# Recent Jet Results and Jet Reconstruction in Relativistic Heavy Ion Collisions

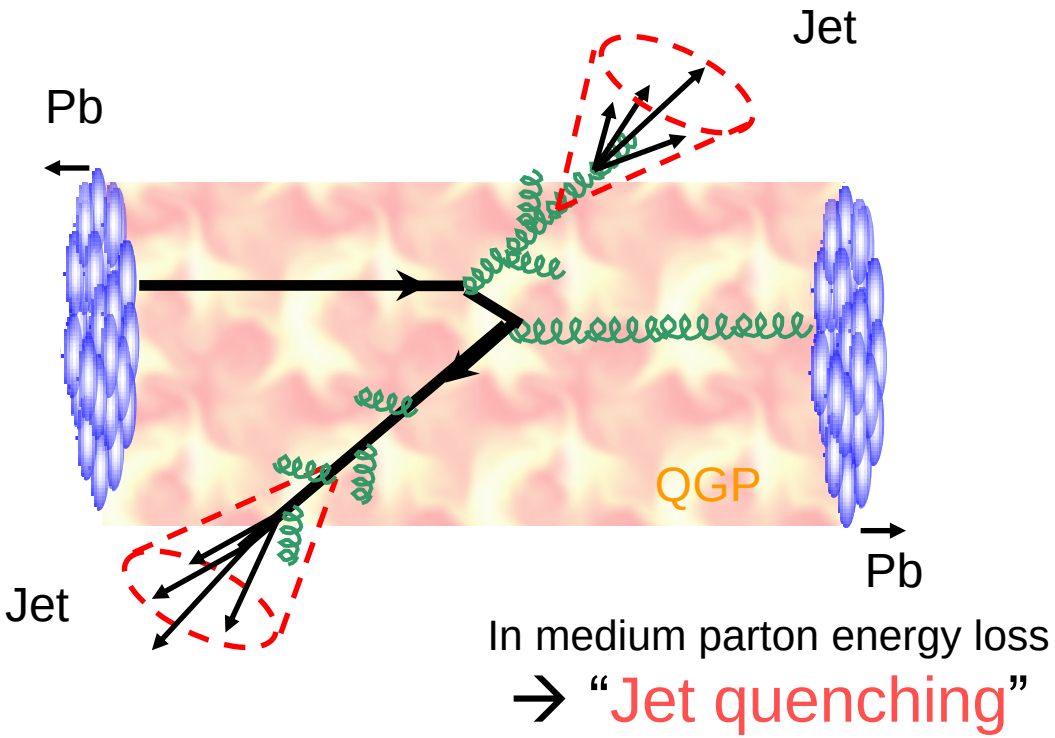

Yen-Jie Lee (MIT)
for the CMS collaboration

**Boston Jet Workshop**

22 January, 2014

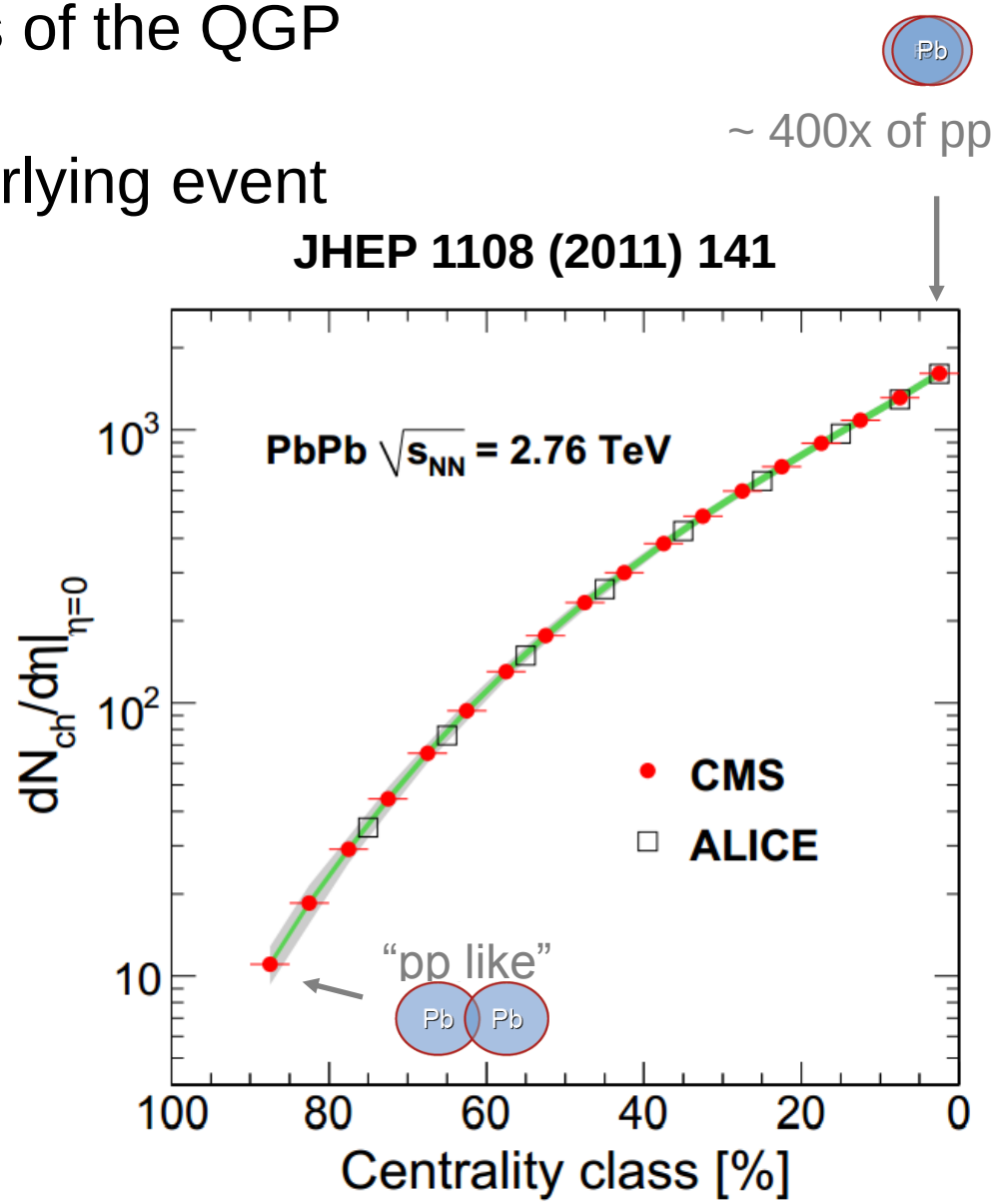
# Introduction

- Goal: Understand the transport and thermodynamical properties of the QGP
- Tool: Jets from high $p_T$ processes
- Challenge: Large fluctuating underlying event

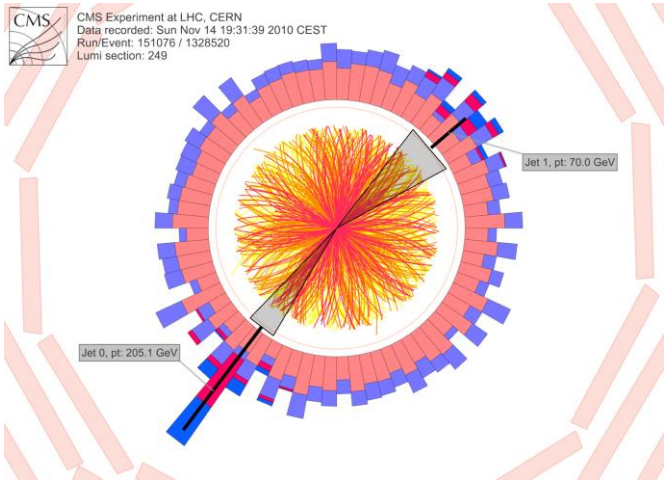


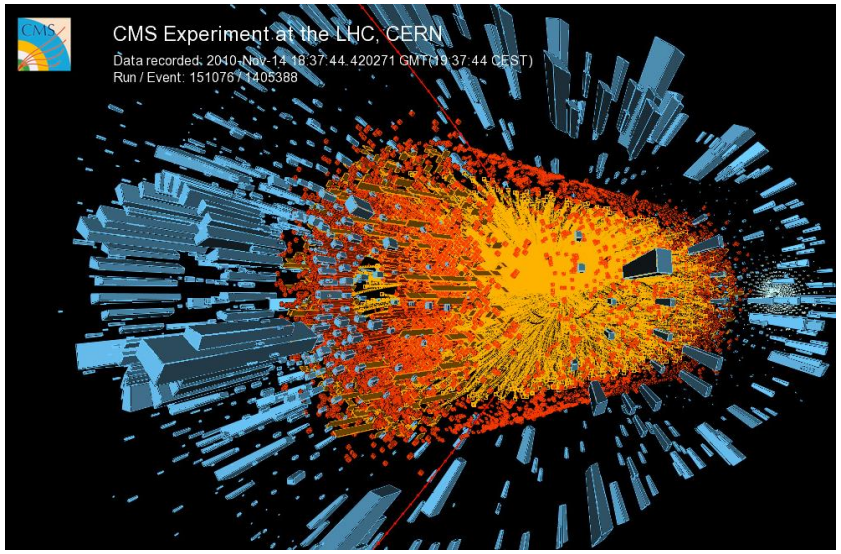

In medium parton energy loss

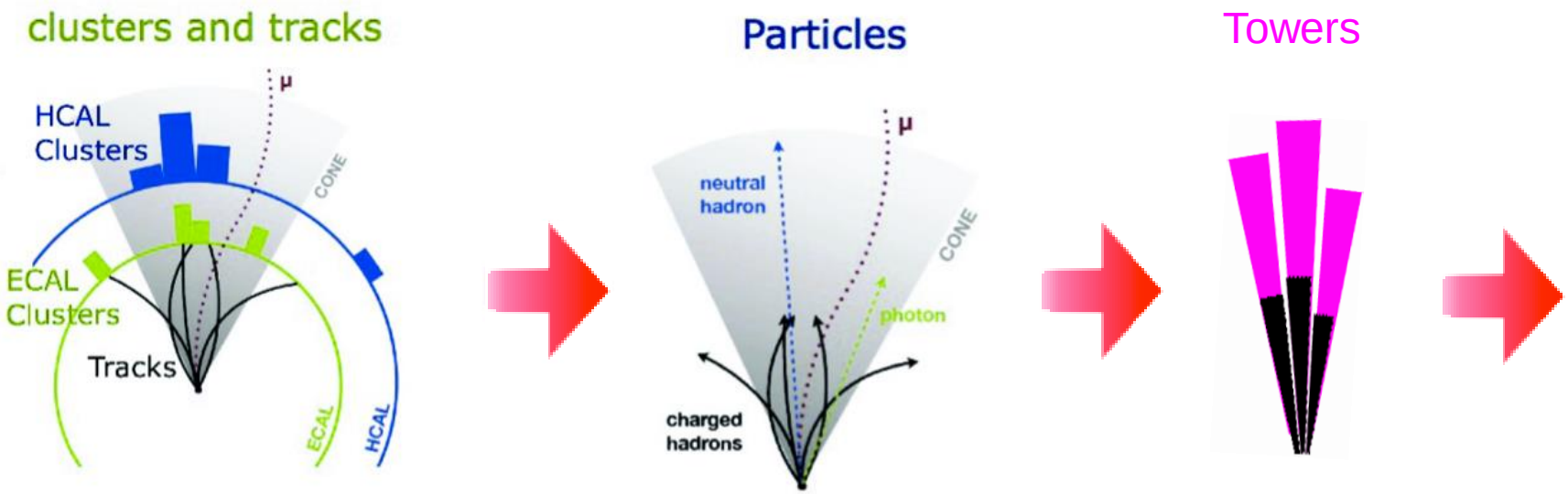
→ "Jet quenching"



# CMS Jet Reconstruction in Heavy Ion Collisions



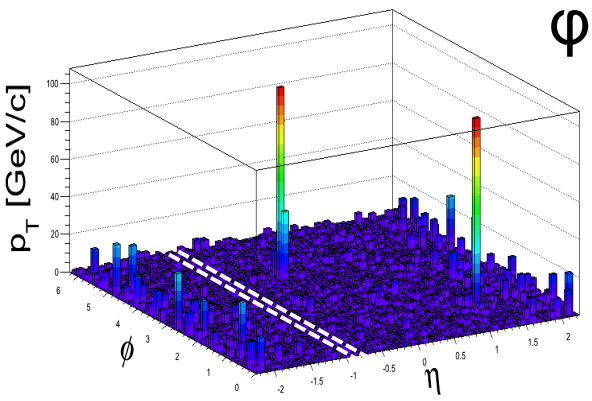



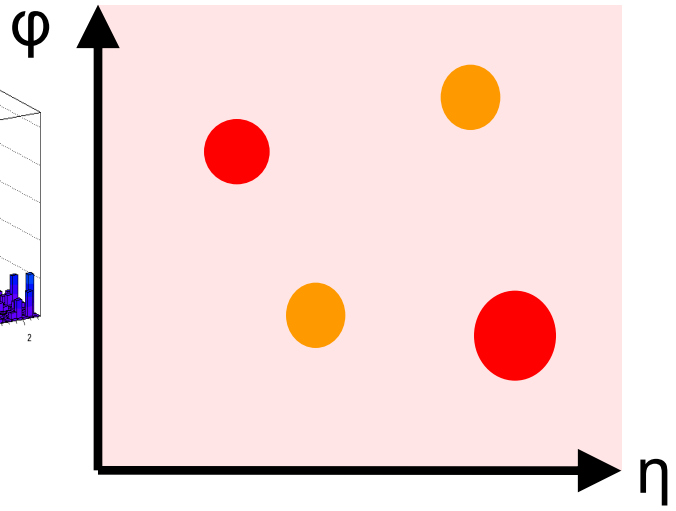

Anti-$k_T$ algorithm is used in most of CMS publications

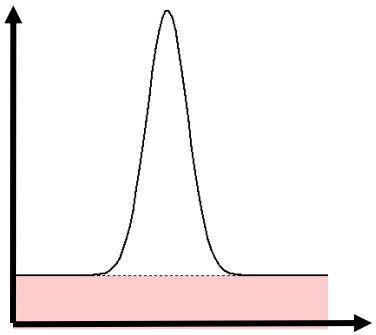
For instance, $\Delta\eta \times \Delta\phi$ 0.076 x 0.076 in barrel

**Background subtraction** and jet clustering

# Background Subtraction



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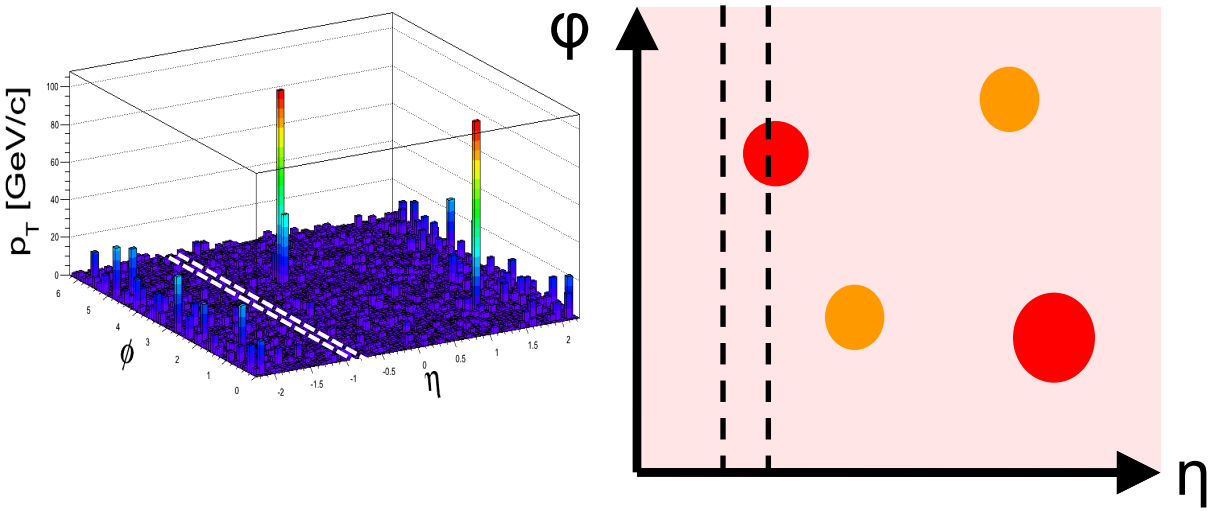


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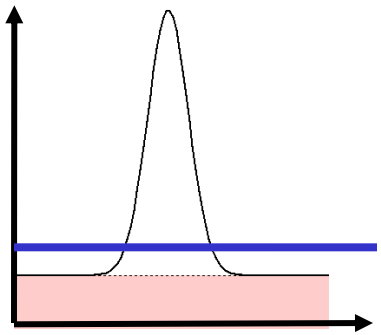
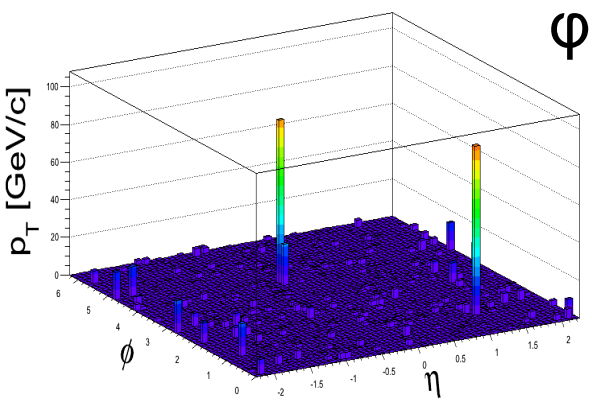
Subtract $\langle p_T \rangle + N*\sigma(p_T)$ (Noise suppression)

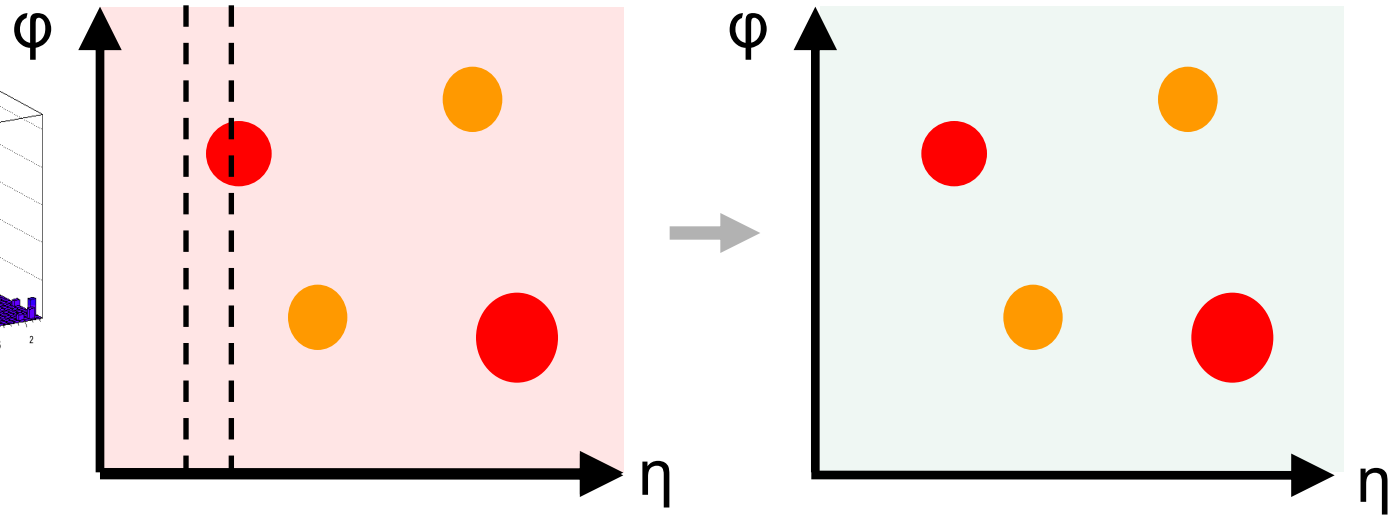


Background level

Estimate background
for each tower ring of constant η
estimated background = $\langle p_T \rangle + N*\sigma(p_T)$
- Captures dN/dη of background
- Misses ϕ modulation – to be improved

# Background Subtraction

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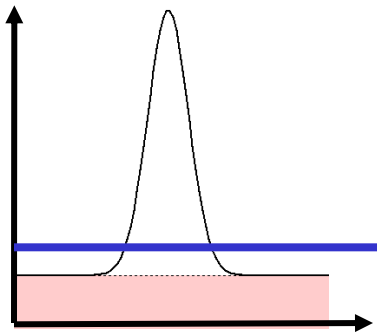

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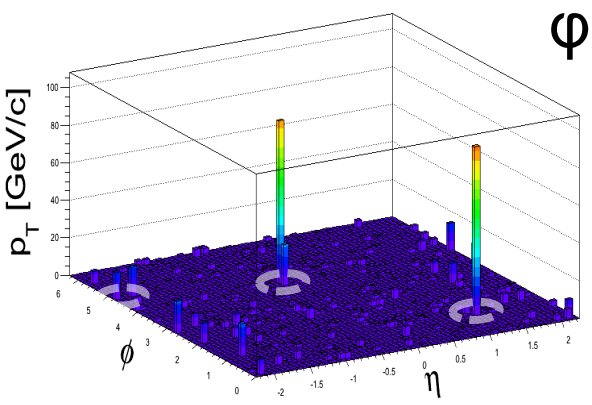


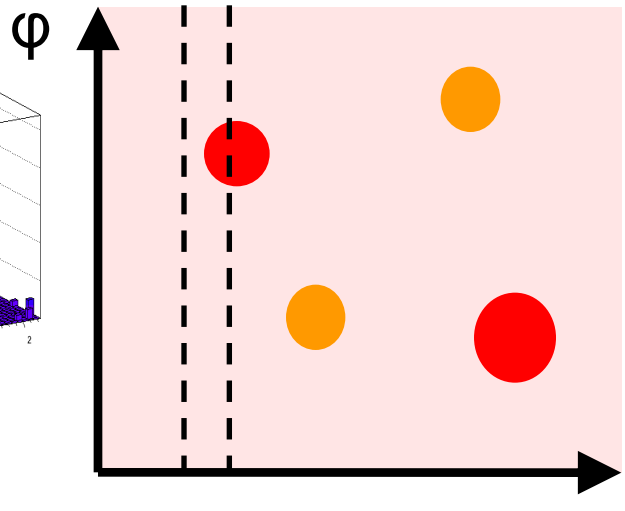


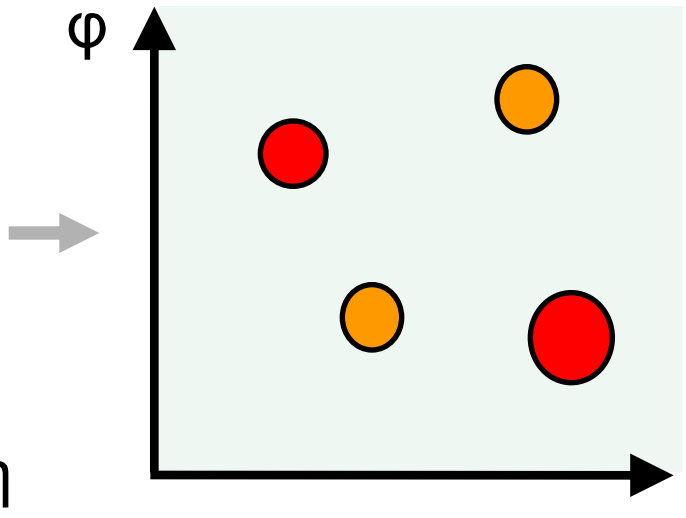


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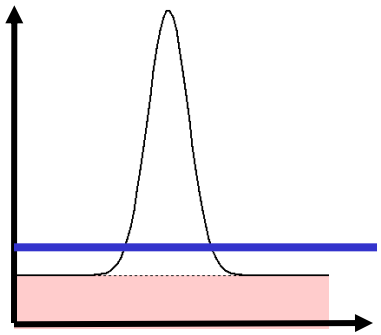
2. Run anti $k_T$ algorithm on background subtracted towers



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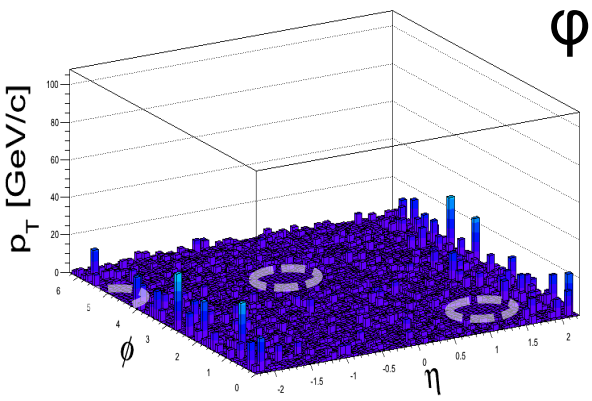


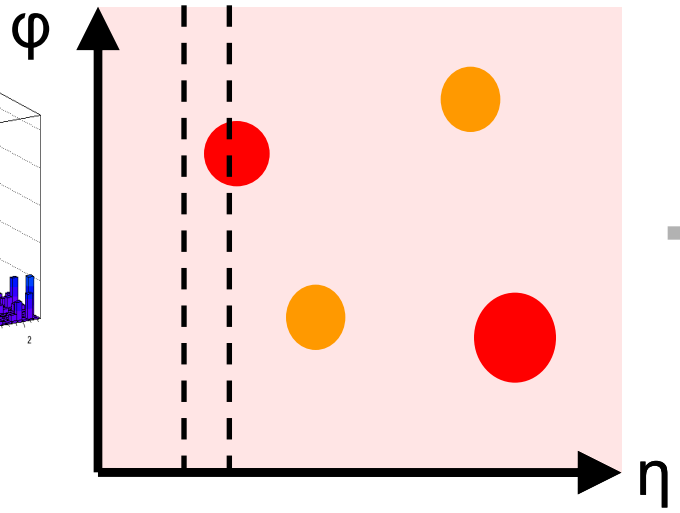


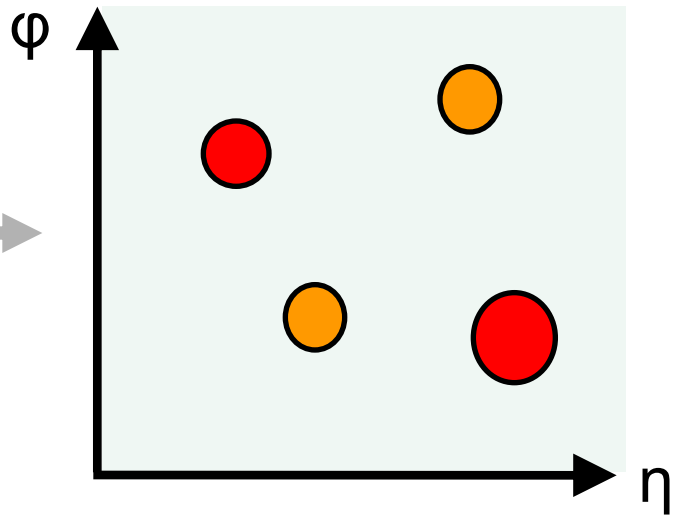


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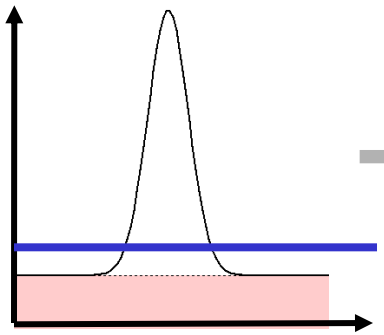

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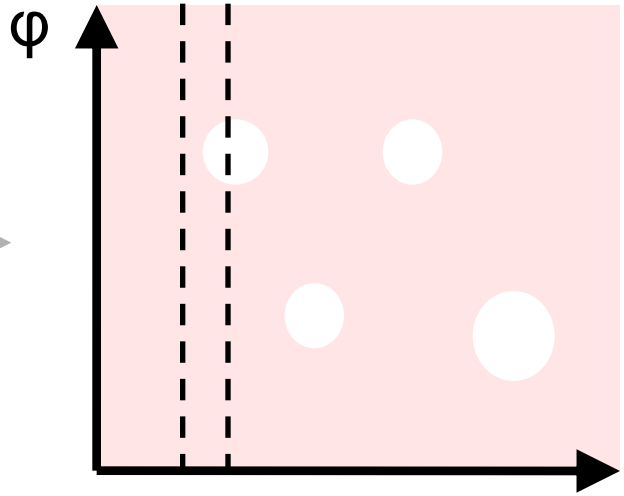


3. Exclude reconstructed jets

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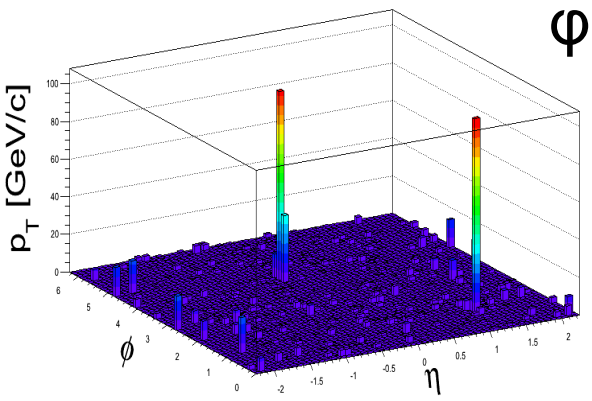


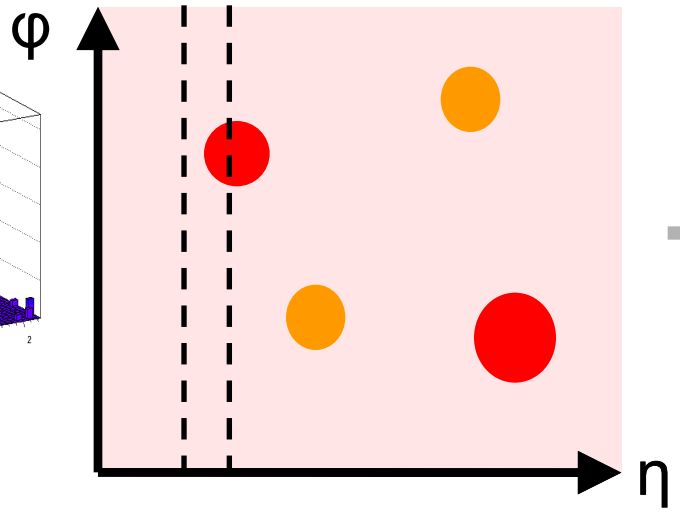


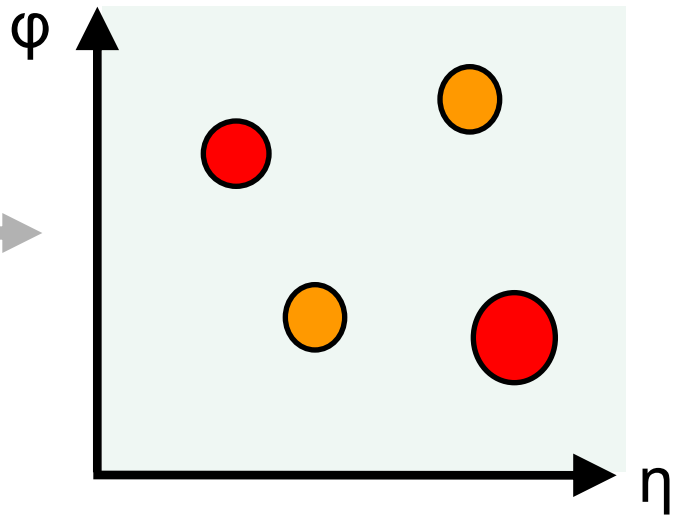


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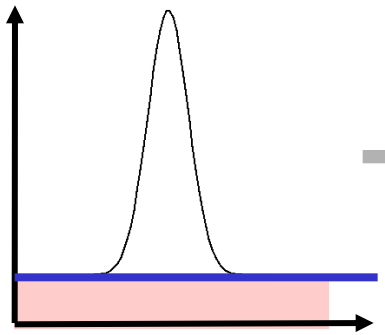

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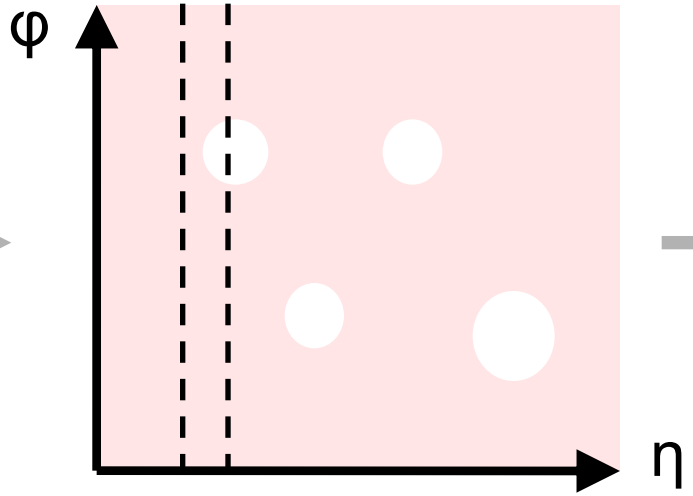


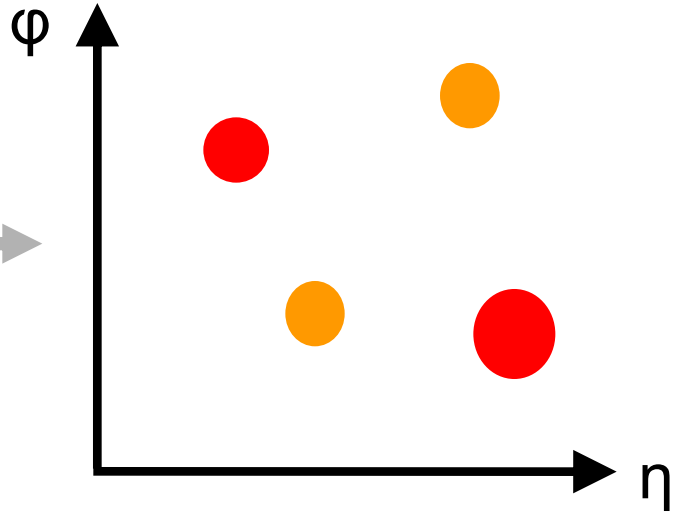


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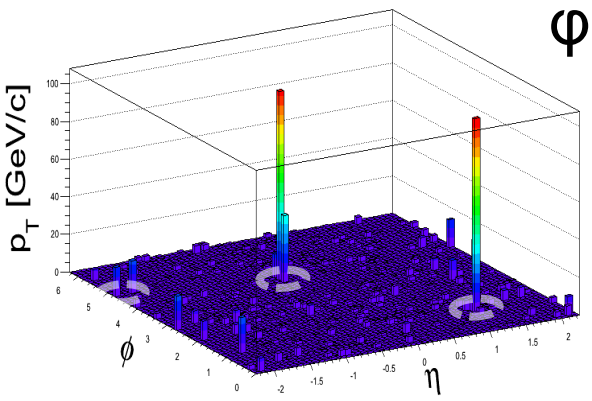
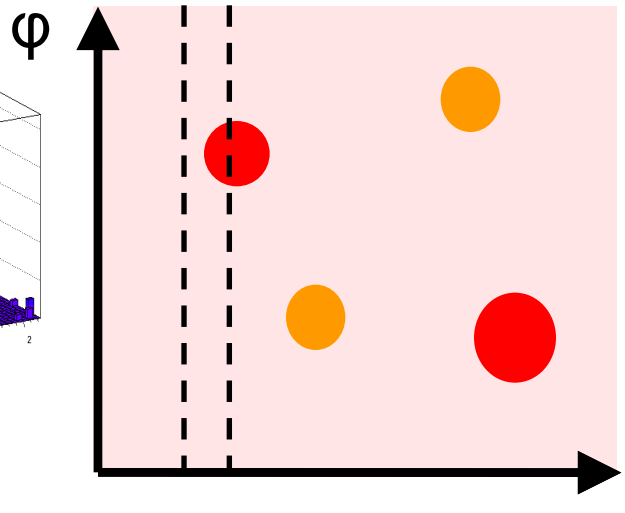
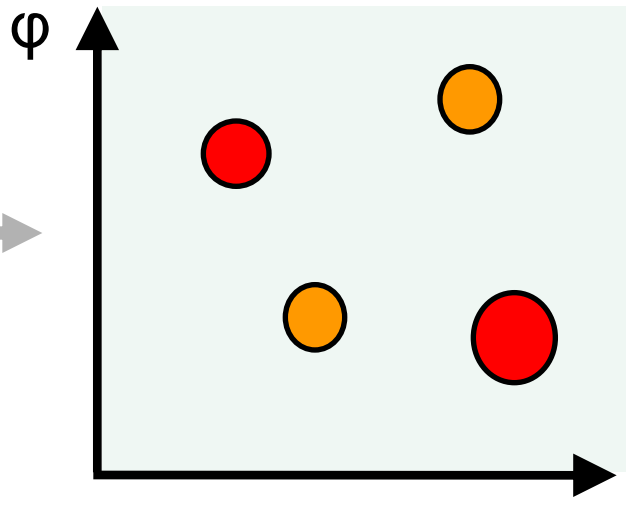
# Background Subtraction

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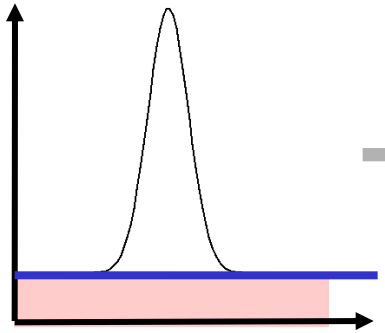

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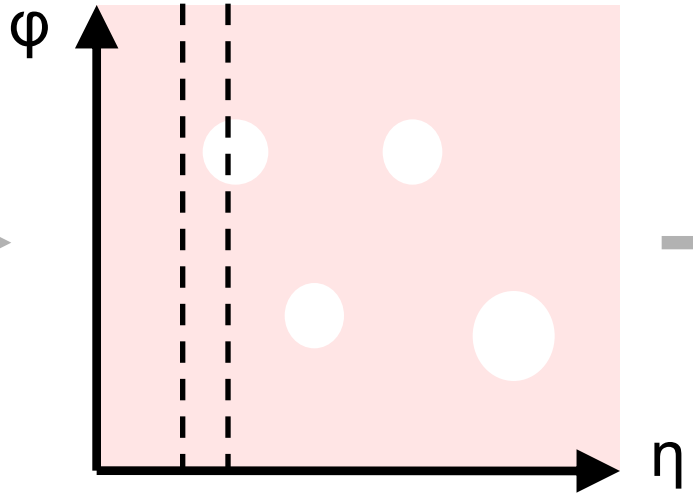


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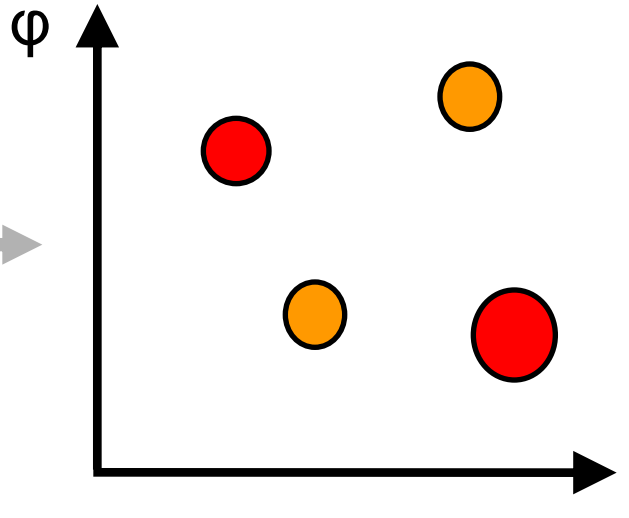
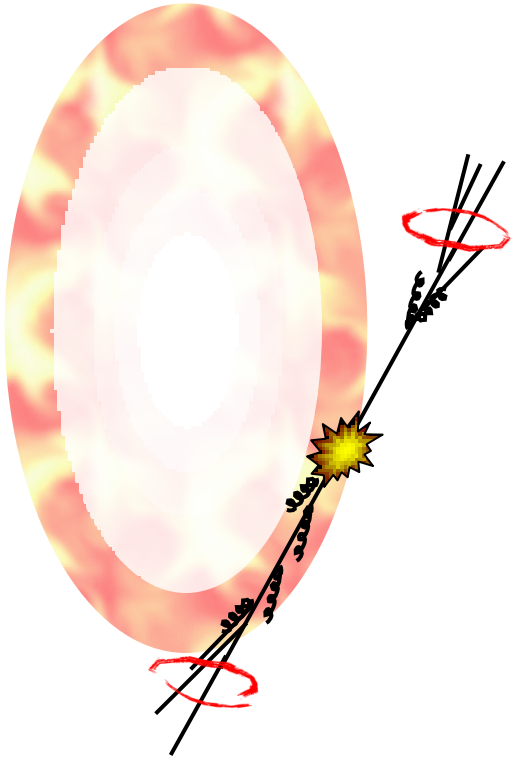



4. Run anti $k_T$ algorithm on background subtracted towers to get final jets

# Physics results

Dijet

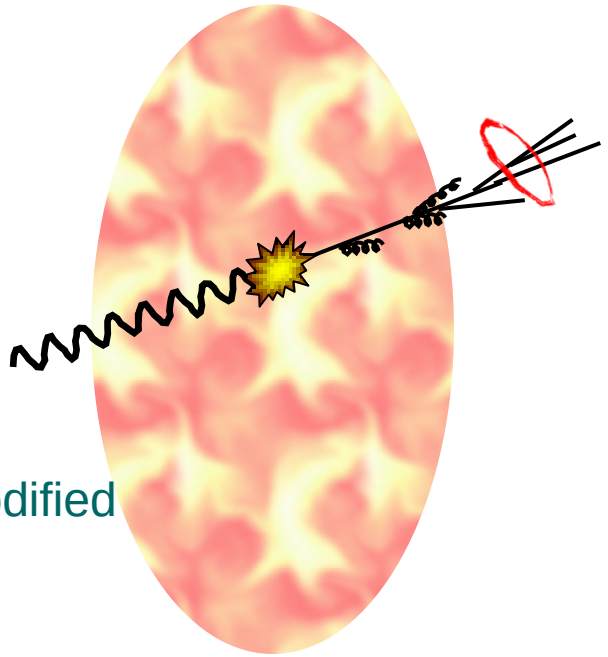


High $p_T$ leading jet triggered sample

High statistics, with surface bias

Photon → unmodified jet energy tag

Photon-jet



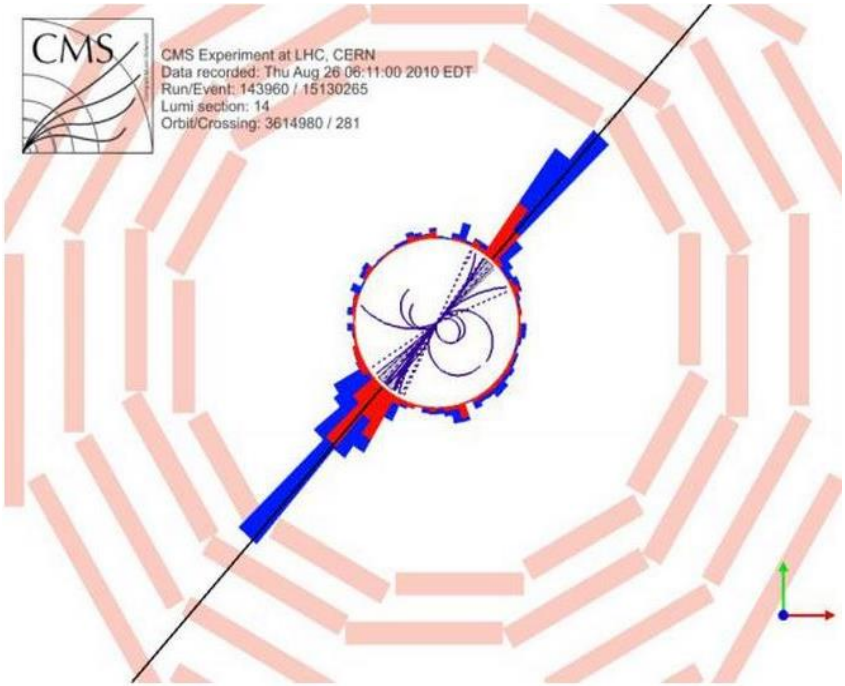
High $p_T$ photon triggered sample

Lower statistics, without surface bias

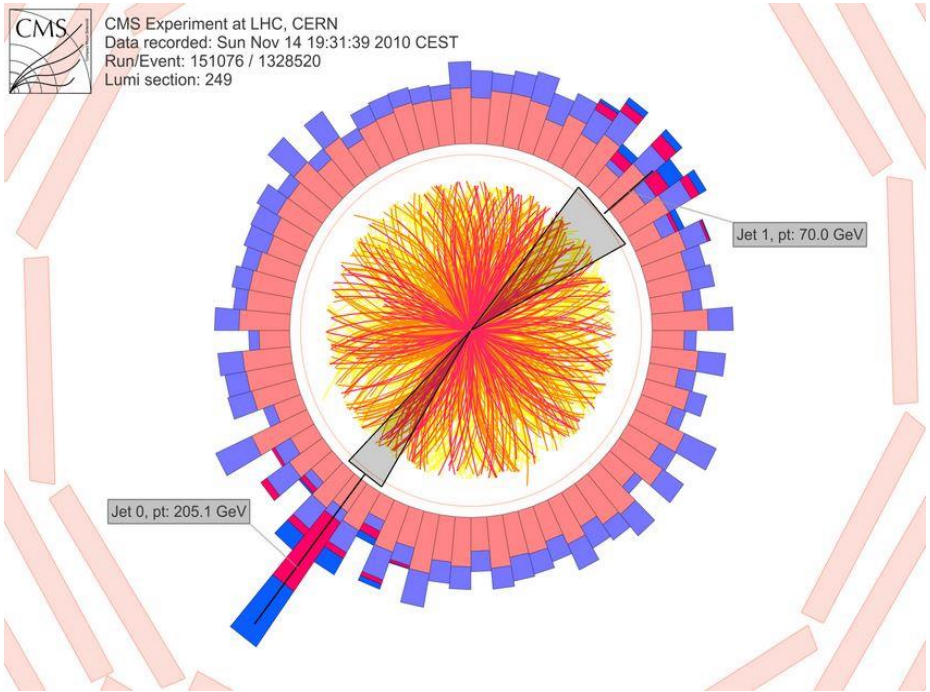
# Probe the QGP with High Energy Quarks (Gluons)

Quark-gluon plasma is incredibly strongly interacting – It even stops very high energy quarks and gluons passing through it

P + P

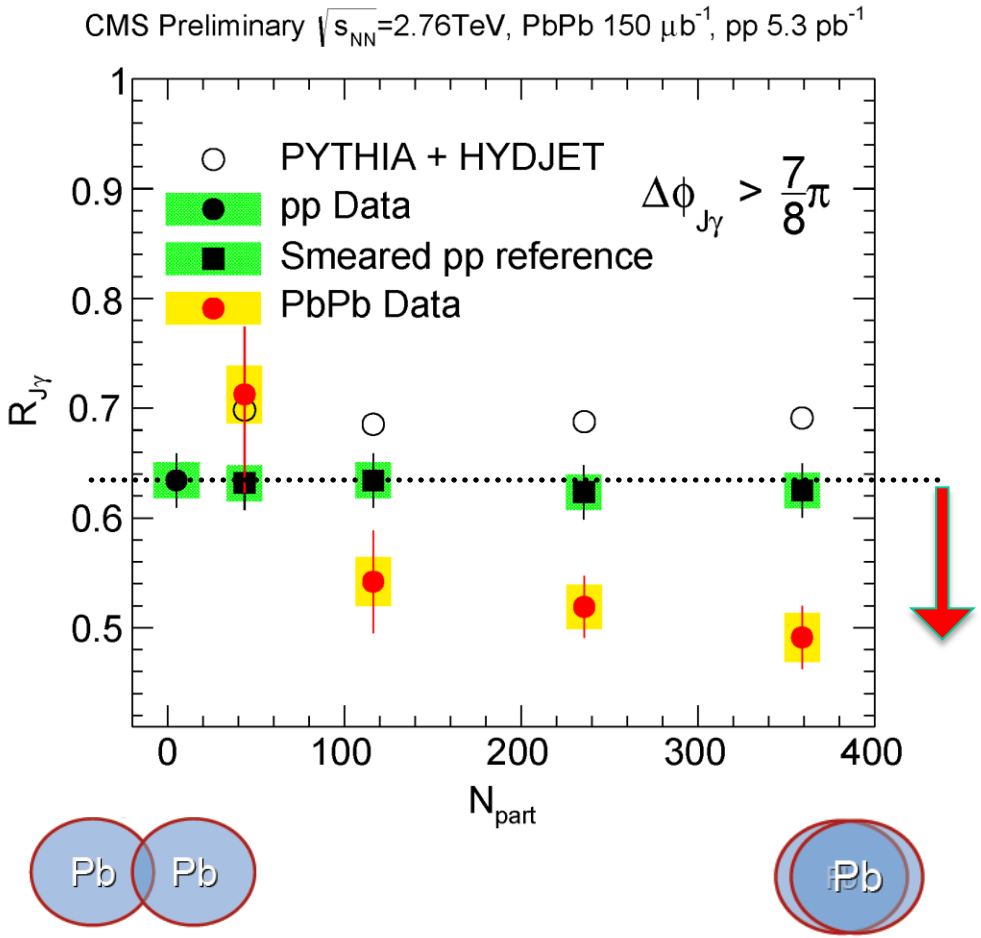


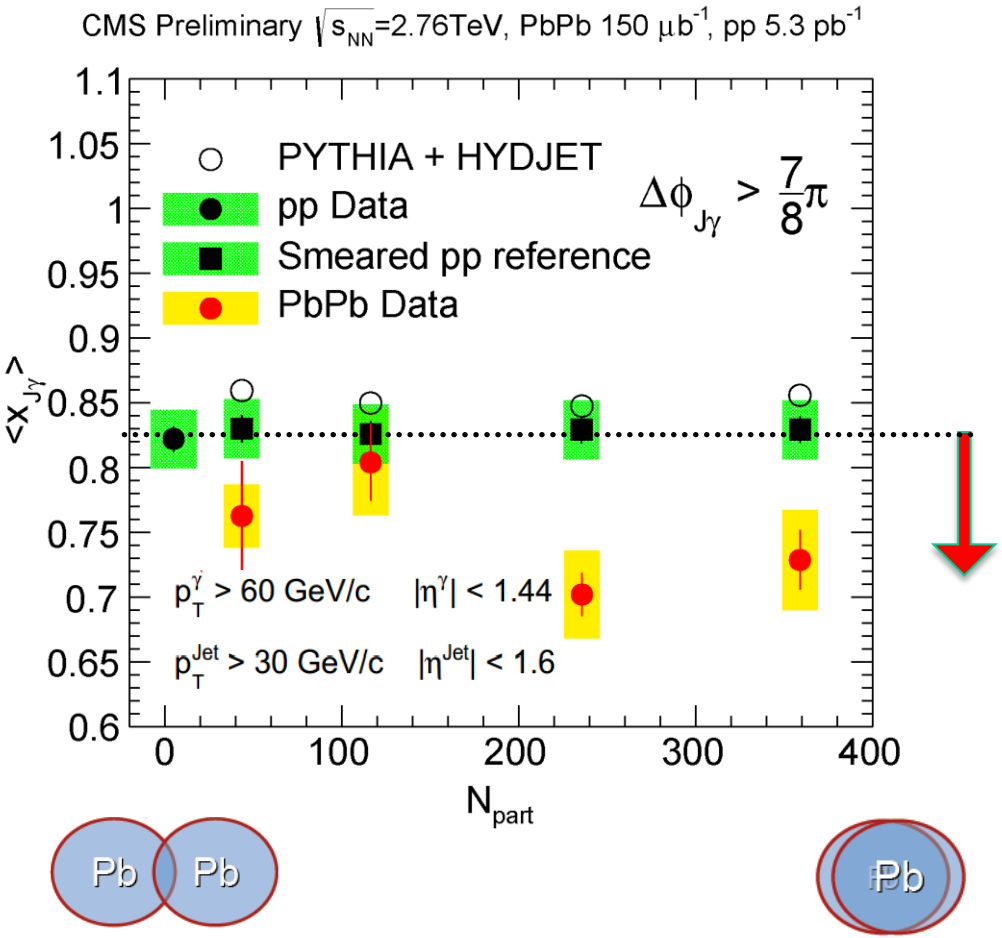

Pb + Pb




PRC 84 (2011) 024906

# γ+jet Correlation




Fraction of photons with jet partner

Jet-photon $p_T$(im)balance

PLB 718 (2013) 773

Detailed studies vs photon $p_T$ can be found in CMS-PAS-HIN-13-006

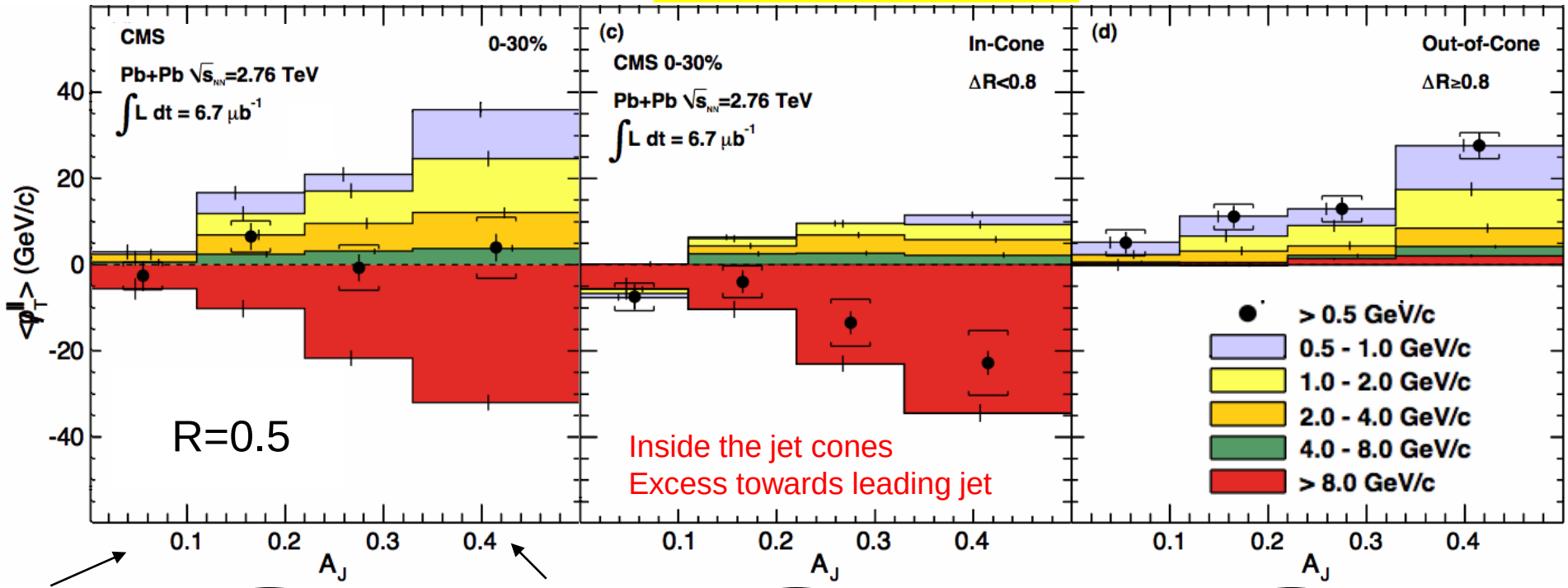
# Missing-$p_T^{||}$ in Dijet Events

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

0-30% Central PbPb

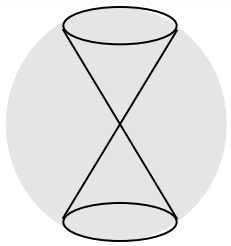
PRC 84 (2011) 024906

Out of the jet cones
Excess towards sub-leading jet

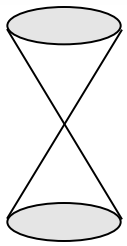



balanced jets

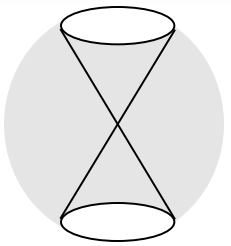
unbalanced jets



All tracks



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



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

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

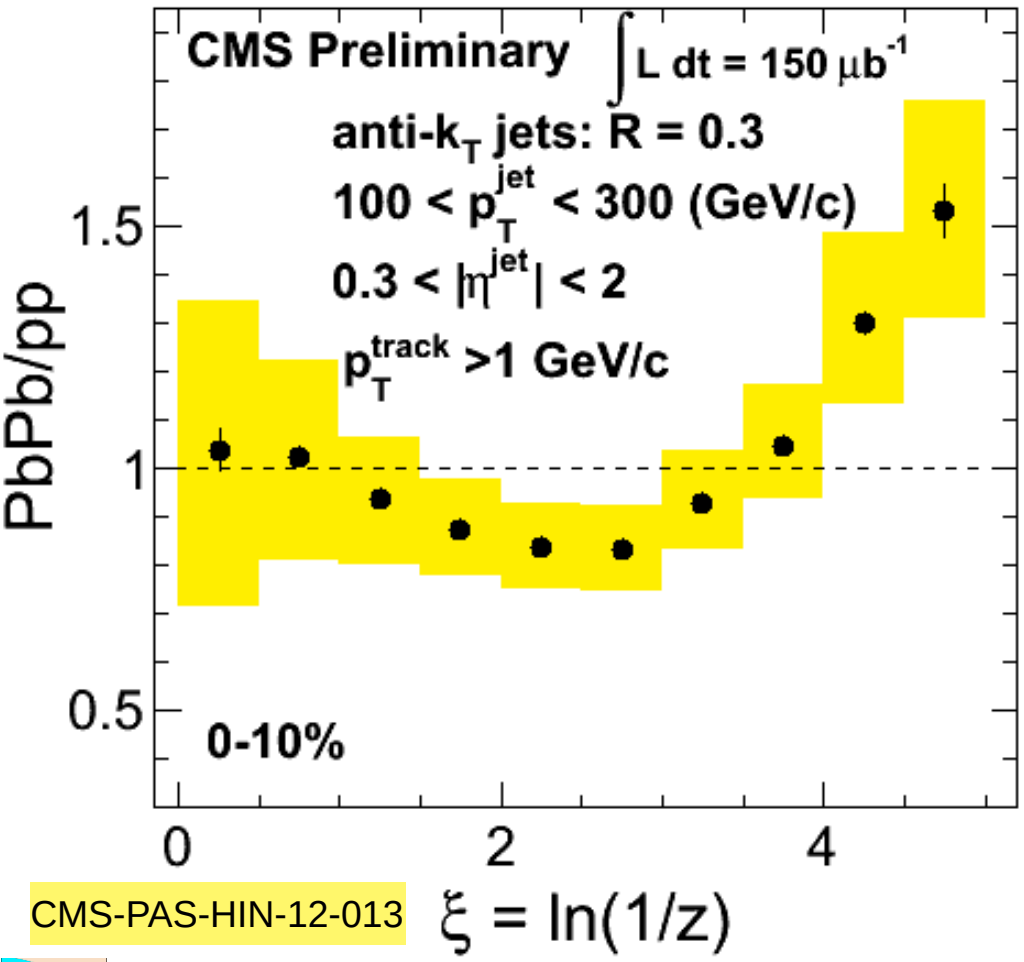
The momentum difference in the dijet is balanced by low $p_T$ particles outside the jet cone

# Fragmentation Function and Jet Shapes

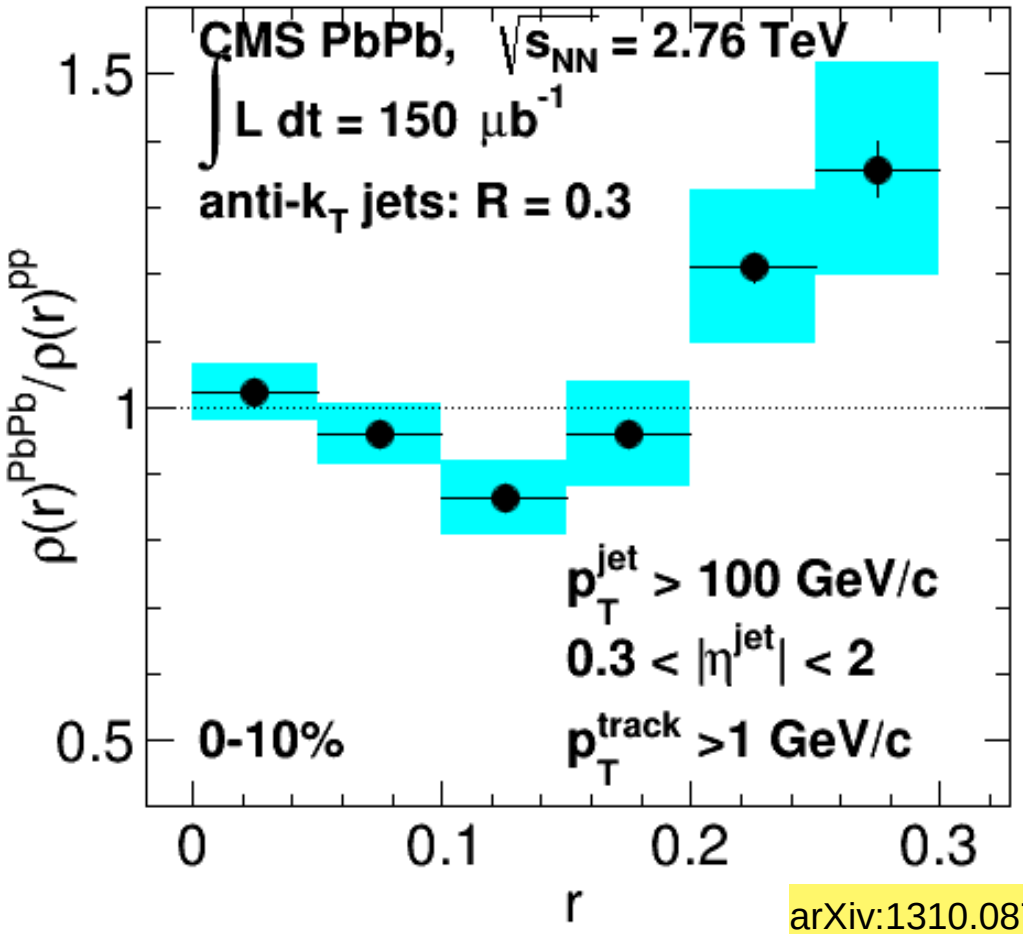
Is the jet energy in PbPb redistributed in particle $p_T$ ?
*Fragmentation functions*

Is the jet energy in PbPb redistributed in radius ?
*Differential jet-shapes*

Depletion at mid particle $p_T$ and radius; enhancement at low particle $p_T$ and larger radius



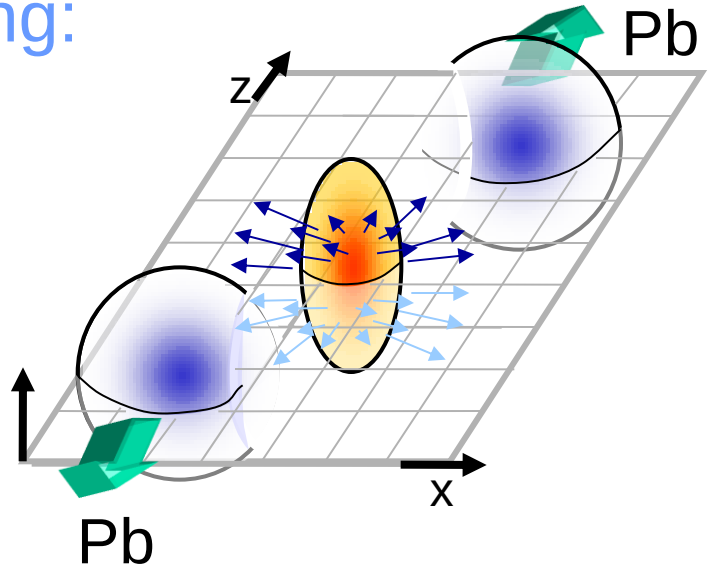

CMS-PAS-HIN-12-013

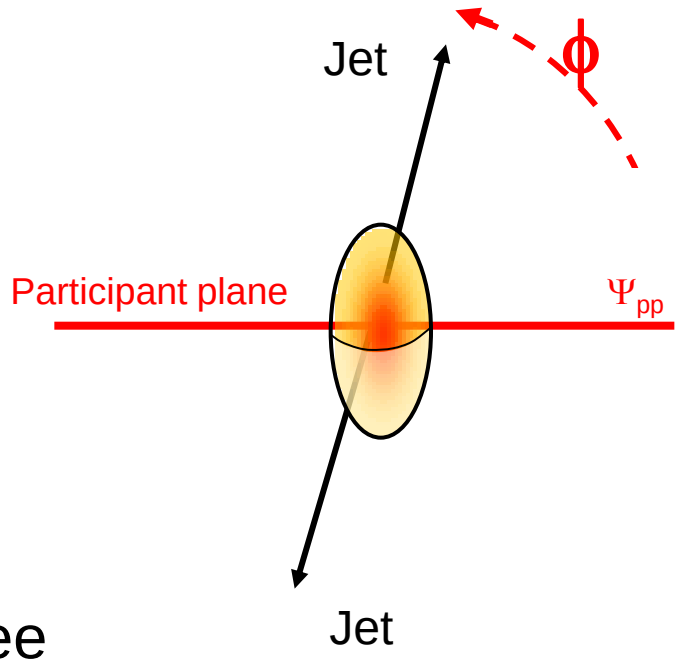



arXiv:1310.0878

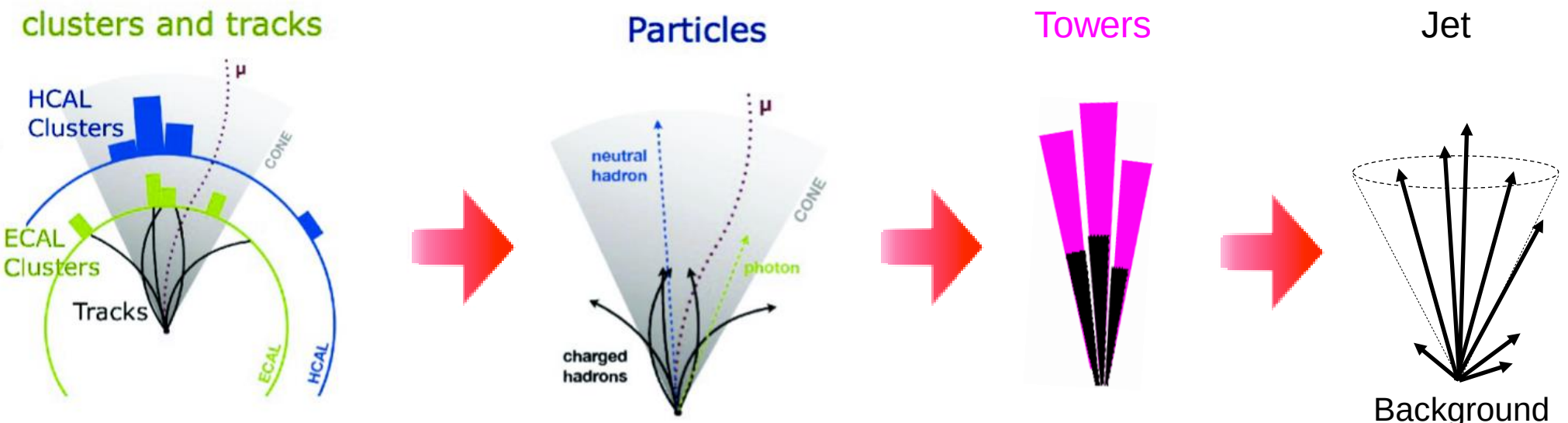
# Possible Future Measurements

- Event plane dependence of jet quenching:
  - Need to remove flow modulation
- Study of medium response:
  - Need to estimate the UE level with detector far from the jets
- Flavor dependence of jet quenching:
  - Lower the track $p_T$ cut-off
  - Keep individual “particle-flow” objects
  - Improve secondary track reconstruction for heavy-flavor jet reconstruction
- Multi-jet correlation:
  - Need to reconstruct low $p_T$ jets
  - Remove / fine tune noise suppression
  - Need an algorithm which is jet threshold free



# 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

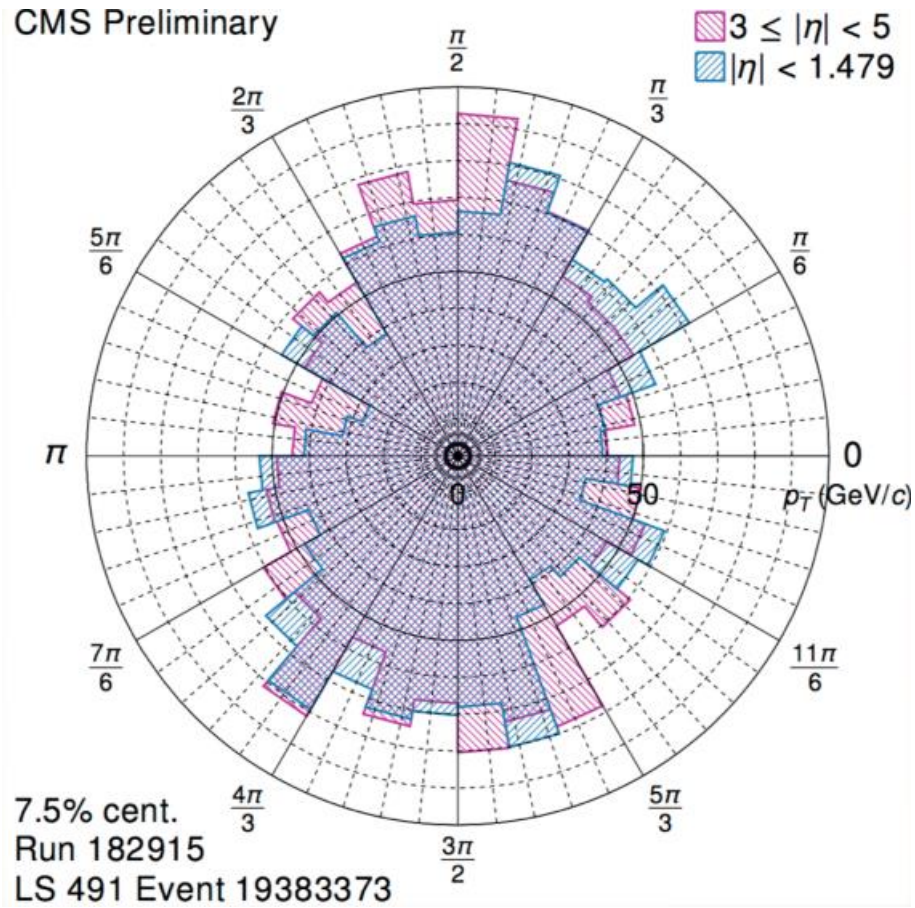
Background subtraction and jet clustering

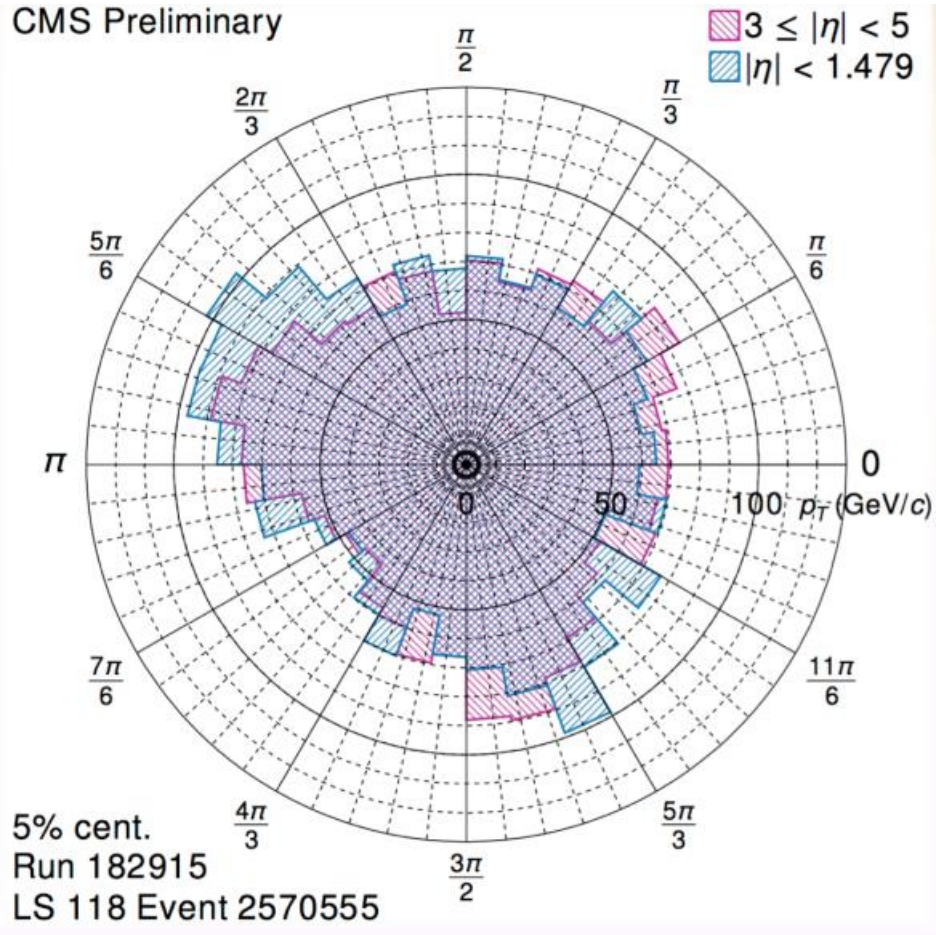
- Lower the track $p_T$ cut off (0.9 GeV/c → 0.4-0.5 GeV/c)

- 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

# Underlying Event in Heavy Ion Collisions




Strategy: use the forward calorimeter energy to "predict" the underlying event in the mid-rapidity (optimized by SVD method)

Training done with minimum-bias events

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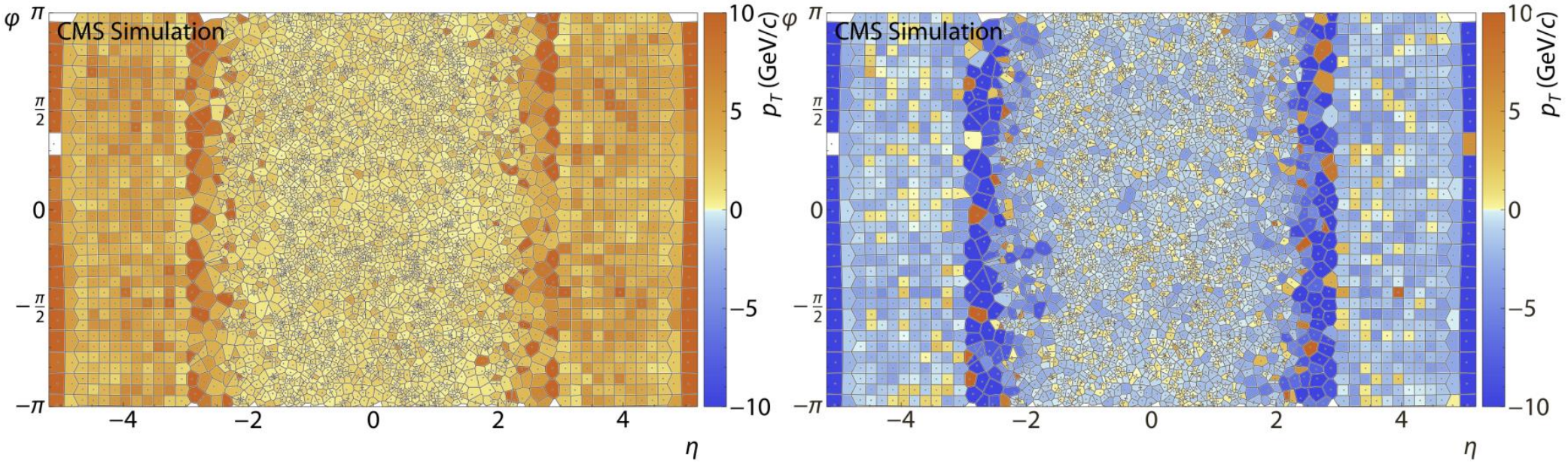
# Underlying Event Subtraction




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

- Subtraction algorithm matches the particle-flow candidate position with the area where the nearest neighbor of a given point is that particle-flow candidate

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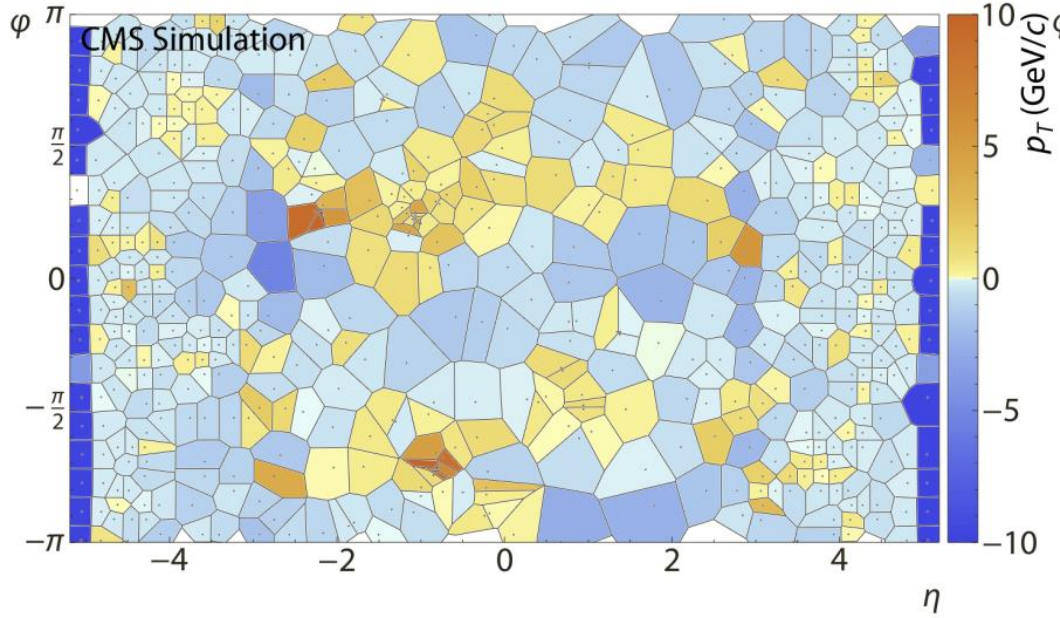
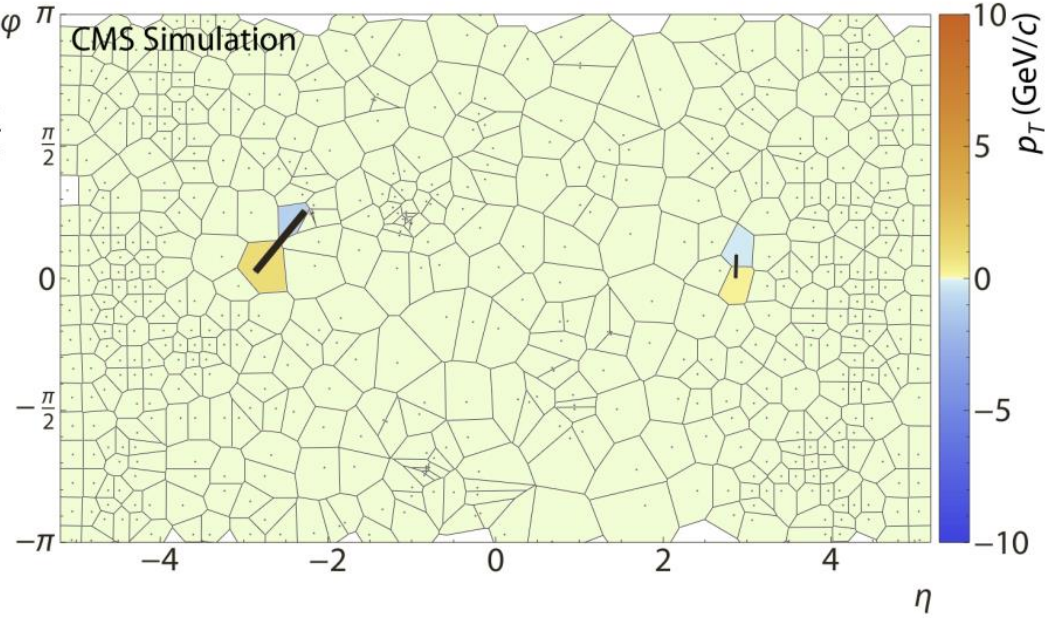
# Negative Energy Balancing




- 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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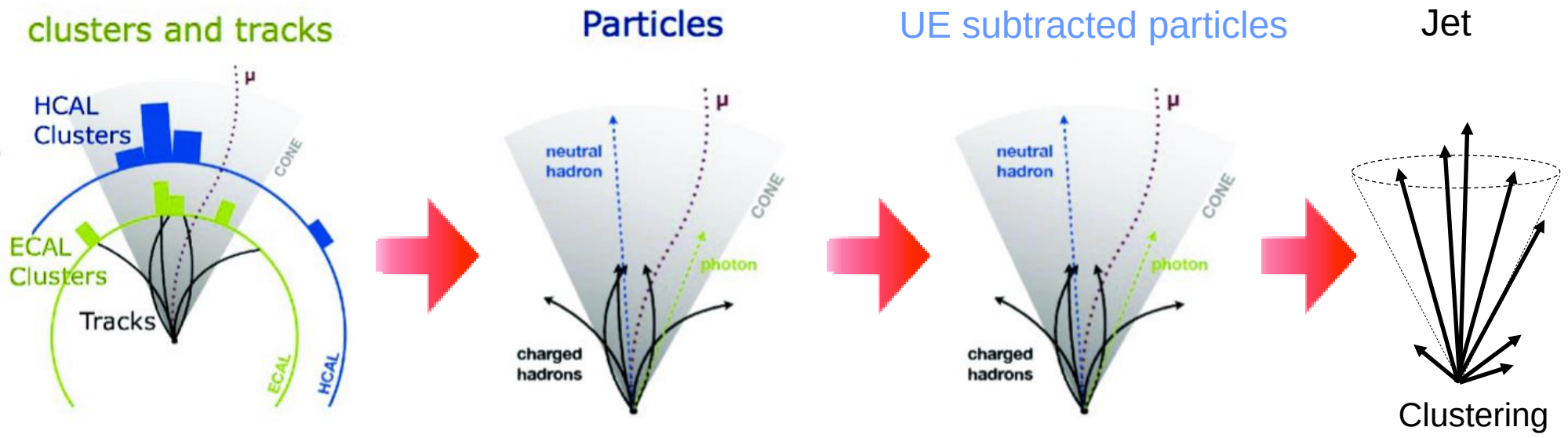
# New HI Jet Algorithm

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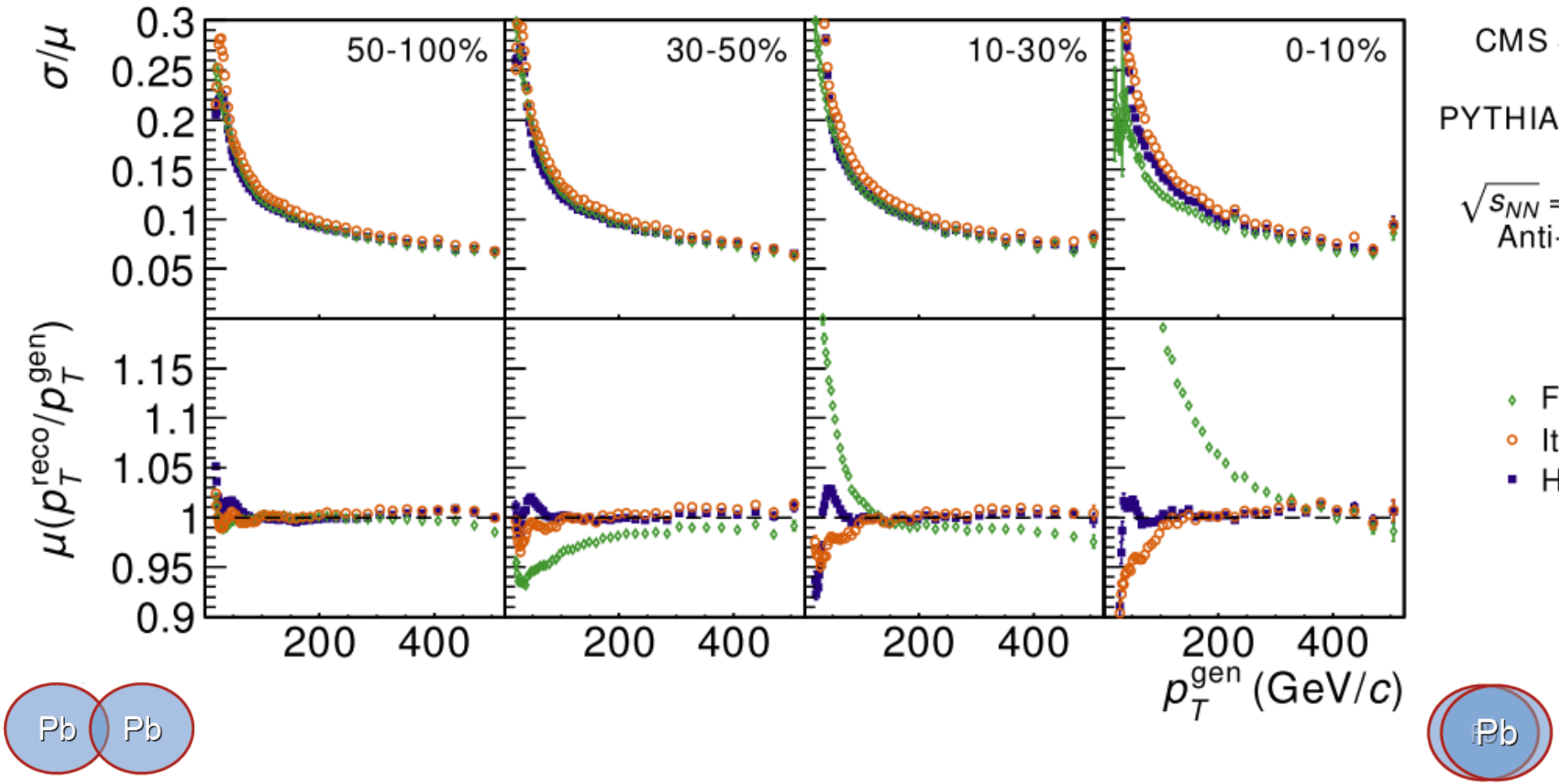
# Performance




Improvement in the jet energy resolution and jet energy closure compared to iterative UE subtraction

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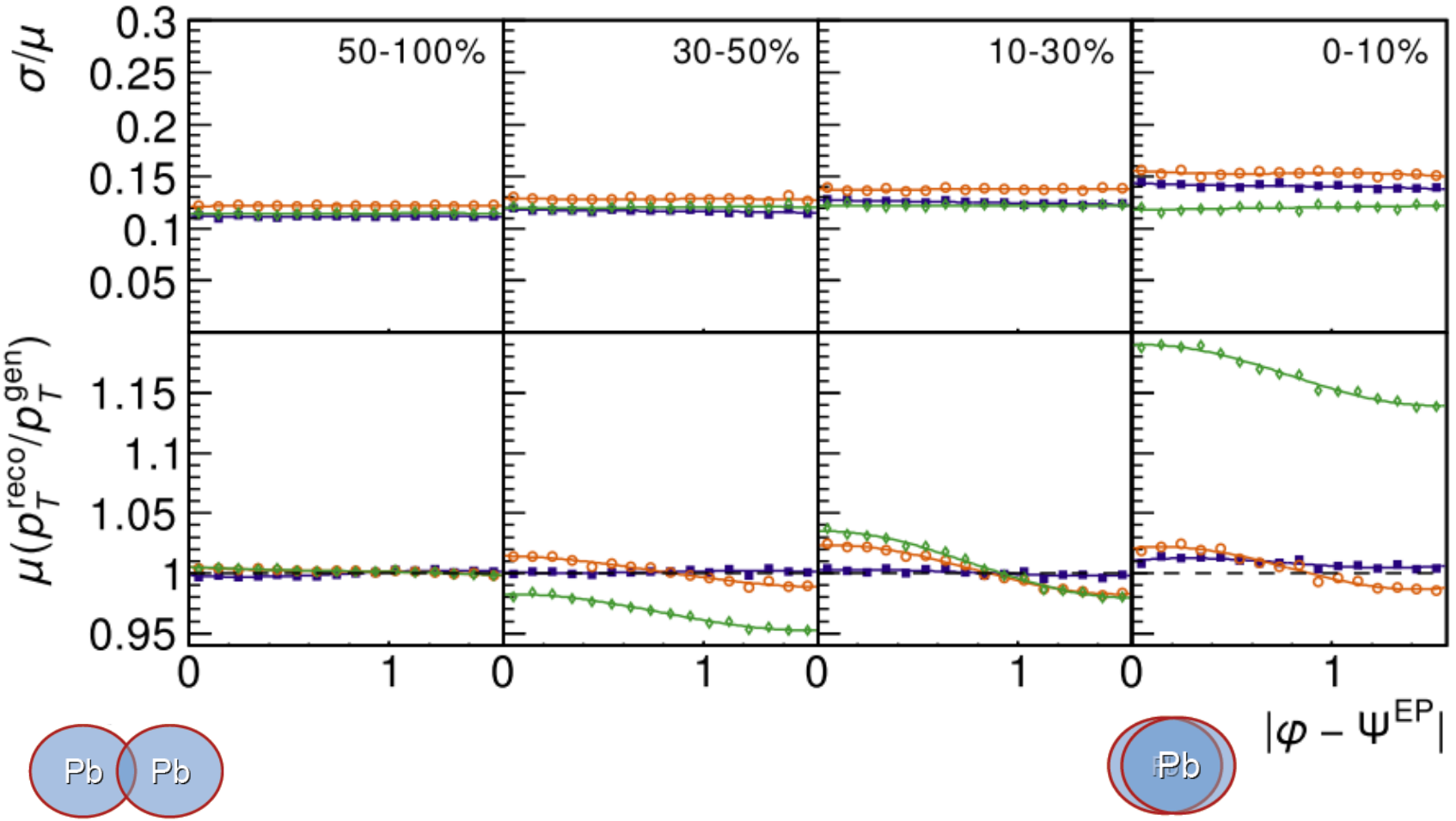
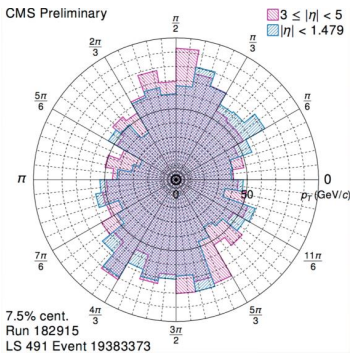
# Performance v.s. Event Plane Angle




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 $\rho A$
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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# Summary

- CMS has presented interesting jet measurements in heavy ion collisions
  - Large dijet and photon-jet momentum imbalance
  - Modification of jet shapes and fragmentation functions
  - The momentum difference in the dijet is balanced by low $p_T$ particles outside the jet cone

- An improved algorithm which attempts to remove HI UE
  - Remove flow modulation of the HI underlying events
  - Visible performance improvements

# Backup slides

# CMS detector