QGP Physics – from Fixed Target to LHC

8. Hard scattering, Jets, and Jet Quenching

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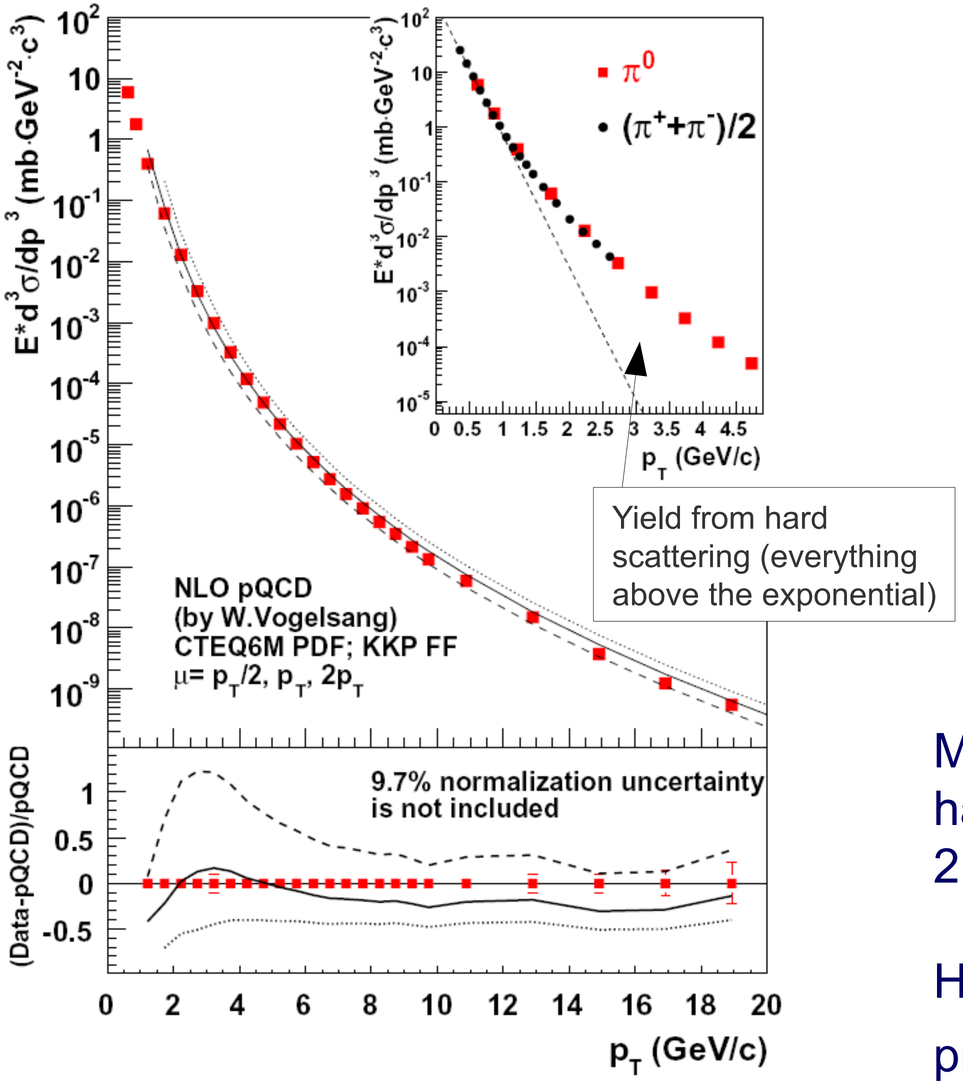
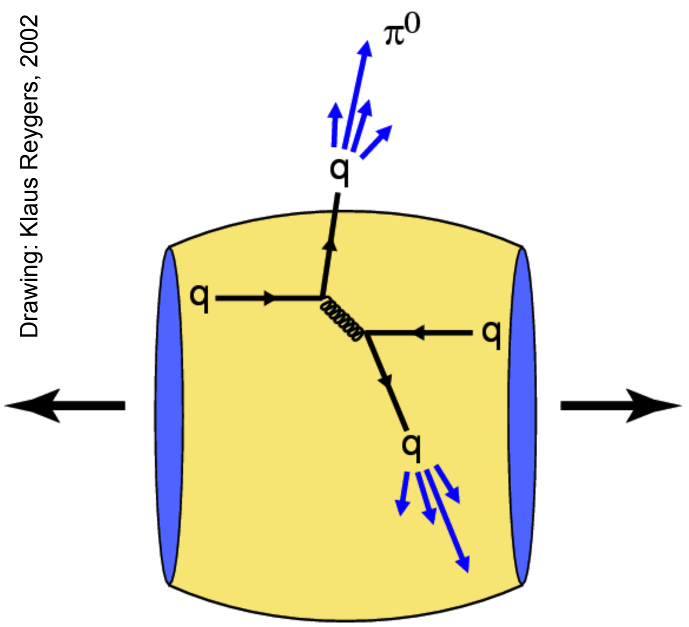
SS 2015

Hard Scattering

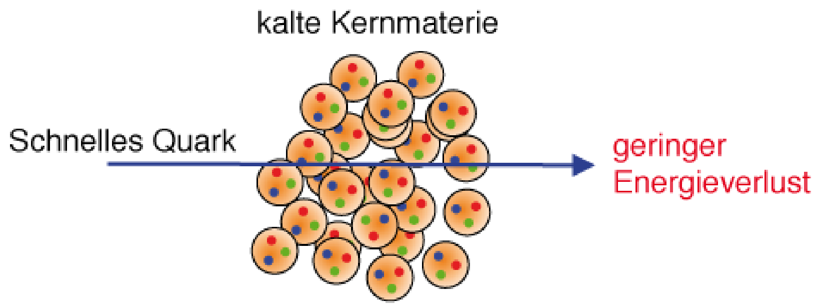




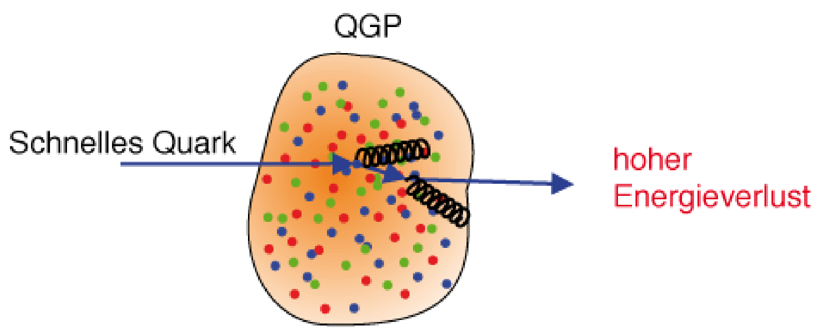
More than 99% of all particles (the bulk) have transverse momenta less than 2 GeV/c.

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

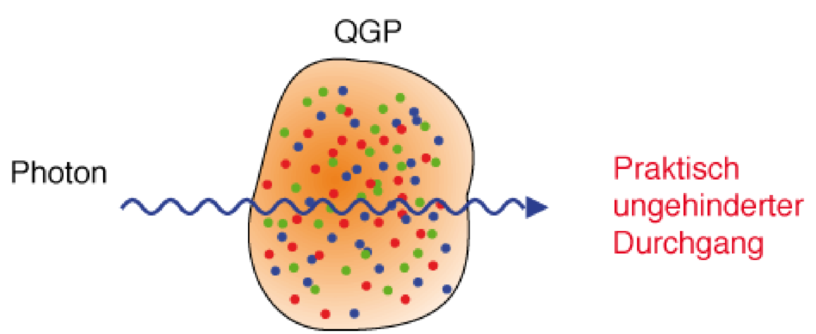
Jet Quenching: Basic Idea



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 (thermalized) $\Rightarrow$ / $\not\Leftarrow$ Suppression of hadrons at high p_T

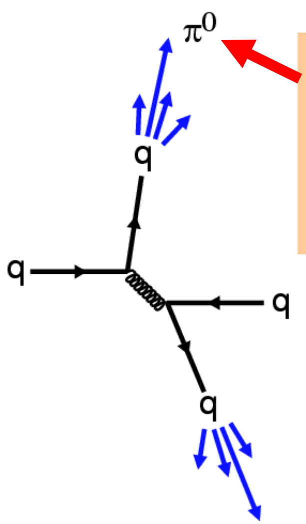
How Can We Study Jet Quenching?

- 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

Hard Scattering in p+p

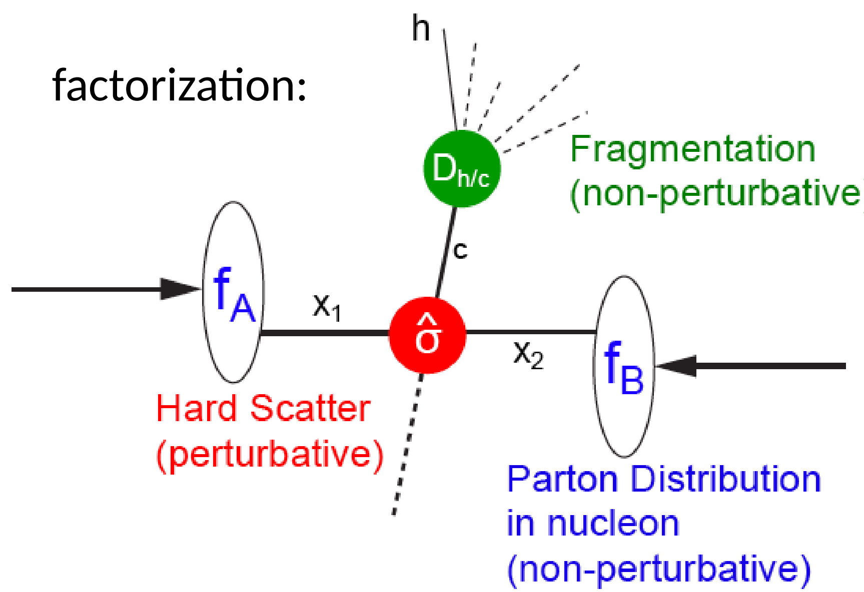
Theoretical Description of High-p_T Particle Production: Perturbative QCD

- 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:

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



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

Hadron Production in Leading Order QCD

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

Inv. Cross section

Fragmentation function

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

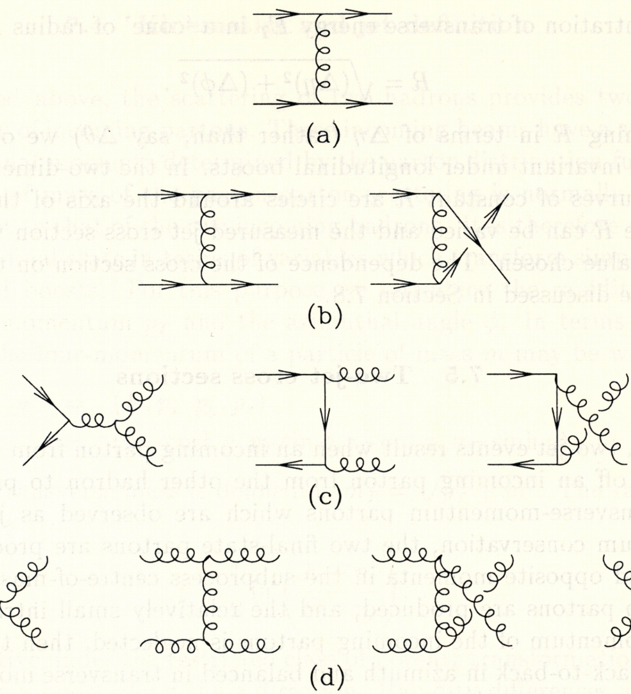
Phenomenological factor which takes higher order contributions into account

Elementary QCD parton-parton cross section

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

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
$q\,\overline{q'} \to q\,\overline{q'}$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	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
$q\,\overline{q} \to q'\,\overline{q'}$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\,\overline{q} \to q\,\overline{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.59
$q\,\overline{q} \to g\,g$	$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	1.04
$g\,g \to q\,\overline{q}$	$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	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

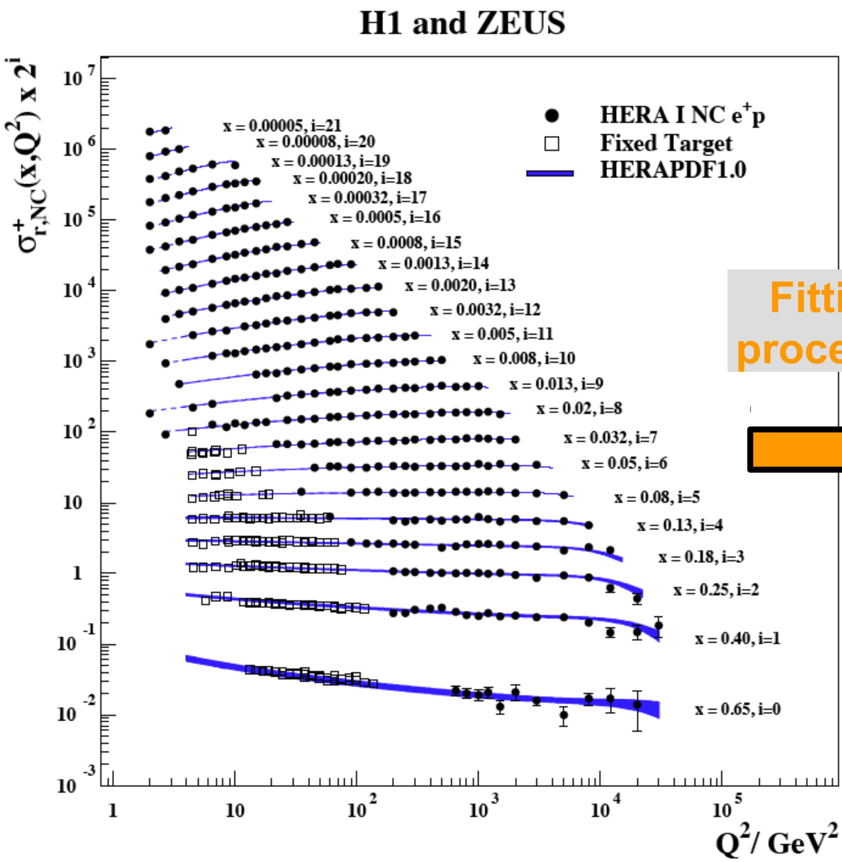


Relative importance
at equal parton luminosities

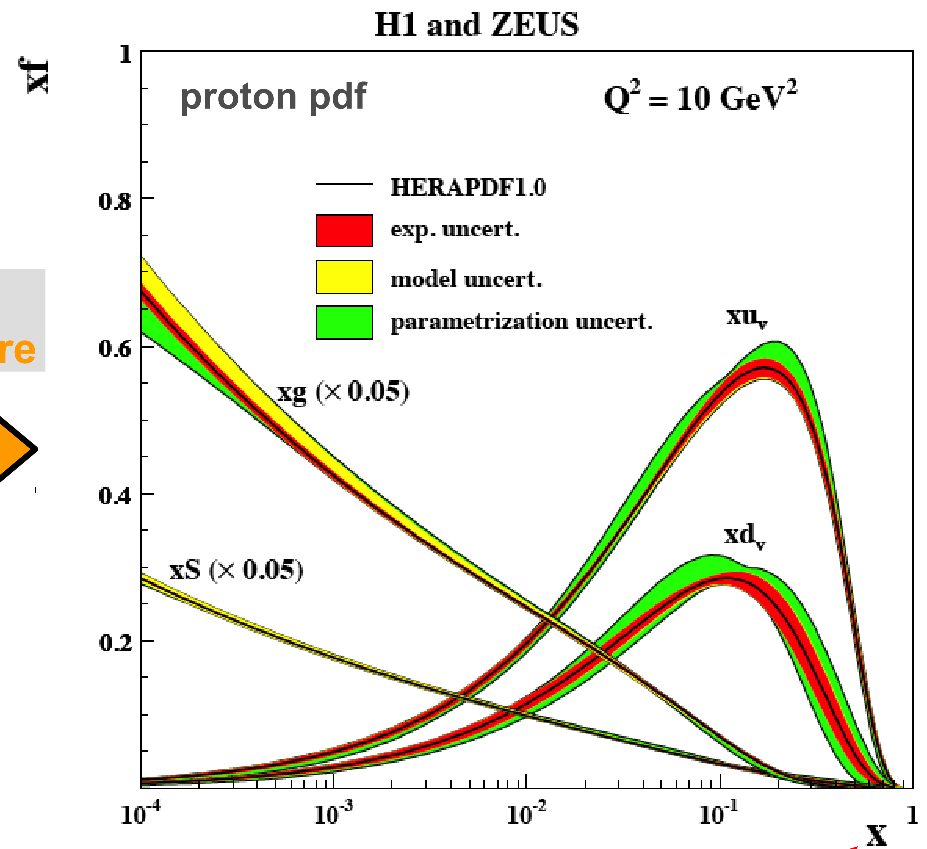
Parton Distributions: High Precision Data from HERA

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

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



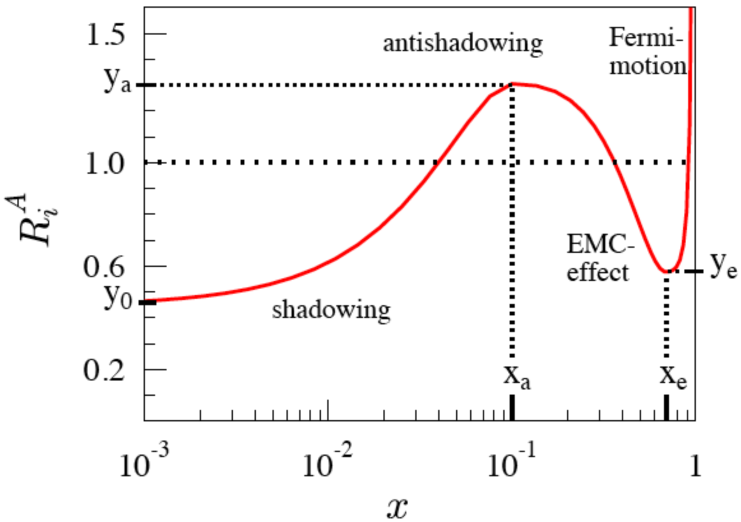
Fitting procedure



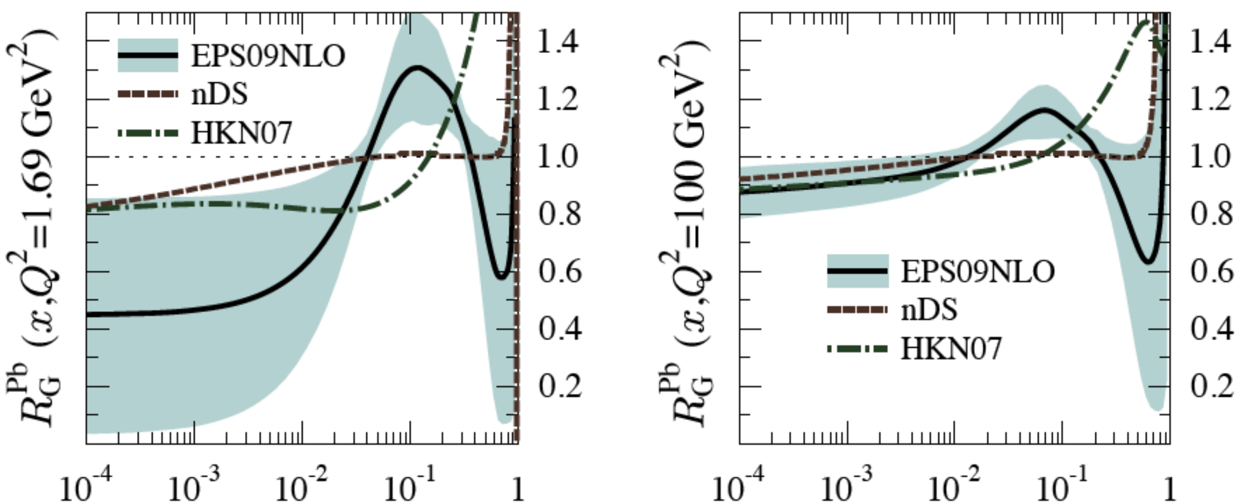
Bjorken-*x*

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



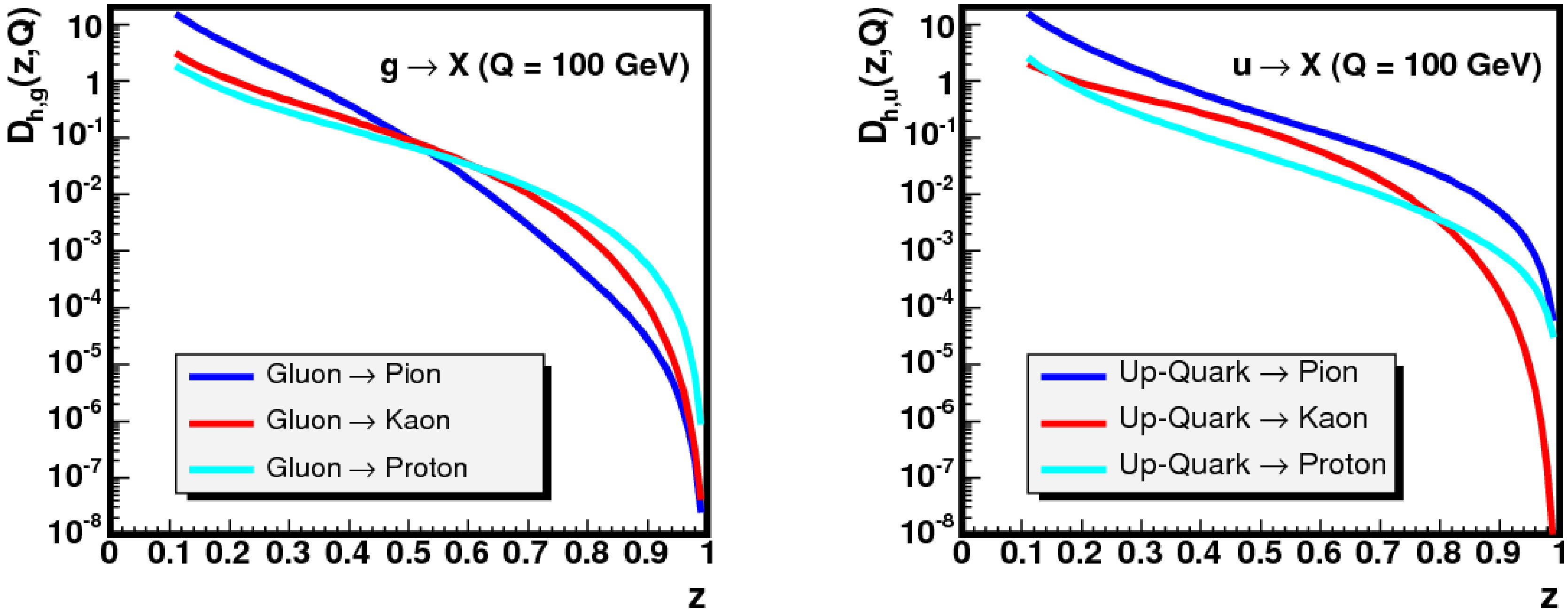
EPS09 gluon nPDF ratios

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

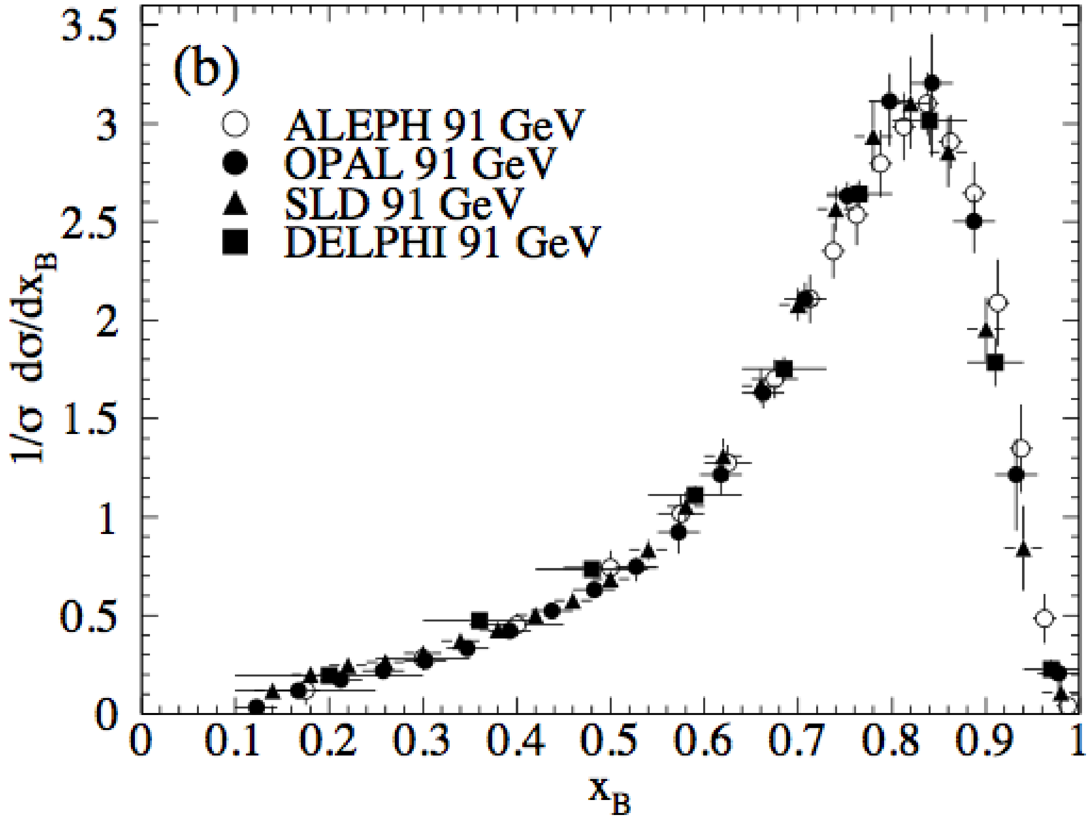
Albino, Kniehl, Kramer, Nucl. Phys. B 725 (2005), 181

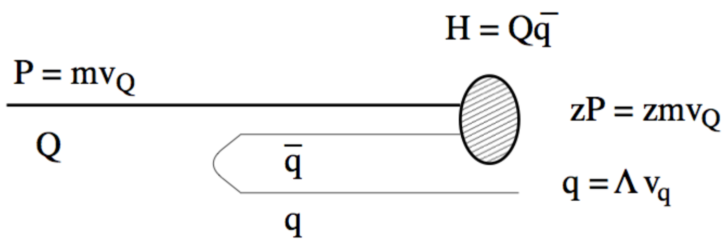


$$z = \frac{p_{\mathrm{hadron}}}{p_{\mathrm{parton}}}$$

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

Heavy Quark Fragmentation





- Heavy quark jets fragment hard into leading heavy meson
- Qualitatively different than g/uds → π
- Qualitative argument: heavy quark Q only marginally slowed down when picking up a light quark to form a heavy meson

J.D. Bjorken, Phys Rev D17, 171 (1978))

Jet Quenching

Jet Quenching History

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

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

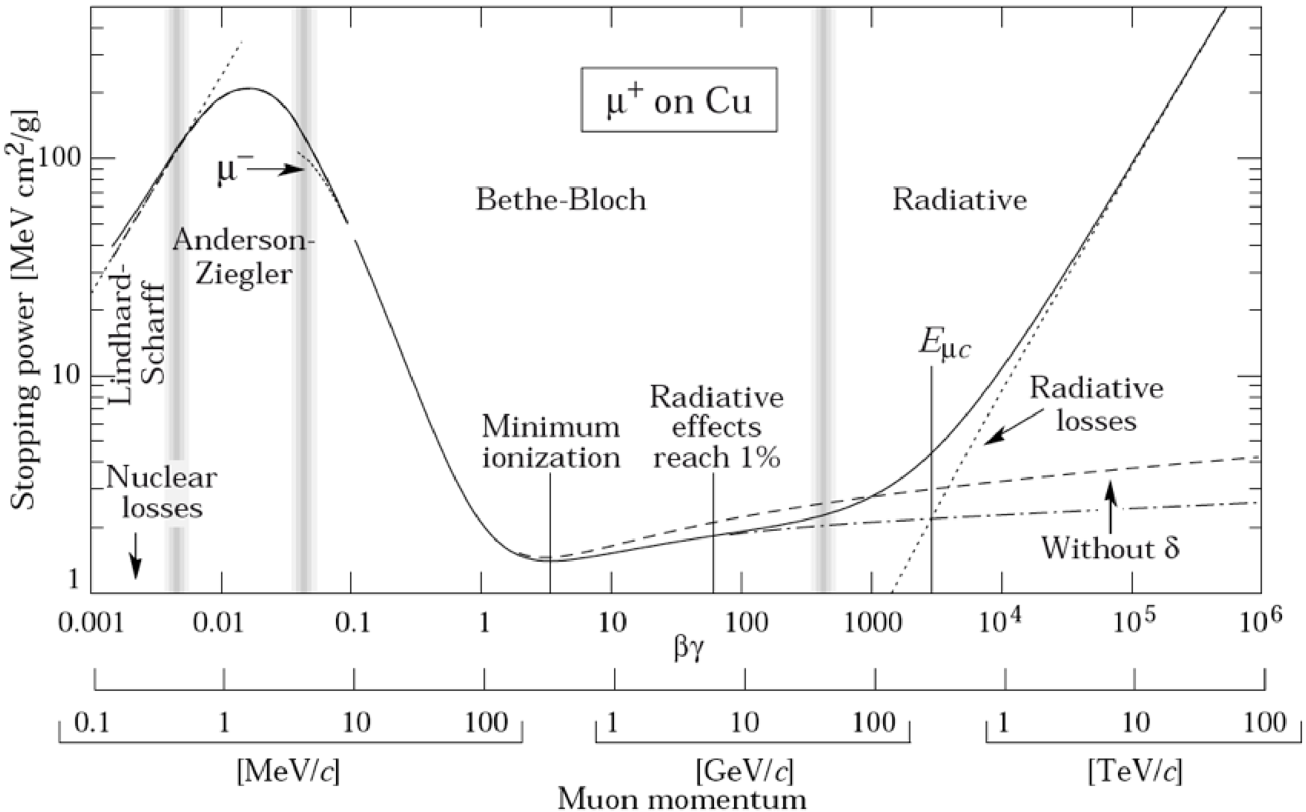
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

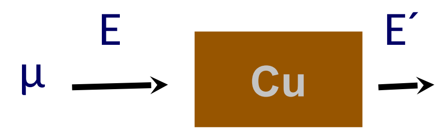
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. 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.

- 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

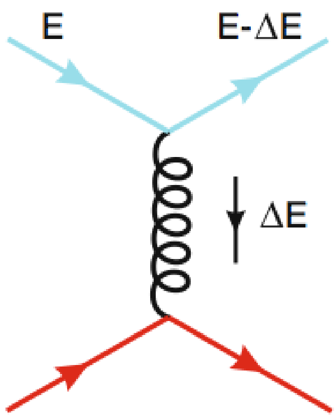




- μ^+ on Cu: Radiational energy loss („bremsstrahlung“) starts to dominate over collisional energy loss („Bethe-Bloch formula“) for *p* >> 100 GeV/c
- For energetic quarks and gluons in QCD matter, radiative energy loss via induced gluon emission is/was expected to be the dominant process

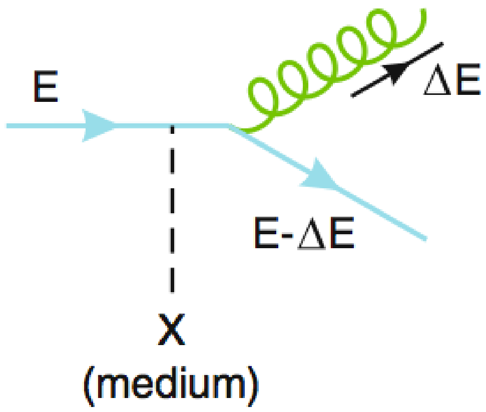
Collisional vs. Radiative Parton energy loss

Collisional energy loss:



- Elastic scatterings with medium constituents
- Dominates at low particle momenta

Radiative energy loss:



- Inelastic scatterings within the medium
- Dominates at higher momenta

Parton Energy Loss

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

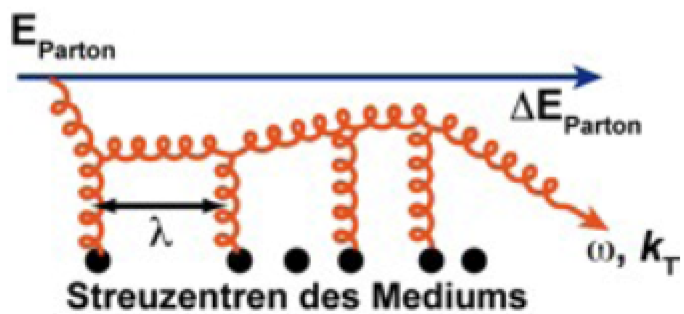
$$\Delta E \propto \alpha_s C_F \hat{q} L^2$$

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

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

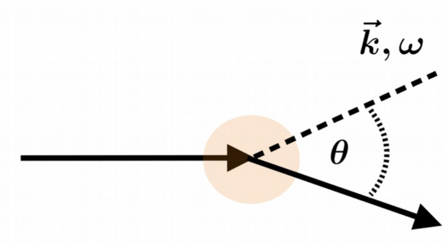
L^2 dependence:
Non-abelian nature of QCD + quantenm. interference



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

Parton Energy Loss: Qualitative Discussion

Consider electric charge passing through matter. At sufficiently high energy it loses energy via bremsstrahlung. At very high energies, the charge scatters coherently off many medium constituents, leading to destructive interference. This so-called Landau-Pomeranchuk-Migdal (LPM) effect greatly reduces the radiatve energy loss.



Formation time of a radiated gluon: ("time for the fast parton to get rid of its virtuality")

$$t_c \simeq \frac{\omega}{k_T^2} \simeq \frac{1}{\omega \theta^2}$$

The gluon acquires additional transverse momentum if it scatters with medium constituents within its formation time (or formation length z_c):

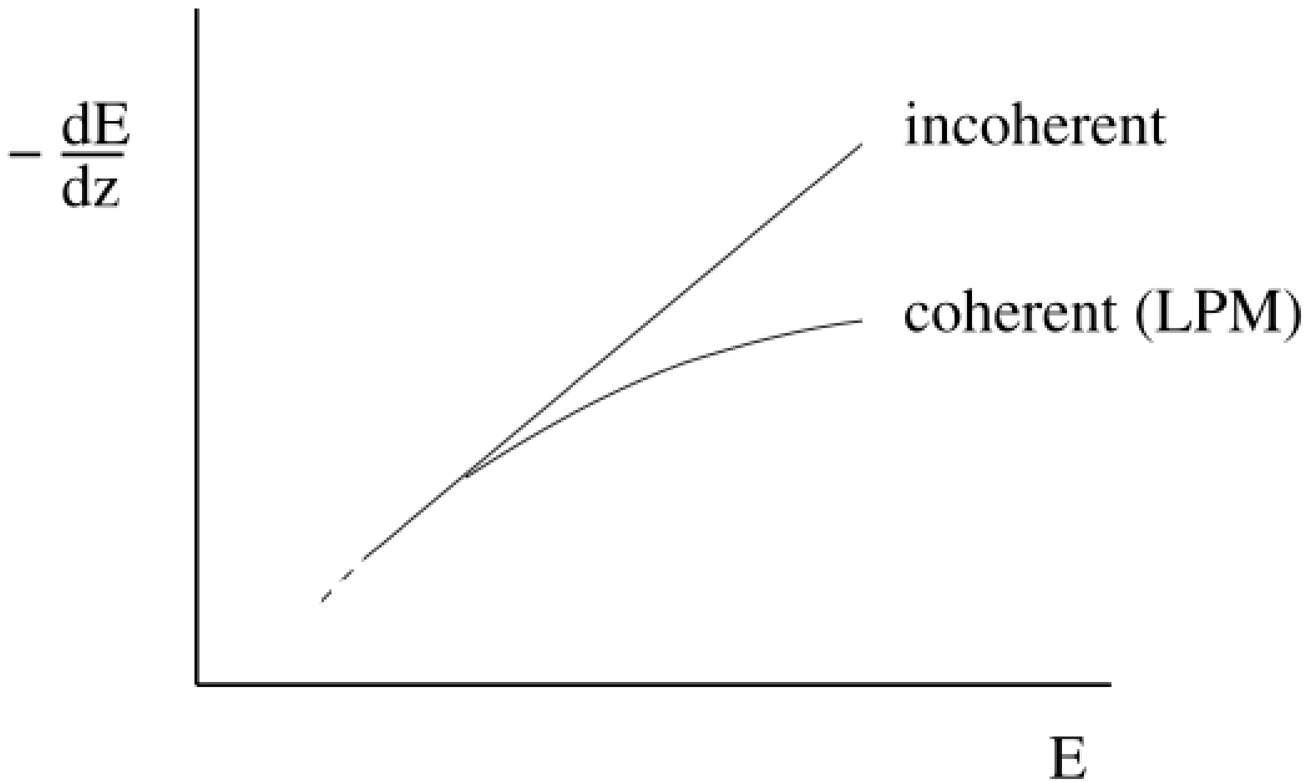
$$k_T^2 \simeq \hat{q} z_c = \frac{\mu^2}{\lambda} z_c$$

This results in a medium-modified formation length: $z_c \simeq \frac{\omega}{k_T^2} \simeq \sqrt{\frac{\omega}{\hat{q}}}$

$\lambda < z_c$: Coherent scattering with destructive interference

$\lambda > z_c$: incoherence

Parton Energy Loss: Qualitative Discussion



For fixed medium thickness L, $z_C = L$ defines a critical energy ω_C: $\omega_c = \hat{q} L^2$

Gluons can be emitted with energies up to this critical energy.

Parton Energy Loss: Qualitative Discussion

There are three regimes for radiative energy loss:

1. Incoherent regime (mean free path $\lambda > z_c$):

$$-\frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \frac{E}{\lambda}$$

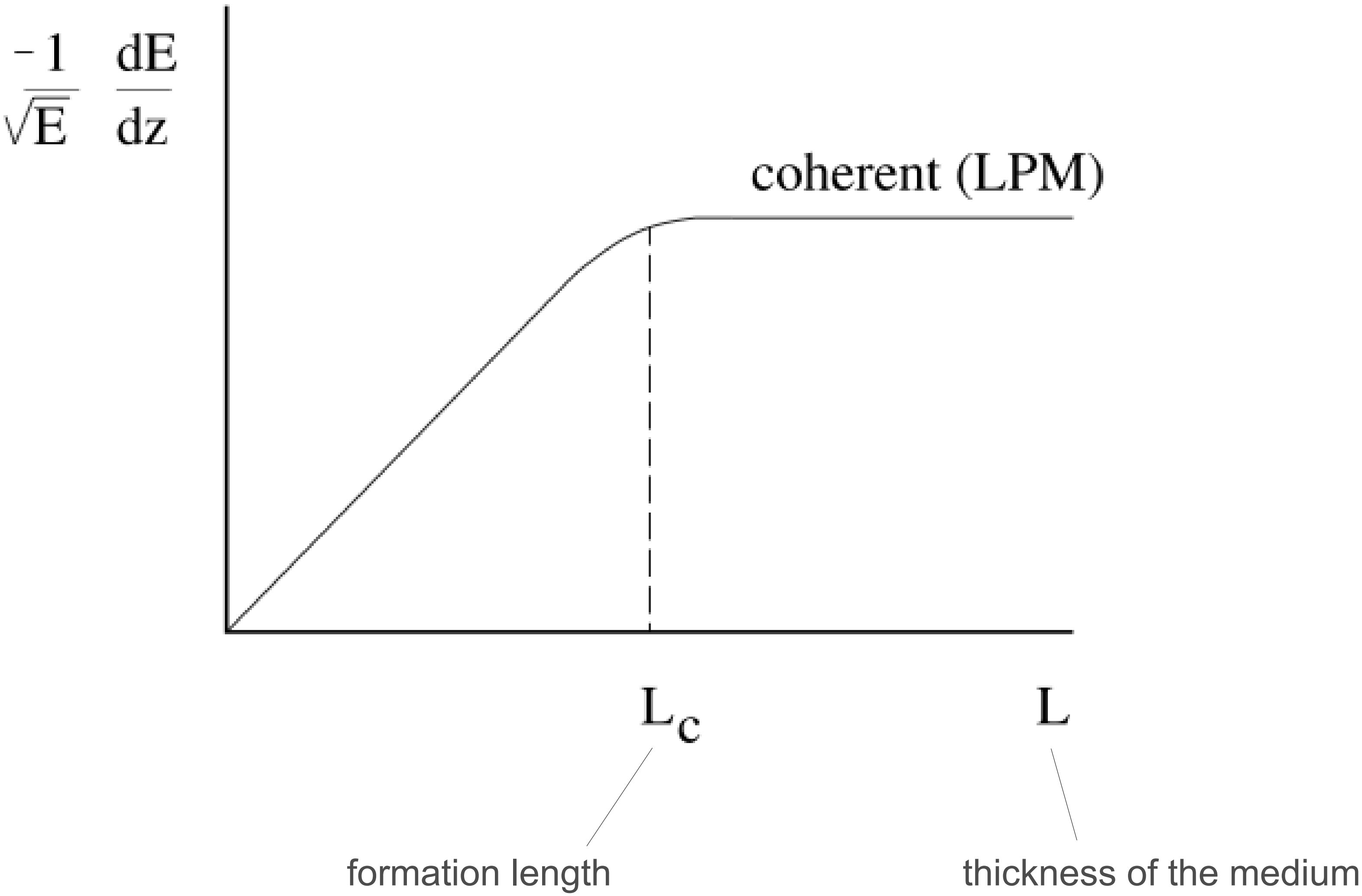
2. Coherent regime ($\lambda < z_C$) with medium thickness $L > z_C$ (saturated LPM regime)

$$-\frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \sqrt{\frac{E}{\hat{q}}}$$

3. Coherent regime ($\lambda < z_C$) with $L < z_C$

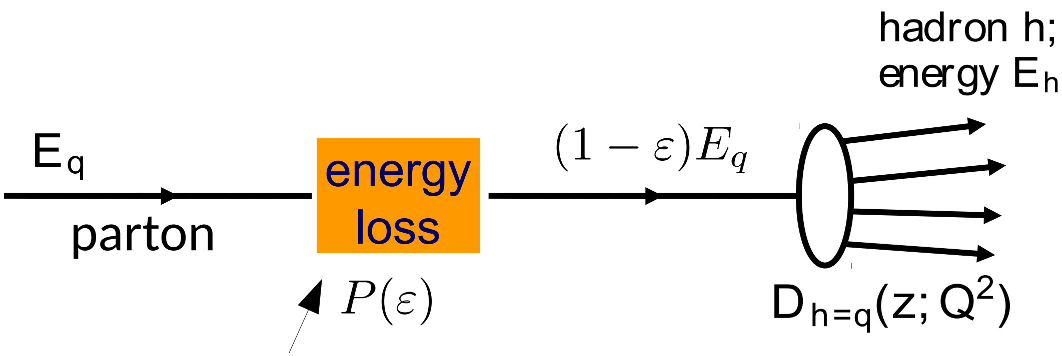
$$-\frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \hat{q} L$$

Parton Energy Loss: Qualitative Discussion



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:

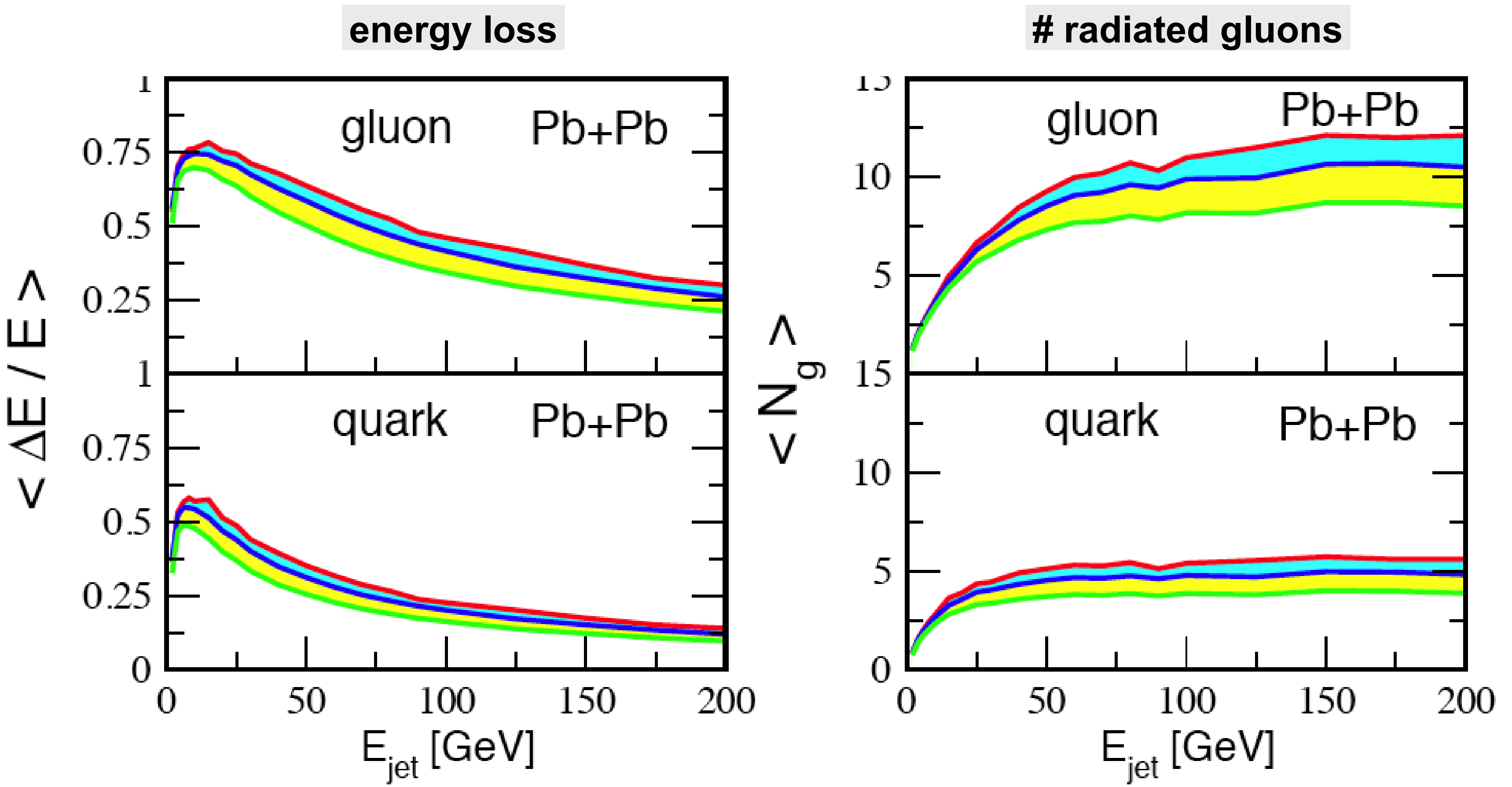
$$D^{\mathrm{med}}_{h/q}(x,Q^2) = \int_0^1 d\varepsilon\, P(\varepsilon)\; D_{h/q}\left(\frac{x}{1-\varepsilon}, Q^2\right)\frac{1}{1-\varepsilon}$$

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

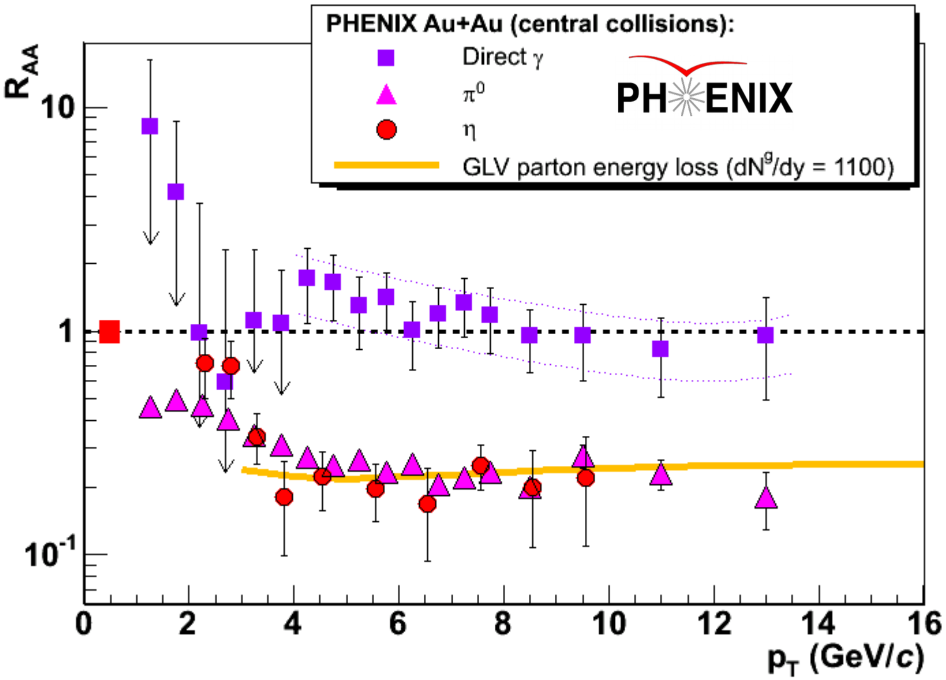
Central Pb+Pb at $\sqrt{s_{NN}}$ = 5500 GeV: L ≈ 6 fm, dN^g/dy = 2000, 3000, 4000



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

The Discovery of Jet Quenching at RHIC

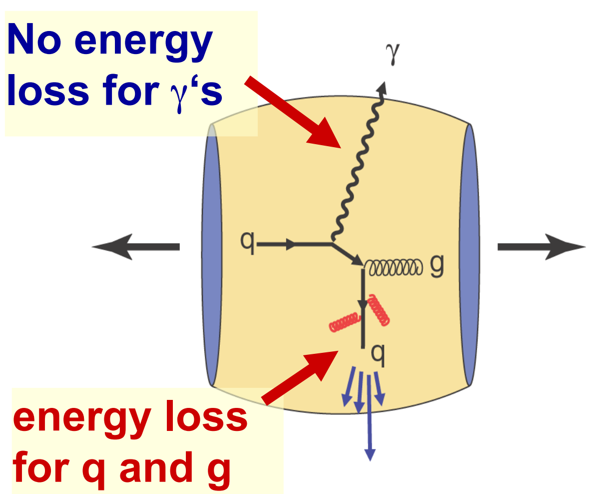
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (I)



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

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

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

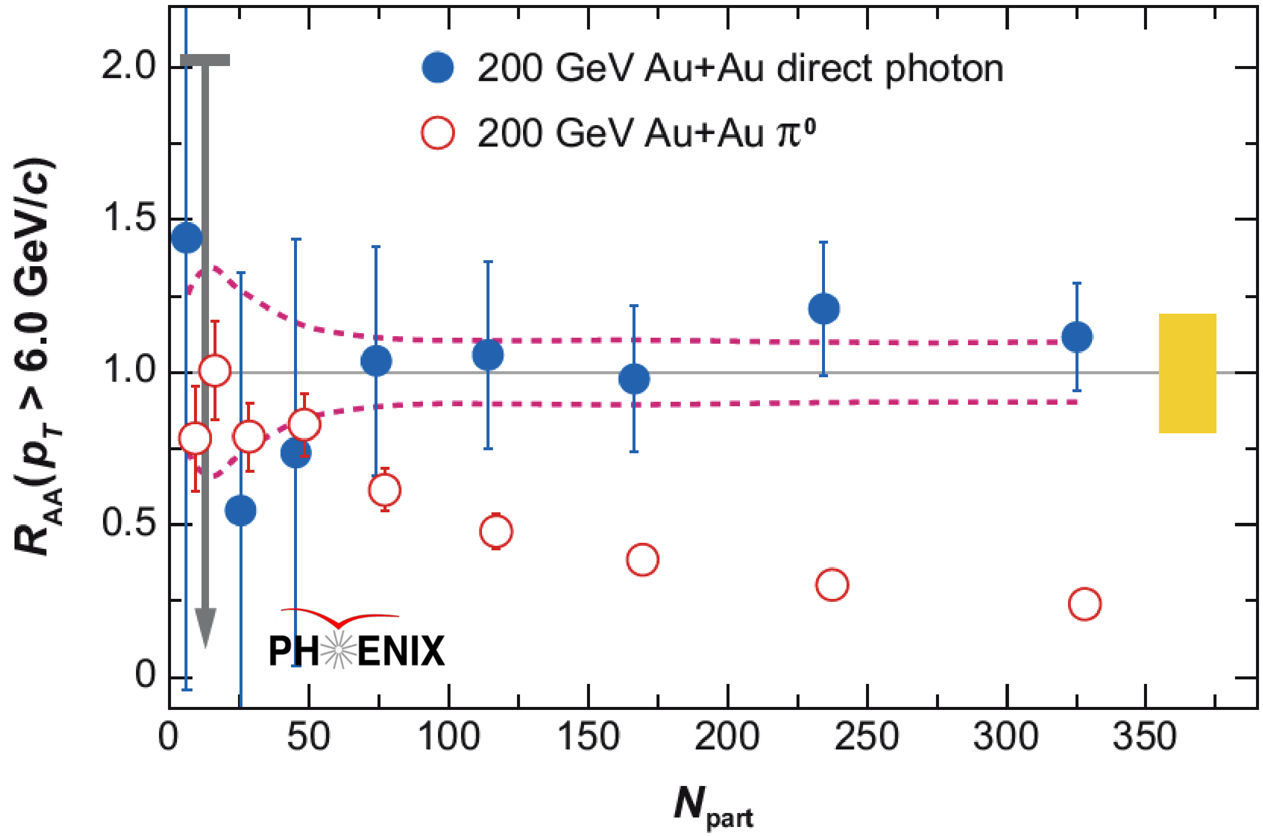


PHENIX: Phys.Rev.Lett.88:022301, 2002
PHENIX: Phys.Rev.Lett.91:072301, 2003
PHENIX: Phys.Rev.Lett.94:232301, 2005

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

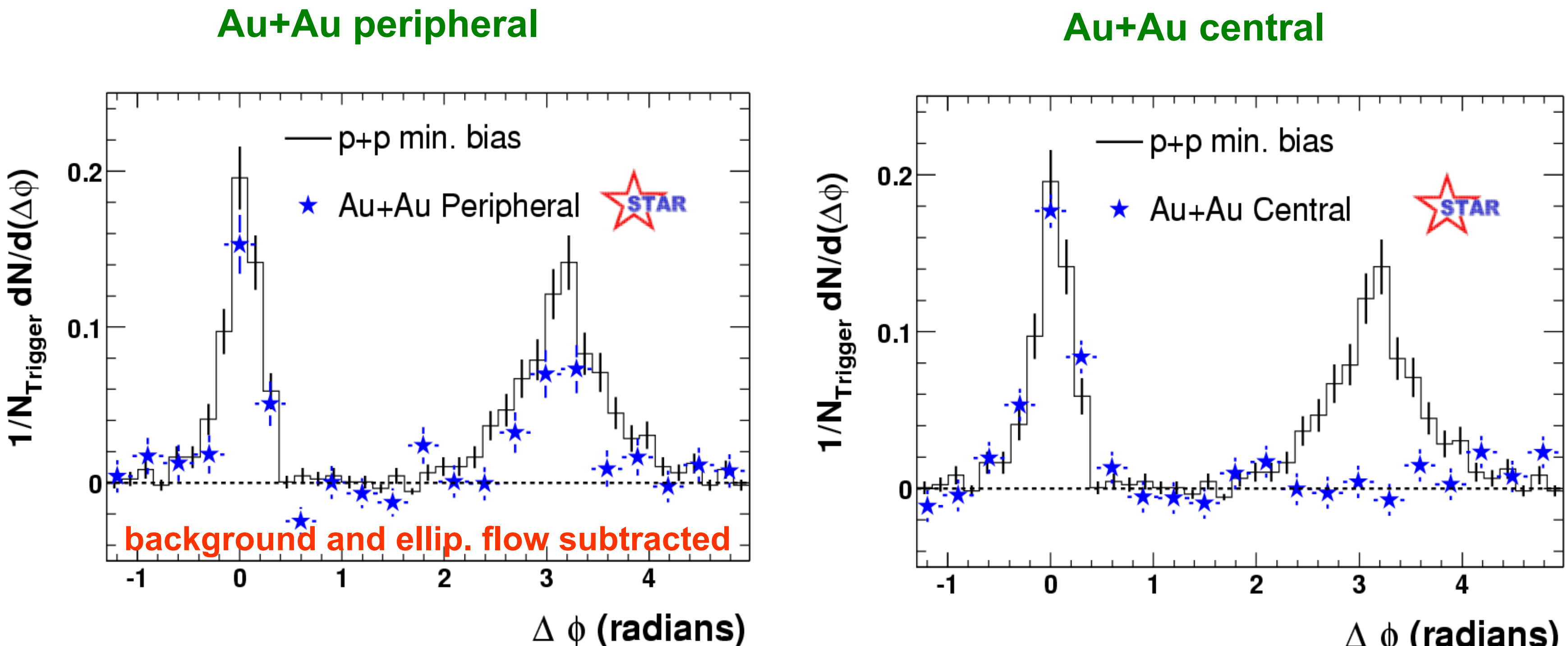
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (II)

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

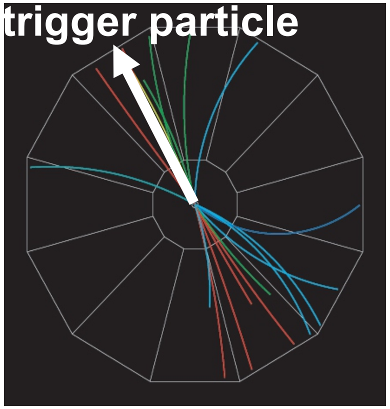


Direct photons follow T_{AB} scaling as expected for a hard probe not affected by the medium

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

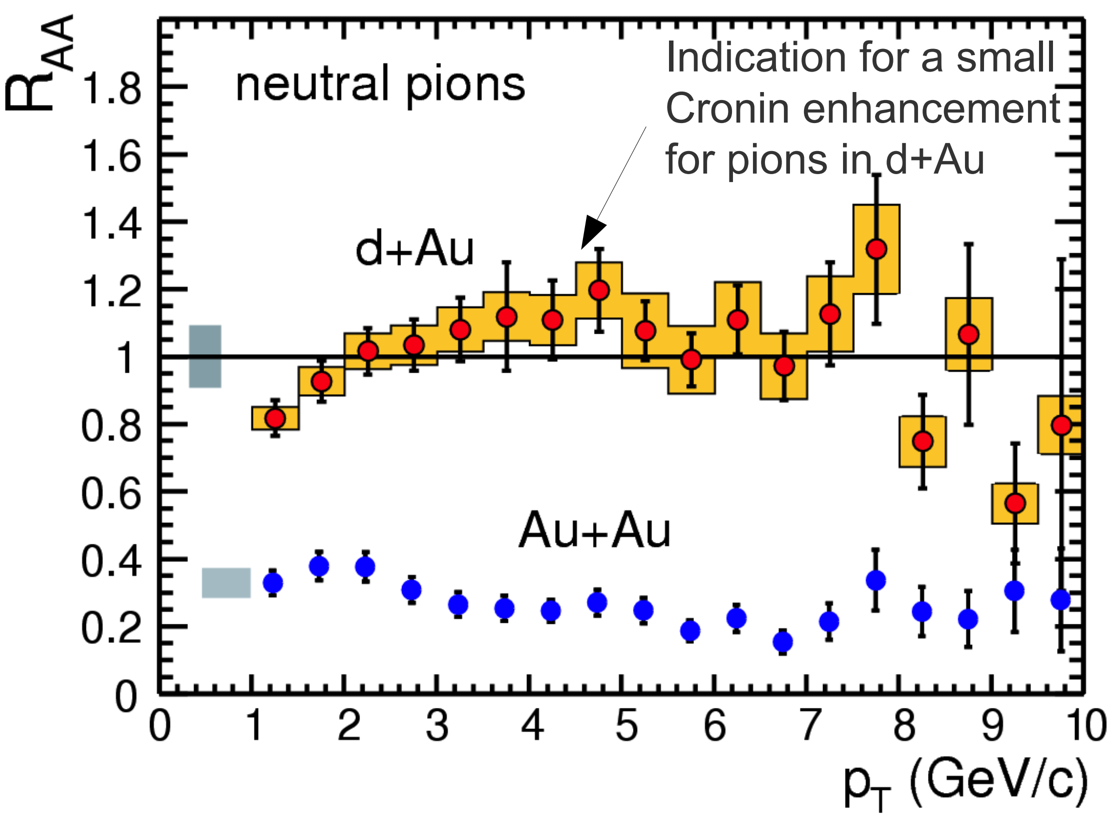


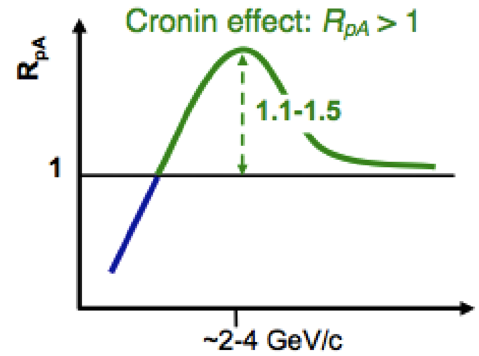
Trigger particle: p_T > 4 GeV/c
Associated particle: p_T > 2 GeV/c



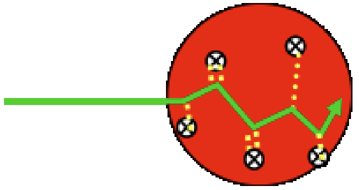
- No jet correlation around 180° in central Au+Au
- Consistent with jet quenching picture

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





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

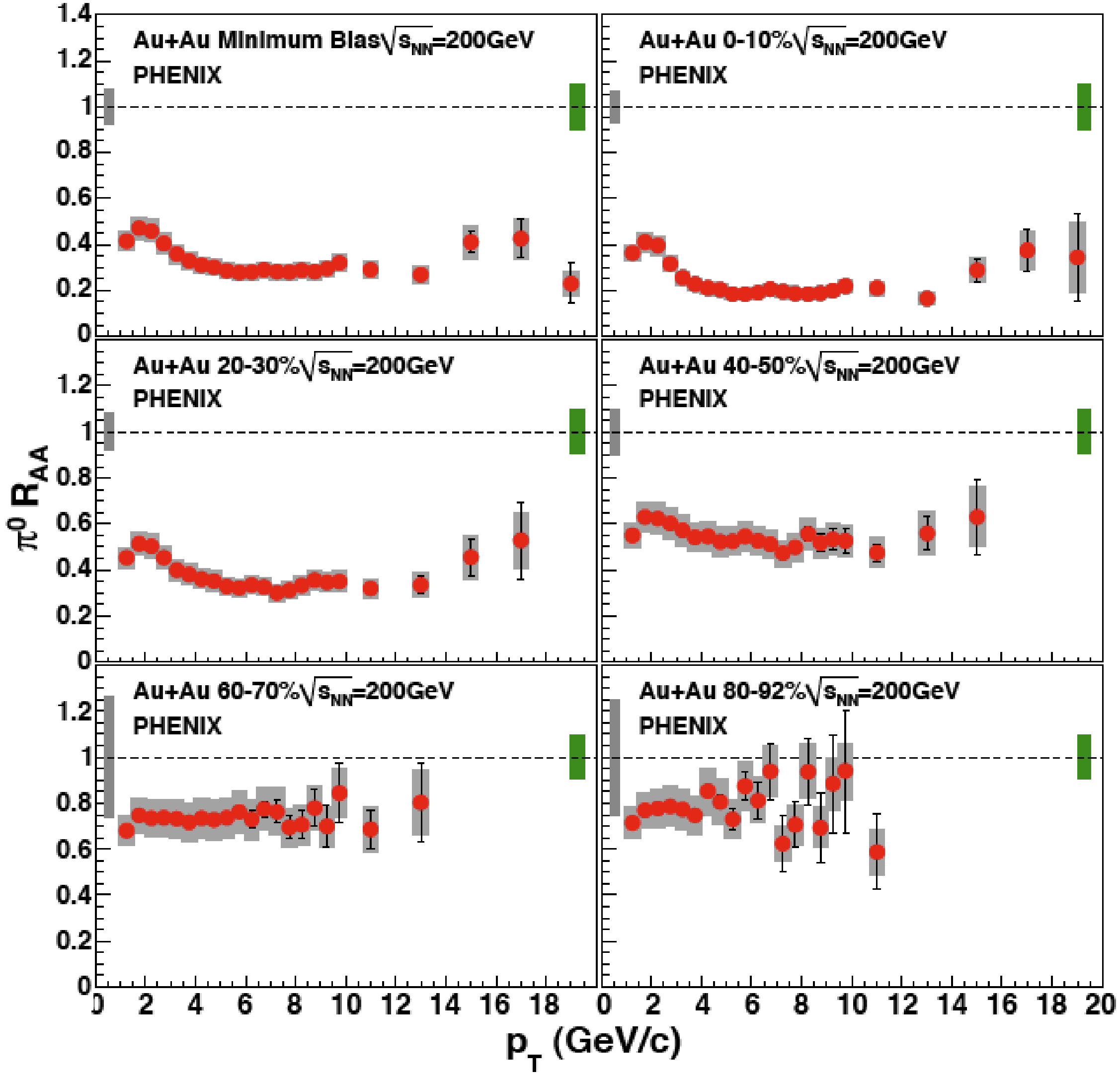


No pion suppression in min. bias d+Au collisions
⇒ pion suppression is a final state effect caused by the created medium

Further RHIC Results Related to Jet Quenching

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

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



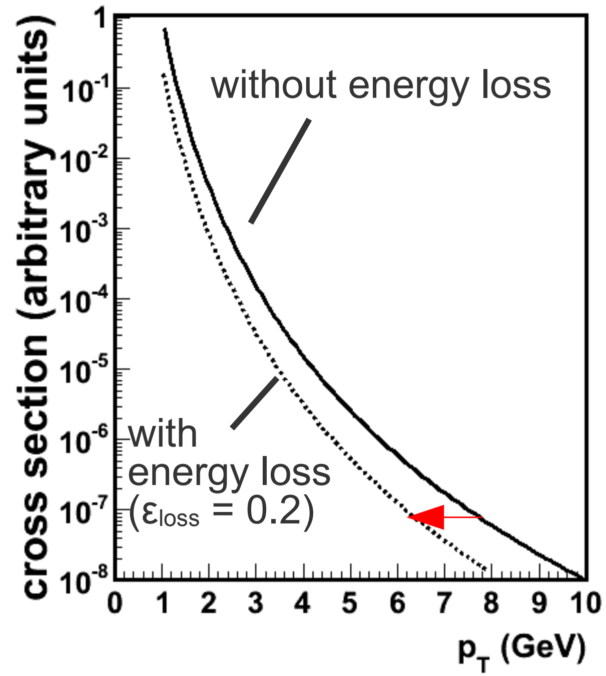
$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}} \rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

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

$R_{AA}(p_T)$ rather flat for p_T > 5 GeV/c

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:

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

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

This leads to:

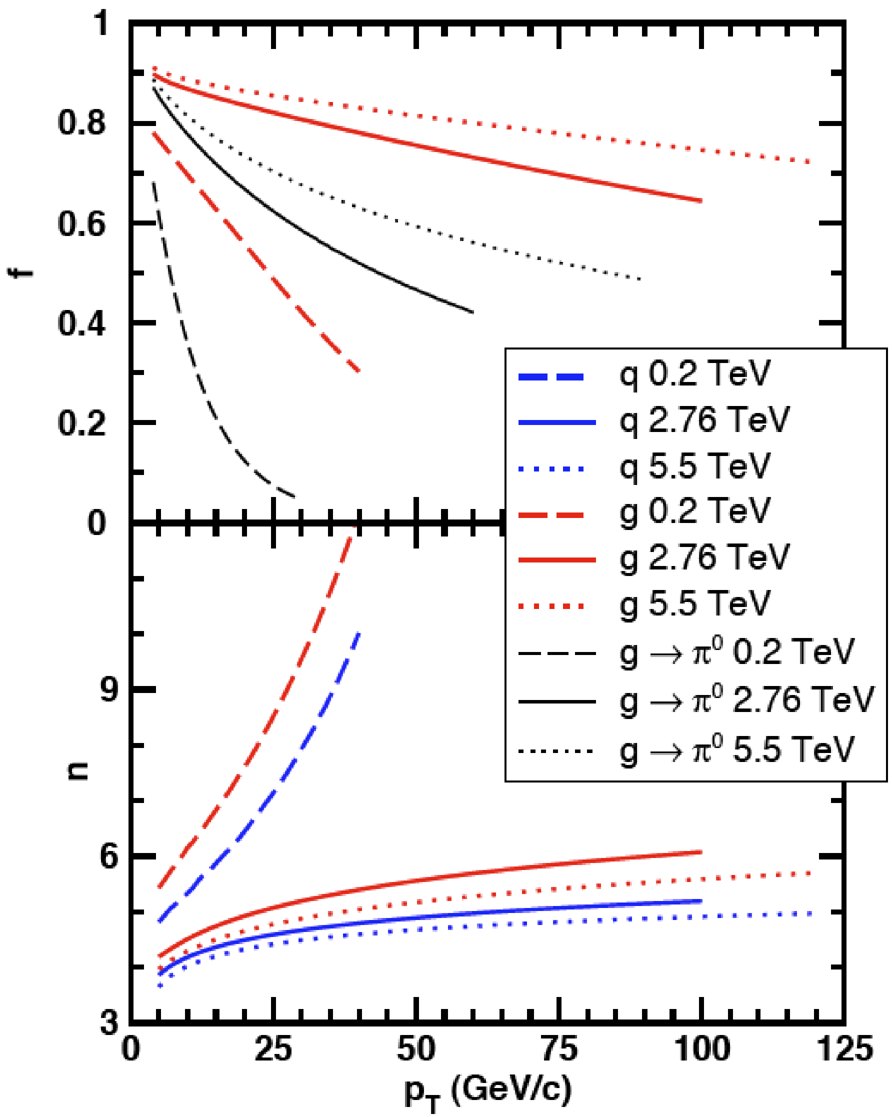
$$R_{AA} = (1-\varepsilon_{\text{loss}})^{n-2} \quad \Rightarrow \quad \varepsilon_{\text{loss}} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

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:

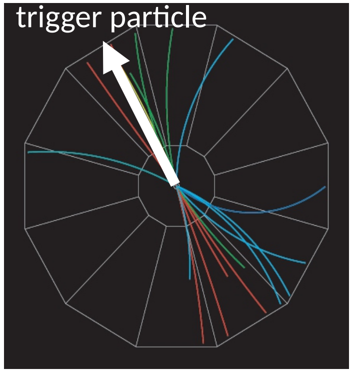
Partonic spectral index $n(p_T)$:

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

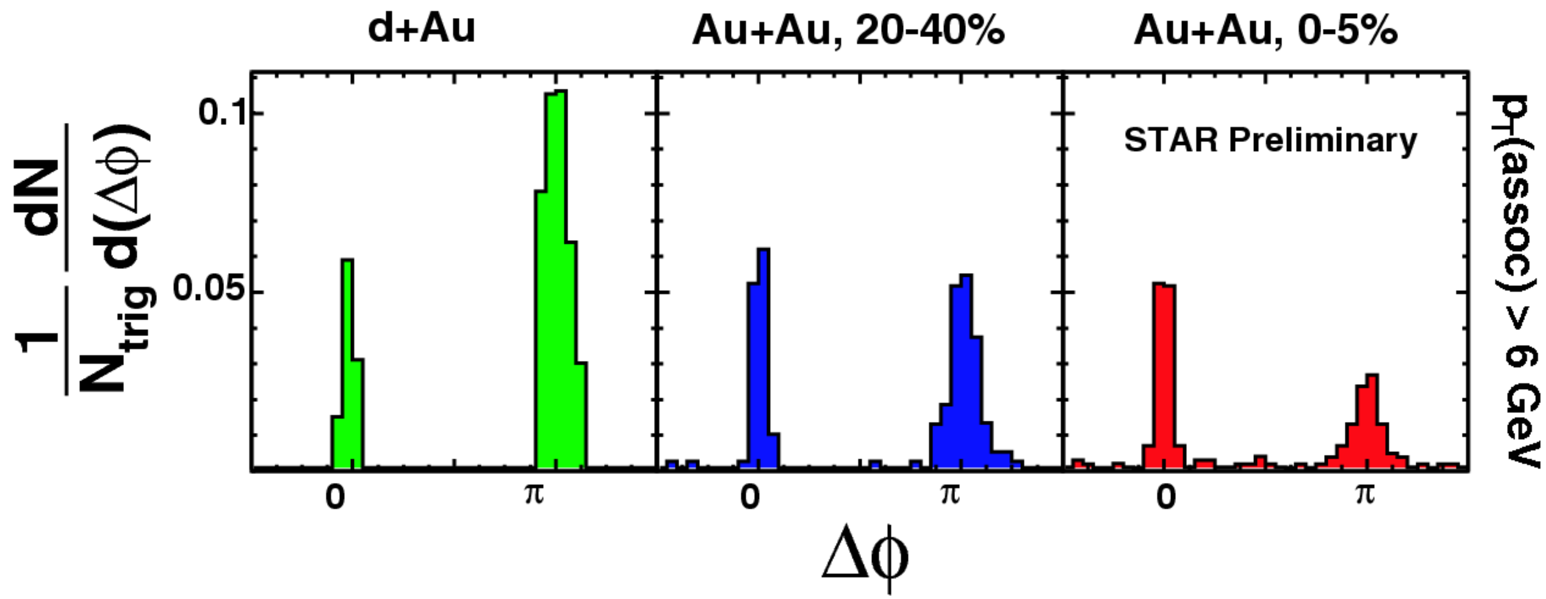
The rather flat R_{AA} at RHIC can be interpreted as an accidental cancellation between

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

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



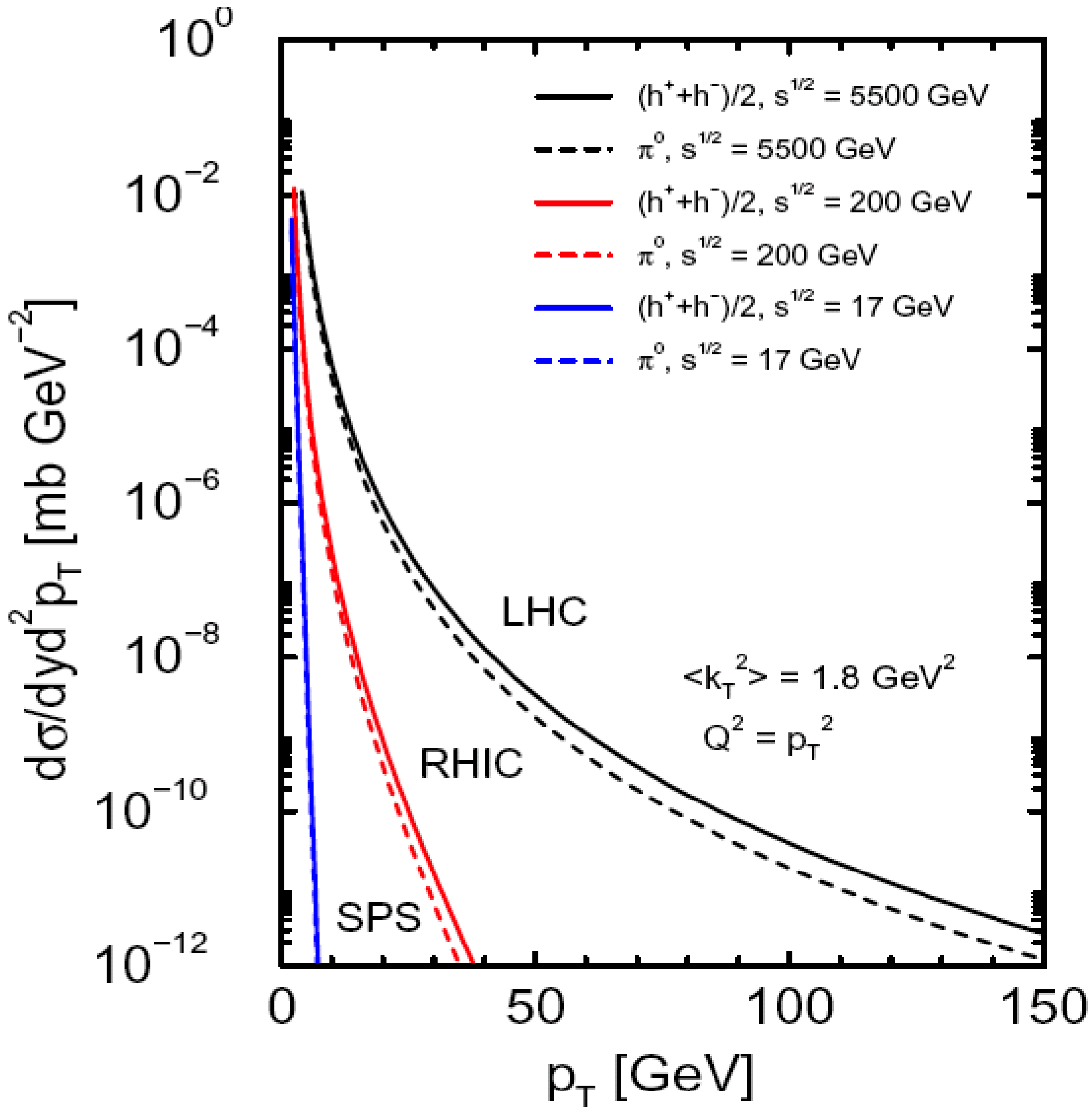
- Charged hadron correlation
- Trigger particle: p_T > 8 GeV/c
- Associated particle: p_T > 6 GeV/c



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

Results from the LHC: 1. Spectra

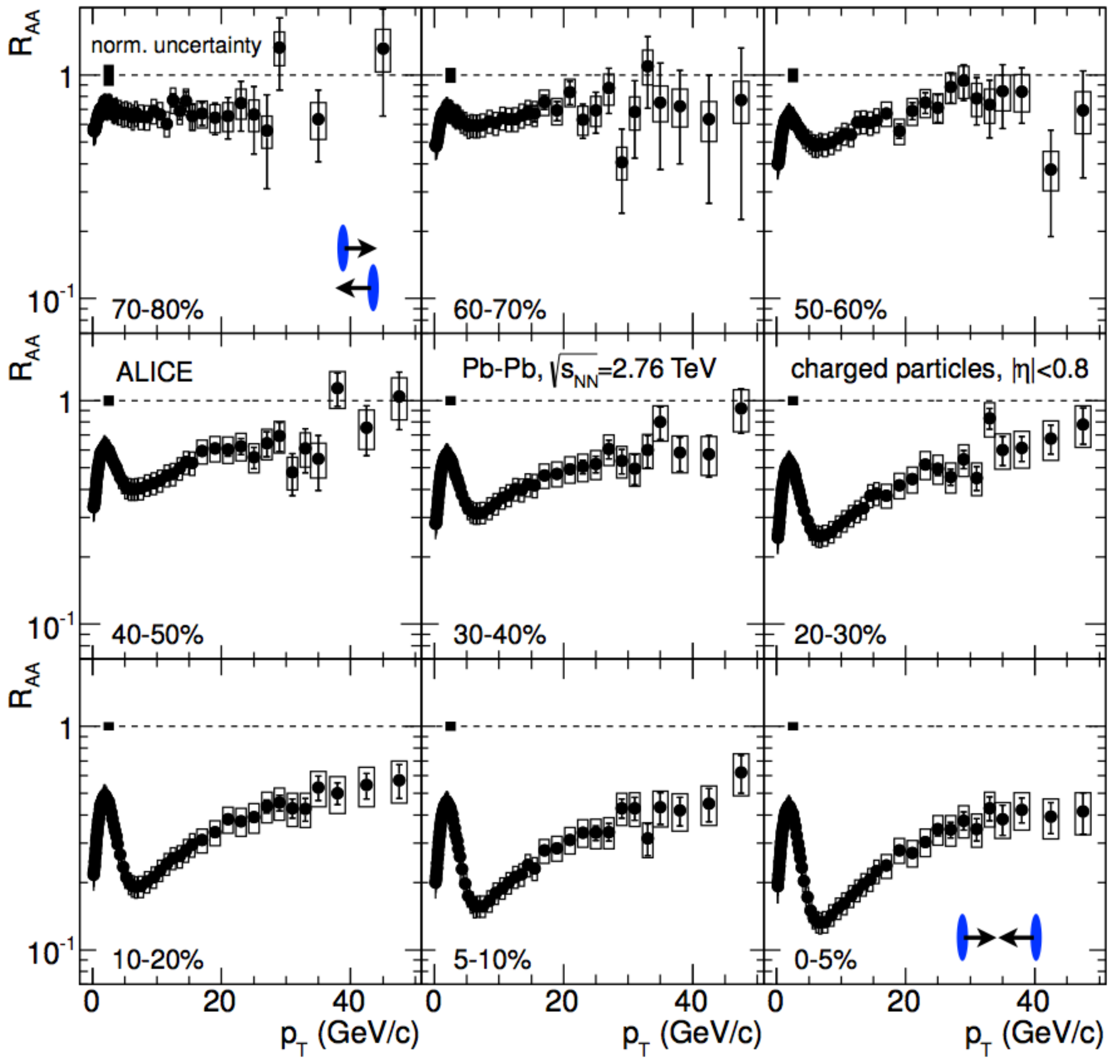
Increase of Hard Scattering Yields with √*s*



Hard probes more abundant at the LHC

Charged Hadron R_{AA} in Pb-Pb at $\sqrt{s}$ = 2.76 TeV

ALICE, Phys. Lett. B720, 42 (2013)



$$R_{AA} = \frac{dN/dp_T(A+A)}{\langle T_{AA}\rangle \times d\sigma/dp_T(p+p)}$$

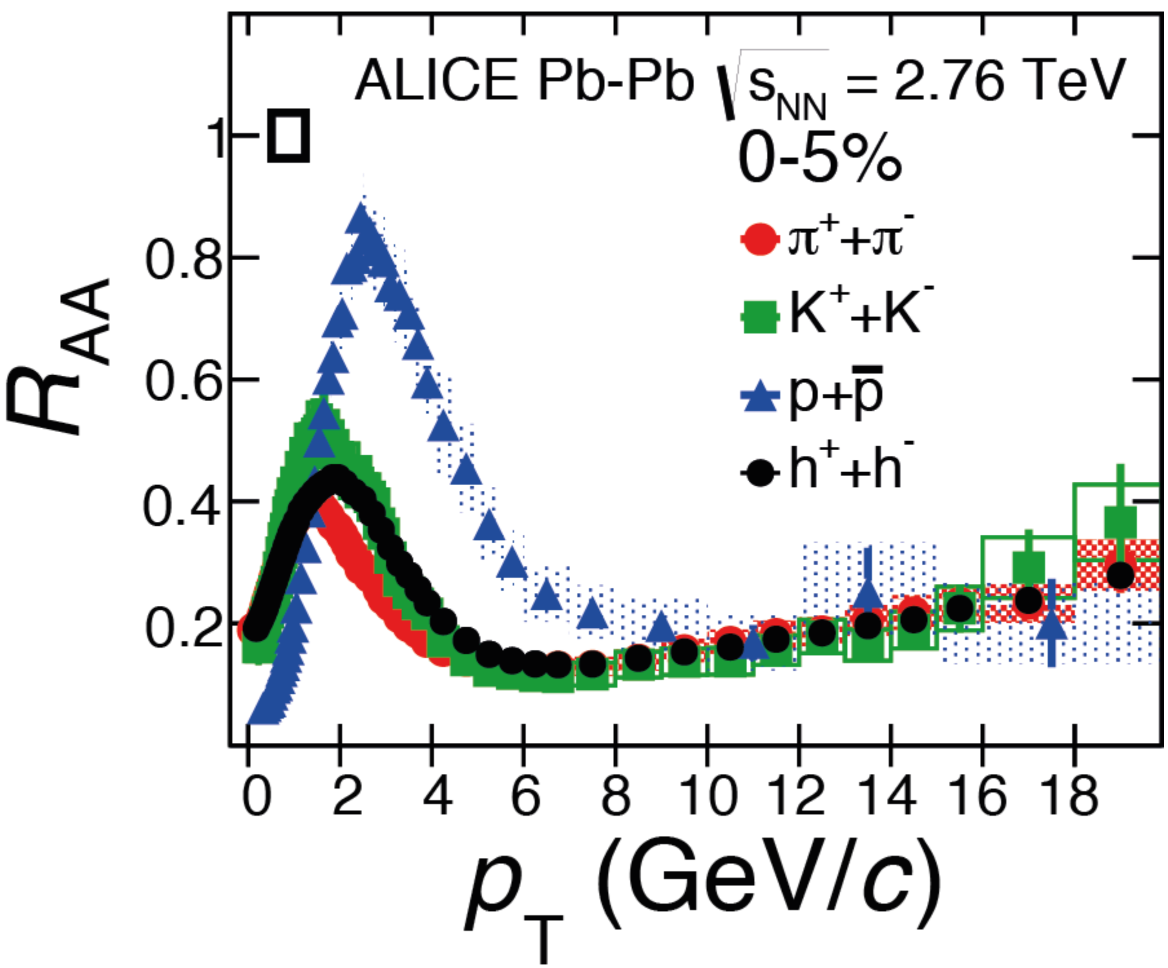
$$\langle T_{AA}\rangle = \langle N_{\text{coll}}\rangle / \sigma_{\text{inel}}^{pp}$$

from Glauber calculation

- Expect R_{AA} = 1 in the hard scattering regime without nuclear effects (p_T > 2 GeV/c)
- Suppression by a factor 7 at $p_T \approx$ 6-7 GeV/c
- Rise of R_{AA} for p_T > 7 GeV/c indicates decrease of relative parton energy loss $\Delta E/E$ with increasing E

R_{AA} for Identified Particles in Central Pb+Pb

arXiv:1506.07287

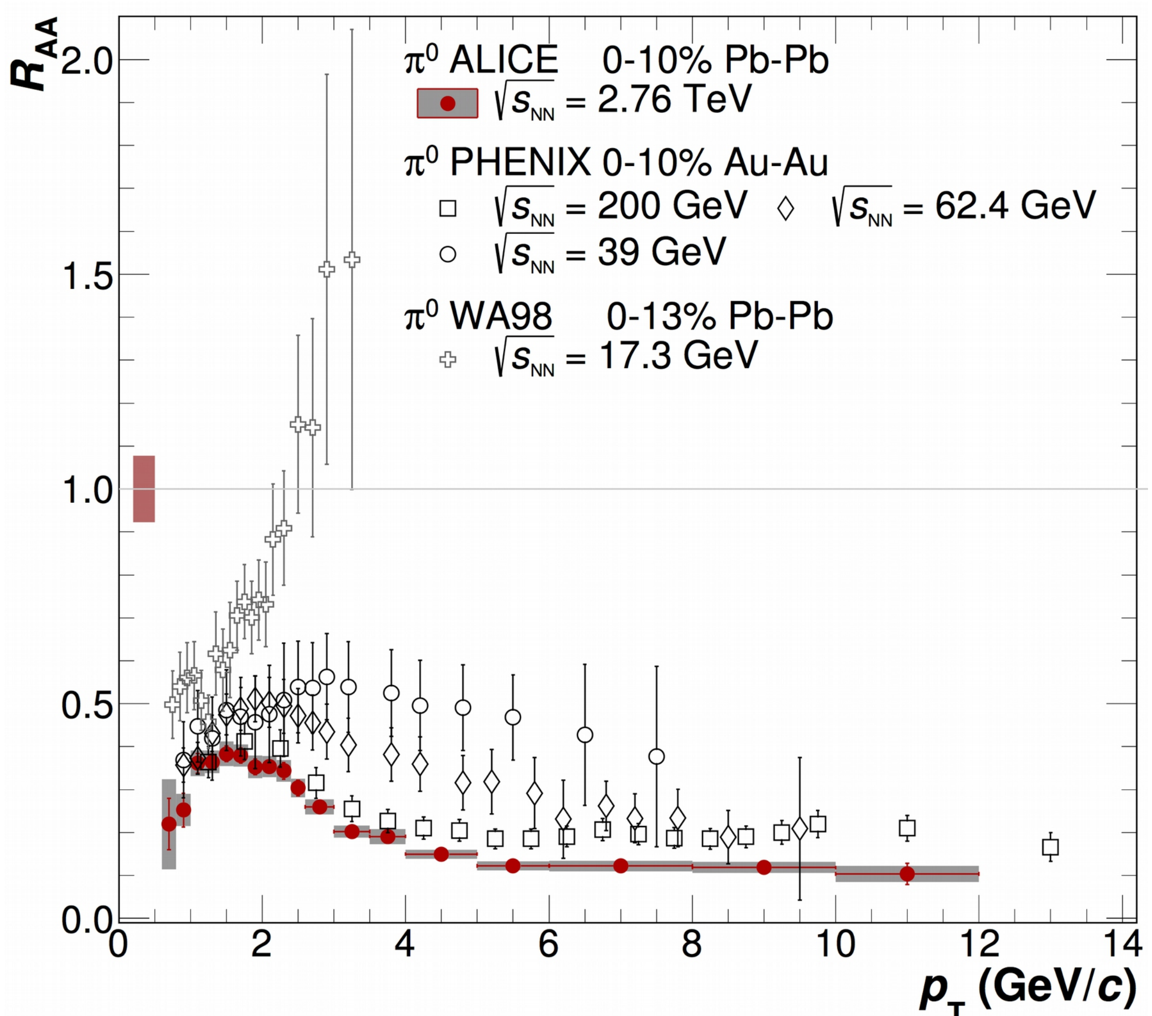


- R_{AA}(p) > R_{AA}(K) ≈ R_{AA}(π) for $3 < p_T < 8$ GeV/c
- Similar p, K and π R_{AA} for $p_T > 8$ GeV/c

Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,hadron}$ > 8 GeV/c?

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

arXiv:1405.3794



R_{AA} at the LHC smaller than at RHIC:
Increased ΔE apparently more important than effect of flatter initial parton spectra

Jet Transport Parameter from Data

- Fit of various models to $R_{AA}(p_T)$ at RHIC and the LHC
- Jet transport parameter
  (for E_{parton} = 10 GeV, QGP thermalization at τ_0 = 0.6 fm/c):

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{ at } \begin{array}{l} \mathrm{T{=}370\ MeV,} \\ \mathrm{T{=}470\ MeV,} \end{array}$$

Jet Coll., Phys.Rev. C90 (2014) 014909

- Result relies on standard hydro description of the medium evolution

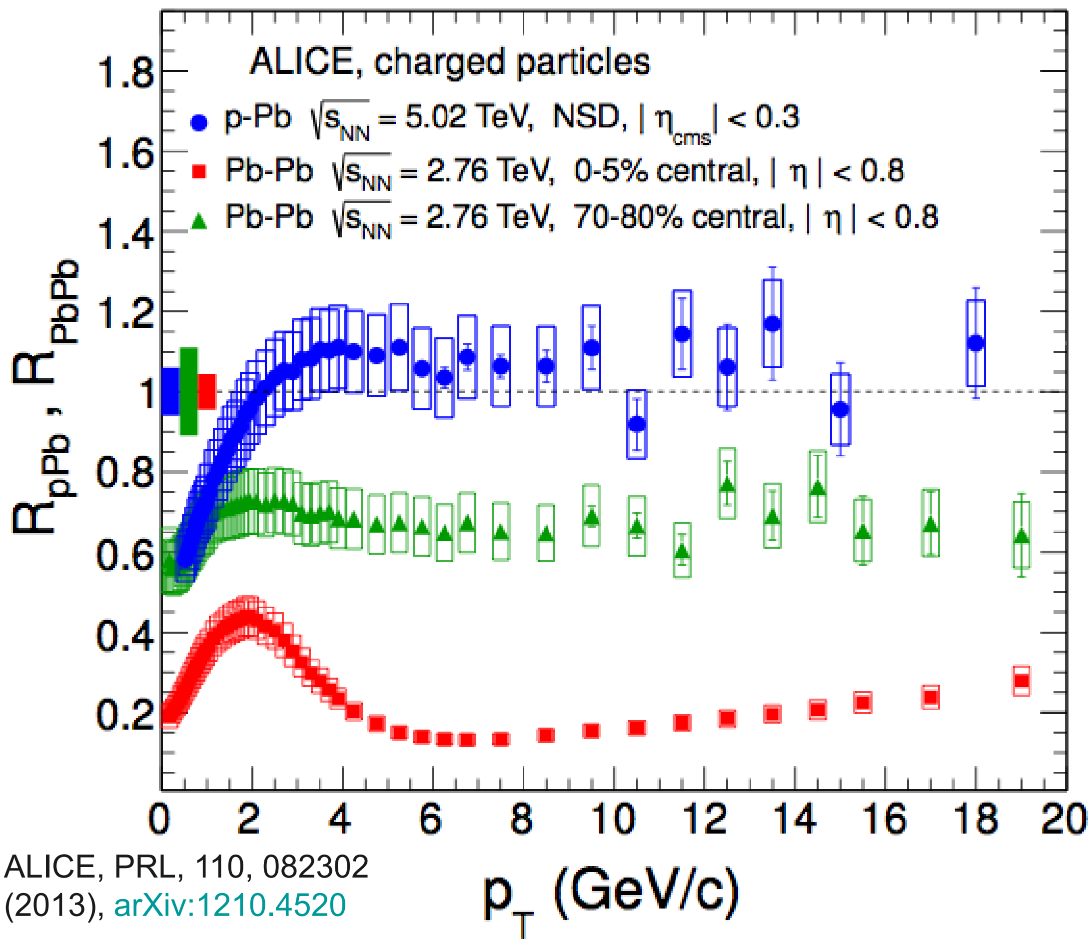
p+Pb at √s = 5.02 TeV: No Suppression

$$R_{pPb} = \frac{dN/dp_T(p+Pb)}{\langle T_{pPb}\rangle \times d\sigma/dp_T(p+p)}$$

$$\langle T_{pPb}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{pp}$$

pp reference interpolated from measurements at √s = 2.76 and 7 TeV

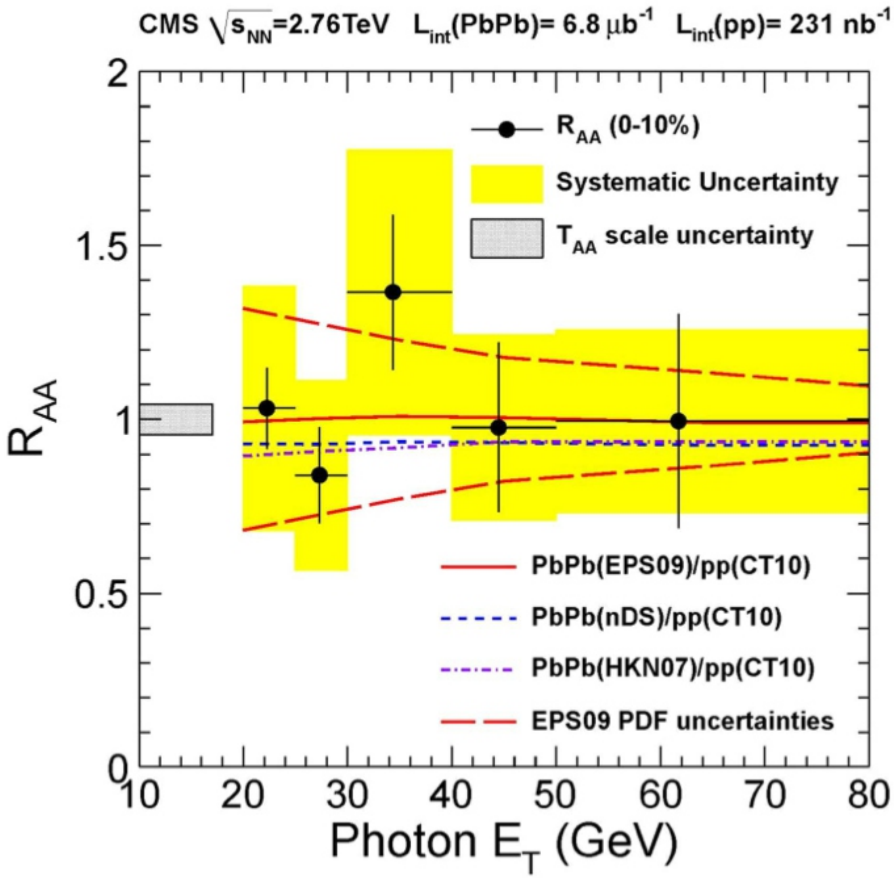
p-Pb data from "pilot" run on Sep 13, 2012



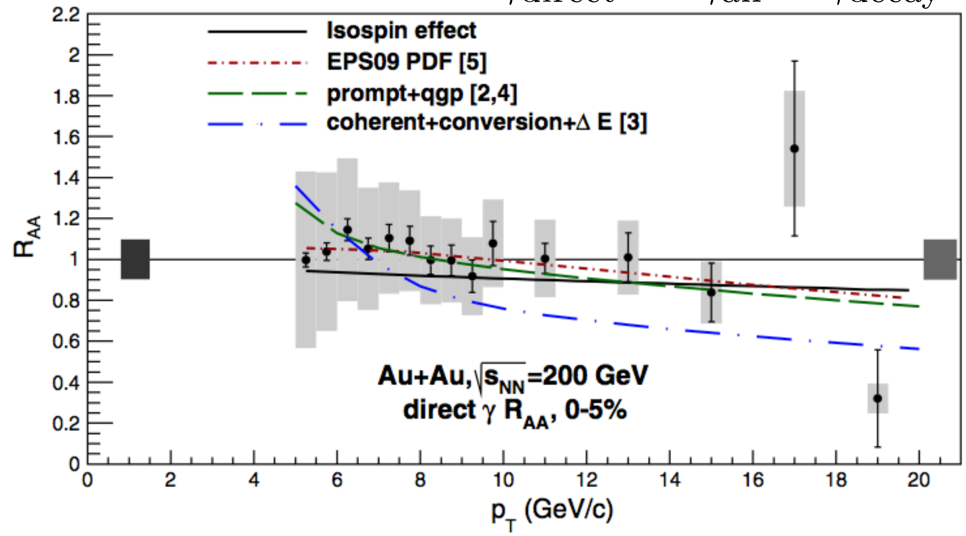
ALICE, PRL, 110, 082302 (2013), arXiv:1210.4520

Absence of suppression in p-Pb confirms that suppression in Pb-Pb is a final-state effect

Verification of T_{AB} Scaling with Hard Photons

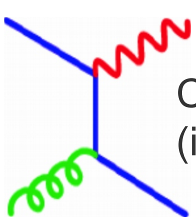


$$\gamma_{\text{direct}} := \gamma_{\text{all}} - \gamma_{\text{decay}}$$

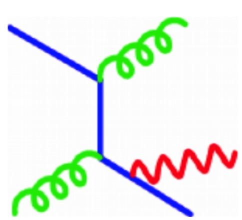


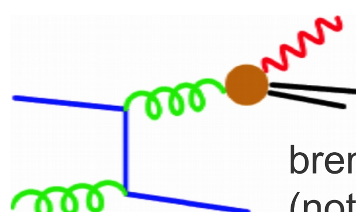
CMS: PLB 710, 256 (2012)
PHENIX: PRL 109, 152302 (2012)

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



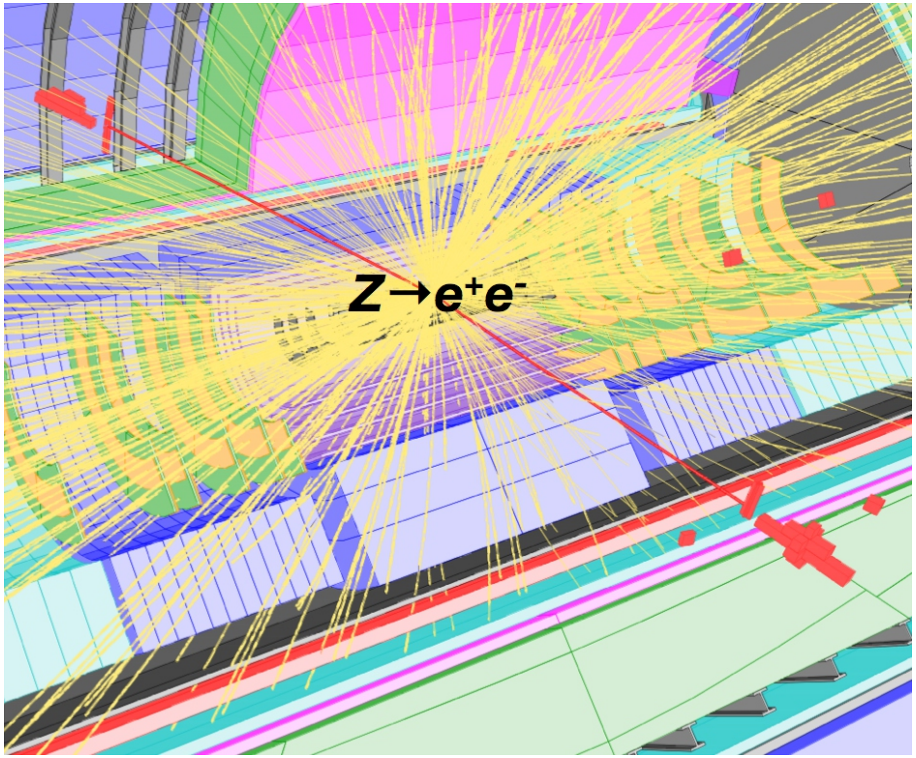
Compton
(isolated)



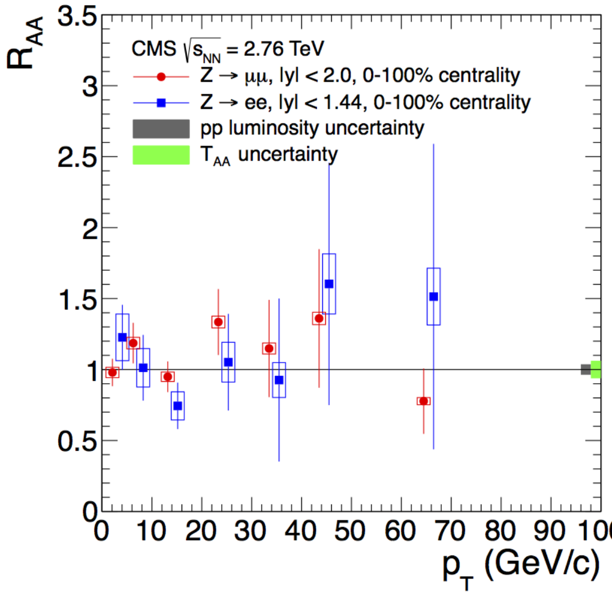


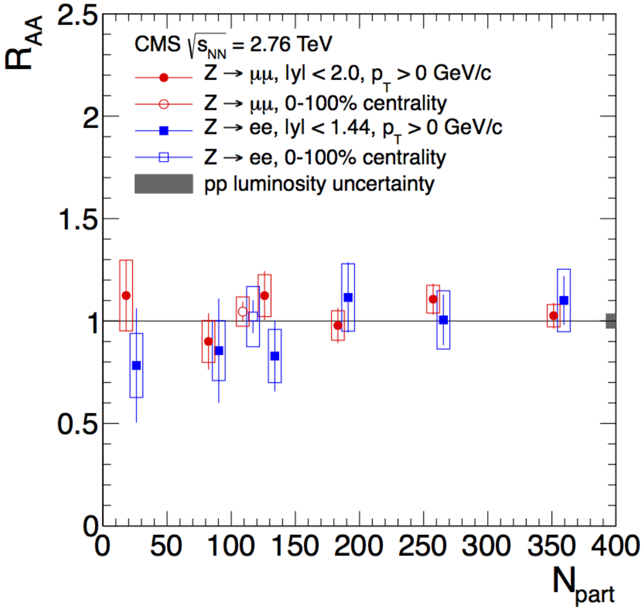
bremsstrahlung, fragmentation
(not isolated)

Z Bosons as Penetrating Probes of the Hot, Dense Medium



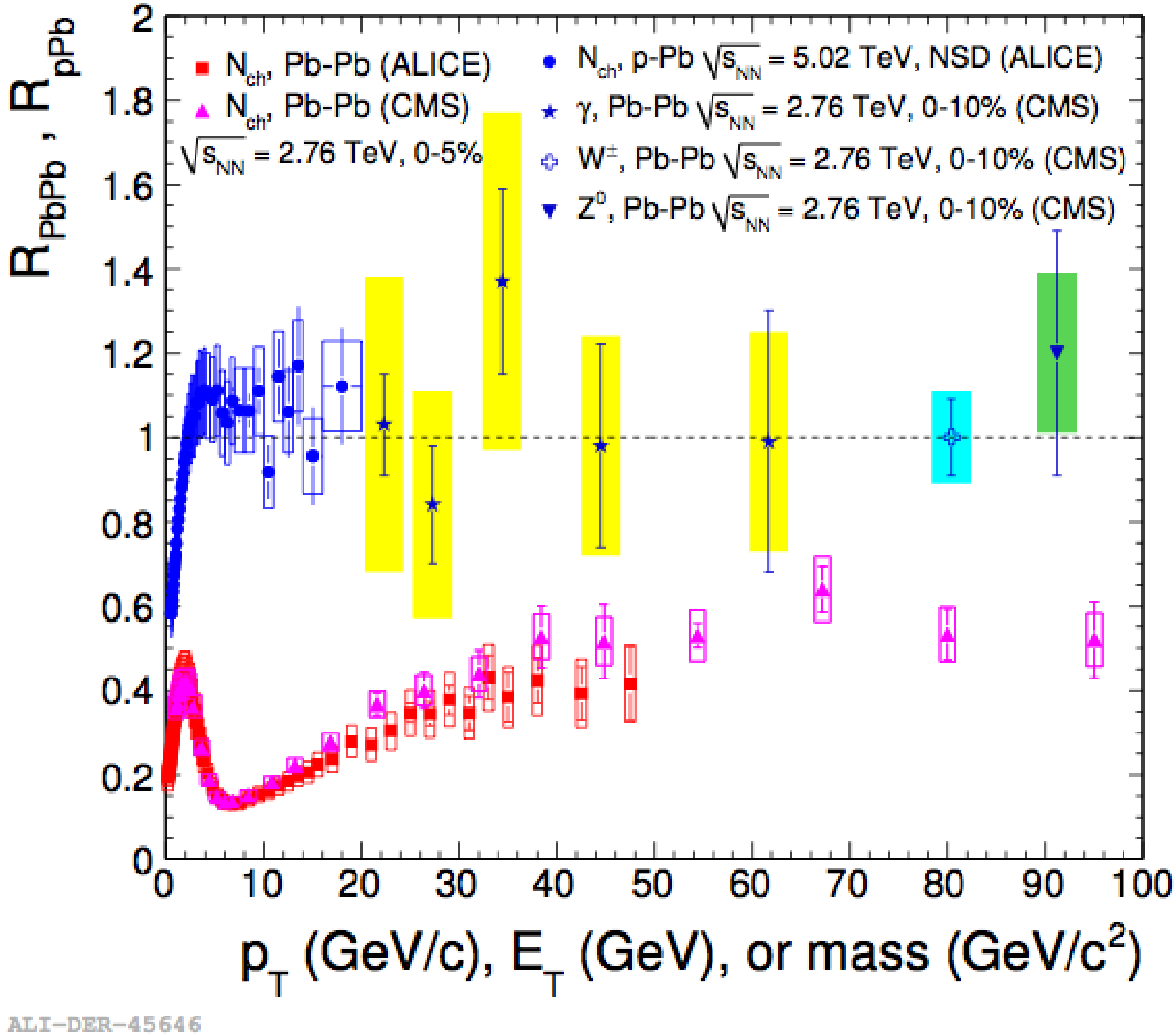
CMS, arXiv:1410.4825





Z bosons in Pb+Pb follow T_{AB} scaling

Summary of Single Particle R_{AA} results



Hierarchy Expected for Different Types of Partons

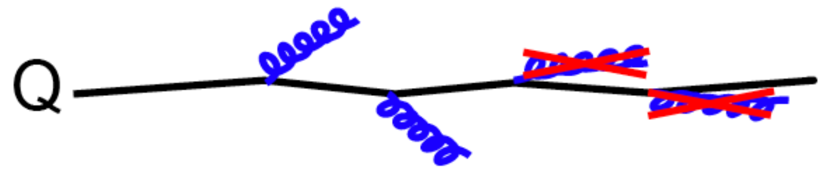
$$\Delta E_{\text{Gluon}} > \Delta E_{\text{Quark},m=0} > \Delta E_{\text{Quark},m\neq 0}$$

larger color factor
for gluons:

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

Emission of gluons at small angles
suppressed.

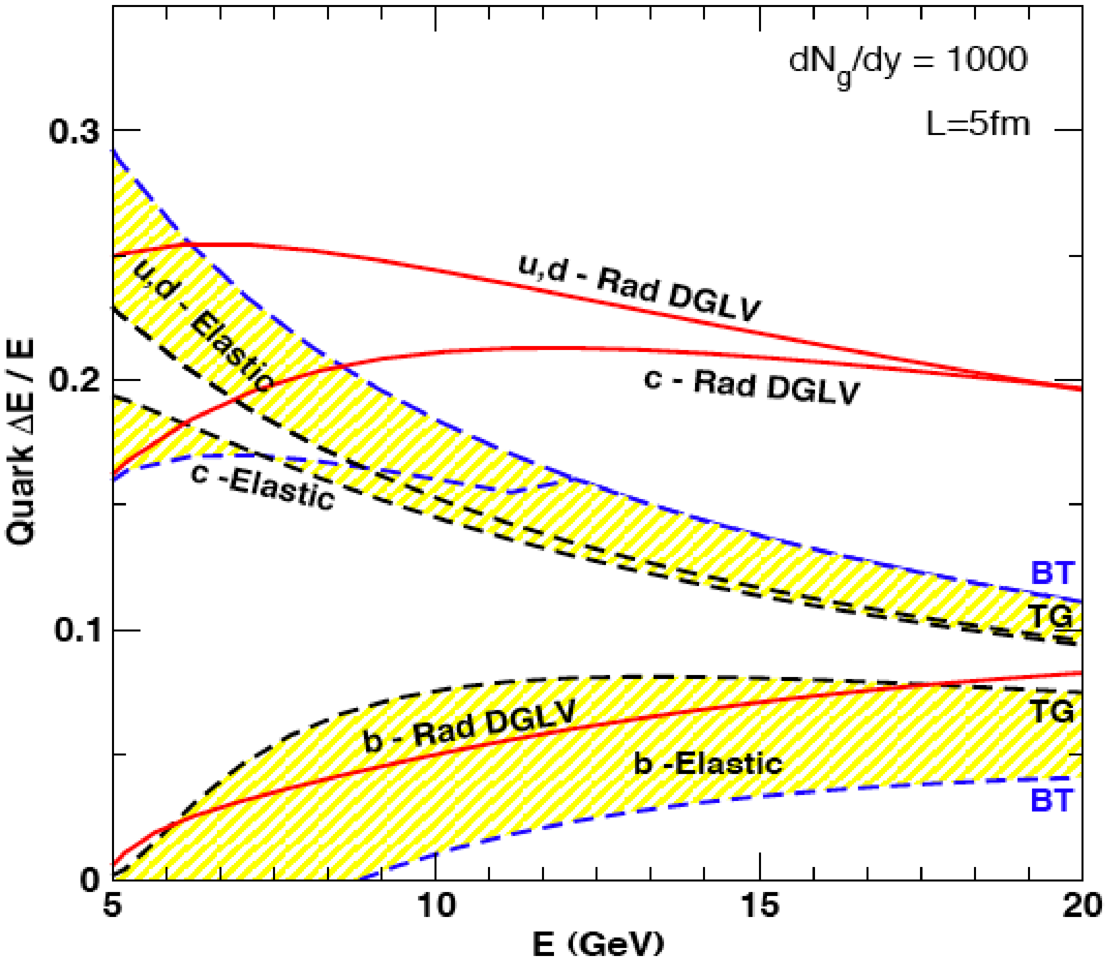
Dead cone effect:
Heavy quarks (c, b)
radiate fewer gluons



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

Dokshitzer & Kharzeev, PLB 519(2001)199

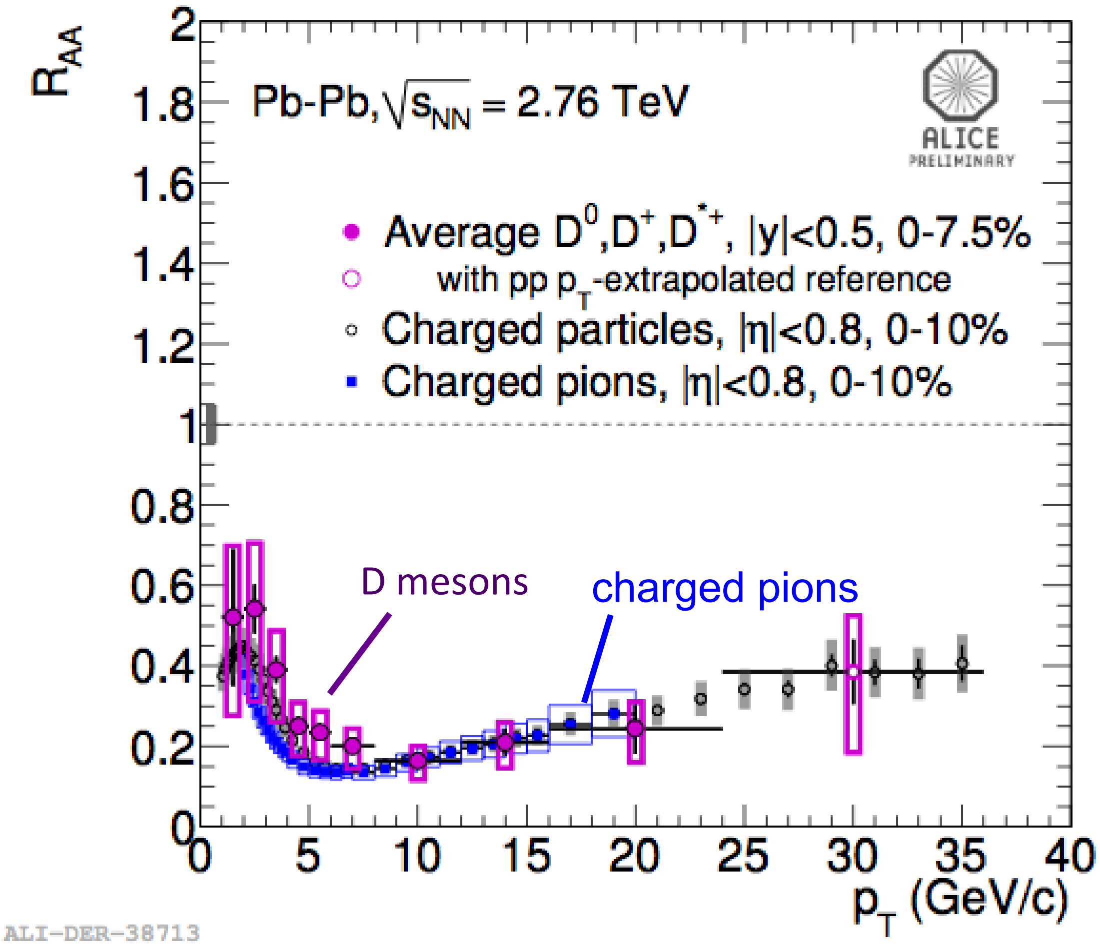
Radiative vs. Collisional (i.e., Elastic) Energy Loss: Maybe $\Delta E_{collisional}$ More Important Than Initially Thought?



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

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

D Meson R_{AA}: Charm Quark Energy Loss Surprisingly Similar to Quark and Gluon Energy Loss



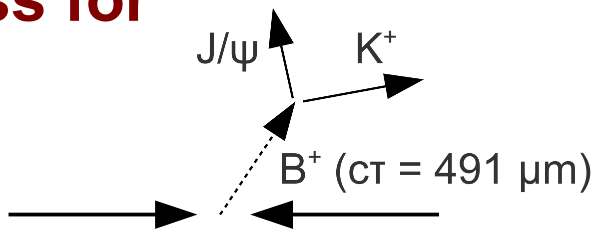
Radiative parton energy loss:

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

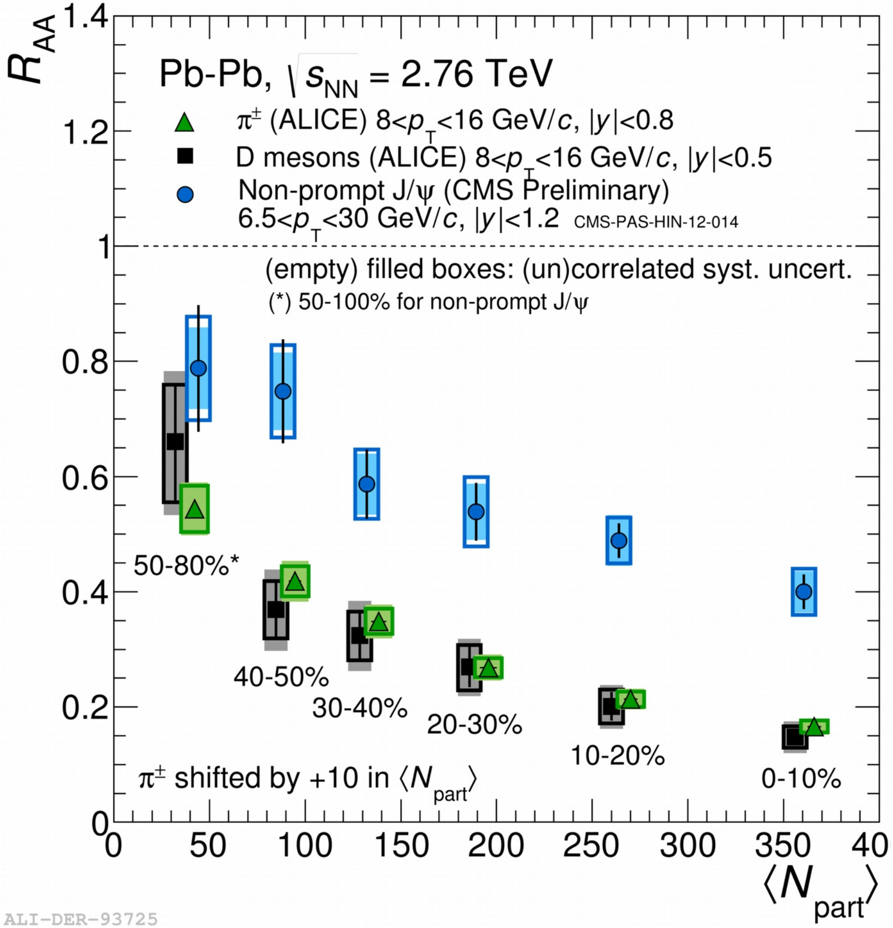
color factor — dead cone effect

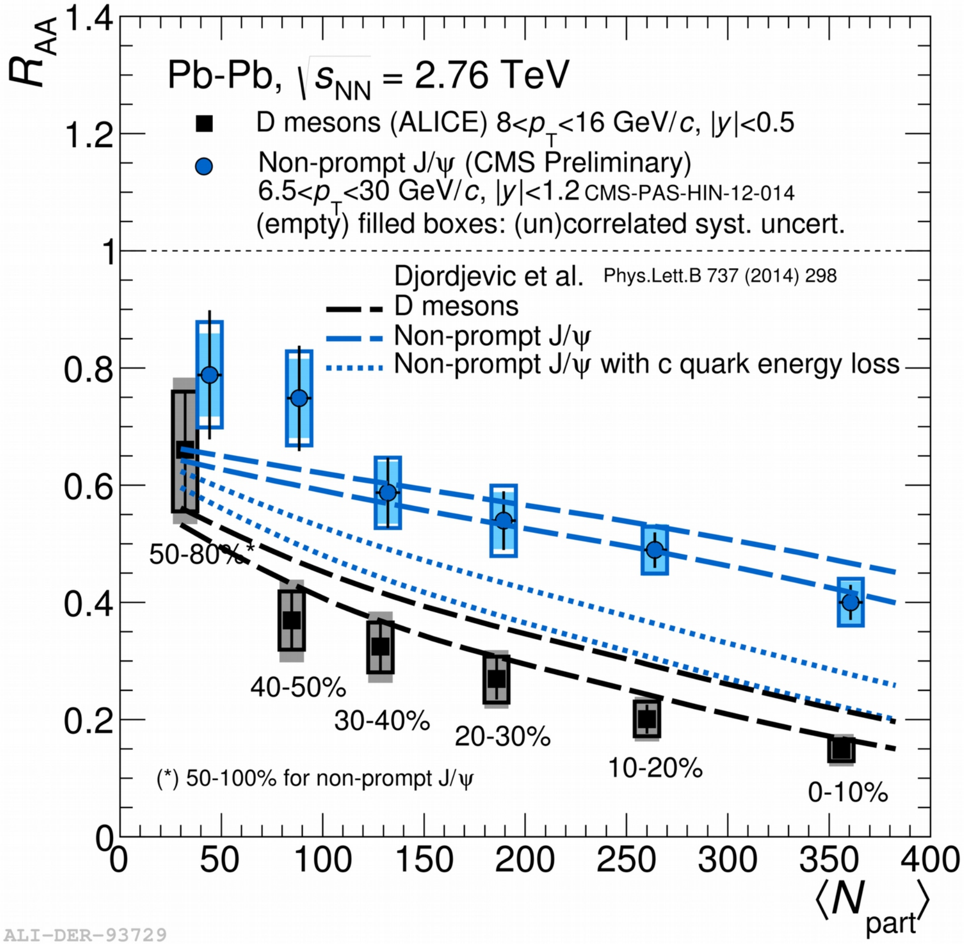
- Strong suppression also for D mesons (which cannot be explained by shadowing)
- Suppression of D mesons and pions surprisingly similar
  - pions mainly from gluons
  - dead cone effect for c and b
- Little indication for expected hierarchy
(however, need to carefully consider also the steepness of the initial parton spectra)

First Indication of a Different Energy Loss for c and b Quarks



B Mesons identified via displaced (non-prompt) J/ψ

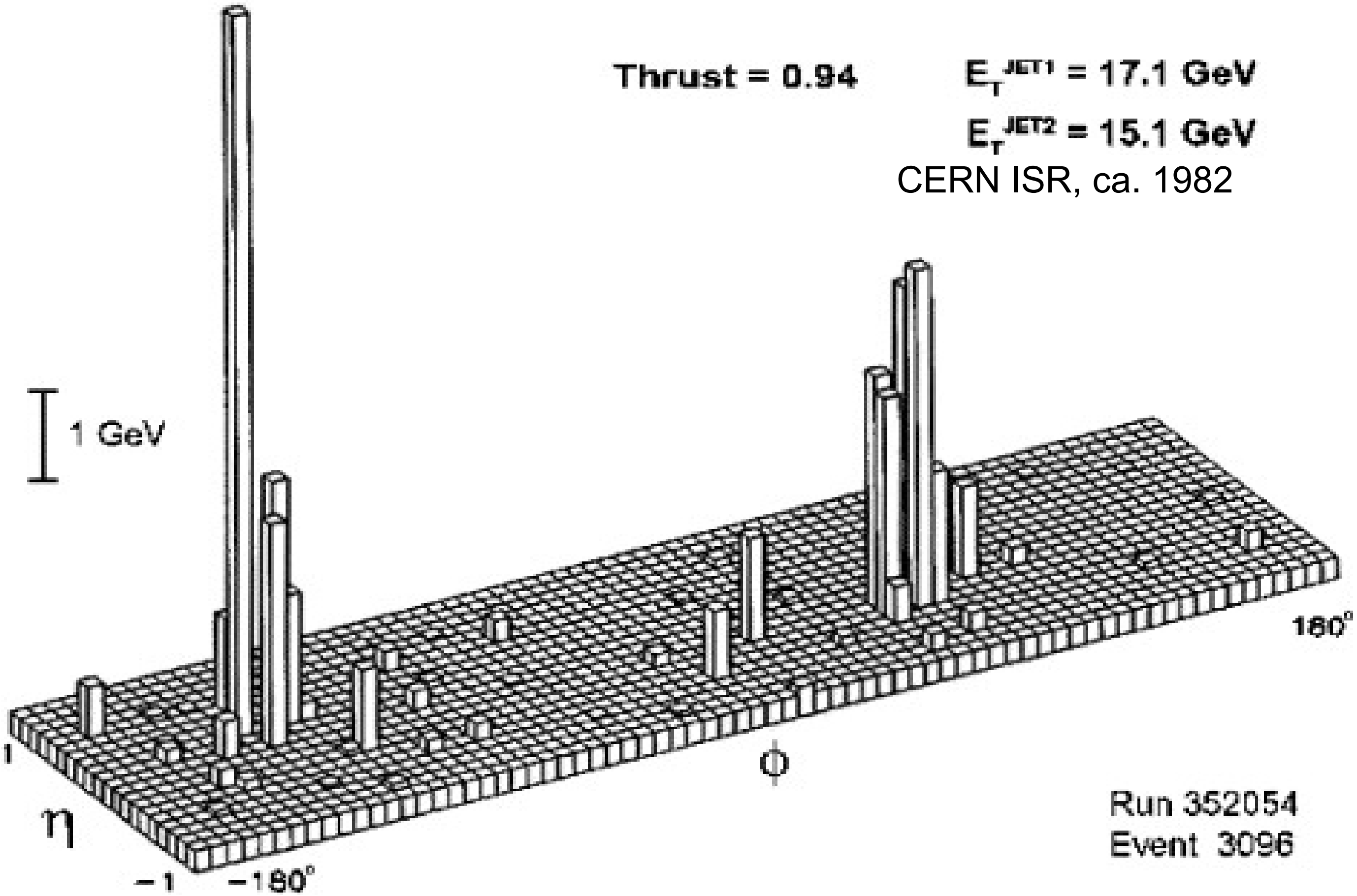




Results from the LHC: 2. Jets

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

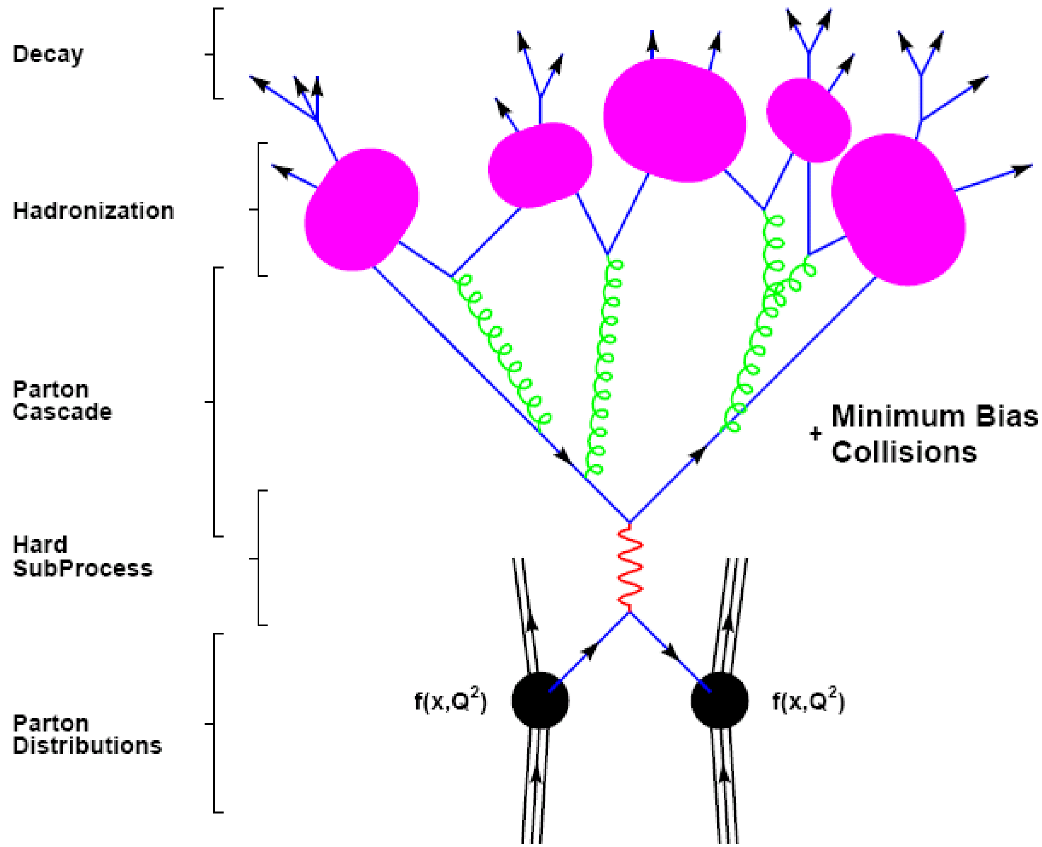
Lego plot shows energy vs. pseudorapidity η and azimuthal angle φ



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



Hard Process → Parton Cascade → Hadronization

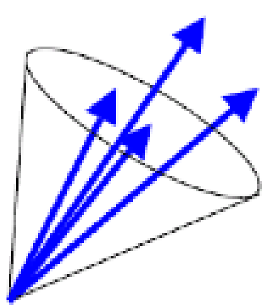
describable with pQCD

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

Cone algorithm:

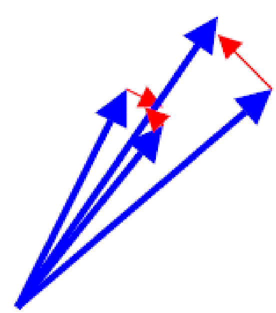


Sum content in cone with radius

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

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

k_T jet algorithm

- Algorithms 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

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

- For D = 1 and ΔR_{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

Anti-k_T algorithm

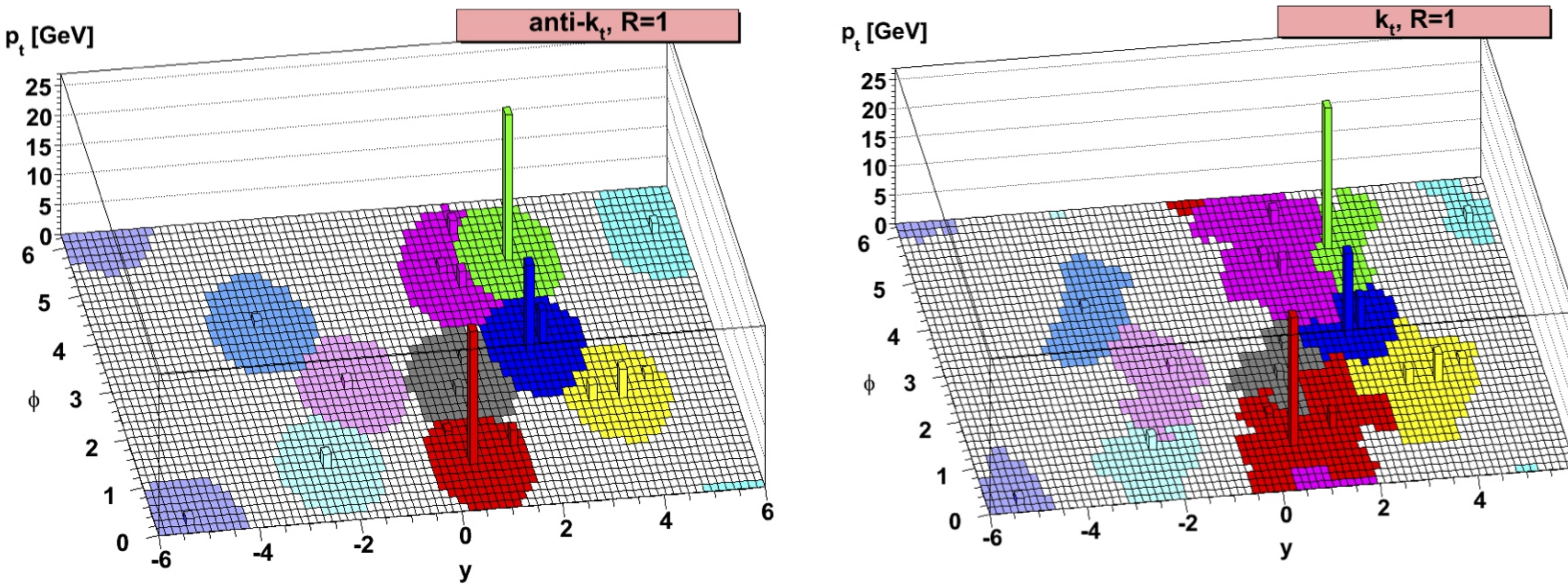
- Jets reconstructed with the k_T algorithm don't have a well defined shape/area
- This makes the subtraction of the energy from the underlying event difficult
- Therefore, the anti-k_T algorithm is the standard choice for the LHC experiments

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta_{i,j}^2}{R^2}, \quad d_i = p_{T,i}^{2p}$$

$$p = 1 : k_T \text{ algorithm}$$

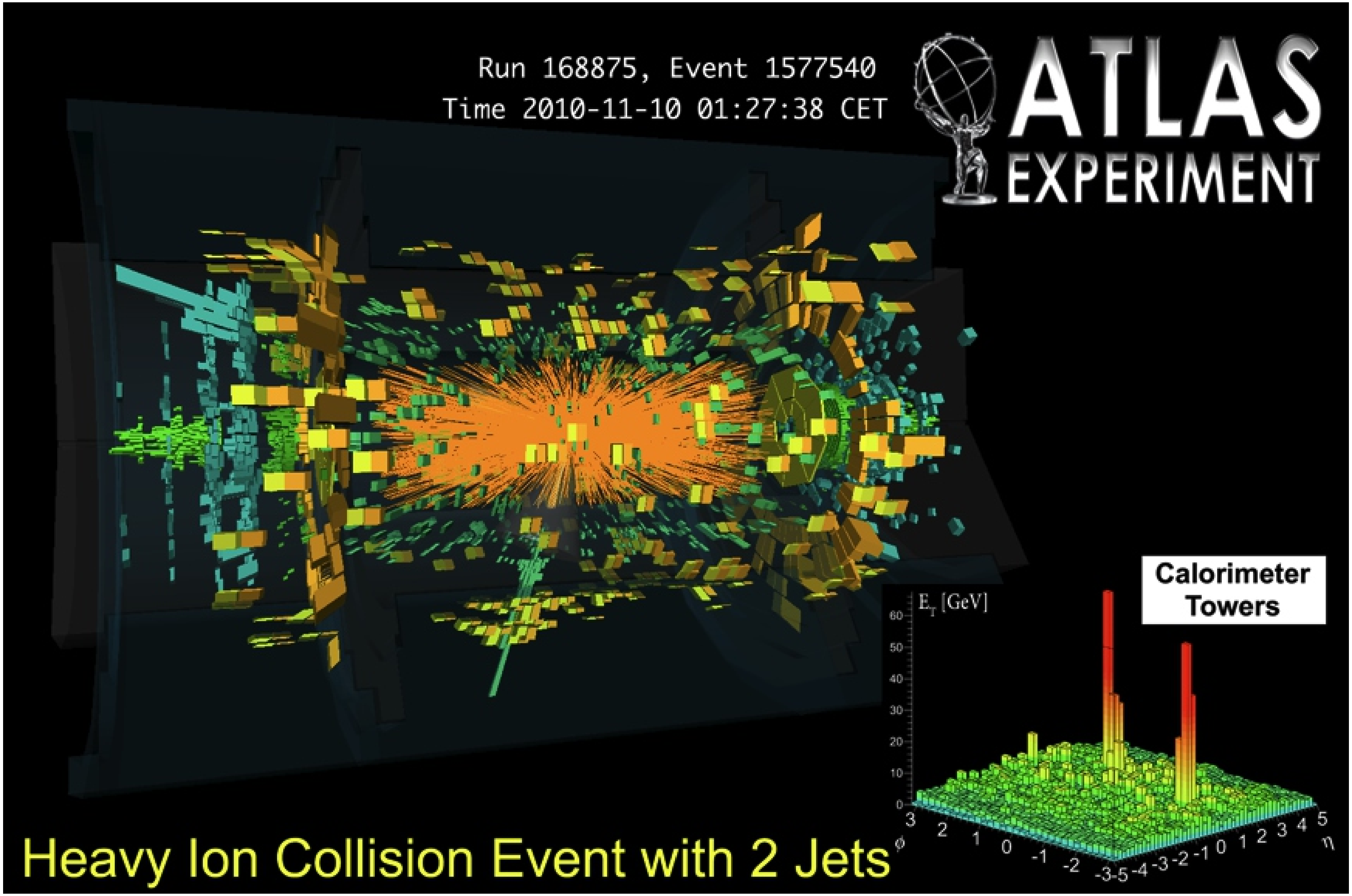
$$p = -1 : \text{anti-}k_T \text{ algorithm}$$

Anti-k_T algorithm vs. k_T algorithm

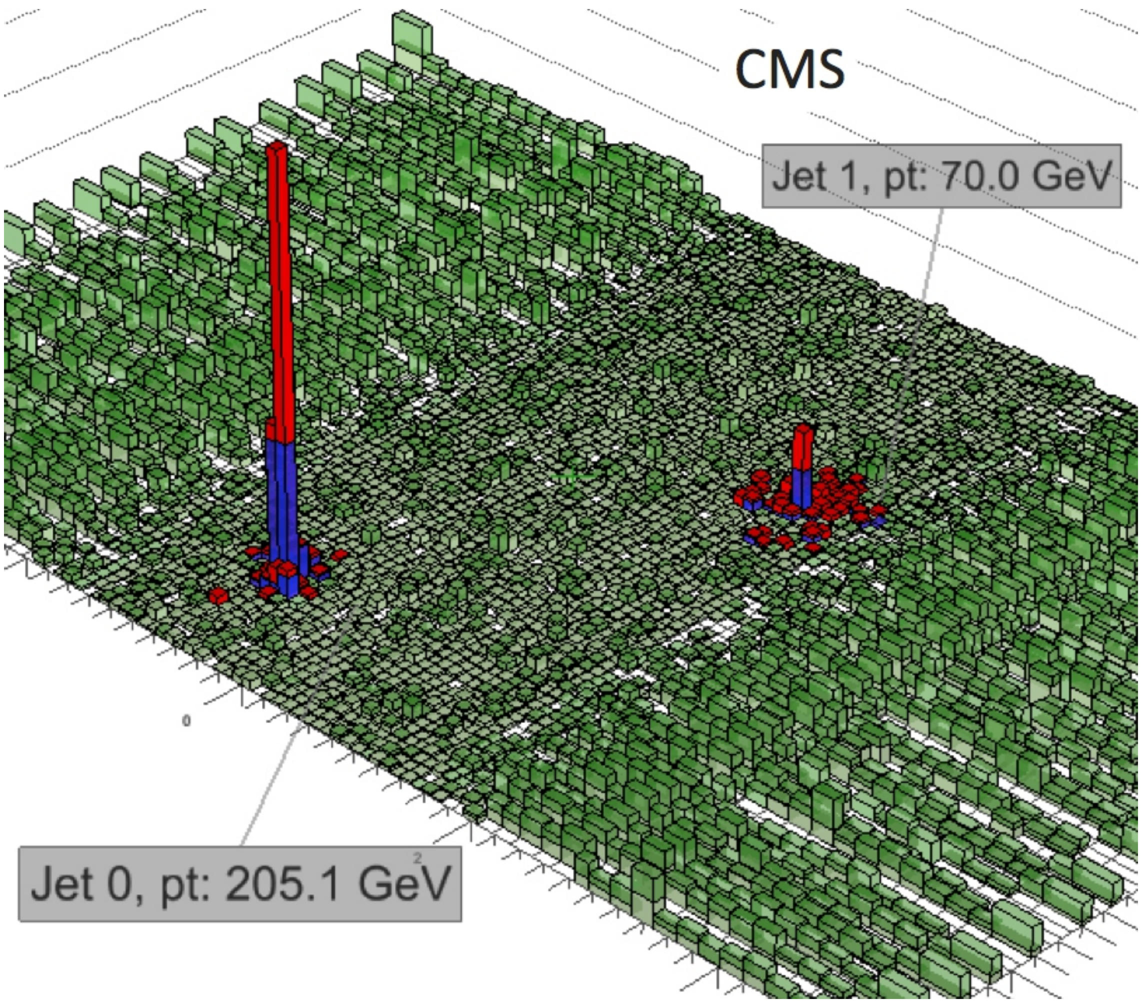


arXiv:0802.1189

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



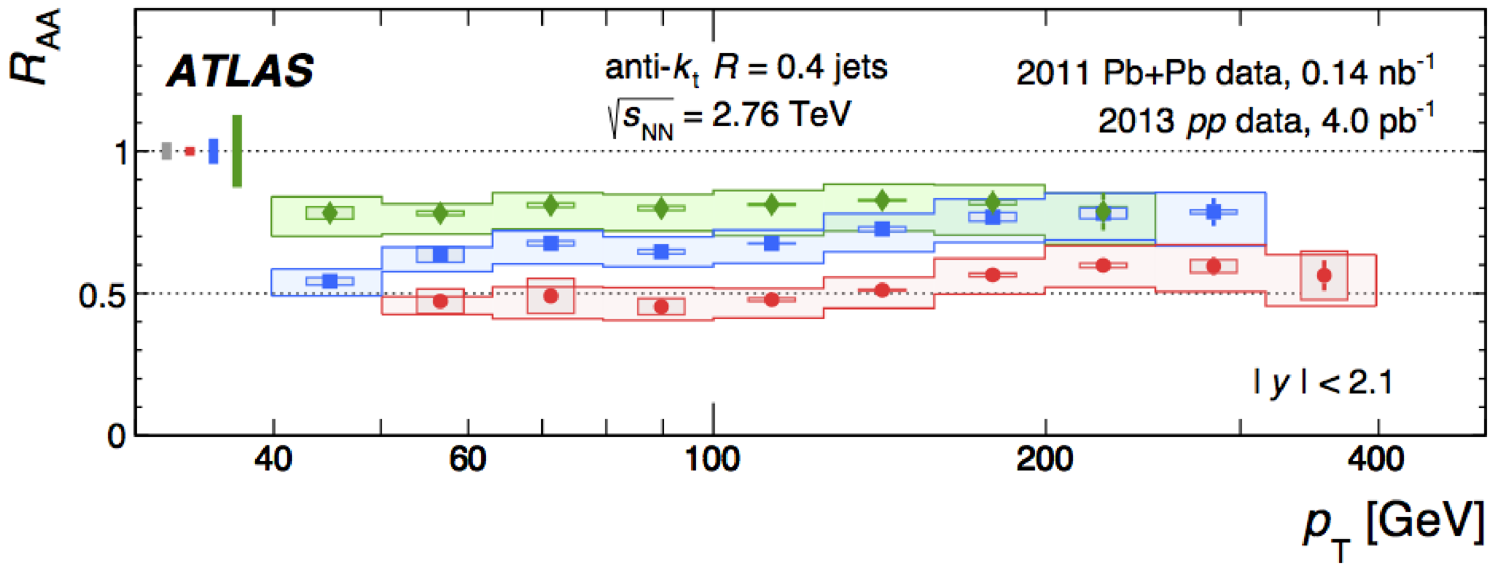
Dijet Energy Asymmetry in Pb+Pb

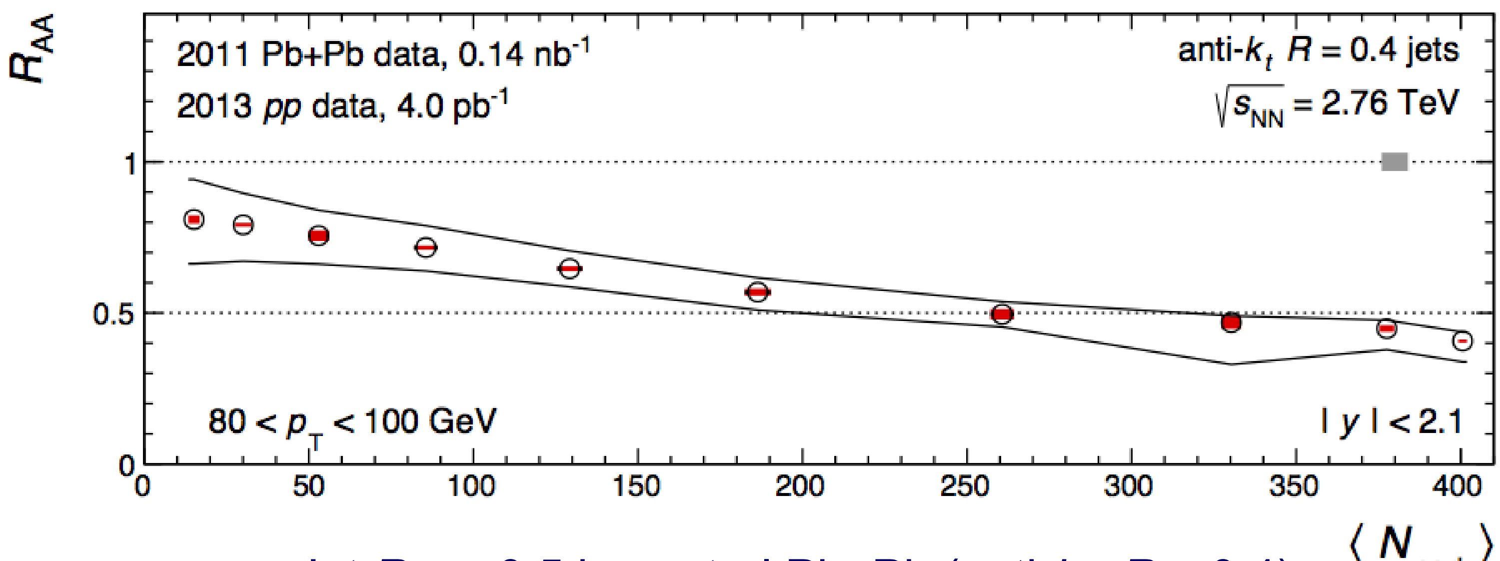


- ATLAS and CMS find large asymmetry in energy of dijets in Pb+Pb
- Observations
  - Dijets in Pb+Pb still back-to-back [no angular decorrelation]

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

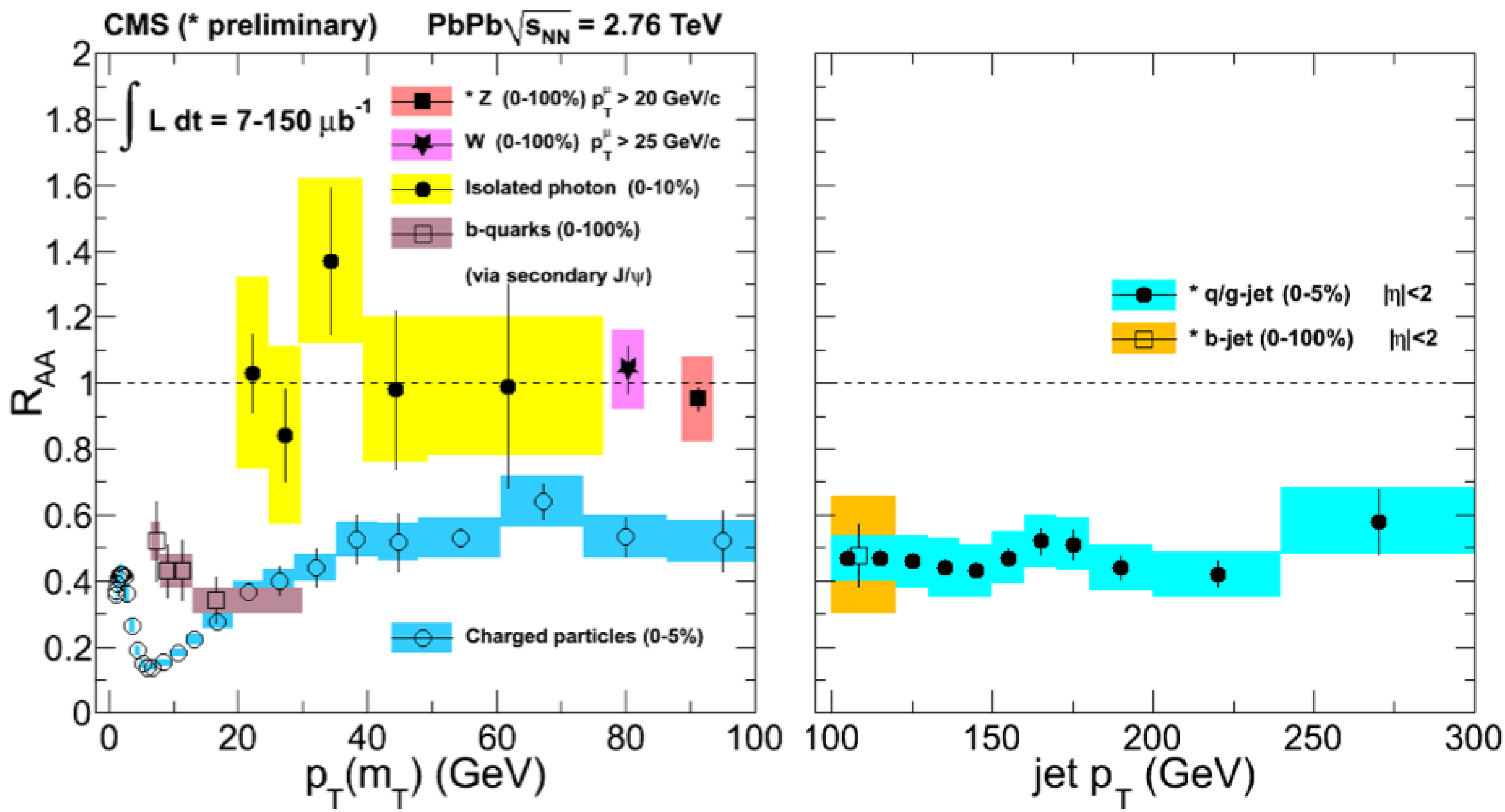
ATLAS, arXiv:1411.2357





Jet R_{AA} ≈ 0.5 in central Pb+Pb (anti-k_T, R = 0.4)

CMS Jet Results in Pb+Pb



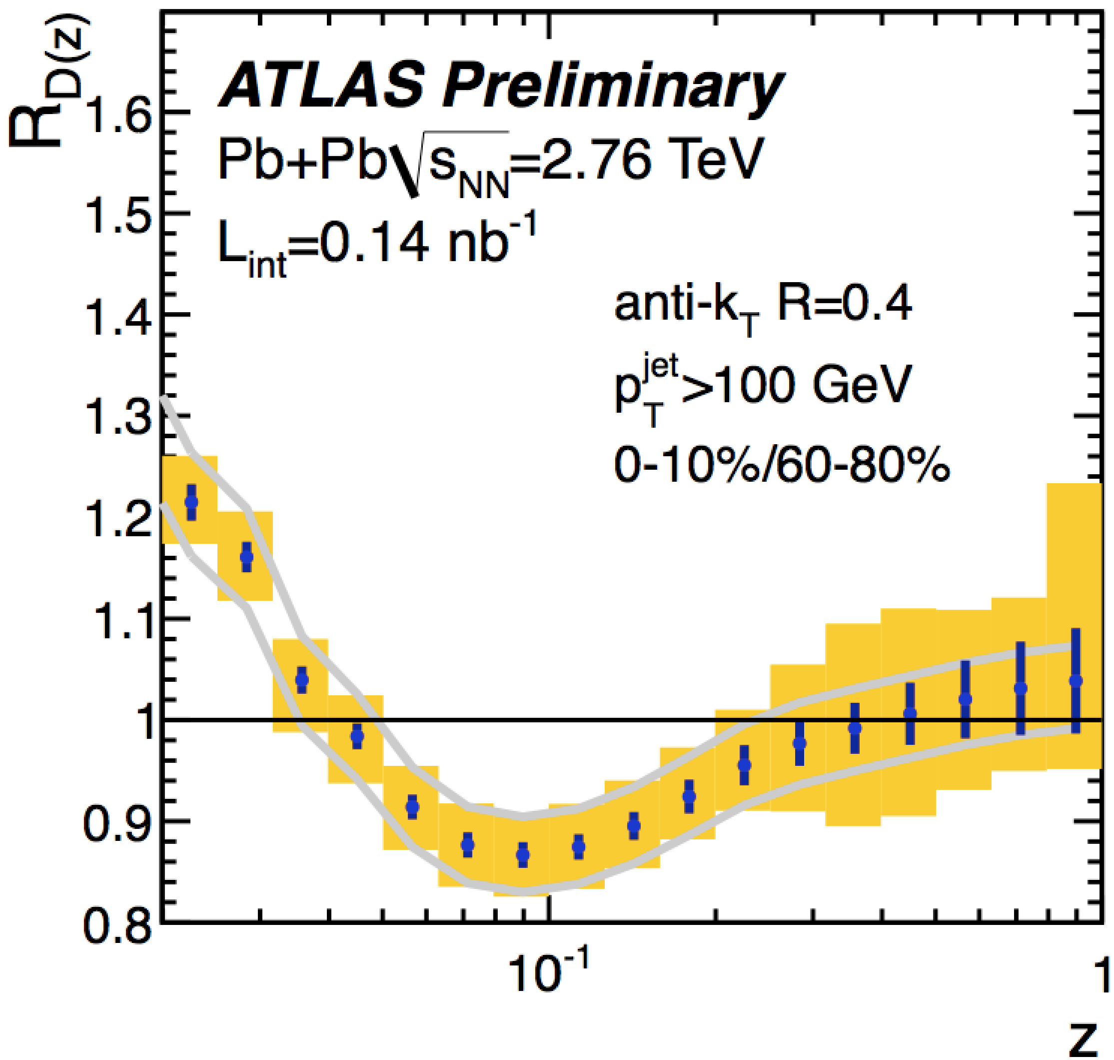
- Single particle R_{AA} and jet R_{AA} consistent

  ($z = p_T(\text{track})/p_T(\text{jet})$ = 0.4 – 0.6 for charged particles with p_T = 50-100 GeV)

- b-quark jet suppression similar to light quark jet suppression

Modification of Jet Fragmentation in central Pb+Pb

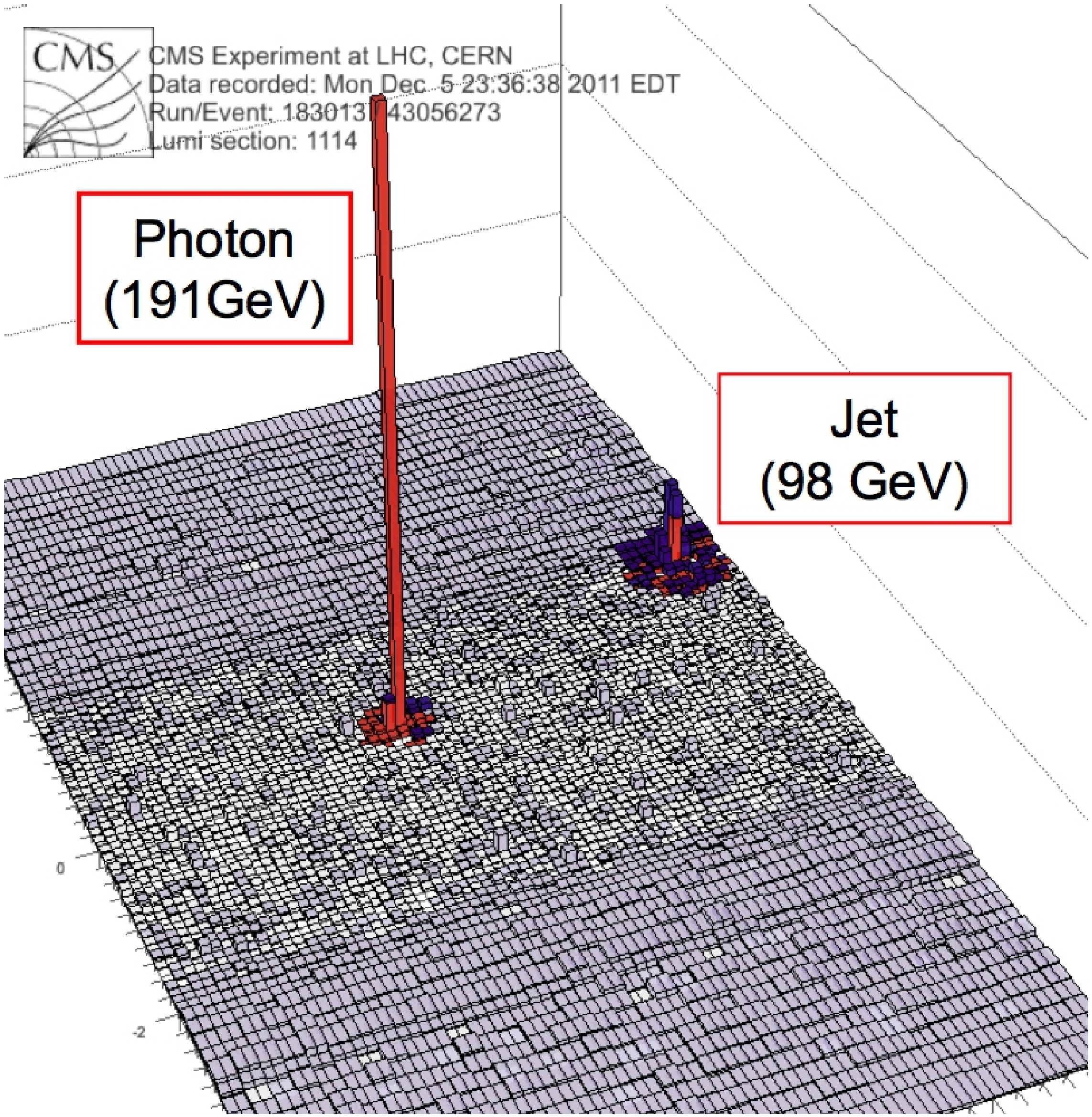
ATLAS-CONF-2012-115

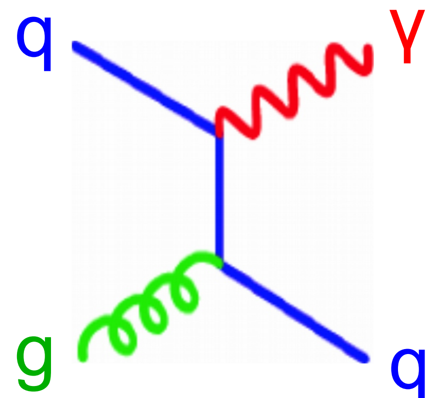


$$z = p_T^{\mathrm{ch}} \cos\Delta\alpha / p_T^{\mathrm{jet}}$$

$$R_{D(z)} = \frac{D(z)_{0-10\%}}{D(z)_{60-80\%}}$$

Gamma-Jet Correlations





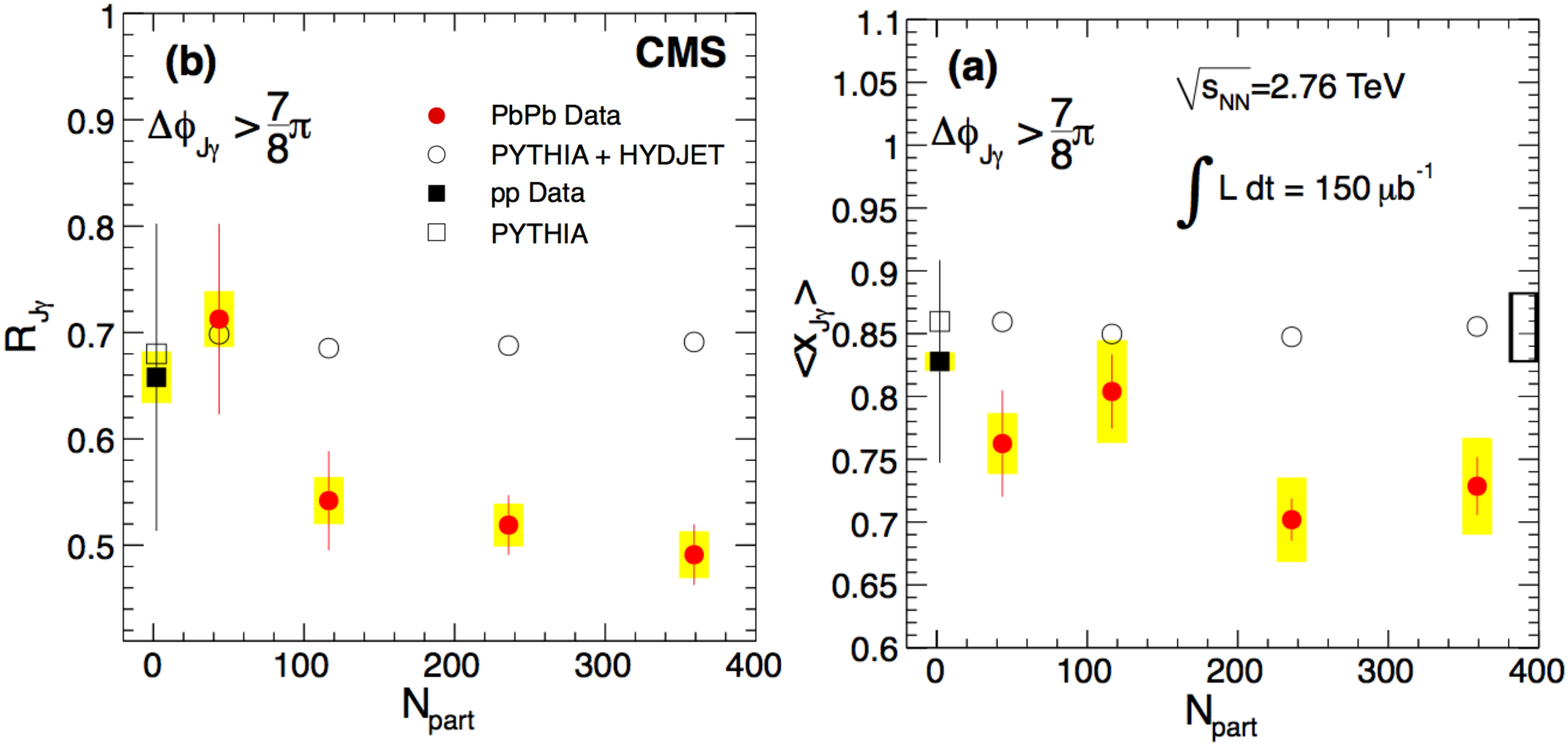
Gamma-Jet Correlations

$p_T^{\gamma} > 60$ GeV/c $|\eta^{\gamma}| < 1.44$

$p_T^{Jet} > 30$ GeV/c $|\eta^{Jet}| < 1.6$

Average fraction of isolated photons with an associated jet above 30 GeV/c

Average ratio of jet p_T to photon p_T

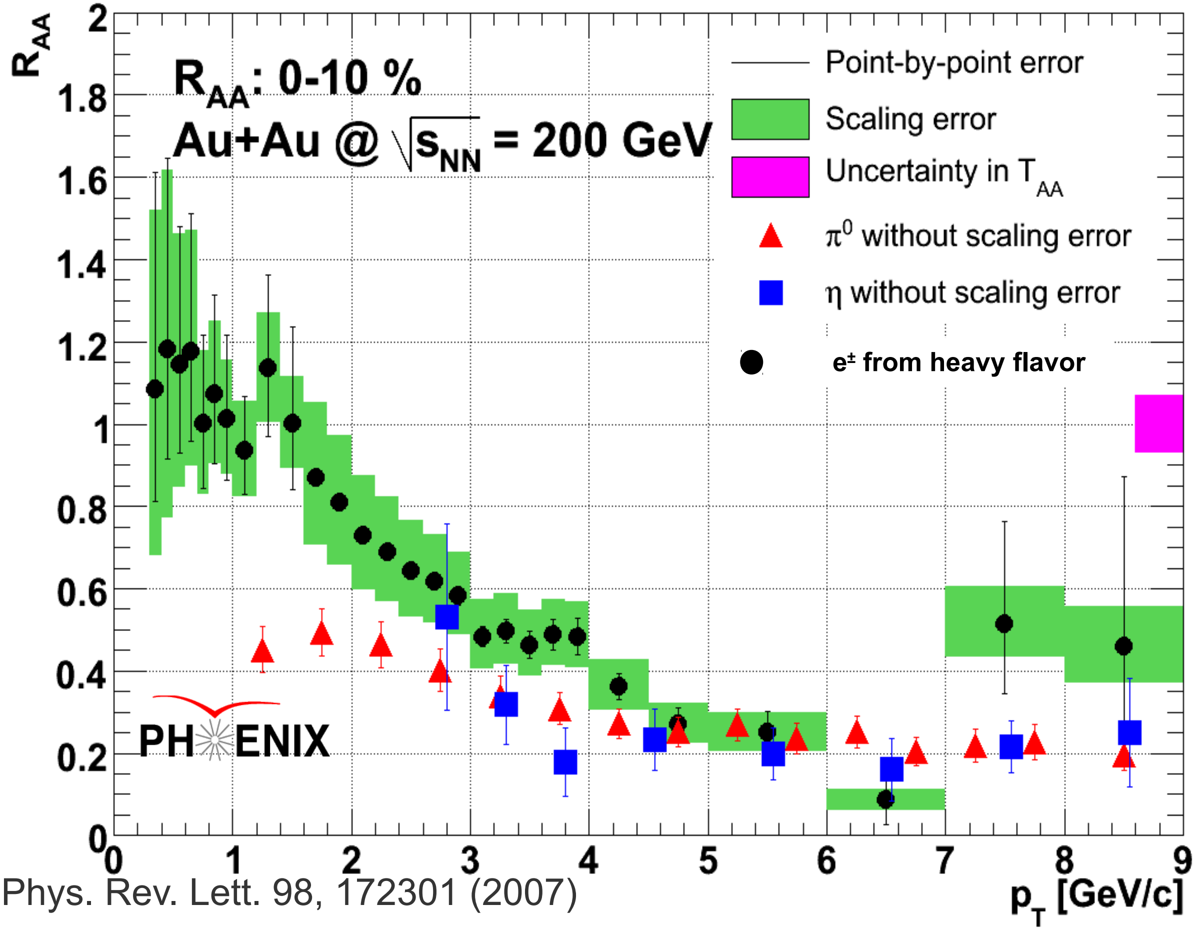


Points to Take Home

- 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 one to study parton energy loss in Pb+Pb collisions with full jet reconstruction at the LHC

Extra slides

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



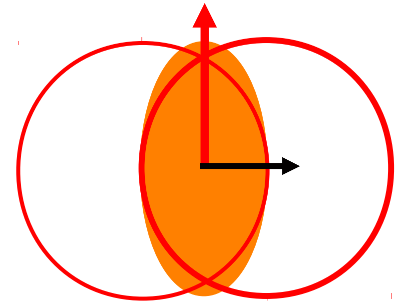
Phys. Rev. Lett. 98, 172301 (2007)

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

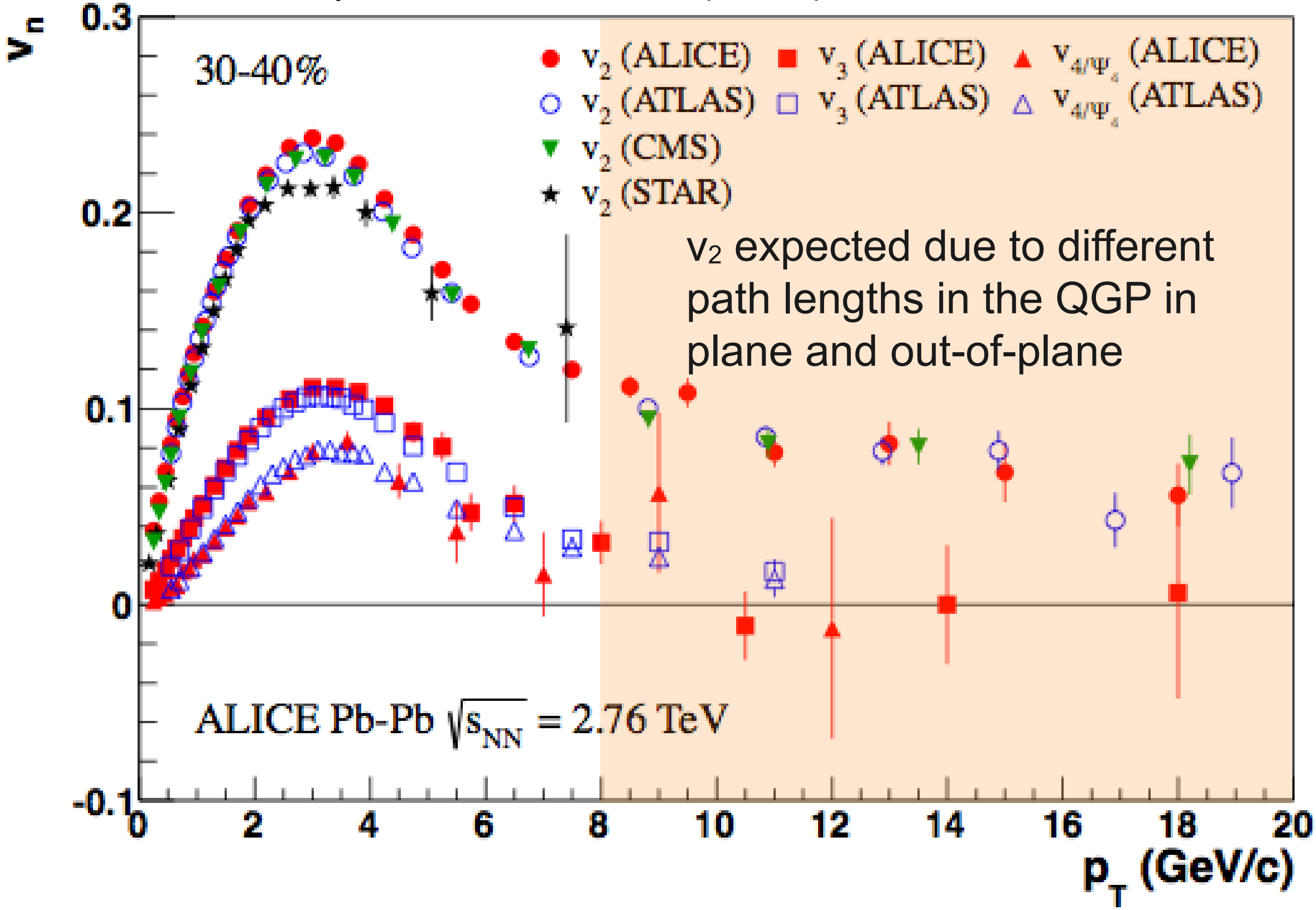
$\Delta E_{\mathrm{Gluon}} > \Delta E_{\mathrm{Quark},m=0} > \Delta E_{\mathrm{Quark},m\neq 0}$ not observed!

$v_2 > 0$ at Large p_T: Parton Energy Loss

in plane
out-of-plane

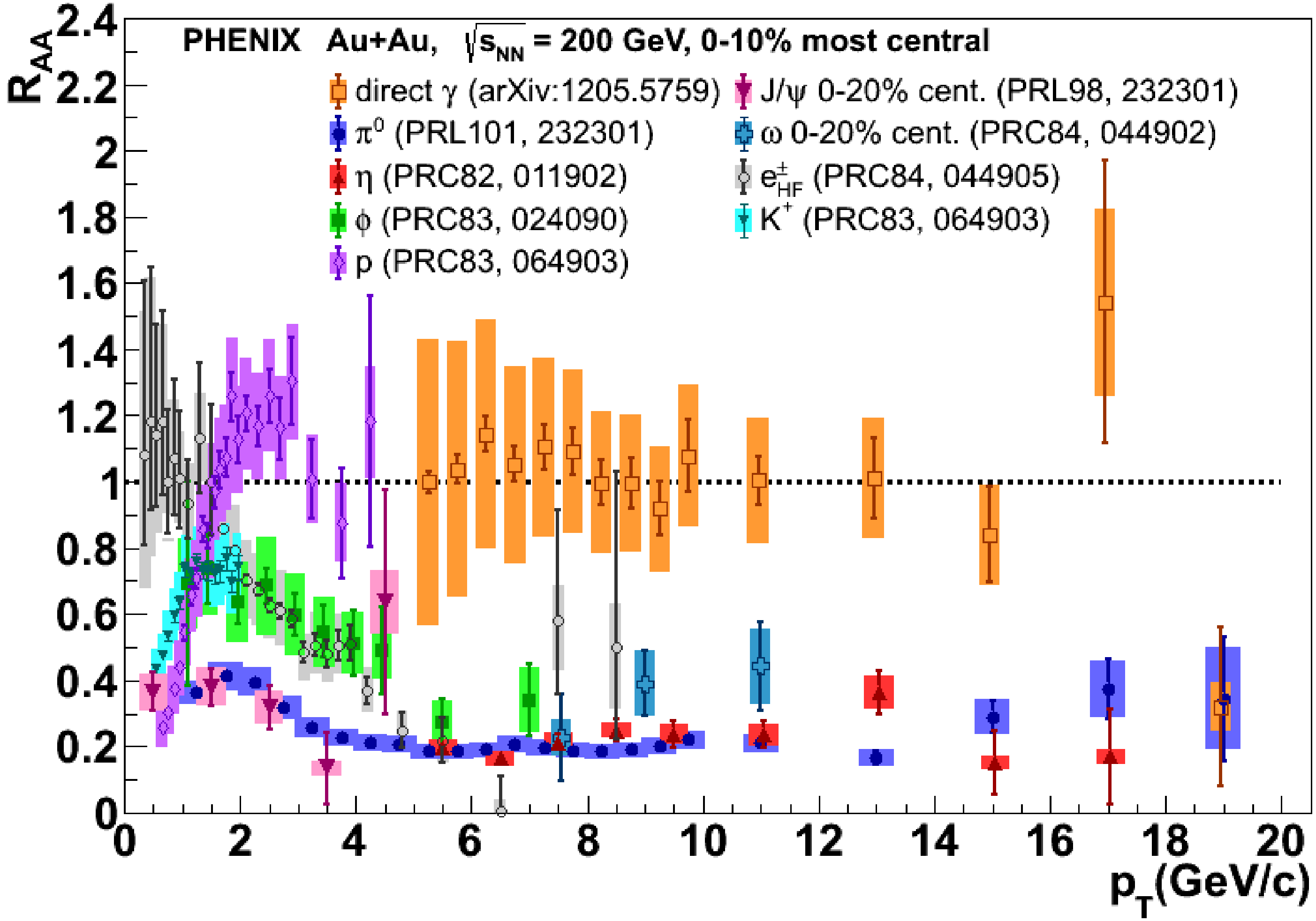


ALICE, Physics Letters B 719 (2013) 18

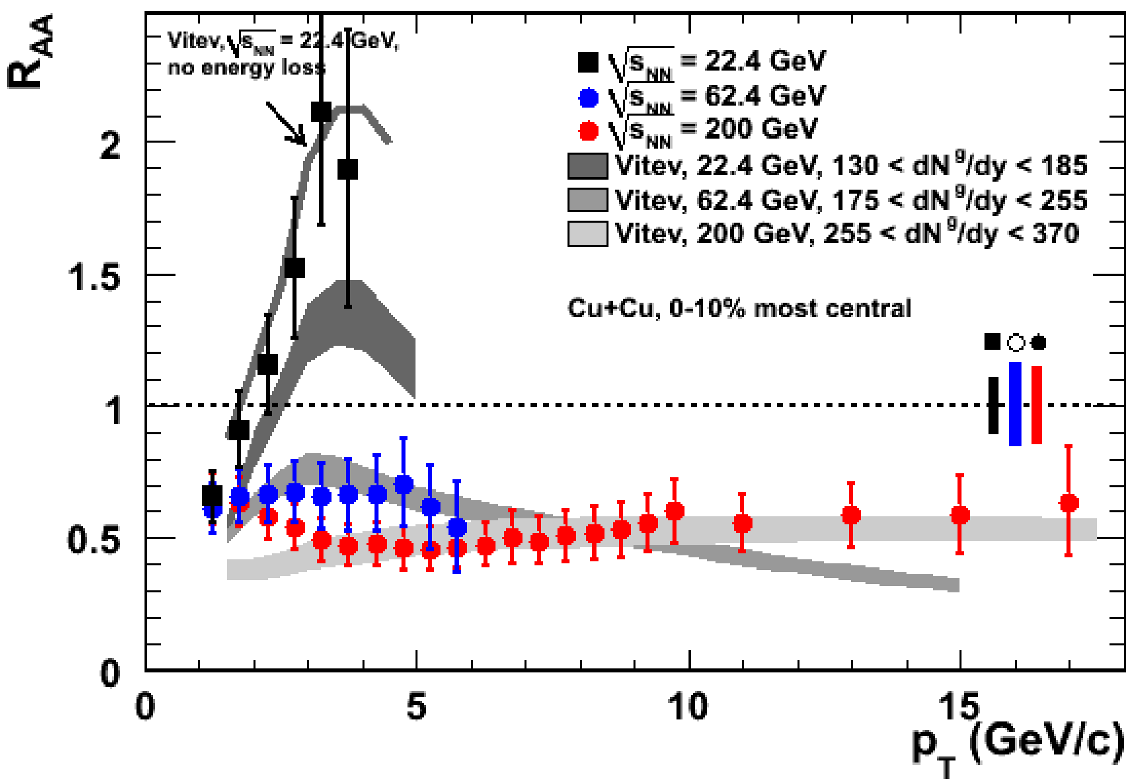


v_2 expected due to different path lengths in the QGP in plane and out-of-plane

Particle Species Dependence of R_{AA}



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

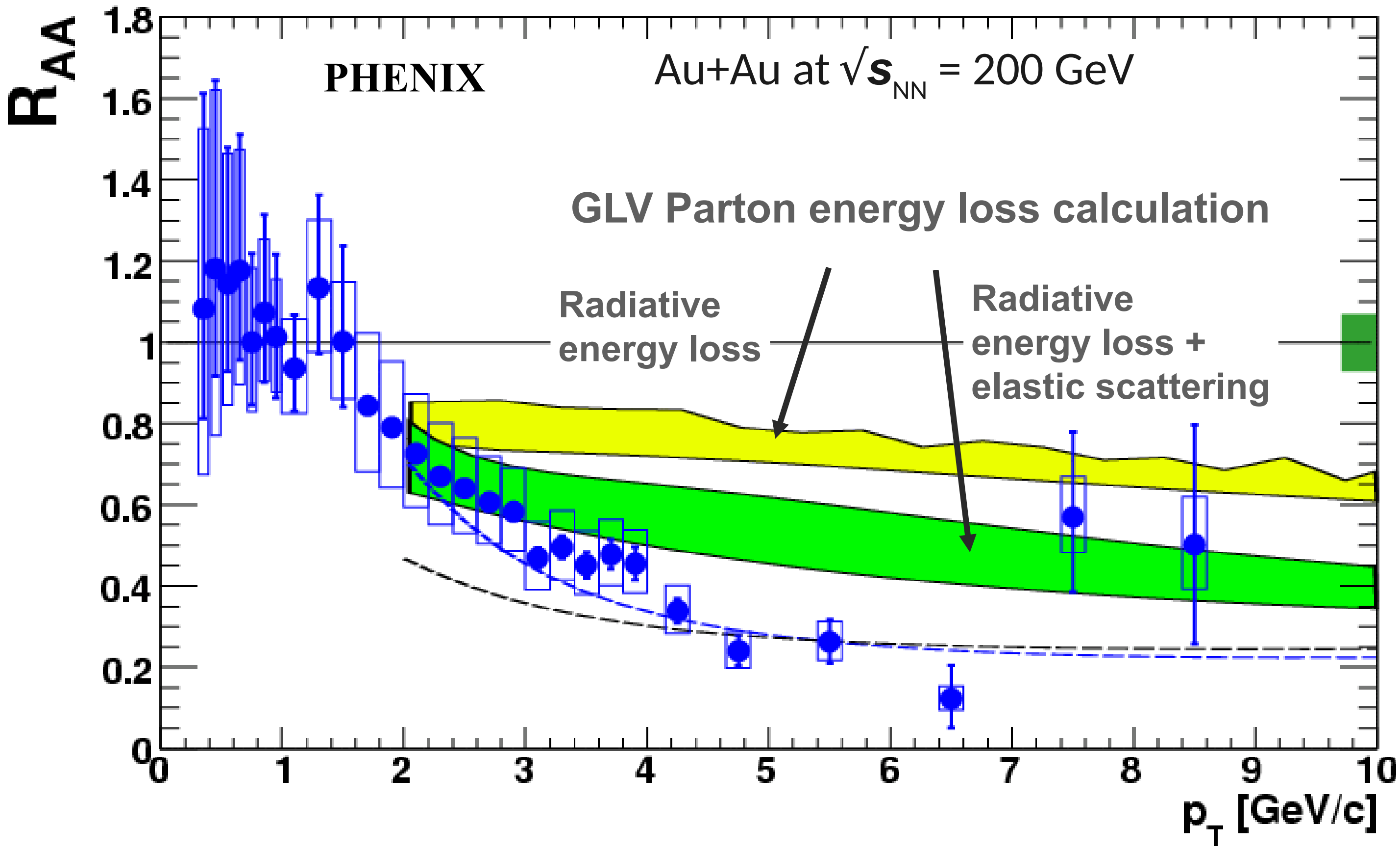
π^0 production less suppressed than in Au+Au

22.4 GeV

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

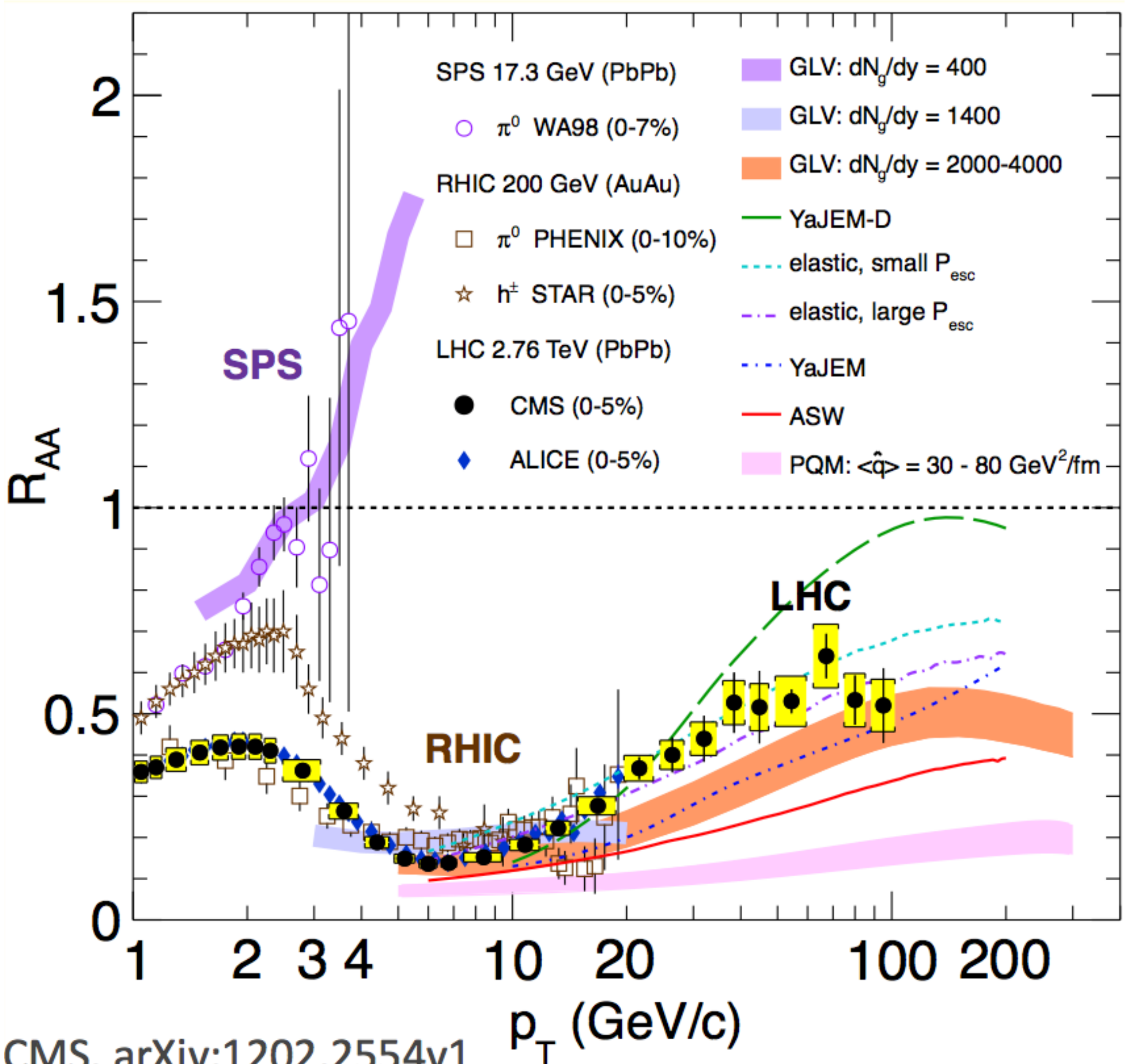
Same conclusion as for heavier nuclei:
Parton energy loss starts to prevail over Cronin enhancement between $\sqrt{s_{NN}}$ = 22.4 GeV and 62.4 GeV

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

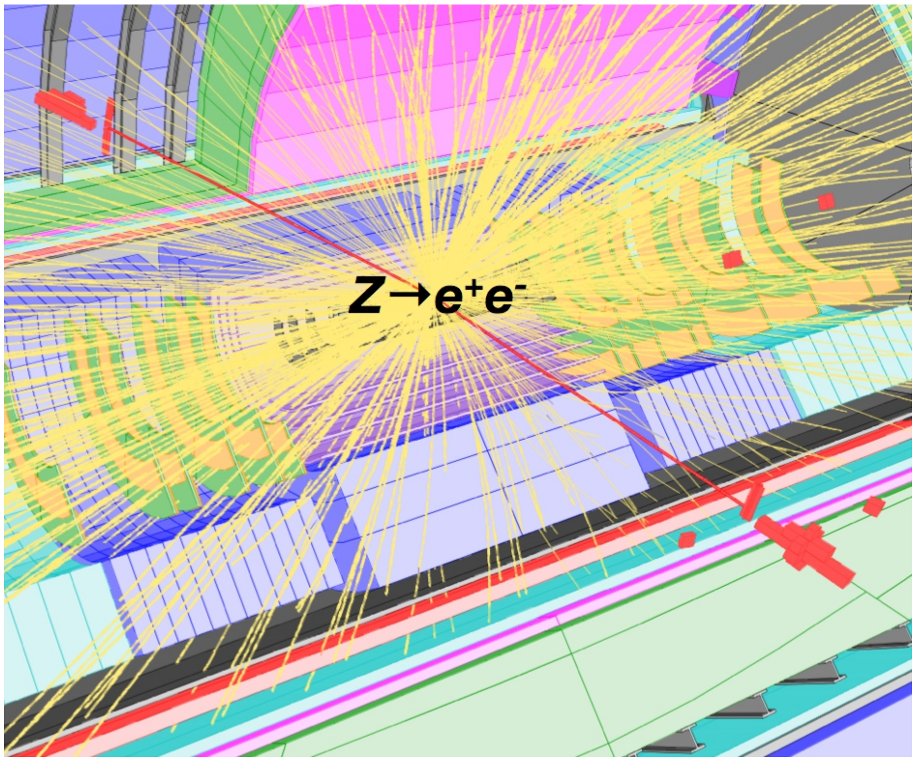
Charged Hadron R_{AA} at high p_T

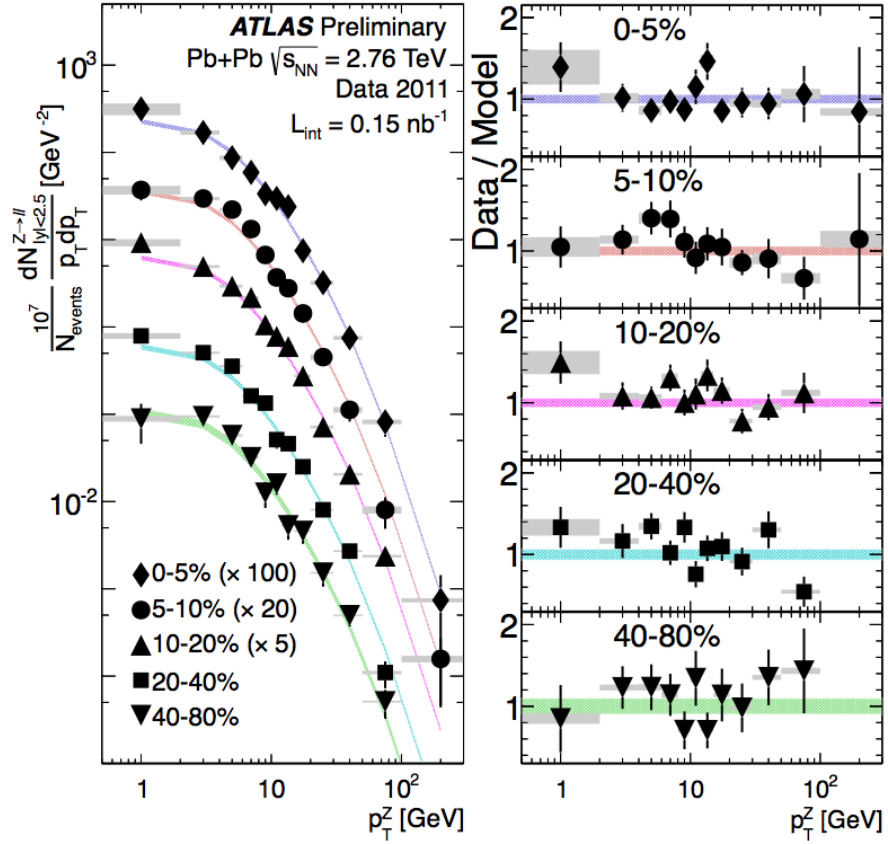


CMS, arXiv:1202.2554v1

- Rise of R_{AA} with p_T for the first time established at the LHC
- Large p_T reach helps unveil dependence of parton energy loss on initial parton energy

Z Bosons as Penetrating Probes of the Hot, Dense Medium



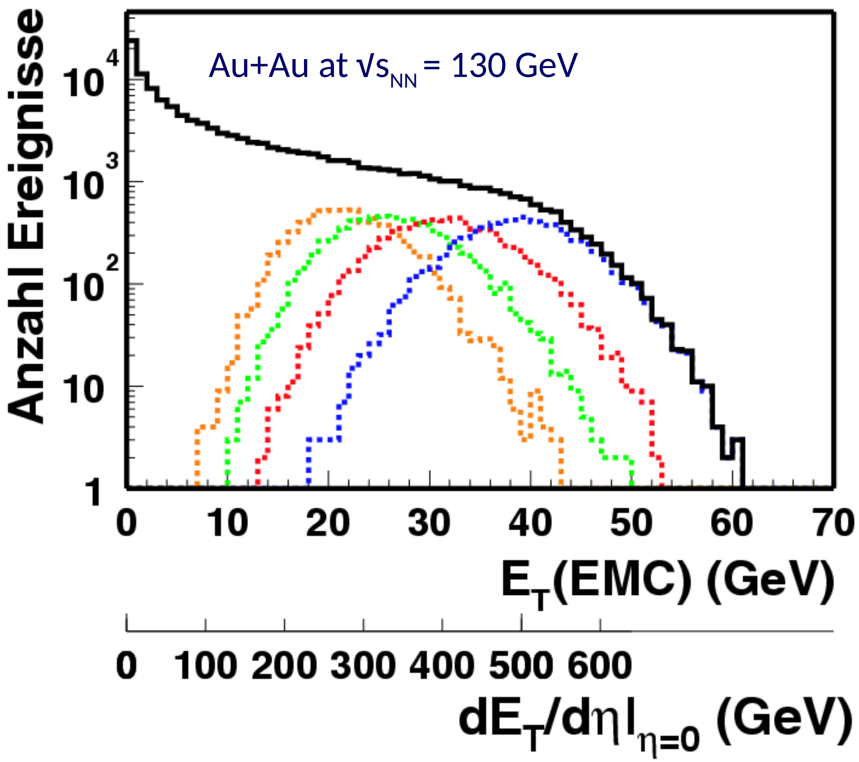


Good agreement with Pythia shape normalized to σ_{NNLO} & scaled by N_{coll}

Z bosons in Pb+Pb follow T_{AB} scaling

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:

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

Consider jet cone with radius *R*:

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

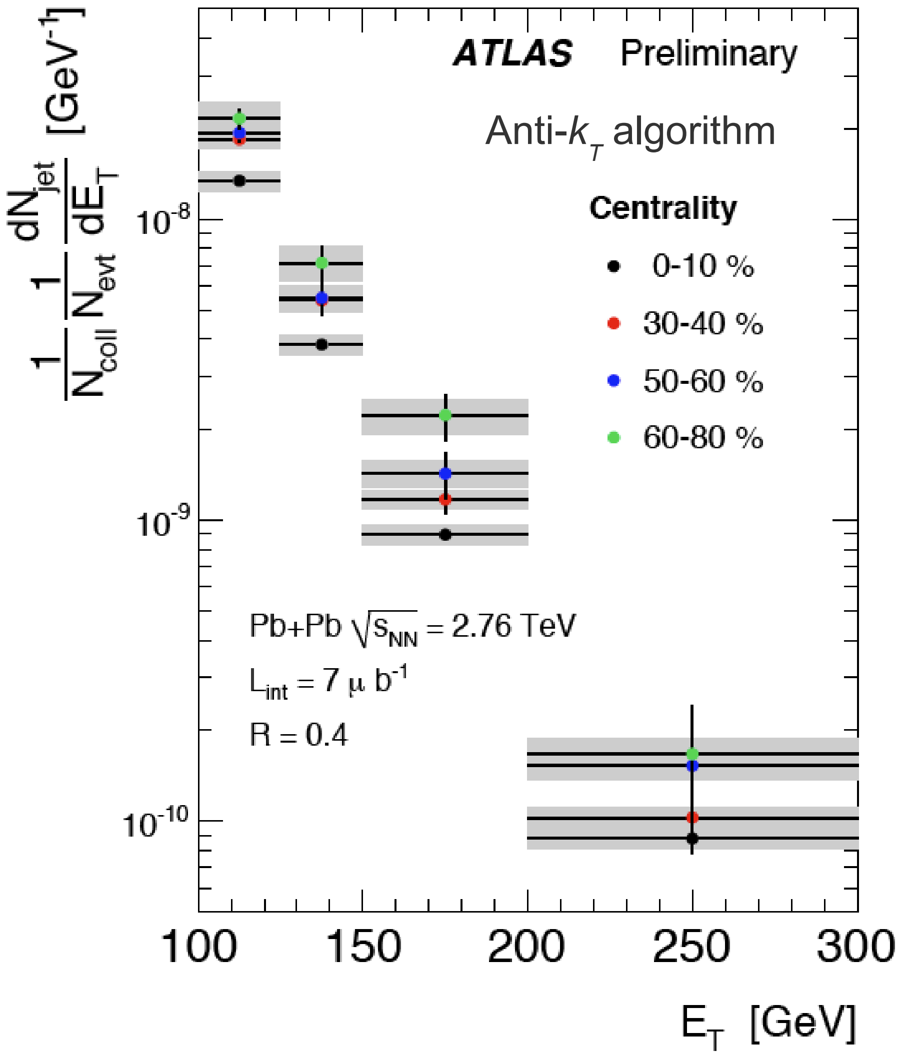
Total transverse energy in this cone:

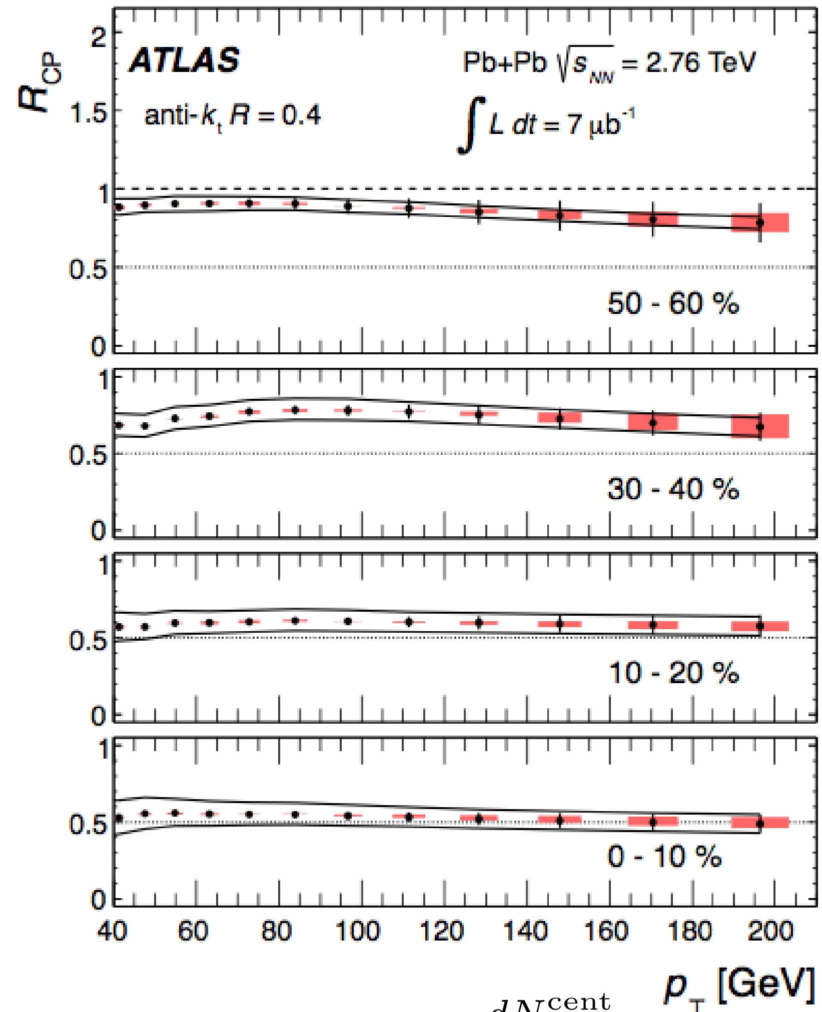
$$E_T^{\mathrm{cone}} = \frac{d^2 E_T}{d\eta d\phi} \cdot \pi R^2 = \frac{1}{2\pi}\frac{dE_T}{d\eta} \cdot \pi R^2 \approx 40\,\mathrm{GeV}$$

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

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

PLB 719, 220 (2013)





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

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