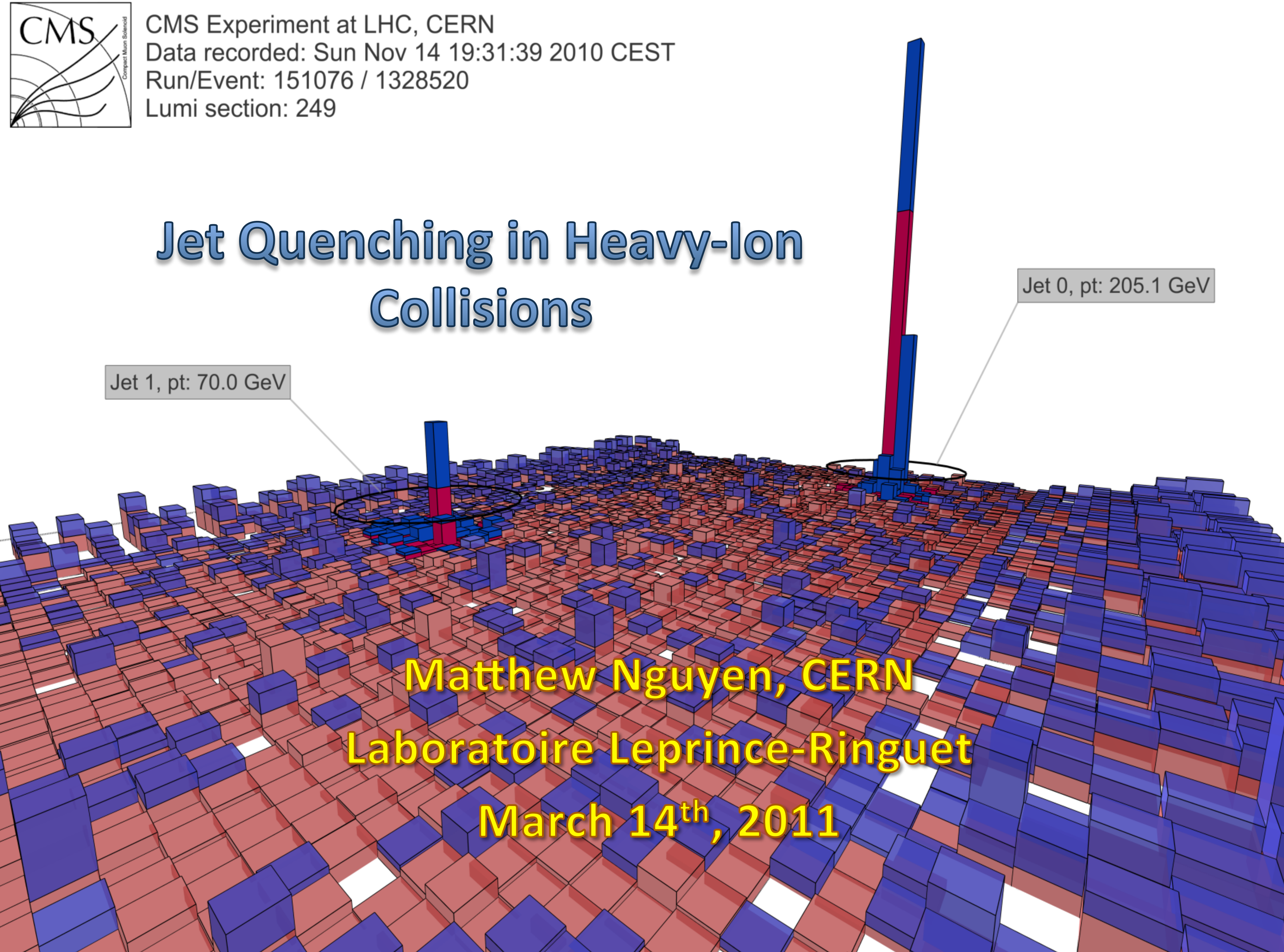
Jet Quenching in Heavy-Ion Collisions



Matthew Nguyen, CERN
Laboratoire Leprince-Ringuet

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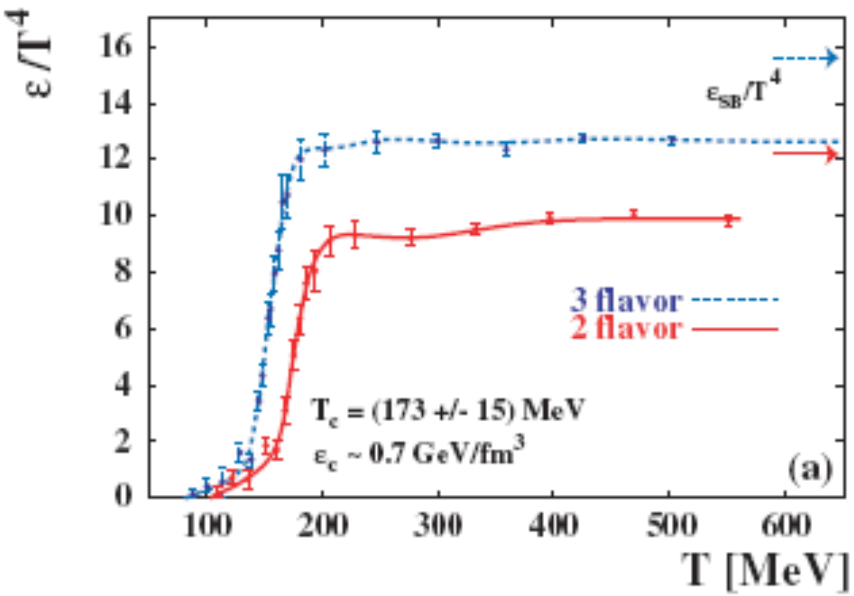
Overview

- An introduction to jet quenching in heavy-Ion collisions
- A (biased) overview of results from RHIC
  - Single Particle Spectra
  - Two-Particle Correlations
- Fully reconstructed jets in heavy ions with CMS
  - Dijet Asymmetries arXiv:1102.1957
  - Jet-Track Correlations
- Outlook

The Quark Gluon Plasma

- Above T_c, lattice QCD predicts a phase transition
- Quarks and gluons become relevant d.o.f.'s increasing the effective particle density
- Color fields screened over extended region
  → Quark-Gluon Plasma
- Not quite as Stefan-Boltzman limit → QGP not an ideal gas

Karsch and Laermann *Quark gluon plasma*



Evidence indicates that a QGP is formed in heavy-ion collisions

What is the consequence for hard scattering in such a medium?

Jet Quenching in Heavy Ions

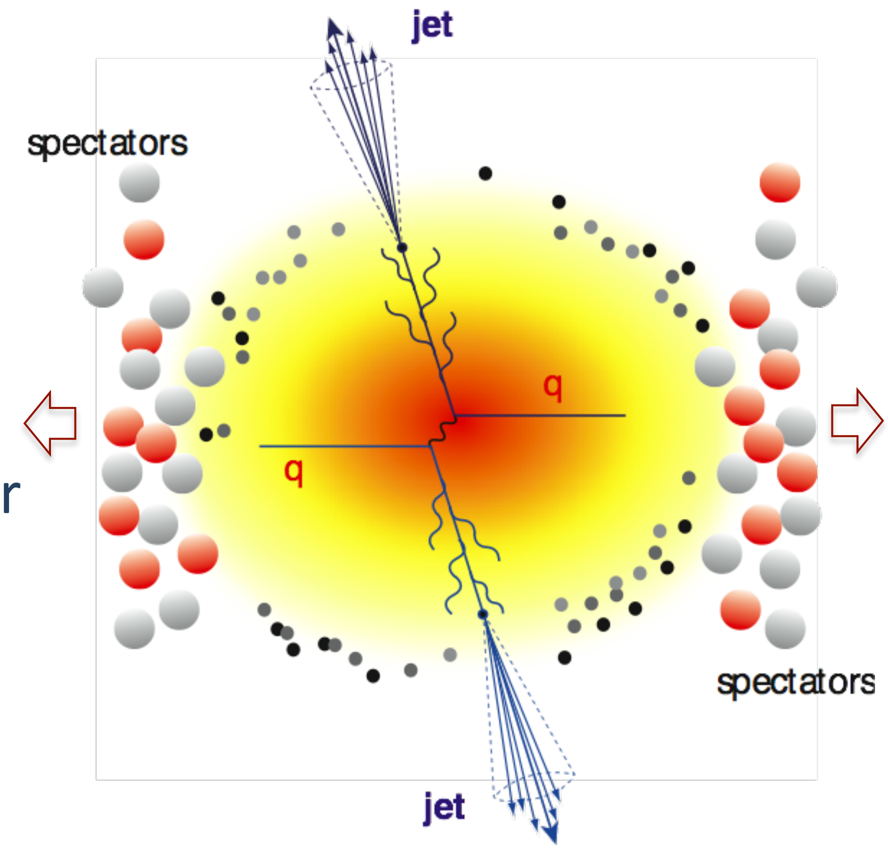
- Partons lose energy as they traverse the dense plasma
- At high p_T energy loss is dominated by gluon radiation
- Hadronization thought to occur outside of medium
- Characterize eloss by, e.g., the *medium transport coefficient*

$$\hat{q} \propto m_D^2 \sigma \rho$$

Debye mass (~gT)

parton x-section

density



"Jet tomography":
Use eloss to probe the properties of the medium

QCD Radiation in Medium

- Eloss amounts to calculation of the spectrum of radiated gluons
- For thick media (λ<<L), scattering is coherent (LPM regime)

$$\omega \frac{dI_{rad}}{d\omega} = \alpha_S \sqrt{\hat{q}L^2 / \omega} \Rightarrow \Delta E_{rad} \approx \alpha_S \hat{q} L^2$$

L^2 Dependence

- Various theoretical frameworks:
  - Multiple soft scattering (BDMPS-type)
  - Few hard scattering (GLV-type)
  - Other approaches: Higher-twist, AdS-CFT, etc.
- Models vary in their treatment of
  - The space-time evolution of the system $\hat{q} \equiv \hat{q}(\vec{x}, t)$
  - Approximations in their treatment of the radiation itself
- Different models give quantitatively different results!

Pessimist: "Hard partons are not a well calibrated probe of medium properties"

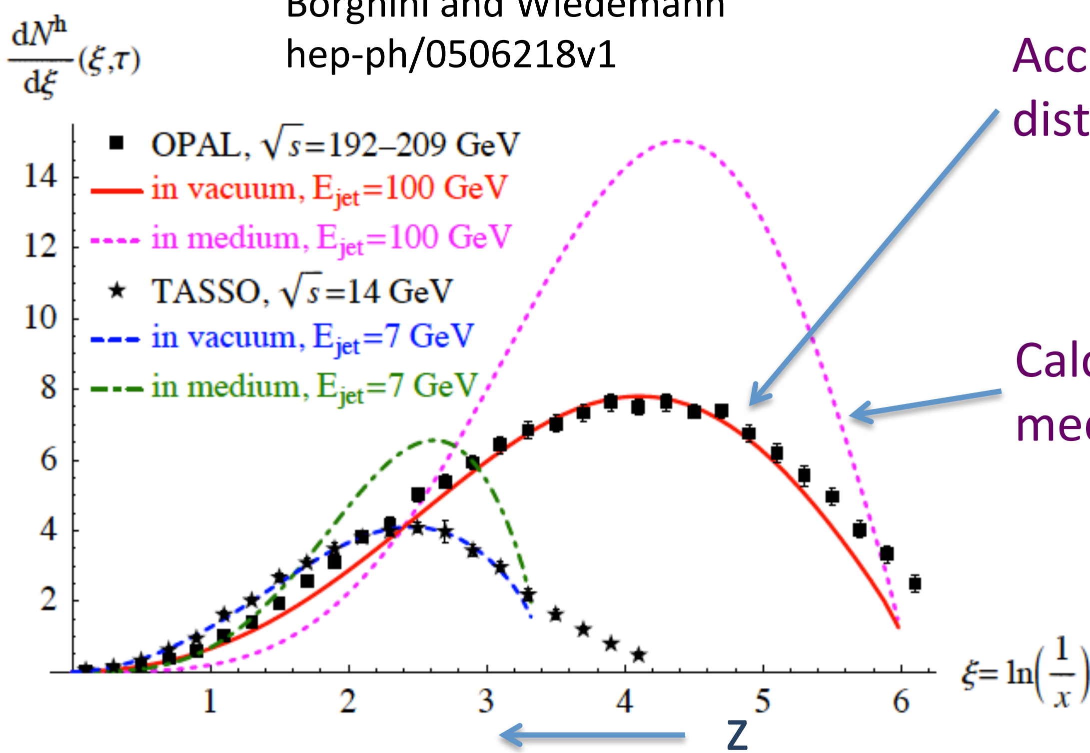
Optimist: "QCD radiation far from vacuum is a fertile area of research"

Jet Fragmentation in-Medium

Typical approach: Eloss of parton followed by vacuum FF

A recent approach takes into account the full evolution

Borghini and Wiedemann
hep-ph/0506218v1



Accurately calculates hadron distribution in vacuum (e+e-)

Calculates enhancement of medium enhancement of low p_T

E_{jet} = 100 GeV, ξ = 4.6
→ Hadron p_T = 1 GeV/c

Theory: Important to consider radiation beyond the leading parton

Experiment: Important to probe wide dynamic range

Medium Effects on Spectra

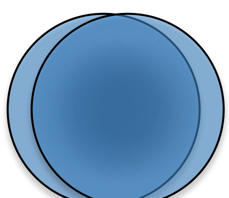
The Nuclear Modification Factor quantifies the departure of particle yields from "vacuum" QCD

$$R_{AA} \equiv \frac{N_{AA}}{\langle N_{coll} \rangle N_{pp}} \sim \frac{\text{Medium-Modified}}{\text{Vacuum-Like}}$$

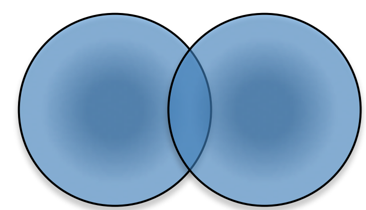
The baseline is p+p scaled by the *number of binary collisions* (N_{coll})
→ assumes A+A is the product of incoherent p+p collisions (high p_T)

A *Glauber Model* is used to relate measured particle multiplicities to N_{coll} and other geometric quantities (e.g., impact parameter)

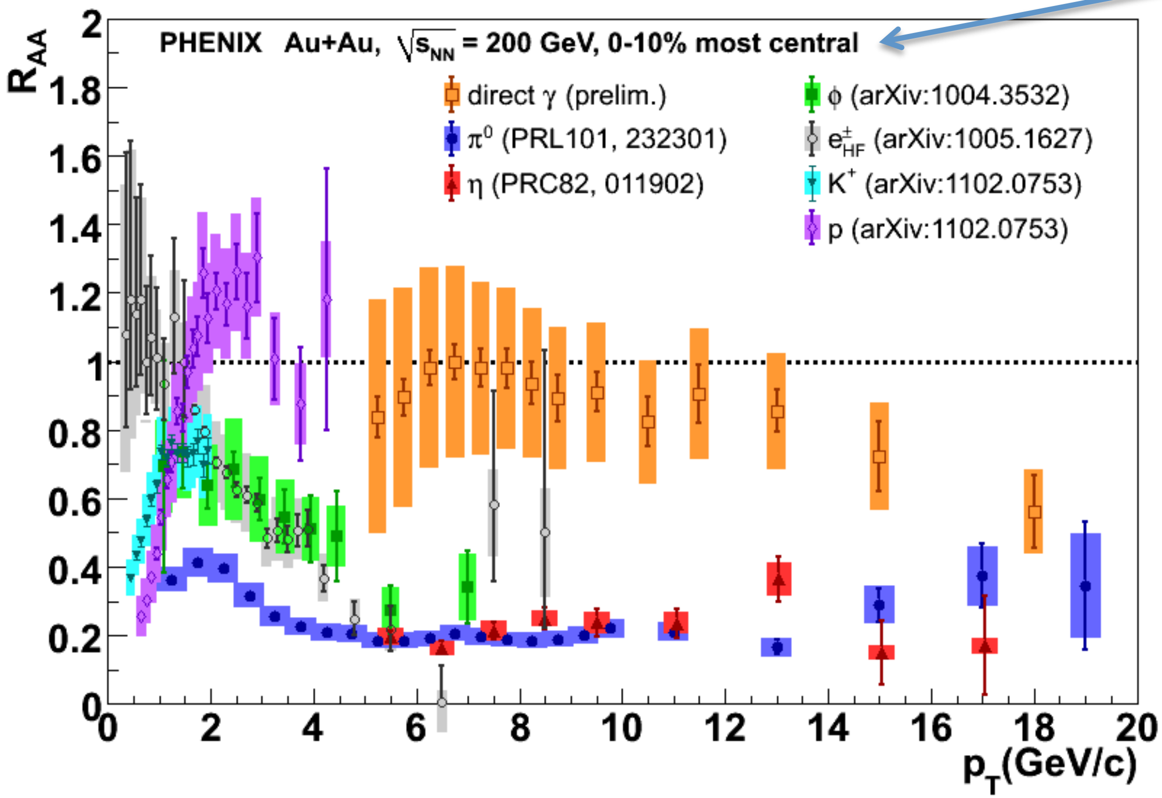
Hence, we can tell a *central* collision:

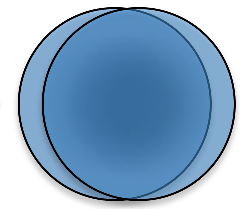


From a *peripheral* one:



Single Particles at RHIC



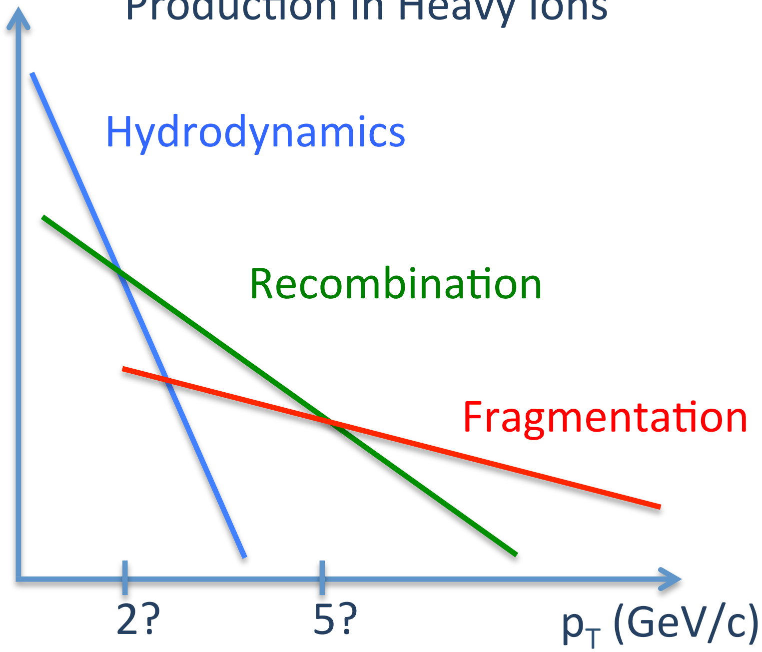


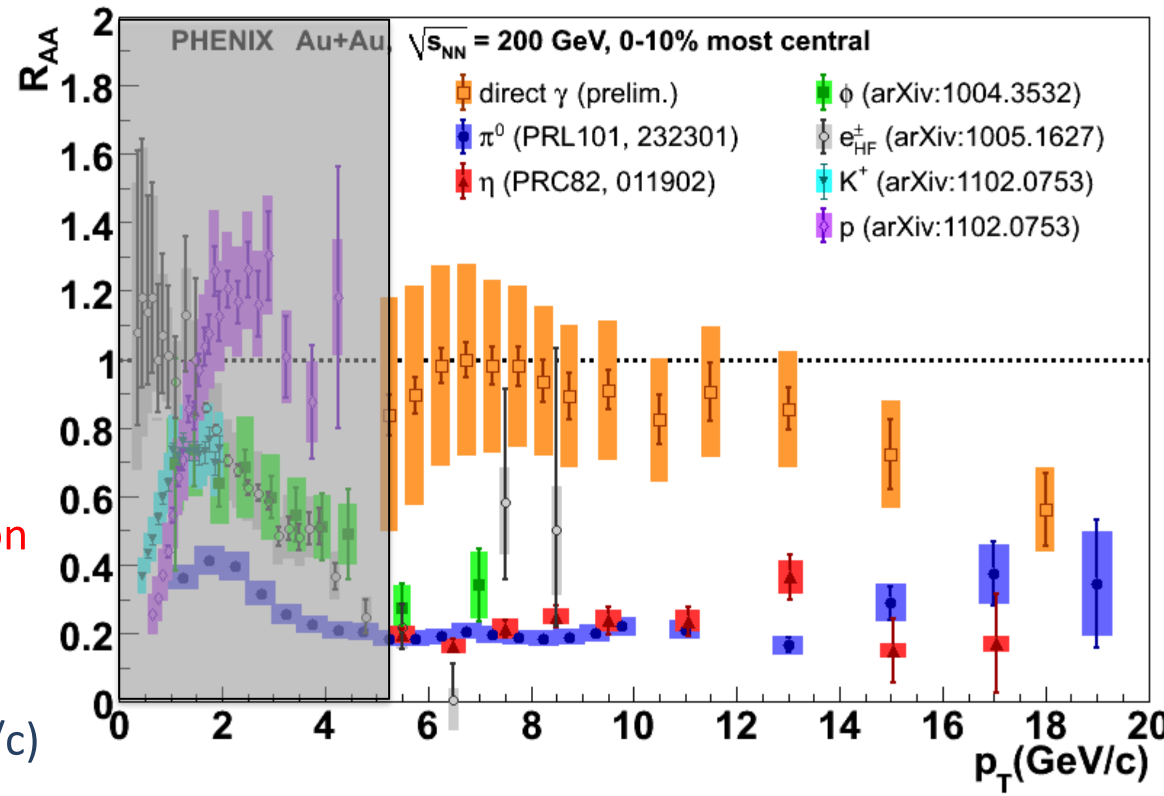
Strong dependence of R_{AA} on particle species

What can we learn from all this?

Particle Production in HI

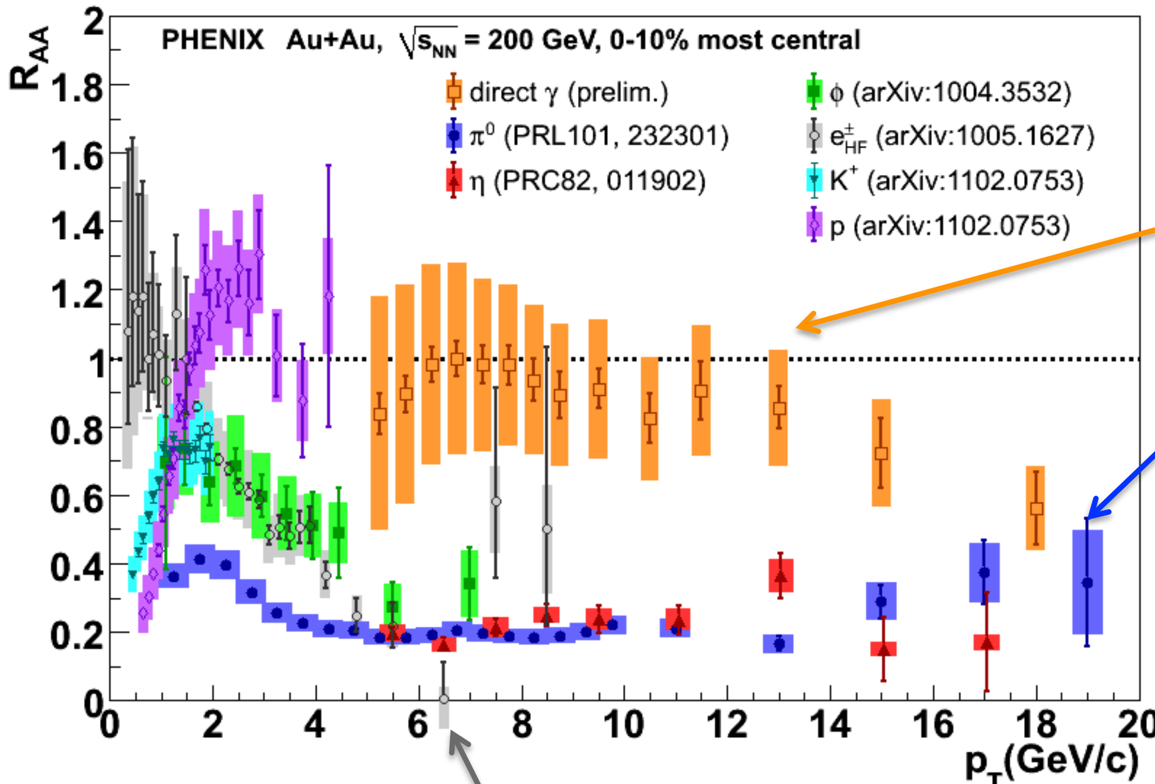
Schematic View of Particle Production in Heavy Ions





- Thermal production dominates at low p_T (hydrodyamics)
- At intermediate p_T phase space is dense enough for coalescence, particle production driven by # of valence quarks
- Only hard processes scale with N_{coll}, focus on p_T > 5-6 GeV/c where fragmentation dominates

R_{AA} at High p_T



Photons are "color-blind" they don't radiate

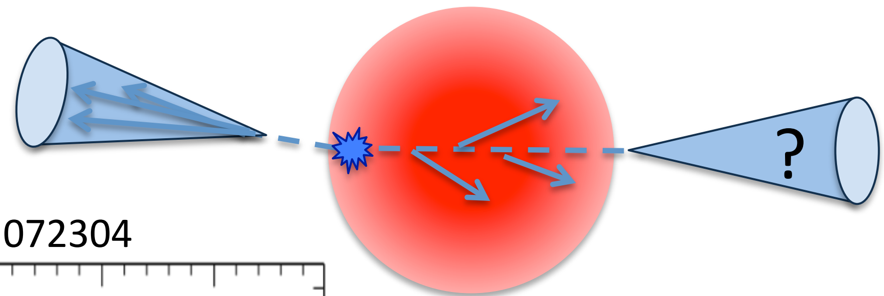
Light mesons suppressed by 5x → strong energy loss for light quarks and gluons

Heavy quark shouldn't radiate, yet electrons from heavy–flavor lose energy

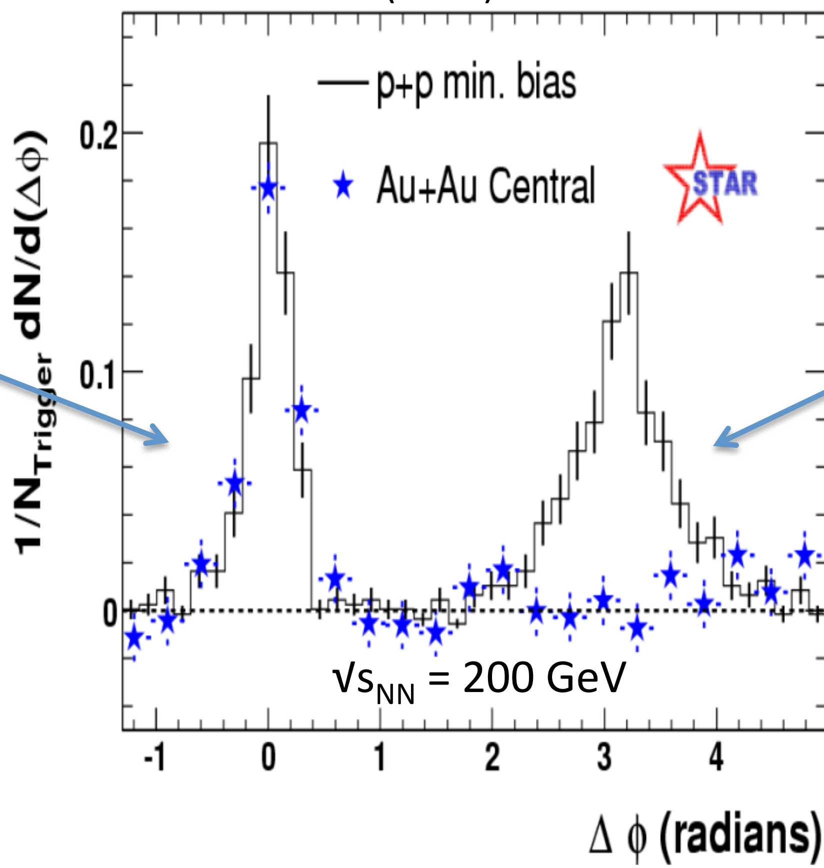
Suggests picture of Eloss is incomplete → collisional Eloss?

Dihadron Correlations at RHIC

4 GeV/c < $p_{T,\ trigger}$ < 6 GeV/c
2 GeV/c < $p_{T,\ partner}$ < $p_{T,\ trigger}$



PRL91 (2003) 072304



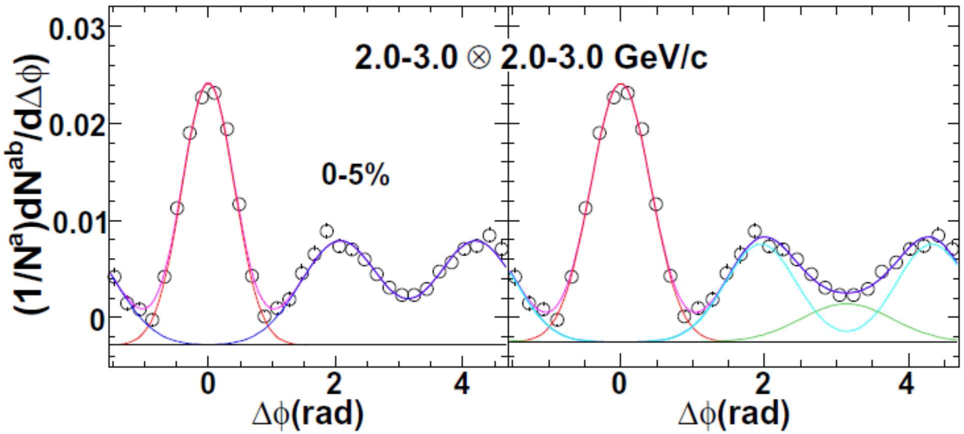
Near-side: Unmodified jet correlation → supports surface bias

Away-side: Near complete extinction of jet correlations

Low P_T Correlations

At lower p_T, jet(?) correlations are recovered, but with very non-jet-like shapes

PHENIX PRC78, 014901 (2008)



Correlations can be fit to a two-component ansatz:

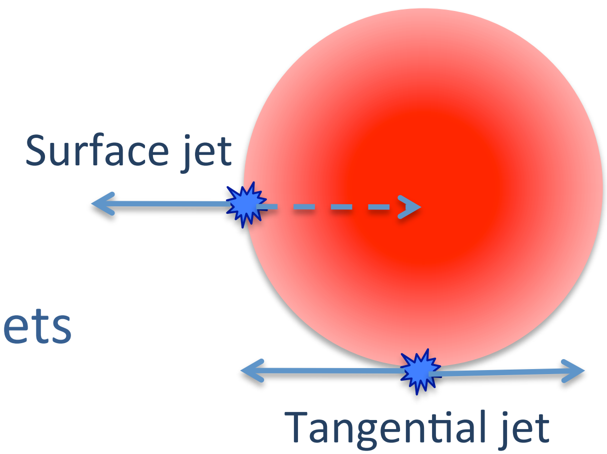
1) Broadened peak with a dip at $\Delta\varphi = \pi$
2) Suppressed, but un-modified jet peak

What is the source of modified shape?

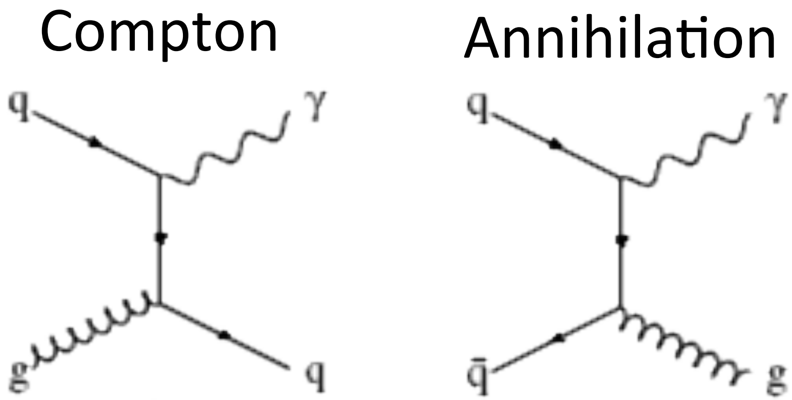
- Enhancement of large angle radiation?
- A jet-medium interaction, e.g., a Mach cone?
- Systematic effect from subtraction of the underlying event?

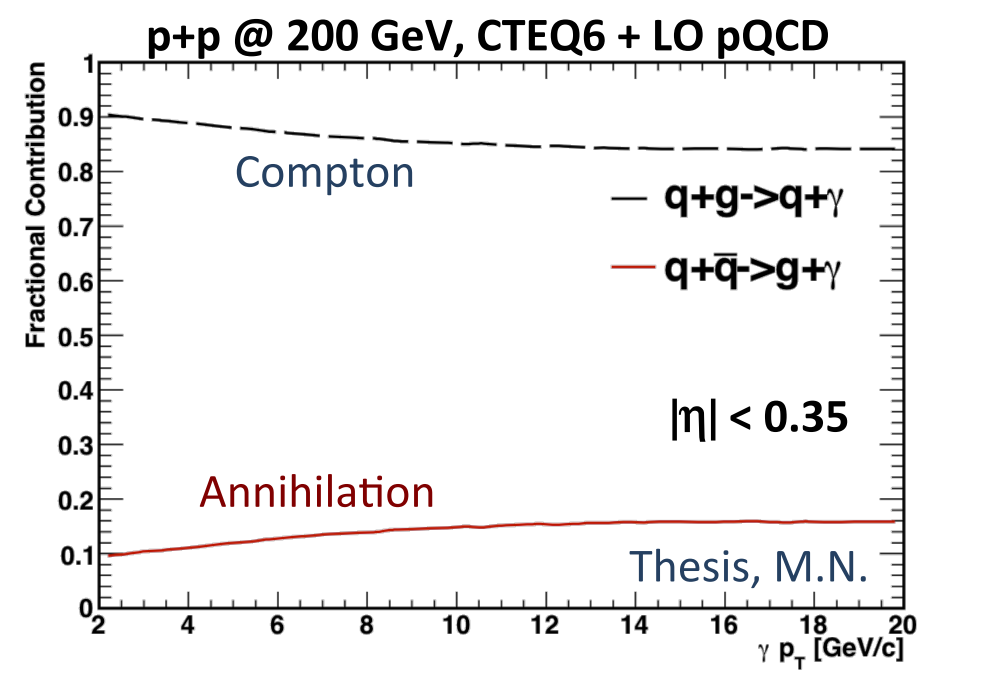
Limitations

- Complicated dependence on geometry
  - High p_T trigger bias towards surface jets
  - High p_T partner bias towards tangential jets
- Near-side fragmentation bias
  - Initial parton energy depends on p_T of trigger and partner
  - Makes it difficult to extract initial parton energy
- Two solutions:
  - Correlations using direct photons
  - Full jet reconstruction

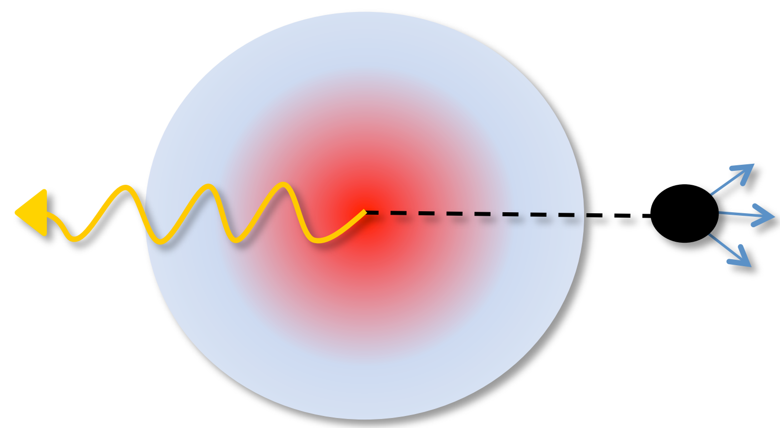


Direct γ–h Correlations



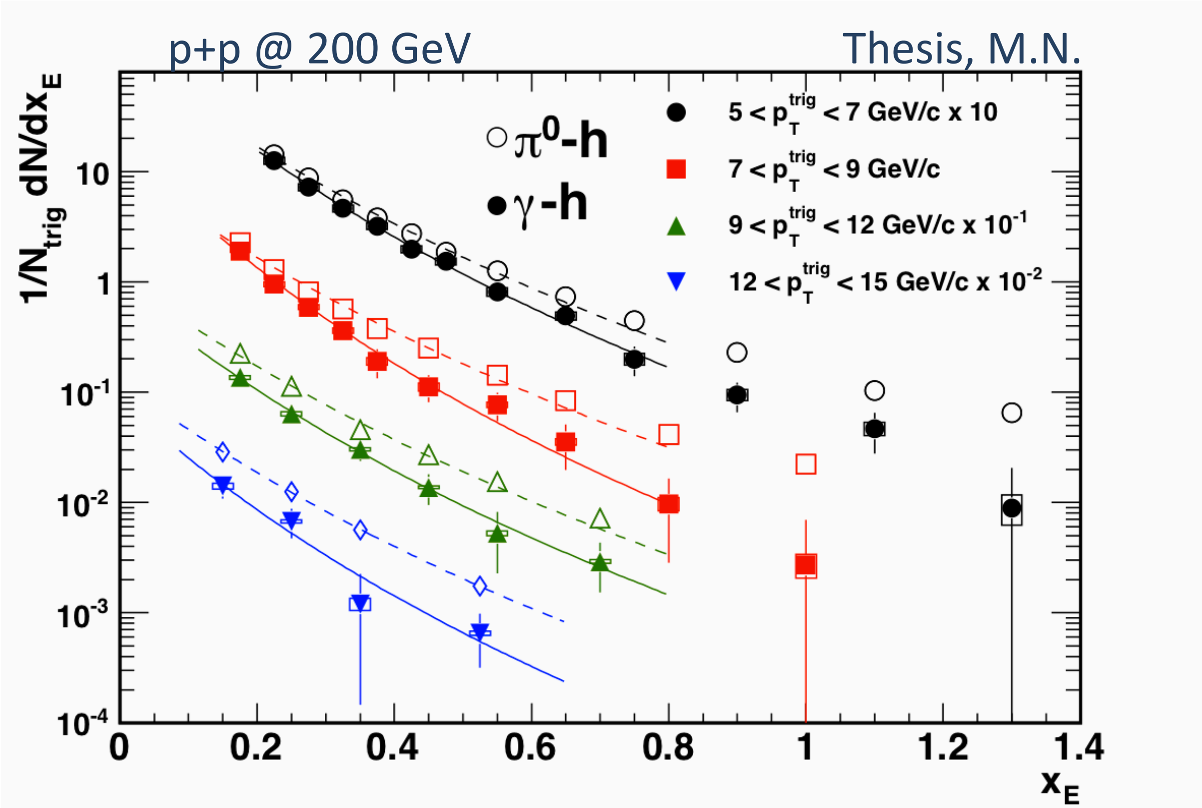


- Compton scattering dominant
  → Study the eloss of quarks
- To LO, γ p_T = Inital parton p_T
- Transparent to medium (R_{AA} ~ 1)
- γ's tag an unbiased sample of jets!



γ+jet In Medium

FF's from γ-h



$$x_E \equiv \frac{\text{hadron } p_{\mathrm{T},\parallel}}{\text{photon } p_{\mathrm{T}}}$$

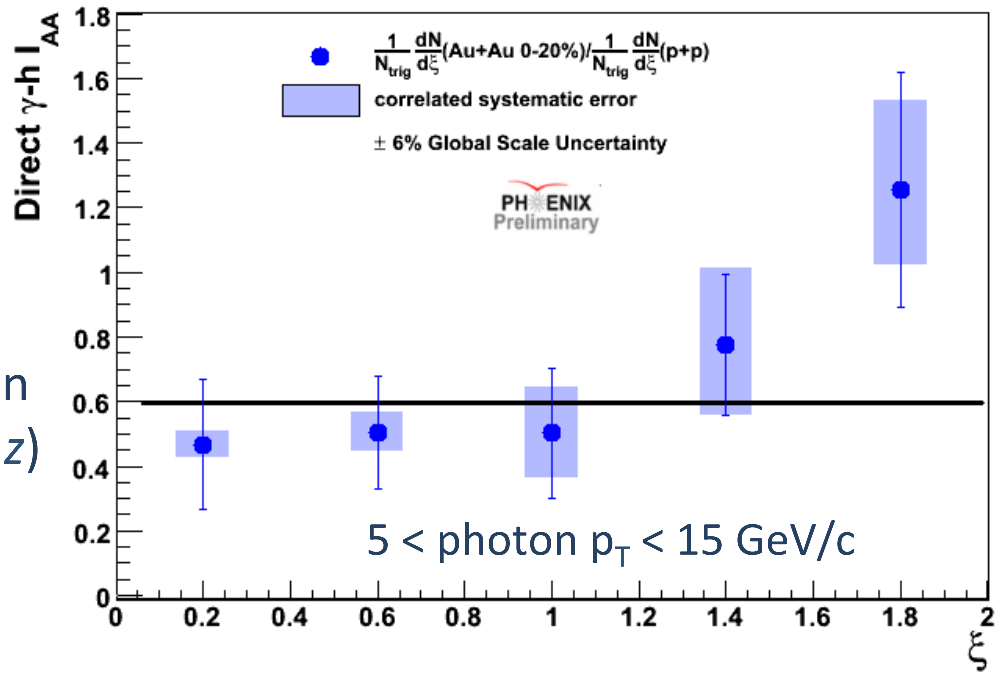
$$\text{photon } p_{\mathrm{T}} \approx \text{parton } p_{\mathrm{T}} \therefore x_E \approx z \rightarrow \frac{dN}{dx_E} \propto D(z)$$

Fragmentation function measurable from photon-hadron correlations

Medium-Modified FF's

I_{AA} ~ the ratio the medium to vacuum fragmentation functions

$$I_{AA}(\xi) \approx \frac{D_{\text{med}}(\xi)}{D_{\text{vac}}(\xi)}$$



Enhancement of high ξ (low z) fragments

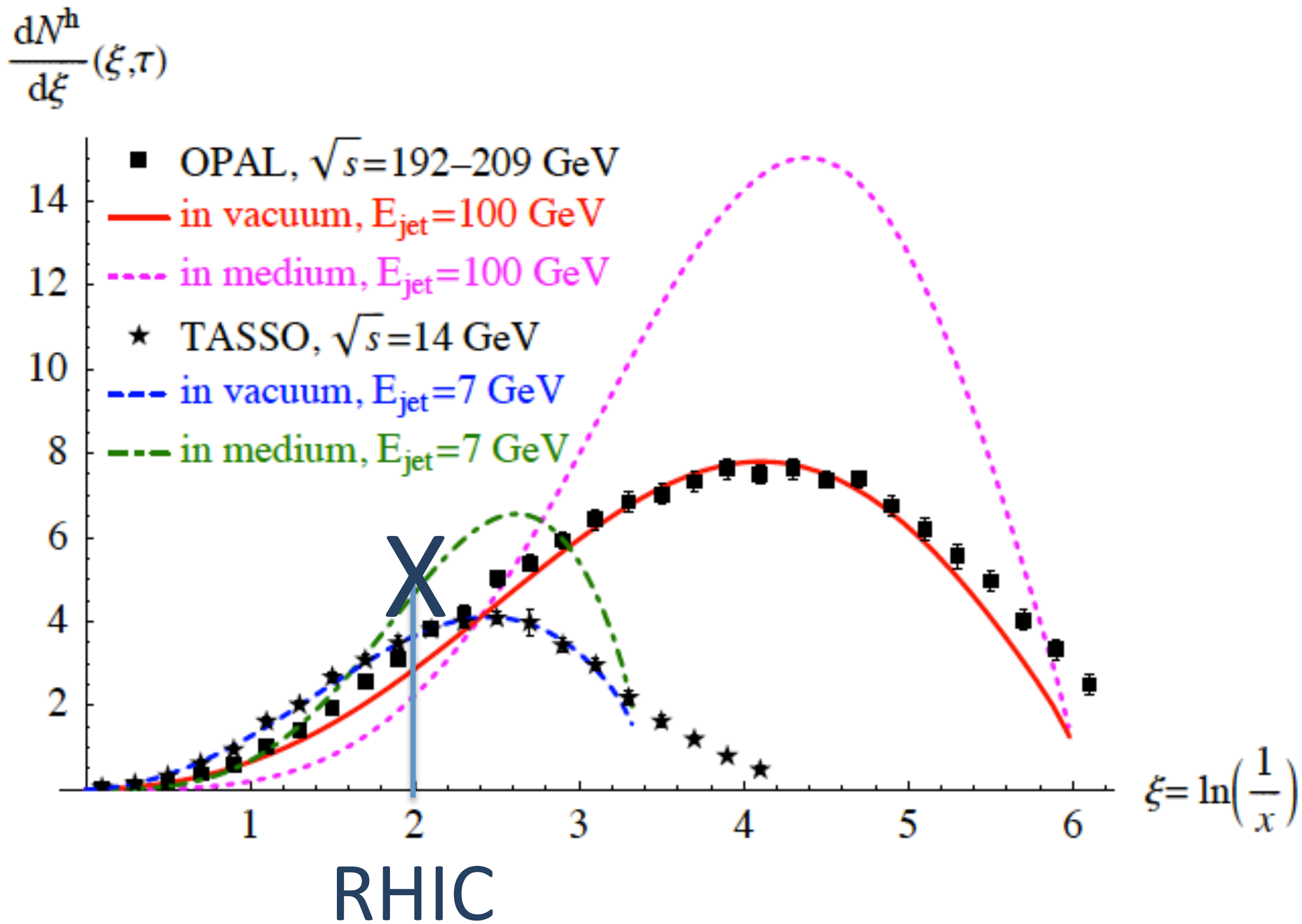
Familiar suppression at large low ξ (high *z*)

← z, x_E

Starting to probe the evolution of parton shower in-medium

However, further reach is limited by both statistics and systematics

Where Are We?

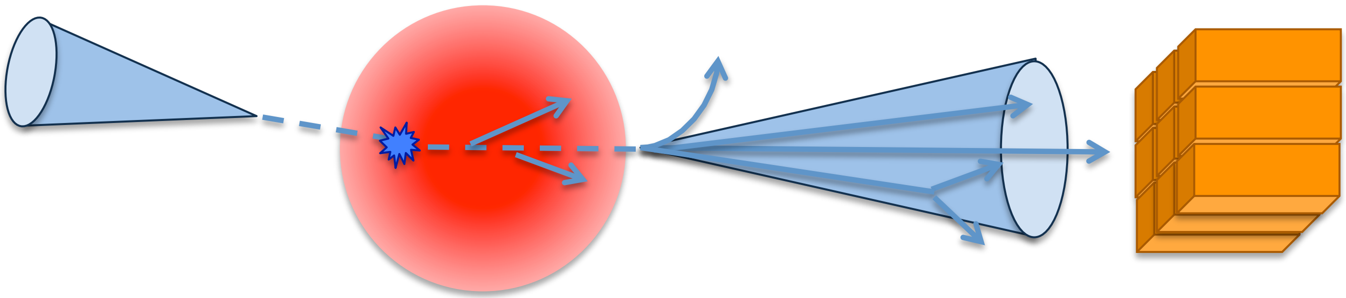


$\frac{dN^h}{d\xi}(\xi,\tau)$
OPAL, $\sqrt{s}$=192–209 GeV
in vacuum, E_{jet}=100 GeV
in medium, E_{jet}=100 GeV
TASSO, $\sqrt{s}$=14 GeV
in vacuum, E_{jet}=7 GeV
in medium, E_{jet}=7 GeV
X
$\xi = \ln\left(\frac{1}{x}\right)$
RHIC

Jet Measurements in AA

Large background of soft particles, $dN_{ch}/d\eta$ ~ 1600 for 5% central PbPb @ 2.76 TeV

A schematic view of a jet measurement in heavy ions



Jets are reconstructed from energy reaching calorimeters

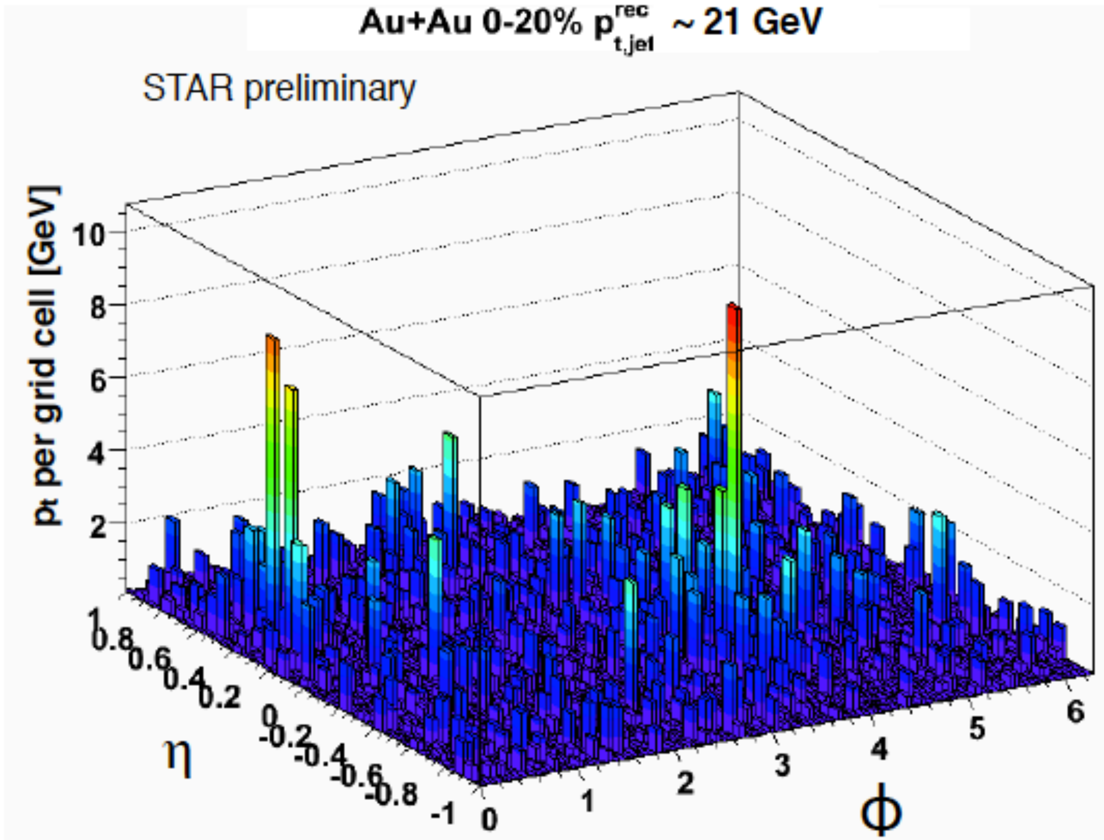
Partons lose energy as they traverse the dense medium

Some jet energy lost to
- Low p_T particles
- Large angle radiation
- Material interactions, decays, etc.

Modified jet fragmentation may result in:
- A different fraction of jet energy reaching the calorimeters
- A different response for non-linear calorimeters

Jet Reconstruction at RHIC

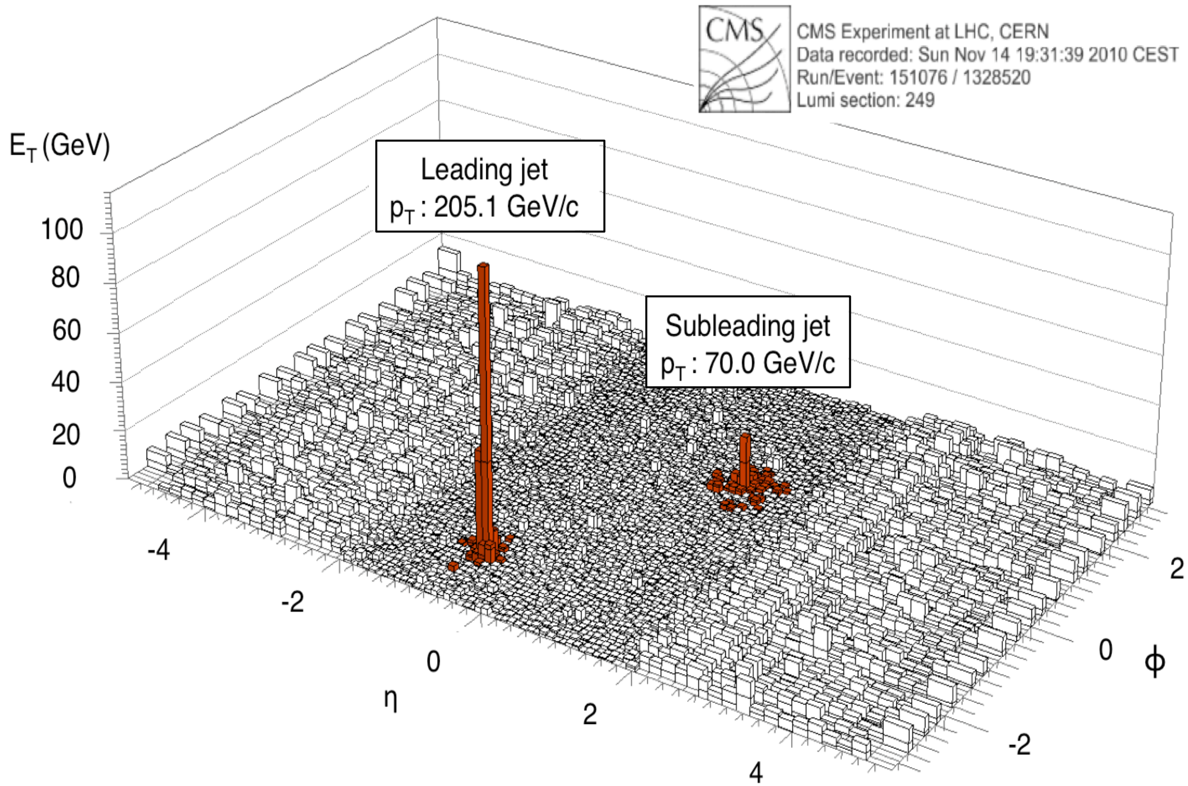
A dijet in a central Au+Au Collision in STAR



At RHIC, difficult to disentangle jets from the soft background

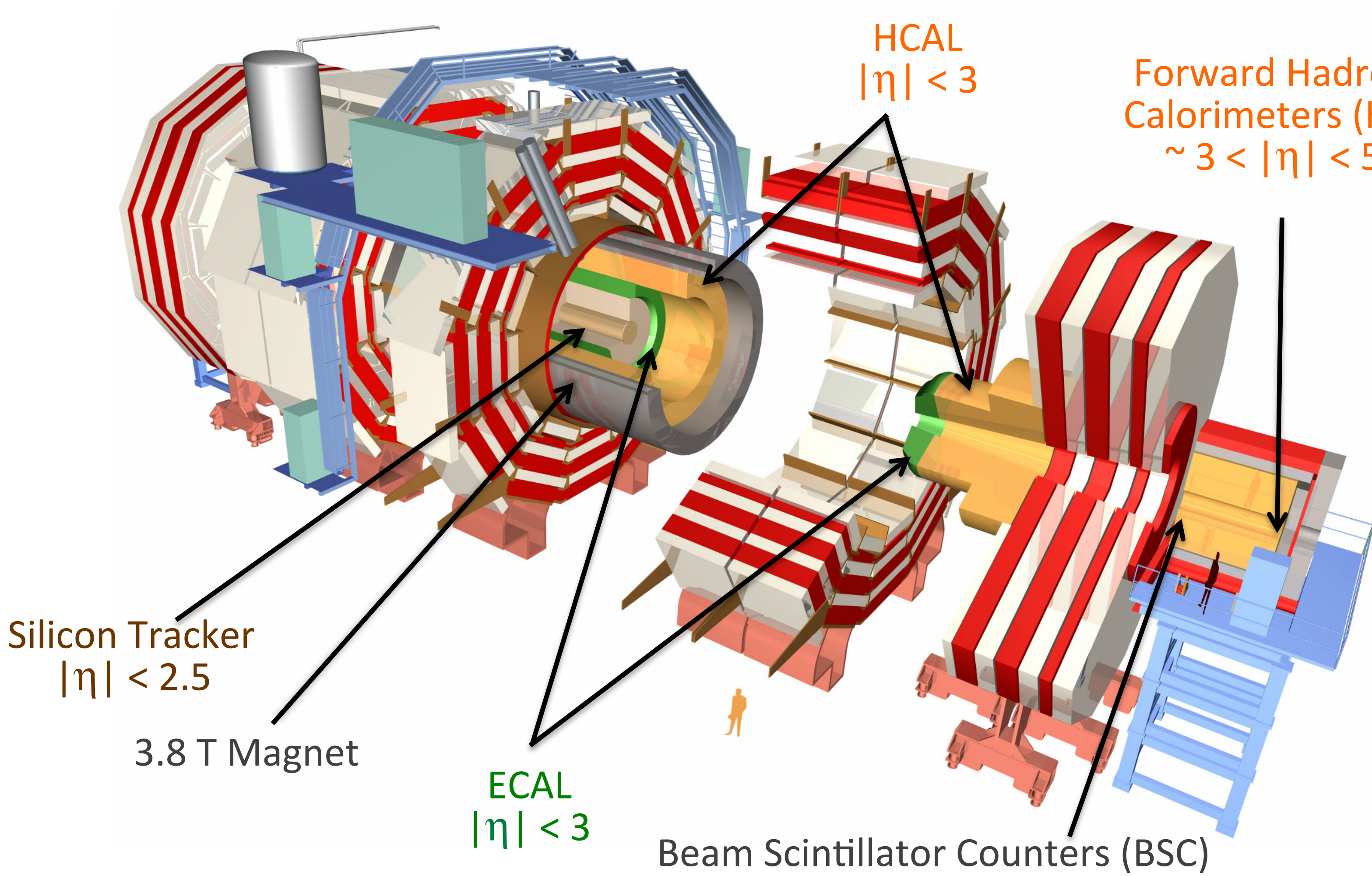
Jets at the LHC

A dijet in a central PbPb collision in CMS



At LHC energies, jets with p_T of order 100 GeV/c cleanly separable from background fluctuations in central PbPb collisions

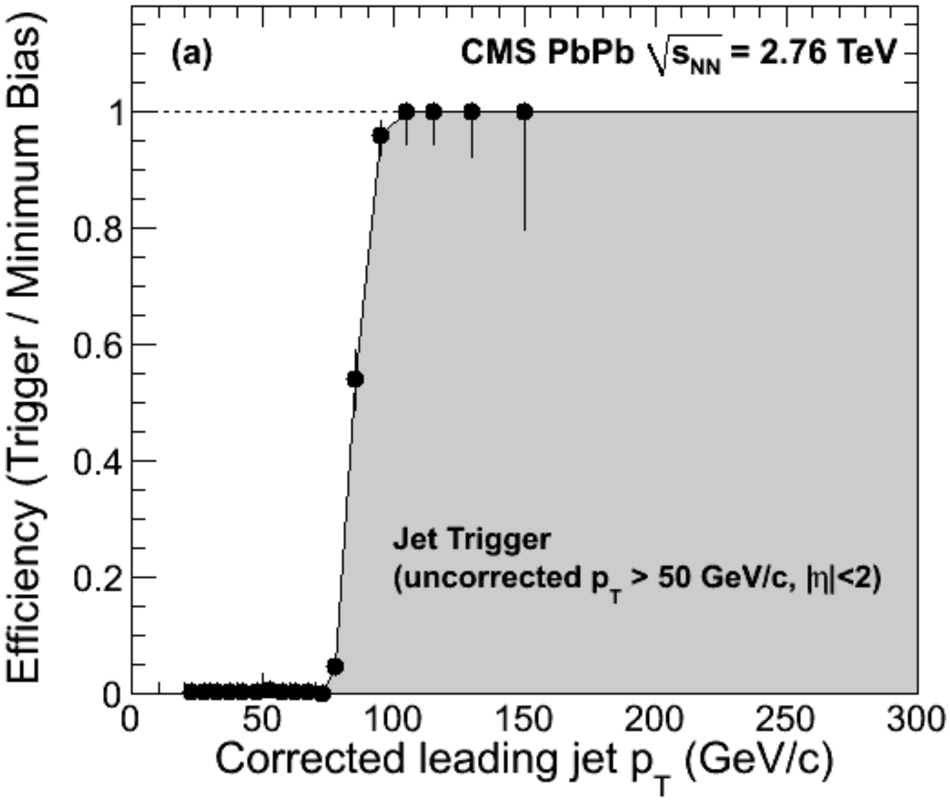
The CMS Detector



Ideal to reconstruct jets of p_T > 100 GeV/c and charged tracks down to < 1 GeV/c
→ Allows to measure jet fragmentation out ξ of 4-5

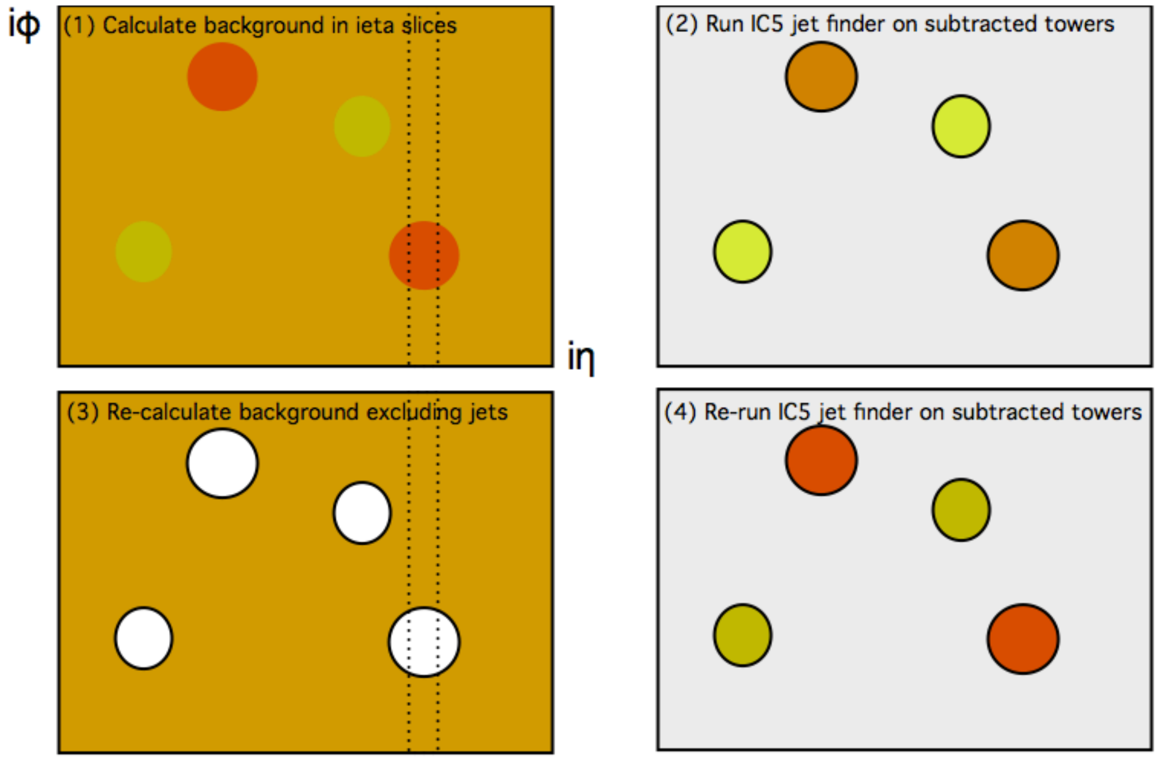
Triggers

- Minimum bias collisions are triggered by a coincidence on either side of the HF or BSC
- Jet are triggered at HLT with a p_T = 50 GeV/c threshold (uncorrected, background subtracted)
- The jet trigger is fully efficient around corrected p_T of 100 GeV/c



Background Subtraction Method

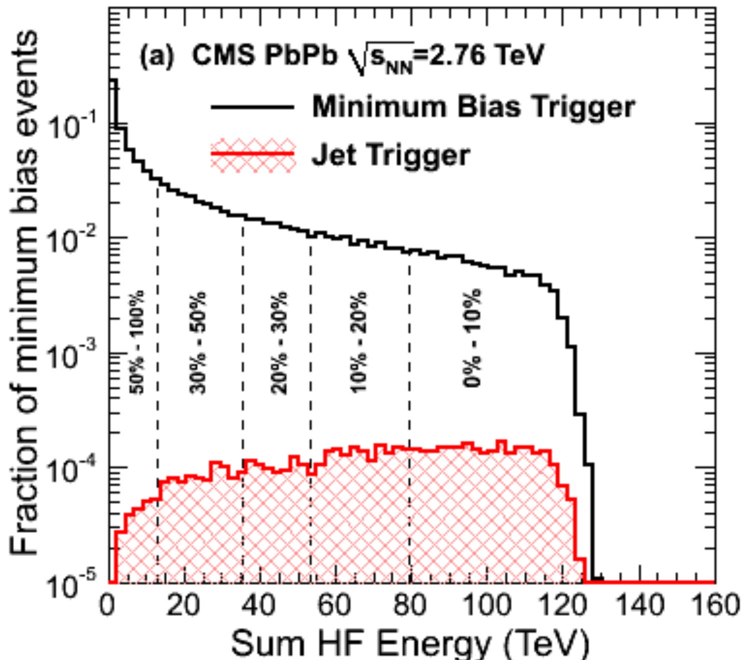
1. Background energy per tower calculated in strips of η.
2. Iterative Cone (R=0.5) algorithm run on subtracted towers
3. Background energy recalculated excluding jets
4. Jet algorithm rerun on background subtracted towers, now excluding jets, to obtain final jets



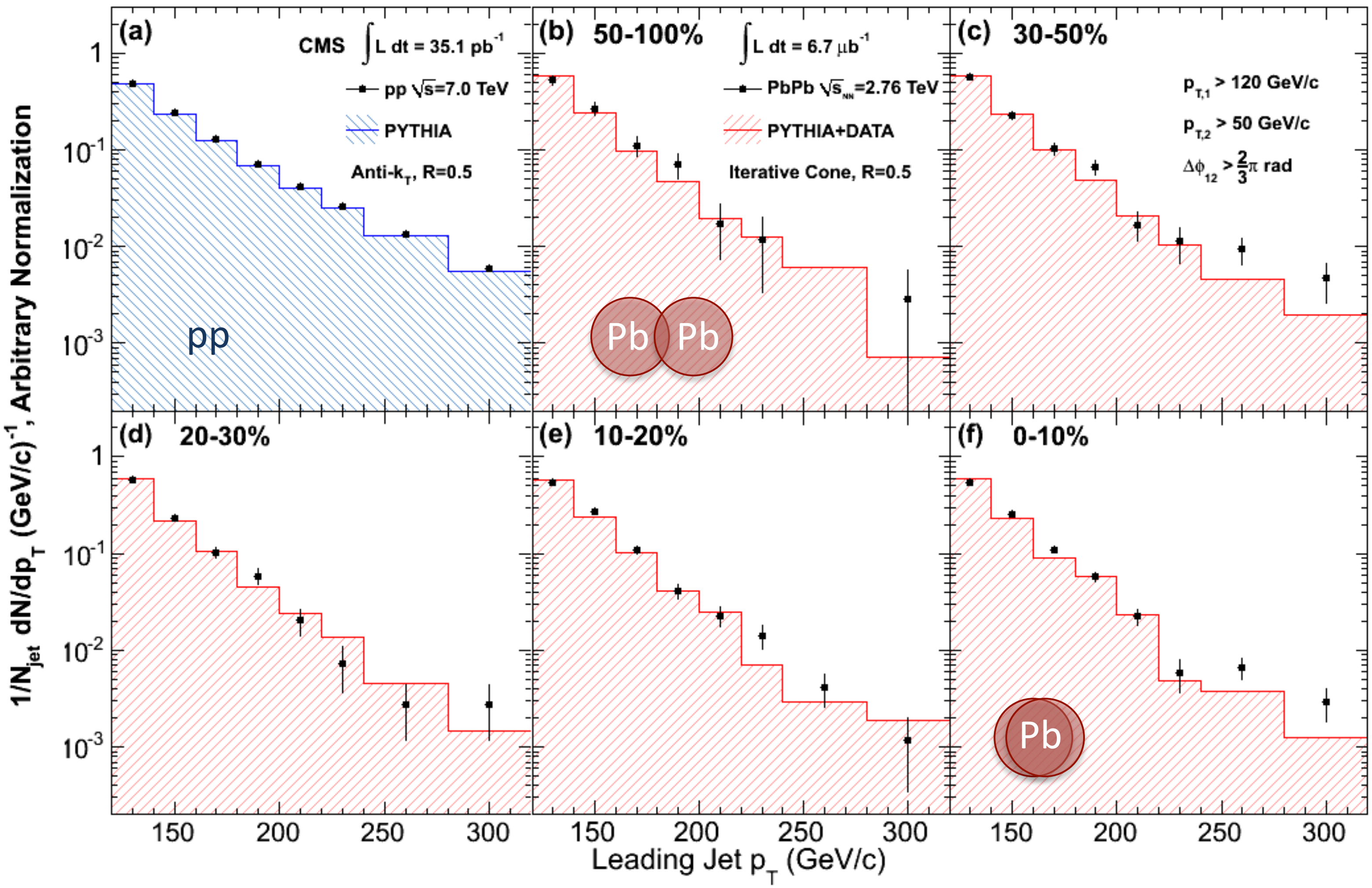
Method: O. Kodolova et al., EPJC (2007) 117.

Analysis Details

- Collision centrality determined from the energy in the forward calorimeters
- Dijet Selection
  - Leading jet: $p_{T,1} > 120$ GeV/c, $|\eta| < 2$
  - Subleading jet: $p_{T,2} > 50$ GeV/c, $|\eta| < 2$
  - Azimuthal Angle: $\Delta\varphi_{12} > 2/3\ \pi$ radians
- Monte Carlo
  - PYTHIA 6.423, tune D6T
  - Adjusted for isospin ratio of Pb(208)
  - Embedded in real data or simulated data using the HYDJET generator

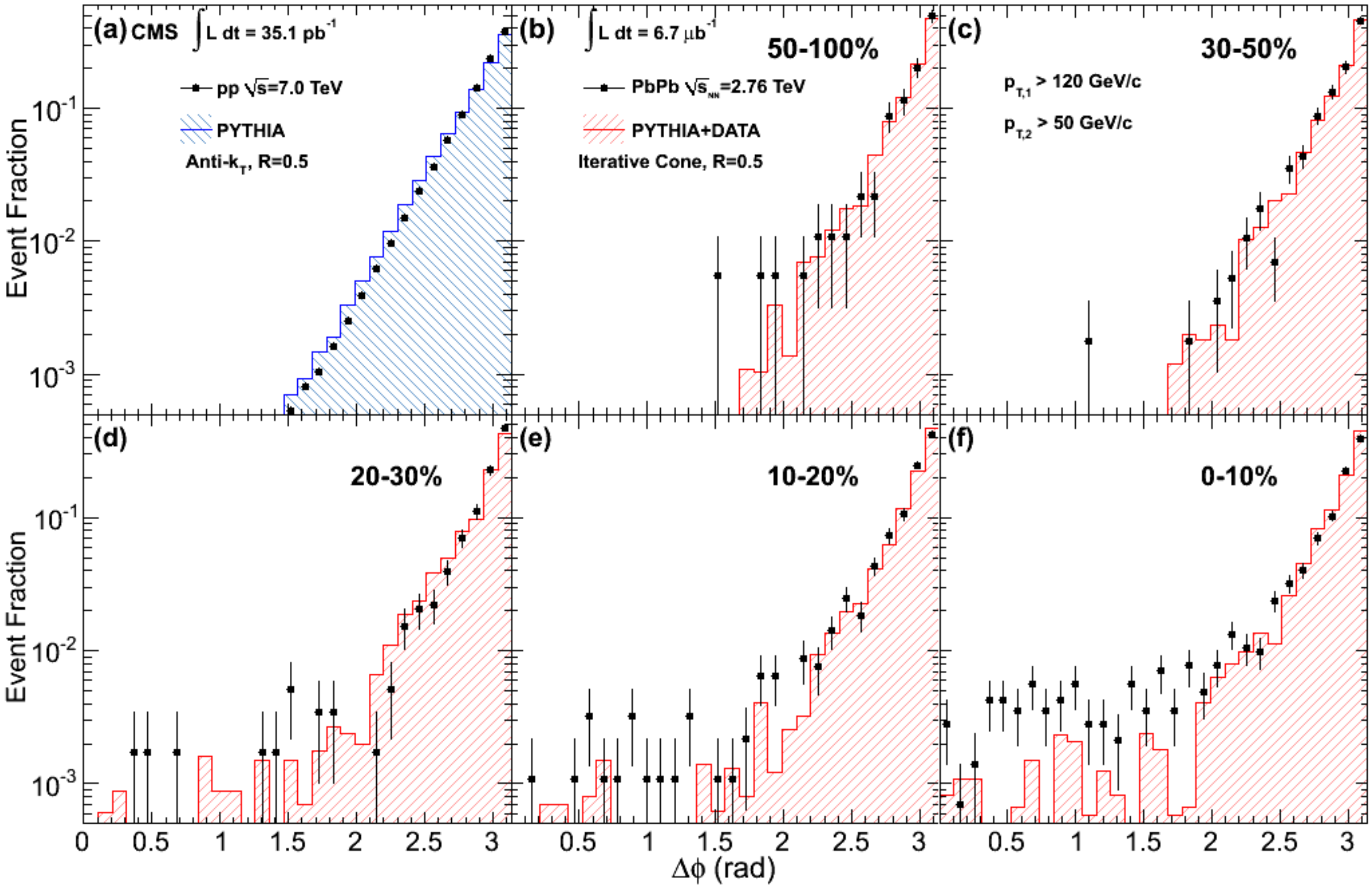


Leading Jet p_T Distributions



No strong modification to shape of leading jet spectrum

Dijet Azimuthal Correlations

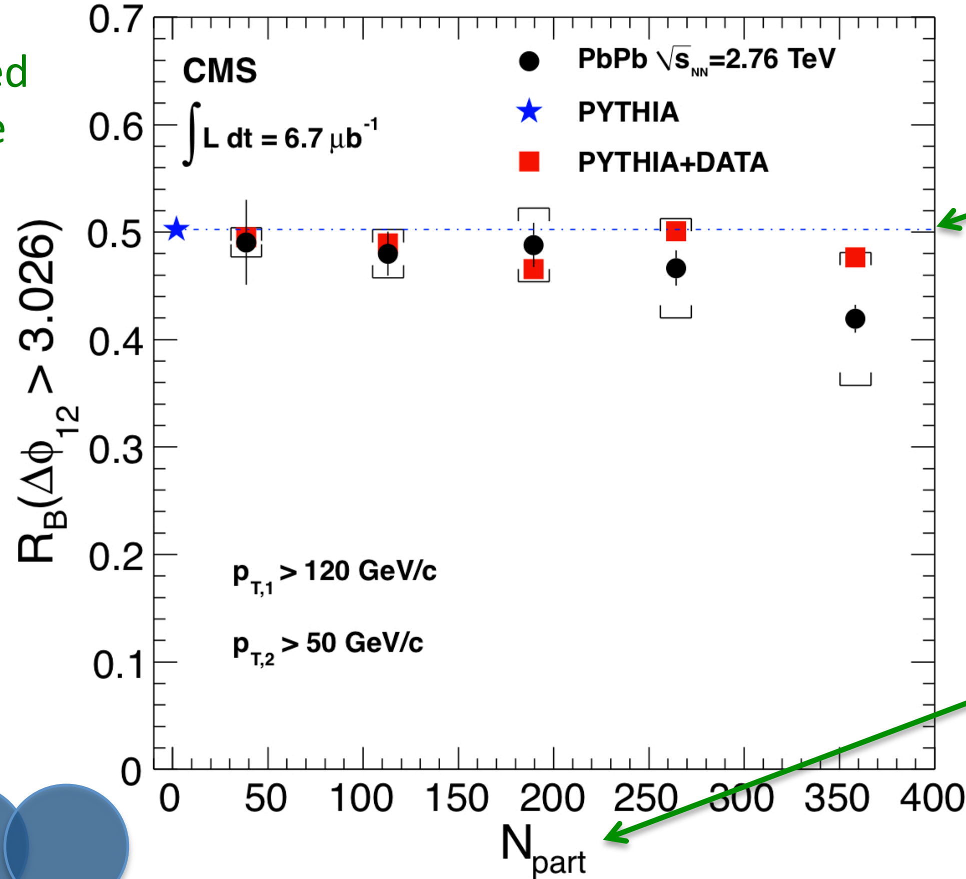


No strong angular deflection of reconstructed jets

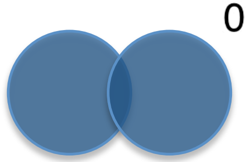
Angular Decorrelation Quantified

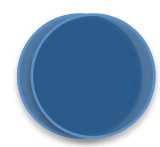
$R_B(\Delta\phi)$ is the fraction of dijets which are balanced in azimuthal angle

The threshold of 3.026 radians is the median value from PYTHIA



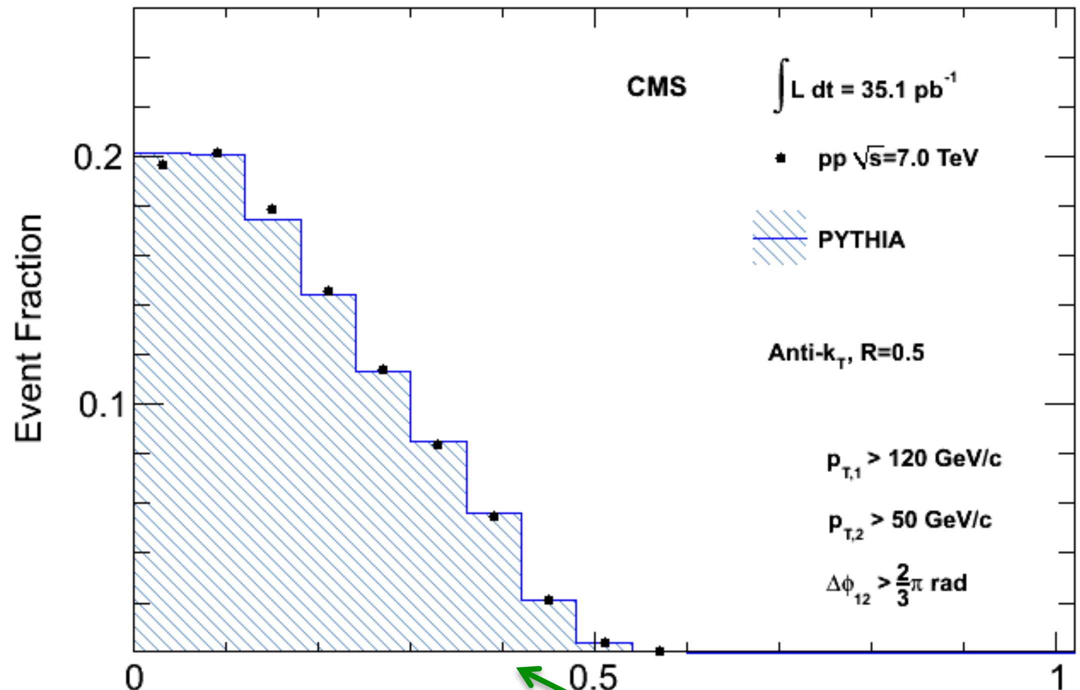
N_{part} is the number of participating nucleons





No angular decorrelation beyond systematic uncertainties

Dijet p_T Asymmetry

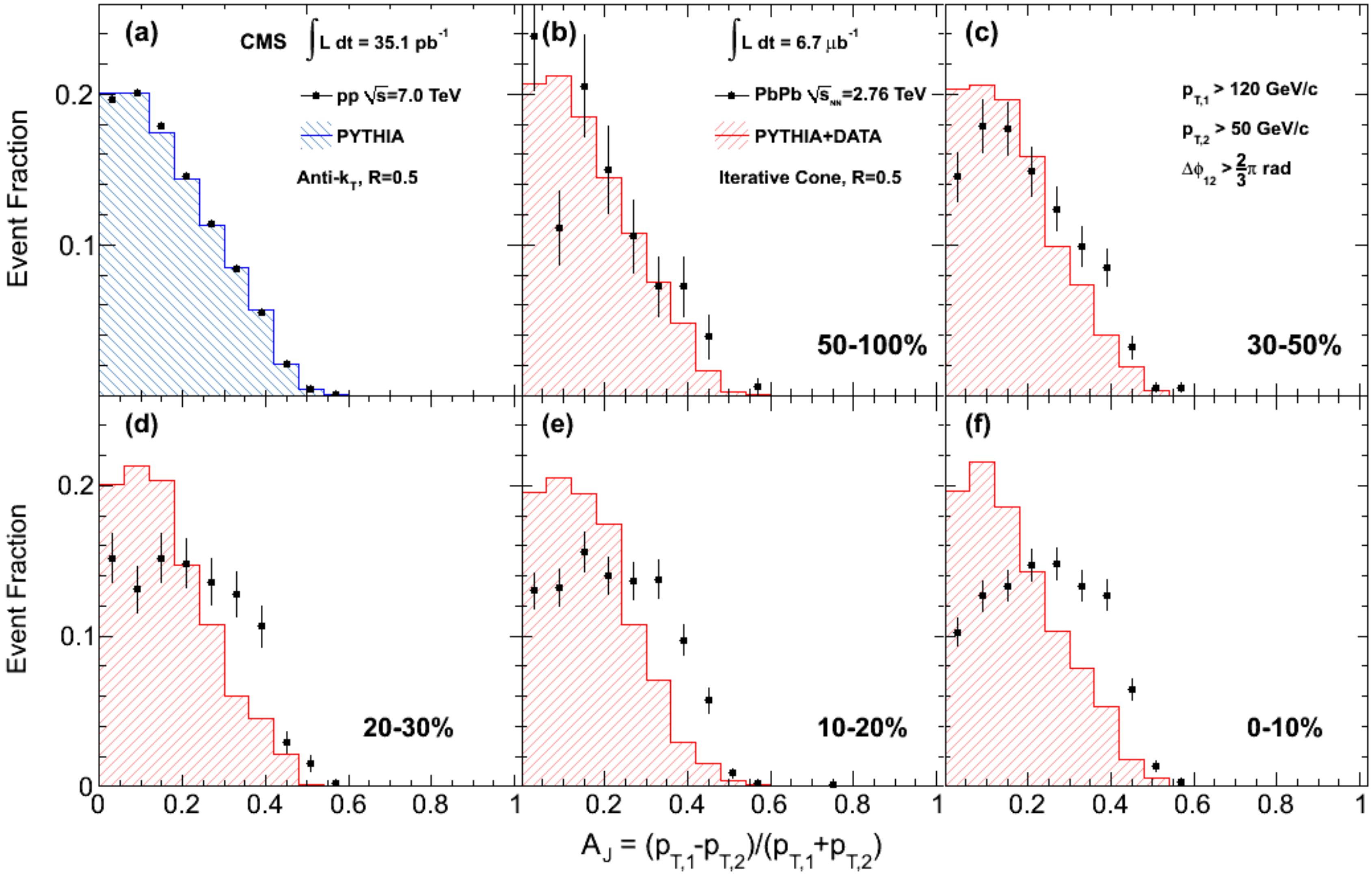


$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet asymmetry quantified by A_J → insensitive to shift in energy scale

Jet p_T cuts place a threshold on A_J
e.g., $p_{T,1}$=120 & $p_{T,2}$=50 GeV/c → A_J < 0.41

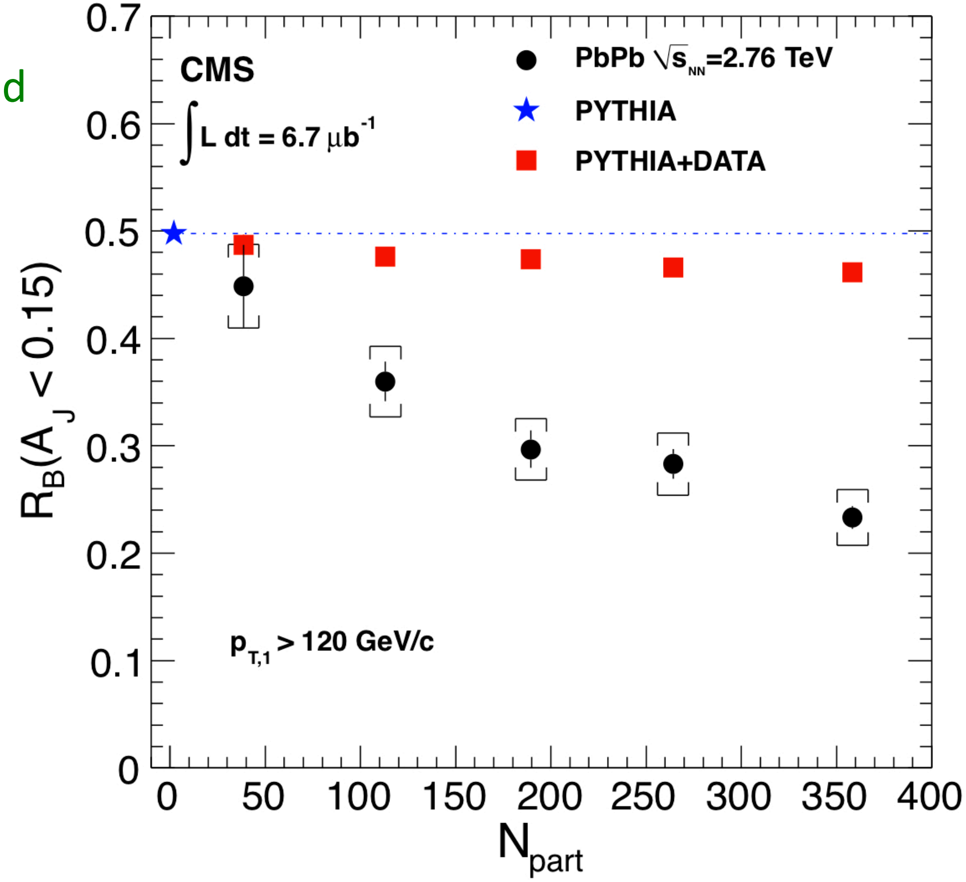
Dijet p_T Asymmetry



Striking enhancement of asymmetry with increasing centrality

Dijet Imbalance Quantified

Here $R_B(A_J)$ is the fraction of dijets which are balanced in momentum



Smooth decrease in the fraction of balanced jets with increasing centrality

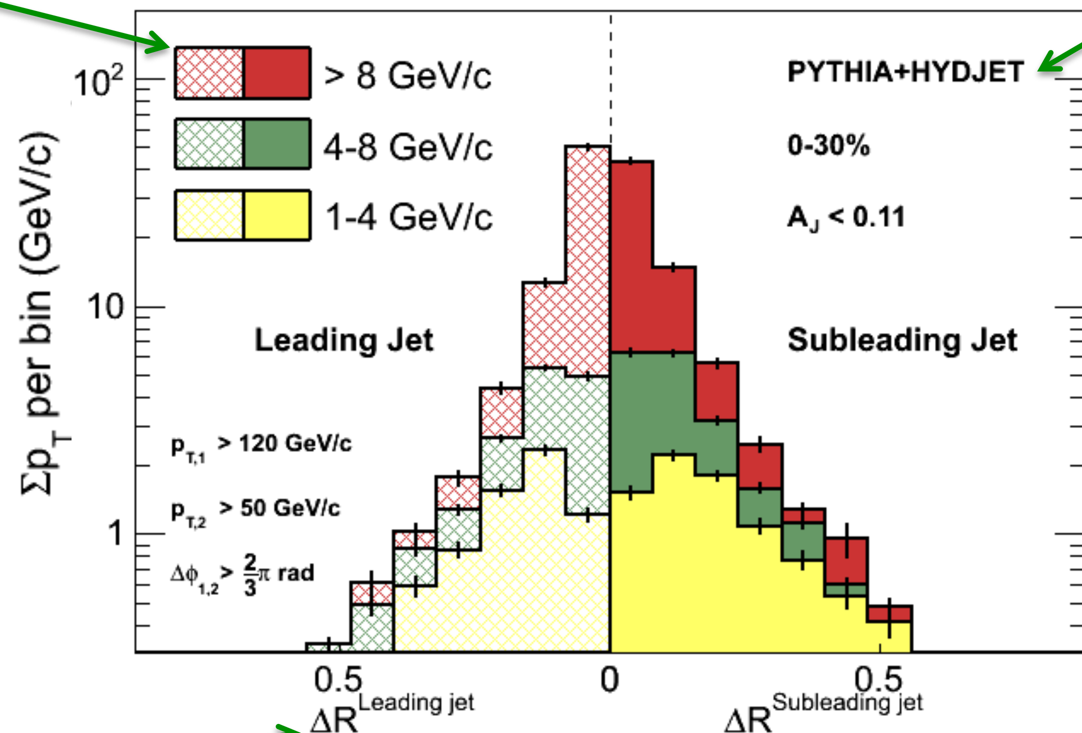
Note: Dijets in which no subleading jet found above threshold are included

Jet-Track Correlations

Main idea: Use charged tracks to trace the fate of the energy lost by subleading jet

Look at the sum p_T of charged tracks in 3 different p_T ranges

Baseline is PYTHIA+HYDJET where generator information is available for charged particles

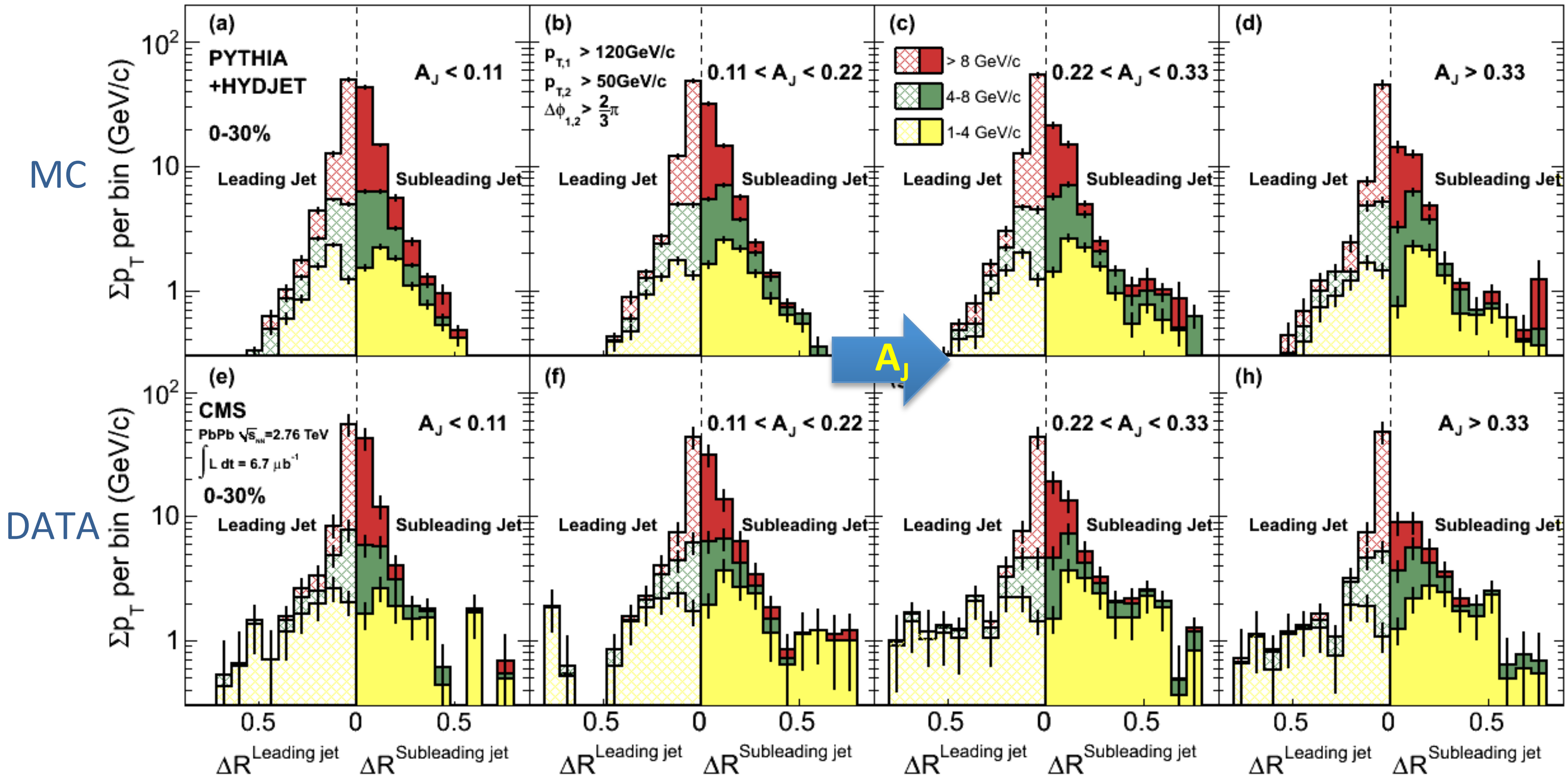


Plot against ΔR from the jet axis for both the leading and subleading jet

Background is subtracted using a cone at same ϕ, but reflected in η ($\eta \rightarrow -\eta$)

Asymmetry Dependence of Fragmentation

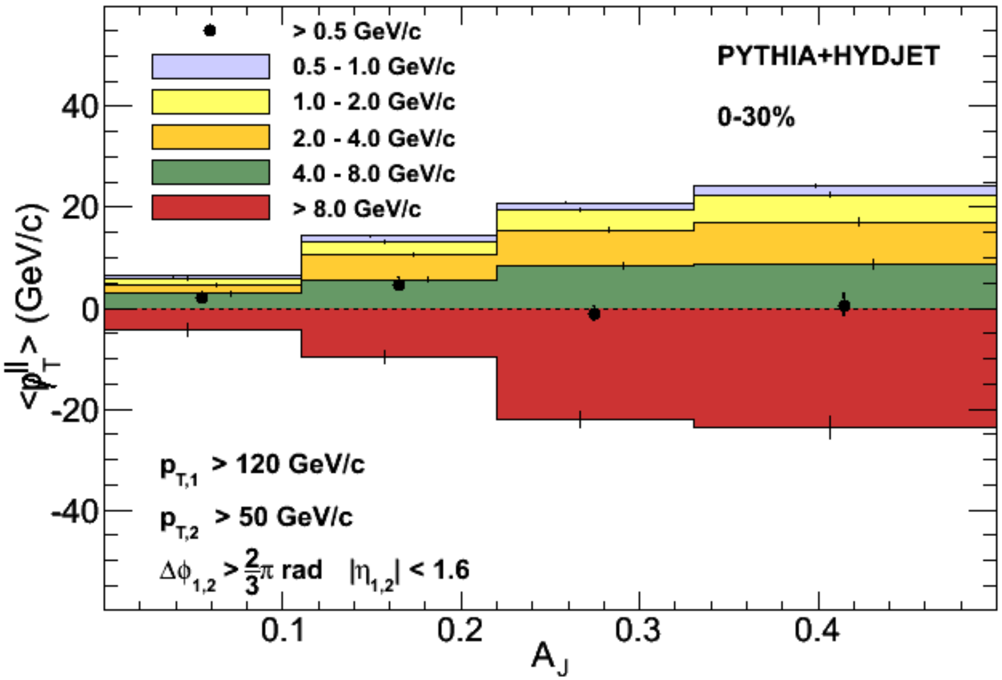
- Both data and MC show that dijet asymmetry is also apparent in charged tracks
- In MC, rare asymmetric dijets are due to the presence of a third jet
- Relative abundance of tracks in the 3 ranges is largely unchanged with asymmetry



- In data the fraction of energy carried by low p_T tracks increases with asymmetry
- An enhancement of low p_T tracks at large angles is observed in asymmetric dijets

Missing p_T

To explore momentum balance to low p_T over all angles, calculate the "missing p_T"

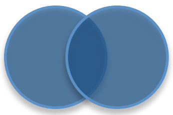


Sum the track transverse momenta projected onto the leading jet axis:

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\mathrm{T,track}} \cos\left(\phi_{\mathrm{track}} - \phi_{\mathrm{leading\ jet}}\right)$$

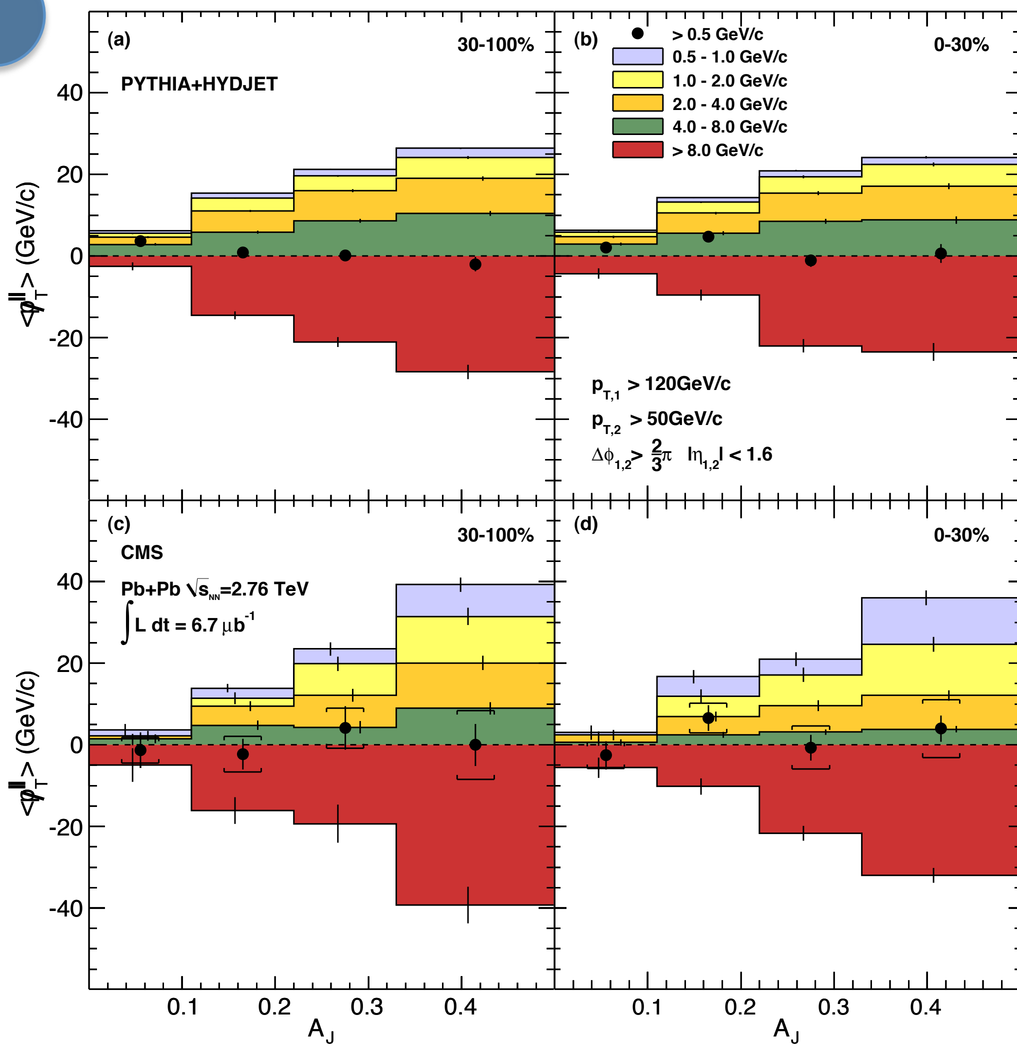
Defined such that tracks on the away side give a positive contribution

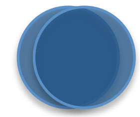
Missing p_T: Data vs. MC



MC

DATA



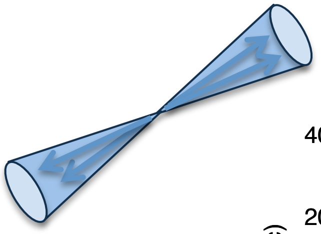


In MC, events are balanced, p_T composition is independent of centrality

For p_T > 500 MeV, p_T balance recovered!

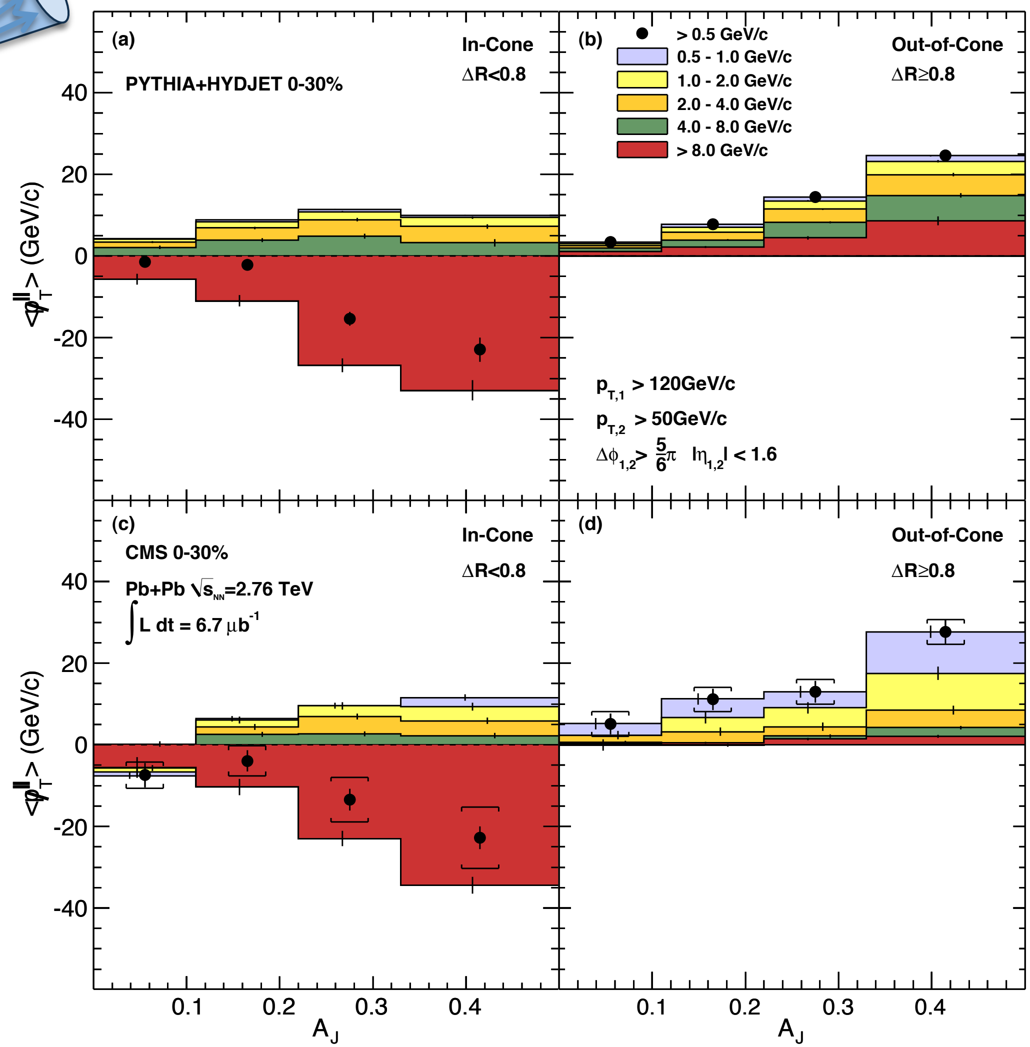
In data, for asymmetric events, leading jet is balanced by low p_T tracks, particularly in central events

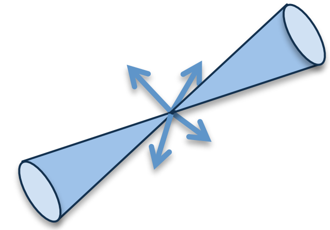
Missing p_T: In vs. Out-of-Cone



MC

DATA





Asymmetric events in MC show significant energy beyond R=0.8, carried by high p_T tracks → 3 jet events

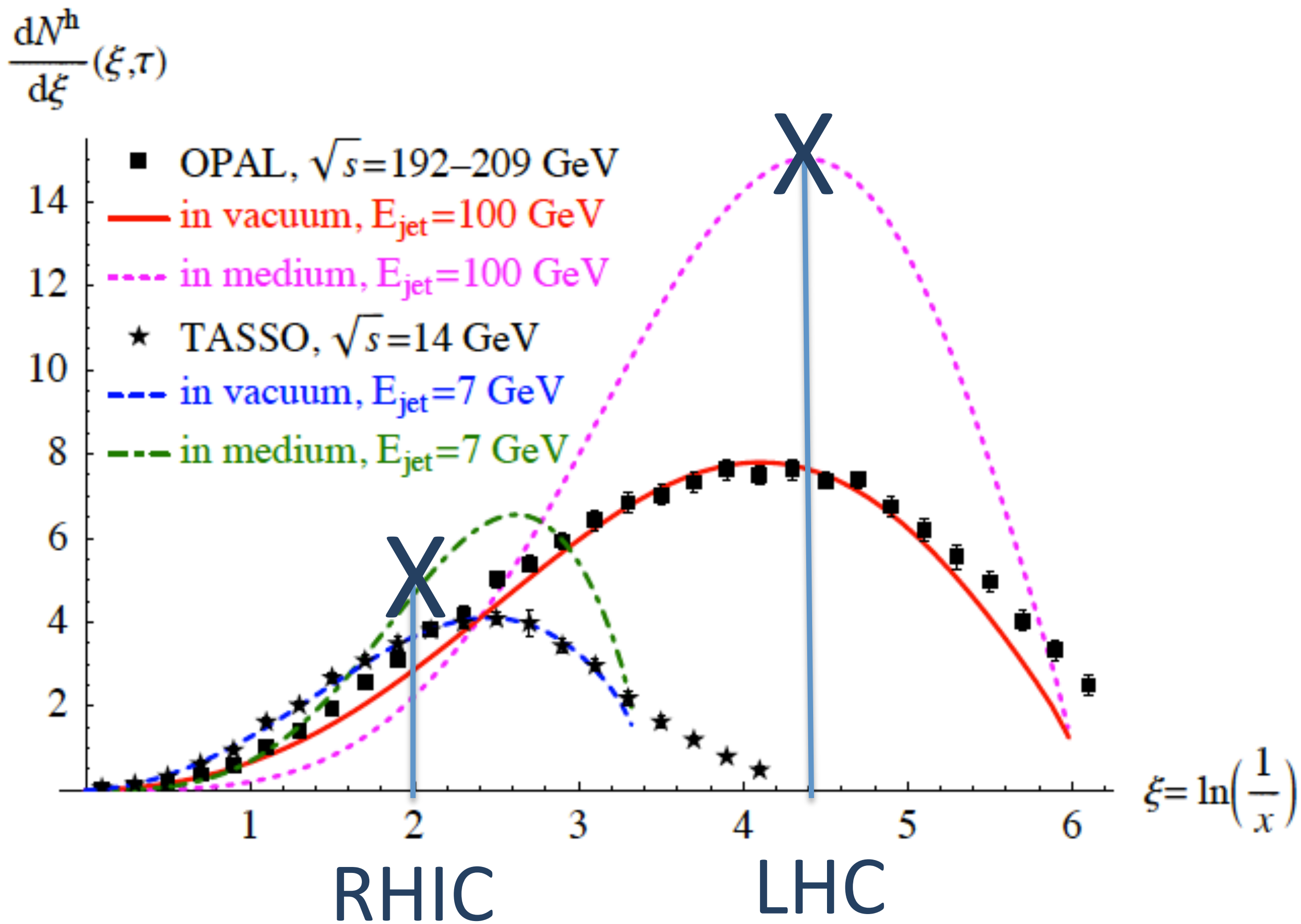
Little modification of jet fragmentation in-cone

Majority of p_T balance recovered by low p_T tracks outside of R=0.8 cone

Conclusions

- Jet quenching well established at RHIC, but details elusive
- Large jet quenching in PbPb collisions leads to new observations
  - No large azimuthal decorrelation
  - Large momentum imbalance of jets
- Jet-track correlations demonstrate that
  - Energy is transferred to very low z particles
  - This energy is deposited outside the typical jet radius
- Data places constraints on the nature of parton energy loss and should challenge conventional models

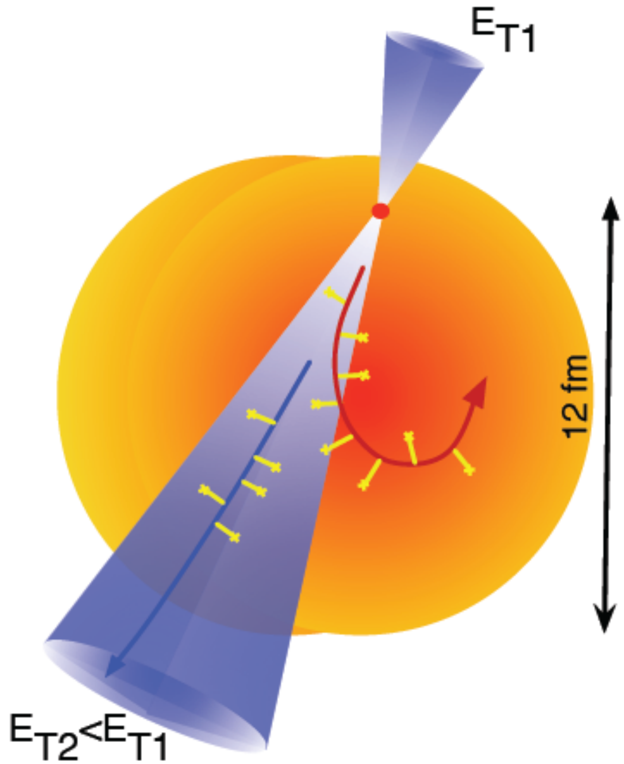
Where Are We?



We've gained insight into where the radiated energy *doesn't* go
Localizing it in phase space is a work in progress

New Theoretical Ideas

Casalderrey-Solana, Milhano, Wiedemann
arXiv:1012.0745

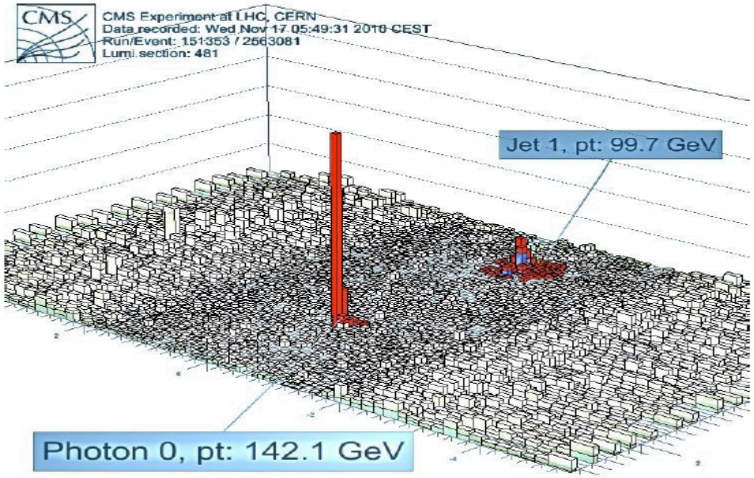


Medium acts as "frequency collimator" effectively decoupling the soft modes of the jet

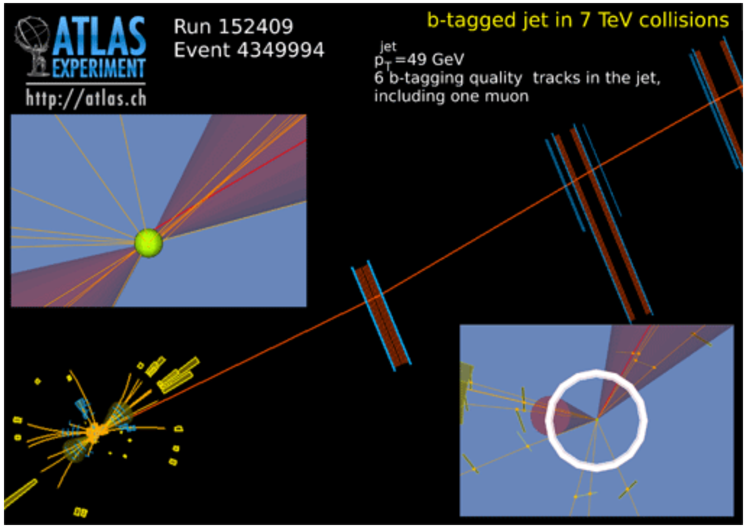
Identified Jets

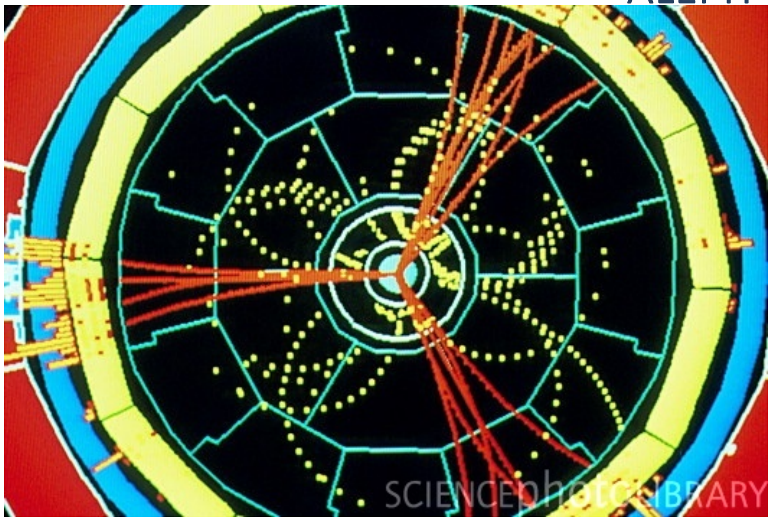
Identified jets probe the flavor dependence of Eloss

- γ+jet → quark jets
- 3 jet events → gluon jets
- μ-tagged, displaced vertex → b-quark jets



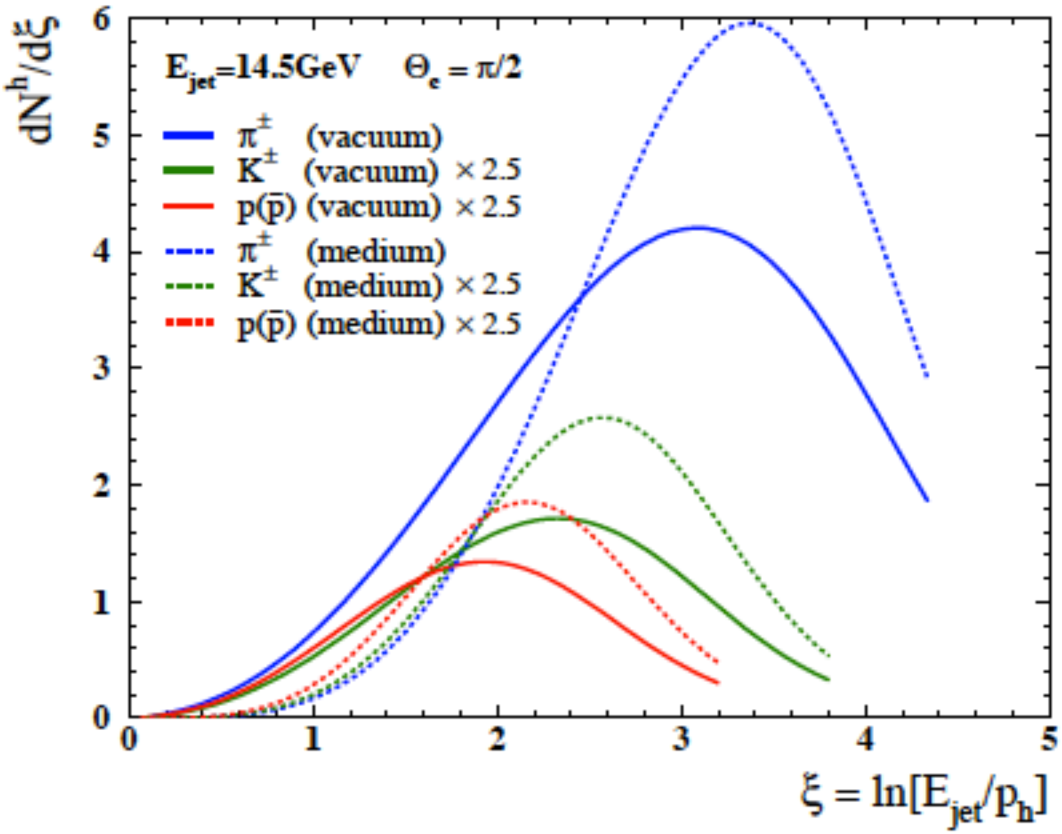
ALEPH





Jet Hadro-Chemistry

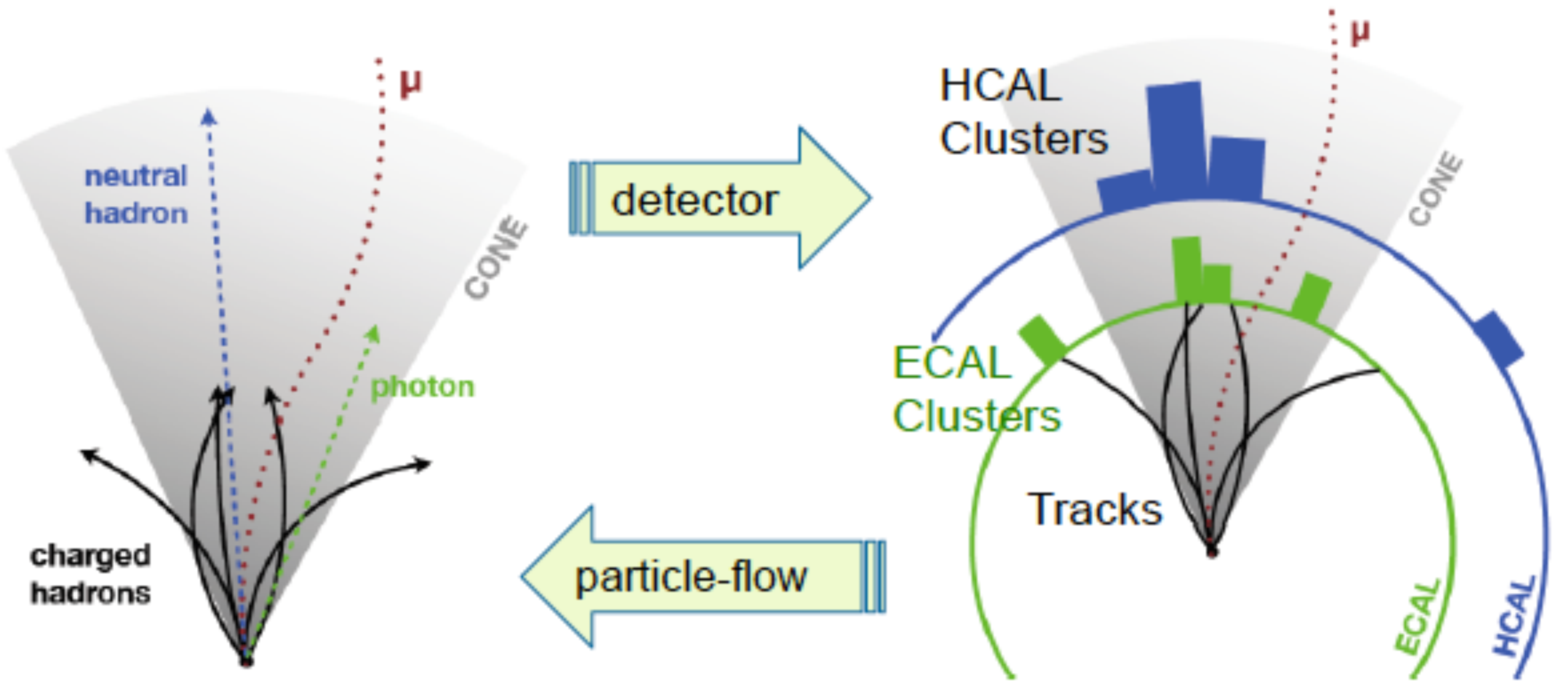
Medium expected to change the hadro-chemistry of jet framgentation



PID'd fragmentation functions can be measured with ALICE

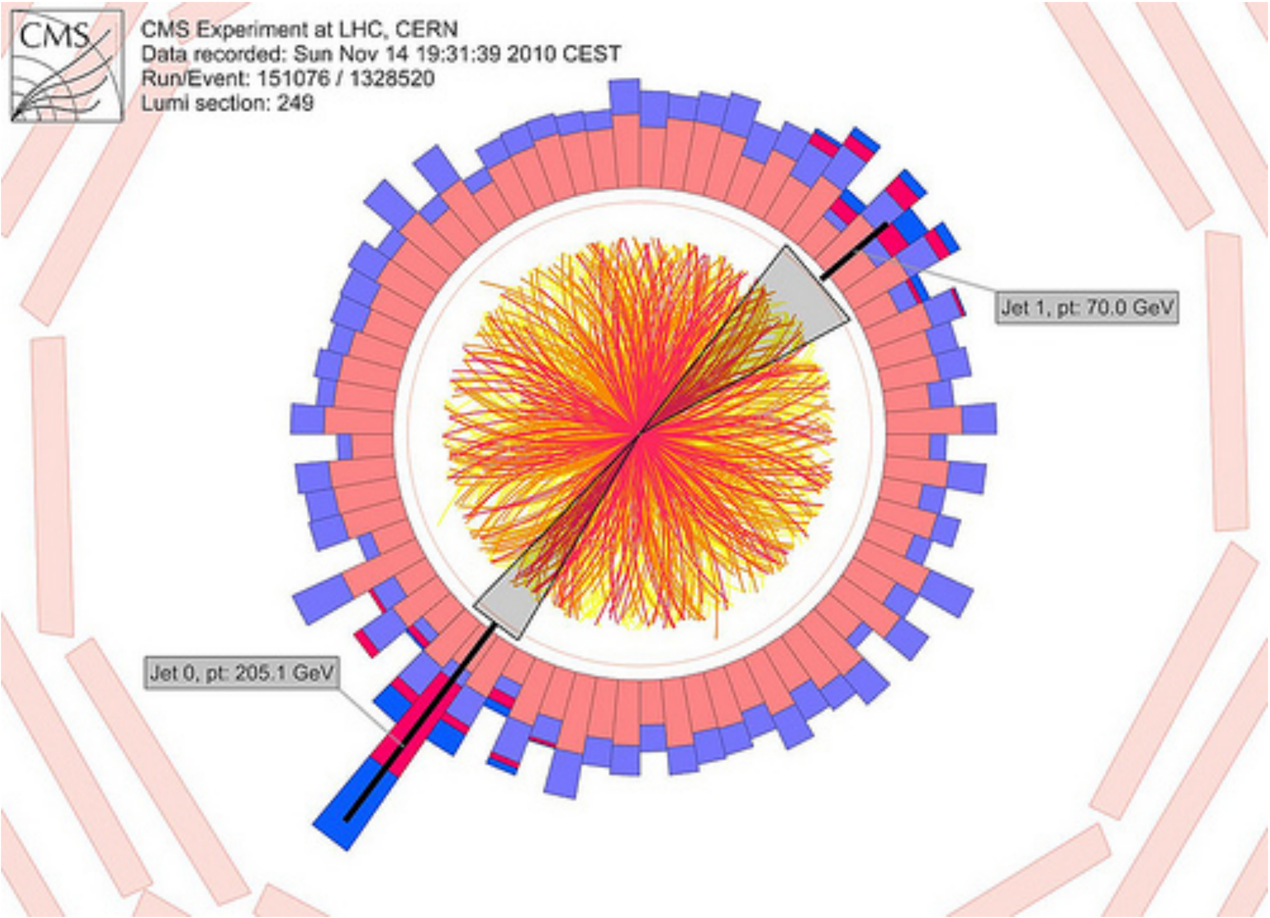
Particle Flow in Heavy-Ions

Currently a work in progress



Particle flow jet reconstruction clusters individual particles

→ Use of charged particle tracks reduces sensitivity of jet energy scale to quenching effects



Tracking in the high multipicity environment is challenging!