Outline

- Previously
  - Jet clustering
  - Jet fragmenation

- Today
  SubJet clustering
  Background subtraction

Reminder of jet clustering algorithm

- We learned a jet clustering (anti-k_T) algorithm. What can be the basic building block in clustering algorithm?
- In theoretical calculation or MC simulation, obviously it is the final stable particles, with accurate kinematic information
- In the real experiment, it is Energy block having finite position/energy resolution
- If the detector has 100% efficiency and perfect momentum resolution, then the sum of the energy blocks must be same to the true jet energy

Compact Muon Solenoid

Si tracker

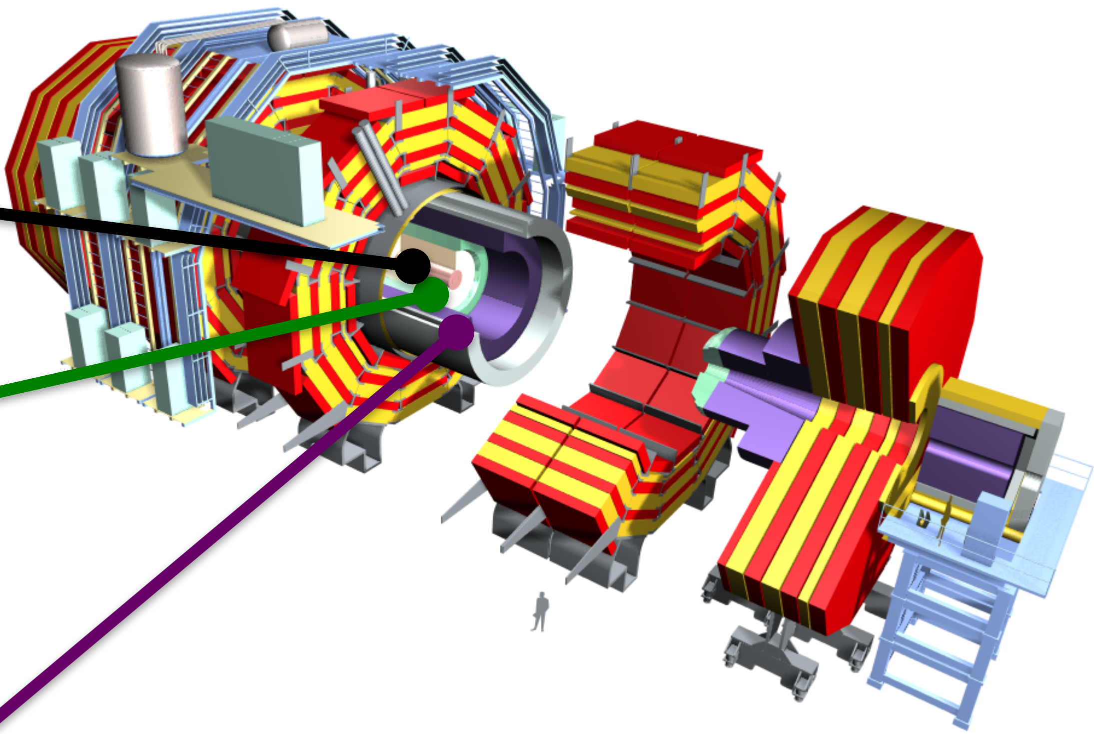
Charged particles

EMcal

Photon, electron

Hcal

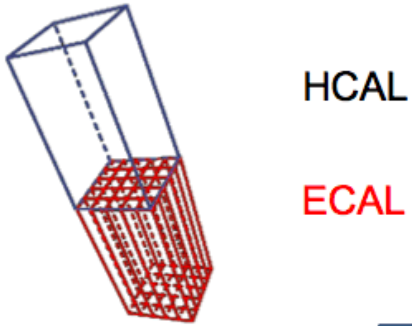
Jet

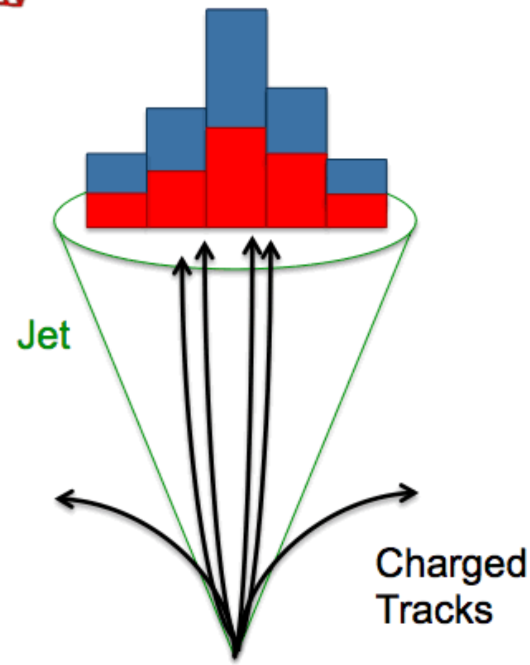


Covers 2π radians in azimuthal angle and very wide pseudo-rapidity

Calorimeter Jet : Traditional method

- "Traditional" jet reconstruction
- Calorimeter Towers
  - 1 HCAL cell ~ 0.1 ($\Delta\phi \times \Delta\eta$)
  - 25 ECAL crystals ~ 0.01 ($\Delta\phi \times \Delta\eta$)
- Does not make use of ECAL granularity
- Jet resolution driven by HCAL:
  - HCAL resolution ~ $100\%/\sqrt{E}$
  - non-compensating → non-linear response
- Low p_T charged hadrons bent outside jet

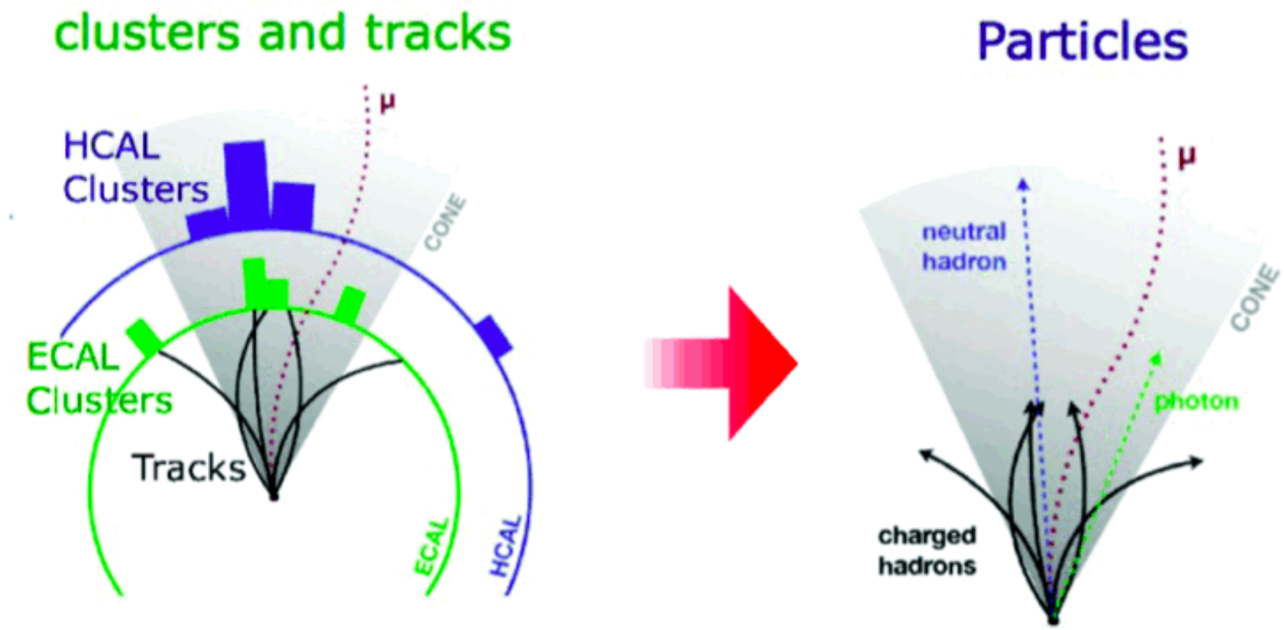




Purely calorimetric jet reconstruction does not take advantage of the full versatility of CMS

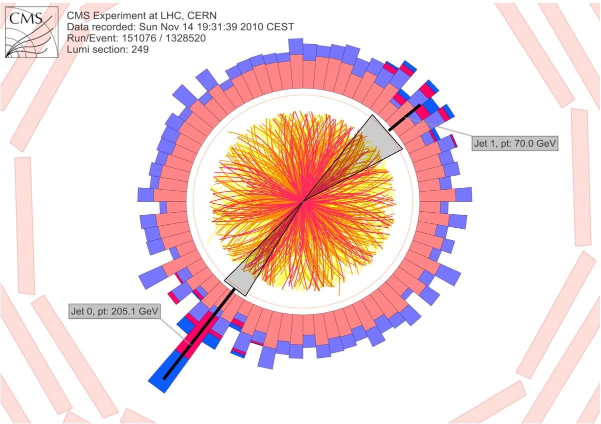
Particle Flow as the jet component block

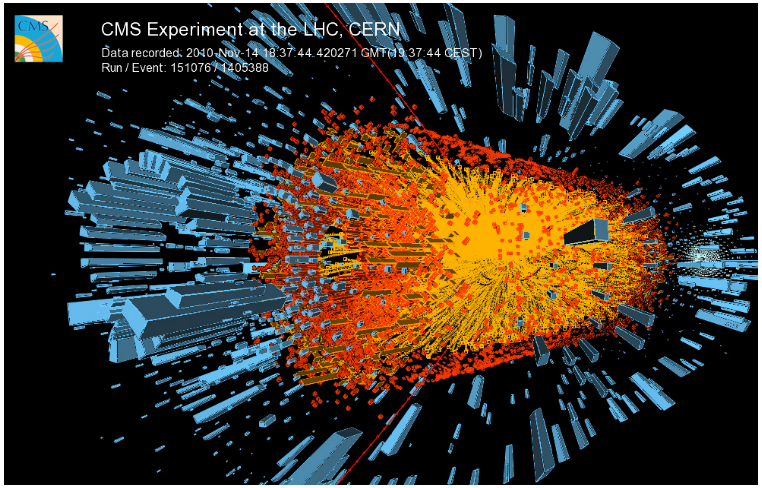
Particle flow reconstructs all stable particle in the event: $h^{+/-}$, γ, h^0, e, μ

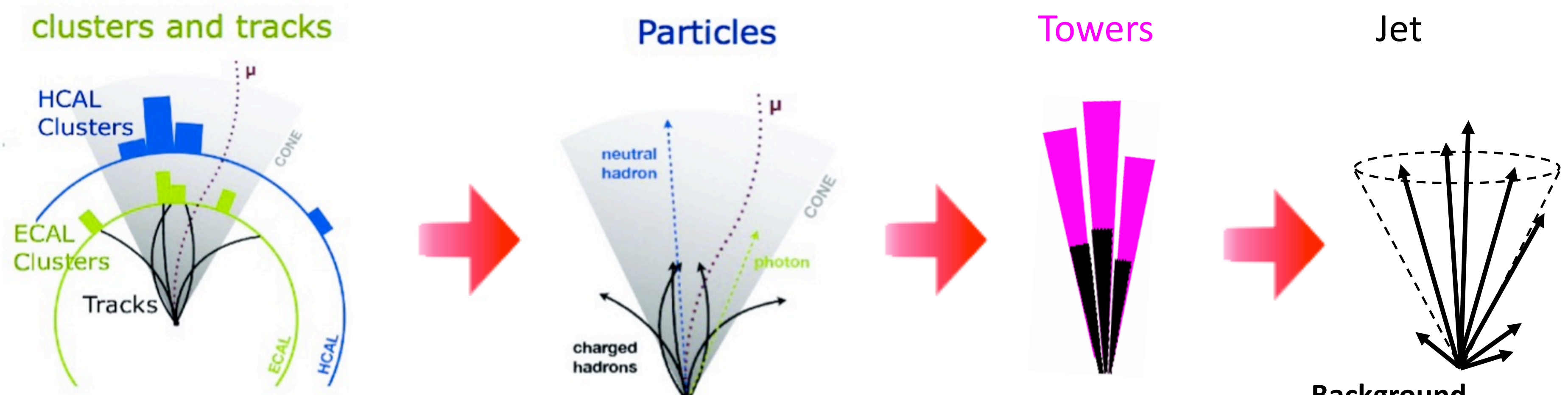


- On average jets are:
  ~ 65% charged hadrons, ~ 25% photons, ~ 10 % neutral hadrons
- Using the silicon tracker (vs. HCAL) to measure charged hadrons
  - Improves resolution, avoids non-linearity
  - Decreases sensitivity to the fragmentation pattern of jets
- Used extensively in ALEPH, CMS and proposed for the ILC

Subtraction of background by underlying event





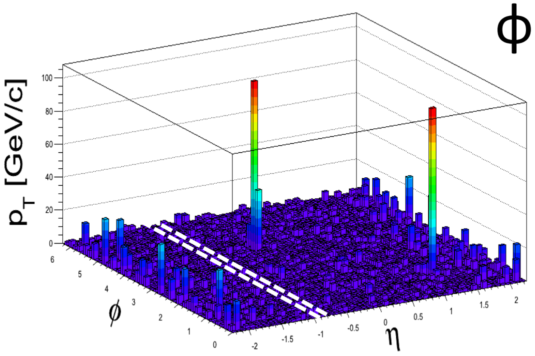


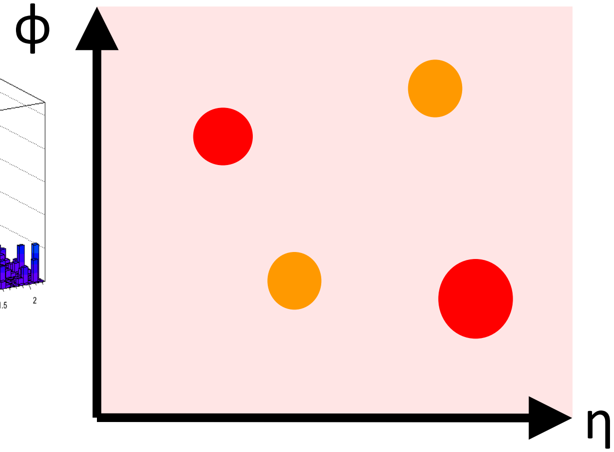
Background subtraction and jet clustering

Anti-k_T algorithm is used in most of CMS publications

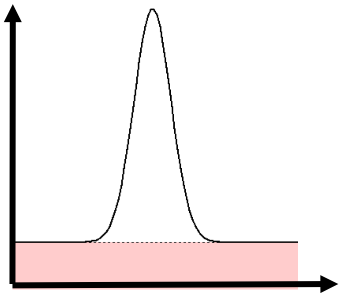
For instance, Δη x Δϕ 0.076 x 0.076 in barrel

Pileup Subtraction

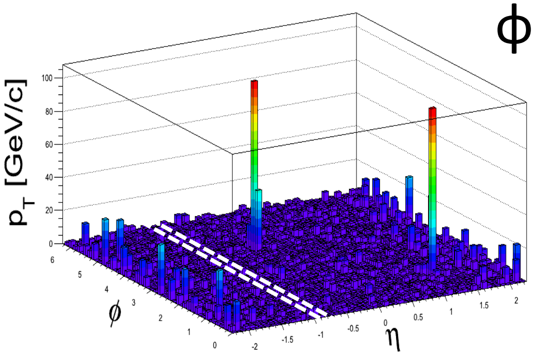


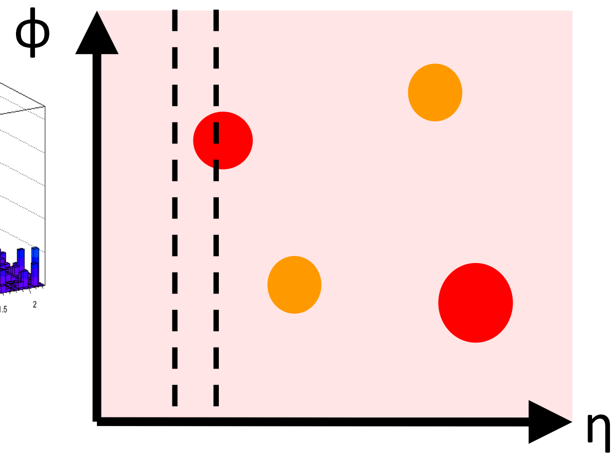


Boston Jet Workshop '14



Pileup Subtraction

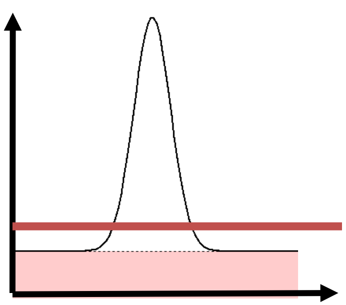




1. Background energy per tower calculated in strips of η.

Determine $<p_T>$ and $\sigma(p_T)$

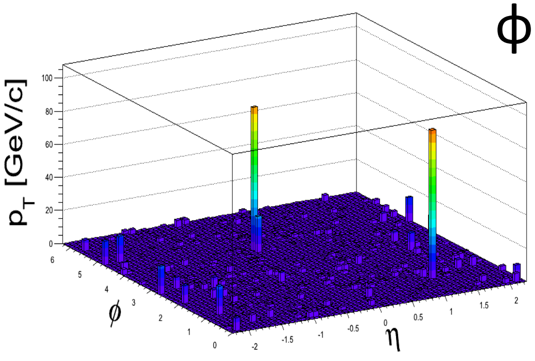
Subtract $<p_T> + N*\sigma(p_T)$ (Noise suppression)

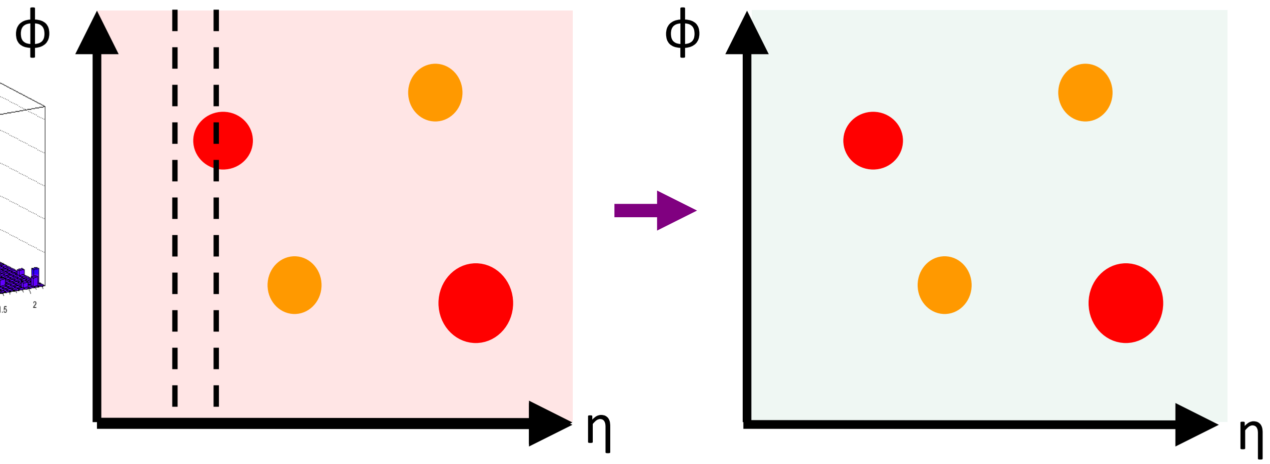


Background level

Estimate background
for each tower ring of constant η
estimated background = $<p_T> + N*\sigma(p_T)$

Pileup Subtraction





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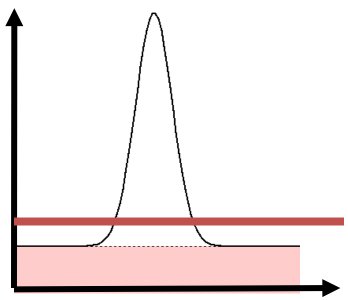
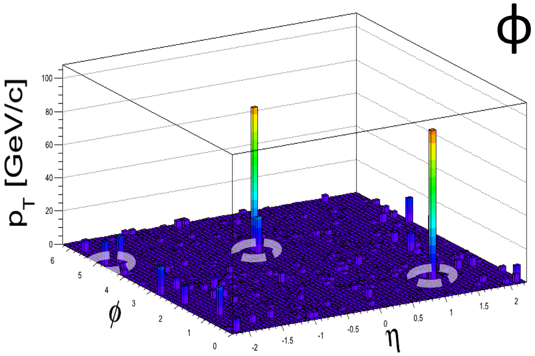
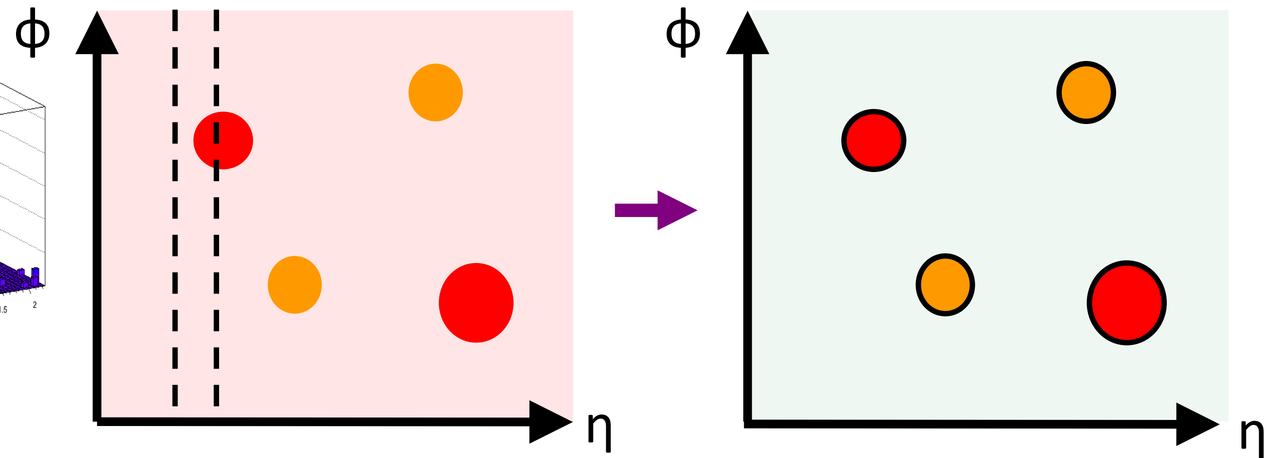


Background level

Pileup Subtraction





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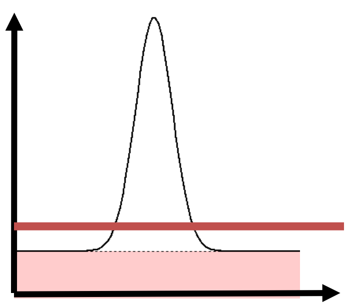
2. Run anti k_T algorithm on background subtracted towers



Background level

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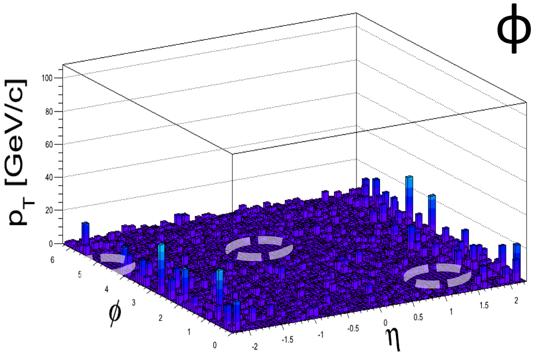

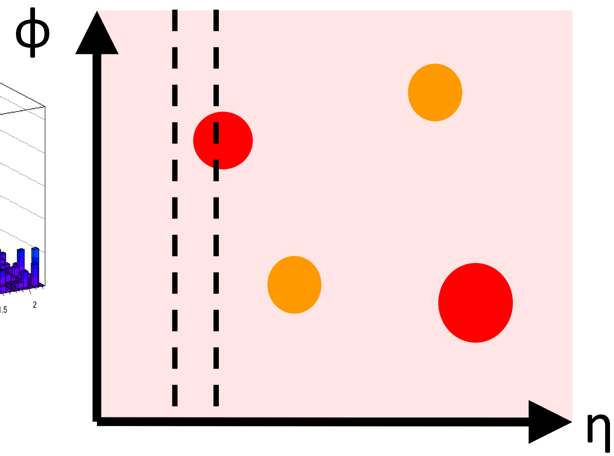

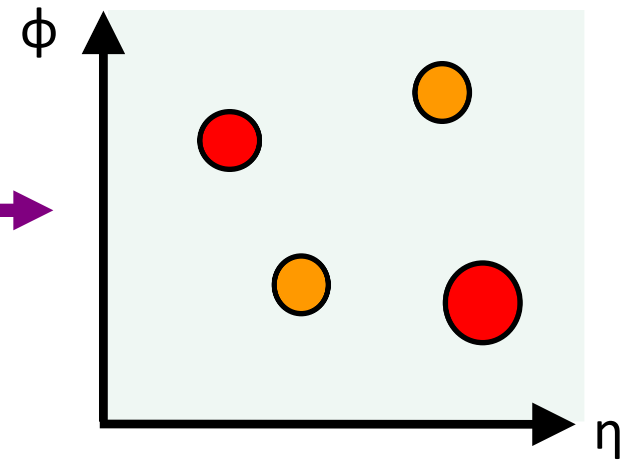

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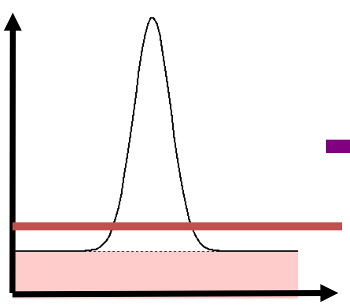
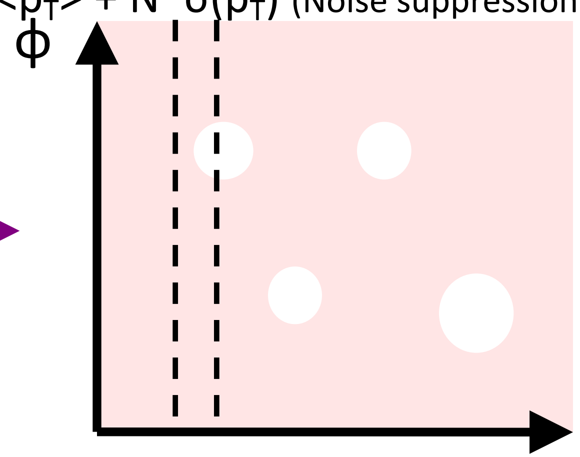
Boston Jet Workshop '14

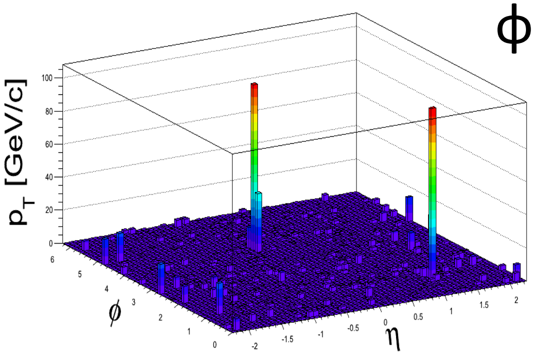


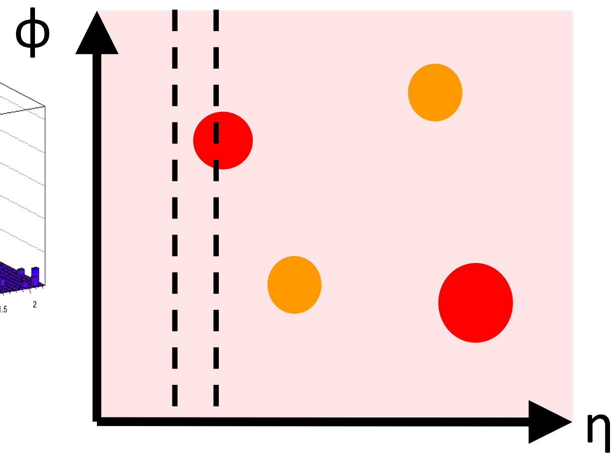


Background level

3. Exclude reconstructed jets

Pileup Subtraction





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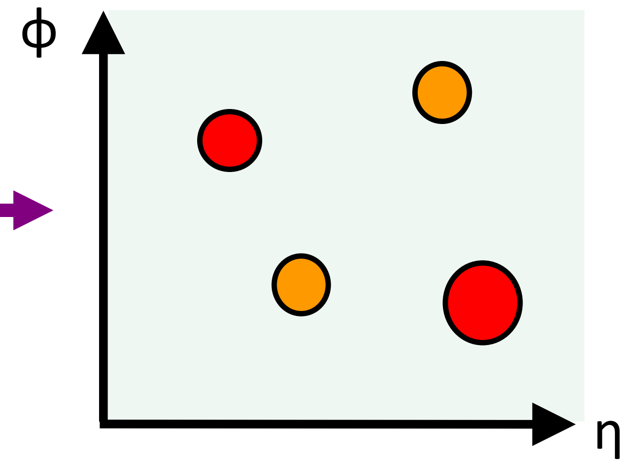

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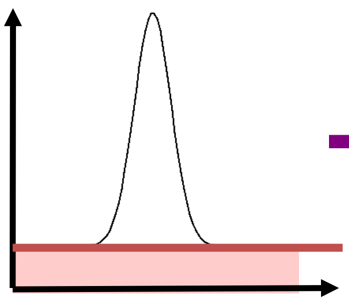

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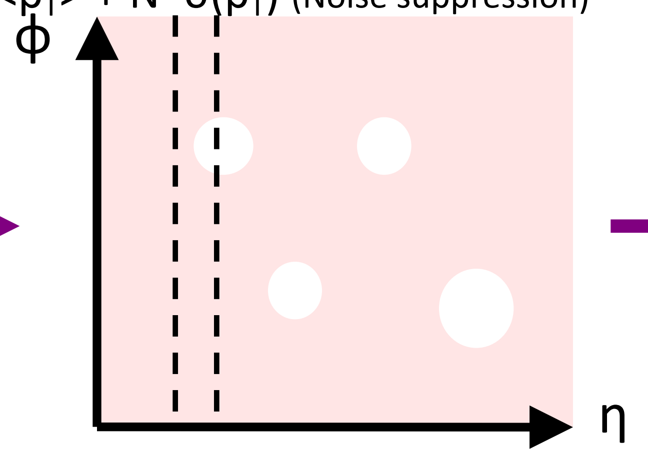

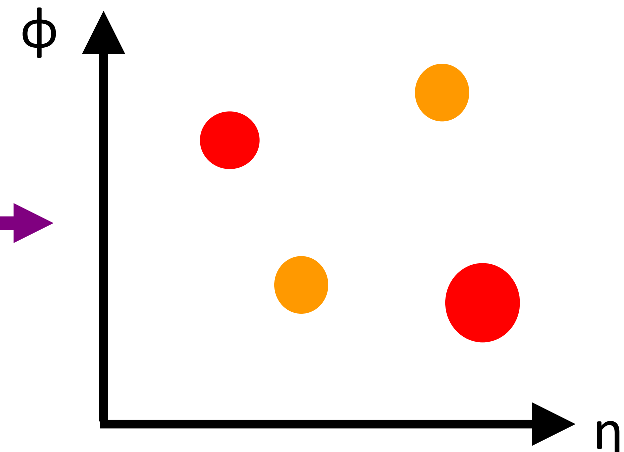

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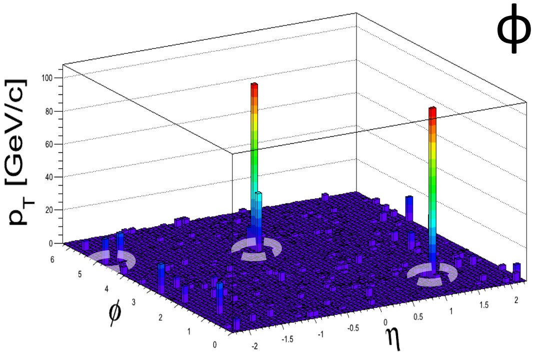
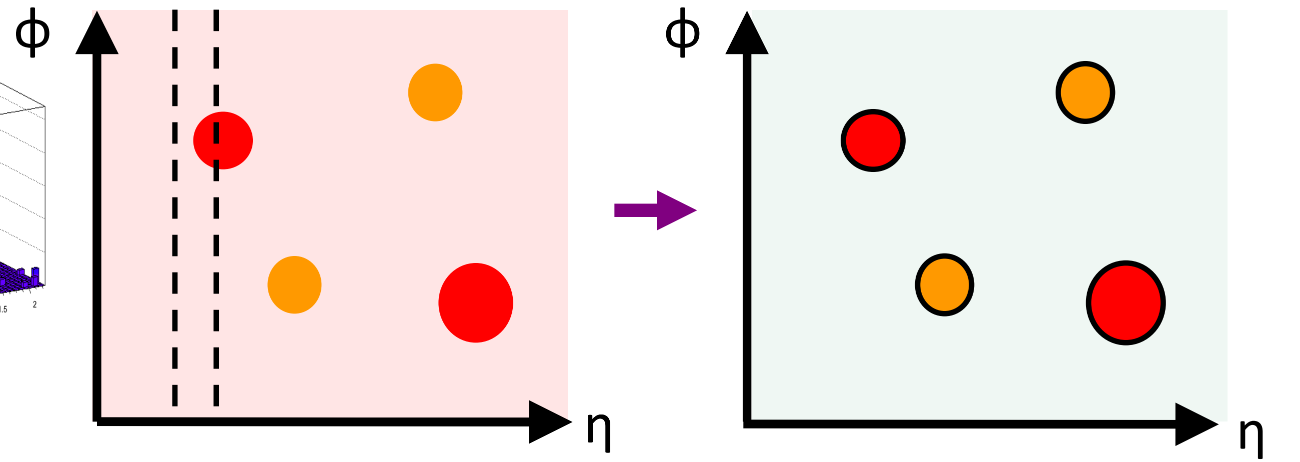
Recalculate the background energy
Subtract $\langle p_T \rangle + N^*\sigma(p_T)$ (Noise suppression)

Pileup Subtraction





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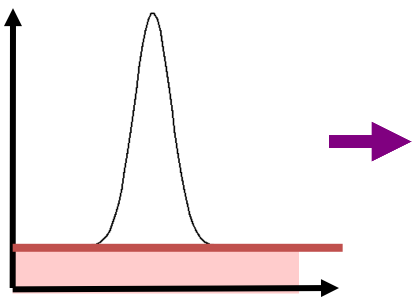
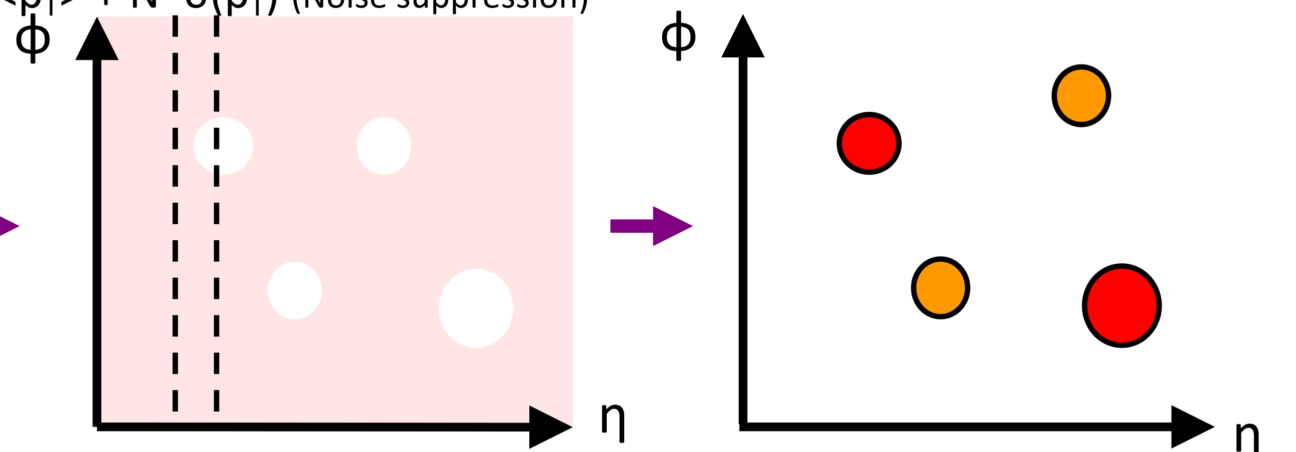


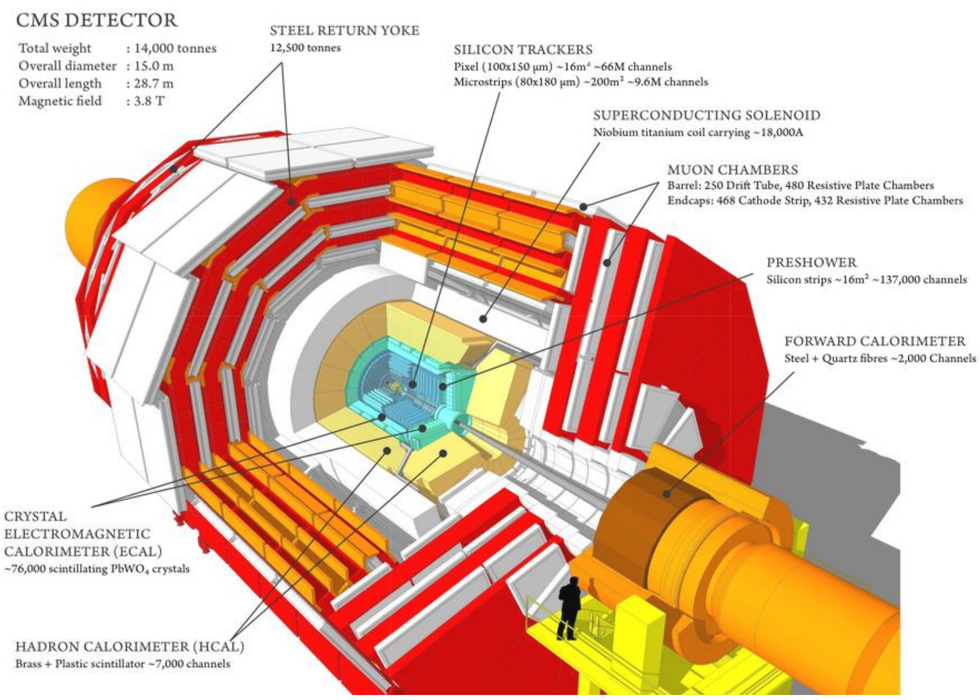
Background level

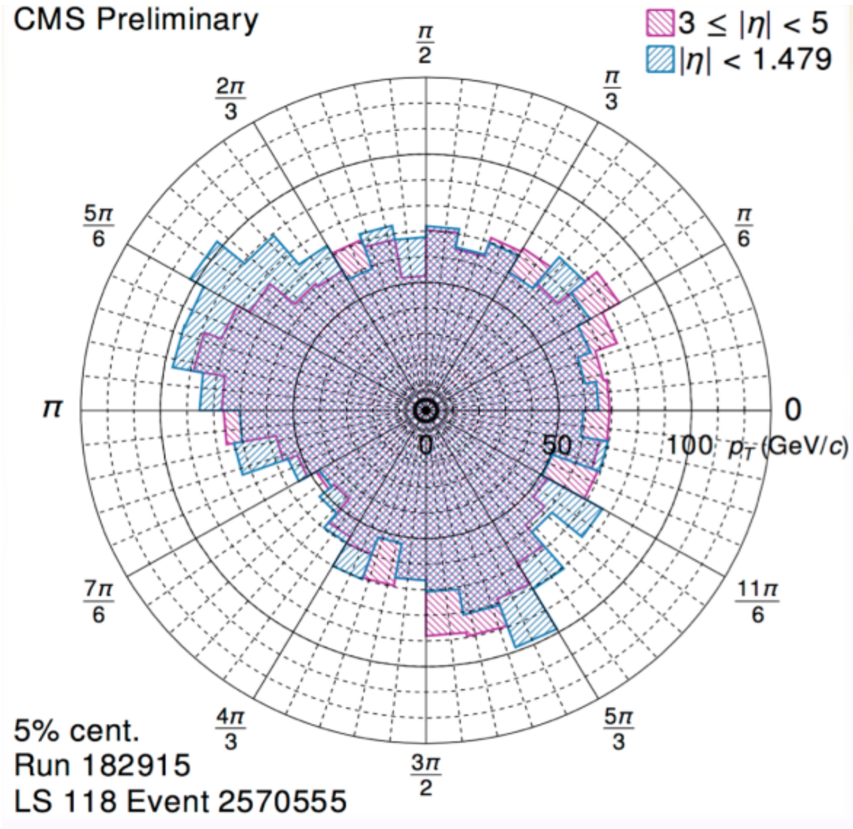


3. Exclude reconstructed jets
Recalculate the background energy
Subtract $<p_T> + N*\sigma(p_T)$ (Noise suppression)

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

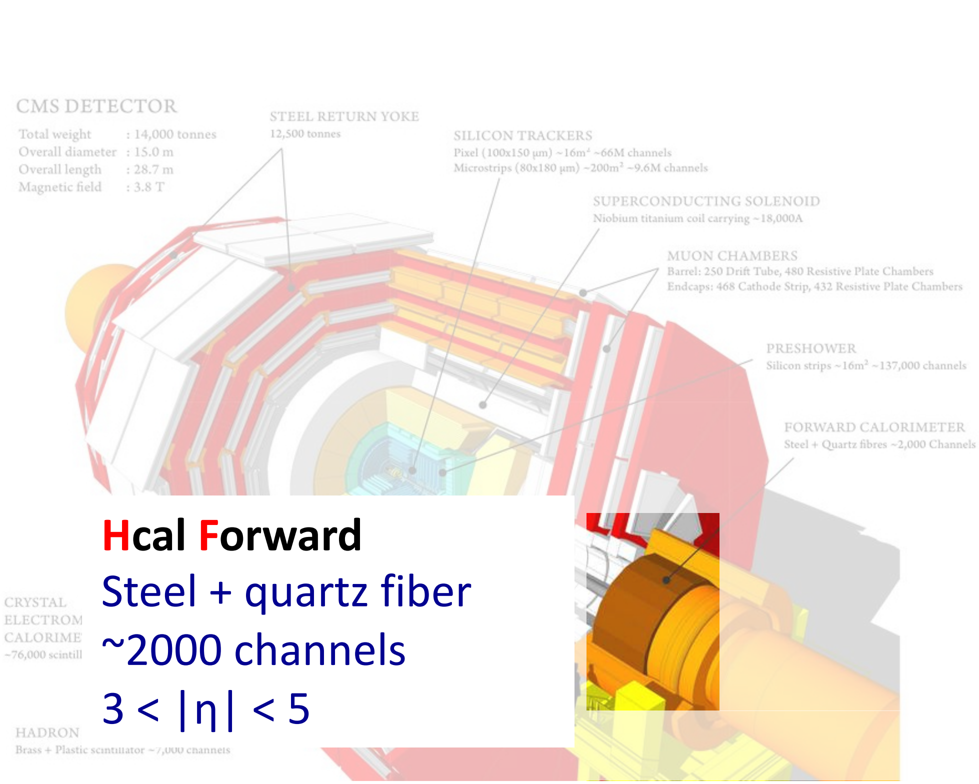
New algorithm using Forward calorimeter





- 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

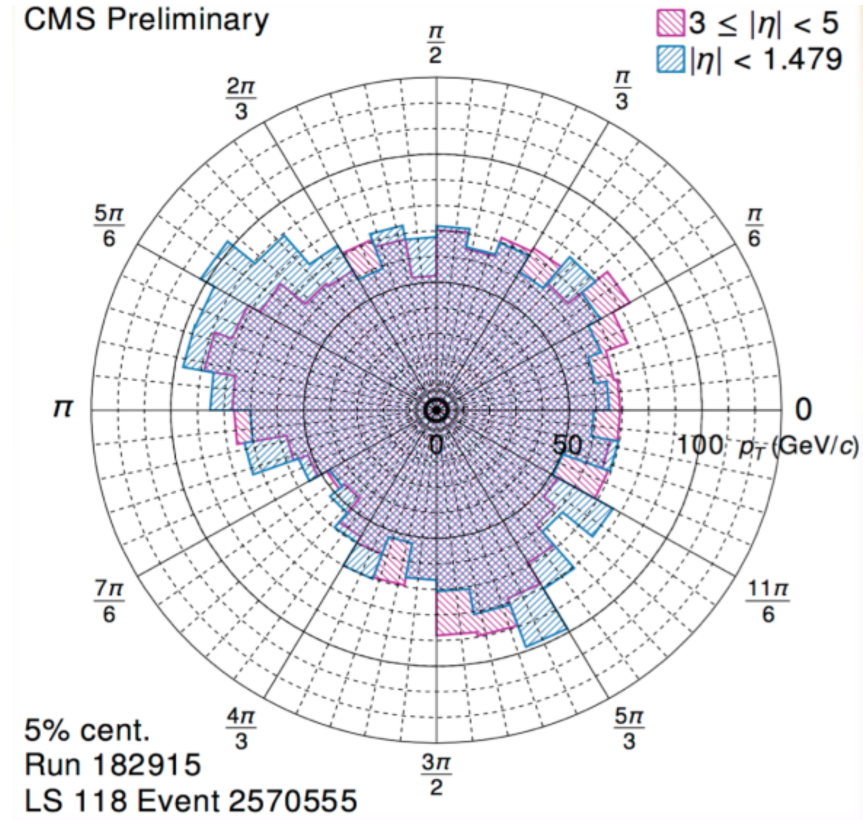


Hcal Forward

Steel + quartz fiber

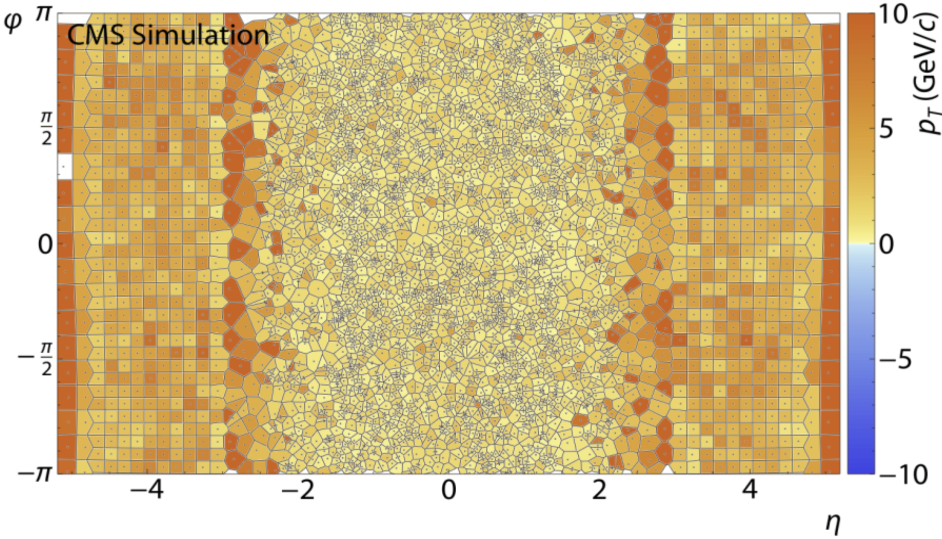
~2000 channels

$3 < |\eta| < 5$

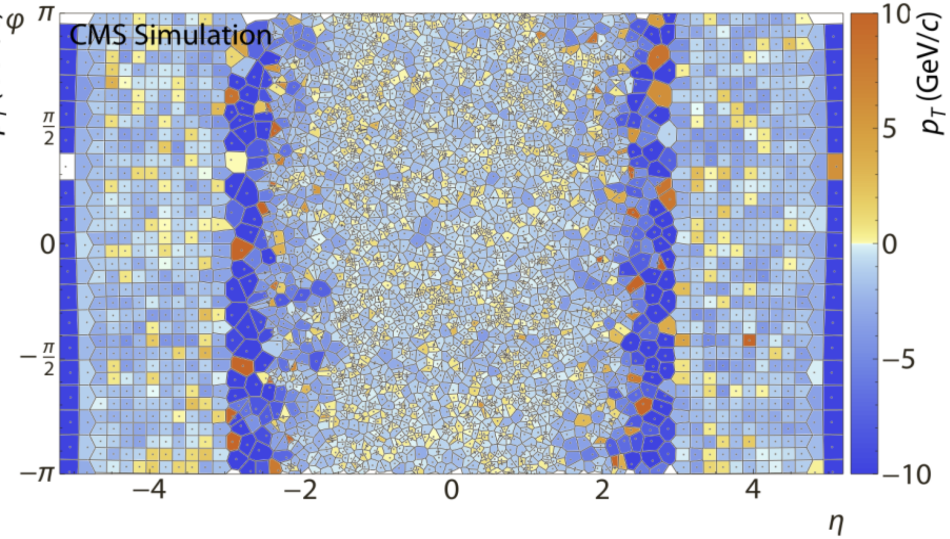


- Energy deposited at the forward calorimeter is used to estimate the underlying event energy distribution in the mid-rapidity
- Training done with minimum-bias events

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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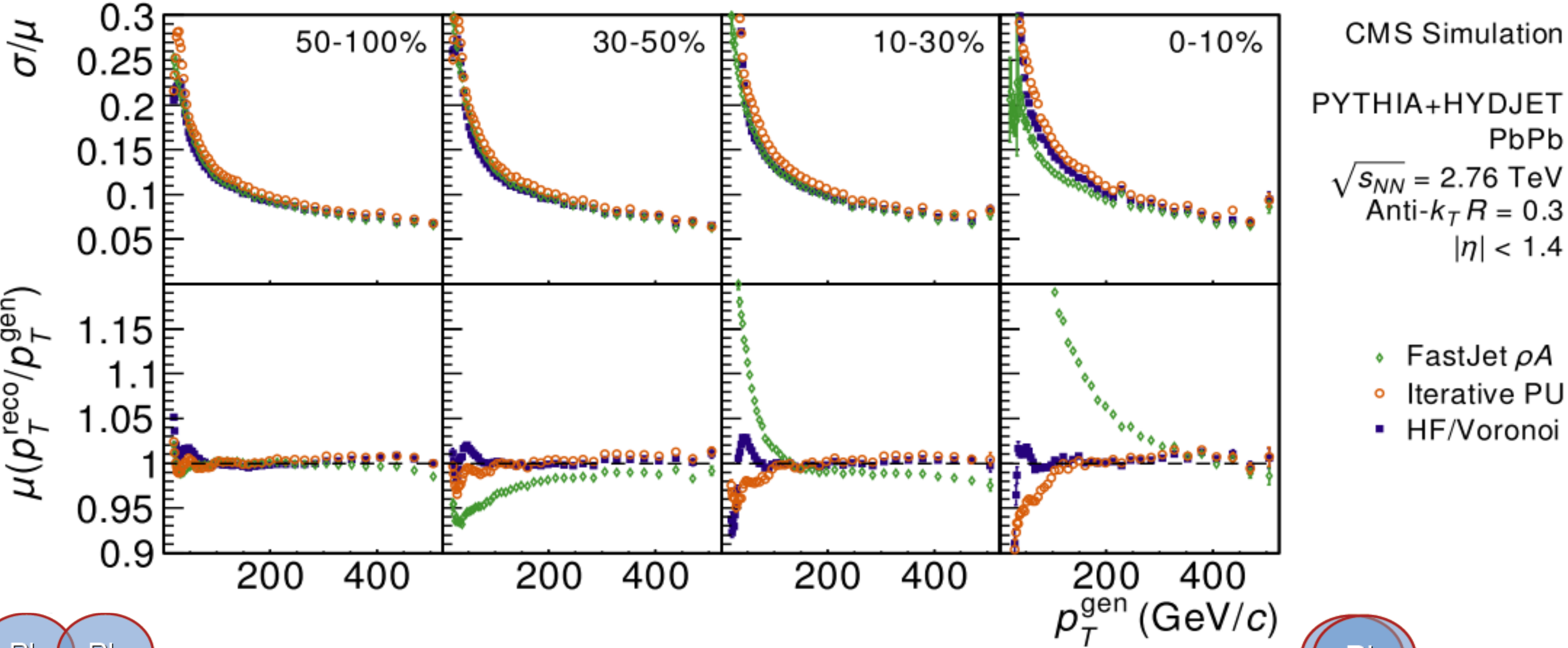
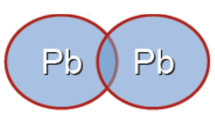
Performance





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

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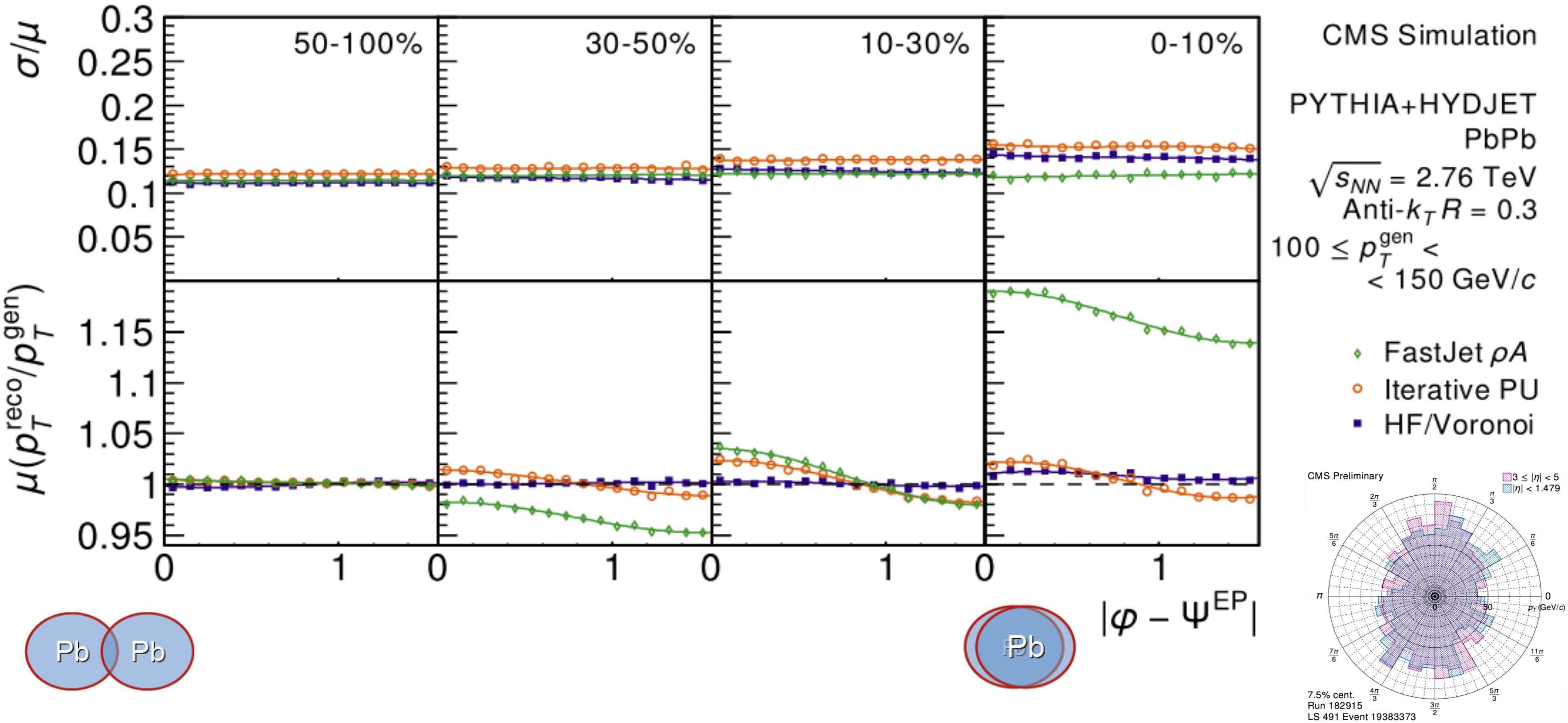
Performance v.s. Event Plane Angle



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

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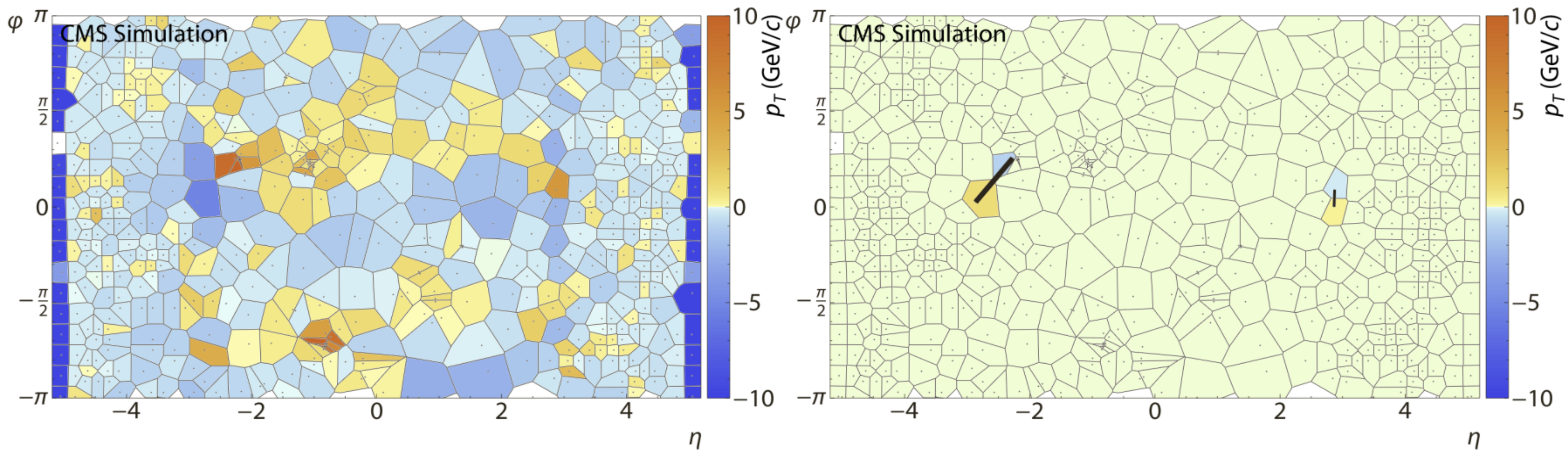
Negative Energy Balancing



- 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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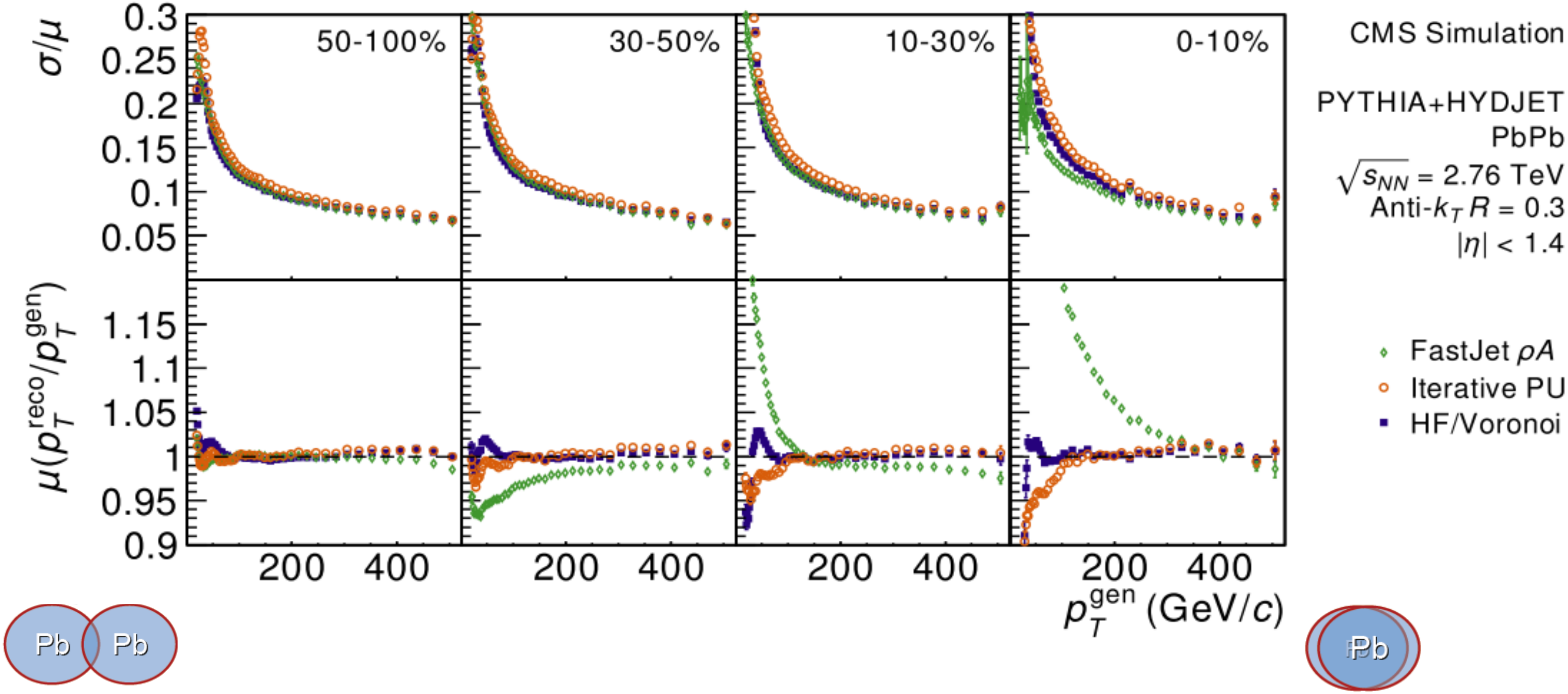
Underlying event subtraction algorithm



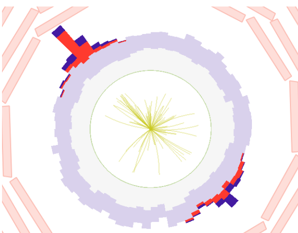
Improvement in the jet energy resolution and jet energy closure compared to previous algorithm

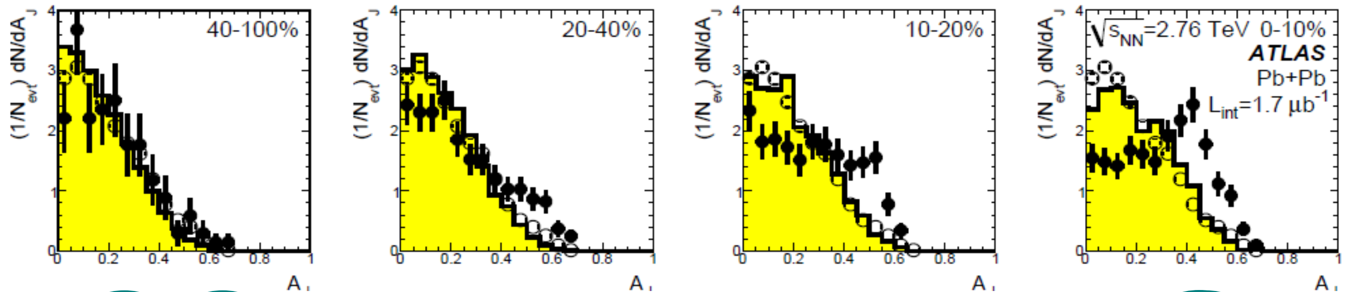
Correlation study: Di-jet imbalance

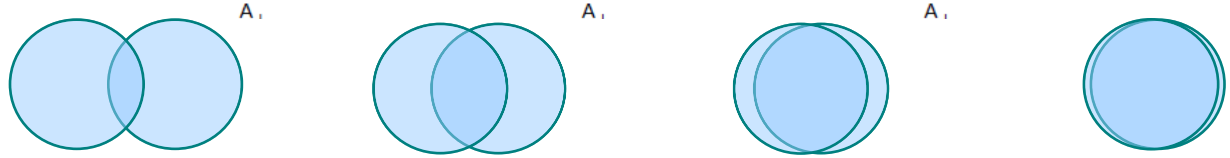
PRL 105 (2010) 252303

Quantified the momentum impalance of di-jet pairs by

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







Peripheral coll.
Small QGP

Central coll.
Bigger QGP

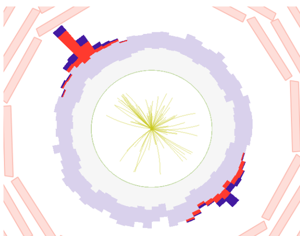
Physics messages

1. Significant **Di-jet energy imbalance** was observed in the head-on PbPb collision

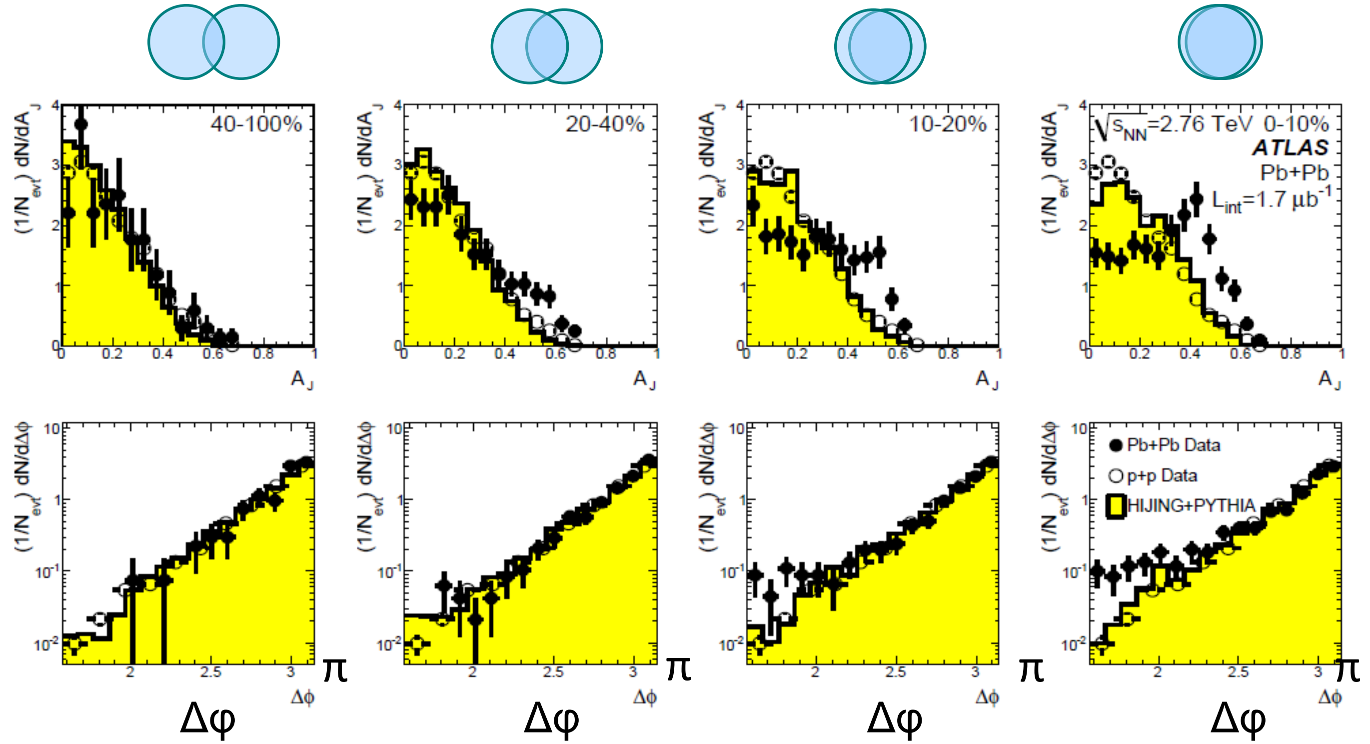
Correlation study: Di-jet imbalance

PRL 105 (2010) 252303

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



$\Delta\phi = | \phi_1 - \phi_2 |$

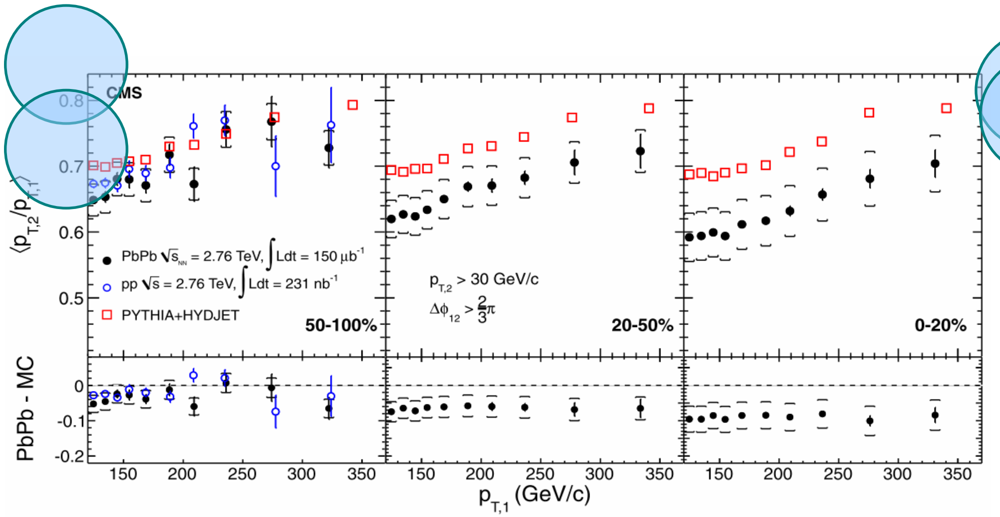


Physics messages

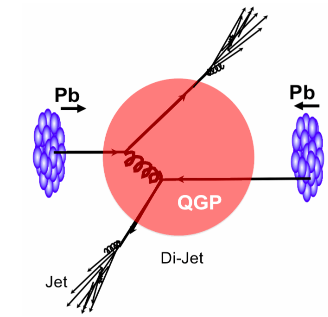
1. Significant **Di-jet energy imbalance** was observed in the head-on PbPb collision

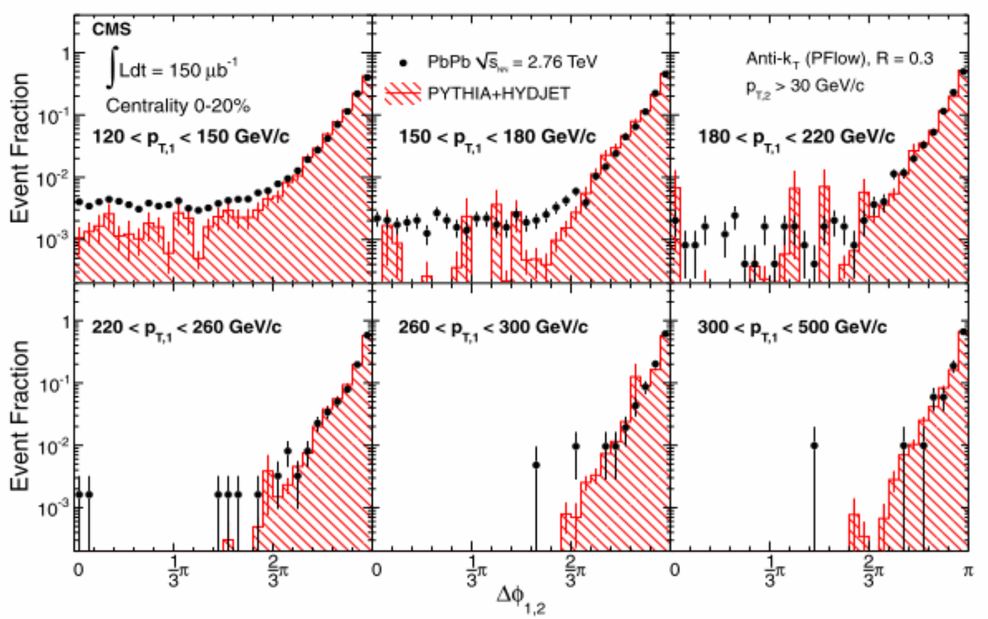
2. **Angular correlation of jet pairs is consistent** with pp collision

Momentum correlation of di-jets



PLB 712 (2012) 176



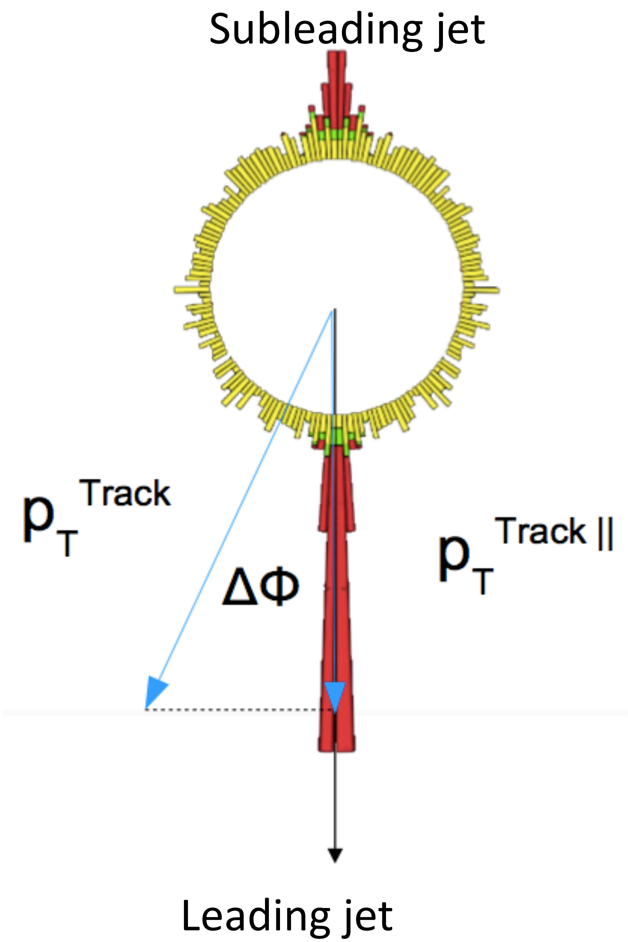


Significant asymmetry of energy of jets observed while angular correlation is kept.
Monotonic to pT of jet

Newton's 3rd law

Investigate the momentum of all charged particles projected on the leading jet axis

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



Newton's 3rd law

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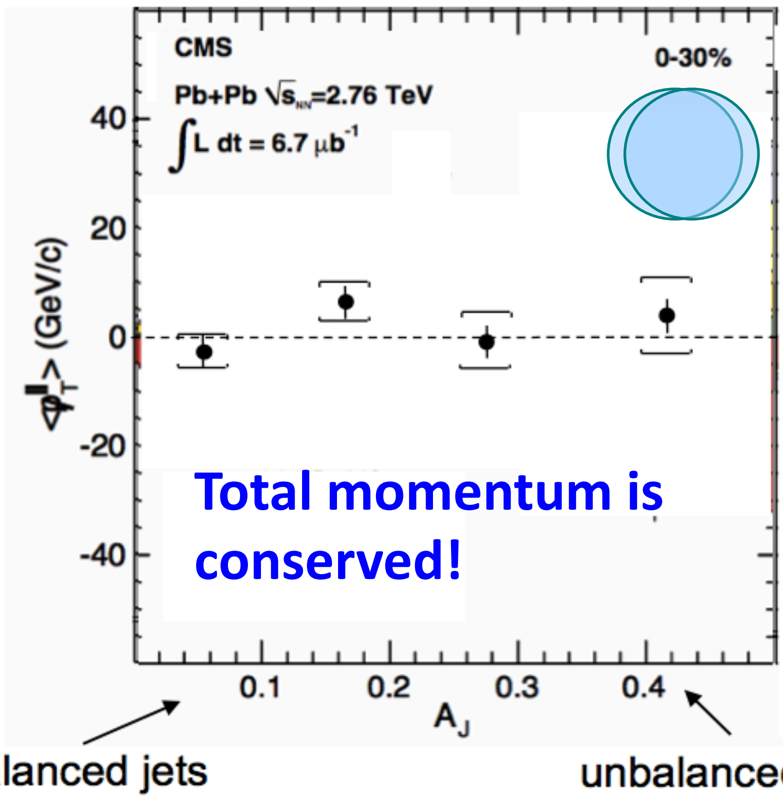
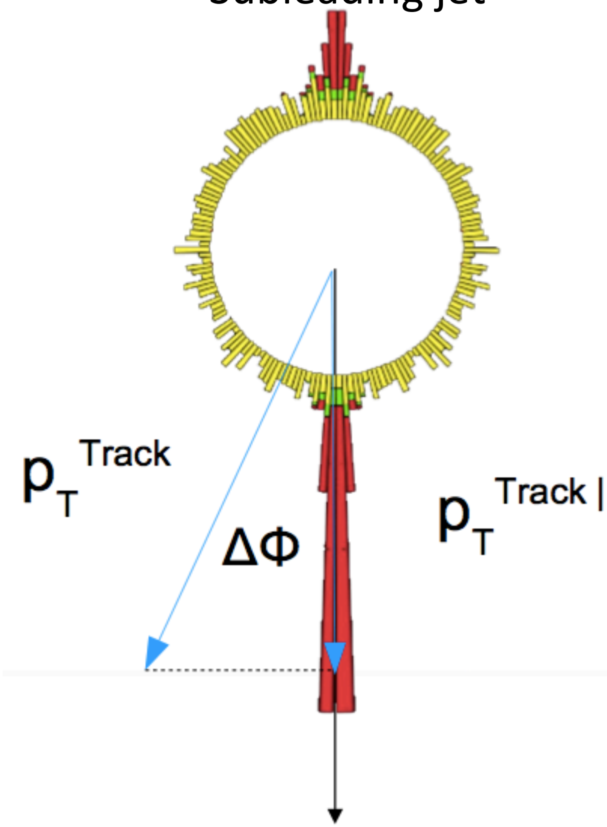
0-30% Central PbPb



excess away from leading jet

excess towards leading jet

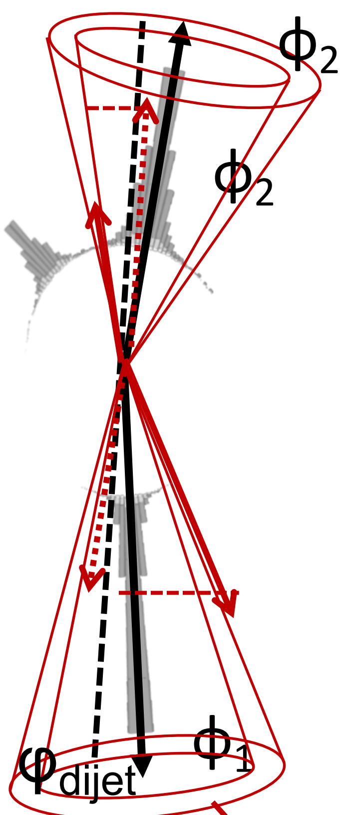


$$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$$

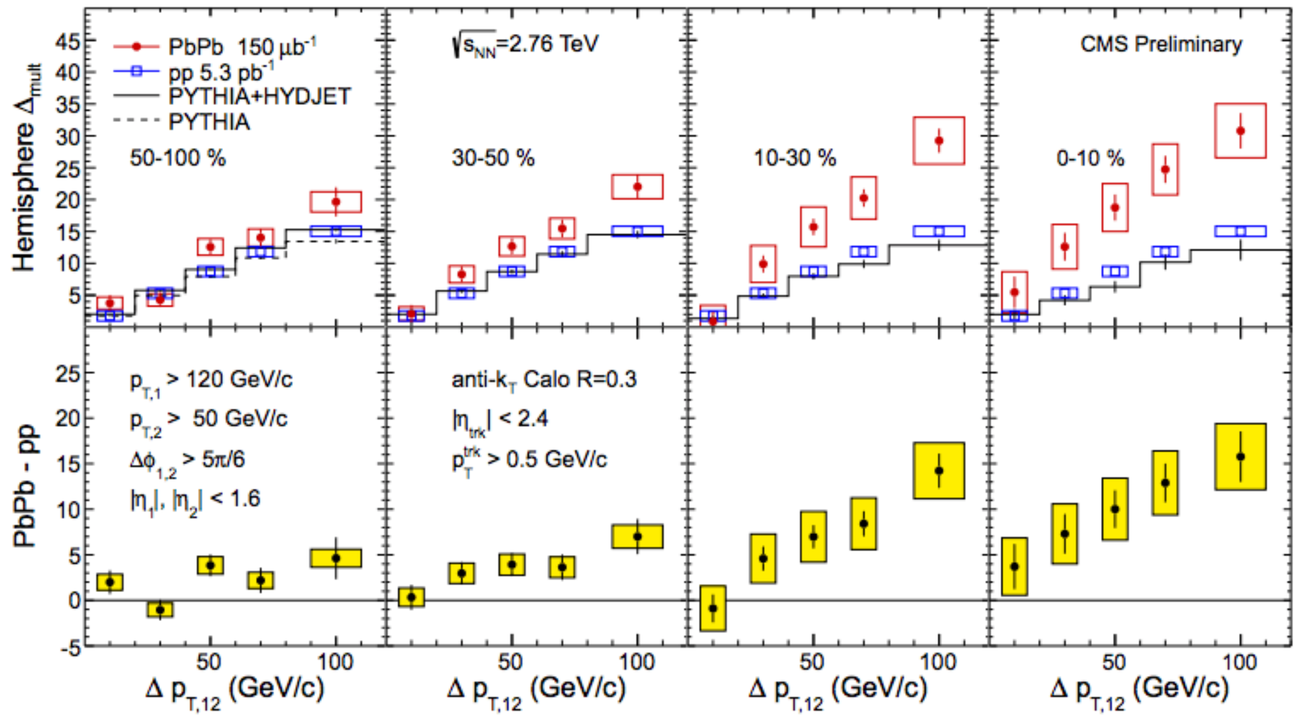
Newton's 3rd law

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



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

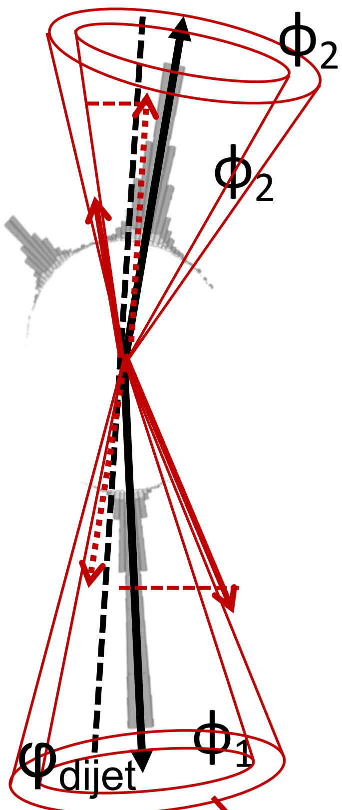


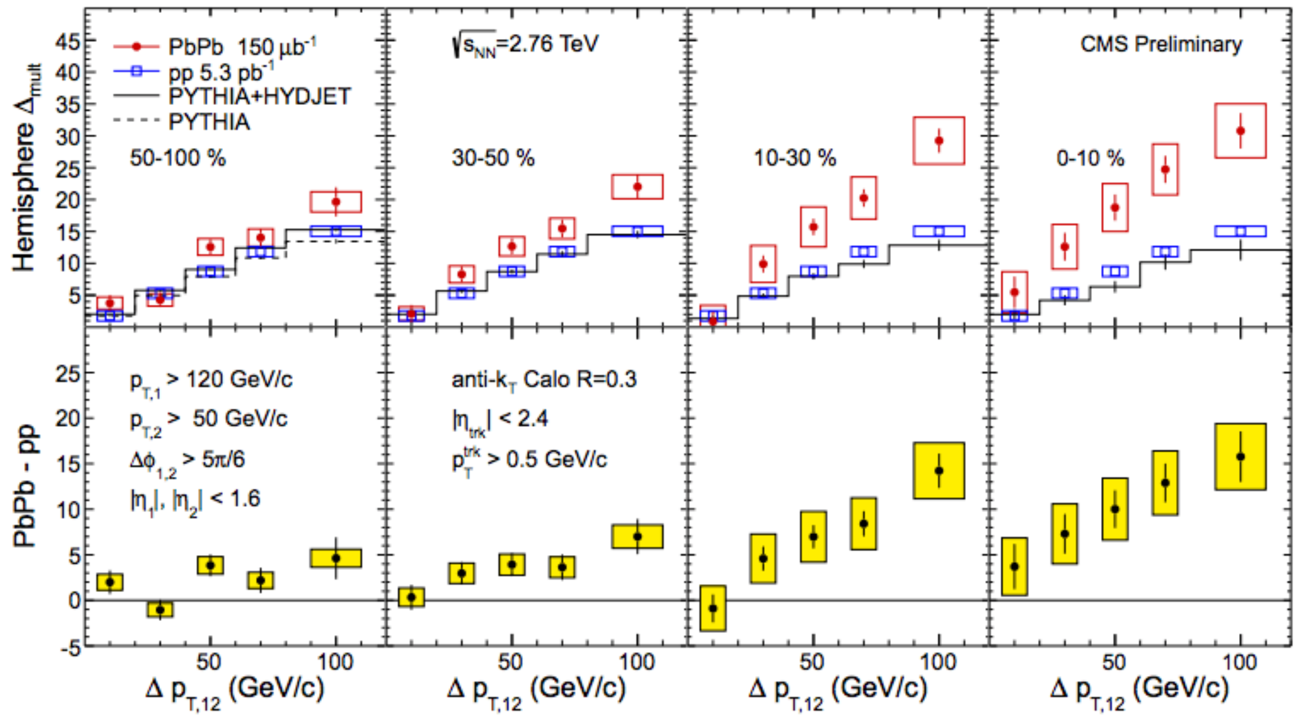
Multiplicity difference

Newton's 3rd law

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





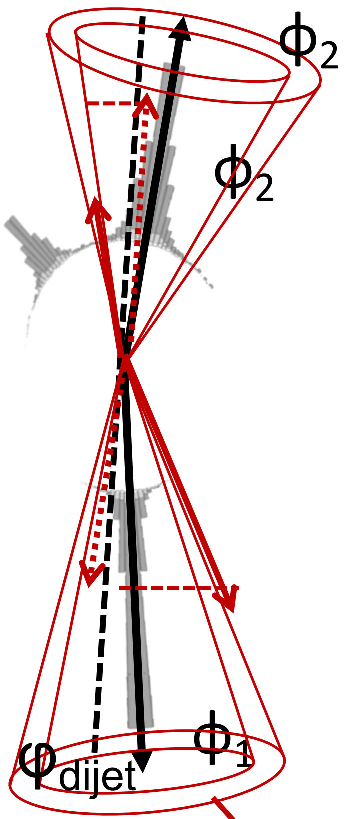
Multiplicity difference

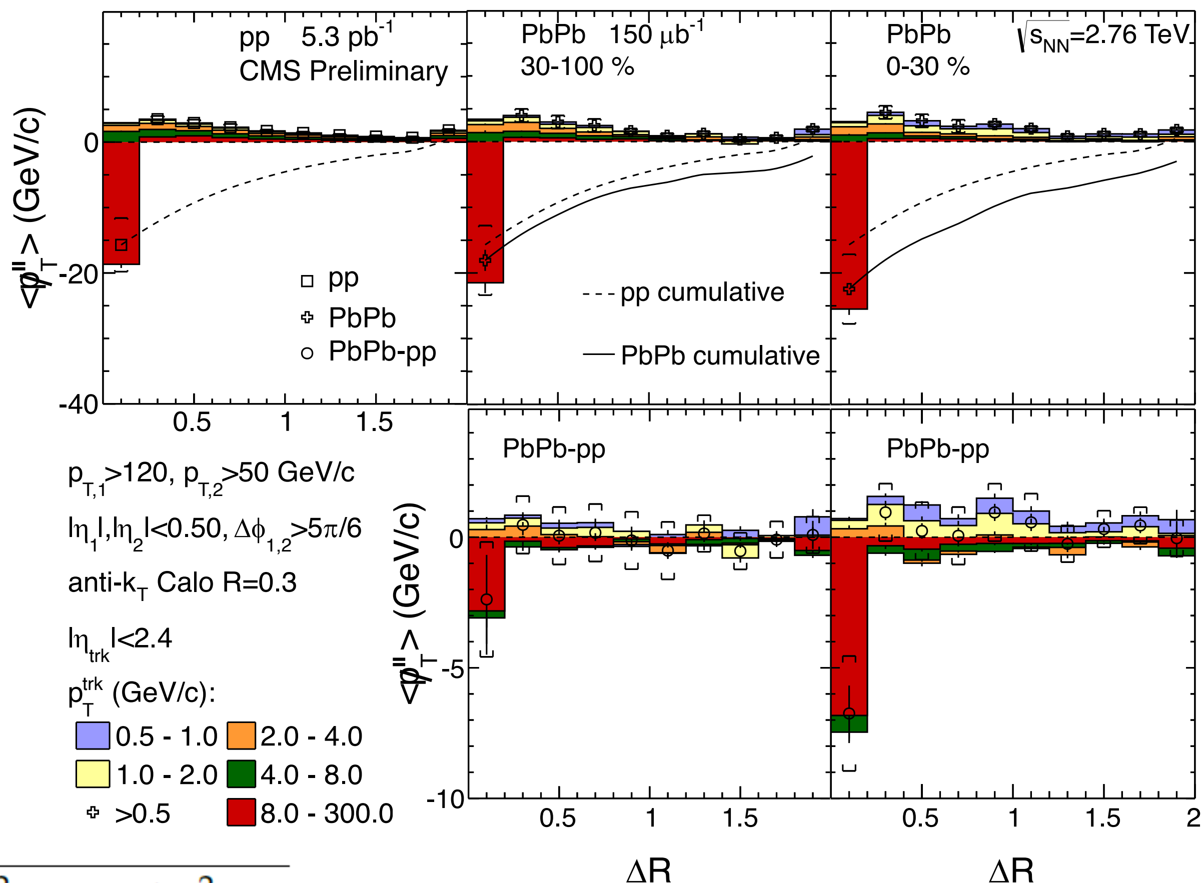
$$\Delta R = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

Newton's 3rd law

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

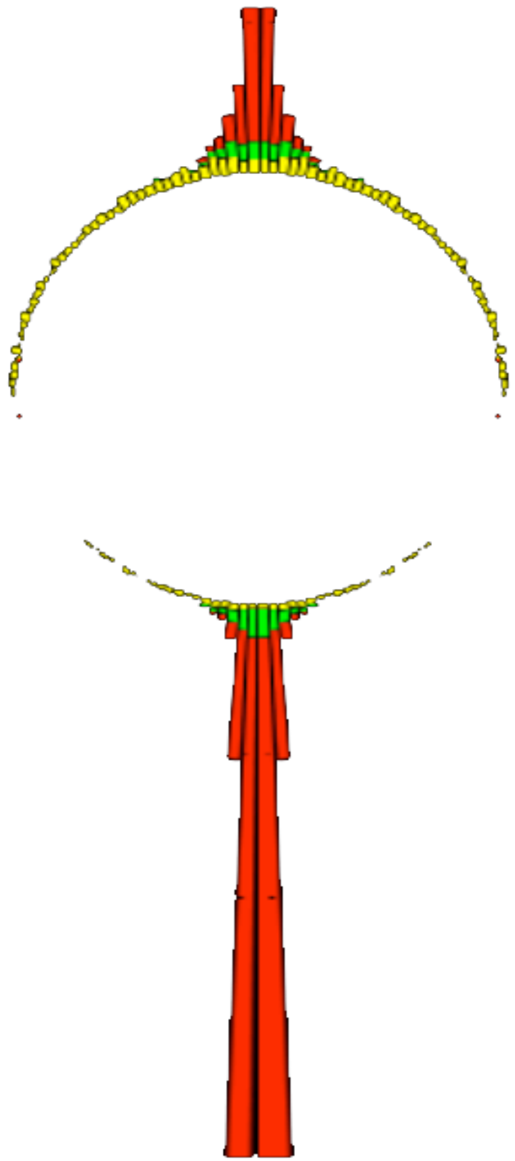
- High p_T imbalance at small ΔR
- was balanced by low p_T particles in subleading jet direction upto large ΔR





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

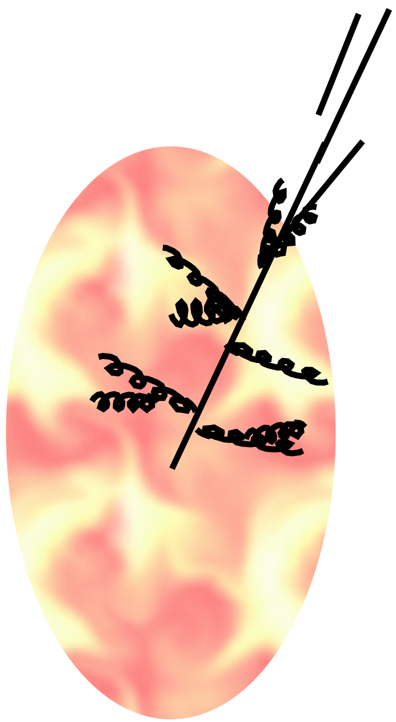
Overall observation



1. Missing energy was converted into **multiple soft particles** pT ~ O(1) GeV

2. Missing energy is **largely deviated from jet axis** ΔR > 0.8 (>45 deg)

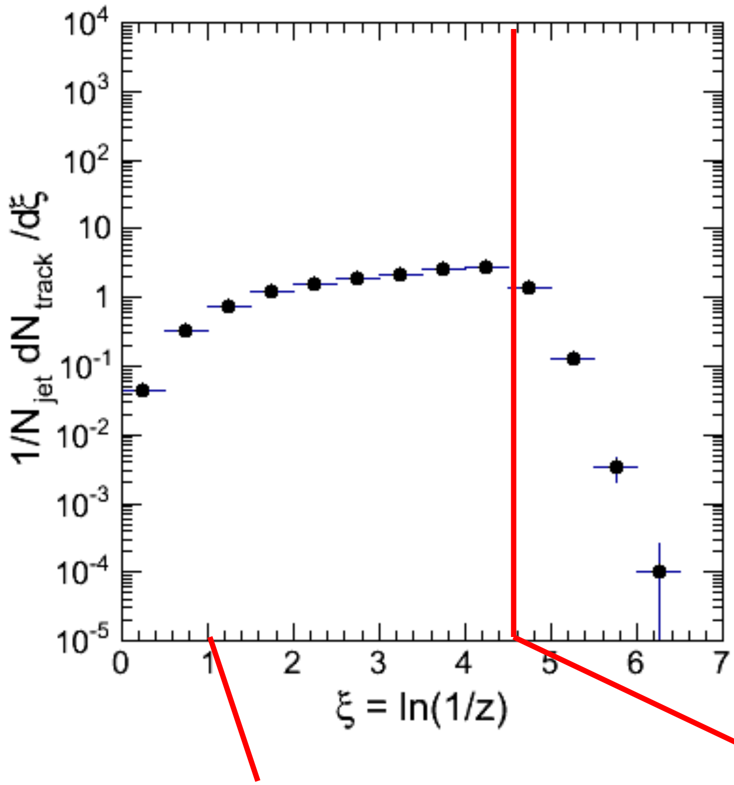
Result supports the QGP heating model



Large angle soft radiation
"QGP heating"

AdS/CFT
JHEP 1010 (2010) 099
Phys.Rev. D79 (2009)
JHEP 0810 (2008)
JHEP 0805 (2008) 037

Fragmentation Function of jet



Track p_T = 35 GeV/c

Track p_T = 1 GeV/c

at Jet p_T = 100 GeV/c

Observable:

$$\xi = \ln\frac{1}{z} \quad , \quad z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}$$

In jet cone R < 0.3,
Track p_T > 1 GeV/c

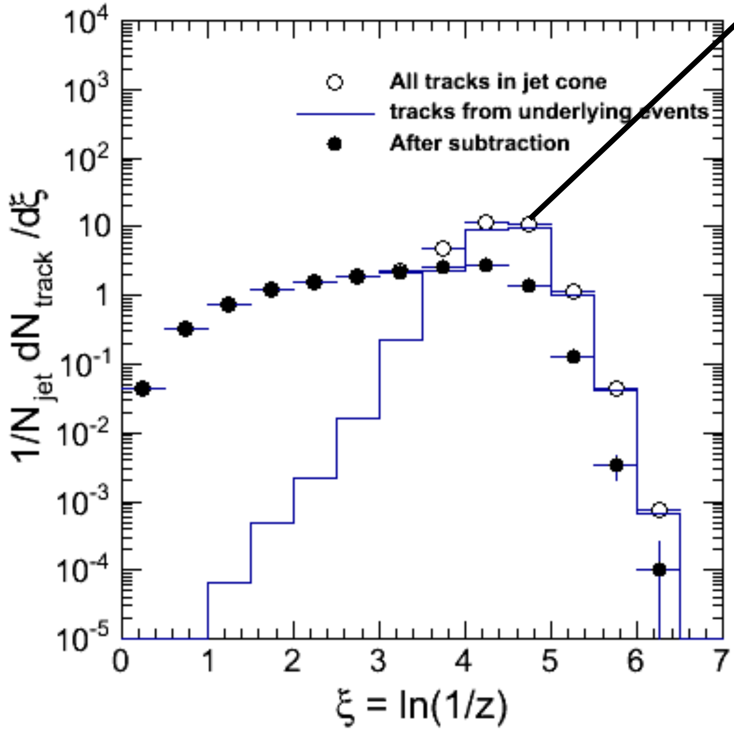
Per Jet Normalization:

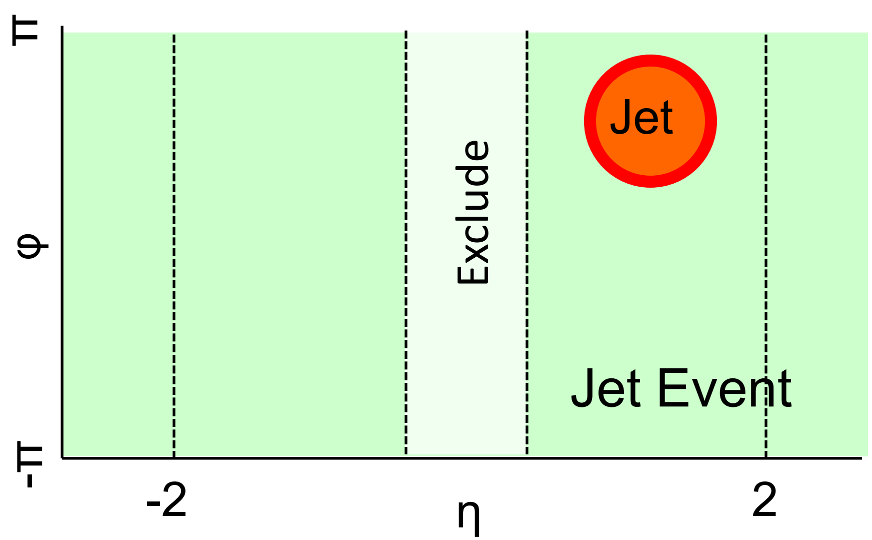
FF integral = # of particles per jet

FF – underlying event subtraction

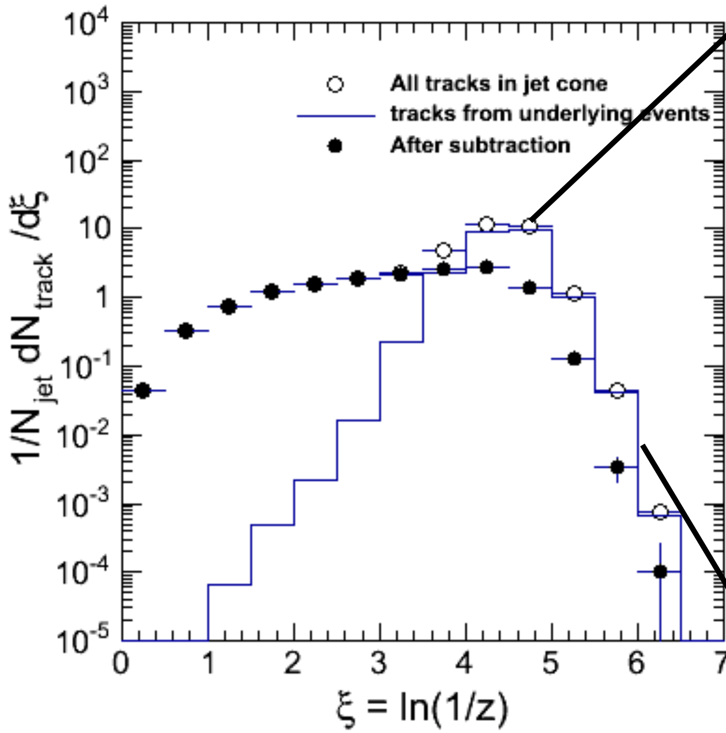
(1) Plot raw FF in jet cone

○ **All tracks in jet cone**



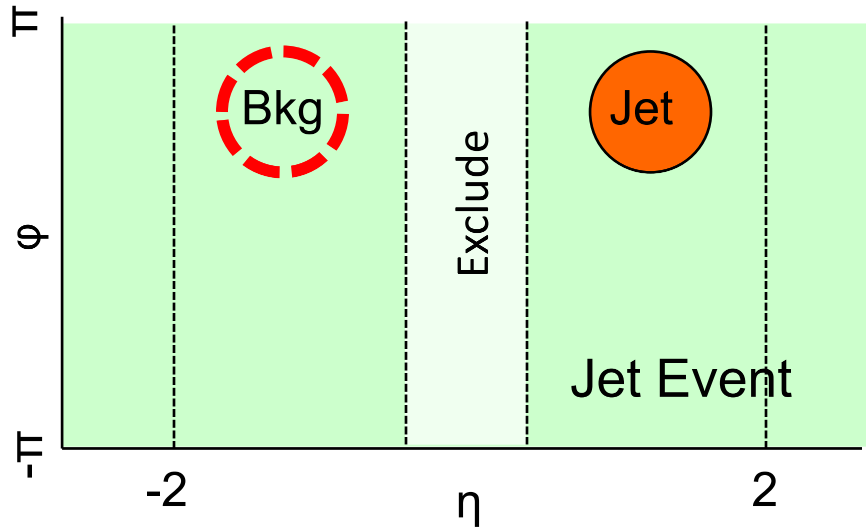


FF – underlying event subtraction



(1) Plot raw FF in jet cone

○ **All tracks in jet cone**



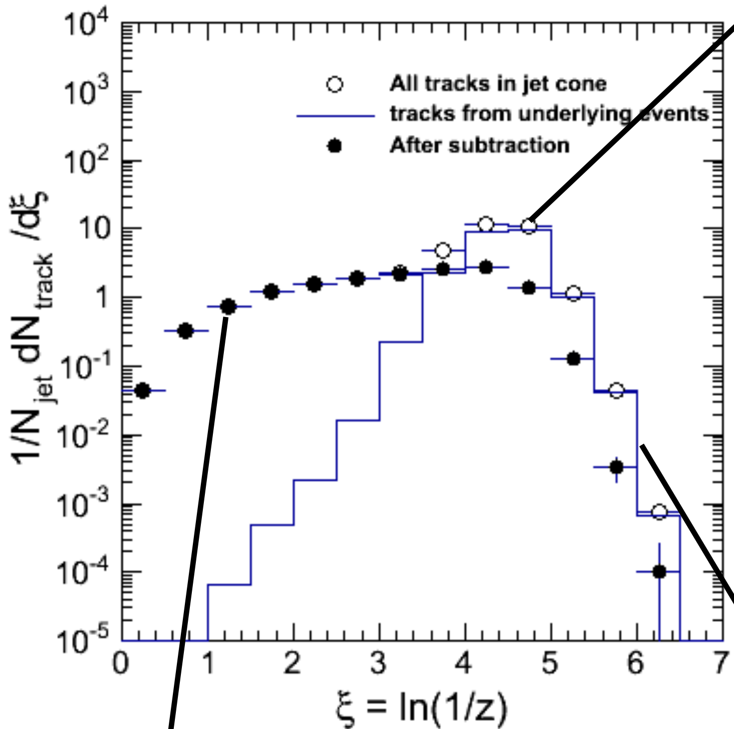
(2) Obtain FF contribution from heavy ion background using η reflected cone.

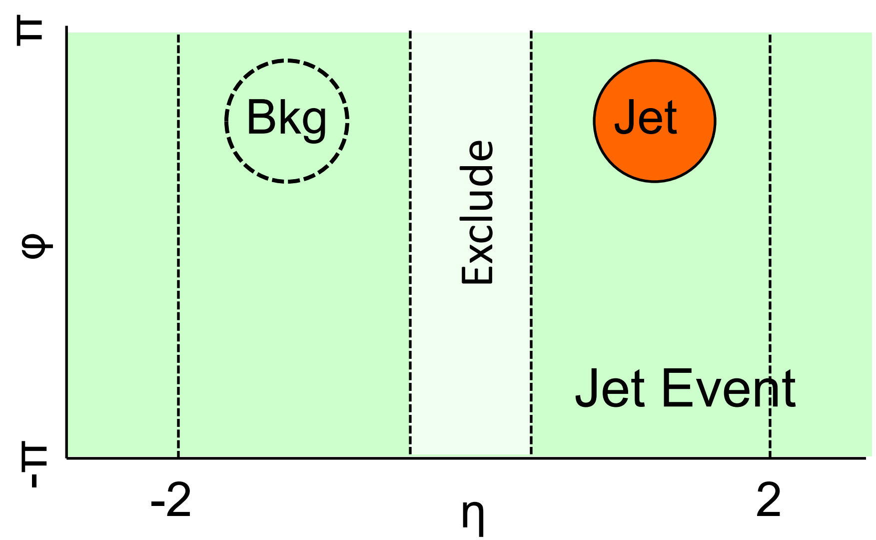
—— **tracks from underlying events**

FF – underlying event subtraction

(1) Plot raw FF in jet cone

○ **All tracks in jet cone**





(2) Obtain FF contribution from heavy ion background using η reflected cone.

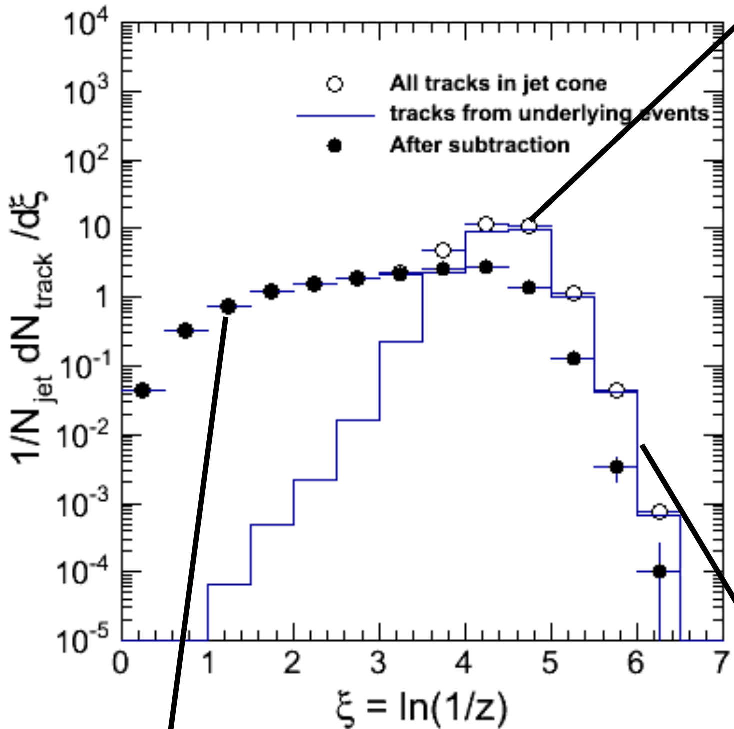
—— **tracks from underlying events**

(3) Subtract (2) from (1)

● **After subtraction**

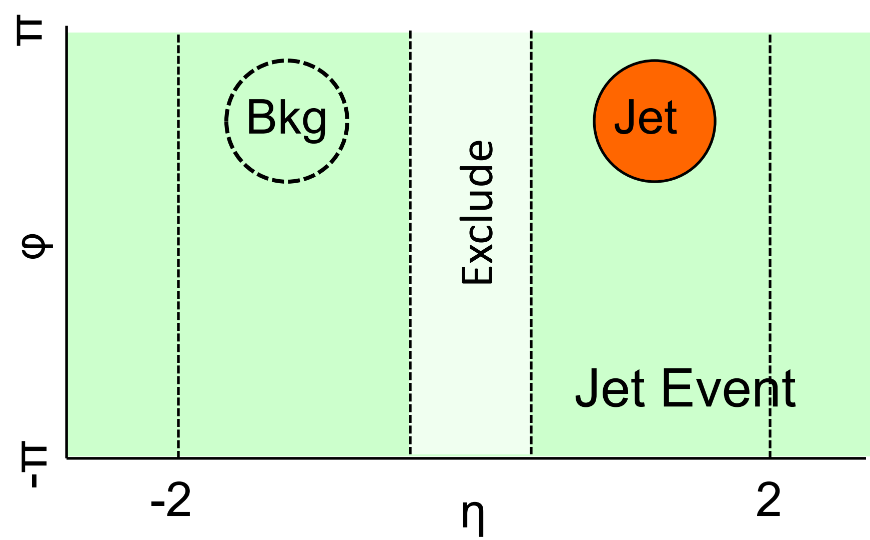
FF – underlying event subtraction

(4) Compare to pp reference (fragmentation in vacuum)



(1) Plot raw FF in jet cone

○ **All tracks in jet cone**



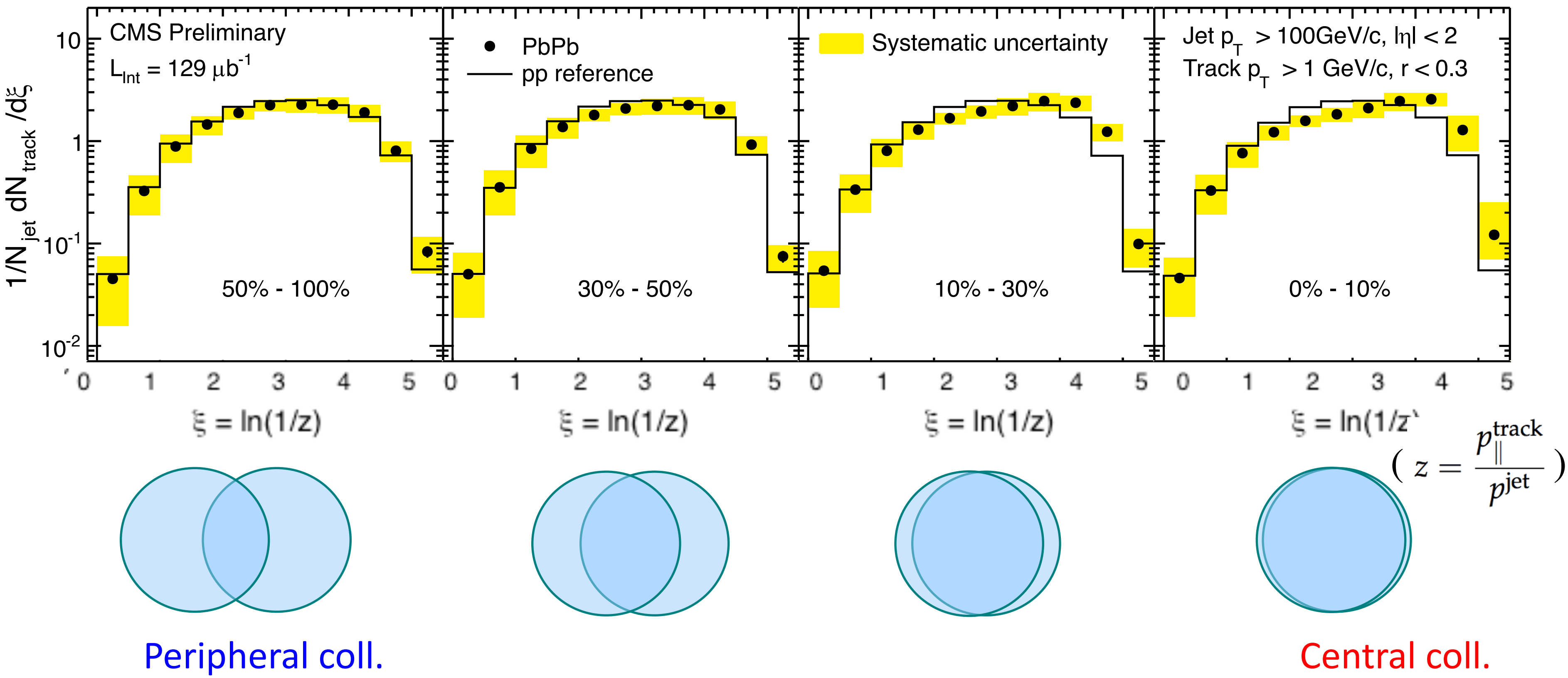
(2) Obtain FF contribution from heavy ion background using η reflected cone.

—— **tracks from underlying events**

(3) Subtract (2) from (1)

● **After subtraction**

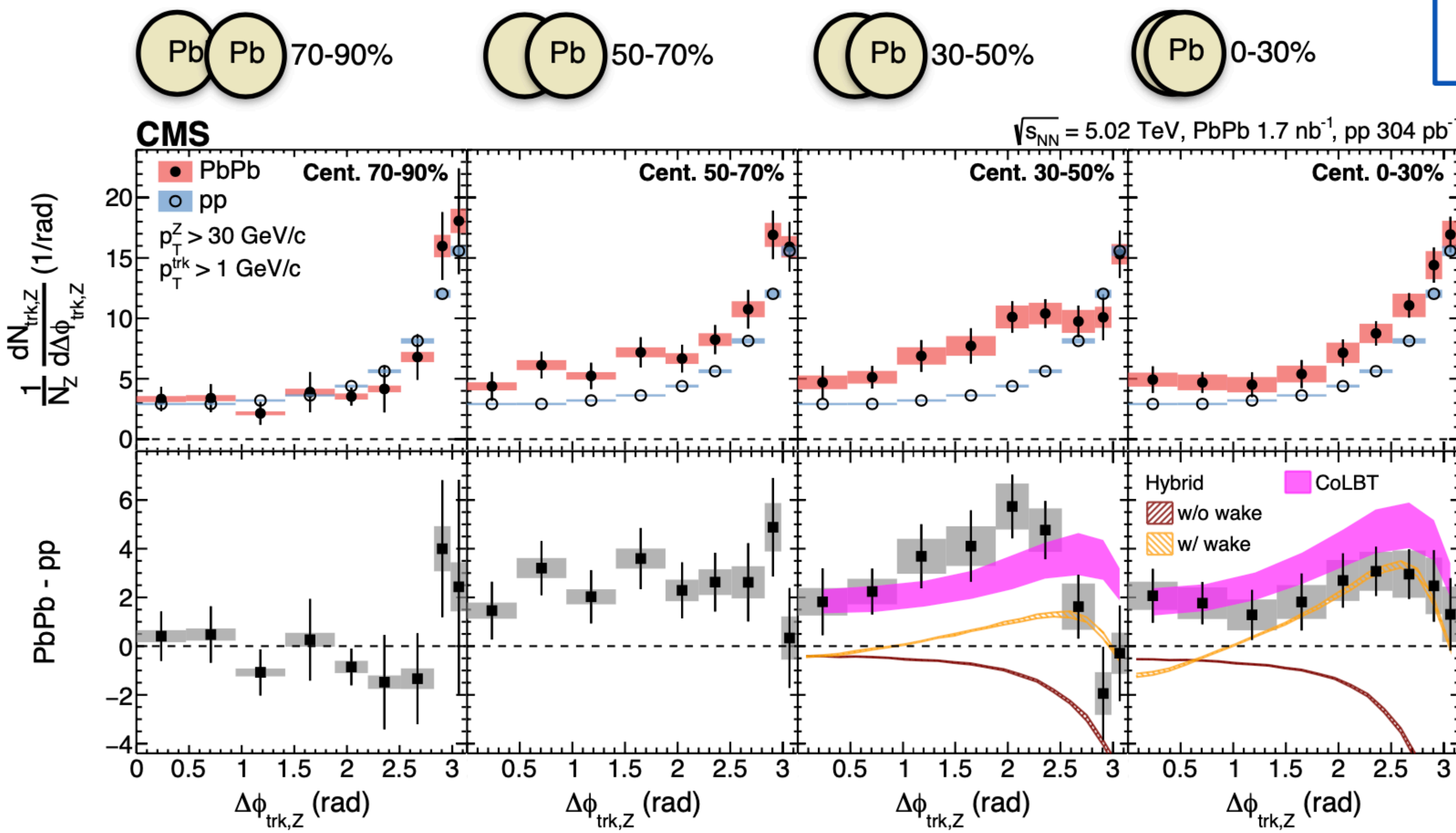
Jet Fragmentation Function



Shock wave of Z-tagged jet seen in 4π angle

PRL 128 (2022) 122301

Tues 5:10 PM
Kaya Tatar

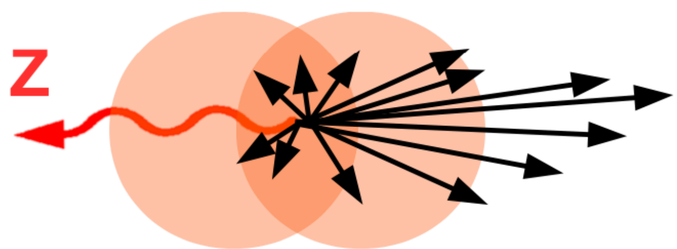


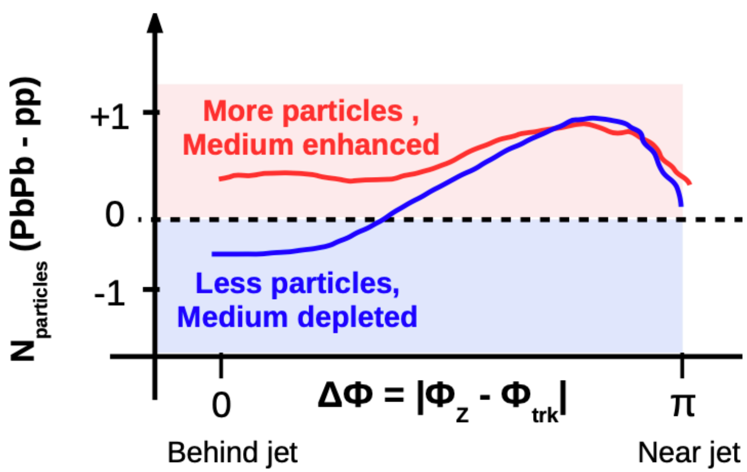
- Direction of parton's initial momentum is obtained from Z, thus allowing precise measurement of angular correlation

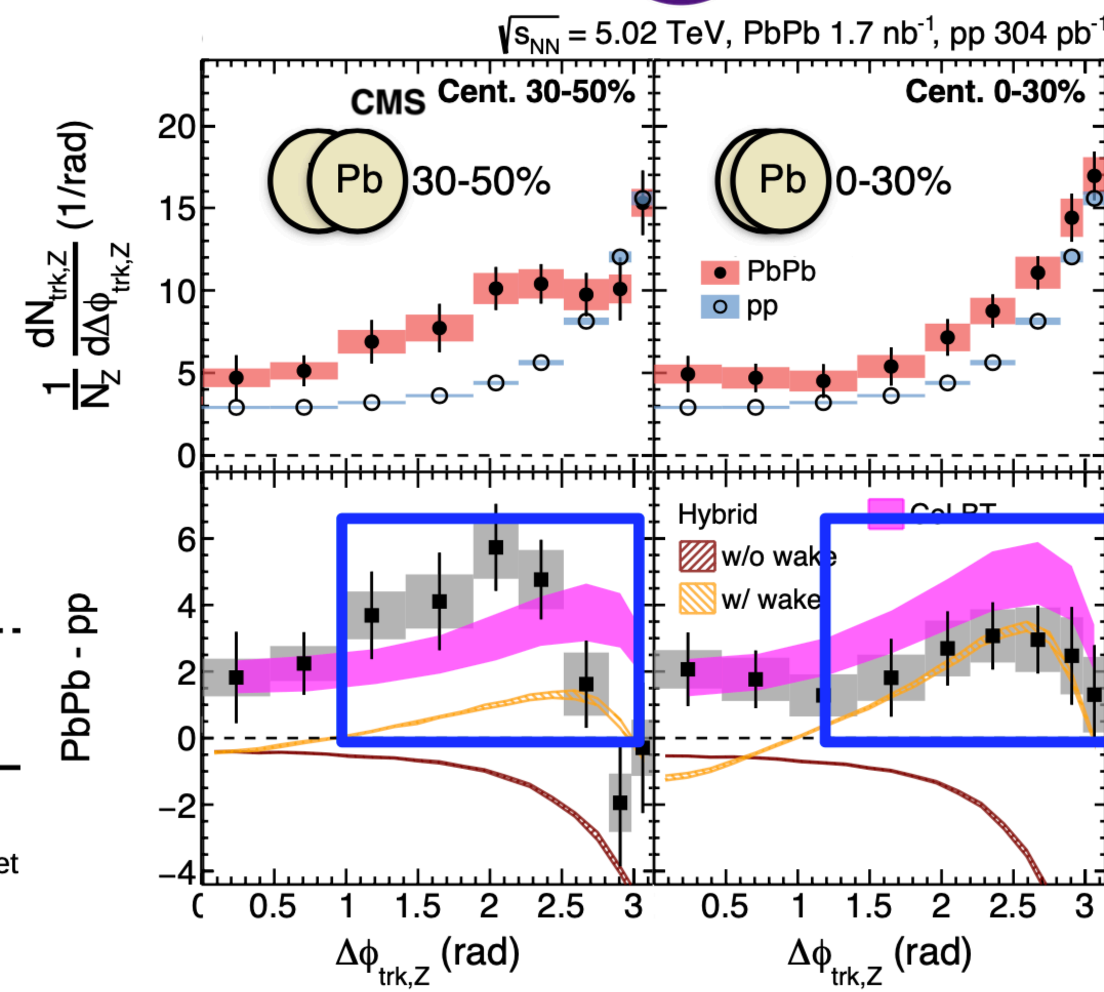
Shock wave of Z-tagged jet seen in 4π angle

PRL 128 (2022) 122301

Tues 5:10 PM
Kaya Tatar







- More particles enhanced by medium depending on $\Delta\phi$
- Provides novel constraints for modeling medium-parton interaction

Part II
Jet substructure

Science
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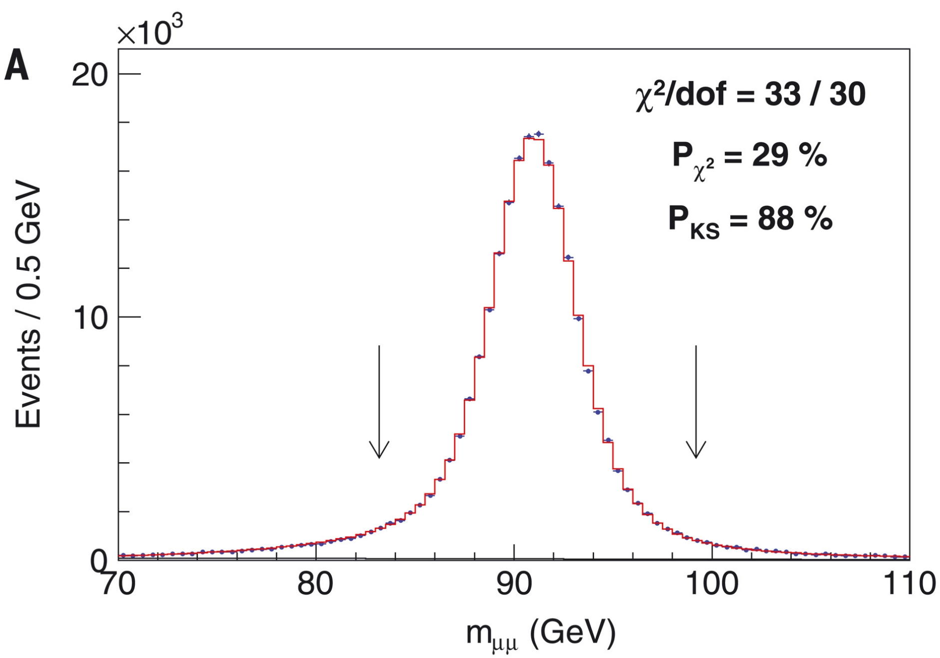
HOME > SCIENCE > VOL. 376, NO. 6589 > HIGH-PRECISION MEASUREMENT OF THE W BOSON MASS WITH THE CDF II DETECTOR

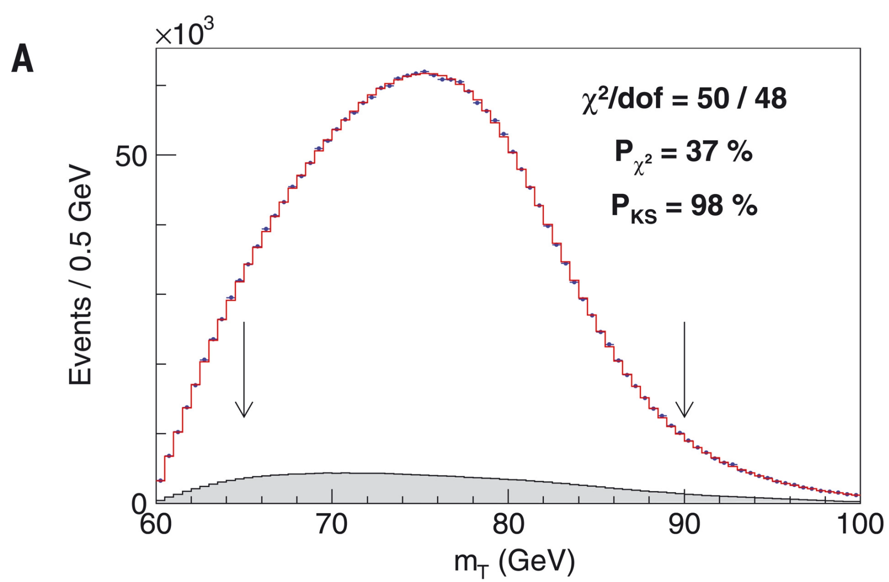
RESEARCH ARTICLE | PARTICLE PHYSICS

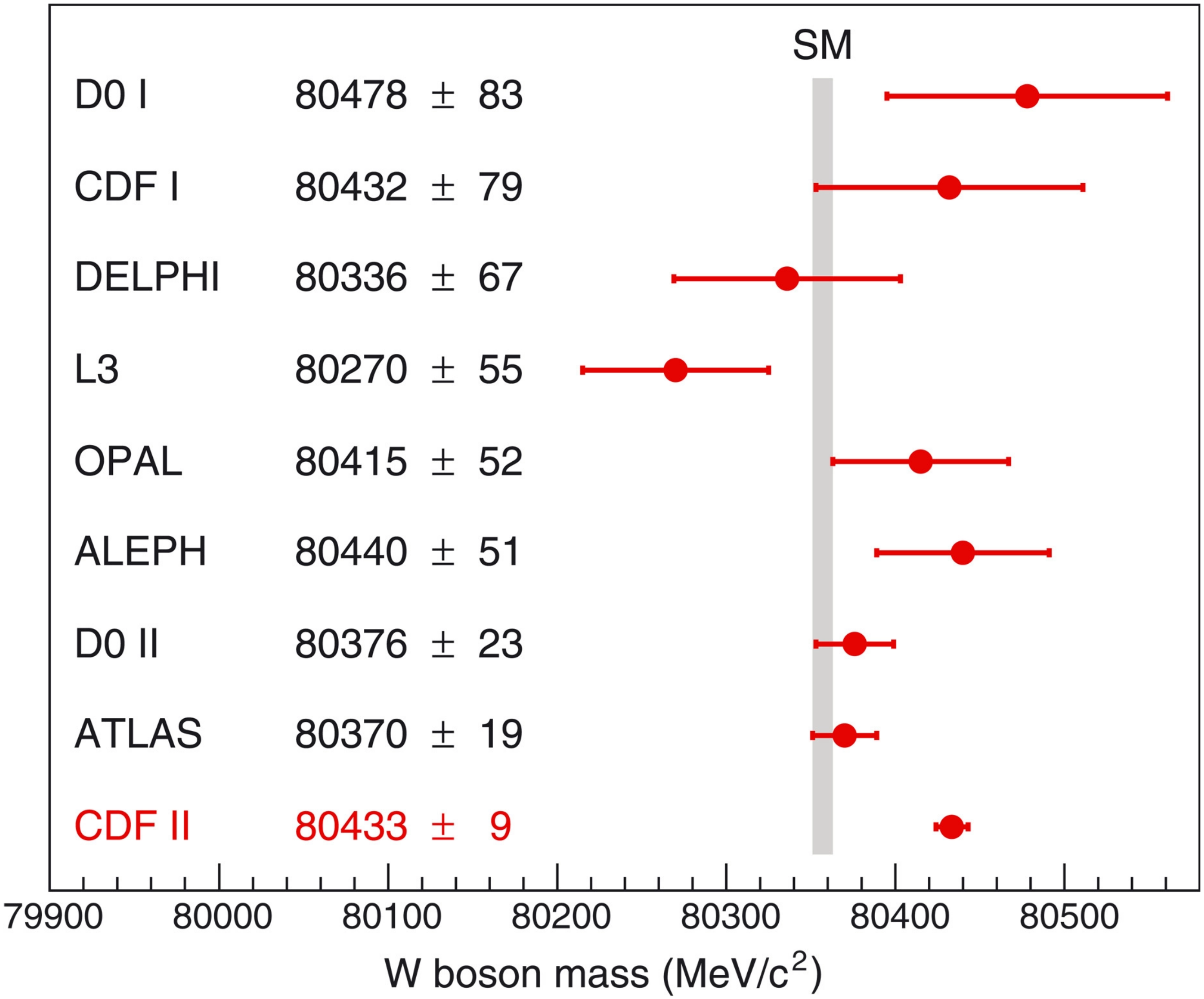
High-precision measurement of the *W* boson mass with the CDF II detector

CDF COLLABORATION†‡, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASTASSOV, A. ANNOVI, J. ANTOS, ... Show All ..., AND S. ZUCCHELLI

SCIENCE • 7 Apr 2022 • Vol 376, Issue 6589 • pp. 170-176 • DOI: 10.1126/science.abk1781






SM
D0 I 80478 ± 83
CDF I 80432 ± 79
DELPHI 80336 ± 67
L3 80270 ± 55
OPAL 80415 ± 52
ALEPH 80440 ± 51
D0 II 80376 ± 23
ATLAS 80370 ± 19
CDF II 80433 ± 9
79900
80000
80100
80200
80300
80400
80500
W boson mass (MeV/c²)

High Energy Physics – Phenomenology

[Submitted on 8 Apr 2022]

The W boson Mass and Muon $g-2$: Hadronic Uncertainties or New Physics?

Peter Athron, Andrew Fowlie, Chih-Ting Lu, Lei Wu, Yongcheng Wu, Bin Zhu

There are now two single measurements of precision observables that have major anomalies in the Standard Model: the recent CDF measurement of the W mass shows a 7σ deviation and the Muon $g-2$ experiment at FNAL confirmed a long-standing anomaly, implying a 4.2σ deviation. Doubts regarding new physics interpretations of these anomalies could stem from uncertainties in the common hadronic contributions. We demonstrate that the two anomalies pull the hadronic contributions in opposite directions by performing electroweak fits in which the hadronic contribution was allowed to float. The fits show that including the $g-2$ measurement worsens the tension with the CDF measurement and conversely that adjustments that alleviate the CDF tension worsen the $g-2$ tension beyond 5σ. This means that if we adopt the CDF W boson measurement, the case for new physics is inescapable regardless of the size of the SM hadronic contributions. Lastly, we demonstrate that a mixed scalar leptoquark extension of the

High Energy Physics – Phenomenology

[Submitted on 8 Apr 2022 (v1), last revised 13 Apr 2022 (this version, v2)]

Explaining The Muon $g-2$ Anomaly and New CDF II W-Boson Mass in the Framework of (Extra)Ordinary Gauge Mediation

Xiao Kang Du, Zhuang Li, Fei Wang, Ying Kai Zhang

The SUSY contributions Δa_μ to muon $g-2$ anomaly can not even reach 3σ in ordinary gauge mediated SUSY breaking (GMSB) scenarios because of the strong correlations between the colored sparticle masses and the uncolored EW sparticle masses. An interesting extension to GMSB is the (Extra)Ordinary Gauge Mediation (EOGM), which can relax the correlations between squarks and sleptons with non-universal choices for $N_{eff,3}$ and $N_{eff,2}$. We find that EOGM scenarios with $N_{eff,3} \ll N_{eff,2}$ can explain the muon $g-2$ anomaly within 3σ range, however can not explain the new W-boson mass by CDF II. We also propose to extend EOGM with additional adjoint Σ_8 and Σ_3 messengers at a high scale of order 1.0×10^{14} GeV, which can shift the gauge coupling unification scale to the string scale. Such EOGM extension scenarios with adjoint messengers could spoil the unwanted gaugino mass ratios and give large SUSY contributions to Δa_μ for $N_{eff,3} \ll N_{eff,2}$, which can explain the muon $g-2$ anomaly within 1σ. Besides, because of the large messenger scale of order 1.0×10^{14} GeV, such scenarios will in general lead to large $|A_t|$ at the EW scale, which can accommodate the 125 GeV Higgs easily and possibly lead to smaller EWFT as well as BGFT. We discuss the possibility to explain the new CDF II W-boson mass in the GMSB-type framework at one-loop level. We find that SUSY contributions may marginally account for the new W-boson mass in the region with both sleptons and wino being light.

High Energy Physics – Phenomenology

[Submitted on 8 Apr 2022 (v1), last revised 15 Apr 2022 (this version, v2)]

Low energy SUSY confronted with new measurements of W-boson mass and muon g-2

Jin Min Yang, Yang Zhang

The new CDF II measurement of W-boson mass shows a 7σ deviation from the Standard Model (SM) prediction, while the recent FNAL measurement of the muon $g-2$ shows a 4.2σ deviation (combined with the BNL result) from the SM. Both of them strongly indicate new physics beyond the SM. In this work we study the implication of both measurements on low energy supersymmetry. With an extensive exploration of the parameter space of the minimal supersymmetric standard model (MSSM), we find that in the parameter space allowed by current experimental constraints from colliders and dark matter detections, the MSSM can simultaneously explain both measurements at 2σ level. The favored parameter space, characterized by a compressed spectrum between bino, wino and stau, with the stop being around 1 TeV, may be covered in the near future LHC searches.

Comments: 16 pages, 4 figures, 3 tabels, Refs and more samples are added, the benchmark point is updated
Subjects: High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:2204.04202 [hep-ph]
(or arXiv:2204.04202v2 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2204.04202

Submission history

From: Yang Zhang [view email]

High Energy Physics – Phenomenology

[Submitted on 11 Apr 2022]

A Model of Vector-like Leptons for the Muon $g-2$ and the W Boson Mass

Hyun Min Lee, Kimiko Yamashita

We consider a simple extension of the Standard Model (SM) with a vector-like lepton and a local $U(1)'$ symmetry, motivated by the recent experimental anomalies in the muon $g-2$ and the W boson mass. The $U(1)'$ symmetry is spontaneously broken by the VEVs of the dark Higgs scalar and the second Higgs doublet, giving rise to the mixing between the muon and the vector-like lepton. As a result, we obtain the desirable corrections to the muon $g-2$ and the W boson mass simultaneously, dominantly due to the Z' gauge interactions. We also discuss the consistency of the model with the Z boson decay width and the Higgs couplings.

Comments: 14 pages, 2 figures
Subjects: High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:2204.05024 [hep-ph]
(or arXiv:2204.05024v1 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2204.05024

Submission history

From: Hyun Min Lee [view email]

arXiv > hep-ph > arXiv:2204.03996

High Energy Physics – Phenomenology

[Submitted on 8 Apr 2022]

The W boson Mass and Muon $g-2$: Hadronic Uncertainties or New Physics?

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High Energy Physics – Phenomenology

[Submitted on 8 Apr 2022 (v1), last revised 13 Apr 2022 (this version, v2)]

Explaining The Muon $g-2$ Anomaly and New CDF II W-Boson Mass in the Framework of (Extra)Ordinary Gauge

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High-precision measurement of the W boson mass with the CDF II detector

CDF Collaboration • T. Aaltonen (Helsinki U. and Helsinki Inst. of Phys.) Show All(398)

Apr 8, 2022

7 pages

Published in: *Science* 376 (2022) 6589, 170-176

Published: Apr 8, 2022

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Report number: FERMILAB-PUB-22-254-PPD

Experiments: FNAL-E-0830

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Comments: 16 pages, 4 figures, 3 tabels, Refs and more samples are added, the benchmark point is updated

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(or arXiv:2204.04202v2 **[hep-ph]** for this version)

https://doi.org/10.48550/arXiv.2204.04202

Submission history

From: Yang Zhang [view email]

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References & Citations

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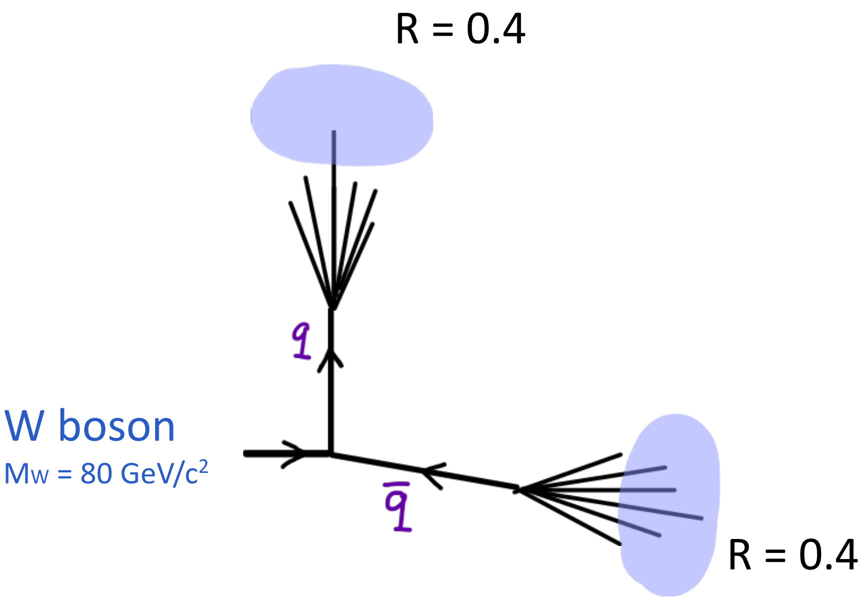
https://doi.org/10.48550/arXiv.2204.05024

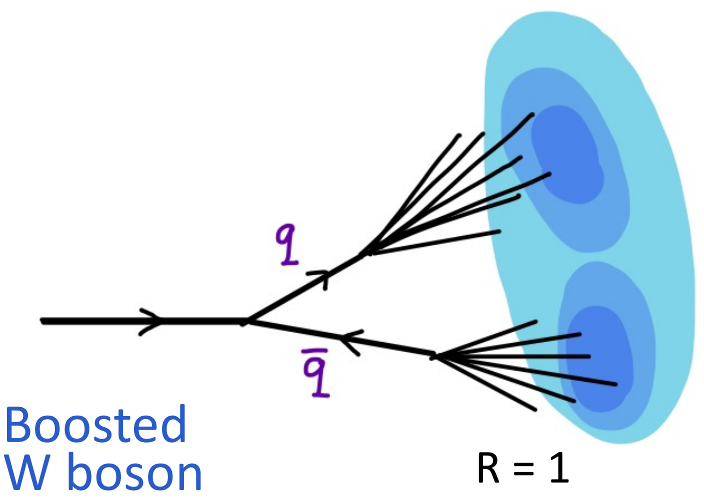
Submission history

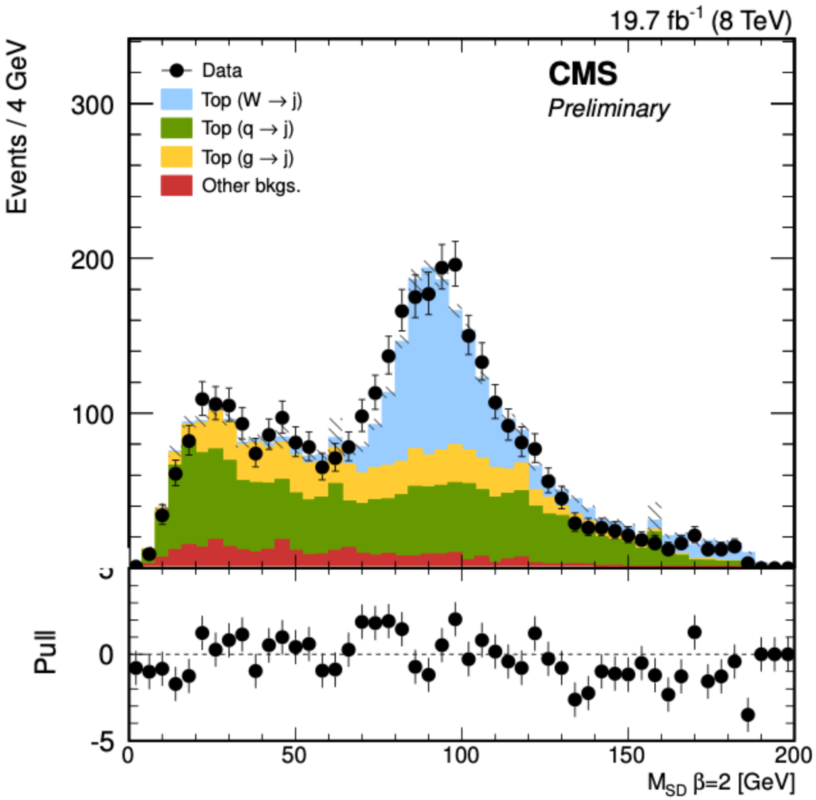
From: Hyun Min Lee [view email]

W jet before LHC era



W jet today





High p_T W bosons merges two jets forming one **fat jet**
Should cope with UE background

- Development of jet grooming
- e.g. pruning, trimming, MDT, SoftDrop …

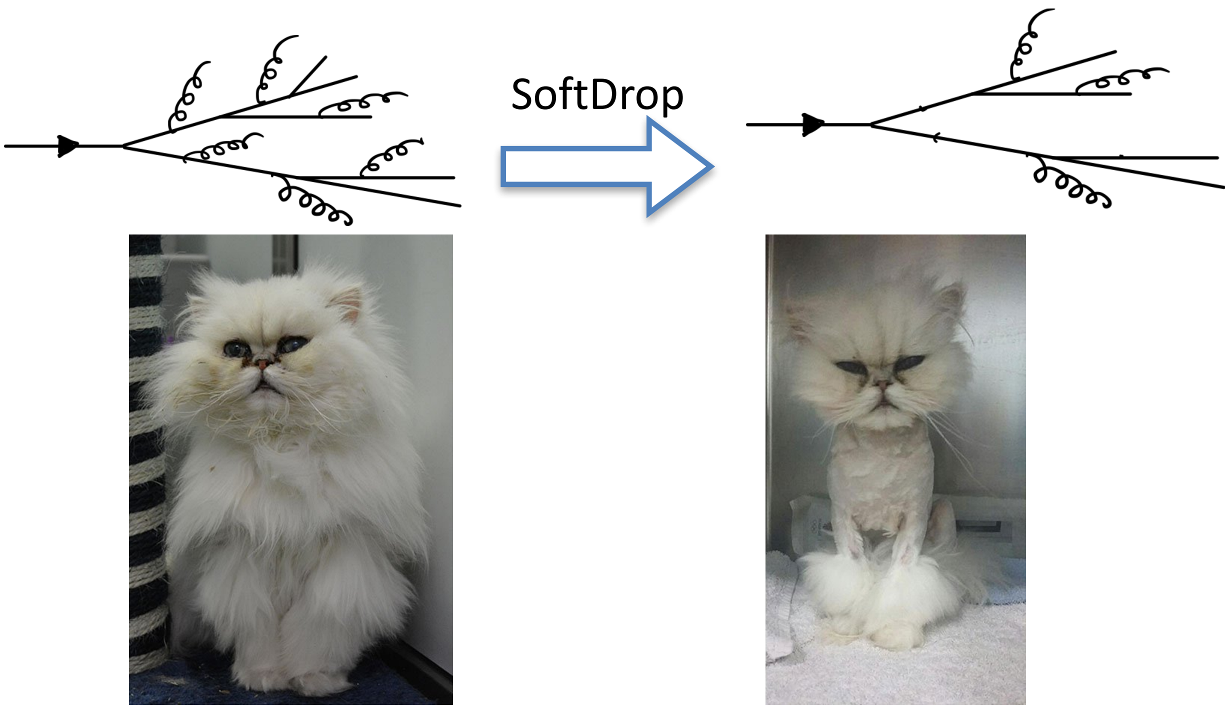
Jet grooming for QCD jets

Jet grooming is useful to remove soft divergences, thus converges the experiments to analytic calculations (e.g. NLLO)

Useful for study of jet substructure

SoftDrop (Larkoski et al)

- Sudakov safe and insensitive to α_s



Before

After

SoftDrop Example

Jet from PYTHIA

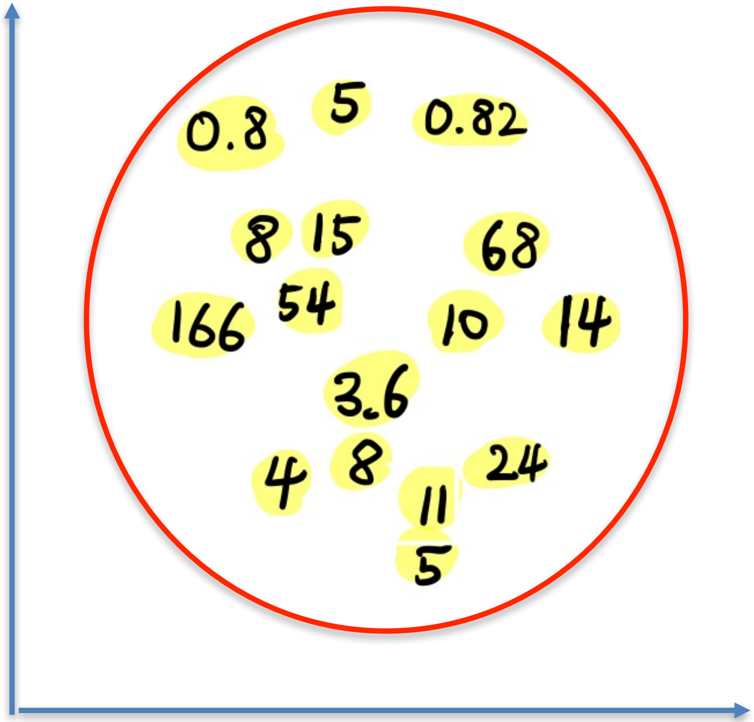
- p_T = 400 GeV
- 15 constituent particles

Softdrop condition :

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

Typically z=0.1, ß = 0

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > 0.1$$

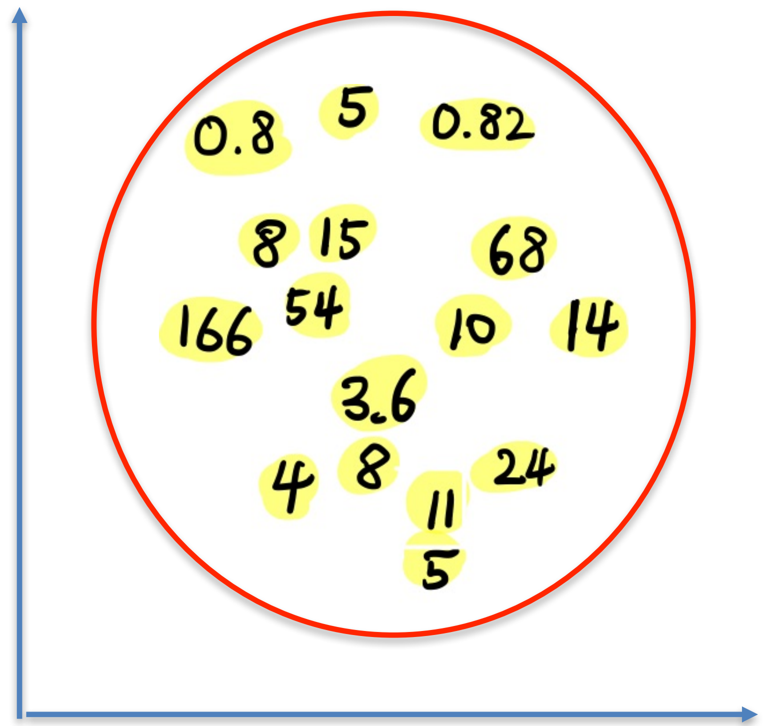


Numbers mean the p_T of each constituent (GeV)

SoftDrop Example

Step 1
Recluster constituents with Cambridge/Aachen algorithm.

C/A algo merges the closest constituents regardless the p_T



SoftDrop Example

Step 1

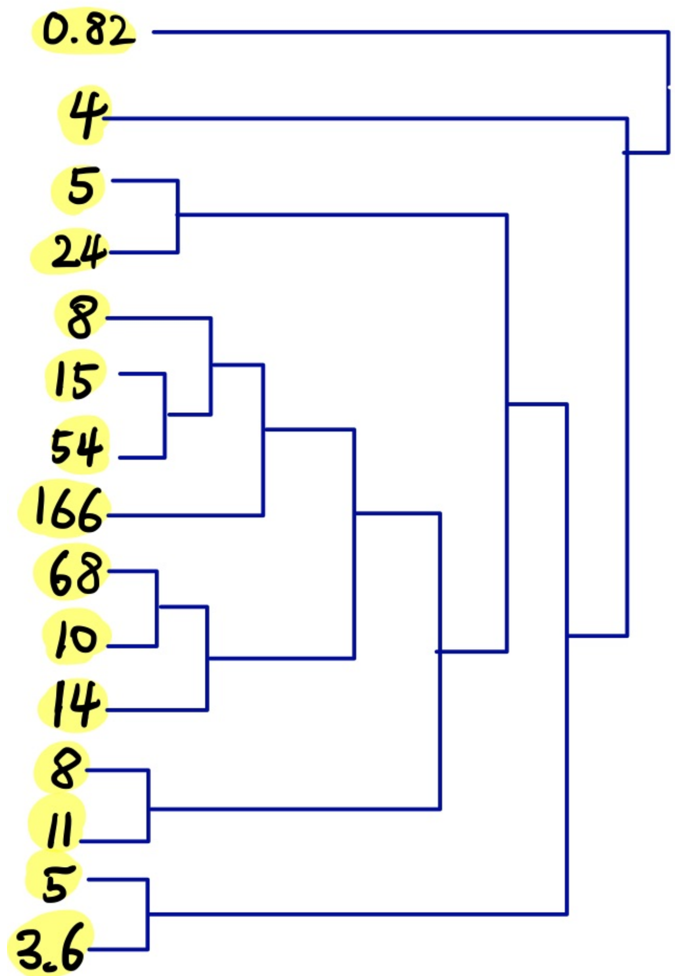
Recluster constituents with Cambridge/Aachen algorithm.

C/A algo merges the closest constituents regardless of p_T.

This purely **geographical** clustering makes the tree of

2 -> 1 branches.

It also represents the chronicle order of jet branching



Early nodes

Latest node

C/A clustering order

SoftDrop Example

Step 2

In order from latest to earliest nodes, check SoftDrop condition

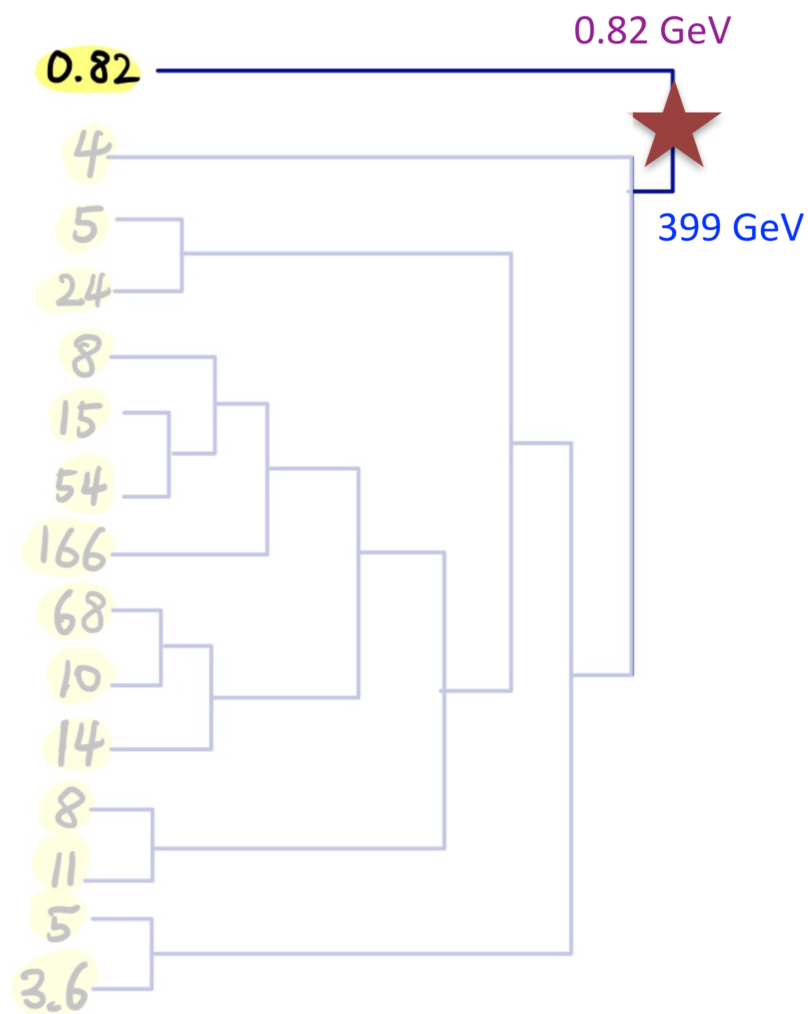
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > 0.1$$

In this iteration,

p_T1 = 0.82 GeV

p_T2 = 399 GeV

=> SoftDrop condition fails , and 0.82 GeV branch is dropped

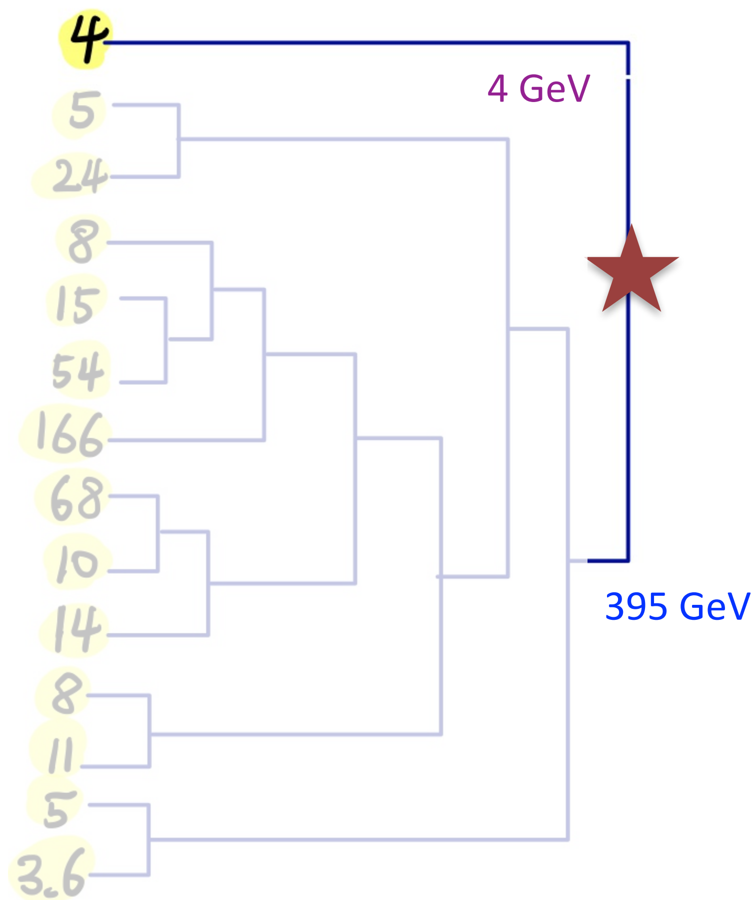


SoftDrop Example

Step 2
Check the SoftDrop condition at the joints, in the inverse order of re-clustering

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > 0.1$$

In this iteration,
p_T1 = 4 GeV
p_T2 = 395 GeV
=> SoftDrop condition fails , and the branch is dropped



SoftDrop Example

Step 2

Check the SoftDrop condition at the joints, in the inverse order of re-clustering

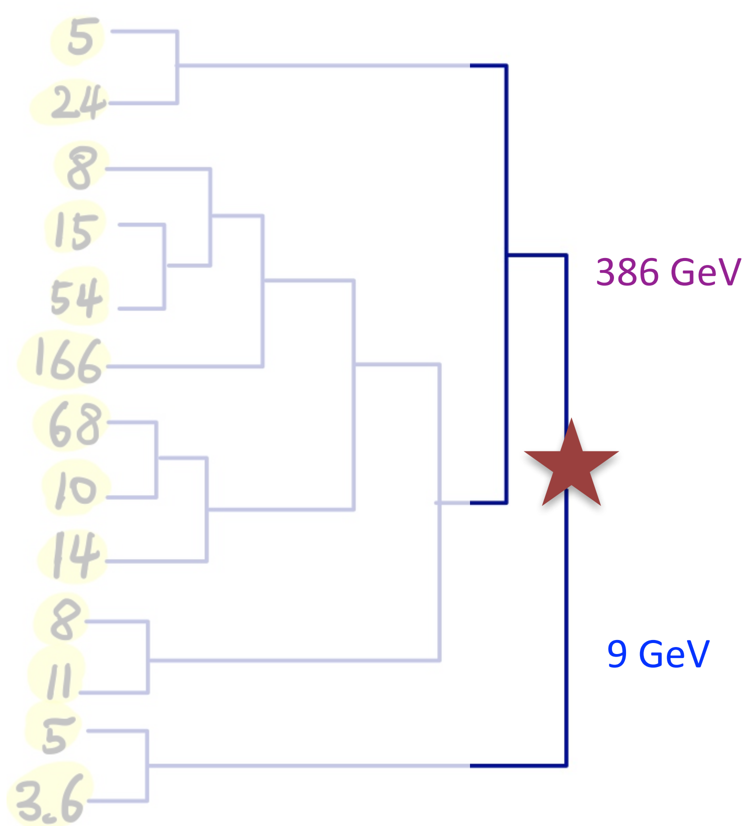
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > 0.1$$

In this iteration,

p_T1 = 9 GeV

p_T2 = 386 GeV

=> SoftDrop condition fails , and the branch is dropped

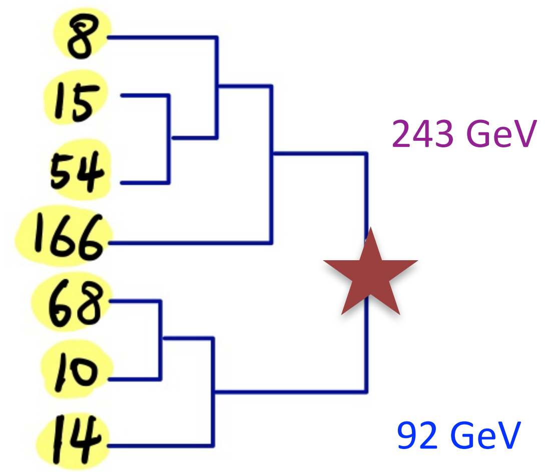


SoftDrop Example

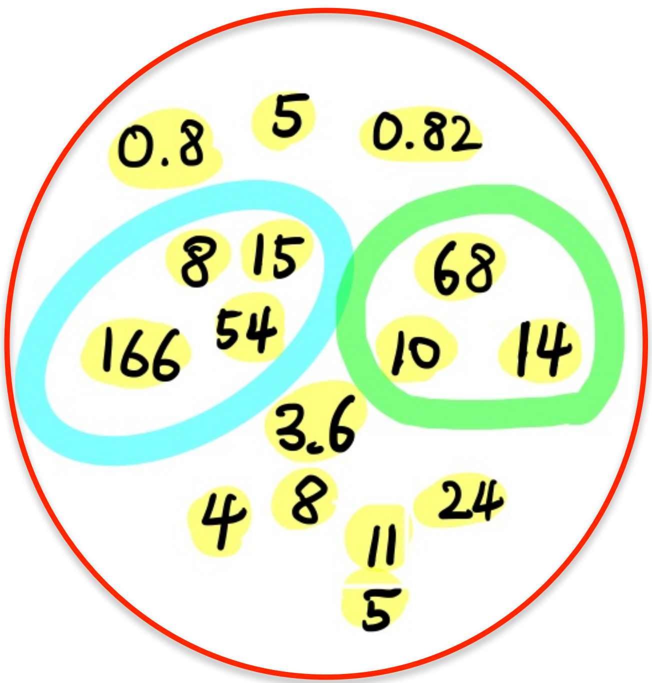
Step 2
Check the SoftDrop condition at the joints, in the inverse order of re-clustering

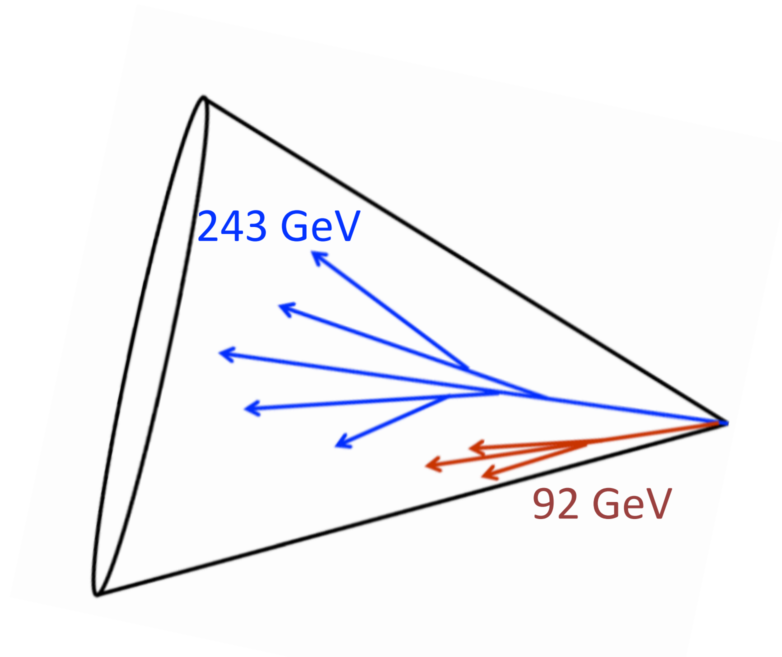
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > 0.1$$

In this iteration,
p_T1 = 92 GeV
p_T2 = 243 GeV
=> SoftDrop condition is met, thus Iteration ends.



SoftDrop Example





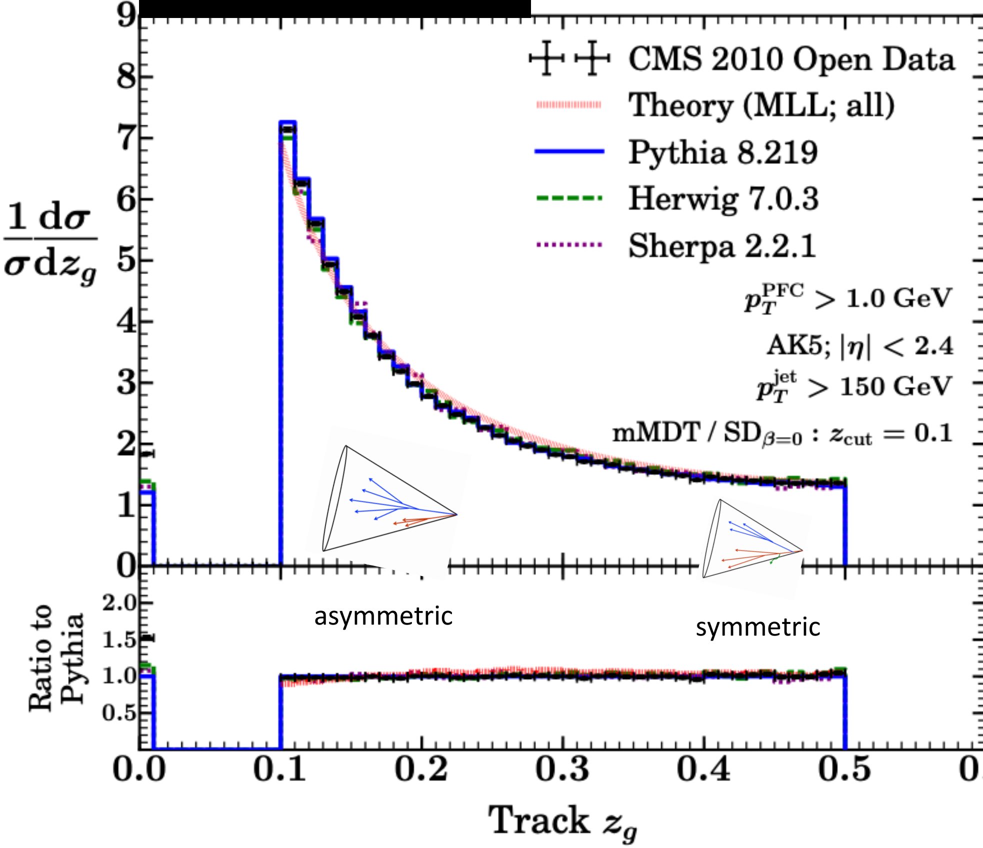
$$z_g = \frac{92}{243 + 92} = 0.27$$

Jet splitting function z_g is an important substructure variable

provides the earliest fragmentation of jet

Jet splitting function in pp data

PRL 119.132003



$$z_g = \frac{p_{T,2}}{p_{T,1} + p_T}$$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Editors' Suggestion

Exposing the QCD Splitting Function with CMS Open Data

Andrew Larkoski, Simone Marzani, Jesse Thaler, Aashish Tripathee, and Wei Xue

Phys. Rev. Lett. **119**, 132003 – Published 26 September 2017

QCD Splitting Function using CMS Open Data

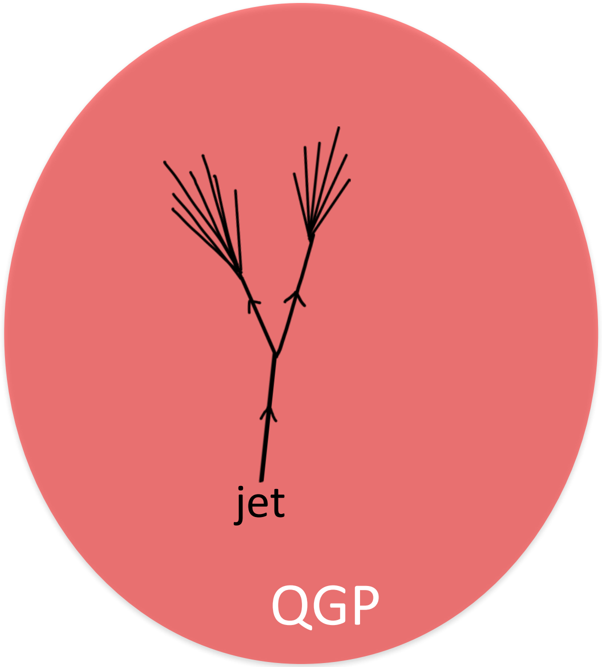
SoftDrop results in data and various models converges for any jet splitting configuration!

Gluon radiation mechanism induced by QGP

First splitting happens

before the jet escapes the QGP

Then, would QGP *see* this splitting?



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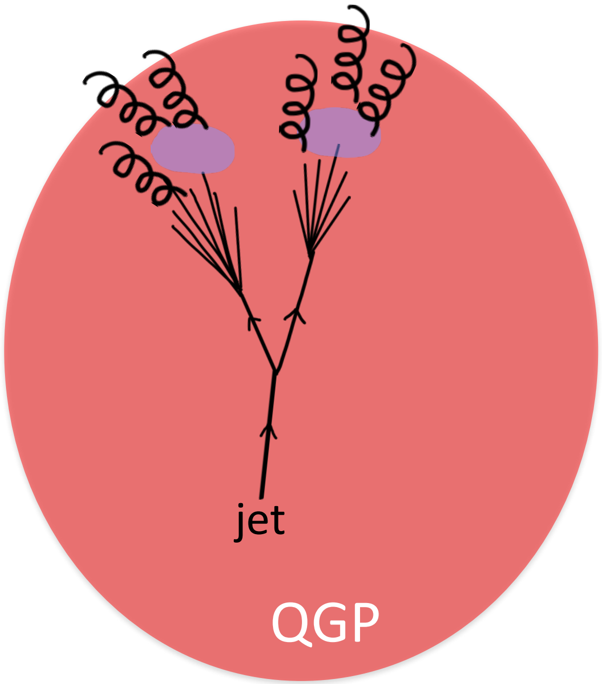

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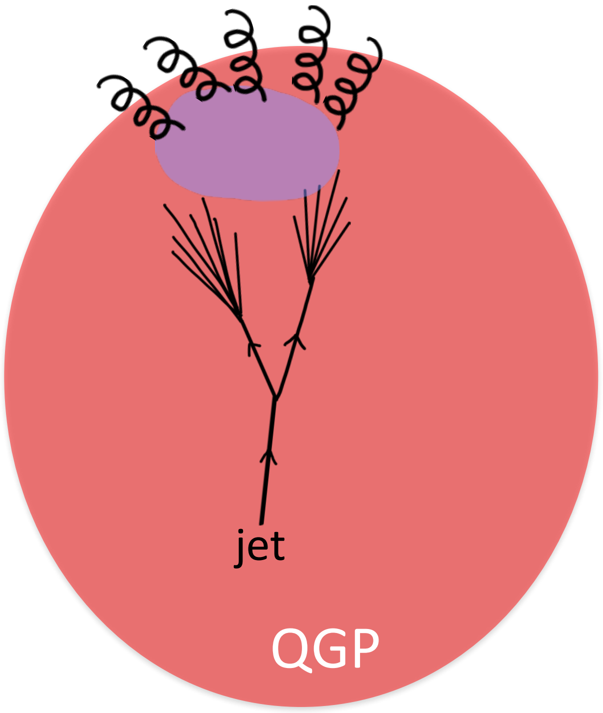

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PLB 725 (2013), 357 Casalderre-Solana et al.

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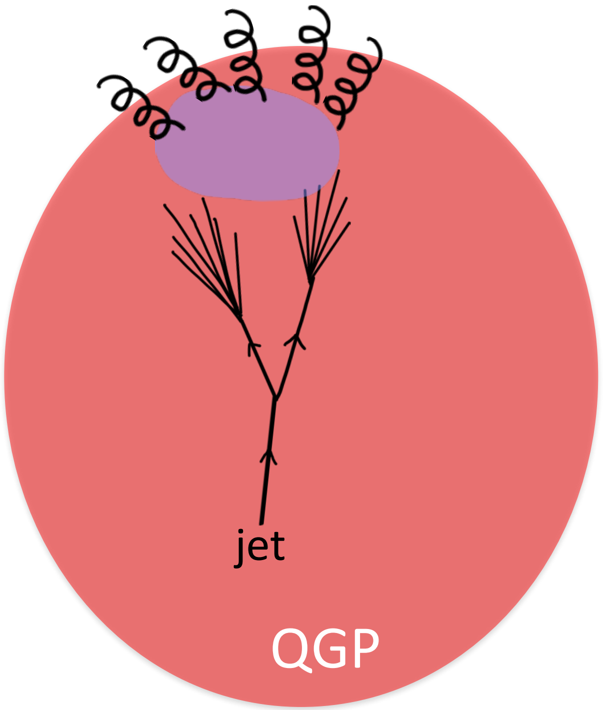


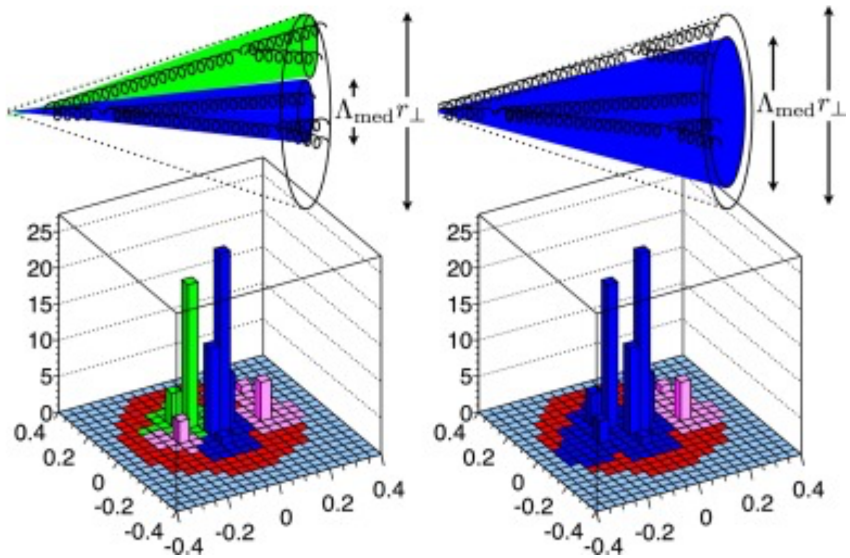
In the *antenna radiation picture*, the resolution scale of gluon emitter is determined by the medium properties

If medium can resolve splitting of sub-jets, the medium-induced radiation comes from two emitters

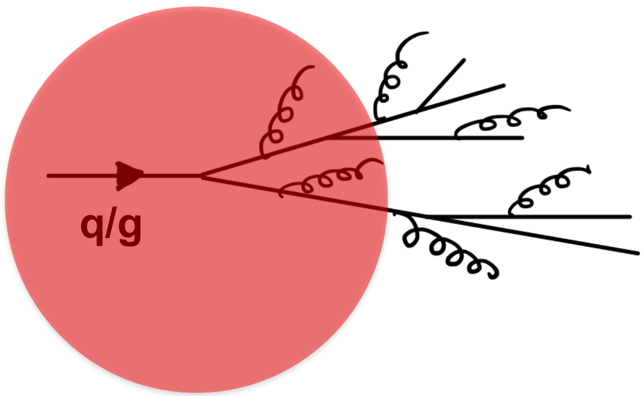
PLB 725 (2013), 357 Casalderre-Solana et al.

Quenching can modify jet substructure

arxiv1210.7765



Loss of coherence reduces the correlation between subjets
—> Suppression would modify the jet splitting function



Radiation of gluons induced by QGP modifies the virtuality of jet
—> would modify jet mass

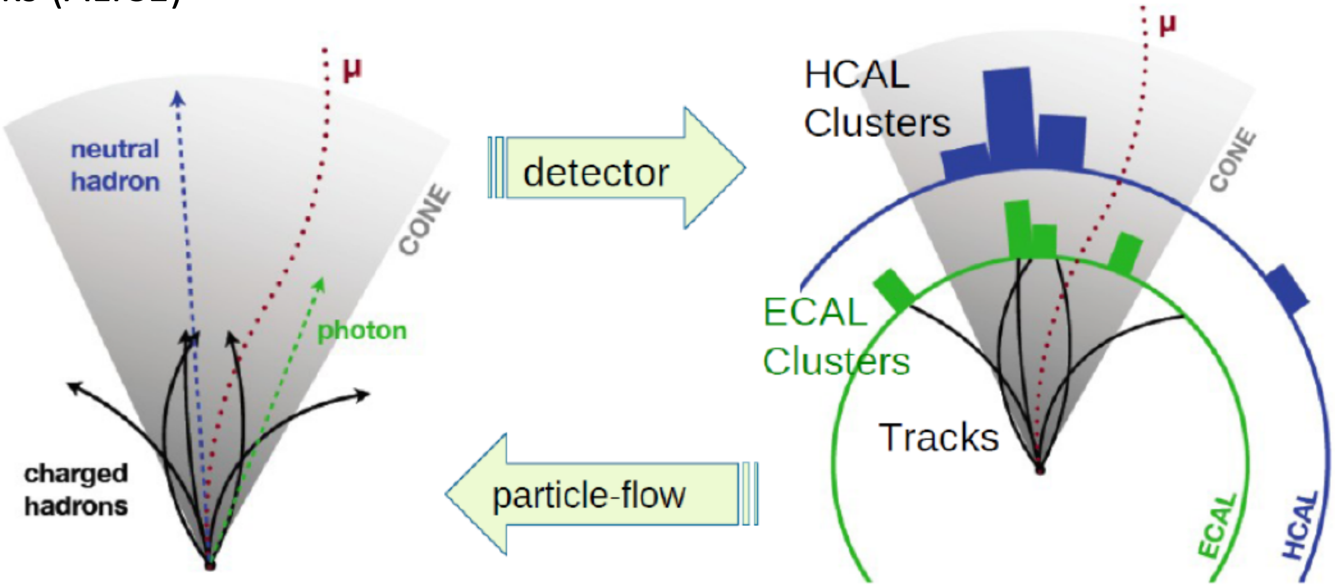
Challenge in heavy ion experiment

Large UE background

- Should subtract up to 150 GeV for a R=0.4 cone
- Should subtract up to 100 particles
- Particle-level subtraction is necessary instead of cone-integrated one
- **Constituent subtraction** algorithm can solve this problem

Reclustering in Softdrop requires high spatial resolution of constituents

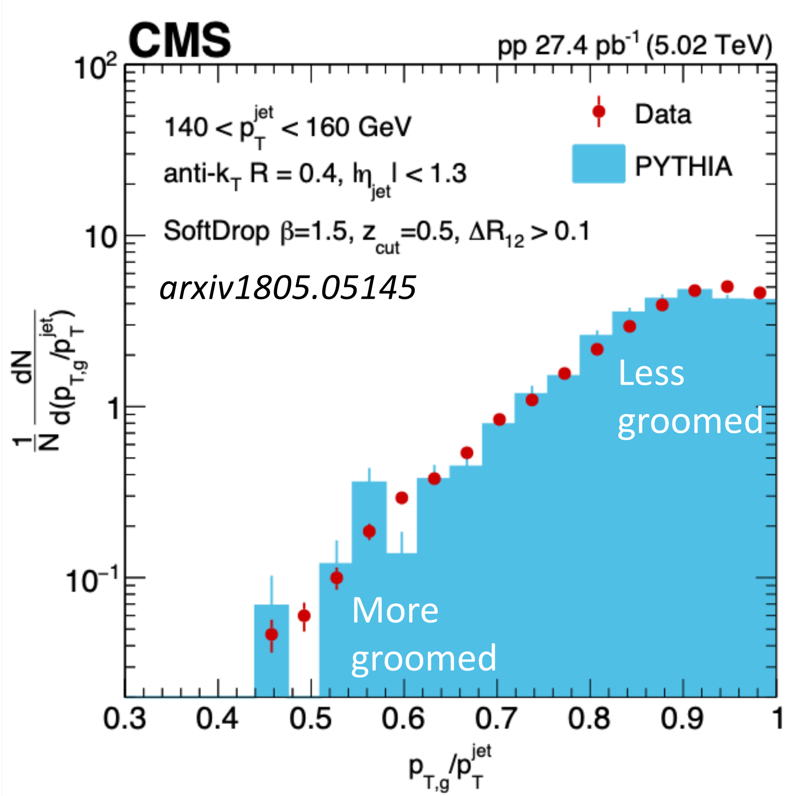
- ParticleFlow (CMS)
- Tracks (ALICE)

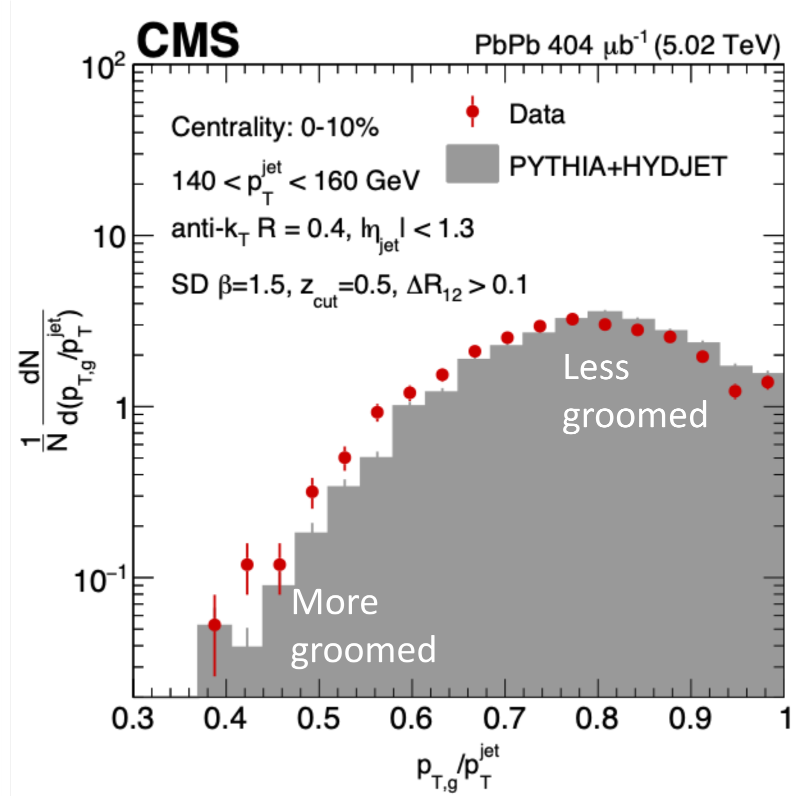


ParticleFlow algorithm in CMS

SoftDrop performance in CMS framework

Distribution of z_g in MC and data



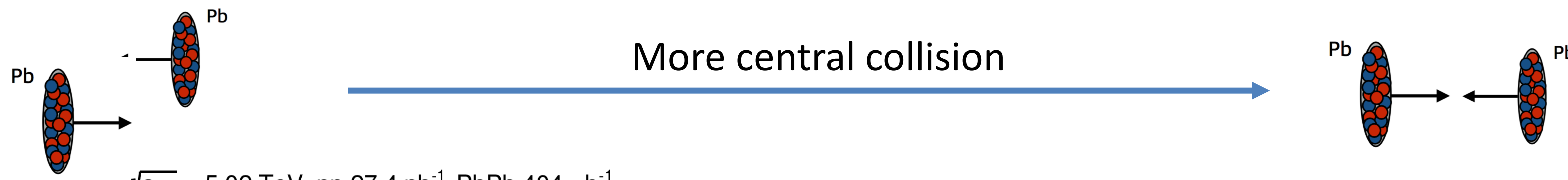


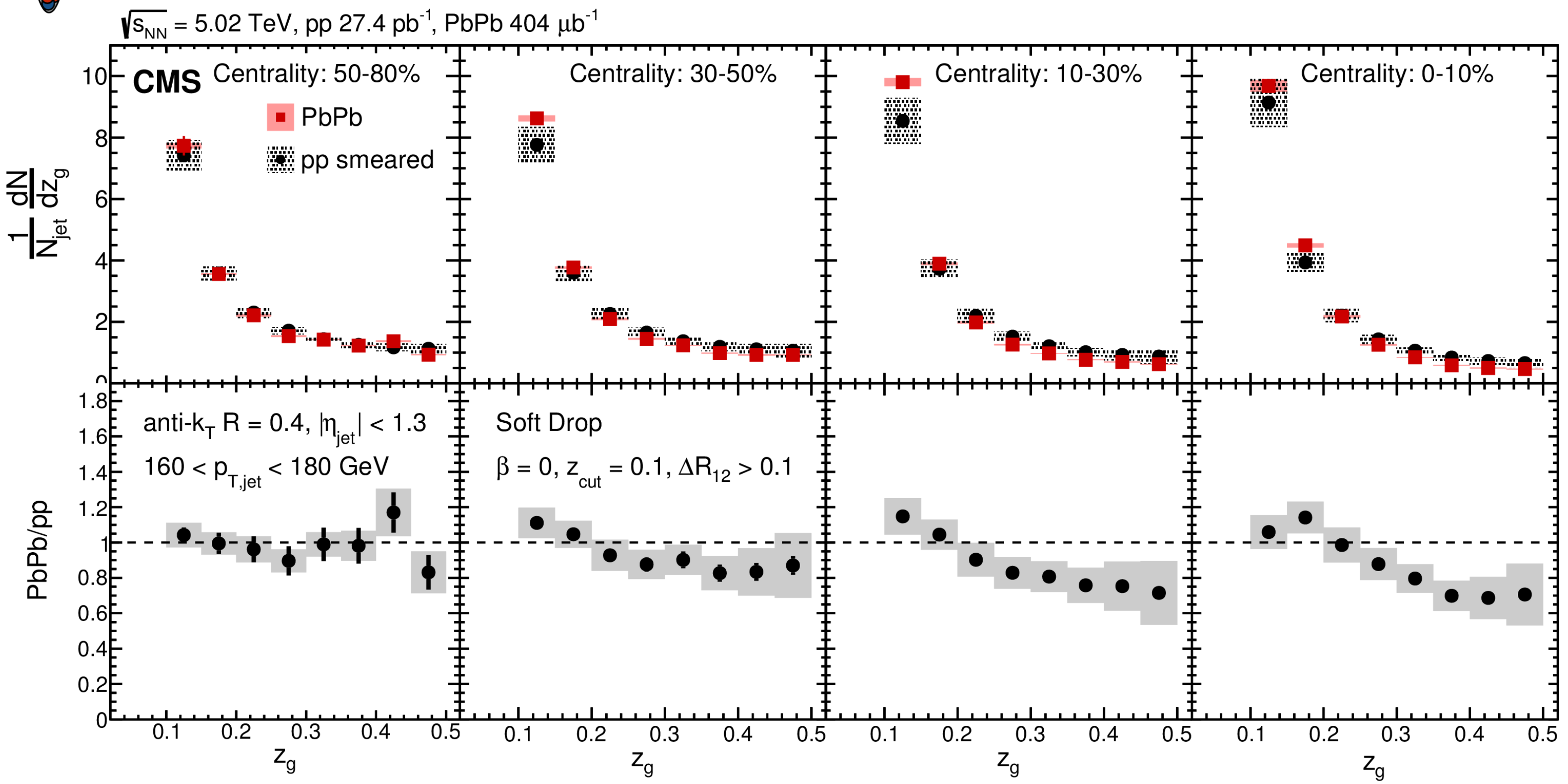
pp data vs MC

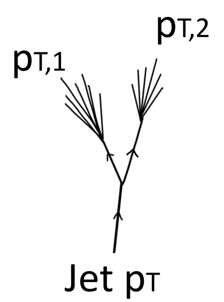
PbPb data vs MC

For PbPb case, the peak is shifted and smeared by resolution, but the simulation reproduces the data well

Jet splitting function in PbPb vs pp (CMS)







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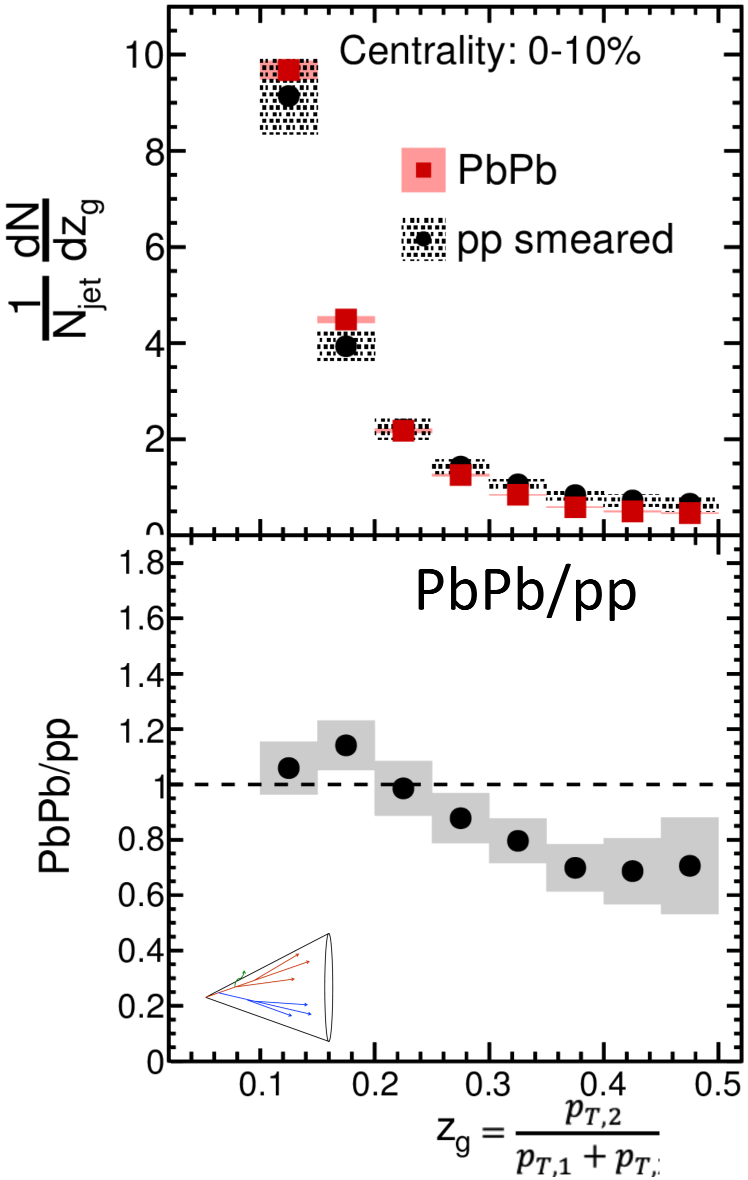
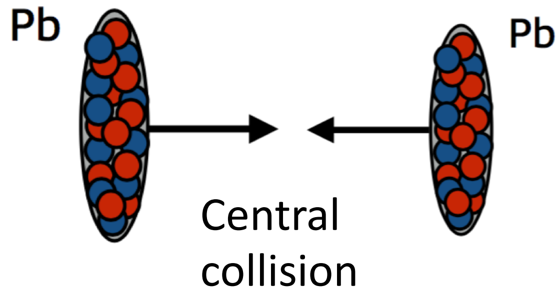
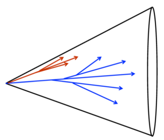




The subjet pairs became more imbalanced in central PbPb collisions.

QGP can recognize the splitting pattern of jets!



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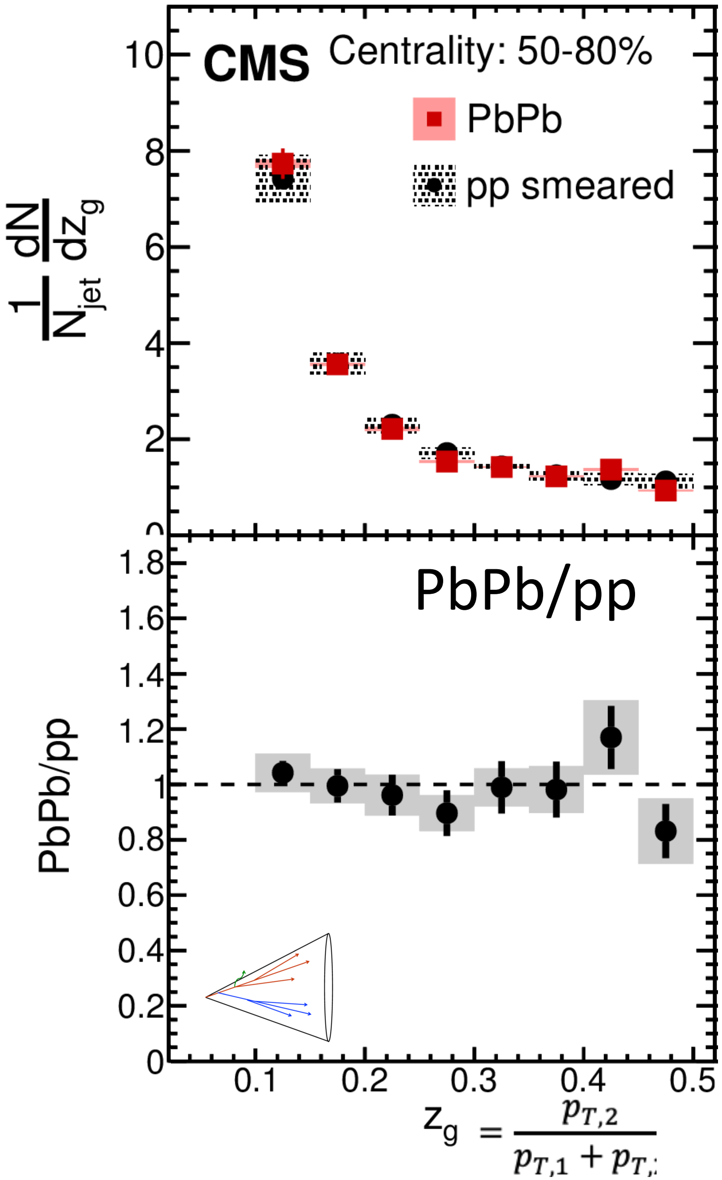
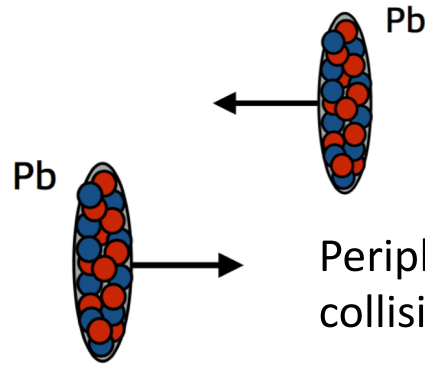


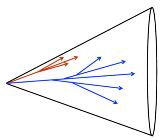


Peripheral collision

The subjet pairs became more imbalanced in central PbPb collisions.

QGP can recognize the splitting pattern of jets!

No signal for peripheral collisions



Take Home Messages

Jet Quenching is the energy loss phenomenon of a jet via gluon radiation induced by QGP. Precision measurement of jets can shed light on the pQCD of high energy parton and QGP medium

Jet Substructure is a great tool to test the state-of-the-arts pQCD calculation, and an interesting signal to probe QGP