Jet quenching from RHIC to LHC

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Outline

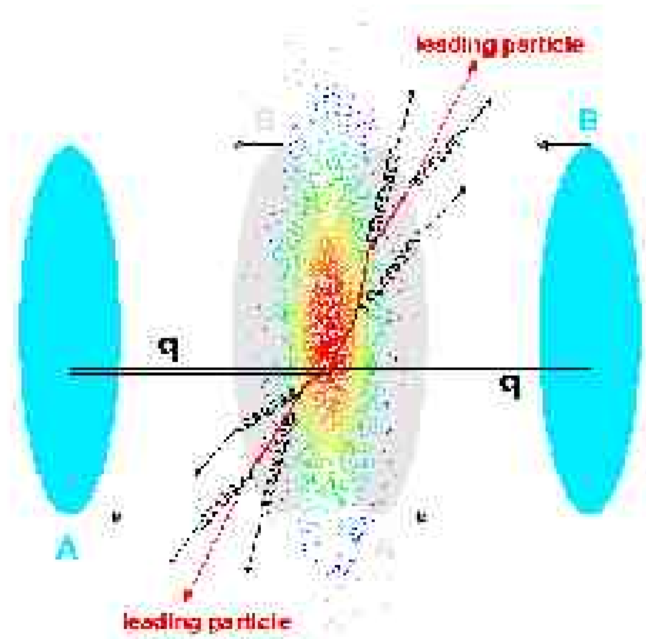
- Parton Quenching Model for RHIC high-p_t data
- Jet reconstruction at LHC
- Modelling jet quenching at LHC

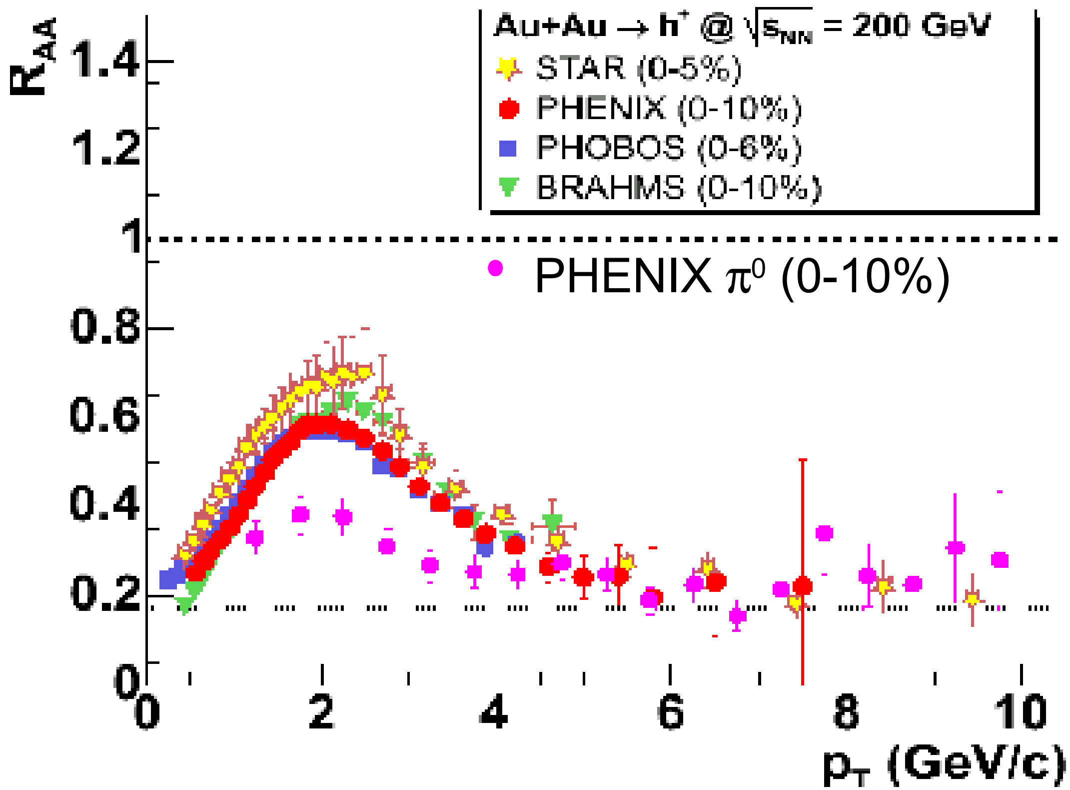
Experimental discoveries at RHIC

High-p_T suppression observed by comparing p_T distributions of leading particles in pp and AA (for different centralities)

Nuclear modification factor

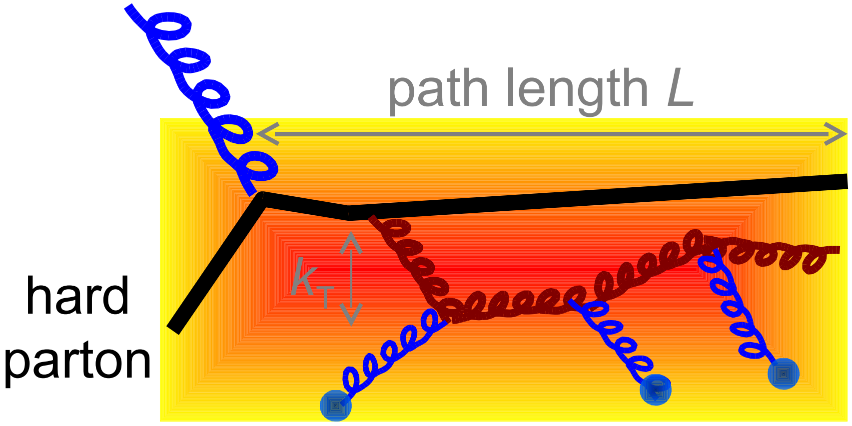
$$R_{AA}(p_T) \quad \frac{1}{\langle N_{coll} \rangle_C} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





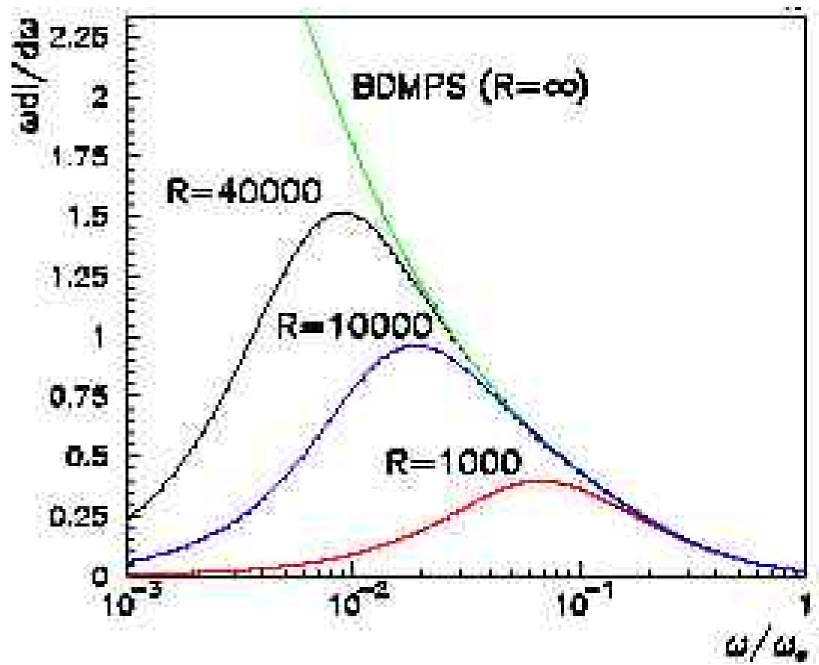
Parton energy loss inspired by pQCD

- Partons travel ~4 fm in the high **color**-density medium
- Successive calculations: a QCD mechanism dominates: ***medium-induced gluon radiation***
- Coherent wave-function gluon acummulates k_T due to multiple inelastic scatterings in the medium until decoheres and is radiated



Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Peigne', Schiff, Levai, Vitev, Zhakarov, Salgado, Wiedemann, ...

Calculating Parton Energy Loss (BDMPS-Z)



STATIC MEDIUM

BDMPS-Z formalism

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

(BDMPS case)

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \begin{cases} \sqrt{\omega_c / \omega} & \text{for } \omega < \omega_c \\ (\omega_c / \omega)^2 & \text{for } \omega \geq \omega_c \end{cases}$$

C_R Casimir coupling factor: 4/3 for q, 3 for g

$\omega_c = \hat{q} L^2 / 2$ sets the scale of the radiated energy

$R = \omega_c L$ related to constraint $k_T < \omega$, controls shape at $\omega \ll \omega_c$

Baier, Dokshitzer, Mueller, Peigne‘, Schiff, NPB 483 (1997) 291
Zakharov, JTEPL 63 (1996) 952
Salgado, Wiedemann, PRD 68(2003) 014008

Calculating the energy loss

$$\langle \Delta E \rangle \approx \int_0^{\omega_c} \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s\, C_R\, \omega_c \propto \alpha_s\, C_R\, \hat{q}\, L^2$$

$\langle \Delta E \rangle \propto \hat{q} \propto$ <u>gluons volume-density and interaction cross section</u>

➡ **Probe the medium**

Finite parton energy (qualitatively)

- If $E < \omega_c$ (e.g. small p_T parton with large L):

$$\langle \Delta E \rangle \approx \int_0^{E} \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s\, C_R \sqrt{E\omega_c} \propto \alpha_s\, C_R \sqrt{E}\sqrt{\hat{q}}\, L$$

  - Introduces dependence on parton energy
  - $\hat{q} \rightarrow \hat{q}^{1/2}$: smaller sensitivity to density
  - $L^2 \rightarrow L$: linear dep. on path length

- Goal: compute high-p_T suppression in BDMPS-Z framework
- *QW* = energy loss probability distributions

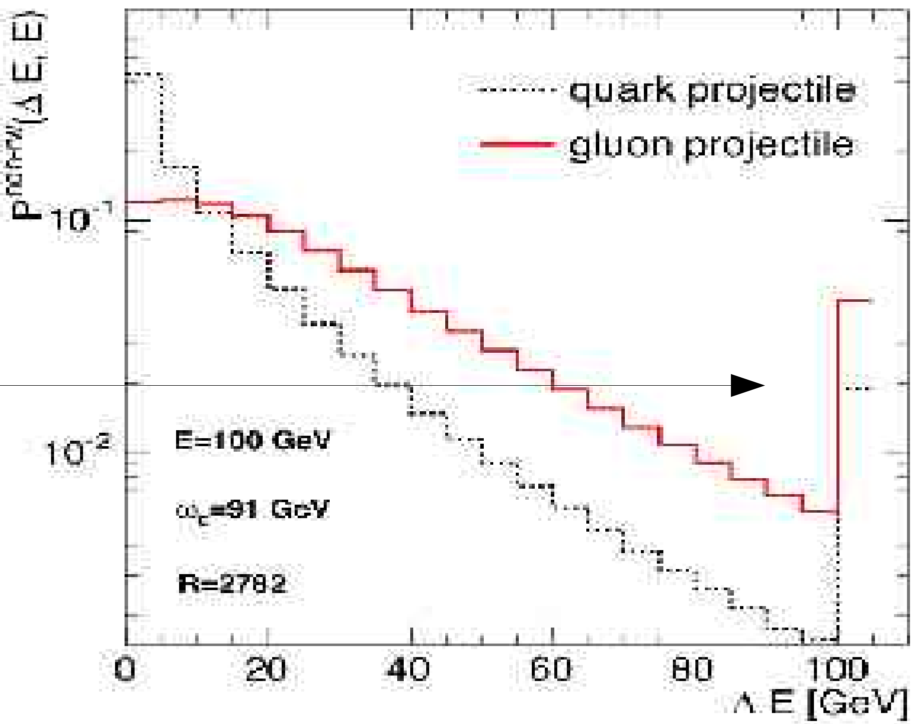
$$P(\Delta E; C_R, \hat{q}, L) \qquad [\alpha_s = 1/3]$$

- Calculated from $\omega\, dI/d\omega$, in $E \to \infty$ approximation

need construct constraint weights

$$\Rightarrow P(\Delta E; C_R, \hat{q}, L, E)$$

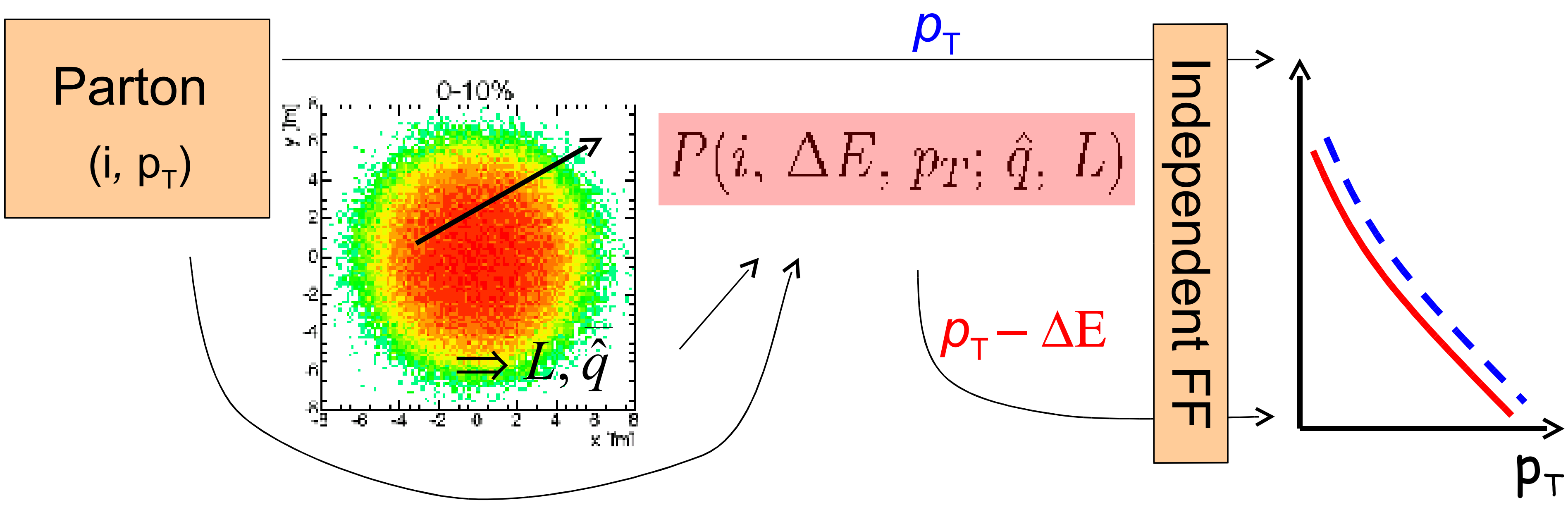
which fulfill $\Delta E < E$



BDMS, JHEP 0109 (2001) 033
SW, PRD 68 (2003) 014008

Application: Parton Quenching Model

- QW + Glauber + PYTHIA for parton generation and fragmentation func.
- The Monte Carlo procedure in short:
  - generate parton (q or g) with PYTHIA (or back-to-back pair)
  - calculate its L and average $\hat{q}$ along the path $[\hat{q}(\vec{s}) \propto T_A T_B(\vec{s})]$
  - use quenching weights to get energy loss
  - quench parton and then hadronize it (independent fragm.)

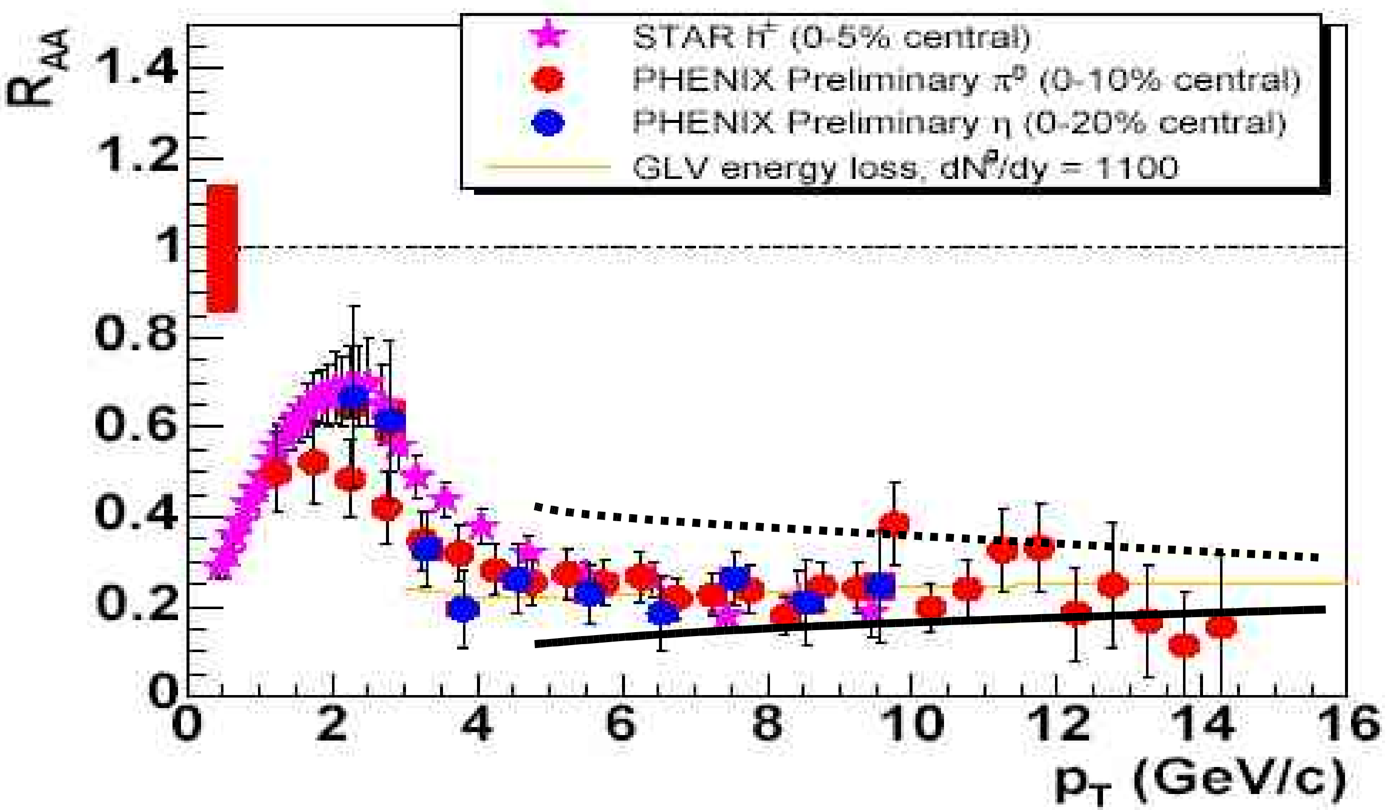


A.Dainese, C.L., G.Paic, EPJC38 (2005), 461

PQM: R_{AA} for Au+Au at 200 GeV

Density ($\hat{q}$) "tuned" to match R_{AA} in central Au+Au at 200 GeV

Need $\langle\hat{q}\rangle$ = 14 GeV^2/fm to describe data

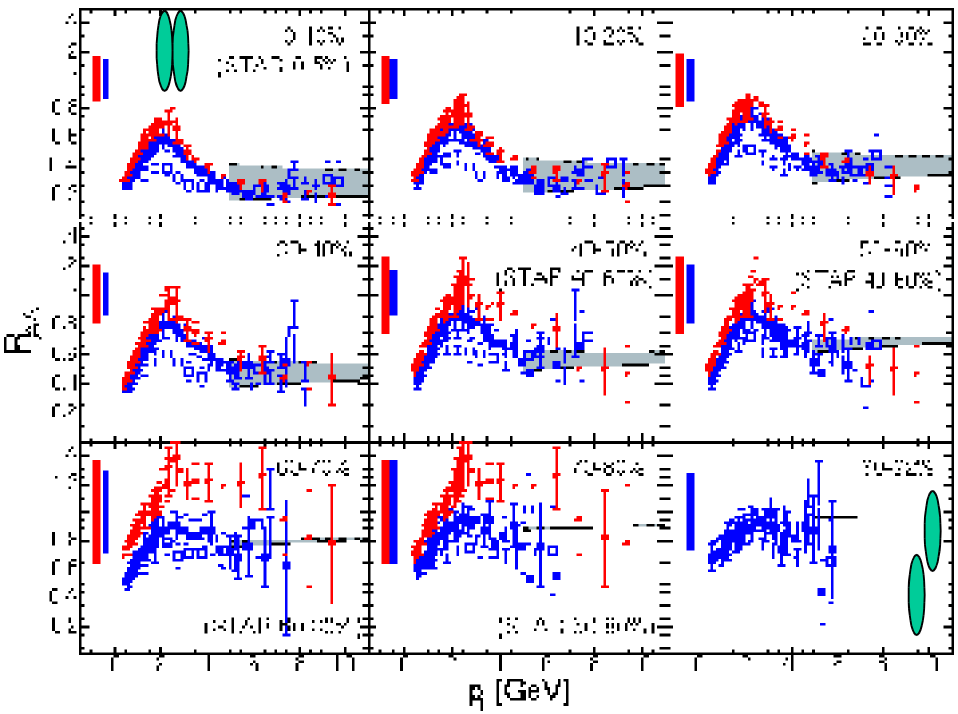


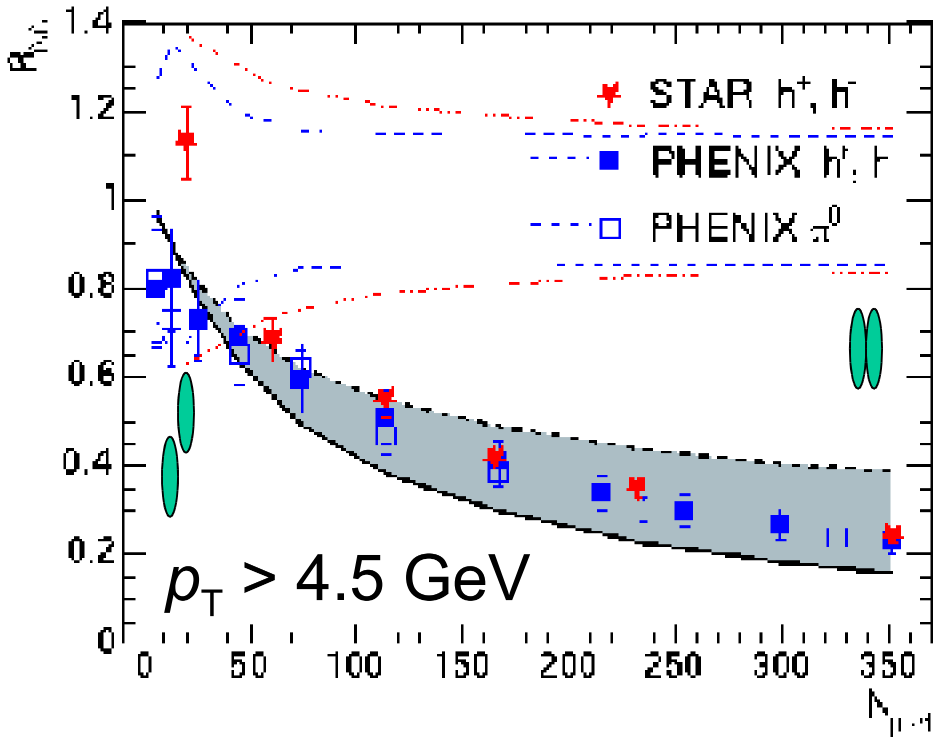
nitial-state effects and
edium hadronization:
lts given for p_t > 5 GeV

d represents systematic
oretical) uncertainty
duced by the constraints
nite (and small) parton
energies

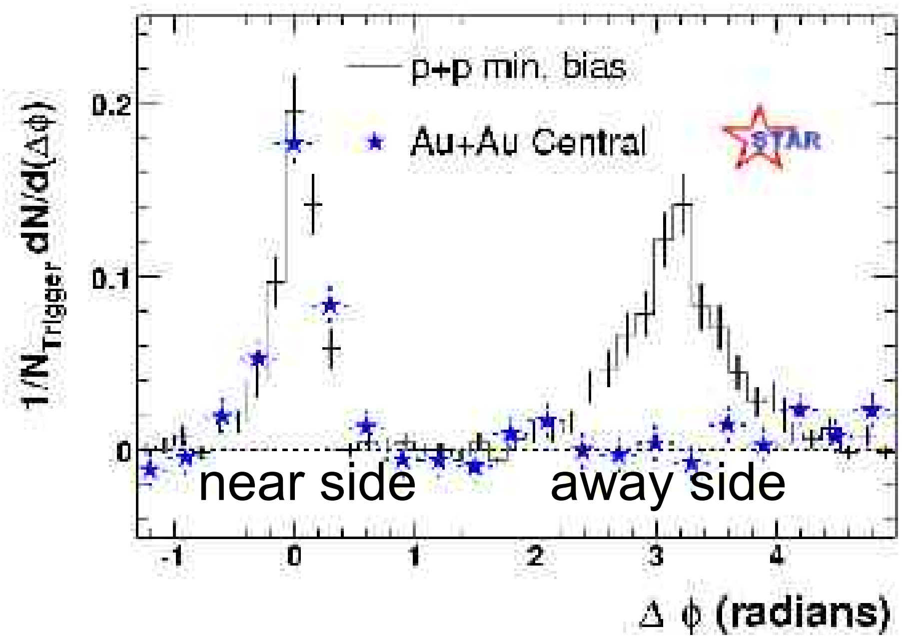
- Centrality evolution according to Glauber-model collision geometry

$$\hat{q}(\vec{s};b) = k \times T_A T_B(\vec{s};b)$$

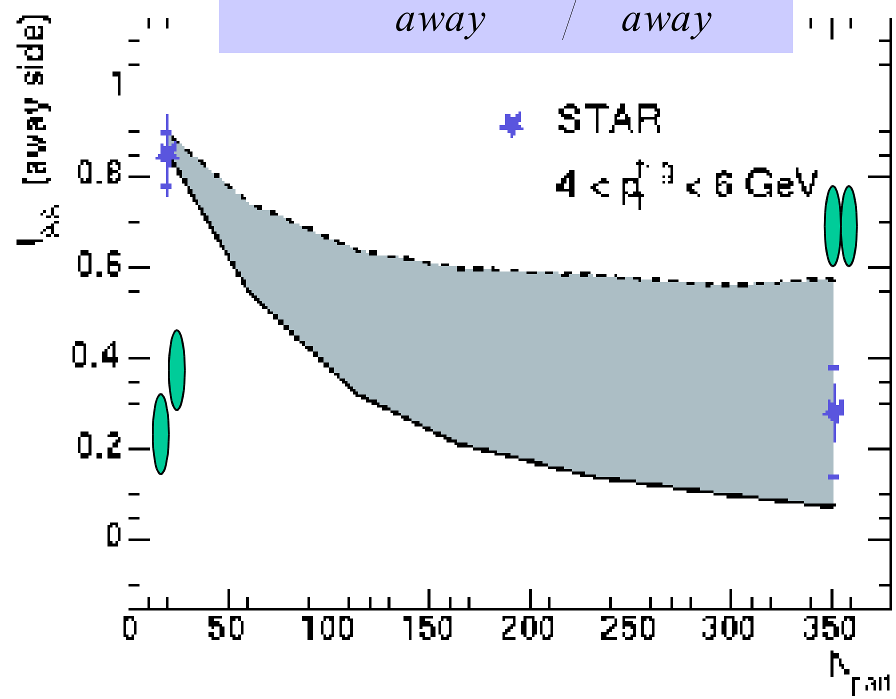




PQM: Disapearance of the away-side jet



$$I_{AA} = \int_{away} AA \Big/ \int_{away} pp$$

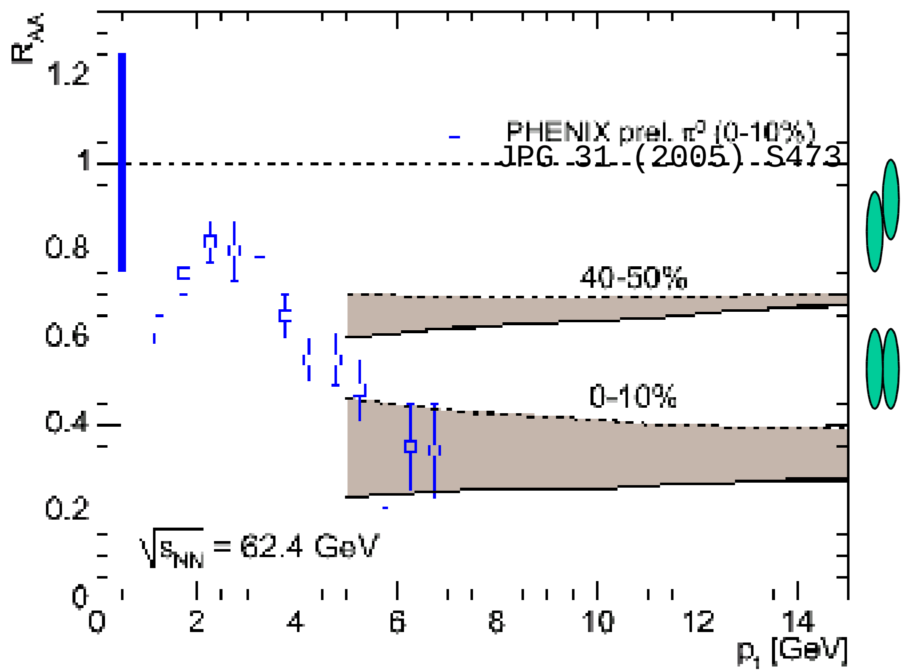


STAR Coll., PRL 90 (2003) 082302
STAR Coll., nucl-ex/0501016

PQM: Extrapolation to other cms energy

- Extrapolation in $\sqrt{s}$: assuming $\hat{q} \propto N_{gluons}$/volume $\propto (\sqrt{s})^{0.6}$ (EKRT saturation model, NPB 570 (2000) 379)
- First test:

$$\hat{q}_{62\,\mathrm{GeV}} \approx \hat{q}_{200\,\mathrm{GeV}} / 2 \approx 7\,\mathrm{GeV}^2/\mathrm{fm}$$

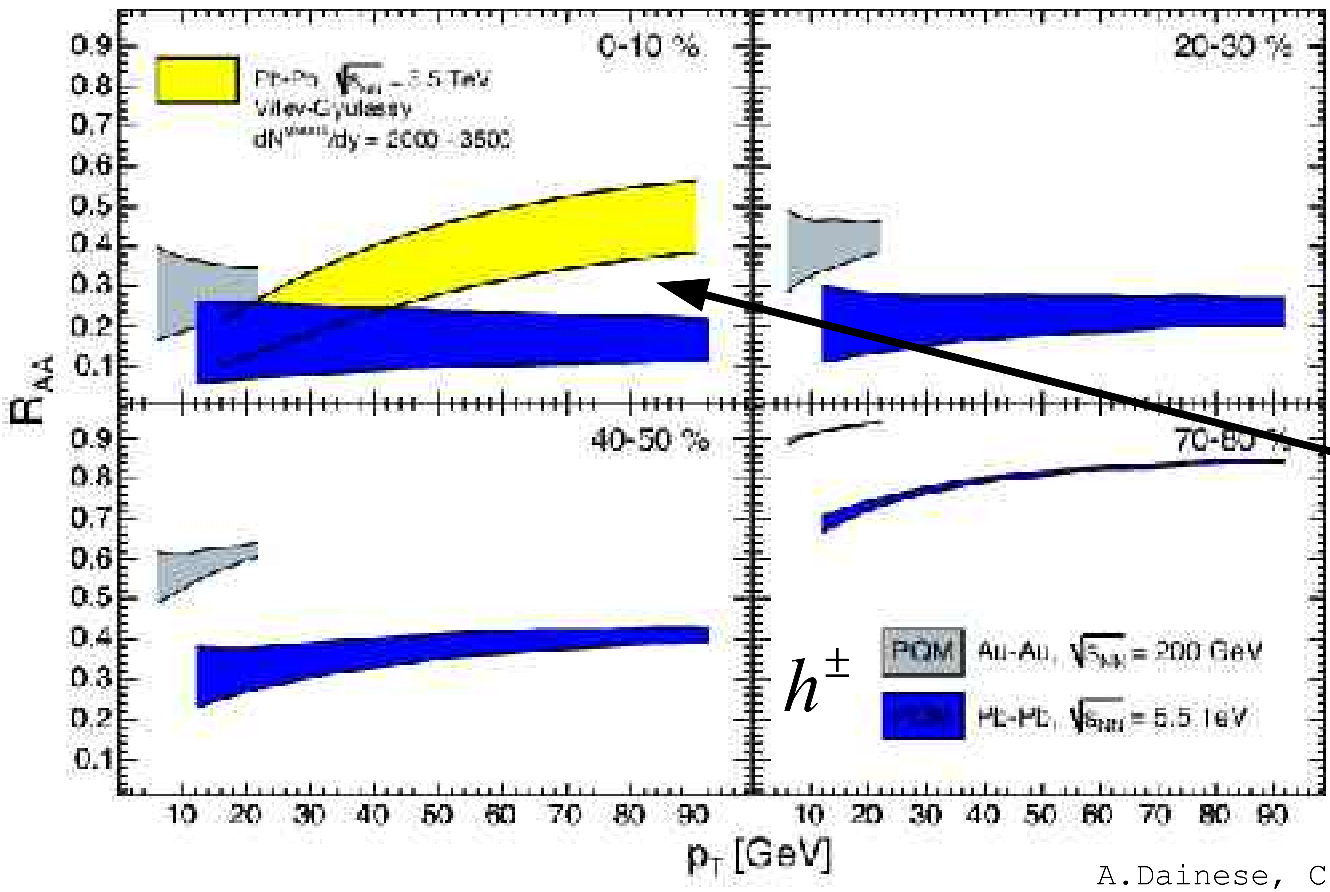


→ energy extrapolation works reasonably well

PQM: Prediction for LHC

Scaling according to saturation model leads to $\langle \hat{q} \rangle$ = 100 GeV^2/ fm (for central collisions)

PQM predicts flat (p_T-independent) R_{AA}

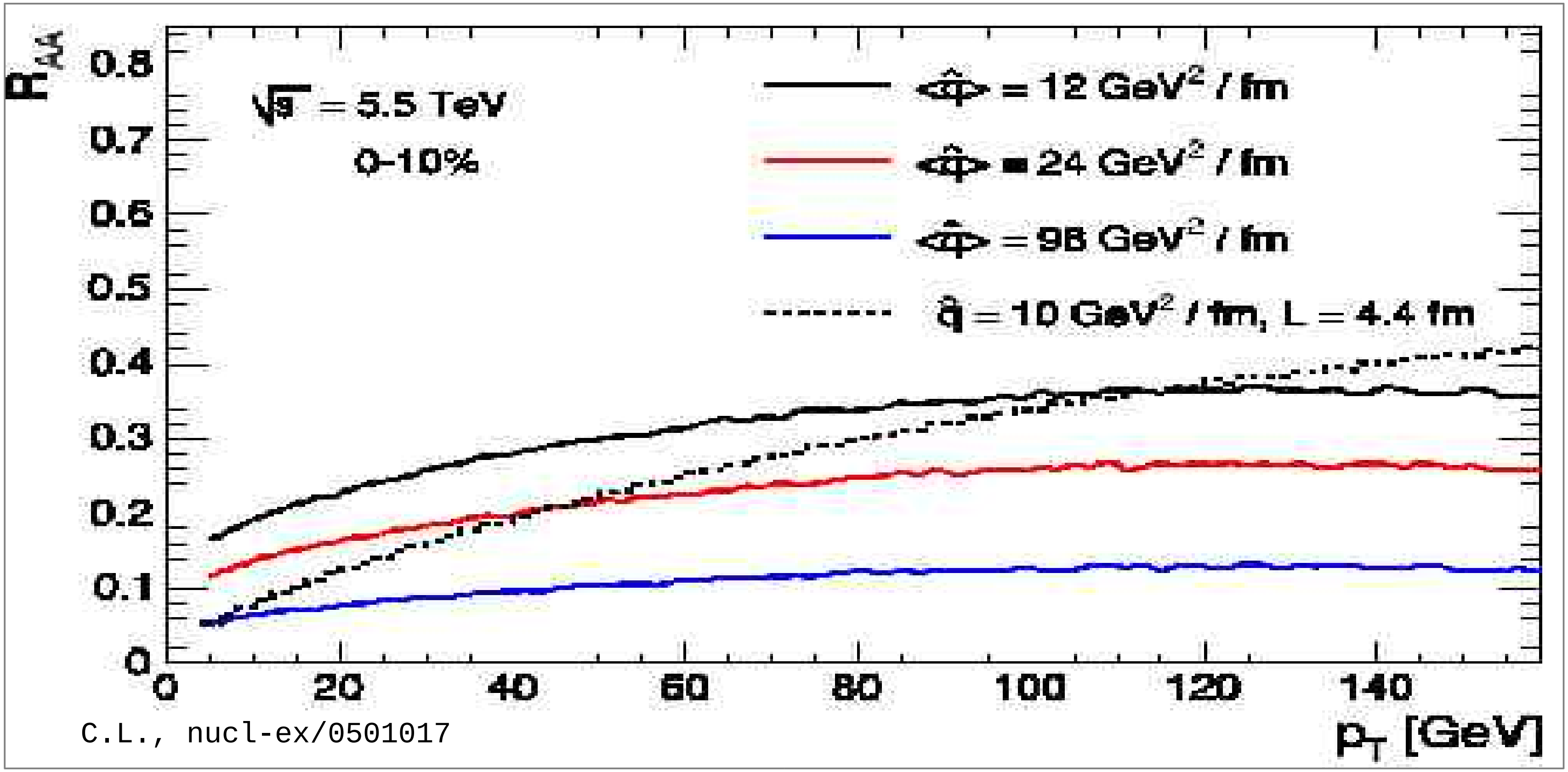


$$R_{AA}^{5.5\ \mathrm{TeV}} \approx \frac{R_{AA}^{200\ \mathrm{GeV}}}{2}$$

Interesting(?) difference in predicions.

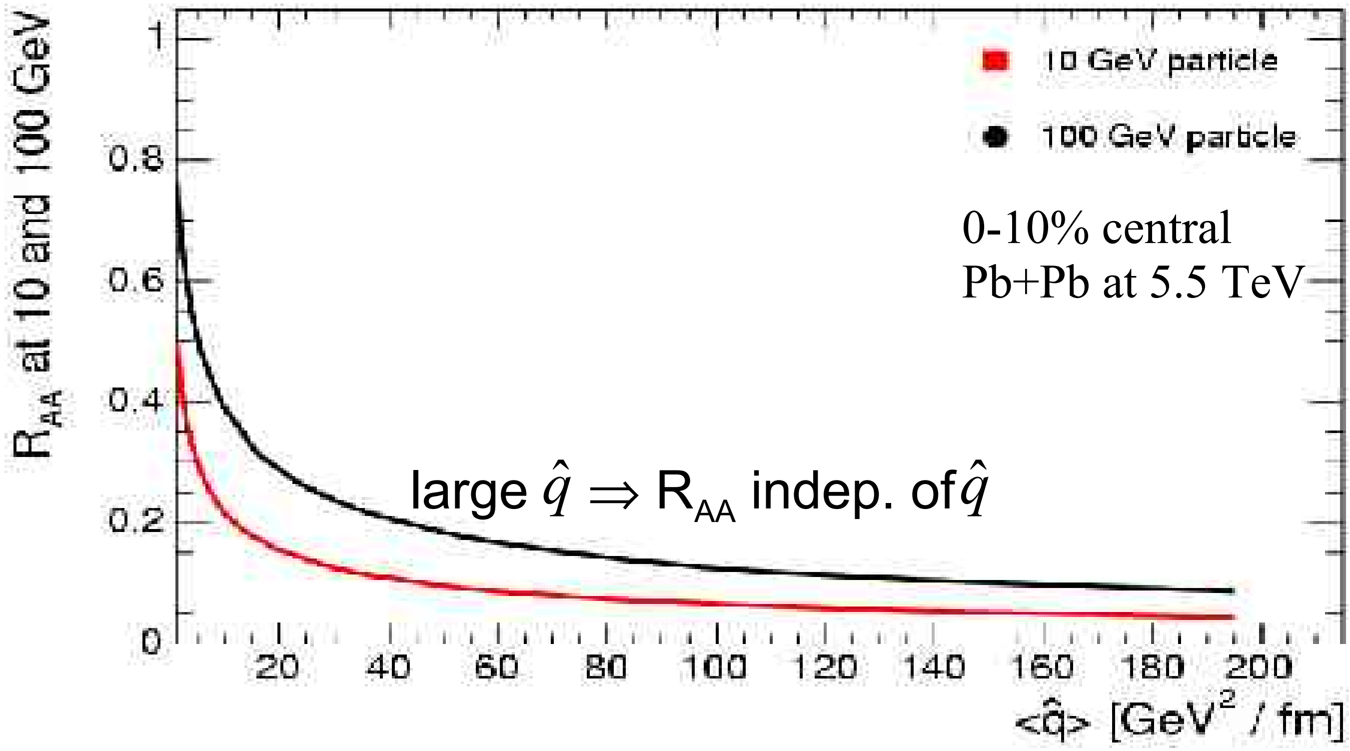
A.Dainese, C.L., G.Paic, EPJC38 (2005), 461
Vitev and Gyulassy, PRL 89 (2002) 252301

Why R_{AA} is flat ↔ Surface effect



- Long path lengths exploited only by high energy partons
  - R_{AA} doesn't increase at high p_T
  - Exercise: $L \equiv \langle L \rangle \Rightarrow$ R_{AA} increases with p_T

Limited sensitivity of R_{AA}



"Leading-particle probes are fragile!"

➡ Study more differentially observables

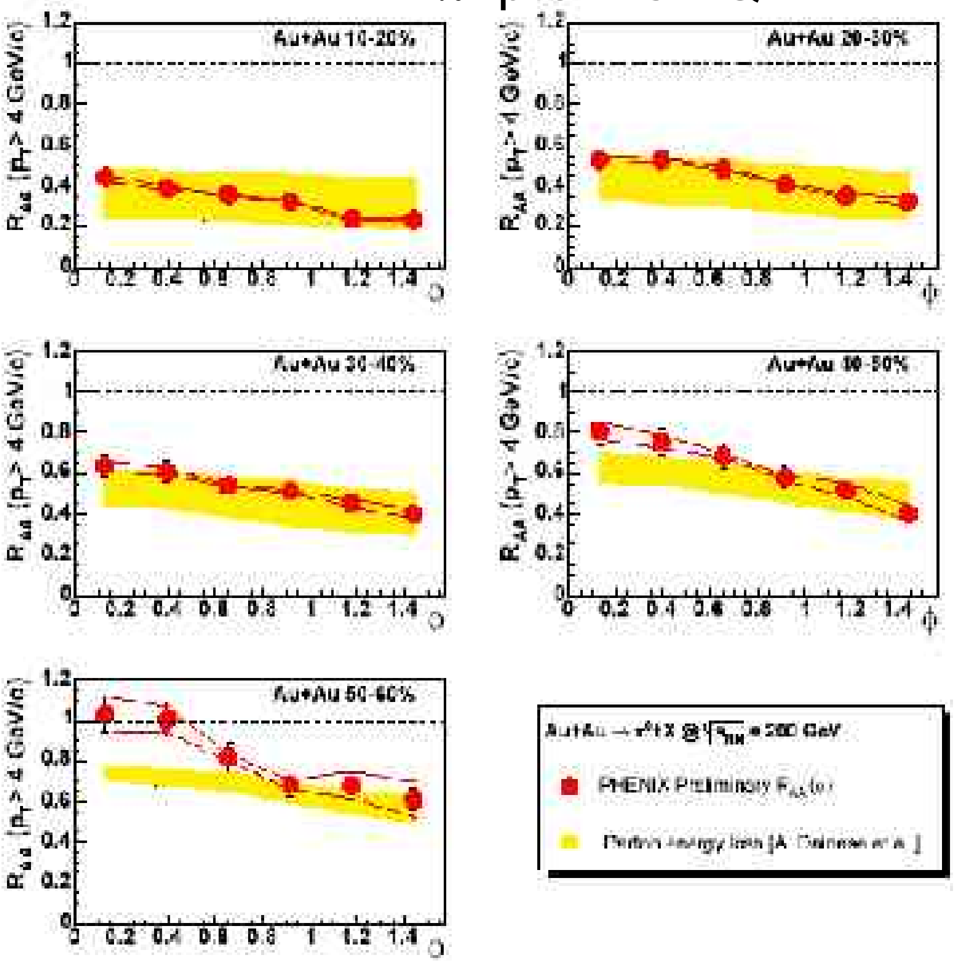
- R_{AA} vs reaction plane
- massive partons
- study of jet shapes
- ...

K.Escola, H.Honkanen, C.Salgado, U.Wiedemann, NPA747 (2005) 511
C.L., nucl-ex/0501017

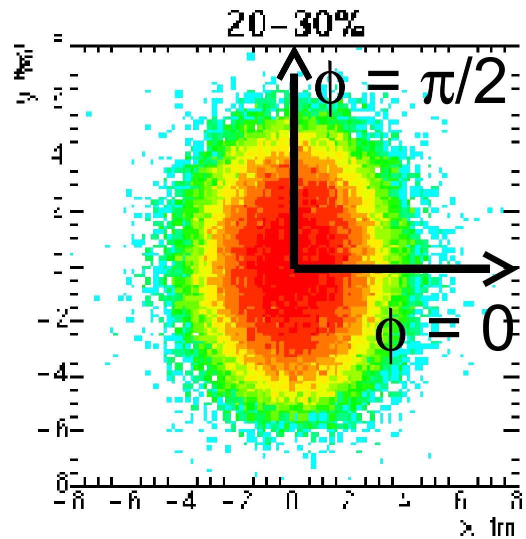
First data of R_{AA} vs ϕ appearing …

→ Further handle on *L*-dependence*

PHENIX π^0 prel. vs PQM



D. d'Enterria (nucl-ex/0504001)

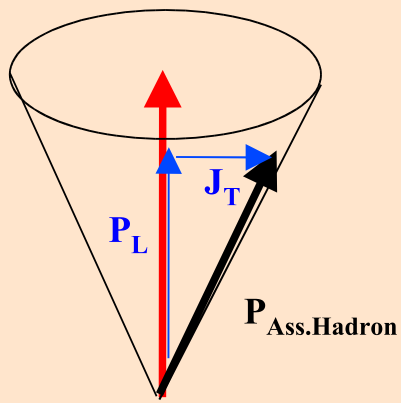


- Data show stronger ϕ dep. than PQM model

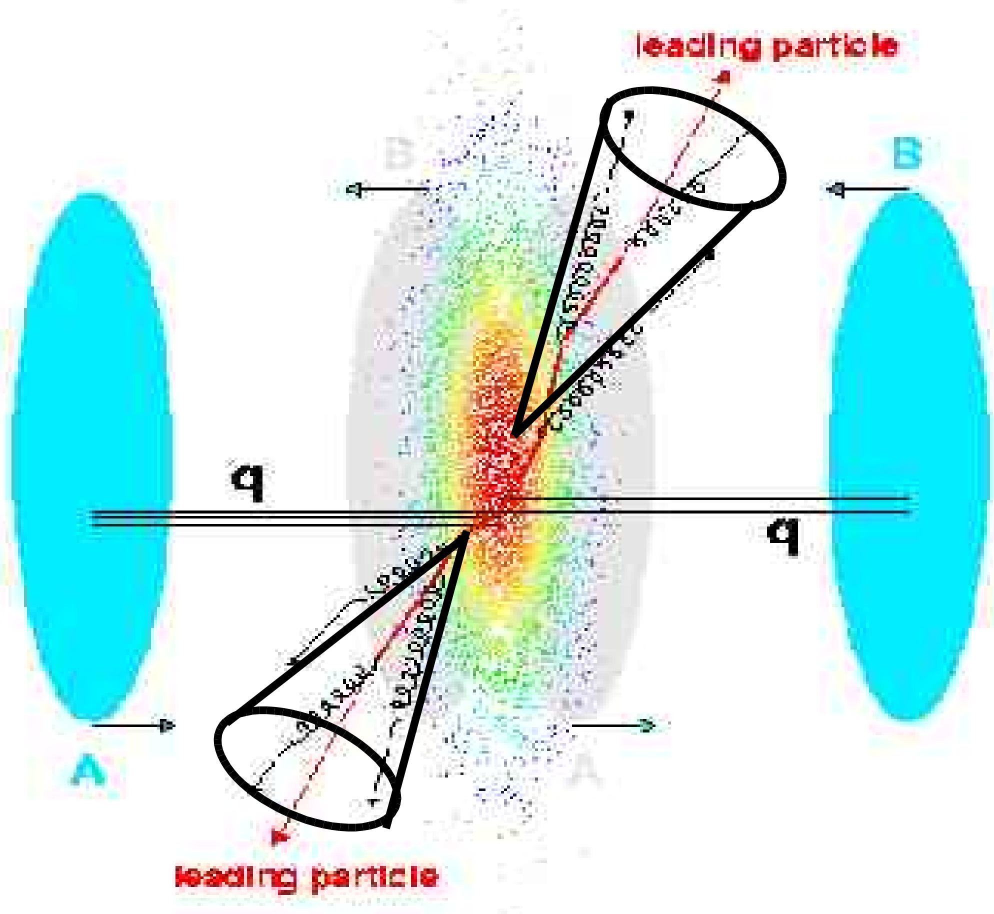
- Note: model is not $\Delta E \propto L^2$, rather $\Delta E \propto L$
- * ***Beware:*** effect of collective flow on R_{AA} vs ϕ !?!

Motivation for reconstructed jets in A+B

- Reconstructed jets allow one to measure the 4-momentum of the original parton
- The associated particles measure the jet structure



- Ideally: Map out observables as function of jet (parton) energy

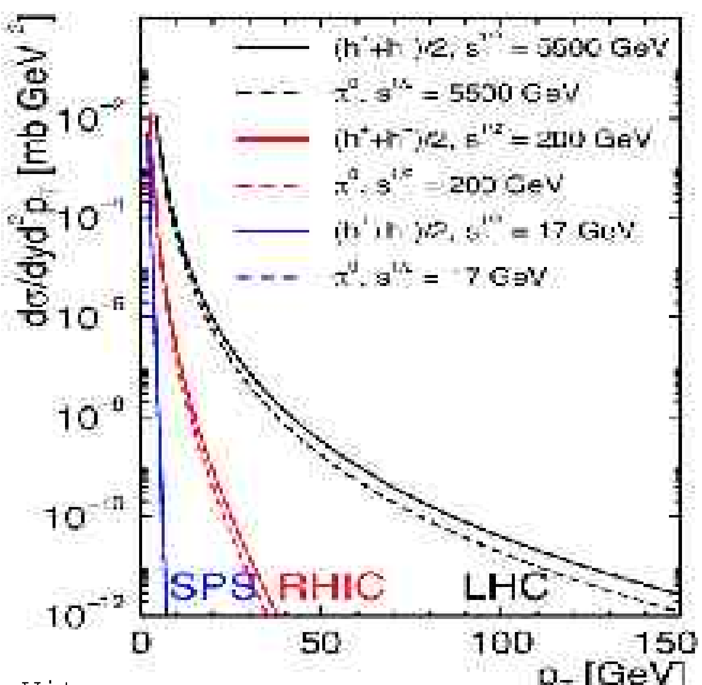


LHC provides factor 30 jump in cms energy w.r.t. RHIC

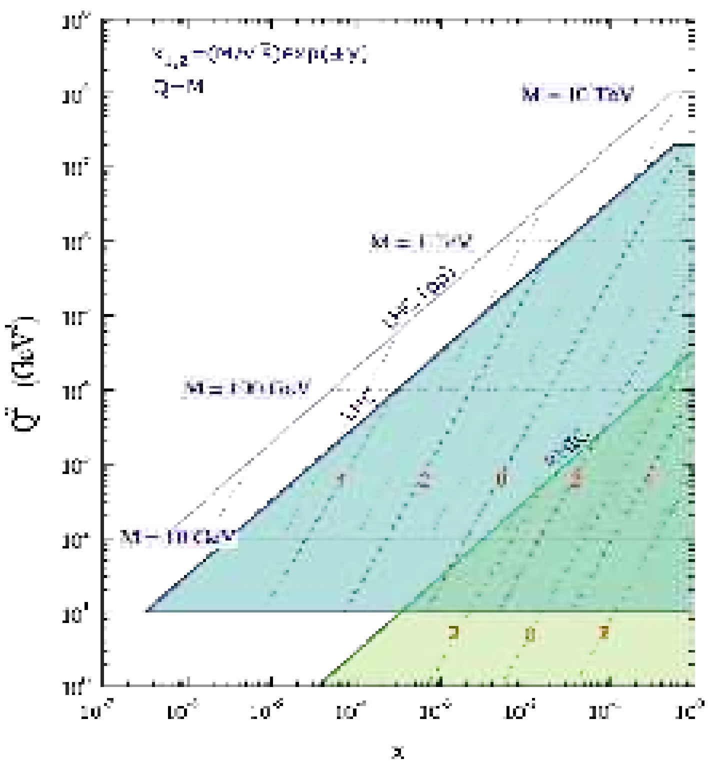
Larger "dynamic" range implies:

- QGP even more dominant compared to final-state hadron interactions
- Higher ε_0 at earlier time τ_0 (sQGP $\rightarrow$ QGP?)
- Main novalities: Plentyful hard processes and wide kinematical window

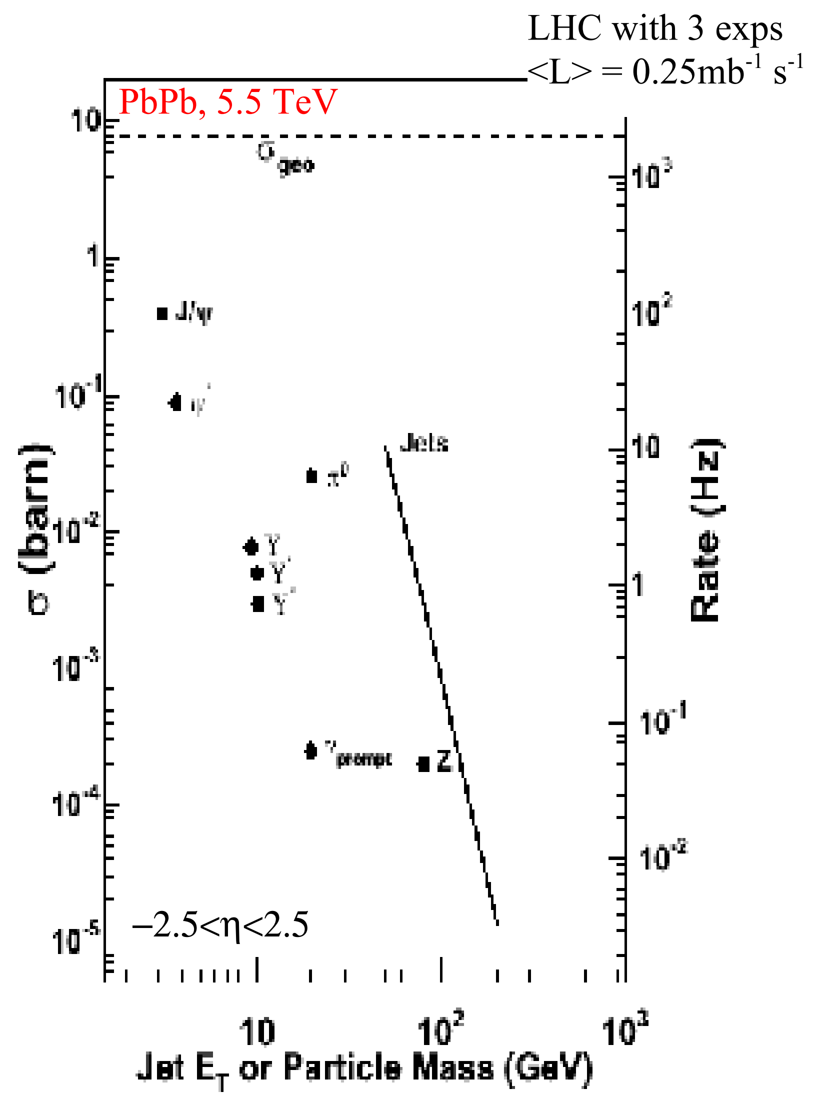
Leading hadron spectrum



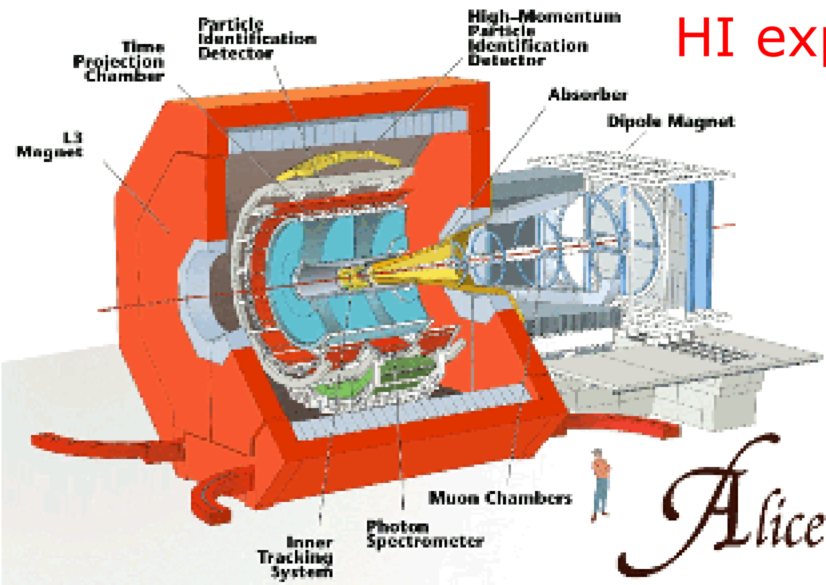
Vitev, hep-ph/0212109



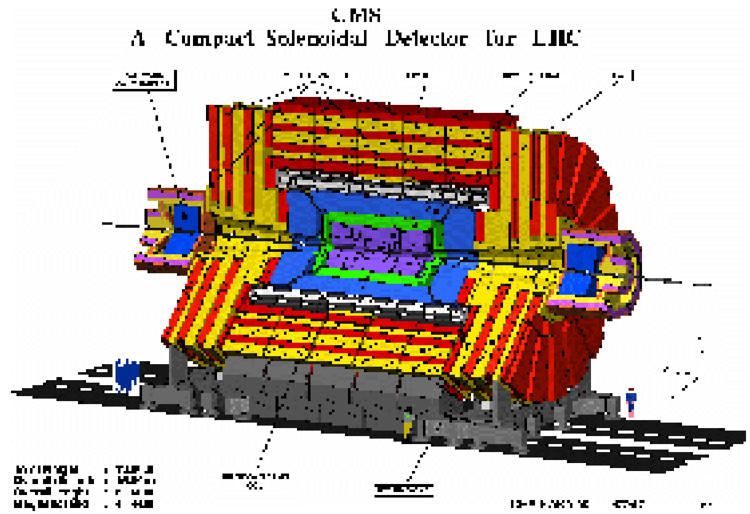
- Medium modification at high p_T
  - "Mass" production of high p_T particles (also containing heavy flavours)
- Melting of members of Υ family
  - Large cross section for *J/ψ* and Υ family production
- Medium effects on jets
  - Jets shape and jet fragmentation modified by the medium
  - Jet tomography
  - Dijet/monojet ratio
  - Jet-γ and Jet-Z^0
  - B-tagged jets
  - Multi jets



ALICE: dedicated HI experiment

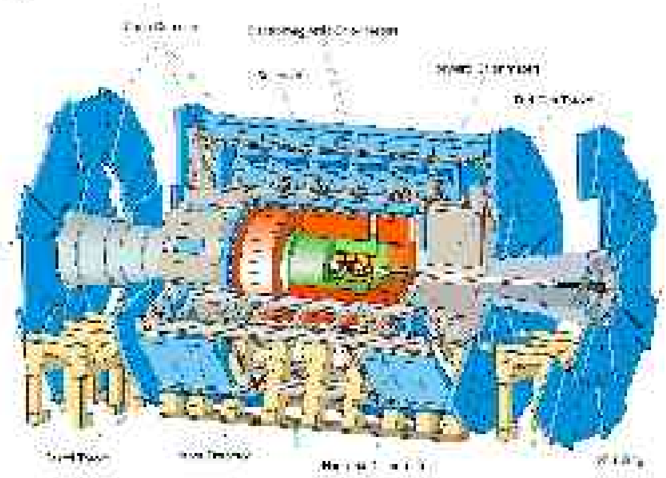


$-0.9 < \eta < 0.9$, $p_t > 0.2$ GeV, PID



CMS: pp experiment with HI program

$|\eta| < 2.5$, $p_t > 1$ GeV+~1%resolution, full calorimetry ($|\eta| < 5$), high rates



ATLAS: pp experiment, HI proposal in progress

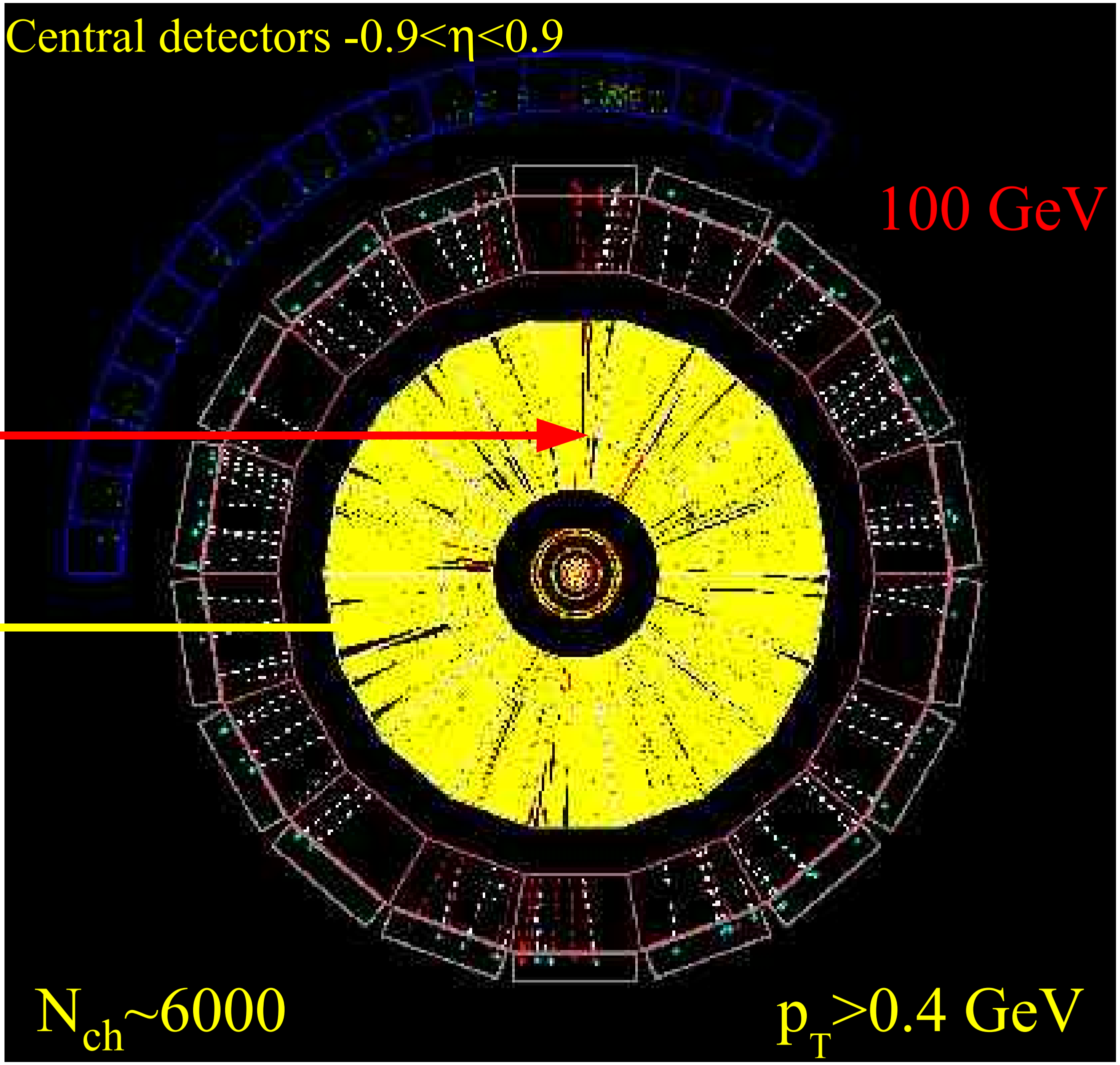
100 GeV Jets in ALICE (Pb+Pb at 5.5 TeV)

High-energy jets produced within central Pb+Pb collisions

Signal

Background

HIJING quenched

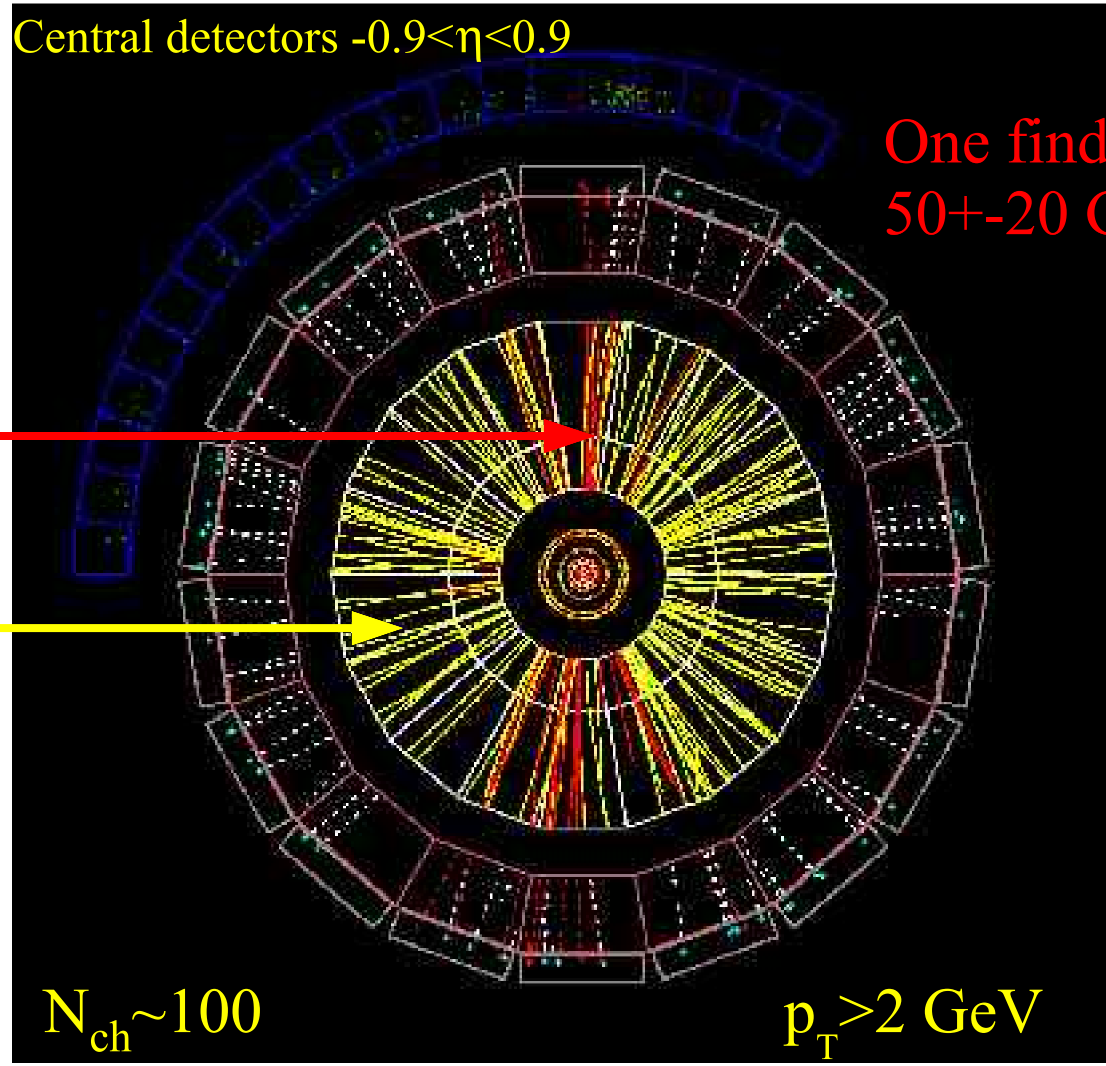


Jets in ALICE (Pb+Pb at 5.5 TeV)

High-energy jets produced within central Pb+Pb collisions

Signal

Background



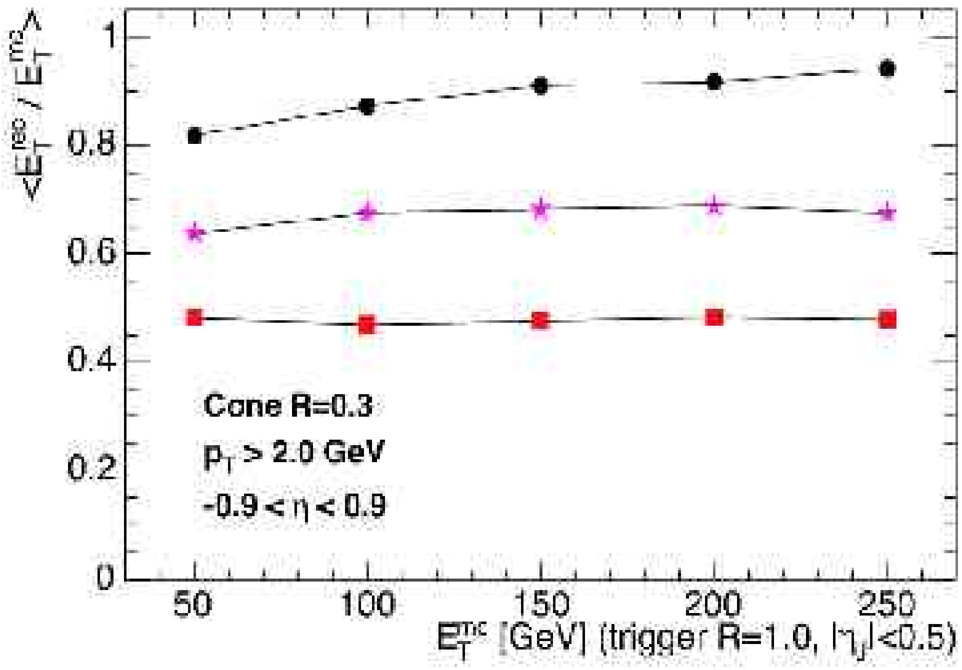
One finds
50+-20 GeV

Use R=0.3 (up to 0.5) and p_T-cut of 2 GeV for charged particles:

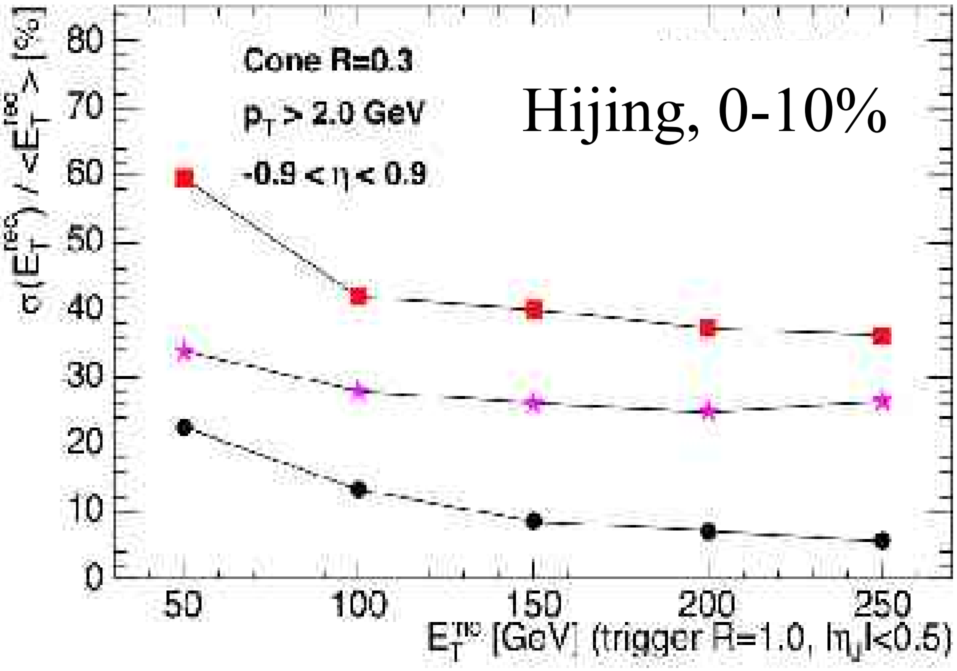
For 100 GeV one finds on average 50+-20 GeV

Monte Carlo: Jet reconstruction

Fraction of reconstructed energy



Rel. resolution of reconstructed energy



"CMS/ATLAS" type

"ALICE with EMCAL" type

"ALICE without EMCAL" type

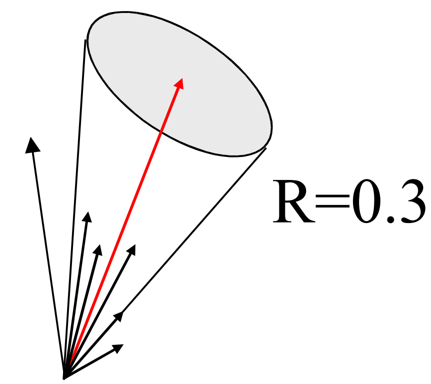
Between 50-100 GeV jets become identifiable objetcts.

C.L., nucl-ex/0501017

Consequences of small cone size

Reduced cone size & p_T-cut lead to less reconstructed energy and hence $\sigma(E_T)/\langle E_T \rangle$ increases

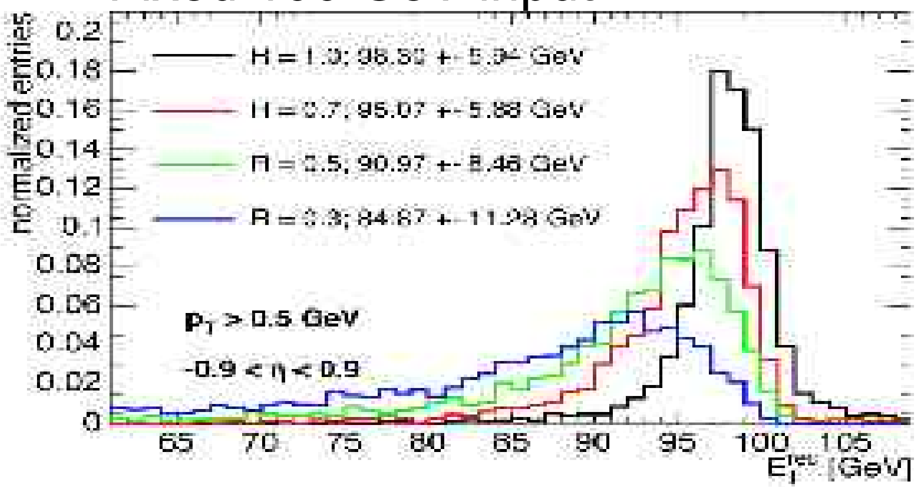
Also for full calorimetry



➡ Systematic underestimation of parton energy possible (~15% for 100 GeV)

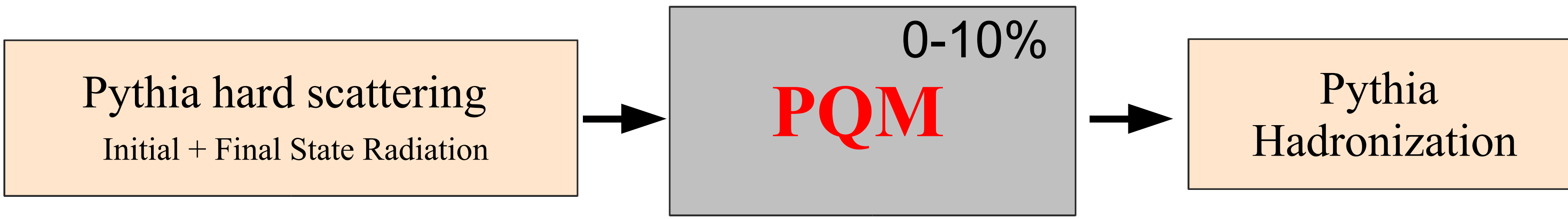
- $z=p_L/E_{jet}$ increases
- Corrections not obvious since shape of quenched jets is not known from pp

Fixed 100 GeV input



PYTHIA + PQM toy model

MC event generator combining consistently parton shower evolution and in-medium gluon radiation is not available.



Parton jet (E) → Parton jet (E-ΔE) + N gluons(ΔE/N)

Quenching of the final partonic jet system and radiation of $1 \leq N \leq 6$ additional gluons

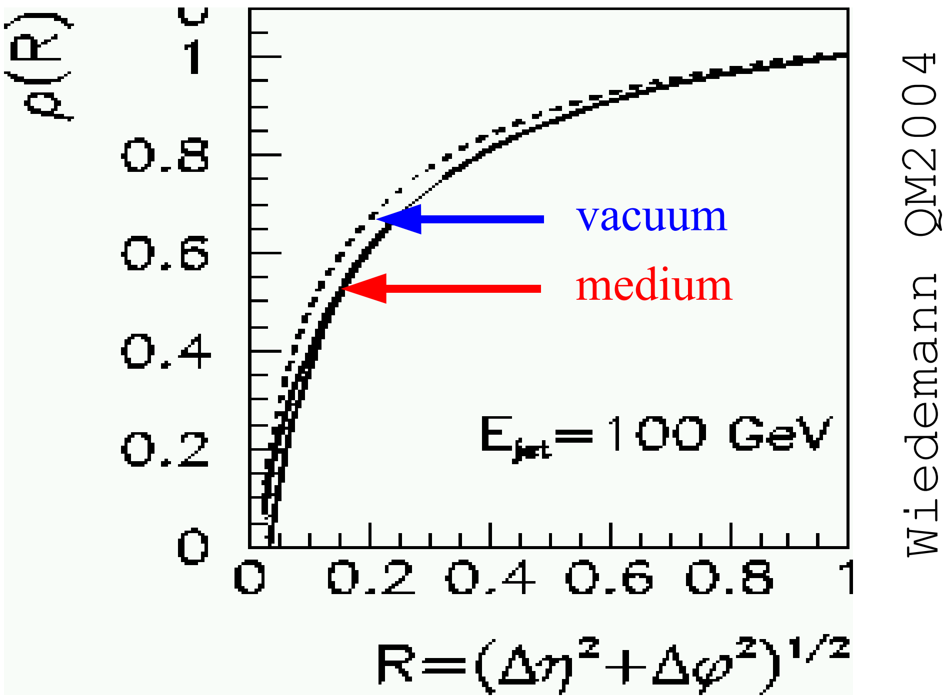
Use PQM for $\langle \hat{q} \rangle$ =1.2, 12 and 24 GeV^2 / fm

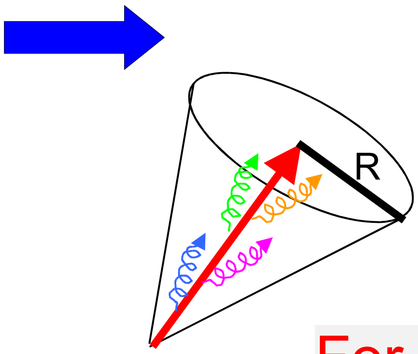
Embed quenched jets into 0-10% central HIJING events

Medium induced out-of-cone radiation

Crucial question: Does or how much of the medium-induced radiated energy remains inside the cone?

Note: See also Vitevs talk, who says the effect can be up to 50% !





Most energy radiated INSIDE cone

For 100 GeV
- 85% at R=0.3
- ~100% at R=0.7

Caveat: Calculation only at parton level and for low medium density.

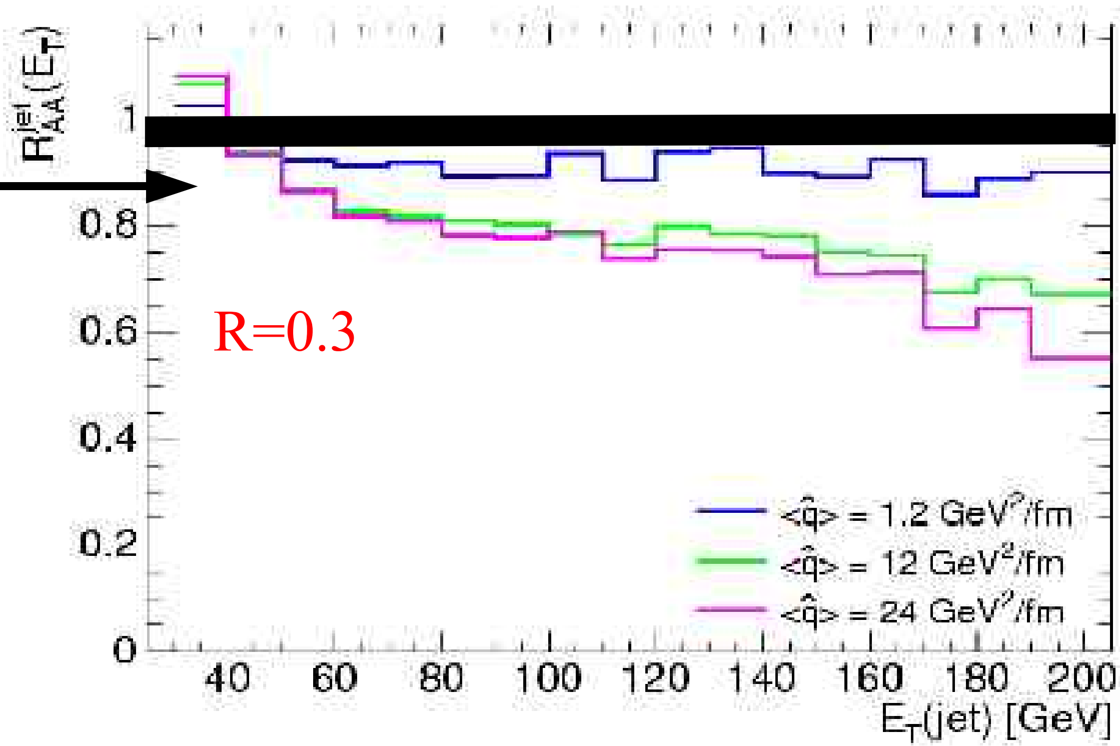
SW PRL93 (2004) 042301

$$R_{AA}^{Jet} = \frac{1}{\langle N_{coll} \rangle_C} \times \frac{\mathrm{d}N_{AA}/\mathrm{d}E_T}{\mathrm{d}N_{pp}/\mathrm{d}E_T}$$

Implicitly depends on R

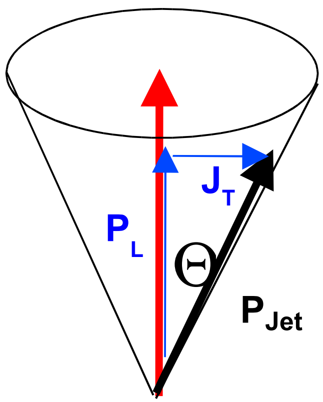
Most direct measurement, however need to control background and need calorimetry

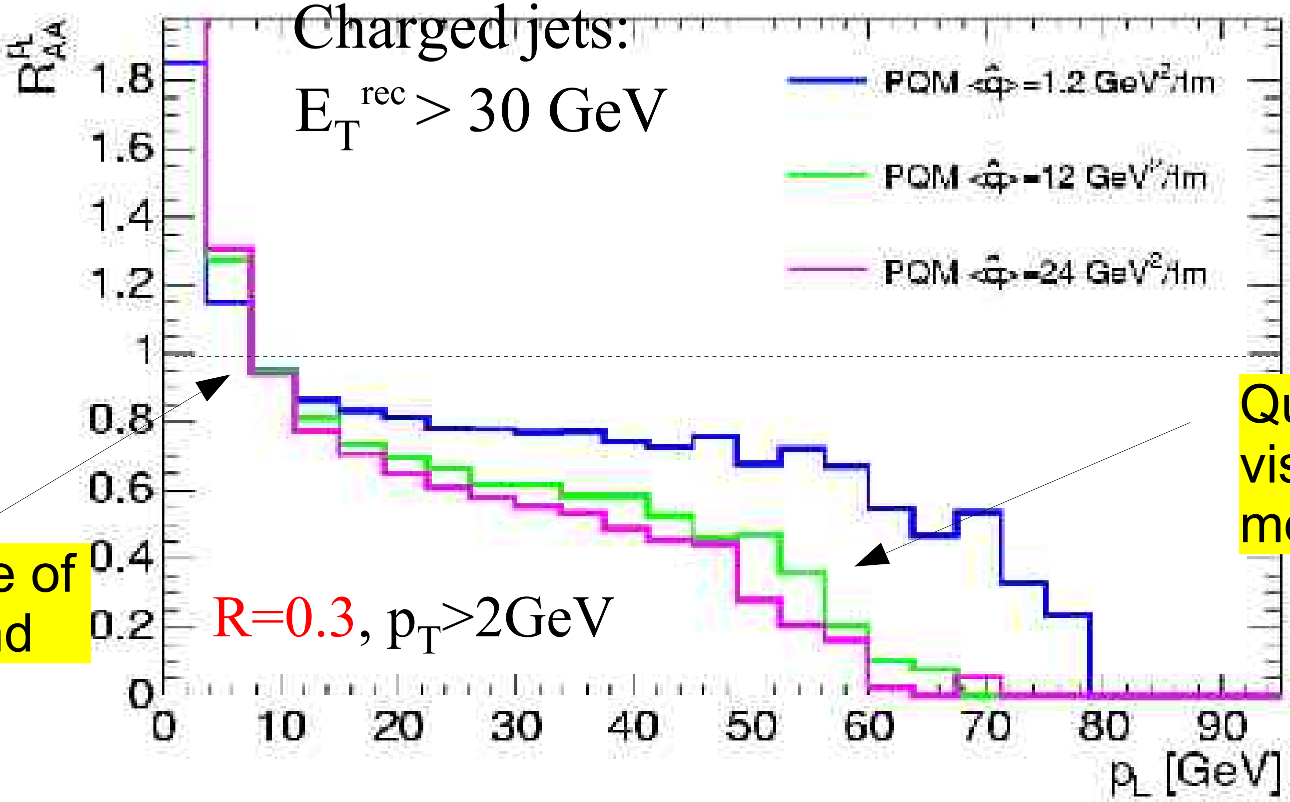
Influence of soft background and quenched jets overlap



Modification of longitudinal particle distribution

$$R^{p_L}_{AA}(p_L) = \frac{1}{N_{jets}} \times \frac{\mathrm{d}N_{jet\,in\,AA}/\mathrm{d}p_L}{\mathrm{d}N_{jet\,in\,pp}/\mathrm{d}p_L}$$

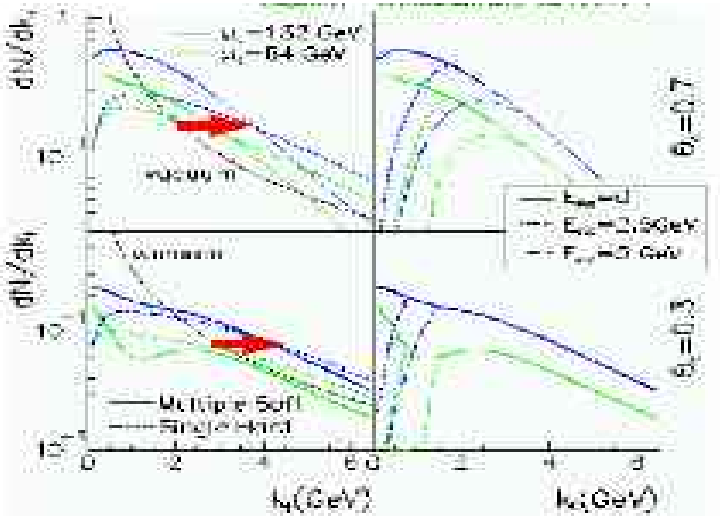




Slight influence of soft background

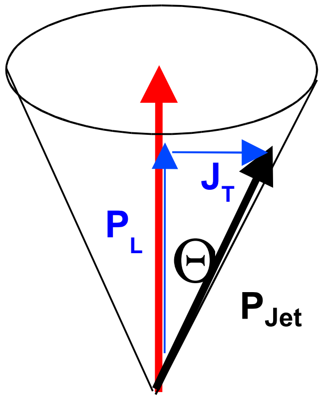
Quenching effect visible in high momentum region

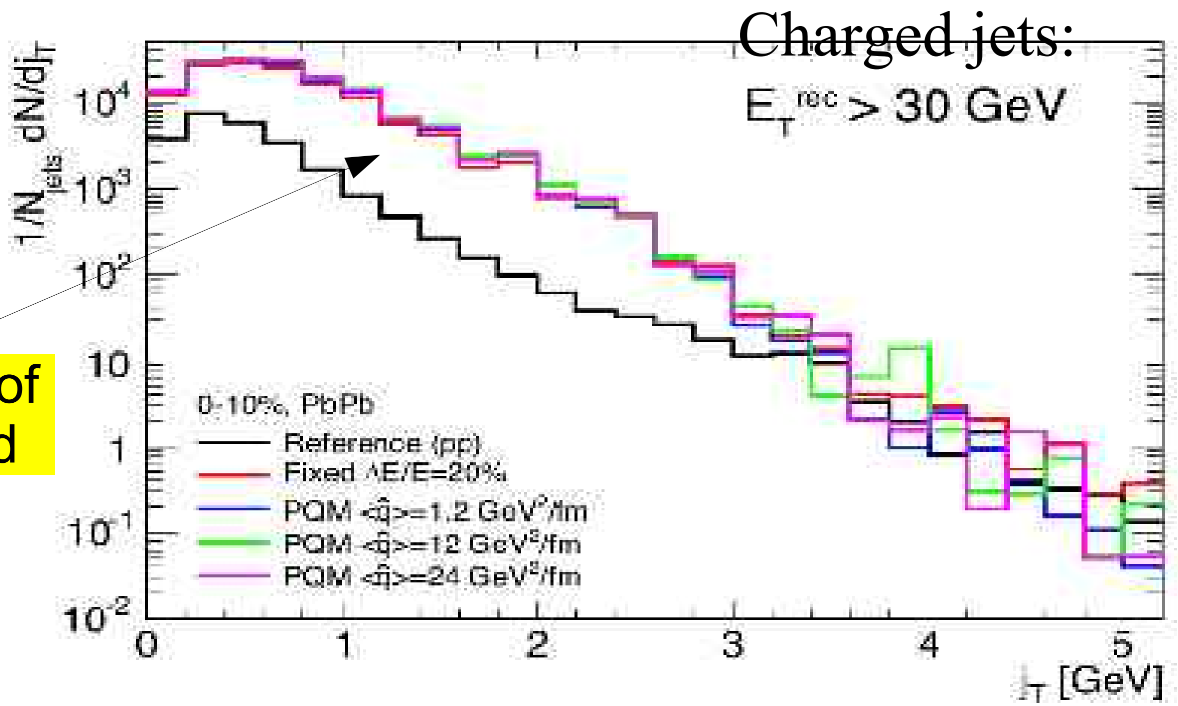
Transverse fragmentation



SW PRL93 (2004) 042301

Theory predicts k_T-broading (not implemented in the afterburner)





Pure influence of soft background

Summary

- PQM combines the BDMPS framework with Glauber geometry for calculation of high-p_t suppression
  - Strong medium effect expected at LHC
  - R_{AA} prediction for LHC is independent of p_t
- At LHC, jets can be identified on top of background starting 50-100 GeV; resolution depends on type of detector and heavy-ion background (centrality)
- R_{AA} for jets or modification of jet fragmentation can be modelled in MC; detailed detector simulations needed.