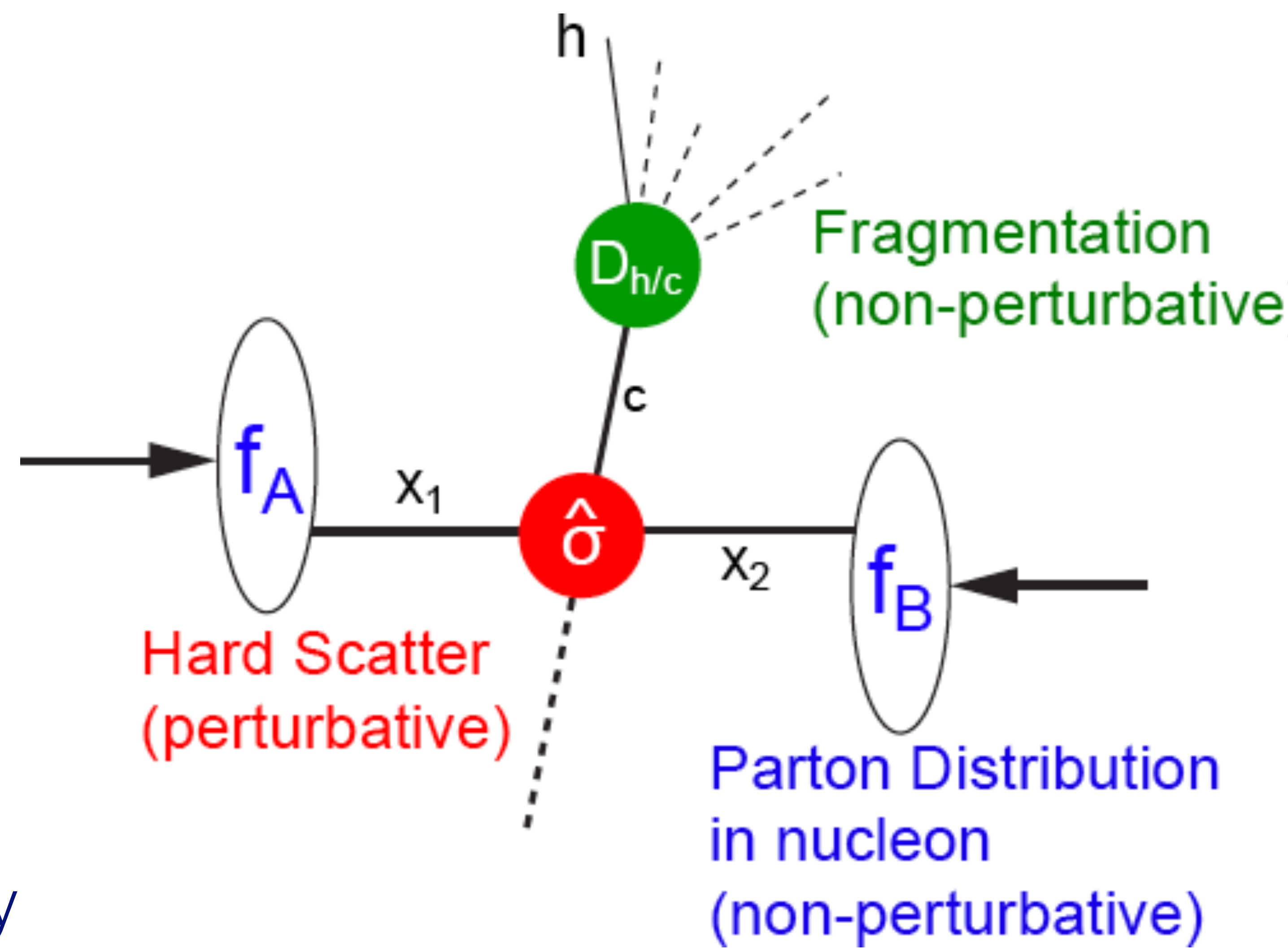
Quark-Gluon Plasma Physics

8. Hard Scattering, Jets and Jet Quenching

Prof. Dr. Braun-Munzinger
Prof. Dr. Klaus Reygers
Prof. Dr. Johanna Stachel
Heidelberg University
SS 2023

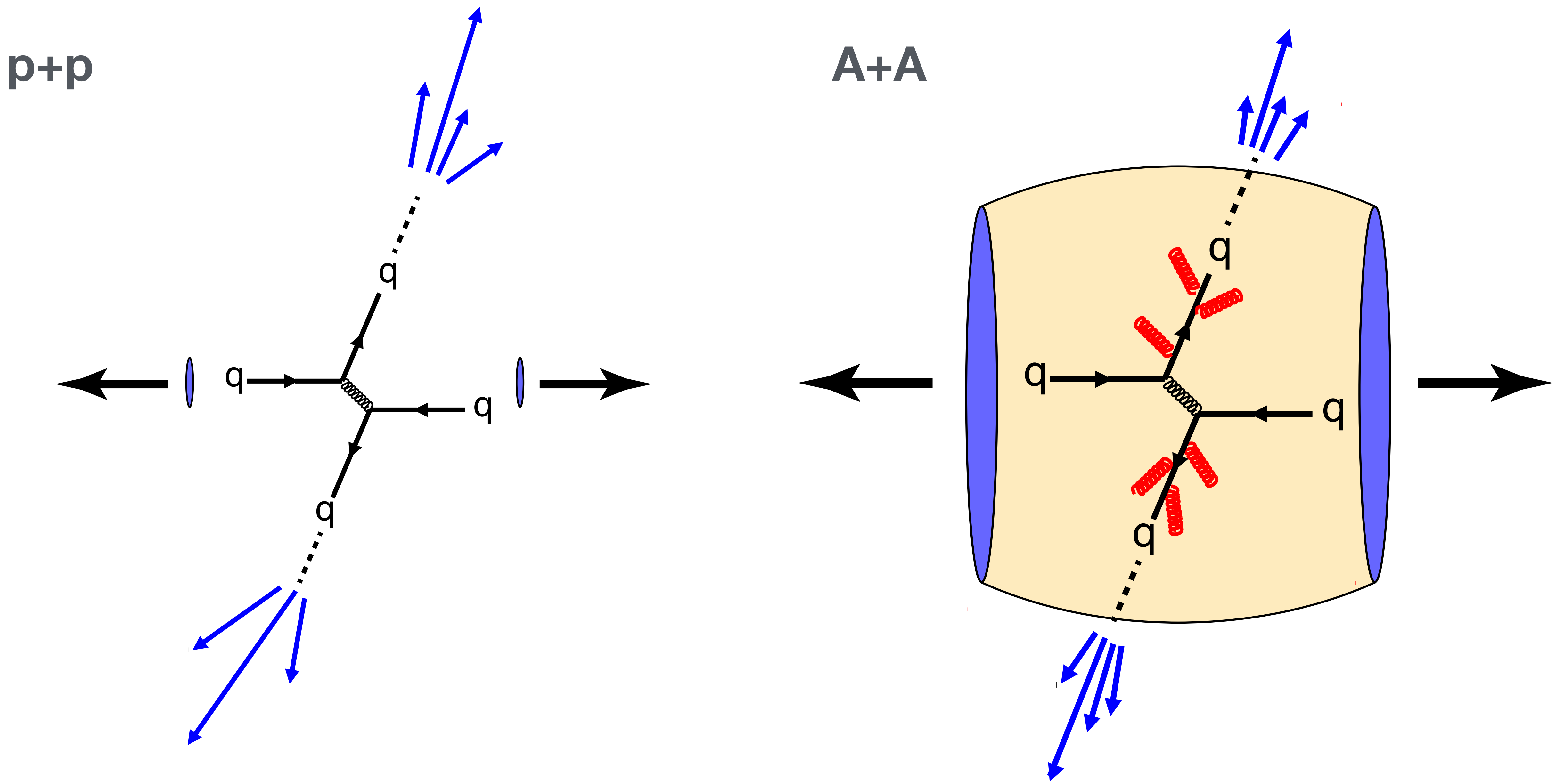
Theoretical description of High-p_T particle production: Perturbative QCD

- 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
- Particle production dominated by hard scattering for $p_T \gtrsim 3$ GeV/c
  - However, 99% or so of all particle from soft processes



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

Jet quenching in heavy-ion collisions



A-A collision: shower evolution in the medium, energy loss of the leading parton

Jet quenching history

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

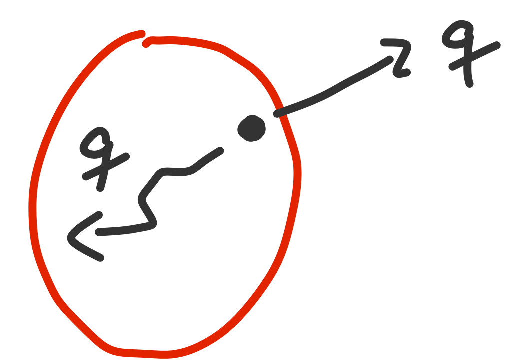
FERMILAB-Pub-82/59-THY
August, 1982

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

Abstract

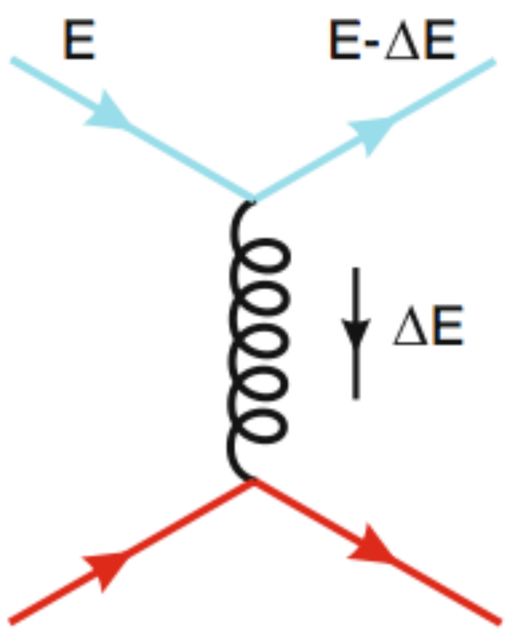
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square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

It is now believed that radiative energy loss (gluon bremsstrahlung) is more important than elastic scattering



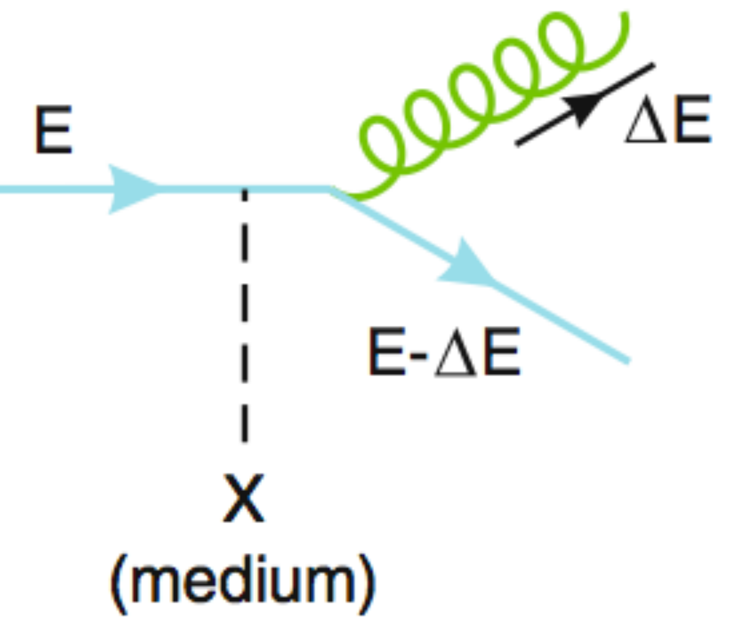
Collisional vs. radiative parton energy loss

Collisional energy loss:



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

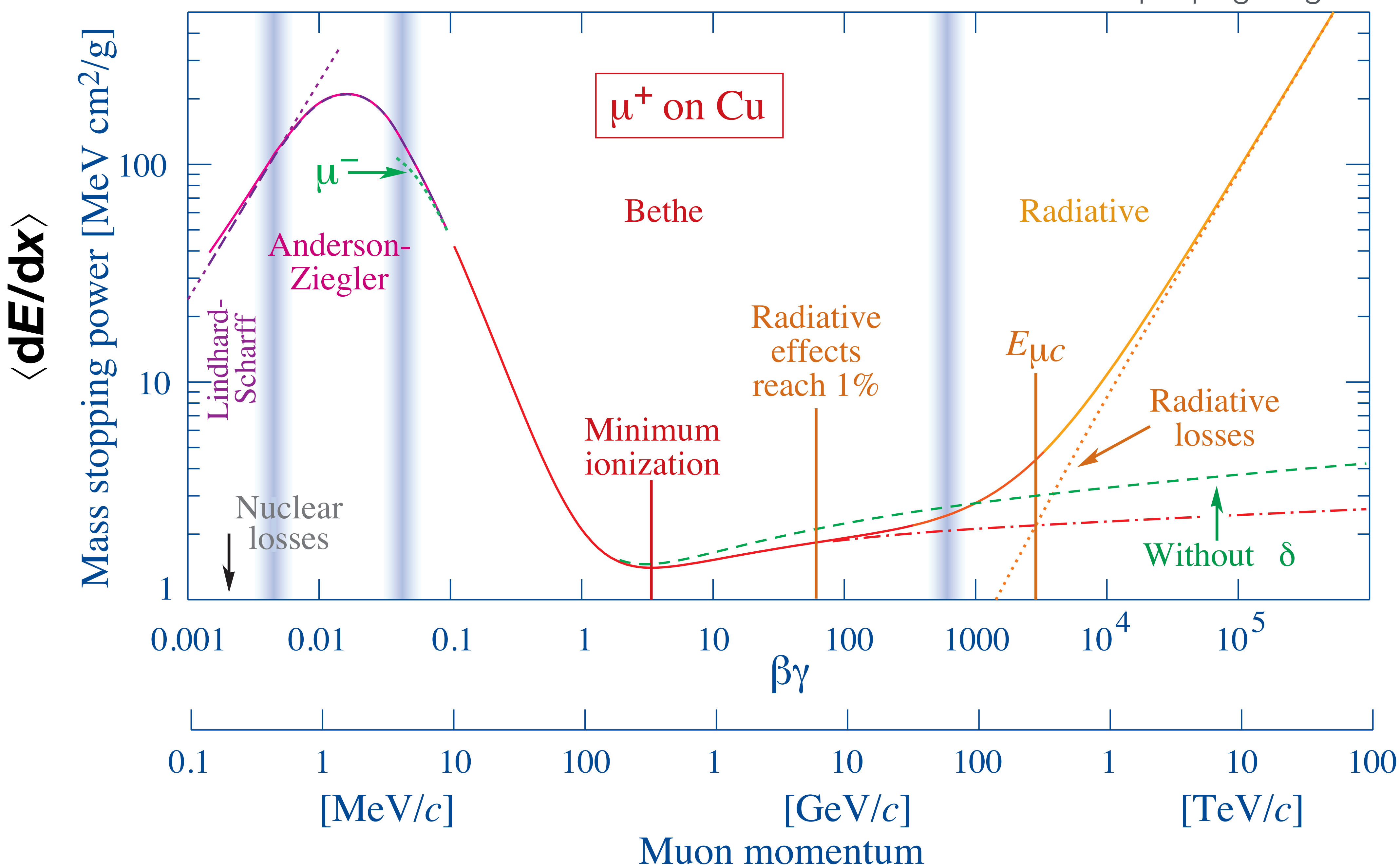
Radiative energy loss:



- Inelastic scatterings within the medium
- Dominates at higher momenta

Analogy:
Energy loss of charged particles in ordinary matter

http://pdg.lbl.gov



μ⁺ on Cu: Radiational energy loss ("bremsstrahlung") starts to dominate over collisional energy loss ("Bethe-Bloch") for $p \gg 100$ GeV/c

Basics of radiative parton energy loss (1)

- Energy loss E in a static medium of length L for a parton energy $E \rightarrow \infty$:

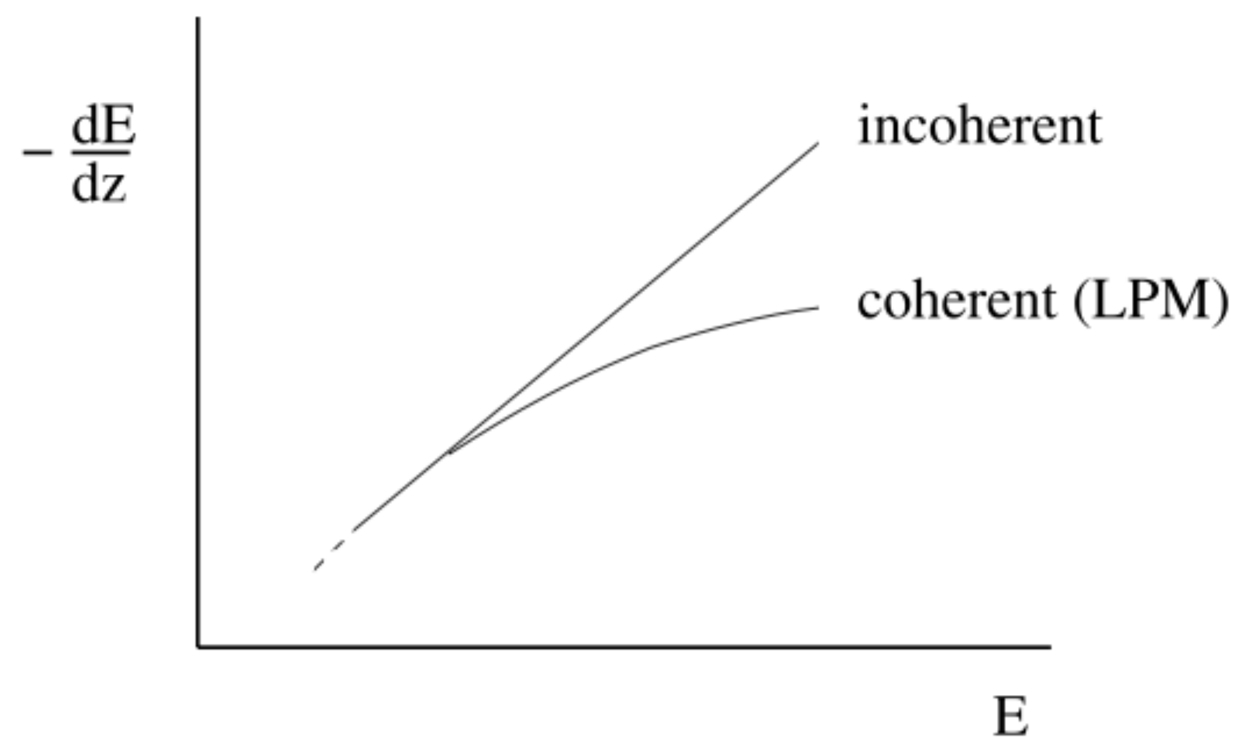
$$\Delta E \propto \alpha_s C_F \hat{q} L^2 \qquad \hat{q} = \frac{\mu^2}{\lambda} \qquad C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

μ^2 : typical momentum transfer from medium to parton per collision

λ : mean free path length in the medium

BDMPS result, Nucl. Phys. B 483, 291, 1997

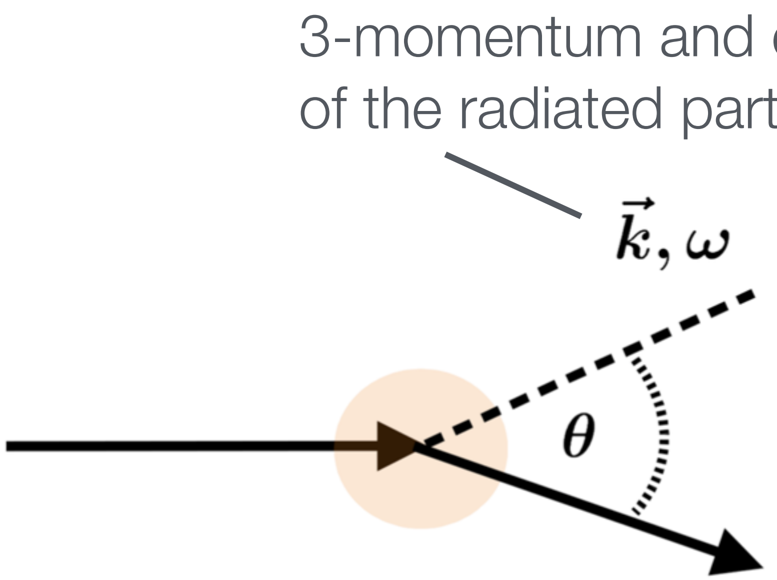
- Landau-Pomeranchuk-Migdal (LPM) effect
  - Parton scatters coherently off many medium constituents: destructive interference
  - Reduces radiative energy loss



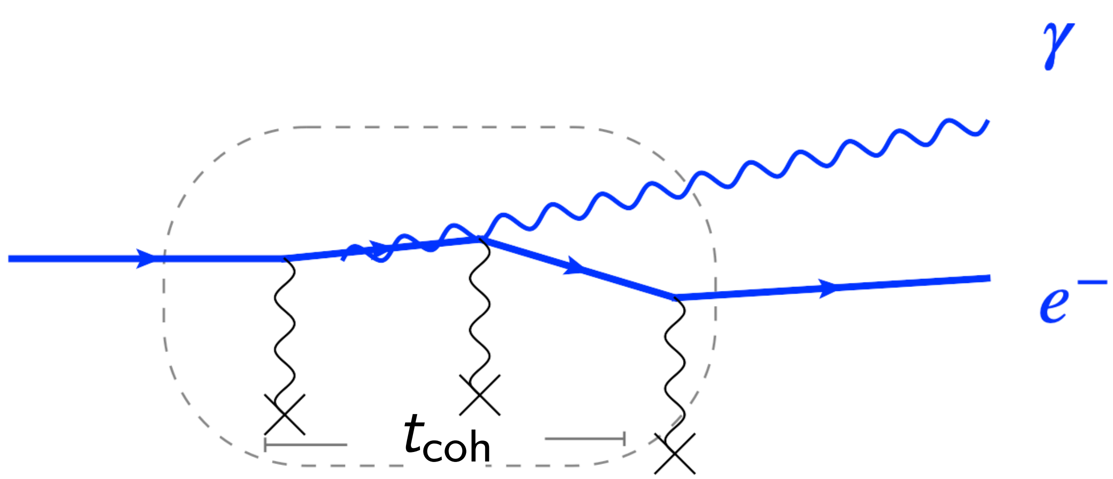
Basics of radiative parton energy loss (2)

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

$$z_{\mathrm{coh}} = t_{\mathrm{coh}} \simeq \frac{\omega}{k_T^2} \simeq \frac{1}{\omega \theta^2}$$



Landau-Pomeranchuk-Migdal effect in QED



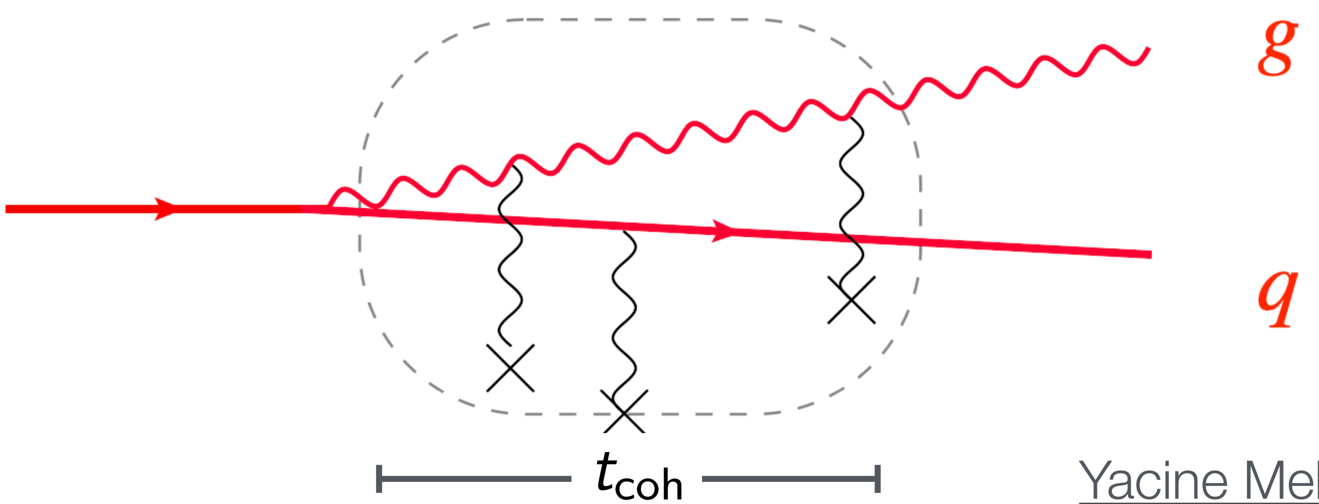
Yacine Mehtar-Tani

During the quantum mechanical formation time N_{coh} scattering centers act coherently reducing the radiation spectrum:

$$\omega \frac{dI_{\mathrm{LPM}}}{d\omega} \sim \alpha_{\mathrm{em}} N_{\mathrm{eff}} \sim \alpha_{\mathrm{em}} \frac{N_{\mathrm{scatt}}}{N_{\mathrm{coh}}} \sim \alpha_{\mathrm{em}} \frac{L}{t_{\mathrm{coh}}(\omega)}$$

Basics of radiative parton energy loss (3)

Same effect in QCD except the gluon interacts with the plasma:



Yacine Mehtar-Tani

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

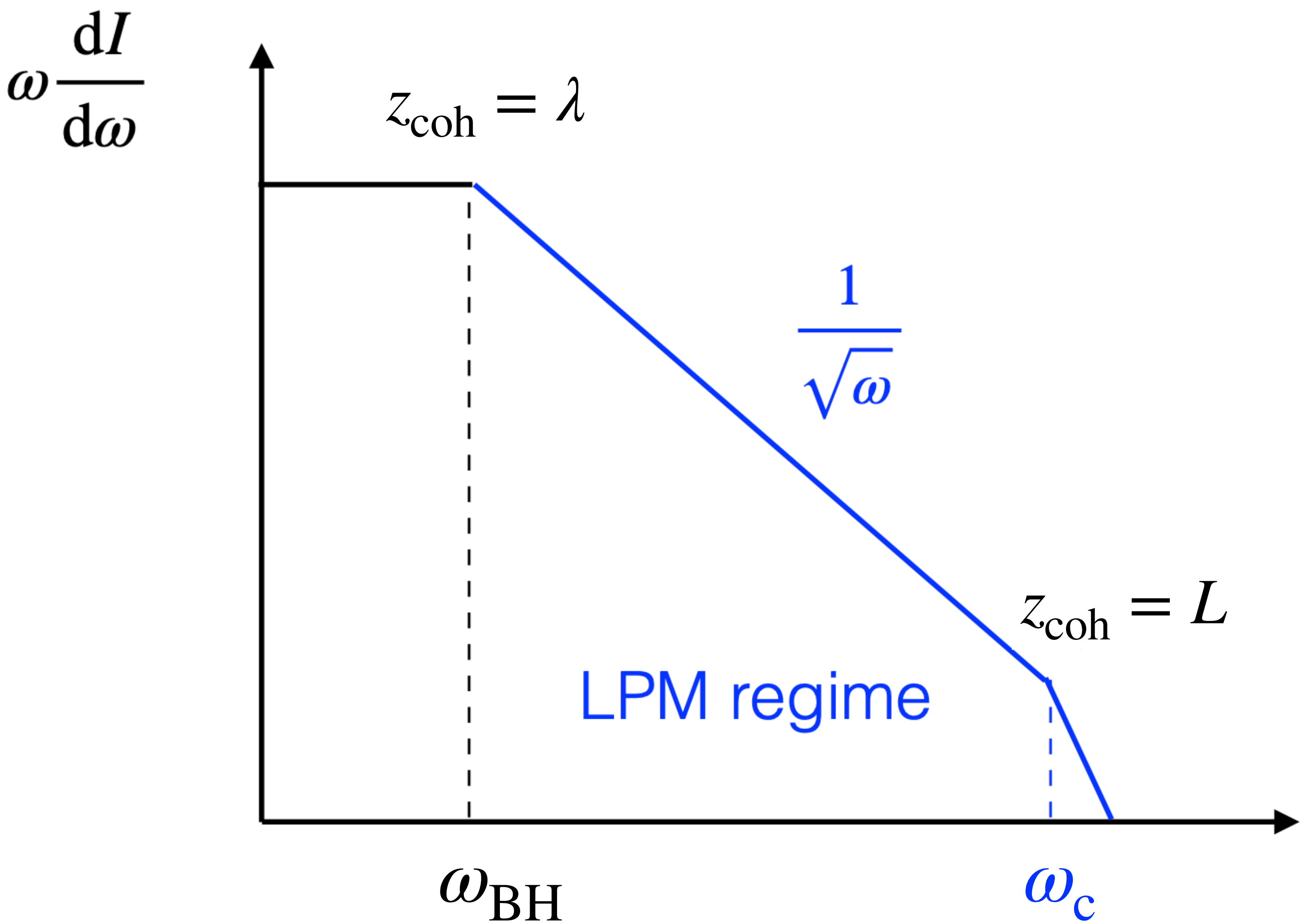
$$k_T^2 \simeq \hat{q} z_{coh} = \frac{\mu^2}{\lambda} z_{coh}$$

This results in a medium-modified formation length:

$$z_{coh} \simeq \frac{\omega}{k_T^2} \simeq \frac{\omega}{\hat{q} z_{coh}} \rightsquigarrow z_{coh} \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

Basics of radiative parton energy loss (4)

$$\omega \frac{dI_{LPM}}{d\omega} \sim \alpha_s \frac{L}{t_{coh}(\omega)} \sim \frac{L}{\sqrt{\omega/\hat{q}}} \propto \frac{1}{\sqrt{\omega}}$$



Maximum radiation frequency:

$$z_{coh} = \sqrt{\frac{\omega_c}{\hat{q}}} = L \quad \rightsquigarrow \quad \omega_c = \hat{q} L^2$$

Maximum radiation frequency:

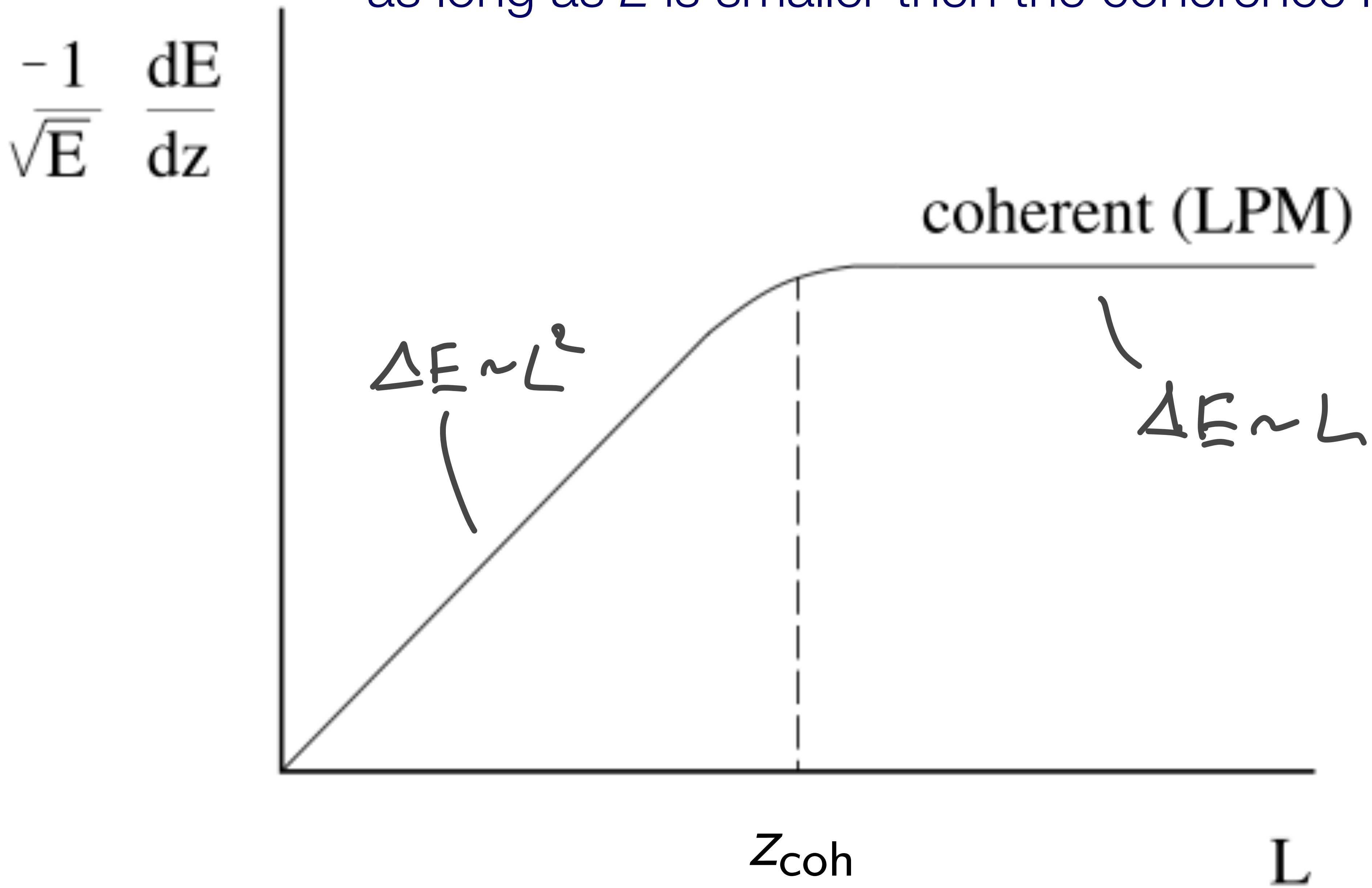
$$z_{coh} = \sqrt{\frac{\omega_{BH}}{\hat{q}}} = \lambda \quad \rightsquigarrow \quad \omega_{BH} = \hat{q} \lambda^2$$

$z_{coh} < \lambda$: incoherent multiple scattering (Bethe-Heitler regime)

$z_{coh} > \lambda$: coherent scattering with destructive interference (LPM regime)

Basics of radiative parton energy loss (5)

dE/dz increases linearly with medium thickness L as long as L is smaller then the coherence length z_{coh}

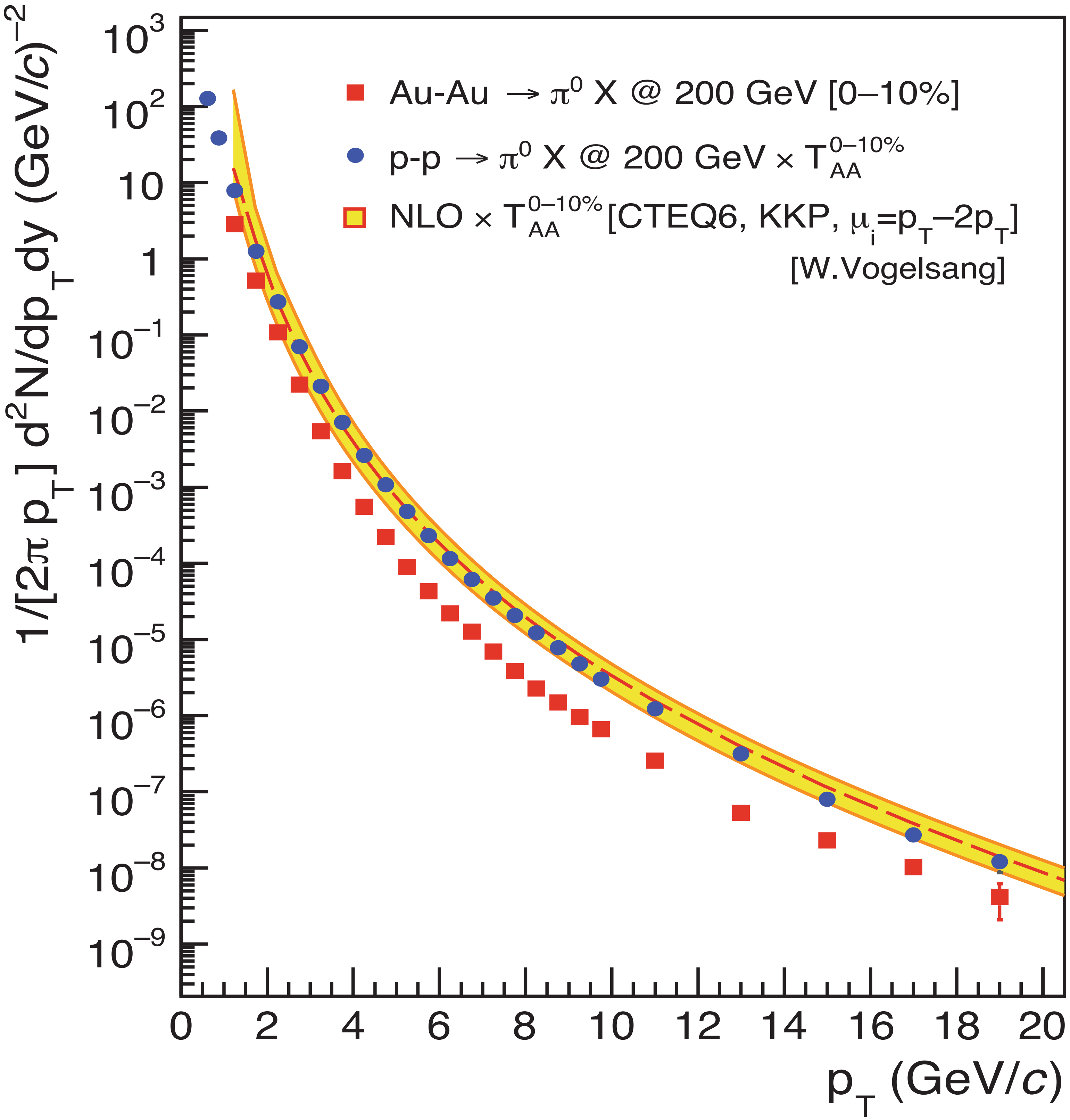


$$\Delta E_{\mathrm{rad}} \sim \int \mathrm{d}\omega\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \hat{q} L^2$$

coherence length

thickness of the medium

N_{coll}-scaled π^0 yields in pp compared to Au-Au



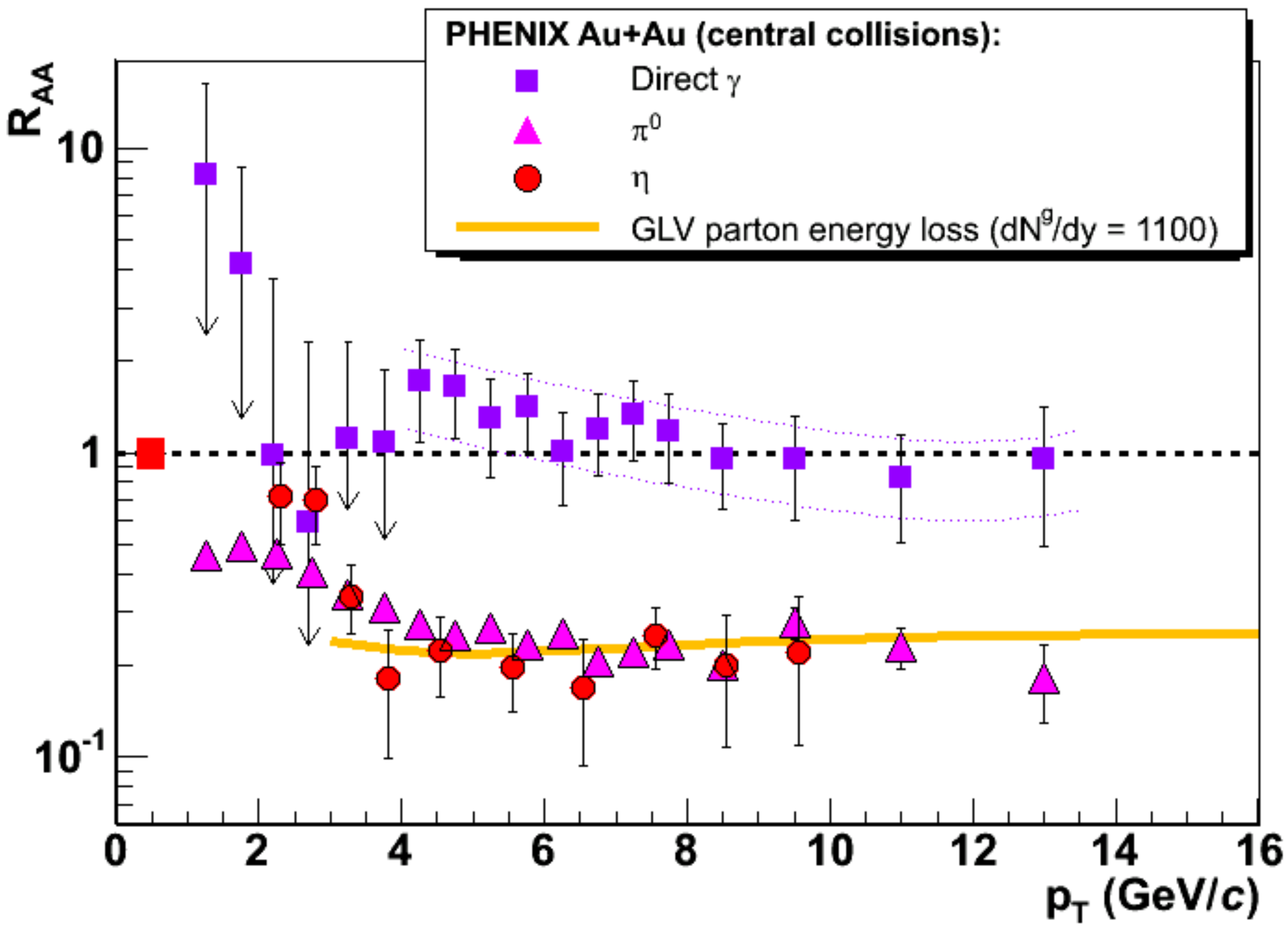
$T_{AA} = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$

"increase in parton luminosity" per collision when going from pp to AA"

Without a medium, hadron yields for $p_T \gtrsim$ 2-3 GeV are expected to scale with N_{coll}

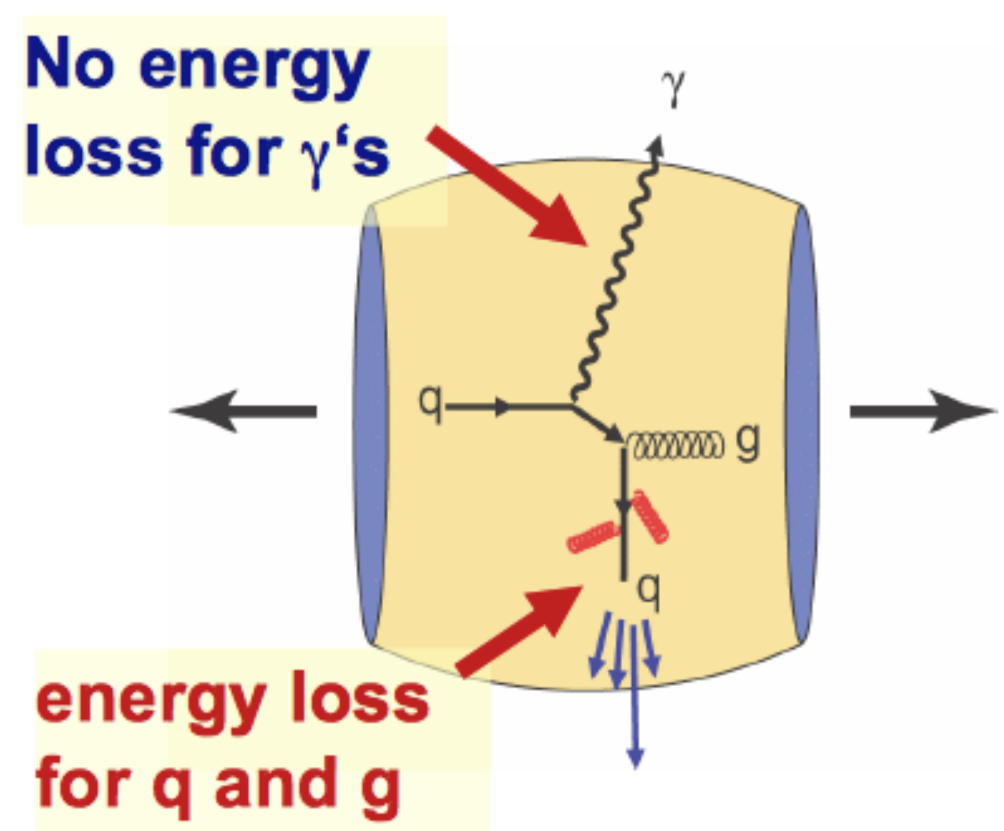
Observation:
Clear suppression w.r.t. N_{coll} scaling

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



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

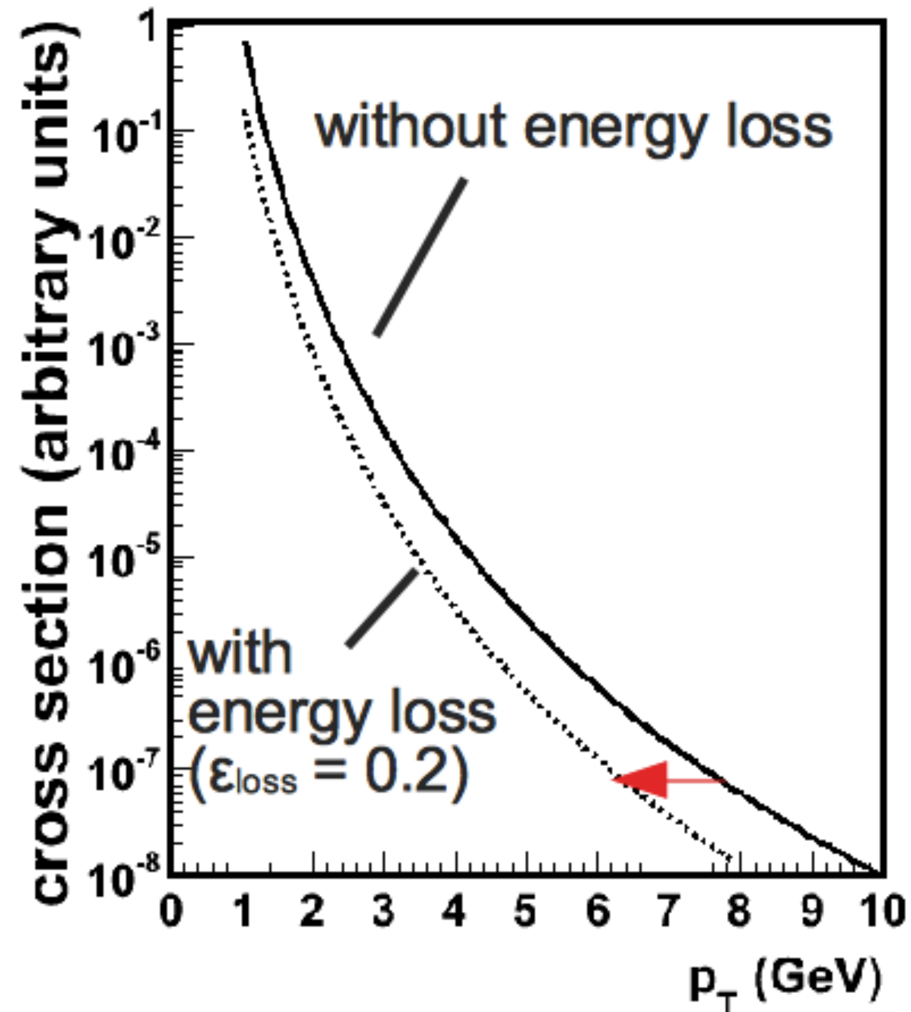
$$\text{where} \quad \langle T_{AB}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$



- Hadrons are suppressed, direct photons are not
- Evidence for parton energy loss

A simple explanation for the rather flat R_{AA} at RHIC: a constant fractional parton energy loss

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:

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

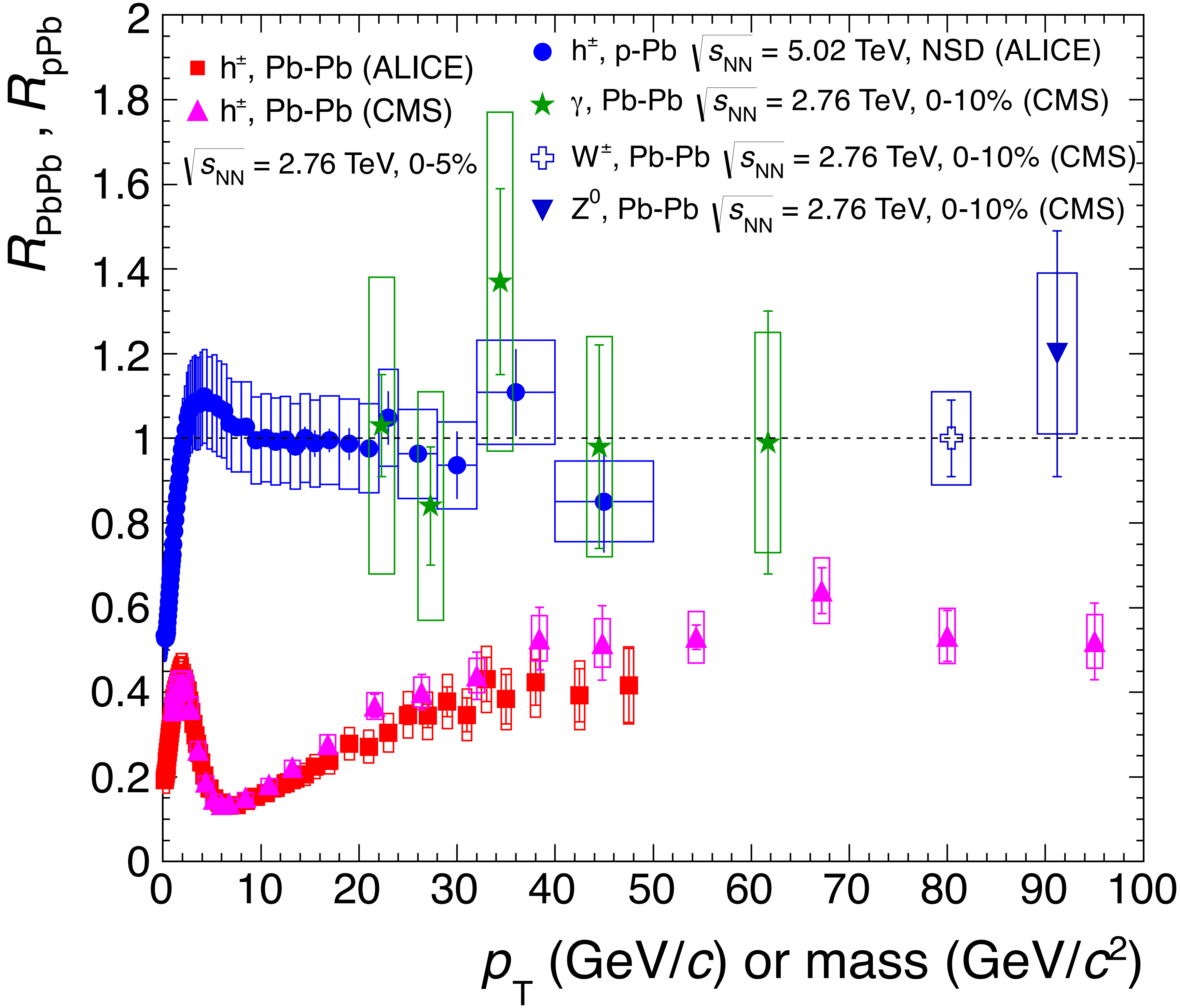
Resulting R_{AA}:

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

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

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

Single-particle R_{AA} in Pb-Pb at the LHC: Qualitatively similar observation as for RHIC energies



- No suppression for γ, W^{+-}, Z^0 in Pb-Pb
- No suppression of hadrons in p-Pb
- Strong suppression of hadrons in Pb-Pb

Medium properties from charged hadron $R_{AA}(p_T)$

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

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

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

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

- Result relies on standard hydro description of the medium evolution
- Conjectured relation to η/s:

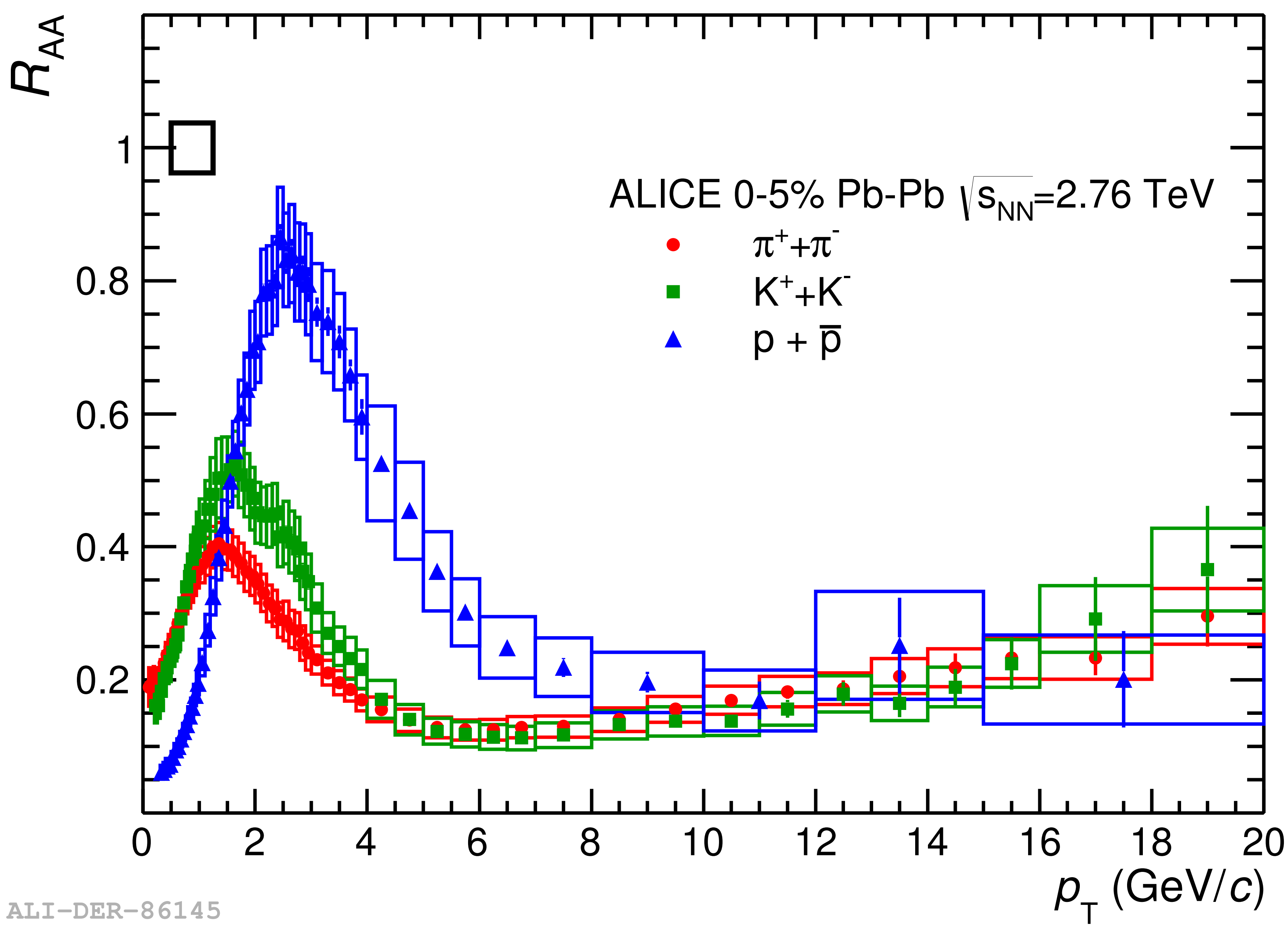
$$\frac{T^3}{\hat{q}} = K \frac{\eta}{s}$$

weakly-coupled QGP: $K \approx 1$
strongly-coupled QGP: $K \ll 1$

Majumder, Müller, Wang, PRL, 99 (2007) 192301

π, K, p R_{AA}: Suppression independent of hadron species for $p_T \gtrsim 8$ GeV/c

ALICE, arXiv:1506.07287

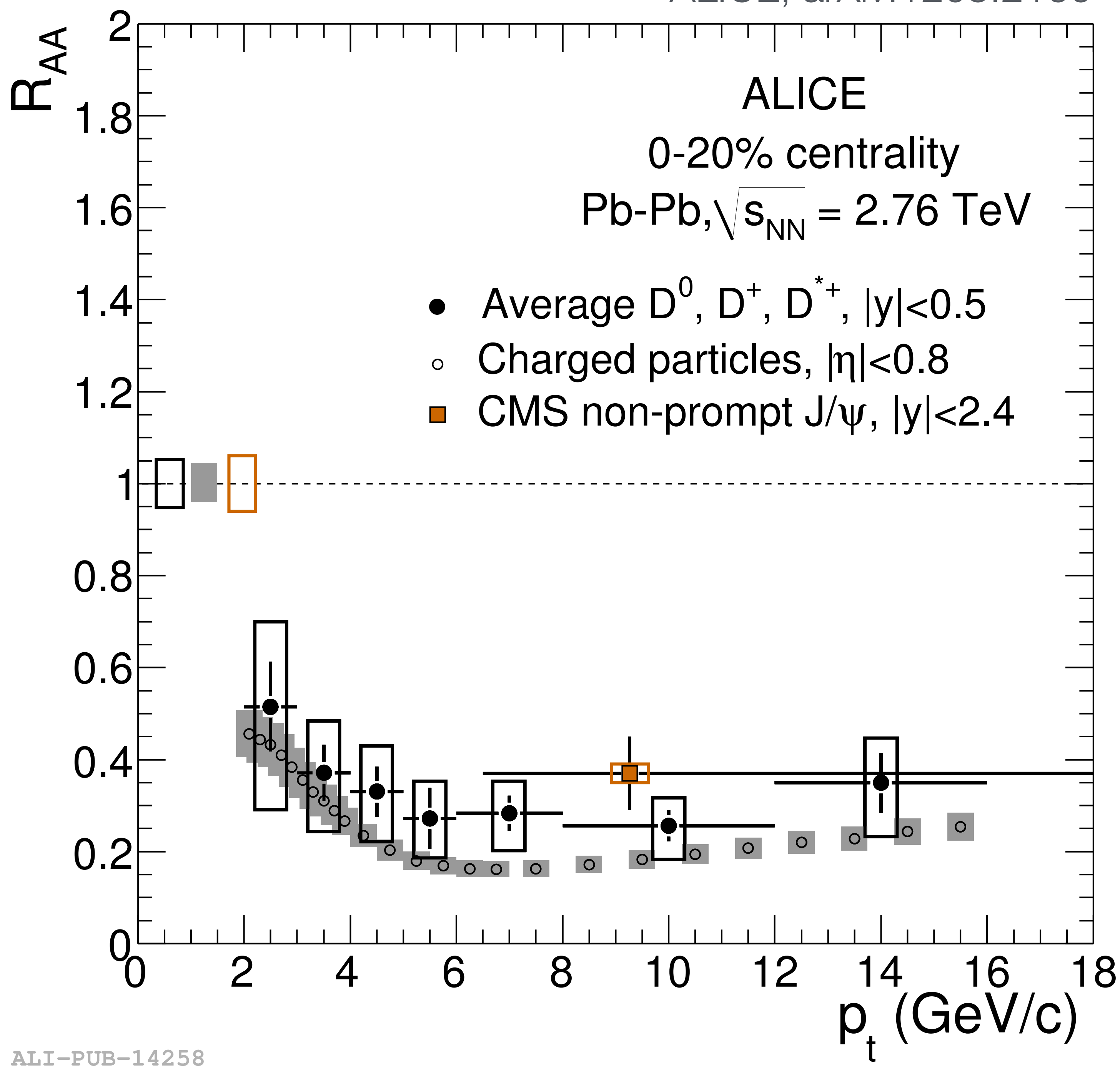


Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,\text{hadron}}$ > 8 GeV/c?

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

D meson R_{AA}: Charm quark energy loss similar to quark and gluon energy loss

ALICE, arXiv:1203.2160



ALI-PUB-14258

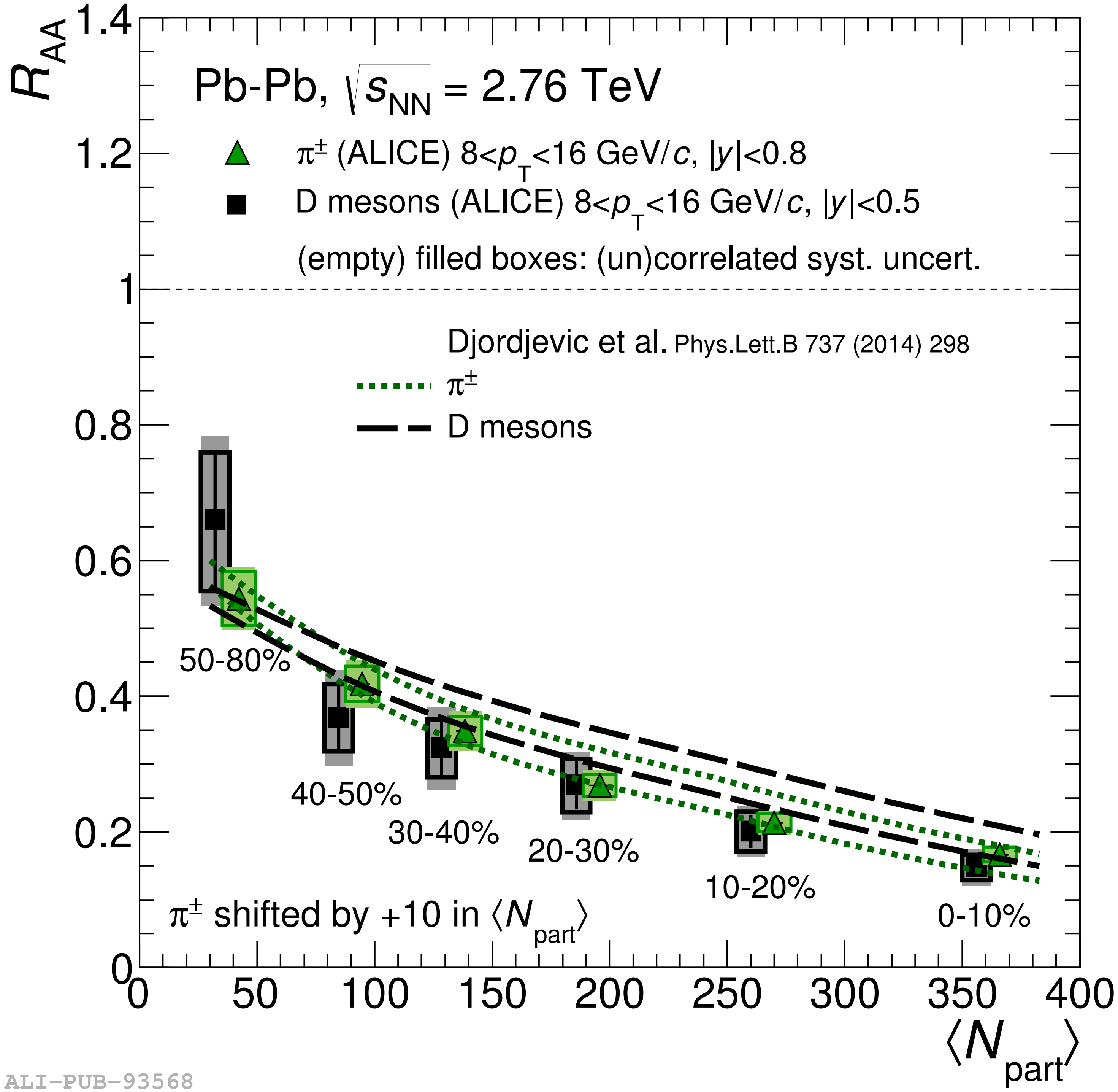
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

color factor **dead cone effect**
(gluon emission suppressed at forward angles for slow quarks)

- 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
- Still hint for expected hierarchy?
  - However, need to carefully consider also the steepness of the initial parton spectra

Centrality dependence of R_{AA} for pions and D mesons

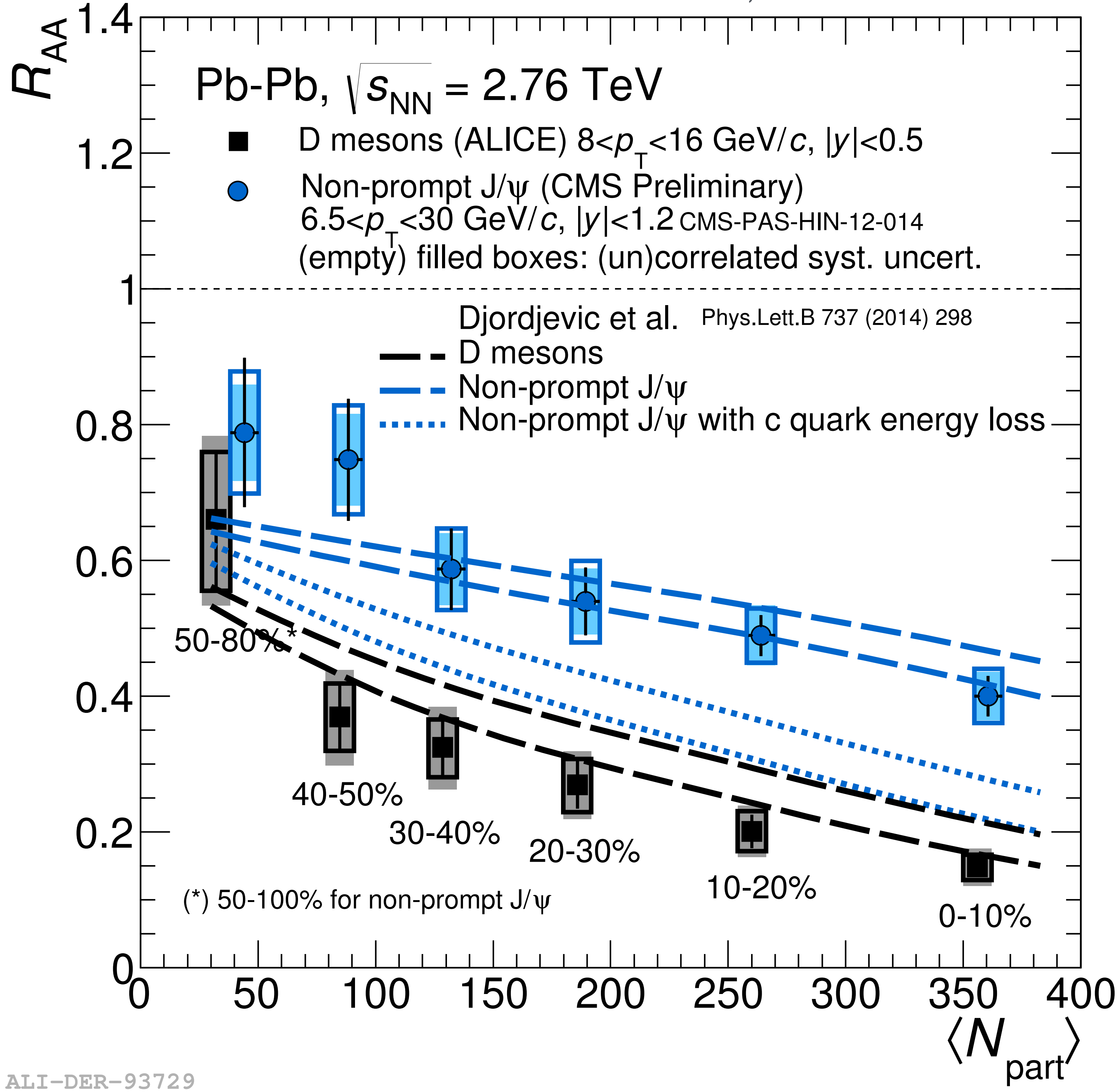
ALICE, arXiv:1506.06604



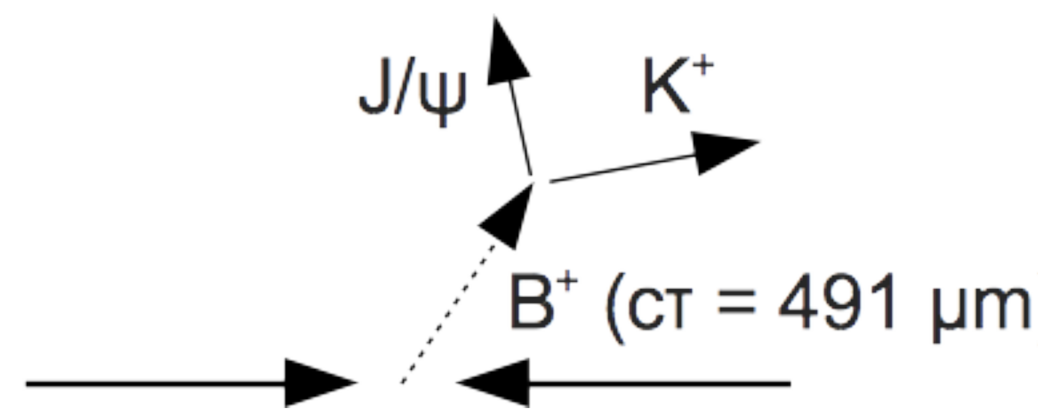
- N_{part} dependence similar for pions and D mesons
- Actually expected in parton energy loss calculation

Evidence for smaller energy loss for b quarks than for c quarks

ALICE, arXiv:1506.06604

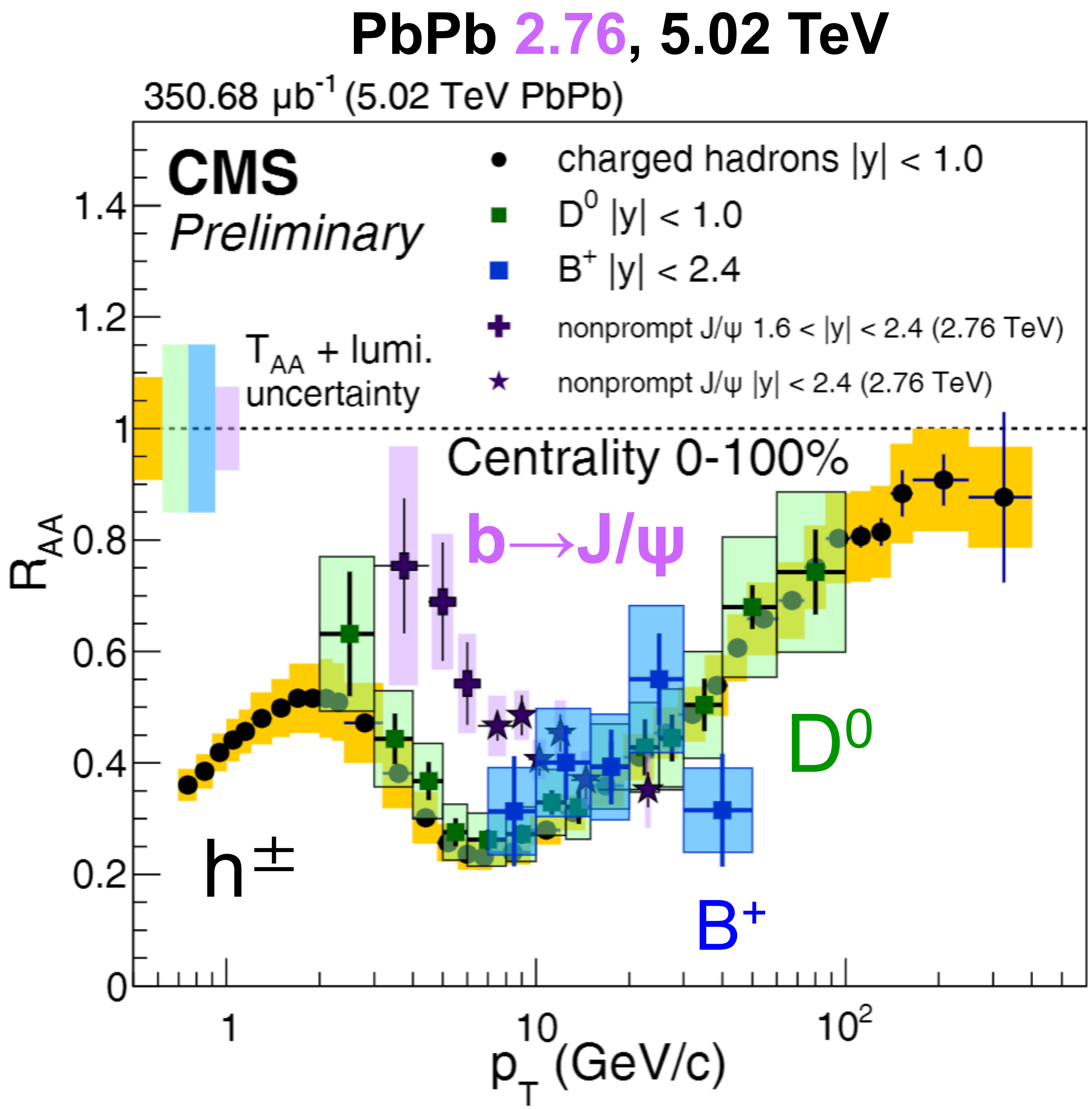


b quark energy loss via non-prompt J/ψ:



Evidence for the expected energy loss hierarchy between c and b quarks

B-Meson $R_{AA}(p_T)$

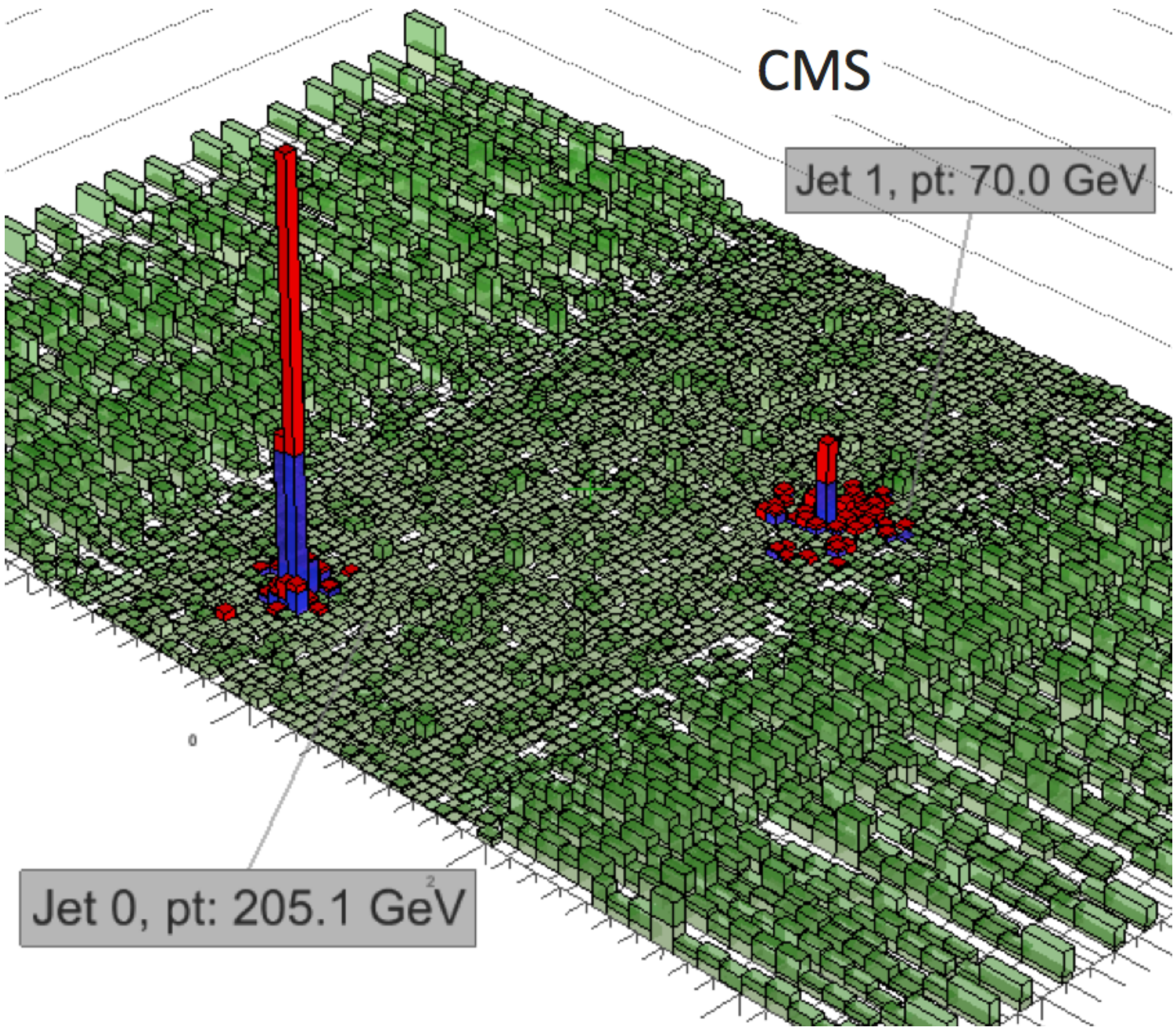


No quark flavor dependence of $R_{AA}(p_T)$ for $p_T \gtrsim 10$ GeV/c

Indication for quark flavor dependence at lower p_T from $B \rightarrow J/\psi + X$

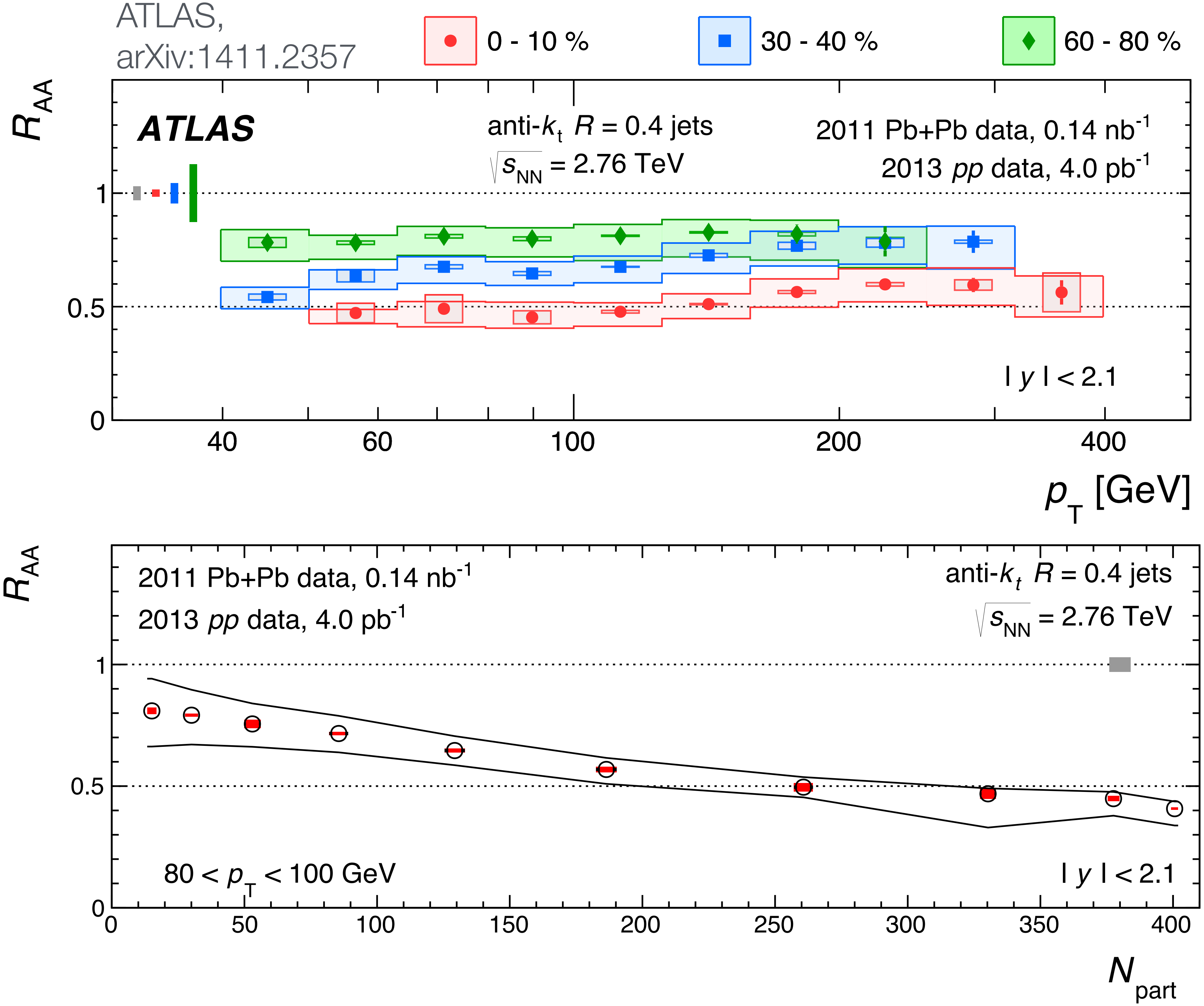
CMS, 1705.04727
also arXiv:1810.11102

Studying jet quenching with jets: Large dijet energy asymmetries in Pb-Pb



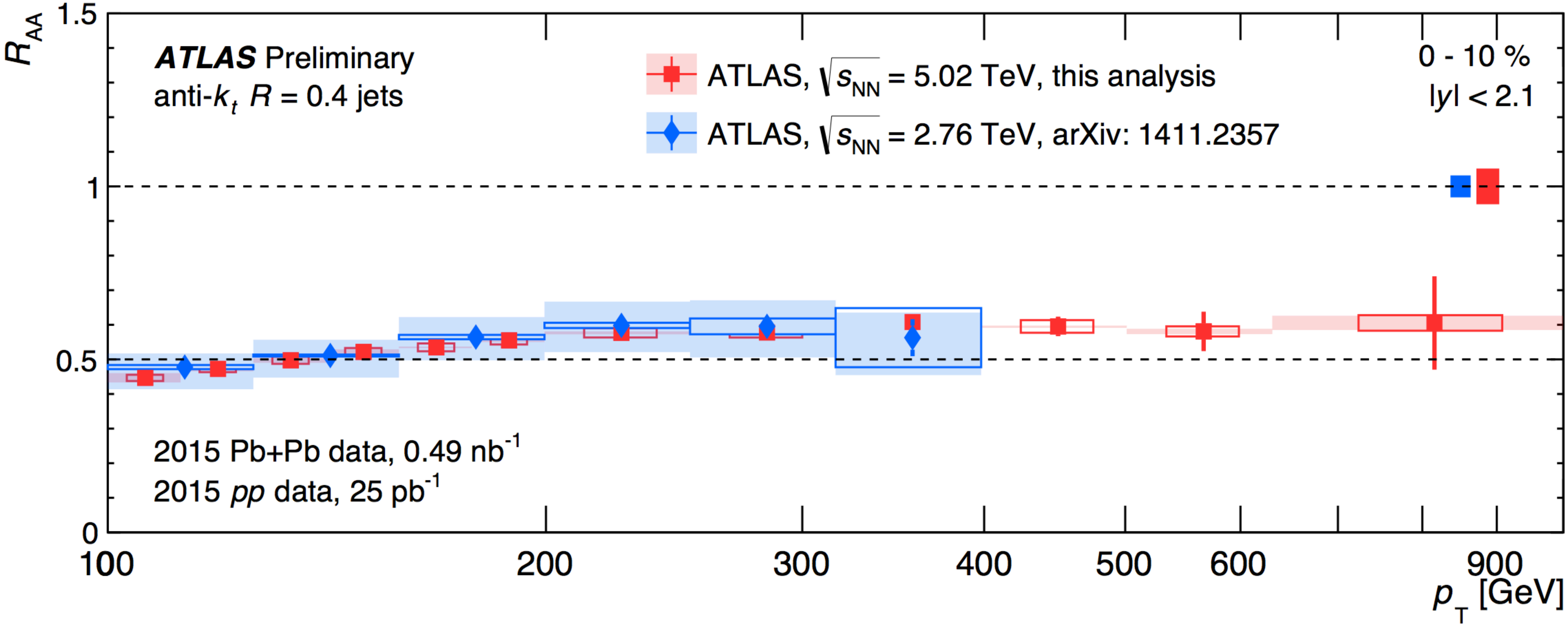
Jet suppression in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV: $R_{AA} \approx 0.5$ in central collisions

ATLAS, arXiv:1411.2357



Interestingly, there is not much of a p_T dependence of the jet suppression

Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV: Jet R_{AA} up to p_T = 1 TeV



ATLAS-CONF-2017-009, http://cds.cern.ch/record/2244820

Summary/questions jet quenching

- Collisional and radiative parton energy loss
  - Radiative energy loss expected to be dominant for light quarks
- Evidence for expected quark mass dependence of the energy loss
- QCD inspired models are capable of reproducing many features seen in the data
  - Medium properties can be constrained
- What's next?
  - First generation of models focussed on leading-particle energy loss ("medium-modified fragmentation function")
  - Need to describe full parton shower evolution in the medium
  - Can one eventually describe parton energy loss based on first principles?
  - Can one connect heavy-quark energy loss to string theory via the gauge/gravity duality?