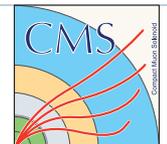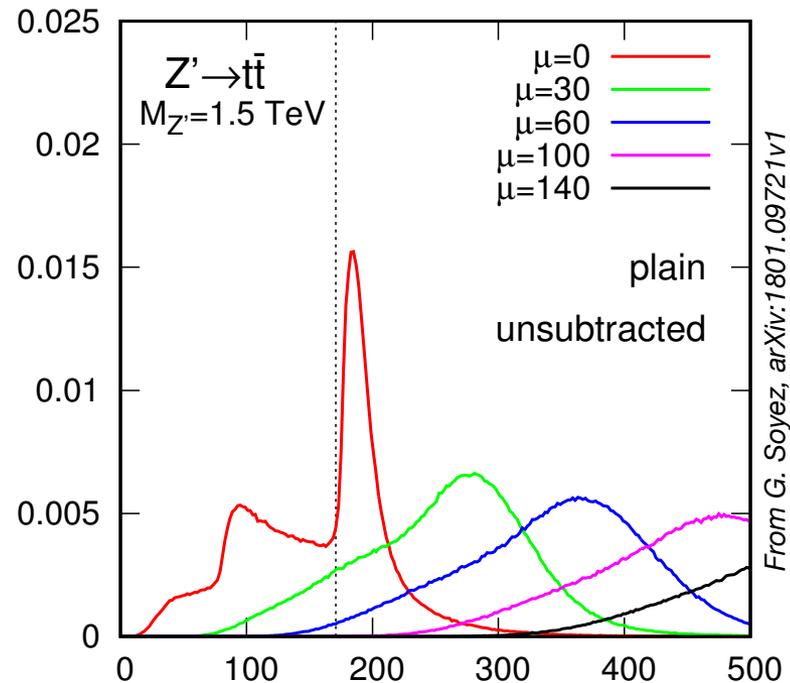# Pileup suppression in CMS

Henning Kirschenmann

(Helsinki Institute of Physics)

UNIVERSITY OF HELSINKI
AND
HELSINKI INSTITUTE OF PHYSICS

UNIVERSITY OF HELSINKI

HELSINKI
INSTITUTE OF
PHYSICS

58-2-941 505
mikko.voutilainen@helsinki.fi
mikko.voutilainen@cern.ch
voutila.web.cern.ch

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

CMS

Pileup degrades performance

[if nothing done about it]

CMS Average Pileup (pp, $\sqrt{s}$=13 TeV)

Run II: < : 34
2018: $<\mu$
2017: $<\mu$ 38
2016: $<\mu>$ 27
2015: $<\mu>$ = 13

σ_{in}^{pp} (13 TeV) = 80.0 mb

HiLumi
HL-LHC PROJECT

CMS   19.7 fb^{-1} (8 TeV)

Energy fraction

Markers: Data
Histogram: MC
▲ Leptons
◆ Neutral hadrons
■ Photons
● Charged hadrons
○ Charged PU hadrons

$|\eta| < 1.3$
$56 < p_T < 84$ GeV
Anti-k_T R=0.5

Data-MC (%)

μ

$Z' \rightarrow t\bar{t}$
$M_{Z'}$=1.5 TeV

μ=0
μ=30
μ=60
μ=100
μ=140

plain

unsubtracted

From G. Soyez, arXiv:1801.09721v1
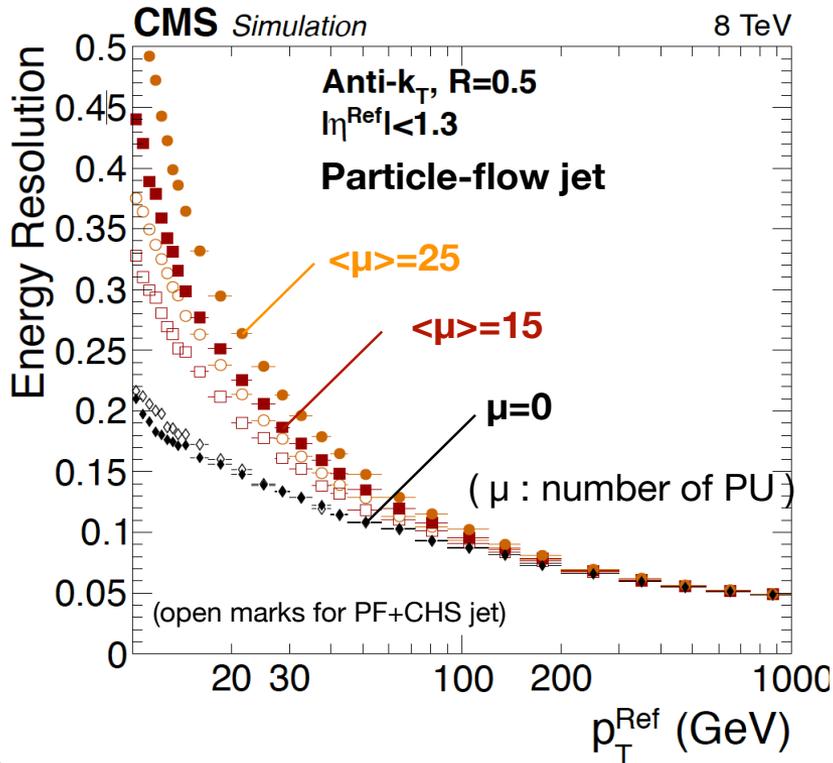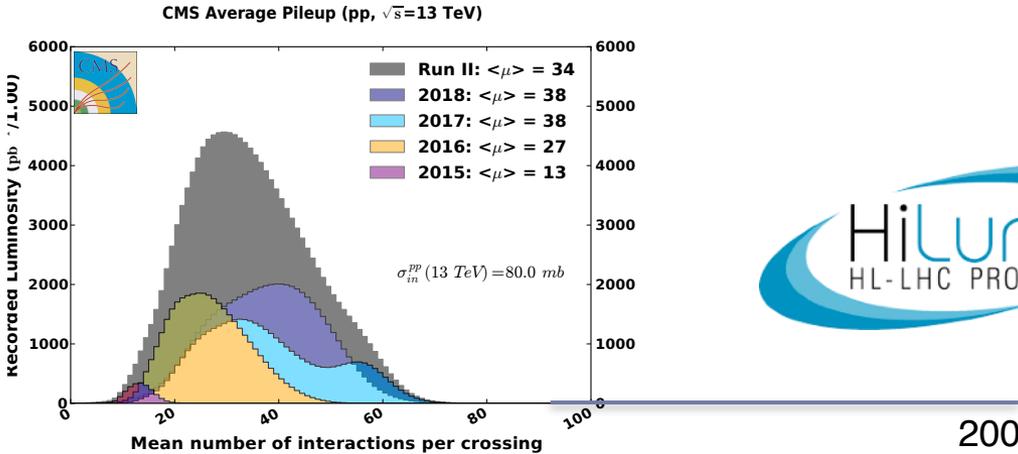
(a) raw, ungroomed jets

Pileup suppression at the hit/cluster level (ECAL/HCAL) [out of time PU]

HCAL

ECAL

Particle Flow

Photon

Charged hadrons

Neutral hadron

Parton level

π, K, ...

q, g

p

p
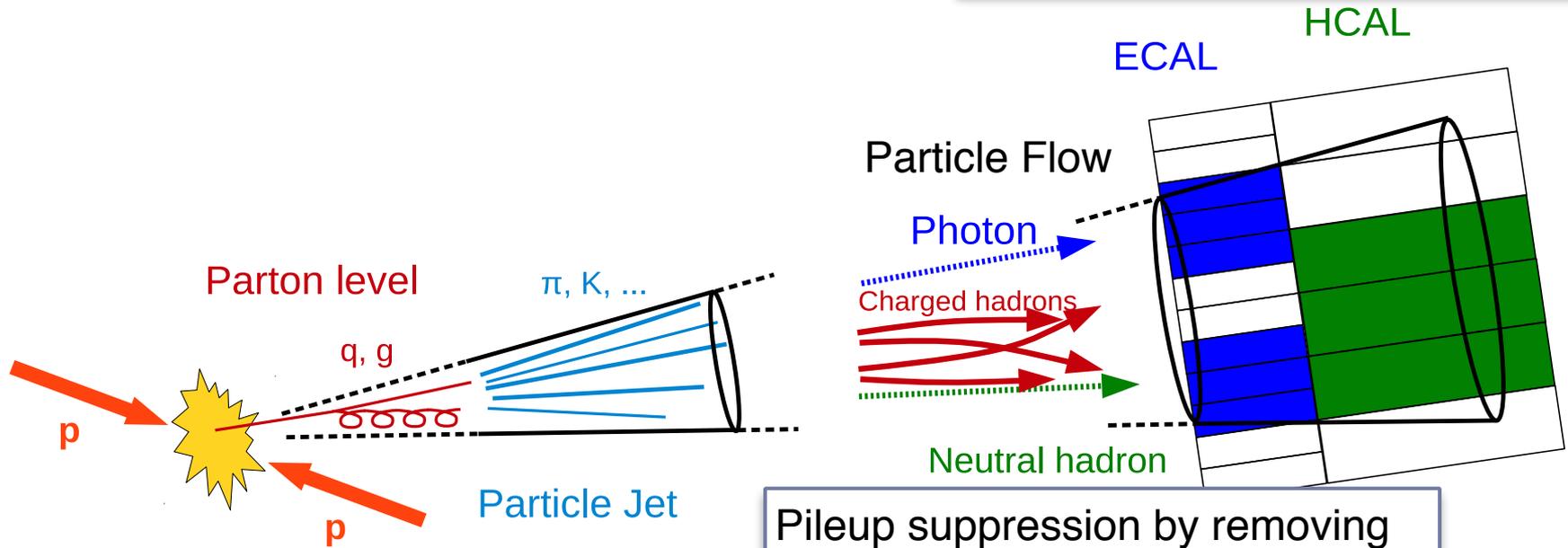
Particle Jet

Pileup suppression by removing charged hadrons from PU vertices (CHS)

Going beyond: PUPPI already used now for many substructure observables, even more important at higher PU
+ hardware upgrades for HL-LHC

Particle Flow (PF) approach

Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Transverse slice through CMS

D.Barney, CERN, February 2004
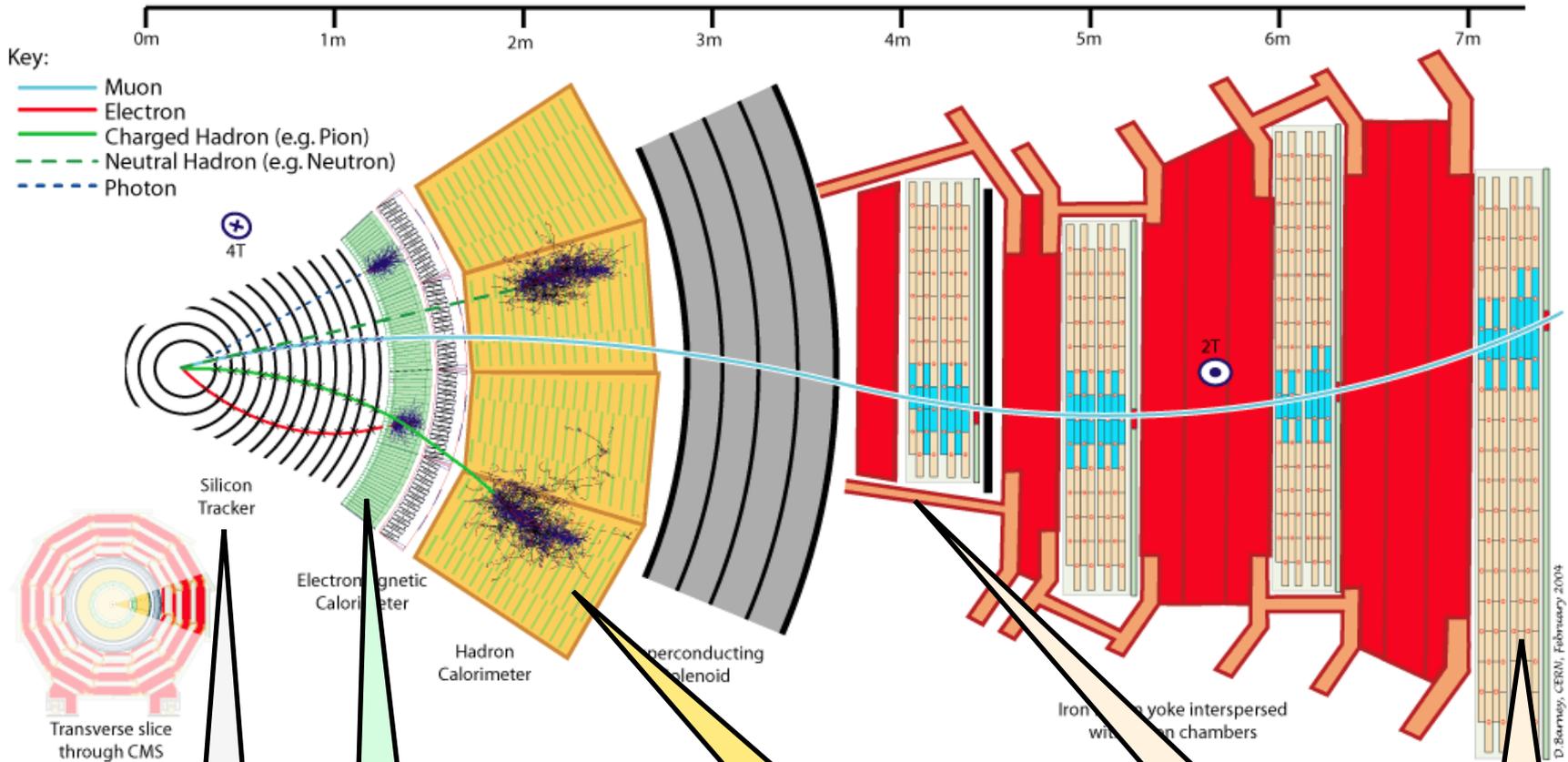
Silicon Tracker

Position, momentum of charged particles : $e^\pm$, $\pi^\pm$, $\mu^\pm$

Electromagnetic Calorimeter

Position & ID, energy of $e^\pm$, γ, π^0

Hadron Calorimeter
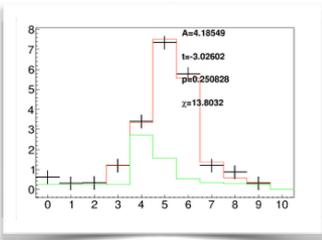
Energy of hadrons : p, n, $\pi^\pm$, K ..

Muon Chambers

Position & momentum of $\mu^\pm$
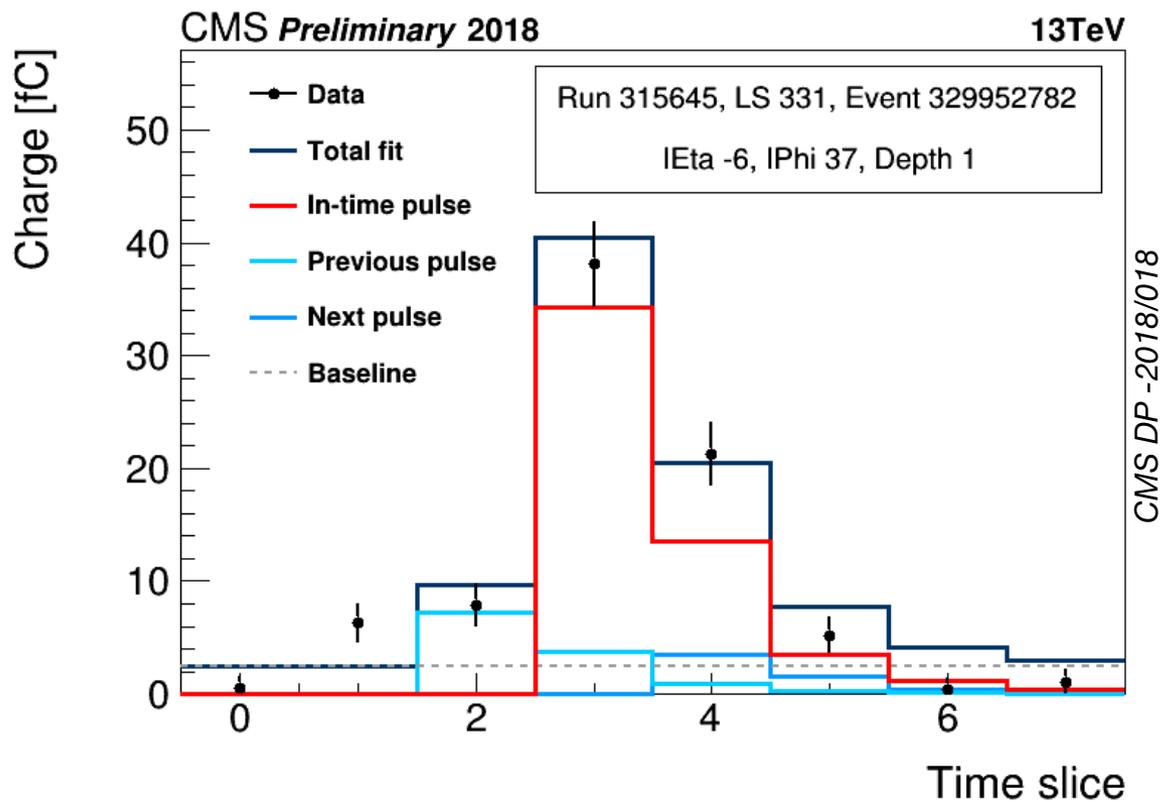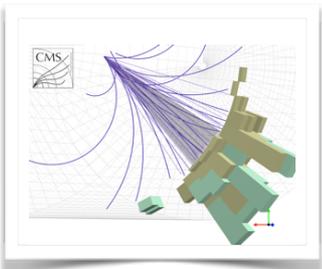
Particle Flow (PF) approach

ECAL
pulse reconstruction

HCAL
pulse reconstruction

Track
reconstruction

Figure 6: Simulated particle-level offset versus (left). Average p_T offset density versus jet distance to a random-cone offset density versus cone radiu to πR^2.

Particle Flow
linking
and particle
reconstruction
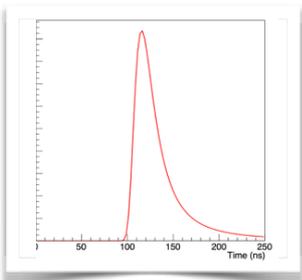
Per particle
pileup removal
(CHS, PUPPI)
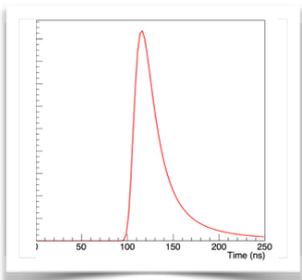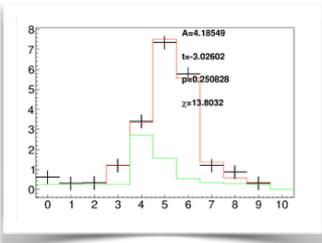
Pulse shape not contained within 25ns bins →
Overlap from previous/following bunch crossing
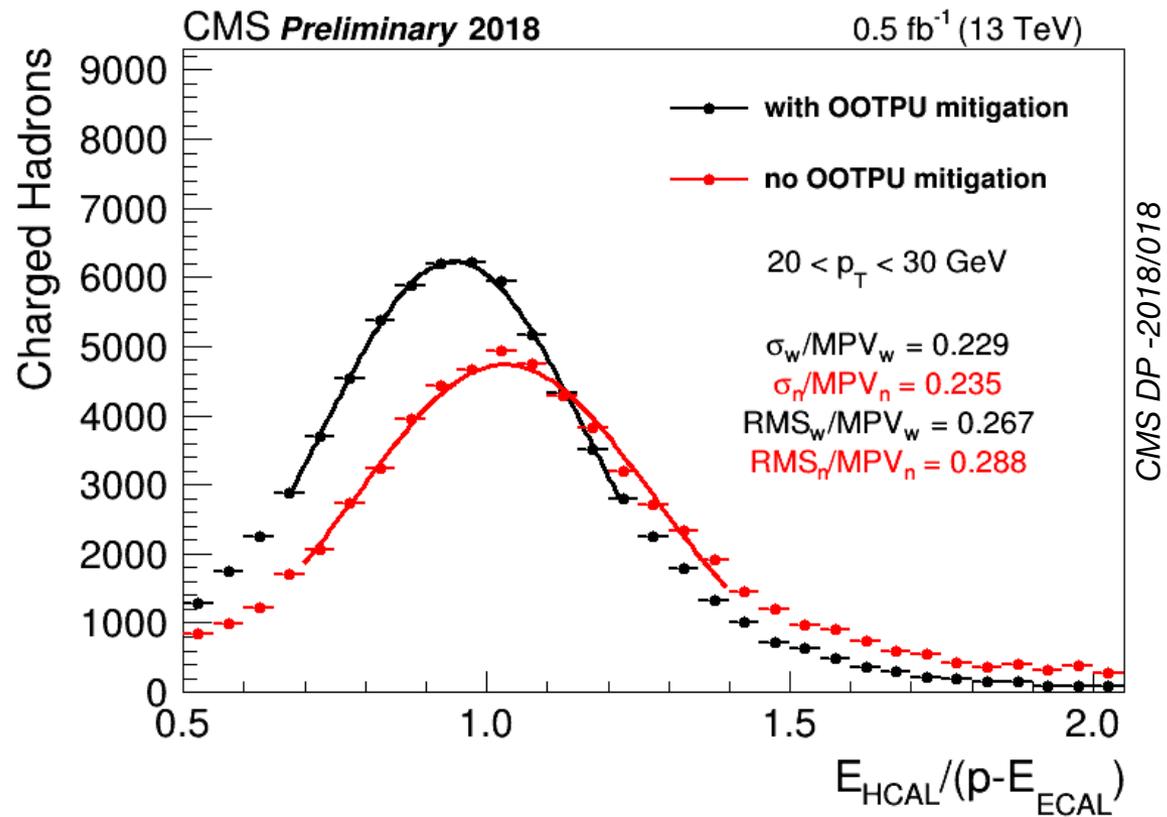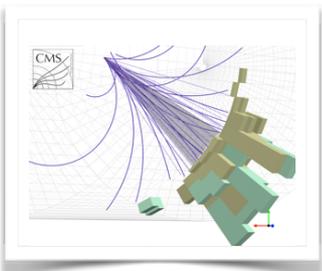→ Fit of ECAL/HCAL pulses to subtract OOT-PU

Schematic by J. Dolen

Particle Flow (PF) approach

ECAL pulse reconstruction

HCAL pulse reconstruction

Track reconstruction

Particle Flow linking and particle reconstruction

Per particle pileup removal (CHS, PUPPI)

Improved resolution/scale with OOTPU mitigation

CMS *Preliminary* 2018

Charged Hadrons

CMS *Simulation*

Anti-k_T, R=0.5 (PF+CHS)
$|\eta|<1.3$
- Photons
- Neutral hadrons
- Unassoc. ch. hadrons
- Charged hadrons

$\langle p_{T,offset} \rangle / \langle \mu \rangle$ (GeV)

(8 TeV)

CMS *Simulation*

$\eta = 0.0$, PF
- $p_{T,ptcl} = 100$ GeV
- $p_{T,ptcl} = 50$ GeV
- $p_{T,ptcl} = 30$ GeV
- $p_{T,ptcl} = 10$ GeV
- Random cone

$\overline{\Sigma} / (\langle \mu \rangle \times A_J)$ (GeV)

(8 TeV)

$p_{T,ptcl}$ (GeV)

Figure 6: Simulated particle-level offset versus (left). Average p_T offset density versus jet distance to a random-cone offset density versus cone radius to πR^2.

σ/MPV = 0.23

Normalized Distribution

AK R=0.8
$|\eta|<2.4$
CMS
Simulation Preliminary
- W PF-jets p_T=0.5 TeV, <0.515>, σ=
- W PF-jets p_T=1.5 TeV, <0.382>, σ=
- W PF-jets p_T=3.5 TeV, <0.271>, σ=

13

jet C

Distribution

13 TeV

AK R=0.8
$1.2 < p_T$ (W) < 1.8 TeV
$|\eta|<2.4$

CMS
Simulation Preliminary
- default tracking mean=0.380, RMS=0.215
- jet core tracking mean=0.416, RMS=0.216
- jet core tracking and cluster splitting mean=0.431, RMS=0.215

jet CHF

Schematic by J. Dolen

Particle Flow (PF) approach

ECAL
pulse reconstruction

HCAL
pulse reconstruction

Track
reconstruction

Particle Flow
Cluster
reconstruction
and calibration

Particle Flow
linking
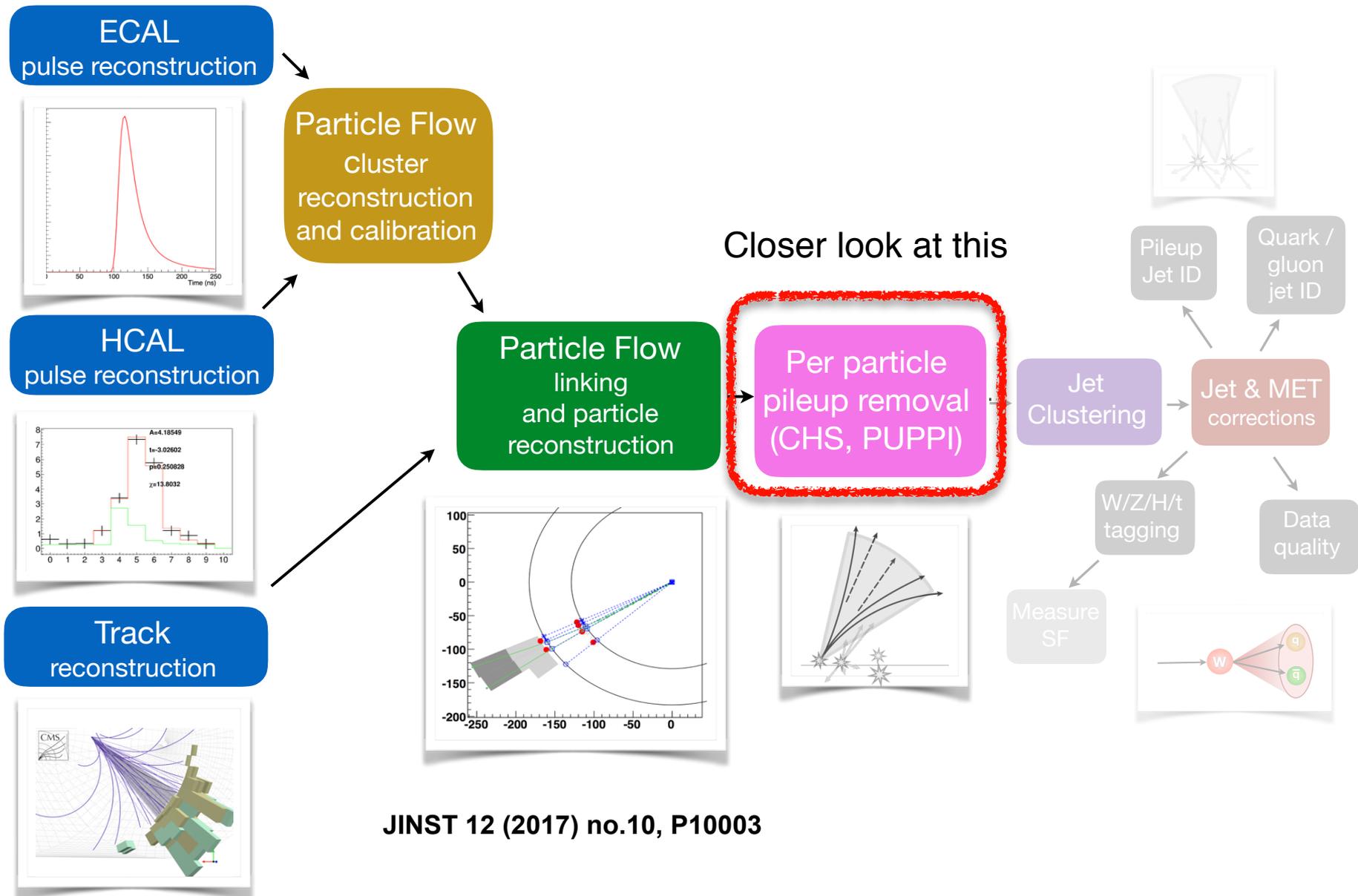and particle
reconstruction

JINST 12 (2017) no.10, P10003

Try to reconstruct individual particle candidates, combining information from various detectors

- Charged hadrons (tracker)
- Photons (ECAL)
- Neutral hadrons (HCAL)
- +Electrons/muons

‣ Form jets and MET using particle candidates
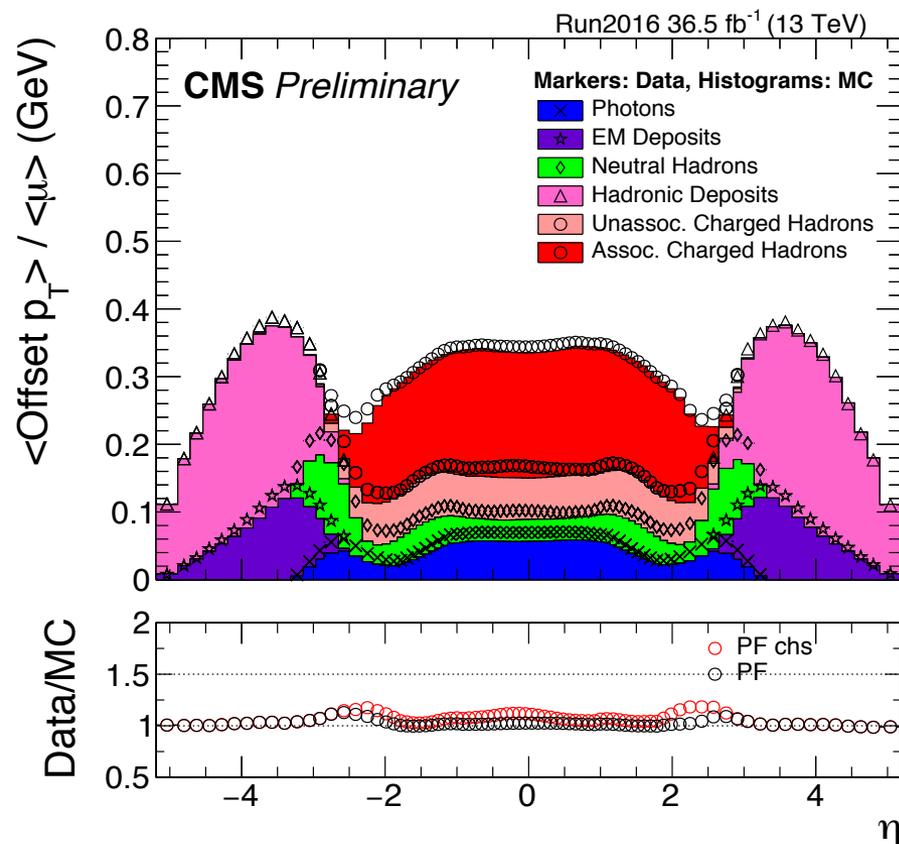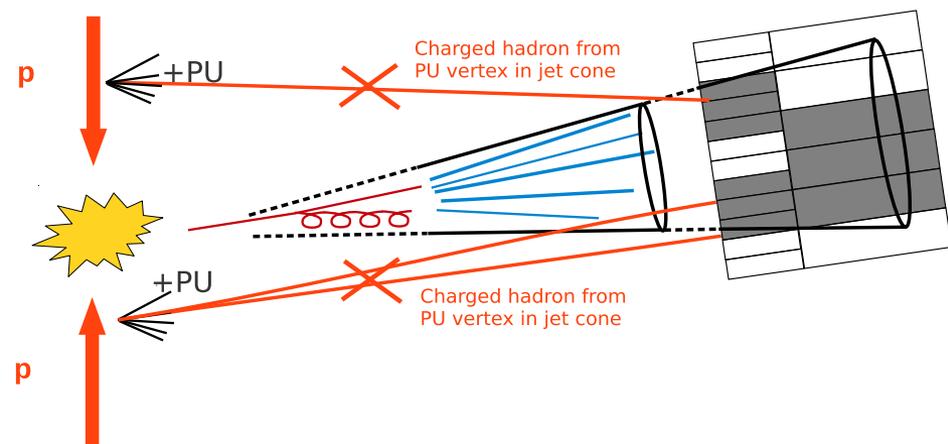‣ PF greatly improves CMS jet energy resolution as compared to calorimeter-only reconstruction.

Schematic by J. Dolen

Particle Flow (PF) approach

ECAL
pulse reconstruction

Particle Flow
Cluster
reconstruction
and calibration

HCAL
pulse reconstruction

Particle Flow
linking
and particle
reconstruction

Closer look at this

Per particle
pileup removal
(CHS, PUPPI)

Pileup
Jet ID

Quark /
gluon
jet ID

Jet
Clustering

Jet & MET
corrections

W/Z/H/t
tagging

Data
quality

Measure
SF

Track
reconstruction

JINST 12 (2017) no.10, P10003

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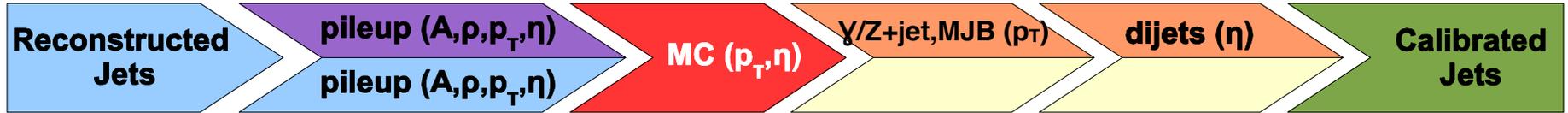Schematic by J. Dolen

Charged Hadron Subtraction for jets

Particle Flow Charged Hadron Subtraction (CHS)

- Majority of pileup is from charged particles
- CHS removes individual charged hadrons from pileup vertices (ca. 2/3 of offset energy in barrel)
- Inherent limitation: Only works in tracker-covered region, only works on charged component

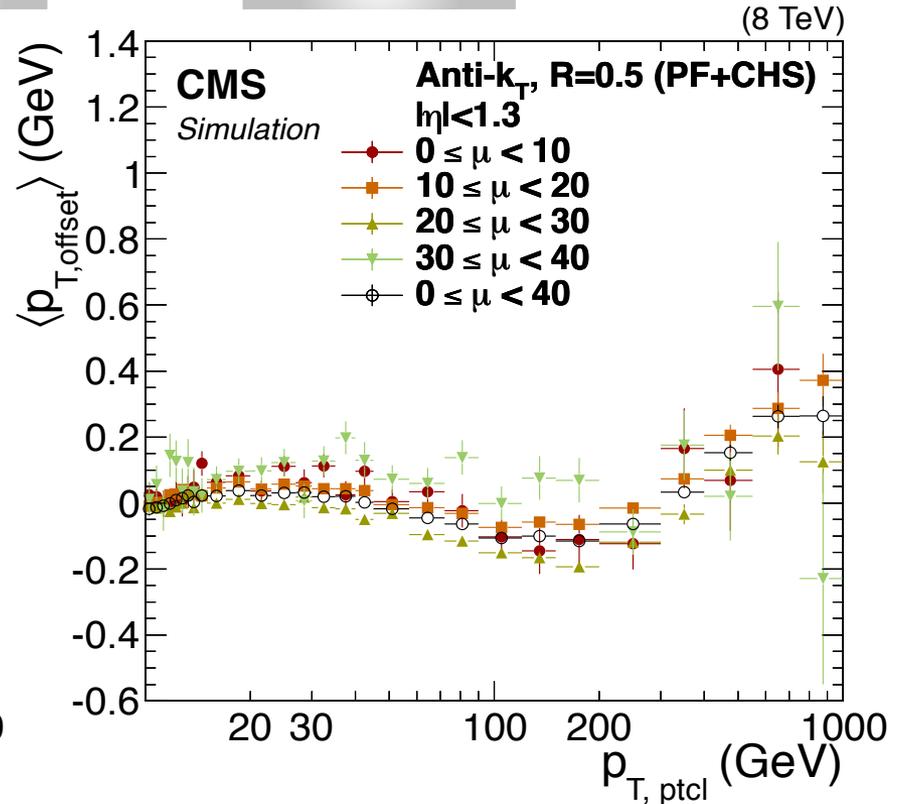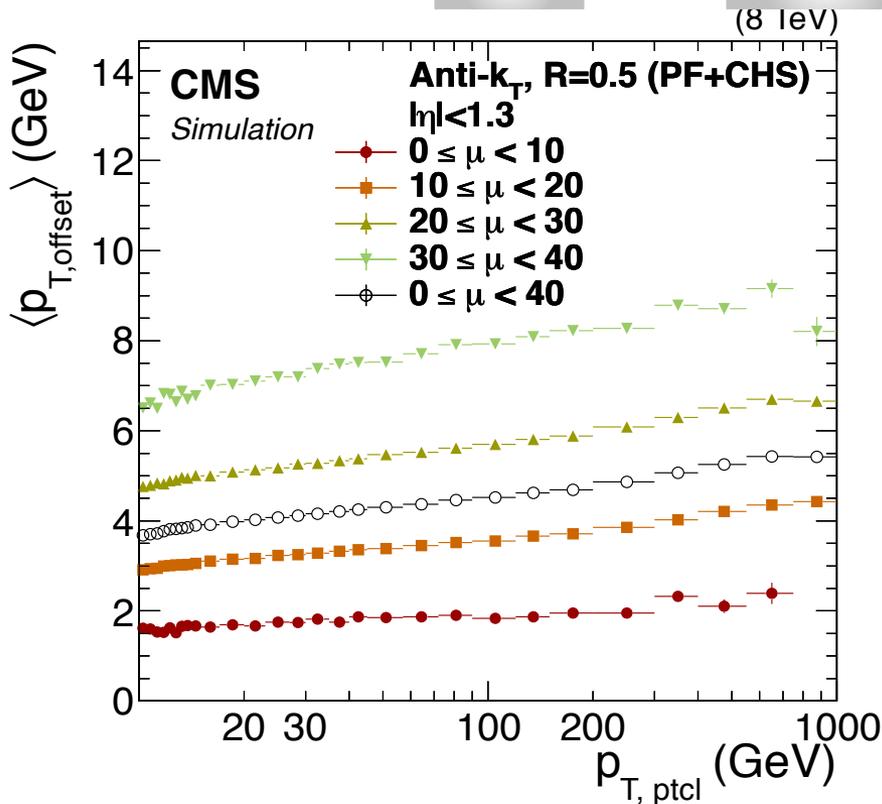# Offset energy left after CHS: Part of JEC

applied on data →

| Reconstructed Jets | pileup (A, ρ, p_T, η) pileup (A, ρ, p_T, η) | MC (p_T, η) | γ/Z+jet,MJB (p_T) | dijets (η) | Calibrated Jets |

applied on MC →

L1   **L2L3**   **L2L3Res**

(8 TeV)

CMS *Simulation*

Anti-k_T, R=0.5 (PF+CHS)
$|\eta|<1.3$

- $0 \le \mu < 10$
- $10 \le \mu < 20$
- $20 \le \mu < 30$
- $30 \le \mu < 40$
- $0 \le \mu < 40$

$\langle p_{T,offset} \rangle$ (GeV)

$p_{T, ptcl}$ (GeV)

(8 TeV)

CMS *Simulation*

Anti-k_T, R=0.5 (PF+CHS)
$|\eta|<1.3$

- $0 \le \mu < 10$
- $10 \le \mu < 20$
- $20 \le \mu < 30$
- $30 \le \mu < 40$
- $0 \le \mu < 40$

$\langle p_{T,offset} \rangle$ (GeV)

$p_{T, ptcl}$ (GeV)
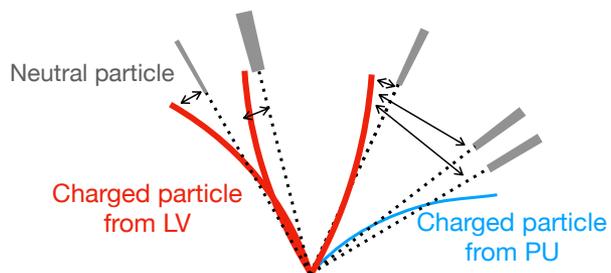
- Remaining offset energy (1/3 in barrel) corrected for by ρ/jet area-based correction

▶ •10 N.B.: Not needed for PUPPI jets

Concept : neutral particles close to **charged particles from LV** are likely to be from LV.

Neutral particle

Charged particle from LV

Charged particle from PU

Define a metric :

$$\alpha_i \equiv \log \sum_{\substack{j \in LV \\ j \neq i, \Delta R_{ij} < 0.4}} \left(\frac{P_T^j}{\Delta R_{ij}} \right)^2$$
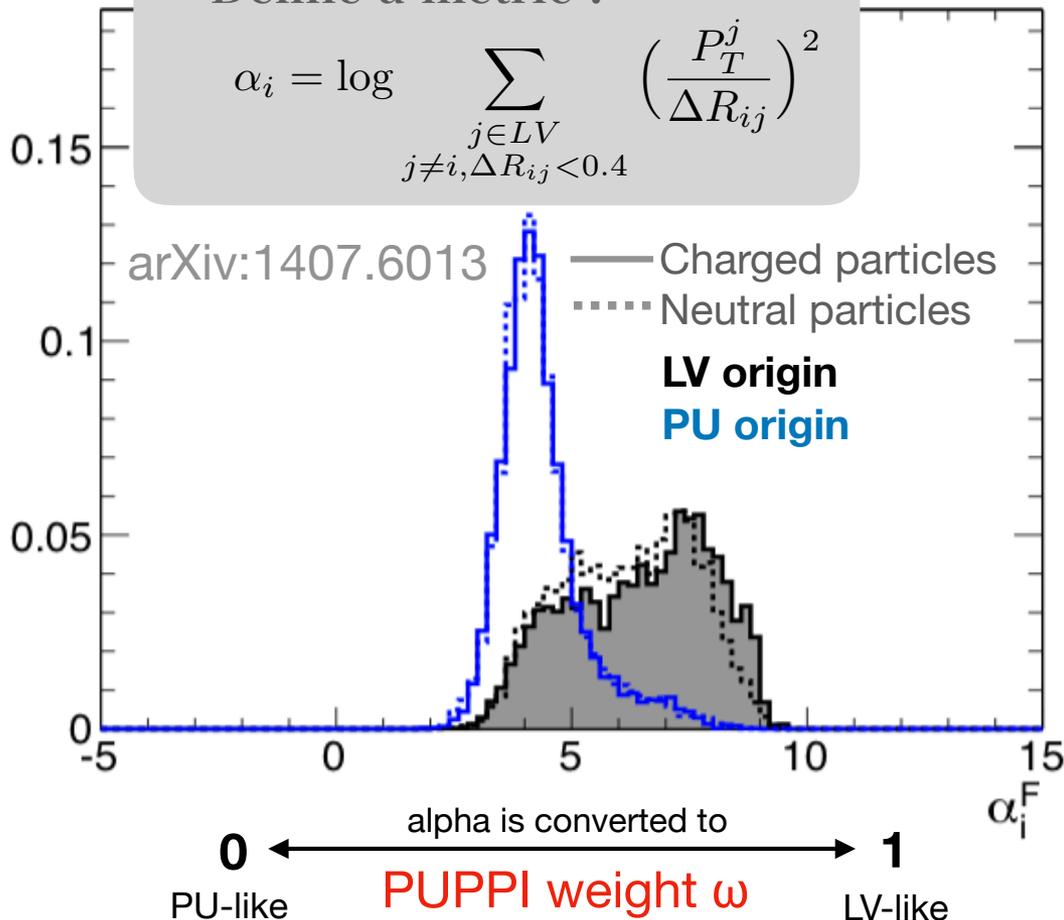
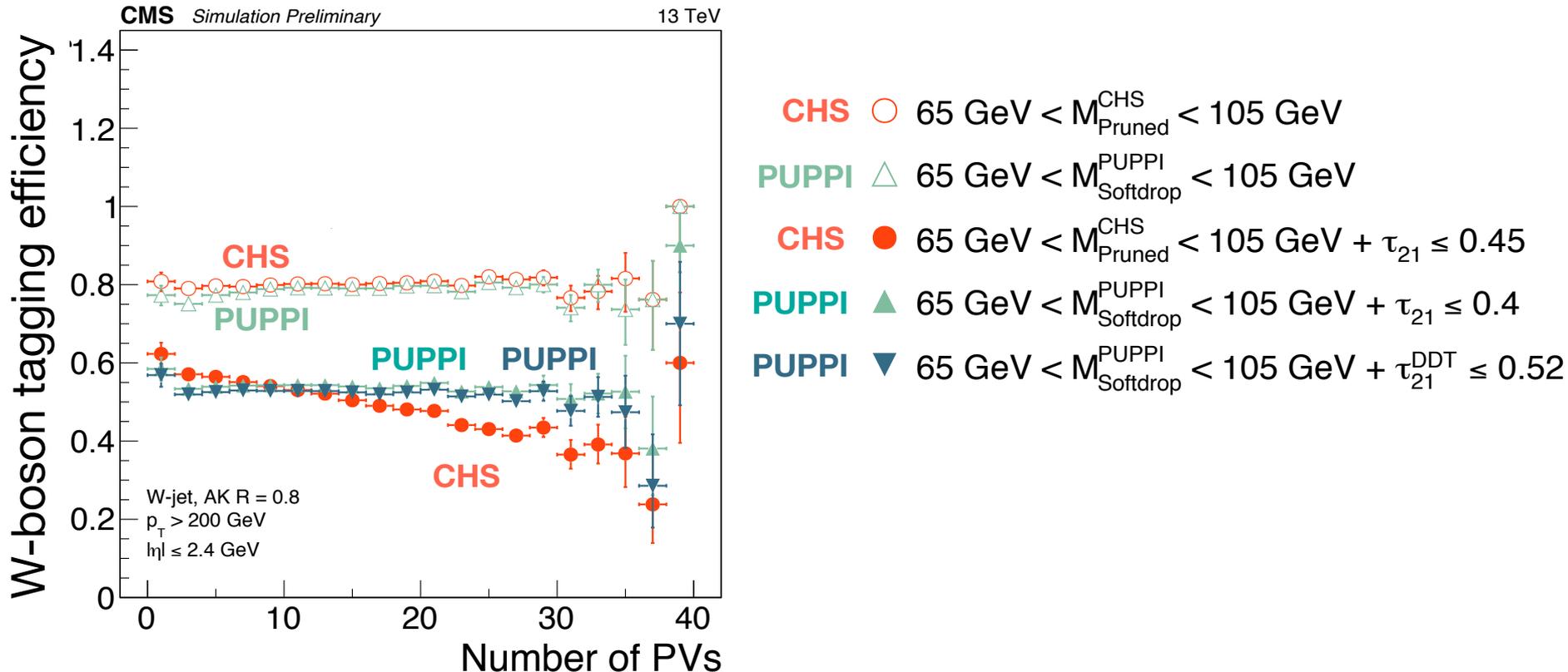Scale momentum by its PUPPI weight :

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

PUPPI is extendable to the forward region by re- defining alpha with charged+neutral particles.

fraction of particles

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

arXiv:1407.6013 —— Charged particles
····· Neutral particles

LV origin
PU origin

0.15

0.1

0.05

0

-5   0   5   10   15

α_i^F

alpha is converted to

0 ⟷ 1

PUPPI weight ω

PU-like   LV-like

Schematic by S. Hasegawa

PUPPI and substructure

PUPPI works particularly well for jet substructure; most current substructure analyses at CMS use PUPPI.

Retains flat efficiency as a function of PU, when cutting on PU-susceptible observables like subjettiness/ [ungroomed] mass
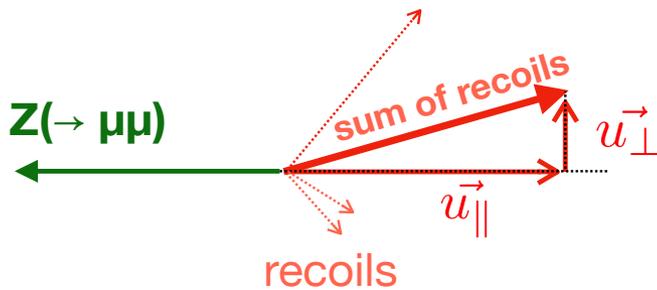
Standard PFMET:
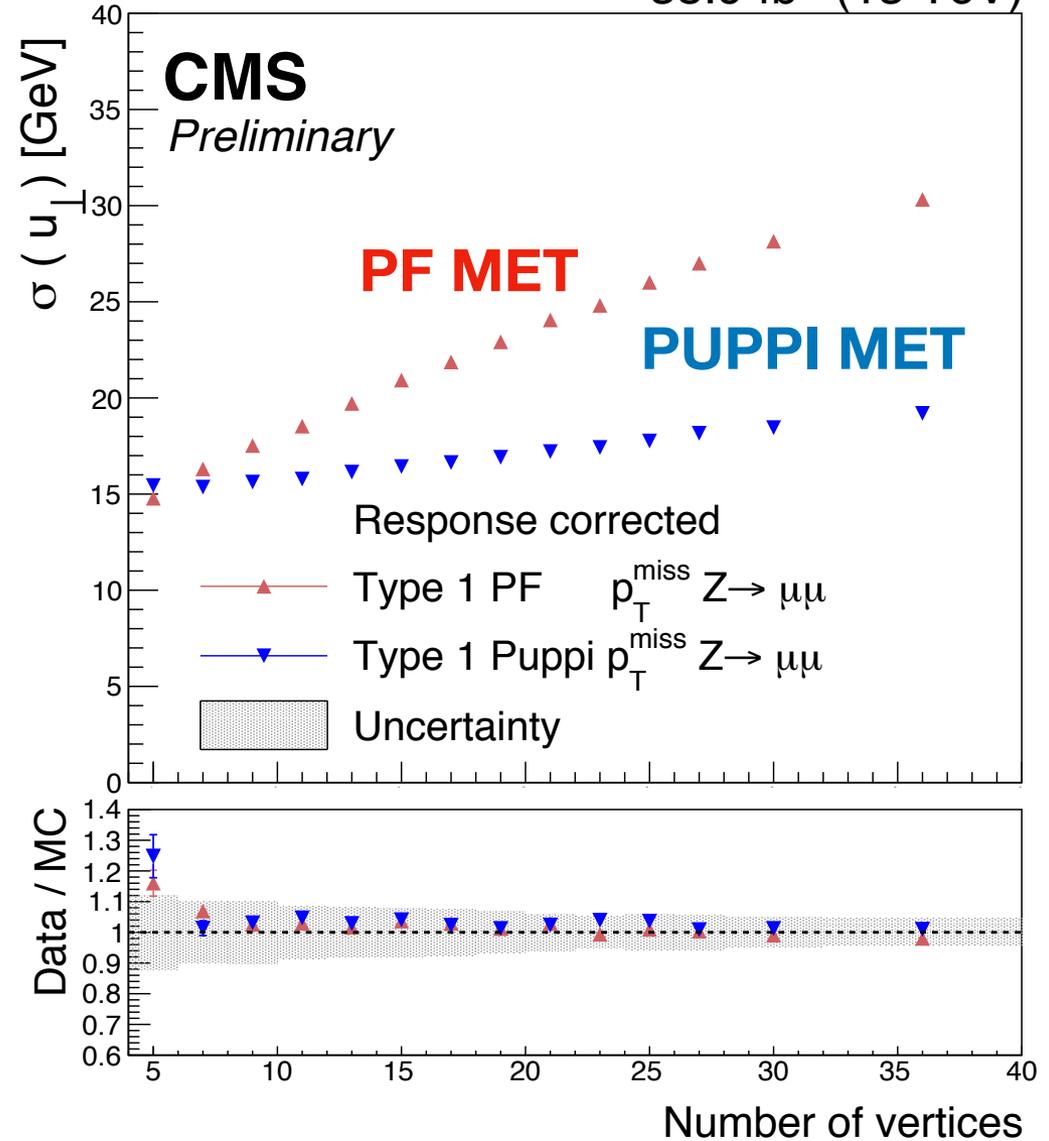
$$\vec{MET} = -\sum_{i=\text{PF particles}} \vec{P}_T^i$$

Adding PUPPI weight ω^i

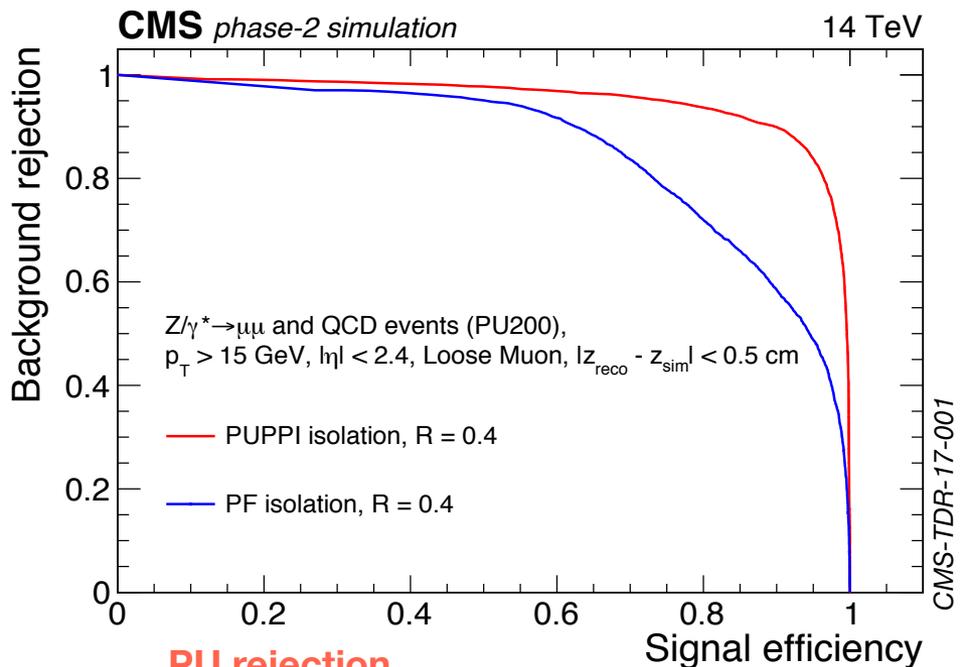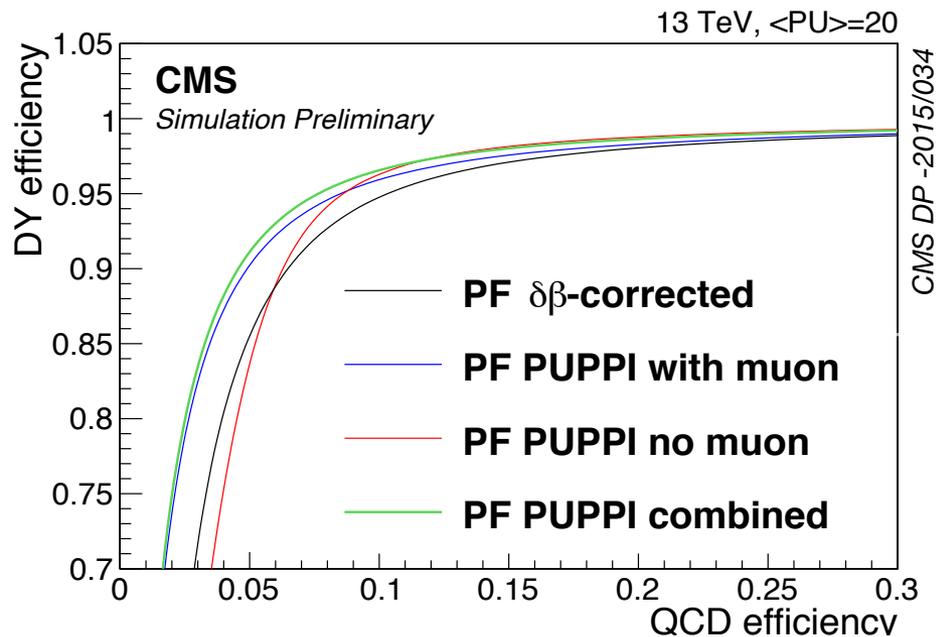$$\vec{PUPPI\text{-}MET} = -\sum_{i=\text{PF particles}} \vec{P}_T^i \omega^i$$

Z(→ μμ)

sum of recoils

$\vec{u_\perp}$

$\vec{u_\parallel}$

recoils

Z(→μμ) as standard candle: measure MET resolution

35.9 fb^{-1} (13

$\sigma(u_\perp)$ [GeV]

CMS
Preliminary

Response corrected

Type 1 PF $\quad$ p_T^{miss} Z→ μμ

Type 1 Puppi p_T^{miss} Z→ μμ

Uncertainty

Data / MC

Number of v

Schematic by S. Hasegawa

PUPPI and muon i...

CMS
Simulation Preliminary

DY efficiency

13 TeV, <PU>=20

CMS DP -2015/034

- **PF** $\delta\beta$-**corrected**
- **PF PUPPI with muon**
- **PF PUPPI no muon**

$$\delta\beta \text{ iso} = \sum_{dR<0.4}^{\text{Charged,LV}} P_T^i + \max(0, \sum_{dR<0.4}^{\text{neutrals}} P_T^i ...$$

QCD efficiency

Background rejection

CMS *phase-2 simulation*

Estimates contributi...
particles from PU ba...
of charged particles...

PF PUPPI

Isolation calculated...

$Z/\gamma^* \to \mu\mu$ and QCD events (PU2...

— PUPPI isolation, R = 0.4
— PF isolation, R = 0.4

PF PUPP...

PUPPI weight calcu...
muons as input

PF $\delta\beta$ **c...**

CMS
Simulation

prompt muon effi...

PF PUPPI

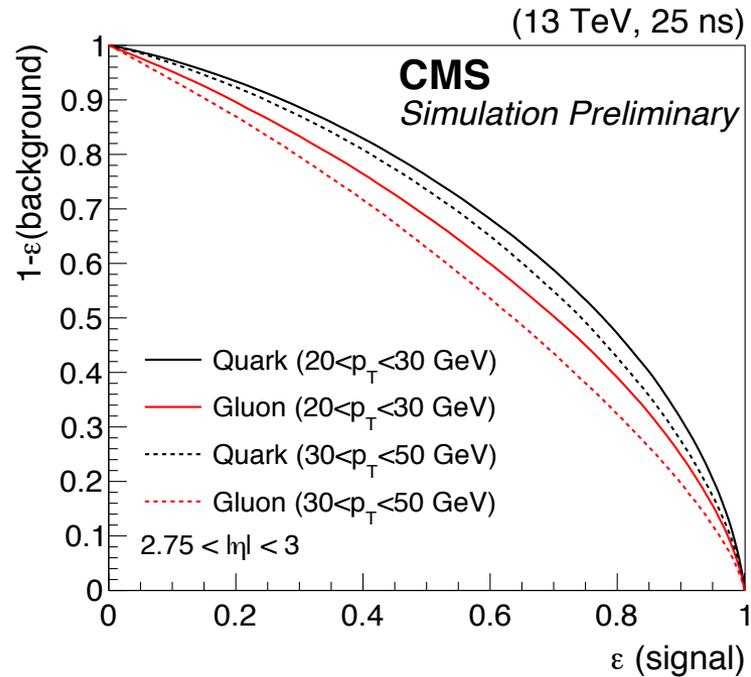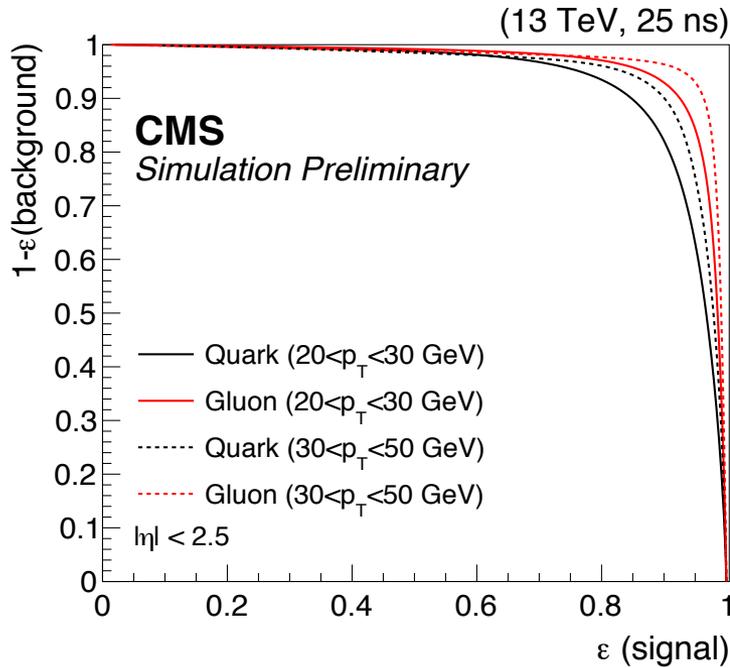$$\delta\beta \text{ iso} = \sum_{dR<0.4}^{\text{Charged,LV}} P_T^i + \max(0, \sum_{dR<0.4}^{\text{neutrals}} P_T^i - \frac{1}{2} \sum_{dR<0.4}^{\text{Charged,PU}} P_T^i)$$

PU rejection

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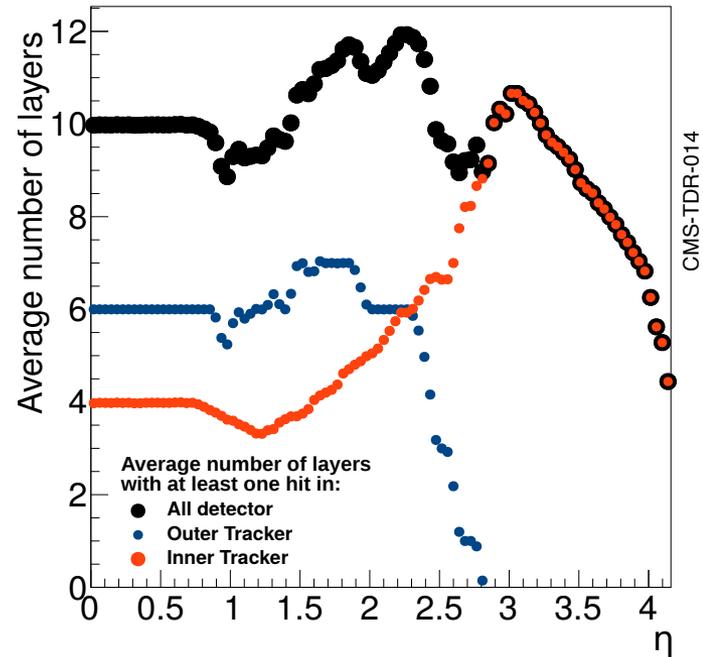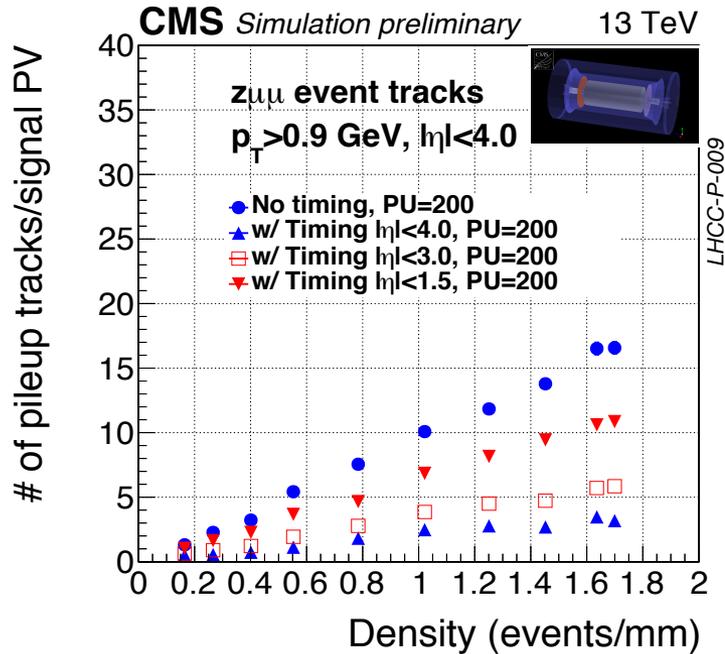
PU rejection

by PUPPI weight

PUPPI muon isolation slightly better at current LHC conditions
PUPPI sustains performance at HL-LHC conditions (PF isolation breaks down)

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In the absence of tracking

(13 TeV, 25 ns)

CMS
Simulation Preliminary

— Quark (20<p_T<30 GeV)
— Gluon (20<p_T<30 GeV)
---- Quark (30<p_T<50 GeV)
---- Gluon (30<p_T<50 GeV)

$|\eta| < 2.5$

(13 TeV, 25 ns)

CMS
Simulation Preliminary

— Quark (20<p_T<30 GeV)
— Gluon (20<p_T<30 GeV)
---- Quark (30<p_T<50 GeV)
---- Gluon (30<p_T<50 GeV)

$2.75 < |\eta| < 3$

— Quark
— Gluon
---- Quark
---- Gluon

$3 < |\eta| < 5$

Life is much harder, but PUPPI and PileupJetID (shown above) also provide at
least some power for mitigating pileup jets in endcap/forward

(13 TeV, 25 ns)

CMS
Simulation Preliminary

— Quark (20<p_T<30 GeV)
— Gluon (20<p_T<30 GeV)

(13 TeV, 25 ns)

CMS
Simulation Preliminary

— Quark (20<p_T<30 GeV)
— Gluon (20<p_T<30 GeV)

In the absence of tracking + future

Life is much harder, but PUPPI and PileupJetID (shown above) also provide at least some power for mitigating pileup jets in endcap/forward.

Future much brighter: Tracking up to |η|<4; Timing detector; HGCAL

fast timing layers: the CMS example   *Andrea Davide Benaglia et al.*

Krakow   16:40 - 17:00

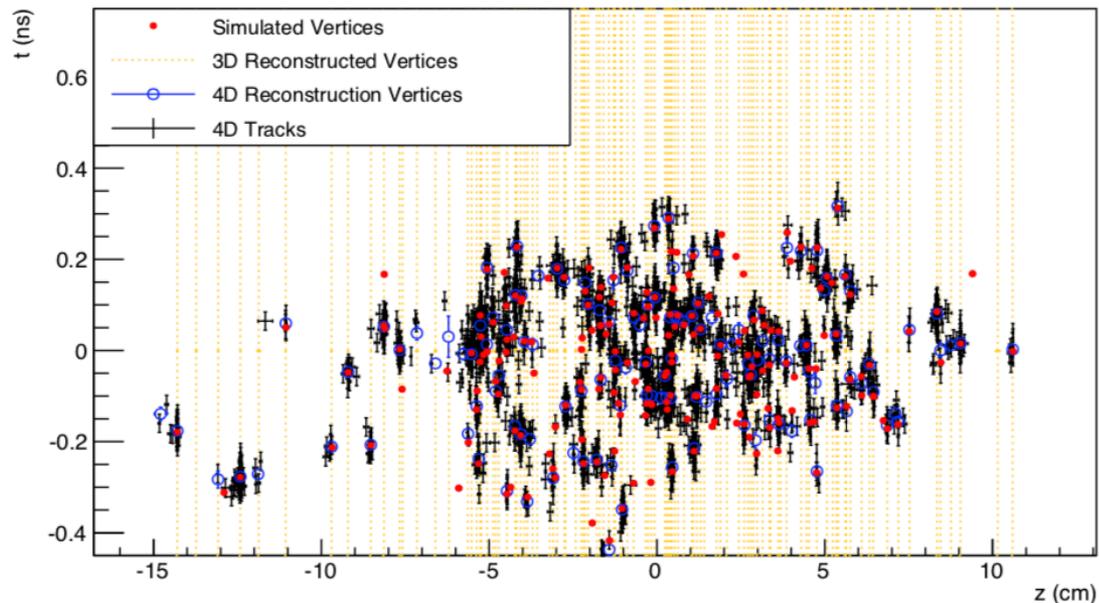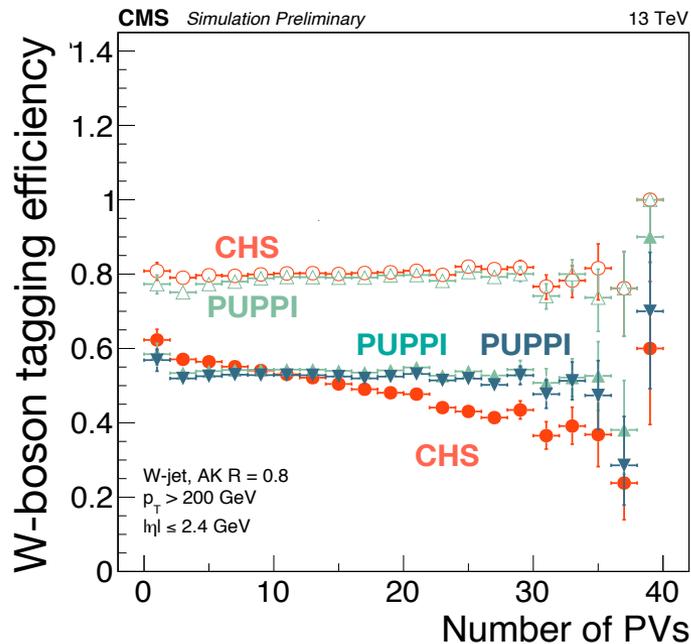**Highly granular forward calorimetry**   *Clemens Lange et al.*

Krakow   11:00 - 11:20
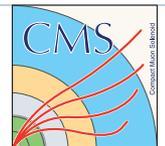
Conclusions

- Pileup is a serious threat to physics performance, but the price we pay for ever higher luminosity
- Run 2 conditions well under control (especially in tracker-covered region)
- Tackling the challenge from many directions: low level reconstruction (pulse shapes), per particle removal, grooming for substructure
- Towards HL-LHC: Tracking up to $|\eta|<4$; Timing detector; HGCAL
  - + plenty of time for algorithm development

Backup

UNIVERSITY OF HELSINKI
AND
HELSINKI INSTITUTE OF PHYSICS

Gustaf Hällströmin katu 2
P.O.Box 64
00014 University of Helsinki
FINLAND

T +358-2-941 50564
mikko.voutilainen@helsinki.fi
mikko.voutilainen@cern.ch
voutila.web.cern.ch
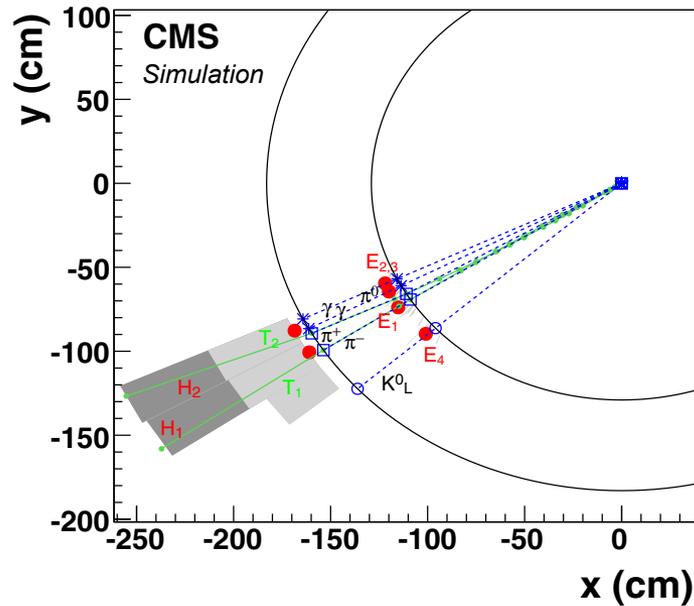
UNIVERSITY OF HELSINKI

Particle flow

Figure: Event display of an illustrative jet made of five particles only in the (x, y) view (upper panel), and in the (η, φ) view on the ECAL surface (lower left) and the HCAL surface (lower right). In the top view, these two surfaces are represented as circles centred around the interaction point. The K_L^0, the π^-, and the two photons from the π^0 decay are detected as four well-separated ECAL clusters denoted $E_{1,2,3,4}$. The π^+ does not create a cluster in the ECAL. The two charged pions are reconstructed as charged-particle tracks $T_{1,2}$, appearing as vertical solid lines in the (η, φ) views and circular arcs in the (x, y) view. These tracks point towards two HCAL clusters $H_{1,2}$. In the bottom views, the ECAL and HCAL cells are represented as squares, with an inner area proportional to the logarithm of the cell energy. Cells with an energy larger than those of the neighbouring cells are shown in dark grey. In all three views, the cluster positions are represented by dots, the simulated particles by dashed lines, and the positions of their impacts on the calorimeter surfaces by various open markers.

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