Hot QCD Matter

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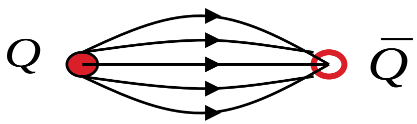
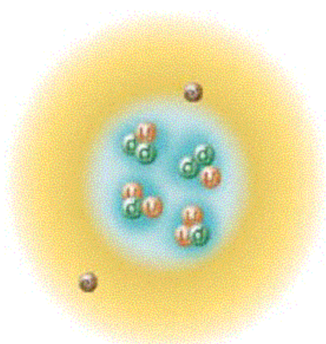
Lecture 1: Tools
Lecture 2: Initial conditions: partonic structure and global observables
Lecture 3: Collective flow and hydrodynamics
Lecture 4: Jets and other hard probes

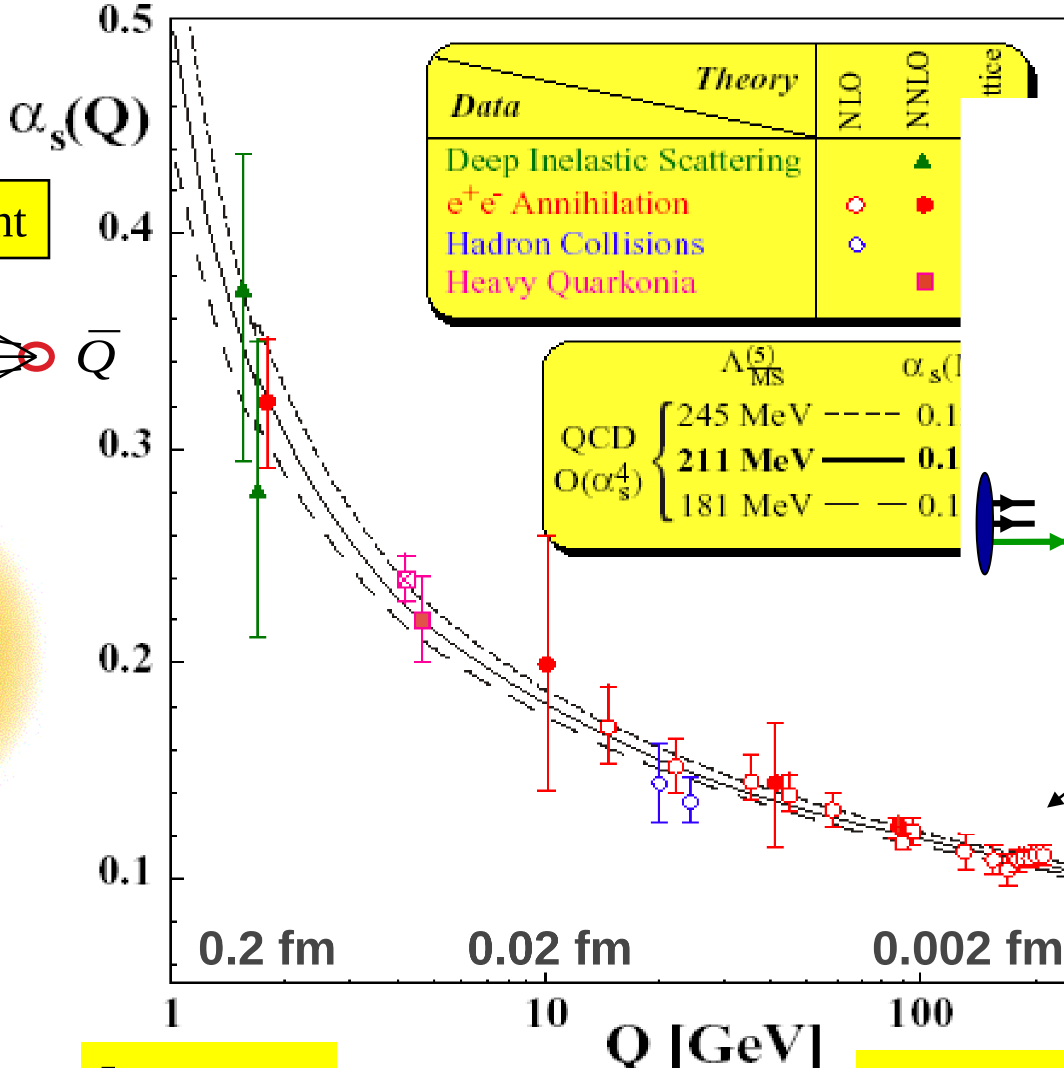
QCD: running of α_s

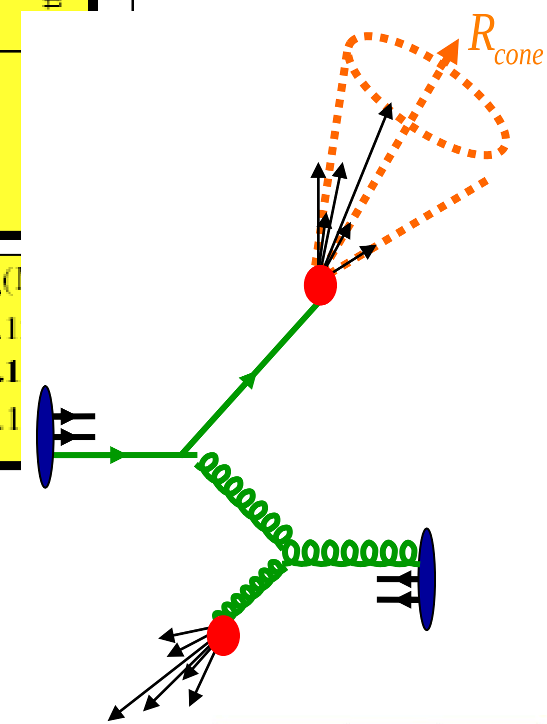
Asymptotic Freedom

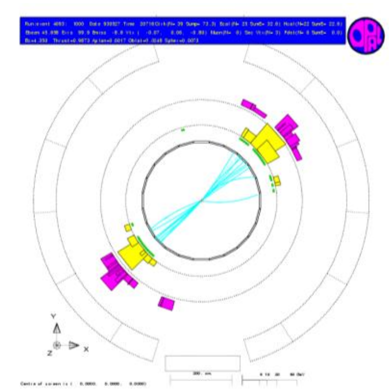
Confinement











Low momentum

High momentum

Perturbative QCD factorization in hadronic collisions

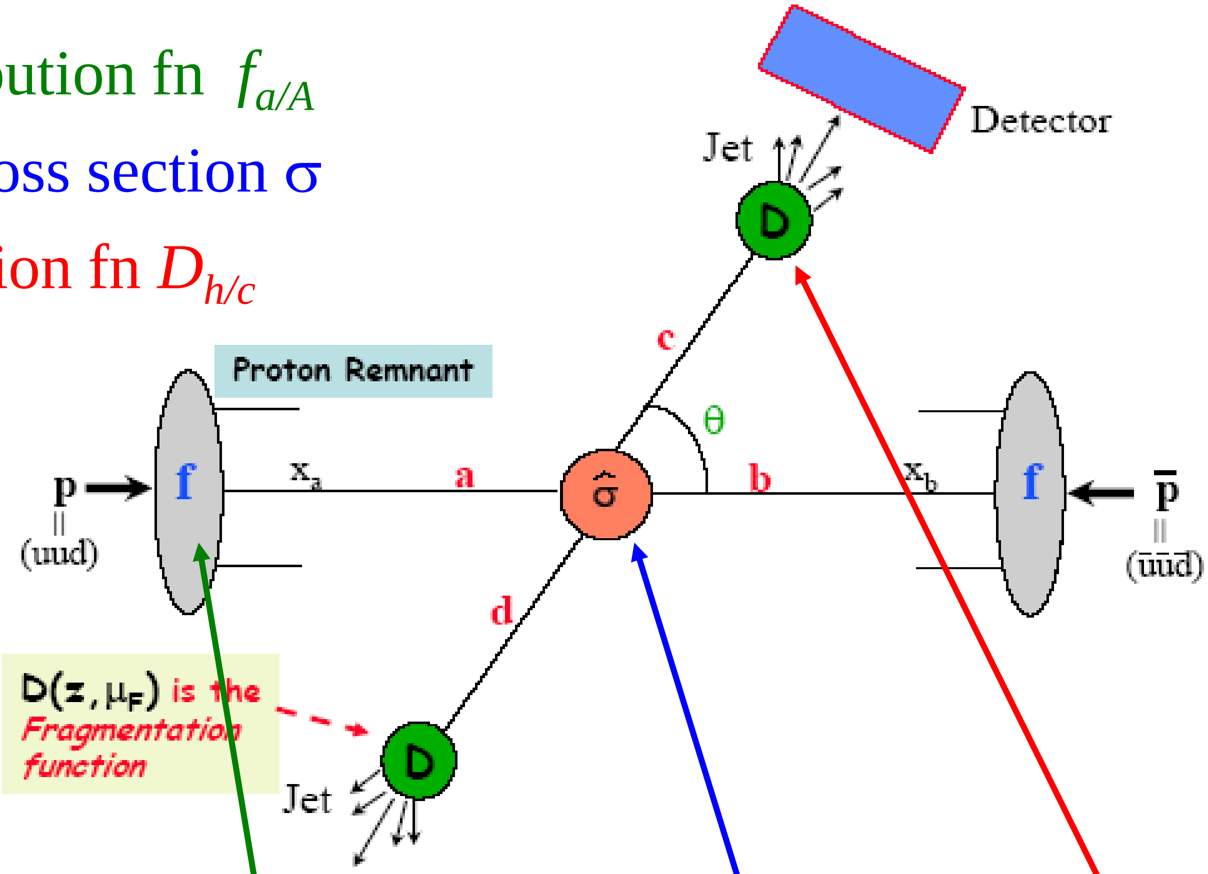
Hard process scale $Q^2 >> \Lambda^2_{QCD}$

pQCD factorization:

parton distribution fn $f_{a/A}$

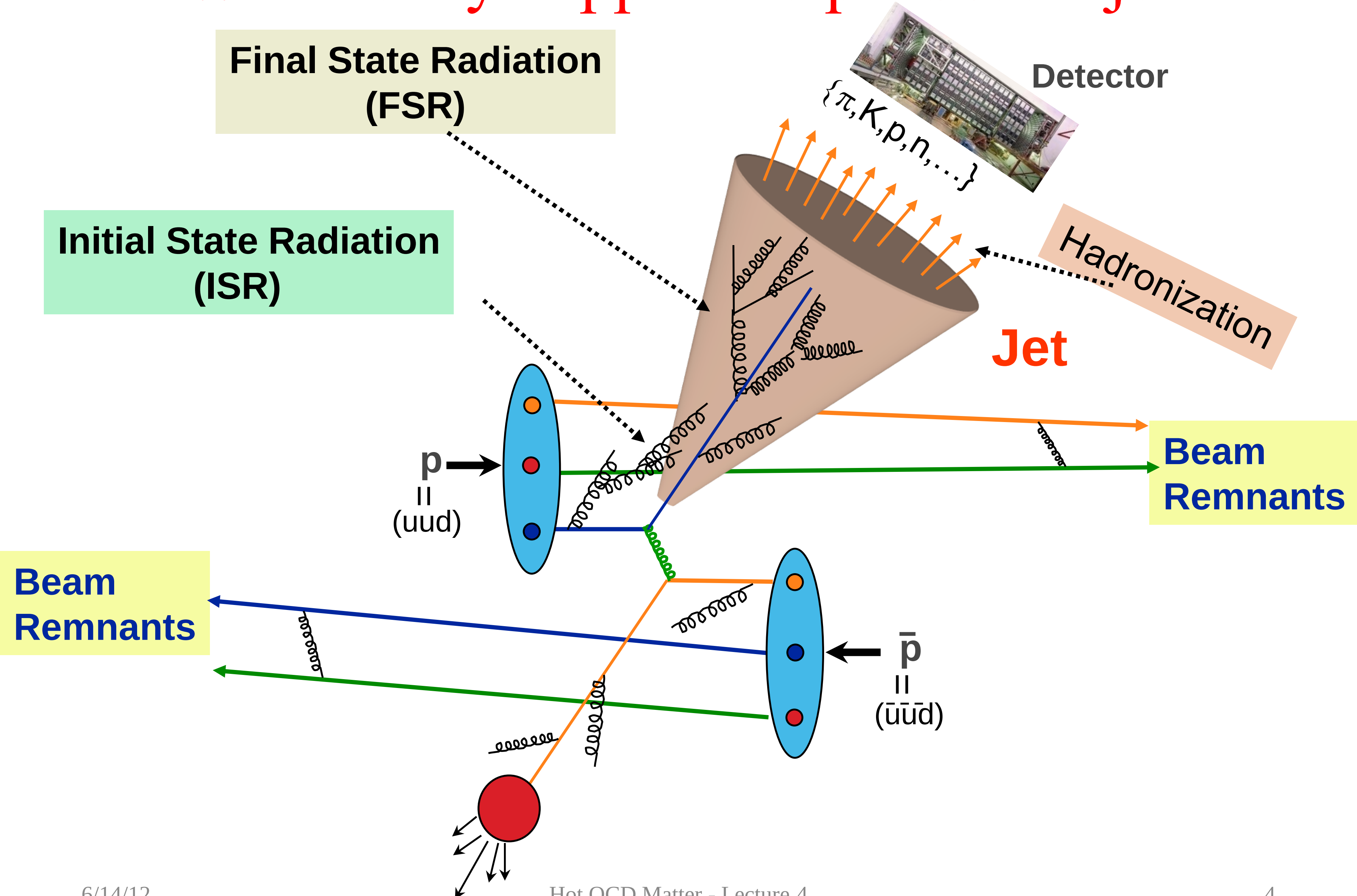
+ partonic cross section σ

+ fragmentation fn $D_{h/c}$

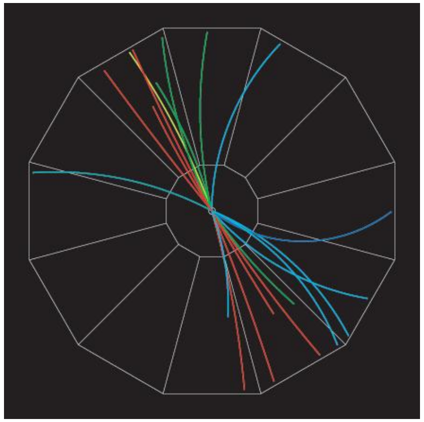


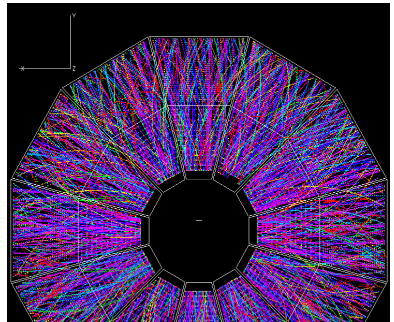
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a, Q^2\right) \otimes f_{b/B}\left(x_b, Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}\left(z_c, Q^2\right)$$

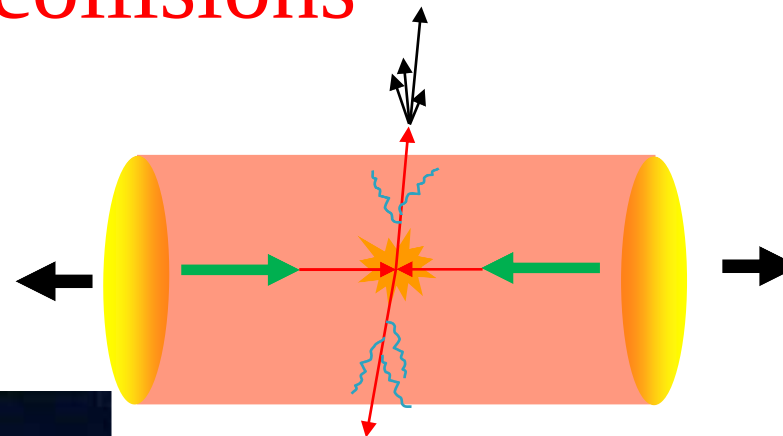
What really happens to produce a jet…

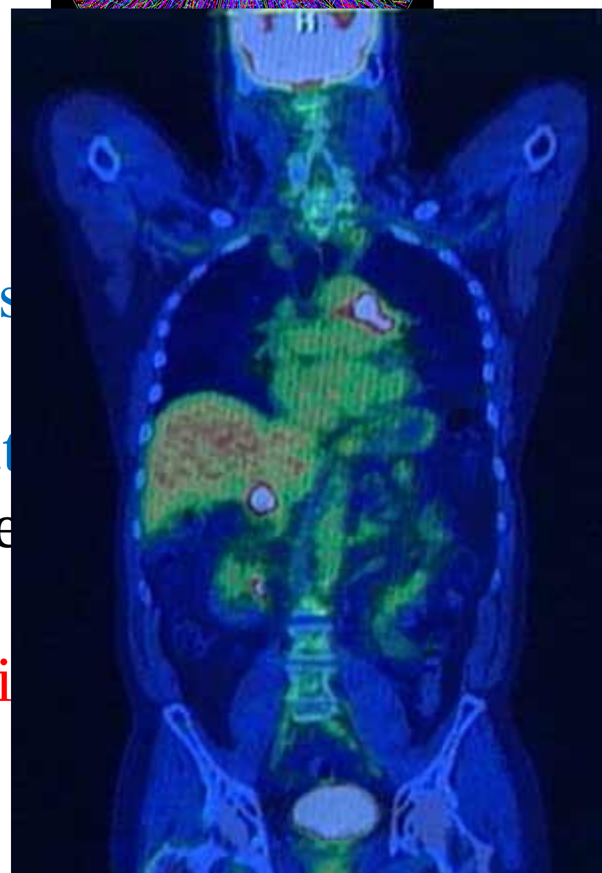


Jets in heavy ion collisions





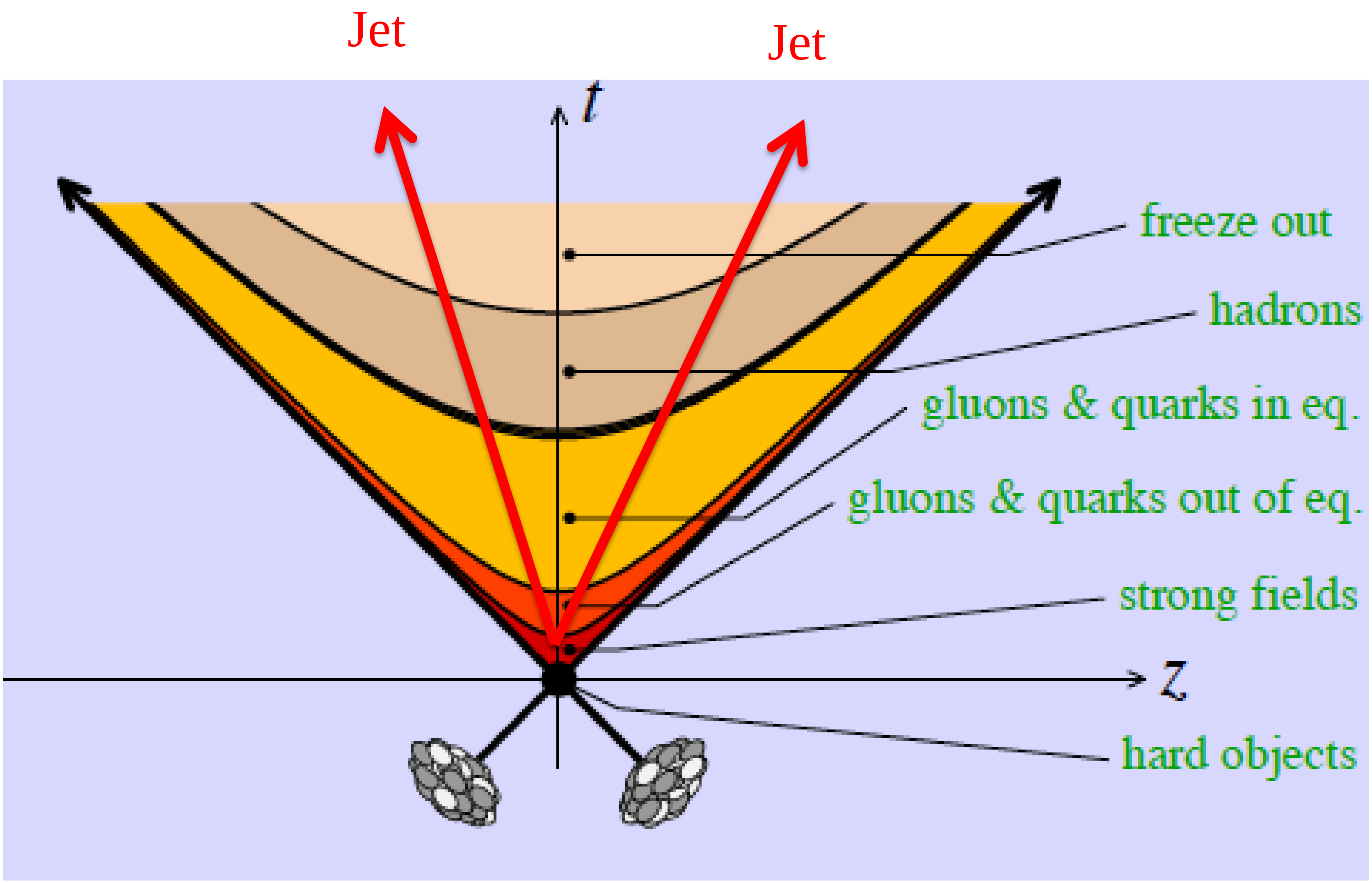




Controlled "beams ... ntensity

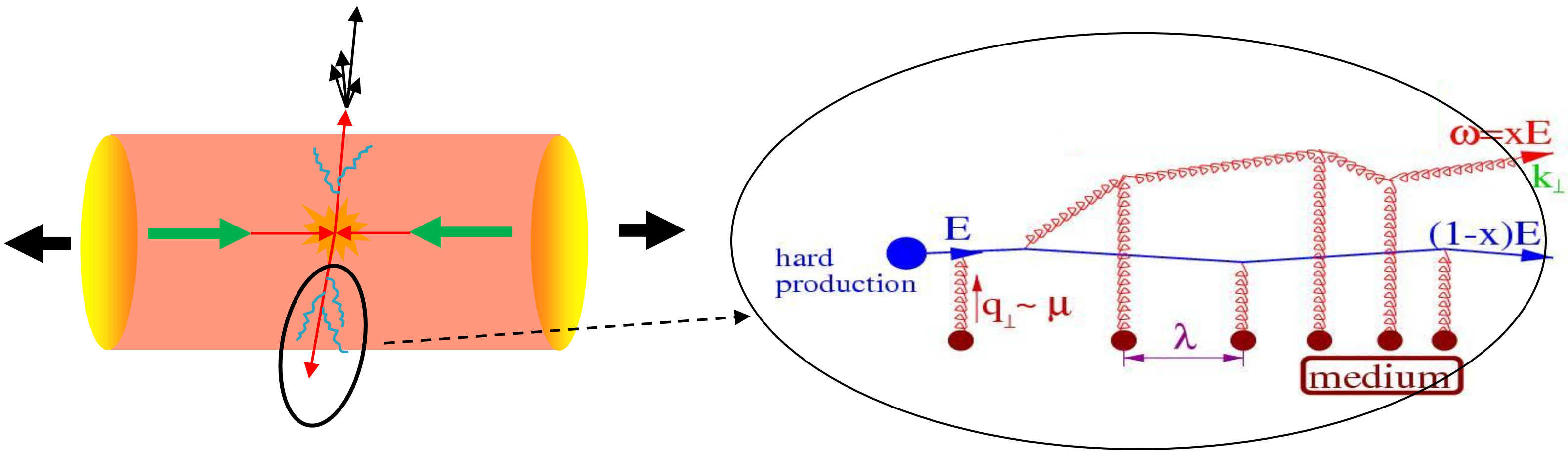
Final-state interact ... er are calculable
using controlle

→ tomographi ... luon Plasma


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

Jet quenching

Radiative energy loss in QCD (multiple soft scattering):



Plasma transport coefficient:

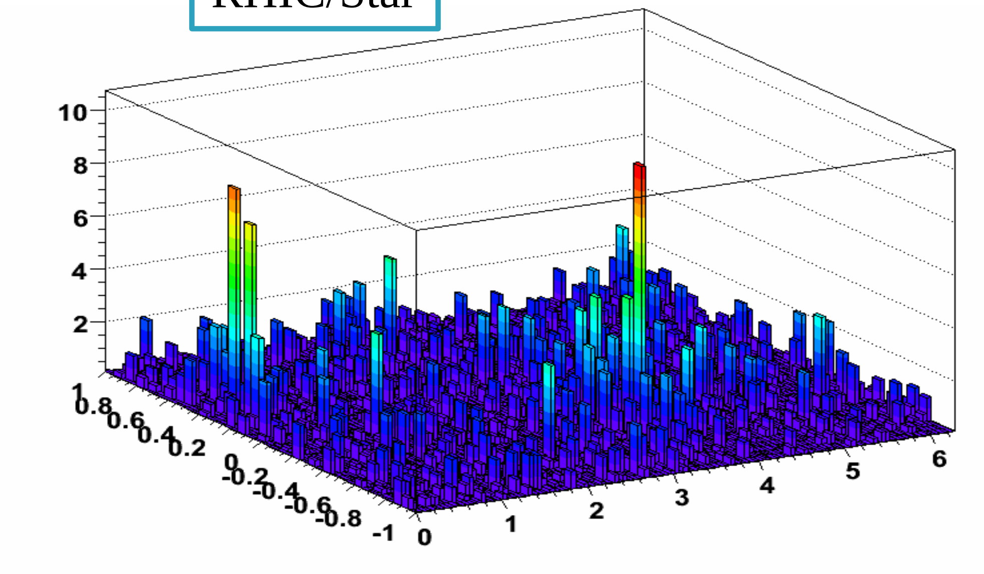
$$\hat{q} = \frac{< (\text{momentum transfer})^2 >}{\text{mean free path}} = \frac{\mu^2}{\lambda}$$

Total medium-induced energy loss:

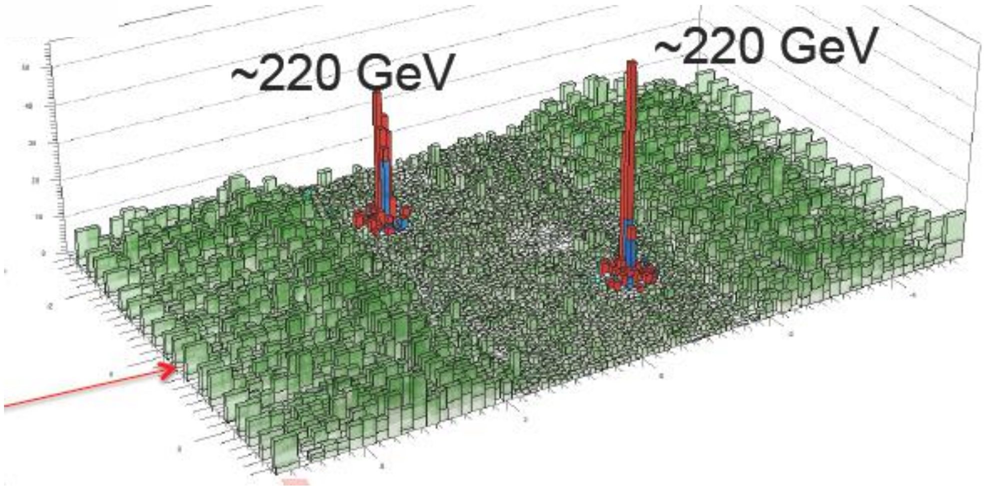
$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

Jets in real heavy ion collisions

RHIC/Star

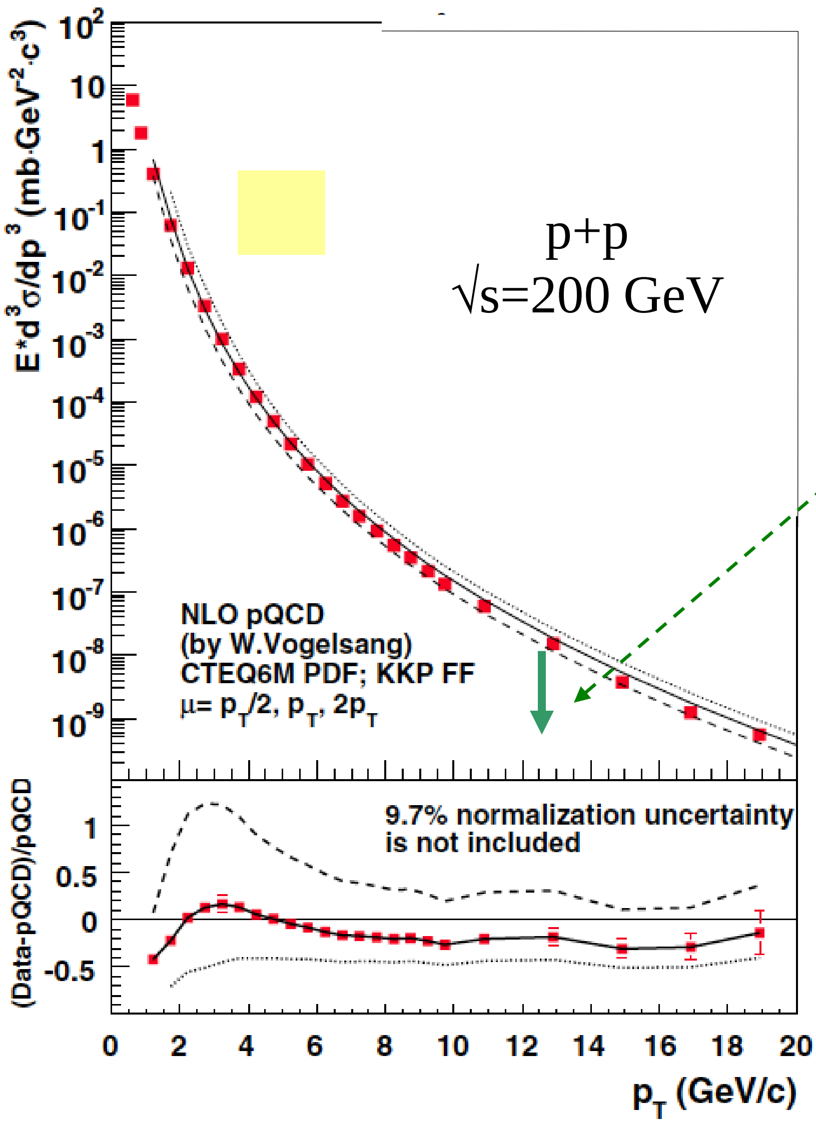


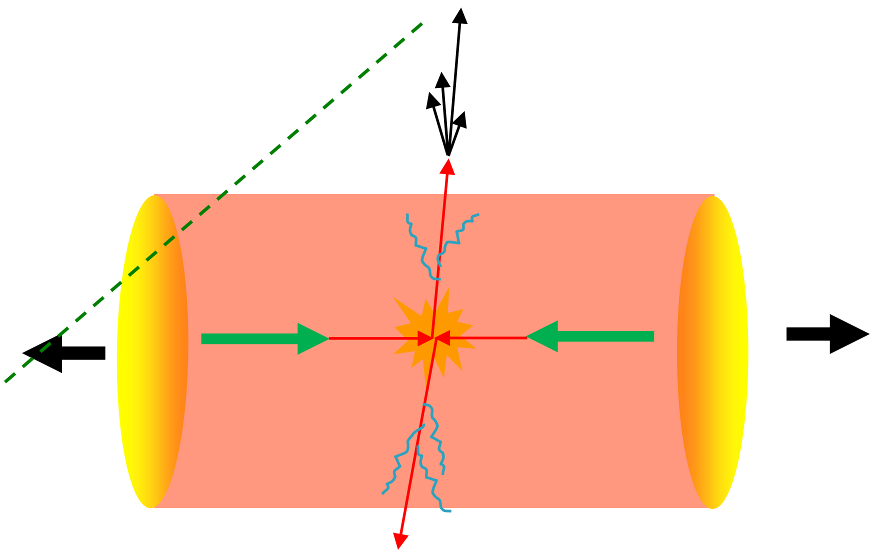
LHC/CMS



Leading hadron as a jet surrogate

PHENIX Phys Rev D76, 051106





Energy loss ⇒ softening of fragmentation
⇒ suppression of leading hadron yield

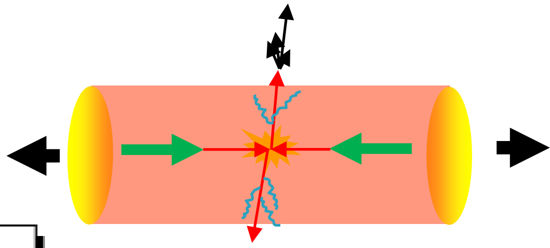
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

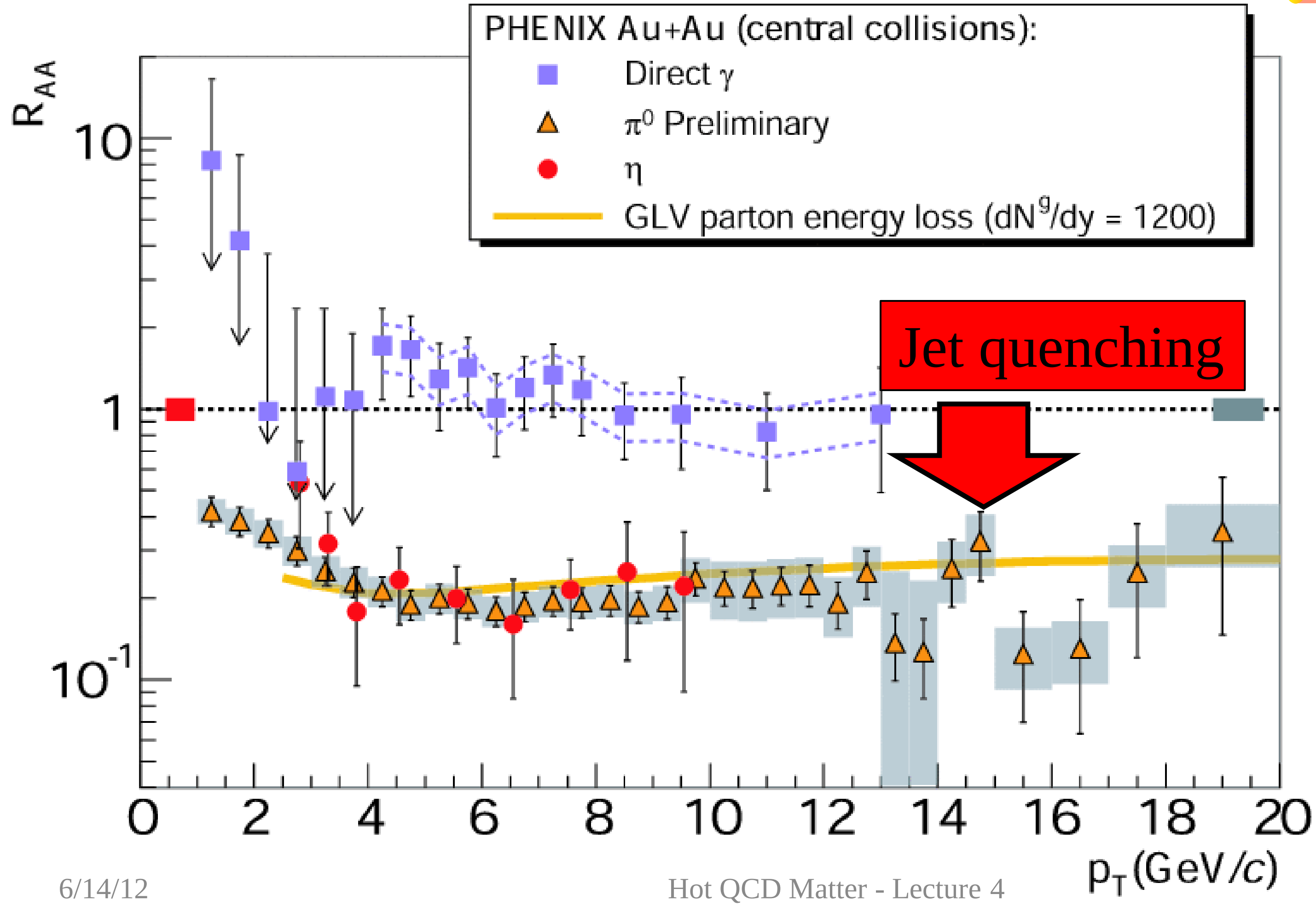
Binary collision scaling

p+p reference

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

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

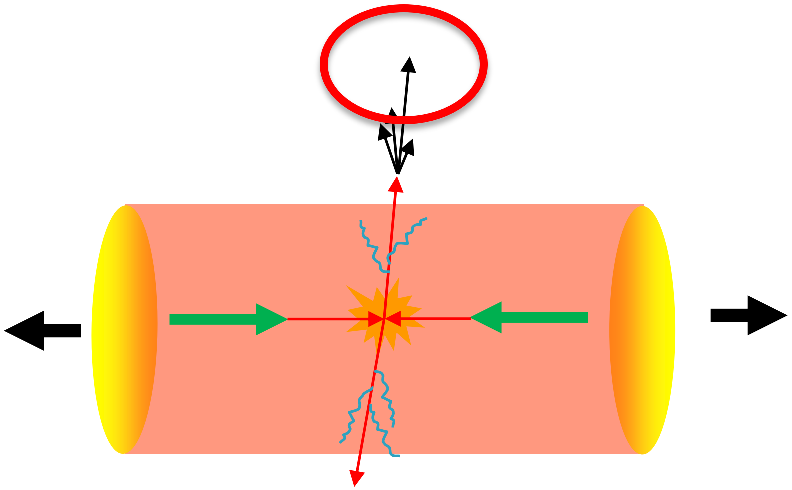




Photons (color-neutral)

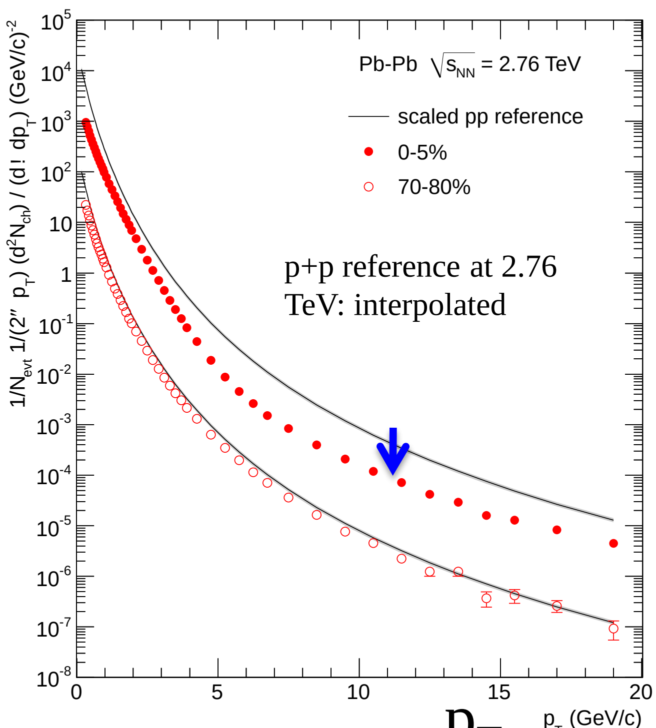
Jet fragments (color-charged)

Jet quenching at the LHC: ALICE

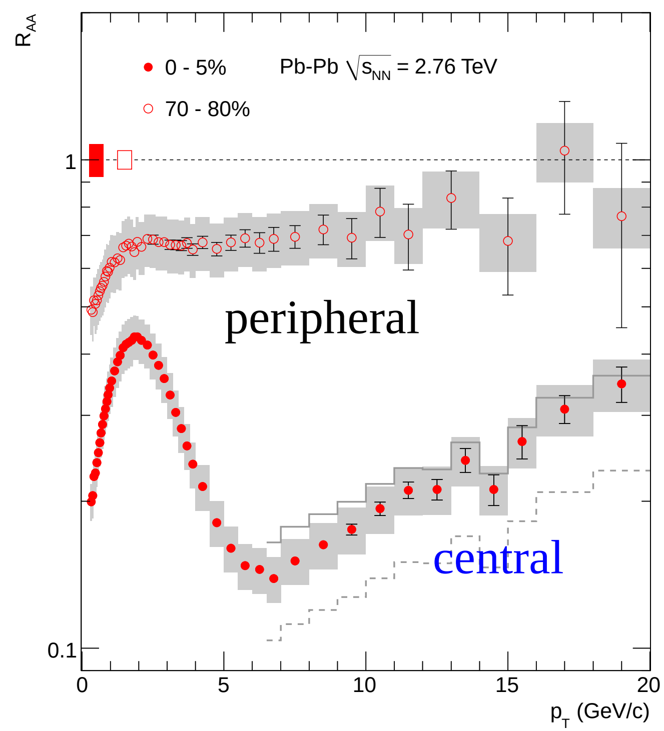


Phys. Lett. B 696 (2011)

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



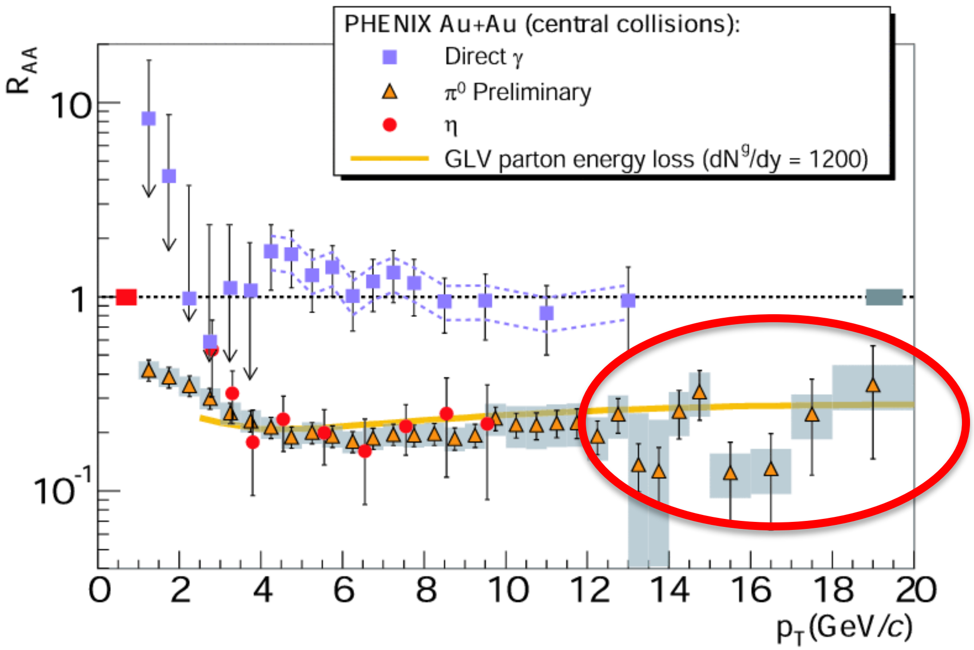
p_T



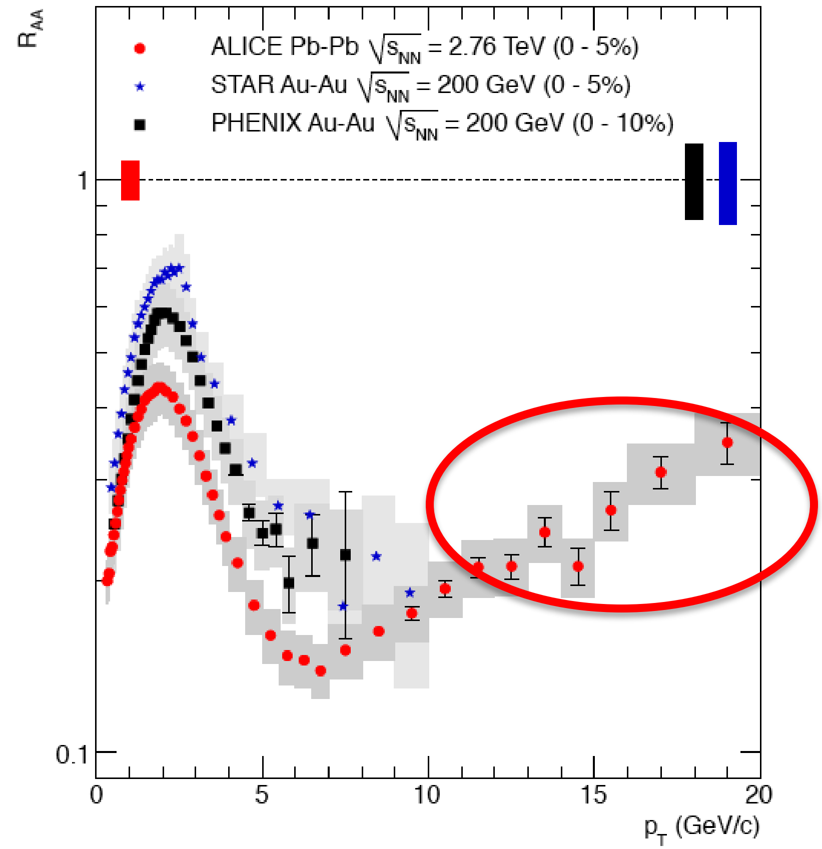
p_T

Jet quenching: RHIC vs LHC

RHIC π^0, η, direct γ

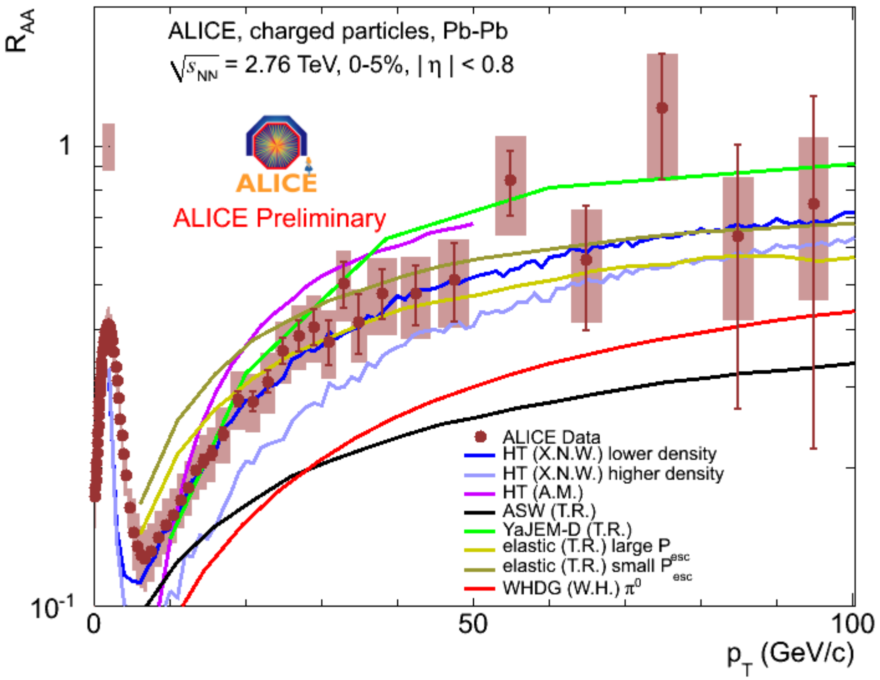


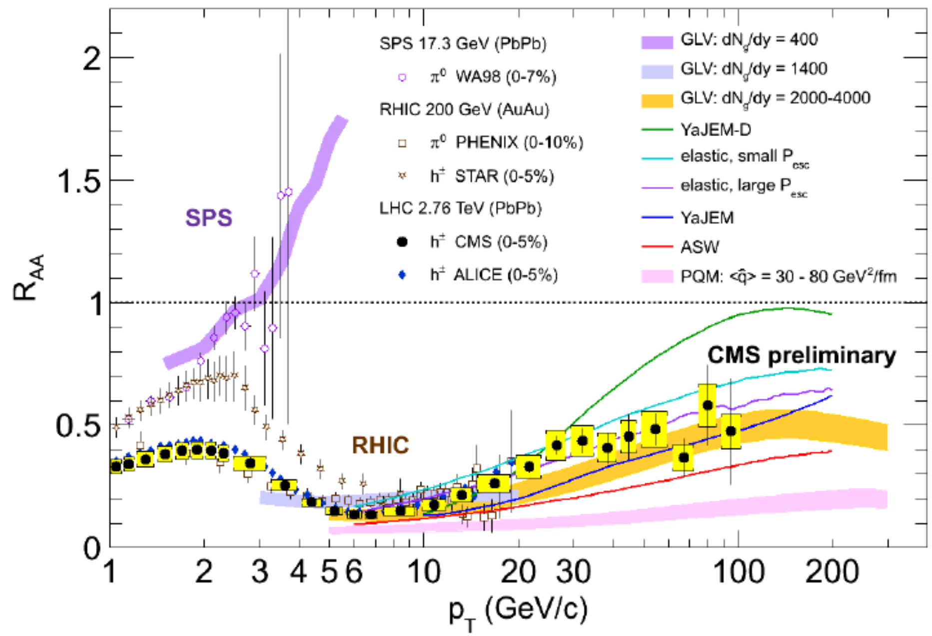
RHIC/LHC charged hadrons



- 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

Calculation of quenching parameter qhat: pQCD vs AdS/CFT

Weakly coupled medium: perturbative QCD (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 AdS/CFT (Liu, Rajagopal and Wiedemann):

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

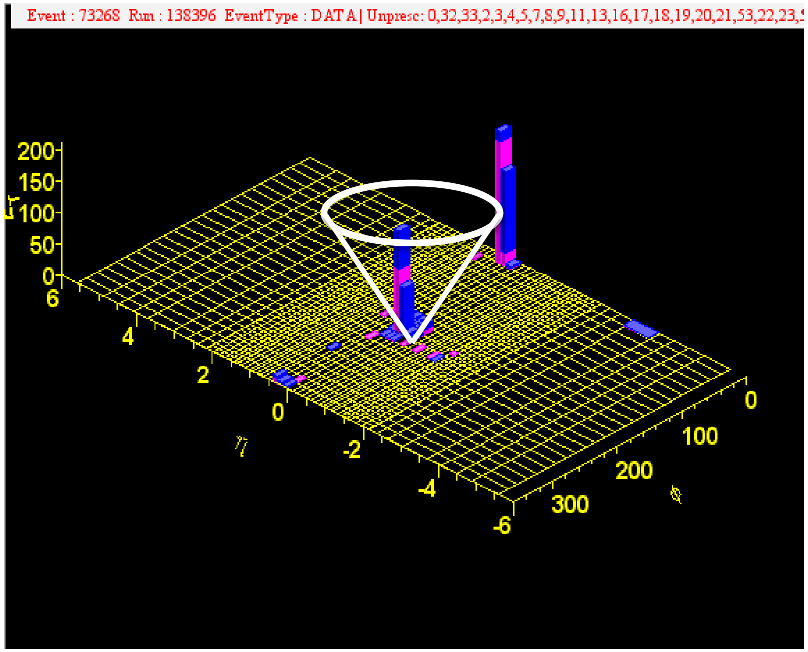
NOT proportional to N_C^2 ~ entropy density

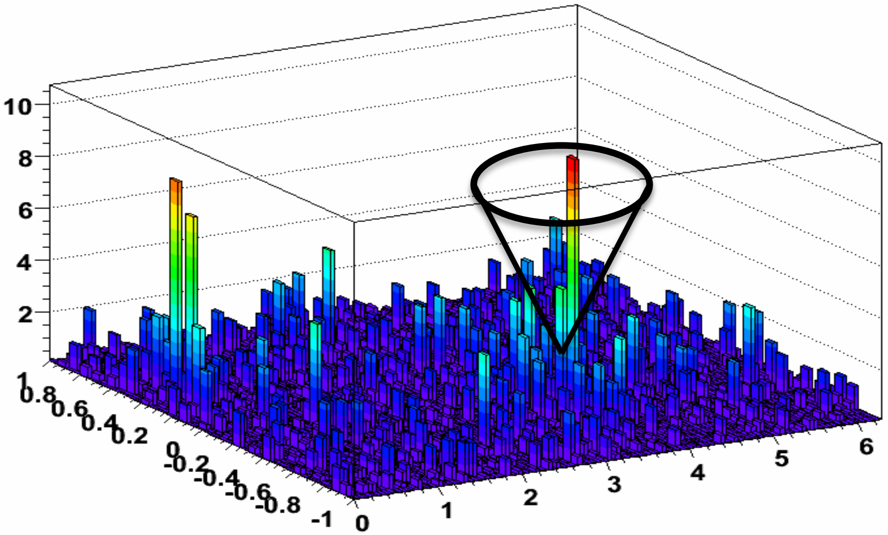
Roughly $\hat{q}_{data} \sim 1 - 5 \; GeV/fm^2$

Full jet reconstruction

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

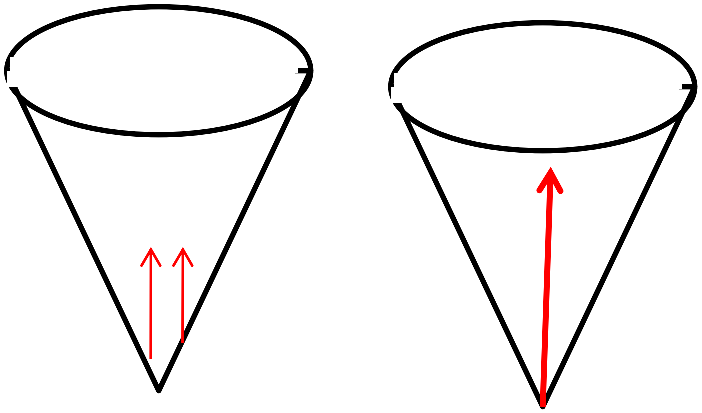
Jet reconstruction: capture the entire spray of hadrons to reconstruct the kinematics of the parent quark or gluon

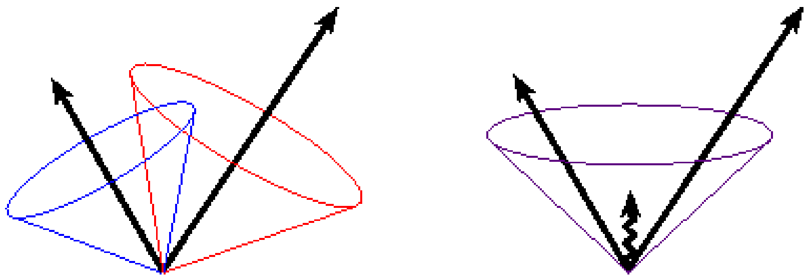




Jet measurements in practice: experiment and theory

Fermilab Run II jet physics
hep-ex/0005012



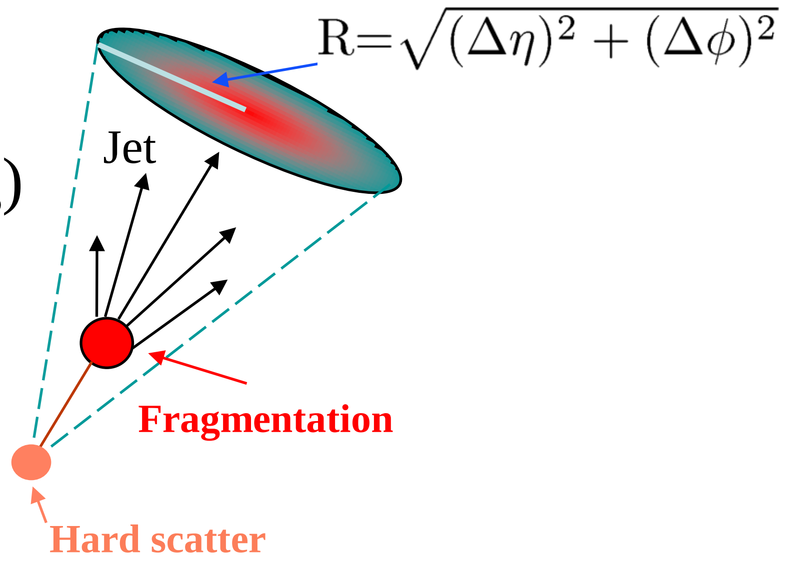


colinear safety:
finite seed threshold misses jet on left?

infrared safety:
one or two jets?

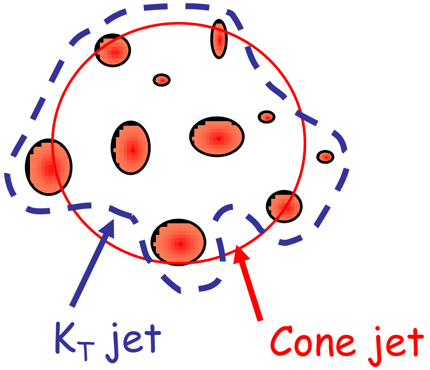
Algorithmic requirements:
- same jets at parton/particle/detector levels
- independence of algorithmic details (ordering of seeds etc)

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



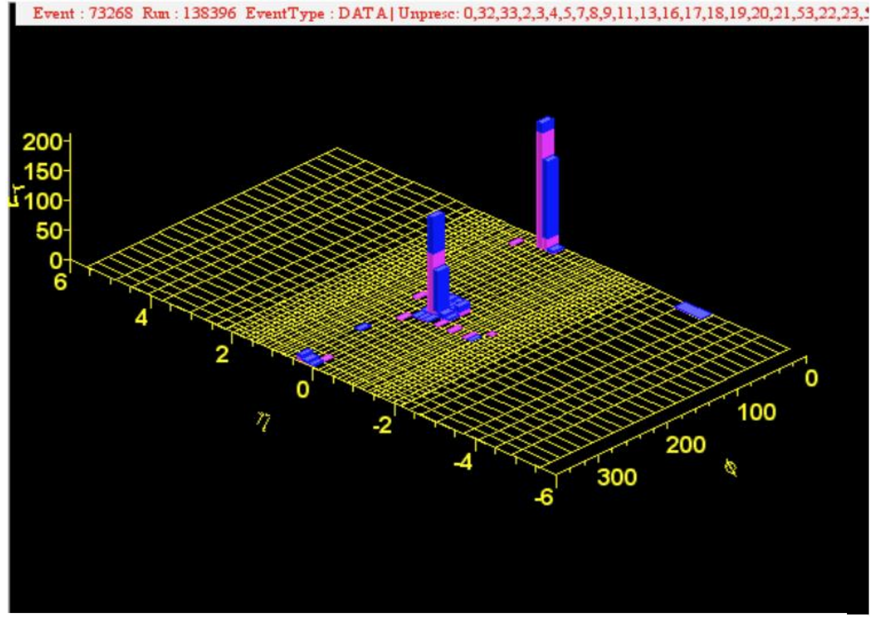
Algorithms differ in recombination metric:

→ different ordering of recombination

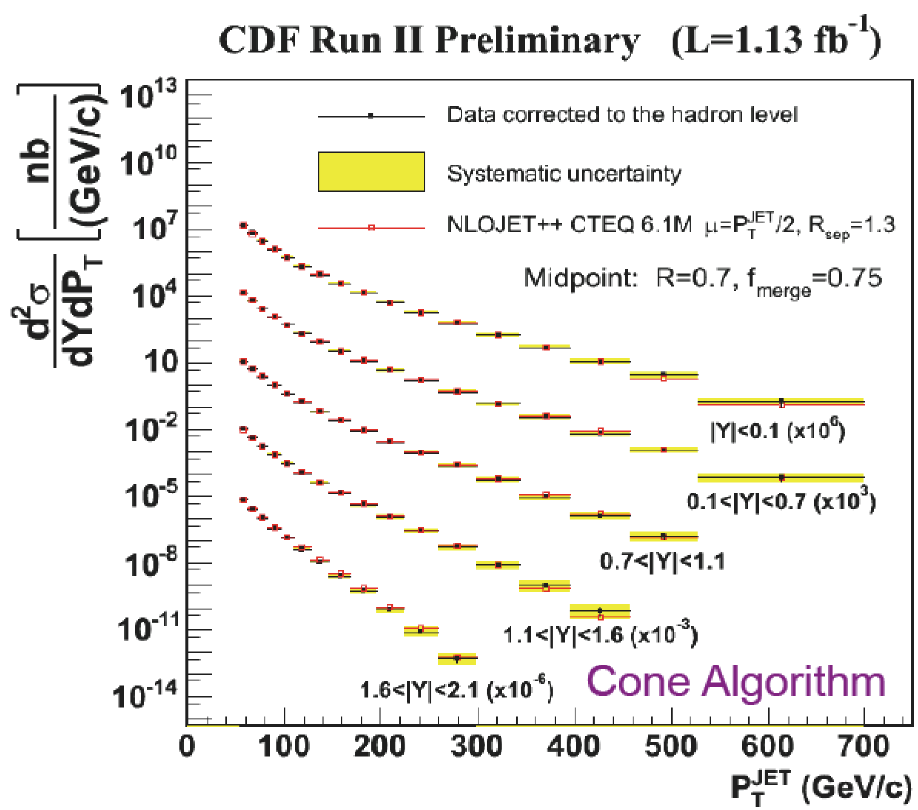
→ different event background sensitivities

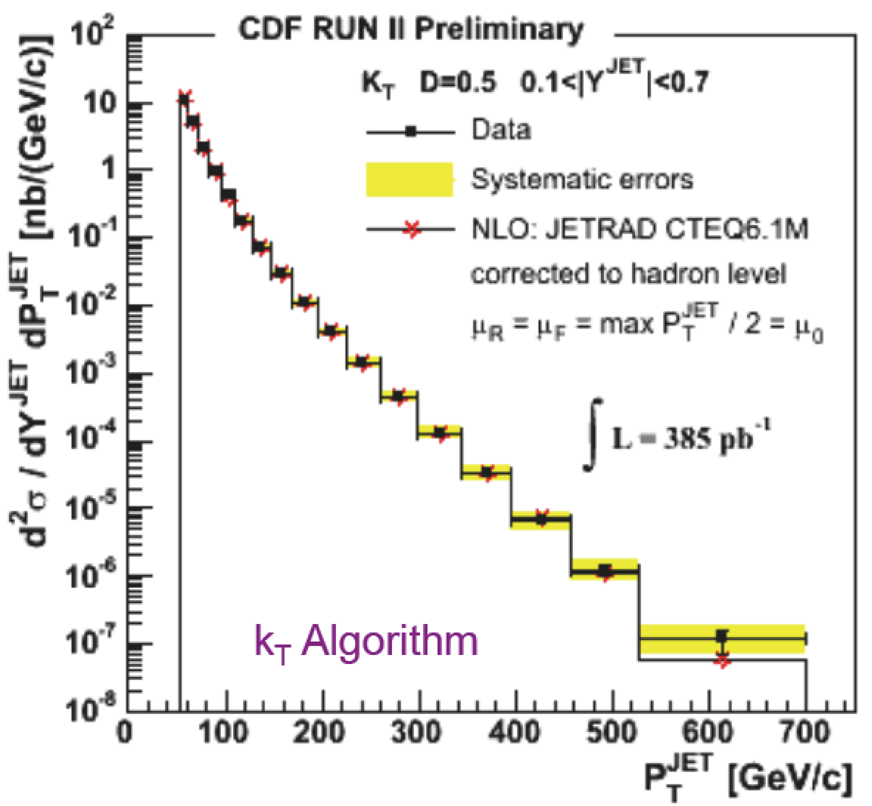
Modern implementation: FastJet (M. Cacciari, G. Salam, G. Soyez JHEP 0804:005 (2008))

Jet production at collider energies

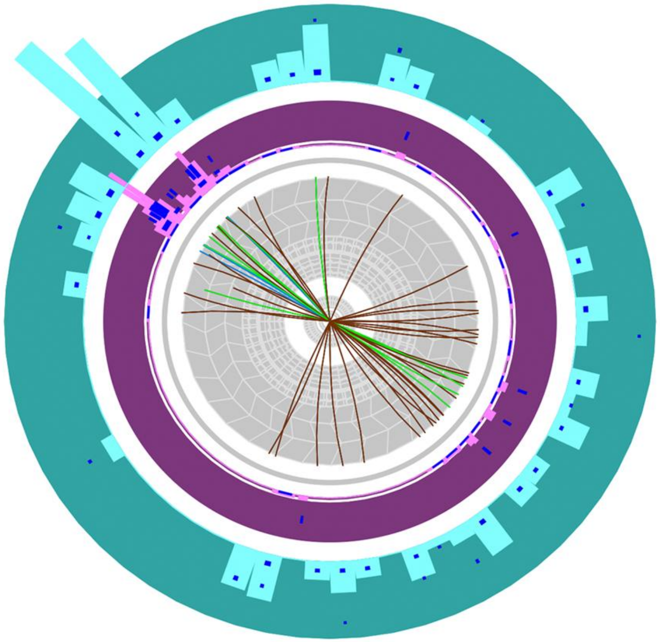


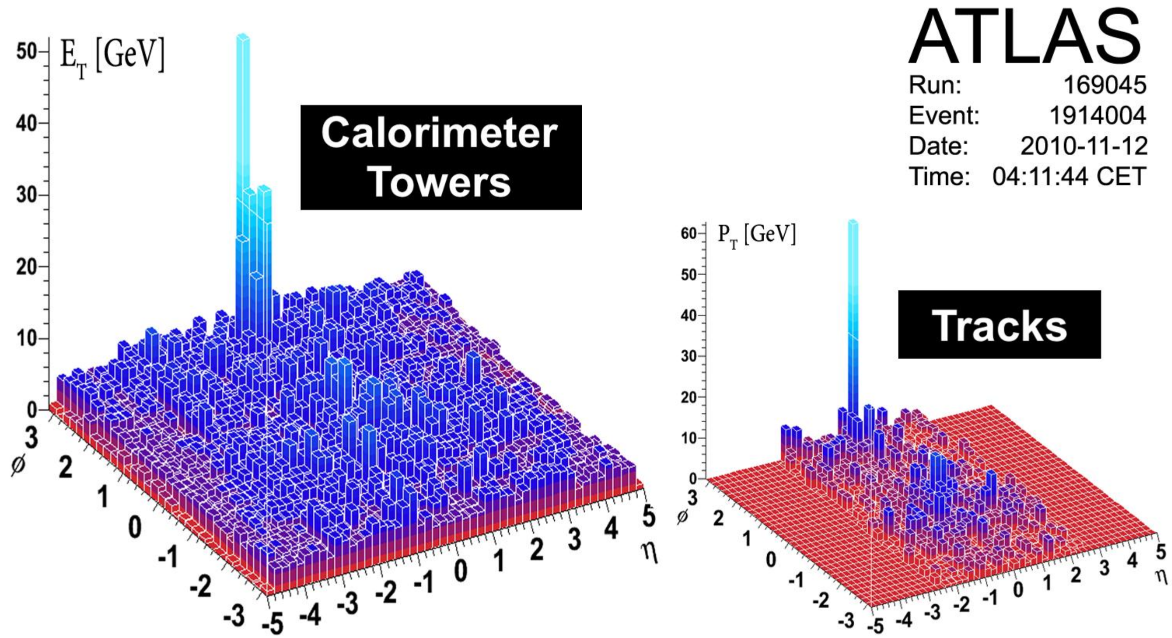
Good agreement with NLO pQCD

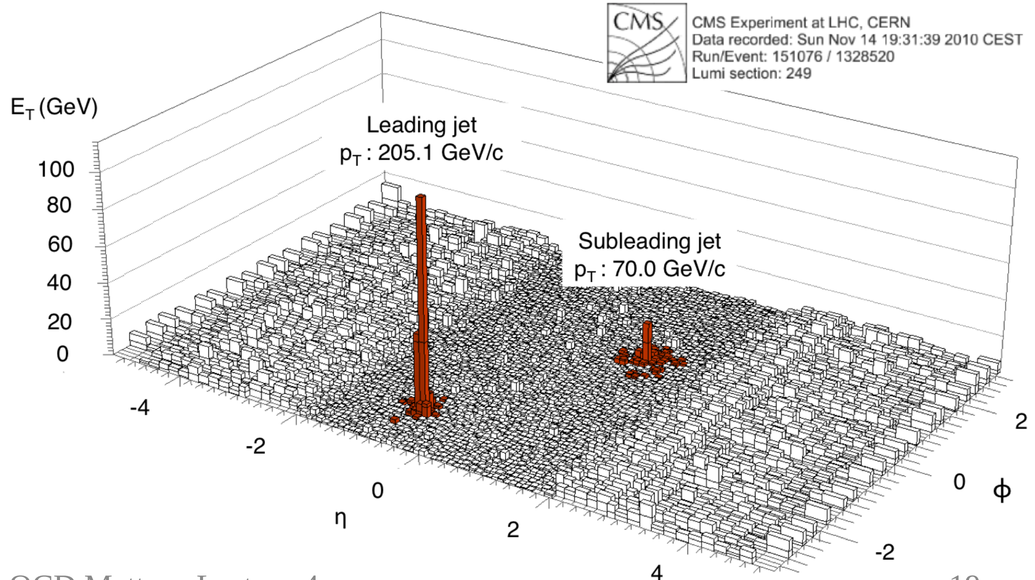


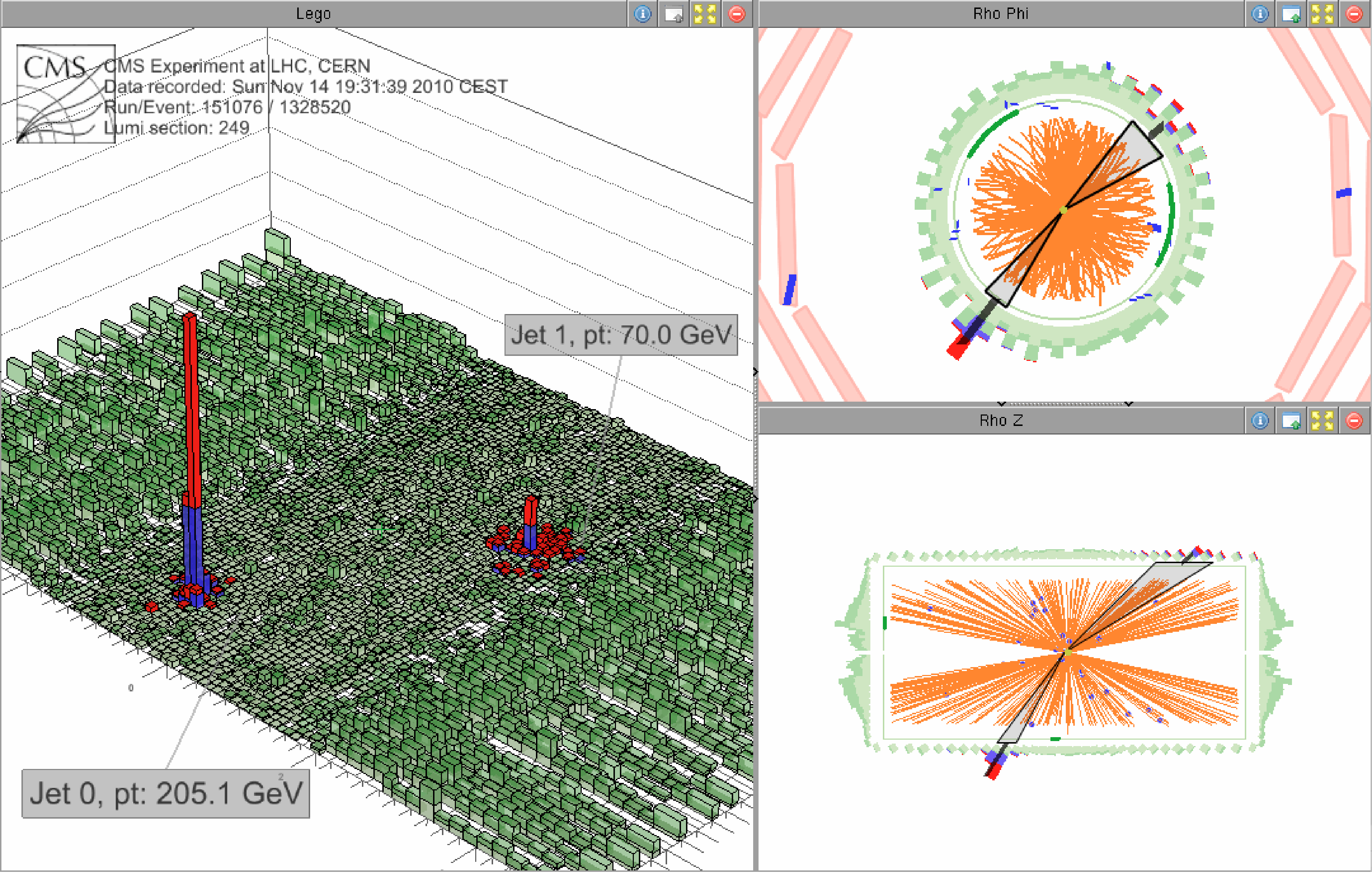


Jets in LHC Heavy Ion Collisions



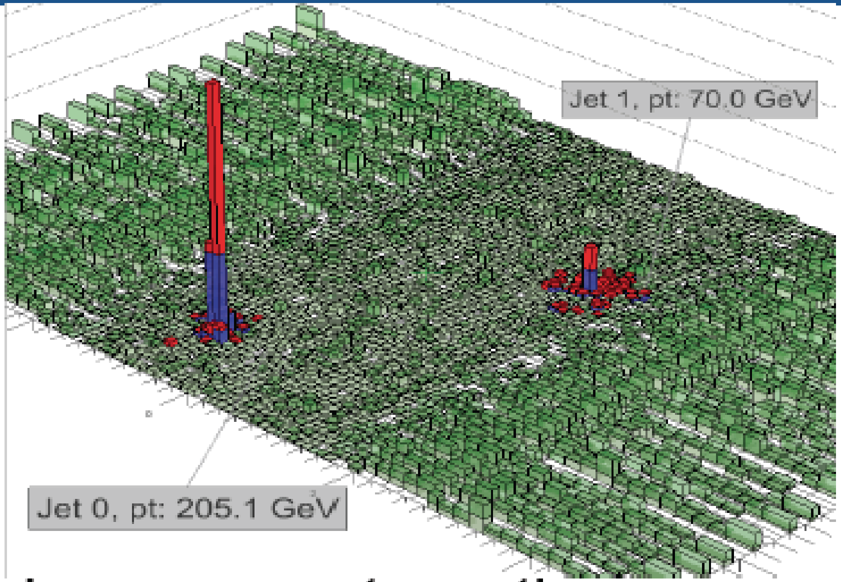






Lego
CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV
Rho Phi
Rho Z

Dijet Asymmetry

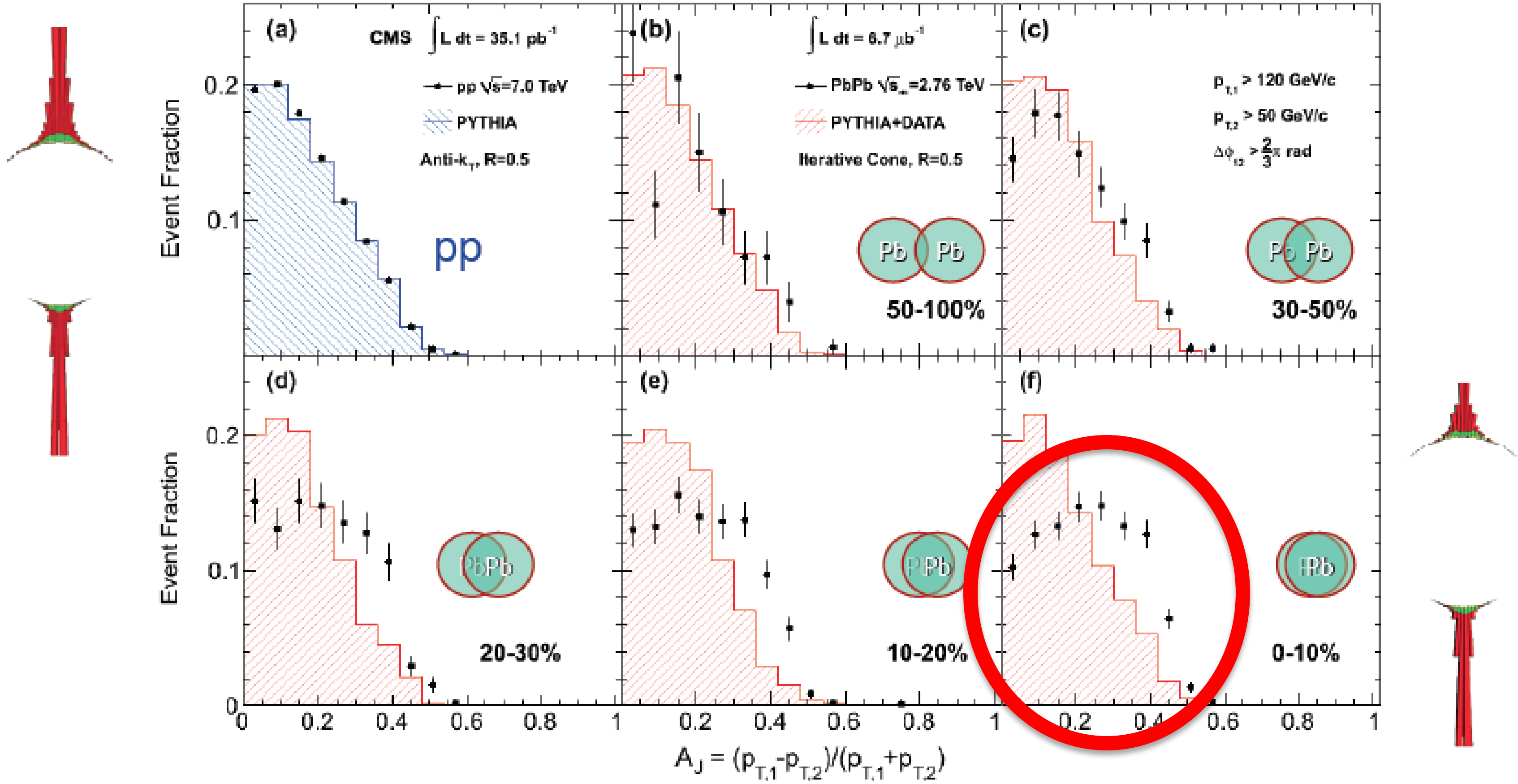


- Dijet selection:
  - $|\eta^{Jet}| < 2$
  - Leading jet $p_{T,1} > 120$GeV/c
  - Subleading jet $p_{T,2} > 50$GeV/c
  - $\Delta\phi_{1,2} > 2\pi/3$
- Quantify dijet energy imbalance by asymmetry ratio:

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

- Removes uncertainties in overall jet energy scale

LHC Pb+Pb: Dijet energy imbalance

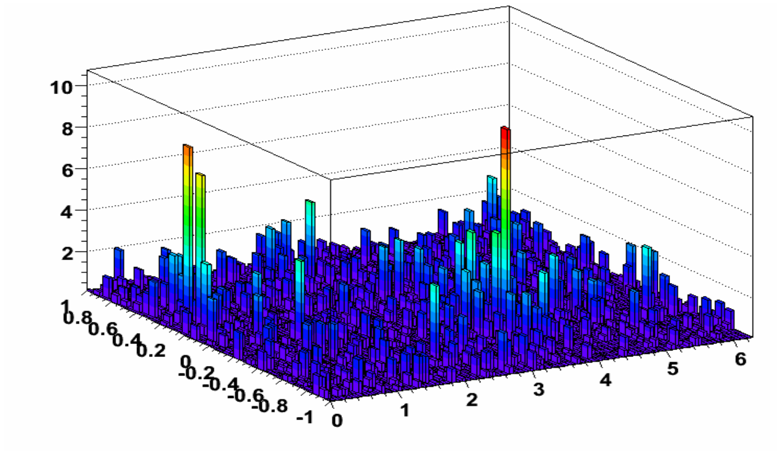


Large energy asymmetry in central collisions (seen by both CMS and ATLAS)

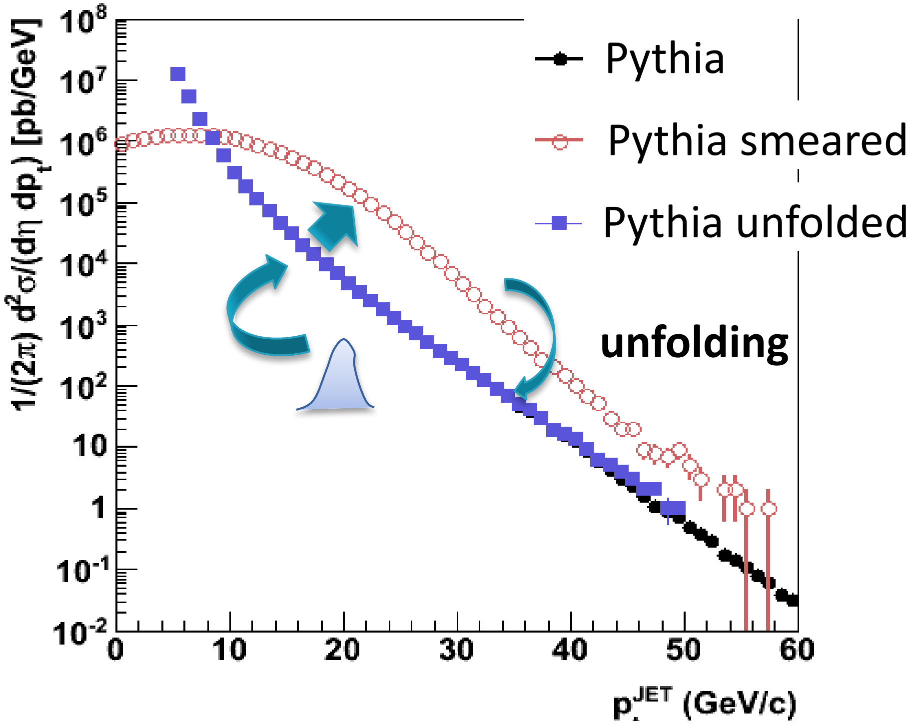
Is this jet quenching?

Jet measurements over large background

Background fluctuations distort measured inclusive cross section



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



Warning: this is a large effect even for high energy jets at the LHC

But not corrected by ATLAS or CMS

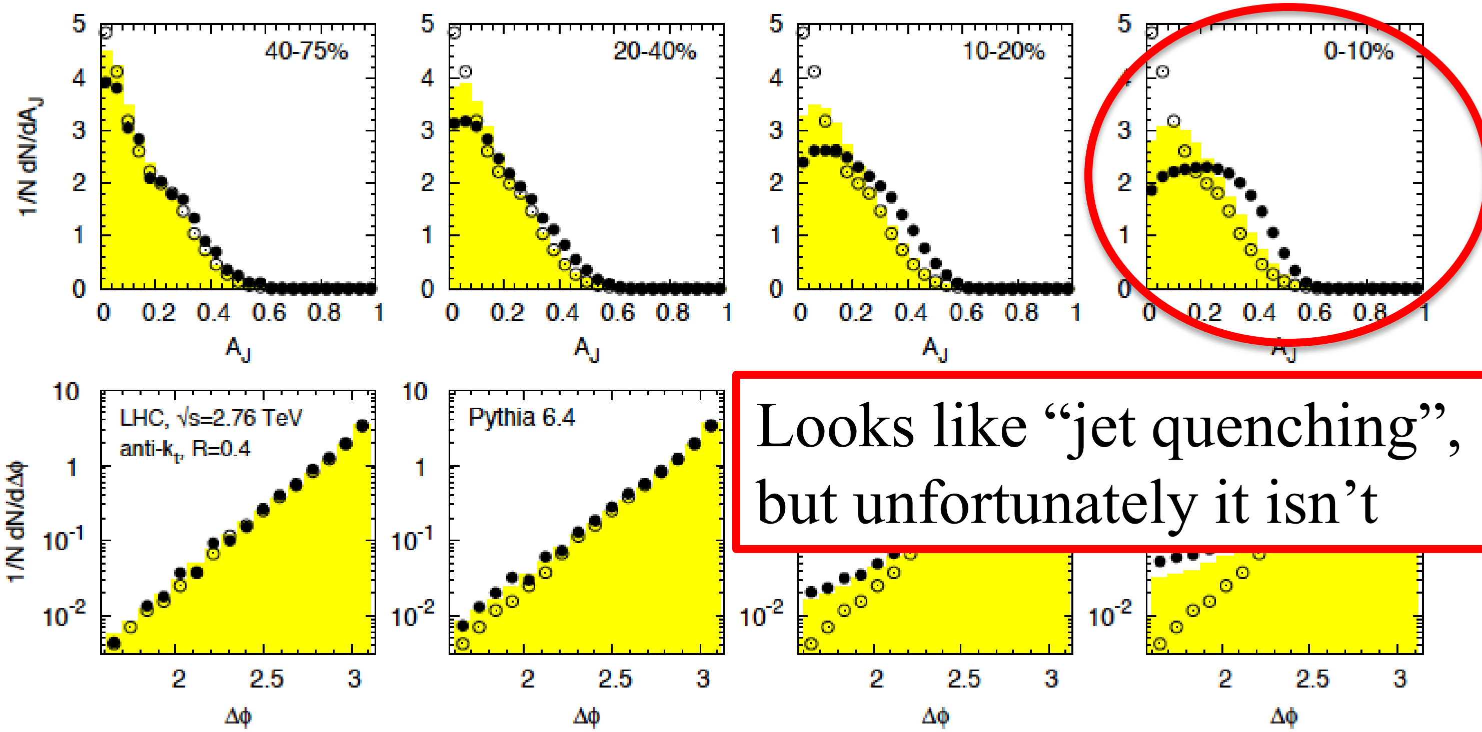
- Instead, each makes ad hoc cuts to suppress magnitude of fluctuations and uses MC to estimate residual effects

Jet quenching = unknown modification of fragmentation; correct procedure?

Test: PYTHIA+Fluctuations (no quenching)

Salam, Cacciari and Soyez ‘11

[Extras] **Results from Hydjet embedding (ATLAS cuts)**

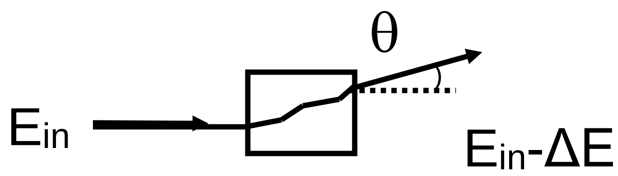


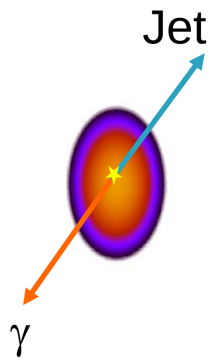
Looks like “jet quenching”, but unfortunately it isn’t

- Effect of fluctuations appears significant — Cacciari, GPS & Soyez ’11
- It is crucial to include sufficiently low-p_t Pythia events

For the fluctuations present in Hydjet, original ATLAS choice of generation cut, 70 GeV, fails to reveal the true impact of fluctuations

CMS: γ-Jet Correlations

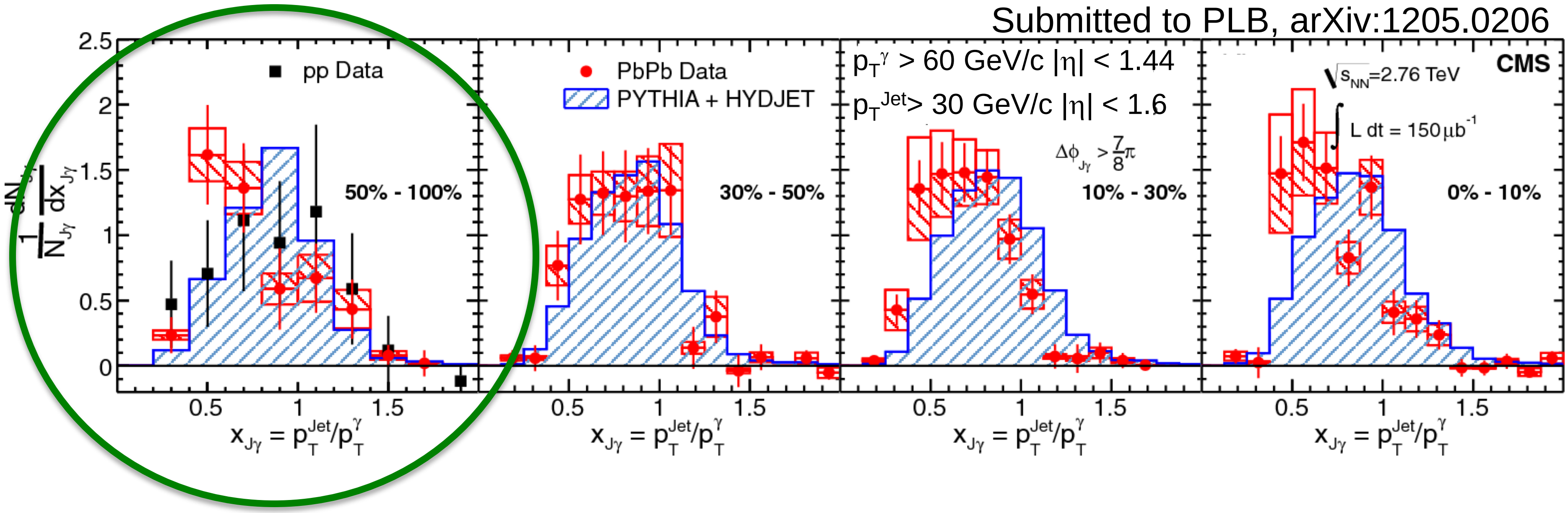




- Correlate Isolated Photons with Jets
  - Photons do not interact with the medium
    - Tag initial parton energy and direction
  - γ-Jet channel selects predominantly quark jets

CMS: γ-Jet Momentum Balance

Submitted to PLB, arXiv:1205.0206

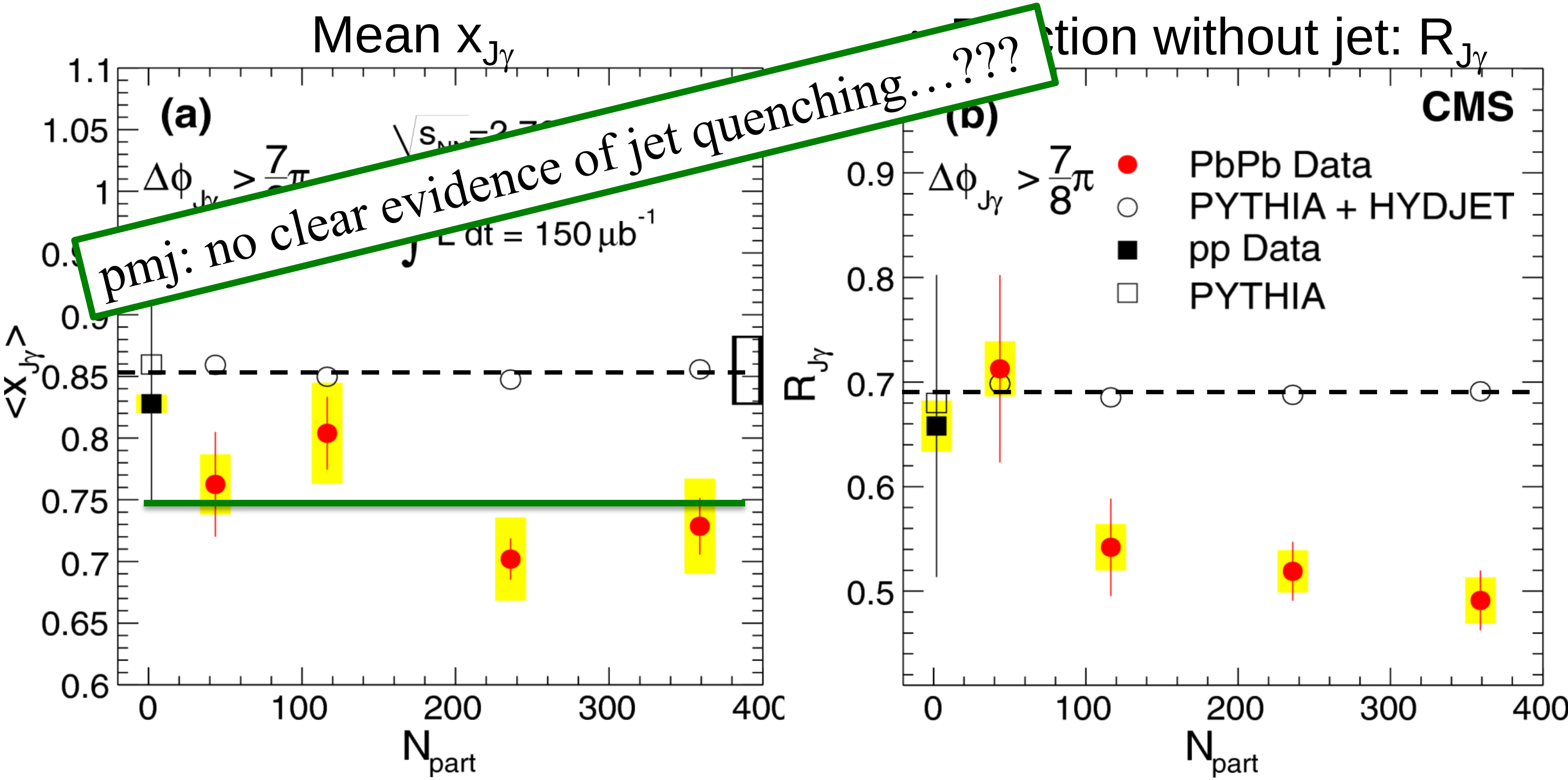


Peripheral collisions: no quenching expected

- MC (blue) and Data (red) distributions should match
- but they don’t: issues with MC, residual fluctuations, biased jet reconstruction,…?

C. Roland, Hard Probes ‘12

CMS: γ-Jet Momentum Balance vs. Centrality

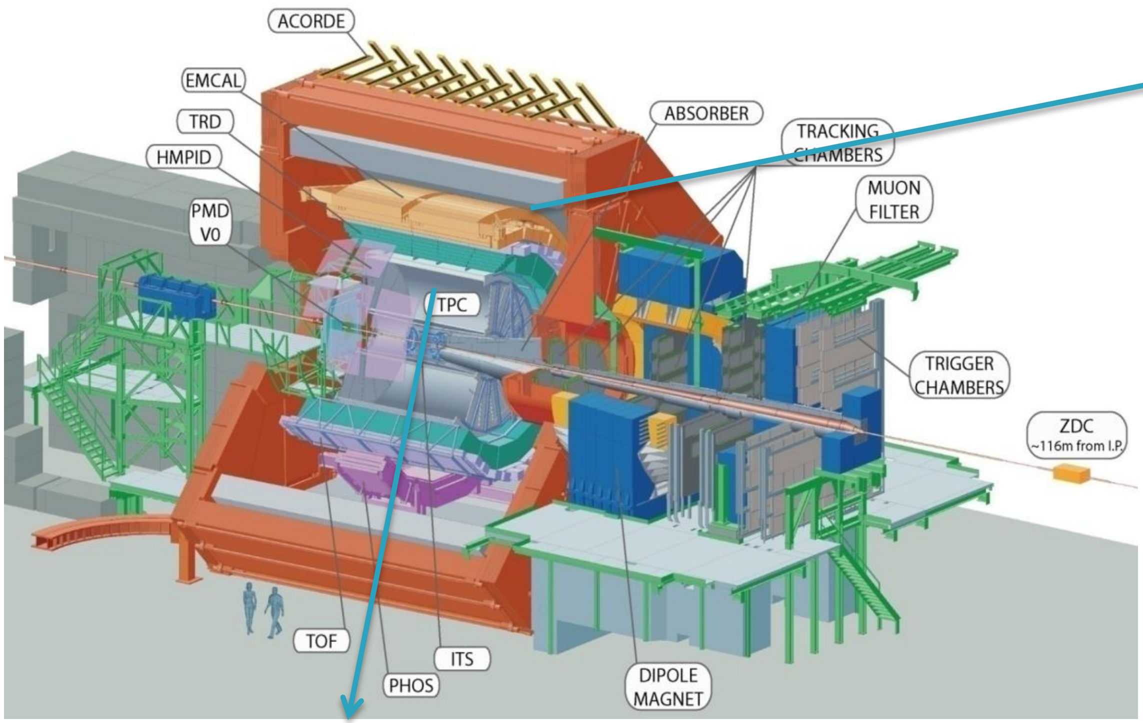


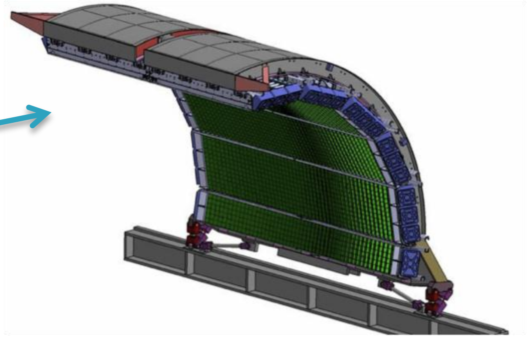
CMS speaker's comments:

- Significant deviation of $\langle x_{J\gamma} \rangle$ in PbPb compared to PYTHIA + HYDJET
- The centrality dependence is mostly visible in $R_{J\gamma}$
  - jet p_T shifting below the 30 GeV threshold

Yue Shi Lai, Parallel VB, Thursday 16:30

ALICE jet measurements





- EMCal: Pb-scintillator sampling calorimeter which covers: $|\eta|<0.7$, $80° < \varphi < 180°$
- 11520 towers with each covers $\Delta\eta \times \Delta\phi \sim 0.014 \times 0.014$

Tracking: $|\eta|<0.9$, $0<\varphi<360°$
TPC: gas detector
ITS: silicon detector

Charged constituents → Jet ← ***Neutral constituents***

ALICE jet measurement strategy

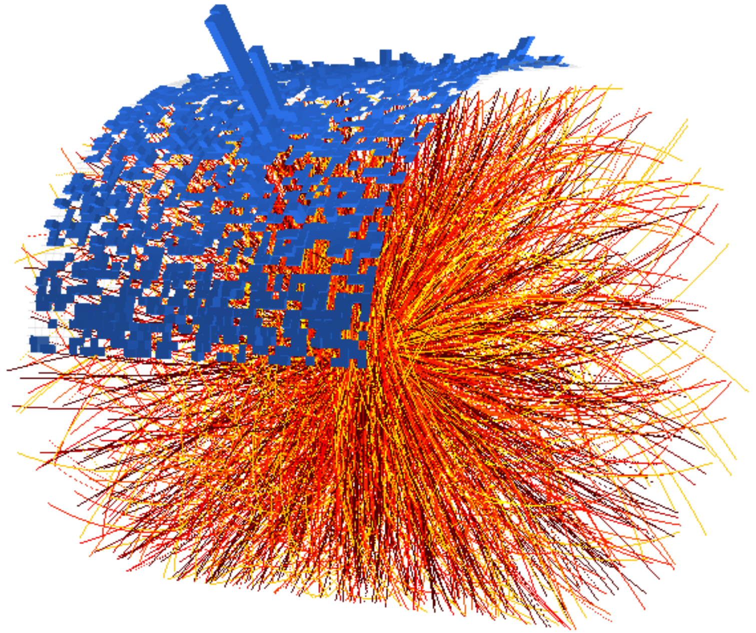
Measure almost all jet constituents explicitly

- Efficient charged particle tracking over wide p_T range
- Highly granular EM calorimetry

pp collisions: well controlled systematics

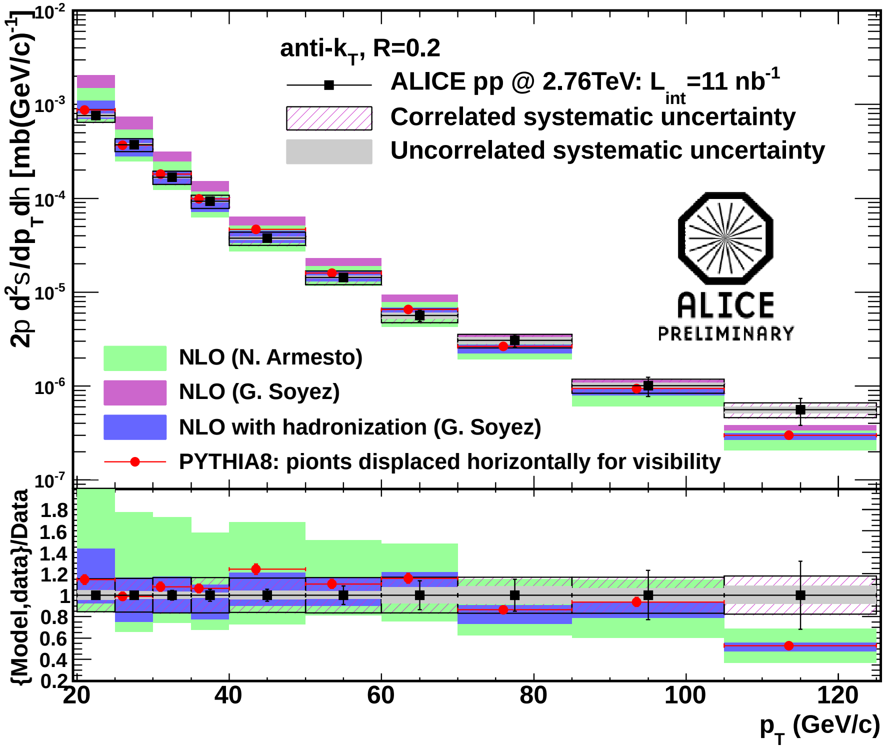
- Jet Energy Scale uncertainty ~4% at p_T=100 GeV/c

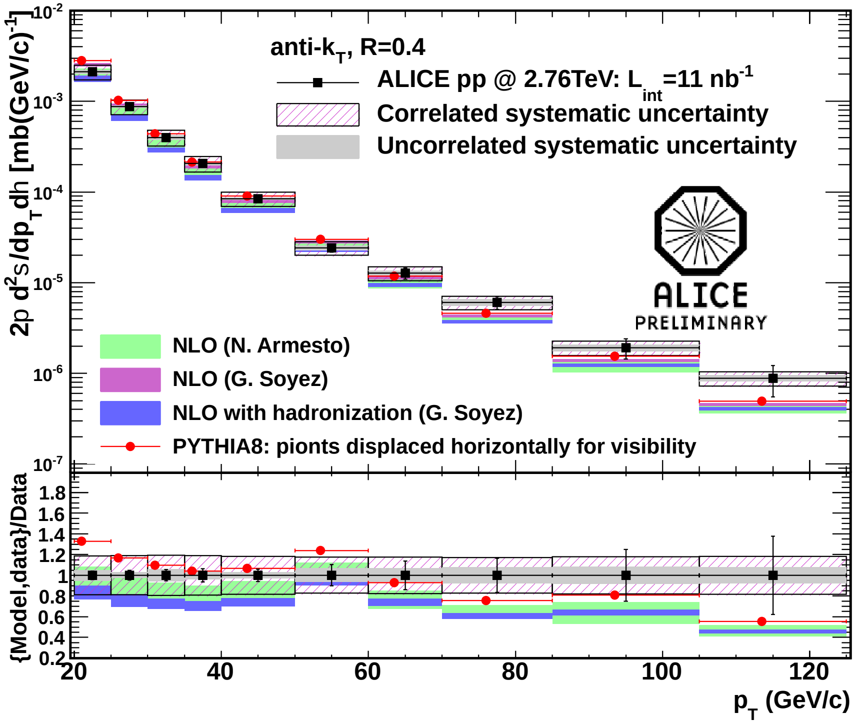
  ➔ ~20% cross section uncertainty



pp at $\sqrt{s}$ = 2.76 TeV: inclusive jet cross section

Talk: R. Ma



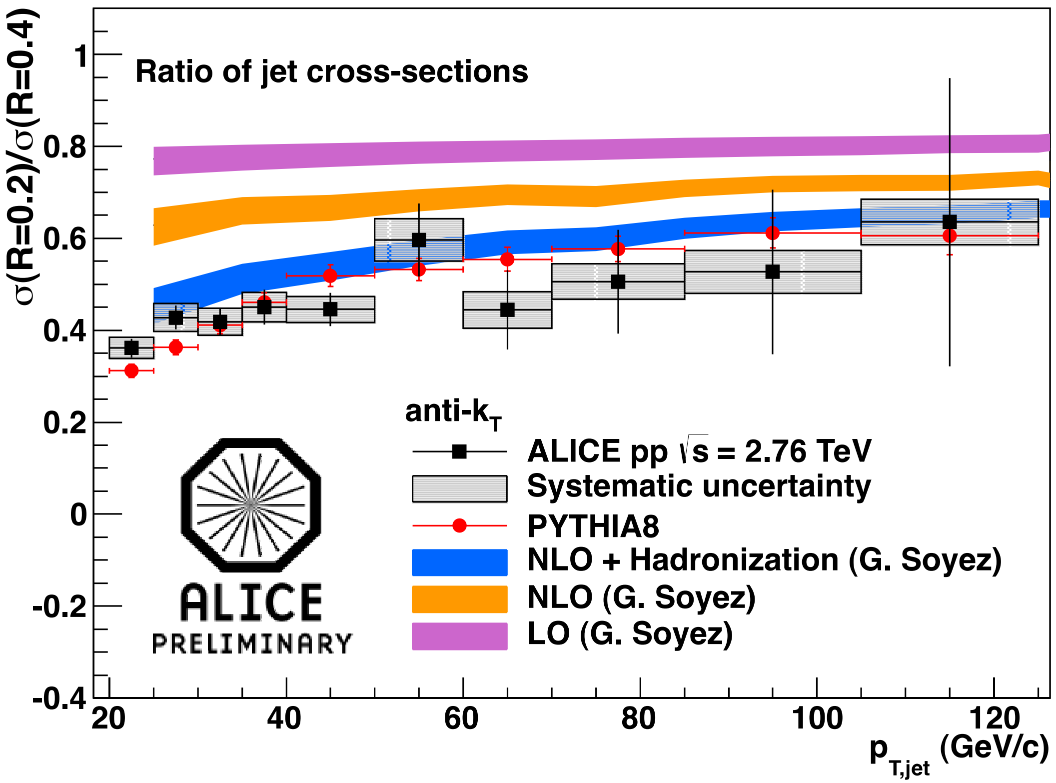


Agreement within uncertainties with NLO pQCD, PYTHIA8

pp at $\sqrt{s}$ = 2.76 TeV: ratio of jet cross-sections R=0.2/R=0.4

Talk: R. Ma

Probe of jet structure



Soyez '12: direct calculation of ratio is effectively NNLO
Reasonable agreement with NLO+hadronization

ALICE Jets in heavy ions: coming soon, with very different systematics…

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?

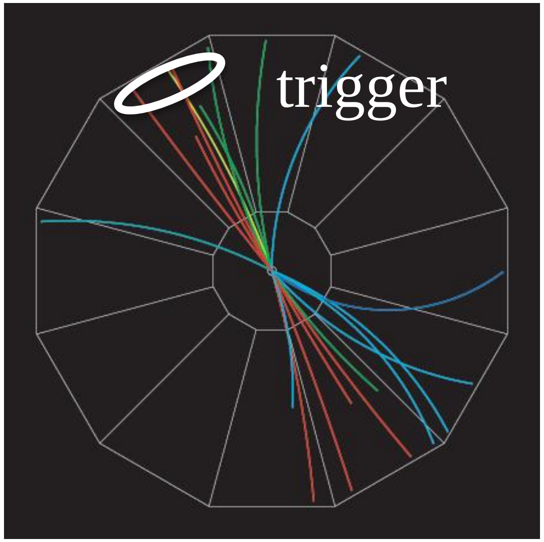
- What is the order of the (de-)confinement transition?
- How is chiral symmetry restored at high T, and how?
- Is there a QCD critical point?
- What are its transport properties?

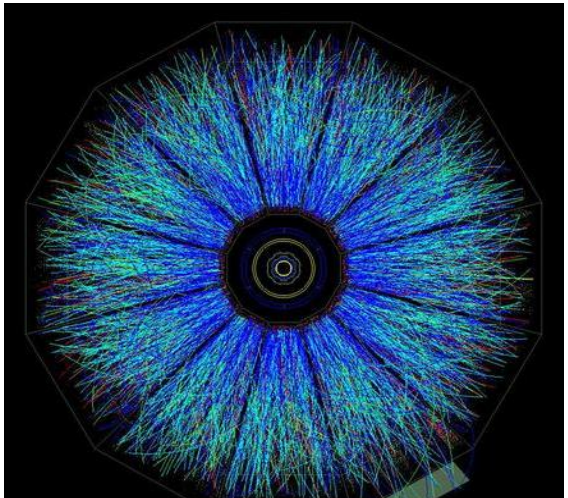
Can QCD matter be related to other physical systems?

Can we study hot QCD matter experimentally?

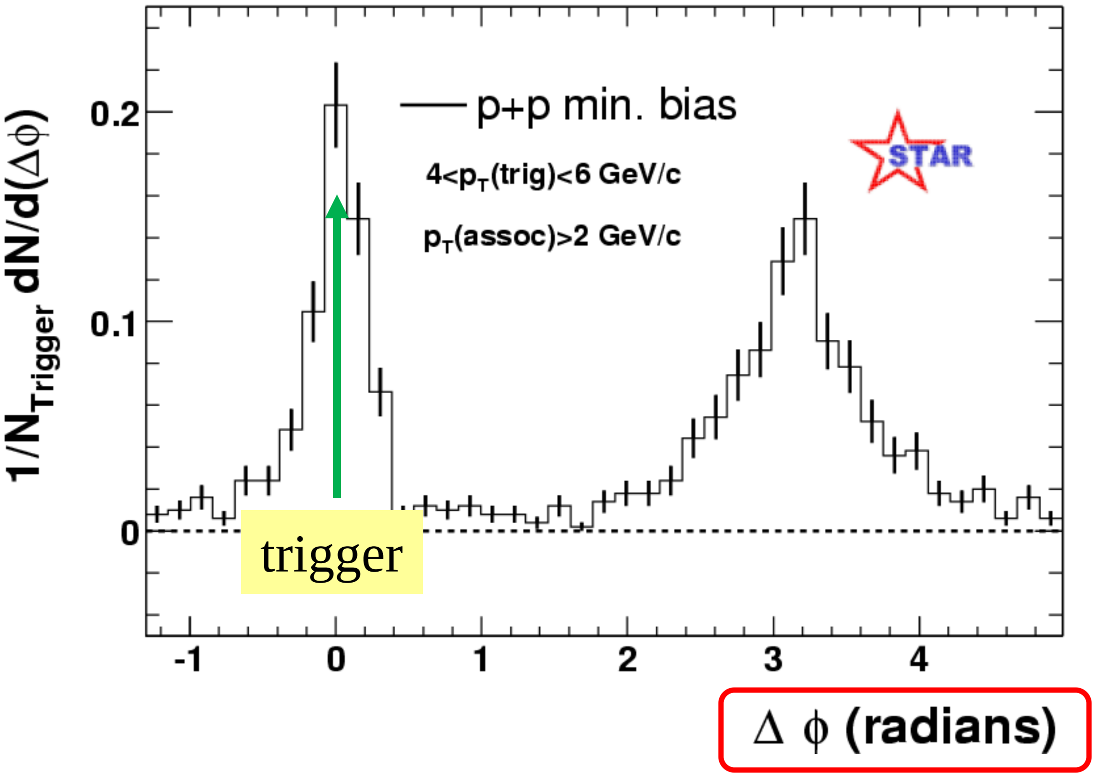
Backup

Di-hadron correlations as a jet surrogate

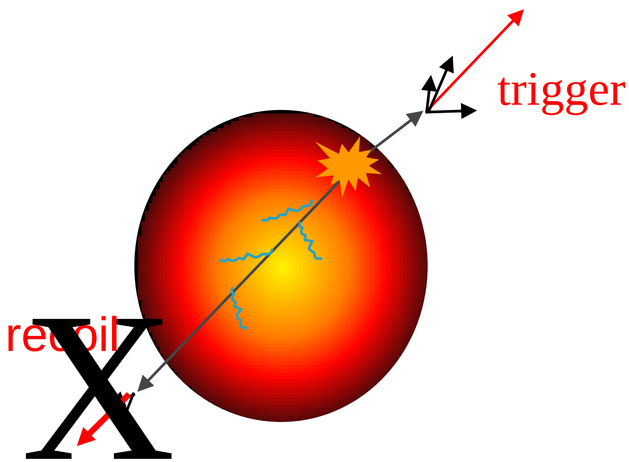


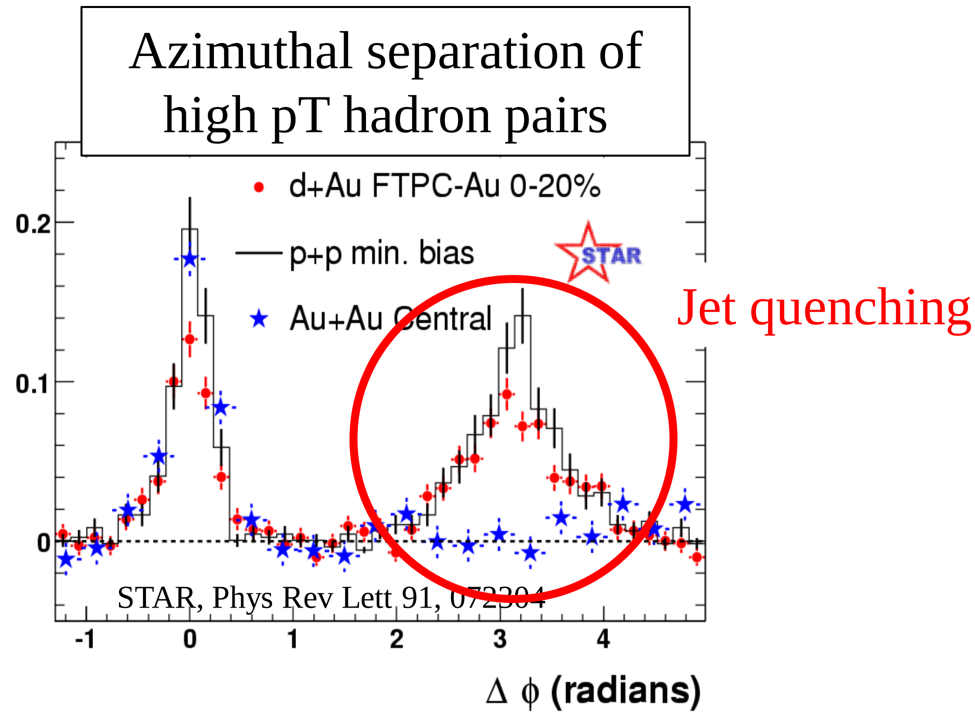


STAR, Phys Rev Lett 90, 082302



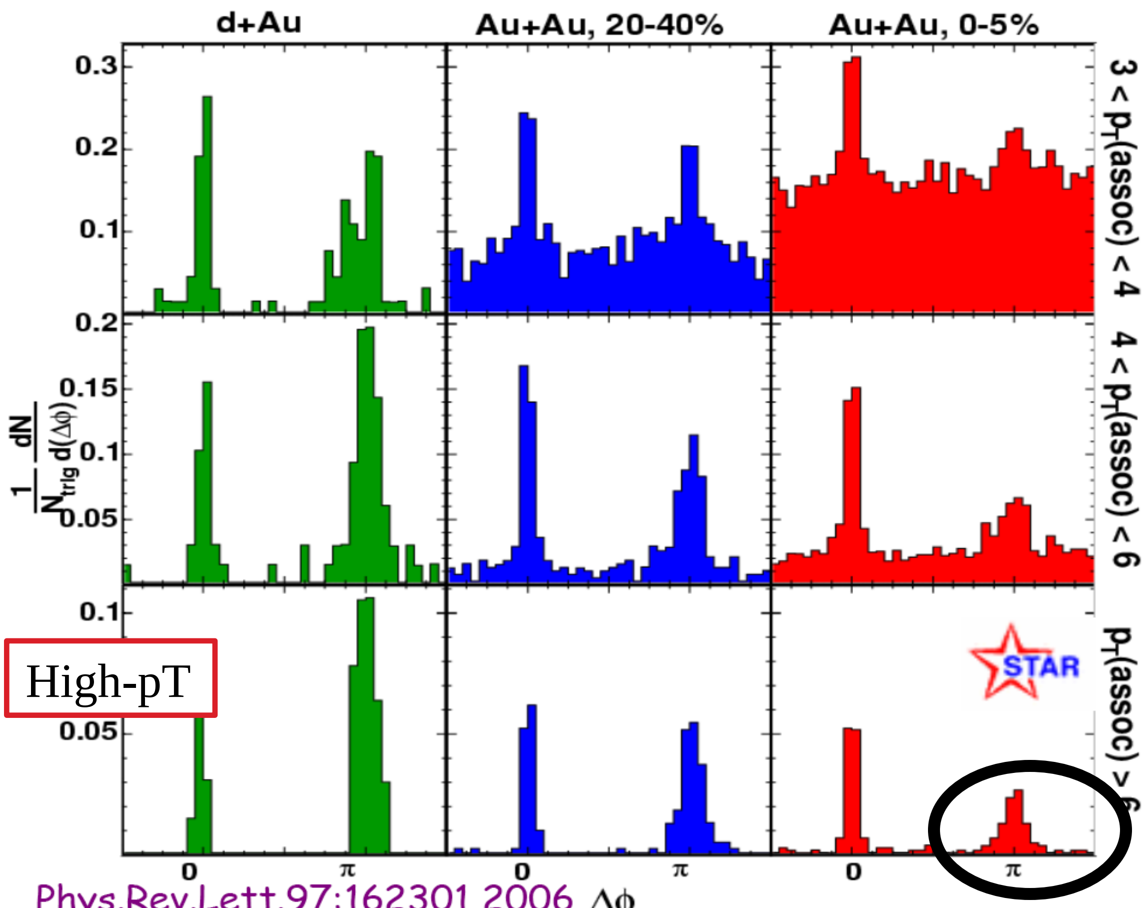
Jet quenching II: di-hadrons





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

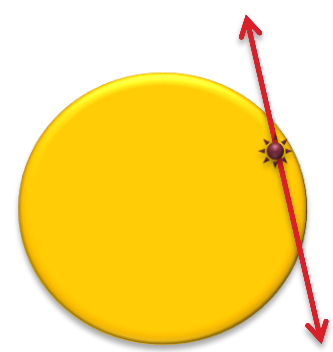
Di-hadron correlations at high-pt



Reaperance of the away side peak at high-assoc.-pT:

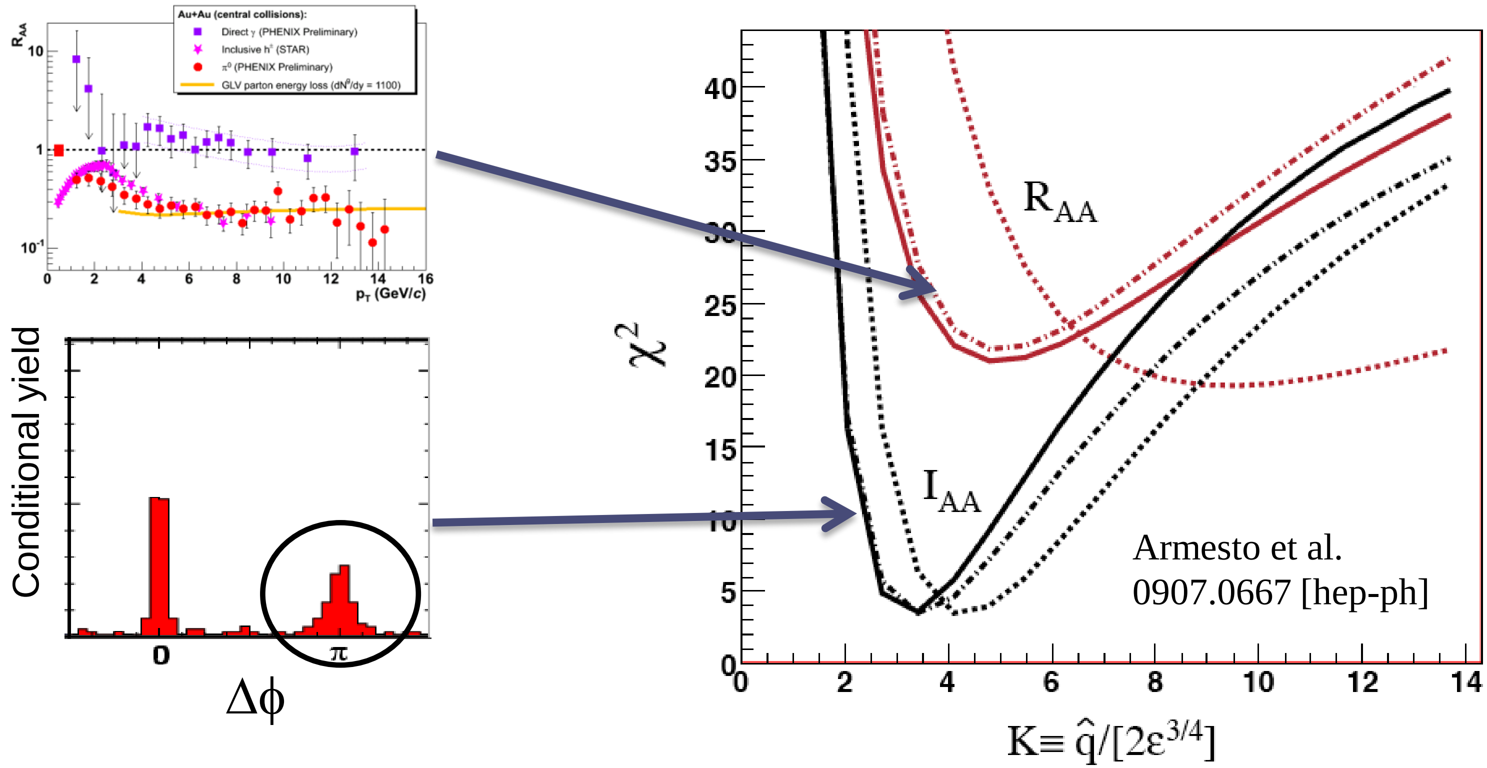
- similar suppression as inclusive spectra
- no angular broadening

Differential measurement of jets w/o interaction



QCD analysis of jet quenching

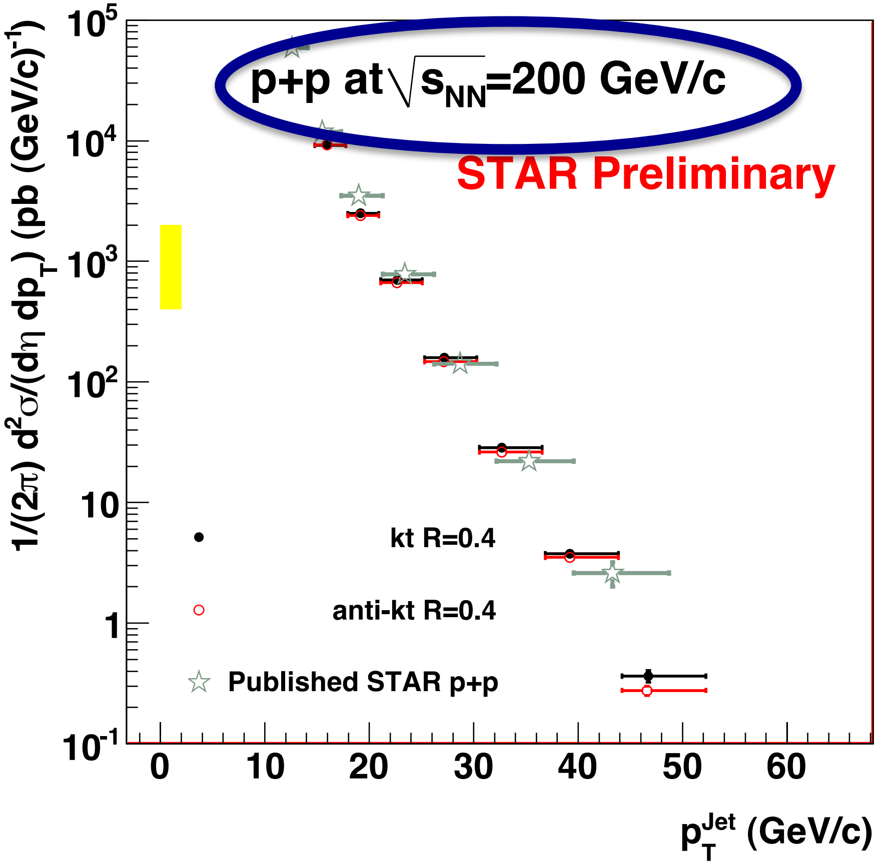
Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

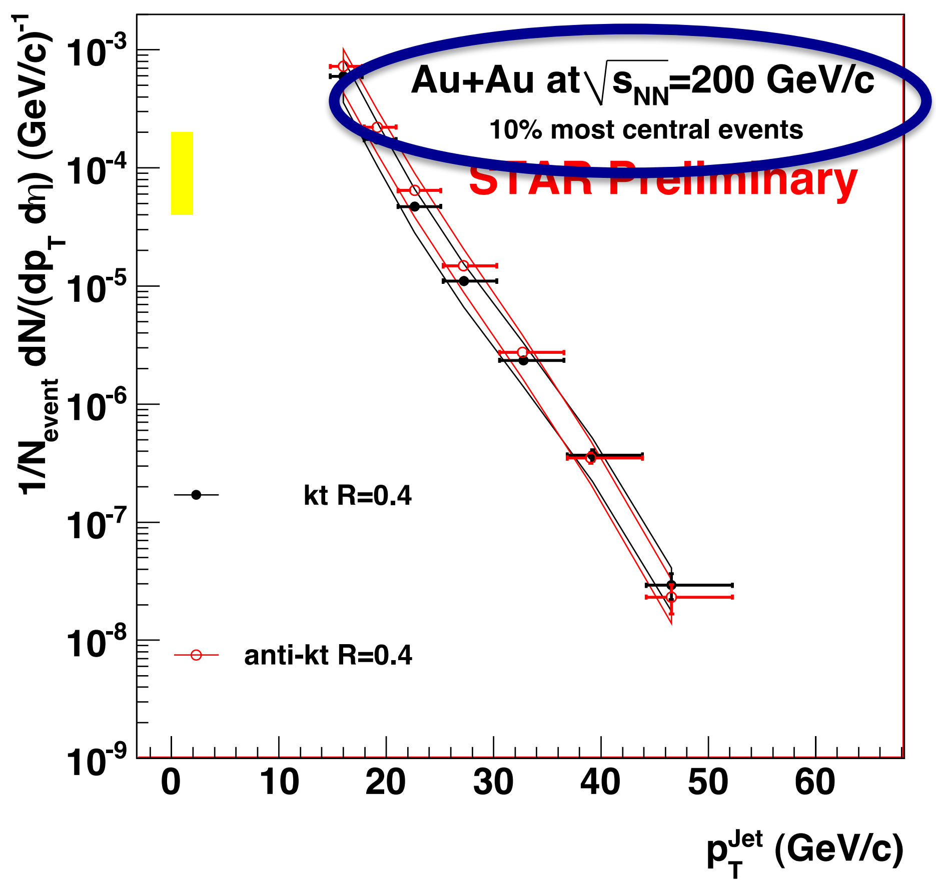


- ~Self-consistent fit of independent observables
- Data have good precision: limitation is accuracy of the theory

Inclusive jet cross sections at √s=200 GeV

M. Ploskon QM09



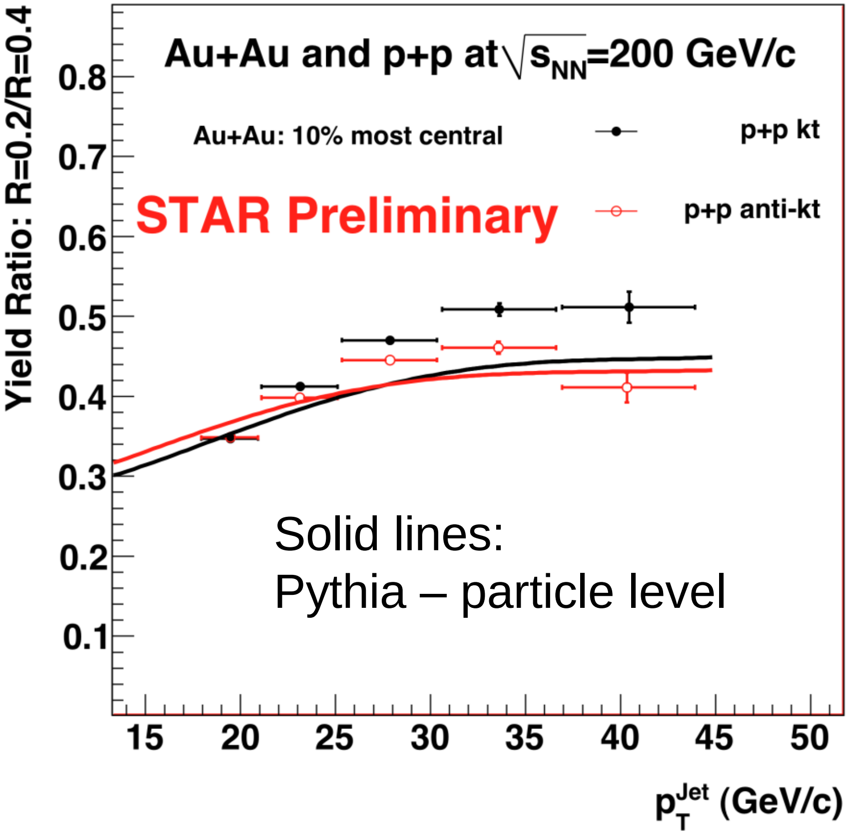


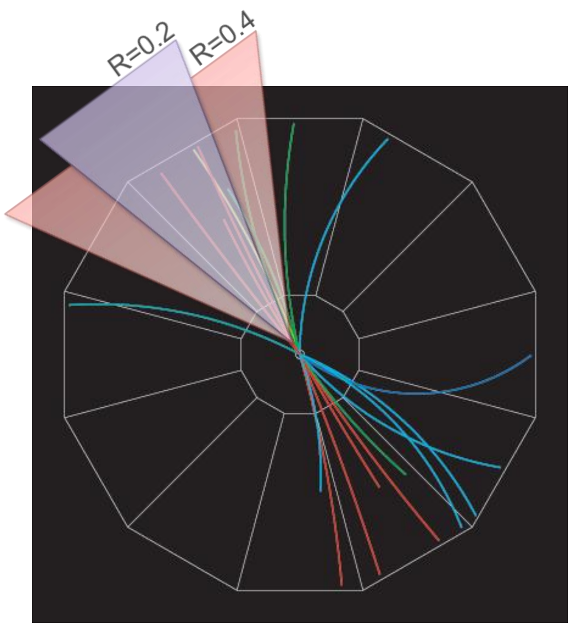
Consistent results from different algorithms

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}

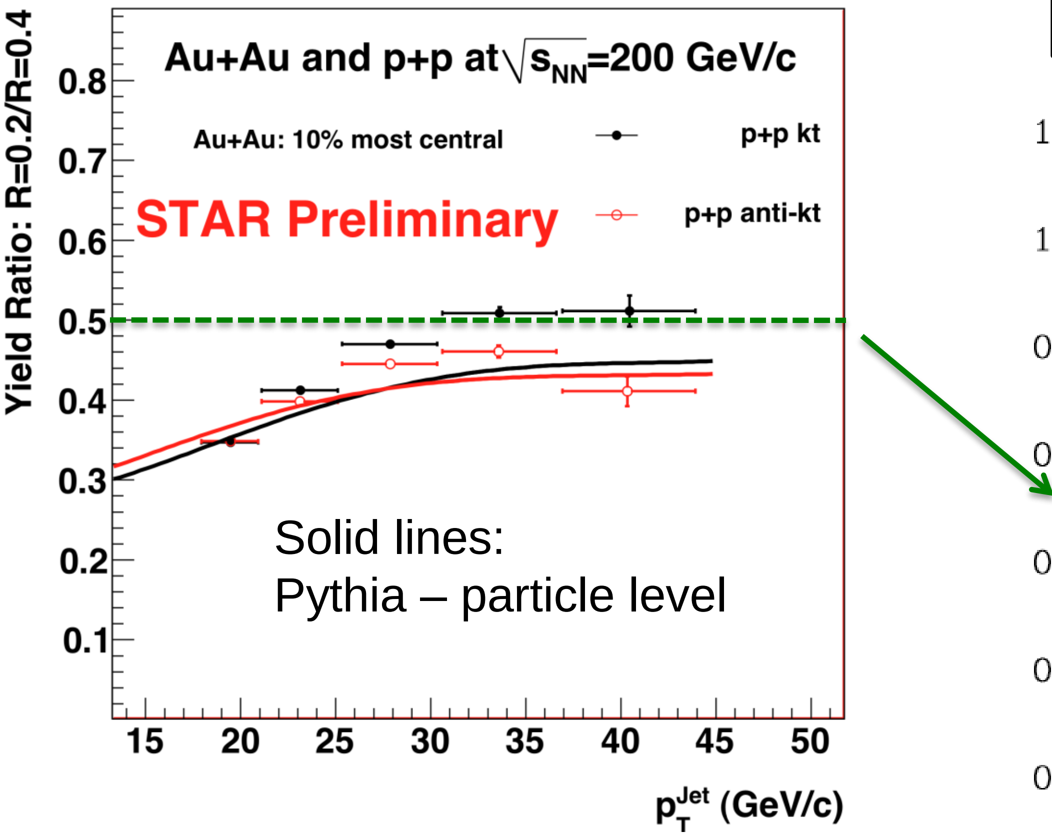


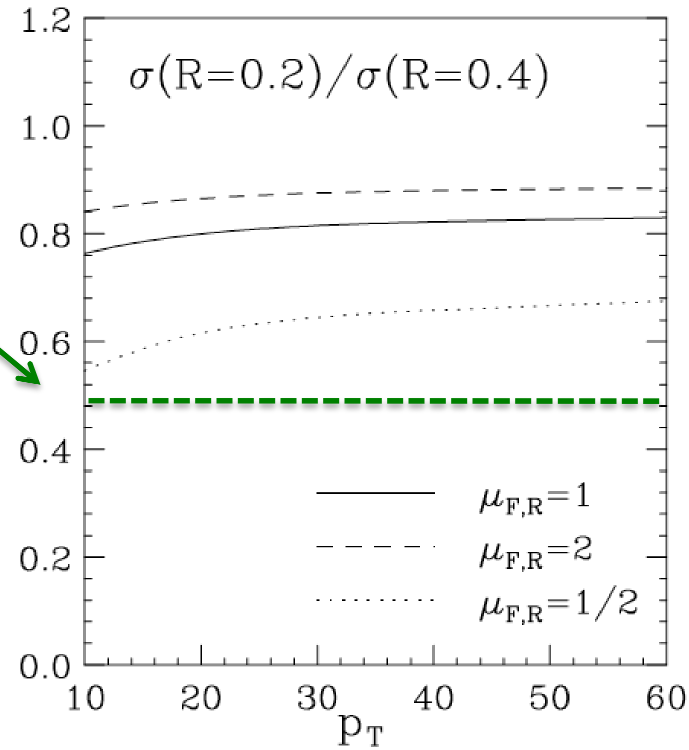


Narrowing of the jet structure with increasing jet energy

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

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





Narrowing of structure with increasing energy

NLO: narrower jet profile
➔hadronization effects?

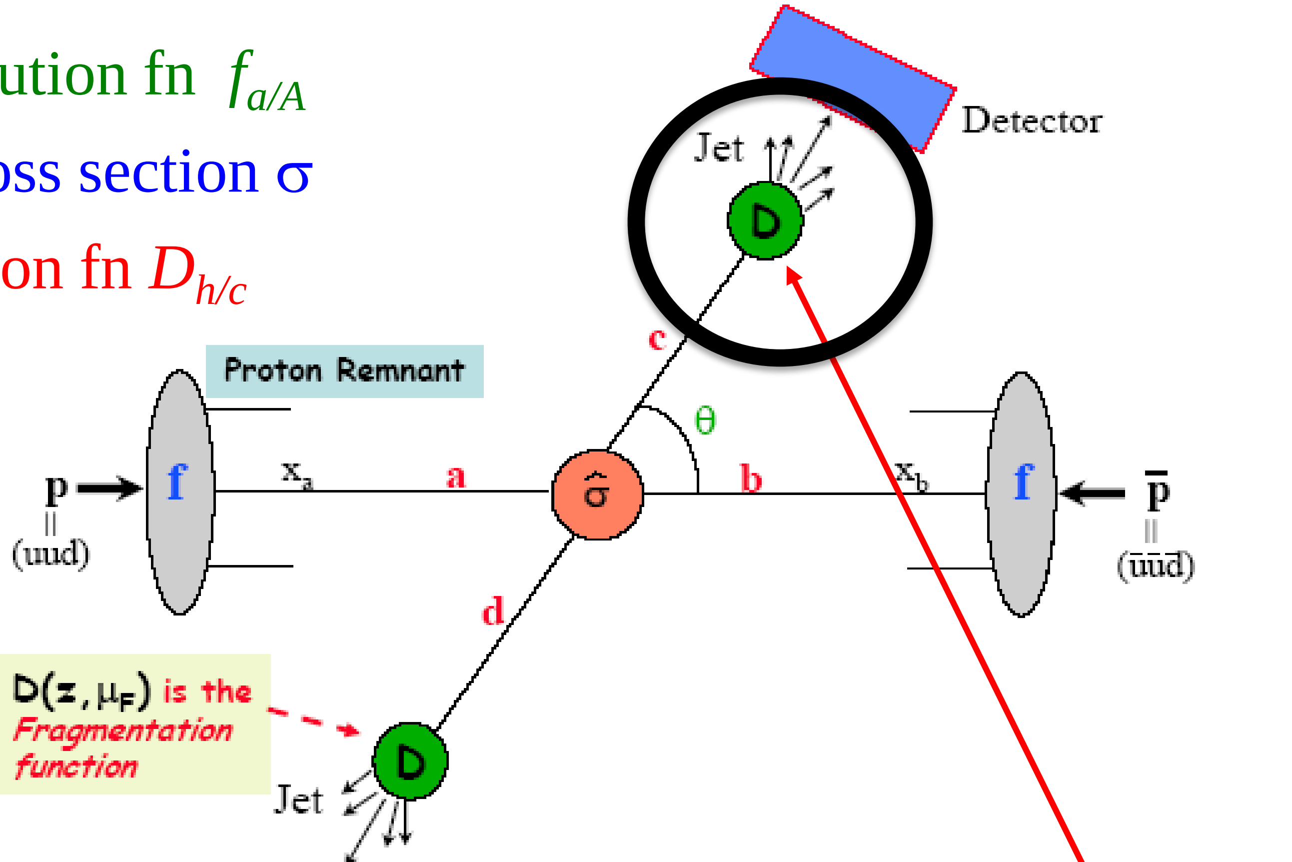
Jet hadronization

pQCD factorization:

parton distribution fn $f_{a/A}$

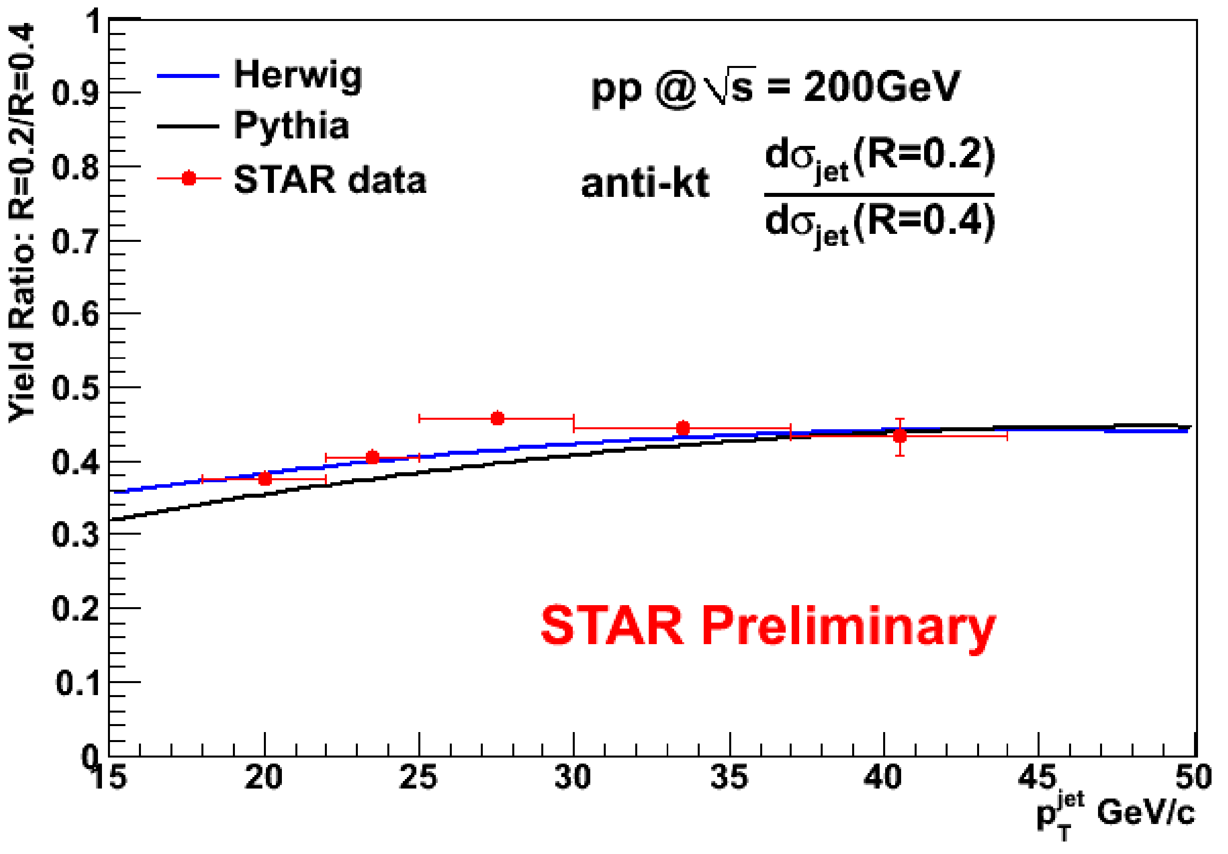
+ partonic cross section σ

+ fragmentation fn $D_{h/c}$



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

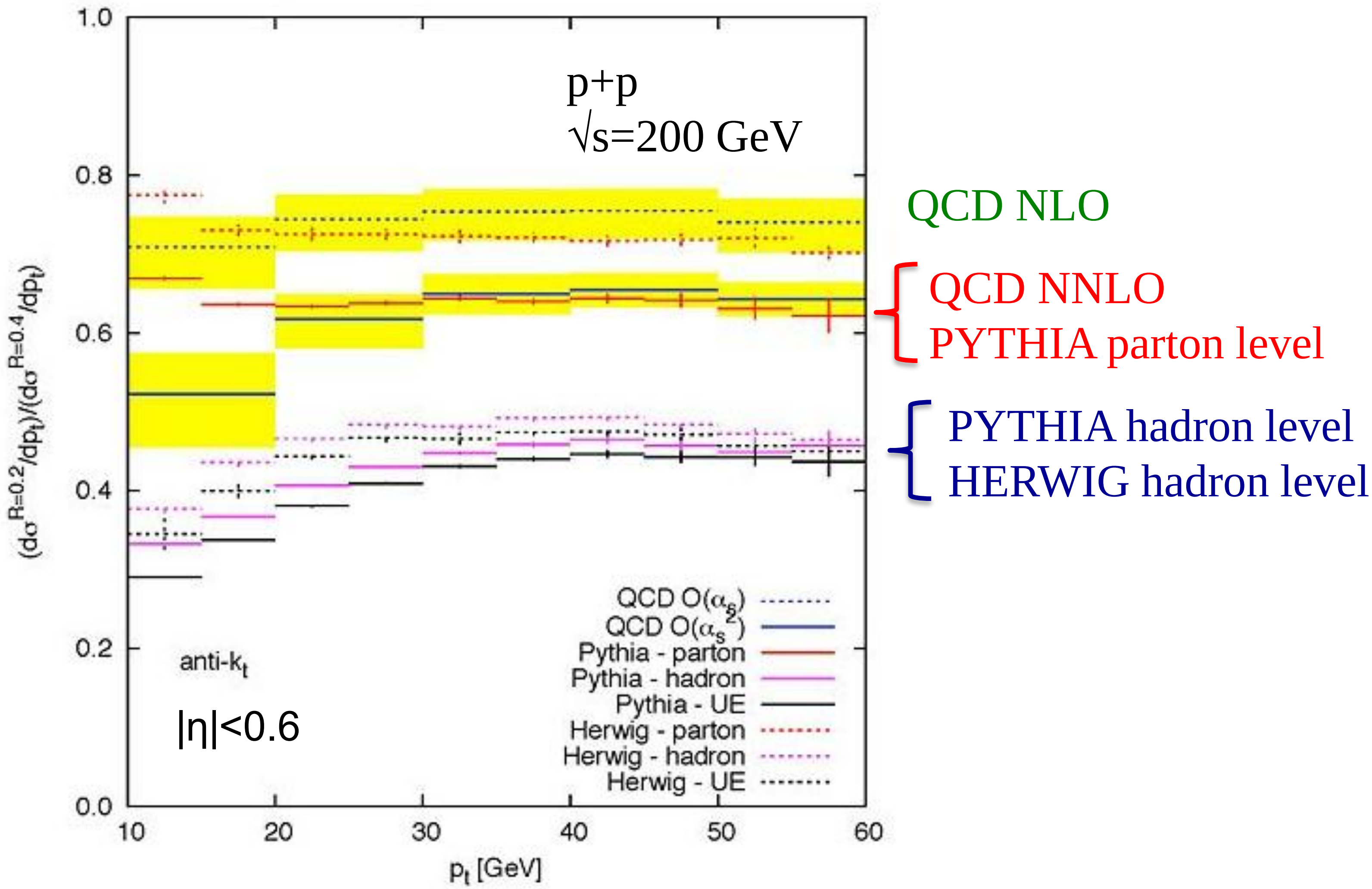
Hadronization effects: HERWIG vs. PYTHIA



Different hadronization models generate closely similar ratios

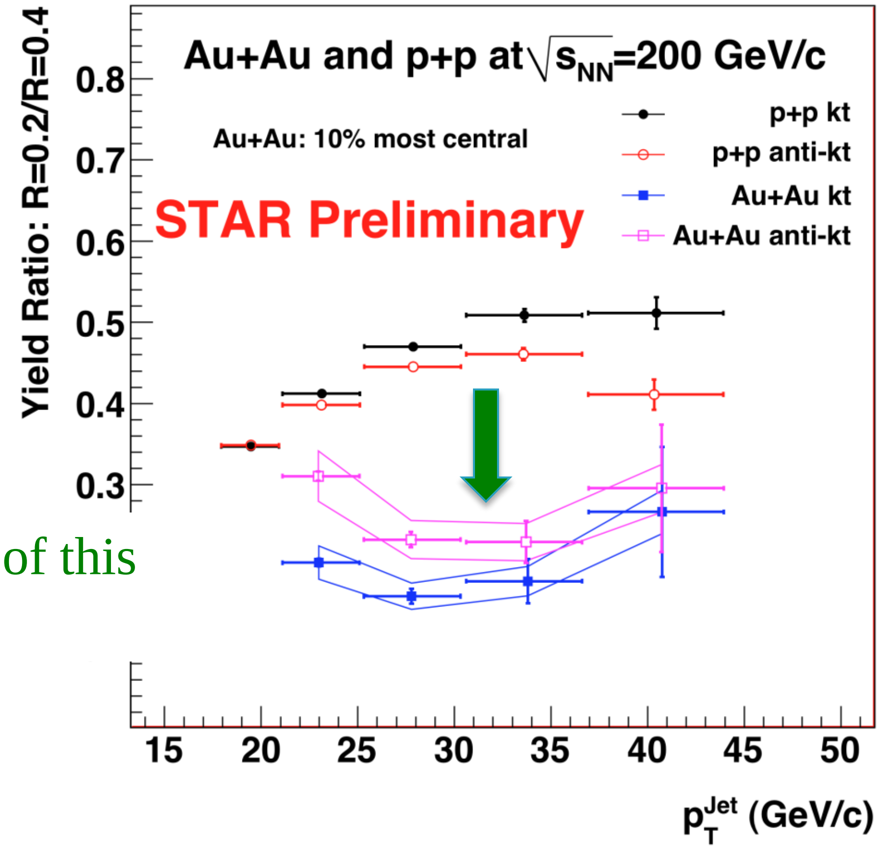
σ(R=0.2)/σ(R=0.4) : NNLO calculation

G. Soyez, private communication

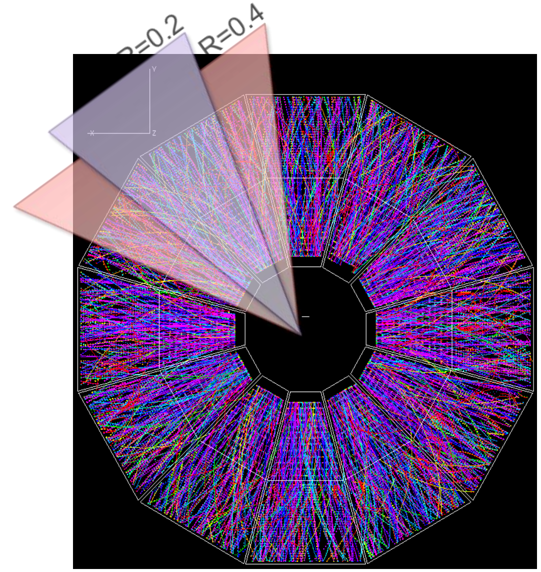


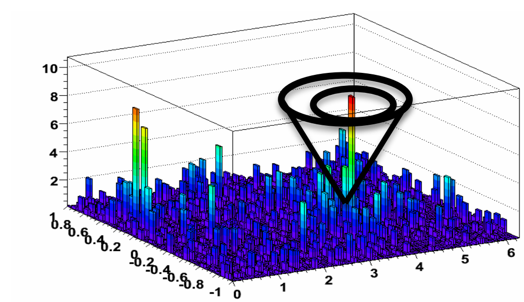
Broadening due to combined effects of higher order corrections and hadronization

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



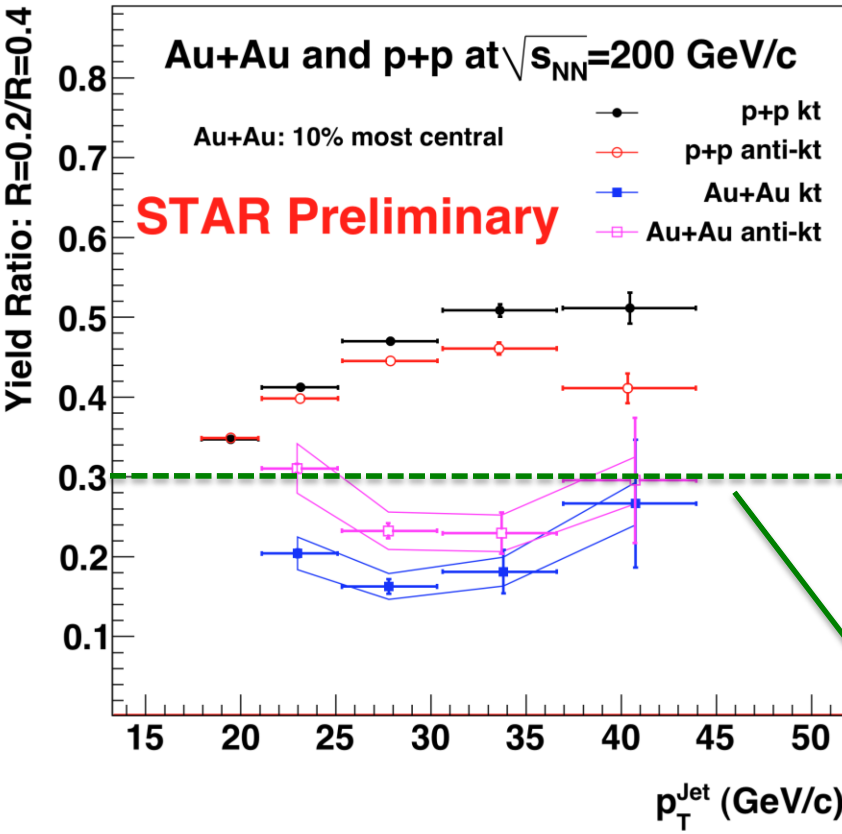
Main result of this analysis



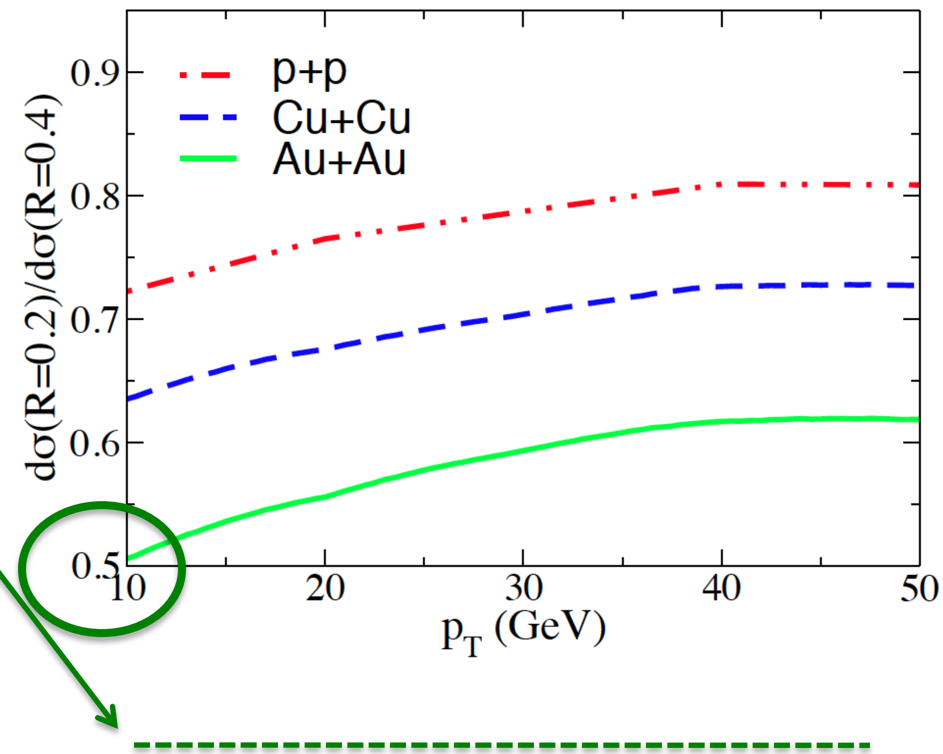


Marked suppression of ratio relative to p+p
➔medium-induced jet broadening

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…