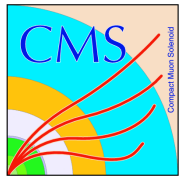
Recent results of jets and heavy quarks from the CMS heavy ion program

Yongsun Kim

Quadrangle2014 @Wuhan

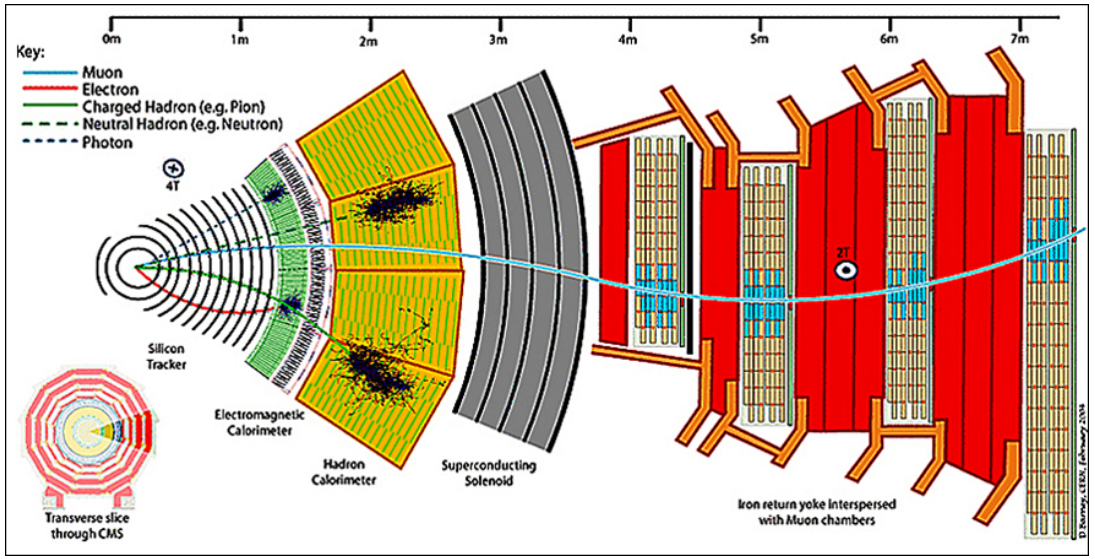
23-Sep-14



Outline

- Part I. Modification of jets in PbPb collision
- Part II. pPb is NOT similar to PbPb
  - Search for energy loss of jets in pPb collision
- Part III. pPb is NEITHER similar to pp
  - Study of Cold Nuclear Matter effect in jets and heavy quark particles

Using **C**ompact
Muon
Solenoid



Part I : Modification of jets in PbPb

- Photon-jet
- Inclusive jet R_{AA}
- B-jet R_{AA}
- Modification of Jet fragmentation pattern
- Track-jet correlation

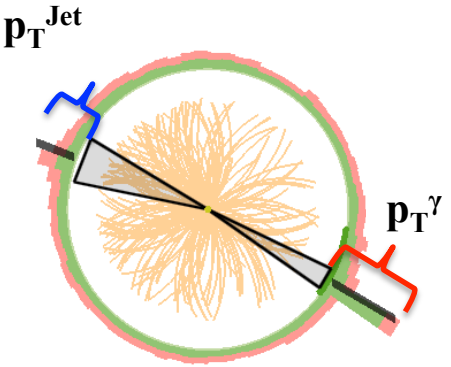
In PbPb collisions at 2.76TeV

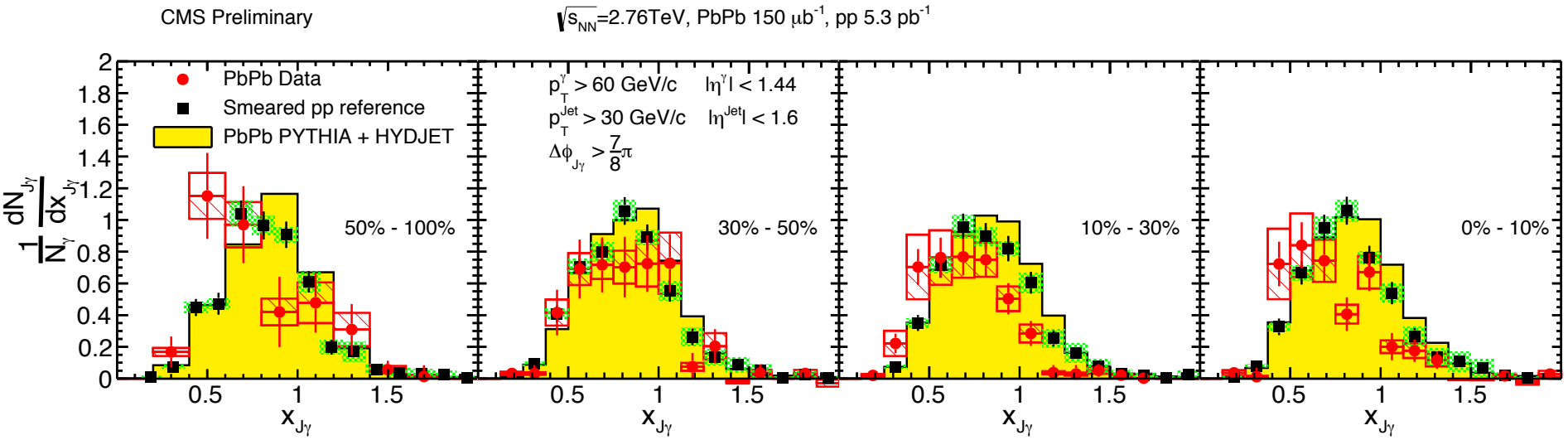
Let's start from gamma-jet results

Direct observation of jet quenching

1. The momentum imbalance of gamma-jet pairs increases in PbPb compared to pp
2. Significant fraction of jets have gone below reconstruction threshold

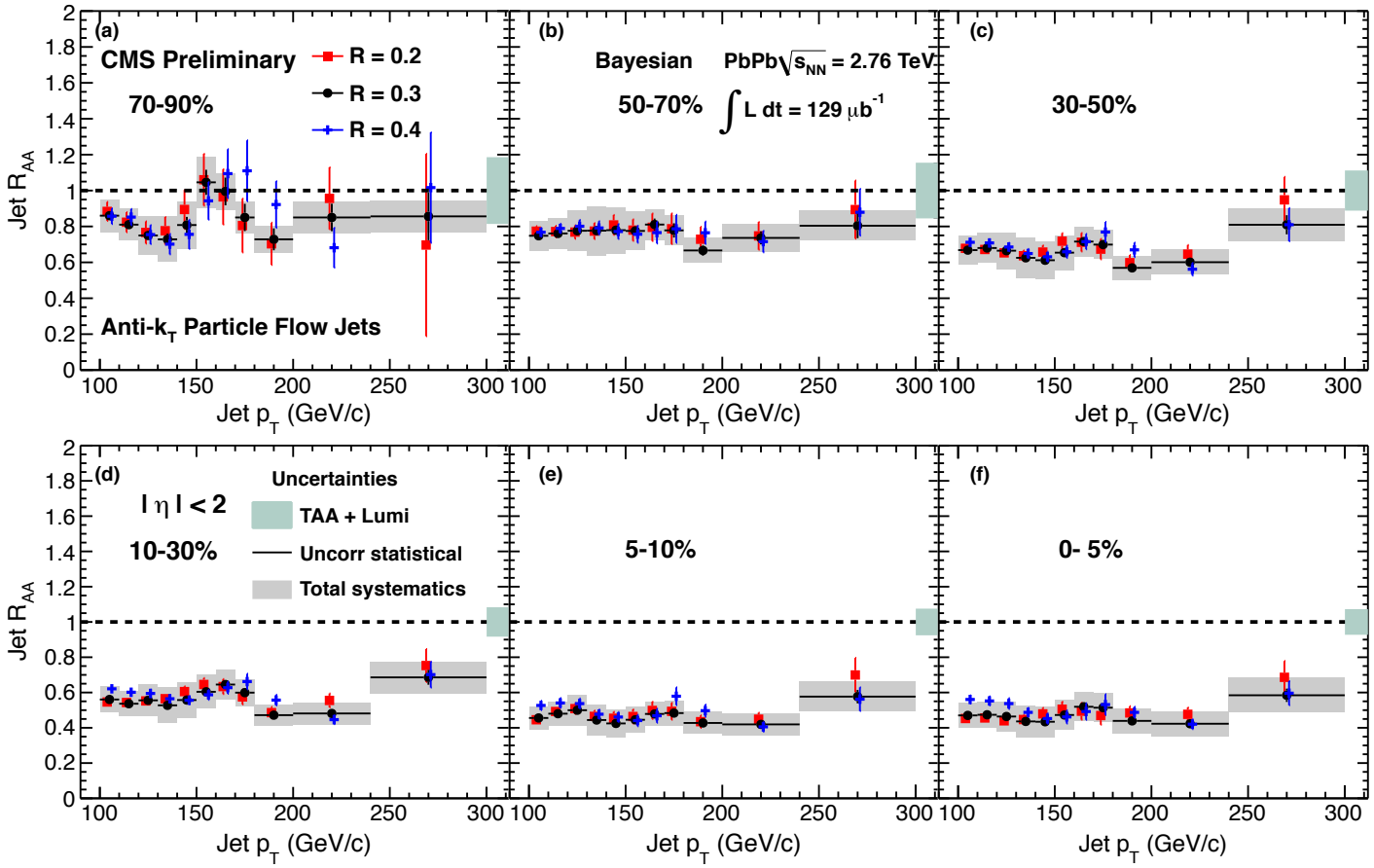
$$x_{J\gamma} \equiv \frac{p_T^{jet}}{p_T^{\gamma}}$$





Suppression of inclusive jets

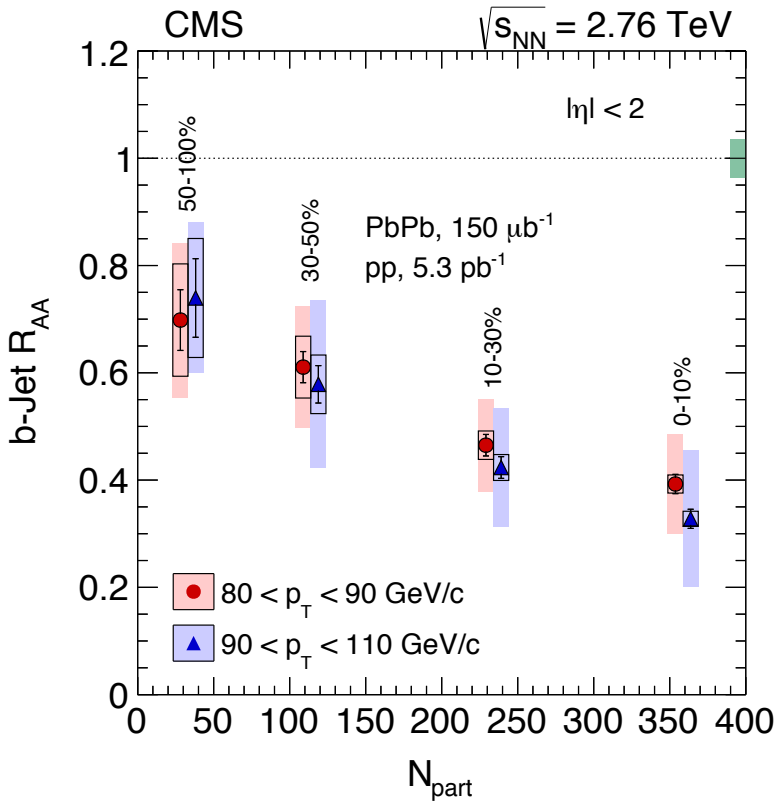
In addition, we observed the significant drop of jet yields in the central collisions
- Jet R_{AA} in various jet resolution parameters

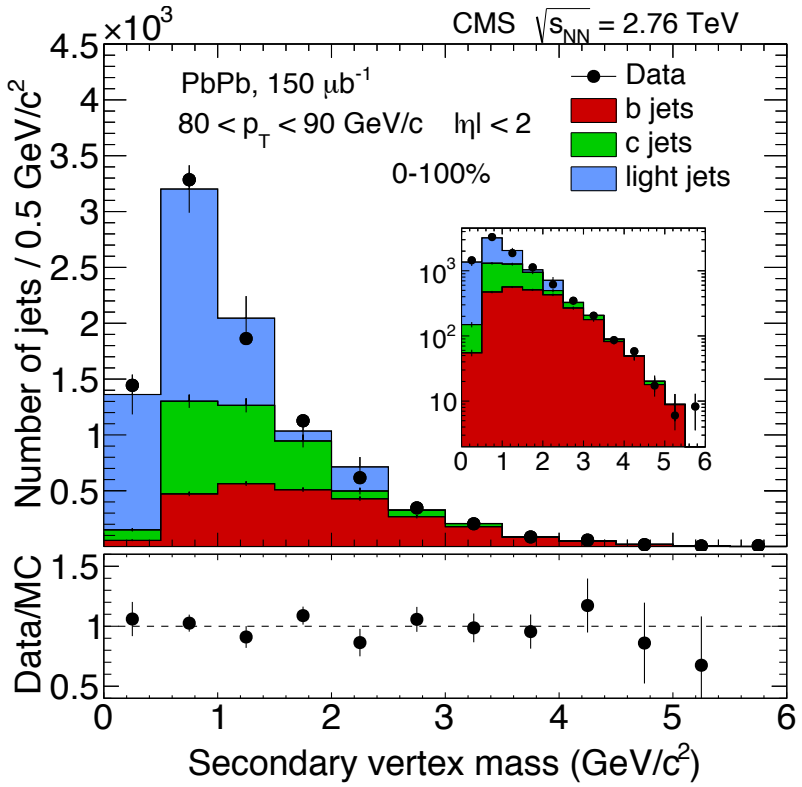


Suppression of b quark Jets

We also found the centrality dependent suppression of b-quark jets

- B jets were identified by the secondary vertex reconstruction of B meson and secondary vertex mass fitting





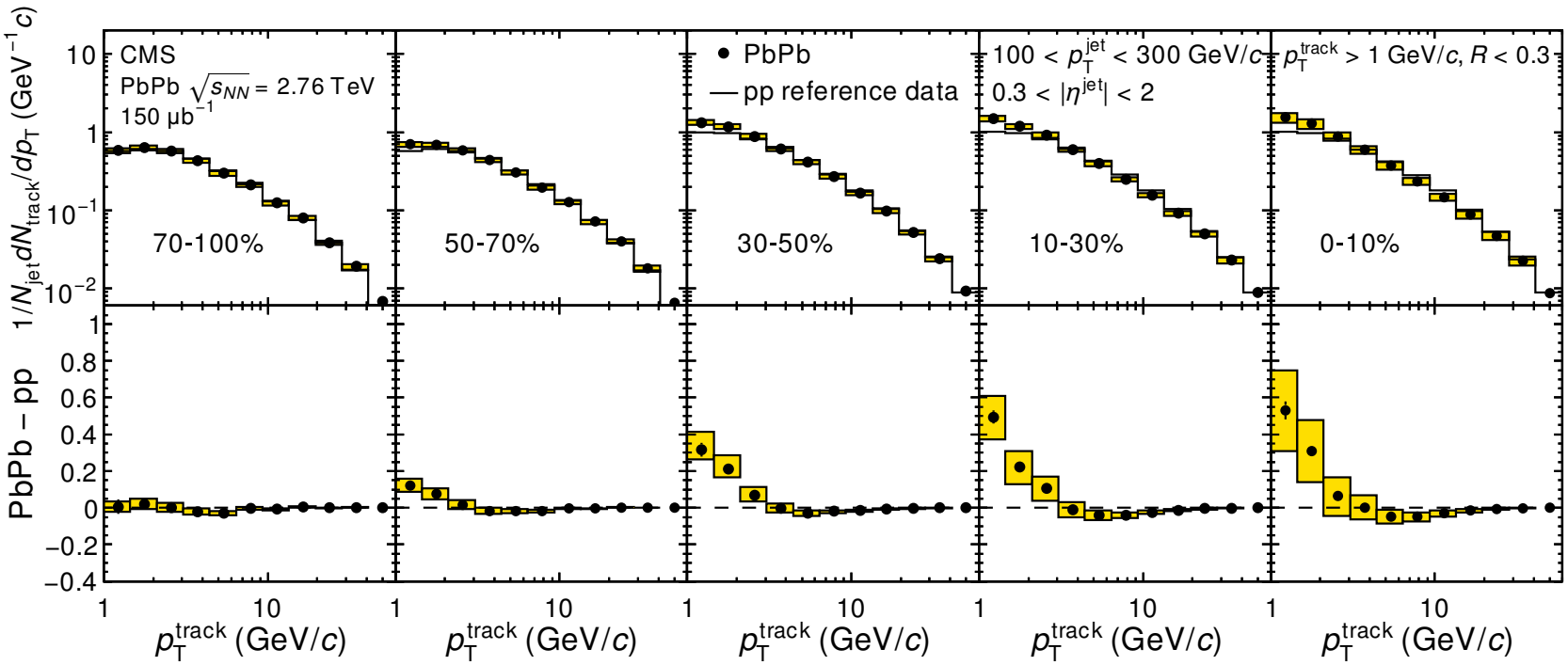
Arxiv 1312.4198
Accepted by PRL

Not only energy, but also **Jet Fragmentation**

The fragmentation function of jets in PbPb turned out to be different from pp

- Excess of particles below 3GeV
- Deficit of particles in the intermediate p_T range 3-10GeV
- Consistent particle distribution in p_T > 10GeV

PRC 90 (2014) 024908



Plus, modification of jet shape

The jet shape, defined as the transverse profile of momentum distribution in jet, were also modified

- Excess of energy density at farther distance from jet center r > 0.2
- Deficit of energy density at 0.1 < r < 0.2

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks}\in[r_a,\,r_b)} p_{\text{T}}^{\text{track}}}{p_{\text{T}}^{\text{jet}}}$$

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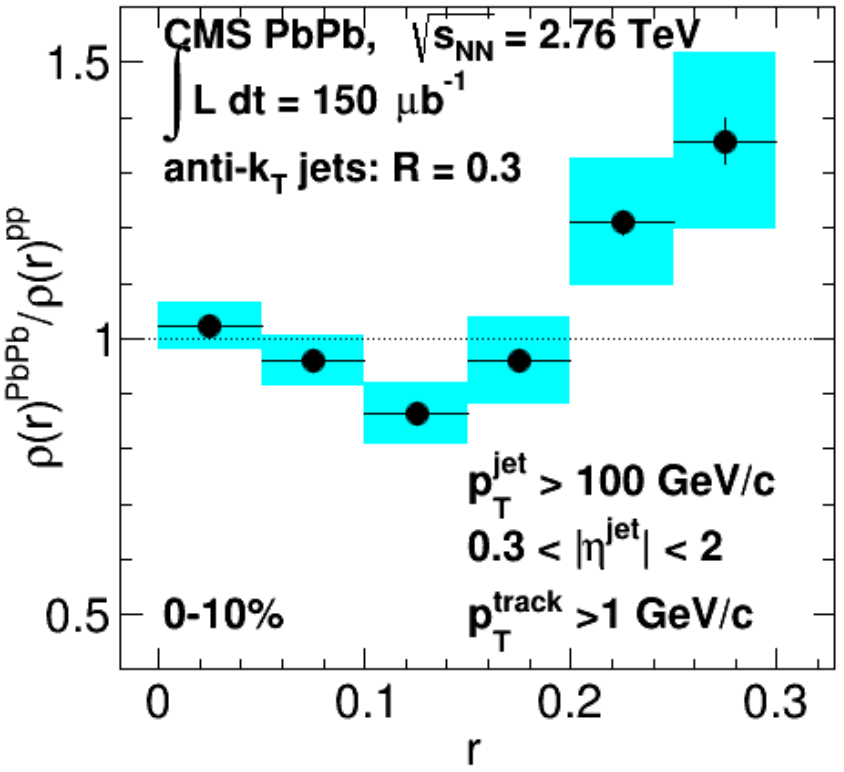
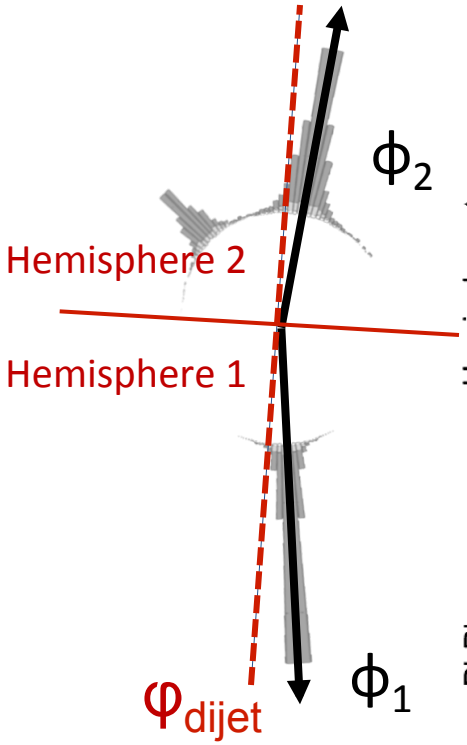


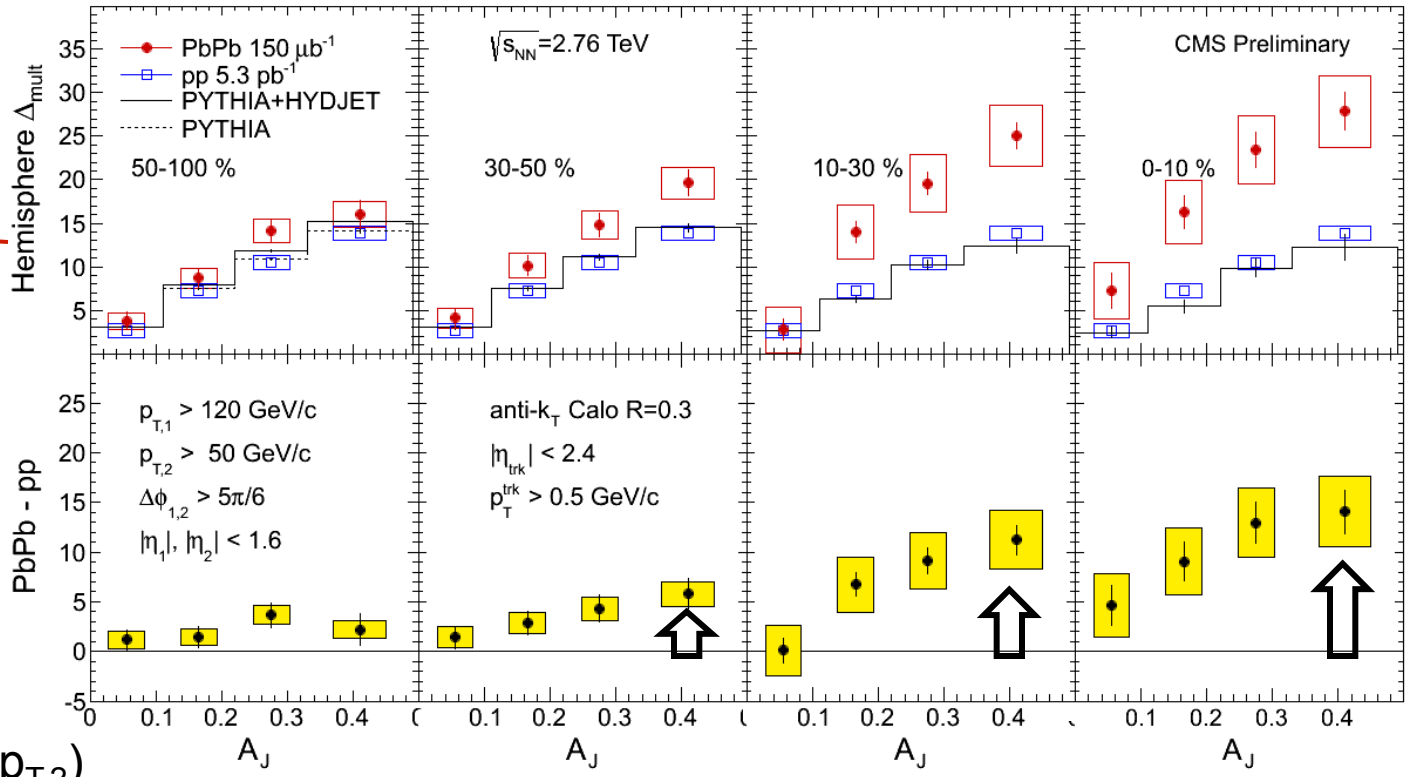
Law of action and reaction

The response of medium by hard probe was also studied using jet-track correlation

- Asymmetry of particle multiplicity was compared with pp reference
- The enhancement in PbPb compared to pp increases with centrality and A_J



CMS-PAS-HIN-14-010

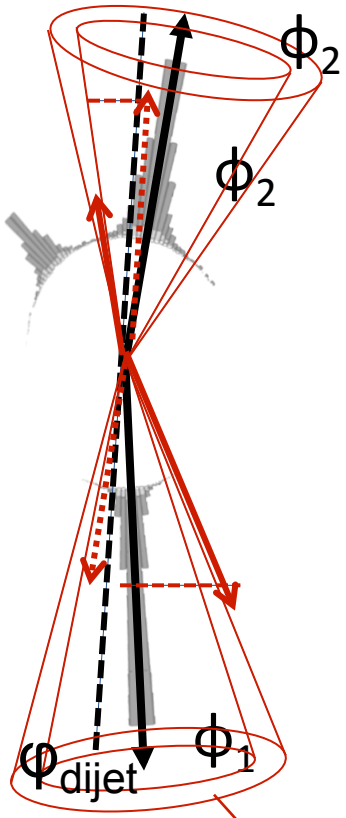


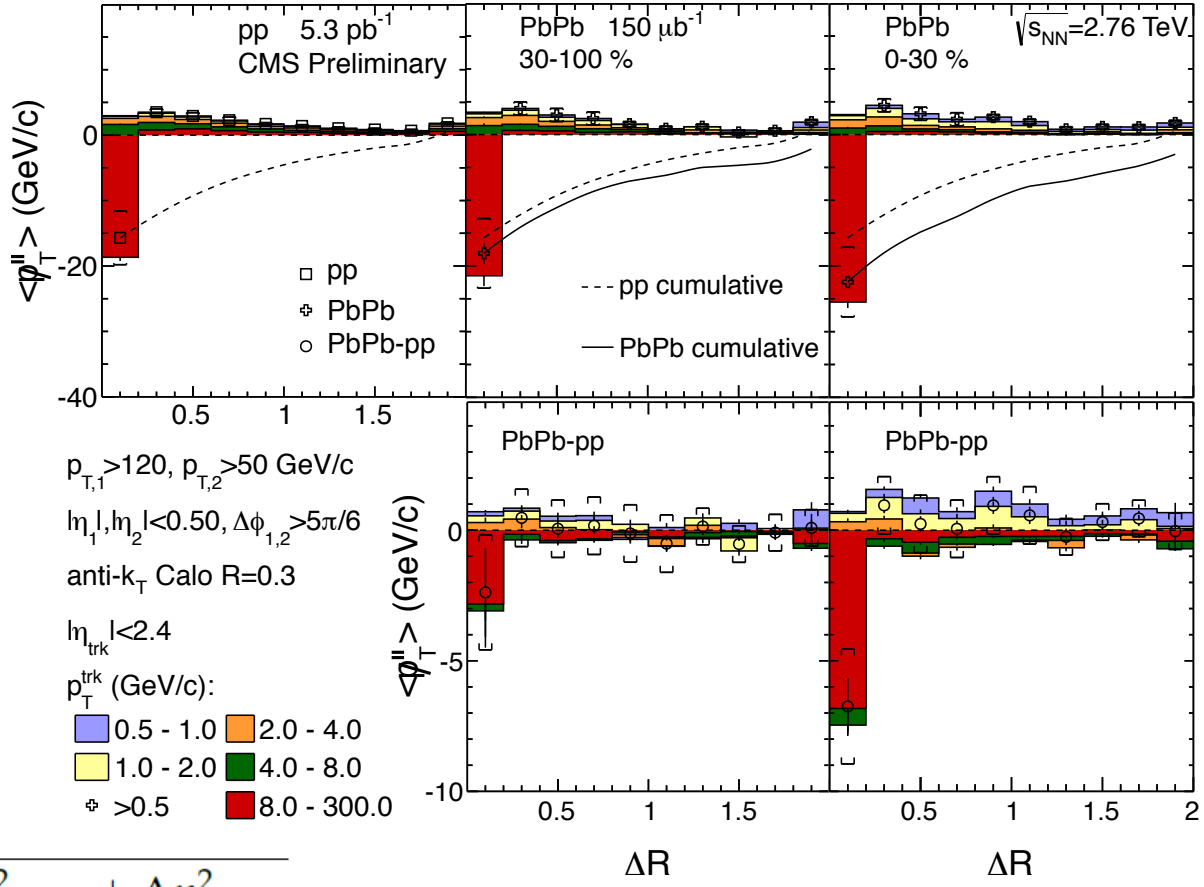
$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

Law of action and reaction

Differential profile as a function of distance from leading jet was studied

- High p_T imbalance at small ΔR
- was balanced by low p_T particles in subleading jet direction upto large ΔR





$$\Delta R = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

Part II : pPb is similar to pp

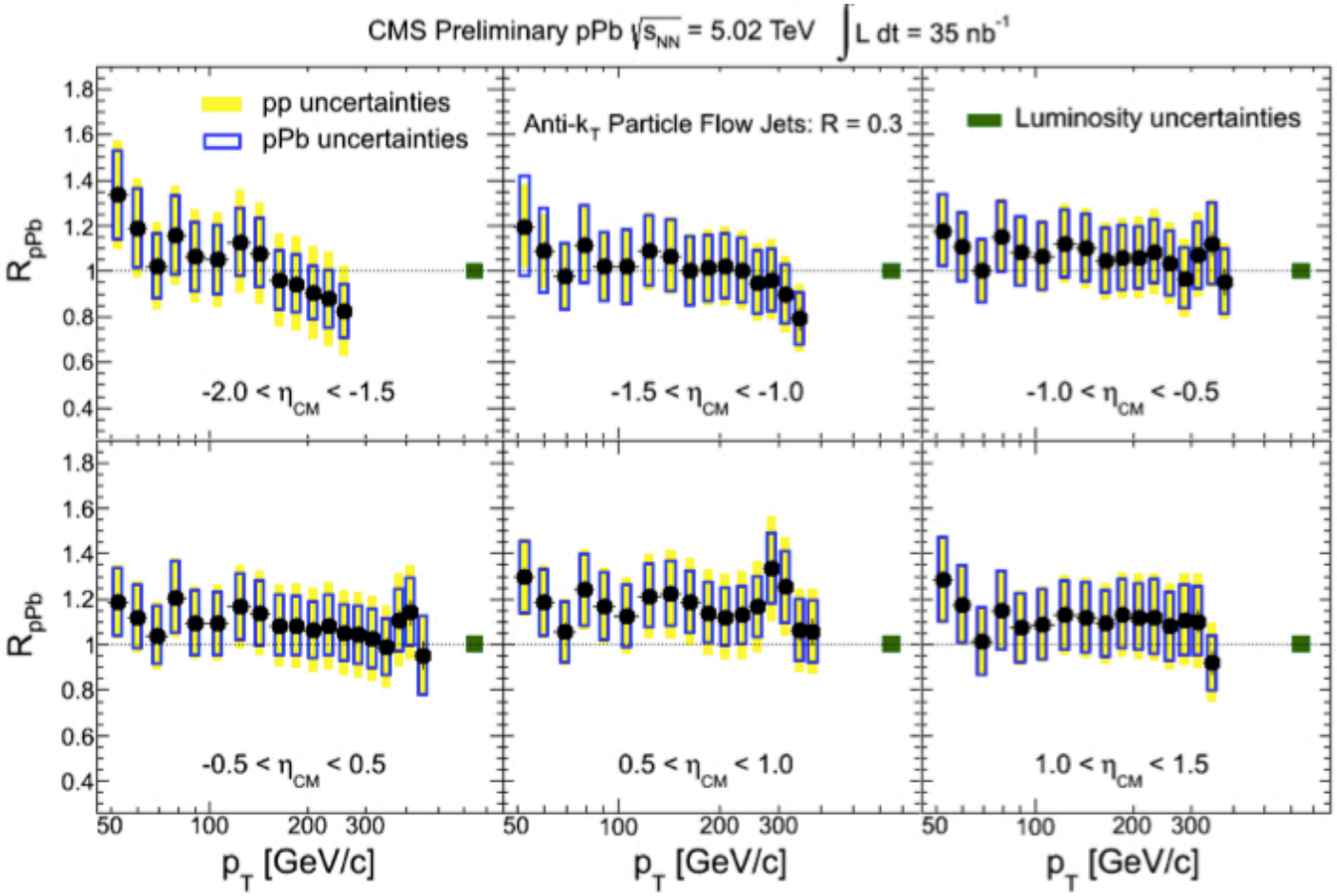
- Inclusive jet spectra
- Ratio of excited to ground states of Bottomonia
- Measurement of open B mesons
- Modification of Jet fragmentation pattern

In pPb collisions at 5TeV

Spectra of inclusive jets

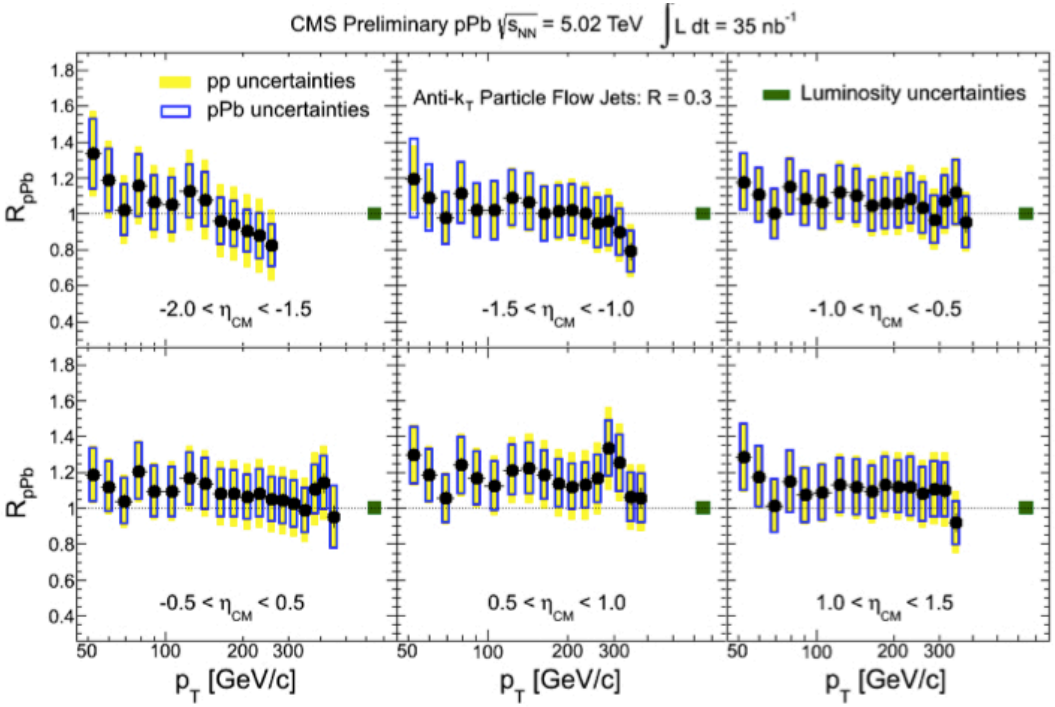
No evidence of jet quenching found in pPb collisions

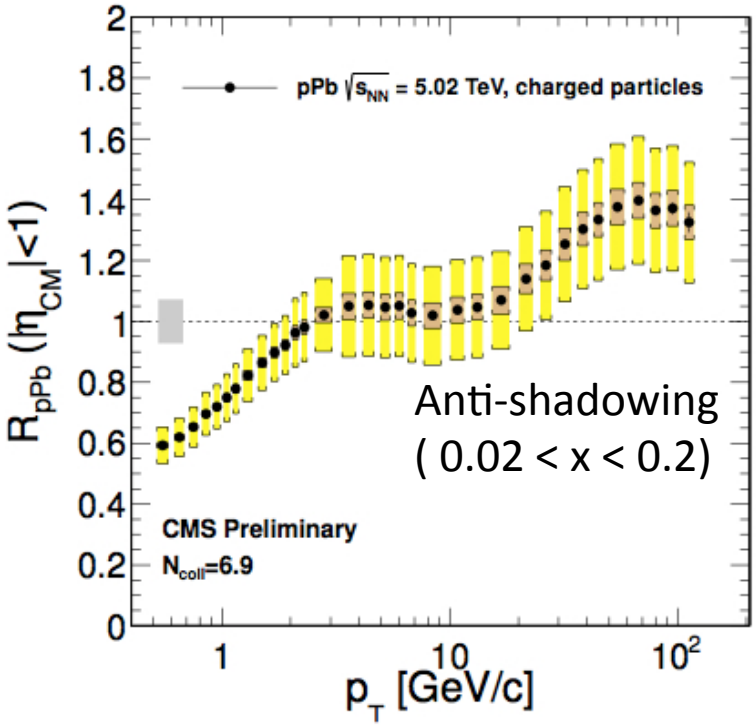
Suppression of half yield in PbPb collisions are final state effect



Spectra of charged particles

- Rather than suppression, enhancement in anti-shadowing region





Different shape of R_{pA} …

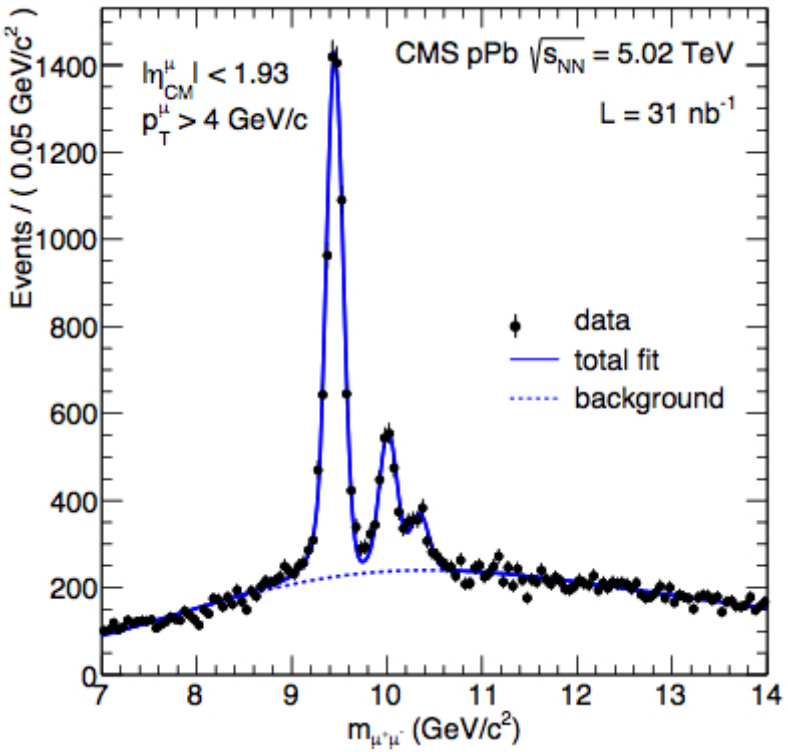
Note that the pp references were obtained in different method.

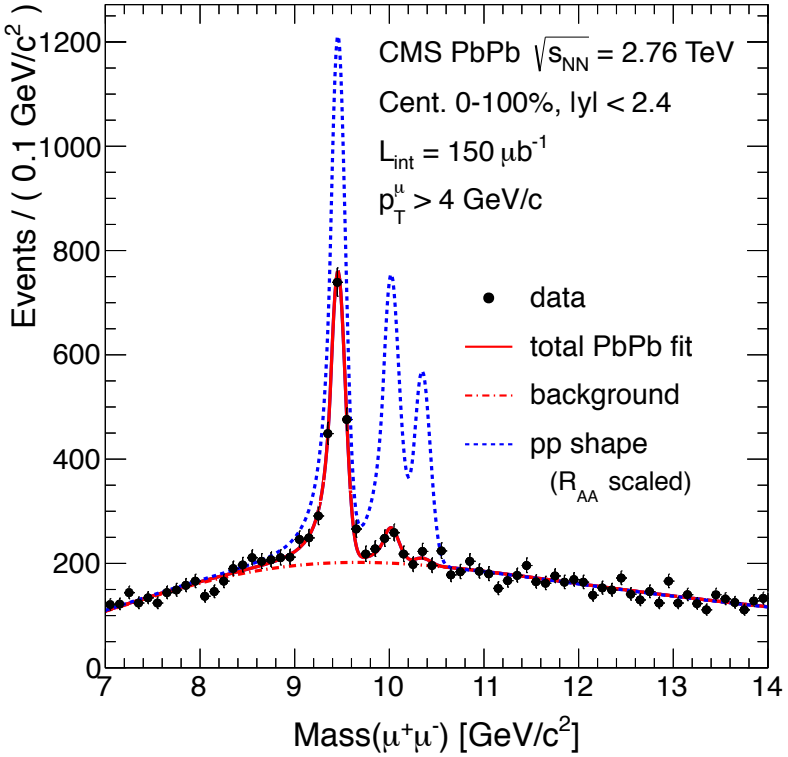
- Charged hadrons : global fit of pp collisions at various energy
- Jet : Extrapolation from 7TeV results at CMS using pT scaling

Collisional data in pp @ 5TeV are needed to pin down this question.

Measurement of Bottomonia

- Υ(1S), Υ(2S) and Υ(3S) are measured via di-muon decay mode
- The significantly low Υ(nS)/Υ(1S) ratio in PbPb – compared to pp reference – was restored in pPb collision





Measurement of Bottomonia

- ϒ(1S), ϒ(2S) and ϒ(3S) are measured via di-muon decay mode
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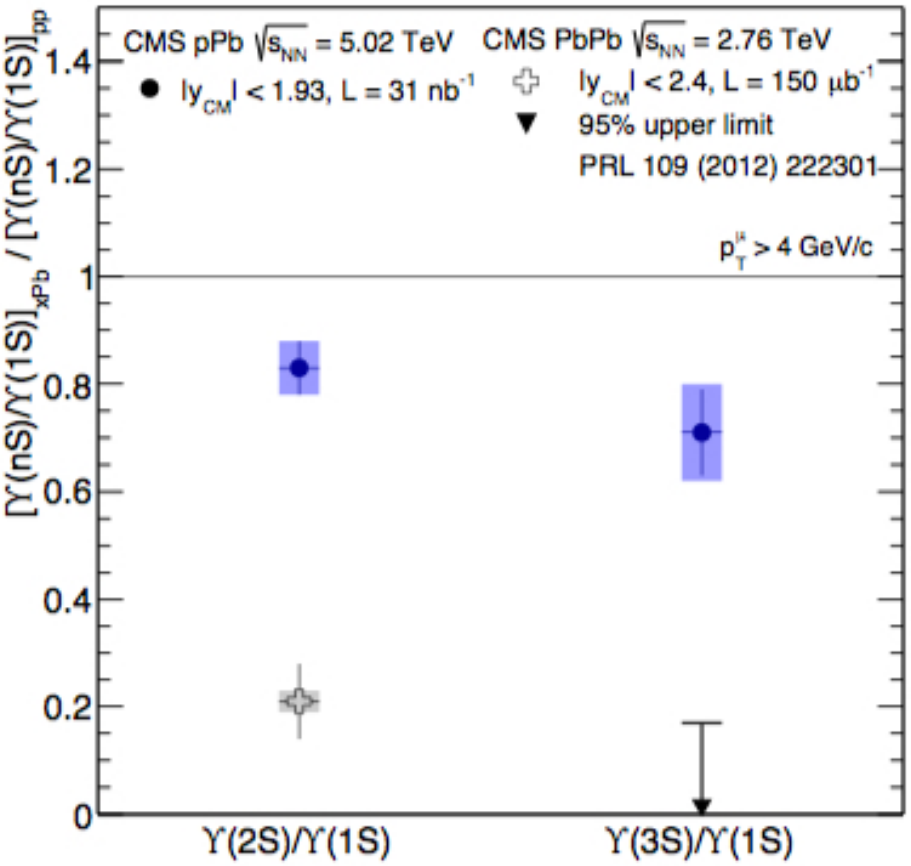
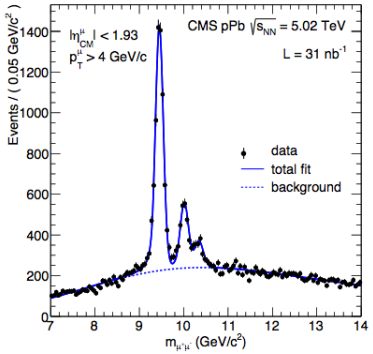
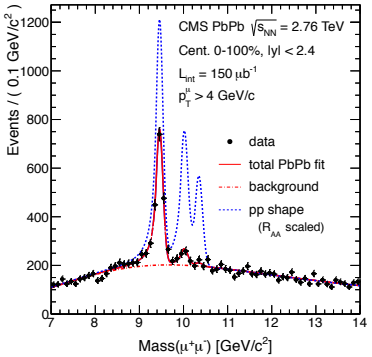




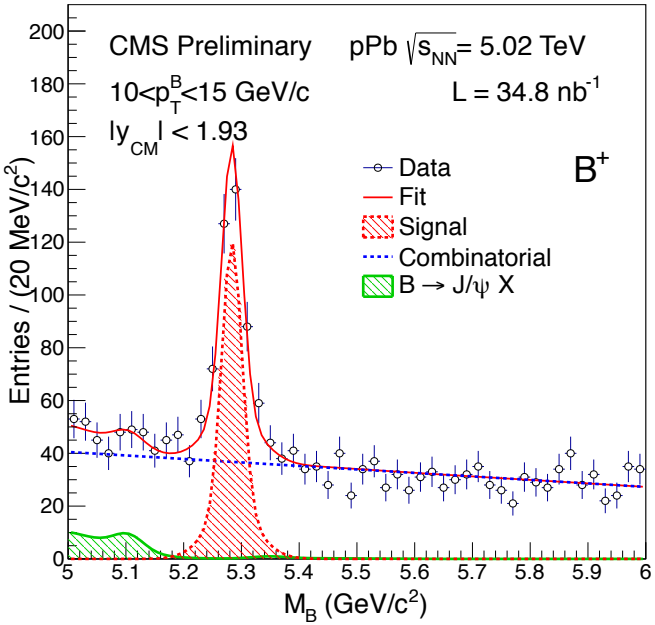
Pb+Pb / p+p

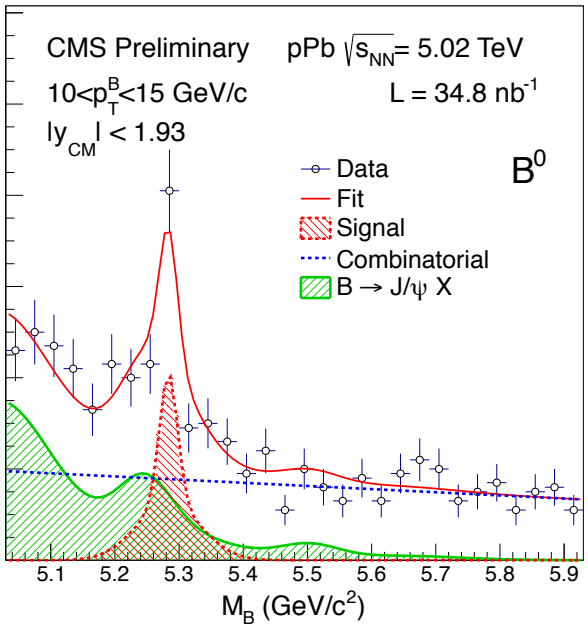


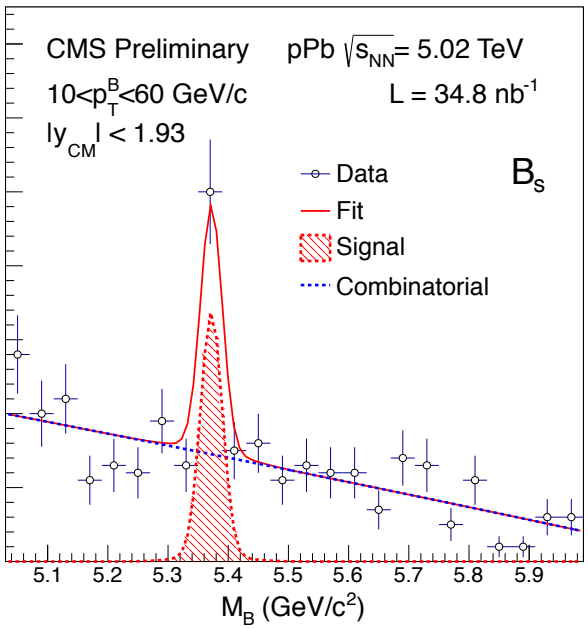
p+pb / p+p

Cross-check with heavy quark results

- CMS also measured charged B, B^0 and Bs
- R_{pA} is consistent to unitiy for all B meson brothers
- FONLL was used to obtain pp reference







Cross-check with heavy quark results

- CMS also measured charged B, B^0 and Bs
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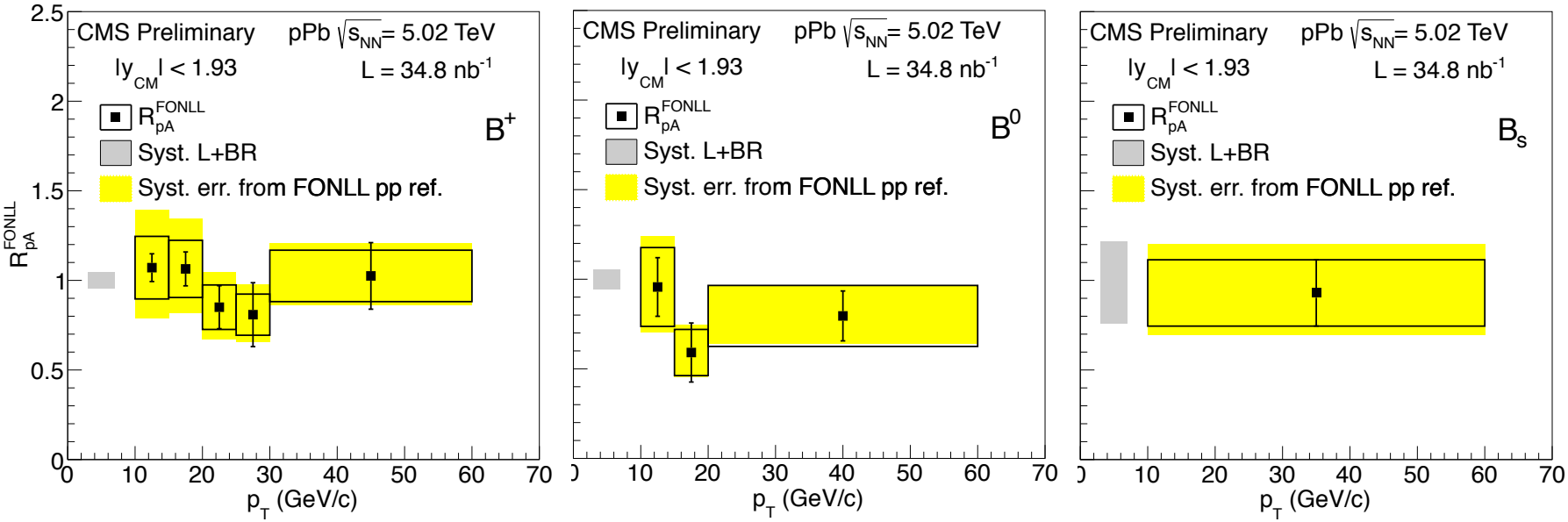
- R_{pPb} of B mesons is consistent with unity



Part III : pPb is different from pp

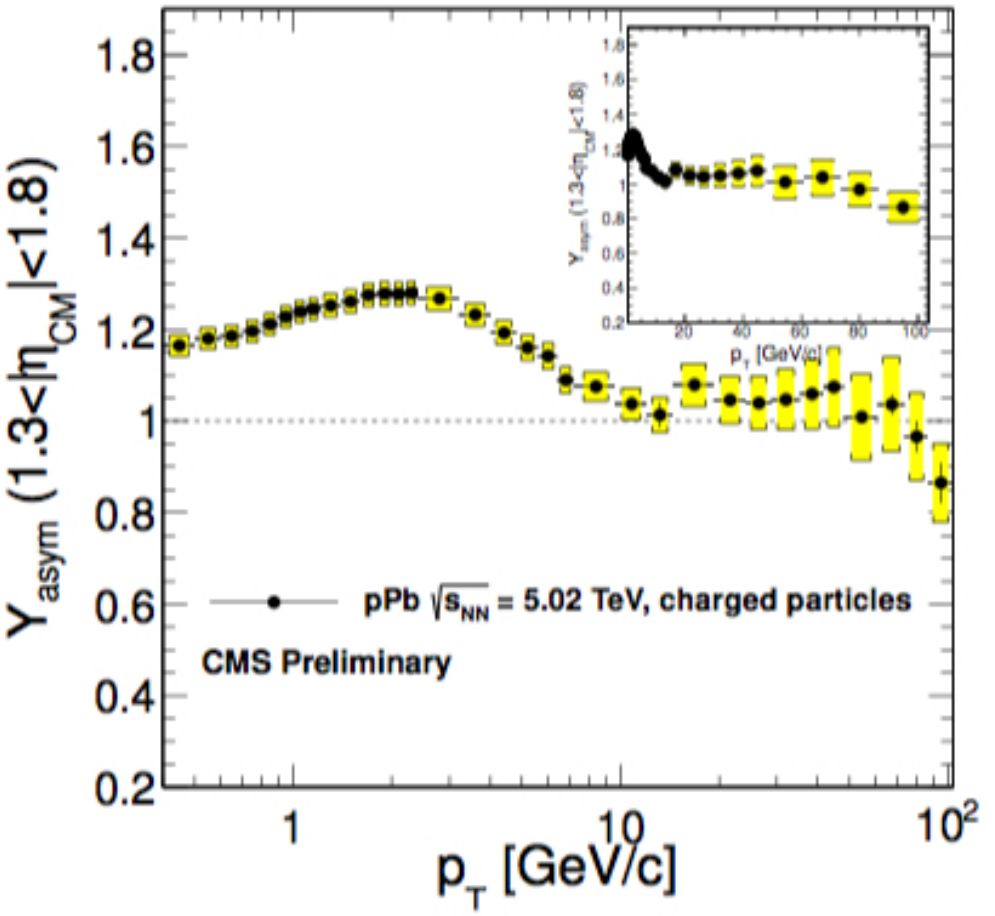
- Forward/backward asymmetry of charged particles spectra
- Pseudorapidity distribution of di-jet
- $\Upsilon(2S)/\Upsilon(1S)$ revisited

In pPb collisions at 5TeV

charged particle spectra revisited

- No evidence of energy loss was discovered in p+Pb at 5TeV
- Yet, it does not mean that p+Pb boring!
- Large forward/backward asymmetry was observed in charged particle production
- Provides a strong constraints in the initial state modification models

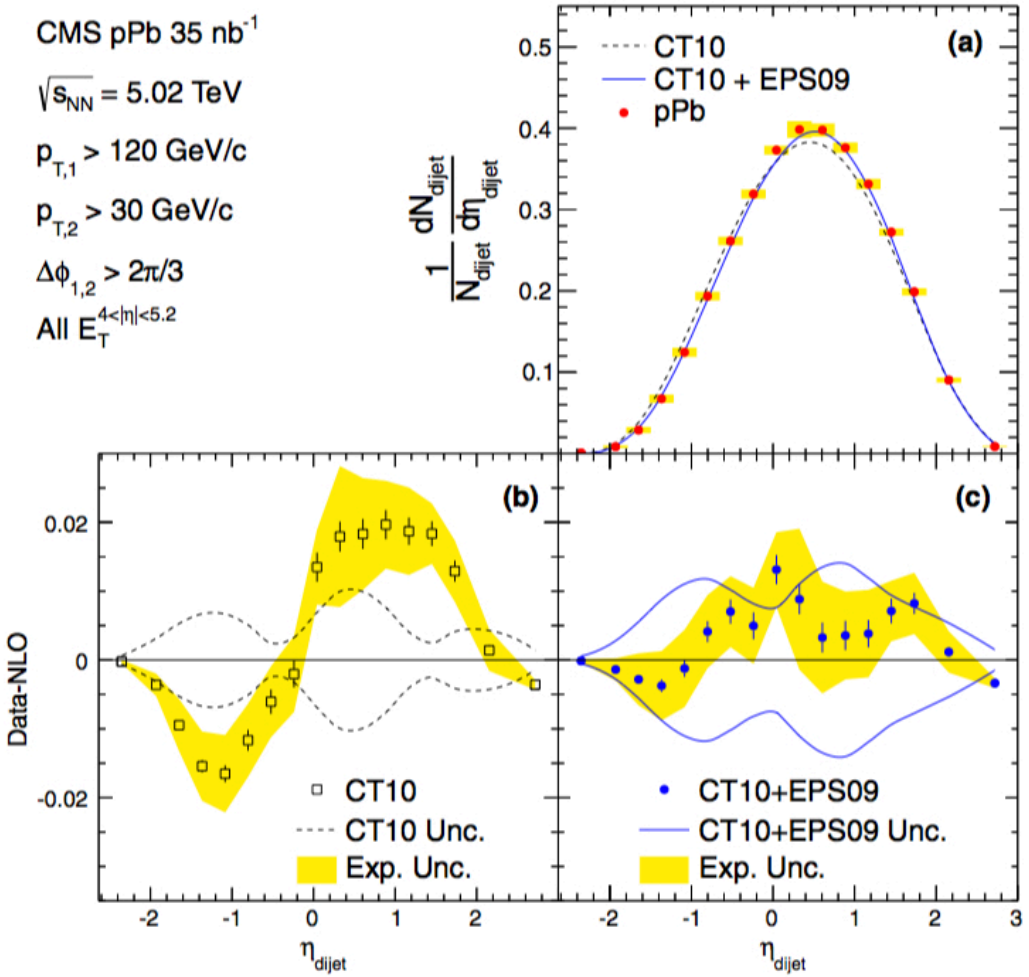
$$Y_{\mathrm{asym}}(p_{\mathrm{T}}) = \frac{d^2N_{ch}(p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}|_{\eta_{\mathrm{CM}}\in[-b,-a]}}{d^2N_{ch}(p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}|_{\eta_{\mathrm{CM}}\in[a,b]}},$$



Pseudorapidity distribution of di-jet in pPb

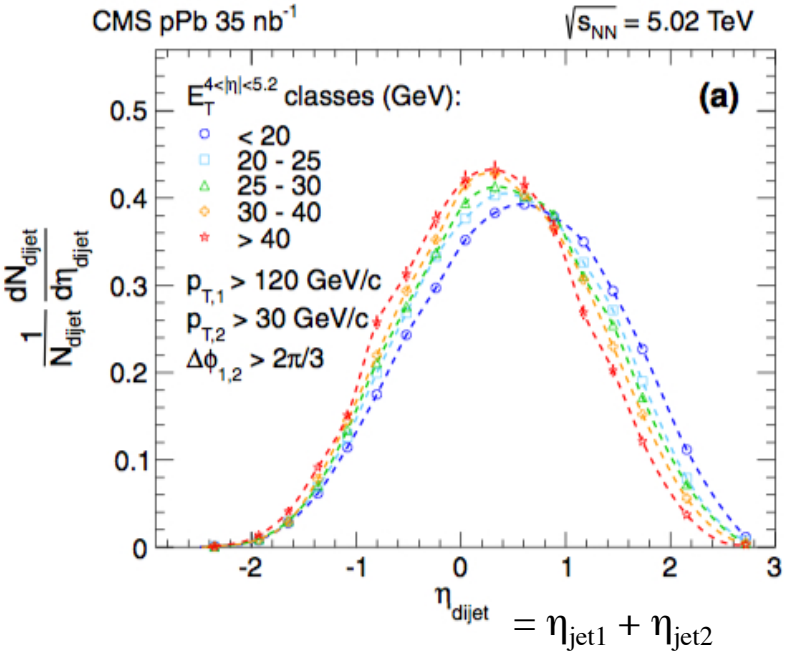
- Collisional Data had different η_{dijet} distribution from PYTHIA reference or CT10 calculation
- Consistent with NLO calculation based on CT10+EPS09 PDFs, within combined theoretical and experimental uncertainty
- Detailed studies were carried out to understand the dependence on collision size or centrality

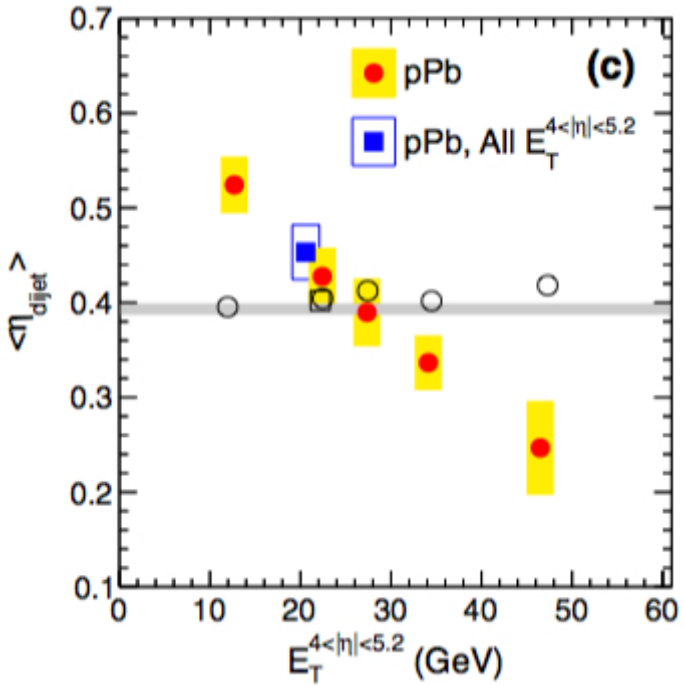
$$\eta_{dijet} = \eta_{jet1} + \eta_{jet2}$$



…using HF sub-detector

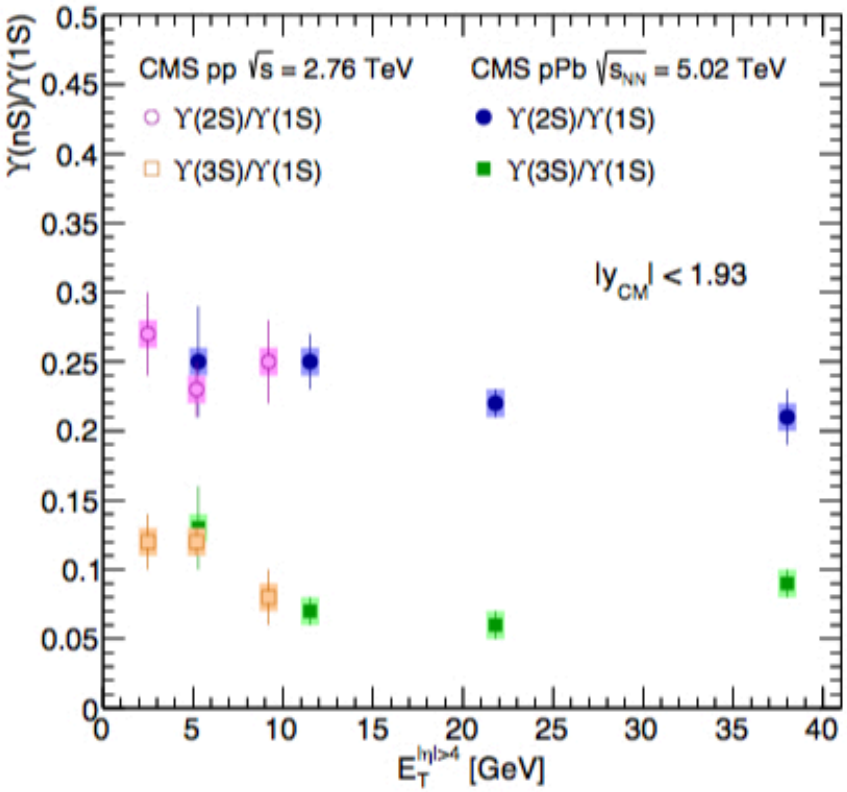
- Strong correlation between forward energy activity and di-jet pseudo-rapidity was observed

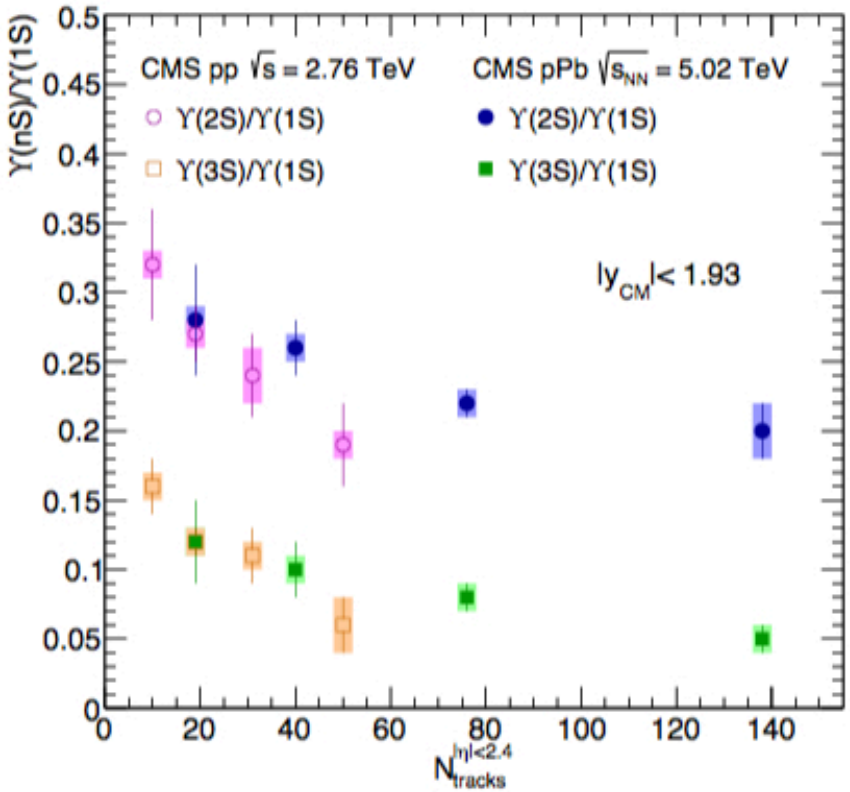




- It is more correlated to the energy emitted in proton-going side than that in Pb-going side (BACKUP)

ϒ(2S)/ϒ(1S) revisited





Correlation with Forward energy is weak

But the correlation with particle multiplicity is substantial.

Two possible scenarios

1. ϒ(1S) is systematically produced with other particles
2. ϒ(nS) are affected by interaction with surrounding environment

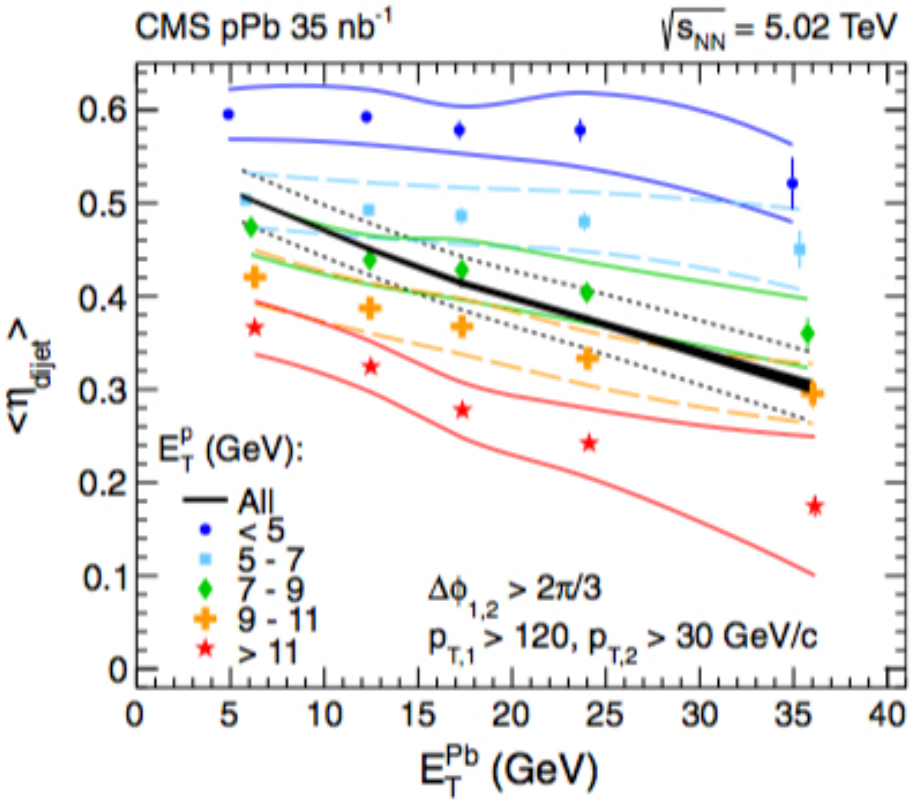
Summary

- The recent results of jets and heavy quarks in CMS heavy ion experiments were reviewed

- Clear modifications of jet energy and fragmentation patterns was revealed via various hard probes

- Considerable jet quenching was not observed in pPb collisions, but the recent CMS results on charged hadron and jet spectra provide a strong constraints in the initial state effect including nPDF

backup



More dependent on the energy emitted in proton-going side than that in Pb-going side (BACKUP)

Technical obstacles in Heavy Ion collisions

Thousands of soft particles in the underlying events

Disentangling heavy ion underlying events from jet component has been big challenge in experiment

Subtraction of background energy in jet cone and photon isolation cone mandatory for hard probe analysis

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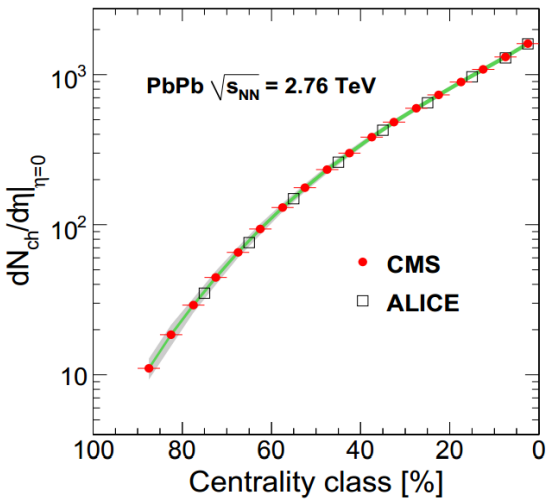
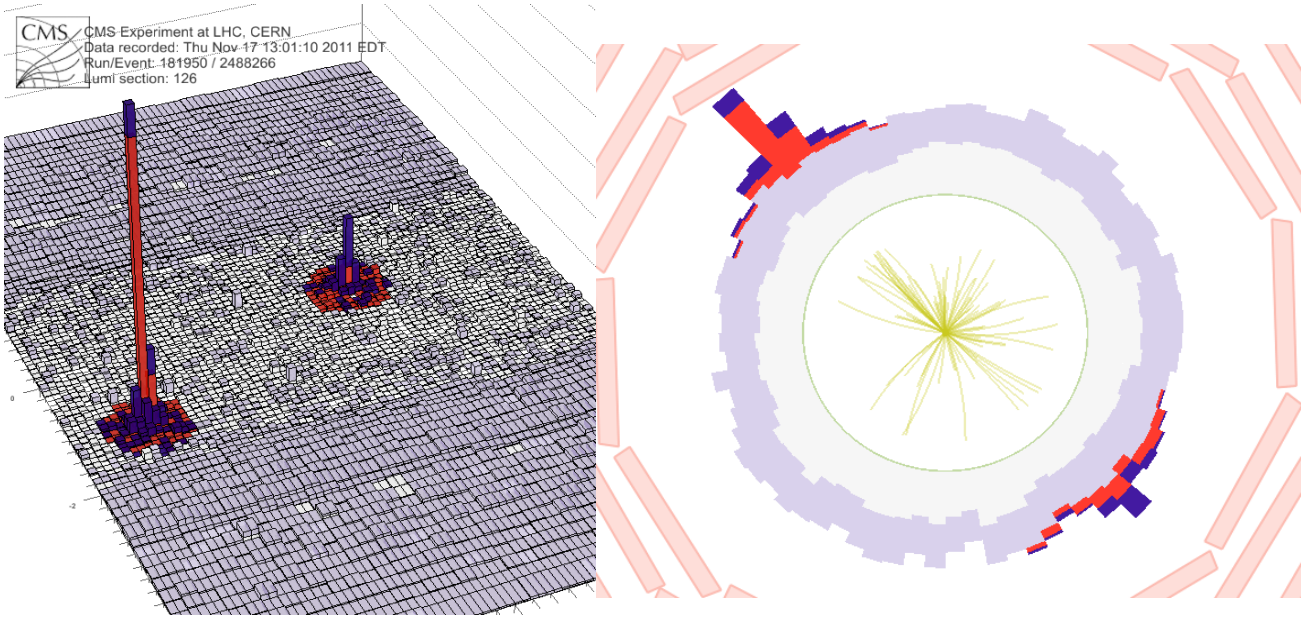
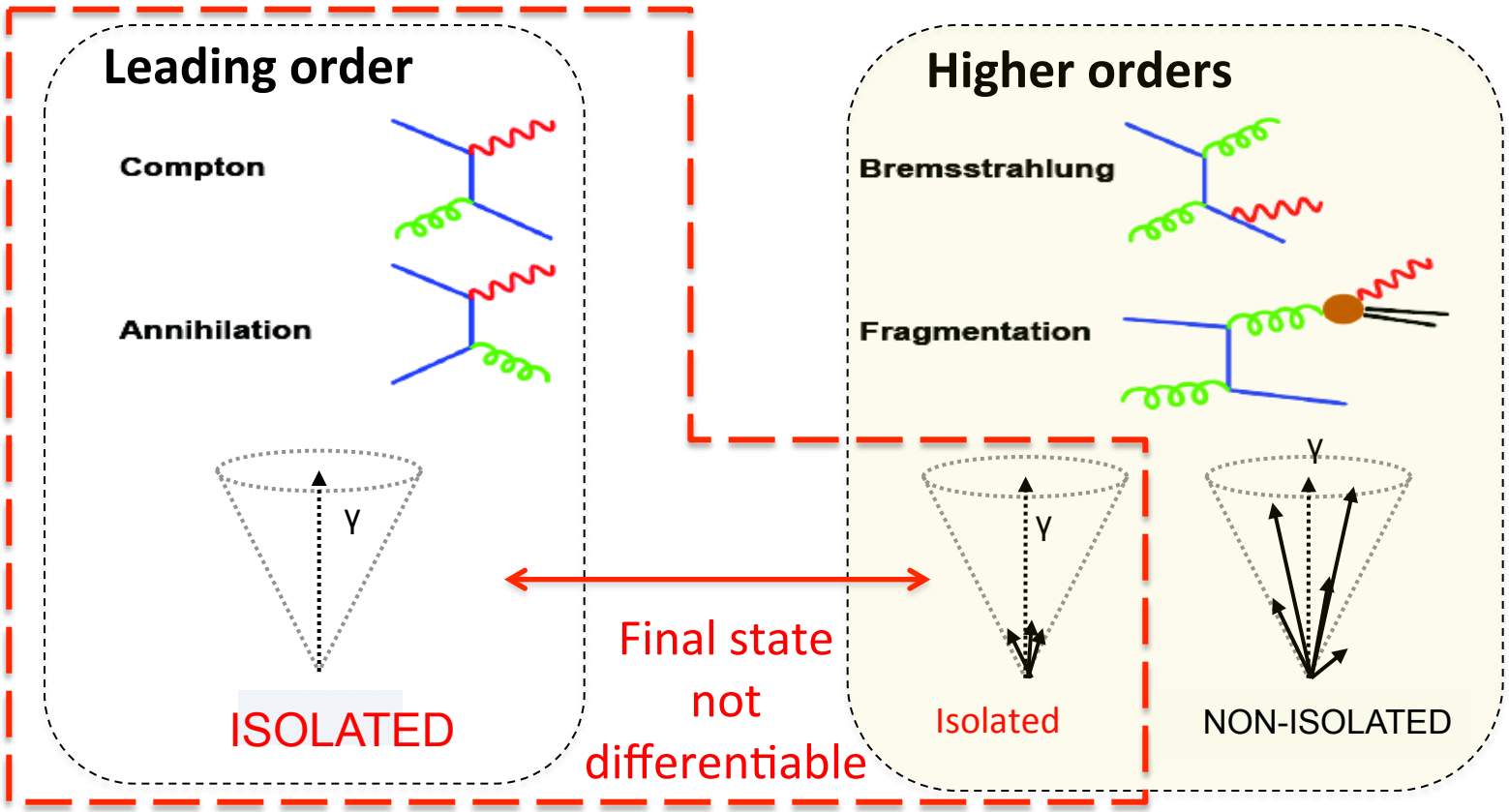


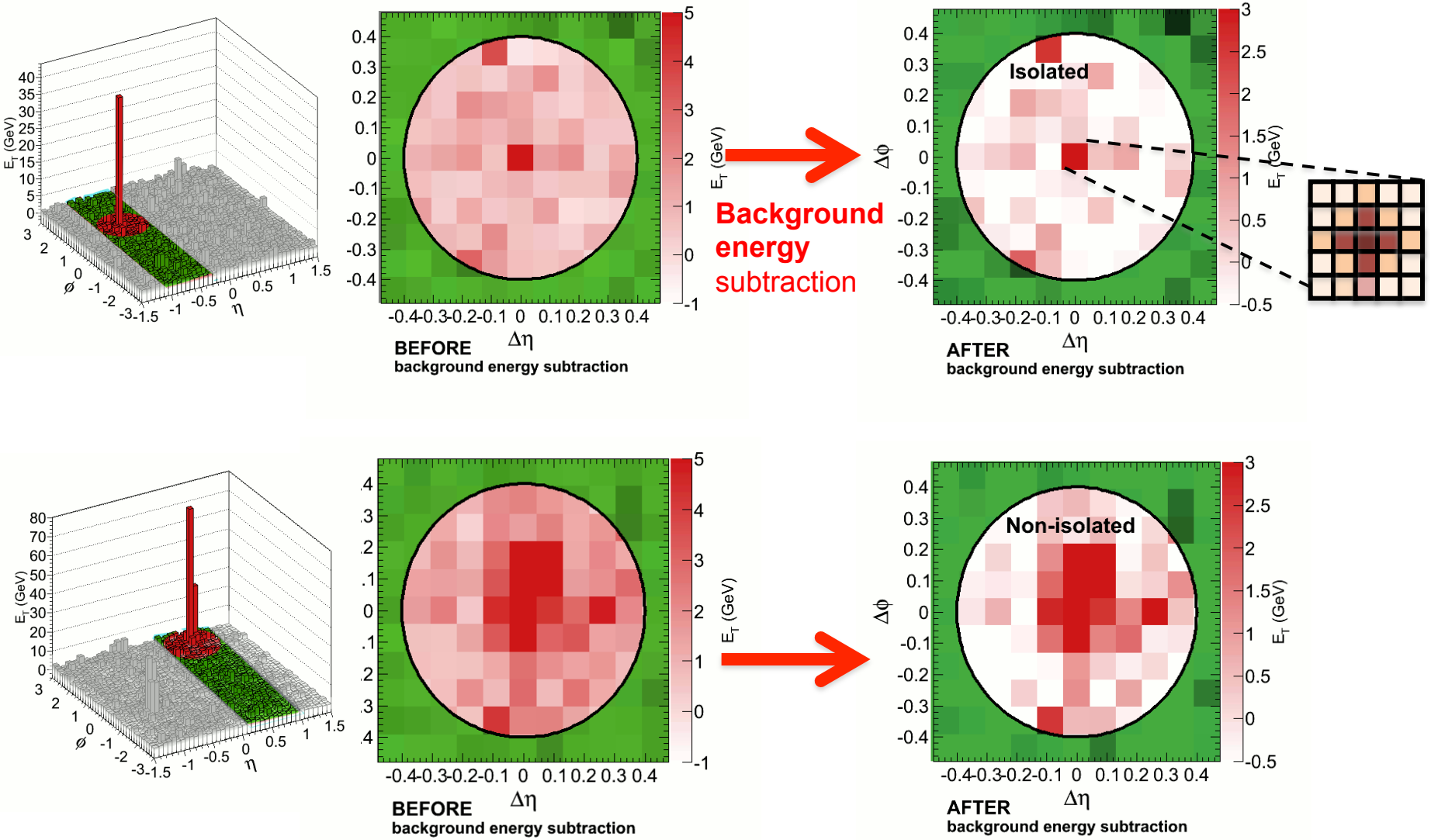


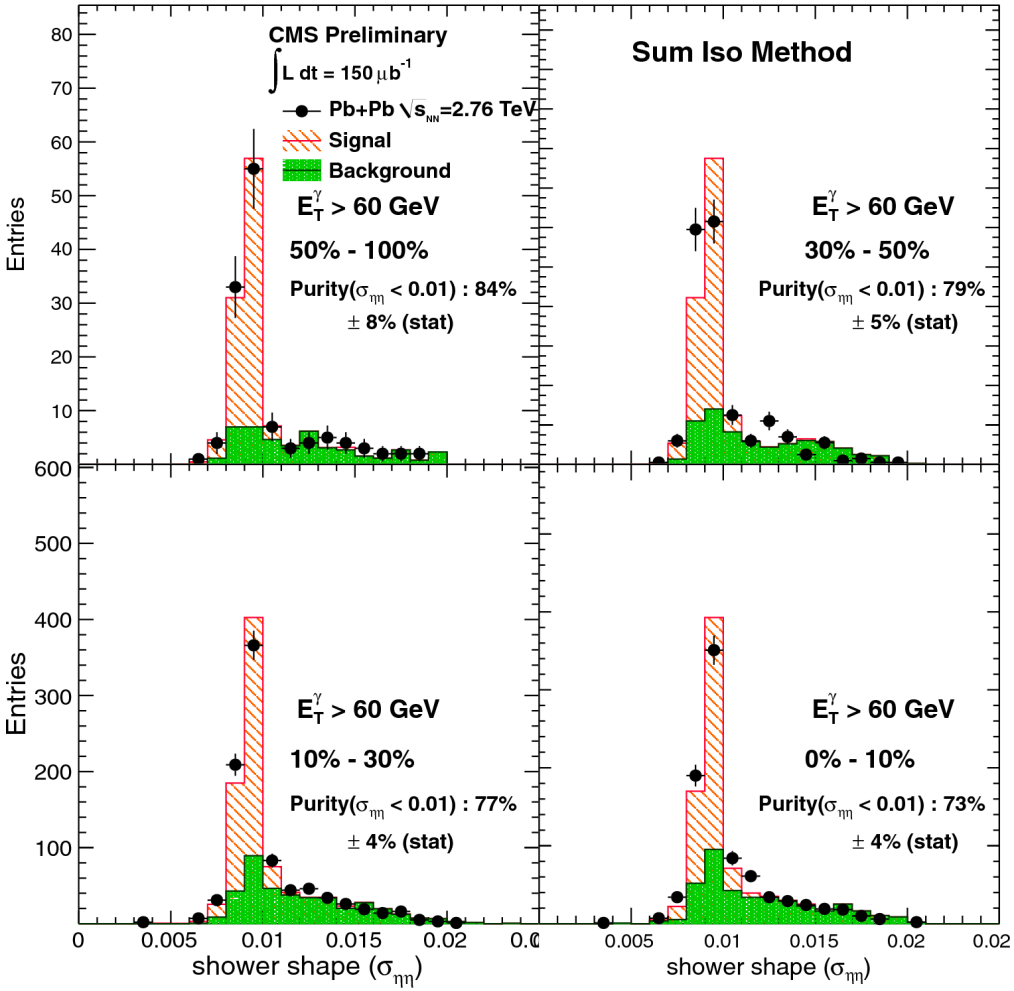
Definition of Isolation photon



- SumIso = uncorrected Track + ECAL + HCAL E_T in $R < 0.4$
- GenIso = generator level particle energy in $R < 0.4$
- Isolated prompt (non-decay) photons with SumIso < 1 GeV
- Comparison to MC definition GenIso < 5 GeV
- SumIso ≠ GenIso due to PbPb underlying event fluctuation

Isolation in heavy ion environment





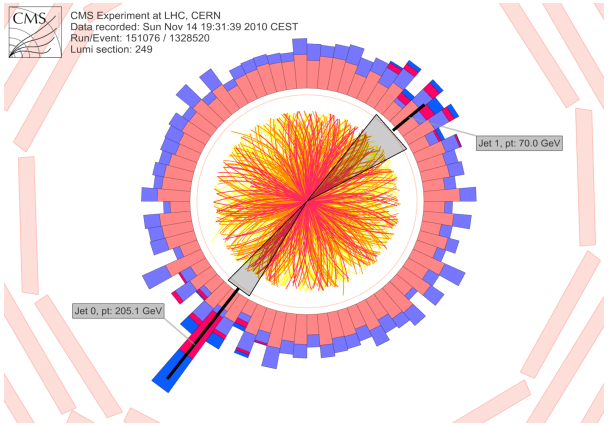
- Shower shape
  $\sigma_{\eta\eta} = \sum_i^{5\times5} w_i (\eta_i - \eta_{5\times5})^2 / \sum_i^{5\times5} w_i$
  $w_i = \max(0, c + \ln E_i/E_{5\times5})$
- Decay photons largely removed by cutting on $\sigma_{\eta\eta} < 0.01$
- S/(S+B) > 80% with this isolation cut
- Isolation efficiency > 70% for photons with $p_T > 40$GeV

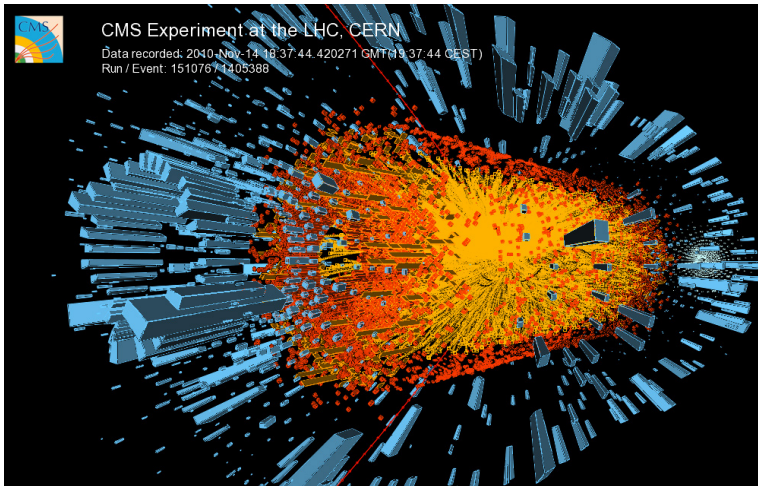
Part II

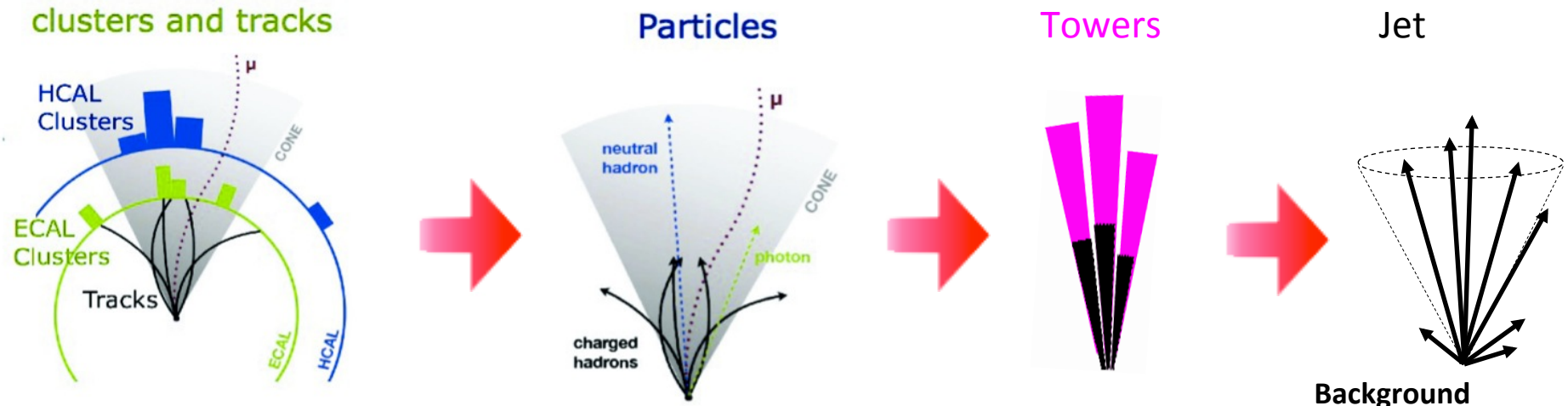
Estimation of Pileup Energy in Jet Cone

1. Background subtraction used so far
2. Newly developed algorithm using forward calorimeter

Jet reconstruction in CMS





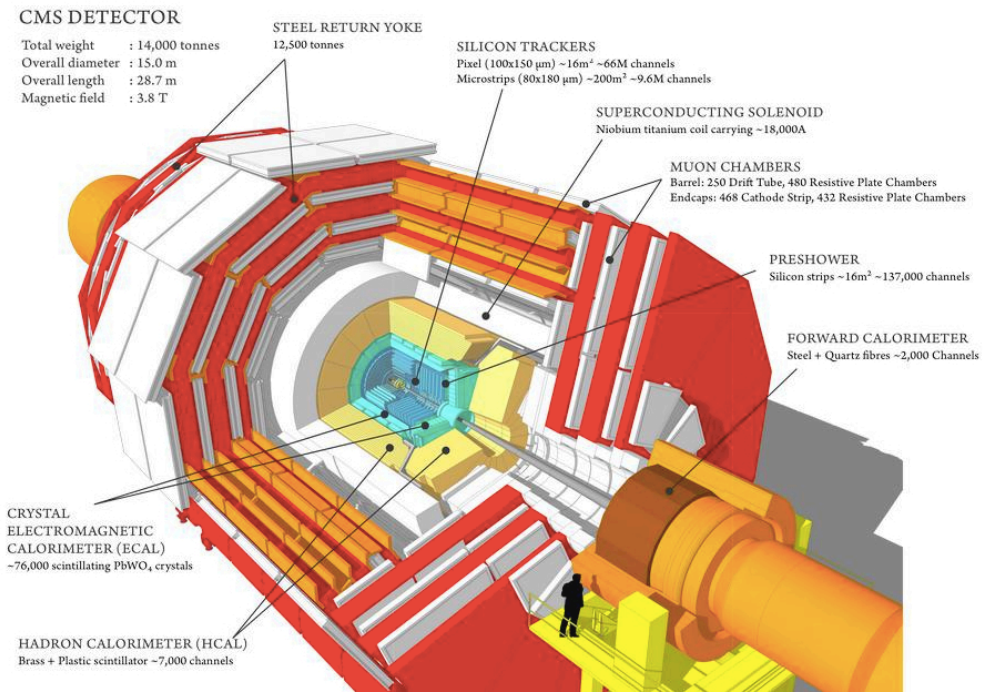


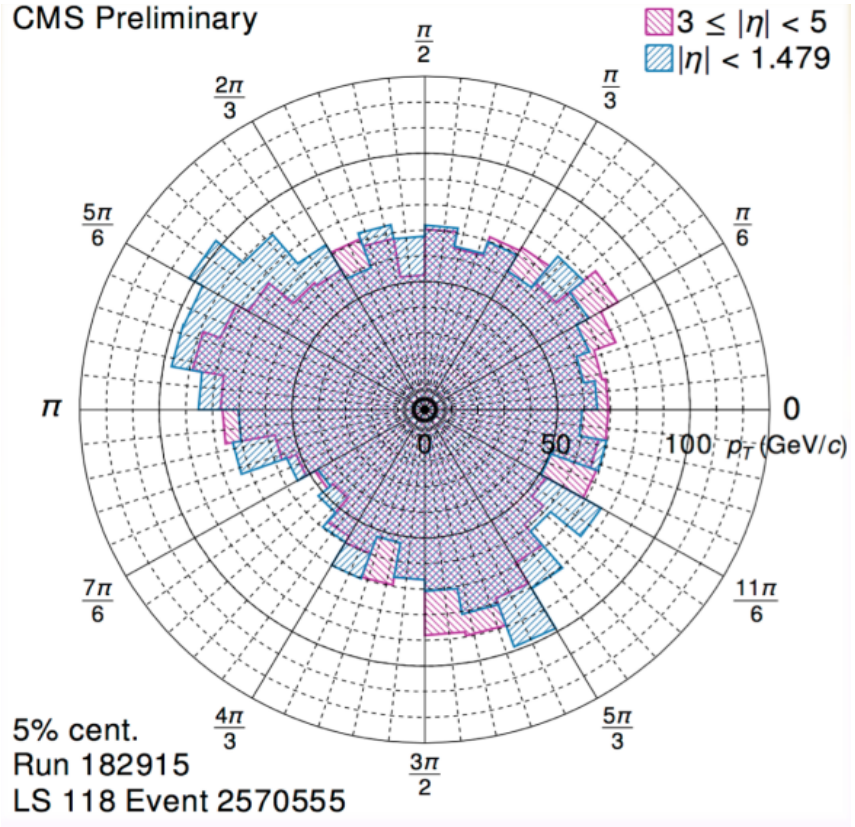
Anti-k_T algorithm is used in most of CMS publications

For instance, $\Delta\eta \times \Delta\phi$ 0.076 x 0.076 in barrel

Background subtraction and jet clustering

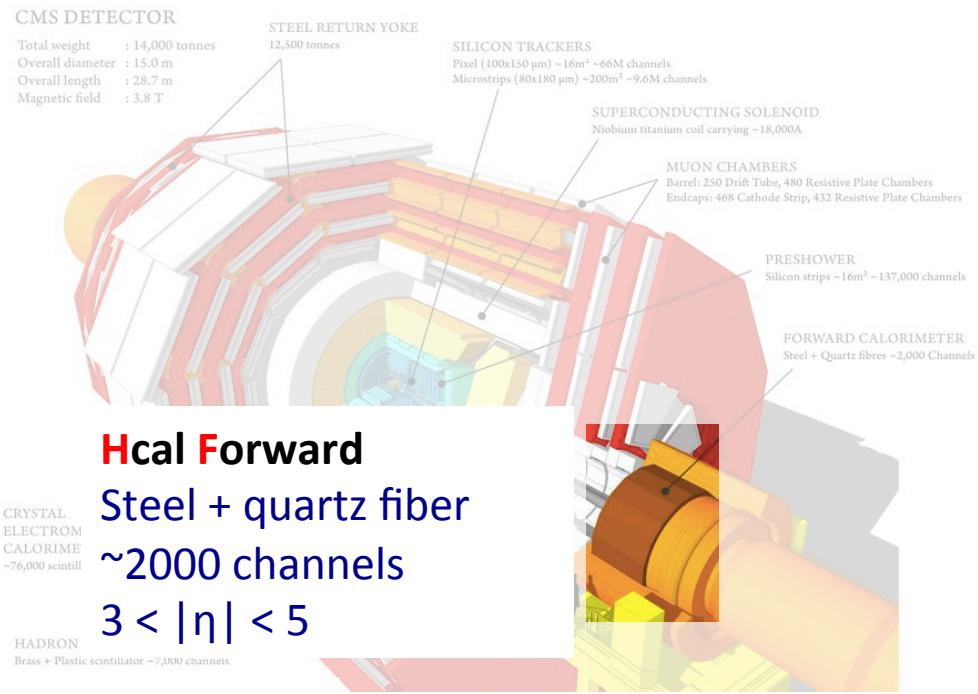
New algorithm using Forward calorimeter

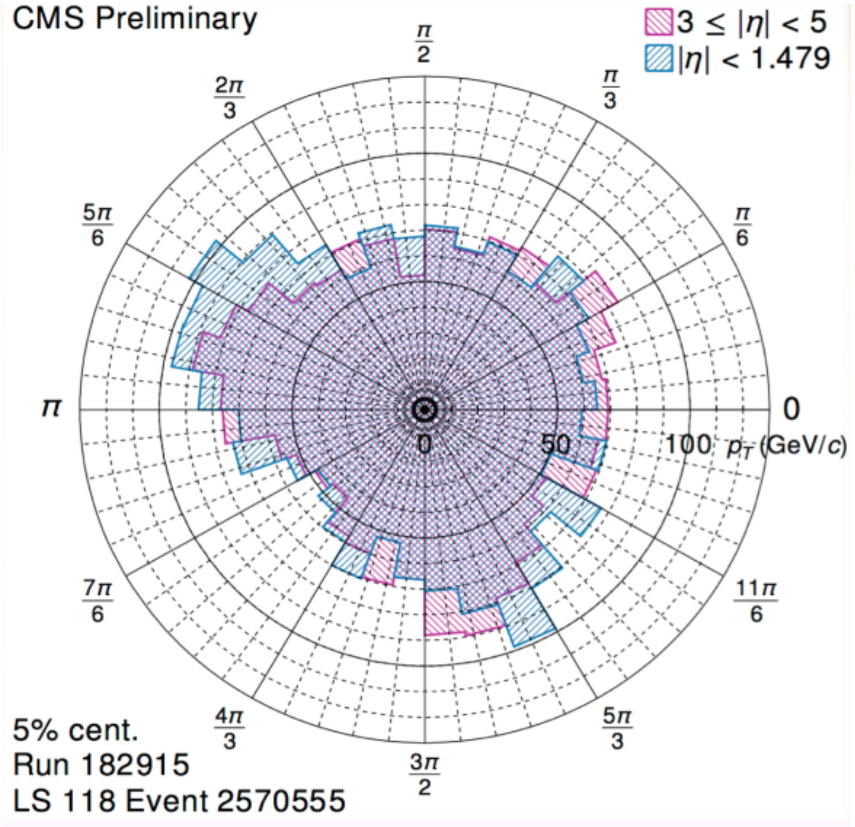




- Energy deposited at the forward calorimeter is used to estimate the underlying event energy distribution in the mid-rapidity
- Training done with minimum-bias events

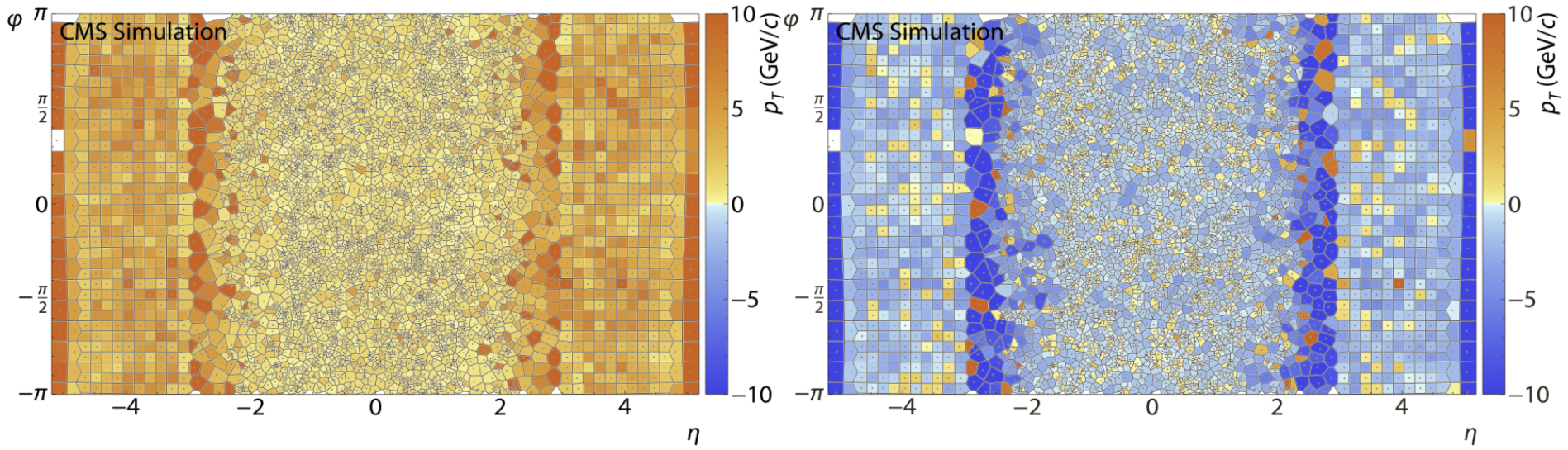
New algorithm using Forward calorimeter





- Energy deposited at the forward calorimeter is used to estimate the underlying event energy distribution in the mid-rapidity
- Training done with minimum-bias events

Underlying Event Subtraction



Before UE subtraction

After UE subtraction

- In order to subtract UE energy from each particle-flow candidate, a Voronoi algorithm is used to estimate the associated area

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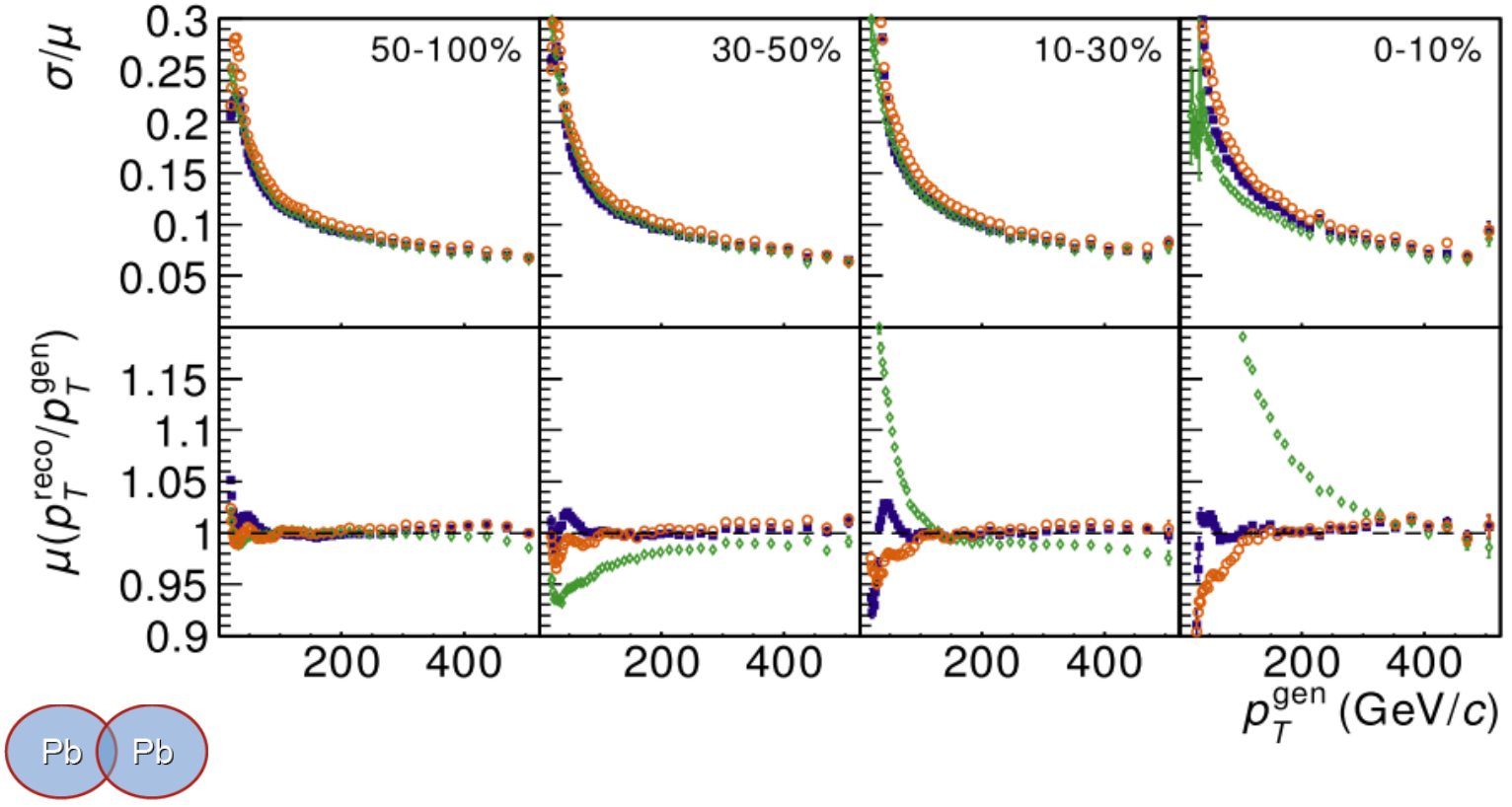
Performance



Improvement in the jet energy resolution and jet energy closure compared to iterative algorithm

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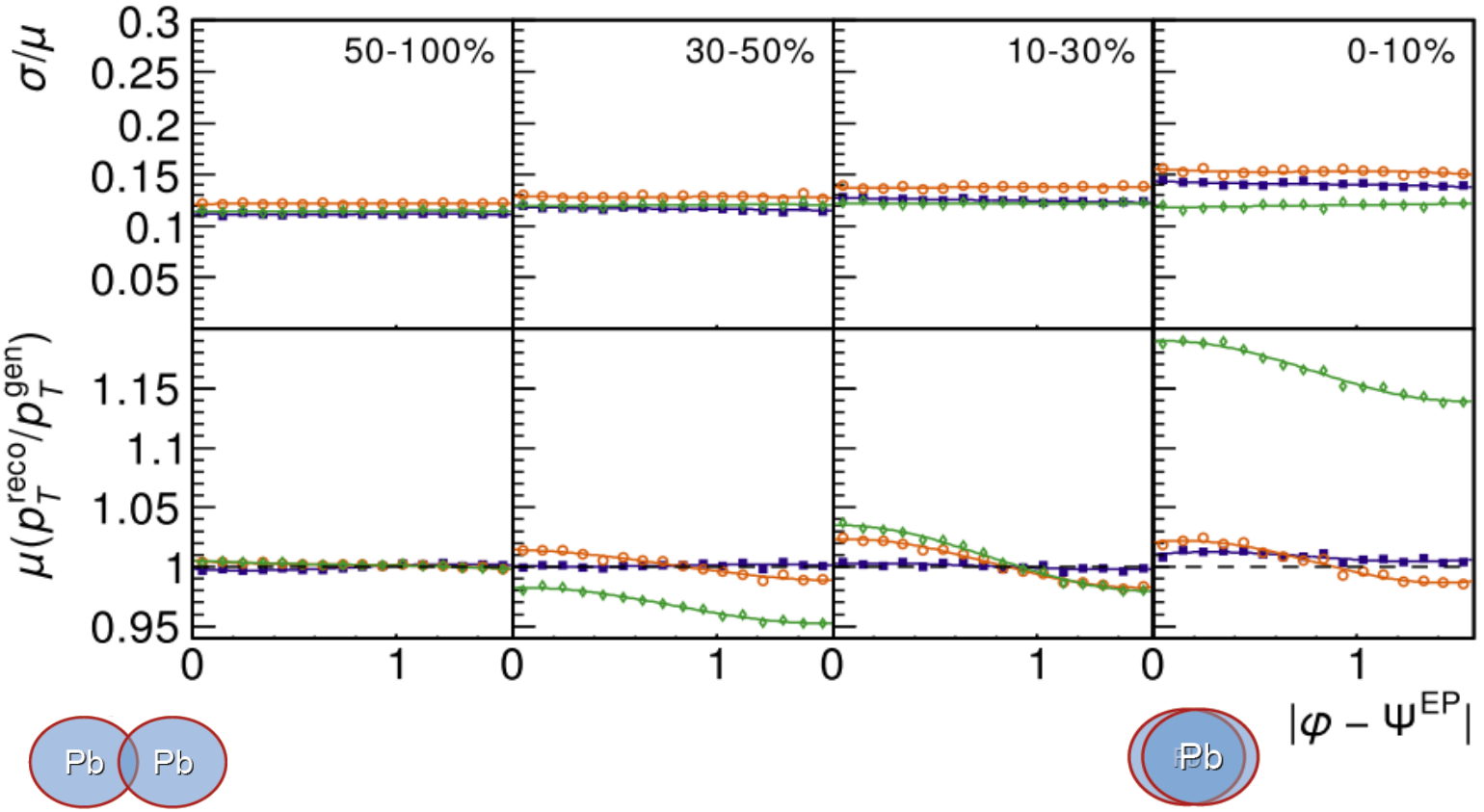
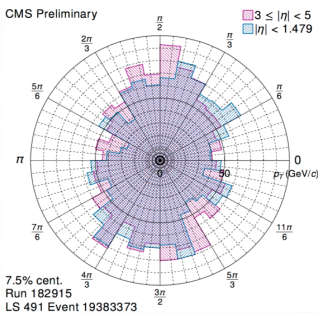
Performance v.s. Event Plane Angle



CMS Simulation

PYTHIA+HYDJET
PbPb
$\sqrt{s_{NN}}$ = 2.76 TeV
Anti-k_T R = 0.3
$100 \leq p_T^{gen} <$
< 150 GeV/c

- FastJet ρA
- Iterative PU
- HF/Voronoi



Improvement in the jet energy resolution and jet energy scale closure as a function of $|\varphi-\psi_{EP}|$

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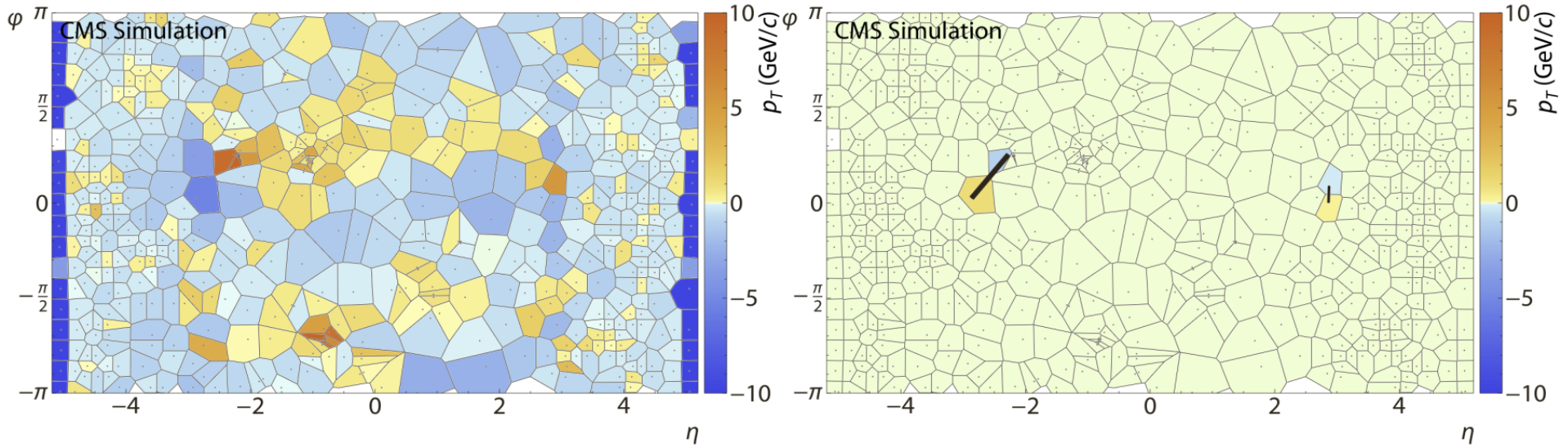
Negative Energy Balancing



- A equalization step is introduced to balance the negative fluctuation (after subtraction) with the positive fluctuation to reduce the positive bias in jet energy reconstruction
- Optimization is based on the worst remaining negative energy in a cell, and minimum overall energy transfer, and expressed as a linear optimization problem
- Right: Thickness of the black line indicates amount of energy transfer, red/blue energy gain/loss

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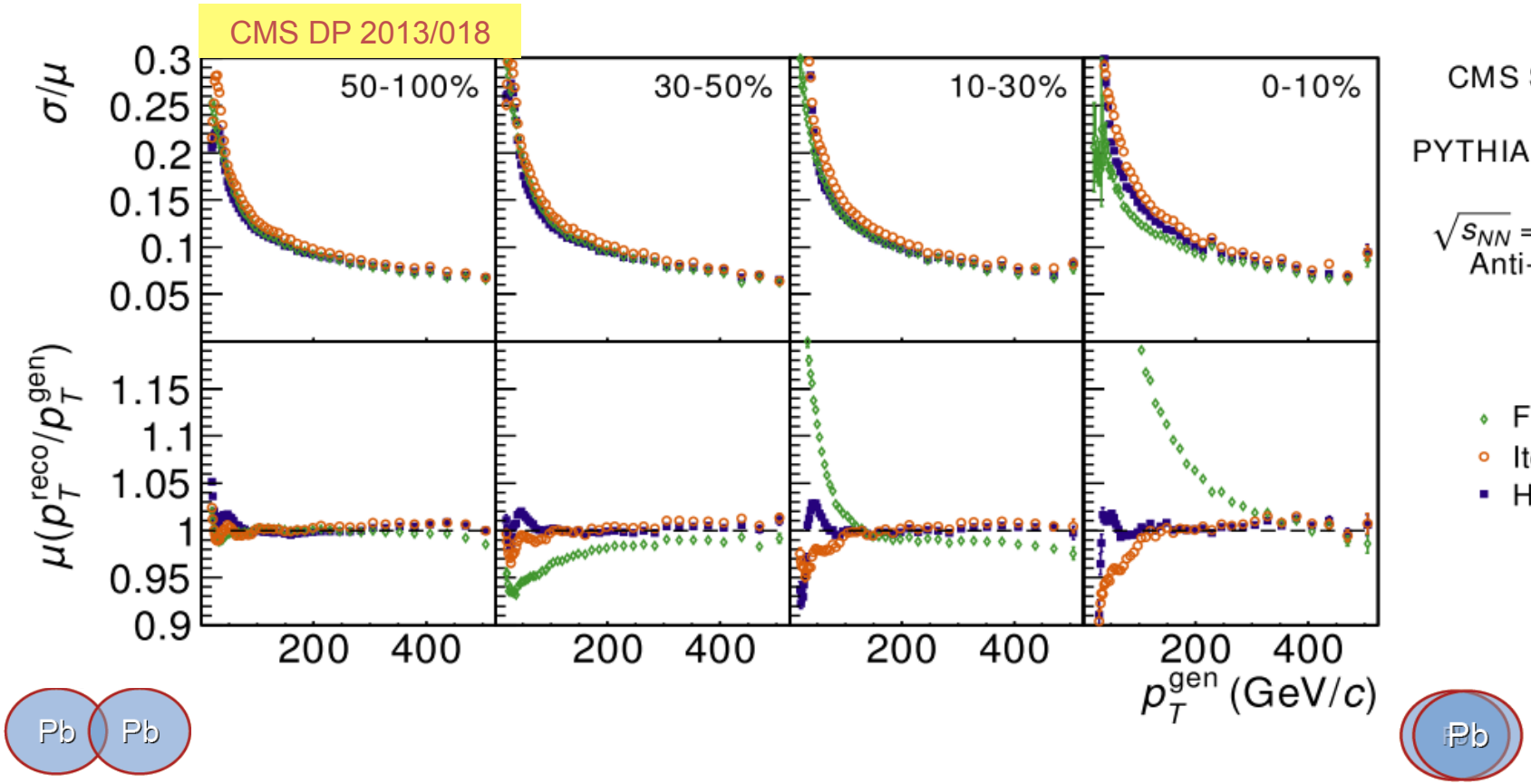
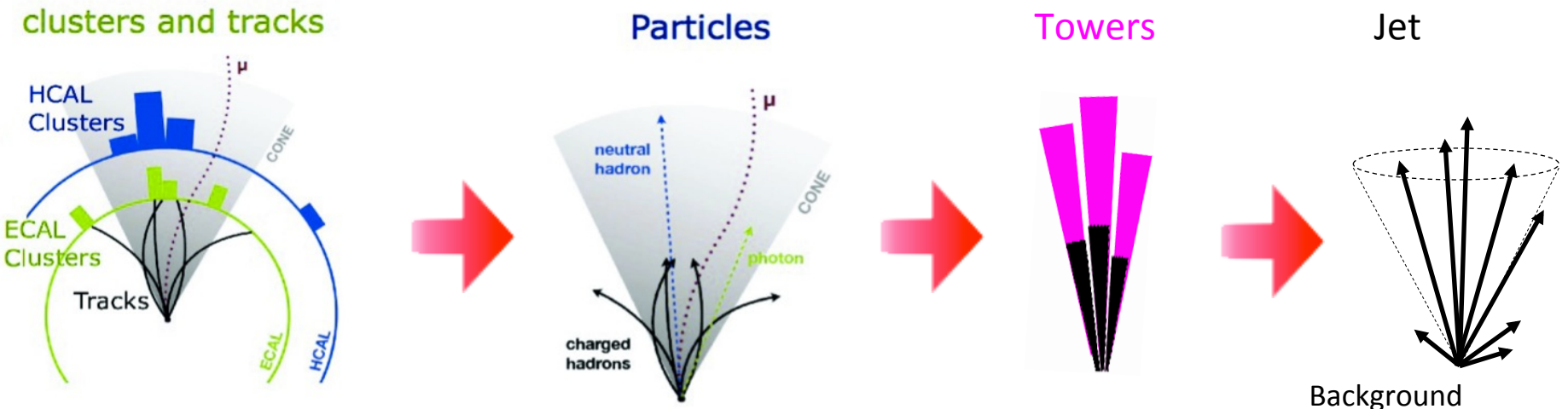
New underlying event subtraction algorithm



Improvement in the jet energy resolution and jet energy closure compared to previous algorithm

Possible Improvements on the HI Jet Algorithm



Anti-k_T algorithm is used in most of CMS publications

For instance, $\Delta\eta \times \Delta\phi$ 0.076 x 0.076 in barrel

Background subtraction and jet clustering

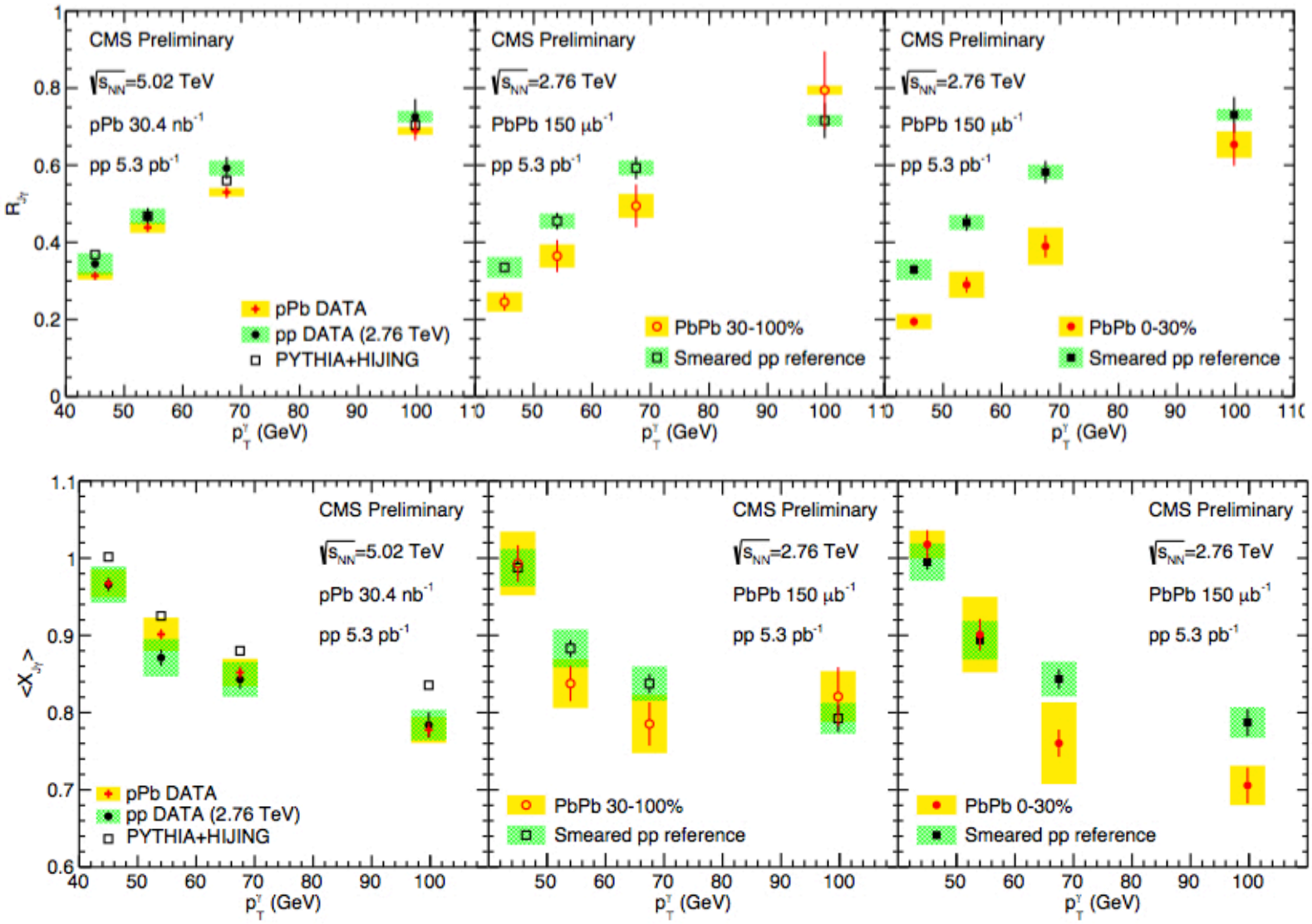
- Lower the track p_T cut off (0.9 GeV/c → 0.4-0.5 GeV/c)

Boston Jet Workshop '14

- Improve jet pointing resolution: remove the pseudo-tower implementation

- Account for the flow modulation of the HI UE
- Noise suppression may lower the sensitivity to low p_T particles
- Remove the jet exclusion in the iterative procedure to avoid threshold effects

Photon-jet


CMS Preliminary
√sNN=5.02 TeV
pPb 30.4 nb-1
pp 5.3 pb-1
pPb DATA
pp DATA (2.76 TeV)
PYTHIA+HIJING
CMS Preliminary
√sNN=2.76 TeV
PbPb 150 μb-1
pp 5.3 pb-1
PbPb 30-100%
Smeared pp reference
CMS Preliminary
√sNN=2.76 TeV
PbPb 150 μb-1
pp 5.3 pb-1
PbPb 0-30%
Smeared pp reference
RγJ
pTγ (GeV)
CMS Preliminary
√sNN=5.02 TeV
pPb 30.4 nb-1
pp 5.3 pb-1
pPb DATA
pp DATA (2.76 TeV)
PYTHIA+HIJING
CMS Preliminary
√sNN=2.76 TeV
PbPb 150 μb-1
pp 5.3 pb-1
PbPb 30-100%
Smeared pp reference
CMS Preliminary
√sNN=2.76 TeV
PbPb 150 μb-1
pp 5.3 pb-1
PbPb 0-30%
Smeared pp reference
<XγJ>
pTγ (GeV)

GREEKs

- ΑΒΓΔΕΖΗΘΙΚΛΝΜΞΟΠΡΣΤΥΦΦΧΨΩ
- αβγδεζηθικλμνξοπρσςτυφχψωϑϒφϖ

- $\eta_{dijet} = \eta_{jet1} + \eta_{jet2}$