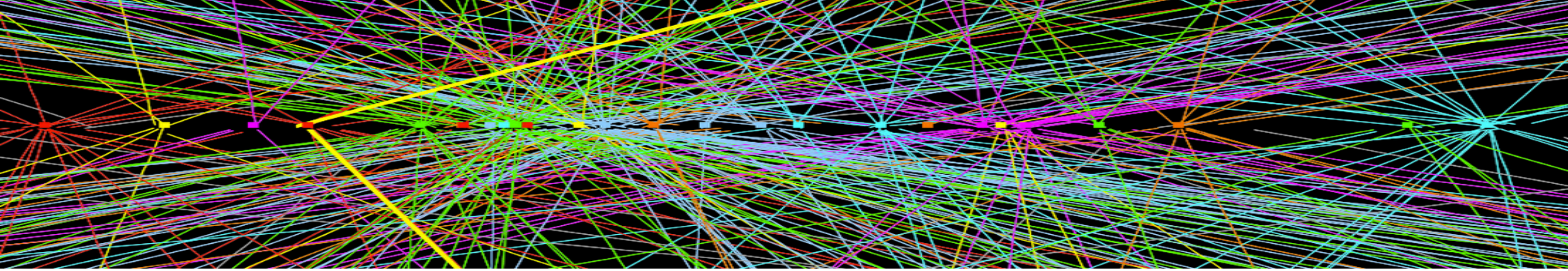
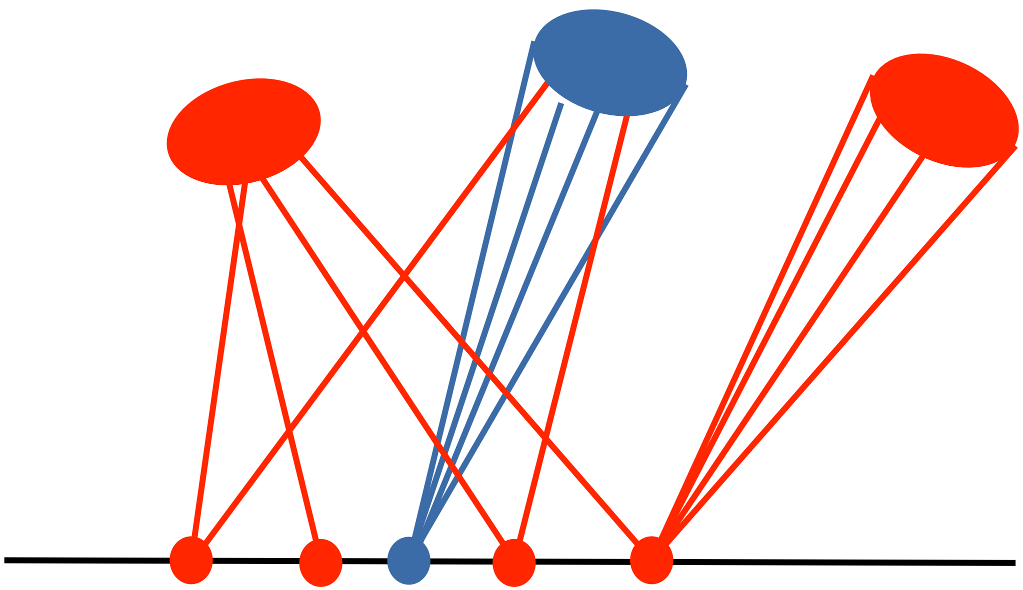


Pileup Mitigation

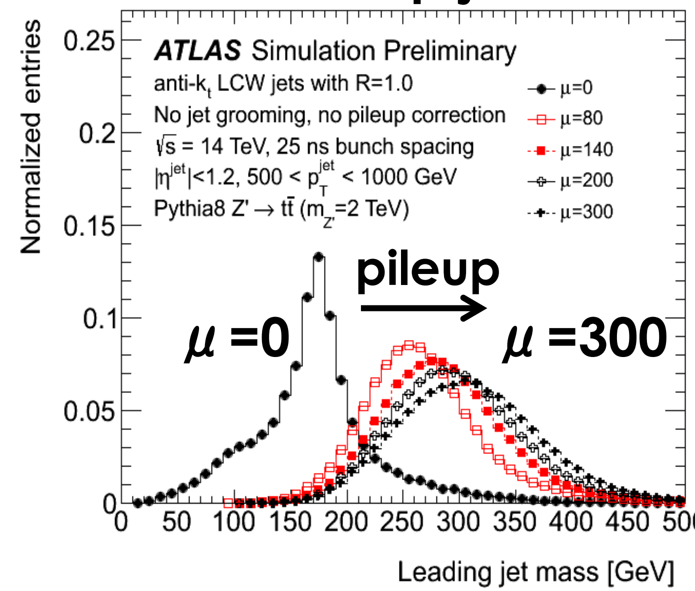
Ariel Schwartzman
SLAC

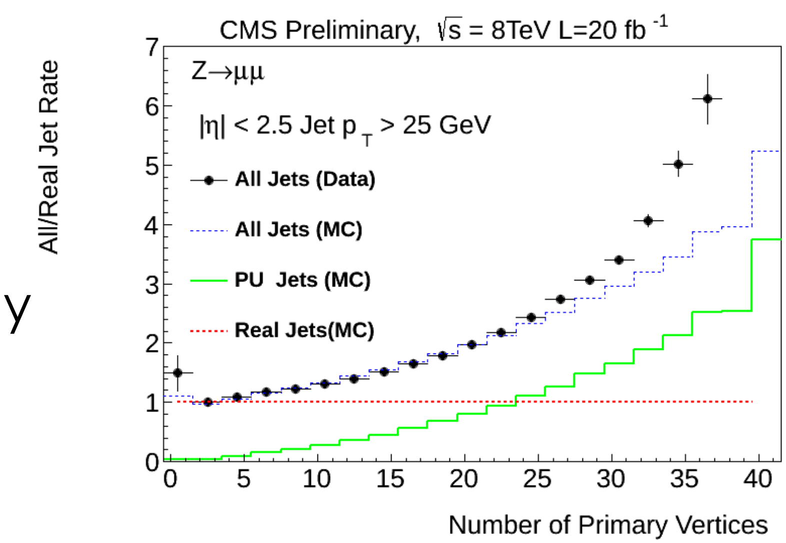
Preparing for the High-Luminosity Run of the LHC
Perimeter Institute, 09 June 2015

The challenge of pileup



Boosted top jet mass





- **Additional energy** (offset)
- **Fluctuations:**
  - Reduce accuracy of the jet energy and mass determination
  - Additional fake pileup jets

Pileup mitigation in Run 1: four key ideas

1. Topoclusters/ Charged Hadron Subtraction

Constituent-level pileup suppression

2. Jet Area Subtraction

$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

3. Jet-Vertex Tagging

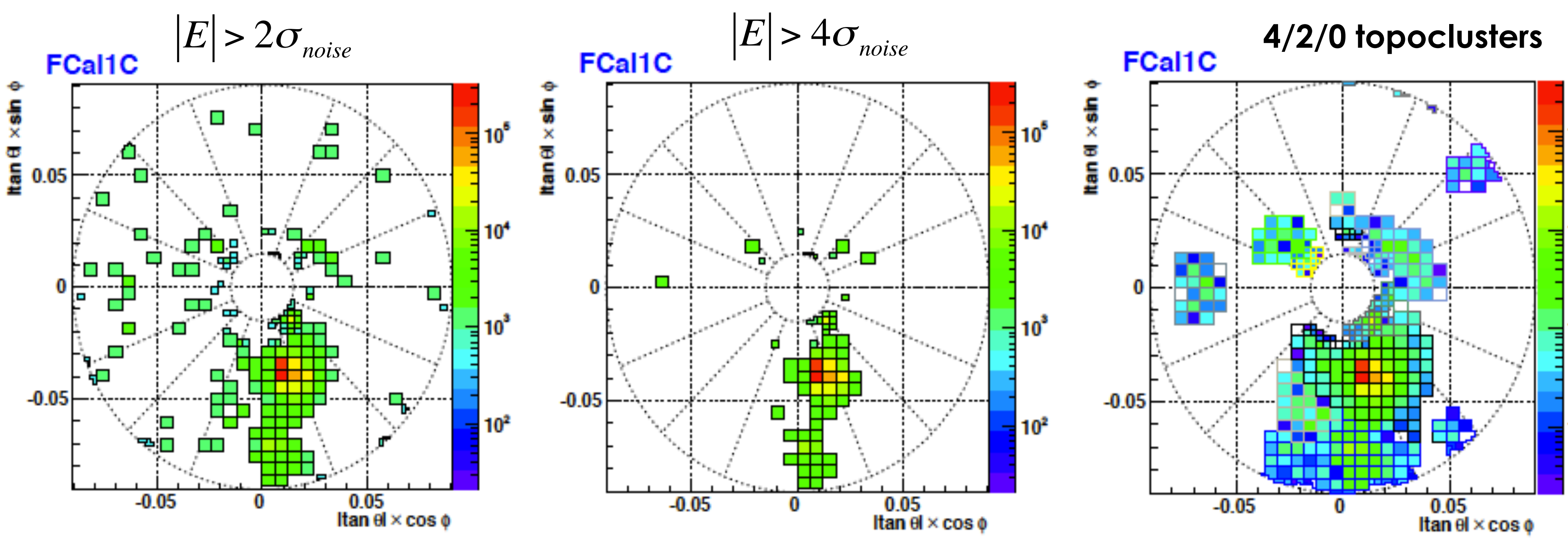
Use of tracking information to reject jets from pileup

4. Grooming

Reduce local fluctuations of pileup (Large-R jets)

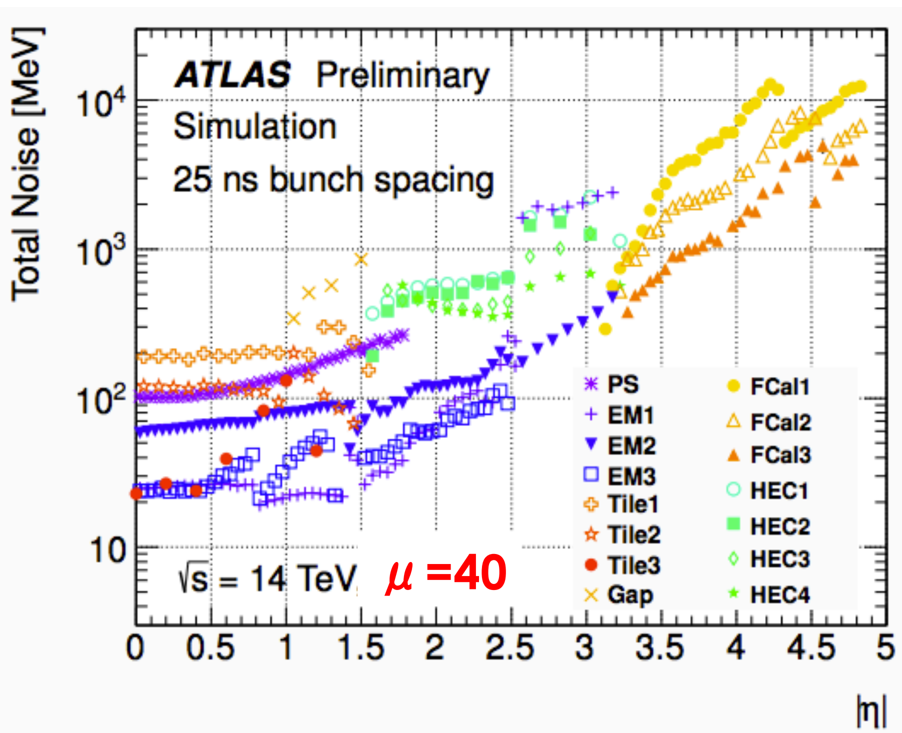
Topoclustering

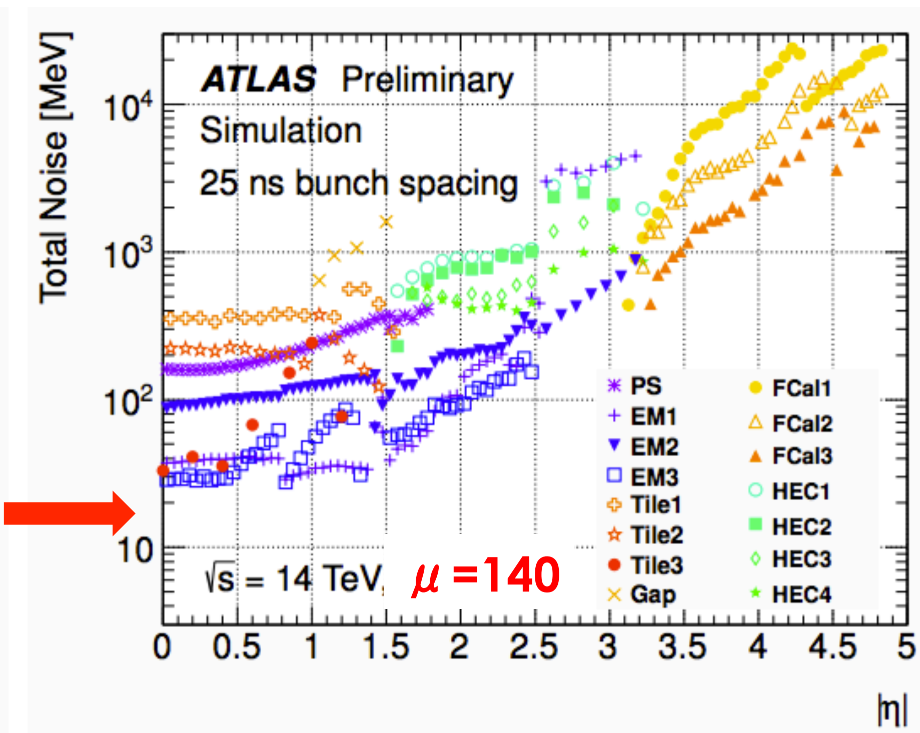
- **Topological clusters:**
  - 3D nearest-neighbor algorithm that clusters calorimeter cells with energy significance ($|E_{cell}|/\sigma$)>**4** for the seed, >**2** for neighbors, and >**0** at the boundary



Topoclustering

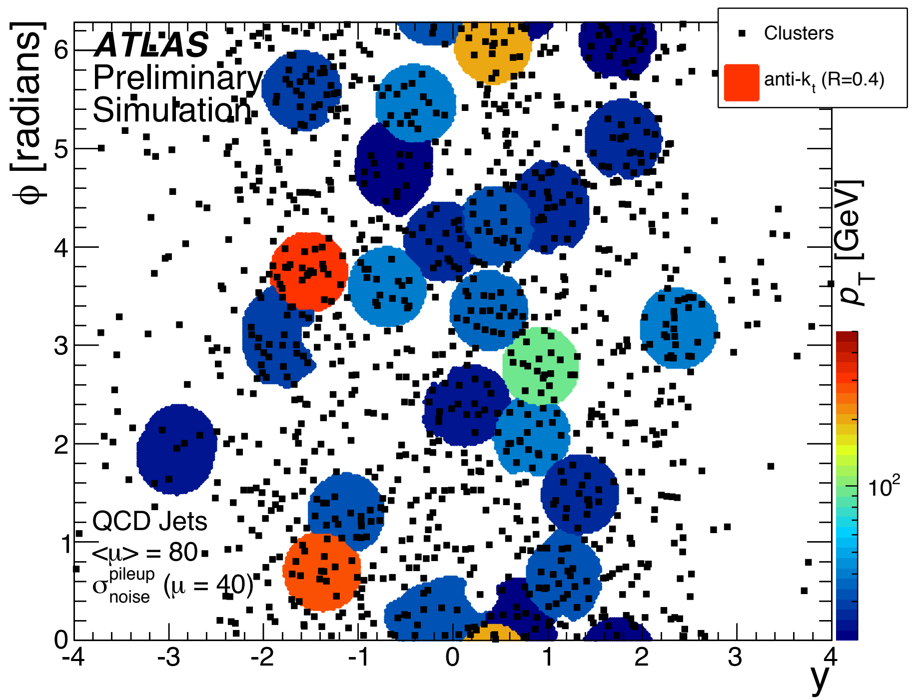
- **Sigma noise**: electronic + pileup noise
  - Adjusted with μ for **pileup noise suppression**
    - $\sigma = \sigma(\mu=8)$ **in 2011,** $\sigma = \sigma(\mu=30)$ **in 2012**





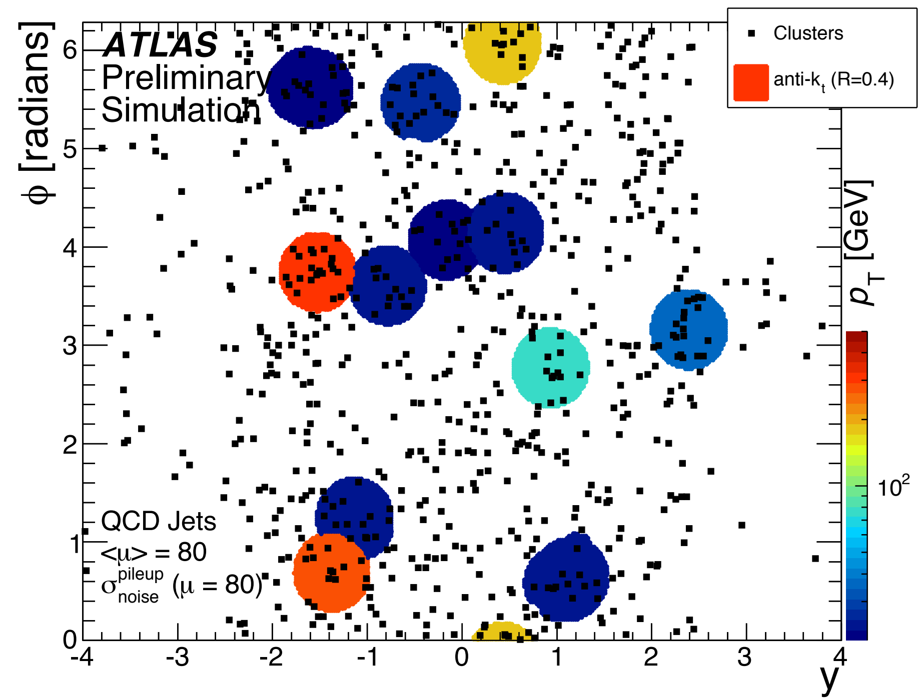
Topoclustering pileup suppression

mu=80



$$\sigma_{noise}^{pileup}(\mu = 40)$$

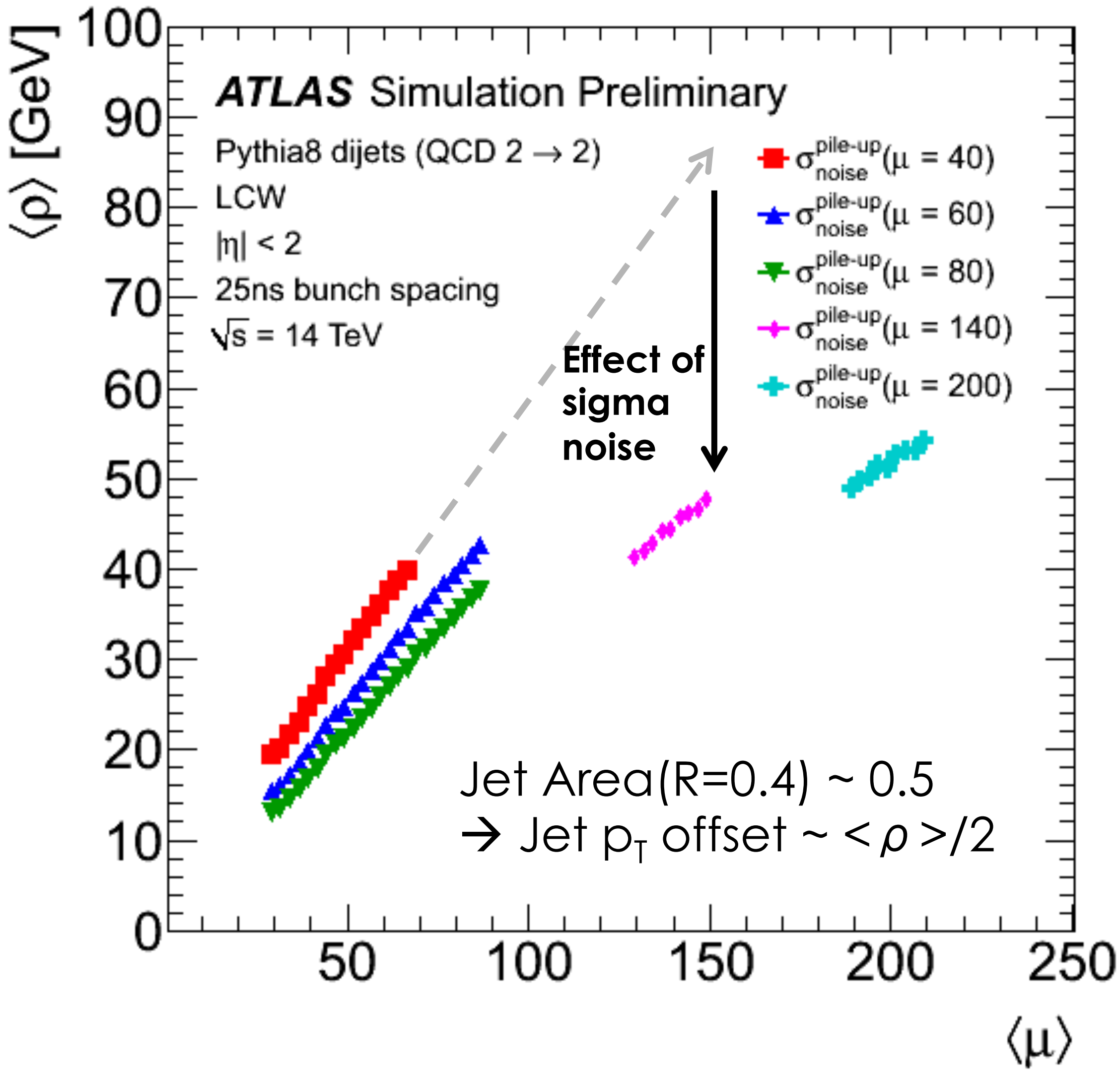
mu=80



$$\sigma_{noise}^{pileup}(\mu = 80)$$

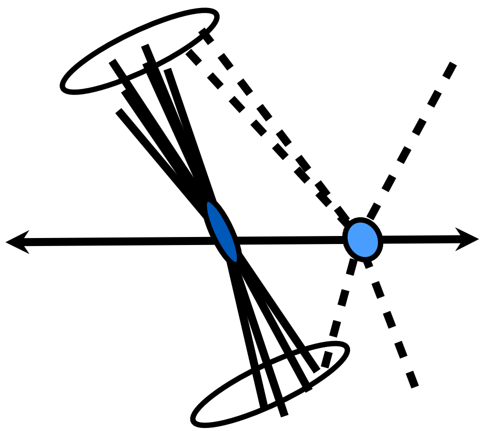
Sigma noise provides particle (cluster) level pileup suppression

Topoclustering pileup suppression

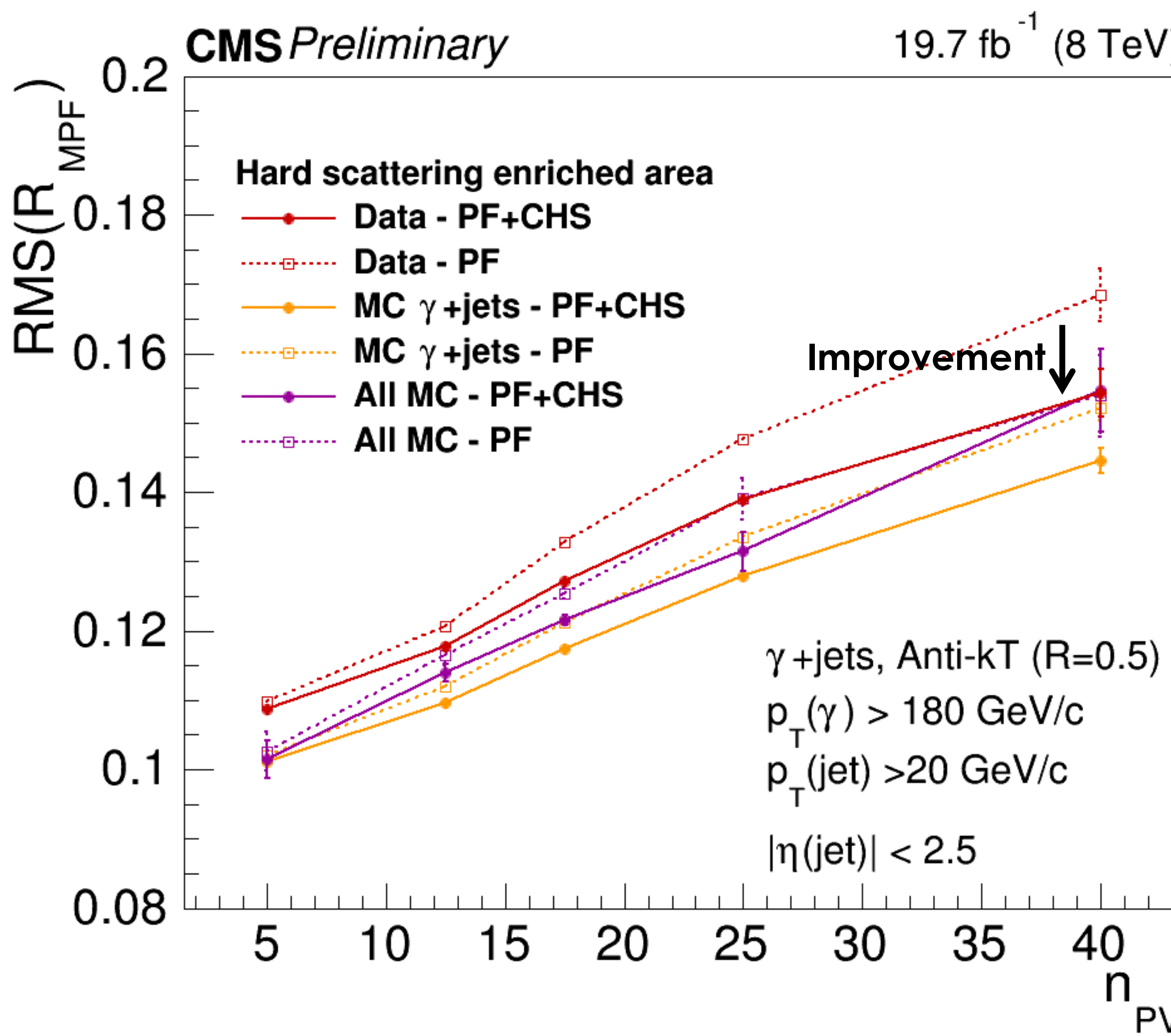


- Linear behavior of rho up to high mu for fixed sigma noise values
- Higher pileup sigma noise values lead to partial suppression of pileup
- **Optimization of topoclustering sigma noise is key to reconstruct jets at high luminosity**

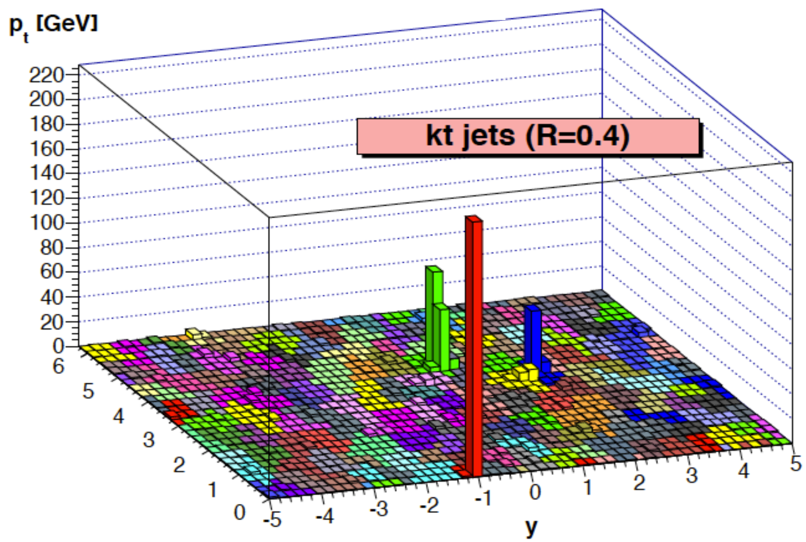
Charged hadron subtraction



- Remove pflow objects associated to PU vertices before jet reconstruction
- Improves jet energy resolution



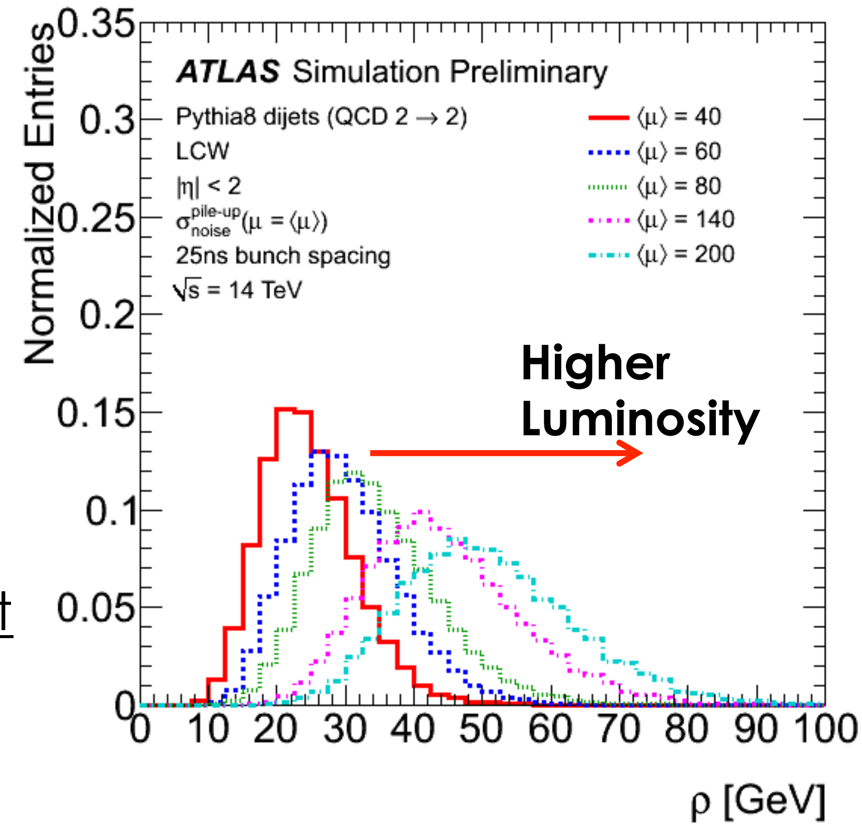
Pileup subtraction



- Determine the density of pileup p_T per unit of area (ρ) <u>event-by-event</u>

$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

- Need residual correction to account for higher occupancy inside jets, noise thresholds, and out-of-time pileup effects

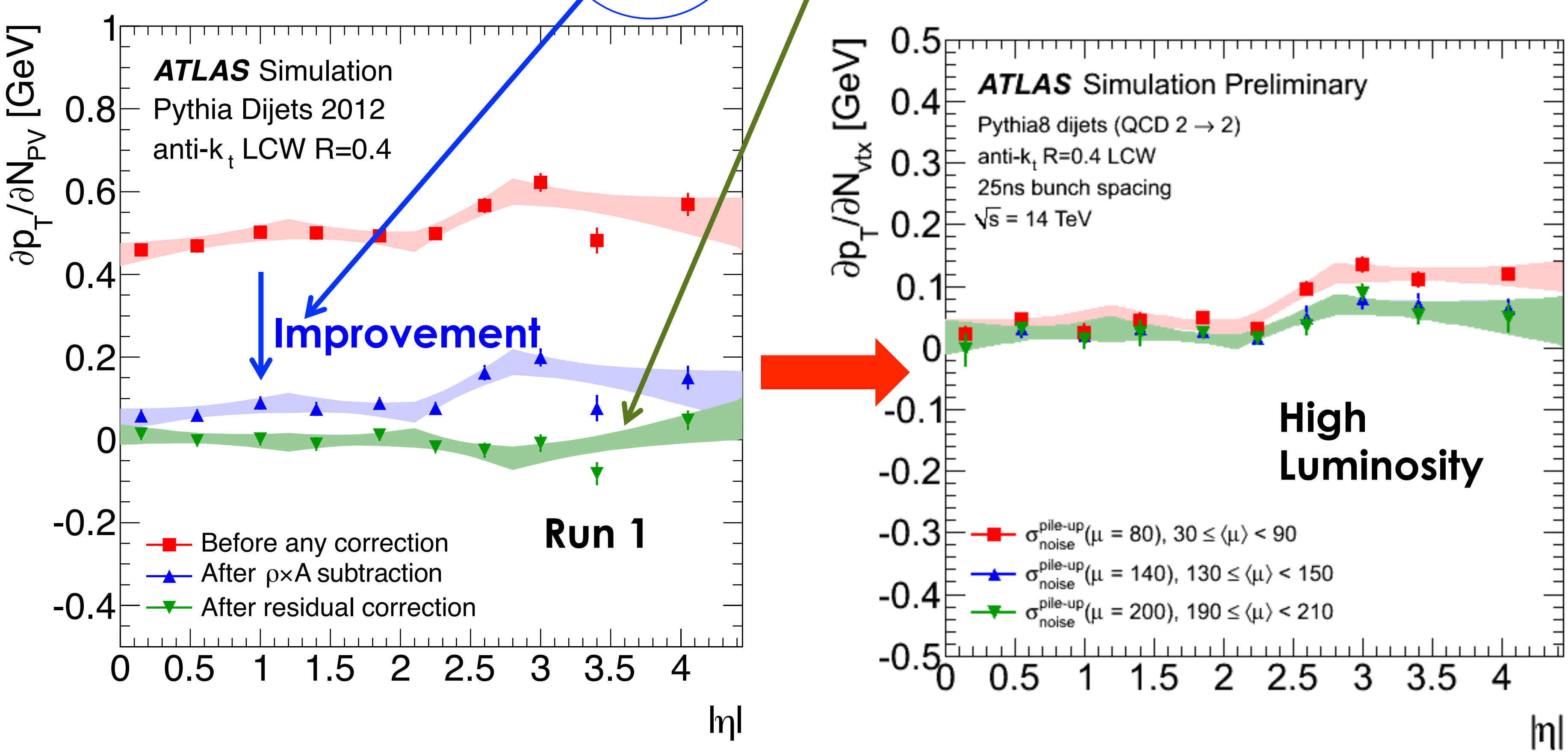


arXiv:0707.1378 [hep-ph]

Pileup subtraction

Residual correction

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho A_{\mathrm{T}} - \alpha(N_{\mathrm{PV}} - 1) - \beta\langle\mu\rangle$$



- Residual offset is mostly pileup independent, *after adjusting sigma noise*
- **Topoclustering and jet areas subtraction work well up to very high luminosity**

New approaches

Run 1

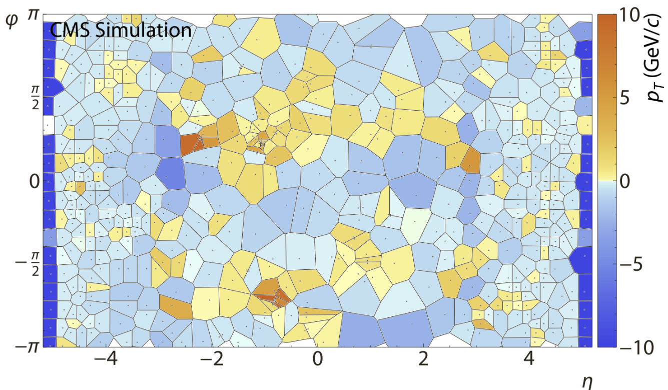
Run >1

More use of local information to suppress local fluctuations of pileup

- Performance gains
- Corrects jet shapes

Constituent Subtraction

CMS Voronoi subtraction (Heavy Ion)



- Applicable to the whole event
- Corrects jet kinematics and jet/event shapes
- Can use any type of constituent as input

Constituent subtraction:

JHEP 06 (2014) 092 P. Berta, R. Leinter, D. Miller. M. Spousta

The correction procedure

- for each event
  1. estimate the background p_{T} density, ρ, in the event,
  2. add ghosts (infinitesimally small p_{T}^{g}) among particles in the event and apply jet algorithm to all particles and ghosts $\Rightarrow$ the jets are composited from particles and ghosts,
- for each jet in the event
  3. set for each ghost $p_{\mathrm{T}}^{g} = \rho A_g$
  4. evaluate distance $\Delta R_{i,k}$ between particle i and ghost k for each possible particle-ghost pair and sort them:

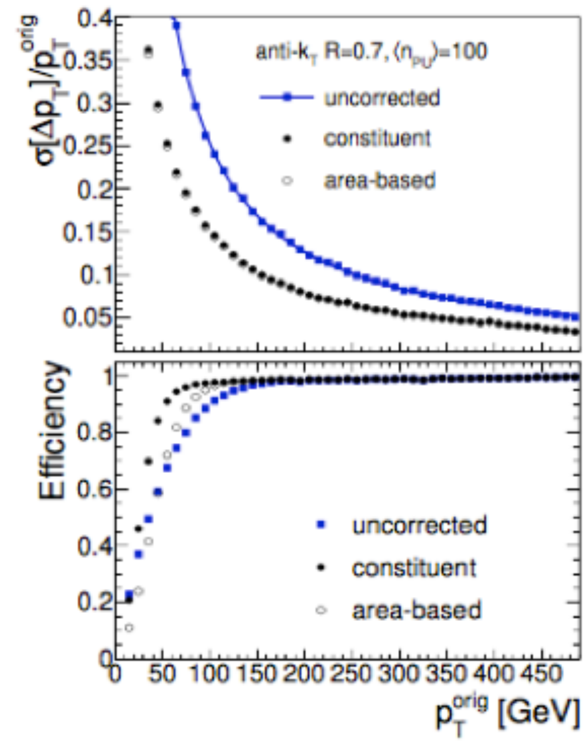
$$\Delta R_{i,k} = p_{\mathrm{T}i}^{\alpha} \cdot \sqrt{(y_i - y_k^g)^2 + (\phi_i - \phi_k^g)^2}. \quad (6)$$

  5. iteratively change transverse momenta by applying the following procedure for each ghost-particle pair until no more pairs remain or $\Delta R_{i,k} > \Delta R^{\max}$:

$$\text{If } p_{\mathrm{T}i} \geq p_{\mathrm{T}k}^{g}: \quad p_{\mathrm{T}i} \to p_{\mathrm{T}i} - p_{\mathrm{T}k}^{g}, \quad p_{\mathrm{T}k}^{g} \to 0; \qquad \text{otherwise:} \quad p_{\mathrm{T}i} \to 0, \quad p_{\mathrm{T}k}^{g} \to p_{\mathrm{T}k}^{g} - p_{\mathrm{T}i}. \quad (7)$$

  6. after the iterative process, discard all particles with zero transverse momentum.

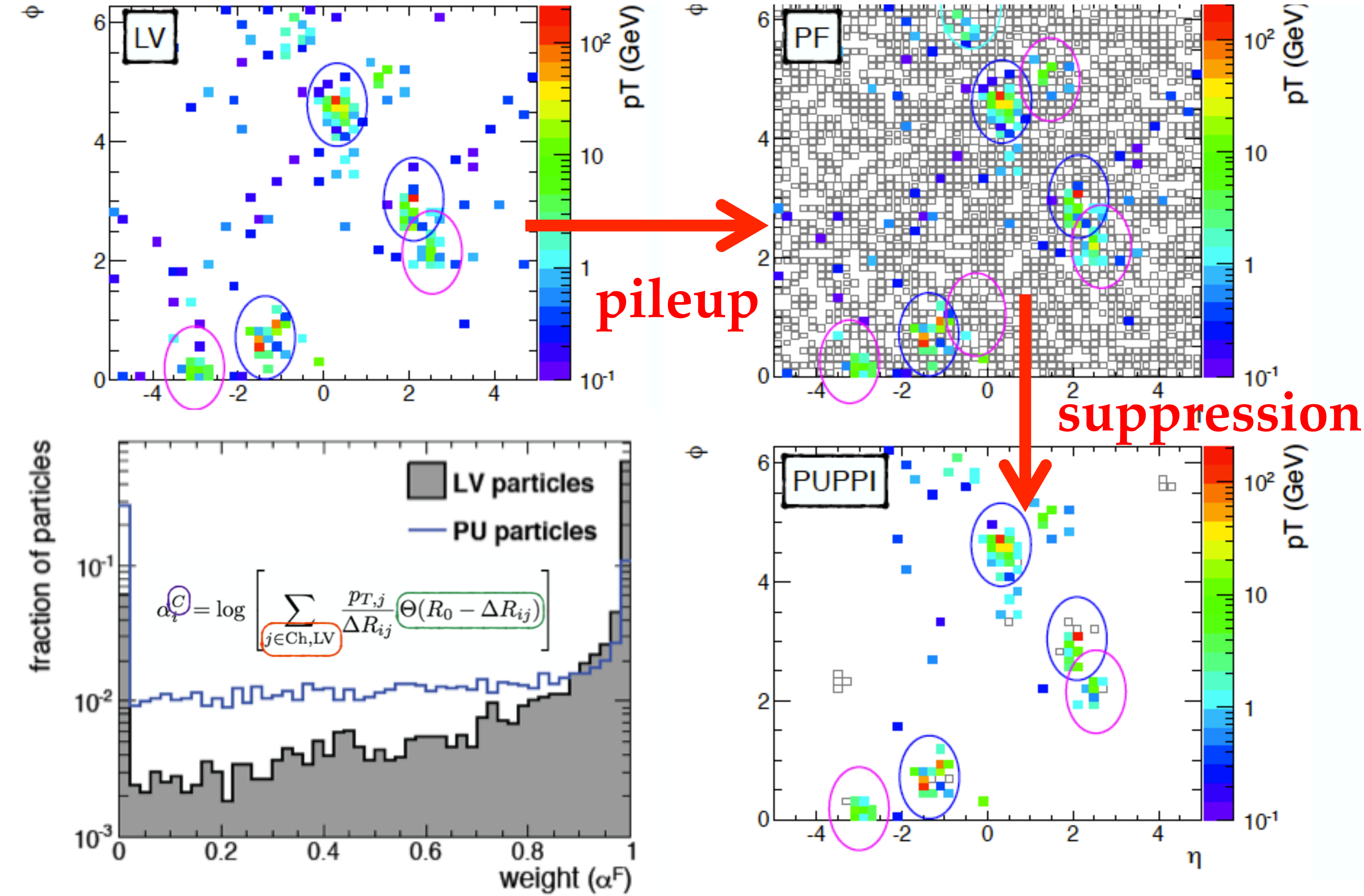
P. Berta (Charles University in Prague) | Constituent subtraction | 16th May 2014 | 12 / 25



arXiv:1407.6013 [hep-ph]
D. Bertolini, P. Harris, M. Low, N. Tran

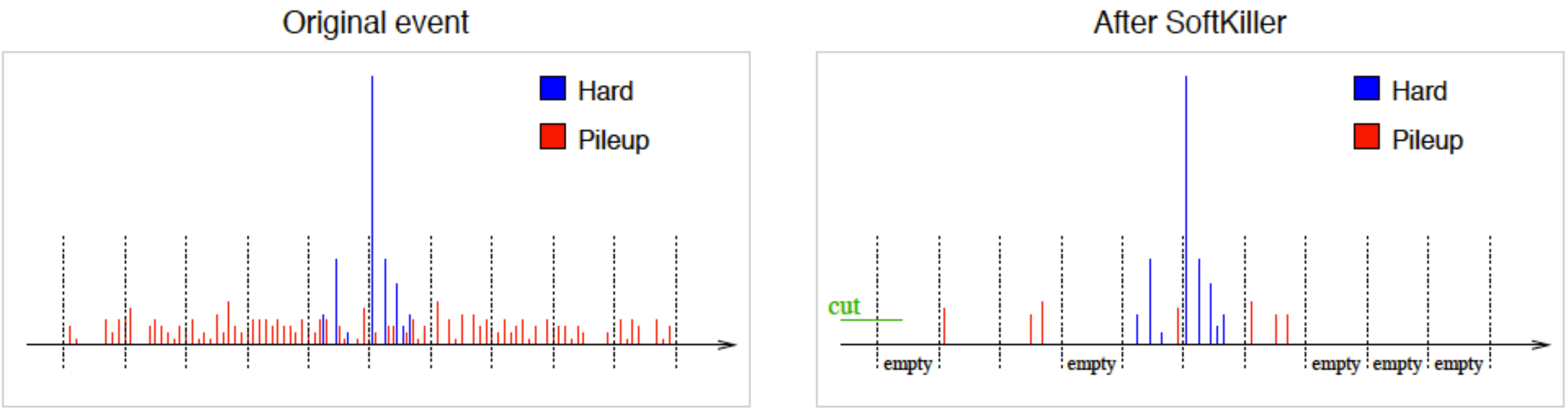
PUPPI

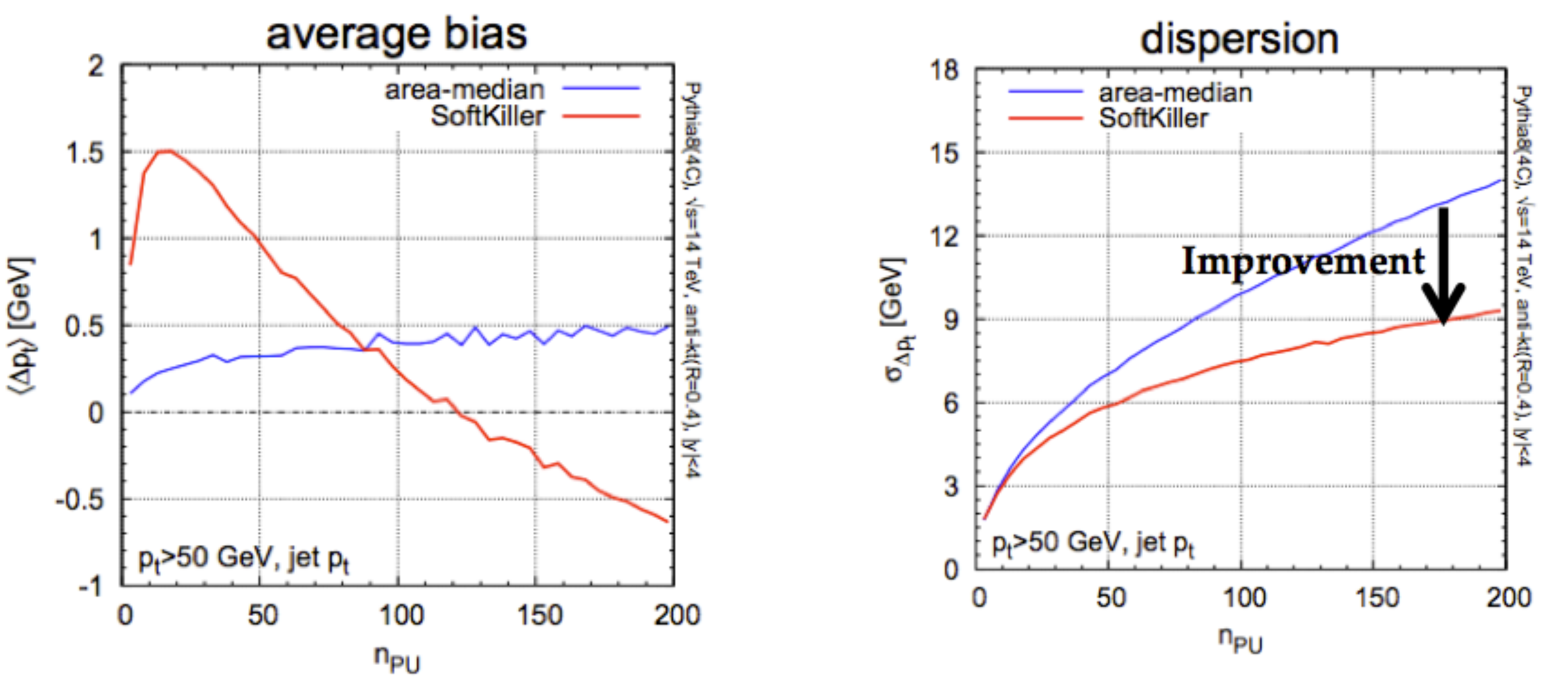
mu=80



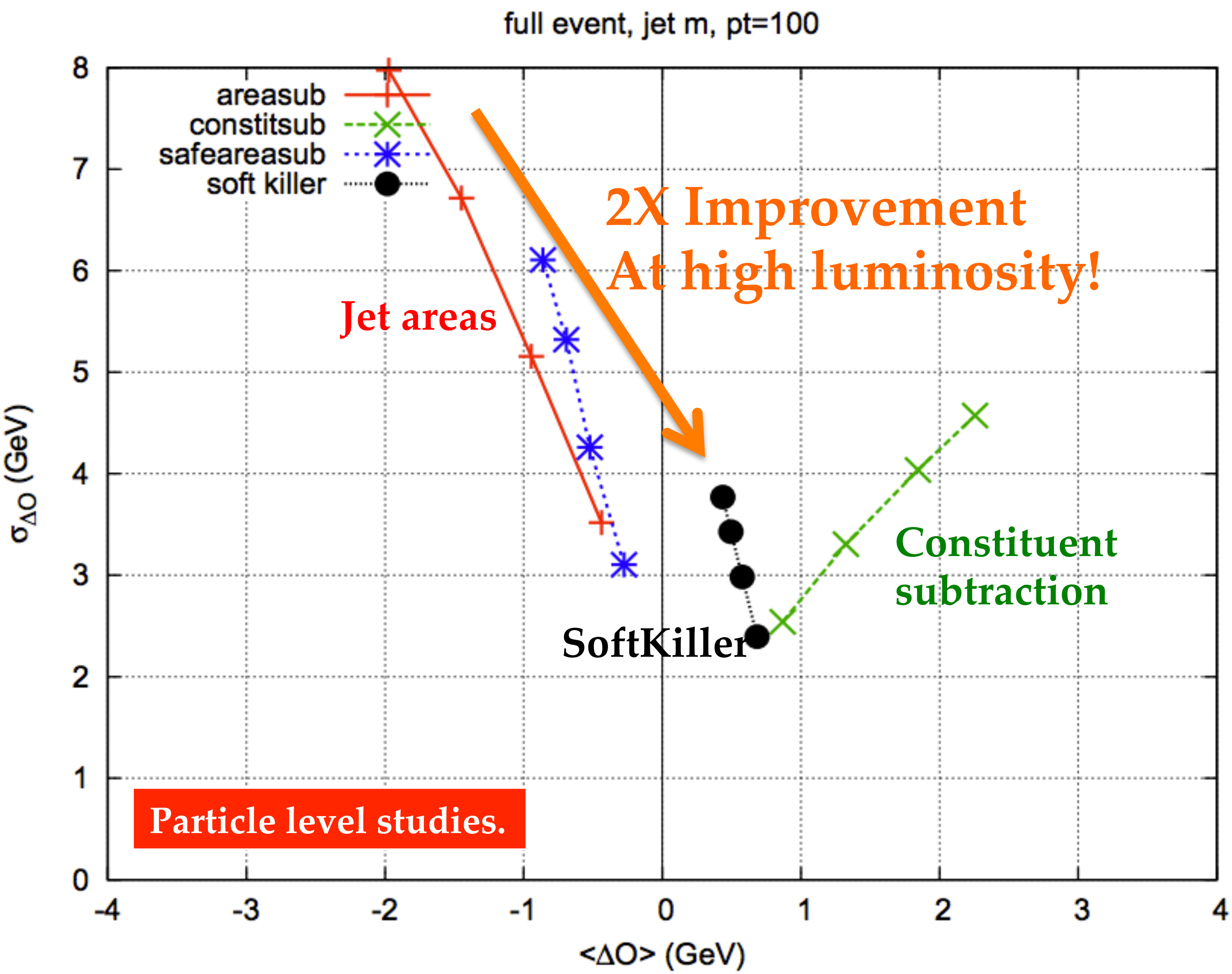
Soft Killer

arXiv:1407.0408
M. Cacciari, G. Salam, G. Soyez



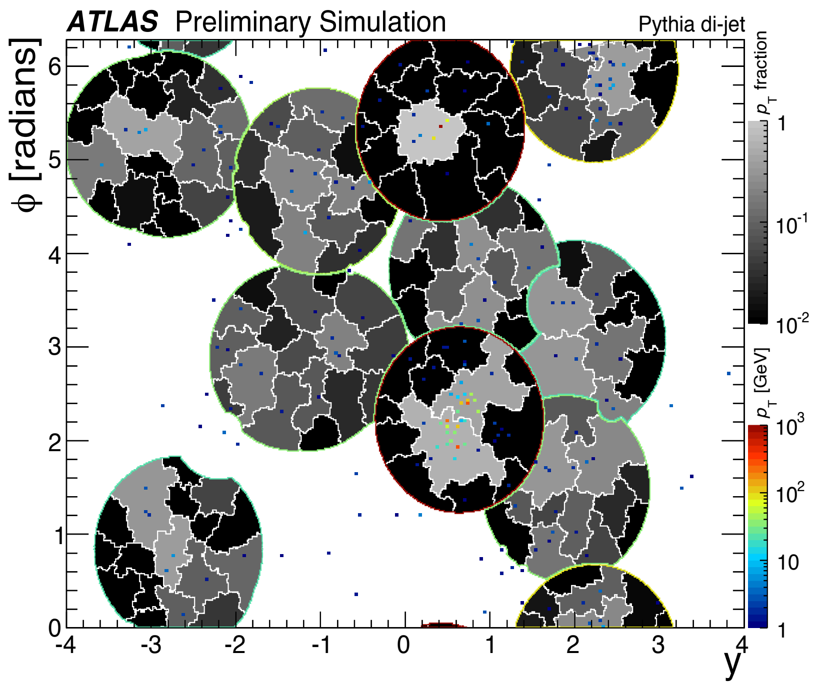


Performance Improvement



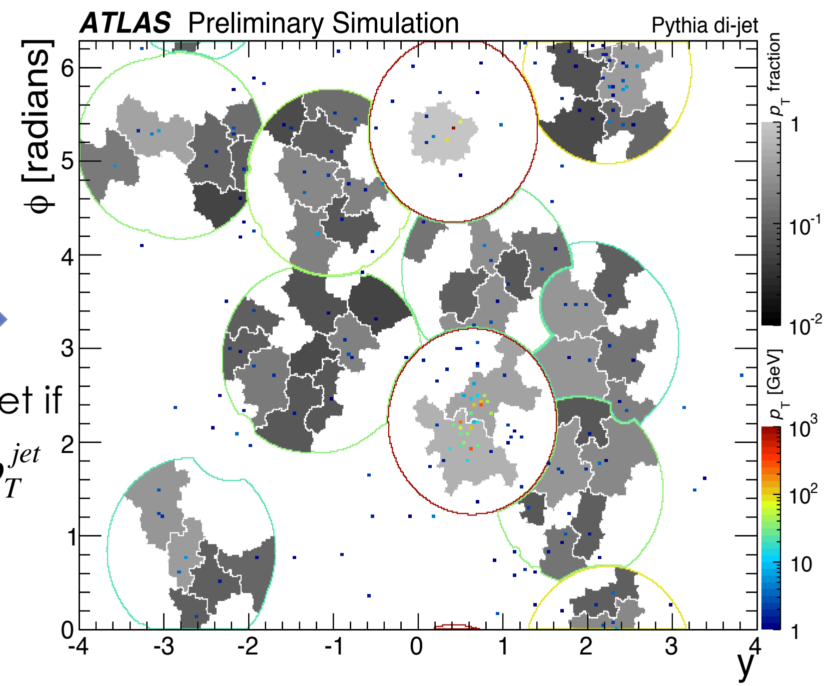
Grooming

- Jet contamination from pileup and underlying event is softer than hard-scatter partons: **Remove soft components of the jet**



Discard subjet if

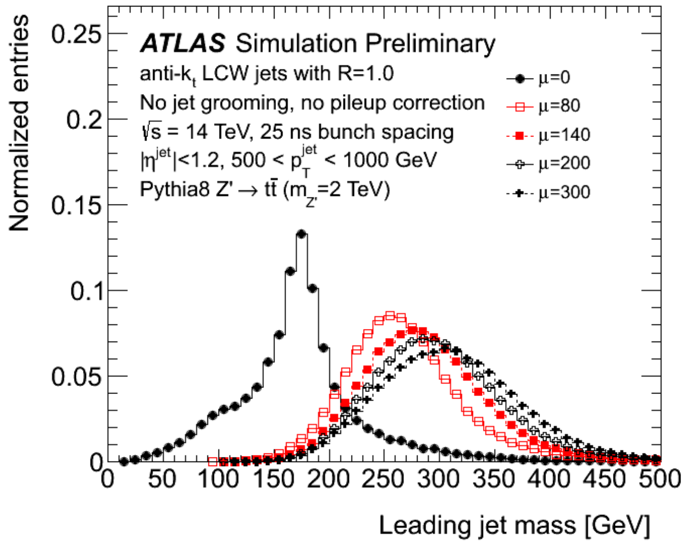
$$p_T < f_{cut} . p_T^{jet}$$



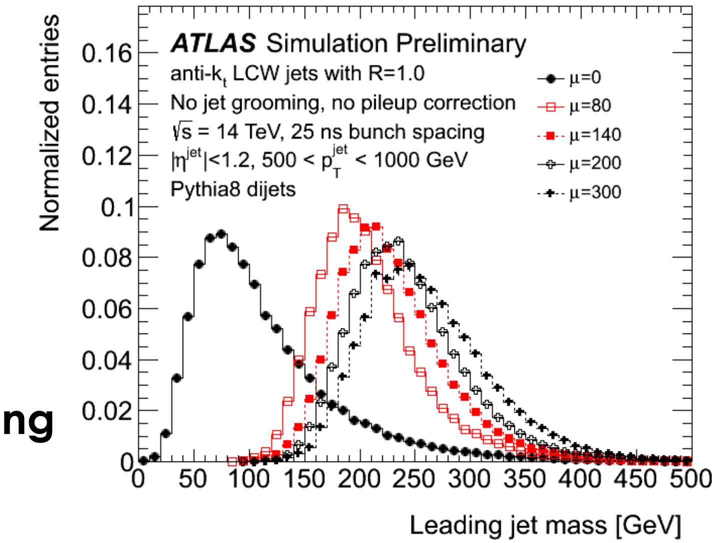
Grooming effectively reduces the area of jet, reducing the jet sensitivity to local (within the same event) pileup fluctuations

Top quark mass with 300 PU

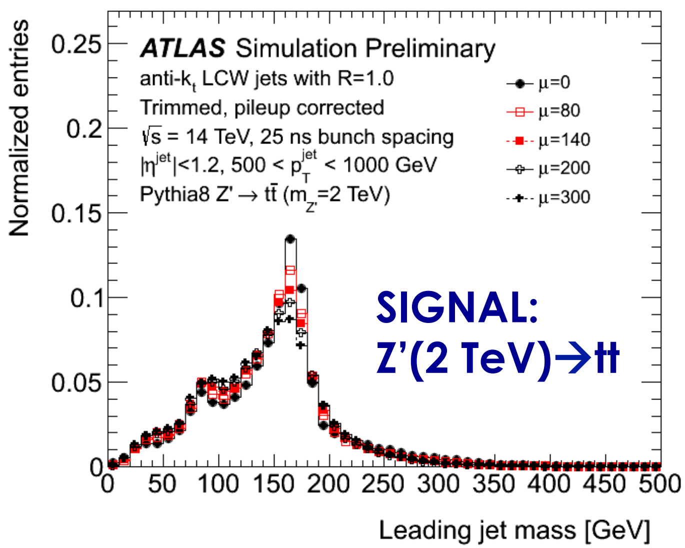
SIGNAL: Z'(2 TeV)→tt

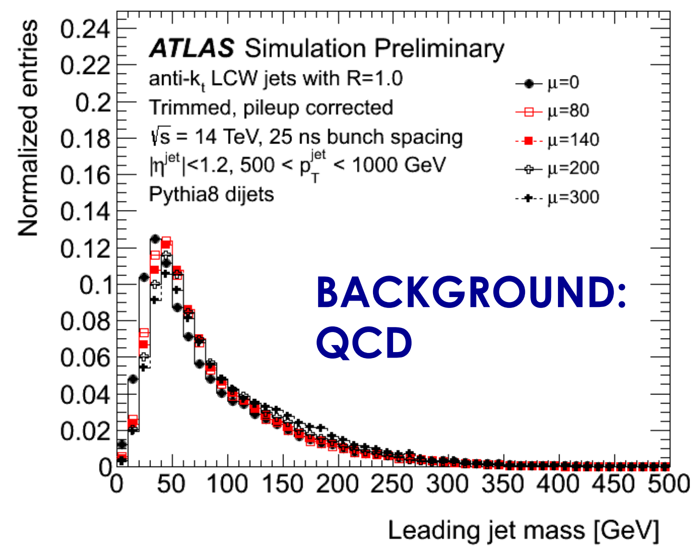


BACKGROUND: QCD



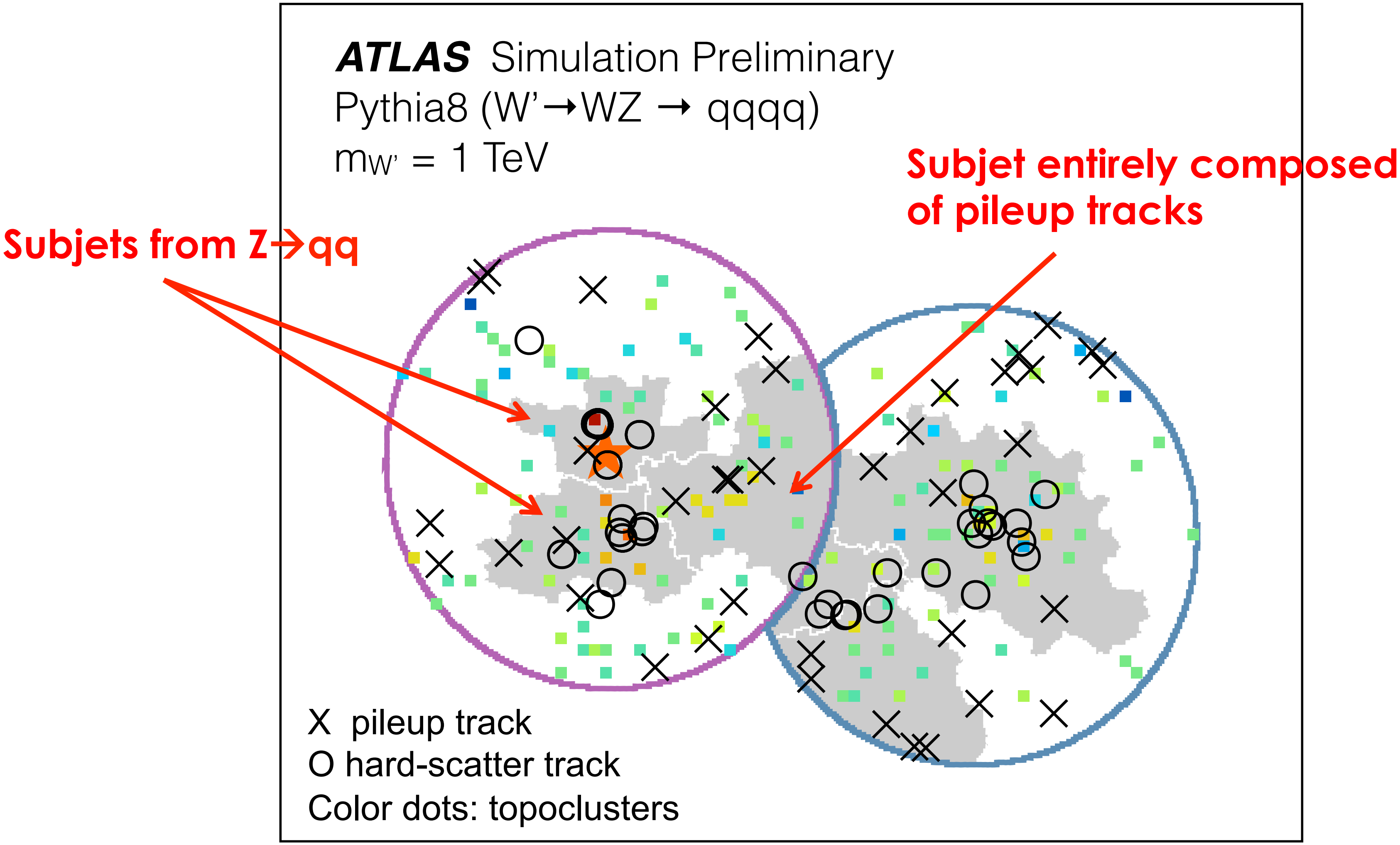
grooming





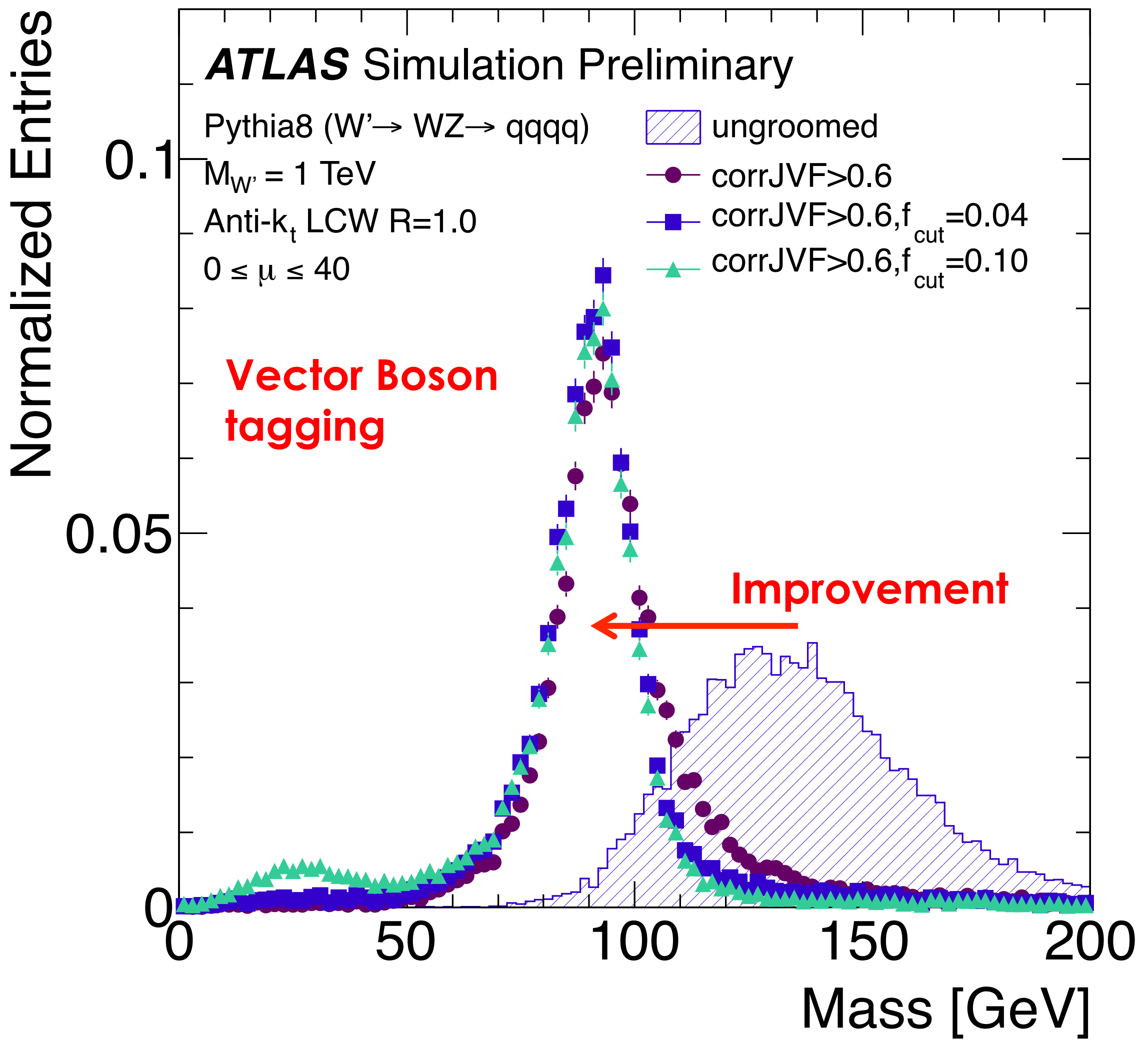
Track-based grooming

Remove subjets based on track-vertex information



ATLAS-CONF-2014-018

Track grooming performance



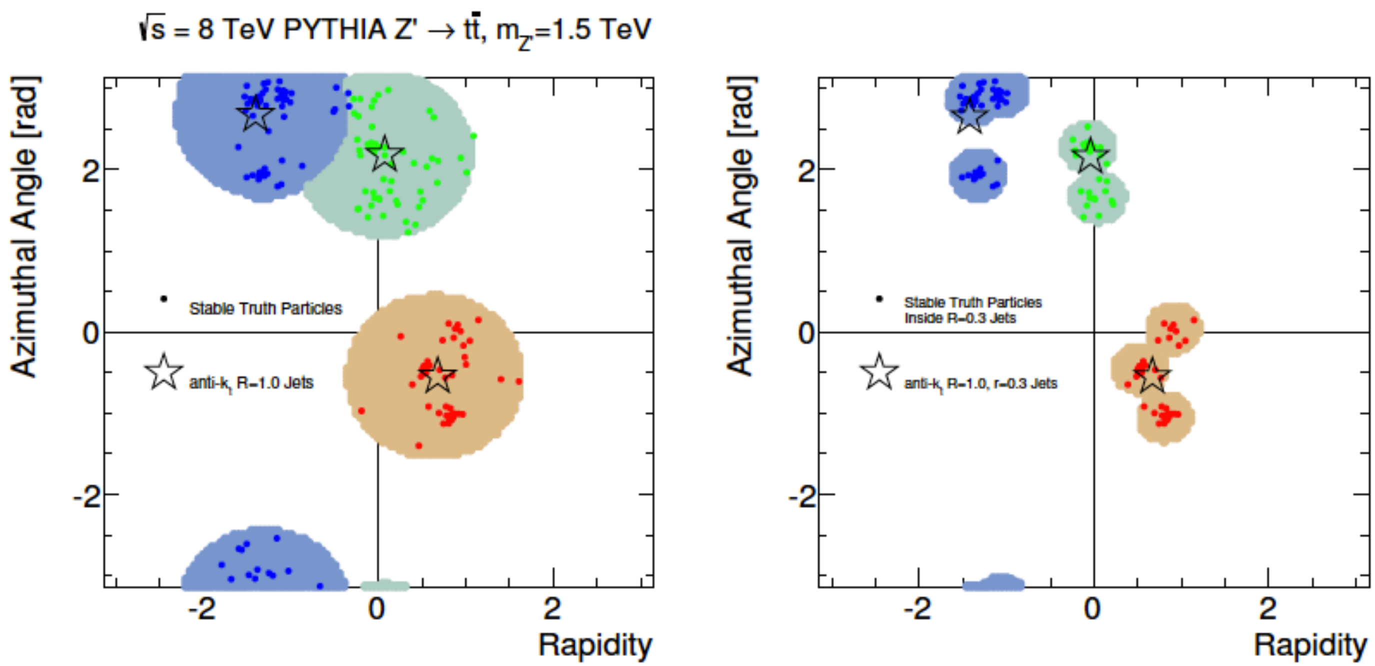
- **Key advantage with respect to existing grooming methods:**
  - No p_T threshold involved in the removal of subjets
  - In the limit of no pileup, track-based grooming does not remove any signal, unlike trimming
  - **Alternative method for HL-LHC**

Jet reclustering

- **Build jets from jets**

JHEP 02 (2015) 075
B. Nachman, P. Nef, A.S, M. Swiatlowski

- **Introduce a new angular scale r < R at which jets are calibrated**
- **Cluster radius r jets into radius R jets**
  - Large-R jet calibrations (and uncertainties!) propagate from r to R

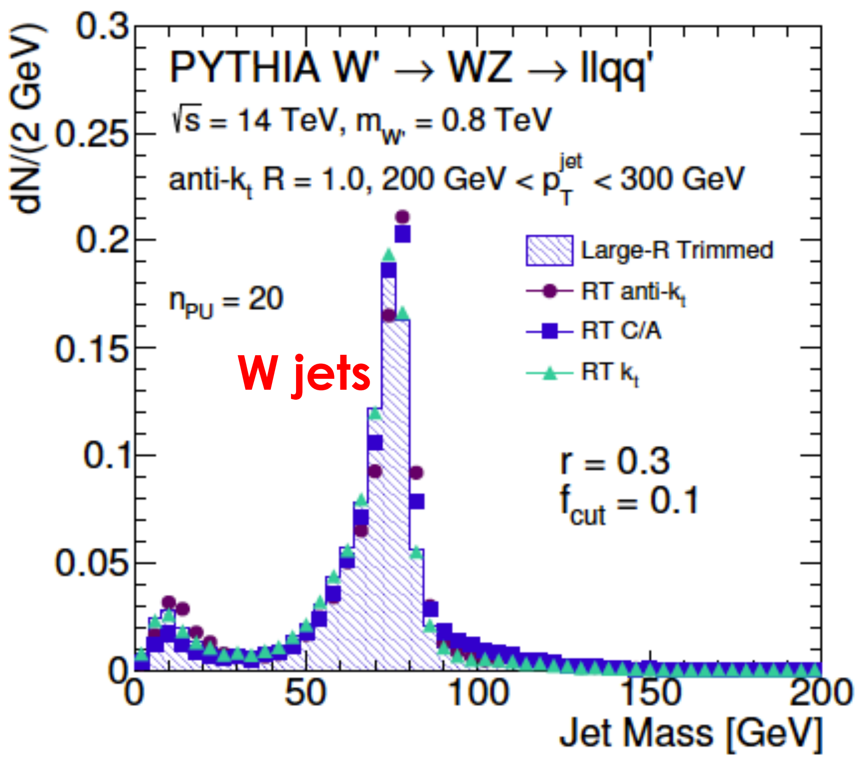


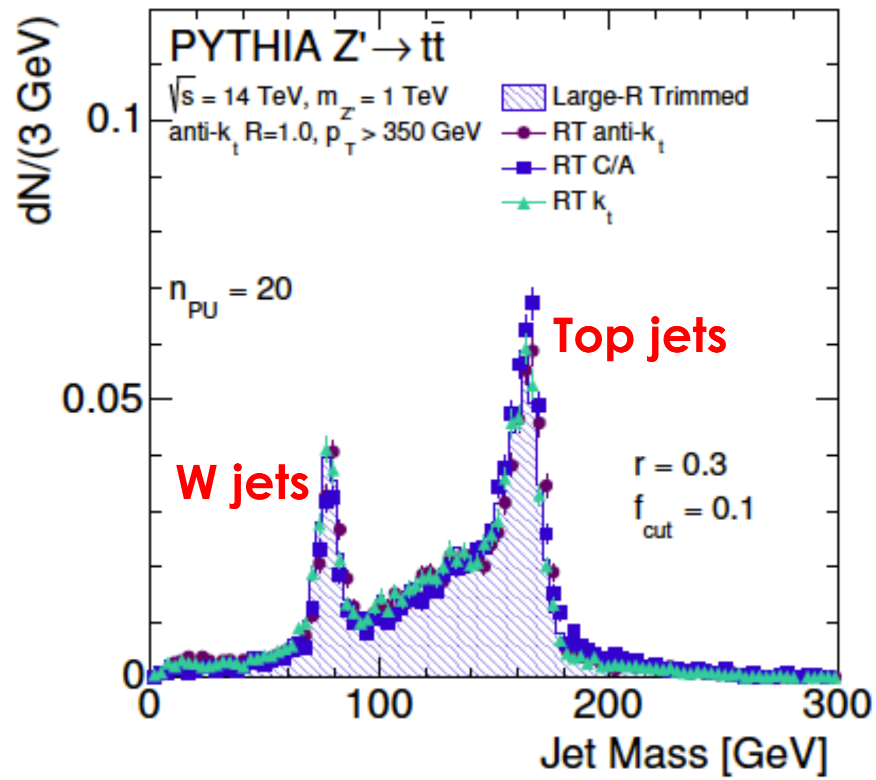
- **Alternative to grooming algorithms**
- **More flexibility**

Reclustered grooming

- Discard small radius r jets *i* re-clustered into large-R jet *J* if:

$$p_{T,i} < f_{cut} . p_T^J$$

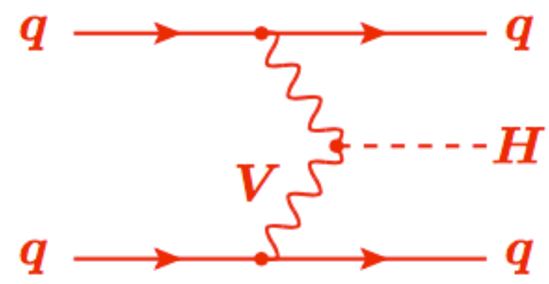


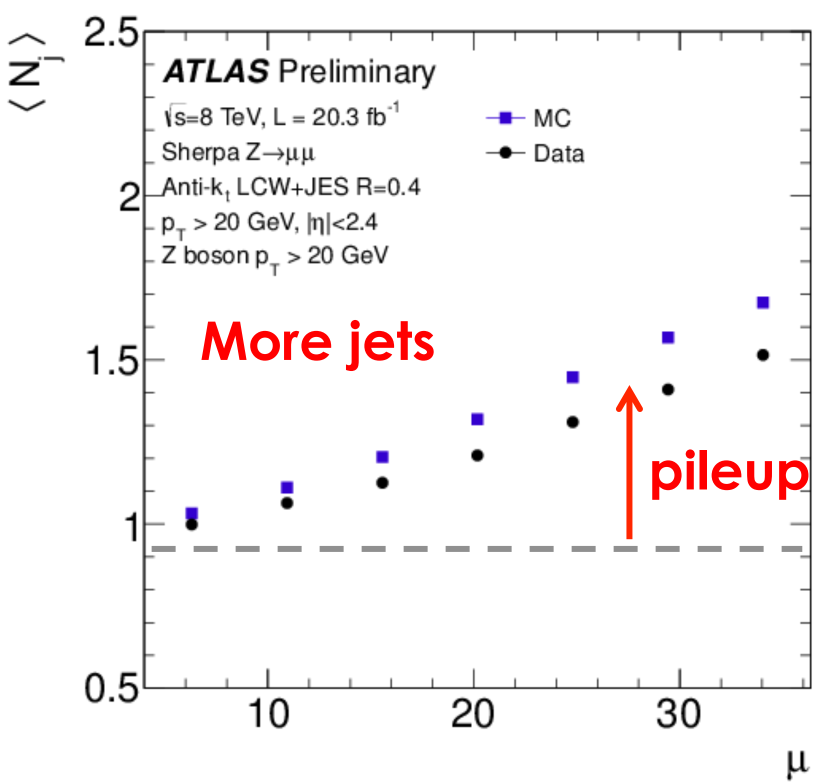


- Enables a natural transition between large- and small-R jets

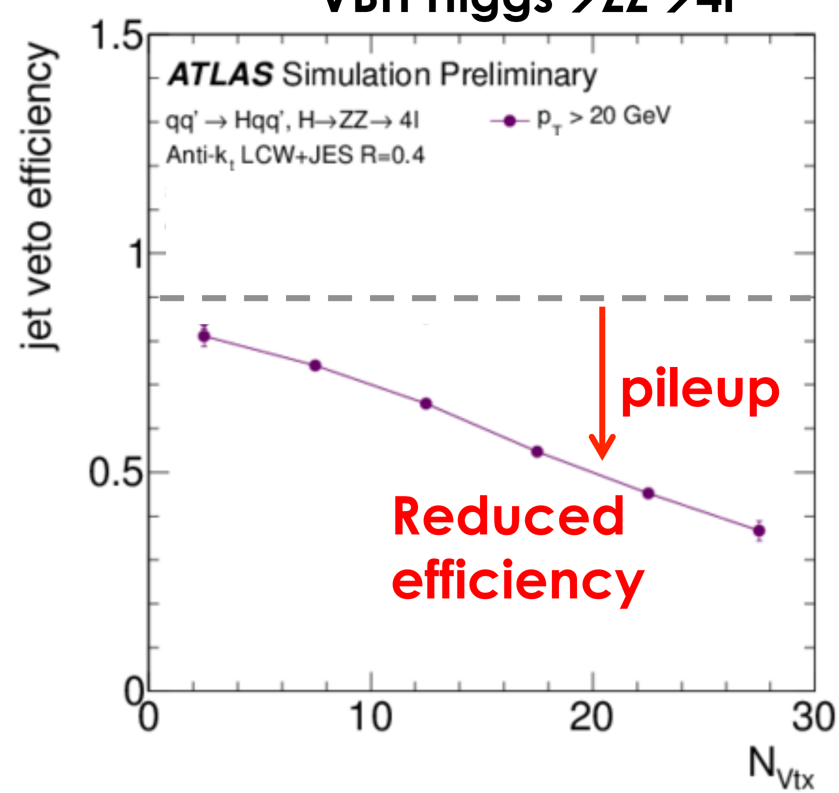
Rejecting jets from pileup

- **Pileup can create pileup jets:**
  - QCD jets originating from a pileup vertex
  - Random combination of particles from multiple pileup interactions ("stochastic pileup jets")

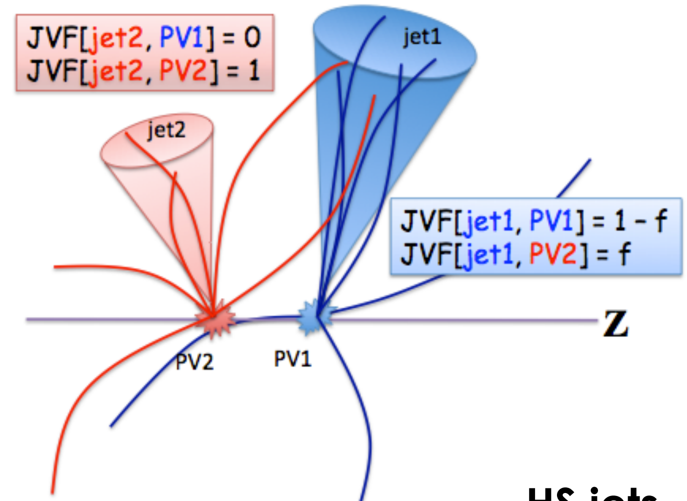




VBH Higgs→ZZ→4l

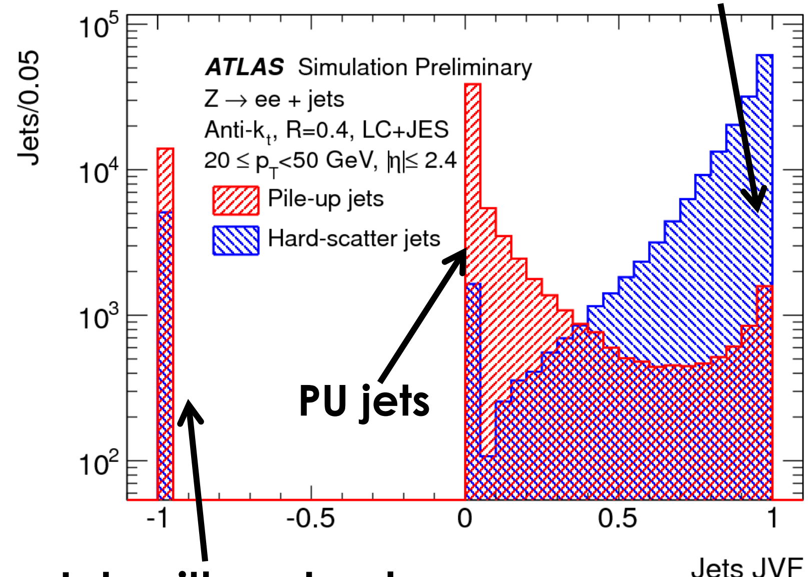


Jet Vertex Tagging / JetID



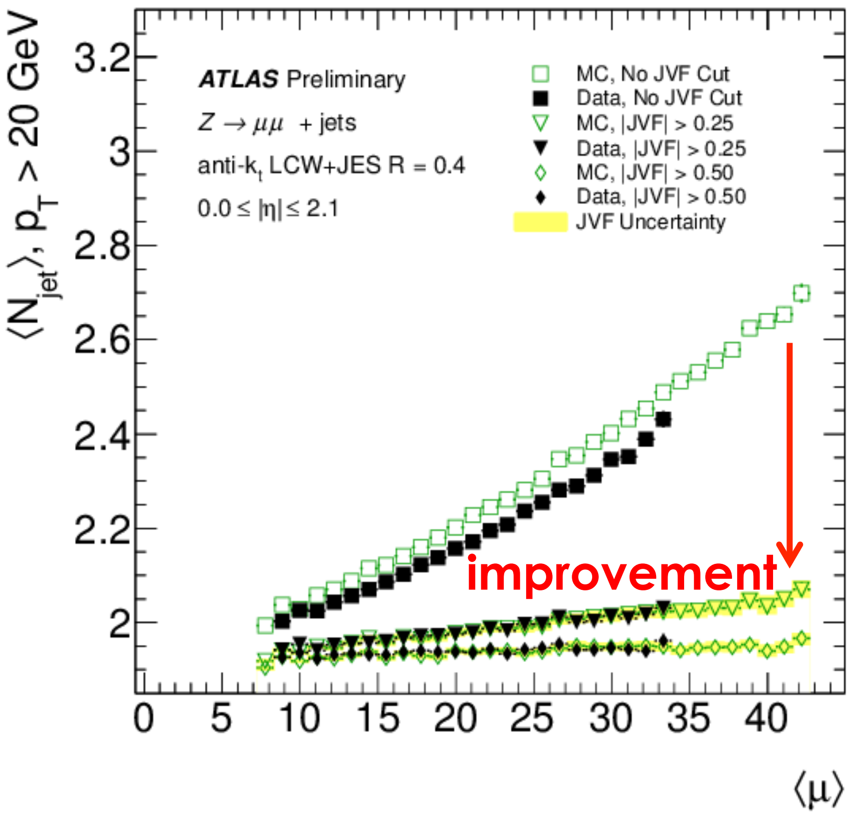
- **Jet vertex fraction algorithm (JVF)**
  - Tag and reject pileup jets using tracking and vertexing information

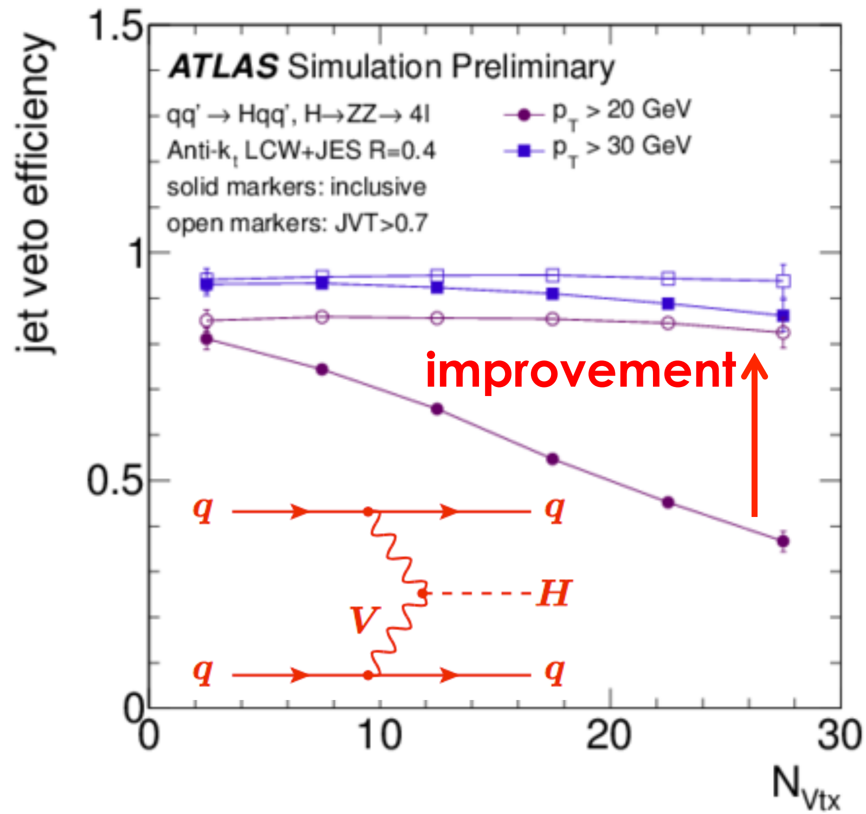
$$JVF = \frac{\Sigma p_T^{trk}(PV_0)}{\Sigma p_T^{trk}(PV_0) + \Sigma p_T^{trk}(PU_n)}$$



ATLAS-CONF-2013-083
CMS PU Jet ID: CMS PAS JME-13-005

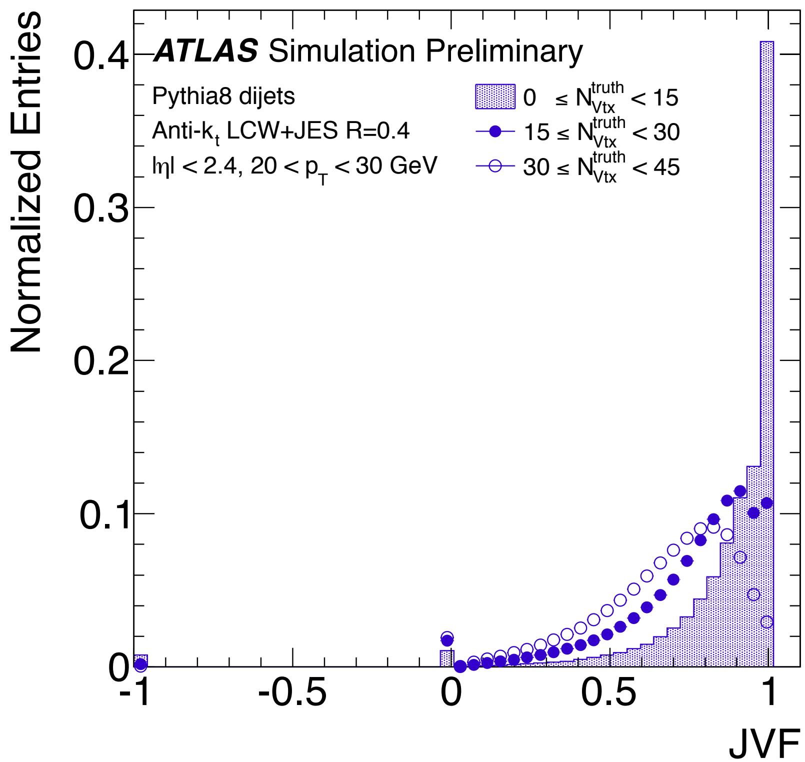
JVF pileup jet suppression

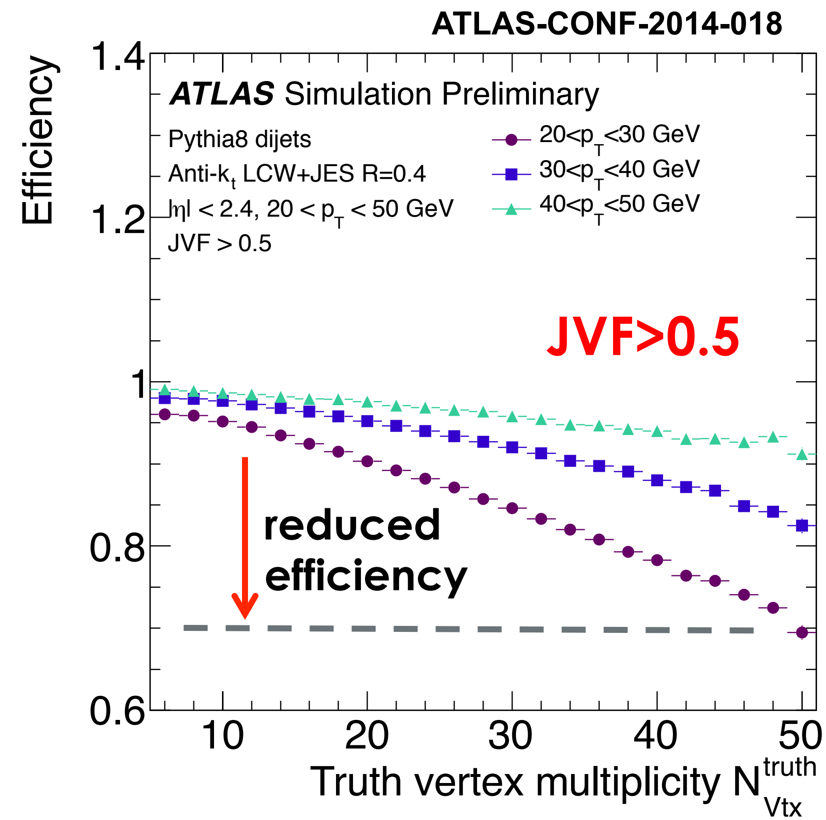




- JVF restores the N_{jet} distribution as a function of pileup
- Improves the data/MC agreement
- JVF makes the jet veto efficiency stable with pileup without the need to raise the jet p_T threshold

JVF at high luminosity





- JVF measures the fraction of track p_T from the hard-scatter primary vertex:
  - JVF decreases with increasing luminosity:
  - **<u>Pileup-dependent jet selection efficiency for fixed JVF cuts</u>**

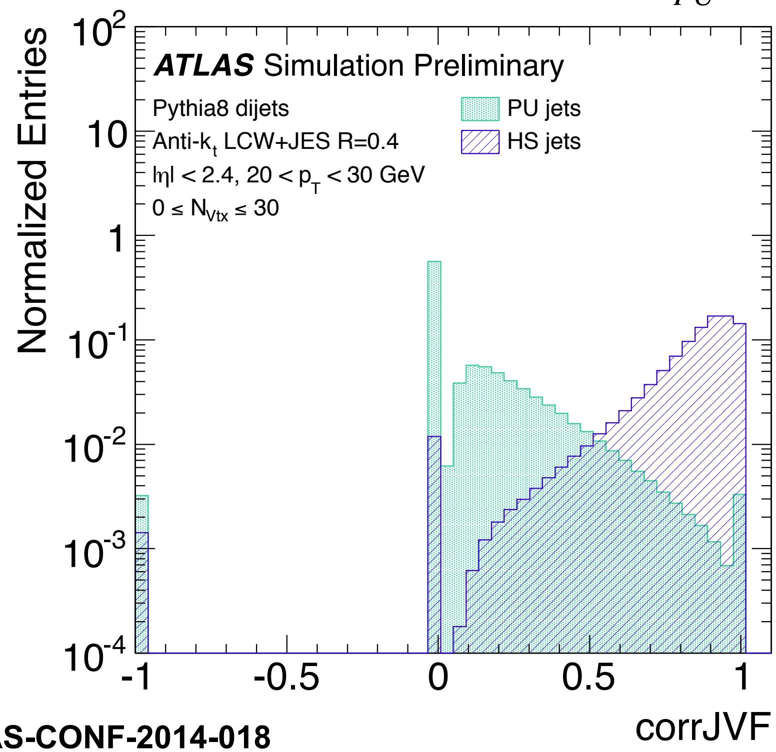
New jet-vertex tagging variables

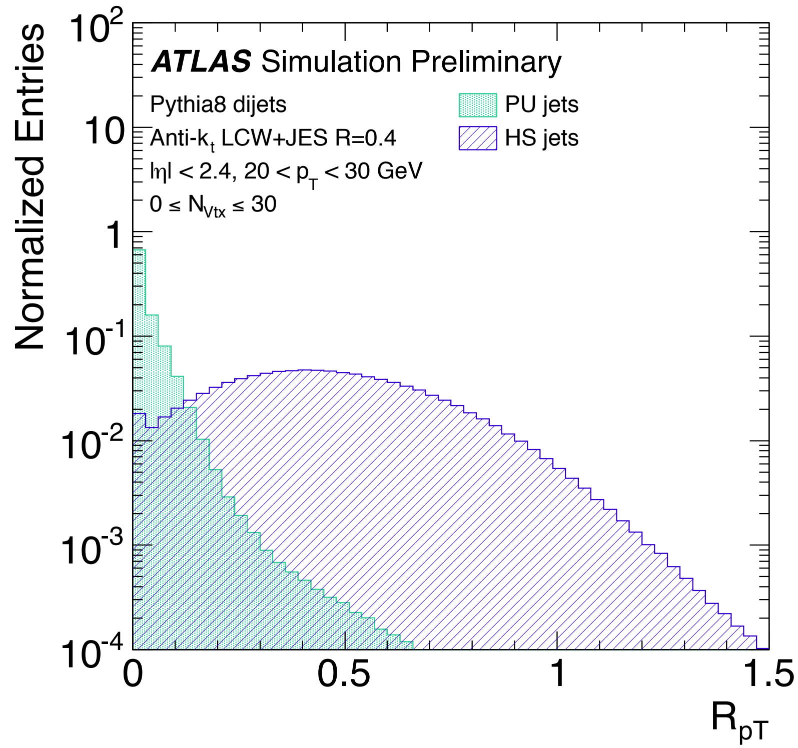
- Correct JVF for its pileup dependence:

$$CorrJVF = \frac{\Sigma p_T^{trk}(PV_0)}{\Sigma p_T^{trk}(PV_0) + \frac{\Sigma p_T^{trk}(PU_n)}{k\, n_{PU}^{trk}}}$$

- Use pileup-corrected observables:

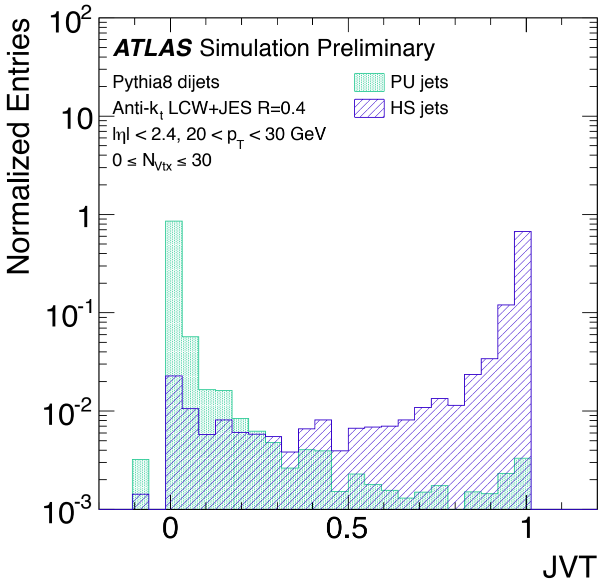
$$R_{pT} = \frac{\Sigma p_T^{trk}(PV_0)}{p_T^{jet}}$$

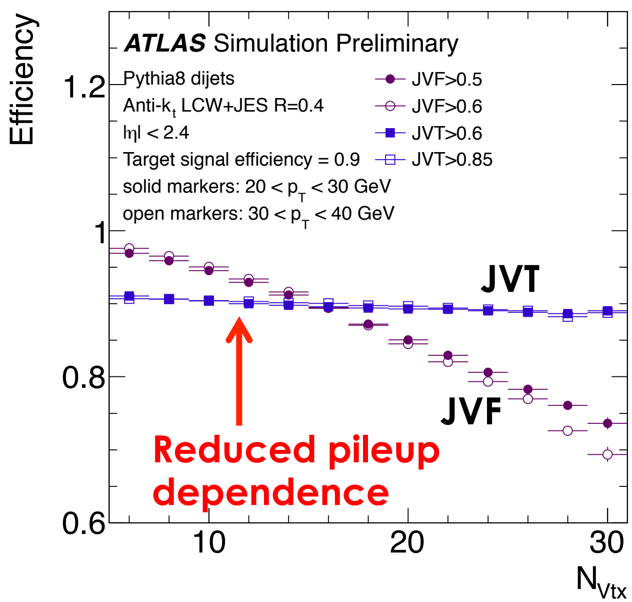




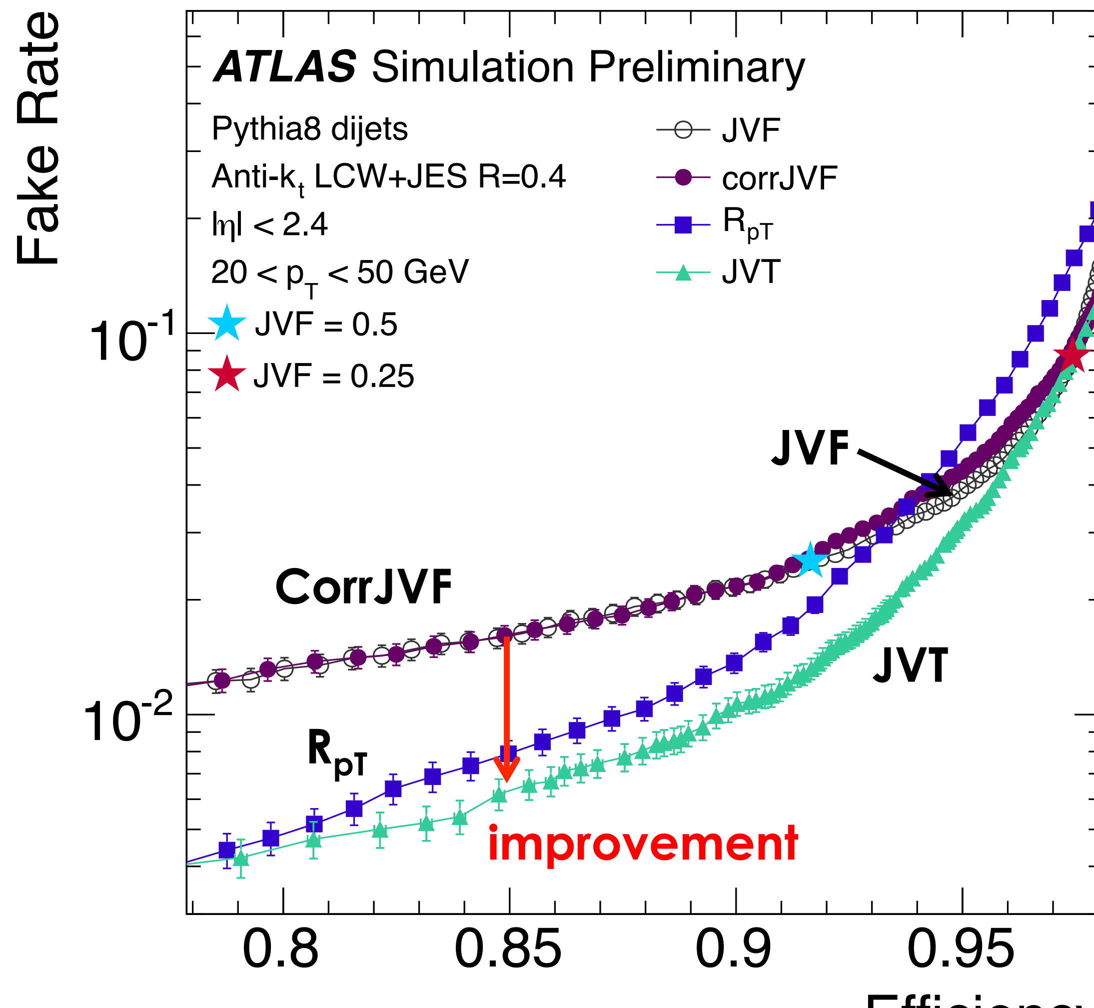
ATLAS-CONF-2014-018

Jet Vertex Tagger (JVT)





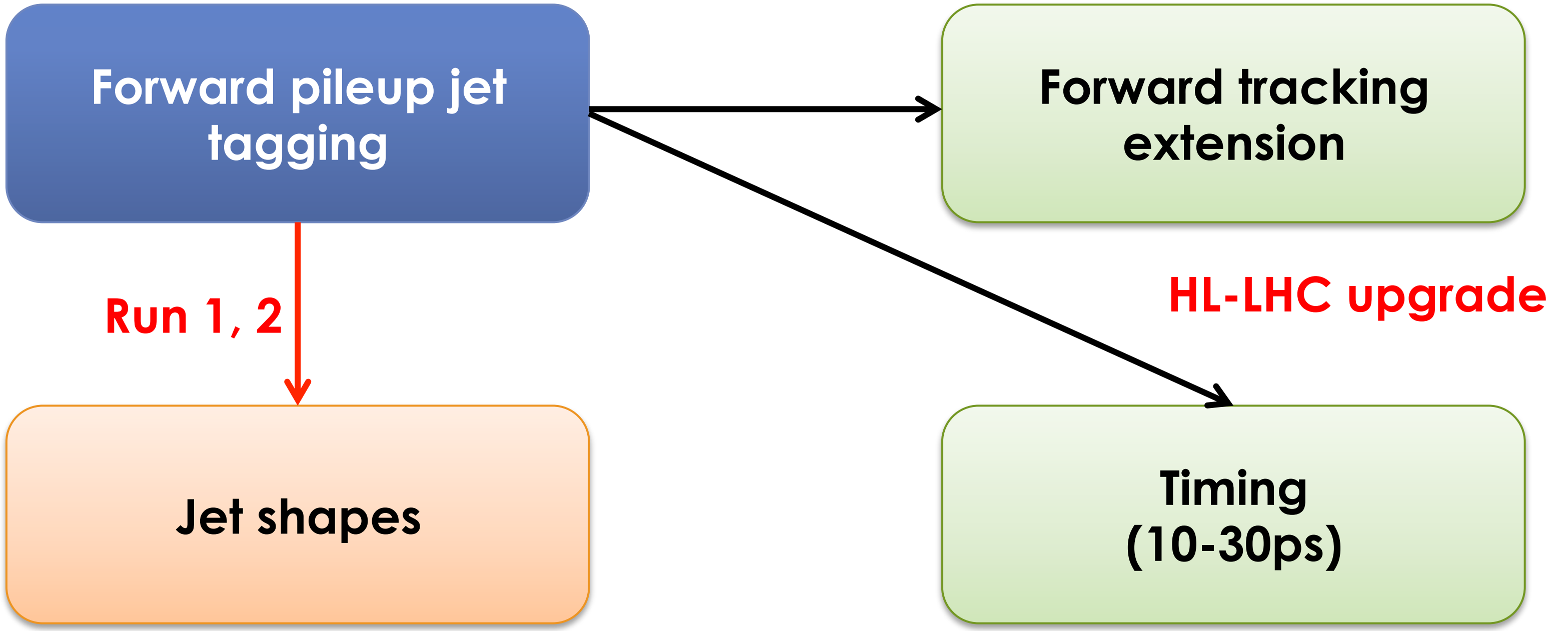
2D likelihood combining CorrJVF and RpT



ATLAS-CONF-2014-018

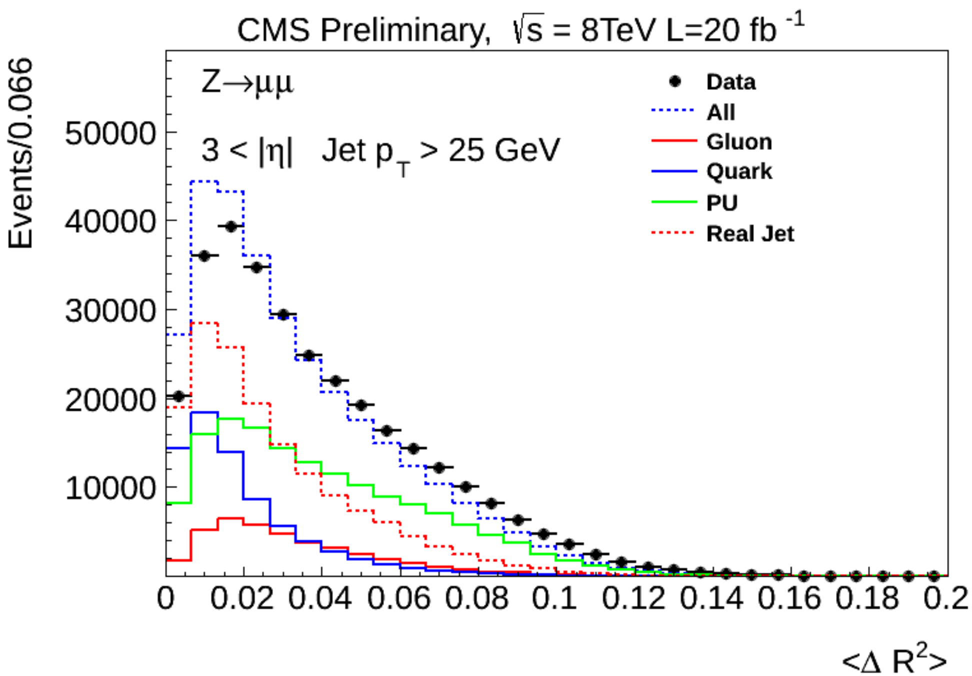
Pileup jet suppression in the forward region

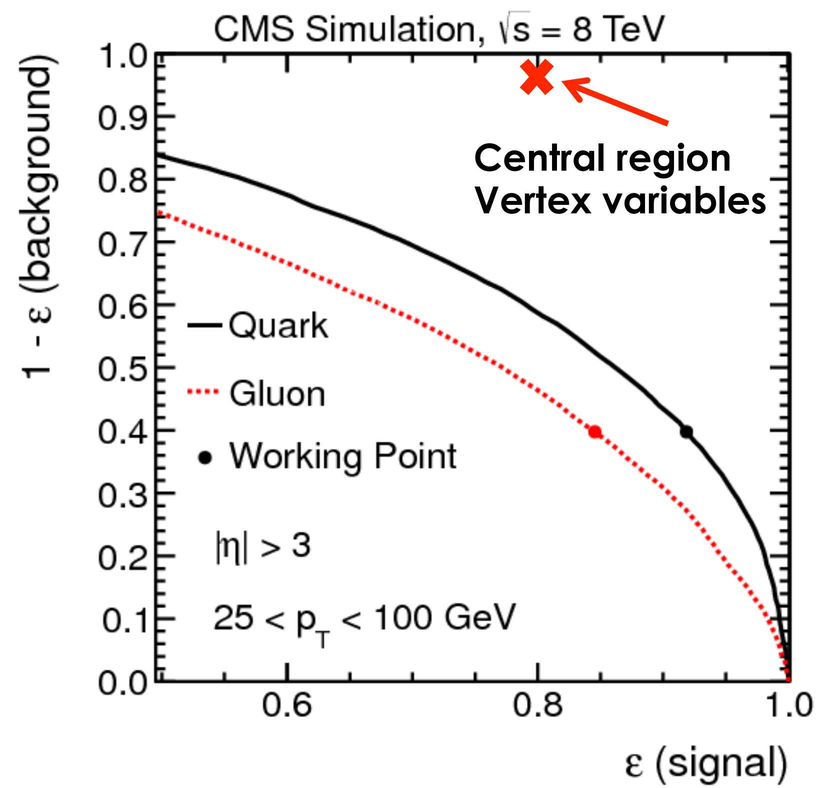
- Key for VBF physics analyses



PU jet tagging with jet shapes

- CMS Pileup Jet ID algorithm: **CMS PAS JME-13-005**



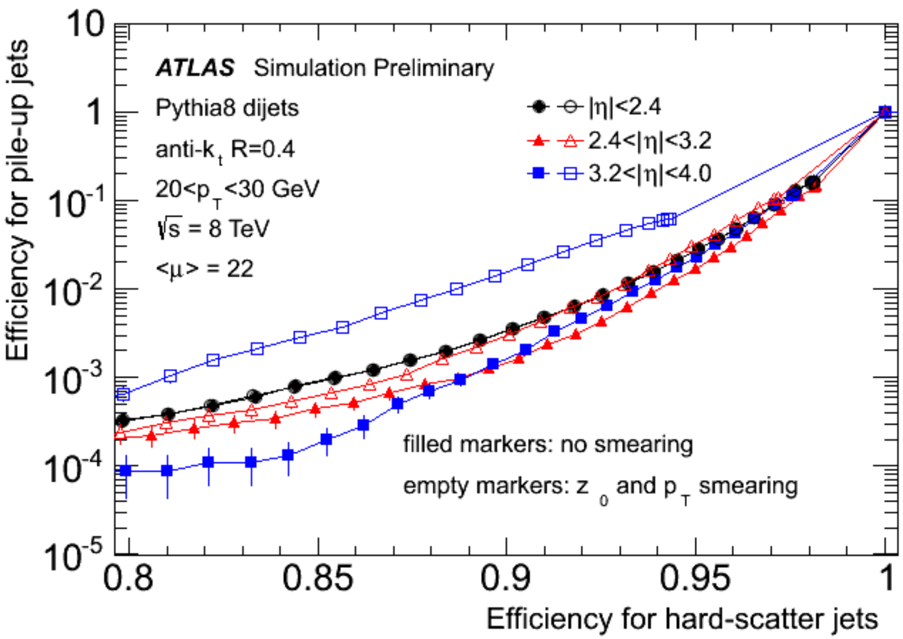


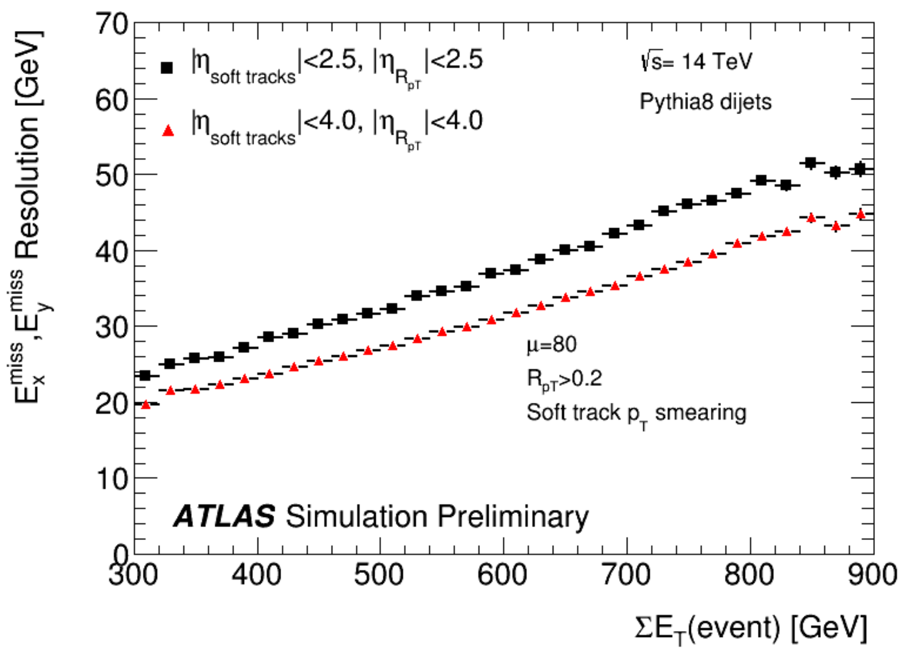
- Input variables:
  - <DR^2>, A<DR<A+0.1, p^D_T

Is there more information to tag forward PU jets to be exploited with existing detector technologies?

Forward tracker

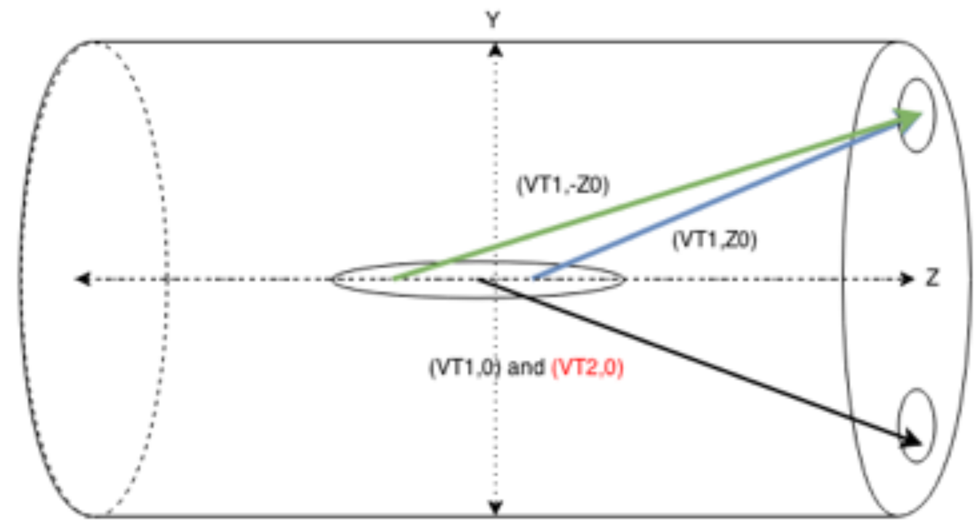
- **Consider tracker extension up to $|\eta|$=4**
  - Can provide forward PU jet tagging capability
  - Improved missing ET resolution
    - Primarily due to the rejection of forward pileup jets





Precision timing

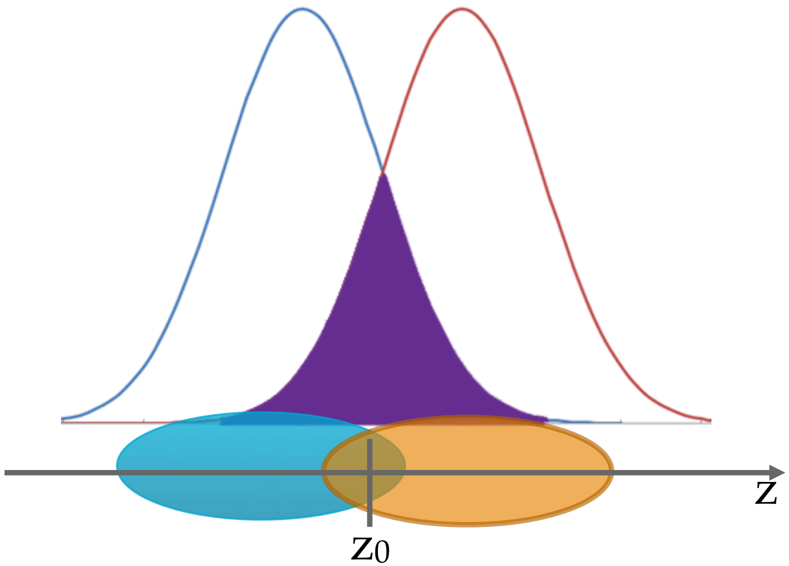
Pythia level studies (no ATLAS)

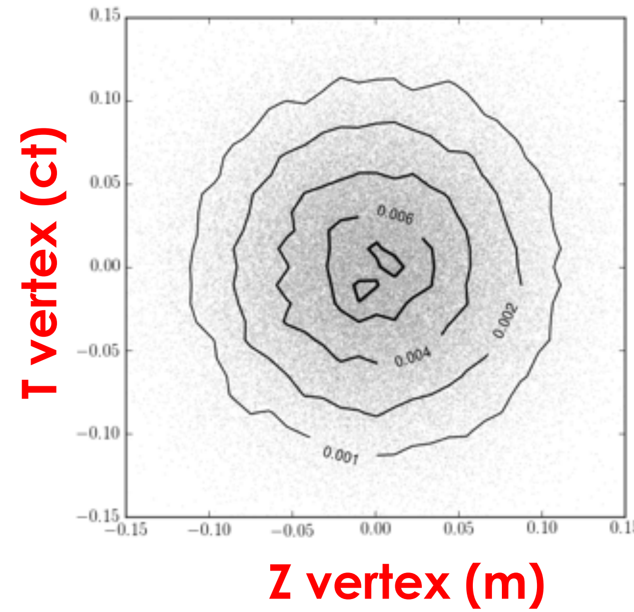


- **(Absolute) Timing information in Run 1 is limited by time profile of PU interactions** (~200ps)
- Study the effect of crab-kissing HL-LHC bunch configurations with reduced time spread on the capabilities of a potential precision timing detector for pileup jet mitigation

Precision timing

Run 1 LHC bunch configuration:





Space-time PU density interaction probability:

$$p_{col}(z,t) = \frac{c}{\pi\sigma_b^2}\exp\left[-\frac{1}{2\sigma_b^2}\left((z-ct)^2+(z+ct)^2\right)\right]$$

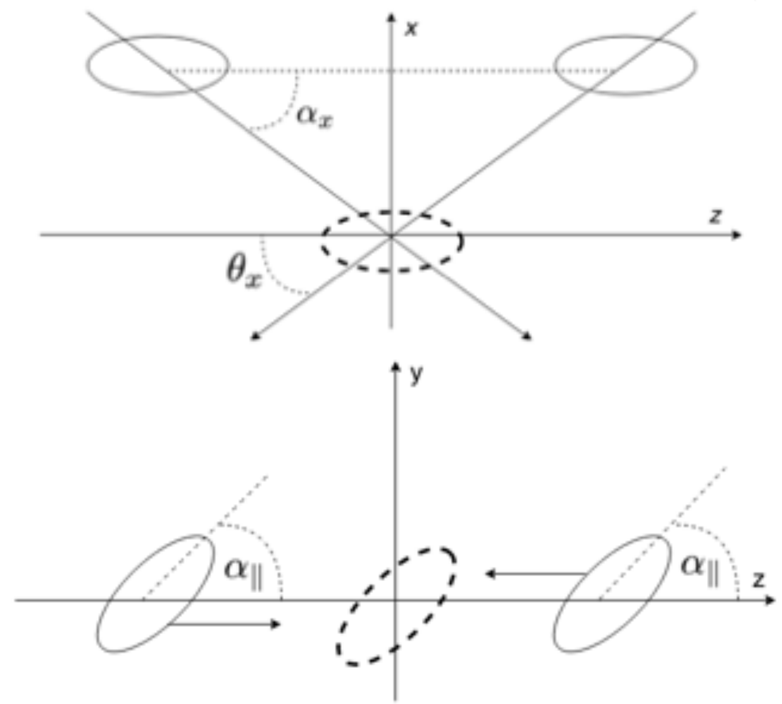
$$p_{col}(z,t) \sim \exp\left[-\frac{z^2+c^2t^2}{\sigma_b^2}\right]$$

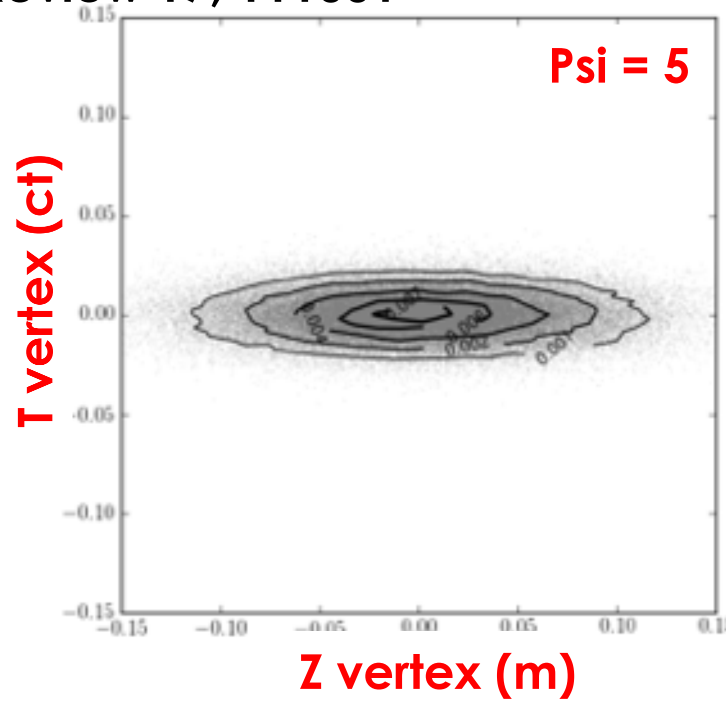
Time spread of collisions:

$$p_{col}(t) \sim \exp\left[-\frac{c^2t^2}{\sigma_b^2}\right] \quad \sigma_t = \sigma_b/\sqrt{2}c$$

Crab-kissing scheme

S. Fartoukh
Physics Review 17, 111001 (2014)



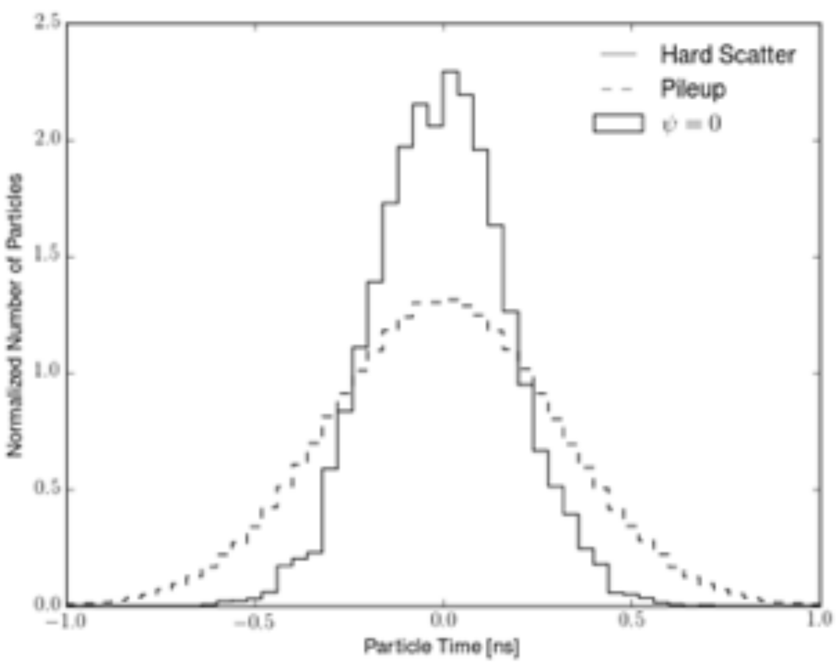


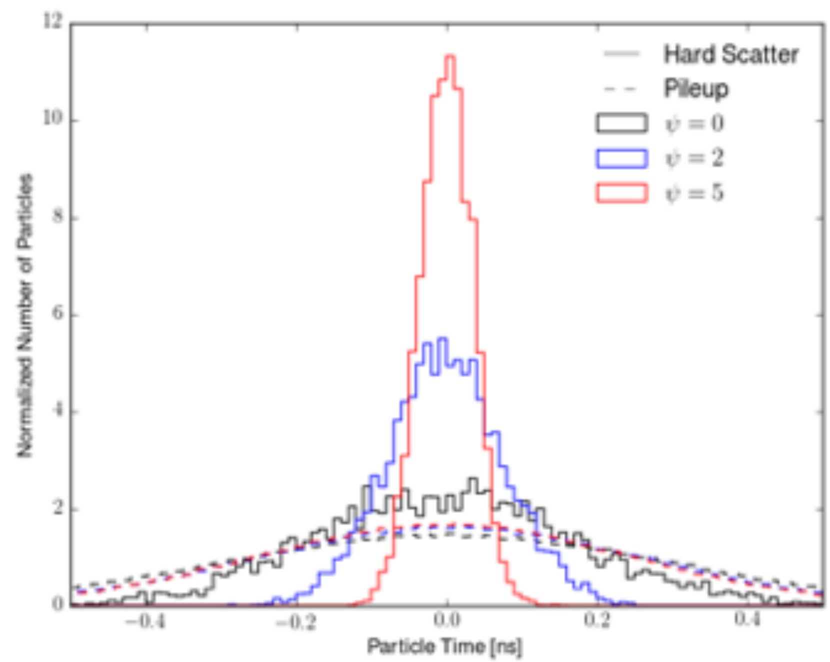
- **Introduce collision crossing angles and spatial rotation of the bunches such that collisions take place almost at the same time:**
  - Significant reduction of the time spread between PU vertices

$$p_{col}(z,t) \sim \exp\left[-\frac{\gamma^2 z^2 + c^2 t^2}{\Sigma^2}\right]$$

$$\sigma_t = \frac{\sigma_b}{\sqrt{2(1+\Psi^2)}} \qquad \Psi \sim \frac{\alpha_\parallel \sigma_z}{\beta^*}$$

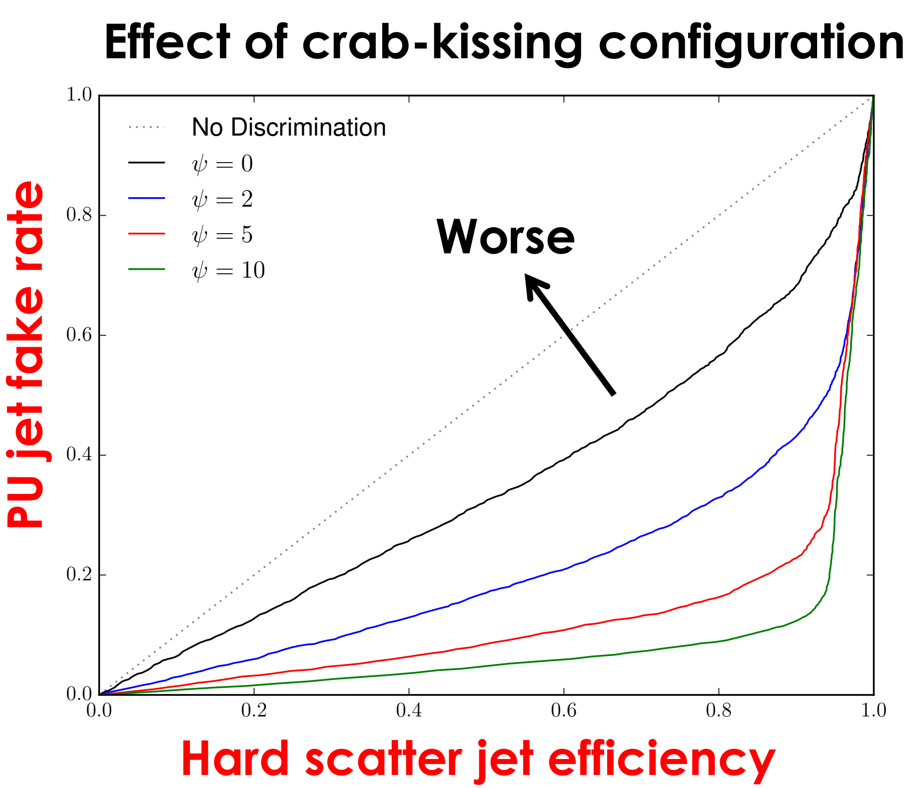
Precision timing

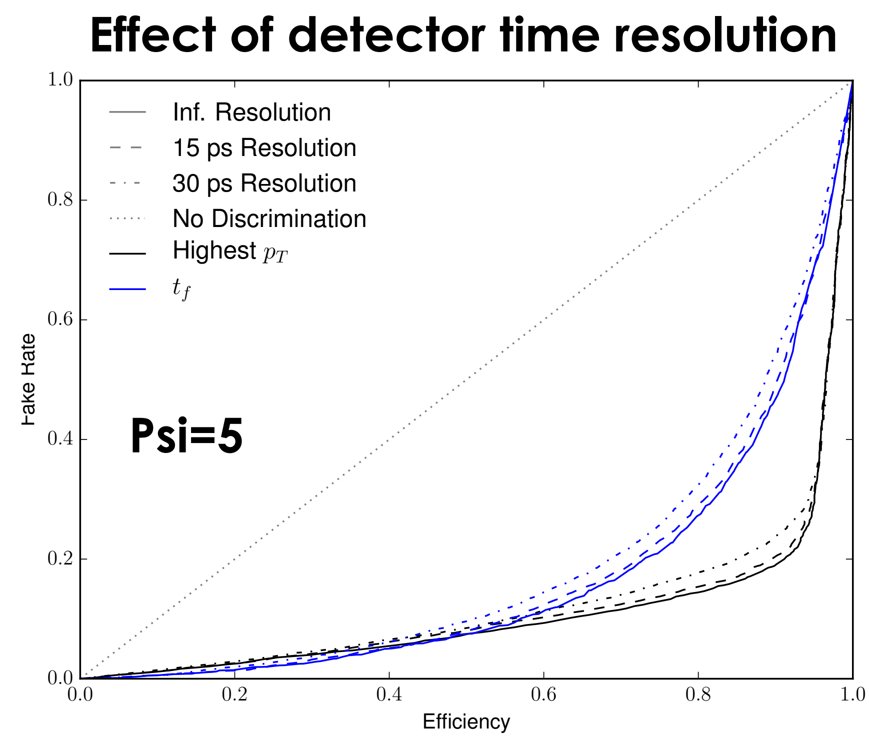




Crab kissing

Forward PU jet tagging with timing





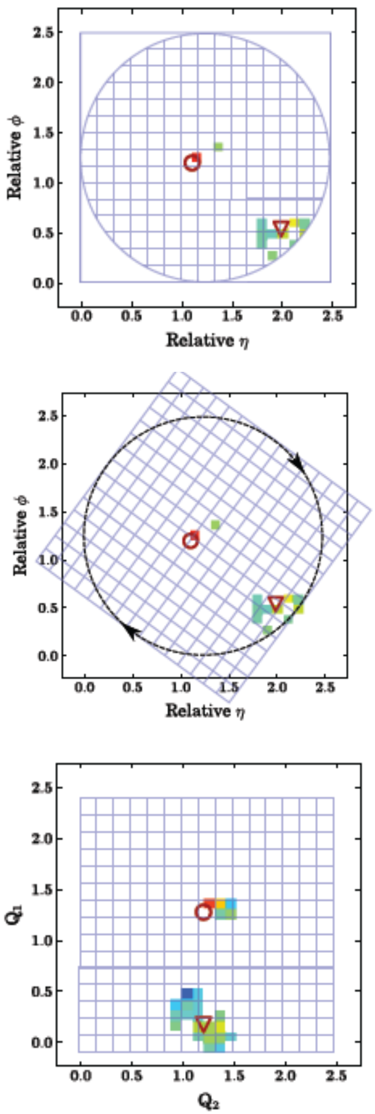
- 5mm square sensors, 30ps resolution could achieve >5 PU jet rejection @ 80% hard scatter efficiency
  - **Truth-level very simplified studies!**

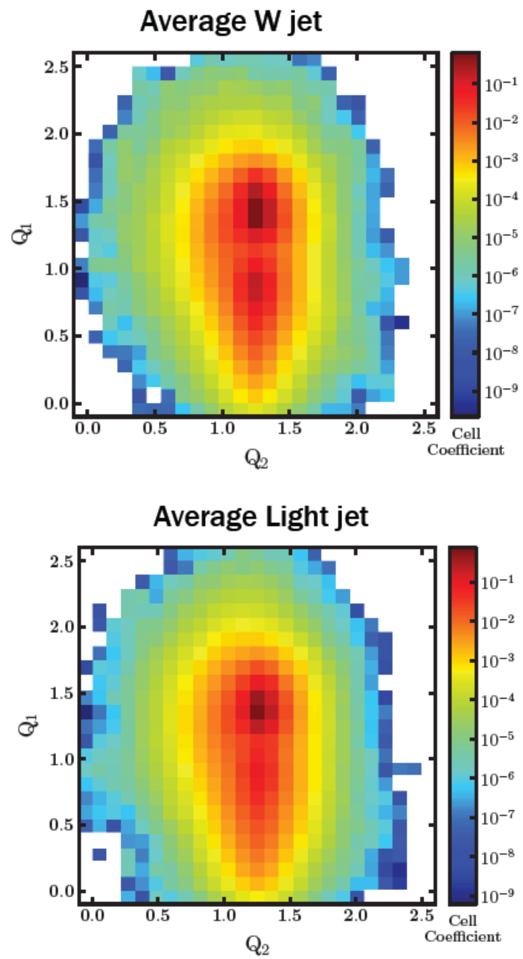
Out of the box

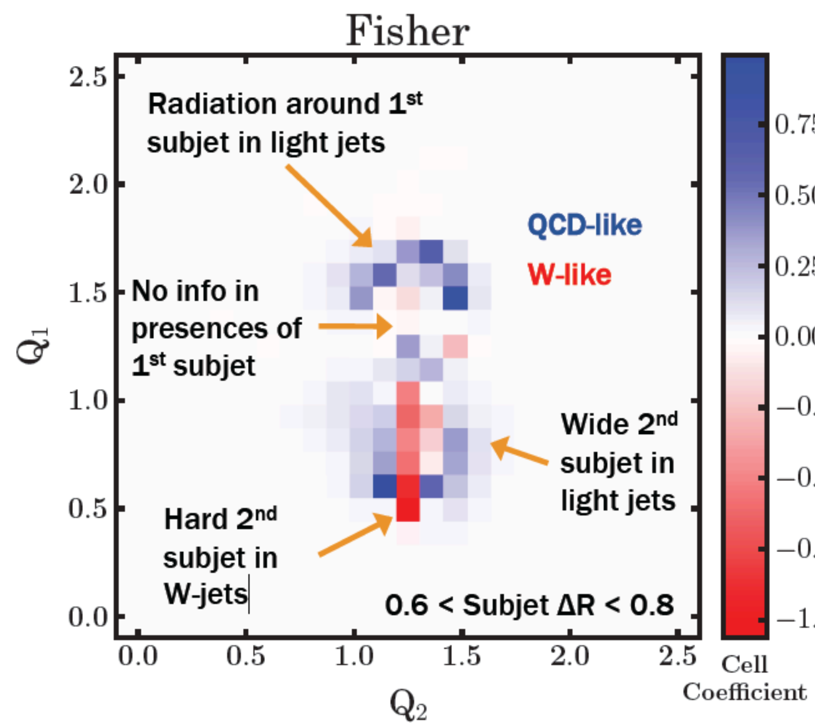
- Image processing and computer vision to analyze LHC events

Computer vision: jet images

JHEP 02 (2015) 118
J. Cogan, M. Kagan, M. Strauss, A.S.

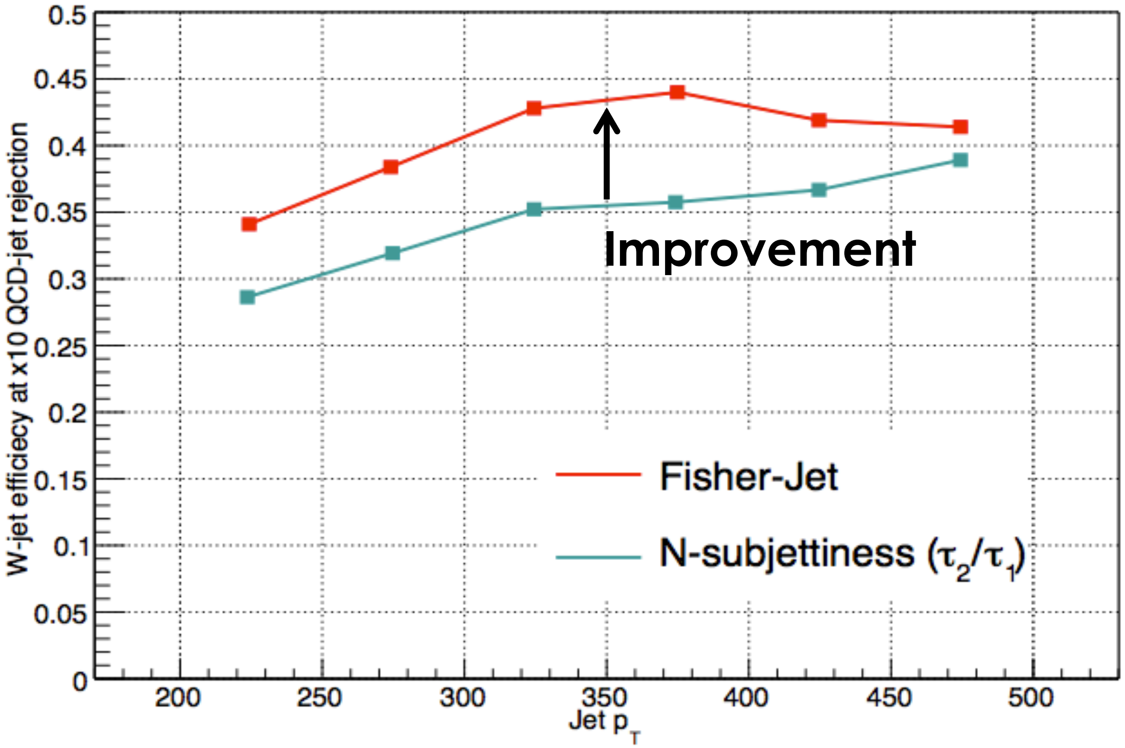


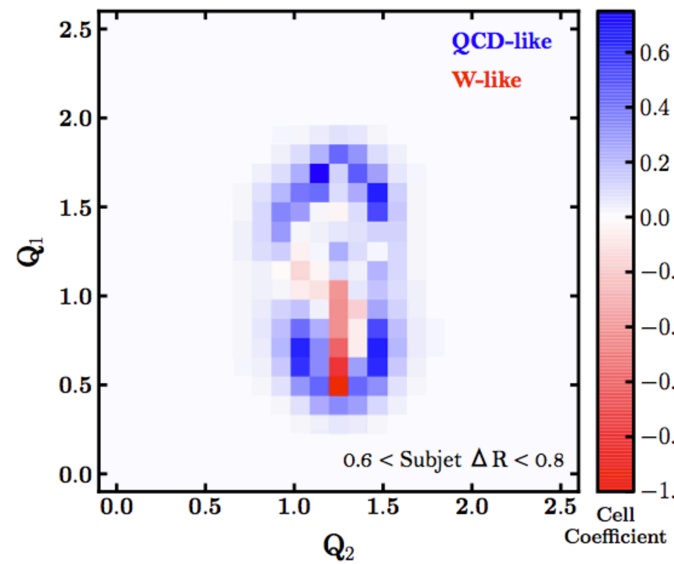




Fisher discriminant

Jet-image W tagging





- Connection between jets and images enabled the use of computer vision algorithms to jet tagging
- Visualization of the discriminant adds a new capability to understand the physics within jets and design more powerful jet tagging methods
- **Many potential applications!**

Summary

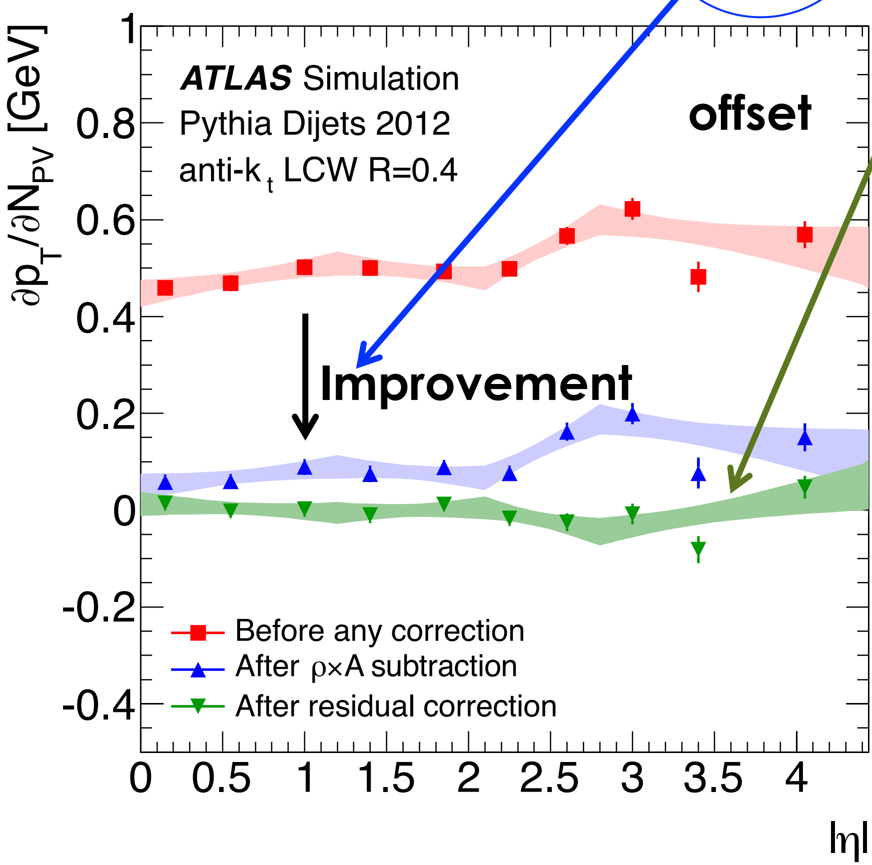
- **LHC Run 1 PU mitigations techniques continue to work well up to very high luminosity**
    - Topoclustering / charged hadron subtraction
    - Event-by-event pileup subtraction
    - Pileup jet suppression using jet-vertex tagging
    - Grooming
- **Performance limited by local fluctuations of pileup**
    - o Several promising new ideas recently proposed can bring further improvements:
        - **Constituent level subtraction and suppression**
        - **Forward pileup jet tagging**
            - o Jet shapes
            - o Extended tracker
            - o Timing

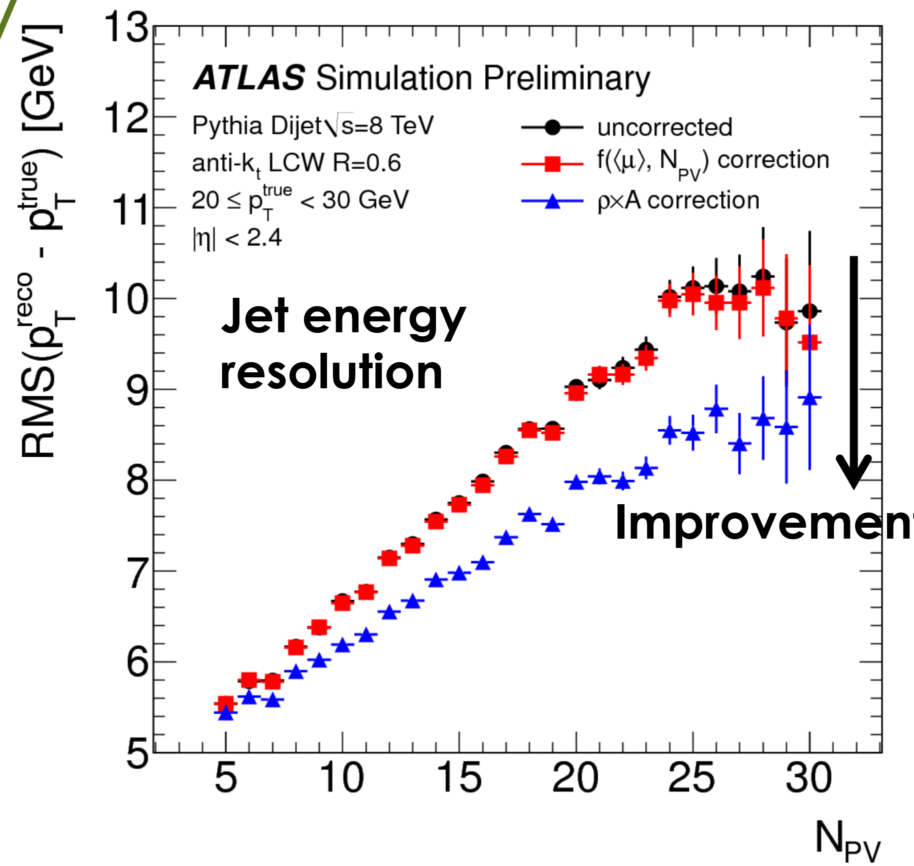
Backup

Pileup subtraction (I)

Residual correction

$$p_T^{corr} = p_T - \rho A_T - \alpha(N_{PV} - 1) - \beta\langle\mu\rangle$$

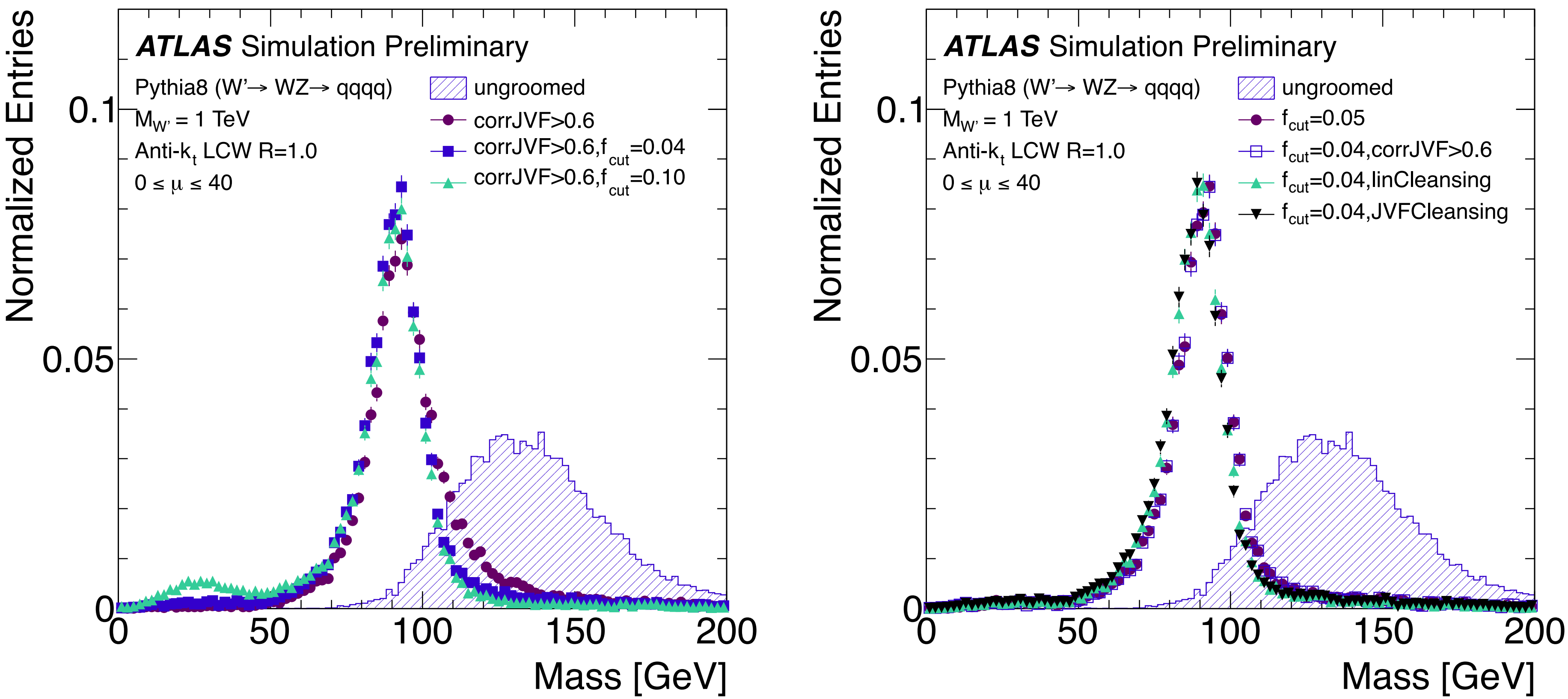




- Significant improvement of the jet p_T resolution
- **10-20% reduction in jet-by-jet pileup fluctuations**

Track grooming performance

- Best performance for CorrJVF>0.6 and f_{cut}=4%
  - **Similar performance than calorimeter-only trimming (f_{cut}=5%) and linear cleansing** (arXiv:1309.4777)



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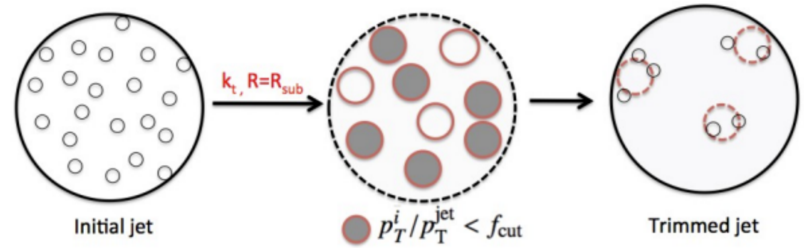
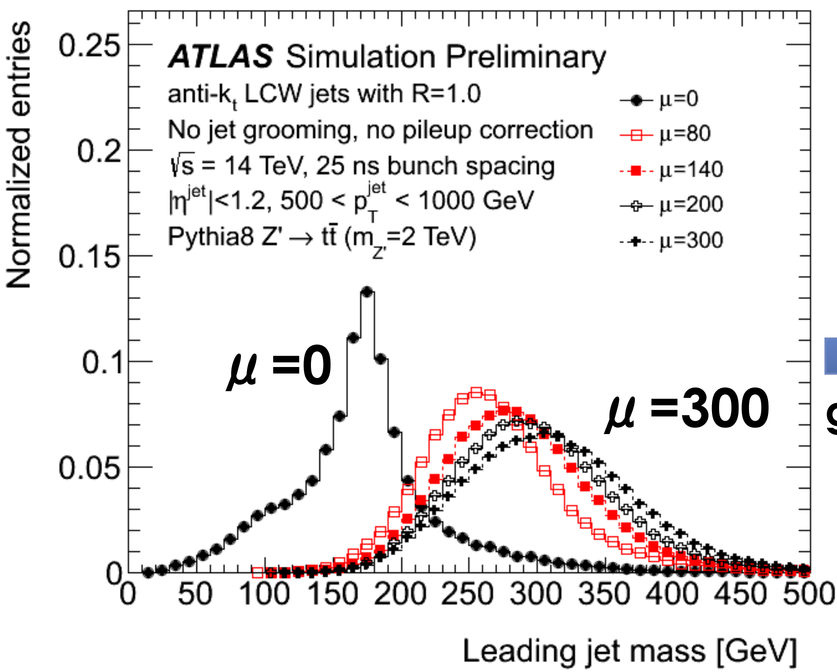
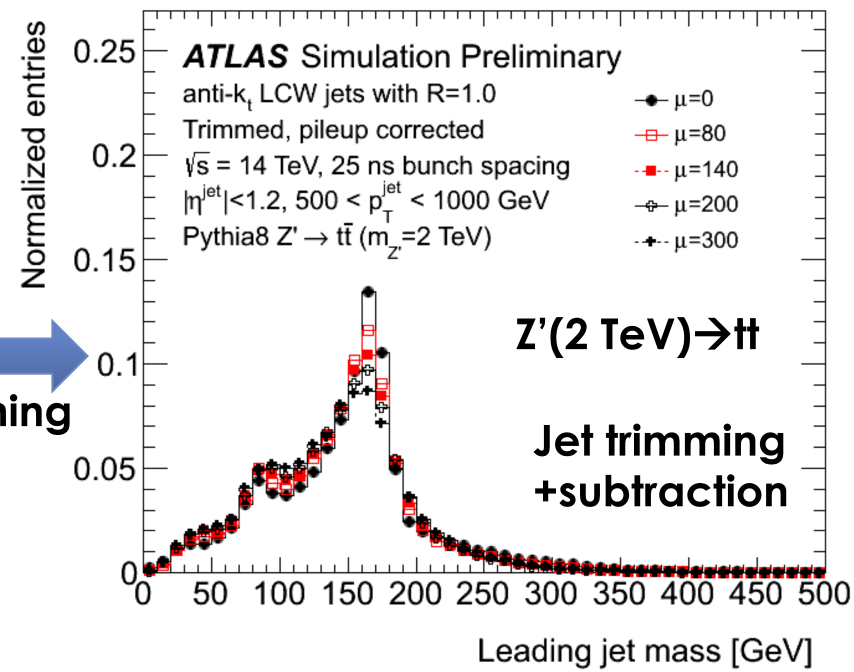
Jet substructure (I)

- **Jet trimming:**
  - anti-k_t R=1.0
  - R_{kt}=0.3, f=5%



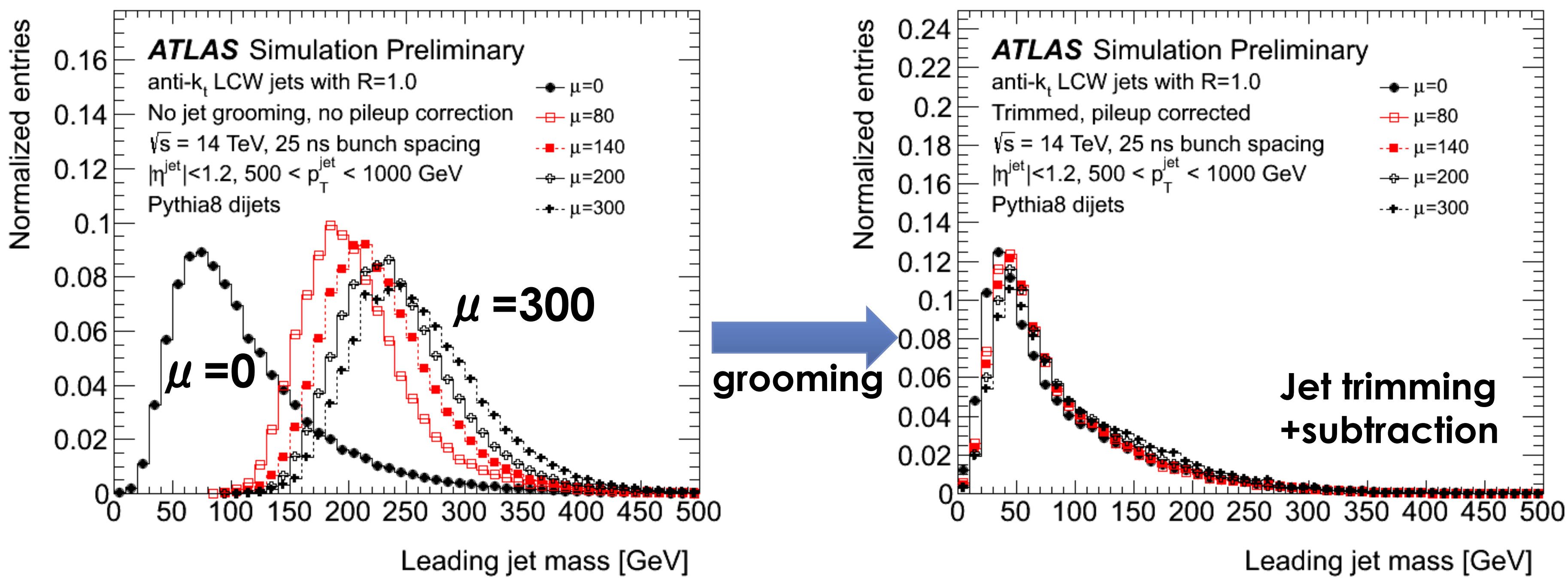


grooming



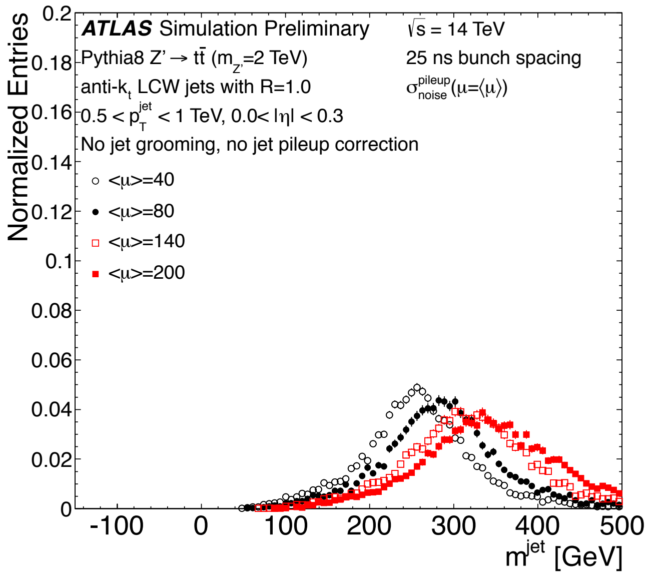
Jet substructure (II)

- **Trimming performance on QCD jets:**

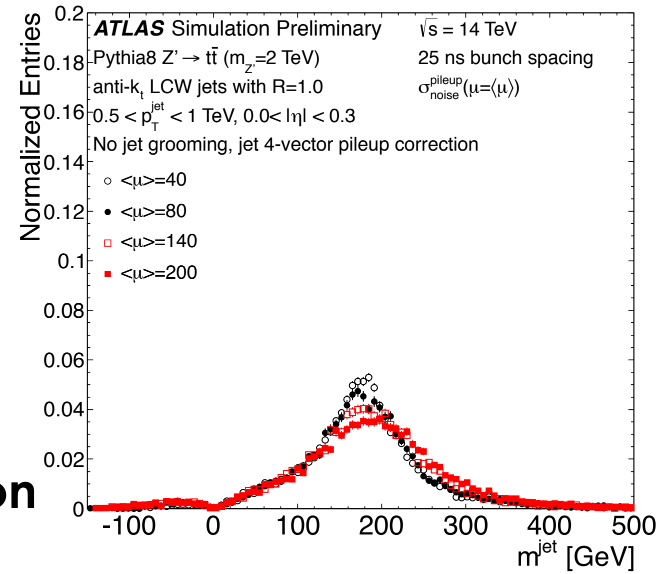


- **Trimming continues to works up to μ =300!**
  - Jet mass distribution stable with μ up to very high luminosity

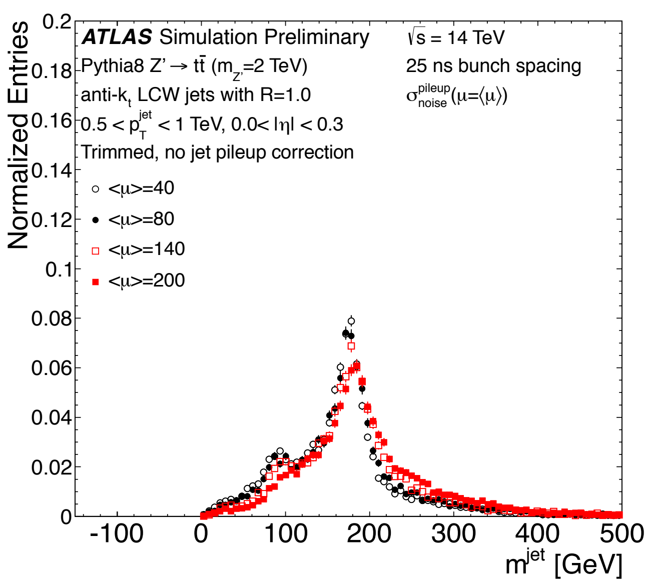
Jet substructure (II)

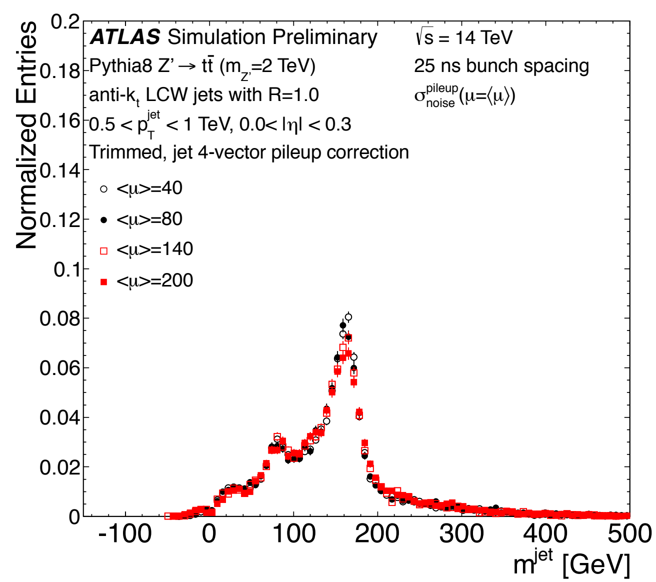


Pileup subtraction



grooming





Trimming
R_{kt}=0.3
f=5%

Jet calibration

Jet energy scale

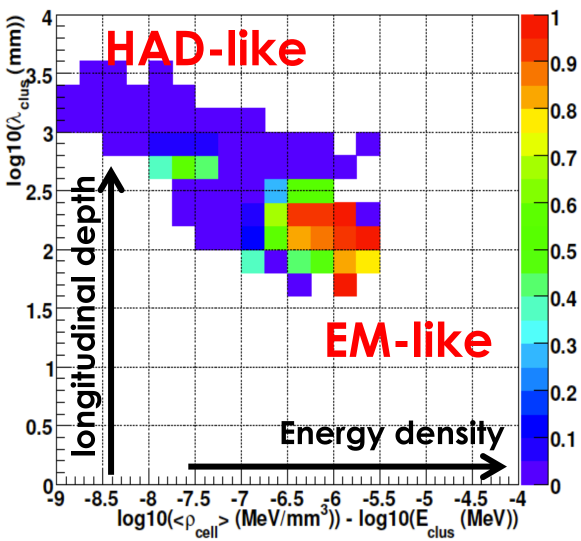
inputs

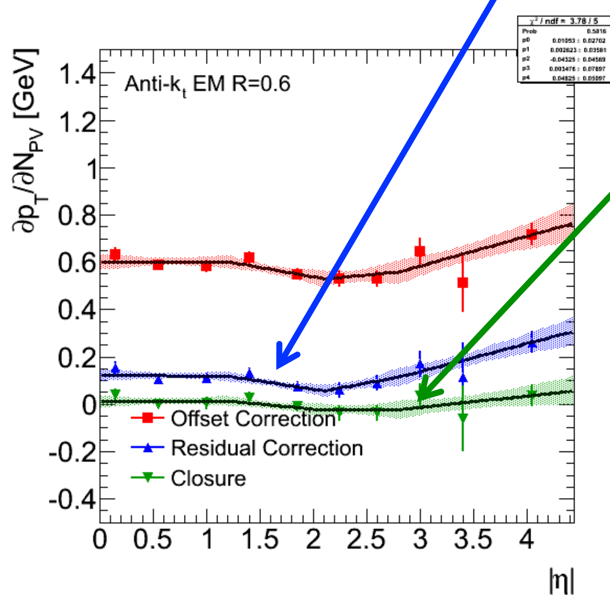
Topo-clusters (pileup noise threshold) → Local cluster weighting (LCW) → Event-by-event pileup subtraction → Residual offset (out-of-time, occupancy) → Jet Energy Scale

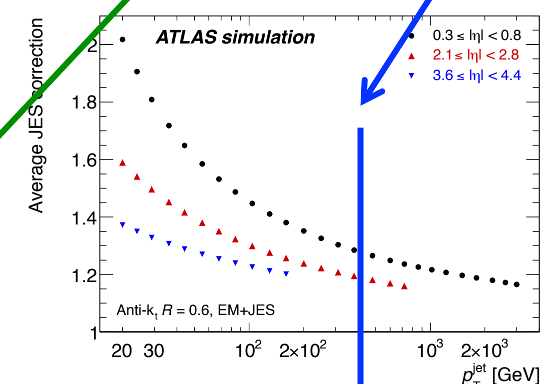
Pileup noise:
σ(μ)

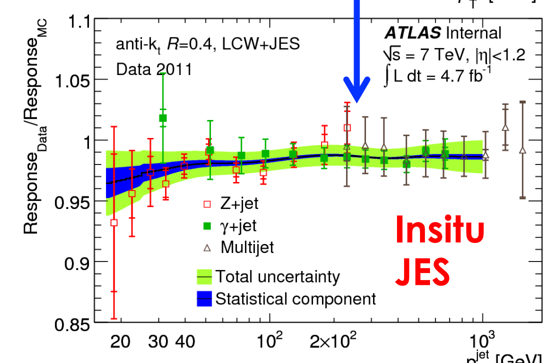
EM/HAD classification

$$p_T^{calib} = \left(p_T - \rho A - \alpha (N_{PV} - 1) - \beta \langle \mu \rangle \right) \times JES$$

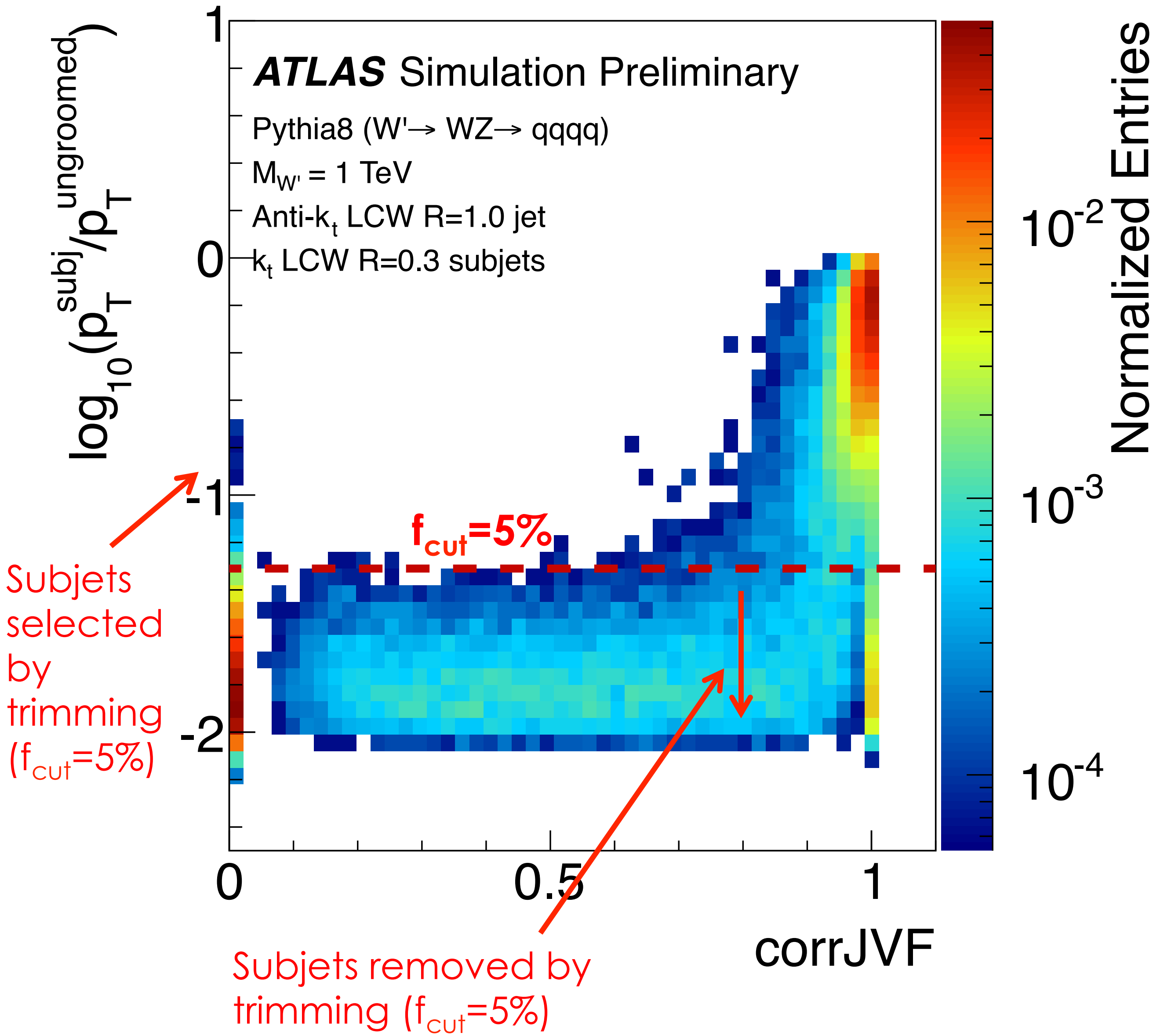


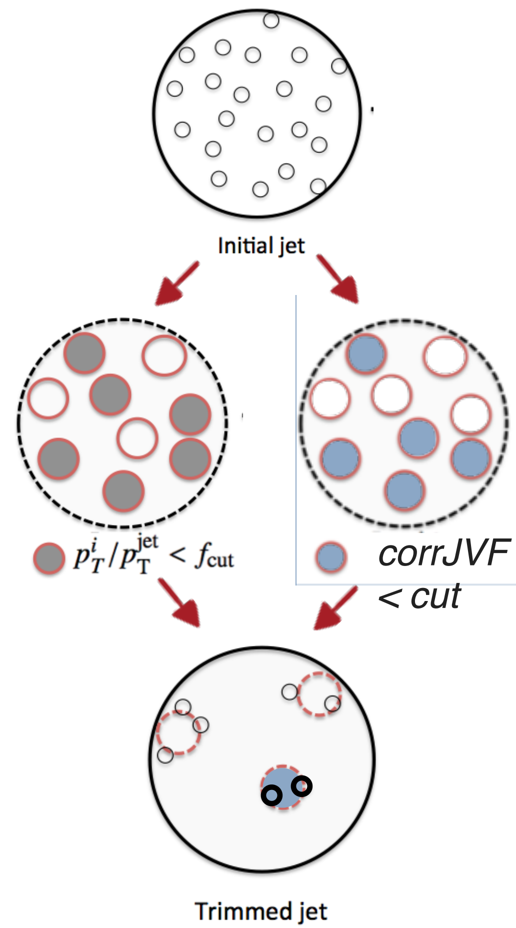






CorrJVF Trimming





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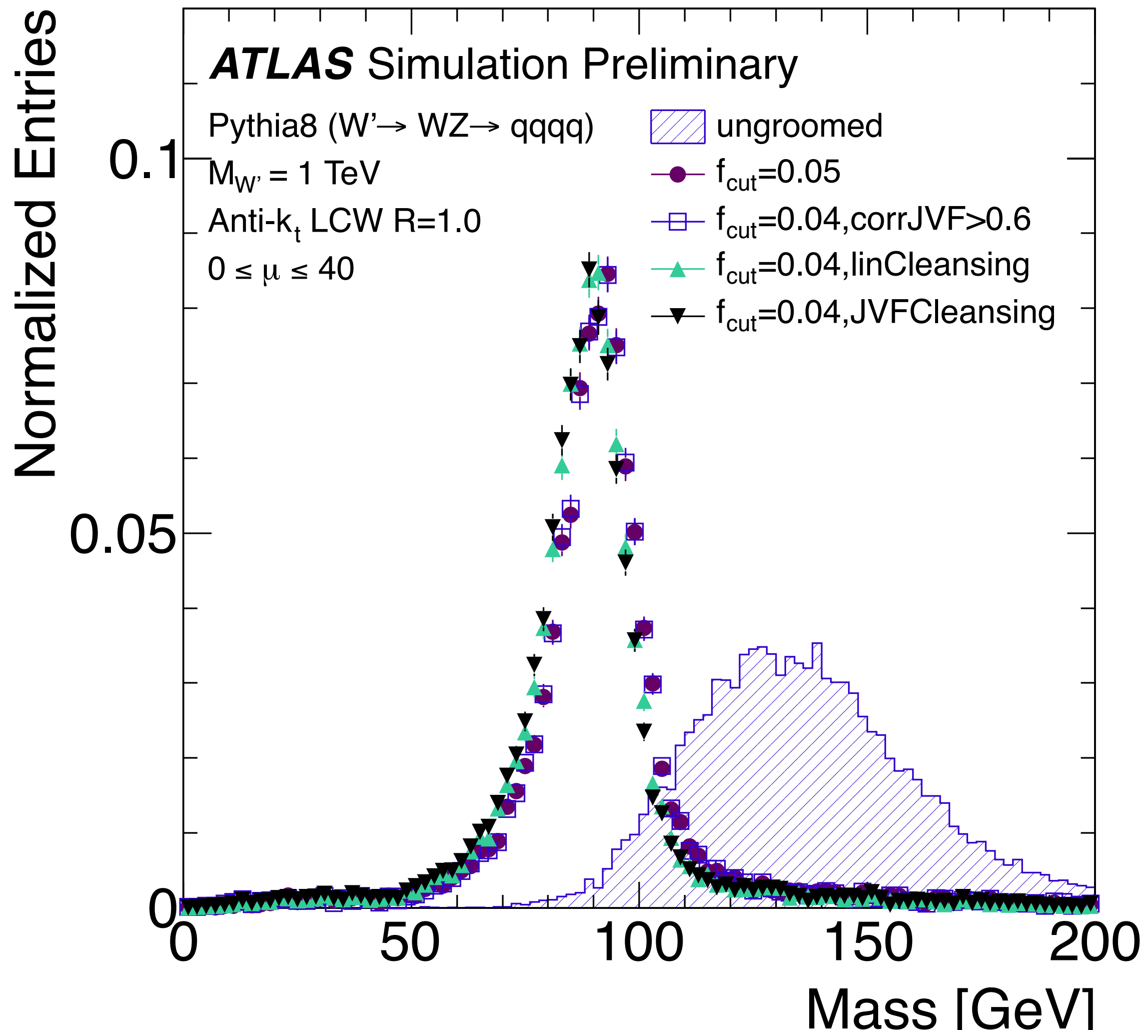
Track grooming performance



Jet cleansing: arXiv:1309.4777

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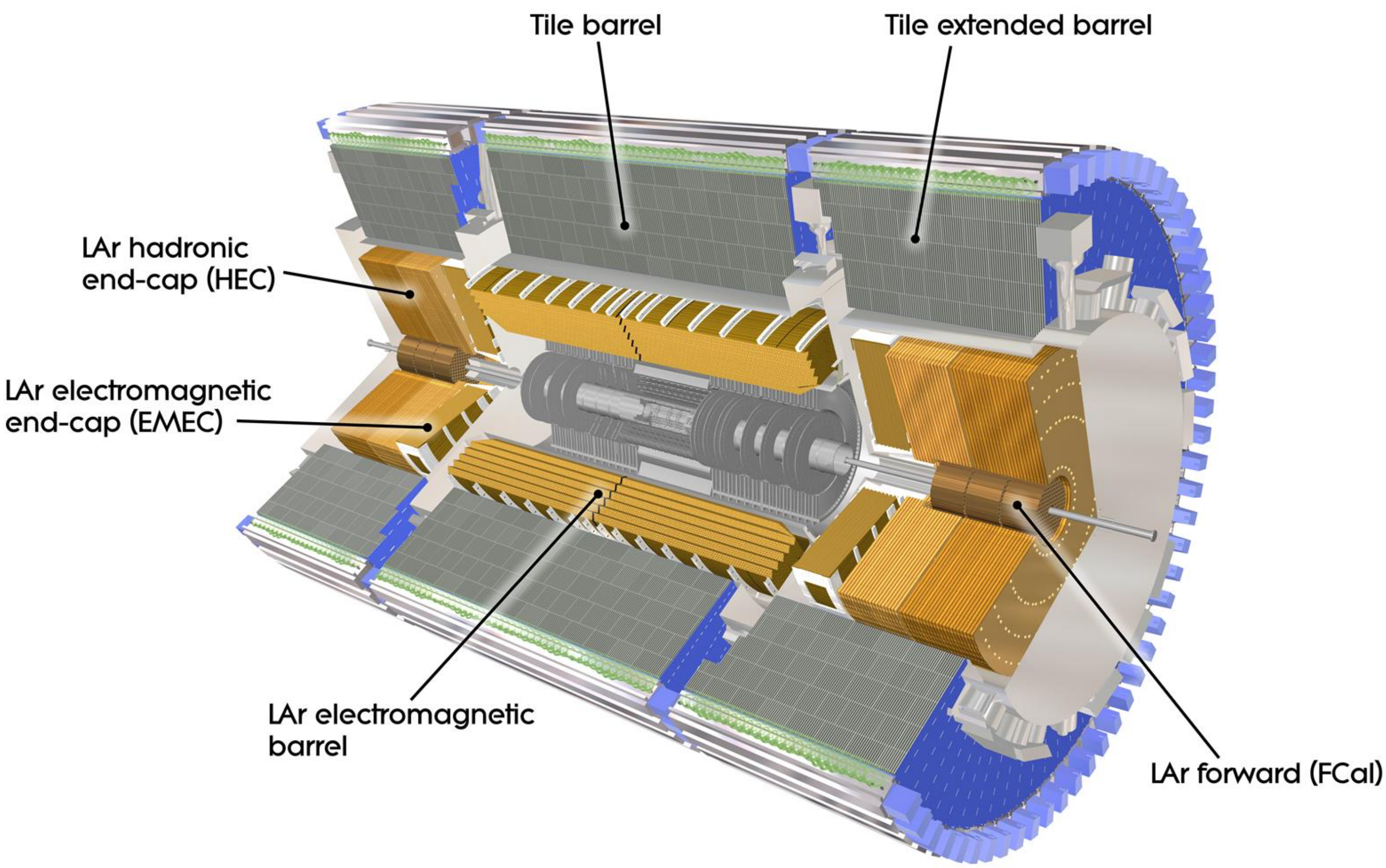
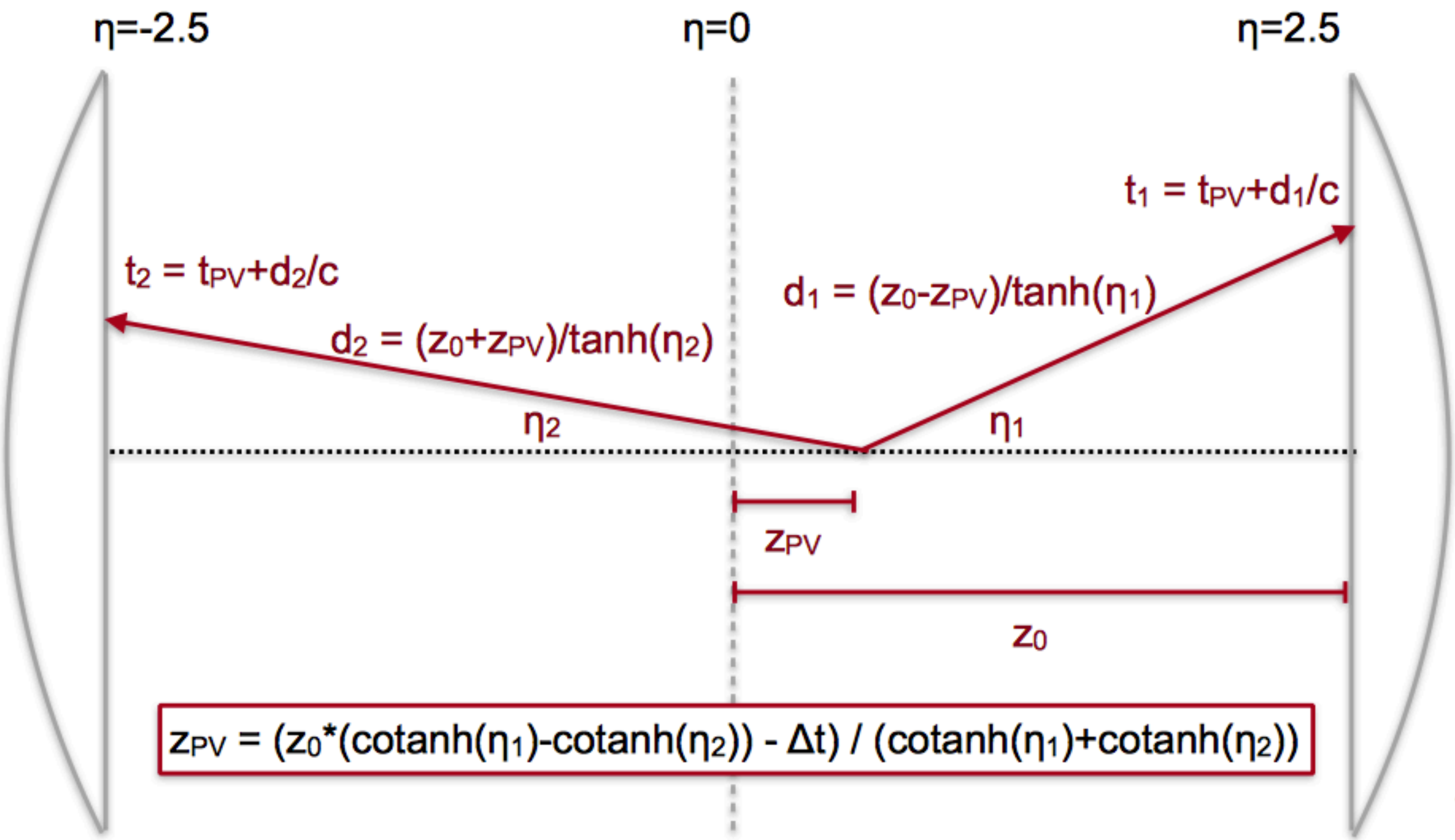

Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

Vertex position

Use forward-backward timing measurements to improve the HS vertex selection/identification in VBF events.



$$z_{PV} = (z_0 * (\mathrm{cotanh}(\eta_1) - \mathrm{cotanh}(\eta_2)) - \Delta t) / (\mathrm{cotanh}(\eta_1) + \mathrm{cotanh}(\eta_2))$$