Jets and MET with ATLAS and CMS

25 May 2023

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on behalf of the ATLAS and CMS Collaborations

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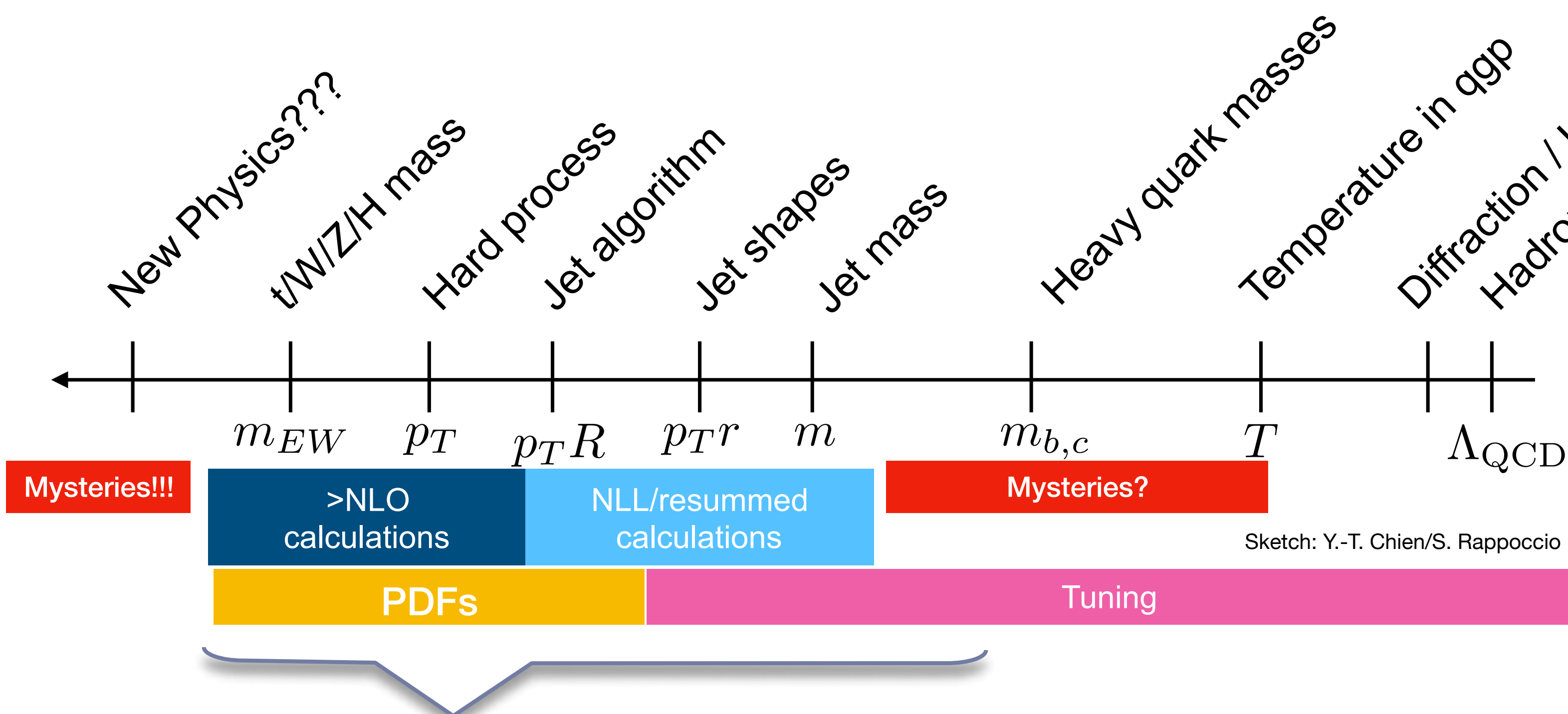
LHCPhysics
Belgrade, 22 - 26 May 2023

ATLAS
EXPERIMENT

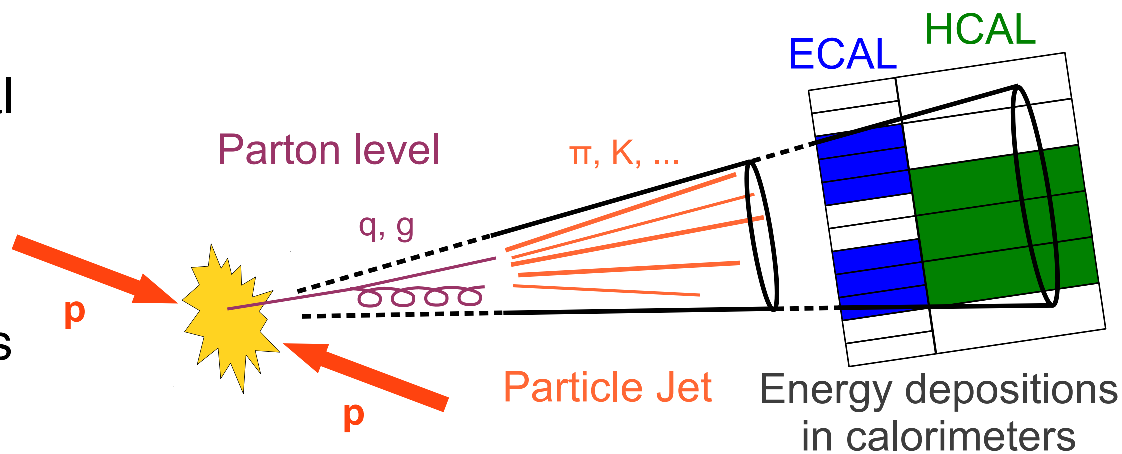
CMS

Jets …

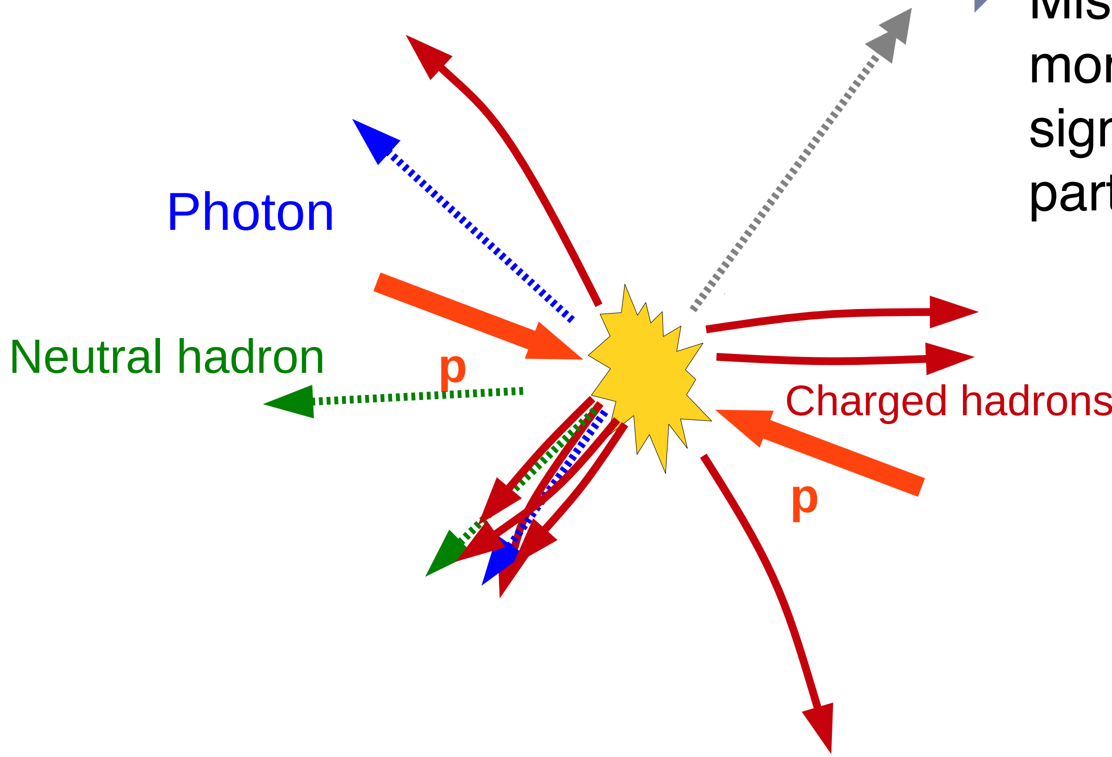


https://www.particlezoo.net/

- Jets "today" are [also] experimental signatures of quarks/gluon
- Hadronic final states are a major part of the LHC physics program: Backgrounds/ signals/pileup



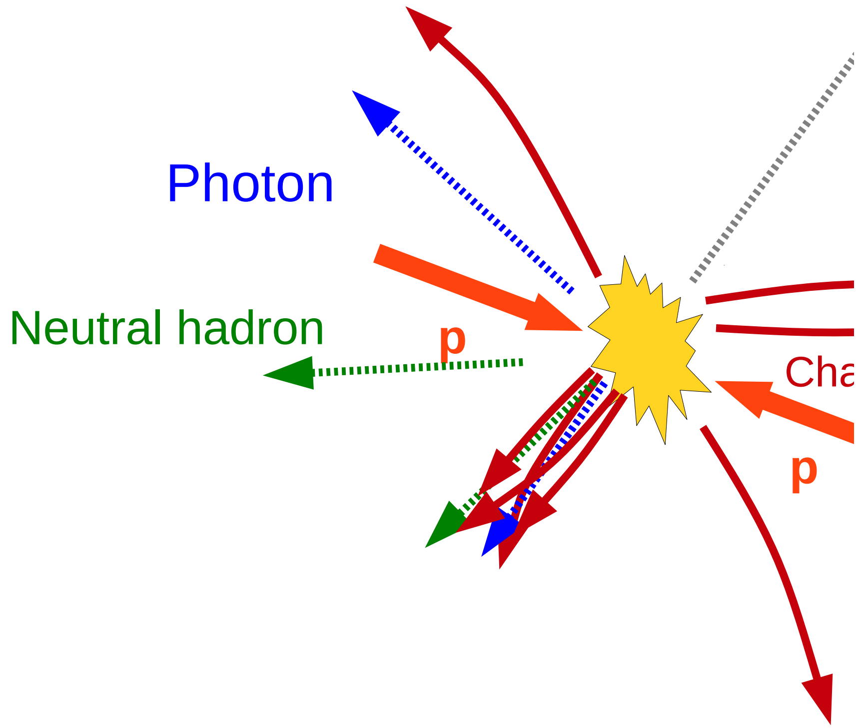
… and missing transverse momentum

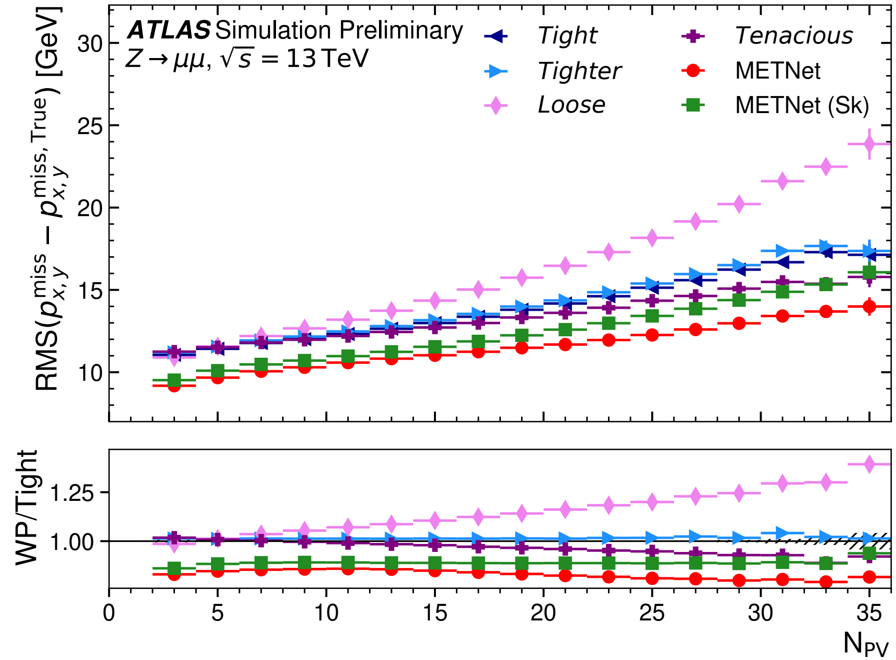


- Missing transverse momentum: 'Detector signature' for invisible particles...

- Negative vector sum of p_T of objects in the event
  - CMS: all PF candidates (weighted in the case of PUPPI MET)
  - ATLAS: $$p_T^{miss} = -\left| \underbrace{\sum_{\substack{\text{selected}\\ \text{electrons}}} p_T^e + \sum_{\substack{\text{accepted}\\ \text{photons}}} p_T^\gamma + \sum_{\substack{\text{accepted}\\ \tau-\text{leptons}}} p_T^\tau + \sum_{\substack{\text{selected}\\ \mu}} p_T^\mu + \sum_{\substack{\text{accepted}\\ \text{jets}}} p_T^{\text{jet}}}_{\text{hard term}} + \underbrace{\sum_{\substack{\text{unused}\\ \text{tracks}}} p_T^{\text{track}}}_{\text{soft term}} \right|$$
- Always: Lower-level detector calibration crucial for p_T^{miss}

… and missing transverse momentum

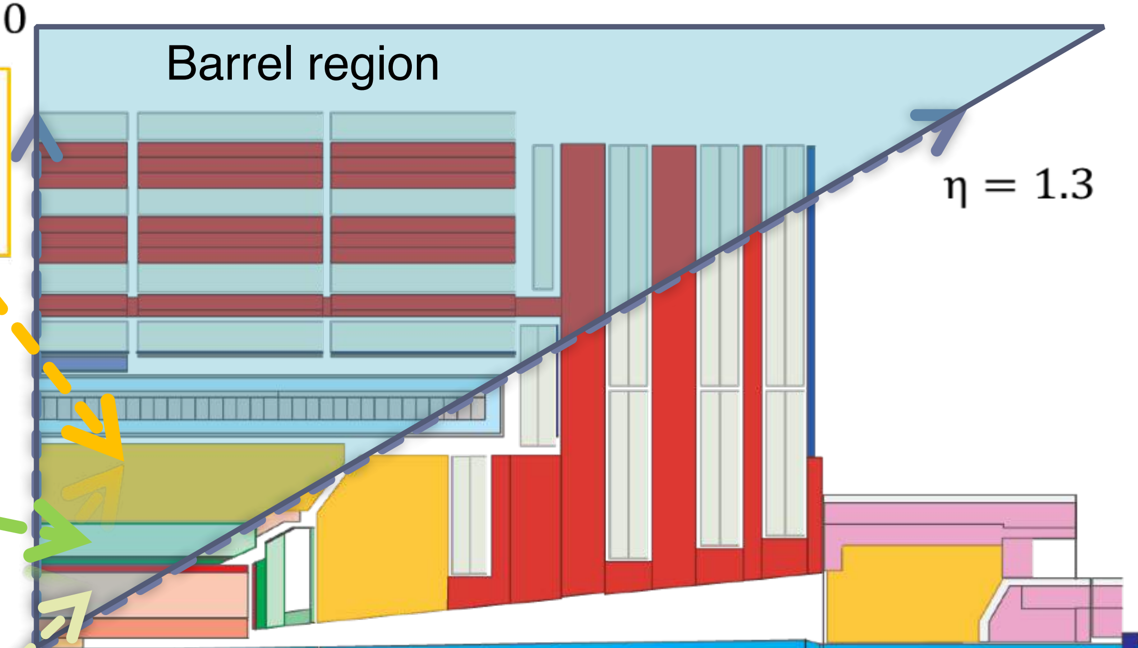




- Negative vector sum of p_T of objects
  - CMS: all PF candidates (weighte
  - ATLAS: $p_T^{miss} = -\Big| \sum_{\substack{\text{selected}\\ \text{electrons}}} p_T^e + \sum_{\substack{\text{accepted}\\ \text{photons}}} p_T^\gamma + \sum_{\substack{\text{accepted}\\ \tau\text{-leptons}}} p$ … (hard term)
- Always: Lower-level detector calibra

- METNet as machine learning p_T^{miss}
  - Considers different WPs for jets to output improved estimate
    - Better resolution
  - Also investigating MET significance

CMS detector (for jets)



HCAL: Brass/scintillator($|\eta| < 3$)
$\frac{\sigma(E)}{E} \sim 18\%$ for 50 GeV $\pi^{+/-}$
→Hadrons

ECAL: $PbWO_4$ Crystal calorimeter
$\frac{\sigma(E)}{E} \sim 2\%$ for 50 GeV e^-
→Electrons, photons

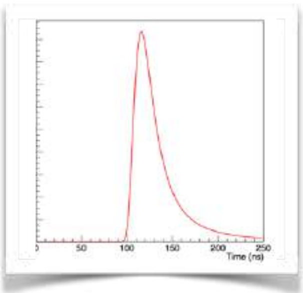
Tracker: Silicon Pixel and Strip detector
$\frac{\sigma(p_T)}{p_T} \sim 0.7\%$ at 10 GeV
→ Charged particles

CMS specifics

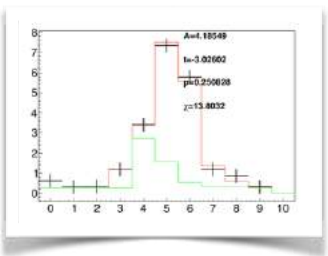
- Very precise tracker and ECAL
- Highly granular ECAL
- Tracking and calorimeters contained within superconducting magnet
- Strong magnetic field (3.8 T)

CMS (jets and MET) reconstruction

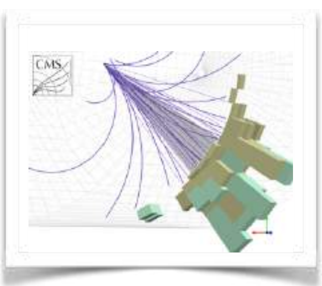
ECAL
pulse reconstruction



HCAL
pulse reconstruction

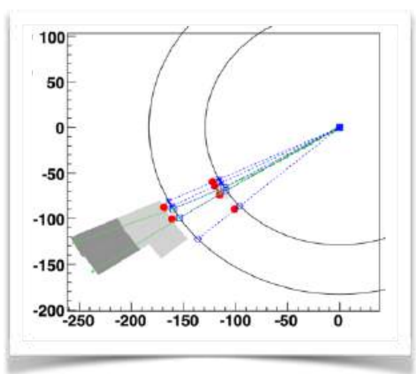


Track
reconstruction



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

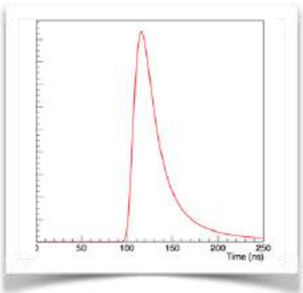
- Charged hadrons (tracker)
- Photons (ECAL)
- Neutral hadrons (HCAL)
- +Electrons/muons

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

Schematic by J. Dolen

CMS (jets and MET) reconstruction

ECAL
pulse reconstruction



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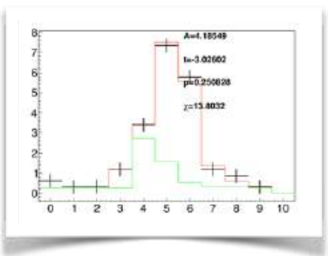

Track
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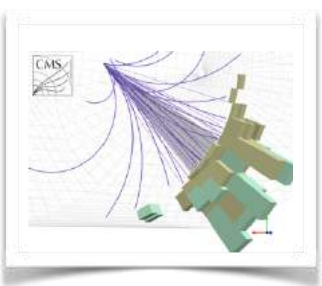

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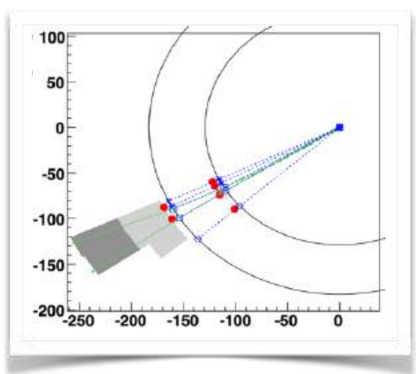

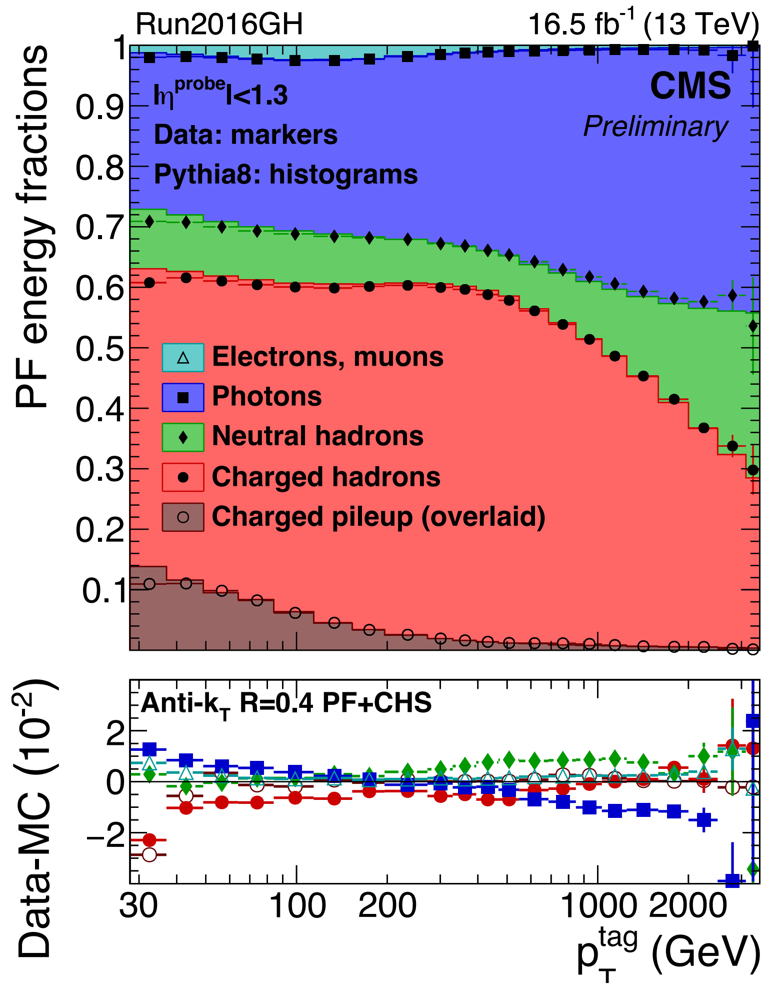

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CMS (jets and MET) reconstruction

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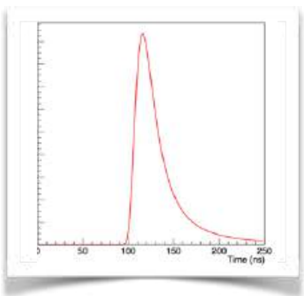

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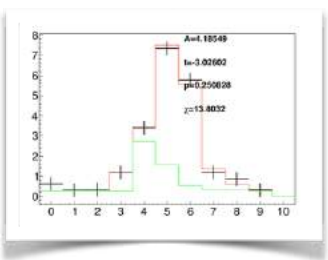

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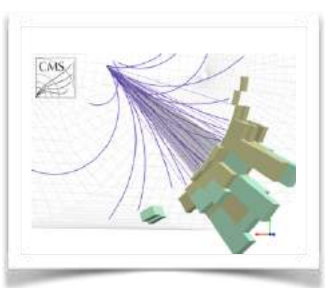

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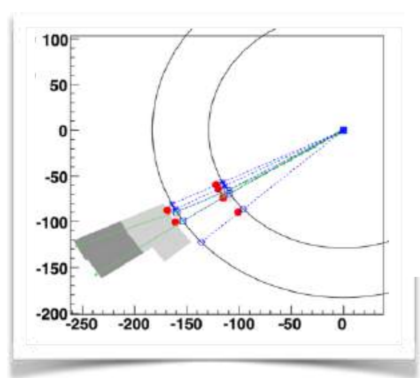

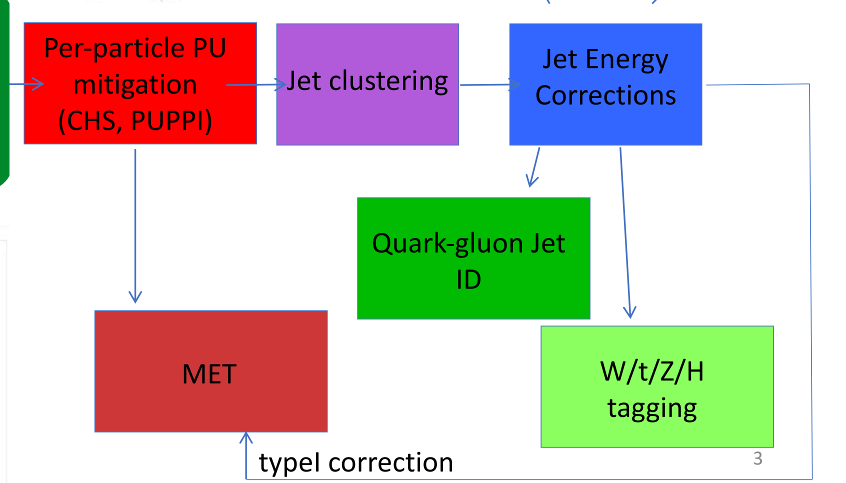

Thomas will cover Flavor tagging and boosted objects

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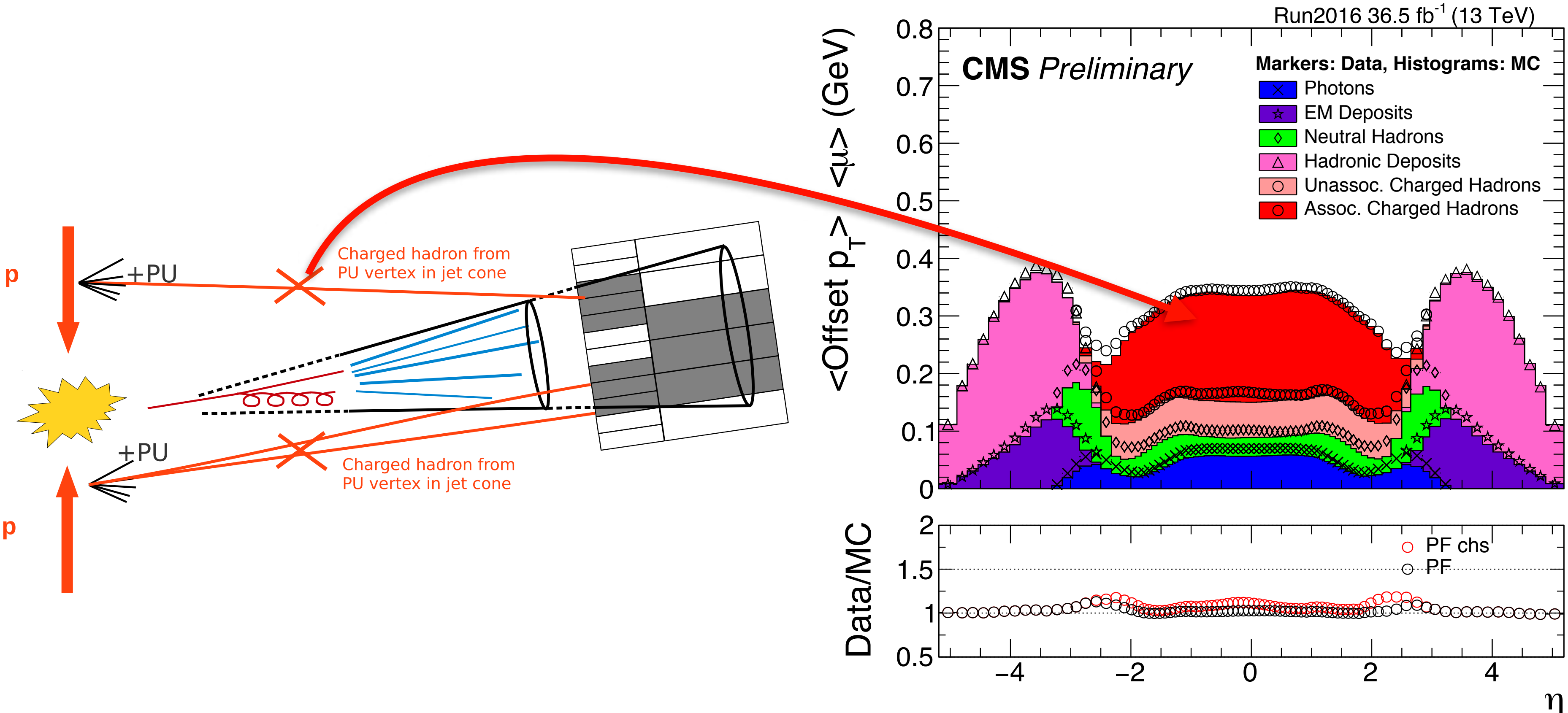
Schematic by J. Dolen

Charged Hadron Subtraction for jets

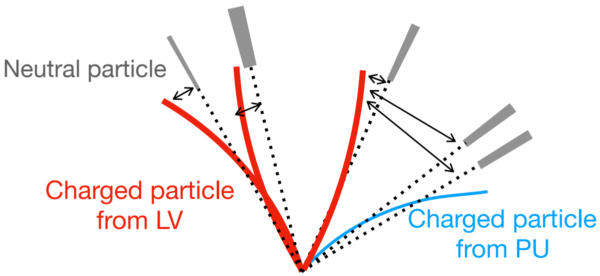


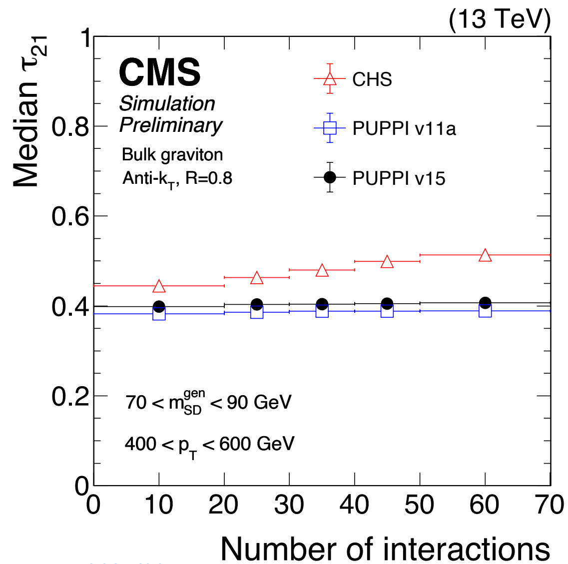
Particle Flow Charged Hadron Subtraction (CHS)

- 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

Run 3: PUPPI consistently used for AK4, too

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





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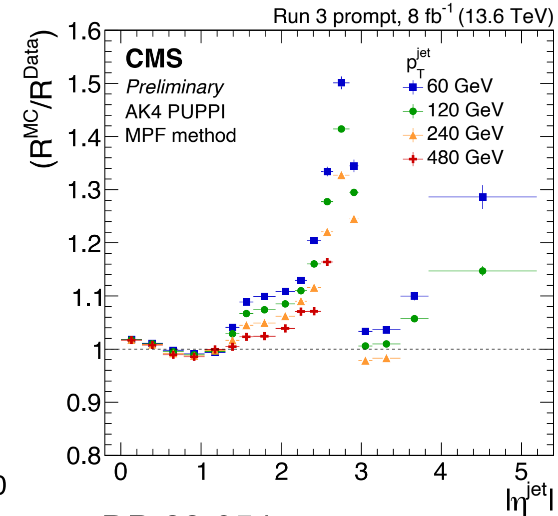
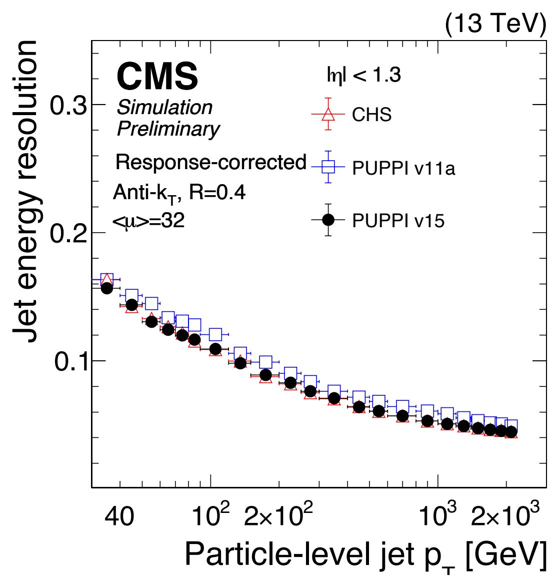


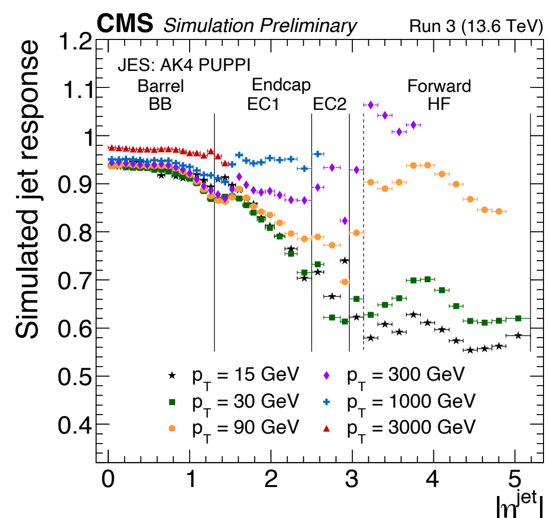
DP-22-054

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 redefining alpha with charged+neutral particles. Use for Run 3 as default (also AK4)





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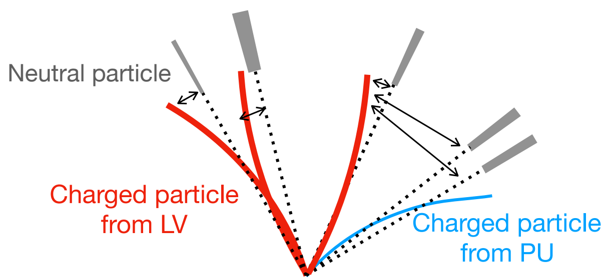

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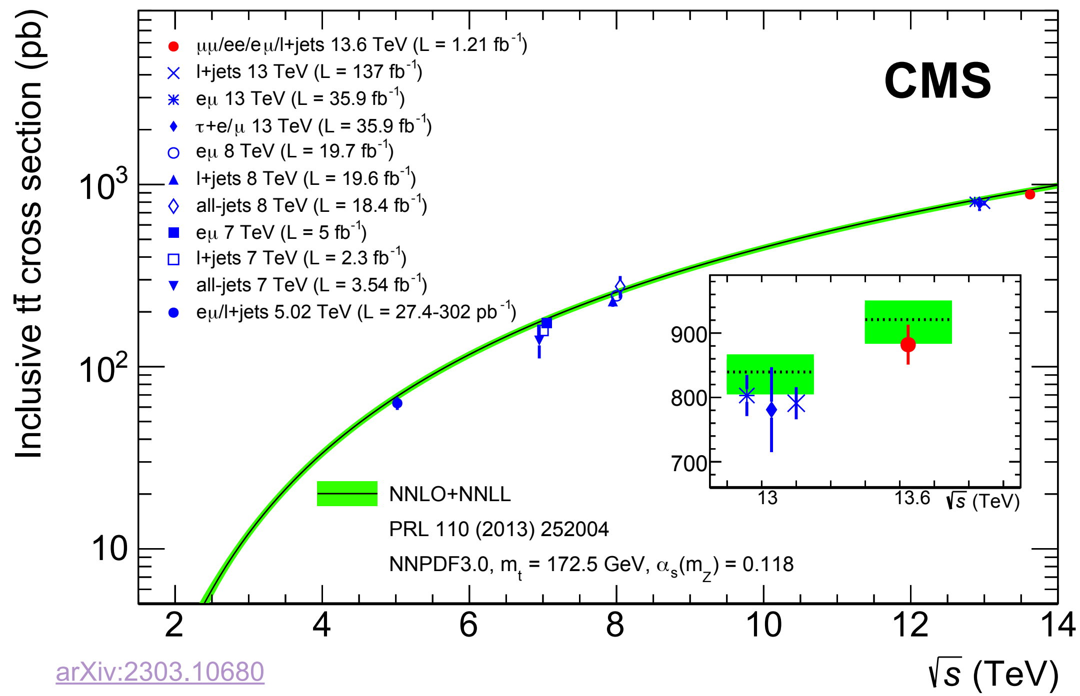
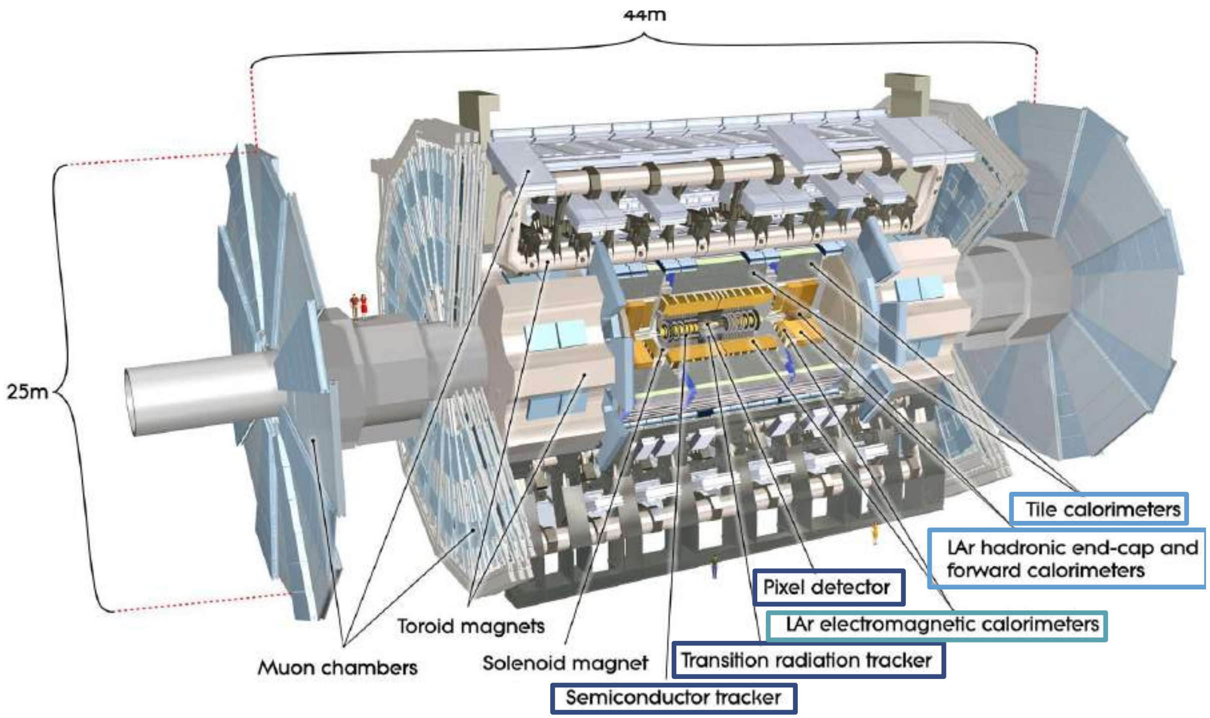
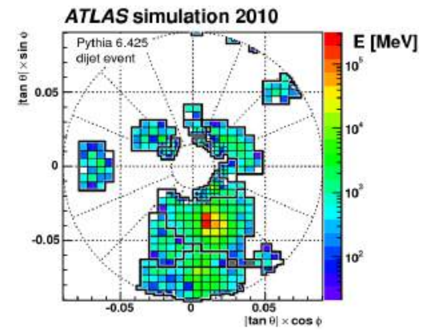


arXiv:2303.10680

- First public result with 13.6 TeV was top cross section measurement (Sep 2022)
- Use W mass to control jet-energy scale for early measurement
- Smooth commissioning of AK4PUPPI for Run 3

ATLAS: Calorimeter hits as starting point





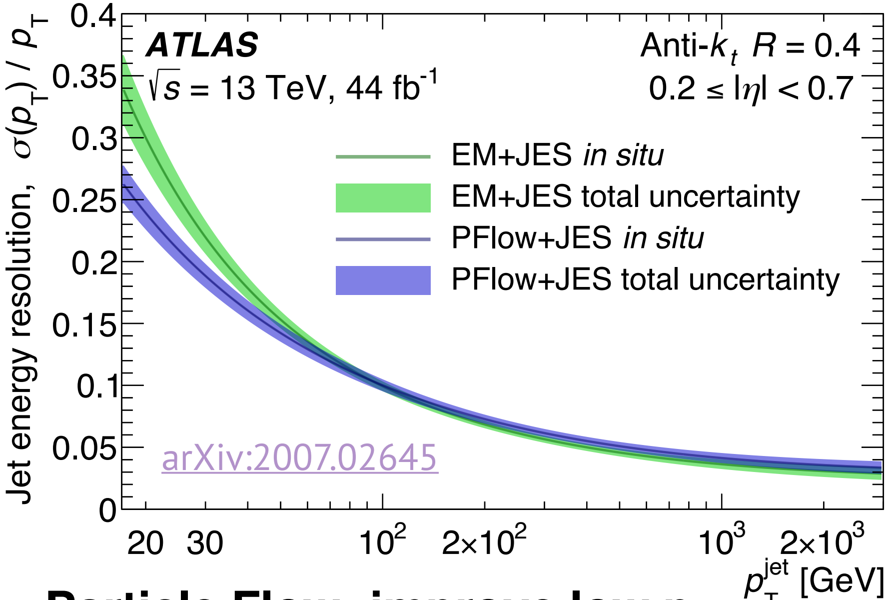
Inner Detector
- Charged particle tracks
- Decay vertices e.g. Hard-Scatter vertex "PV"
- $|\eta| < 2.5$

EM Calorimeter
- EM Showers
- e/γ Energy & direction
- $|\eta| < 4.9$
- $\Delta\eta \times \Delta\phi = 0.025 * \pi/128$

Hadronic Calorimeter
- HAD showers
- Charged & neutral hadron Energy & direction
- $|\eta| < 4.9$

- ATLAS LAr calorimeters more finely segmented
- TopoClusters as main input for jets: 3D clusters of noise-suppressed calo. cells
- With Run 2 Particle Flow became default, Track Calo Clusters, and Unified Flow Objects to improve substructure: Large-R jet paper
- ML Pion reconstruction

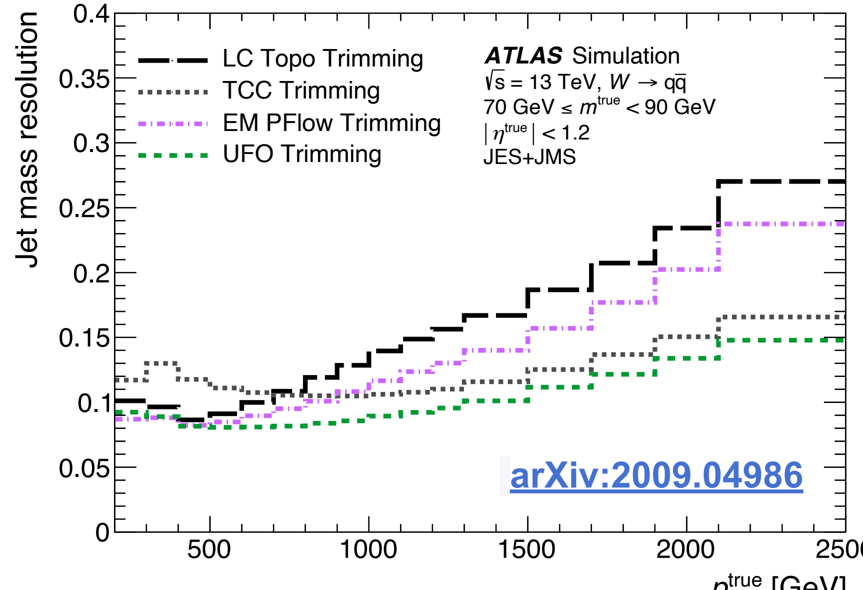
ATLAS: Different jet types



Particle Flow: improve low p_T

Combine calorimeter + tracks without double counting

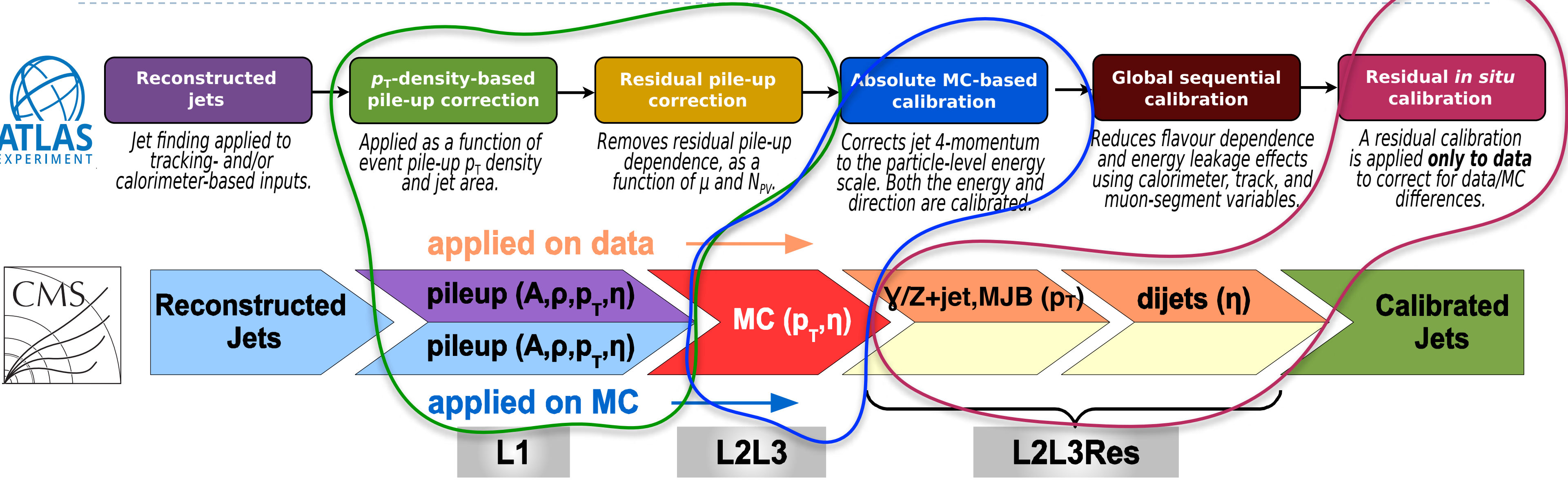
- Associate tracks with ≥ 1 topoclusters
- Subtract calo energy deposits matching a track.
- Remove PU tracks at the end using Charged Hadron Subtraction (CHS)



Track Calo Clusters: Improve subjets
Unified Flow Objects: Combine PF+TCC

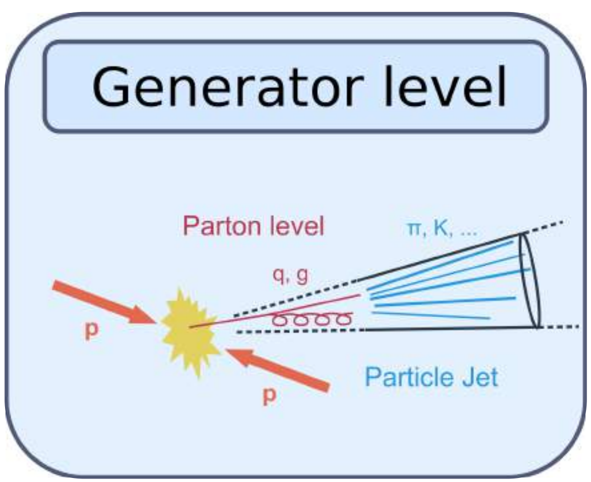
- **TCC** to improve angular resolution at high p_T
- **UFO** to optimize performance across whole p_T range
  1. Start with tracks and PF objects
  2. Reduce PU
  3. Sparse environment PFOs → UFO
  4. Remainder → TCC split → UFO
- Improves jet mass res. and PU dependence
- **Run 3: UFO with CS + SK and SoftDrop default large-R jets (and good for narrow-R jets)**

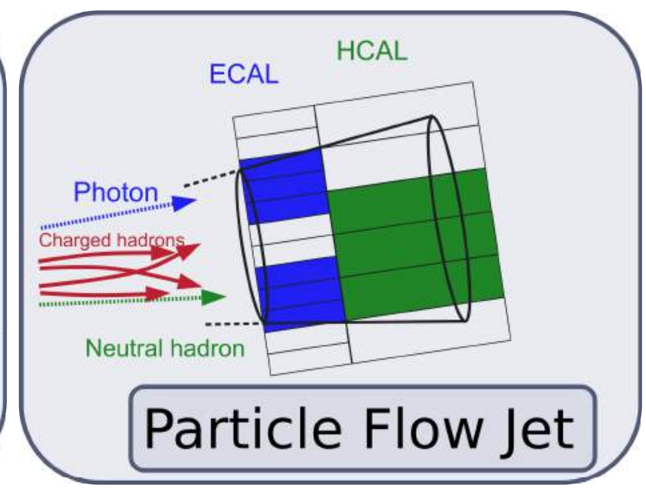
Jet energy corrections (base schema)



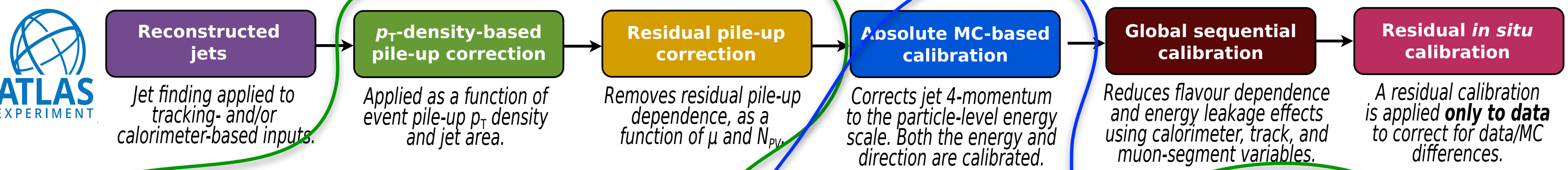
JEC corrects reconstructed jets - on average - back to particle level $< p_T^{reco} > / < p_T^{gen} > = 1$

(vs. p_T^{gen} , η, A, pileup μ)



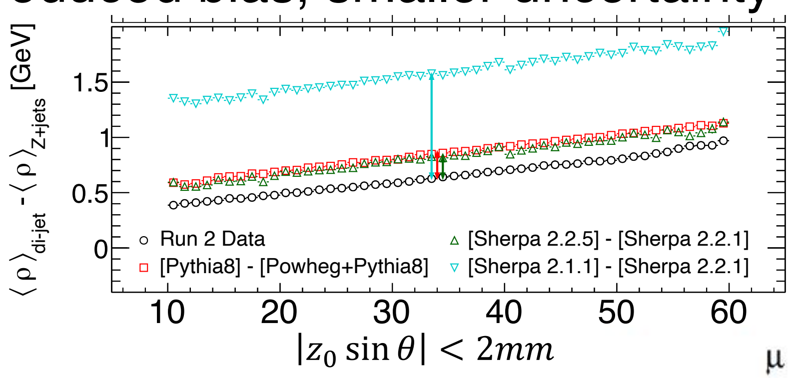


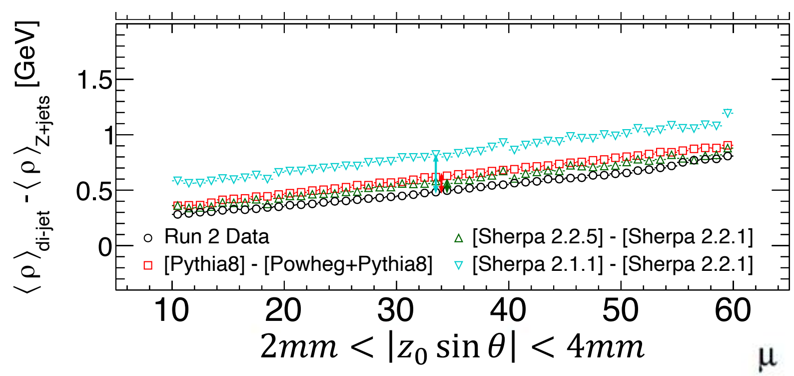
Jet energy corrections (new developments)



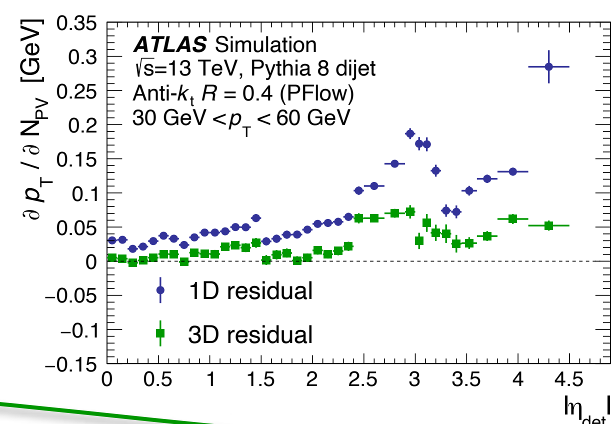
Using splines

- Change rho definition, use jets in impact-parameter sideband → reduced bias, smaller uncertainty





- 1D → 3D residual correction: adds correlation, corrections for extra detector effects
- Improved closure



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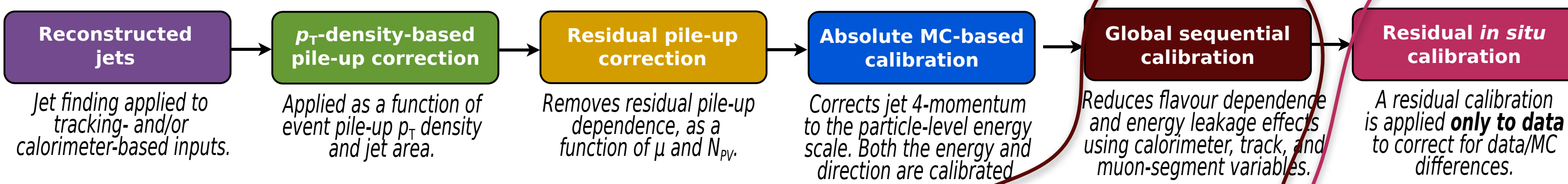
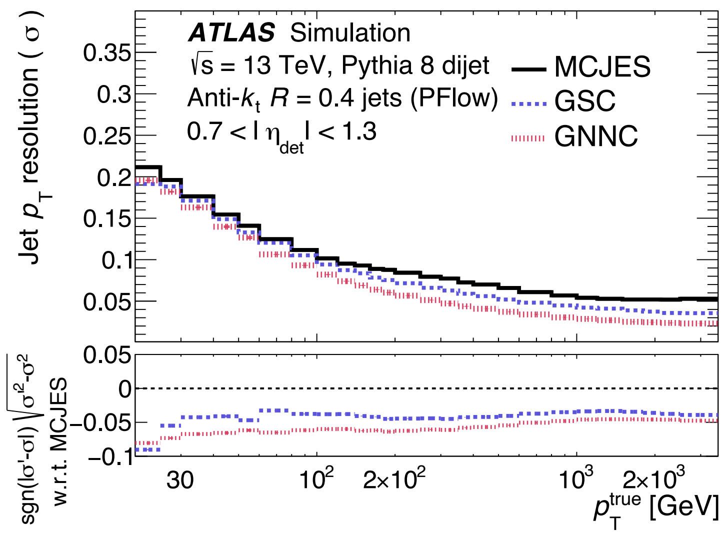
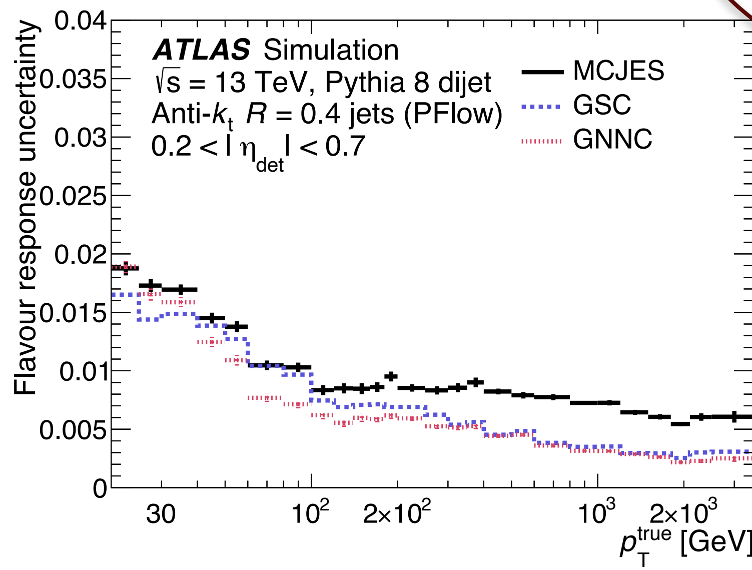


b-jet JES via γ+jet

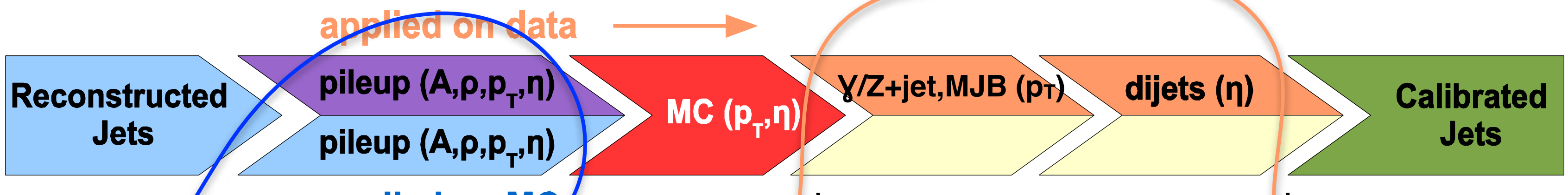
Global Sequential Calibration → Global Neural Network Calibration

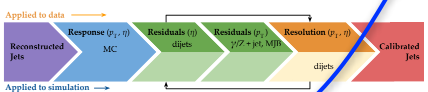


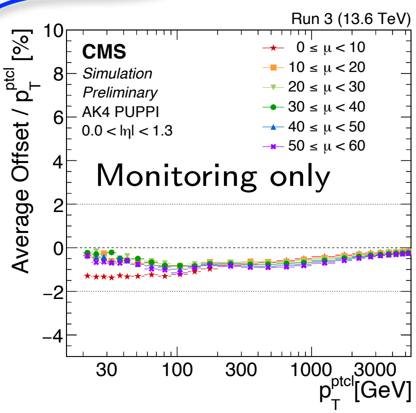


Add more observables
Account for correlations
Improves Response & Resolution & JES Flavour uncs.

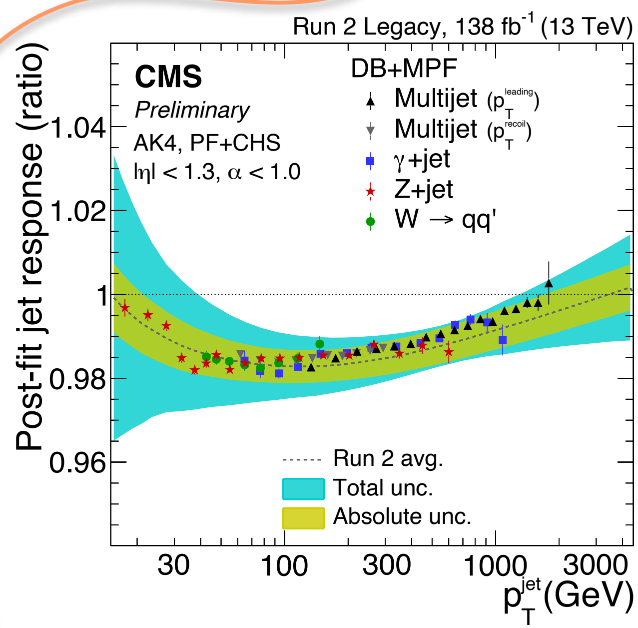
Jet energy corrections (new developments)

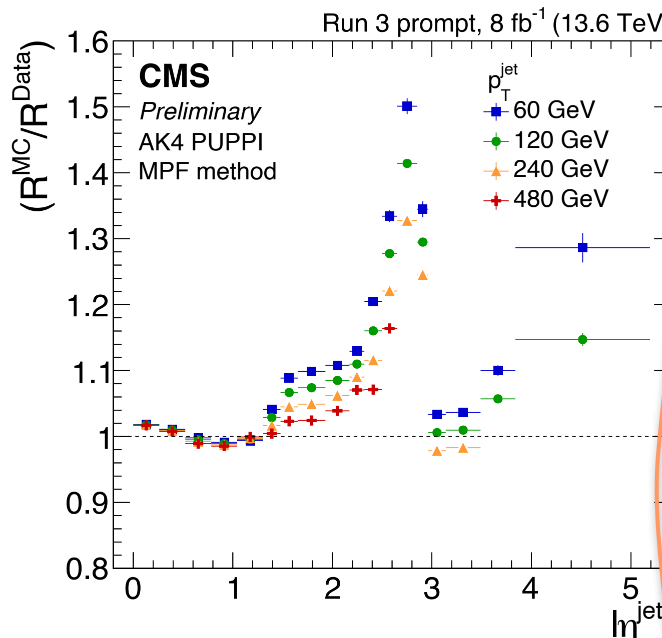






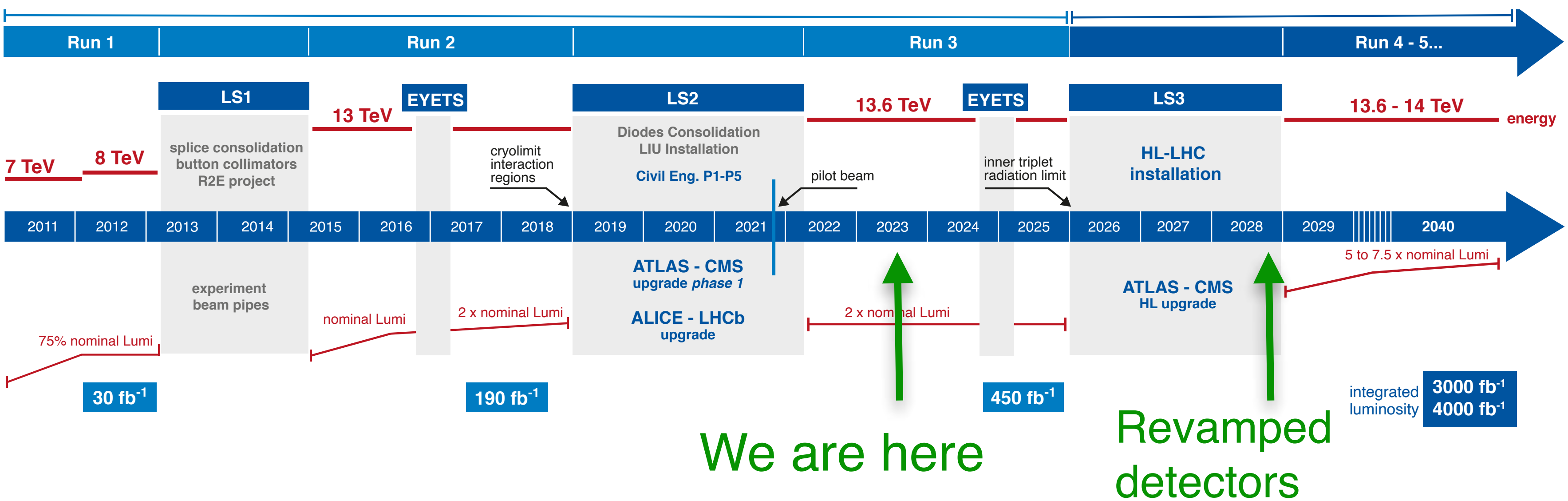
- Not applied to PUPPI jets in Run 3, just monitored





- More inputs to global fit of residual corrections
- Transition to PUPPI for Run 3 (and first Run 3 publication with AK4 PUPPI jets)

Conclusions

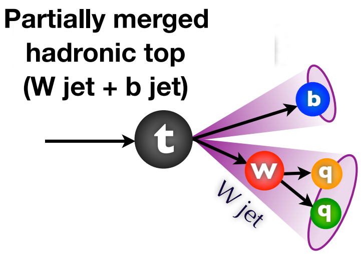


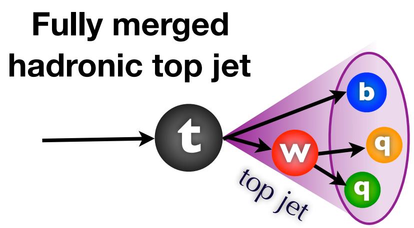
- Hadronic final states are a major part of the LHC physics program: Backgrounds/signals/pileup
  - Improved "defaults" for Run 3, improved methods
  - Close interplay with low-level reconstruction
  - Machine learning crucial tool to improve performance

- Also important: HL-LHC around the corner - new playground for exploiting detector upgrades

Backup

Standard heavy object tagging

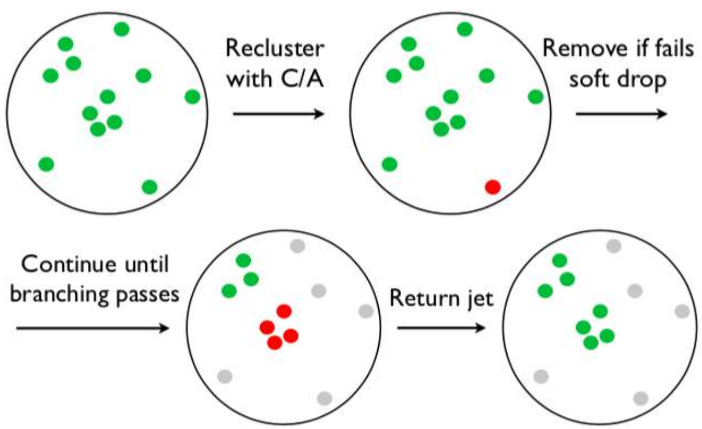




Two main questions:

A. What is the mass of the object?

- Need to remove softer constituents (QCD radiation)
- CMS “baseline”: PUPPI soft drop mass

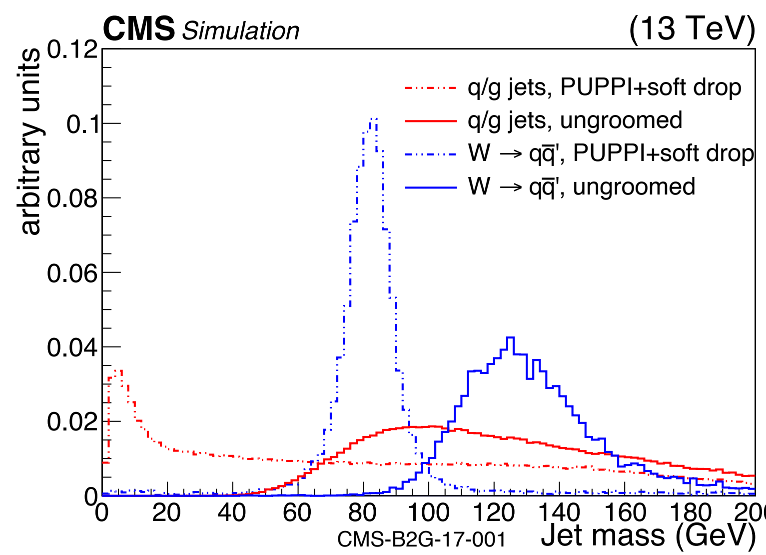


Softdrop/mMDT

- C/A declustering, stop if

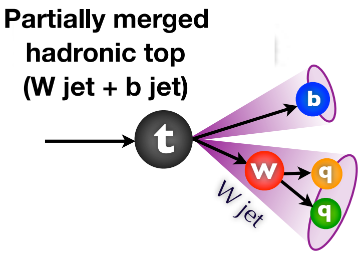
$$\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

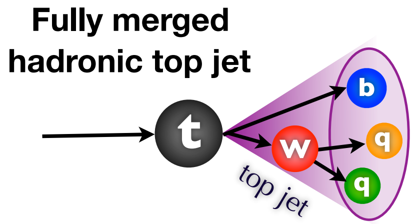
CMS: $\beta = 0$ and $z = 0.1$



Jet mass: $m_{QCD} \rightarrow 0$

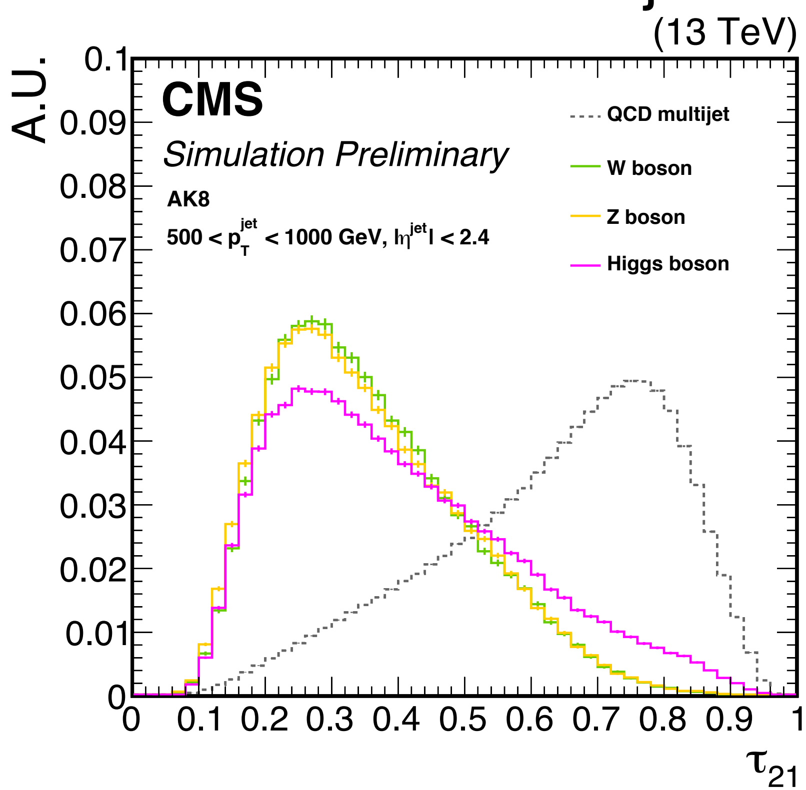
Standard heavy object tagging

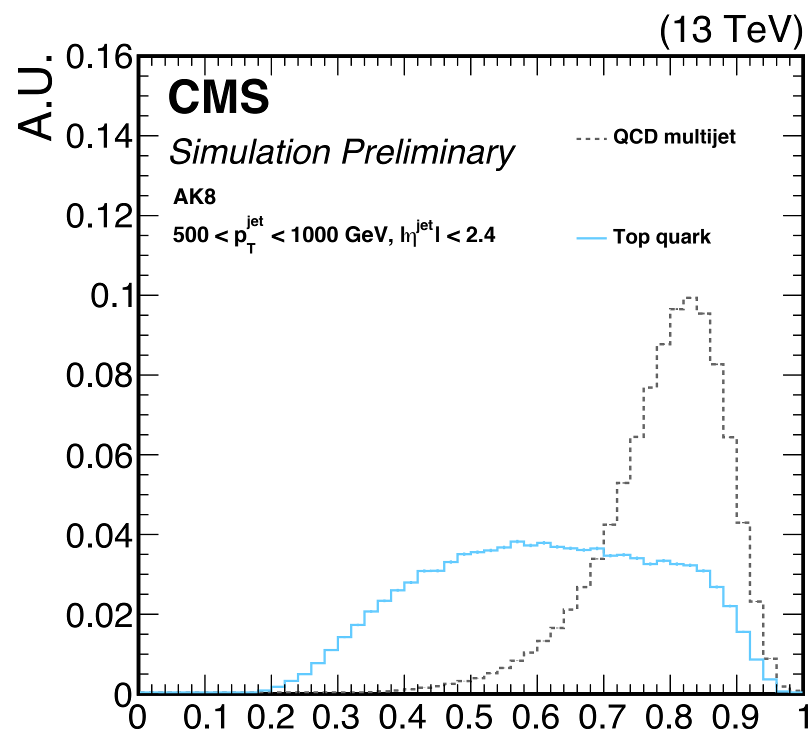




Two main questions:
A. What is the mass of the object?
B. What is inside this object?

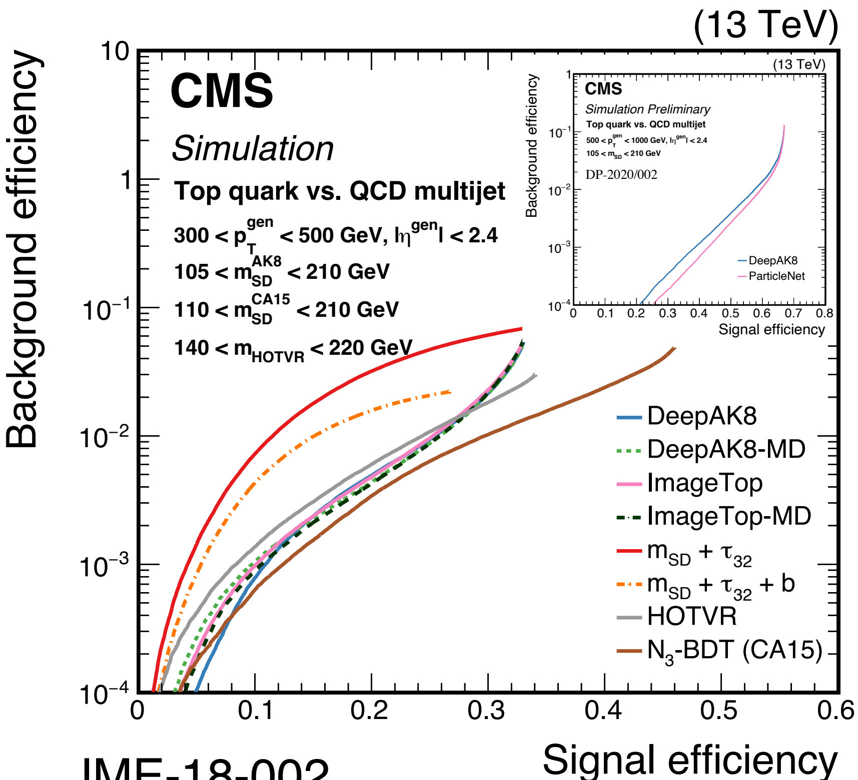
- Quantify how well a jet can be subdivided into sub-jets
- CMS “baseline”: N-subjettiness ratio



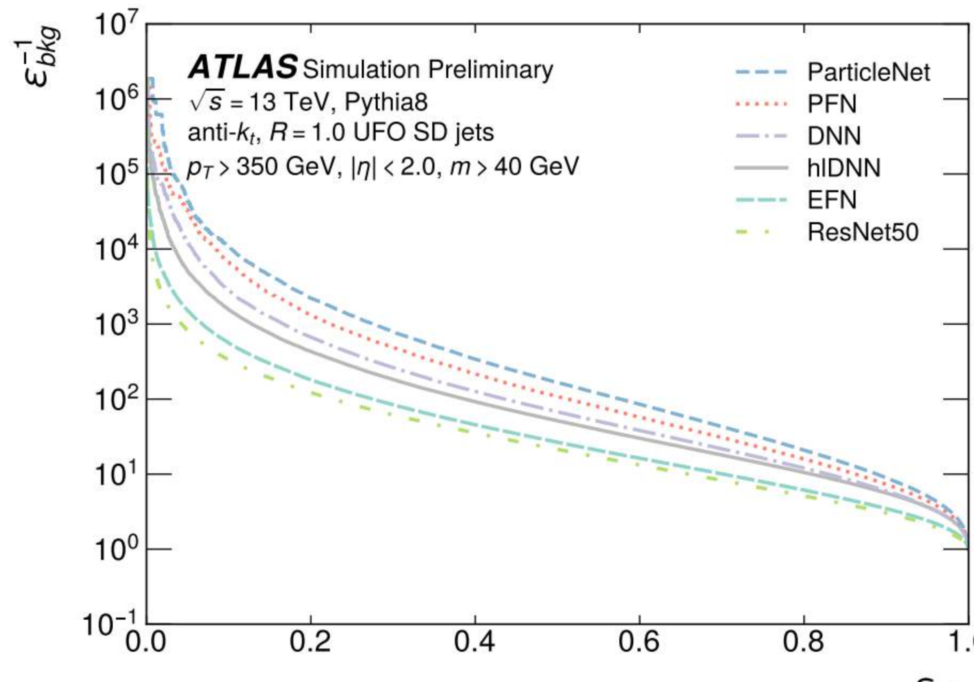


JME-18-002

High-level → jet-constituent-based



JME-18-002



ATL-PHYS-PUB-2022-039

- For optimal performance access to jet-constituents more powerful than high-level observables (cf. e.g. JME-18-002)
- Recent comprehensive comparison study ATL-PHYS-PUB-2022-039 on dataset made publicly available
- ParticleNet best, though some increase in modelling uncs.