Pileup mitigation in CMS and ATLAS

QCD at LHC 2018 Workshop, 27-31 Aug 2018, Dresden, Germany

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On behalf of CMS and ATLAS collaborations

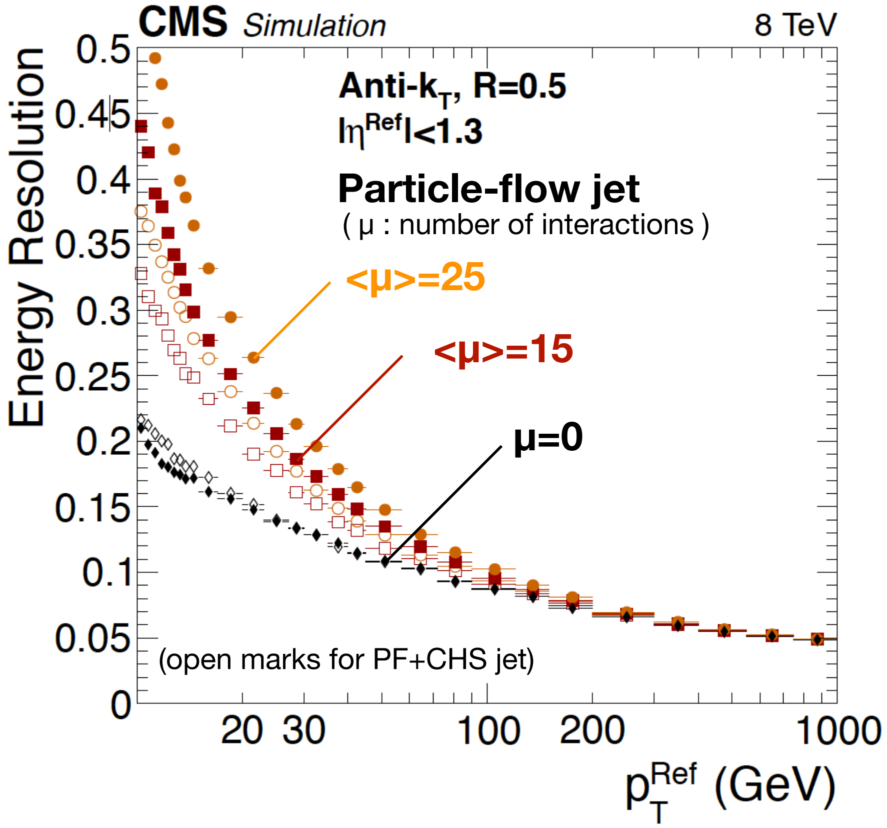
Why we care about PU

It degrades analysis performance

Worse resolution

Induced fake objects (mainly PU origin jets)

Jet energy resolution
worsen by pileup



The amount of PU increases

The amount of interaction per bunch crossing (μ)

2015 : $<\mu>=14$

2018 : $<\mu>=38$. tail up to 60.

HighLuminosity-LHC :$<\mu>=140\text{-}200$.

We must be armed to minimize the impact of PU contamination, otherwise we spoil high statistics brought by LHC.

Figure from "*Particle-flow reconstruction and global event description with the CMS detector*", arXiv:1706.04965

Topics to be discussed

Develop and improve PU mitigation techniques

PU mitigations at constituent level.

PU jet rejection using event topology.

Upgrading detector to add information

Faster timing and higher granularity detectors for PU mitigation for HL-LHC

PU mitigation at analysis level

At reconstruction of constituents

Calorimeter cells → clusters

Low energy cells below PU fluctuation cannot be cluster seeds.

Particle flow

Combine information from sub-detectors as particle flow objects, and reject charged particles from PU (Charged Hadron Subtraction, CHS)

After jet reconstruction

PU mitigation at analysis level

At reconstruction of constituents

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Combine information from sub-detectors as particle flow objects, and reject charged particles from PU (Charged Hadron Subtraction, CHS)

After jet reconstruction

PU offset subtraction

Calibration energy offset based on jet area.

$$P_T^{\mathrm{corr}} = P_T - \rho \times A$$

ρ : offset energy density

A : jet area

PU jet rejection

Jet vertex fraction (JVF) in central region.

$$\mathrm{JVF}(\mathrm{jet}^i) = \frac{\sum_m P_T^m(\mathrm{track} \in \mathrm{jet}^i, \mathrm{from\ LV})}{\sum_m P_T^m(\mathrm{track} \in \mathrm{jet}^i, \mathrm{from\ LV + PU})}$$

MVA PU jet ID exploiting jet shape in central and forward regions.

PU mitigation at analysis level

At reconstruction of constituents

Calorimeter cells → clusters

Low energy cells below PU fluctuation cannot be cluster seeds.

More PU subtraction at constituent level

Deploy particle flow

Particle flow

Combine information from sub-detectors as particle flow objects, and reject charged particles from PU (Charged Hadron Subtraction, CHS)

"PUPPI" on top of particle flow

After jet reconstruction

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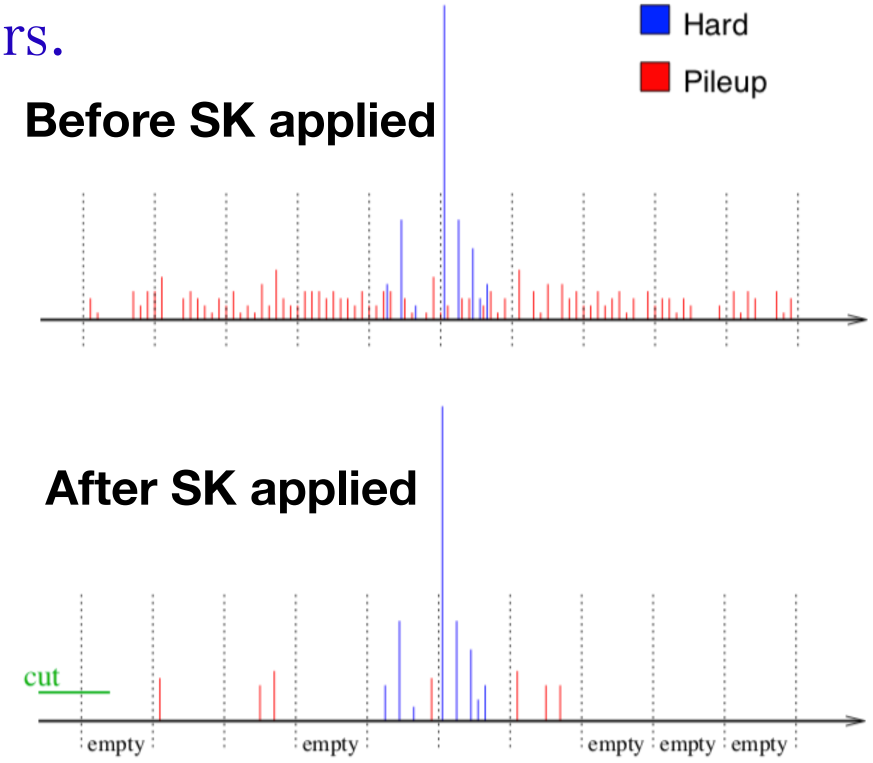
PU jet rejection in forward region

MVA PU jet ID exploiting jet shape in central and forward regions.

PU mitigation at constituent level

Can be better than mitigation at jet level.

In ATLAS, the following four techniques are tested with clusters.



1. SoftKiller(SK)

- Remove low energy cluster below a threshold = soft.
- Set a grid on eta-phi space, and determine the threshold so that half of bins are empty.
- Grid size is optimized based on JER.

2. Constituent Subtraction (CS)

- Scatters “ghost” particles with $P_T = -0.01\rho$ on $\eta \times \phi = 0.1 \times 0.1$ grid.
- ρ : offset energy density, same as the one used for jet-area correction
- Merged with nearby(<R_{max}) clusters until all negative energy is completely absorbed.
- The maximum distance R_{max} is optimized base on JER.

Figure from “SoftKiller, a particle-level pileup removal method”, arXiv:1407.0408

PU mitigation at constituent level

3. Voronoi subtraction

Application of idea of jet-area correction to clusters.

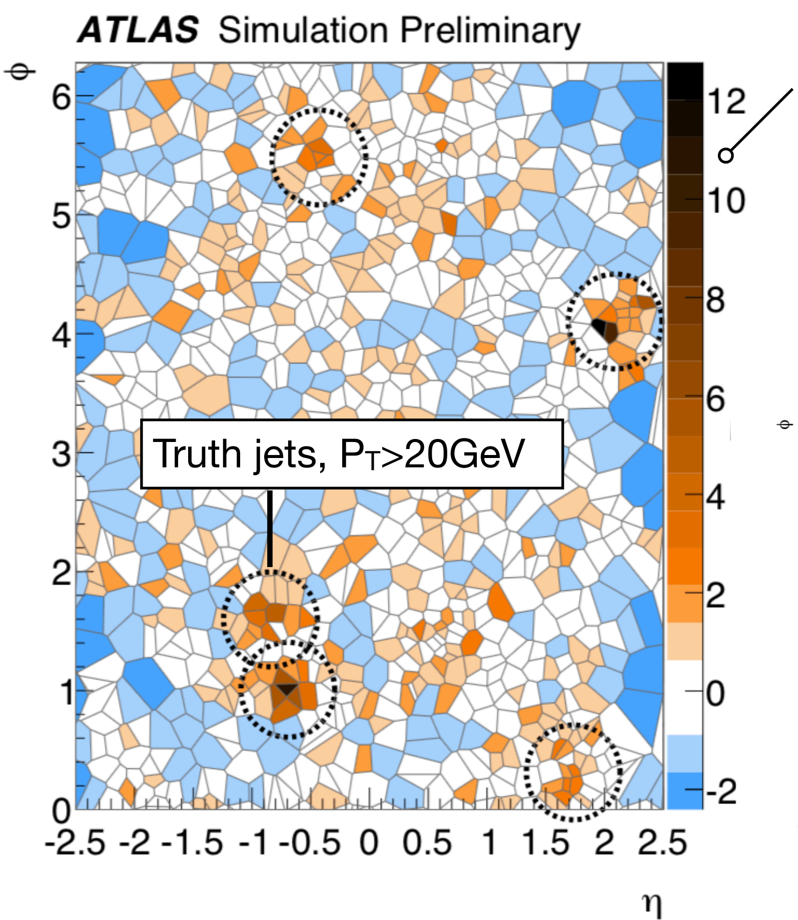
Cluster area is defined as area of Voronoi cell.

$$P_T^{\text{cluster, corr}} = P_T^{\text{cluster}} - \rho \times A_{\text{Voronoi cell}}^{\text{cluster}}$$

ρ : offset energy density, same one used in jet-area correction.

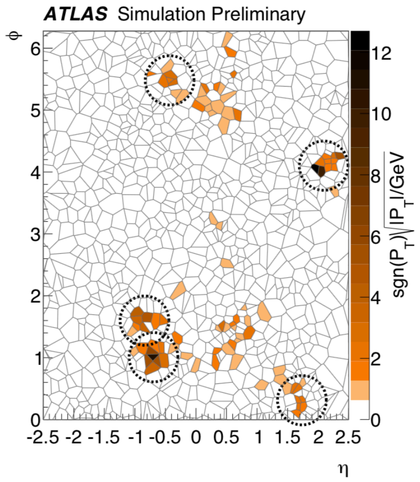
Negative energies are either ignored or spread to their neighbors.

Cluster energy after subtraction



$sgn(P_T) \times \sqrt{\frac{|P_T|}{[\text{GeV}]}}$

After spreading negative energy



4. Cluster Vertex Fraction (CVF)

Application of idea of JVF to clusters.

Remove low P_T clusters matched to a PU track.

Usually zero or only one track from either LV or PU is associated to one cluster.

P_T threshold is optimized based on JER

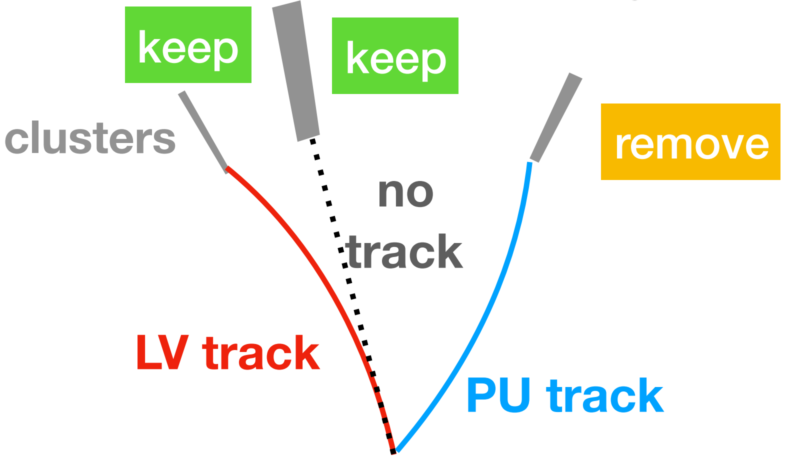


Figure from "Mitigating pile-up in jets before jet reconstruction", ATLAS-CONF-2017-065

Resolution with mitigation techniques

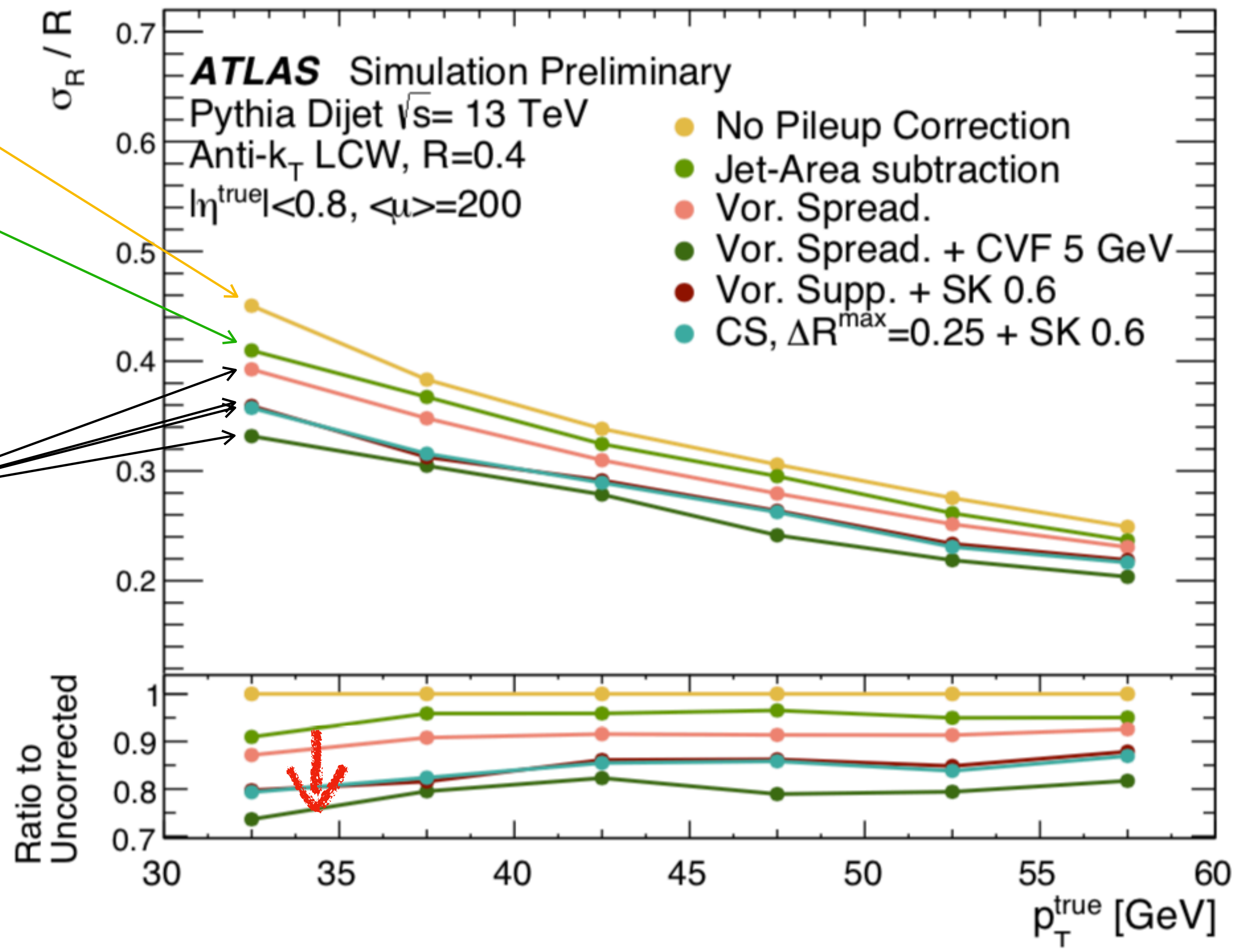
Jet energy resolution in **200 PU** events

No pileup correction

Correction after jet reconstruction,
based on jet-area
(current standard method)

$$P_T^{\mathrm{corr}} = P_T - \rho \times A$$

Corrections at constituent level



PU mitigation at constituent level gains resolution by ~20%

Figure from "Mitigating pile-up in jets before jet reconstruction", ATLAS-CONF-2017-065

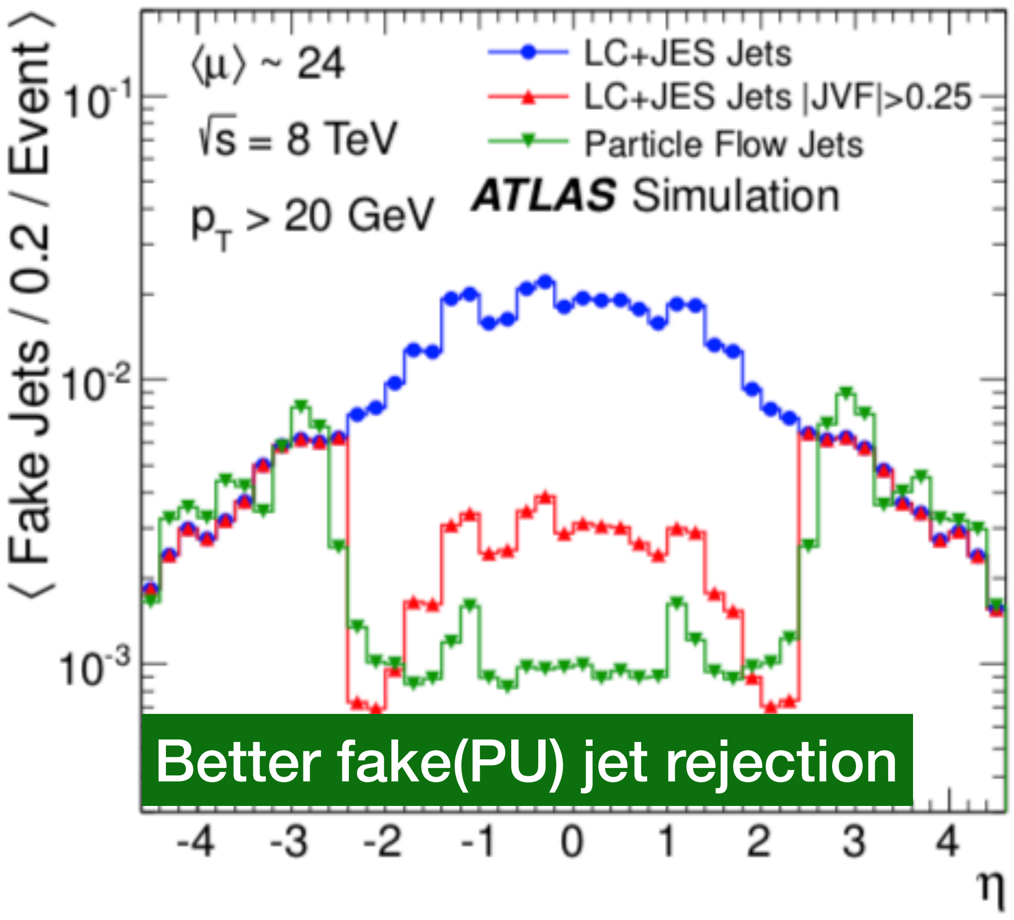
Particle flow and PU jets

Traditionally, ATLAS has been using calorimeter and tracking information separately.

Particle-flow algorithm combines the two.

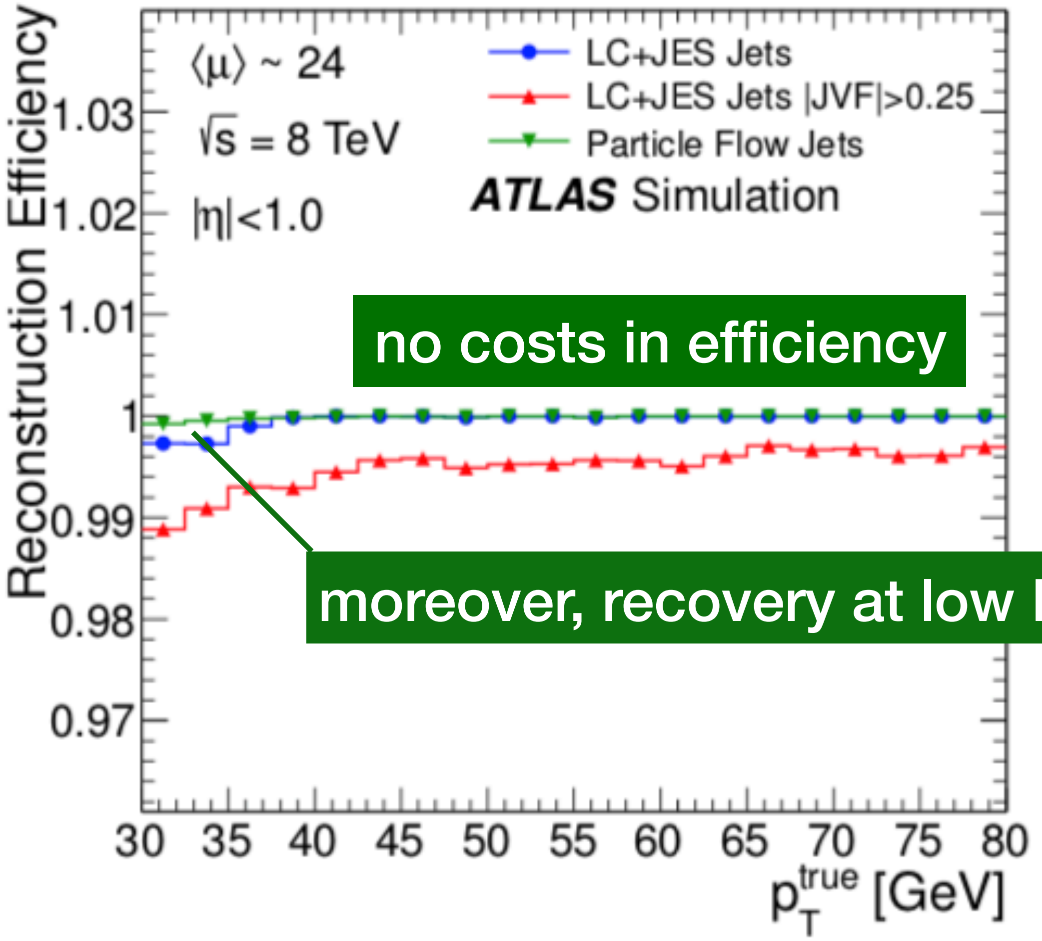
Tracking information helps measurement of low energy objects, providing vertex information.

Amount of "fake"(PU origin) jets



Better fake(PU) jet rejection

Reconstruction efficiency of "real" jet



no costs in efficiency

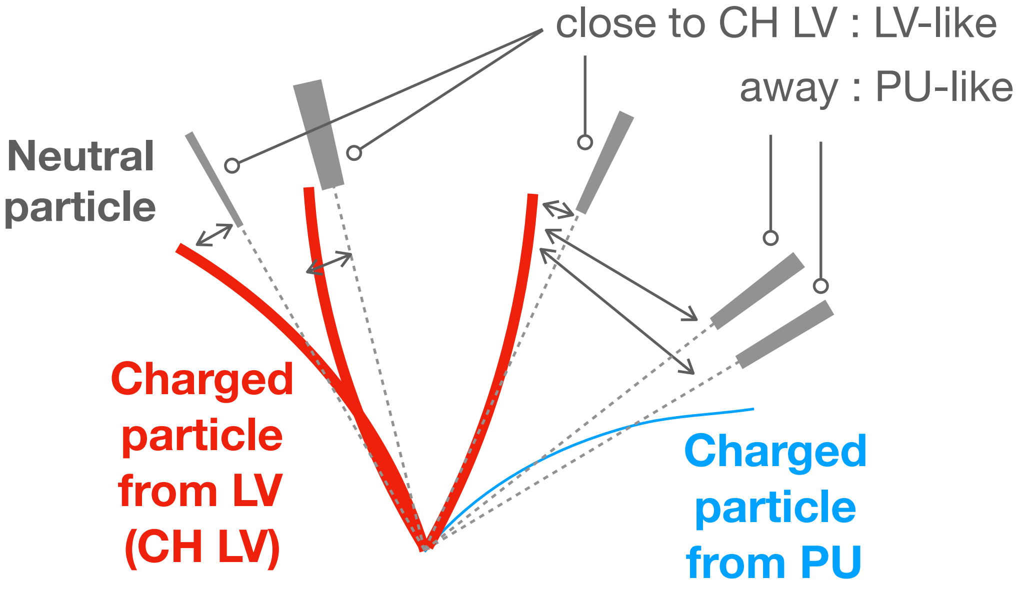
moreover, recovery at low P_T

Figures from “*Jet reconstruction and performance using particle flow with the ATLAS Detector* ”, Eur. Phys. J. C (2017) 77: 466.

PUPPI in CMS

PileUp-Per-Particle-Identification (PUPPI) mitigate PU for neutral particle-flow particles

Point : closeness to LV charged particles



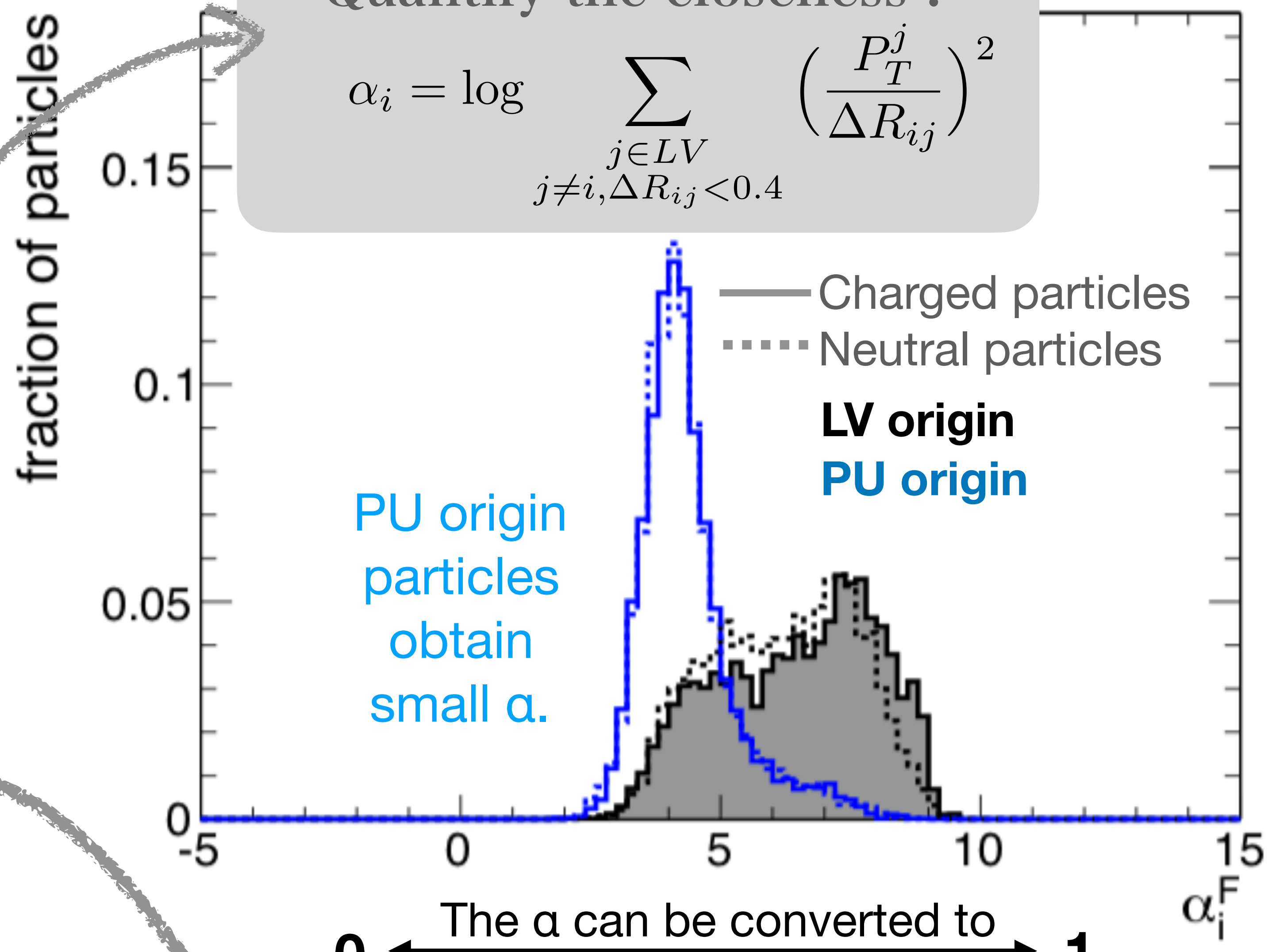
PU subtraction is done by :

$$P_T^{i,\ \mathrm{PUPPI}} = P_T^i \times \omega_{\mathrm{PUPPI}}(\alpha^i)$$

PUPPI is extendable to the forward region by taking the sum in the metric α for all particles.

Quantify the closeness :

$$\alpha_i = \log \sum_{\substack{j\in LV \\ j\neq i,\Delta R_{ij}<0.4}} \left(\frac{P_T^j}{\Delta R_{ij}}\right)^2$$



PU origin particles obtain small α.

The α can be converted to PUPPI weight ω

0 PU-like ⟷ **1** LV-like

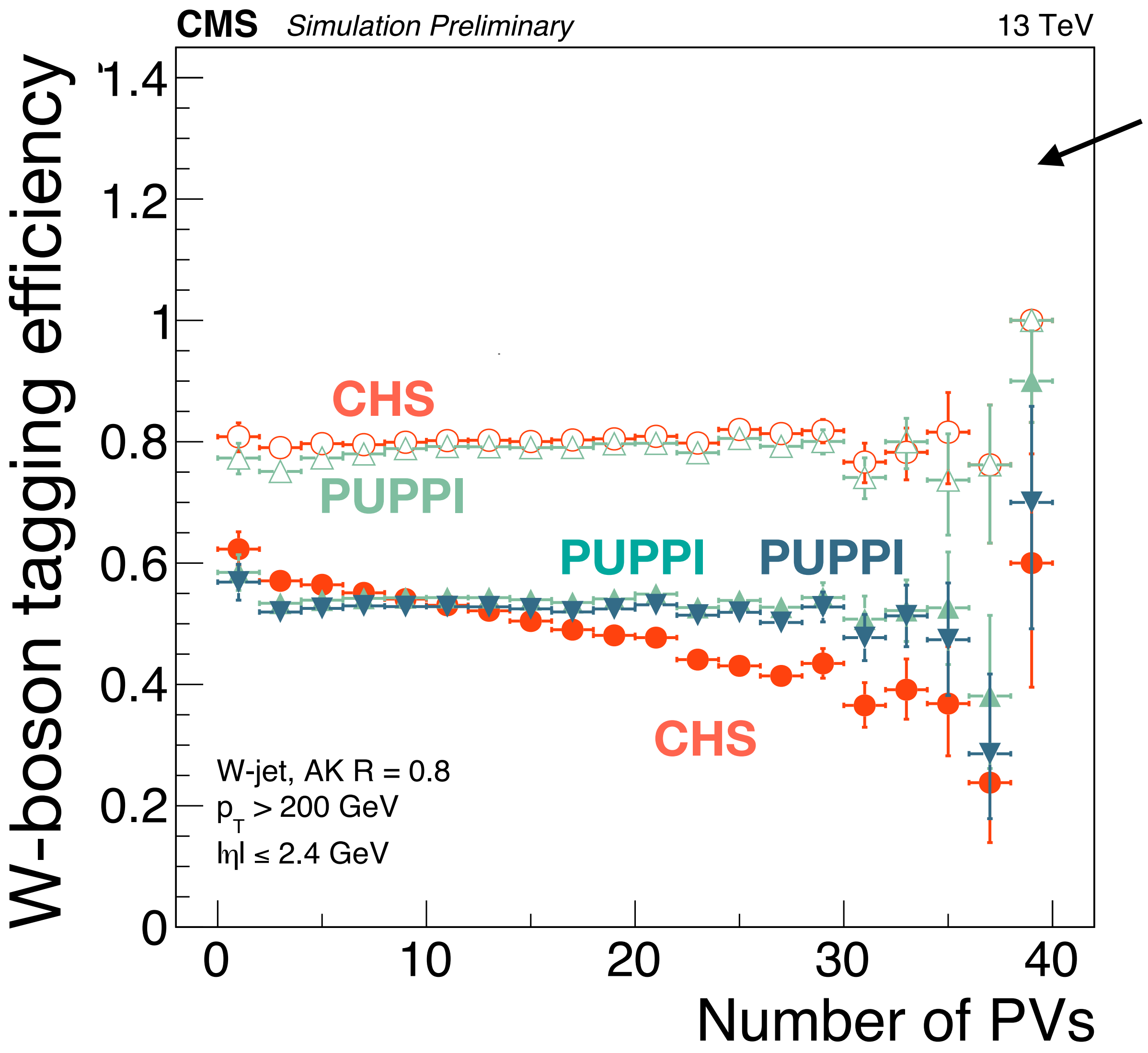
Figure can be found in “*Pileup Per Particle Identification*”, arXive:1407.6013.

PUPPI and boosted objects

PUPPI works especially for jet substructure

Large cone jets (e.g. ak8) are used for tagging boosted heavy particles like W-bosons.

Substructure of jets such as mass and subjettiness are sensitive to PU.



W-tagging performance of two types of jet at various working points

CHS ○ 65 GeV < M^{CHS}_{Pruned} < 105 GeV

PUPPI △ 65 GeV < $M^{PUPPI}_{Softdrop}$ < 105 GeV

CHS ● 65 GeV < M^{CHS}_{Pruned} < 105 GeV + $\tau_{21} \leq 0.45$

PUPPI ▲ 65 GeV < $M^{PUPPI}_{Softdrop}$ < 105 GeV + $\tau_{21} \leq 0.4$

PUPPI ▼ 65 GeV < $M^{PUPPI}_{Softdrop}$ < 105 GeV + $\tau^{DDT}_{21} \leq 0.52$

Figures can be found in "*Jet algorithms performance in 13 TeV data*" CMS-PAS-JME-16-003

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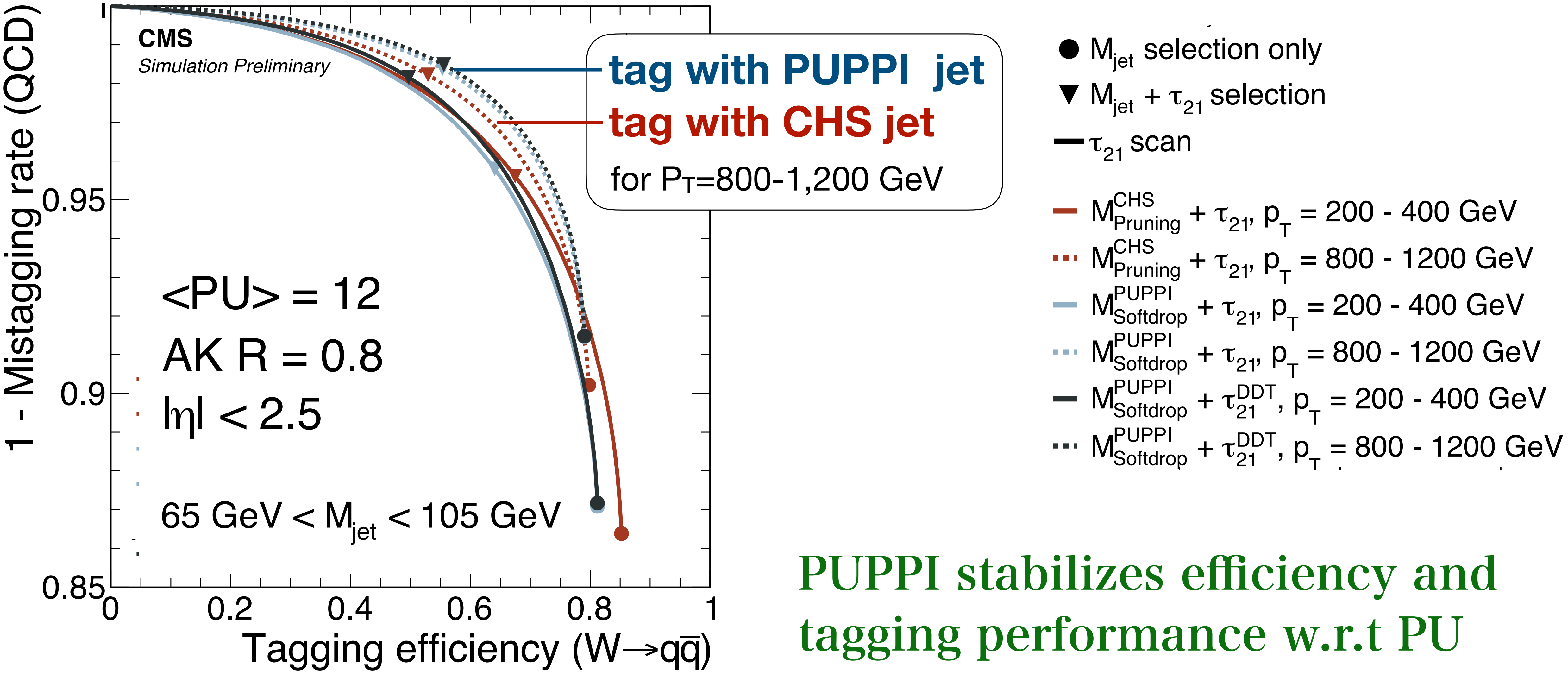


tag with PUPPI jet

tag with CHS jet

for P_T=800-1,200 GeV

PUPPI stabilizes efficiency and tagging performance w.r.t PU

Figures can be found in “*Jet algorithms performance in 13 TeV data*” CMS-PAS-JME-16-003

PUPPI MET

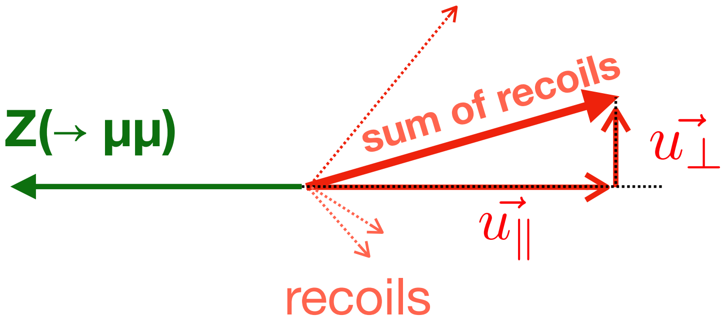
The standard MET is defined as

$$\mathrm{MET} = -\sum_{i=\mathrm{PF\ particles}} \vec{P}_T^i$$

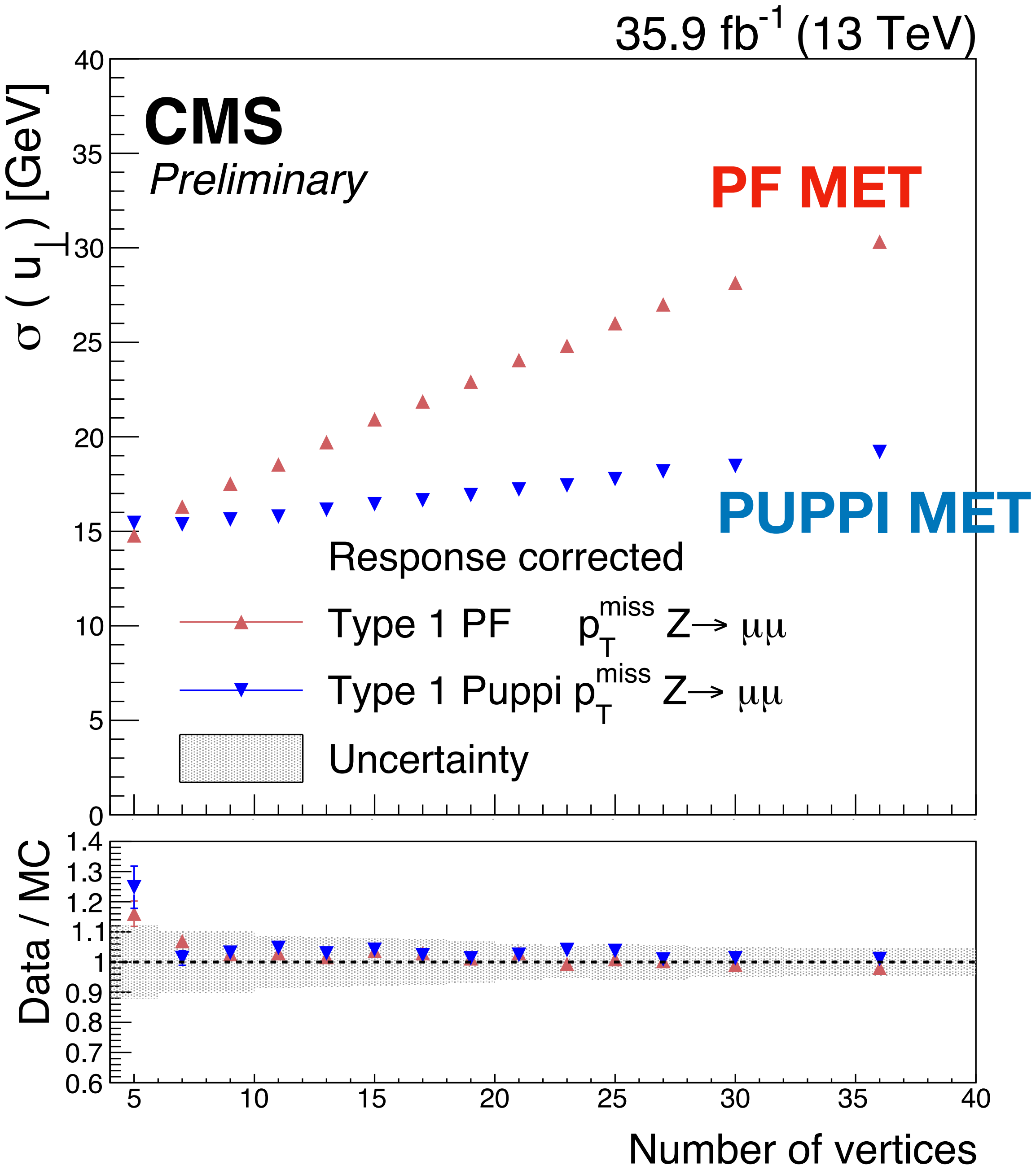
PUPPI MET calculates it with PUPPI weight ω.

$$\mathrm{PUPPI\ MET} = -\sum_{i=\mathrm{PF\ particles}} \vec{P}_T^i \omega^i$$

Performance evaluation in DY events



- Precisely reconstructed Z(→ μ μ) can be used to evaluate recoil measurement.
- σ (u⊥) and σ (u∥) represent σ (MET).



PUPPI provides stabler and better performance.

Figures can be found in "*Performance of missing transverse momentum in pp collisions at sqrt(s)=13 TeV using the CMS detector*" CMS-PAS-JME-17-001

PUPPI muon isolation

Isolation is also affected by PU.

It is defined as P_T sum of surrounding particles.

Used to distinguish prompt lepton from non-prompt

CHS works, but **neutral PU particles remains.**

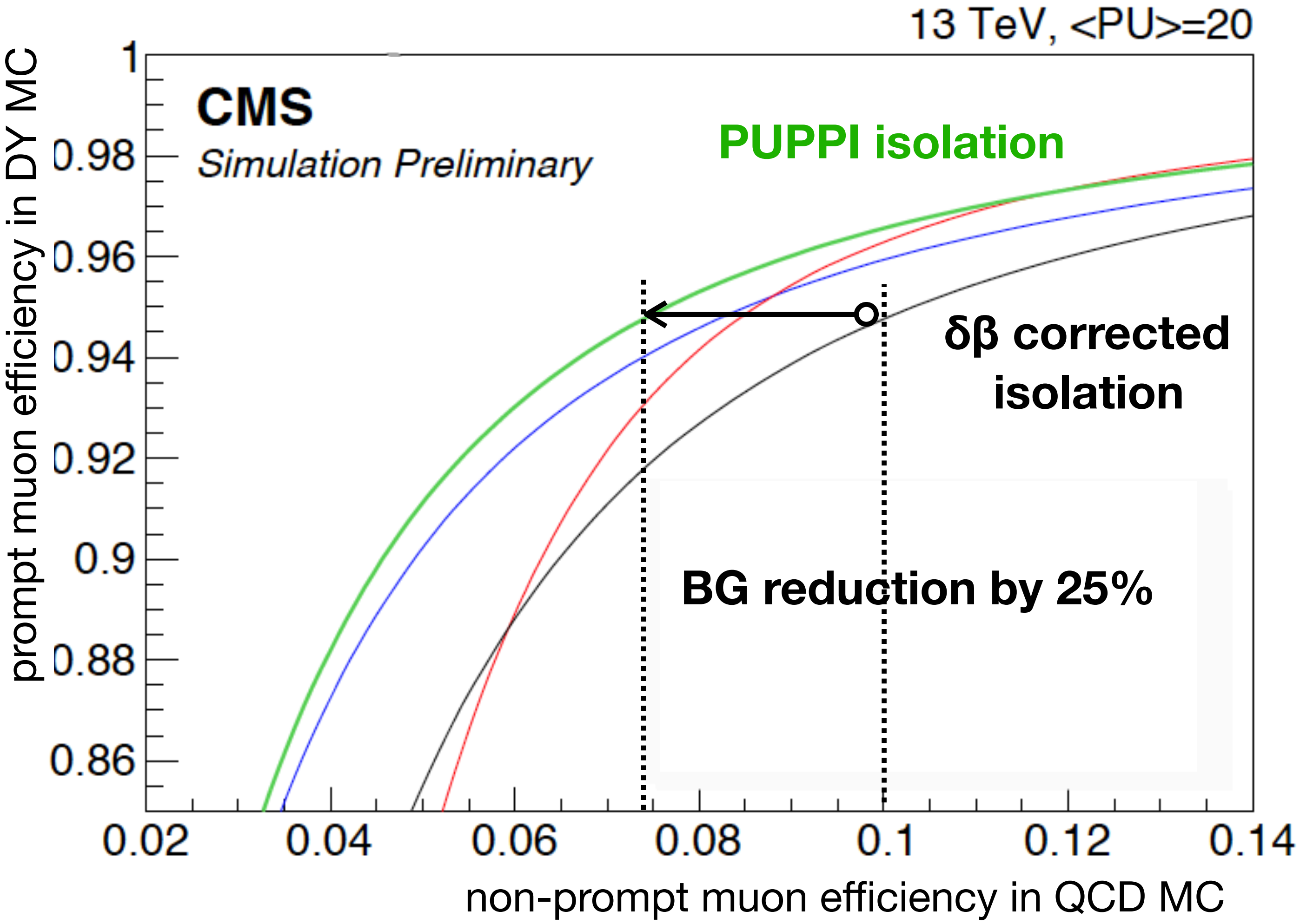
One of standard methods : $\delta\ \beta$-correction

Estimates the amount of neutral from PU from charged from PU.

PU rejection

$$\delta\beta\ \text{iso} = \sum_{dR<0.4}^{\text{Charged,LV}} P_T^i + \max(0, \sum_{dR<0.4}^{\text{neutrals}} P_T^i - \boxed{\frac{1}{2}\sum_{dR<0.4}^{\text{Charged,PU}} P_T^i)}$$

(1/2 comes from isospin limit)



PUPPI muon isolation

subtracts PU contamination at constituent level.

PU rejection

$$\text{PUPPI iso} = \sum_{dR<0.4}^{\text{Charged,LV}} P_T^i + \sum_{dR<0.4}^{\text{neutrals}} P_T^i \boxed{\omega_i}$$

by PUPPI weight

Tested also for LH-LHC

PUPPI muon isolation does not show breakdown at PU=200.

(figure in backup slide)

Figure from CMS DP-2015/034

Forward PU jet rejection

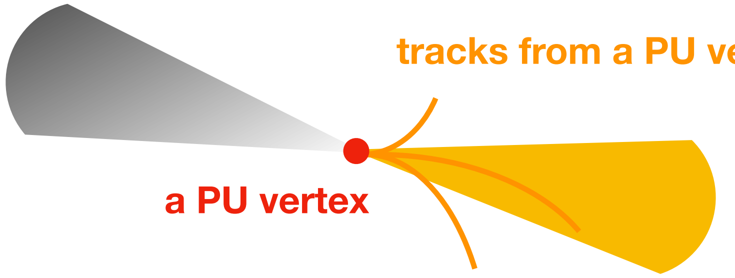
Important but not easy

Forward jets are an important signature - e.g. VBF, VBS

PU jet rejection in the forward region is not easy since tracking is not available beyond | η |~2.5.

Exploit P_T balance for each PU vertex

Concept :



forward jet in question

tracks from a PU vertex

a PU vertex

central jet associated to a PU vertex

In case of good PT-balance, the forward jet likely from the PU vertex

First, define momentum missing from a PU vertex

$$\left\langle \vec{P}^{\text{miss}}_{T,i} \right\rangle = -\frac{1}{2}\left(k \sum_{\text{tracks}\in \text{PV}_i} \vec{P_T}^{\text{track}} + \sum_{\text{jets}\in\text{PV}_i} \vec{P_T}^{\text{jets}} \right)$$

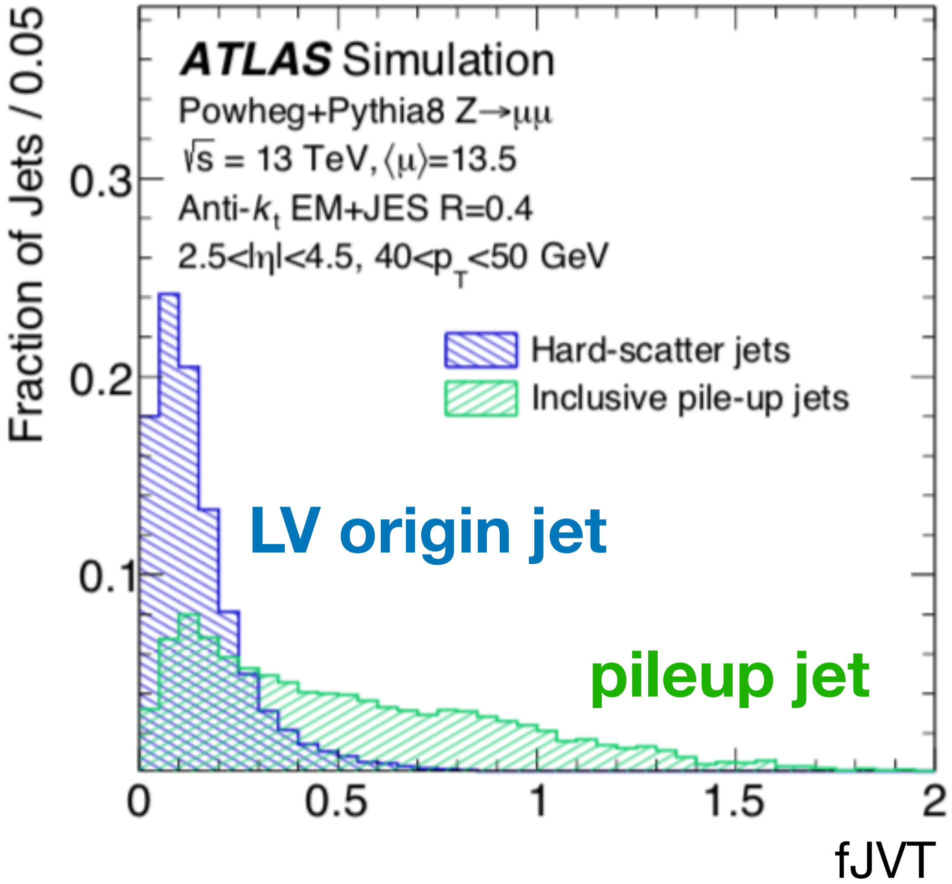
And define a discriminant : **forward Jet Vertex Tagger** (fJVT)

$$fJVT_i = \frac{\left\langle \vec{P}^{\text{miss}}_{T,i}\right\rangle \cdot \vec{u_T}^{\text{forward jet}}}{|P_T^{\text{forward jet}}|}$$

uT : unit vector of the P_T of the forward jet.

denominator for normalization

In case of PT-balance, large tagger value.



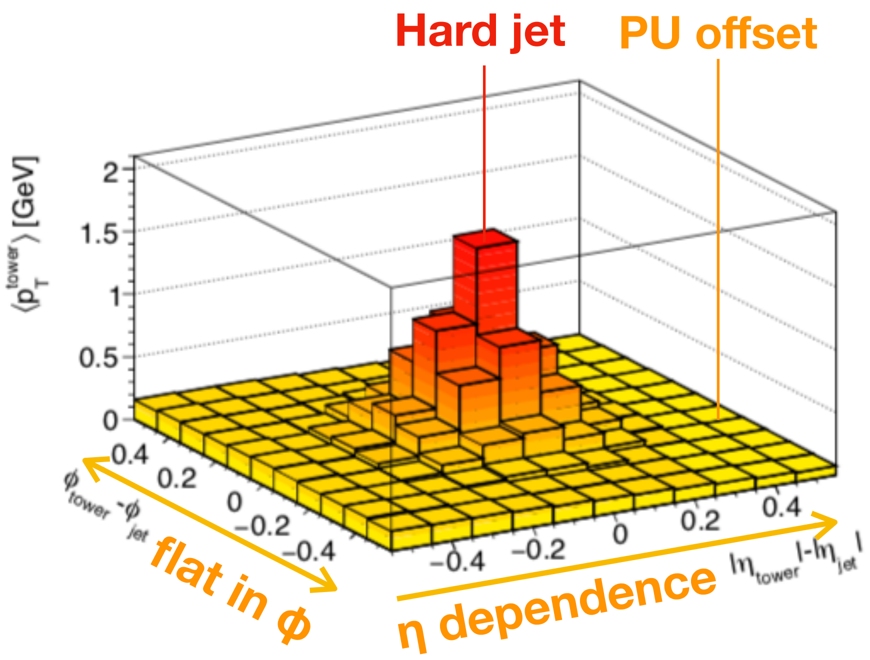
LV origin jet

pileup jet

Figures from "*Identification and rejection of pile-up jets at high pseudorapidity with the ATLAS detector*" ,Eur. Phys. J. C (2017) 77: 580.

Forward PU jet rejection

Better indicator for forward jet energy

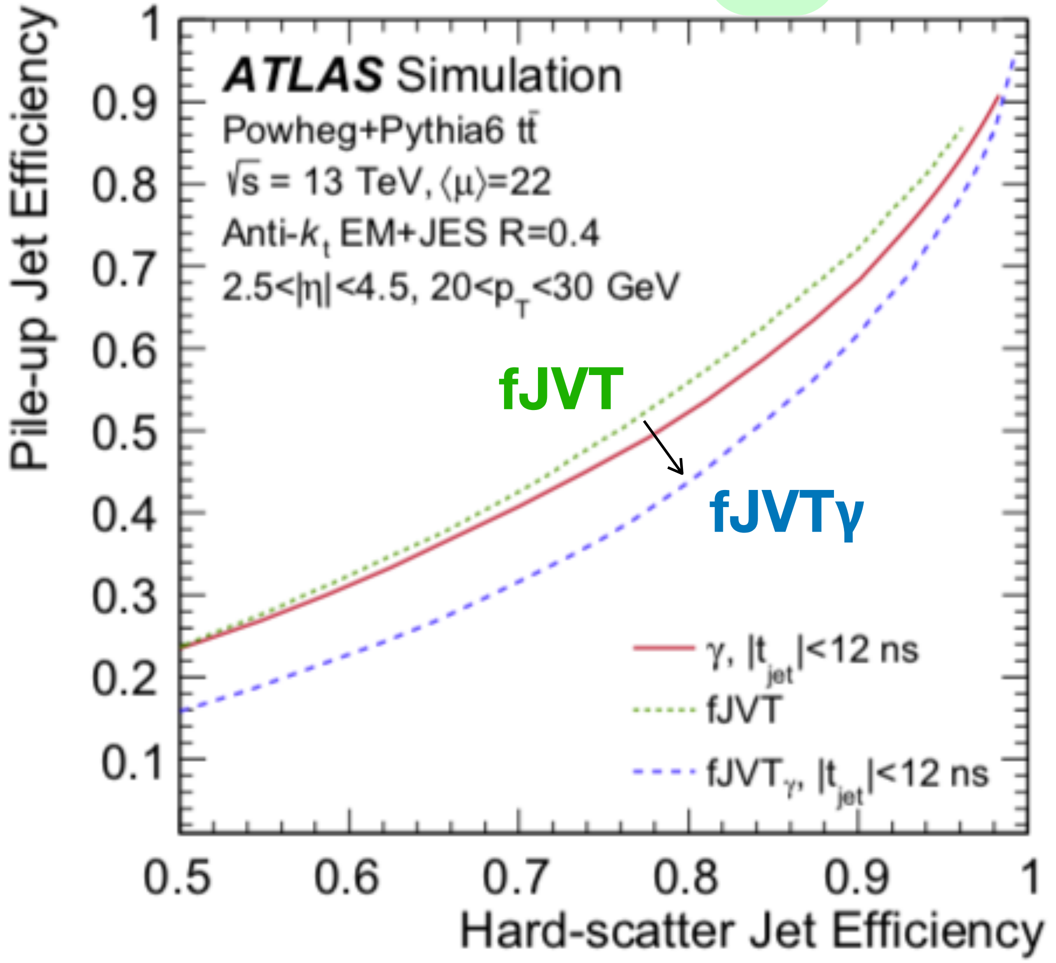


$$F = \underbrace{\alpha + \beta\Delta\eta}_{\text{PU offset terms}} + \underbrace{\gamma \exp[-\frac{(\Delta\eta/0.1)^2 + (\Delta\phi/0.1)^2}{2}]}_{\text{2D-gaussian}}$$

γ does not mean directly P_T or energy, but it represents magnitude of the energy of pure hard jet.

Redefine the tagger :

$$fJVT_\gamma = \frac{\left\langle \vec{P}^{\text{miss}}_{T,i} \right\rangle \cdot \vec{u_T}^{\text{forward jet}}}{\gamma}$$



Figures from "*Identification and rejection of pile-up jets at high pseudorapidity with the ATLAS detector*" ,Eur. Phys. J. C (2017) 77: 580.

Detector Upgrade for higher luminosity

To handle high PU of HL-LHC, need to add information in data.

Increase granularity and coverage:

Inner tracker of both experiments will be extended to $|\eta|$=4.0 with finer pixels.

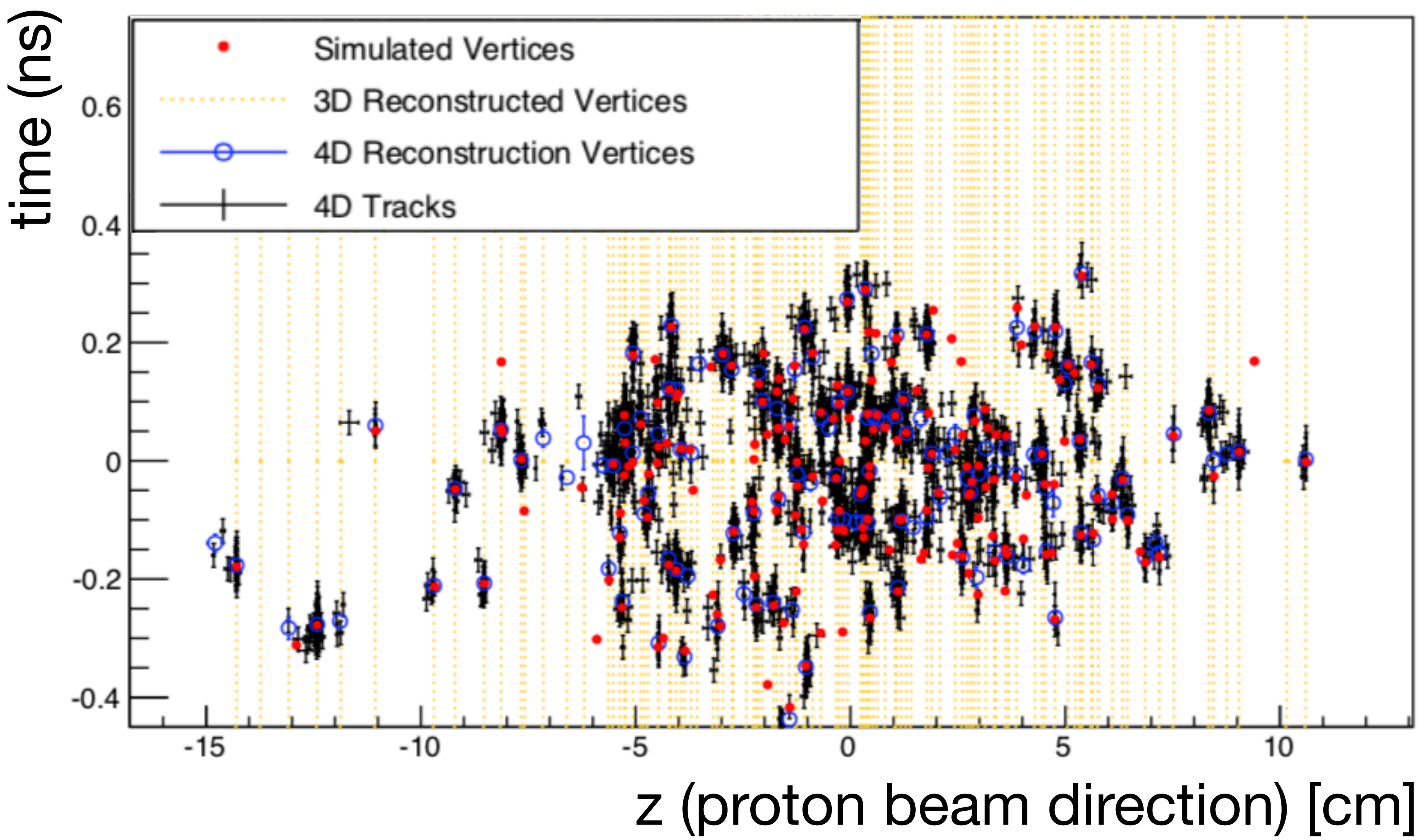
High granularity calorimeters : HGCal in CMS, sFCal in ATLAS.

Pico-second timing detectors in both experiments.

Timing information for PU rejection

4D vertex reconstruction by adding time information

Vertex positions of simulated 200 interactions

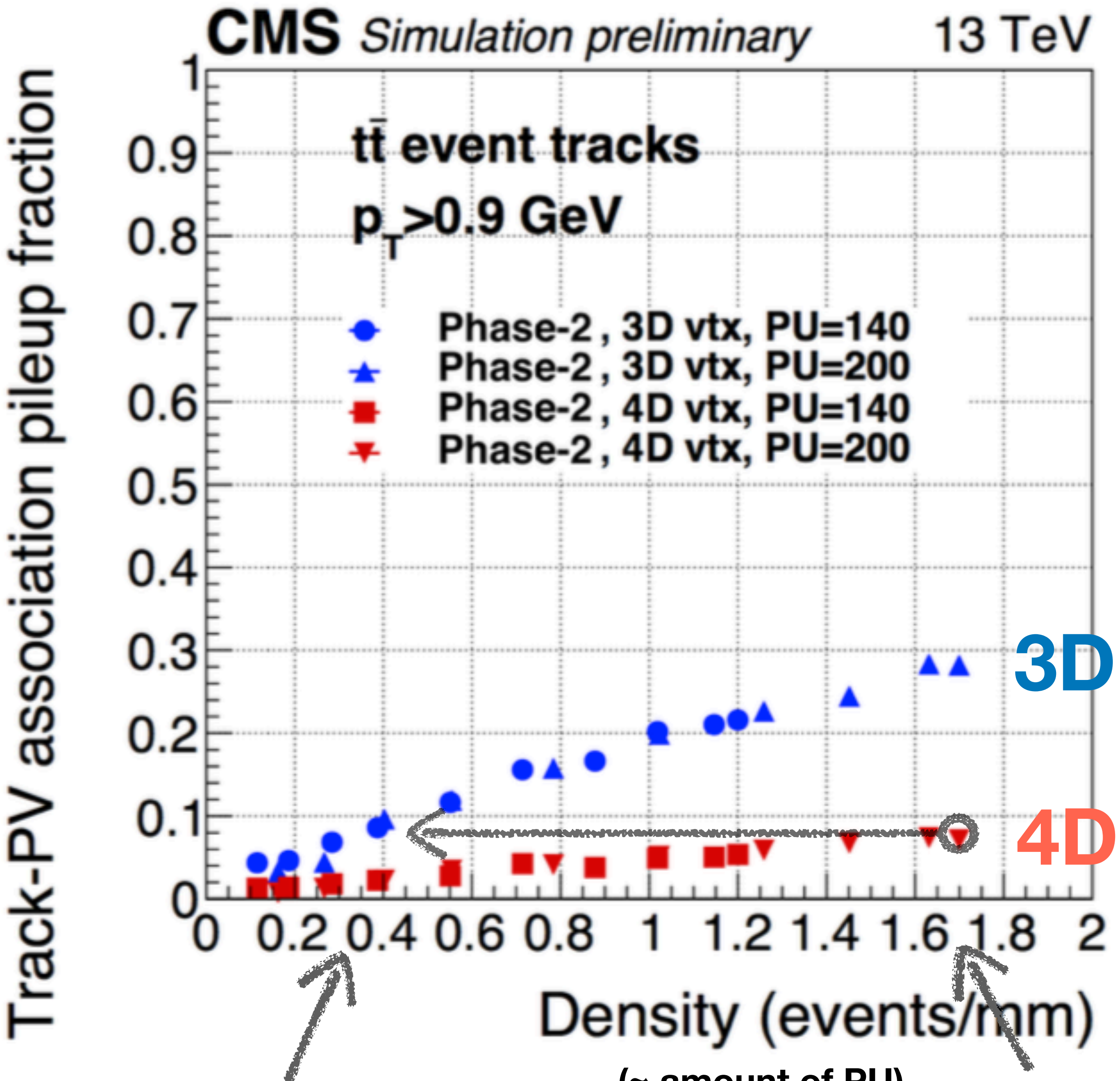


- 3D reconstruction cannon distinguish two vertices on the same z.
- 4D reconstruction can.
  - Interactions spread in time, RMS ~ 200ps.
  - Having time resolution of 30ps, "effective PU" is reduced to current LHC-level

Figures can be found in LHCC-P-009, "*TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE*"

Timing information for PU rejection

4D vertex reconstruction by adding time information



3D vertex

4D vertex

(~ amount of PU)

current LHC

HL-LHC

- 3D reconstruction cannon distinguish two vertices on the same z.
- 4D reconstruction can.
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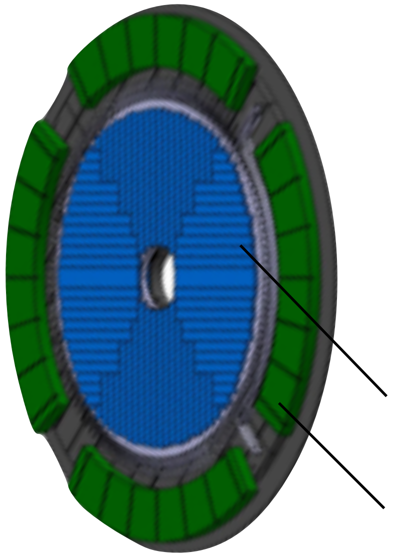
Timing dedicated sub-detectors

Aiming at O(30)ps precision timing for MIPs.

ATLAS : High-Granularity Timing Detector



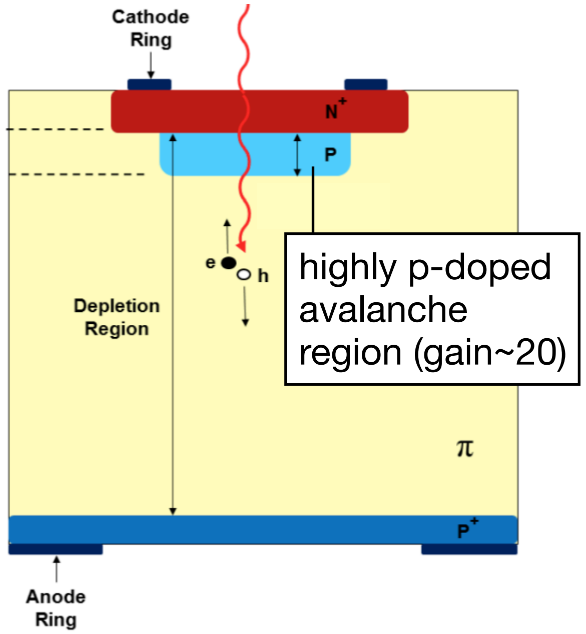
$2.4 <|\eta|<4.0$

In front of the Endcap calorimeter cryostat

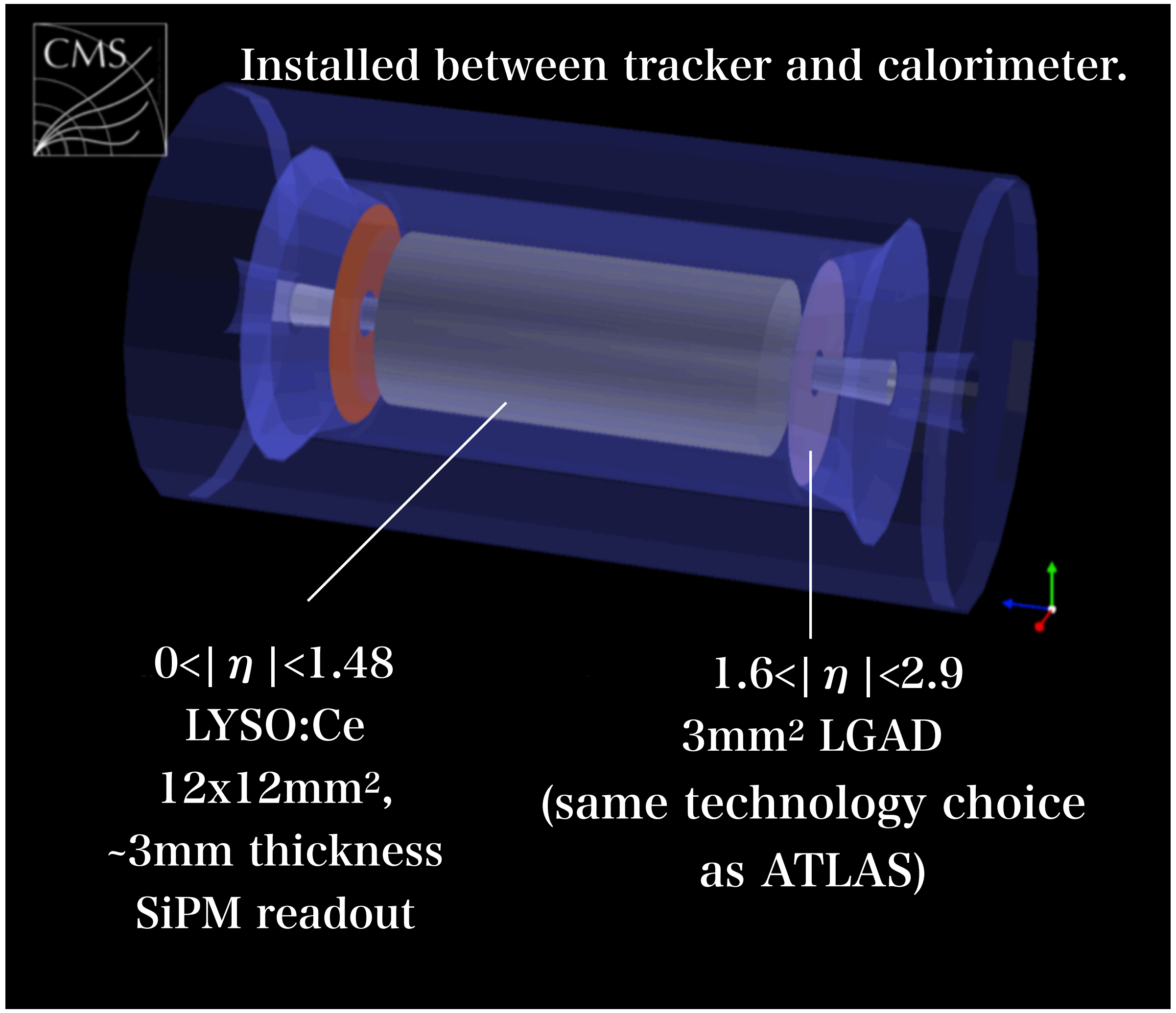
Low Gain Avalanche Detector (LGAD)

50um thickness,

1.3x1.3mm^2 pixels



CMS : MIP Timing Detector



Installed between tracker and calorimeter.

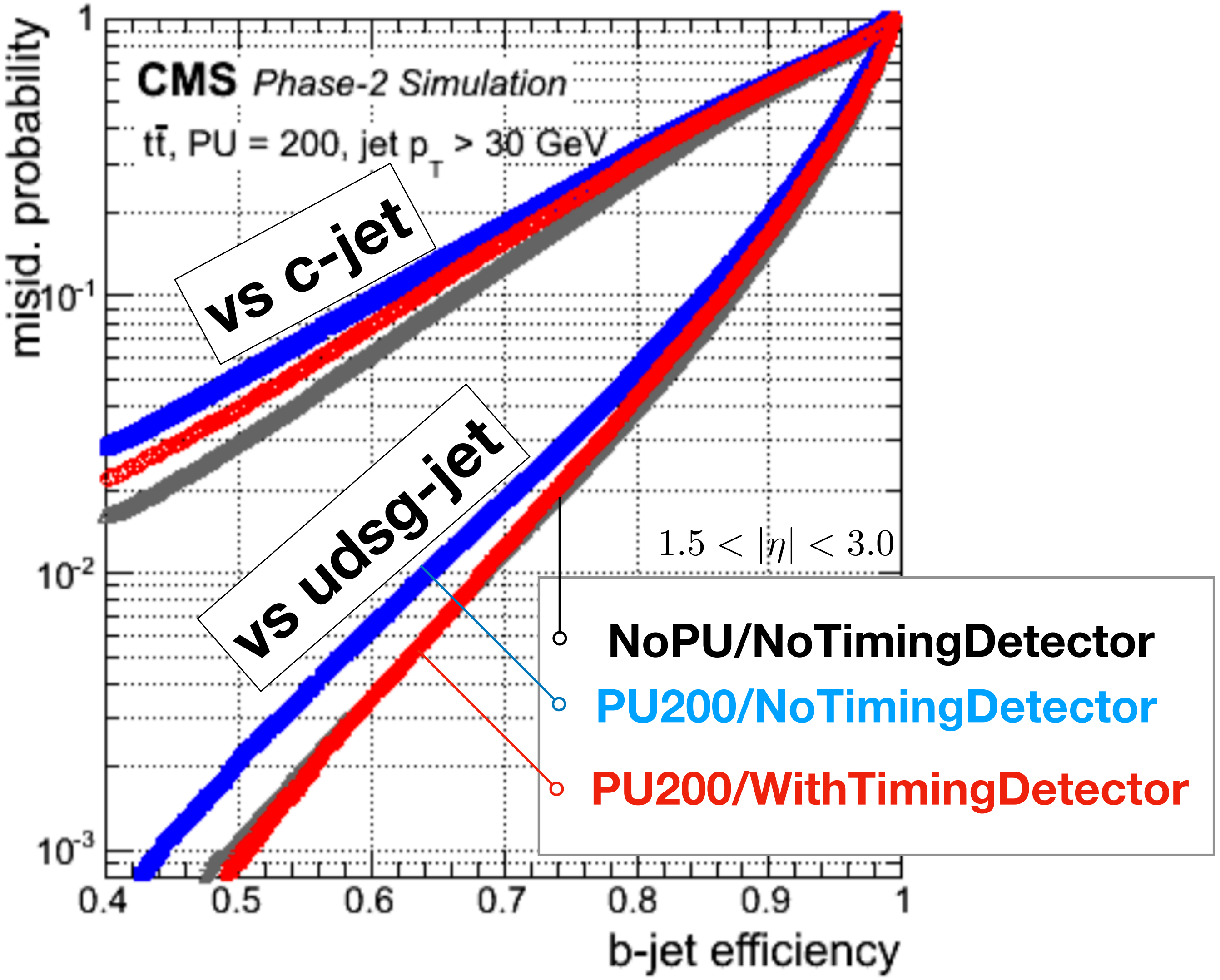
$0<|\eta|<1.48$
LYSO:Ce
12x12mm^2,
~3mm thickness
SiPM readout

$1.6<|\eta|<2.9$
3mm^2 LGAD
(same technology choice as ATLAS)

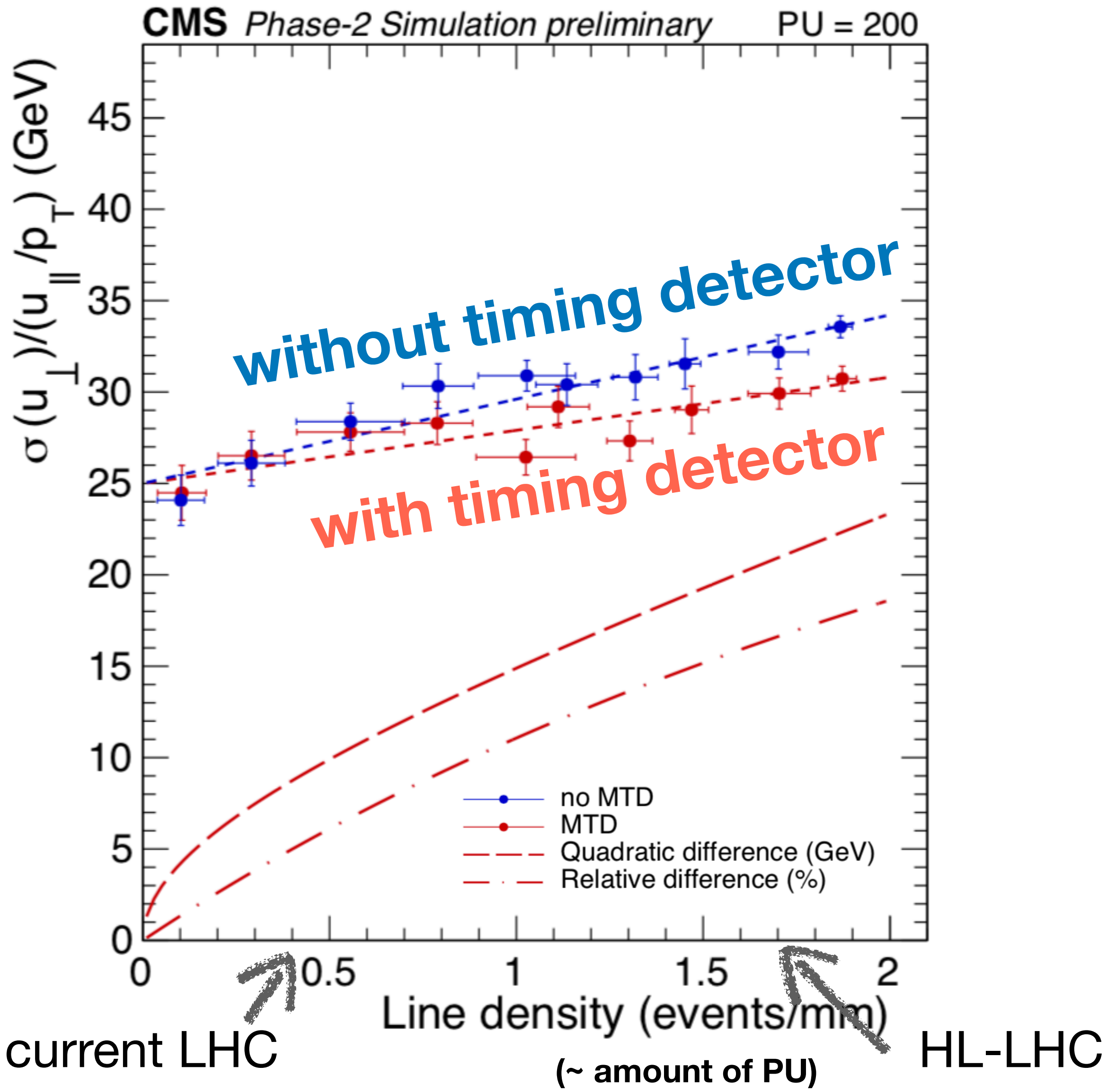
Figures can be found in LHCC-P-009 (CMS) and ATL-LARG-PROC-2018-003 (ATLAS)

Improvement by timing information

b-tagging performance



MET resolution



The timing detectors mitigates the impact of 200 PU,
and those improvements propagate to analysis performance.

Figures can be found in LHCC-P-009

Summary

As PU increases, more powerful PU mitigation is required.

More and more sophisticated techniques deployed.

- Various PU mitigations at constituent level improve JER by 20% at PU=200 compared to mitigation at jet level only.
- Particle-flow (ATLAS) and PUPPI with particle-flow (CMS) deployed.
- Forward PU ID tagging with PT balance is promising.

Improvement from detector side is also mandatory.

Timing detector with 30 ps resolution— HGTD in ATLAS and MTD in CMS —will reduce the impact of PU at HL-LHC to the current level.

By combining of the efforts from the two sides, we will be able to fully exploit the high statistics LHC data up to 200 PU.

QCD@LHC
Dresden, August 2018

Pileup modelling and mitigation at the LHC

A theorist's view

Matteo Cacciari
LPTHE Paris
Université Paris Diderot

The challenge

Events in proton-proton often contain many particles (underlying event, pileup, ...) largely **unrelated** with the the hard collision of interest

From the point of view of a jet, this translates into **soft, large-angle radiation** unrelated with its fundamental structure, that one must remove in order to facilitate **precision measurements**, and/or **tag** relevant features

(aim: limit contamination from background while retaining bulk of perturbative radiation)

Pilup mitigation

In order to mitigate pileup, you can

subtract, or

groom, or

(machine) learn.

(Or any combination of these)

See review by G. Soyez, 1801.09721

Subtraction

The estimated contamination from pileup (or underlying event) is **subtracted directly at the observable level** (e.g. the p_t of a jet or the value of a jet shape)

- Examples:
  - $\mathbf{p_t^{sub} = p_t^{raw} - \rho A}$ (MC, Salam 0707.1378)
  - Analytical calculations of susceptibility for selected jet shapes (Sapeta et al. 1009.1143, Alon et al. 1101.3002)
  - Moments of jet fragmentation functions (MC, Quiroga, Salam, Soyez, 1209.6086)
  - Generic (numerical) approach to susceptibility determination for any shape (Soyez et al. 1211.2811)
  - Cleansing (Krohn, Schwartz, Low, Wang, 1309.4777)
  - Neutral-proportional-to-Charged (MC, Salam, Soyez 1404.7353)
  - ....

Glossary

Grooming

Action is taken directly **at the constituent level.** Declustering or clustering differently in case of a jet, or acting on the full event at the particle level.

NB. I am now **extending** the "grooming" nomenclature (see Marzani's talk) to pileup mitigation methods that act directly at the level of the constituents (i.e. particles, calorimeter cells, tracks,...)

- Examples:
  - MDT/Filtering (Butterworth et al. 0802.2470), trimming (Krohn, Thaler, Wang, 0912.1342), pruning (S.Ellis et al, 0903.5081), Soft Drop (Larkoski, Marzani, Soyez, Thaler, 1402.2657)
  - CMS Voronoi method (Lai, unpubl., circa 2013)
  - Constituent Subtraction (Berta, Spousta, Miller, Leitner, 1403.3108)
  - PUPPI (Bertolini, Harris, Low, Tran, 1407.6013)
  - SoftKiller (MC, Salam, Soyez, 1407.0408)
  - VoronoiKiller (Salam, Soyez, unpubl. 1801.09721), Voronoi Subtraction (ATLAS-CONF-2017-065)
  - ....

Machine Learning

Machine learning (a.k.a. artificial intelligence) techniques are used to **perform a regression task**, estimating the pileup and subtracting the expected contamination

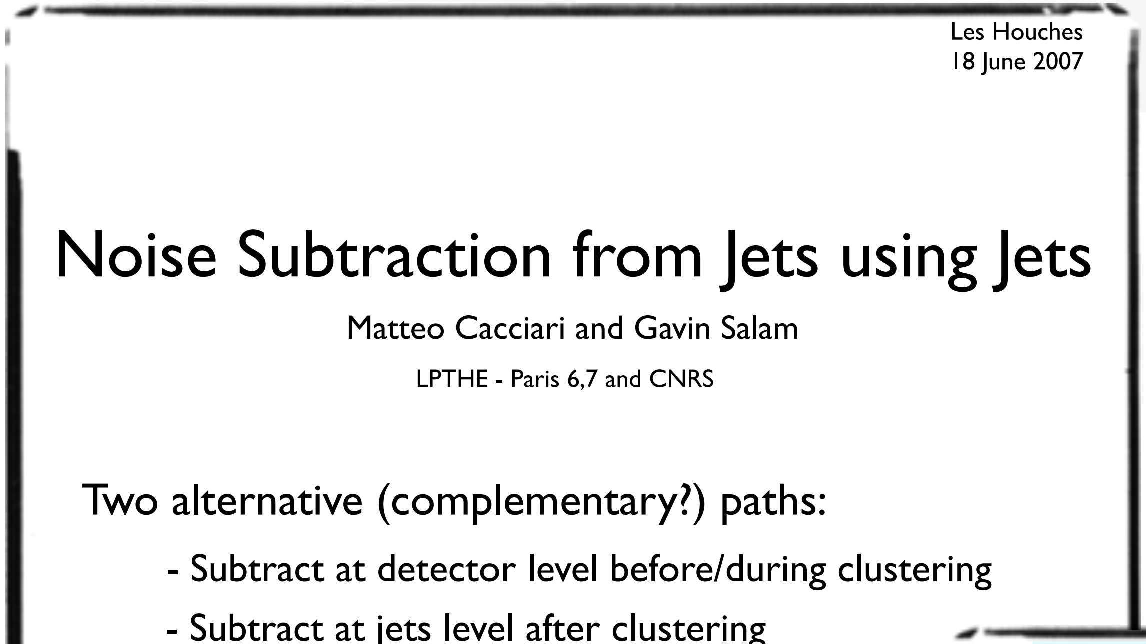
(NB this is different from - and ostensibly harder than - a classification task, used for instance in tagging. Classification estimates a 'label', regression estimates a 'quantity')

- Examples:
  - A number of papers studying classification tasks, aiming at tagging and quark/gluon discrimination (1511.05190, 1603.09349, 1609.00607, 1701.08784, 1612.01551,...)
  - Pileup mitigation with Machine Learning (PUMML) (Komiske et al. 1707.08600)
  - California Science & Engineering Fair project (high school students) (Milan Ganai, http://csef.usc.edu/History/2018/Projects/S1807.pdf)
  - ...

Subtraction

ρA Subtraction

0707.1378



Les Houches
18 June 2007

Noise Subtraction from Jets using Jets

Matteo Cacciari and Gavin Salam

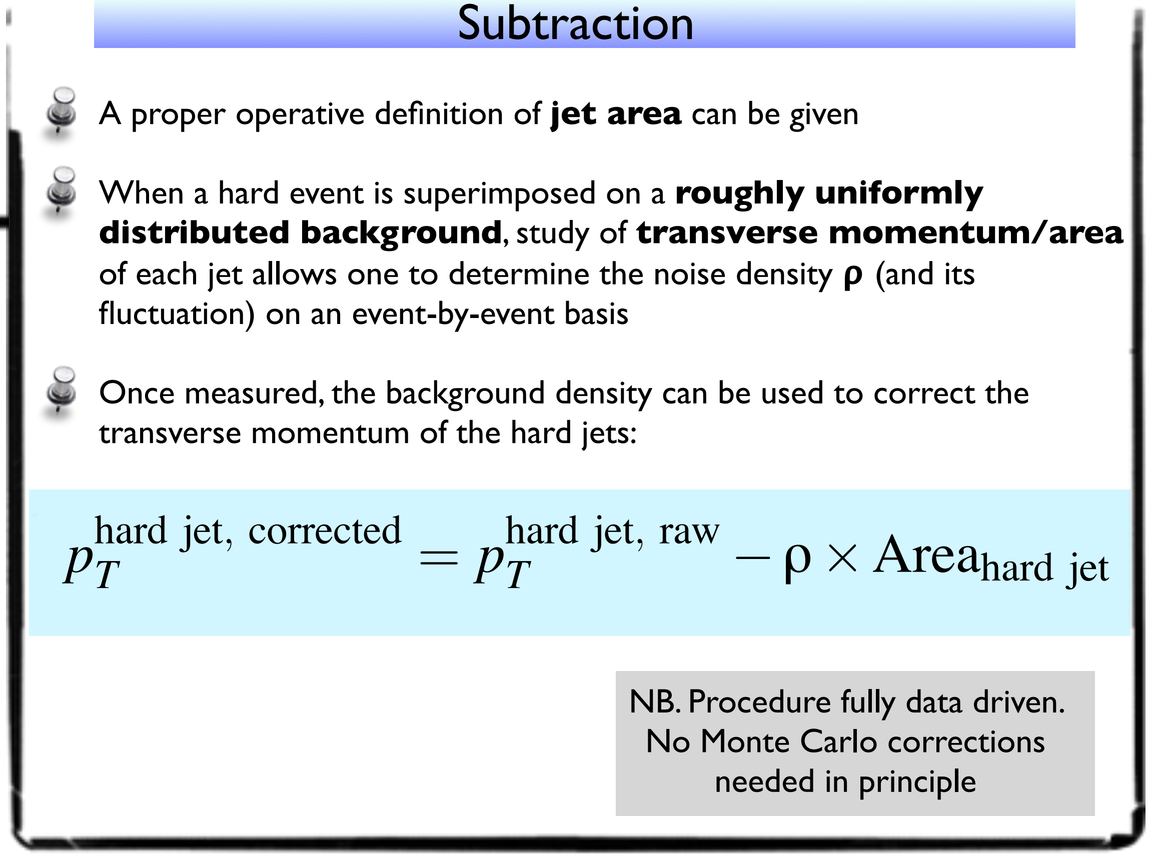
LPTHE - Paris 6,7 and CNRS

Two alternative (complementary?) paths:

- Subtract at detector level before/during clustering
- Subtract at jets level after clustering

First introduced
at Les Houches 2007.
Also called ‘area-median’

Early hint of separation between ‘grooming’ and ‘subtraction’ approaches



Subtraction

- A proper operative definition of **jet area** can be given
- When a hard event is superimposed on a **roughly uniformly distributed background**, study of **transverse momentum/area** of each jet allows one to determine the noise density **ρ** (and its fluctuation) on an event-by-event basis
- Once measured, the background density can be used to correct the transverse momentum of the hard jets:

$$p_T^{\text{hard jet, corrected}} = p_T^{\text{hard jet, raw}} - \rho \times \text{Area}_{\text{hard jet}}$$

NB. Procedure fully data driven.
No Monte Carlo corrections
needed in principle

ρA Subtraction

Two components:

1. Determine **ρ**, the pileup transverse momentum density
2. Subtract **ρA** from the jet p_t

The second step is **exact**, because the **jet area** is defined (and calculated) as the **susceptibility** of a jet's p_t to contamination from an approximately uniform background

This can lead to an **unbiased** subtraction$^{(*)}$ **IF** ρ has been estimated correctly. This makes area subtraction a convenient benchmark that other methods can compare to.

(*) Up to backreaction effects (0802.1188)

ρ estimation

Initial suggestion for ρ estimation:

$$\rho \equiv \text{median}\left[\left\{\frac{p_t^{jet}}{\text{Area}_{jet}}\right\}\right]$$

Median over patches of reasonable size'

Potential issues :

- jets must be kt or C/A. Hence need to recluster if using anti-kt ==> time consuming
- ρ varies slightly over the phase space, in rapidity and (in case of flow in heavy ion collisions) also azimuth

Solution exist since a long time:

- Use FastJet's `GridMedianBackgroundEstimator`, it uses patches and does not cluster ==> much faster
- rescale ρ with appropriate rapidity or azimuth variation to compensate for known variations

These fixes can improve considerably the performance of area subtraction. Nevertheless, new methods are often compared to naive area subtraction, possibly artificially enhancing their own improvements

Beyond transverse momentum

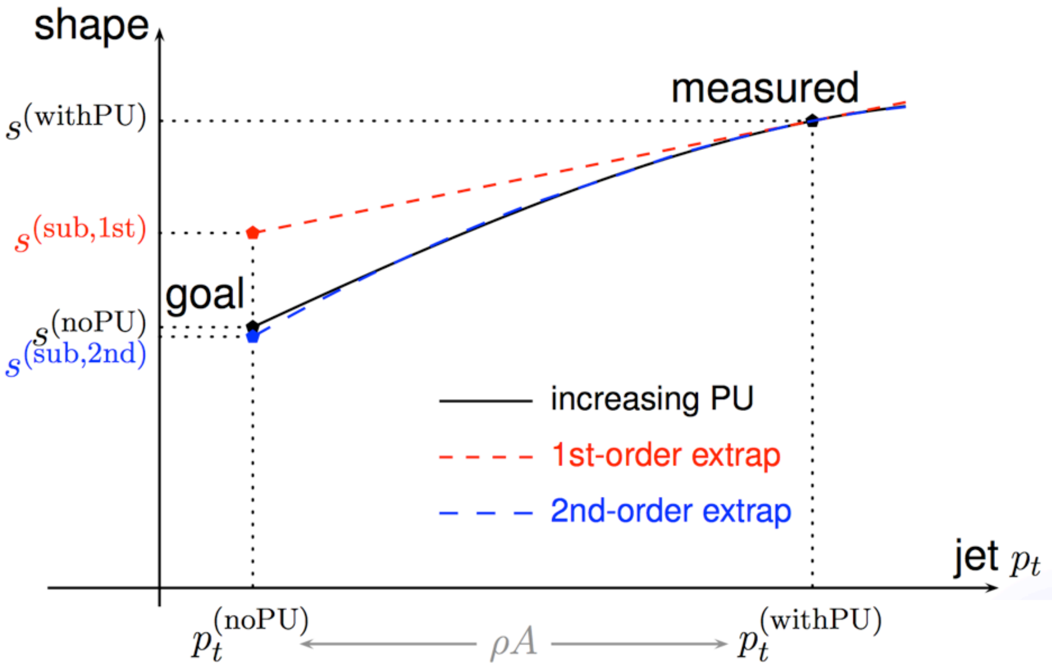
$p_t - \rho A$ only applies to transverse momentum subtraction.
What about other observables (e.g. jet shapes?)

- One can calculate effect of pileup contamination for individual observables (Sapeta et al. 1009.1143, Alon et al. 1101.3002, MC, Quiroga, Salam, Soyez, 1209.6086, ...).
Time consuming and potentially complicated

- Alternatively, generalise the ρA subtraction method (Soyez et al, 1211.2811)

Numerical jet shape correction

Soyez et al. 1211.2811



A generic **jet shape** (a function of the momenta of all constituents of a jet) is modified by the addition of pileup

Correct it by calculating numerically the derivatives that enter its Taylor expansion and subtracting (this generalises the jet area/median subtraction for transverse mom.)

Pileup momentum density

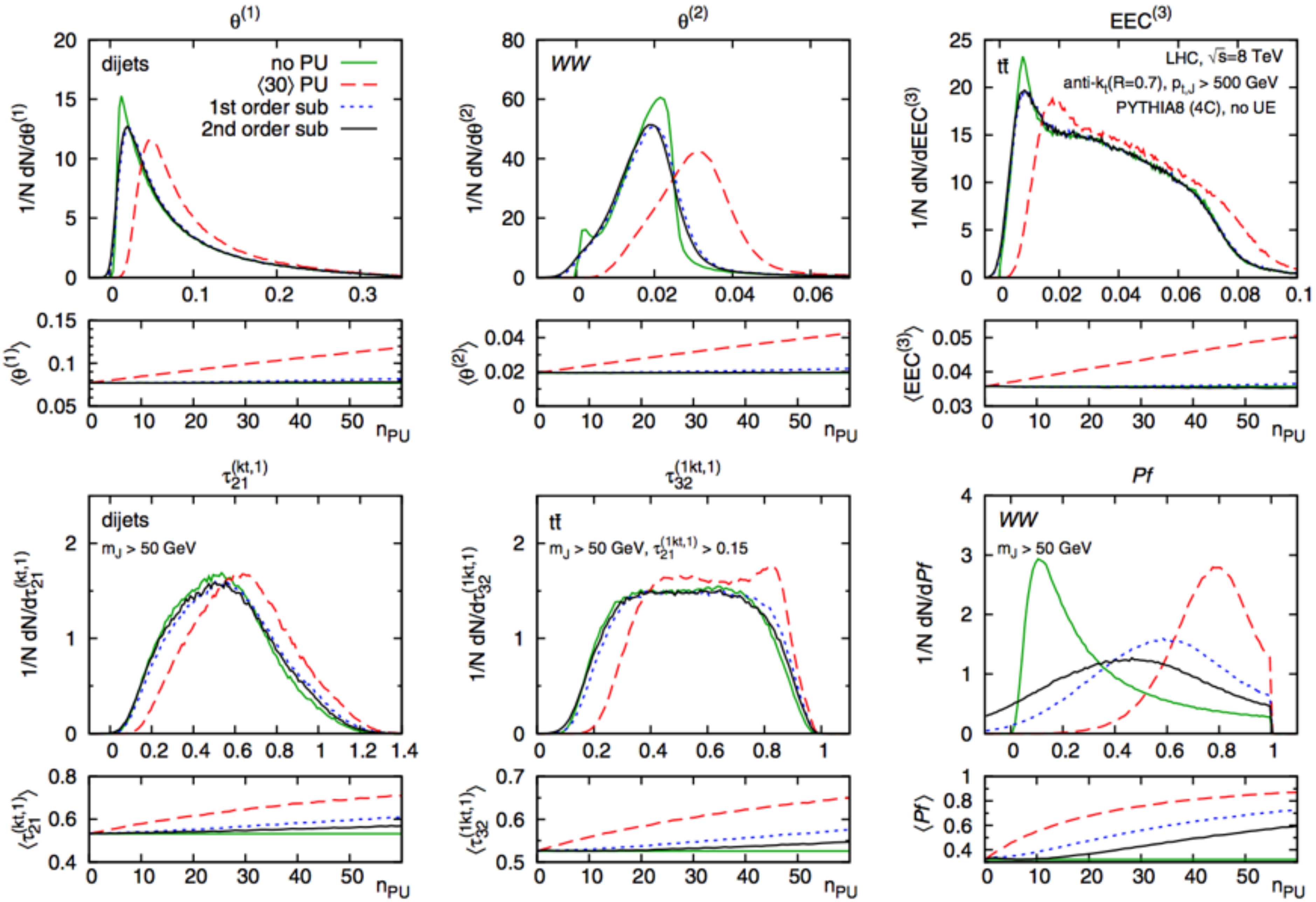
Numerical derivatives w.r.t. ghosts momenta

$$V_{\mathrm{jet,sub}} = V_{\mathrm{jet}} - \rho V_{\mathrm{jet}}^{[1]} + \frac{1}{2}\rho^2 V_{\mathrm{jet}}^{[2]} + \cdots$$

[Actual formula slightly more complex due to taking into consideration the possibility of having massive particles in pileup]

Numerical jet shape correction

Soyez et al. 1211.2811



Shortcomings of subtraction

While a useful reference because potentially unbiased, subtraction methods suffer from a number of shortcomings

- general shape subtraction is numerically cumbersome
- it only works for IRC-safe observables, while interests of pileup mitigation go beyond these (lepton isolation, MET, ...)
- because of pileup fluctuations the dispersion of the corrected quantity inevitably scales like $\sqrt{N_{PU}}$, becoming large for high pileup levels
- No use is made of additional information available to experiments (e.g. charged tracks coming from secondary vertices) (but one can use area-subtraction after Charged Hadron Subtraction)

Grooming

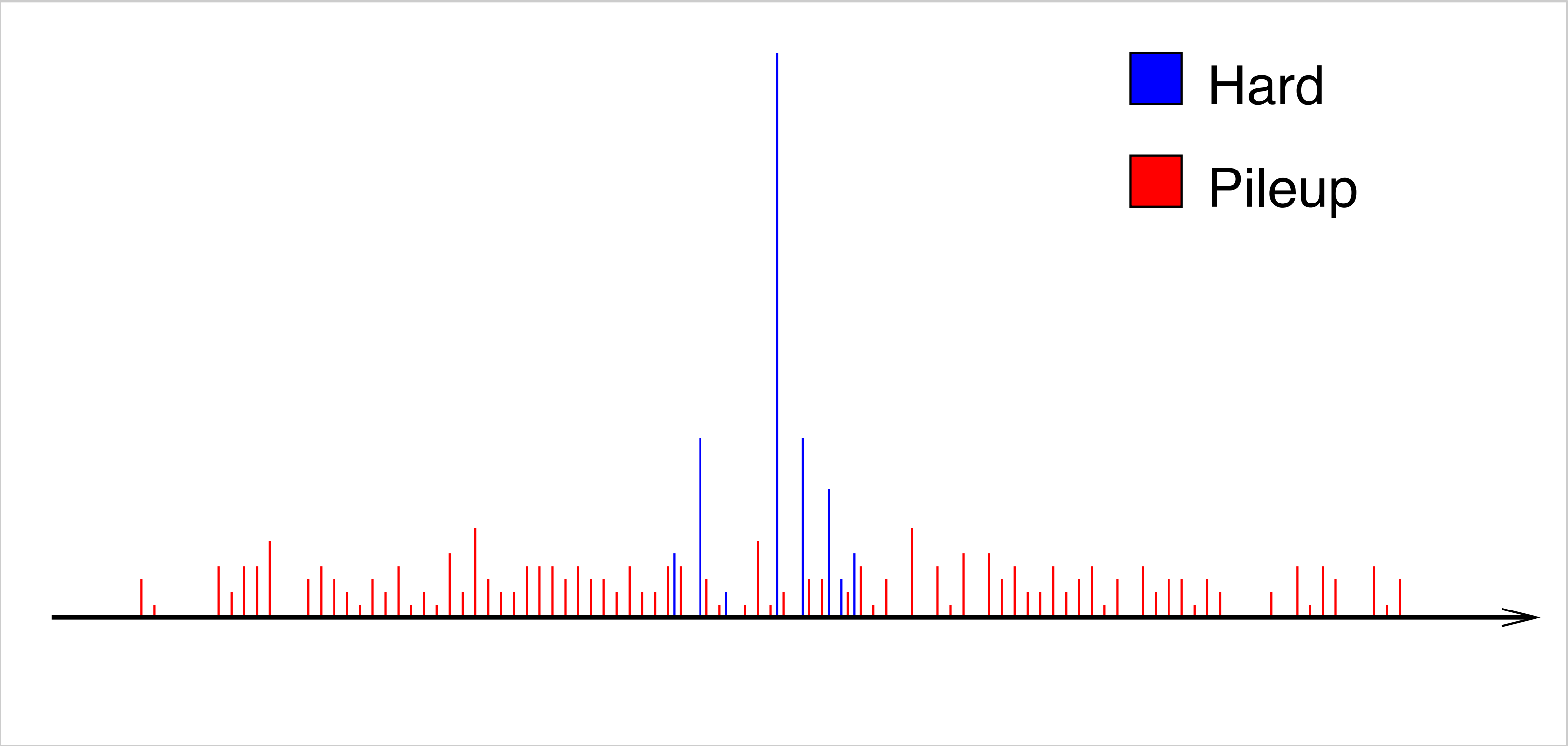
Event groomers

Consider two of the particle-based methods that are often used today, i.e. **SoftKiller** and **ConstituentSubtractor**

In both cases, they eliminate from the event particles whose transverse momentum scale makes them suspect of being of pileup origin. They also both have a distance scale as a tunable parameter.

Differently from area subtraction methods, these methods are not naturally unbiased and must be tuned. They advantage resides in being fast, in leading to smaller dispersions (because they reduce the numbers of particles), and even in producing ‘cleaned’ events that are faster to cluster (again, because they contain fewer particles)

An event: particle level



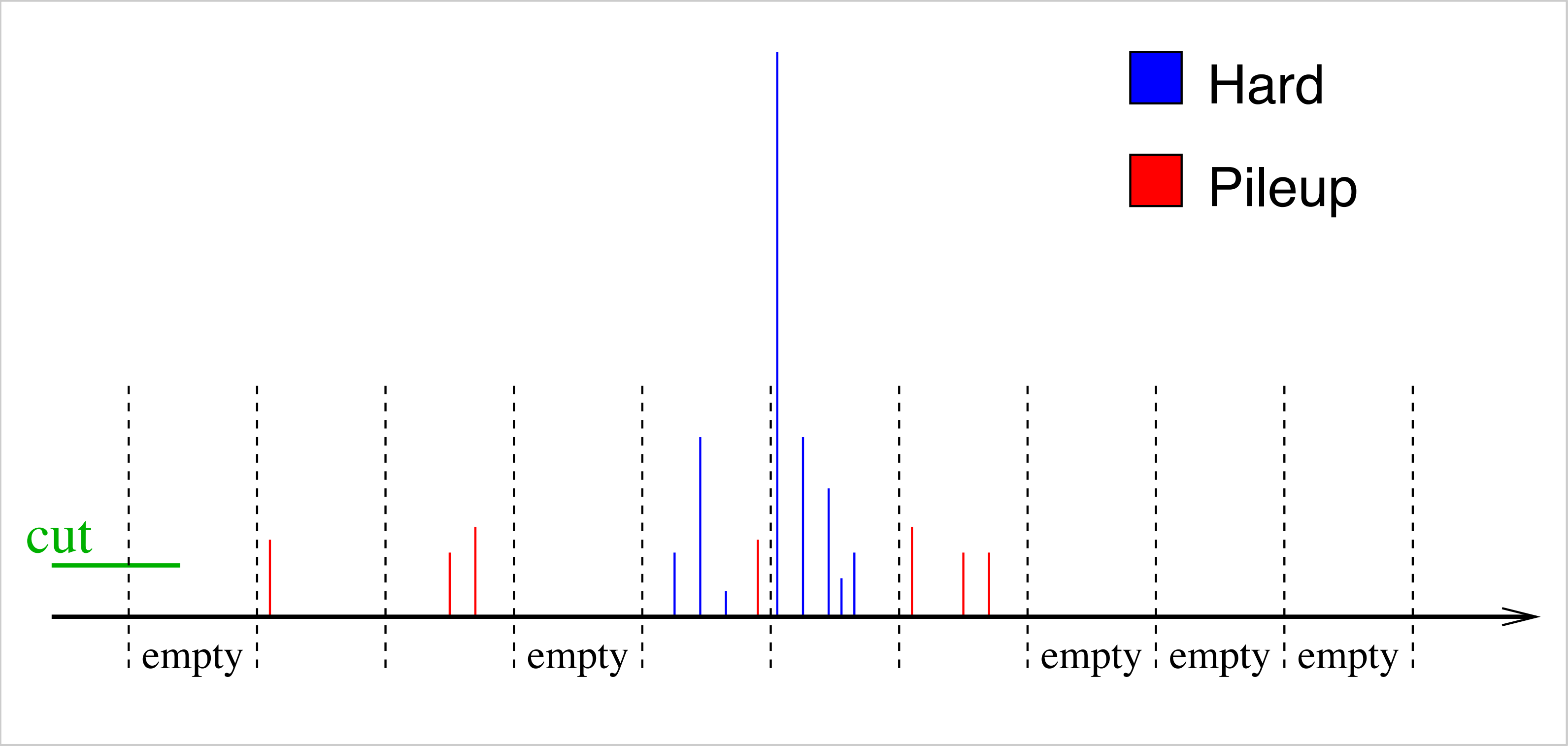
G. Soyez

Soft Killer introduces a **particle momentum cut** such that the median momentum density (ρ) of the event is zero

Constituent Subtractor subtracts each constituent using iterative **local pairings to ghosts** whose momentum is set by ρ

Soft Killer

MC, Salam, Soyez, 1407.0408



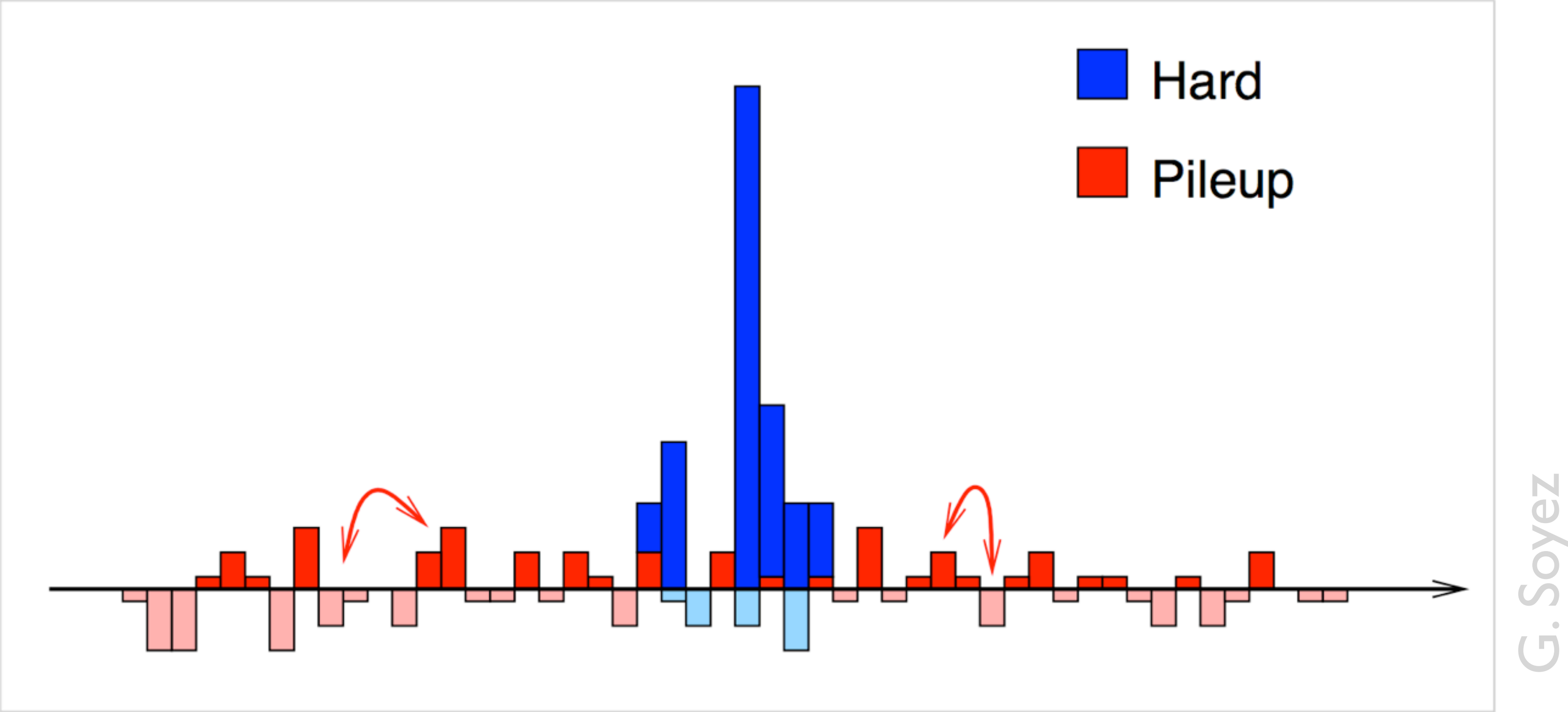
G. Soyez

Half of the event is empty ⊠ **ρ = 0** (because it’s the median)

NB. SK needs tuning of the size of the patches used to calculate ρ.
0.4 was found to be a good choice for R=0.4 jets

Constituent Subtractor

Berta, Spousta, Miller, Leitner, 1403.3108

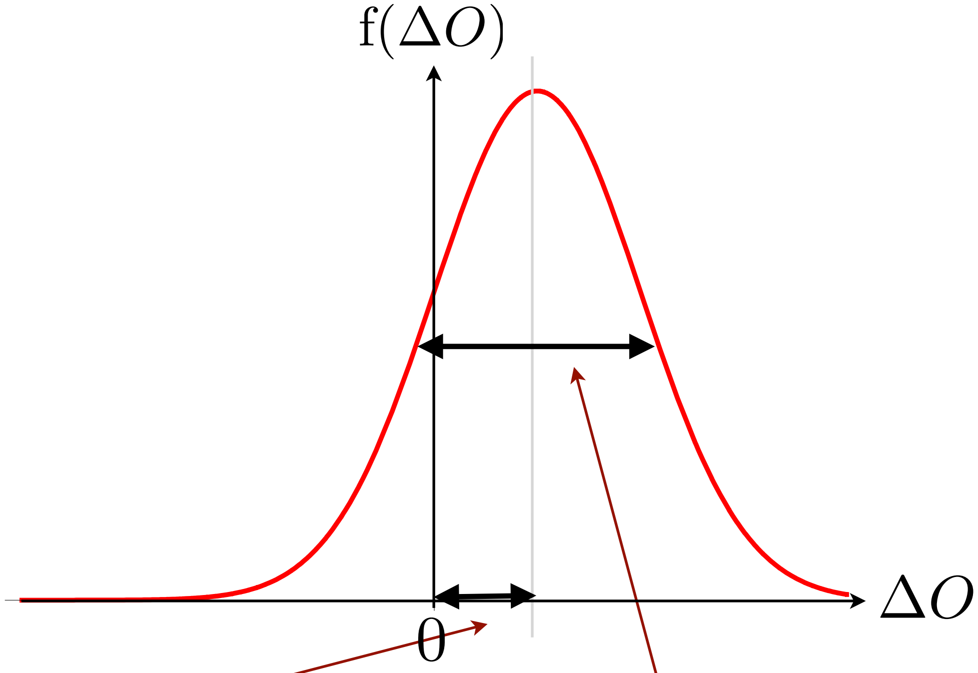


Constituent Subtractor uses local pairings to ghosts to subtract iteratively momentum from constituents, reshuffling it to ghosts when oversubtracting, so as to maintain overall balance. Can also be applied jet-by-jet.

A recent update introduces rapidity-azimuth rescaling for ghosts and an iterative version (CS applied multiple times) that performs better

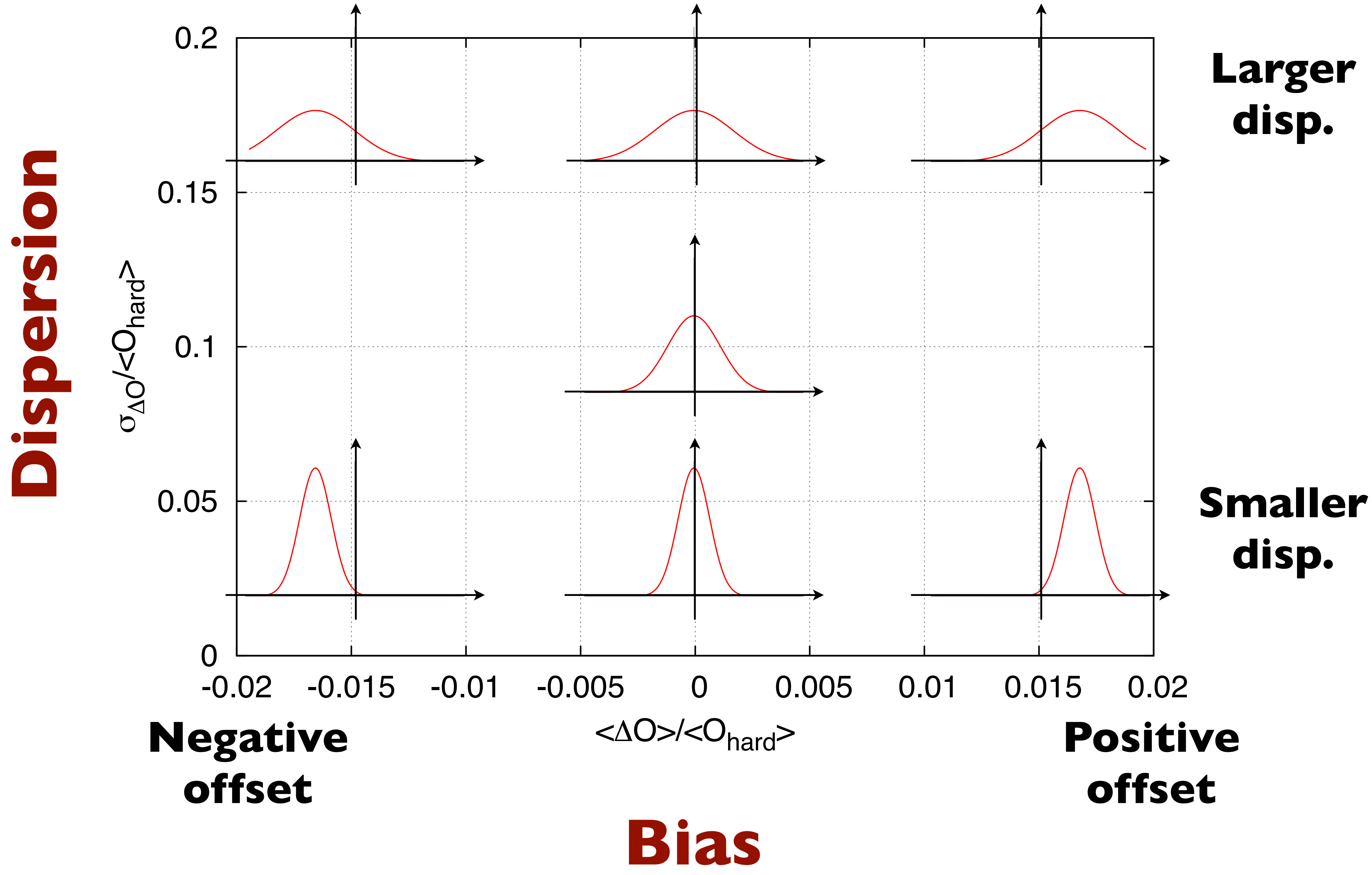
Quality measures

Given an observable *O*, define quality measures for pileup subtraction in terms of **average offset ⟨ΔO⟩** and **dispersion σ_{ΔO}**

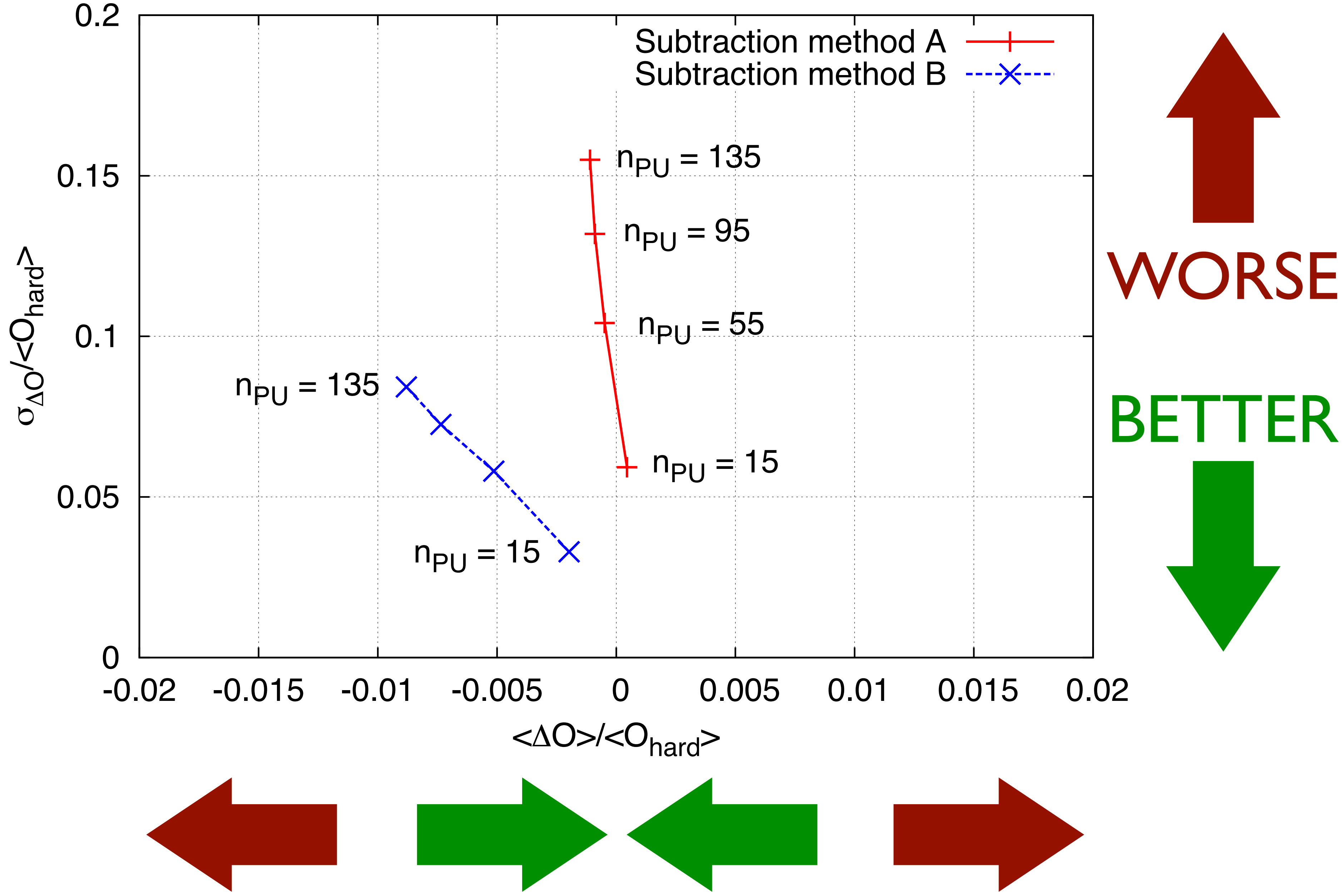


$$\langle \Delta O \rangle \equiv \langle O^{\mathrm{sub}} - O^{\mathrm{hard}} \rangle \qquad \sigma_{\Delta O} = \langle \Delta O^2 \rangle - \langle \Delta O \rangle^2$$

Representation of quality measures



Representation of quality measures



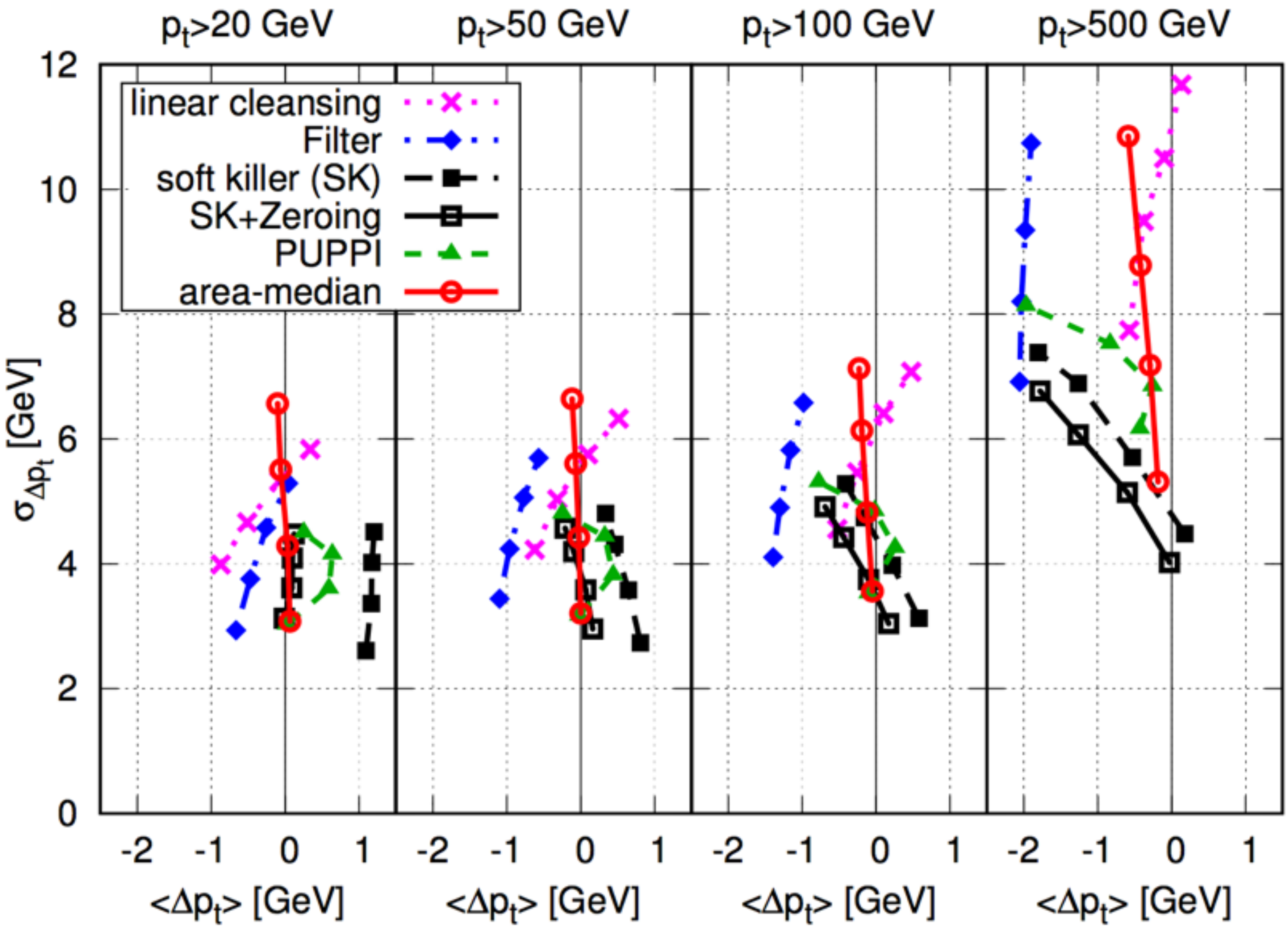
WORSE

BETTER

Comparisons

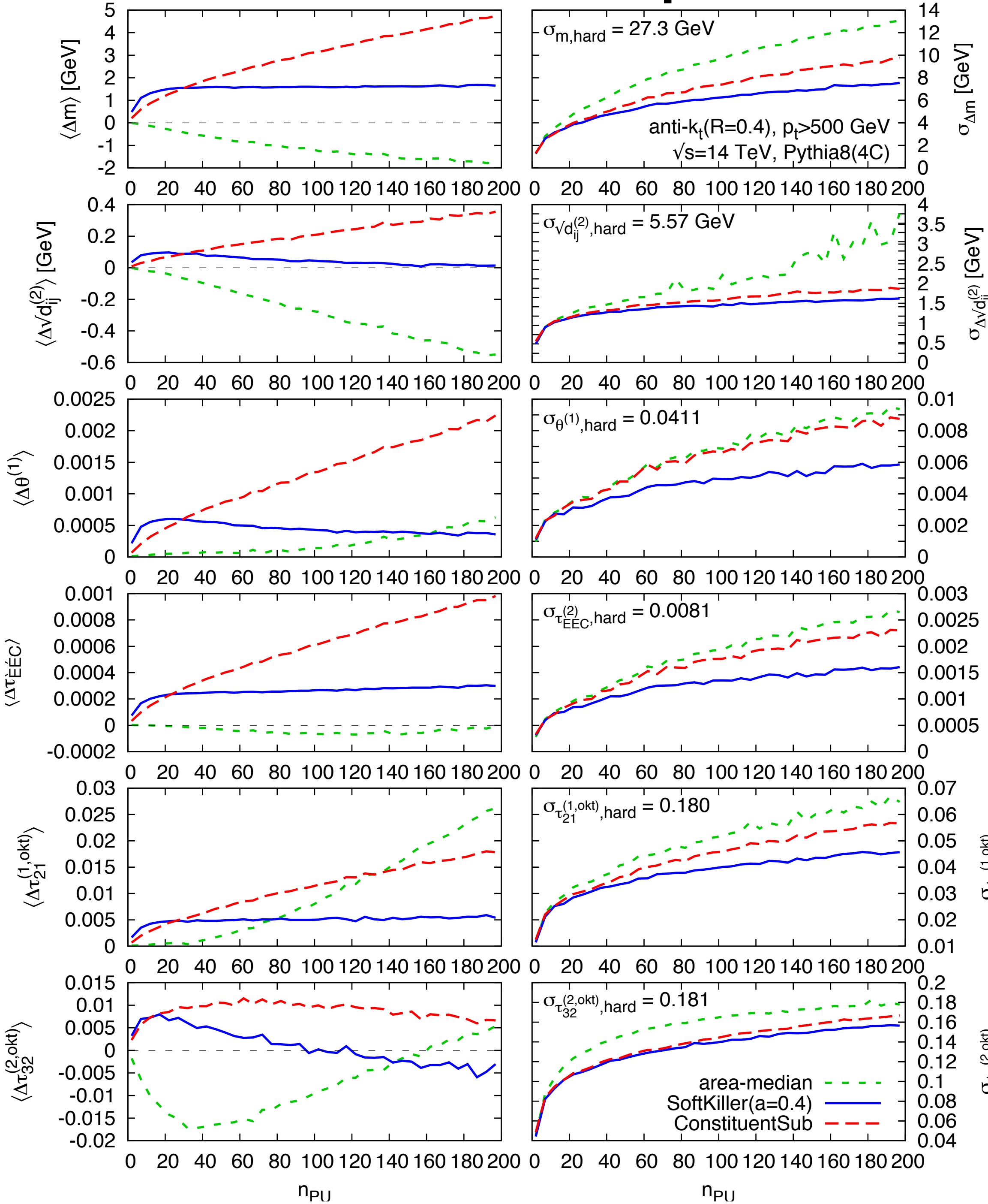
(After Charged Hadron Subtraction)

Soyez 1801.09721



Comparisons

Bias Dispersion



Area-median

Soft Killer

Constituent Subtractor

Various jet shapes:

- jet mass
- kt clustering scale
- jet width (= broadening, = girth)
- energy-energy correlation moment
- τ_{21} and τ_{32} N-subjettiness ratios

Examples in HI collisions

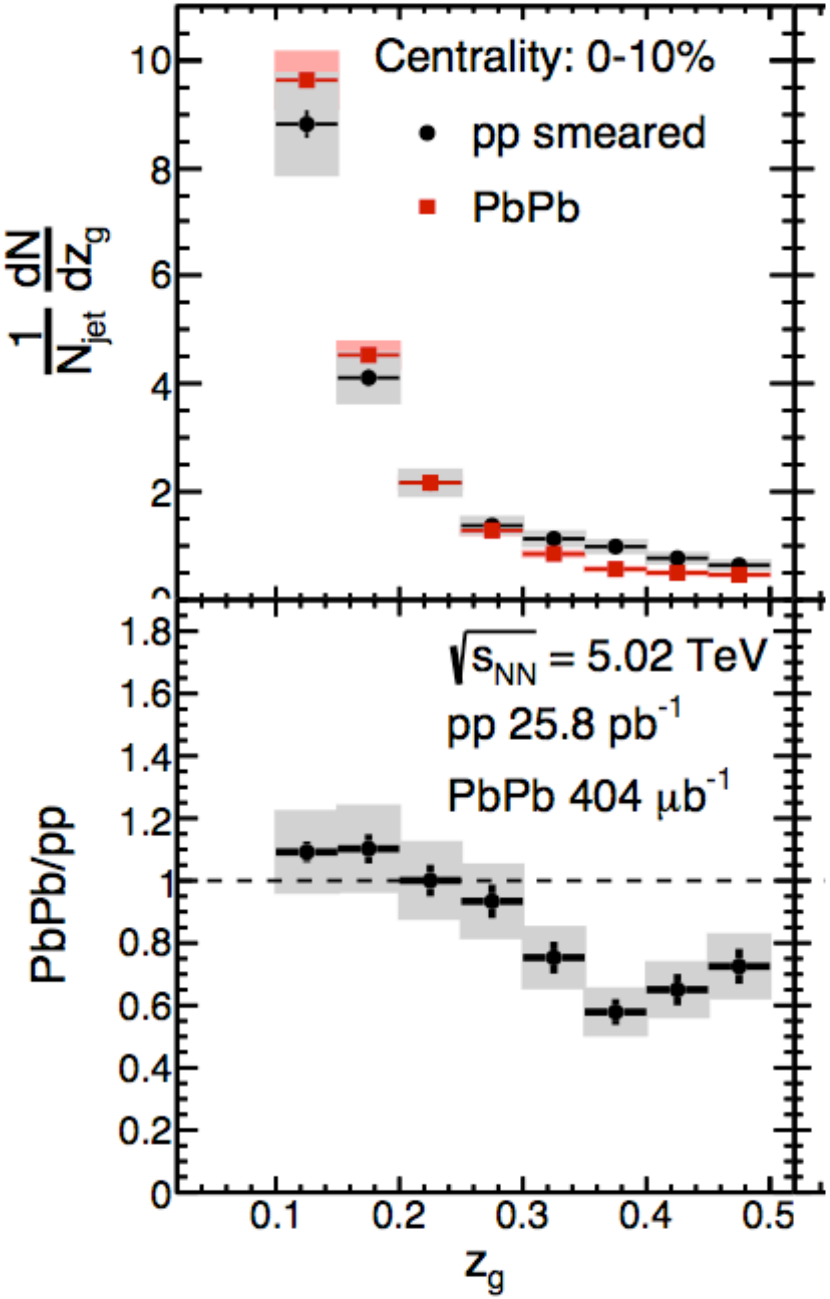
Events in heavy ion collisions are characterized by a huge background

(ρ~250 GeV in central collisions PbPb at LHC, to be compared with ρ~3 GeV for the underlying event in pp, and ρ~0.7 GeV/vertex for pileup)

This needs to be subtracted, but one must keep in mind that the subtraction becomes part of the definition of the observable, because in HI there's no 'ideal' situation without the background.
Hence, handle with care!

CMS splitting function

CMS PAS HIN-16-006



CMS has measured the momentum fraction of the 'first splitting',

$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

Definition:
reduction of event using **Constituent Subtractor**, then grooming using **Soft Drop (β=0, z_{cut}=0.1)**

ALICE jet shapes

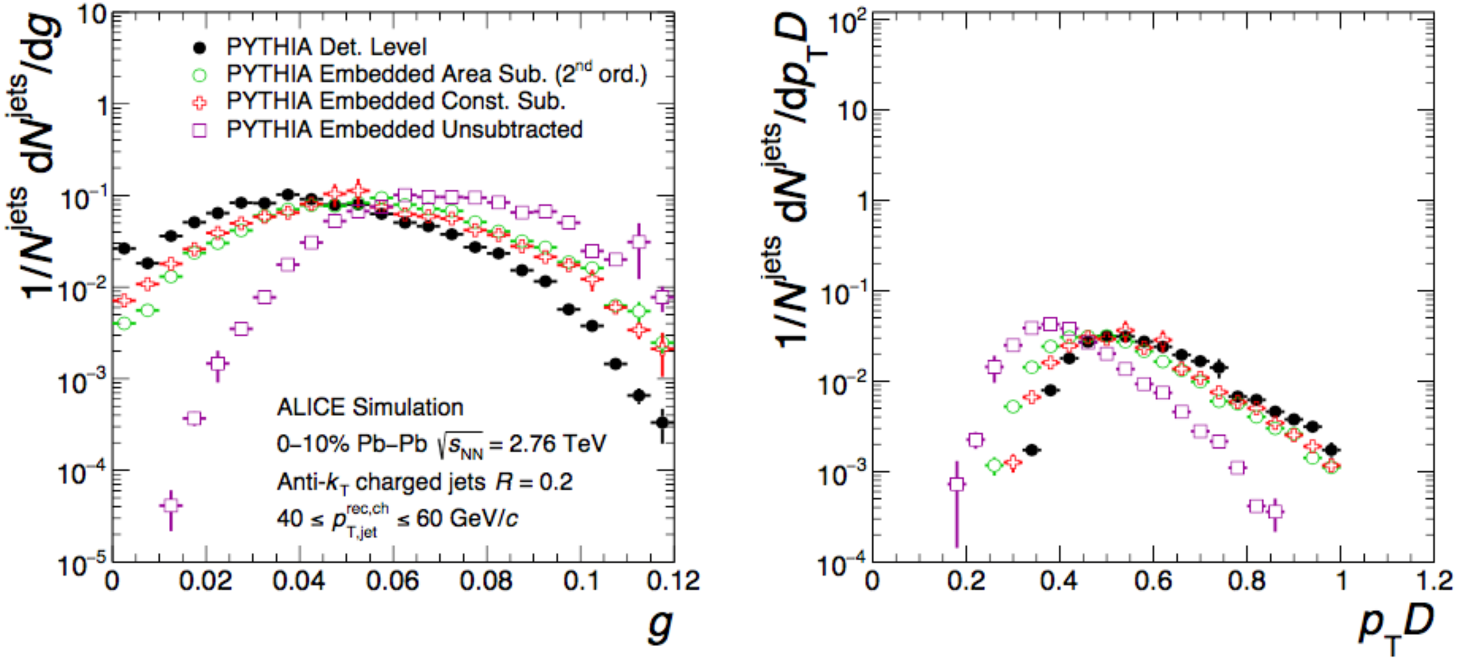
ALICE has studied the first radial moment and the second moment of the constituent momentum distribution in jets

$$g = \sum_{i\in jet} \frac{p_{\mathrm{T}}^{\mathrm{i}}}{p_{\mathrm{T,jet}}} |\Delta R_{\mathrm{i,jet}}|$$

$$p_T D = \frac{\sqrt{\sum_{i\in jet} p_{\mathrm{T,i}}^2}}{\sum_{i\in jet} p_{\mathrm{T,i}}}$$

Tests of background subtraction

1807.06854



Approach: **numerical area-median** correction for shapes, cross-checked with **Constituent Subtraction**, plus unfolding

ALICE jet shapes

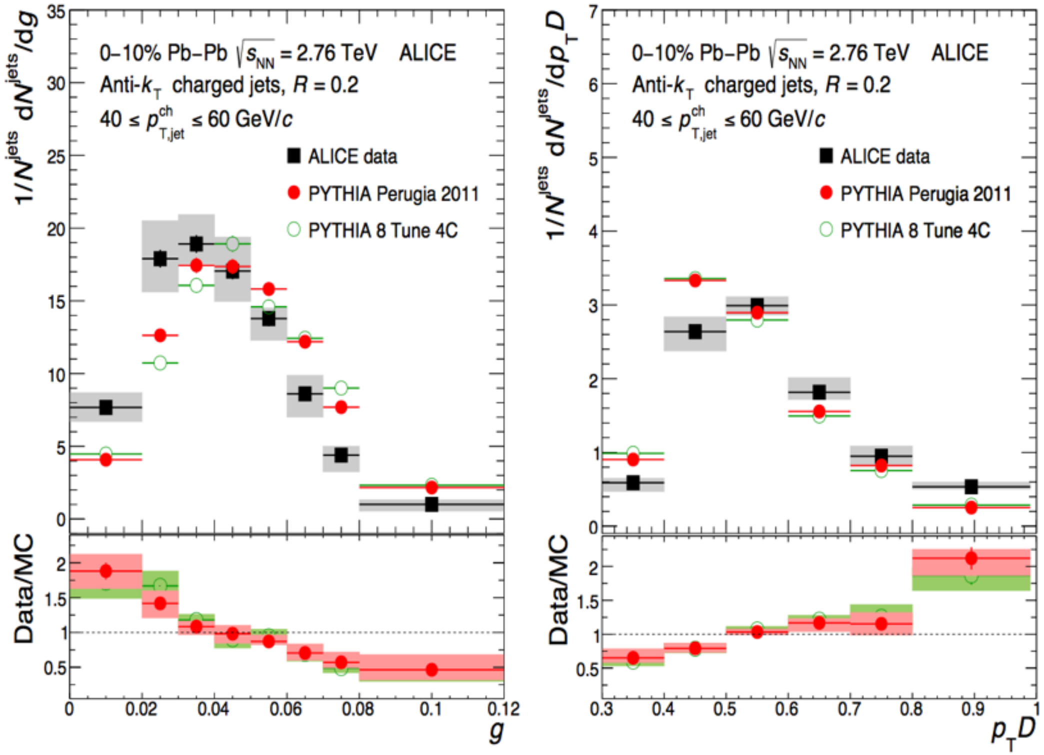
ALICE has studied the first radial moment and the second moment of the constituent momentum distribution in jets

$$g = \sum_{i\in jet} \frac{p_{\mathrm{T}}^{\mathrm{i}}}{p_{\mathrm{T,jet}}} |\Delta R_{\mathrm{i,jet}}| \qquad p_T D = \frac{\sqrt{\sum_{i\in jet} p_{\mathrm{T,i}}^2}}{\sum_{i\in jet} p_{\mathrm{T,i}}}$$

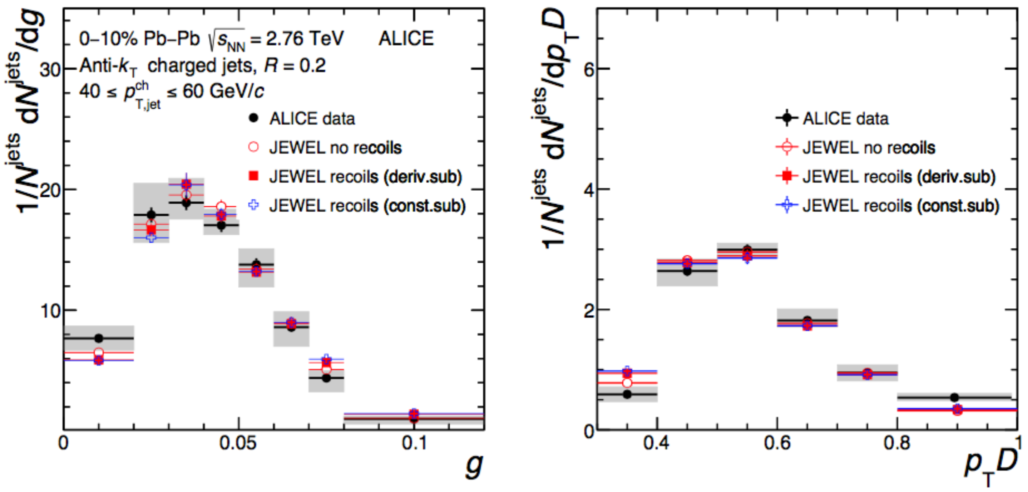
Measurements in PbPb

1807.06854

Comparison to PYTHIA (pp)



Comparison to JEWEL (PbPb)

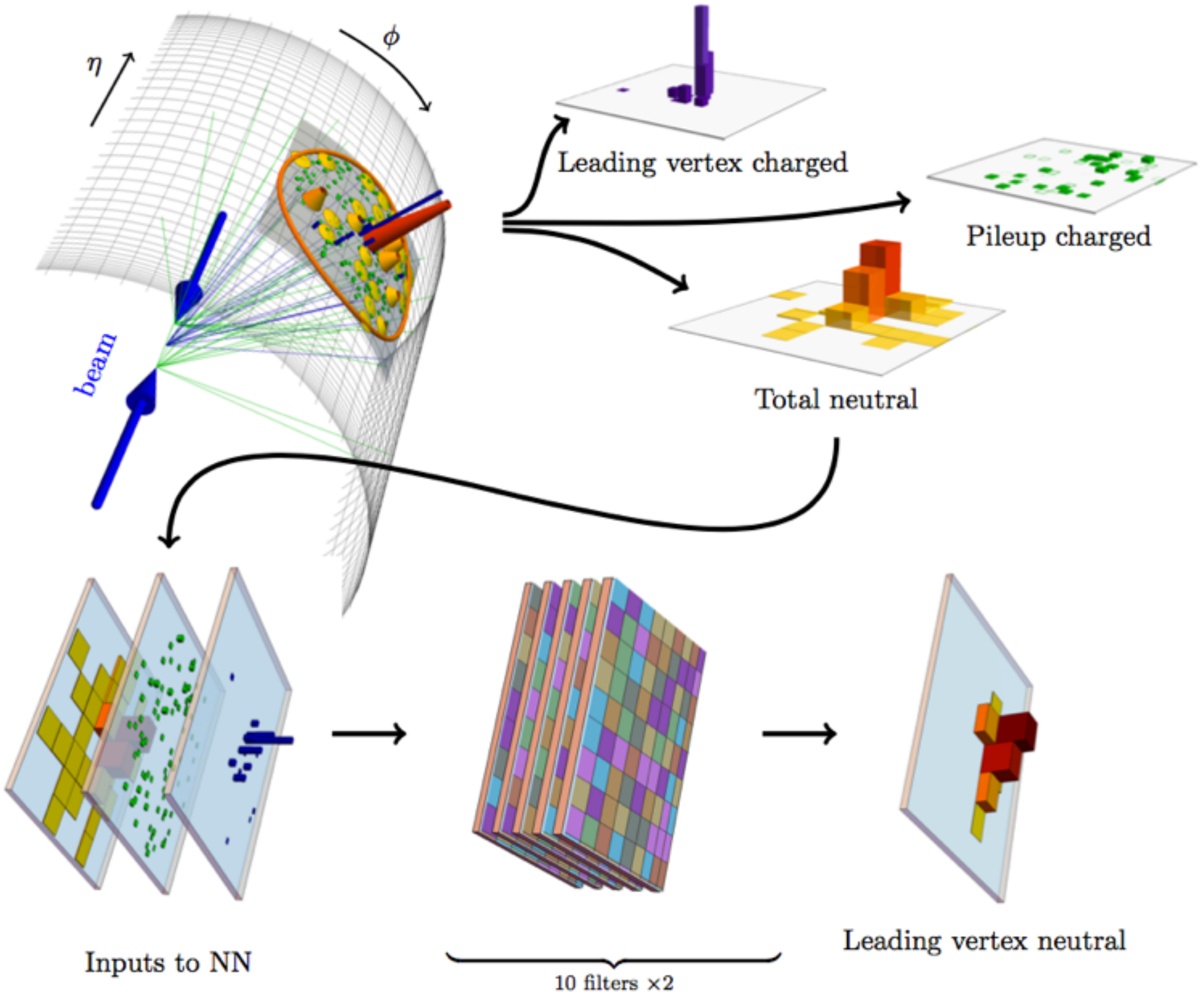


Machine Learning

PUMML

1707.08600

Inputs: p_t of charged leading vertex, charged pileup, all neutral particles
Output: leading vertex energy neutral energy distribution



PUMML

1707.08600

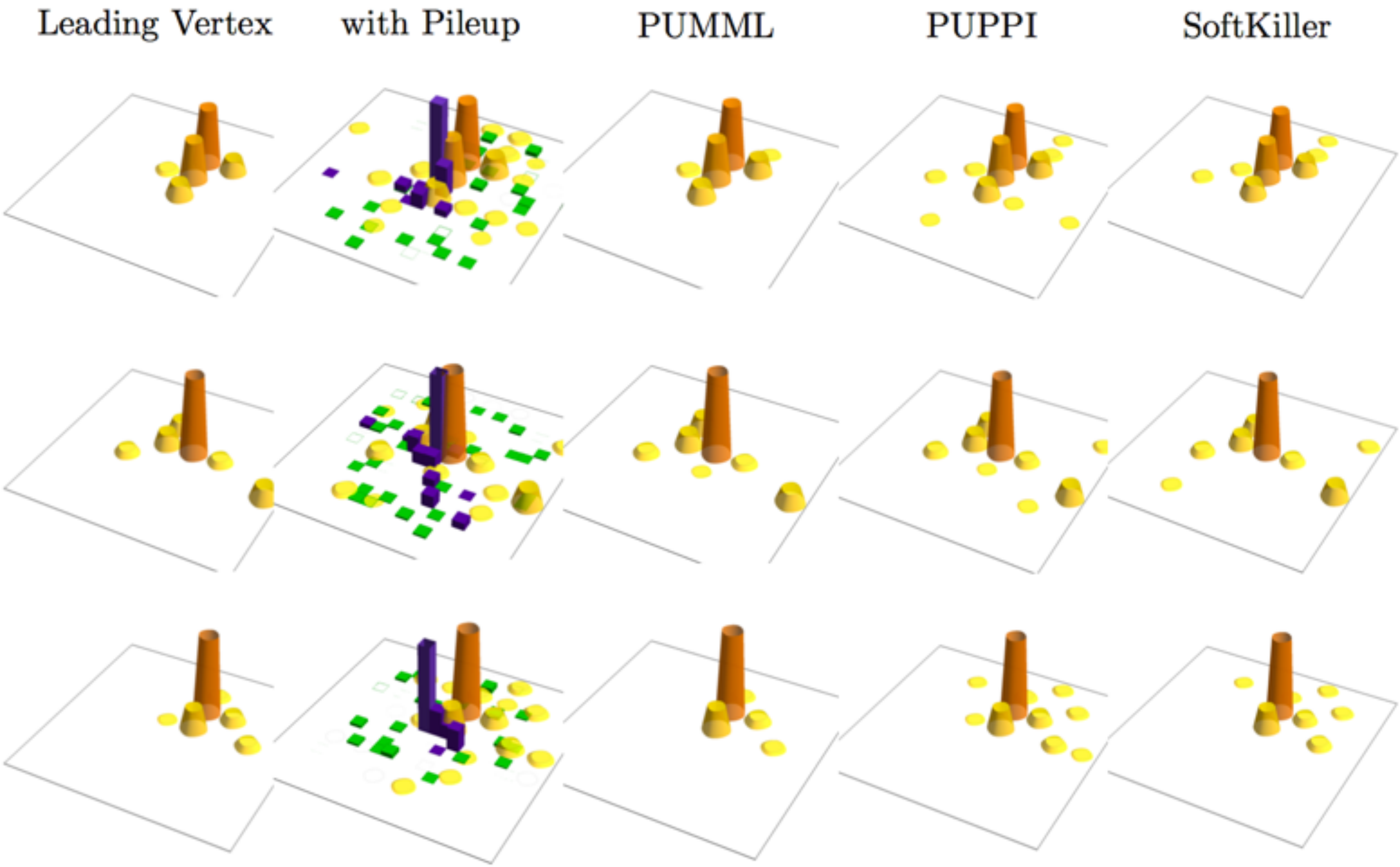
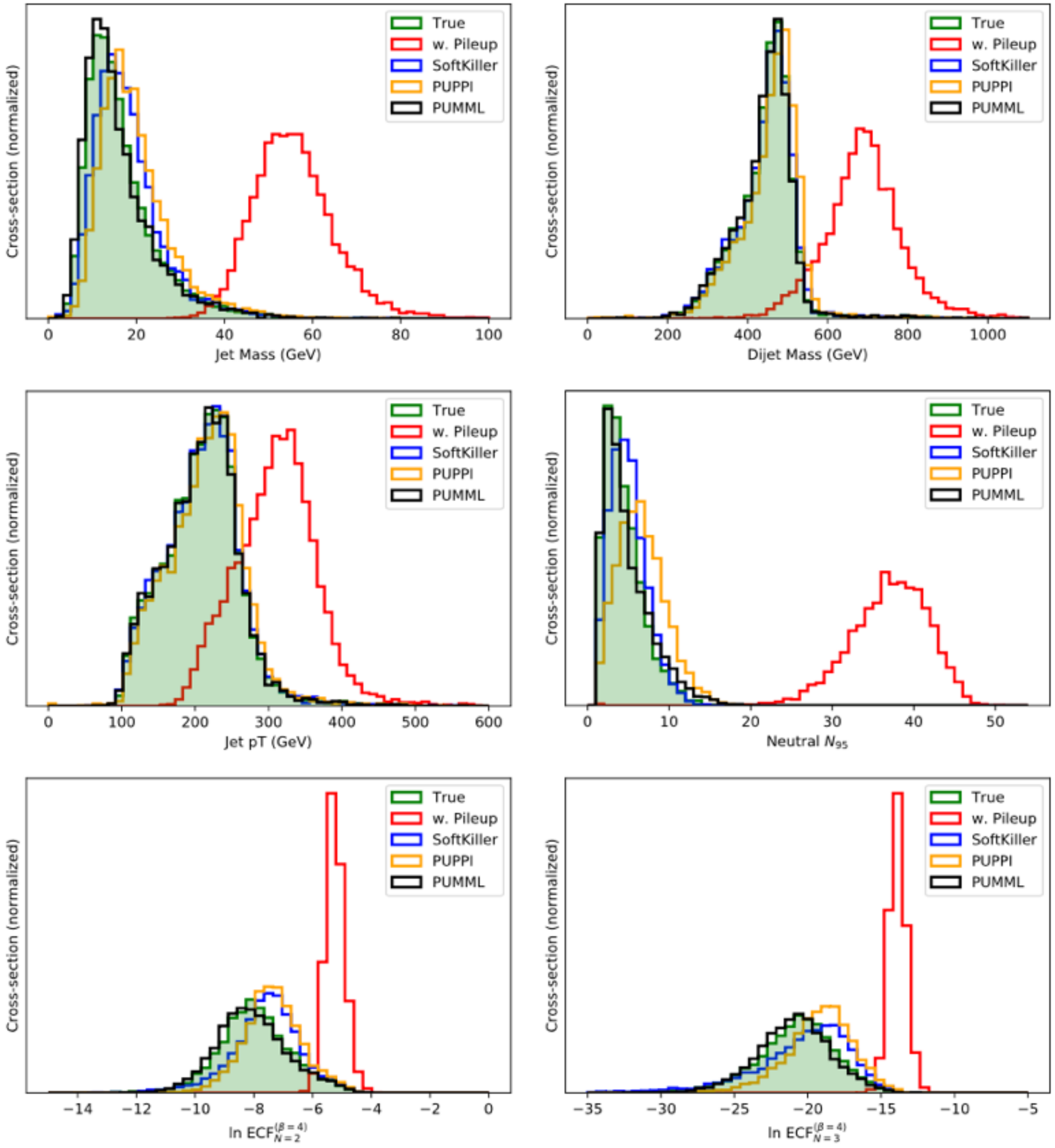


Figure 3: Depictions of three randomly chosen leading jets. Blue/purple represents charged radiation from the leading vertex, green is charged pileup radiation, and yellow/orange/red is the neutral radiation. Shown from left to right are the true neutral leading vertex particles, the event with pileup and charged leading vertex information, followed by the neutral leading vertex particles predicted by PUMML, PUPPI, and SoftKiller. From examining these events, it appears that PUMML has learned an effective pileup mitigation strategy.

PUMML

1707.08600



PUMML competitive with other common pileup mitigation methods

Conclusions

- Pileup/background mitigation is crucial in pp and HI collisions at the LHC (and future colliders)

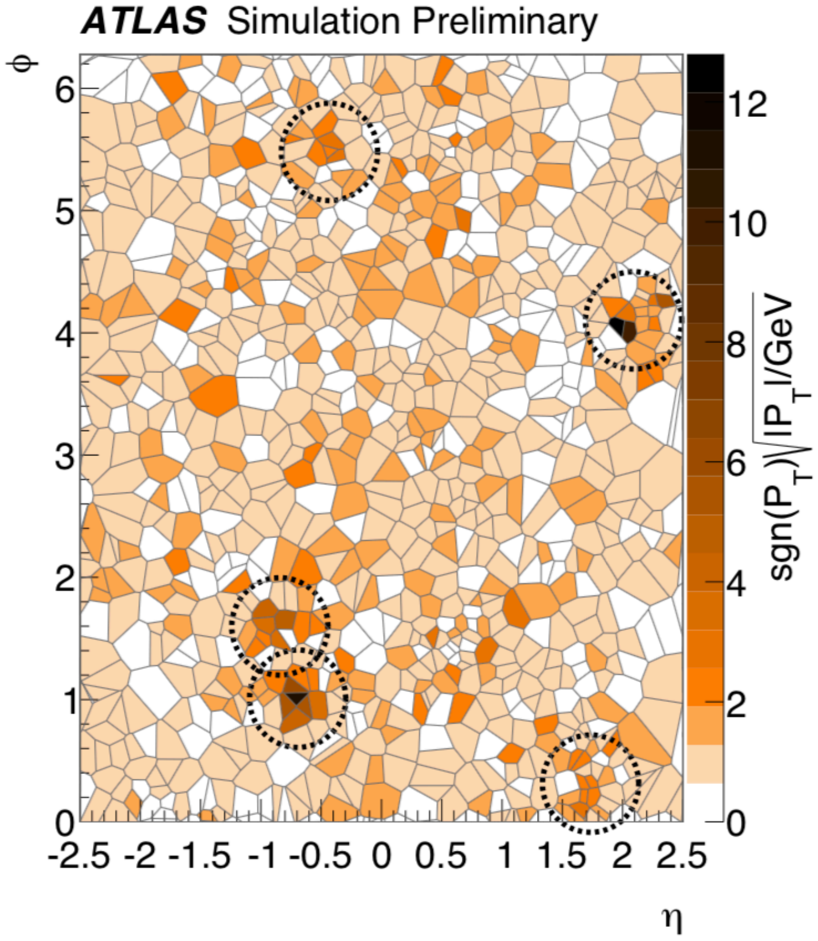
- Various approaches have been developed, with varying degree of complexity and tunability.
  - Many are coded in public implementations ==> crucial for maintenance, cross-testing and reproducibility

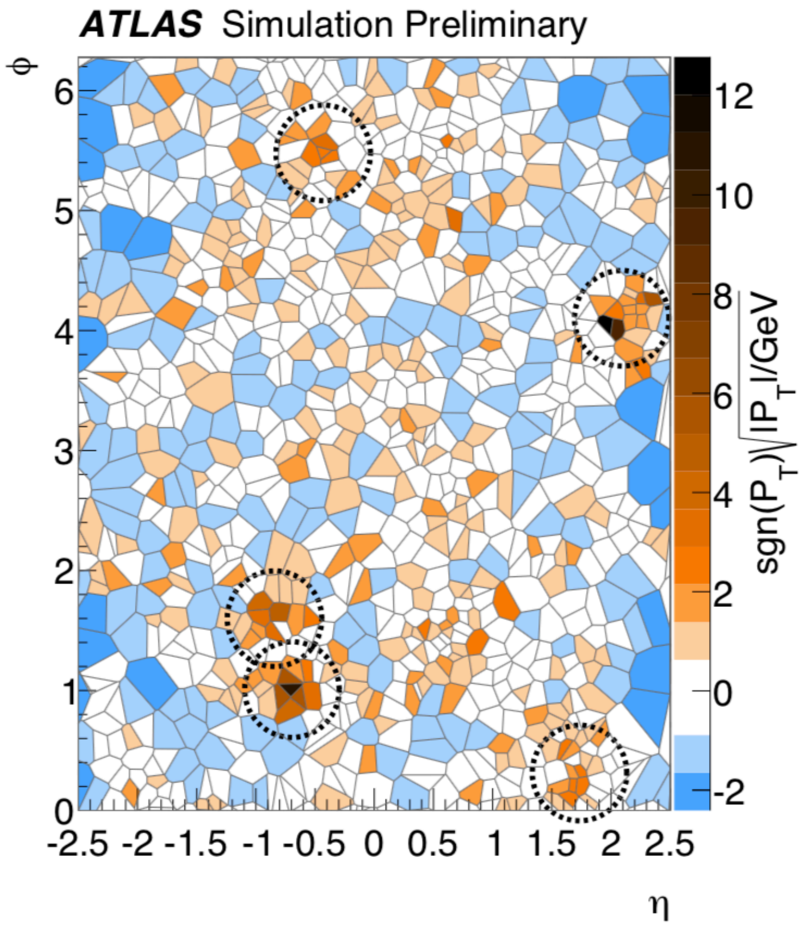
- Different methods can be complementary, and in some cases have been successfully combined

- While margins for improvement likely still exist, with present experimental energy resolutions and typical pileup levels, the problem of pileup can be probably considered as largely solved

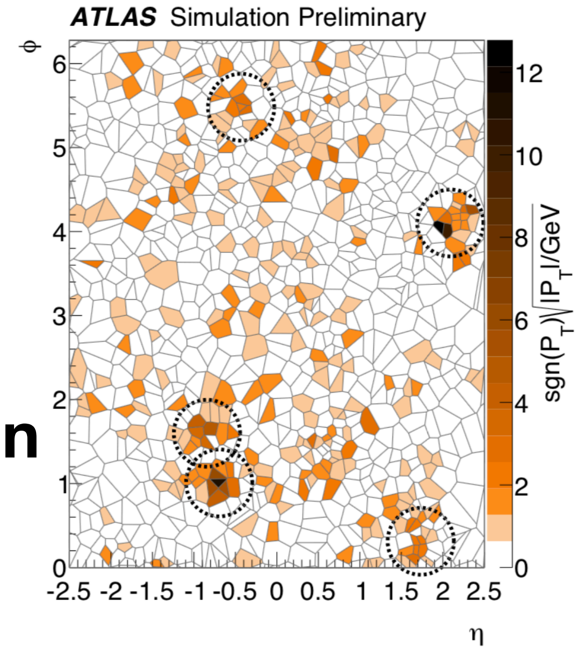
extra slides

Veronoi subtraction

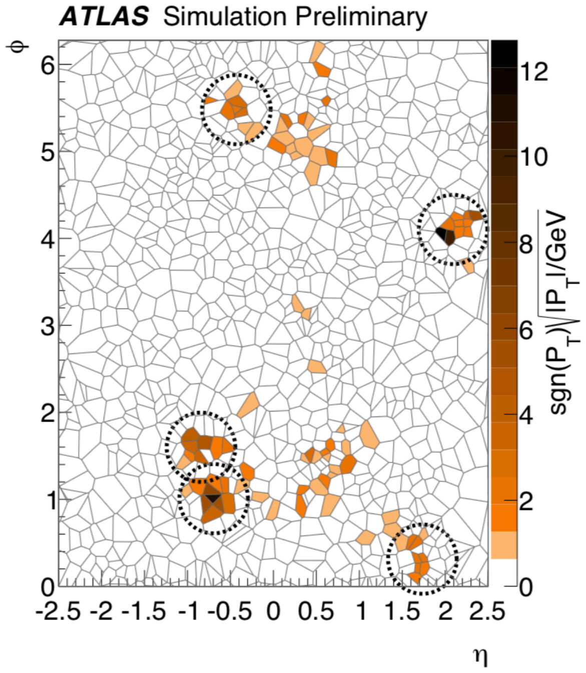




1-sigma suppression

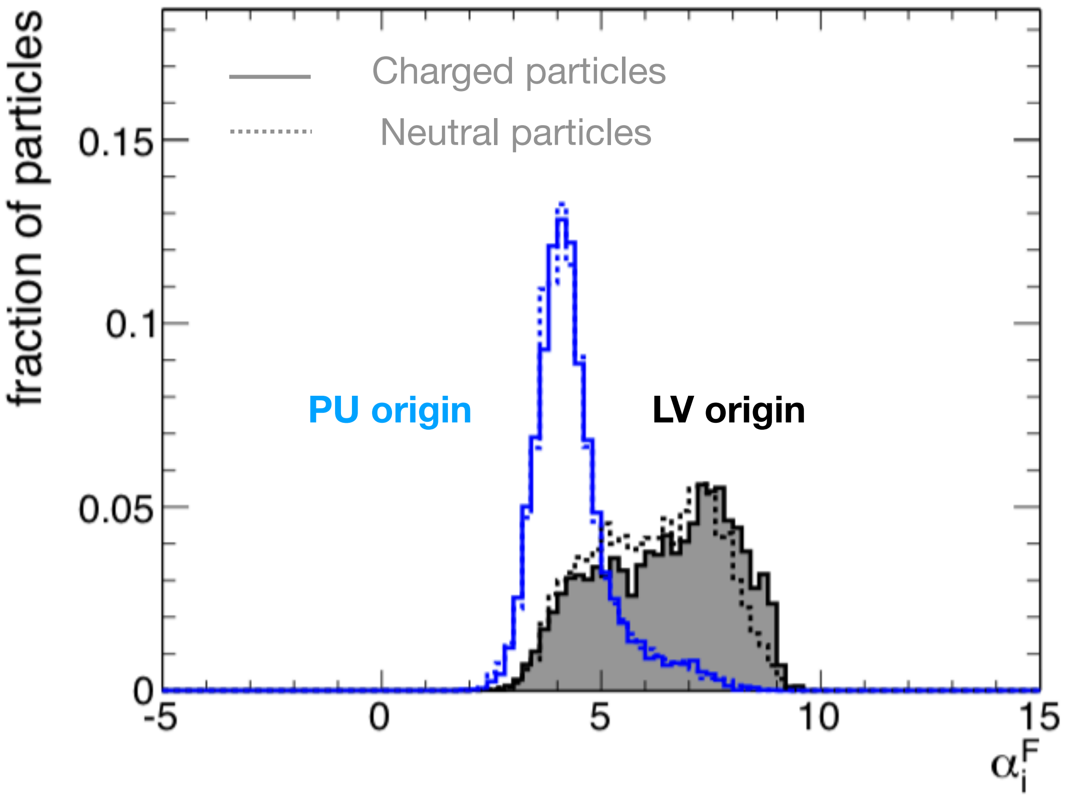


Spread



PUPPI in CMS, detail

alpha-to-weight conversion is done event-by-event.



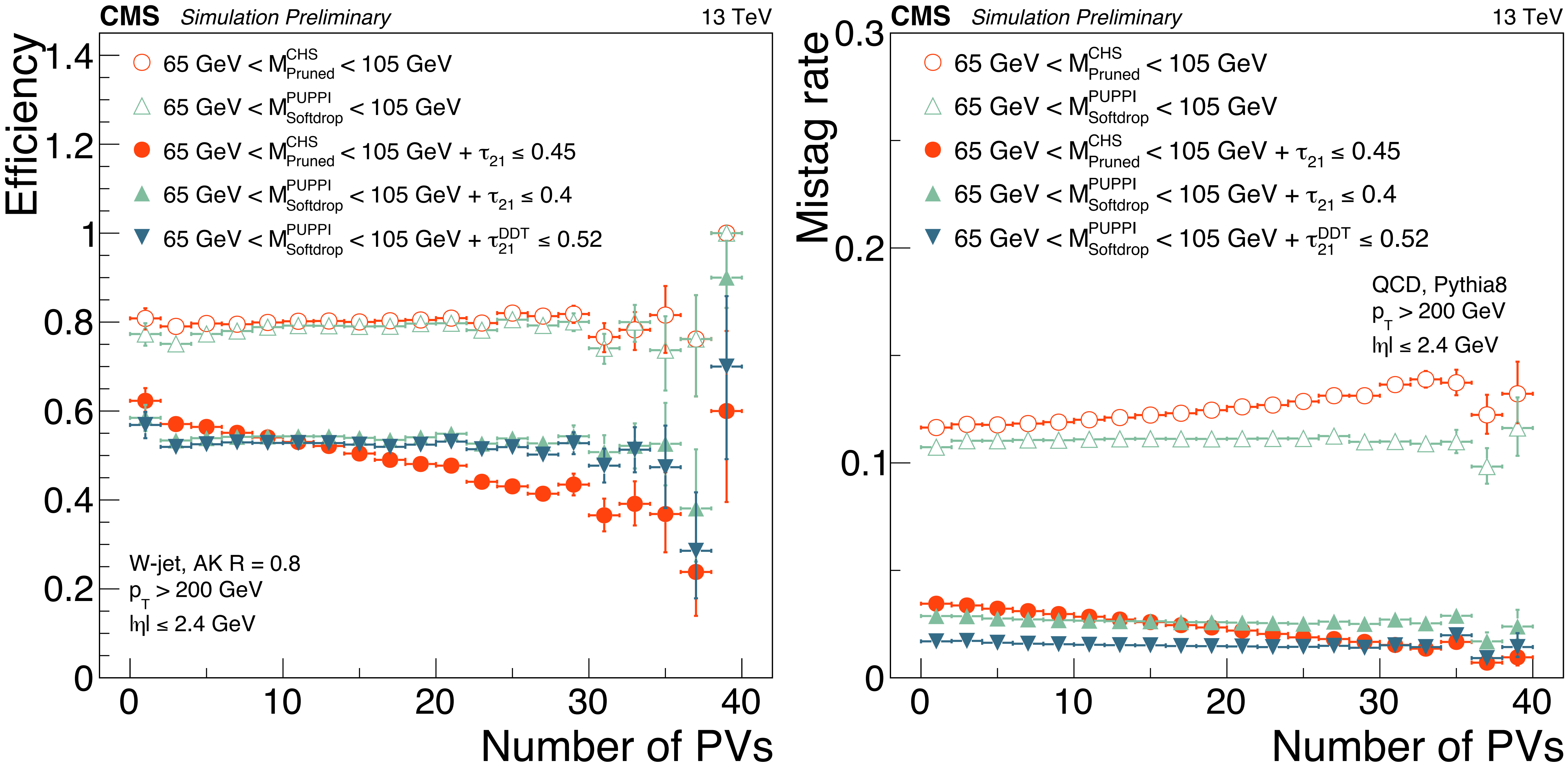
Alpha distribution of **charged particles from PU** represents PU characteristic in the event.

$$\alpha^i_{\substack{\text{neutral}\\\text{particle}}} \xrightarrow{\substack{\alpha\text{ distribution of}\\\text{charged particles}\\\text{from PU}}} \text{Prob}^i_{\text{PU origin}} \to \text{weight} = [0,1]\begin{cases}1:\text{LV-like}\\0:\text{PU-like}\end{cases}$$

Take the mean and RMS of alpha distribution of **charged particles from PU,** and convert neutral particle alpha using a PDF of gaussian with the mean and RMS. (The "log" in the definition of alpha is to make the distribution gaussian-like.)

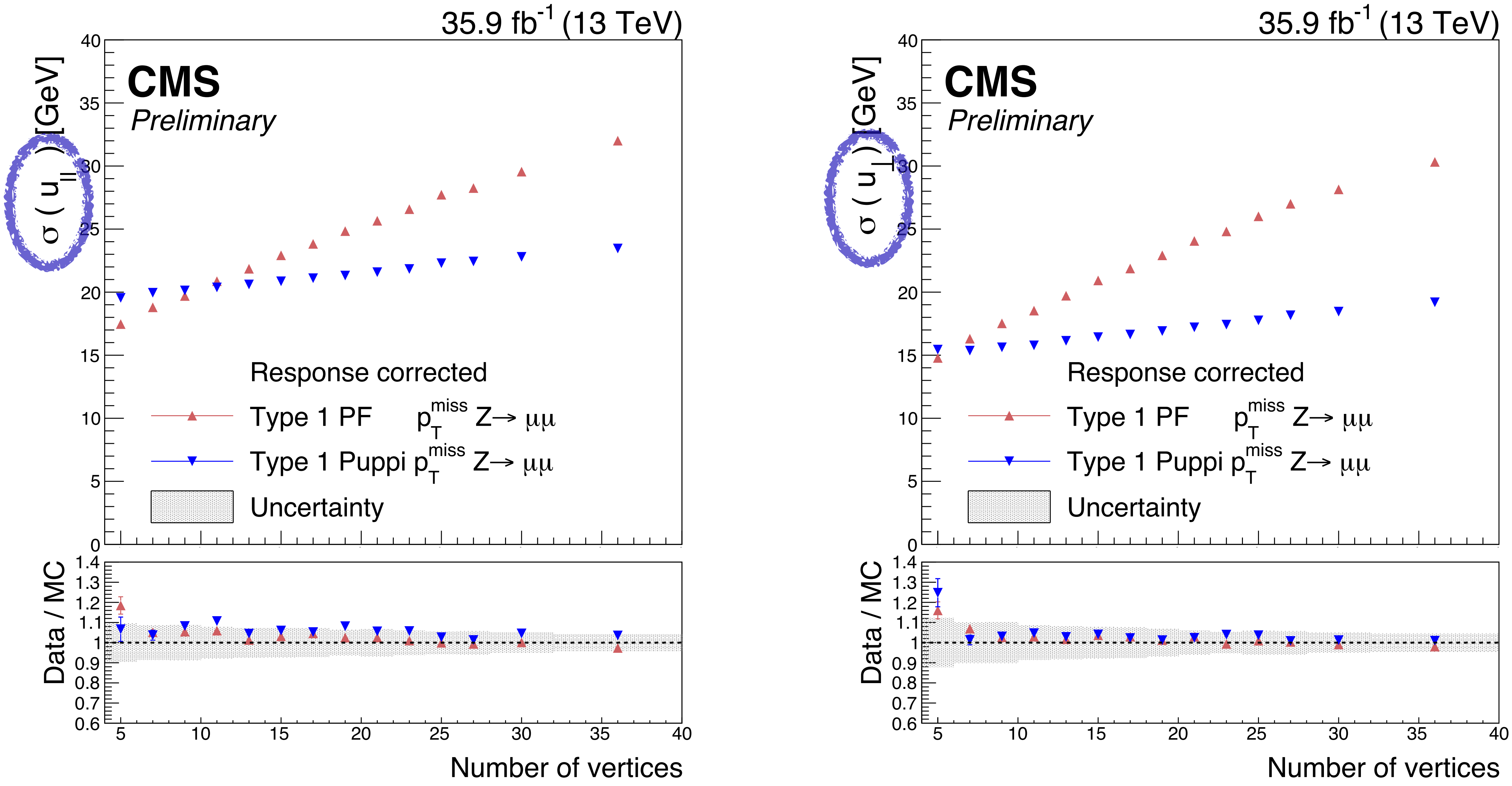
Figures can be found in "*Pileup Per Particle Identification*", arXive:1407.6013.

PUPPI and boosted objects



Figures can be found in "*Jet algorithms performance in 13 TeV data*" CMS-PAS-JME-16-003

PUPPI MET



Figures can be found in “*Performance of missing transverse momentum in pp collisions at sqrt(s)=13 TeV using the CMS detector*” CMS-PAS-JME-17-001

Forward PU rejection

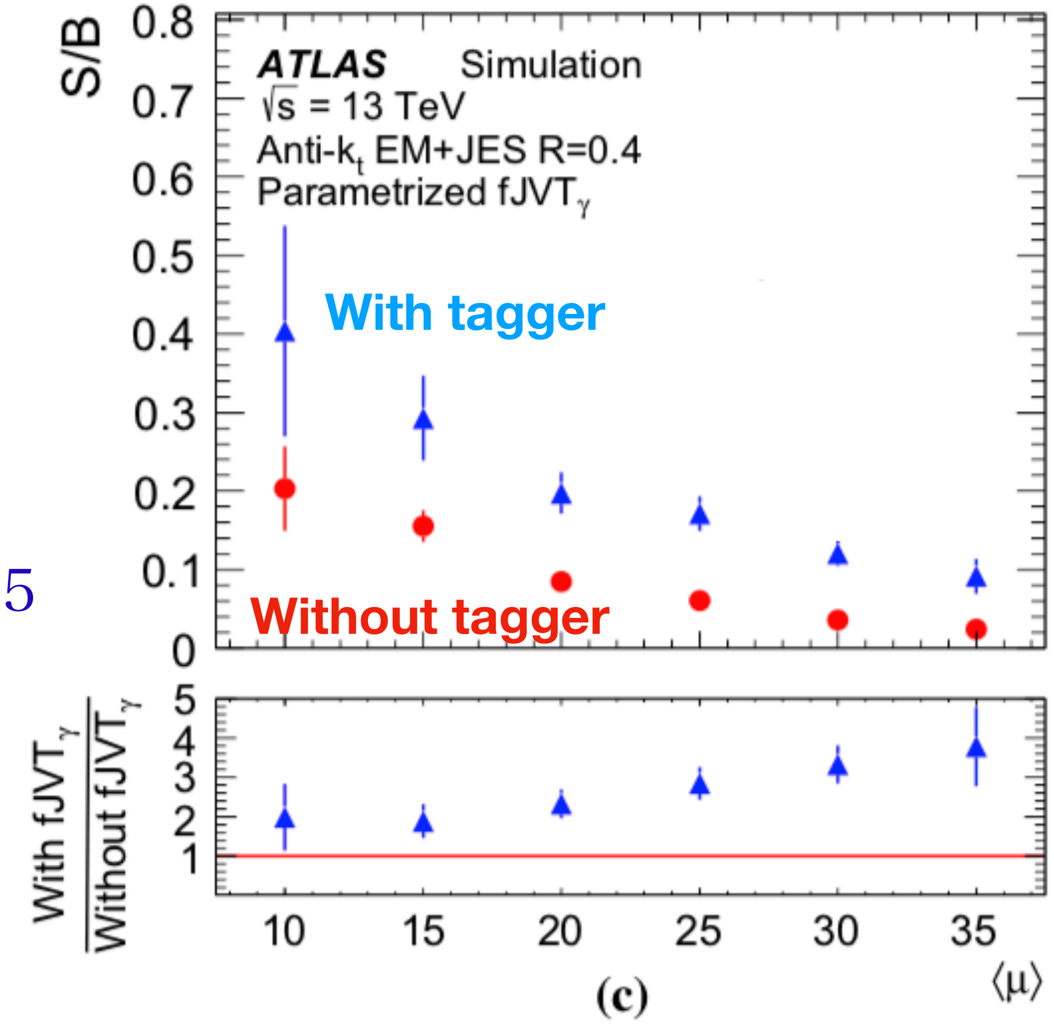
fJVT$_\gamma$ in VBF H -> τ τ signature

Signal : H-> τ τ , decaying to leptons.

Background : DY -> ll(e/ μ / τ)

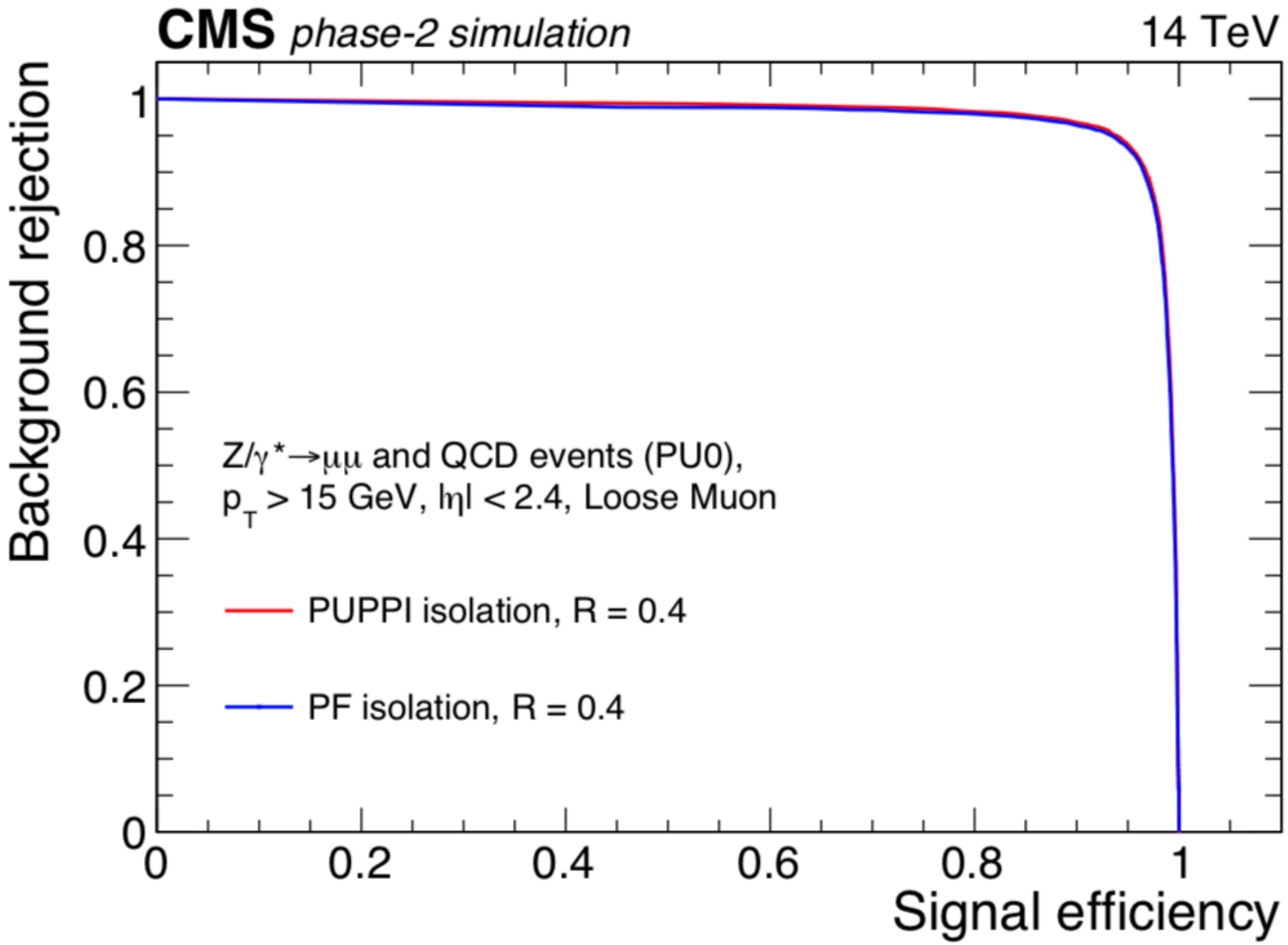
fJVT reduces background by ~80% @ PU=35

fJVT looses signal efficiency by ~20% @ PU=35



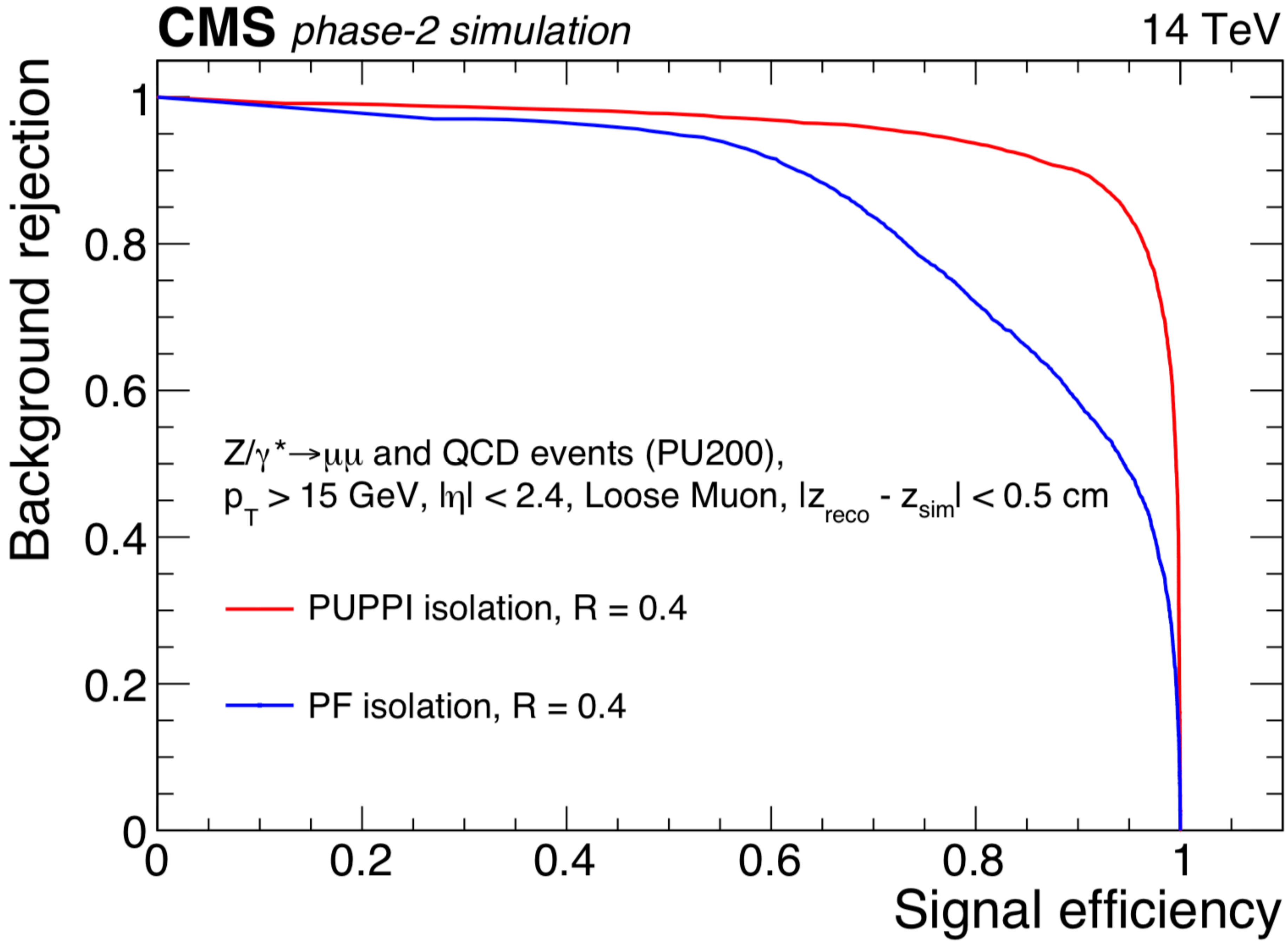
Figures from "*Identification and rejection of pile-up jets at high pseudorapidity with the ATLAS detector*" ,Eur. Phys. J. C (2017) 77: 580.

PUPPI muon isolation at PU=0



Figures can be found in LHCC-P-009, “Figures can be found in CMS-TDR-014, “*TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE*””

PUPPI muon isolation at PU=200



Figures can be found in LHCC-P-009, "Figures can be found in CMS-TDR-014, "*TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE*""