Exploring Hot Dense Matter at RHIC and LHC

Peter Jacobs

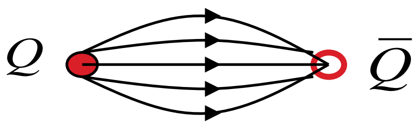
Lawrence Berkeley National Laboratory

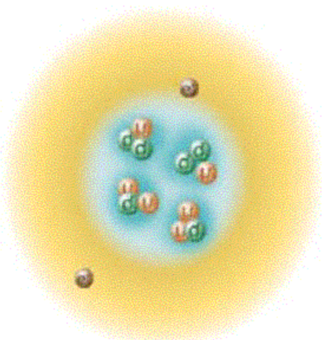
Lecture 4: Jets and jet quenching

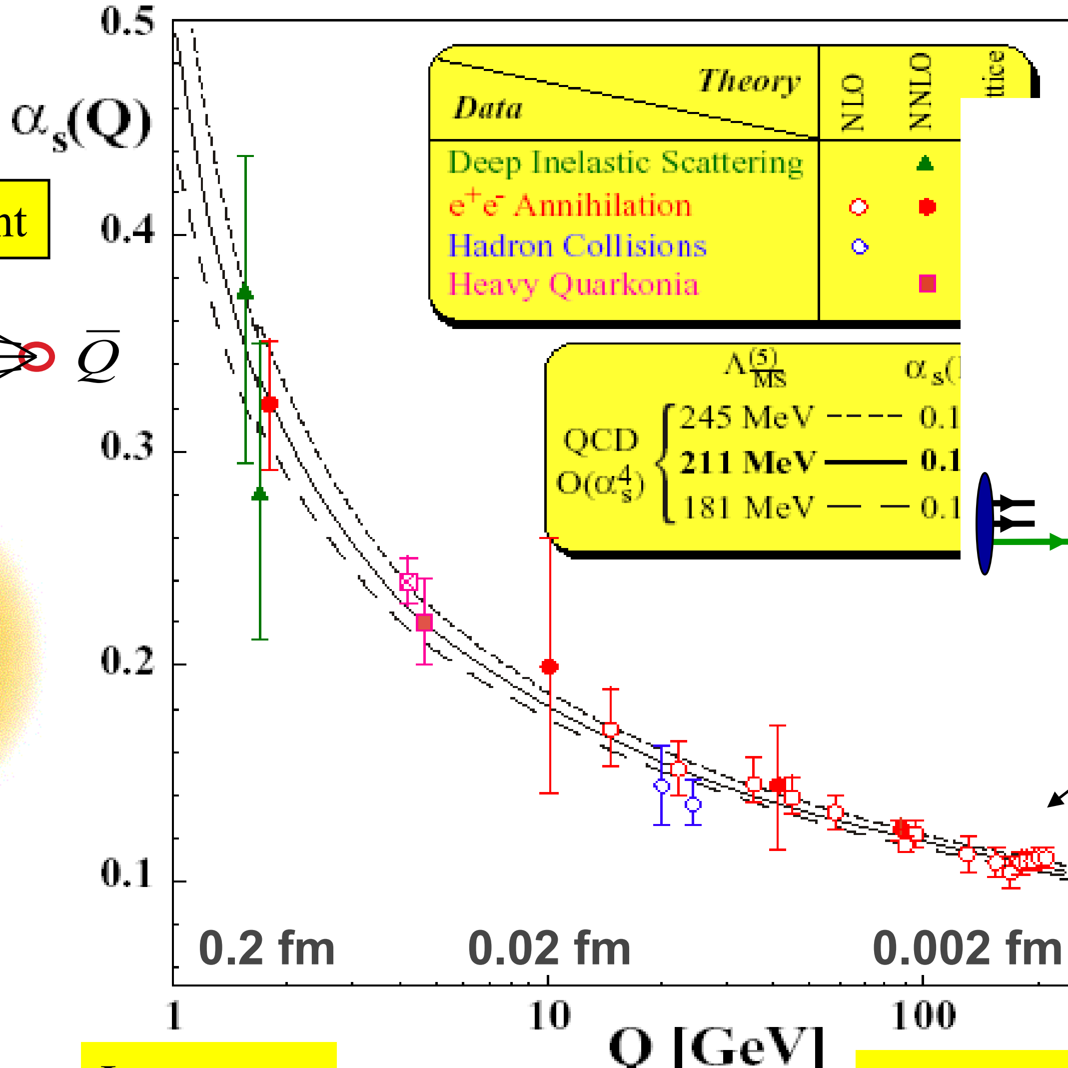
QCD: running of α_S

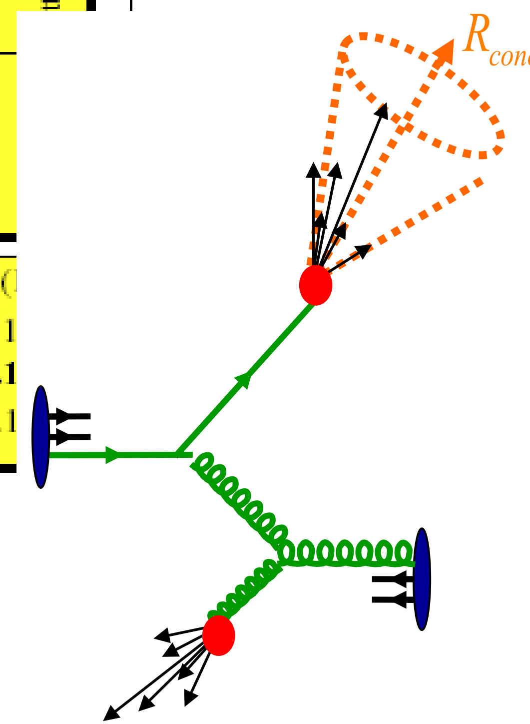
Asymptotic Freedom

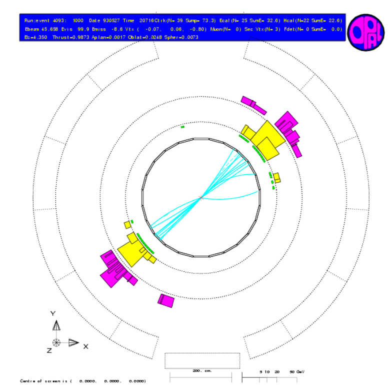
Confinement











Low momentum

High momentum

Perturbative QCD factorization in hadronic collisions

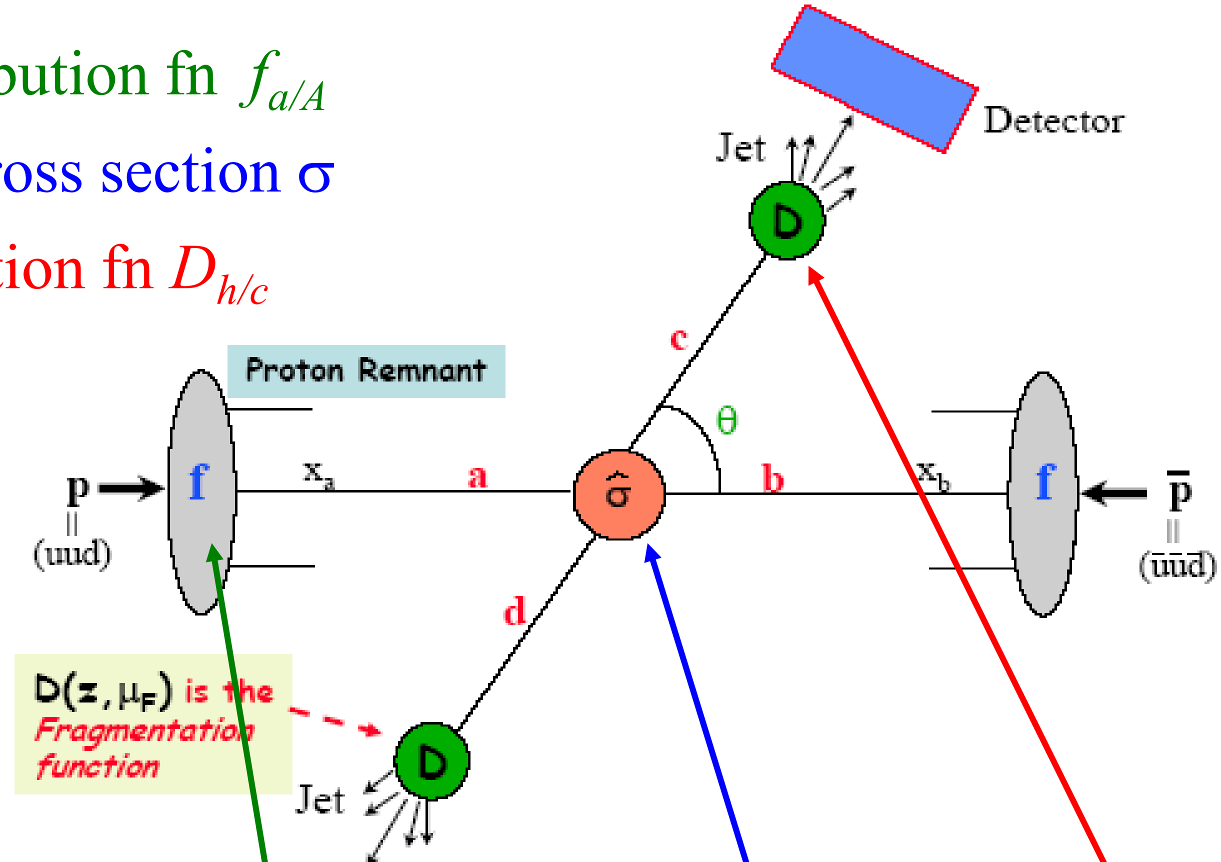
Hard process scale $Q^2 >> \Lambda^2_{QCD}$

pQCD factorization:

parton distribution fn $f_{a/A}$

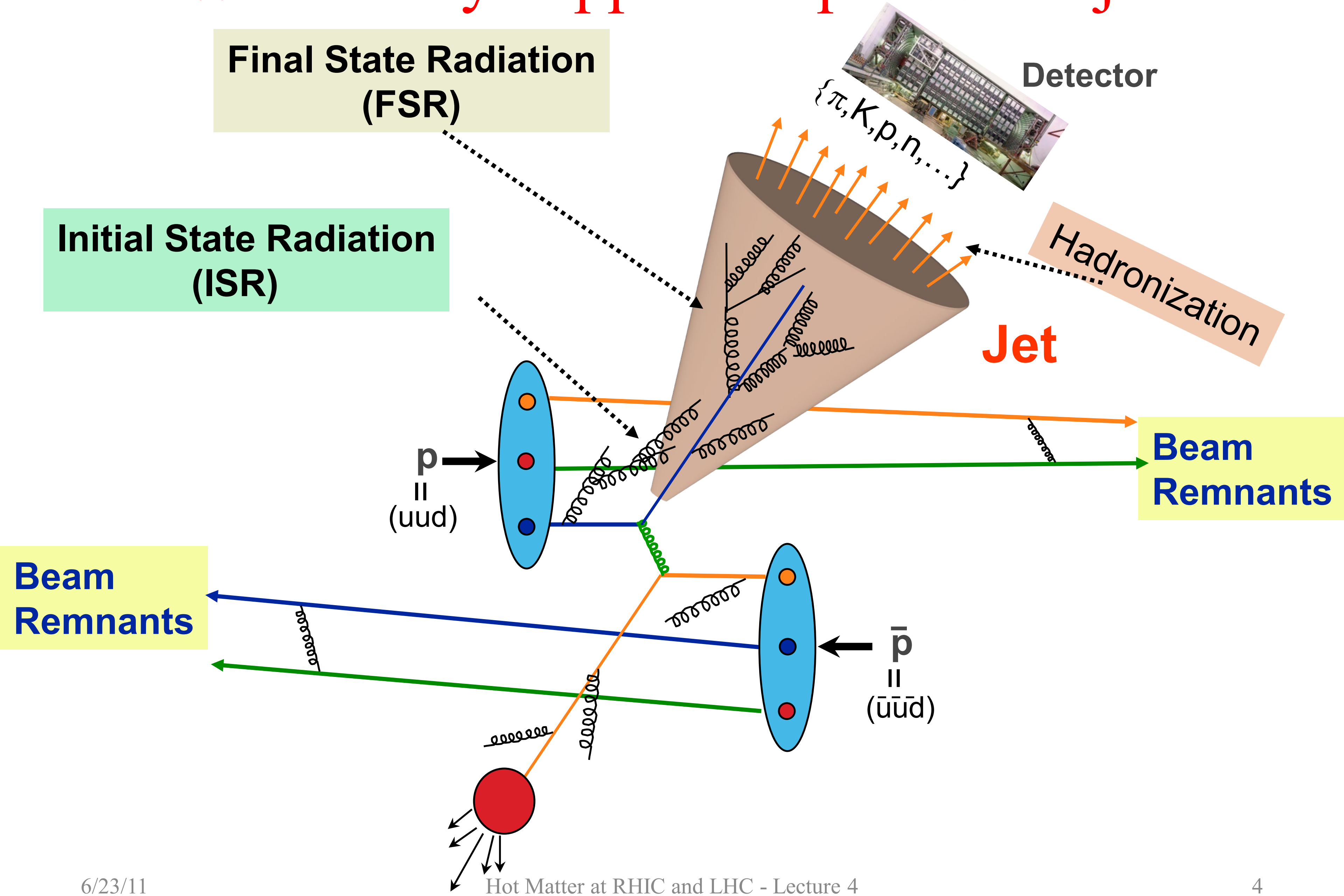
+ partonic cross section σ

+ fragmentation fn $D_{h/c}$

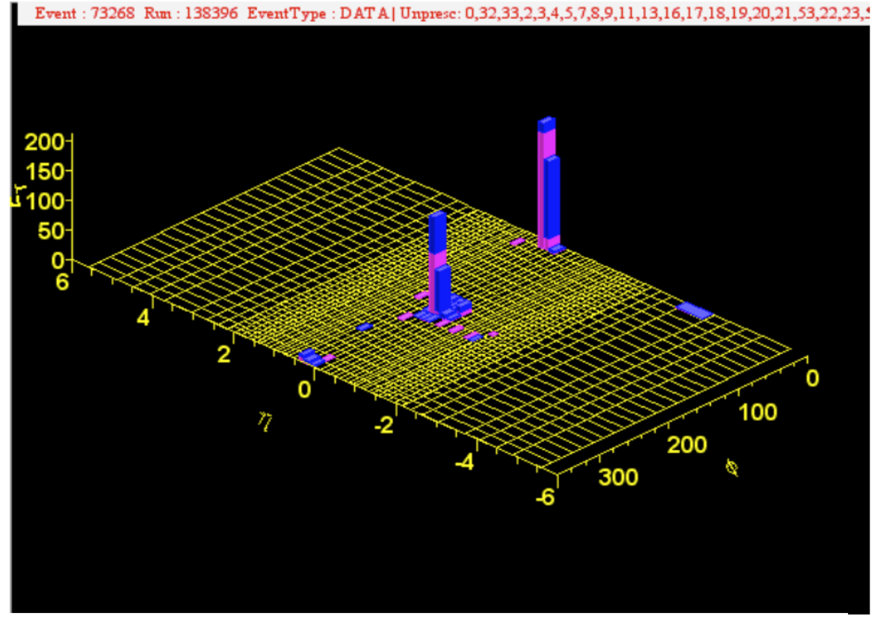


$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a, Q^2\right) \otimes f_{b/B}\left(x_b, Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}\left(z_c, Q^2\right)$$

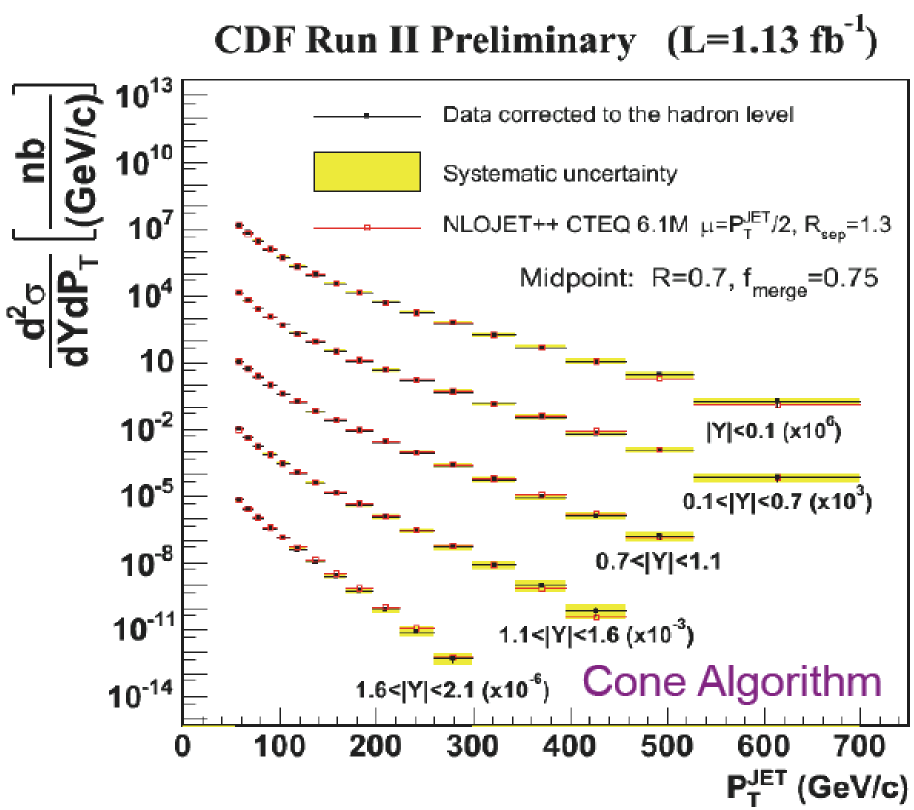
What really happens to produce a jet…

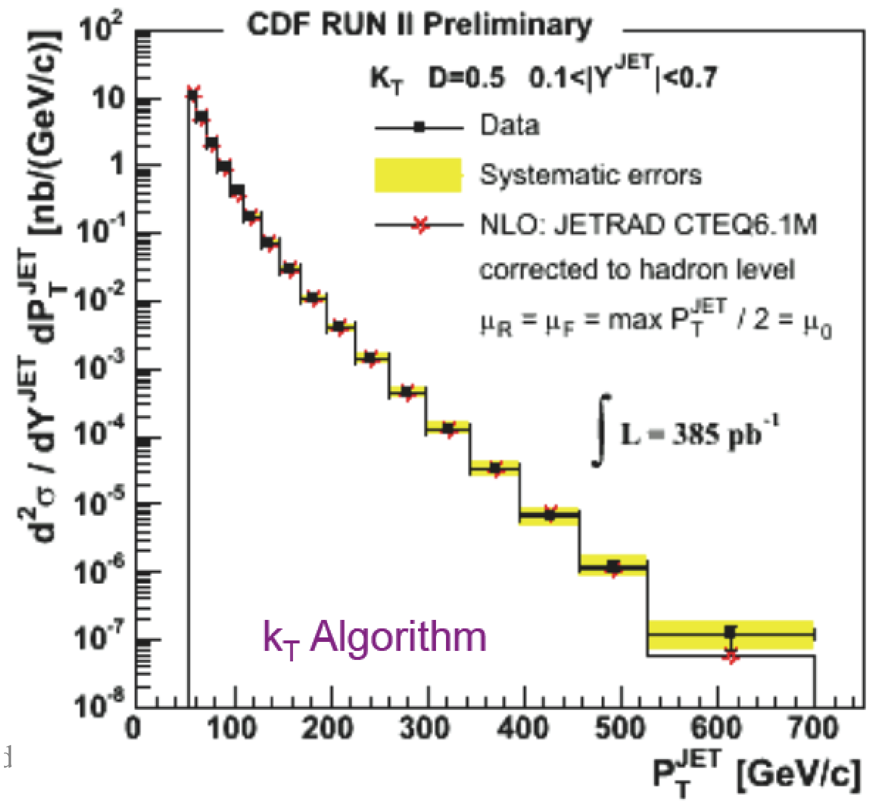


Jets at CDF/Tevatron

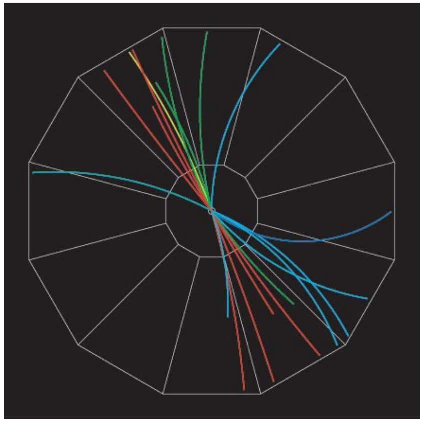


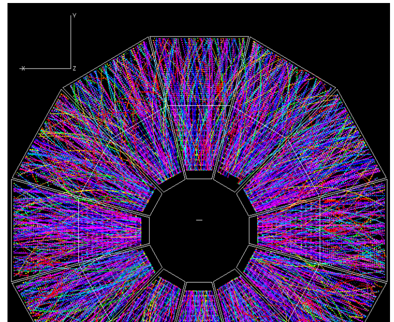
Good with NLO pQCD

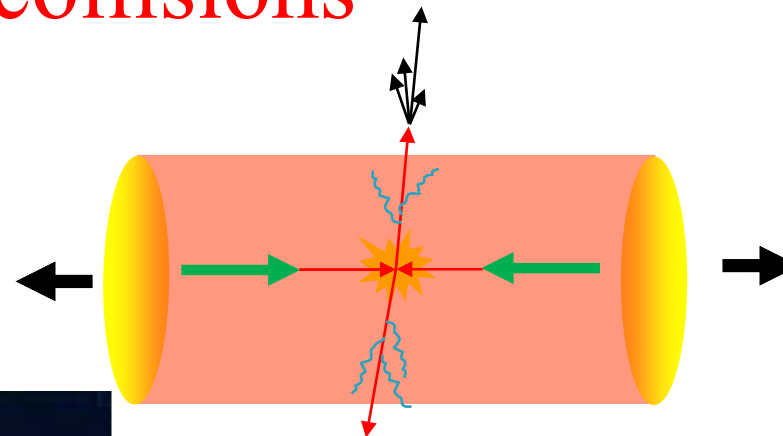


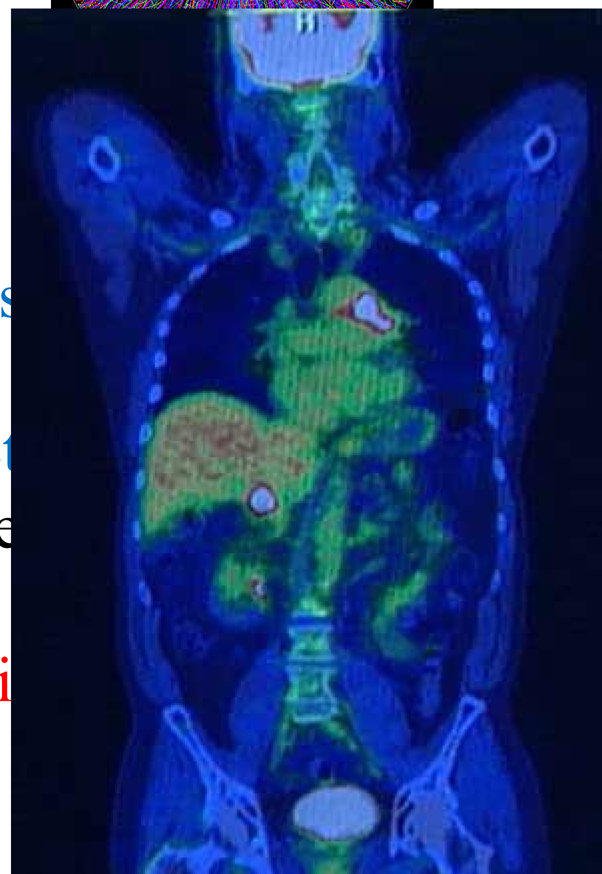


Jets in heavy ion collisions





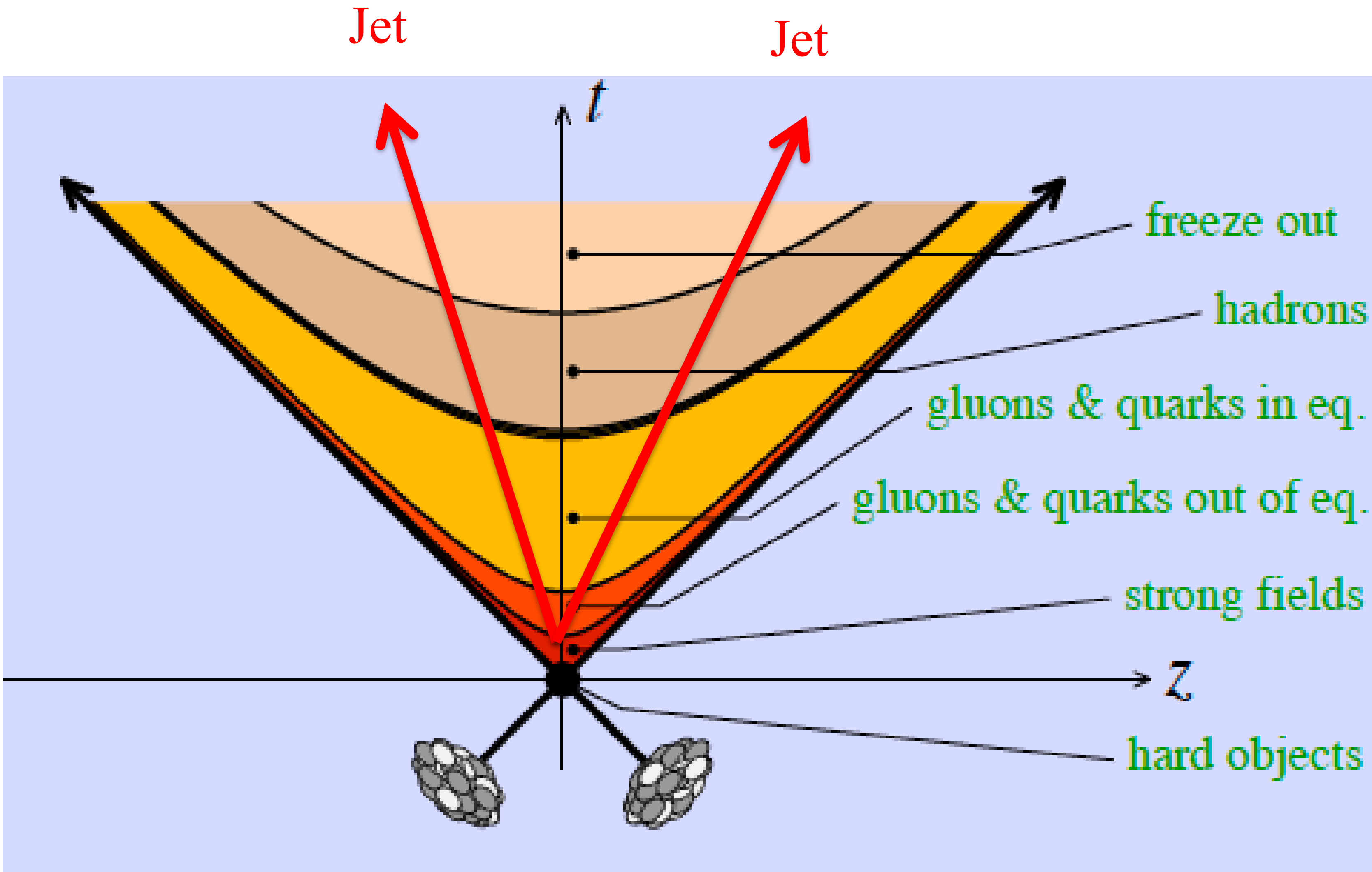




Controlled "beams ... ntensity

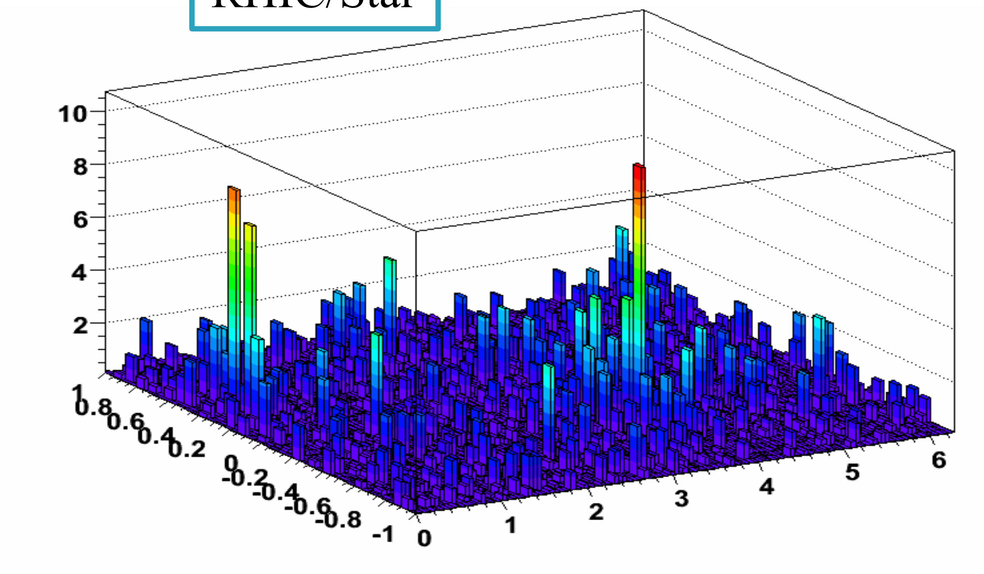
Final-state interact ... er are calculable
using controlle

→ tomographi ... luon Plasma

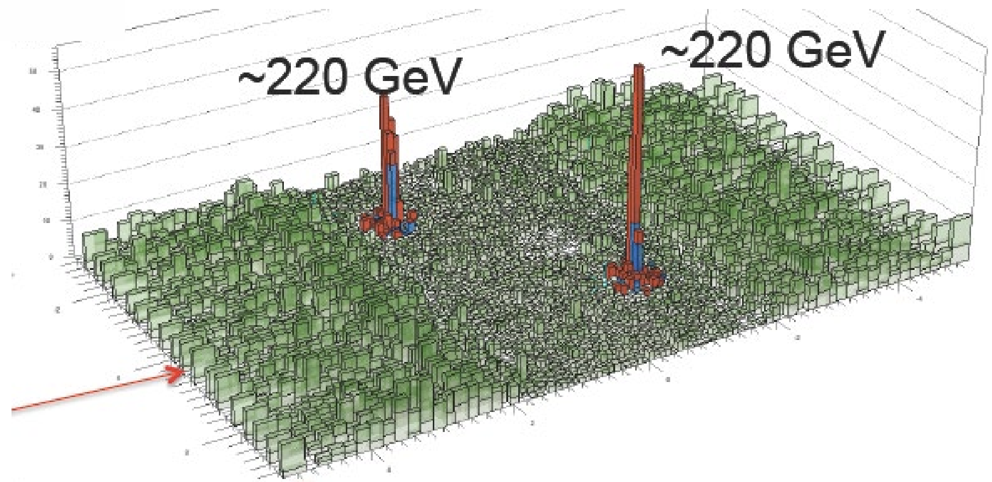

Jet
Jet
t
freeze out
hadrons
gluons & quarks in eq.
gluons & quarks out of eq.
strong fields
z
hard objects

Jets in real heavy ion collisions

RHIC/Star

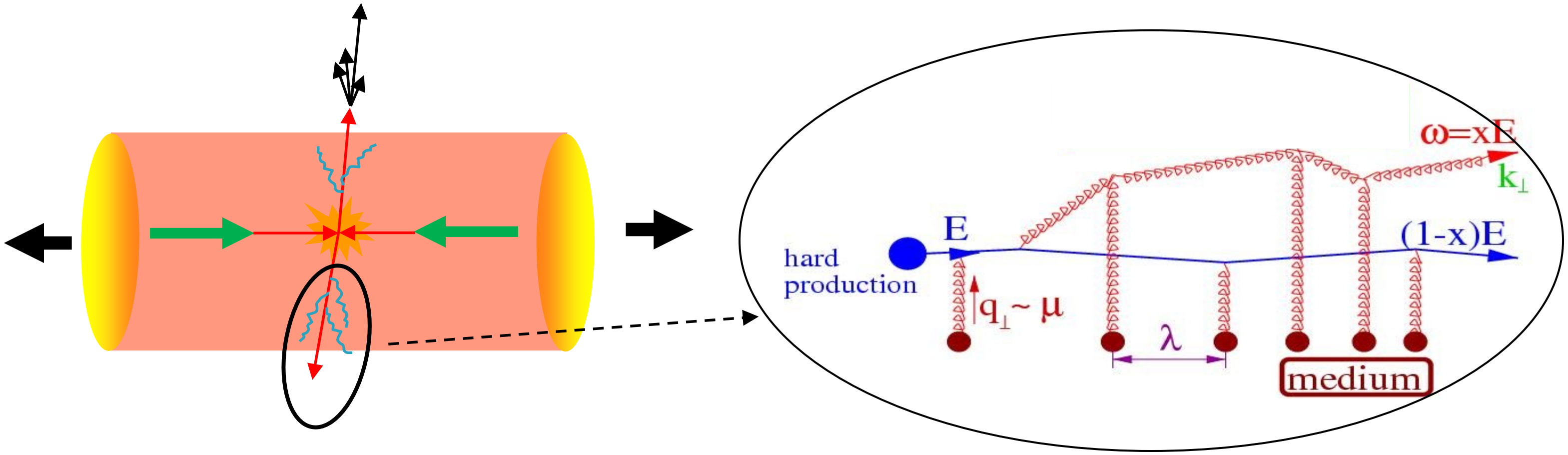


LHC/CMS



Jet quenching

Radiative energy loss in QCD (multiple soft scattering):



Plasma transport coefficient:

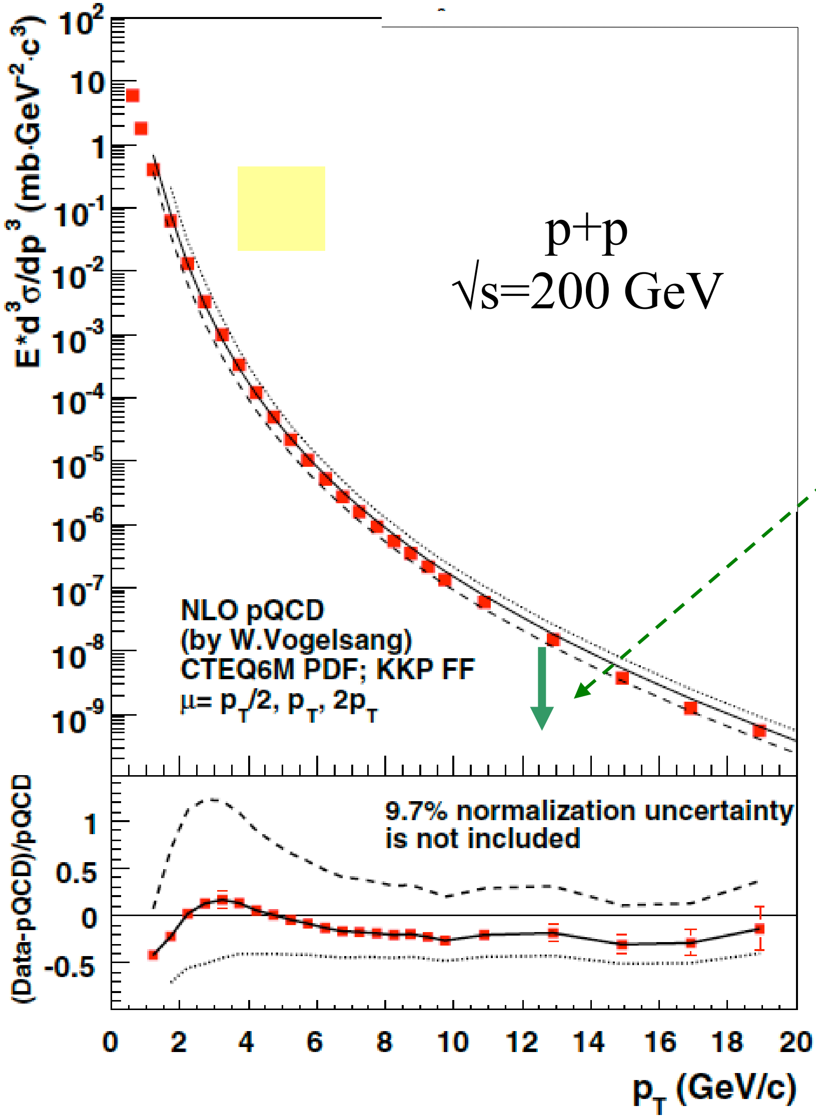
$$\hat{q} = \frac{<(\text{momentum transfer})^2>}{\text{mean free path}} = \frac{\mu^2}{\lambda}$$

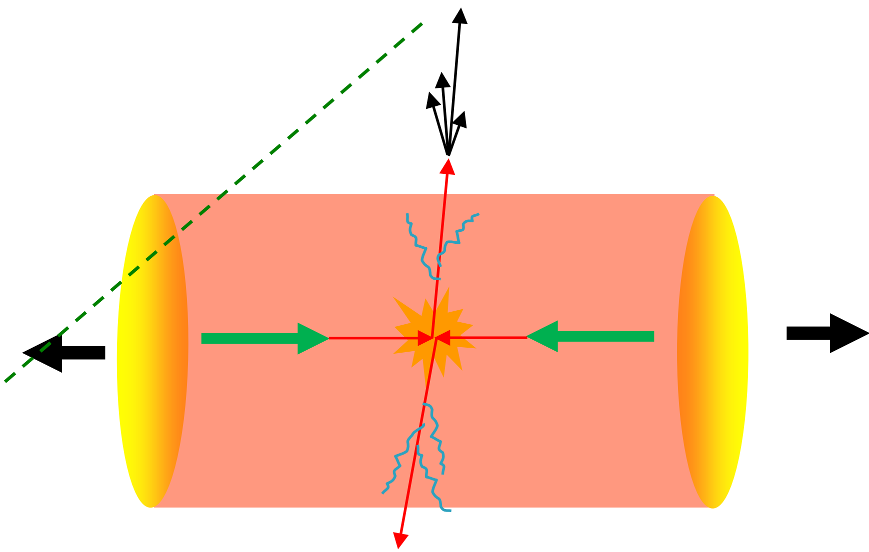
Total medium-induced energy loss:

$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

Leading hadron as a jet surrogate

PHENIX Phys Rev D76, 051106





Energy loss $\Rightarrow$ softening of fragmentation

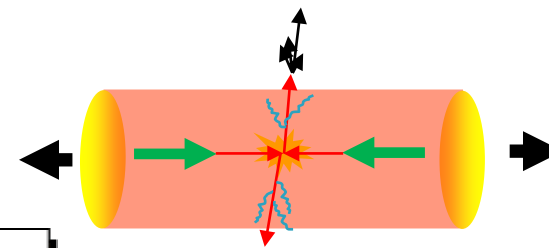
$\Rightarrow$ suppression of leading hadron yield

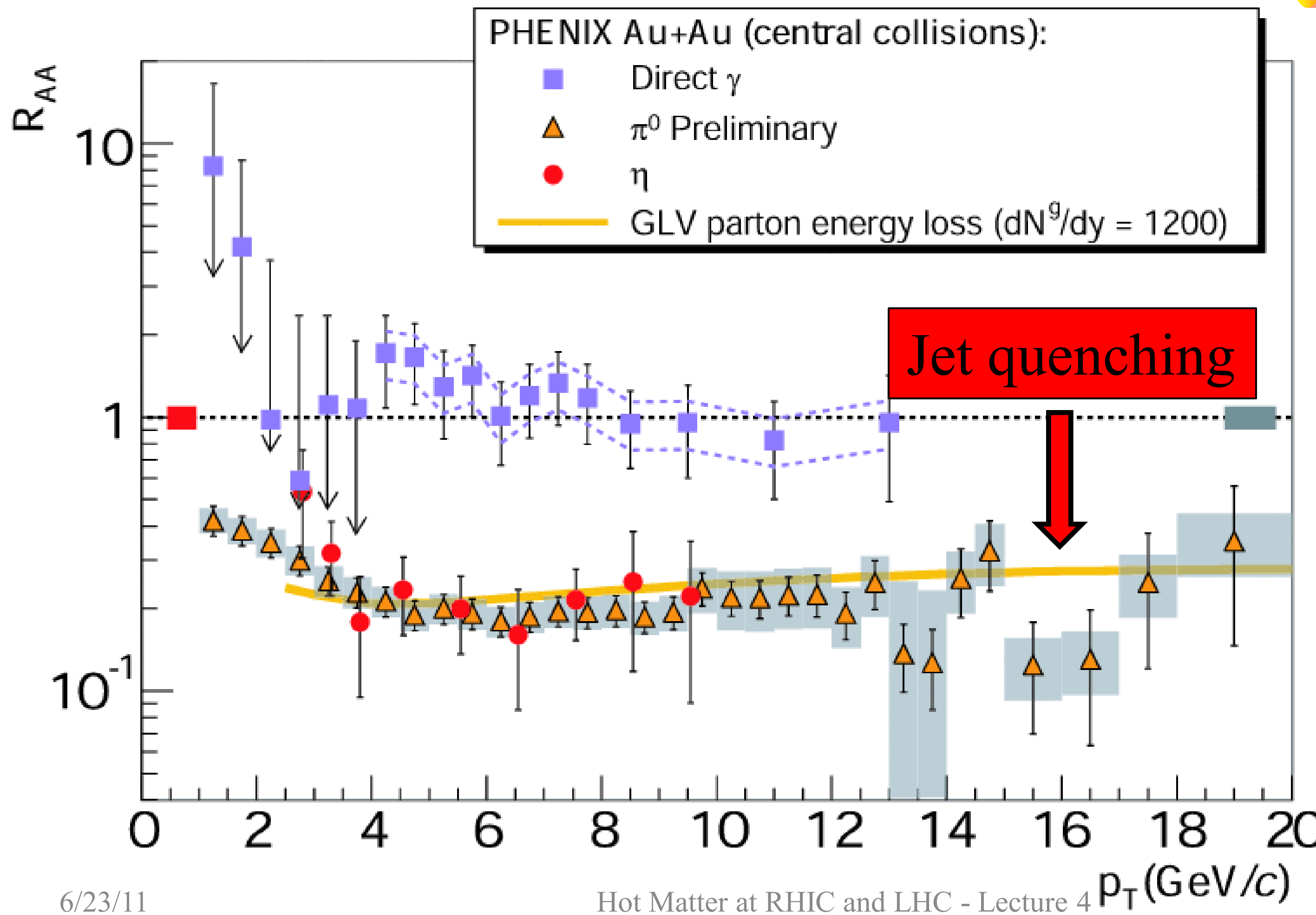
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

Binary collision scaling   p+p reference

Jet quenching I: leading hadrons are suppressed, photons are not

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

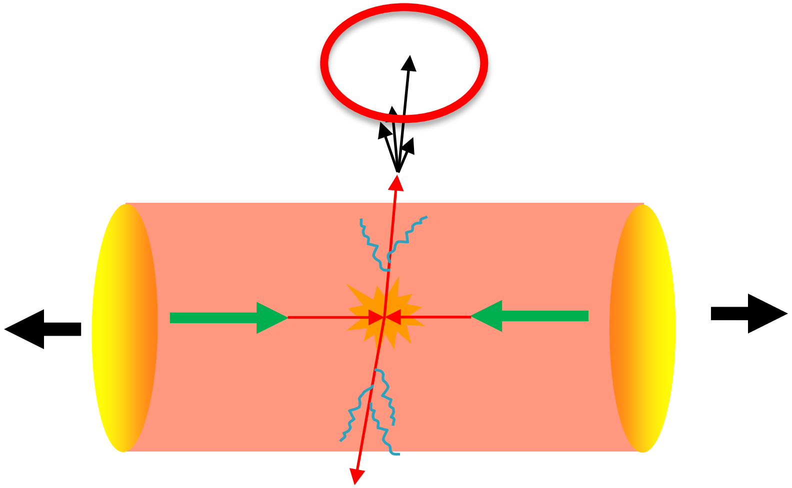




Photons (color-neutral)

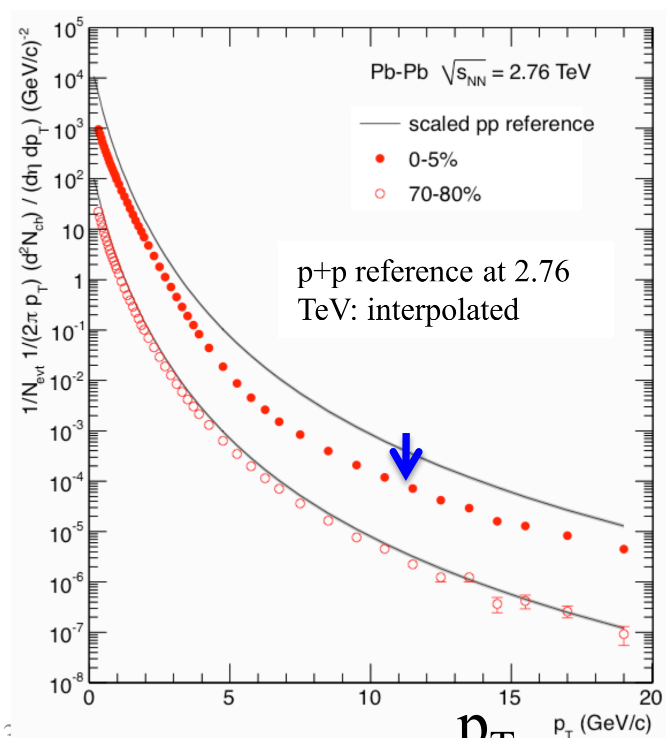
Jet fragments (color-charged)

Jet quenching at the LHC: ALICE

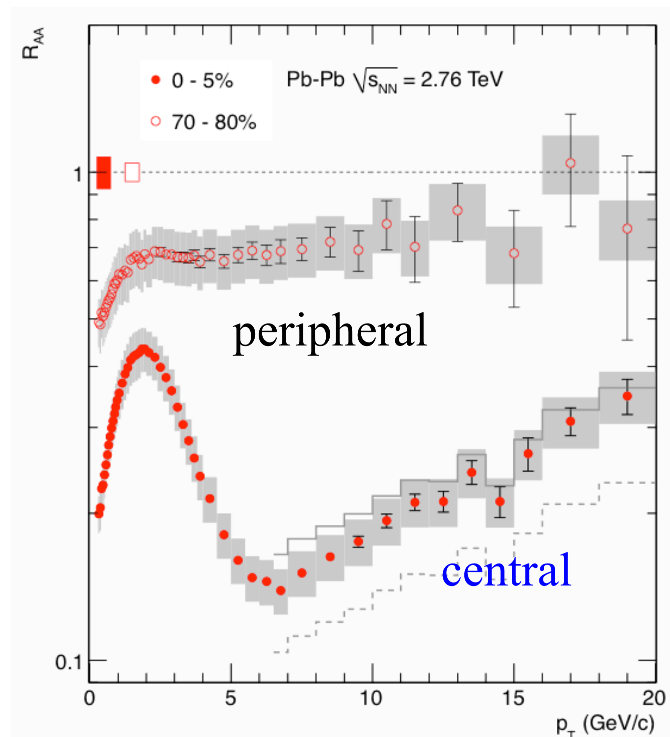


Phys. Lett. B 696 (2011)

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA} \cdot d\sigma_{pp}/dp_T}$$



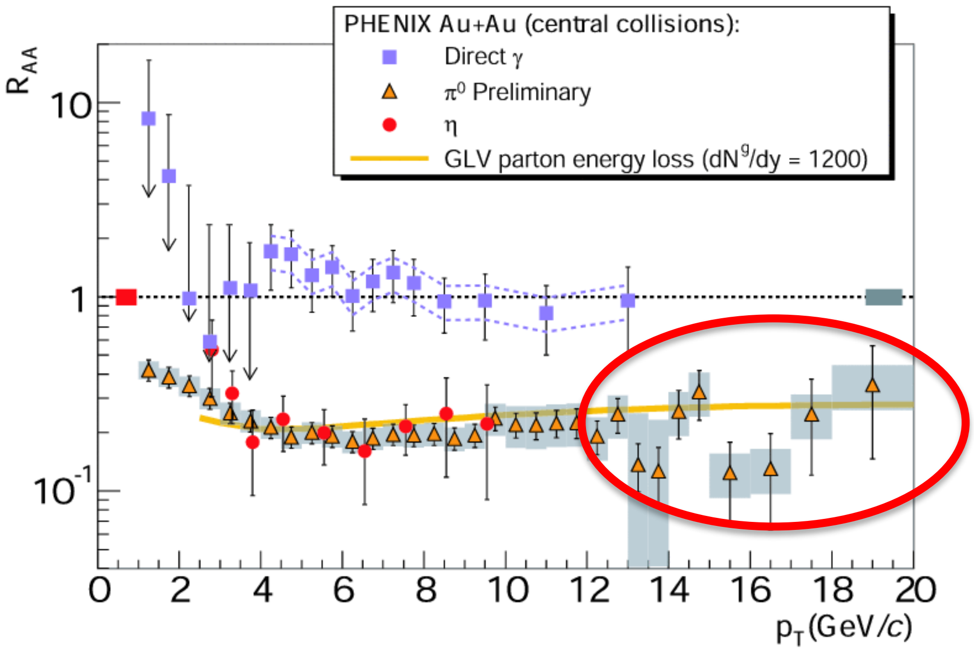
p_T



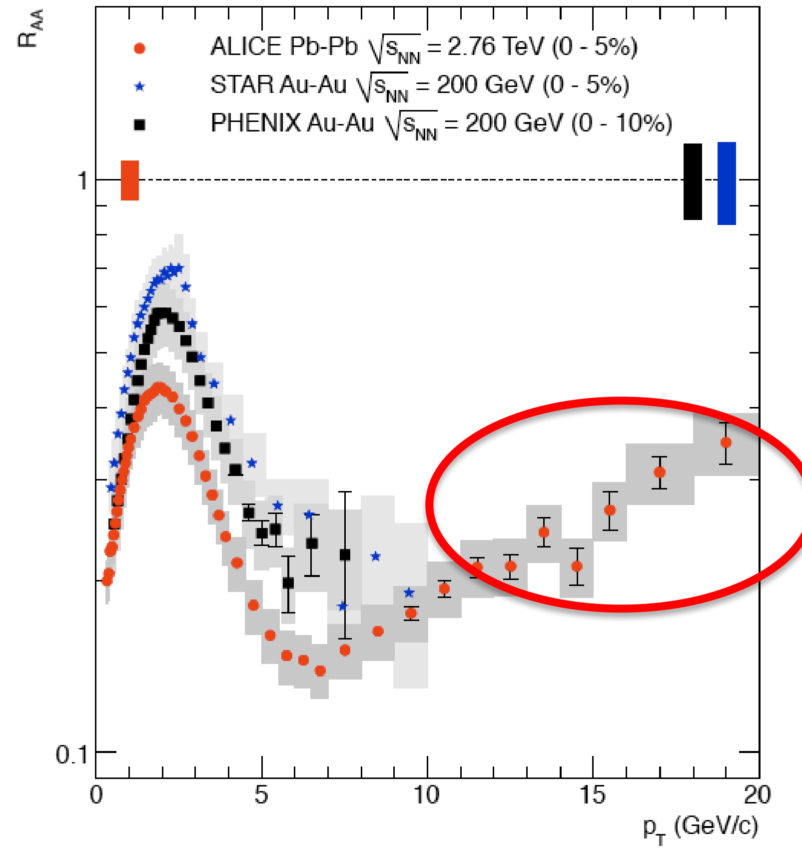
p_T

Jet quenching: RHIC vs LHC

RHIC π^0, η, direct γ

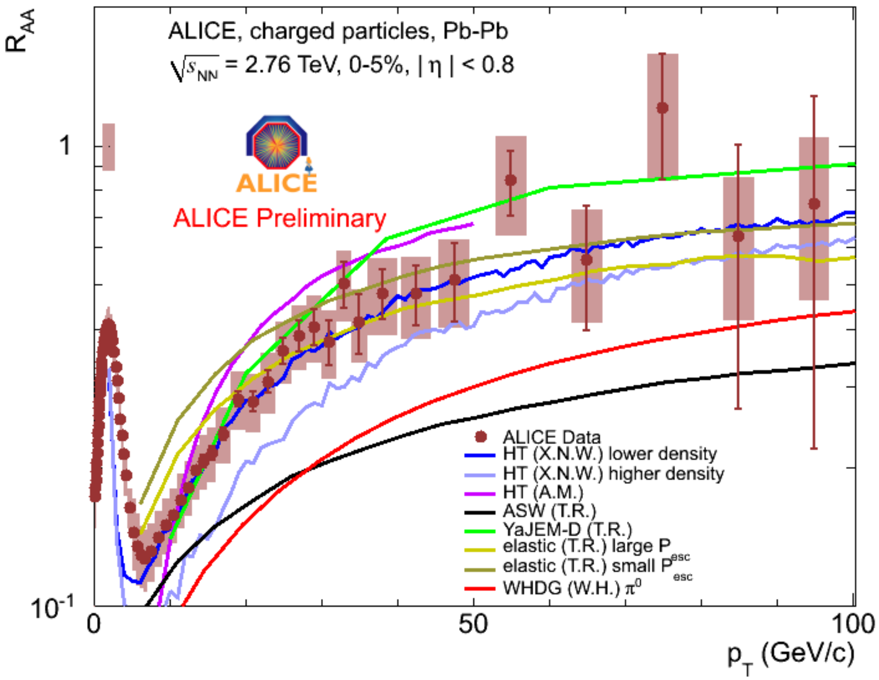


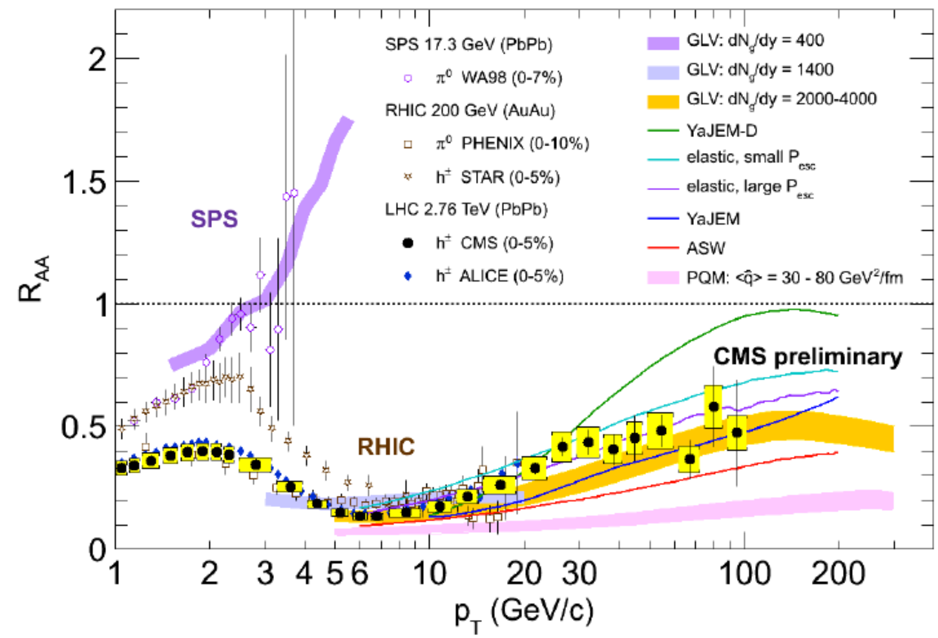
RHIC/LHC charged hadrons



- RHIC/LHC: Qualitatively similar, quantitatively different
- Where comparable, LHC quenching is larger
  - ➔higher color charge density

LHC jet quenching: comparison to pQCD-based models



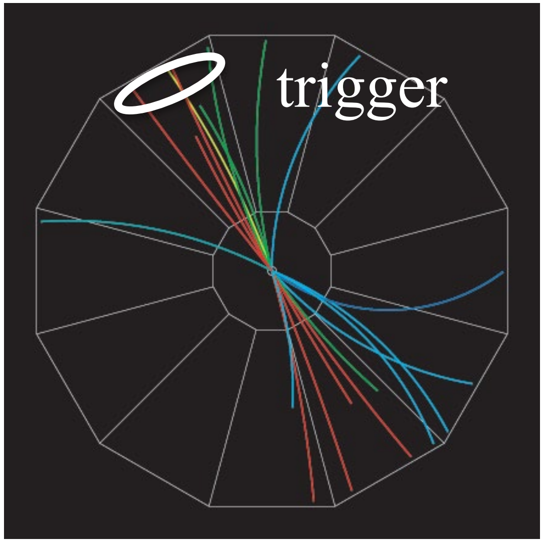


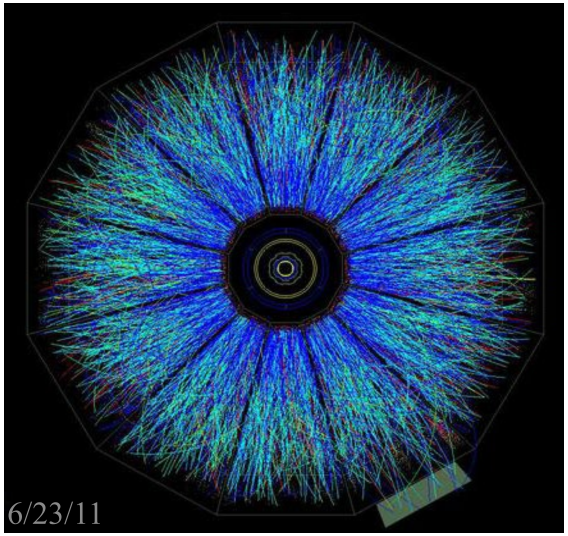
- Main variation amongst models:
  implementations of radiative and elastic energy loss
- Models calibrated at RHIC, scaled to LHC via multiplicity growth

Key prediction: p_T-dependence of R_{AA} ($\Delta E \sim \log(E)$) - OK

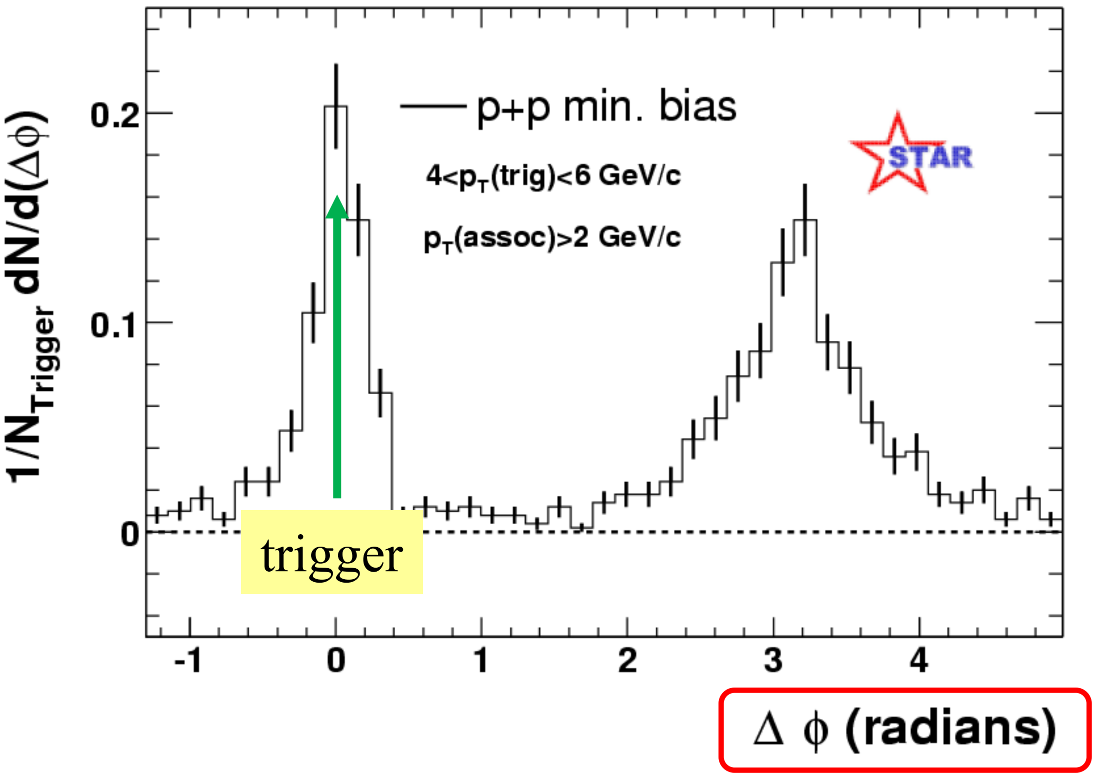
- Qualitatively: pQCD-based energy loss picture consistent with measurements
- We can now refine the details towards a quantitative description

Di-hadron correlations as a jet surrogate

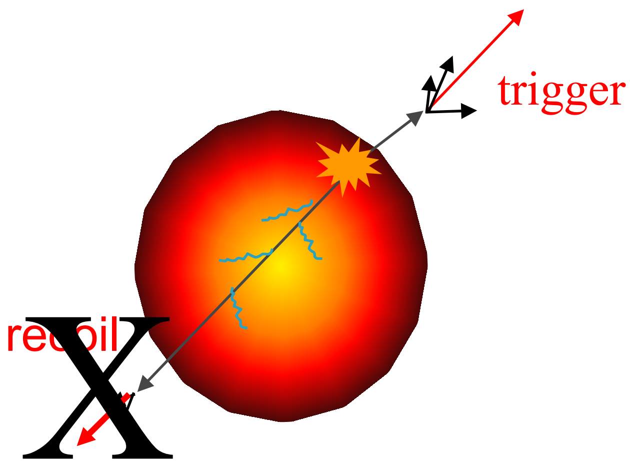


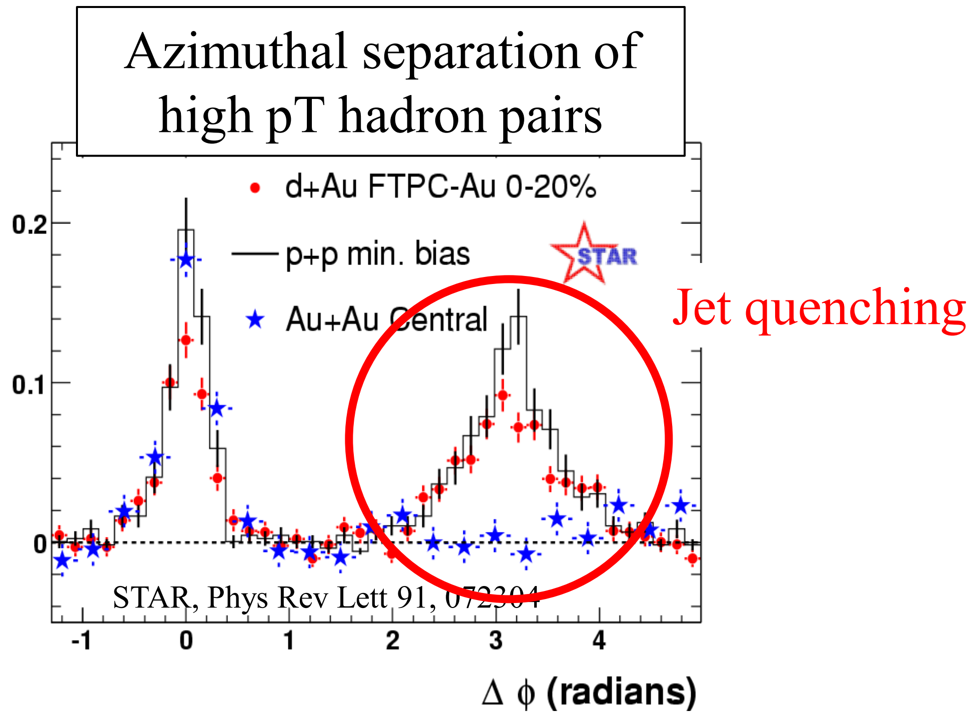


STAR, Phys Rev Lett 90, 082302



Jet quenching II: di-hadrons

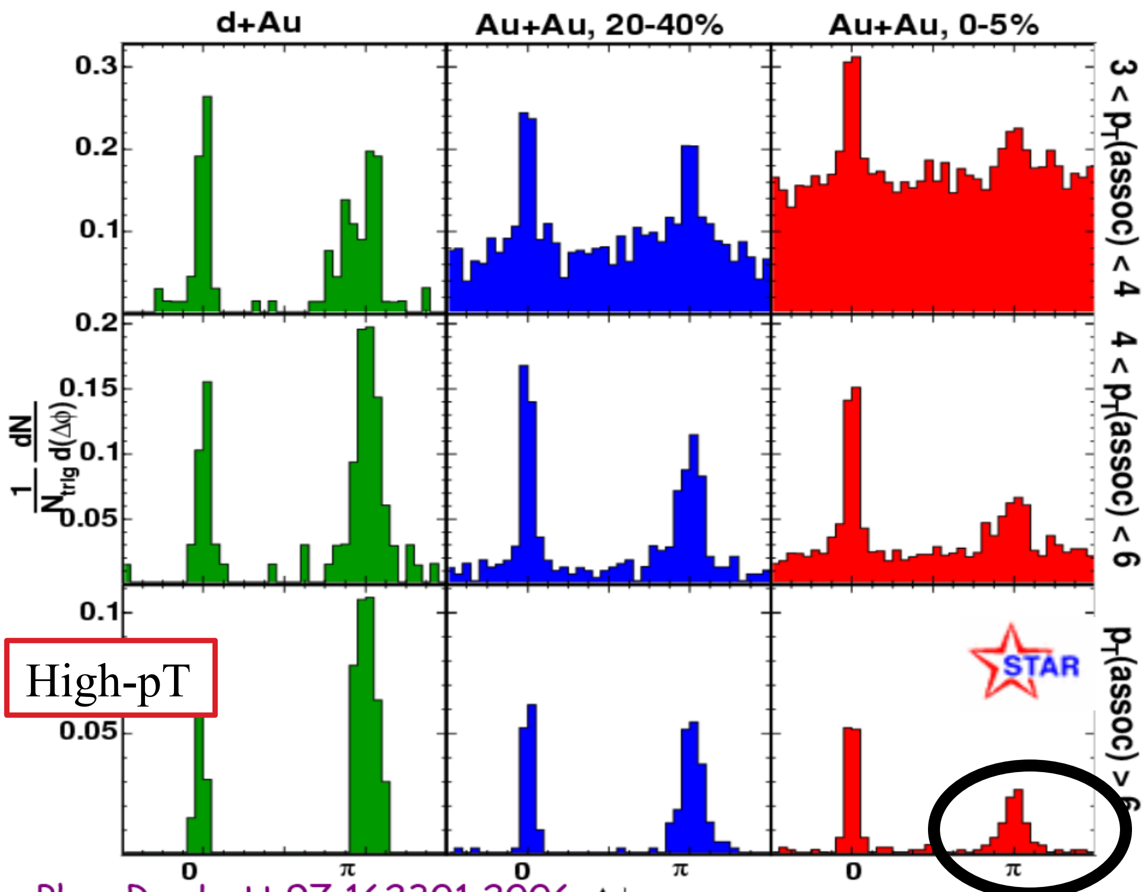




- Recoiling jet is strongly altered by medium
- Clear evidence for presence of very high density matter

Di-hadron correlations at high-pt

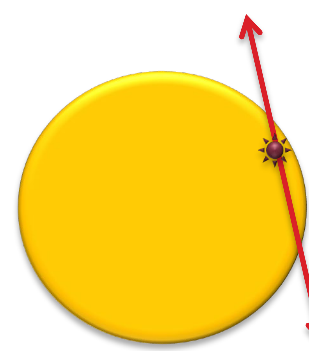
Central collisions



Phys.Rev.Lett.97:162301,2006

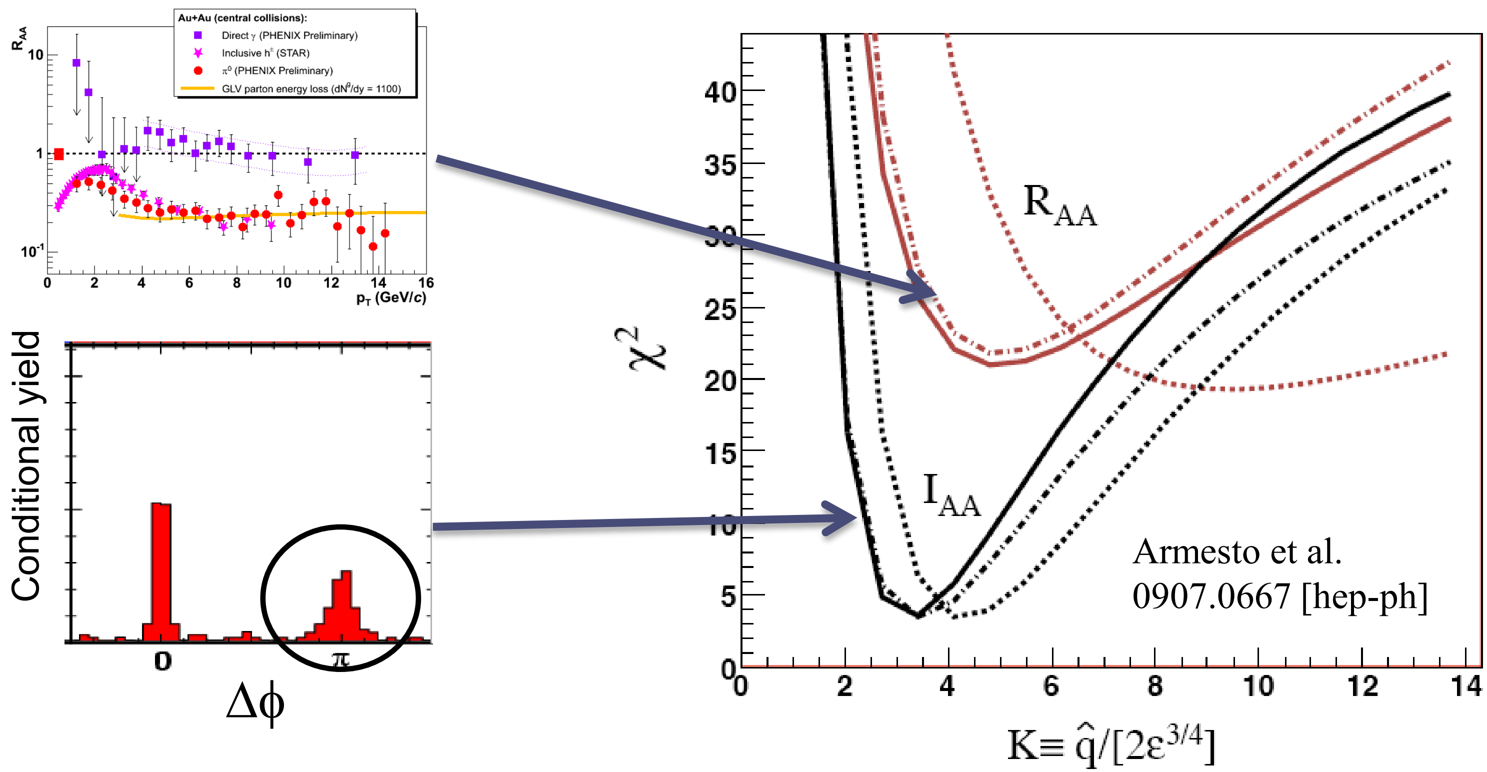
Reaperance of the away side peak at high-assoc.-pT:
- similar suppression as inclusive spectra
- no angular broadening

Differential measurement of jets w/o interaction



QCD analysis of jet quenching

Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.



- ~Self-consistent fit of independent observables
- Data have good precision: limitation is accuracy of the theory

Jet quenching: pQCD vs AdS/CFT

Weak-coupling pQCD (Baier et al.):

$$\hat{q}_{pQCD} = \frac{8\varsigma(3)}{\pi}\alpha_S^2 N_{color}^2 T^3 \sim 0.94\frac{GeV^2}{fm} \text{ at } T = 300 \text{ MeV}$$

Proportional to N_C^2 ~ entropy density

Strong-coupling *N*=4 SYM (Liu, Rajagopal and Wiedemann):

$$\hat{q}_{AdS/CFT} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\alpha_{SYM} N_{color}}\, T^3 \sim 4.5\frac{GeV^2}{fm} \text{ at } T = 300 \text{ MeV}$$

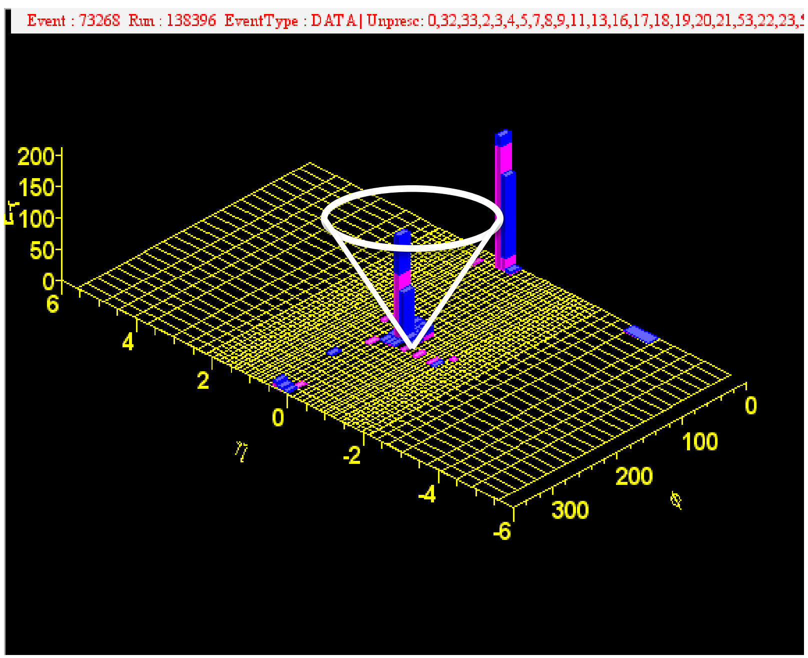
NOT proportional to N_C^2 ~ entropy density

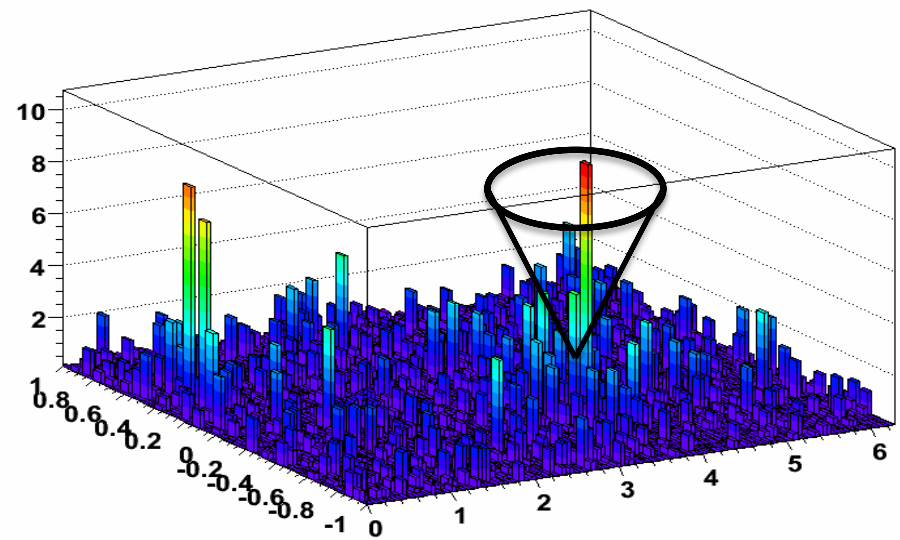
Roughly $\hat{q}_{data} \sim 1 - 5\ GeV/fm^2$

Full jet reconstruction

Jet quenching is a **partonic** process: can we study it at the partonic level?

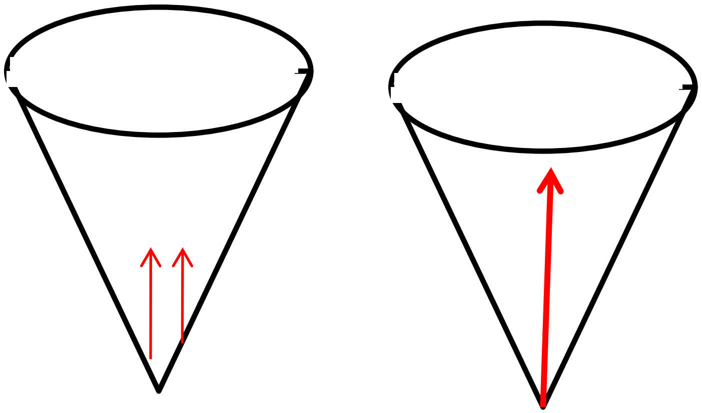
Jet reconstruction: capture the entire spray of hadrons to reconstruct the kinematics of the parent quark or gluon

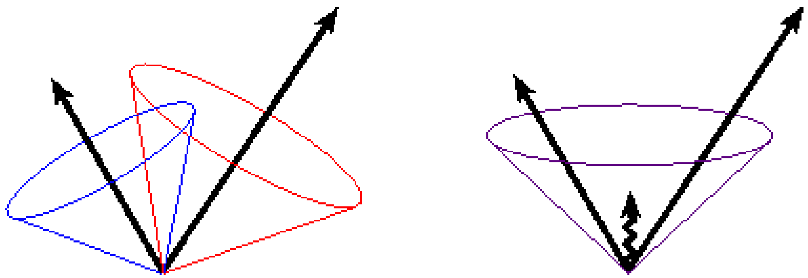




Jet measurements in practice: experiment and theory

Fermilab Run II jet physics
hep-ex/0005012





colinear safety:

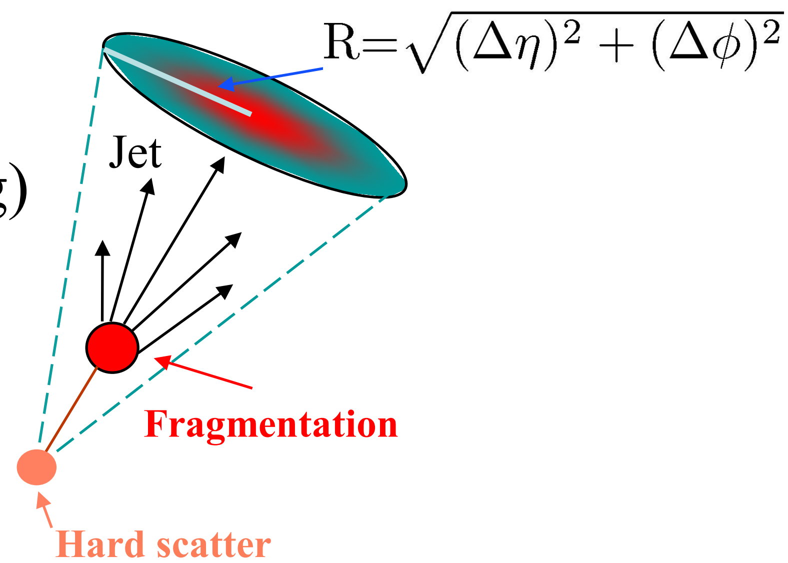
finite seed threshold misses jet on left?

infrared safety:

one or two jets?

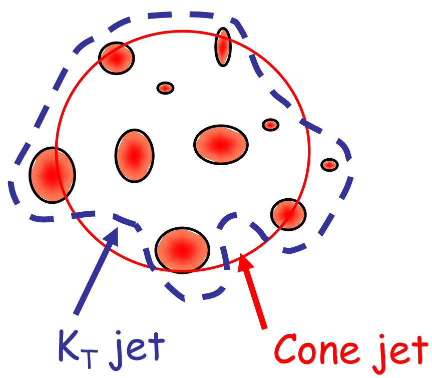
Algorithmic requirements:
- same jets at parton/particle/detector levels
- independence of algorithmic details (ordering of seeds etc)

Modern jet reconstruction algorithms



- Cone algorithms
  - Mid Point Cone (merging + splitting)
  - SISCone (seedless, infr-red safe)

- Sequential recombination algorithms
  - k_T
  - anti-k_T
  - Cambridge/ Aachen



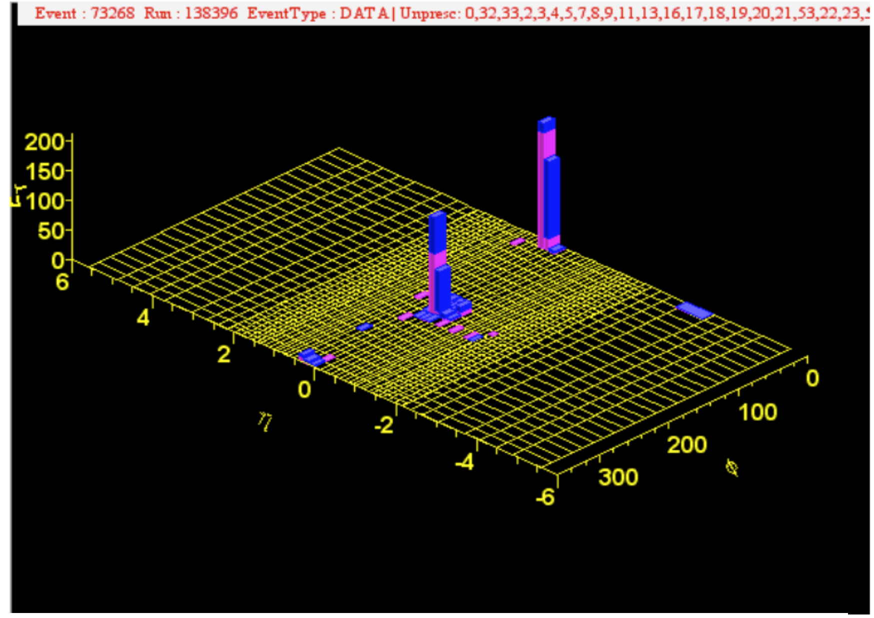
Algorithms differ in recombination metric:

➔different ordering of recombination

➔different event background sensitivities

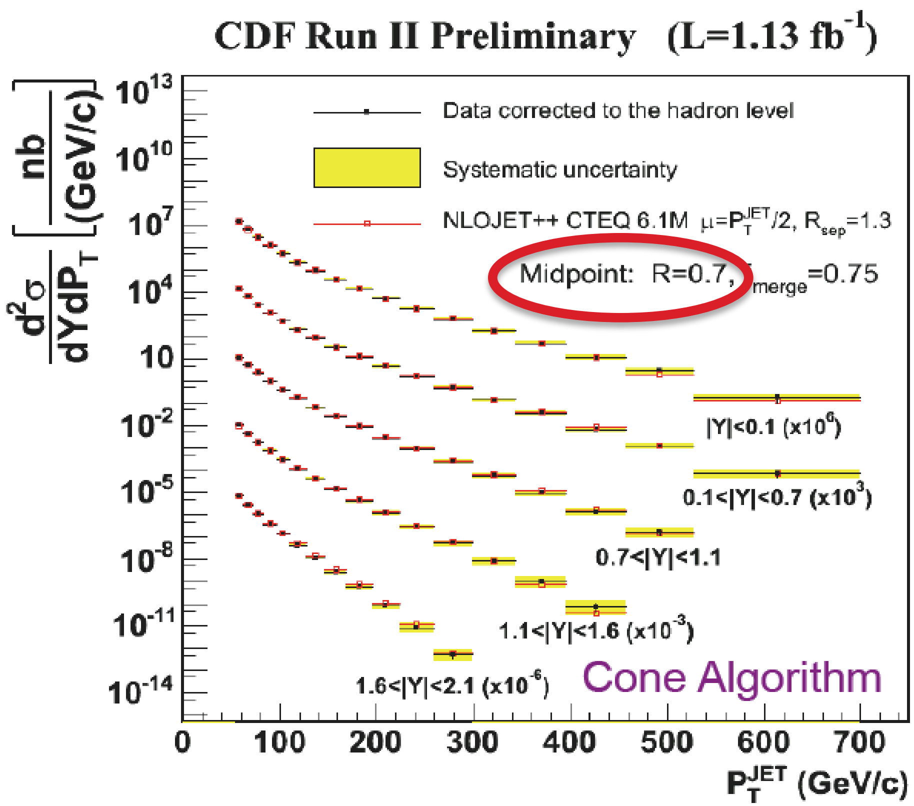
Modern implementation: FastJet (M. Cacciari, G. Salam, G. Soyez JHEP 0804:005 (2008))

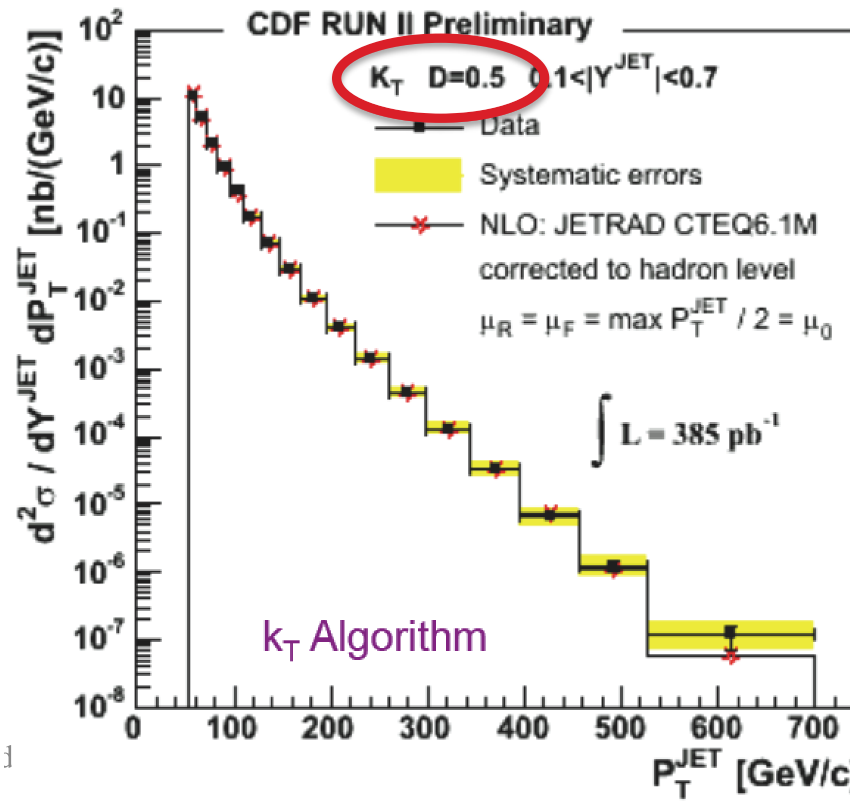
Jets at CDF/Tevatron



Good with NLO pQCD

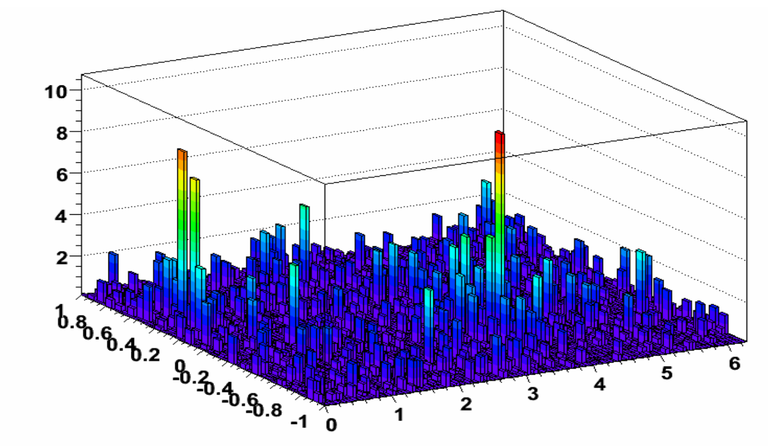
Multiple algorithms give consistent results



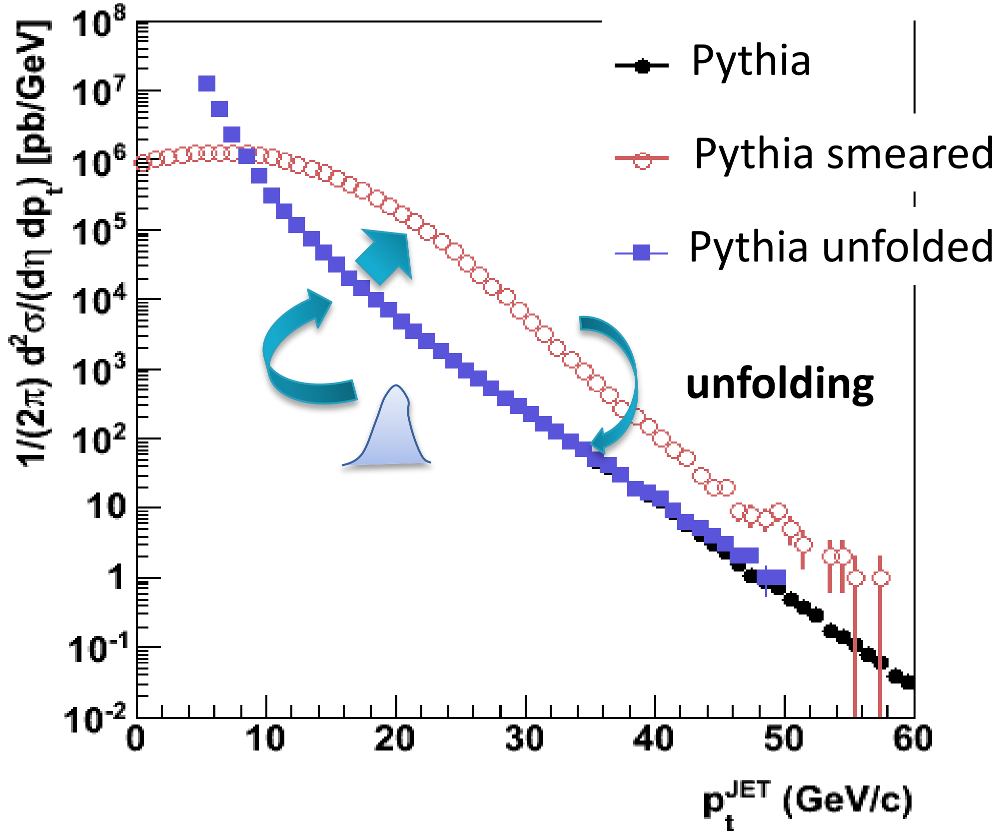


Jet measurements over large background

Background fluctuations distort measured inclusive cross section

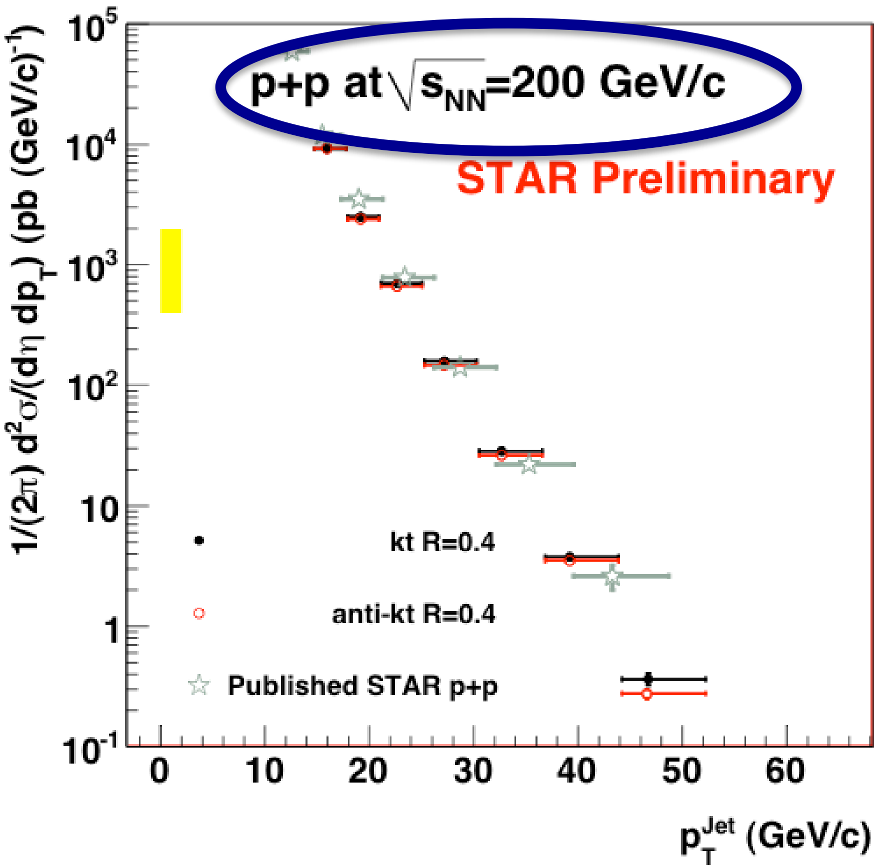


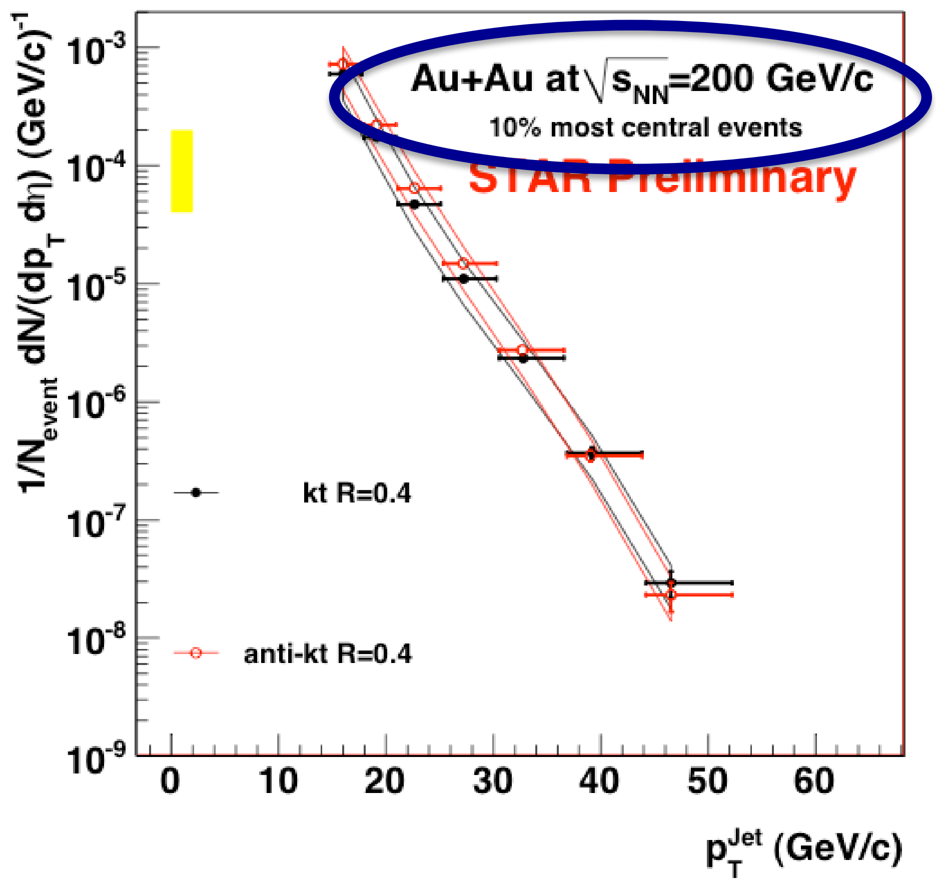
$$\frac{dN^{\mathrm{Meas}}}{dp_T} = \frac{dN^{\mathrm{True}}}{dp_T} \otimes f^{\mathrm{Resol}}(\delta\rho)$$



Inclusive jet cross sections at √s=200 GeV

M. Ploskon QM09



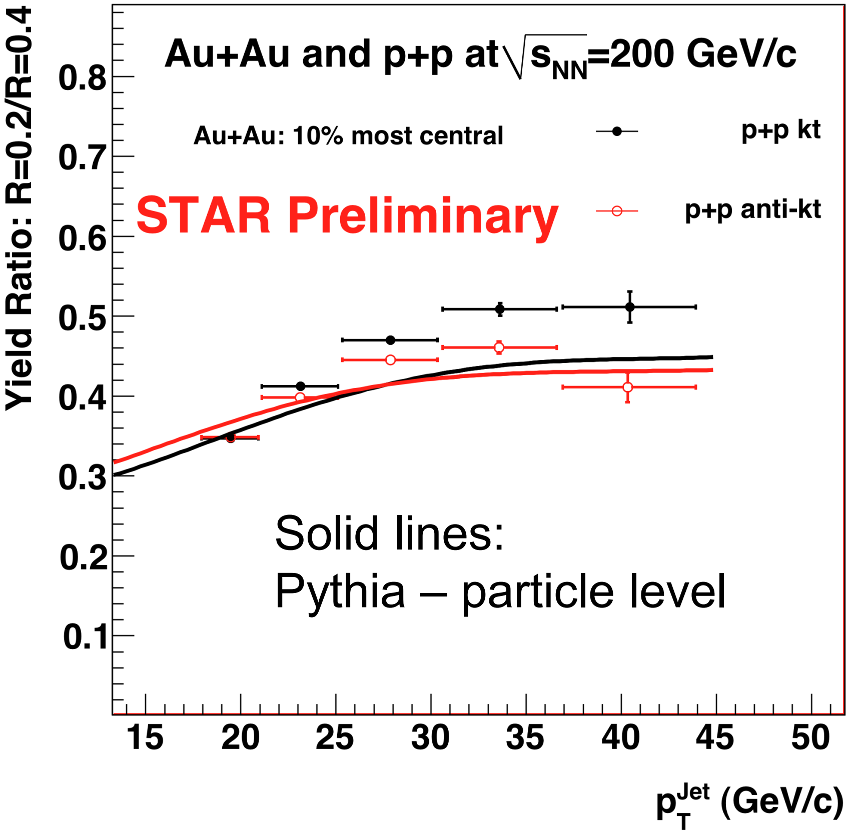


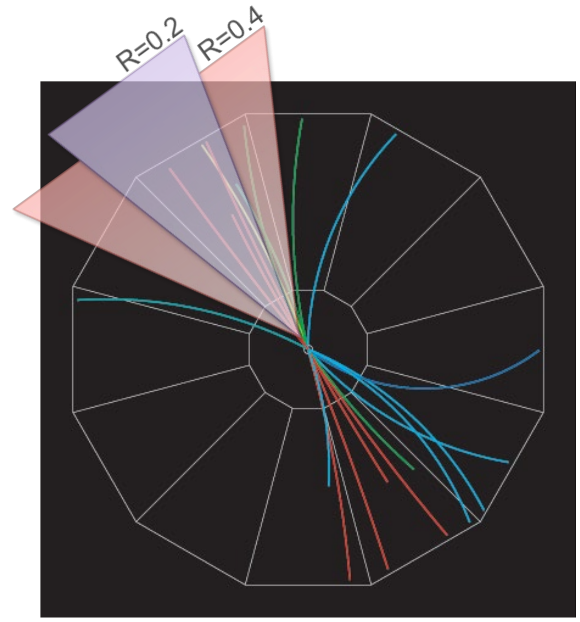
Consistent results from different algorithms

Background correction ~ factor 2 uncertainty in xsection

Inclusive cross-section ratio: p+p R=0.2/R=0.4

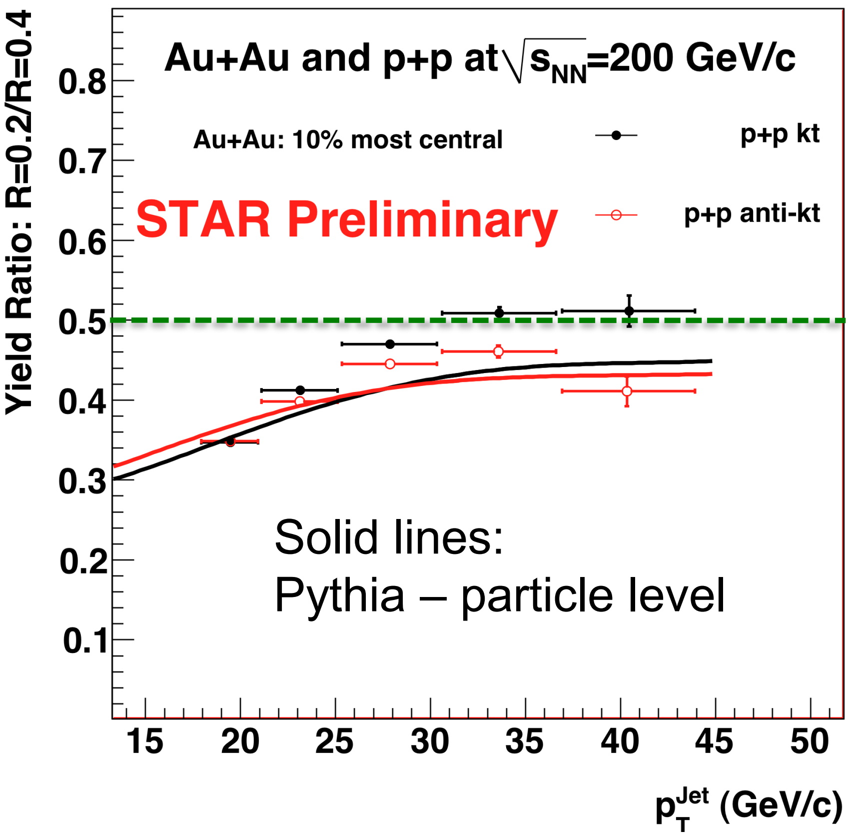
compare within same dataset: systematically better controlled than R_{AA}





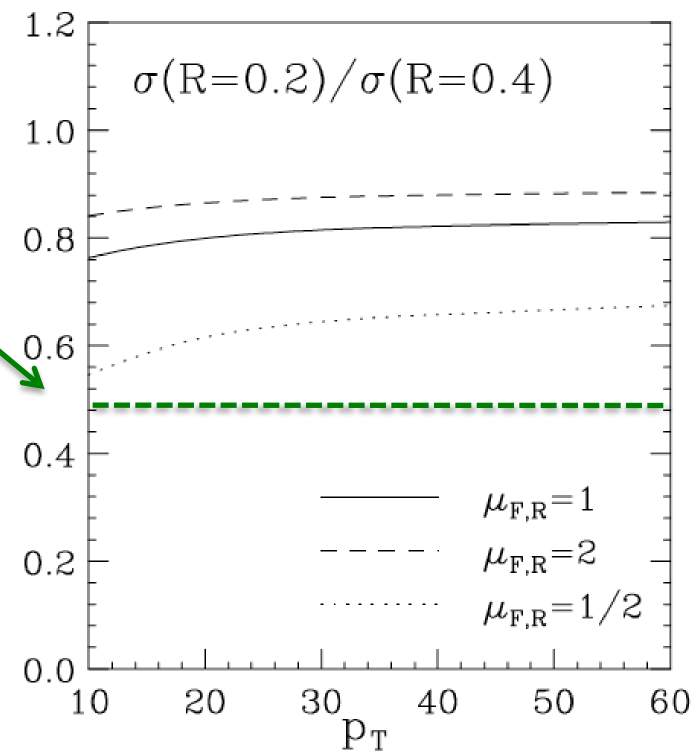
Narrowing of the jet structure with increasing jet energy

Inclusive cross-section ratio in p+p: compare to NLO pQCD



Narrowing of structure with increasing energy

NLO pQCD calculation
W. Vogelsang – priv. comm. 2009



NLO: narrower jet profile
➔hadronization effects?

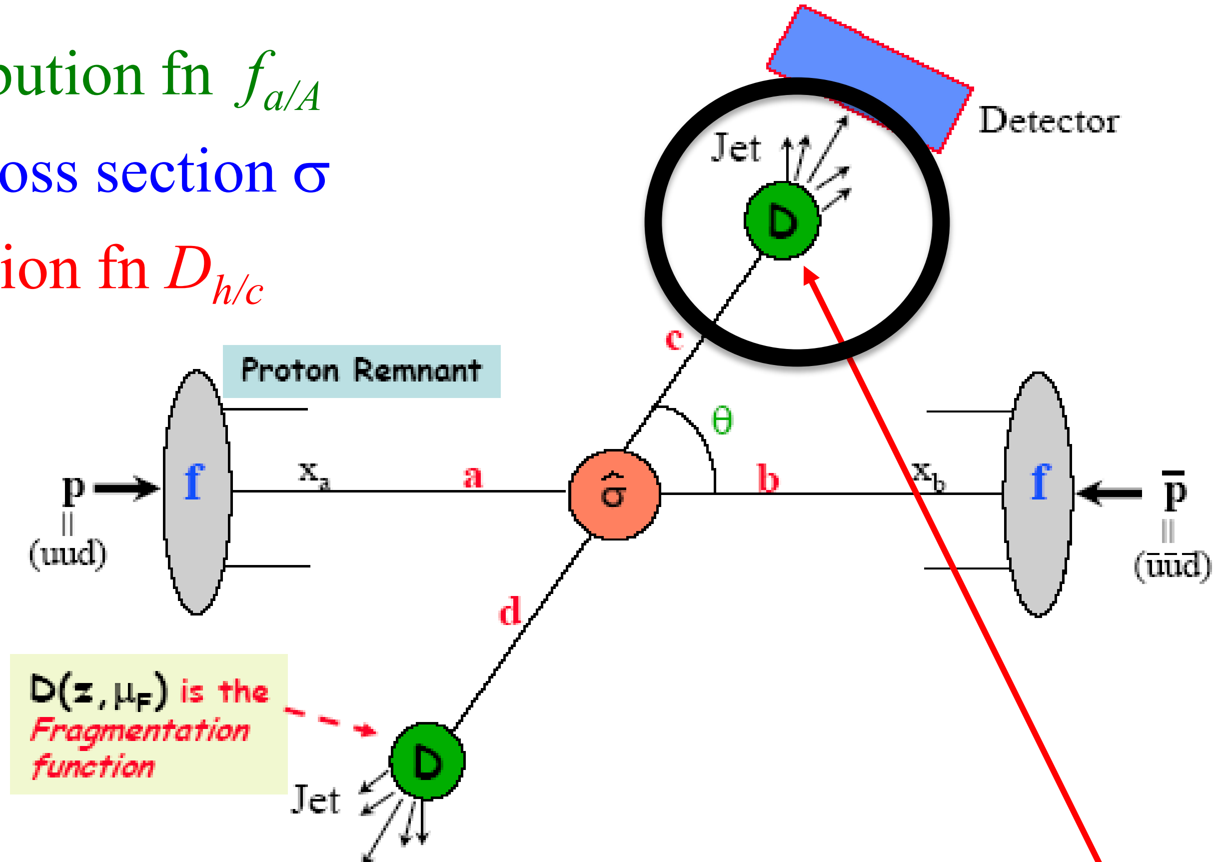
Jet hadronization

pQCD factorization:

parton distribution fn $f_{a/A}$

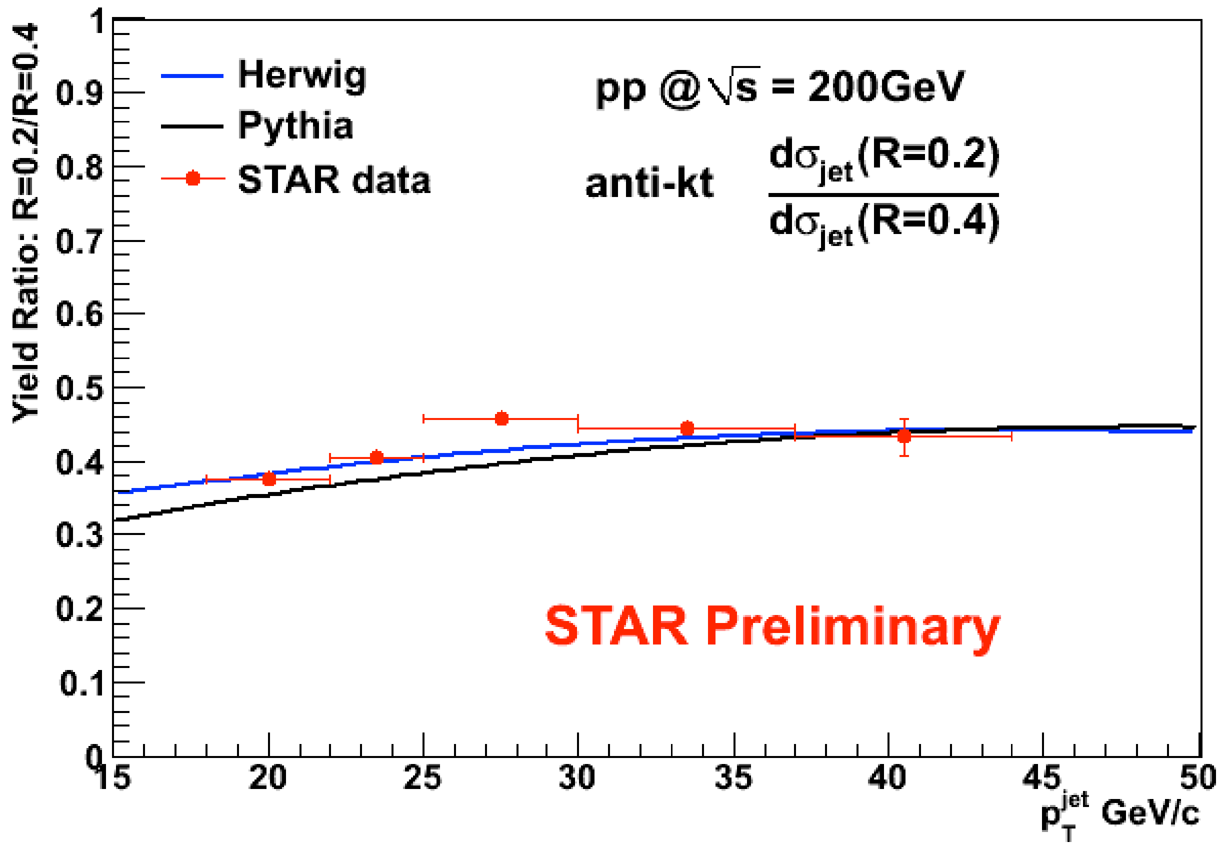
\+ partonic cross section σ

\+ fragmentation fn $D_{h/c}$



$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a,Q^2\right) \otimes f_{b/B}\left(x_b,Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}\left(z_c,Q^2\right)$$

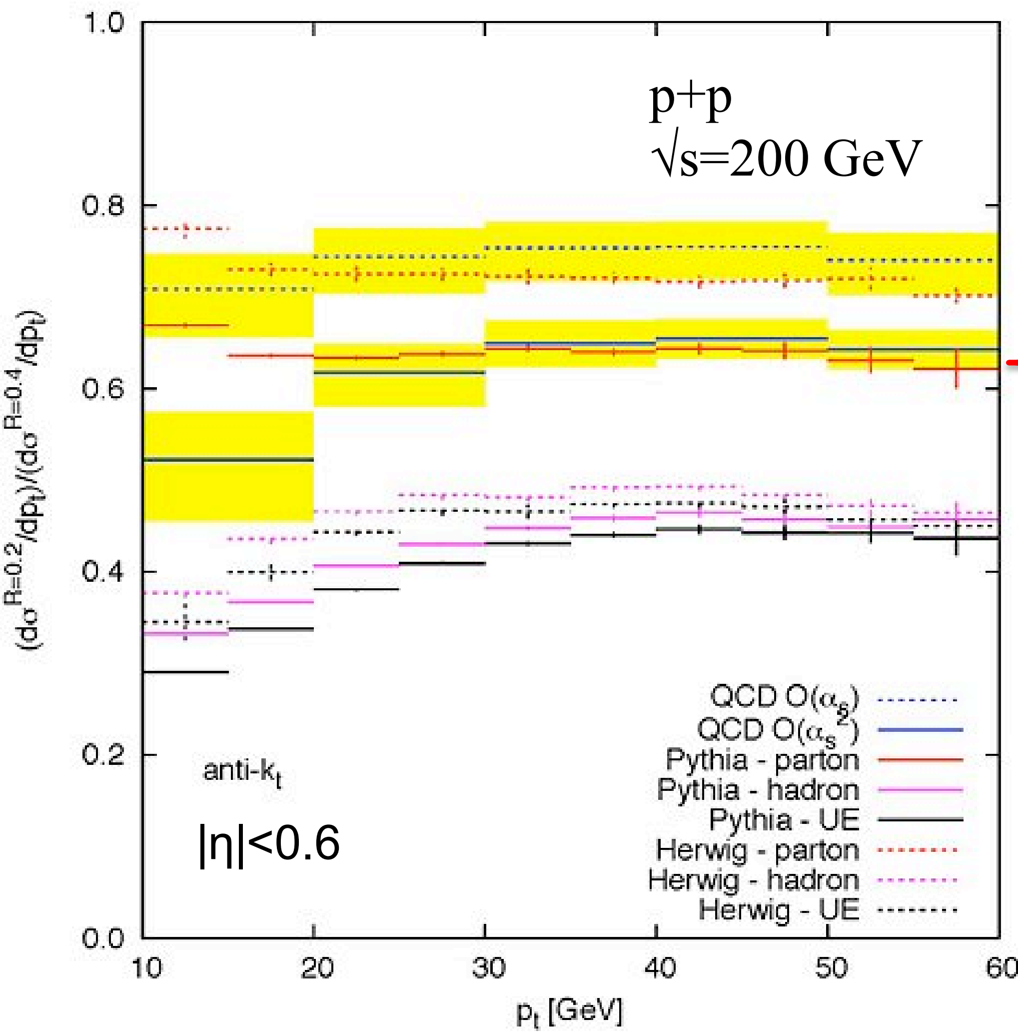
Hadronization effects: HERWIG vs. PYTHIA



Different hadronization models generate closely similar ratios

σ(R=0.2)/σ(R=0.4) : NNLO calculation

G. Soyez, private communication



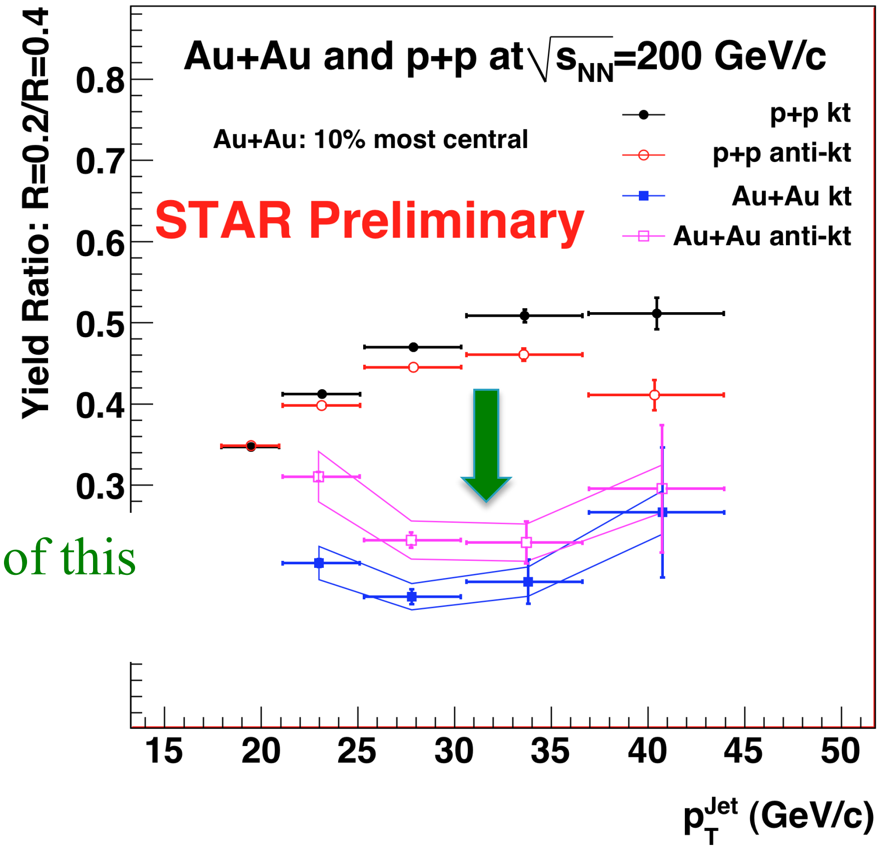
QCD NLO

QCD NNLO
PYTHIA parton level

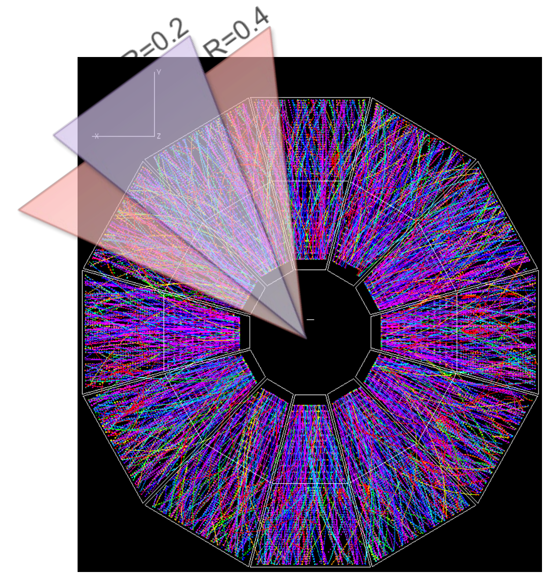
PYTHIA hadron level
HERWIG hadron level

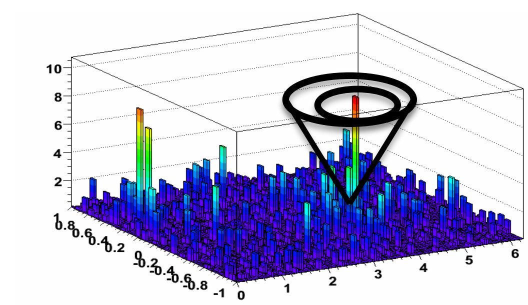
Broadening due to combined effects of higher order corrections and hadronization

Incl. cross-section ratio: Au+Au R=0.2/R=0.4



Main result of this analysis

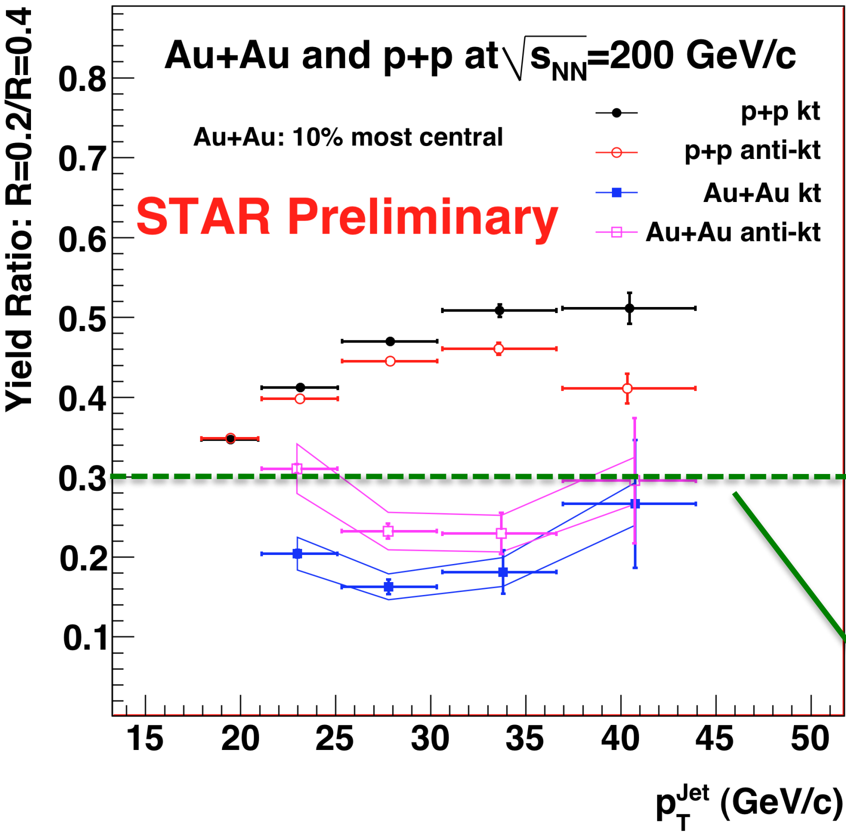


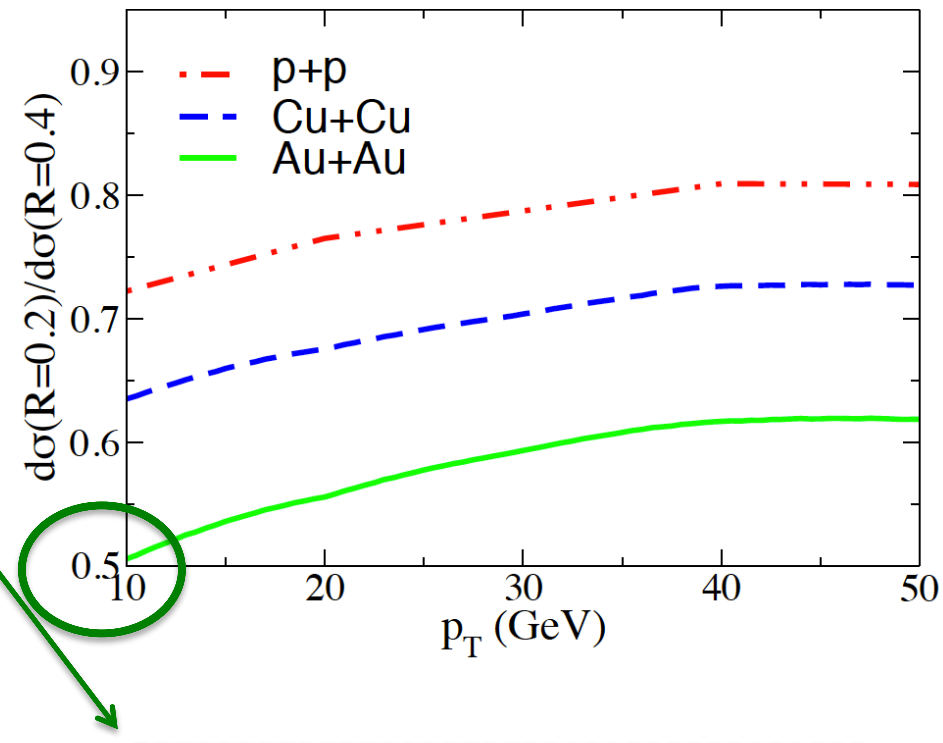


Marked suppression of ratio relative to p+p
➔medium-induced jet broadening

Incl. cross-section ratio Au+Au: compare to NLO

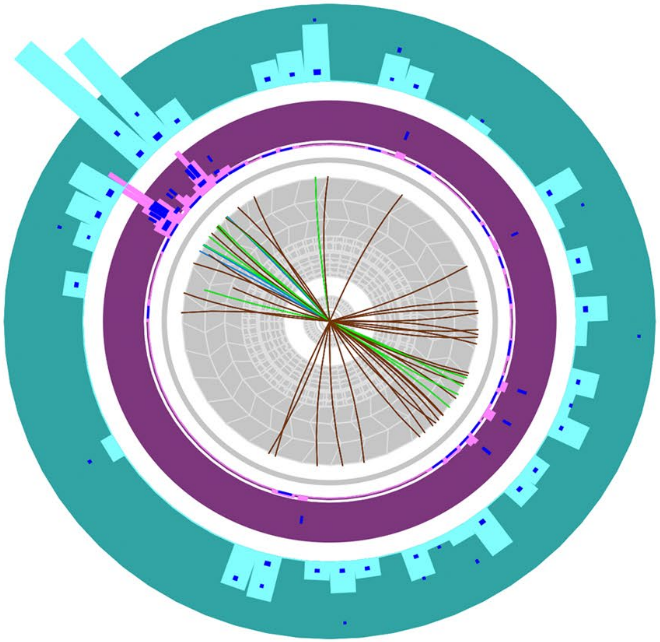
NLO with jet quenching (GLV)
B.-W. Zhang and I. Vitev
Phys. Rev. Lett. 104, 132001 (2010)

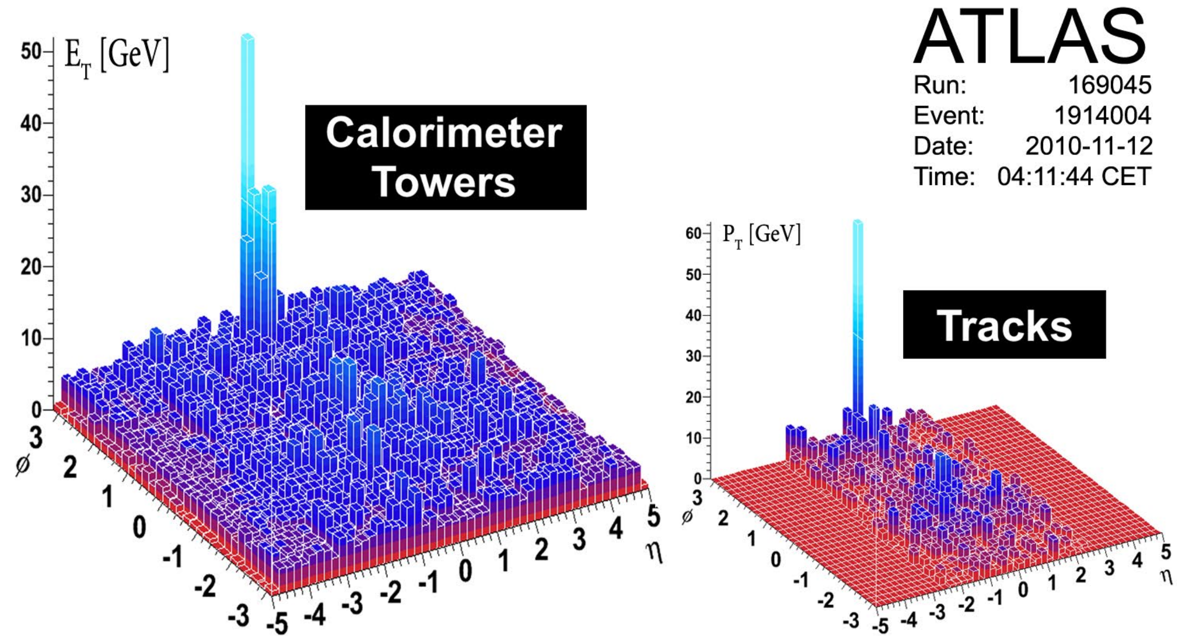




Stronger broadening in measurement than NLO
…work in progress for both experiment and theory…

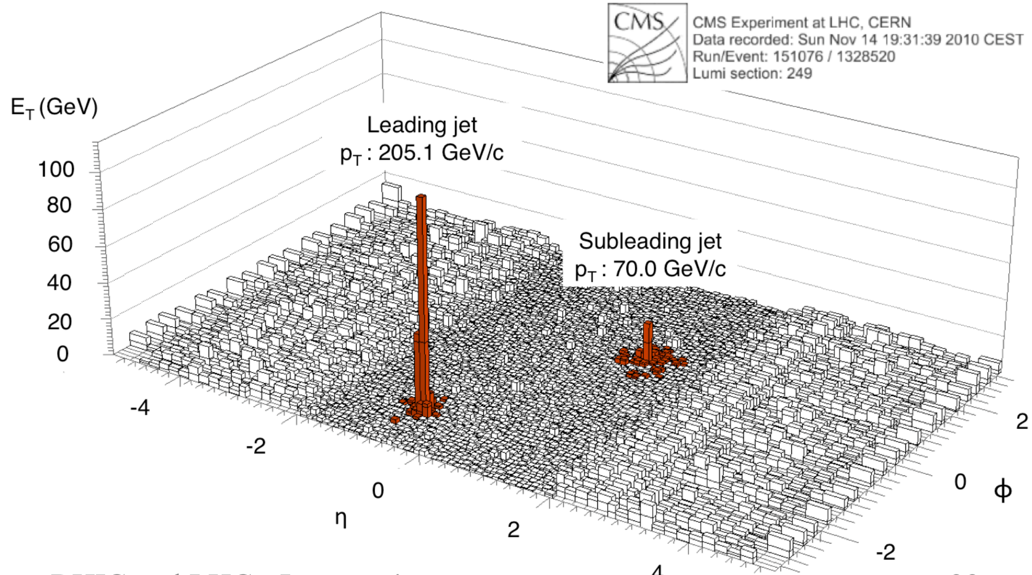
Jets at LHC

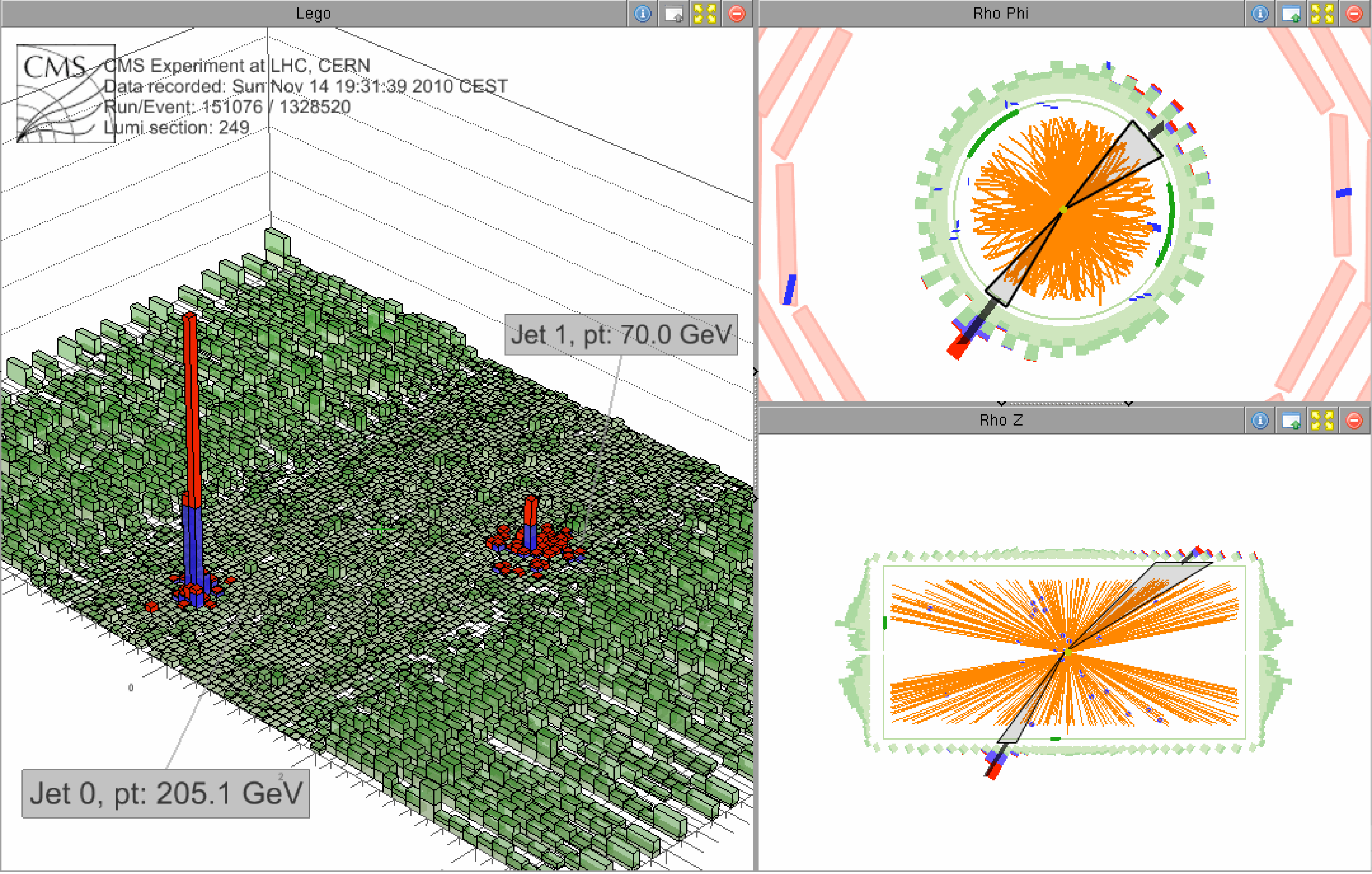




LHC: jet energies up to ~200 GeV in Pb+Pb from 1 'short' run

Large energy asymmetry observed for central events

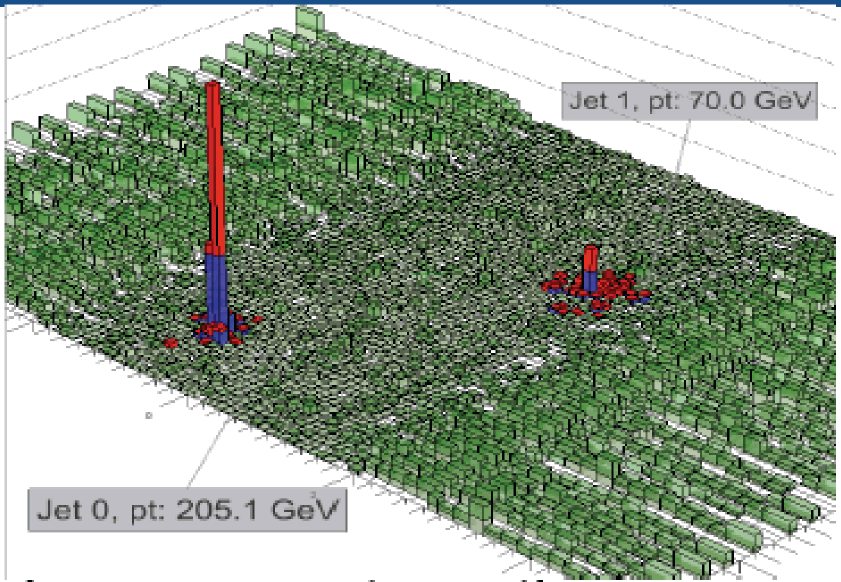




Lego
Rho Phi
Rho Z
CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

Dijet Asymmetry

- Dijet selection:
  - $|\eta^{Jet}| < 2$
  - Leading jet $p_{T,1} > 120GeV/c$
  - Subleading jet $p_{T,2} > 50GeV/c$
  - $\Delta\phi_{1,2} > 2\pi/3$

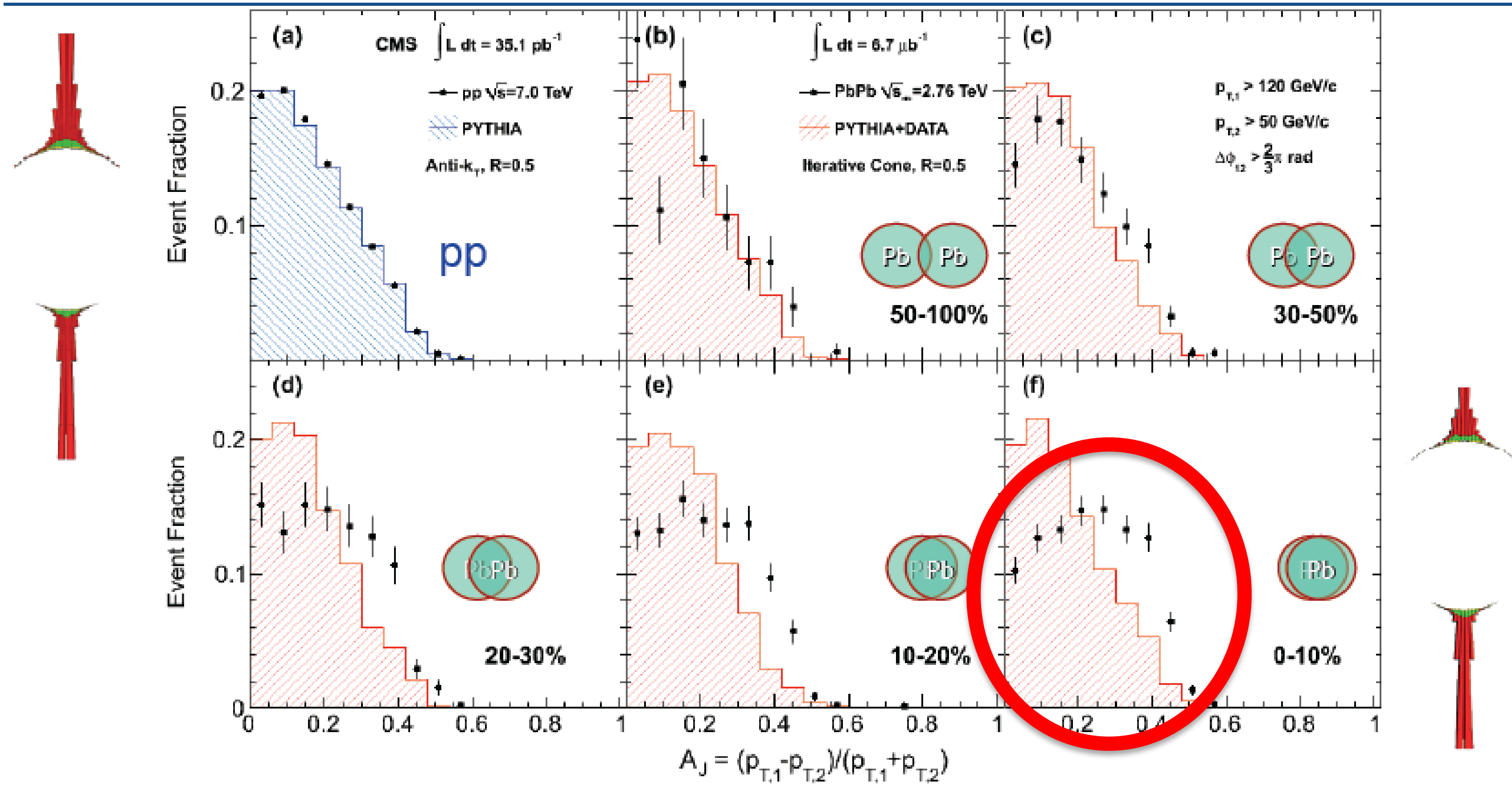


- Quantify dijet energy imbalance by asymmetry ratio:

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Removes uncertainties in overall jet energy scale

LHC Pb+Pb: Dijet energy imbalance



Large energy asymmetry in central collisions: seen by CMS and ATLAS

Purely calorimetric measurement:

significant (unknown?) systematic uncertainties due to cutoffs and non-linearities for low p_T hadrons

➔connection to jet quenching?

Recall the summary of Lecture 1: scorecard

Red=progress
Blue=interesting ideas
Black=still thinking

What is the nature of QCD Matter at finite temperature?

- What is its phase structure?
- What is its equation of state?
- What are its effective degrees of freedom?
  - Is it a (trivial) gas of non-interacting quarks and gluons, or a fluid of interacting quasi-particles?
- What are its symmetries?
- Is it correctly described by Lattice QCD or does it require new approaches, and why?

What are the dynamics of QCD matter at finite temperature?

- What is the order of the (de-)confinement transition?
- How is chiral symmetry restored at high T, and how?
- Is there a QCD critical point?
- What are its transport properties?

Can QCD matter be related to other physical systems?

Can we study hot QCD matter experimentally?