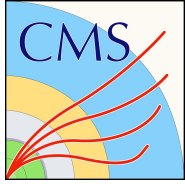
中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences



Missing transverse energy (MET) and pileup (PU) short exercise

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3nd China Winter Camp – Jan 18th, 2025

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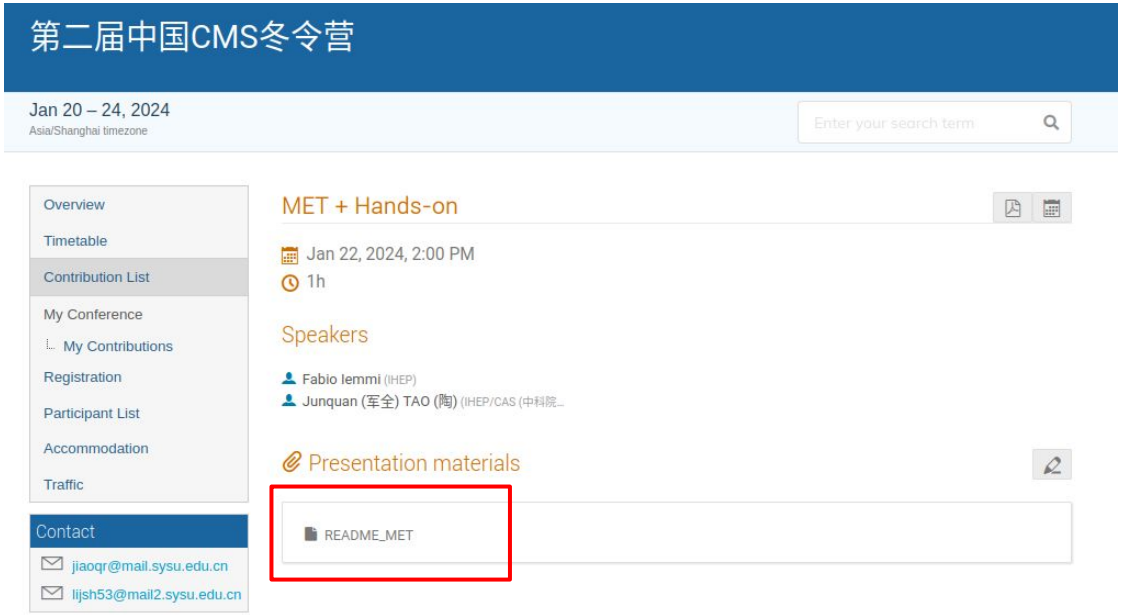
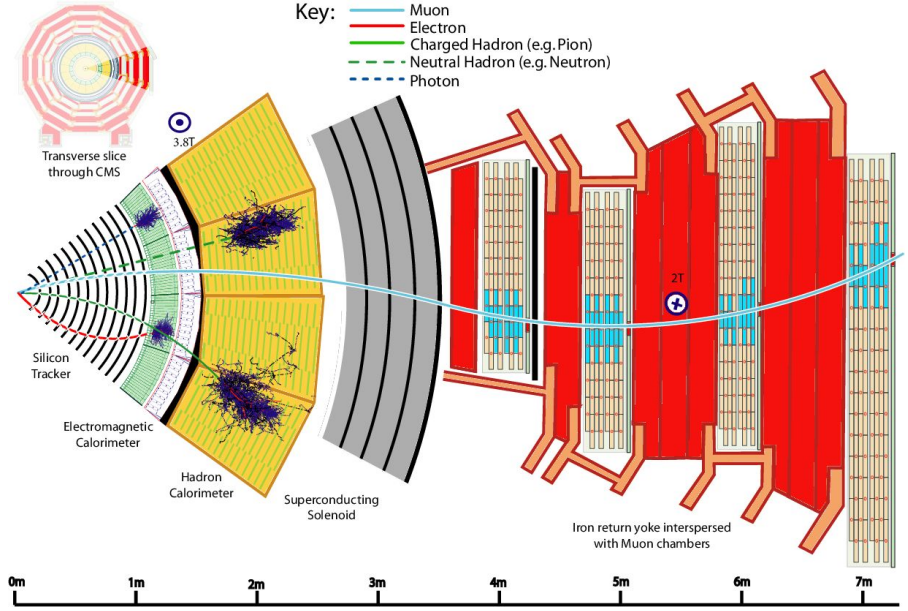
Before we start: introductory links

- Open the readme [link]



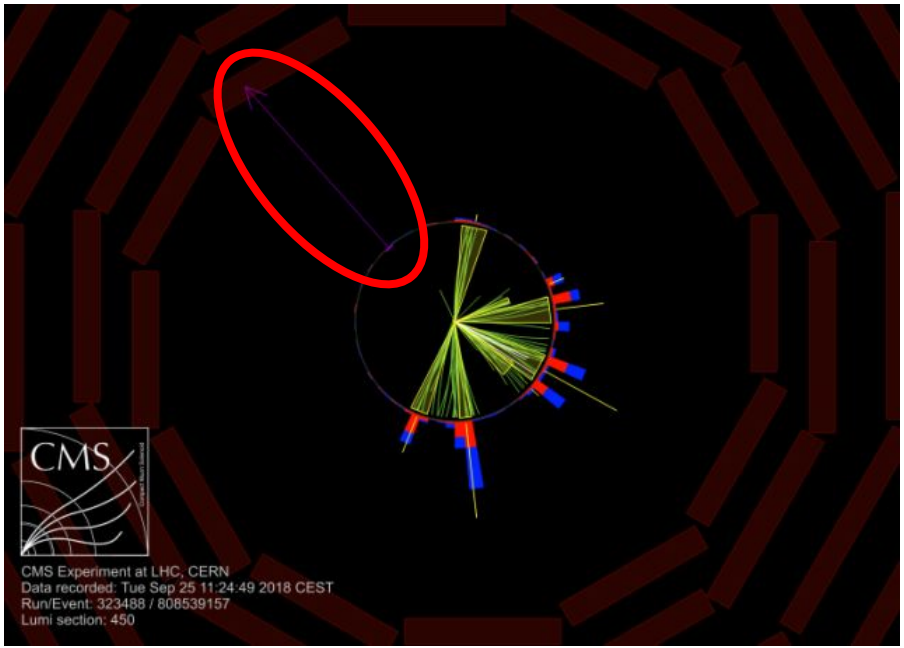
- Open the exercise TWiki [link]

Introduction: event reconstruction in CMS



- Particles are reconstructed combining information from all subdetectors
  - **Particle flow (PF) algorithm**
- Output of PF is a collection of **PF candidates** (i.e., reconstructed particles)
  - Electrons, muons, photons, charged hadrons, neutral hadrons
- PF candidates are used to build high-level objects
  - Jets, MET, isolated electrons/photons/muons, hadronic taus

Momentum balance in the transverse plane



- In plane transverse to beam direction, **zero momentum before collision**
- **Momentum is conserved**, so total transverse momentum must be zero after collision too
- Weakly interacting particles (e.g., neutrinos, dark matter) leave no signal in the detector
- Infer their presence by **looking for imbalance in transverse momentum** (MET)

Missing transverse energy (MET)

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=1}^{\mathrm{N_{PF}}} \vec{p}_{\mathrm{T},i}$$

- MET is the **negative vector sum of transverse momenta of all PF candidates** in the collision event
- Since it's made out of PF candidates, we usually **call it PFMET**
- Crucial ingredient for Standard Model (SM) measurements involving neutrinos
- Crucial ingredient for beyond Standard Model (BSM) searches involving dark matter, SUSY, …

Missing transverse energy (MET)

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=1}^{\mathrm{N_{PF}}} \vec{p}_{\mathrm{T},i}$$

- MET calculated with this formula is referred to as **raw PFMET**
- Raw PFMET is inaccurate due to several factors:
  - Calorimeters p_T thresholds to remove noise
  - Nonlinearity in calorimeters response
  - Reconstruction inefficiencies
- In CMS, we **normally use a corrected version of raw MET**
  - **Type-1 (T1) corrected PFMET**
- We will get familiar with it during the exercise

Hands-on 1: event content in MiniAOD* data tier

* AOD = Analysis Object Data

Hands-on 1: event content in MiniAOD data tier

- Goals: get familiar with:
  - Event content in MiniAOD data tier
  - MET collections in MiniAOD data tier
  - Tools to browse MiniAOD content
- At the end of the exercise you should be able to see:
  - MET collections stored in MiniAOD data tier

```
vector<pat::MET>                "slimmedMETs"           ""              "PAT"
vector<pat::MET>                "slimmedMETsNoHF"       ""              "PAT"
vector<pat::MET>                "slimmedMETsPuppi"      ""              "PAT"
```

Hands-on 2: access to MET objects in MiniAOD

Clustered & unclustered MET; type-1 corrected MET

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=1}^{\mathrm{N_{PF}}} \vec{p}_{\mathrm{T},i}$$

$$= -\left(\sum_{i=1}^{\mathrm{N_{PF\text{-}clust}}} \vec{p}_{\mathrm{T},i} + \sum_{i=j}^{\mathrm{N_{PF\text{-}unclust}}} \vec{p}_{\mathrm{T},j} \right)$$

$$= -\left(\sum_{k=1}^{\mathrm{N_{jet}}} \vec{p}_{\mathrm{T},k} + \sum_{i=j}^{\mathrm{N_{PF\text{-}unclust}}} \vec{p}_{\mathrm{T},j} \right)$$

$$= -\sum_{k=1}^{\mathrm{N_{jet}}} \vec{p}_{\mathrm{T},k} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss,\ uncl}}$$

Apply JES to this part!

- MET can be decomposed in clustered and unclustered part
  - Clustered: PF candidates that are clustered into jets
  - Unclustered: PF candidates that are not clustered in to jets
- We can **apply jet energy scale corrections** (JES) **to the clustered part**: **type-1 (T1)** correction
  - When no JECs applied: **raw PFMET**
  - When JECs applied: **T1 PFMET**
- **Additional (optional) corrections**:
  - Jet energy resolution (JER)
  - XY shift correction
  - More at [this link]

MET uncertainties

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=1}^{\mathrm{N_{PF}}} \vec{p}_{\mathrm{T},i}$$

$$= -\left(\sum_{i=1}^{\mathrm{N_{PF\text{-}clust}}} \vec{p}_{\mathrm{T},i} + \sum_{i=j}^{\mathrm{N_{PF\text{-}unclust}}} \vec{p}_{\mathrm{T},j} \right)$$

$$= -\left(\sum_{k=1}^{\mathrm{N_{jet}}} \vec{p}_{\mathrm{T},k} + \sum_{i=j}^{\mathrm{N_{PF\text{-}unclust}}} \vec{p}_{\mathrm{T},j} \right)$$

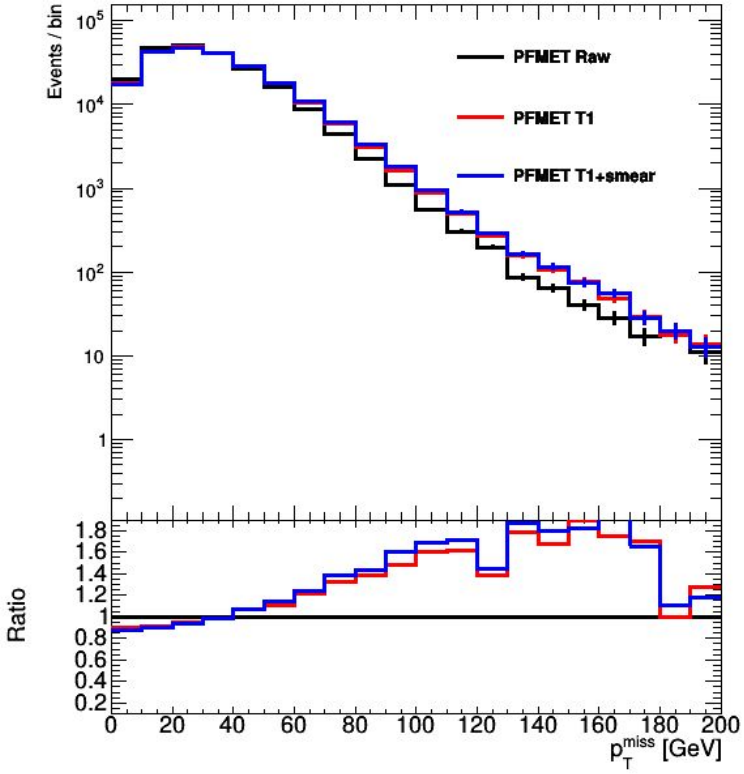
$$= -\sum_{k=1}^{\mathrm{N_{jet}}} \vec{p}_{\mathrm{T},k} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss,\ uncl}}$$

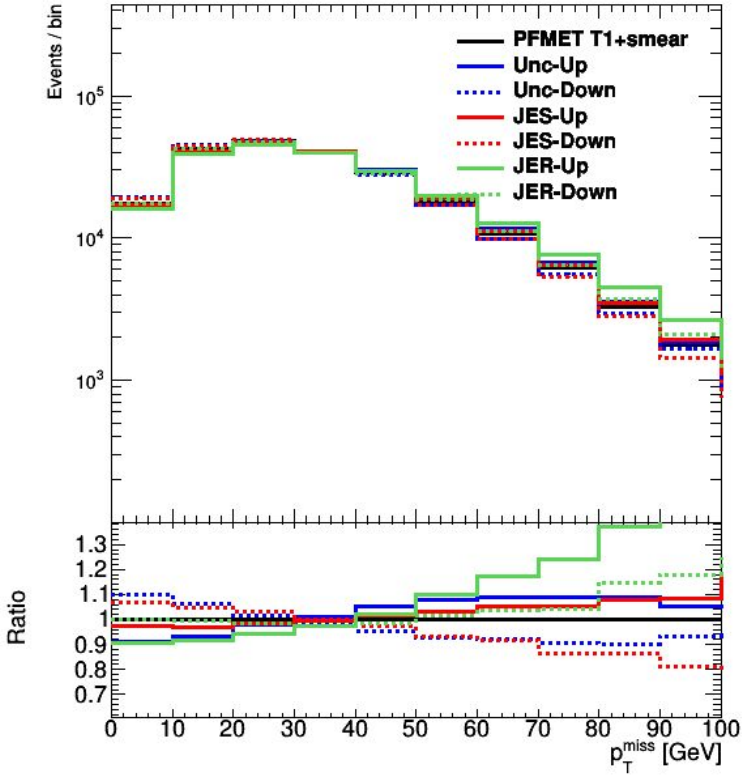
Affected by JES/JER uncertainty

Affected by uncl. energy uncertainty

- **MET** is a composite object and i**s not measured directly**
- Instead, **it is inferred** from other high-level objects
- **Each class of high-level object affects the MET** uncertainties:
  - Jets, muons, electrons, taus, photons
- We will focus on three sources of uncertainty
  - **JES & JER**: propagate uncertainties on JES & JER to MET
  - **Unclustered energy**: vary each particle type by his own resolution

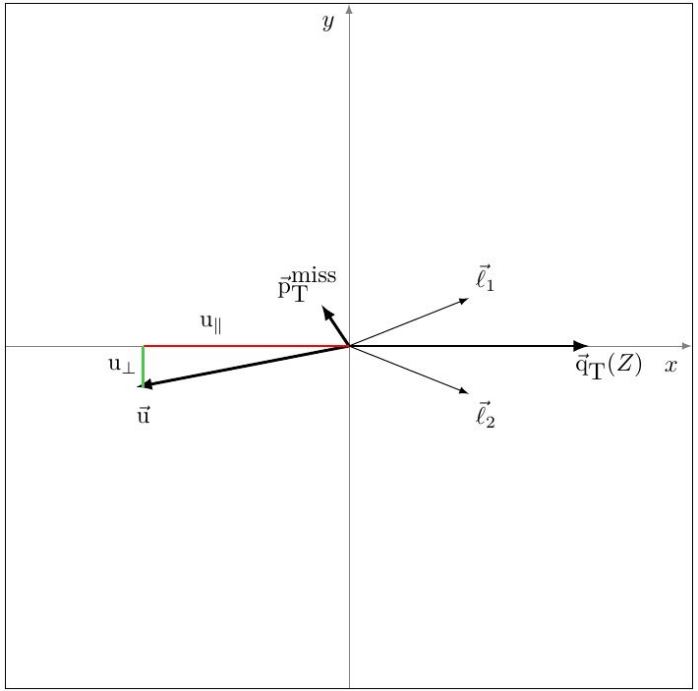
Hands-on 2: what you should be seeing





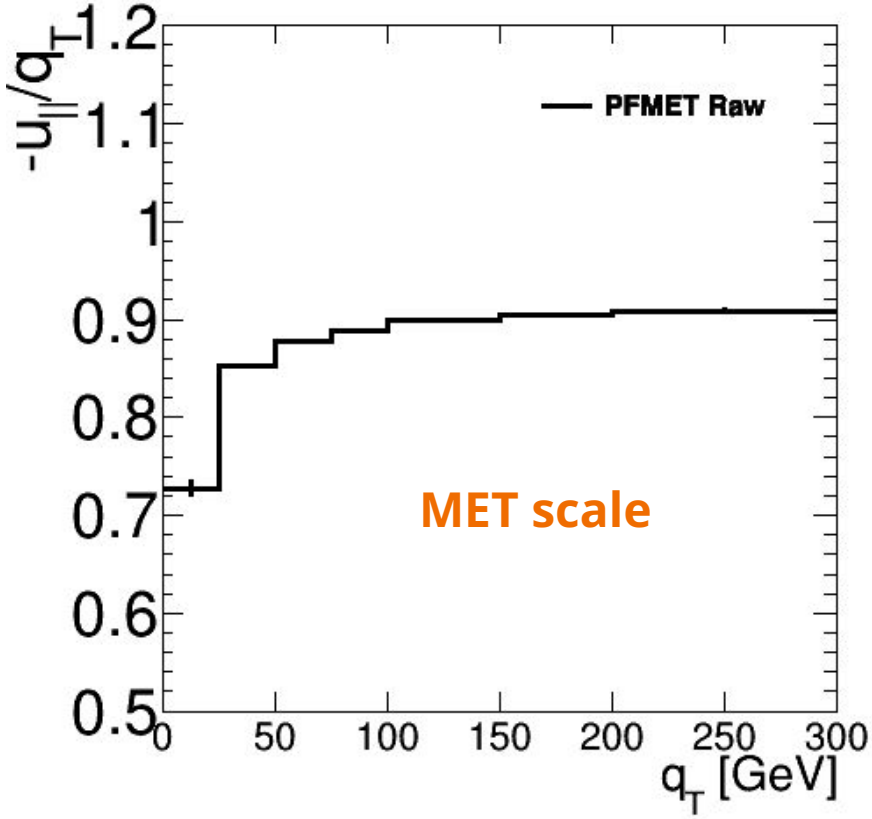
Hands-on 3: MET calibration and performance

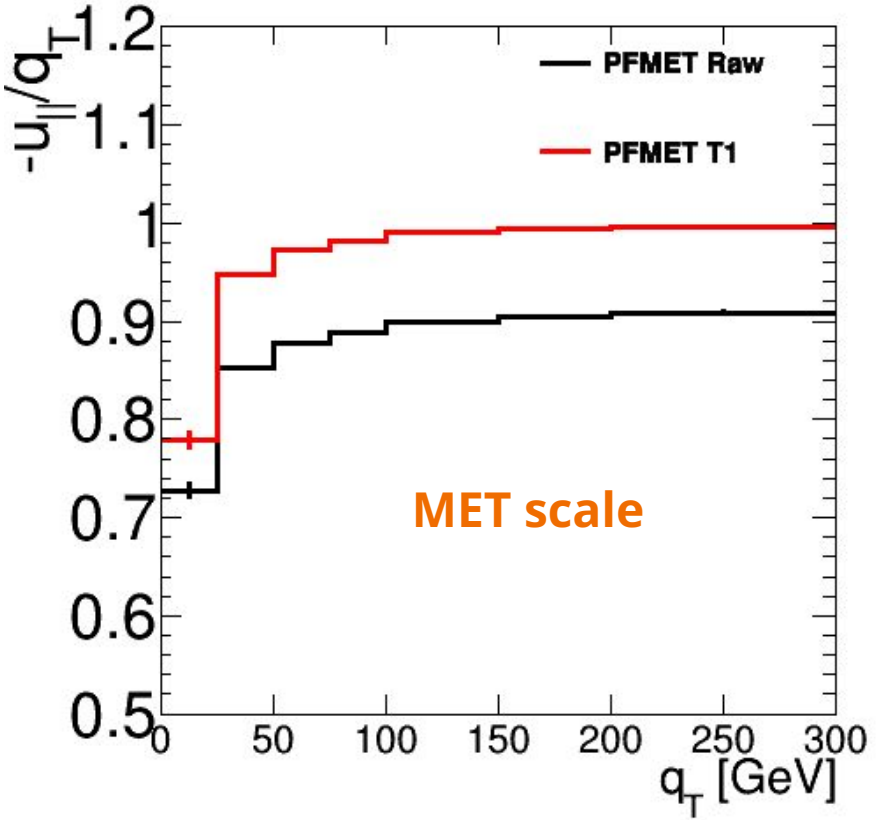
Drell-Yan + jets phase space



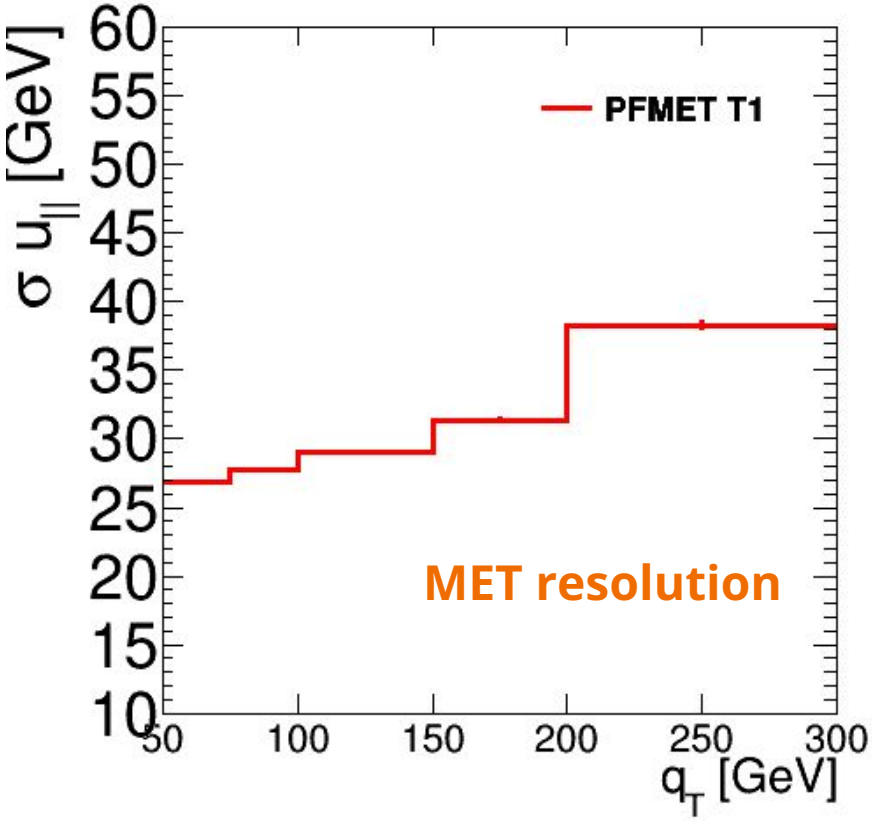
- **Z/γ(ll) + jets** events used to study MET
- **Little to no genuine MET** in such events
  - Most of the MET comes from detector effects
- **Hadronic activity** (jets) recoils against the vector boson
- Vector boson p_T (q_T) and hadronic recoil p_T (u) are balanced by a small amount of MET
- **Two components** for the hadronic recoil
  - Parallel to Z boson direction: $u_{||}$
  - Perpendicular to Z boson direction: $u_\perp$
- Use $u_{||}$ and $u_\perp$ as proxies for MET performance
- What values do you expect for $u_{||}$ and $u_\perp$?

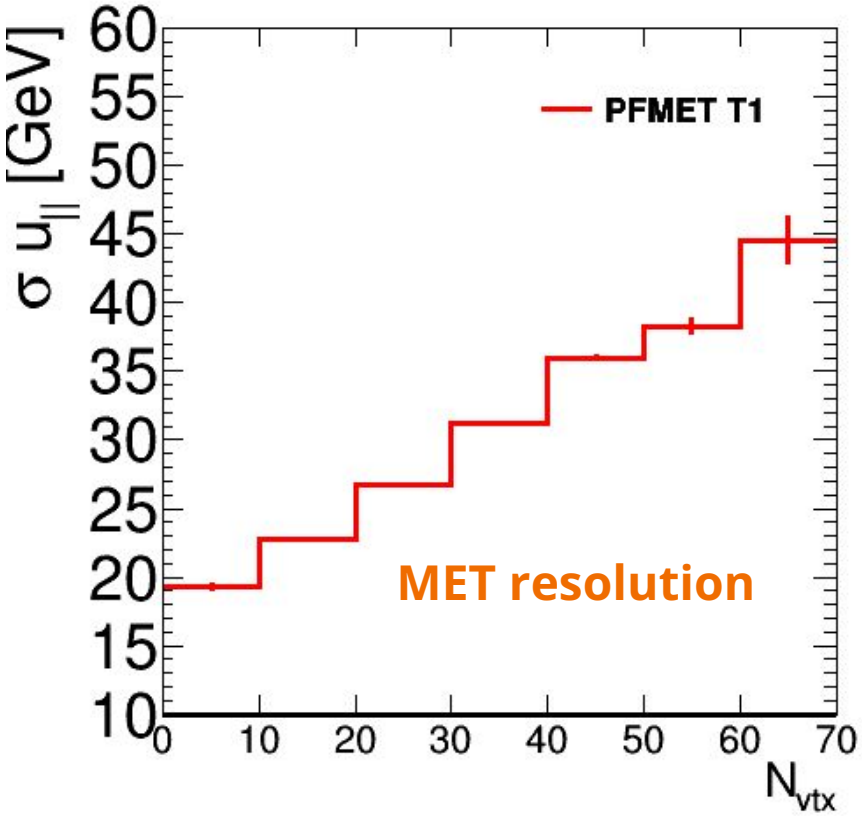
Hands-on 3: what you should be seeing



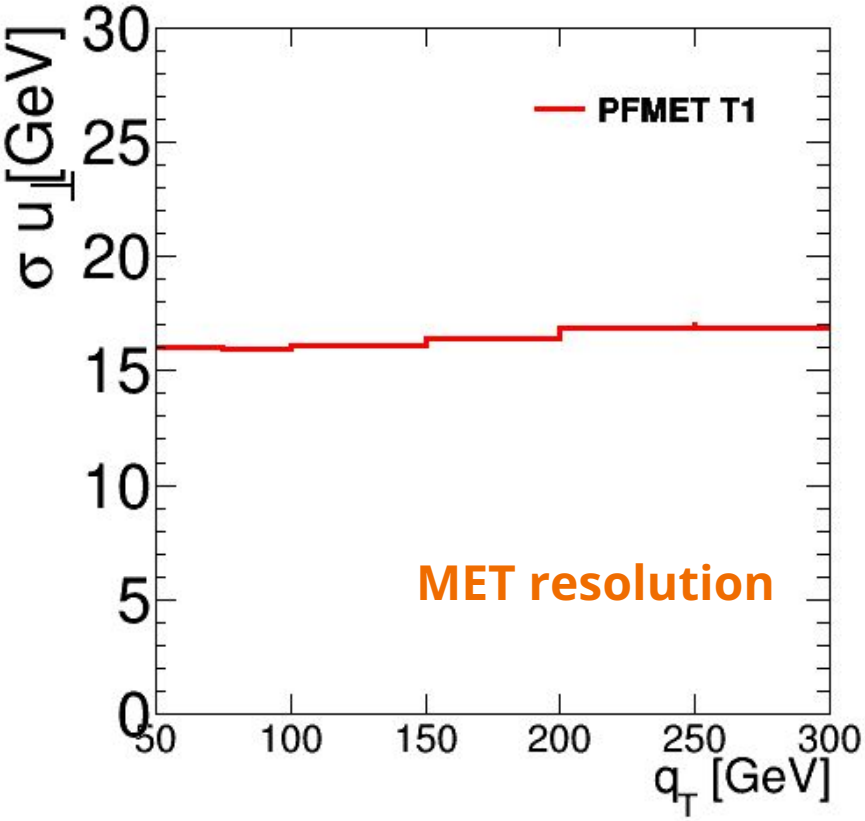


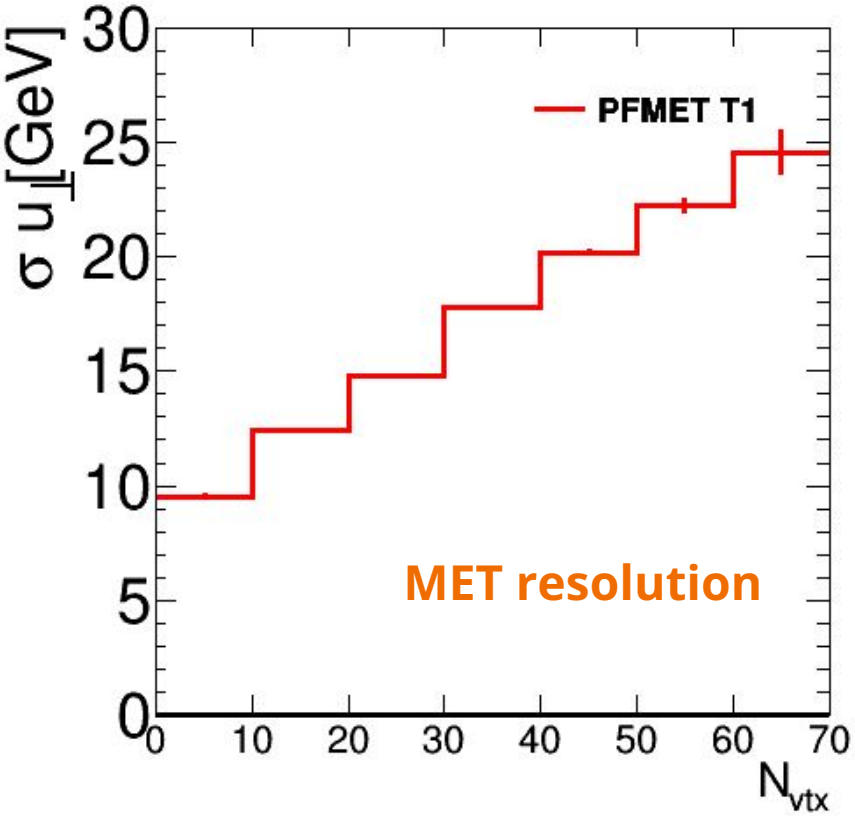
Hands-on 3: what you should be seeing





Hands-on 3: what you should be seeing

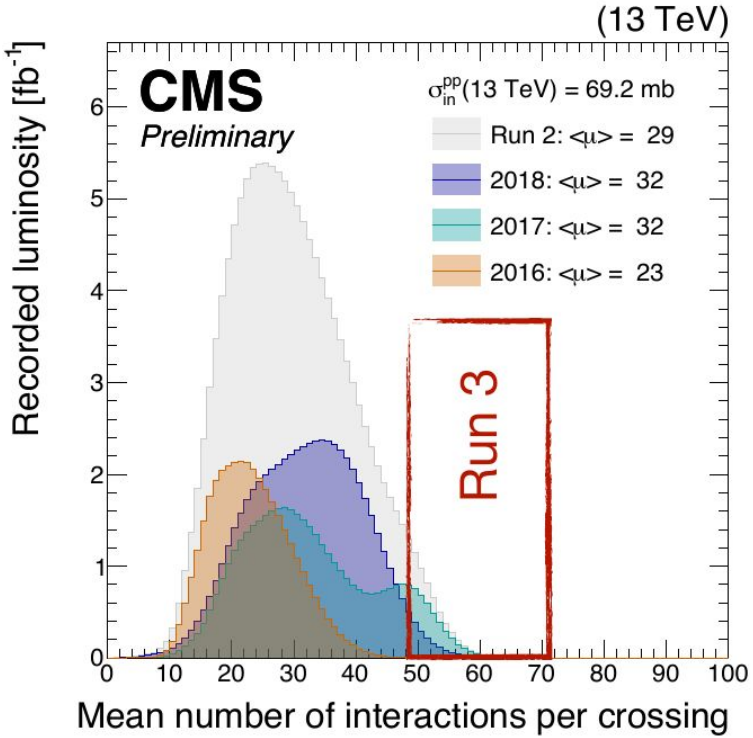




Hands-on 4: Pileup

Introduction: state of the art in PU mitigation

- **Pileup:** additional proton-proton collisions in the same (or neighboring) bunch crossing
- **Pileup is ubiquitous** at hadron colliders
- PU doubled in Run3 wrt Run2
  - Will reach <PU> = 140 at HL-LHC
- **State of the art** PU mitigation in CMS: **PUPPI**
  - **Default algorithm for Run3**
  - **Cut based algorithm**
  - For each particle, check activity in a small cone around it
  - Obtain a per-particle probability to be LV
    - PUPPI weights w_i

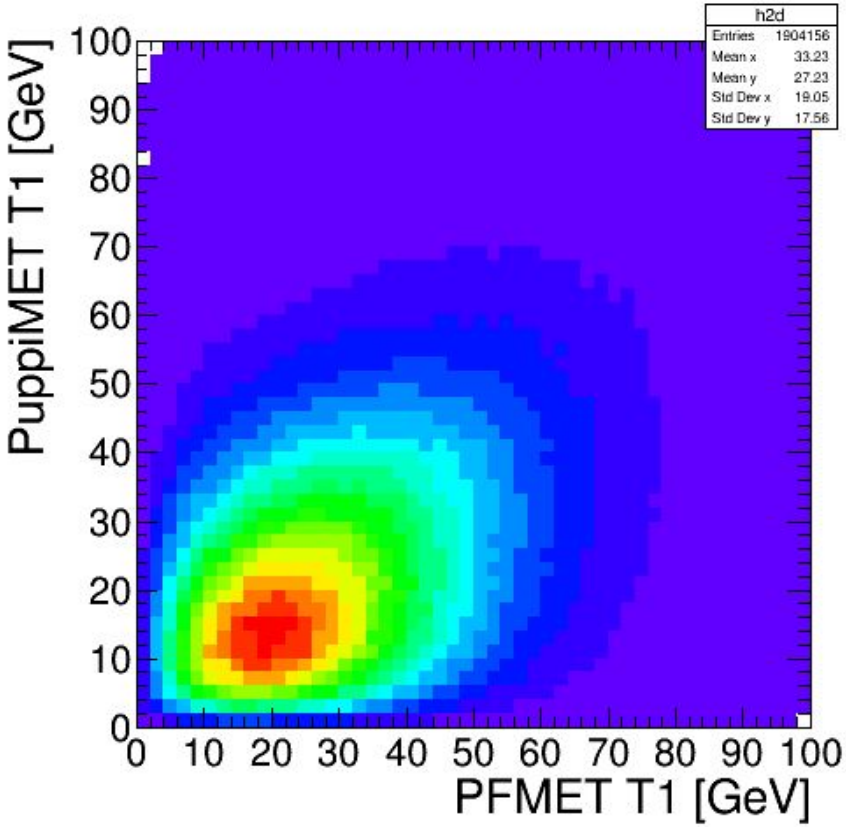


PUPPI MET

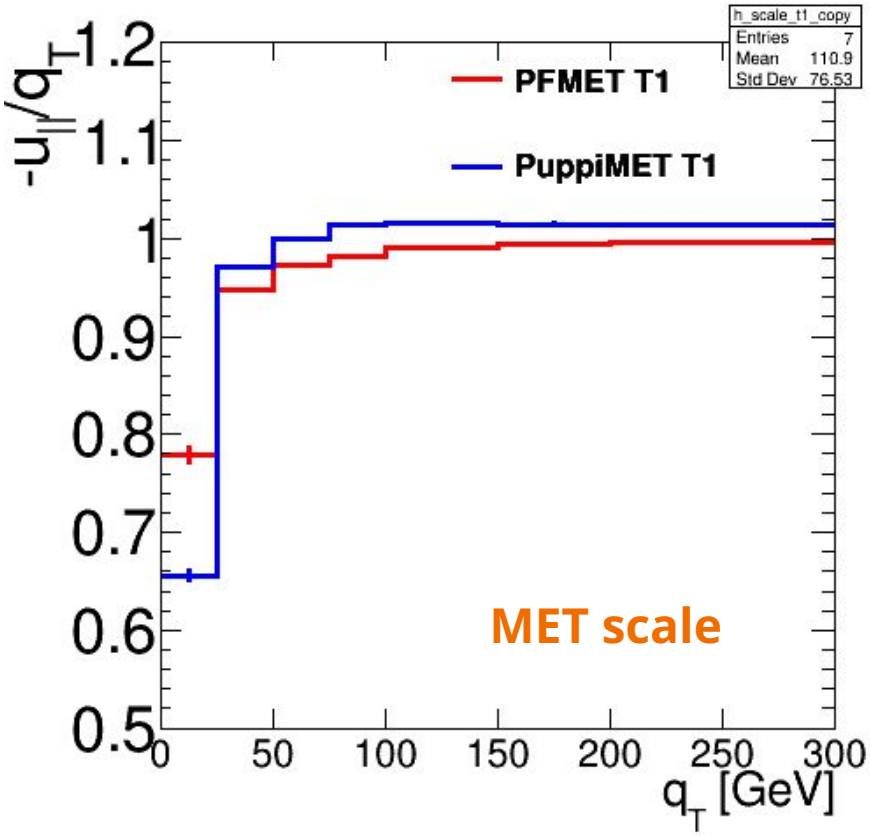
$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=1}^{\mathrm{N_{PF}}} w_i \cdot \vec{p}_{\mathrm{T},i}$$

- PUPPI MET is obtained by **weighting each PF candidate** in the event **by it's PUPPI weight** w_i
- We expect PUPPI MET to have better scale than PFMET
- We expect PUPPI MET to be **more robust against pileup**
- **PUPPI MET is the default MET flavor in Run3**

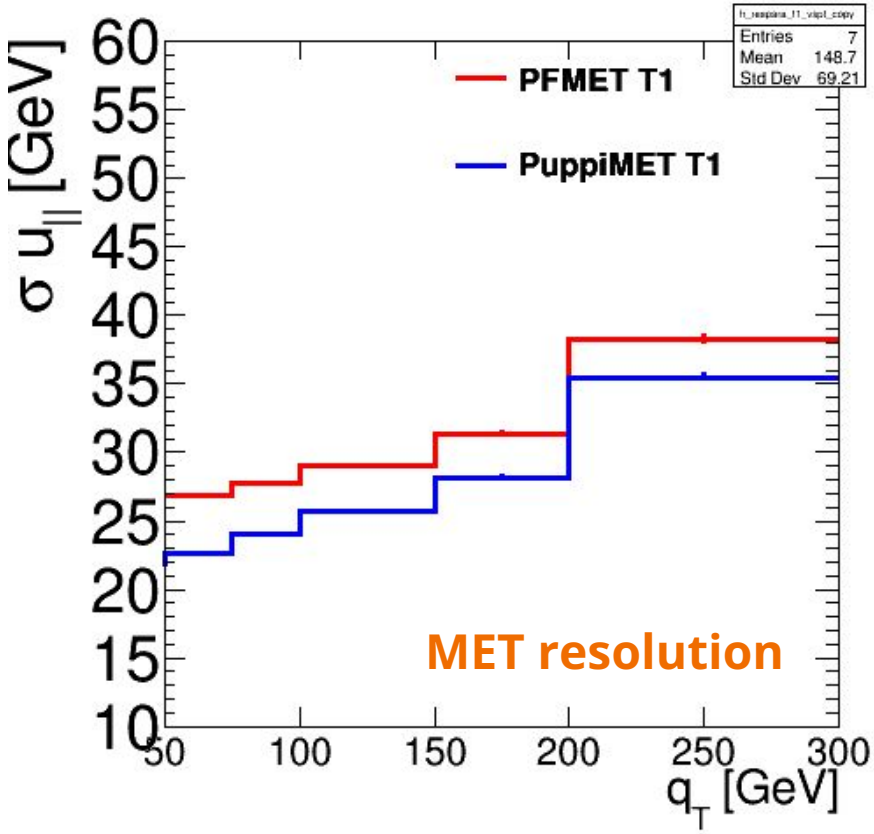
Hands-on 4: what you should be seeing

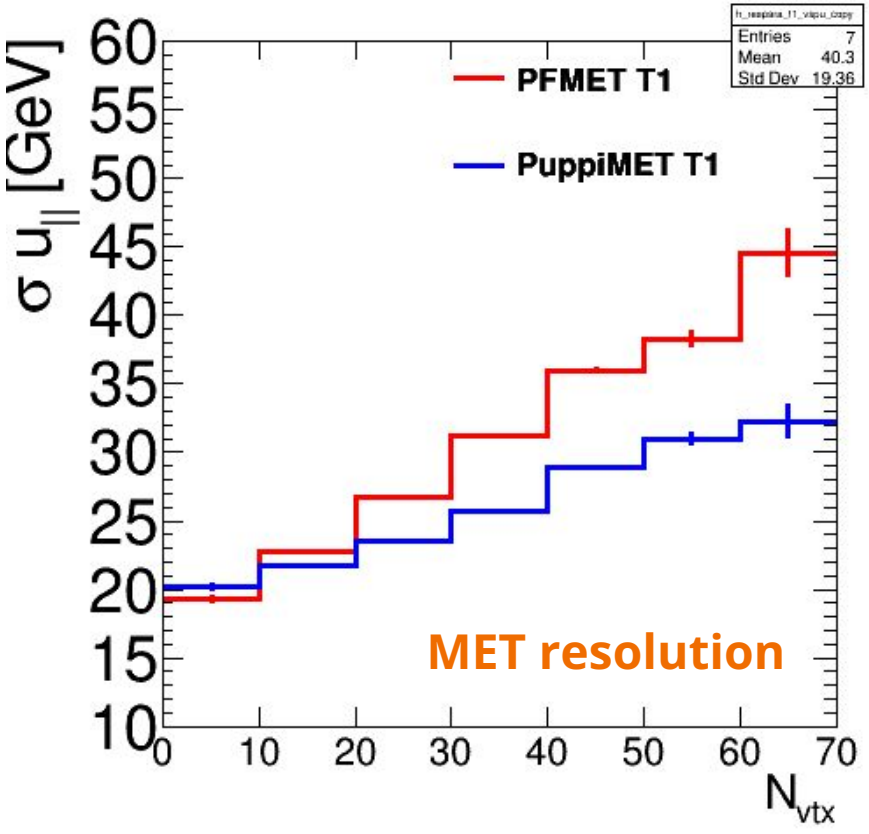


Hands-on 4: what you should be seeing

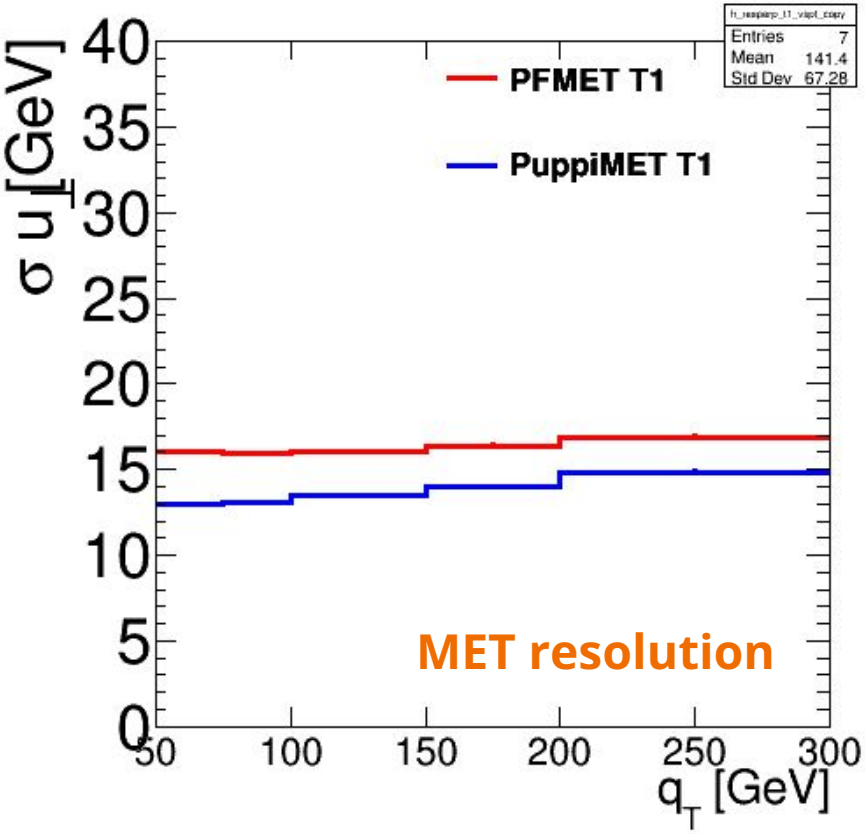


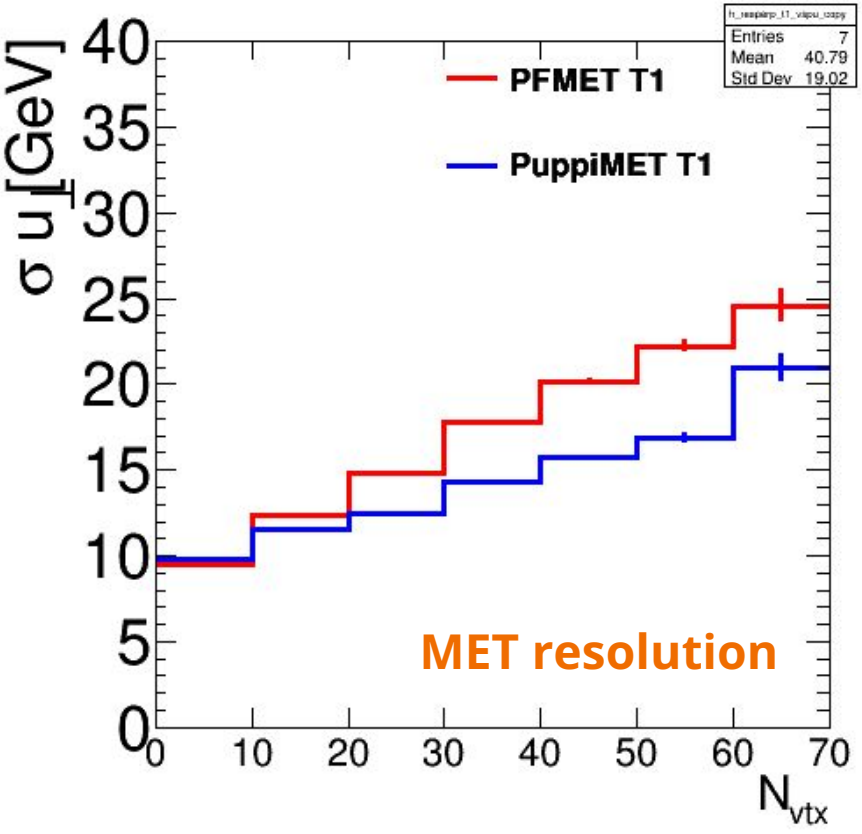
Hands-on 4: what you should be seeing





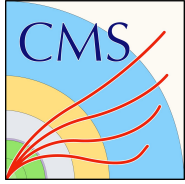
Hands-on 4: what you should be seeing





Hands-on 5: sources of fake MET and MET filters

Fake MET and noise filters (previously MET filters)



- Anomalous high-MET events can be reconstructed (even if no genuine MET is expected) due to:
  - Detector noise (e.g., from ECAL/HCAL readout)
  - Detector inefficiencies (dead calorimetric cells)
  - Machine-induced backgrounds (beam halo)
  - Misreconstruction of physics objects (e.g., bad PF muons, i.e., cosmic muons)
- Noise filters are designed to reject events with anomalous high-MET
- **Their use is recommended for all CMS analyses (including analyses not using MET!)**
- At the end of the exercise you should be able to see:
  - Effect of noise filters on MiniAOD events

Backup slides