Heavy Ion Jet Measurements in CMS

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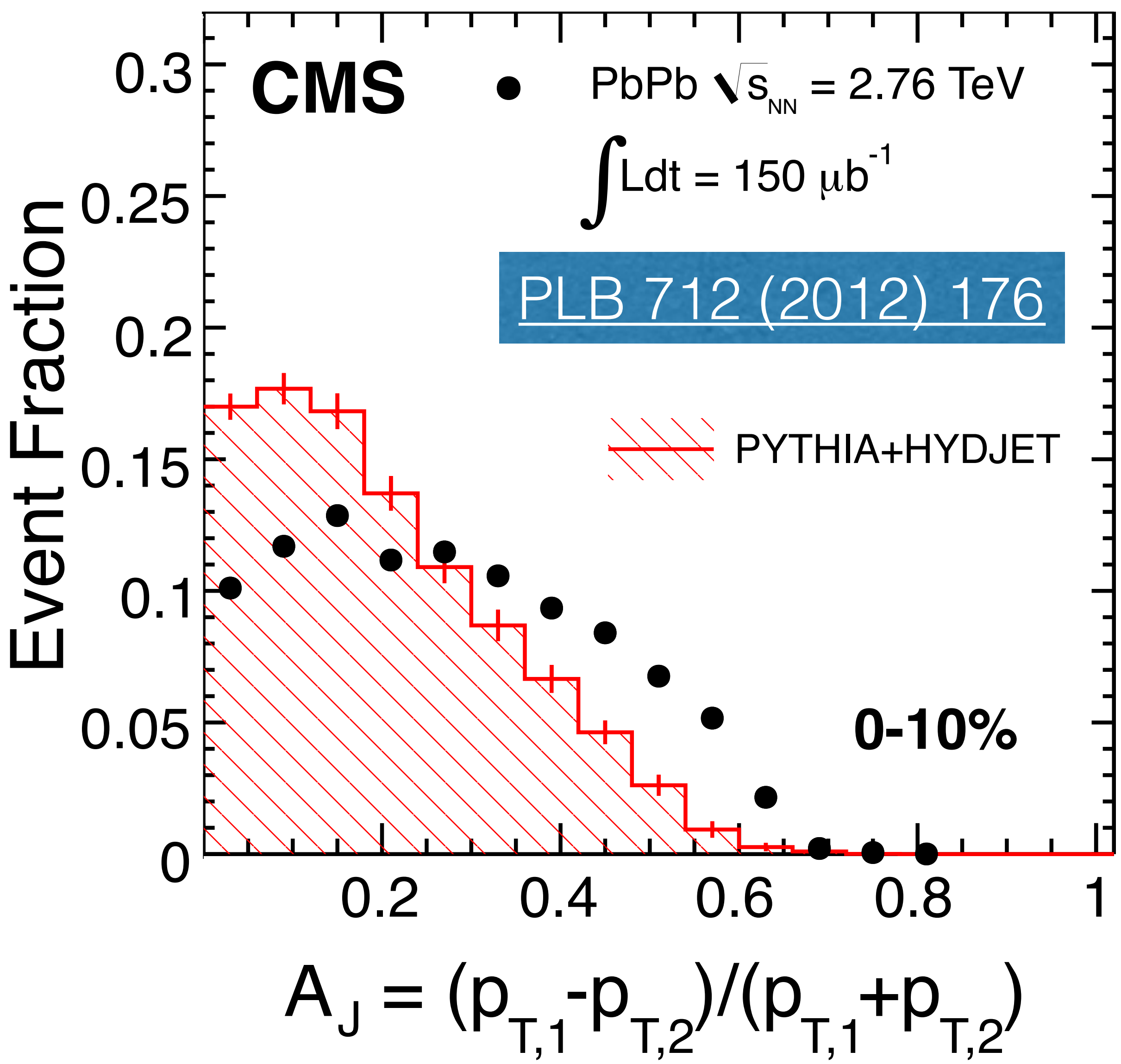
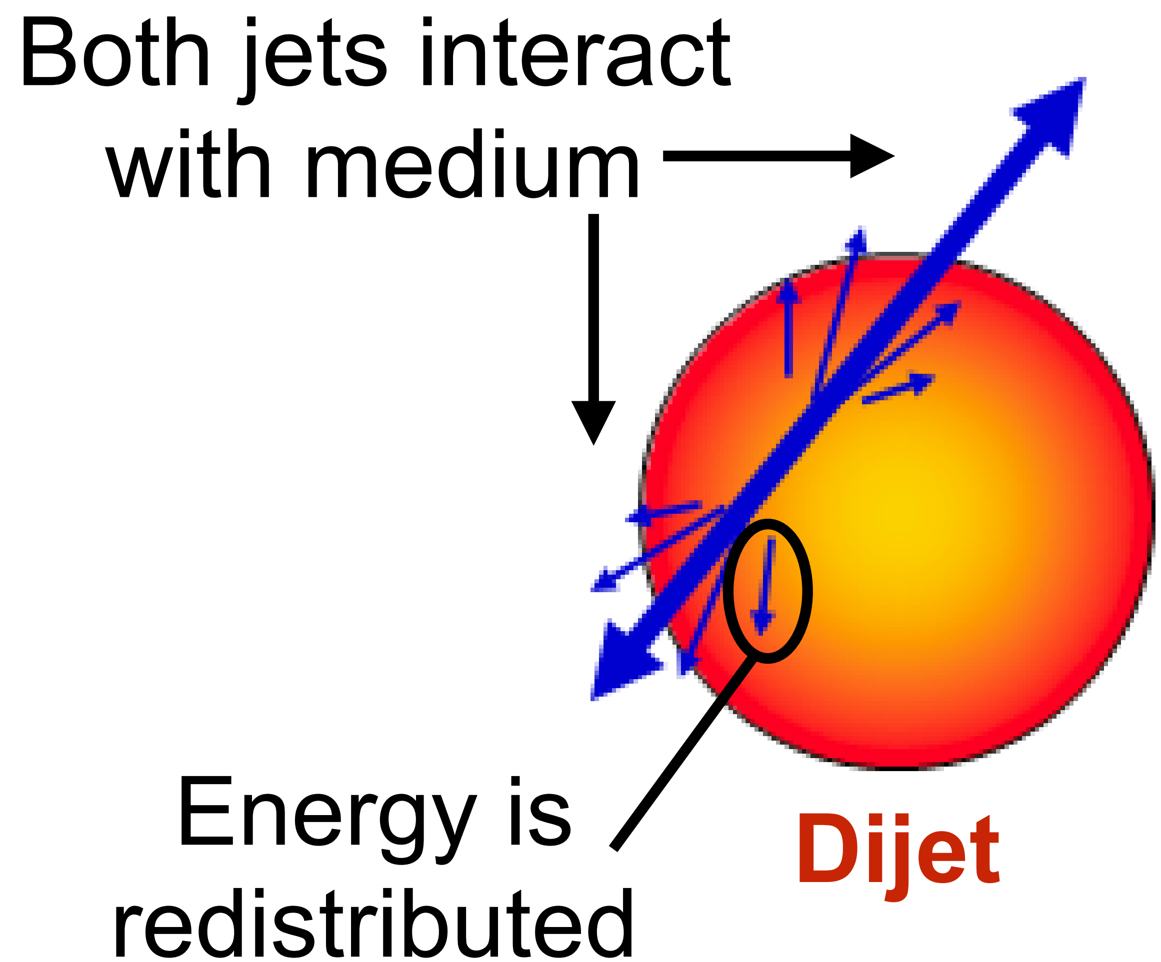
Dijet Asymmetry in PbPb





- Observed strong modification in medium compared to MC and pp
- Energy is redistributed in and out-of-cone
    - How can this be studied?

CMS Results on Jet Quenching

Inclusive/Dijet	2p76TeVPbPbDijetImb	2p76TeVPbPbJetRAA
	2p76TeVPbPbDijetImbMPt	5TeVpPbJetRpA
Inclusive/Dijet+Track	2p76TeVPbPbFrag1, 2	2p76TeVPbPbShapes
	2p76TeVPbPbMPt	2p76TeVPbPbJetTrackCorr
	2p76TeVPbPbJetTrackMom	5TeVPbPbJetTrackCorr
Boson+Jet	2p76TeVPbPbPhotonJet	5TeVPbPbZJet
	5TeVPbPbPhotonJet	
Heavy Flavor Jet	2p76TeVPbPbBJetRAA	5TeVpPbCJetSpect
	5TeVPbPbDInJets	5TeVBJetRpA
	5TeVPbPbDiBjetImb	
Boson+Jet+Track	5TeVPbPbPhotonTagShapes	5TeVPbPbPhotonTagFrag
Inclusive Substructure	5TeVPbPbSplitting	5TeVPbPbGroomJetMass

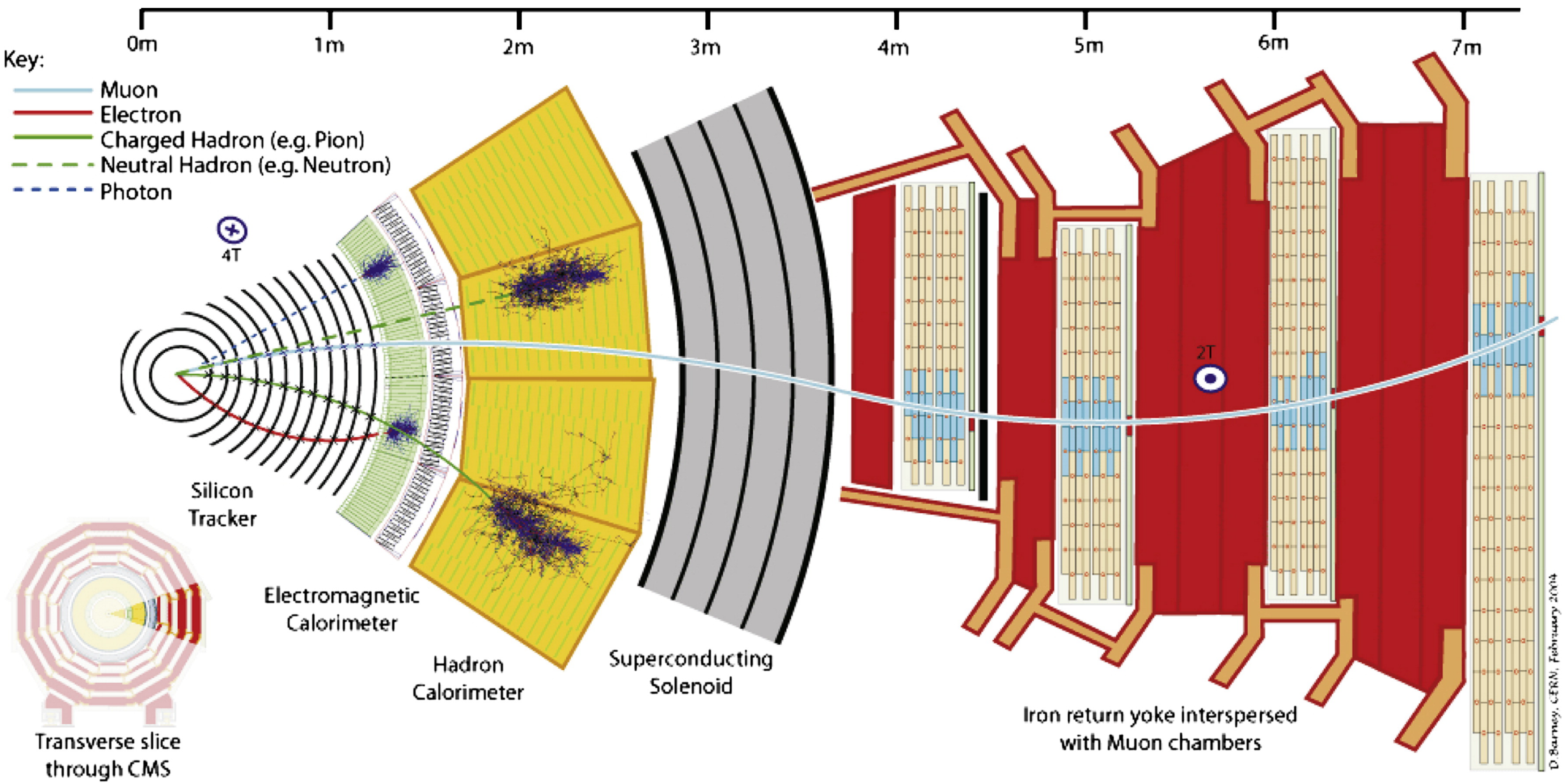
- Excluding the related particle suppression results

CMS Results on Jet Quenching

Inclusive/Dijet	2p76TeVPbPbDijetImb	2p76TeVPbPbJetRAA
	2p76TeVPbPbDijetImbMPt	5TeVpPbJetRpA
Inclusive/Dijet+Track	2p76TeVPbPbFrag1, 2	2p76TeVPbPbShapes
	2p76TeVPbPbMPt	2p76TeVPbPbJetTrackCorr
	2p76TeVPbPbJetTrackMom	5TeVPbPbJetTrackCorr
Boson+Jet	2p76TeVPbPbPhotonJet	5TeVPbPbZJet
	5TeVPbPbPhotonJet	
Heavy Flavor Jet	2p76TeVPbPbBJetRAA	5TeVpPbCJetSpect
	5TeVPbPbDInJets	5TeVBJetRpA
	5TeVPbPbDiBjetImb	
Boson+Jet+Track	5TeVPbPbPhotonTagShapes	5TeVPbPbPhotonTagFrag
Inclusive Substructure	5TeVPbPbSplitting	5TeVPbPbGroomJetMass

- Focus on a few recent results

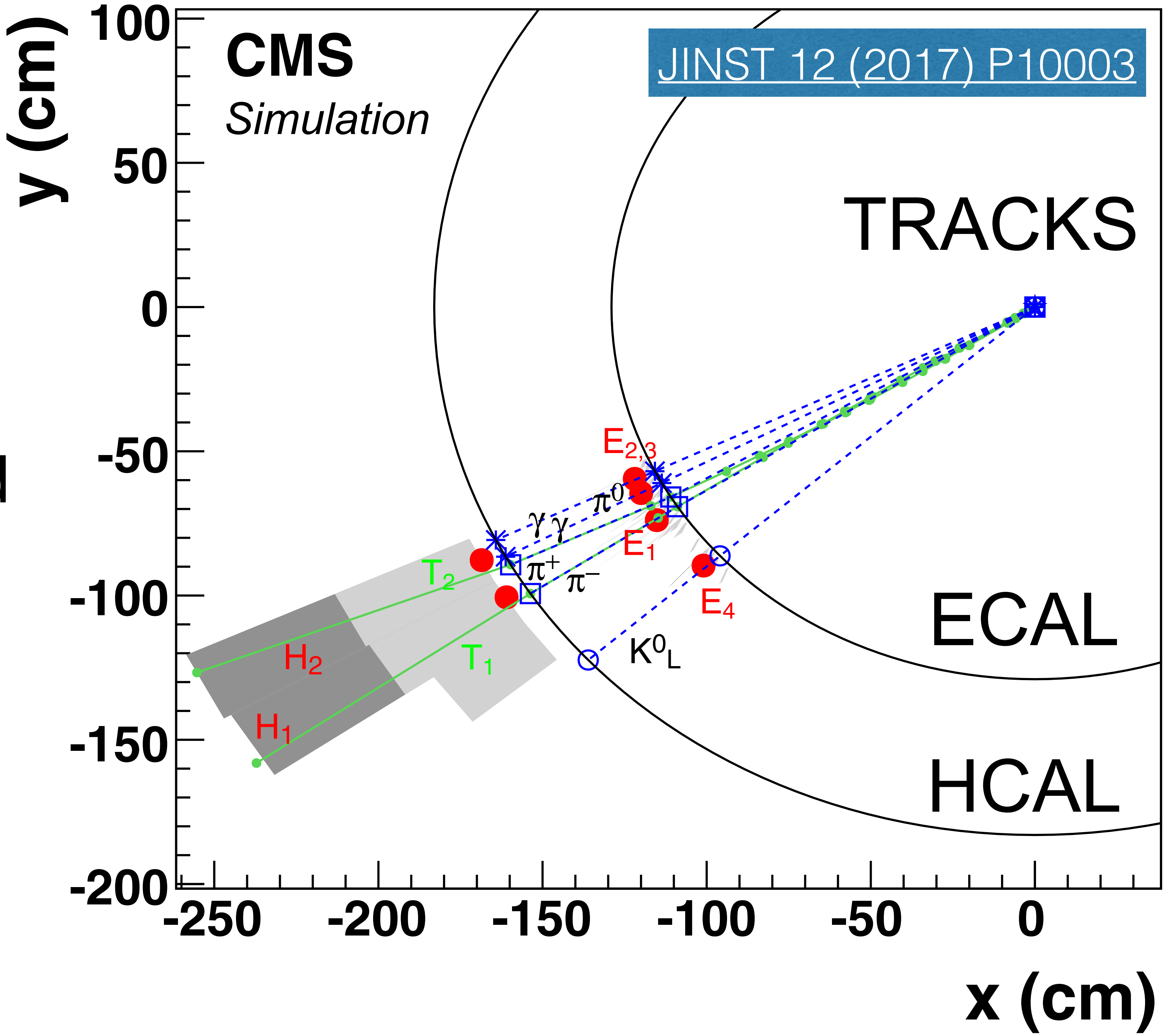
The CMS Detector



- Jet reconstruction combines all subdetectors
  - Dominated by tracking, ECal, and HCal (~.6, ~.3, ~.1)

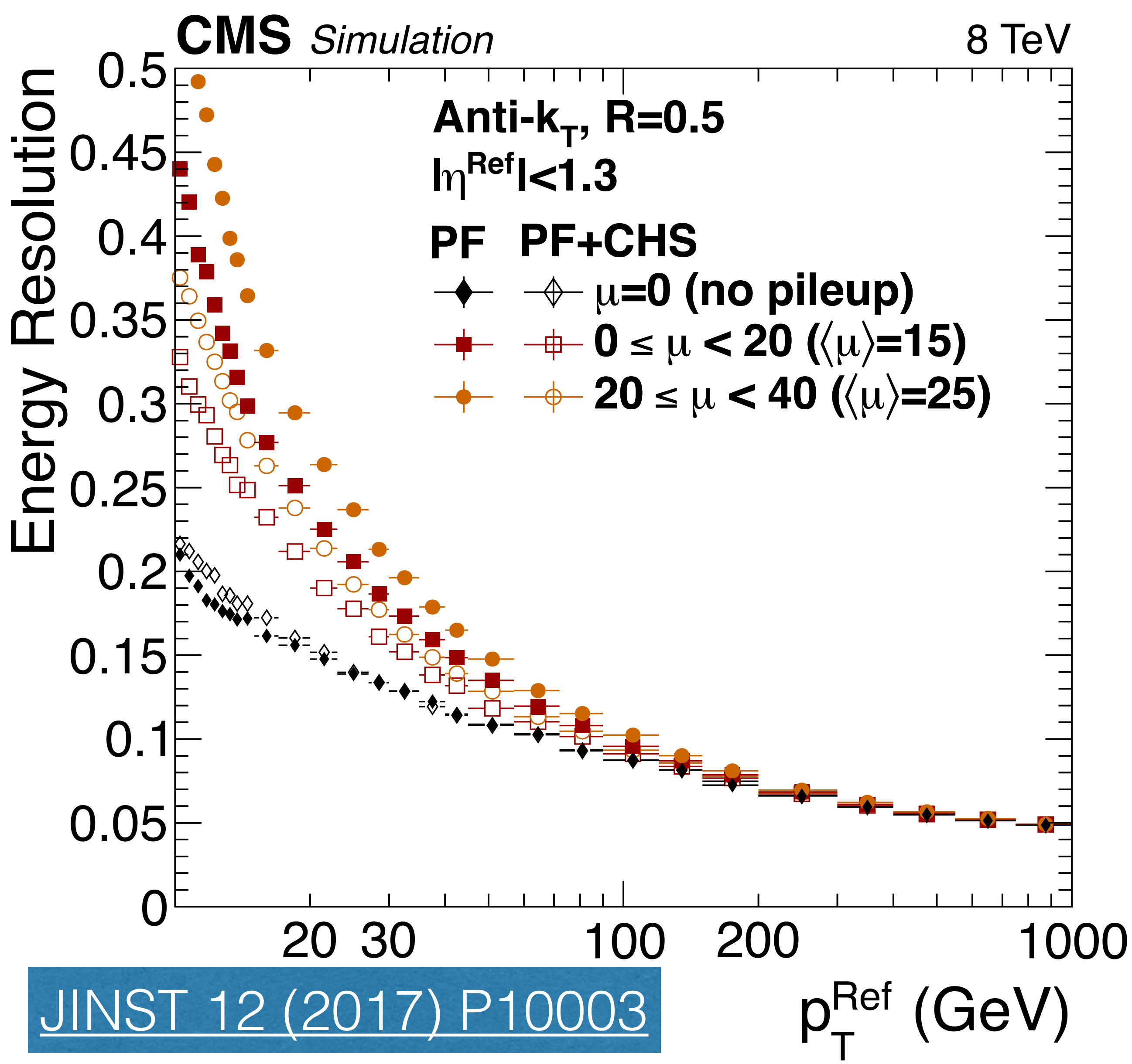
Particle Flow at CMS

1. Reconstruct subdetector objects
2. Subdetector objects are matched topologically
3. “ID” can be assigned (is this a track that left some energy in ECal? perhaps e+/-)
4. These final subdetector objects are clustered into jets

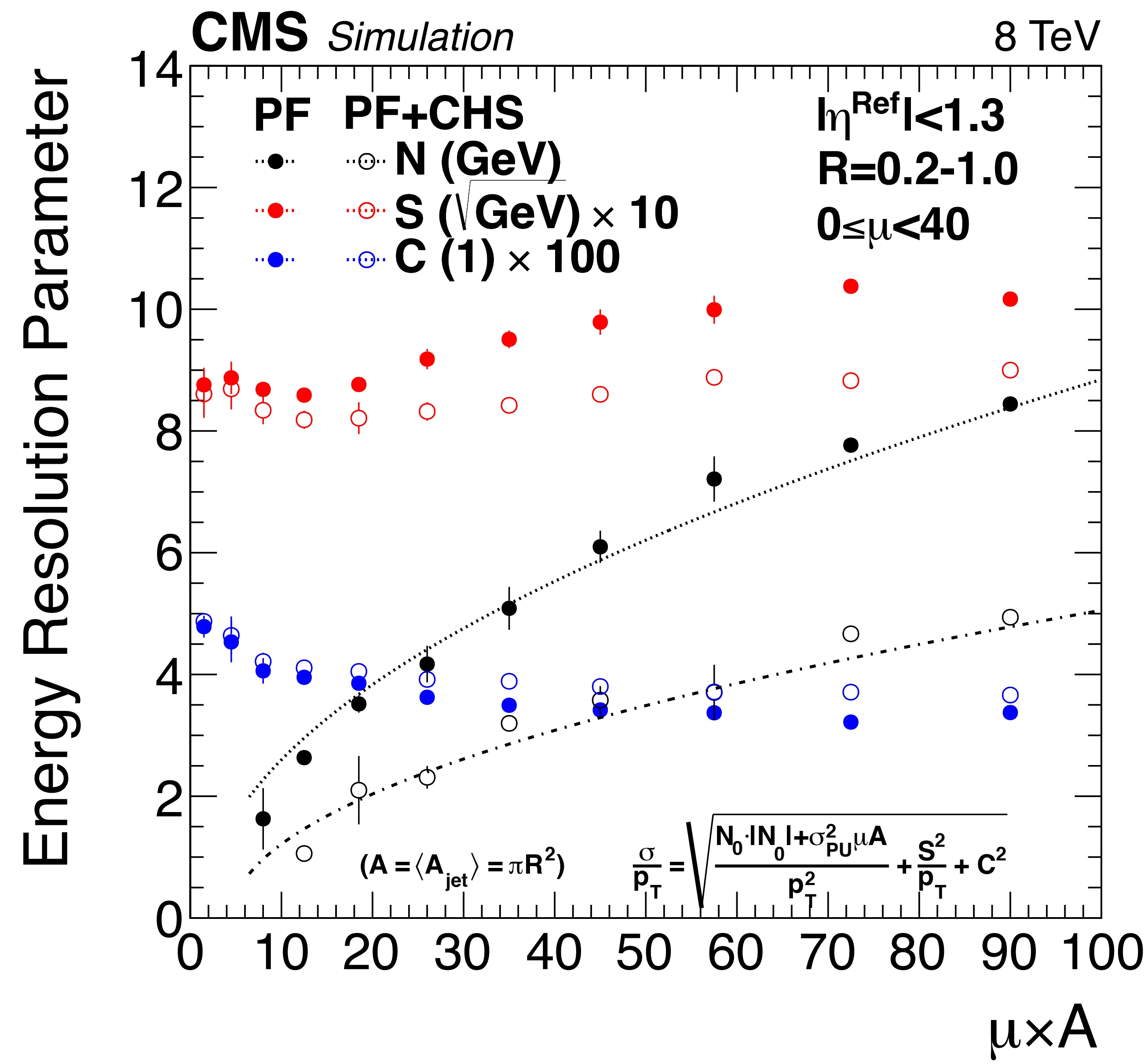


ATLAS PF-> EPJC 77 (2017) 466

Jet Reconstruction with CMS in pp



JINST 12 (2017) P10003



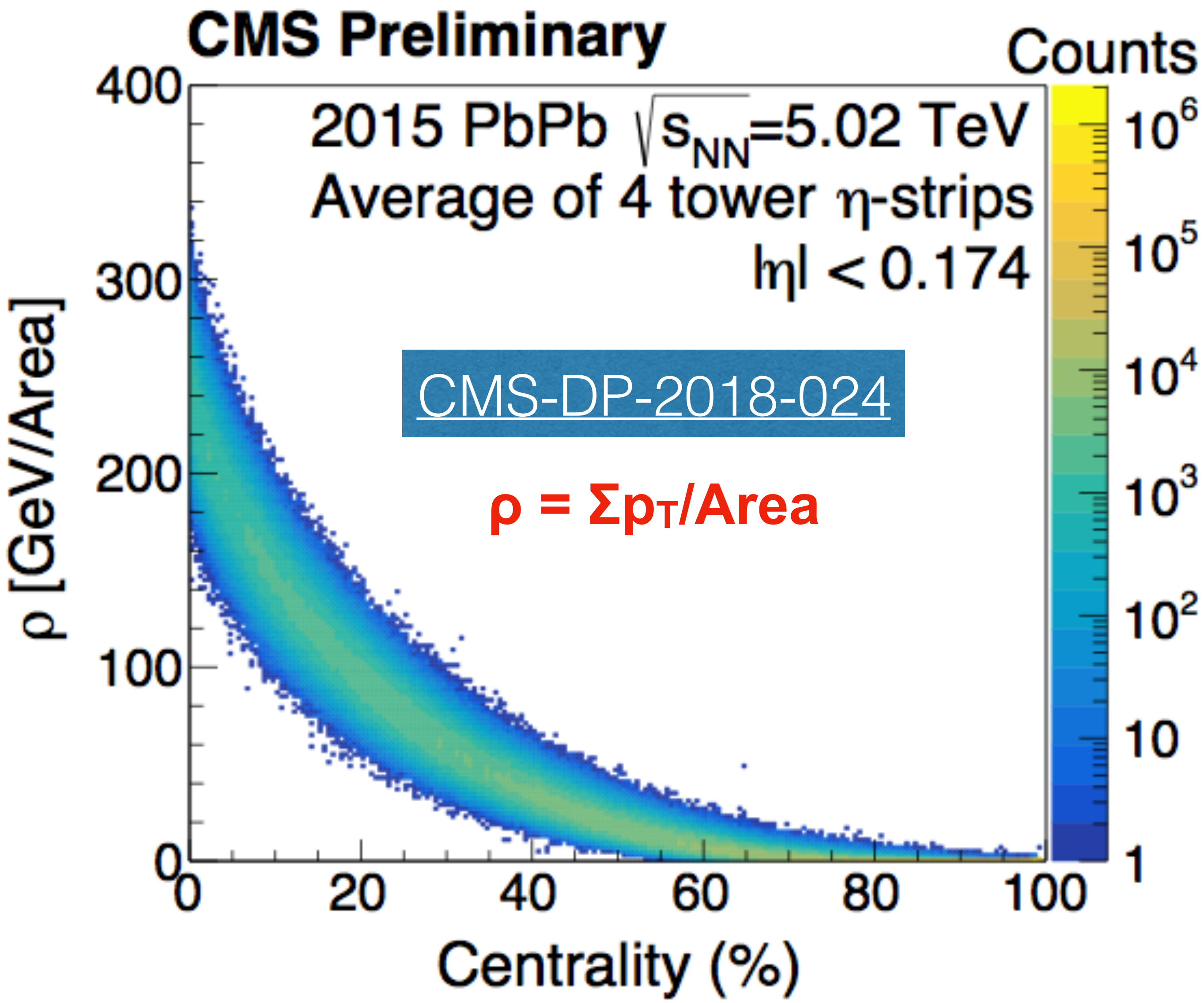
- Good performance just using vertex info to subtract at typical levels of LHC pileup
  - Typical level -> peripheral-most in PbPb

Jet Reconstruction with CMS in PbPb

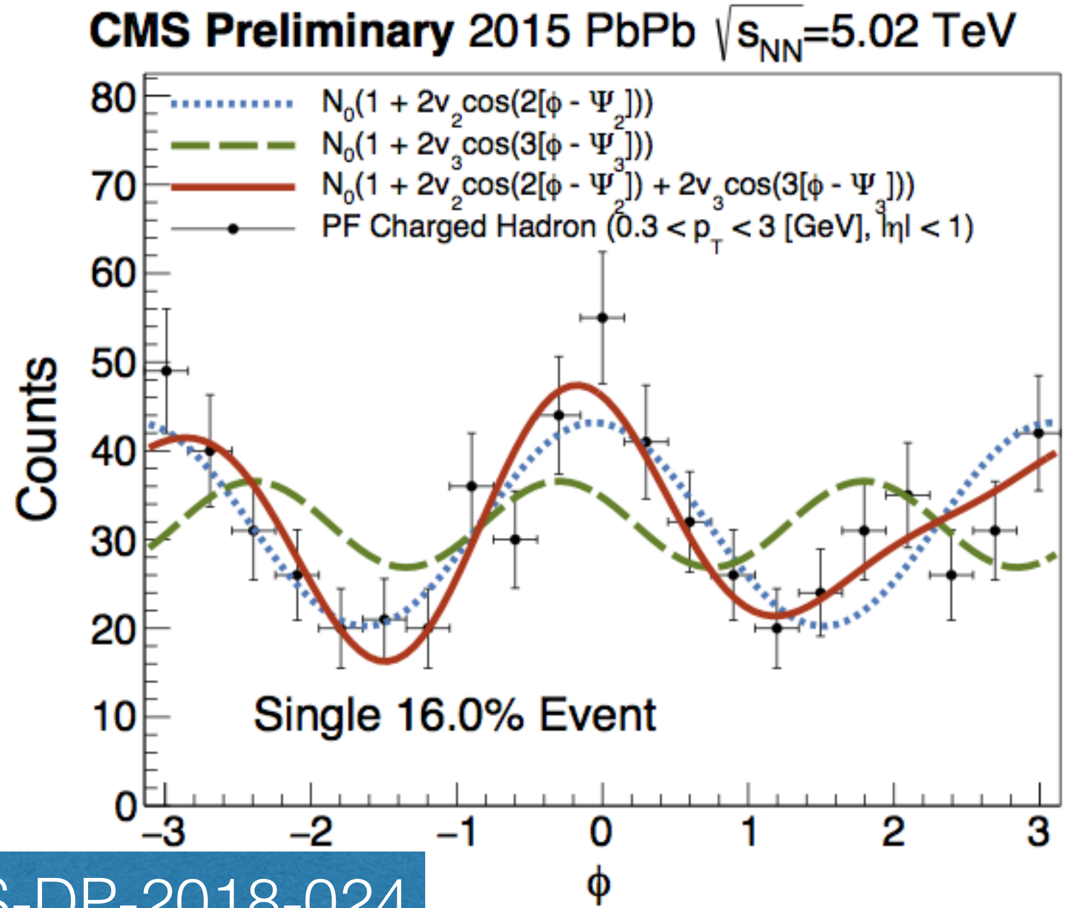
- Fluctuations in ρ contribute to jet resolution as N term:

$$\sigma\left(\frac{p_T^{RECO}}{p_T^{GEN}}\right)=\sqrt{C^2+\frac{S^2}{p_T^{GEN}}+\frac{N^2}{(p_T^{GEN})^2}}$$

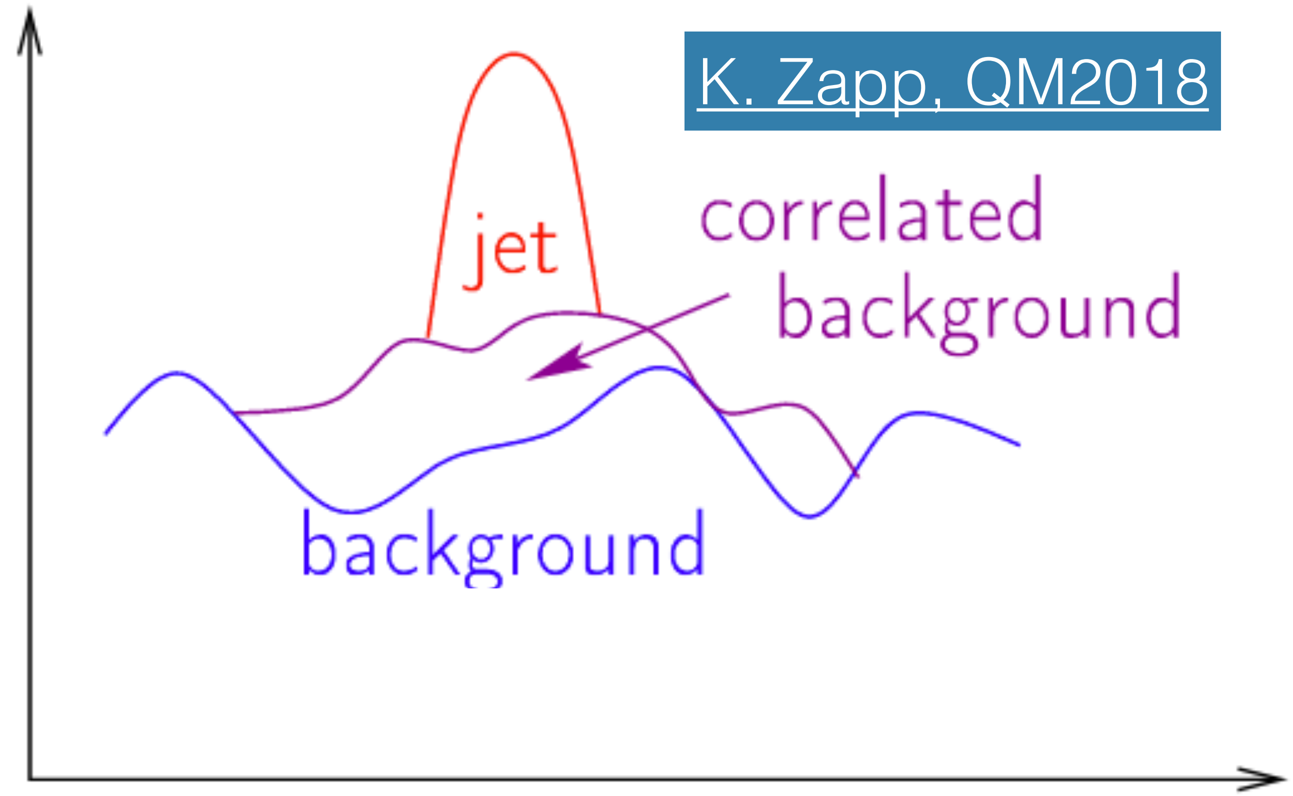
- Typically HI chooses small cone and low-p_T to reduce impact of UE
- ~15 GeV one-sigma fluctuation
- All results shown use R=0.3 or 0.4
- All results w/ 2015 PbPb and pp reference



Additional Complications in PbPb



CMS-DP-2018-024



K. Zapp, QM2018

Phys.Lett. B 753 (2016) 511-525 for ALICE implementation

- Hard and soft components from single vertex O(fm)
- Background is modulated in φ (flow of medium)
- Jet-medium interaction gives ambiguous correlated background

Subtracting Underlying Event in HI at CMS

- Considering subtraction as **two** separate problems
  1. What amount of UE to subtract
  2. How to subtract

For substructure:

Constituent Subtraction (CS)

1: Estimated by median unsubtracted k_t jet

2: Add “ghost” particles randomly with fixed area and p_T according to rho, subtracting from real particles iteratively until gone

See JHEP06 (2014) 092

For gamma/flavor tagged jets

Iterative Pedestal (PU)

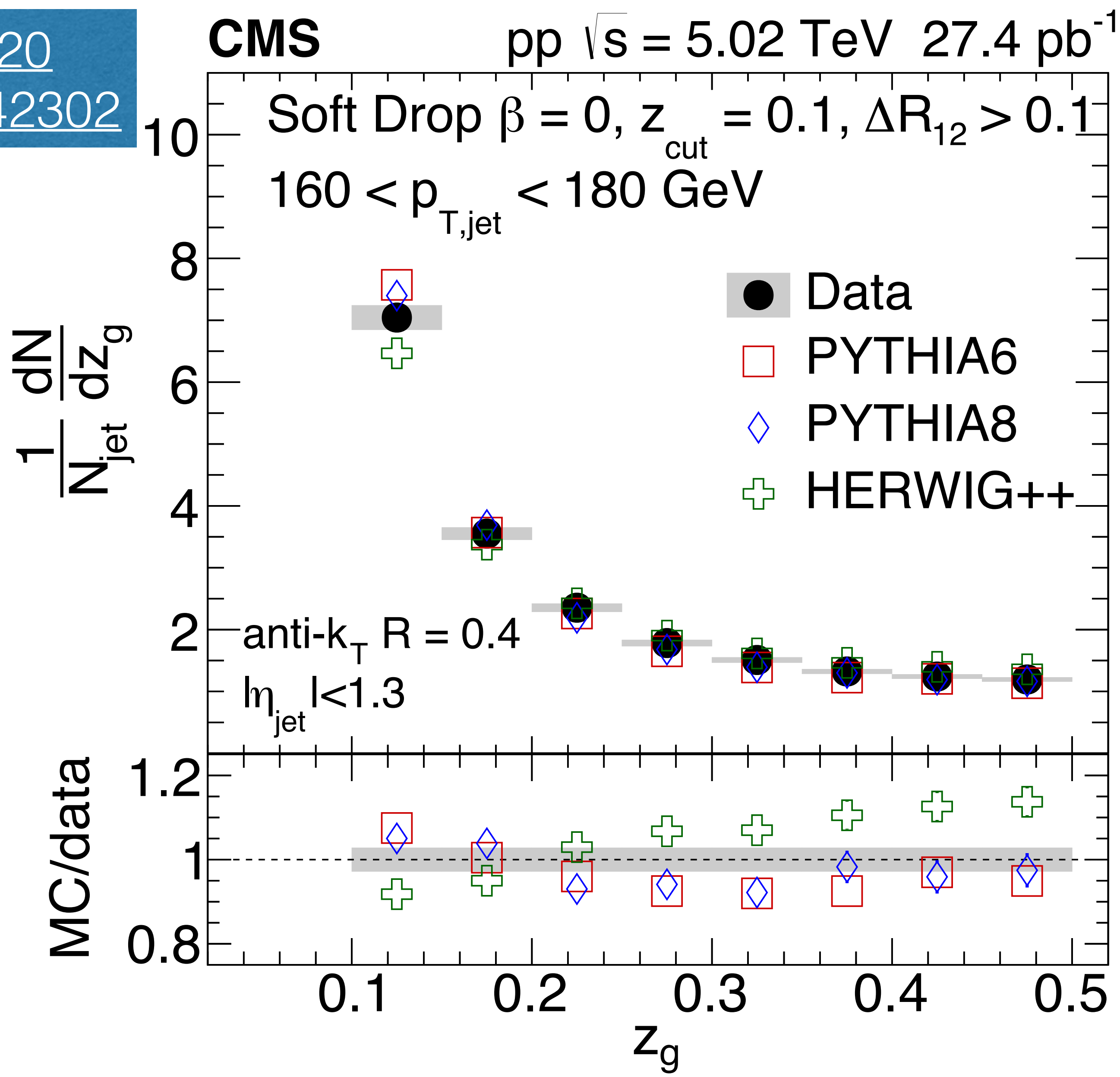
1: Estimated by mean energy inside tower eta strips (excluding jets from first iteration in second)

2: Subtract mean + compensating sigma from pseudo-tower constituents. Zero negative towers

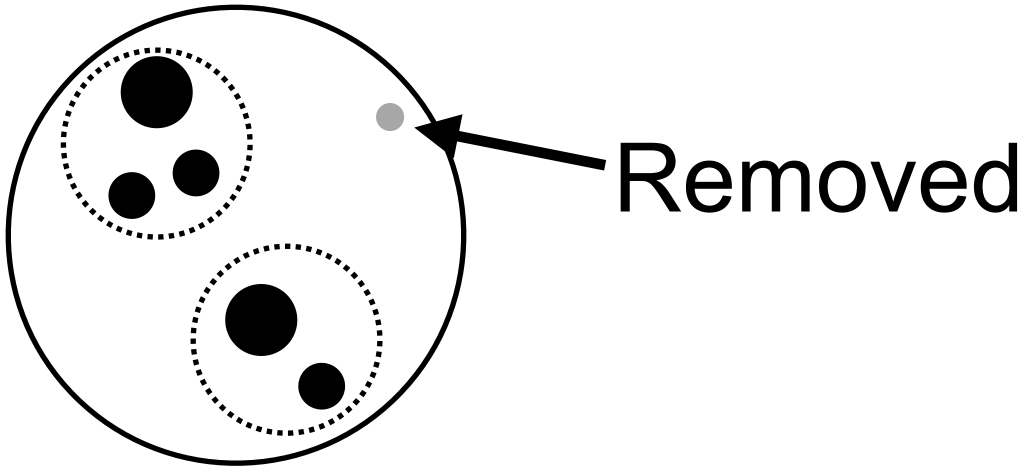
See EPJC 50 (2007) 117

CMS Analysis of z_g in pp

[PRL 120 (2018) 142302](PRL 120 (2018) 142302)



Work back thru clustering history

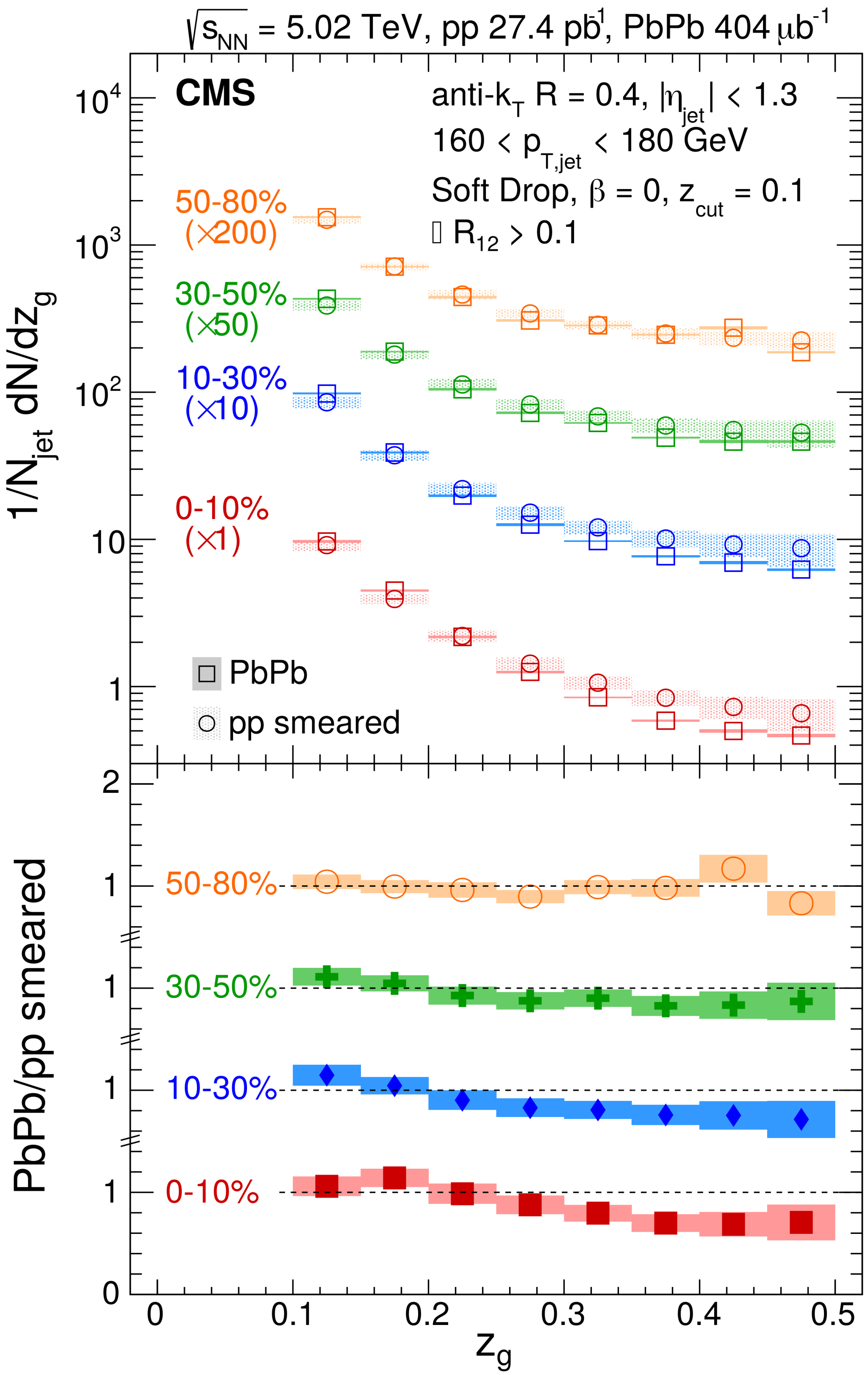


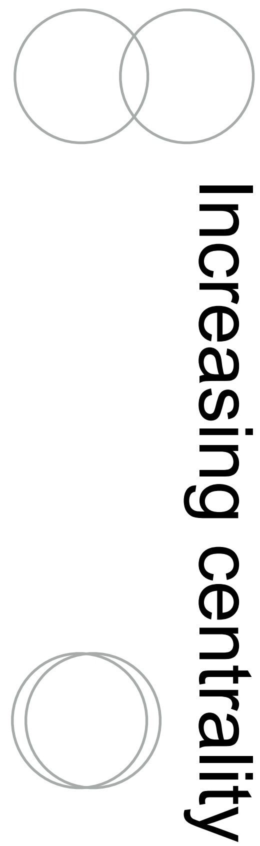
Identify subjets satisfying condition:

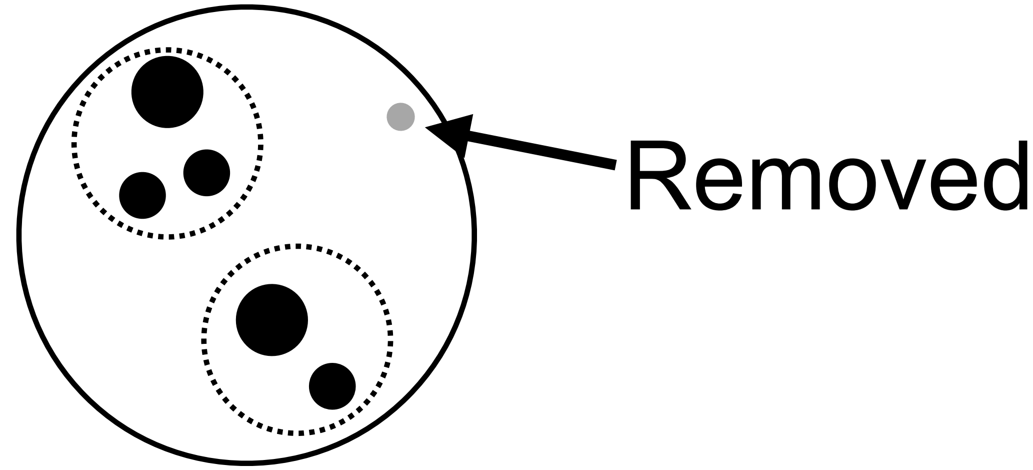
$$\frac{\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})}{p_{\mathrm{T},i} + p_{\mathrm{T},j}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

- PYTHIA6, PYTHIA8, and HERWIG++ all describe distribution shape to ~15%
- Given reasonable baseline, how does it look in PbPb?

CMS Analysis of z_g in PbPb







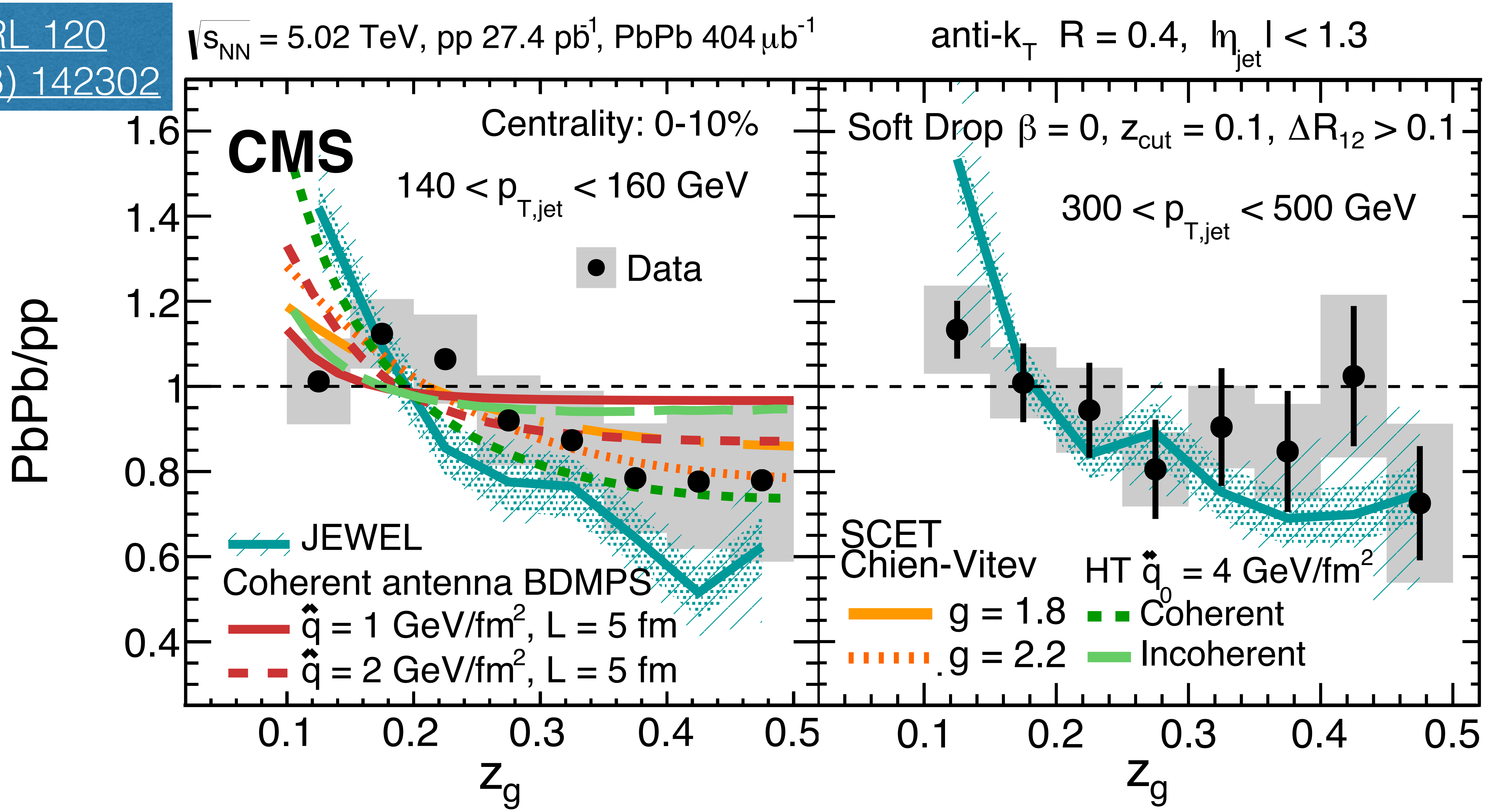
$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

- z_{cut} and β here are "Flat" grooming setting
- Shape modification with increasing centrality

PRL 120 (2018) 142302

CMS Analysis of z_g in PbPb

PRL 120 (2018) 142302



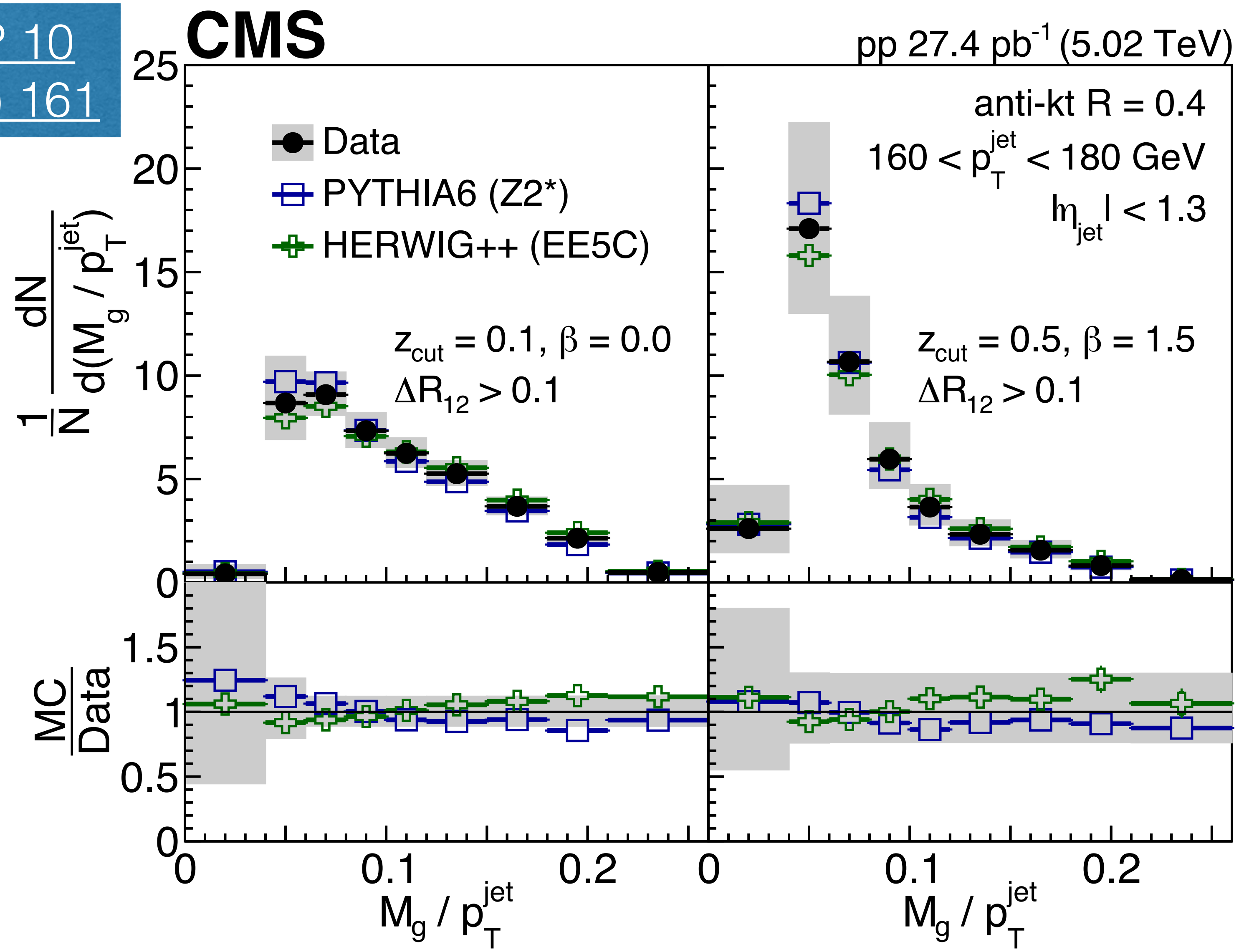
Fixed Centrality

Increasing jet p_T

- Persistent effect thru large p_T range
  - Consistent at highest p_T, but limited by statistics

CMS Analysis of Groomed Mass in pp

JHEP 10 (2018) 161



Identify subjets satisfying condition:

$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

Calculate:

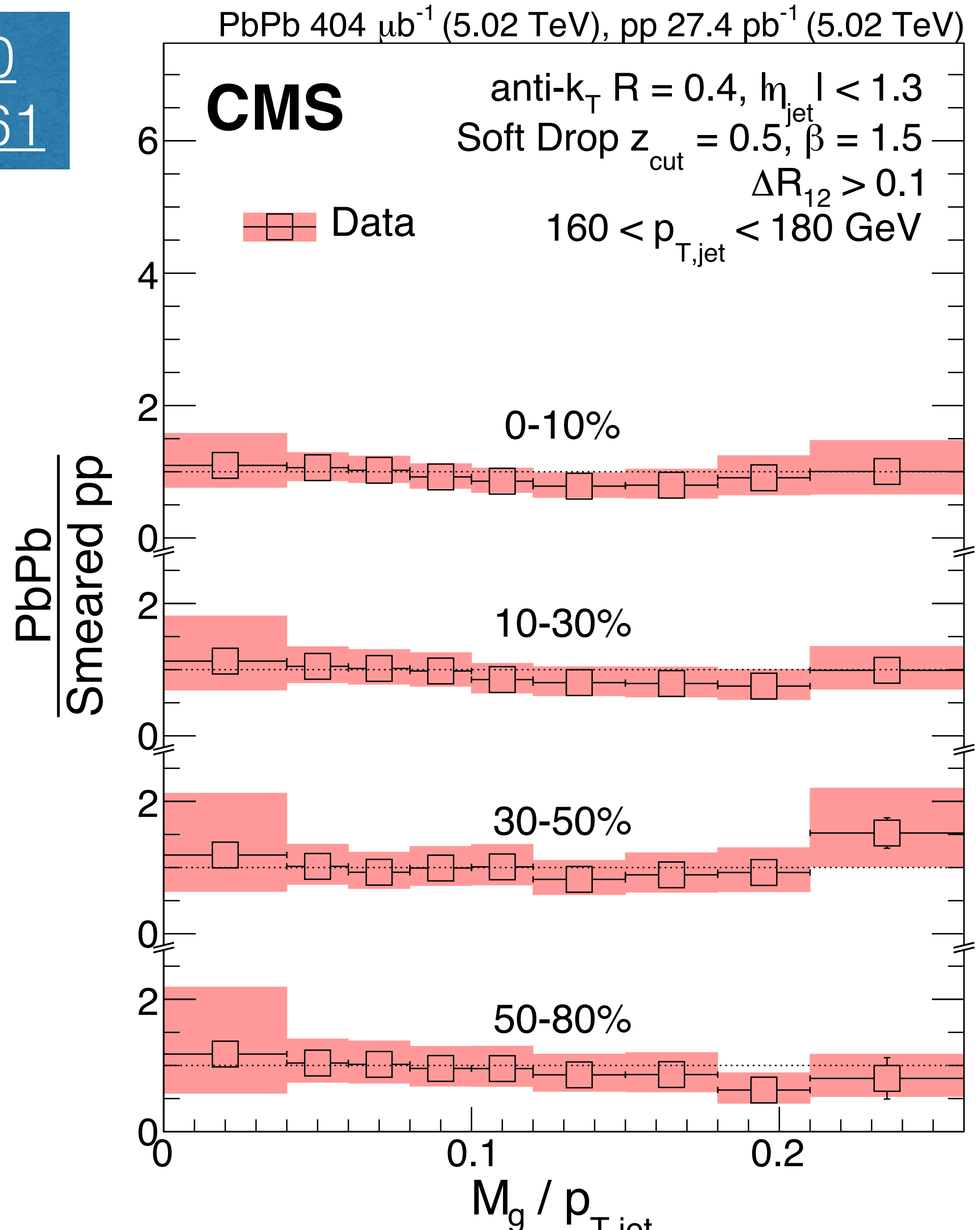
$M_g = (p_{1\mu}\, p_2^{\mu})^{0.5}$

Normalize by jet p_T

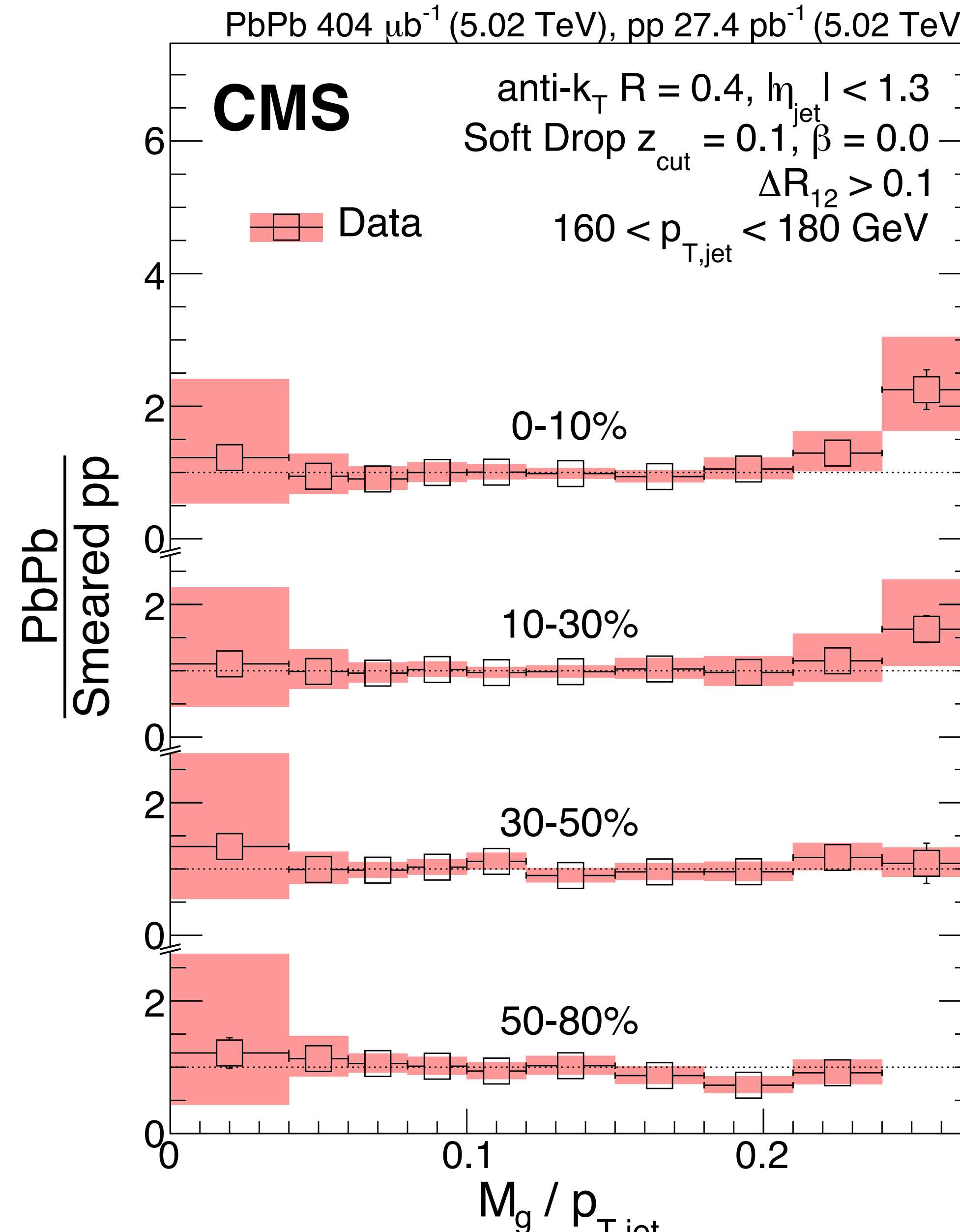
- Left: Grooming does not consider radial distance (β=0, "Flat")
- Right: Grooming preferentially selects jet "Core"
- PYTHIA6, HERWIG++ show good agreement with data

CMS Analysis of Groomed Mass in PbPb

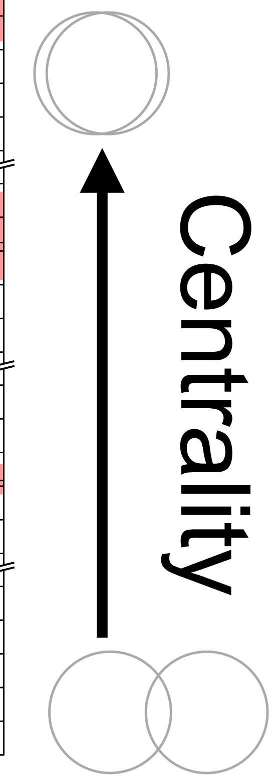
JHEP 10 (2018) 161



“Core” grooming



“Flat” grooming



- “Core” grooming shows no modification
- “Flat” grooming shows shape modified at large M_g/p_T

No simultaneous MC description of M_g/p_T

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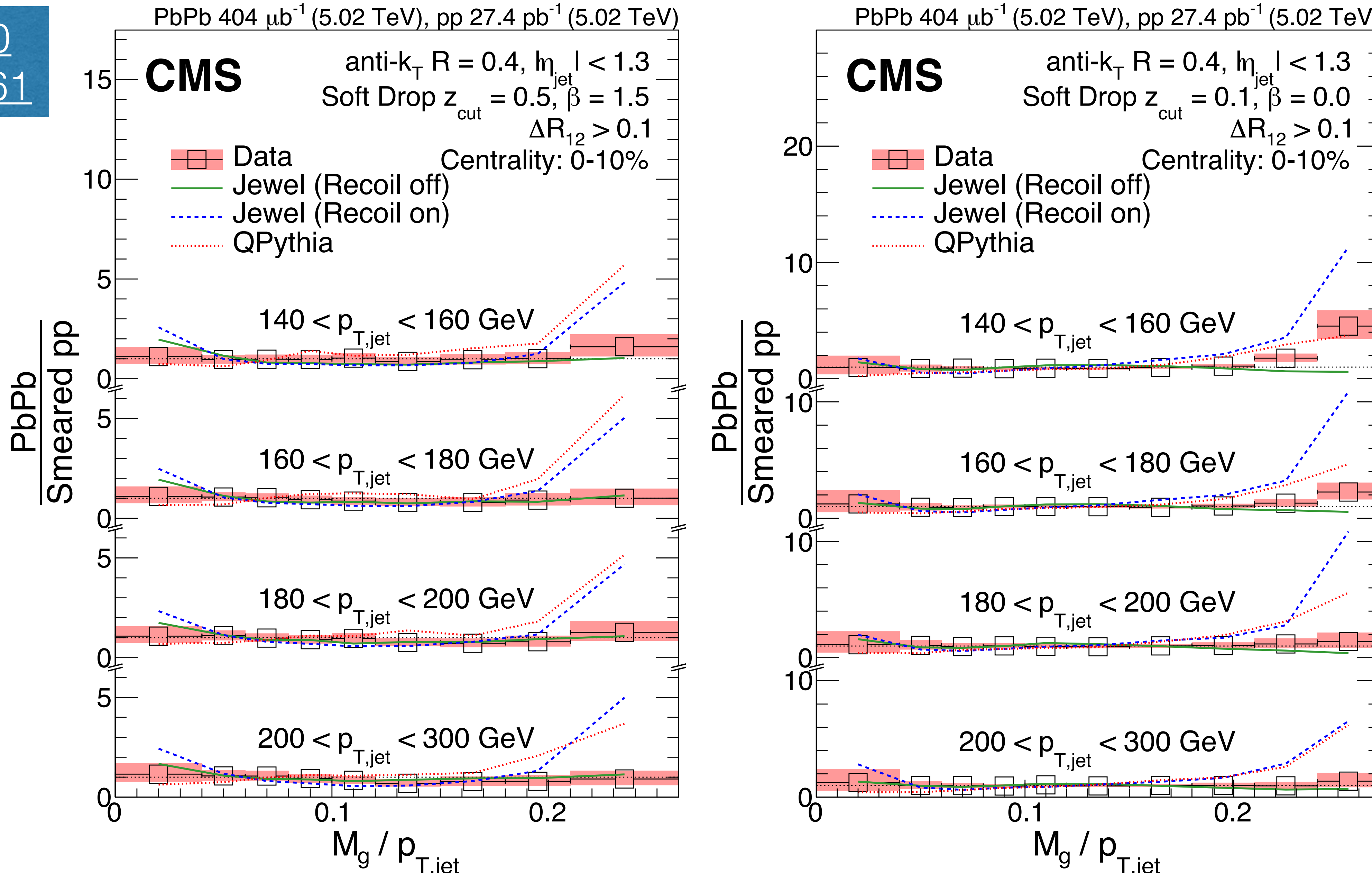


“Core” grooming

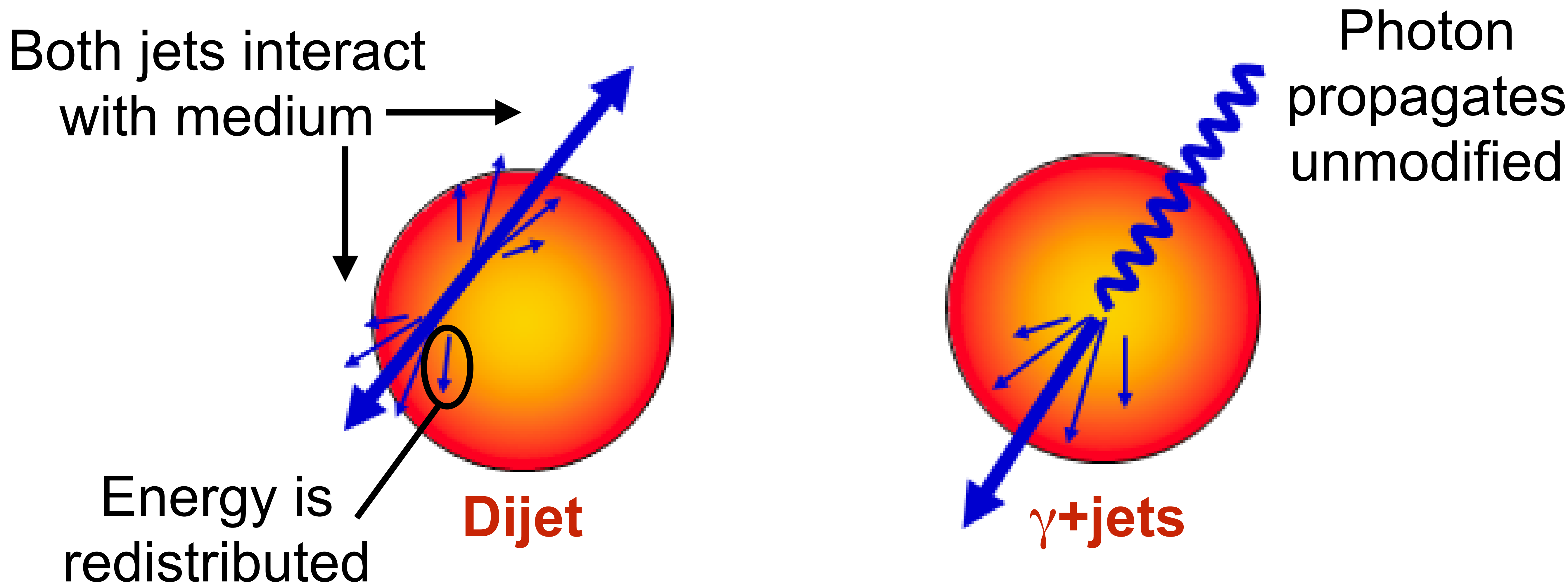
“Flat” grooming

Fixed Centrality

Jet p_T

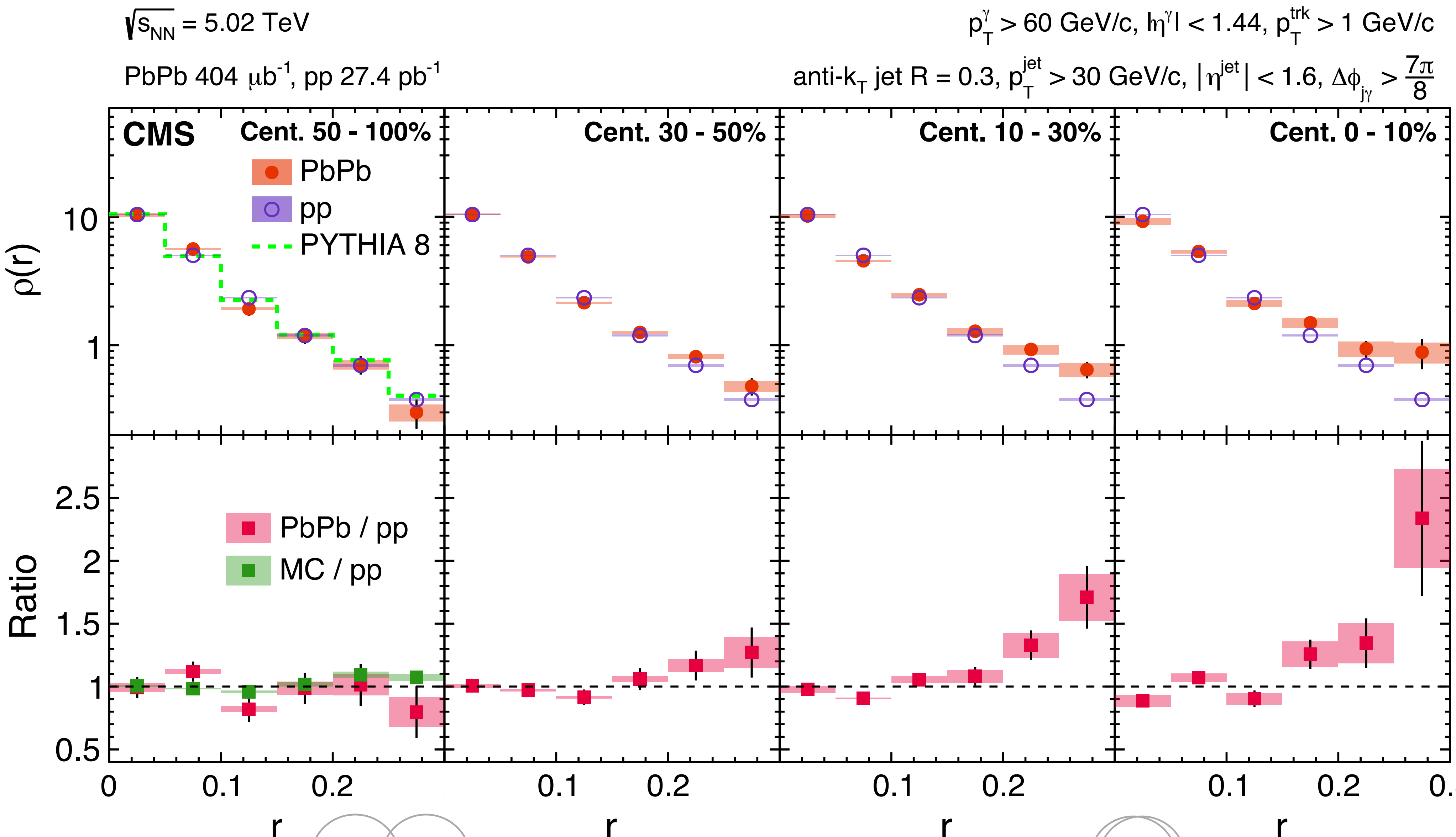
- Models that describe enhancement in “Flat” grooming also show large M_g/p_T in “Core” grooming

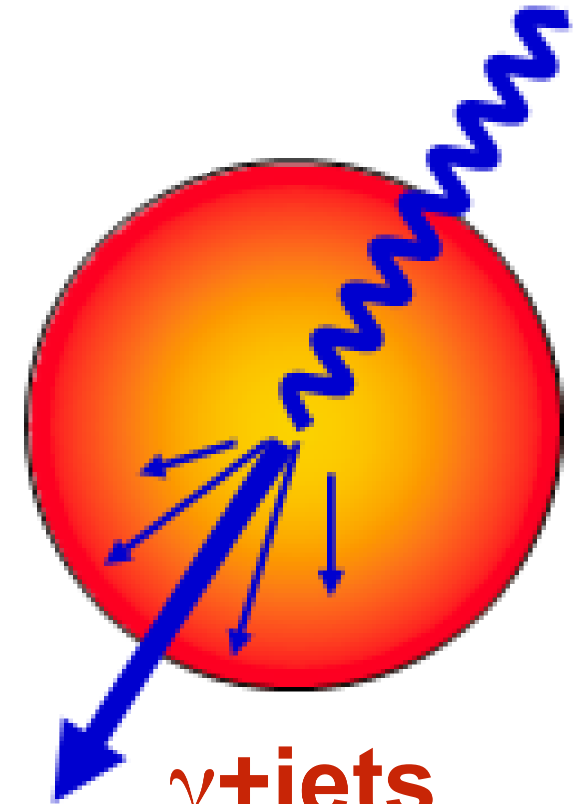
Controlling Initial Momentum w/ Boson



- Photon gives a clean tag of the starting momentum
  - Also probes a different q/g fraction (see backup)
  - Measurements at much lower p_T than corresponding inclusive measurements

Measuring Jet Shapes with a Boson Tag



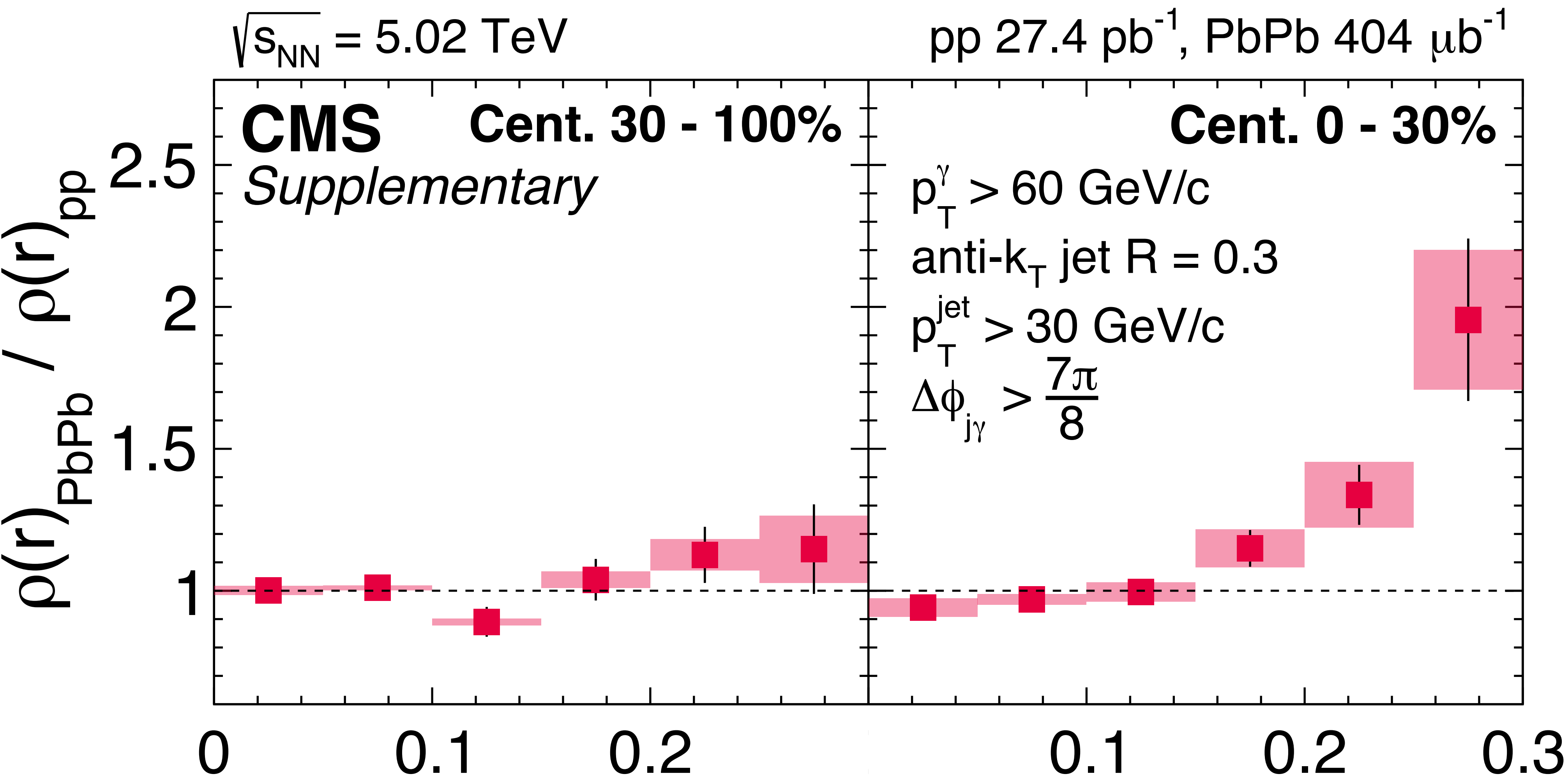


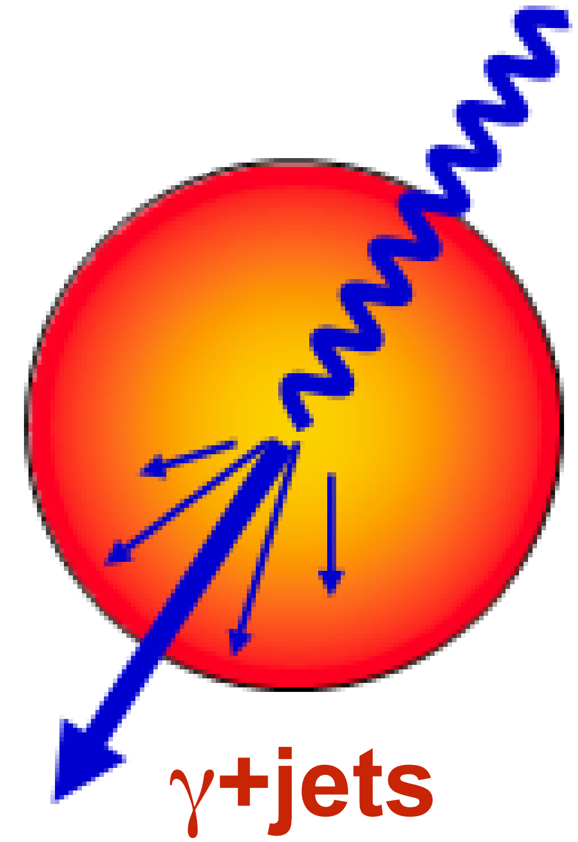
Submitted to PRL

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk}\in[r_a,r_b)} (p_T^{\text{trk}}/p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk}\in[0,r_f)} (p_T^{\text{trk}}/p_T^{\text{jet}})}$$

- Look at track sums in rings around the jet axis, normalized to the full jet charged energy

Measuring Jet Shapes with a Boson Tag



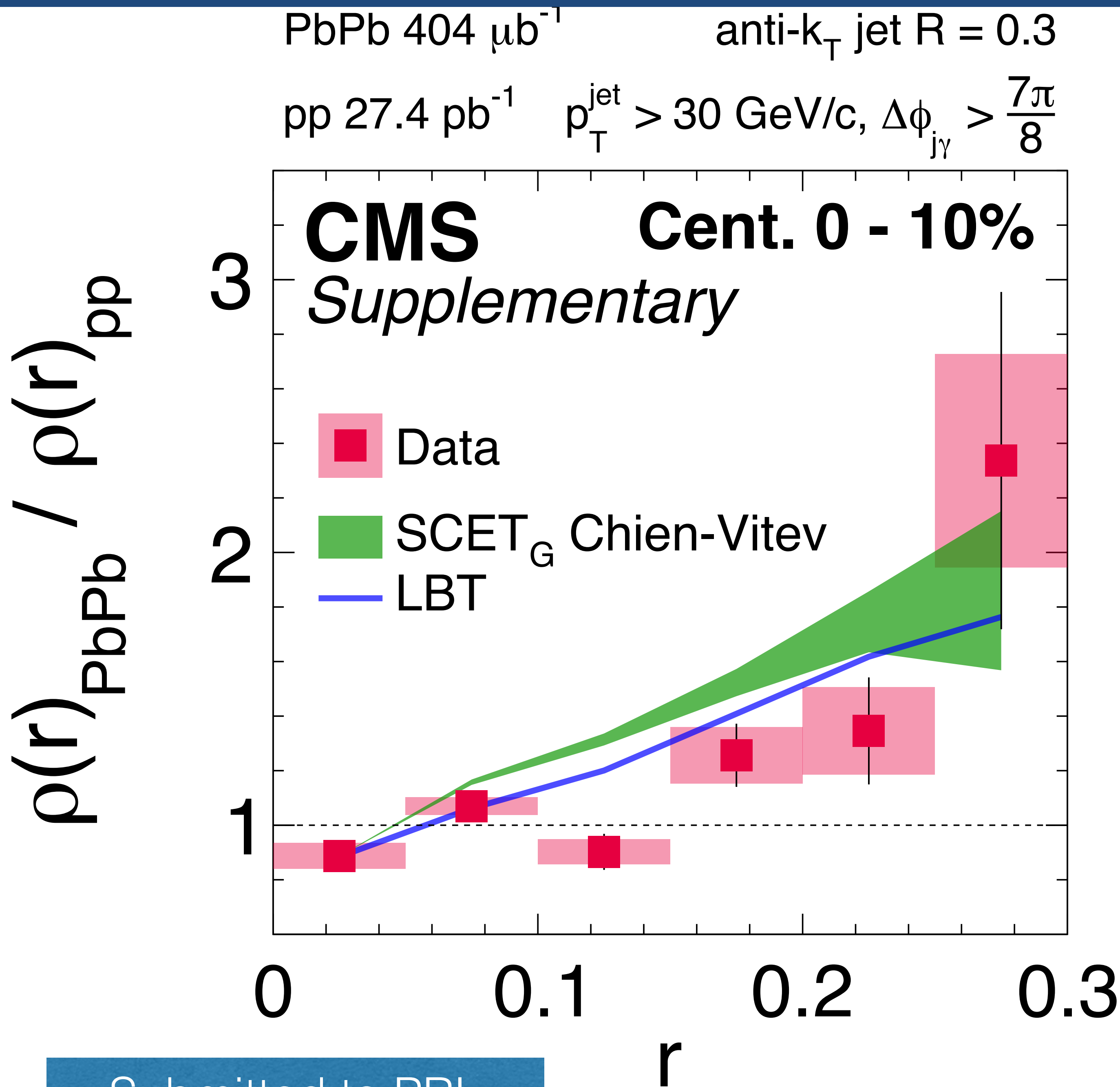


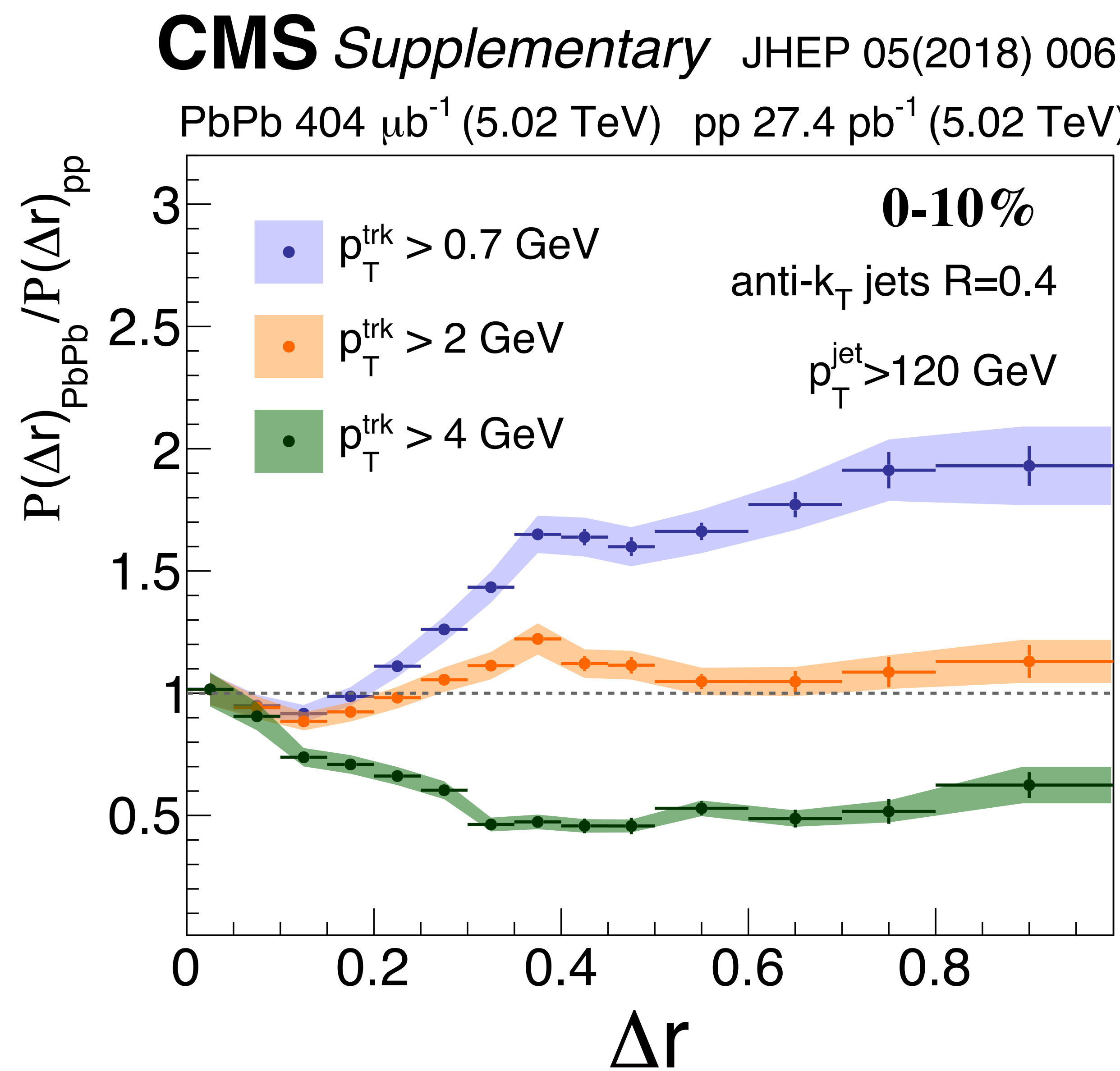
$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk}\in[r_a, r_b)} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk}\in[0, r_f)} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$

Submitted to PRL

- In central PbPb, observe enhancement of periphery particles
  - Comparable to results of groomed jet mass with β=0

Comparison w/ Inclusive Jet Shapes



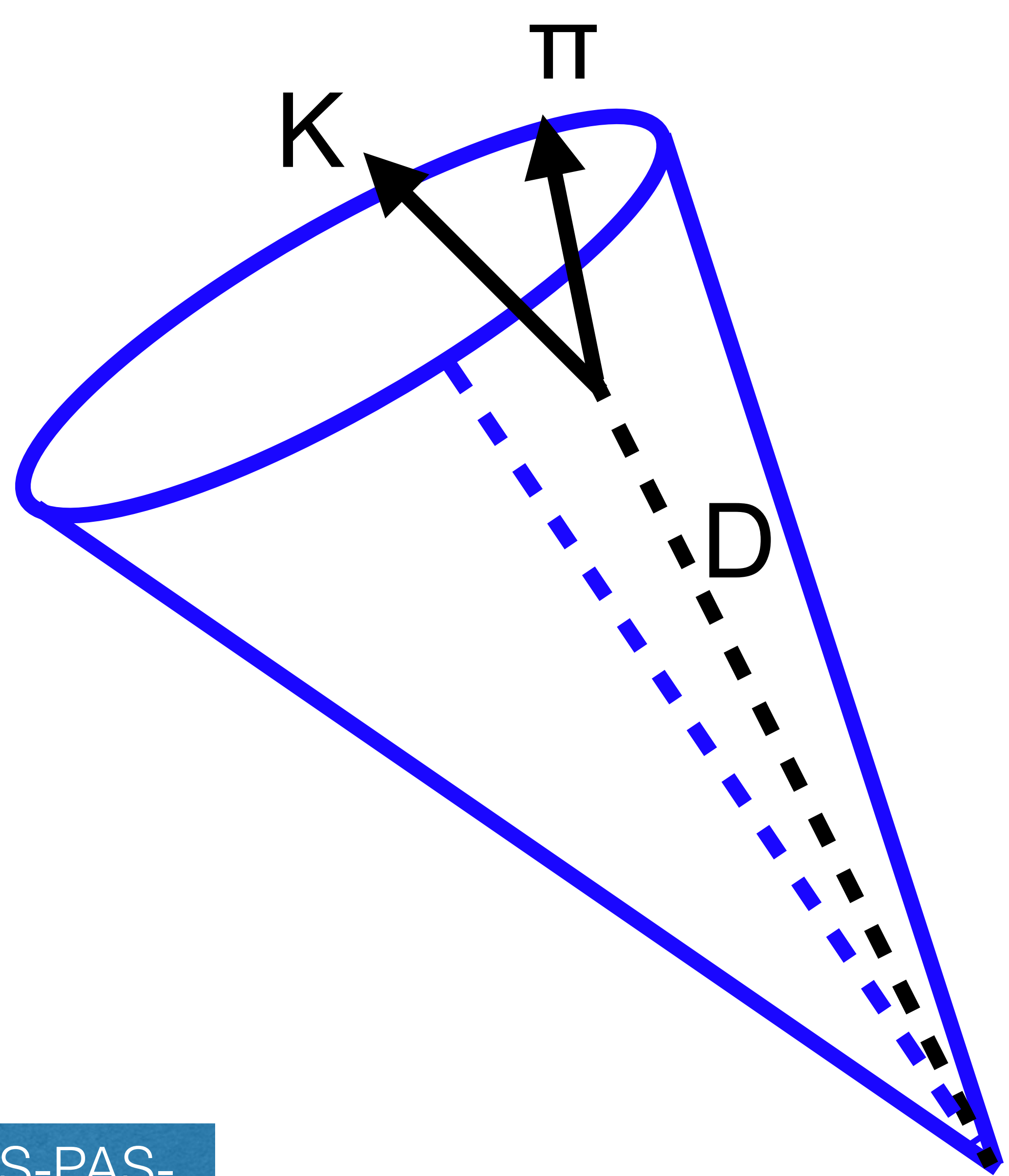


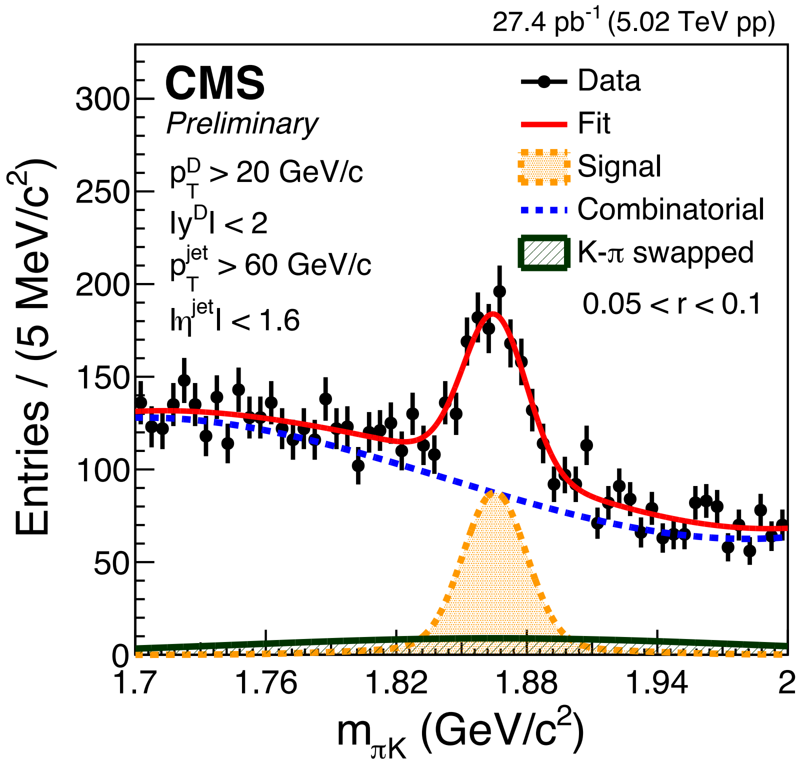
Submitted to PRL

JHEP 05(2018) 006

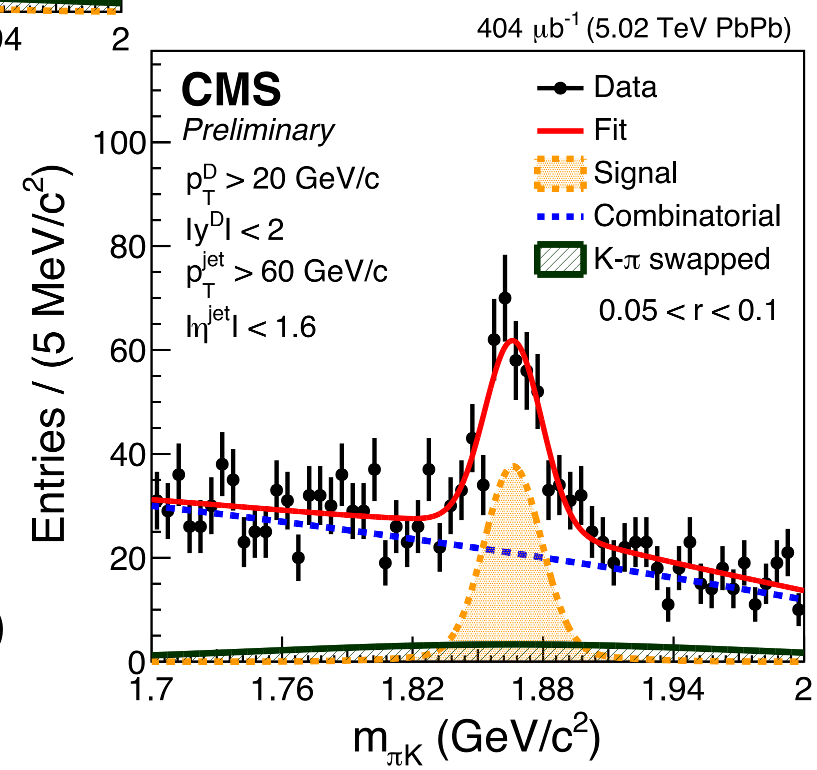
- Inclusive jet near-cone depletion is not seen in gamma+jets
- Note the jet pT of these results differ by ~60 GeV

D+jet Correlations to Study Quenching





In pp

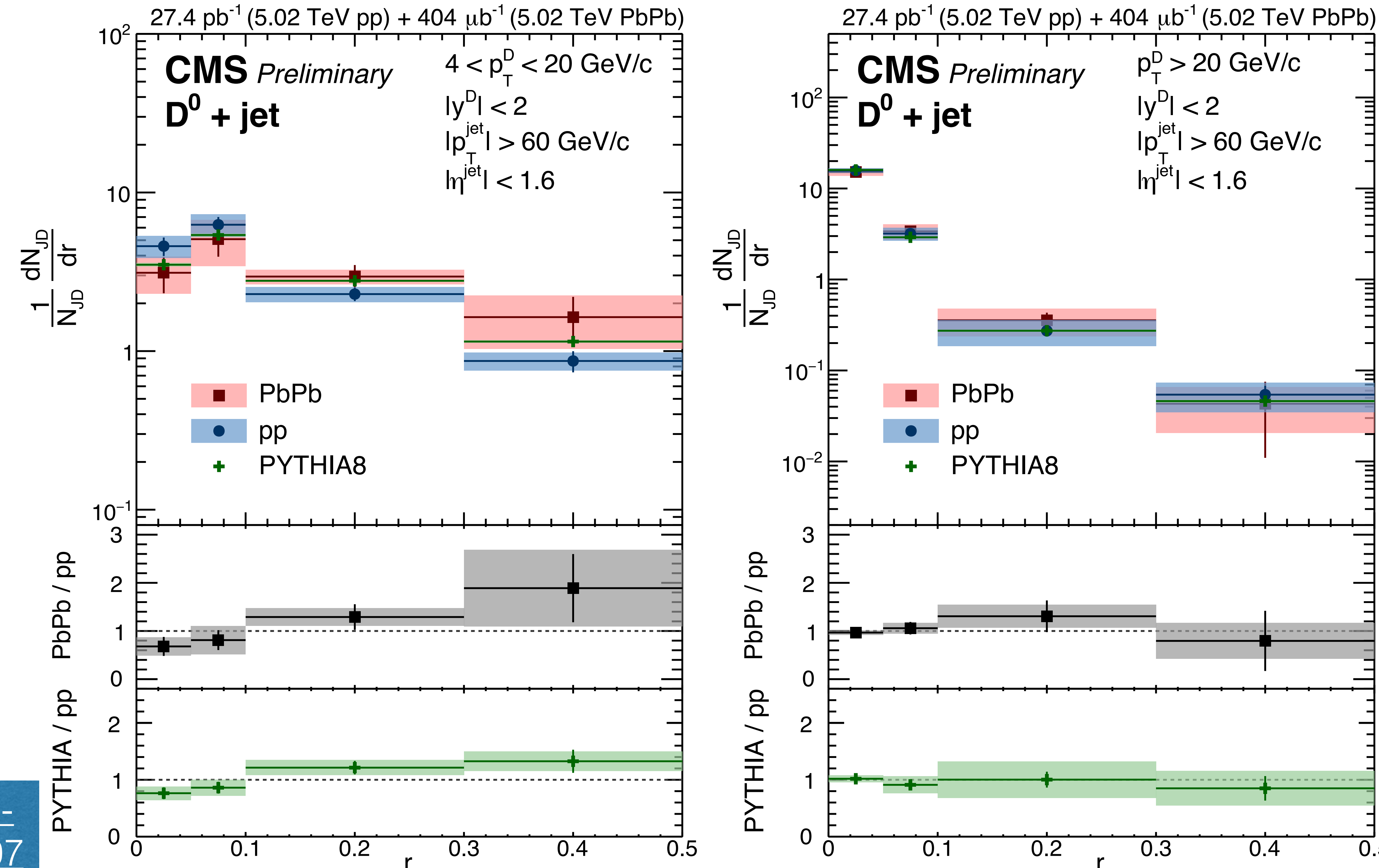


In PbPb

CMS-PAS-HIN-18-007

- Can also study energy redistribution by tagging constituent
- Replace lighter masses with charm mass

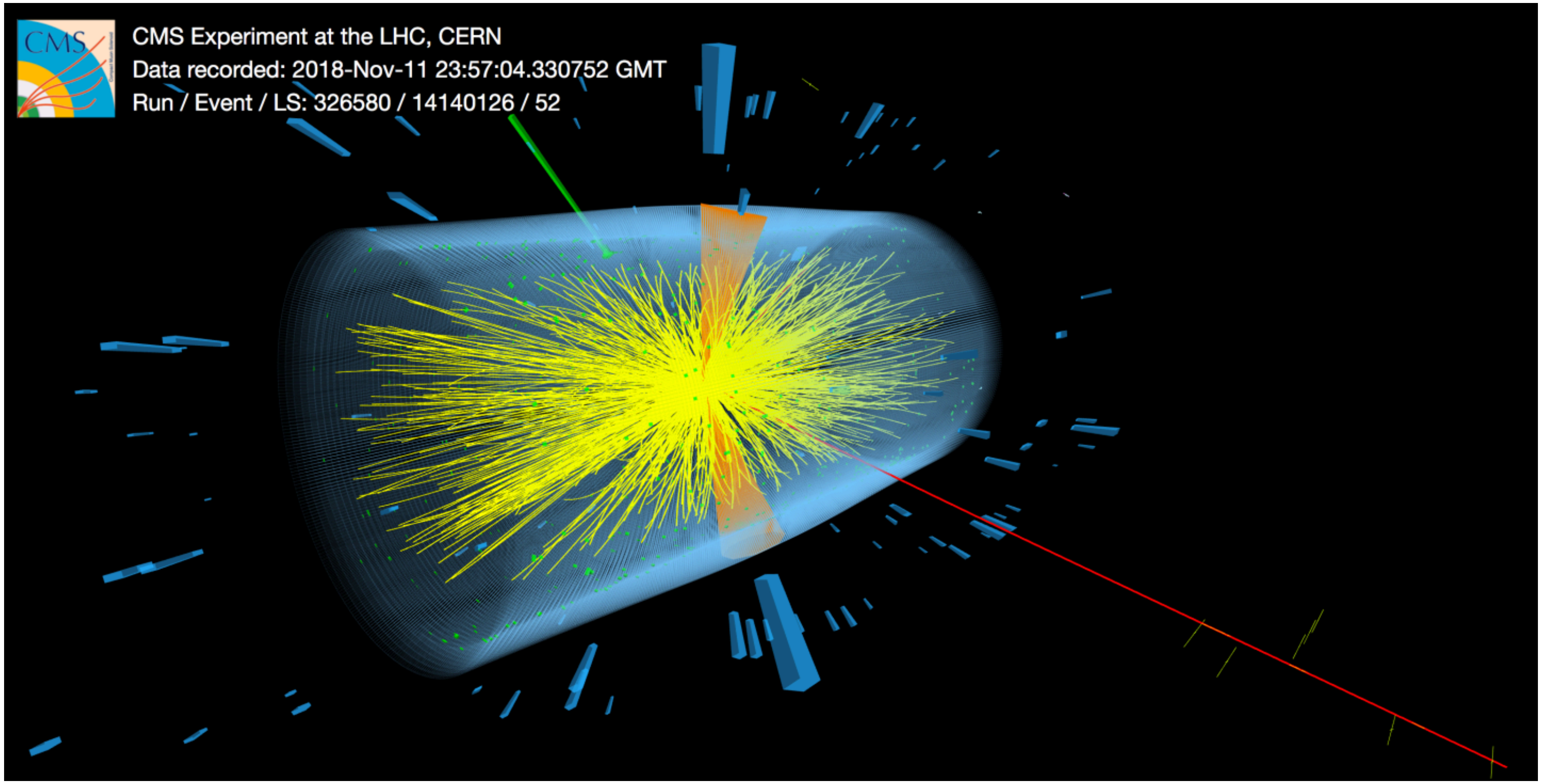
D+jet Correlations Results



CMS-PAS-HIN-18-007

- No modification observed for high-pT D in PbPb
- Low-pT D shape modified (normalization N_{JD})

Future Directions



- Successful data-taking at end of 2018!
- Two exciting analysis programs
  - Continue current progression with boson/HF-tagged substructure, addition of new substructure observables
  - New probes

Updating Constituent Subtraction at CMS

- Substitute iterative pedestal estimation of underlying event in η-strips into CS (see backup)
  - Expanding CS jets to forward region, |η| > 1.3
- Add modulation to underlying event in φ to account for flow

Constituent Subtraction (CS)

1: ~~Estimated by median unsubtracted k_t jet~~

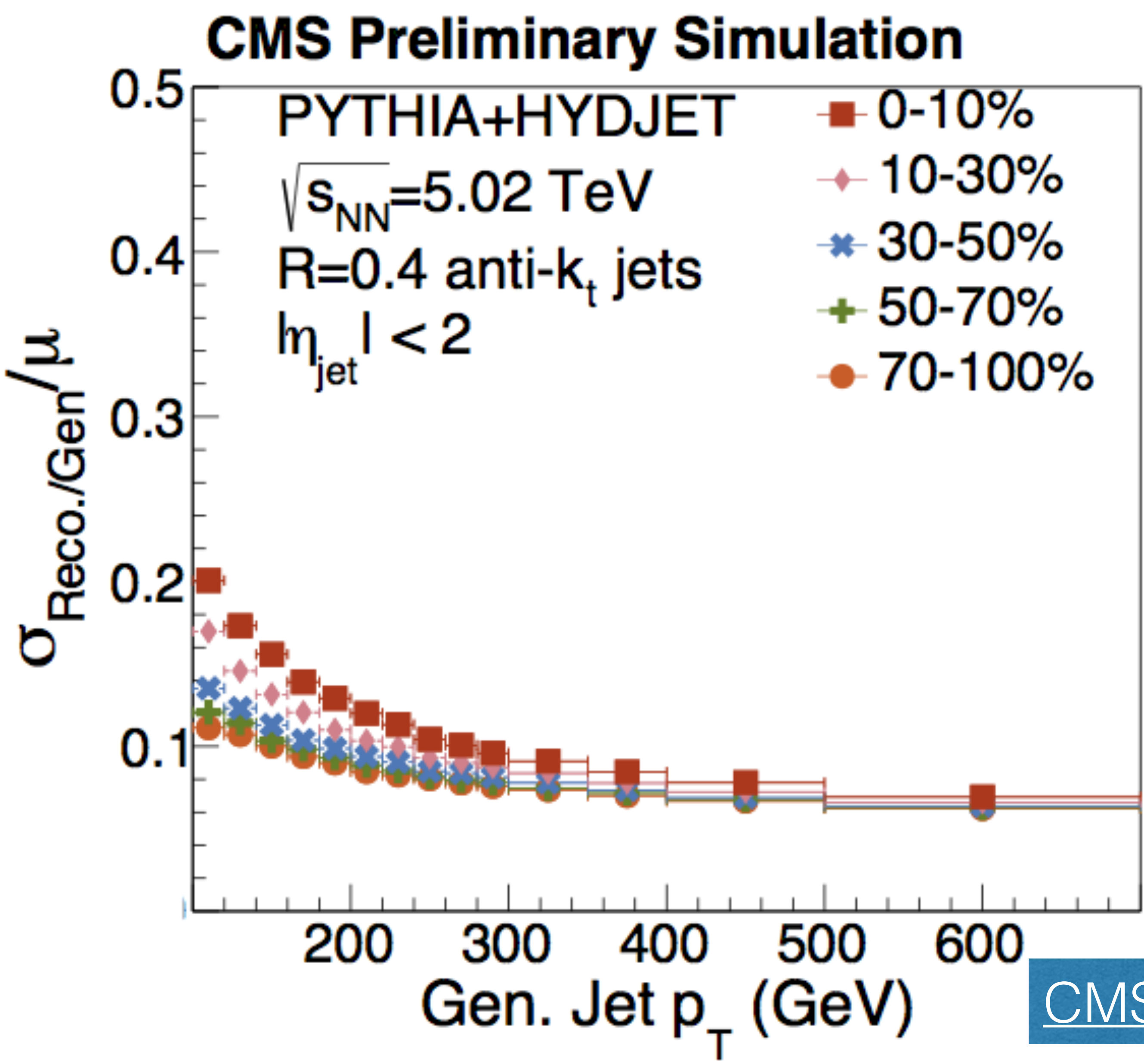
2: Add "ghost" particles randomly with fixed area and p_T according to rho, subtracting from real particles iteratively until gone

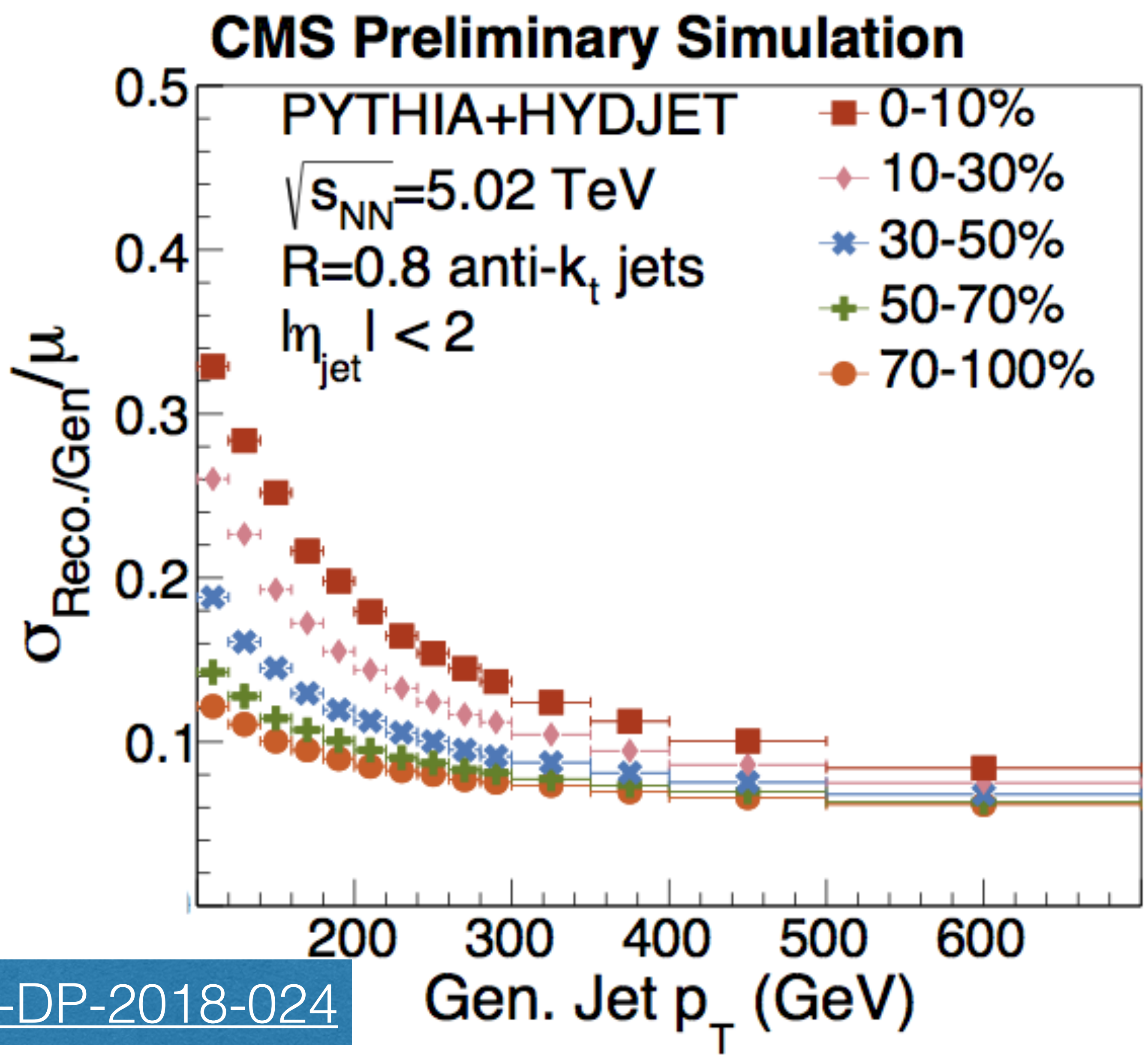
See JHEP06 (2014) 092

→ 1a: ρ estimated in η-strips defined by detector geometry

1b: Add event-by-event φ modulation

Jet Energy Resolution at R=0.4 and R=0.8

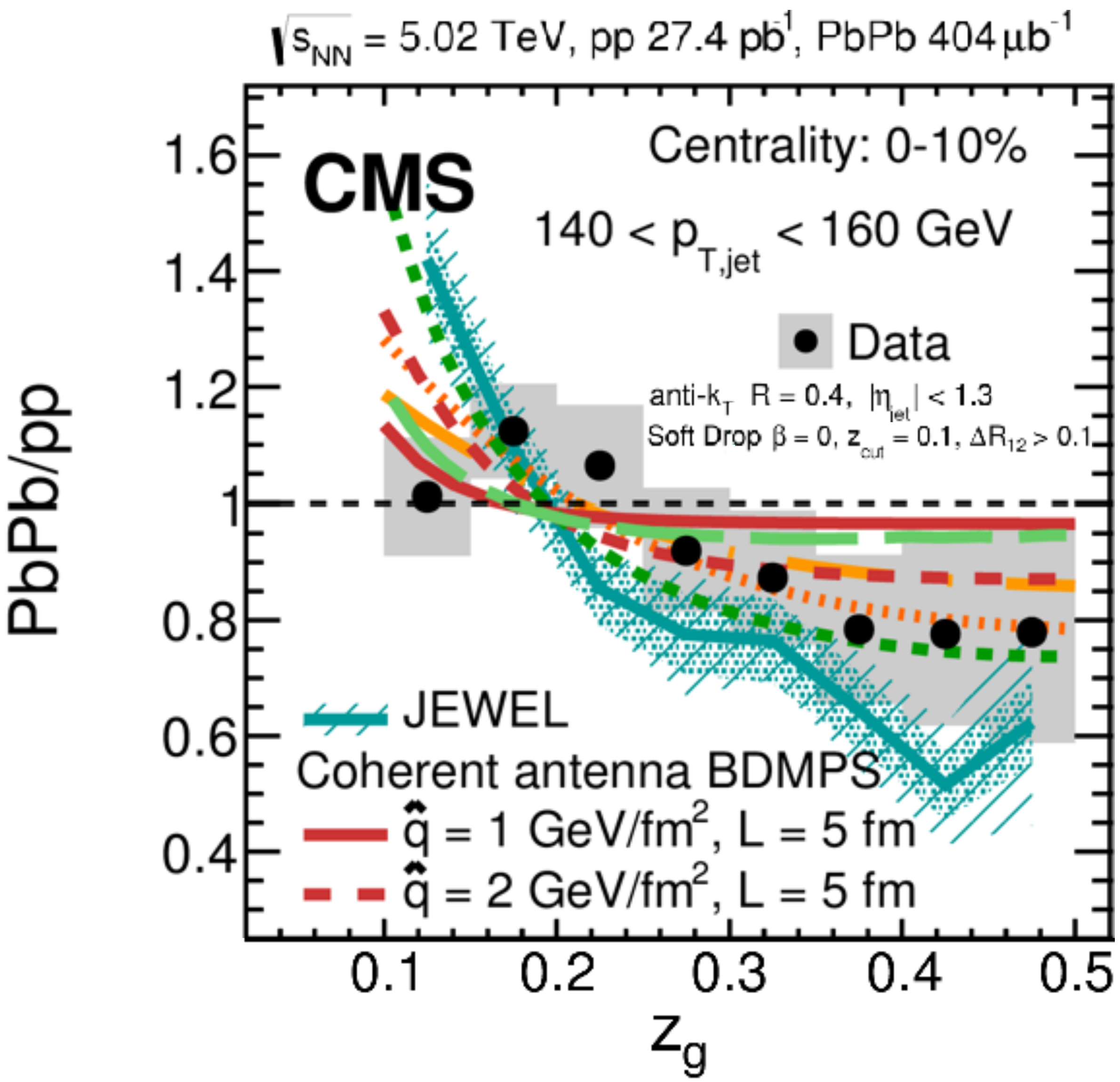


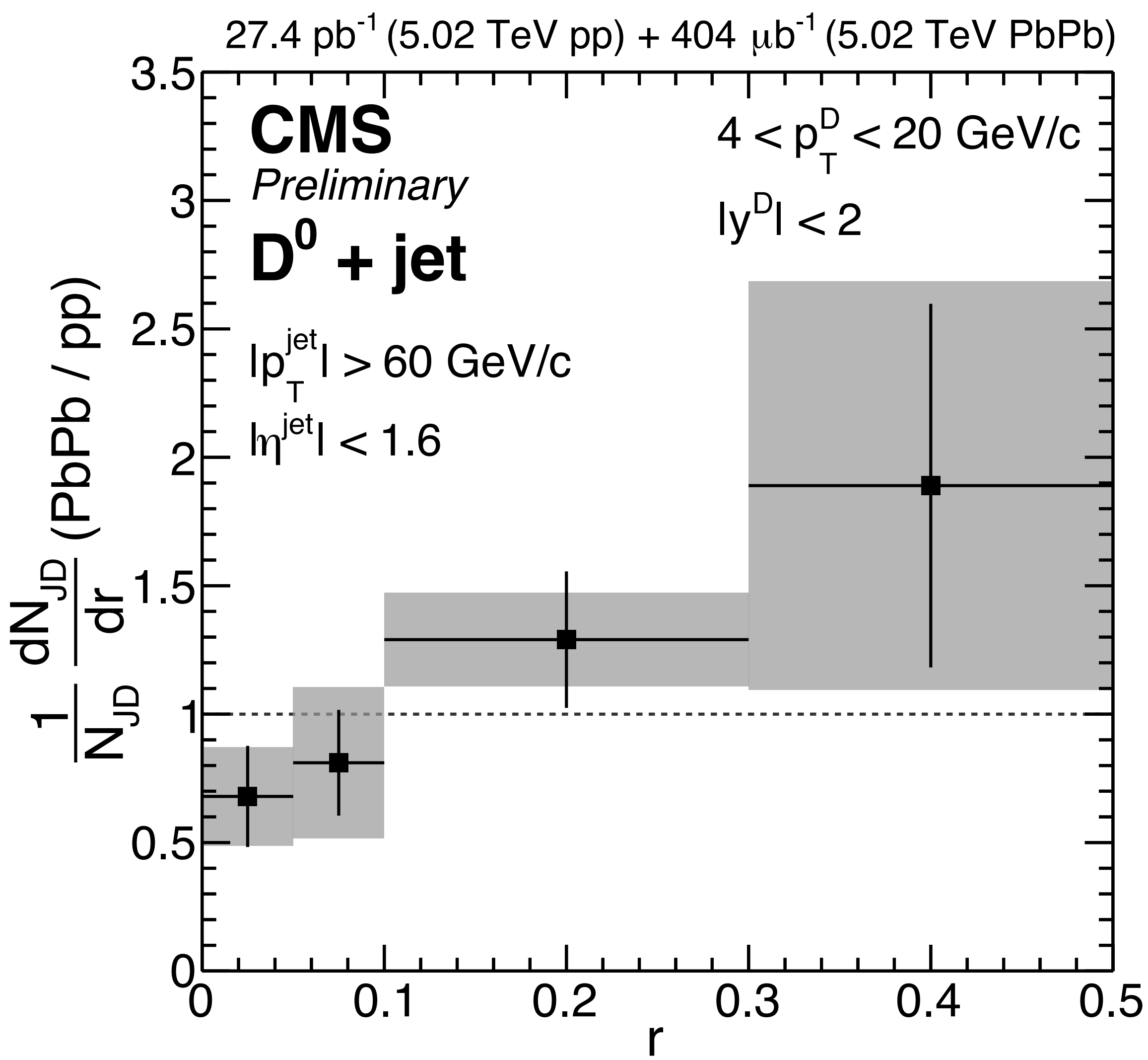


CMS-DP-2018-024

- Energy resolution of R=0.4 (**Left**) and R=0.8 (**Right**) jets with new CS
- In large cone, UE drives high resolution at low-p_T
  - JER ~18% at 200 GeV (R=0.8)

Conclusions



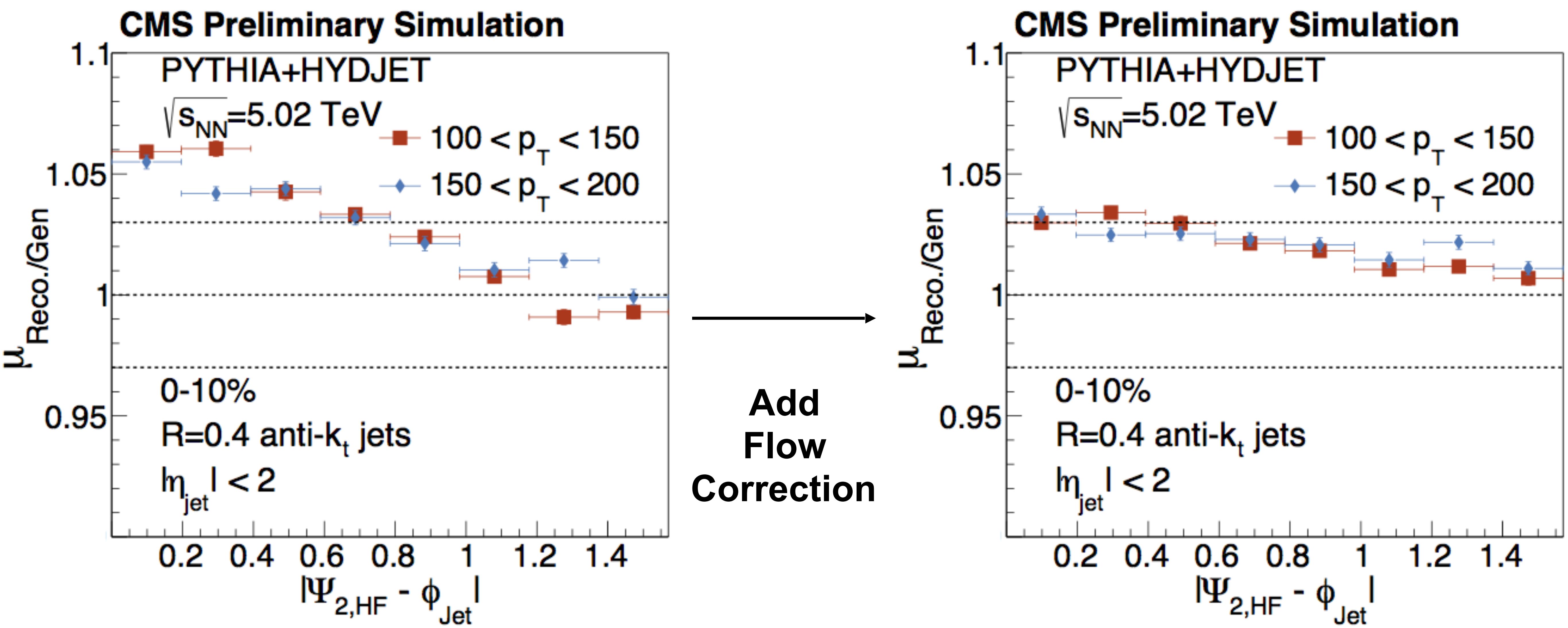


- Inclusive jet substructure measurements show no modification with “core” grooming
  - Modification observed with “flat” grooming in z_g, M_g/p_T
- Jet shapes are studied with photon tags and by jet correlation with charm

The MIT group’s work was supported by US DOE-NP

Backup

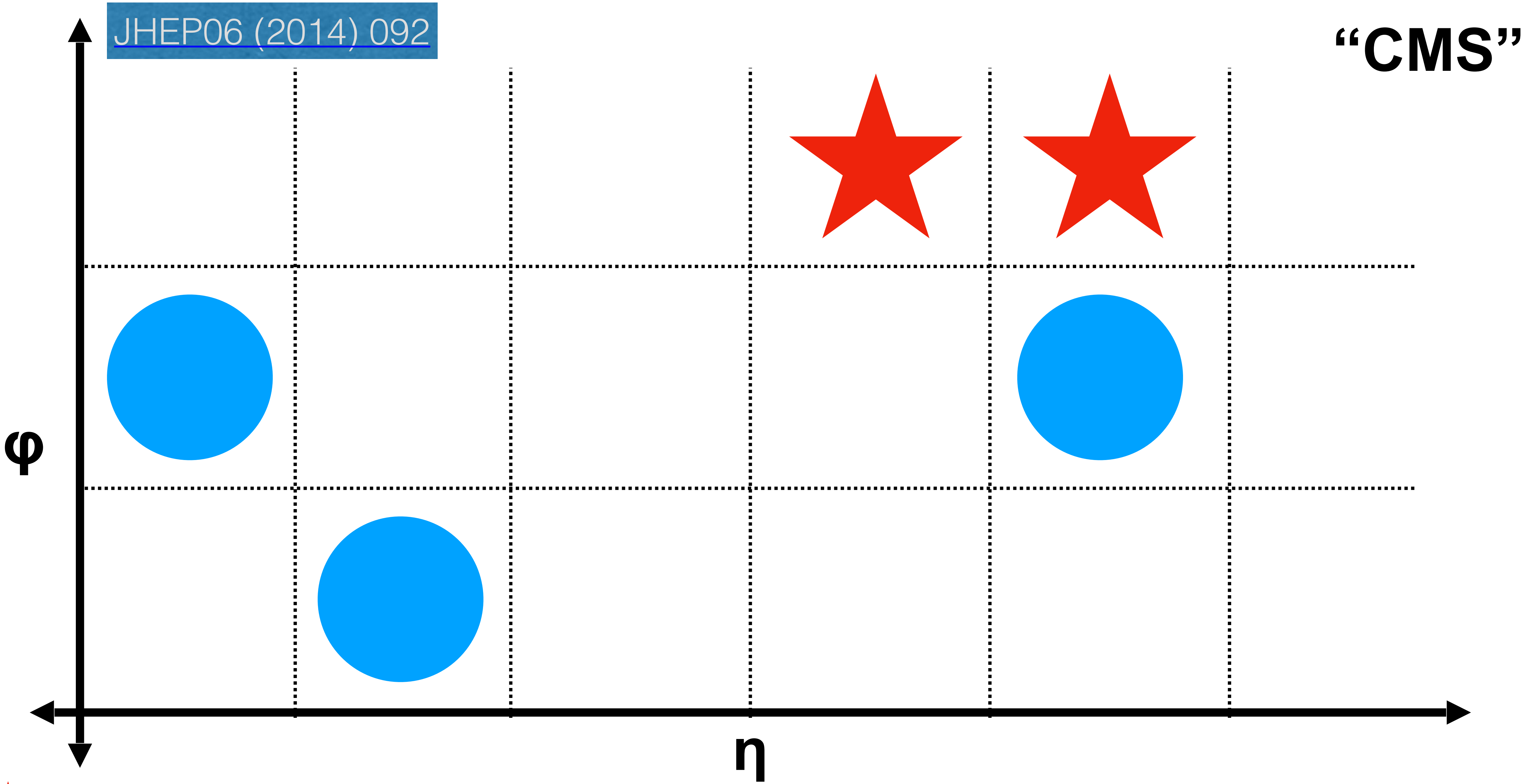
Scale Closure vs. Event Plane (R=0.4)



- Jet energy scale closure as function of event plane for R=0.4 w/o flow correction (**Left**) and with flow correction (**Right**)
- Some flattening of scale less than corresponding R=0.8 case

Illustration of CS Subtraction Iterations

Constituent Subtraction



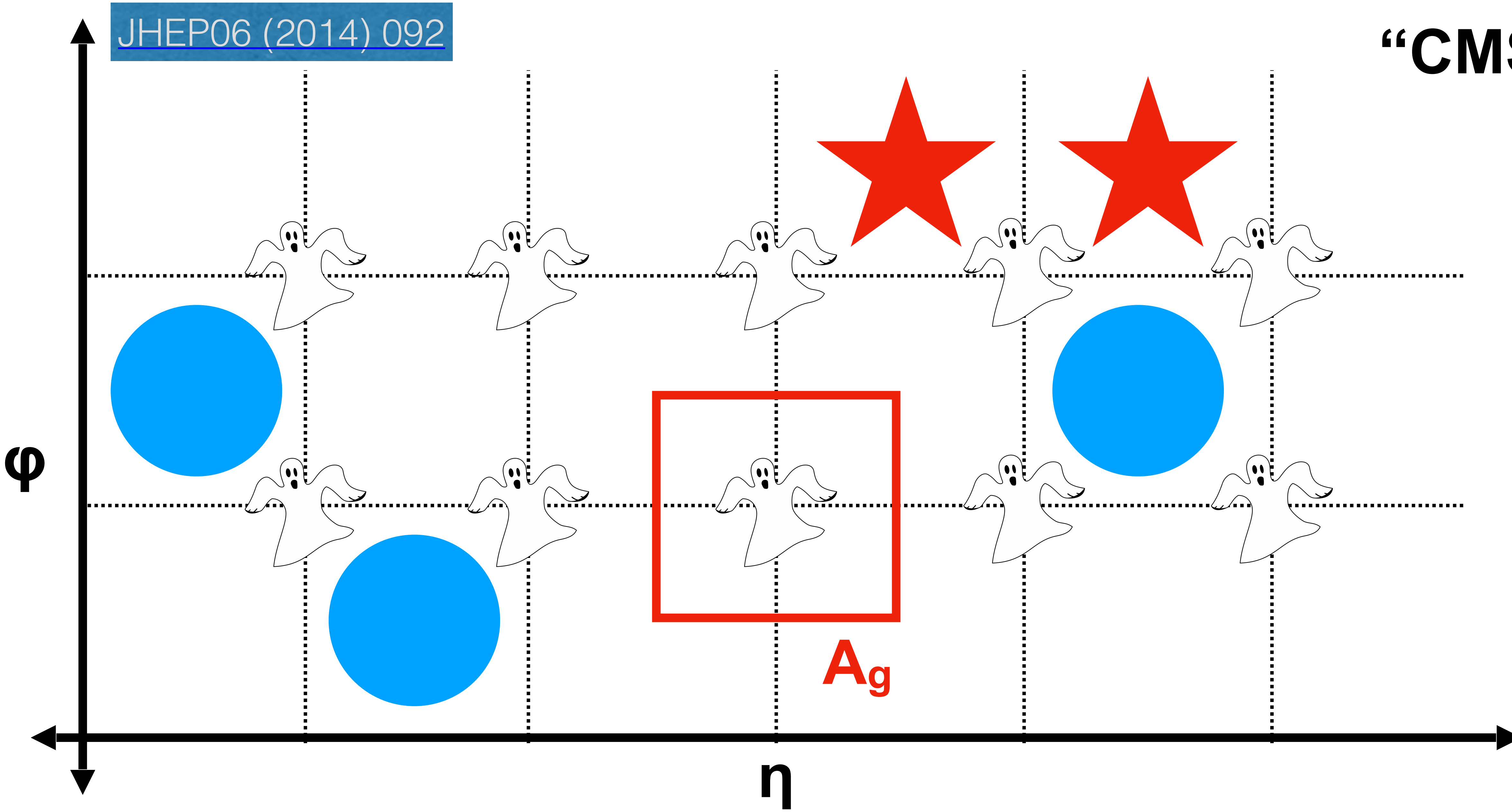
SIGNAL: Hard-scattering in PbPb collision producing jets

UNDERLYING EVENT: Uncorrelated particles from other nucleon-nucleon interactions

Constituent Subtraction

JHEP06 (2014) 092

“CMS”



GHOST PARTICLES: Artificial particles added to the event with fixed area. Ghosts are given a p_T according to ρ times the area the inhabit, A_g

Constituent Subtraction

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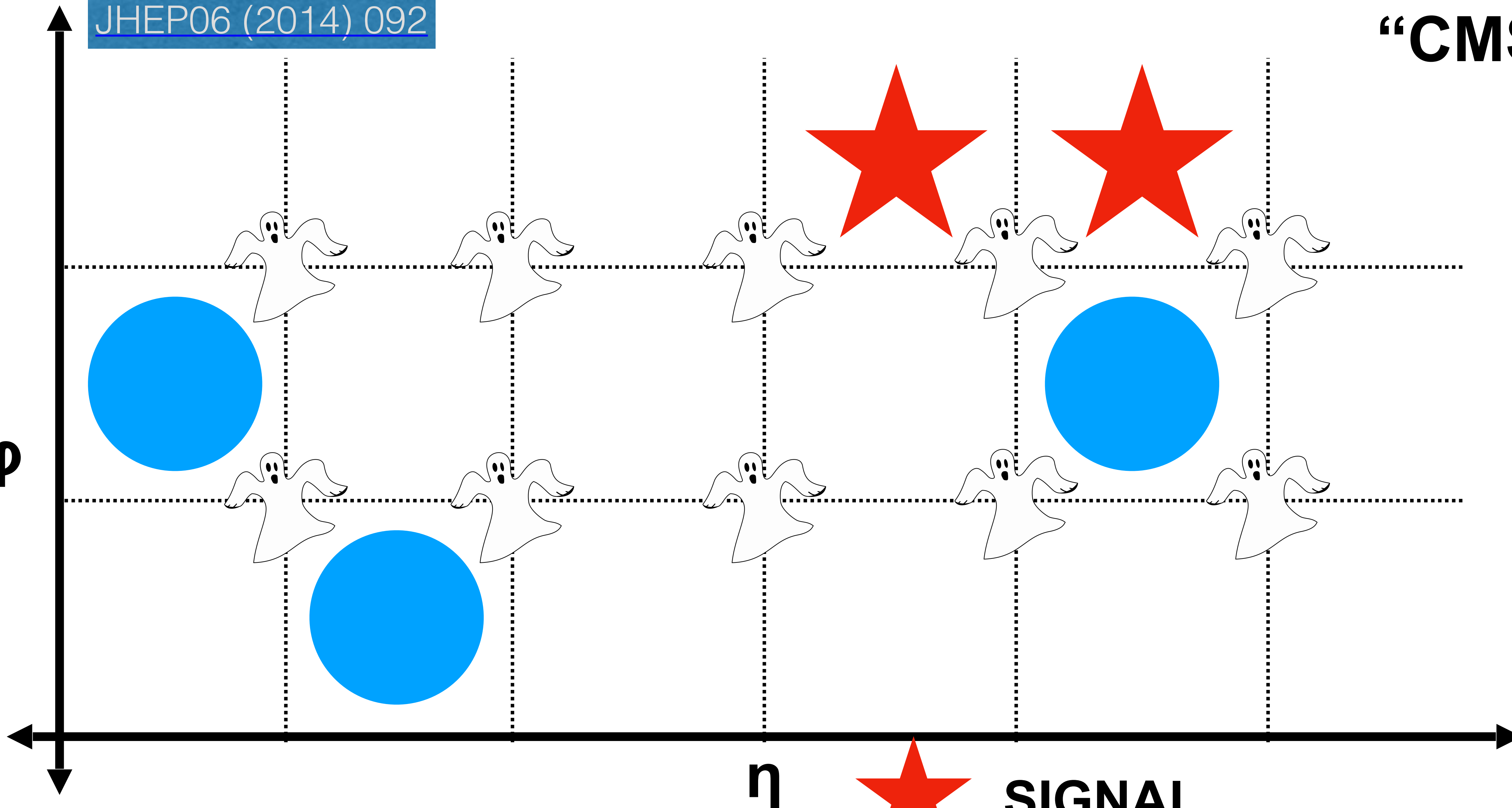
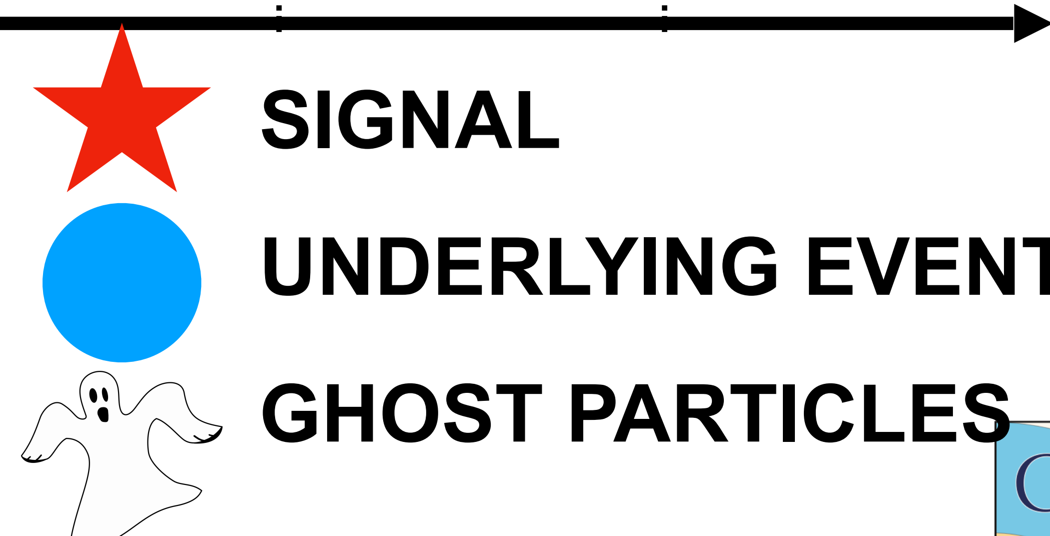
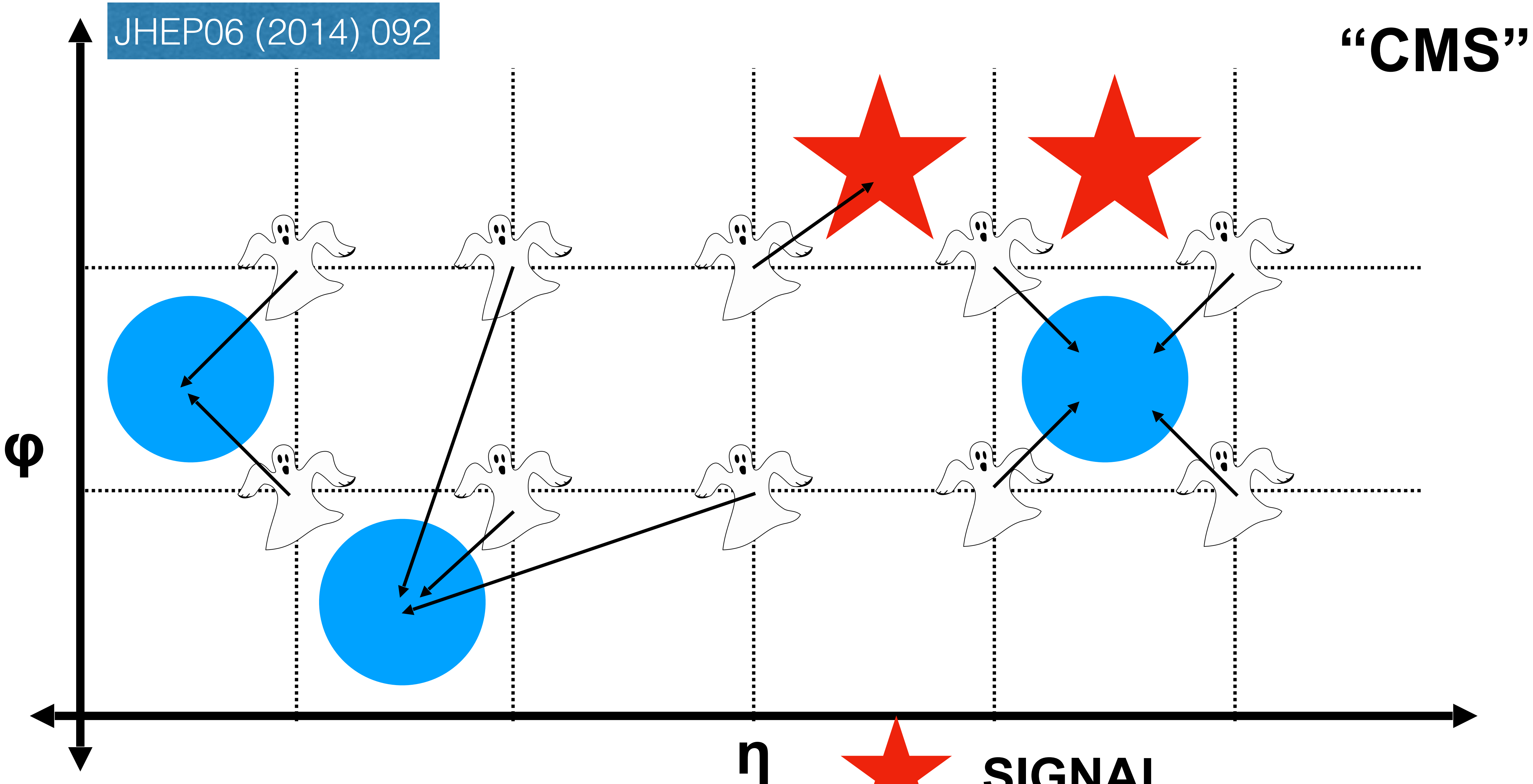


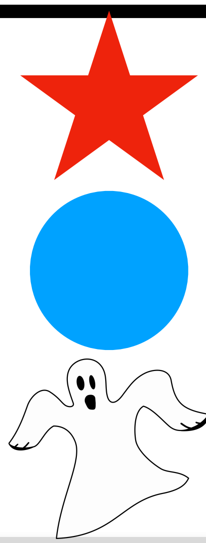


- Add "ghost" particles with fixed area according to: $p_{\mathrm{T}}^{g} = A_g \cdot \rho,$

$$m_{\delta}^{g} = A_g \cdot \rho_m.$$

Constituent Subtraction

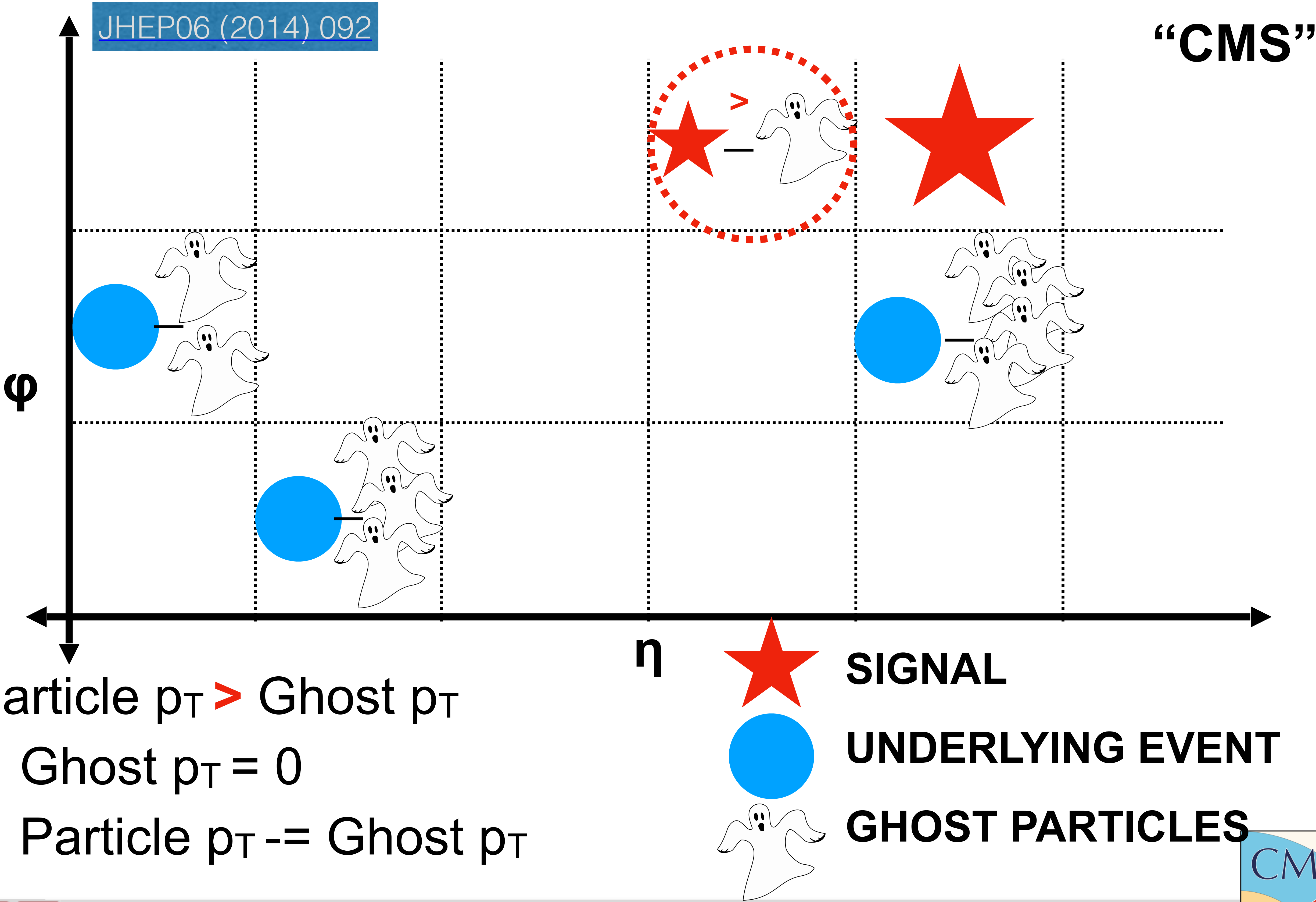




- Combine iteratively with real particles by minimizing metric:

$$\Delta R_{i,k} = p_{\mathrm{T}i}^{g} \cdot \sqrt{\left(y_i - y_k^g\right)^2 + \left(\phi_i - \phi_k^g\right)^2}.$$

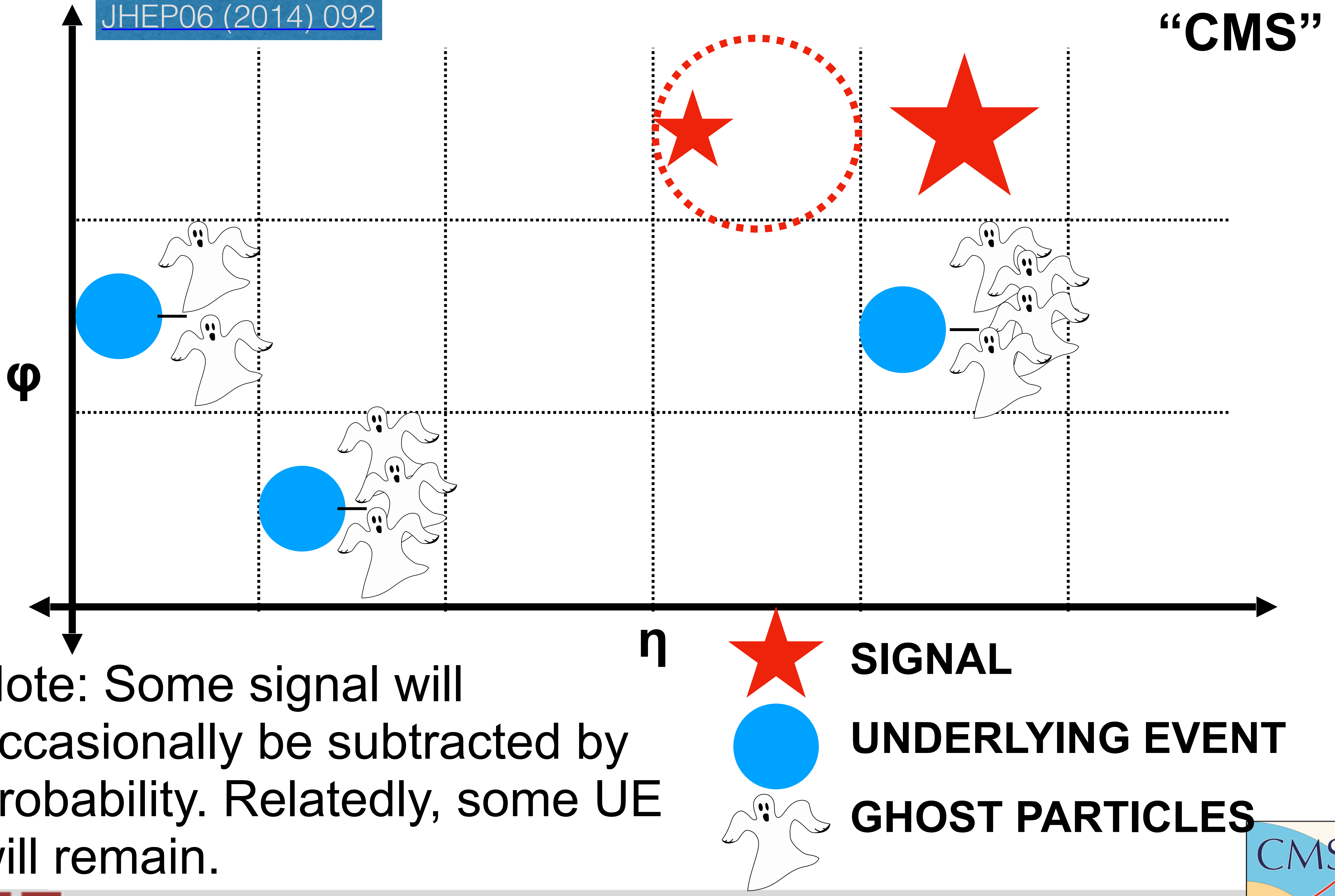
Constituent Subtraction



- Particle p_T > Ghost p_T
  - Ghost $p_T = 0$
  - Particle p_T -= Ghost p_T

Constituent Subtraction

JHEP06 (2014) 092

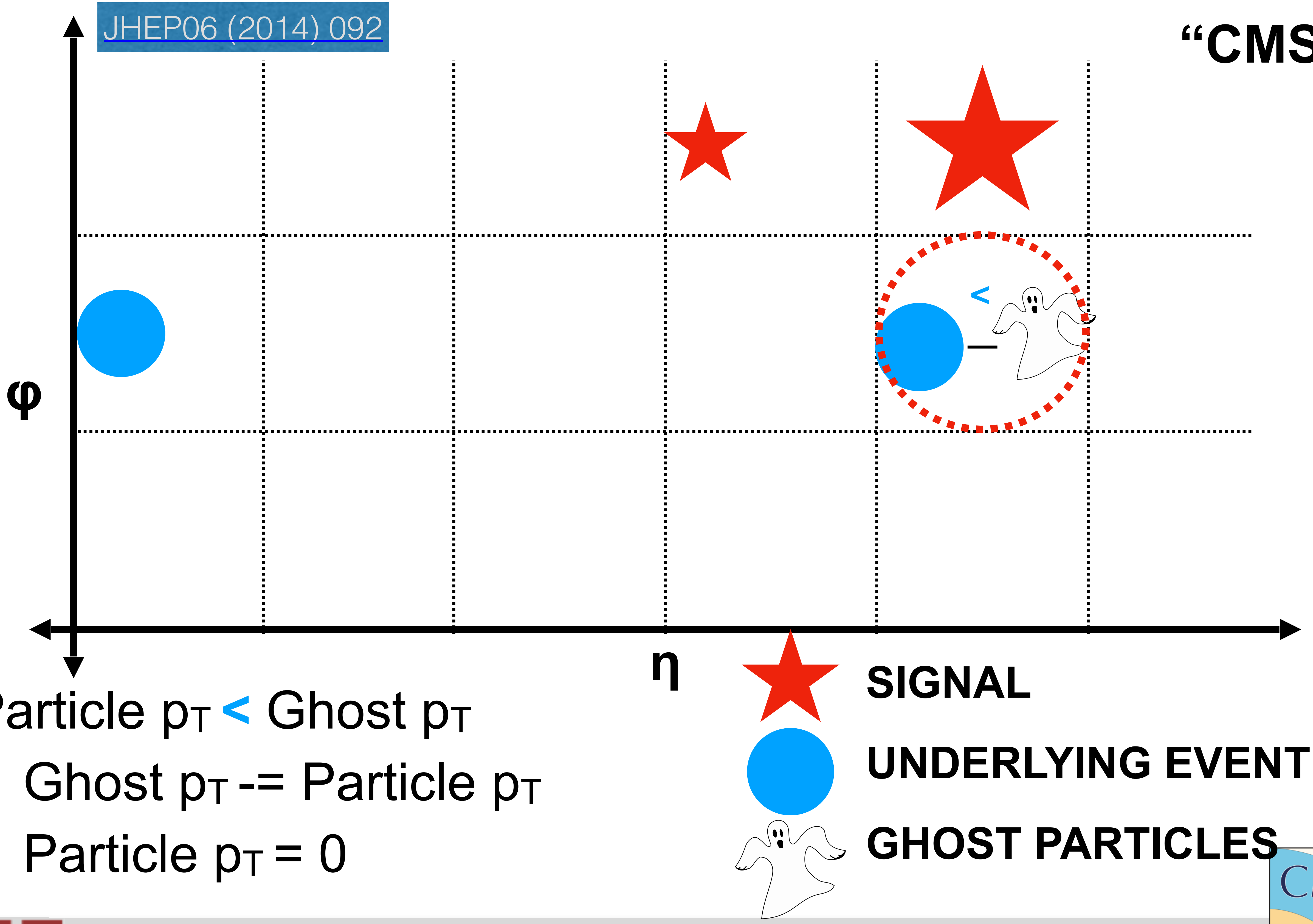


- Note: Some signal will occasionally be subtracted by probability. Relatedly, some UE will remain.

Constituent Subtraction

JHEP06 (2014) 092

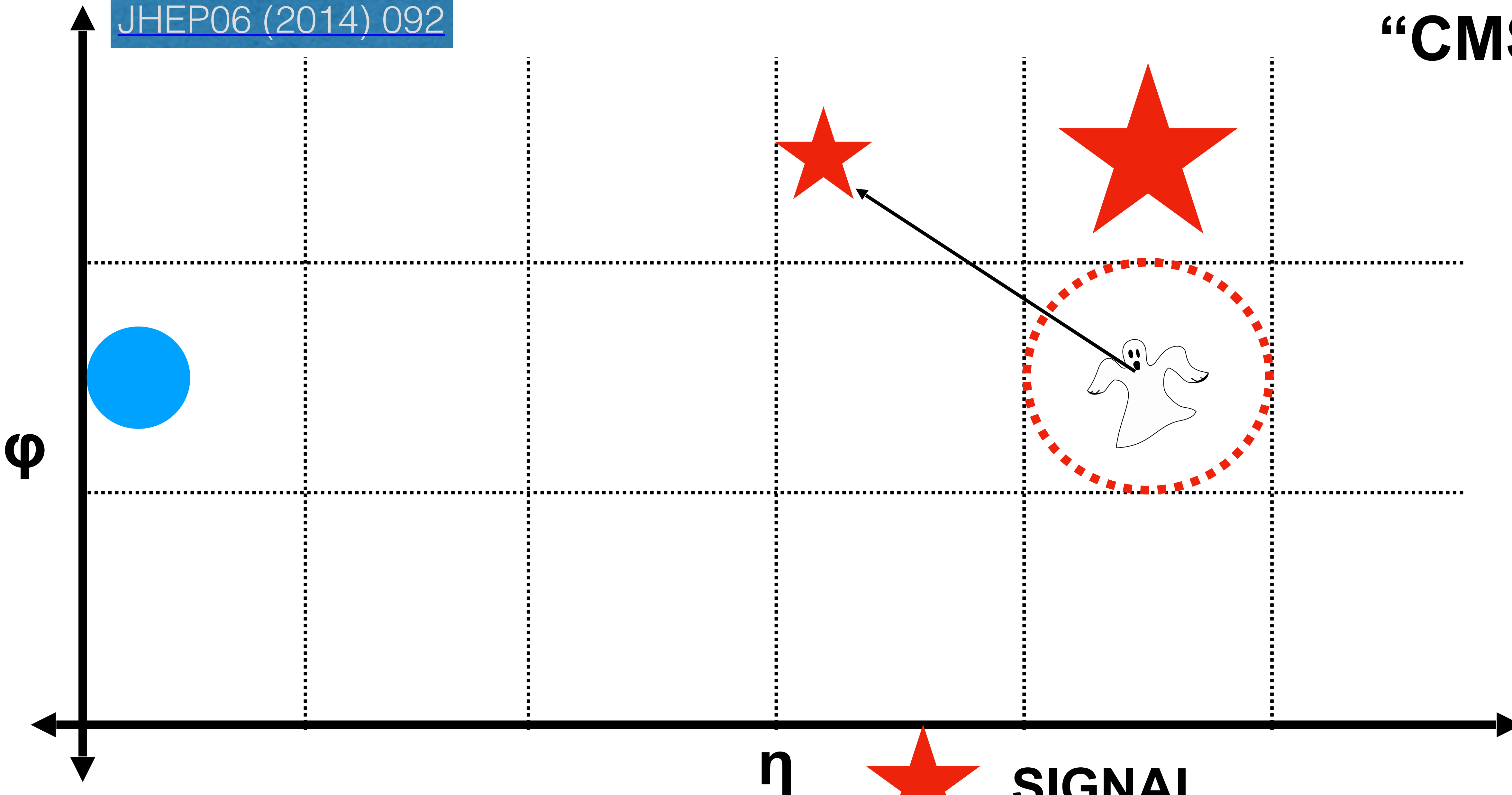
“CMS”

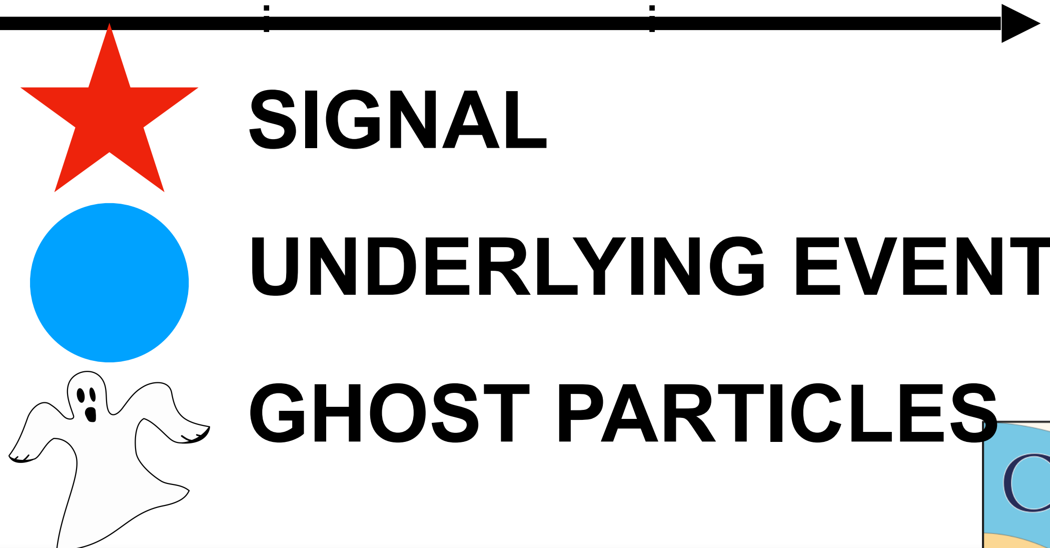


- Particle p_T < Ghost p_T
  - Ghost p_T -= Particle p_T
  - Particle $p_T = 0$

Constituent Subtraction

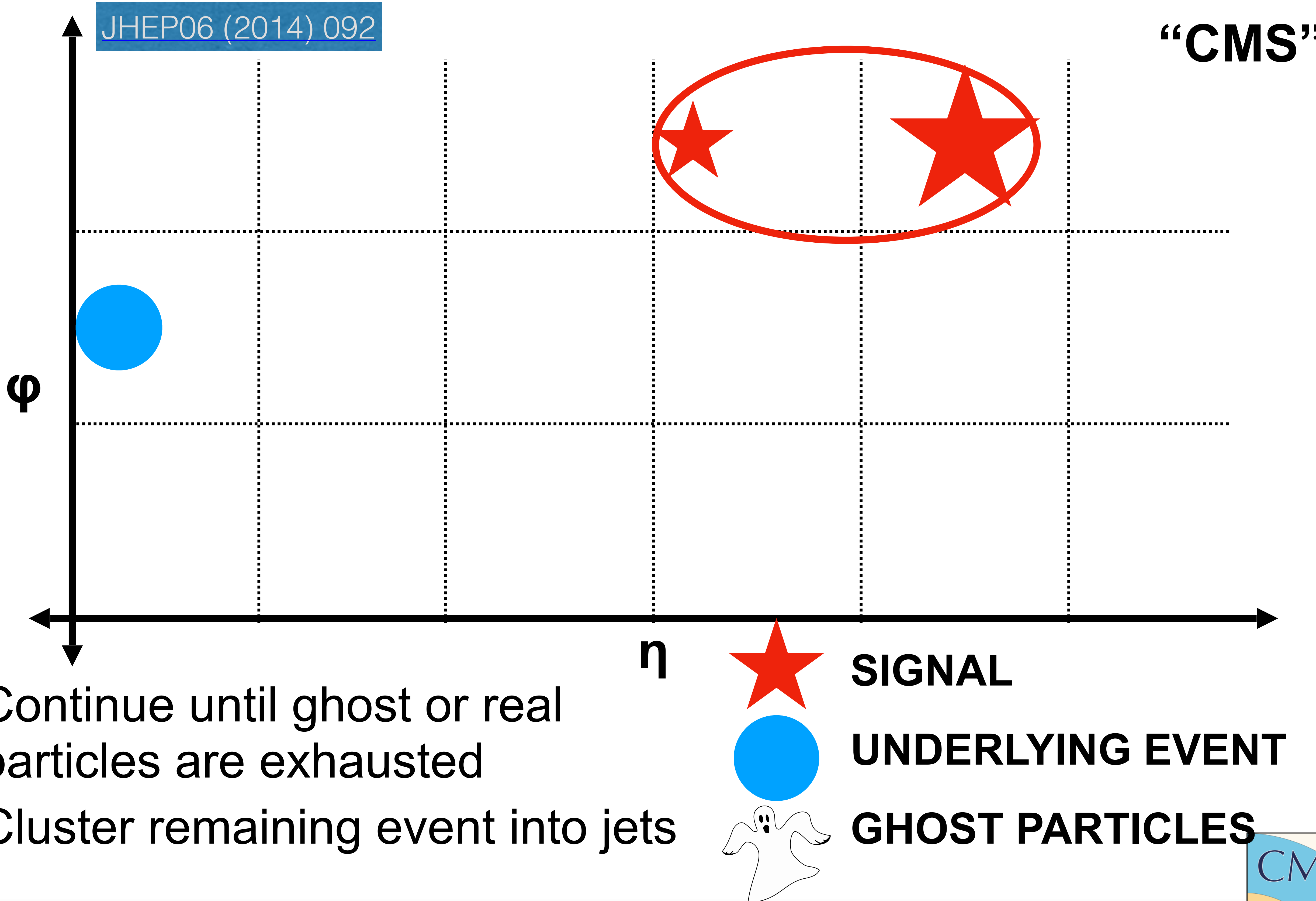
JHEP06 (2014) 092





- Particle p_T < Ghost p_T
  - Ghost p_T -= Particle p_T
  - Particle p_T = 0

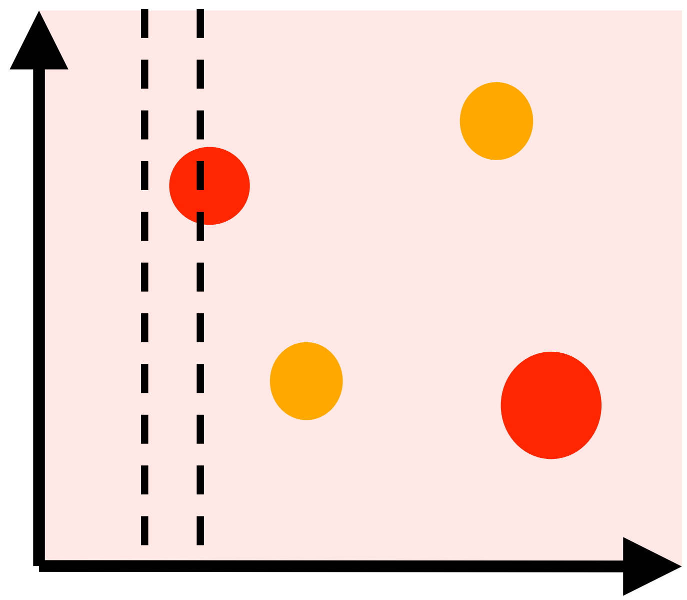
Constituent Subtraction



- Continue until ghost or real particles are exhausted
- Cluster remaining event into jets

Illustration of PU Subtraction Iterations

Iterative Pedestal Algorithm



1. $\langle E_T \rangle$ calculated in strips of η.
Subtract $\langle E_T \rangle + \sigma$

- ρ or $\langle E_T \rangle$ is calculated in strips of rapidity
  - Follows HCal tower geometry ($\Delta\eta$=0.087 at mid-rapidity)
- Constituents are combined into pseudotowers
- Pseudotower energy is reduced by $\langle E_T \rangle$ plus a compensating $\sigma(E_T)$
- Negative towers are zeroed

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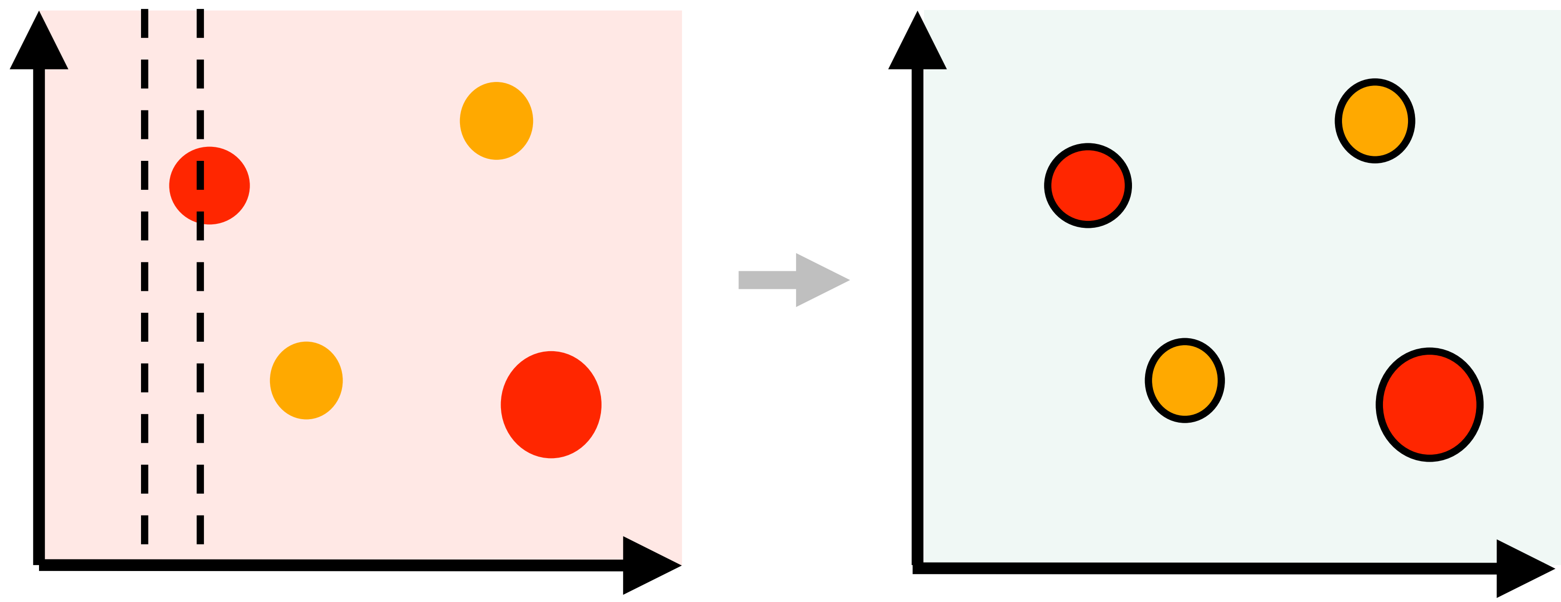
Iterative Pedestal Algorithm



1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$

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

- Subtracted towers are clustered into anti-k_t jets
- On first iteration, jets are necessarily oversubtracted
  - Included in estimation of underlying event

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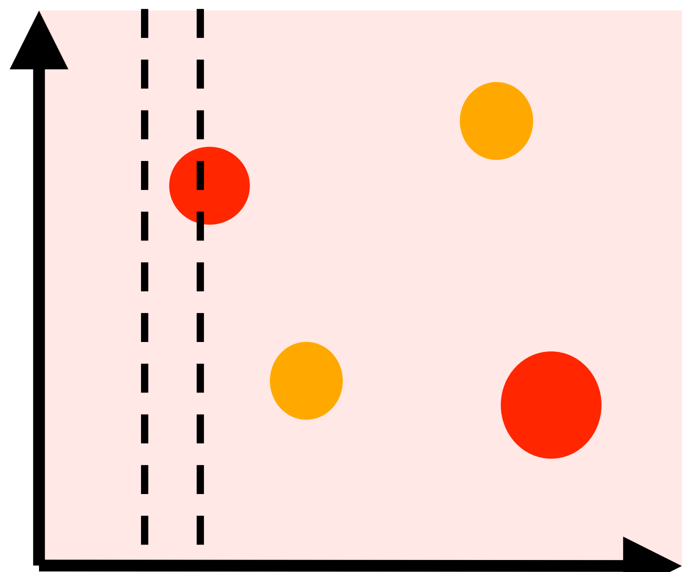
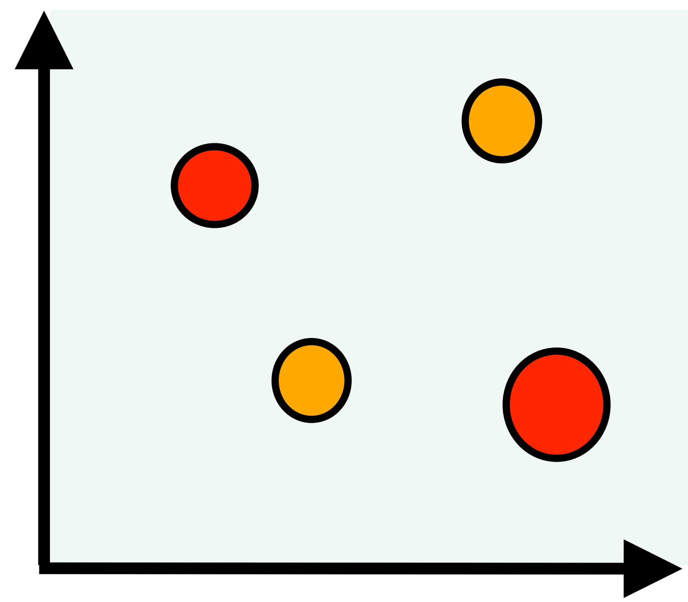
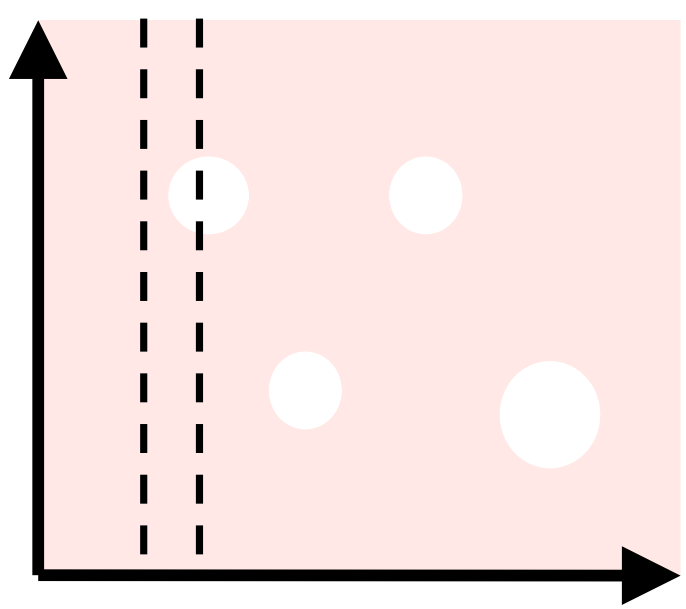
Iterative Pedestal Algorithm



1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$



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



3. Exclude reconstructed jets and re-estimate background

- A second iteration is run excluding “jetty” regions of the detector from each η-strip extraction
- Reduced jet bias to estimation of underlying event

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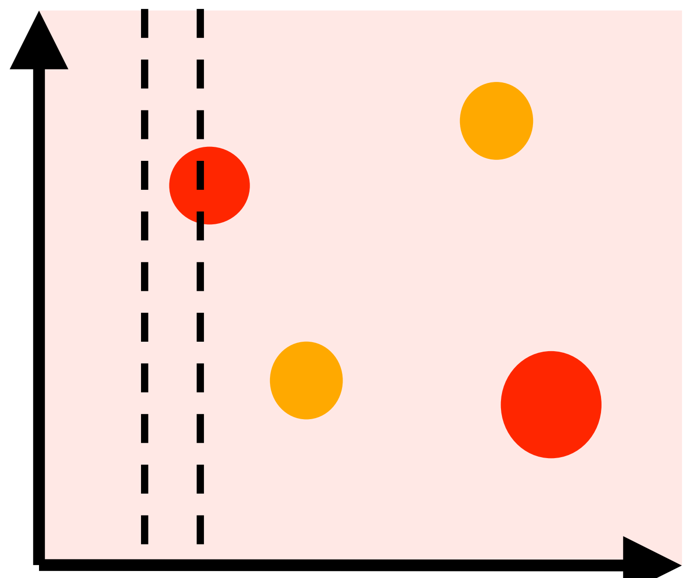
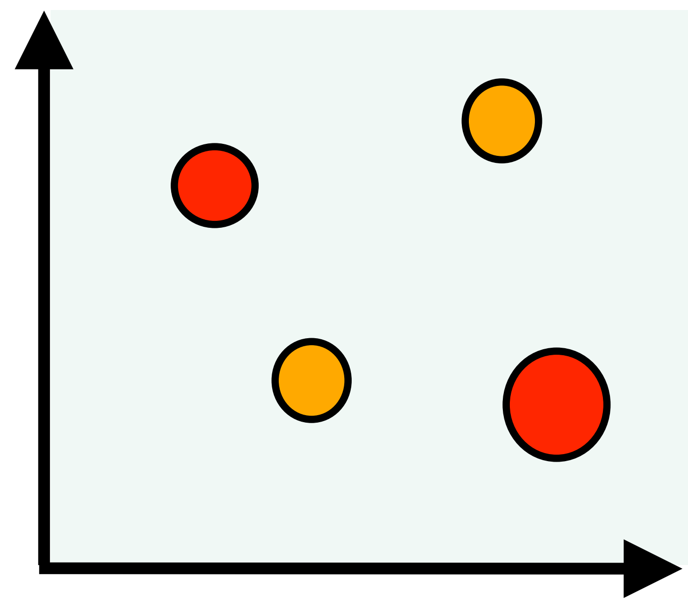
Iterative Pedestal Algorithm



1. $\langle E_T \rangle$ calculated in strips of η.
Subtract $\langle E_T \rangle + \sigma$



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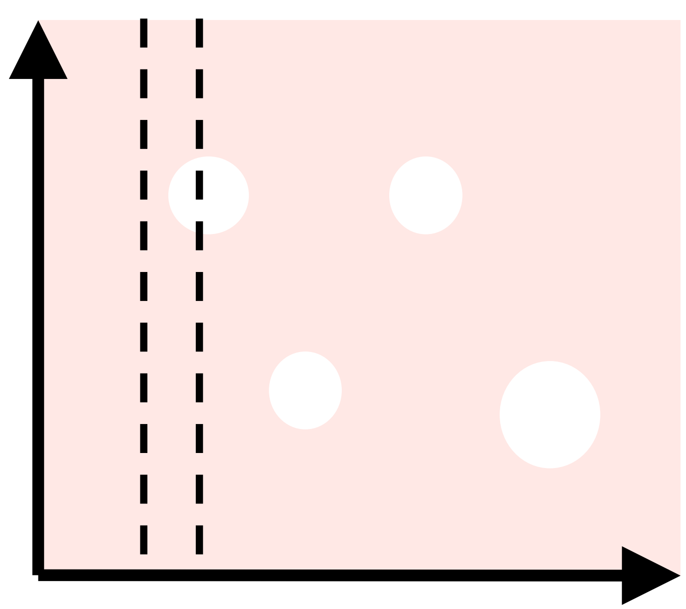

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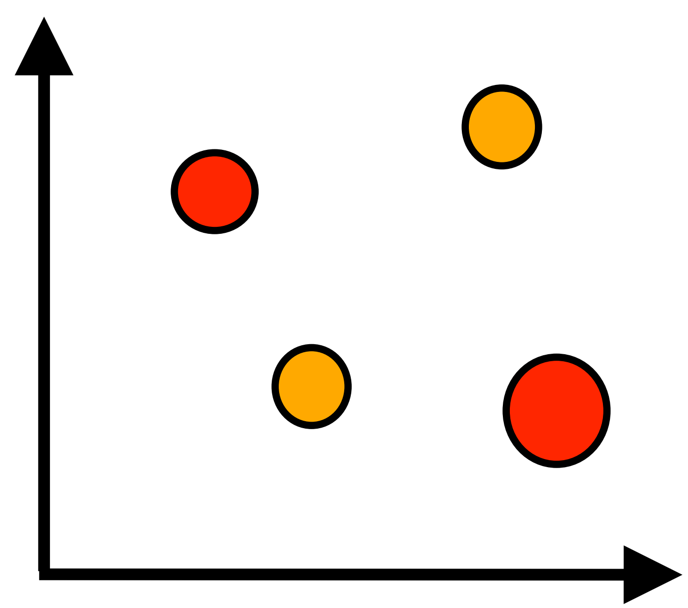

4. Re-run anti-k_T algorithm to get final jets

- Subtract towers according to new estimate in same manner as first iteration
- Cluster newly subtracted towers into final set of anti-k_t jets

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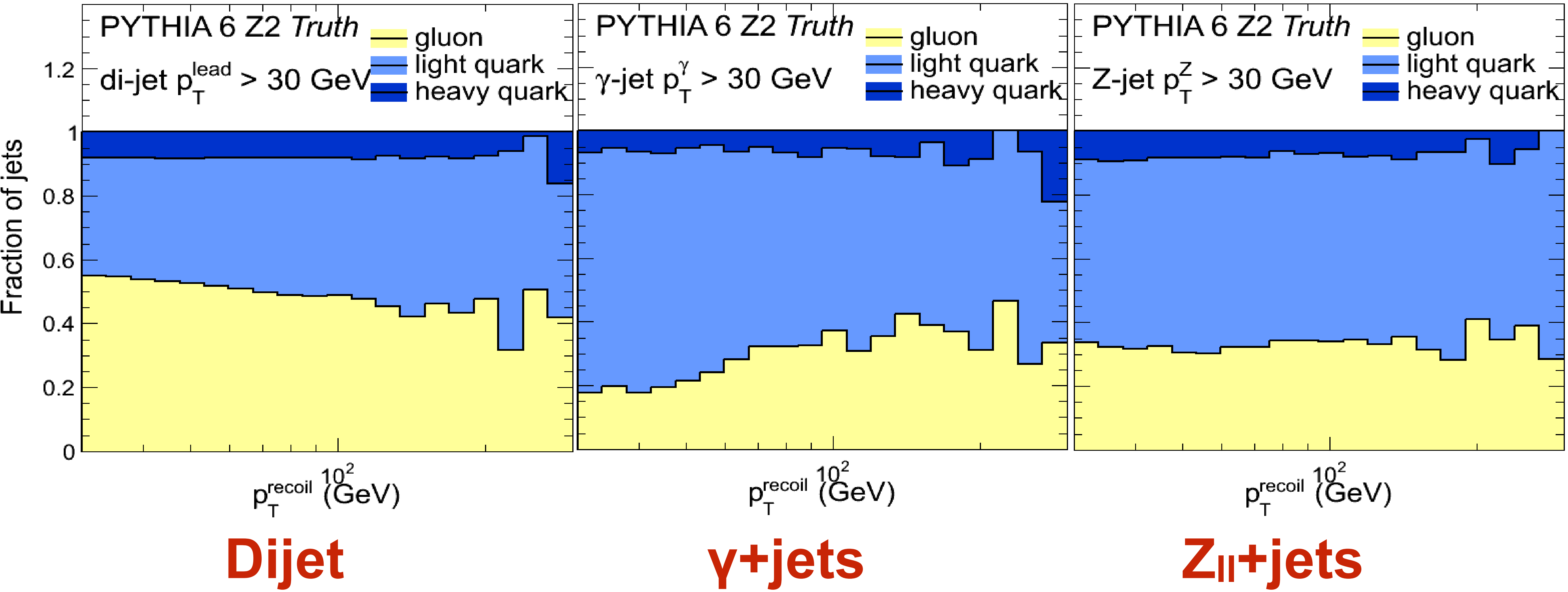
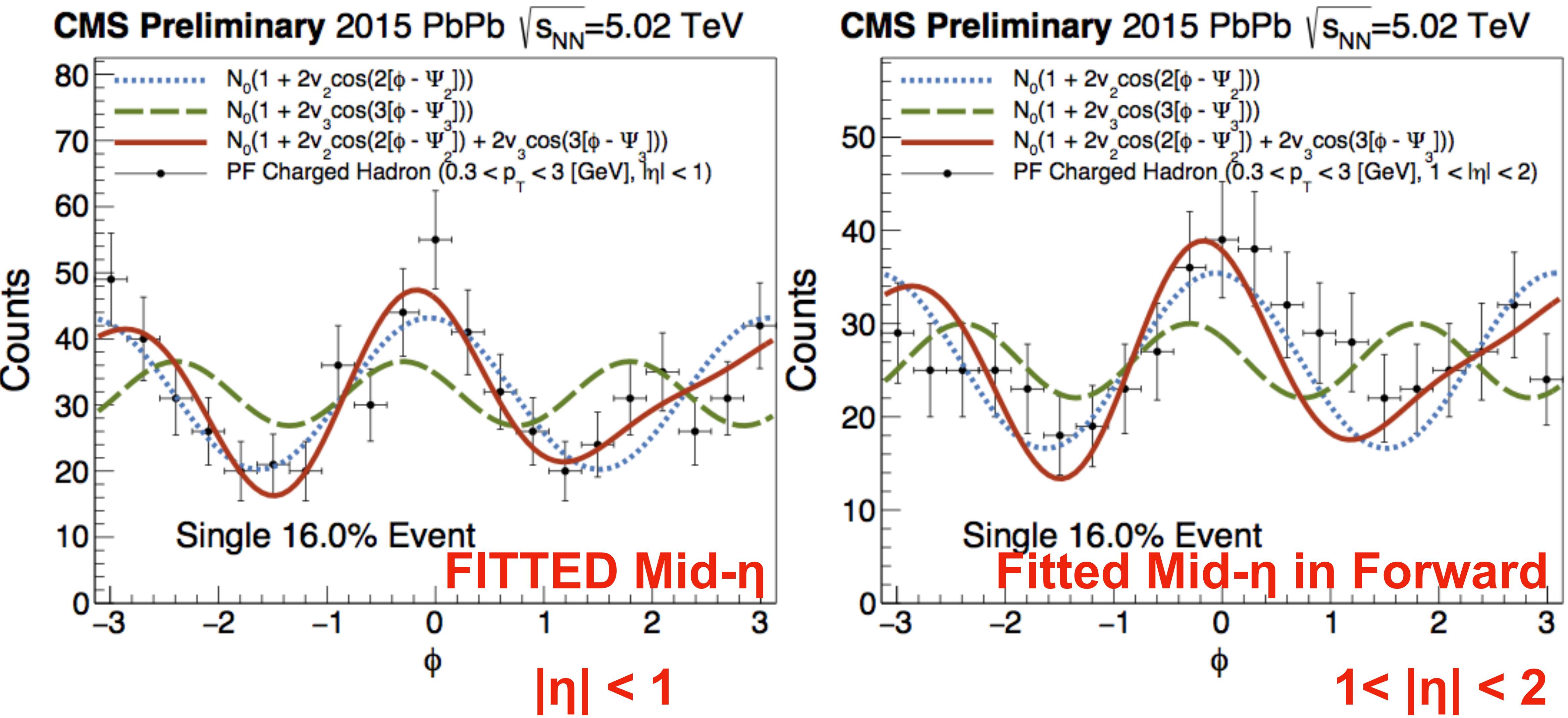
Q/G Fraction of Dijet and Boson+Jet



- Dijet has greater fraction of gluon relative to both boson+jets
- Z and γ + jets fraction comparable above 100 GeV
- Below 100, γ has greater fraction quark than Z

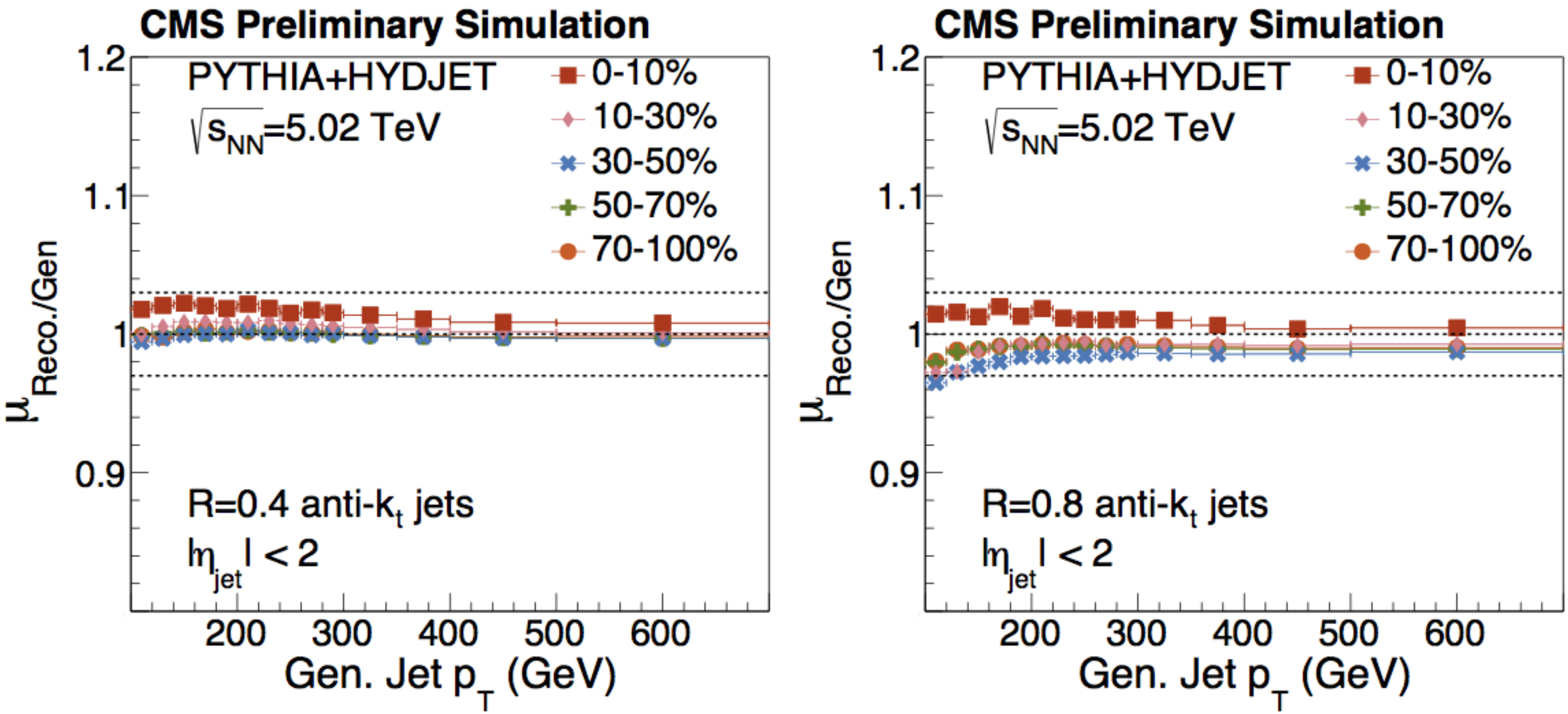
Estimating Flow Event-by-Event



Following Example Of: Phys.Lett. B 753 (2016) 511-525

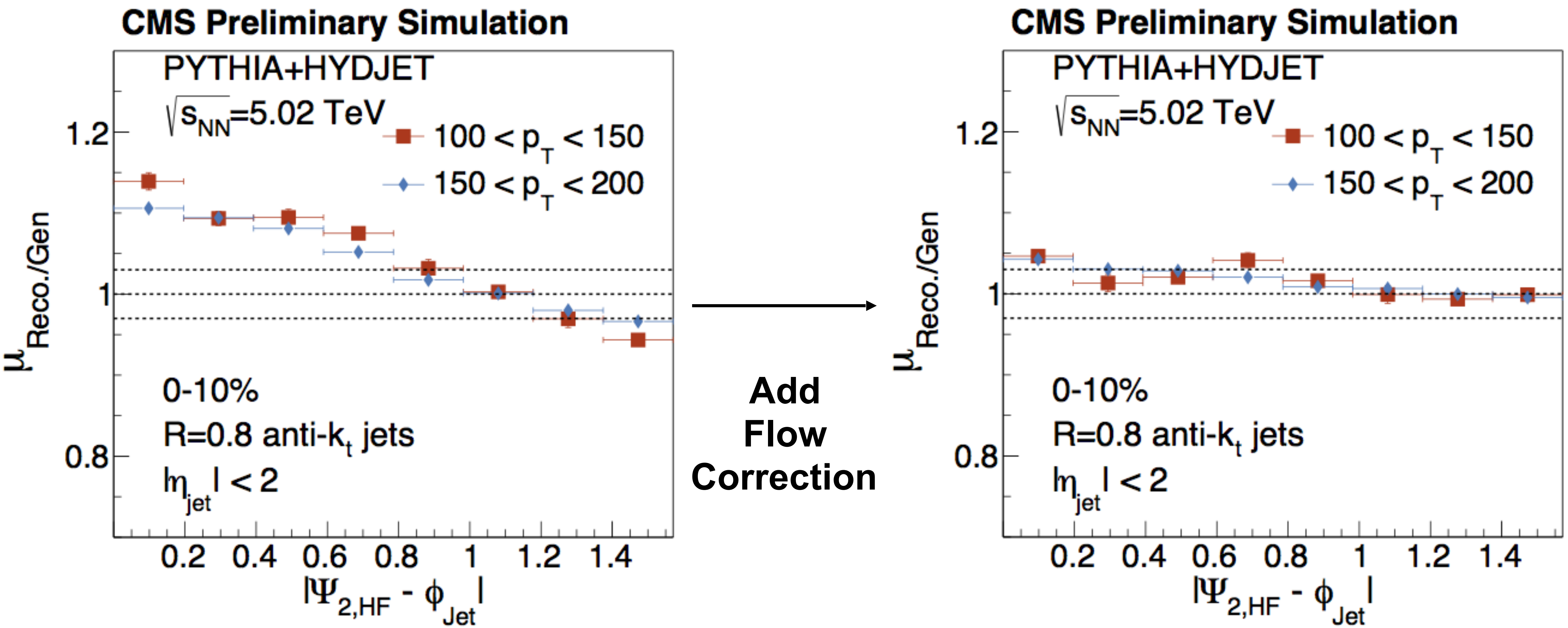
- Extract an event-by-event v_2 and v_3 by fitting particle flow candidates
- Extracted $v_2(v_3)$ are used to modulate CS ρ to add ghost particles

Jet Energy Scale at R=0.4 and R=0.8



- Scale closure of R=0.4 (**Left**) and R=0.8 (**Right**) jets over all centrality
- Identical corrections applied to all centrality, derived from unsubtracted jets in PYTHIA events

Scale Closure vs. Event Plane (R=0.8)



- Jet energy scale closure as function of event plane for R=0.8 w/o flow correction (**Left**) and with flow correction (**Right**)
- Significant flattening of scale translates directly to resolution reduction