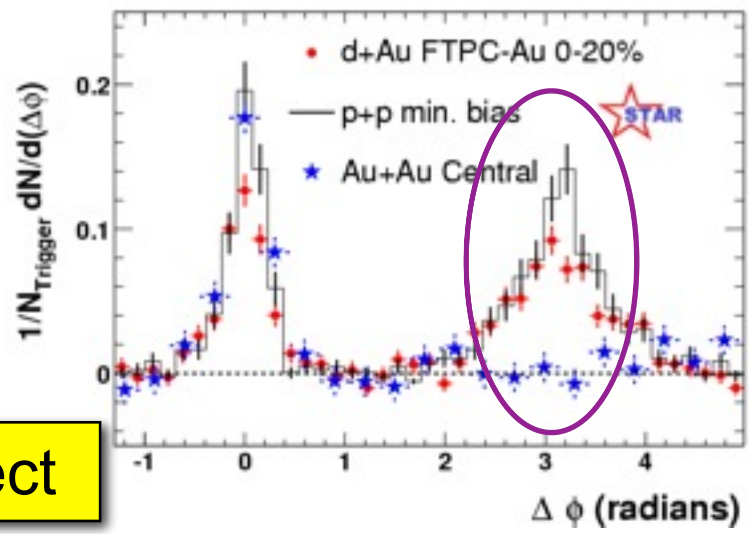
- Au-Au highly suppressed
- d-Au enhanced in same p_T range
- Suppression is a final state effect

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



di-hadrons

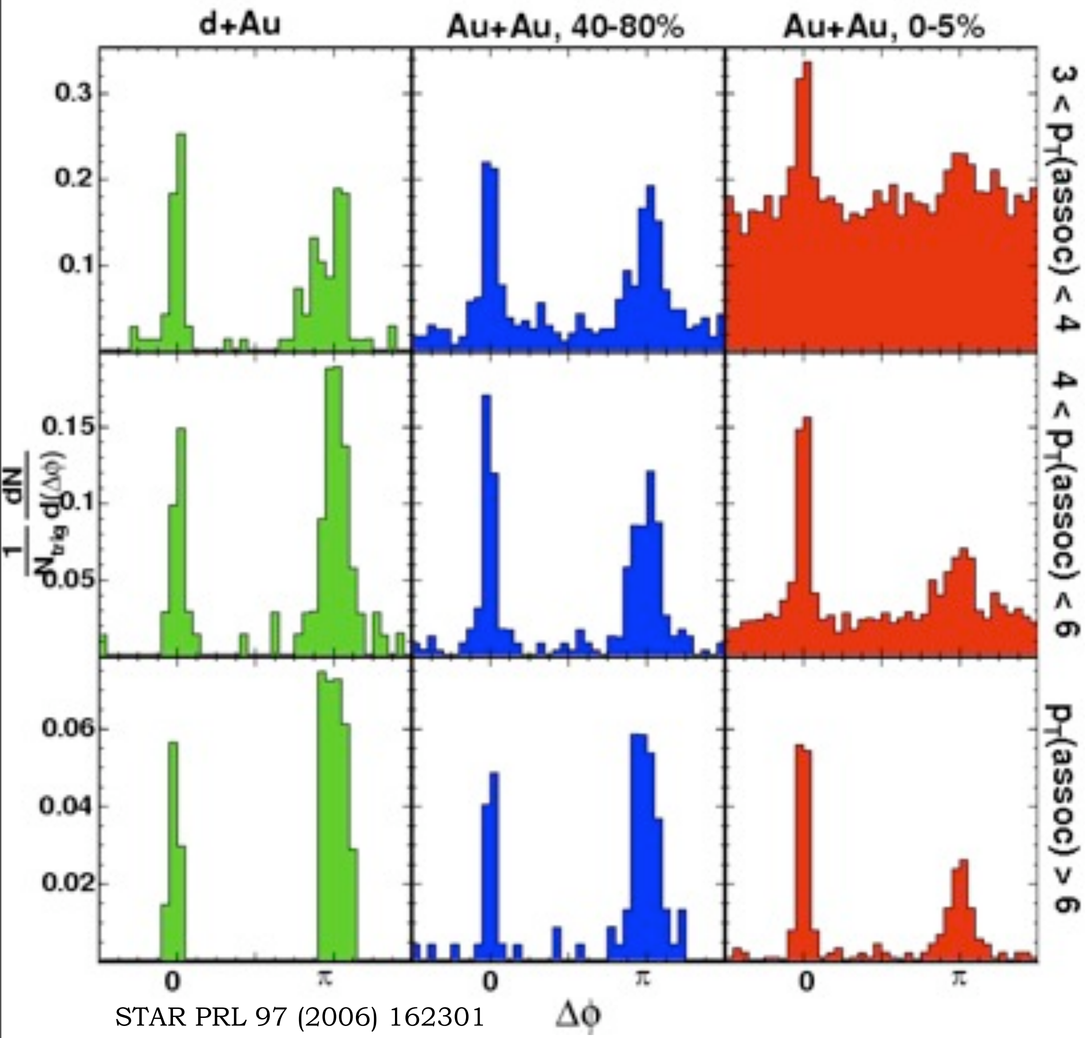
- Au-Au Back-to-back jets suppressed
- d-Au similar to p-p



Quenching is a final state effect

Observation of "Punch through"

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



STAR PRL 97 (2006) 162301

If use high-p_T triggers:

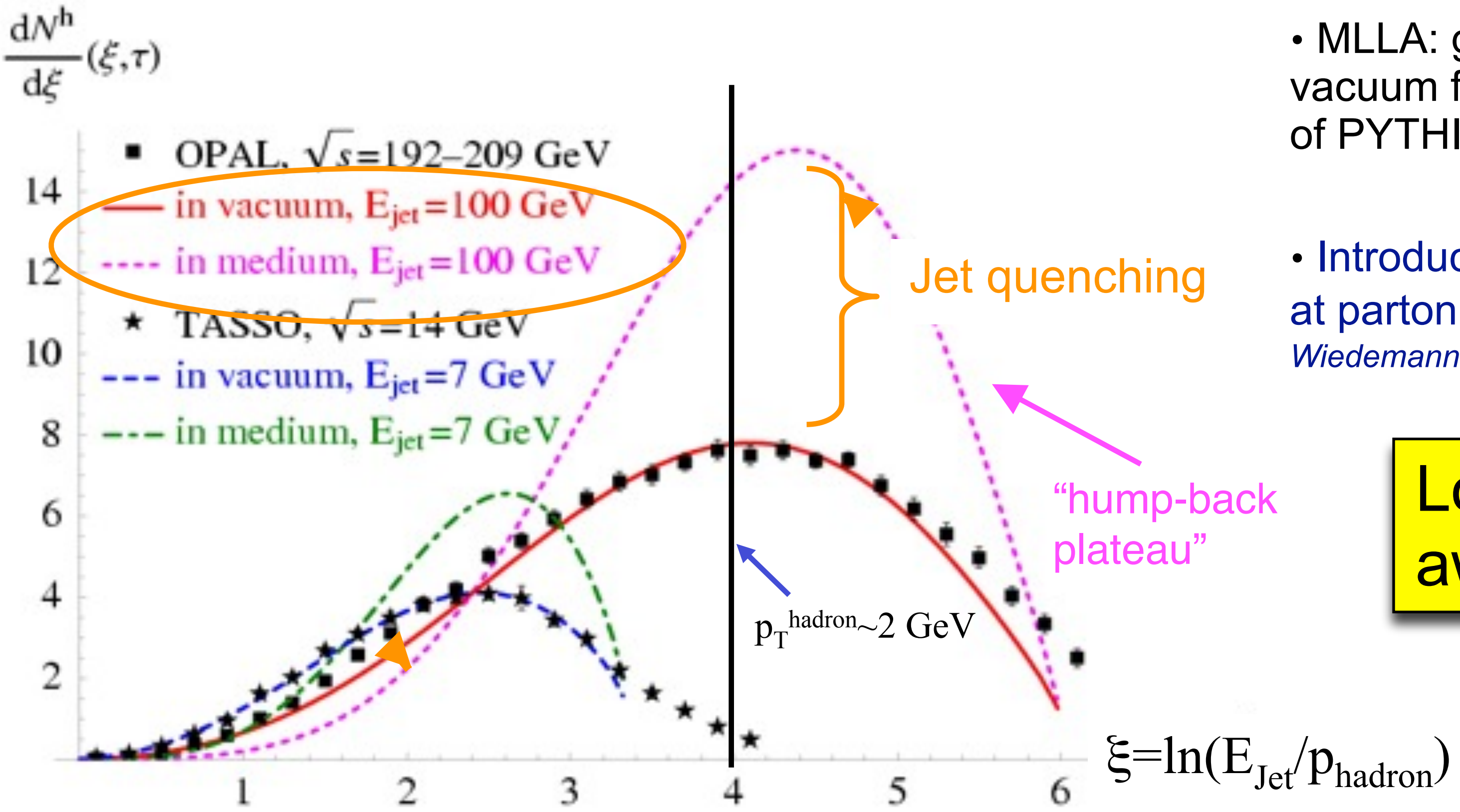
- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background

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*

Look at away-side FF

Away-side di-hadron fragmentation functions

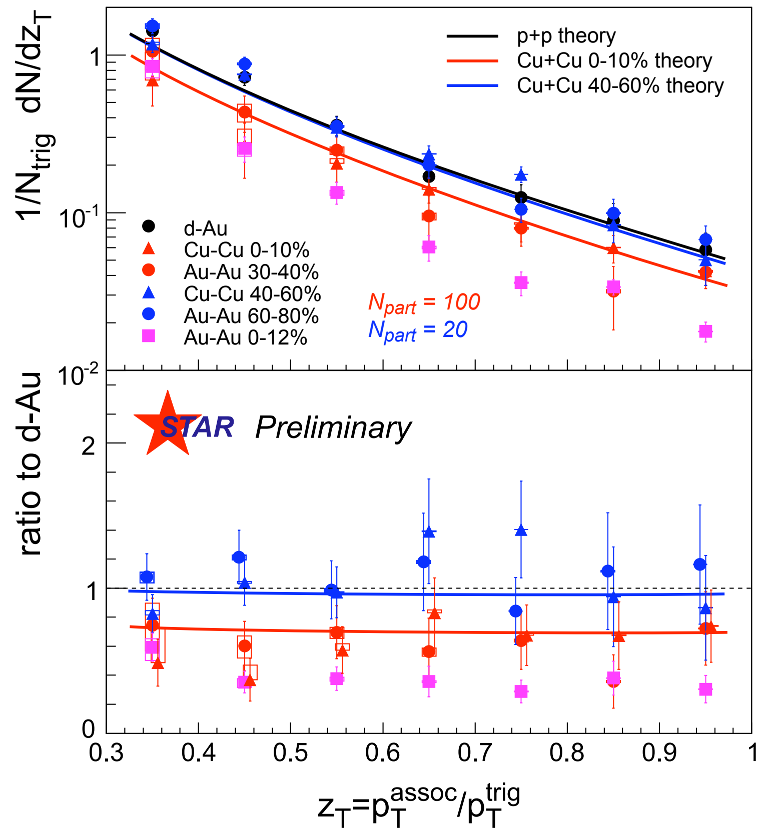
- Measure fraction of parton energy each hadron carries

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

- 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

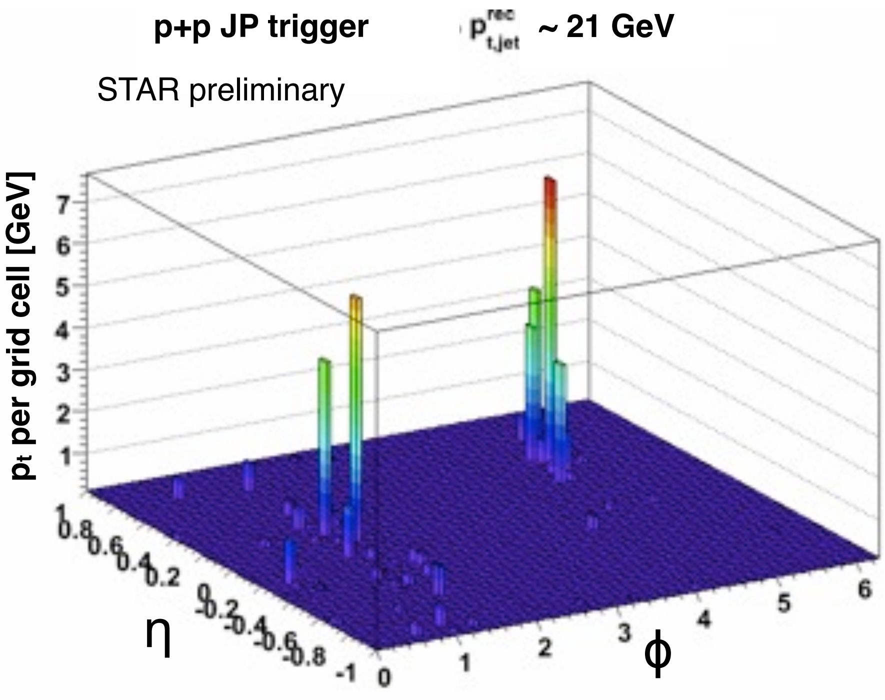
Vacuum fragmentation after parton E_{loss} in the medium

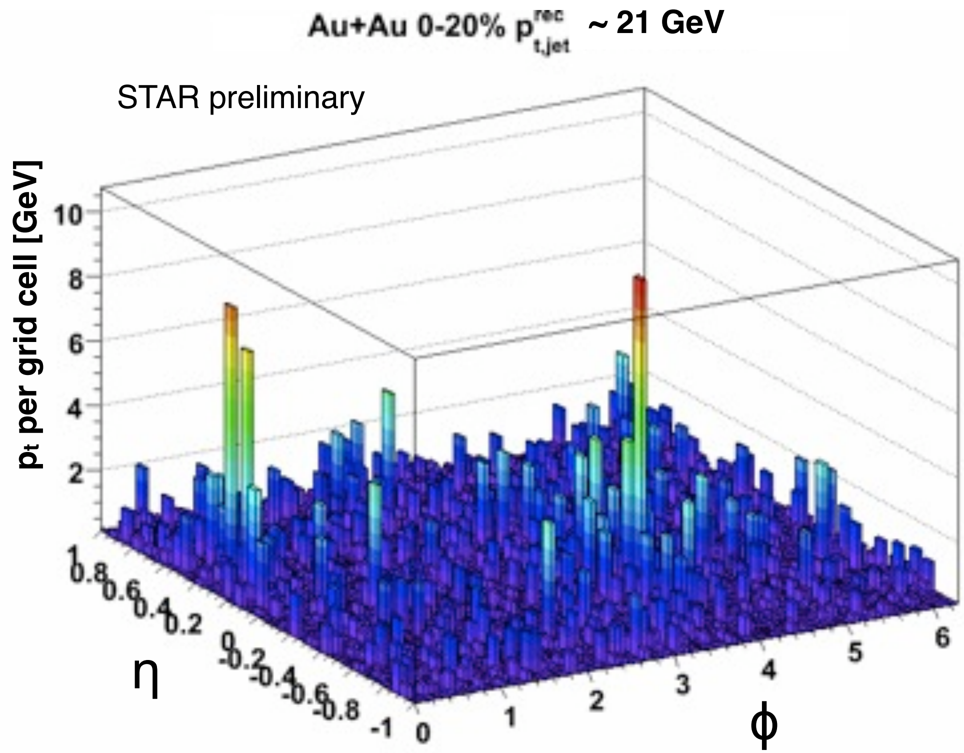
Similar medium for similar N_{part}

Full-jet reconstruction in HI collisions

Di-hadrons *indirect* measurements of jet quenching !

- Full jet reconstruction needed





In p-p jet clearly visible

In Au-Au more challenging

Underlying event background a significant challenge - magnitude and fluctuations

Jet definitions ⇔ Jet algorithm

The construction of a jet is unavoidably ambiguous. On at least two

- w
- H

Jet Definition

$\{p_i\}$ —jet algorithm→ $\{j_k\}$

particles
4-momenta,
calorimeter towers

jets

+ parameters (at least the jet cone radius R)

+ recombination scheme

Jet definitions ⇔ Jet algorithm

The construction of a jet is unavoidably ambiguous. On at least two fronts:

- which particles get put together into a common jet?
- How do you combine their momenta?

Modern Jet Finder Algorithms	
Sequential Recombination	**Cone**
• bottom-up • successively undoes QCD branching	• top-down • centred around idea of an 'invariant', directed energy flow
▸ k_T algorithm ▸ anti-k_T algorithm ▸ Cambidge-Aachen algorithm	▸ CDF JetClu ▸ CDF MidPoint ▸ D0 (run II) Cone ▸ PxCone ▸ CMS Iterative Cone ▸ ATLAS Cone ▸ PyCell/CellJet ▸ GetJet ▸ SISCone

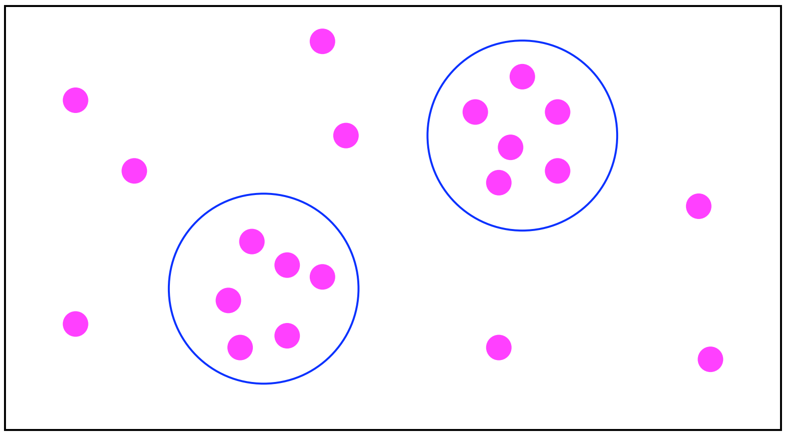
Cone algorithms

Jet Cones

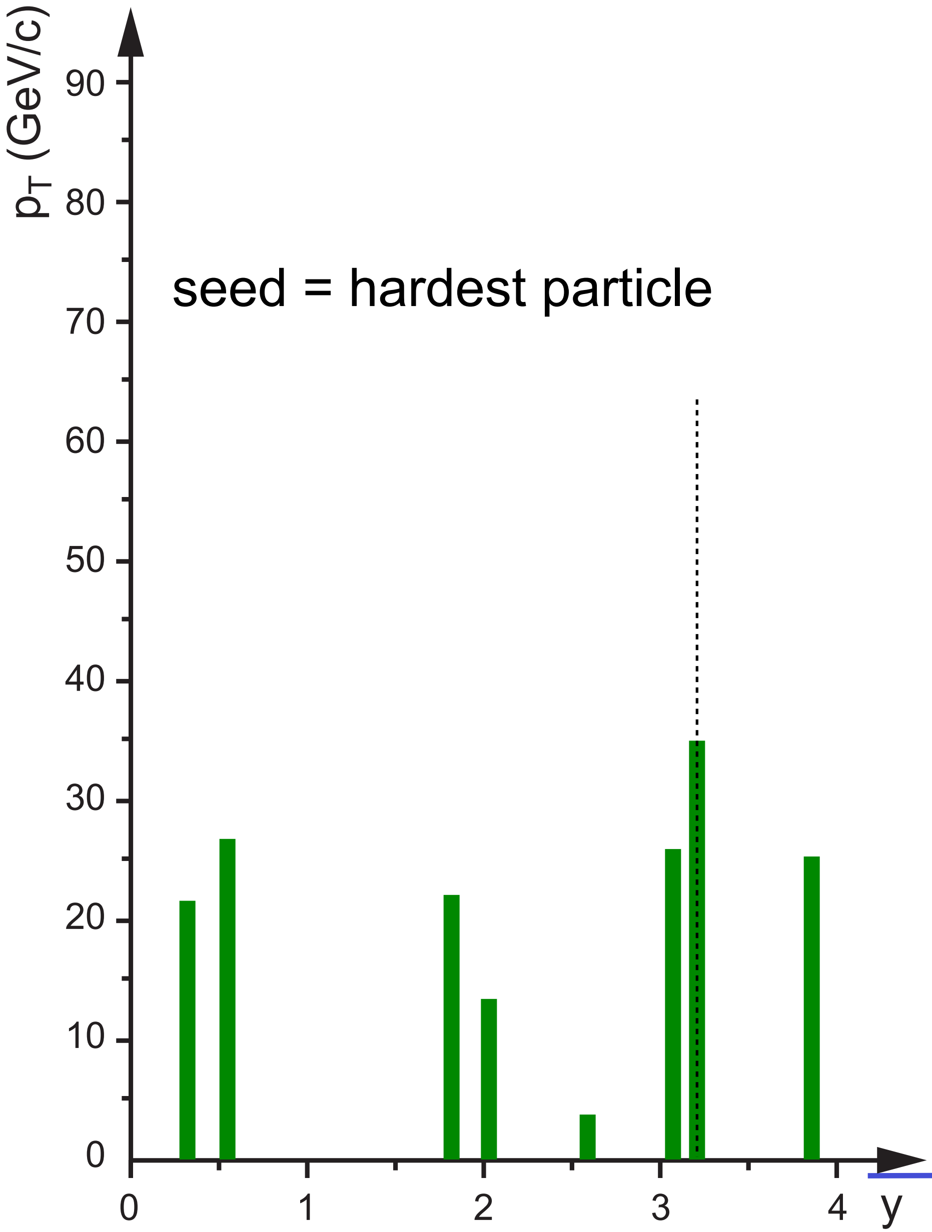
- Cones are always understood as circles in rapidity (y) and azimuth φ.
- A particle i is within the cone of radius R around the axis a if
  - $\Delta R^2_{ia} = (y_i - y_a)^2 + (\varphi_i - \varphi_a)^2 < R^2$
  - ... usual hadron collider variables
- Typical: R = 0.4 - 0.7 (more later)

Basic Idea:

- Find directions of dominant energy flow find ALL stable cones
- centre of the cone ≡ direction of the total momentum of its particle contents



Example: iterative cone, Prog. Removal

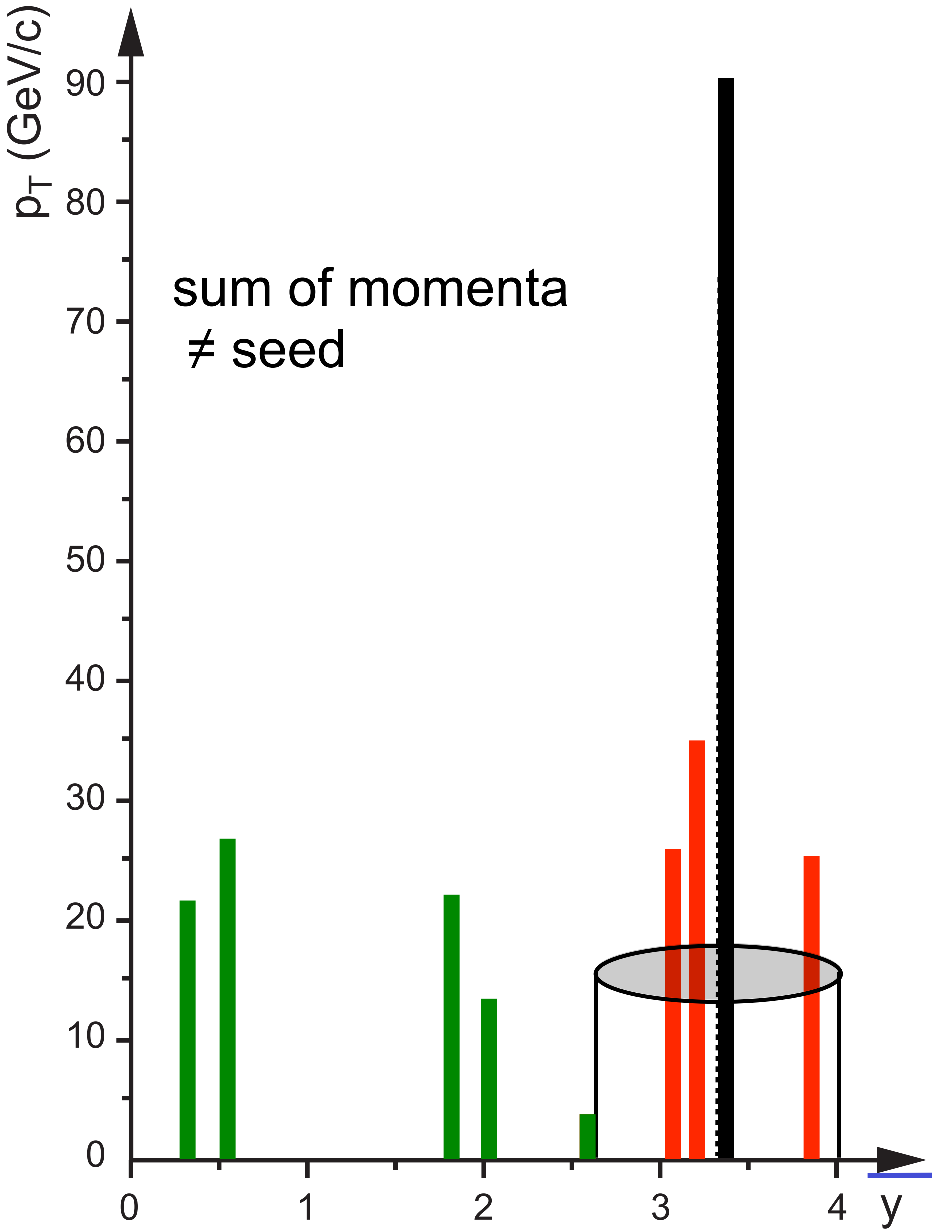


Simple Cone Algorithm

(e.g. CMS iterative cone)

- Take hardest particle as seed for cone axis

Example: iterative cone, Prog. Removal

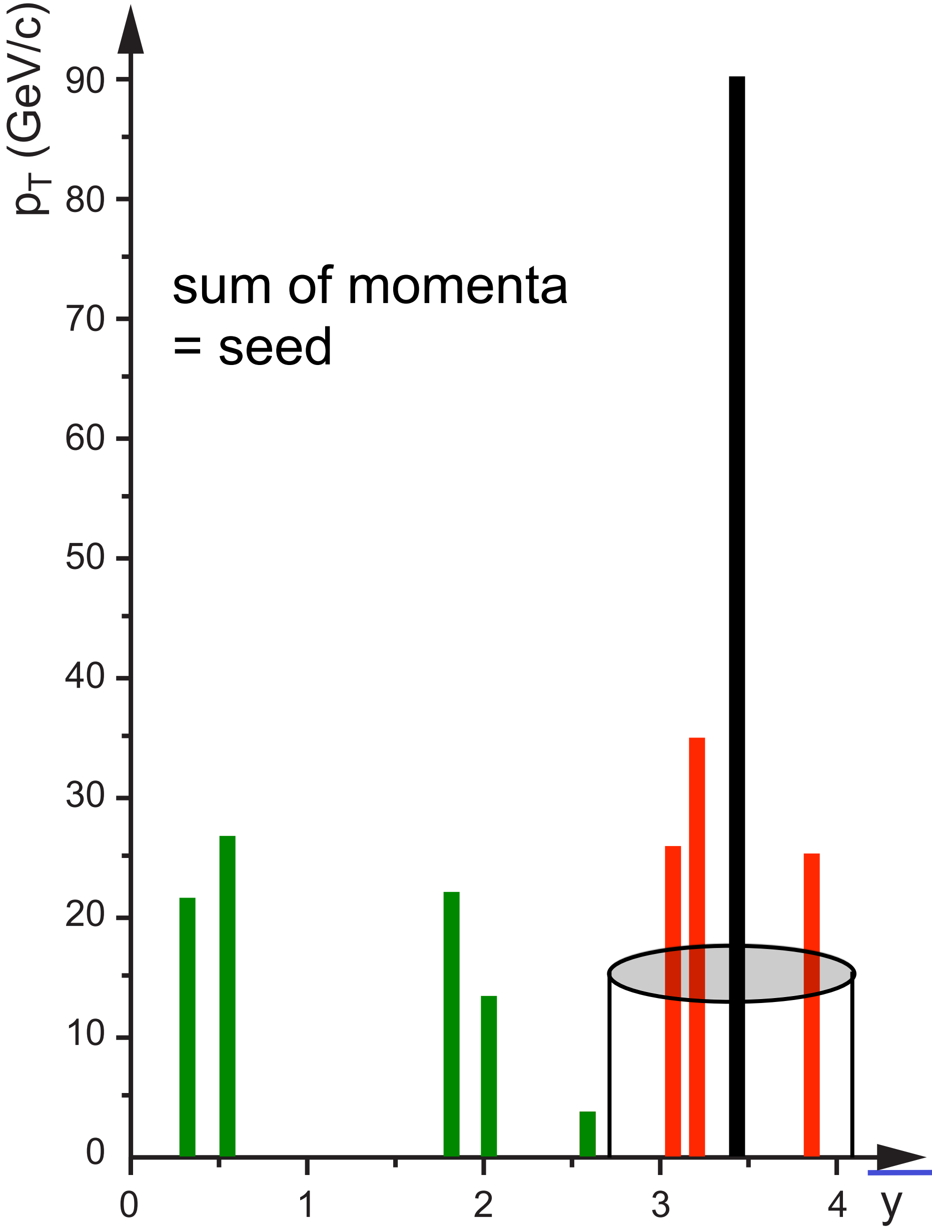


Simple Cone Algorithm

(e.g. CMS iterative cone)

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable

Example: iterative cone, Prog. Removal



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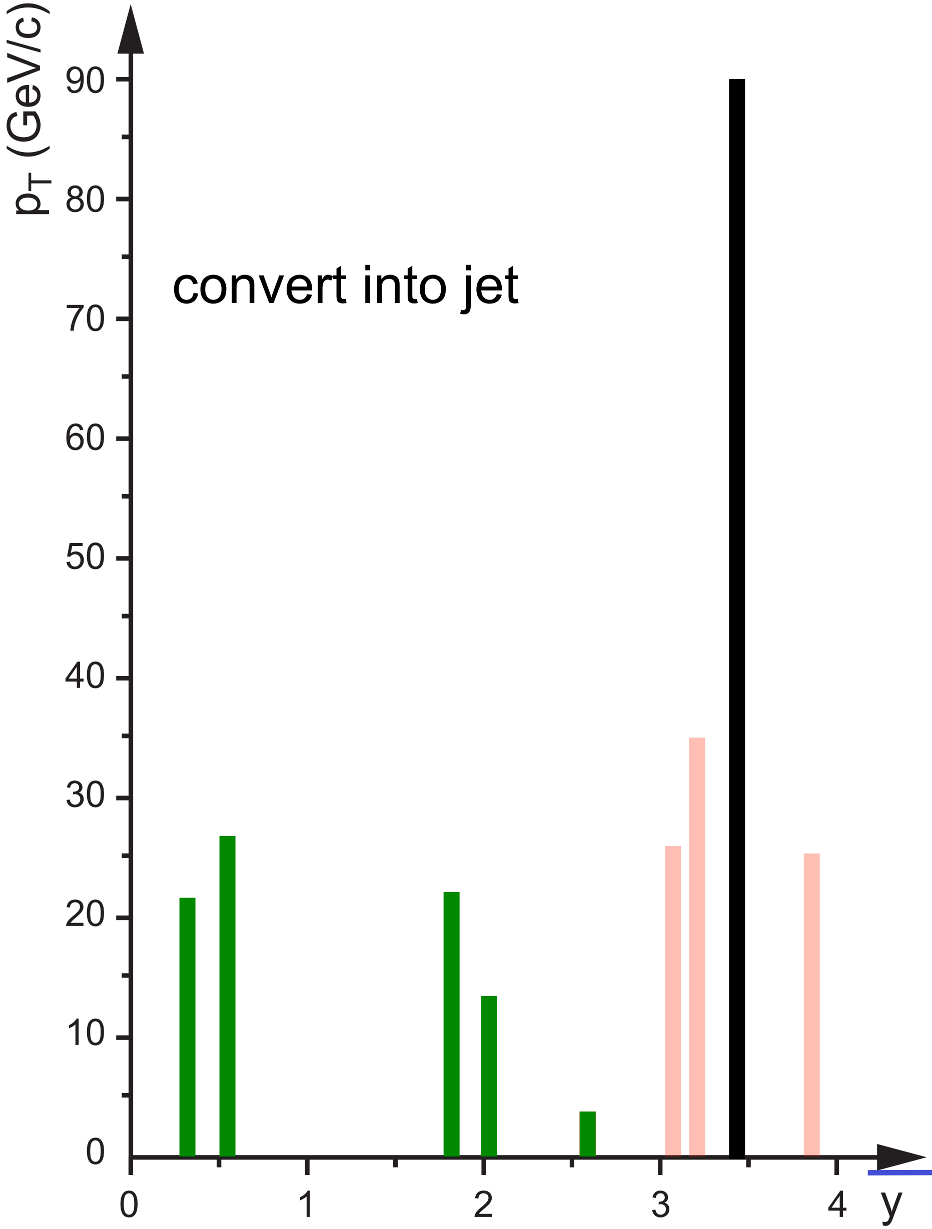

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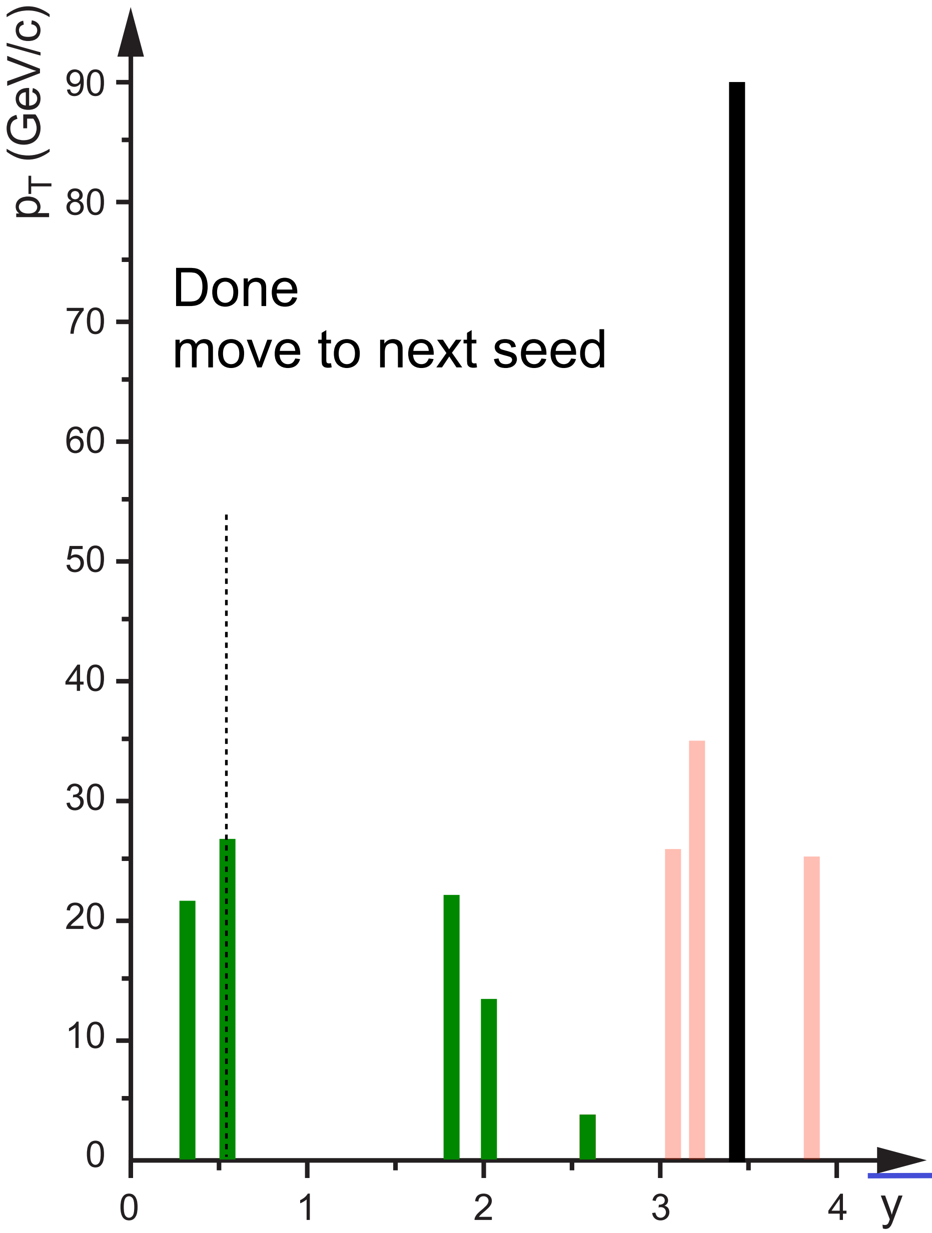

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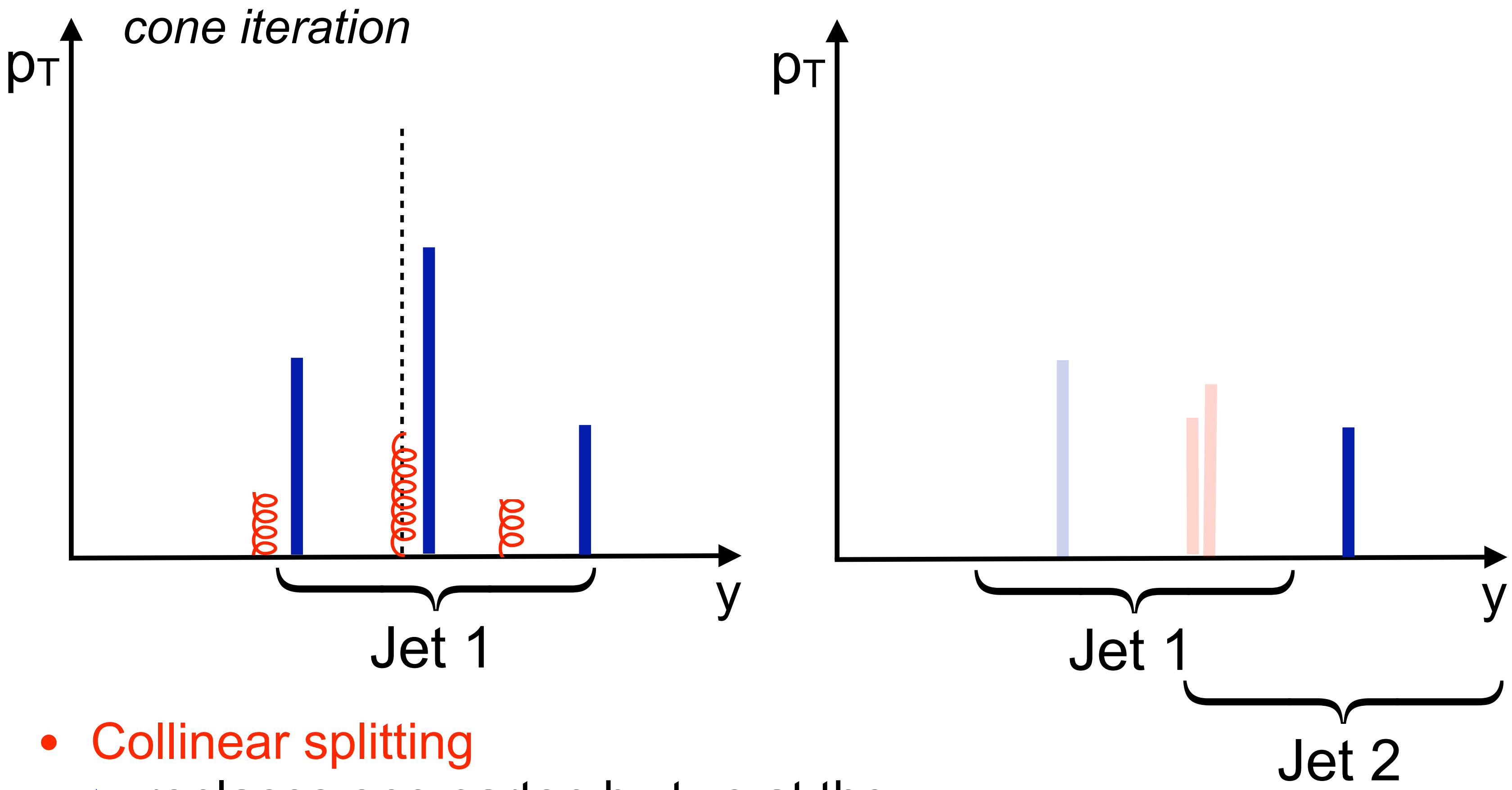
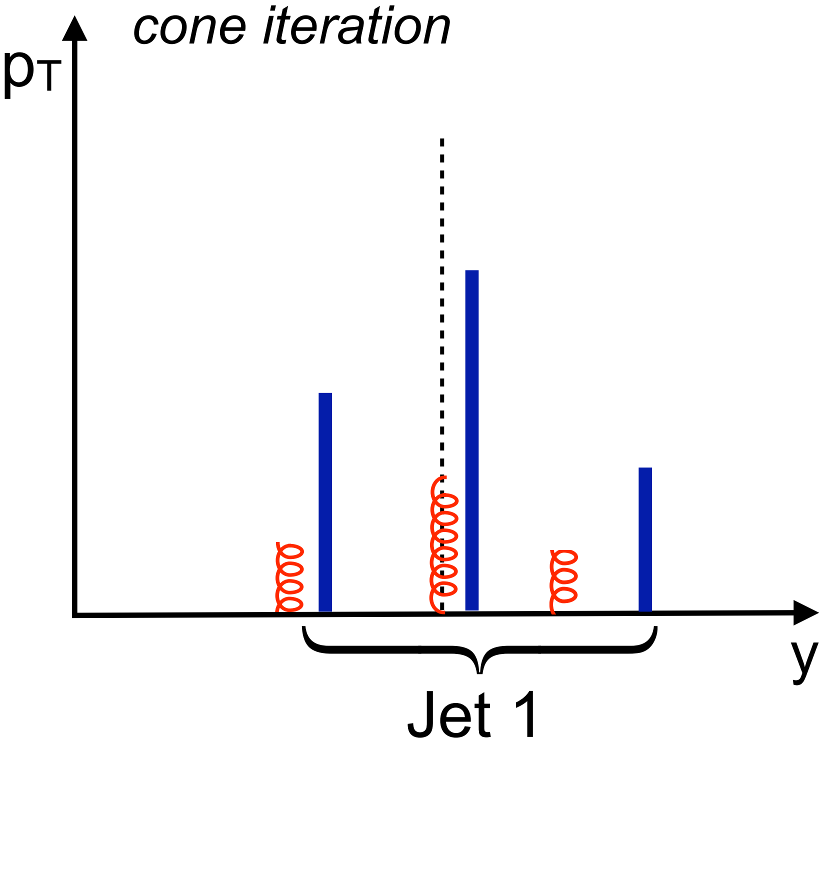
- Convert contents into a “jet” and remove from event

Problems: IR and collinear issues



- Collinear splitting
  - replaces one parton by two at the same place
- Infared issues
  - a soft emissions that add very soft gluon

Problems: IR and collinear issues



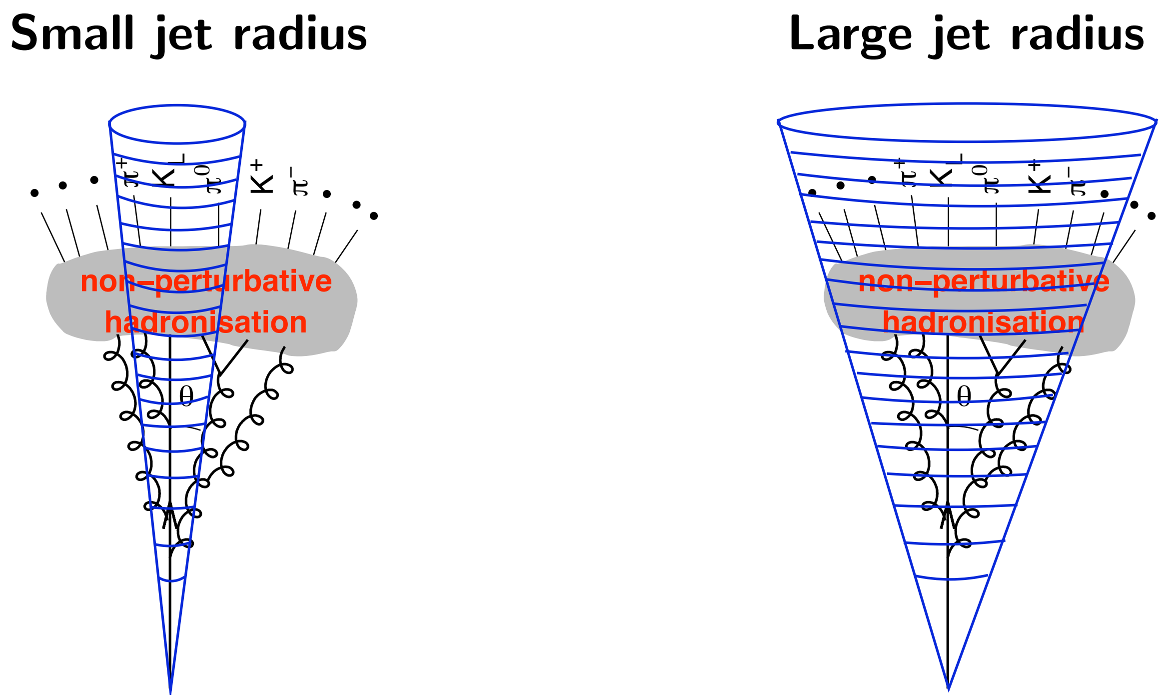
Collinear splitting can modify the hard jets: many cone algorithms are collinear unsafe

⇒ Bad for measurements and theory (perturbative calculations give ∞)

It is all about R!

To first approx:

various algs. moderately different but R can matter a lot more



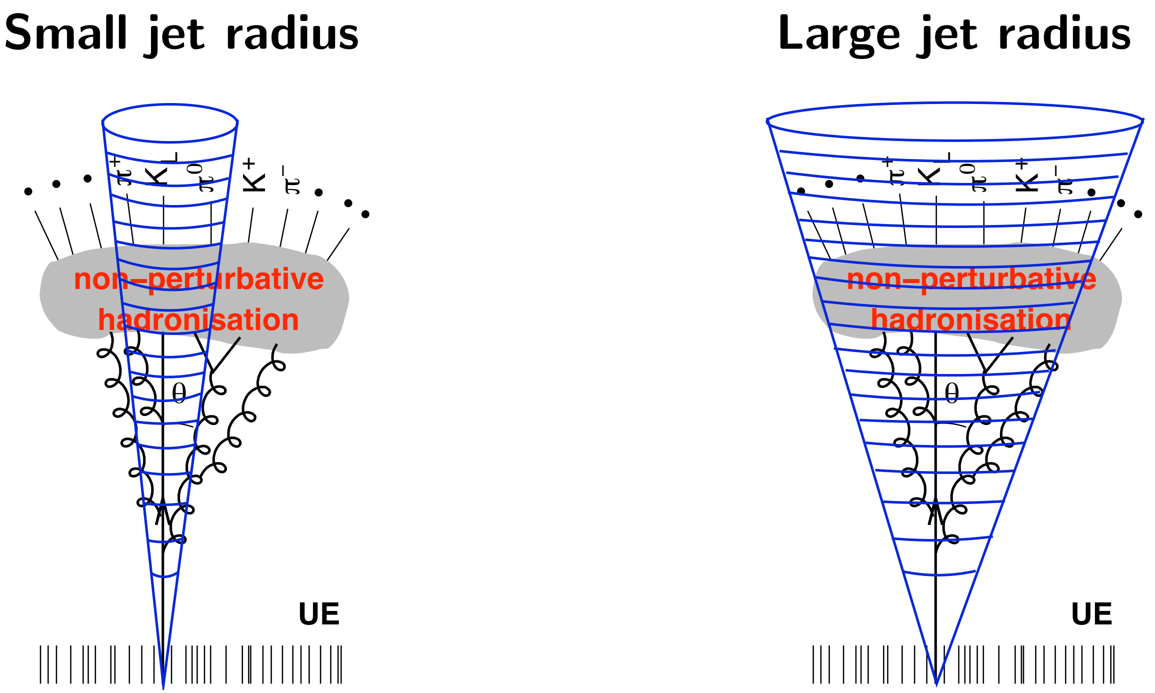
non-perturbative fragmentation: **large jet radius better**

(it captures more)

It is all about R!

To first approx:

various algs. moderately different but R can matter a lot more



underlying ev. & pileup "noise": **small jet radius better**
(it captures less)

It is all about R!

To first approx:

various algs. moderately different but R can matter a lot more

R depends on:

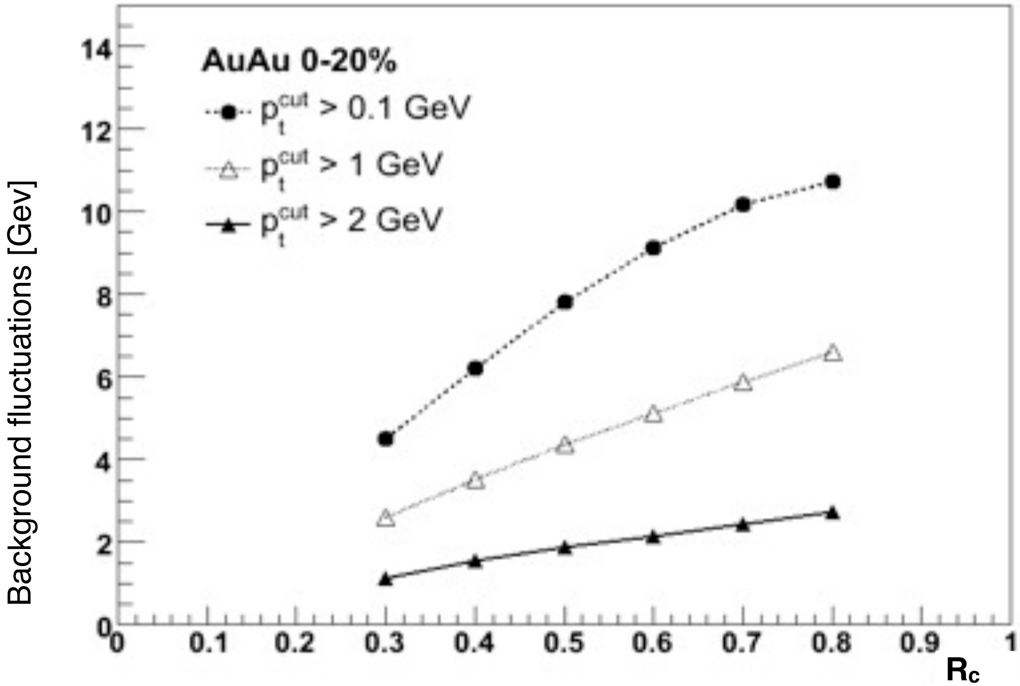
- the question you want answered
- the environment (pp, pA, AA, ee, ep, eA)
- the algorithm used
- What's best? ⇒ requires lots of systematic studies

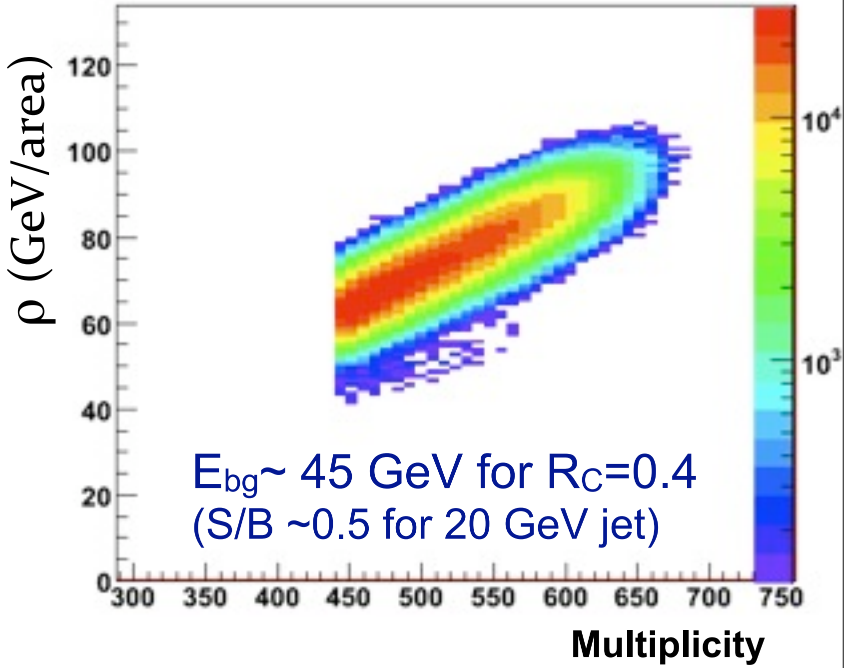
Background - central Au-Au collisions

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + ρ A ± σ √A

ρ - background energy per unit area
A - jet area





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

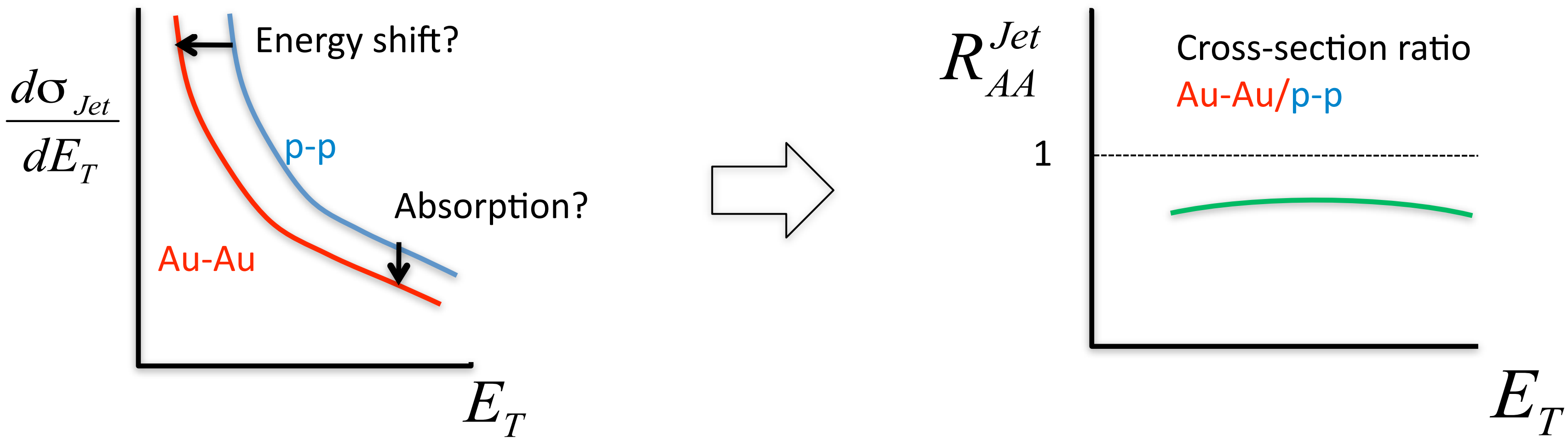
p and E MUST be conserved even with quenched jets

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

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

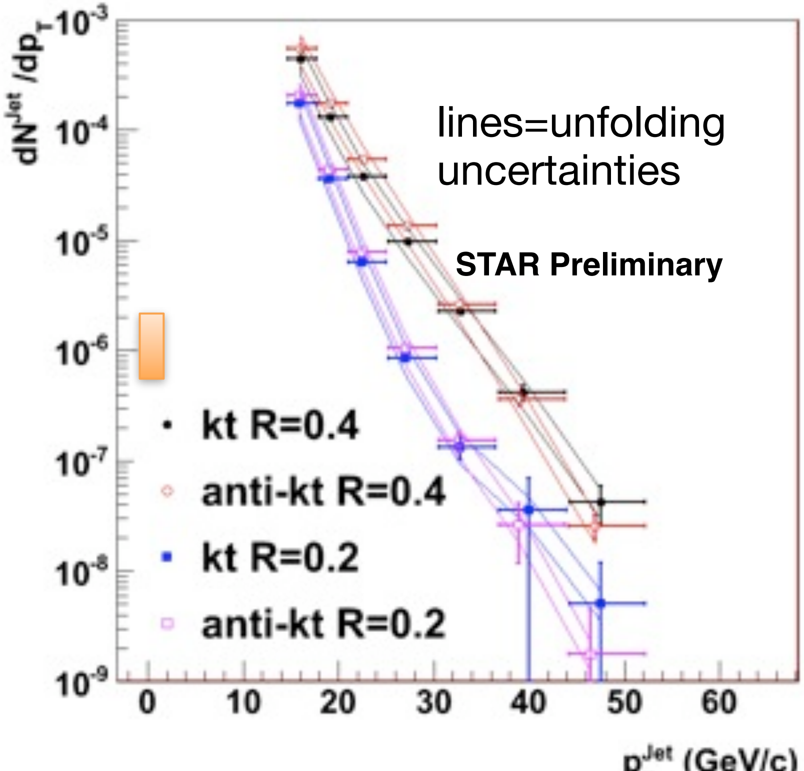
Average number of p-p collision in A-A collision

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

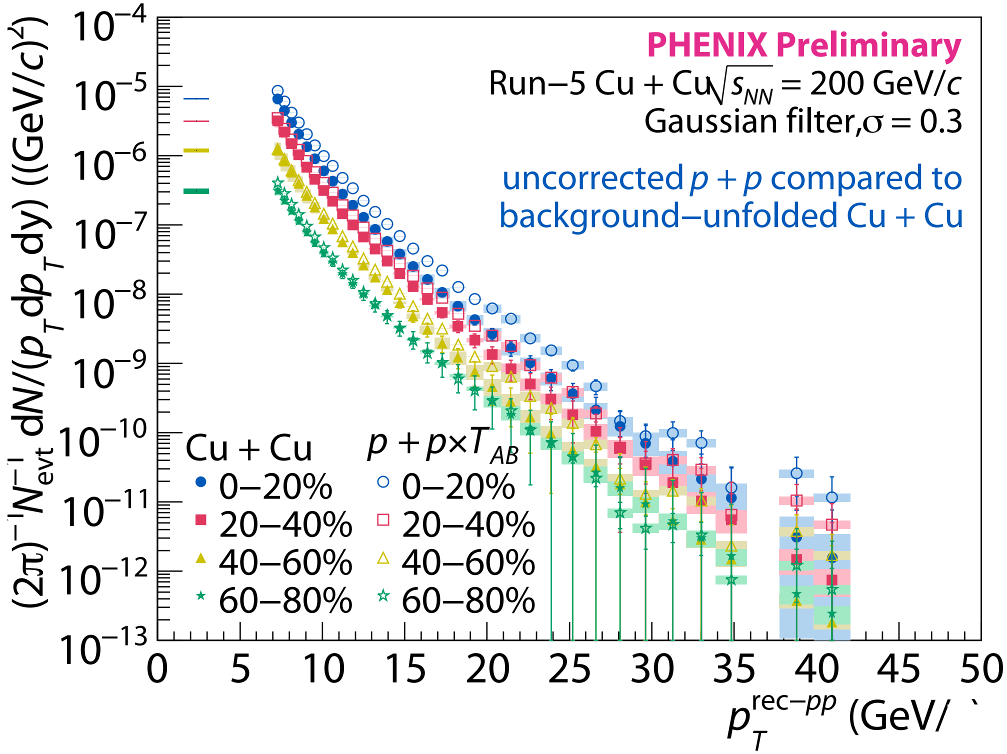


Inclusive jet x-section in Au-Au and Cu-Cu

Au-Au collisions 0-10%



M.Ploskon QM2009

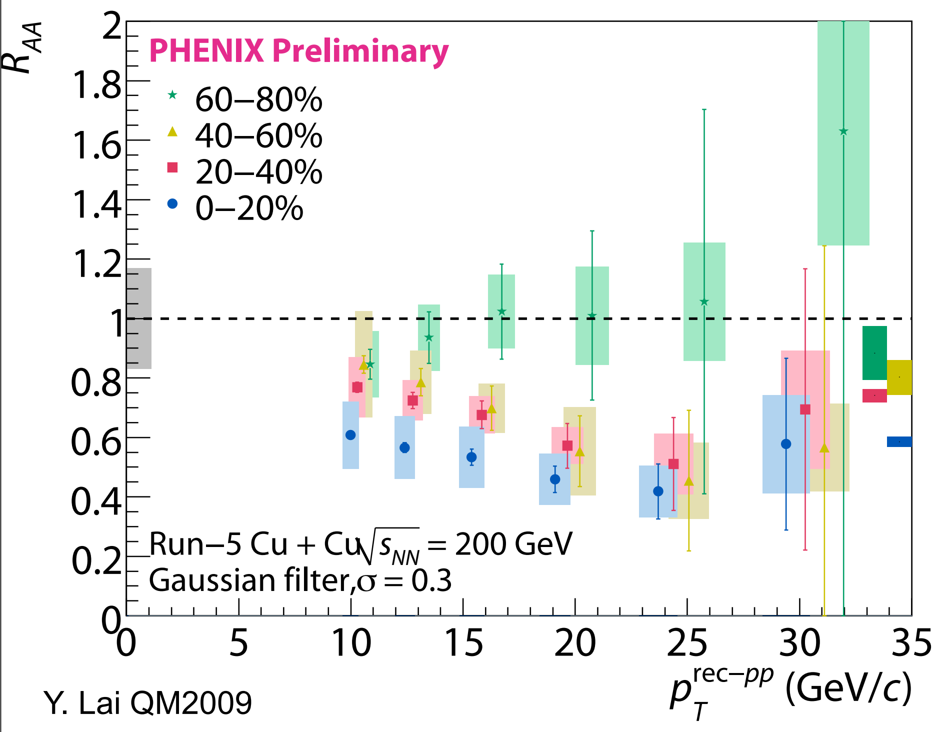


Y. Lai QM2009

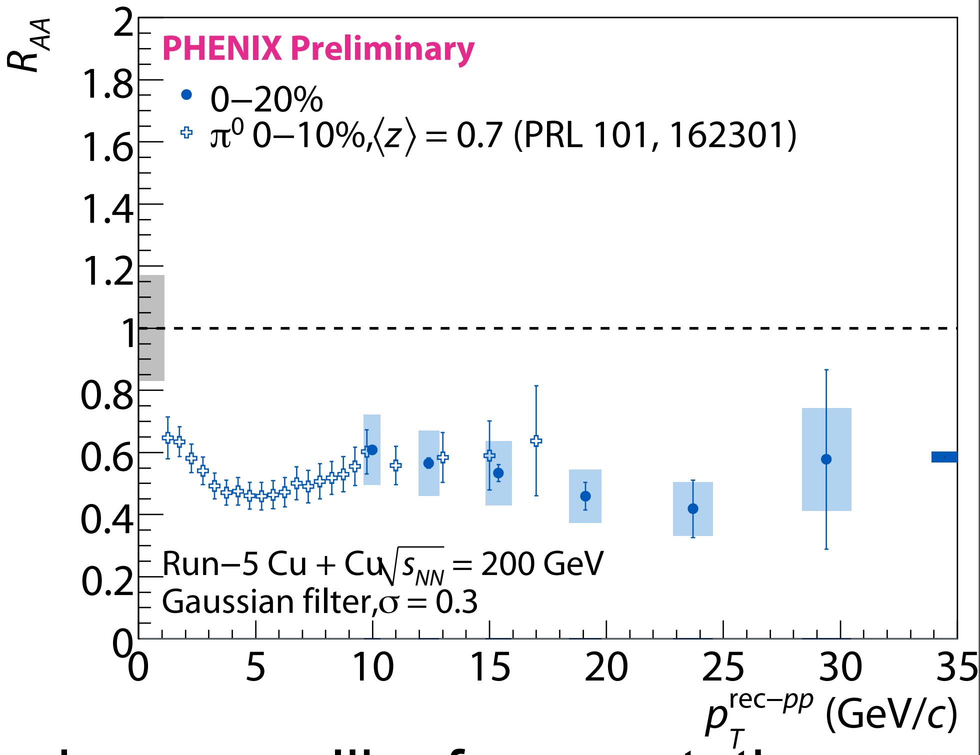
Inclusive jet spectrum measured in A-A collisions for first time

Extends reach of jet quenching studies to p_T > 40 GeV

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



Y. Lai QM2009

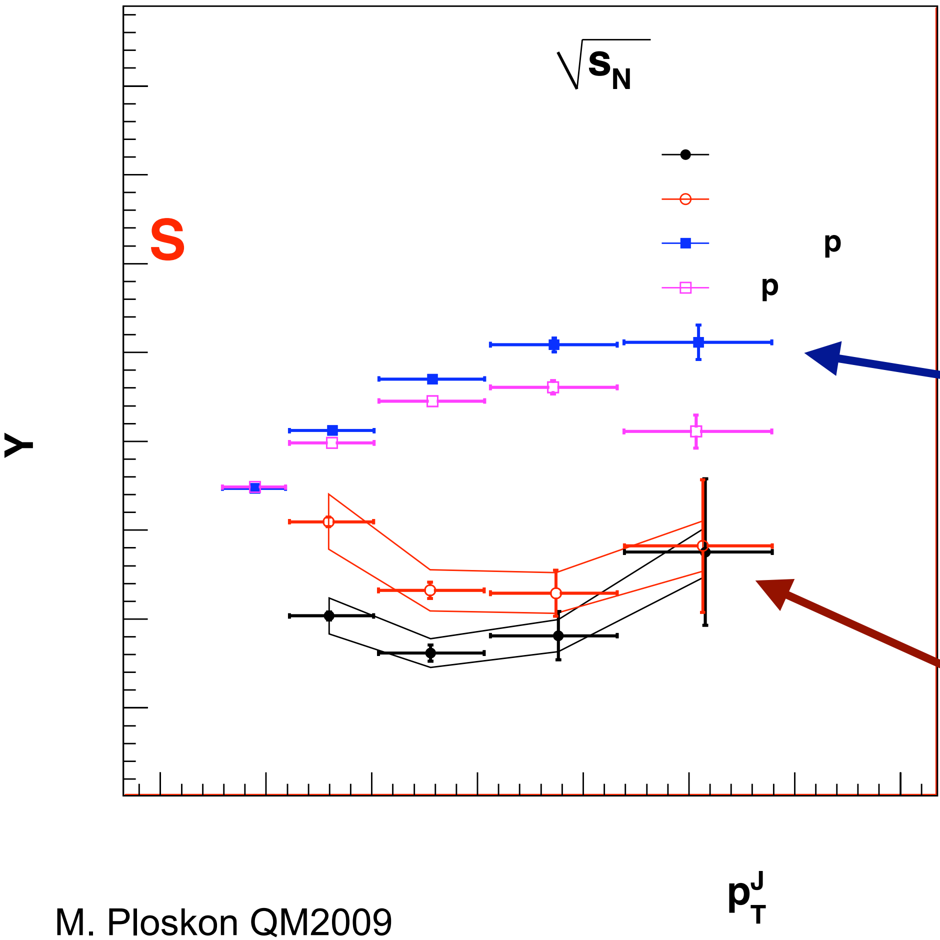


Gaussian Filter: designed to find vacuum like fragmentation

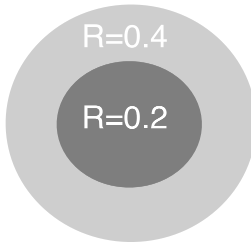
- Reconstructed jets highly suppressed in central collisions
- Jets as suppressed as single particles

Energy shift or jet not reconstructed?

Look at the jet energy profile



M. Ploskon QM2009

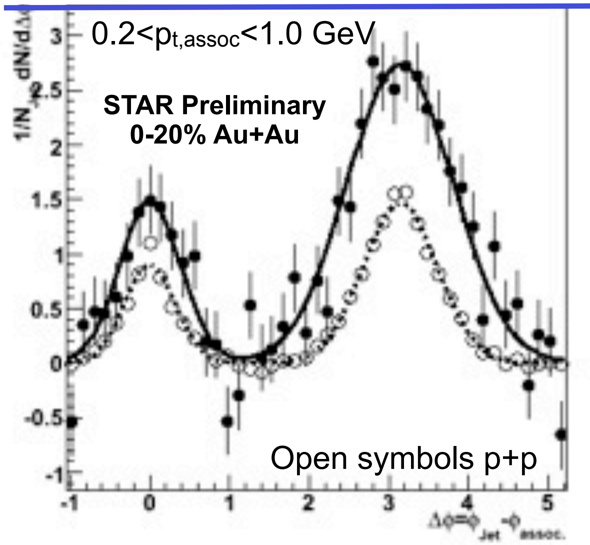


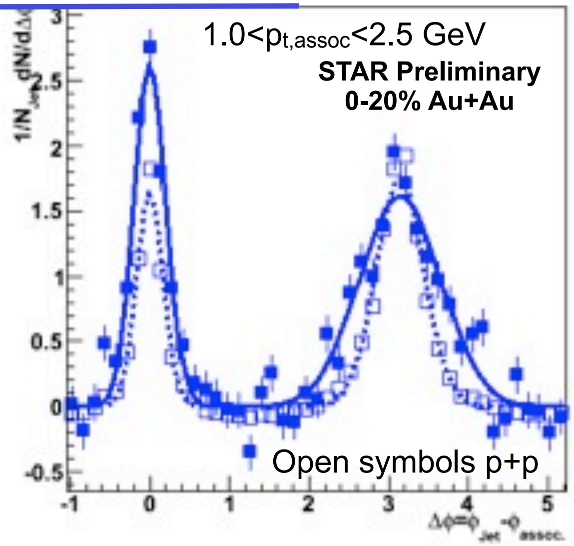
p-p:
“Focussing” of jet fragmentation with increasing jet energy

Au-Au:
“Broadening” of jet fragmentation with increasing jet energy

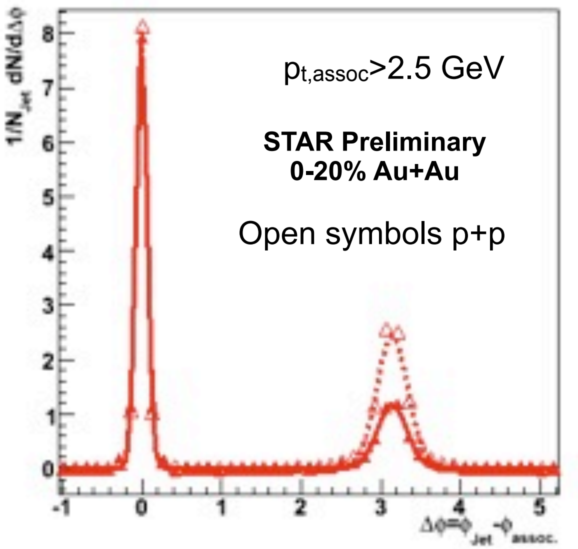
De-focussing of energy profile when jet passes through sQGP

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





J.Putschke RHIC/AGS 2009



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

- 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