QGP and High-p_T Physics

Lecture 2: Jets and Jet Quenching

Helmholtz Graduate School of Fundamental Physics

Winter School Obergurgl 2010

January 29 - February 2, 2010

PD Dr. Klaus Reygers
Physikalisches Institut
Universität Heidelberg

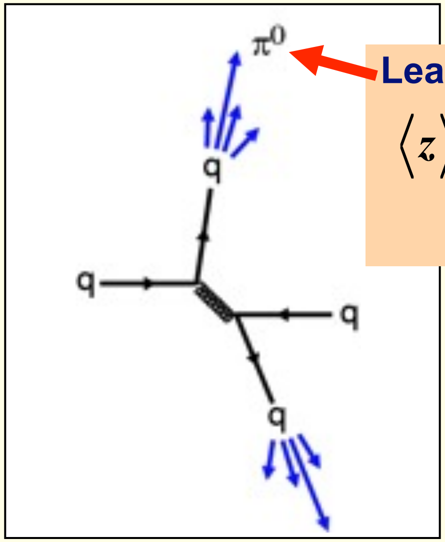
Outline

- Introduction: Hard Scattering and Jet Quenching
- The Discovery Phase (ca. 2000 - 2003)
- Further Experimental Results Related to Jet Quenching
- Future Jet Quenching Measurements

Introduction:
Hard Scattering and Jet Quenching

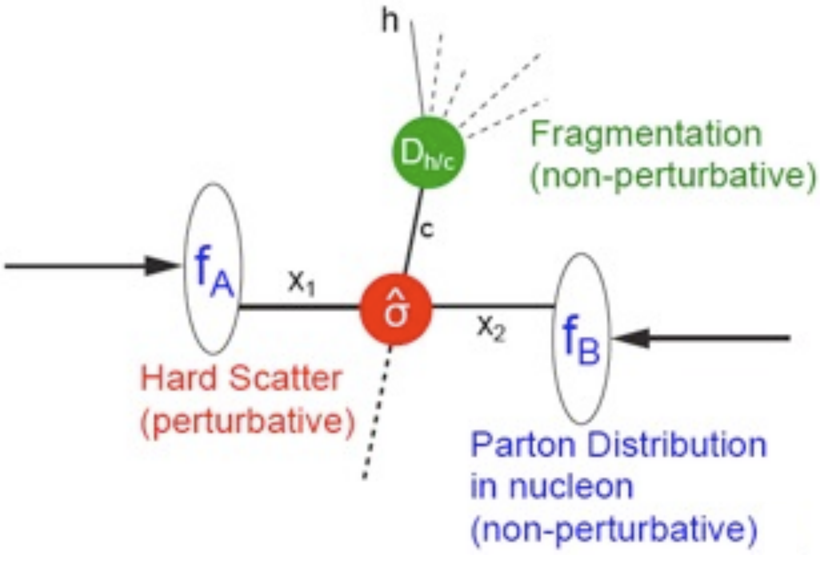
Theoretical Description of High-p_T Particle Production: Perturbative QCD

- Scattering of pointlike partons described by QCD perturbation theory (pQCD)
- Soft processes described by universal, phenomenological functions
  - Parton distribution function from deep inelastic scattering
  - Fragmentation functions from e^+e^- collisions



$$\langle z \rangle = \langle p_{\text{hadron}} / p_{\text{parton}} \rangle \approx 0.25$$

factorization:



$$d\sigma = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^c_{ab} \otimes D_c^{Hadron}$$

Hadron Production in Leading Order QCD

Parton distributions (functions of x_{Bjorken} and momentum transfer Q^2)

Fragmentation function

Inv. Cross section

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = K \sum_{a,b,c,d=q,\bar{q},g} \int_{x_{a,\min}}^{1} \mathrm{d}x_a \int_{x_{b,\min}}^{1} \mathrm{d}x_b \; f_{\mathrm{a/A}}\left(x_\mathrm{a},Q^2\right) f_{\mathrm{b/B}}\left(x_\mathrm{b},Q^2\right) \frac{\mathrm{d}\sigma^{\mathrm{ab}\to\mathrm{cd}}}{\mathrm{d}\hat{t}} \frac{1}{\pi z_c} D_{\mathrm{h/c}}\left(z_c,Q^2\right)$$

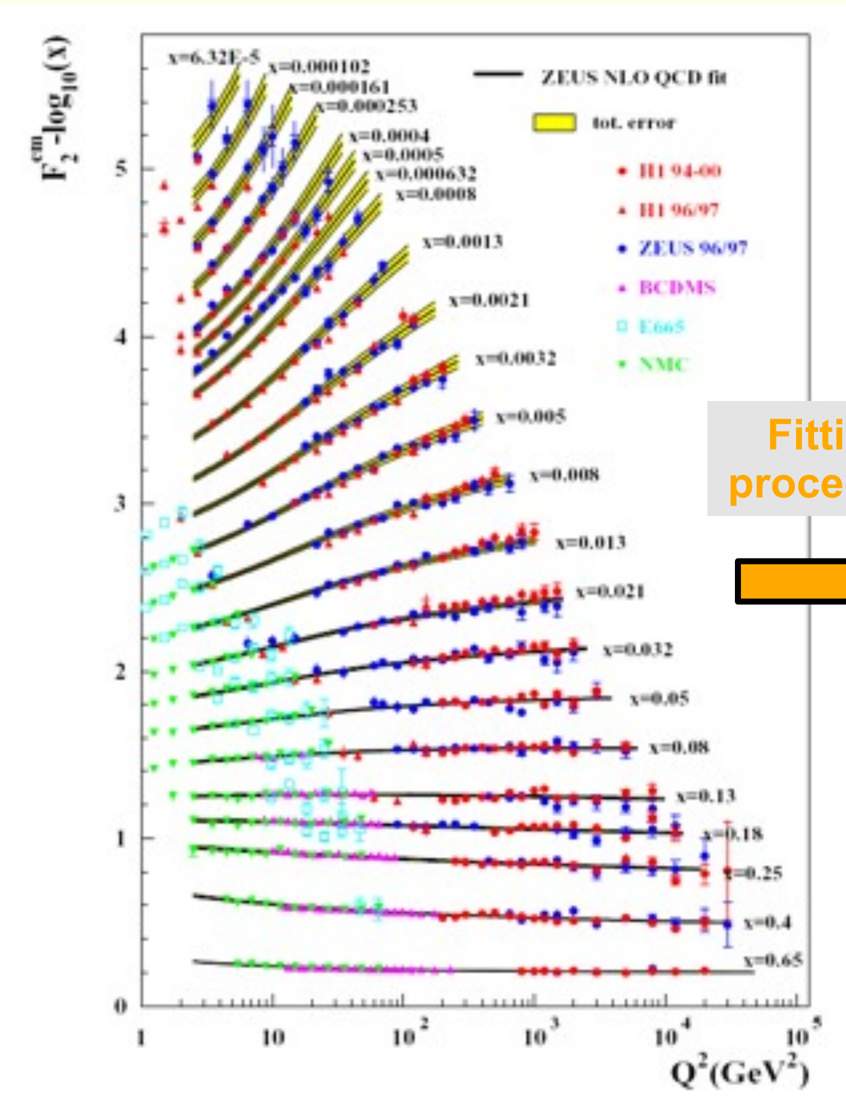
Phenomenological factor which takes higher order contributions into account

Elementary QCD parton-parton cross section

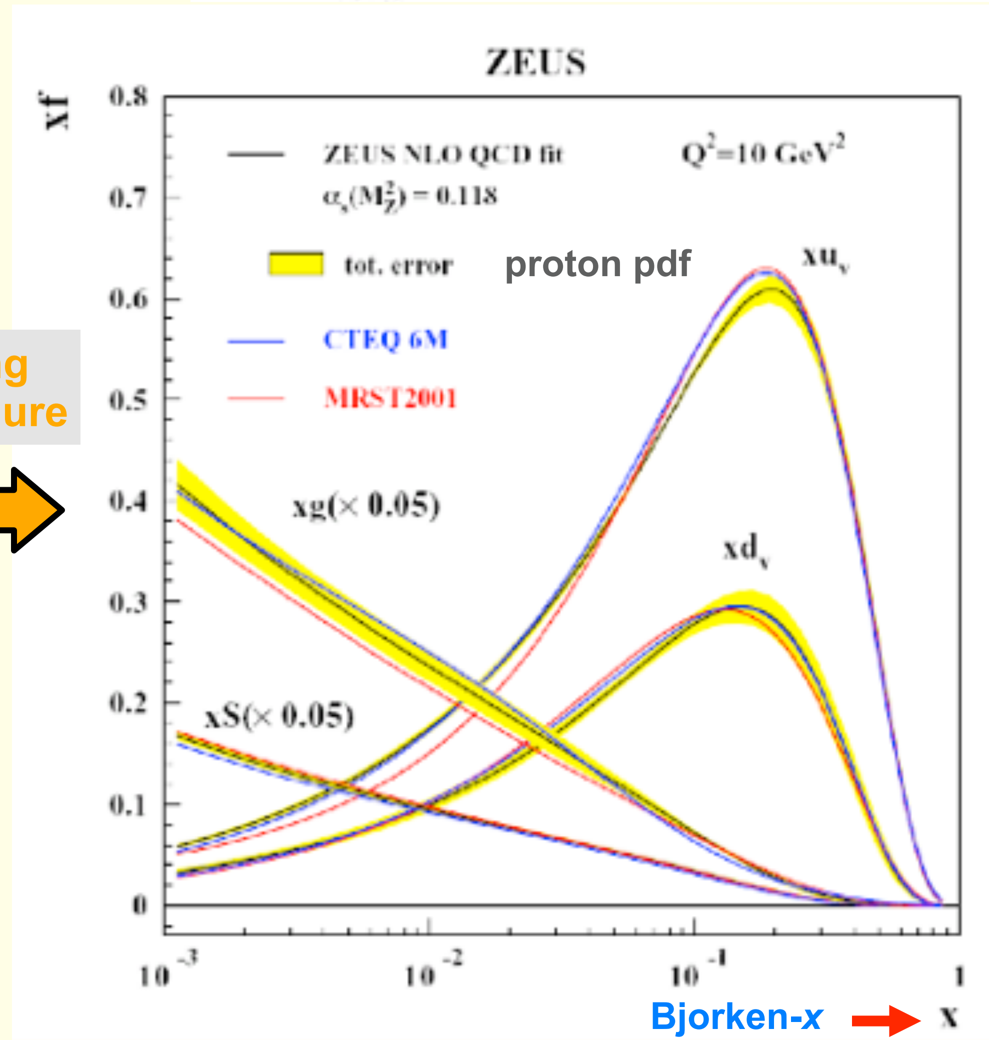
$z_c = p_{\mathrm{T,Hadron}} \,/\, p_{\mathrm{T,c}}$

Parton Distributions: High Precision Data from HERA

$$d\sigma = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{c}_{ab} \otimes D_c^{Hadron}$$

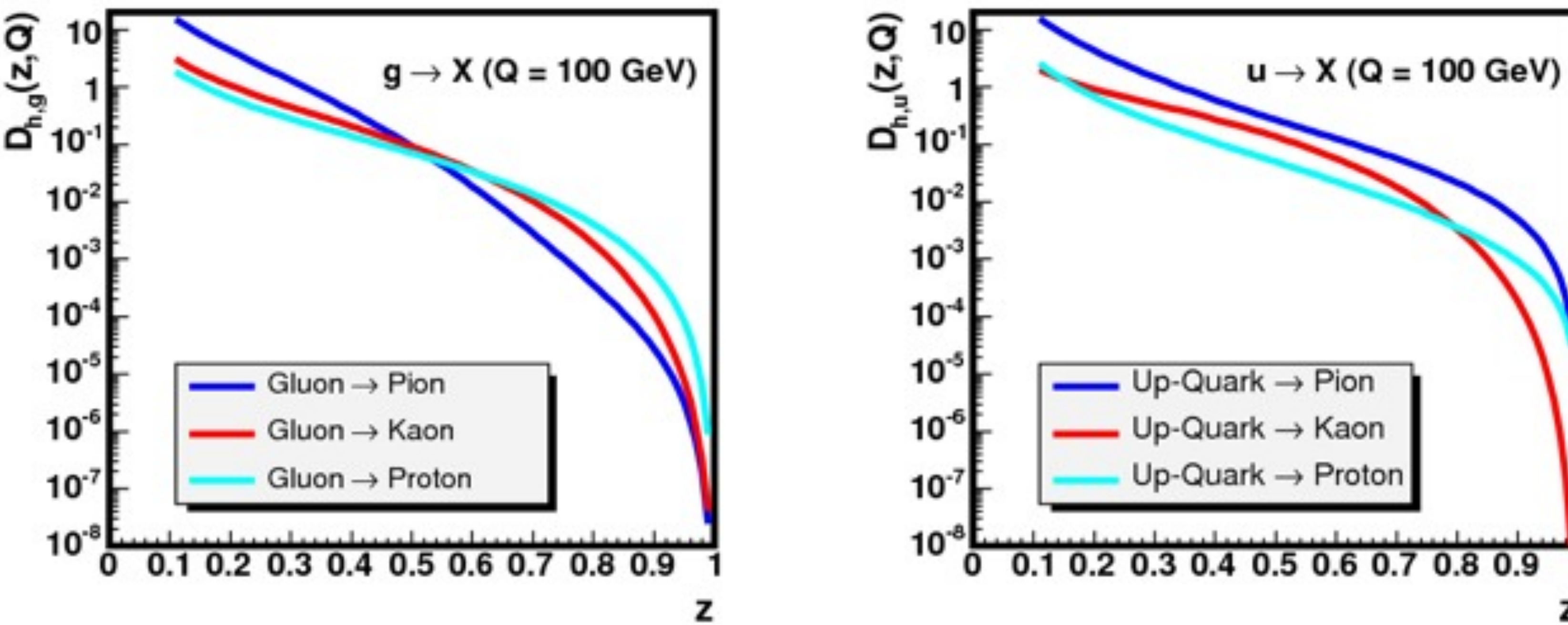


Fitting procedure



Example: Gluon and u-Quark Fragmentation Functions

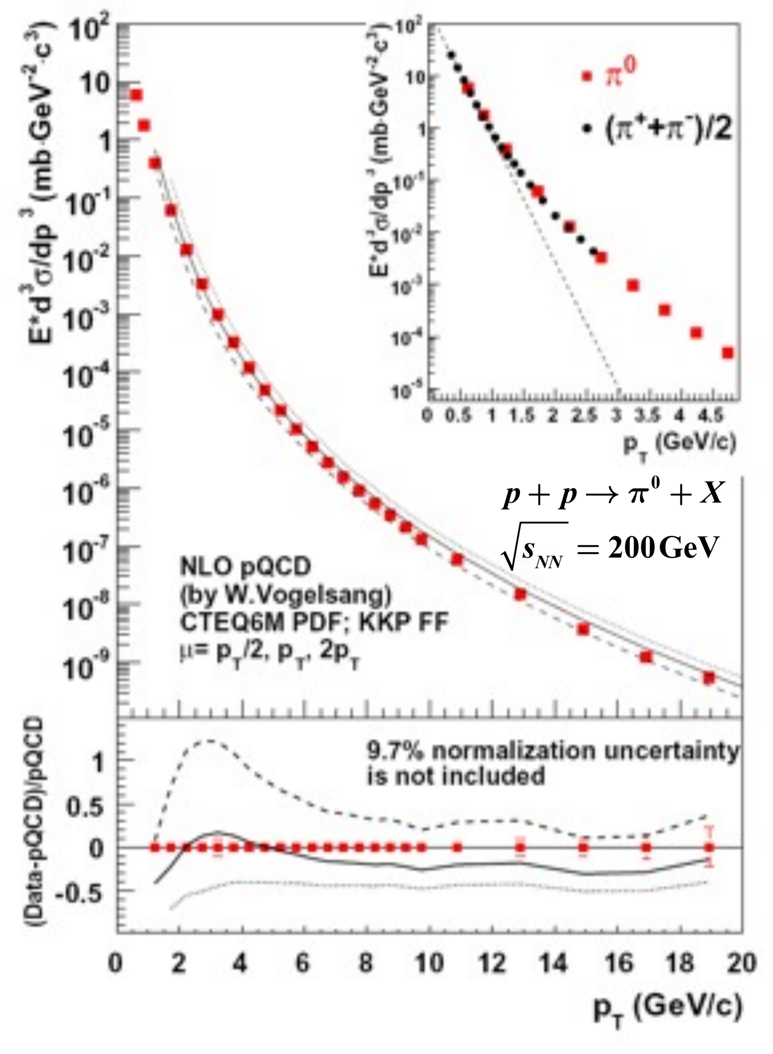
Albino, Kniehl, Kramer, Nucl. Phys. B 725 (2005), 181

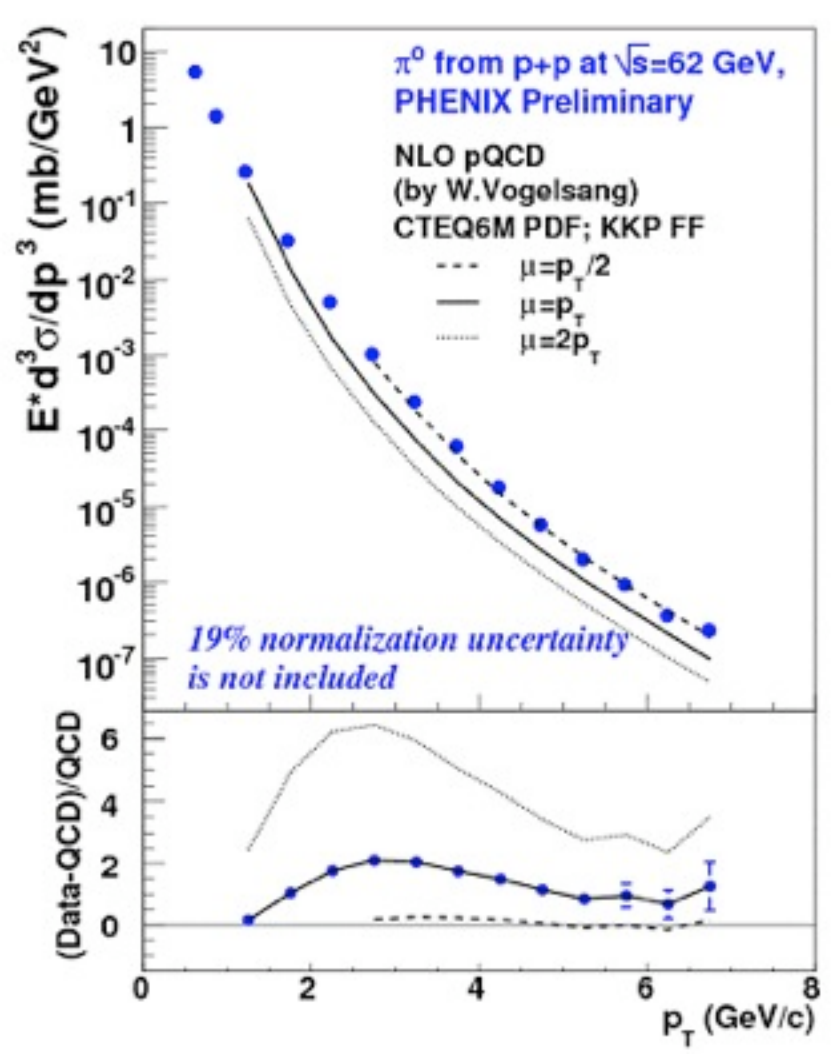


$$z = \frac{p_{\text{Hadron}}}{p_{\text{Parton}}}$$

Fragmentation functions:
Number density for the production of a hadron h
with fractional energy *z* in the fragmentation of a parton
(e.g. determined from $e^+e^- \to Z^0 \to q\bar{q}$)

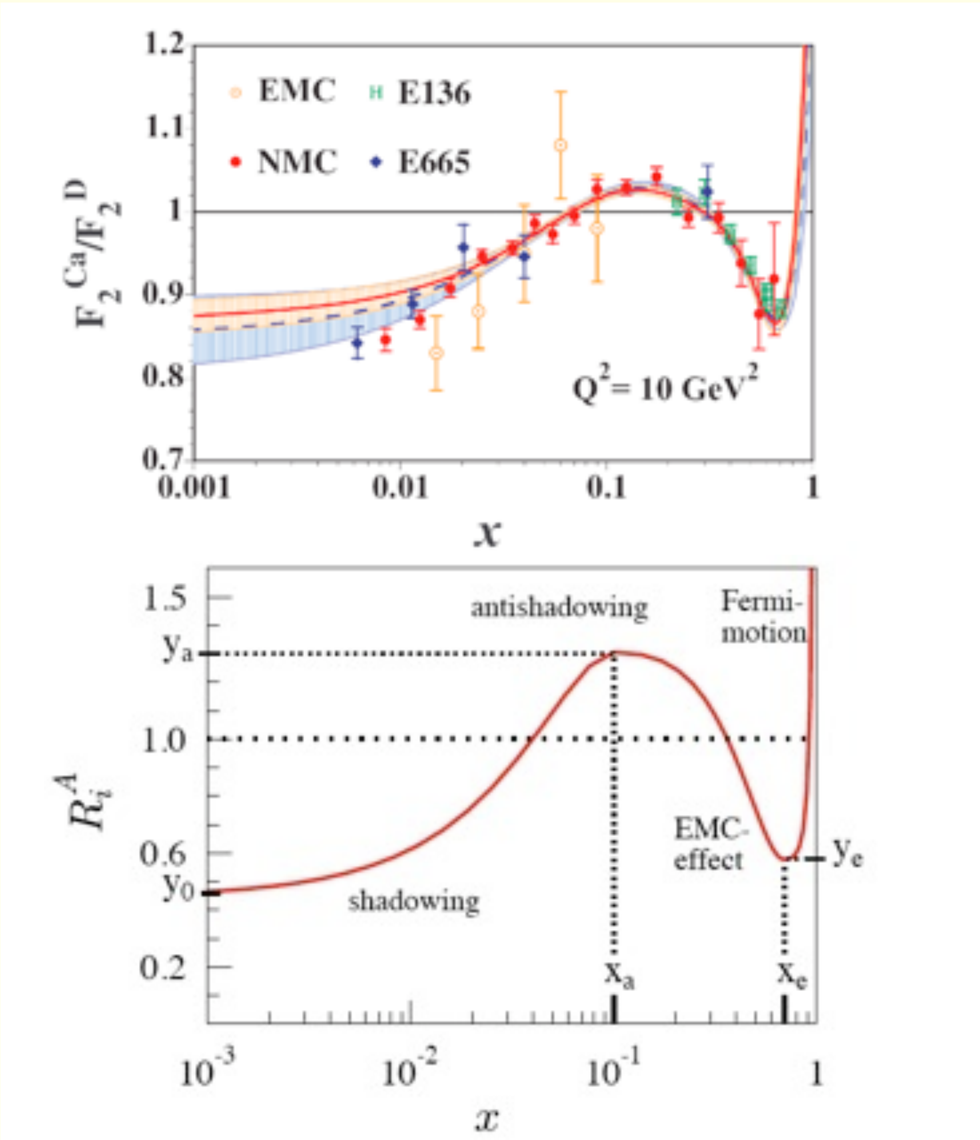
NLO pQCD Works at RHIC





Agreement with pQCD in p+p shows that high-p_T pions are a calibrated probe of the medium created in A+A collisions

Modification of the Structure Functions in Nuclei



$x < 0.1$: "shadowing region"

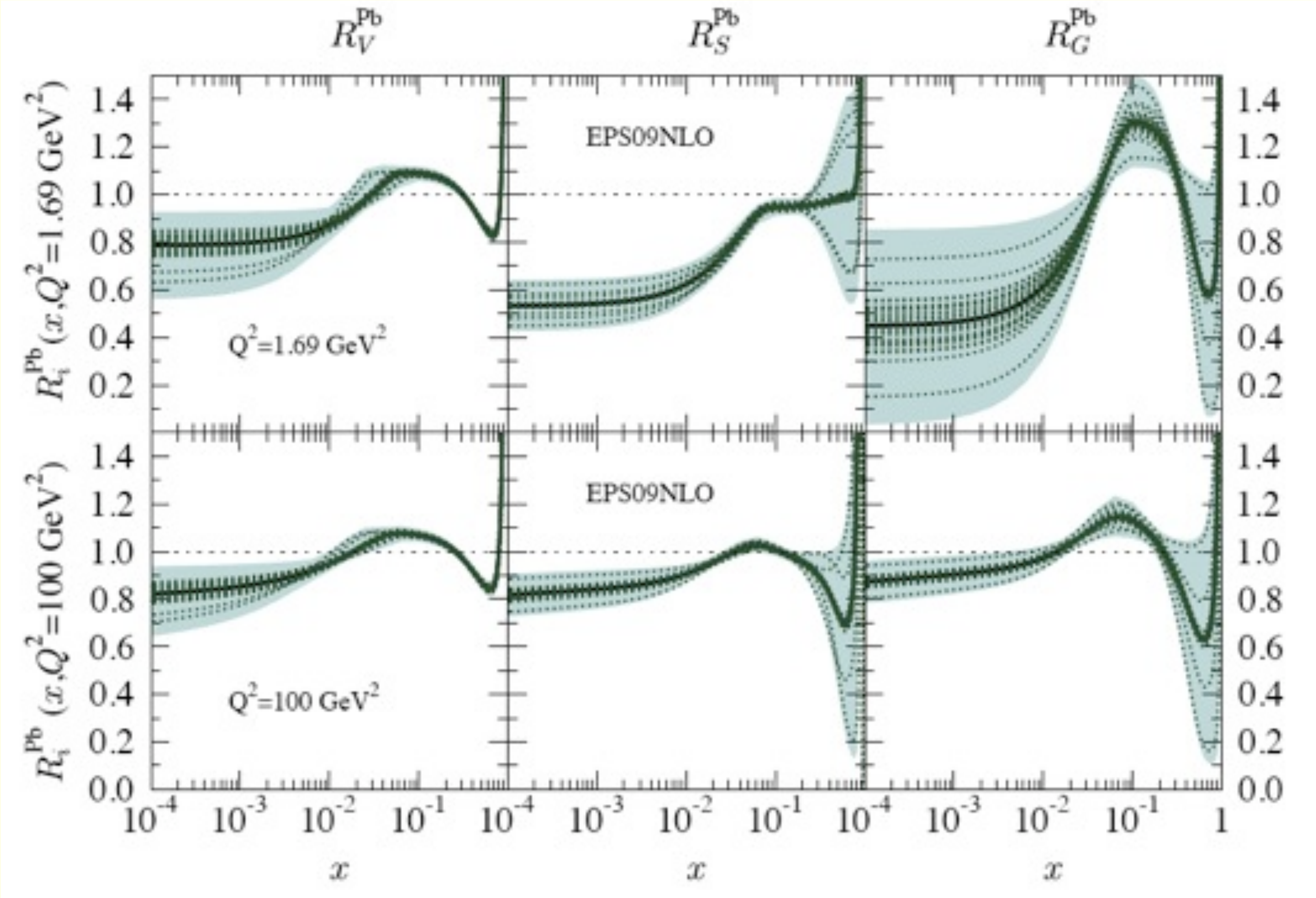
$0.1 < x < 0.3$: "anti-shadowing"

$0.3 < x < 0.7$: "EMC effect"

$0.7 < x < 1.0$: Fermi-motion of nucleons in nuclei

An Example: Nuclear PDF's in Pb (EPS09NLO)

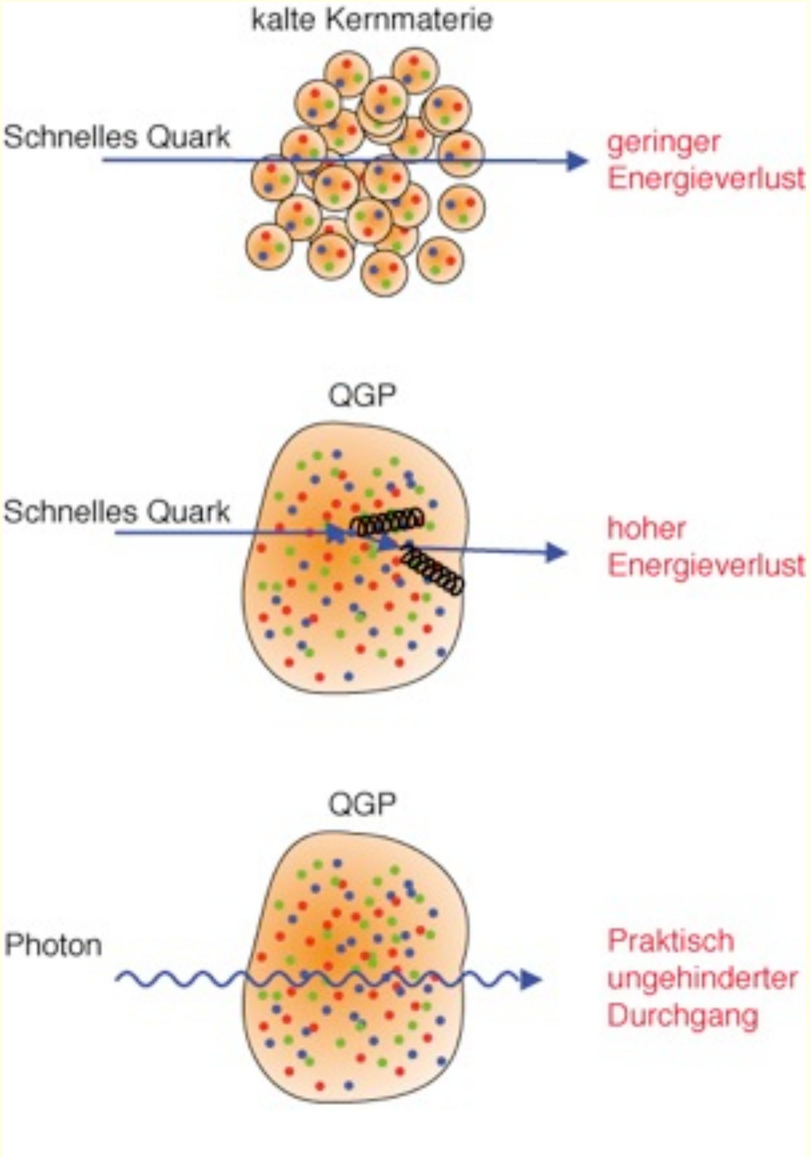
Valence quarks Sea quarks gluons



Large uncertainties for gluon PDF's at small *x*

Eskola et al., arXiv:0902.4154v2 [hep-ph]

Jet Quenching: Basic Idea



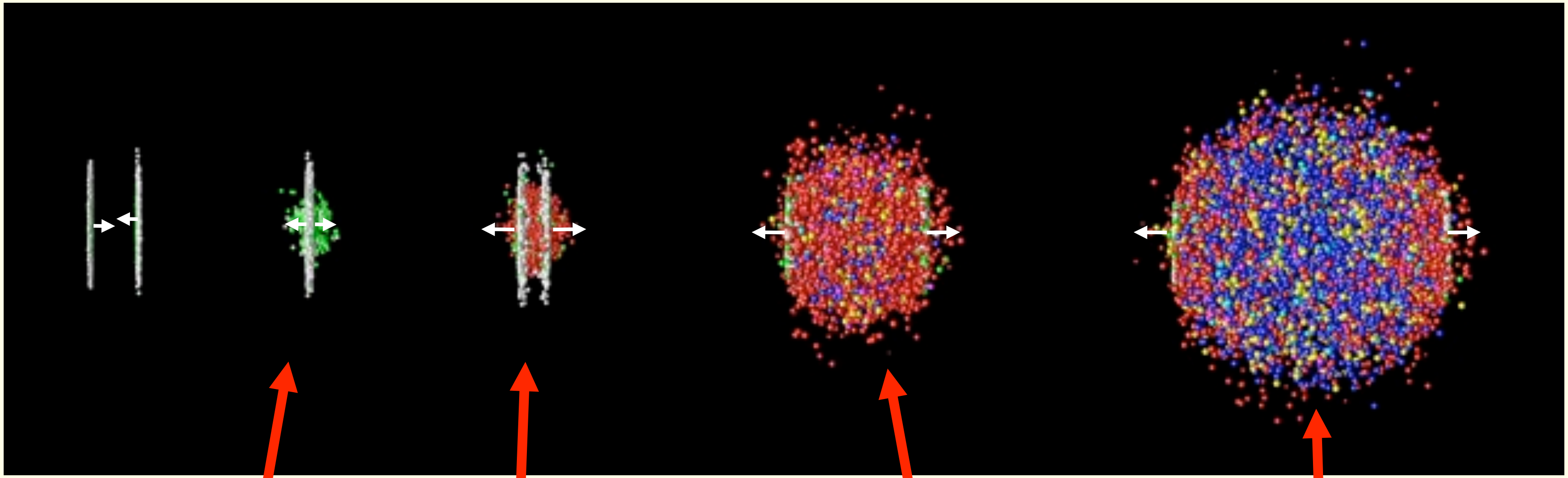
Expectation:
Simple scaling from p+p to d+Au

Expectation:
Pion suppression in A+A

Expectation:
Simple scaling from p+p to A+A for direct photons

Jets as Auto-Generated Probes of the QGP

time →



Early hard parton-parton scatterings ($Q^2 >> \Lambda^2_{QCD}$)

Thermalized medium (QGP!?) ($T_0 > T_c$, $T_c \approx$ 150–200 MeV)

Transition QGP → hadron gas

Freeze-out

- Thermalization of the deconfined quark-gluon matter expected at $\tau_0 < \sim 1$ fm/c
- Hard probes (jets, high-p_T direct photons, c- and b-quarks) produced in early hard parton scatterings prior to QGP ⇒ ideal QGP probes

What Can We Hope to Learn from Jet Quenching?

- Objectives of heavy-ion physics:
  - Learn something about QCD in the regime of high temperatures and densities (QCD thermodynamics)
  - Study the deconfinement transition at T_c = 150 - 200 MeV predicted by lattice QCD calculations

- Observables related to Jet Quenching may help to
  - characterize the new state of matter above T_c
  - understand the mechanism of parton energy loss

- Basic logic

QGP $\Rightarrow$ / $\not\Leftarrow$ Suppression of hadrons at high p_T

How Can We Study Jet Quenching?

- Measurement of particle multiplicities at high p_T
- Measurement of two-particle angular correlations
- Jet reconstruction on an event-by-event basis
  - Challenging in central nucleus-nucleus collisions at RHIC due to large particle multiplicity from the underlying event
  - Situation improves significantly for Pb+Pb at the LHC due to the increased cross section for jet production

Jet Quenching History

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

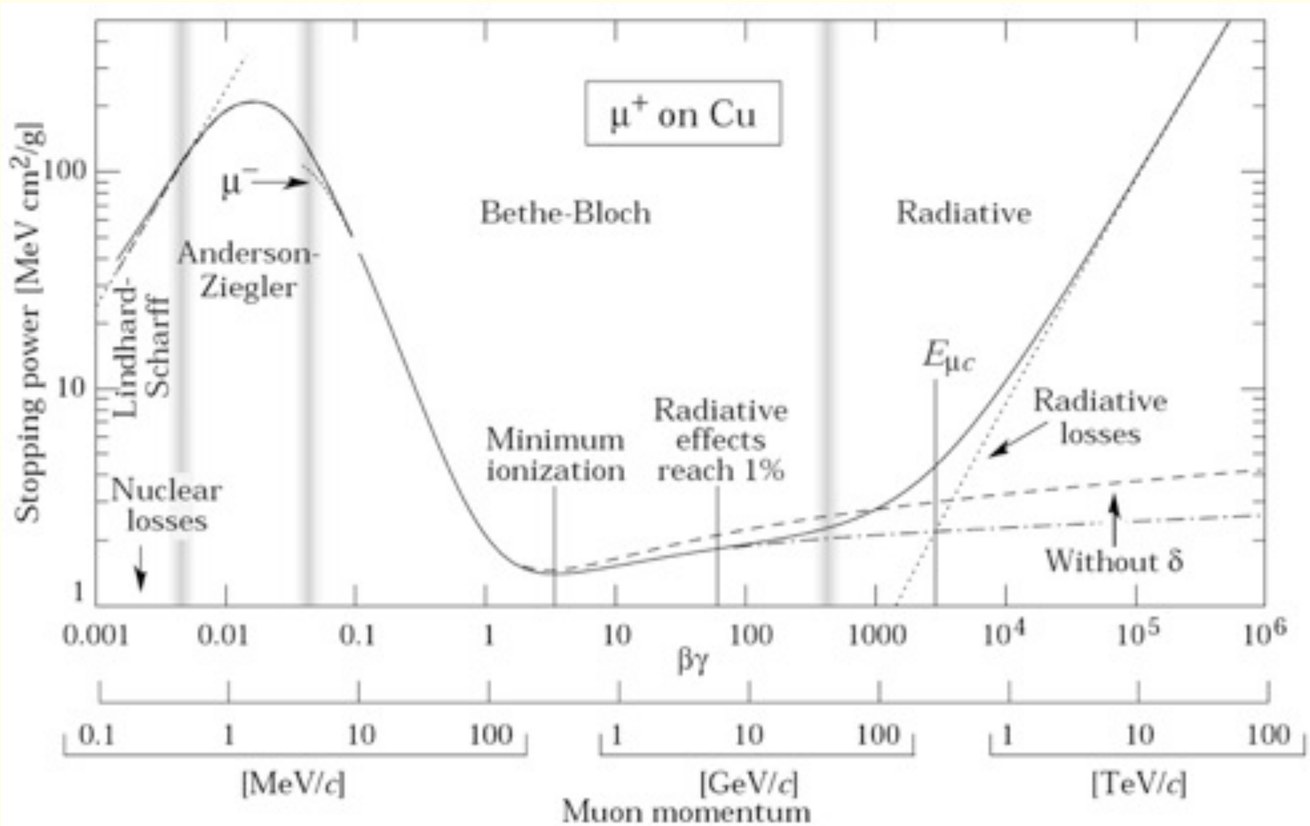
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

FERMILAB-Pub-82/59-THY
August, 1982

- Energy loss via elastic scattering was later believed to have only a minor effect on jets
- Radiative energy loss was discussed in the literature from 1992 on by Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Pegne, Schiff, Levai, Vitev, Zhakarov, Wang, Salgado, Wiedemann, …

Analogy: Energy loss of Charged Particles in Normal Matter



- μ^+ on Cu: Radiational energy loss („bremsstrahlung") starts to dominate over collisional energy loss („Bethe-Bloch formula") for p >> 100 GeV/c
- For energetic quarks and gluons in QCD matter, radiative energy loss via induced gluon emission is/was expected to be the dominant process

Parton Energy Loss – Expected Properties

Radiative energy loss dominant (?):

$$dE_{rad} / dx \gg dE_{coll} / dx$$

Medium parameter $\hat{q} = \frac{\mu^2}{\lambda}$

μ^2 : Typical momentum transfer from the medium to the parton

λ : Mean free path

Nucl.Phys.B483:291-320,1997

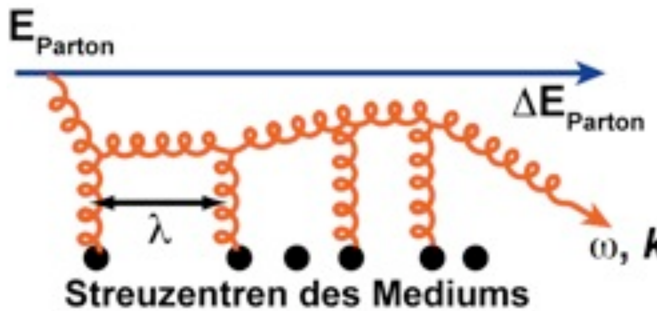
$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

Energy loss ΔE in a static medium of length L for $E \to \infty$ (BDMPS results)

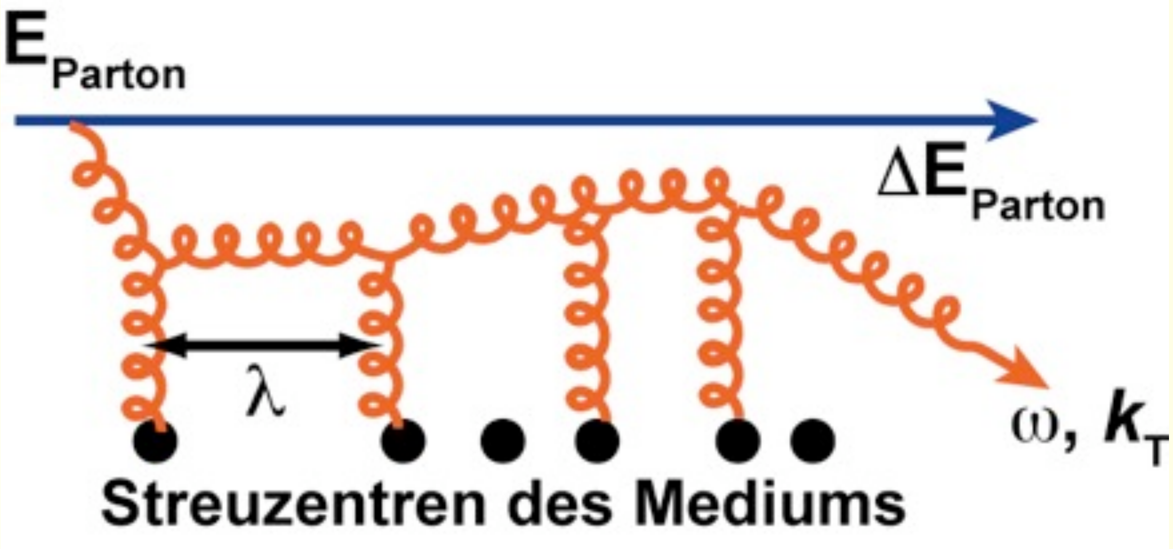
Energy loss for gluon jets larger than for quark jets

$$C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

L^2 dependence:
Non-abelian nature of QCD + quantenm. interference



Parton Energy Loss: Why $\Delta E \propto L^2$?

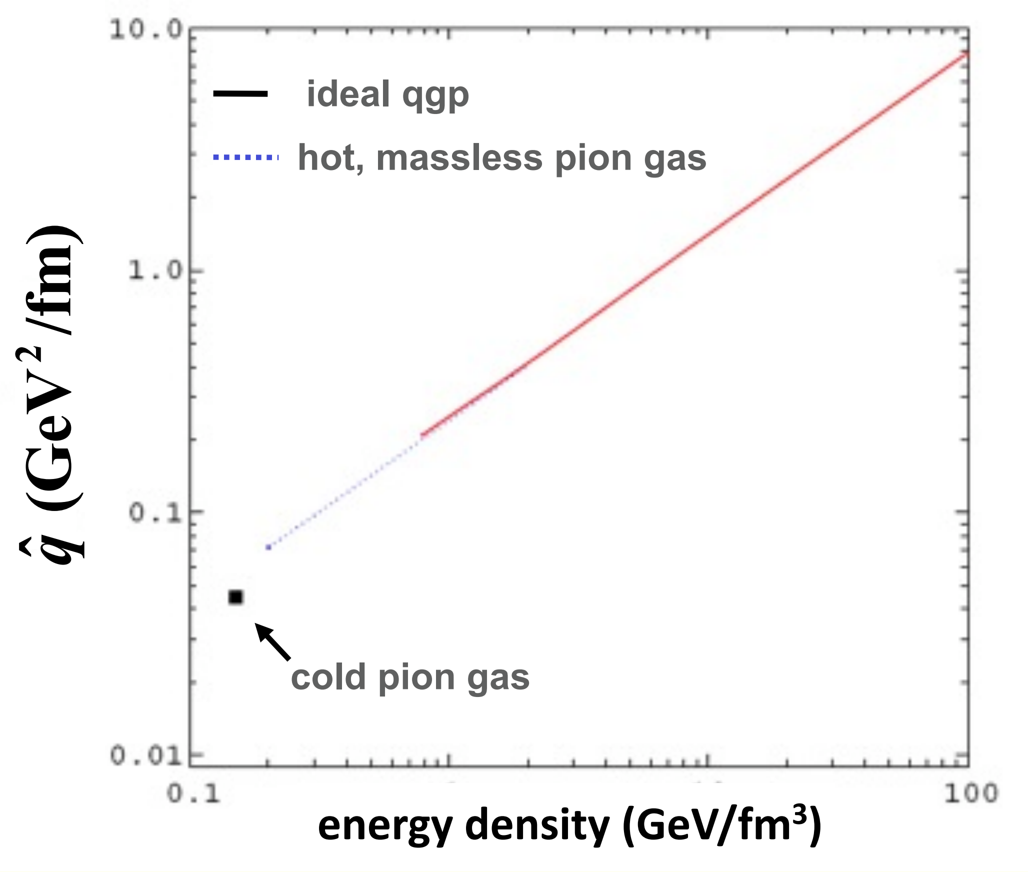


Probability for radiating a gluon: $\propto L$

Coherent gluon wave function accumulates transverse momentum k_T.
Number of scatterings with momentum transfer k_T until it decoheres: $\propto L$

Total energy loss: $\Delta E \propto L^2$

Relation between Transport Coefficient and Energy Density of the Medium



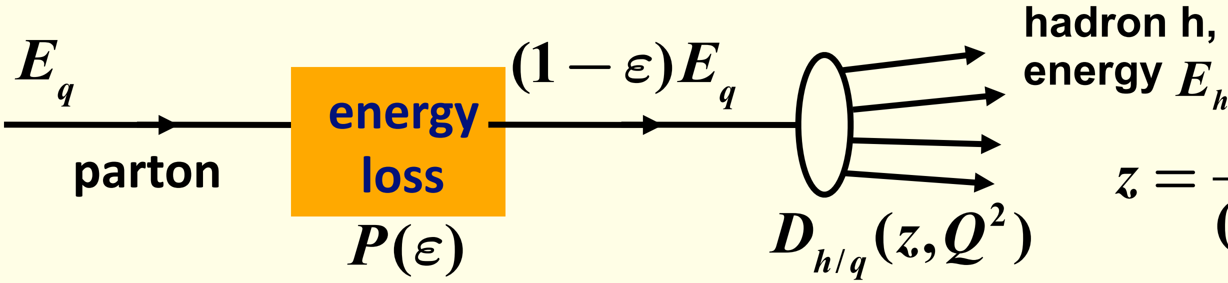
- $\hat{q}$ increases smoothly with energy density
- Nuclear matter
  $$\hat{q}_{\text{nuclear matter}} < 0.5 - 1 \text{ GeV}^2 / \text{fm}$$
- QGP (and hot hadron gas):
  $$\hat{q}_{\text{qgp}} \gg \hat{q}_{\text{nuclear matter}}$$

Medium characterized by

$\hat{q} = \mu^2 / \lambda$ (Momentum transfer per mean free path)

Medium-Modified Fragmentation Functions

Parton energy loss can be conveniently included in a pQCD calculation via modified fragmentation functions



Prob. Distr. for parton energy loss ε ("Quenching weight")

$$z = \frac{E_h}{(1-\varepsilon)E_q}, \qquad x = \frac{E_h}{E_q}$$

$$= \frac{x}{(1-\varepsilon)}$$

Consider fixed parton energy loss ε:

$$\frac{dn}{dx} = \frac{dn}{dz} \cdot \frac{dz}{dx} = D_{h/q}(z,Q^2) \cdot \frac{1}{1-\varepsilon}$$

Average over energy loss probability:

$$D_{h/q}^{\mathrm{med}}(x,Q^2) = \int_0^1 d\varepsilon\, P(\varepsilon)\; D_{h/q}\left(\frac{x}{1-\varepsilon},Q^2\right) \frac{1}{1-\varepsilon}$$

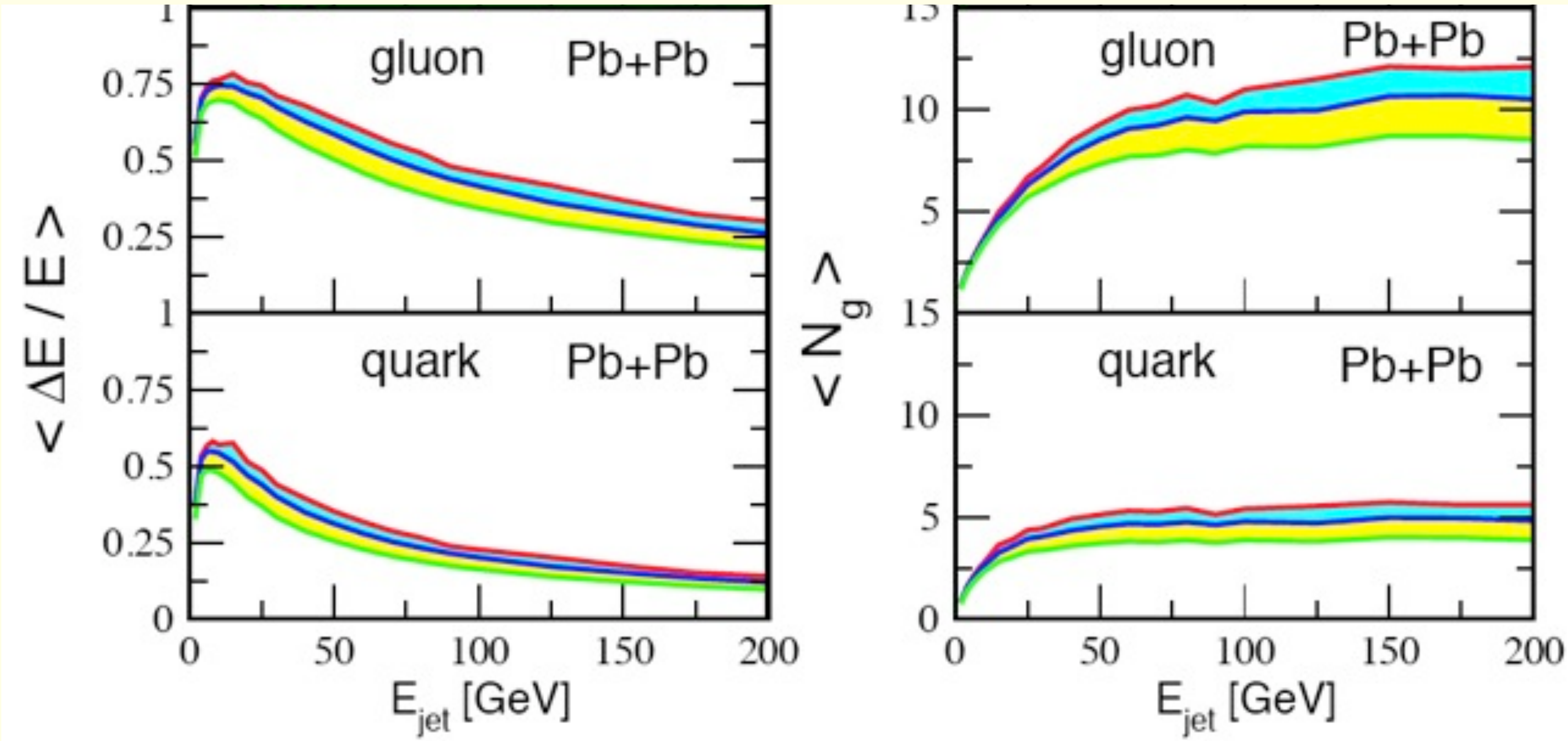
Hadrons resulting from gluon bremsstrahlung neglected

Energy loss in the GLV Formalism for Pb+Pb at the LHC

I. Vitev, Phys.Lett.B639:38-45,2006

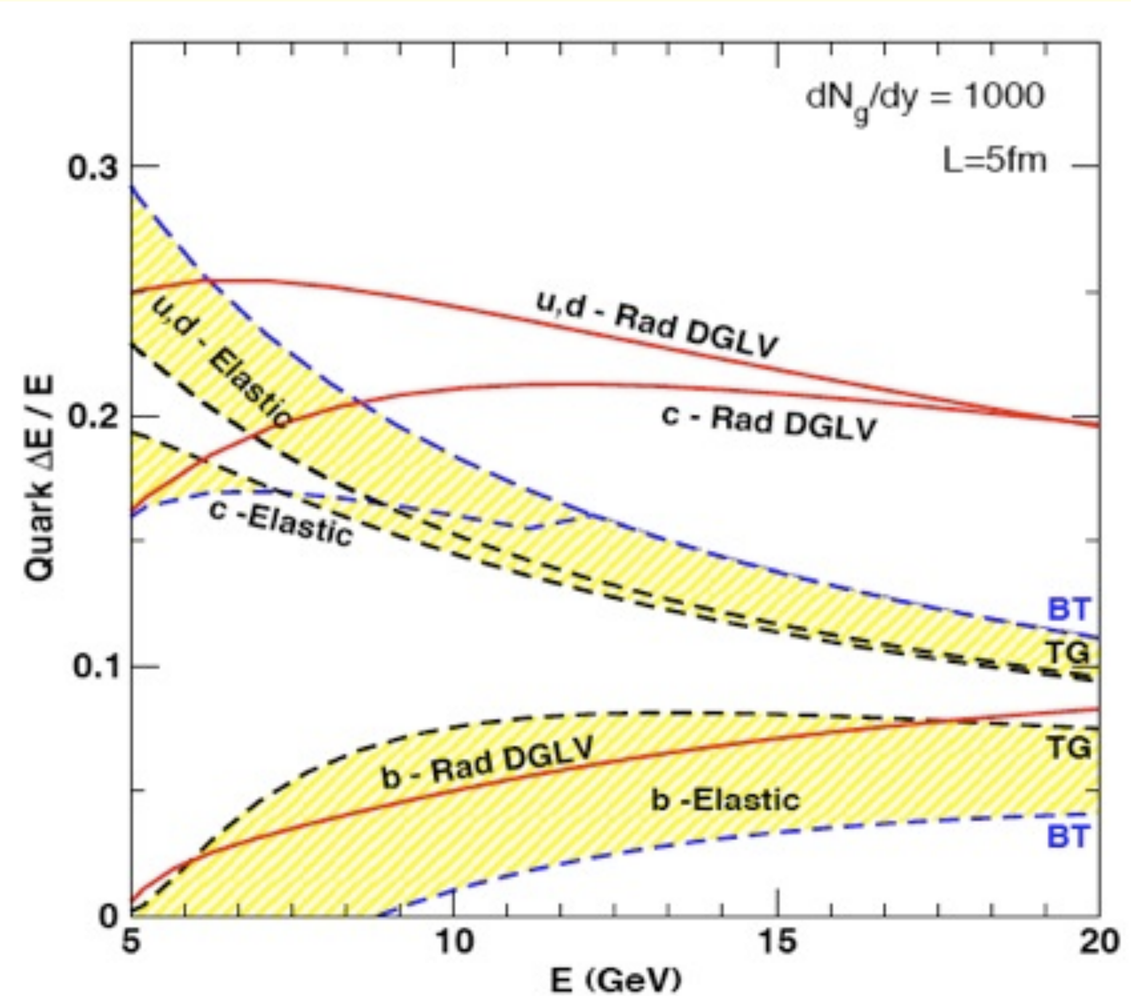
Central Pb+Pb at $\sqrt{s_{NN}}$ = 5500 GeV: $L \approx 6$ fm, dN^g/dy = 2000, 3000, 4000

energy loss | # radiated gluons



$\Delta E_{gluon} / \Delta E_{quark} = 9/4$ only in the limit $E \to \infty$

Radiative vs. Collisional (i.e., Elastic) Energy Loss



- $\Delta E_{radiative} > \Delta E_{collisonal}$ for u, d as well as c quarks with $E > 10$ GeV
- $\Delta E_{radiative} \approx \Delta E_{collisonal}$ for b quarks

Wicks, Horowitz, Djordjevic Gyulassy, Nucl. Phys. A784, 426-442

The Nuclear Modification Factor (I): Digression: Luminosity of a Collider

Rate of events for a given physics process:

$$N = L \cdot \sigma$$

Event rate [s^{-1}]

Cross section [cm^2]

Luminosity [$(s \cdot cm^2)^{-1}$]

If two bunches of particles collide with frequency *f* then :

n_i: number of particles in bunch *i*

$$L = f \frac{n_1 n_2}{A_{\text{beam}}} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

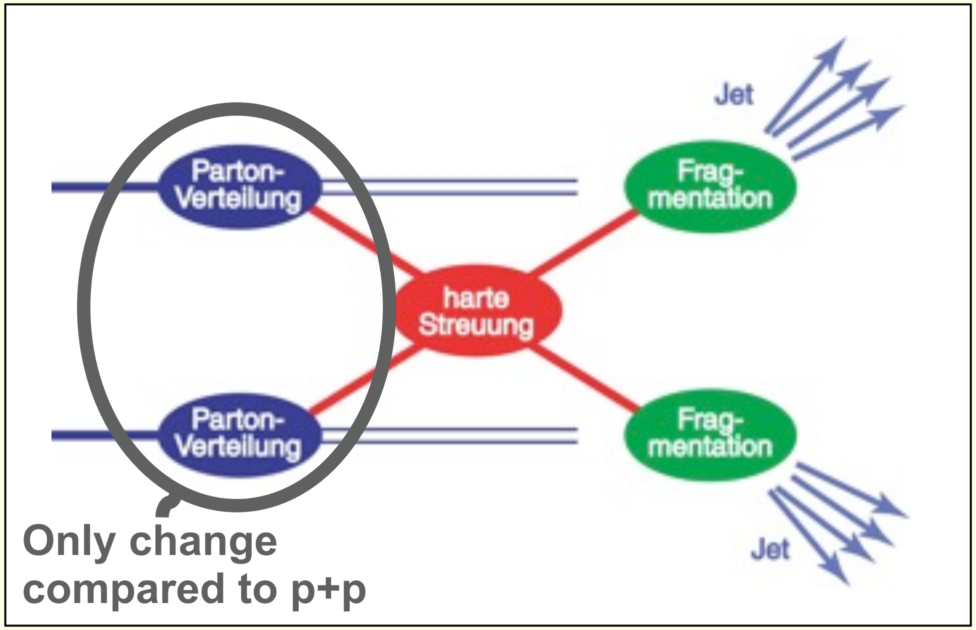
Transverse area of the beam

Example:
Au+Au at RHIC: $L = 2 \times 10^{26}$ cm^{-2} s^{-1}

The Nuclear Modification Factor (II): Particle Yields from Hard Scattering in A+A

$$\frac{dN^{A+B}_{\text{hart}}}{dp_T} = T_{\text{AB}} \cdot \frac{d\sigma^{p+p}_{\text{hart}}}{dp_T}$$

$$T_{\text{AB}} = N_{\text{coll}} \,/\, \sigma^{\text{unel.}}_{\text{NN}}$$



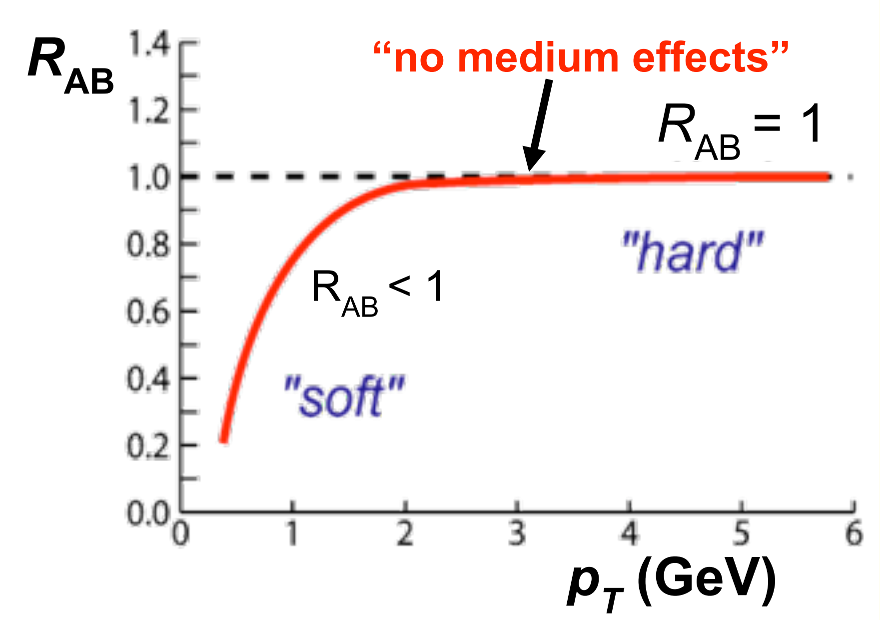
- Calculate increase of the effective luminosity of nucleons (or partons, respectively) based on known nuclear geometry
- Result:
  Particle yields scale with the average number $\langle N_{\text{coll}} \rangle$ of inelastic nucleon-nucleon collisions in the absence of nuclear effects

The Nuclear Modification Factor (III): $R_{AA}(p_T)$

$$R_{AB}(p_T) = \frac{d^2N/dp_T dy|_{A+B}}{\langle N_{coll}\rangle \times d^2N/dp_T dy|_{p+p}} = \frac{d^2N/dp_T dy|_{A+B}}{\langle T_{AB}\rangle \times d^2\sigma/dp_T dy|_{p+p}}$$

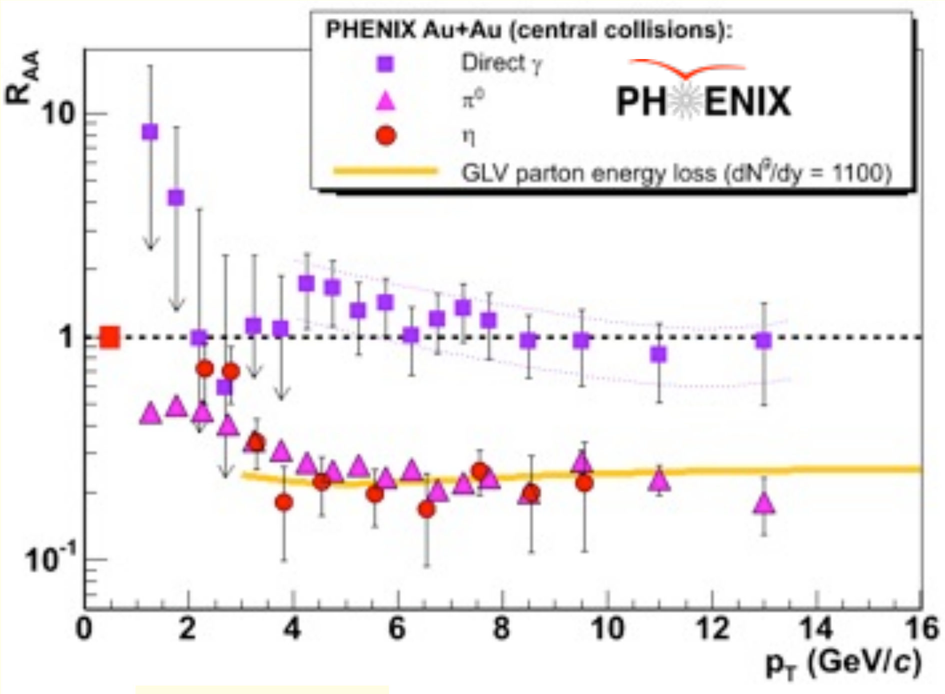
$$\langle T_{AB}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$

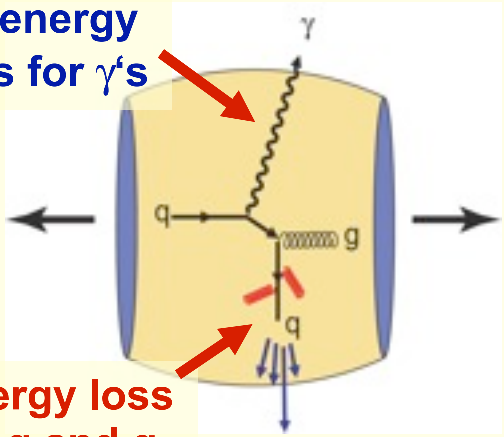
- T_{AB} is the effective nucleon or parton luminosity per A+A collision
- In practice: $\langle N_{coll}\rangle$ from Glauber Monte Carlo calculation
- In the absence of nuclear effects: $R_{AB} = 1$ at high p_T ($p_T > 2$ GeV/c)
- This follows implicitly from the factorization theorem



The discovery phase (ca. 2000 - 2003)

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (I)





$$R_{AB} = \frac{dN / dp_T\big|_{A+B}}{\langle T_{AB} \rangle \times d\sigma_{inv} / dp_T\big|_{p+p}},$$

$$\text{where } \langle T_{AB} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{NN}$$

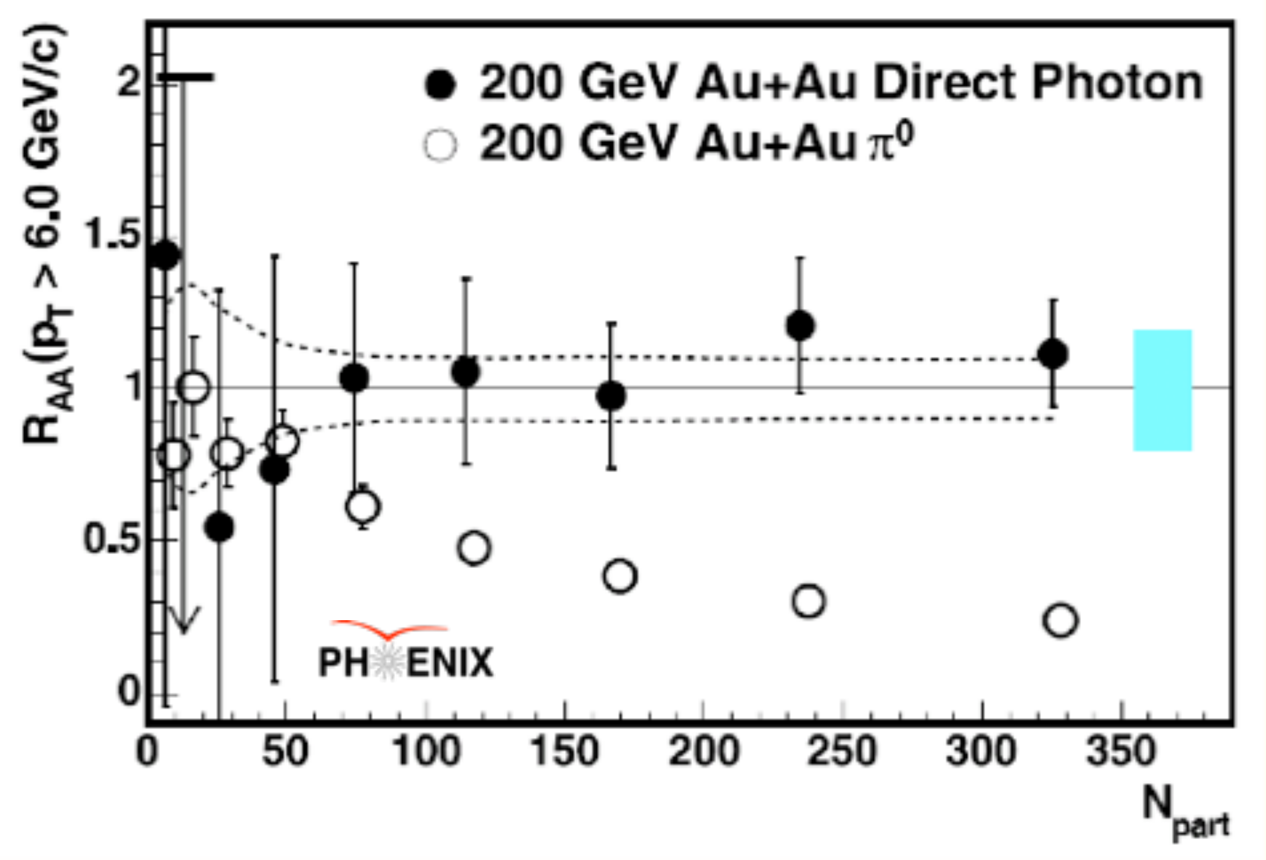
- Hadrons are suppressed, direct photons are not
- No suppression in d+Au (not shown here)
- Evidence for parton energy loss

PHENIX: Phys.Rev.Lett.88:022301, 2002
PHENIX: Phys.Rev.Lett.91:072301, 2003
PHENIX: Phys.Rev.Lett.94:232301, 2005

STAR: Phys.Rev.Lett.89:202301,2002
STAR: Phys.Rev.Lett.90:082302,2003
STAR: Phys.Rev.Lett.91:172302,2003

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (II)

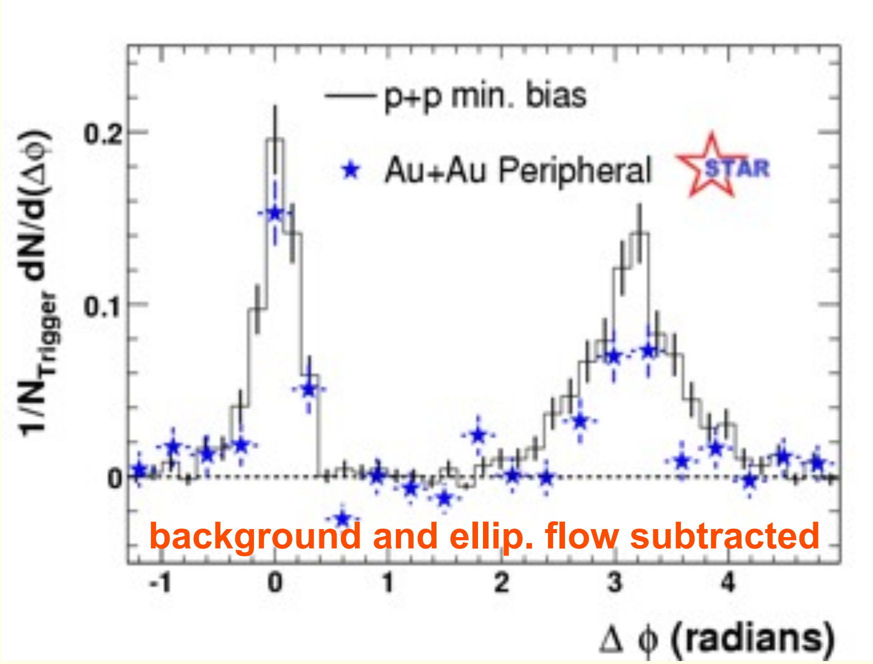
Centrality Dependence of the π^0 and direct γ R_{AA}:



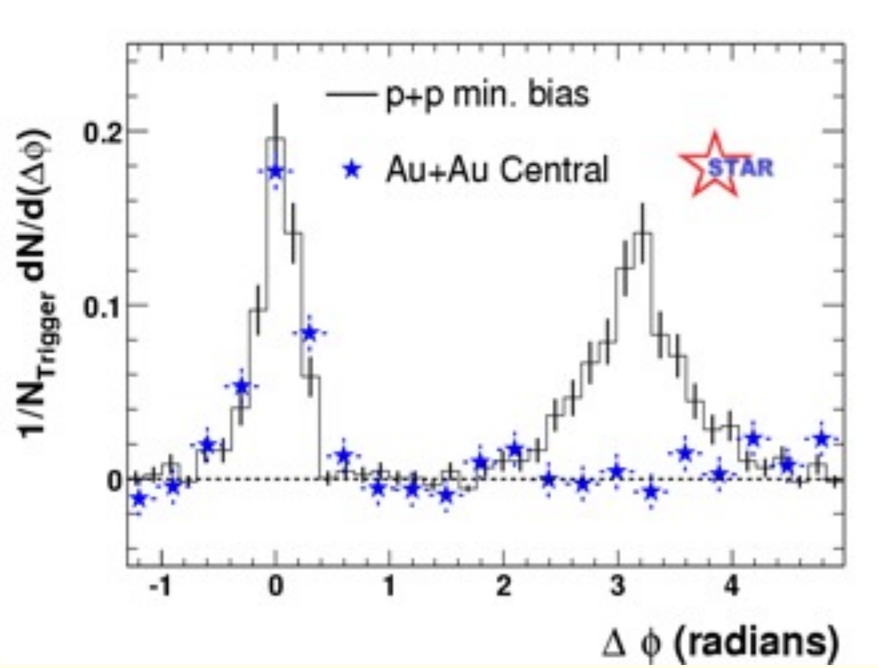
Direct photons follow T_{AB} scaling as expected for a hard probe not affected by the medium

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (III)

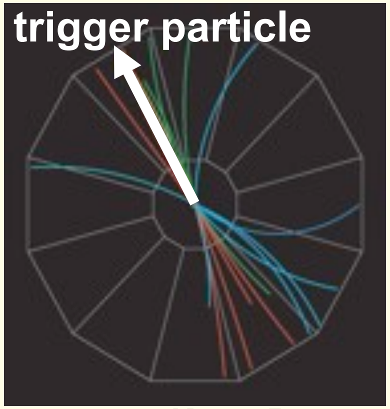
Au+Au peripheral



Au+Au central



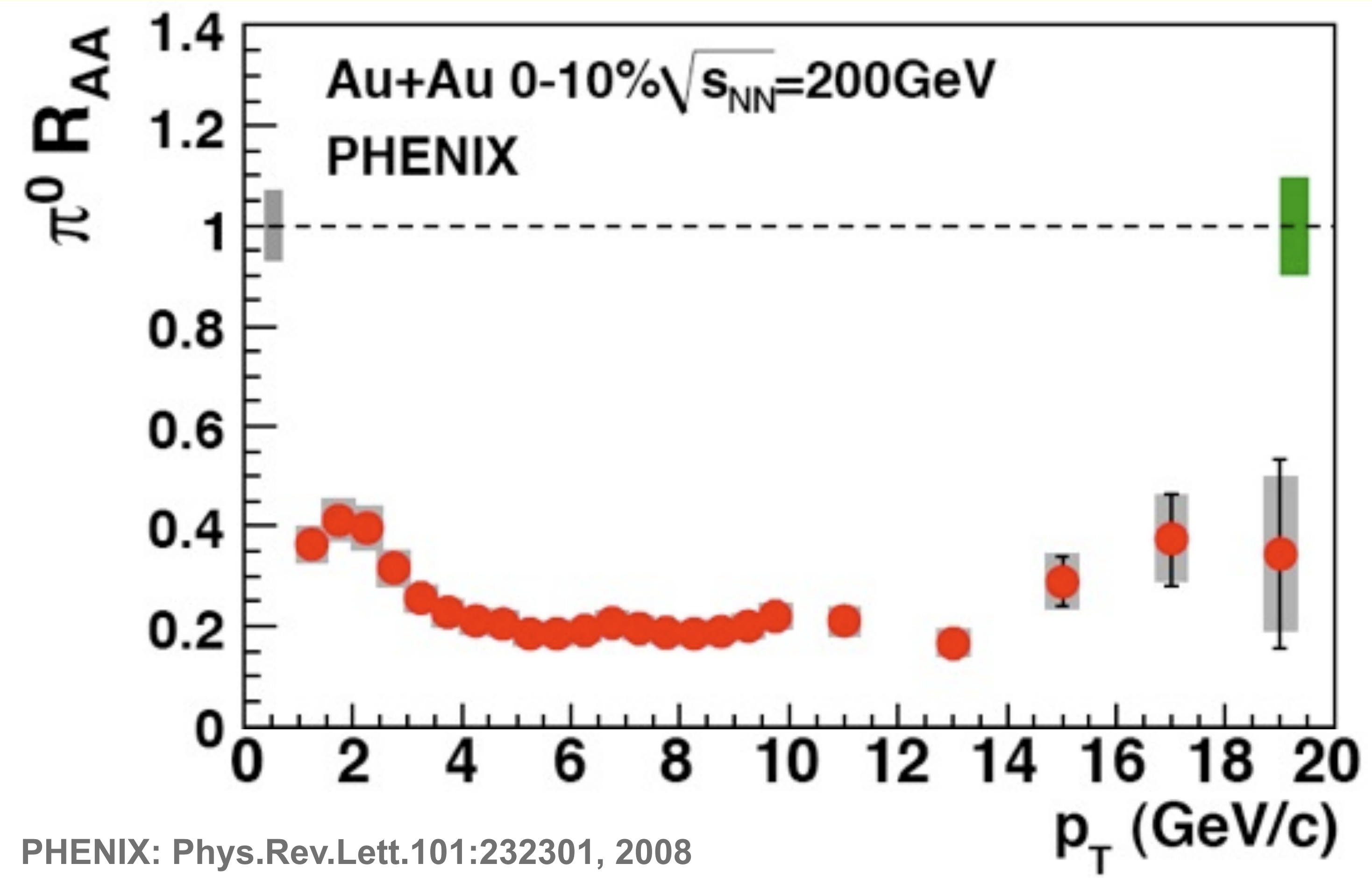
Trigger particle: p_T > 4 GeV/c
Associated particle: p_T > 2 GeV/c



- No jet correlation around 180° in central Au+Au
- Consistent with jet quenching picture

Further Experimental Results Related to Jet Quenching

R_{AA} with Higher Statistics (2004 Run)



PHENIX: Phys.Rev.Lett.101:232301, 2008

R_{AA} approximately constant up p_T = 20 GeV/c

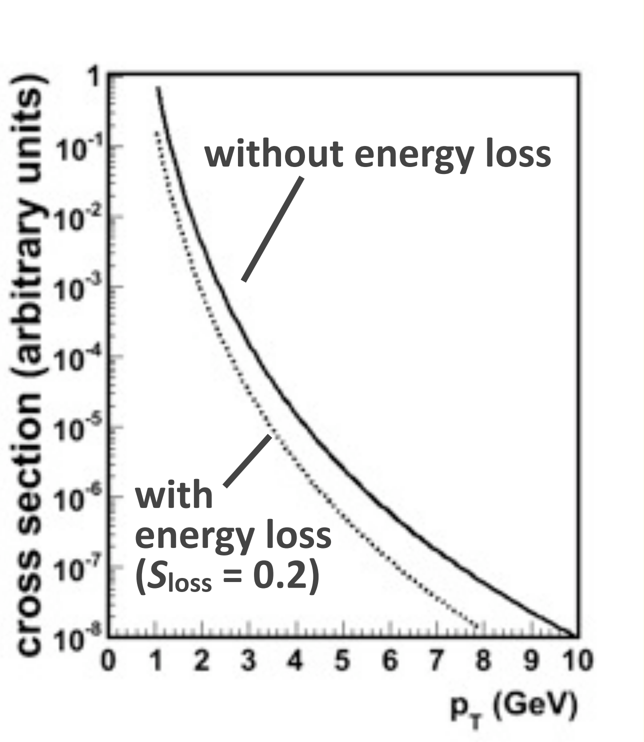
Simple Interpretation of the Constant R_{AA}

π^0 spectrum without energy loss: $$\frac{\mathrm{d}N}{\mathrm{d}p_T} \propto p_T^{-n+1}$$

π^0 spectra at RHIC energy ($\sqrt{s_{NN}}$ = 200 GeV) described with $n \approx 8$

Constant fractional energy loss:

$$S_{\mathrm{Loss}} := \frac{-\Delta p_T}{p_T}, \text{ i.e., } p_T' = (1 - S_{\mathrm{Loss}})\, p_T$$

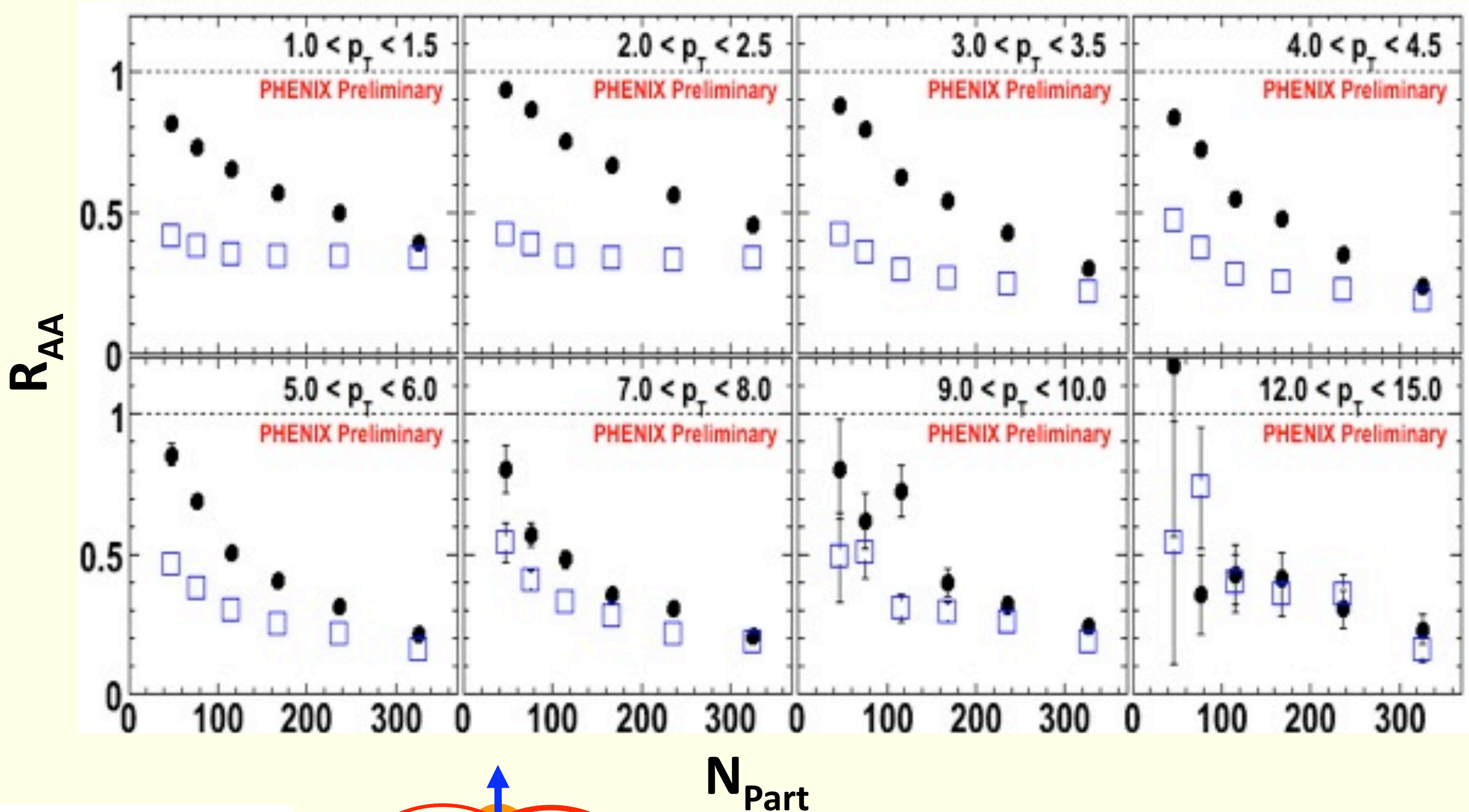


This leads to:

$$R_{AA} = (1 - S_{\mathrm{loss}})^{n-2} \Rightarrow S_{\mathrm{loss}} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

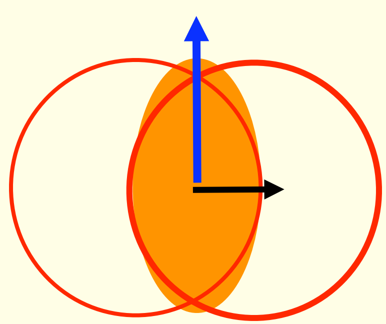
In this simplistic view the constant $R_{AA} \approx 0.25$ implies a constant fractional energy loss of about 20% in central Au+Au at 200 GeV

Path Length Dependence:
π^0 R_{AA} as a Function of the Angle w.r.t. the Reaction Plane



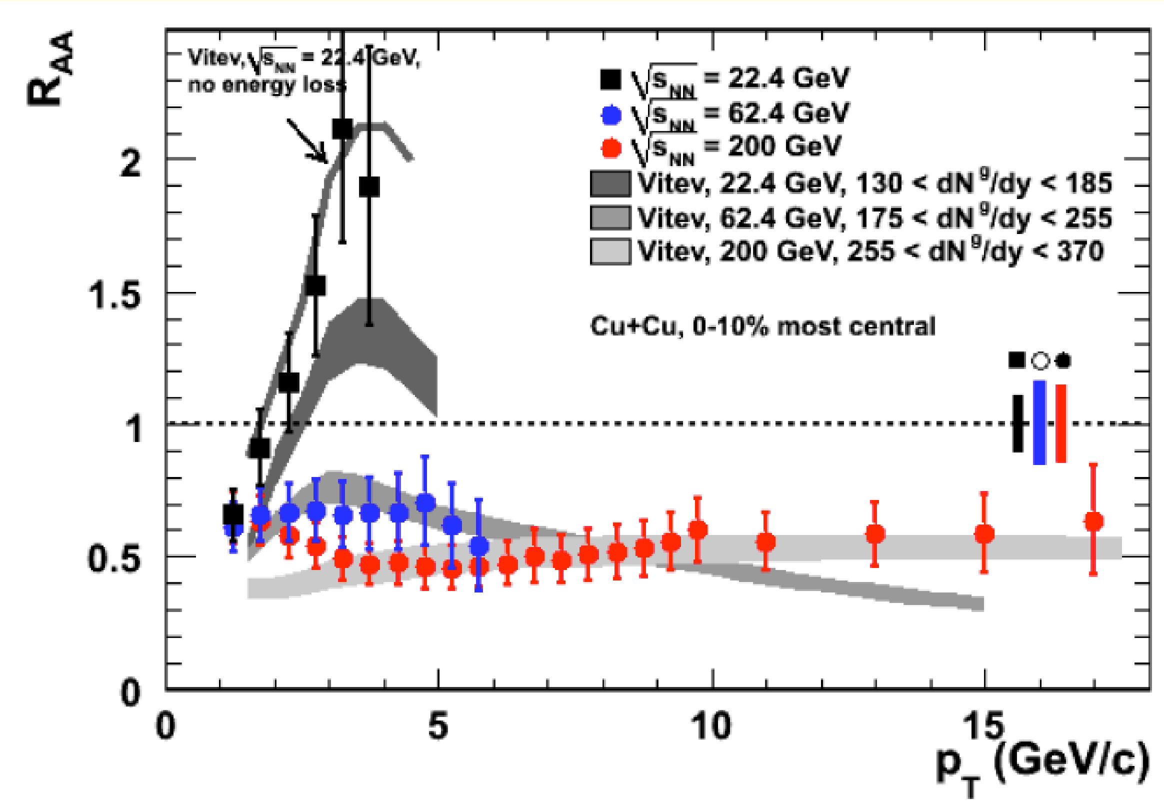
• in-plane

□ out-of-plane



- Longer path length for out-of-plane jets
- Hence, stronger suppression for out-of-plane jets in qualitative agreement with parton energy loss

Dependence on the Size of the Nucleus: $\sqrt{s_{NN}}$ Dependence of the π^0 R_{AA} for Cu+Cu (A = 63)



Phenix, Physical Review Letters 101,162301 (2008)

62.4 and 200 GeV

π^0 production less suppressed than in Au+Au

22.4 GeV

- No suppression
- Enhancement consistent with a calculation that describes Cronin effect in p+A

Same conclusion as for heavier nuclei:
Parton energy loss starts to prevail over Cronin enhancement between $\sqrt{s_{NN}}$ = 22.4 GeV and 62.4 GeV

Hierarchy Expected for Different Types of Partons

$$\Delta E_{\mathrm{Gluon}} > \Delta E_{\mathrm{Quark},m=0} > \Delta E_{\mathrm{Quark},m\neq 0}$$

larger color factor
for gluons:

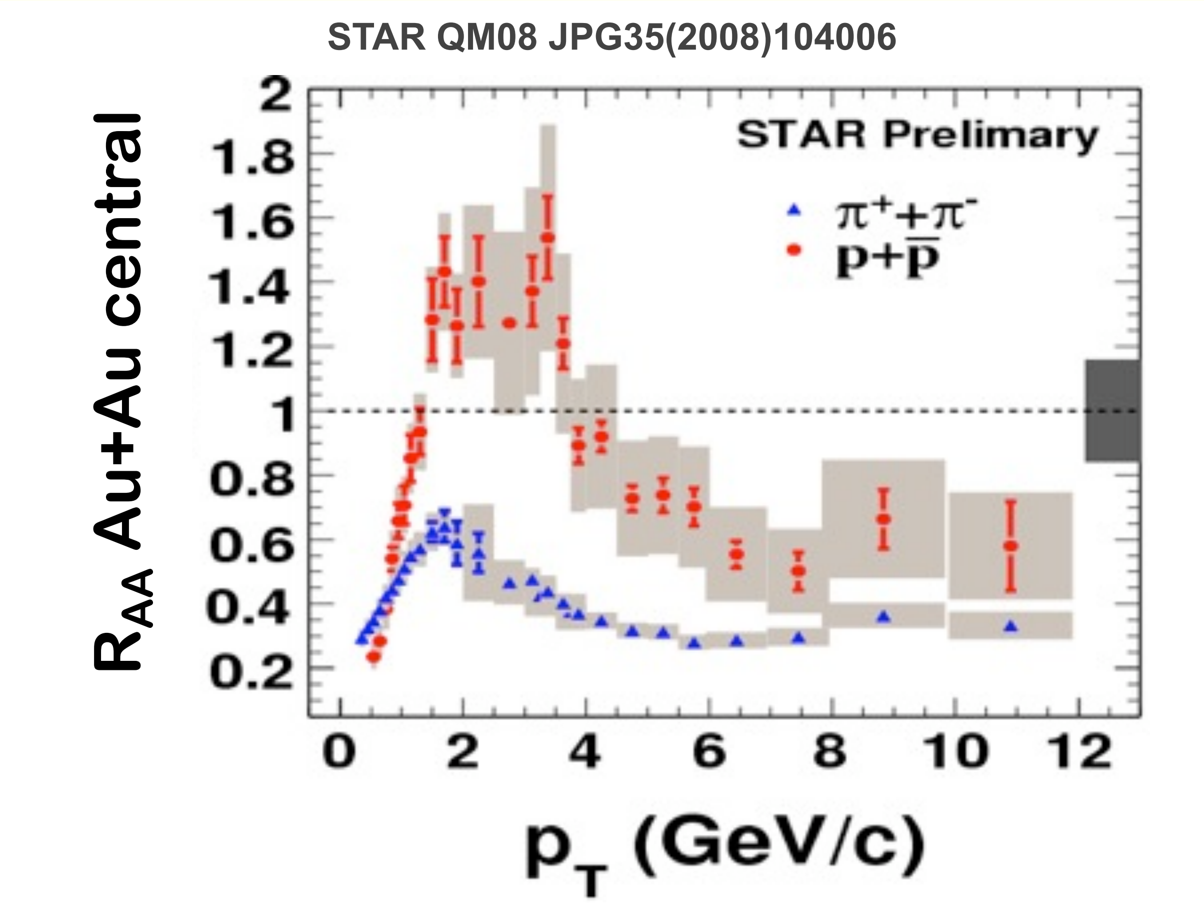
$$C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

Dead cone effect:
Heavy quarks (c, b) are
slower and radiate fewer gluons

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

Dokshitzer & Kharzeev, PLB 519(2001)199

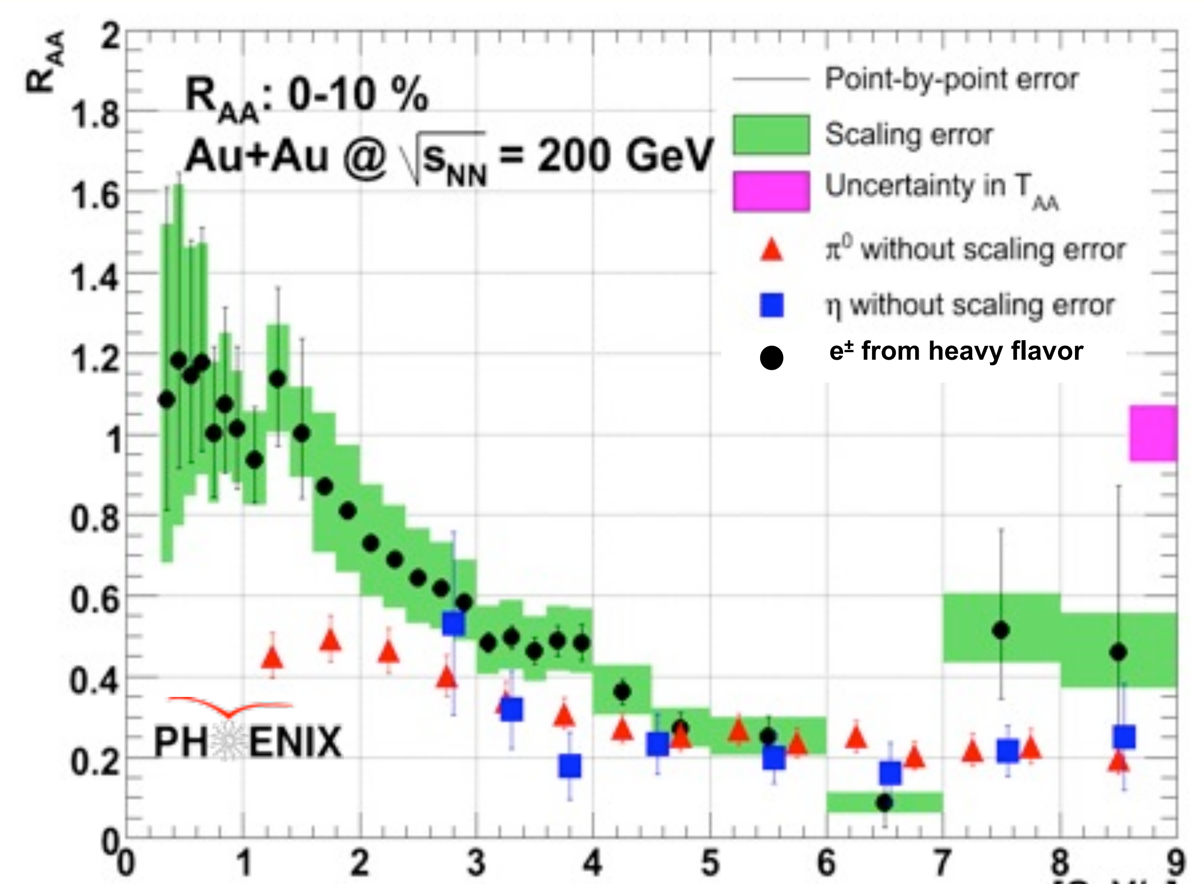
Pion R_{AA} vs. Proton R_{AA}



p R_{AA} > π R_{AA} even though protons result mostly from gluon fragmentation:

→ Difference between quark and gluon energy loss not observed

R_{AA} for Electrons from c- and b-Quark Decays

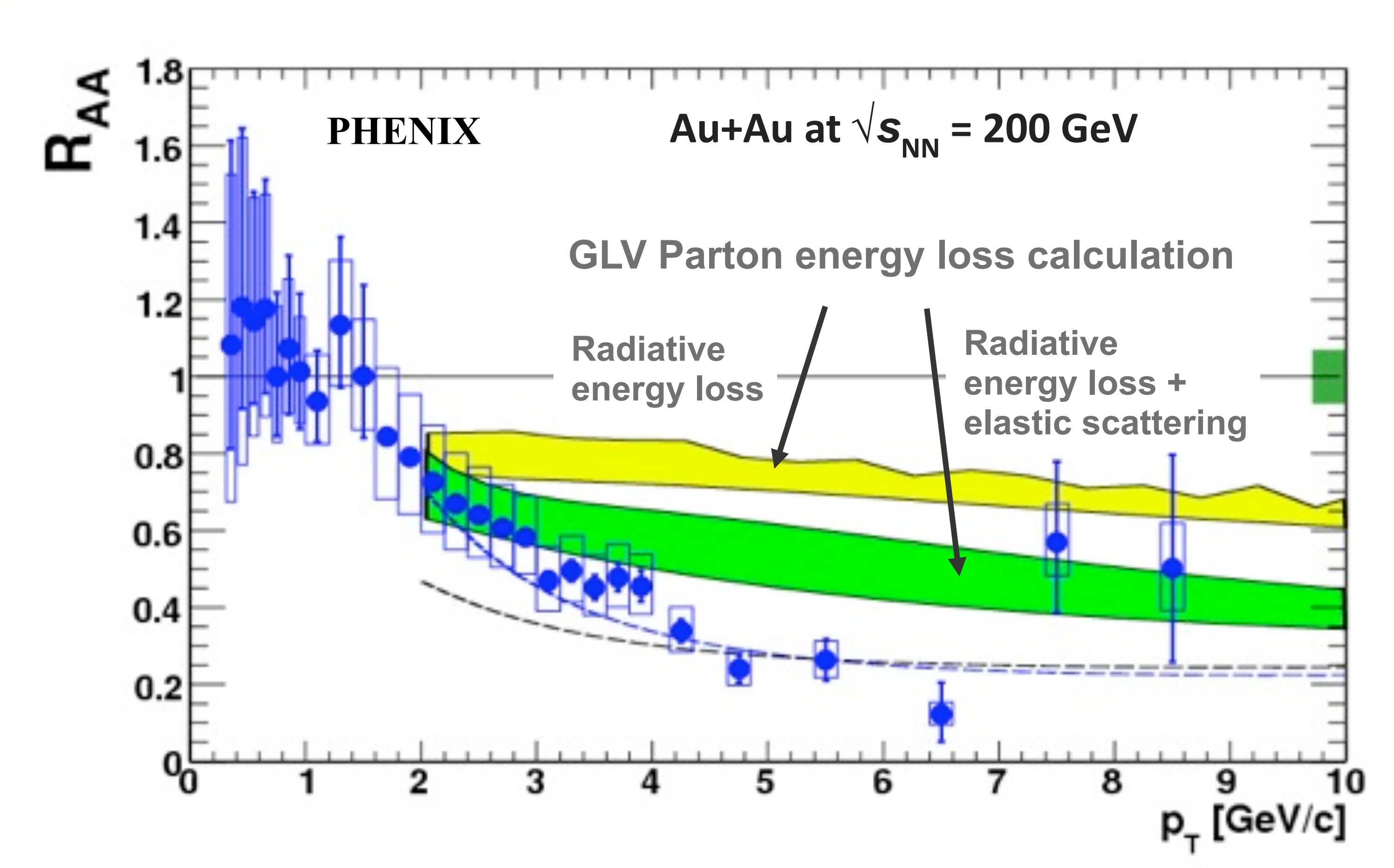


Phys. Rev. Lett. 98, 172301 (2007)

e^+ and e^- from c and b decays as strongly suppressed as pions:

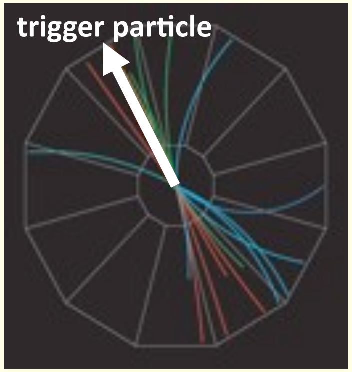
$\Delta E_{\text{Gluon}} > \Delta E_{\text{Quark},m=0} > \Delta E_{\text{Quark},m\neq 0}$ not observed!

R_{AA} for Electrons from Heavy Quarks: Not Understood with Current Energy Loss Models

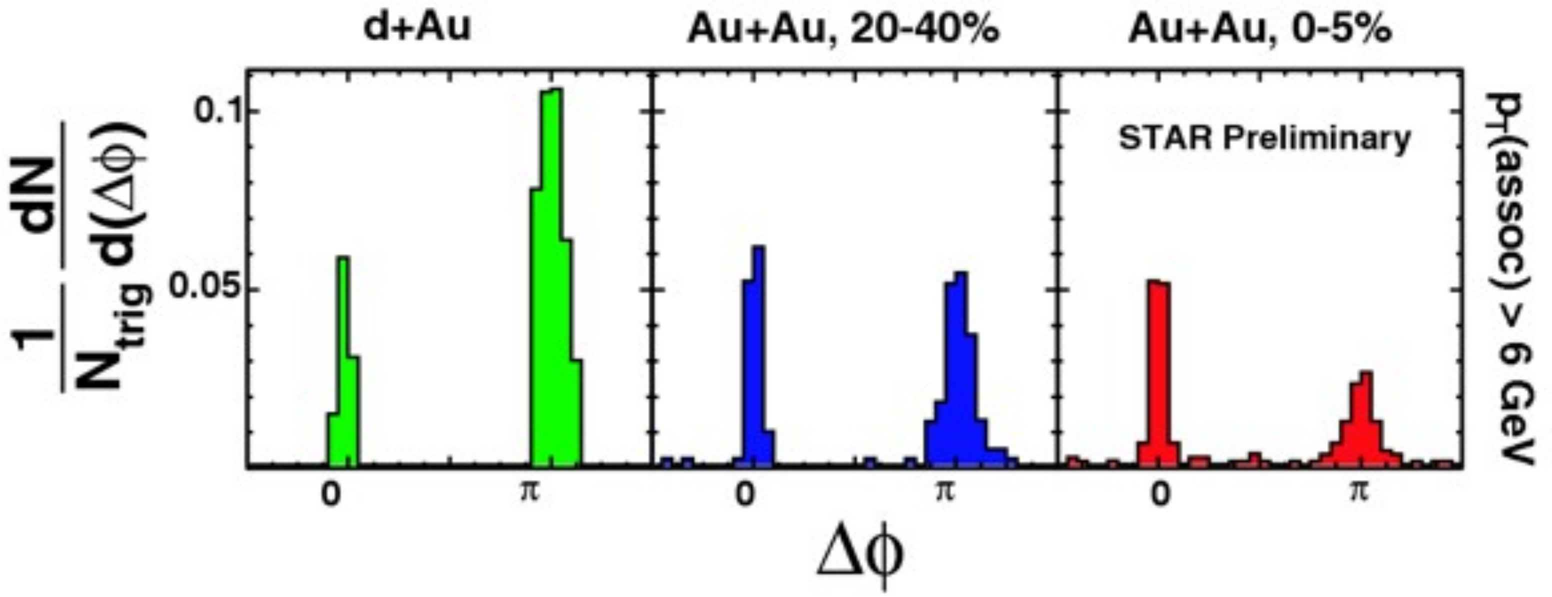


- Radiative energy loss not sufficient to describe excess electron R_{AA}
- Including elastic scattering improves the situation only slightly

Further Results from Two-Particle Correlations (I): Away-Side Jets Visible Again For Higher Jet p_T

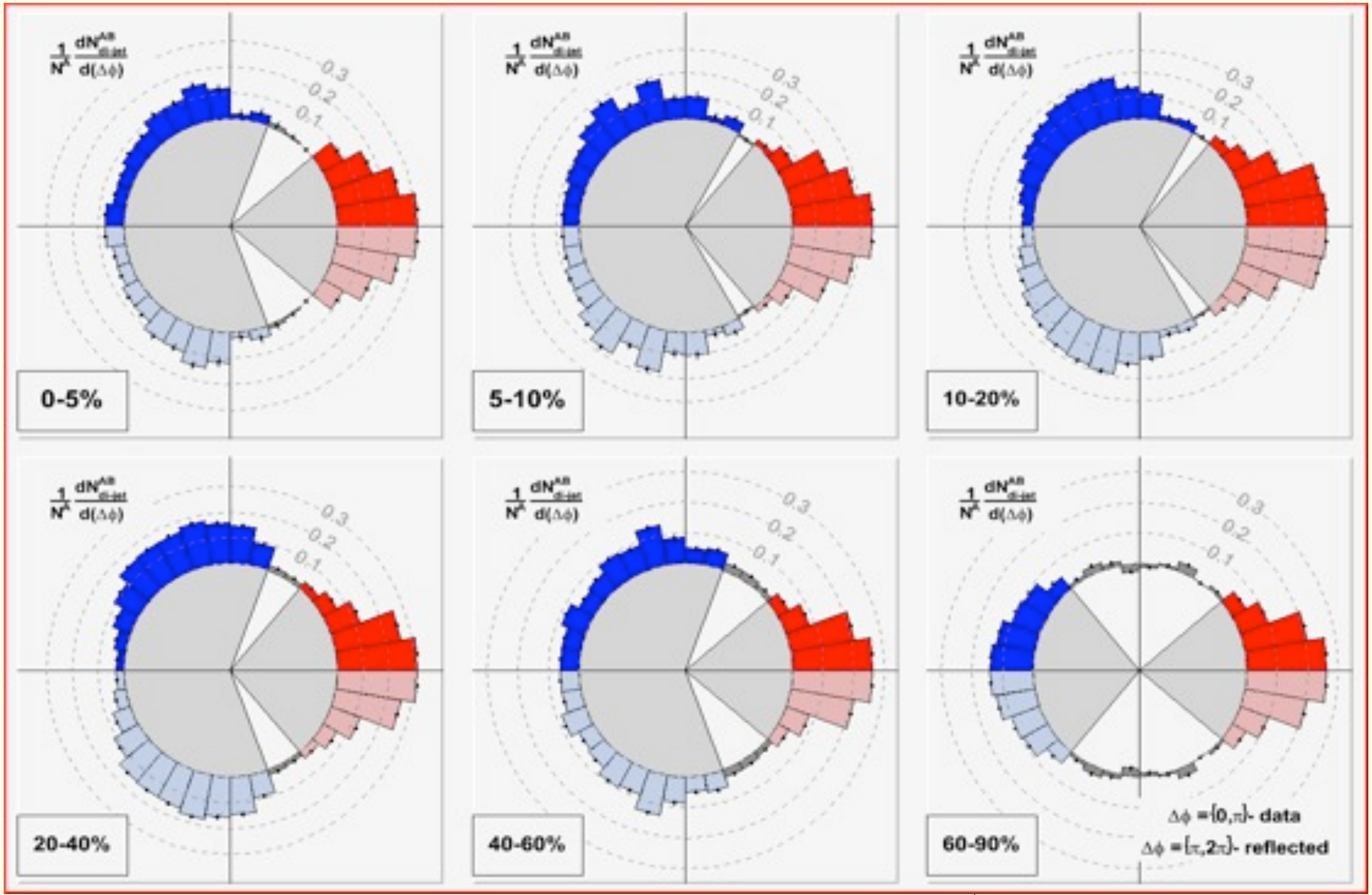


- Charged hadron correlation
- Trigger particle: $p_T > 8$ GeV/c
- Associated particle: $p_T > 6$ GeV/c

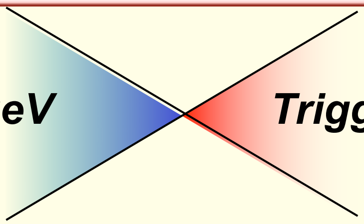


For higher jet energies the correlation at $\Delta\phi = 180°$ in central Au+Au is not fully suppressed anymore

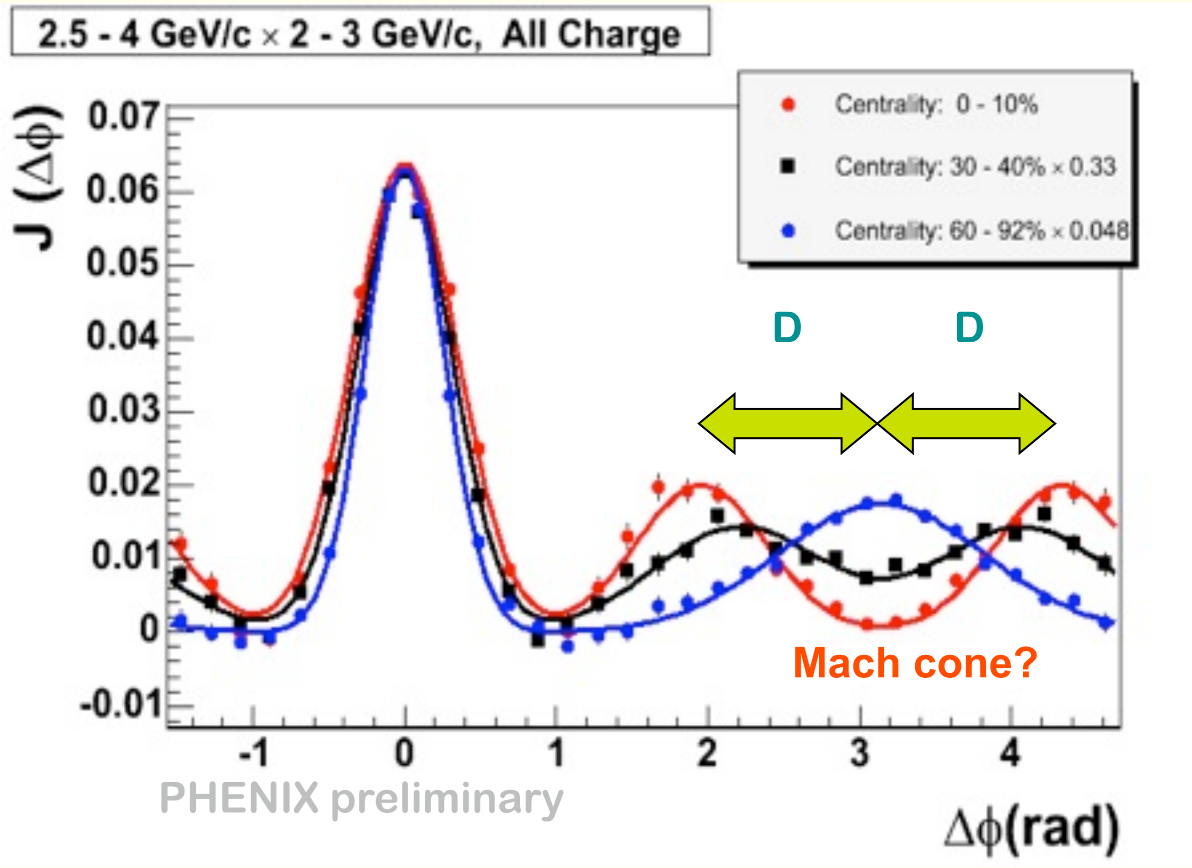
Further Results from Two-Particle Correlations (IIa): Striking Modification of the Away-Side at Low p_T



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



Further Results from Two-Particle Correlations (IIb): Away-Side Correlation at Low-p_T Not Fully Understood



Possible explanations of the splitting of the away-side peak include

- Mach cones
- flow induced jet deflection
- and many more ….

Current Status of Jet Quenching Models (I)

- Currently four major theoretical parton energy loss schemes: (HT, BDMPS-Z-ASW, AMY, GLV)
- Schemes make different approximations and model the medium differently
- All schemes based on pQCD factorization approach
- The final hadronization is always assumed to occur in the vacuum (after some energy loss)

medium modified fragmentation function

vacuum fragmentation function

For example: $$D_{h/q}^{\text{med}}(x, Q^2) = \int_0^1 d\varepsilon \, P(\varepsilon) \, D_{h/q}\left(\frac{x}{1-\varepsilon}, Q^2\right) \frac{1}{1-\varepsilon}$$

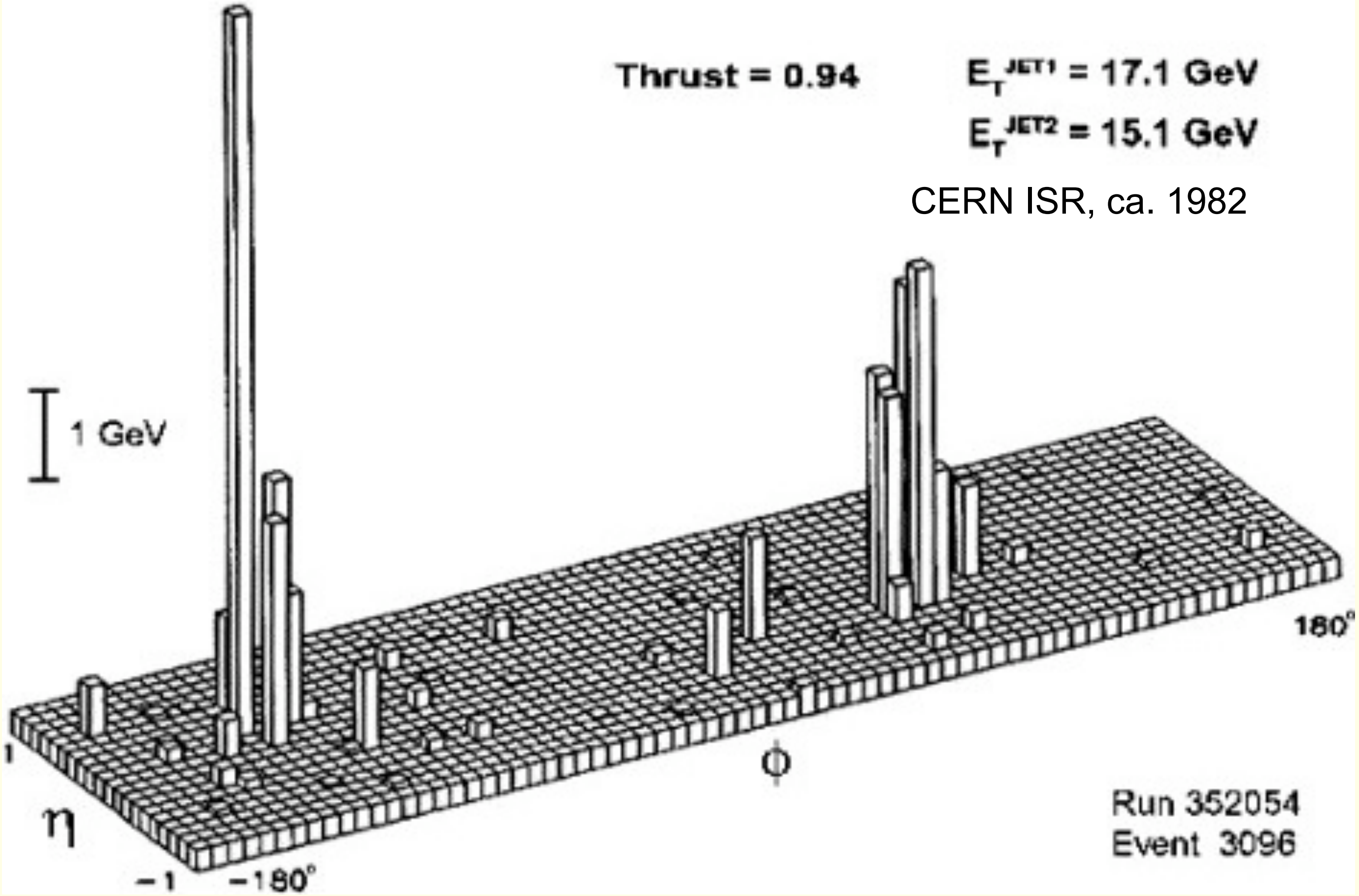
energy loss probability

Current Status of Jet Quenching Models

- All schemes can essentially be reduced to 1-parameter models (parameter e.g. fixed by fitting the pion $R_{AA}(p_T)$)
- No scheme describes all of the observed high-p_T observables (R_{AA} for light and heavy quarks, R_{AA} vs. reaction plane, R_{AA} for different particle species, two-particle correlations)
- Large differences (up to a factor 4) between extracted medium parameters like $\hat{q}$
- So far: „Advantage Data“

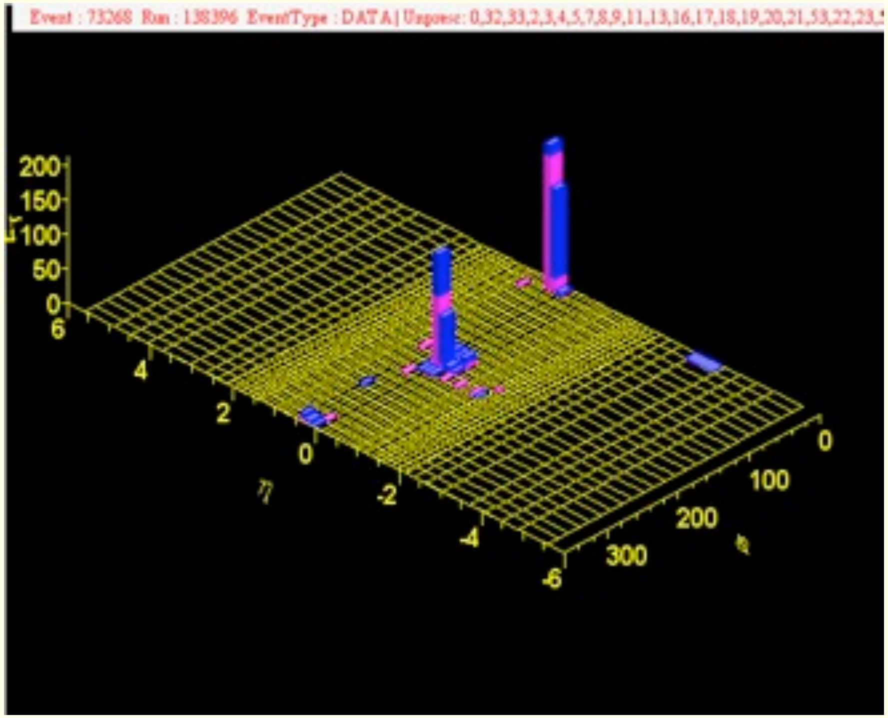
Jet Algorithms

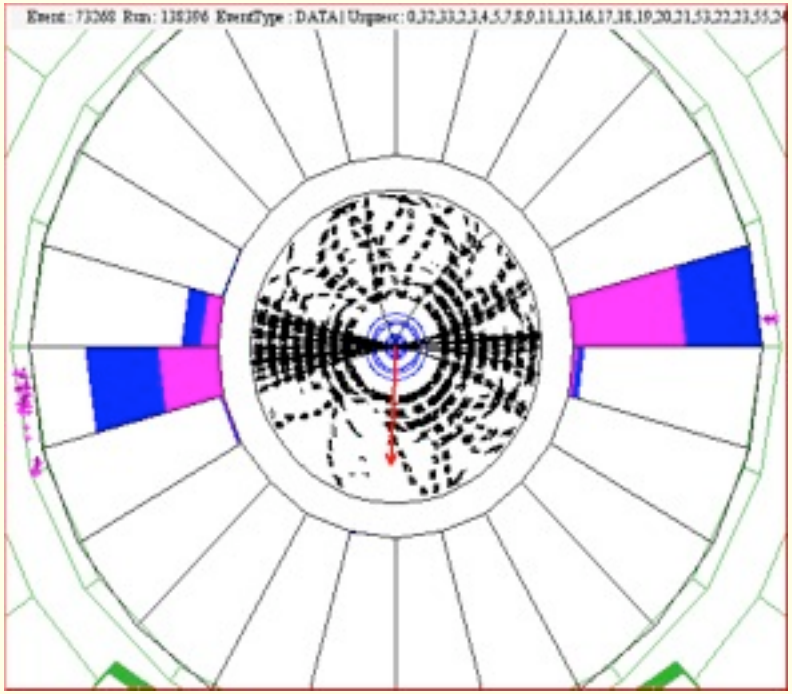
Jet Event in a p+p Collision at $\sqrt{s}$ = 63 GeV



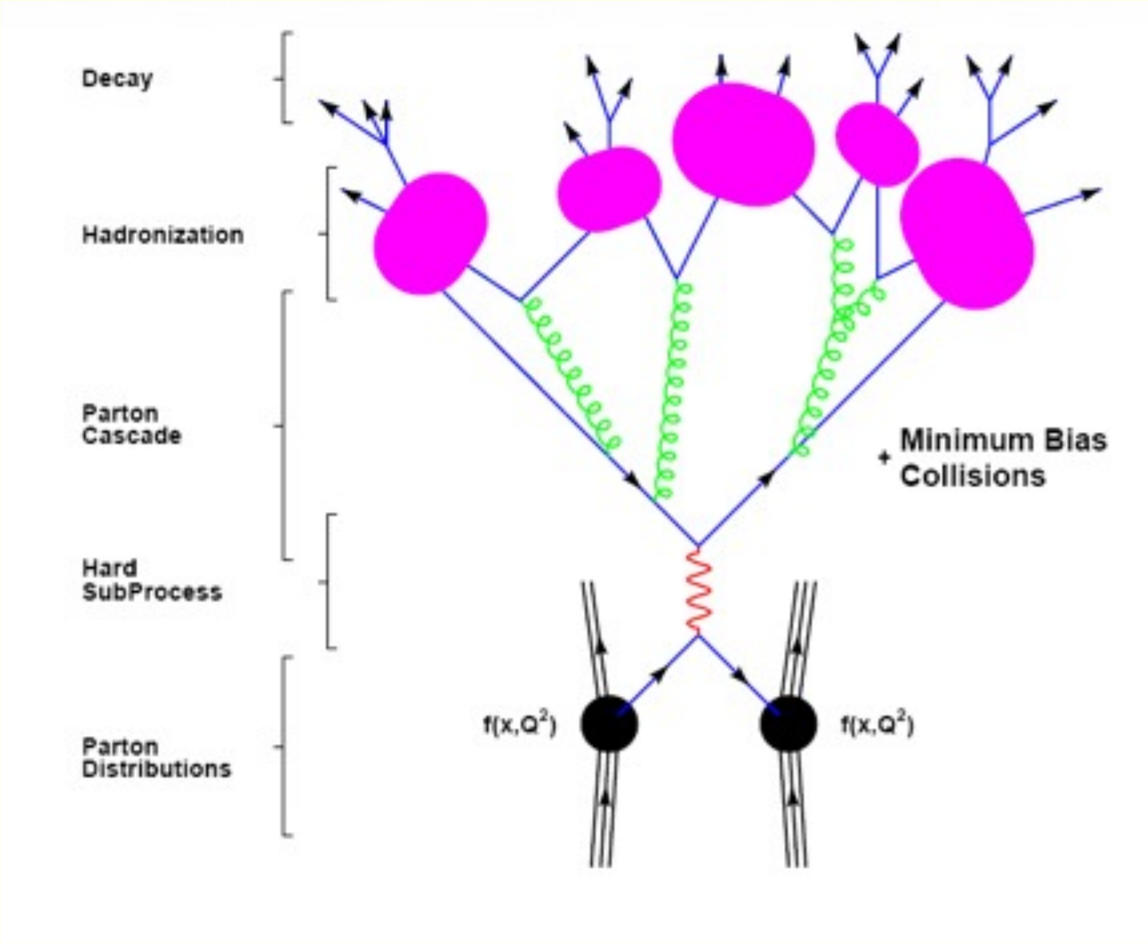
Lego plot shows energy vs. pseudorapidity η and azimuthal angle ϕ

Jet Event at the Tevatron





Evolution of a Jet Event



Hard Process → Parton Cascade → Hadronization

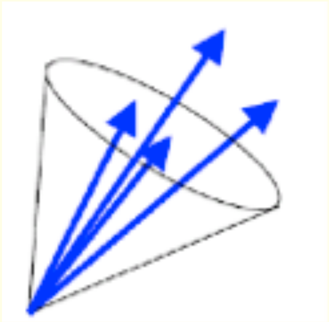
describable with pQCD

not describable with pQCD
(only phenomenological models)

Jet-Finding Algorithms

- Objective: reconstruct energy and direction of initial parton
- Must be unambiguously applicable at the level of experimental data (tracks/towers) and in perturbative QCD calculation (parton level)
- Starting point: list of calorimeter towers and/or charged hadron tracks
- Two classes of algorithms:
  - Cone algorithm: traditional choice in hadron-hadron collisions
  - k_T algorithm: traditional choice in e+e- collisions

Cone algorithm:

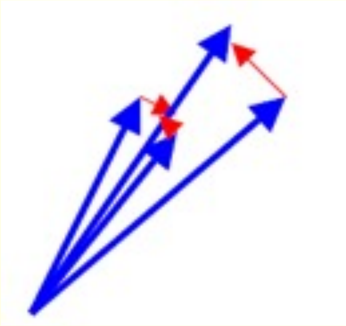


Sum content in cone with radius

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$

Typical choice:
$R = 0.7$

k_T algorithm:



Successively merge "particles" in order of relative transverse momentum.

Termination of merging controlled by a parameter D

Cone Algorithm

Fermilab Run II jet physics: hep-ex/0005012

- (Normally) start with seed (e.g. calorimeter module with high energy)
- Consider all particles in cone around seed and calculate

$$\eta^C = \frac{\sum_{i \subset C} E_T^i \eta^i}{E_T^C}, \quad \phi^C = \frac{\sum_{i \subset C} E_T^i \phi^i}{E_T^C}$$

$$\left(E_T = E \sin \vartheta \right)$$

- Repeat this procedure with new cone center (η^C, ϕ^C)
- Terminate when "flow" of cone center stops
- Calculate jet energy as

$$E_T^C = \sum_{i \subset C} E_T^i$$

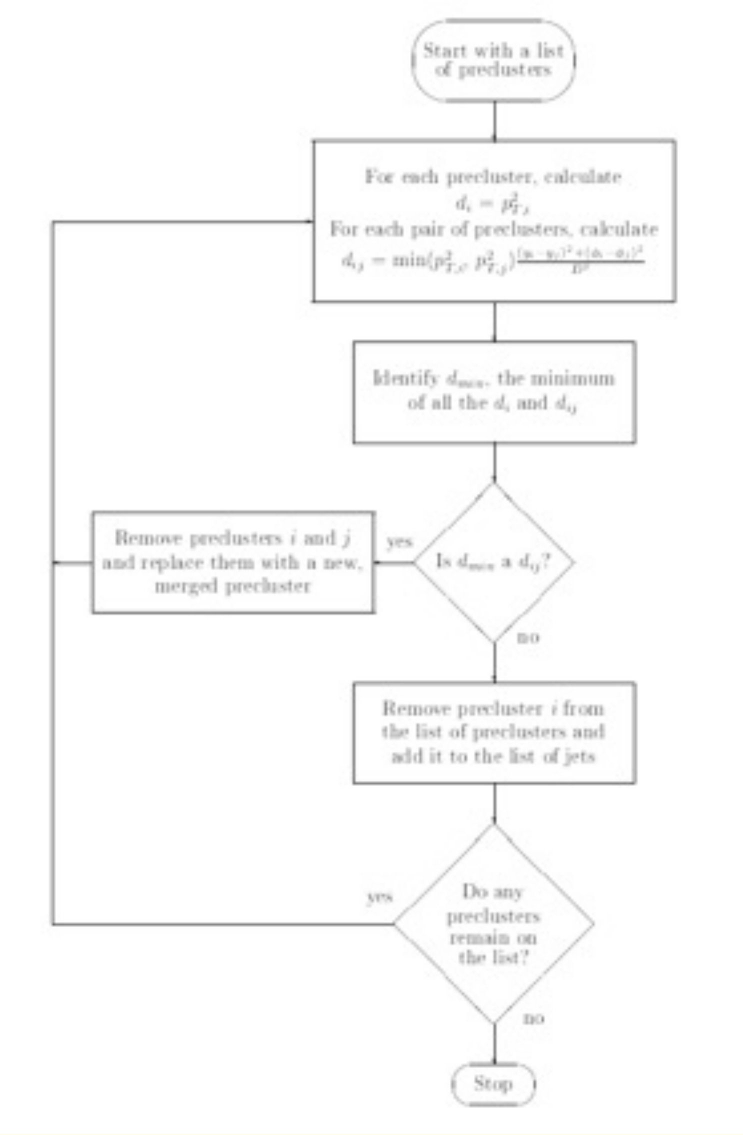
- A particle may belong to two cones:
  split energy among jets
- Subtract background energy from underlying event

k_T Algorithm (I)

- Alorithms starts with a list of preclusters (calorimeter cells, particles, or partons)
- Calculate p_T and rapidity y for each precluster
- For each precluster define $d_i = p_{T,i}^2$
- For each pair (i,j) of preclusters define

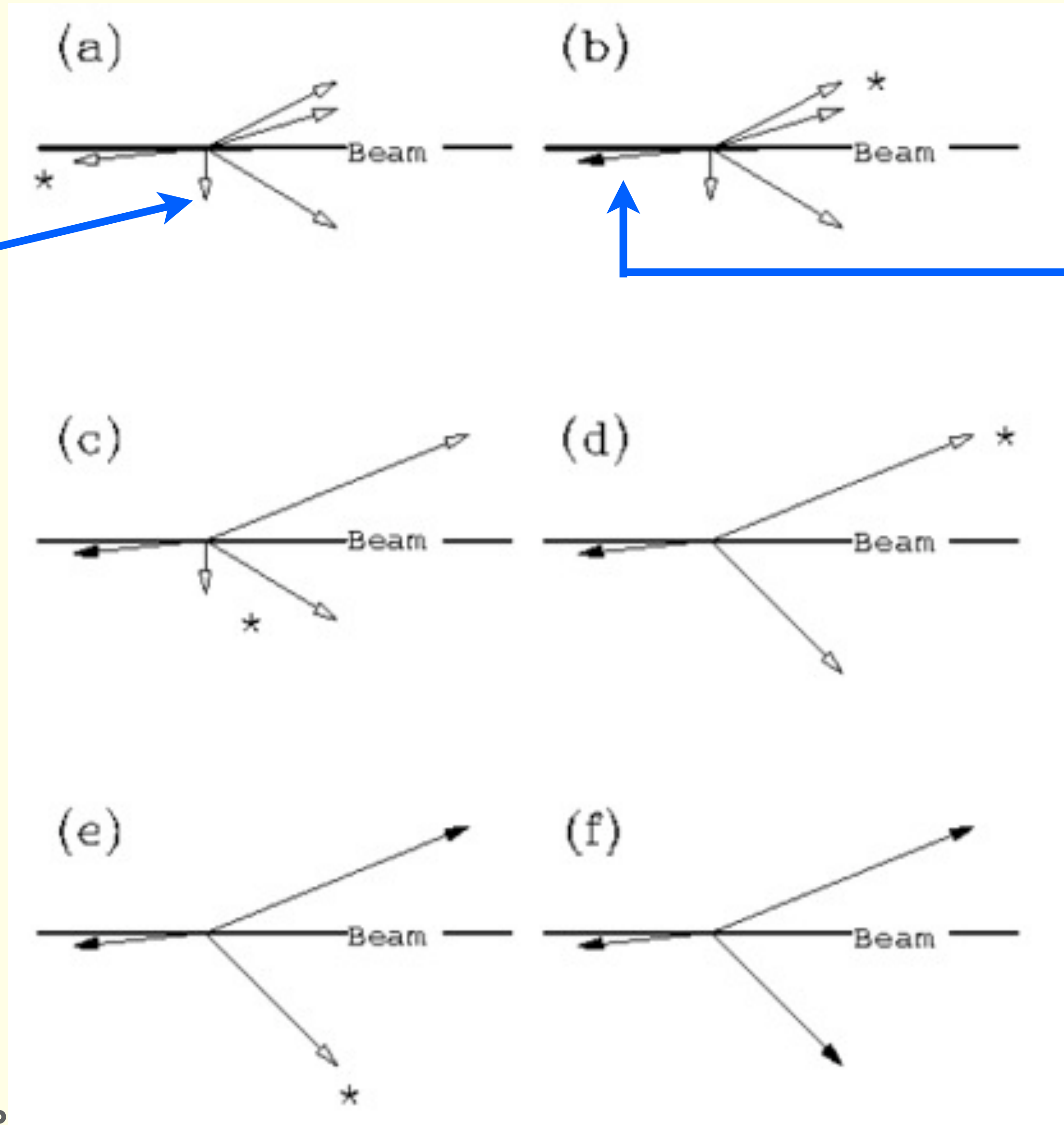
$$d_{ij} = \min\left(p_{T,i}^2, p_{T,j}^2\right) \frac{\Delta\mathcal{R}_{ij}^2}{D^2} = \min\left(p_{T,i}^2, p_{T,j}^2\right) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{D^2}$$

- For $D = 1$ and $\Delta R_{ij}^2 << 1$, d_{ij} is the minimal transverse momentum k_T (squared) of one vector with respect to the other
- Find minimum d_{min} of all d_i and d_{ij}
- Merge preclusters i and j if d_{min} is a d_{ij}
- Else: Remove precluster i with $d_{min} = d_i$ from list of preclusters and add it to the list of jets
- Repeat until list of preclusters is empty



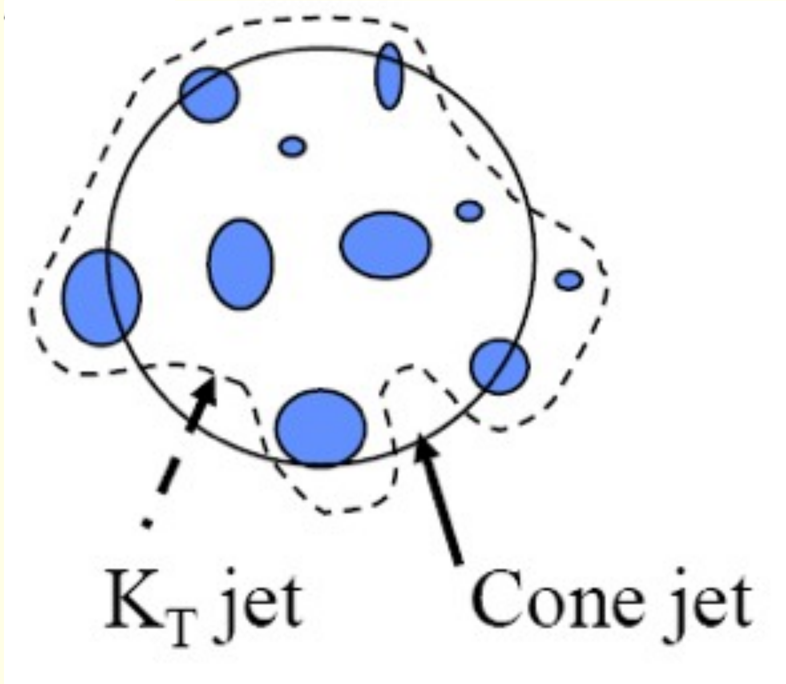
k_T Algorithm (II): A Simple Example

open arrows:
preclusters



closed arrows:
jets

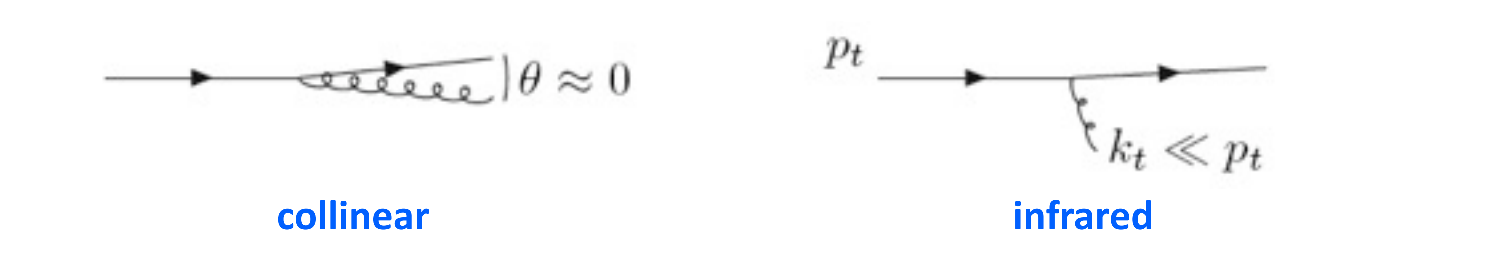
Why the k_T Algorithm is Typically Only used in e^+e^- Collisions?



k_T jet has no fixed shape/area
→ Difficult to subtract background from underlying event

Jet Finding Algorithms: Typical Requirements (I)

Two types of divergences:



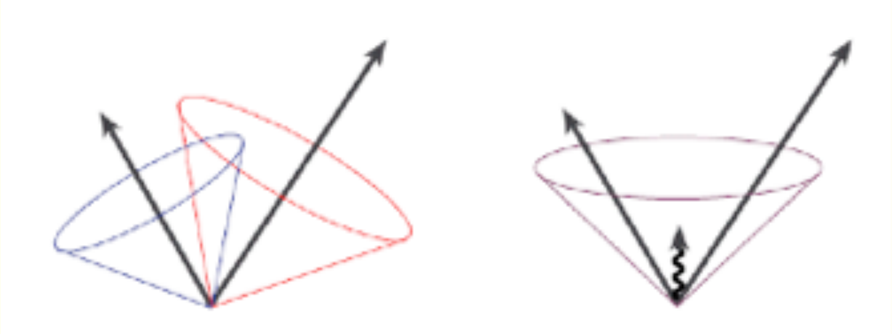
The reconstructed jets should not change in case of

- **collinear splitting, i.e., if one parton is replaced by two partons at the same place**
- **soft emission, i.e., if a low energy parton is added**

Jet Finding Algorithms: Typical Requirements (II)

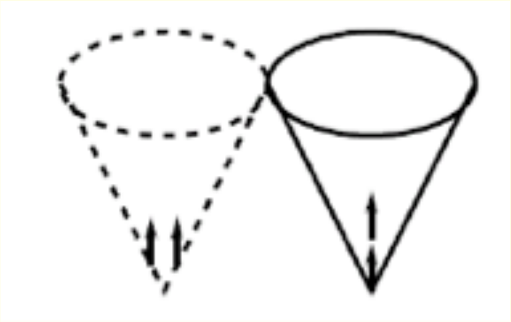
- **Infrared safety**

Fermilab Run II jet physics: hep-ex/0005012

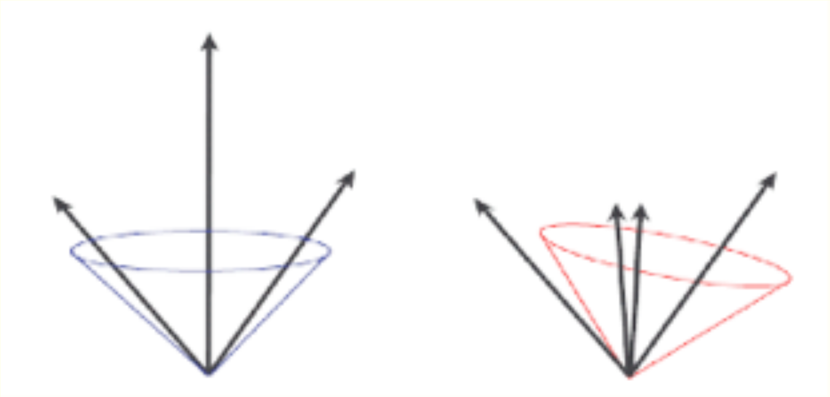


Example of infrared sensitivity:
Soft radiation (right plot) causes merging of jets which would have been separated otherwise

- **Collinear safety**



Example of collinear sensitivity:
Seed and therefore jet not found in left picture

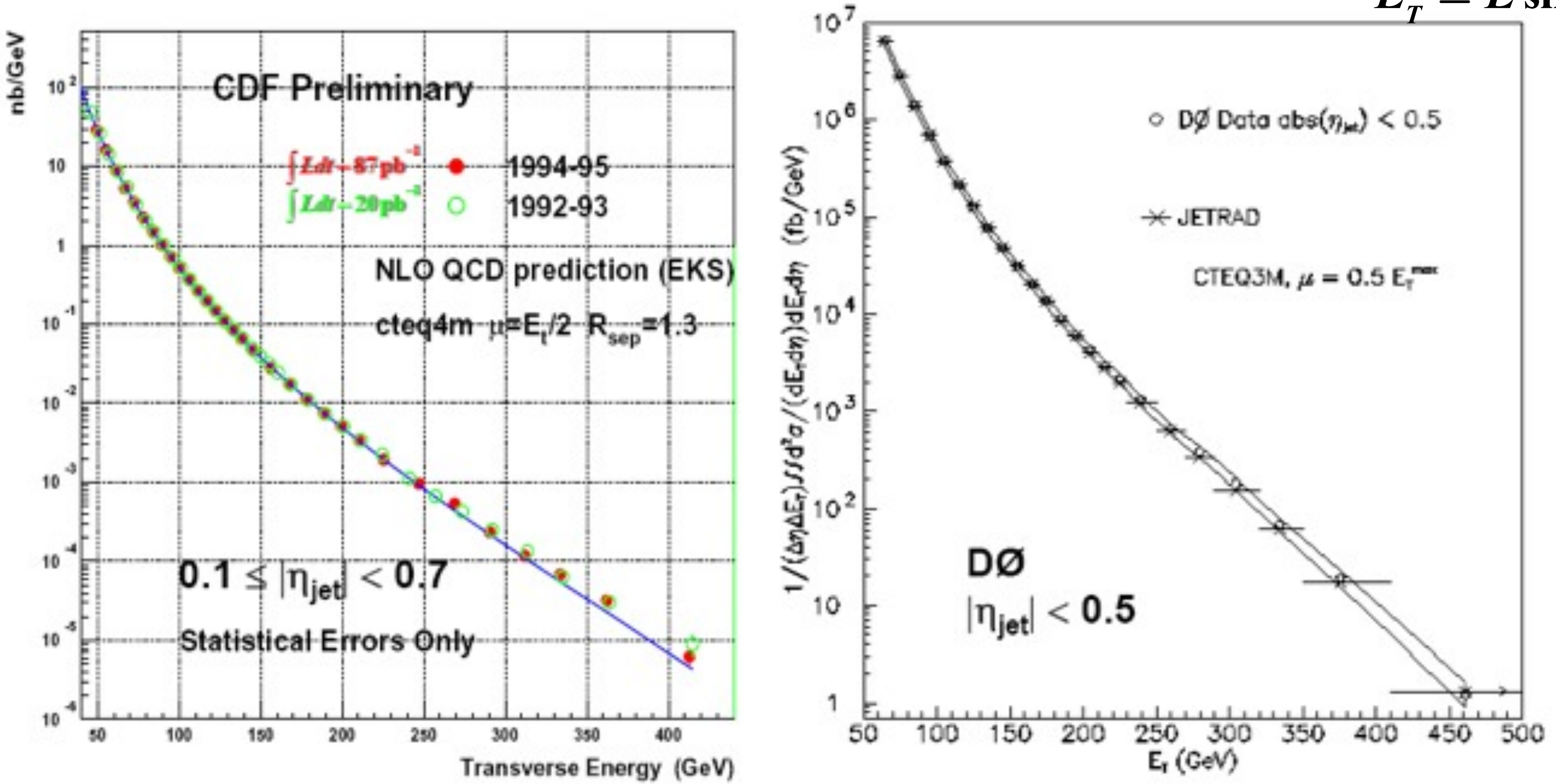


Example of collinear sensitivity:
Reconstructed jet depends on seed

Jet Cross Sections at the Tevatron

http://www-d0.fnal.gov/Run2Physics/displays/presentations/klima_lecture_jan2003/Lecture_1.pdf

$$E_T = E \sin\vartheta$$



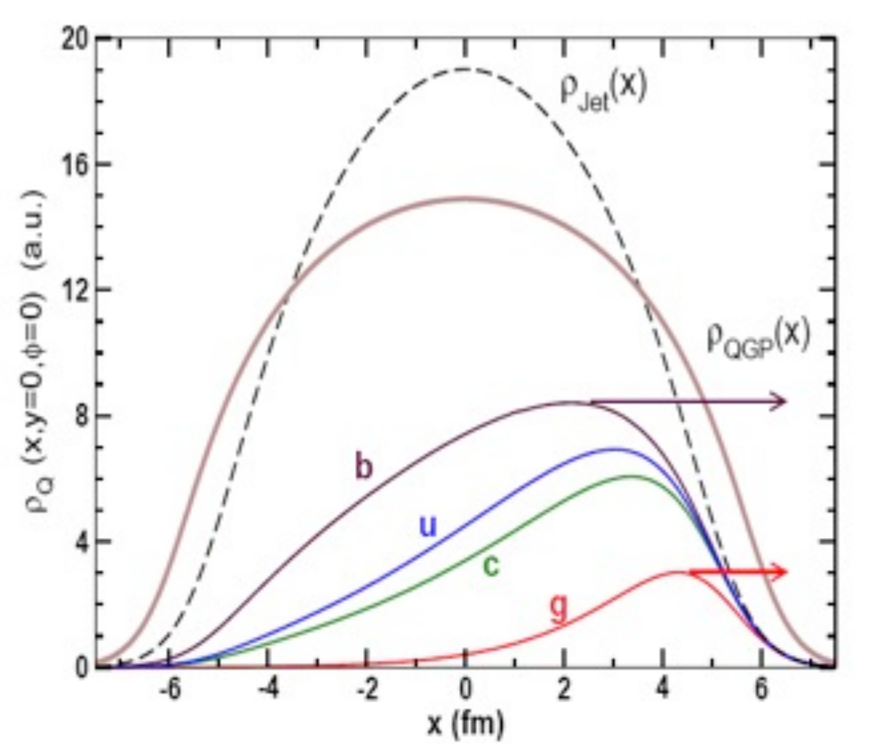
Pretty good agreement between data and NLO pQCD predictions

Future Jet Quenching Measurements

Problems with Relying on Hadron Spectra

- Energy loss bias
  - Hadrons biased to jets that lose the least energy
  - Geometry („surface bias“)
  - Radiation fluctuations
- Averaging
  - Hadron measurements average over jet energies
  - Indirect measurement of jet quenching
- Solutions
  - Direct γ - hadron correlation
  - Full jet reconstruction

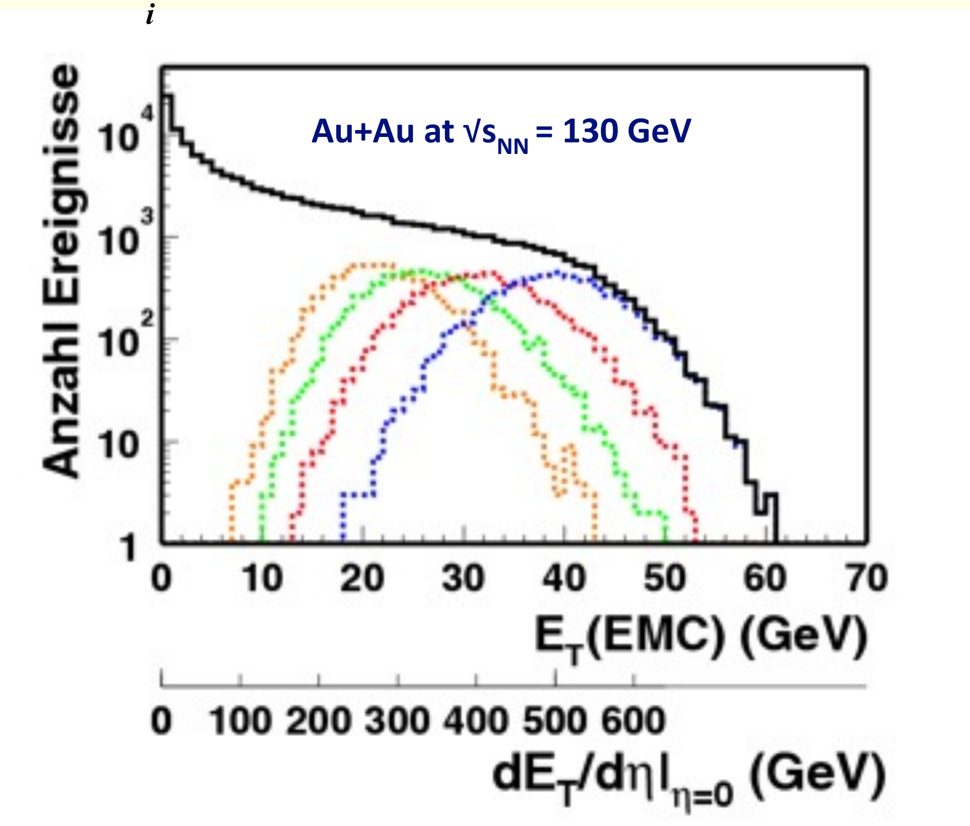
Surface bias:
Surviving jets biased towards the surface of the overlap region:
Difficult to probe the hot core of the QGP



Wicks, Horowitz, Djordjevic Gyulassy, Nucl. Phys. A784, 426-442

Why is Jet Reconstruction Difficult in Central Au+Au Collisions at RHIC ?

$$E_T = \sum_i E_i \sin\vartheta_i, \;\; dE_T/d\eta \approx \langle m_T \rangle \cdot dN_{ch}/d\eta$$



Central Au+Au collision at $\sqrt{s_{NN}}$ = 130 GeV:

$$\left.\frac{dE_T}{d\eta}\right|_{\eta=0} \approx 500 \text{ GeV}$$

Consider jet cone with radius *R*:

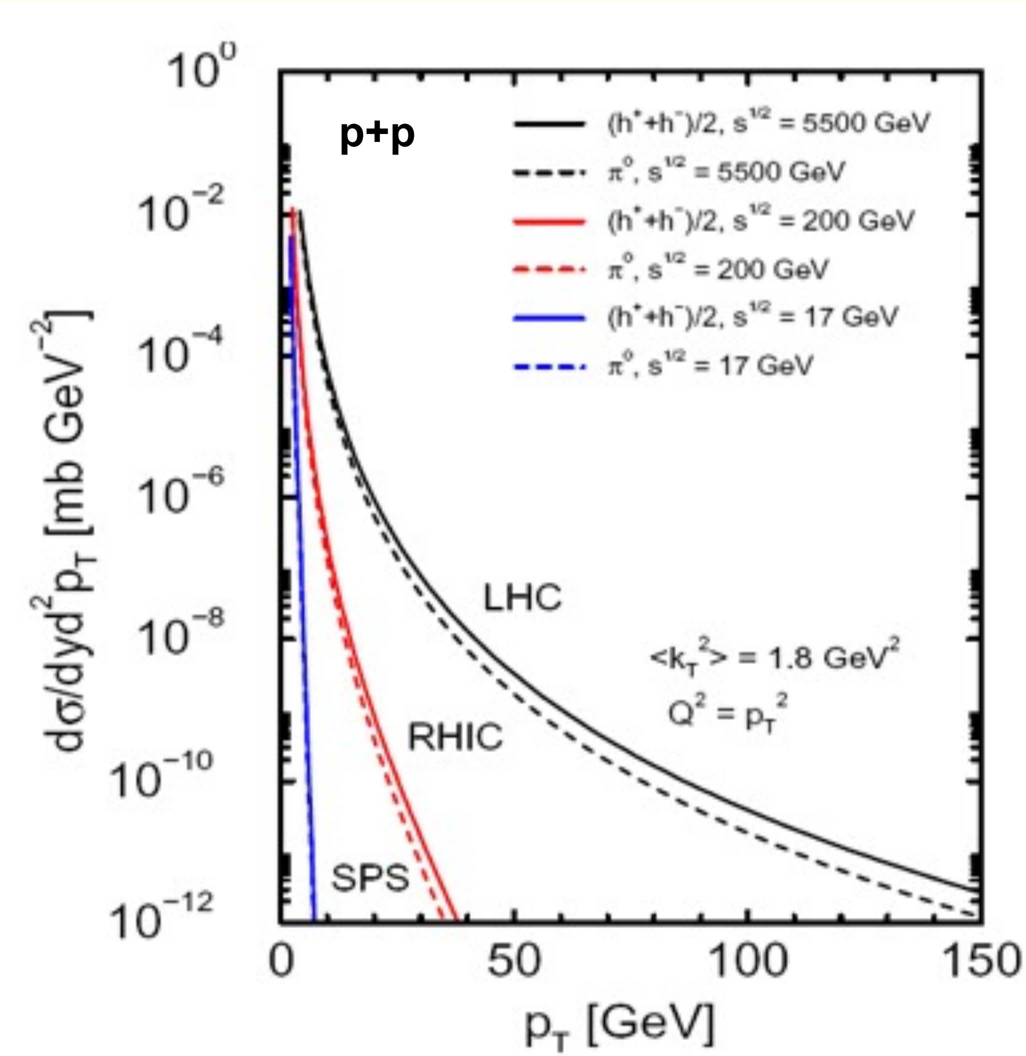
$$R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.4$$

Total transverse energy in this cone:

$$E_T^{\text{cone}} = \frac{d^2 E_T}{d\eta d\varphi} \cdot \pi R^2 = \frac{1}{2\pi}\frac{dE_T}{d\eta} \cdot \pi R^2 \approx 40 \text{ GeV}$$

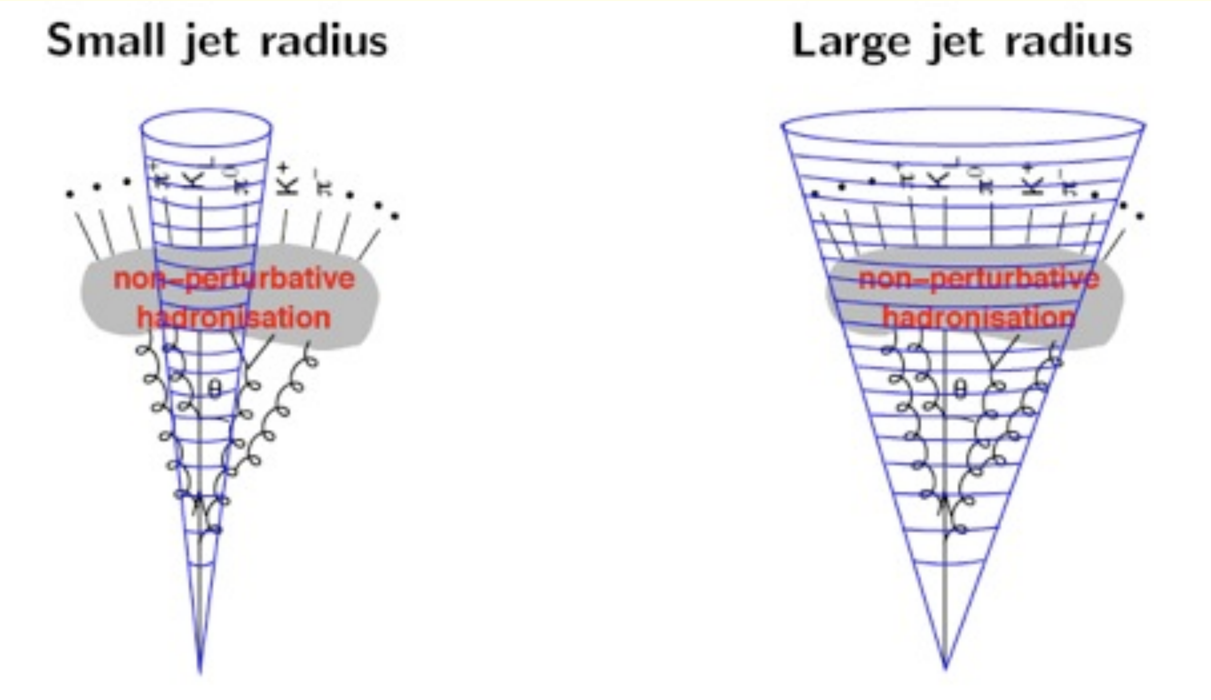
- Background energy large compared to jet energy in A+A at RHIC.
- Increased jet cross section helps at LHC energies

Single Particle Cross Section at the LHC



Hard scattering cross sections increase significantly at the LHC

Choice of the Optimal Cone Radius



Small cone radius:
Small background from the underlying event at the expense of some loss of jet particles

Large cone radius:
Large background from the underlying event but nearly all jet particles included

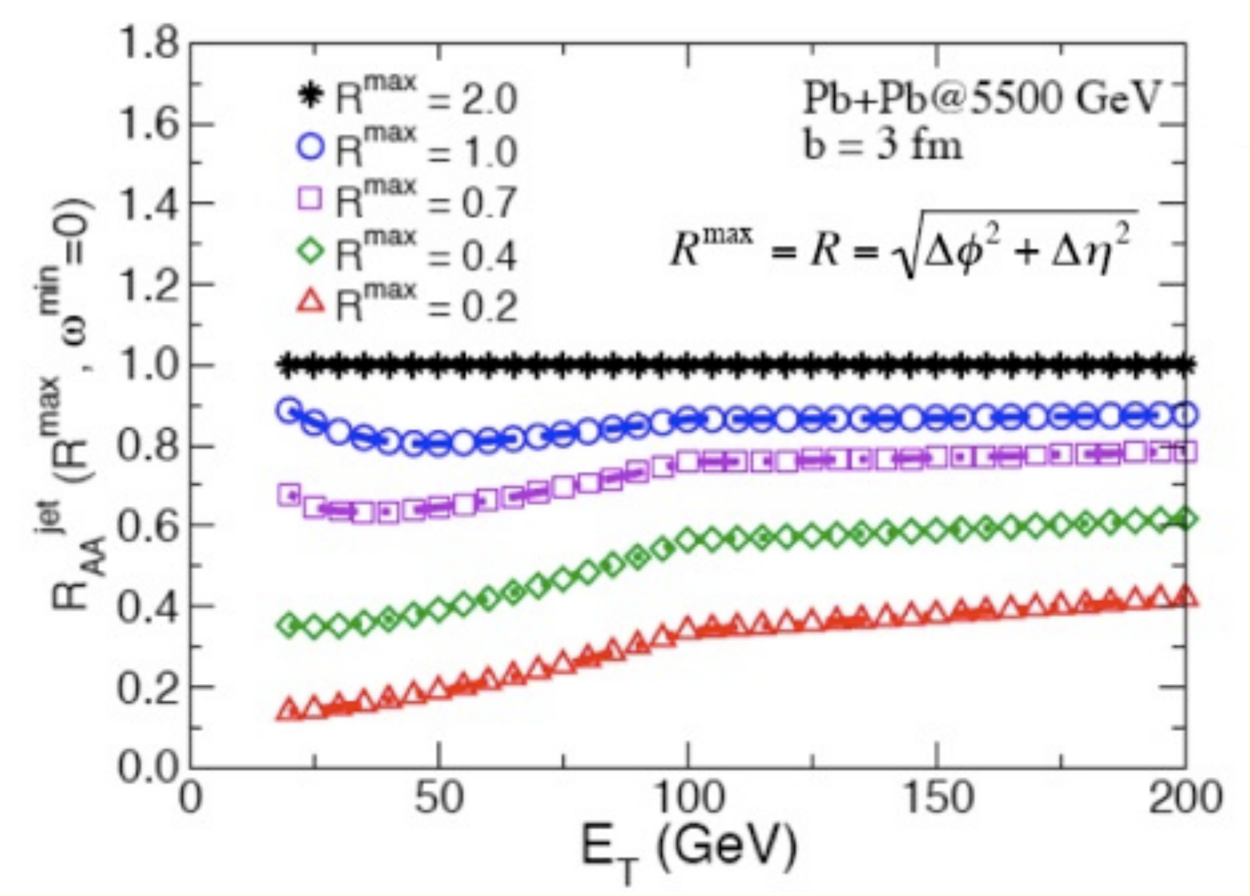
Due to higher backgrounds the cone radius in heavy-ion collisions typically smaller than in p+p (R ~ 0.3 - 0.4 is a good compromise in A+A)

How Can One Study Parton Energy Loss with Reconstructed Jets at the LHC?

- Measure Jet R_{AA} for different cone radii R
- Study medium induced modification of lateral jet profile
- Study modification of the fragmentation function

Jet R_{AA} for Different Cone Radii R

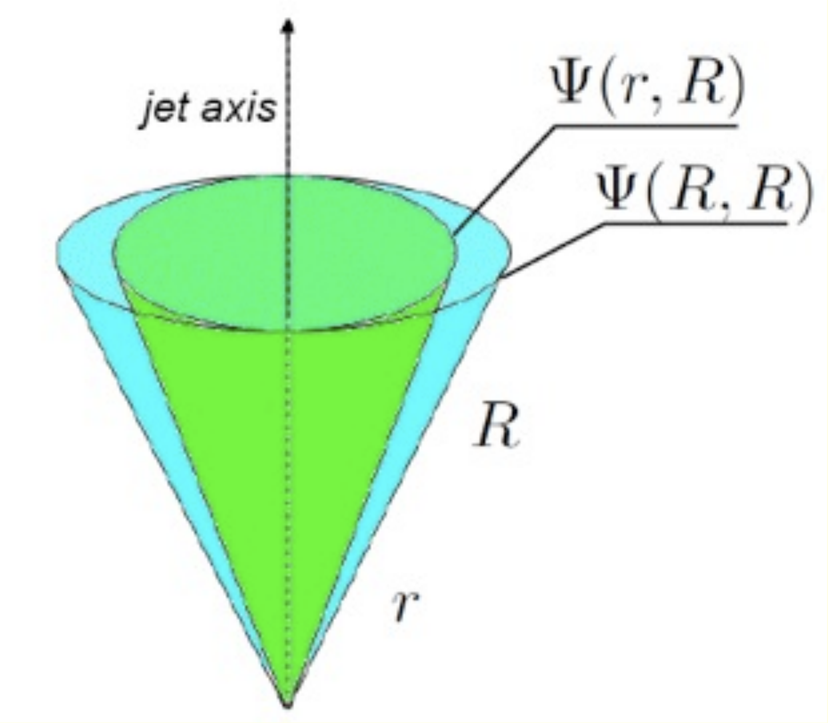
Calculation by Vitev, Wicks, and Zhang (JHEP 11, (2008), 093):



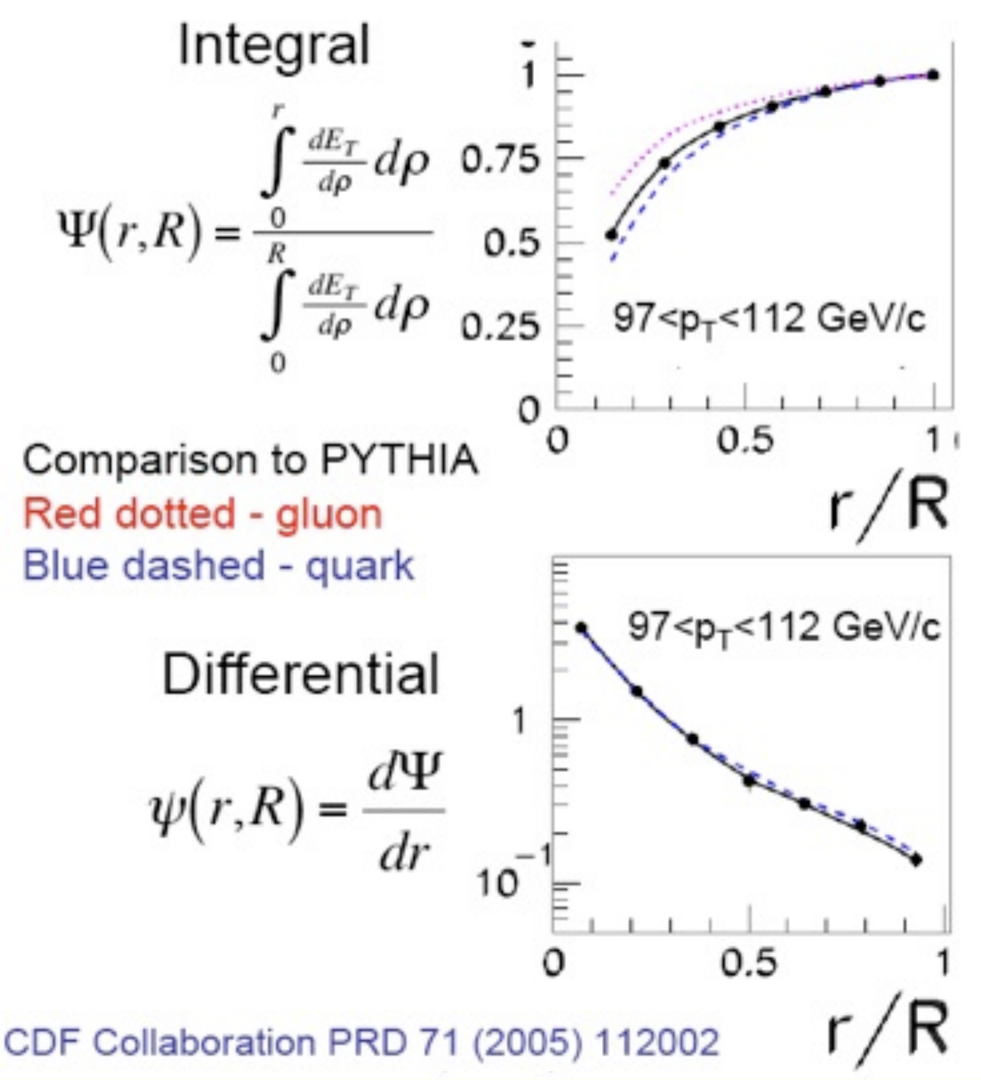
$$R_{AA}^{jet} = \frac{Pb + Pb \text{ Jet Yield}}{\langle N_{coll} \rangle p + p \text{ Jet Yield}}$$

- Large cone radius R: All energy lost will be recovered: $R_{AA}^{jet} = 1$
- Out of cone radiation will reduce R_{AA}
- Study energy loss by reconstructing jets with different R

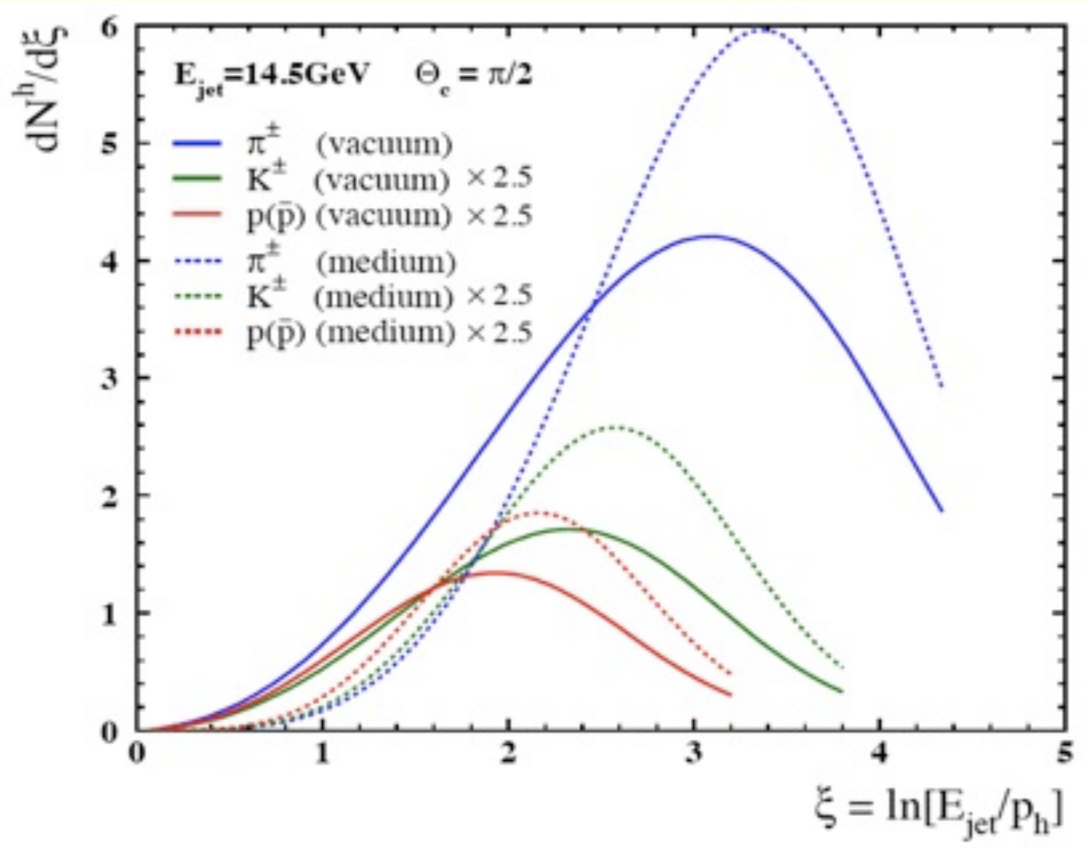
Lateral Jet Profile



Broadening of the energy distribution expected in Pb+Pb



Medium-Modified Fragmentation Functions



Sapeta, Wiedemann, Eur.Phys.J.C55:293-302,2008.

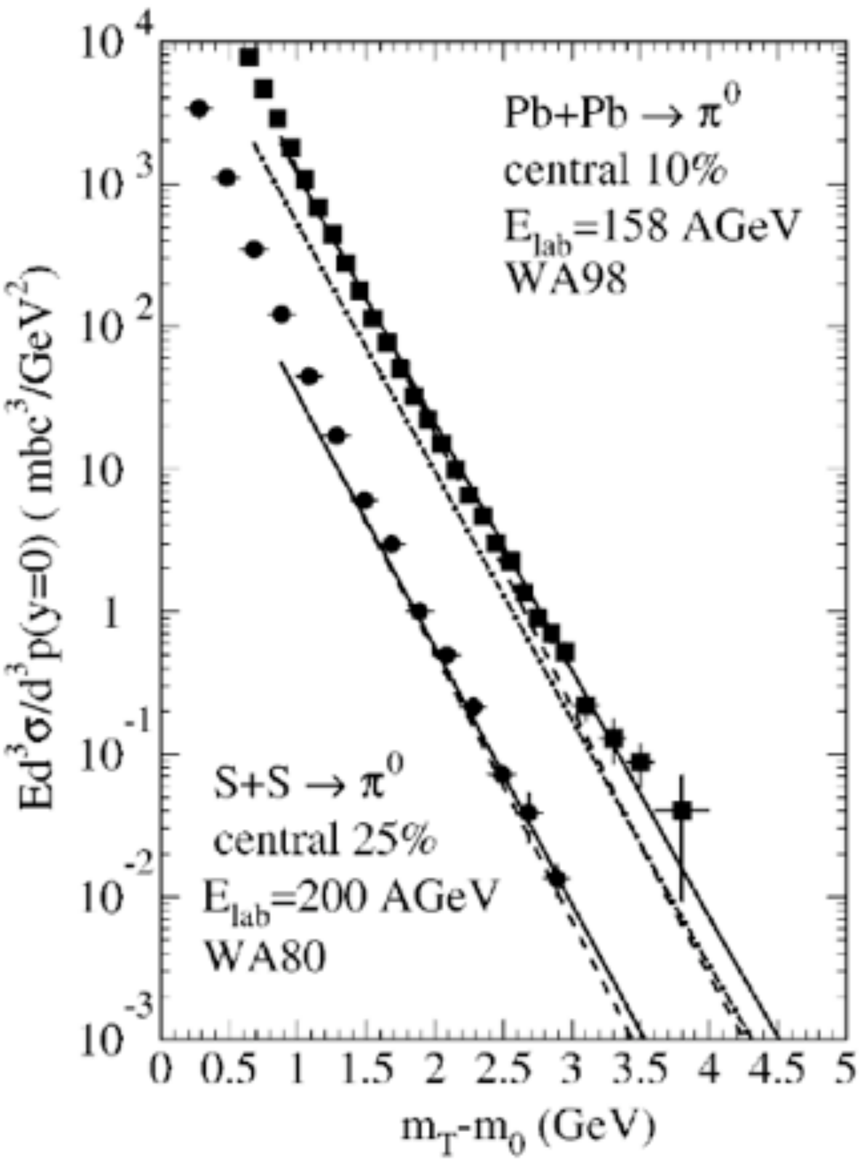
- Reconstruction of the full jet energy allows to measure fragmentation function
- Parton energy loss will shift particles to low z (and thus higher ξ)
- Moreover, the medium is expected to change the particle composition of the jet, e.g., the K/π ratio
- Promising measurement for Alice due to its excellent low p_T particle ID

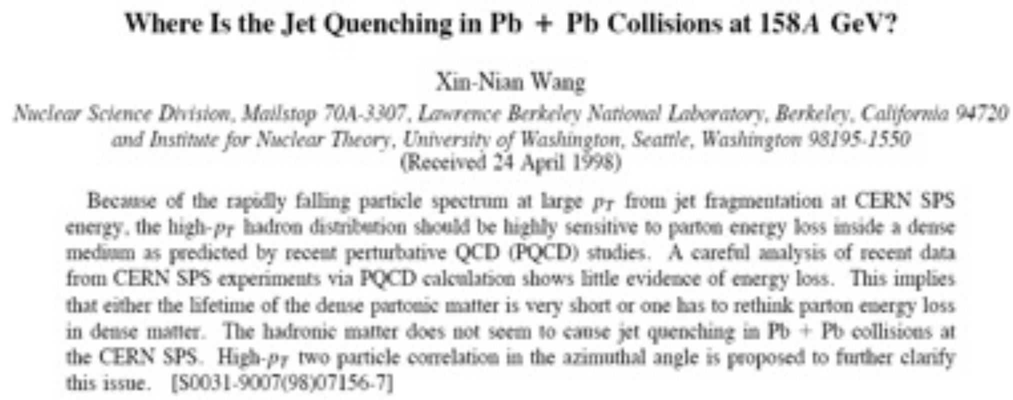
Points to Take Home

- RHIC results have established jet quenching as an experimental fact
- Heavy quarks are as strongly suppressed as light quarks which is not fully understood in current jet quenching models
- The ultimate goal, the consistent characterization of the medium, is not yet possible since different models yield different results
- PHENIX and STAR are working on full jet reconstruction in A+A collisions
- Increased jet cross section makes full jet reconstruction easer at LHC energies

Extra Slides

Search for Jet Quenching in the 1990‘s: S+S and Pb+Pb at $\sqrt{s_{NN}} \approx 20$ GeV at the CERN SPS





Where Is the Jet Quenching in Pb + Pb Collisions at 158A GeV?

Xin-Nian Wang

Nuclear Science Division, Mailstop 70A-3307, Lawrence Berkeley National Laboratory, Berkeley, California 94720 and Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550

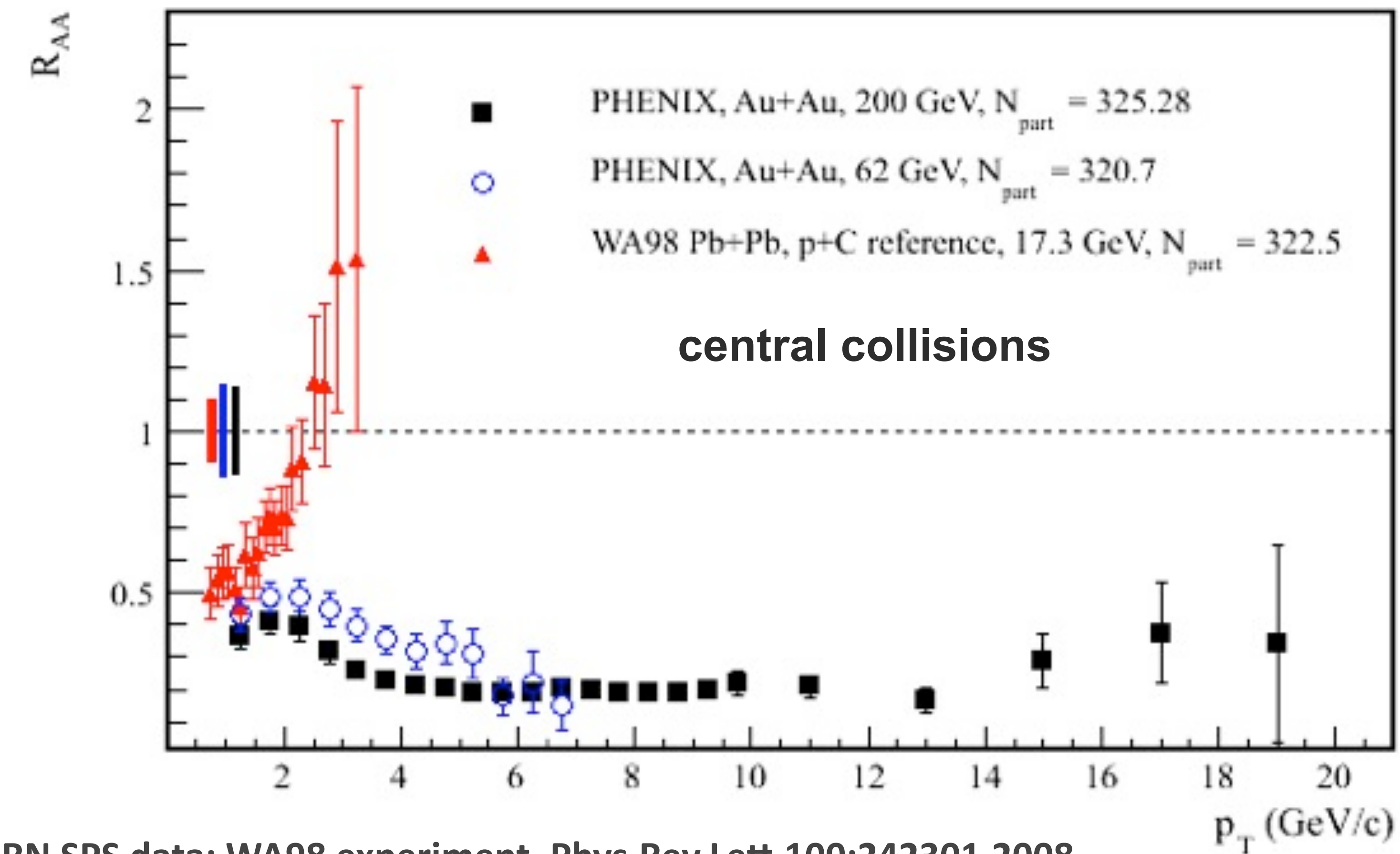
(Received 24 April 1998)

Because of the rapidly falling particle spectrum at large p_T from jet fragmentation at CERN SPS energy, the high-p_T hadron distribution should be highly sensitive to parton energy loss inside a dense medium as predicted by recent perturbative QCD (PQCD) studies. A careful analysis of recent data from CERN SPS experiments via PQCD calculation shows little evidence of energy loss. This implies that either the lifetime of the dense partonic matter is very short or one has to rethink parton energy loss in dense matter. The hadronic matter does not seem to cause jet quenching in Pb + Pb collisions at the CERN SPS. High-p_T two particle correlation in the azimuthal angle is proposed to further clarify this issue. [S0031-9007(98)07156-7]

X.N. Wang, PRL 98, 2655, 1998

- pQCD + Cronin enhancement describes data:
  apparently no parton energy loss
- Conclusions
  - No QGP at CERN SPS
    (or very short-lived)
  - No particle suppression at high p_T due to interactions in the hadronic phase
    (advantageous for RHIC!)

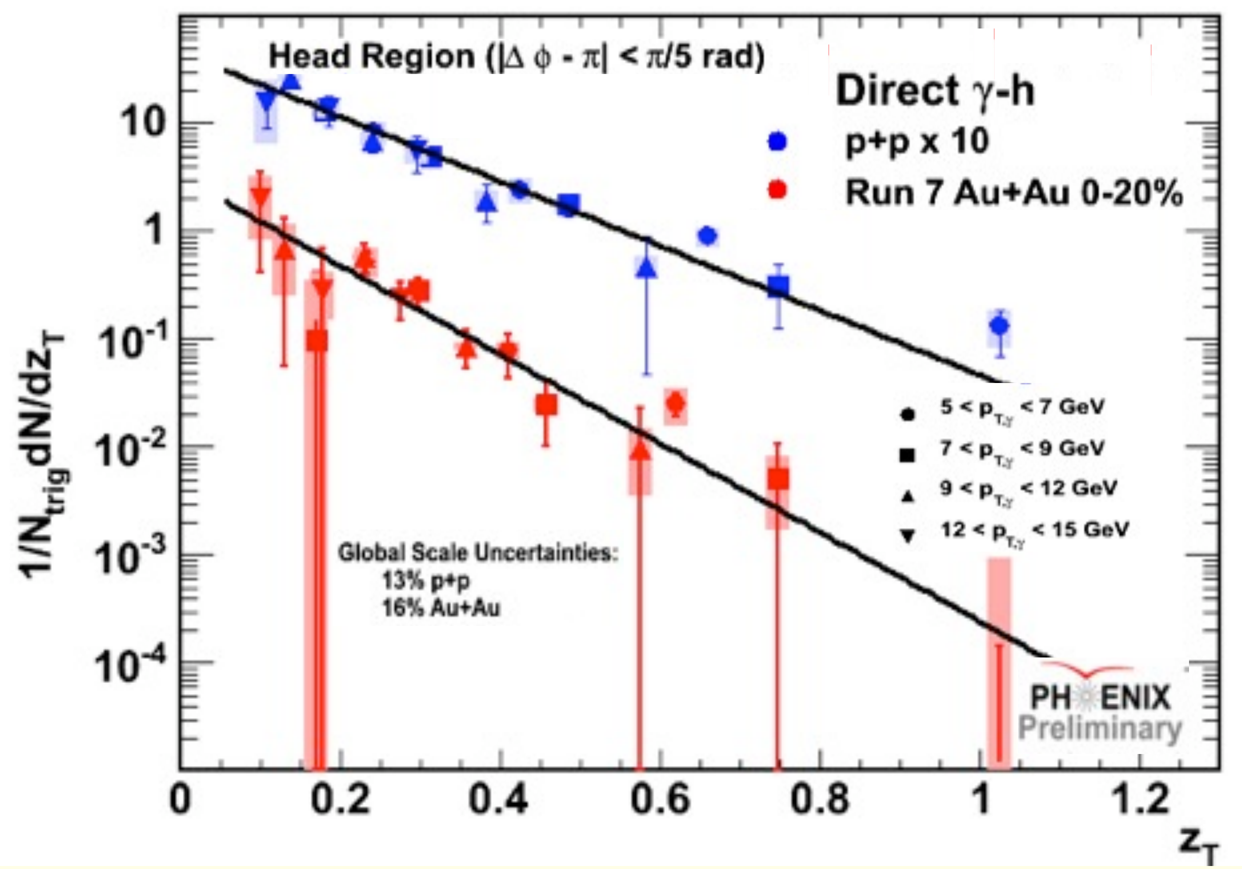
$\sqrt{s_{NN}}$ Dependence: π^0 R_{AA} for Heavy Nuclei at $\sqrt{s_{NN}}$ = 17.3, 62.4, and 200 GeV



CERN SPS data: WA98 experiment, Phys.Rev.Lett.100:242301,2008

Onset of suppression between $\sqrt{s_{NN}}$ = ~ 20 GeV und 62.4 GeV

Direct-γ-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au



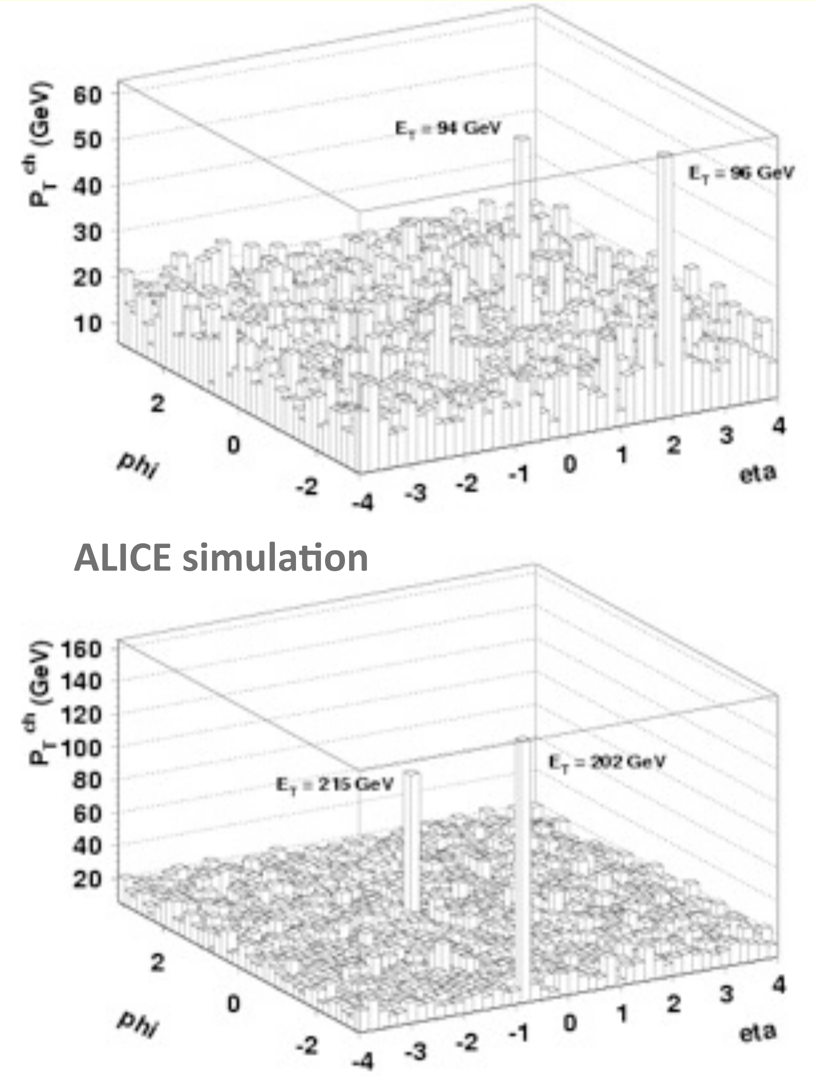
- No surface bias for γ as trigger particle
- Jet energy known: $E_{jet} \approx E_\gamma$
- Effective fragmentation function $D(z_T)$ can be measured:

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

$$D(z_T) = \frac{1}{N_{trig}} \frac{dN(z_T)}{dz_T}$$

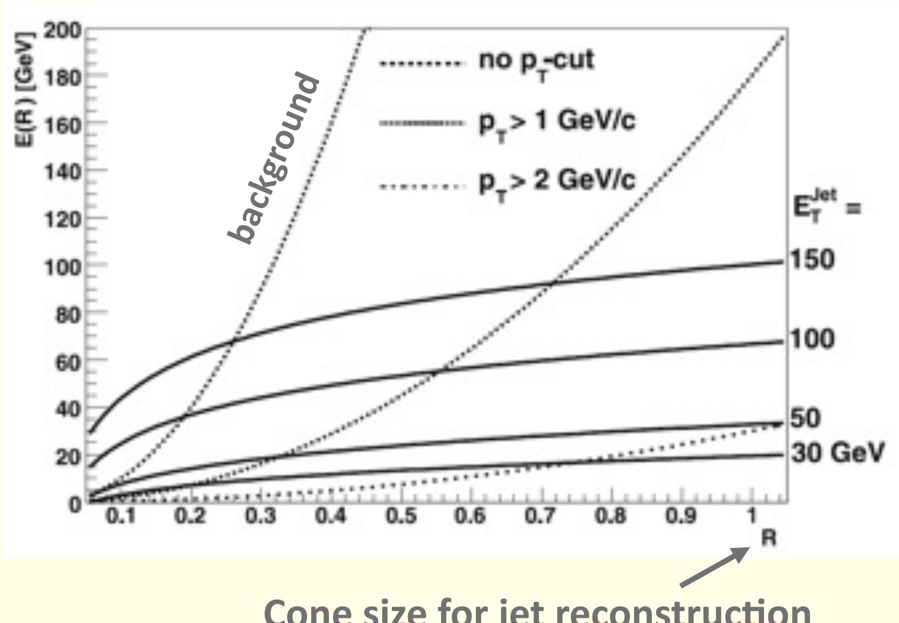
- Different slope of $D(z_T)$ in p+p and Au+Au reflects influence of the medium
- Data with higher precision needed to draw quantitative conclusions

Jets in Pb+Pb at the LHC

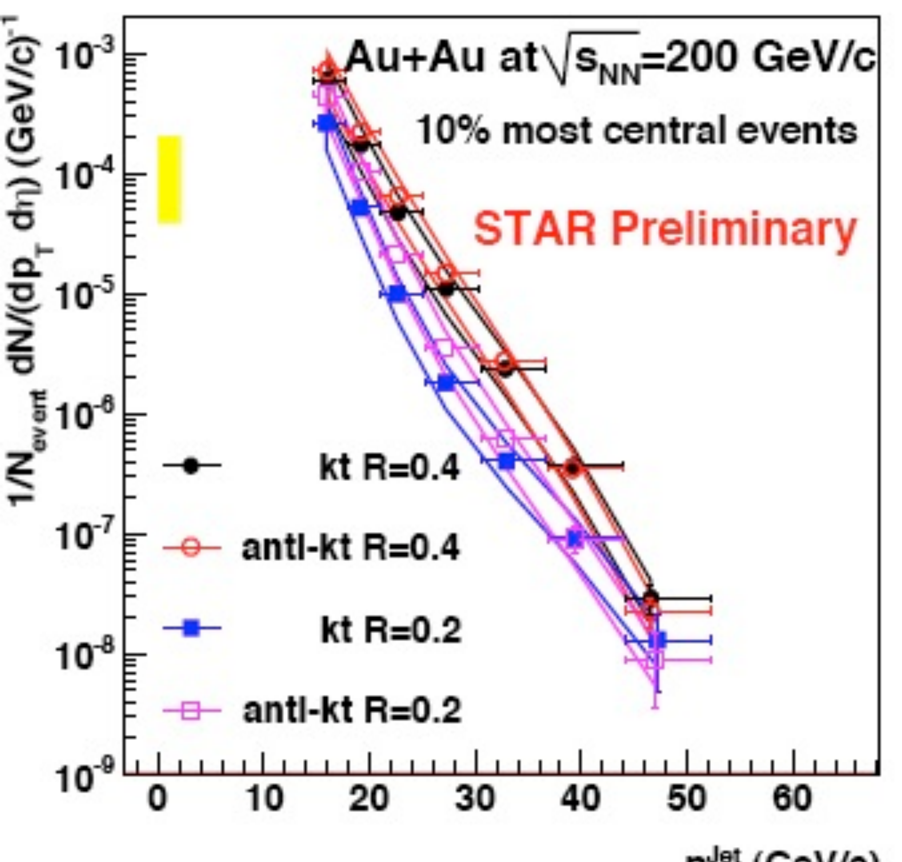


Jets with E_T > ~ 50 GeV in Pb+Pb at √*s* = 5500 GeV at the LHC can be identified above the background on an event-by-event basis

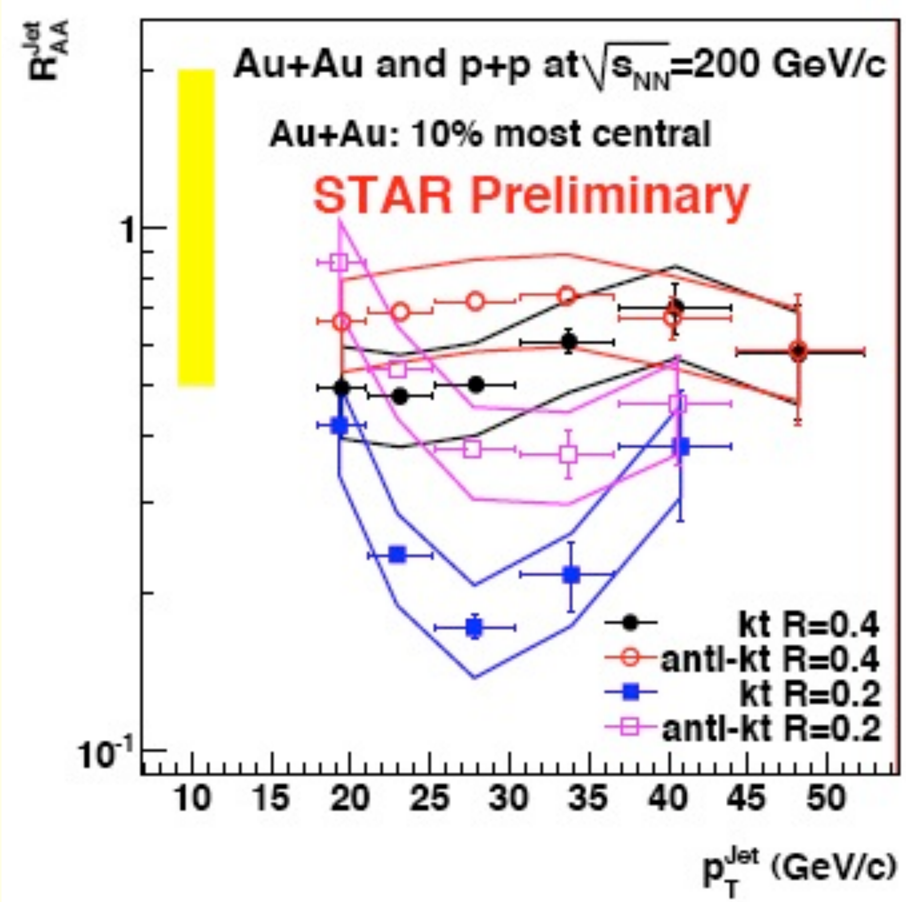
Influence of background from the underlying event minimized with cone size *R* ~ 0.3 – 0.4



First Results from Full Jet Reconstruction at RHIC: Jet R_{AA} in Au+Au at 200 GeV from STAR

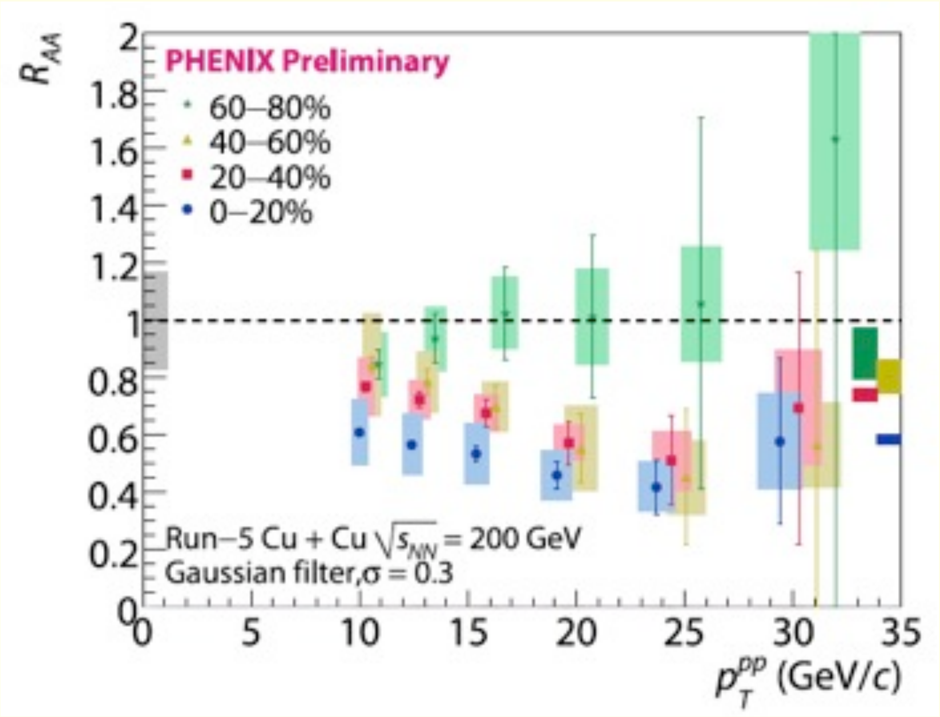


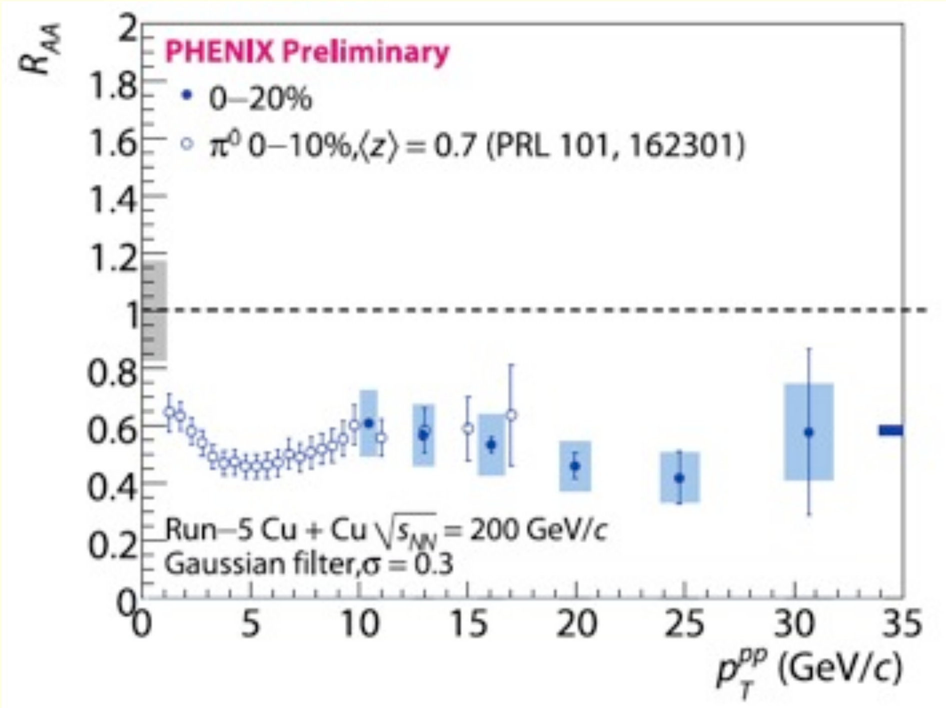
STAR, arXiv0908.1799v3



- Evidence for jet broadening in Au+Au at RHIC
- Situation much more favorable at the LHC (increased jet cross section)

First Results from Full Jet Reconstruction at RHIC: Jet R_{AA} in Cu+Cu at 200 GeV from PHENIX





Y.-s. Lai (PHENIX collaboration), arXiv:0911.3399

- PHENIX has developed a cone-like algorithm (Gaussian filter) where the cone radius is replaced by a Gaussian width σ
- Jet suppression observed in central Cu+Cu at 200 GeV for σ = 0.3