Pile-Up in Jets in ATLAS

BOOST 2013 | Sven Menke, MPP München | 12-16. Aug 2013, Flagstaff, AZ
on behalf of the ATLAS Collaboration

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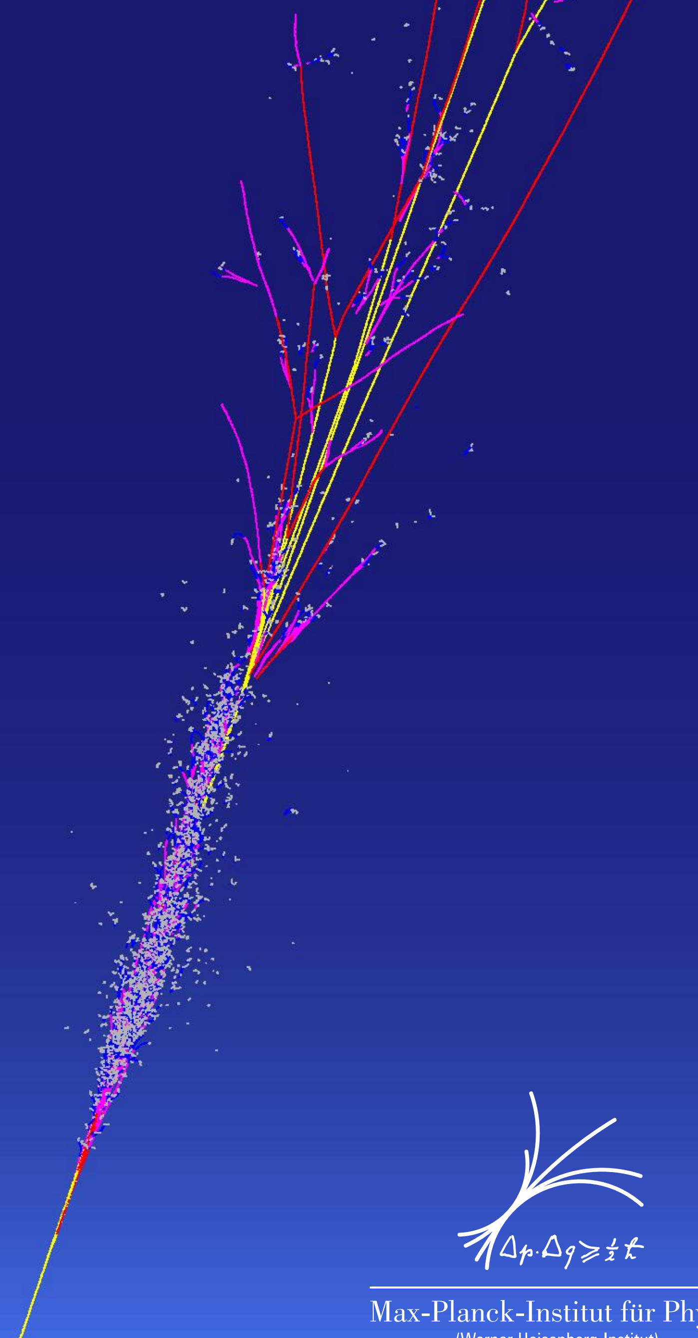

ATLAS EXPERIMENT

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

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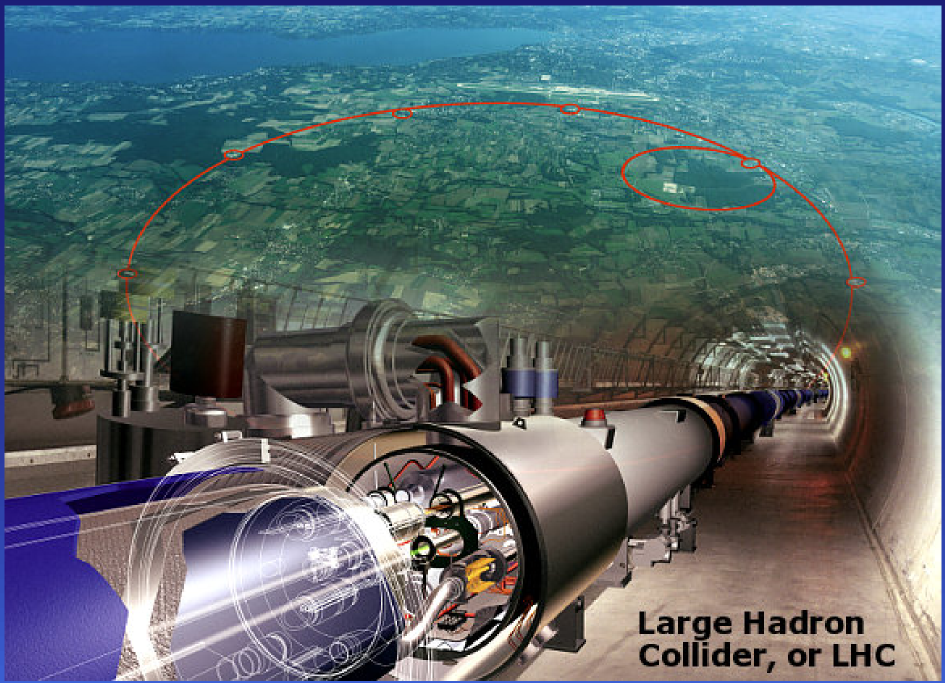
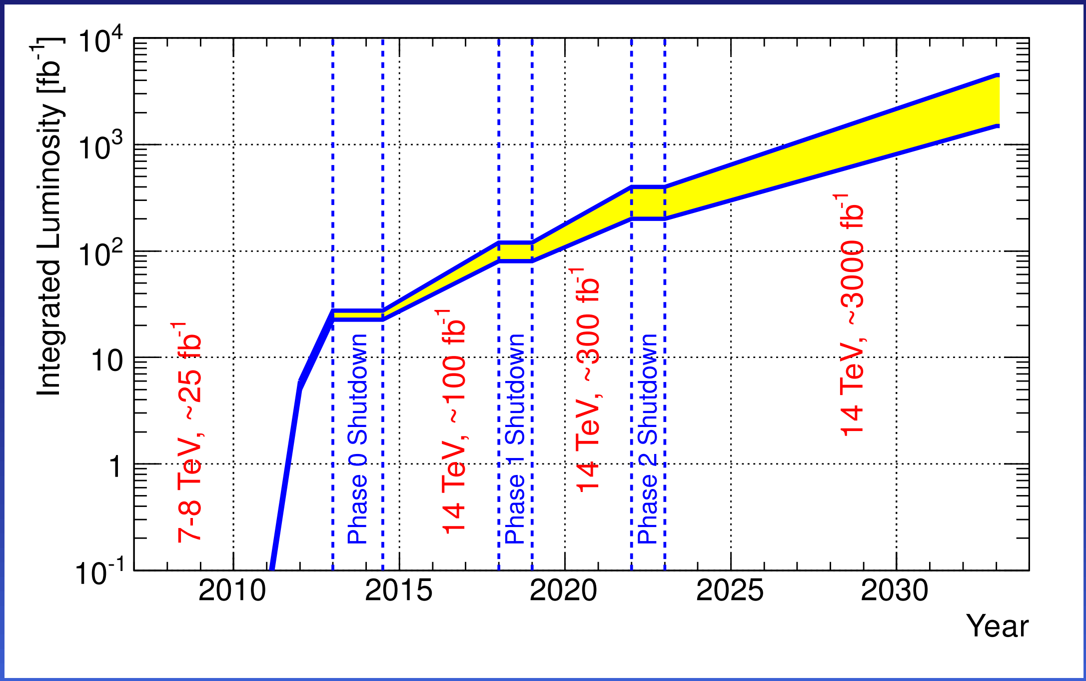
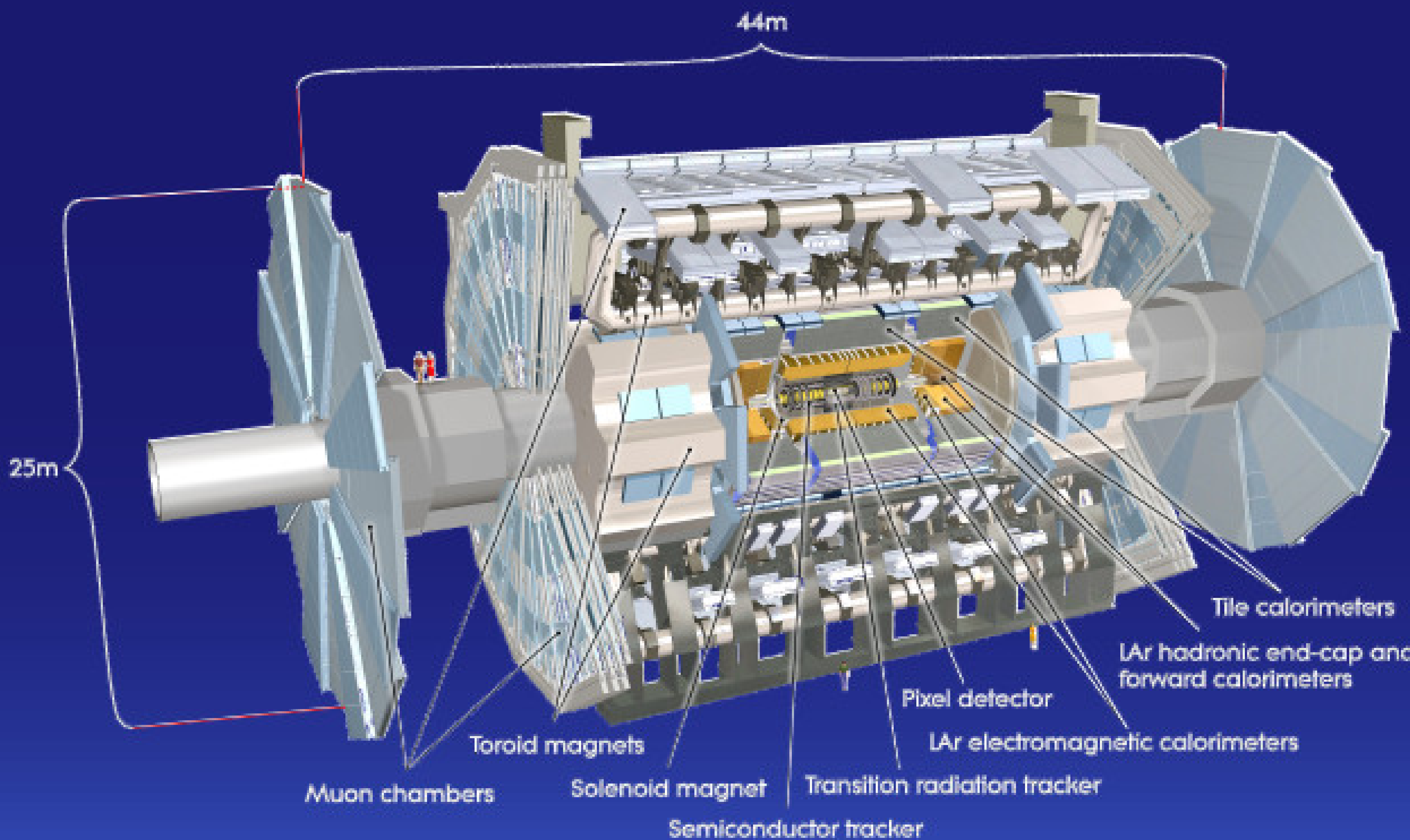
ATLAS and the LHC

- LHC: pp collisions at $\sqrt{s} = 7\,\text{TeV}$ 2010 - 2011 and at $\sqrt{s} = 8\,\text{TeV}$ since March 2012
- several upgrade phases (energy and luminosity) are foreseen until 2023:
  - end of 2012: $\sim 25\,\text{fb}^{-1}$ pp collisions at 7-8 TeV
  - Phase 0 (until 2019): $\sim 100\,\text{fb}^{-1}$ pp collisions at $13/14\,\text{TeV}$
  - Phase 1 (until 2022): $\sim 300\,\text{fb}^{-1}$ pp collisions at $14\,\text{TeV}$
  - Phase 2 (beyond 2023): $\sim 3000\,\text{fb}^{-1}$ pp collisions at $14\,\text{TeV}$



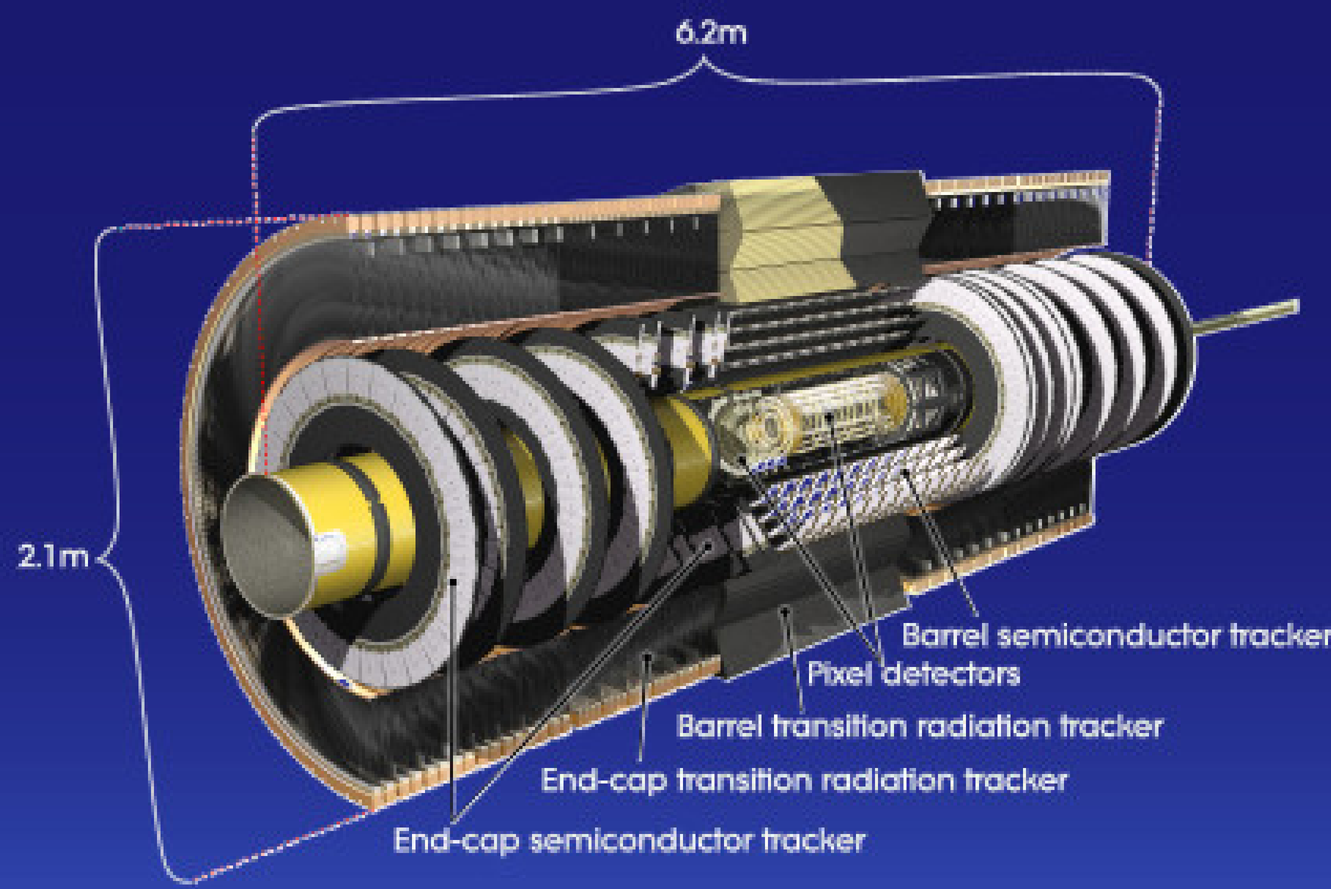


The ATLAS Detector



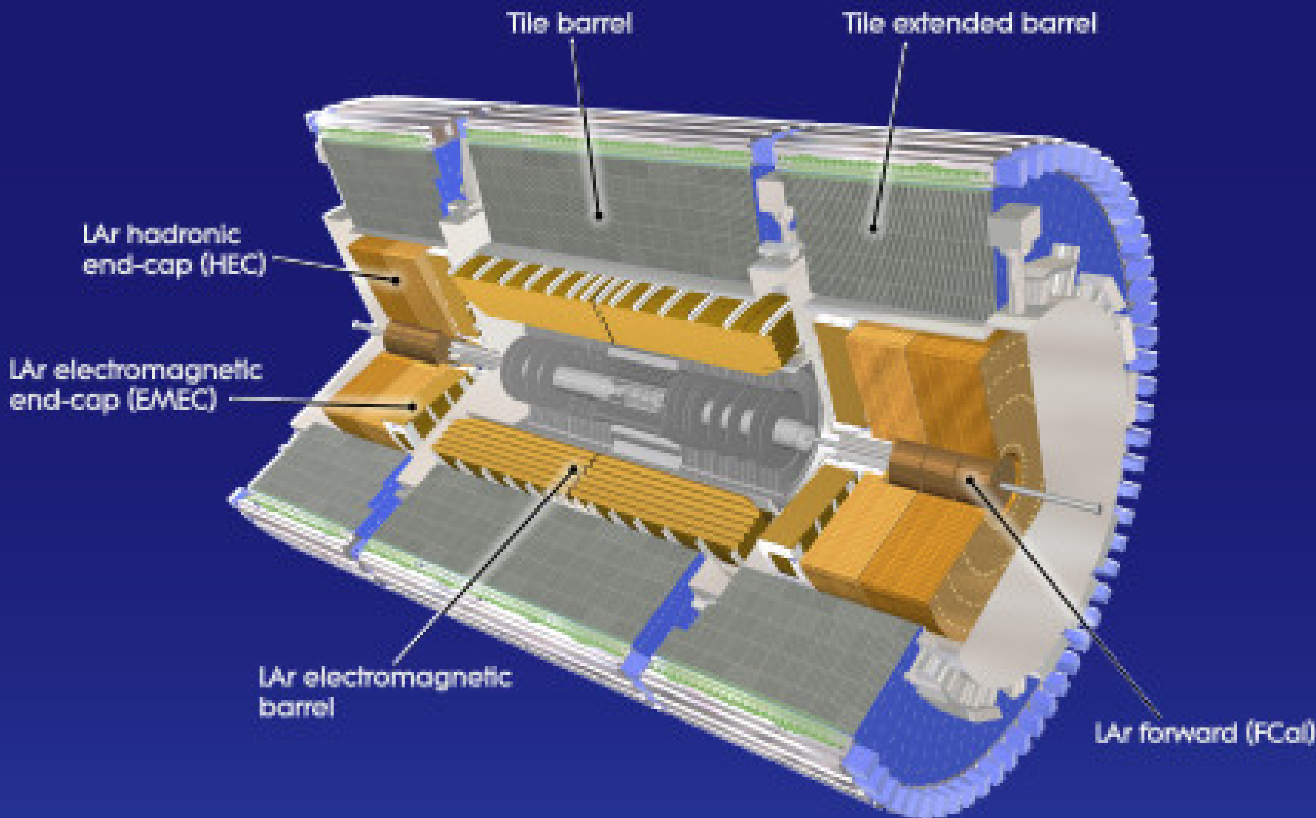
A Torodial **L**HC **A**pparatu**S**: 25 m high; 44 m long; 7000 t heavy

- Precision Tracking up to $|\eta| < 2.5$ in Silicon Detectors (Pixel- and Strip-detectors)
- Immersed in 2 T B-field
- 80.4×10^6 pixel sensors
- 6.3×10^6 silicon strips
- 351×10^3 straw tubes add track points and measure transition radiation up to $|\eta| < 2.0$



- Tracking performance: $\sigma_{p_T}/p_T = 0.038\% p_T(\text{GeV}) \oplus 1.5\%$

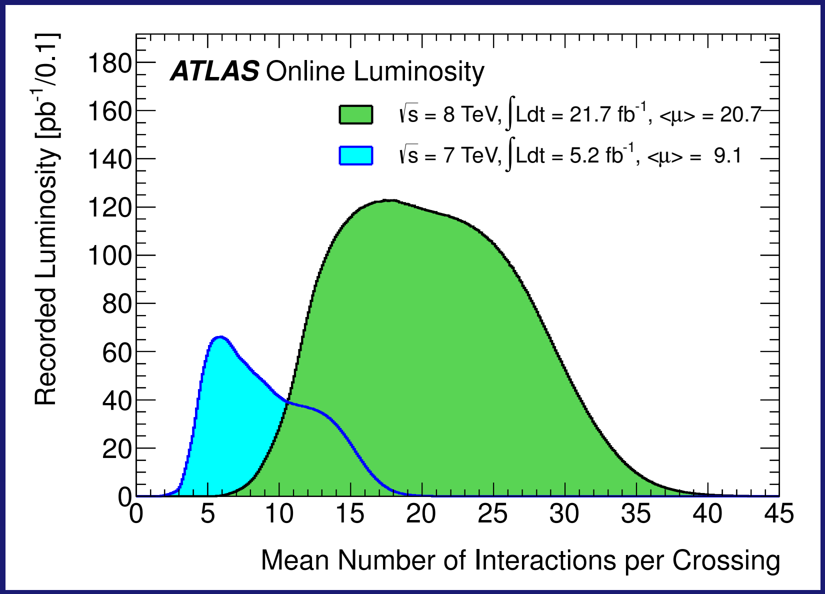
- Calorimeter coverage up to $|\eta| < 4.9$
- EM: LAr/Pb Accordion $|\eta| < 1.475/1.375 < |\eta| < 3.2$
- Had Barrel: steel/scintillating tiles $|\eta| \lesssim 1.7$
- Had Endcap: LAr/Cu parallel plates $1.7 \lesssim |\eta| \lesssim 3.2$
- Forward: LAr/Cu(W) tubular electrodes $3.2 \lesssim |\eta| \lesssim 4.9$
- 3 to 7 samplings
- 188×10^3 cells in total



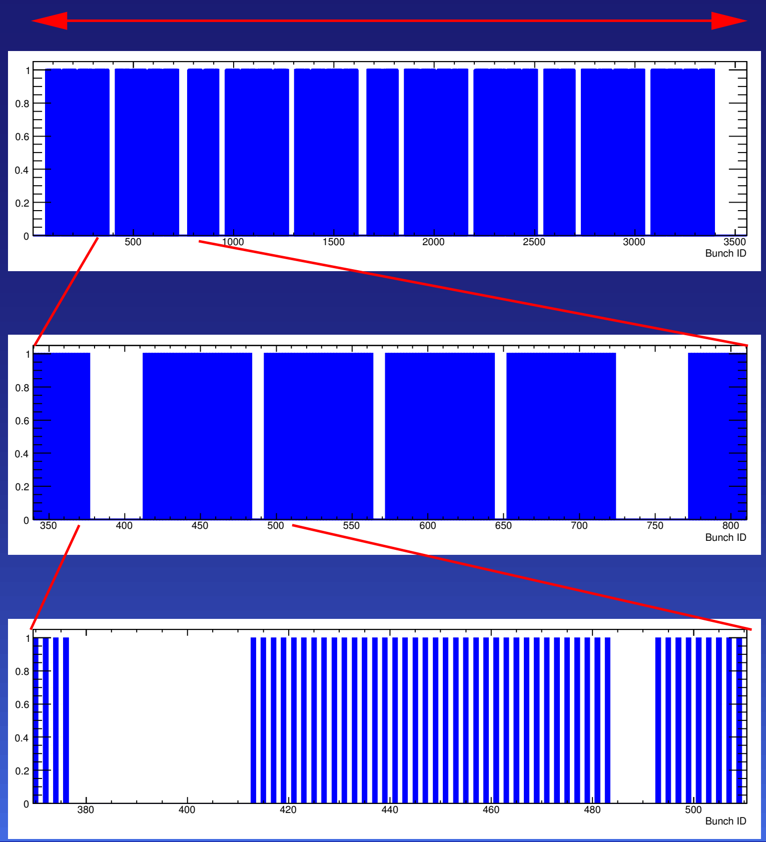
- e/γ: $\sigma_E/E \simeq 10\%/\sqrt{E}$
- jets: $\sigma_E/E \simeq 50\%/\sqrt{E} \oplus 3\%$

Pile-Up ► important parameters

- μ: average number of interactions per bunch
- N_{PV}: number of rec. primary vertices
  $\sim 44\%\mu + 3$ at high μ
- Δt: bunch distance
  50 ns in 2012
- signal integration time
  ~ 500 ns for the LAr

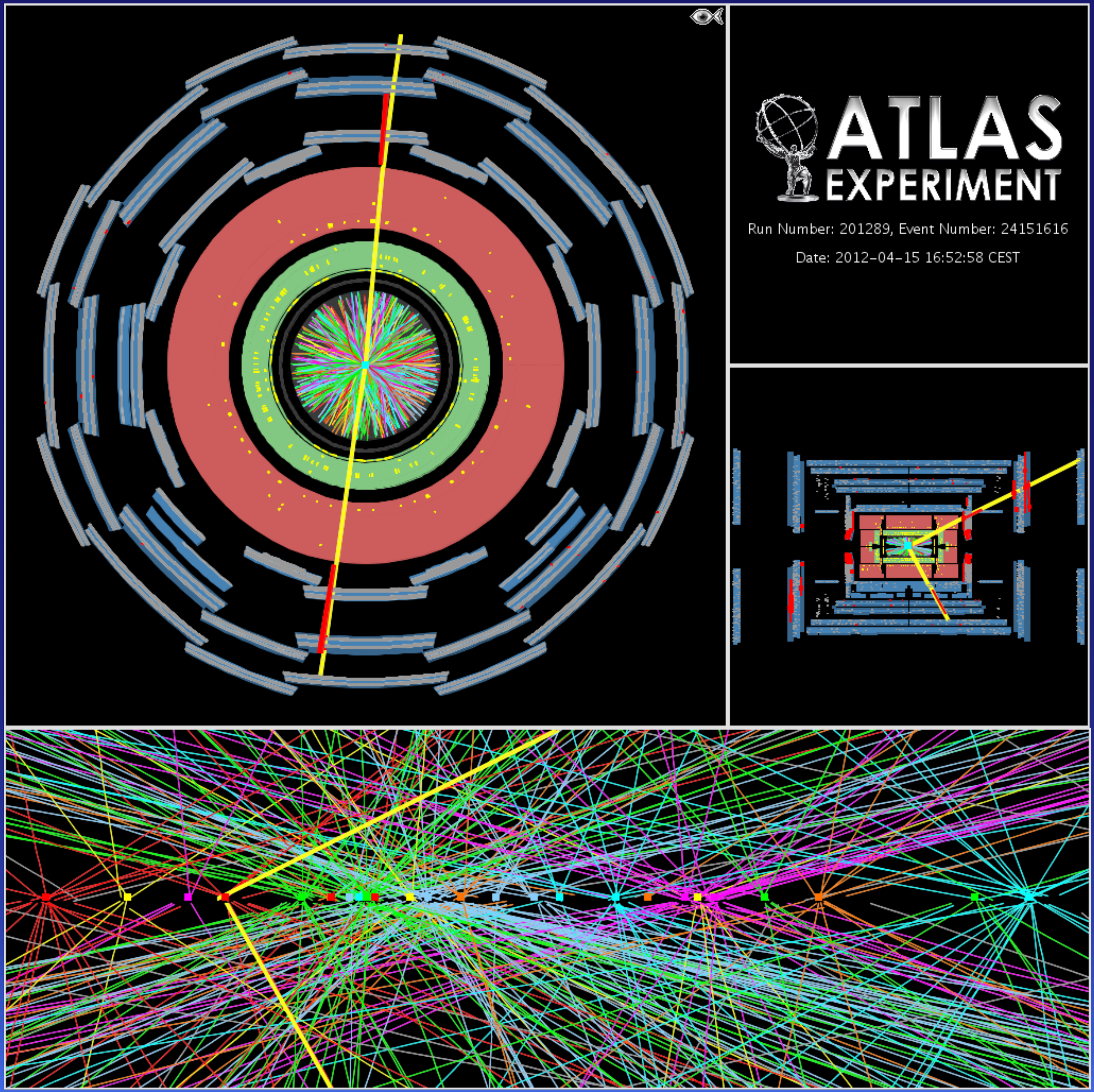


26.7 km $\equiv$ 3560 bunch places each $\Delta t = 25$ ns



► typical LHC bunch structure in 2012
- ~ 1400 colliding bunch pairs
- up to 11 trains ~ 1000 ns appart
- 2-4 sub-trains each ~ 250 ns
- 36 filled bunches
  ► Pile-up impact depends on bunch crossing Number (BCID)
  ► up to 10 colliding bunch pairs contribute to signal

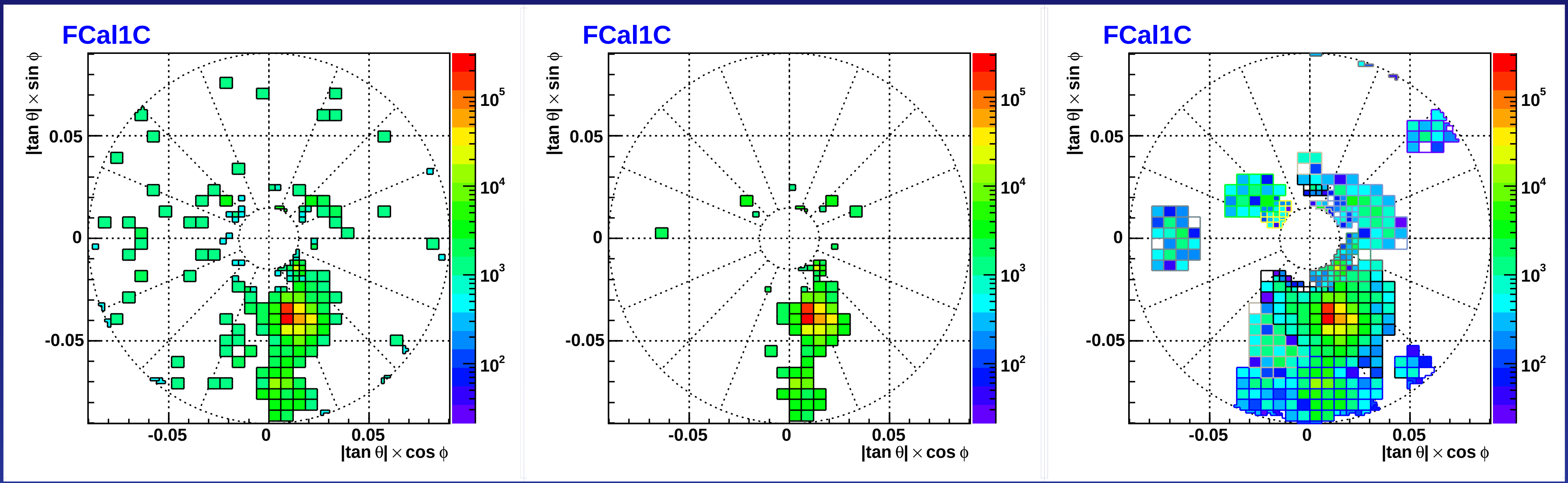
Pile-Up ► $Z^0 \to \mu\mu$ candidate event with $N_{PV} = 25$ from 2012



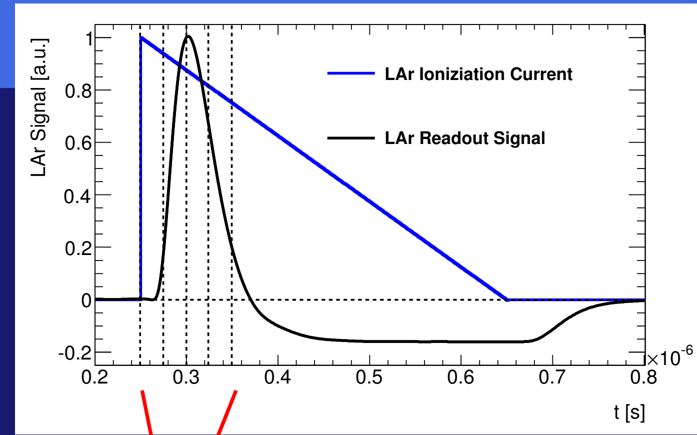
Jets

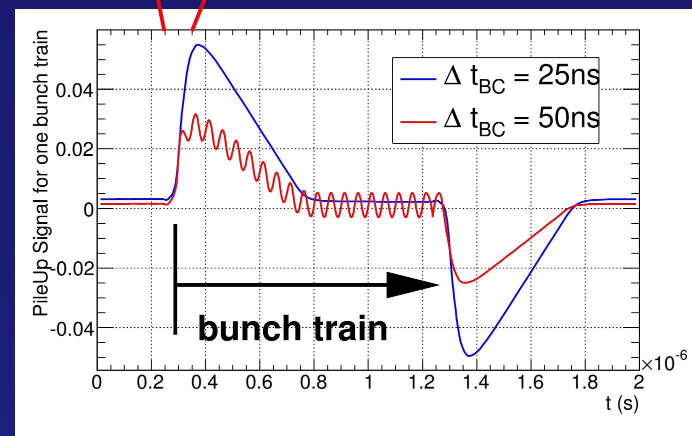
- jets in ATLAS are made out of "topological clusters"
  - 3d energy blobs of neighboring calorimeter cells around seed cell with $|E| > 4\sigma$
  - direct seed neighbors with $|E| > 2\sigma$ become seeds too
  - re-clustering of this reduced cell set around local maxima

$|E| > 2\,\sigma_{\text{noise}}$ $|E| > 4\,\sigma_{\text{noise}}$ $4/2/0$ topological clusters



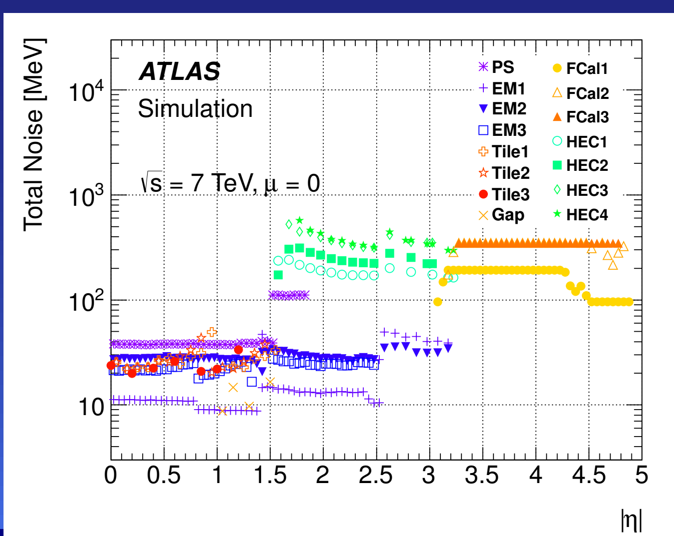
- $2\,\sigma$ cut is removing cells from the signal region
- $4\,\sigma$ cut shows seeds for the cluster maker
- after clustering all cells in the signal regions are kept
- cluster splitter finds hot spots



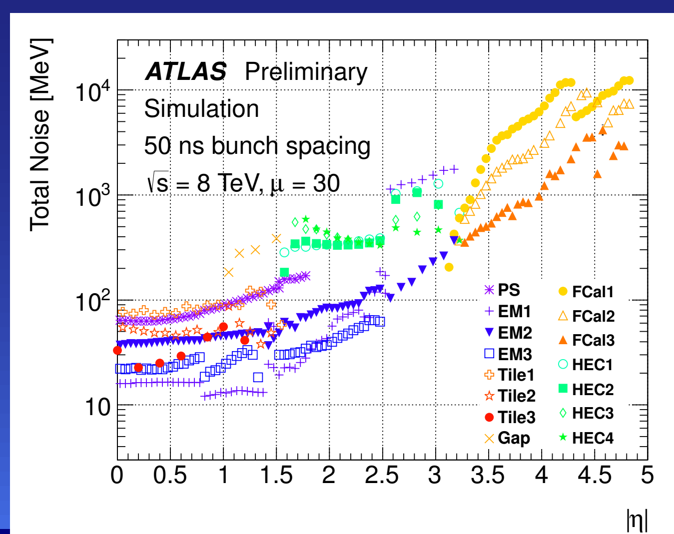


- Noise is $\sigma_{\text{elec}} \oplus \sigma_{\text{pile-up}}$
  - σ_{elec} relevant for no pile-up
  - $\sigma_{\text{pile-up}}$ grows with $\sqrt{\mu}$
- a 20% increase in noise means $20\times$ more clusters for fixed thresholds!
- thresholds and filter weights are adjusted to expected maximum $\langle\mu\rangle$
  - modified weights slightly increase σ_{elec} and decrease $\sigma_{\text{pile-up}}$ from $\sqrt{\mu}$ scaling
- average cell-level bias
  - $f(\text{BCID}) \lesssim O(0.3\sigma_{\text{pile-up}})$ corrected in 2012

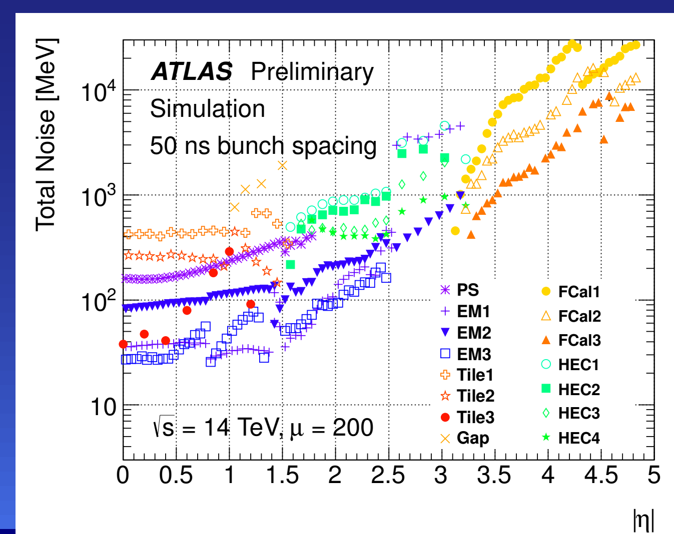
2010 $\mu = 0$



2012 $\mu = 30$



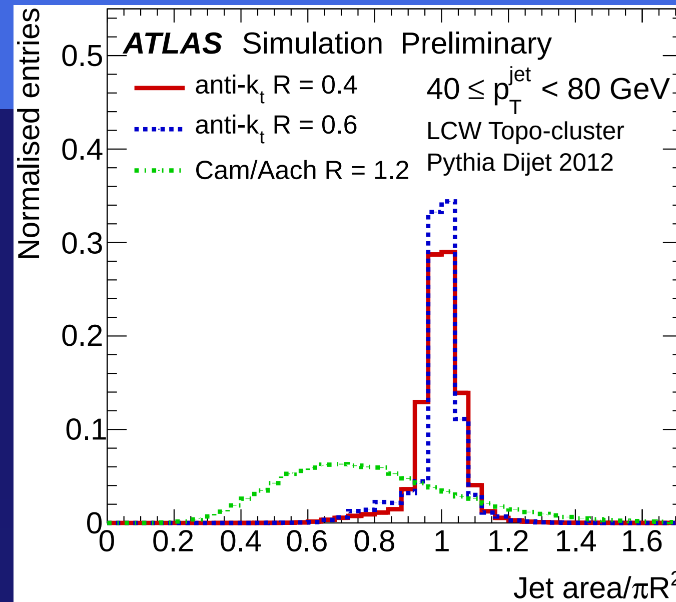
2022 $\mu = 200?$

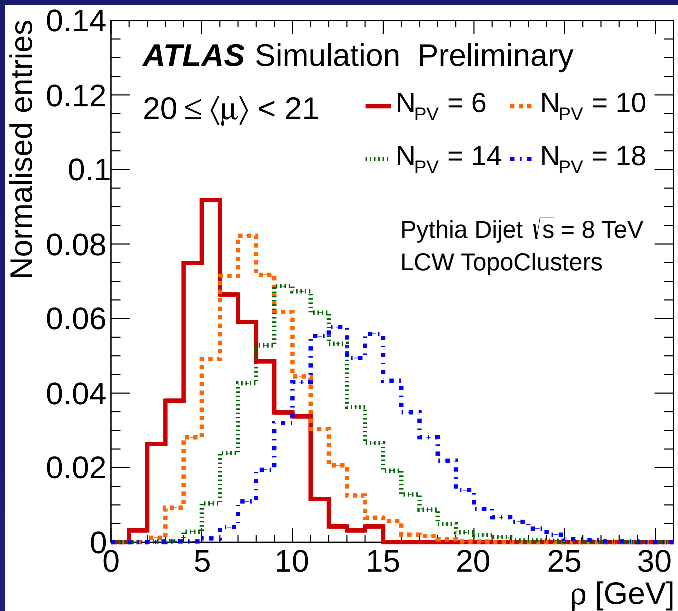


Jet Area Method

ATLAS-CONF-2013-083

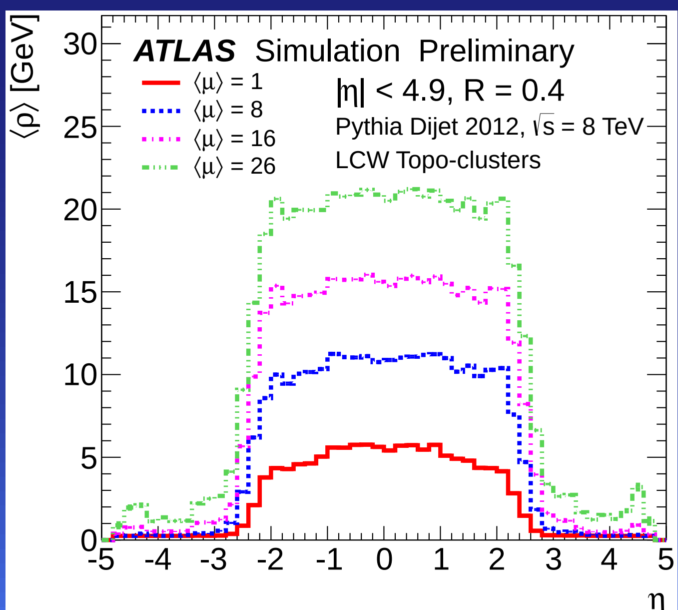
- jet area A_{jet} (arXiv:0802.1188) measures jet susceptibility to soft particles





- by adding many soft particles (ghosts) during the jet forming
- $A_{\text{jet}} = N_g^{\text{jet}} / \nu_g$
  N_g^{jet} number of ghosts in jet
  ν_g number density of ghosts in $y - \phi$

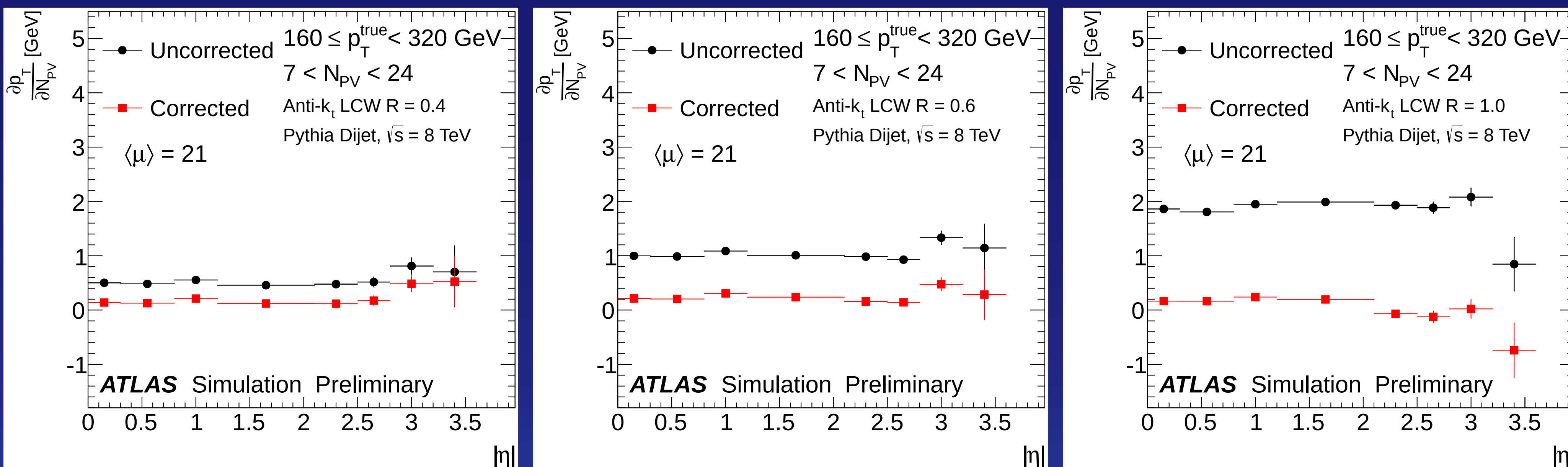
- momentum density: $\rho_{\text{jet}} = p_\perp^{\text{jet}} / A_{\text{jet}}$
- $\rho = \text{median}\{\rho_{\text{jet},i}\}$ measures event pile-up activity (arXiv:0707.1378)
  - median suppresses bias from hard scatter
  - event-by-event follows pile-up fluctuations
  - `kT` jets with $R = 0.4$ for $|\eta_{\text{jet}}| < 2.0$
    - less pile-up jets in forward region



- any jet in the event can then be corrected:
  $p_\perp^{\text{jet,corr}} = p_\perp^{\text{jet}} - A_{\text{jet}} \times \rho$
  - jet algorithm/size can differ from the one used for ρ

Jet Area Method ► Performance

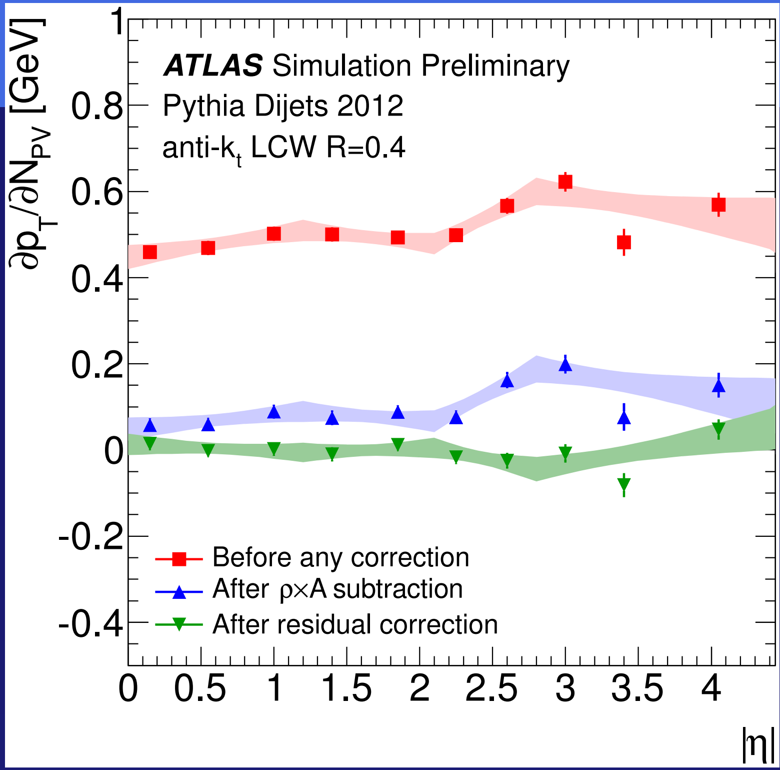
- dependency of $p_\perp^{\text{jet}}$ on in-time pile-up (N_{PV})
  - before and after jet area pile-up correction
  - in simulated di-jet events for $160 < p_\perp < 320\,\text{GeV}$ jets vs. $|\eta|$
  - for `AntiKt` jets with $R = 0.4$, $R = 0.6$ and $R = 1.0$

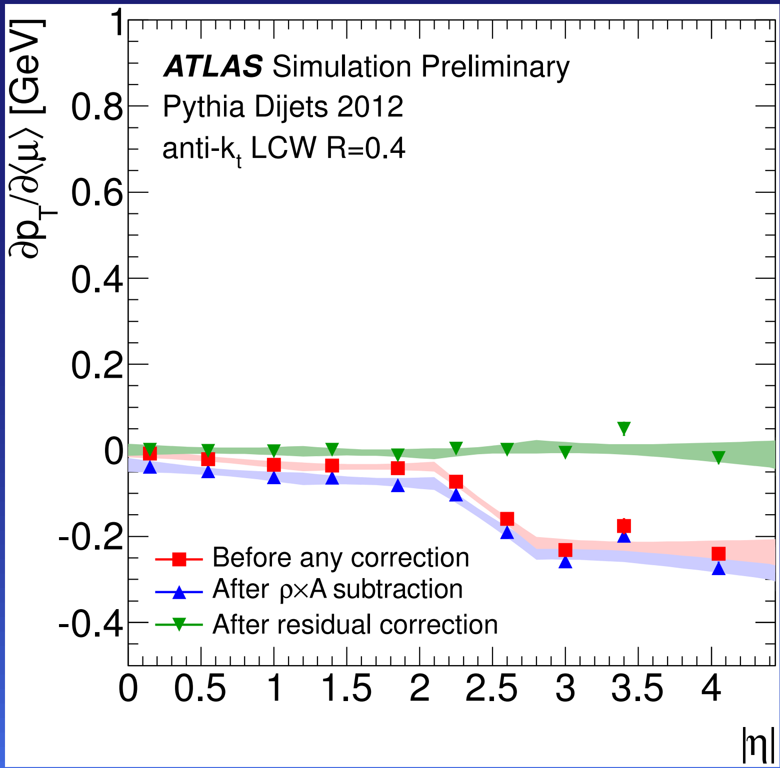


- $0.5 - 2\,\text{GeV}/\text{vtx}$ before correction with large dependency on R
- $< 0.2\,\text{GeV}/\text{vtx}$ after jet-area correction
  ► and no dependency on R

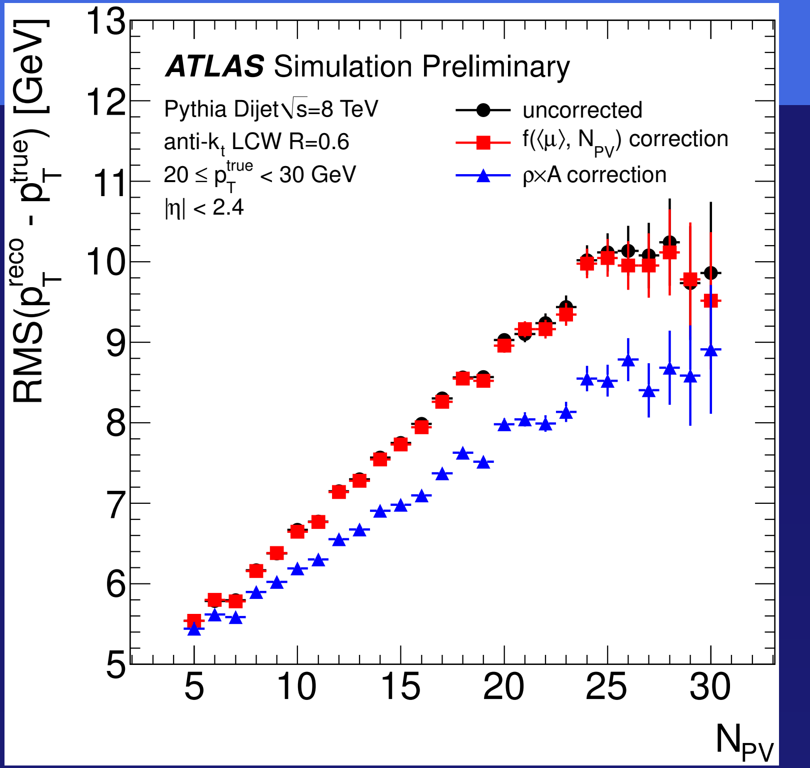
Jet Area Method ► Residual Corrections

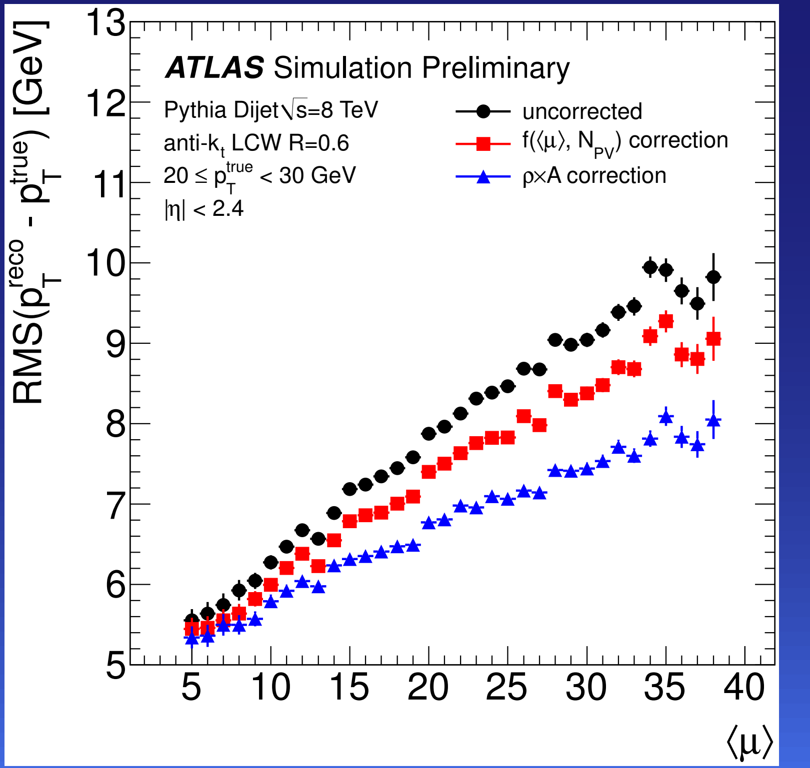
- jet area method reduces mostly pile-up from additional calorimeter clusters not belonging to the hard scatter
- inside the jets belonging to the hard scatter the noise suppression is reduced – the pile-up overlaps with the signal
- this can be addressed by a residual correction after the jet area based correction
  - linear fits to $p_{\perp}^{\rm reco} - p_{\perp}^{\rm true}$ vs. $N_{\rm PV}$ ($\langle\mu\rangle$)
  - most relevant in forward direction
- dependency of $p_{\perp}^{\rm jet}$ on in-time pile-up: $N_{\rm PV}$ for fixed $\langle\mu\rangle$ and out-of-time pile-up: $\langle\mu\rangle$ for fixed $N_{\rm PV}$
  - before, after jet area and after residual correction
  - for `AntiKt` jets with $R = 0.4$
  - small improvement for in-time pile-up
  - large improvement in the forward region for out-of-time pile-up



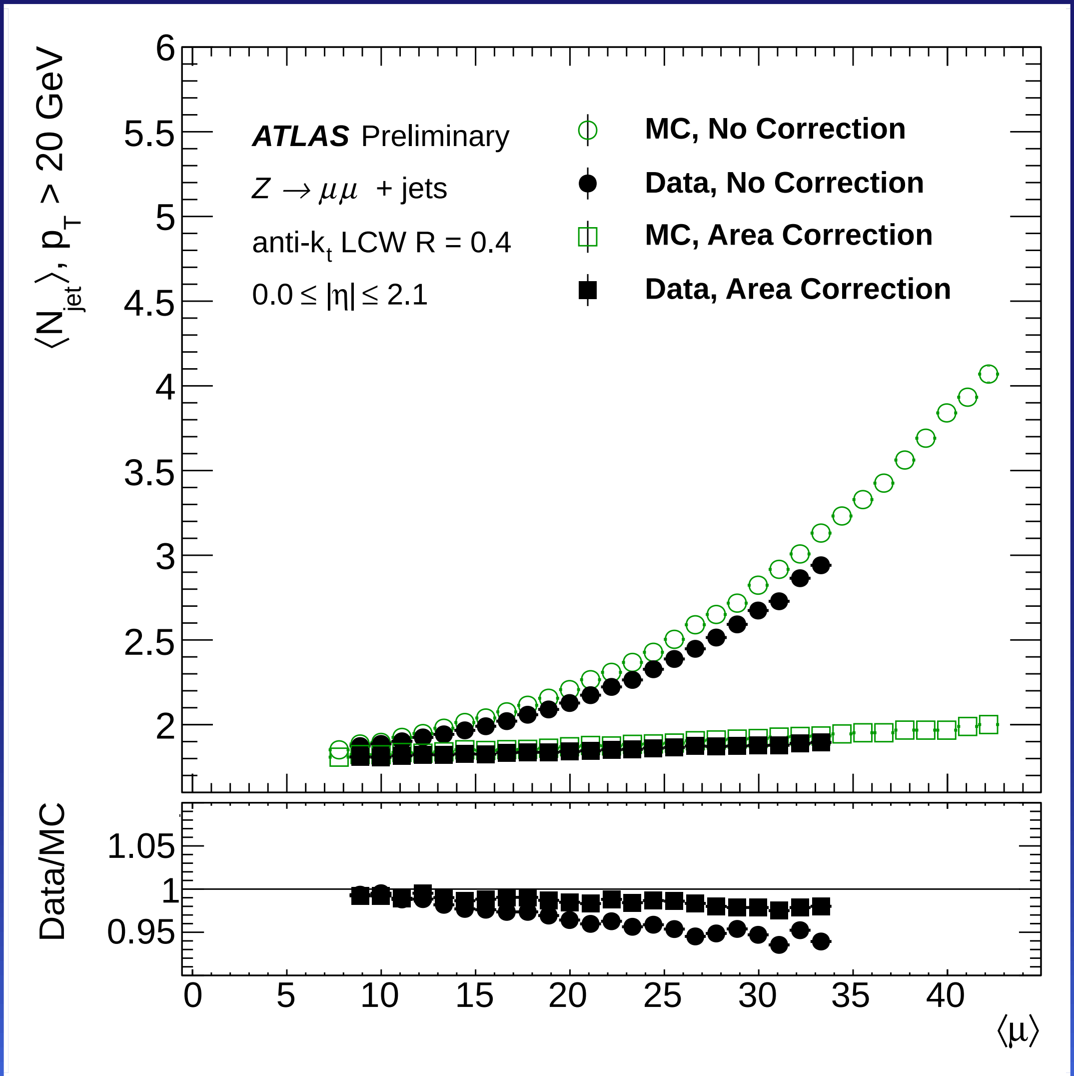


- $p_\perp$ resolution for jets in simulated di-jet events
  - uncorrected
  - offset corrected
  - jet area corrected
- as a function of in-time pile-up, N_{PV}
- as a function of out-of-time pile-up, $\langle\mu\rangle$
  - for 20 GeV $< p_\perp^{\mathrm{true}} <$ 30 GeV
  - $|\eta| < 2.4$
- jet area method improves resolution w.r.t. previous offset method
- still local pile-up fluctuations cause RMS to remain rising with N_{PV} and $\langle\mu\rangle$





- pile-up subtraction with jet area method reduces amount of pile-up inside jets
- but also suppresses jets with $p_\perp^{\text{jet}} < \rho \times A_{\text{jet}}$



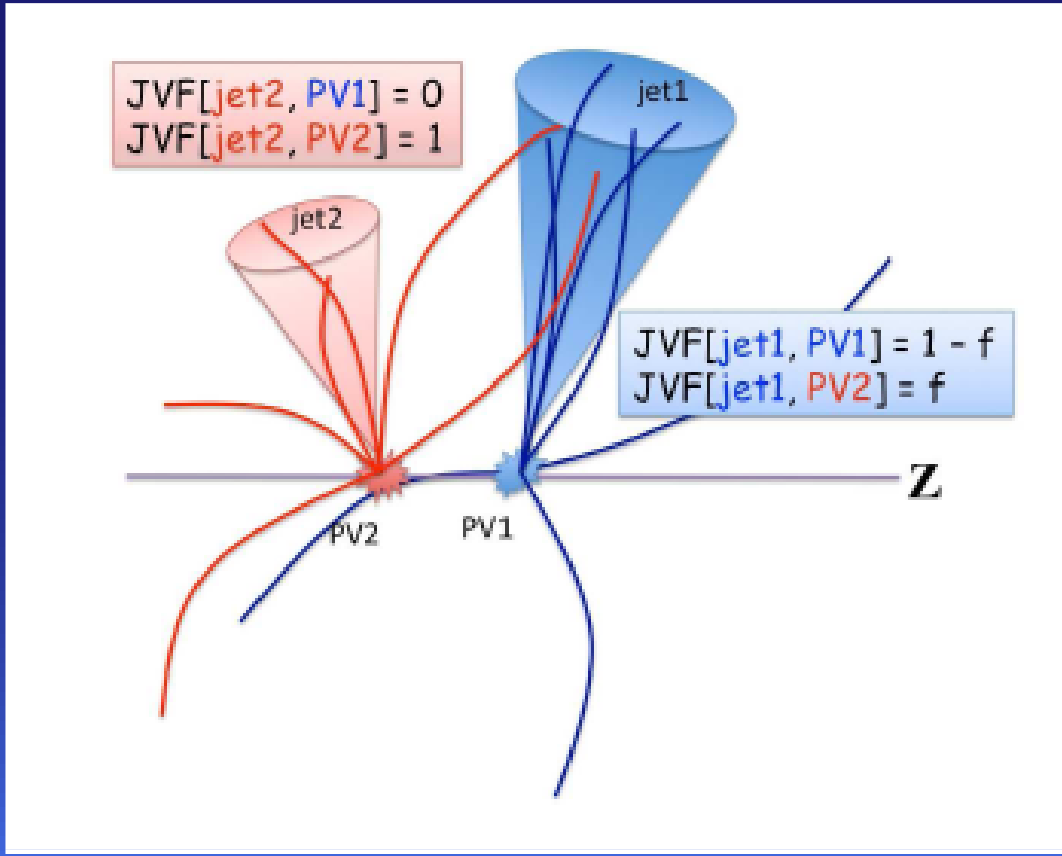
- jet multiplicity as function of $\langle\mu\rangle$ in $Z \to \mu\mu + \text{jets}$ events before and after pile-up correction
  - pile-up correction improves data/MC agreement
  - reduced μ dependency
- still some jets remain due to localized pile-up fluctuations

Jet Vertex Fraction

- track-based observables can help to remove those jets
  - the Jet Vertex Fraction (JVF)

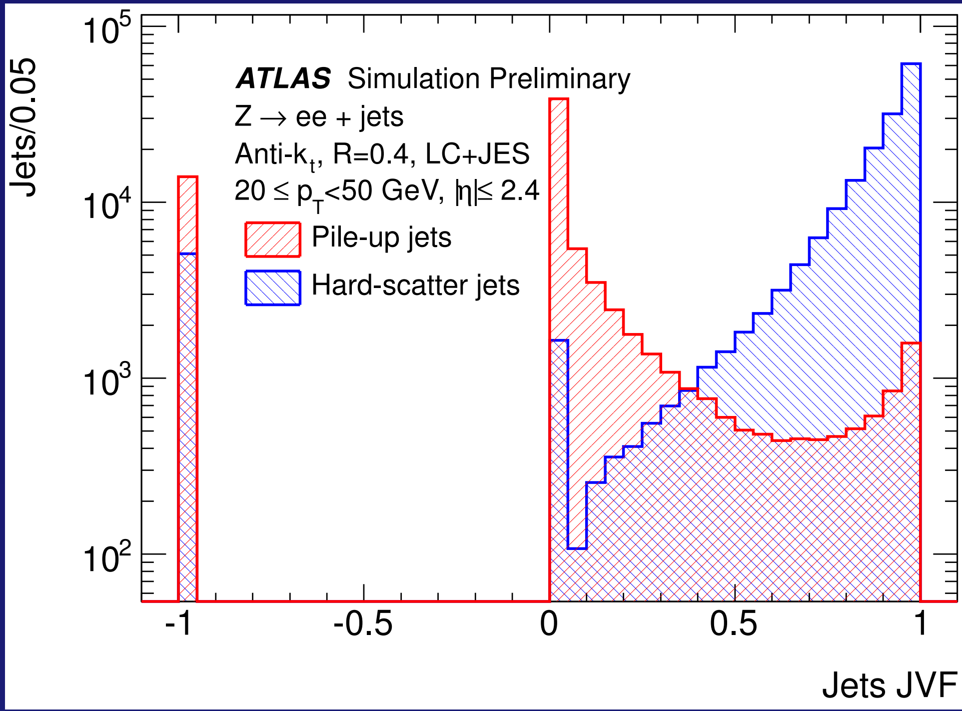
$$\mathrm{JVF}(\mathrm{jet}, \mathrm{PV}_j) = \frac{\sum_k p_\perp(\mathrm{track}_k^{\mathrm{jet}}, \mathrm{PV}_j)}{\sum_n \sum_l p_\perp(\mathrm{track}_l^{\mathrm{jet}}, \mathrm{PV}_n)}$$

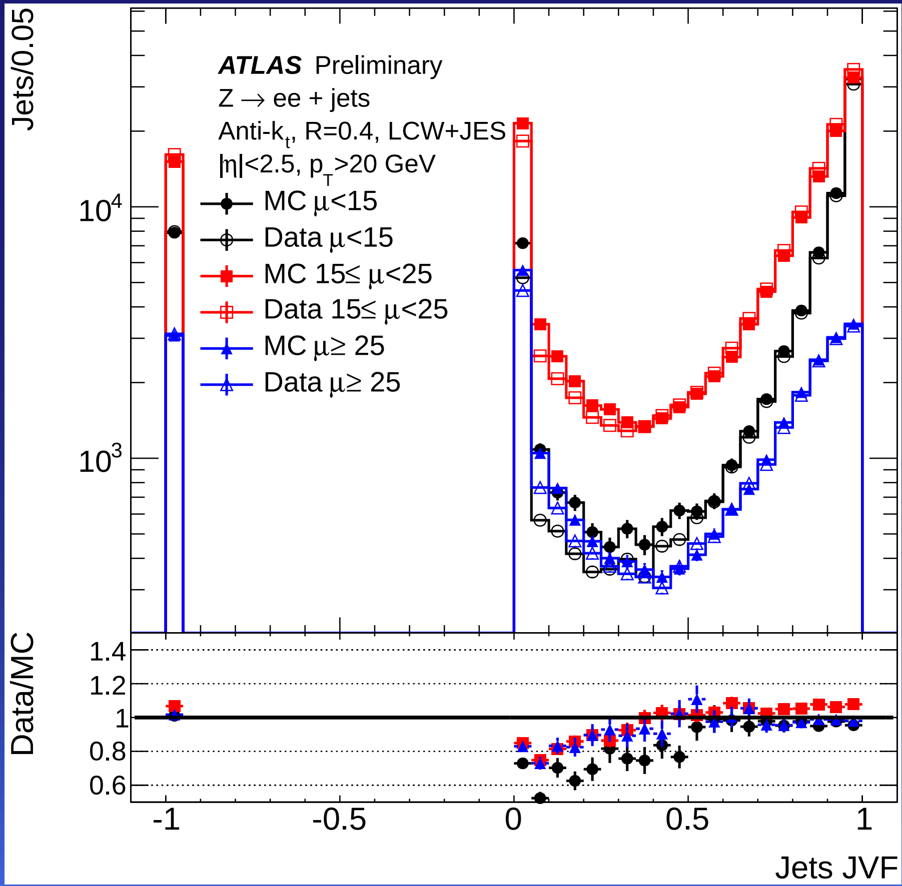
- counts fraction of $p_\perp$-sum of all tracks associated to the jet and a given vertex over the track-$p_\perp$-sum for all vertices for that jet
- properties of JVF assuming one hard vertex w.r.t. this vertex:
  - 0 for pile-up
  - 1 for the hard scatter signal
  - -1 for jets without associated tracks



Jet Vertex Fraction ► Performance

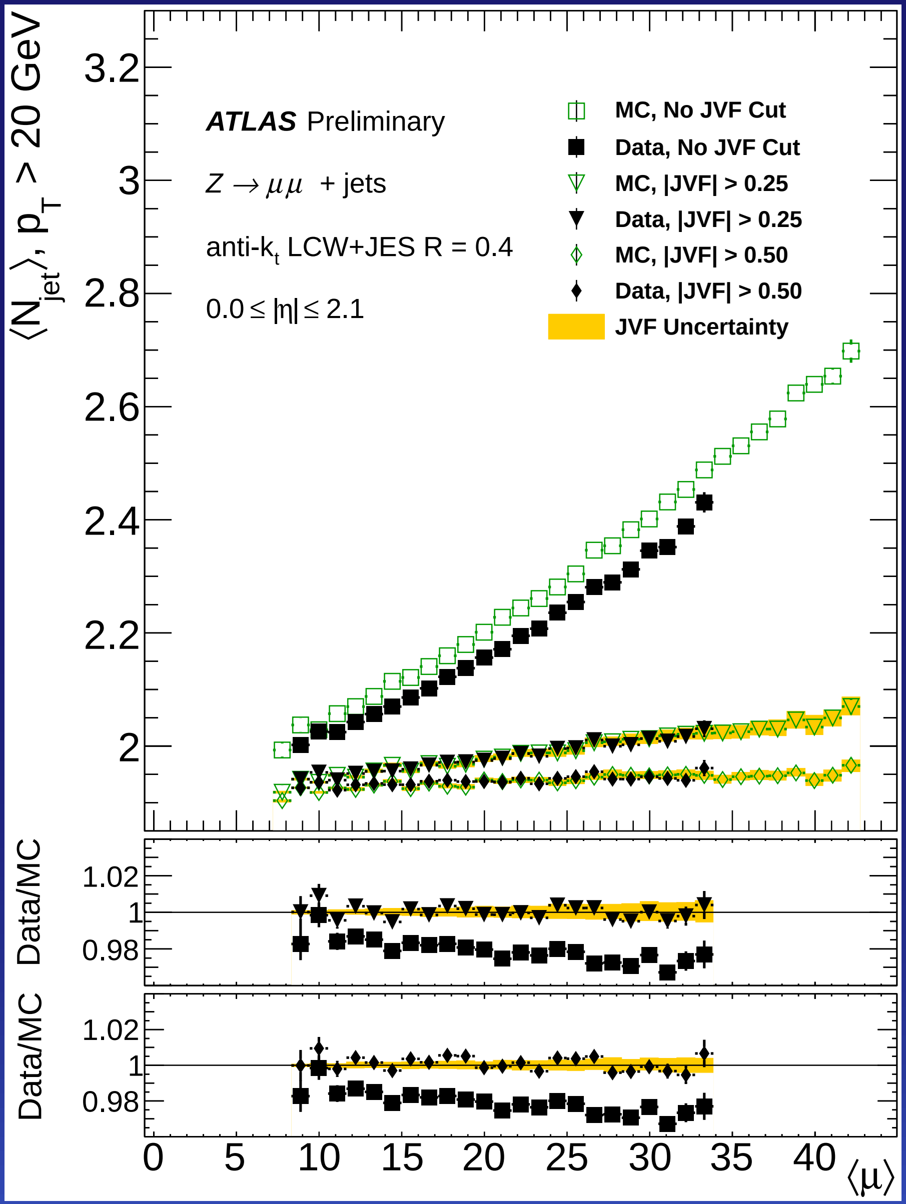
- $Z \to ee + \text{jets}$ events to identify one hard PV with leptons
- check in MC the JVF distribution for jets from the hard scatter and from pile-up





- compare JVF in data and MC for different μ
  - for larger μ the peak at $\text{JVF} = 0$ rises
  - MC reproduces data distributions quite well

Jet Vertex Fraction ► Performance

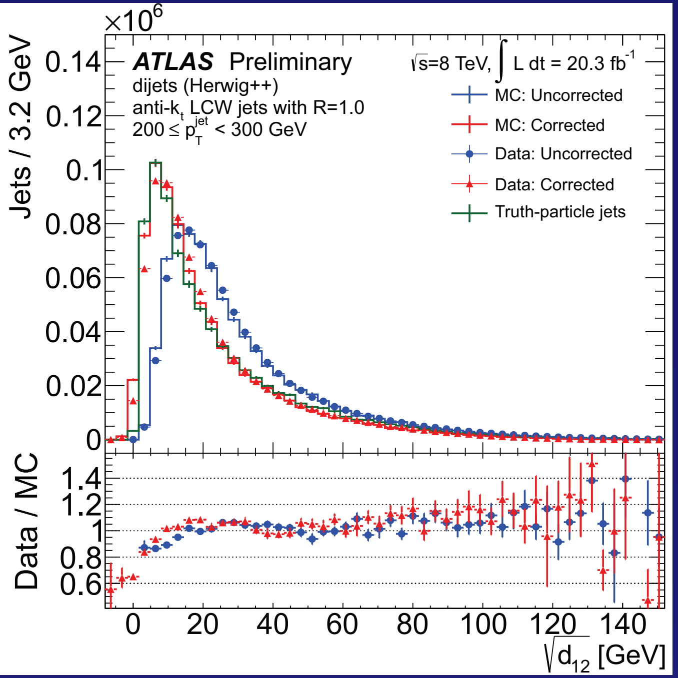


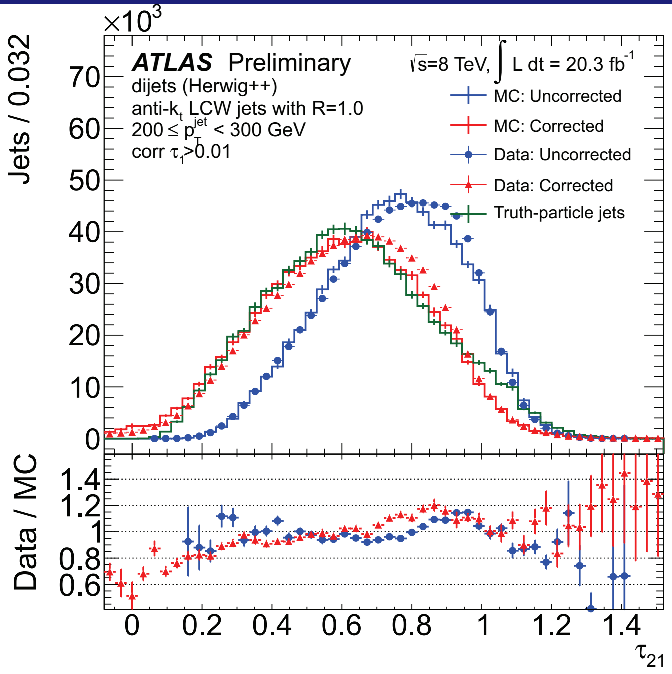
- use JVF to suppress pile-up:
- jet multiplicity for two $|JVF|$ cuts in $Z \to \mu\mu +$ jets data and MC compared to no cut vs. $\langle \mu \rangle$
  - $|\text{JVF}| > 0.25$
    ► reduces pile-up jet already significantly
  - $|\text{JVF}| > 0.5$
    ► the dependency on μ vanishes
  - both lead to good data/MC agreement

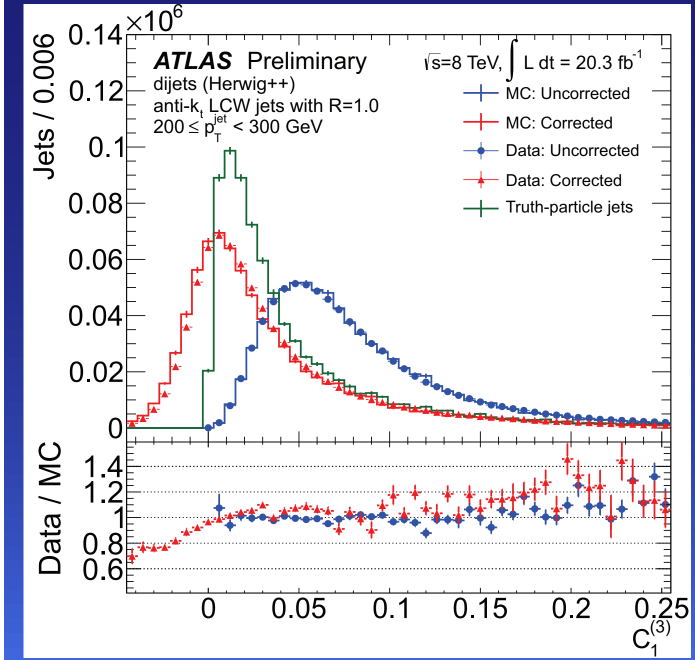
Jet Shapes

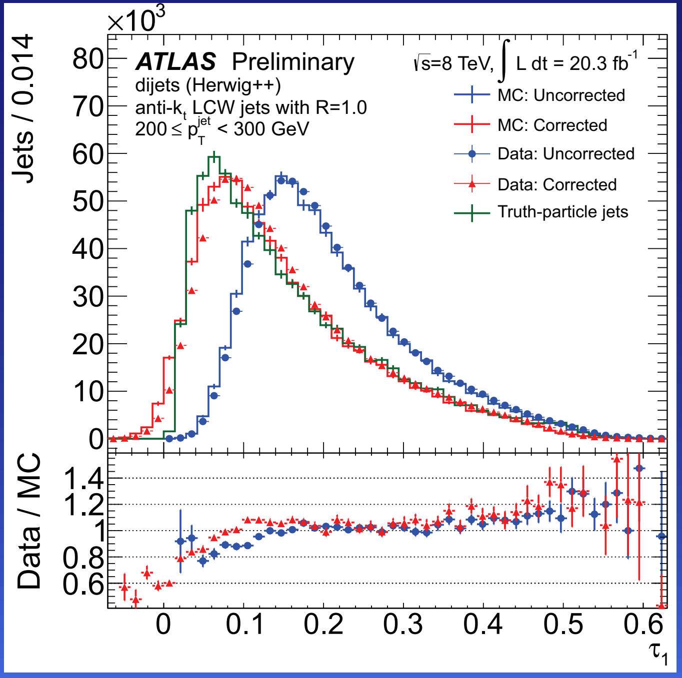
- pile-up subtraction for jet shapes (arXiv:1211.2811) is an extension of the jet area correction approach beyond the $p_\perp$ of the jet
  - first ingredient is the ghost's 4-vectors $g_\mu = g_\perp[\cos\phi, \sin\phi, \sinh y, \cosh y]$ with area $A_g = 1/\nu_g$
  - their addition during the jet forming change jet shapes $\mathcal{V}(\rho, g_\perp)$ slightly
  - by varying the ghost's transverse momentum scale $g_\perp$ the effect on any shape can be evaluated
  - and eventually subtracted
- instead of subtracting the average $\rho \times A_{\text{jet}}$ from the jet $p_\perp$ the corresponding subtraction is done for the ghosts
  - measured shape: $\mathcal{V}(\rho = \rho_0, g_\perp = 0)$
  - desired shape: $\mathcal{V}(\rho = 0, g_\perp = 0)$
  - correction principle: $\mathcal{V}(\rho + \delta, g_\perp) = \mathcal{V}(\rho, g_\perp + \delta \times A_g)$
  - evaluate: $\mathcal{V}(\rho = 0, g_\perp = 0) = \mathcal{V}(\rho = \rho_0, g_\perp = -\rho_0 \times A_g)$
- calculated with first 3 terms of Taylor expansion

- several shapes tested in 2012 data and MC
  - splitting scale $\sqrt{d_{ij}} = \min(p_{\perp,i}, p_{\perp,j})\Delta R_{ij}$, with the distance of two subjets ΔR_{ij}
    $i = 1, j = 2$ for the last two sub-jets in jet forming
  - N-subjettiness
    $\tau_N = \sum_k p_{\perp,k} \min(\Delta R_{1,k}, \ldots, \Delta R_{N,k}) / \sum_k p_{\perp,k} R$, close to 0 if the jet can be described by N or less sub-jets
  - ratios of τ_N, $\tau_{ij} = \tau_i/\tau_j$
  - energy-energy correlations (EEC) of the jet constituents, $C_1^{(\beta)} = \left(\sum_{i<j} p_{\perp,i} p_{\perp,j} (\Delta R_{ij})^\beta\right) / \left(\sum_k p_{\perp,k}\right)^2$
- examples for di-jet events
- corrected shapes closer to truth



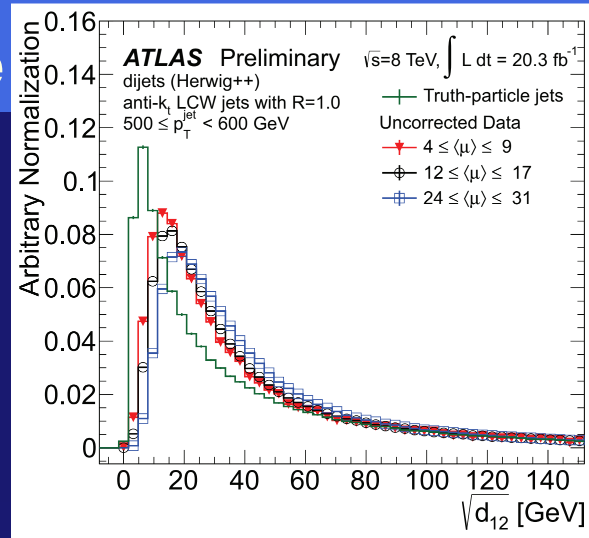


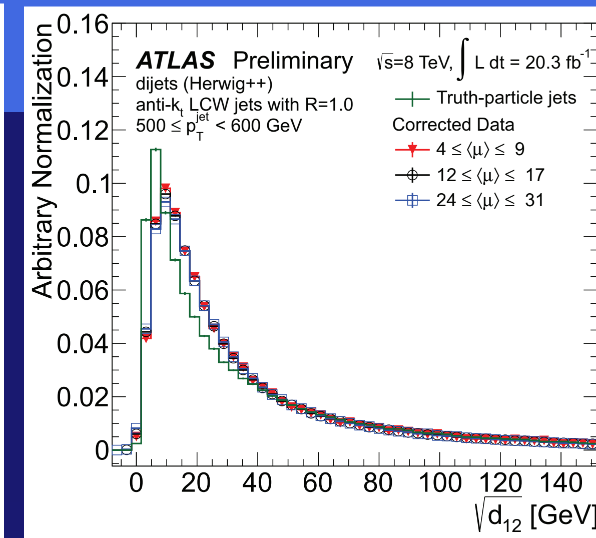


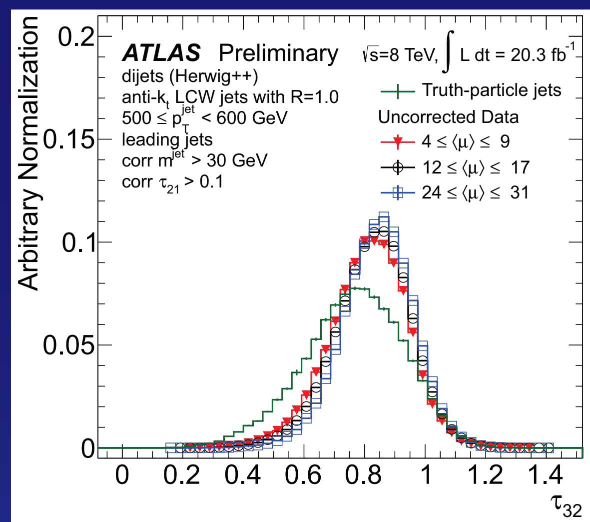


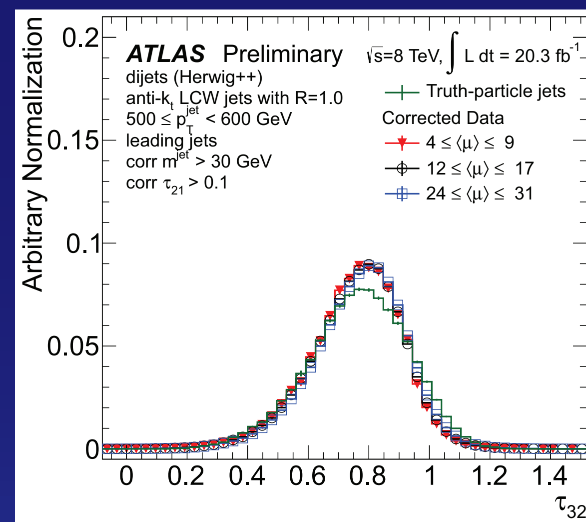
Jet Shapes ► μ Dependence

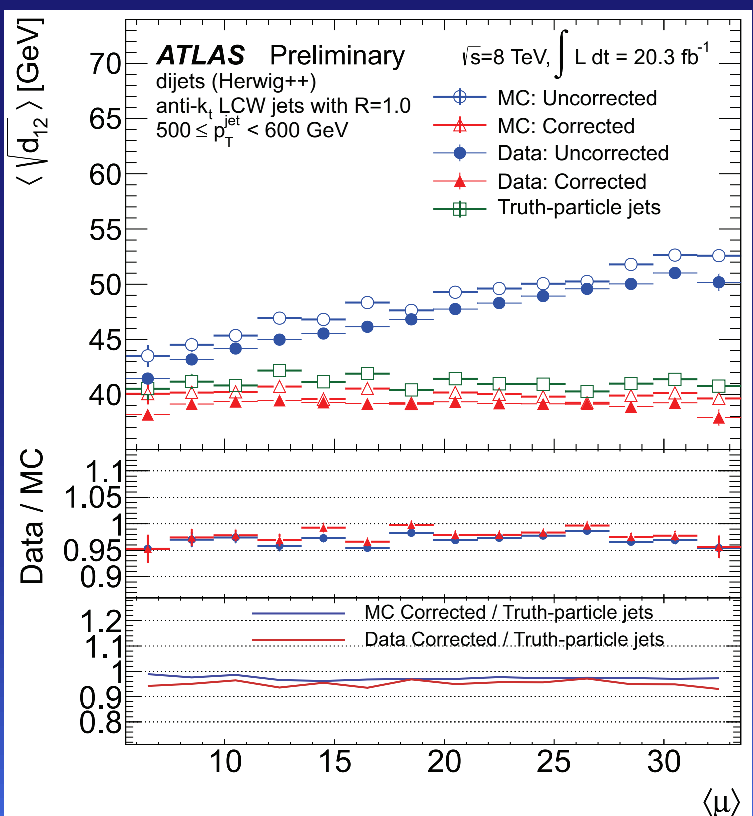
- shapes before and after correction for different μ
- for di-jet events with $500\,\mathrm{GeV} < p_\perp < 600\,\mathrm{GeV}$
- correction reduces μ dependence and moves corrected data close to MC truth











- average shapes for same events vs. μ
- splitting scale $\sqrt{d_{12}}$ as typical example ► also for the average shapes the correction removes μ dependence and improves agreement with non pile-up truth

Conclusions

- Pile-up reached in 2012 unprecedented levels in ATLAS
  - even surpassed design levels at the beginning of some fills
- It will become even larger after the long shutdown
- Methods to subtract and to suppress pile-up have been improved for the 2012 data
- Corrections:
  - corrections are mainly based on jet areas and the median transverse momentum density in the event
  - works as $p_\perp$ subtraction for jets
  - and also with ghost subtraction approach for jet shapes
- Suppression:
  - direct suppression by adapting the calorimeters noise definition
  - track based suppression with the jet vertex fraction to identify jets with mostly pile-up
- similar methods also used for missing transvere momentum measurements