High-Energy Collisions with ALICE at the LHC

4. Hard Scattering and Jets in A+A Collisions

Graduate Days

of the Graduate School of Fundamental Physics

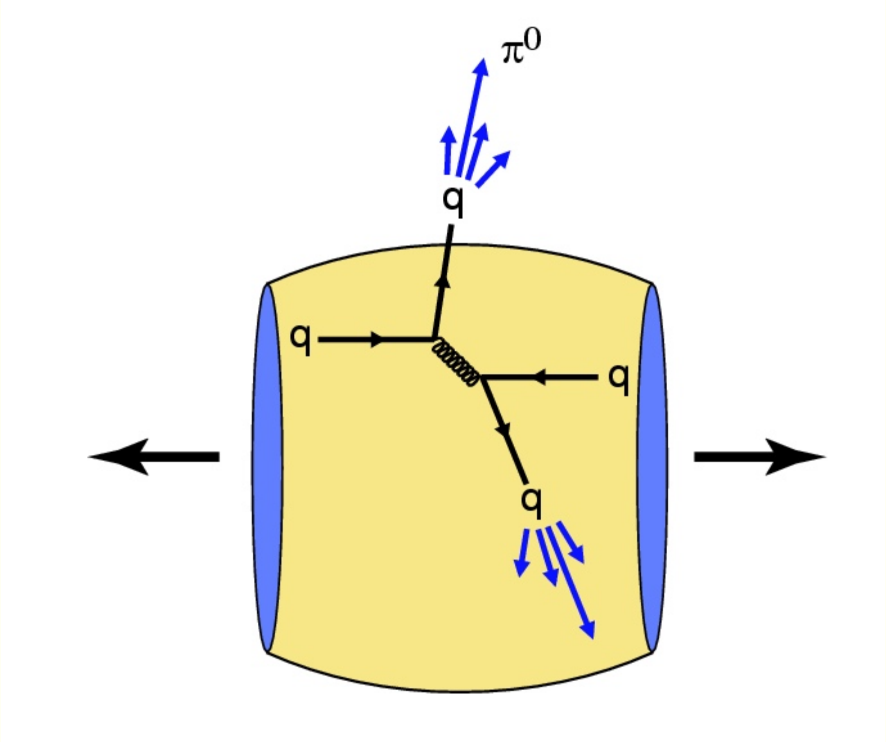
Heidelberg, 5. - 9. October 2009

PD Dr. Klaus Reygers
Physikalisches Institut
Universität Heidelberg

Content

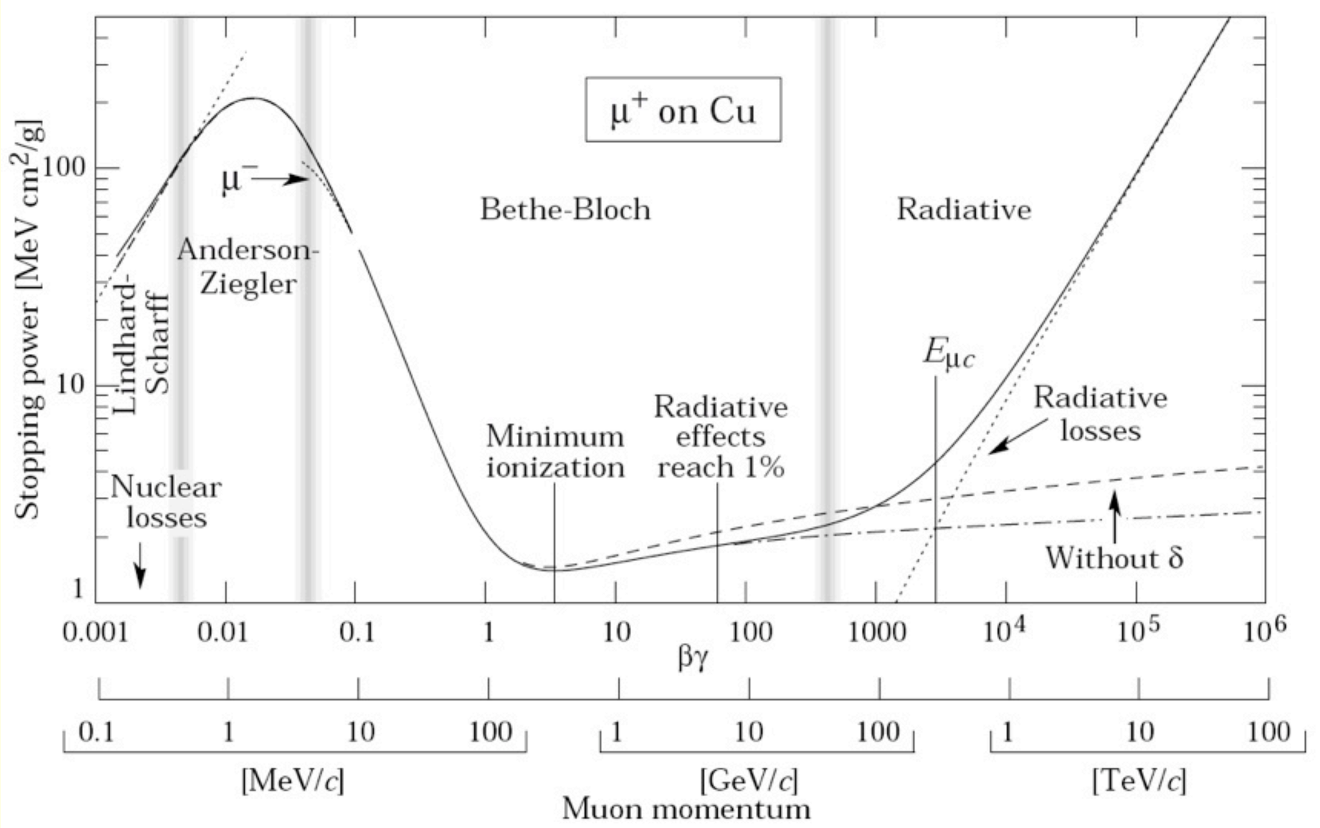
4.1 Parton Energy Loss

Jet Tomography in A+A Collisions



- **Hard parton-parton scatterings take place in initial phase, prior to the formation of the QGP**
- **Scattered quarks und gluons sensitive to medium properties: „jet tomography"**

Anology: 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
- For energetic quarks and gluons in QCD matter, radiative energy loss (induced gluon emission) is/was expected to be the dominant process

The Idea of Jet Quenching due to Collisional Parton Energy Loss was Already Formulated in 1982

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.

...

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.

- Collisional energy loss 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, …

Parton Energy Loss – Expected Properties

Radiative energy loss dominant (?):

$$\mathrm{d}E_{\mathrm{rad}} / \mathrm{d}x \gg \mathrm{d}E_{\mathrm{coll}} / \mathrm{d}x$$

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

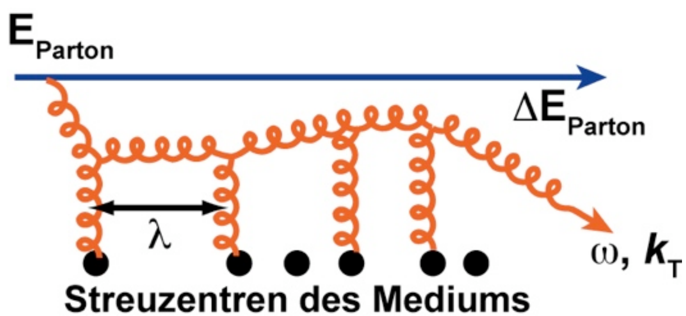
$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

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

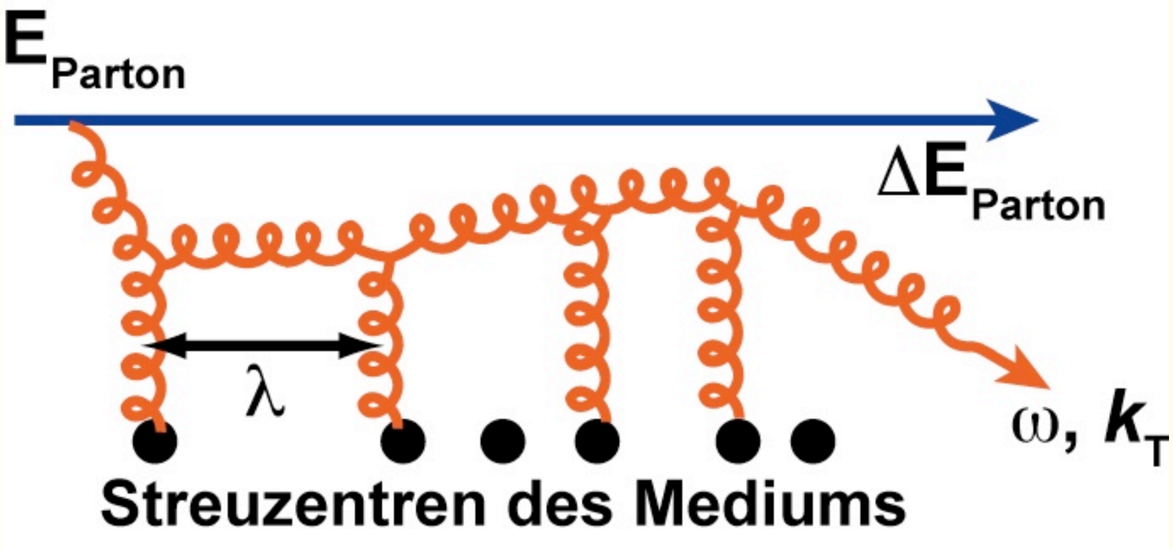
Energy loss for gluon jets larger than for quark jets

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

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



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

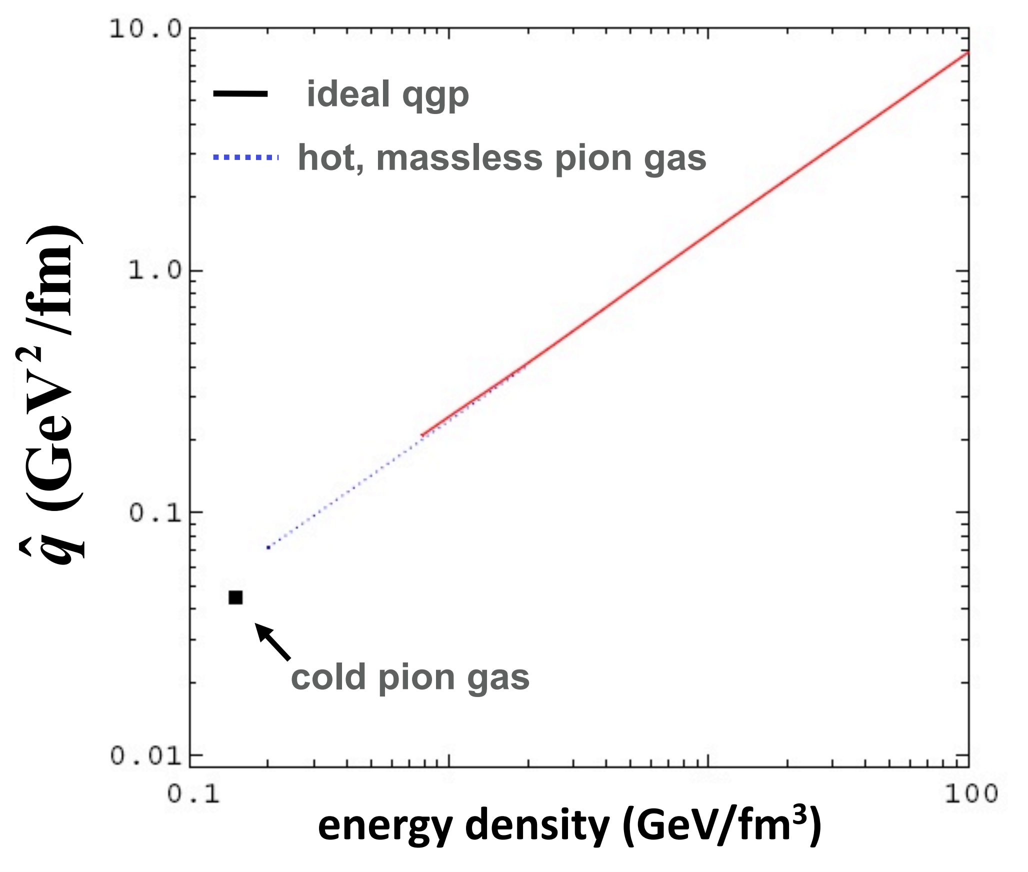


Probability for radiating a gluon: $\propto L$

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):

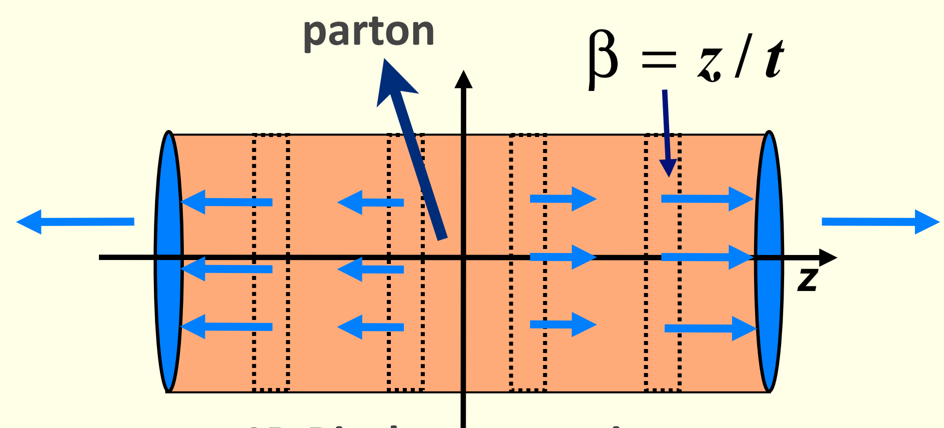
$$\hat{q}_{\text{qgp}} \gg \hat{q}_{\text{nuclear matter}}$$

Medium characterized by

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

Parton Energy Loss in an Expanding Medium

Taking into account the expansion of the fireball (Bjorken Model):



1D Bjorken expansion

Medium parameterized by initial gluon densitiy

$$\Delta E = -C\alpha_s^3 \frac{9\pi}{4} \frac{1}{A_T} \frac{\mathrm{d}N_{\mathrm{Gluon}}}{\mathrm{d}y} L \ln\left(\frac{2E}{\mu^2 L} + \ldots \right)$$

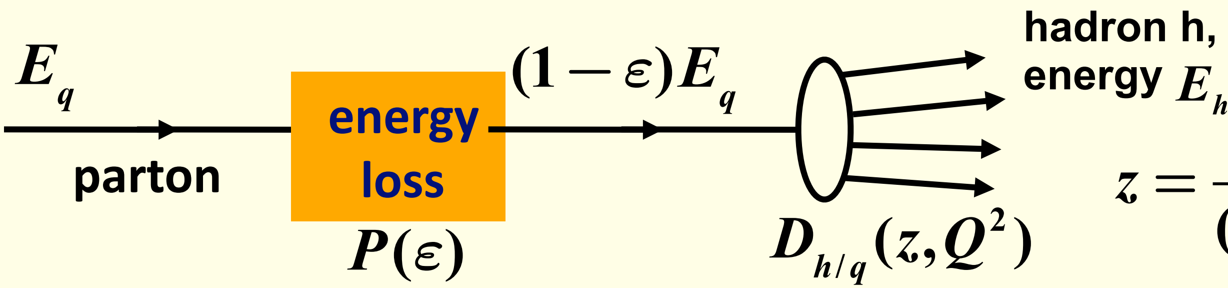
Transverse area ($A_T \sim R^{1/3}$ für $b = 0$)

Energy loss becomes linear in L in case of Bjorken expansion

Energy loss becomes linear in *L* for 1D Bjorken expansion

Medium-Modified Fragmentation Functions (I)

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:

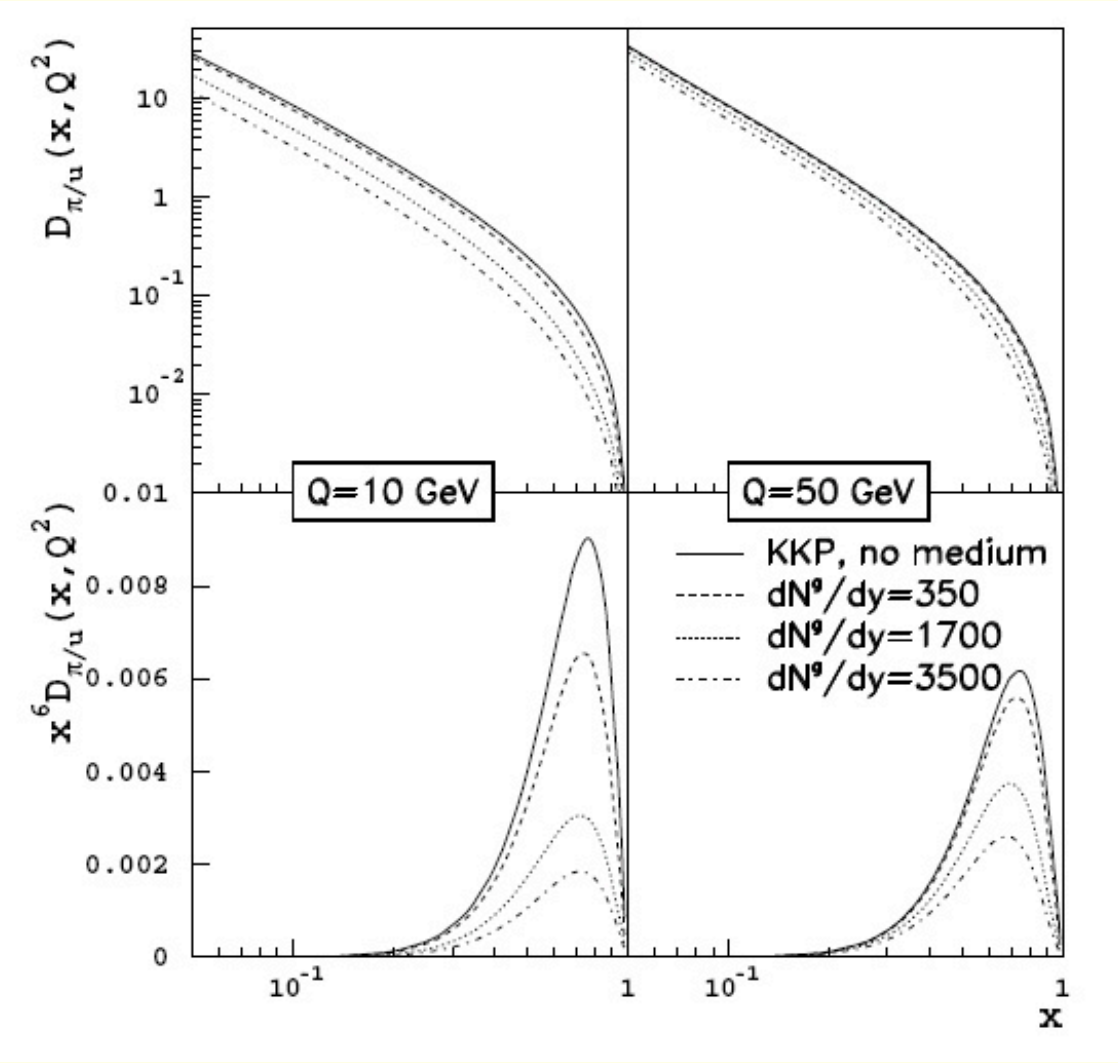
$$\frac{dn}{dx} = \frac{dn}{dz}\cdot\frac{dz}{dx} = D_{h/q}(z,Q^2)\cdot\frac{1}{1-\varepsilon}$$

Average over energy loss probability:

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

Hadrons resulting from gluon bremsstrahlung neglected

Medium-Modified Fragmentation Functions (II)



Fragmentation function $u \rightarrow \pi$ for a medium with *L* = 7 fm and various gluon densities

Quenching Weights (I)

quenching weight — continuous quenching weight

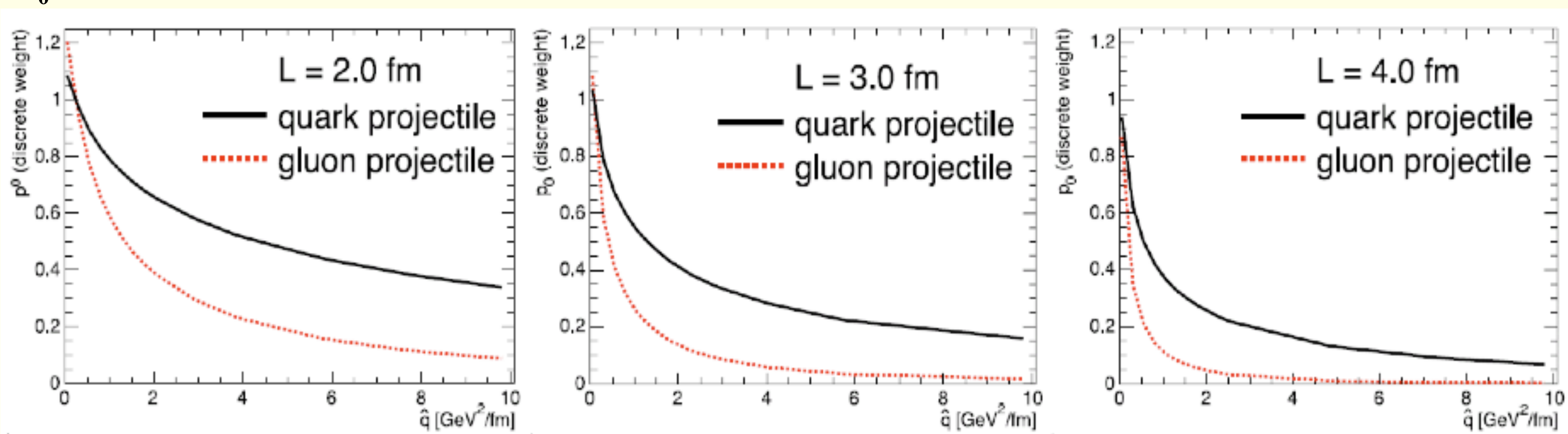
$$\int d\epsilon\, P(\epsilon) = p_0 + \int d\epsilon\, p(\epsilon) = 1$$

probability to have no induced gluon radiation

Note that $P(\Delta E)$ is a generalized probability which can take negative values as long as this equation holds

p_0 as function of $\hat{q}$ in the limit $E \to \infty$:

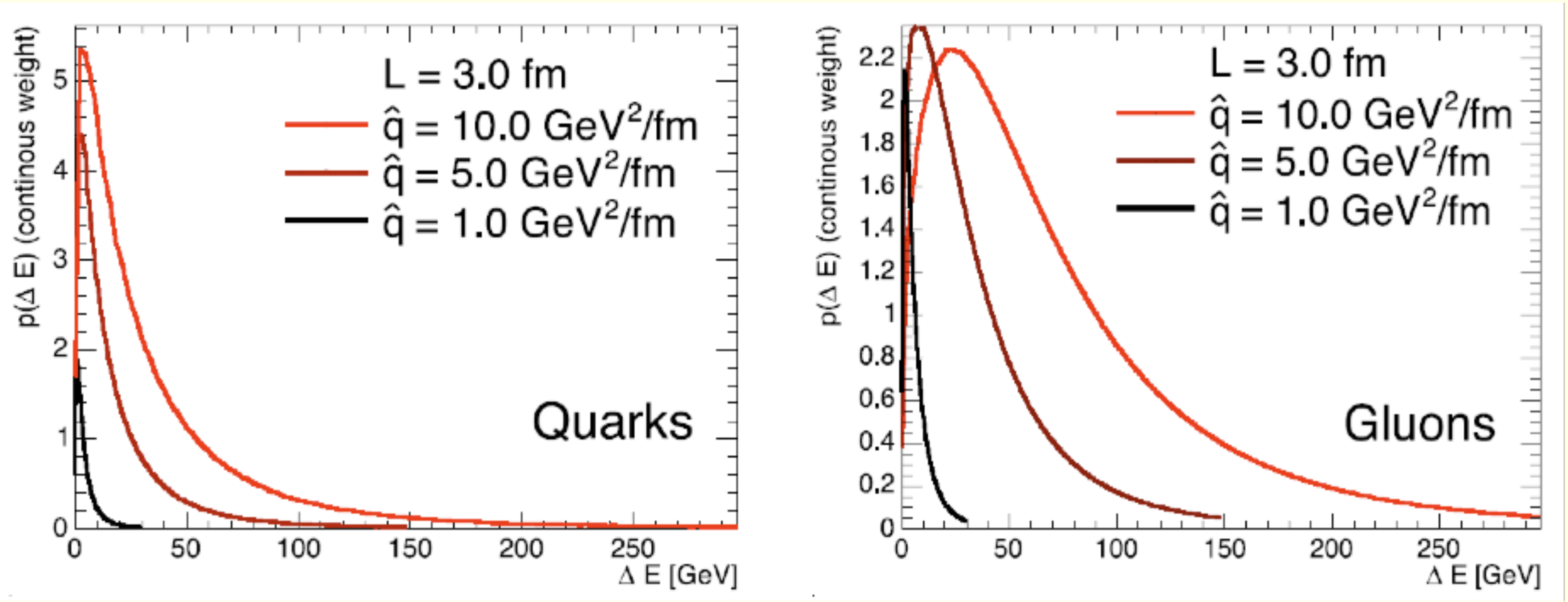
taken from PhD thesis of C. Loizides



Salgado, Wiedemann, PRD 68 (2003) 014008

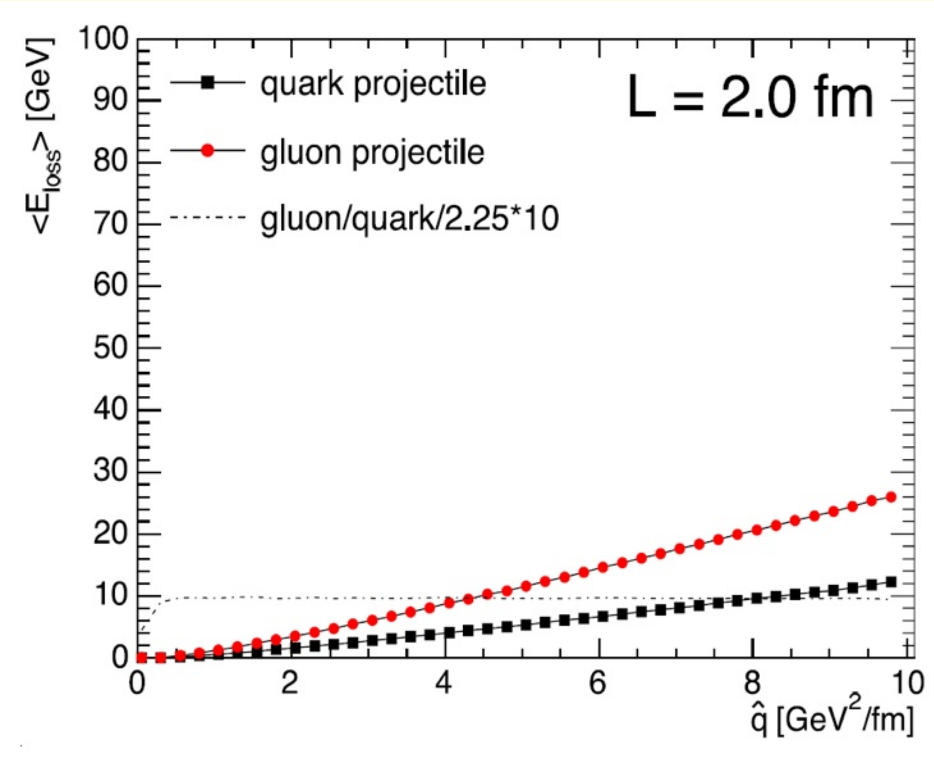
Quenching Weights (II): Continuous Weight

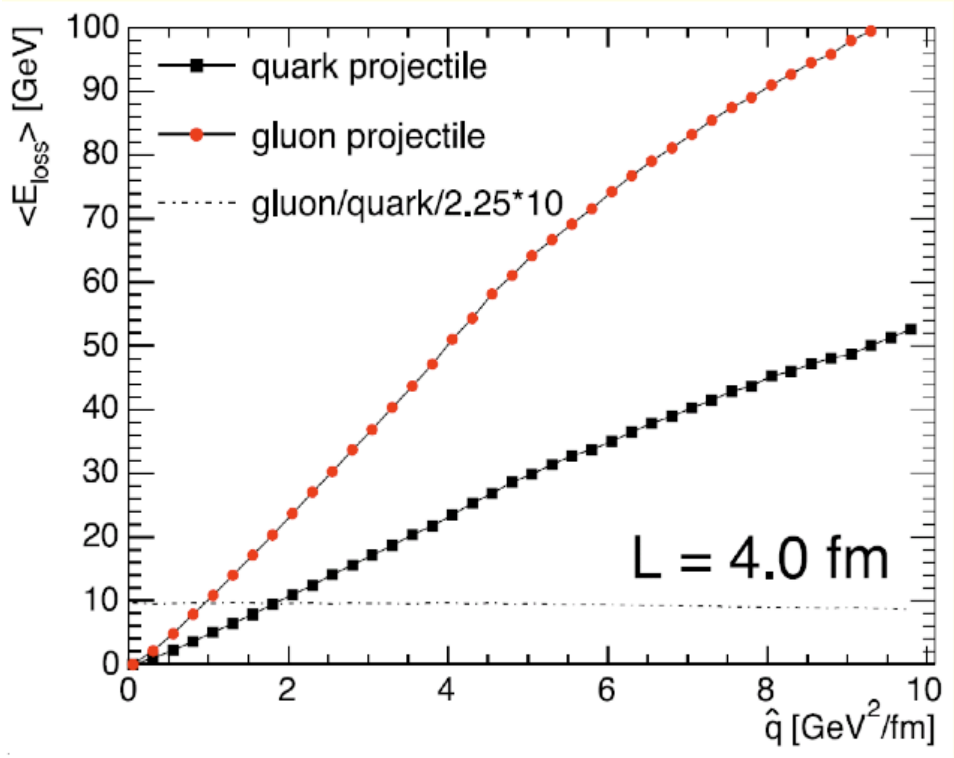
taken from PhD thesis of C. Loizides



These quenching weights hold for parton energies $E \to \infty$

Parton Energy Loss in the Limit $E \longrightarrow \infty$





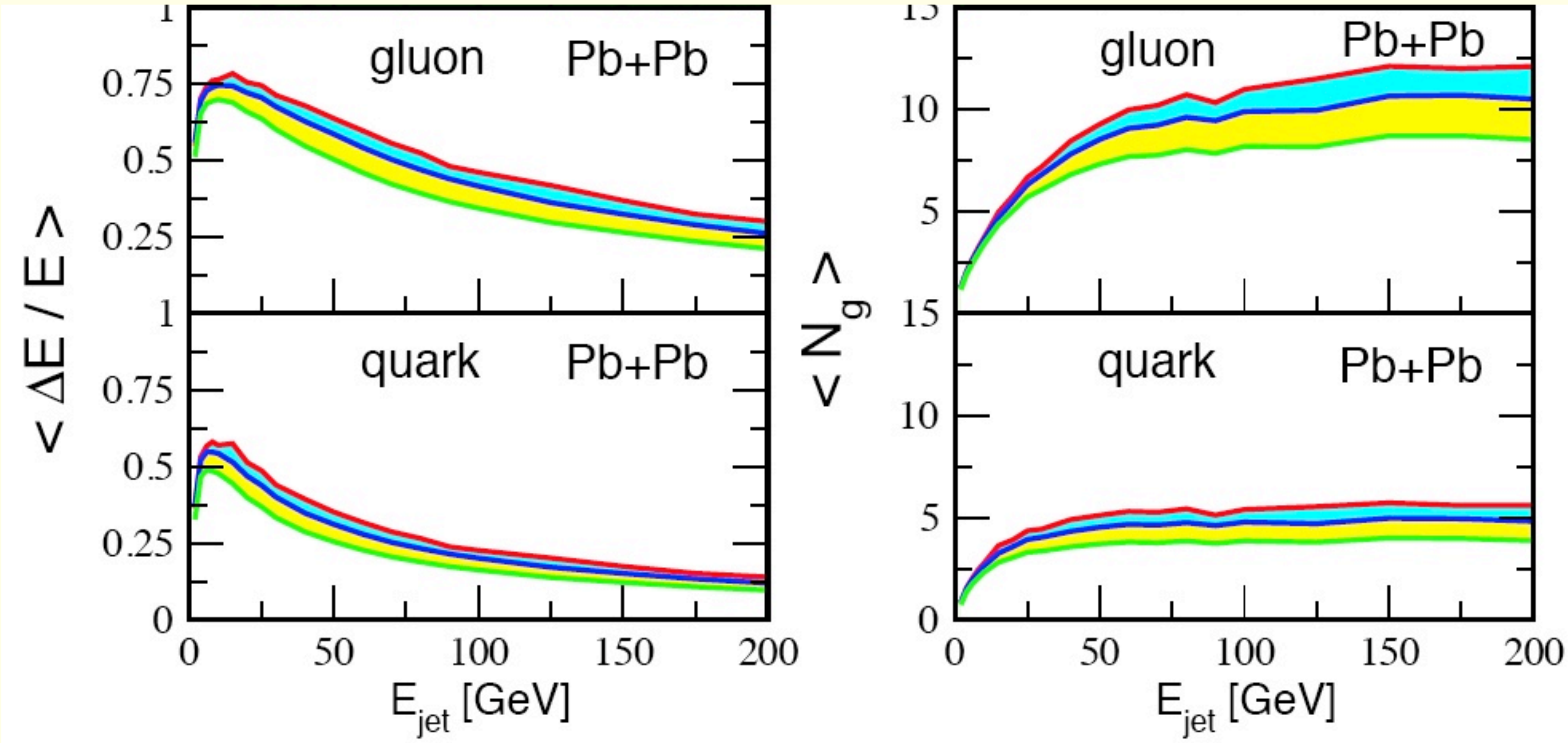
More realistic models need to take finite parton energies into account

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

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

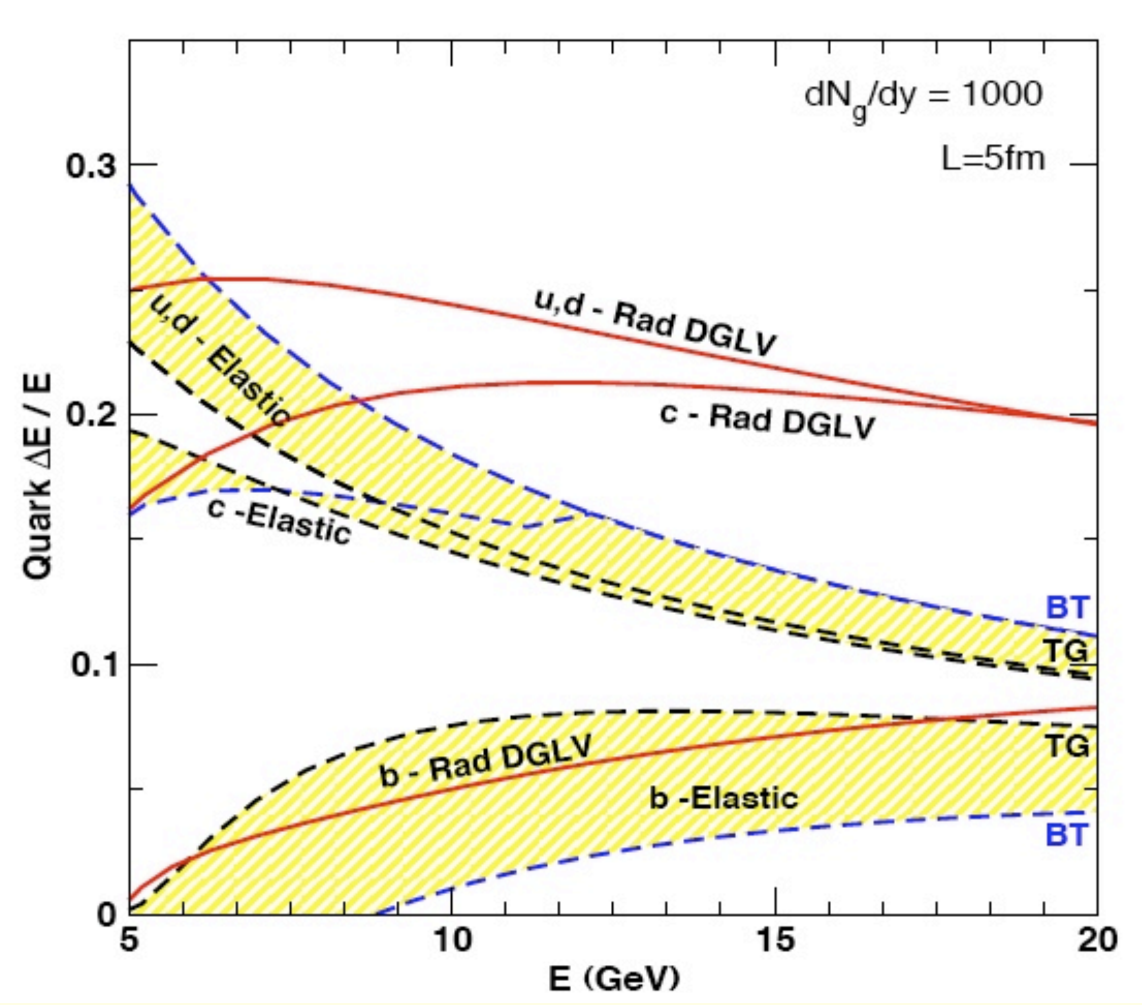
Central Pb+Pb at $\sqrt{s_{NN}}$ = 5500 GeV: $L \approx 6$ fm, dN^g/dy = 2000, 3000, 4000

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



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

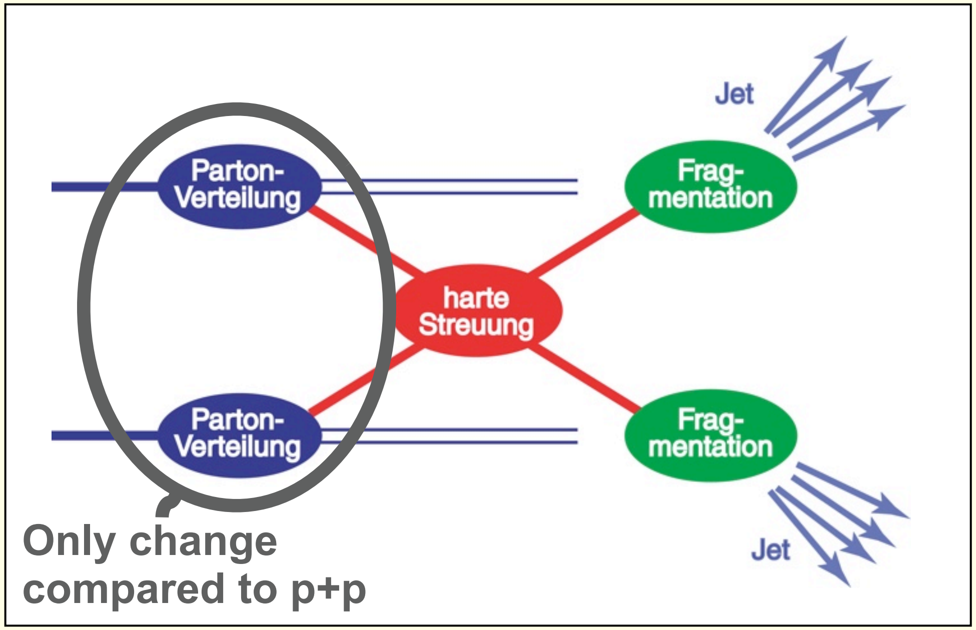
Wicks, Horowitz, Djordjevic Gyulassy, Nucl. Phys. A784, 426-442

4.2 Point-like Scaling

Expectation for Particle Yields from Hard Scattering Processes in A+A collisions

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

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



- **Calculate increase of the effective luminosity of nucleons (and 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

Digression: Luminosity of a Collider

Rate of events for a given physics process:

$$N = L \cdot \sigma$$

Event rate [s^{-1}]

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

Cross section [cm^2]

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

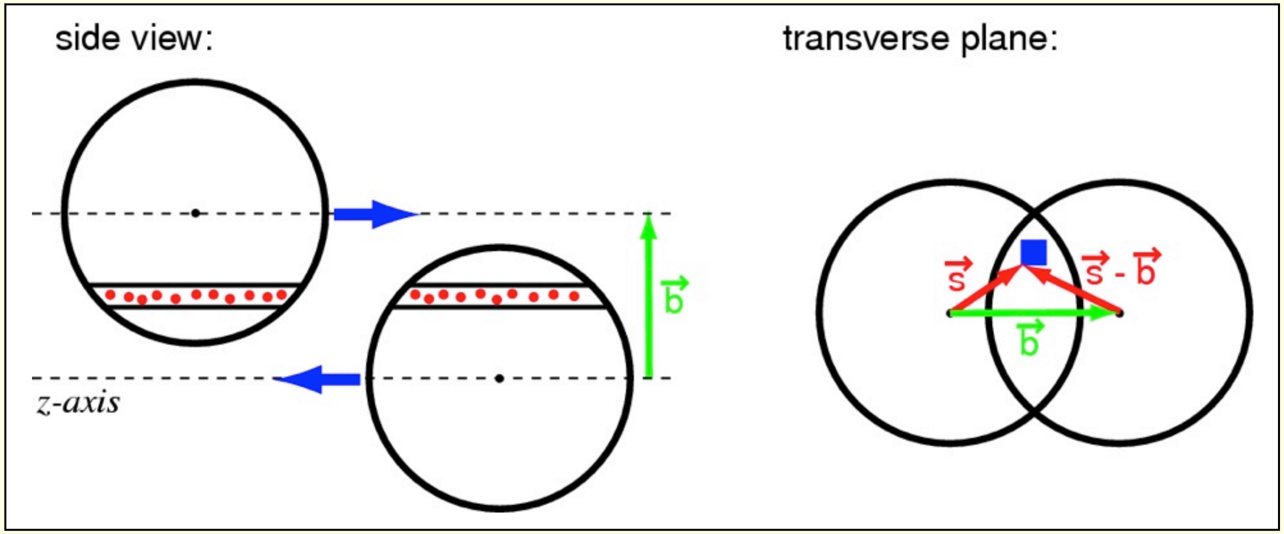
$$L = f \frac{n_1 n_2}{A_{\mathrm{beam}}} = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$$

n_i: number of particles in bunch i

Transverse area of the beam

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

Effective Nucleon Luminosity: The Nuclear Overlap Function



Nuclear thickness:

$$T_A(\vec{s}) := \int \rho_A(\vec{s}, z)\,\mathrm{d}z$$

Normalization:

$$\int T_A(\vec{s})\,\mathrm{d}^2 s = A$$

"nucleon luminosity" in area $\mathrm{d}^2 s$ at $\vec{s}$: $\mathrm{d}T_{AB}(\vec{s}) = T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b})\,\mathrm{d}^2 s$

"Total nucleon luminosity" for collisions at impact parameter *b* (*nuclear overlap function*):

unit: 1/area

$$T_{AB}(b) = \int T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b})\,\mathrm{d}^2 s$$

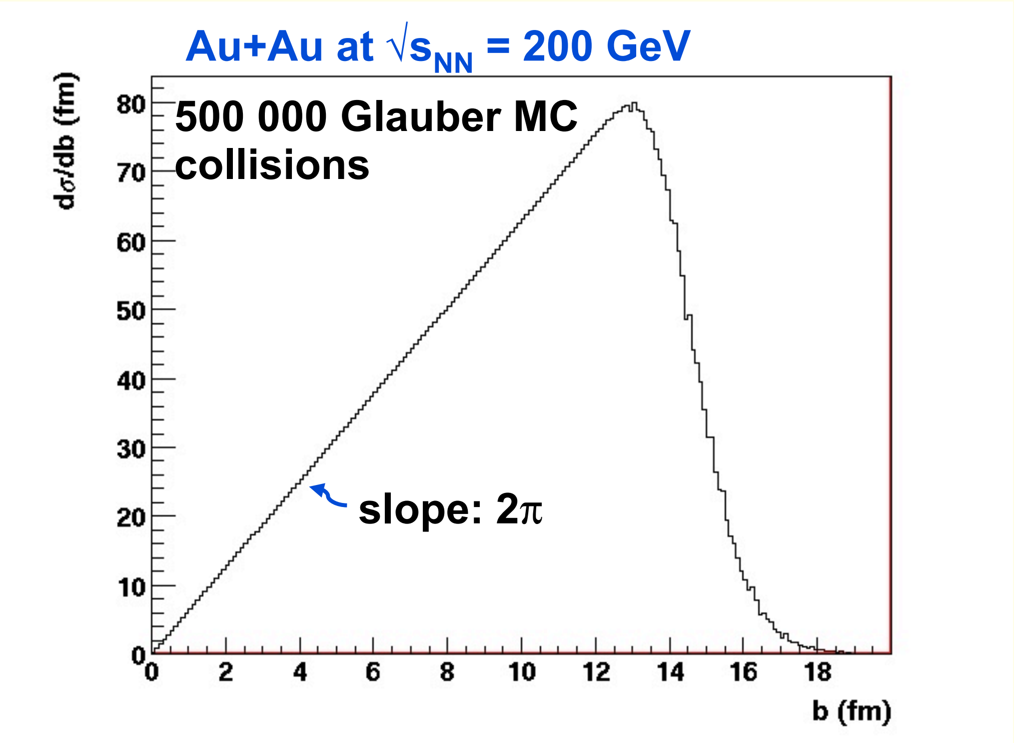
Thus, number of interactions for a process with cross section σ_{int}:

$$\langle N_{\mathrm{int}}(b) \rangle = T_{AB}(b) \cdot \sigma_{\mathrm{int}}$$

In particular: $\langle N_{\mathrm{coll}}(b) \rangle = T_{AB}(b) \cdot \sigma_{\mathrm{inel}}^{\mathrm{p+p}}$

Impact Parameter Distribution of a A+A collisions

Glauber MC:



Analytic approximation:

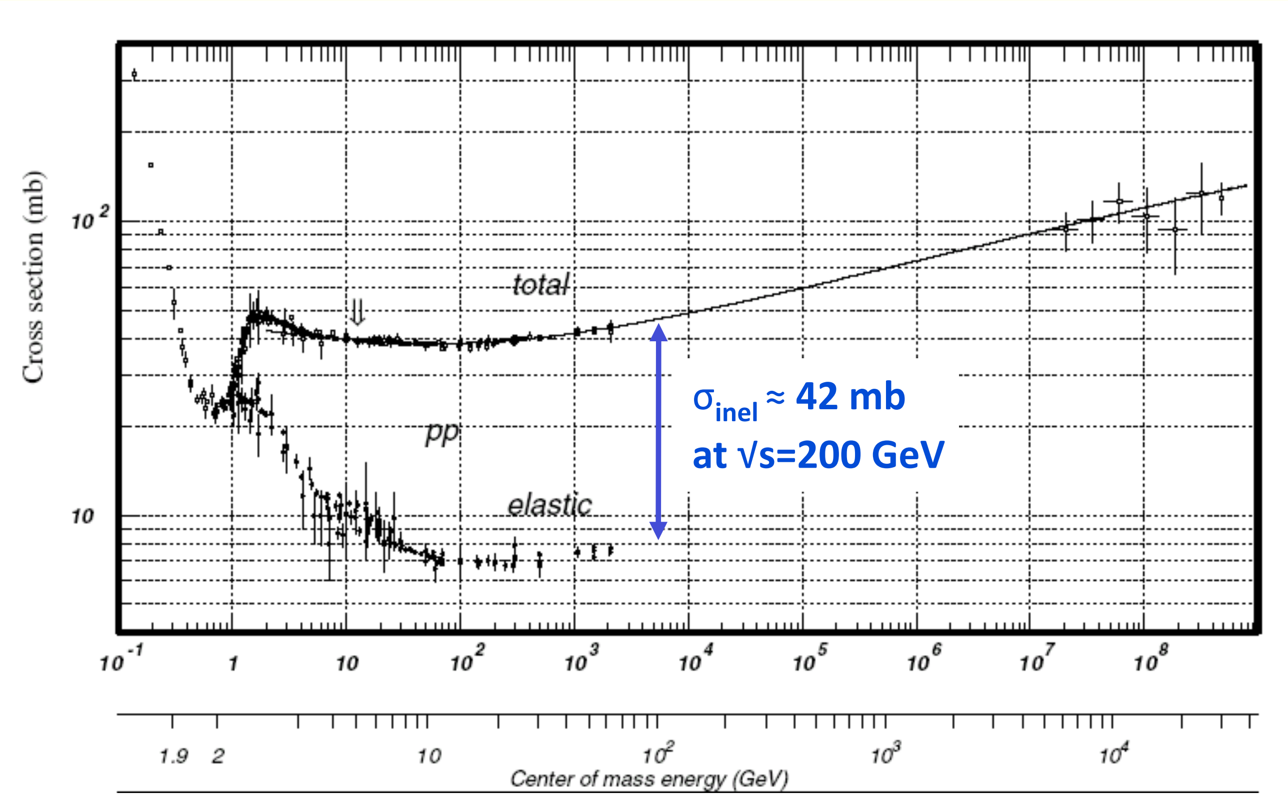
$$p_{\mathrm{inel}}^{\mathrm{A+B}}(b) = 1 - \exp(-T_{AB}(b) \cdot \sigma_{\mathrm{inel}}^{\mathrm{NN}})$$

probability for an inelastic A+B collision at impact parameter *b*

$$\frac{\mathrm{d}\sigma}{\mathrm{d}b} = 2\pi\, b\, p_{\mathrm{inel}}^{\mathrm{A+B}}(b)$$

$$\sigma_{\mathrm{inel}}^{\mathrm{A+B}} = \int_0^\infty \frac{\mathrm{d}\sigma}{\mathrm{d}b}\mathrm{d}b$$

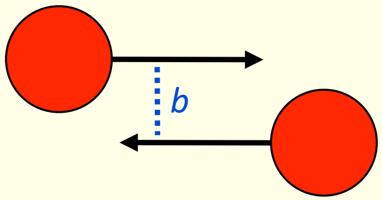
Total cross section: $\sigma_{\mathrm{inel}}^{\mathrm{Au+Au@200GeV}} \approx 6.9\ \mathrm{b}$



$\sqrt{s}$ (GeV)	σ_{inel}(p+p)
17.2	32 mb
200	42 mb
5500	72 mb

$$\sigma_{\text{inel}} = \sigma_{\text{total}} - \sigma_{\text{elastic}}$$

Naive expectation for the order of magnitude of the p+p cross section:



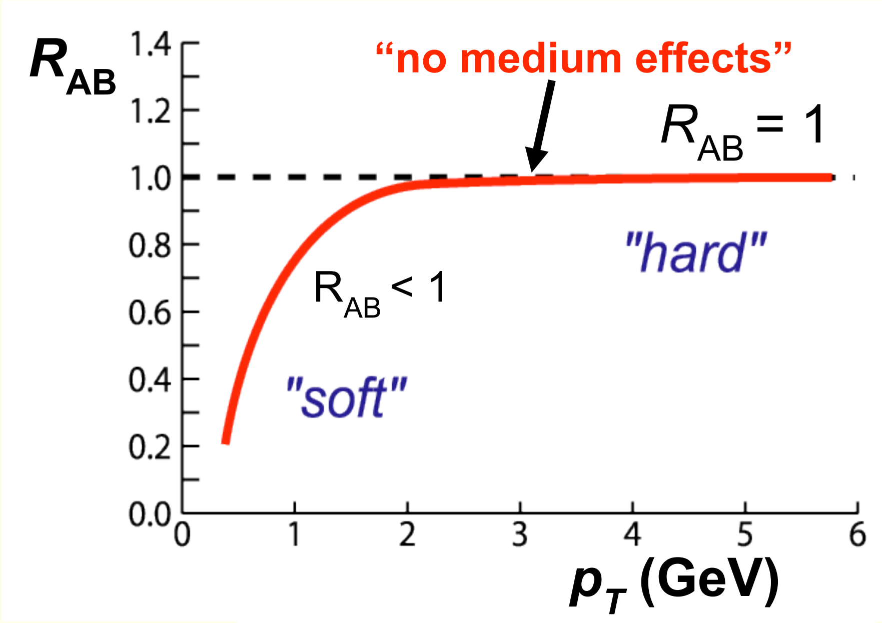
$$\sigma_{geo} = \pi \cdot b_{\max}^2 = \pi \cdot (2 r_{\text{Proton}})^2 = \pi \cdot (1{,}6\ \text{fm}^2) = 80\ \text{mb}$$

$$1\ \text{b} = 10^{-28}\ \text{m}^2,\ 1\ \text{fm}^2 = 10^{-30}\,\text{m}^2 = 10\ \text{mb}$$

Nuclear Modification Factor

$$R_{AB}(p_T) = \frac{\mathrm{d}^2 N / \mathrm{d}p_T \mathrm{d}y \big|_{A+B}}{\langle N_{\mathrm{coll}} \rangle \times \mathrm{d}^2 N / \mathrm{d}p_T \mathrm{d}y \big|_{p+p}}$$

- $\langle N_{\mathrm{coll}} \rangle$ from Glauber Monte-Carlo calculation
- In the absence of nuclear effects: $R_{AB} = 1$ at high p_T ($p_T > 2$ GeV/c)

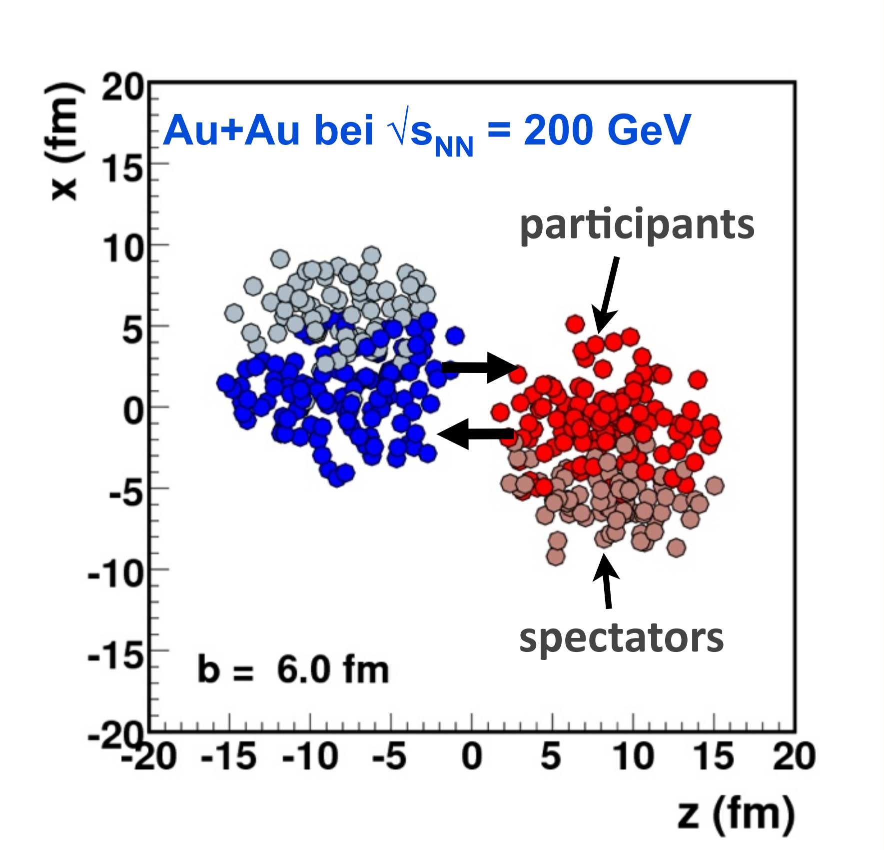


Glauber Monte-Carlo Approach

- Nucleons of both nuclei randomly distributed in space according to Woods-Saxon distribution
- Impact parameter b drawn from distribution $d\sigma/db = 2\pi b$
- Collision between two nucleons take place if their distance d in the transverse plane satisfies

$$d \leq \sqrt{\sigma_{\text{inel}}^{\text{NN}} / \pi}$$

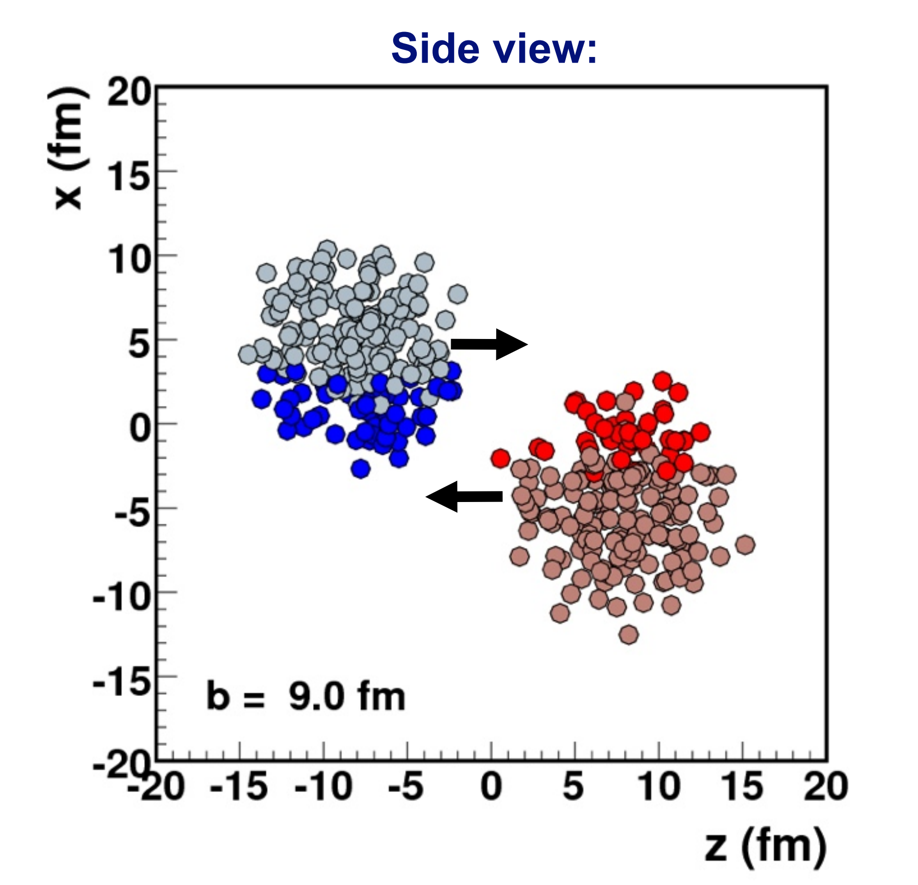
- $\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$ through simulation of many A+B collisions (typically ~ 10^6)

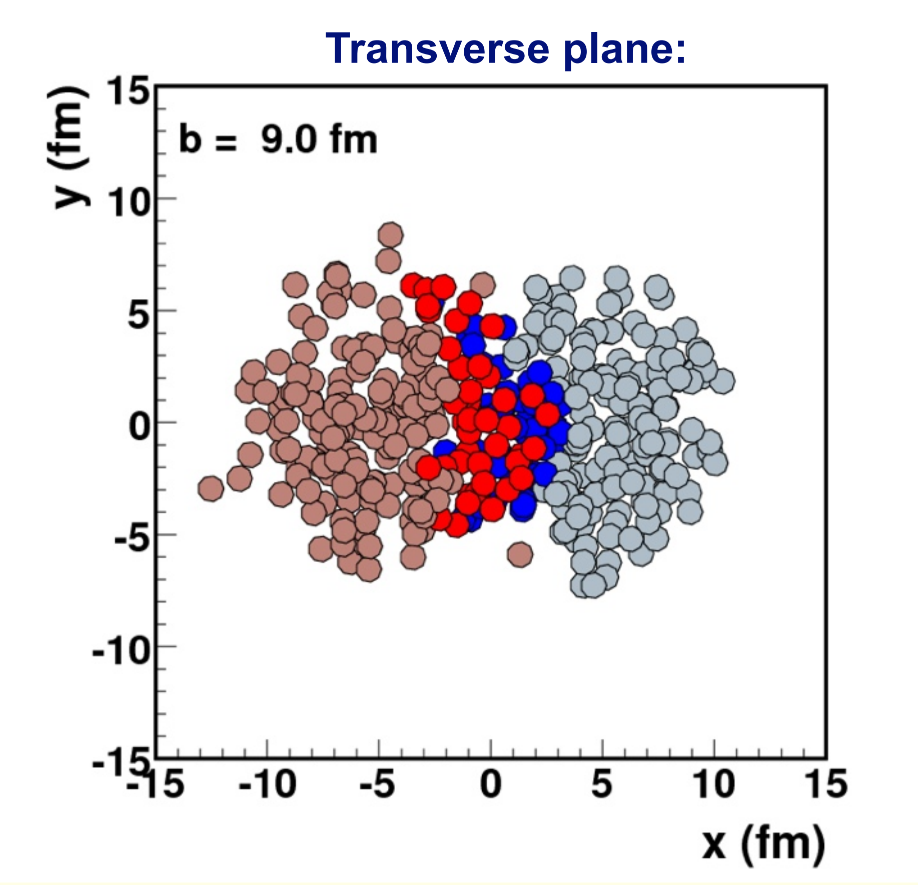


$$\sigma_{\text{inel}}^{\text{NN}} \approx 42 \text{ mb at } \sqrt{s_{NN}} = 200 \text{ GeV}$$

Examples of Glauber-MC Events (I)

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

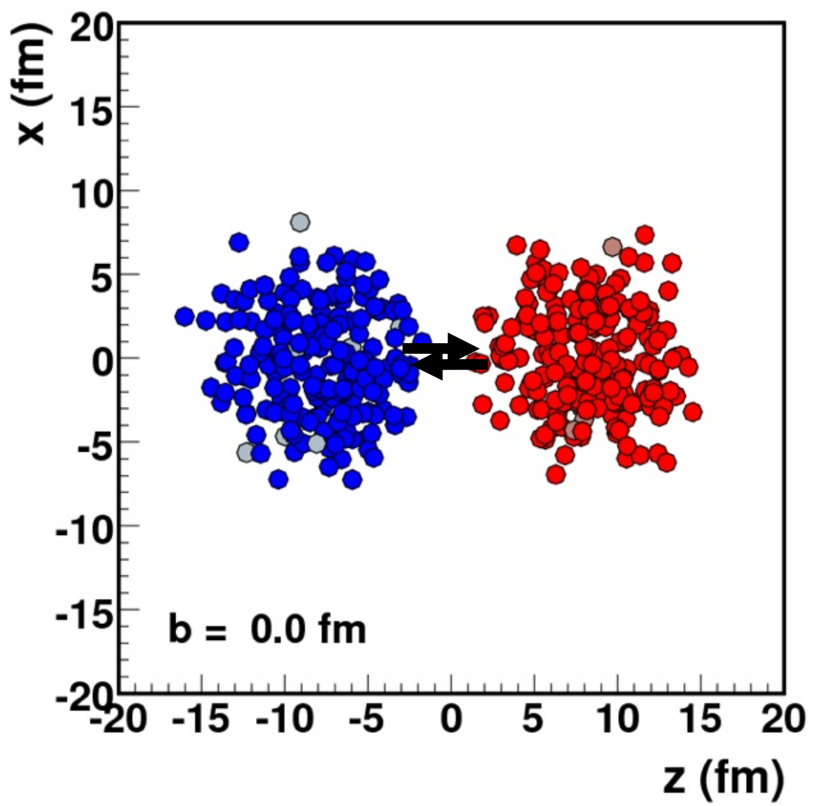




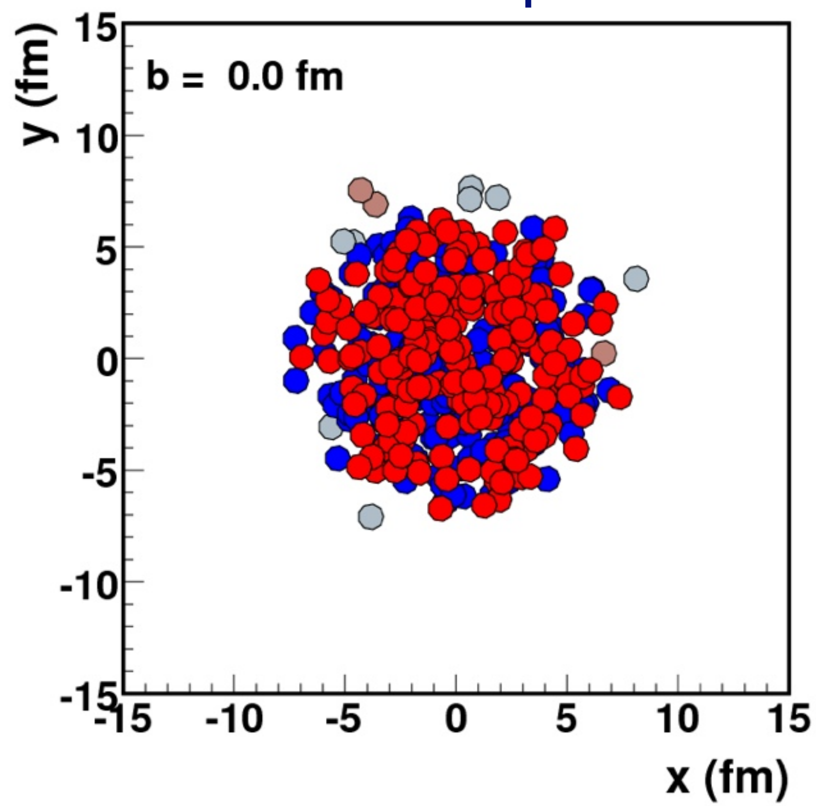
Examples of Glauber-MC Events (II)

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

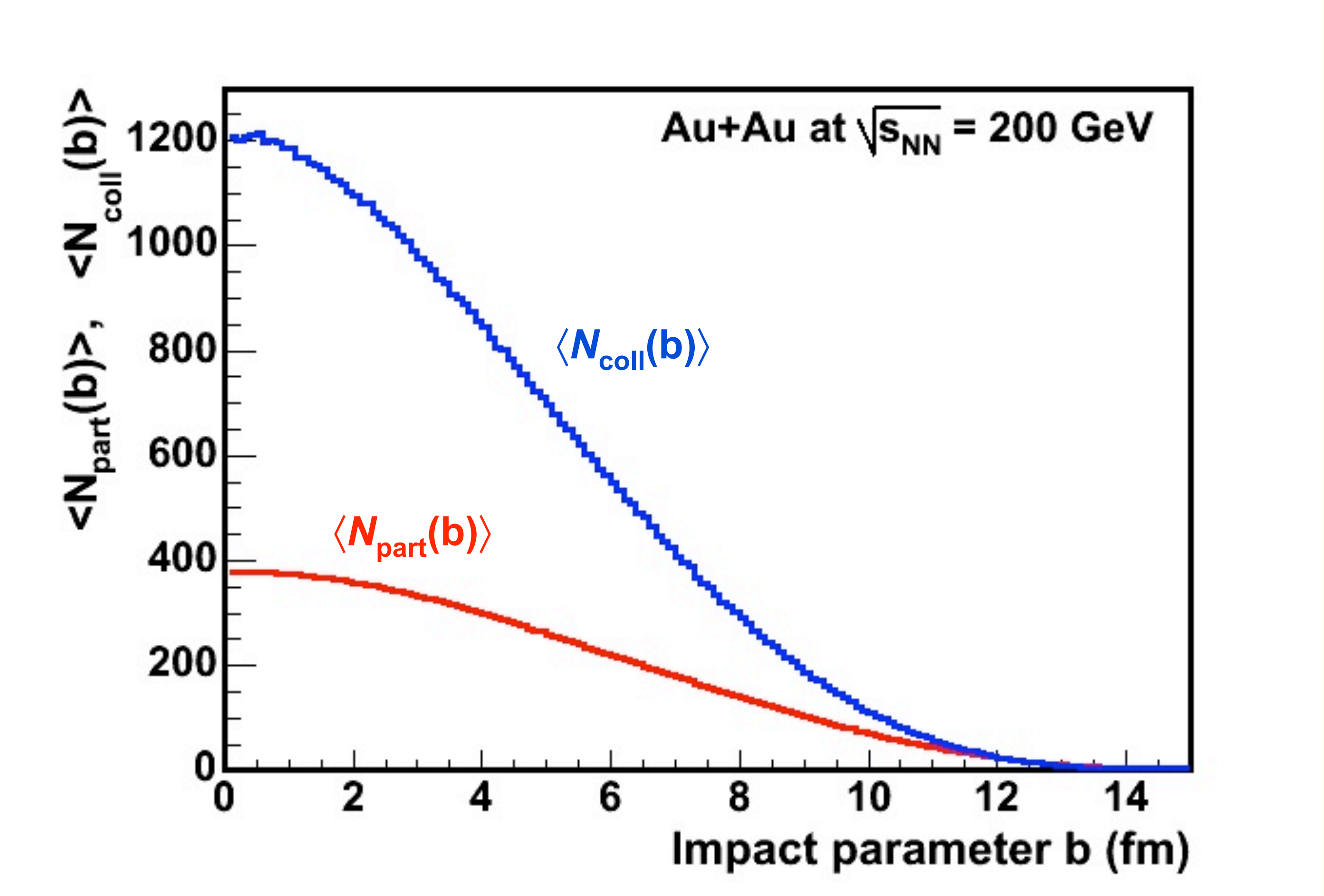
Side view:



Transverse plane:



N_{part} und N_{coll} vs. Impact Parameter



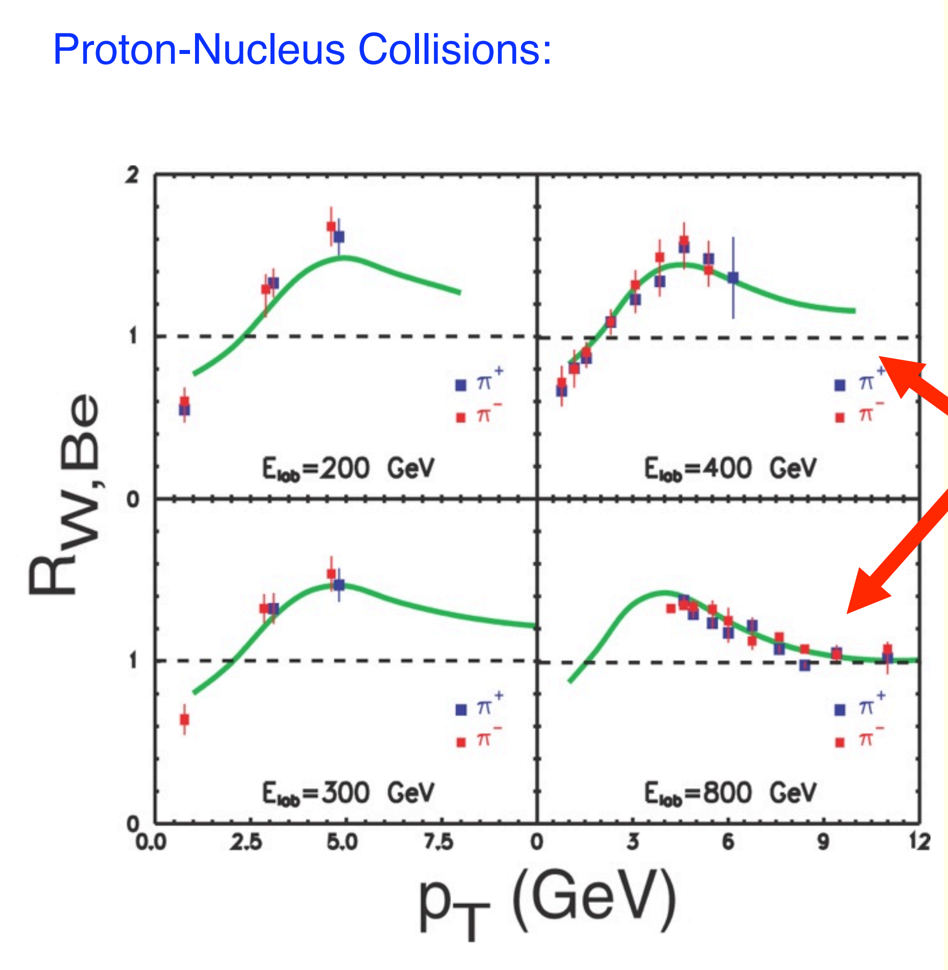
Approximate relation between N_{part} and N_{coll}: $N_{coll} \propto N_{part}^{4/3}$

4.3 Particle Yields and Direct Photons at High-p_T

How Can One Study Jet Production?

- **Measurement of particle multiplicities at high p_T**
- **Measurement of two-particle angular correlations**
- **Jet reconstruction on single event basis**
  - **Possible in $p + \overline{p}$ collisions at the Tevatron**
  - **Very difficult in central nucleus-nucleus collisions at RHIC due to large particle multiplicity from underlying event**
  - **Situation improves significantly in central Pb+Pb at the LHC due to the increased cross section for jet production**

Cronin Effect in p+A Collisions



p+A Collisions:

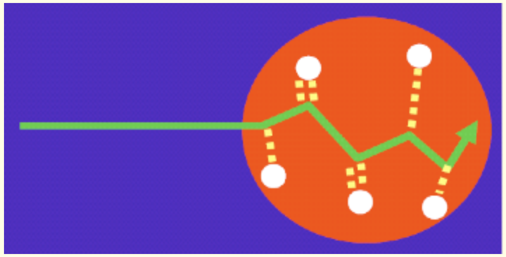
Nuclear modification factor

$R_{pA} > 1$, at intermediate p_T,

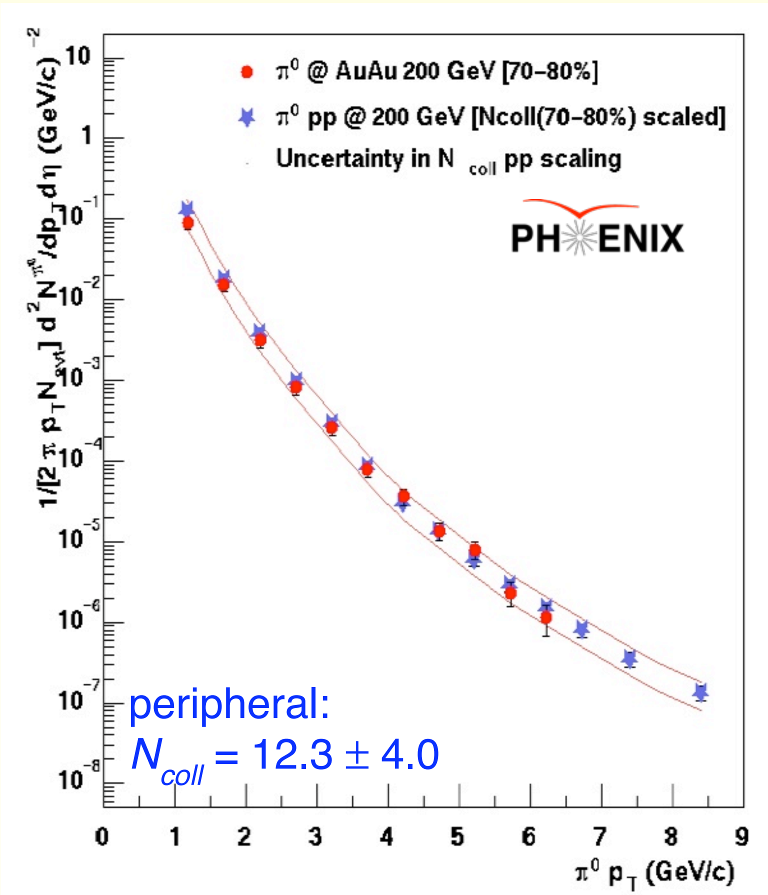
before $R_{pA} = 1$ is reached in the limit

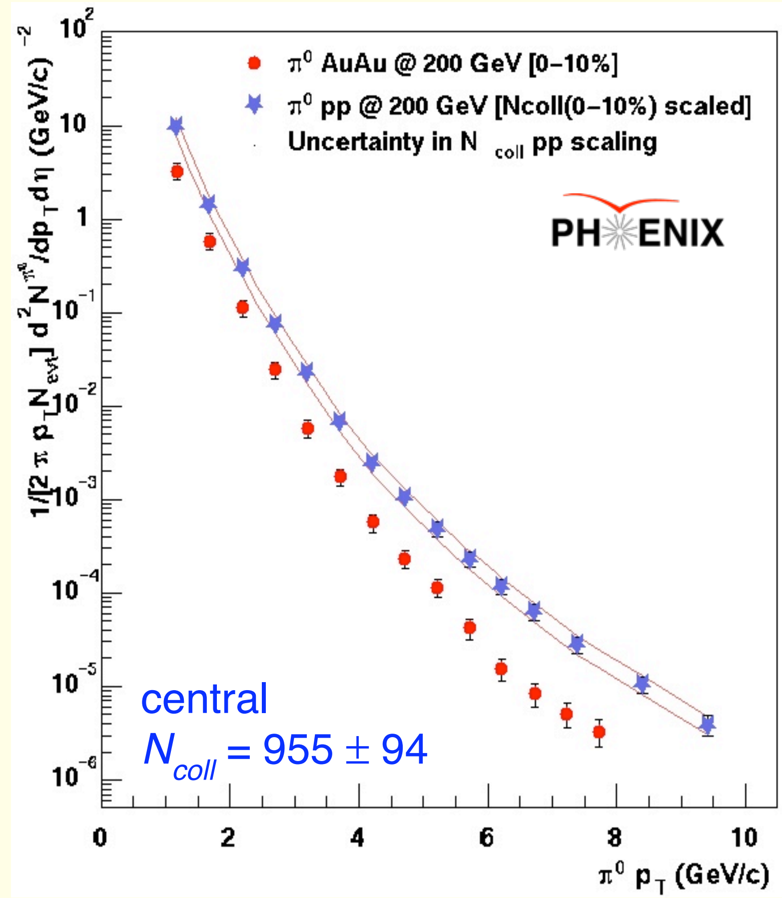
of very high p_T

Common explanation of the Cronin effect:
Multiple soft scattering in p+A leads to additional transverse momentum k_T



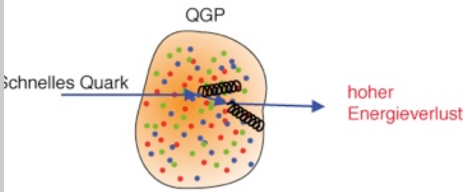
π^0 spectra in p+p- and Au+Au Collisionen

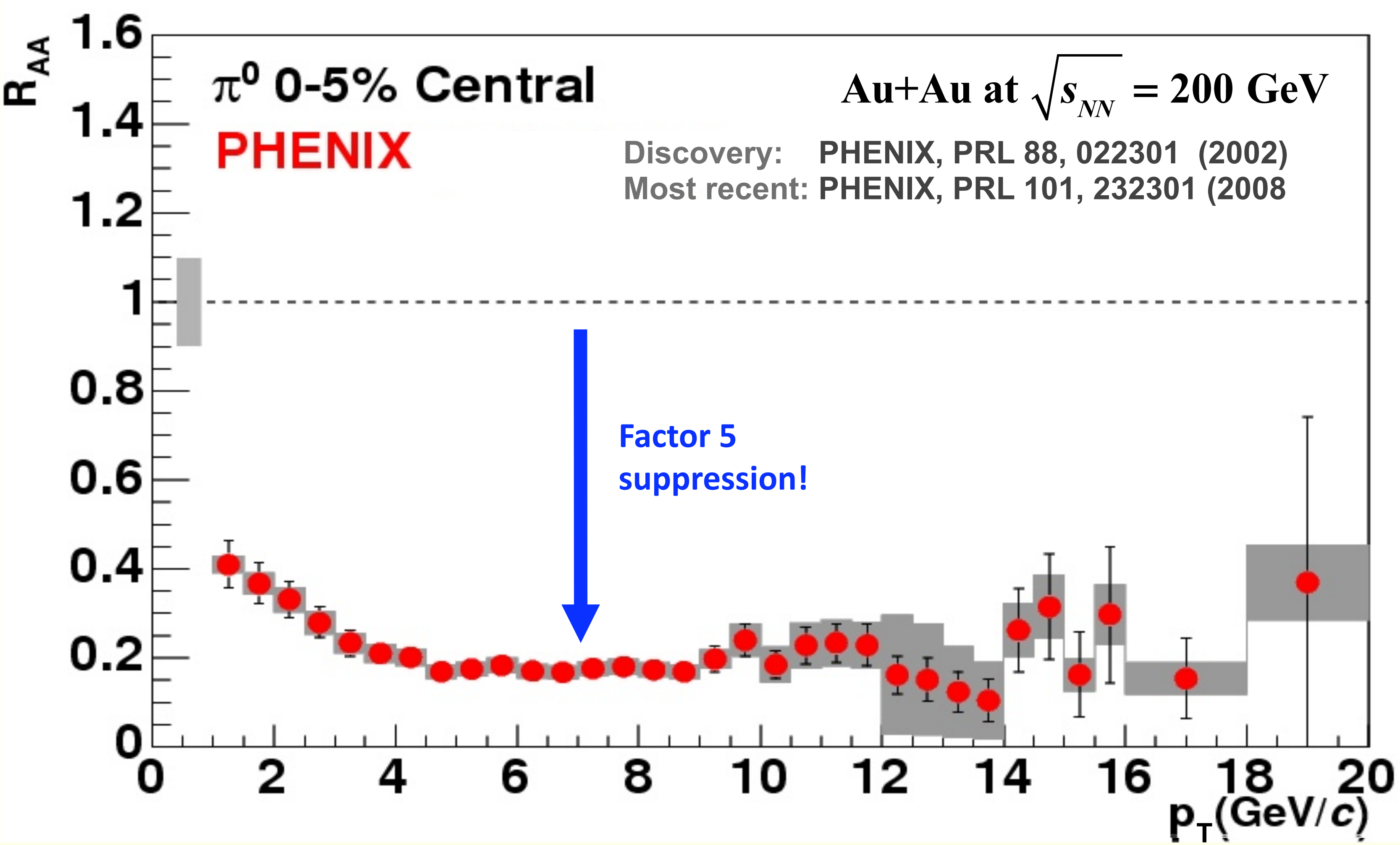




Strong suppression of the π^0 spectrum in central Au+Au collisions relative to N_{coll}-scaled p+p spectrum

π^0 Production in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV





Strong suppression in central collisions

Alternative Explanation: Effects of Cold Nuclear Matter ?

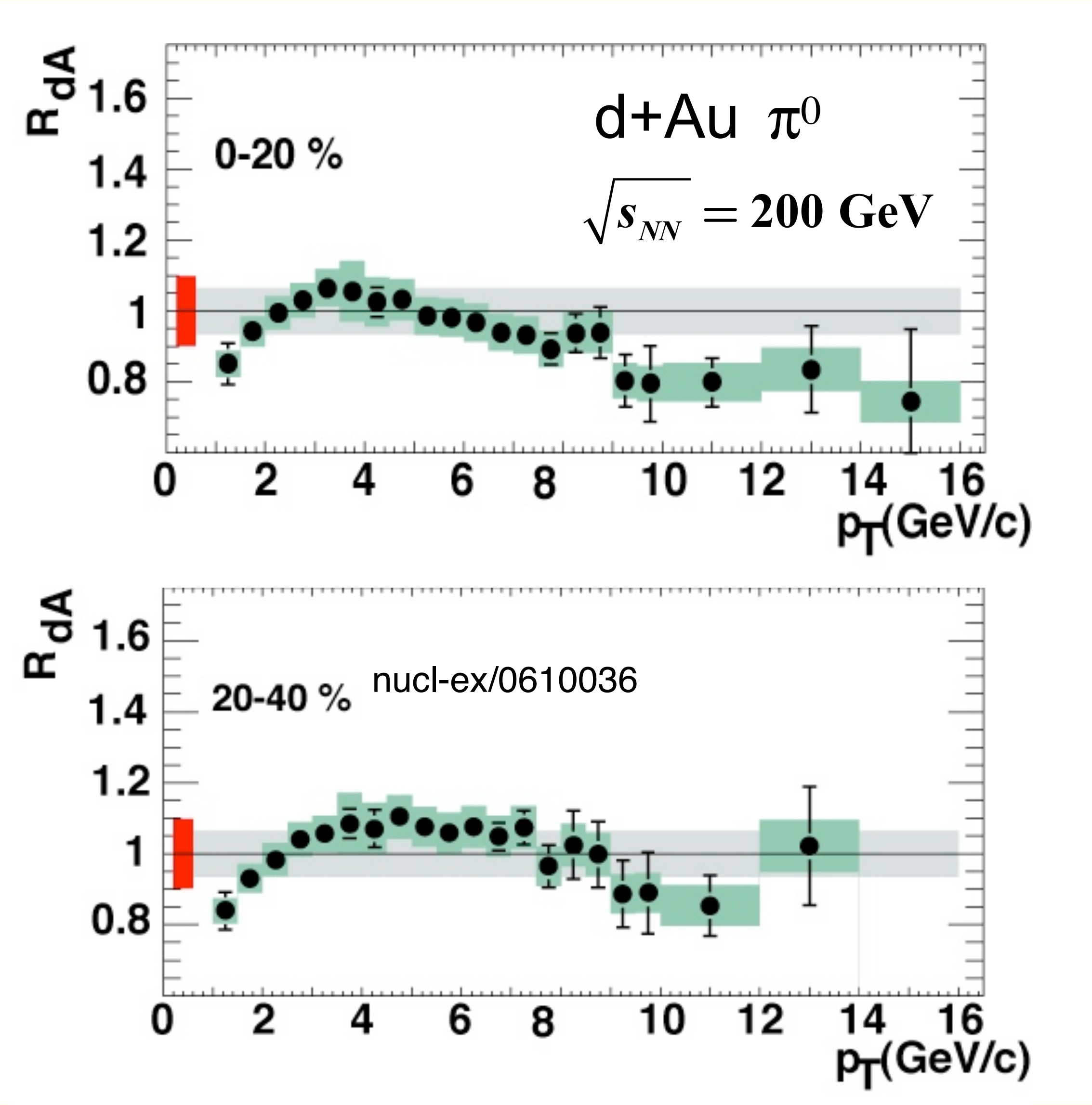
- **Hadron suppression e.g. due to strong modification of parton distributions in heavy nuclei (initial state effects)?**

- **Example: Color Glass Condensate Model**
  - **Fewer gluons in wavefunction of incoming Au nuclei**
  - **Result: Fewer hard parton-parton scatterings and therefore fewer particles at high p_T**
  - **Hadron suppression in Au+Au can be described!**

    Kharzeev, Levin, McLerran,
    Phys.Lett. B 561, 93 (2003)

- **Control Measurements**
  - **Hadron production in d+Au**
  - **High-p_T direct photons in Au+Au**

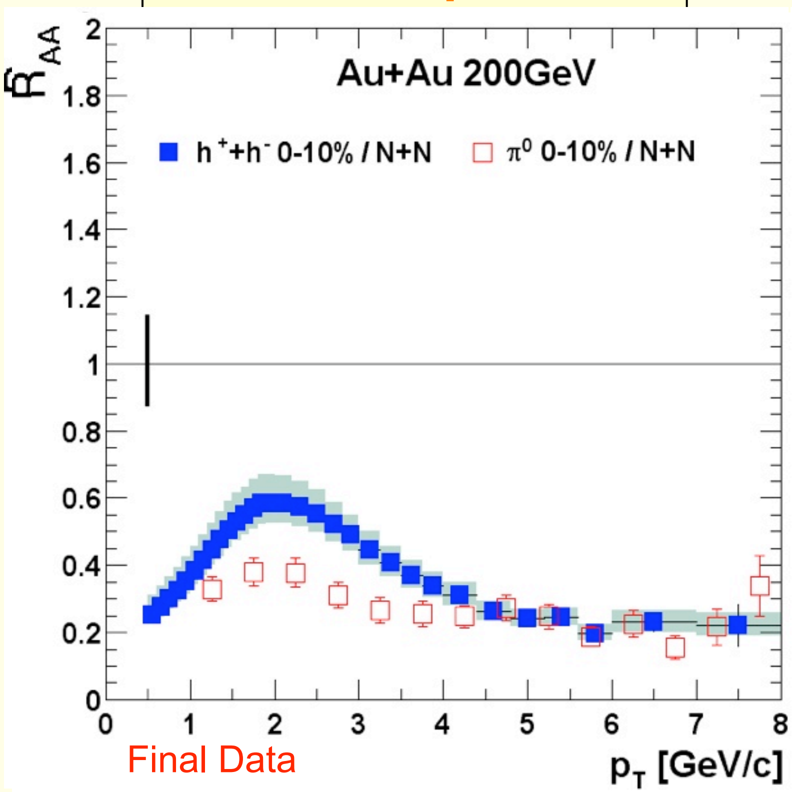
Cold Nuclear Matter Effects studied at RHIC with d+Au



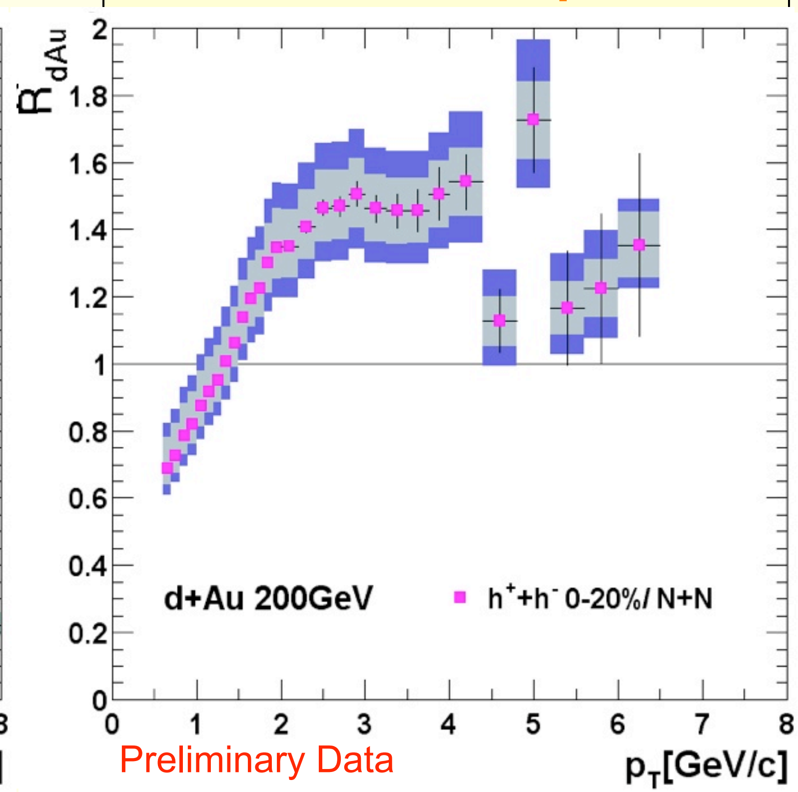
$R_{dA} \approx 1$:
Cold nuclear matter effects are small at $\sqrt{s_{NN}} = 200$ GeV

Centrality Dependence of R_{AA} in d+Au and Au+Au

Au + Au Experiment



d + Au Control Experiment

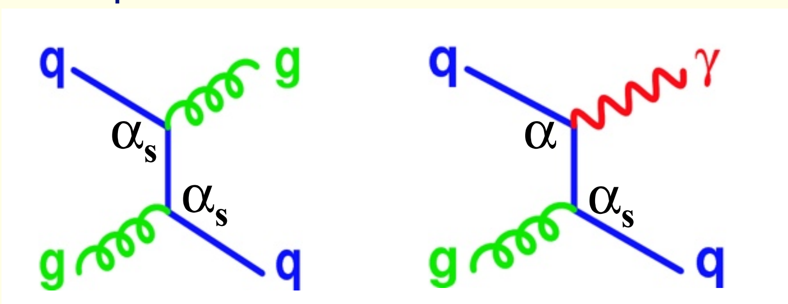


Upshot: Effects of cold nuclear matter cannot explain the suppression in central A+A

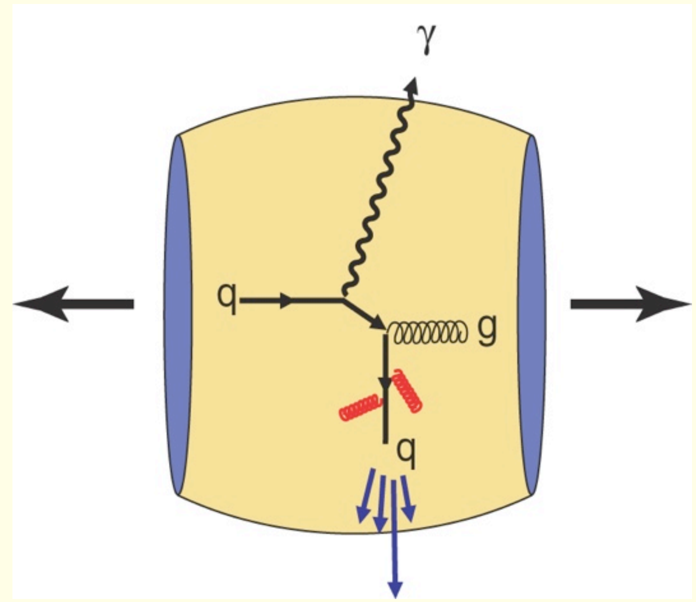
Direct Photons at high p_T

- **Production of direct photons and hadrons at high p_T sensitive to the same parton luminosity**

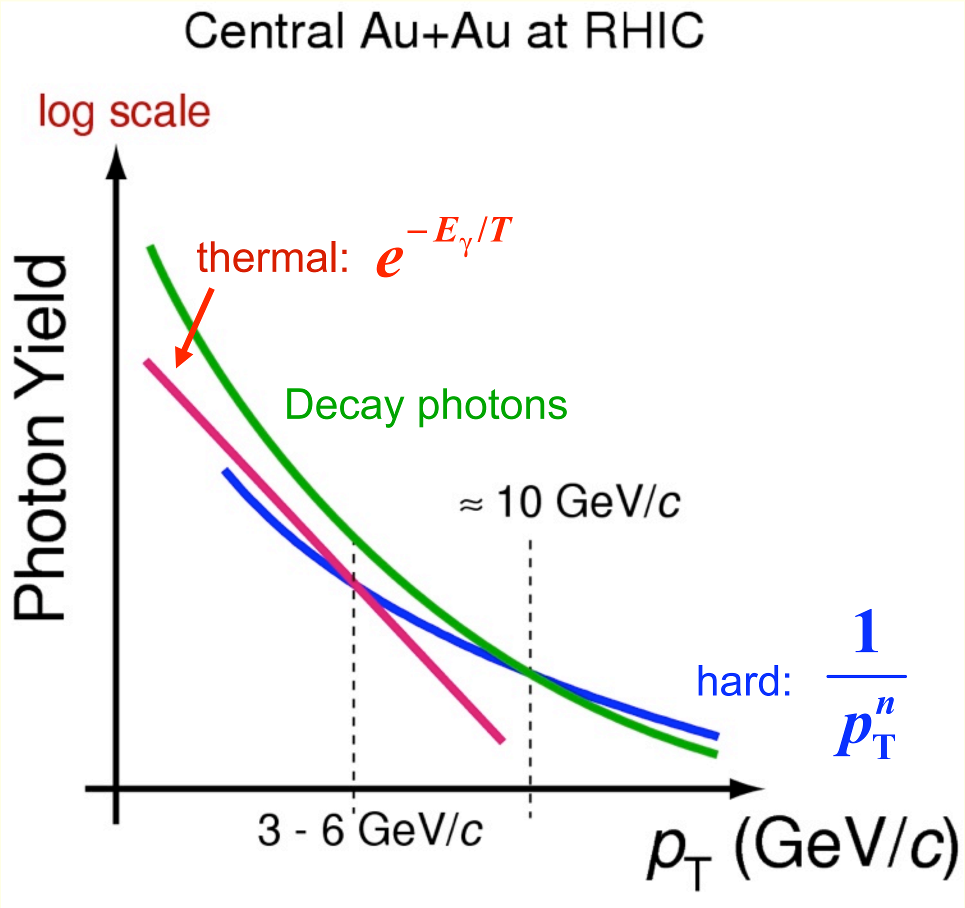
Example:



- **Direct photons escape the medium unscathed**



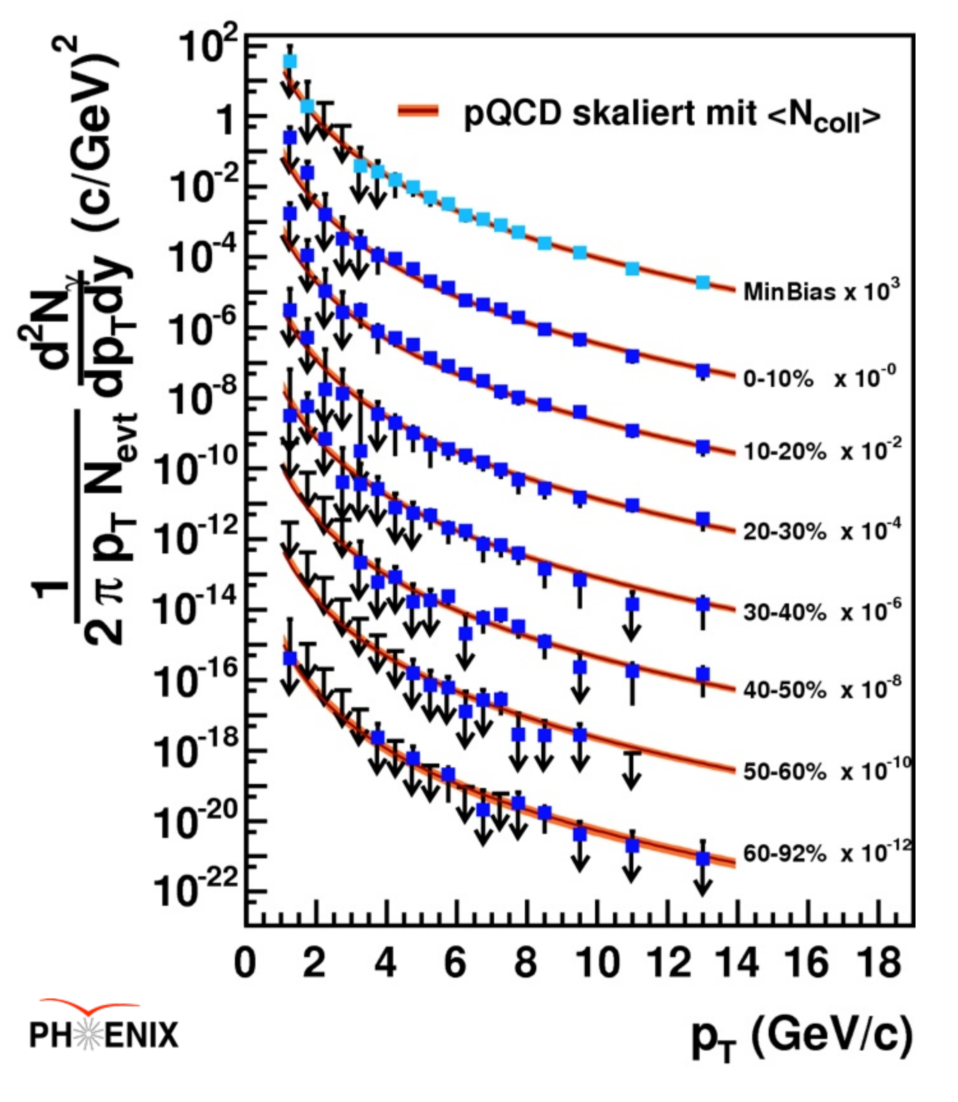
Photon Sources in A+A Collisions



- **Direct photons from hard scattering dominate at high p_T**
- **Experimental challenge: Background from hadron decays, e.g.**
  $\pi^0 \to \gamma + \gamma$, $\eta \to \gamma + \gamma$
- **Method:**
  $\gamma_{direct} = \gamma_{total} - \gamma_{decay}$

Direct Photons in Au+Au

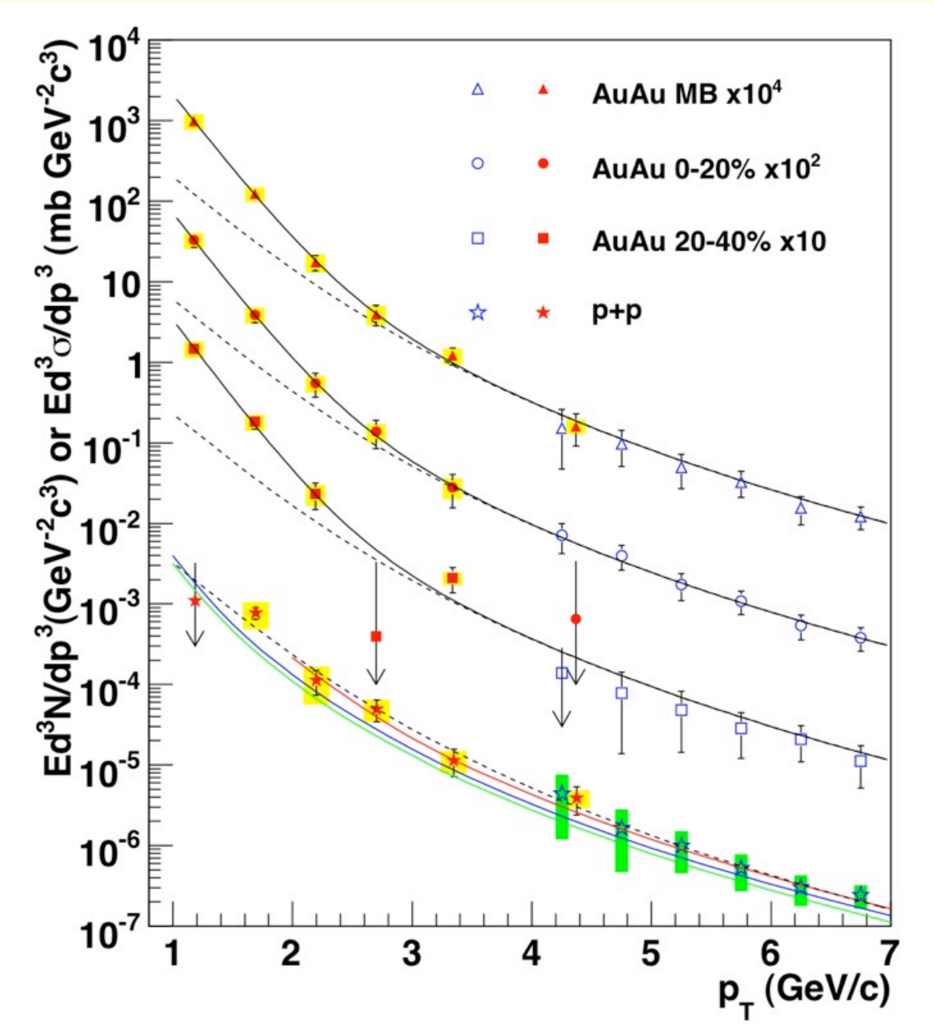
Au+Au bei $\sqrt{s_{NN}}$ = 200 GeV



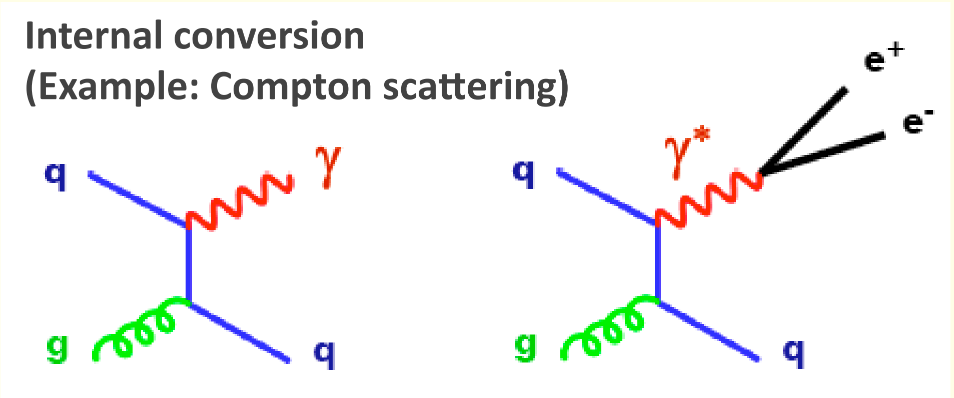
QCD + N_{coll} scaling describes direct photon spectra in Au+Au

Phys.Rev.Lett.94:232301,2005

A Further Important Result: Evidence for Thermal Photons in Au+Au

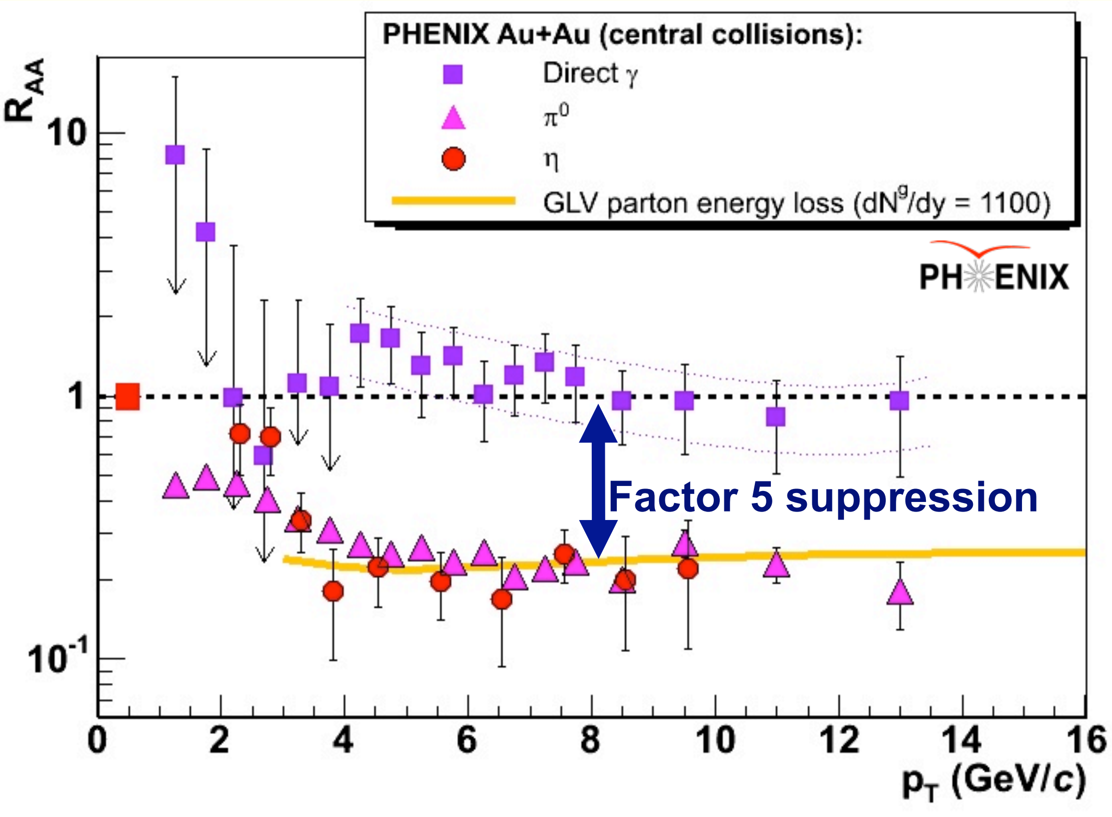


PHENIX, arXiv:0804.4168v1

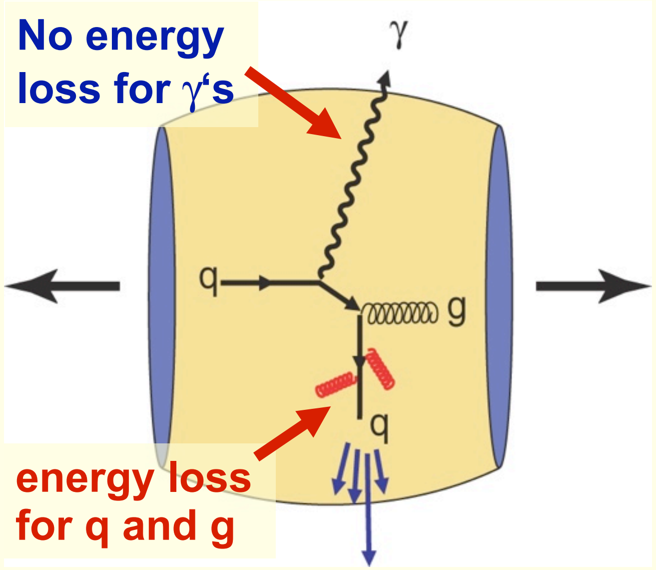


- Direct γ's via internal conversion
- p+p:
  Direct γ's consistent with pQCD
- Au+Au:
  - Excess above scaled p+p for $p_T < 3$ GeV/c
  - Shape: $\exp(-p_T/T)$ with $T = (221 \pm 23 \pm 18)$ MeV
- A real breakthrough!

Nuclear Modification factor for direct Photons

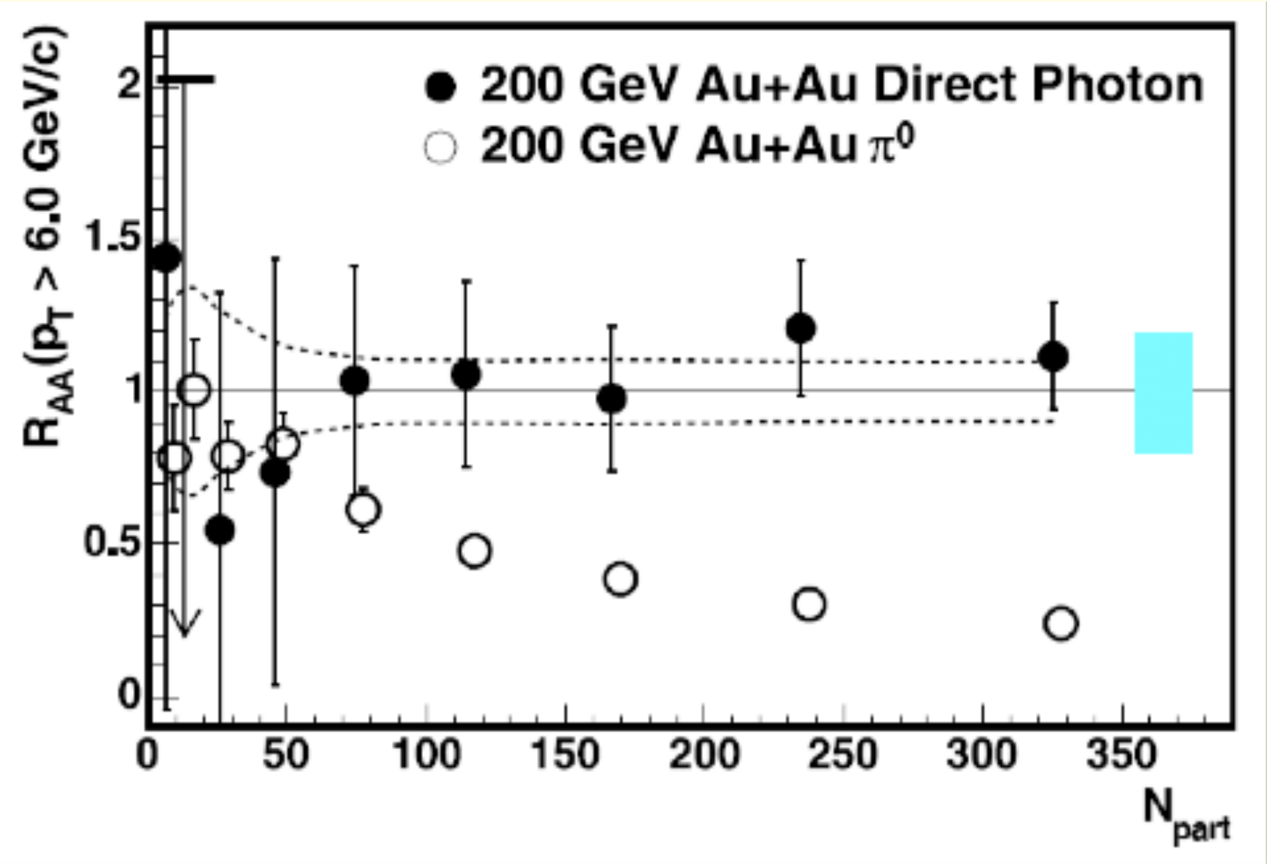


$$R_{AB} = \frac{dN/dp_T\big|_{A+B}}{\langle N_{coll} \rangle \times dN/dp_T\big|_{p+p}}$$



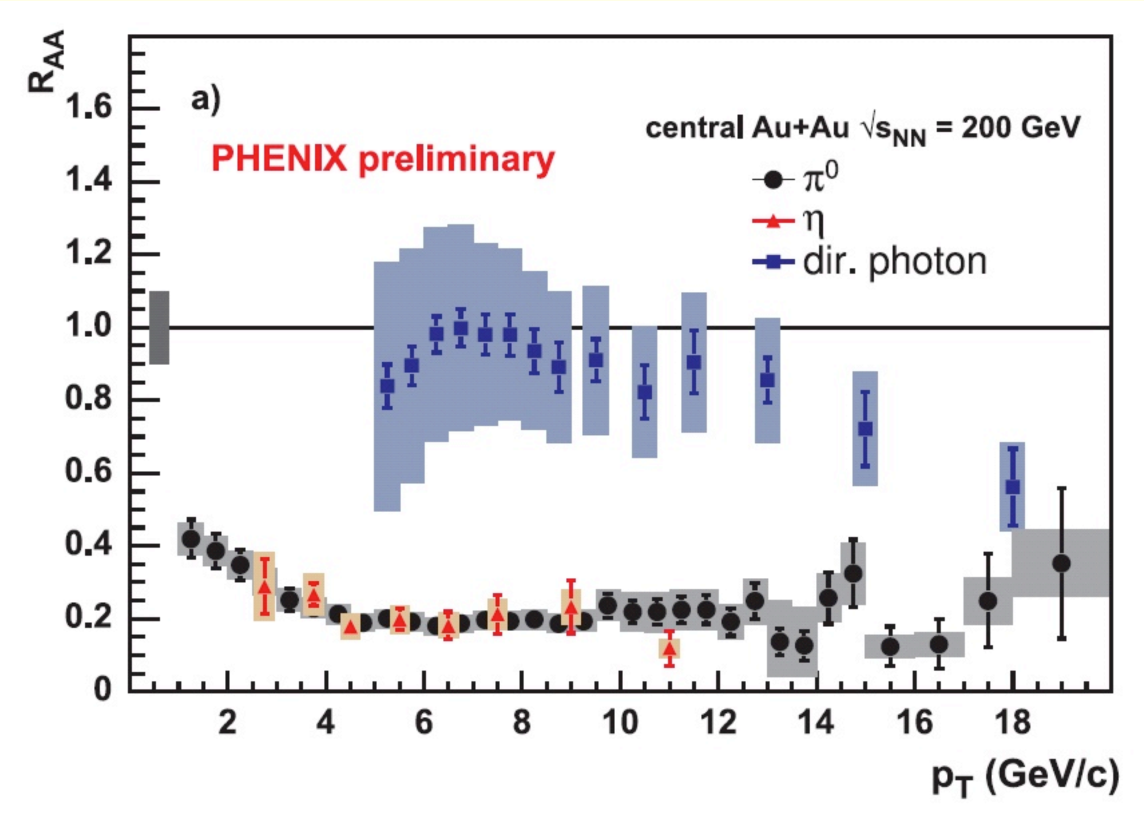
Hadrons are suppressed whereas direct photons are not: Evidence for parton energy loss (as expected in the QGP)

Centrality Dependence of π^0 and Direct Photon Production in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



Direct photons follow N_{coll} scaling expected for hard processes

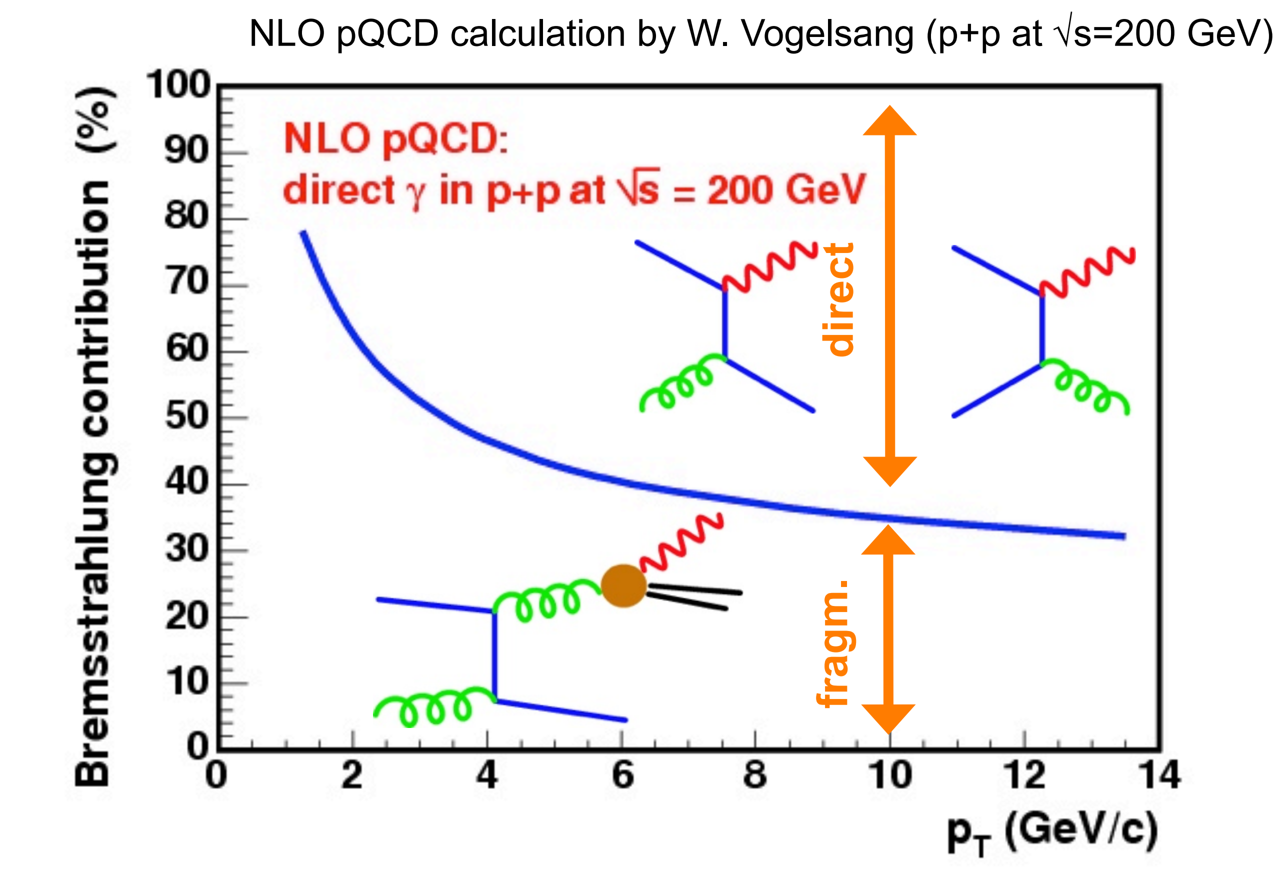
More Recent Data with Higher Statistics



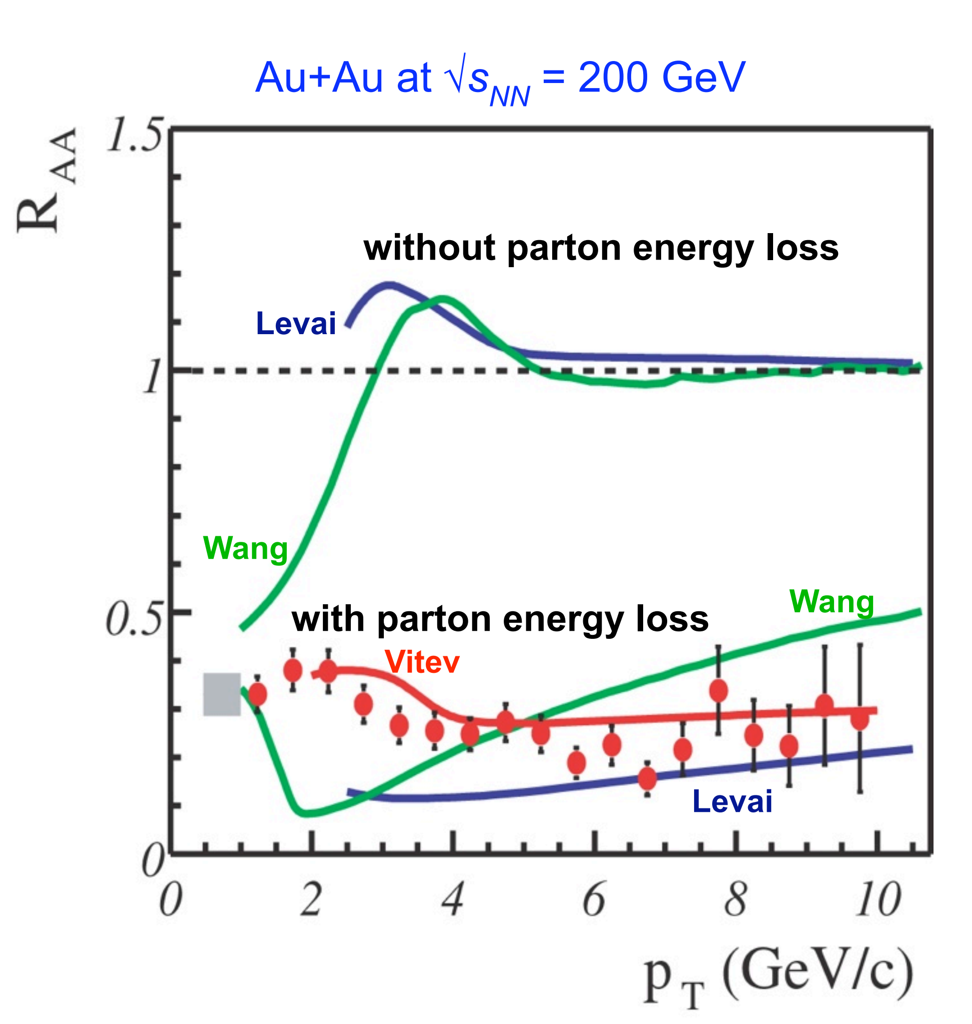
Possible Explanations for direct photon suppression at $p_T \approx 18$ GeV/c:

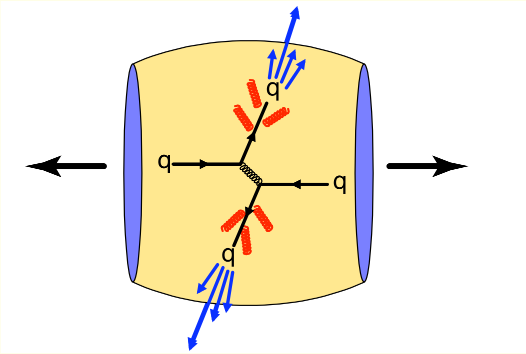
- **Proton/neutron difference**
- **Modification of parton distribution (EMC effect?)**
- **Quenching of fragmentation photons**

Direct and Fragmentation Component



Jet Quenching: Quantifying the Stopping Power of the Medium

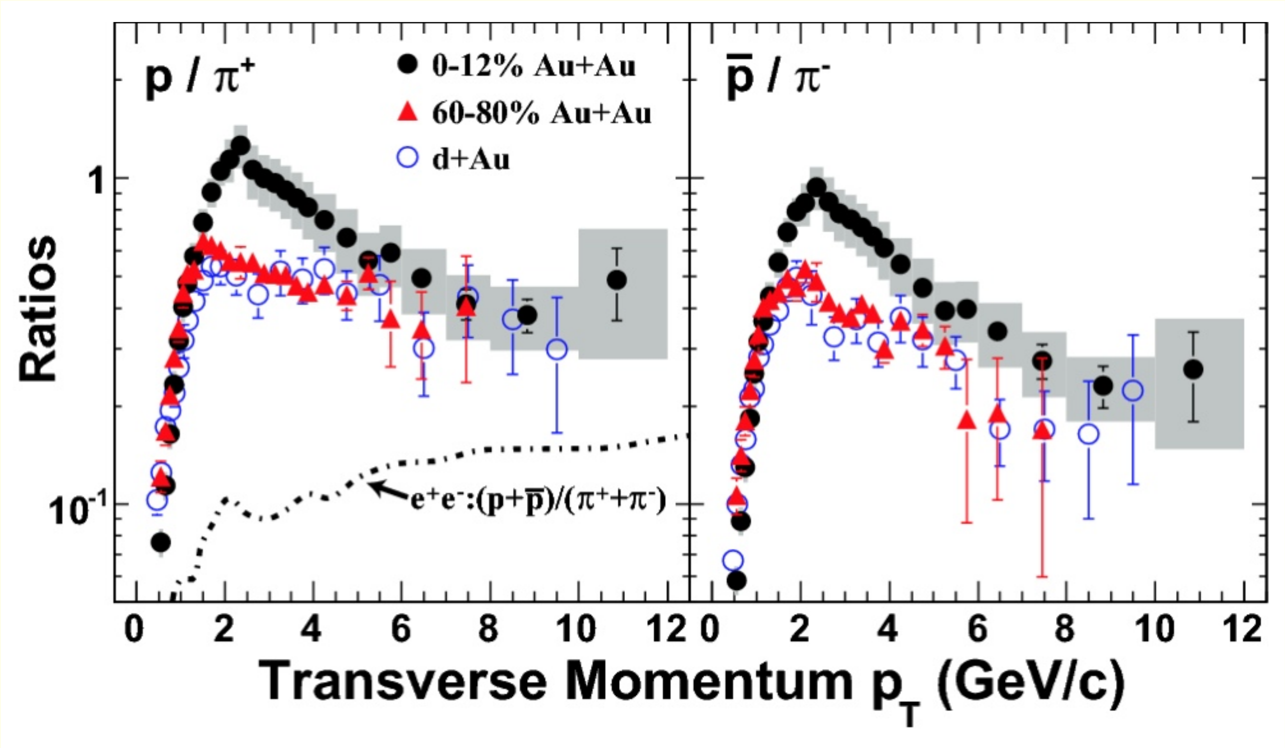




- Data imply
  - high initial gluon density
    $dN_{\mathrm{Gluonen}} / dy \approx 1000 \pm 200$
  - high energy density
    $\varepsilon > 10 \text{ GeV/fm}^3 \gg \varepsilon_c$
- Energy loss for a 10 GeV quark:

$$\Delta E = 1{,}5 - 2 \text{ GeV}$$

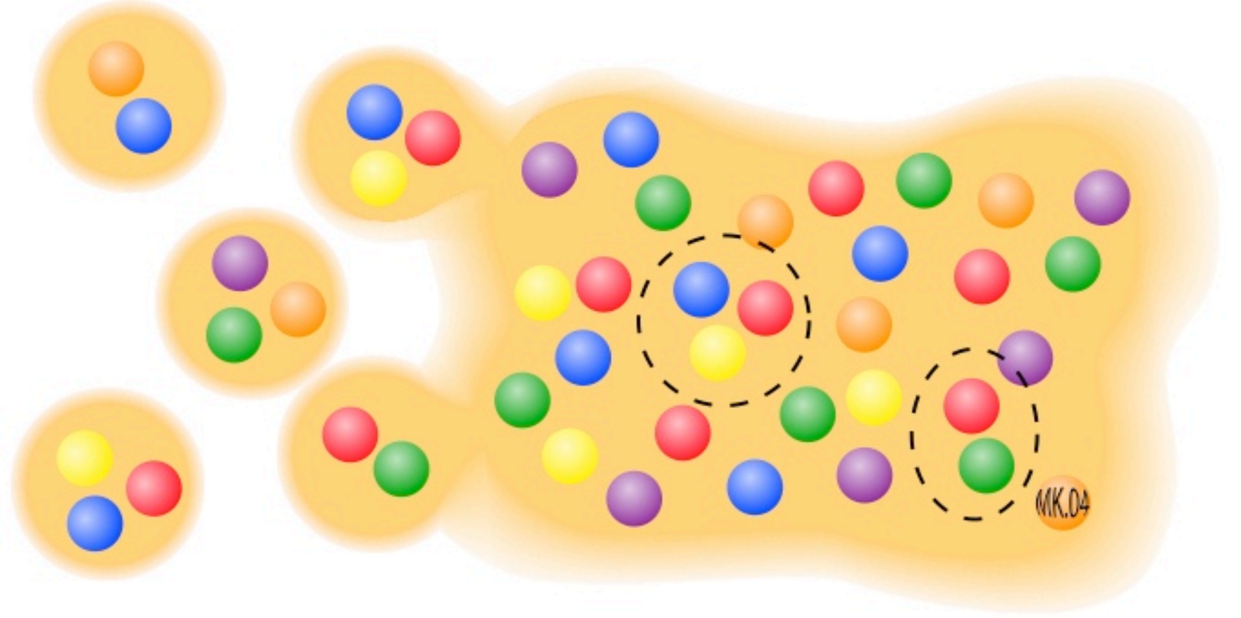
Particle Composition at Intermediate p_T: Unusually Large p/π Ratio for $2 < p_T < 6$ GeV/c



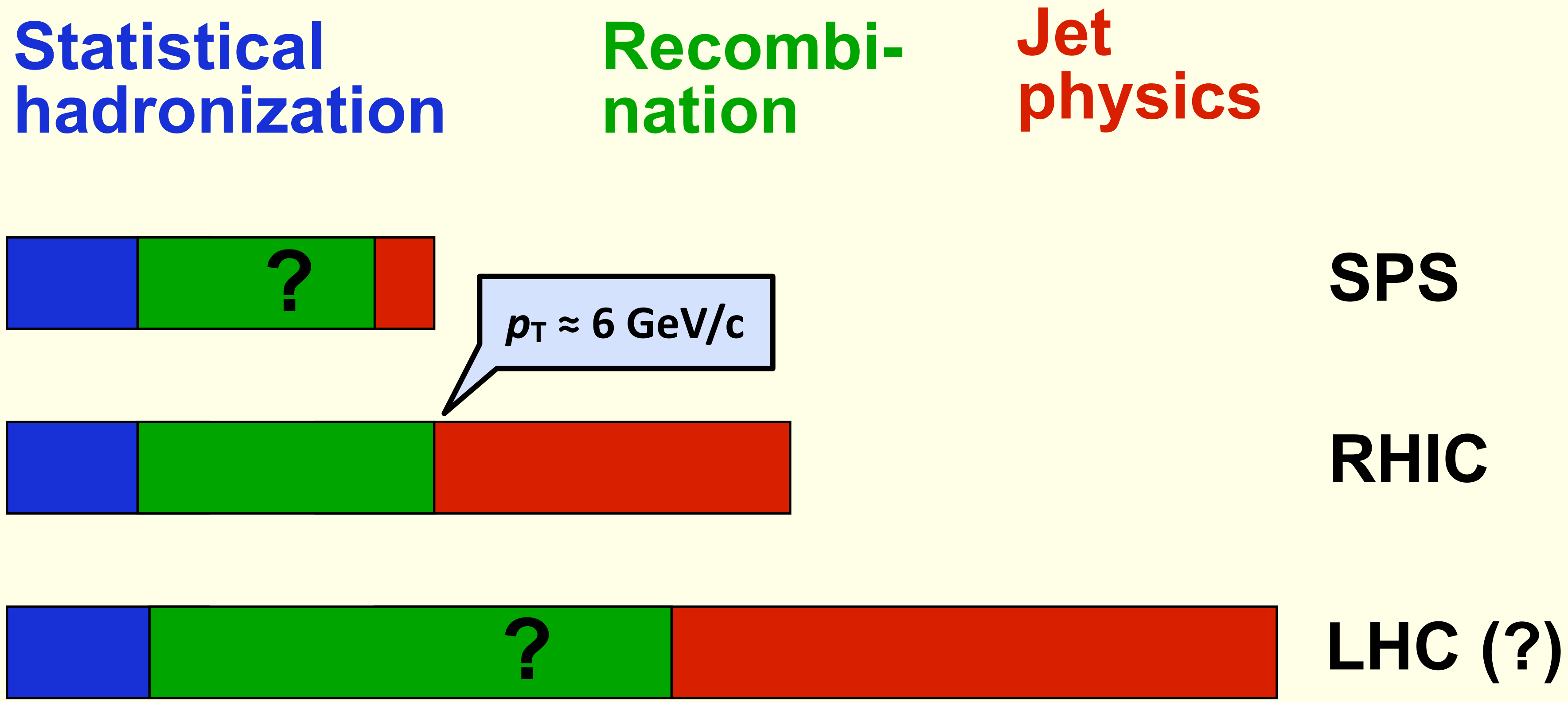
- For a parton that hadronizes in the vacuum after traversing the medium (A+A collision), particle ratios should be similar to those in d+Au or e^++e^-
- This is indeed approximately true for $p_T > 6$ GeV/c
- $2 < p_T < 6$ GeV/c: quark coalescence ?

What's going on at Intermediate p_T (~2 < p_T < ~6 GeV/c) ?

Coalescence of quarks from the QGP is a conceivable model for hadronization at intermediate p_T:



Different Physical Pictures at Different p_T Ranges in Heavy-ion Collisions



Berndt Mueller,
Quark Matter 2008

4.4 Further Tests of Parton Energy Loss

Is Parton Energy Loss Really the Correct Explanation?

Dependence on parton species:

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

Dependence of hadron suppression
on centrality and
mass number *A*

parton energy loss

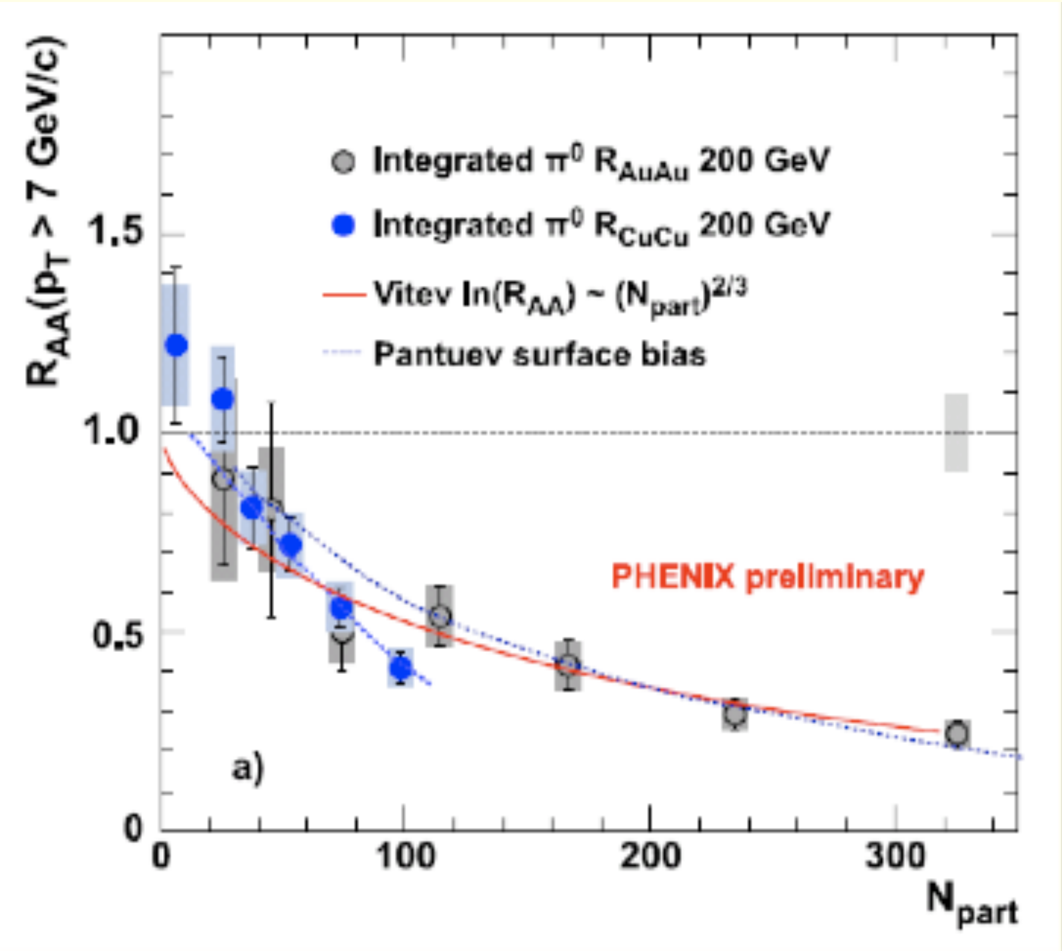
Dependence on
path length *L*

p_T dependence of
hadron suppression

Dependence on CMS
energy $\sqrt{s_{NN}}$

Dependence on particle
species (direct photons,
different hadron species)

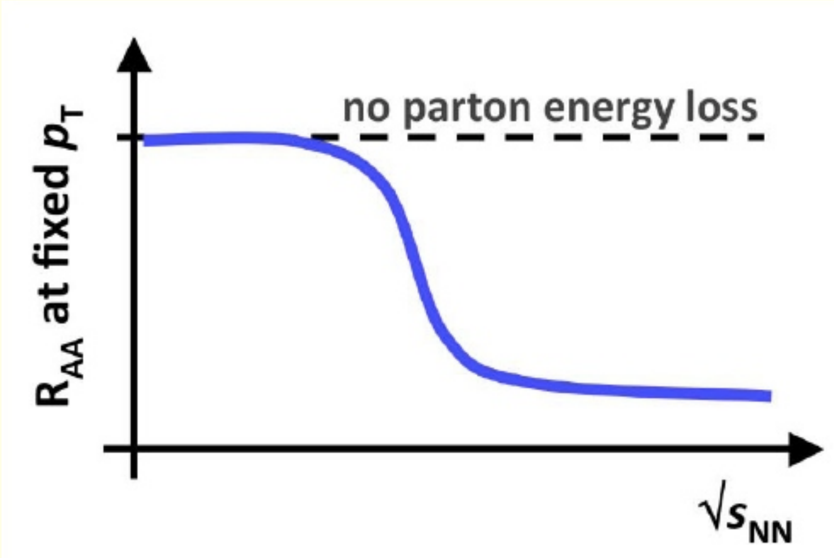
Dependence of the Suppression on the Size of the Nuclei: π^0 R_{AA} in Au+Au and Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV



Approximately same R_{AA} in Au+Au and Cu+Cu for similar N_{part} values in accordance with jet quenching models

$\sqrt{s_{NN}}$ Dependence of Parton Energy Loss

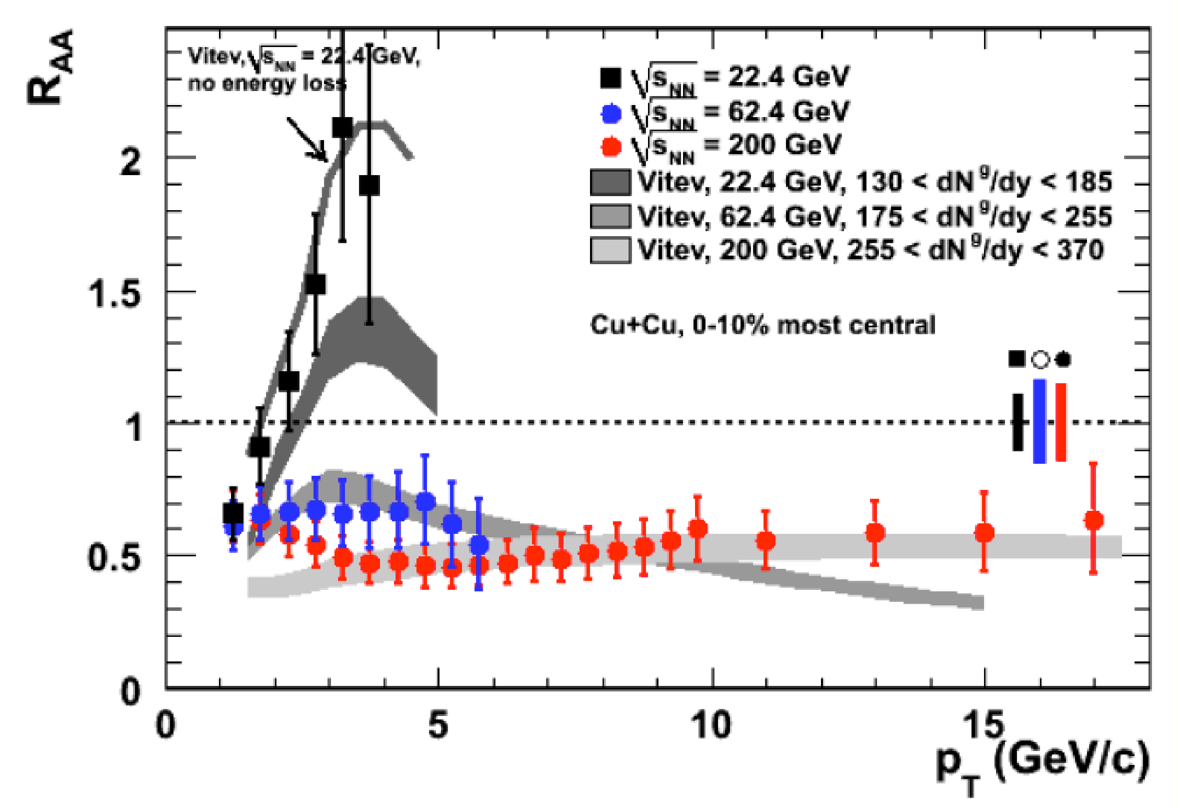
QGP $\overset{\Rightarrow}{\not\Leftarrow}$ **Suppression of hadrons at high p_T**



Onset of hadron suppression at a certain $\sqrt{s_{NN,min}}$?

How do properties of the created QGP depend on $\sqrt{s_{NN}}$?

Cu+Cu at $\sqrt{s_{NN}}$ = 22.4, 62.4 and 200 GeV



Phenix, Physical Review Letters 101,162301 (2008)

62.4 and 200 GeV

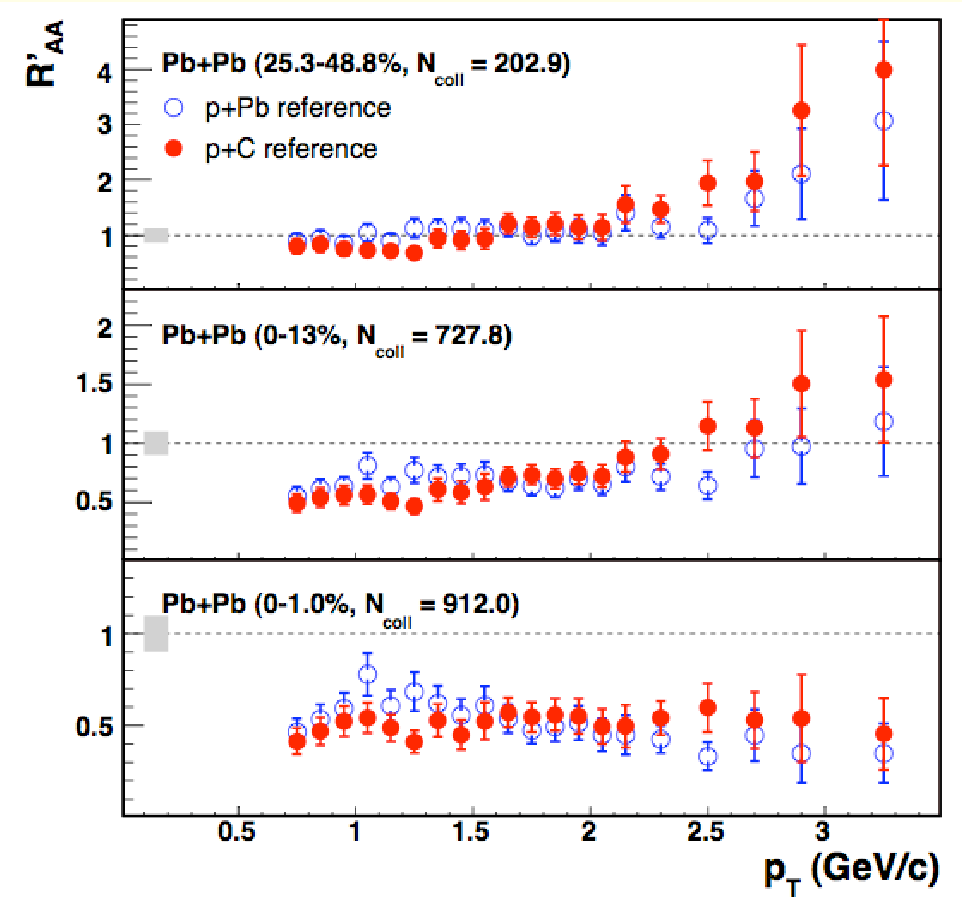
Consistent with parton energy loss model for p_T > 3 GeV/c

22.4 GeV

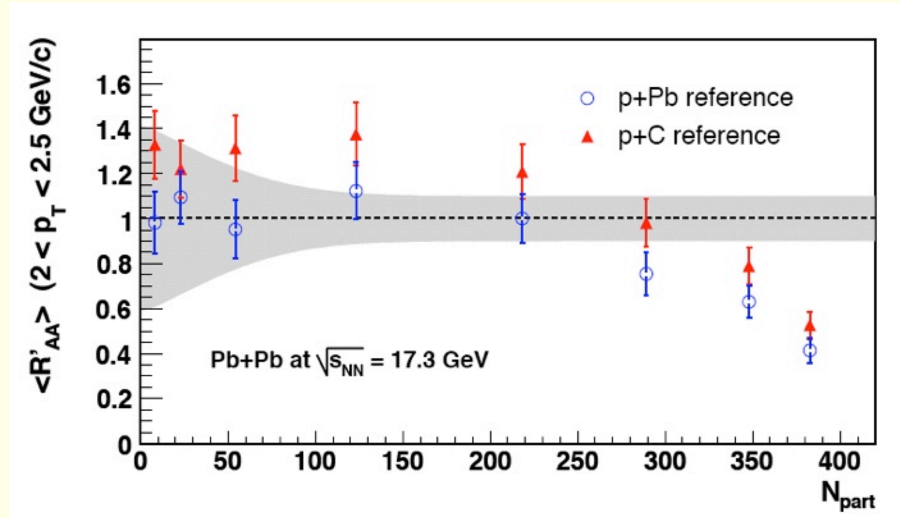
- No suppression
- Enhancement consistent with a calculation that describes Cronin effect in p+A

In Cu+Cu parton energy loss starts to prevail over Cronin enhancement between $\sqrt{s_{NN}}$ = 22.4 GeV und 62.4 GeV

$\sqrt{s_{NN}}$ Dependence of R_{AA} :
R_{AA} in Pb+Pb Collisions at the CERN SPS ($\sqrt{s_{NN}}$ = 17.3 GeV)



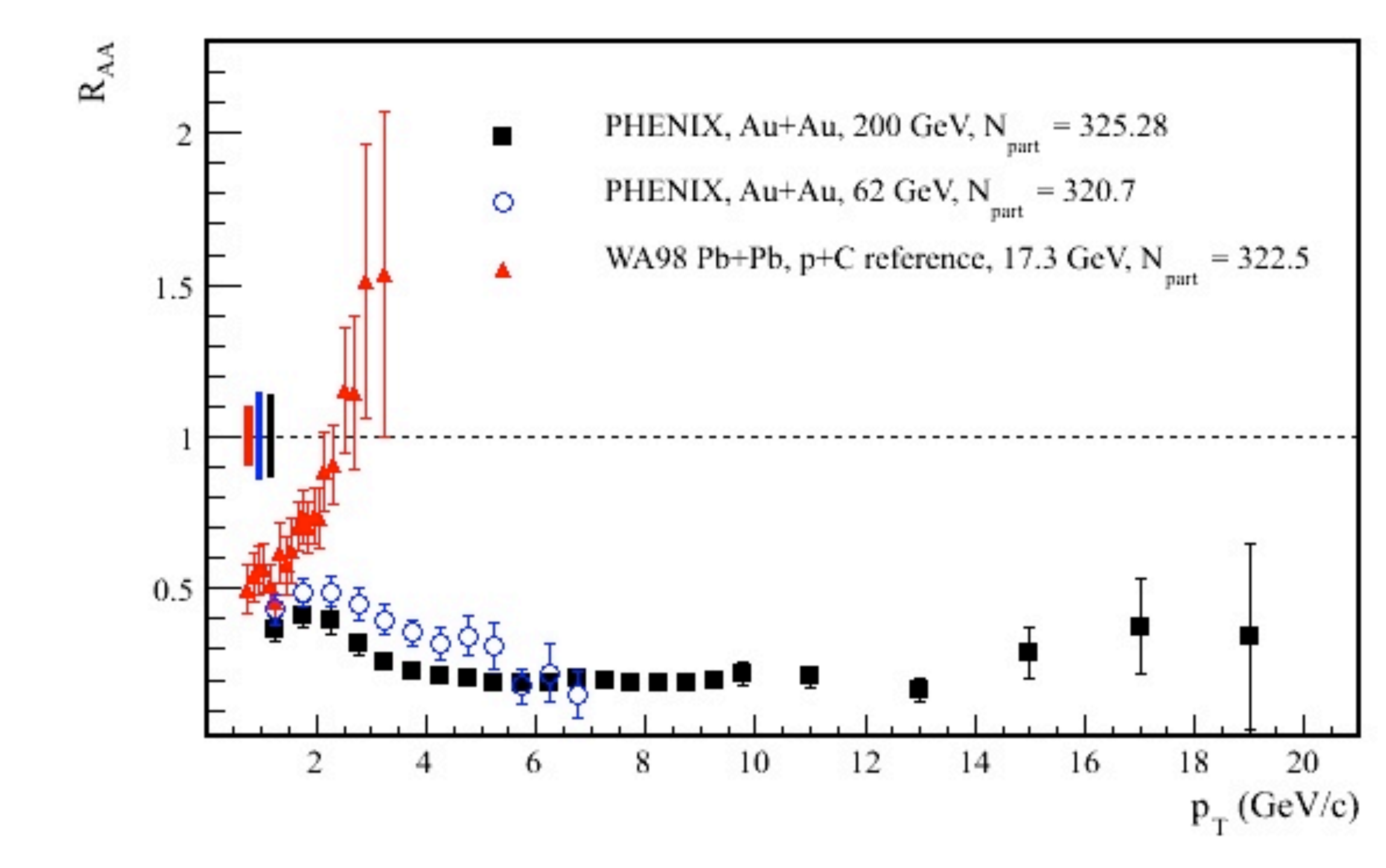
$$R'_{AA} = \frac{\langle N_{coll}^{p+B} \rangle}{\langle N_{coll}^{A+A} \rangle} \frac{dN_{\pi^0}/dp_T|_{A+A}}{dN_{\pi^0}/dp_T|_{p+B}}$$



WA98, Physical Review Letters 100, 242301 (2008)

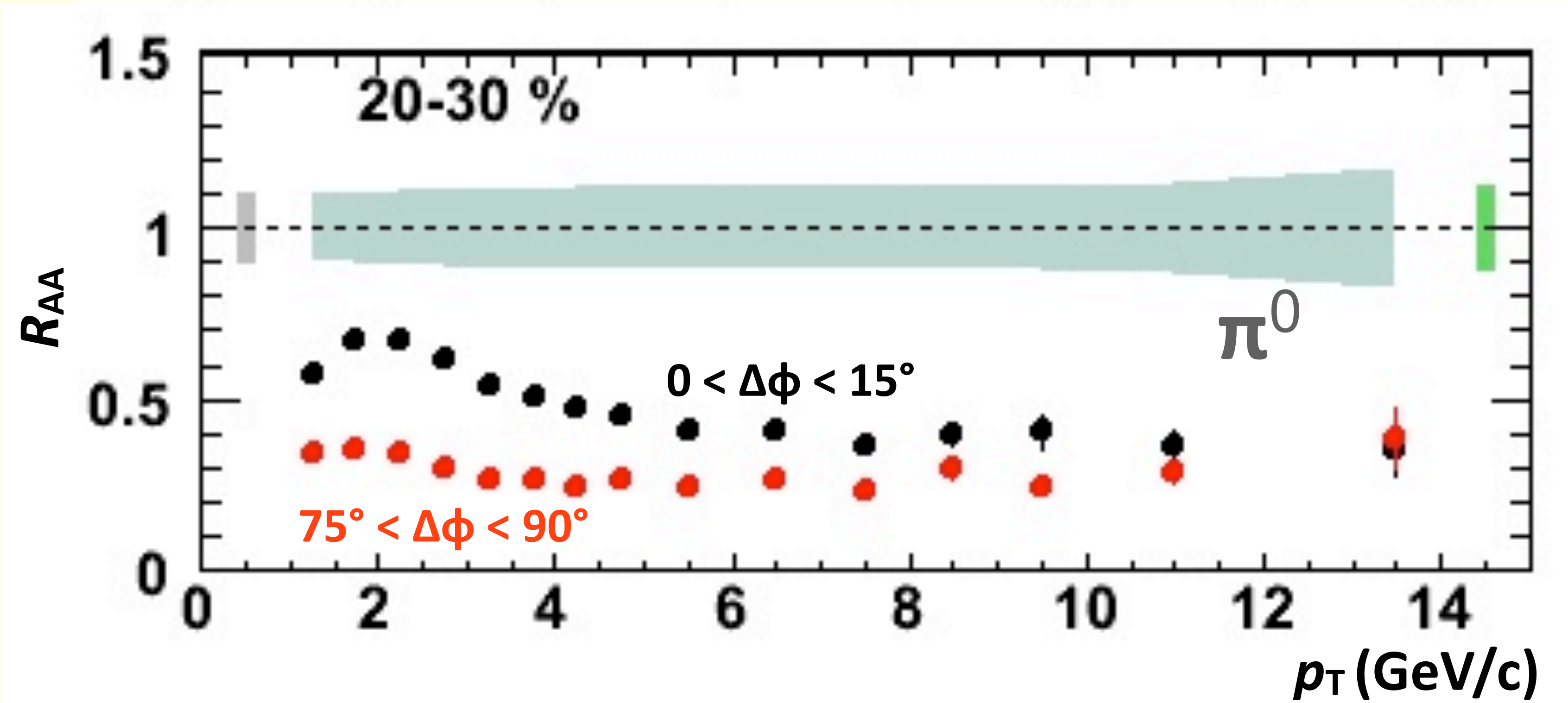
High p_T pion suppression even at SPS, but only in very central Pb+Pb collisions (N_{part} > 300)

Energy Dependence of R_{AA} in central Pb+Pb (Au+Au): $\sqrt{s_{NN}}$ = 17.3, 62.4 and 200 GeV

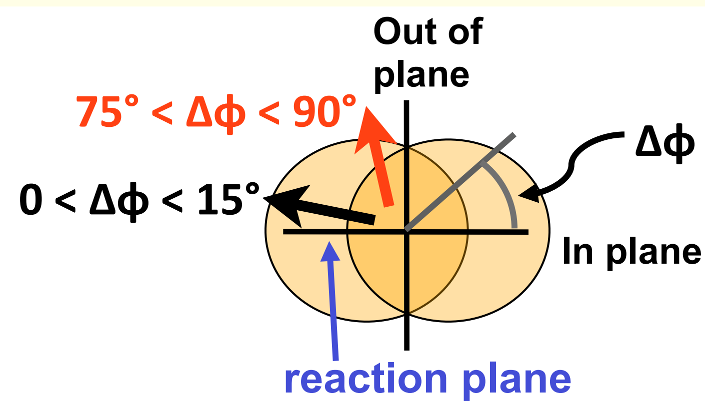


Same observation as in lighter system (Cu+Cu):
Suppression sets in between $\sqrt{s_{NN}}$ = ~ 20 GeV und 62.4 GeV

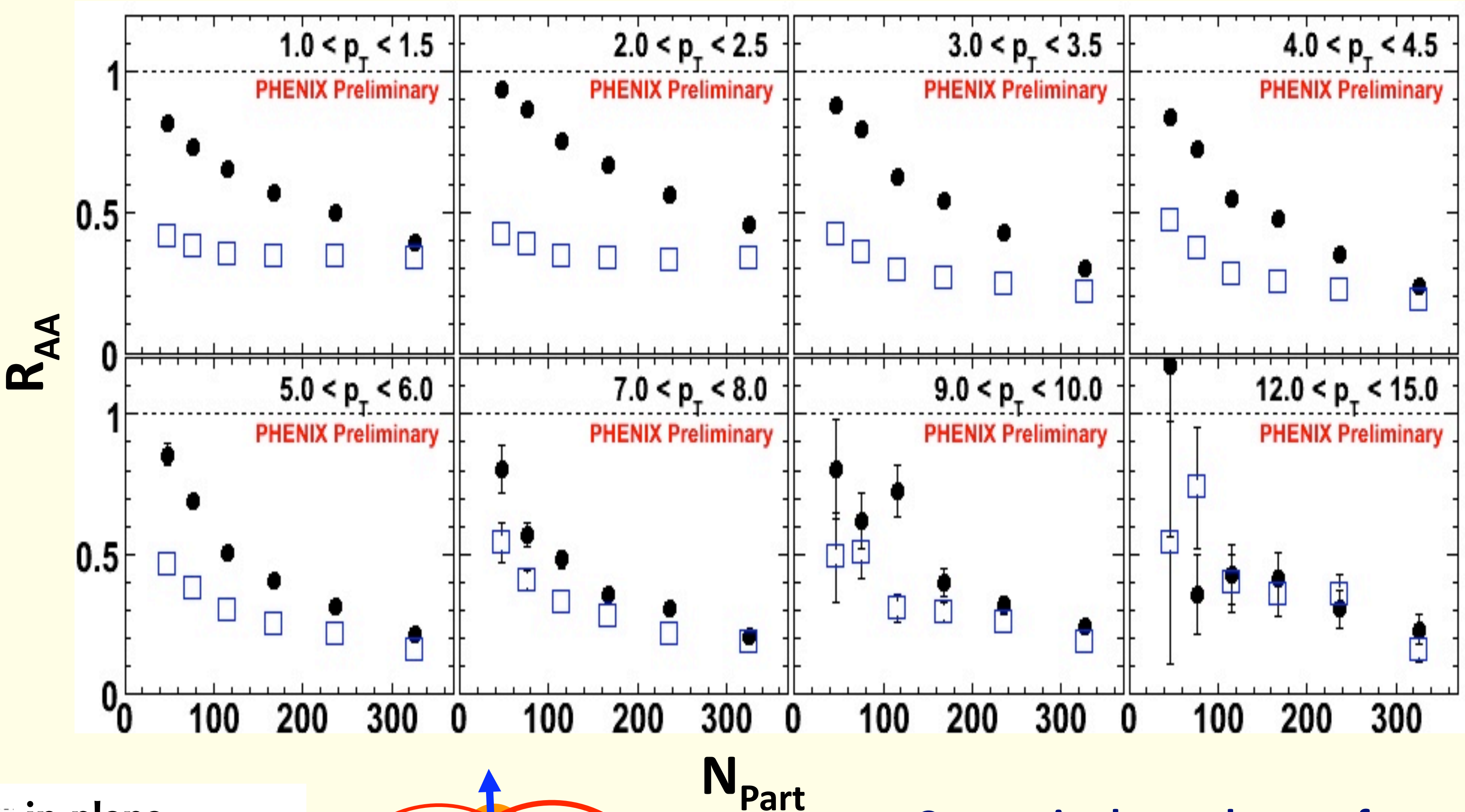
Pathlength Dependence: Studying the Reaction Plane Dependence of R_{AA}



- Pathlength in the medium is longer in the out of plane direction
- R_{AA} expected to smaller ou of plane, indeed observed



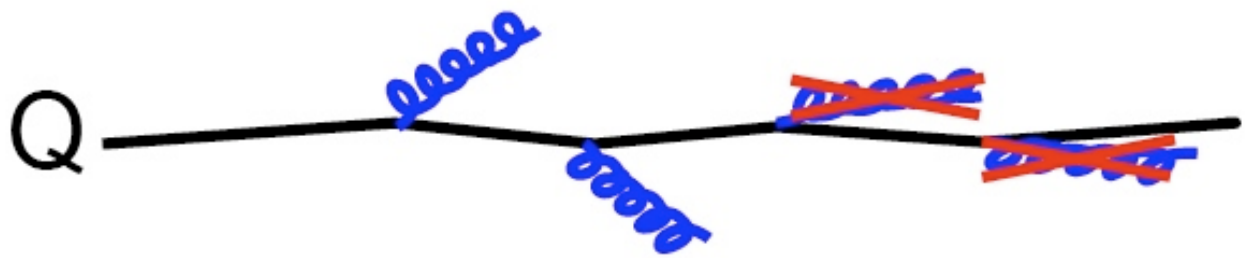
π^0 R_{AA} as a Function of the Angle w.r.t. the Reaction Plane: Centrality Dependence



- Constrain dependence of parton energy loss on geometry/path length
- Unfortunately, this doesn't distinguish between different theoretical approaches so far (talk Majumder)

Dead Cone Effect:

- Gluon emission at small angles suppressed for heavy quarks
- Consequence: Energy loss for heavy quarks expected to be smaller



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

Dokshitzer & Kharzeev, PLB 519(2001)199

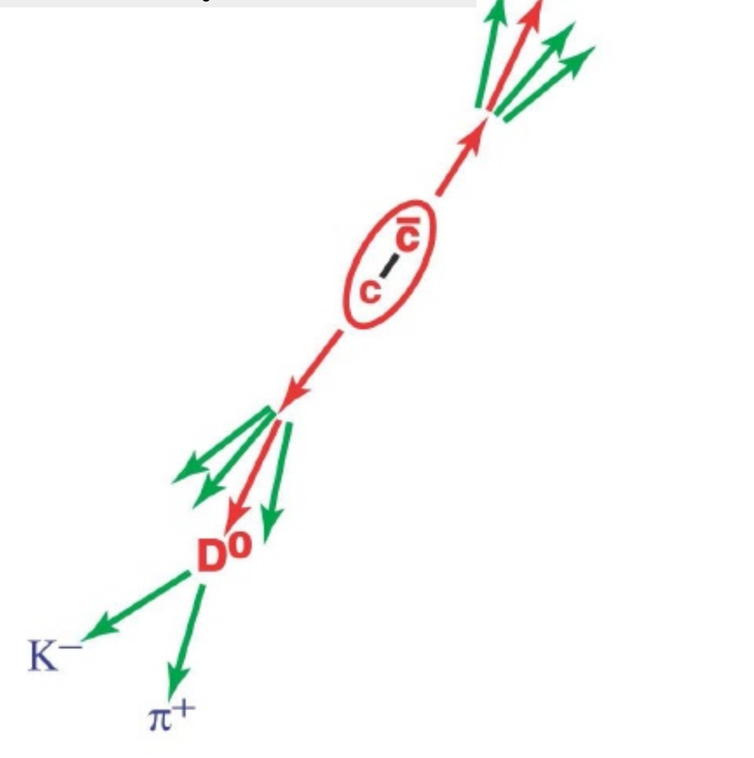
Heavy Quark Energy Loss: Measurement of Charm Production via Electrons

$1 < p_T < 3\,\mathrm{GeV/c}$:

dominated by c decay

$p_T > 4\,\mathrm{GeV/c}$:

dominated by c and b decays



- **Observable:**
  Excess electrons after subtraction of trivial sources (γ conversion, π^0 Dalitz decay [$\pi^0 \rightarrow e^+e^-$], ...)
- **Electrons from decay of charm and bottom quarks dominant source of excess electrons**

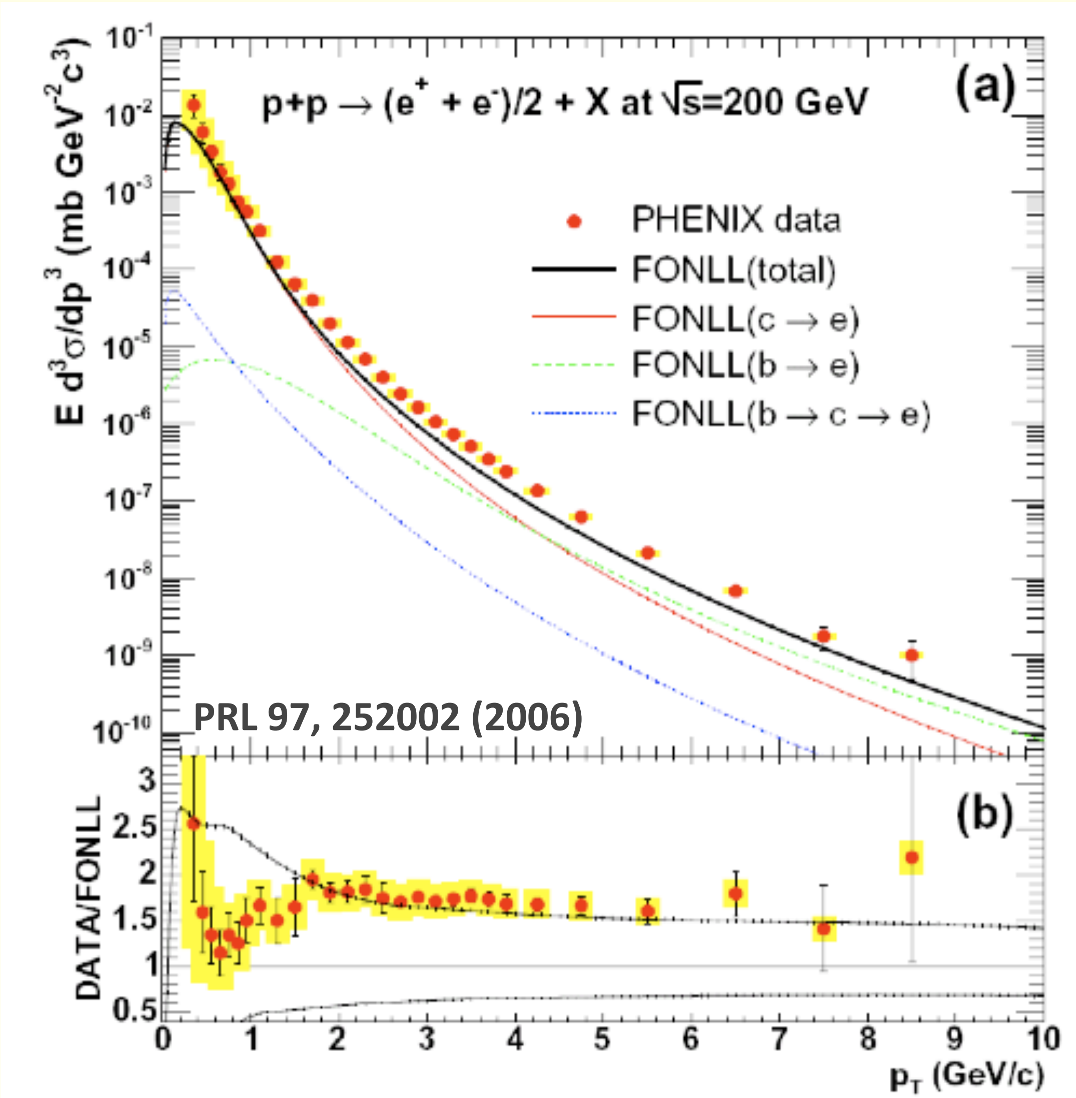
$$D^0(c\bar{u}) \rightarrow K^-(s\bar{u}) + e^+ + \nu_e$$

- **D meson reconstruction via Kπ channel requires good secondary vertex reconstruction:**

$$\mathrm{D}^{+/-}: \; c\tau = 312\ \mu\mathrm{m}$$
$$\mathrm{D}^0: \; c\tau = 123\ \mu\mathrm{m}$$

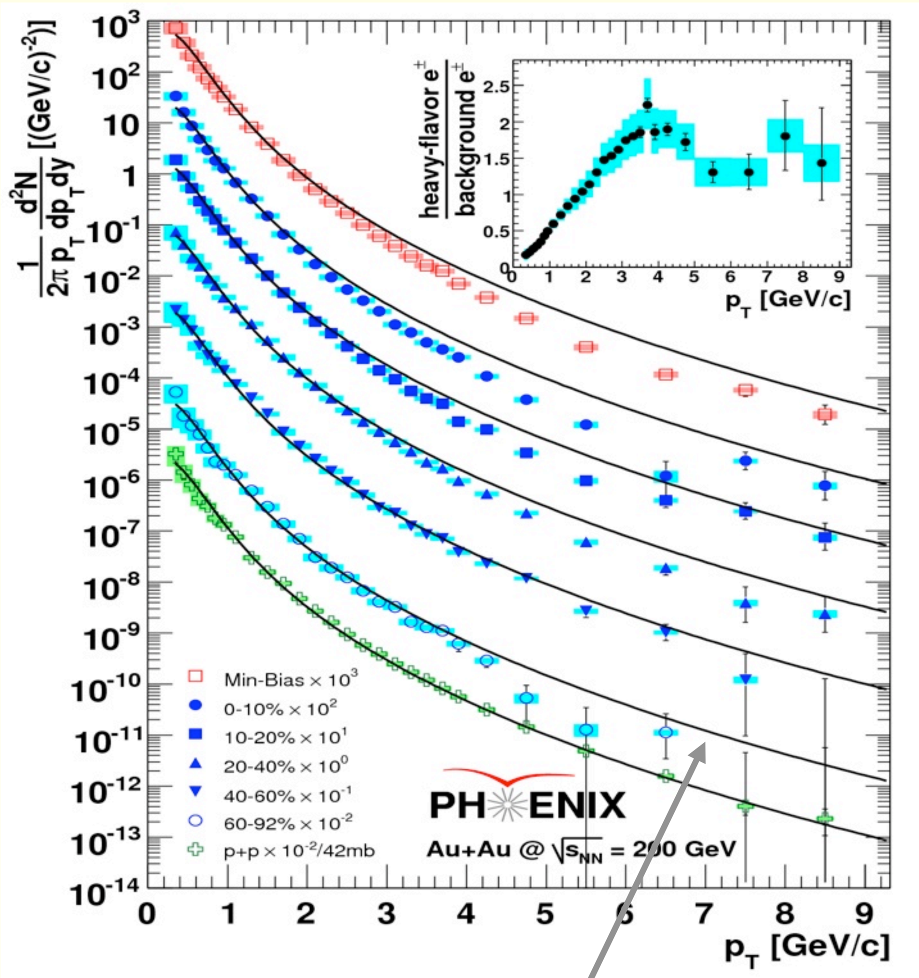
$$L_{\mathrm{lab}} = v \cdot \gamma \cdot \tau = \beta \cdot \gamma \cdot c\tau = \frac{p}{mc} \cdot c\tau$$

Excess Electrons in p+p at $\sqrt{s}$ = 200 GeV

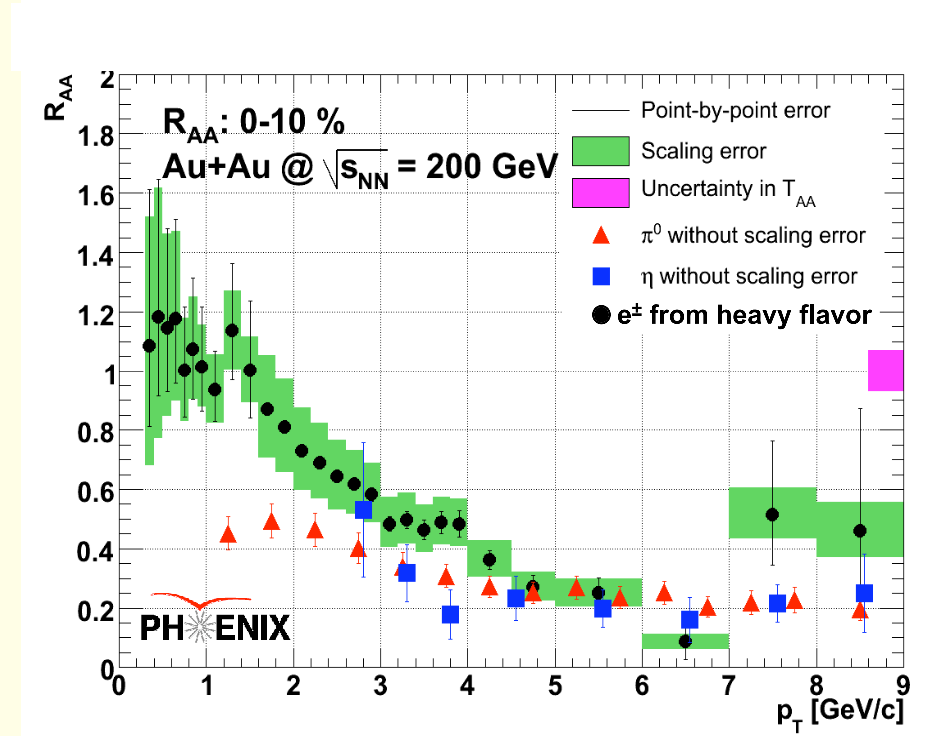


Perturbative QCD calculation (FONLL = Fix-order-next-to-leading-log) in agreement with measurement within systematic uncertainties

Excess Electrons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: As Strongly Suppressed as Pions

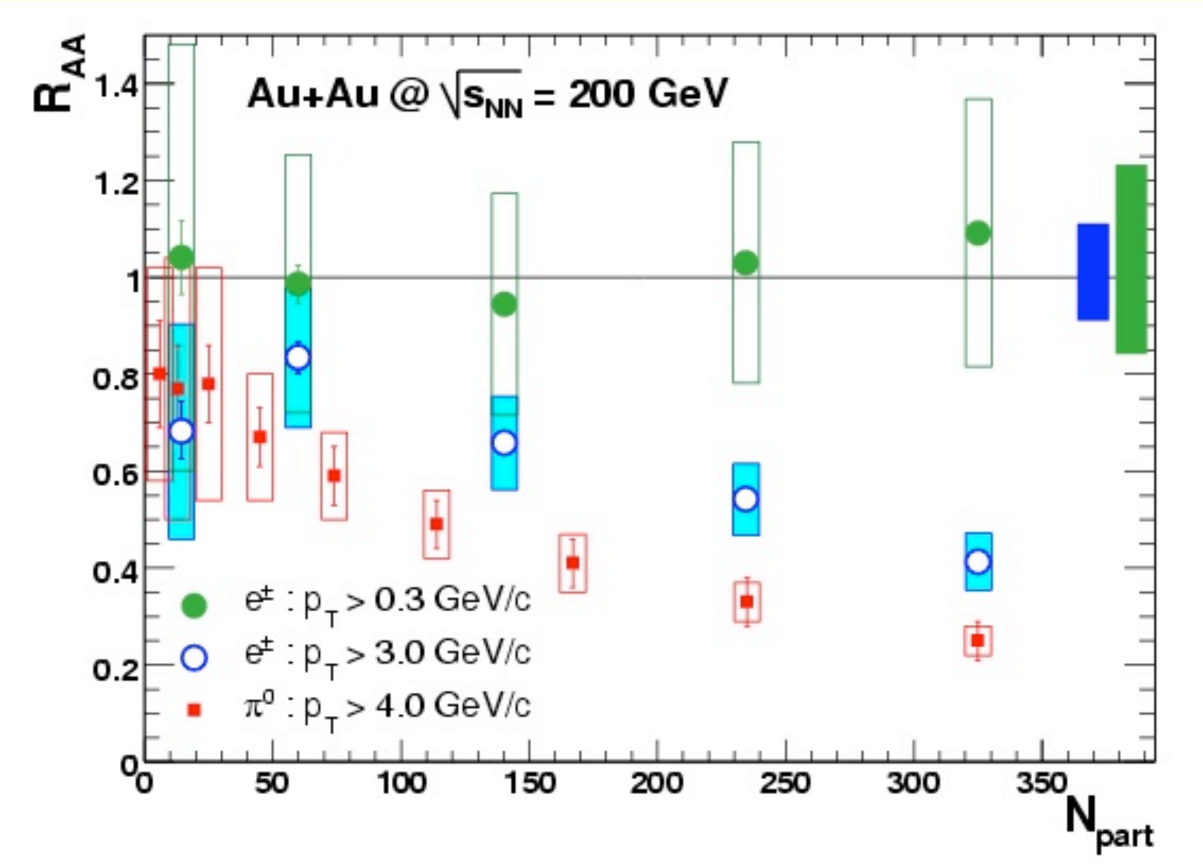


FONLL calculation scaled by T_{AB}



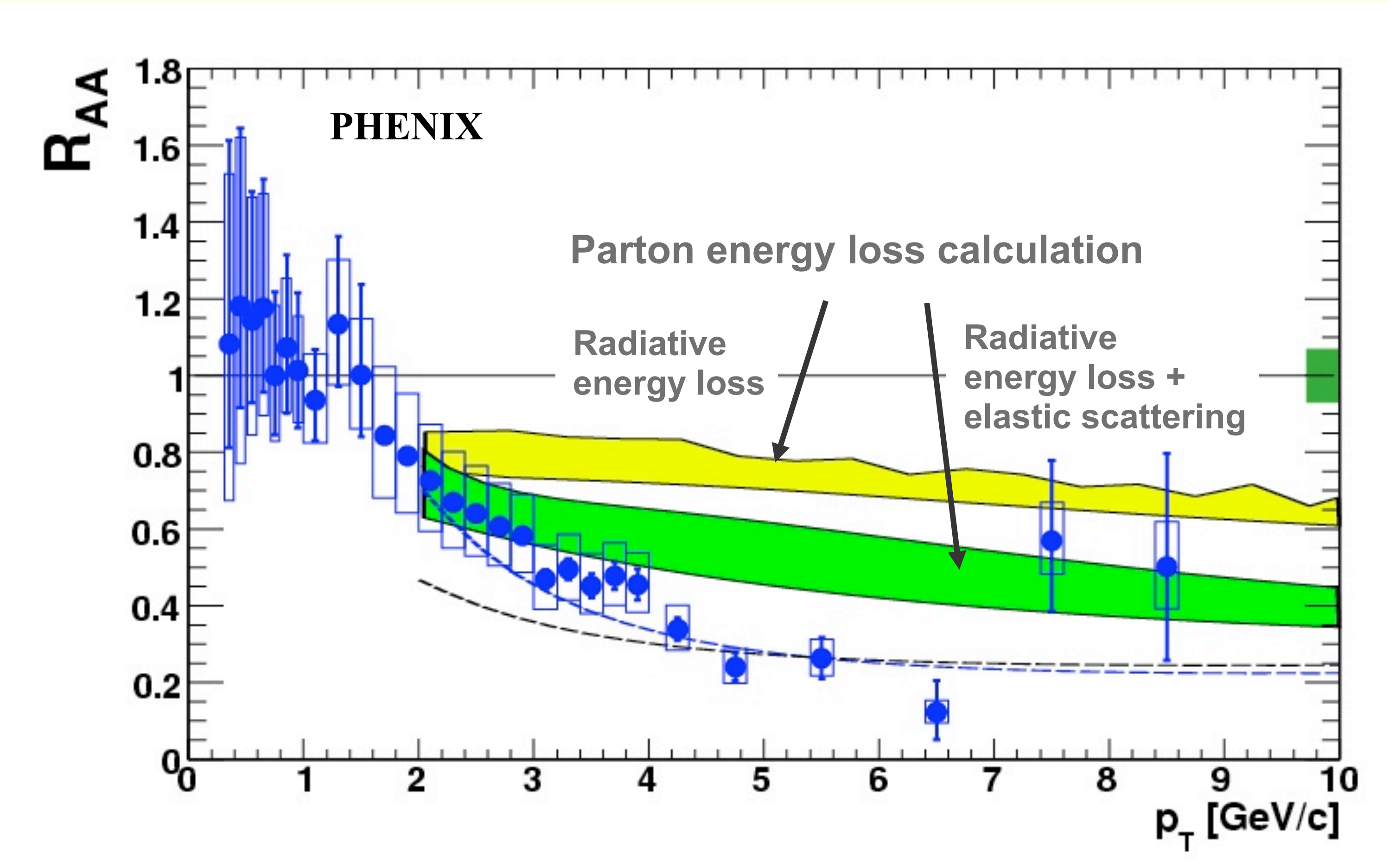
Electrons from heavy quarks as strongly suppressed in central Au+Au as pions

Centrality Dependence of the Electron Suppression



- Total charm yield (i.e. p_T > 0.3 GeV/c) scales with TAB as expected for charm production in hard processes
- High p_T > 4 GeV/*c* charm yields appear to be suppressed in central Au+Au collisions

Excess Electrons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: Not Really Understood with Current Energy Loss Models



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

Is Parton Energy Loss Really the Correct Explanation?

parton energy loss

Dependence of hadron suppression on centrality and mass number *A* ✓

p_T dependence of hadron suppression ✓

Dependence on CMS energy $\sqrt{s_{NN}}$ ✓

Dependence on parton species:

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

Open questions

Dependence on path length *L*

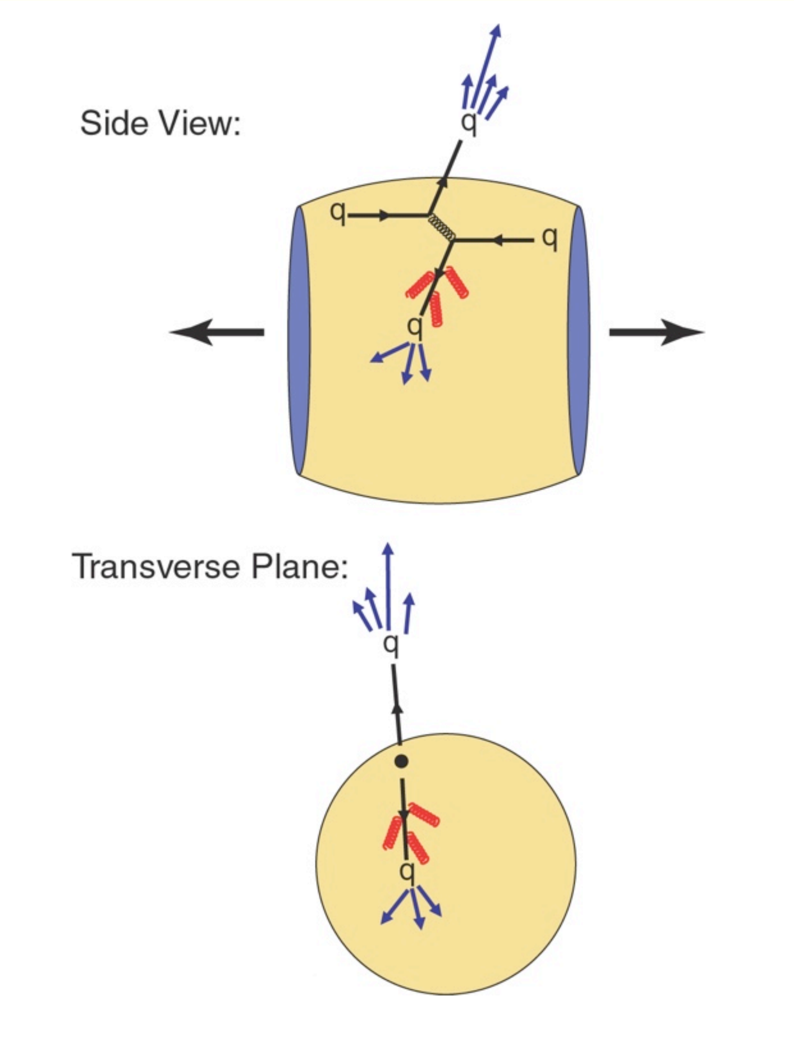
open

Dependence on particle species (direct photons, different hadron species)

some open questions

4.5 Two-Particle Azimuthal Correlations

Two-Particle Correlations

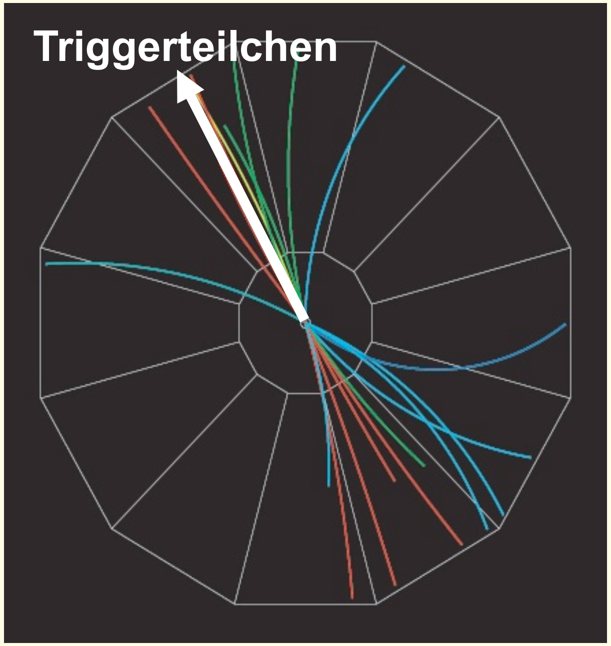


Expectation in jet quenching scenario:

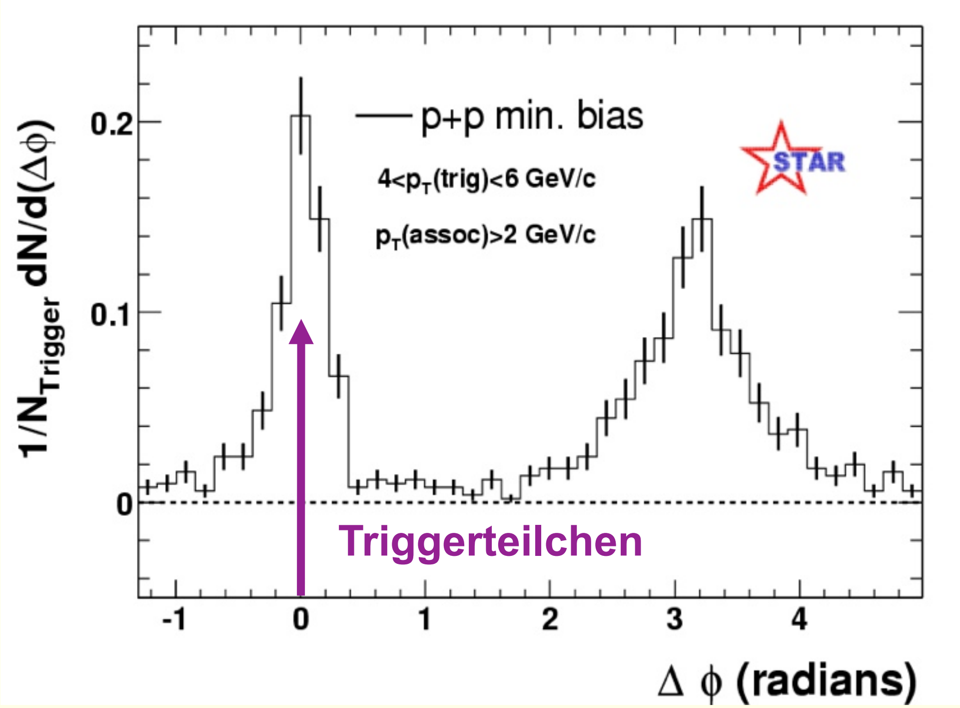
- **Angular correlations around 0° as in p+p**
- **Suppression of angular correlations around 180°**

Two-Particle Correlations in p+p

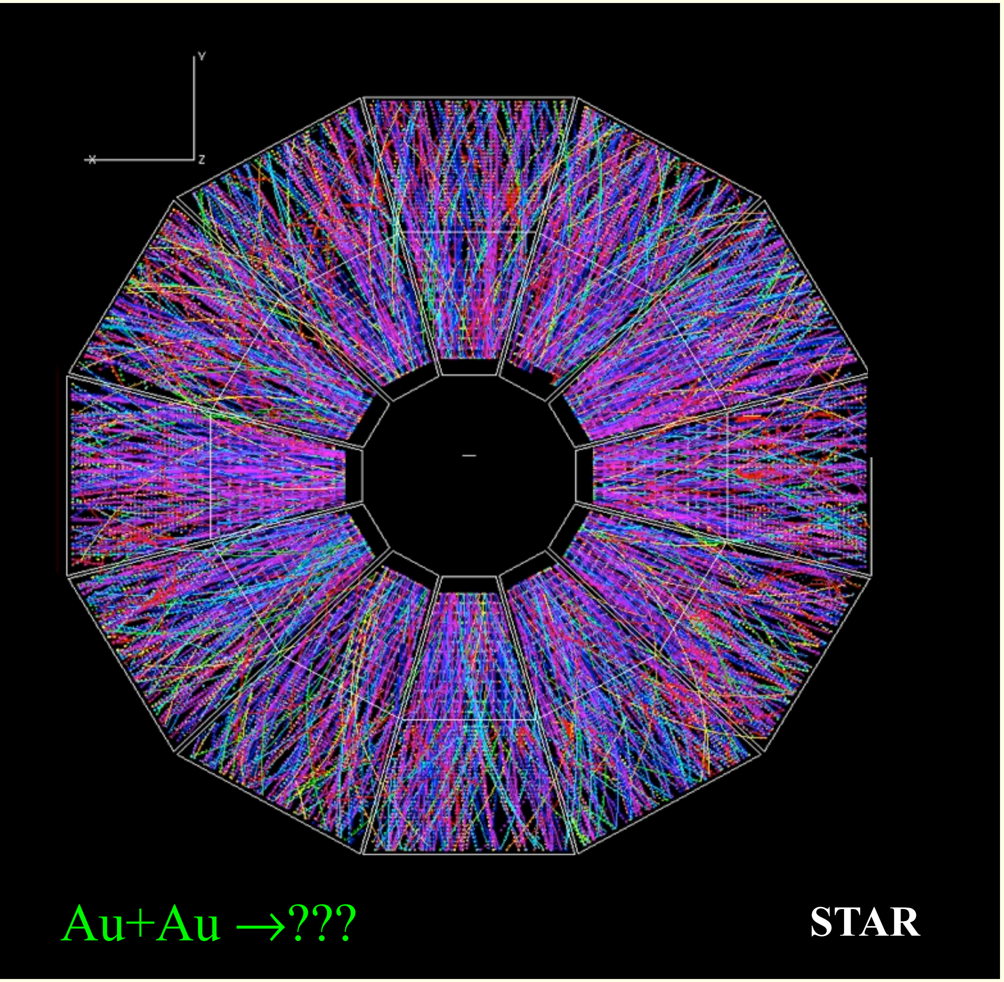
p+p → 2 Jets

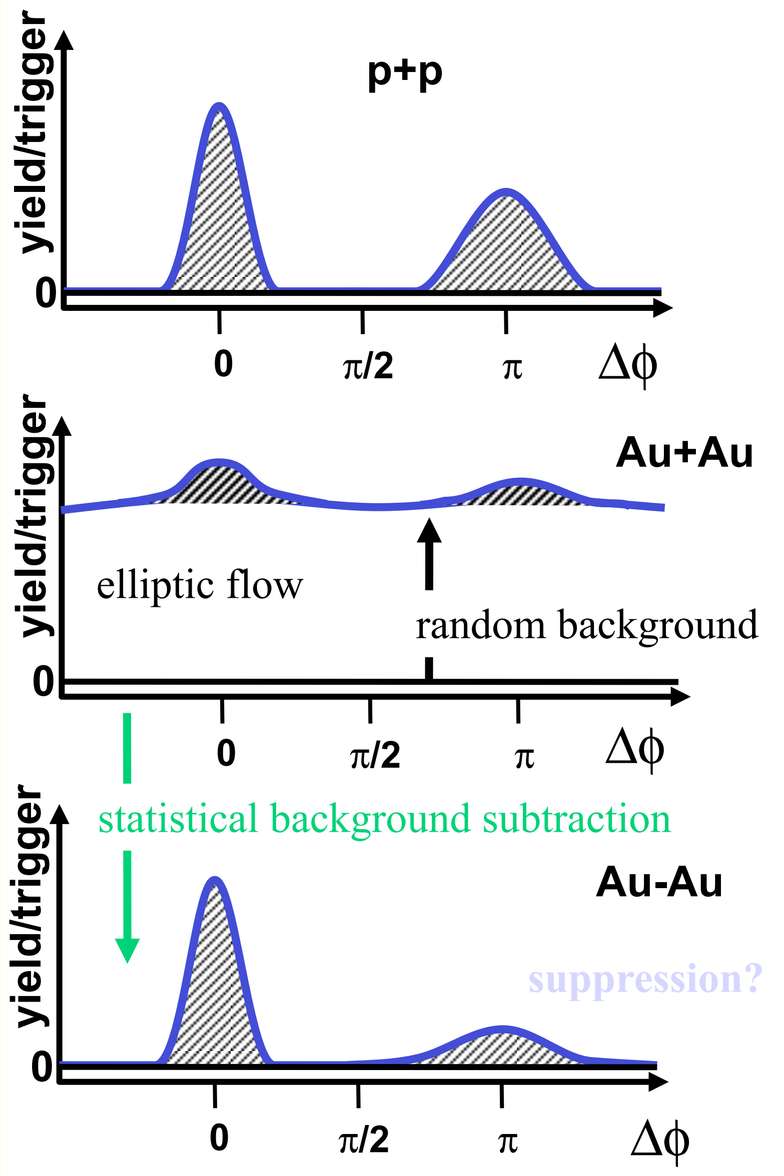


- **Trigger particle: p_T > 4 GeV/c**
- **Associated particle: p_T > 2 GeV/c**



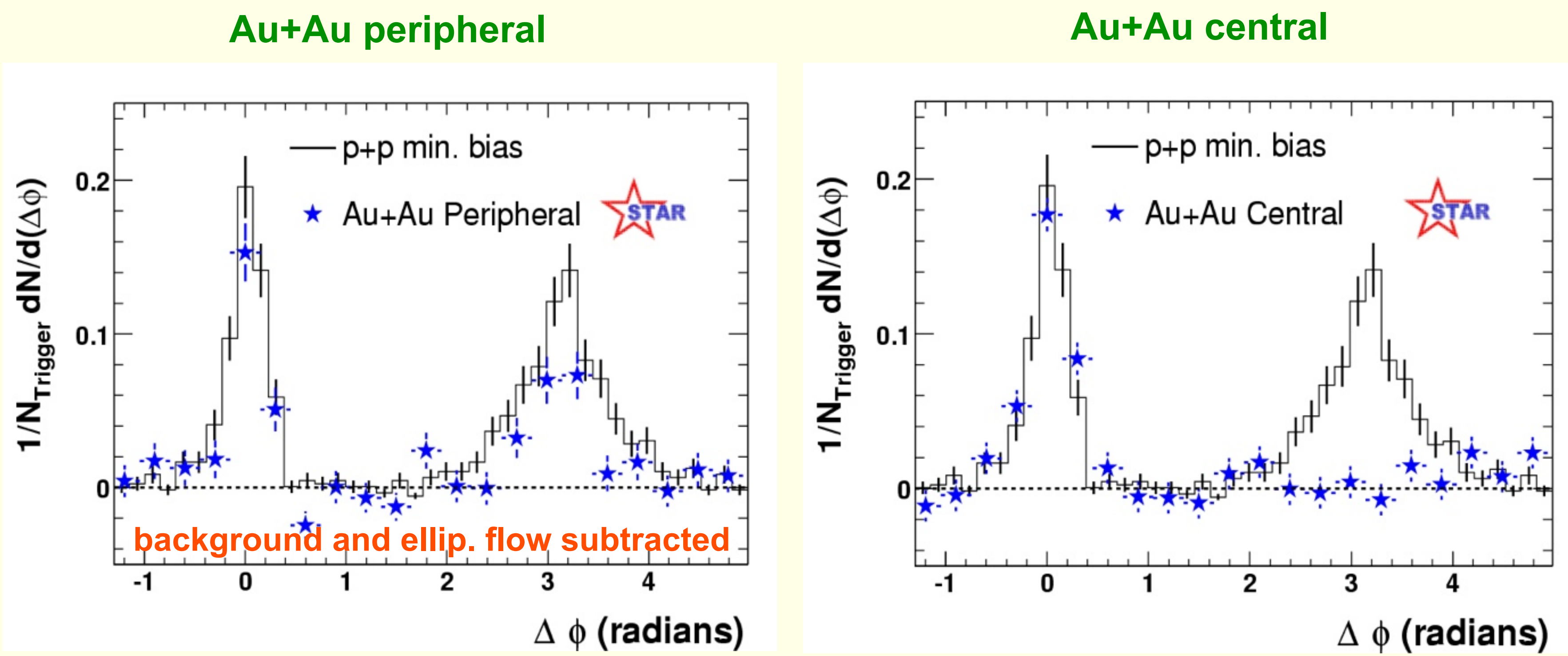
Two-Particle Correlations in A+A





Jet correlations in Au-Au via statistical background subtraction

Two-Particle Correlations in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

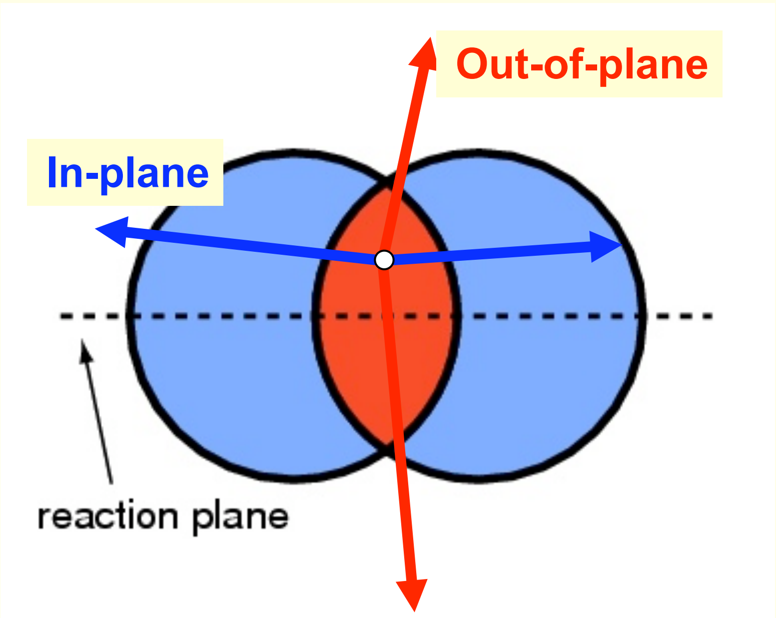


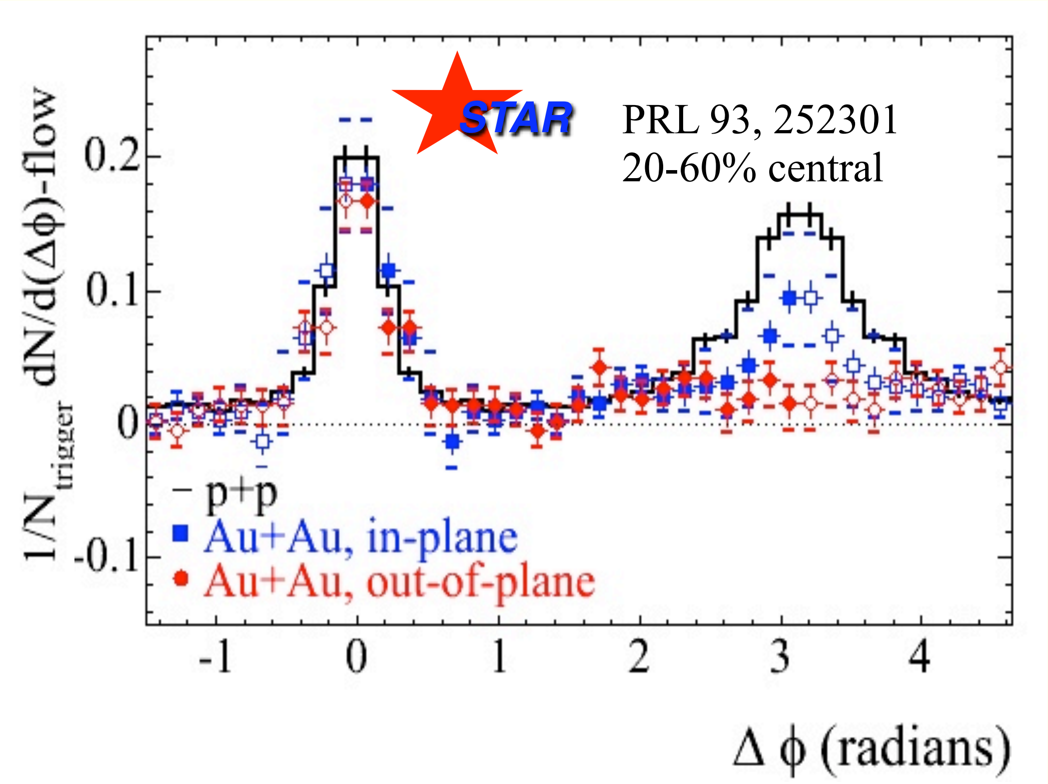
Trigger particle: p_T > 4 GeV/c
Associated particle: p_T > 2 GeV/c

PRL 90, 082302 (2003)

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

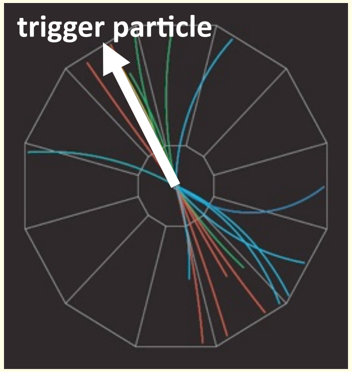
Dependence of the Away-side Peak on Angle w.r.t. the Reaction Plane



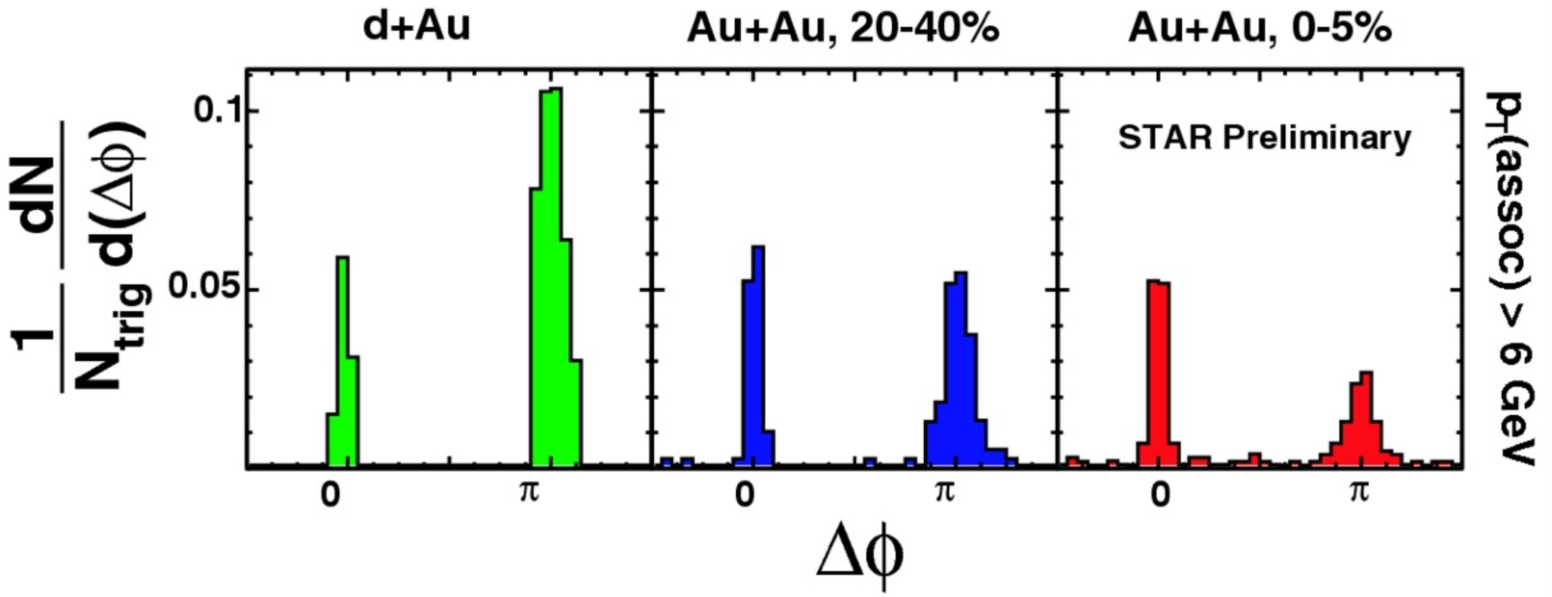


Stronger suppression at $\Delta\phi$ = 180° if jet axis is perpendicular to reaction plane, in line with jet quenching scenario.

Two-Particle Correlations: Towards higher p_T

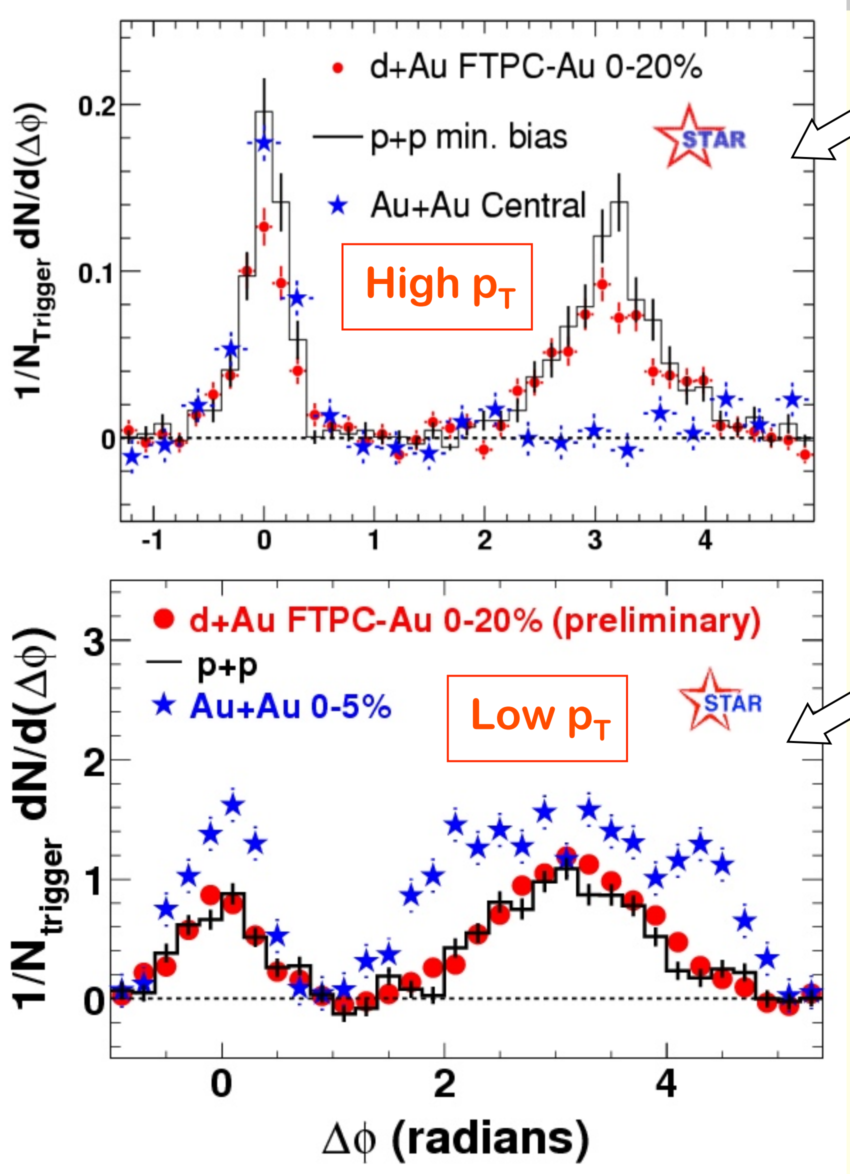


- **Trigger particle: p_T > 8 GeV/*c***
- **Associated particle: p_T > 6 GeV/*c***



For higher jet energies the correlation at Δφ = 180° in central Au+Au is not fully suppressed anymore

What happens to the jet energy ?

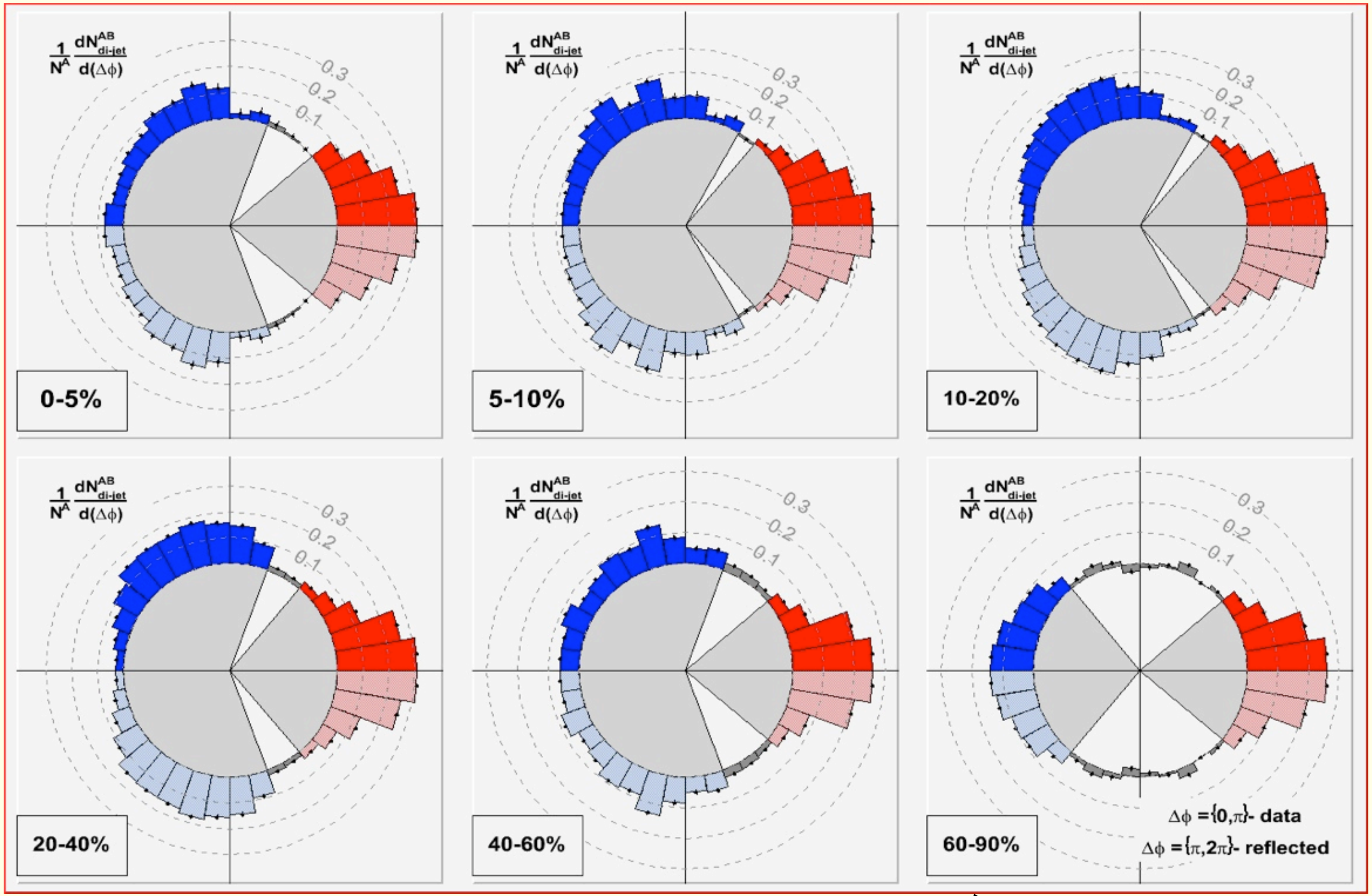


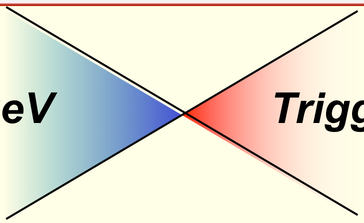
$4 < p_T^{trig} < 6$ GeV/c, $2 < p_T^{assoc} < 4$ GeV/c

$4 < p_T^{trig} < 6$ GeV/c, $0.15 < p_T^{assoc} < 4$ GeV/c

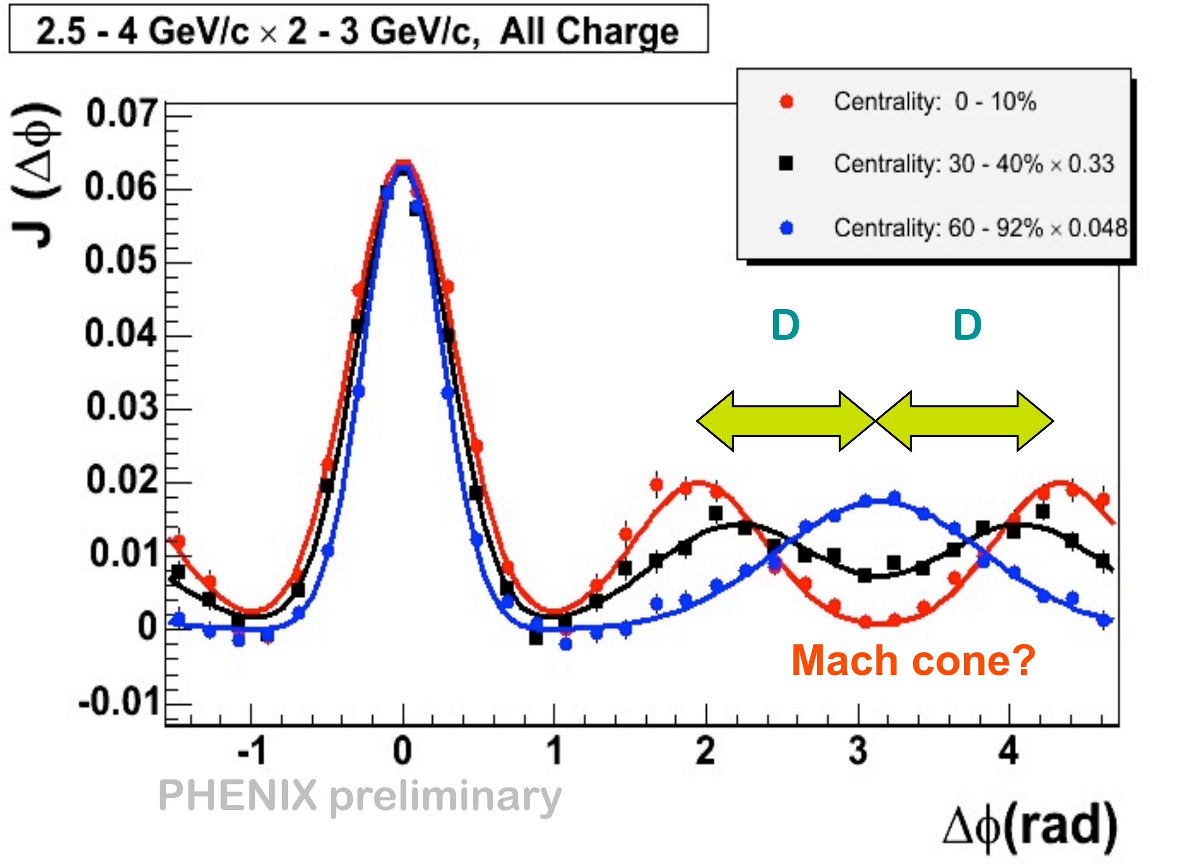
Jet suppression at high p_T accompanied by multiplicity enhancement at lower p_T

What's going on on the Away Side? (I)





What's going on on the Away Side? (II)



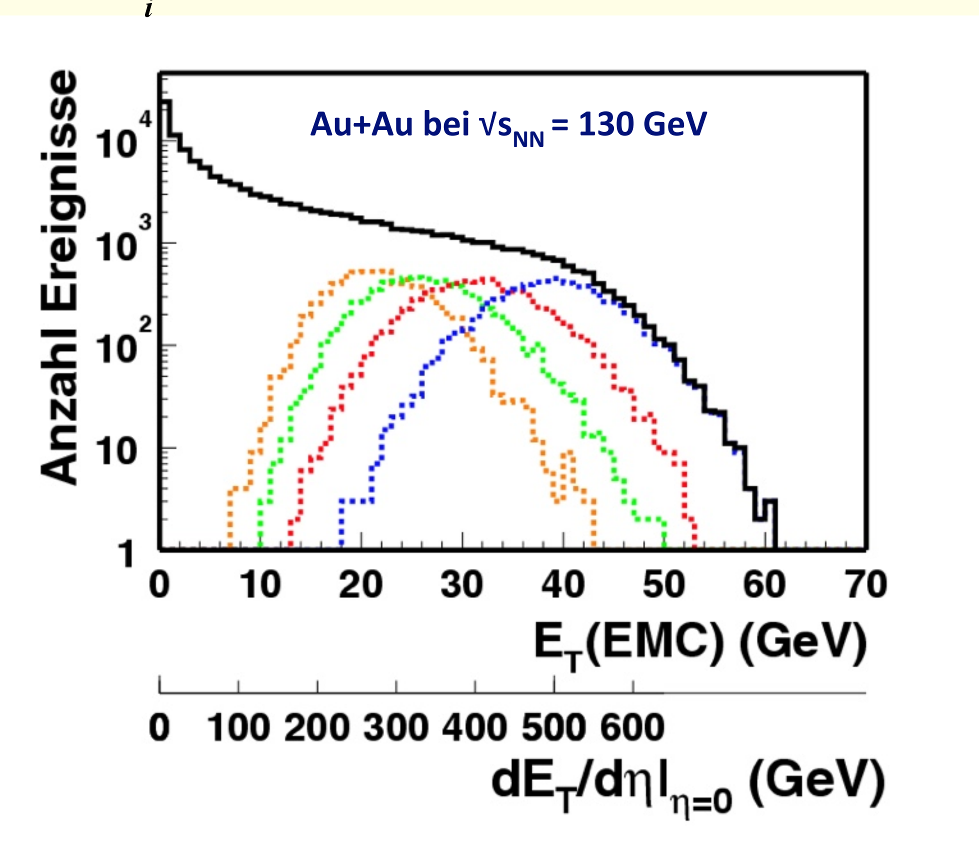
Possible explanations of the splitting of the away-side peak include

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

4.6 Jets in Pb+Pb Collisions at the LHC

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

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



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*:

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.7$$

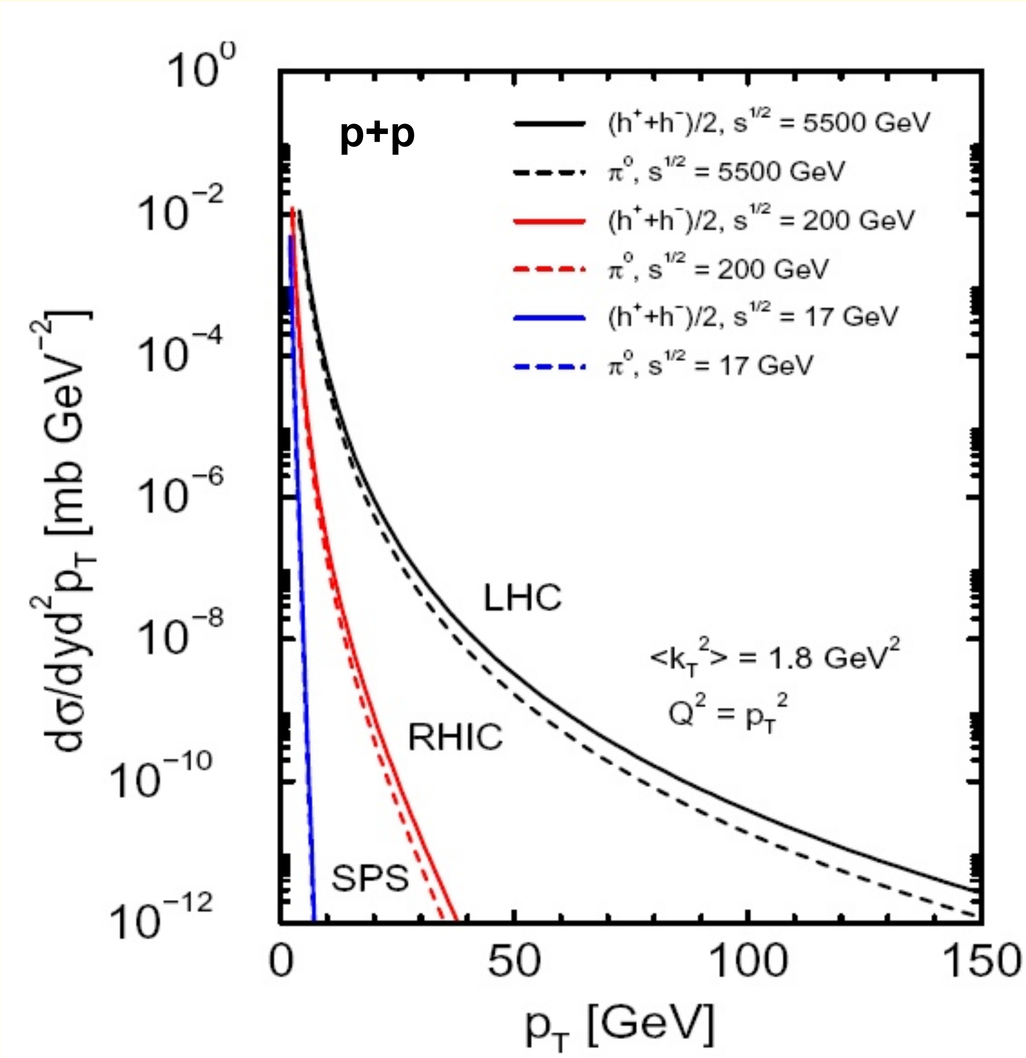
Total transverse energy in this cone

$$E_T^{\text{cone}} = \frac{d^2 E_T}{d\eta d\varphi} \cdot \pi R^2$$

$$= \frac{1}{2\pi} \frac{dE_T}{d\eta} \cdot \pi R^2 \approx 120\ \text{GeV}$$

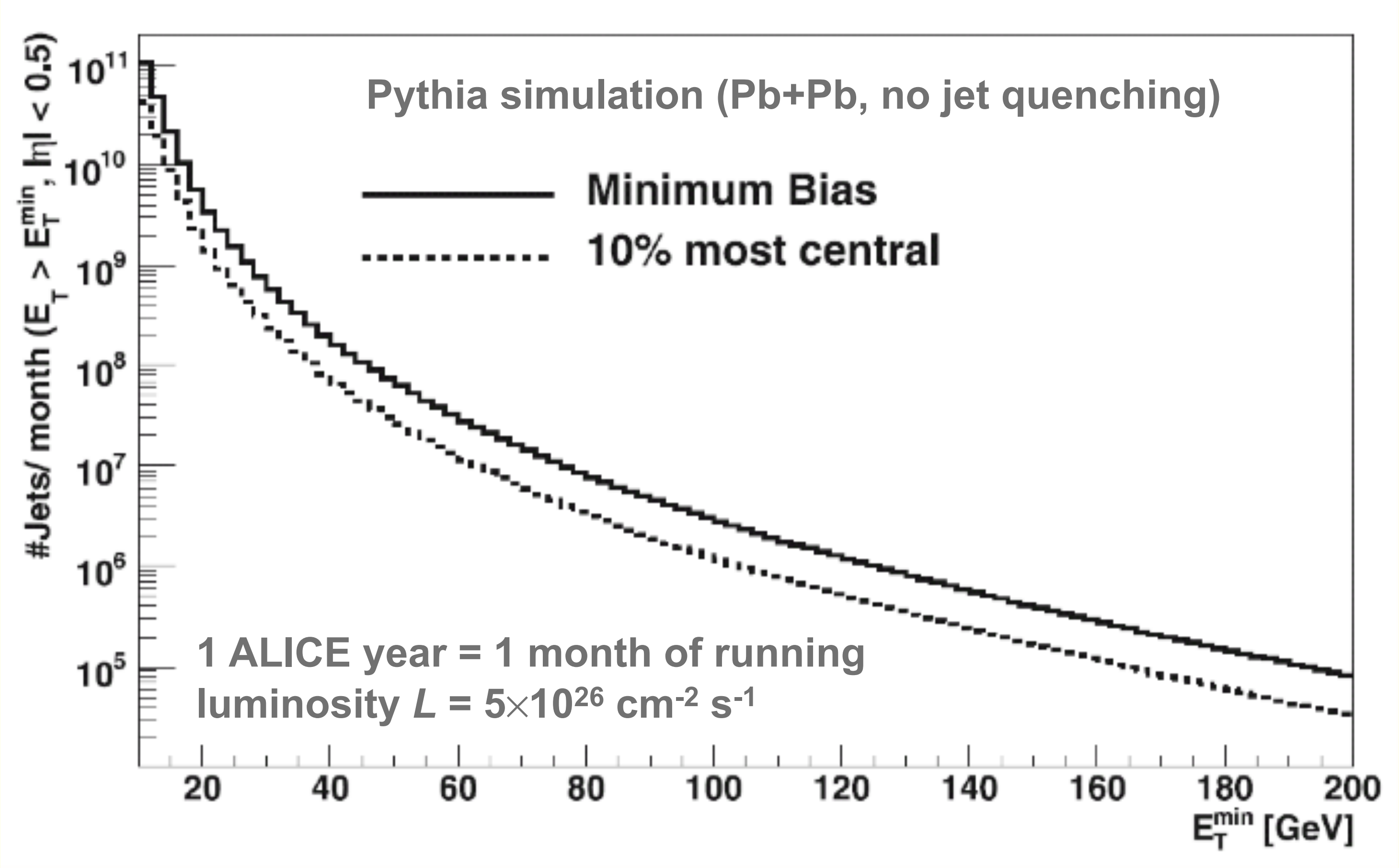
- Background energy large compared to jet energy in A+A at RHIC.
- Nevertheless, attempts are made to reconstruct jets

Single Particle Cross Section at the LHC



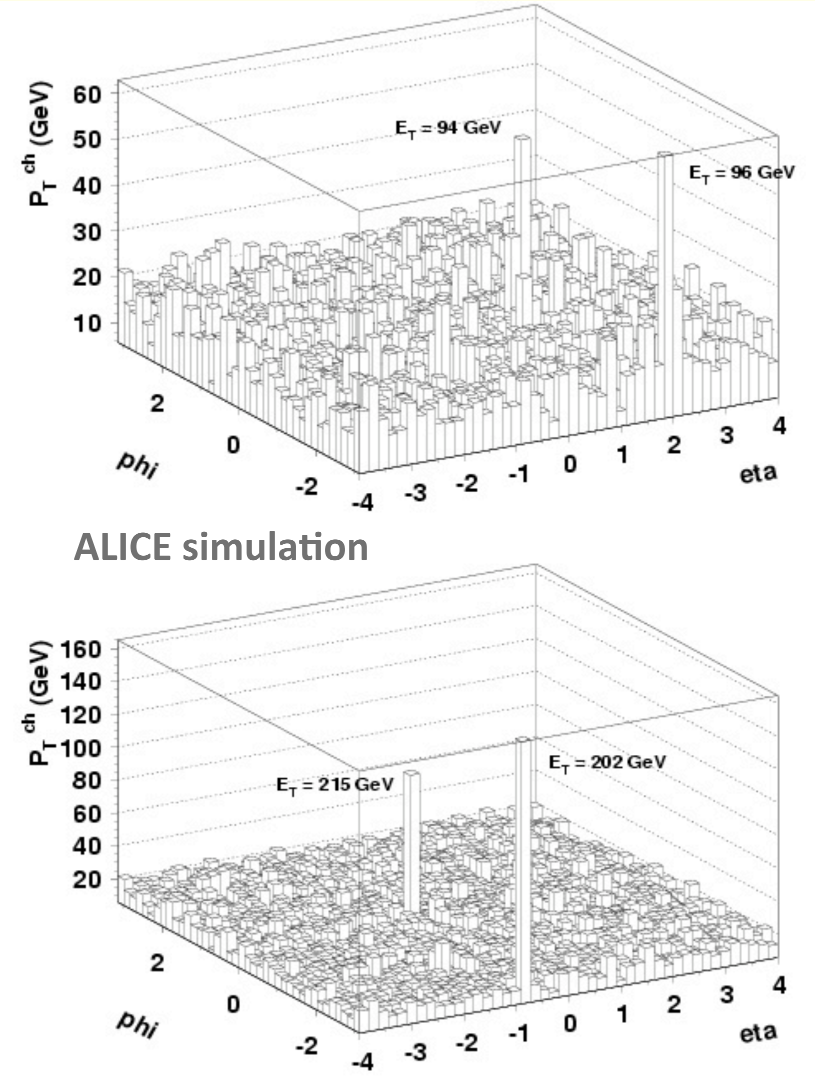
Hard scattering cross sections increase significantly at the LHC

Annual Jet Yield in ALICE Acceptance



Rate of jets with E_T > 100 GeV is greater than 1 Hz

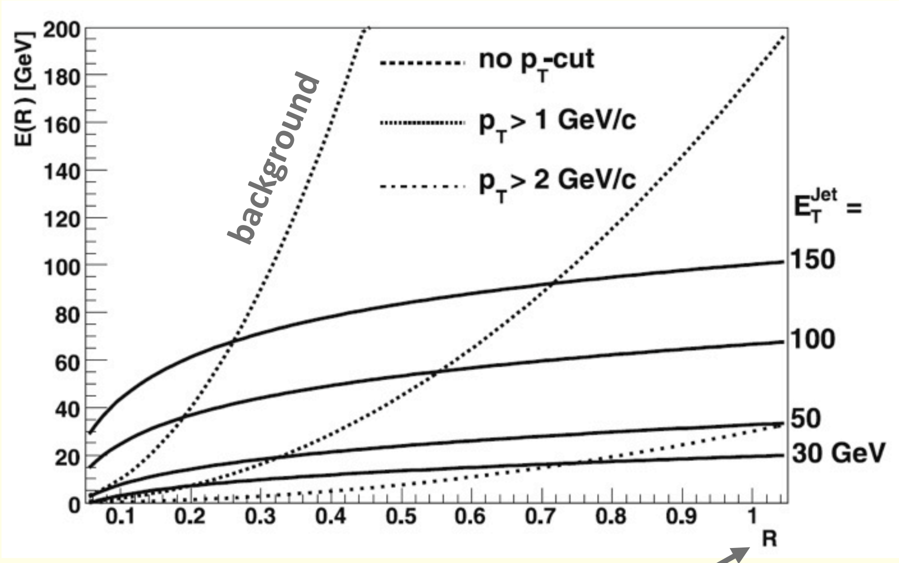
Jets in Pb+Pb at the LHC



ALICE simulation

Jets with E_T > ~ 50 GeV in Pb+Pb at $\sqrt{s}$ = 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



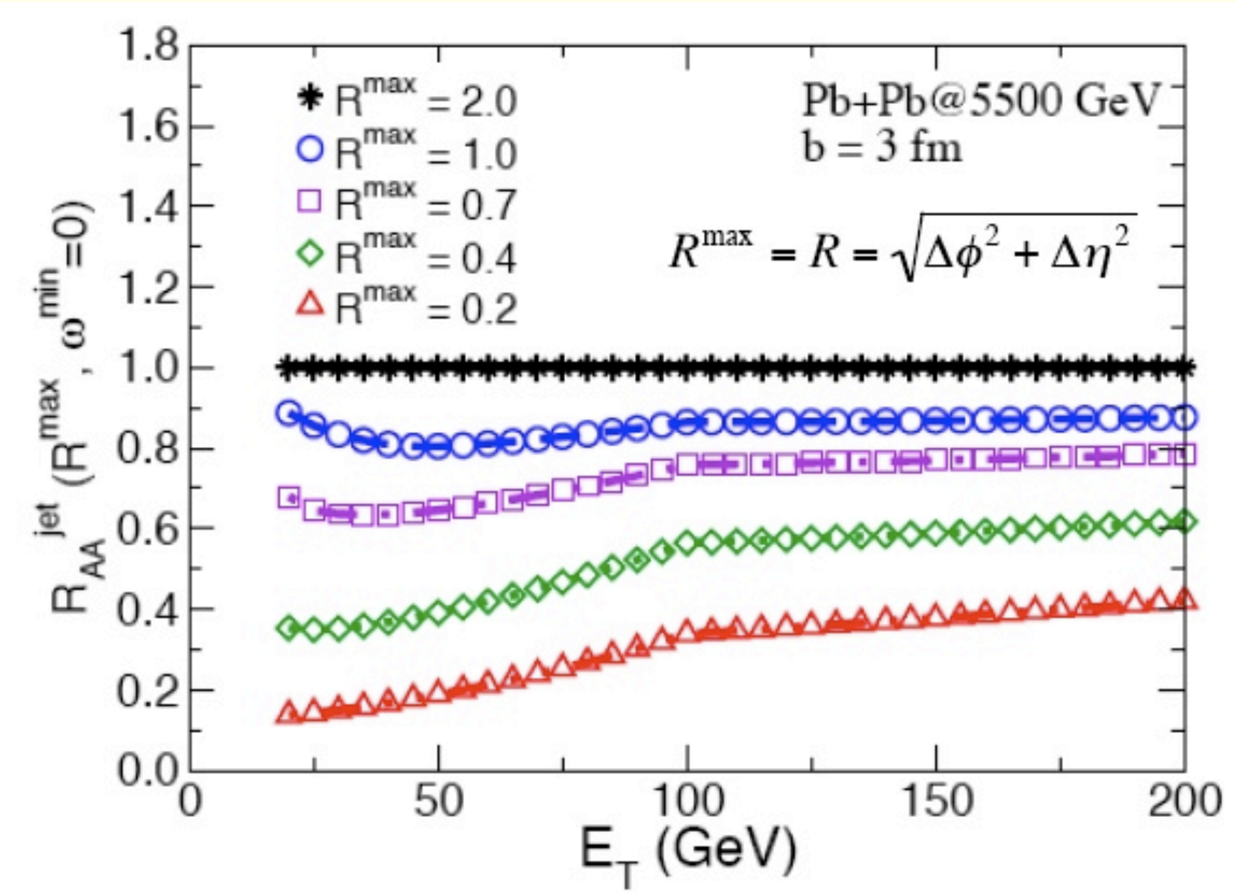
Cone size for jet reconstruction

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 $\Psi(r)$
- Study modification of fragmentation function

Jet R_{AA} for Different Cone Radii R

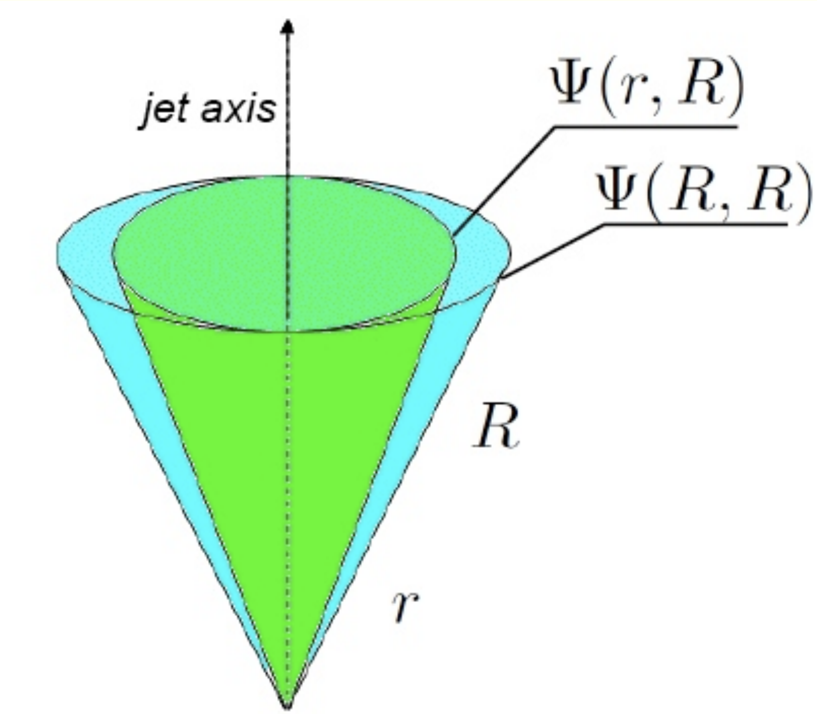
Vitev, Wicks, and Zhang JHEP **11** (2008) 093

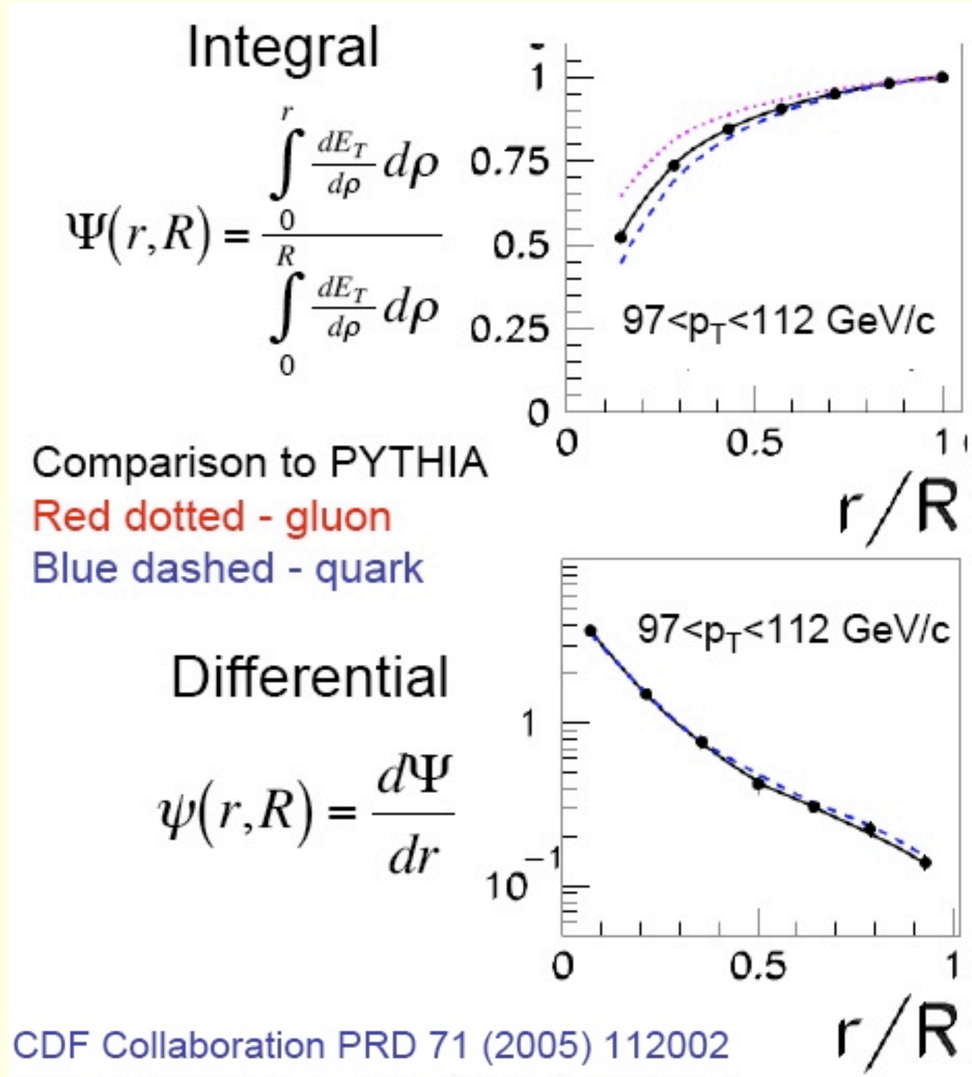


$$R_{AA}^{jet} = \frac{Pb + Pb \text{ Jet Yield}}{\langle N_{coll} \rangle p + p \text{ Jet Yield}}$$

- **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**

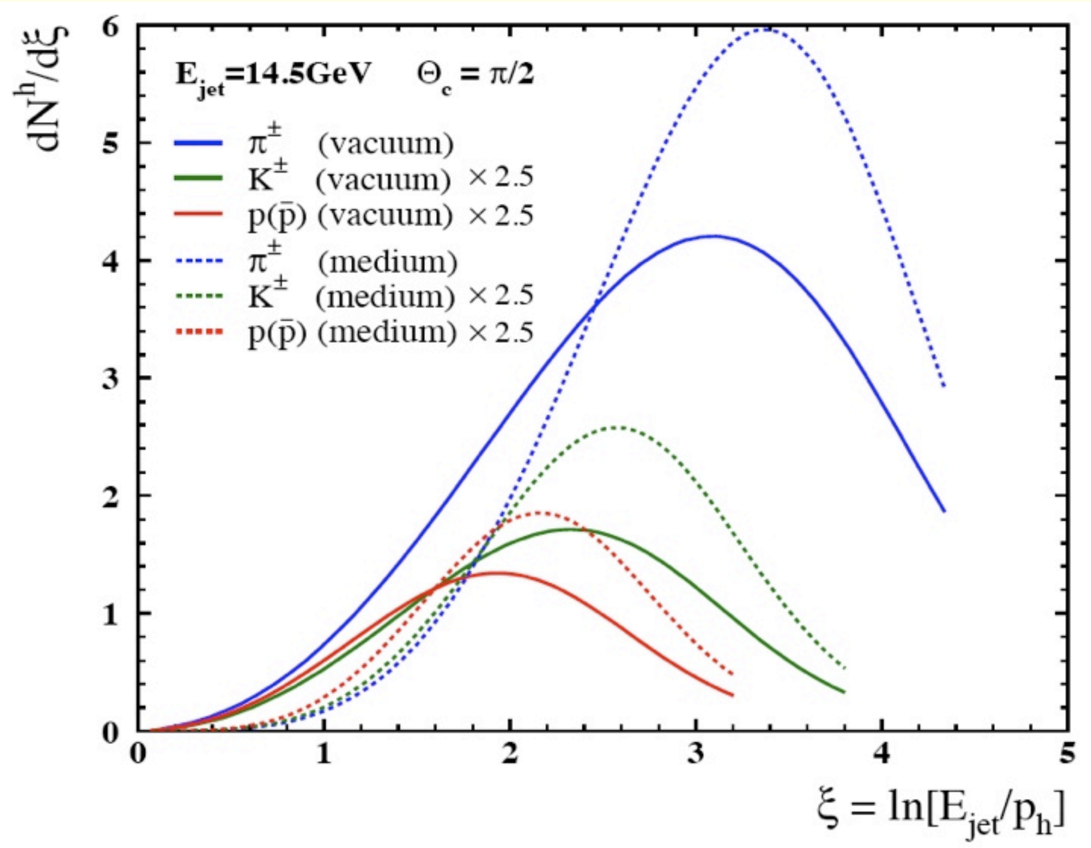
Lateral Jet Profile





Broadening of the energy distribution expected in Pb+Pb

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
- Good low p_T partice ID makes this a promising measurement for Alice

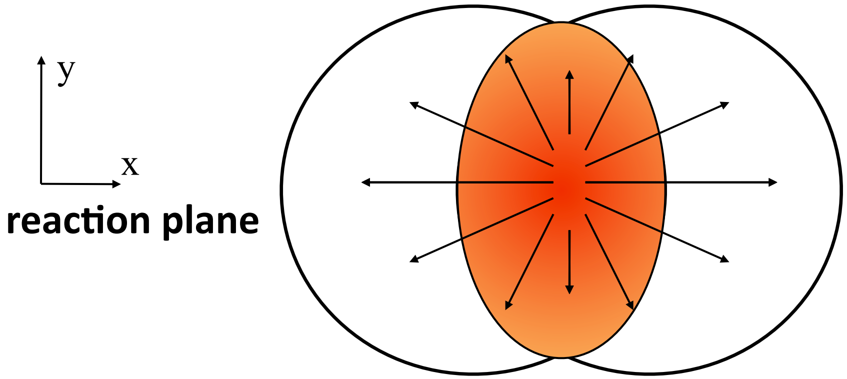
Extra Slides

Jet Quenching and Angular Anisotropy (I)

Anisotropy in particle production related to collision geometry

Common wisdom: low p_T

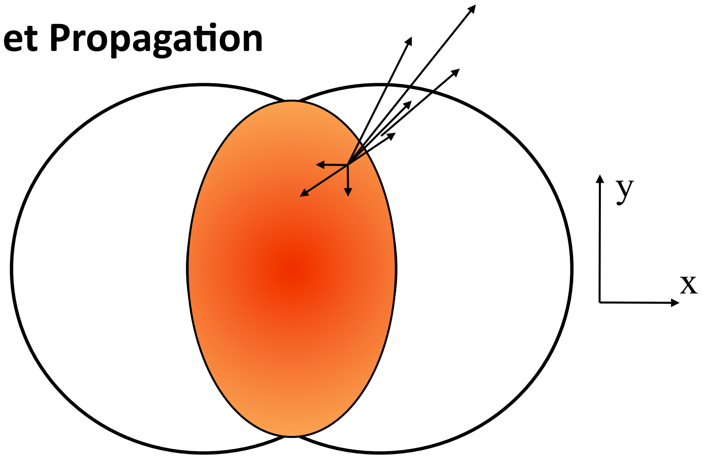
Bulk (Hydrodynamic) Matter



Pressure gradient converts position space anisotropy to momentum space anisotropy

high p_T

Jet Propagation



Energy loss results anisotropy based on location of hard scattering in collision volume

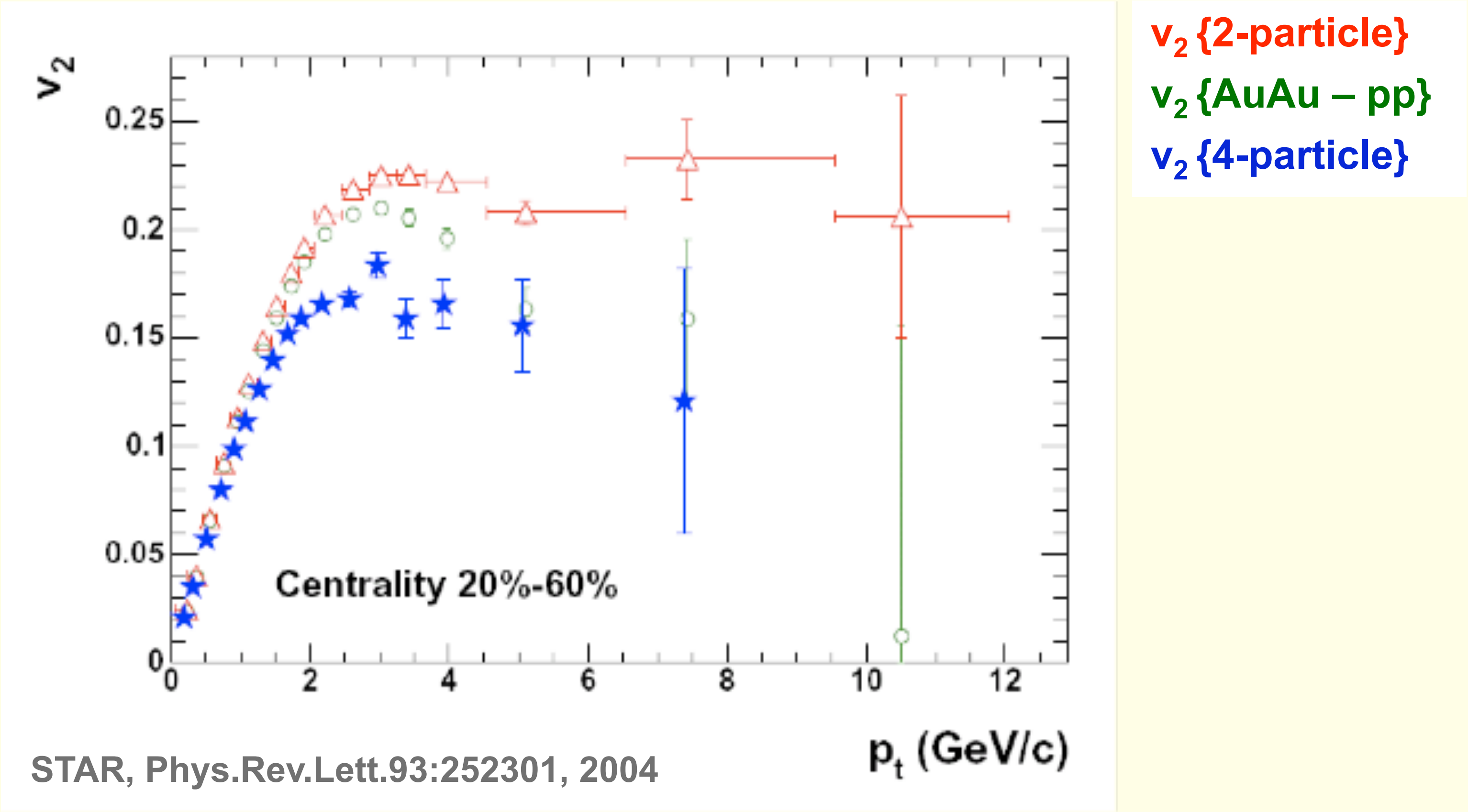
v_2: 2^{nd} harmonic Fourier coefficient in dN/dϕ with respect to the reaction plane

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi-\Psi_r\right)\right)\right) \qquad v_2 = \langle \cos 2\phi \rangle \qquad \phi = \operatorname{atan}\frac{p_y}{p_x}$$

v_2 at high p_T should result from jet quenching

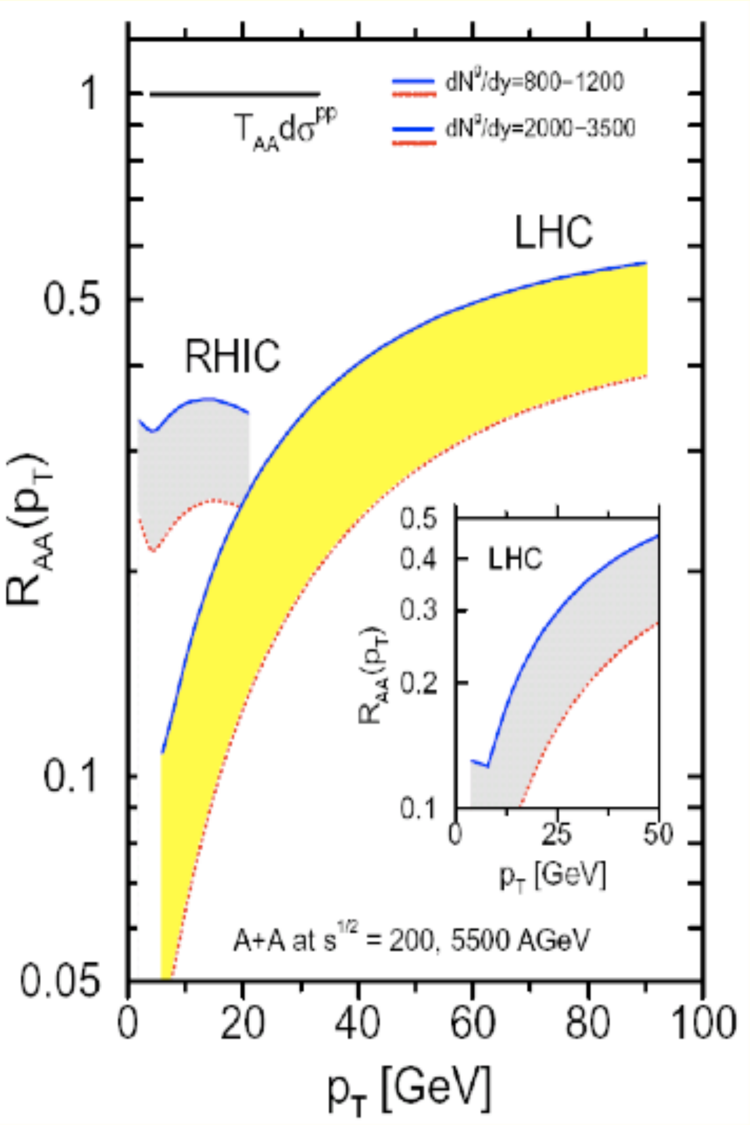
Jet Quenching and Angular Anisotropy (II)

Charged hadron v_2:



- **v_2 remains large at high p_T – too large to be explained by geometry of jet quenching?**
- **Origin of v_2 at high p_T unclear**

A Prediction for R_{AA} in Pb+Pb at the LHC



Parton Energy Loss

- Energy loss due to gluon radiation dominant:

$$\mathrm{d}E_{\mathrm{rad}} / \mathrm{d}x \gg \mathrm{d}E_{\mathrm{coll}} / \mathrm{d}x$$

- Parton energy loss in a finite, *static medium* consisting of color charge carriers

$$\Delta E = -C \frac{\alpha_s}{4} \frac{\mu^2}{\lambda} L^2 \ln\left(\frac{2E}{\mu^2 L}\right) + \ldots$$

L : Path length of the parton in the medium

μ^2 : Typical momentum transfer from medium to parton

λ : Mean free path of the radiated gluons in the medium

- Energy loss for gluon jets larger than for quark jets:

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

- Total energy loss in the medium:

$$\Delta E \sim L^2$$

(effect of quantum mech. interference)

- Detailed numerical calculation shows:

$$\Delta E / E \approx \text{const.}$$

$$\text{for } E < 20 \text{ GeV}$$

Averaging $T_{AB}(b)$ over an Impact Parameter Distribution

Observable: Hard process *per inelastic A+A collisions*, i.e.

$$N_{\text{hard}}^{\text{A+B}}(b) = \frac{T_{AB}(b)}{p_{\text{inel}}^{\text{A+B}}(b)} \cdot \sigma_{\text{hard}}$$

Typical example: p_T dependent pion yield per inelastic event:

$$\frac{1}{N_{\text{inel}}^{A+B}} \frac{dN^{\pi}}{dp_T}(b) = \frac{T_{AB}(b)}{p_{\text{inel}}^{\text{A+B}}(b)} \cdot \frac{d\sigma^{p+p}}{dp_T}$$

Averaging over an impact parameter range f (say $b_1 \leq b \leq b_2$):

weighting factor:

$$p_{\text{inel}}^{\text{A+B}}(b)$$

$$\rightarrow \quad \left.\frac{1}{N_{\text{inel}}^{A+B}} \frac{dN^{\pi}}{dp_T}\right|_f = \frac{\int_{b_1}^{b_2} 2\pi b \, T_{AB}(b) \, db}{\int_{b_1}^{b_2} 2\pi b \, p_{\text{inel}}^{\text{A+B}}(b) \, db} \cdot \frac{d\sigma}{dp_T} \equiv \langle T_{AB} \rangle_f$$

Note that $\int_f \mathrm{d}^2 b = \int_{b_1}^{b_2} 2\pi \, b \, \mathrm{d}b$

Nuclear Modification Factor (I)

Consider special case $b_1 = 0$, $b_2 = \infty$:

$$\frac{1}{N_{\mathrm{inel}}^{A+B}} \frac{dN^{\pi}}{dp_T}\bigg|_f = \frac{\int_0^\infty 2\pi b\, T_{AB}(b)\, db}{\int_0^\infty 2\pi b\, p_{\mathrm{inel}}^{\mathrm{A+B}}(b)\, db} \cdot \frac{d\sigma}{dp_T} = \frac{AB}{\sigma_{\mathrm{inel}}^{\mathrm{A+B}}} \cdot \frac{d\sigma}{dp_T} \quad \rightarrow \quad \frac{d\sigma^{A+B}}{dp_T} = AB \cdot \frac{d\sigma^{p+p}}{dp_T}$$

(holds for hard scattering in the absence of nuclear effects)

Definition of nuclear modification factor:

$$R_{AB}(p_T) = \frac{d\sigma^{A+B} / dp_T}{\left[\int_f d^2b\, T_{AB}(b)\right] \cdot d\sigma^{p+p} / dp_T} = \frac{\frac{1}{N_{\mathrm{inel}}^{A+B}} \frac{dN^{\pi}}{dp_T}\Big|_f}{\langle T_{AB} \rangle_f \cdot d\sigma^{p+p} / dp_T}$$

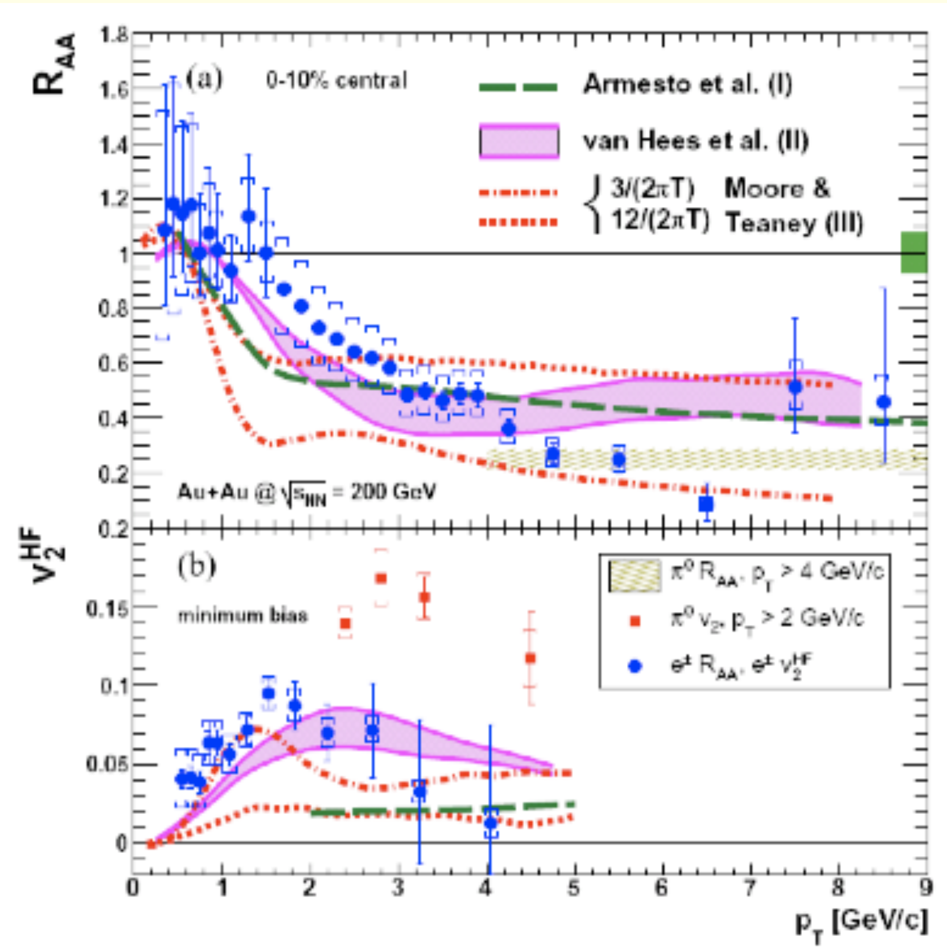
$$= 1$$ ← (in the absence of nuclear effects)

In practice:

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

where $\langle N_{\mathrm{coll}} \rangle_f$ is determined with a Glauber Monte Carlo code

Excess Electrons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (II)



PHENIX, Phys.Rev.Lett.98:172301,2007

- Models based on radiative parton energy loss predict

$$\Delta E_{\text{gluon}} > \Delta E_{\text{quark},m=0} > \Delta E_{\text{quark},m>0}$$

- Thus, electrons from charm and bottom quarks should be less suppressed than pions
- Experimental observation: Electrons from charm (and bottom) decays as strongly suppressed as pions
- Simultaneous measurement of electron flow further constrains energy loss models

Simple Estimate of the Relative Energy Loss

p_T independence of R_{AA} implies constant fractional energy loss:

π^0 spectrum without energy loss:

$$\frac{\mathrm{d}N}{\mathrm{d}p_T} \propto p_T^{-n+1}$$

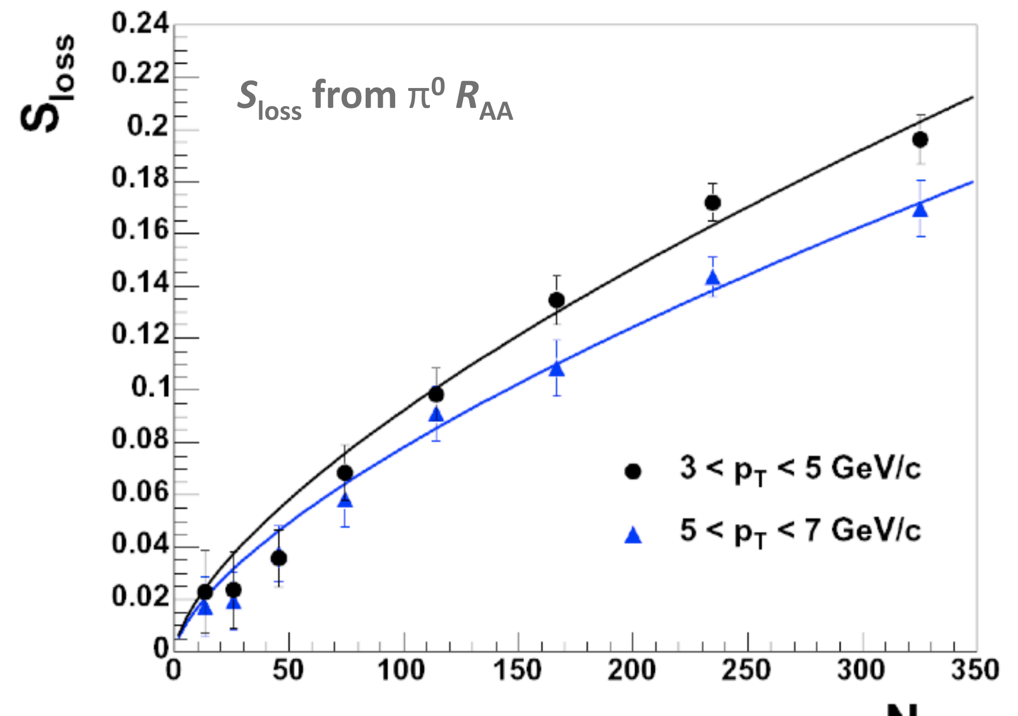
Constant fractional energy loss:

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

This leads to:

$$R_{AA} = \left(1 - S_{\mathrm{Loss}}\right)^{n-2}$$

$$\Rightarrow \quad S_{\mathrm{Loss}} = 1 - R_{AA}^{1/(n-2)}$$

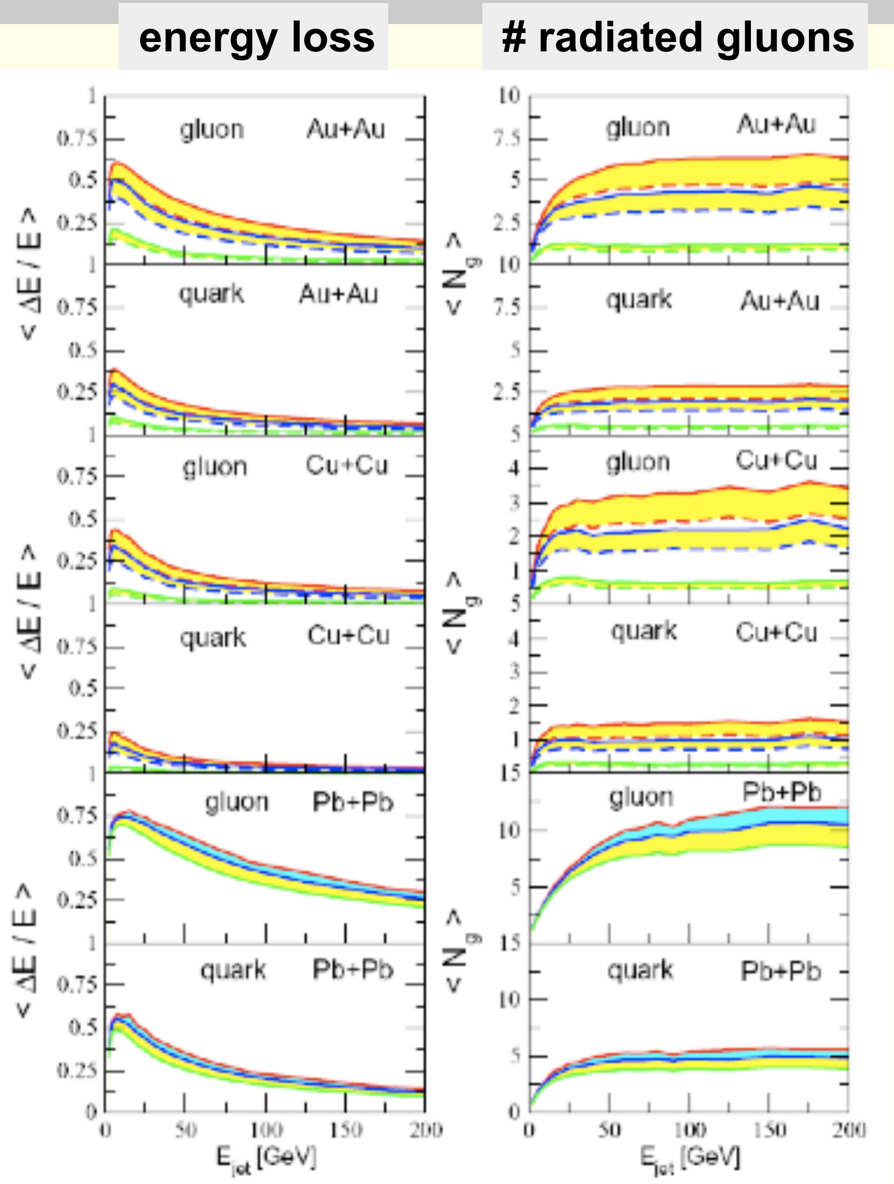


PHENIX, nucl-ex/0611007

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

Energy loss in the GLV Formalism for Cu+Cu, Au+Au, and Pb+Pb

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



Calculated fractional energy loss and number of radiated gluons shown for three centralities in each figure:

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

$Centrality$	$0-10\%$	$20-30\%$	$60-80\%$
N_{part}	328	167	21
dN^g/dy	800 - 1175	410 - 600	50 - 75
L [fm]	6	4.8	2.4
A_{eff}	197	99	12

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

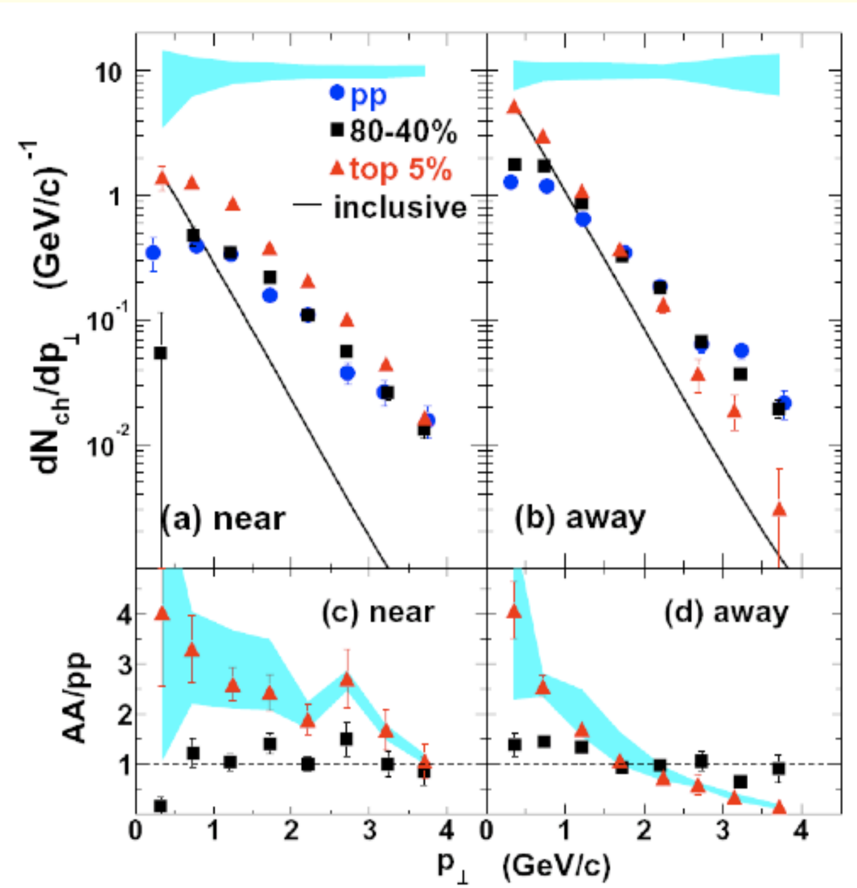
$Centrality$	$0-10\%$	$20-30\%$	$60-80\%$
N_{part}	103	55	9
dN^g/dy	255 - 370	135 - 195	20 - 30
L [fm]	4.1	3.3	1.8
A_{eff}	64	34	6

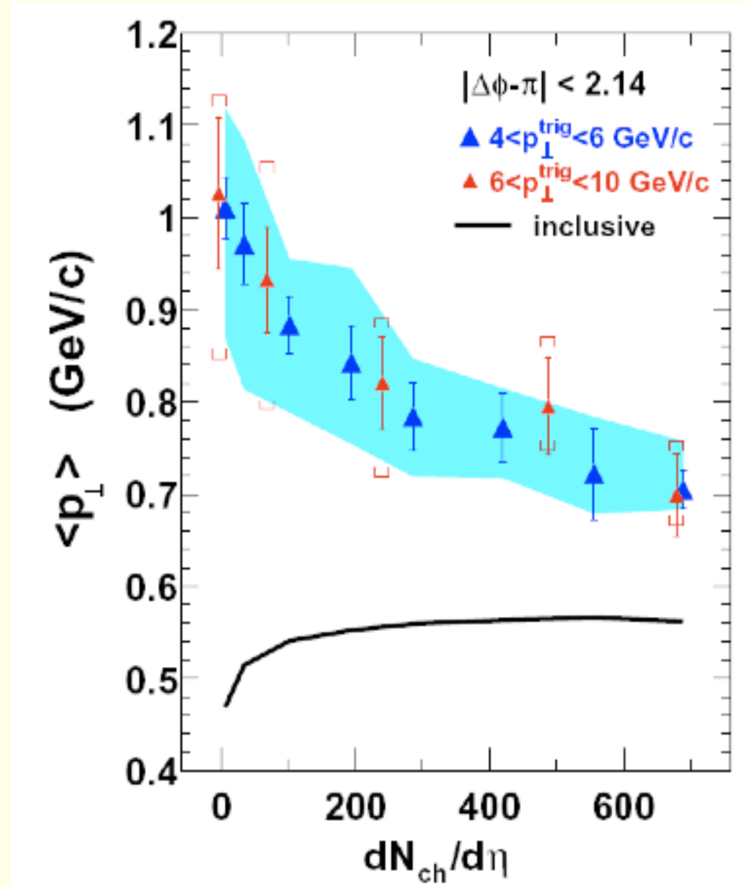
Pb+Pb at $\sqrt{s_{NN}}$ = 5500 GeV:

dN^g/dy = 2000, 3000, 4000

p_T Distributions of Associated Particles

Associated charged hadron p_T distribution
($4 < p_{T,trigger} < 6$ GeV/c)



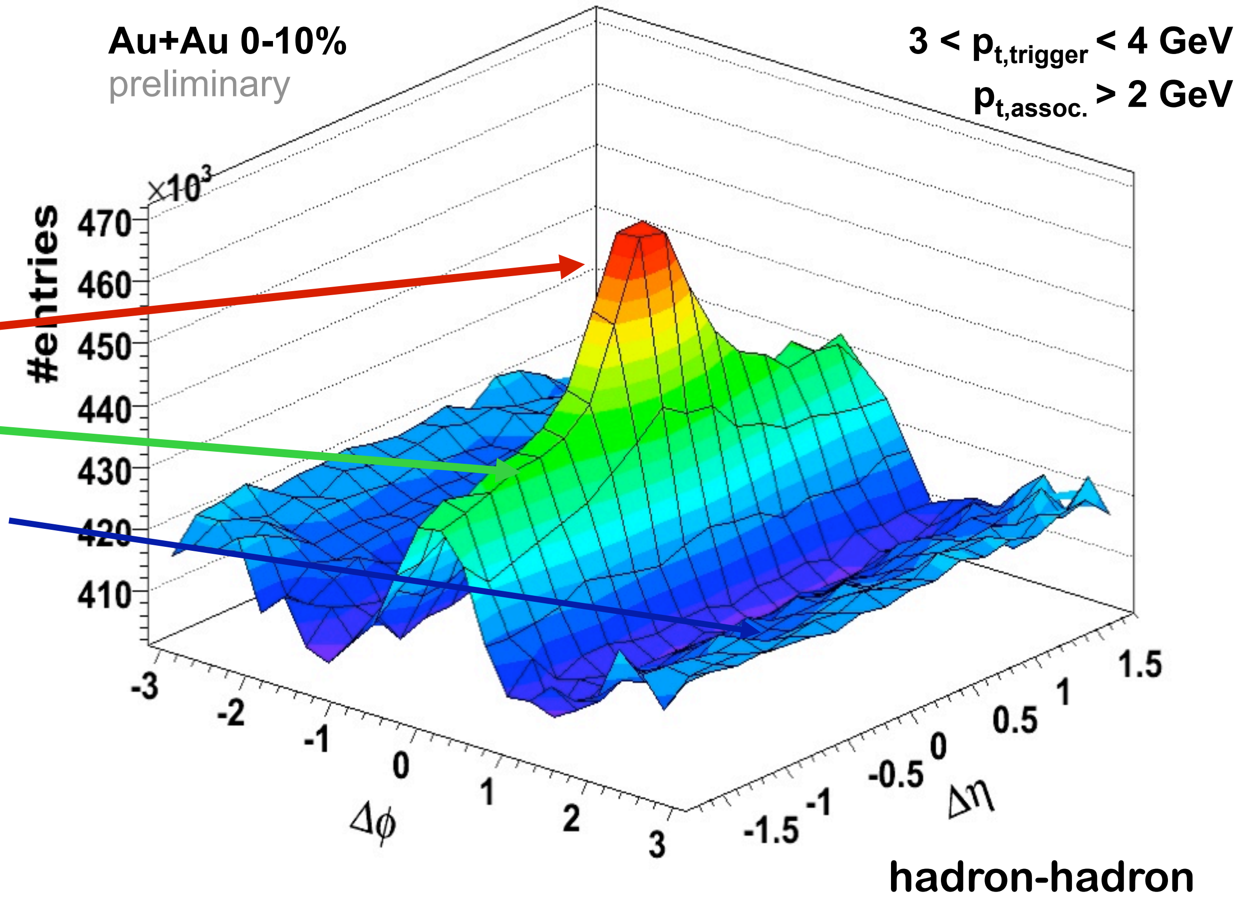


p_T distribution on away side in central Au+Au similar to inclusive distribution: hint of thermalization of hadrons on away side

A so-far Unexplained Phenomenon: The Ridge

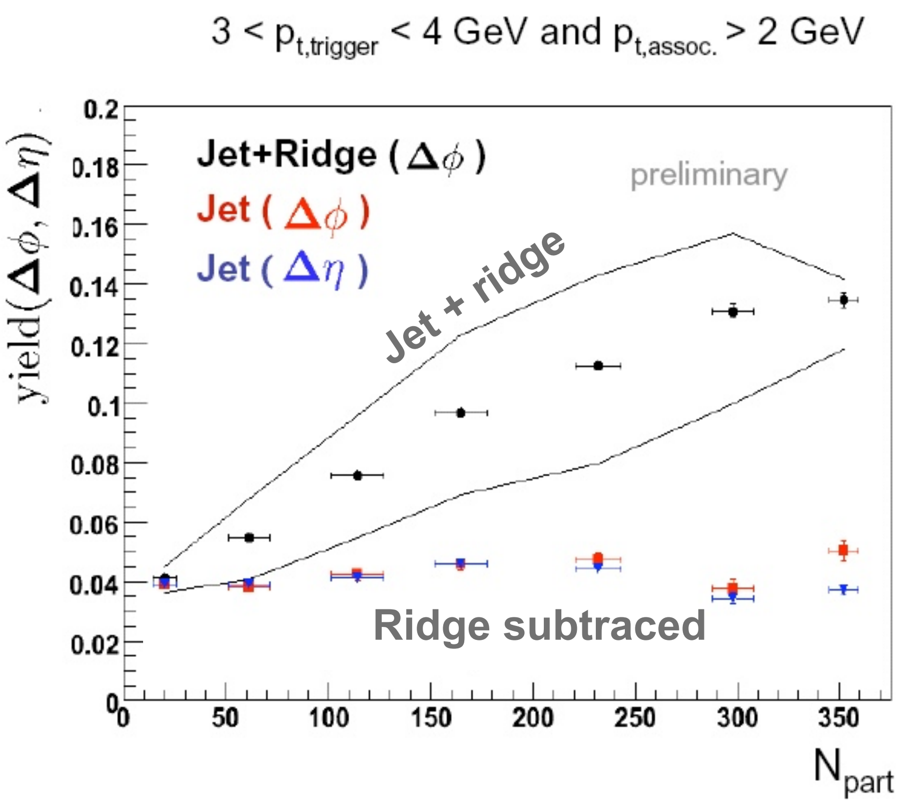
Components

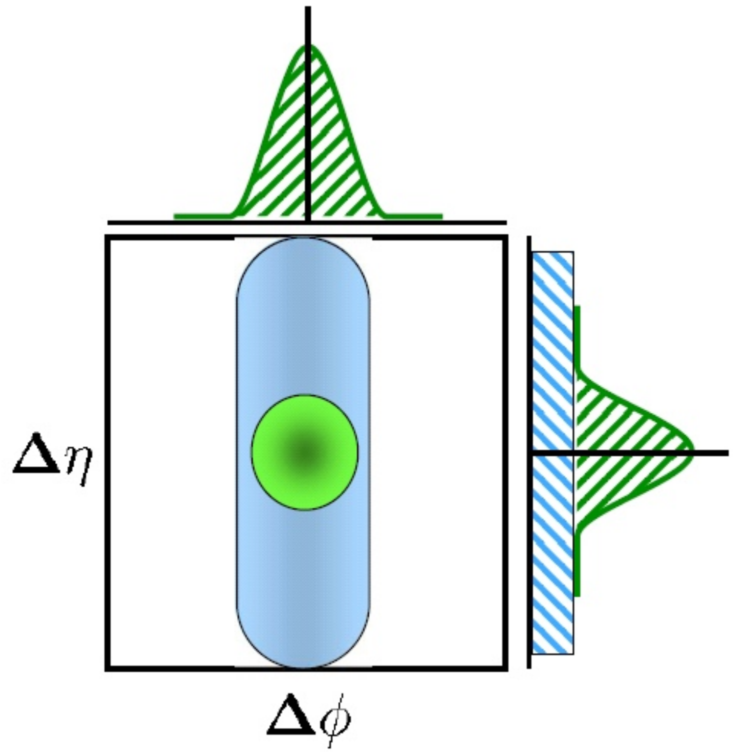
- Near-side jet peak
- Near-side ridge
- Away-side (and v_2)



"ridge" = broad correlation in $\Delta\eta$ on the near side

Near Side Yields per Trigger Particle





After subtraction of the "ridge":
jet-yield per trigger independent of centrality