Ruprecht-Karls-Universität Heidelberg

Jet and High pT Physics

: review of Trento workshop

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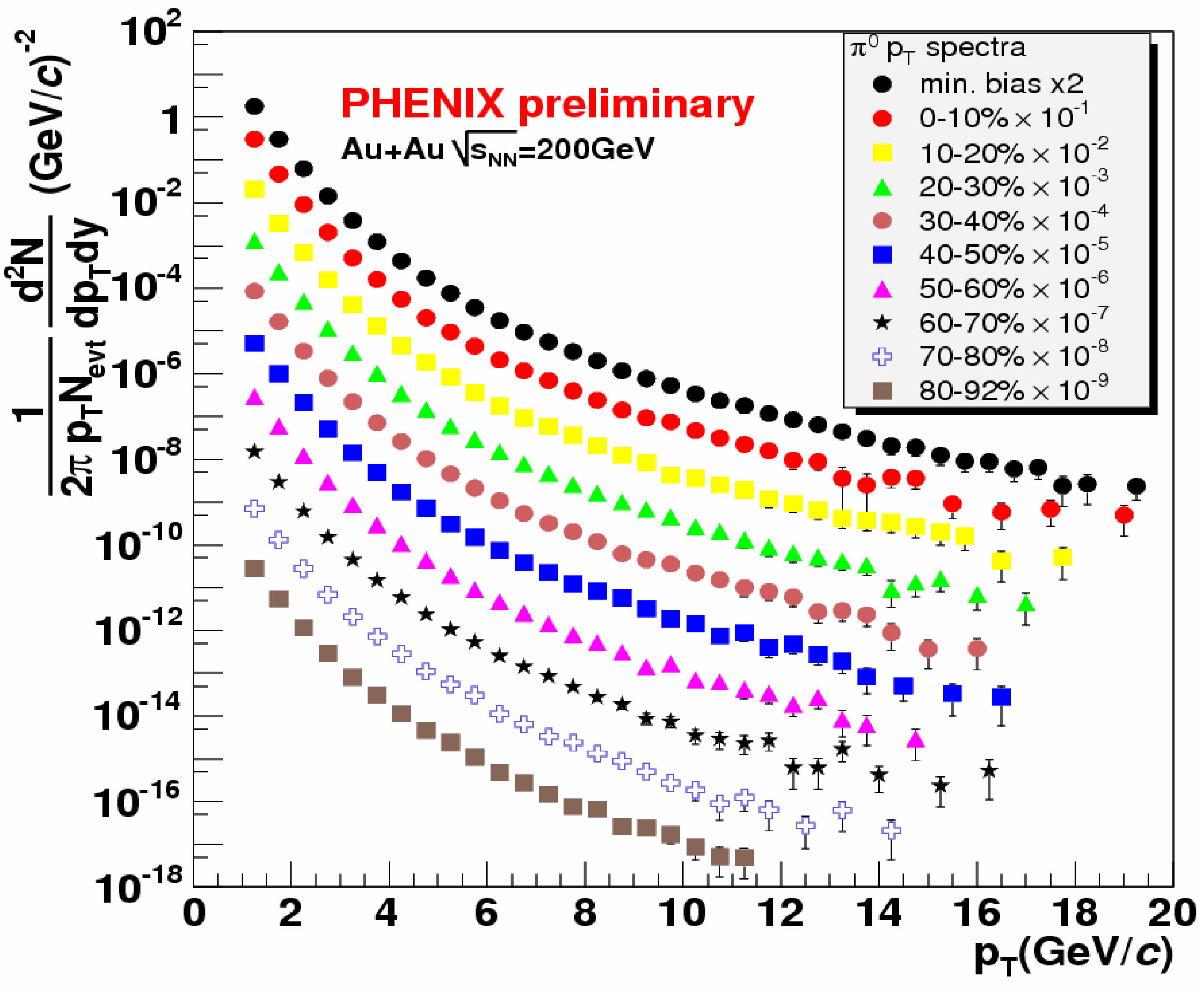
Universitaet Heidelberg

PI Lunch Meeting, Nov. 09. 2006.

What we’ve seen recently

Single hadron production
PHENIX: Au-Au High-p_T π^0 Suppression



We are now measuring out to truly high p_T

Single hadron production

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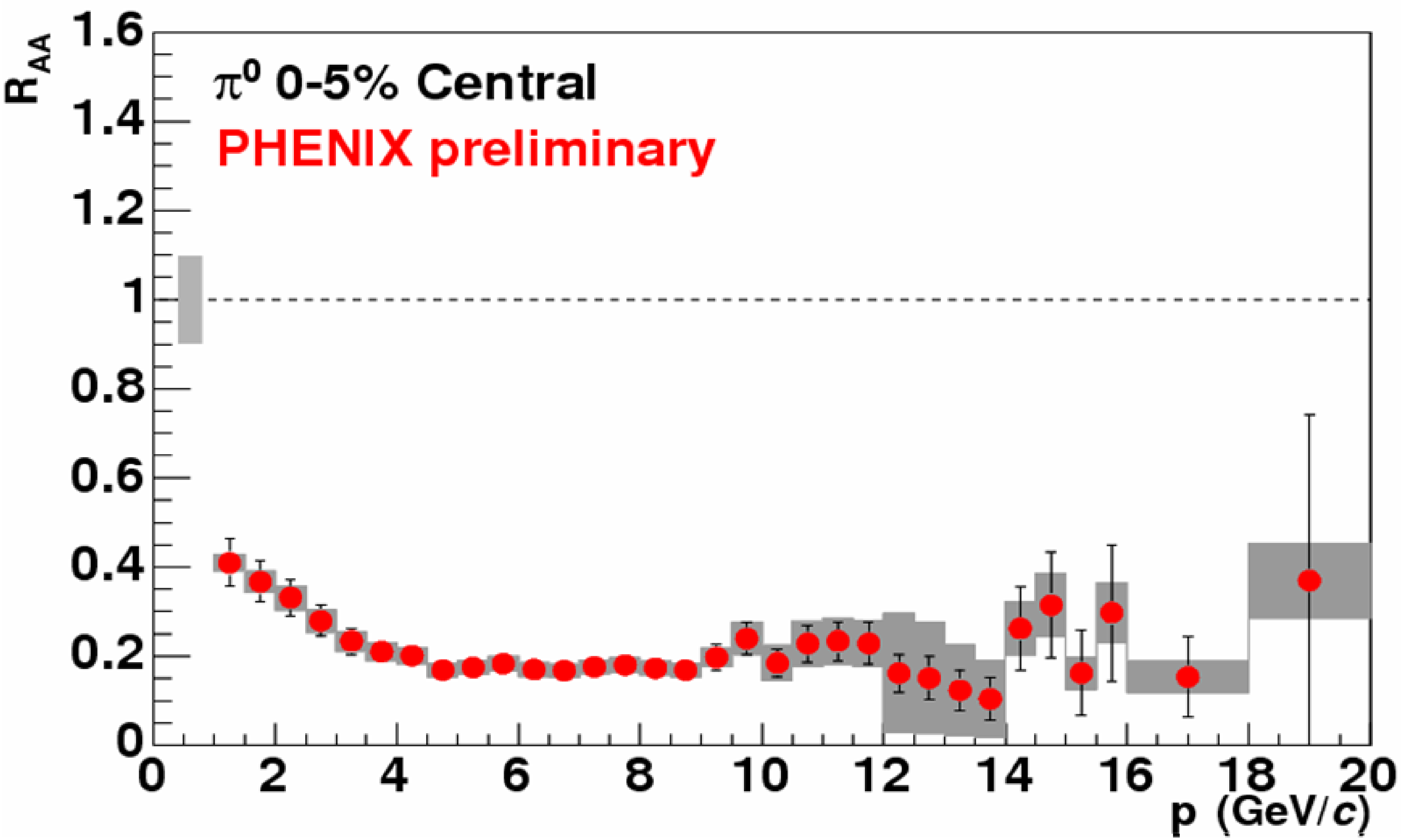
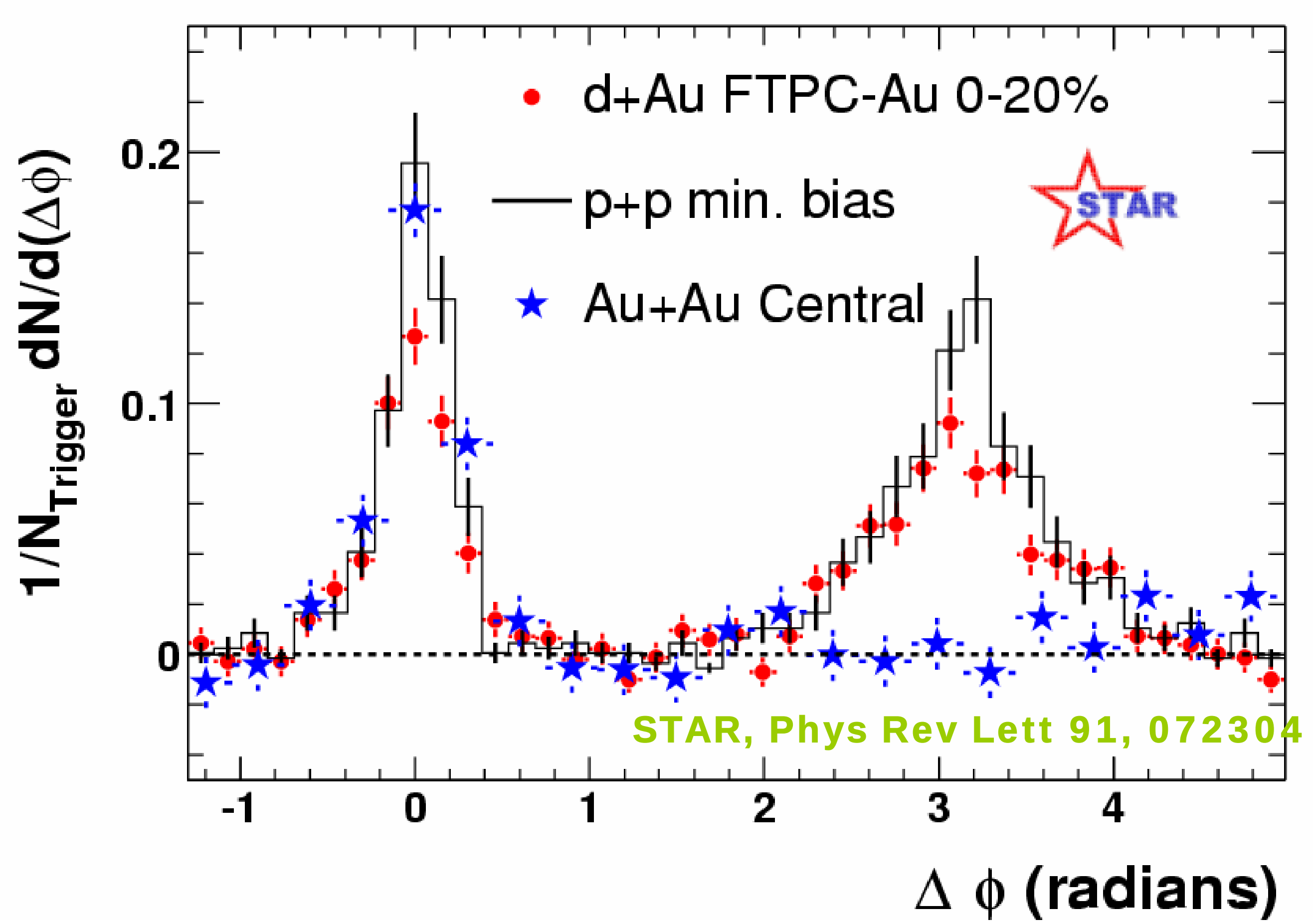


– **What does this suppression tell us?**

Di-hadron correlations at higher p_T

STAR: Au+Au recoiling hadrons suppressed



Compare to d+Au: suppression is final-state effect

What do we want to learn about from measuring such as

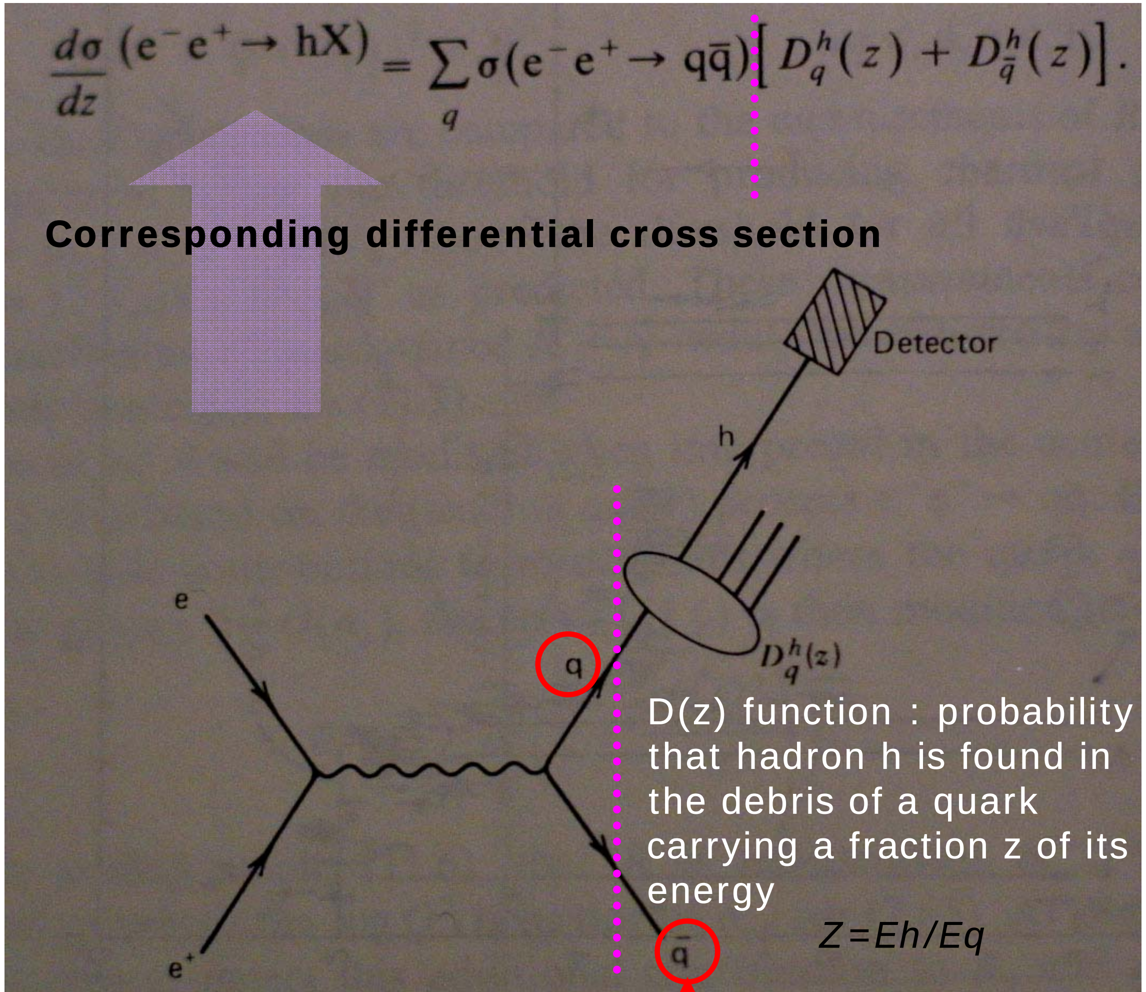
* single high-p_T hadron production
*Azimuthal correlations at higher p_T
etc… more will be listed.

In Heavy Ion Collision

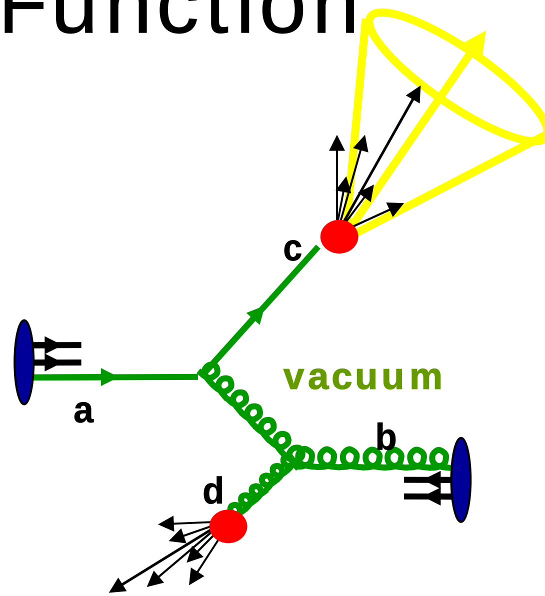
Contents

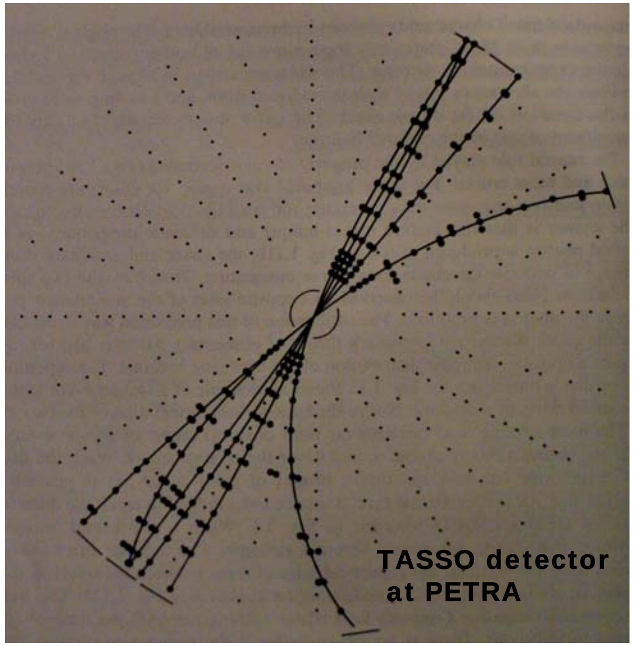
- What are the jets?
- Jet fragmentation function
- Jets in medium (jets in heavy-ion collision)
- Energy loss models in medium
- What can be the observables for this study?
- Result from RHIC, Jet at LHC
- Jet reconstruction algorithm in ALICE
- Some (additional) interesting measurements
- Future of jet quenching

Jets and Fragmentation Function



Partons from initial hard scattering

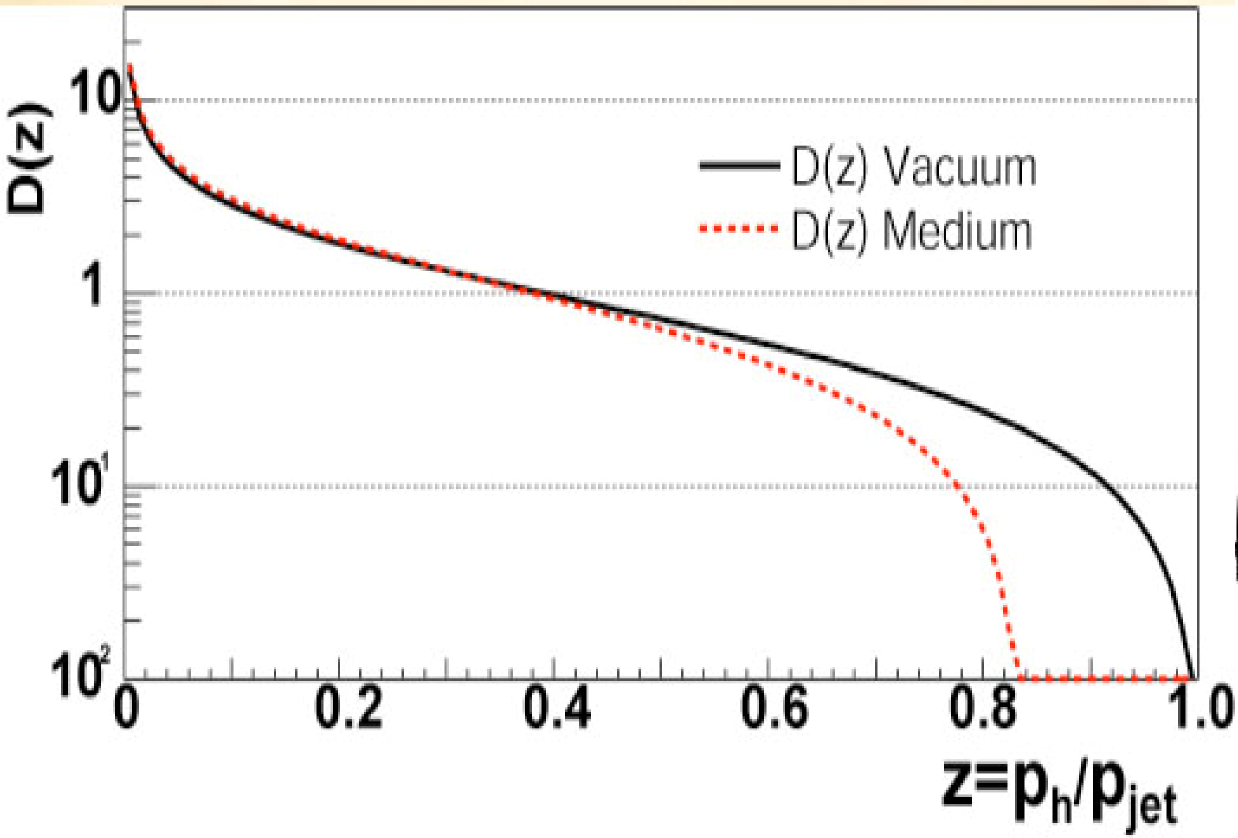


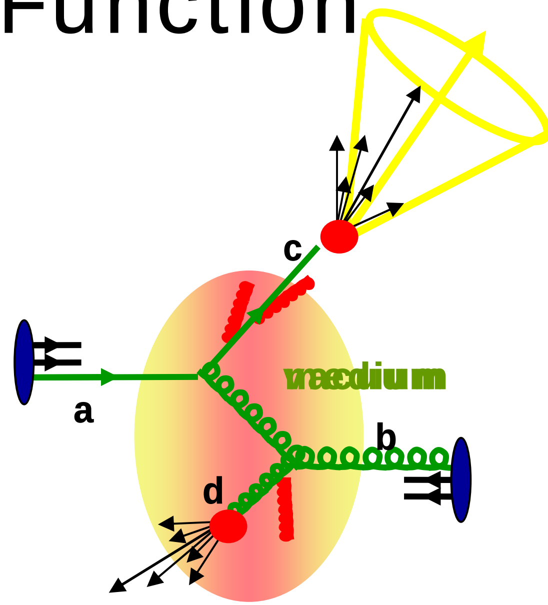


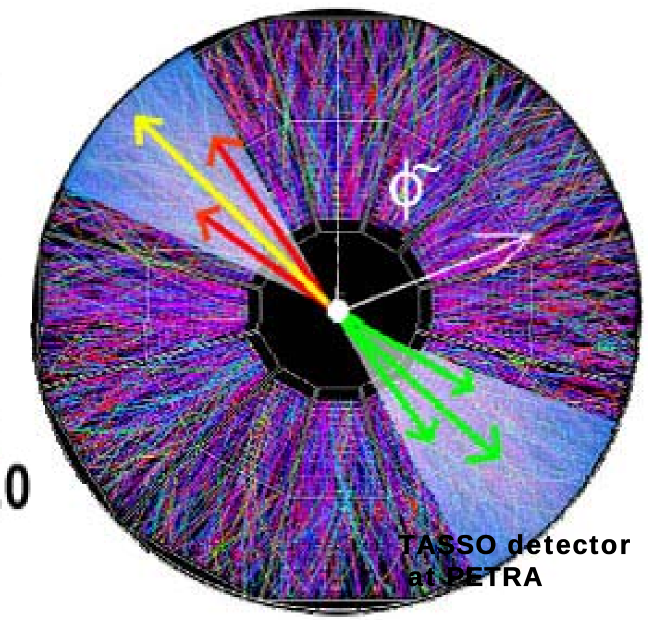
Jets and Fragmentation Function

Gyulassy, Vitev, Wang and Zhang

nucl-th/0302077







Jet Quenching in QCD Medium

Fermi National Accelerator Laboratory

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

High energy nucleus-nucleus collisions: Allow us to

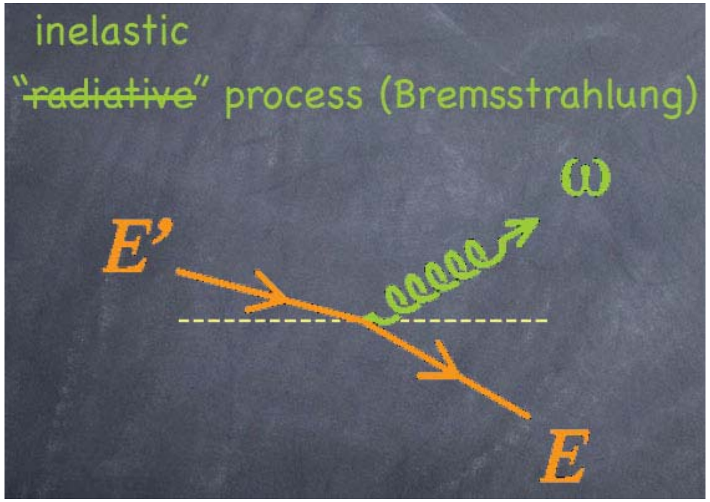
*** Change the scene of parton fragmentation from vacuum to a QCD medium**

*** Study the properties of this medium through <u>modification</u> of the jet-structure**

Due to parton energy loss?

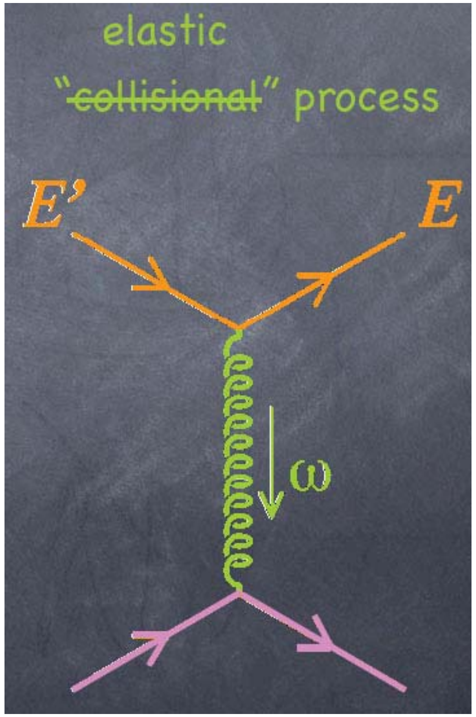
Models of high-p_T parton energy loss

Two different "categories" of models of parton energy loss, depending on the basic underlying process:



Theories and models of radiative energy loss

- **LPM-effect based approaches: BDMPS-Z & AMY**
- **Opacity expansion: GLV; (AS)W**
- **Medium-enhanced higher-twist effects**
- **Medium-modified MLLA**

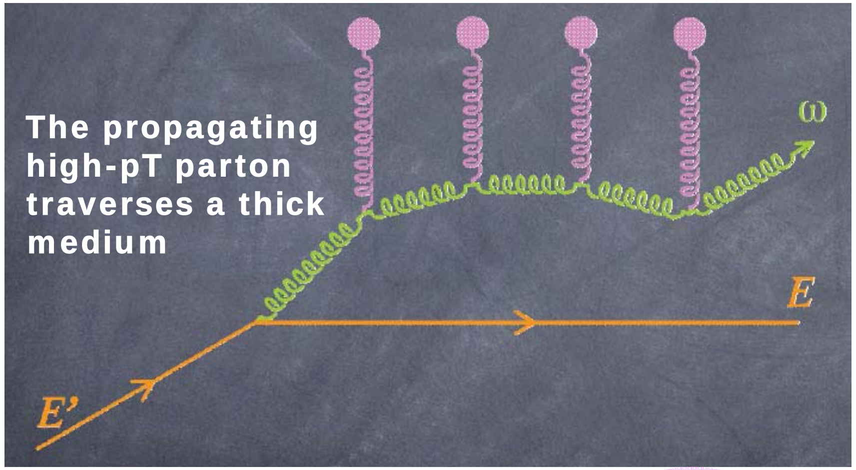


Theories and models of collisional energy loss

- **Regards as negligible!**
- **BUT => it is sizable?**

Energy loss by multiple soft scattering

: Models based on the Landau-Pomeranchuk-Migdal effect



It radiates soft gluons, which scatter coherently on independent color charges in the medium, resulting in a medium-modified gluon energy spectrum

Medium properties can be characterized by a single constant : BDMPS, AMY

e.g. transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$ ‘average k_T-kick per mean-free-path’

$$\omega \frac{dI_{LPM}}{d\omega dz} = \left(\frac{\lambda}{l_{coherent}} \right) \omega \frac{dI_{\text{Bethe Heitler}}}{d\omega dz} = \sqrt{\frac{\hat{q}}{\omega}} \frac{\alpha_S N_C}{\pi}$$: Gluon radiation spectrum

$$\Delta E_{med} = \int^{L} dz \int^{\omega_C} d\omega\, \omega \frac{dI_{LPM}}{d\omega dz} \sim \alpha_S \sqrt{\hat{q}\omega_C} L \sim \alpha_S \hat{q} L^2$$

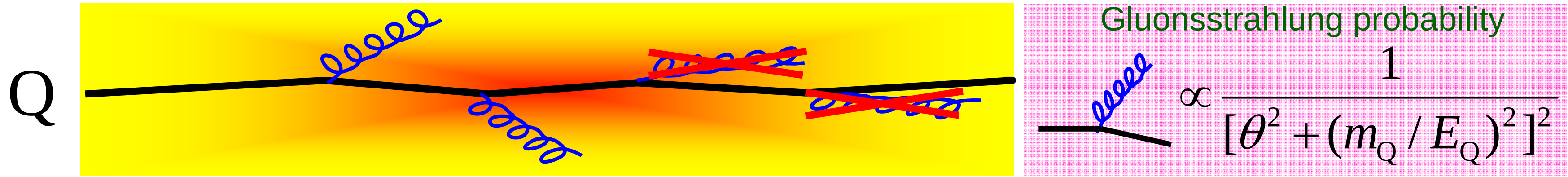
ΔE ∝ L^2 for a static medium

Longitudinal expansion reduces ΔE~L^2 to ΔE~L

Heavy Quark Energy Loss

“Dead cone” effect for heavy quarks:

in vacuum, gluon radiation suppressed at $q < m_Q/E_Q$



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

in medium, dead cone implies lower energy loss

Baier, Dokshitzer, Mueller, Peigne‘, Schiff, NPB 483 (1997) 291. Salgado, Wiedemann, PRD 68(2003) 014008.
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.

So, now we understand that

- Medium energy loss leads to a reduction in the pT of both the partons and their fragments and hence a reduction in the number of partons or fragments at a given pT
- So, jet tomography and high pT hadron spectra are useful and powerful tool for studying properties of medium created in heavy-ion collisions

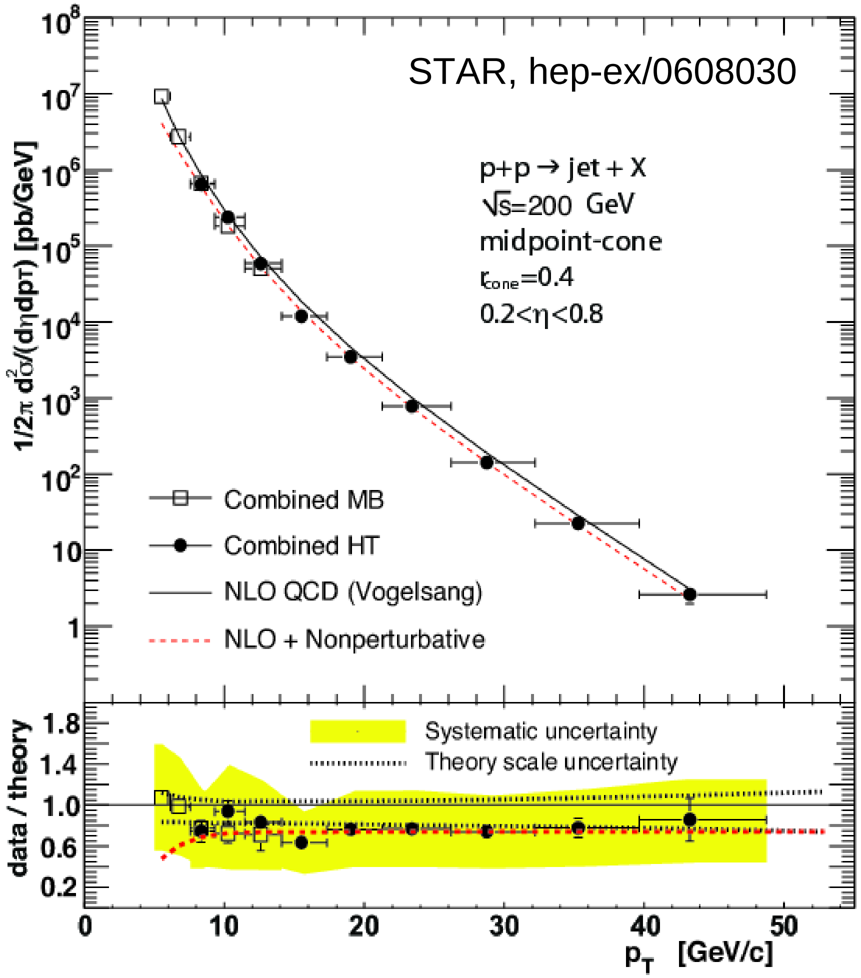
What can be the observables?

- How do we test it and alternatives?
  - Inclusive hadron suppression
  - Multi-hadron correlations (dihadron correlation, angular distribution)
  - Jet energy measurement
  - Systematic dependences on $\sqrt{s}$, p_T, system size, quark mass (heavy quarks, flavor dependence) ,...

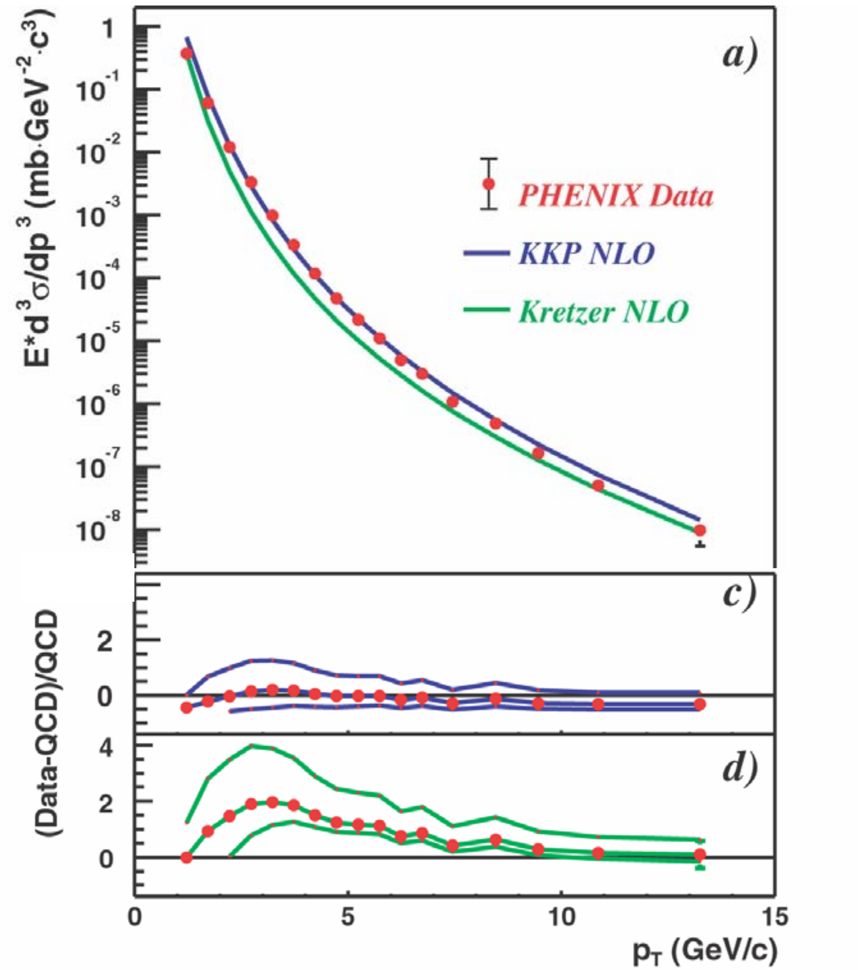
    $\Rightarrow$ Concentrate on highest available p_T

p+p jet and light hadron spectrum @ √s=200 GeV

First Reconstructed jets at RHIC



Light hadron production at RHIC

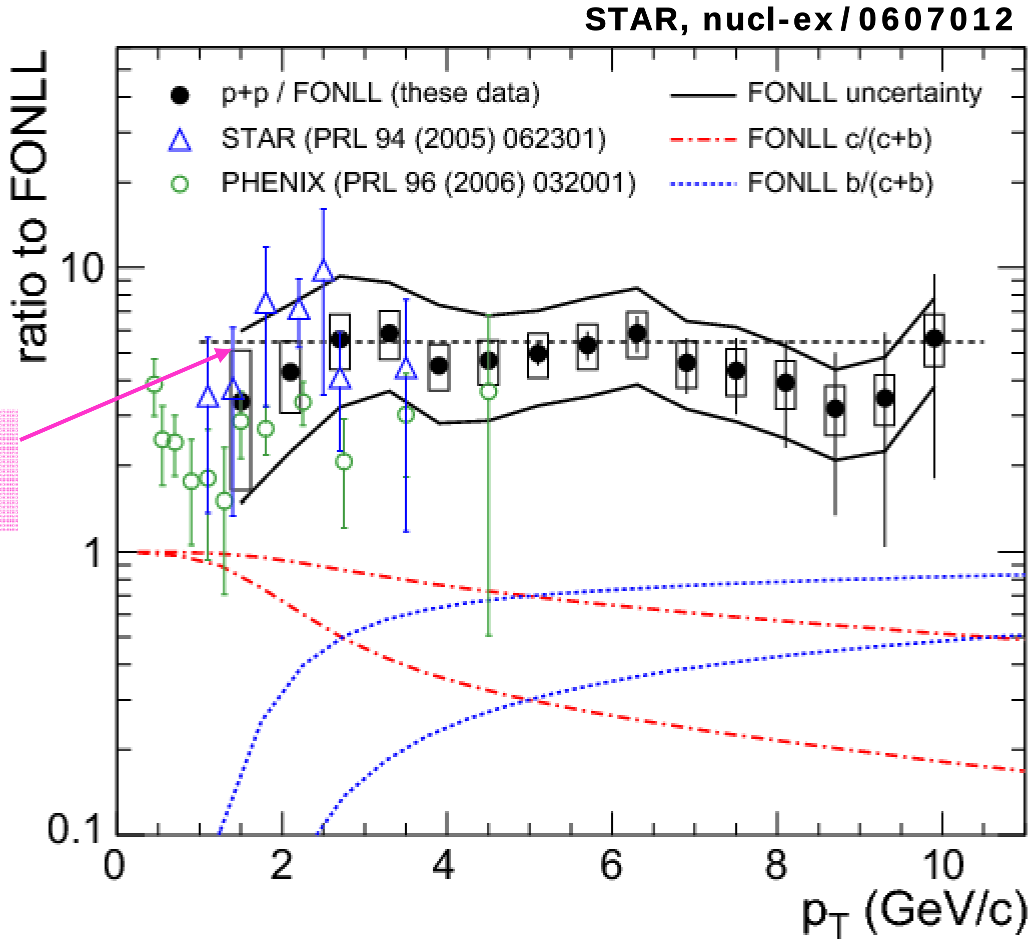


Measured spectrum agrees with NLO pQCD

Heavy quarks

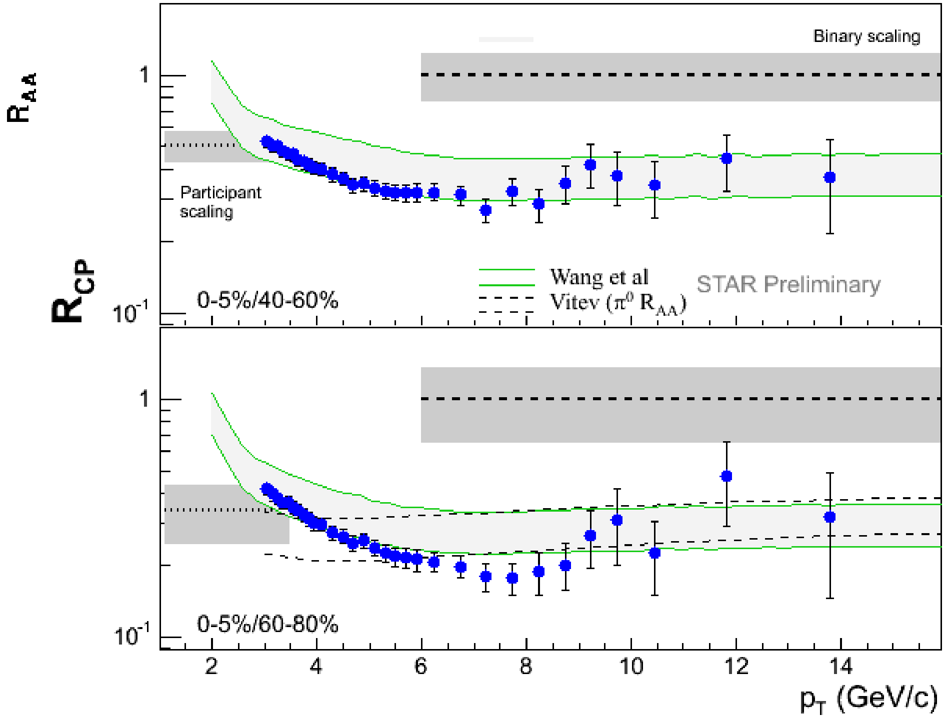
Non-photonic single electrons used to measure charm and bottom at high-p_T

Non-photonic electrons in p+p factor 5 above theory (FONLL)

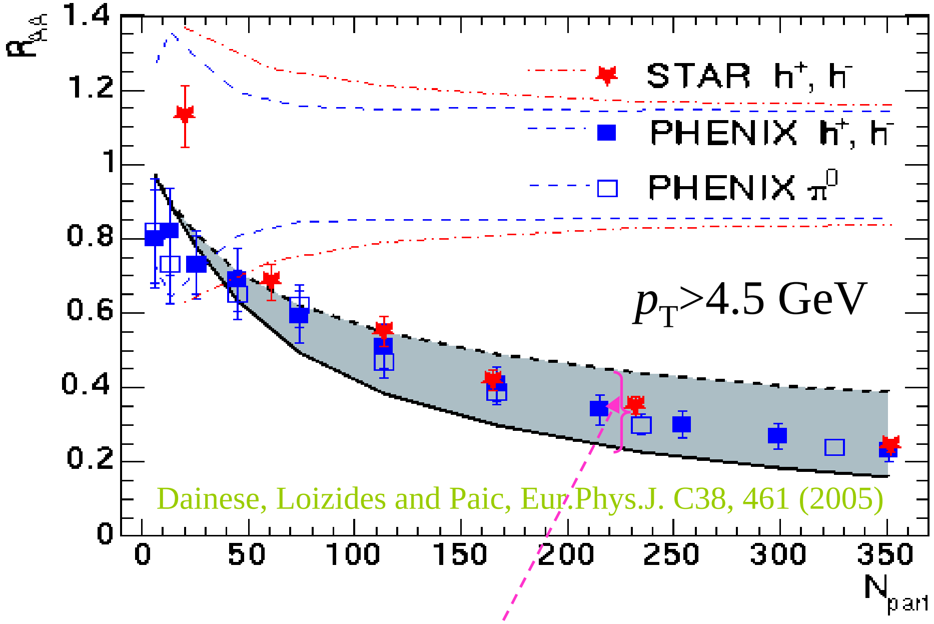


Hadron suppression: $\sqrt{s_{NN}}$=200 GeV Au+Au

Opacity, twist expansions



Multiple soft collisions



significant theoretical uncertainties

- p_T and centrality dependence broadly described by both theoretical approaches
- Energy/gluon densities: dN^g/dy=1100, $\hat{q}$=14-15

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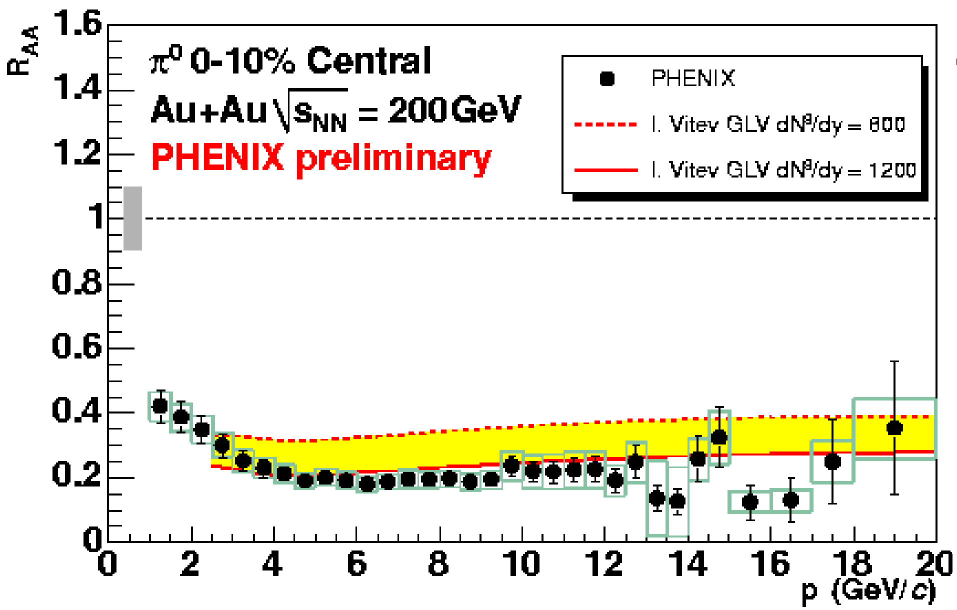

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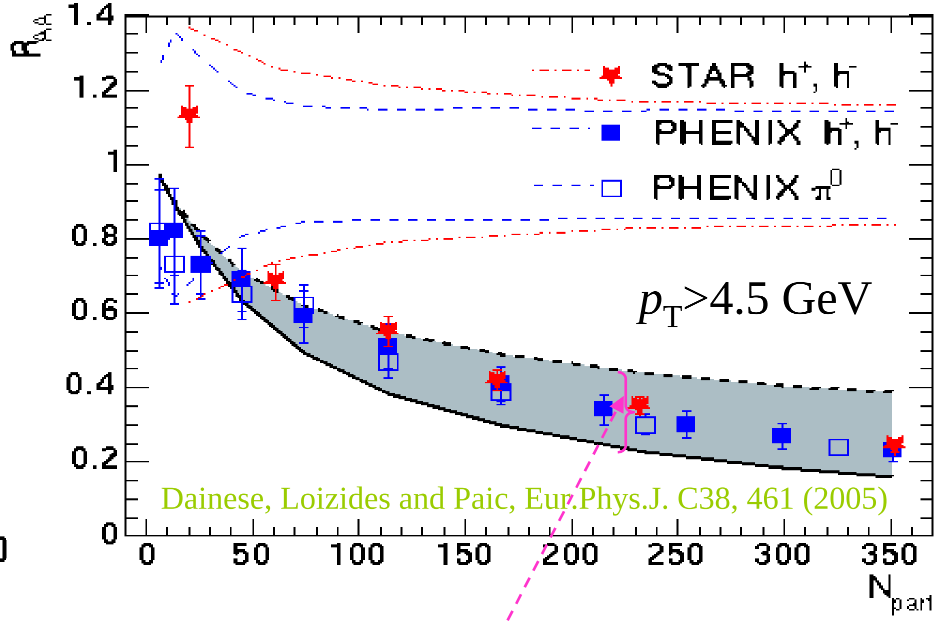

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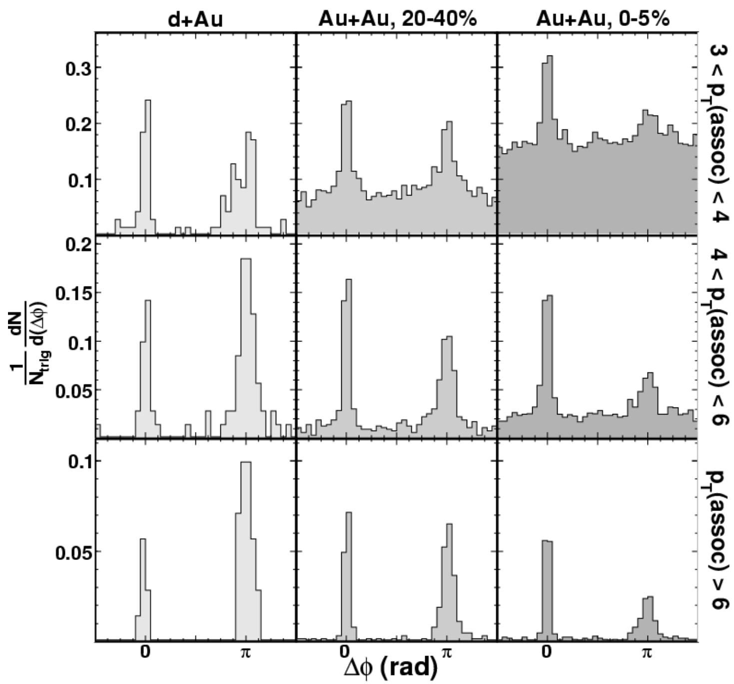
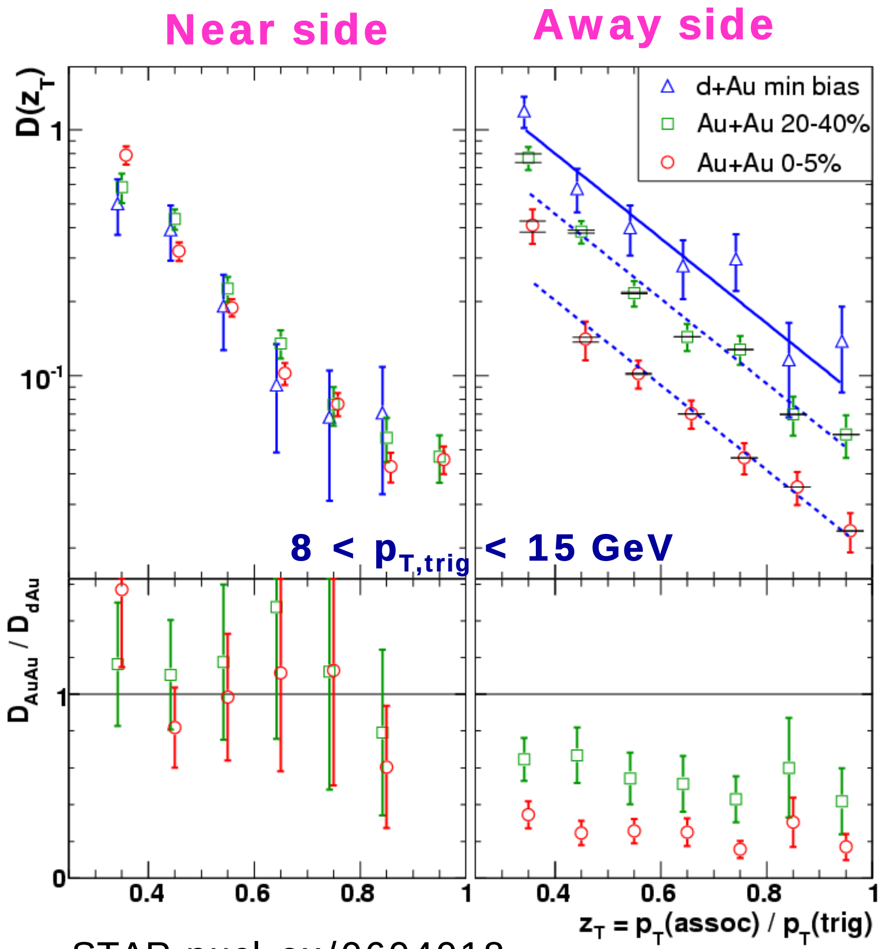
Di-hadron correlation and fragment. function





STAR nucl-ex/0604018

Di-hadron fragmentation function (X.-N. Wang) :

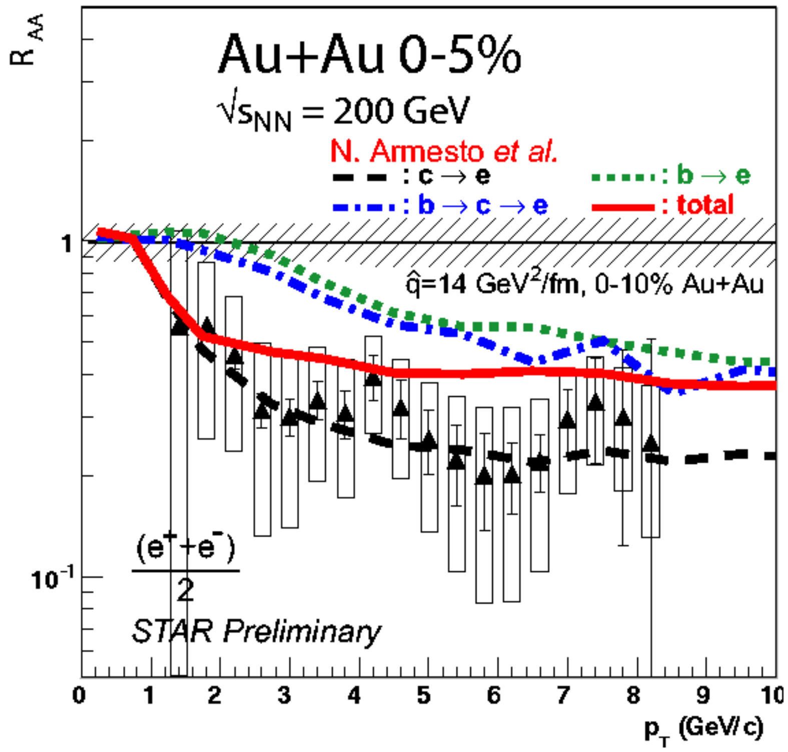
$$D^{h_1h_2}\left(z_T, p_T^{trig}\right) = p_T^{trig}\,\frac{d\sigma_{AA}^{h_1h_2}/dp_T^{trig}dp_T}{d\sigma_{AA}^{h_1}/dp_T^{trig}}$$

$$z_T \equiv \frac{p_T^{assoc}}{p_T^{trig}}$$

Near side: No modification

Away side: Suppression factor 4-5, no shape change

Heavy quark suppression (non-photonic electrons)



Suppression of non-photonic electrons larger than expected
Compatible with charm-dominance up to $p_T \approx 10$ GeV

Collisional energy loss?

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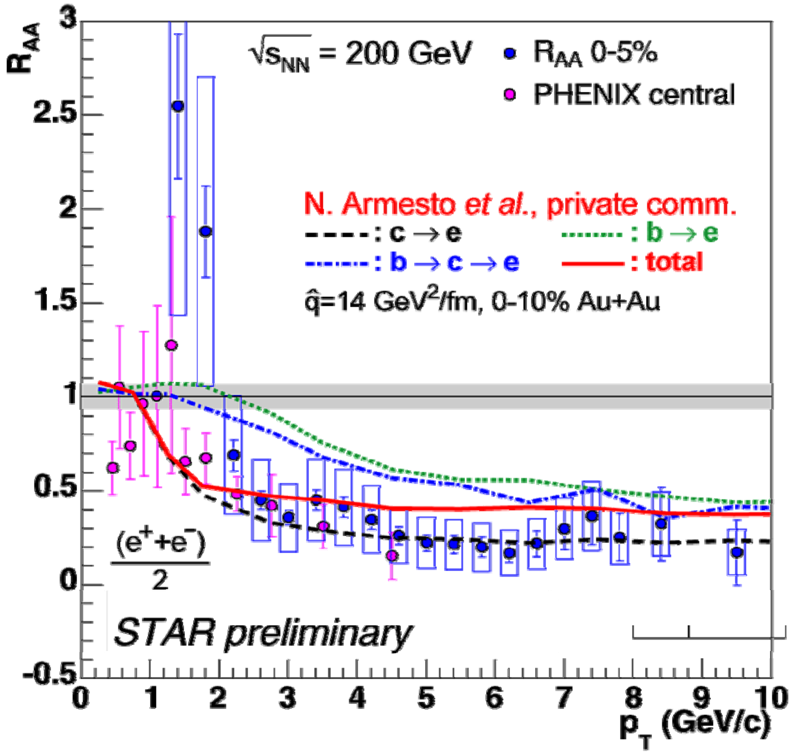

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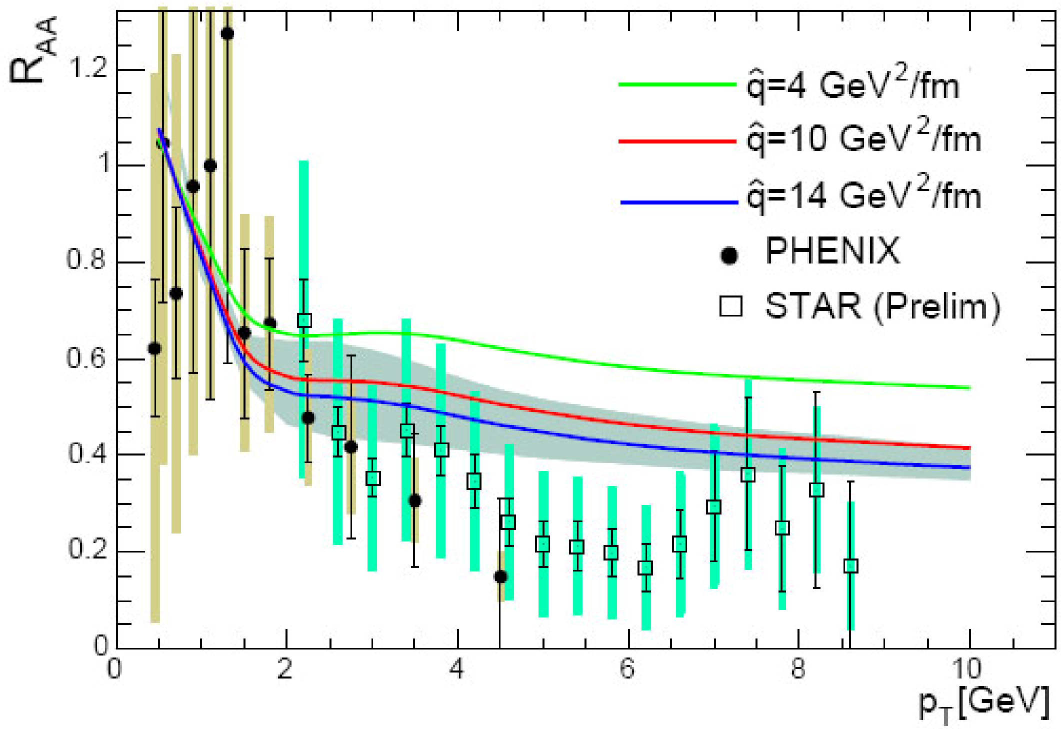
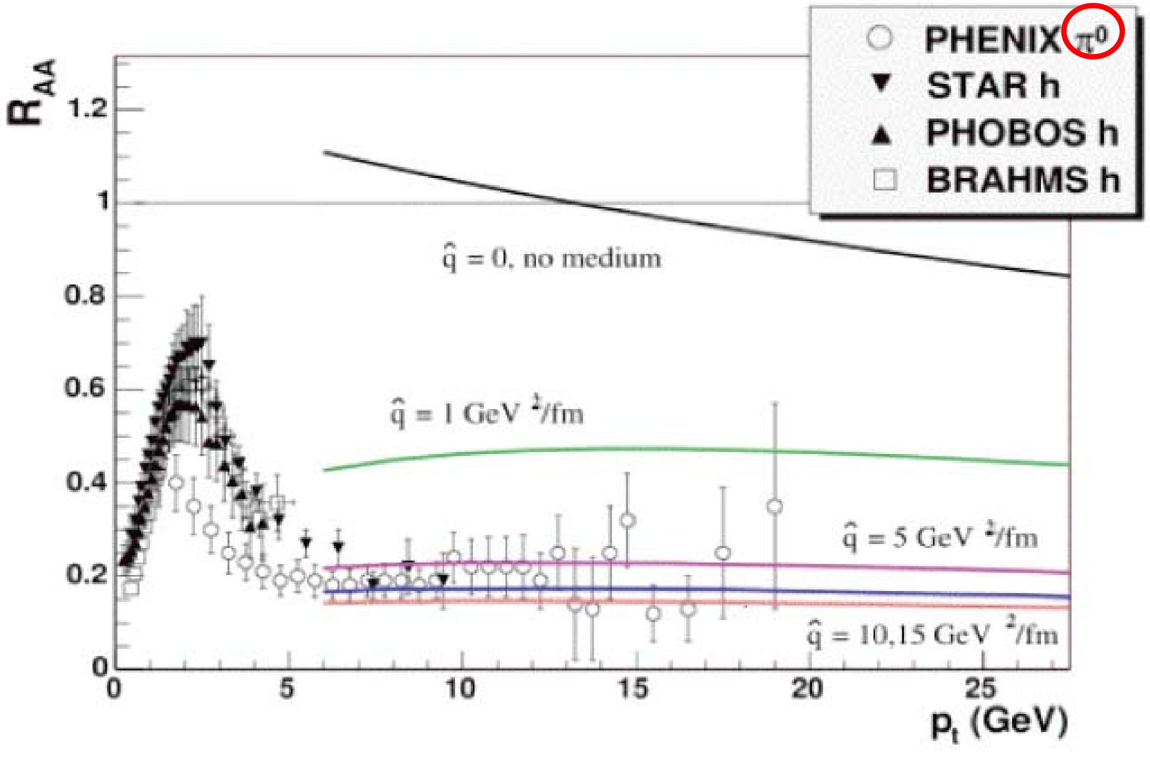


Drawing conclusions from fits to the data may not be easy!
"R_{AA} is fragile" (Eskola, Honkanen, Salgado, Wiedemann)
Data cannot allow to distinguish between q_hat=10 or 15 GeV^2/fm

Heavy quark suppression (non-photonic electrons)



THIS IS ALSO TRUE FOR THE LIGHT HADRON SUPPRESSiON

Data cannot allow to distinguish between q_hat=5 or 15 GeV^2/fm

Jets at LHC

Until RHIC:

- Limited discriminating power in hadron suppression and di-hadron fragmentation for different energy loss/medium density model
- leading hadrons +correlations: strong trigger and geometric biases

Need more 'grey probes'

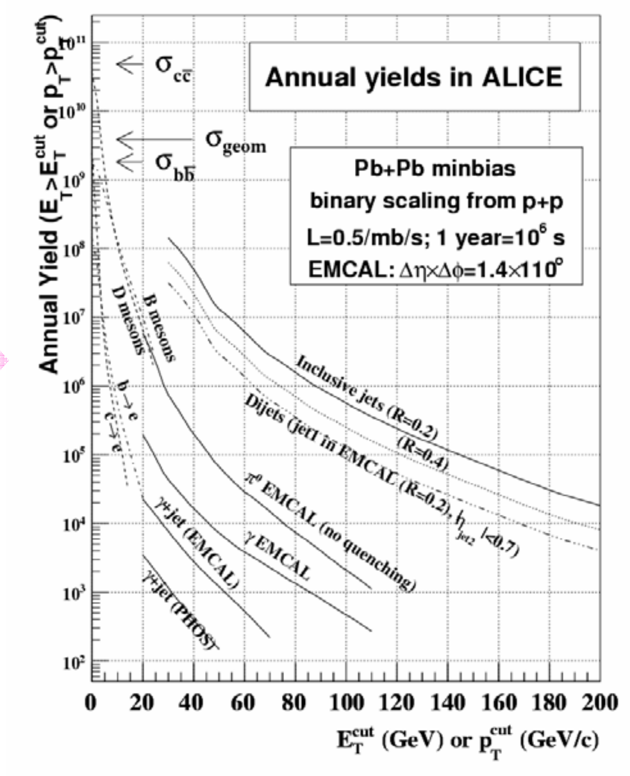
γ-jet and full jet reconstruction are necessary to unravel the mechanisms

unbiased view of medium modifications, interaction of radiation with medium

enabling complete characterization of jet quenching

At LHC:

Large yield of high energy jets: Possibility that multi-particle or calorimetric full jet reconstruction (even in the presence of large background in central nuclear collision)

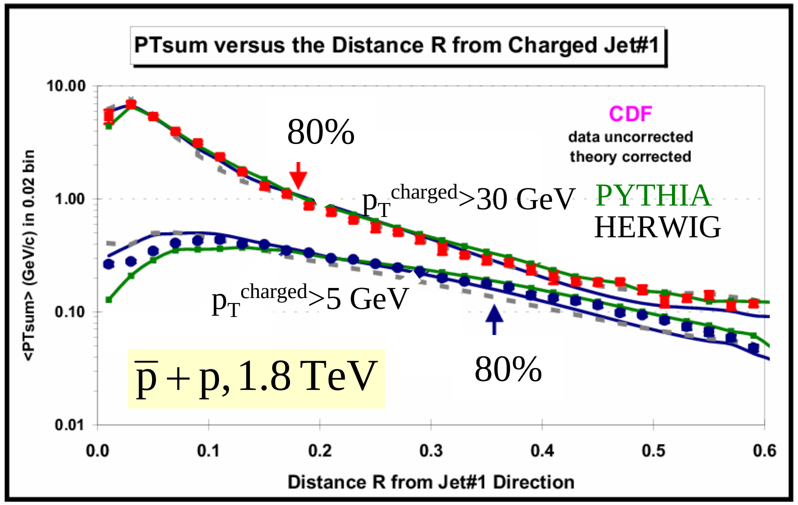


Full jet reconstruction in heavy ion events?

However, jet reconstruction with good energy resolution is not straightforward in central nuclear collisions even at the LHC

CDF, Phys Rev D65, 092002 (2002)

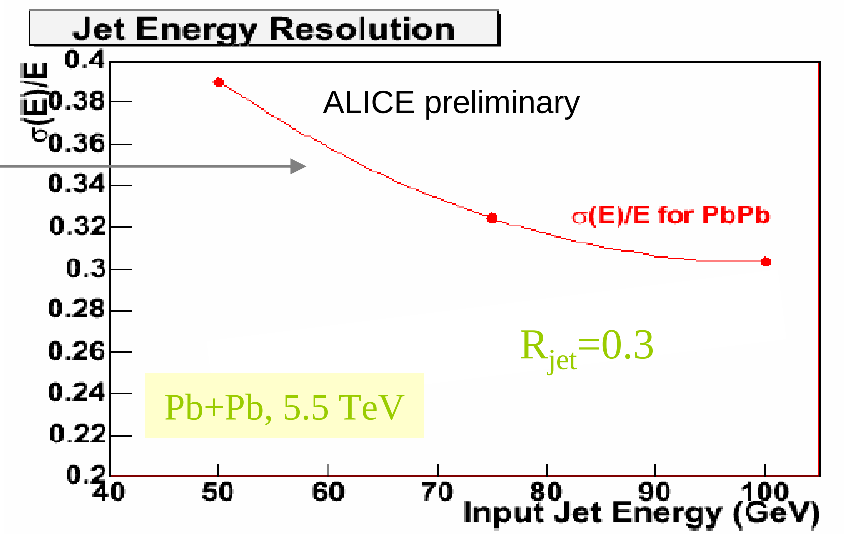
Jet cone: $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



Use small cone radius ~ 0.2 to suppress backgrounds:

- CDF: ~80% of jet energy contained in R<0.2
- Background from 5.5 TeV Pb+Pb:
  $dE_T/d\eta$ ~ 3700 GeV, $E_T(R<0.2)$ ~ 75 GeV
  (Eskola et al, hep-ph/0506049)

Significant irresolutions due to
- out-of-cone radiation
- background fluctuations
- broadening due to energy loss (!)

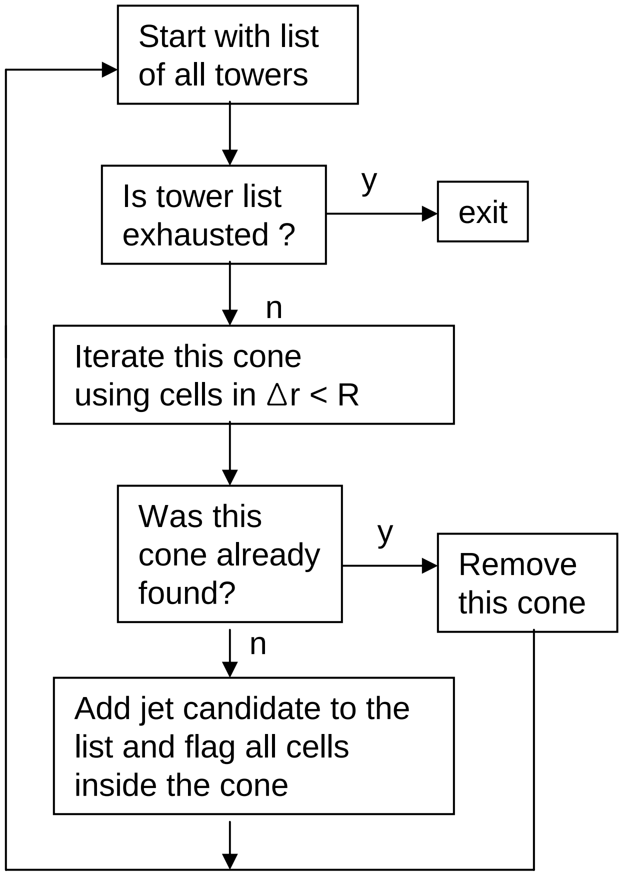


Optimal definition of "jet" awaits data

Jet Reconstruction Algorithms

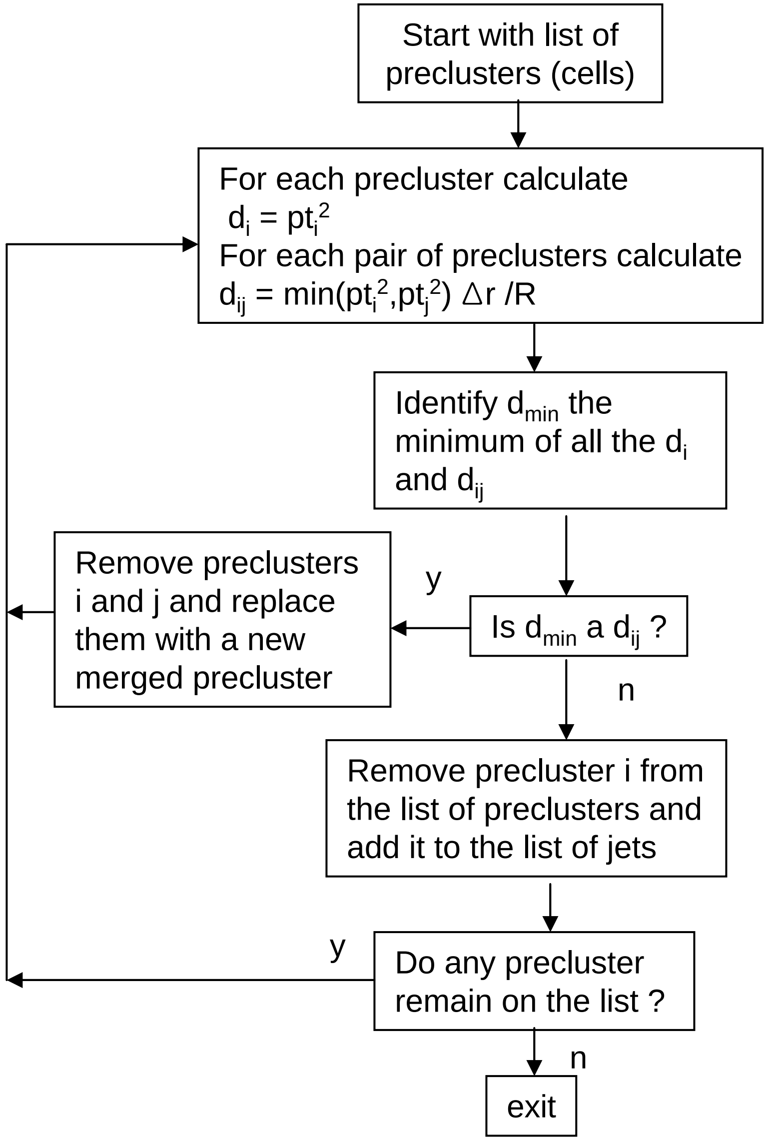
Iterative cone algorithms

JetClus,ILCA, MidPoint, UA1



Clustering algorithm

kt, Cambridge



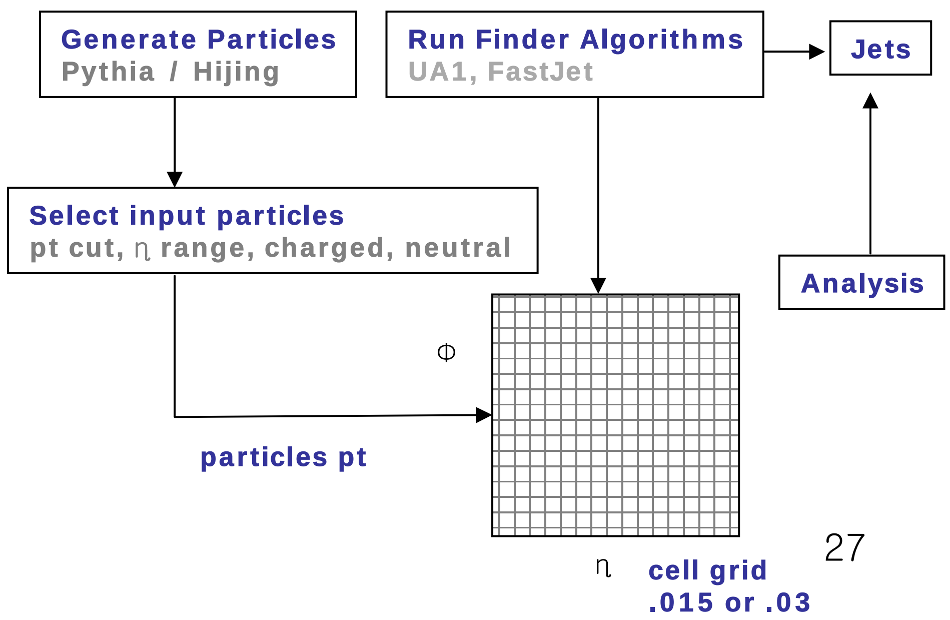
Monte Carlo Jets Generation in ALICE

Pythia 6.2 (p-p Jets)	
Centre mass energy	5.5TeV
Process types	MSEL
Structure Function	CTEQ5L
Initial/final state radiation	On
Multiple interactions	Off
Jet quenching	Off
parton pt hard range	45-150 GeV/c
	65-150
	95-500
	150-1000
	200-1000

HIJING 1.36 (Pb-Pb Underlying event)	
$\sqrt{s_{NN}}$	5.5 TeV
jet quenching	On
Nuclear effects on PDF	On
Initial/final state radiation	On
Resonance decays	Off
Jet trigger	Off
Impact Parameter	0 – 5 fm

The general strategy of the ALICE Offline group for the Monte Carlo simulation of hard and rare process in Pb-Pb collisions at the LHC consists in simulating hard processes in pp collisions and embedding them in the underlying event of the Pb-Pb collisions

How do we proceed ?

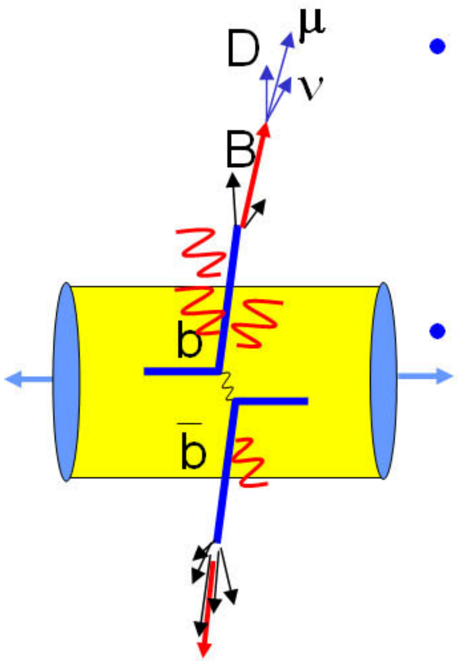


Detector coverage at ALICE

From Ana following other's request

Detector	$\|\eta\|$	ϕ_{min}	ϕ_{max}	%
TPC	0.9	0	2π	100
PHOS	0.12	$11/9\pi$	$16/9\pi$	3.7
EMCAL	0.7	$1/3\pi$	π	26

b-Jet Fragmentation



- **Radiative quark energy loss is qualitatively different for heavy and light quarks.**
  e.g. Y.L.Dokshitzer and D.E. Kharzeev, hep-ph/0106202

- **Reconstruct Jets, tag heavy quark (c,b)-Jets by:**
  - Hadronic decay:
    - secondary vertices from charged tracks
  - Leptonic decay:
    - muons with displaced vertices

In our case (at least central arm), use electrons

- **compare jet shapes/properties of heavy quark jets and of light quark jets.**
  - **Exploit parton mass dependence to study parton energy loss mechanism.**

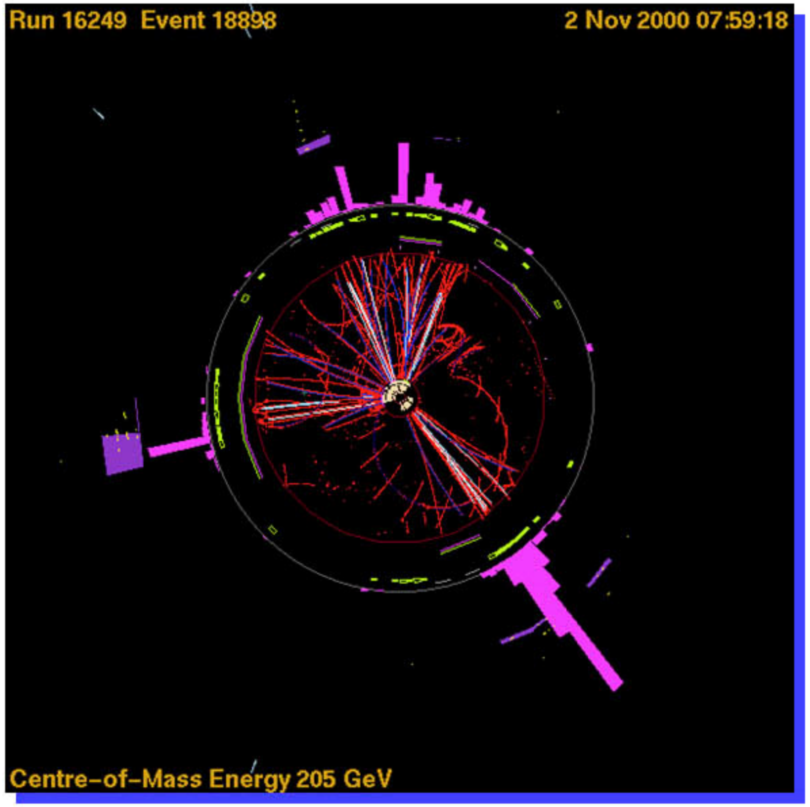
Talk from Christof Roland / MIT for CMS

Three Jet Events?

- **Can we use three jet events to tag gluon jets?**
  - Three jet events consist of two quark jets and a gluon jet
  - Tag the quark jet by heavy quark tagging
  - The remaining jet is a gluon jet
  - Challenging measurement…

- **Energy loss of quarks and gluons should be significantly different in a colored medium**
  - Check jet shapes

a LEP 3 jet event



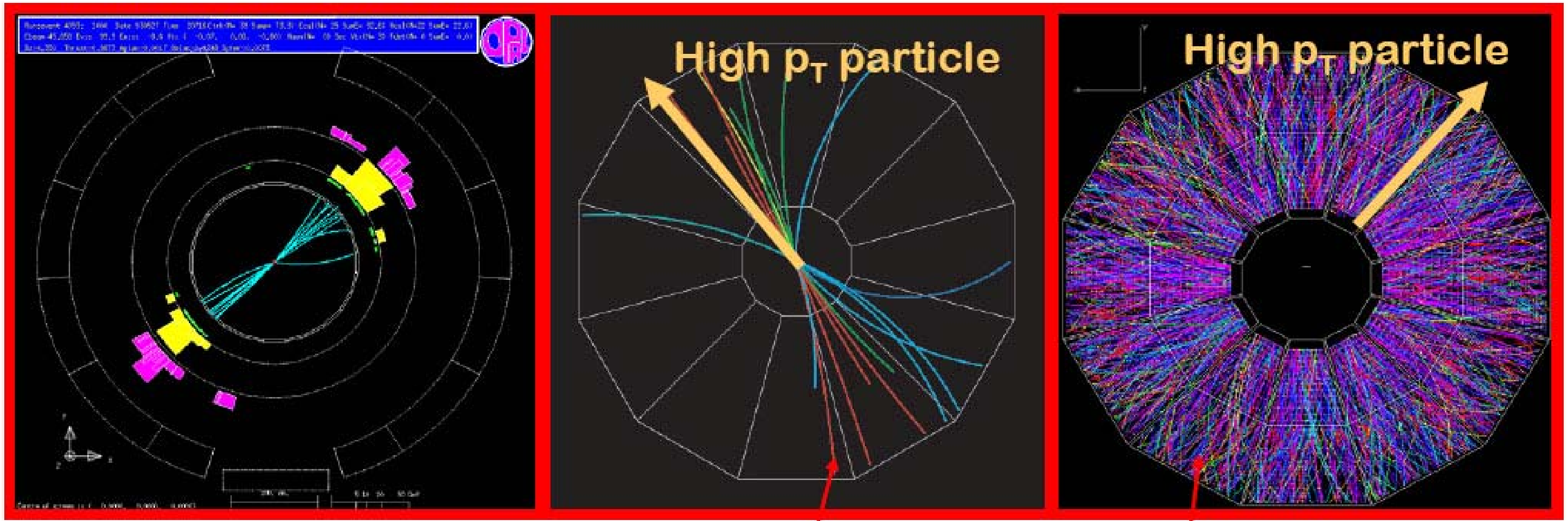
Future of jet quenching

- Gauge boson (γ or Z)-jet Events
  - does not interact with the medium, provide a clean calibration of the momentum transfer in the interaction
  - enable measurement of the true fragmentation of the recoiling jet
- Heavy vs light quarks jets
- Parton recombination at intermediate p_T
- 3D jet tomography
- Incorporate dynamic evolution of bulk matter
- Exploit large dynamic range at LHC to constrain models in detail
- Cross-compare hard probes at LHC and with RHIC to test models

ECT Workshop on Jet Physics in Heavy Ion Collisions at the LHC
http://indico.cern.ch/conferenceOtherViews.py?confId=5144&view=cdsagenda&sho

Backup slides

Jets in various collisions



$e^+ + e^- \rightarrow$ jet + jet

$p + p \rightarrow$ jet + jet

Au + Au $\rightarrow$ stuff + jet + jet

measure these… here?!

F. Wang, RBRC Workshop, March 10, 2005

"We can do it but with some care…"

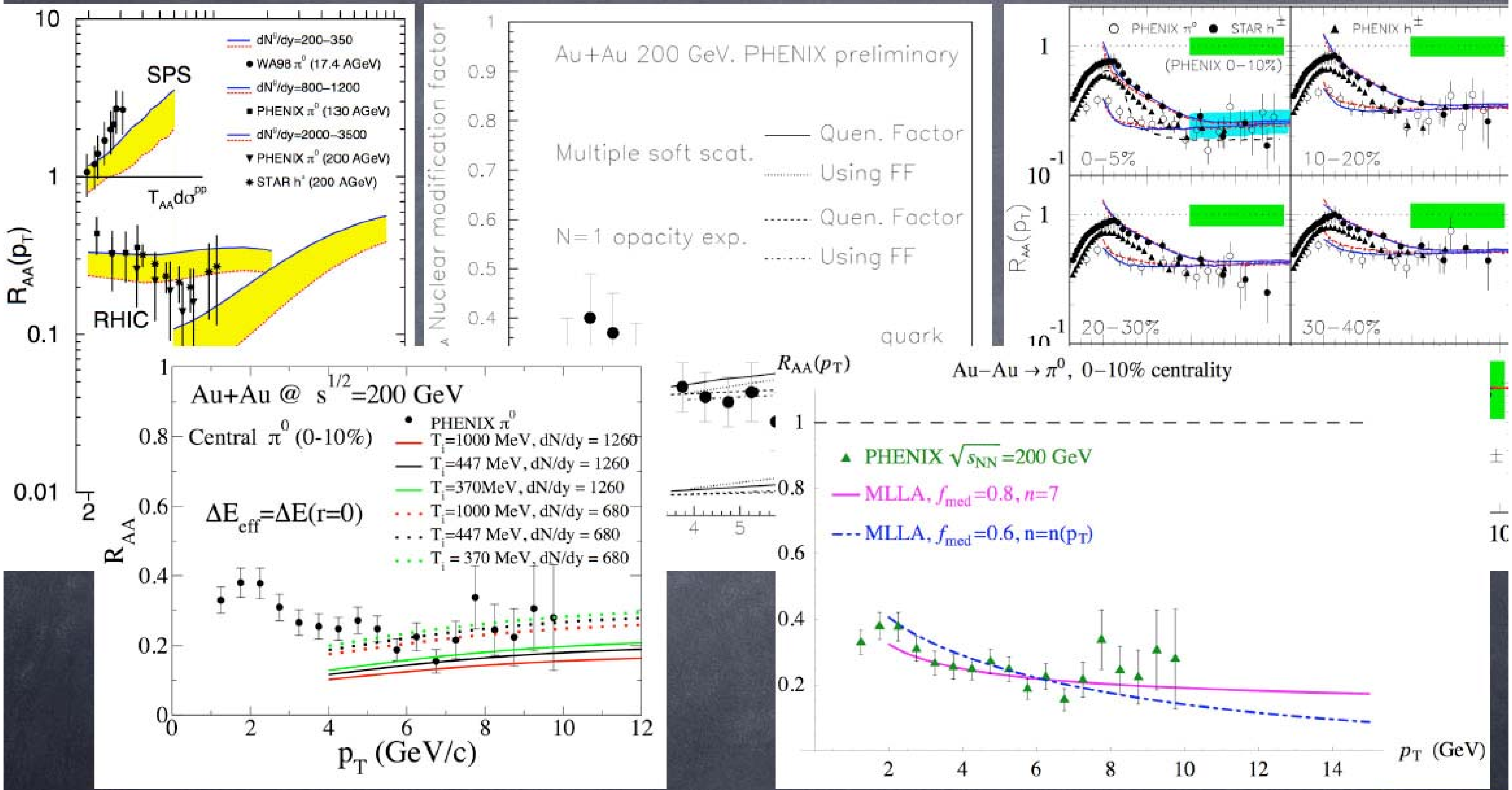
Elastic energy loss

- Bjorken(1984), Thoma & Gyulassy (1991), Braaten & Thoma (1991), Wang, Gyulassy & Plumer (1995), Mustafa et al. (1998), Lin, Vogt & Wang (1998): dEel./dz~0.3-0.5GeV/fm : negligible!
- Then, all of a sudden,,,

  Mustafa & Thoma (2003), Dutt-Majumder et al. (2004), Wicks, Horowitz, Djordjevic & Gyulassy (2006), Peshier (2006): it is sizable! (either for heavy quarks only, for c only, for light quarks as well...)
- Yet, at the same time...

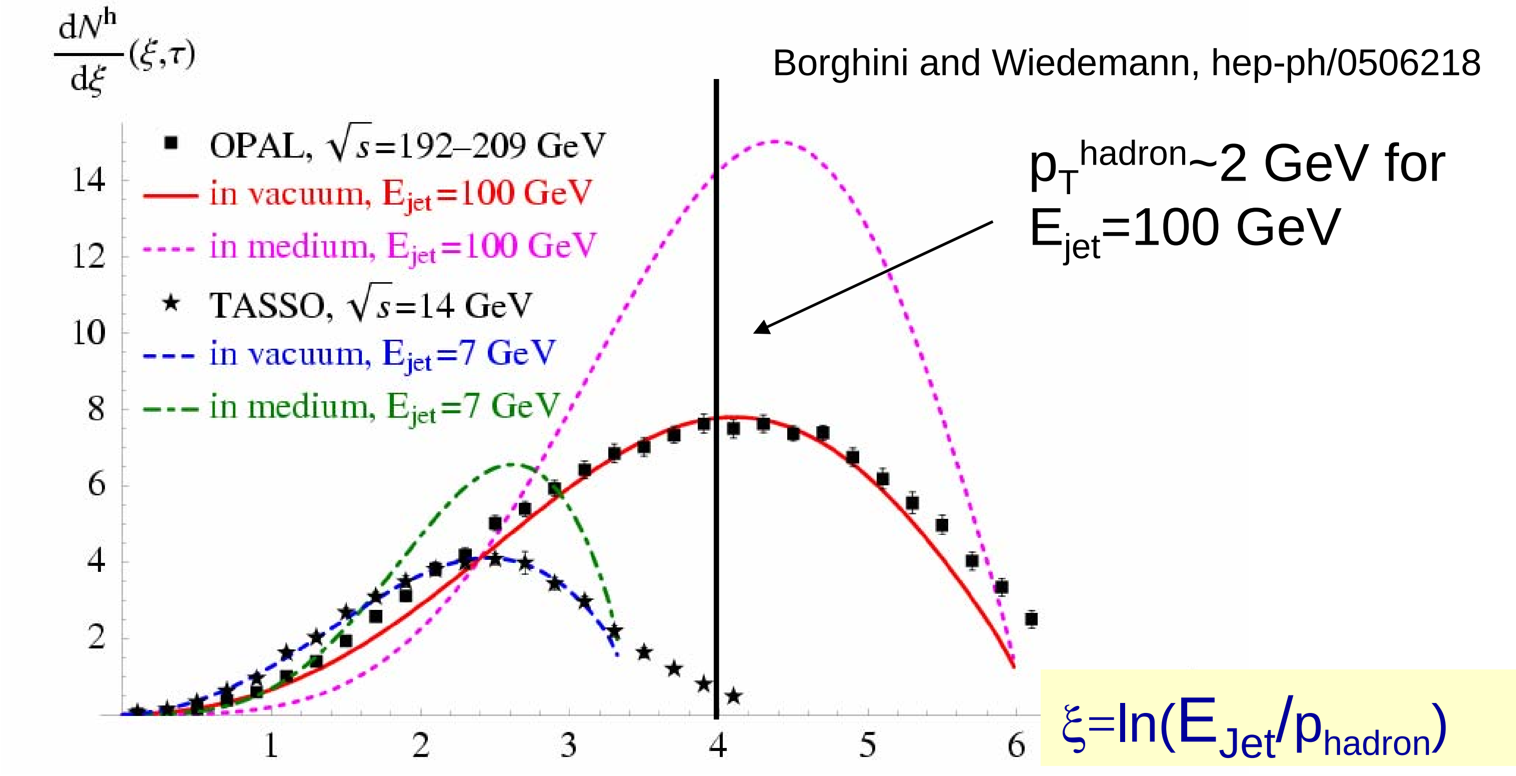
  Peigne, Gossiaus, Gousset (2005): yes, elastic energy loos is negeligible, because the parton is formed inside the medium, not at infinity.

Models of high-p_T parton energy loss reproduce the data remarkably well



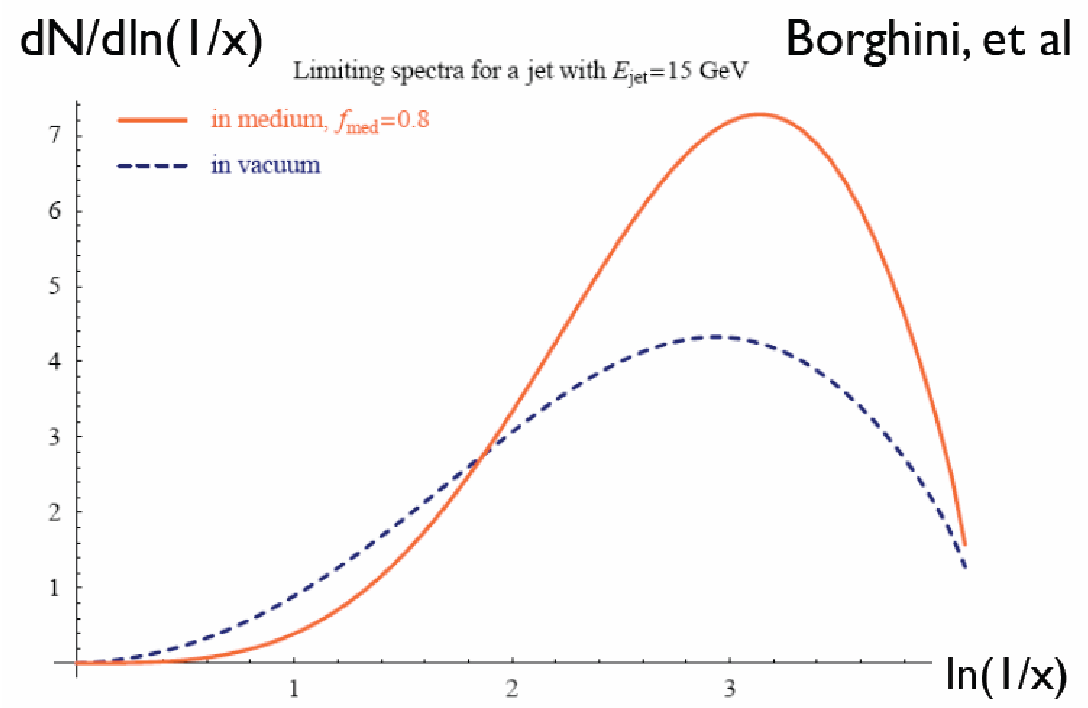
Medium modification of fragmentation

- MLLA: parton splitting+coherence ⇒angle-ordered parton cascade
  - Theoretically controlled, experimentally verified approach
- Medium effects introduced at parton splitting



Fragmentation strongly modified at p_T^{hadron}~1-5 GeV even for the highest energy jets

Predictions for LHC: Fragmentation

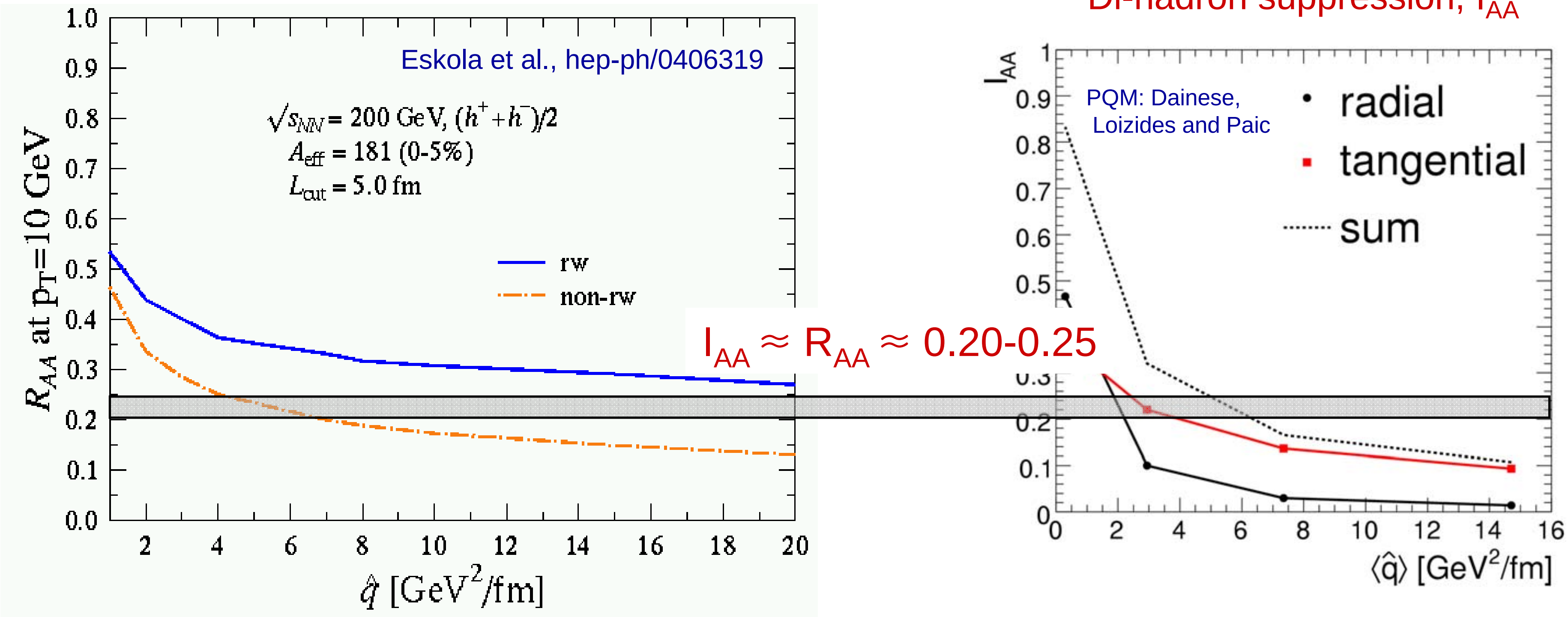


- Measurements of jet fragmentation functions will be possible
- Test of energy loss via the modification of these wrt p+p

Are we there?

Single particle suppression, R_{AA}

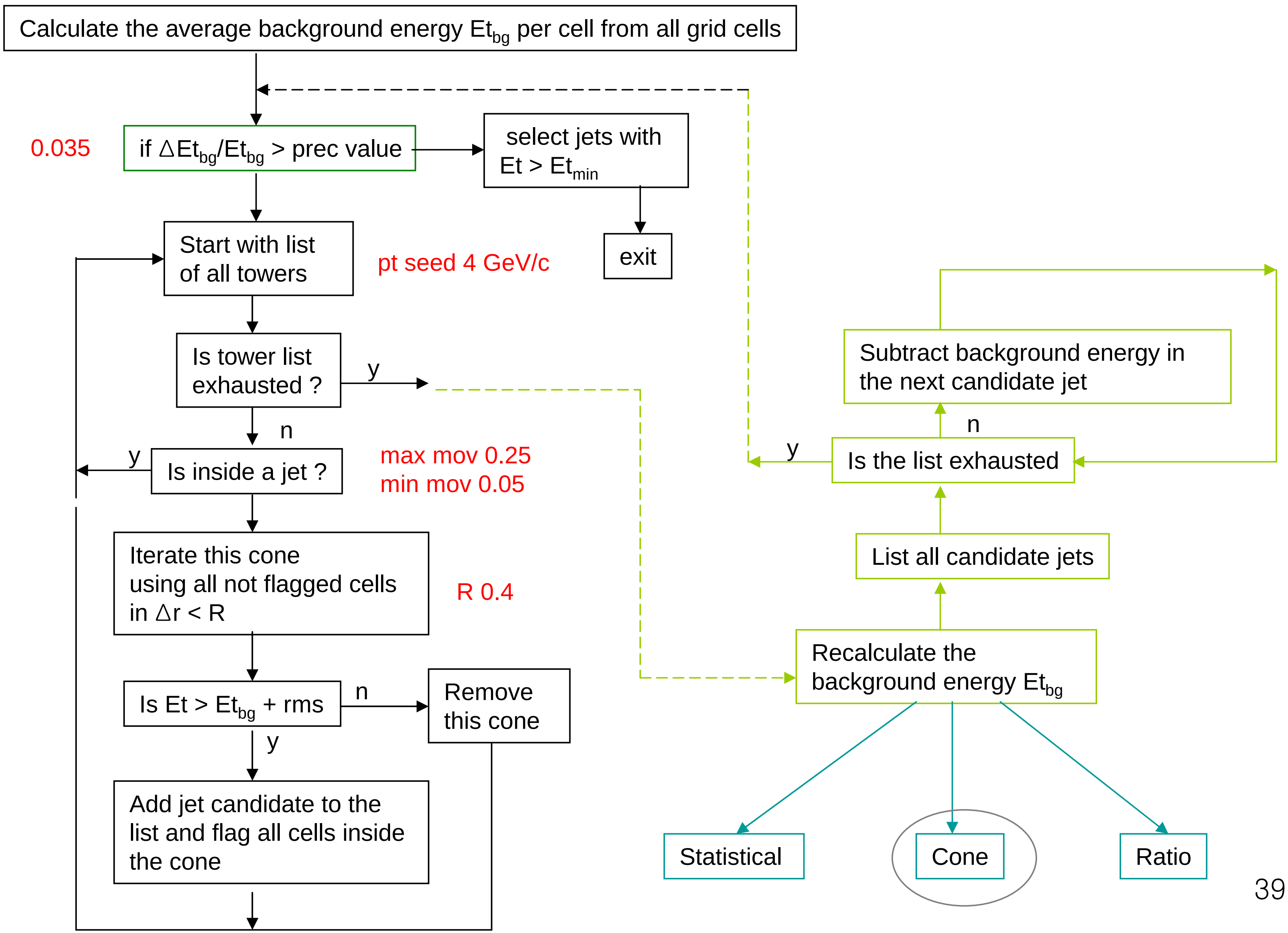
Di-hadron suppression, I_{AA}



Inclusive and di-hadron suppression give consistent medium density transport coefficient $\hat{q} \approx$ 5-7 GeV²/fm in central Au+Au @ RHIC

But significant uncertainties remain:
e.g. energy loss model vs medium density profile

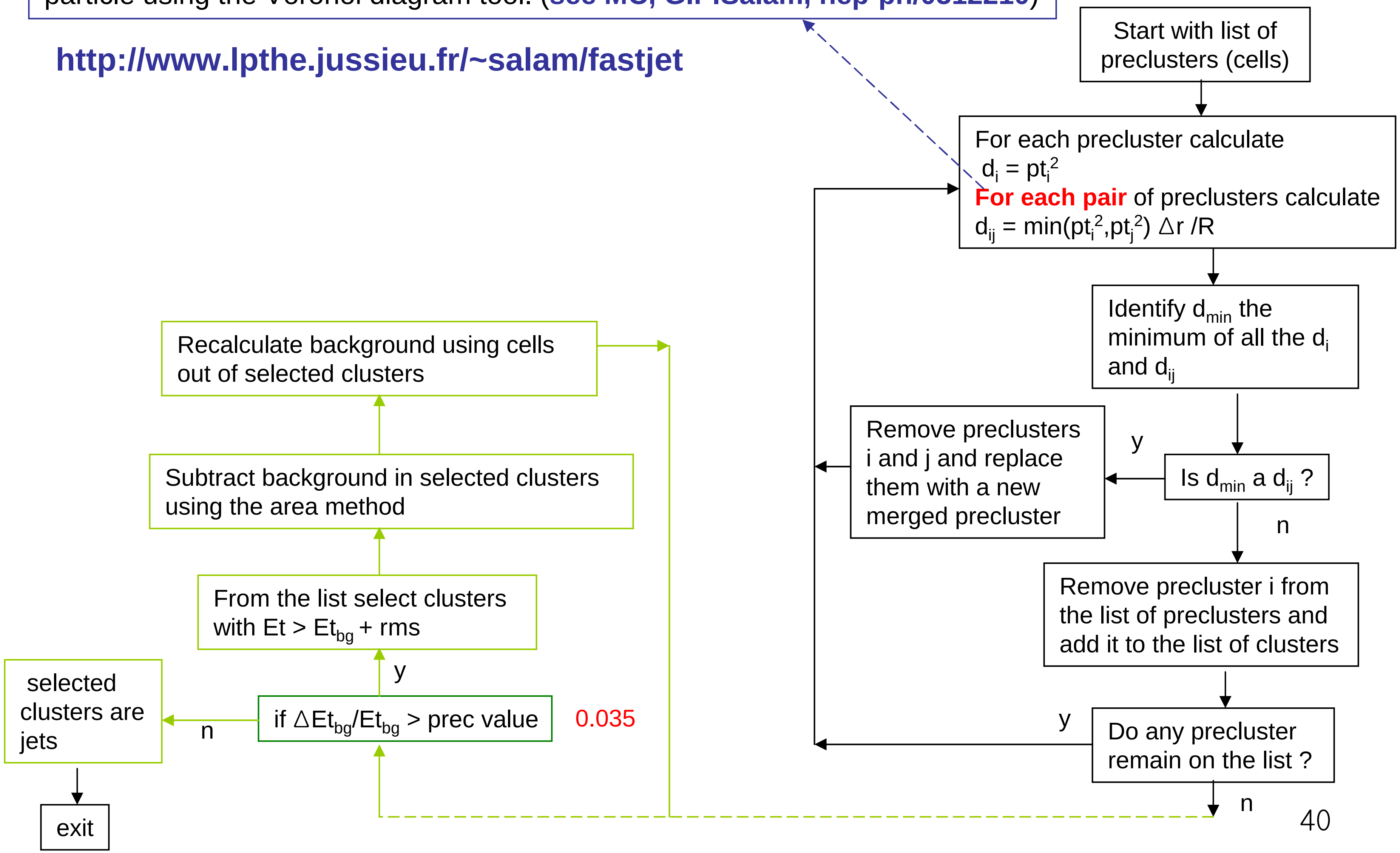
- Background subtraction in UA1 Cone Algorithm



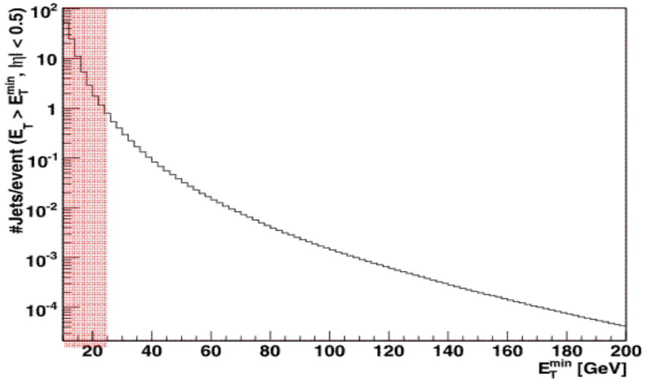
• Background Subtraction in kt FastJet Algorithm

FastJet: look for partners only among the O(N) nearest neighbors of each particle using the Voronoi diagram tool. (**see MC, G.P.Salam, hep-ph/0512210**)

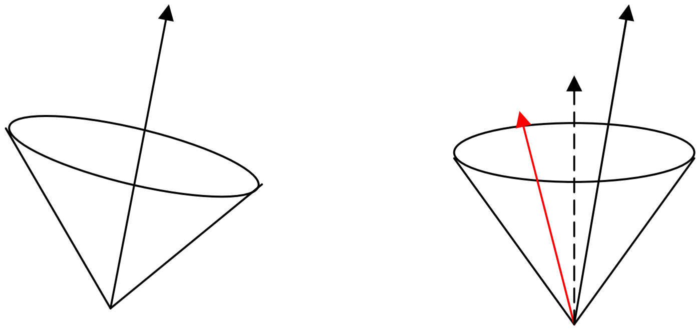
http://www.lpthe.jussieu.fr/~salam/fastjet



- Influence of Background fluctuations in Jet Reconstruction algorithms



Et < 20 GeV several jets overlap in one event



Any strategy to subtract background energy has to deal with possible biases:

1. Jet algorithm sees background when defining jet
2. Background has structure on an event by event basis e.g. probability to see a hadron in a certain eta/phi range is higher if there is already a hadron

UE causes sizeable change of leading jet cross-section

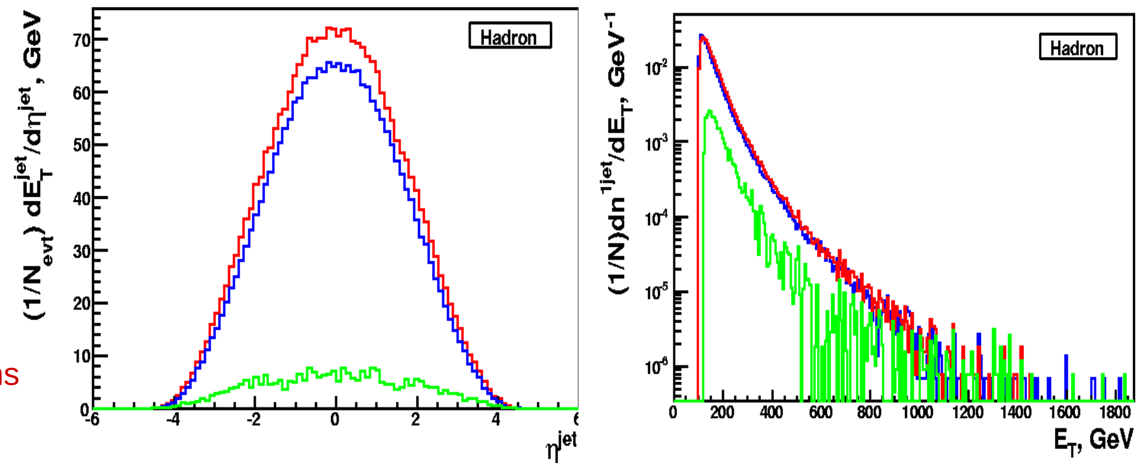
see : Jets and Underlying event
Tancredi Carli
MC4LHC06

Example in p+p D0 version of the Midpoint algorithm

Difference

Use only hadrons from hard scattering

Use all hadrons (including UE)



Jet Reconstruction Analysis for Ideal Detector

Analysis

1- Run Jet Finder Algorithm in p-p with

η range (-2,2)
No pt cut
R 1.0 (default)
all particles

In different parton pt hard range 45-150/ 65-150/95-500/150-1000/200-1000 GeV/c

E_t^{trig} : jet energy reconstructed

Select trigger jet
Jet η range (-0.5,0.5)
E_t^{trig} bin 45 / 70 / 100 / 150 / 200 GeV

2- Run Jet Finder Algorithm in p-p

η range (-0.9,0.9)
pt cut 2 GeV/c
R 0.4
All particles / only charged
In different parton pt range

E_t^{pp} : jet energy reconstructed

Select jet under match condition
- η_{rec} - η_{trig} < 0.5
- Φ_{rec} - Φ_{trig} < 0.5
- E_t^{Pythia}/E_t^{mc} > 0.2

3- Run Jet Finder Algorithm in Pb-Pb

η range (-0.9,0.9)
pt cut 2 GeV/c
R 0.4
All particles / only charged
In different parton pt range

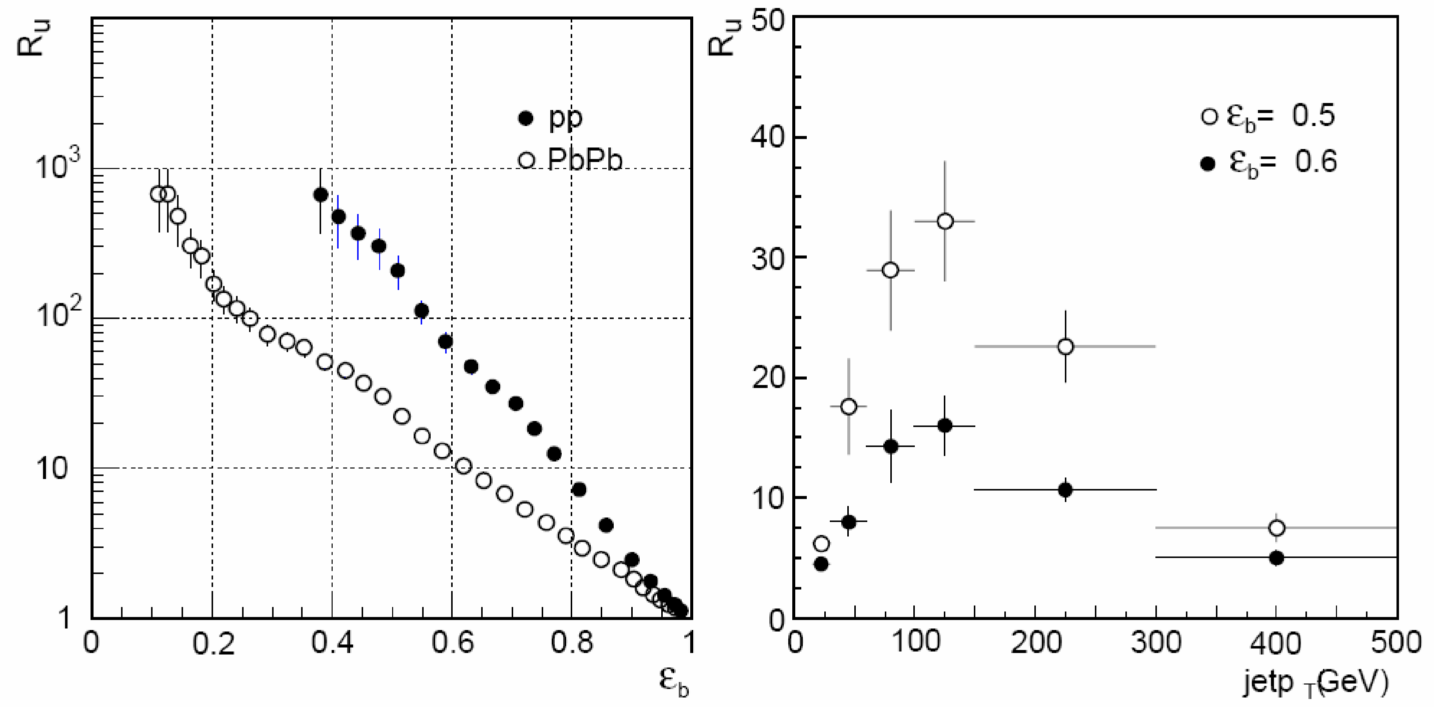
E_t^{rec} : jet energy reconstructed

Select jet under match condition
- η_{rec} - η_{trig} < 0.5
- Φ_{rec} - Φ_{trig} < 0.5
- E_t^{Pythia}/E_t^{rec} > 0.2

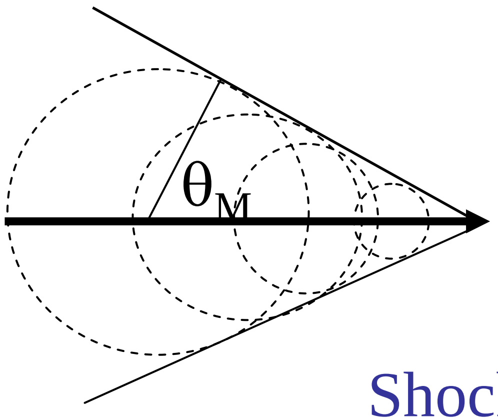
Note : E_t^{Pythia} : energy from Pythia inside jet area

b-tagging

- Analyzed $p+p \to WH \to \ell\bar{\nu}b\bar{b}$, $p+p \to WH \to \ell\bar{\nu}u\bar{u}$ events embedded in HIJING
- Tagged the b by displaced vertex using p+p algorithm
- Also tag jets with high-p_T muon



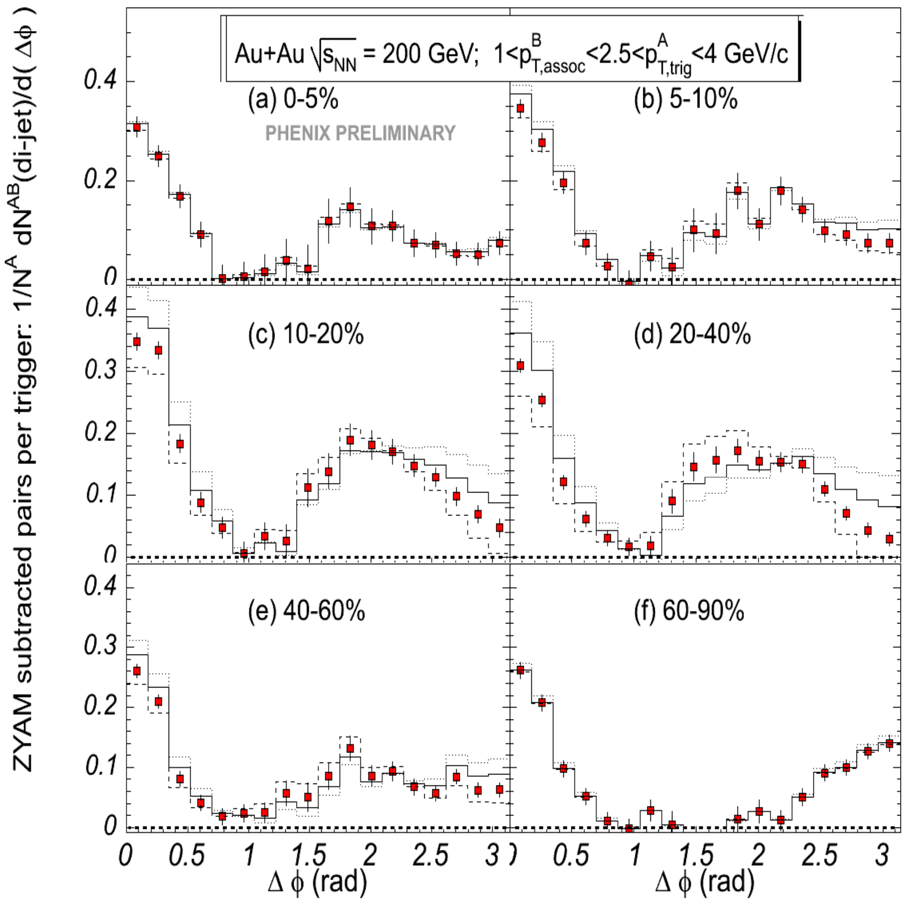
Soft hadrons rings



Shock wave?

$$\cos\theta_M = \frac{1}{\sqrt{c_s}}$$

PHENIX



Stoecker'04

Casalderrey-Solana,Shuryak & Teaney

Casalderrey-Solana (parallel 3b)