QGP Physics – From Fixed Target to LHC

8. Hard Scattering, Jets, and Jet Quenching

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Physikalisches Institut
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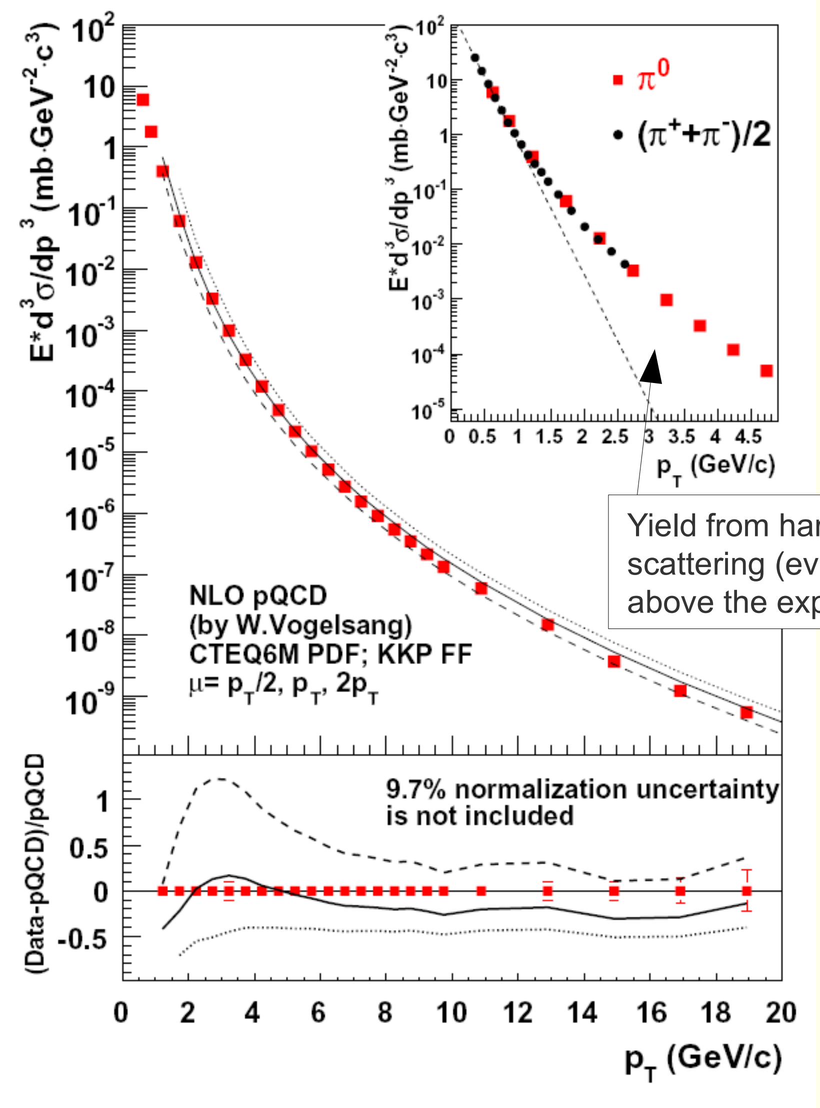
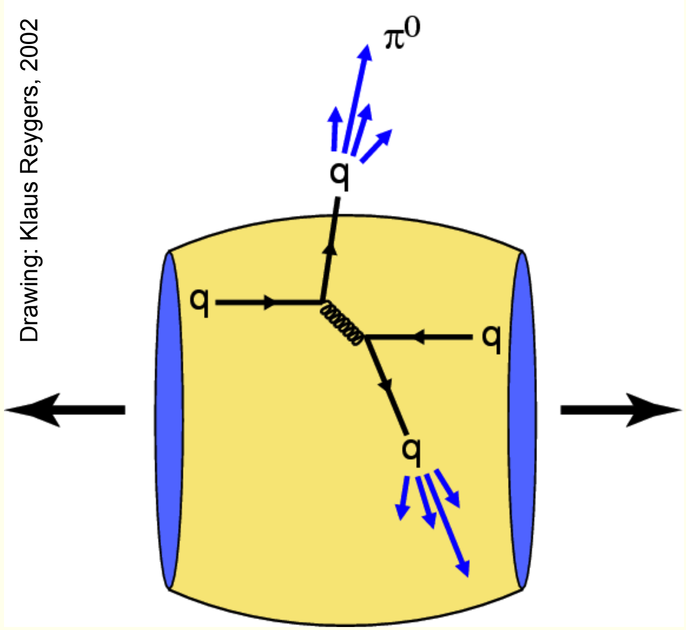
SS 2011

Hard Scattering



Yield from hard scattering (everything above the exponential)

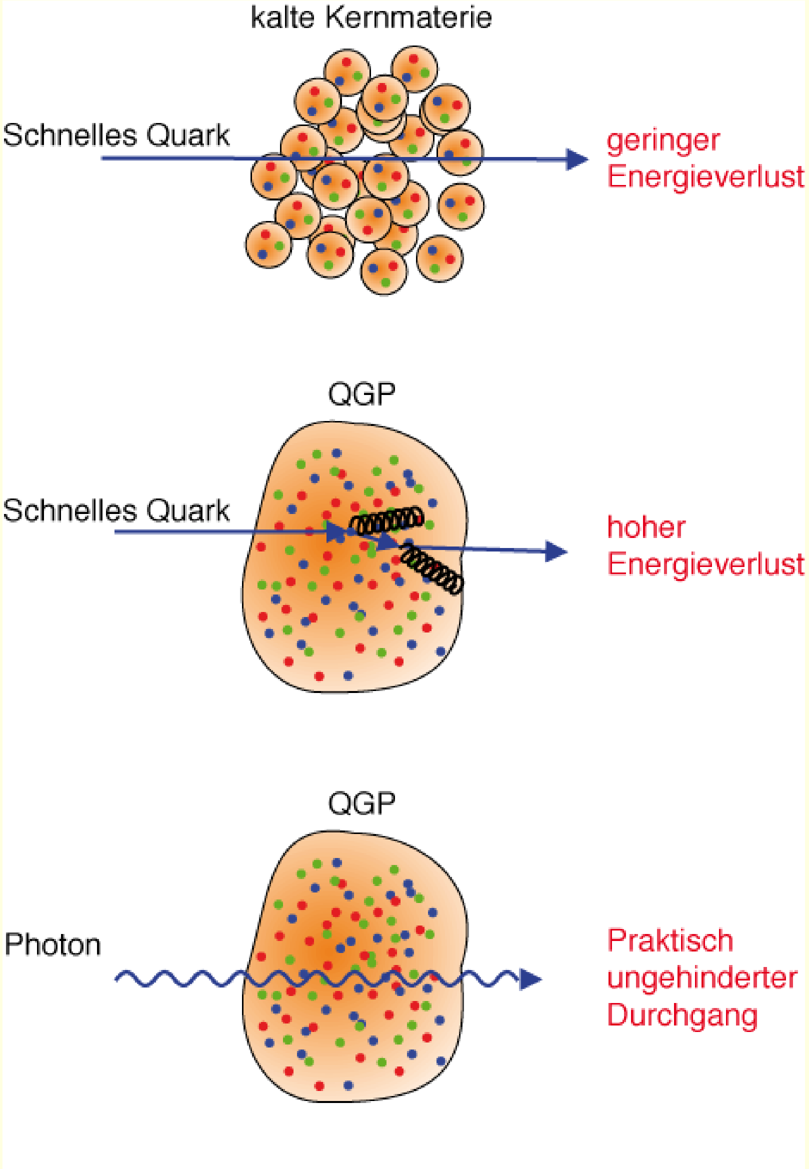


Drawing: Klaus Reygers, 2002

More than 99% of all particles (the bulk) have transverse momenta less than 2 GeV/c.

High-p_T particles in A+A can be used as a probe of the created medium

Jet Quenching: Basic Idea



Expectation:
Simple scaling
from
p+p to p+A
(no suppression)

Expectation:
Pion suppression in A+A

Expectation:
Simple scaling from
p+p to A+A for direct
photons
(no suppression)

What Can We Hope to Learn from Particles at High p_T and Jets?

- In heavy-ion physics, particles at high p_T and jets are of great interest because
  - they are produced in the early stage of a heavy-ion collisions, prior to the formation of the quark-gluon plasma
  - their initial production rate can be calculated with perturbative QCD

- 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 $\underset{\cancel{\Leftarrow}}{\Rightarrow}$ Suppression of hadrons at high p_T

How Can We Study Jet Quenching?

- Measurement of particle multiplicities at high p_T

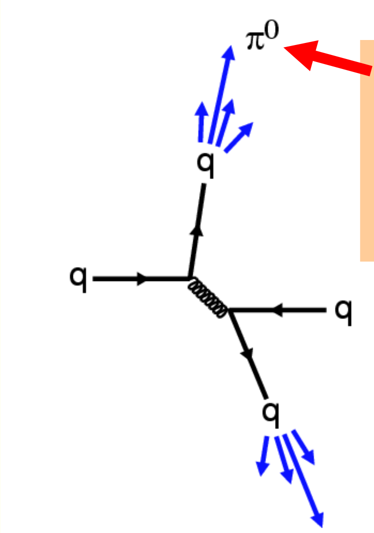
- Measurement of two-particle angular correlations

- 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

Hard Scattering in p+p

Theoretical Description of High-p_T Particle Production: Perturbative QCD

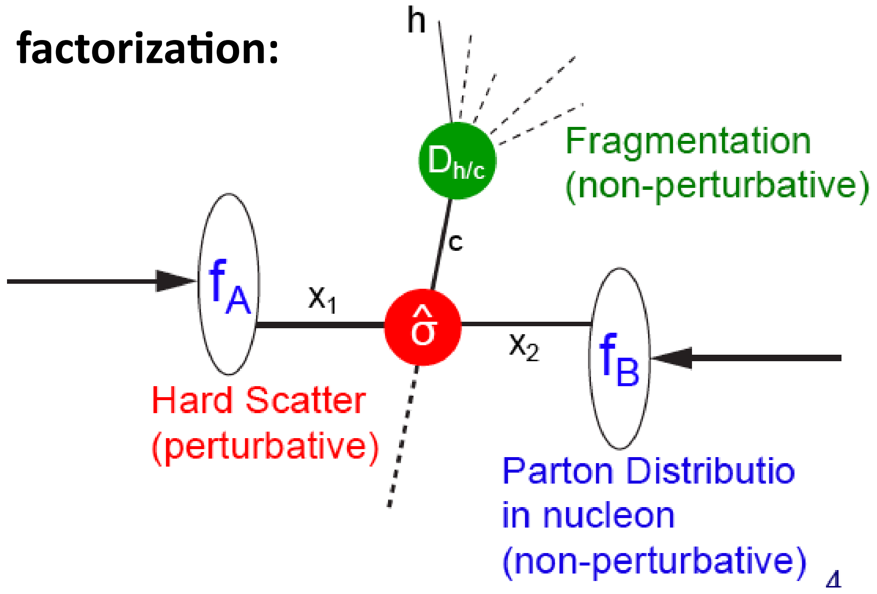
- Scattering of pointlike partons described by QCD perturbation theory (pQCD)
- Soft processes described by universal, phenomenological functions
  - Parton distribution function from deep inelastic scattering
  - Fragmentation functions from e^+e^- collisions



Leading hadron:

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

factorization:



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

Hadron Production in Leading Order QCD

Inv. Cross section

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

Fragmentation function

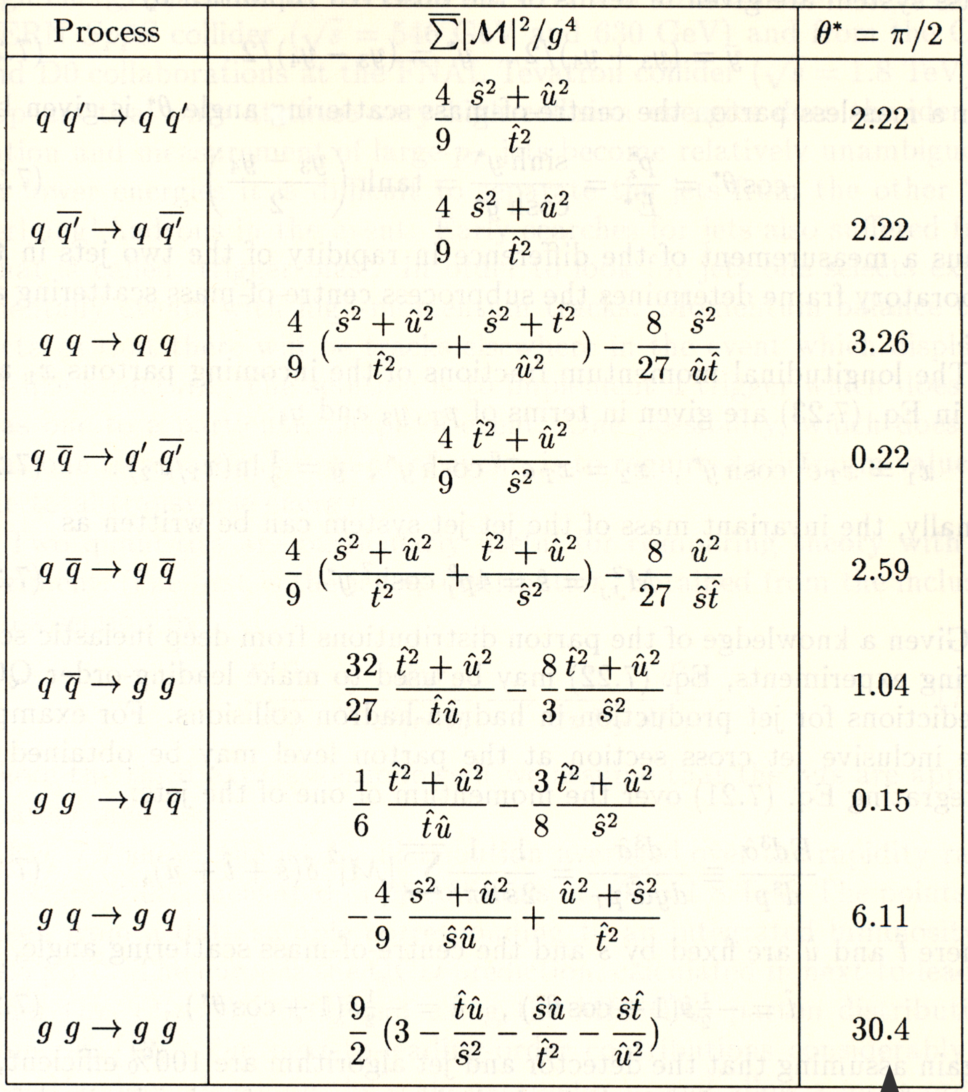
$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = K \sum_{a,b,c,d=q,\bar{q},g} \int_{x_{a,\mathrm{min}}}^{1} \mathrm{d}x_a \int_{x_{b,\mathrm{min}}}^{1} \mathrm{d}x_b \; f_{\mathrm{a/A}}\left(x_{\mathrm{a}}, Q^2\right) f_{\mathrm{b/B}}\left(x_{\mathrm{b}}, Q^2\right) \frac{\mathrm{d}\sigma^{\mathrm{ab}\to\mathrm{cd}}}{\mathrm{d}\hat{t}}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

Phenomenological factor which takes higher order contributions into account

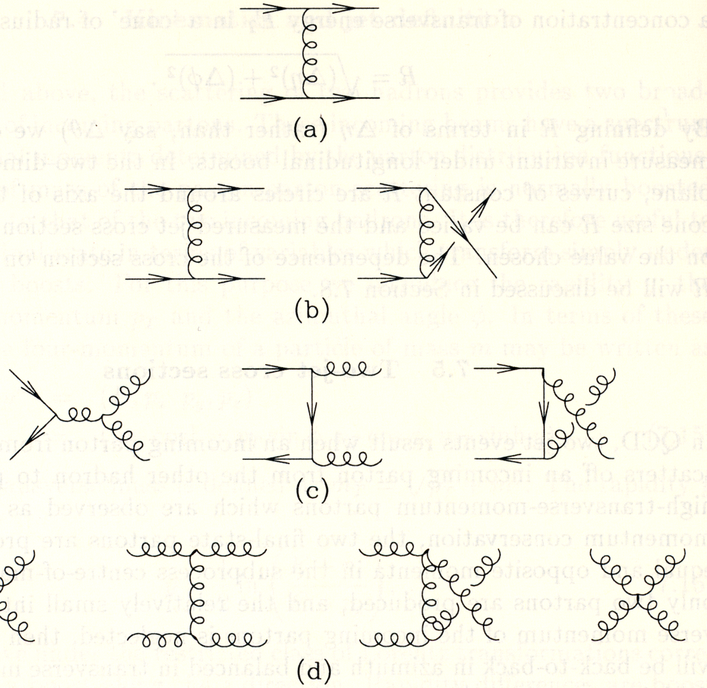
Elementary QCD parton-parton cross section

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

Point Cross Sections at Leading Order



Process	$\overline{\sum}\lvert\mathcal{M}\rvert^2/g^4$	$\theta^* = \pi/2$
$q\,q' \to q\,q'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\,\bar{q}' \to q\,\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\,q \to q\,q$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.26
$q\,\bar{q} \to q'\,\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\,\bar{q} \to q\,\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.59
$q\,\bar{q} \to g\,g$	$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	1.04
$g\,g \to q\,\bar{q}$	$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.15
$g\,q \to g\,q$	$-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$	6.11
$g\,g \to g\,g$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$	30.4

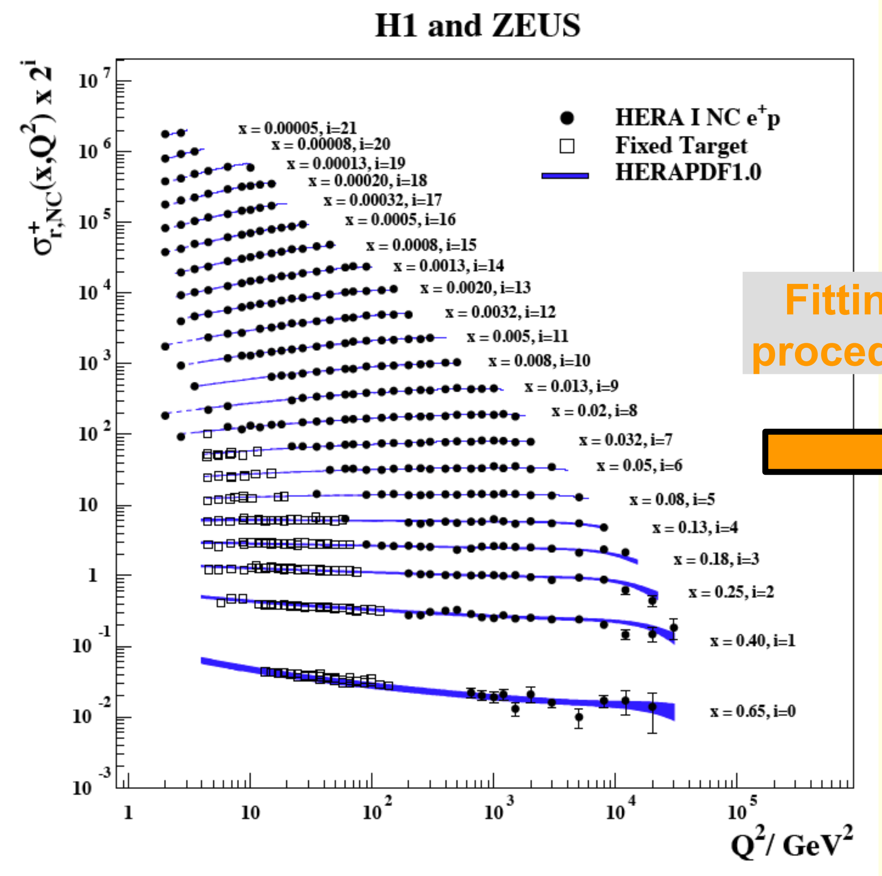


Relative importance
at equal parton luminosities

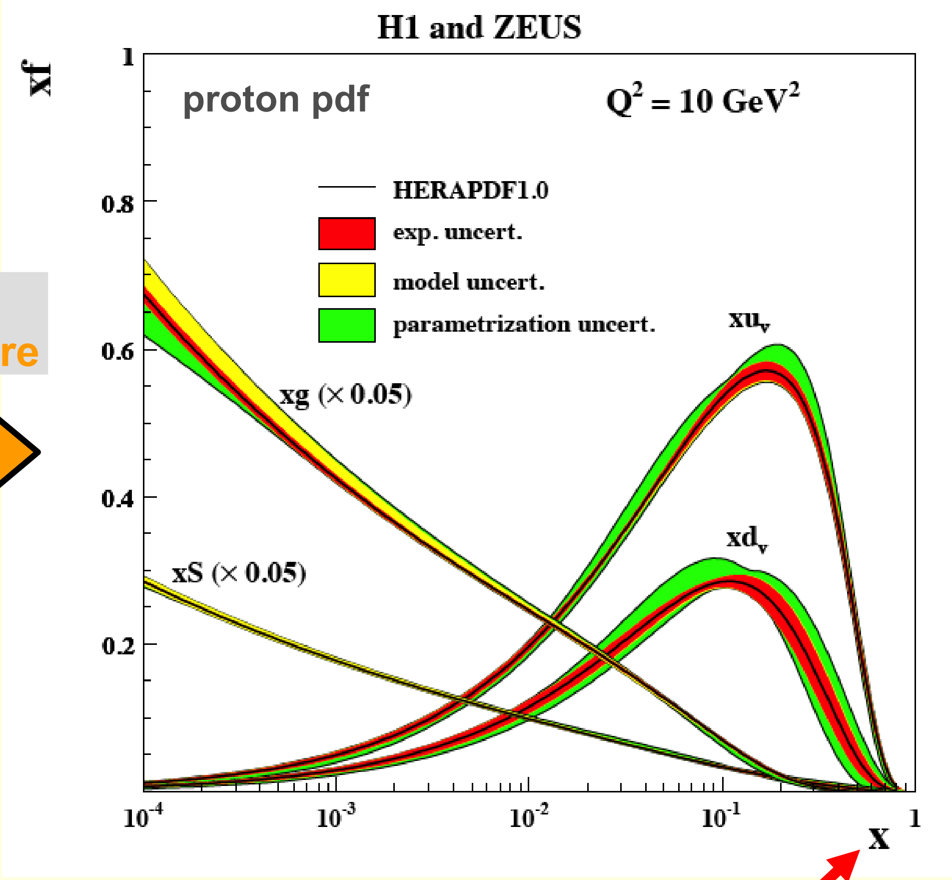
Parton Distributions: High Precision Data from HERA

HERA: $e^{\pm}p$ scattering

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



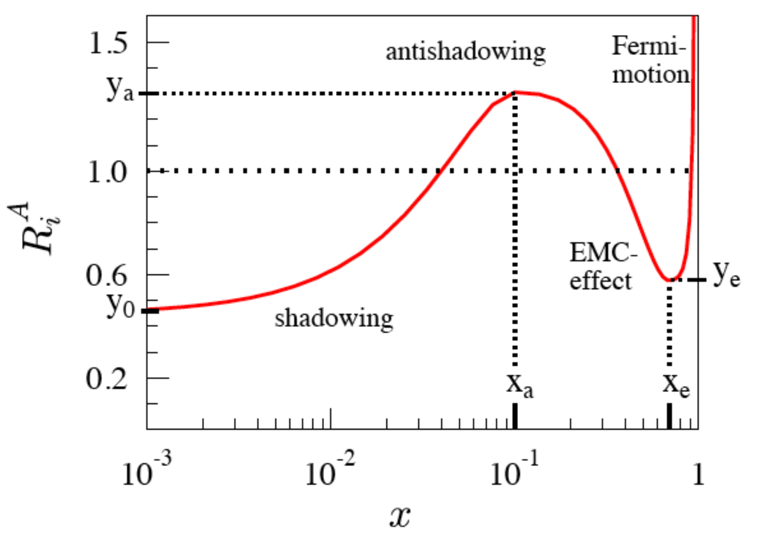
Fitting procedure



Bjorken-*x*

H1 and ZEUS, JHEP 1001:109,2010 (→ link)
Website with combined HERA results (→ link)

Parton Distributions for Nuclei

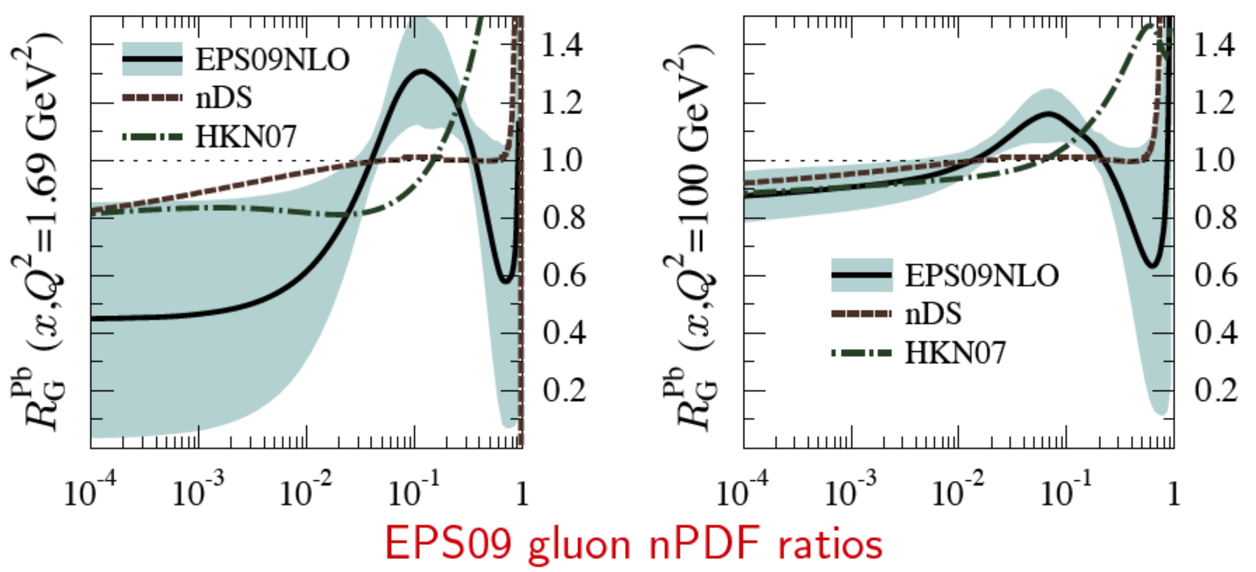


$x < 0.1$: “shadowing region”

$0.1 < x < 0.3$: “anti-shadowing”

$0.3 < x < 0.7$: “EMC effect”

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



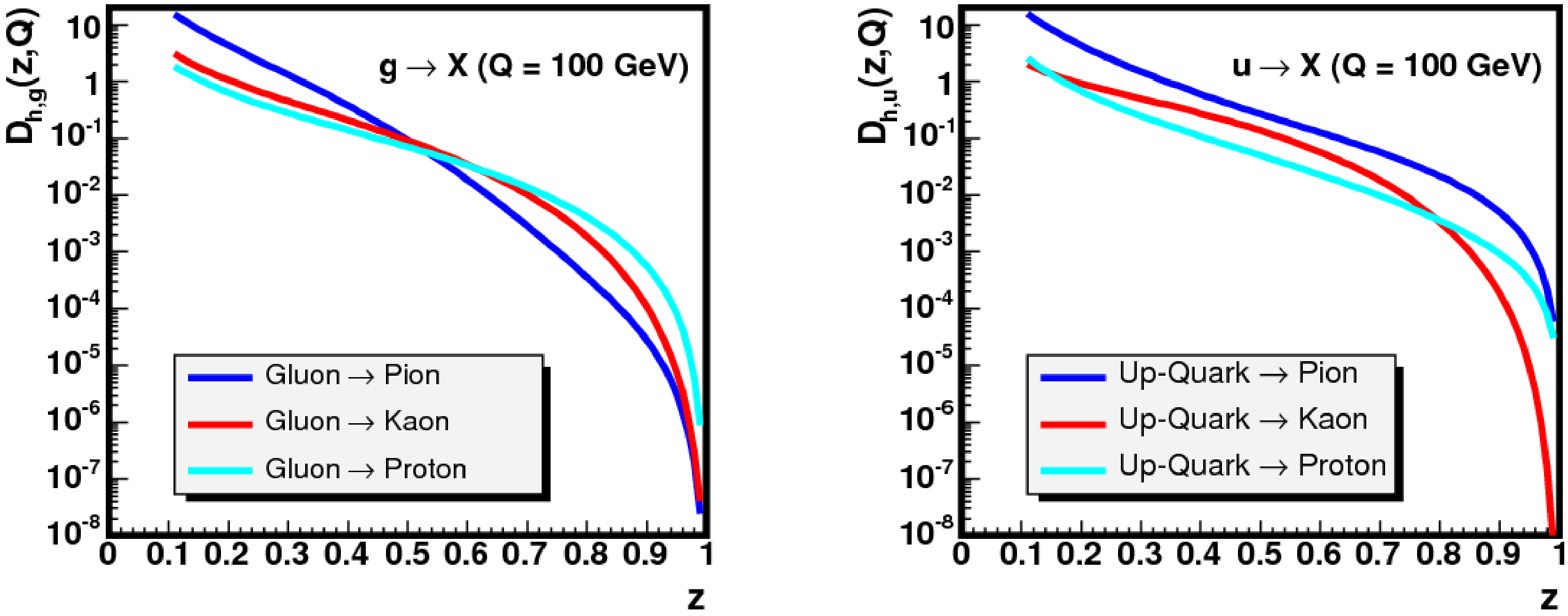
EPS09 gluon nPDF ratios

Nuclear gluon pdf's at low x poorly constrained experimentally

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

Example: Gluon and u-Quark Fragmentation Functions

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

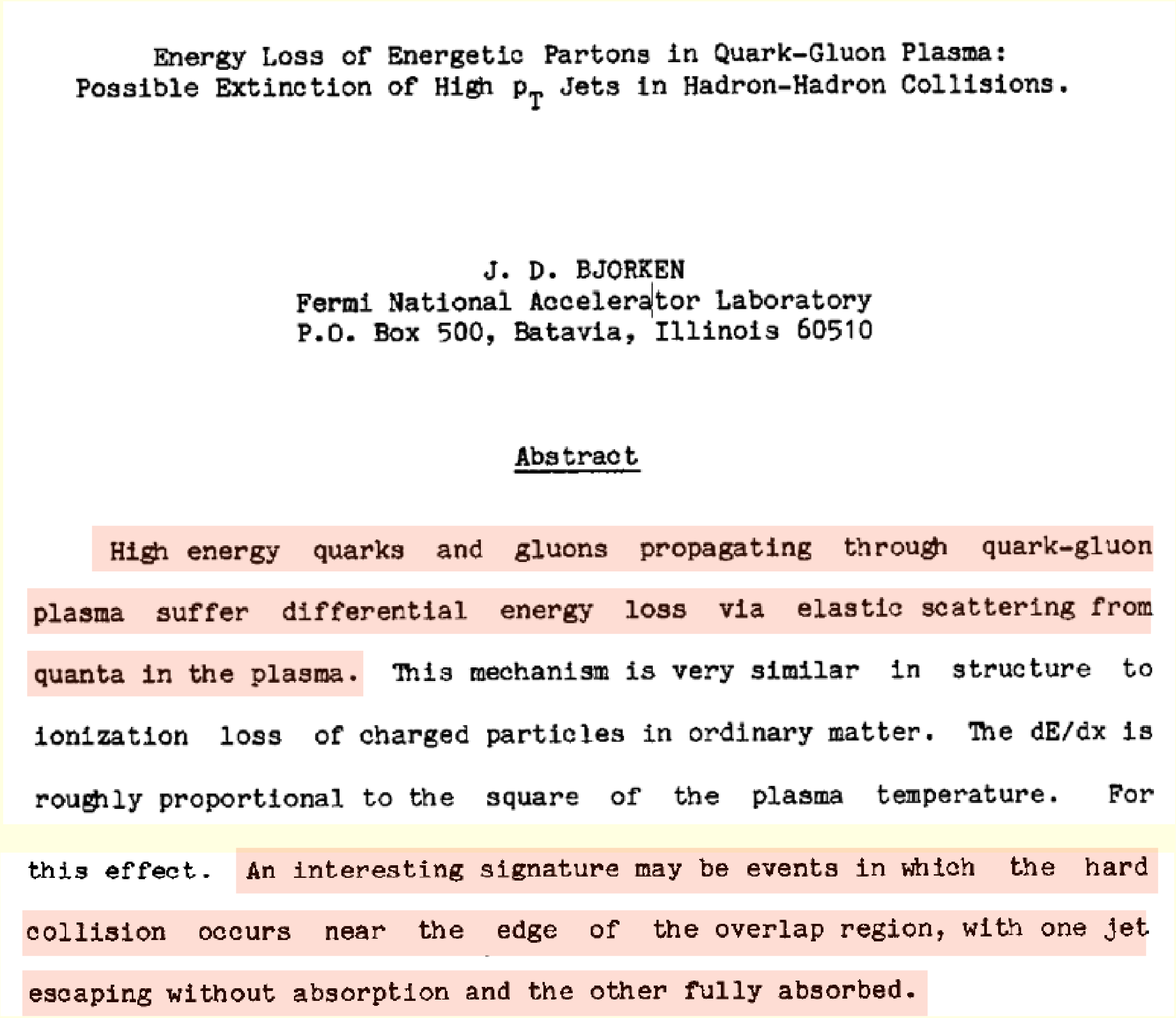


$$z = \frac{p_{\mathrm{hadron}}}{p_{\mathrm{parton}}}$$

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 $e^+e^- \to Z^0 \to q\bar{q}$)

Jet Quenching

Jet Quenching History



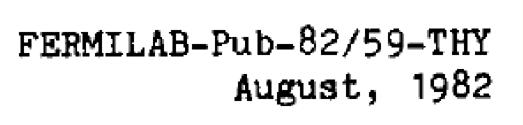
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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

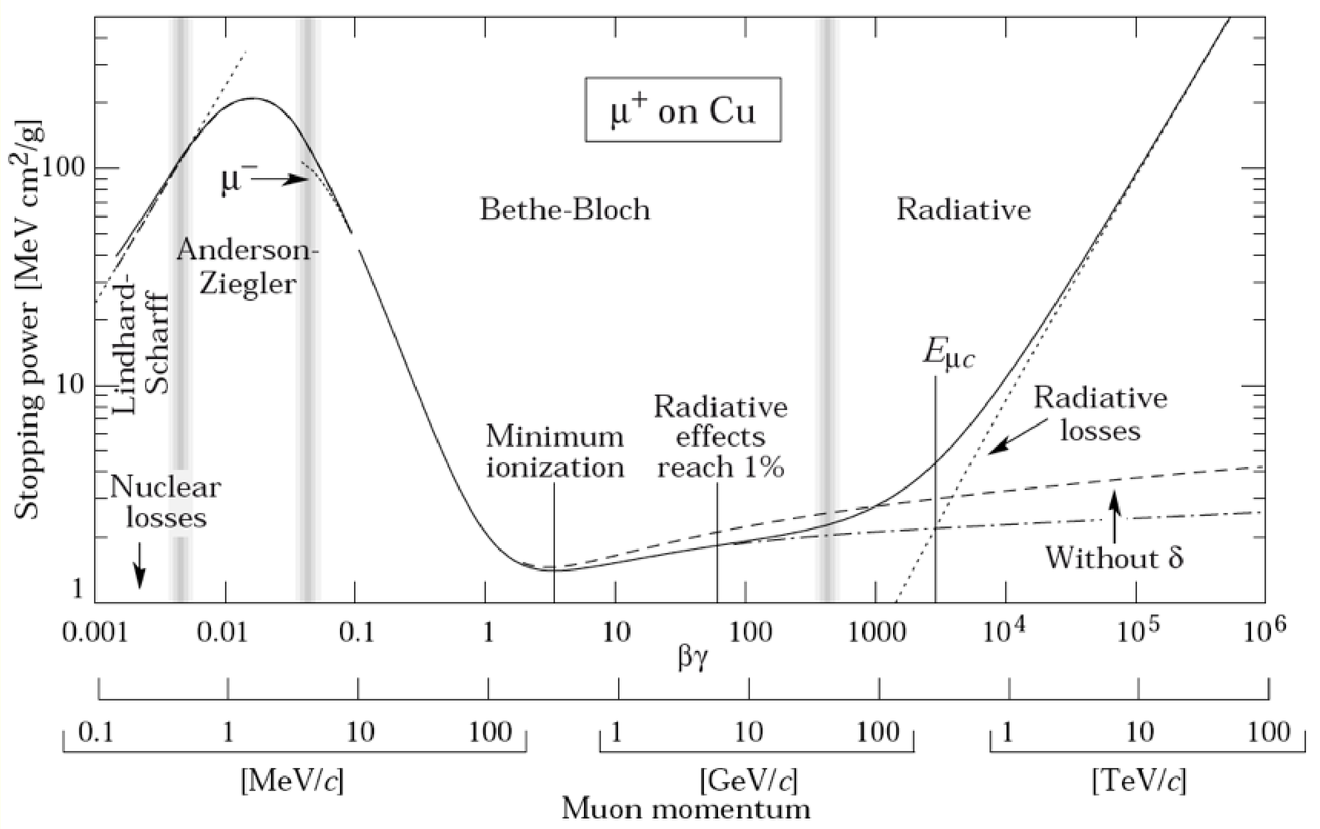
this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



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, Peigne, 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

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

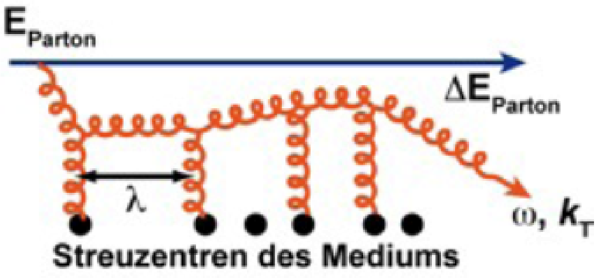
$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

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



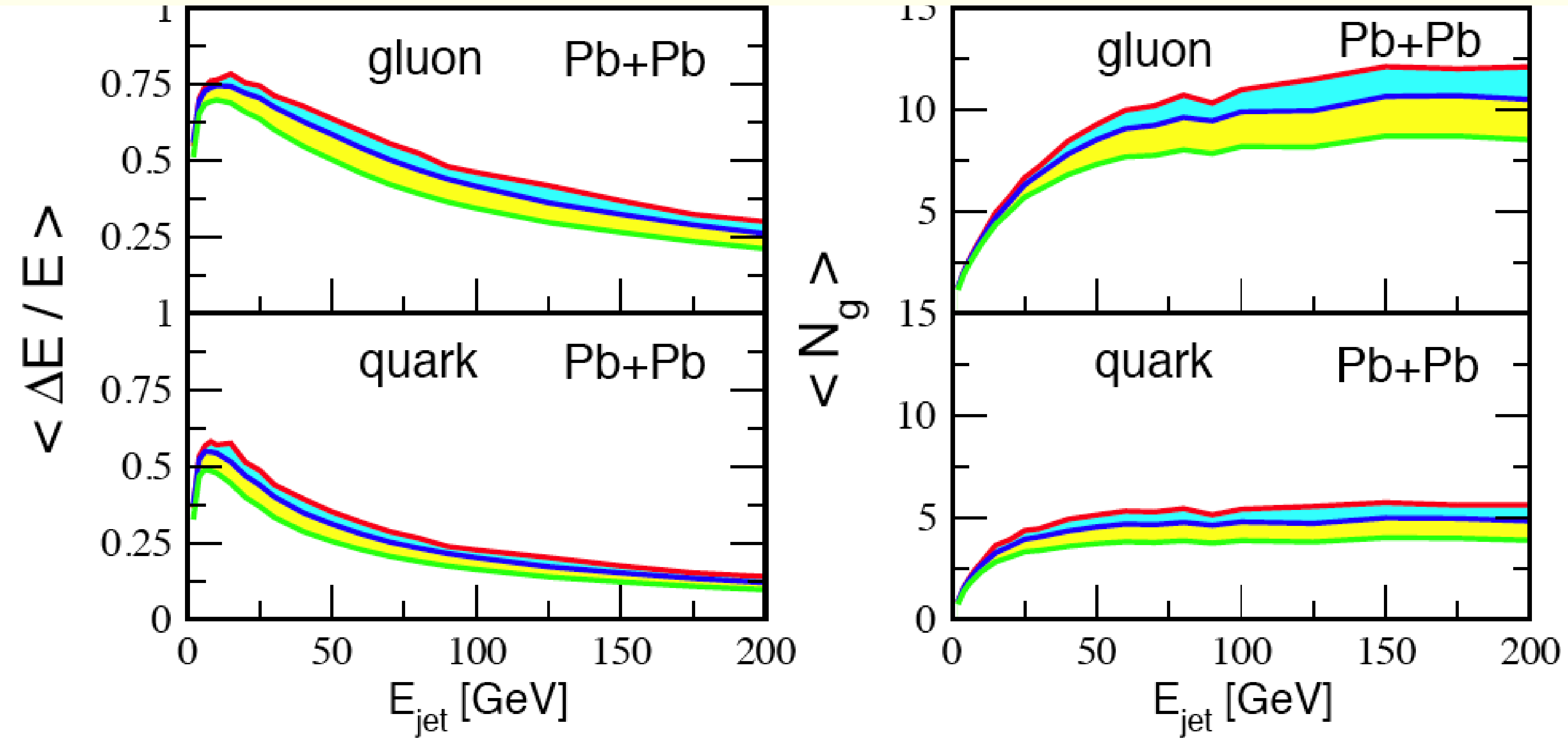
Review: U. Wiedemann, arXiv:0908.2306 (→ link)

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* ≈ 6 fm, dN^g/dy = 2000, 3000, 4000

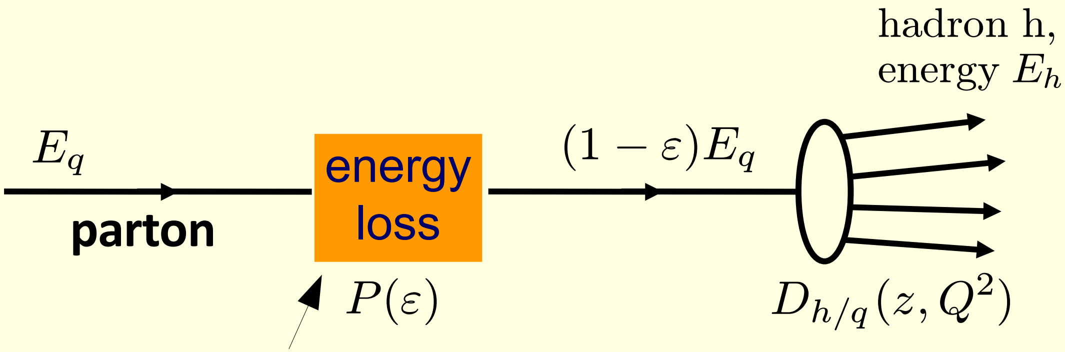
energy loss **# radiated gluons**



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

Medium-Modified Fragmentation Functions

In many parton energy-loss models the fragmentation of the quark and gluon jets is assumed to happen in the vacuum like in p+p. Parton energy loss can then 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:

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

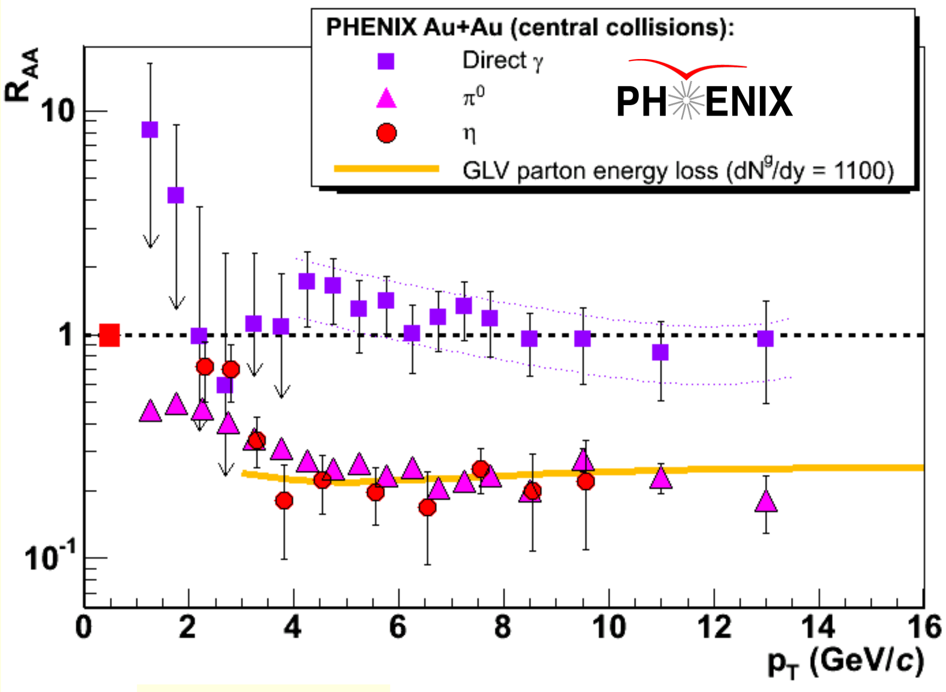
Average over energy loss probability:

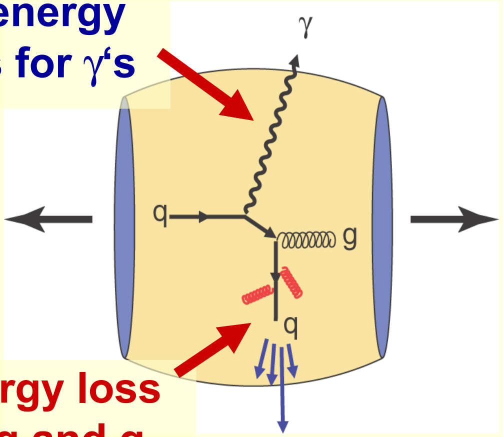
$$D_{h/q}^{\mathrm{med}}(x, Q^2) = \int_0^1 d\varepsilon\, P(\varepsilon)\; D_{h/q}\left(\frac{x}{1-\varepsilon}, Q^2\right) \frac{1}{1-\varepsilon}$$

Hadrons resulting from gluon bremsstrahlung neglected

The Discovery of Jet Quenching at RHIC

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





No energy loss for γ's

energy loss for q and g

$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

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

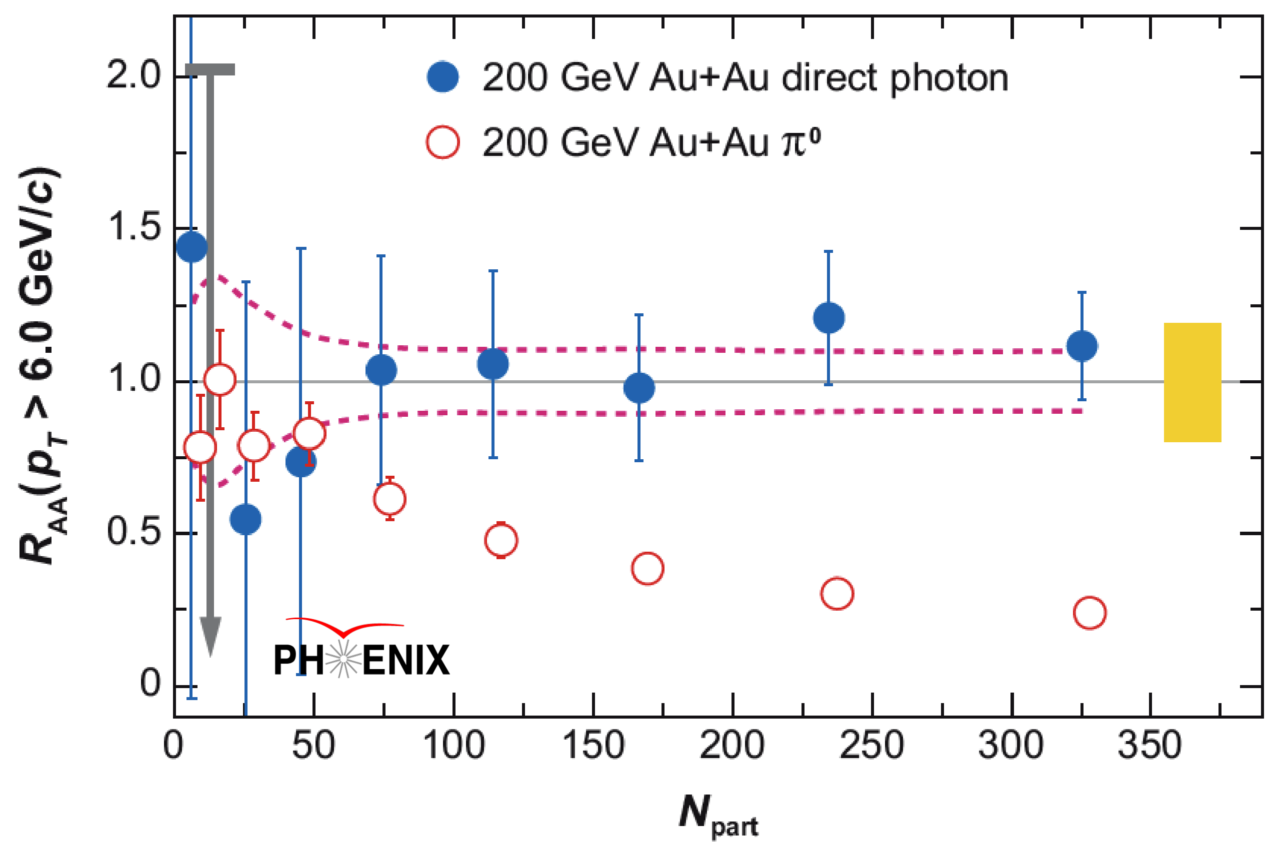
- Hadrons are suppressed, direct photons are not
- No suppression in d+Au (see slide 22)
- Evidence for parton energy loss

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

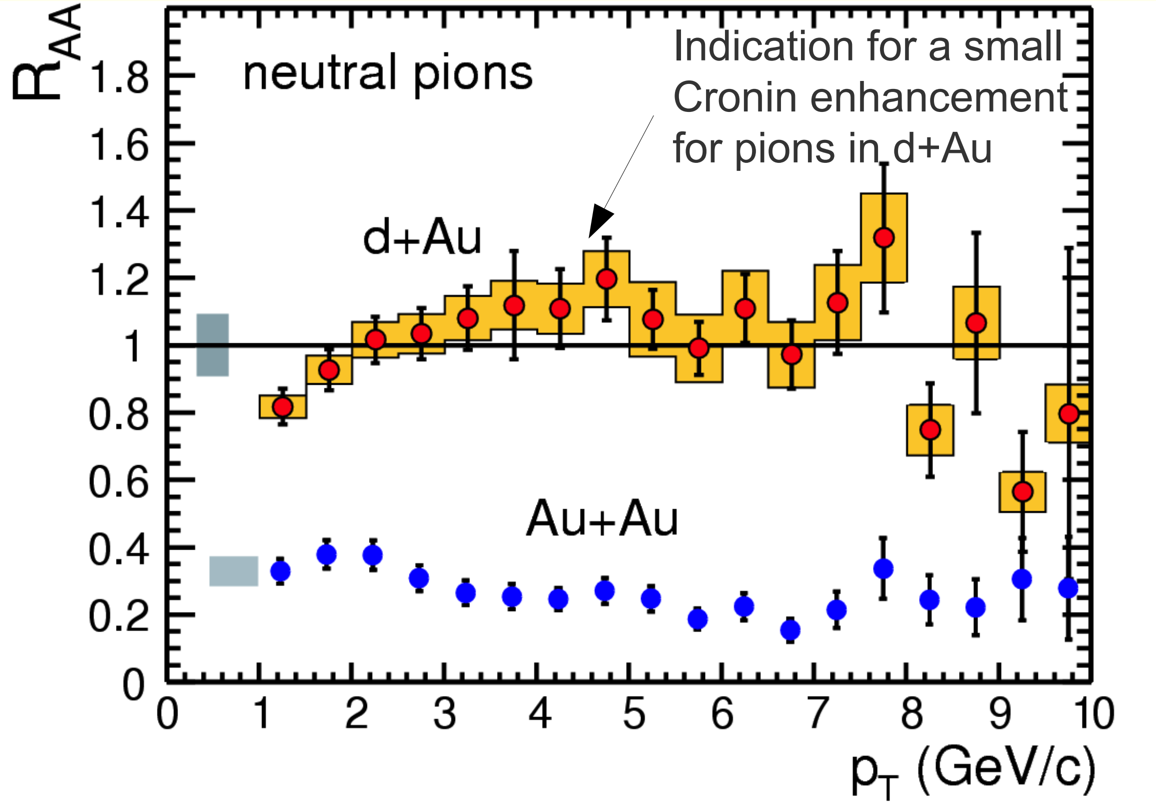
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (II)

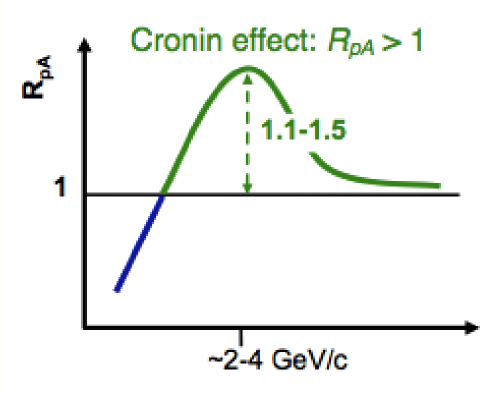
Centrality Dependence of the π^0 and direct γ R_{AA}:



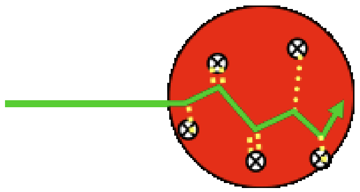
Direct photons follow T_{AB} scaling as expected for a hard probe not affected by the medium

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





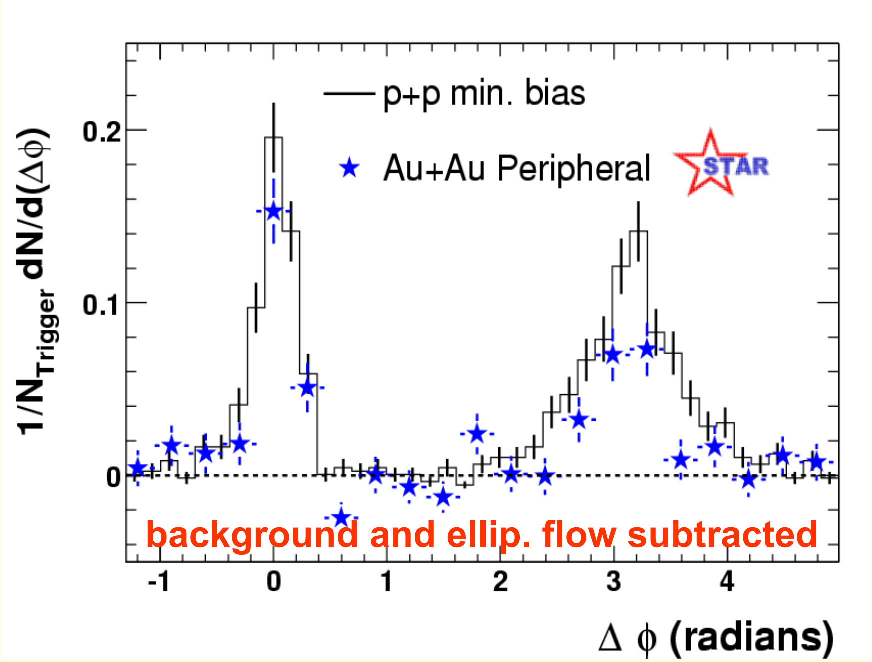
Likely explanation for the Cronin effect: multiple soft scattering in the initial state



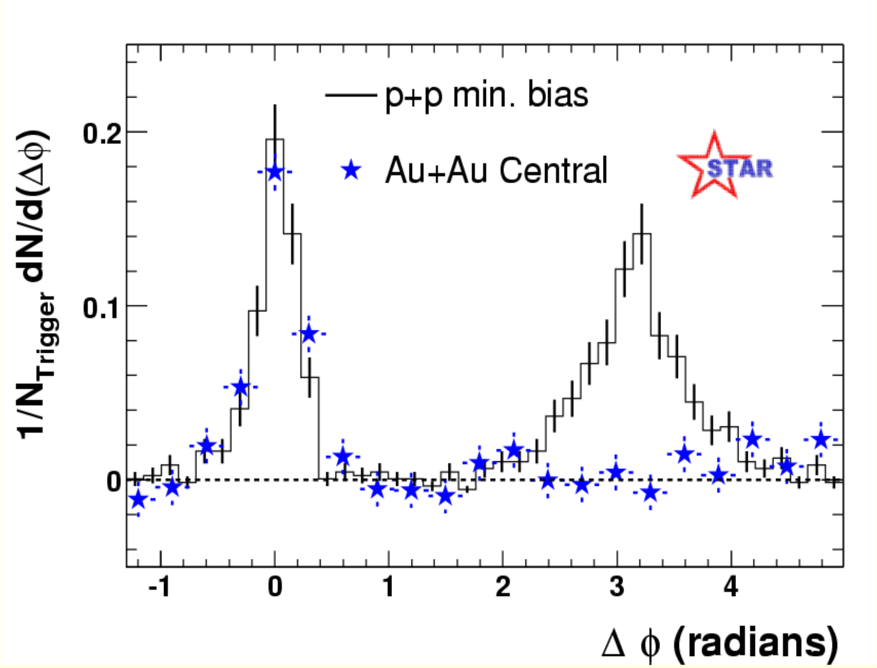
No pion suppression in min. bias d+Au collisions
⇒ pion suppression is a final state effect caused by the created medium

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

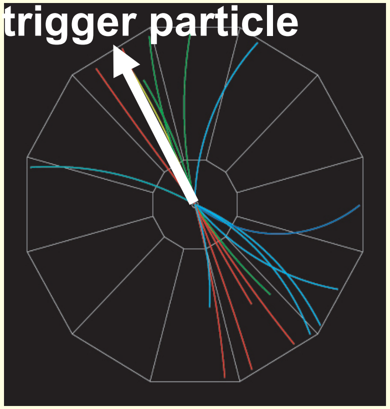
Au+Au peripheral



Au+Au central



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

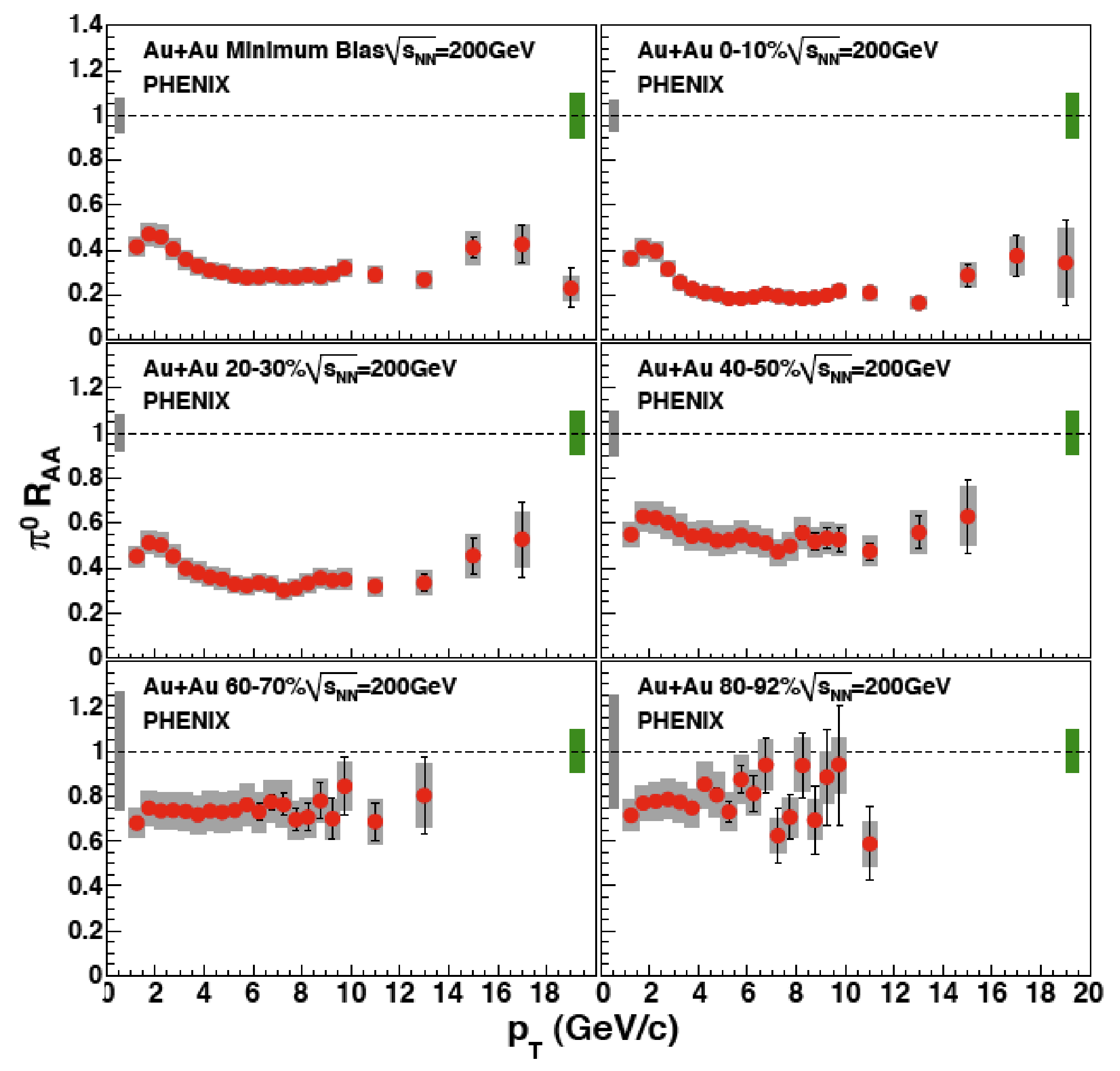


- No jet correlation around 180° in central Au+Au
- Consistent with jet quenching picture

Further Experimental Results Related to Jet Quenching

π^0 R_{AA} with Higher Statistics (Run 4)

Phys. Rev. Lett. 101, 232301 (2008)



$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

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

Simple Interpretation of the Constant R_{AA}

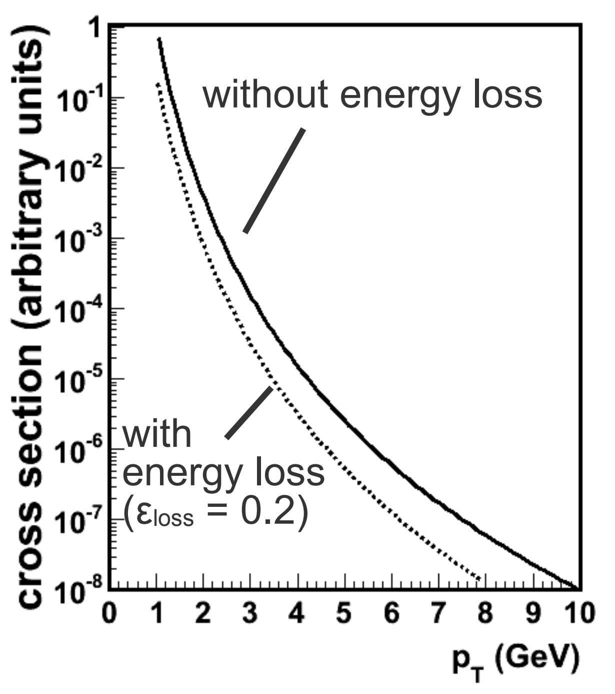
π^0 spectrum without energy loss: $$\frac{1}{p_T}\frac{dN}{dp_T} \propto \frac{1}{p_T^n}$$

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

Constant fractional energy loss:

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

(However, QCD expectation is $\varepsilon_\mathrm{loss} \sim \log(p_T)/p_T$)



This leads to:

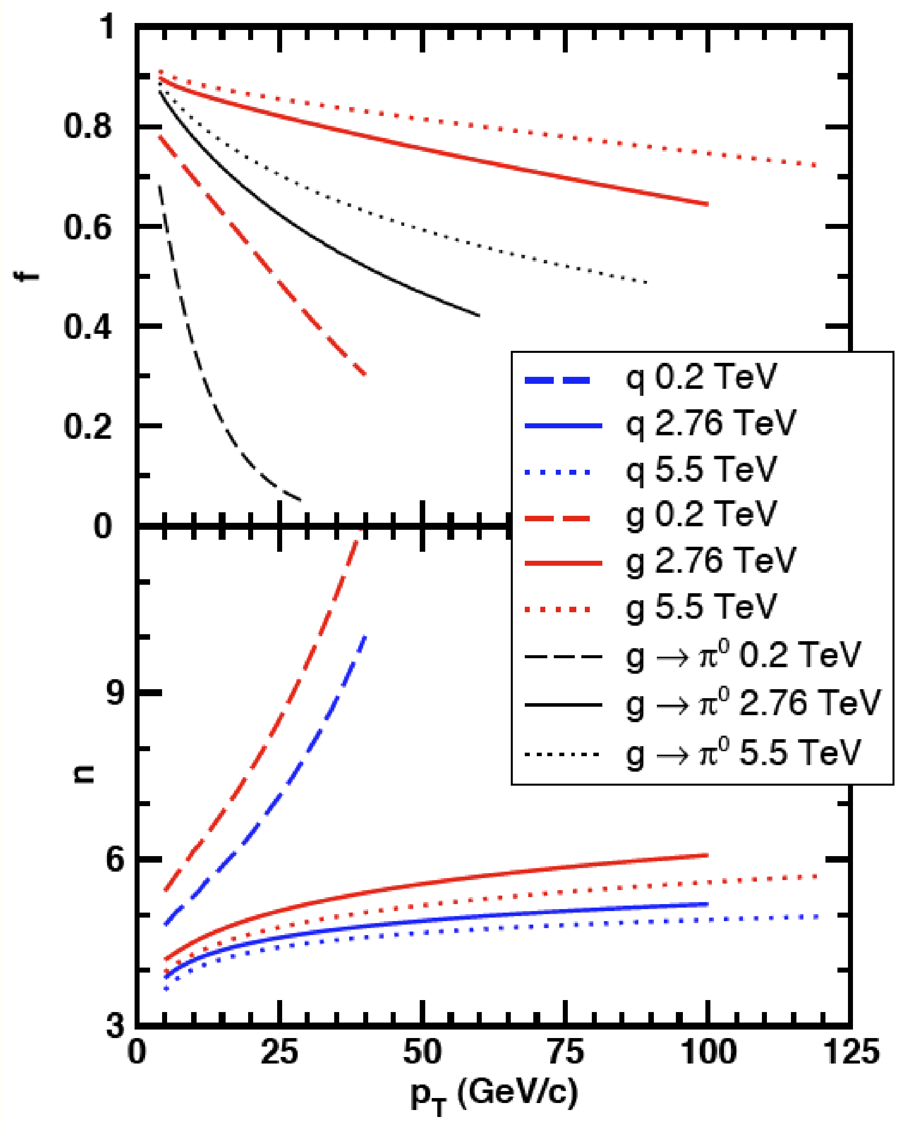
$$R_{AA} = (1-\varepsilon_\mathrm{loss})^{n-2} \quad \Rightarrow \quad \varepsilon_\mathrm{loss} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

R_{AA} depends on the parton energy loss *and* the shape of the p_T spectrum

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

Interpretation of the Rather Flat R_{AA} at RHIC

Horowitz, Gyulassy, arXiv:1104.4958



Upper panel:
Red: Fraction *f* of gluon jets as a function of jet p_T.
Black: fraction of π^0 from gluons as a fct. of pion p_T.

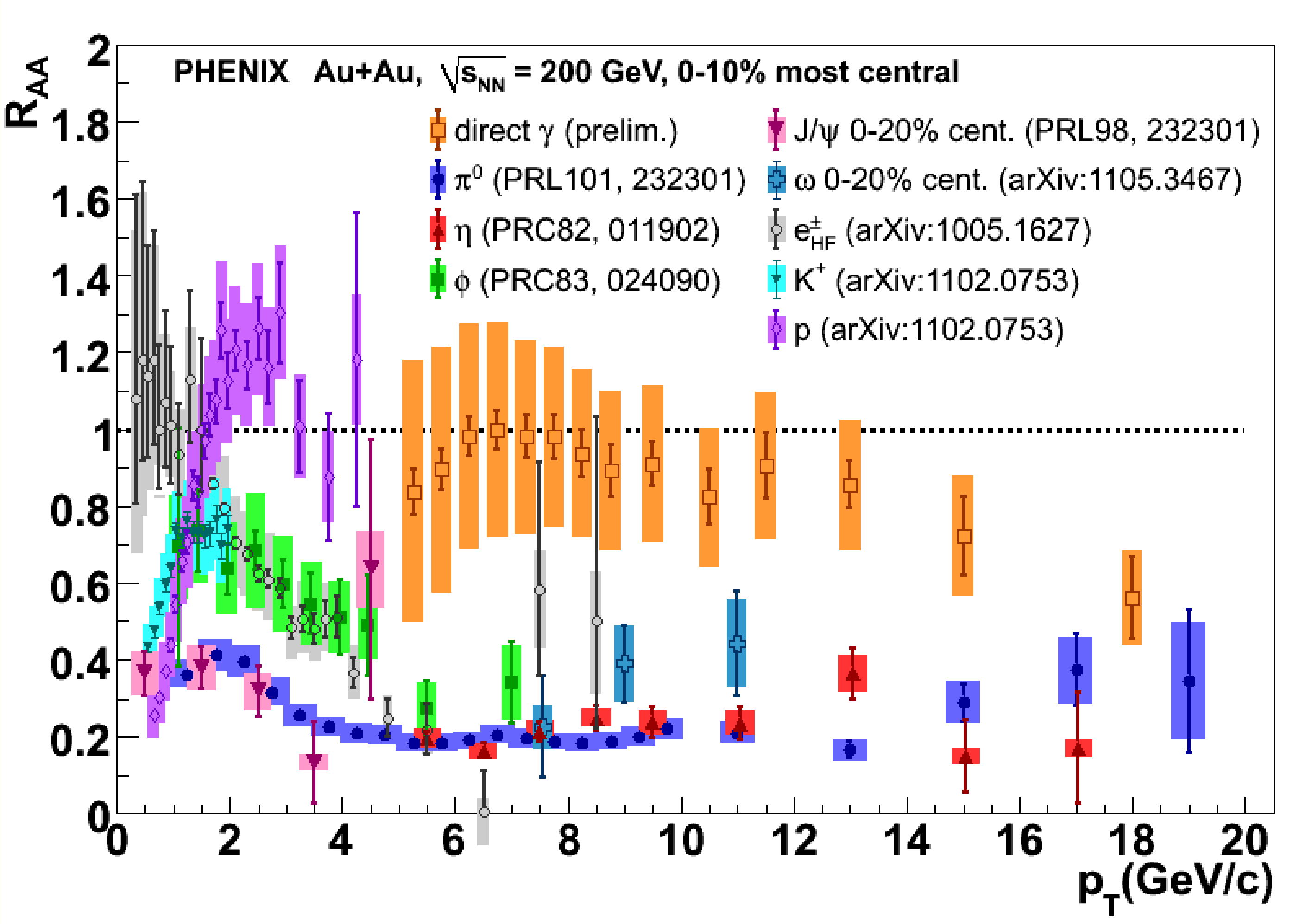
Lower panel:
Partonic spectral index $n(p_T)$:

$$n(p_T) = -\frac{d\log(\frac{dN_{\mathrm{parton}}}{dy\,dp_T})}{d\log(p_T)}$$

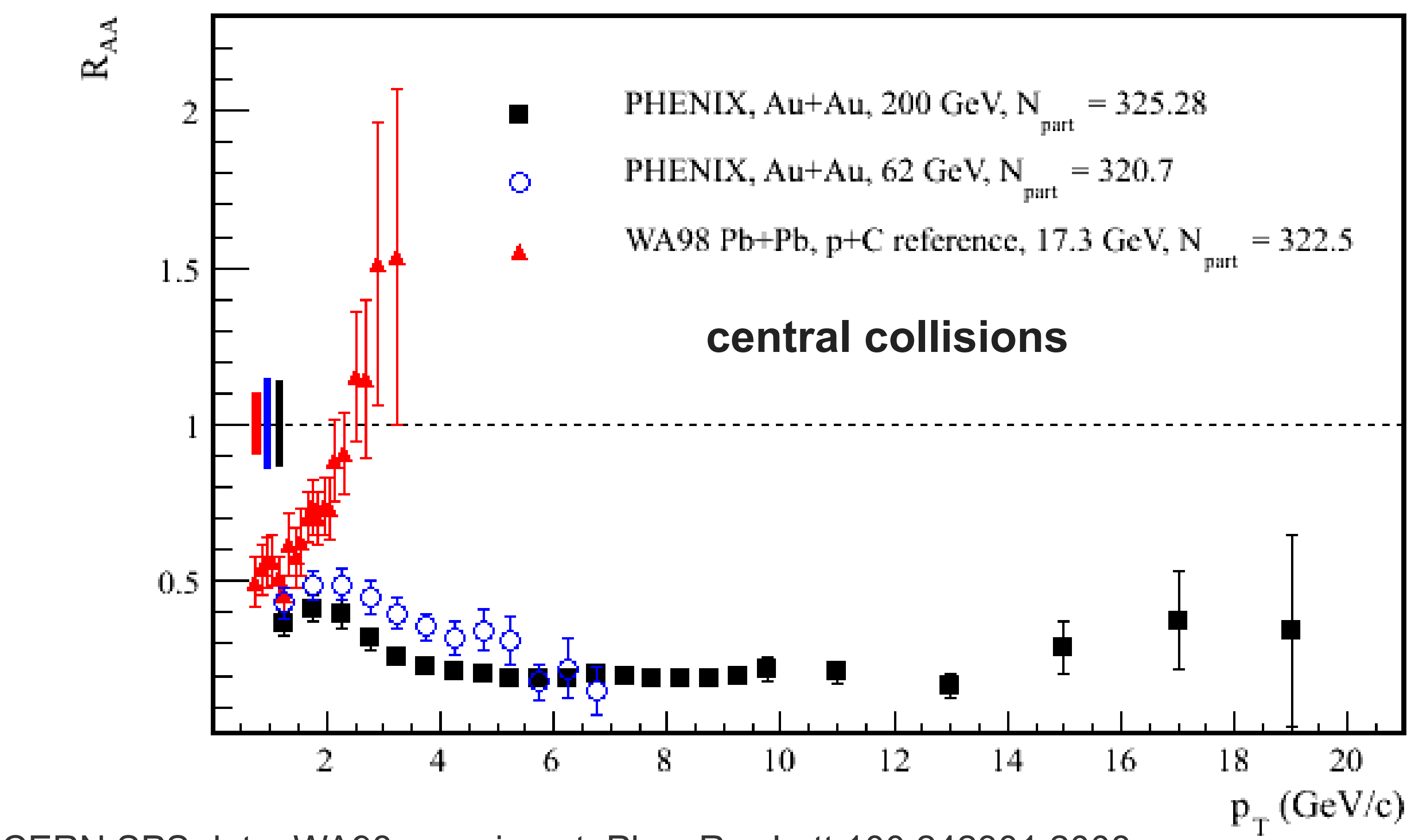
The rather flat R_{AA} at RHIC can be interpreted as an accidental cancellation between

1) The fraction of high-p_T gluons to quarks
2) The hardening of the parton spectrum (increase of $n(p_T)$)
3) The decrease in energy loss as a function of p_T

Particle Species Dependence of R_{AA}



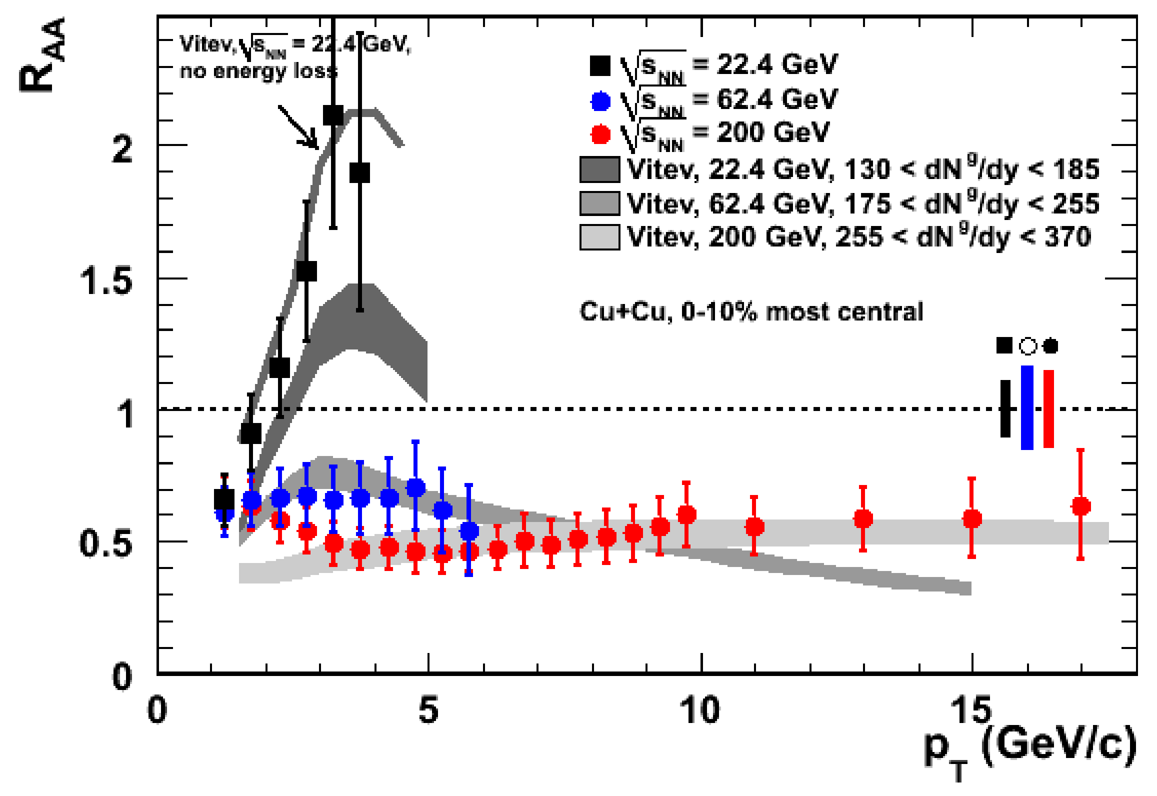
$\sqrt{s_{NN}}$ Dependence: π^0 R_{AA} for Heavy Nuclei at $\sqrt{s_{NN}}$ = 17.3, 62.4, and 200 GeV



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

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

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

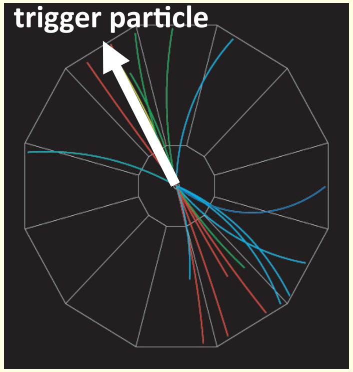
π^0 production less suppressed than in Au+Au

22.4 GeV

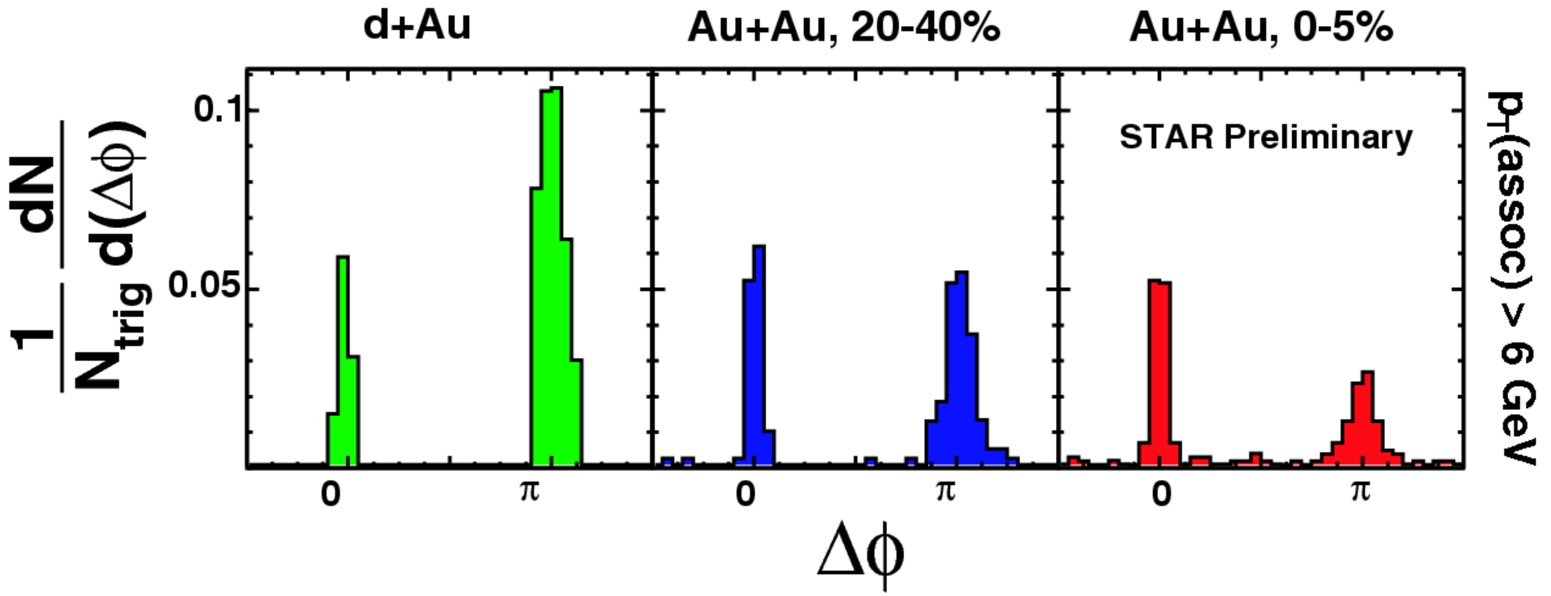
- No suppression
- Enhancement consistent with a calculation that describes Cronin effect in p+A

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

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 $\Delta\varphi = 180°$ in central Au+Au is not fully suppressed anymore

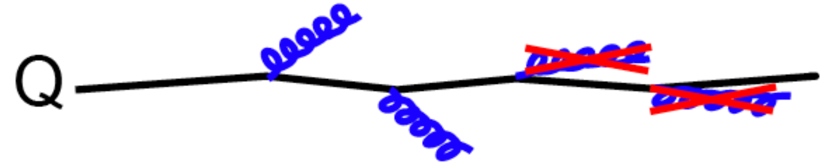
Hierarchy Expected for Different Types of Partons

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

larger color factor
for gluons:

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

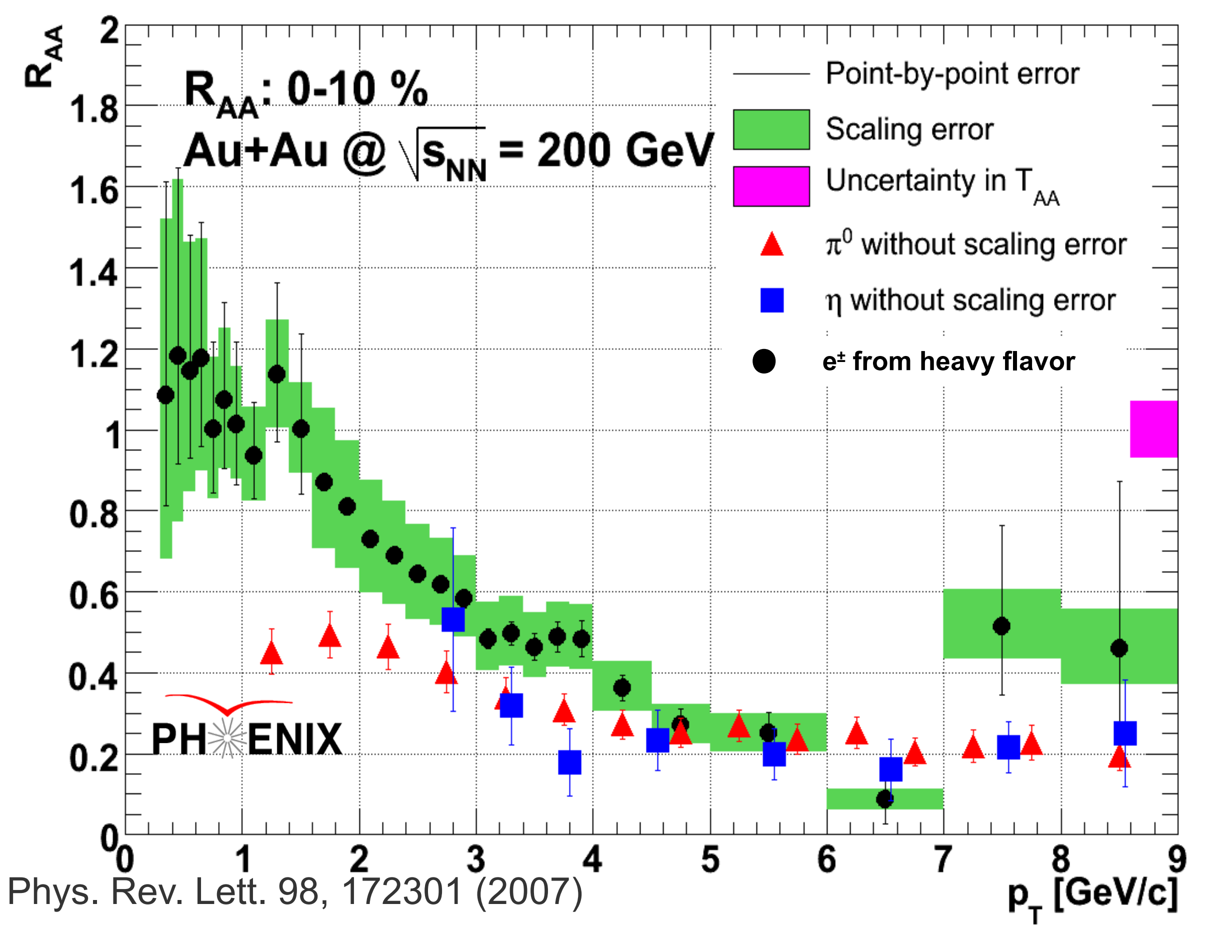
Dead cone effect:
Heavy quarks (c, b) are
slower and radiate fewer gluons



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

Dokshitzer & Kharzeev, PLB 519(2001)199

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

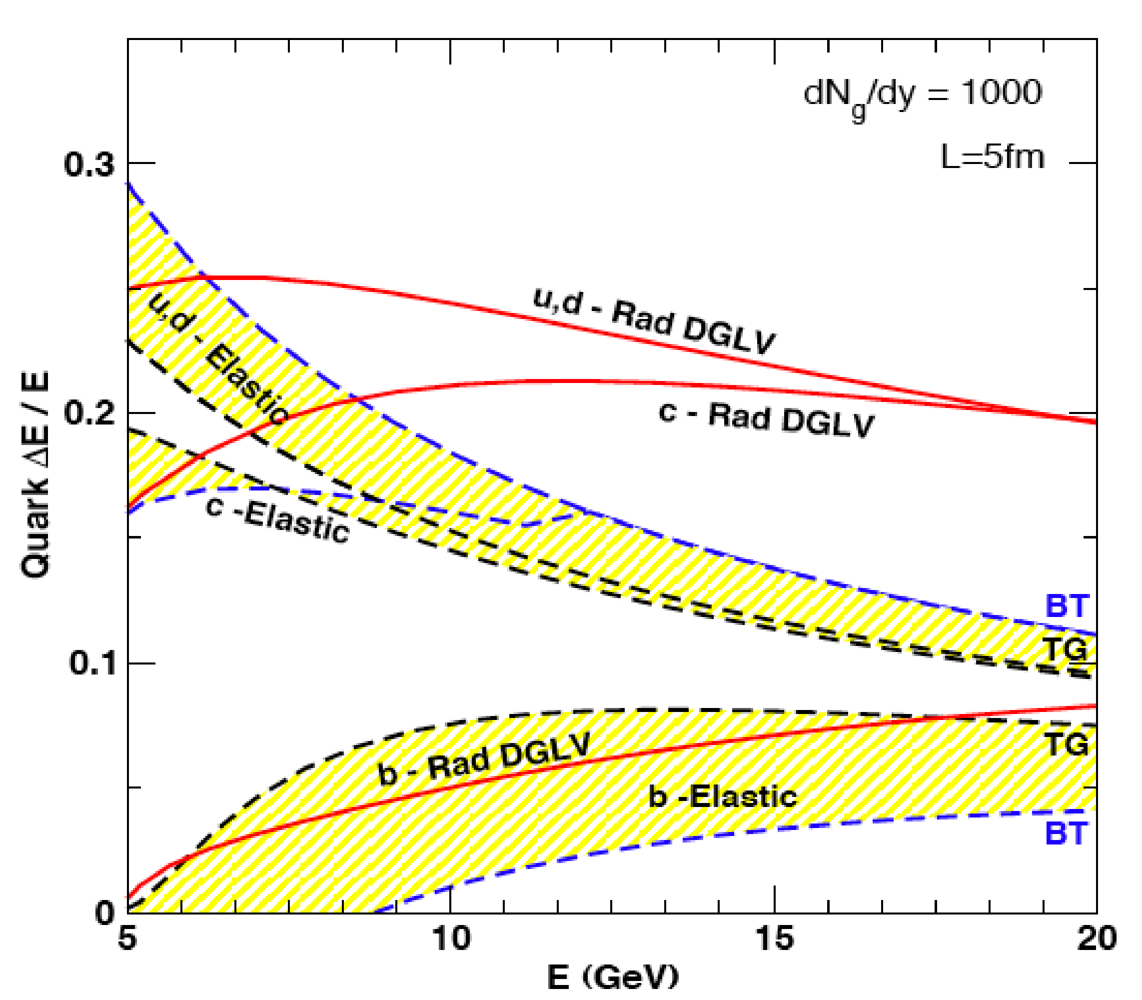


Phys. Rev. Lett. 98, 172301 (2007)

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

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

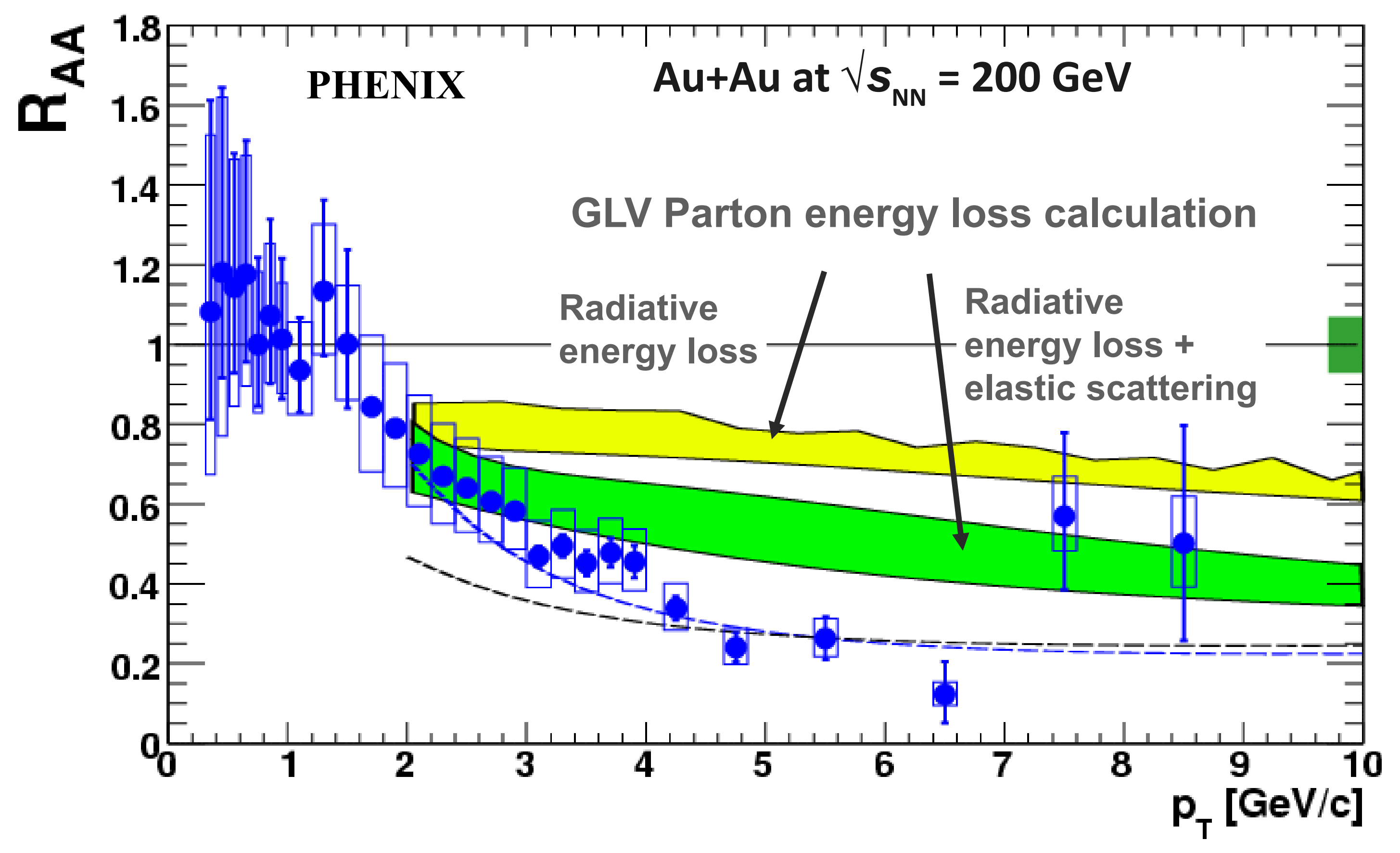
Radiative vs. Collisional (i.e., Elastic) Energy Loss: Maybe $\Delta E_{\text{collisional}}$ More Important Than Initially Thought?



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

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

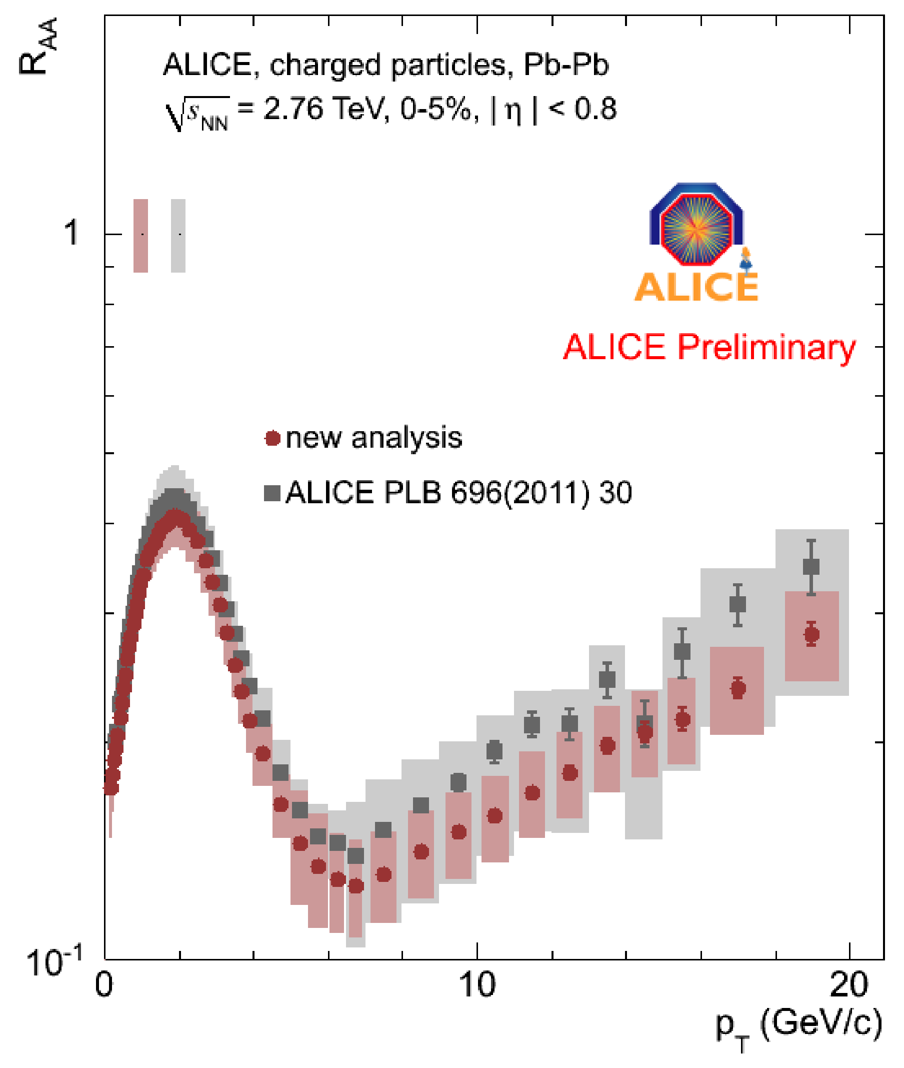
R_{AA} for Electrons from Heavy Quarks: Not Understood with Current Energy Loss Models

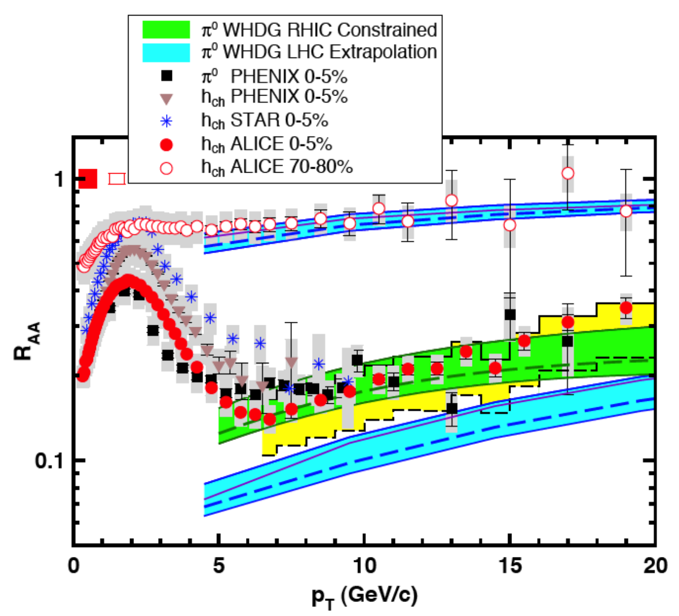


- Radiative energy loss not sufficient to describe excess electron R_{AA}
- Including elastic scattering improves the situation only slightly

Results from the LHC: 1. Spectra

R_{AA} for Charged Particles in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



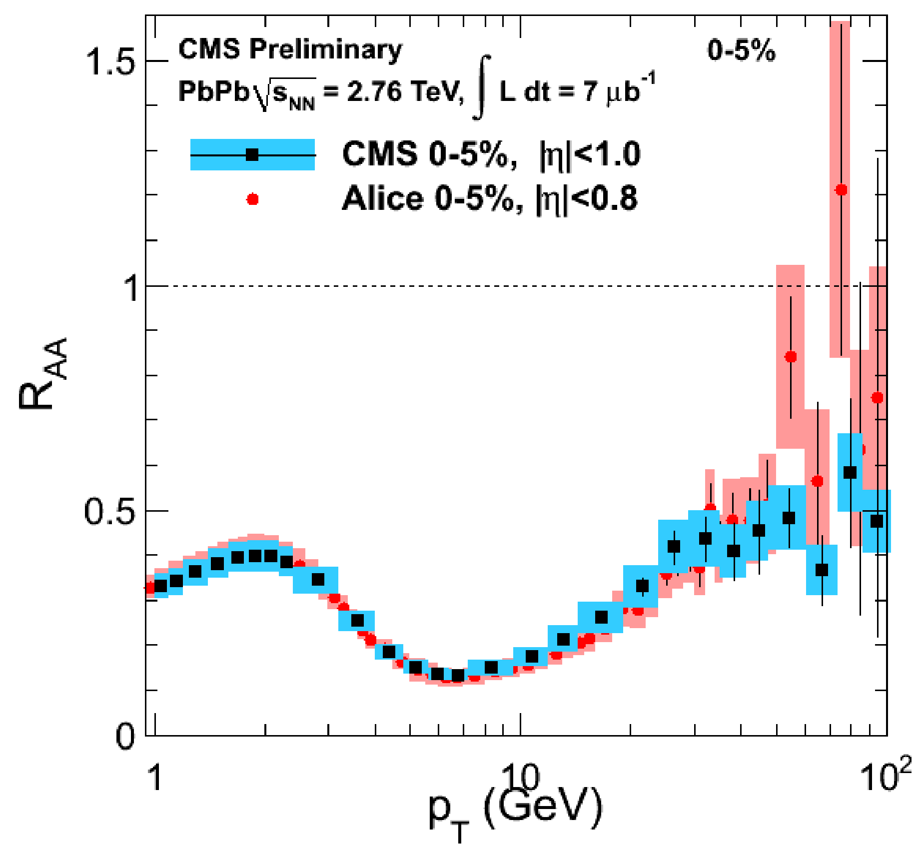


Horowitz, Gyulassy, arXiv:1104.4958

Data test density dependence of light quark and gluon energy loss:
$dN_{ch}/d\eta_{PbPb@2.76TeV} \approx 2\, dN_{ch}/d\eta_{AuAu@0.2TeV}$

The relatively small difference between R_{AA} at RHIC and LHC is a challenge to theory

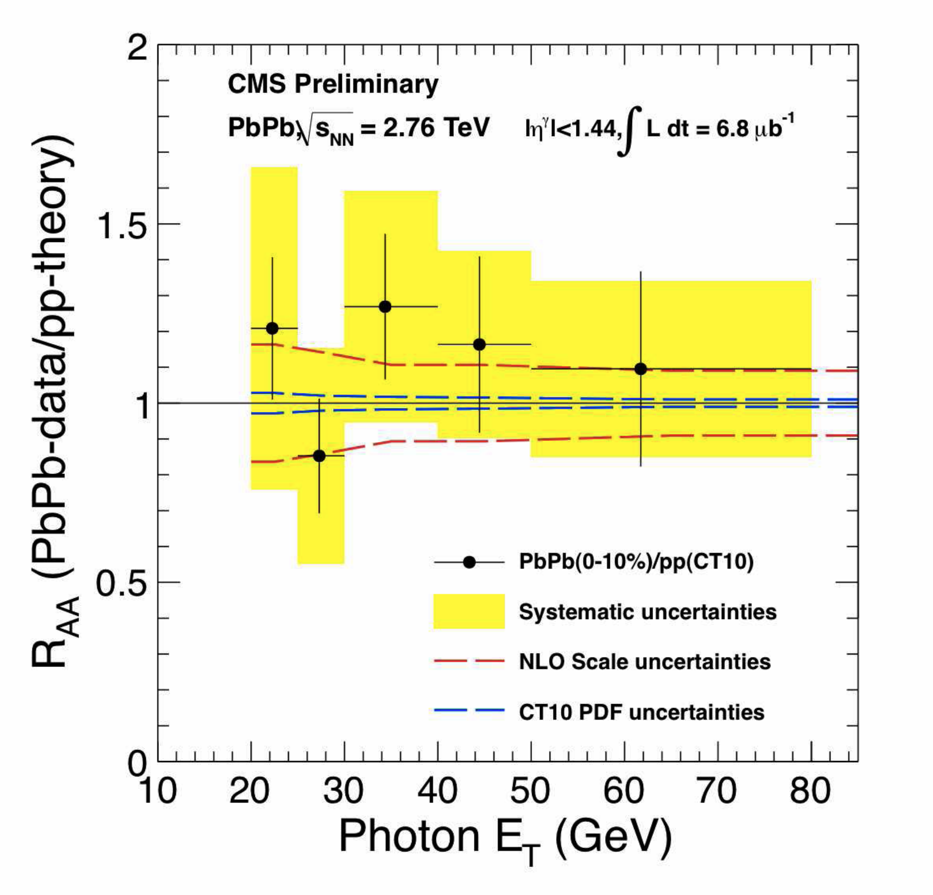
R_{AA} for Charged Particles up to p_T = 100 GeV/c

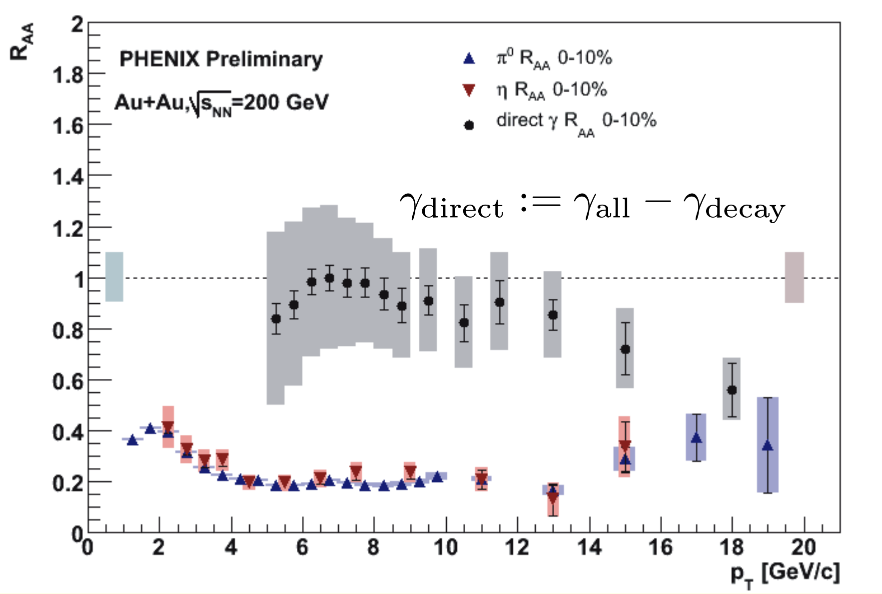


R_{AA} rises with p_T up to $R_{AA} \approx 0.5$.

The increase of R_{AA} is consistent with the expected $\Delta p_T/p_T \sim \log(p_T)/p_T$

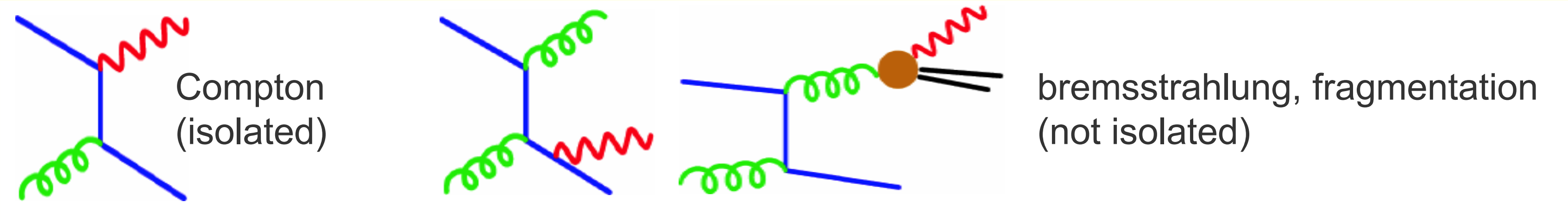
Verification of T_{AB} Scaling with Hard Photons





$$\gamma_{\mathrm{direct}} := \gamma_{\mathrm{all}} - \gamma_{\mathrm{decay}}$$

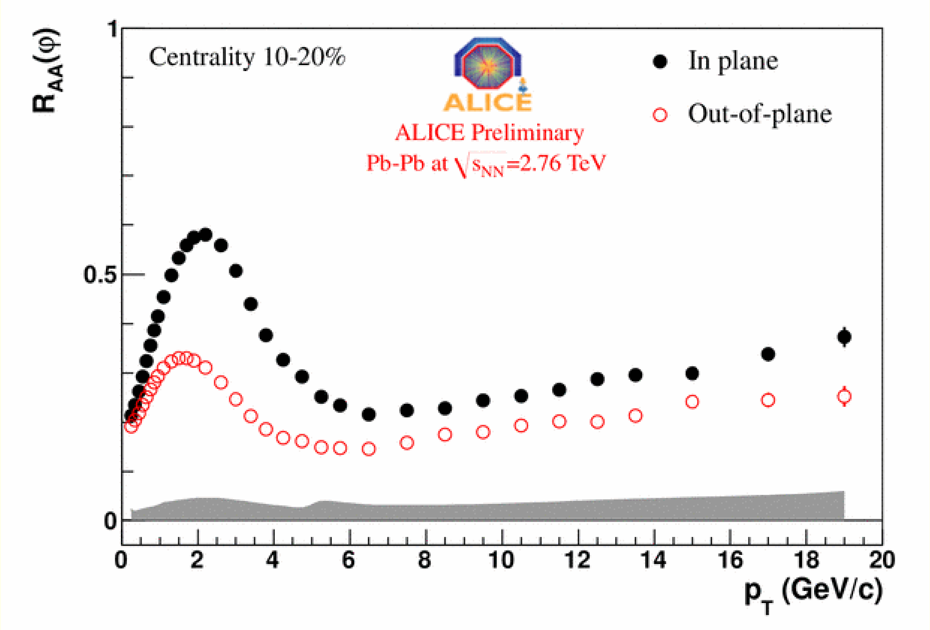
R_{AA} ≈ 1 for isolated photons (CMS) verifies the expected T_{AB} (or N_{coll}) scaling for hard processes

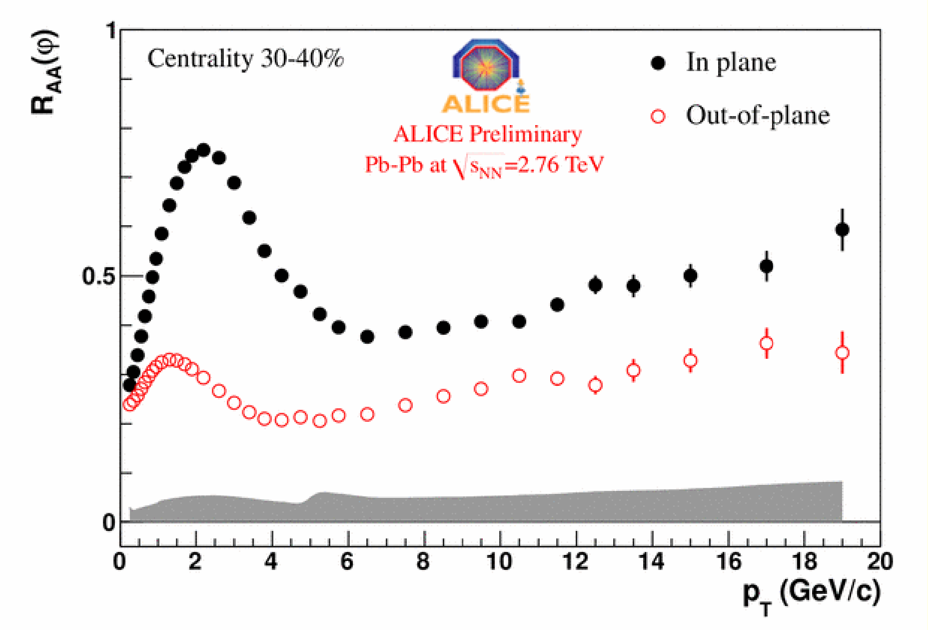


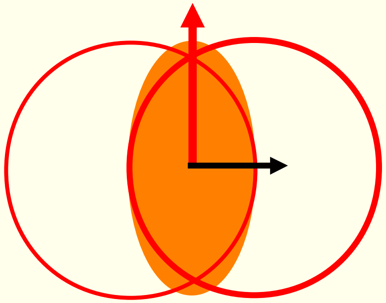
Compton
(isolated)

bremsstrahlung, fragmentation
(not isolated)

Reaction Plane Dependence of R_{AA}







in plane
out-of-plane

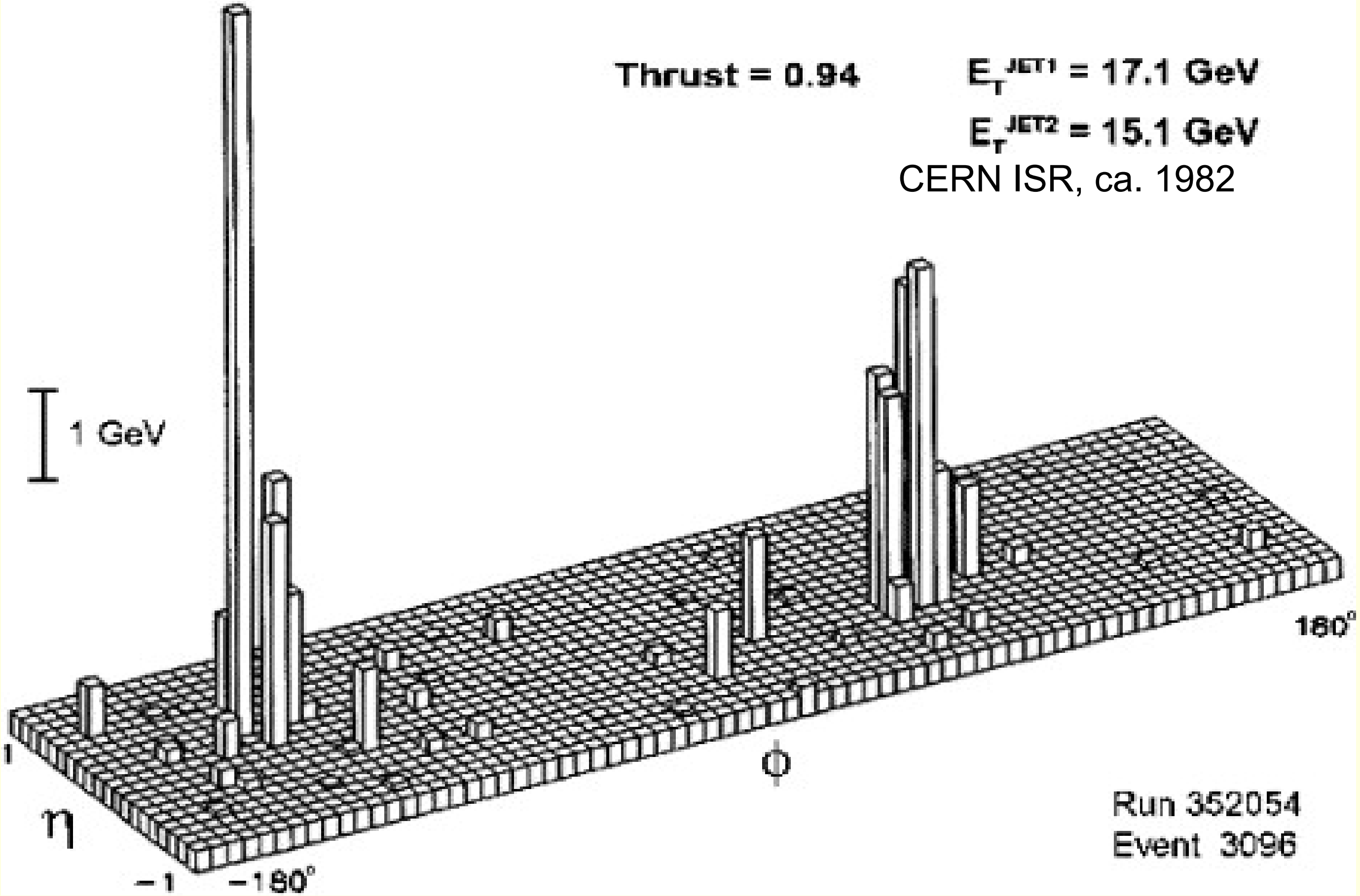
The reaction plane dependence of R_{AA} constrains the path length dependence of parton energy loss

The reaction plane dependence of R_{AA} at RHIC poses a problem to perturbative energy loss models (PHENIX, Phys.Rev.Lett.105:142301,2010)

Results from the LHC: 2. Jets

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

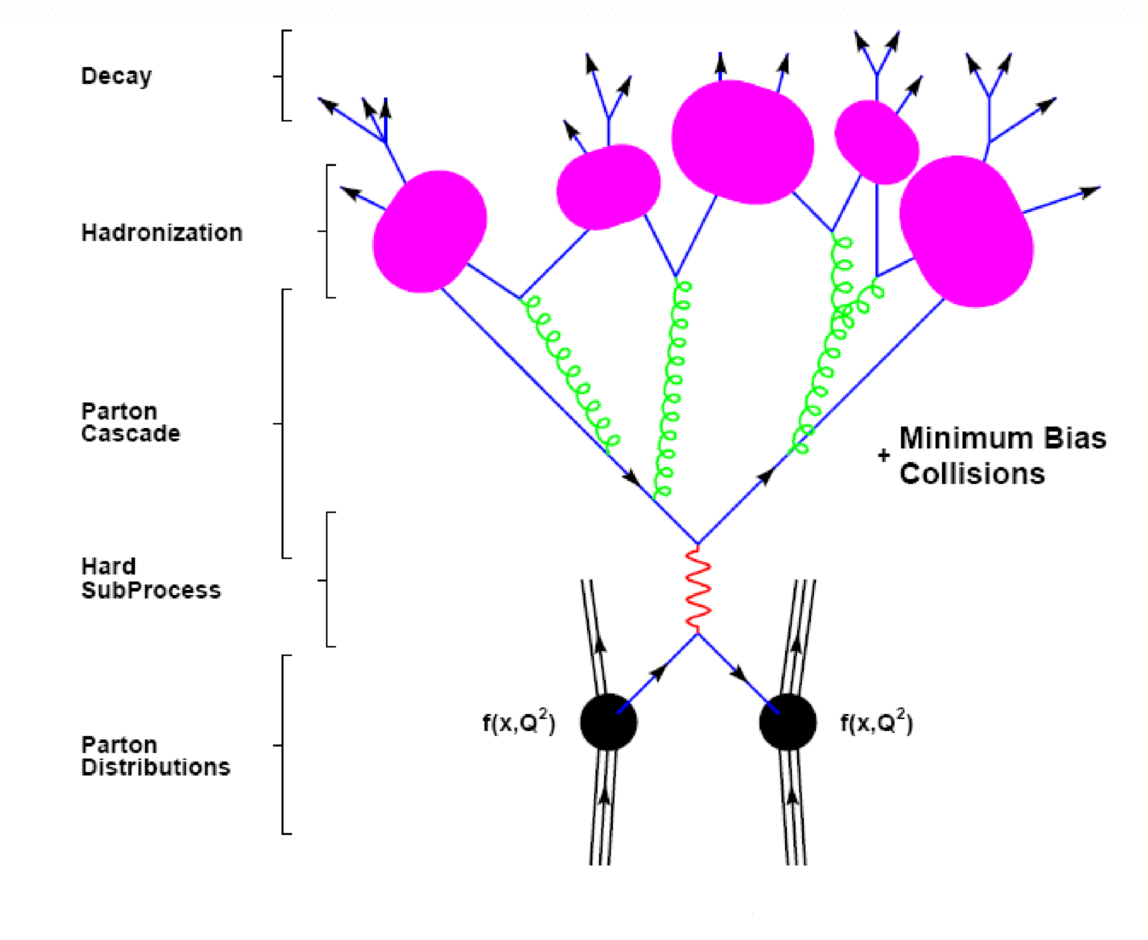
Lego plot shows energy vs. pseudorapidity η and azimuthal angle φ



CERN ISR, ca. 1982

Jets were discovered in e+e- in the late 1970's and then also observed in p+p

Evolution of a Jet Event

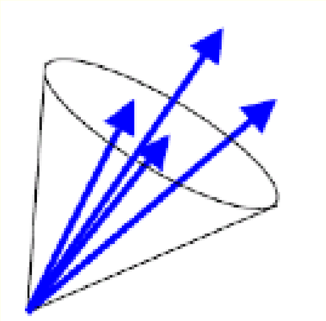


$$\underbrace{\text{Hard Process} \rightarrow \text{Parton Cascade}}_{\text{describable with pQCD}} \rightarrow \underbrace{\text{Hadronization}}_{\substack{\text{not describable with pQCD} \\ \text{(only phenomenological models)}}}$$

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
  - Sequential recombination: traditional choice in e^+e^- collisions (k_T algorithm, anti-k_T algorithm)

Cone algorithm:

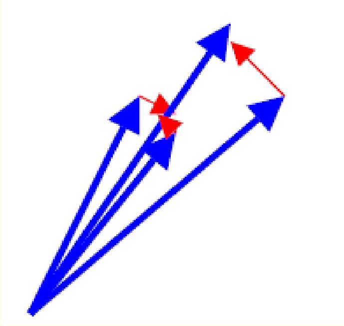


Sum content in cone with radius

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

Typical choice in p+p: $R = 0.7$

k_T algorithm:

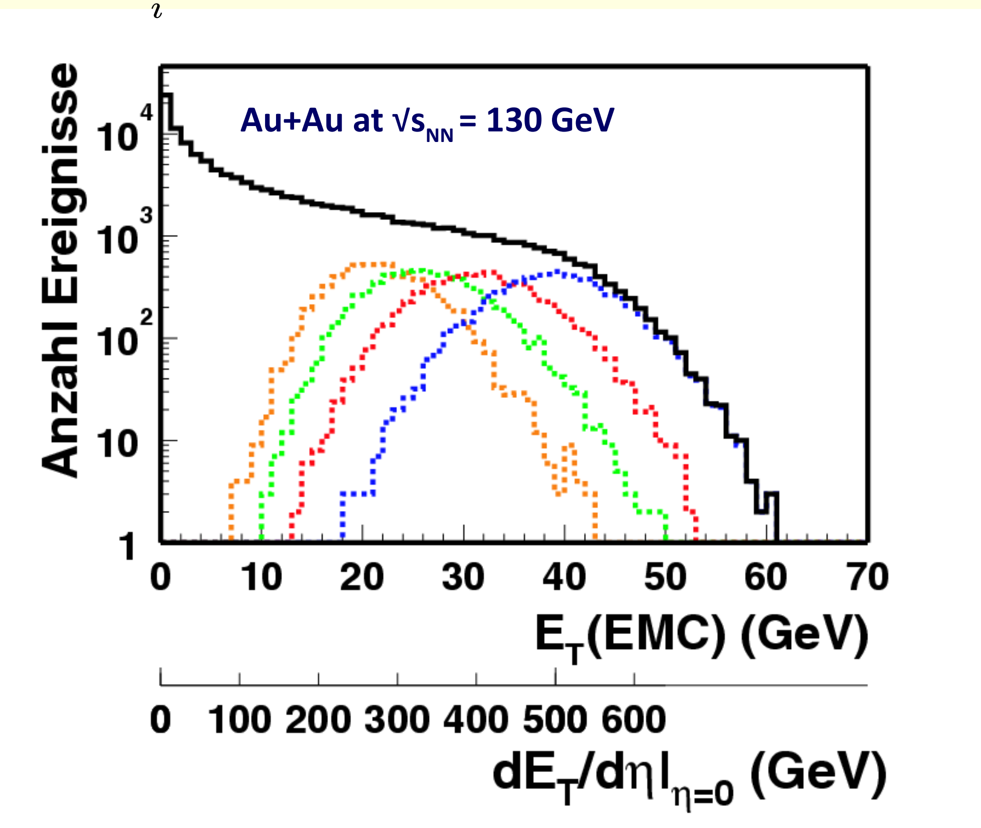


Successively merge "particles" in order of relative transverse momentum ("run parton cascade backwards").

Termination of merging controlled by a parameter D

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

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



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

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

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

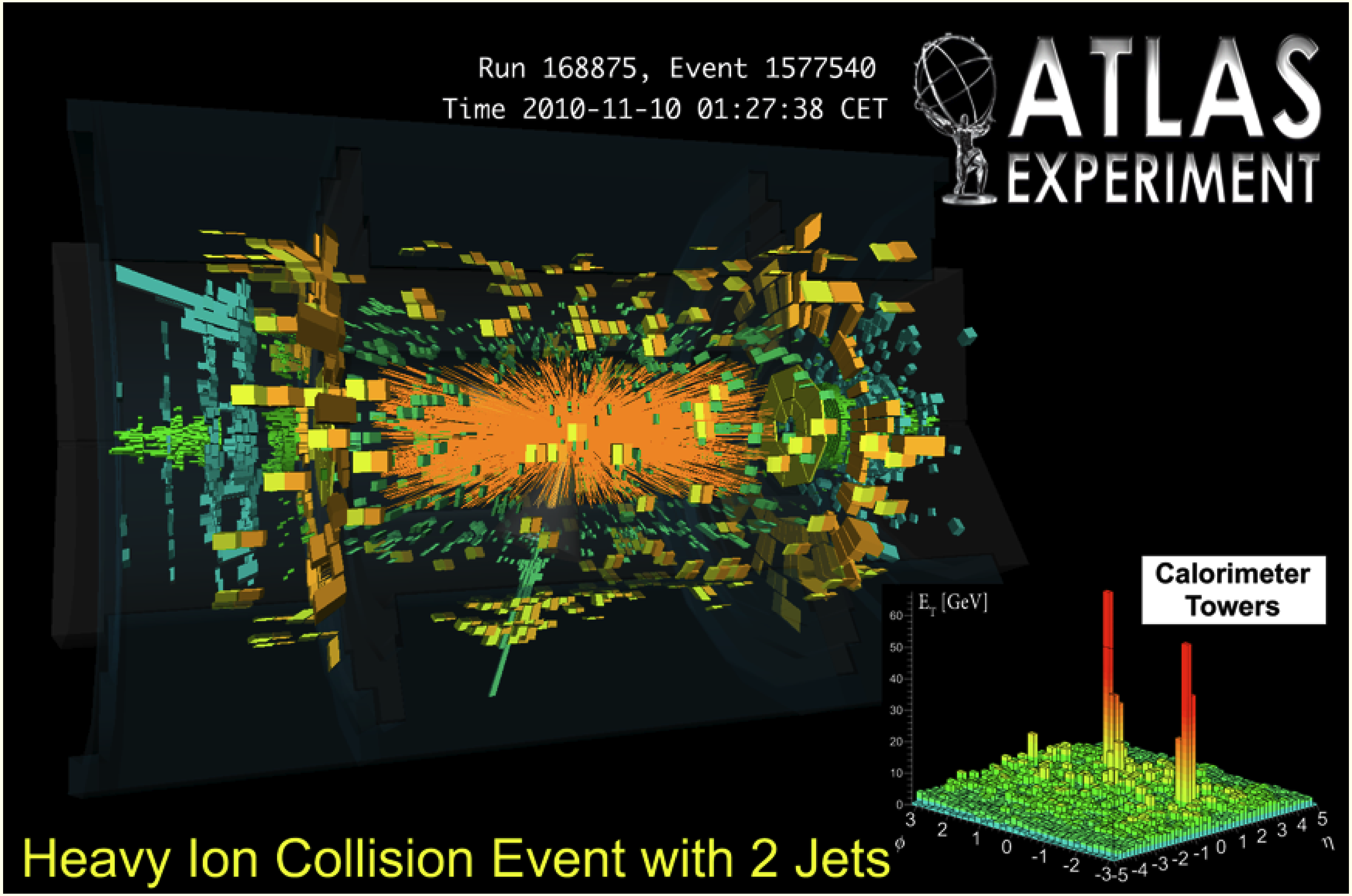
Consider jet cone with radius *R*:

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

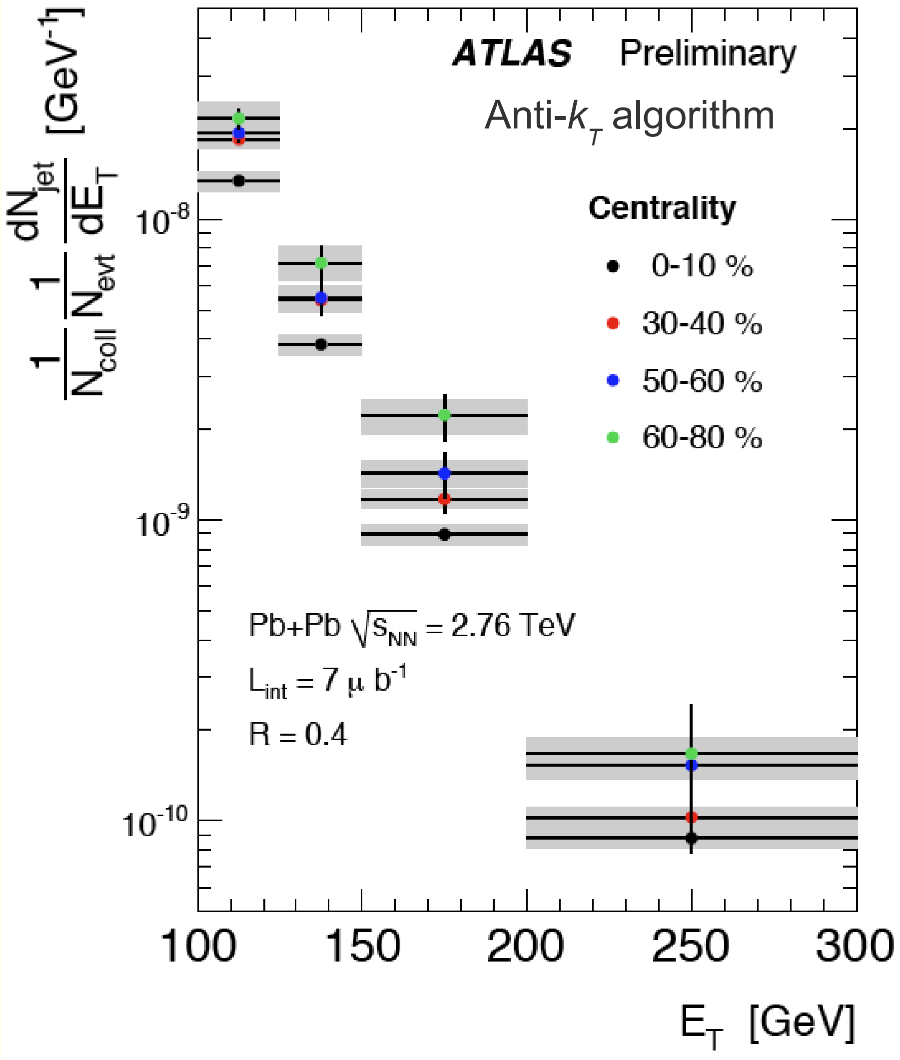
Total transverse energy in this cone:

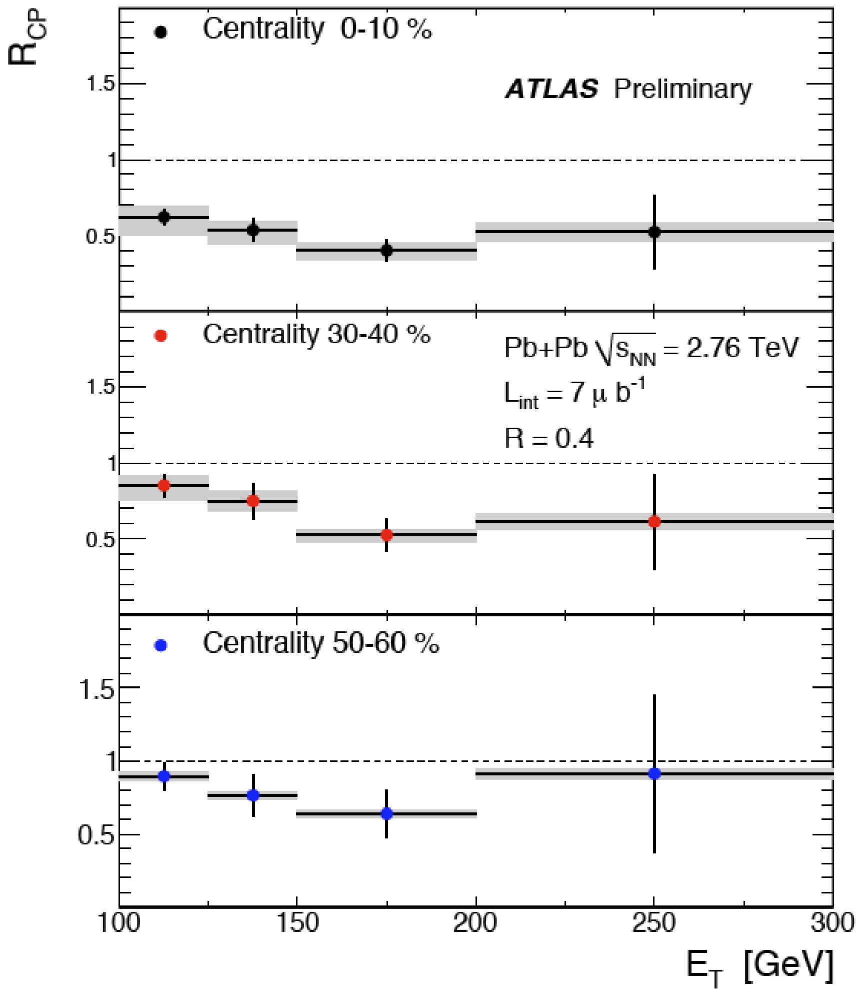
$$E_T^{\mathrm{cone}} = \frac{d^2 E_T}{d\eta d\phi} \cdot \pi R^2 = \frac{1}{2\pi}\frac{dE_T}{d\eta} \cdot \pi R^2 \approx 40\,\mathrm{GeV}$$

Two-Jet Event in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV (ATLAS)



Jet-E_T Spectrum and Jet R_{AA} in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV





$$R_{CP} = \frac{\frac{1}{N_{\rm coll}^{\rm cent}} \frac{dN_{\rm jet}^{\rm cent}}{dE_T}}{\frac{1}{N_{\rm coll}^{60-80\%}} \frac{dN_{\rm jet}^{60-80\%}}{dE_T}}$$

Jet R_{CP} ≈ 0.5 in central Pb+Pb (R = 0.4)

Points to Take Home

- High-p_T particles can be regarded as a probe of the medium created in heavy-ion collisions
- The suppression of high-p_T particles in A+A collisions can be described by parton energy loss in a medium of high color charge density
- Many open issues in parton energy loss theory:
  - Reaction plane dependence of R_{AA}
  - Heavy-quark energy loss
  - Similar R_{AA} at RHIC and LHC
  - ...
- Full jet reconstruction is challenging at RHIC due to large backgrounds
- The increased jet cross section allows to study parton energy loss in Pb+Pb collisions with full jet reconstruction at the LHC