Hot Quarks 2014

Las Nagras, Andalucia, Spain
21 Sept 2014

Jet Measurements in Heavy Ion Collisions with CMS

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Motivations

- Jet quenching observed in AA collisions (strong interaction of medium with high-p_T particles)
  - Is the Jet fragmentation function modified?
  - Are Jet shapes distorted?
  - Can we regain the “lost” energy?
  - Flavor dependence of strong coupling with the medium?
  - Jet quenching at the LHC (CMS, ATLAS, ALICE)

- What can we learn from pPb collisions?
  - Initial state, Cold Nuclear Matter effects?

- Datasets:

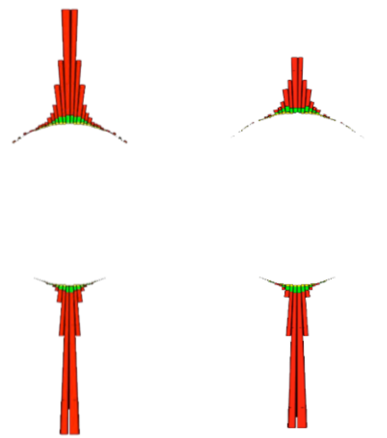
  PbPb (2011) and pp (2013) @ 2.76 TeV

  pPb (2013) @ 5.02 TeV

Goal – Physics Observables

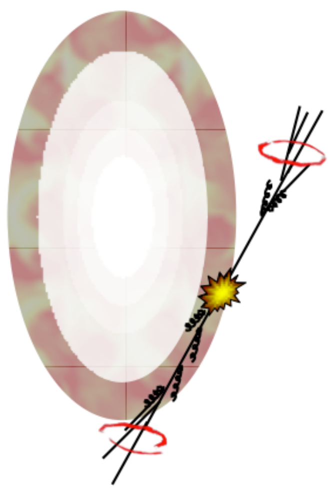
Dijet imbalance

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

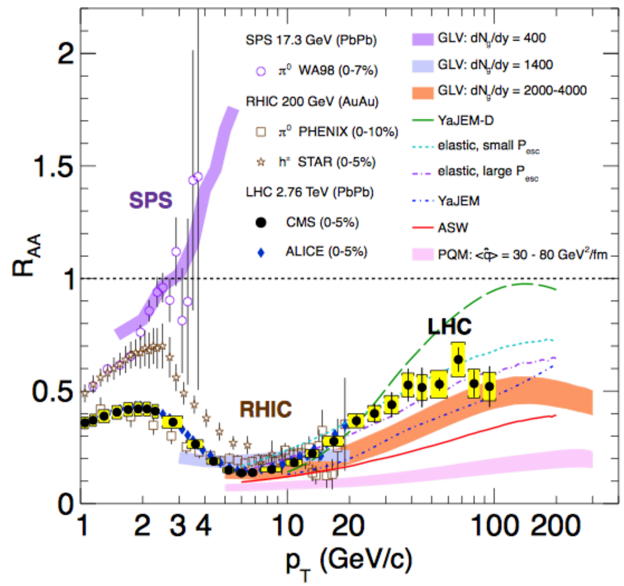


Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)



Nuclear Modification



EPJC 72 (2012) 1945

Charged Particles

$$= \frac{dN^{AA}_{jets}/dp_T}{\langle T_{AA}\rangle\, d\sigma^{pp}_{jets}/dp_T}$$

$\langle N_{coll}\rangle$ - No of participating nuclei per event

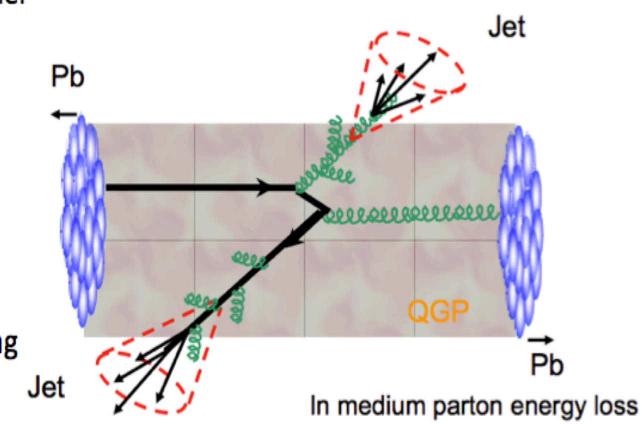
σ - cross section

$\langle T_{AA}\rangle$ - Average value of the nuclear 'thickness' function

$R_{AA} > 1$ – Enhancement

$R_{AA} = 1$ – no medium effect

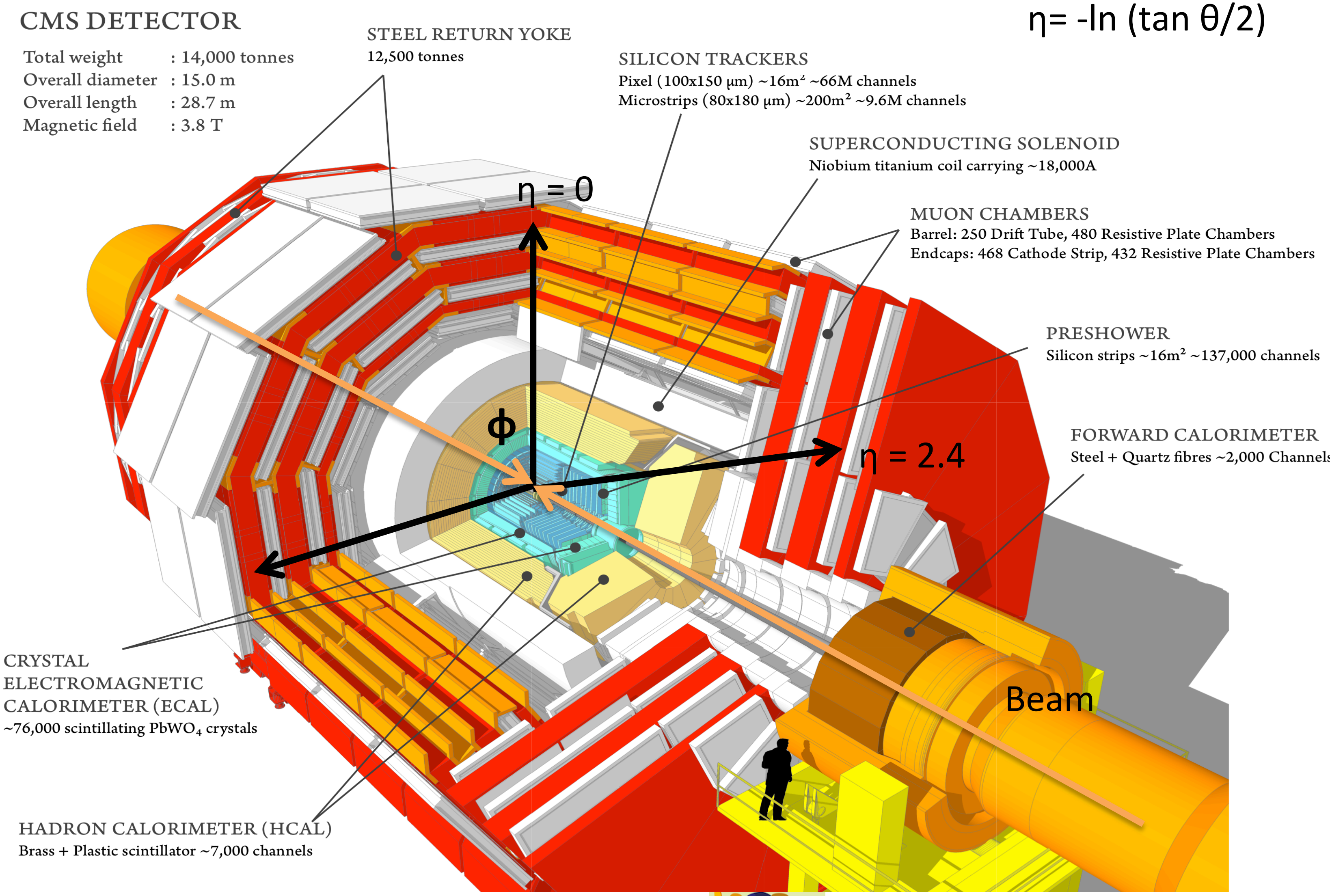
$R_{AA} < 1$ – Suppression/quenching



In medium parton energy loss

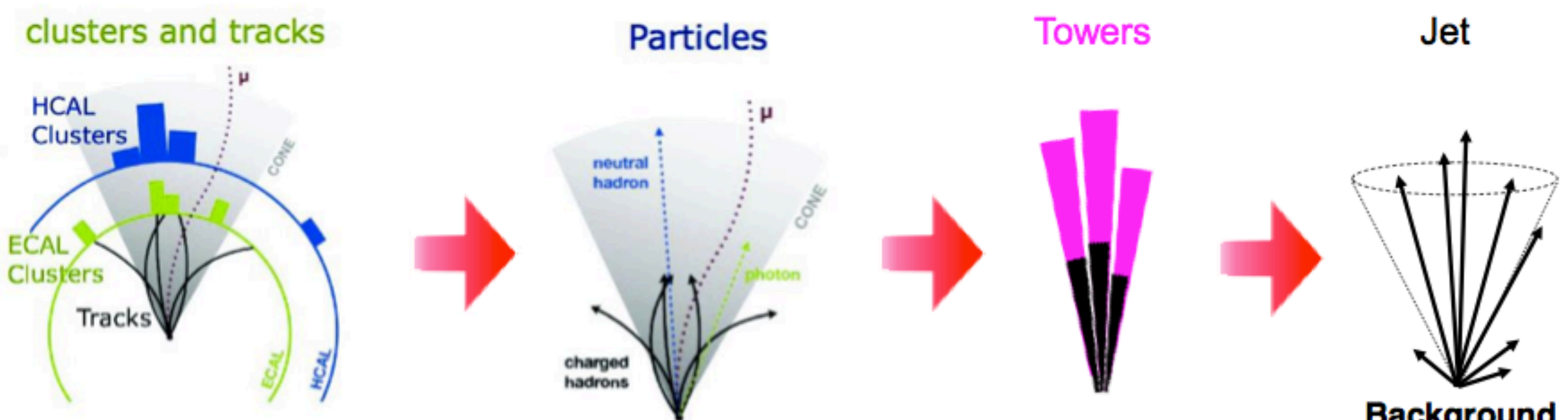
→ "Jet quenching"

CMS



$\eta = -\ln(\tan\theta/2)$

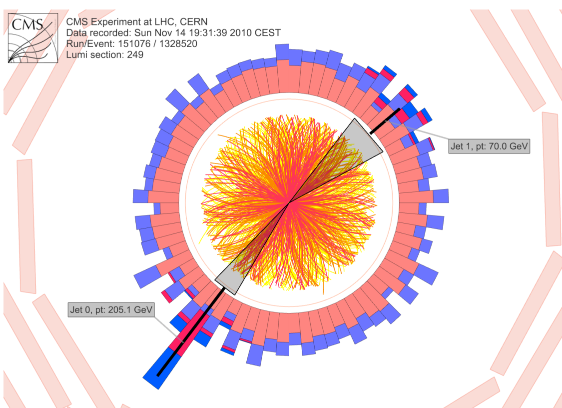
Jets in CMS



Anti-k_T algorithm is used in most of CMS publications

For instance, Δη x Δϕ 0.076 x 0.076 in barrel

Background subtraction and jet clustering



Calorimeter (CALO) Jets: Using Calorimeter energy deposits.

Particle Flow (PF) Jets: Combines information from all sub detectors to make PF candidates, which are then clustered.

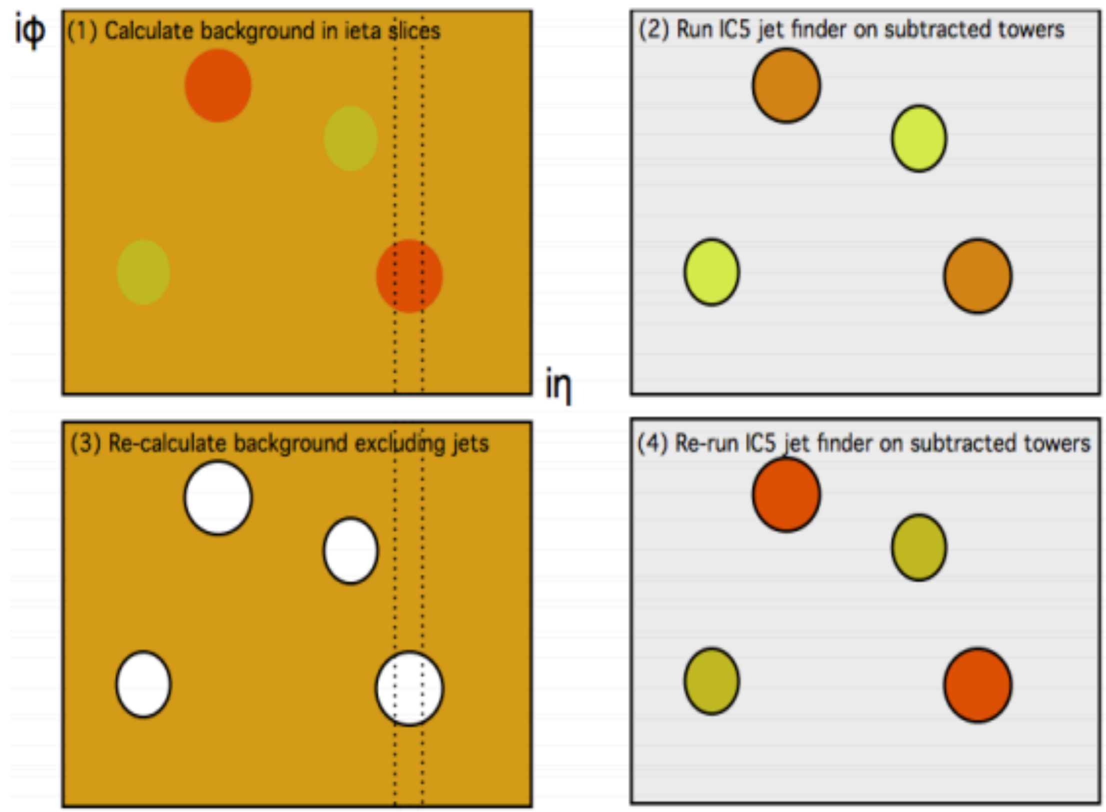
Bkg Subtraction(old)

1. Background (bkg) energy per tower calculated in strips of η

2. Jet finder run on subtracted (sub) towers

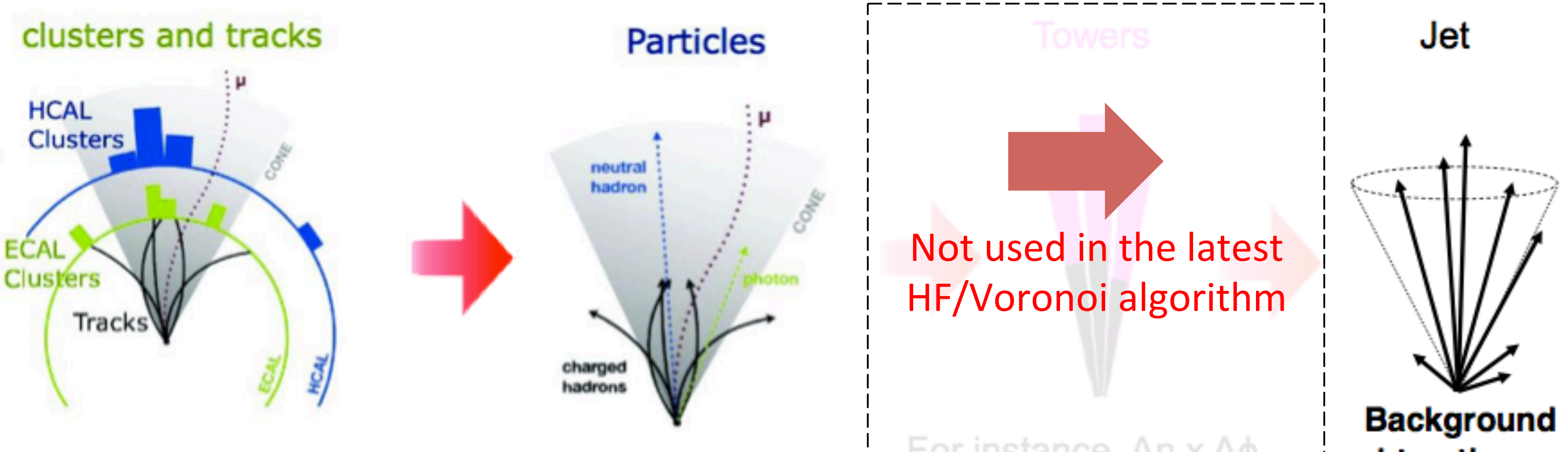
3. Background energy recalculated excluding jets

4. Rerun Jet algo on bkg-sub towers without jets -> get the final jets.



EPJC (2007) 117.

Jets in CMS



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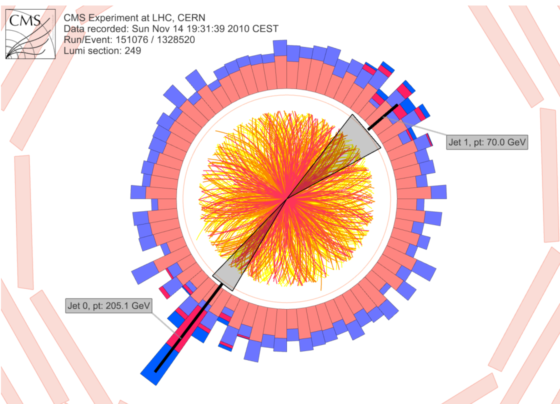

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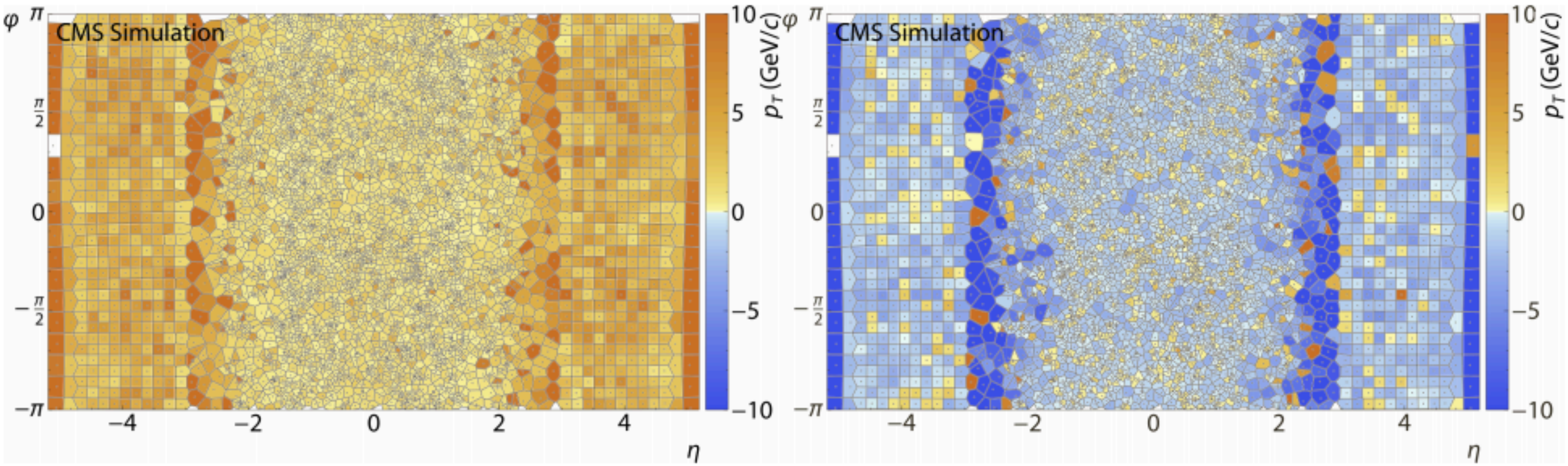
HF/Voronoi algorithm

A Voronoi diagram in the (eta, phi)- plane is used to associate an unique area to each particle such that the UE density can be removed particle-by-particle



Voronoi tessellated HYDJET/GEANT particle-flow event (combined tracks and calorimeter towers) before (left) and after (right) subtraction.

Non physical negative particle/areas are “equalized” to maximally approximate to the original (real) jet distribution of radius R. (backup slides)

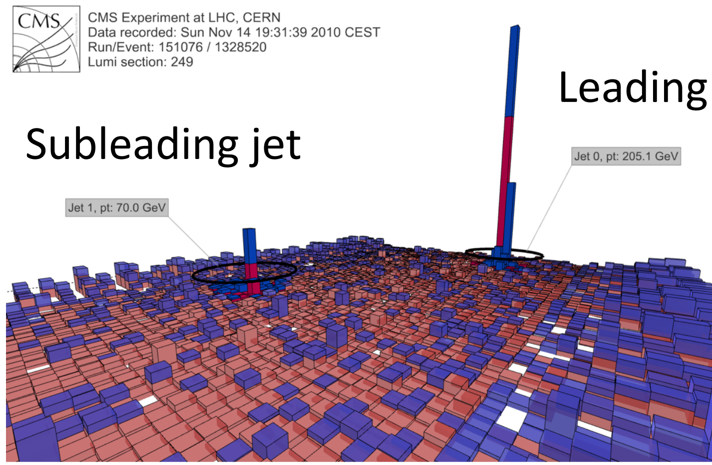
Flow (v2,..,v5) accounted for by projecting the expectation from the HF

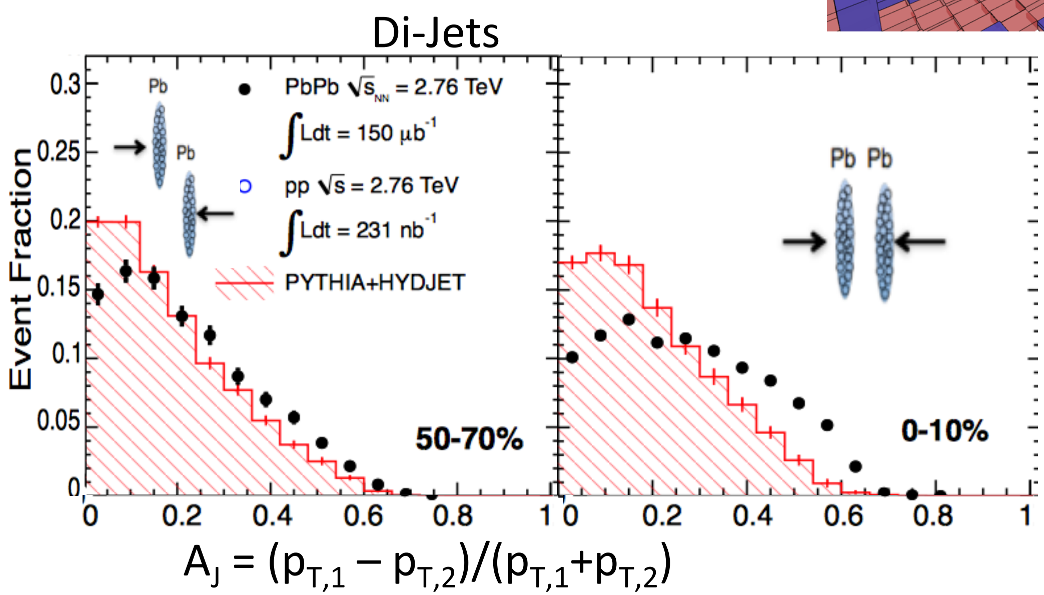
New

CMS-DP-2013-018

Jet Quenching: observation

- Strong jet-quenching in PbPb collisions
- Dijet p_T imbalance observed
- 10% decrease of $\langle p_{T,2}/p_{T,1} \rangle$ for central collisions – subleading jets quenched more than leading jets





PLB 712 (2012) 176

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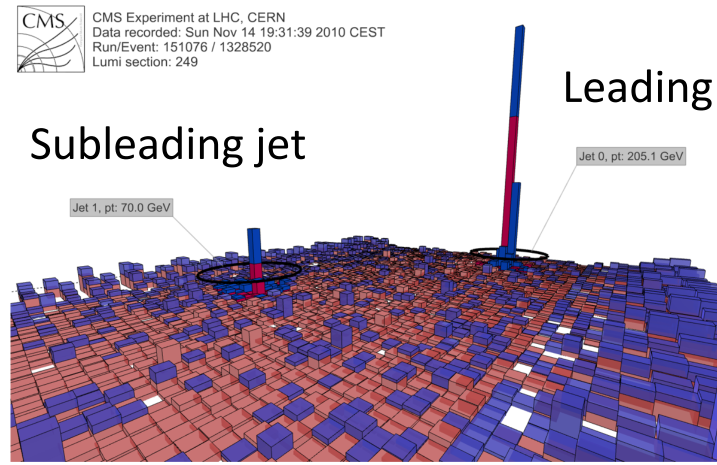
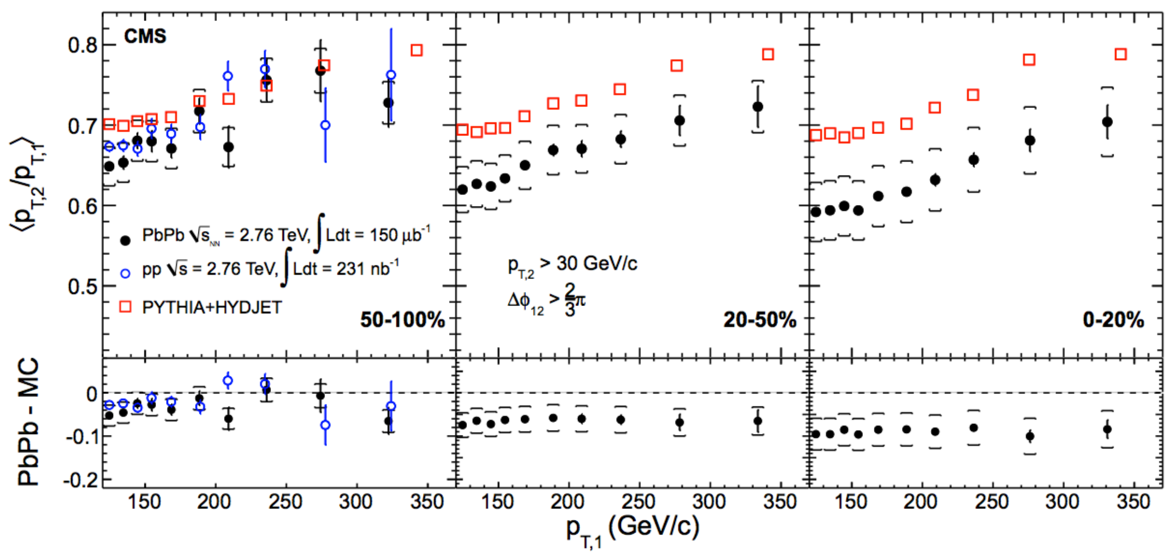
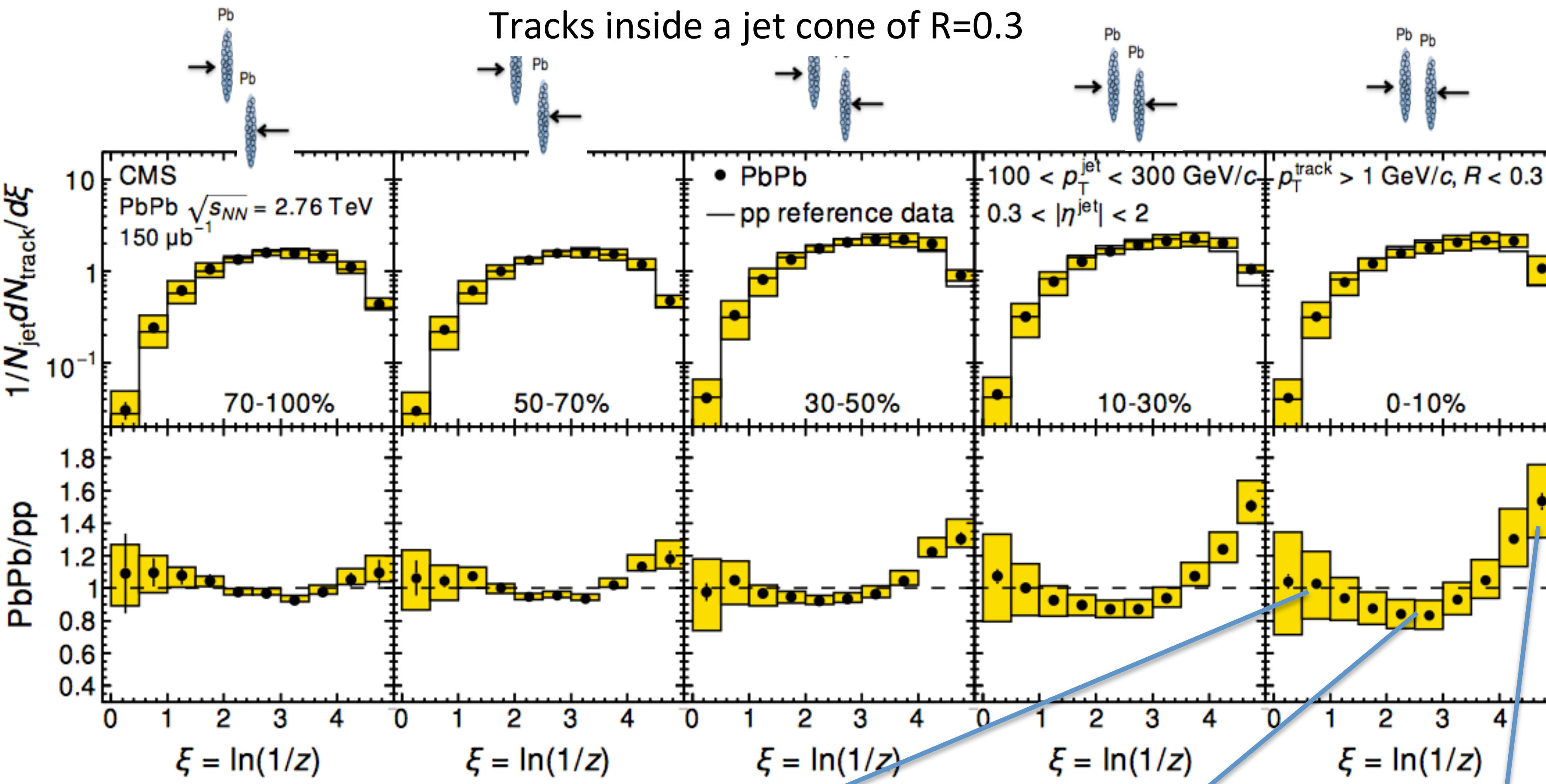




PLB 712 (2012) 176

Jet Fragmentation

Tracks inside a jet cone of R=0.3



$z = p^{track}_{||} / p_{jet}$

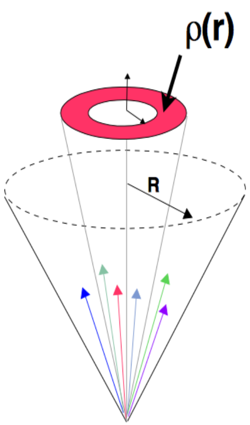
High p_T – no modification

Suppression of intermediate p_T in the cone

Enhancement at low p_T

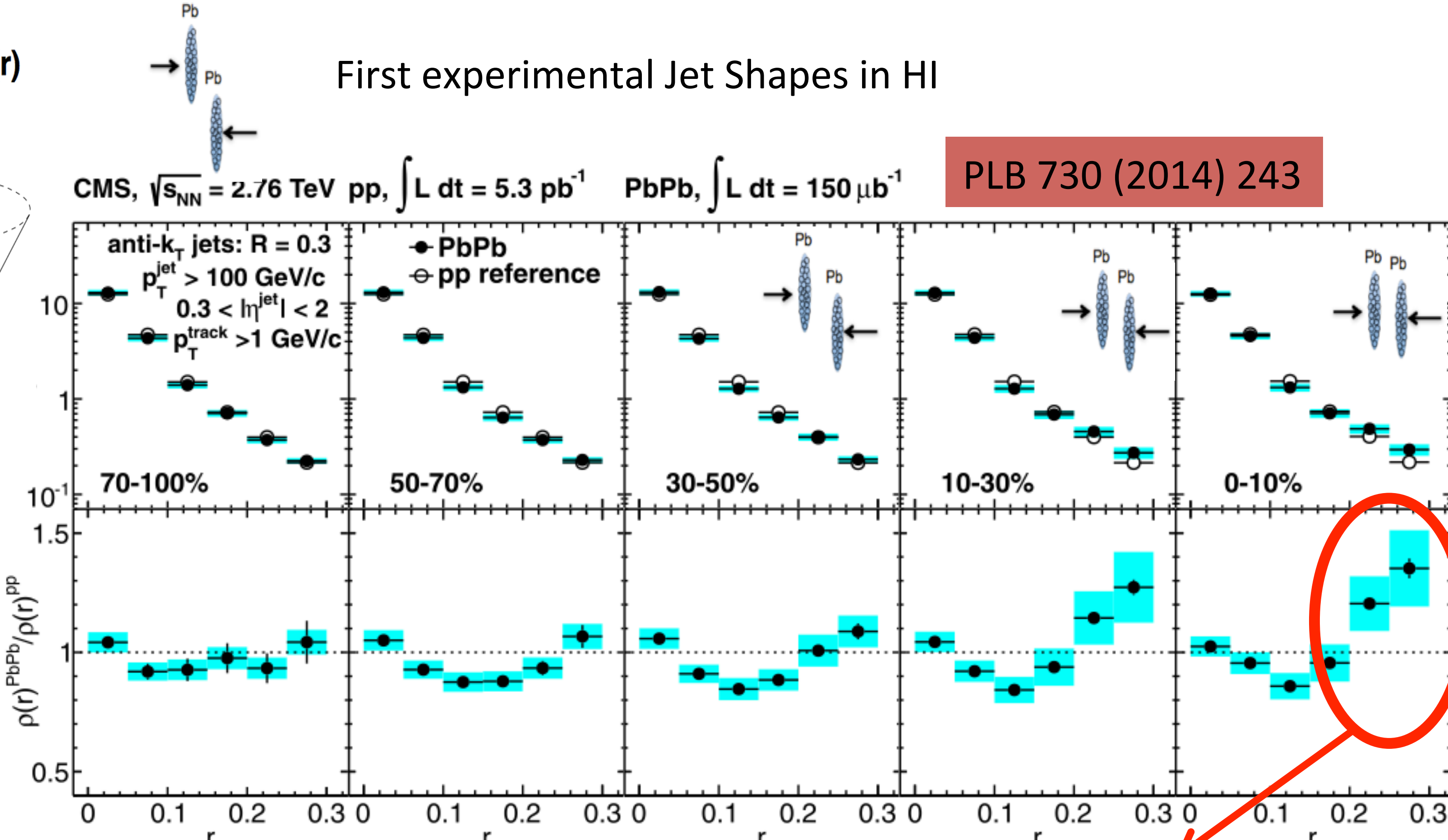
Phys.Rev. C90 (2014) 024908

Jet Shape measurement



First experimental Jet Shapes in HI

PLB 730 (2014) 243



$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{jet}}$$

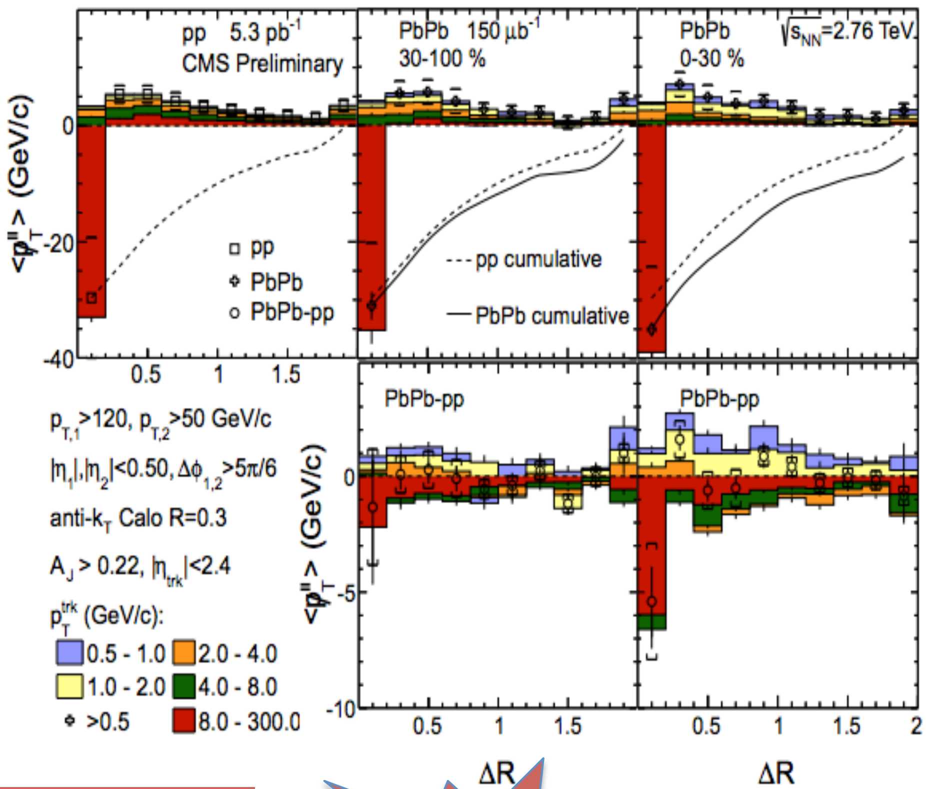
Broader jet shapes in PbPb in most central collisions

Where does the Energy go?

Sum charged particles for unbalanced A_J>0.22 dijets in central (0-30%) PbPb

- 35 GeV/c of high p_T tracks missing from away side jet at ΔR=0.2
- Balanced by low p_T particles up to very large ΔR=2.0
- PbPb-pp : result shows a different p_T distribution
- Take the p_T cumulative of all tracks – total angular pattern is similar in PbPb and pp

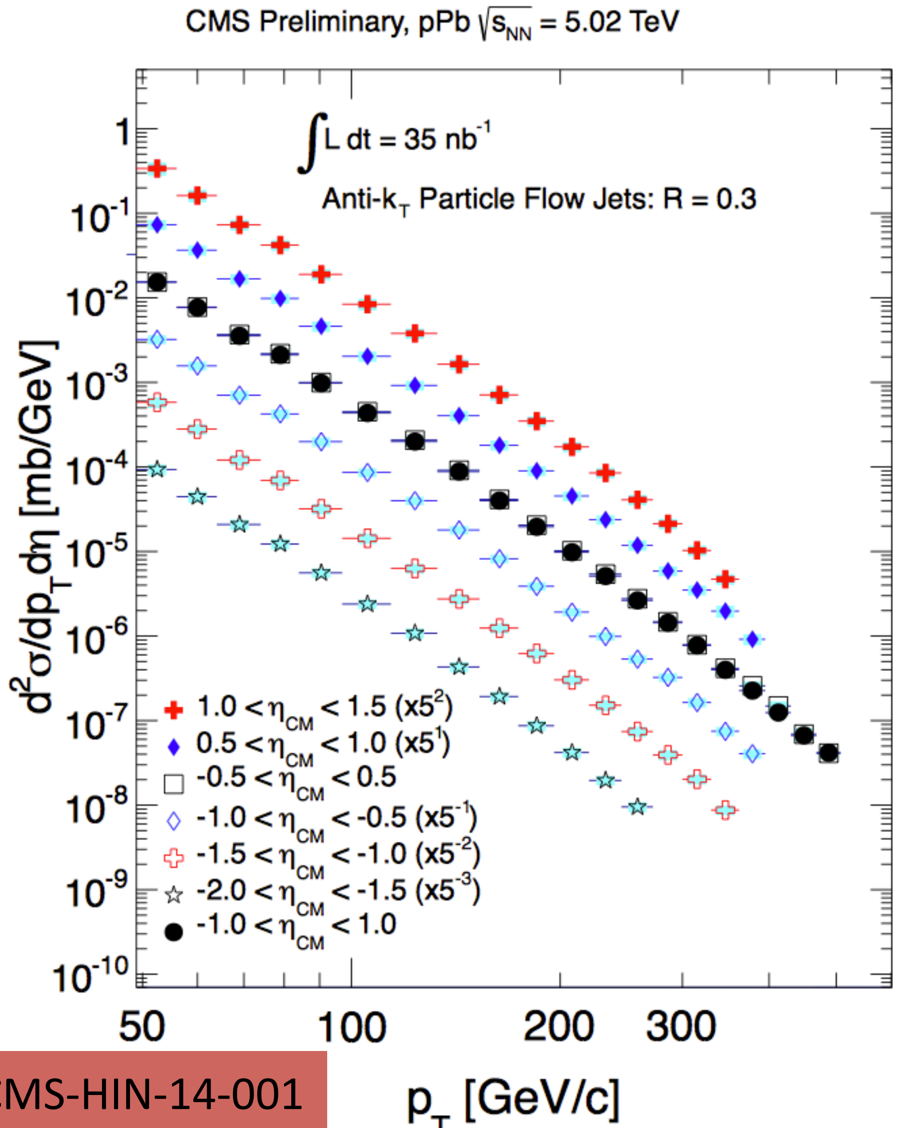
Able to recover the lost energy by going to Large ΔR in the away side jet



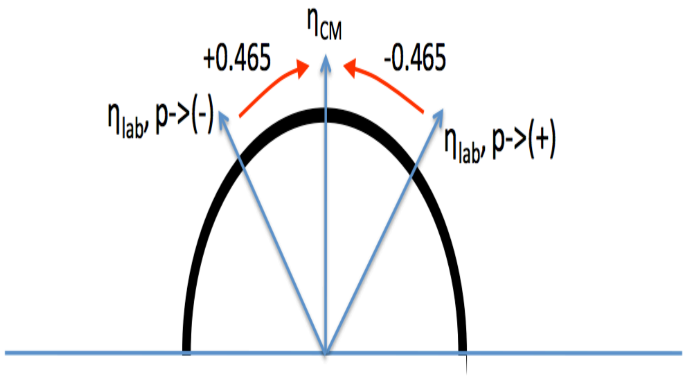
CMS-HIN-14-010

HF/Vs

pPb Inclusive Jets @ 5.02TeV

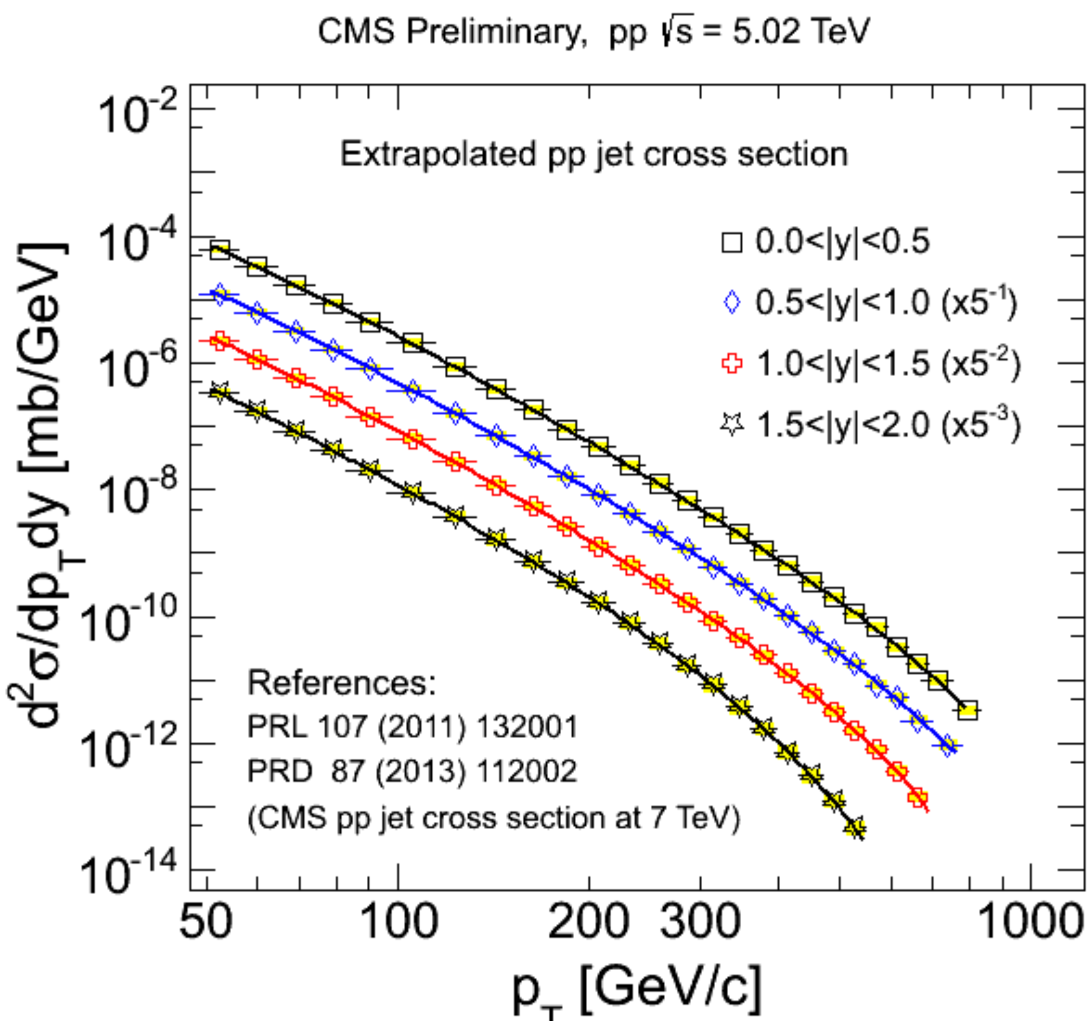


CMS-HIN-14-001



- pPb collisions are natively asymmetric
  - E(proton) = 4 TeV, E(Pb) = 1.58 TeV/N
  - Distributions of jets are centered around ±0.465 units in η
- η distributions are corrected to the center-of-mass eta
- Pbp η distribution is "mirrored" (η -> -η)
  - This ensures consistency when pPb and Pbp results are used together

pp Reference @ 5.02 TeV

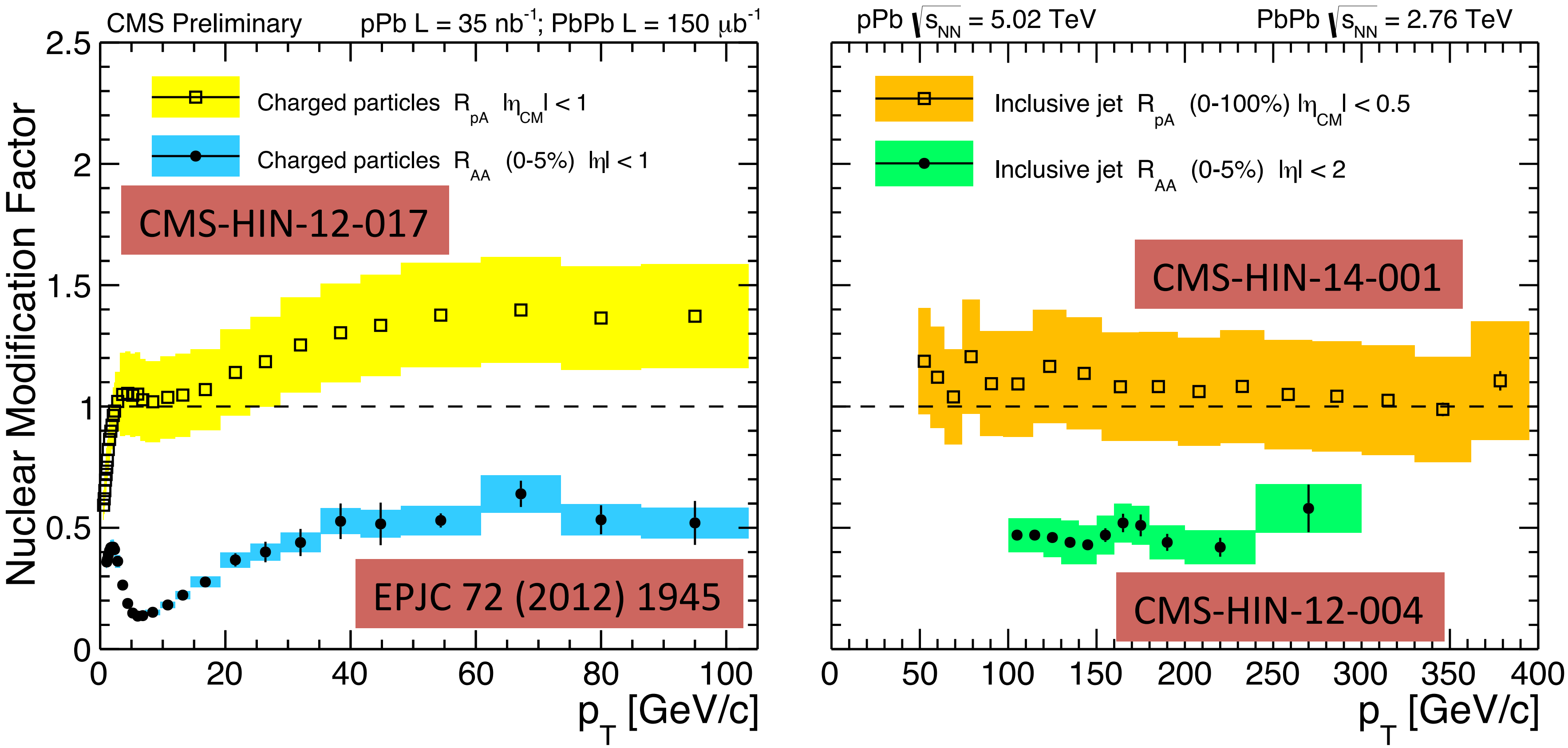


CMS-HIN-14-001

Extrapolated from pp data at 7 TeV.

1. Dependence of the jet radius and the √s on the cross section
2. The above effect was extracted from Pythia and compared with NLO (next to leading order) calculations
3. Applied to generated spectra to derive the reference at 5.02 TeV

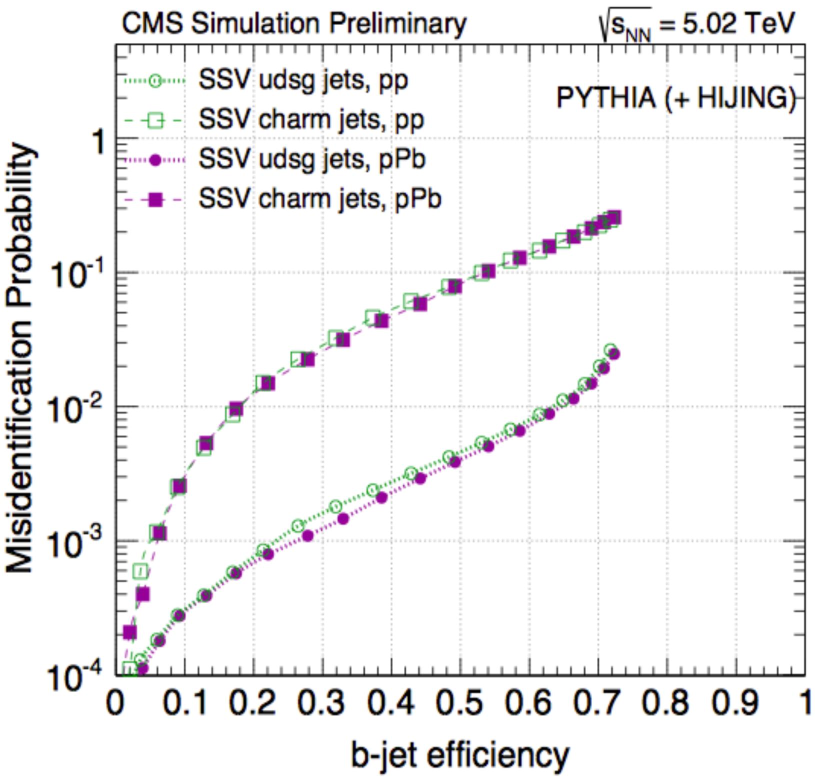
R_{pA} & R_{AA} – Tracks, Jets



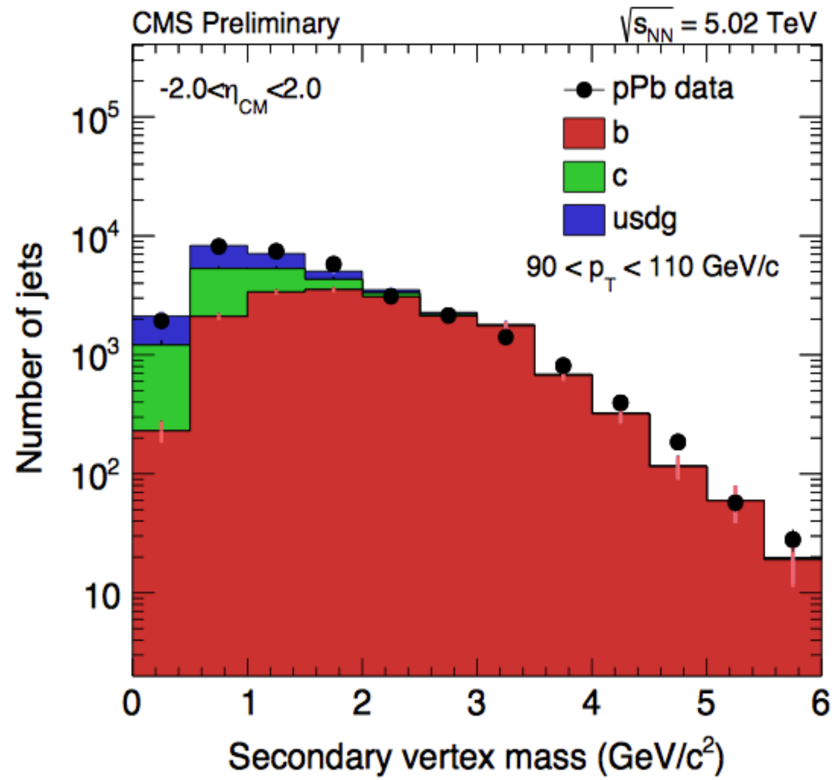
Enhancement observed at p_T ~20GeV !!

R_{pA} – flat at 1 ~ no modification
pp – reference for R_{pA} – extrapolated from 7 TeV. Need data at 5.02 TeV

b-Jet Tagging

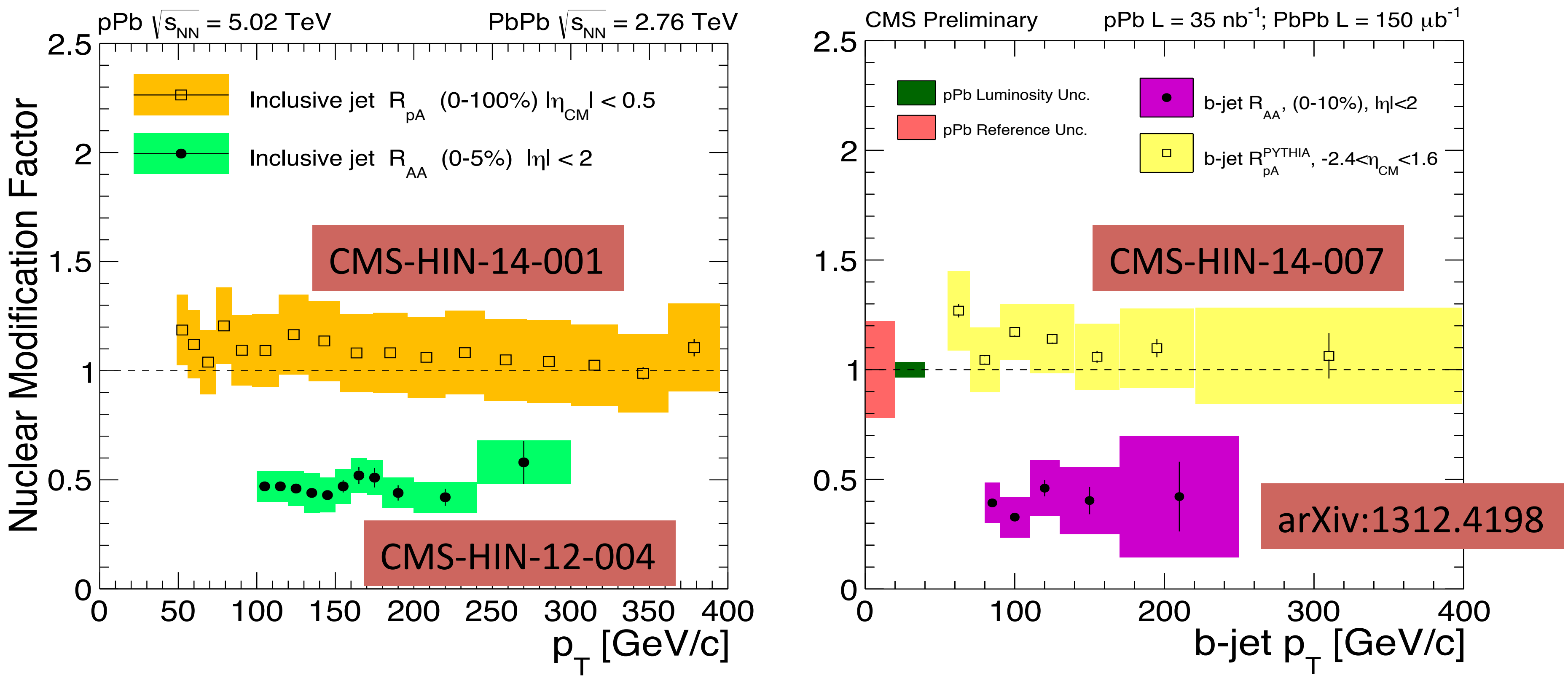


The Simple Secondary Vertex (SSV) tagger is more robust against a combinatorial background due to the secondary vertex requirement



template fit to the SV invariant mass distribution in pPb collisions for jets of $90 < p_T < 110$ GeV/c, where b-jets dominate after 2 GeV/c^2

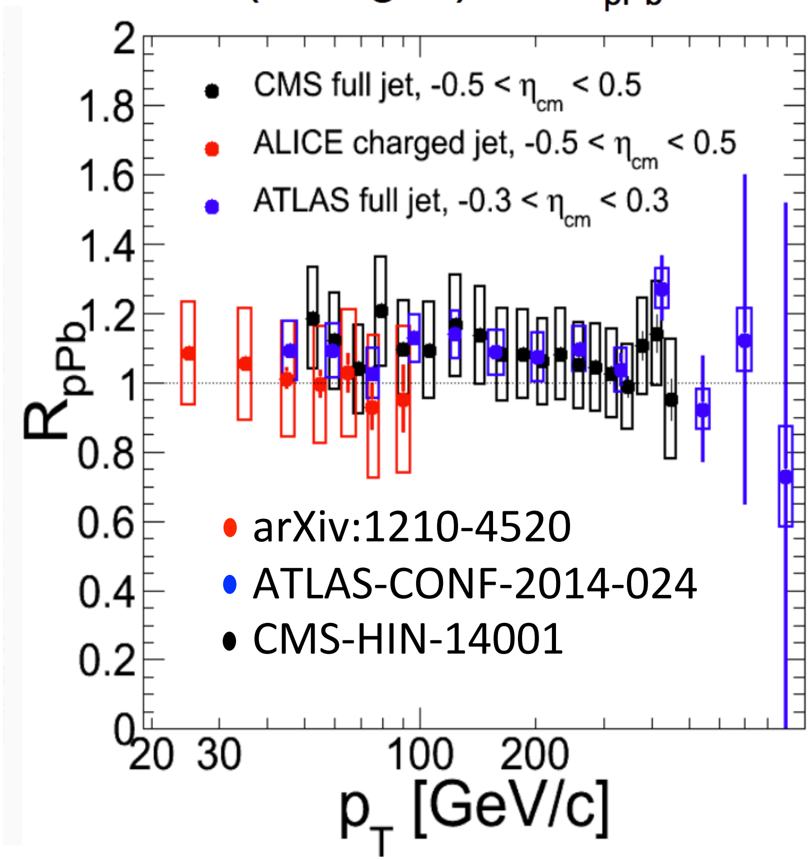
R_{pA} & R_{AA}: Inclusive, b-jets



No observable difference between inclusive and b-jets in the explored p_T range

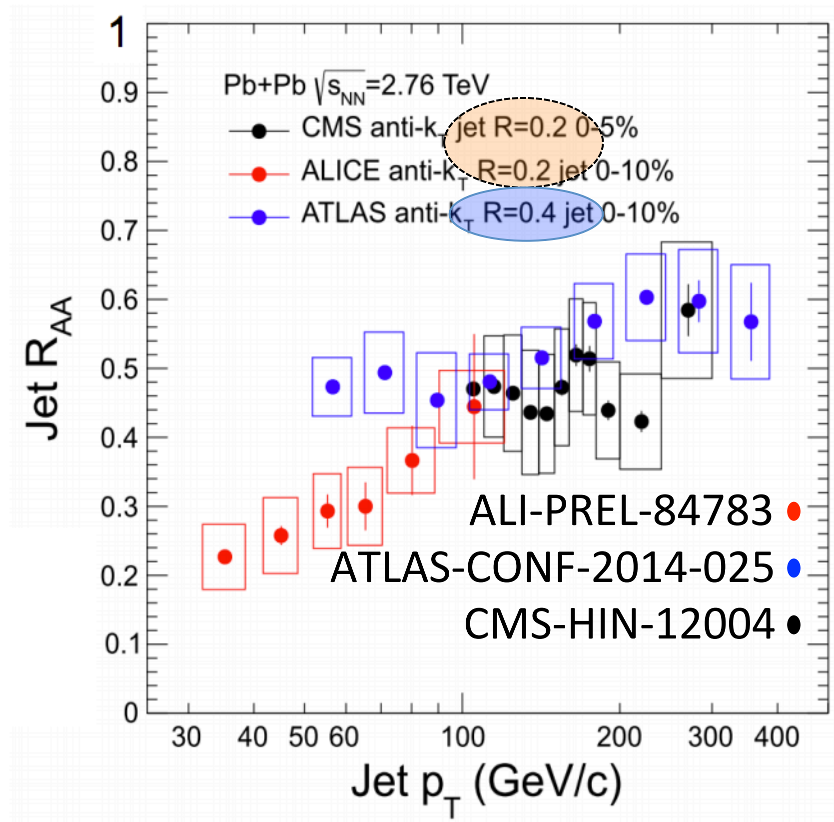
Comparisons

(Charged) Jet R_{pPb}



Good agreement between experiments at mid rapidity

Inclusive Jet R_{AA}



Need CMS R_{AA} at low p_T (50 GeV) – in progress ☺

Conclusion

- Many observables showing independent confirmation of modification of jets in the medium (final state interactions)
- Jets are heavily quenched in most central PbPb collisions

- Jet Structure modification:
  - Excess of low p_T particles inside the jet cone (A_J measurements)
  - Observe quenching of intermediate range p_T particles (Jet Fragmentation)

- Quenched energy recovered by going to higher radii.
  - Lost energy carried away by low p_T particles away from the jet cone (Jet+Track measurements)

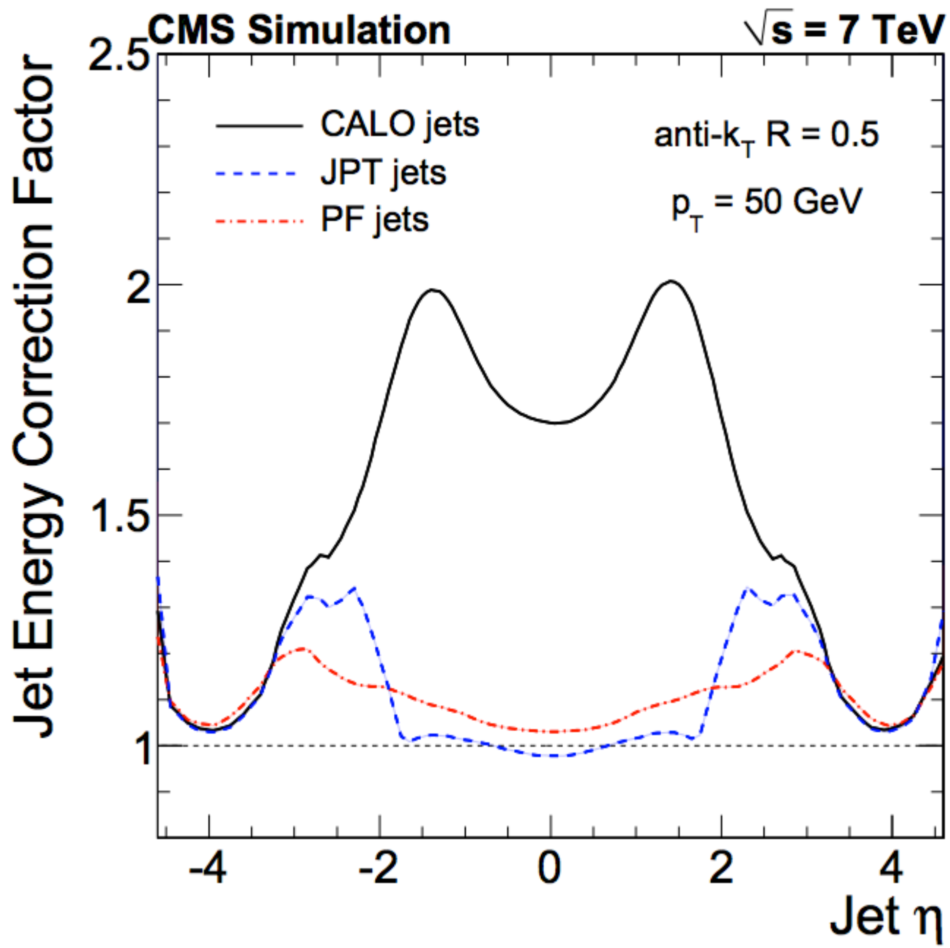
- Flavor dependence: So far no glaring differences between tagged and inclusive jets (in the explored p_T range). Need results from fully reconstructed D, B mesons (in both PbPb and pPb)

- Initial state in pPb collisions can be described by nPDF
  - Inclusive jets are not quenched

Backup

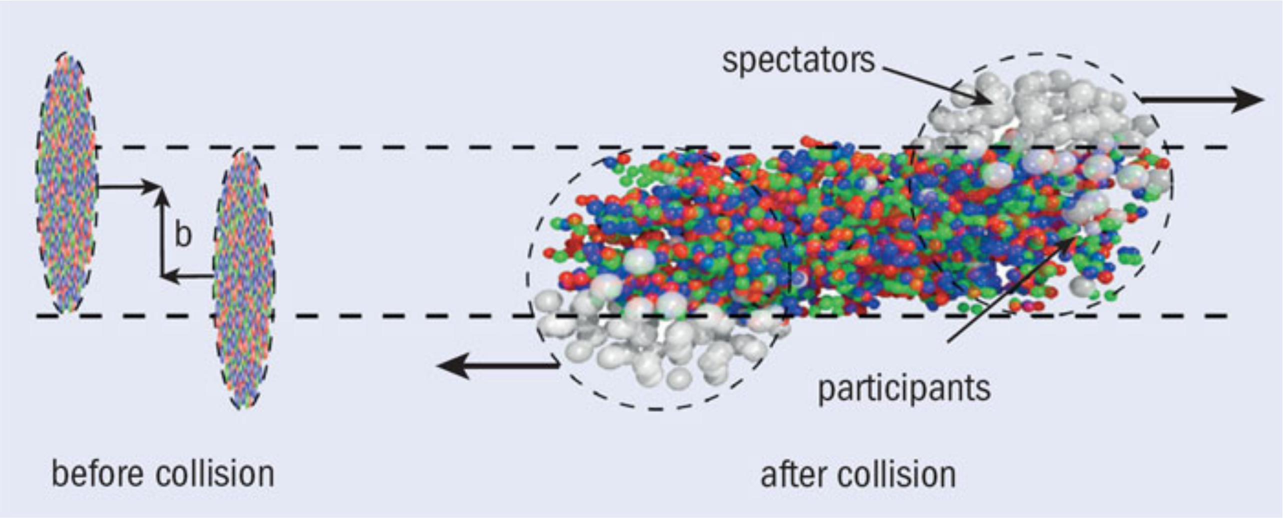
Jet Energy Corrections

1. Offset: pile-up and electronic noise – (Not used in PbPb or pPb – substituted with background subtraction)
2. Relative (η - pseudorapidity): variations in jet response with η relative to a control region.
3. Absolute (p_T – transverse momentum): correction to the particle level versus jet p_T in the control region

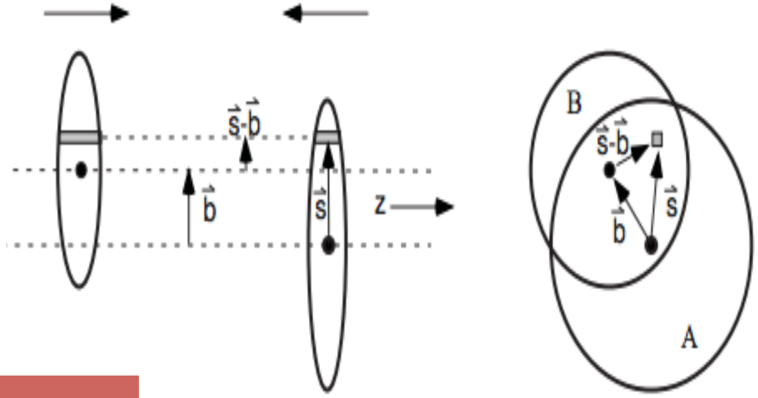


2011 *JINST* **6** P11002

Glauber Model

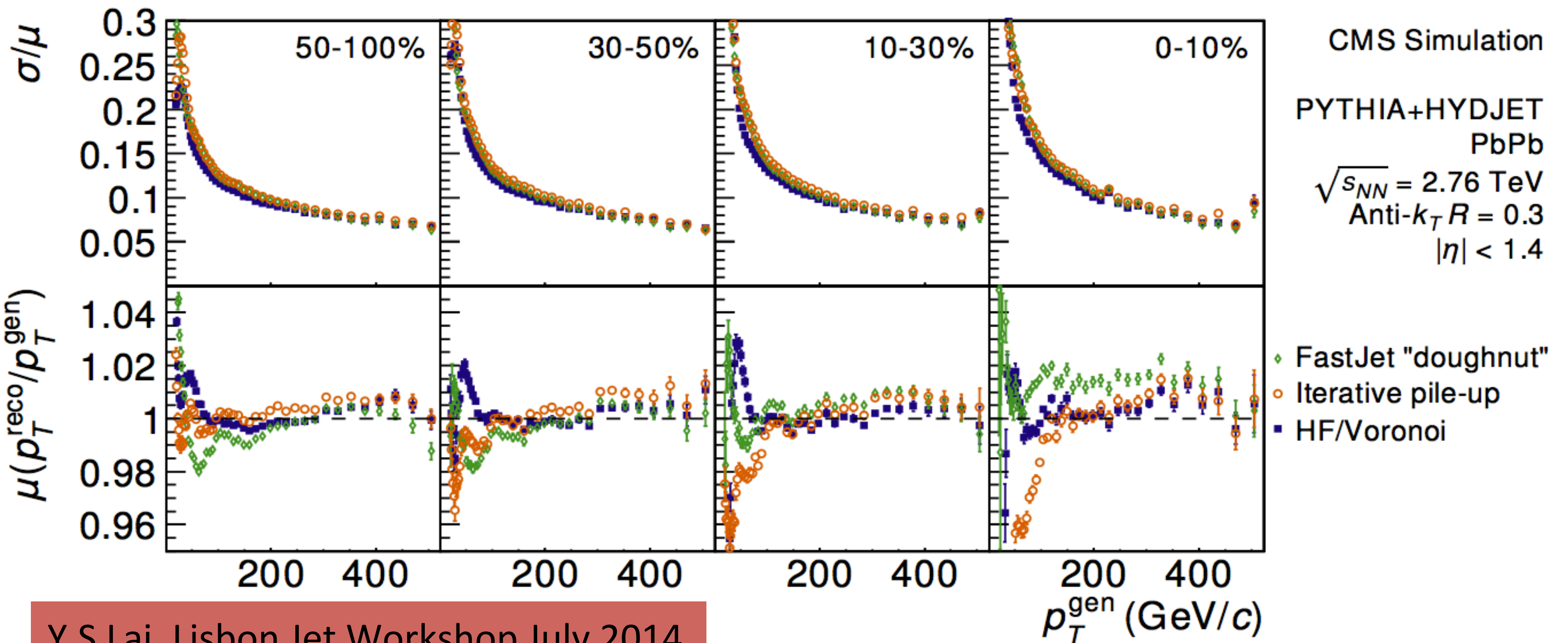


Heavy Ion collisions are split up in terms of the number of colliding nuclei.



Ann.Rev.Nucl.Part.Sci.57:205-243,2007

HF/Vs Performance MC

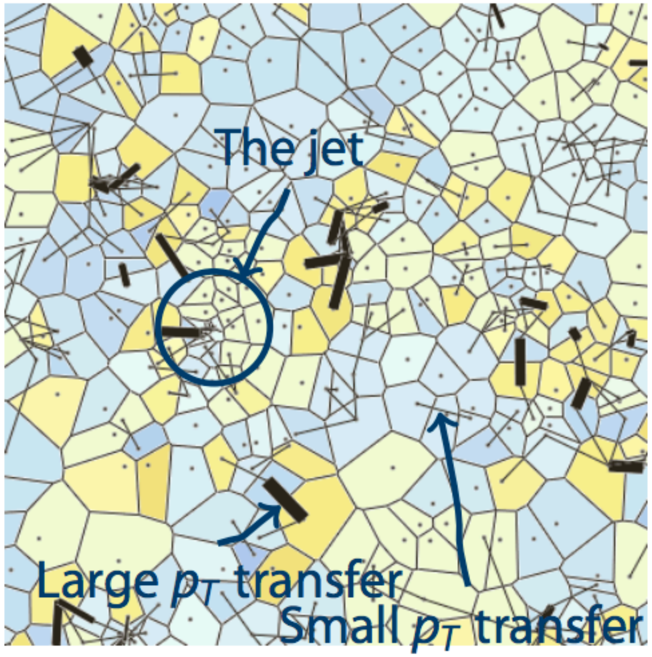


Y.S Lai, Lisbon Jet Workshop July 2014

- $\approx$ 10% improved mid-rapidity jet energy resolution for the new HF/Voronoi algorithm vs. old CMS' iterative pileup (PU)
- Also compared to $(\delta, \Delta) = (0.4, 0.8)$ FastJet "doughnut"

CMS DP-2014/xxx (TBD, approved but not yet assigned a number)

Equalization in Picture



- Ingredient #3: "Equalization" to produce positive event
- Purely a band-aid for iterative, positive-p_T jet reconstruction algorithms
- Balance out negative cells to represent the same event using positive cells only
- Implement a delocalized underlying event on particle level

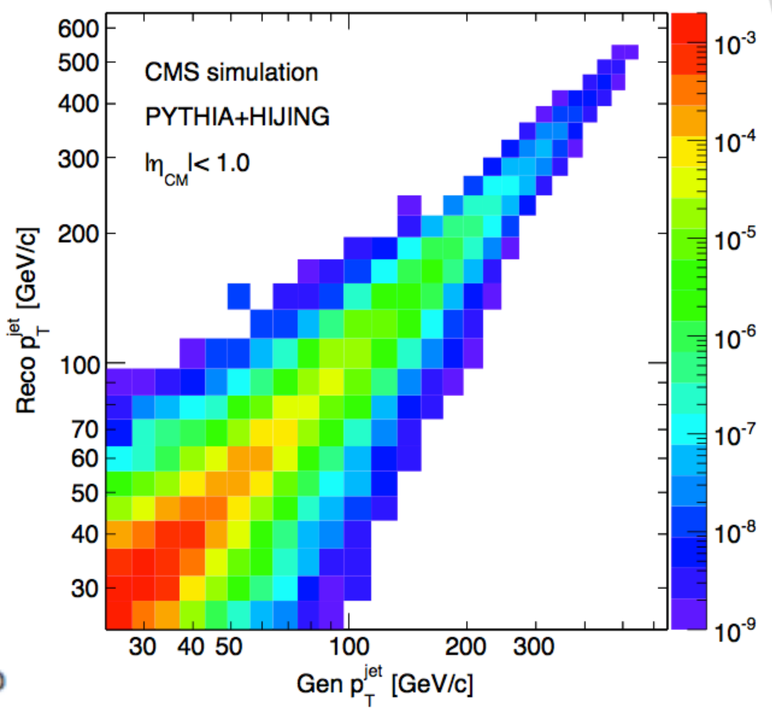
- Similar in idea to a mosaic:
  - Manipulation of color tiles on a small scale
  - "Reconstructs" to a correct visual impression on a coarse scale

Y.S Lai, Lisbon Jet Workshop July 2014

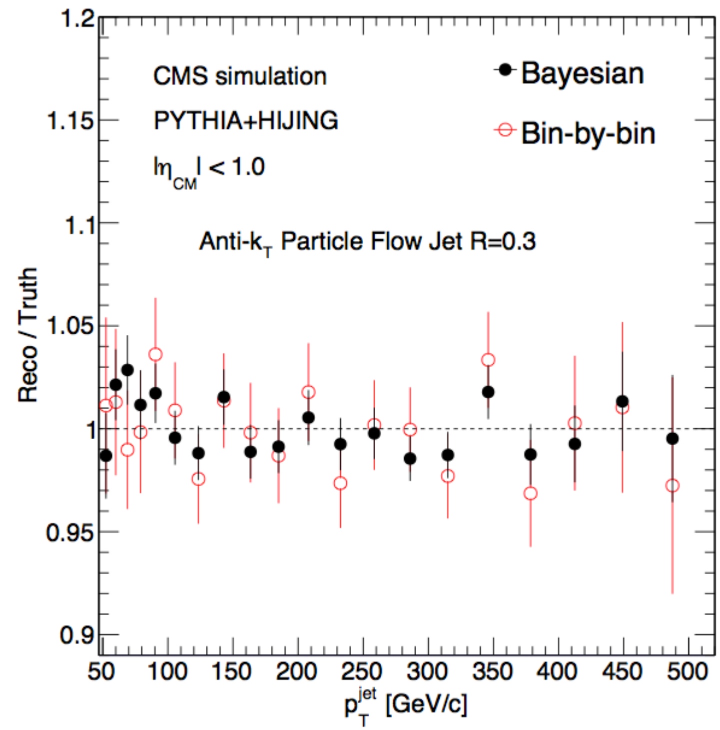
Unfolding on Data

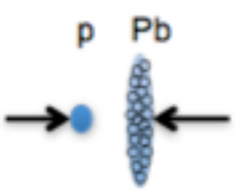
Bayesian Unfolding – Nucl. Instr and Meth., 362(1995),487-498.

Response Matrix



Unfolding MonteCarlo as a cross check

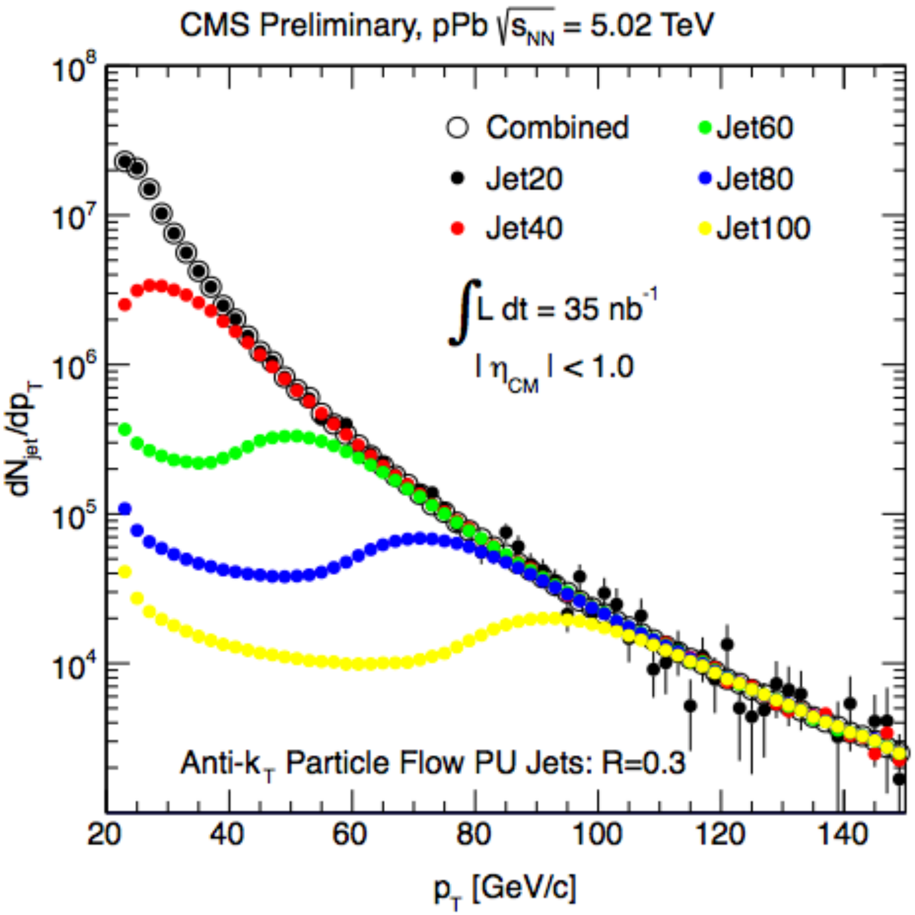


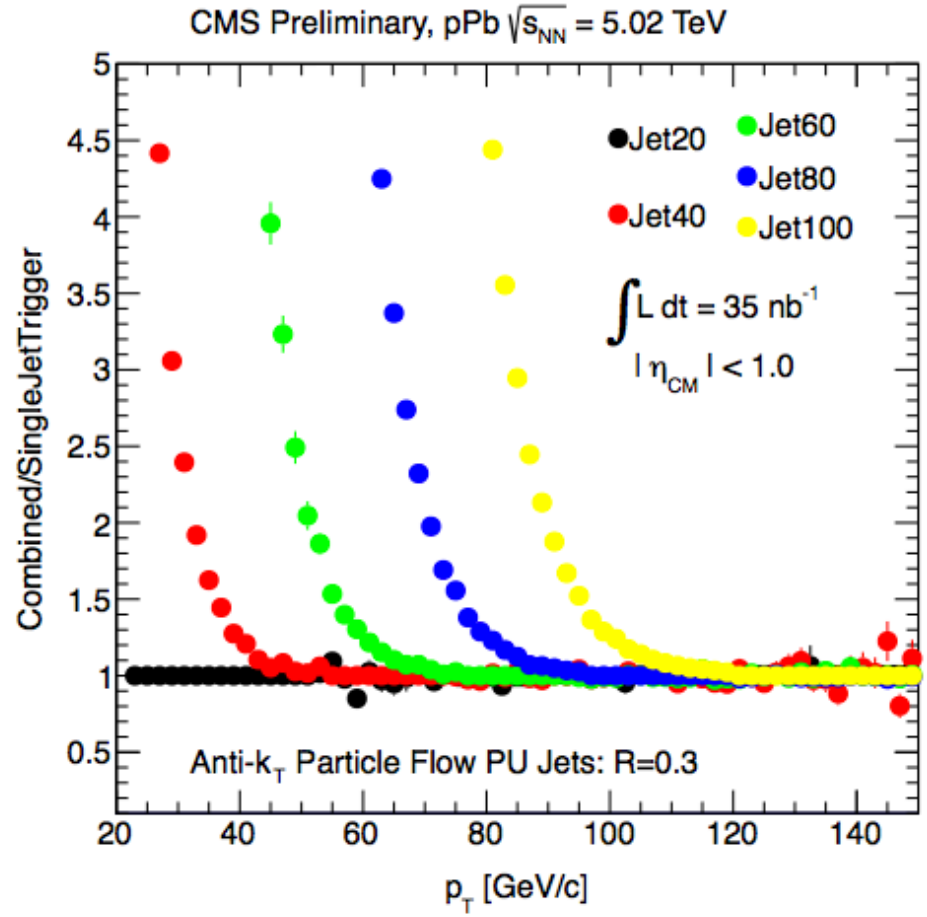


CMS-HIN-14-001

Unfolding removes the detector effects on jets

Trigger combination

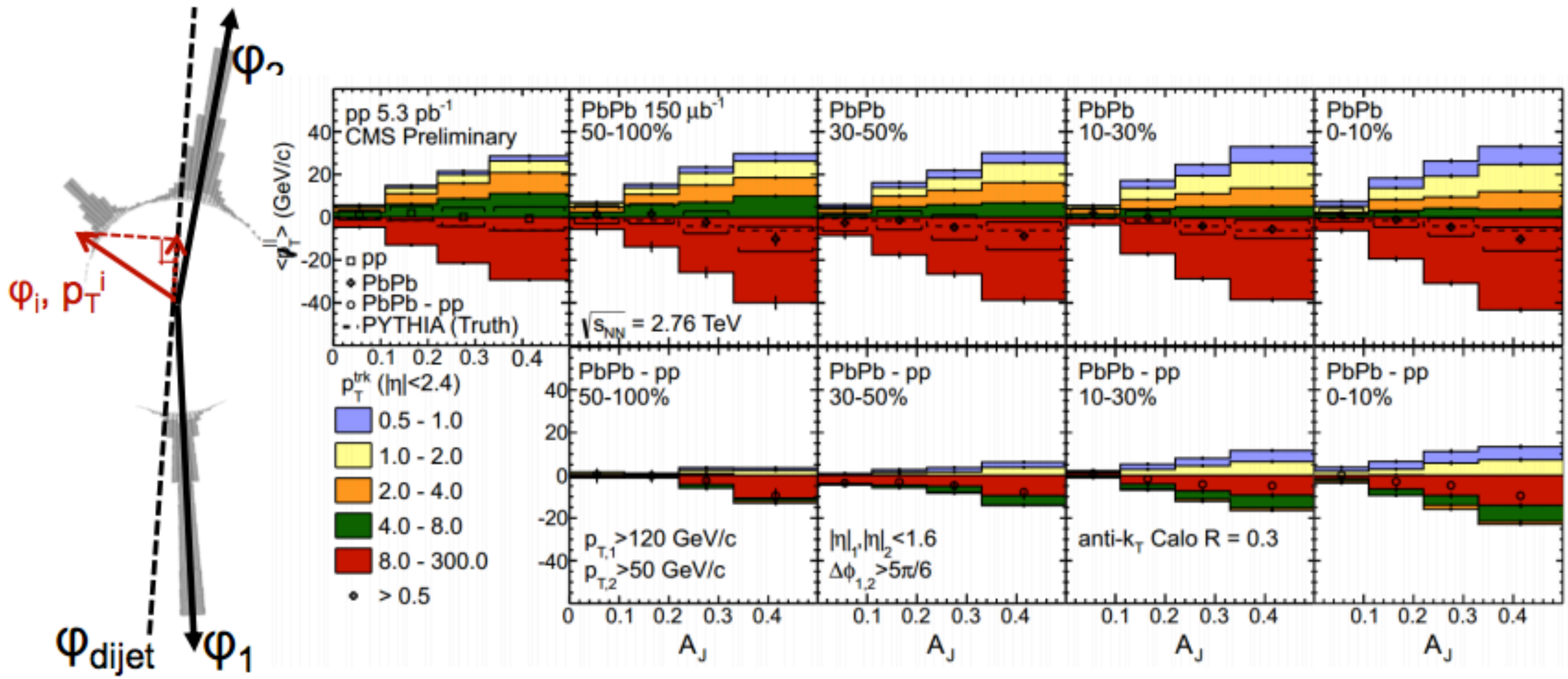




Combining several CMS HLT (high level trigger) datasets by selecting on their trigger Object in the pt ranges of the respective HLT. Extends our kinematics.

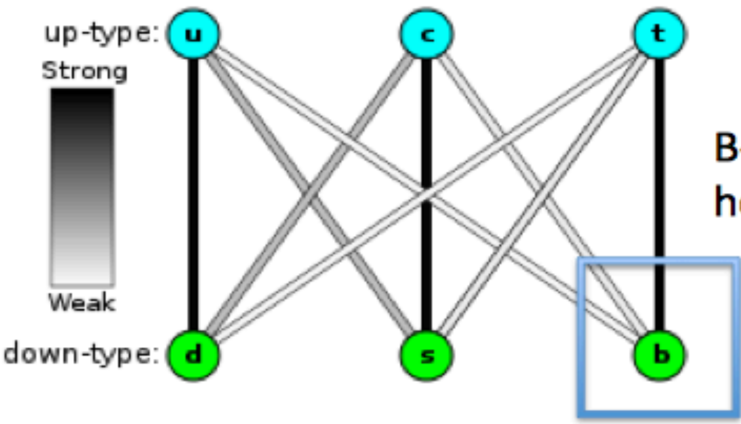
CMS-HIN-14-001

Quenched Energy Flow

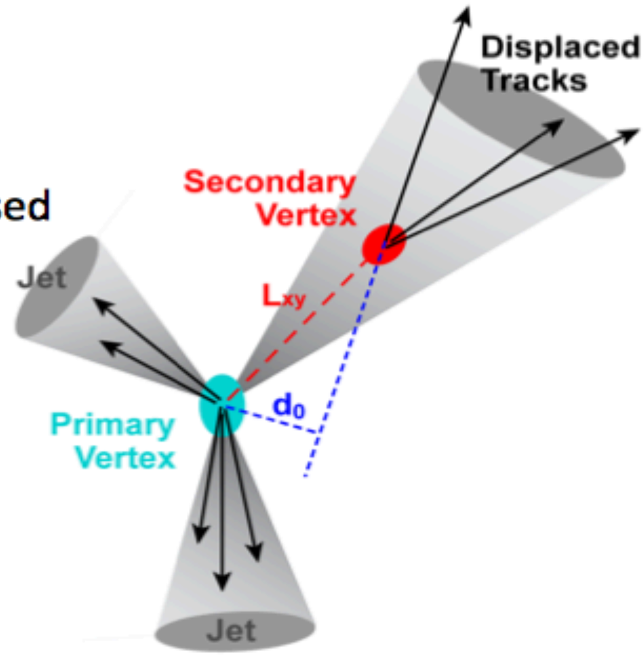


CMS-HIN-14-010

Identifying B-Jets



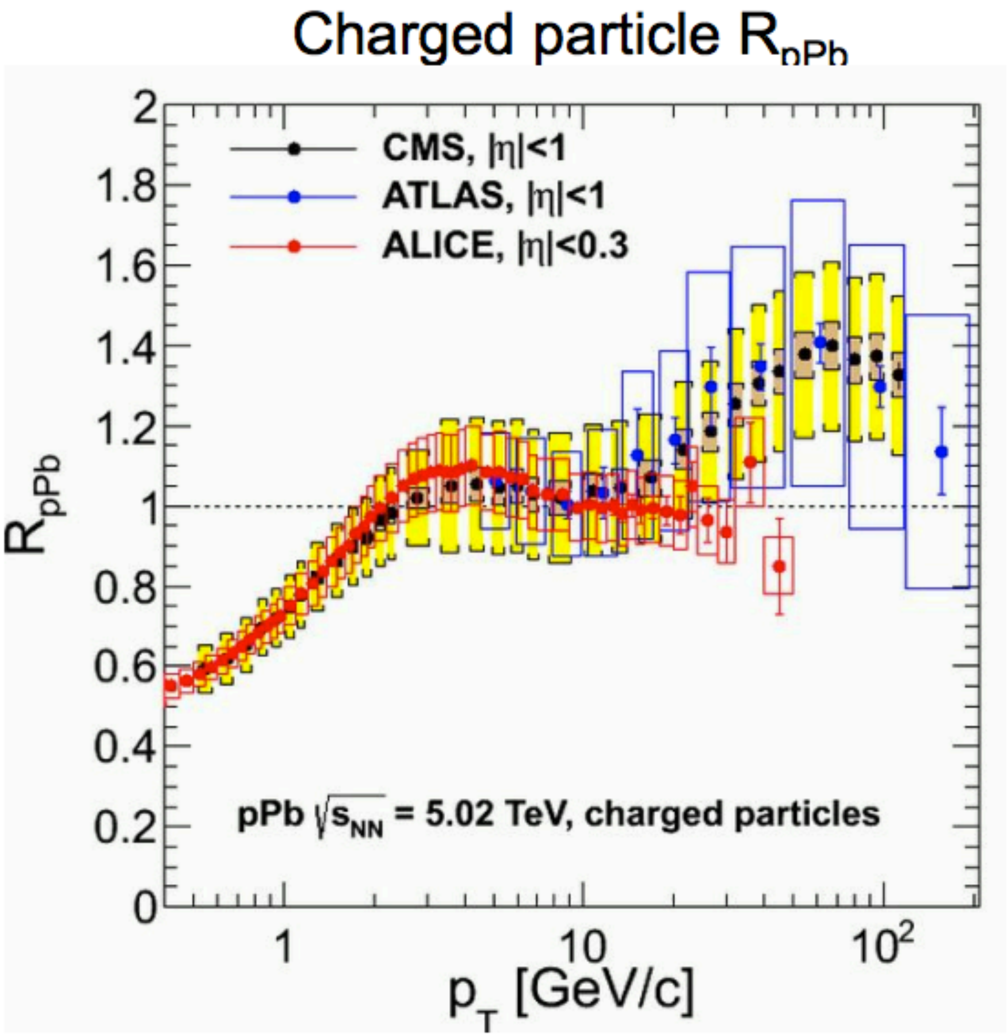
B-quark decays are heavily CKM-suppressed
-> Long lifetimes



- Primary identification method is using a **Secondary Vertex**
  - Long lifetime of b = mm or cm vertex displacement
- Flight distance (L_{xy}) of the secondary vertex used as a discriminating variable
- Tagging methods independent of secondary vertex reconstruction used as cross-check

Algorithms described in:
JINST 8 (2013) P04013

CP-R_{pPb} Status



Reference contributes to about 2/3 of the difference.

Anti-Shadowing from 20GeV/c???
Need pp Data at 5.02 TeV

- CMS-HIN-12-017
- ATLAS-CONF-2014-029
- arXiv:1405.2737