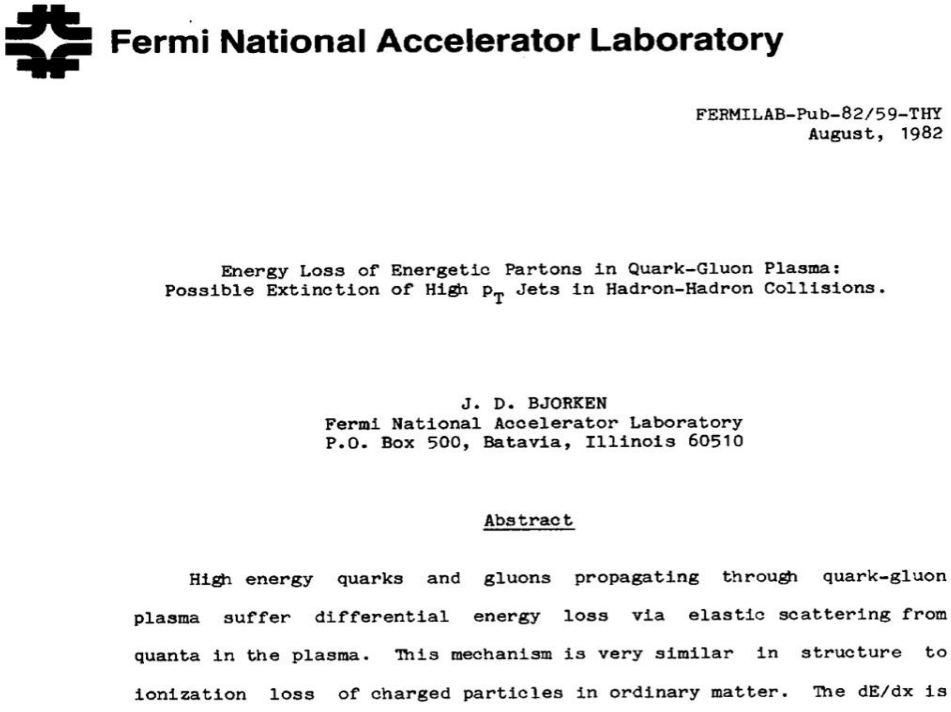
Experimental Overview of Jets

Christof Roland

Massachusetts Institute of Technology

What we are after



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.

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Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is

J.D. Bjorken:

- Energy loss of partons in a Quark Gluon Plasma
  - Study the QGP properties by probing it with fast partons

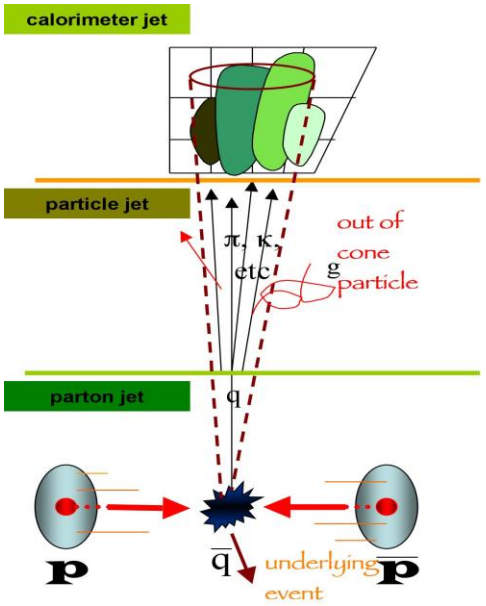
Key ToDo list

1. Learn how to reconstruct Jets in HI environment

2. Develop theories of the parton energy loss and Perform measurements to distinguish between models and constrain the parameters

Jet Reconstruction in pp

- pp prescription to find jets:
  - Take all particles in the event
  - Use a defined prescription to cluster them
  - Keep on clustering until all particles are used up
  - Apply same algorithm in theory and data

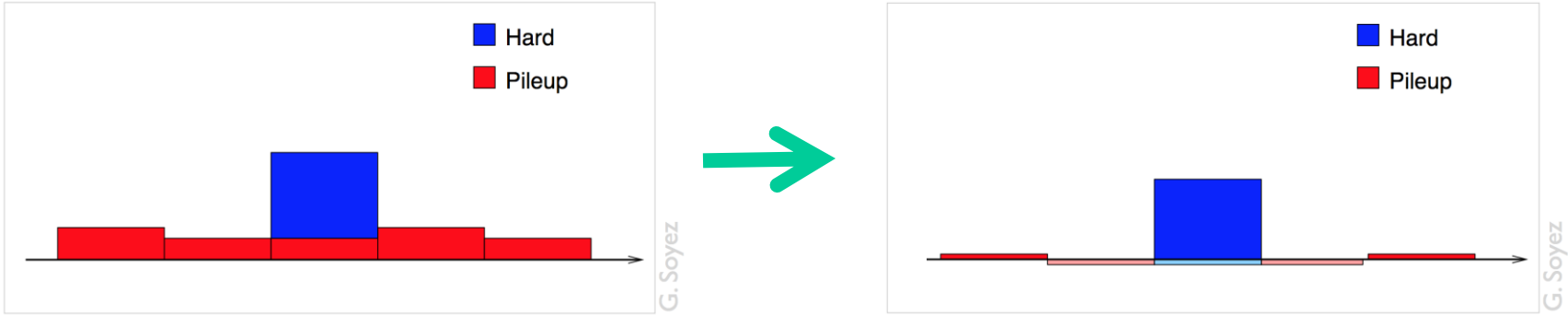


- Current industry standard for clustering:
  - FastJet anti kT algorithm
  - May change with time…

- Jet analysis in pp
  - Take list of all jets
  - Depending on the decay channel one is looking at apply assumptions on the parton flavor and apply jet energy correction to derive parton energies

- Corollary:
  - Jet finding efficiency in pp = 1 by definition
  - Concept of fake jets doesn't exist
  - Calibration point is partons!

Jet Reconstruction in HI



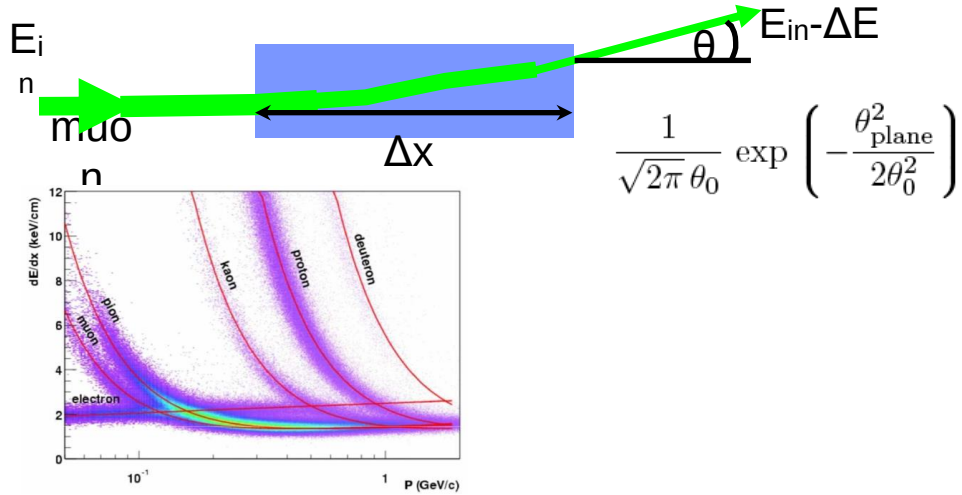
- Find jets in a very high multiplicity underlying event
  - Apply background subtraction of some kind or unfold results for UE fluctuations
    - Remove centrality dependence from jet reconstruction
    - Take azimuthal anisotropy into account
  - Main differences to pp prescription:
    - High background + subtraction procedure
      - No way to distinguish particles from hard scattering and underlying event
      - Finite reconstruction efficiency
      - Fake jets from UE fluctuations
      - Multiple hard scatterings in one event
    - Want to measure parton energy loss
      - Energy relation between initial parton and final state jet is explicitly broken
      - Calibration point is final state particle level!

Key ToDo list

1. Learn how to reconstruct jets in a HI environment
2. Develop theories of the parton energy loss and perform measurements to distinguish between models and constrain the parameters

=> This was done before…

- QED Energy loss Problem

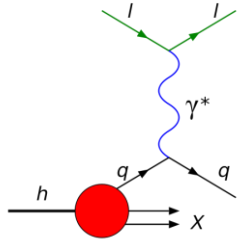


$$\frac{1}{\sqrt{2\pi}\,\theta_0}\exp\left(-\frac{\theta^2_{\text{plane}}}{2\theta_0^2}\right)$$

$$-\left\langle\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

Bethe equation

- DIS like problem

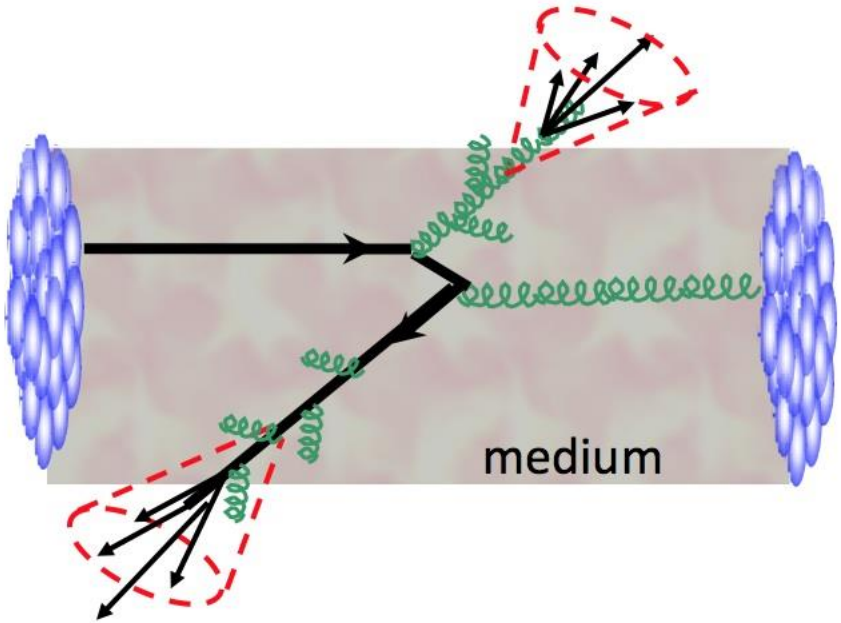


  - Shine a parton beam off the QGP and probe the shortest length scales
    - QGP at natural length scales behaves like a strongly coupled liquid
    - At short enough length scales we know it is composed of quarks and gluons
  - Think of Rutherford…

Ingredients…

2. Is the jet structure modified?

1. What is the initial state?



3. Where does the lost energy go?

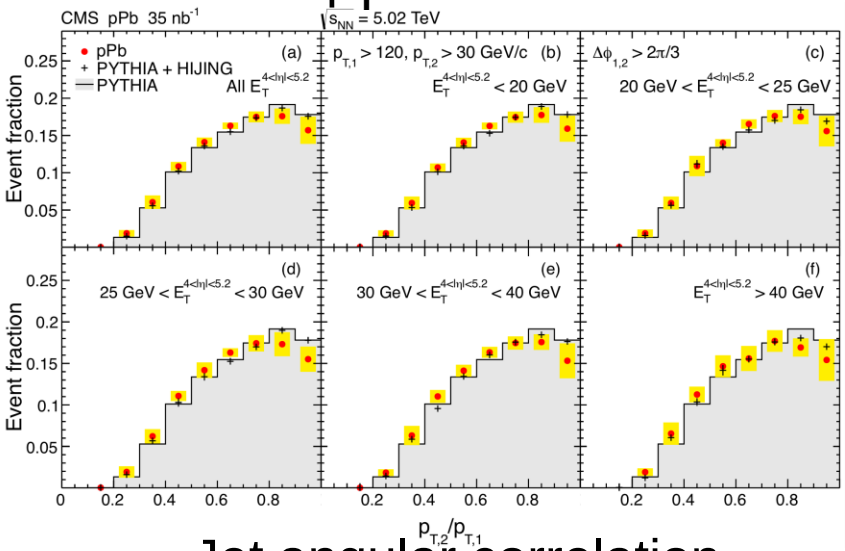
The initial state

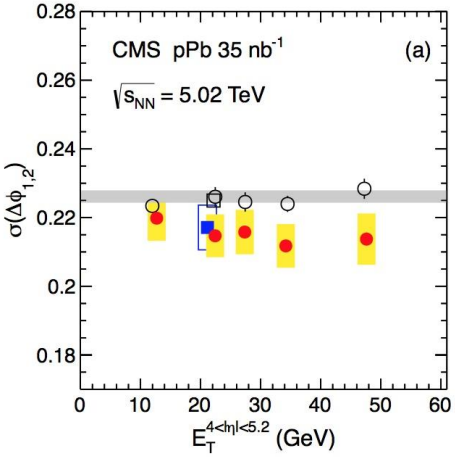
- Check by eliminating the final state
  - Look at pPb collisions
- Scattering a proton off a Pb ion should reveal modifications to the nuclear PDFs
  - Is there a change in the number of scattering centers?
  - Defines the yield of jets in nuclear collisions
- The system produced should be too small to induce significant final state effects
  - Is there an observable jet quenching effect?

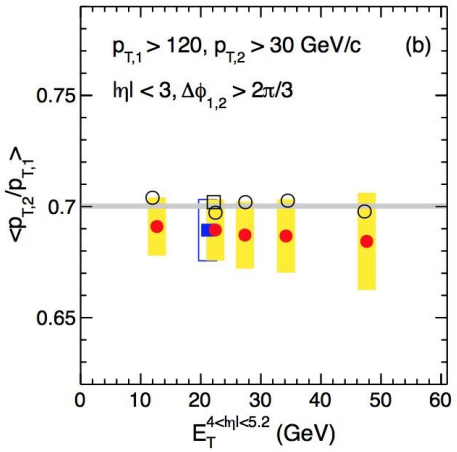
Jet Quenching in pPb?

Jet p_T balance

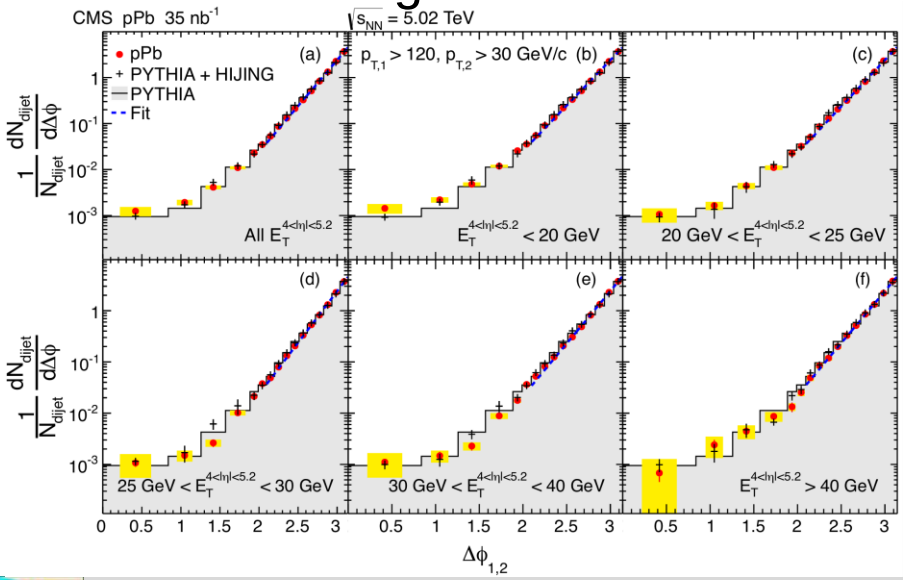
EPJC74 (2014) 2951





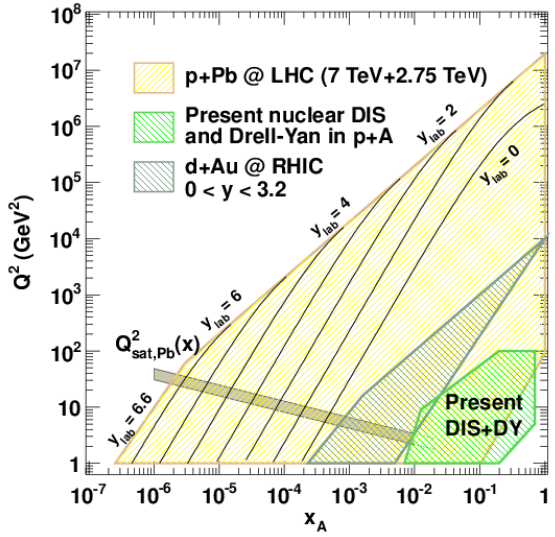


Jet angular correlation



No final-state effects observed in pPb!

nPDF effects



Fix dijet kinematics (Q2)

CMS pPb 35 nb^{-1}

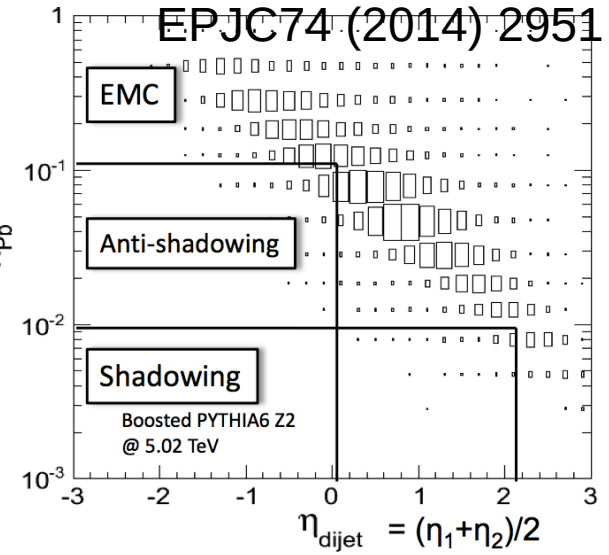
$\sqrt{s_{NN}}$ = 5.02 TeV

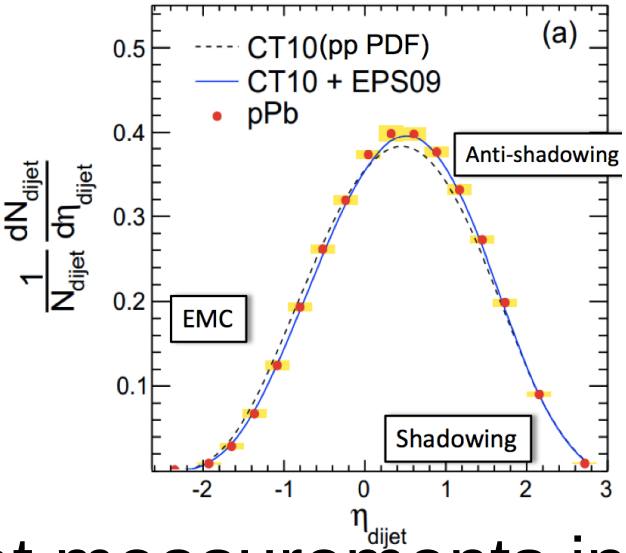
$p_{T,1}$ > 120 GeV/c

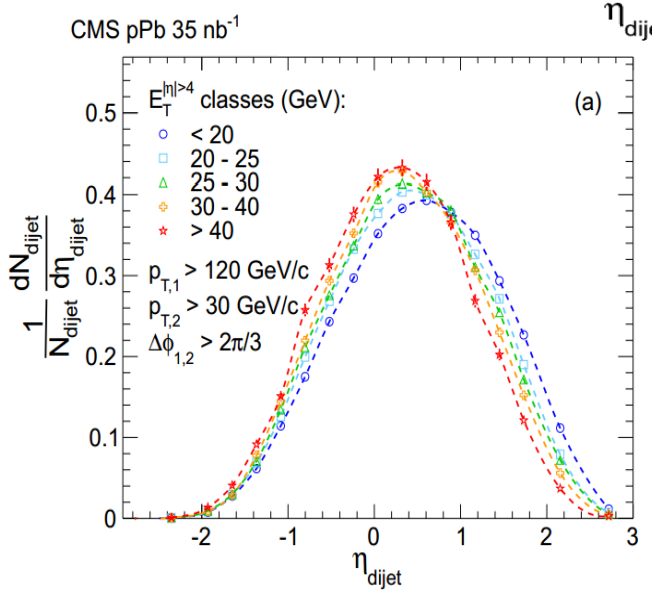
$p_{T,2}$ > 30 GeV/c

$\Delta\phi_{1,2}$ > 2π/3

All $E_T^{|\eta|>4}$



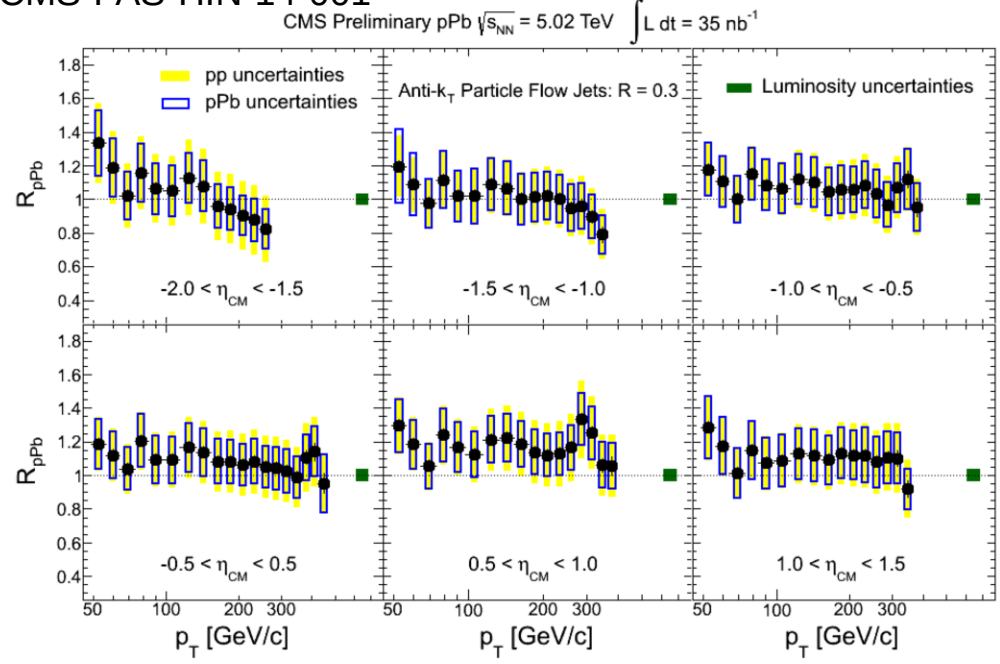


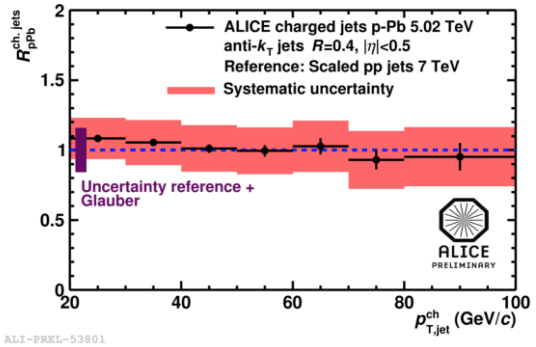


Dijet measurements in pPb are sensitive to nPDFs

(Charged) jet R_{pPb}

CMS-PAS-HIN-14-001





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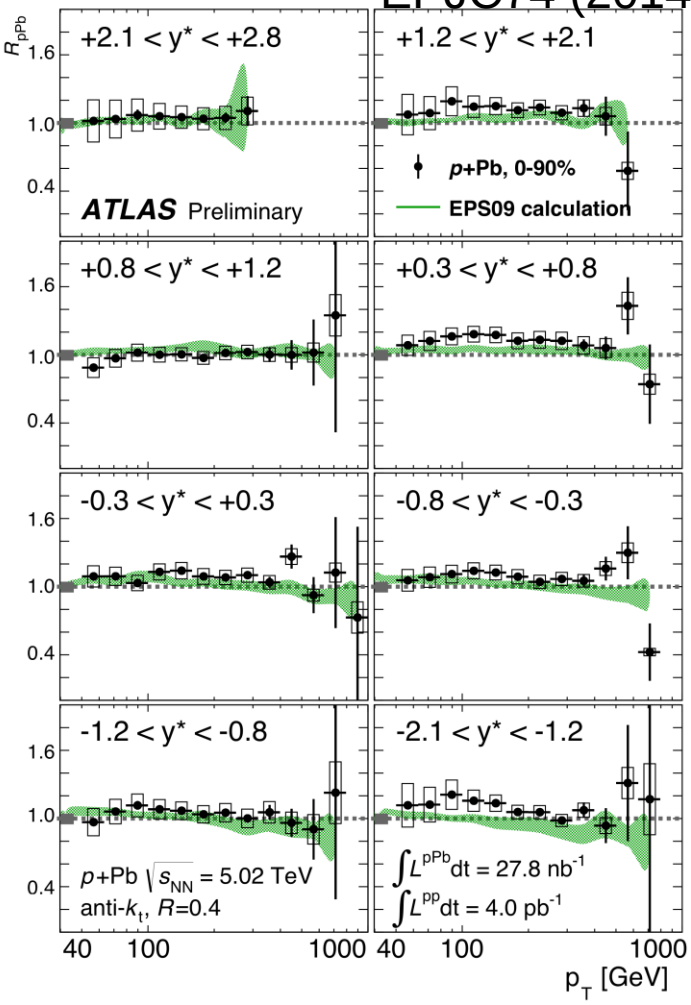
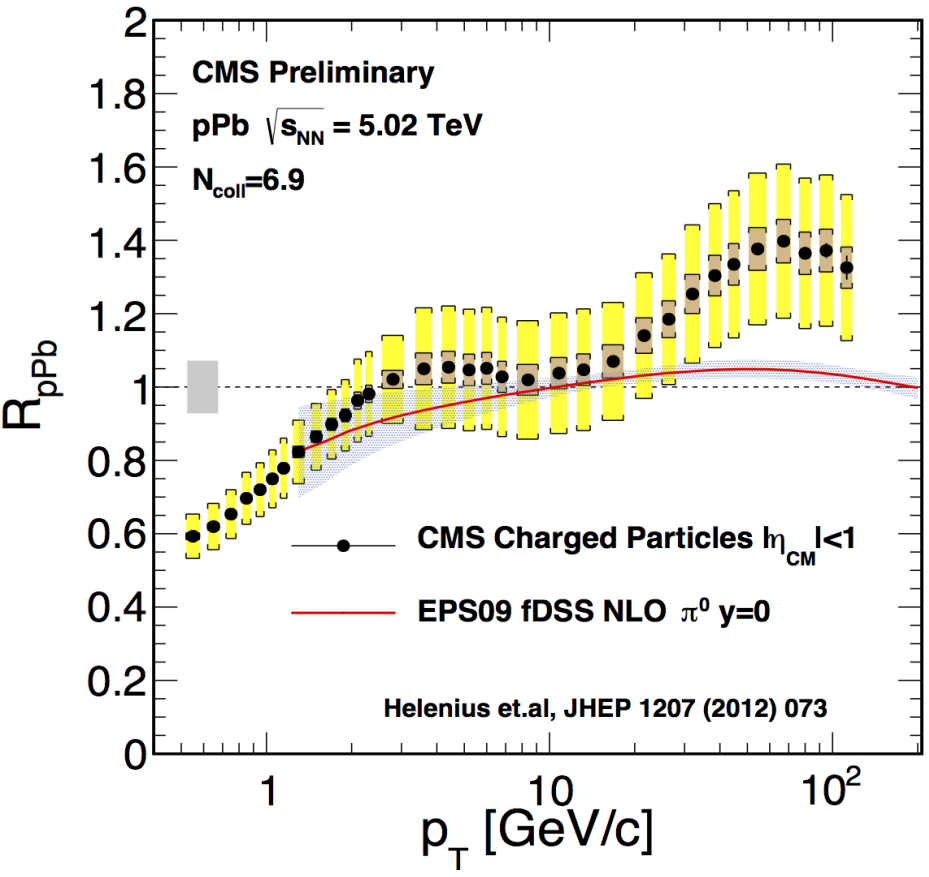
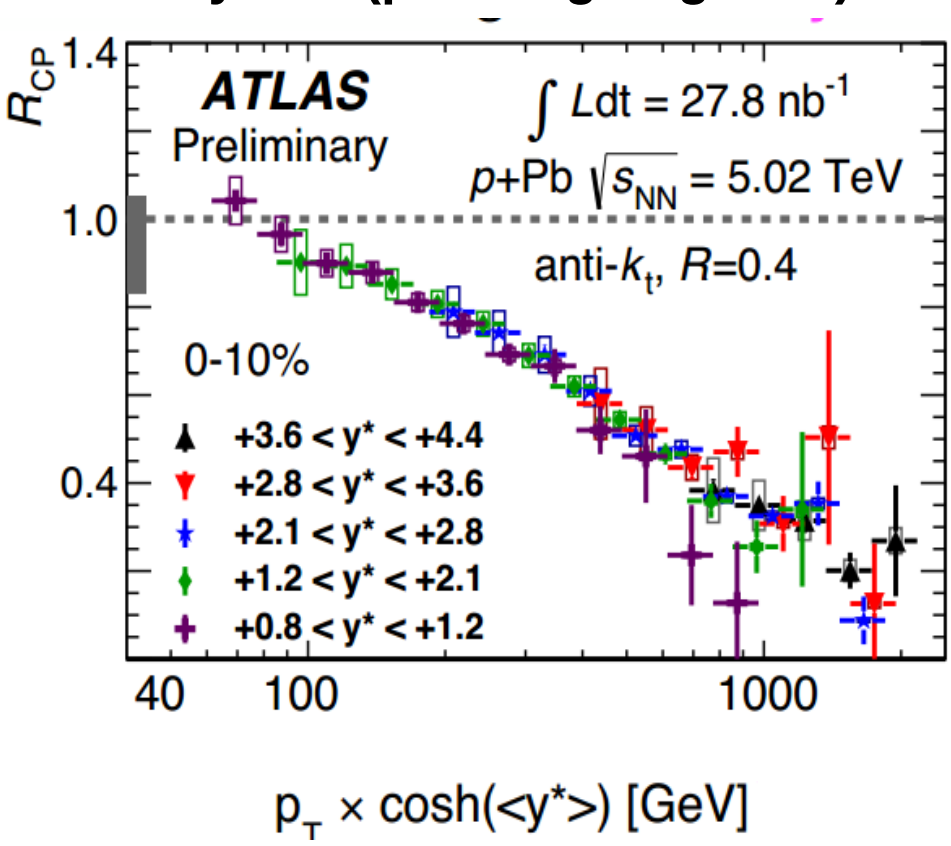


Jet R_{pPb} close to or slightly above one

But then again…





CMS charged particle R_{pPb} can not be described by nPDF (EPS09)

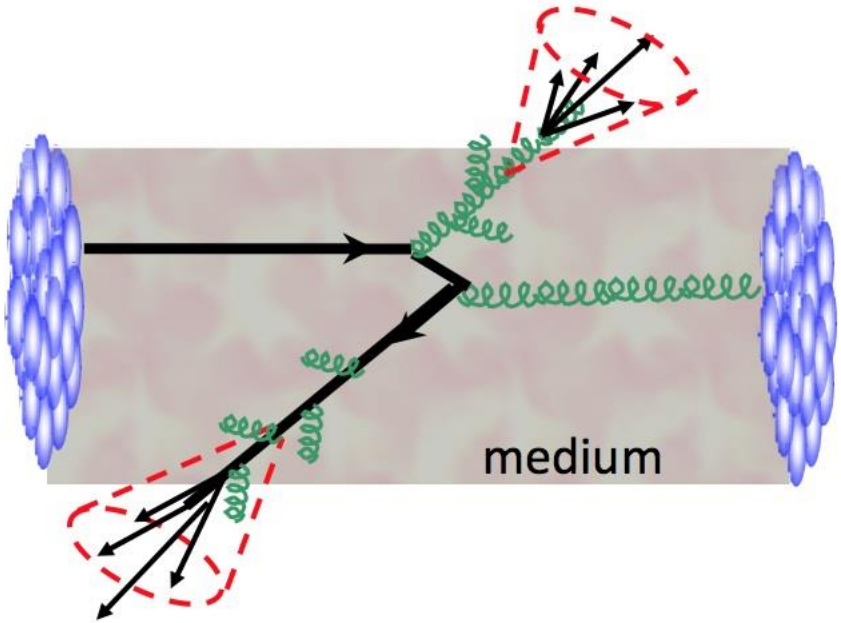
Need to check jet fragmentation function

R_{CP} scaling vs. jet momentum in y*>0 data (proton going side)

Ingredients…

2. Is the jet structure modified?

1. What is the initial state?



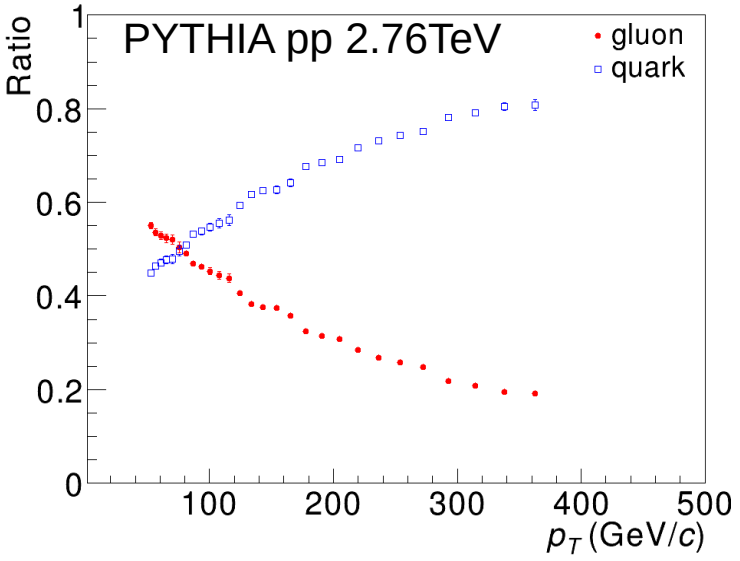
3. Where does the lost energy go?

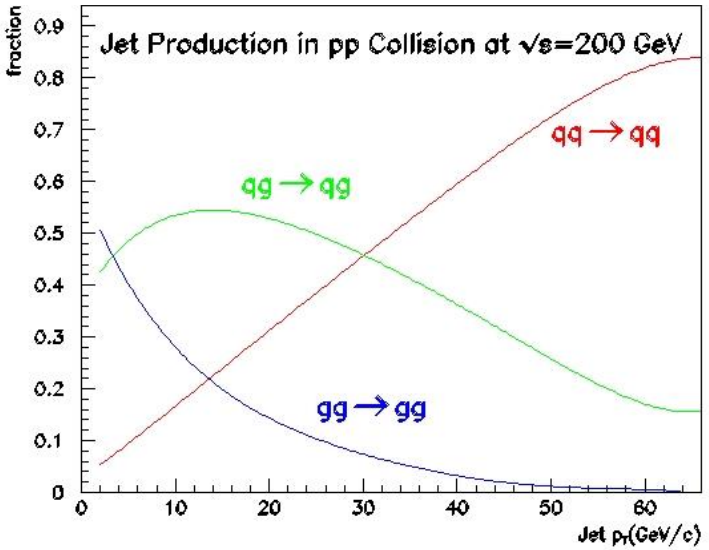
Measuring Jet Modification

- Particle based measurements (R_{AA}, correlations)
  - PRO
    - Experimentally easily accessible
    - Lot of experience on the theory side from RHIC
  - CON
    - Far away from parton level
    - Integrates over many key kinematic ingredients
    - Many possible hidden biases
- Jet based measurements
  - PRO
    - Close to parton level
    - Good control over underlying kinematic distributions
    - Possibility to select underlying parton flavor
    - Unbiased measurements
  - CON
    - Jet themselves are ill defined objects
    - Reconstruction in HI environment can be challenging

Potential biases to keep in mind

- Quark vs Gluon jets
  - Quark jets fragment harder
  - Gluon jets have higher particle multiplicity
- RHIC -> quark jets
- LHC -> gluon jet content



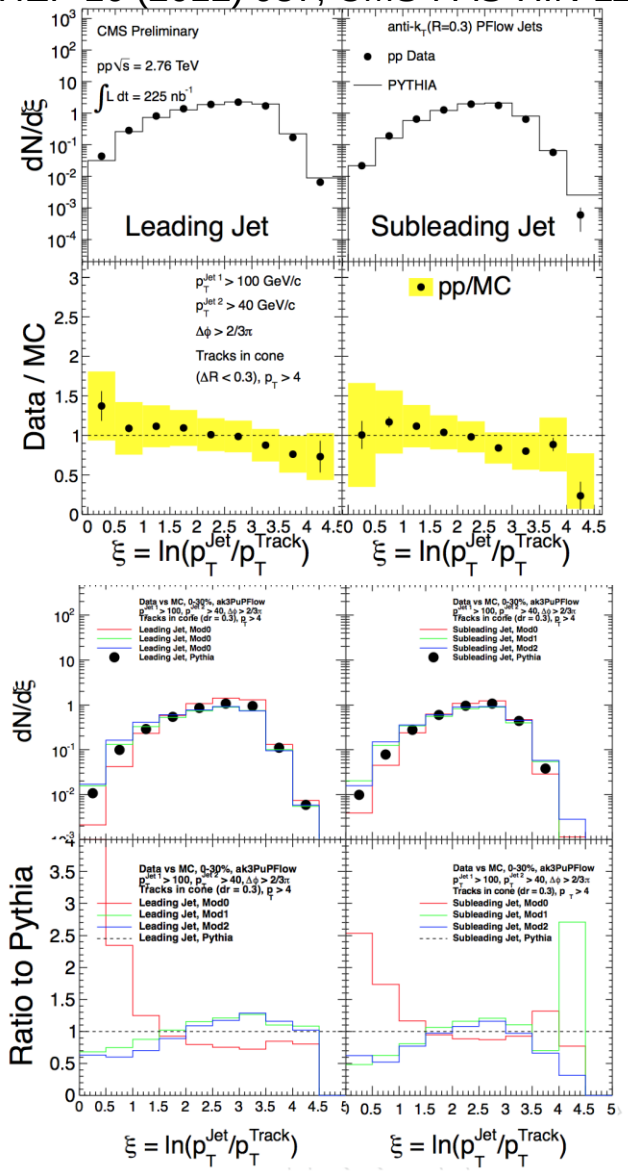


http://ccjsun.riken.go.jp/ccj/doc/plan/

Potential biases to keep in mind II

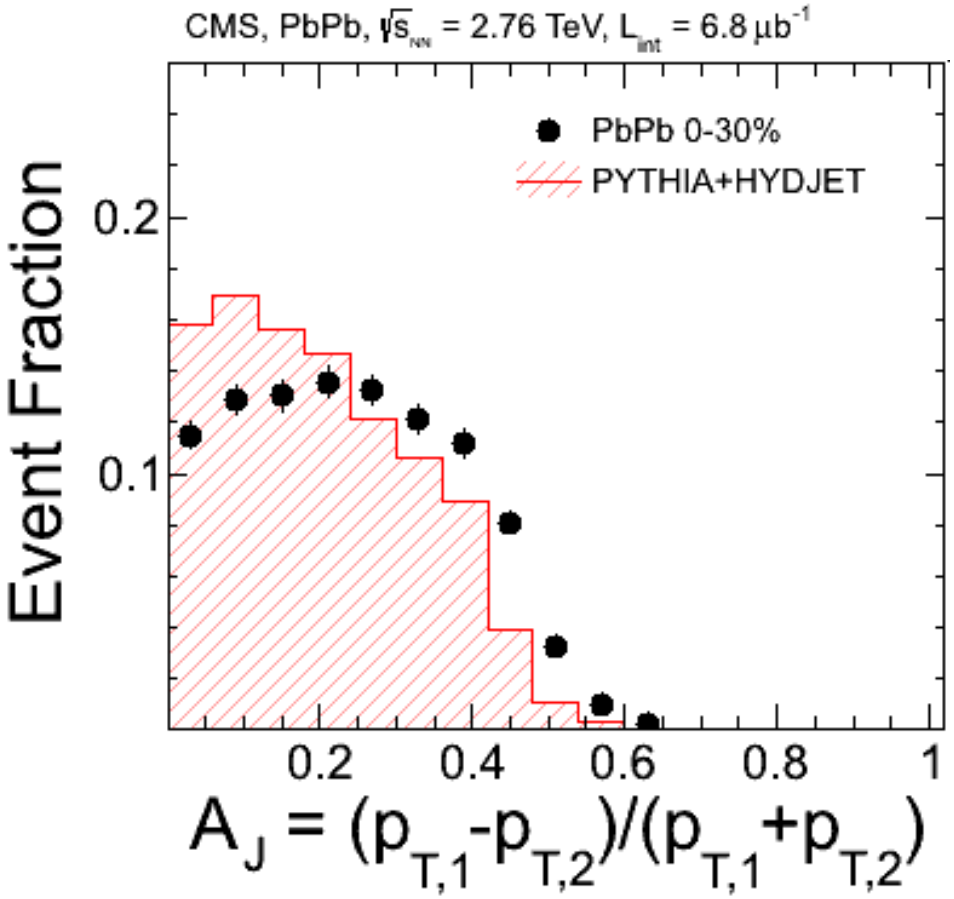
- Jet Fragmentation is ill described in MC
- Fragmentation functions change significantly with parton flavor and energy
- And there are 3 jet events
  - Early branching of a hard gluon that is clustered as a separate jet

JHEP 10 (2012) 087, CMS-PAS-HIN-11-004



Dijet Measurements

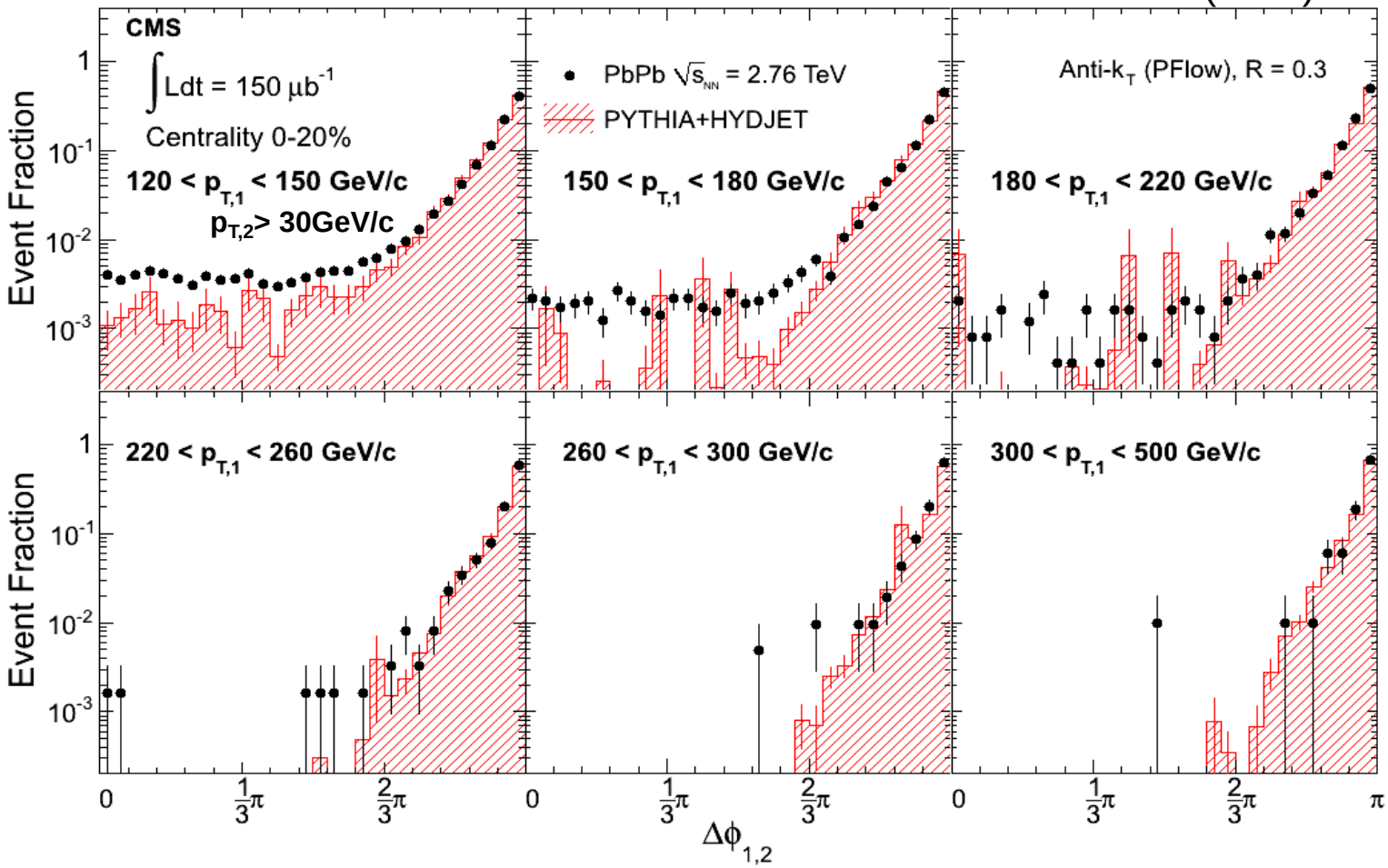
PRC 84 (2011) 024906



Parton Energy Loss directly observed
as Dijet Momentum Imbalance

Dijet Angular Correlations

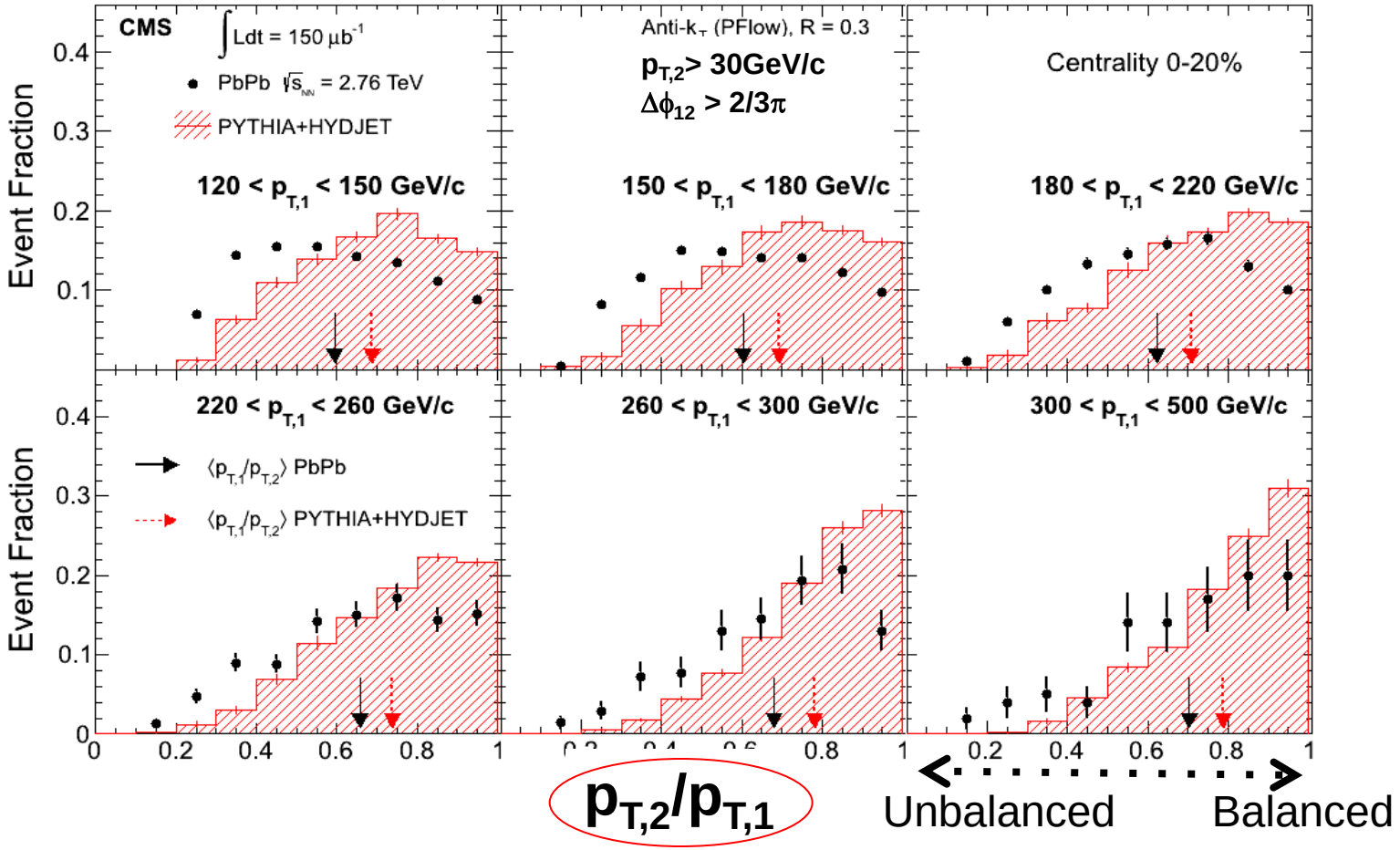
PLB 712 (2012) 176



Correlation peak is the same in data and Pythia across all values of p_T

p_T-dependence of the dijet imbalance

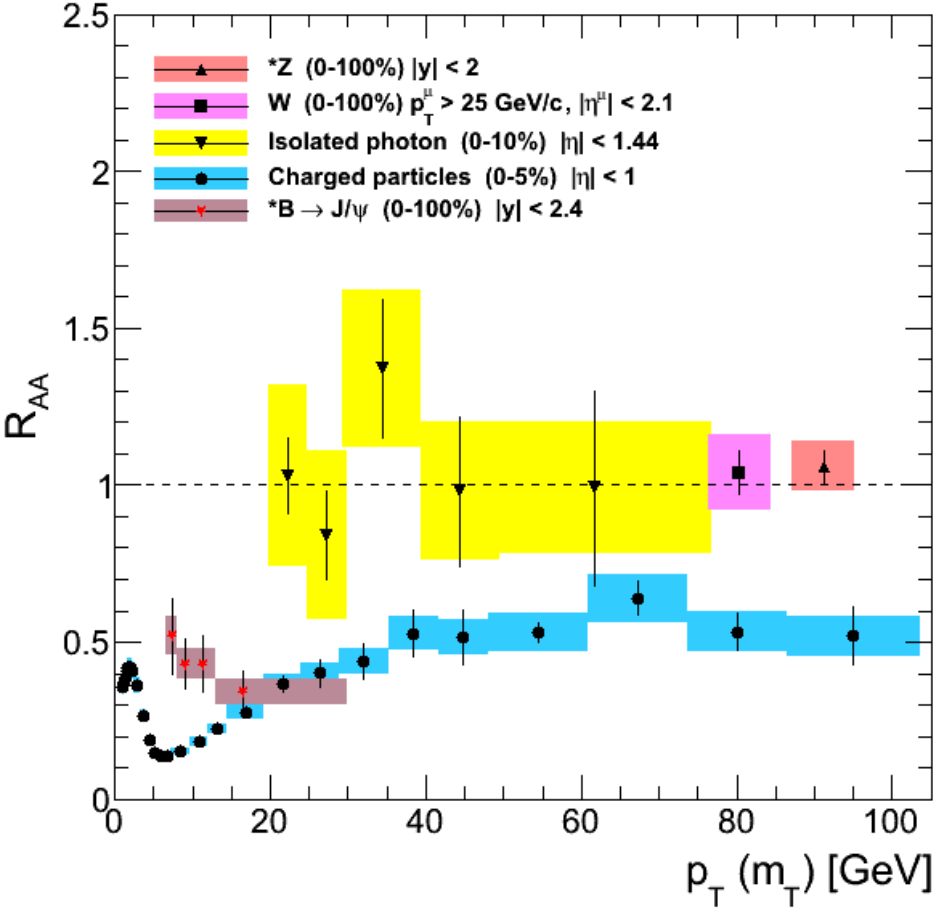
PLB 712 (2012) 176

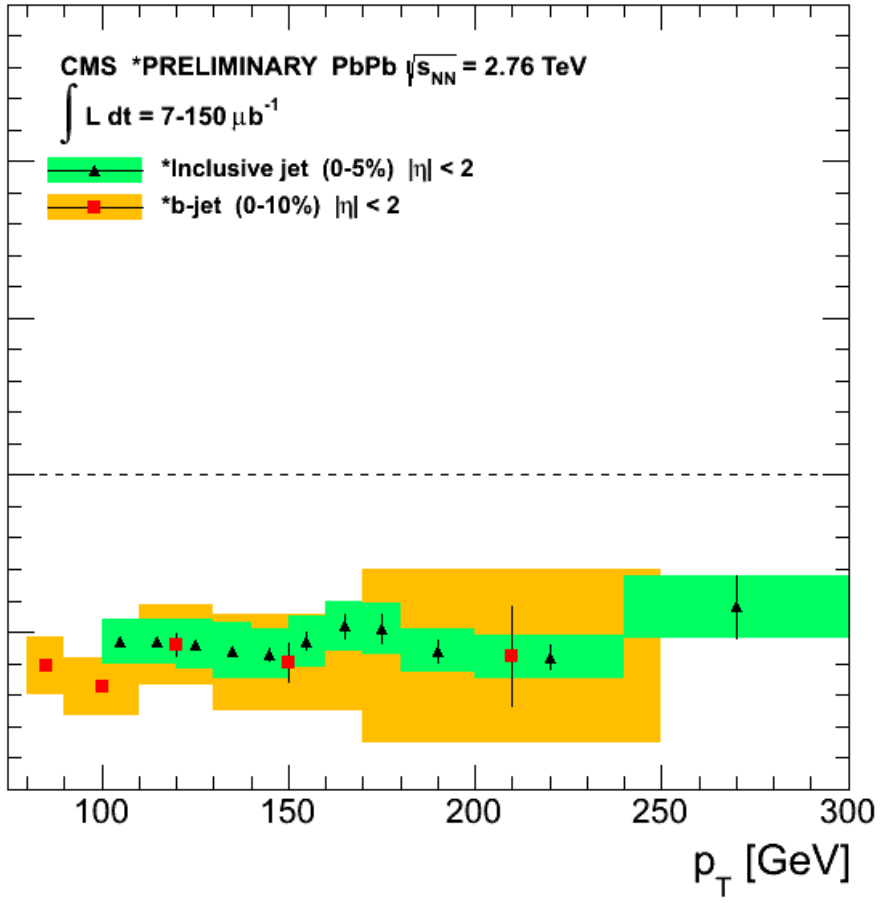


Energy loss apparent in all bins of leading jet p_T

Nuclear Modification Factor R_{AA}

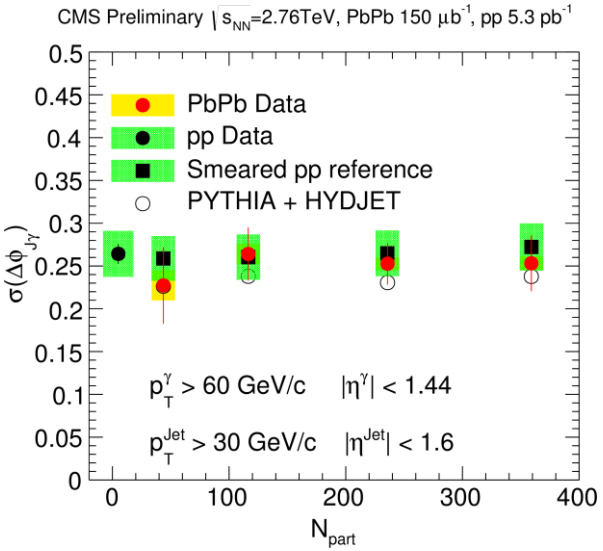
EPJC 72 (2012) 1945 , PLB 715 (2012) 66, PLB 710 (2012) 256
HIN-12-014, HIN-13-004, HIN-12-004, HIN-12-003



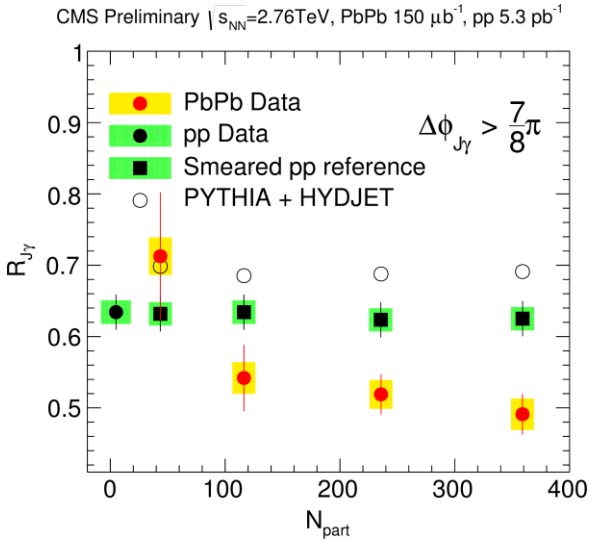


Gamma Jet: defined parton flavor

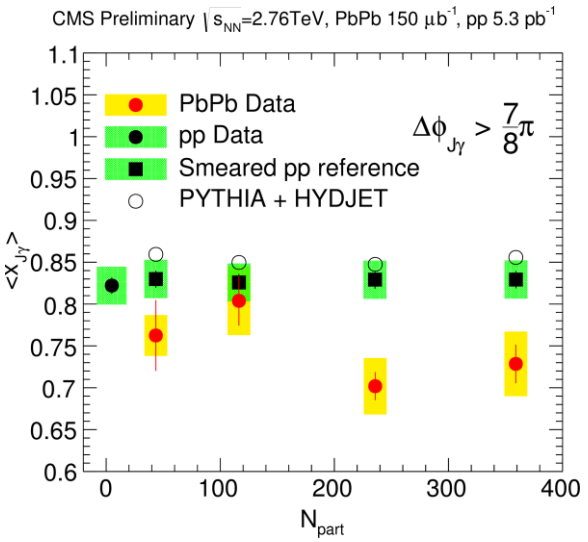
CMS-PAS-HIN-13-006



$\sigma(\Delta\varphi_{J\gamma})$ = azimuthal correlation



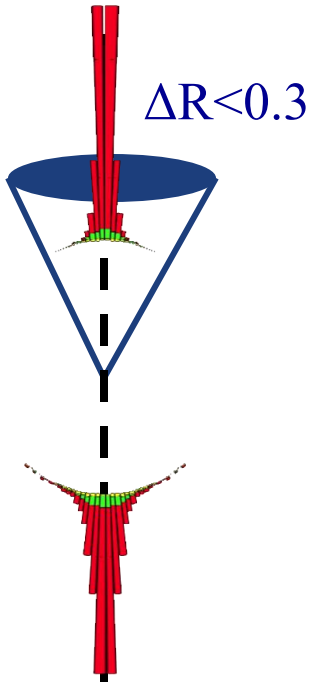
$R_{J\gamma}$ = Fraction of photons with jet partner



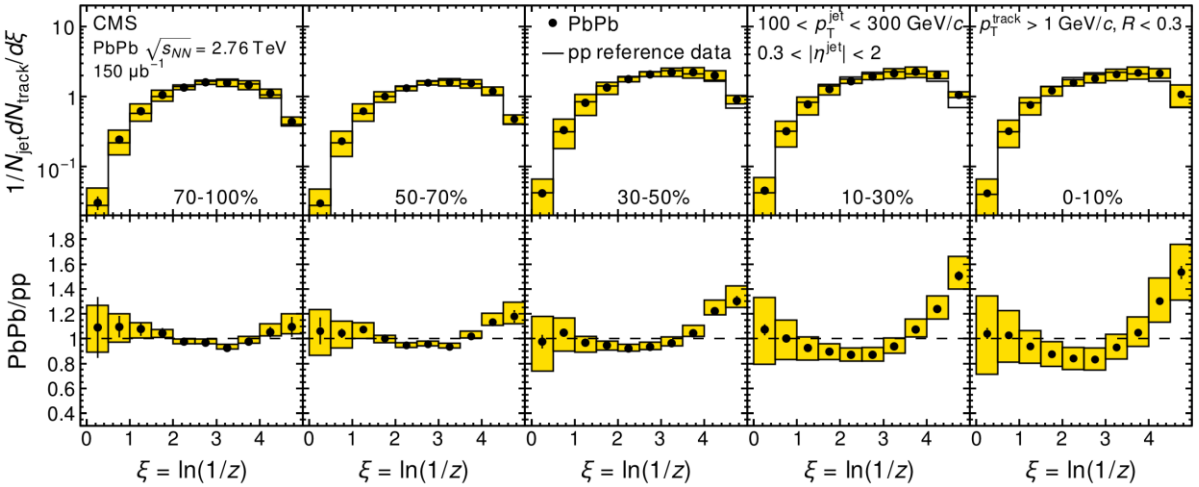
$x_{J\gamma} = p_T^{Jet}/p_T^{\gamma}$

- No jet deflection, but loss of jet partners in PbPb
- Note: pp reference is smeared to match PbPb jet energy resolution in each centrality bin.

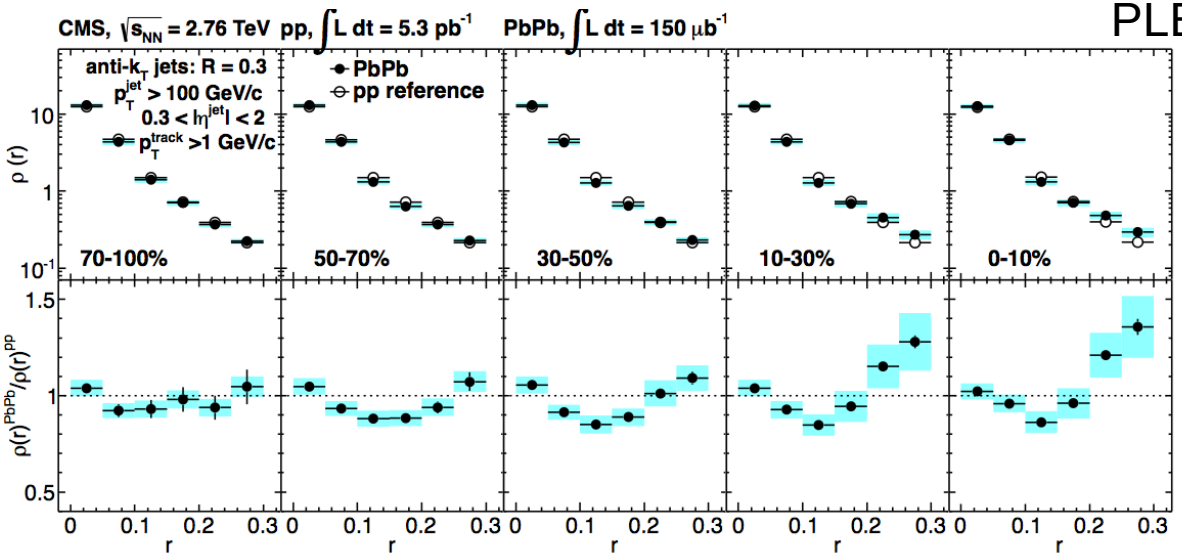
Jet Structure



Jet Fragmentation Functions



Transverse Jet Shapes

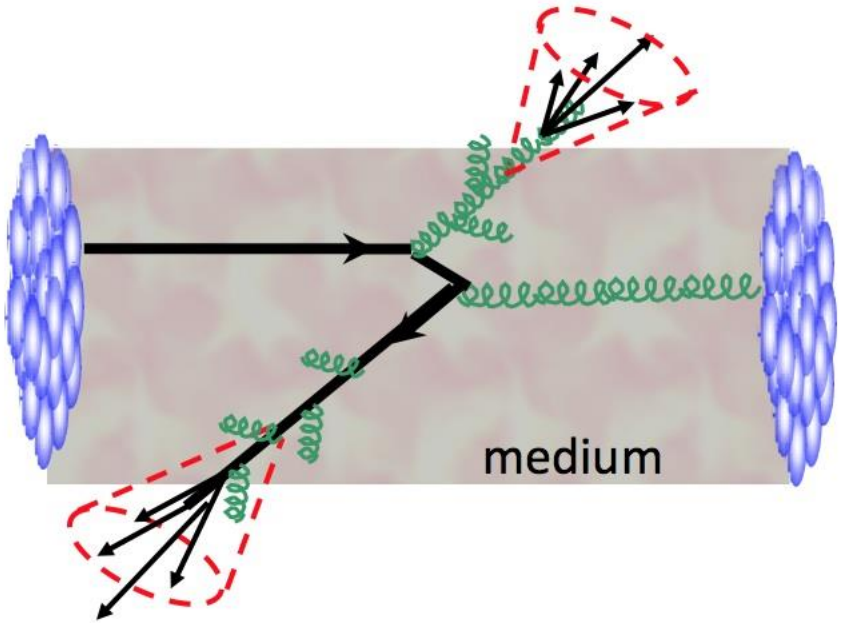


PAS-HIN-12-013
PLB 730 (2014) 243

Ingredients…

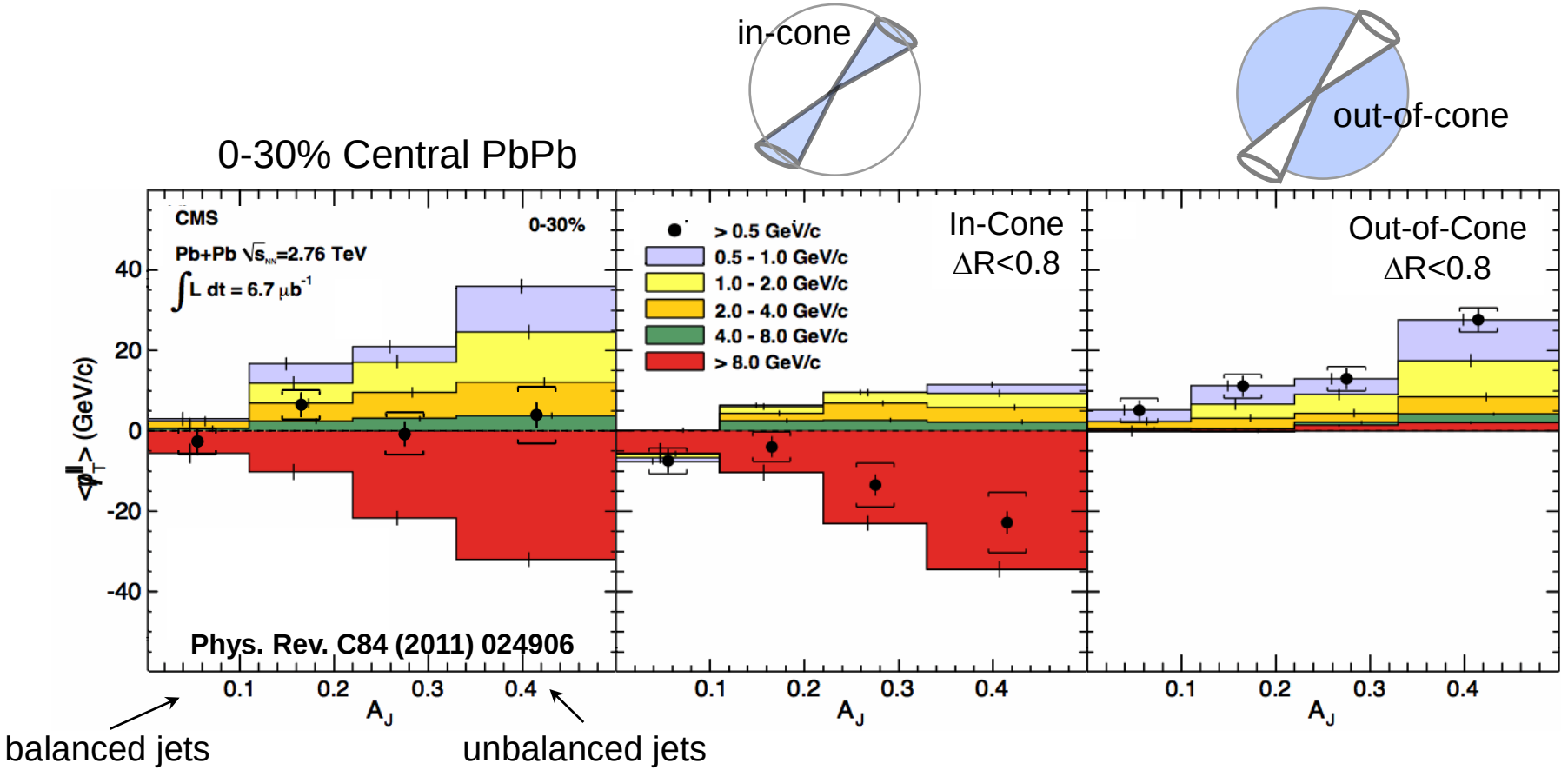
2. Is the jet structure modified?

1. What is the initial state?



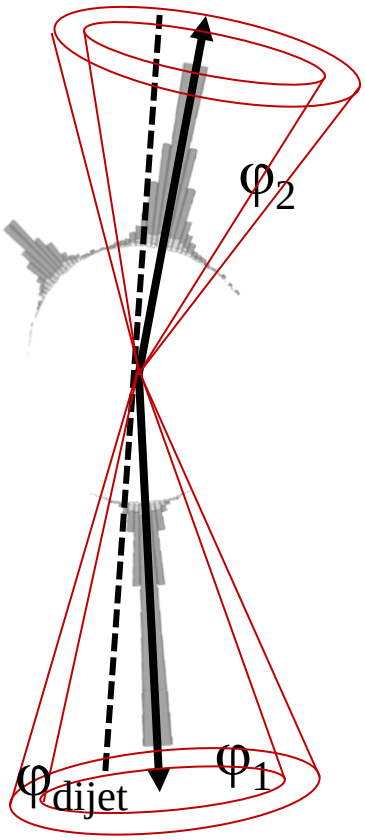
3. Where does the lost energy go?

Lost energy at RHIC and LHC

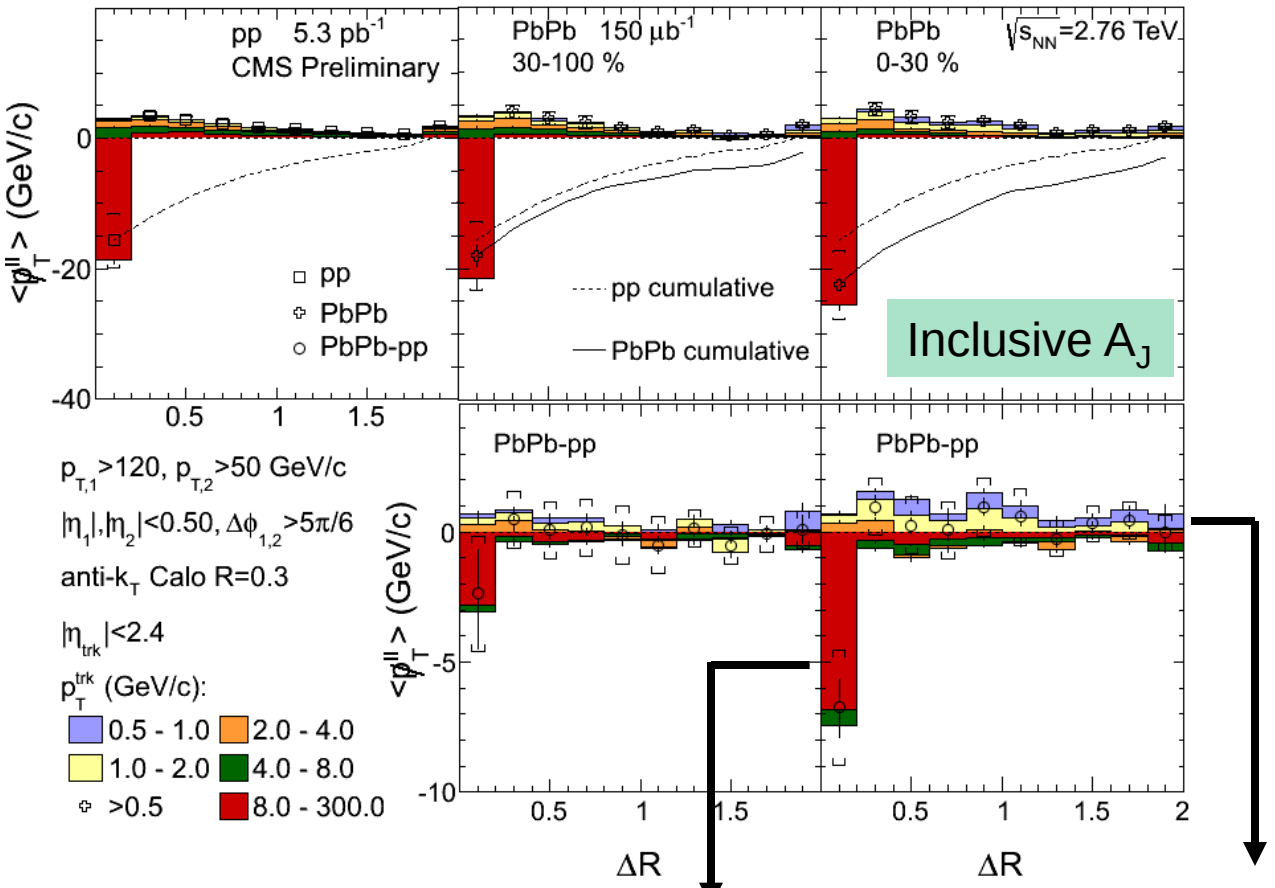


Lost energy: found in large Δφ(ΔR) with respect to the away-side jet, converted to low p_T particles.

Results - Missing p_T vs. ΔR



CMS-PAS-HIN-14-010



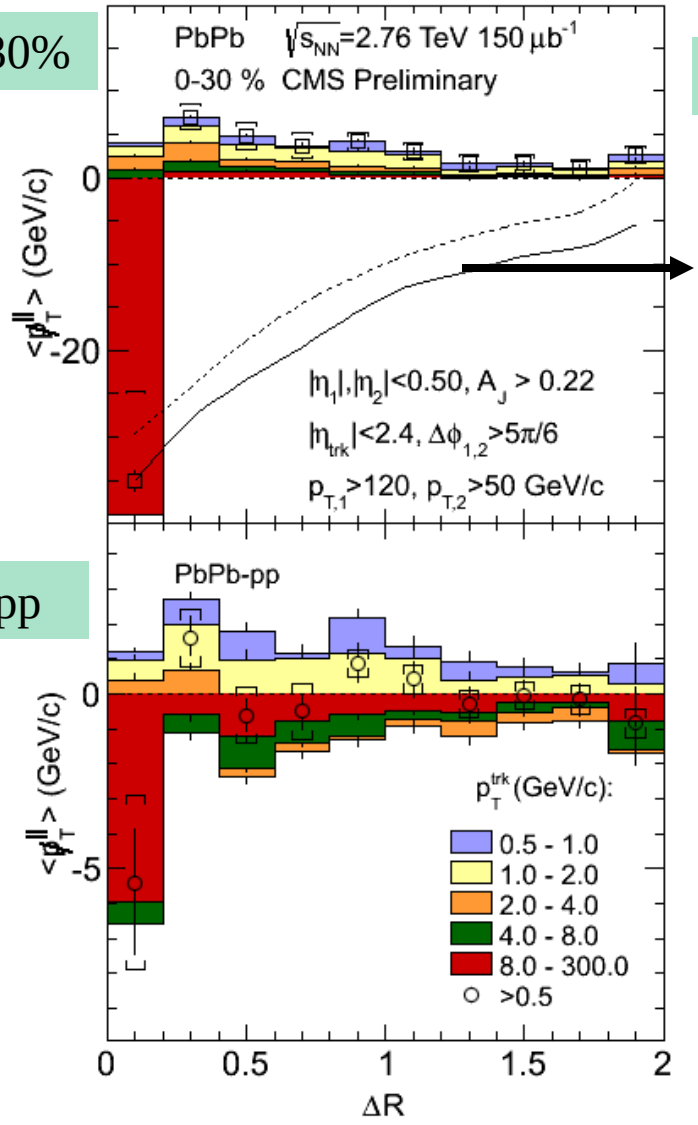
High p_T imbalance at small ΔR

Balanced by low p_T particles in subleading jet direction
Extends upto large ΔR

Results - Missing p_T vs. ΔR – high Aj

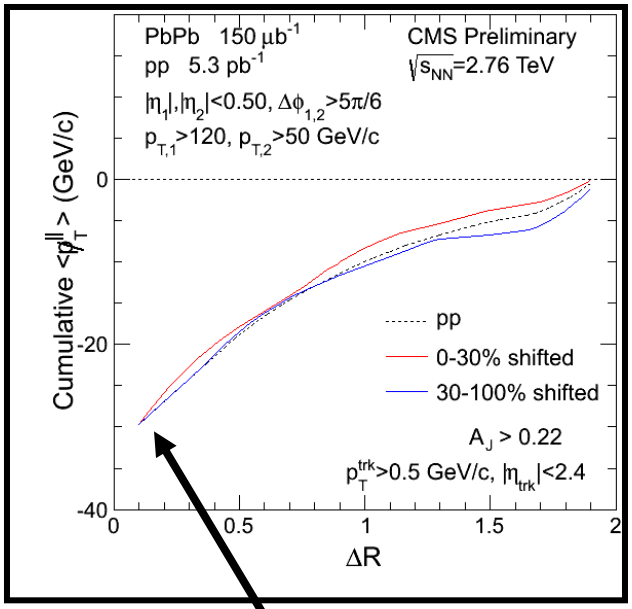
PbPb 0-30%

PbPb –pp



$A_J > 0.22$

Shape of the balancing distribution in pp and PbPb is very similar



After matching the missing p_T at ΔR<0.2

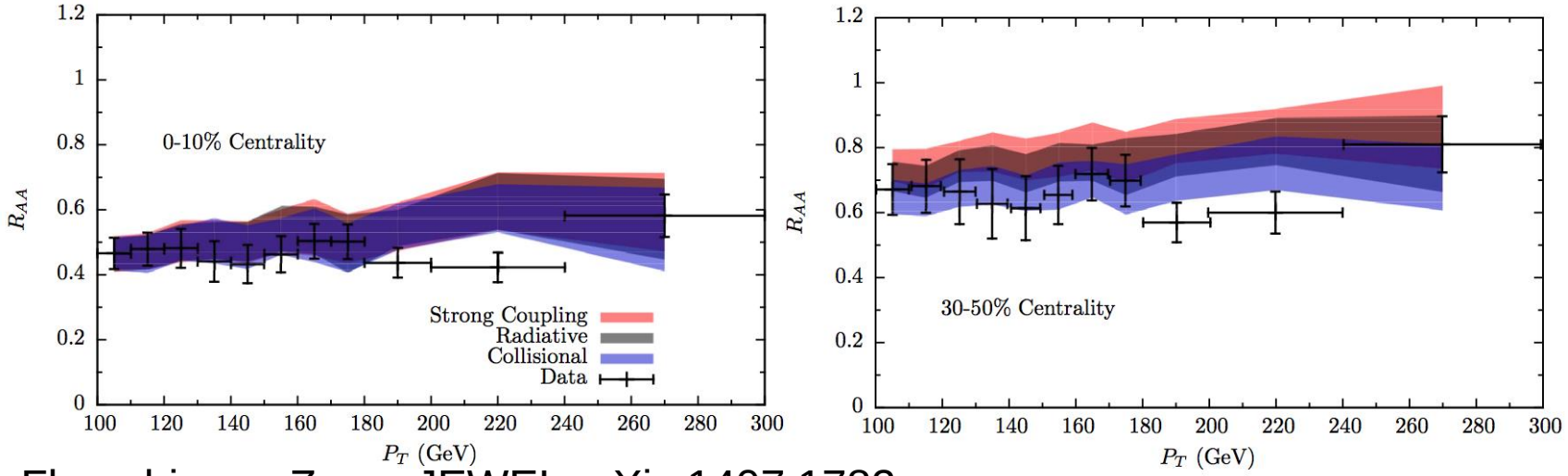
Key ToDo list

1. Learn how to reconstruct Jets in HI environment

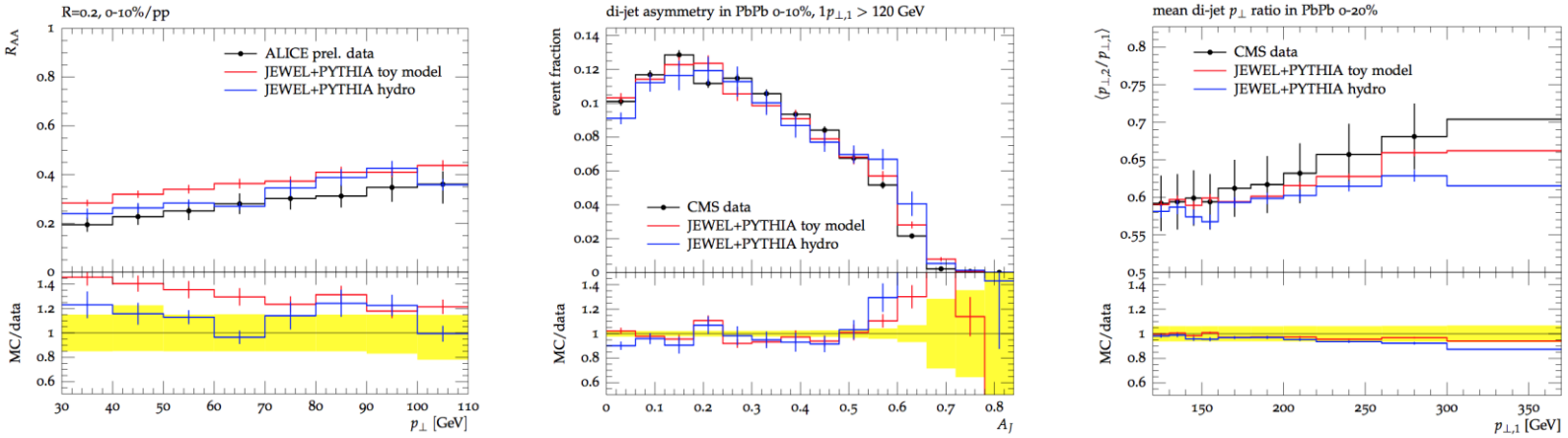
2. Develop theories of the parton energy loss and Perform measurements to distinguish between models and constrain the parameters

Comparing to models: R_{AA}

Gulhan et al. arXiv:1405.3864



Floerchinger, Zapp: JEWEL arXiv:1407.1782

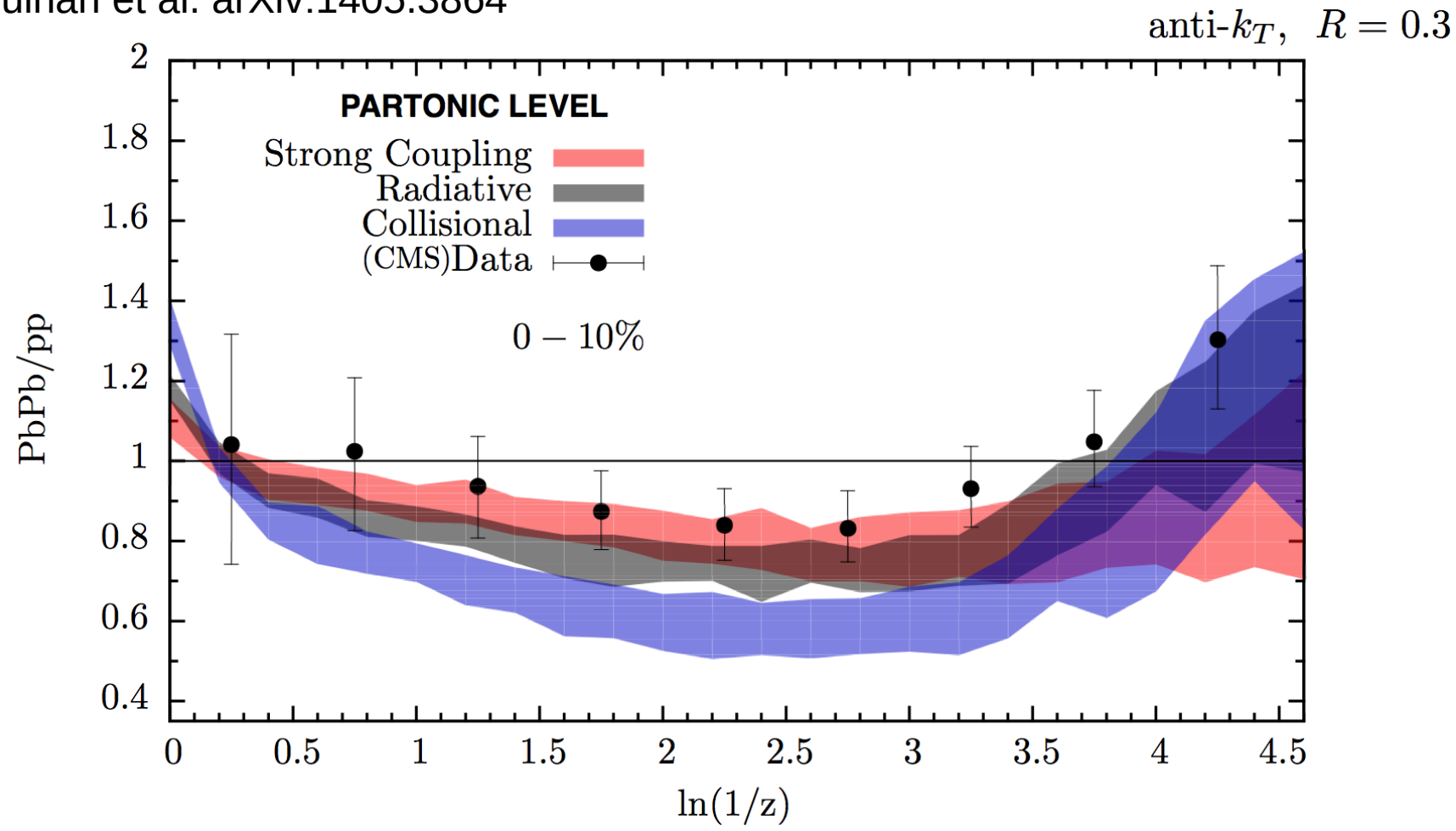


Note 1: Important to follow the experimental procedure to build the physics observable

Note 2: Which observables can distinguish models or constrain parameters?

Comparing to models: Jet Structure

Gulhan et al. arXiv:1405.3864



Observables related to jet structure seem to show sensitivity.

Ideally: Multi-observable comparisons based on MC implementation of model

A historic perspective…

Jet physics in hadronic collisions has always been challenging subject

- In ISR days, Late 70's
  - Jets were postulated but not observed yet
  - First studies of jet properties by looking at 2 particle correlations
- At the SPS and Tevatron, 80's and 90's
  - Many direct jet measurements
  - Better understanding from the theory side
  - Tension between calculations and measurements
  - Solved by close collaboration between theory and experiment
    - MC implementations of theory
    - Explict prescriptions on how to compare data and theory
- At the LHC
  - Precision MC give excellent description of standard model physics
  - Essential to understand the backgrounds in searches for new physics and new particles

A historic perspective…

Jet physics in hadronic collisions has always been challenging subject

D. Hartke QM2002

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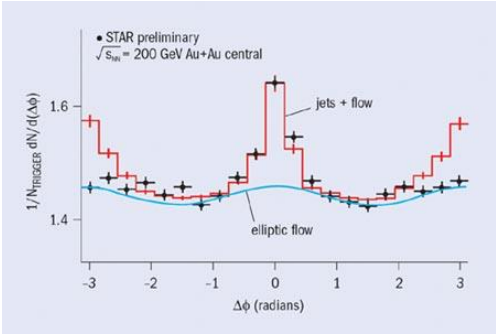
    - Explict prescriptions on how to compare data and theory
- At the LHC
  - Precision MC give excellent description of standard model physics
  - Essential to understand the backgrounds in searches for new physics and new particles

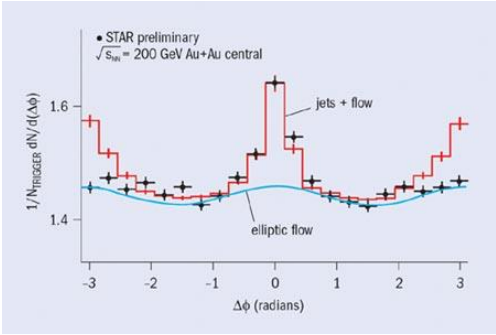


A historic perspective…

Jet physics in hadronic collisions has always been challenging subject

D. Hartke QM2002

- In ISR days, Late 70's
  - Jets were postulated but not observed yet
  - First studies of jet properties by looking at 2 particle correlations



- At the SPS and Tevatron, 80's and 90's
  - Many direct jet measurements
  - Better understanding from the theory side
  - Tension between calculations and measurements
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This is where we are right now!

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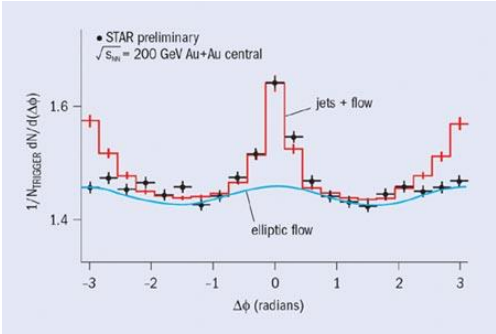

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This is where we need to get to!

Lisbon accord*

[wrap-up from discussion at the 3rd Heavy Ion jet workshop, Lisbon 9-11th July 2014]

*** no ‘accord’ yet**

Lisbon Accord [guiding priciples]

- need to guarantee appropriate legacy of HI experimental results
- need for framework for fair theory [event generators]/data comparison
- validation/comparison framework to be as automated as possible
- should rely on existing standards and, to largest possible extent, standards/codes/procedures used for pp physics should be adopted
- framework [codes, analysis scripts] should be public

Some Specifics

- nPDF parameterizations should be available within LHAPDF [http://lhapdf.hepforge.org]
- RIVET [http://rivet.hepforge.org] is a suitable backbone for implementation of Lisbon Accord
- Jet MC developers to provide running tune as soon as possible
- Experiments provide RIVET analyses
- Logistics if interested:
  - subscribe to heavy-ion-jet-working-group in mmmservices if you have a CERN account
  - send an email to christof.roland@cern.ch or guilherme.milhano@cern.ch if you don't have a CERN account

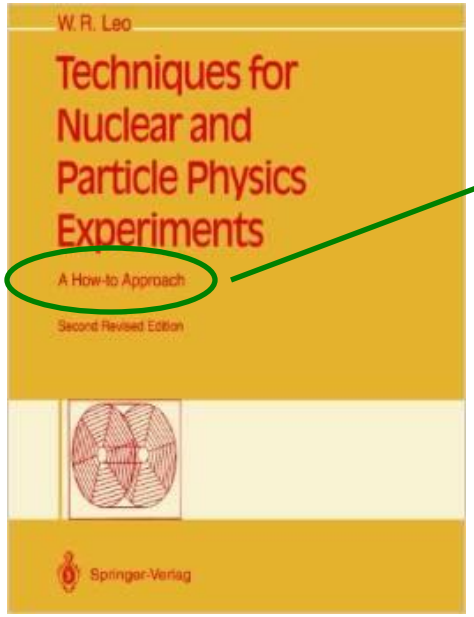
Summary

- Jet physics in heavy ion collisions has made great strides in the last couple of years
  - Many measurements of “observation” type
  - Start providing constraints to models
  - Future LHC/RHIC runs will provide opportunity to make precision studies of parton energy loss

- To significantly solidify and advance our understanding of the QGP using jet studies we have to learn from the HEP community
  - Adopt their way of communicating between theory and experiment
  - Transparent implementations of analysis procedures and theory implementations in models
  - Define rigorous prescriptions of comparing models to measurements

Backup

Experimental Overview of Jets

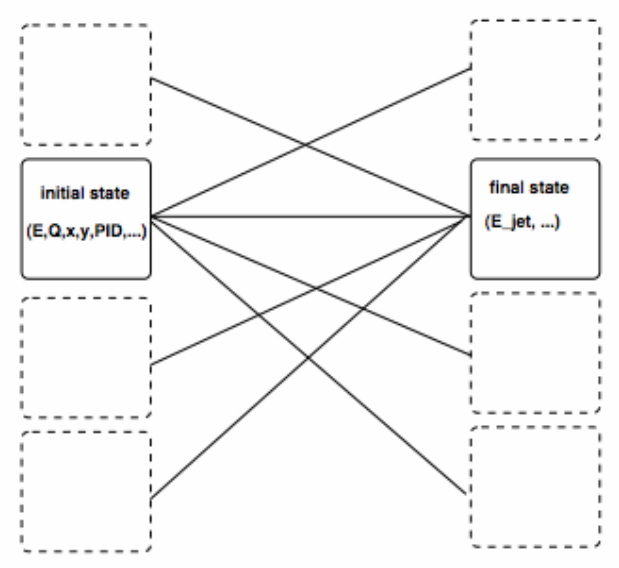


A la W.R.Leo: “A How-To Approach”

Biases

- 2) Which observables and can be compared with ‘raw’ theory?

=> Again remember Thorstens presentation

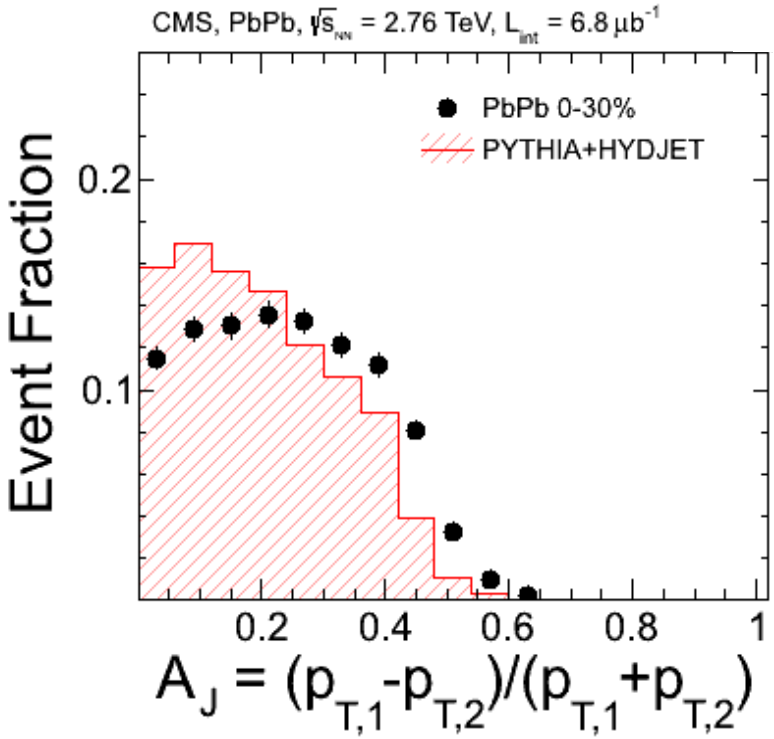


=>A correct comparison requires to compute for all initial states, taking the “biases” by the experimental observation into account

- We have to be careful with “raw” calculations on the theory side
  - Very hard to do precise comparisons without full MC implementation
- Resolutions and UE fluctuations need to be taken into account separately
  - see answer to 1)

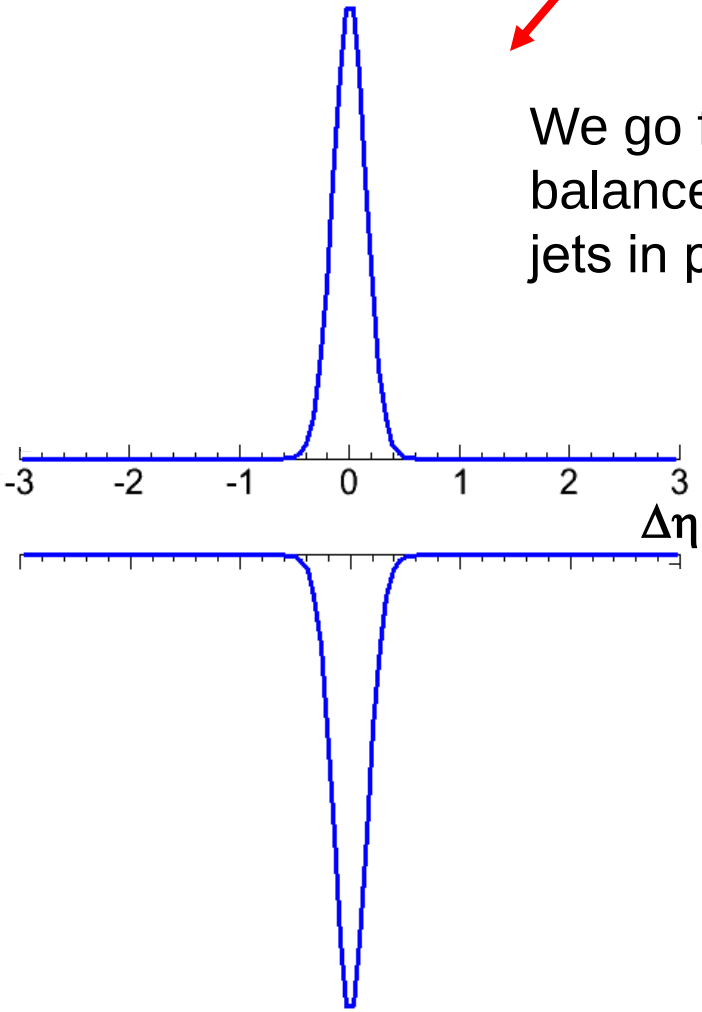
Jet Medium Interactions

My Personal picture…



From QM2011:
Parton Energy Loss observed
as Dijet Momentum Imbalance

Cartoon

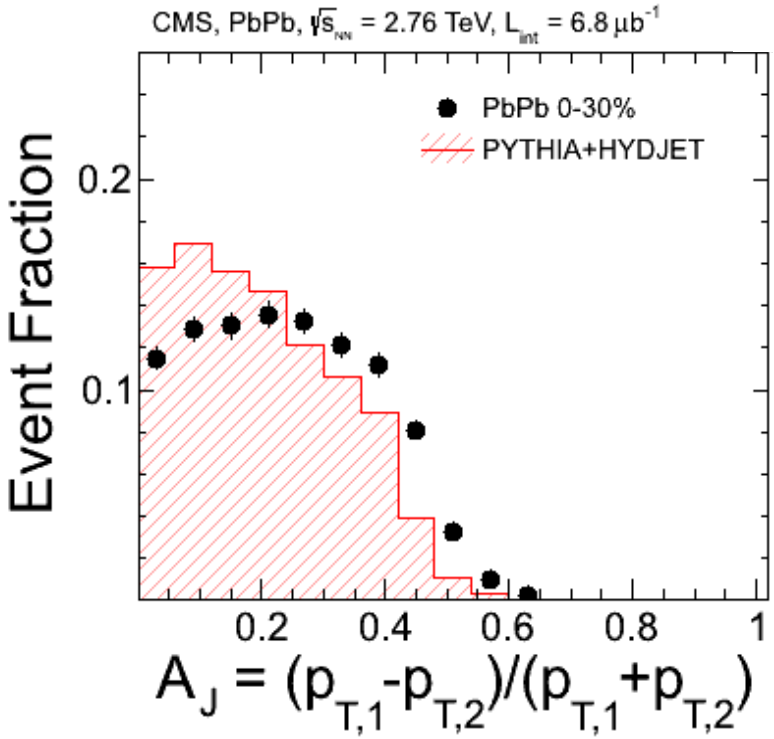


We go from balanced jets in pp…

Jet Medium Interactions

My Personal picture…

Cartoon



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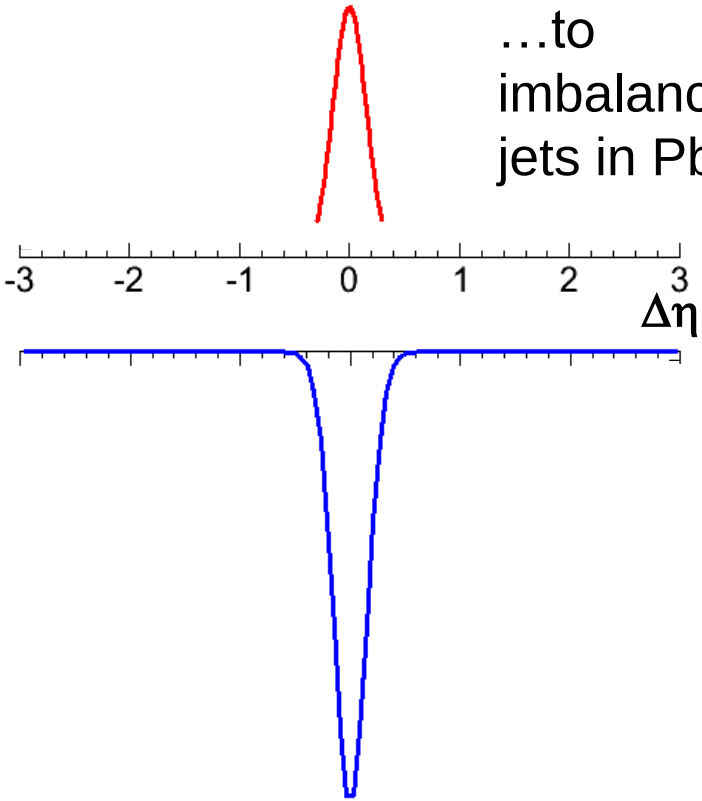
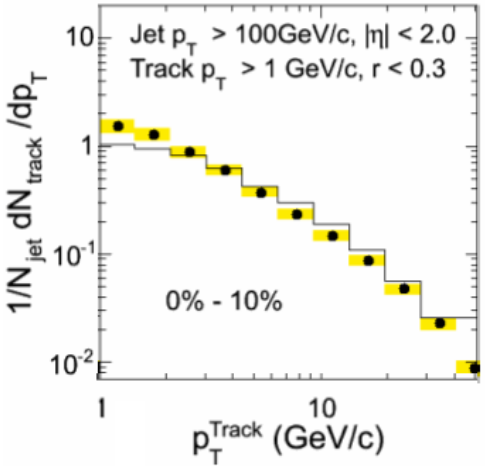
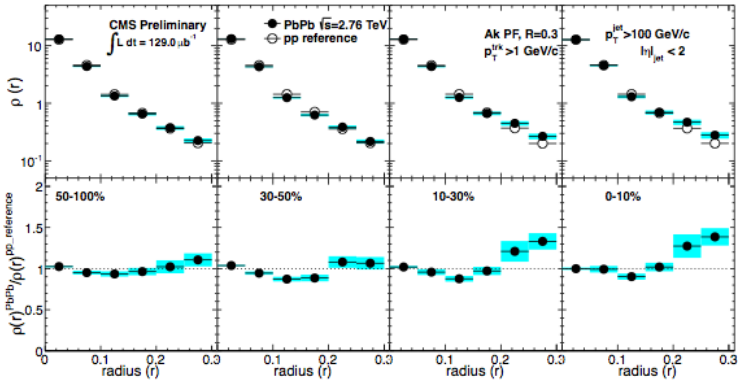


…to imbalanced jets in PbPb

Jet Medium Interactions





My Personal picture…

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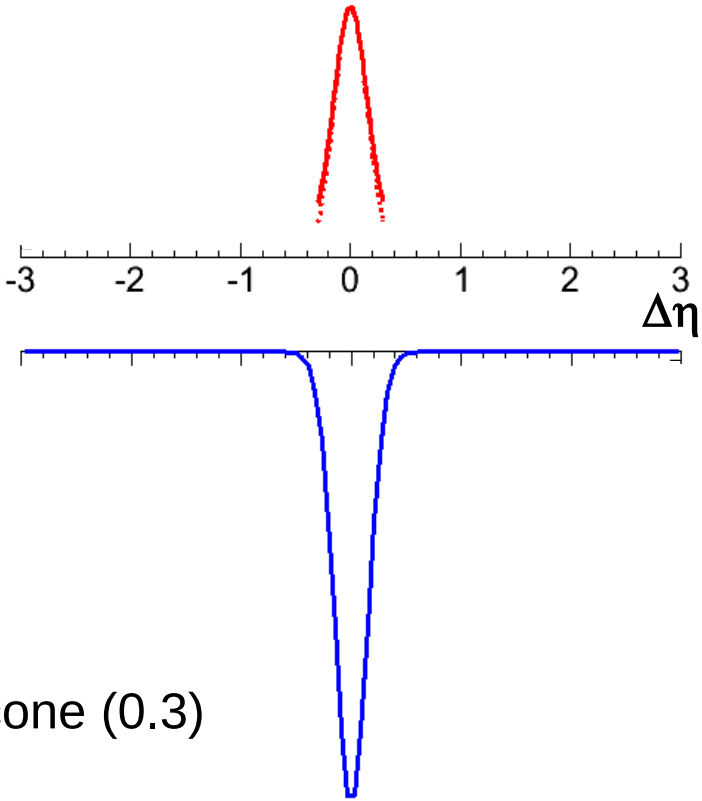
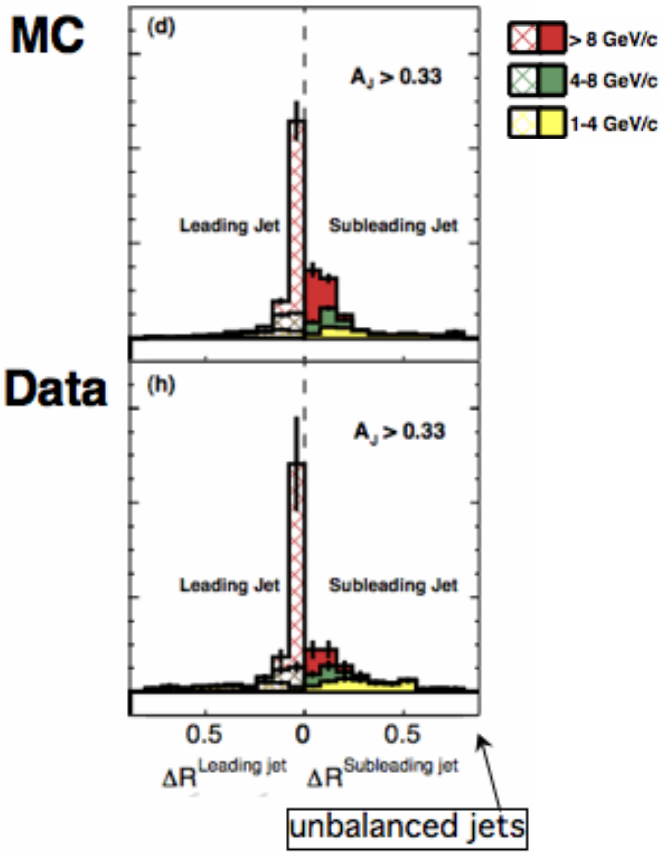


From jet shapes and FF measurements:

Little change of the jet structure inside the jet cone (0.3)

Jet Medium Interactions

Phys. Rev. C84 (2011) 024906



My Personal picture…

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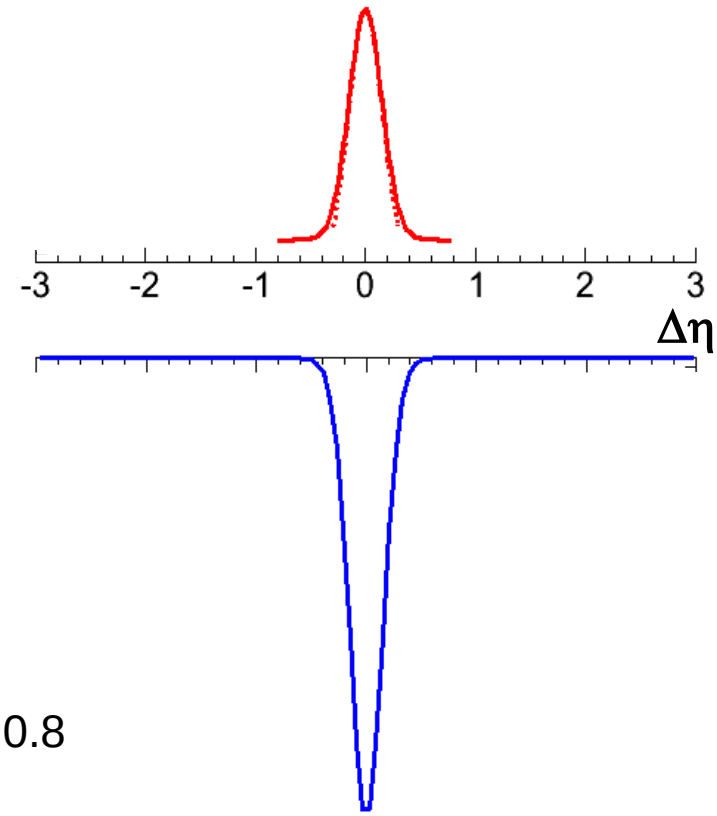


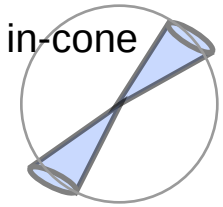
From jet track correlations:

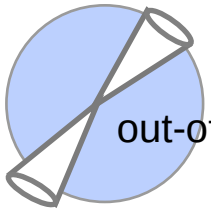
Little extra energy in the vicinity of the jet $0.3 < R < 0.8$

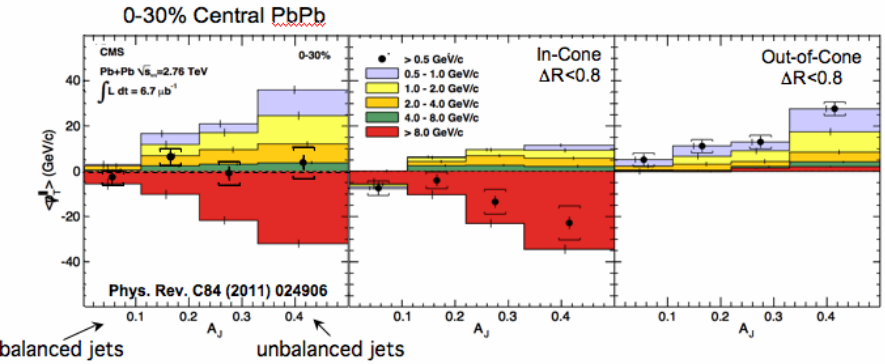
Jet Medium Interactions

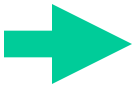
My Personal picture…

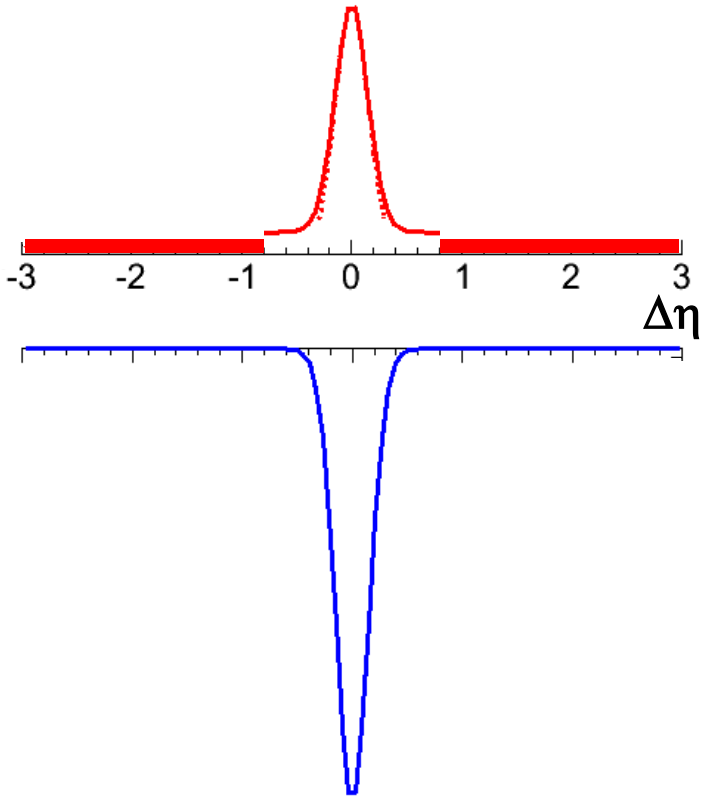
Cartoon











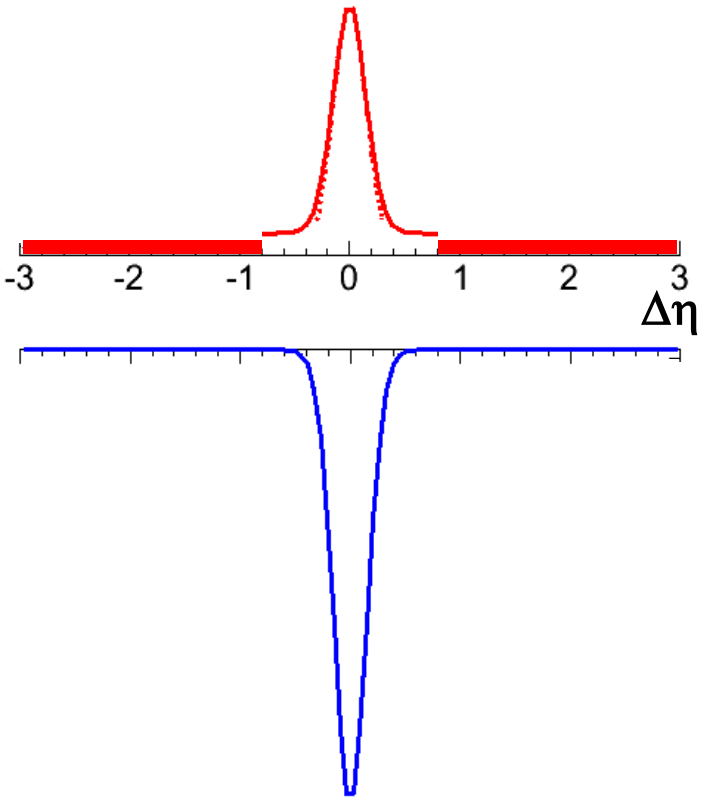
From the missing p_T analysis:
The “lost” energy can be found in form of low p_T particles at R> 0.8

Jet Medium Interactions

My Personal picture…

Cartoon

- The cartoon sums up our incomplete knowledge how the "lost" energy gets redistributed
  - Is pattern directly related to radiation off of the parton
  - Is this energy completely thermalized by the medium and the shape should rather be considered a medium response?
  - All current model agree these days that the energy should go to large angles
    - But how large?
- Now would be a good time for predictions!

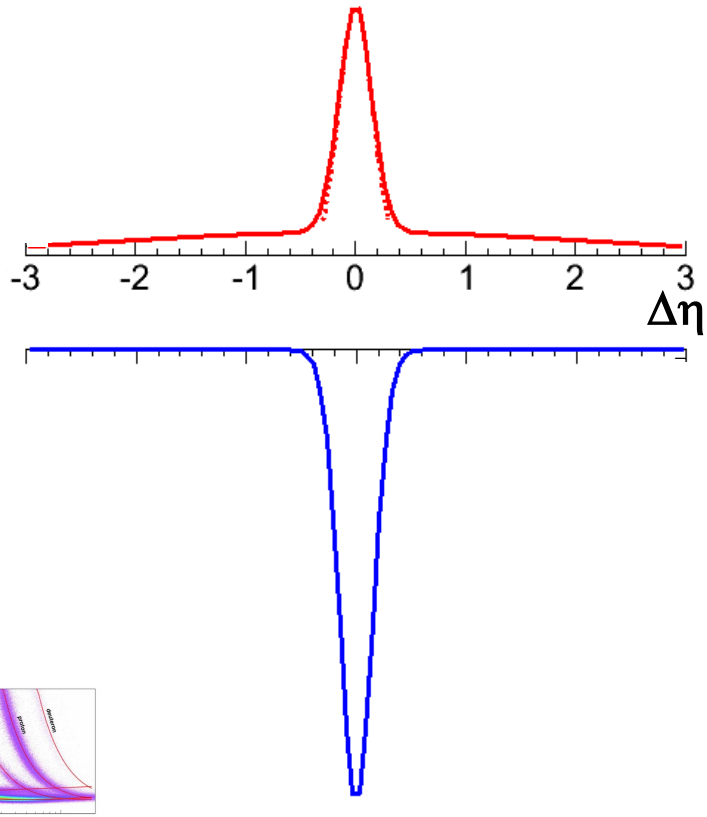


Jet Medium Interactions

My Personal picture…

Cartoon

- We should be able to measure this shape in the near future, e.g by
  - Jet track correlations
  - Energy flow relative to the jet axis
  - Missing p_T vs cone size
  - There is still time to predict the width ;-)



- Can we distinguish many soft particles emitted early (or late?) from the parton from few harder gluons that get thermalized?
  - Event by event observables?
  - HBT analysis in and out of the jet cone to see in which kinematic region jet related particles are coherent with the medium?
- Measure the bethe bloch curve of the QGP analogous to the QED problem
  - ΔE vs. specific ionization