Jet R_{AA} and Dijet asymmetries

Yen-Jie Lee (MIT/CERN)

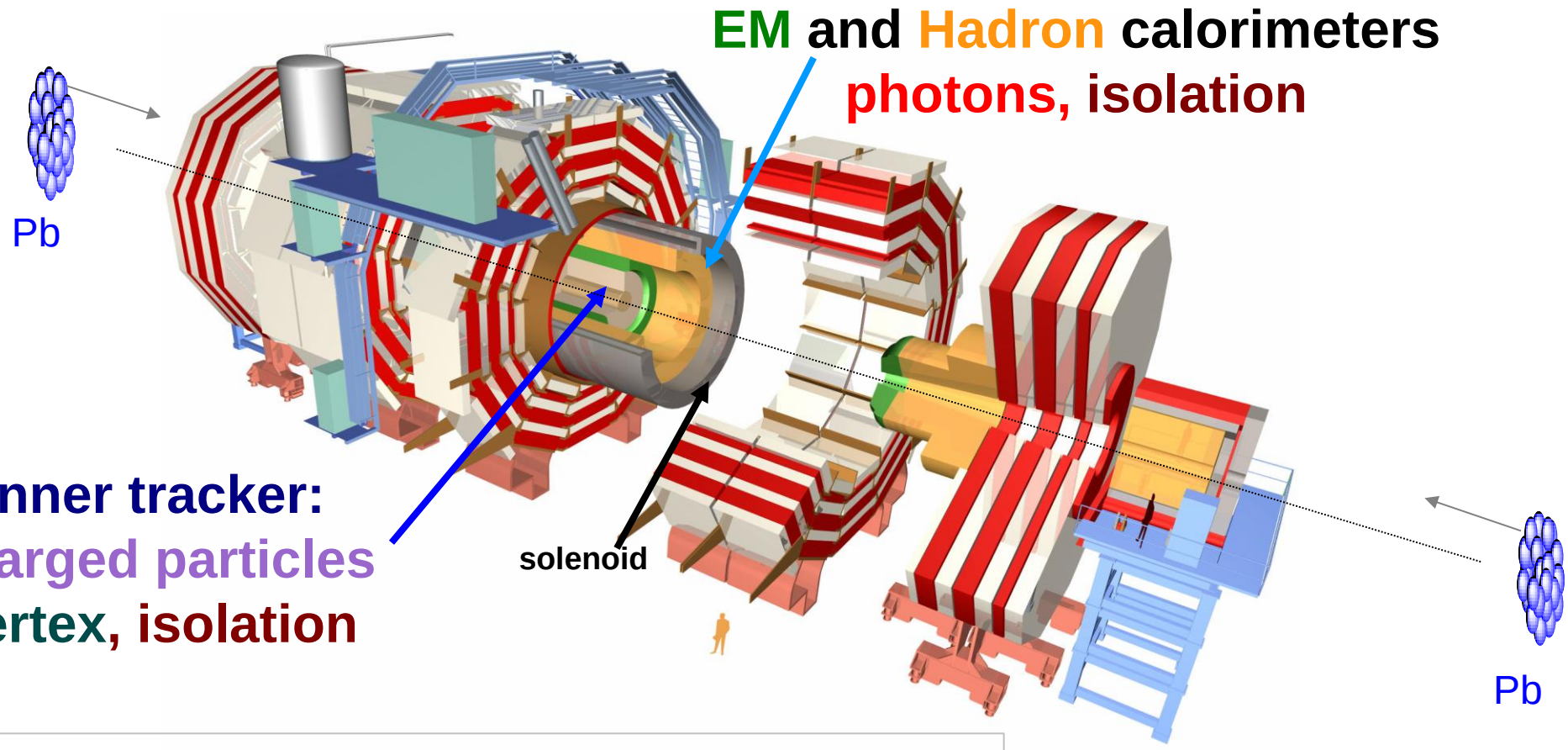
for the CMS Collaboration

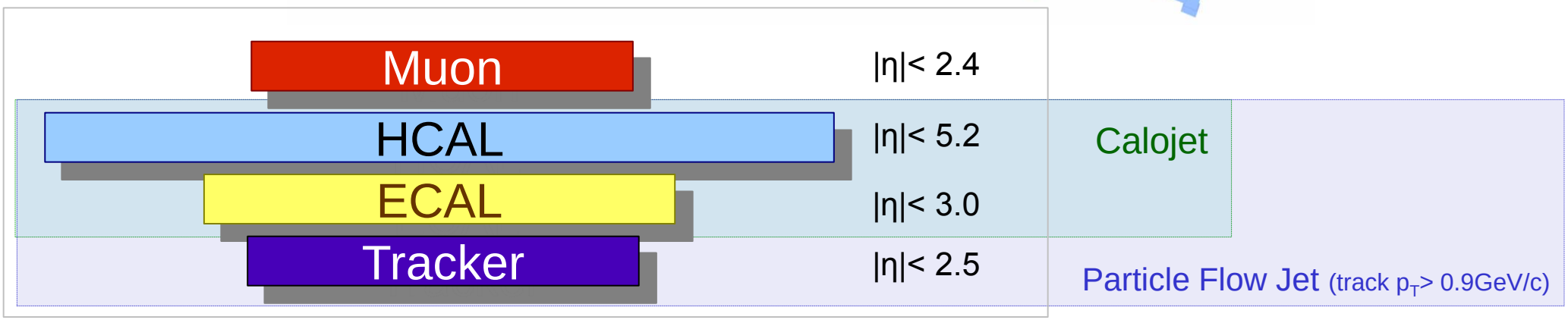
Jet Workshop in HI Collisions

UPMC, Paris, France

1 July, 2013

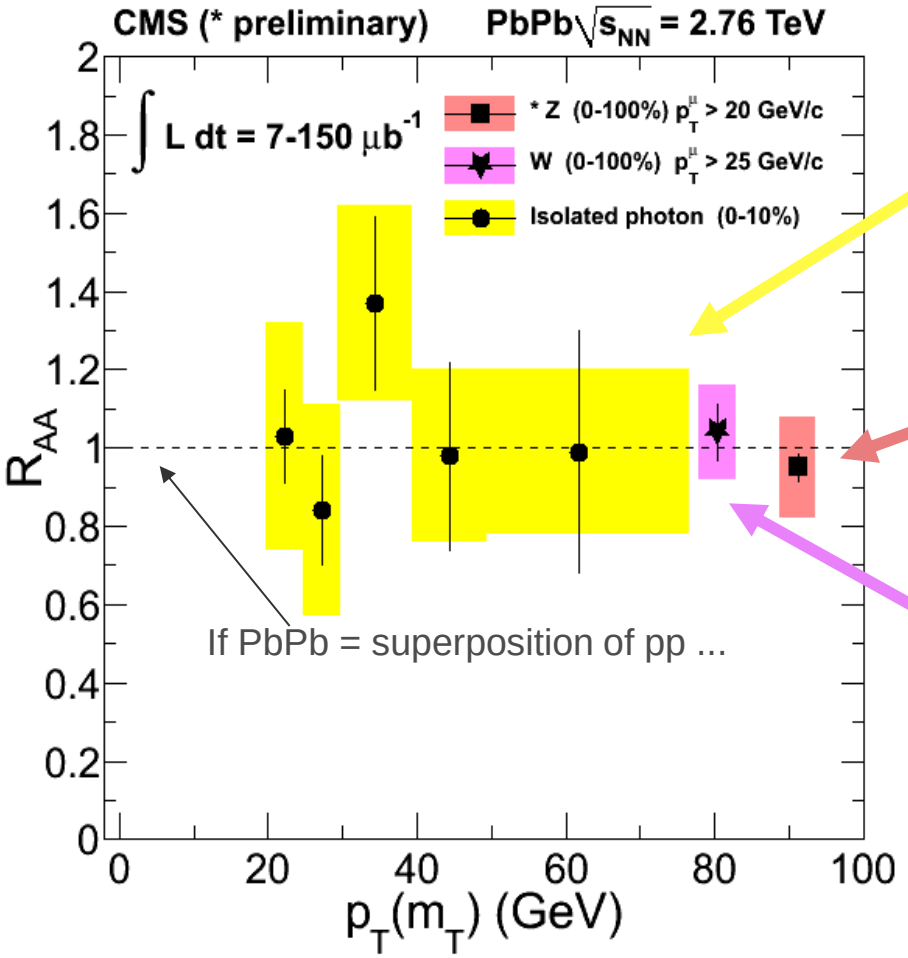
CMS detector





(Non-) Suppression of Colorless Probes

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

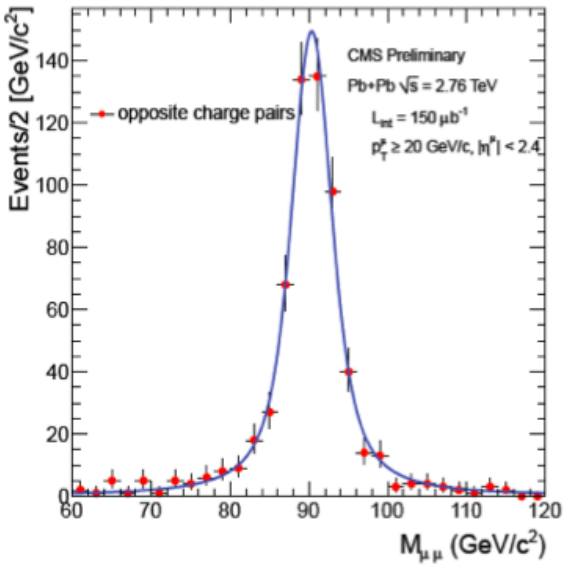


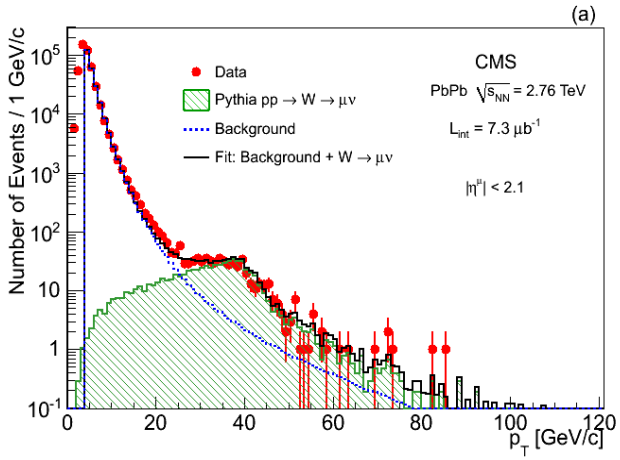
Isolated photon
PLB 710 (2012) 256

$Z^0 \rightarrow \mu^+\mu^-$

$W \rightarrow \mu\nu$ using single muon recoil against missing p_T

PRL 106 (2011) 212301
CMS-PAS HIN-12-008



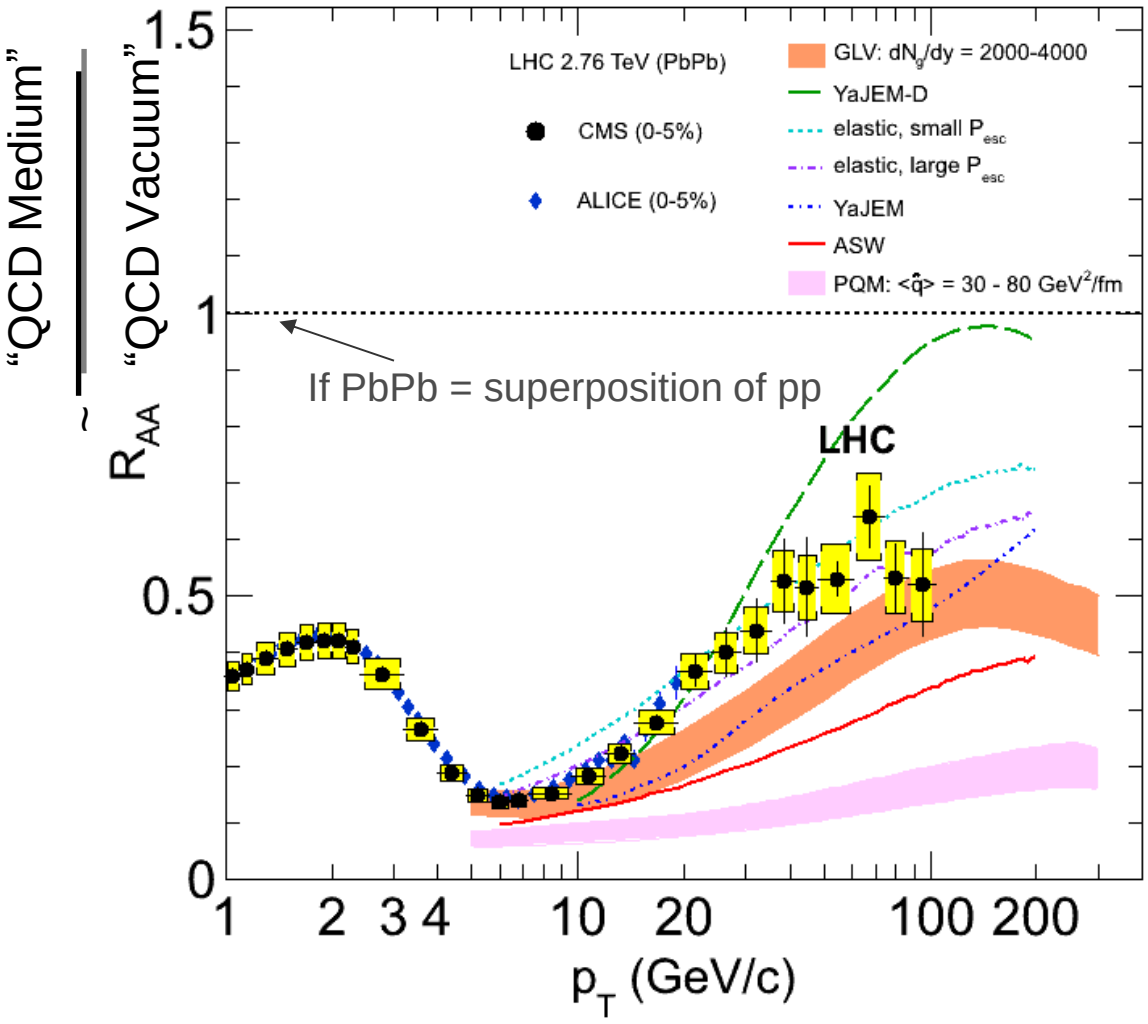


arXiv:1205.6334
PLB 715 (2012) 66

N_{coll} scaling confirmed in PbPb collisions at 2.76 TeV

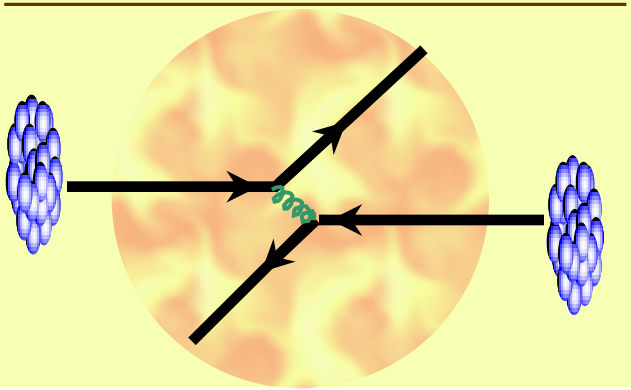
Jet quenching without jet: strong suppression of high p_T particles

EPJC 72 (2012) 1945

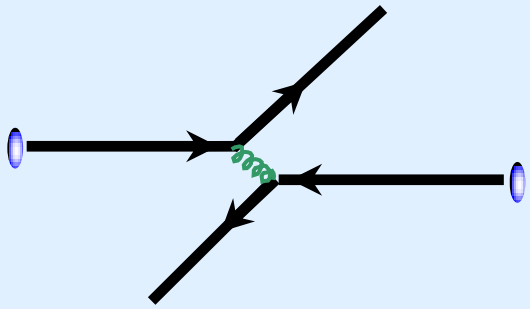


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll}\rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$

PbPb measurements



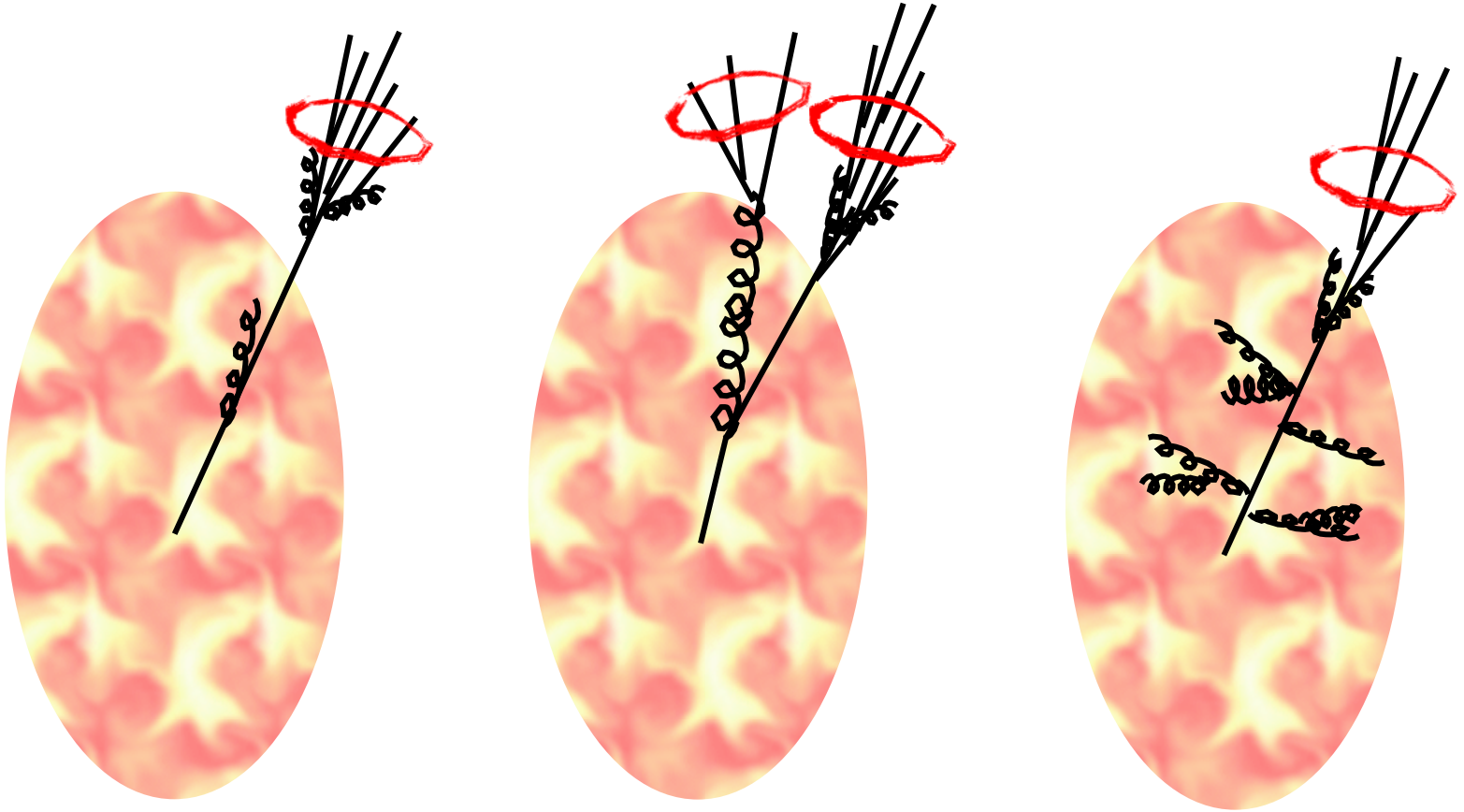
pp reference



High p_T reach up to 100 GeV/c

Constraints on the parton energy loss models

Study of jet quenching in heavy ion collisions



Collinear radiation

GLV + others
(pre-LHC models)

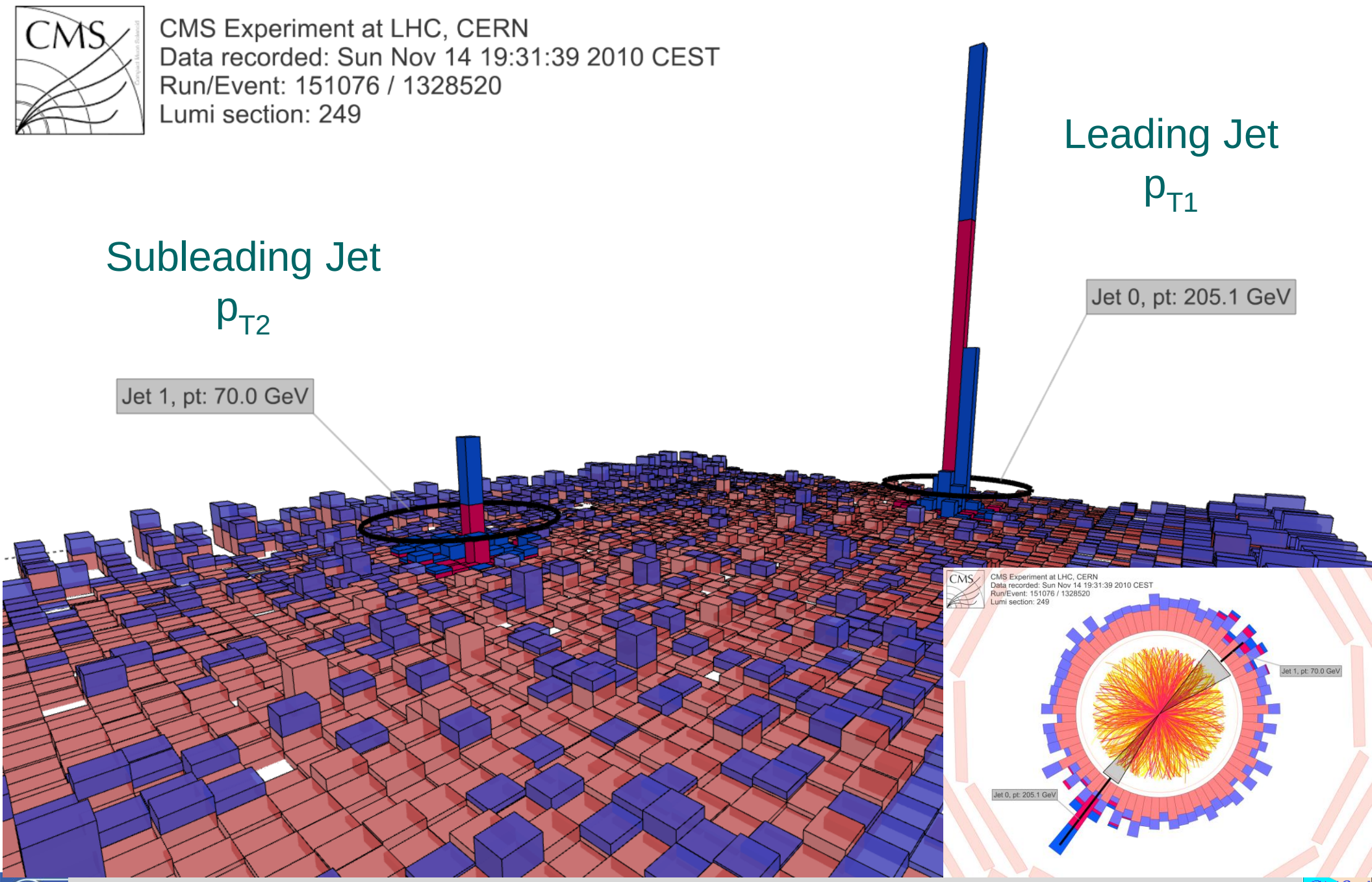
Hard radiation

PYTHIA inspired models
Modified splitting functions

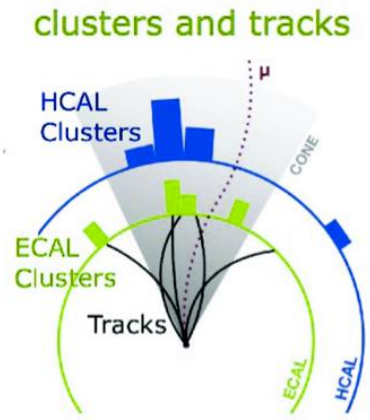
Large angle soft radiation
"QGP heating"
AdS/CFT
Interference

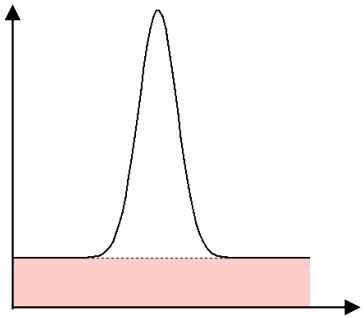
The first question we would like to ask: can we collect the energy back by jet reconstruction? → look at jet p_T spectra

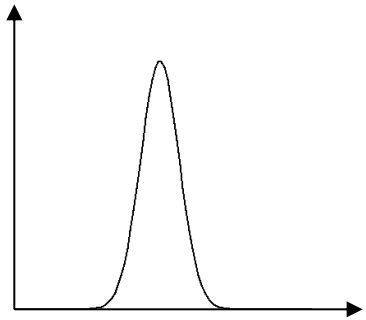
Dijet event in CMS

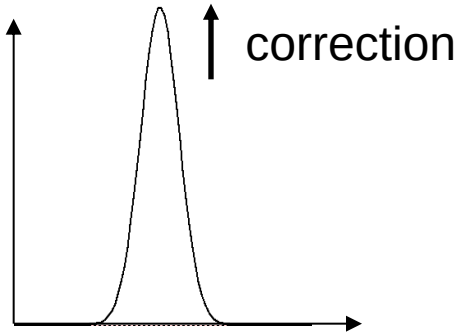


CMS Jet Reconstruction









Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Remove underlying events contribution or pile-up energy

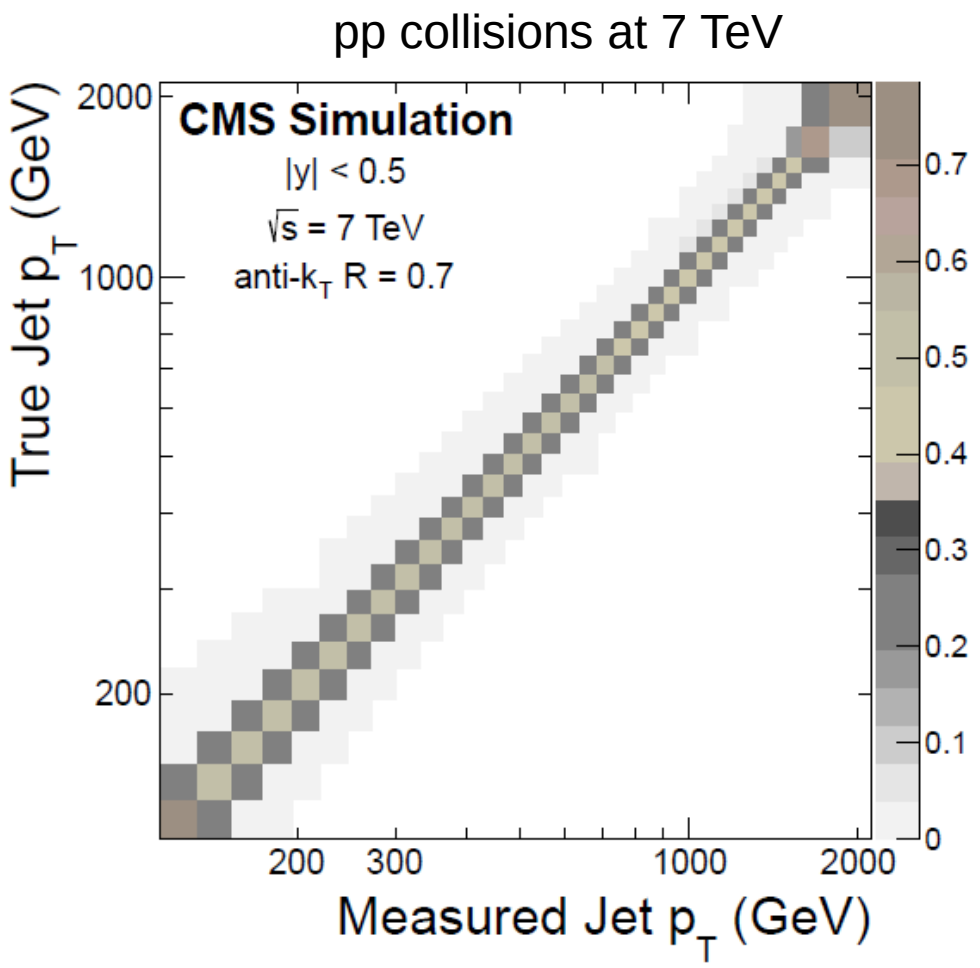
MC Simulation PYTHIA

Jet spectra unfolding

• Measured jet spectra are corrected for jet energy resolution and energy scale using unfolding techniques

• Several unfolding methods are considered:

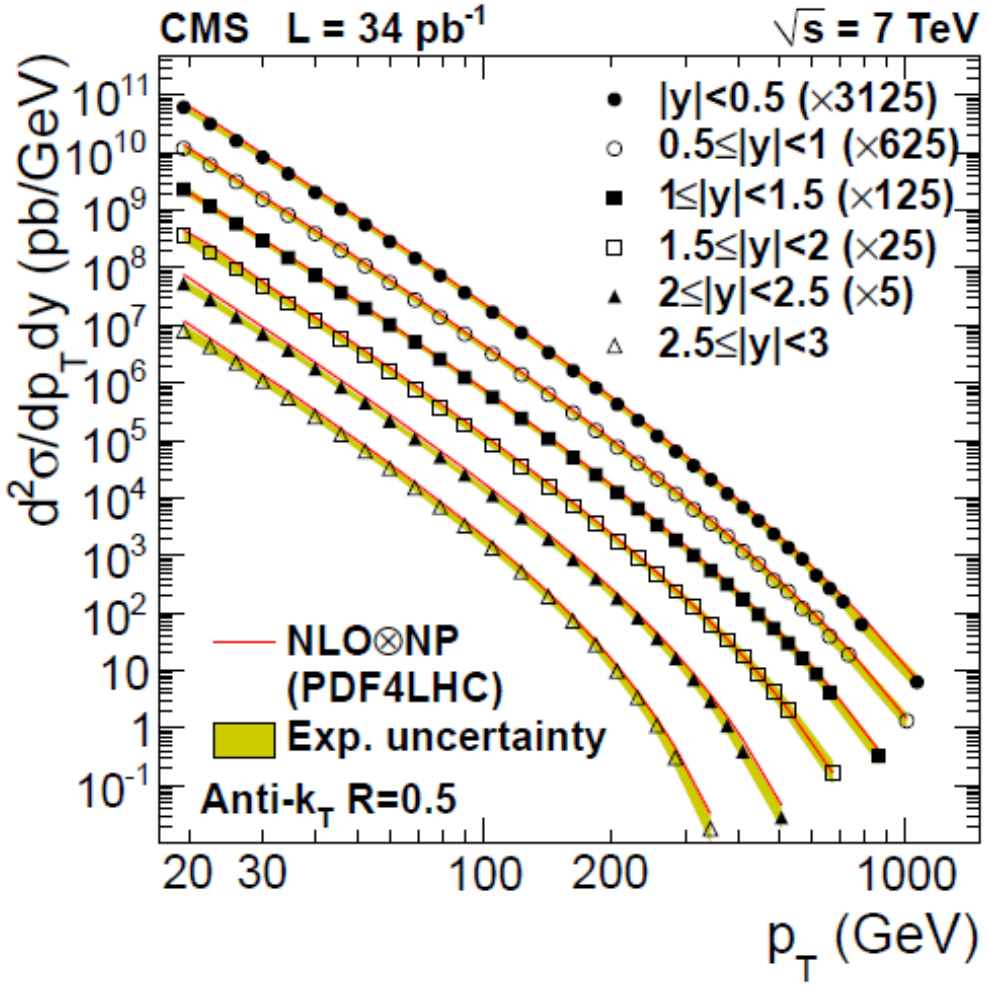
- Bayesian unfolding as main results
- Cross-check with bin-by-bin and SVD unfolding
- Cross-check with “folding” (smear the pp reference)



PRD 87 (2013) 112002

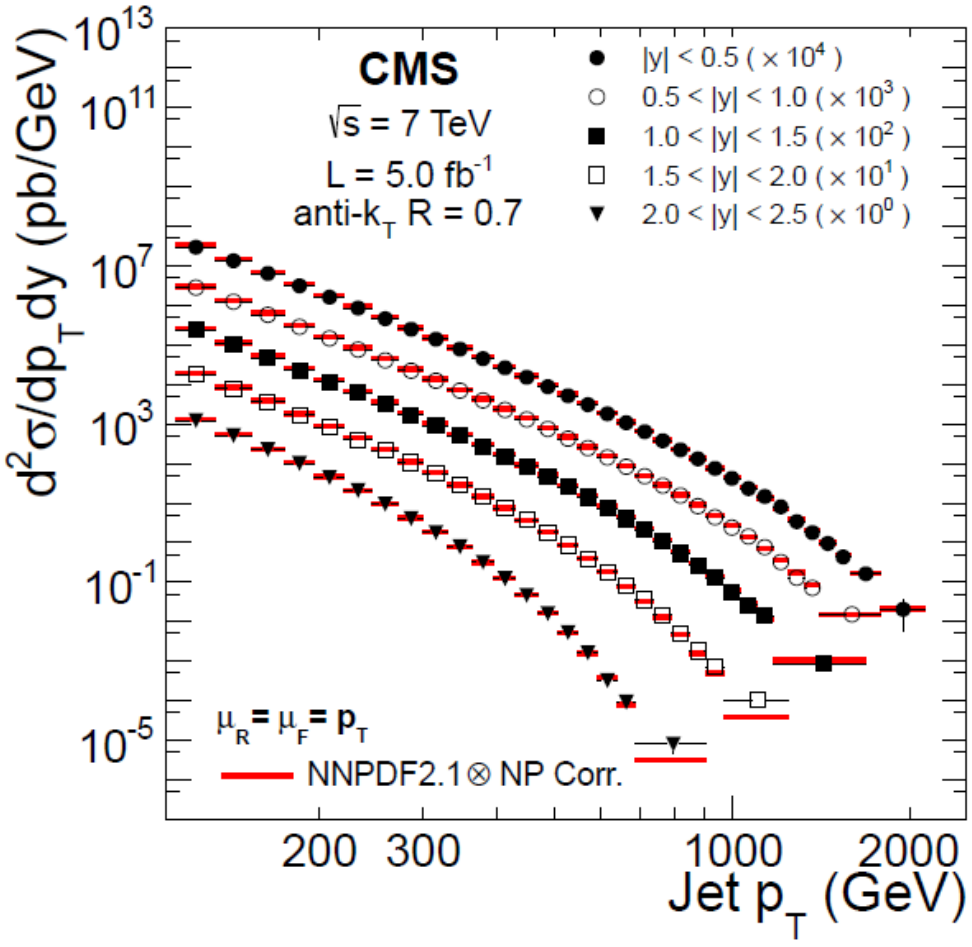
Inclusive jet spectra measurement in pp collisions

Anti-k_T R=0.5



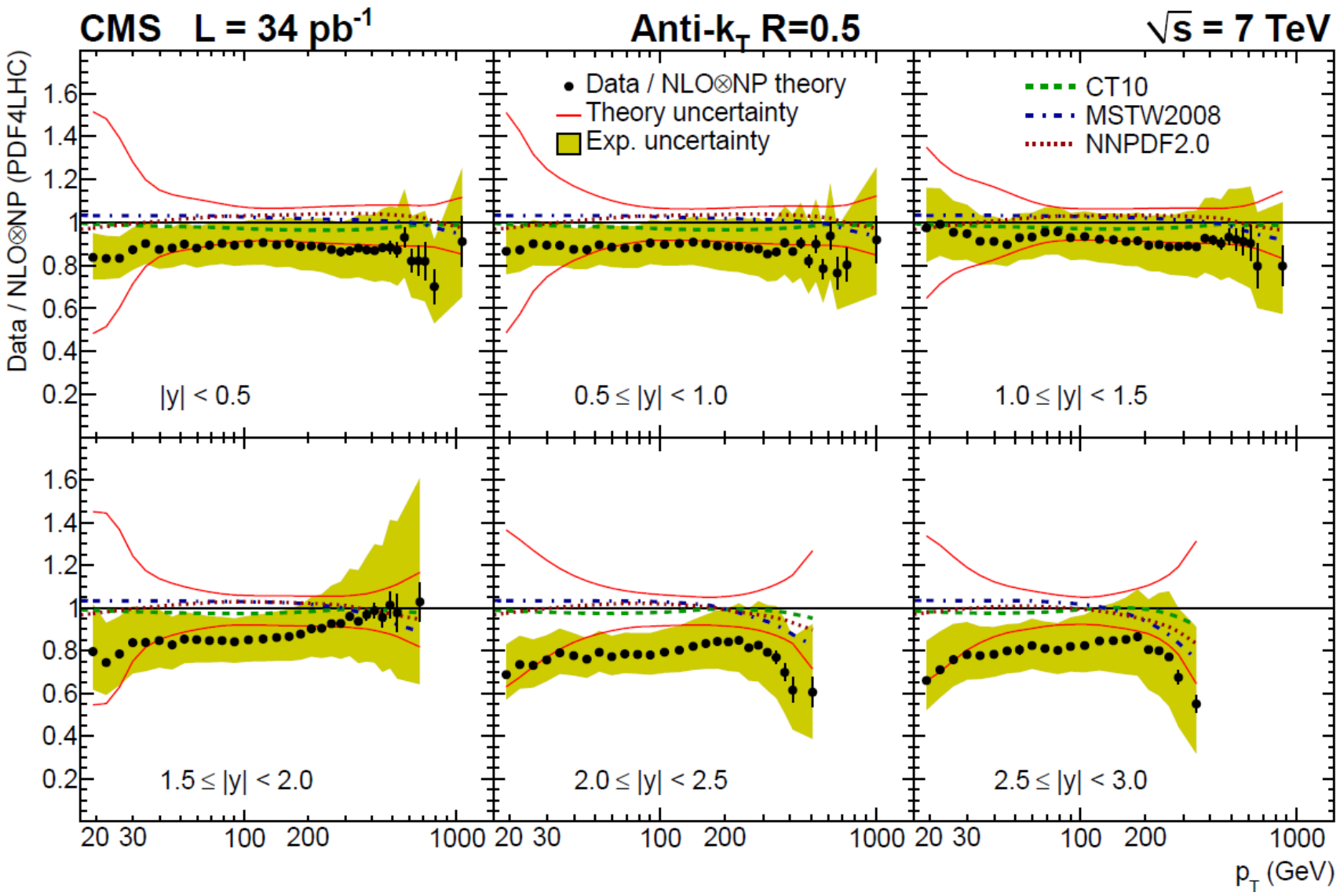
PRL 107 132001 (2011)

Anti-k_T R=0.7



PRD 87 (2013) 112002

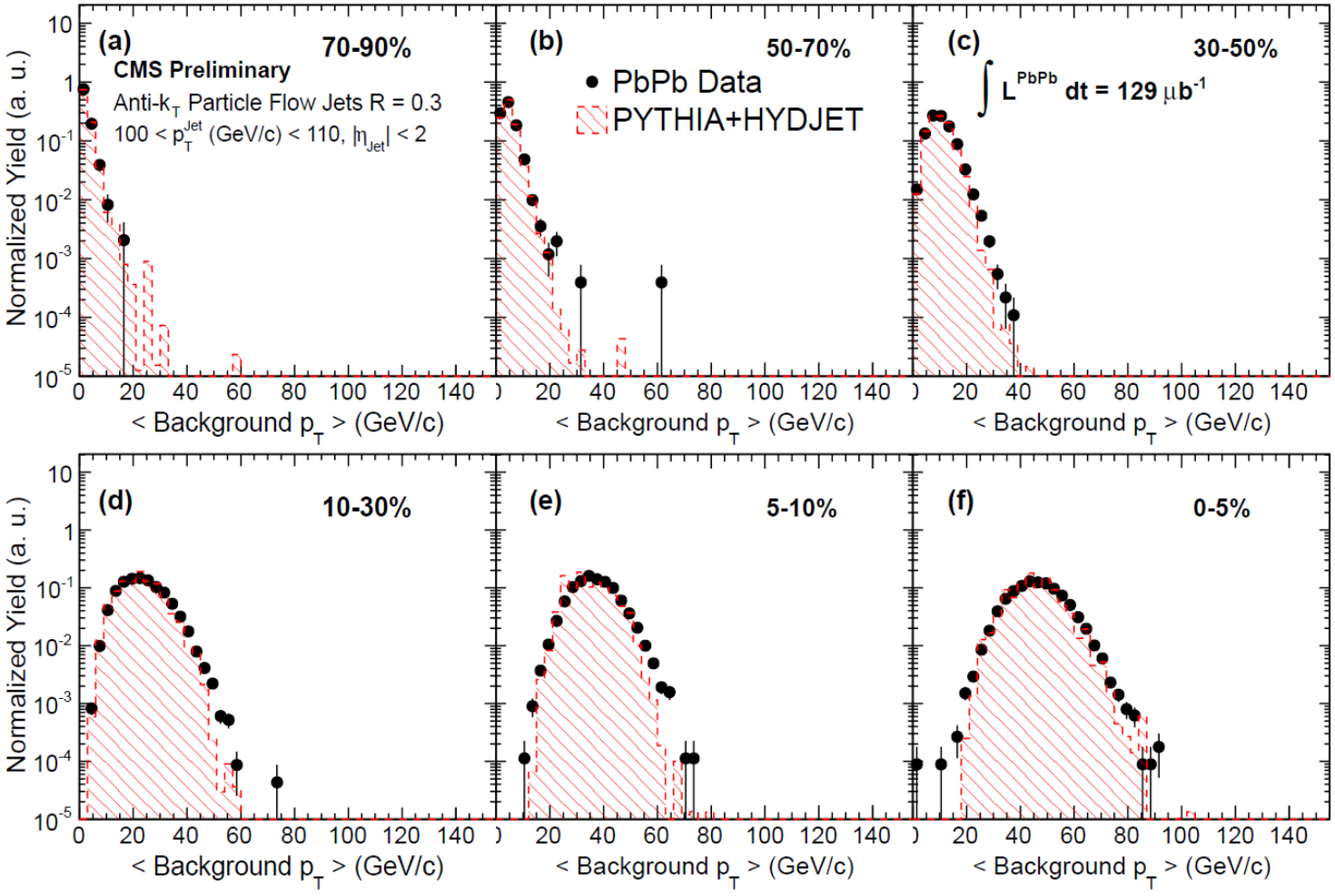
Inclusive jet spectra measurement in pp collisions



Good agreement between corrected spectra and NLO calculation with non-perturbative (NP) correction

PRL 107 132001 (2011)

Subtracted background in PbPb collisions



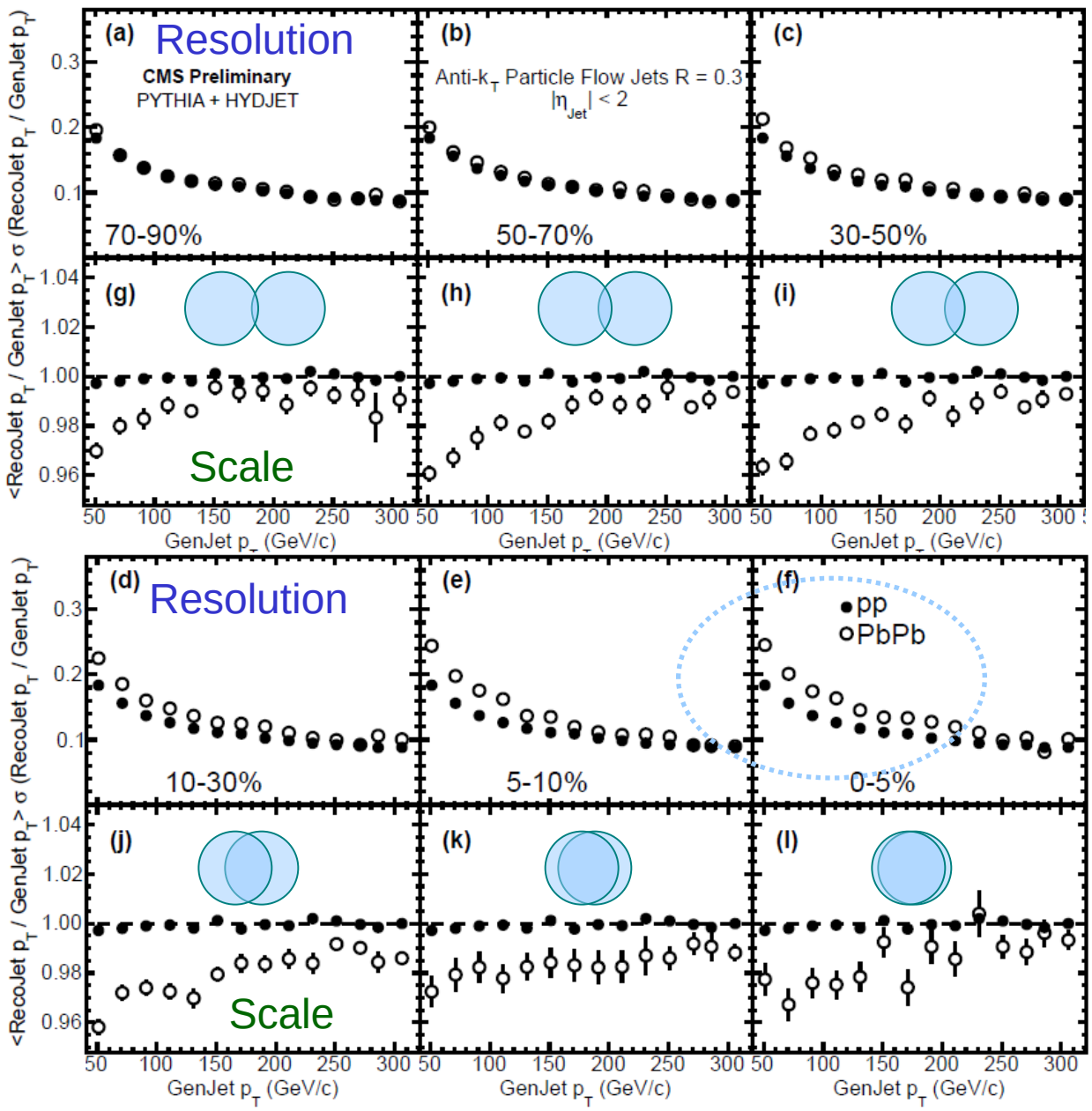
CMS PAS HIN-12-004

- UE background is subtracted event-by-event [See Yue Shi's talk in the morning]
- Iterative PU subtraction method is used in this talk
- HYDJET is tune to describe the UE (as well as its fluctuation)

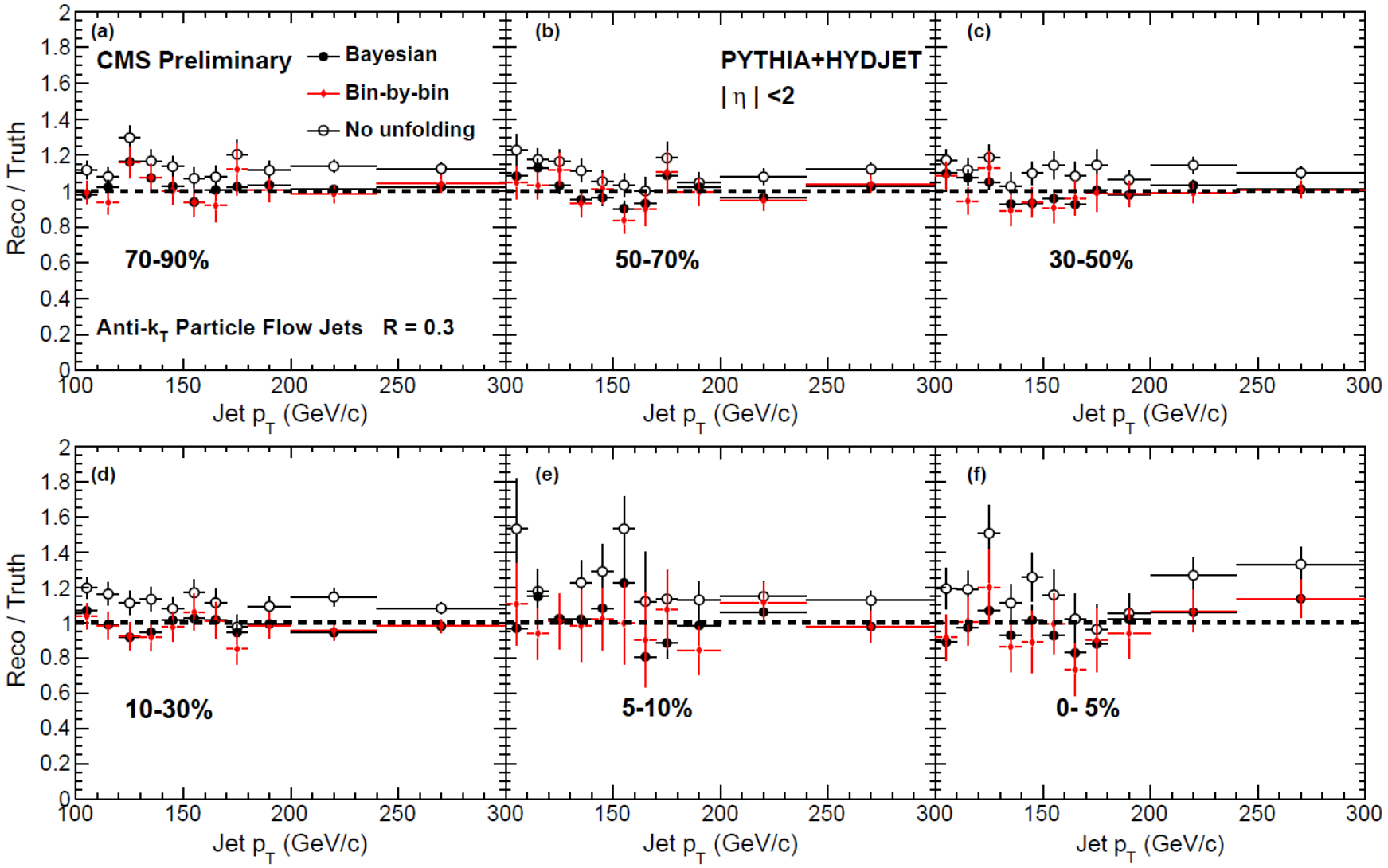
Jet Energy Scale and Resolution

- Jet energy scale and resolution are evaluated from PYTHIA (pp) and PYTHIA+HYDJET (PbPb) simulation
- Jet energy resolution function is Gaussian like in CMS
- Jet energy resolution is slightly worse in central collisions than pp due to UE fluctuations
- Used in jet spectra unfolding

CMS PAS HIN-12-004



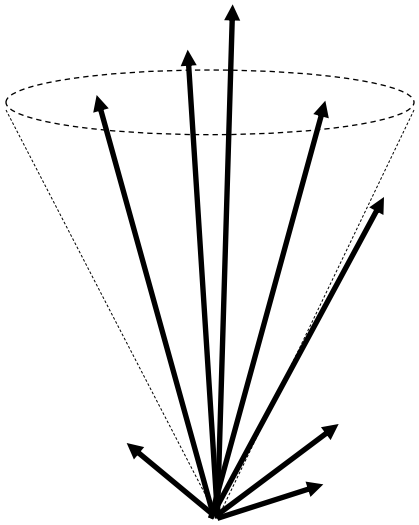
Performance of Spectra Unfolding in PbPb collisions



CMS PAS HIN-12-004

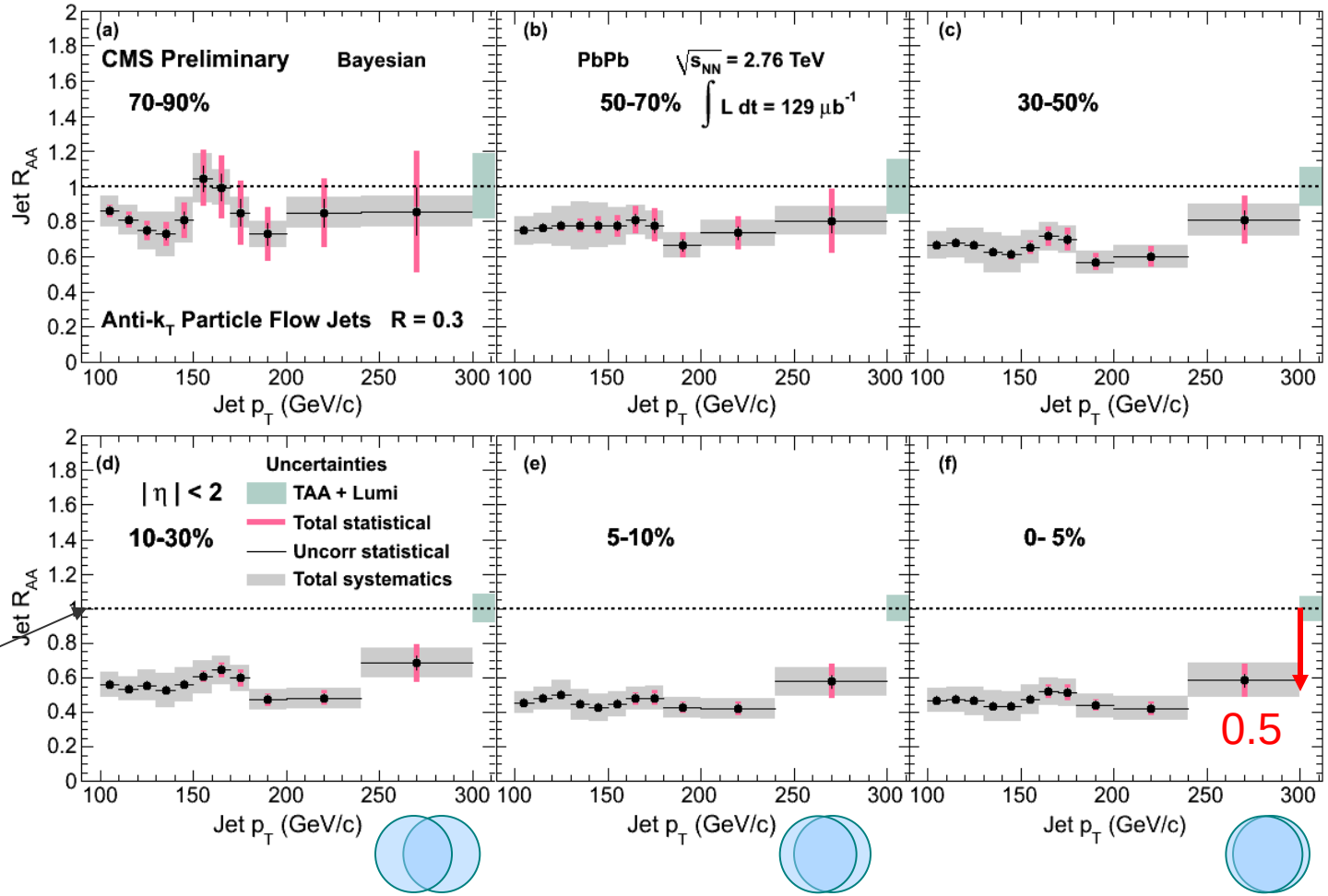
Inclusive jet spectra: jet R_{AA}

Anti-k_T jets with
R = 0.3



If PbPb = superposition of pp

Compare PbPb to pp data

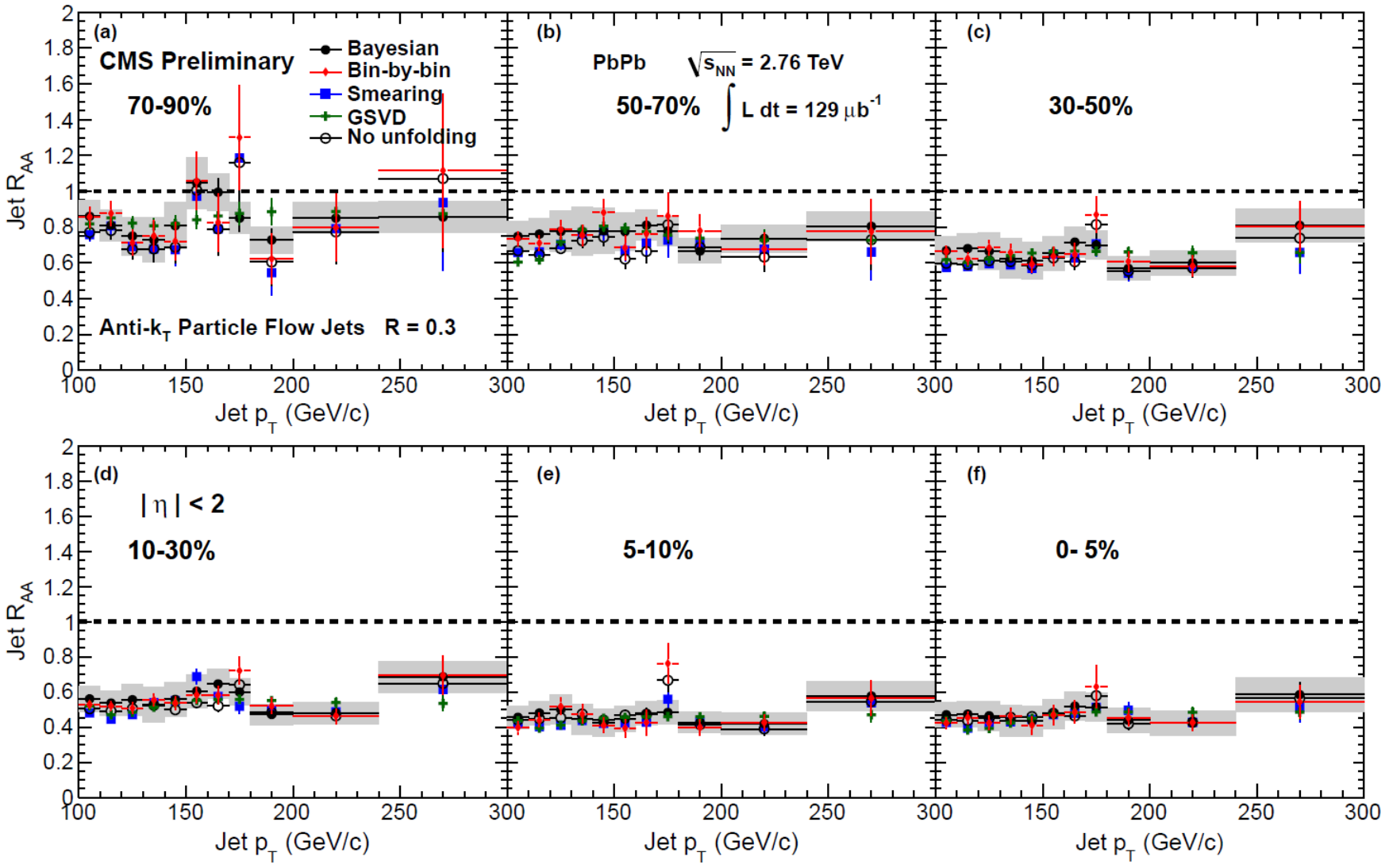


CMS PAS HIN-12-004

Strong suppression of inclusive high p_T jets

Cross-check with different unfolding methods

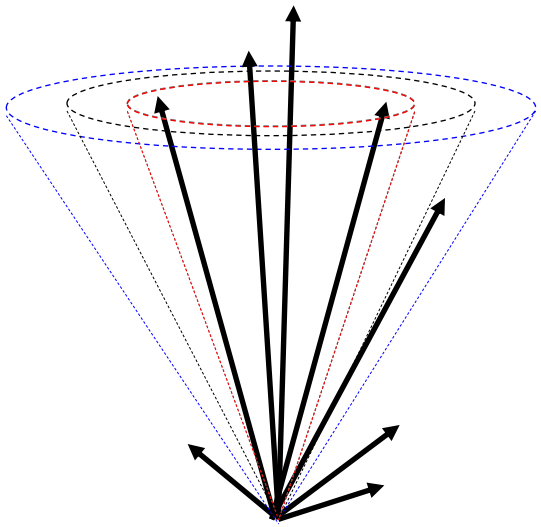
CMS PAS HIN-12-004



Good agreement in different unfolding / folding methods

Inclusive jet spectra: jet R_{AA}

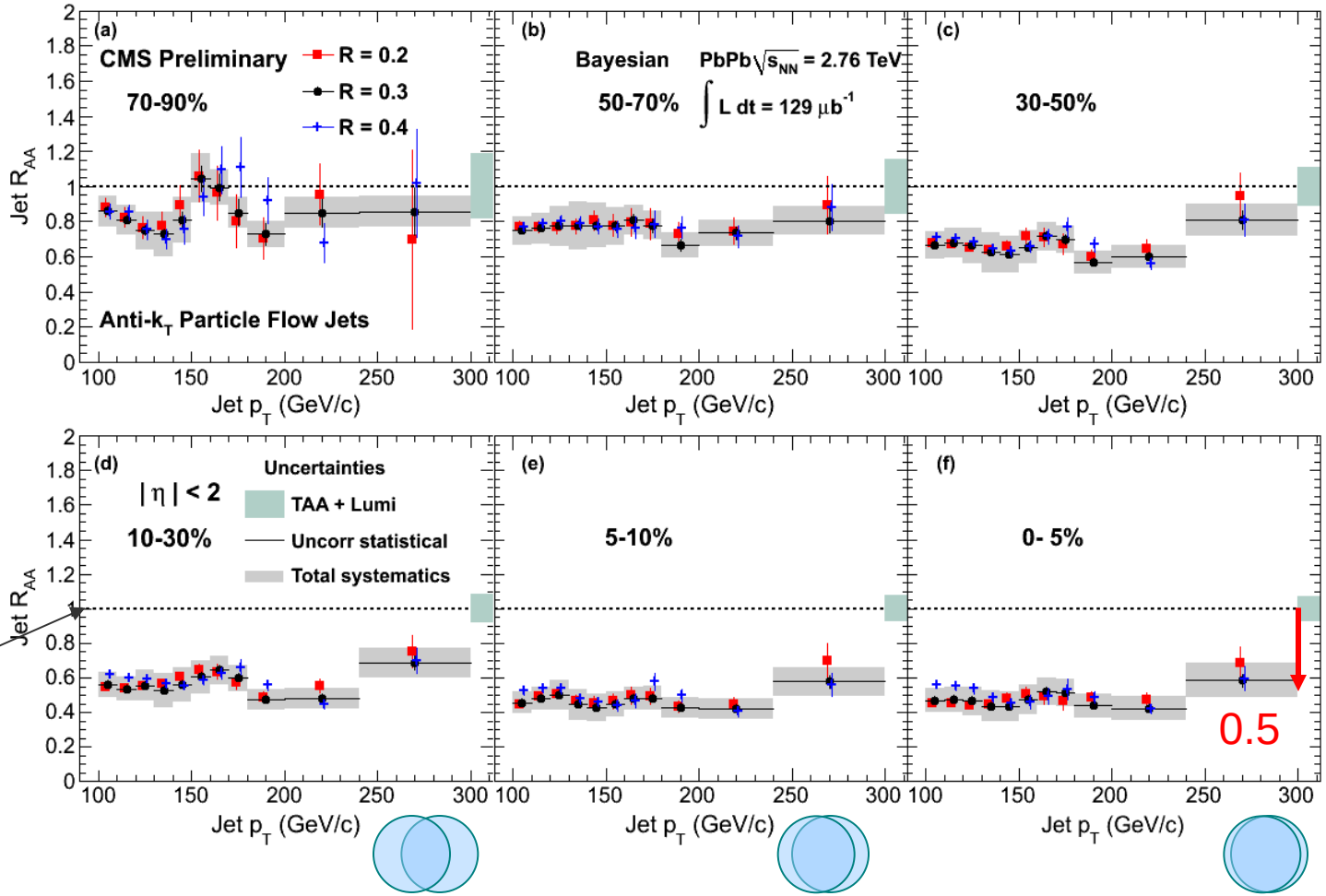
Anti-k_T jets with
R = 0.2, 0.3, 0.4



If PbPb = superposition of pp

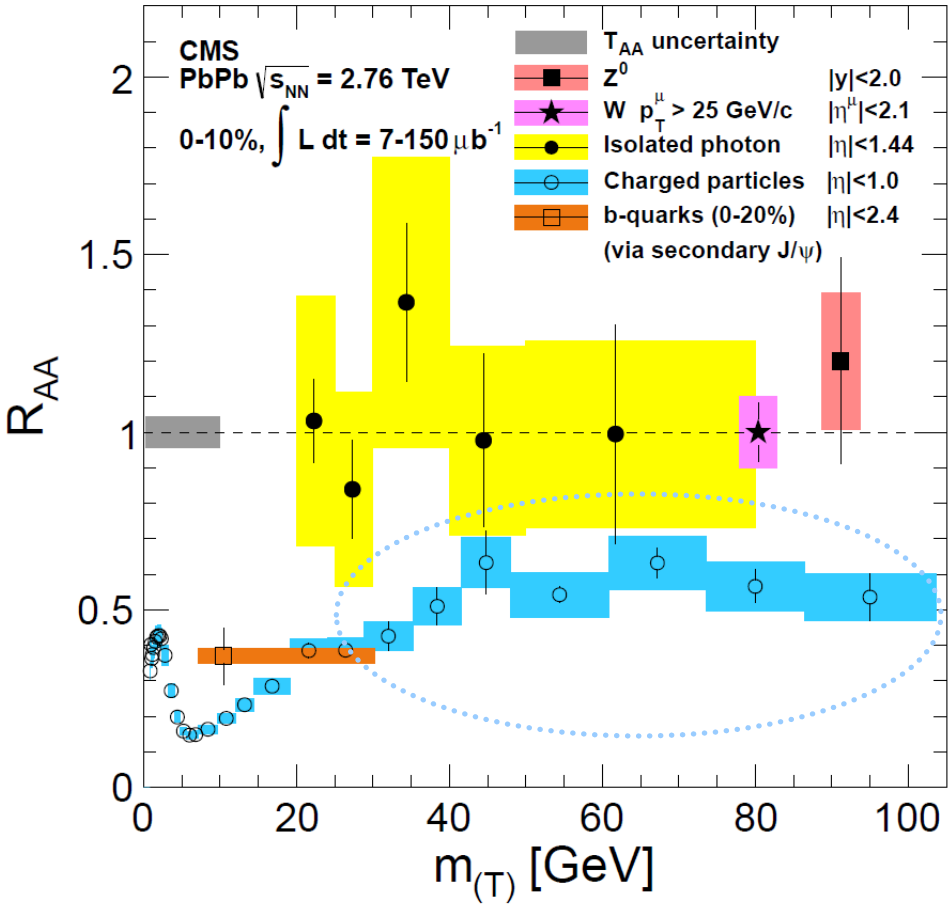
CMS PAS HIN-12-004

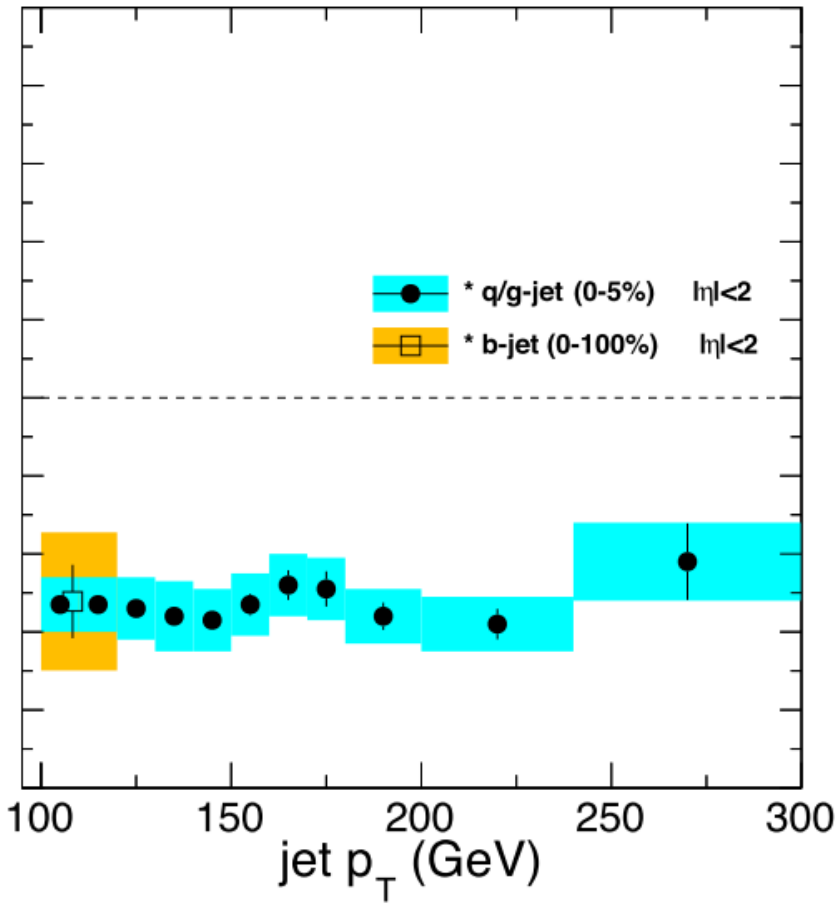
Compare PbPb to pp data



Strong suppression of inclusive high p_T jets
A cone of R=0.2, 0.3, 0.4 doesn't catch all the radiated energy

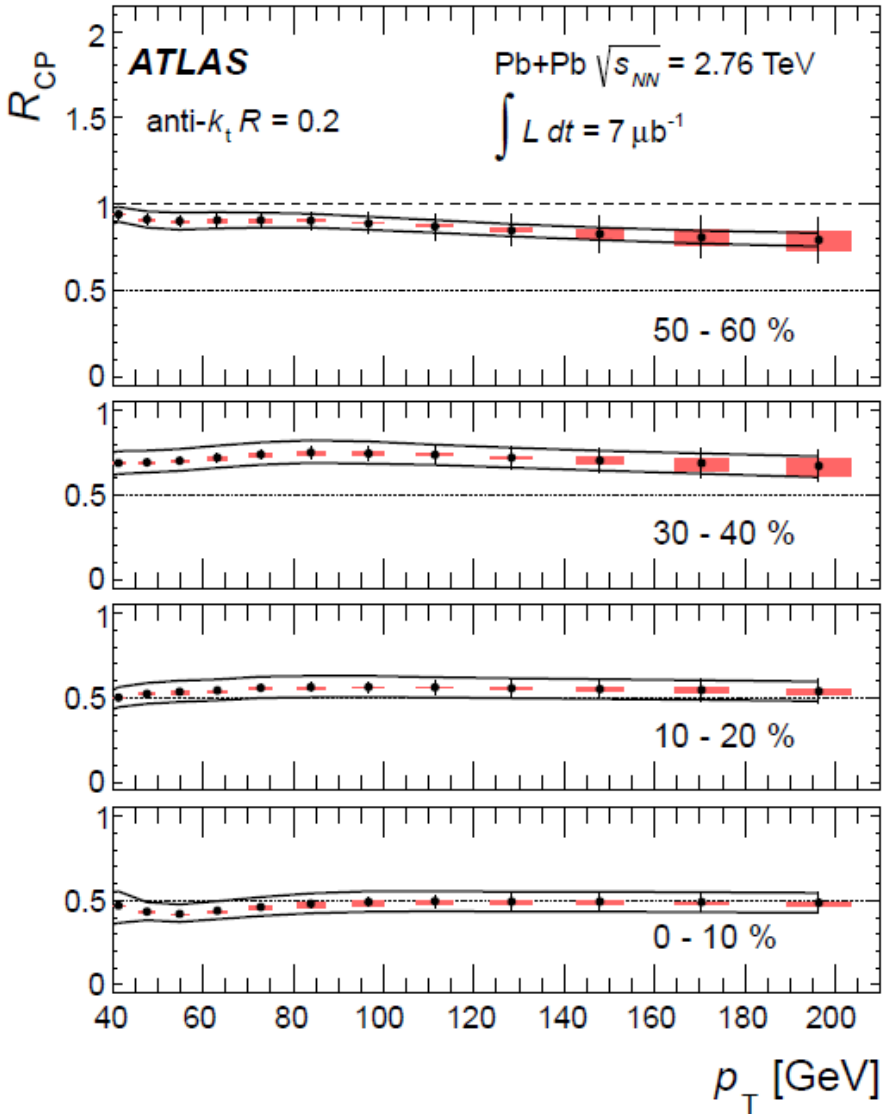
Jet R_{AA} v.s. Track R_{AA}

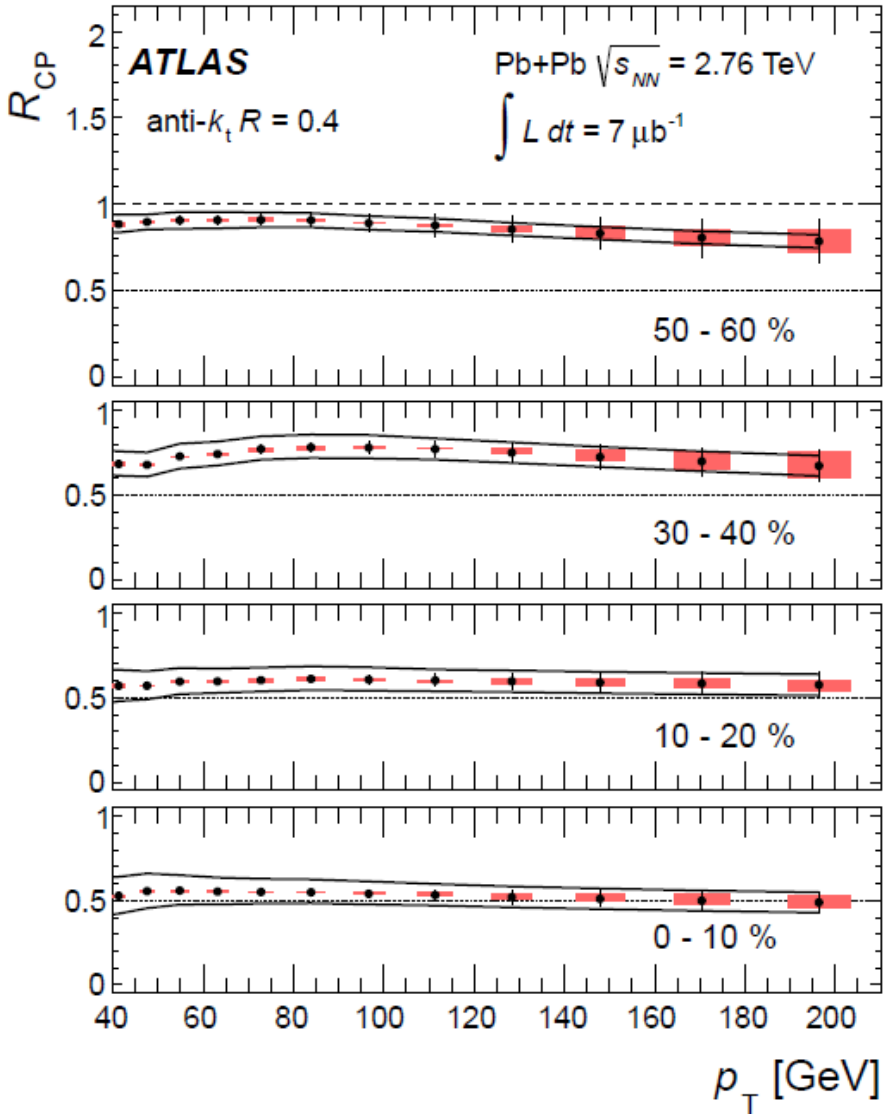




Consistent picture seen in jet and high p_T track R_{AA}

ATLAS R_{CP} measurement

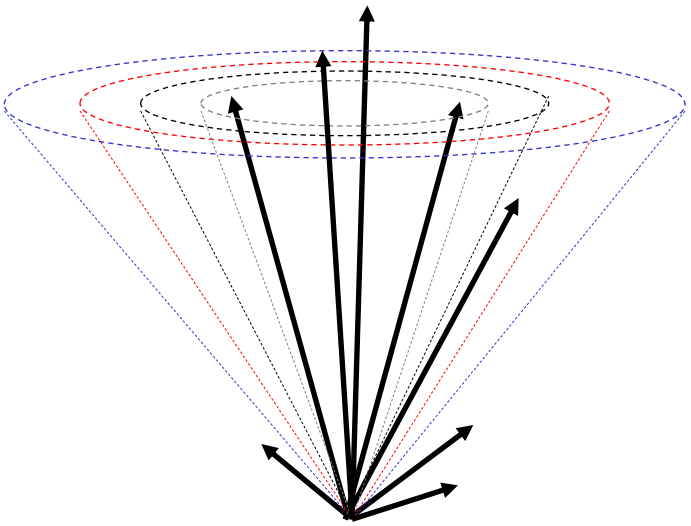


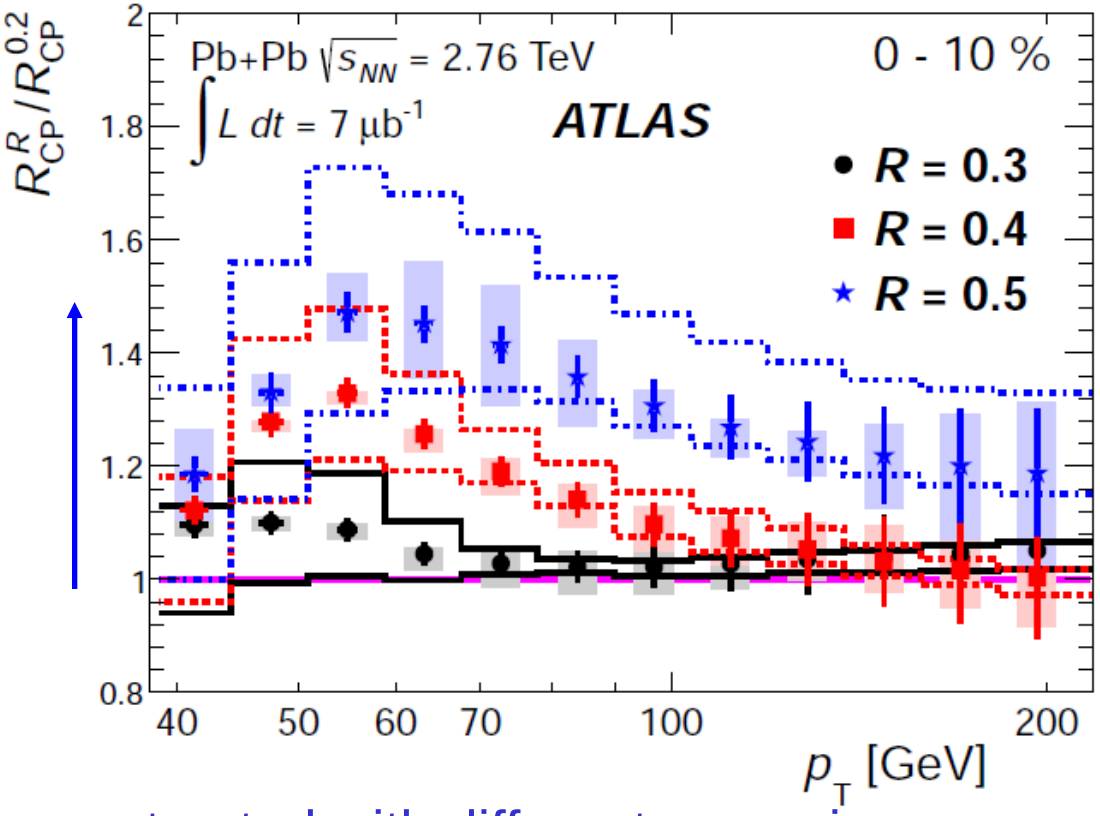


- R_{CP} is constant down to low jet p_T
- Can this be consistent with track $R_{AA(CP)}$?

Do we collect the radiated energy with large cone size?

Anti-k_T jets with
R = 0.2, 0.3, 0.4, 0.5

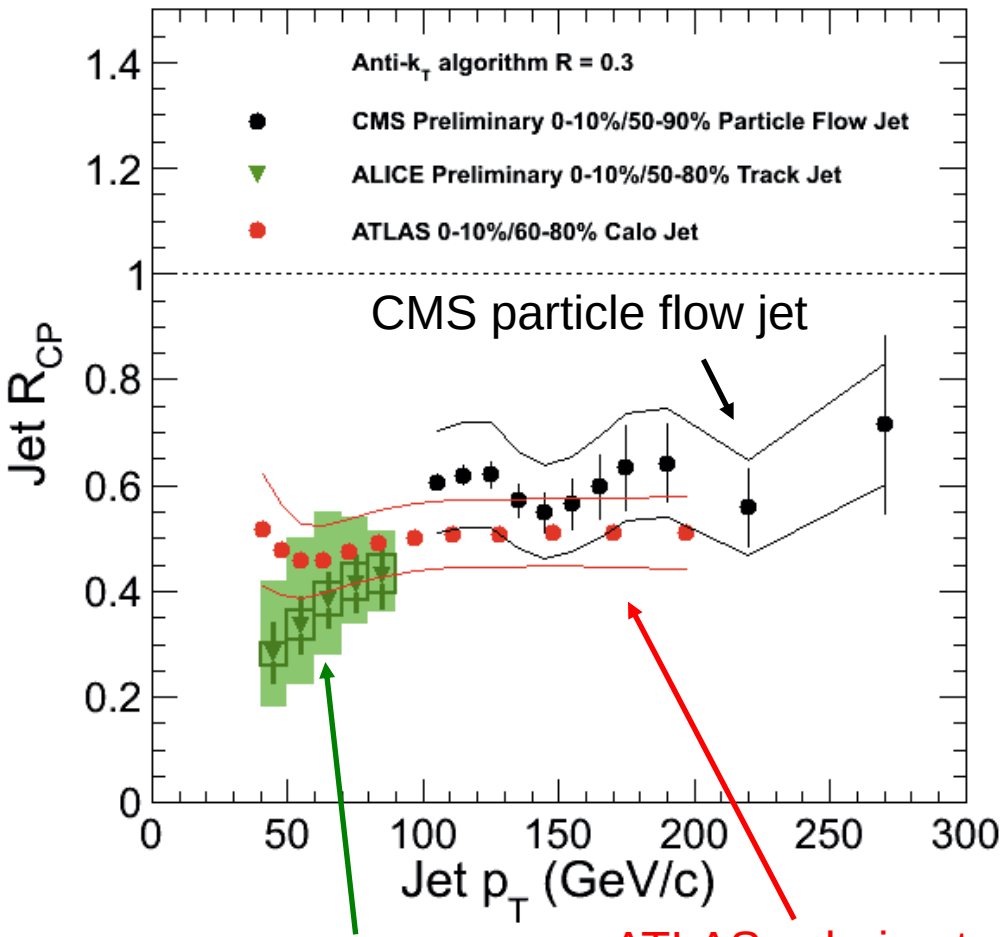




- Ratio of RCP with jets reconstructed with different cone sizes at the same jet p_T
  - Need to treat carefully: actually comparing different parton energy!
- Hint of less suppression with large cone
- Motivate detailed studies on jet shapes

Comparison to ATLAS and ALICE results

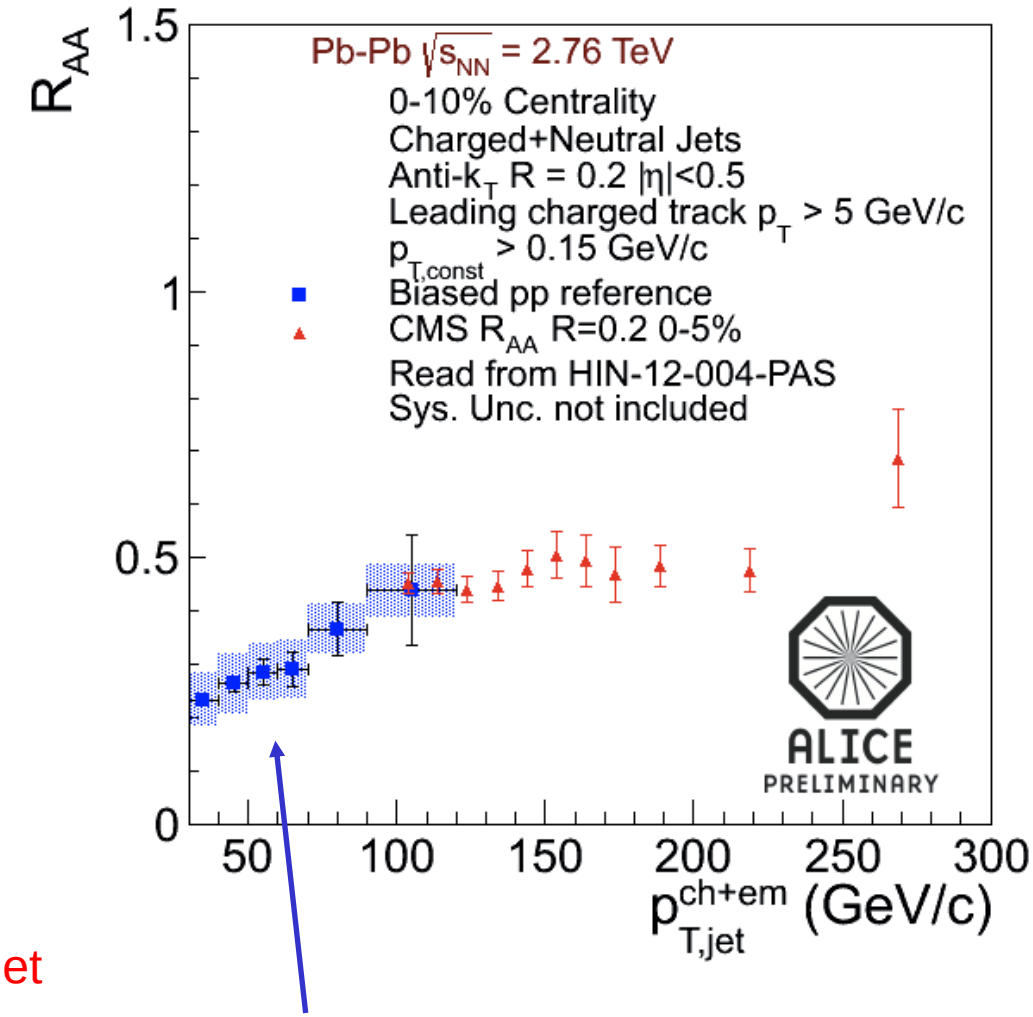
ATLAS do not have R_{AA} measurements
→ Compared R=0.3 R_{CP} results with ATLAS & ALICE presented in QM2012



ATLAS calorimeter jet

ALICE track jet

R=0.2 R_{AA} result comparison
Taken from Rosi Reed's slides presented in HQ2012

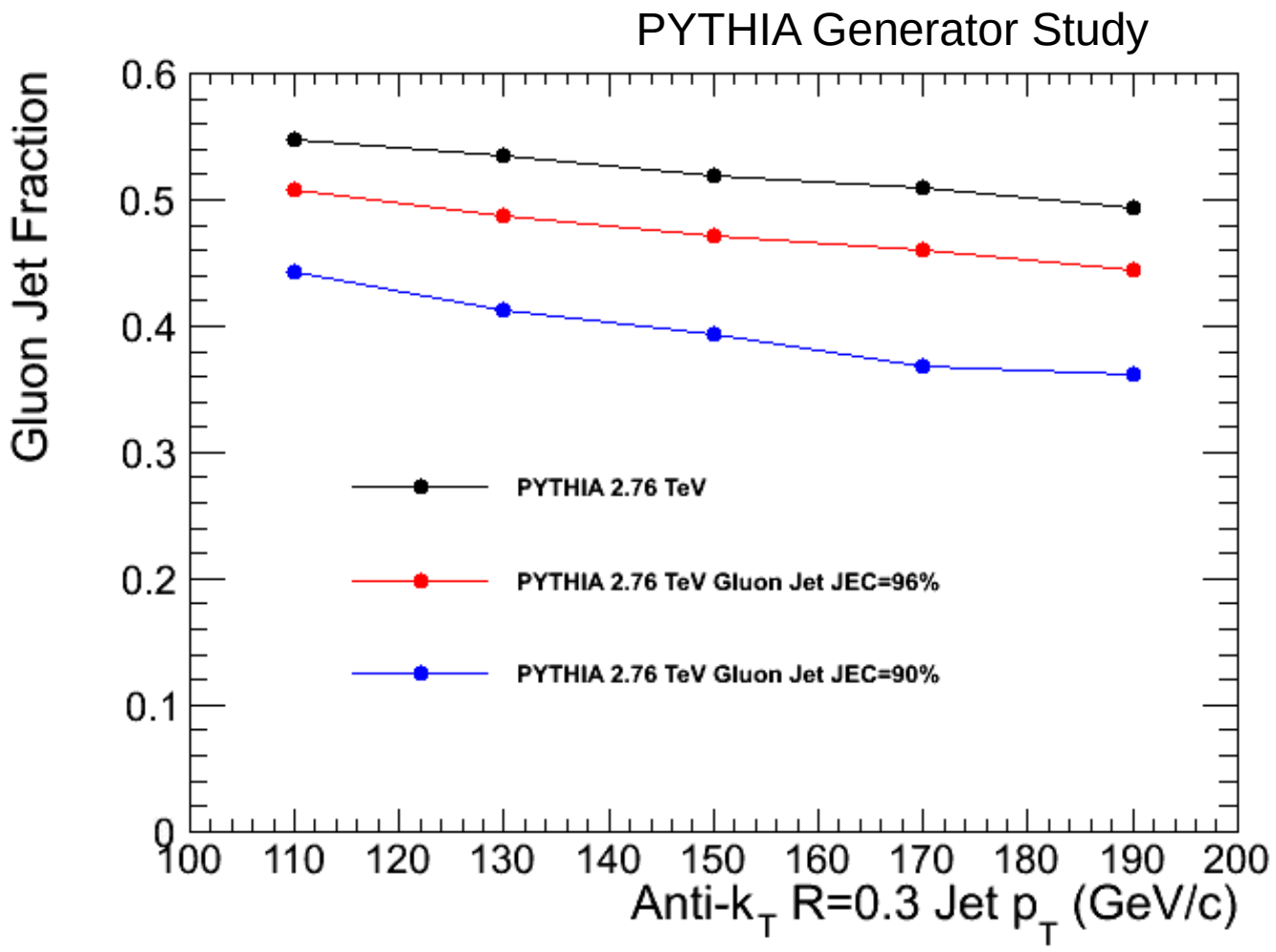


ALICE biased "Charged+Neutral" jet

Open Questions in jet R_{AA} analysis

- Jet energy corrections are obtained from PYTHIA in order to remove the non-linear response of the detector
  - How do we know PYTHA describes the jet fragmentation function (and quark/gluon fraction) in PbPb data?
  - Impact to the jet energy correction
- "Biased selection" and "Noise suppression"
  - Gluon fraction may be changed by requiring a high p_T track in the jet cone or application of "noise suppression" algorithms
  - Jet energy scales of quark jets and gluon jets are different
- How about seriously modified jets?
  - Are they reconstructed? How frequent do they happen?

Generator level studies with PYTHIA



Assuming gluon jet has different jet energy scale compared to quark jet.

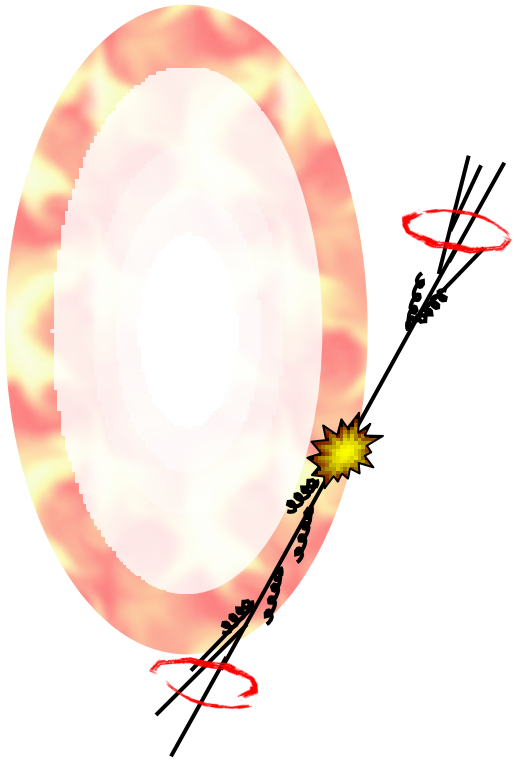
Red line: Gluon jet pT→ 96% * p_T

Red line: Gluon jet pT→ 90% * p_T

PYTHIA 6.4 Z2 Tune
JHEP 0605:026 (2006)

Dijet and photon-jet energy imbalance

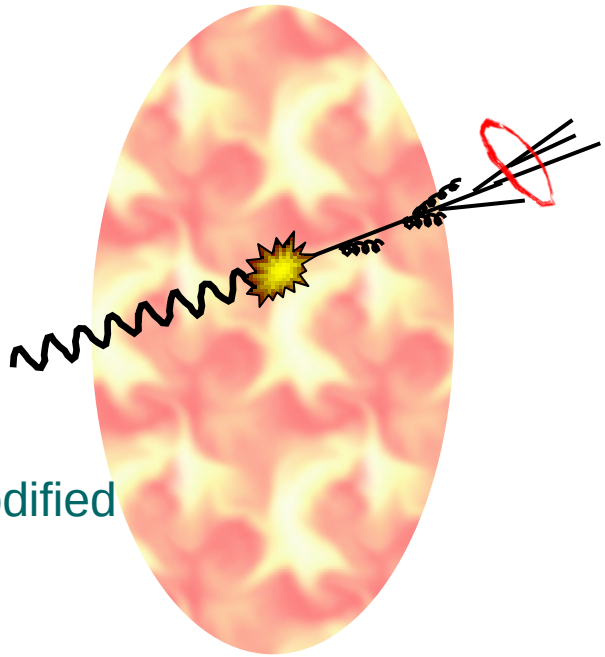
Dijet



High p_T leading jet triggered sample

High statistics, with surface bias

Photon-jet



Photon → unmodified jet energy tag

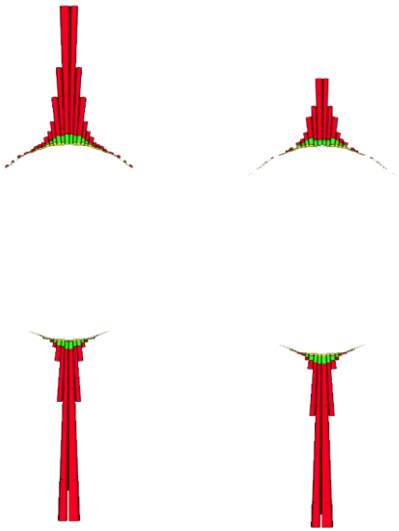
High p_T photon triggered sample

Lower statistics, without surface bias

See Alex Barbieri's talk on 7/2

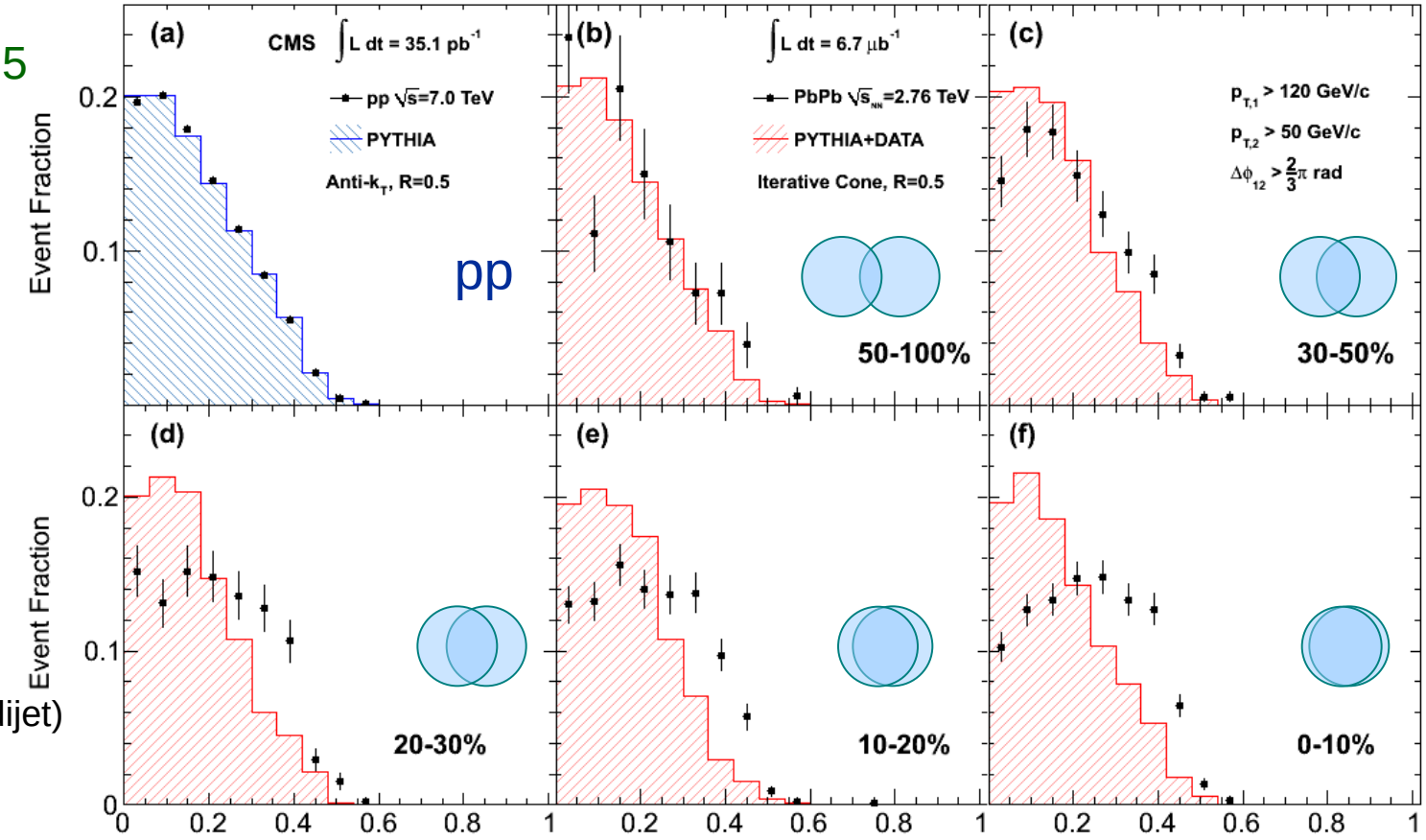
Dijet momentum imbalance

Iterative cone
Calorimeter Jet R = 0.5



Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)



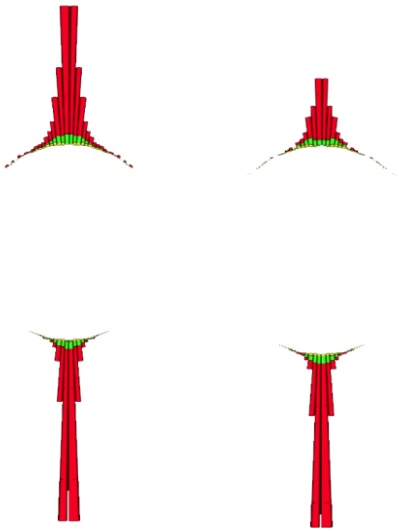
PRC 84 (2011) 024906

$$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$$

Parton energy loss is observed as a pronounced dijet energy imbalance in central PbPb collisions

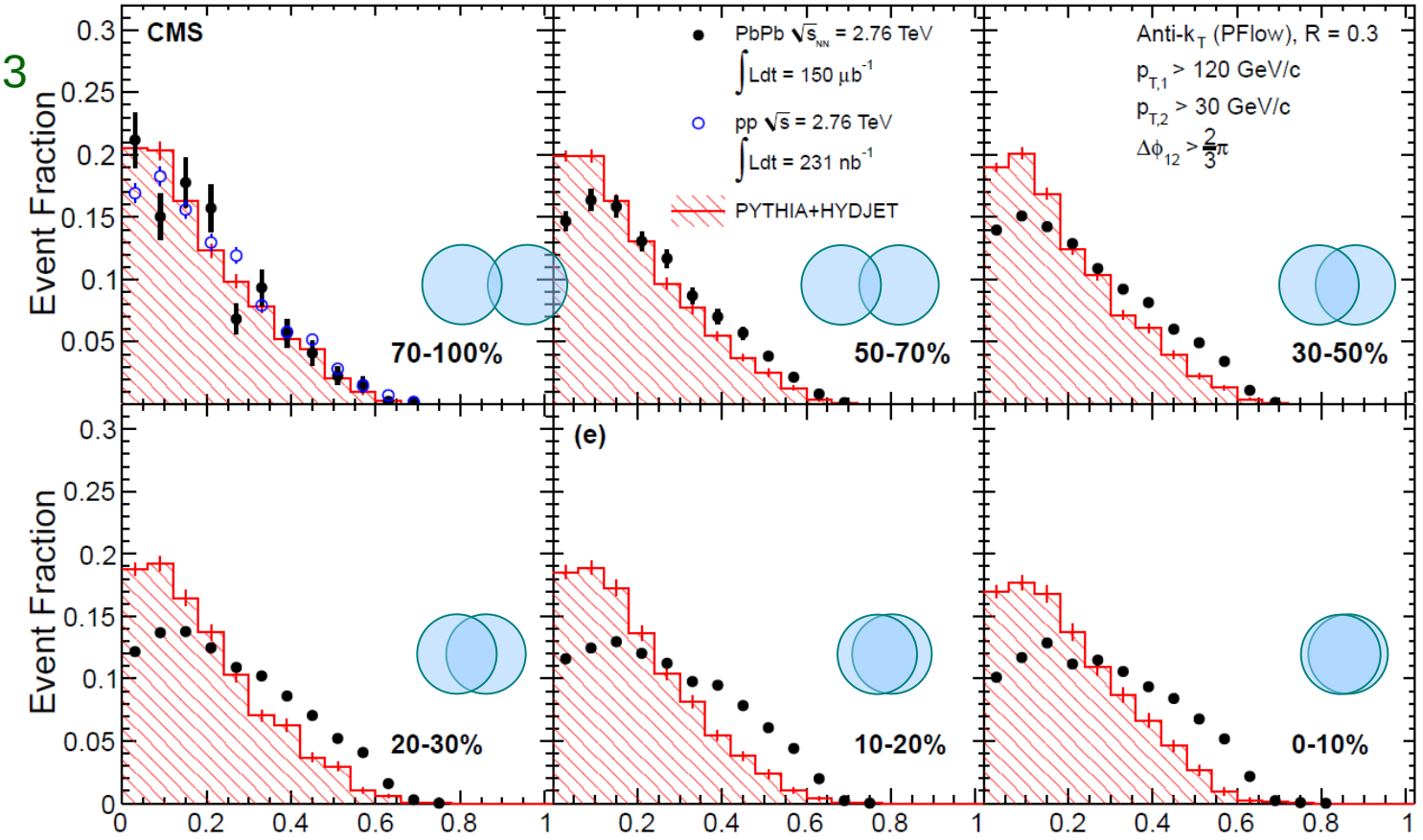
Dijet momentum imbalance

Anti-k_T
Particle Flow Jet R = 0.3



Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)



PLB 712 (2012) 176

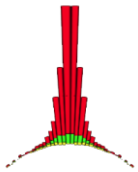
$$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$$

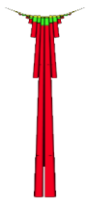
Parton energy loss is observed as a pronounced dijet energy imbalance in central PbPb collisions in dijet reconstructed with R=0.3 and R=0.5

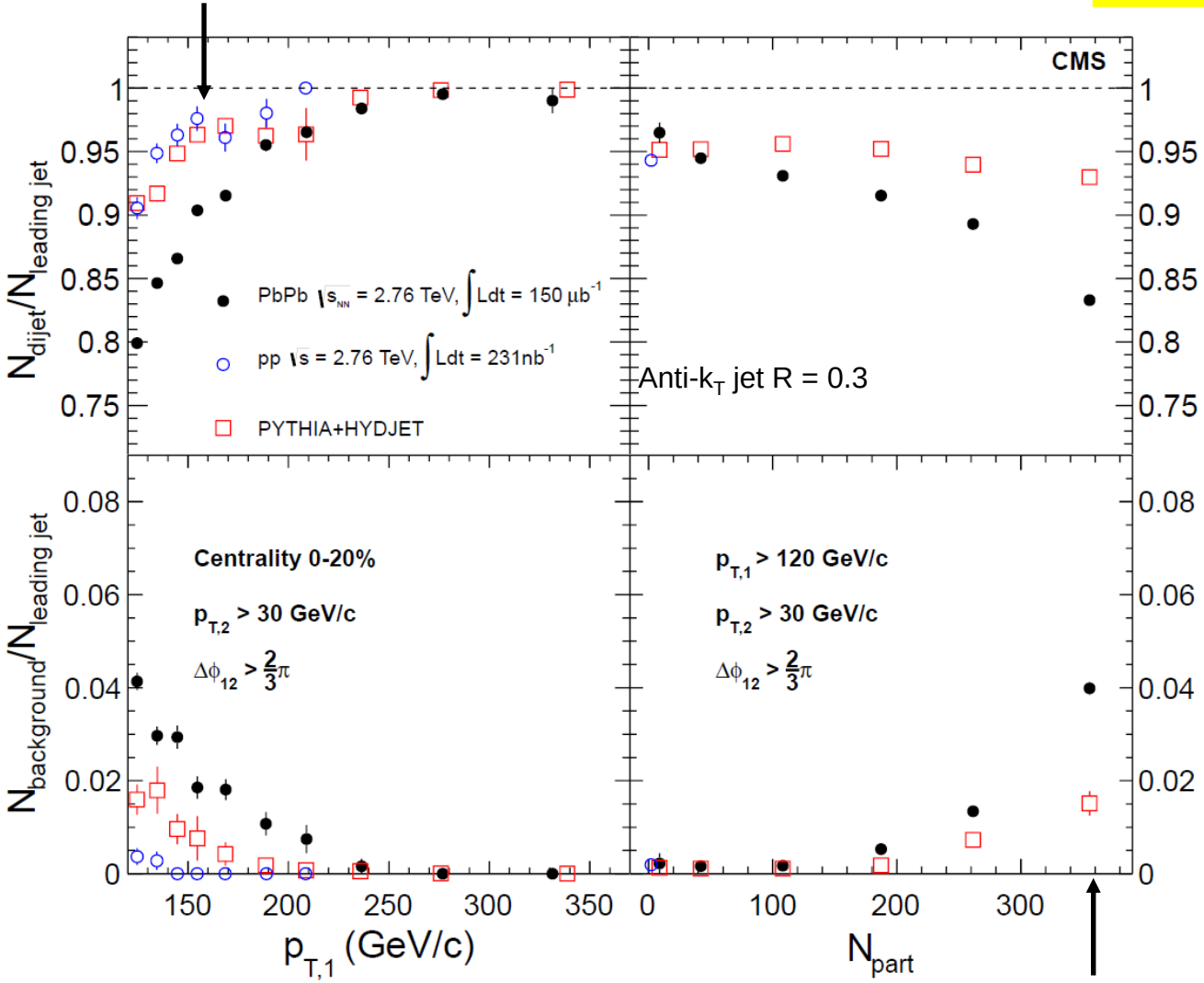
Fraction of leading jets with an away side jet

- Given a leading jet with p_T > 150 GeV/c, >90% of them has a away side partner with p_T > 30 GeV/c

PLB 712 (2012) 176



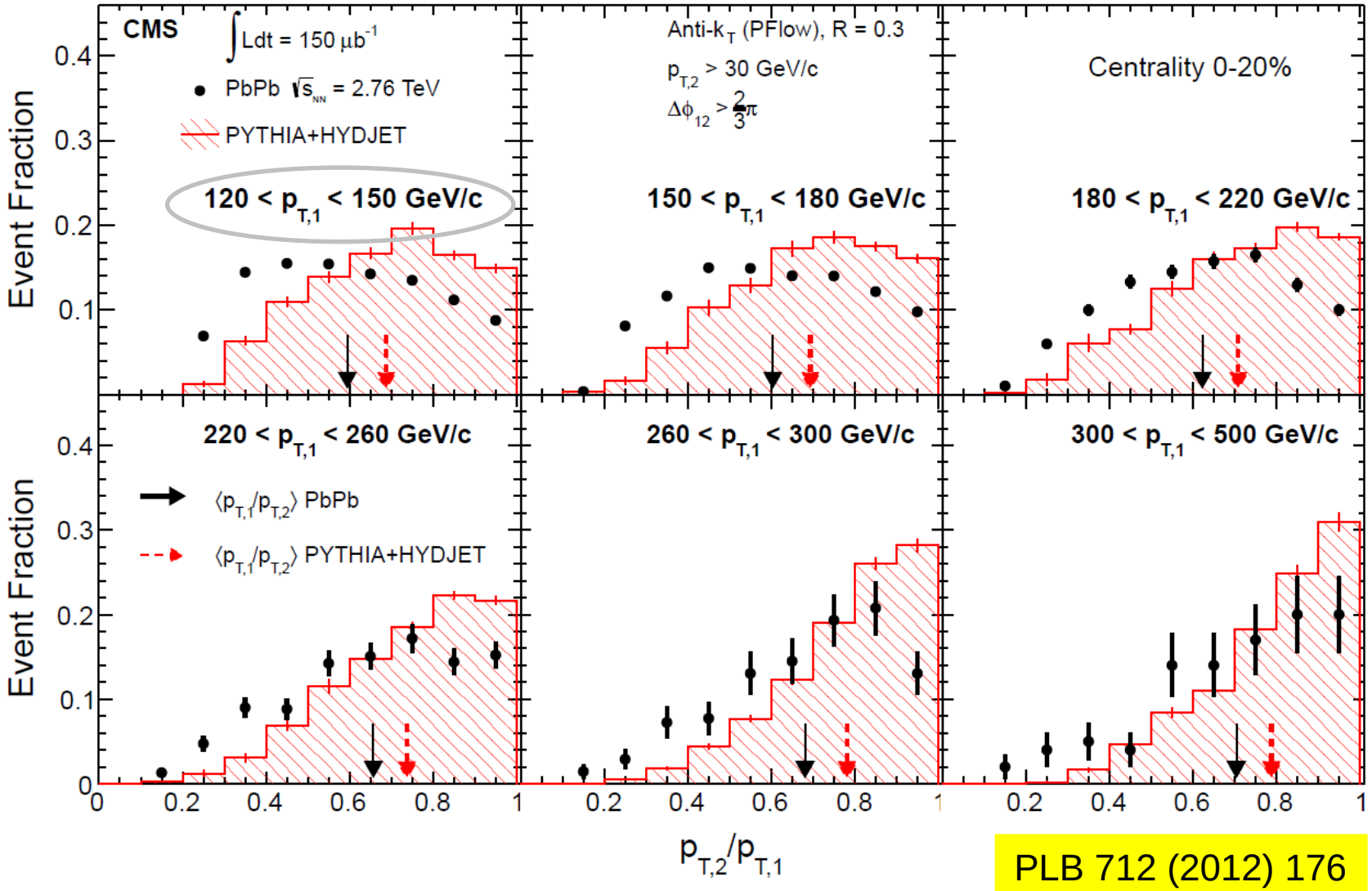




- Fake rate of away side jet is < 4%

Dijet p_T ratio v.s. leading jet p_T

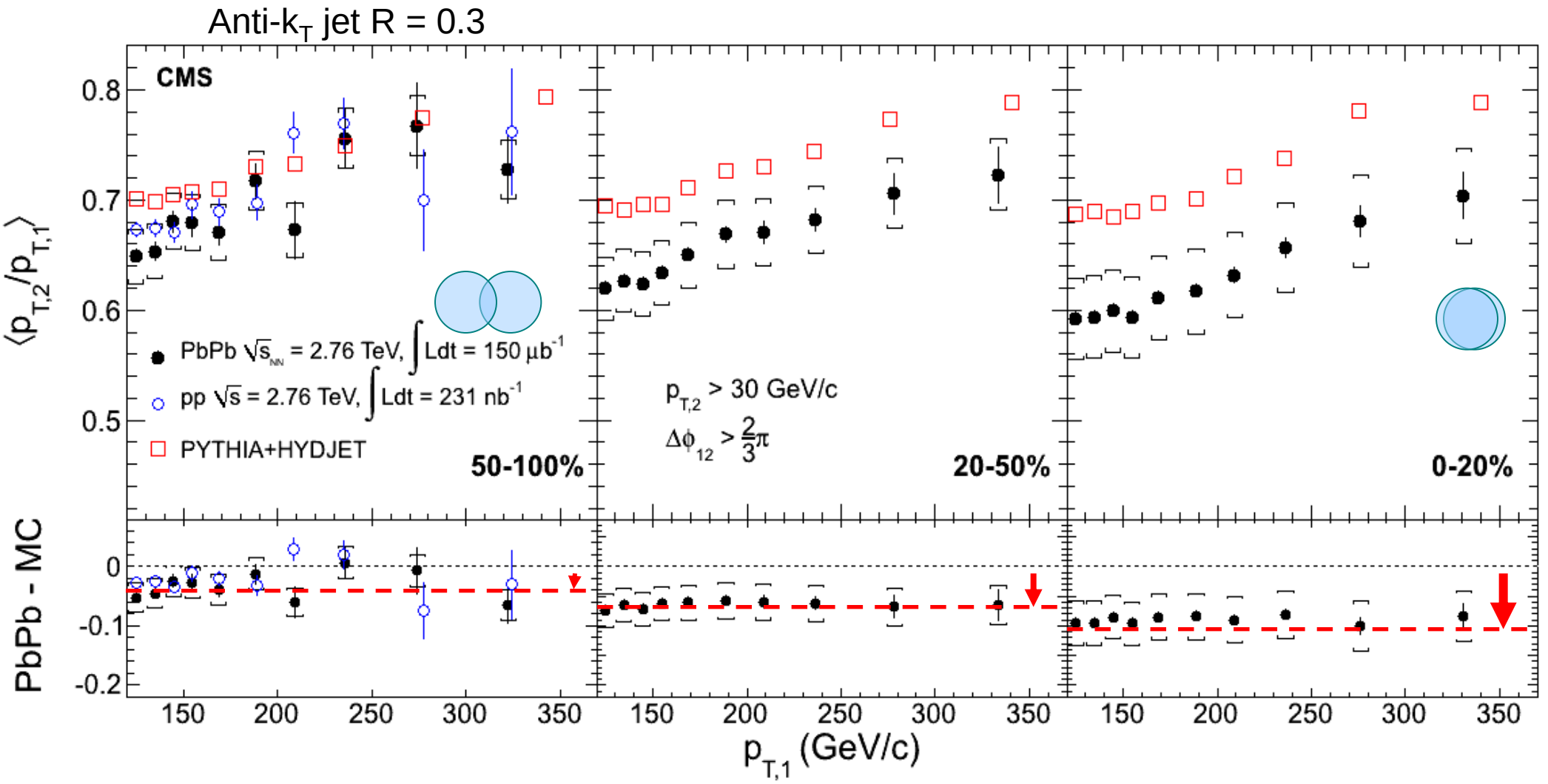
Anti-k_T jet R = 0.3



PLB 712 (2012) 176

- Dijet p_T ratio shape is changing as a function of leading jet p_T
- The highest p_T jets are also quenched

Dijet p_T Ratio (p_{T2}/p_{T1})



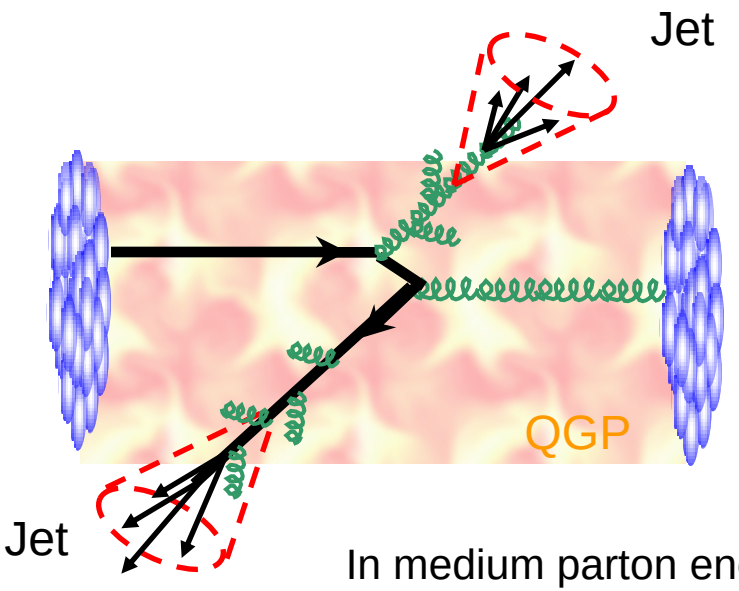
- Energy imbalance increases with centrality
- Very high p_T jets are also quenched

PLB 712 (2012) 176

Dijet azimuthal correlation

Given the large momentum imbalance seen in dijet events

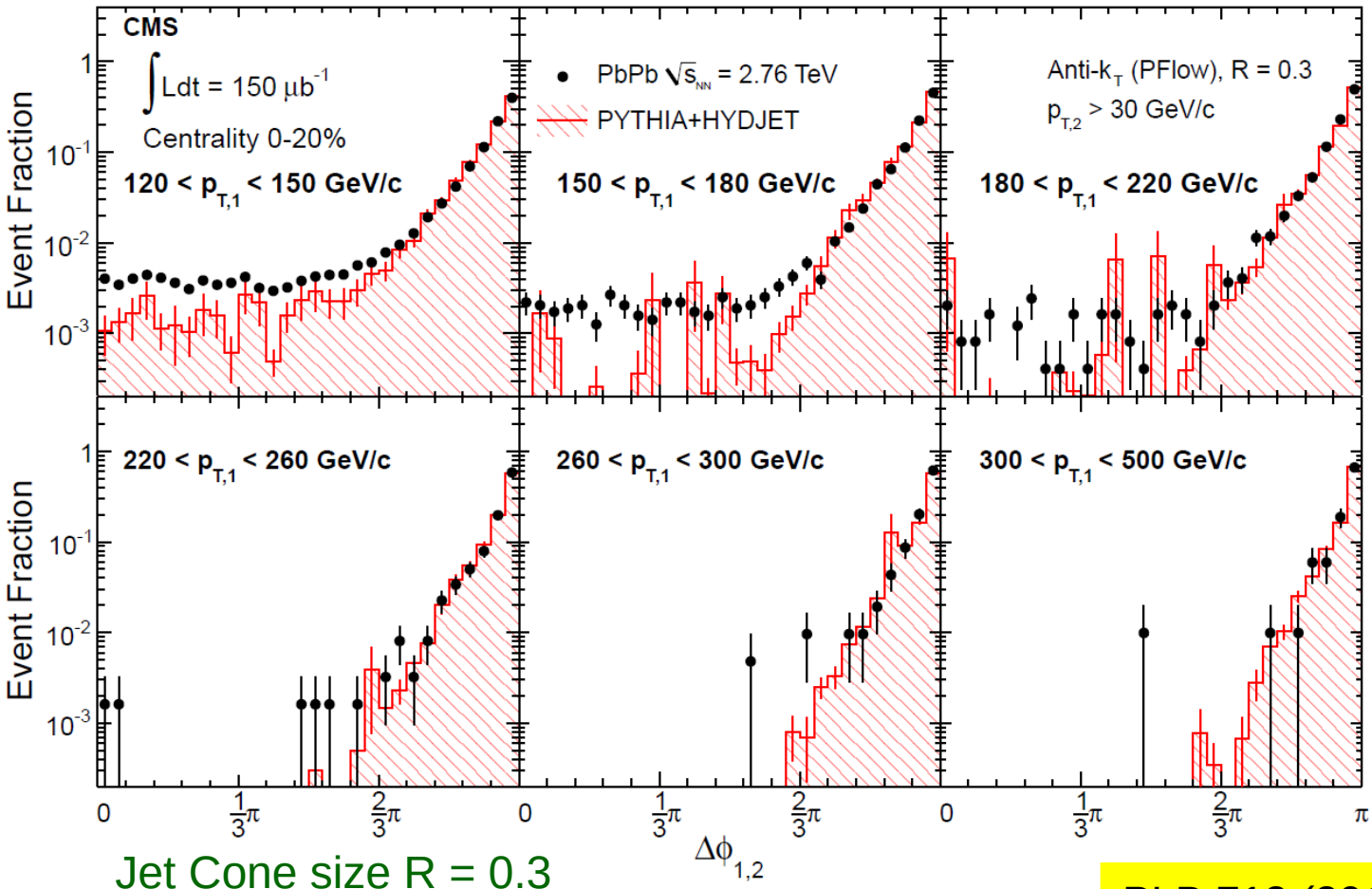
Is the azimuthal correlation modified?



In medium parton energy loss
→ "Jet quenching"

Dijet Azimuthal Angle Correlations

0-20%



Jet Cone size R = 0.3

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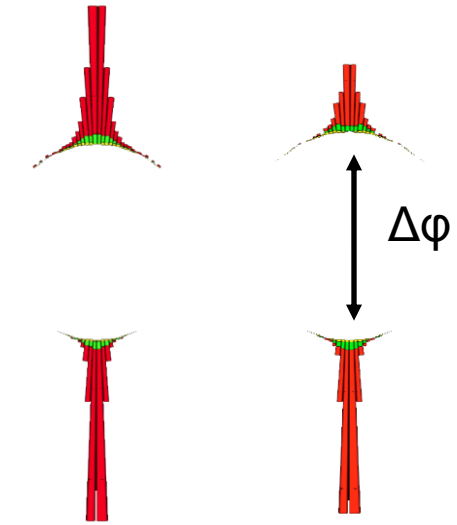
No apparent modification in the dijet Δφ distribution for different jet p_T (still back-to-back)

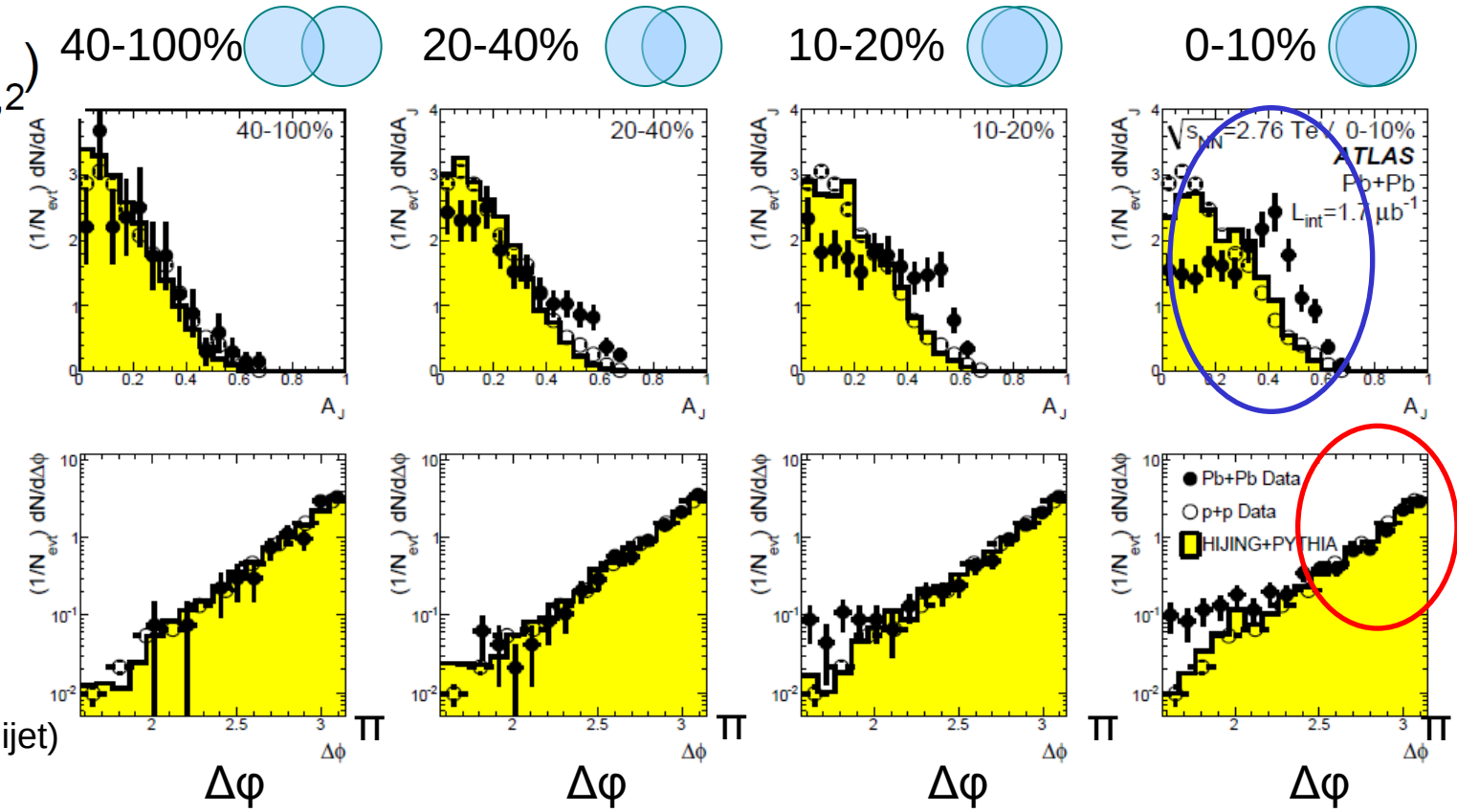
Di-jet imbalance from ATLAS

$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$



Small A_J (Balanced dijet)

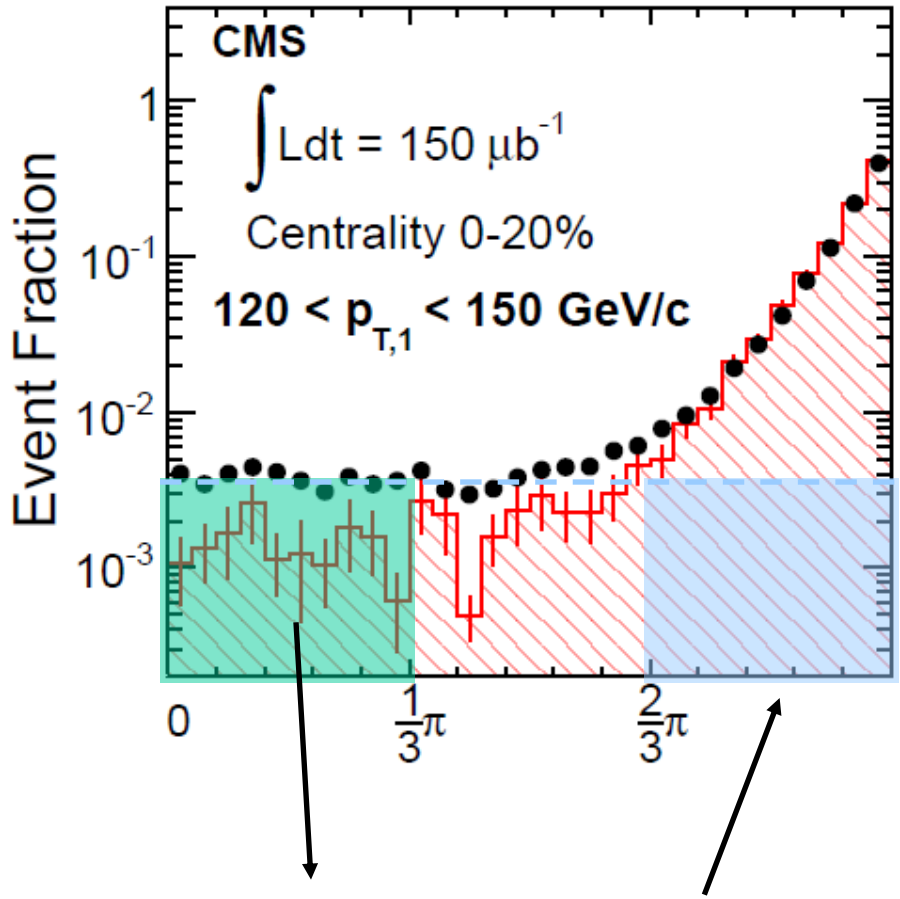
Large A_J (Un-balanced dijet)



- Same conclusion from ATLAS data with different jet kinematics selection (p_{T1}>100 & p_{T2}>25 & Δφ>π/2)
- Contribution of fake jets from UE fluctuation is not removed in ATLAS measurement, shown as a peak structure in 0-10% data

Discussion on the dijet asymmetry measurements

- Consistent picture seen in ATLAS and CMS experiments
  - Results from ALICE?
- A_J and p_T ratio distributions: contribution from fake jets coming from UE fluctuation:
  - CMS treatment: Δφ sideband subtraction
  - ATLAS: no subtraction, check with jets with R=0.2 or fake jet rejection
- Both CMS and ATLAS did not correct the jet resolution smearing
  - Is correction of the jet energy smearing effect possible?
  - CMS: provide smearing function
  - CMS & ATLAS: investigating unfolding of the A_J and p_T ratio spectra



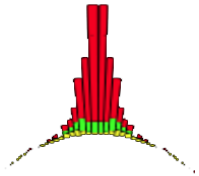
Used to derive leading jet-fake jet A_J or p_T ratio distributions

See the discussion in Yetkin's talk on 7/4

Where does the energy go?

- Suppression of high p_T jets
- Large dijet momentum imbalance

ΔE_T ~ O(10) GeV,
~10% shift in <dijet p_T ratio>



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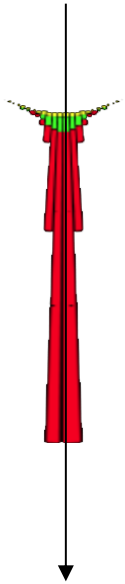


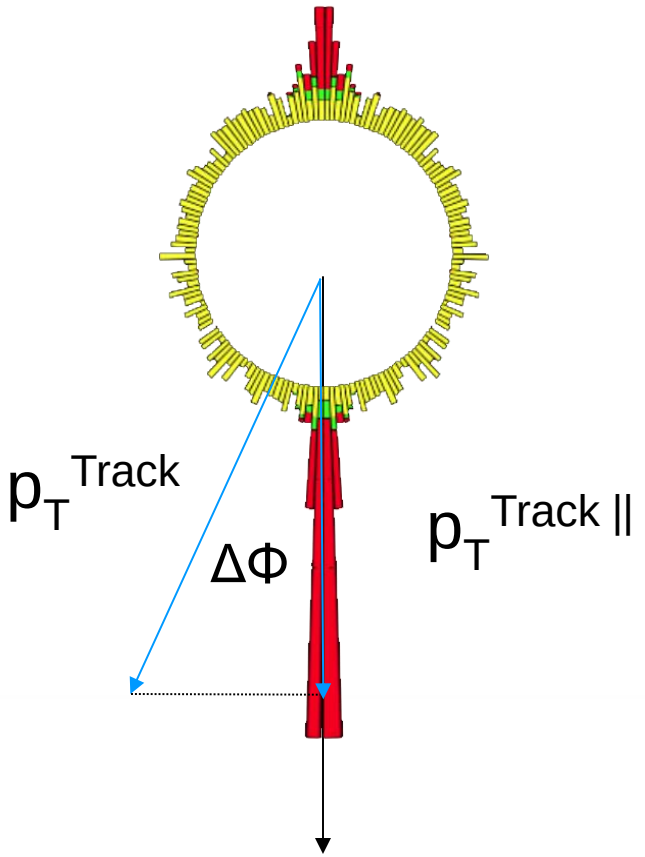
Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Where does the energy go?

- Calculate projection of p_T on leading jet axis and average over selected tracks with

  $p_T > 0.5$ GeV/c and
  $|\eta| < 2.4$



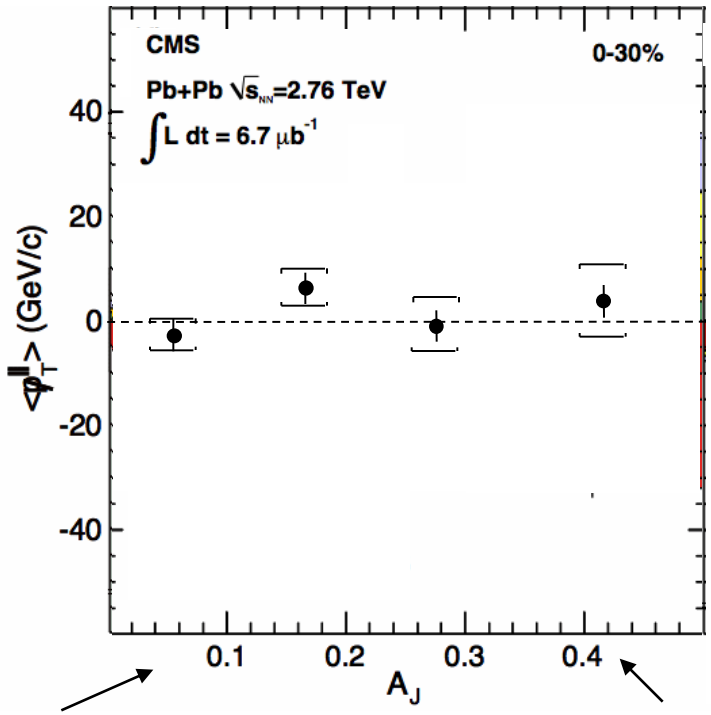
Underlying events cancels

Sum over all tracks in the event

Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

0-30% Central PbPb



balanced jets

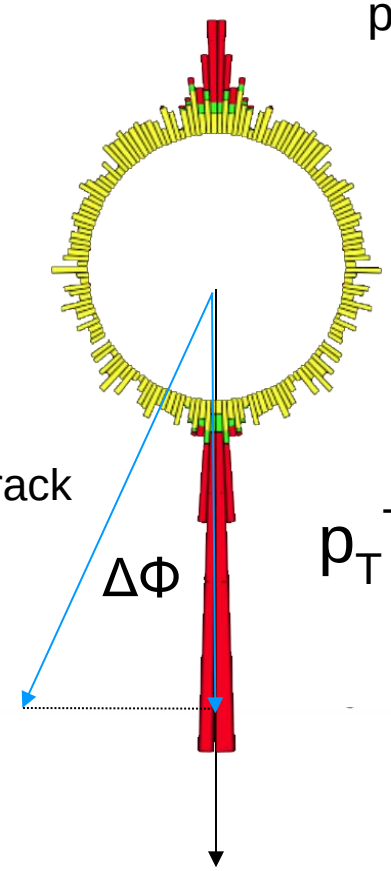
unbalanced jets

excess away from leading jet

Balanced!!

excess towards leading jet

Track
p_T > 0.5 GeV/c



$$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$$

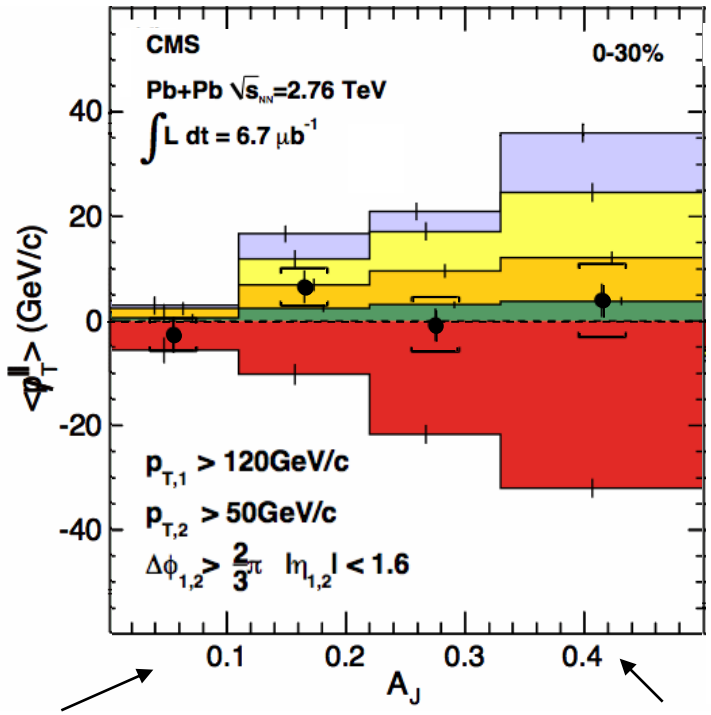
Integrating over the whole event final state

the dijet momentum balance is restored

Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

0-30% Central PbPb

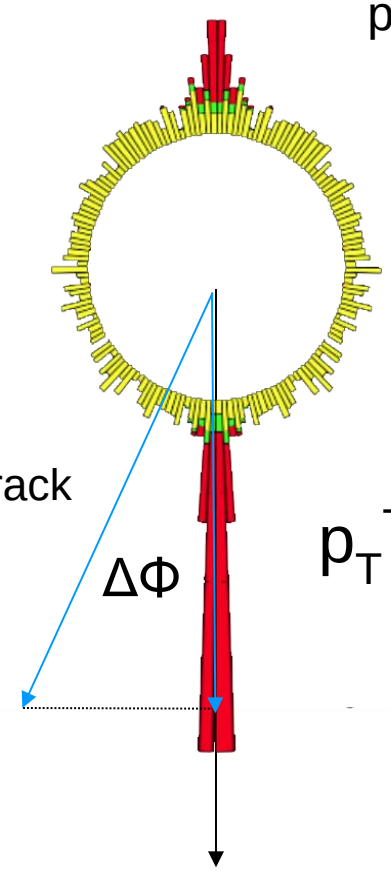


excess away from leading jet

Balanced!!

excess towards leading jet

Track
p_T > 0.5 GeV/c



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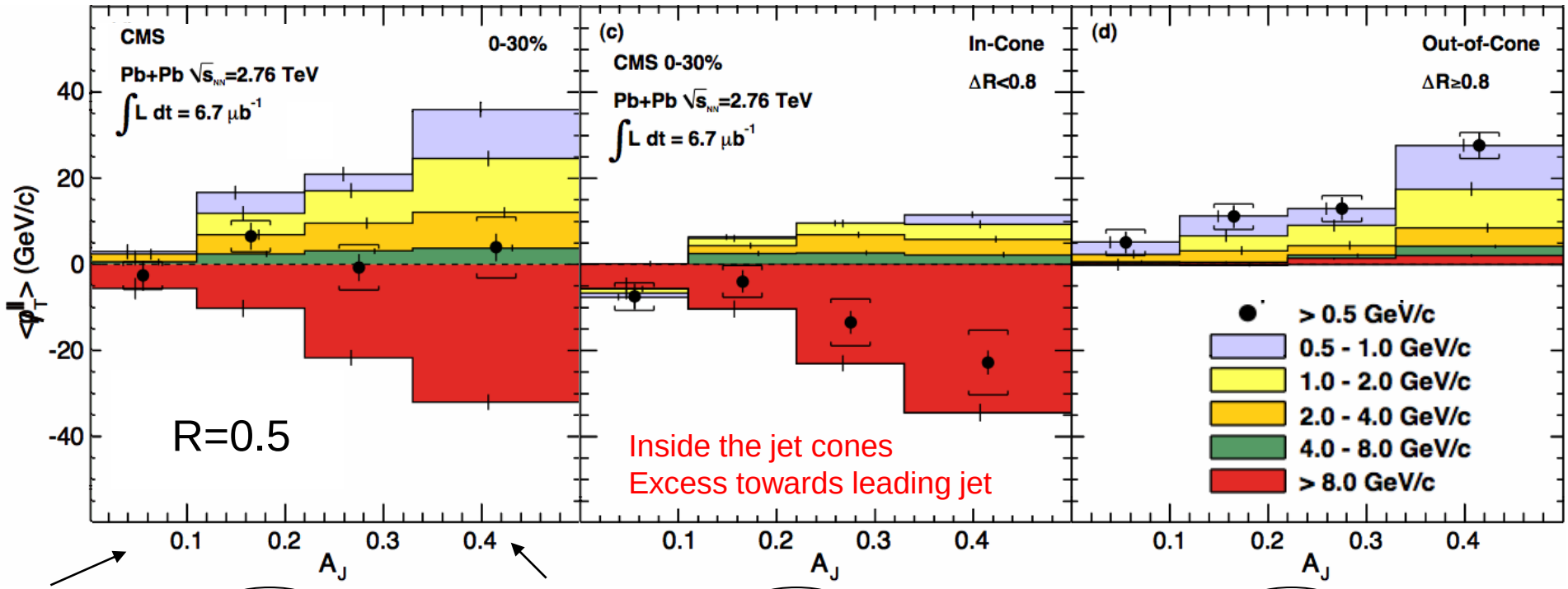
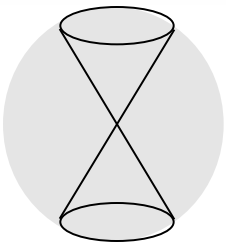
0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet

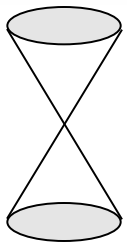


balanced jets

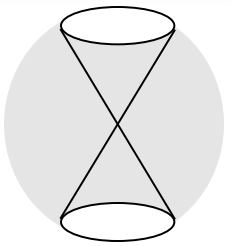
unbalanced jets



All tracks



Tracks in the jet cone $\Delta R<0.8$



Tracks out of the jet cone $\Delta R>0.8$

The momentum difference in the dijet is balanced by low p_T particles outside the jet cone

Summary

- CMS has presented results on the jet R_{AA}, dijet asymmetry and missing p_T analysis using tracks in the dijet system
  - Jet quenching is observed as dijet p_T imbalance in central PbPb collisions
  - Jets with R=0.2-0.5 do not collect all the radiated energy back
  - Missing p_T measurements shows that those energy are carried by low p_T particles far away from the jet axis
- Open questions:
  - Quark & gluon jet fractions in PbPb collisions
    - Impact to the absolute cross-section measurement
    - We may be sampling different fraction of gluon jets even if we use the same offline selection between experiments
  - Impact of the modified fragmentation function to jet energy scale
  - Bias selection on tracks may change / reduce the gluon jets fraction?
  - Different treatment of fake jet contribution between CMS and ATLAS

Backup slides