Timing and pile-up noise performance in the TileCal

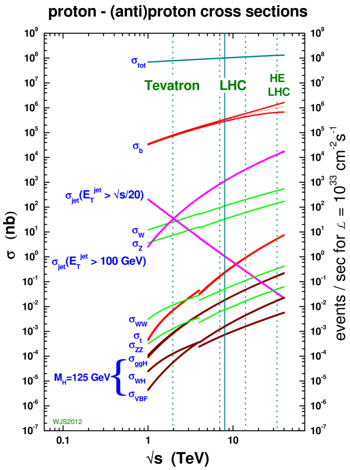
Krystsina Petukhova

Charles University (Prague)

April 9, 2018

LHC. p-p collisions

- pp collisions at $\sqrt{s}$ =13TeV
- bunch collision rate – 40 MHz
- 2808 bunches with 115 bln protons in each beam
- unprecedented lumi $L = \frac{10^{34}}{cm^2 s}$
    - to increase probability of processes and production rate
    - to collect as much as reasonably possible, and eliminate statistical uncertainty of the current measurements
- discovery – 5σ
- extension of previous studies



Strong interaction. Jets

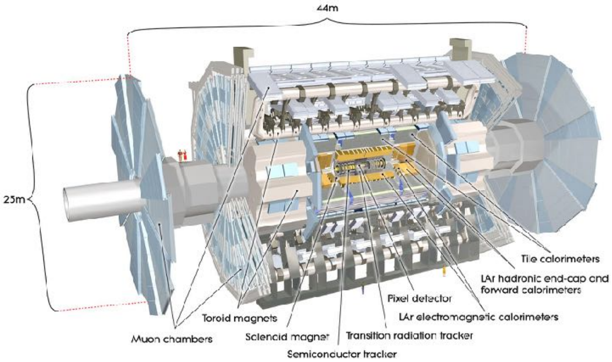
- jets are collimated sprays of hadrons arising from parton level interactions within colliding protons
- jets play important role in many physics analysises and searches for New Physics
- QCD is being developed theory $\leftrightarrow$ effective hadron measurement
- among main limitations is precision of calorimeter measurement
- careful calibration, constant monitoring and maintenance, as well as resolution improvement are important

Jets is the dominant product at LHC:

$$\sigma(pp \to jets) = \sum_{i,j} \int dx_{p_1} f_{i/p_1}(x_{p_1}, \mu_F) \int dx_{p_2} f_{i/p_2}(x_{p_1}, \mu_F) \sigma_{ij \to jets}(\mu_R, \alpha_S, x_{p_1}, x_{p_2})$$

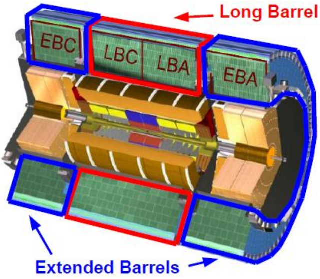
ATLAS experiment at LHC

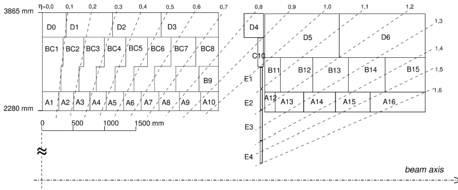
- one of two multipurpose detectors
- accordeon structure
  - inner tracking detectors
  - electromagentic and hadronic detectors
  - external muon chambers



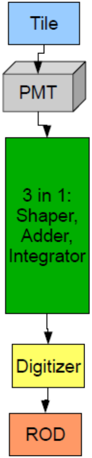
Hadronic Tile calorimeter

- purpose: to measure hadromic final state: hadrons, jets kinematics, taus, $E_T miss$.
- principle of work: scintillating tiles (plastic) are overlaying with absorber layer (lead)
- 3 cylinders: long barrel ($|\eta| < 1.0$) and 2 extended barrels ($0.85 < |\eta| < 1.7$); 64 modules in each barrel
- granularity $\leftrightarrow$ 5182 cells; 3 radial layers

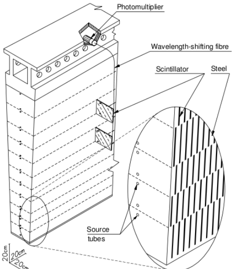


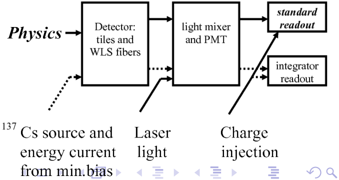


TileCal read-out



- read-out system – 10000 channels
- PMT output signal is shaped & amplified every 25 ns
- digitized samples are sent to ReadOut Driver (ROD)
- trigger selection
- calibration sequence: eV = test beam const [eV/Q] * CIS const [Q/ ADC-count] * Cs const * laser const
- resolution for calorimeters: $\sigma \sim \frac{1}{\sqrt{E}}$



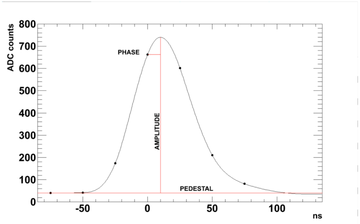


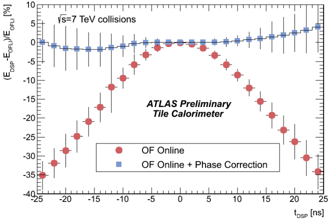
Reconstruction of event

- amplitude, time and quality of the signal are estimated with optimal filtering (OF) algorithm
- non-iterative OF algorithm implies noise variance minimization; weights based on channel pulse shape, expected phase...

$$A = \sum a_i S_i ; t_0 = \frac{1}{A} \sum b_i S_i$$

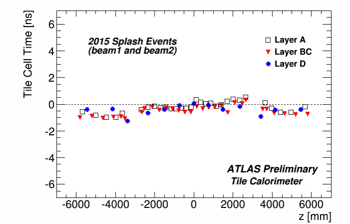
- OF is sensitive to the timing phase $\rightarrow$ timing calibration need
- accurate measurement of energy $\rightarrow$ noise measurement need

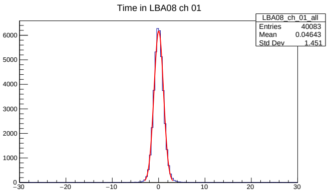




Timing preparation of the TileCal

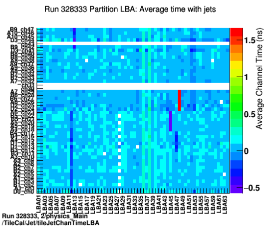
- important for energy reconstruction as well as timing measurements
- digitization timing in the detector should be adjusted to the peak value of registered signal
- initial timing calibration was performed using high-energy muons
- later on, timing constants were tuned with the calibration derived with jet events in collision data: gaussian mean of time distribution
- laser-in-gap events – laser shots during empty orbit in physics runs
- splash events – timing measured in high-energy muon collision; corrected for time-of-fly for each channel

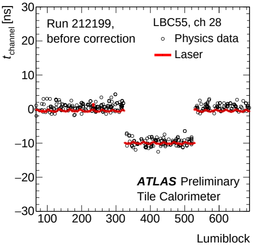


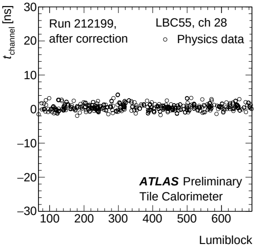


TileCal timing monitoring

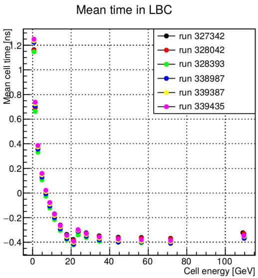
- monitoring of timing stability – comparison of the mean time in channels with the current timing constants:
  1. laser monitoring tool: reporting about timing shifts above 3ns
  2. using jets, similarly to the calibration based on jet data
- status of stability can be checked in a short time after data-taking → correction for time constants before physics analyses
- current situation: stability

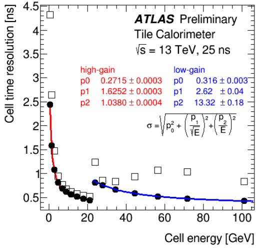


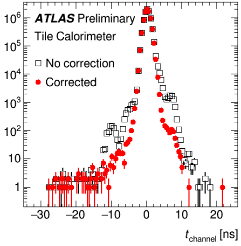




Timing resolution performance







- timing is stable between runs; can be different due to different beam phase wrt LHC clock
- during Run1, time setting were frequently changing; corrections the RMS improves from 0.90 ns to 0.82 ns
- during 2017, only 12 cases of timing jump were detected + timing in 5 individual channels was corrected; timing jumps above 3ns are corrected
- resolution 0.5-0.6ns for $E \sim 20$ GeV, below 1ns for $E_{cell} > 4GeV$

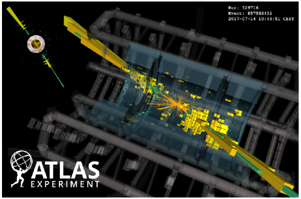
Picture of final state

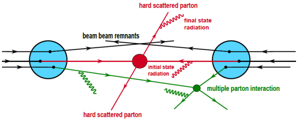
Substracting of background and selection of events-of-interest are of the major importance

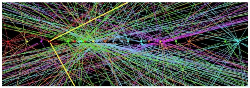
$$< \mu >= \frac{\sigma_{inel}\mathfrak{L}}{f_{LHC} n_{bunch}}$$

Pile-up is multiple p-p interactions at the same bunch crossing.

- events-of-interest = hard high-pt deep inelastic parton-parton scattering (a few, typically 1) +
- soft collisions = inelastic parton-parton interaction at low-pt range (about 25 at the current condition) == noise



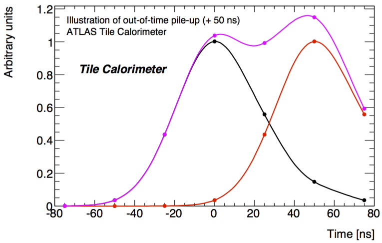


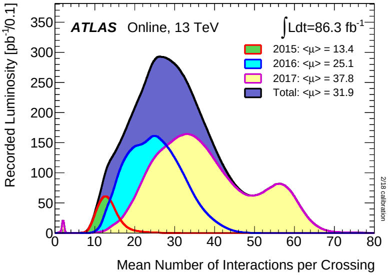


In-time & out-of-time pile-up

Pile-up smears resolution.

- in-time pile-up: simultaneous p-p collisions
- out-of-time pile-up: impact of the past/future collisions on the signal shape in the current bunch-crossing (i.e. slow LAr EM calorimeter charge collection ∼500 ns)





Noise measurement is essential.

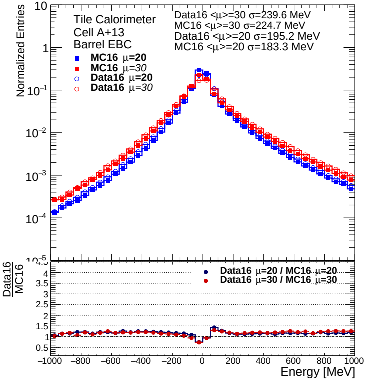
Noise in energy measurement

There are two major sources of noise:

- one brought by electonics, and
- another pile-up raised, which input depends on the number of interaction registred in the event
- noise in a given cell is estimated as standart deviation of energy distribution, in a reasonable assumption of its Gaussian shape

$$\sigma_{total} = \sqrt{\sigma_{elec}^2 + \frac{\sigma_{pile-up}^2 < \mu >}{R}}, \quad (1)$$

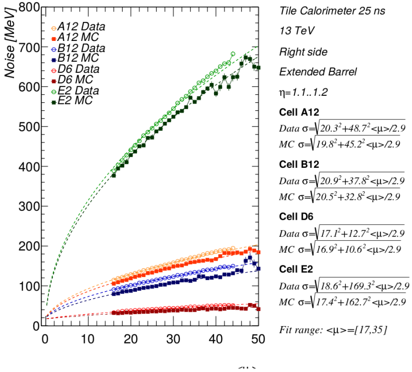
σ_{total} is estimated as RMS depending on $\sigma_{pile-up}$ and R, or rescaling factor used to correct $< \mu >$ value according to luminosity conditions and f_{LHC}.



Pile-up noise measurement

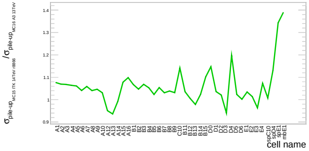
Pile-up noise estimation:

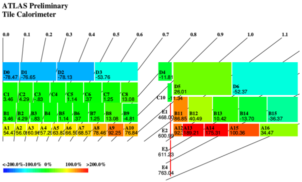
- assuming azimuthally uniform energy distribution
- measurement in data collected & MC simulation
- estimation of RMS of energy distribution at a given $<\mu>$ (number of interactions)
- derivation of PU constants from noise dependence on $<\mu>$
- PU constants received for each cell type are implemented into condDB
- PU calibration is crucial parameter during jet reconstruction

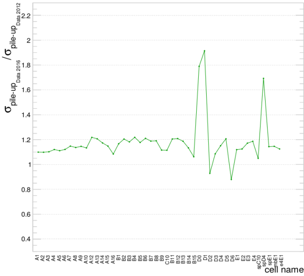


Monitoring of pile-up noise level

- PU noise level depends on the run conditions: $\sqrt{s}$, f_{LHC}, LB structure, etc. and should be constantly monitored
- important for reconstruction of final state physical picture, especially under high-luminosity conditions

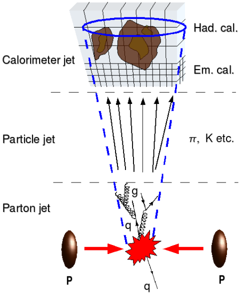


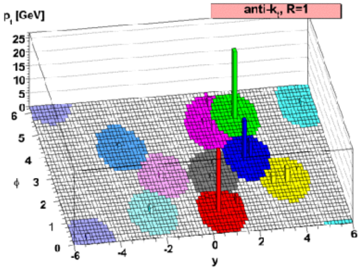




Jet reconstruction

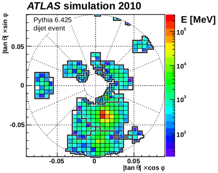
- parton level: partons knocked-out from protons
- particle level: particles as a result of parton evolution (hadronisation)
- reconstruction: using energy deposits in calorimeter – cells or tracks; inputs are topological clusters
- include all entities (clusters/particles) within a cone of a given size (often $\Delta\phi = 0.4$) starting with the most energetic input





Topological clusterization

- topological cluster is a set of topologically connected cells with a significant signal above noise (energy of particles) and particles
- clusterization – formation of topocluster
  1. starting with the most energetic cell $\frac{E}{\sigma} >= 4$ (nominally)
  2. surrounding the seed with neighbouring cells $\frac{E}{\sigma} >= 2$
  3. wrapping protocluster with perimeter cells $\frac{E}{\sigma} >= 0$
- the thresholds 4-2-0 are choisen to suppress reconstruction of noisy clusters and ensure pile-up substraction



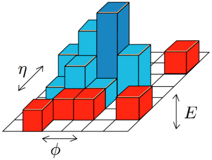
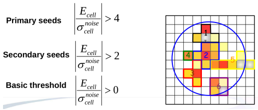


Illustration of a topological cluster:

dark blue seed cell

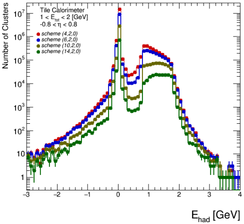
light blue selected adjoint and neighboring cells

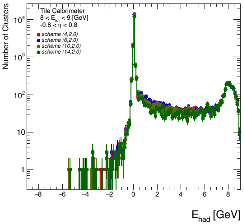
red rejected cells

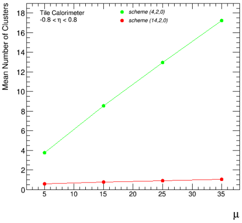


Modified topological clusters

- higher luminosity means increased number of pile-up interactions
- to prevent noise influence on final state freconstruction, updating of topoclusters formation scheme is proposed – modified topological clusterization schemes with higher energetic threshold for seed cell: 6-2-0, 10-2-0, 14-2-0, 20-2-0



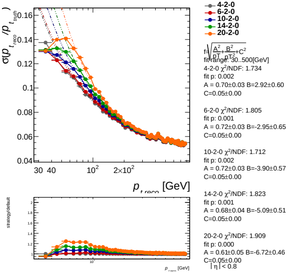


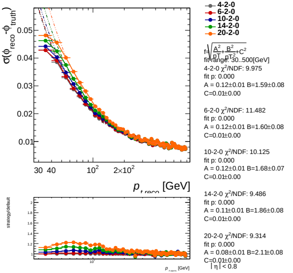


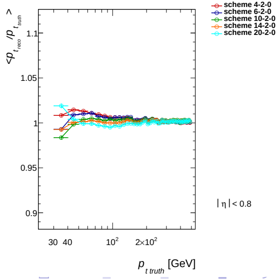
Mod. strategies: impact of small-energy range is reduced; robust under pile-up growing.

Jet Response and Resolution

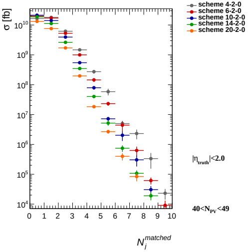
- jets were reconstructed using topological clusters made with enhanced signal-noise criteria
- own JES for each clusterization scheme were derived; jet area pile-up and origin correction were applied
- however, jet resolution is smeared in the mod. strategies
- still, the modified schemes show performance under high μ

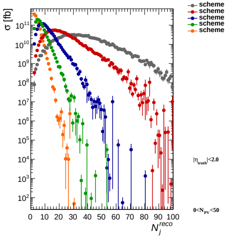


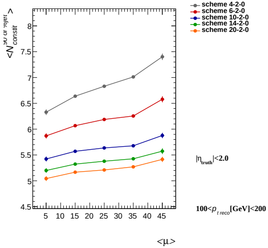




Pile-up suppression in jets reco –1

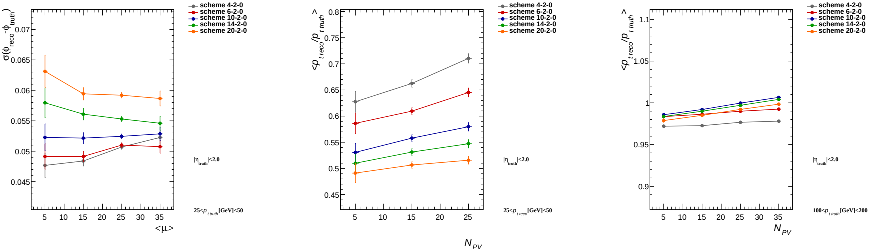






- number of reconstructed jets decreases significantly in higher-t_{seed} strategies
- matching with truth jets shows relevance of the modified schemes in high pile-up conditions
- increased t_{seed} prevent formation of noise-driven topocluster and their consequent input to reconstructed jets

Pile-up suppression in jets reco –2



- angular jet resolution has trend to improve in the modified strategies: raising by 1% at $<\mu>=30$ in the default strategy 4-2-0, and stable under growing pile-up in the mod.strategies
- although absolute value of jet energy resolution increases in the mod.strategies, pile-up mitigation has achieved: jet energy response is not sensitive to growing number of primary vertices in the mod. schemes, while increasing by 1% with addtional 30 interactions in the default startegy

Summary

- jet energy resolution (from data):
  $\sigma(E[GeV])/E[GeV]\ \frac{60\%}{\sqrt{E}} + 3\%$
- decreasing of JES uncertainty (now 1% for jets $55 < p_T[GeV] < 500$ and 3% for $p_T = 20GeV$)
- proposed pile-up mitigation technique – clusterization with increased threshold for a seed cell – shows robustness in high pile-up conditions
- results of the timing monitoring with laser-in-gap and collision data allow to make necessary timing adjustments before data processing for physics analysis
- current timing resolution is below 1ns for $E_{cell} > 4GeV$; during 2017, only a dozen of timing changes were reported in 2017
- nowadays, the TileCal has $\sim$ 0.8% of its cells masked; calibration is stable with precision of $< 1\%$

backup

Jet Resolution

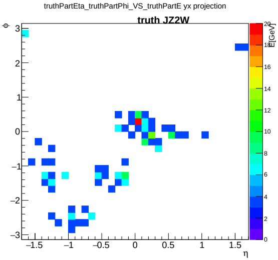
Energy resolution can be estimated by the following equation:

$$\frac{\Delta E}{E} = \sqrt{\frac{a}{E} + \frac{b}{E^2} + c}$$

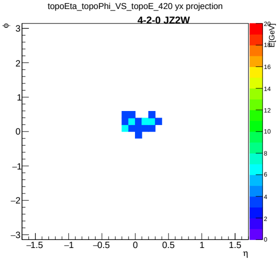
where a is a sampling term describing stochastic effect due to the fluctuation of shower development,
b takes into account energy measurement dependence on noise,
c is systematic error due to technical and machinery specifics, and energy response uniformity.

1. Constant term: Uniformity of the detector medium.
2. Stochastic term: Level of active sampling wrt total detector volume.
3. We should have a look at *noise term* – b which expresses uncertainty in energy measurement.

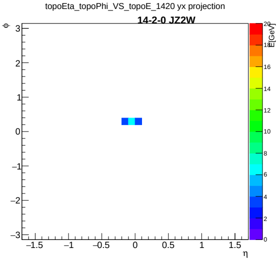
Maps of events – 1 small Pt bin



Truth



4-2-0

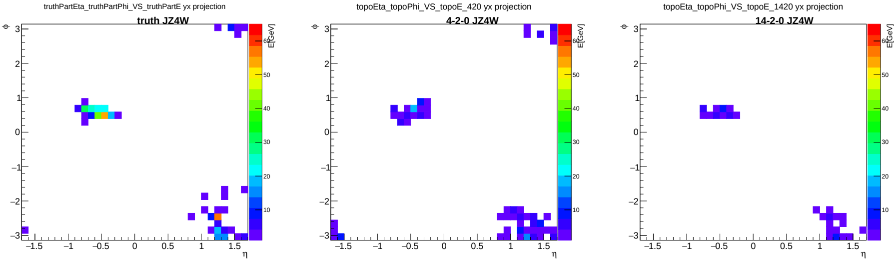


14-2-0

Number of topoclusters being formed is decreasing dramatically with growing t_{seed}: from in the default 4-2-0 to in 14-2-0, and through – in 6-2-0. So reconstructed energy of jet will leak signals from topoclusters non-formed ⇒ larger shift of pT^{reco} w.r.t. pT^{truth}.

One can see that in the modified schemes, the jet axis position is drifting in comparison with its location in the default scheme andor on truth level.

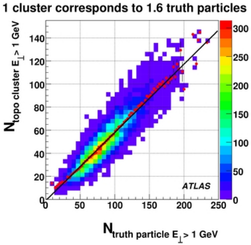
Maps of events – 2 large Pt bin

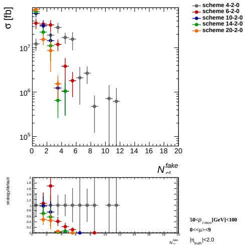


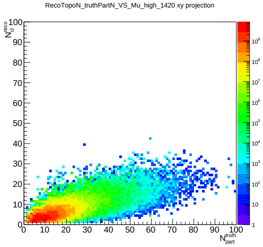
Truth | 4-2-0 | 14-2-0

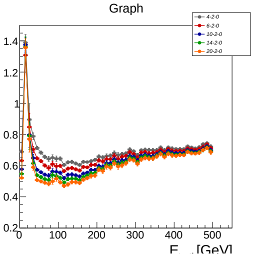
- shift of pT^{reco} w.r.t. pT^{truth}. due to topocluster misreconstruction
- jet axis position shift as low-energetic and peripheral topoclusters do not constibute

Topocluster reconstruction performance









Jet reconstruction performance