Modifications to Jet Spectra and Substructure in PbPb Collisions with CMS

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On Behalf of the CMS Collaboration

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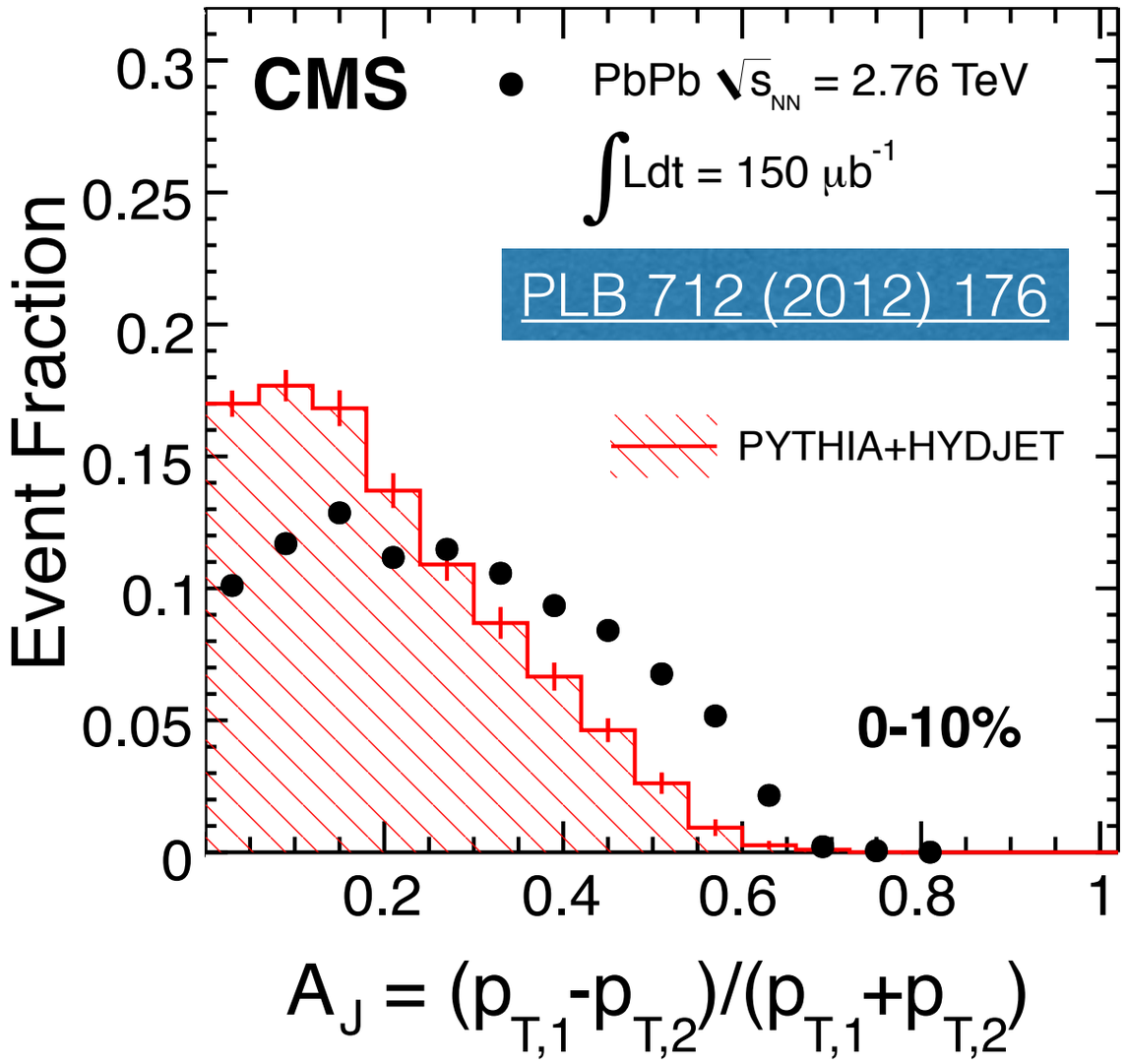
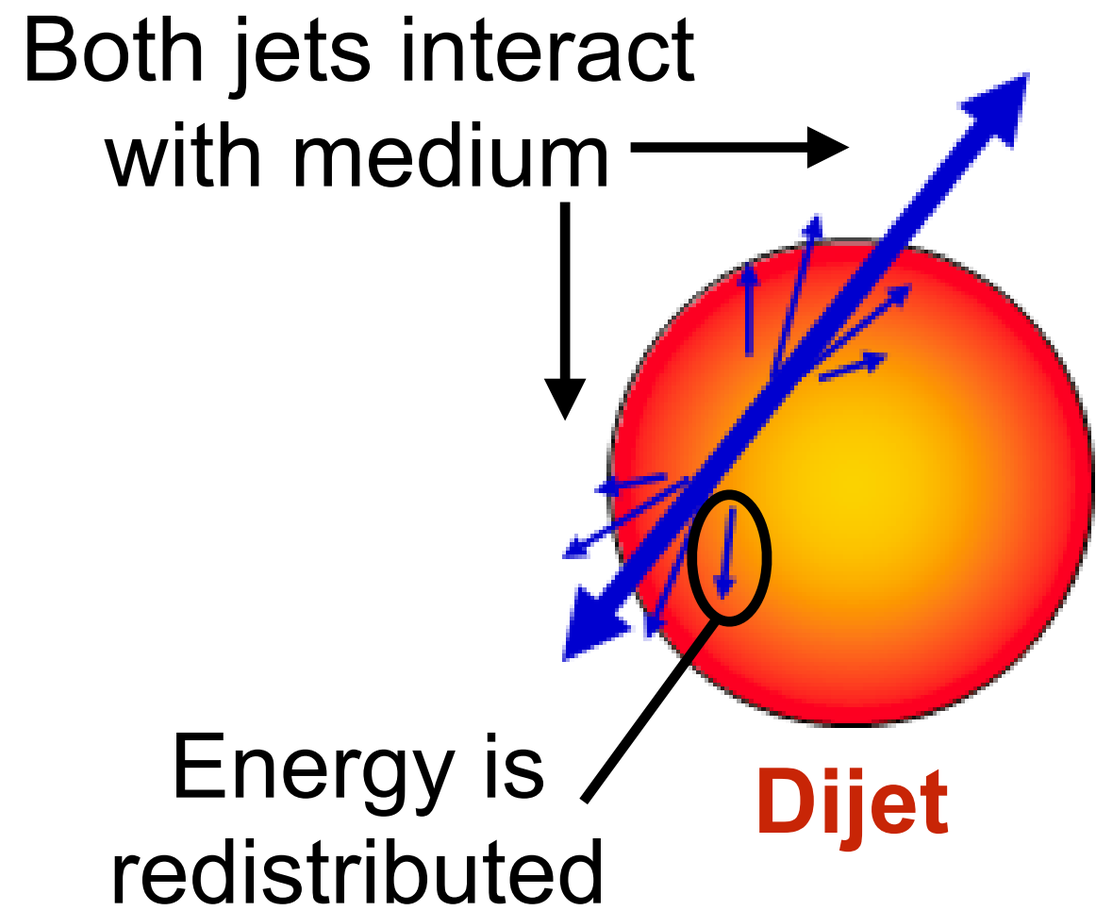
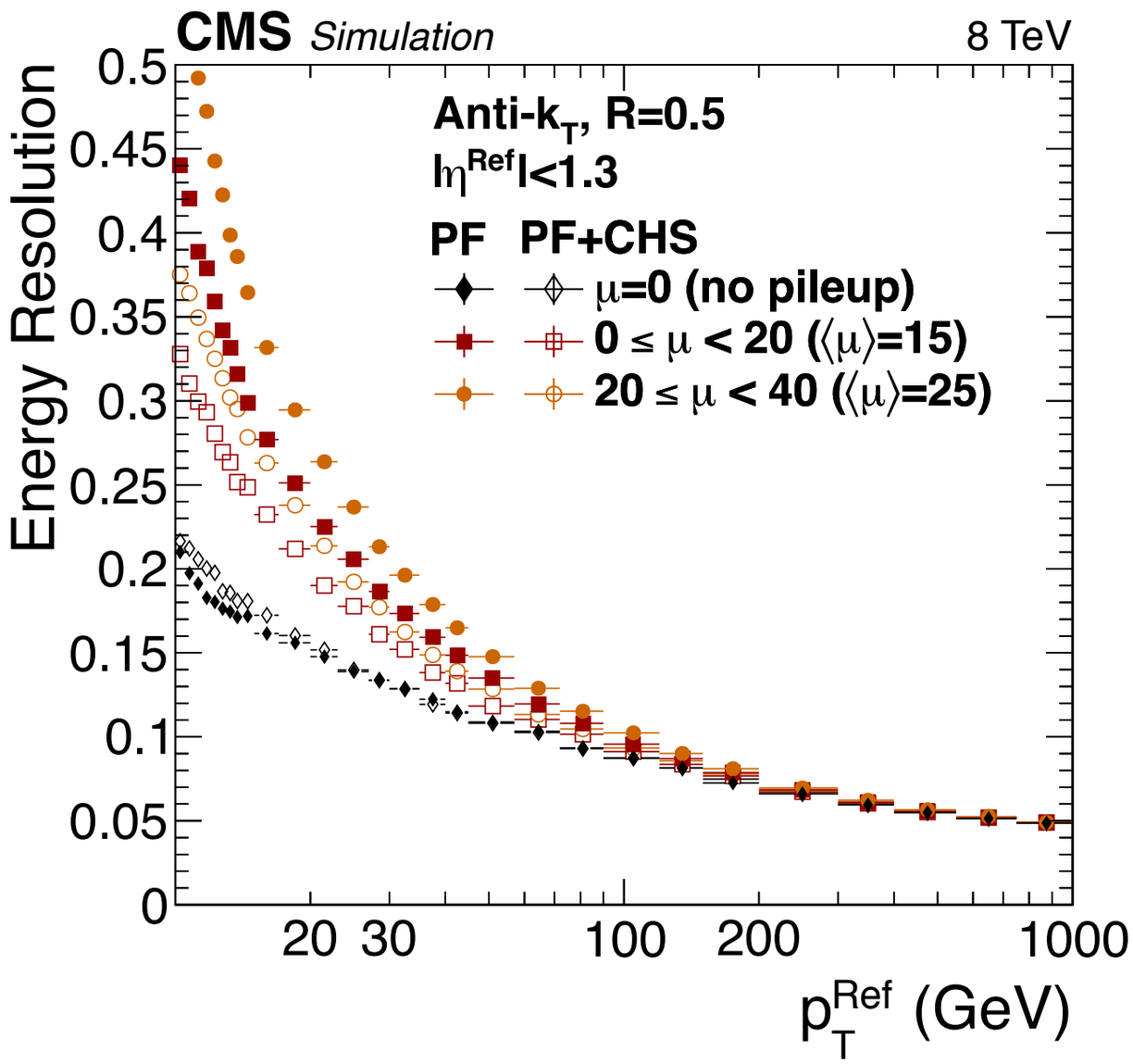
Physics of Jets in Medium

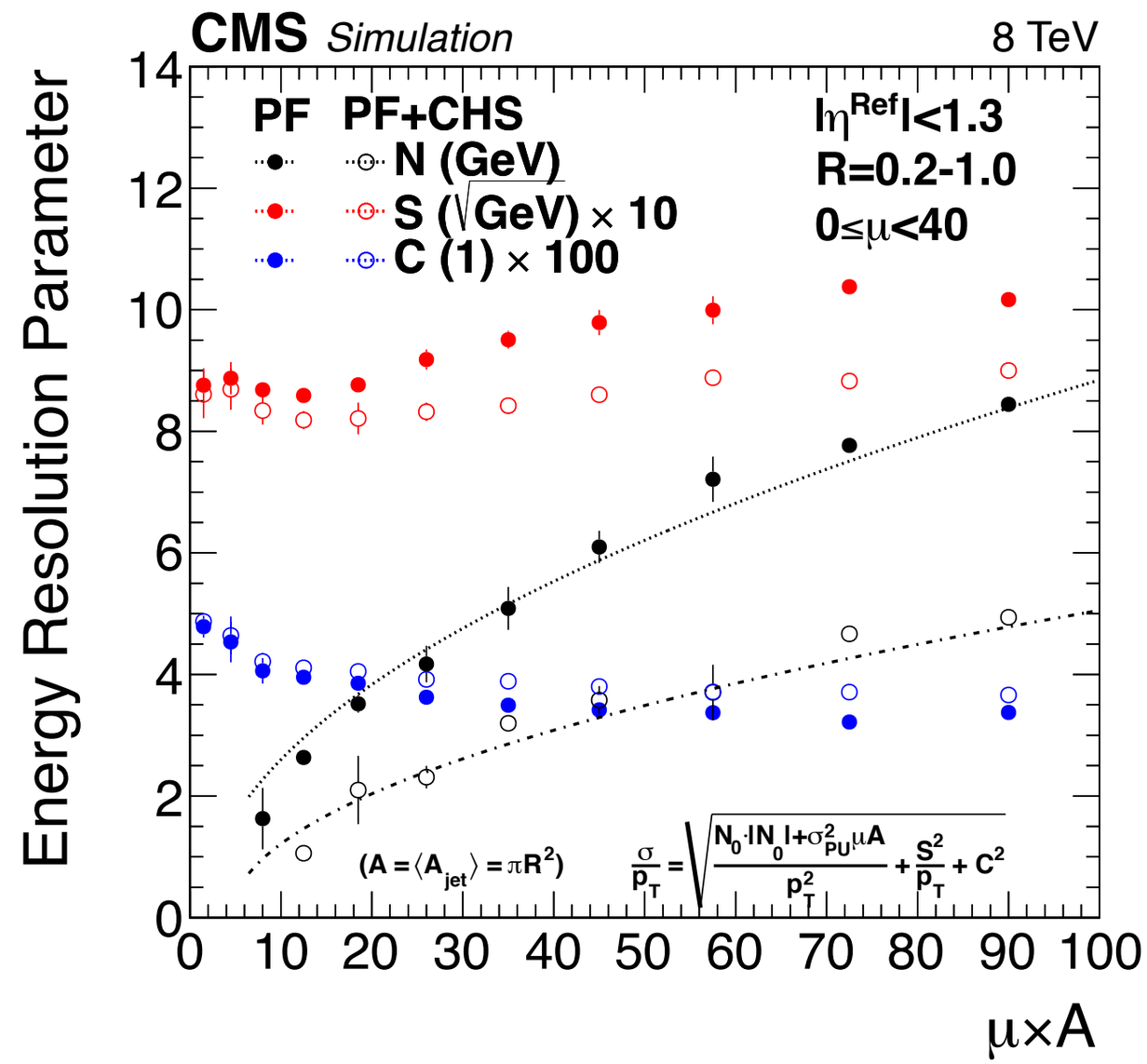




- Modified in medium compared to MonteCarlo and pp reference
  - Energy is redistributed in and out-of-cone
  - Substructure observables are a tool to study this redistribution

Jet Reconstruction with CMS in pp





- Good performance just with CHS at typical levels of pileup
  - Typical level of pileup here -> peripheral-most in PbPb

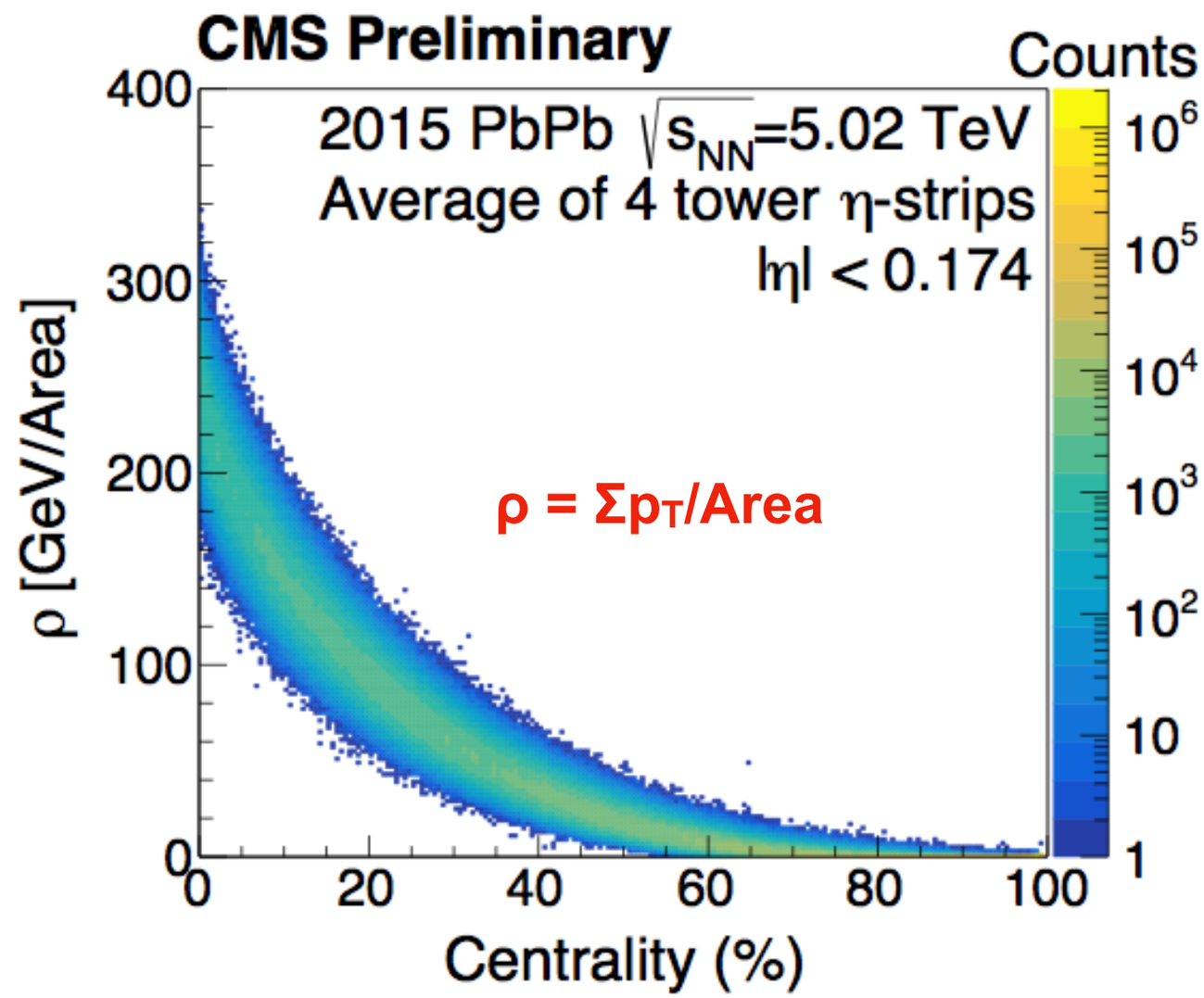
For more details see JINST 12 (2017) P10003 and morning talk from Anna Benecke

Jet Reconstruction with CMS in PbPb

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

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

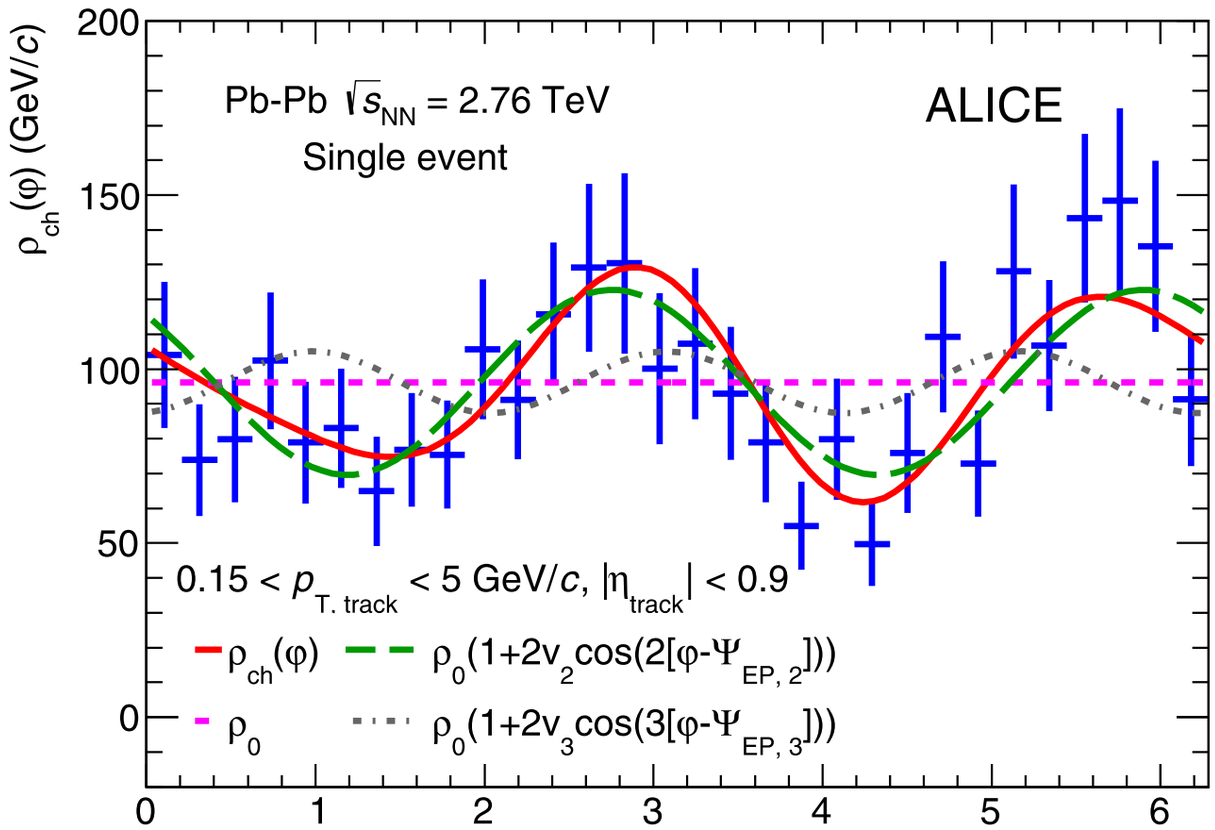
- Typically HI chooses small cone and low-p_T
- Alternatively, scale away **UE** by p_T
  - N/p_T in quadratic sum, and go to large cone



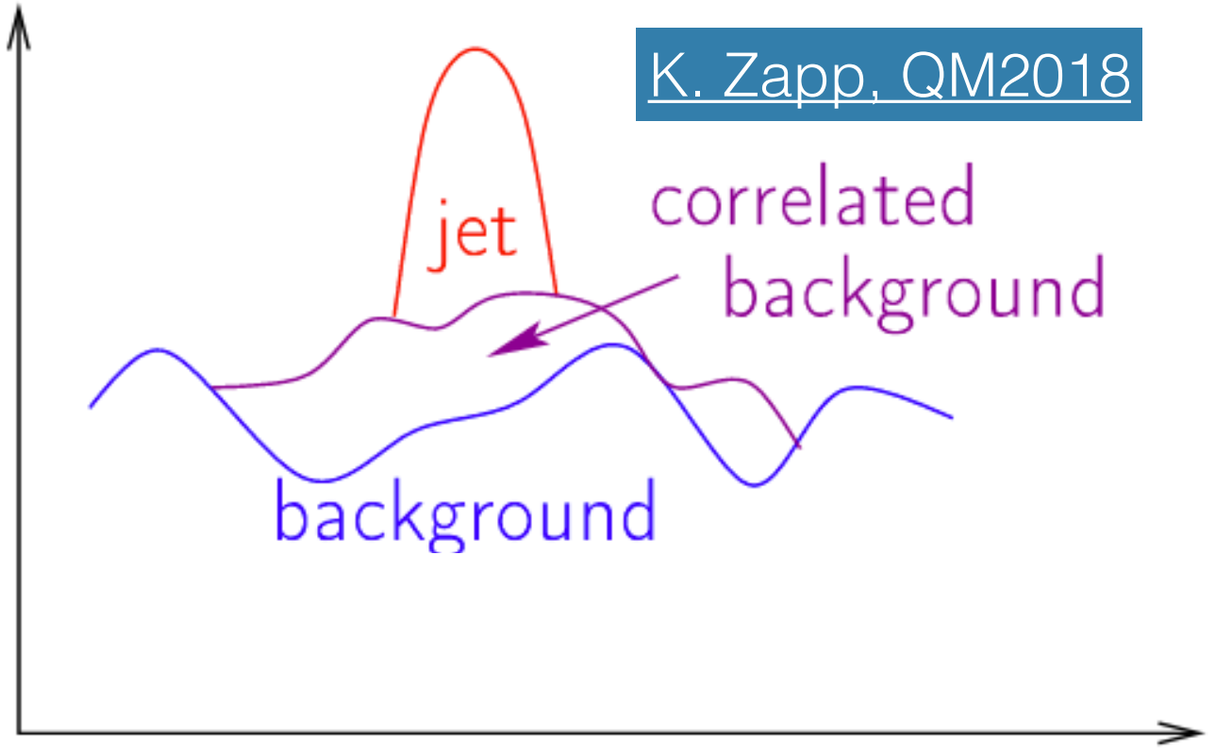
- pp: 27.4 pb^{-1} at 5.02 TeV
- PbPb: 404 μb^{-1} at 5.02 TeV

Fig. From: CMS-DP-2018-024

Additional Complications in PbPb



Phys.Lett. B 753 (2016) 511-525



- Hard and soft components from single vertex O(10 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
- Then for CMS substructure measurements:

Constituent Subtraction (CS)

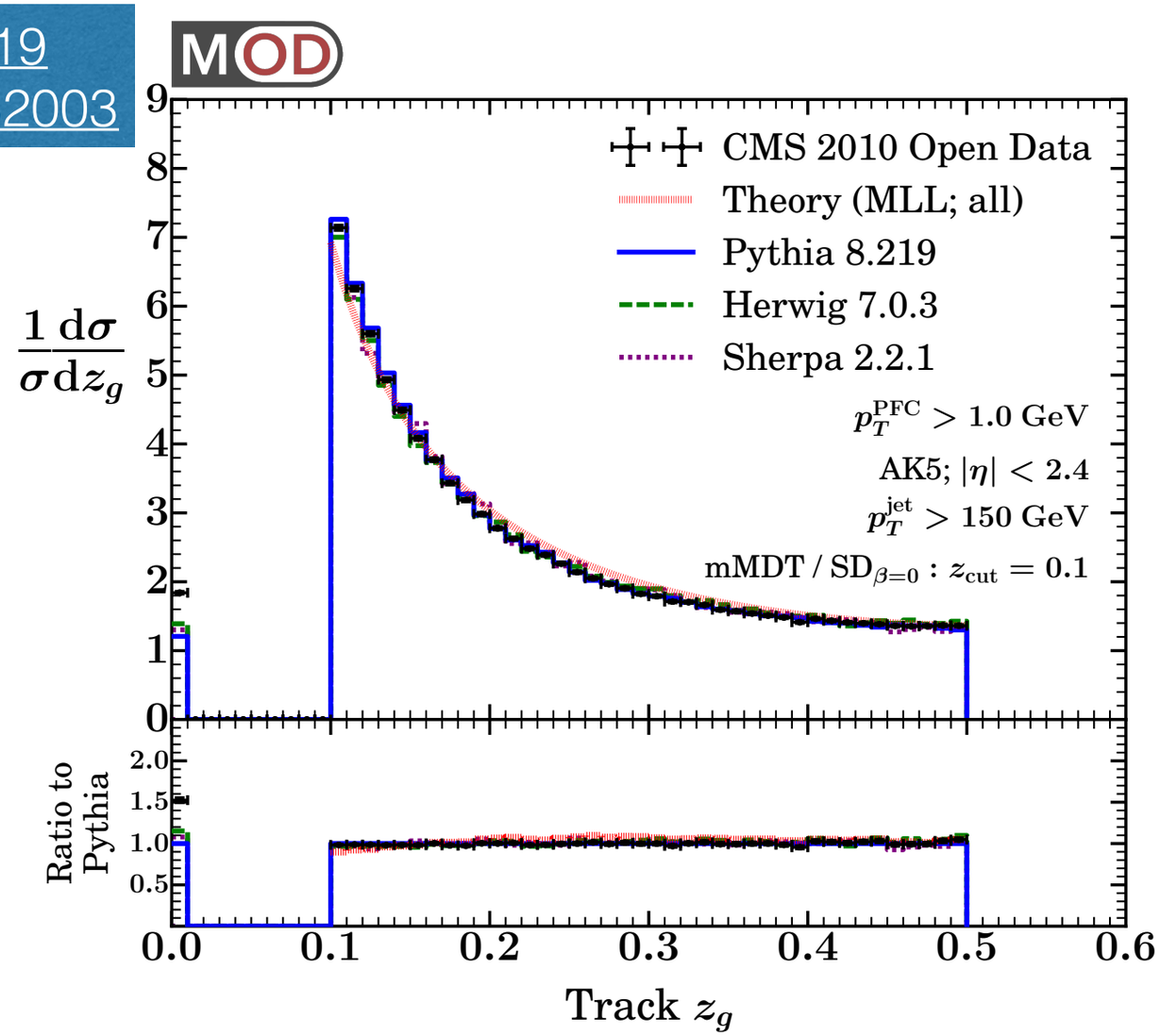
1: Estimated by median unsubtracted k_t jet

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

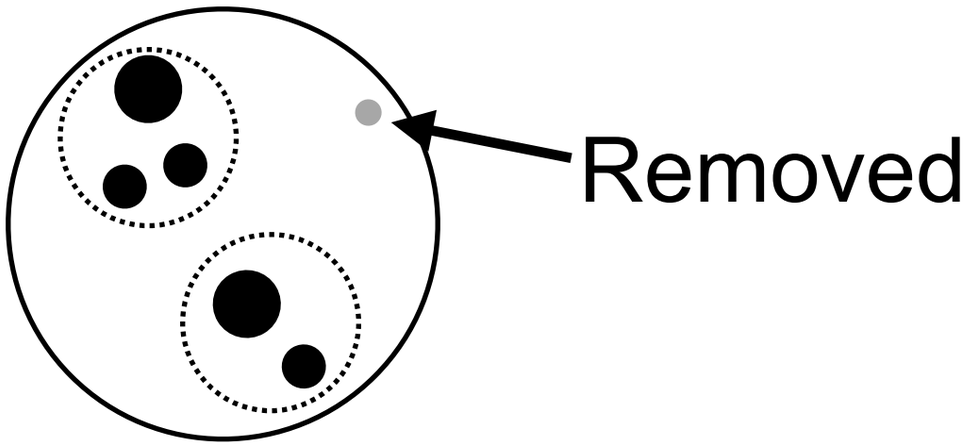
For more details see JHEP06 (2014) 092 and morning talk from Peter Berta

Measurement of z_g in pp w/ Open Data

PRL 119 (2017) 132003



Work back thru clustering history



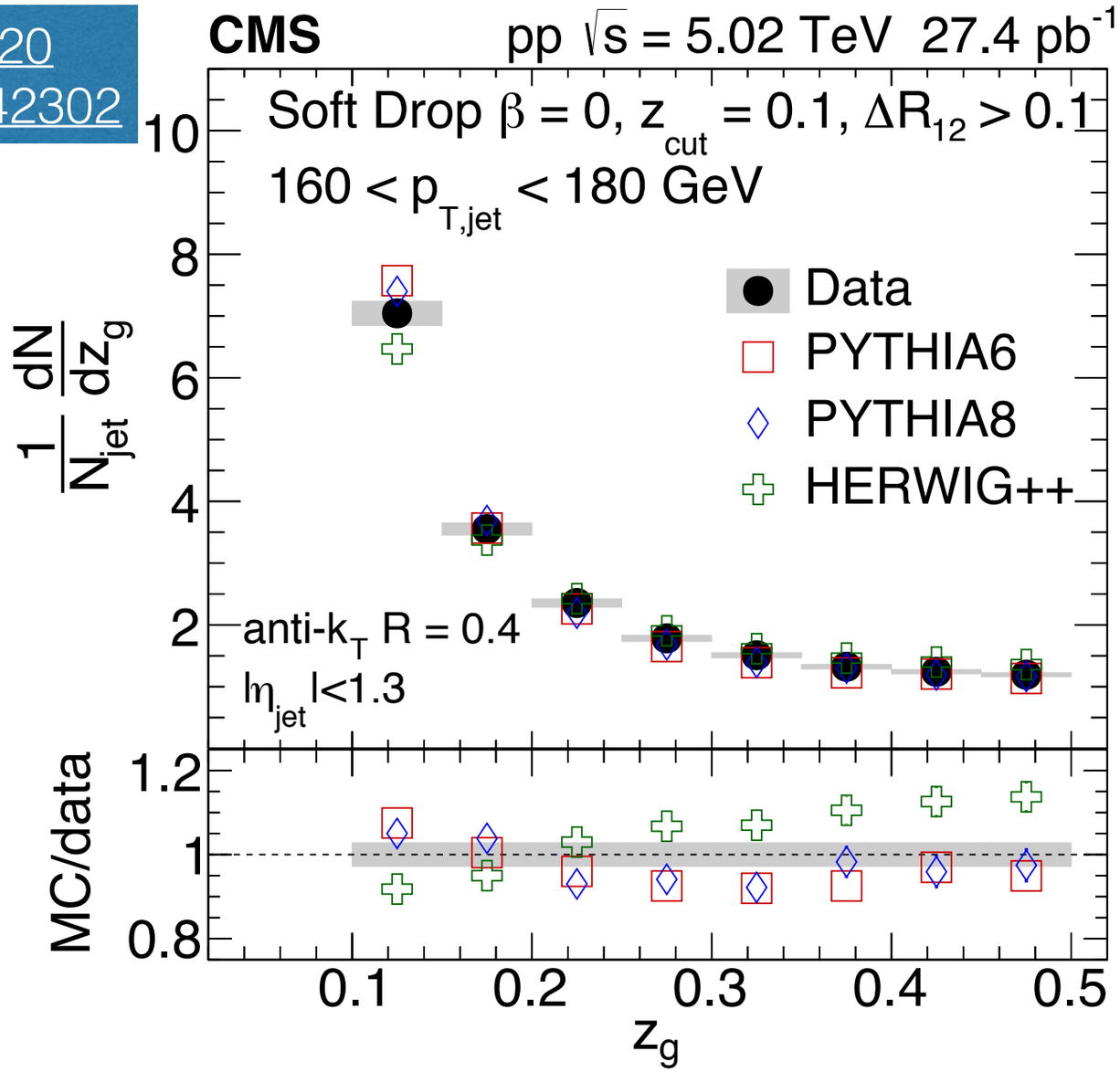
Identify subjets satisfying condition:

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

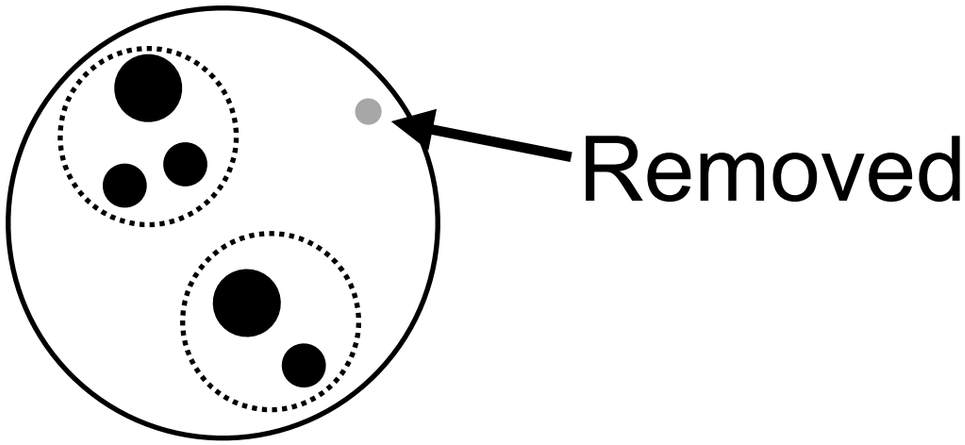
- Successful application in open data with tracks in 7 TeV pp
- Good description by theory and generators

Measurement of z_g in pp

PRL 120 (2018) 142302



Work back thru clustering history



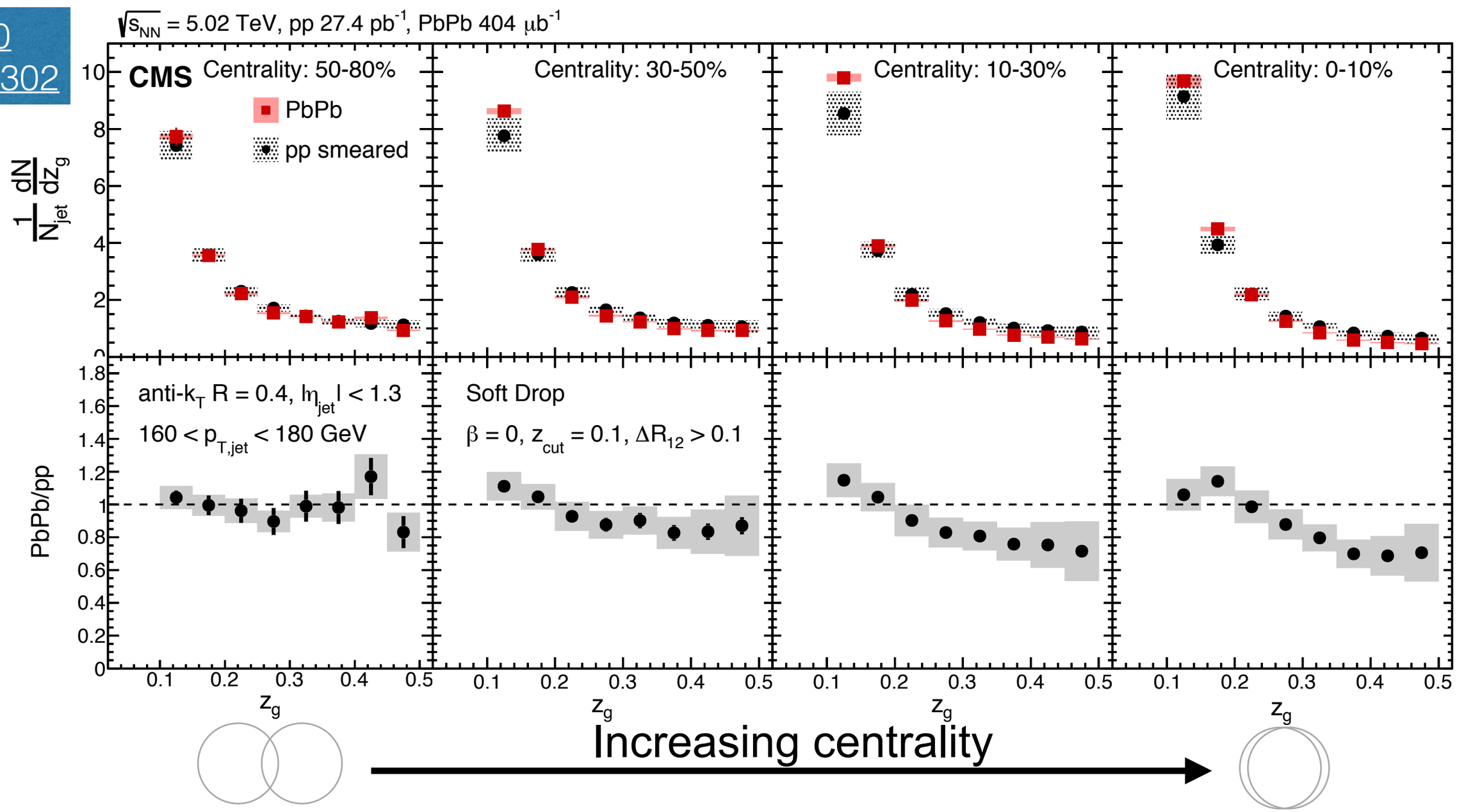
Identify subjets satisfying condition:

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

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

Measurement of z_g in PbPb

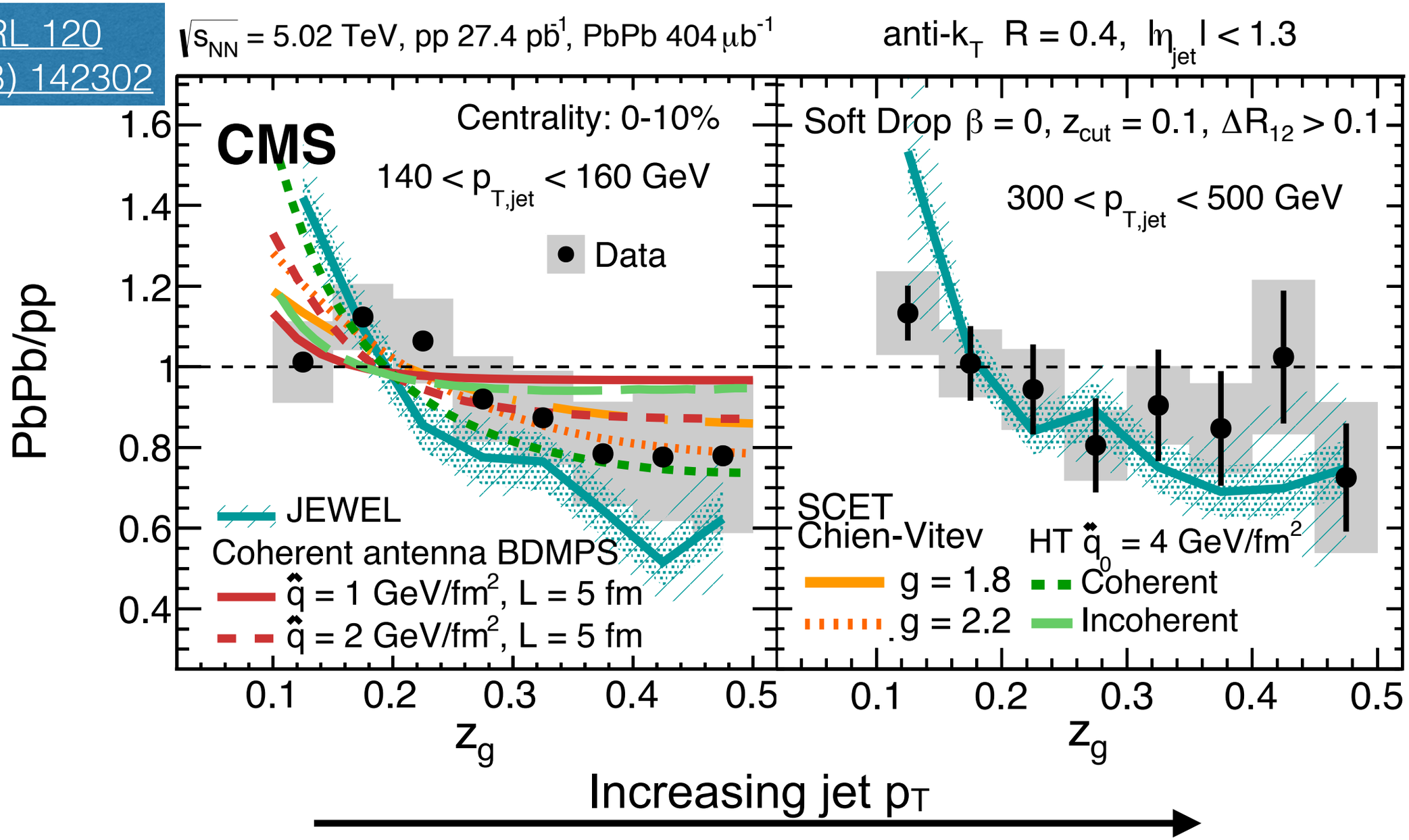
PRL 120 (2018) 142302



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

Measurement of z_g in PbPb

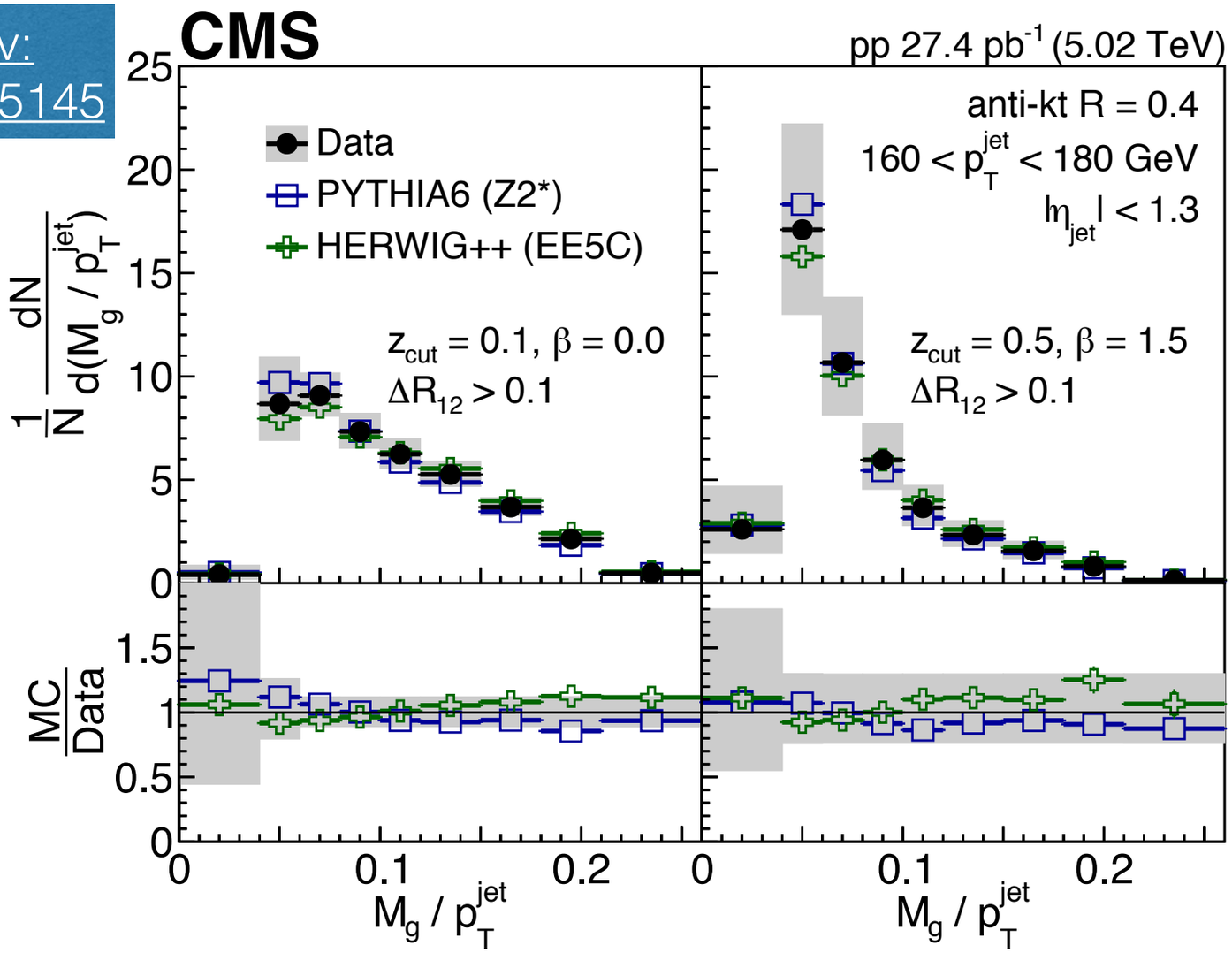
PRL 120 (2018) 142302



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

Measurement of Groomed Mass in pp

arxiv: 1805.05145



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:

$M_g = (p_{1\mu}\, p_{2}^{\mu})^{0.5}$

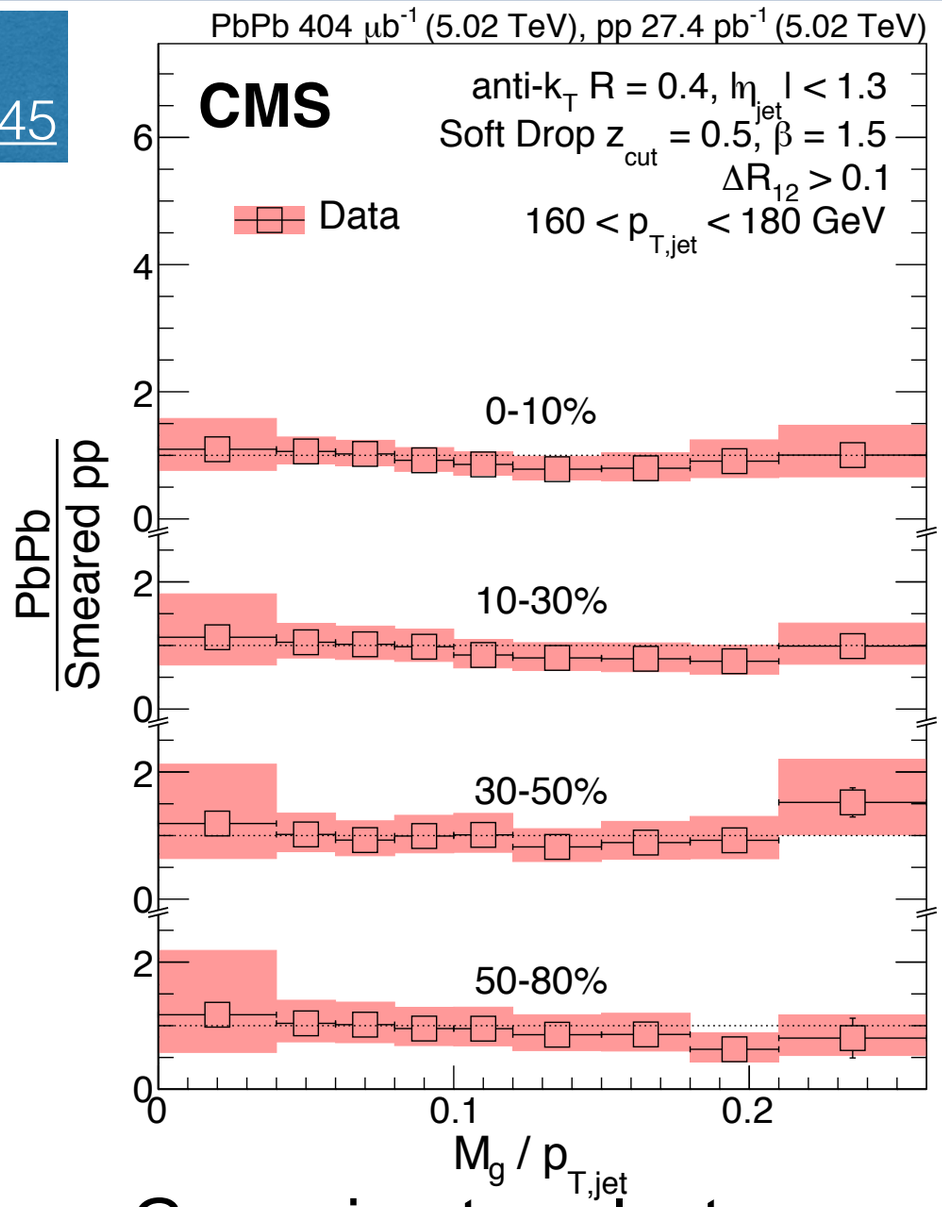
Normalize by jet p_T

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

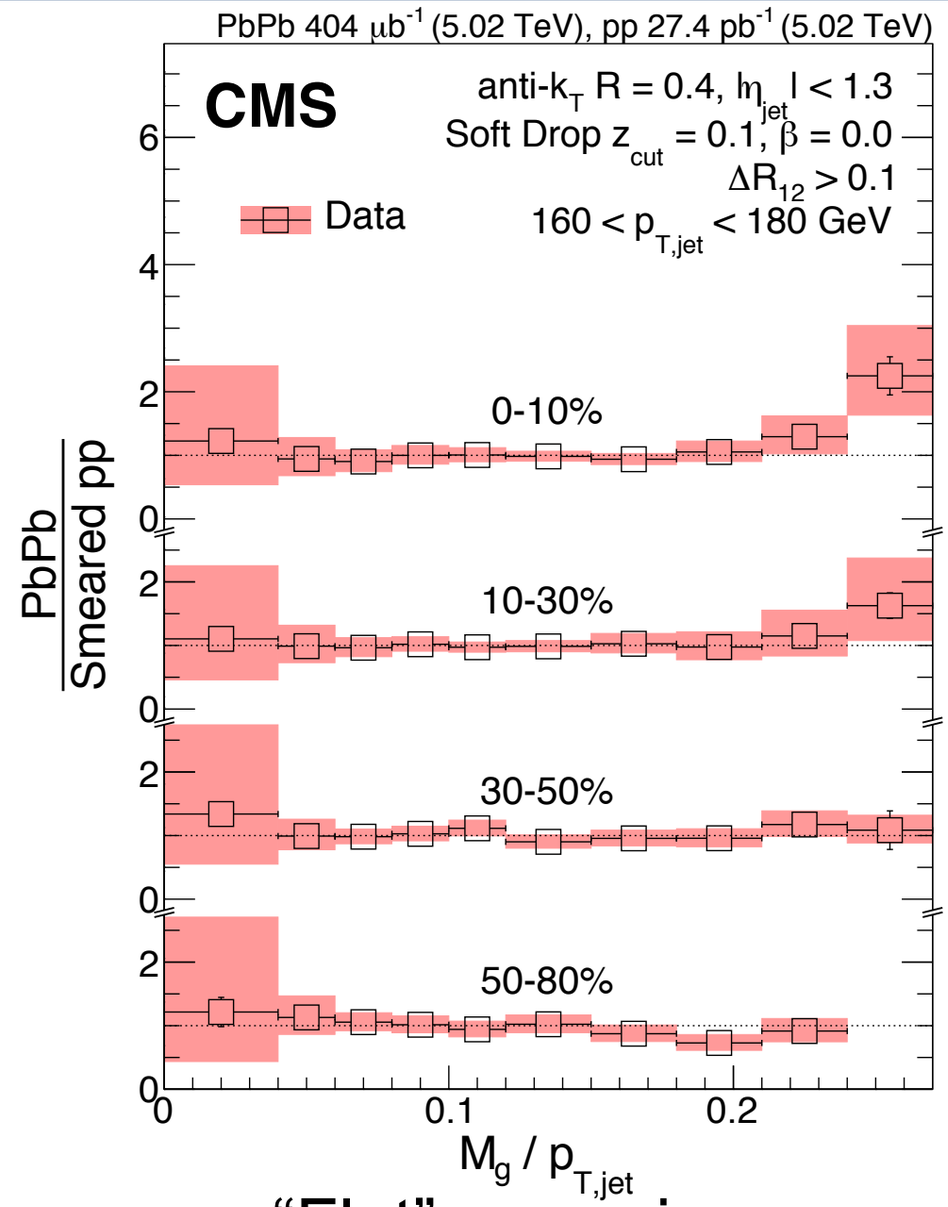
See also CMS-PAS-SMP-16-010 and ATLAS (Sub. PRL) pp groomed jet mass

Measurement of Groomed Mass in PbPb

arxiv: 1805.05145



Grooming to select core

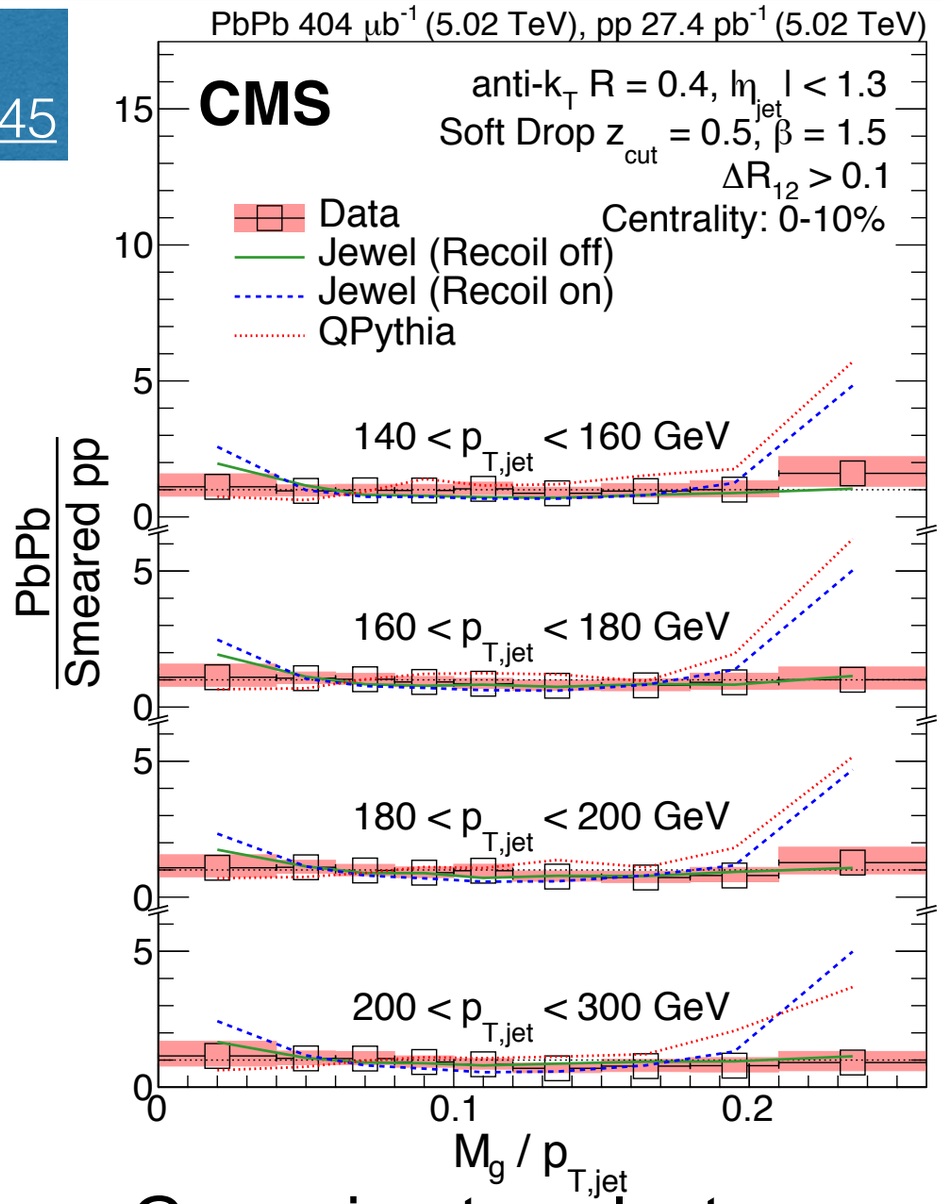


"Flat" grooming

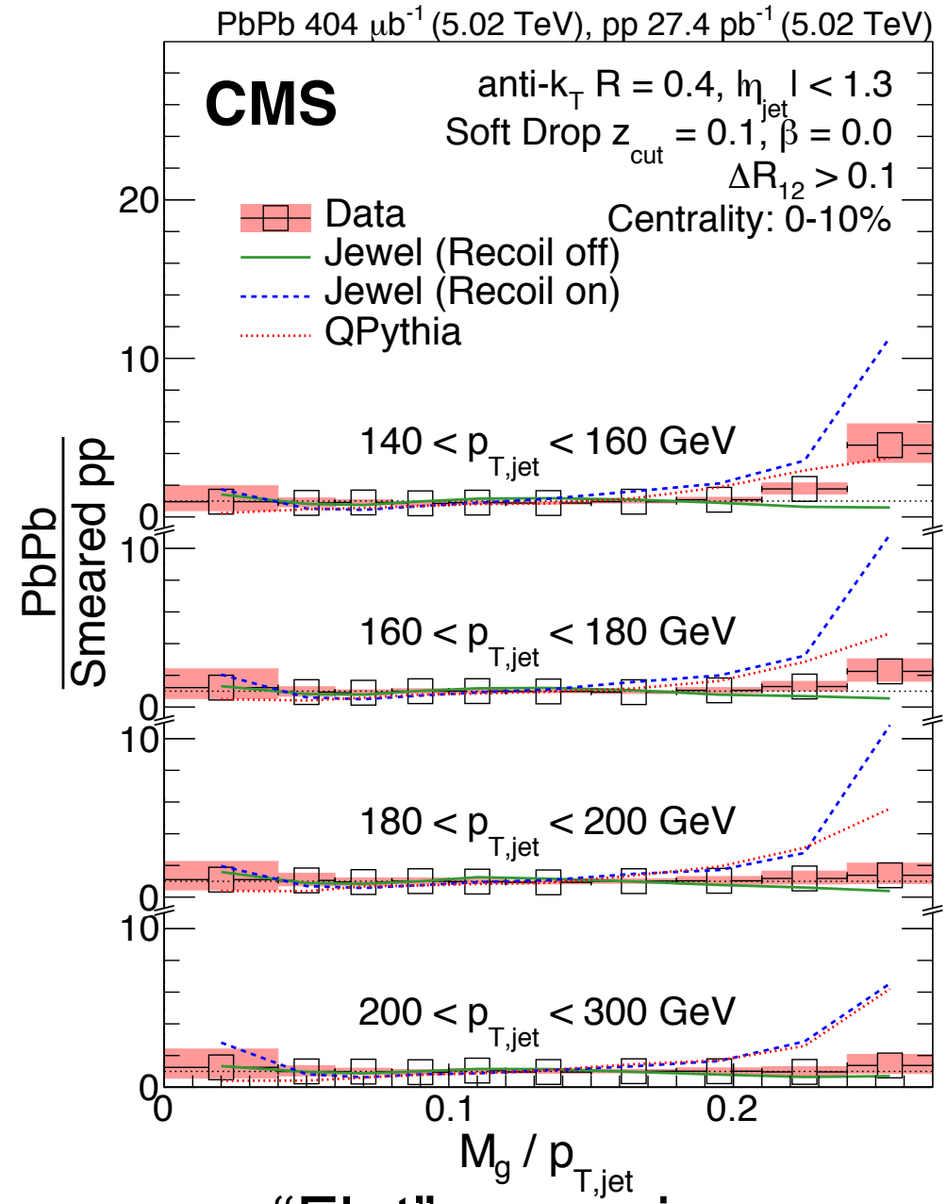
- Core shows no modification
- "Flat" grooming shows shape modified at large M_g/p_T

No simultaneous MC description of M_g/p_T

arxiv: 1805.05145



Grooming to select core



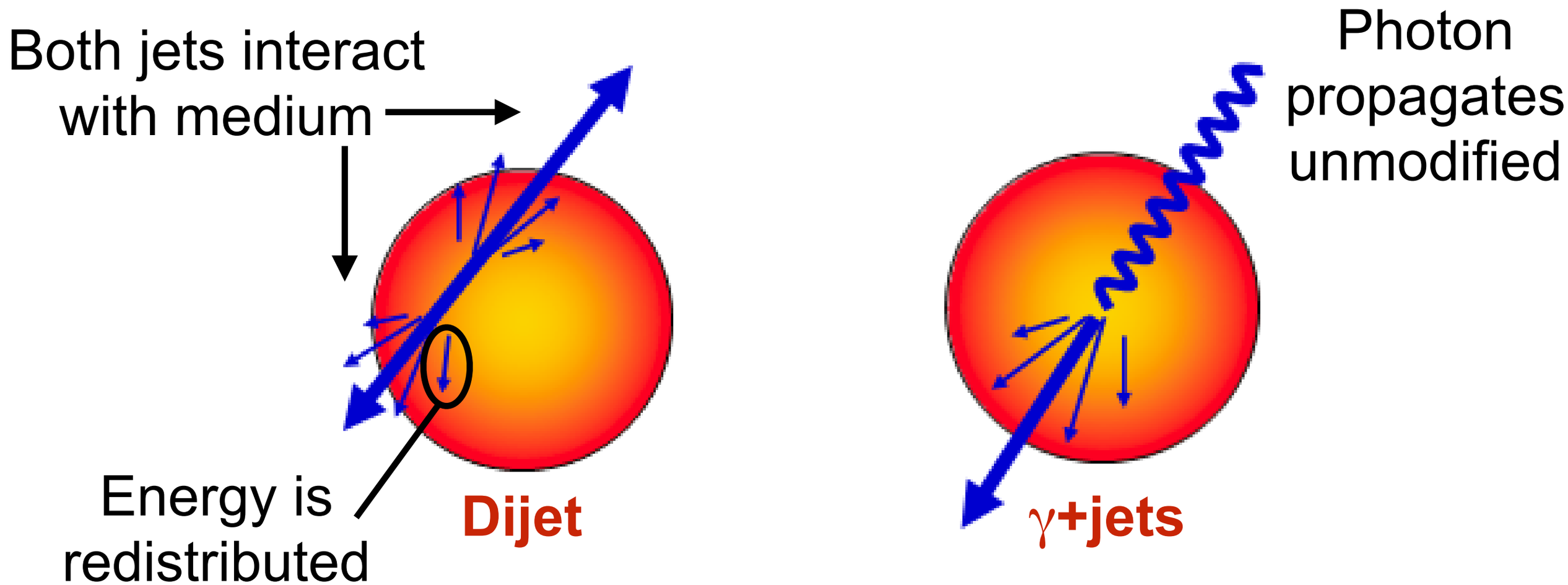
"Flat" grooming

Fixed Centrality

Jet pT

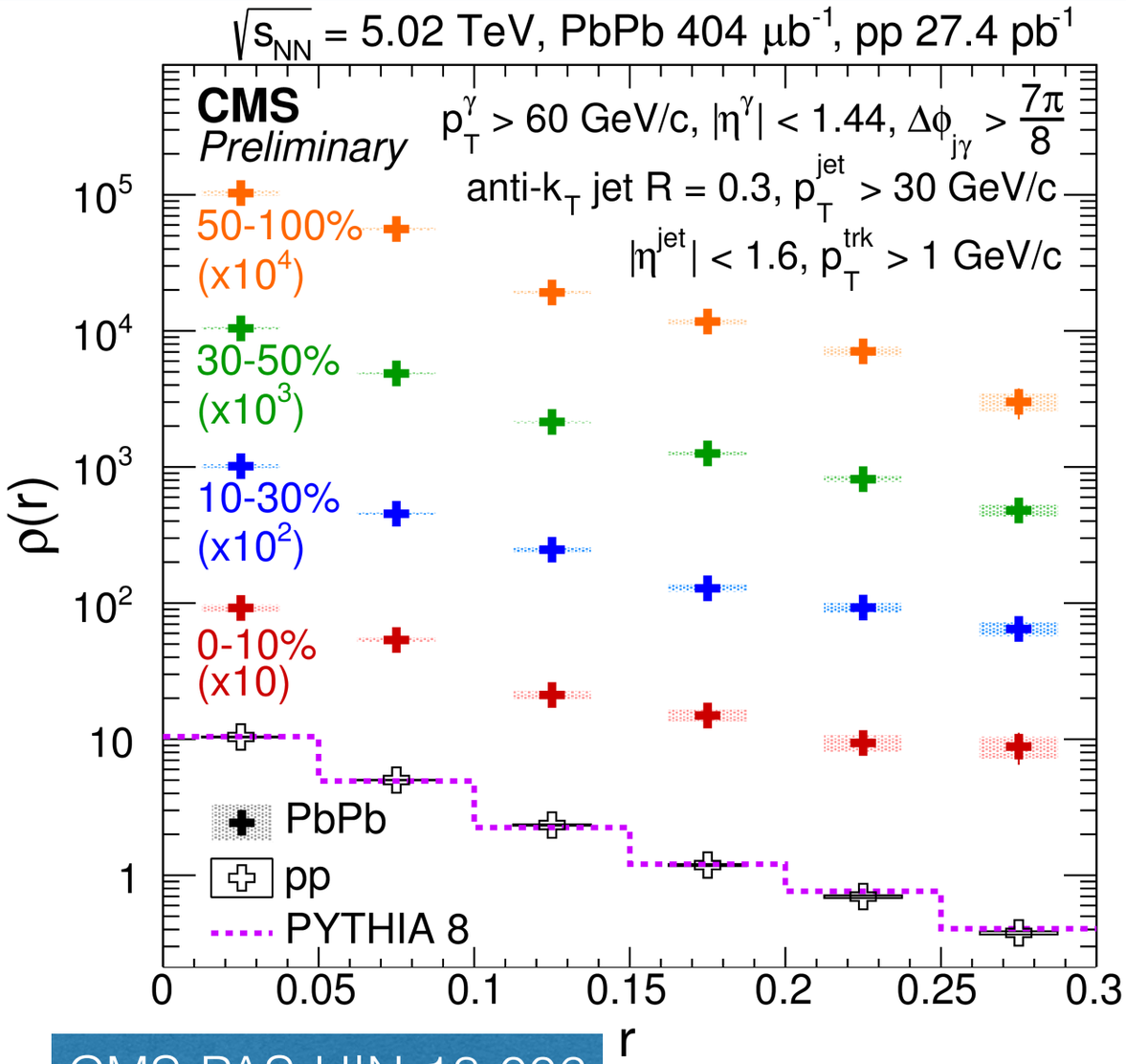
- Models that describe enhancement in "Flat" grooming also show large M_g/p_T in core grooming

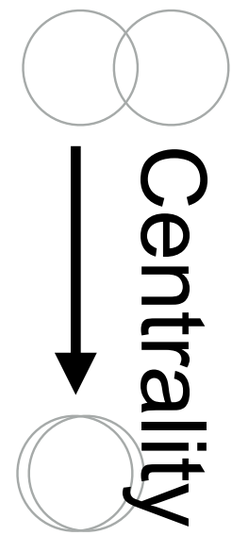
Measuring Jet Shapes with a Boson Tag



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

Measuring Jet Shapes with a Boson Tag



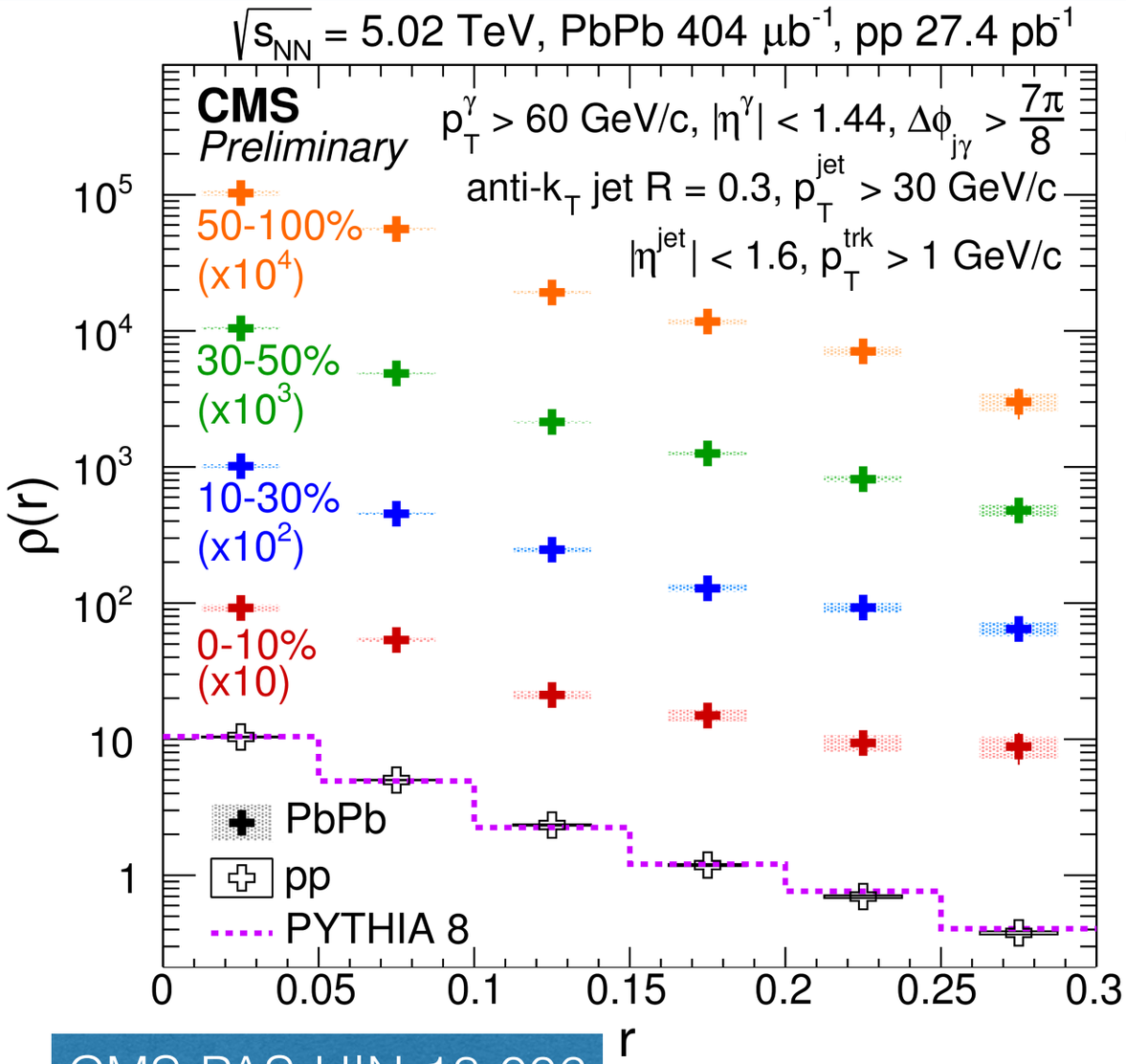


$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk}\in[r_a,r_b)} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk}\in[0,r_f)} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$

CMS-PAS-HIN-18-006

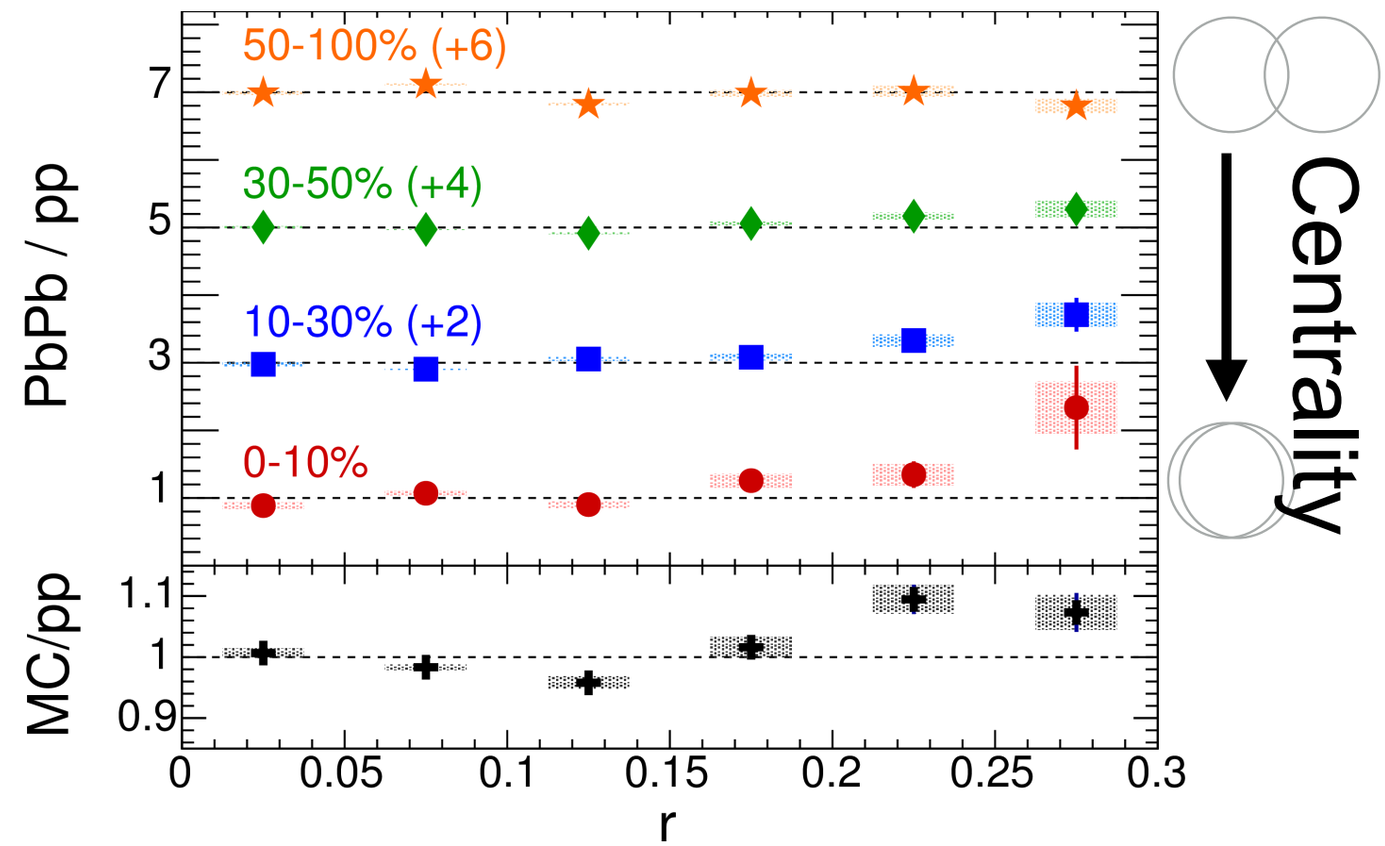
- Look at track sums in rings around the jet axis, normalized to the full jet charged energy

Measuring Jet Shapes with a Boson Tag



CMS-PAS-HIN-18-006

→ Take Ratio w/ pp



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

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, $|\eta| > 1.3$
- Add modulation to underlying event in φ to account for flow

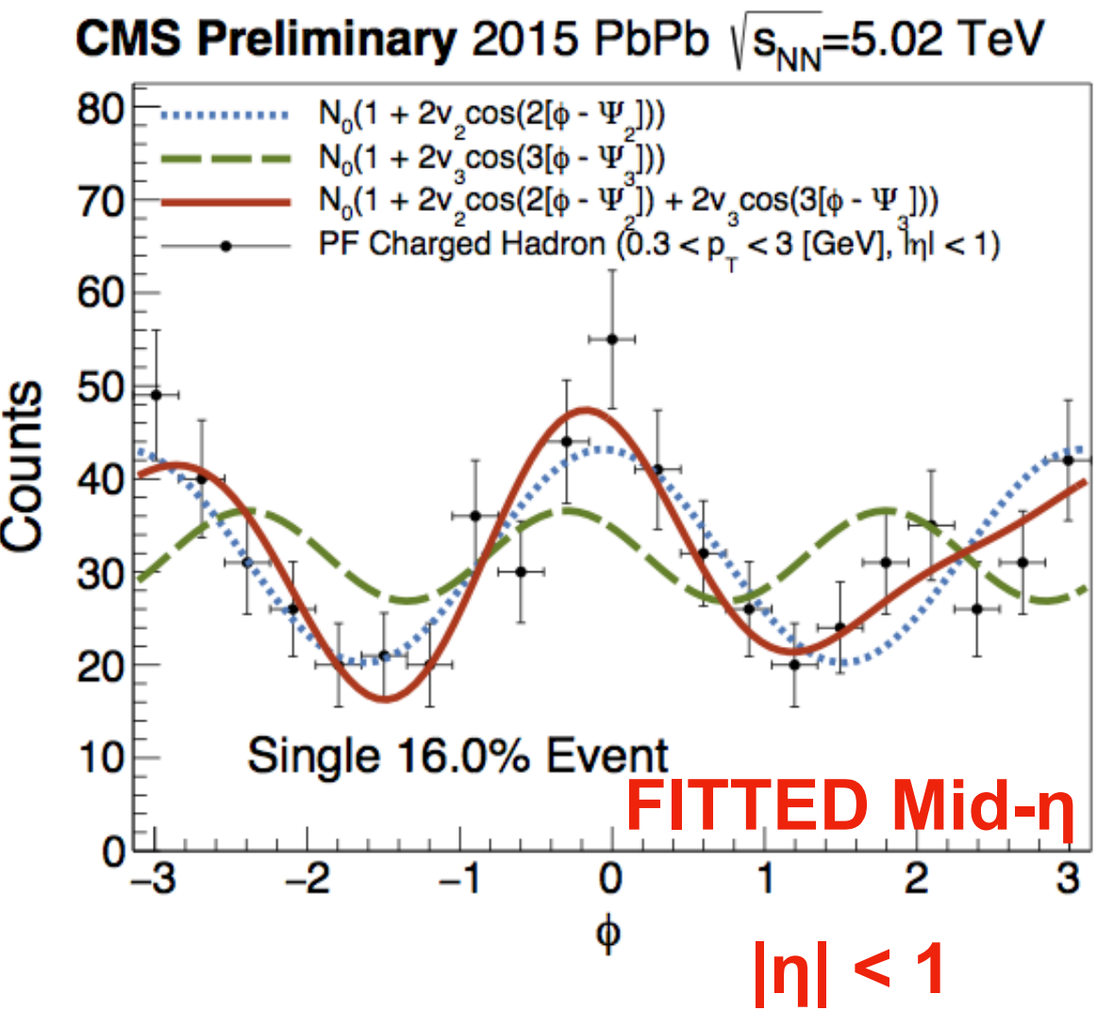
Constituent Subtraction (CS)

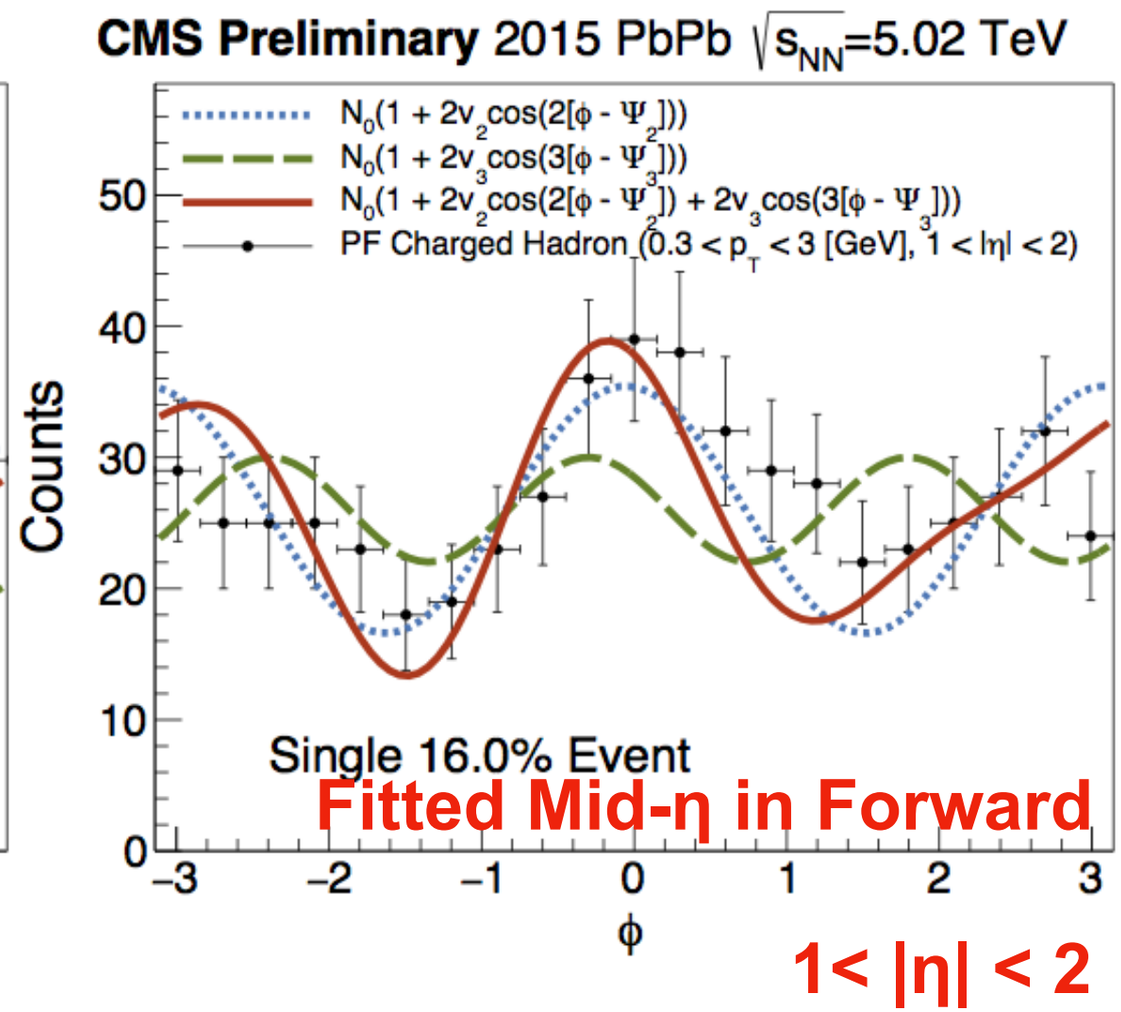
1: ~~Estimated by median unsubtracted k_t jet~~ → 1a: ρ estimated in η-strips defined by detector geometry

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

1b: Add event-by-event φ modulation

Estimating Flow Event-by-Event





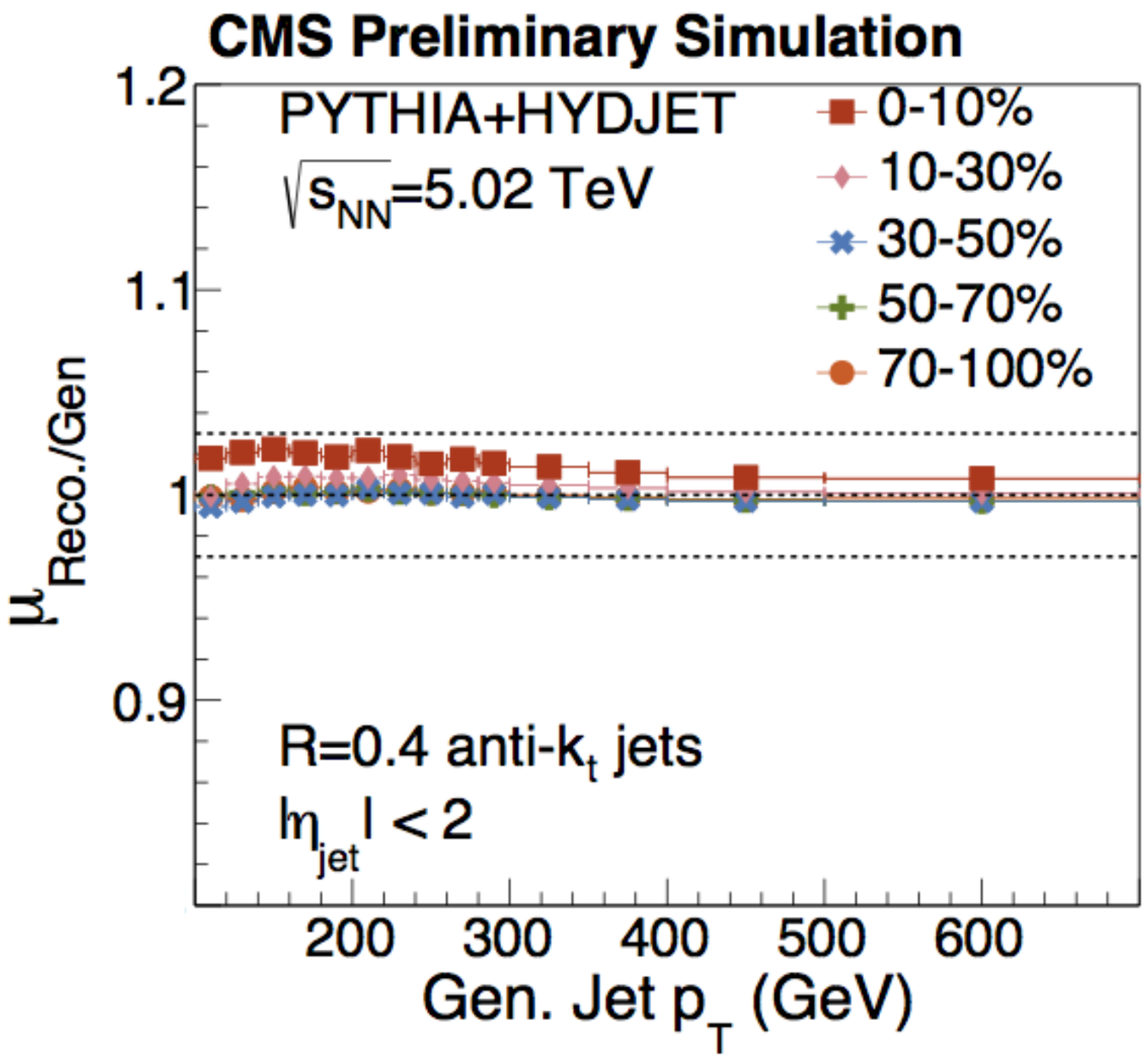
Following Example Of:

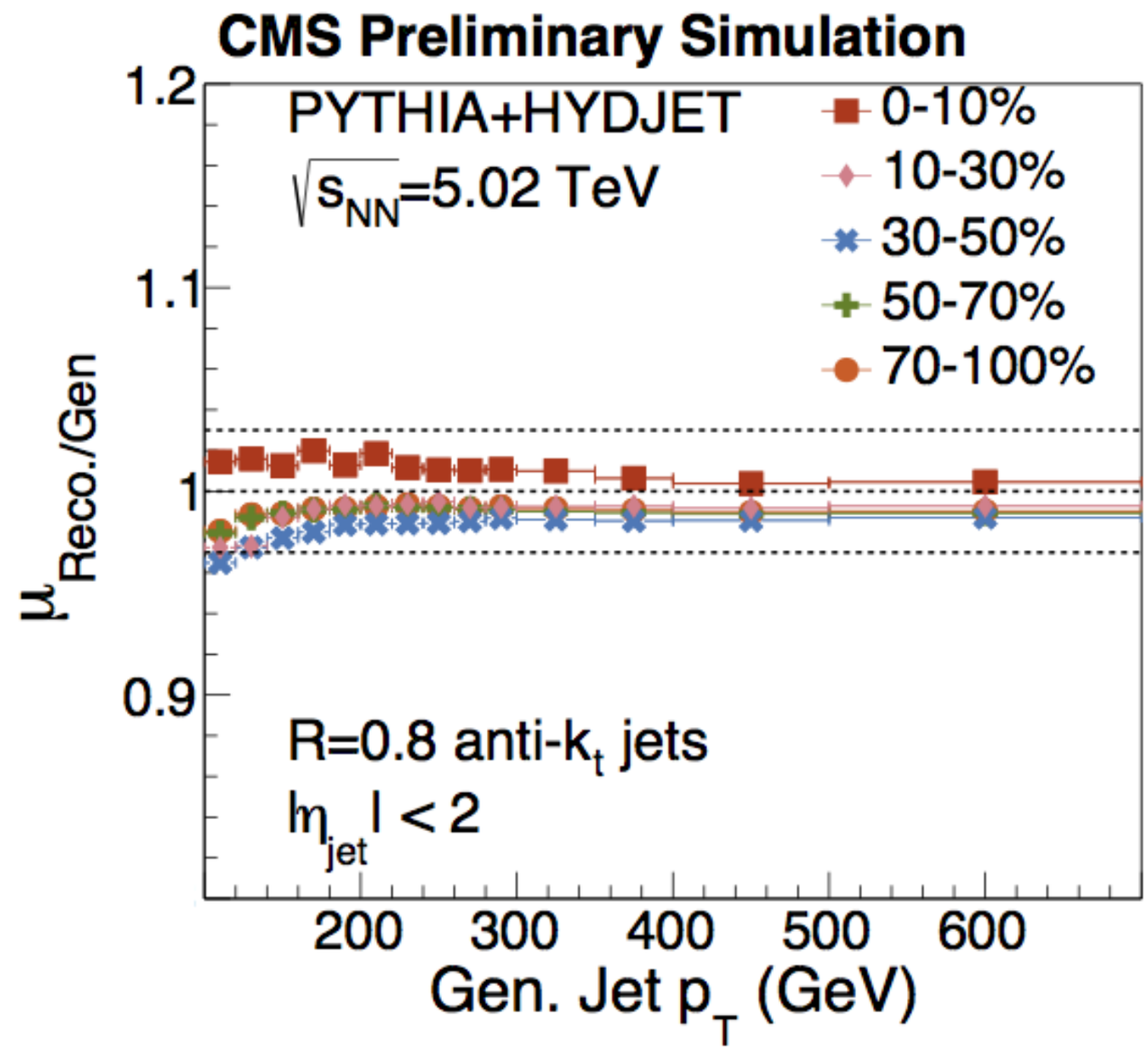
Phys.Lett. B 753 (2016) 511-525

- 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

Fig. From: CMS-DP-2018-024

Jet Energy Scale at R=0.4 and R=0.8

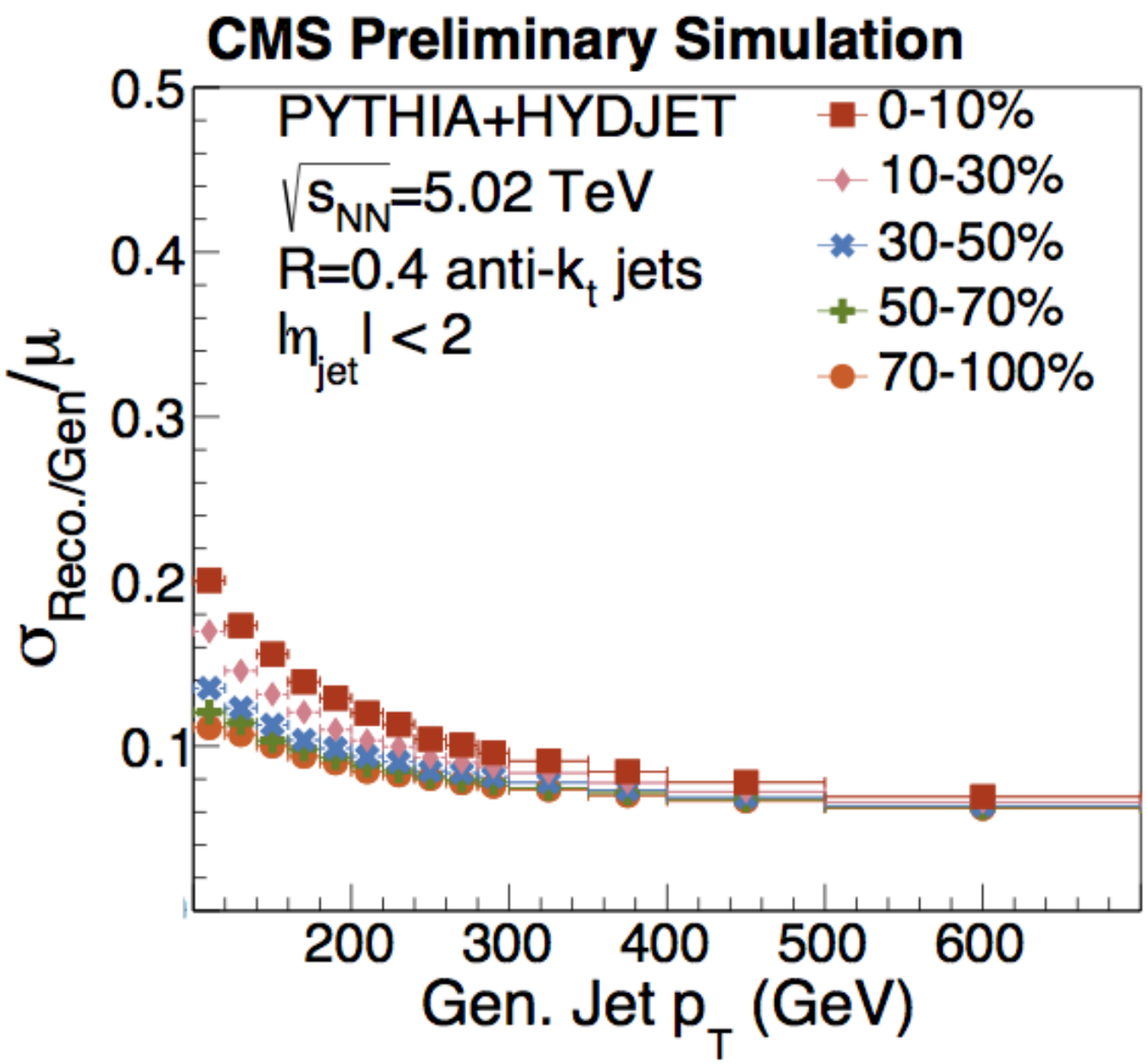


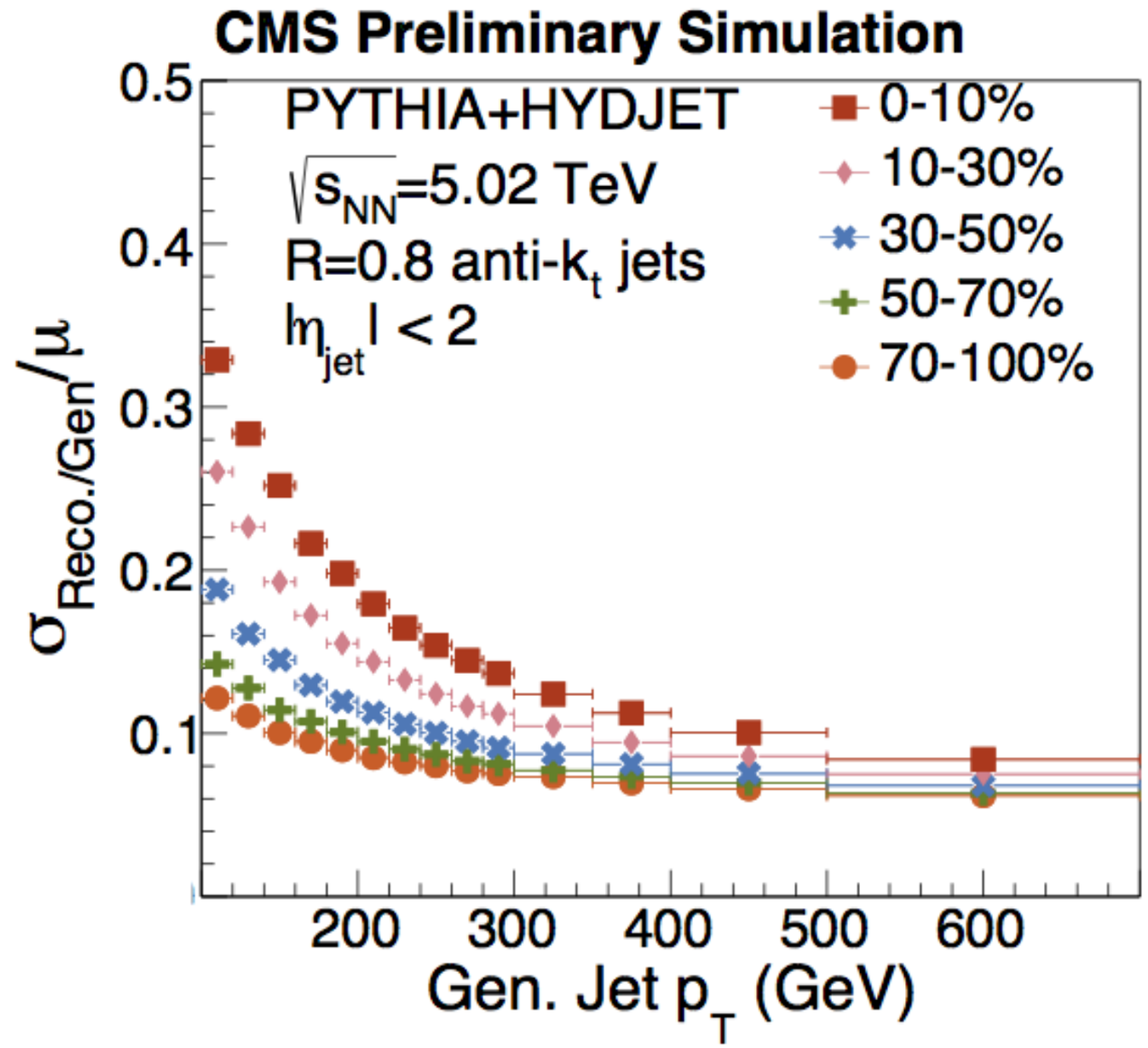


- Scale closure of R=0.4 (**Left**) and R=0.8 (**Right**) jets over all centrality
- Identical corrections applied to all centrality, derived from unsubtracted jets in PYTHIA events

Fig. From: CMS-DP-2018-024

Jet Energy Resolution at R=0.4 and R=0.8

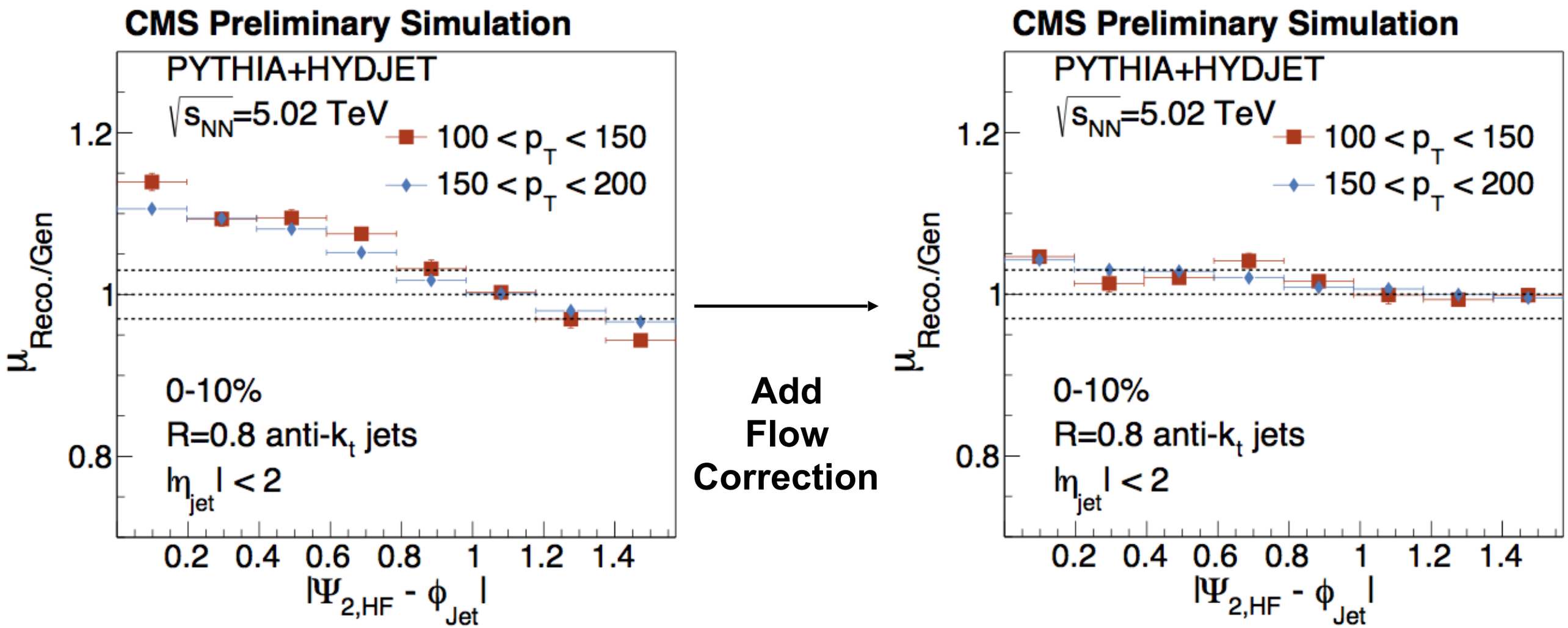




- Energy resolution of R=0.4 (**Left**) and R=0.8 (**Right**) jets over all centrality
- In large cone, UE drives high resolution at low-p_T
  - JER ~18% at 200 GeV (R=0.8)

Fig. From: CMS-DP-2018-024

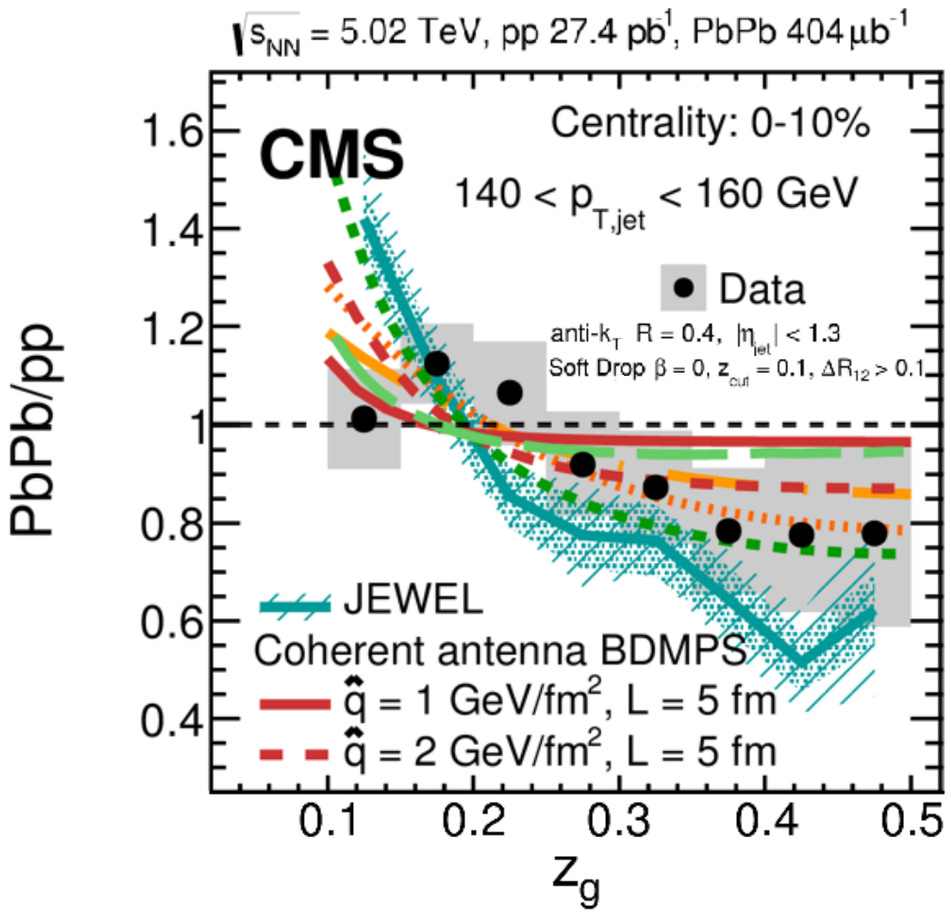
Scale Closure vs. Event Plane (R=0.8)

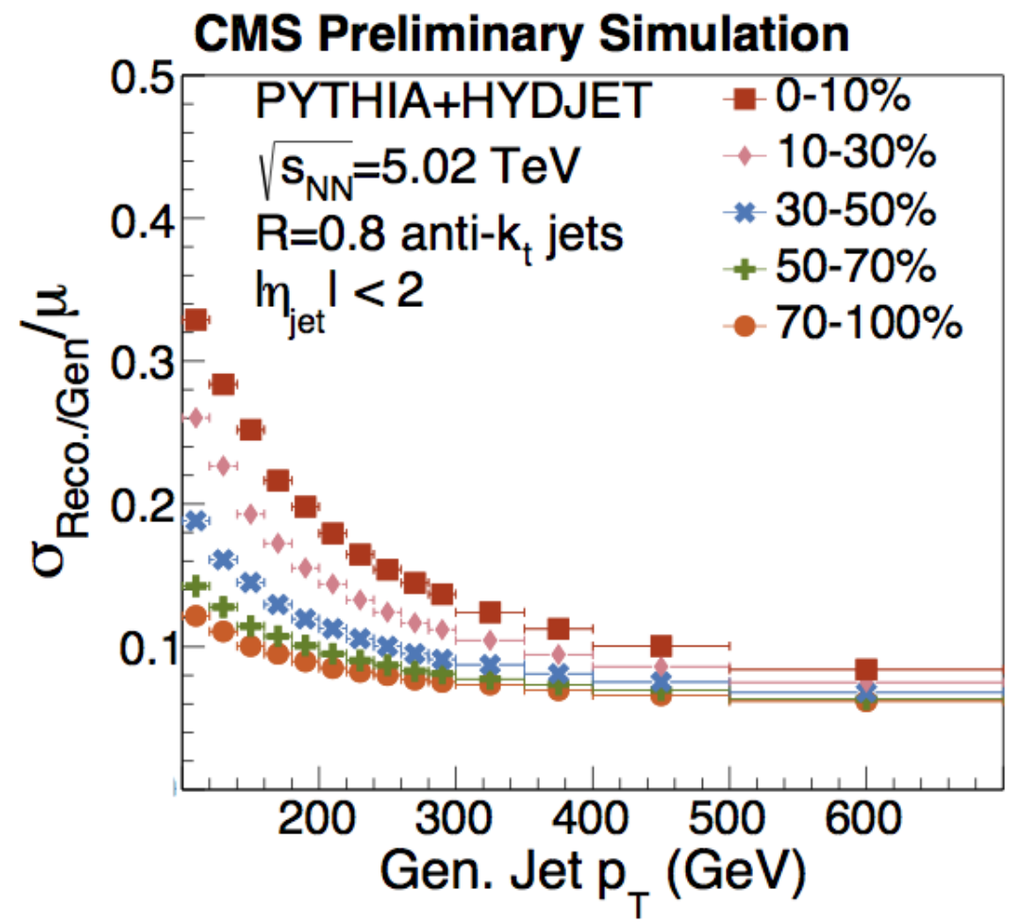


- Jet energy scale closure as function of event plane for R=0.8 w/o flow correction (**Left**) and with flow correction (**Right**)
- Significant flattening of scale translates directly to resolution reduction

Fig. From: CMS-DP-2018-024

Conclusions



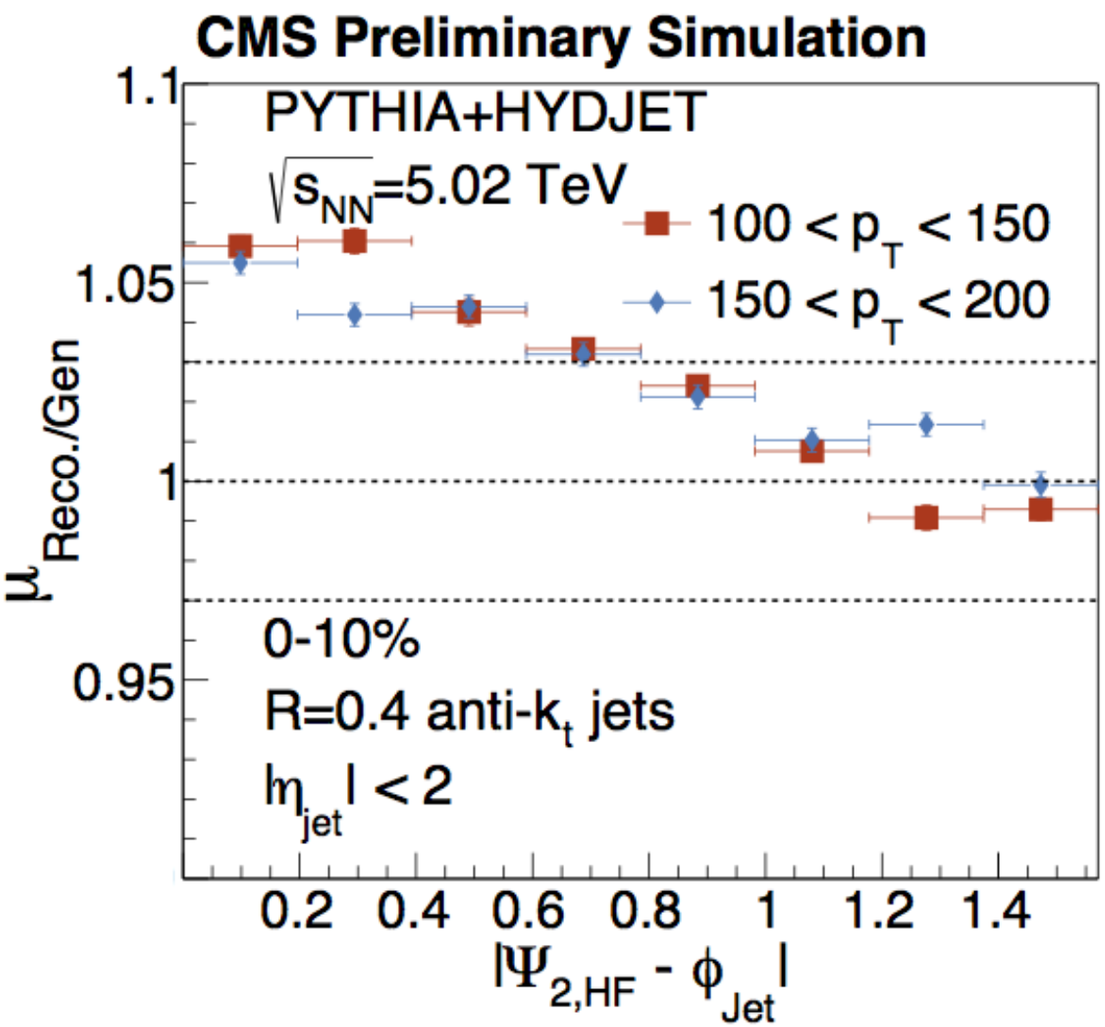


- Inclusive jet substructure measurements show no modification to jet core
  - Modification observed with flat grooming in z_g, M_g/p_T
- Boson tagged jets at lower p_T show energy redistributed out of cone
- HI jets are being commissioned for large-R spectra/substructure

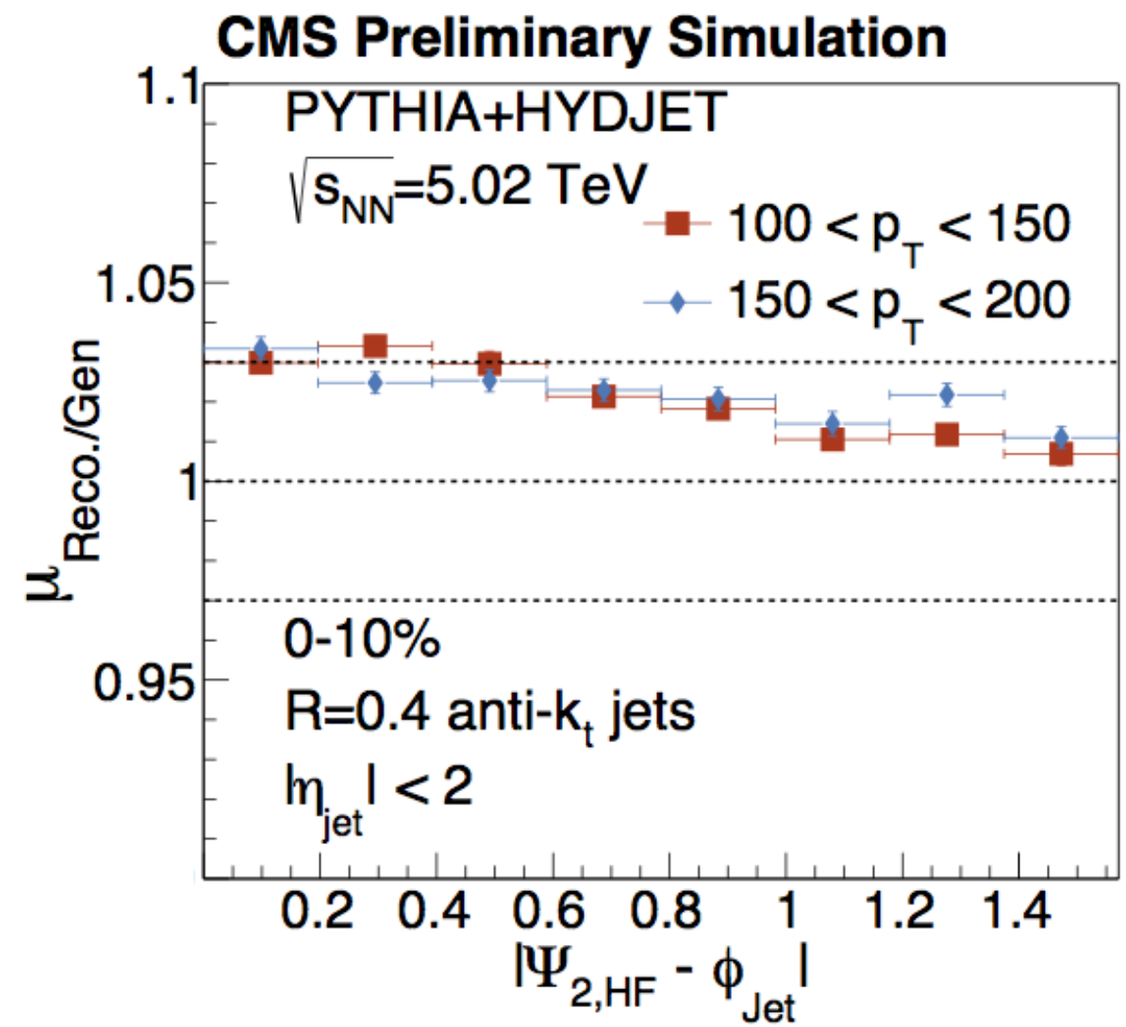
The MIT group's work was supported by US DOE-NP

Backup

Scale Closure vs. Event Plane (R=0.4)



Add Flow Correction



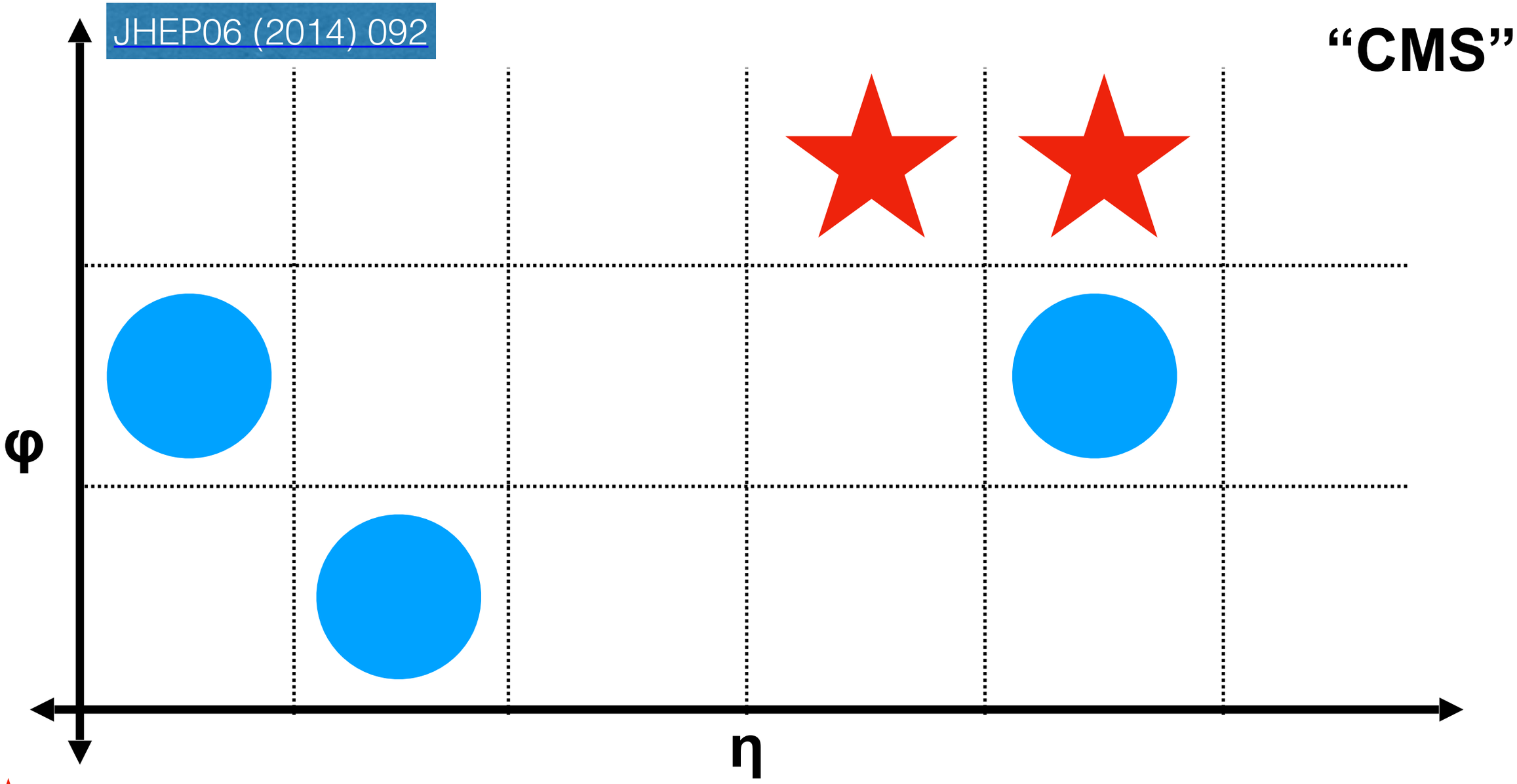
- Jet energy scale closure as function of event plane for R=0.4 w/o flow correction (**Left**) and with flow correction (**Right**)
- Some flattening of scale less than corresponding R=0.8 case

Fig. From: CMS-DP-2018-024

Illustration of CS Subtraction Iterations

Constituent Subtraction

JHEP06 (2014) 092



SIGNAL: Hard-scattering in PbPb collision producing jets

UNDERLYING EVENT: Uncorrelated particles from other nucleon-nucleon interactions

Constituent Subtraction

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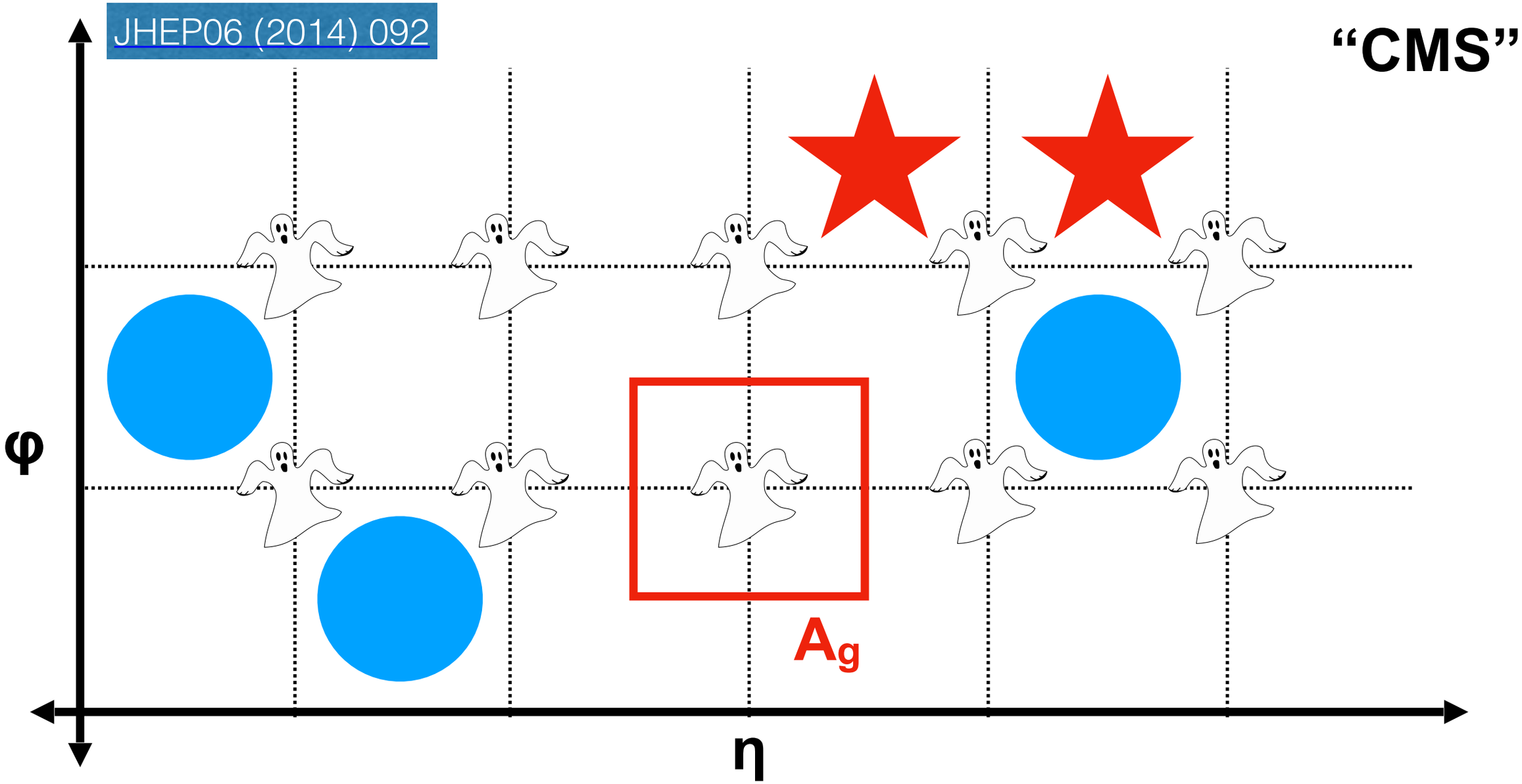

GHOST PARTICLES: Artificial particles added to the event with fixed area. Ghosts are given a p_T according to ρ times the area the inhabit, A_g

Constituent Subtraction

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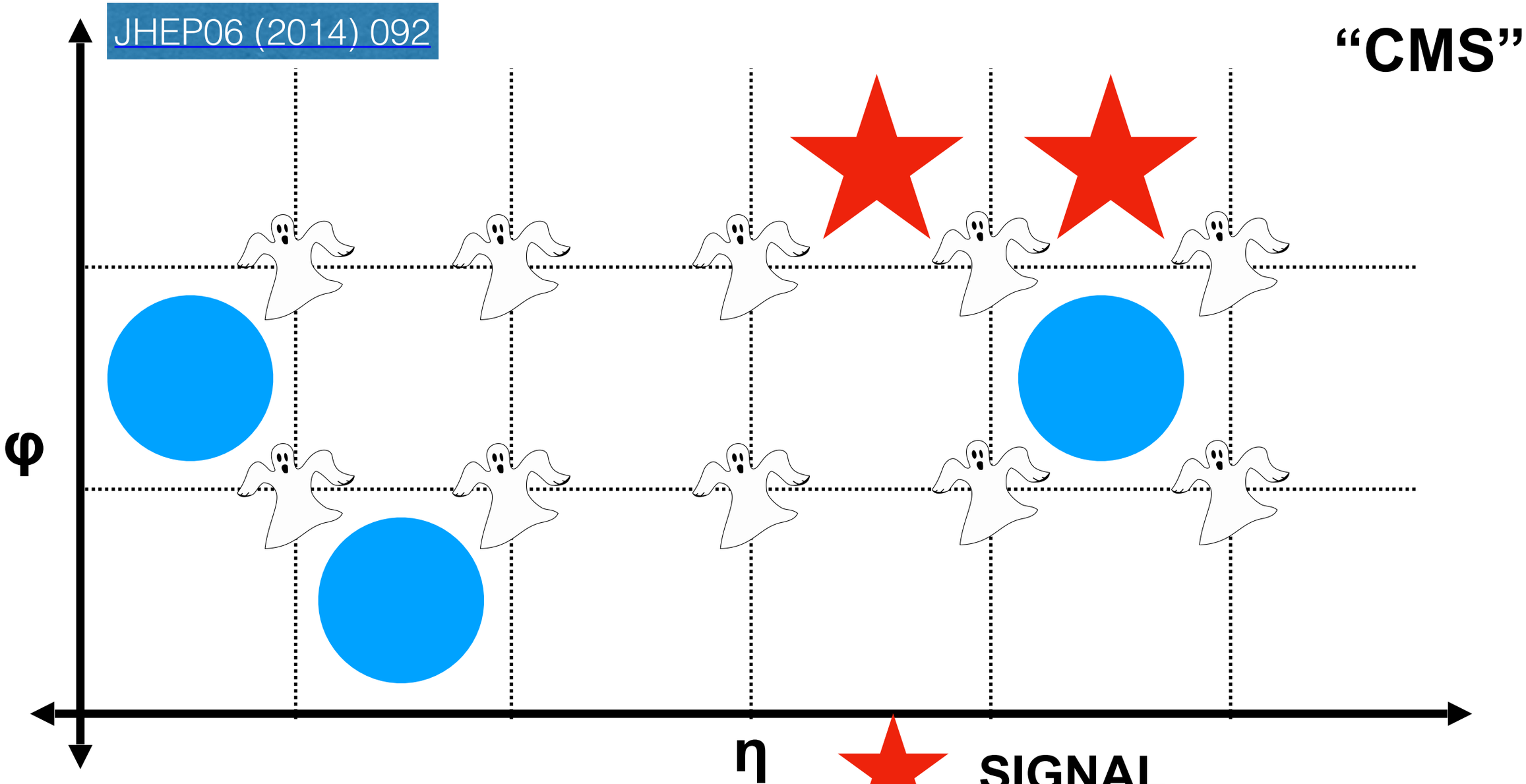
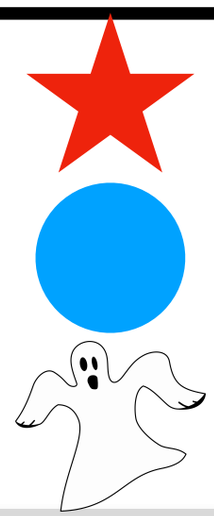


- Add "ghost" particles with fixed area according to:

$$p_T^g = A_g \cdot \rho,$$

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



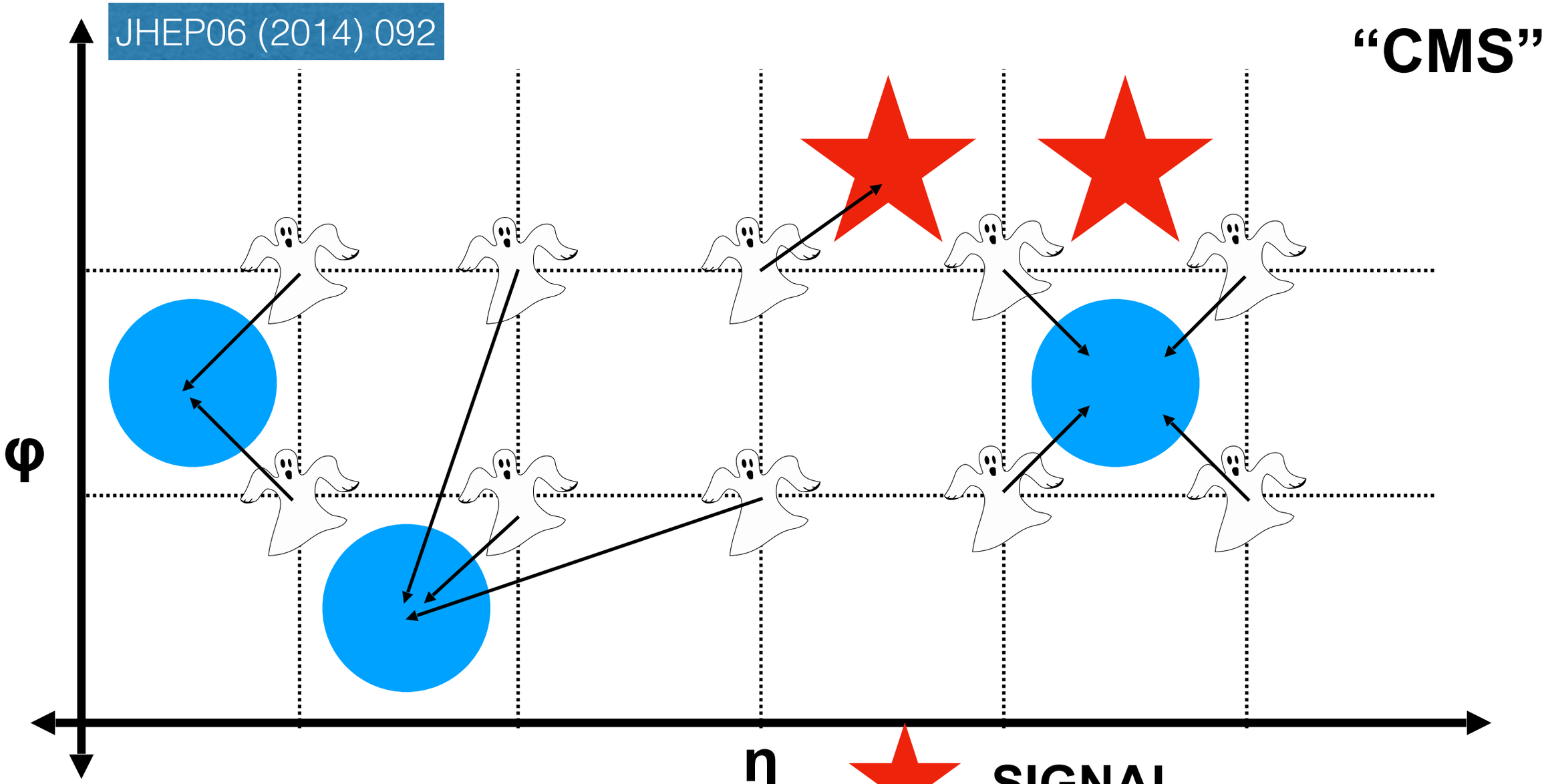
SIGNAL

UNDERLYING EVENT

GHOST PARTICLES

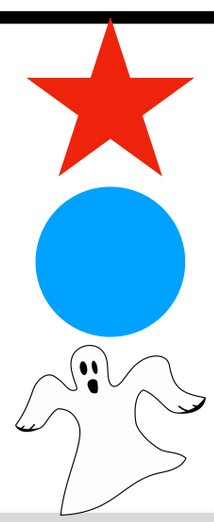
Constituent Subtraction

JHEP06 (2014) 092



- Combine iteratively with real particles by minimizing metric:

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



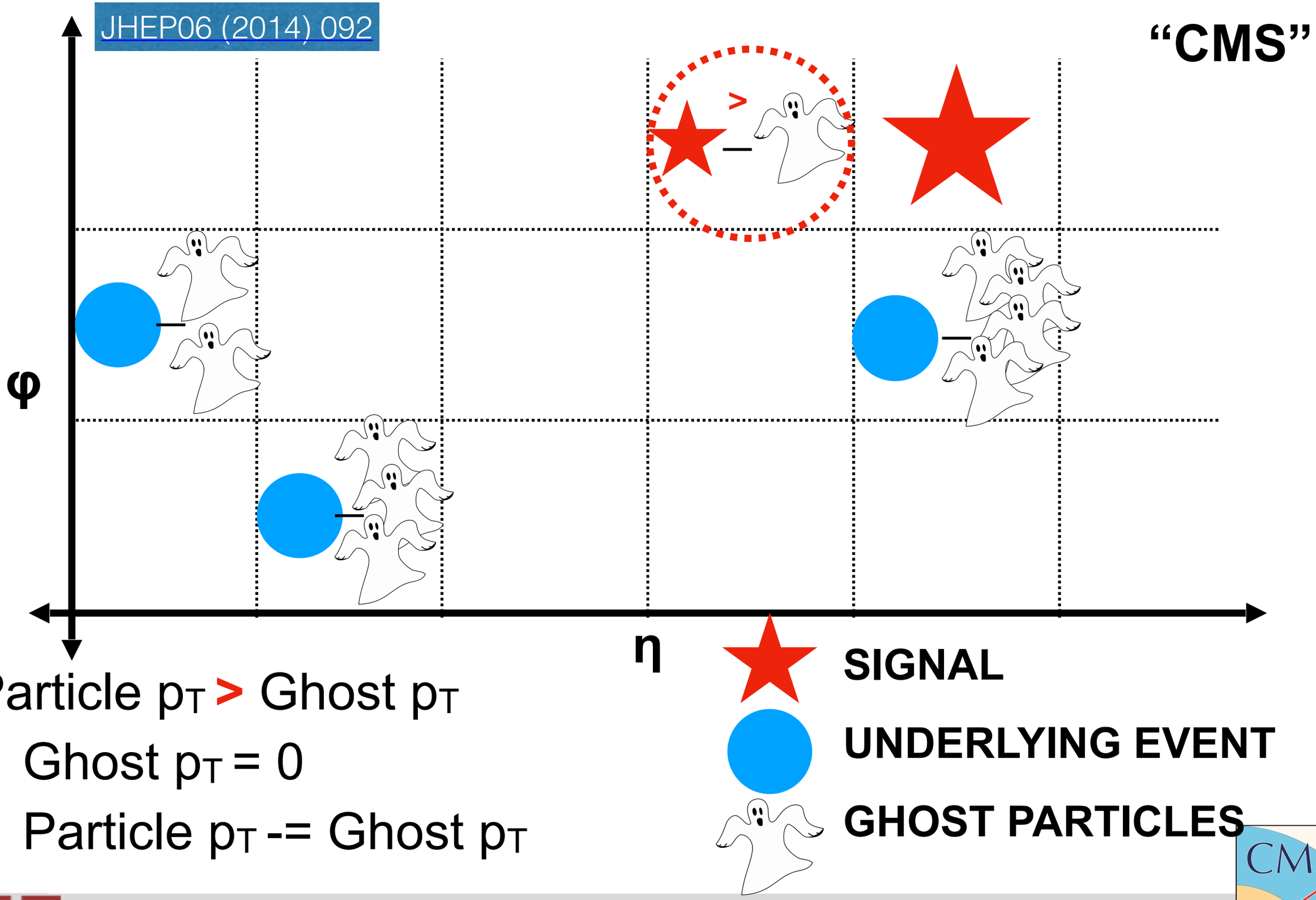
SIGNAL

UNDERLYING EVENT

GHOST PARTICLES

Constituent Subtraction

JHEP06 (2014) 092



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

Constituent Subtraction

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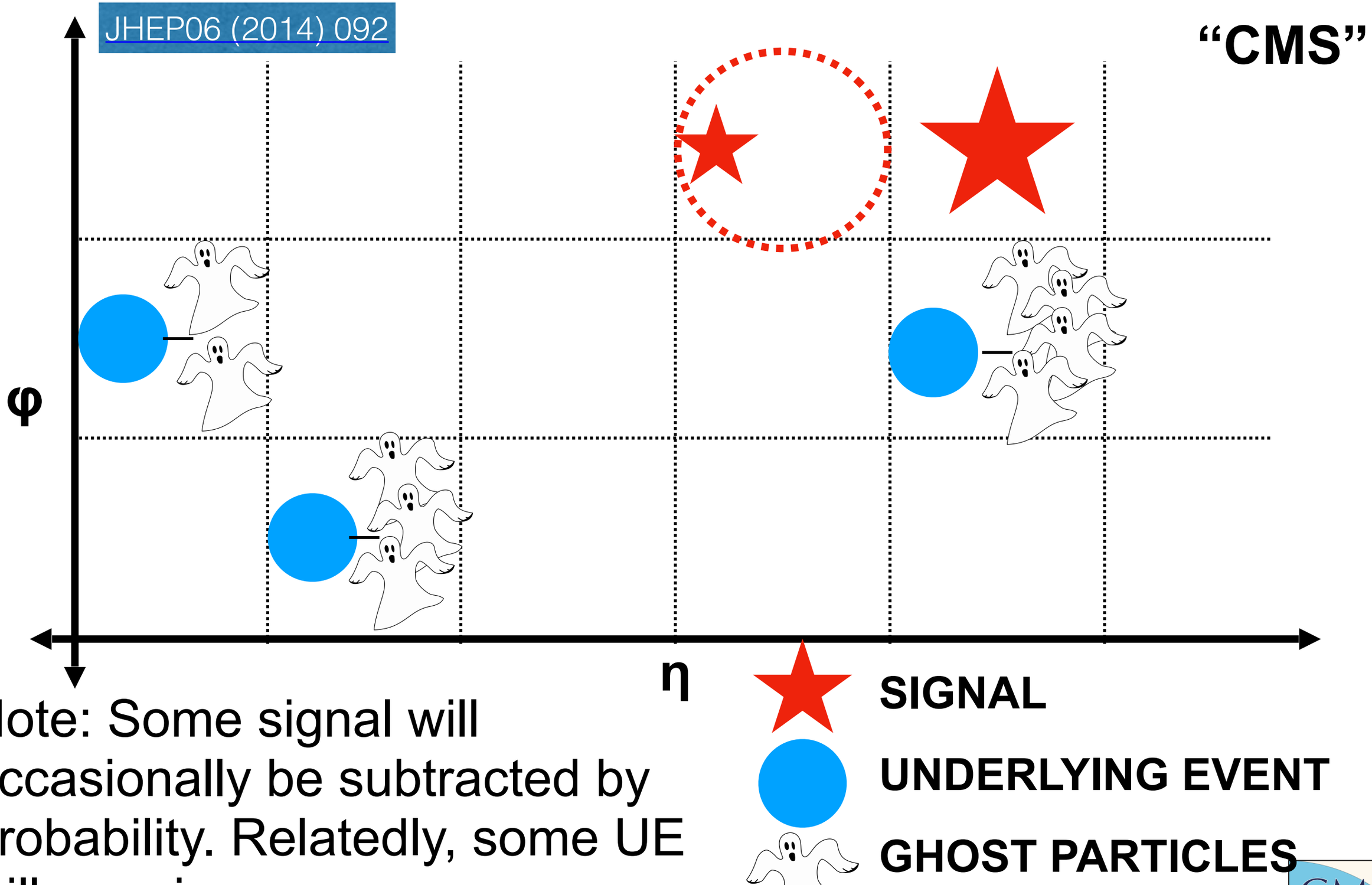
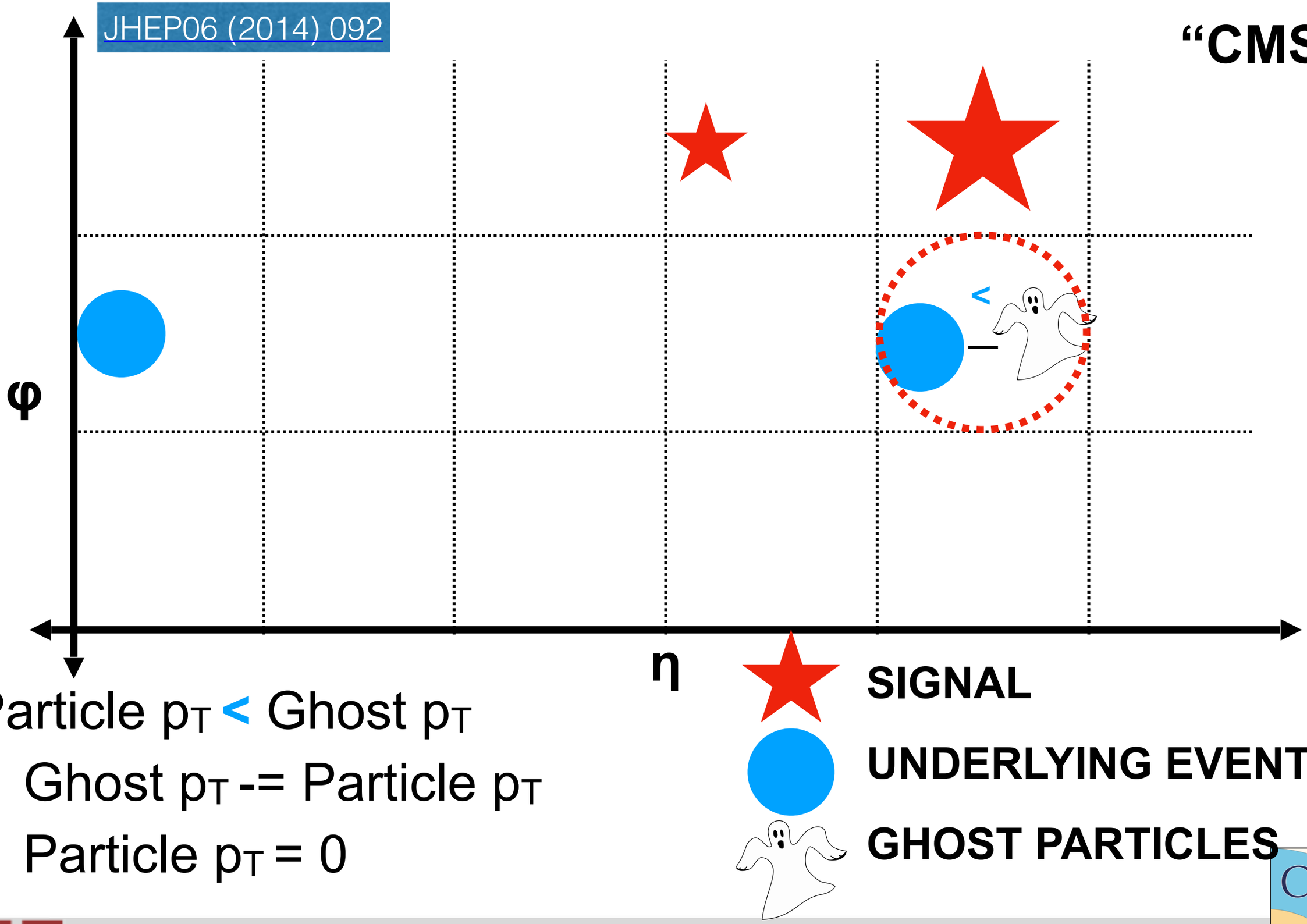


- Note: Some signal will occasionally be subtracted by probability. Relatedly, some UE will remain.

Constituent Subtraction

JHEP06 (2014) 092

"CMS"



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

Constituent Subtraction

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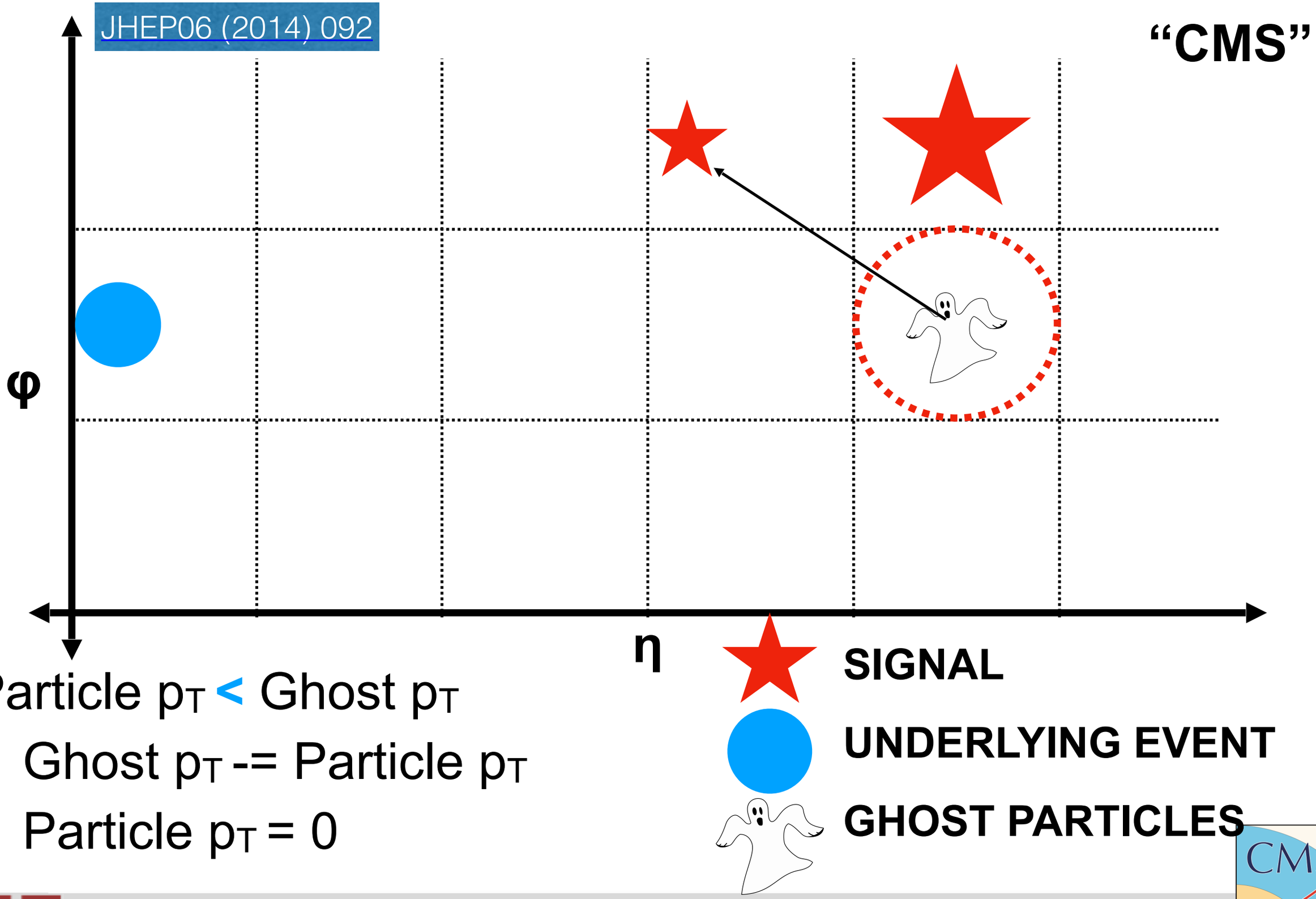

- Particle p_T < Ghost p_T
  - Ghost p_T -= Particle p_T
  - Particle p_T = 0

Constituent Subtraction

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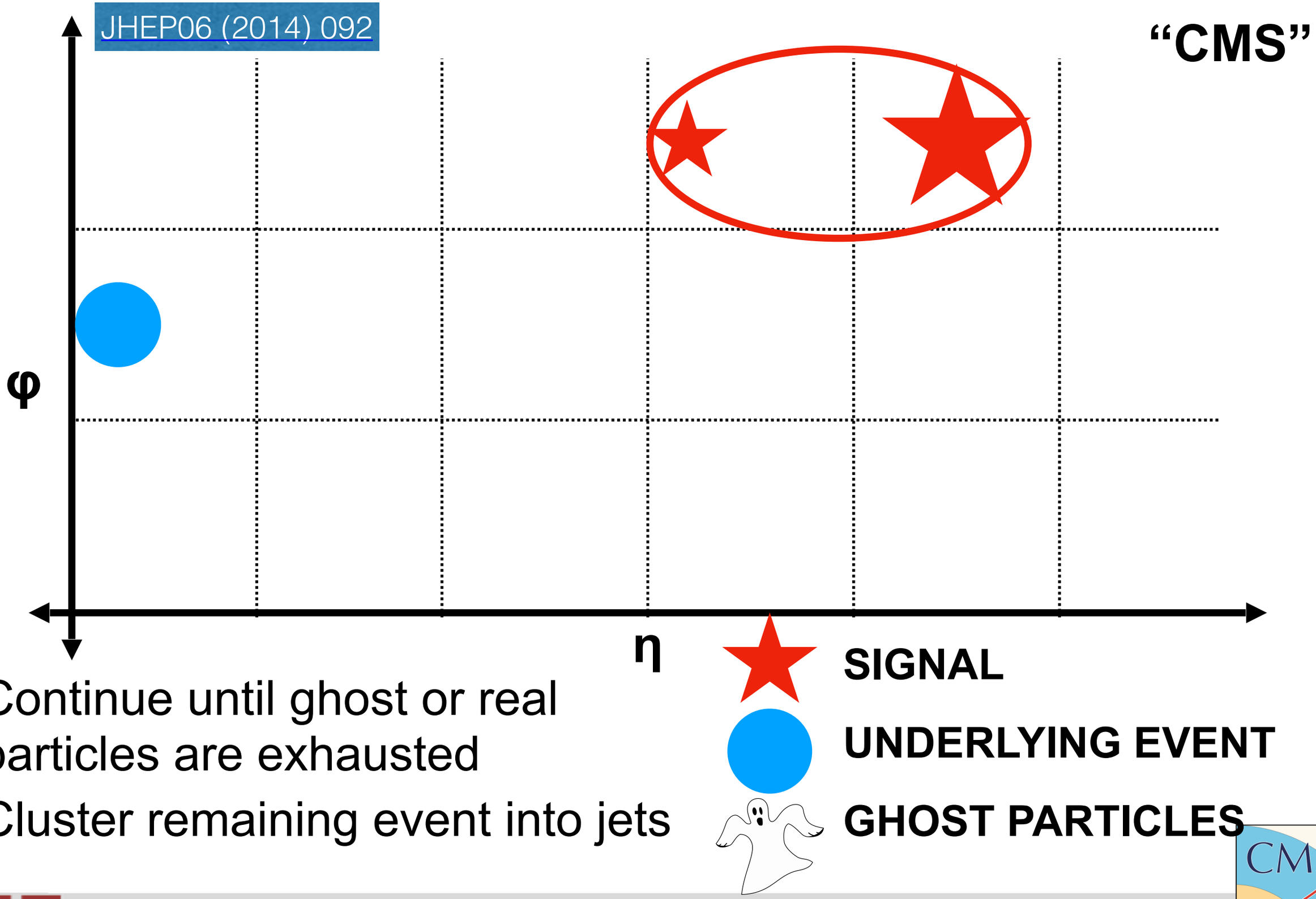
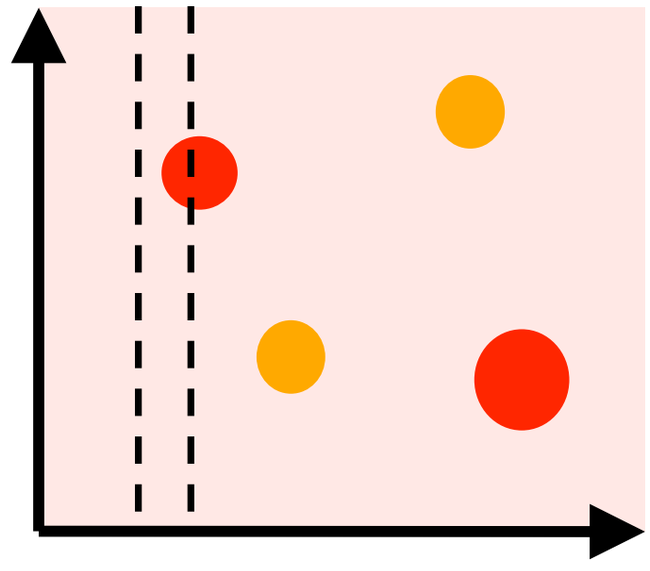


- Continue until ghost or real particles are exhausted
- Cluster remaining event into jets

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 (Δη=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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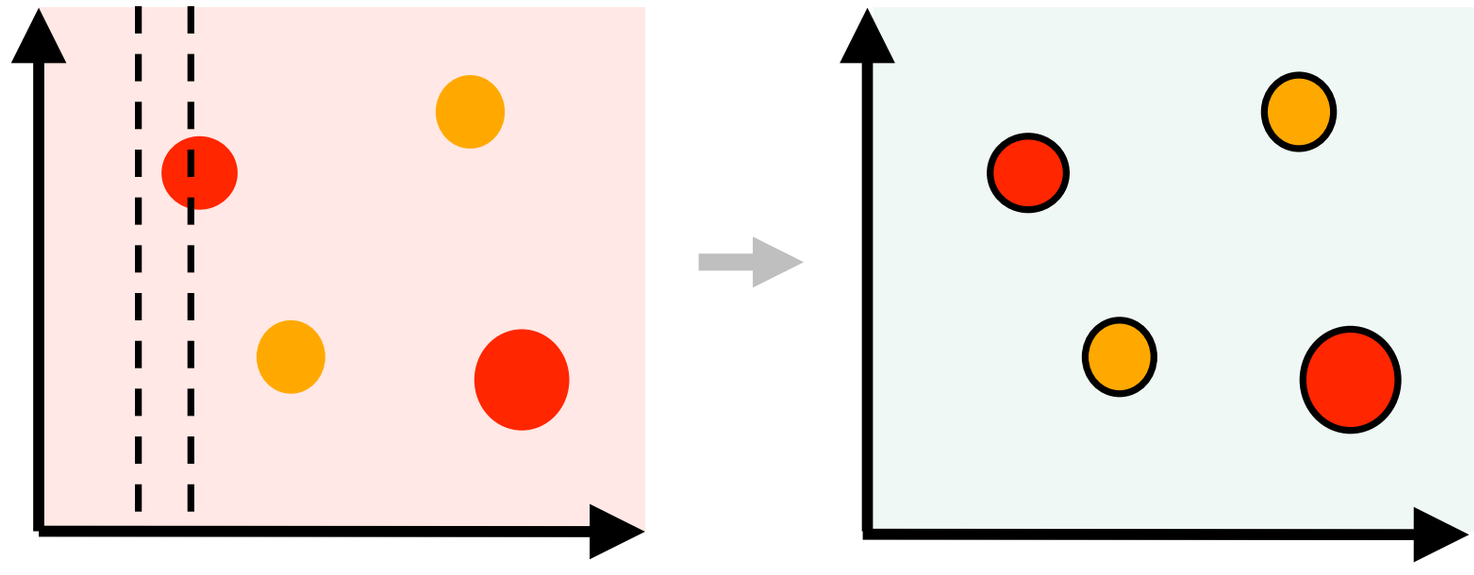
Iterative Pedestal Algorithm



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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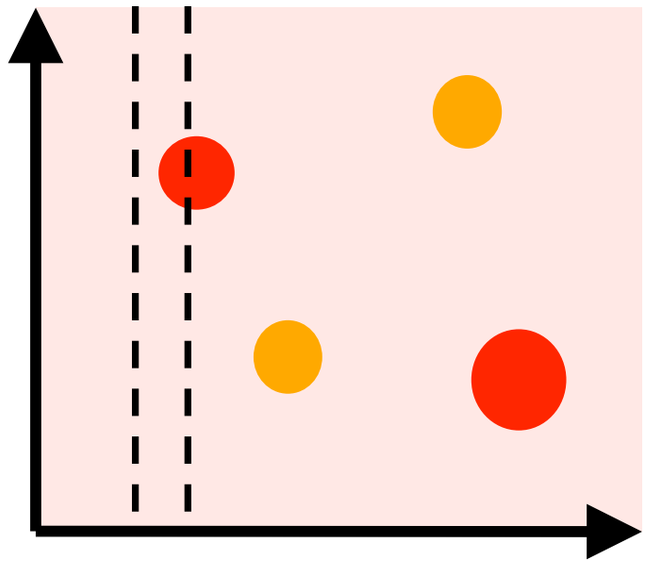
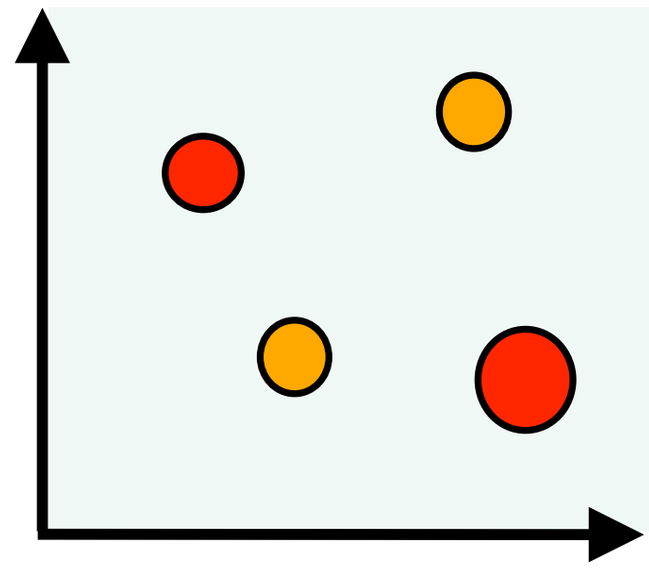
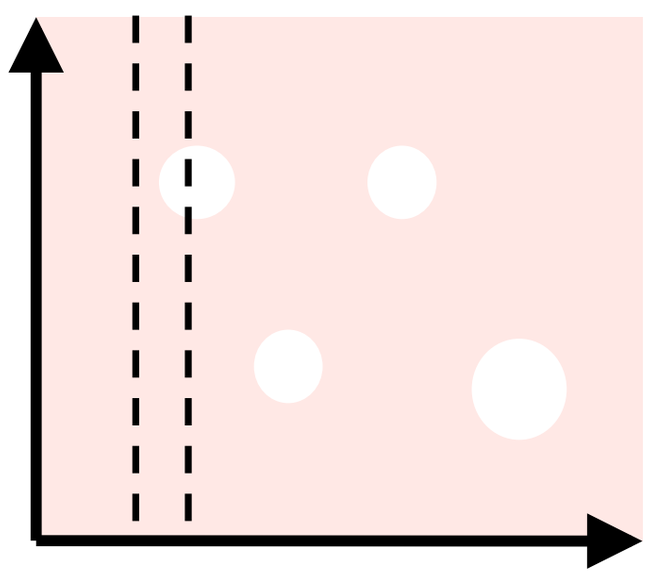
Iterative Pedestal Algorithm



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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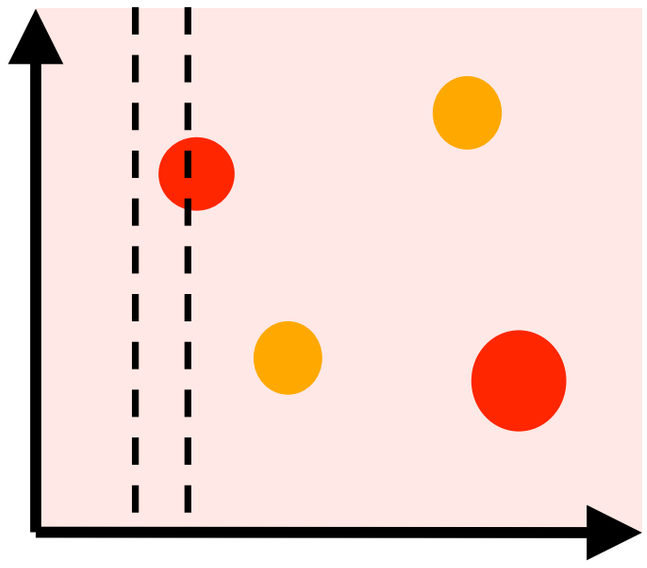
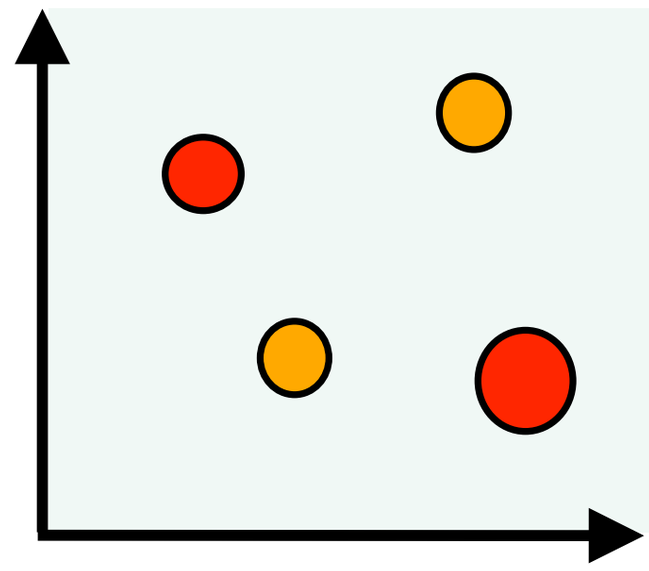
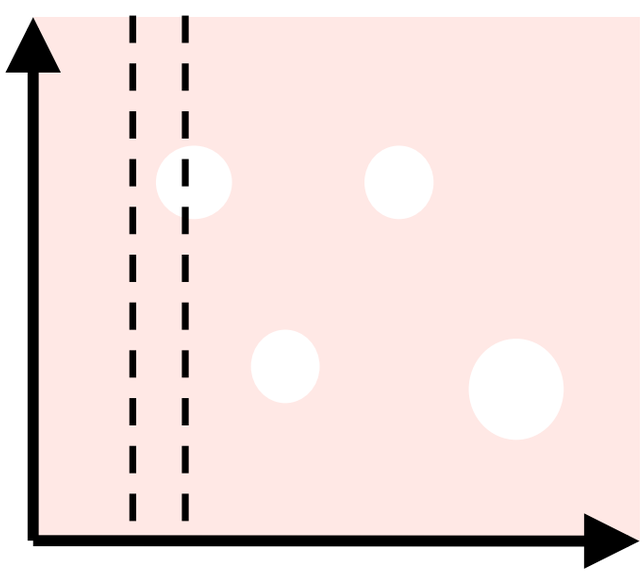
Iterative Pedestal Algorithm



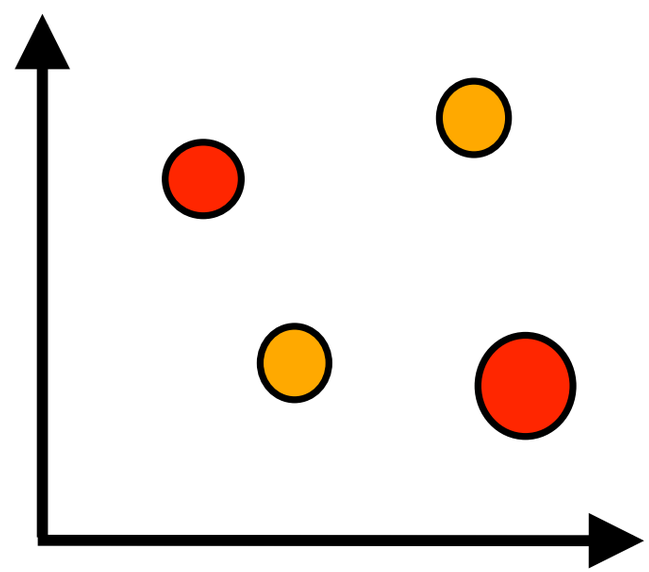
1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$



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



3. Exclude reconstructed jets and re-estimate background



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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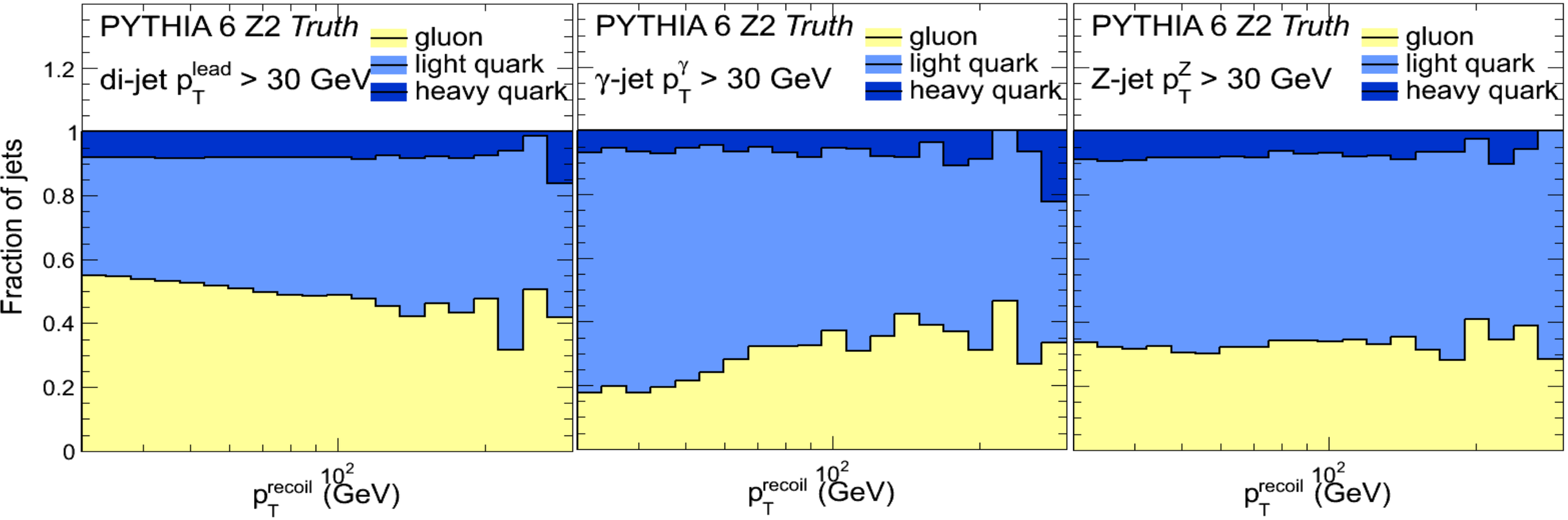
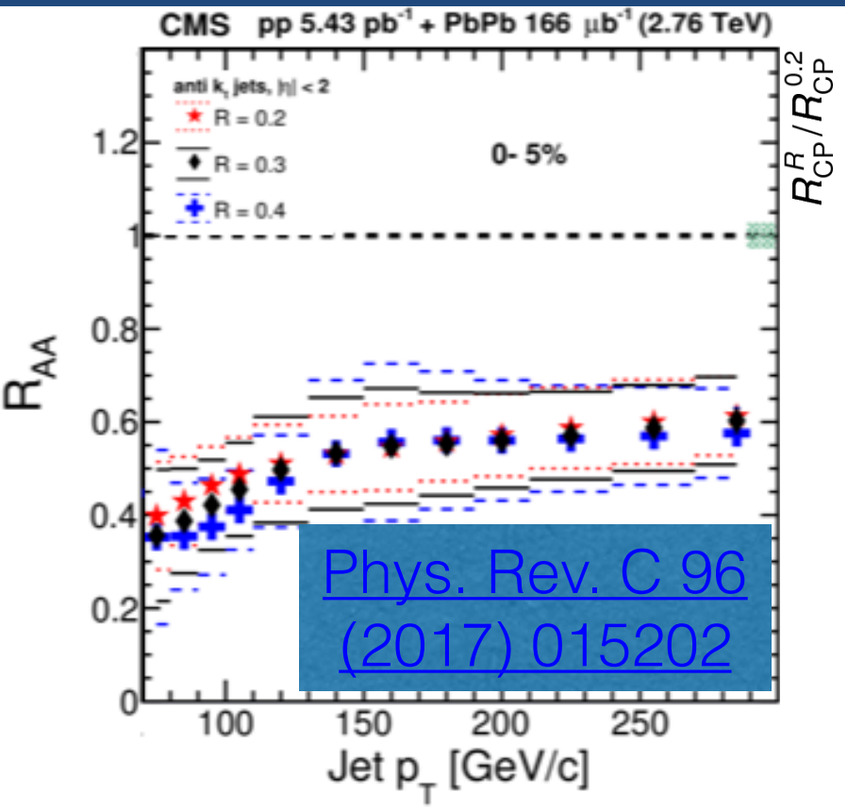
Q/G Fraction of Dijet and Boson+Jet



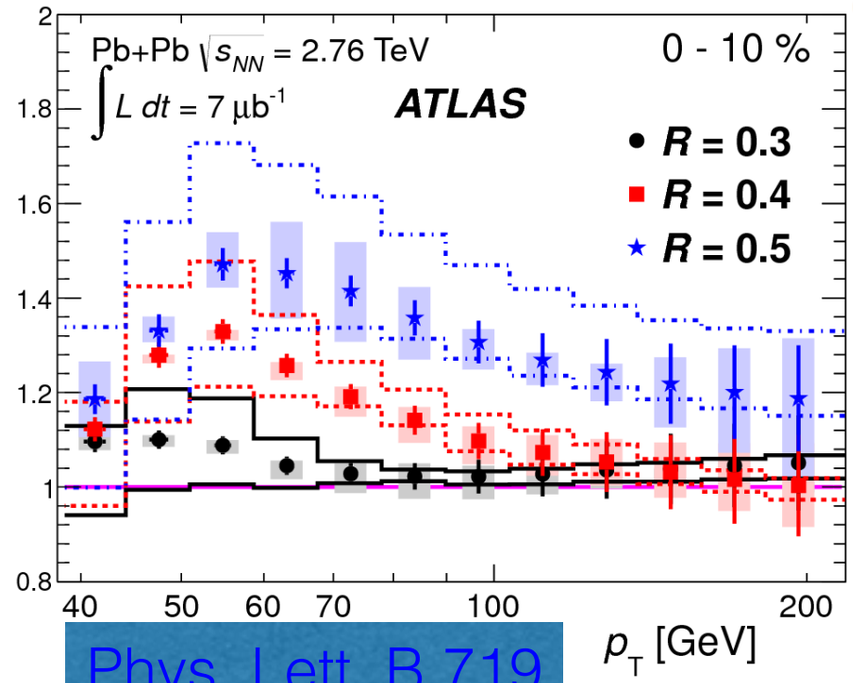
Dijet **γ+jets** **Z_{ll}+jets**

- 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

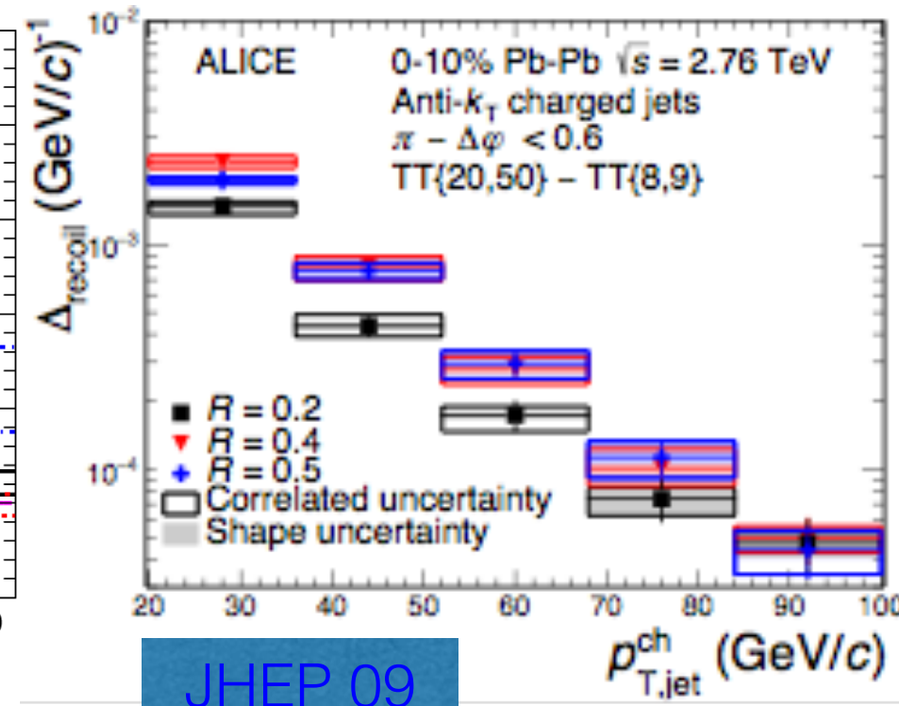
Scanning Jet Radius to Study Quenching



Phys. Rev. C 96 (2017) 015202



Phys. Lett. B 719 (2013) 220-241



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- **Experimental Results:** Measured jet production in R-scans
- Some effect at low-p_T, converges at high-p_T
- Restricted to low-p_T by sample size
- Limited systematically by pp reference being taken during different data-taking periods
- Limited in R by underlying-event (**UE**) at low-p_T