Hard Probes

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Outlook:

1) Hard probes: definitions

2) High p_T hadrons

3) Heavy Flavours

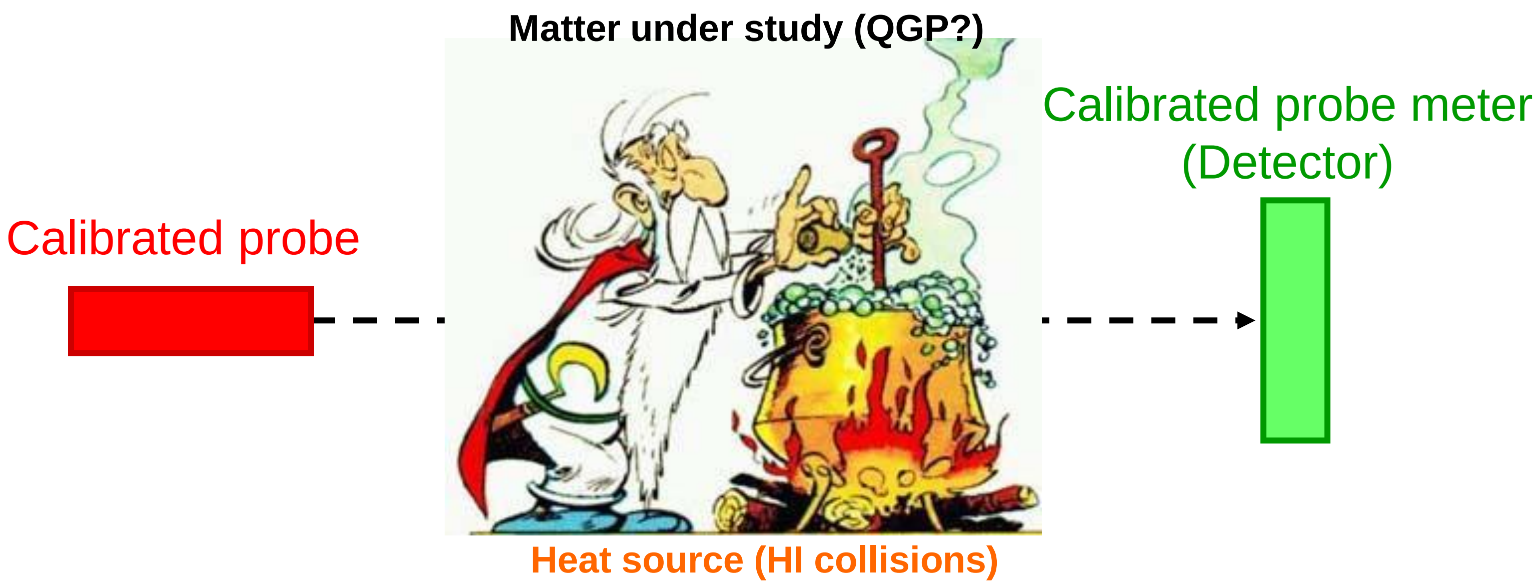
4) Quarkonia

Hot matter created in HI collisions

How can we observe the properties of the created matter?

- Due to the transient nature of the matter created in high energy collisions, external probes cannot be used to study its properties
- However, energetic particles, produced early in the collision, interact with the medium itself, behaving as penetrating probe

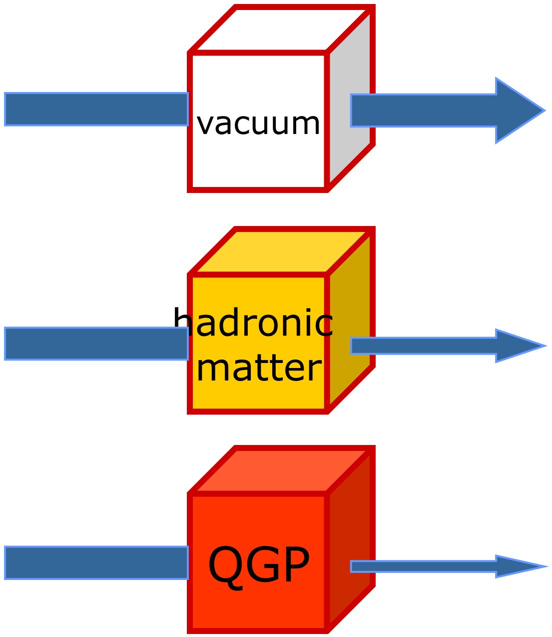
we study how the matter produced in the collisions affects these probes changing the temperature of the system (centrality of the collisions)



Find a good probe…

Which probe should we use to test the QCD matter?

- The probe must be produced early in the collision evolution, so that it is there before the matter to be probed



Well understood in pp collisions

Slightly affected by the hadronic matter and in a well understood way

Strongly affected by the deconfined medium

- The probe must be well calibrated, i.e. its behaviour in "standard" matter should be under control

...and calibrate it

- **How can we calibrate the probe?**

  - Using another probe not affected by the dense QCD matter, to define a baseline reference

    → photons, Drell-Yan dimuons

  - Using "trivial" collision systems, to understand how the probe behaves in absence of "new physics"

    → pp, pA, light ions collisions
    → comparison of peripheral vs. central collisions

Hard Probes

What are the hard probes?

Highly energetic or penetrating

Device to explore something that cannot be viewed directly

Hard probes are highly penetrating observables (particles, radiation) used to explore properties of matter that cannot be viewed directly

Lectures from E. Bruna

- High p_T hadrons, jets
- Open heavy flavors (charm and beauty)
- Quarkonia (J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S))

Hard probes originate from hard processes, characterized by large momentum transfer Q^2, where pQCD can be applied

Hadron production

- High p_T hadrons/open heavy flavours are produced in hard scattering, in the earliest collision time, by fragmentation of high p_T partons

- Hadron production cross section in pp can be calculated in pQCD

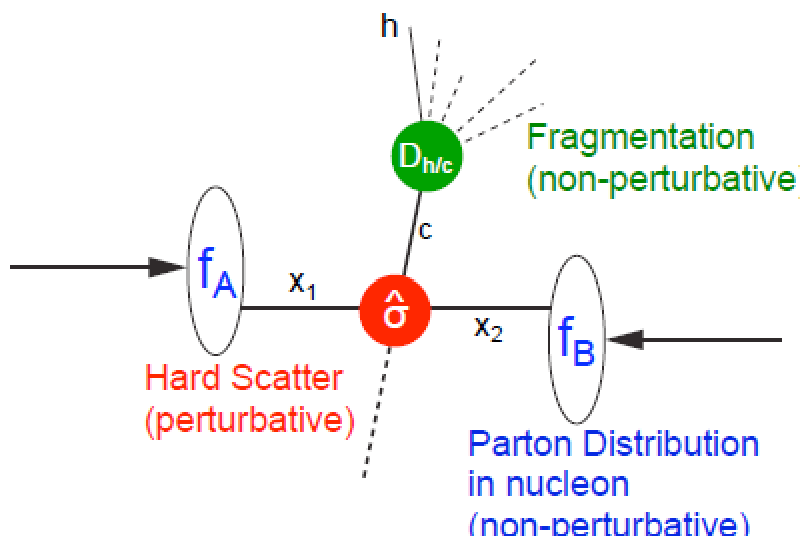
$$\sigma_{hh \to Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \to q\bar{q}} \otimes D_{q \to H}(z_q, Q^2)$$

Parton Distribution Functions
x_a, x_b → fraction of the momentum carried by the a,b partons in the hadron

Partonic σ computed in pQCD

Fragmentation of quark q into the hadron H

- Assumptions:
  - Factorization between the hard part and the non perturbative PDF and fragmentation function $D_{q \to H}(z_q, Q^2)$
  - Universal fragmentation and PDFs (e.g PDF from ep, fragmentation fz. from ee, but used in pp data)



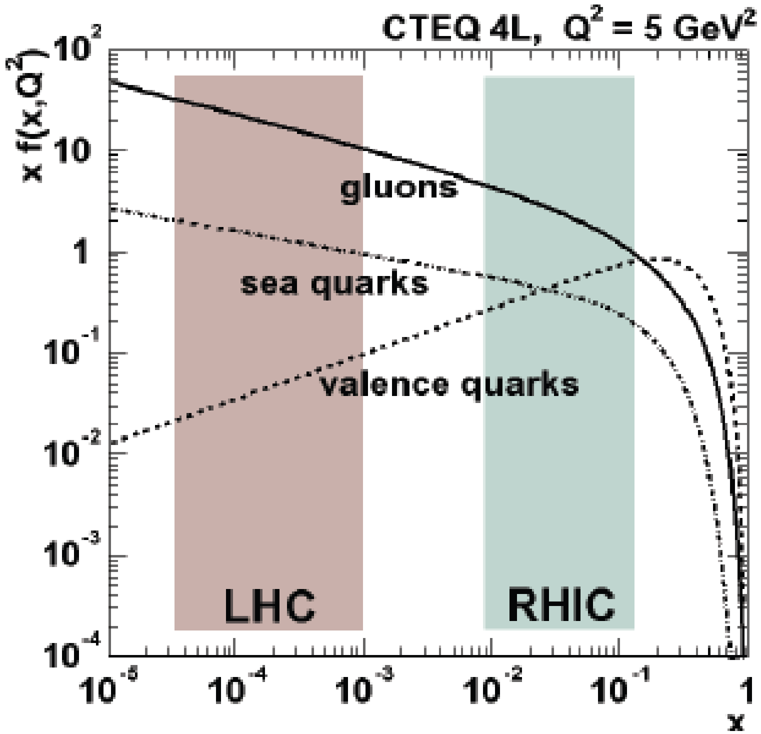
Parton Distribution Functions

- PDFs: probability of finding a parton with a fraction x of the proton momentum, in a hard scattering with momentum transfer Q^2

- PDF are obtained by means of a global fit to experimental data, for one or more physical processes which can be calculated using pQCD, such as deep inelastic scattering and the Drell-Yan process

- PDFs depends on the Q^2 value

- The Q^2 evolution can be calculated in pQCD, using the DGLAP equations



Fragmentation Functions

$D_{q \rightarrow H}(z,Q^2)$ represents the probability, at a given scale Q, that a quark q originates an hadron H, with a momentum p_H which is a fraction of the quark momentum ($p_H = zp_q$)

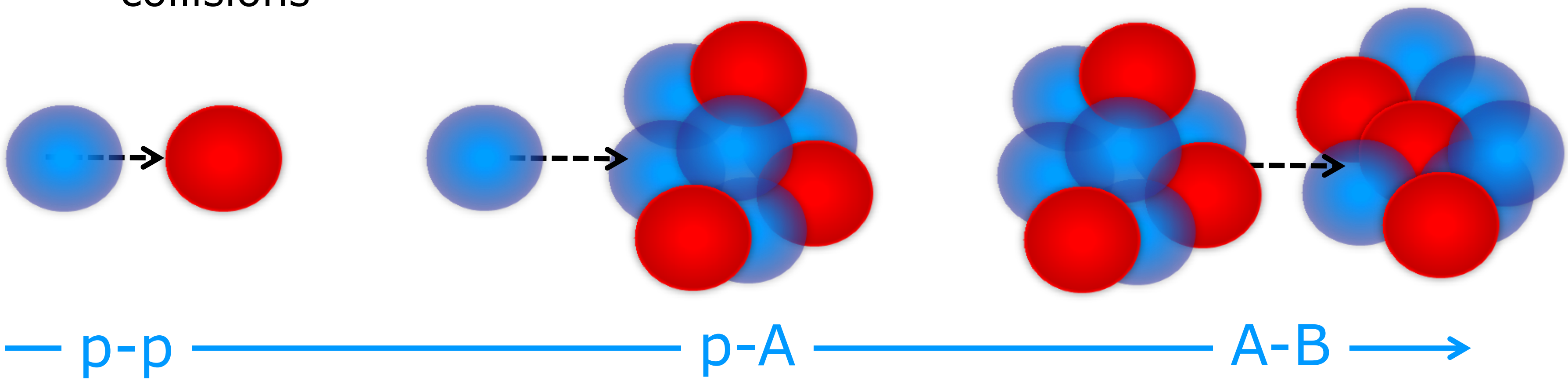
$$q, \bar{q}, g \xrightarrow{D_f^h(z,Q^2)} \pi, K, p, D, B, \gamma, \ldots$$

- Fragmentation functions are extracted from e^+e^- data. Like the PDF, they should be universal

- As for the PDF, these function depend on Q^2
  → they are measured at a given Q^2_0 and their evolution is studied using the DGLAP equations

From pp to pA and AA collisions

p-A, A-B collisions are considered as a sum of nucleon-nucleon collisions



At high energies, high p_T particles are produced by hard scattering → their production cross section in pA or AB collisions will be proportional to the number of possible hard scattering, i.e. to the number of nucleon-nucleon collisions

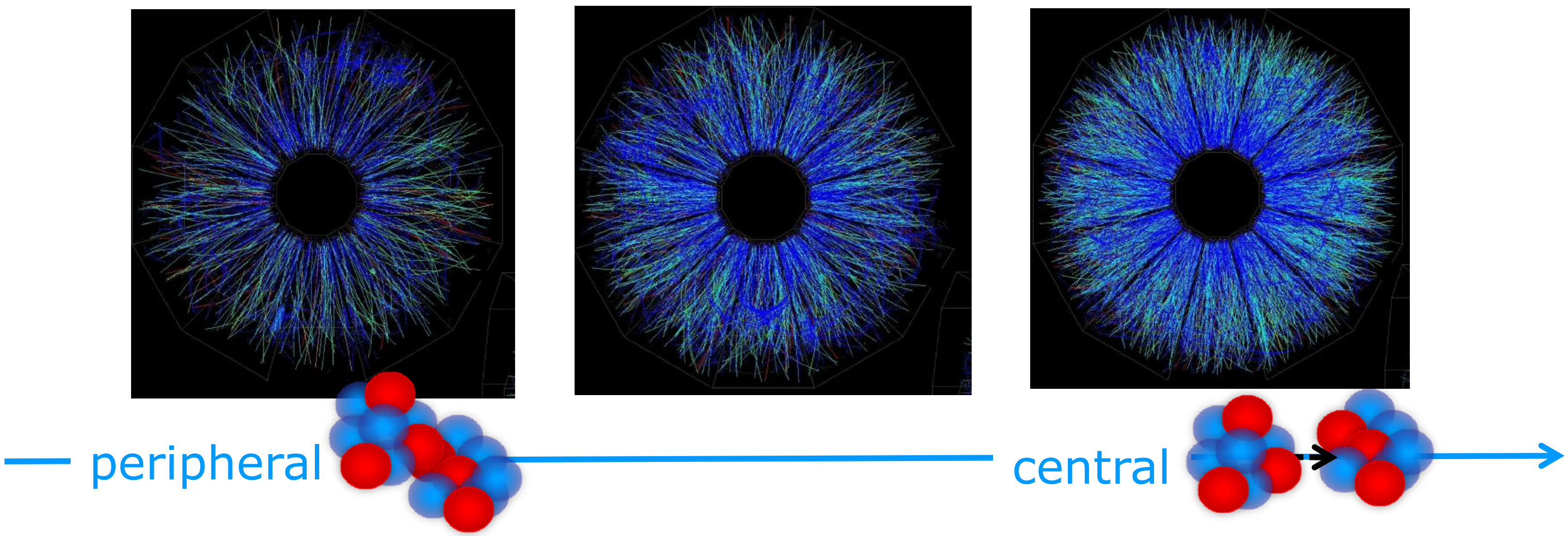
→ Binary scaling

$$\sigma_{pA} = \sigma_{pp} \times A$$

$$\sigma_{AB} = \sigma_{pp} \times AB$$

Centrality dependence

- However, often we need to study the behavior as a function of the centrality of the collision:



- Adopting the Glauber formalism:

$$d\sigma_{AB}{}^{hard} = d\sigma_{pp}{}^{hard} T_{AB}(b)\ d^2 b$$

$T_{AB}(b)$ is the nuclear thickness function

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

$$\int d^2 b\, T_{AB}(b) = AB$$

- For a given b, $T_{AB}(b)$ is related to the number of collisions

$$N_{coll}(b) = AB\sigma_{inel} T_{AB}(b)$$

The nuclear modification factor R_{AA}

How do we compare AB with pp data?

- The comparison is done in terms of the nuclear modification factor R_{AA}

$$R_{AB} = \frac{dN^P{}_{AB}}{\langle N_{Coll} \rangle \, dN^P{}_{NN}}$$

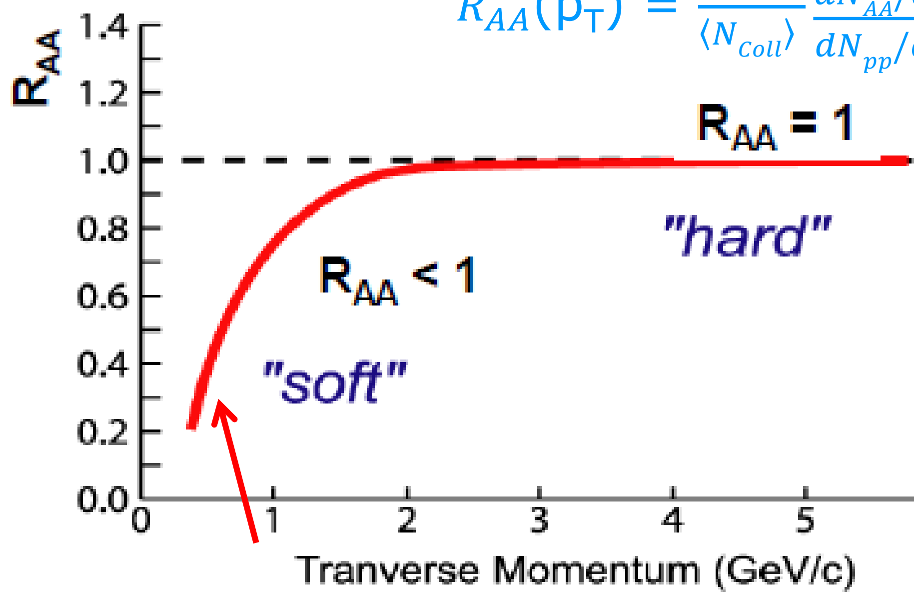
$dN^P{}_{AB}$ is the differential yield for a process P in AB collisions

$dN^P{}_{NN}$ is the differential yield for a process P in NN collisions

- If the yield of the process scales with the number of binary collisions
  → $R_{AA} = 1$

- However, nuclear medium effects in the initial or final state, can modify the expected binary scaling
  → $R_{AA} \neq 1$

$$R_{AA}(p_T) = \frac{1}{\langle N_{Coll} \rangle} \frac{dN_{AA}/dpT}{dN_{pp}/dpT}$$



Soft regime →scaling ∝ N_{Part}

The R_{CP}

Another ratio often used to study how a probe is affected by the medium is the so-called R_{CP} factor
→ the probe behaviour in central and peripheral collisions is compared

$$R_{CP} = \frac{dN^{central} / \langle N_{coll}^{central} \rangle}{dN^{peripheral} / \langle N_{coll}^{peripheral} \rangle}$$

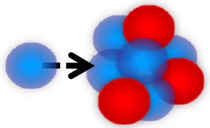
$dN^{central}$ and $dN^{peripheral}$ are the differential yield for a process P in central, peripheral collisions

If the yield of the process scales with the number of binary collisions
→ $R_{CP} = 1$

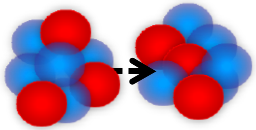
If there are effects affecting in a different way central or peripheral collisions
→ $R_{CP} \neq 1$

Can the binary scaling be broken?

➡ Binary scaling can be broken because of



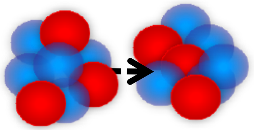
➡ Initial state effects → present in pA and AA collisions



- Cronin effect → inducing changes in the parton momenta
- Nuclear PDF → changes to the PDF in nuclei wrt parton ones
- Color Glass Condensate → gluon saturation at low x

Albacete's lectures

➡ Final state effects → present only in AA collisions



- Energy loss/ jet quenching
- Quarkonium suppression in the hot medium

Cronin effect

- Incident partons increase their transverse momentum, because of multiple scattering in their path through the nucleus A

- Discovered in pA collisions at Fermilab in the '70

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Production of hadrons at large transverse momentum
in 200, 300 and 400 GeV p-p and p-N collisions.*

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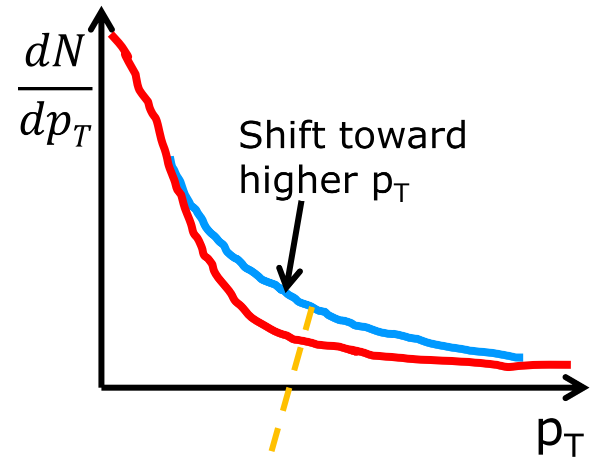
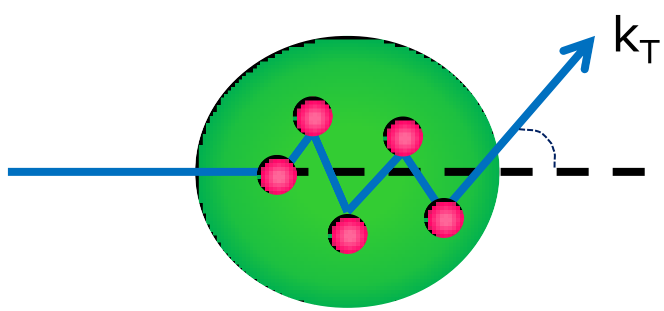
We felt, naively, that for the "hard" collisions only a single nucleon in the nucleus would be involved. It was therefore a surprise when we found that although the cross sections did extrapolate as A^{α}, the power α is a function of $p_{\perp}$ and for all particle types grows to be greater than 1.0 at large $p_{\perp}$,[5,9] implying that more than one nucleon is involved. This work has been verified by other experiments,[17,18] and similar behavior has been observed for dihadron systems.[18]

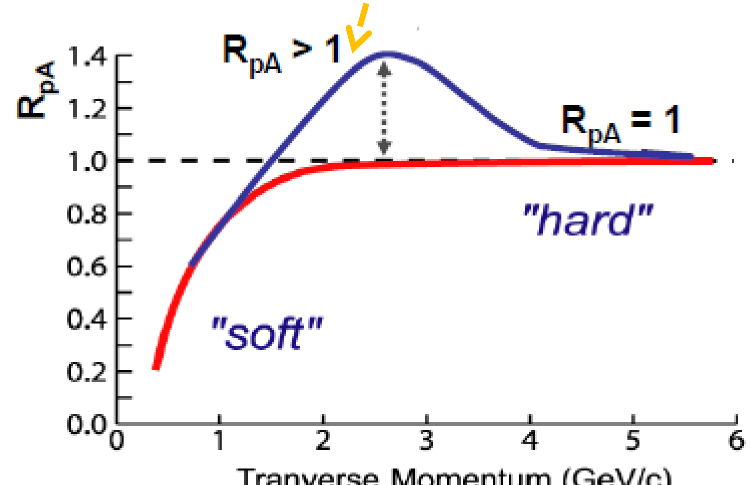
Cronin effect (2)

Projectile partons suffer multiple inelastic collisions with target partons, before the hard scattering which will produce the measured hadrons



- Projectile partons will acquire an extra transverse momentum (k_T) which will contribute to increase the transverse momentum of the produced hadron





- At very high p_T, the contribution of this extra k_T kick will become a negligible fraction of the measured p_T (~0 for $p_T \rightarrow \infty$)

Nuclear PDFs

Parton distributions in nuclei are strongly modified with respect to those in a free nucleon

These nuclear modifications depend on

- Fraction x of the hadron momentum carried by the parton
- Momentum scale Q^2
- Mass number of the nucleus

$$f^A{}_i(x,Q^2) = R_i(A,x,Q^2) \times f^p{}_i(x,Q^2)$$

nPDF: PDF of proton in a nucleus

free proton PDF

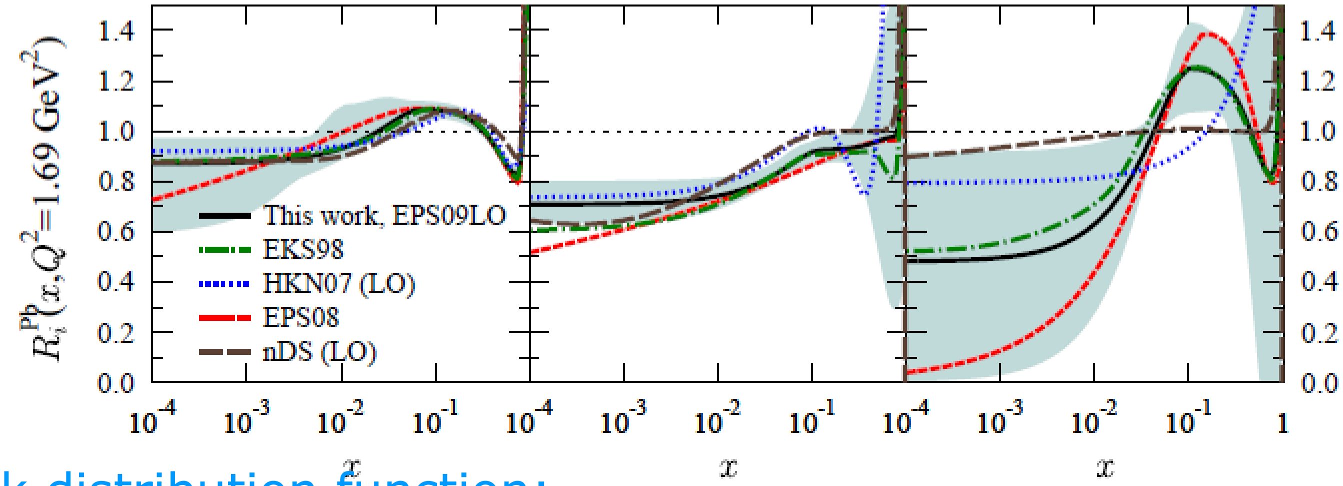
Several parameterizations are available to convert free nucleon distributions into the nuclear one

Comparison between nPDFs

- Comparison between different nPDFs (Pb nuclei)

$$R_i(A,x,Q^2) = \frac{f^A{}_i(x,Q^2)}{f^p{}_i(x,Q^2)}$$

valence quarks   sea quarks   gluons



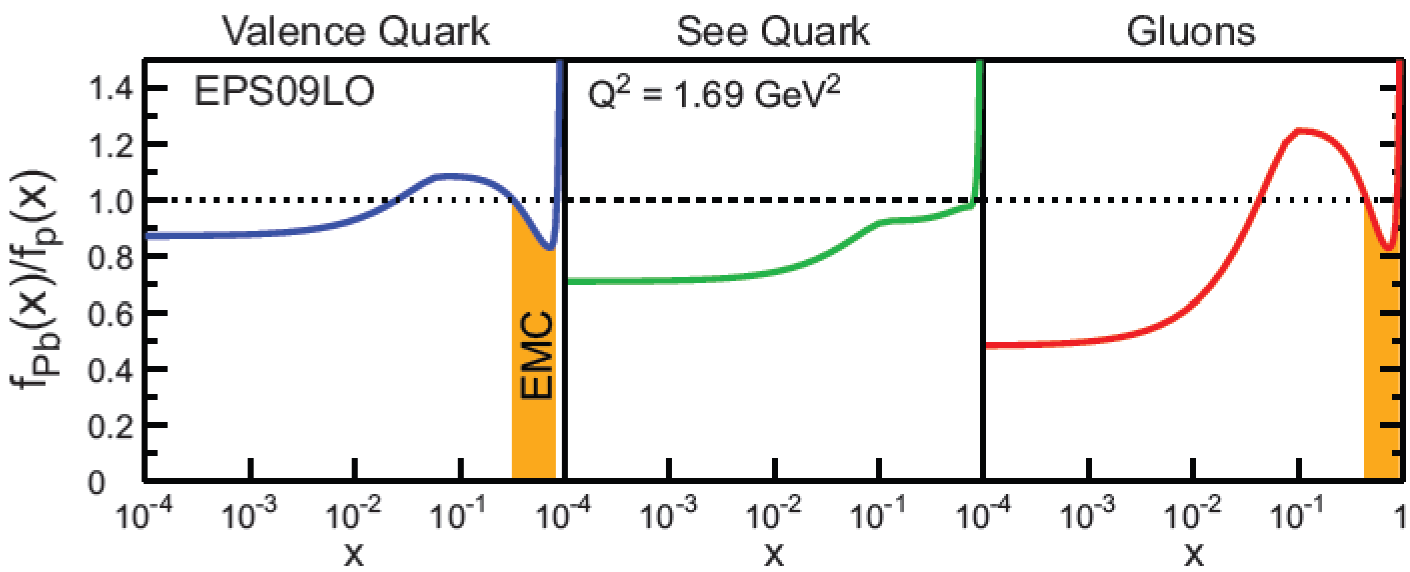
- Quark, antiquark distribution function:
  → probed by DIS and Drell-Yan data
  → nuclear effects well constrained, parameterizations give similar results

- Gluon distribution functions:
  → more indirect connection between gluon densities and data (new inclusive π production in dAu@RHIC included in the most recent nPDF, EPS09)
  → larger spread of parameterizations

- LHC data cover an unexplored domain (small x, large Q^2)!

Shadowing & AntiShadowing

- Several regions are probed, according to the explored x region



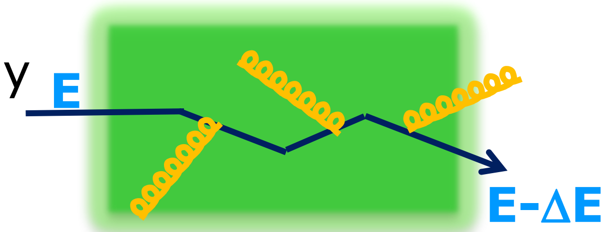
- Shadowing: parton densities in nuclei are depleted wrt free protons
- Anti-Shadowing: parton densities in nuclei are enhanced wrt free protons
- EMC: parton densities in nuclei are depleted wrt free protons

- In a LO 2→1 process: $x_1 = \frac{2m_T}{\sqrt{s}}e^{y}$; $x_2 = \frac{2m_T}{\sqrt{s}}e^{-y}$

  → the probed x region depends on y, m_T and $\sqrt{s}$
  → SPS, RHIC, LHC exp. explore different zones

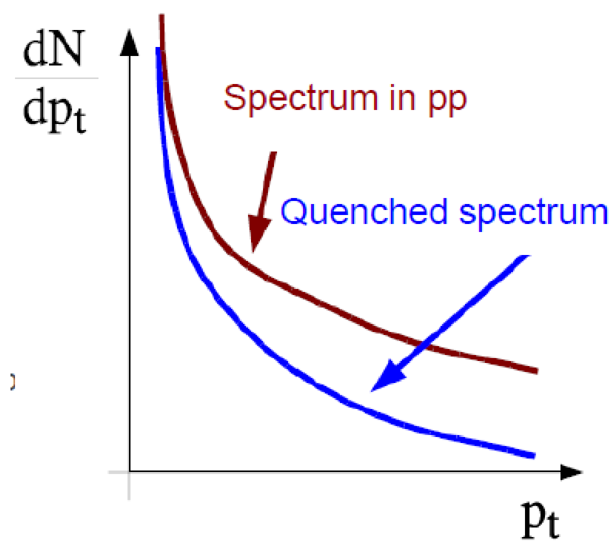
Energy loss

- A parton crossing the medium can lose energy because of two different mechanisms:
  - Scattering with partons → collisional energy loss
    → dominates at low energy
  - Gluon radiation → gluon bremsstrahlung
    → dominates at high energy



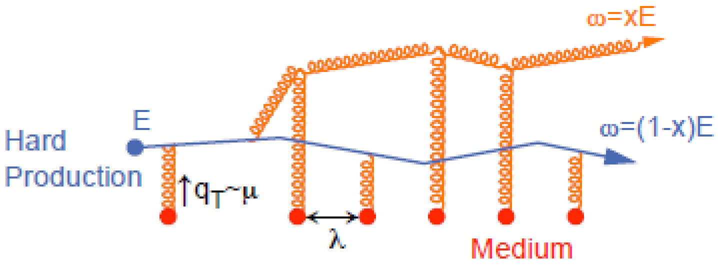
- The reduction in the parton energy translates to a reduction in the average momentum of the produced hadron, i.e. to a reduction of the yield at high p_T wrt pp collisions

- Because of the power-law shape of the p_T spectrum for p_T>3GeV/c, a modest reduction in the parton energy produces a significant decrease in the hadron yield



Radiative energy loss

- Several models are available for the radiative energy loss description



- BDMPS approach:

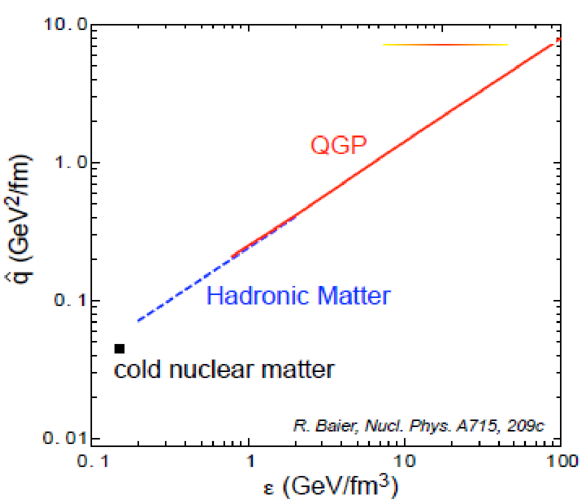
$$\langle \Delta E \rangle \propto \alpha_s\, C_r\, \hat{q}\, L^2$$

Casimir factor
→ 3 for gg interactions
→ 4/3 for qg interactions

En. loss is proportional to L^2, taking into account the probability to emit a bremsstralung gluon and the fact that radiated colored gluons can interact themselves with the medium

$\hat{q}$ = transport coefficient, related to the medium characteristics and to the gluon density dN_g/dy
→ allows an indirect measurement of the medium energy density

$\hat{q}$ ~ 0.05 GeV^2/fm → cold matter
$\hat{q}$ ~ 5-15 GeV^2/fm → RHIC
$\hat{q}$ ~ 100 GeV^2/fm → LHC ?



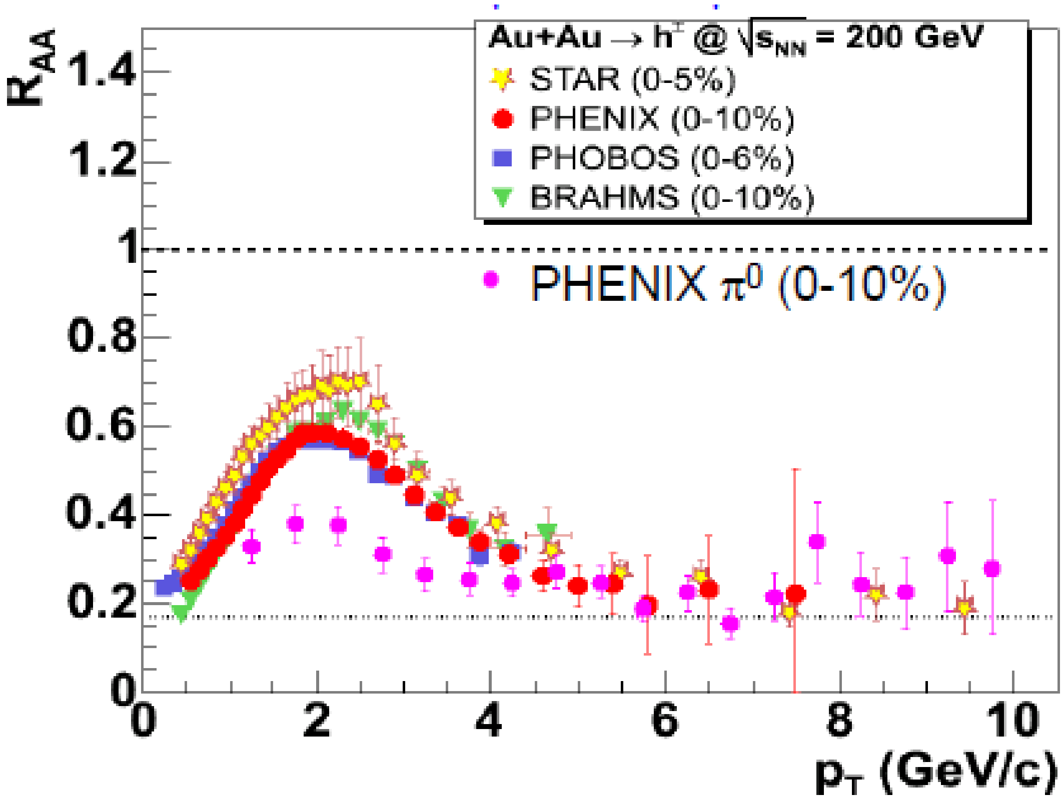
High p_T hadrons in AA collisions: experimental results

1) Charged hadrons R_{AA}

2) Di-hadron correlations

R_{AA} for charged hadrons and π^0

- Important discovery at RHIC! → high p_T suppression, aka jet quenching in central collisions



$$R_{AA}(p_T) = \frac{1}{\langle N_{Coll} \rangle} \frac{dN_{AA}/dpT}{dN_{pp}/dpT}$$

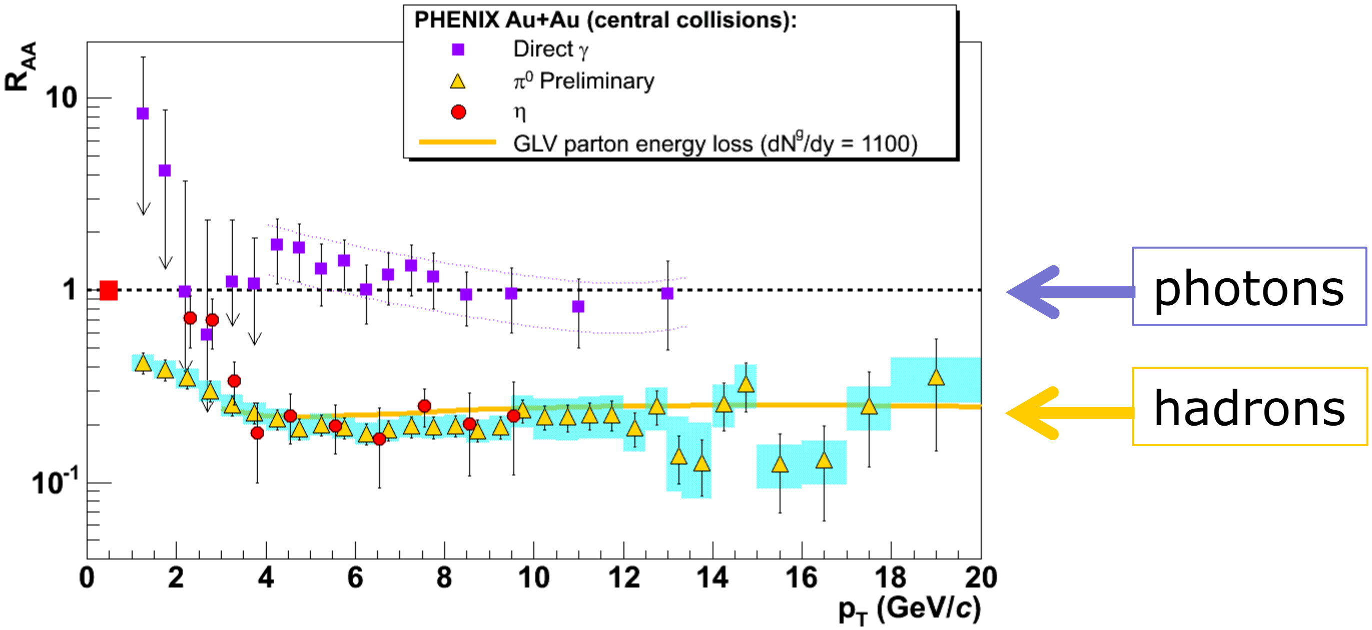
factor ~5 suppression

- Is this behavior due to initial or final state effects?

  - Control experiments needed:
    - γ
    - dAu collisions
    - peripheral AuAu collisions

Control experiment: γ R_{AA} in Au-Au

- Is the observed trend due to final state energy loss or to a reduction of the initial hard production cross section?
  - Control experiment with "medium-blind" probe → γ in Au-Au (no strongly interacting, not sensitive to the created medium)



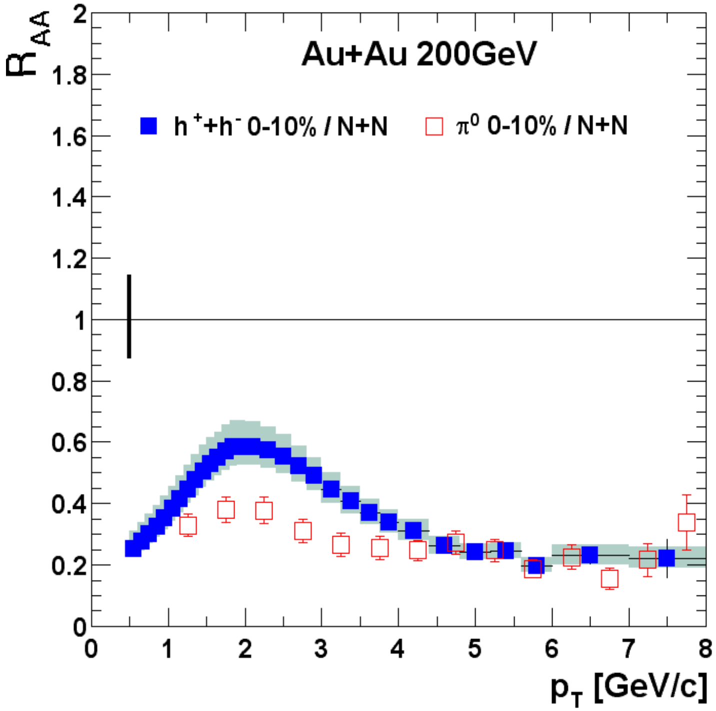
  - R_{AA} for γ show no suppression, but follows the Ncoll scaling

- Binary scaling works: observed pattern for hadron seems due to final state effects!

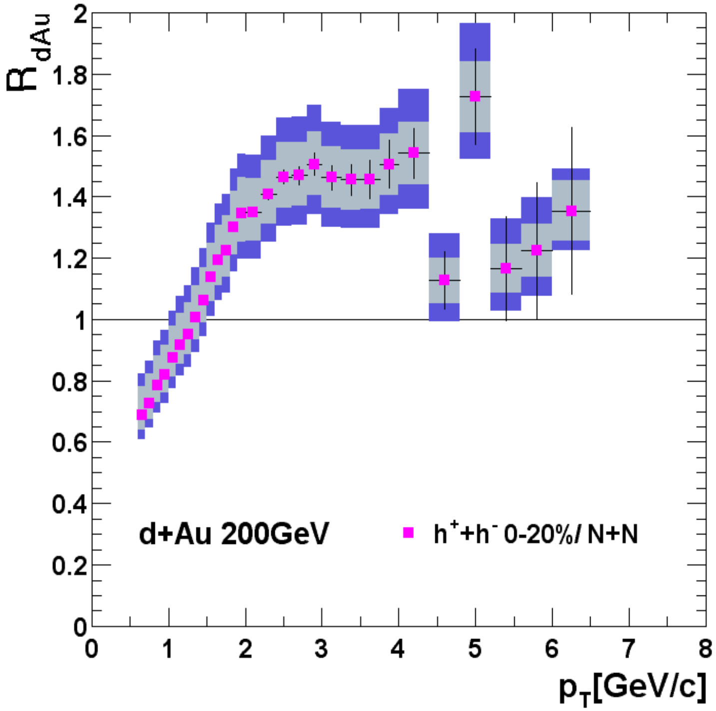
Control experiment: d-Au

- Control experiment to disentangle initial from final state effects:
  - d-Au collisions → No final state effects, only initial state effects

Au + Au Experiment



dAu Control Experiment



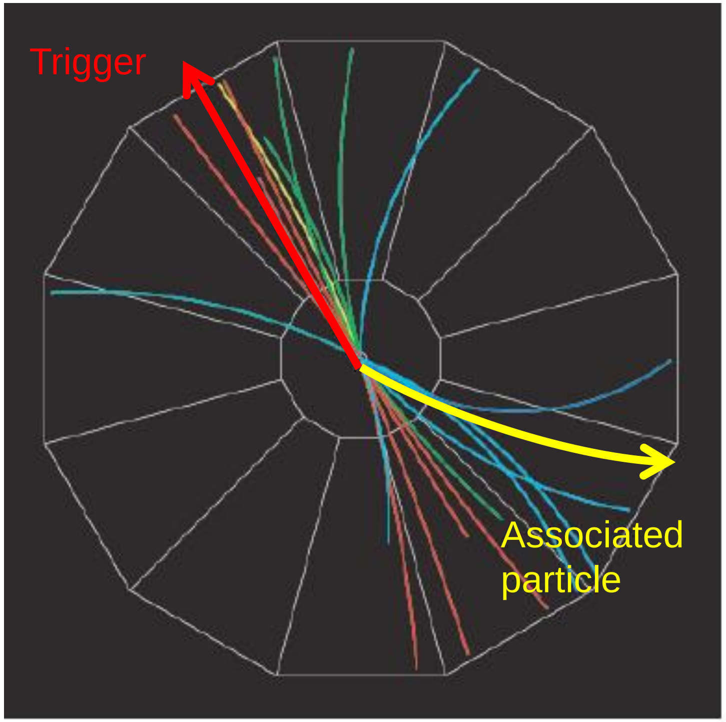
- Expected enhancement due to Cronin effect is observed in dAu

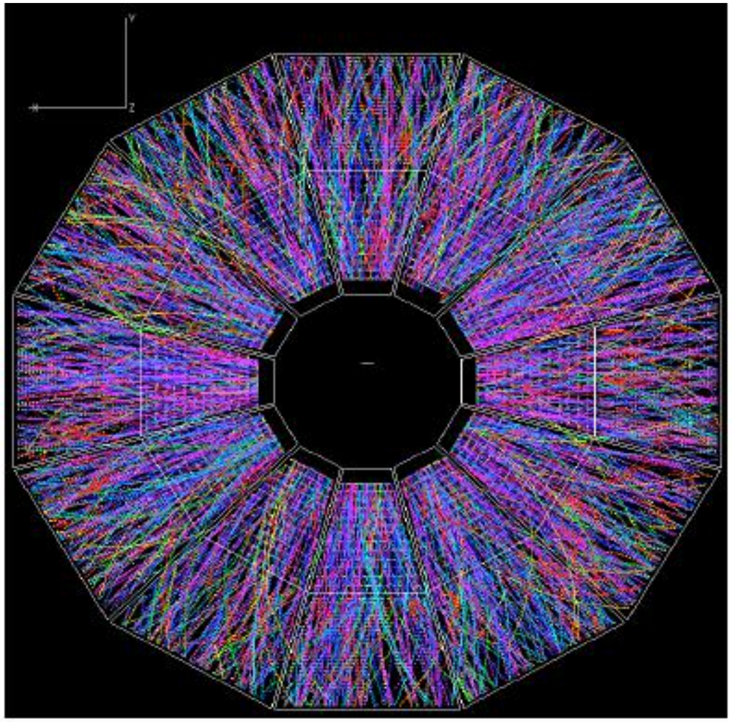
- Different trend in d-Au and Au-Au! → the AuAu pattern is due to effects which are clearly absent in dAu, i.e. final state effects

di-hadron correlations

Further hints can be obtained studying di-hadron correlations, event by event, in the following way:

- Find the trigger particle: hadron with the highest p_T (e.g p_T^{trig}>4GeV/c)
- Build the azimuthal distributions of all hadrons with 2GeV<p_T<p_T^{trig}

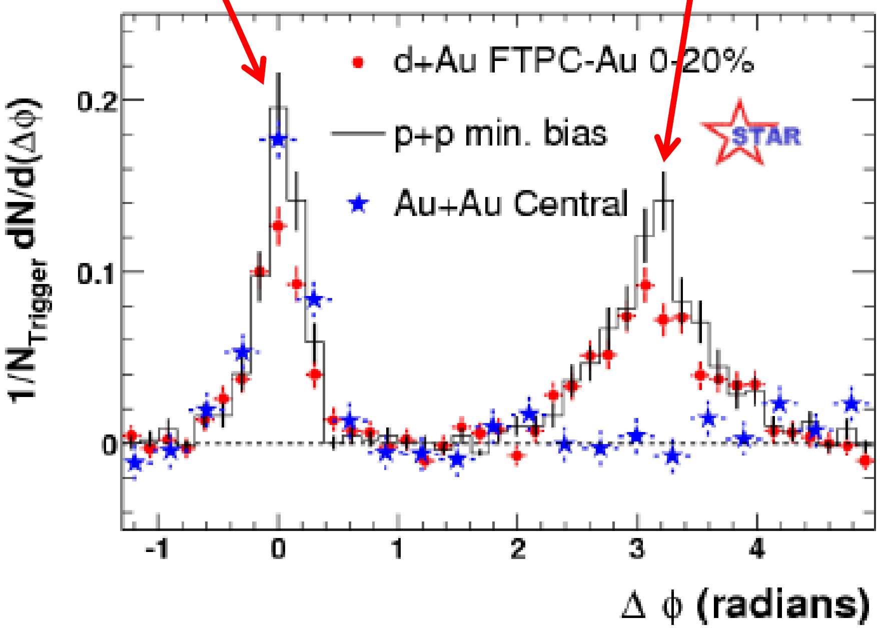




Look for this kind of structure … in this environment!

di-hadron correlations (2)

near side peak away side peak



$\Delta\phi\sim0$ → hadron pair from a single jet
$\Delta\phi\sim\pi$ → back to back di-jet

Central AuAu collisions:

Back to back correlation is absent.

Suppression due to final state effect

→ near side peak arise from partons interacting close to the surface of the collision zone
→ away side peak: partons have to cross a significant length of dense matter and they are absorbed, i.e. jet quenching

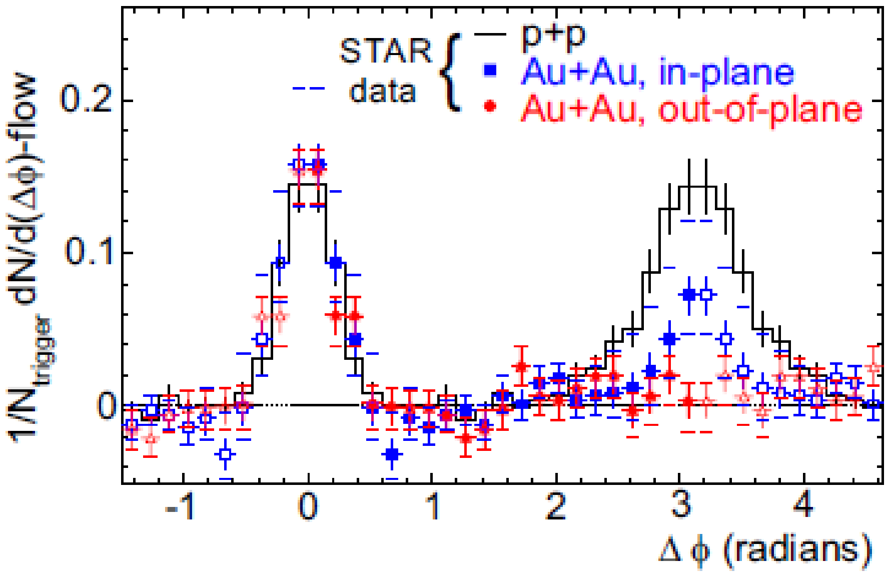
Control experiments

- pp, dAu
- Peripheral AuAu

Back to back correlation is present

di-hadron correlations (3)

- Further insight can be obtained measuring high p_T hadron correlations relative to the orientation of the reaction plane

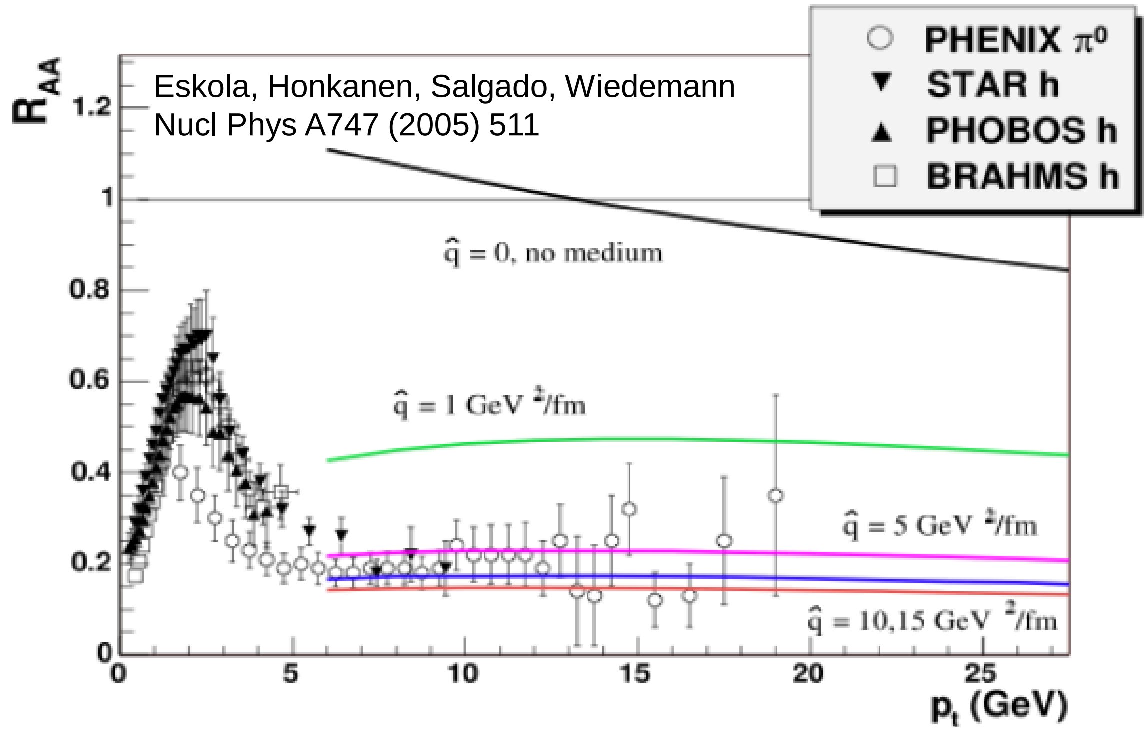


- The path length in medium for a di-jet oriented out of the reaction plane is longer than in the reaction plane

- high p_T hadron behaviour is interpreted in terms of partonic energy loss
  → Data can be described assuming an initial gluon density in the medium about a factor 50 greater than that of cold nuclear matter

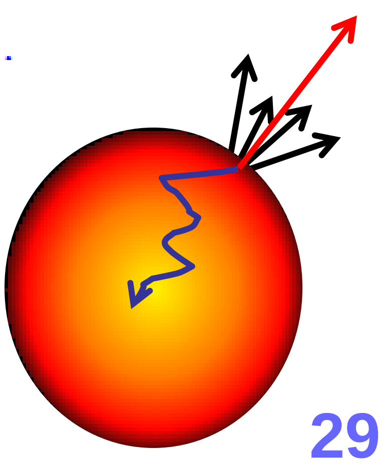
Medium characterization

How to use previous results to extract information on the medium?



From RHIC data: $\hat{q} =$ 5 – 15 GeV^2/fm

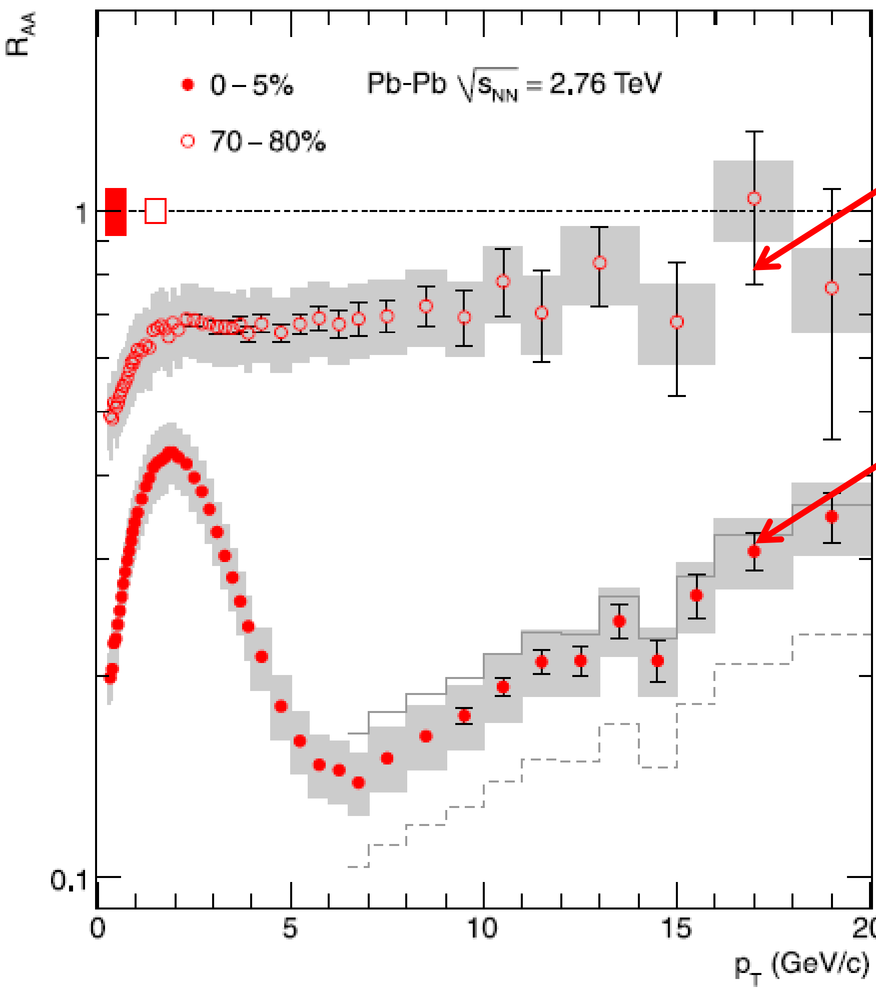
Limited R_{AA} sensitivity to the created medium: measured high-p_T particles are those produced on the surface, not slowed down by the high density medium



Other probes needed?

A first look into LHC PbPb data!

First results on charged particles R_{AA} for PbPb @ $\sqrt{s}$=2.76TeV (ALICE)



peripheral collisions:
weak medium effects

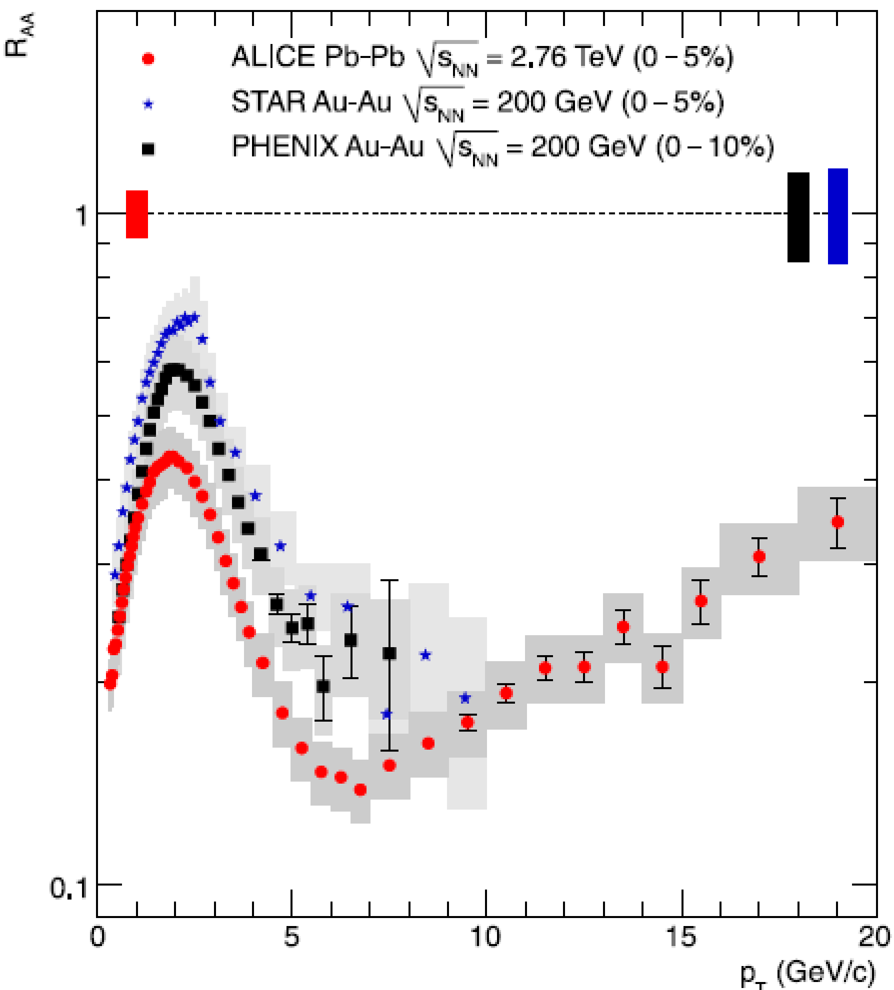
central collisions:
strong suppression, and rise for very high p_T

ALICE PLB 696 (2011) 30

R_{AA} evaluation needs pp data, but pp data @$\sqrt{s}$=2.76TeV not yet available!

Current interpolation based on ALICE pp data @ 0.9 and 7 TeV, but other extrapolations tested using CDF pp data @ 1.96 or NLO scaling

Comparison with RHIC results



ALICE PLB 696 (2011) 30

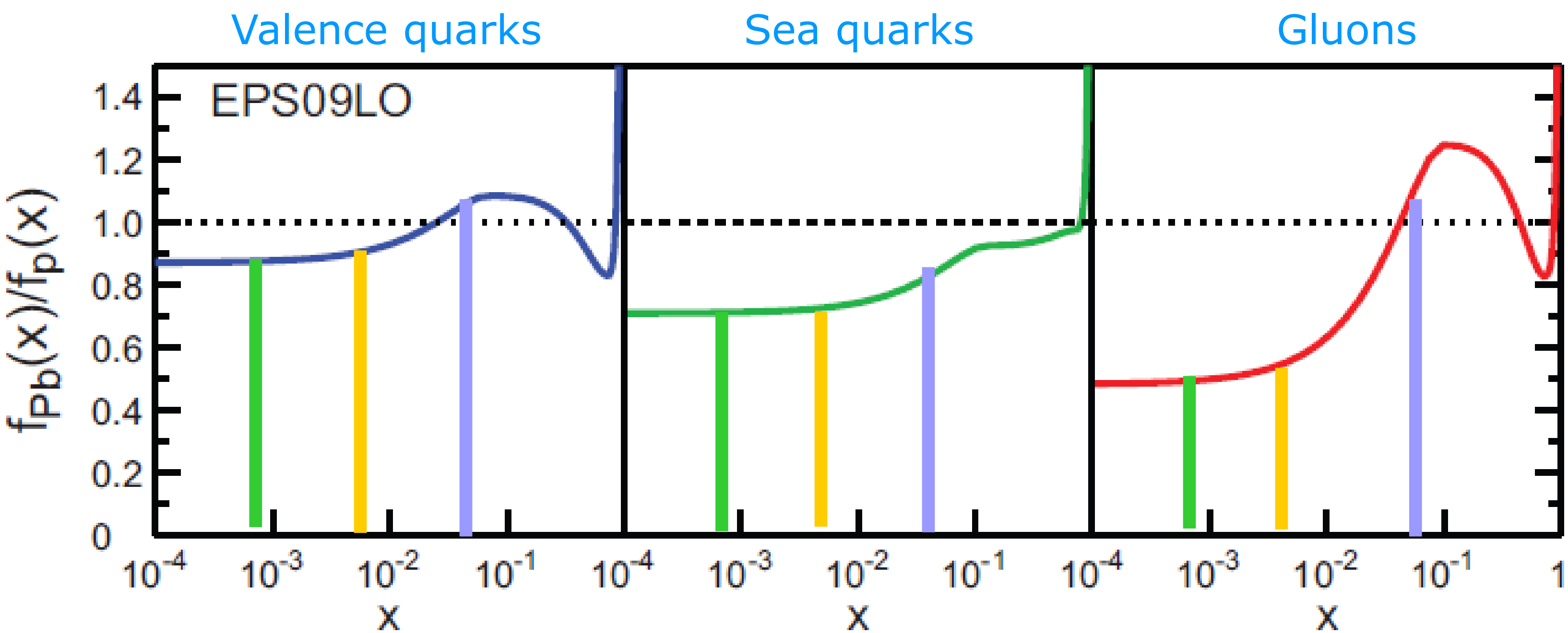
- Comparison of central collisions results from ALICE, PHENIX and STAR
- In the common p_T region, ALICE and RHIC exp. observe a similar R_{AA} shape, with a maximum at p_T ~2GeV/c.
- However, the suppression observed by ALICE is stronger!

Enhanced energy loss, i.e. denser medium at LHC?

Backup

nPDF for SPS, RHIC, LHC

- A given particle probes shad/antishad. region, according to its x value
  - In a LO 2→ process: $x_1 = \frac{2m_T}{\sqrt{s}} e^{y}$; $x_2 = \frac{2m_T}{\sqrt{s}} e^{-y}$
  - → the probed x region depends on y, m_T and √s



- Example (y=0):
  - J/ψ @ p_T=1GeV/c
    SPS(158GeV) x ~ 0.4
    RHIC(200GeV) x ~ 0.03
    LHC(7TeV) x ~ 0.001

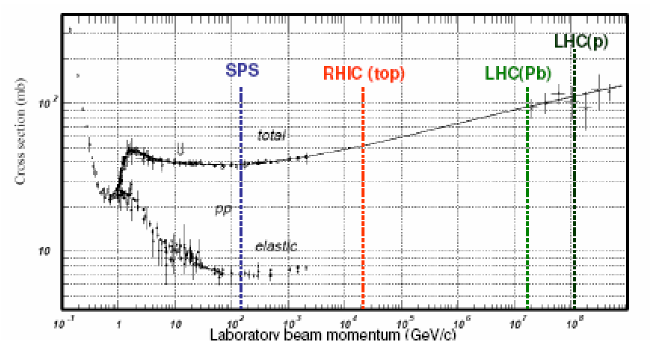
Glauber model

Geometrical model to describe the collision between two nuclei with impact parameter b

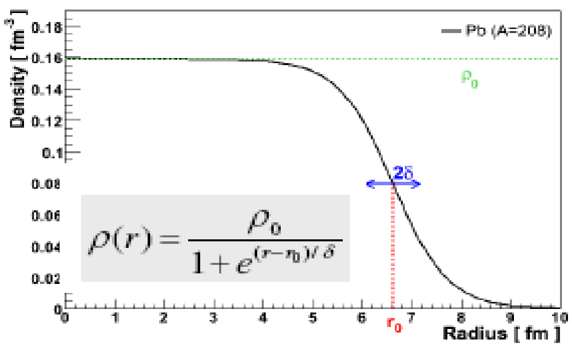
Assumptions: Nucleus-nucleus collisions are described as a superposition of independent nucleon-nucleon collisions

Ingredients:

- the nucleon-nucleon inelastic cross-section (~30mb at SPS)



- the nuclear profile densities e.g a Wood-Saxon distribution



$$\rho(r) = \frac{\rho_0}{1+e^{(r-r_0)/\delta}}$$

Output:

Allow to obtain several information as a function of the impact parameter b:

- num. of participant nucleons
- number of collisions
- overlap region
- …