Jets Under HL-LHC Conditions

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SLAC

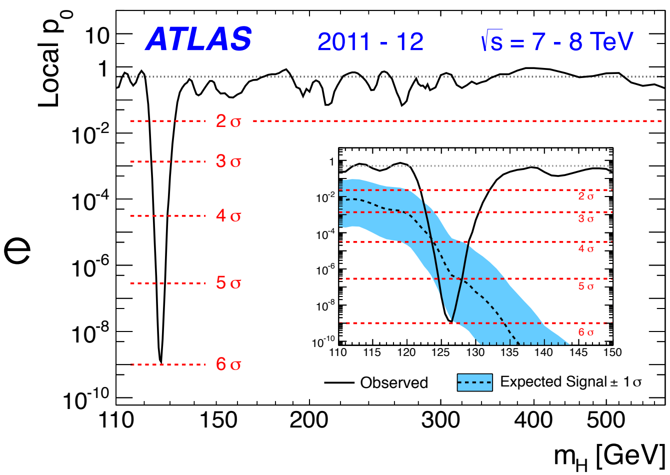
BOOST 2013, 12-Aug-2013

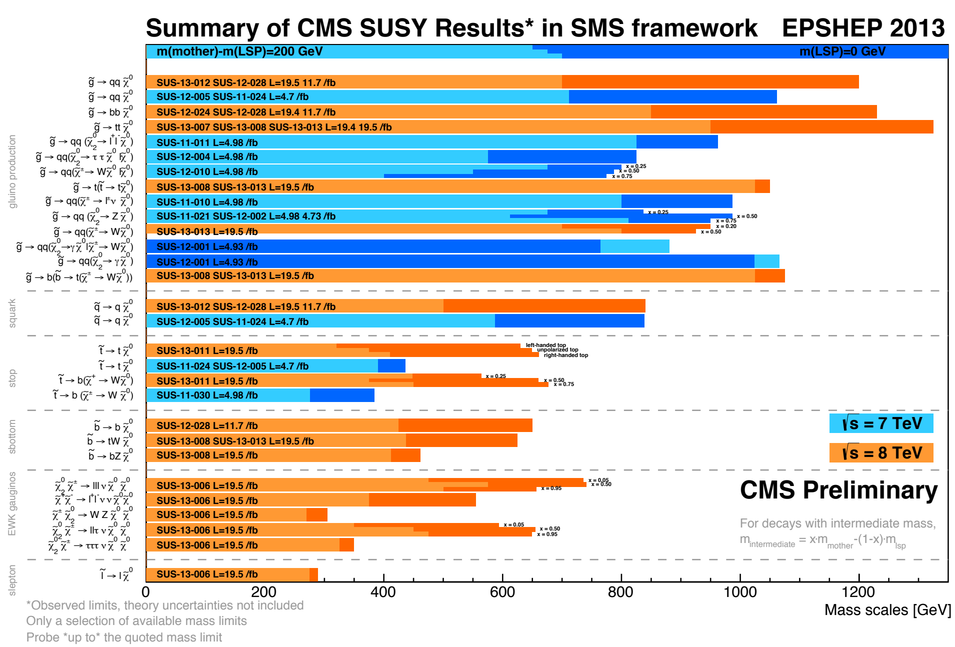
Outline

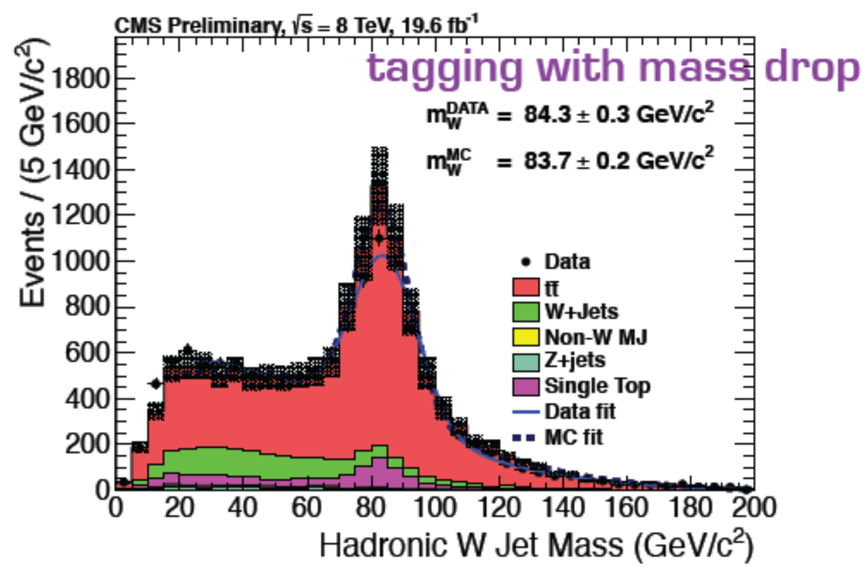
- **LHC beyond 2015**
  - Roadmap
  - Challenges
- **Jet and missing ET reconstruction and performance under HL-LHC conditions**
  - ATLAS Full simulation results
- **Detector upgrades and implications for jet and jet substructure performance**

Introduction

- **LHC Run 1**
  - **Discovery of a Higgs boson** and first measurements of its properties
  - **Precision measurements** of SM processes
  - **Strong limits for new particles** at the TeV scale
  - **Established jet substructure techniques**
    - Commissioning of boost techniques
    - Multiple applications in physics searches and measurements







LHC beyond Run 1

2009 — LHC startup, √s 900 GeV

2010–2012 — √s=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns — Run 1, ~25 fb^{-1} — **PU~20**

2013–2014 (LS1) — Go to design energy, nominal luminosity - Phase 0

2015–2017 — √s=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns — ~75-100 fb^{-1} — **PU~25**

2018 (LS2) — Injector + LHC Phase I upgrade to ultimate design luminosity

2019–2021 — √s=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns — ~350 fb^{-1} — **PU~80**

2022 (LS3) — HL-LHC Phase II upgrade: Interaction Region, crab cavities?

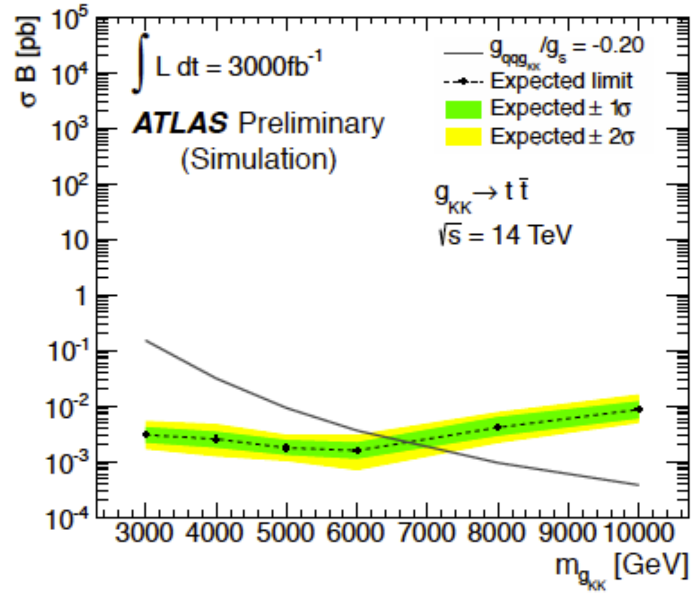
2023 … 2030? — √s=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling — ~3000 fb^{-1} — **PU~140**

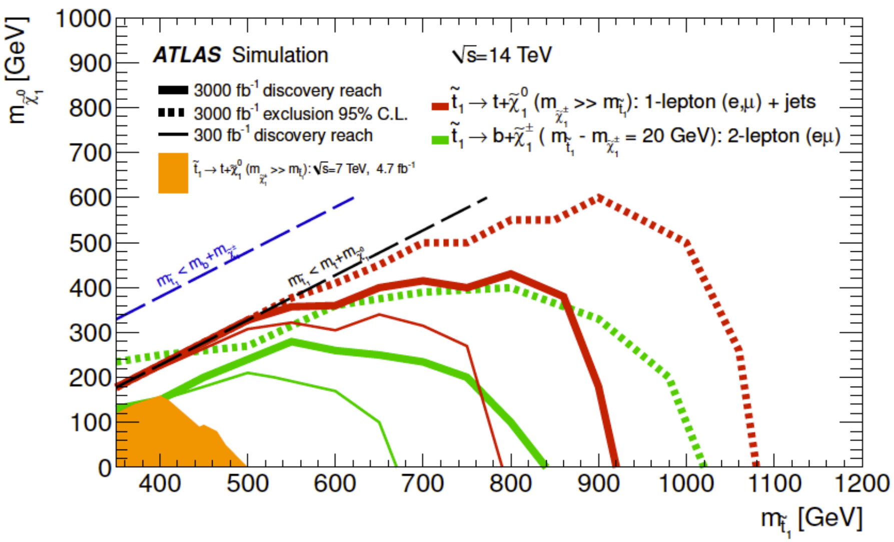
Physics motivations for HL-LHC

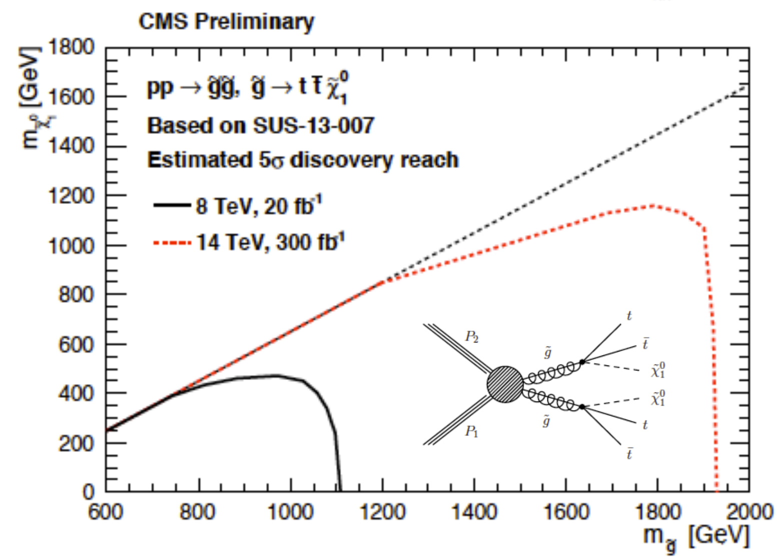
- **LHC** (Phase-0 and Phase-1)
  - Extend discovery reach for new particles into the multi-TeV region (factor of ~2 improvement)
  - Precision measurements of Higgs couplings and properties (~10% accuracy)
  - VV scattering (probe quartic gauge boson couplings)
- **HL-LHC**
  - Characterization of new physics discovered in Phase 1
  - Expand the discovery potential to new particles
    - 95% CL limit for for squark and gluons will be extended to 2.7 TeV
  - Improve precision of Higgs coupling measurements by a factor of 2-3
  - First measurement of Higgs self coupling
  - Searches for extended Higgs bosons
  - Top quark rare decays
- **Boosted techniques will play an even more prominent role in the full exploitation of the physics potential of the LHC**

HL-LHC physics potential

- **ttbar resonances :**
  - Kaluza-Klein gluons reach extended up to 4.3 TeV ($300fb^{-1}$) 6.7 TeV ($3000fb^{-1}$)
  - **Highly boosted top jets**
- **Direct and gluino mediated stop:**
  - Stop discovery potential reach increase up to about 1 TeV, covering most of the range favored by naturalness
  - **Require boosted top signal regions**

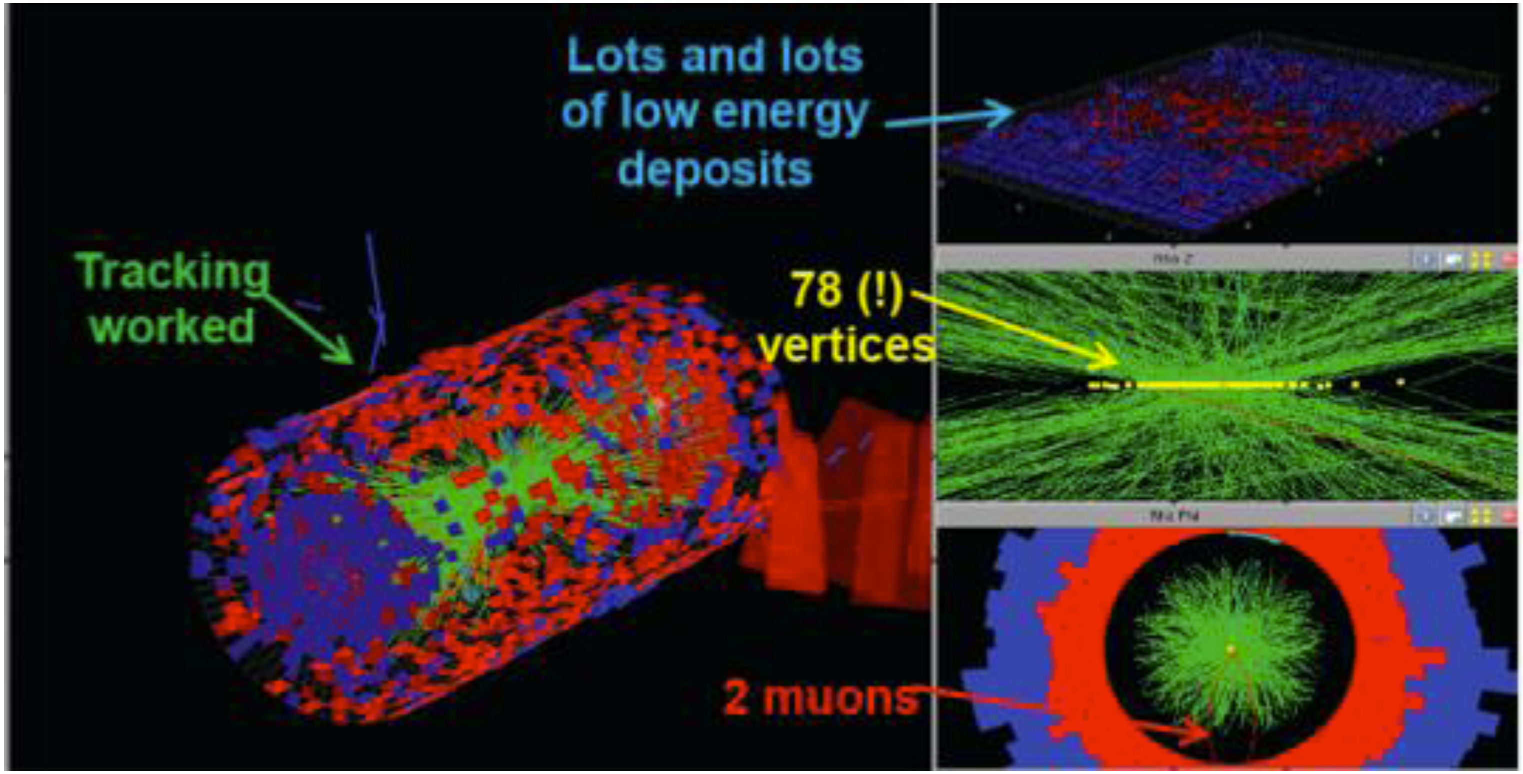






Experimental challenges

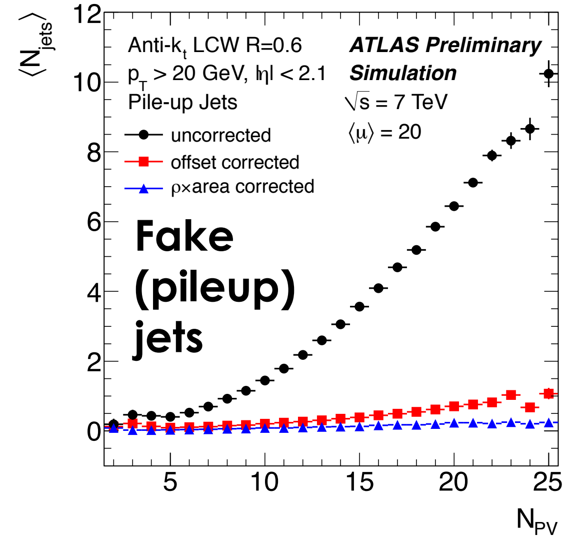
- Event reconstruction in the presence of high pileup
- Triggering
- Radiation damage
- **Need to maintain (or improve) reconstruction performance at much higher luminosity environment, with ~140 additional interactions**

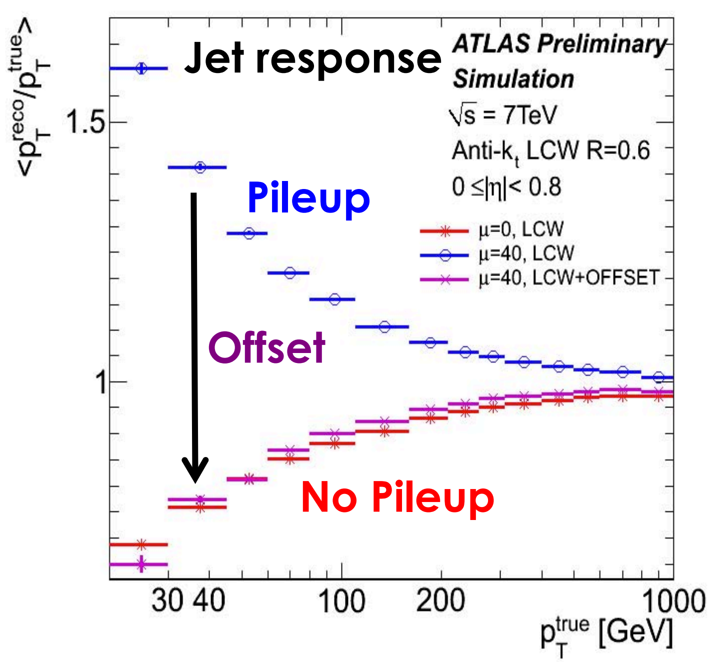


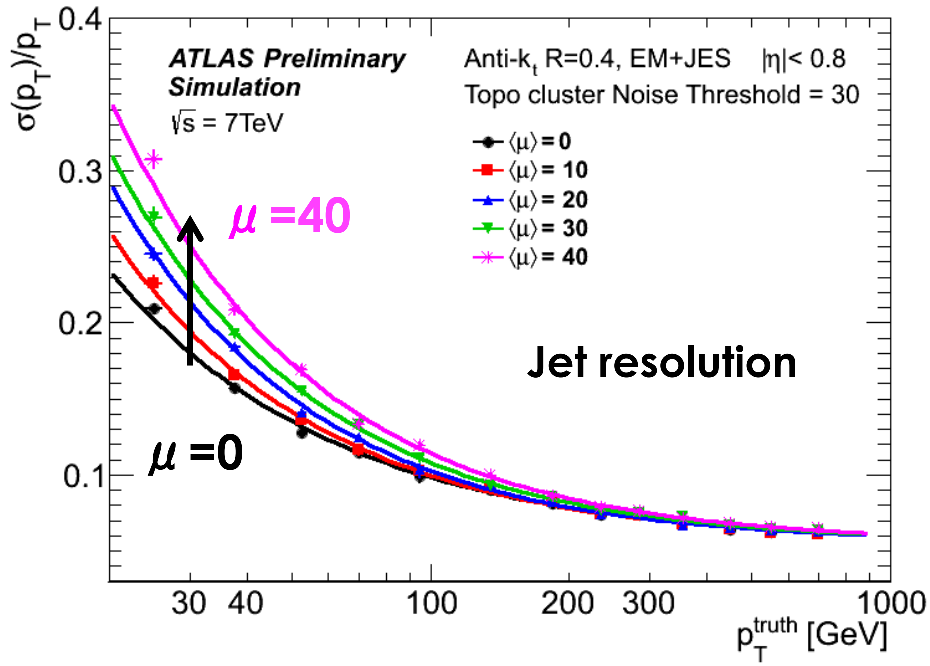
Pileup

Pileup is one of the main challenges for jets and missing ET at the LHC:

- **Additional energy (offset)**
- **Pileup fluctuations:**
  - increase the noise term of the jet **energy resolution** (event-by-event fluctuations)
  - additional **fake jets** (local fluctuations)

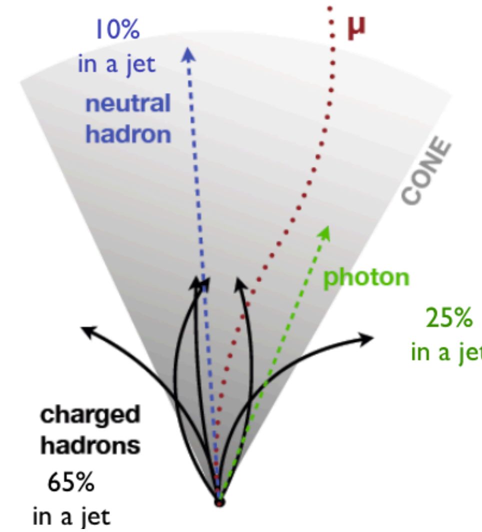


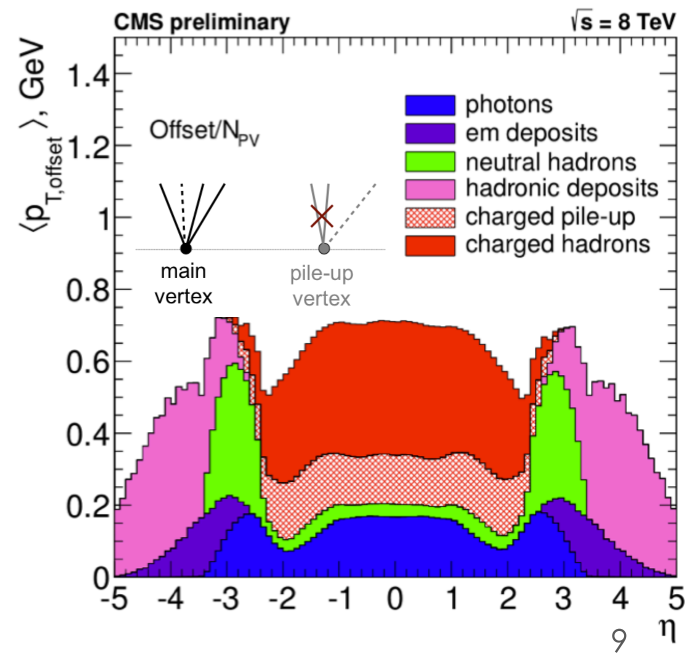




Jet reconstruction at CMS

- **Particle flow: reconstruct individually each particle combining tracking and calorimeter information:**
  - Relies on high granularity and resolution of ECAL and **high magnetic field** to <u>separate individual showers</u>
  - Improved energy and angular resolution and uncertainties
  - Individual "particles" used as input to jet finding:
    - **Ideal for jet substructure**
  - Limited by "confusion" term (ability to separate overlapping showers)
- **<u>Charged Hadron Subtraction</u>**
  - Removes charged particles from pileup vertices before jet finding
  - **Used in combination with jet-areas**

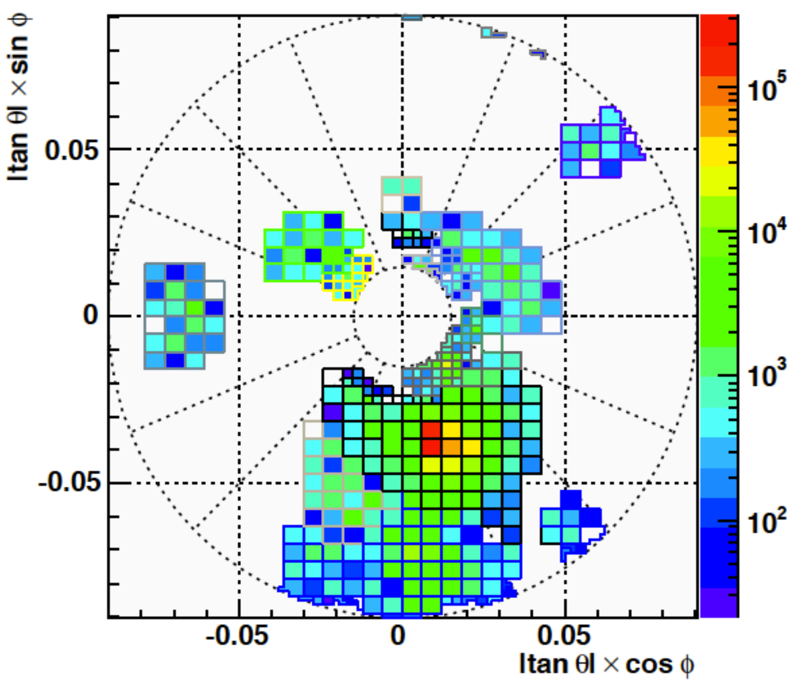


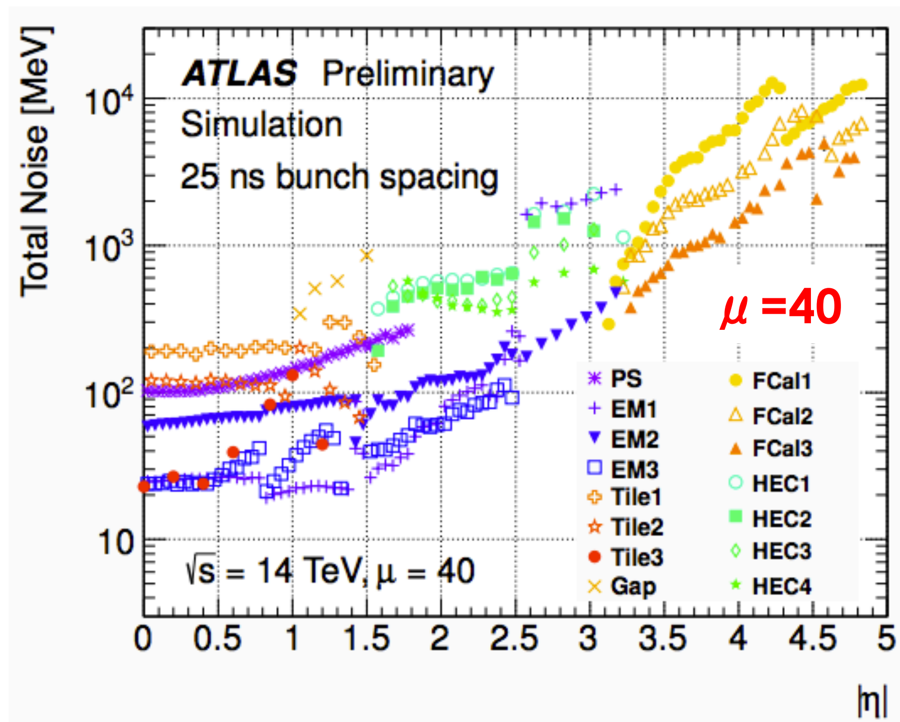


Jet reconstruction at ATLAS

- **Topological clusters:**
  - 3D nearest-neighbor algorithm that clusters calorimeter cells with energy significance ($|E_{cell}|/\sigma$) >**4** for the seed, >**2** for neighbors, and >**0** at the boundary
- **Sigma noise (σ):** electronic + pileup noise
  - Adjusted with $<\mu>$ for **pileup noise suppression**

2010: $\sigma(\mu=0)$
2011: $\sigma(\mu=8)$
2012: $\sigma(\mu=30)$





See Sven Menke's talk, Tuesday

Jet calibration

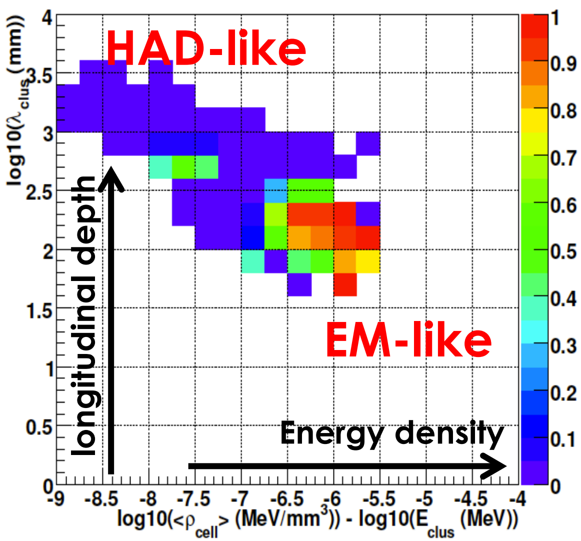
inputs

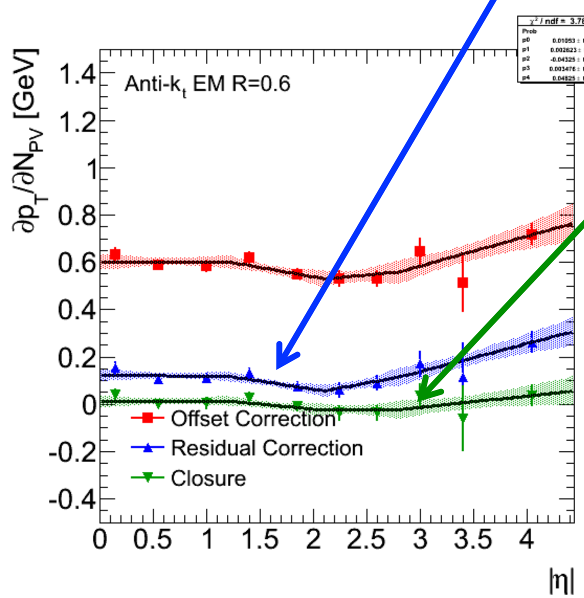
Jet energy scale

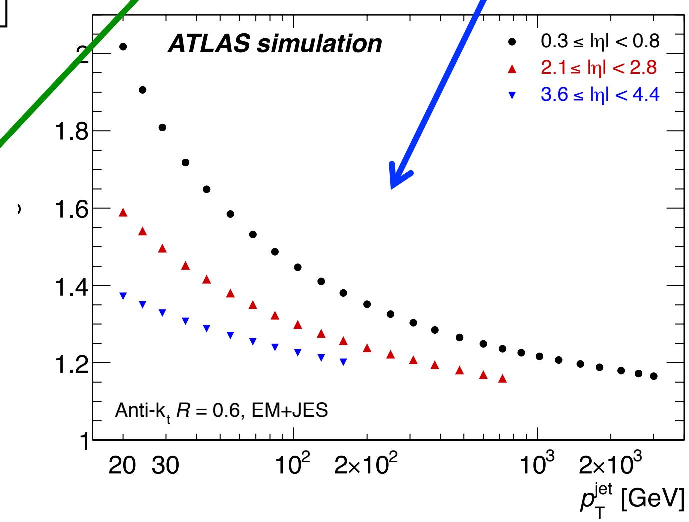
Topo-clusters (pileup noise threshold) → Local cluster weighting (LCW) → Event-by-event pileup subtraction → Residual offset (out-of-time, occupancy) → Jet Energy Scale

Pileup noise: $\sigma(\mu)$
Cluster splitting/merging
EM/HAD classification
Negative energy treatment

$$p_T^{calib} = \left(p_T - \rho A - \alpha(N_{PV} - 1) - \beta\langle\mu\rangle\right) \times JES$$







<u>Jet performance studies require a complete calibration chain:</u>
pileup noise thresholds, LCW, pileup subtraction, and energy scale

ATLAS Jet reconstruction in HL-LHC conditions

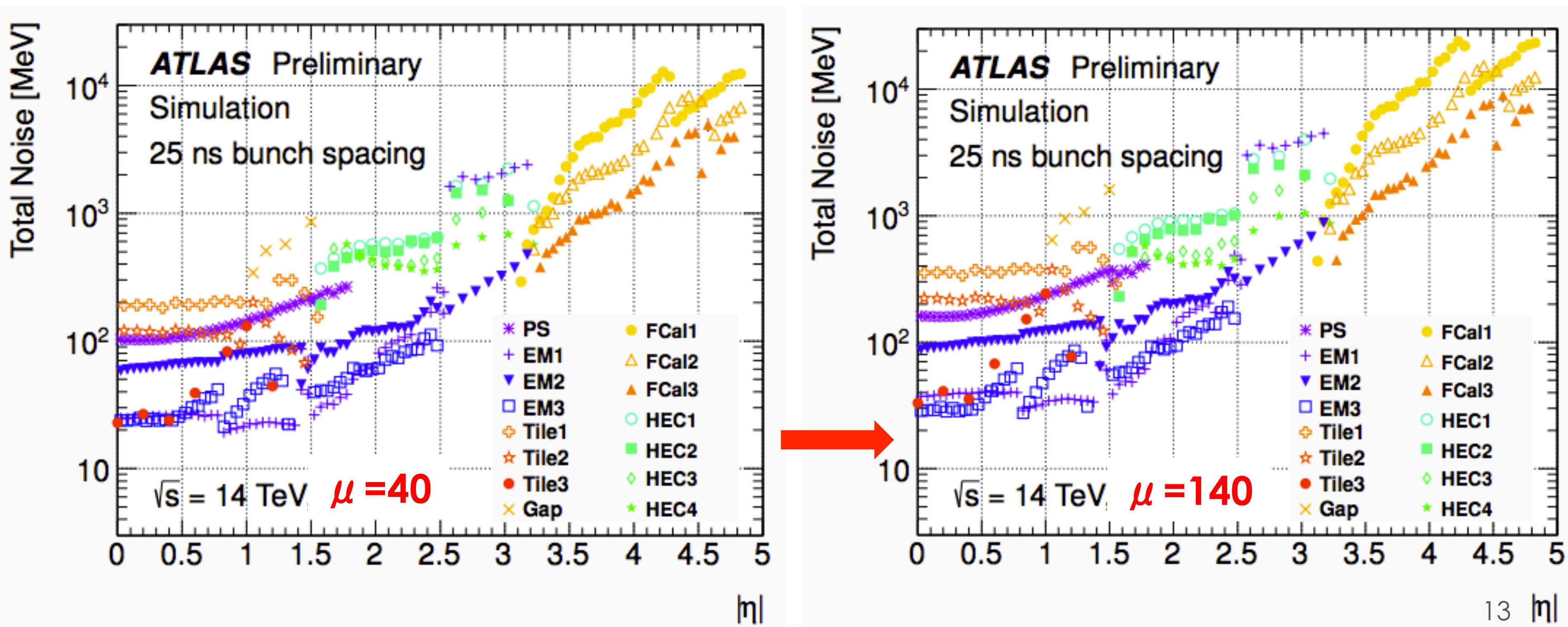
- **Broad program to optimize jet reconstruction and calibration techniques at very high luminosity**
  - Topo-clustering and cluster calibration (pileup noise threshold)
  - Pileup subtraction, residual offset, and jet energy scale
  - Pileup suppression
    - understand the effect and mitigation of pileup fluctuations
  - Grooming and jet algorithms

μ\σ	30	40	60	80	100	140	200
0	**X**	x	x	x	x	x	x
40	x	**X**	x	x			
60	x	x	**X**	x	x		
80			x	**X**	x		
140					x	**X**	x
200						x	**X**

- Production of dedicated datasets at several μ and pileup noise values (σ)
- **Calorimeter-only simulation:**
  - **No tracks available in this analysis**
  - Focus on optimization of calorimeter level reconstruction
  - **Room for improvements utilizing tracks**

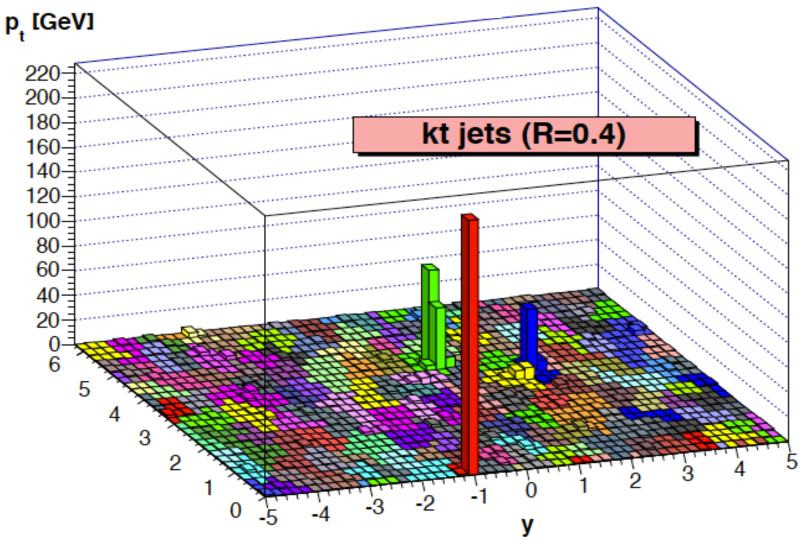
Topo-clustering at high luminosity

- **Adjust σ pileup noise for each μ configuration**
- **Optimization of local calibration for EM/HAD cluster classification for each pileup noise value**
  - Derived from single pion simulation with μ =0 and σ (μ >0)

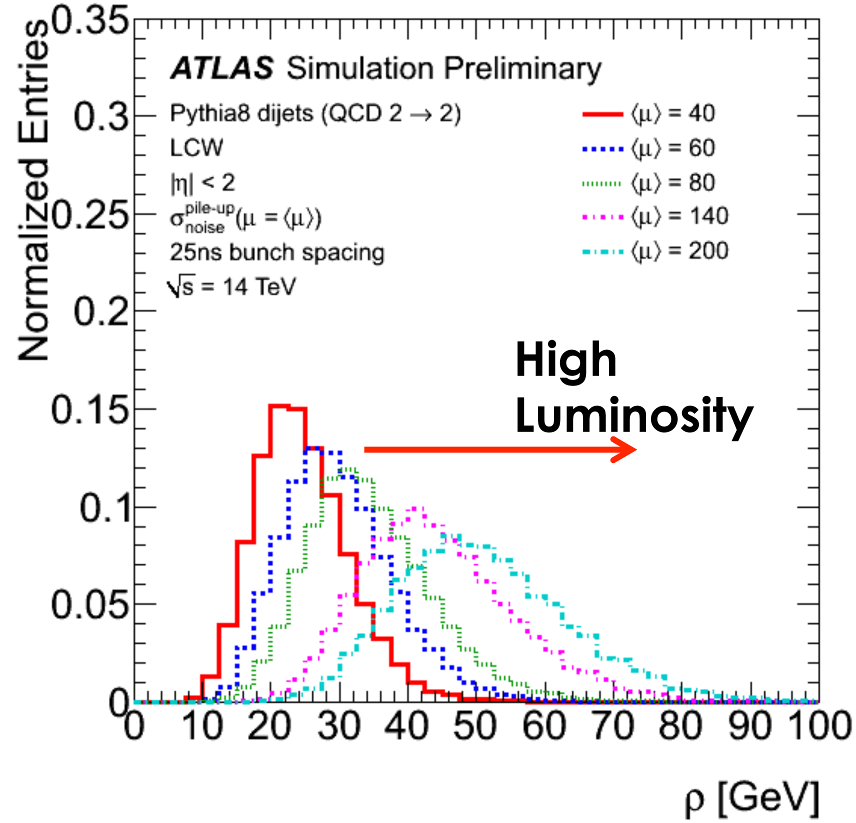


Pileup subtraction (I)

arXiv:0707.1378 [hep-ph]



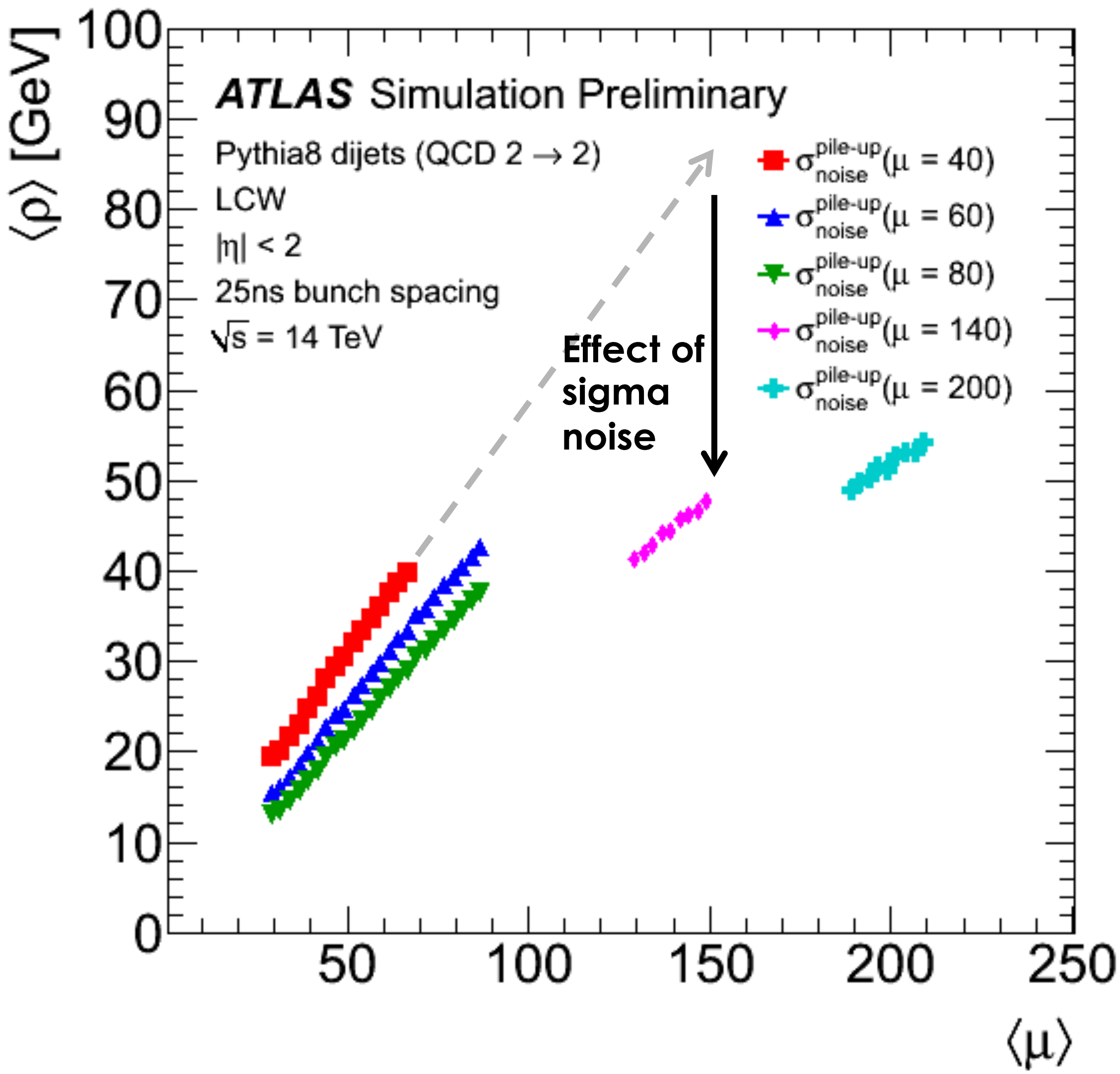
$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$



- **Jet areas subtraction well established at both ATLAS and CMS:**
  - Accounts for *global* pileup fluctuations from one event to another
- **Significant increase on the width of the rho distribution with pileup**
- **Need residual correction to account for higher occupancy inside jets and out-of-time pileup effects**

ATLAS-CONF-2013-083

Pileup subtraction (II)

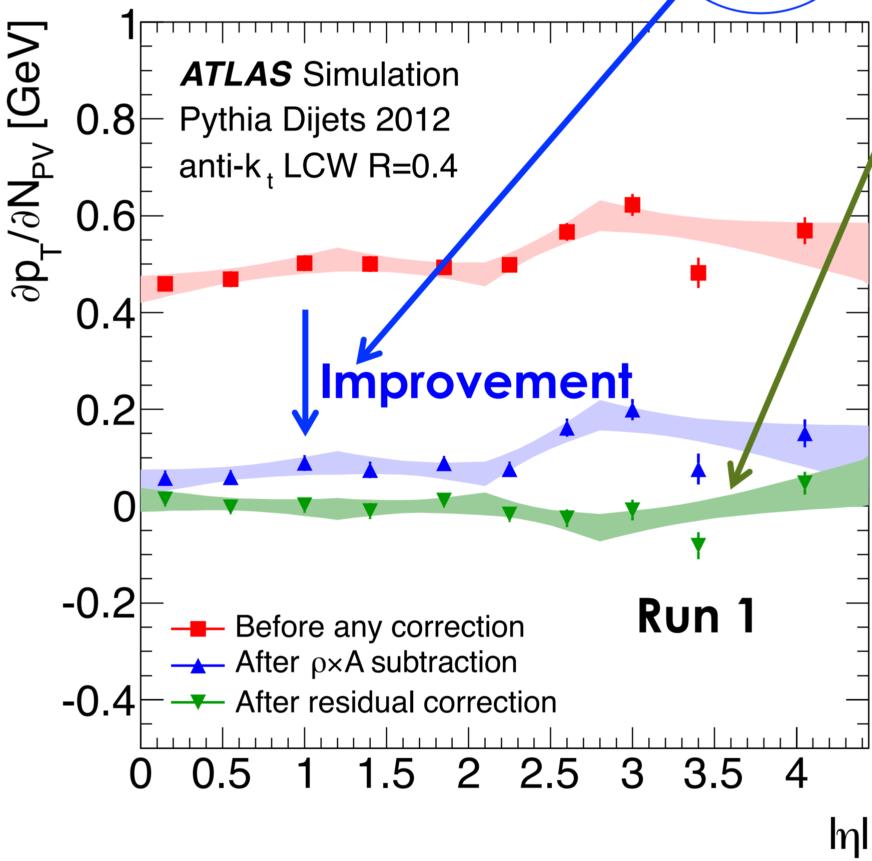


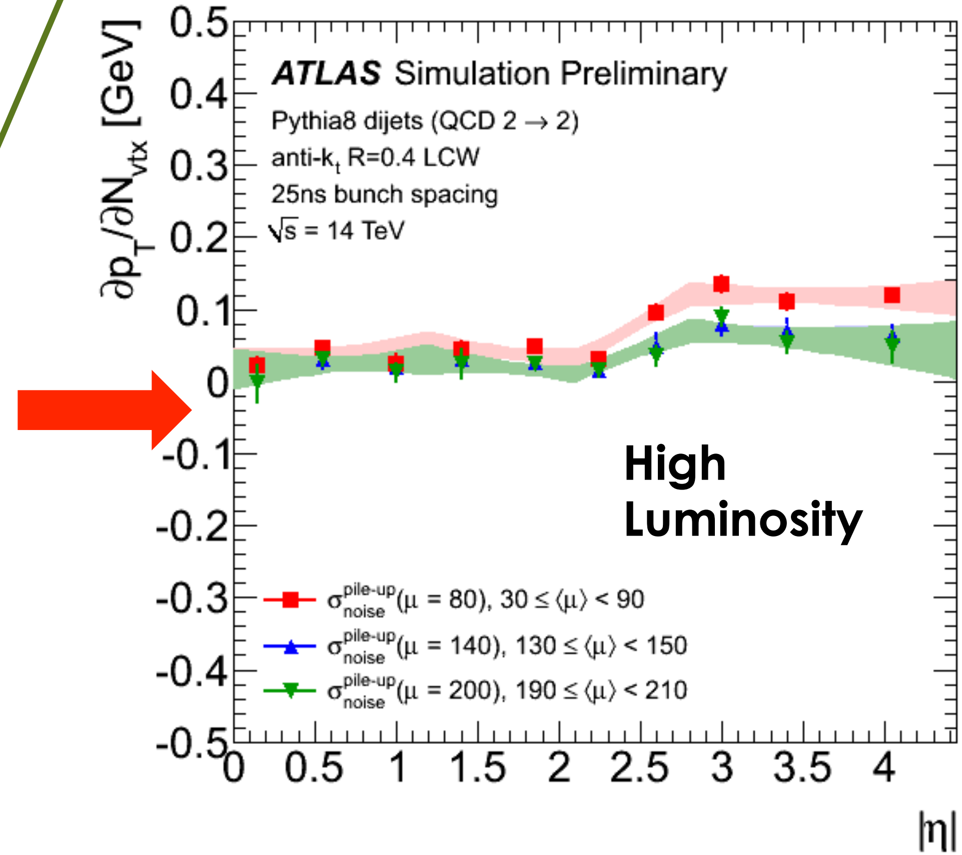
- **Linear behavior of rho up to high mu for fixed pileup noise values**
- **Higher pileup noise values lead to partial suppression of pile-up**
- **Optimization of noise threshold in topo-clustering is key to reconstruct jets at high luminosity**

Pileup subtraction (III)

Residual correction

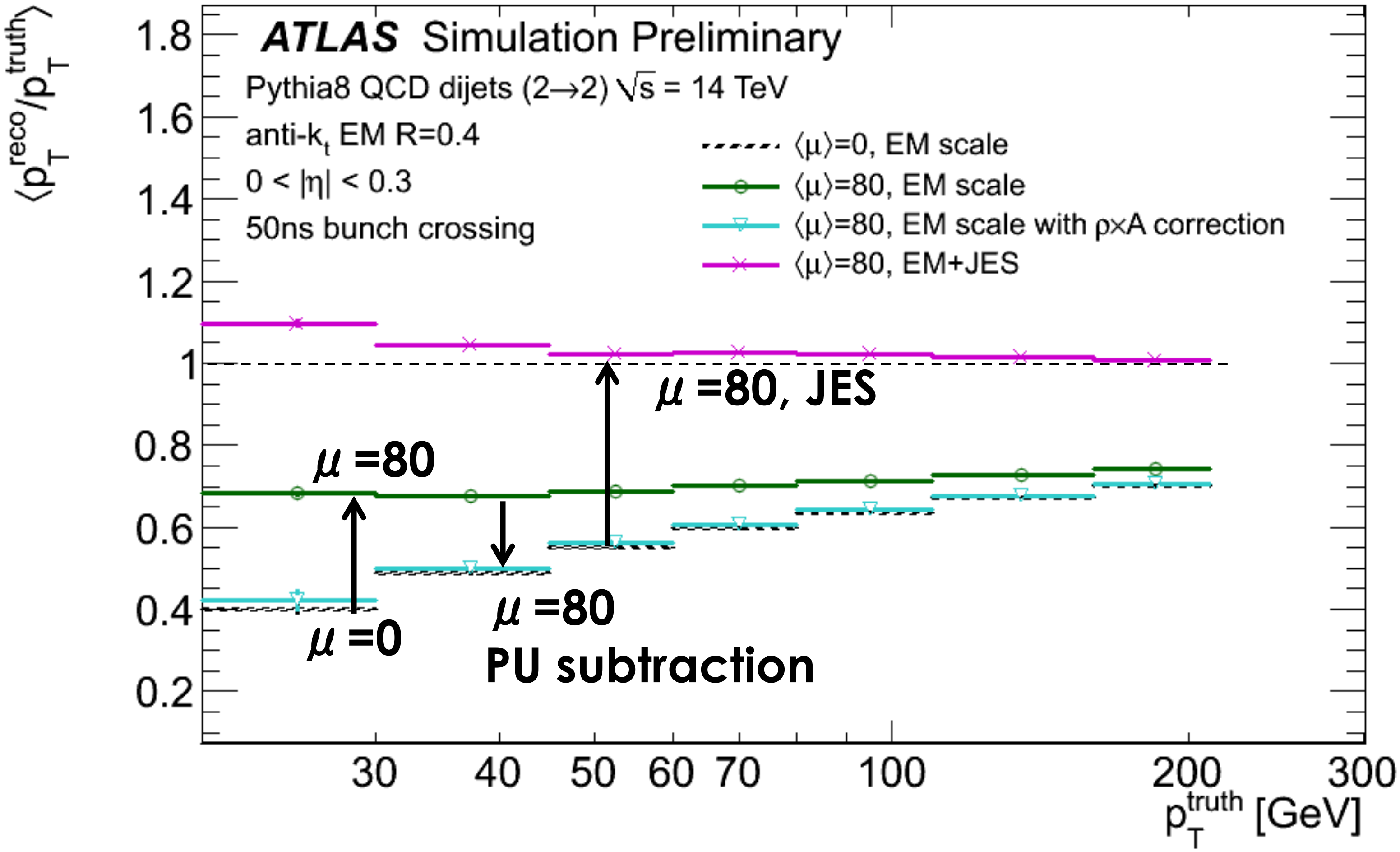
$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho A_{\mathrm{T}} - \alpha(N_{\mathrm{PV}} - 1) - \beta\langle\mu\rangle$$





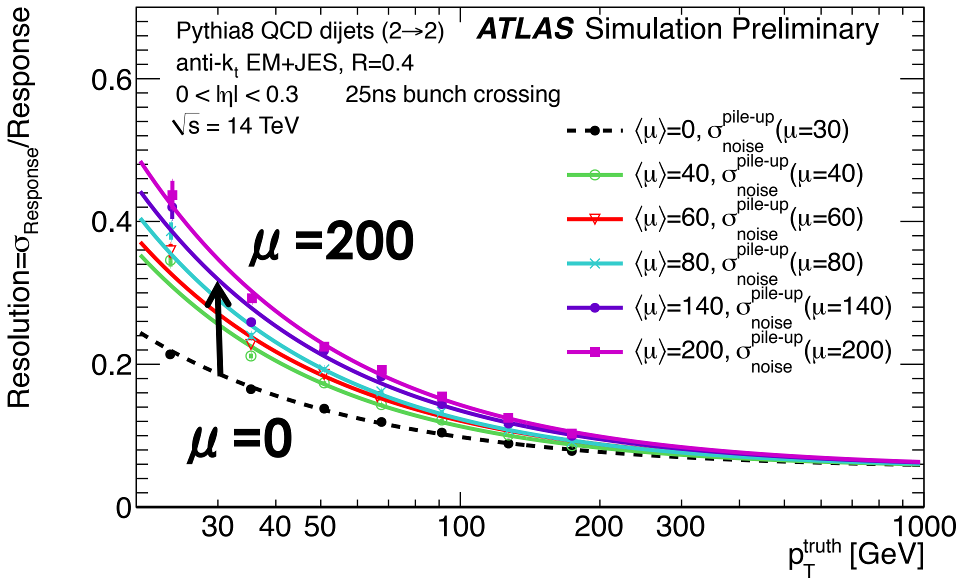
- Residual offset is mostly pileup independent, after adjusting sigma noise
- **Jet areas subtraction, topo-clustering, and local cluster weighting work well at high luminosity**

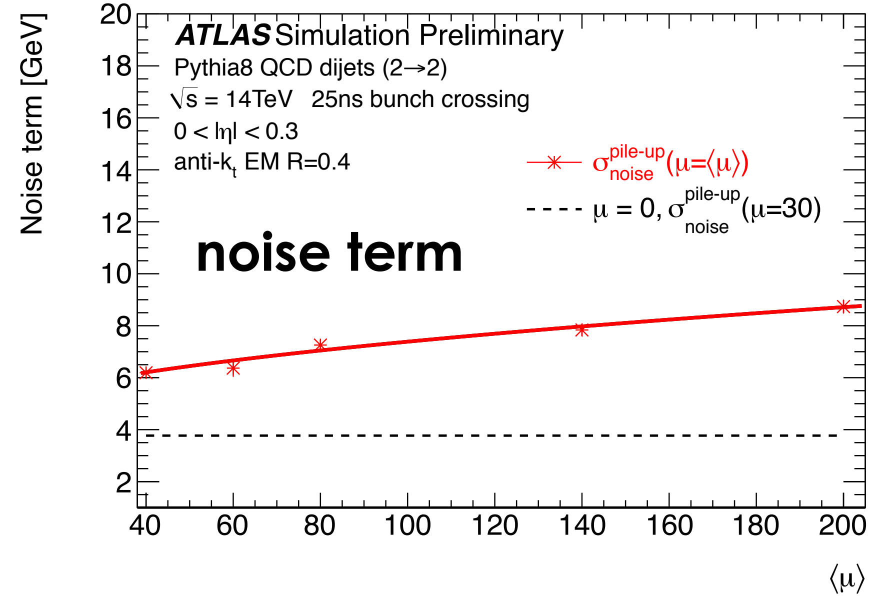
Jet energy scale



- Pile-up subtraction restores the jet response to that of the jets with mu=0
- Jet energy scale restores the response to unity
- **Jet calibration scheme works well up to very high luminosity**

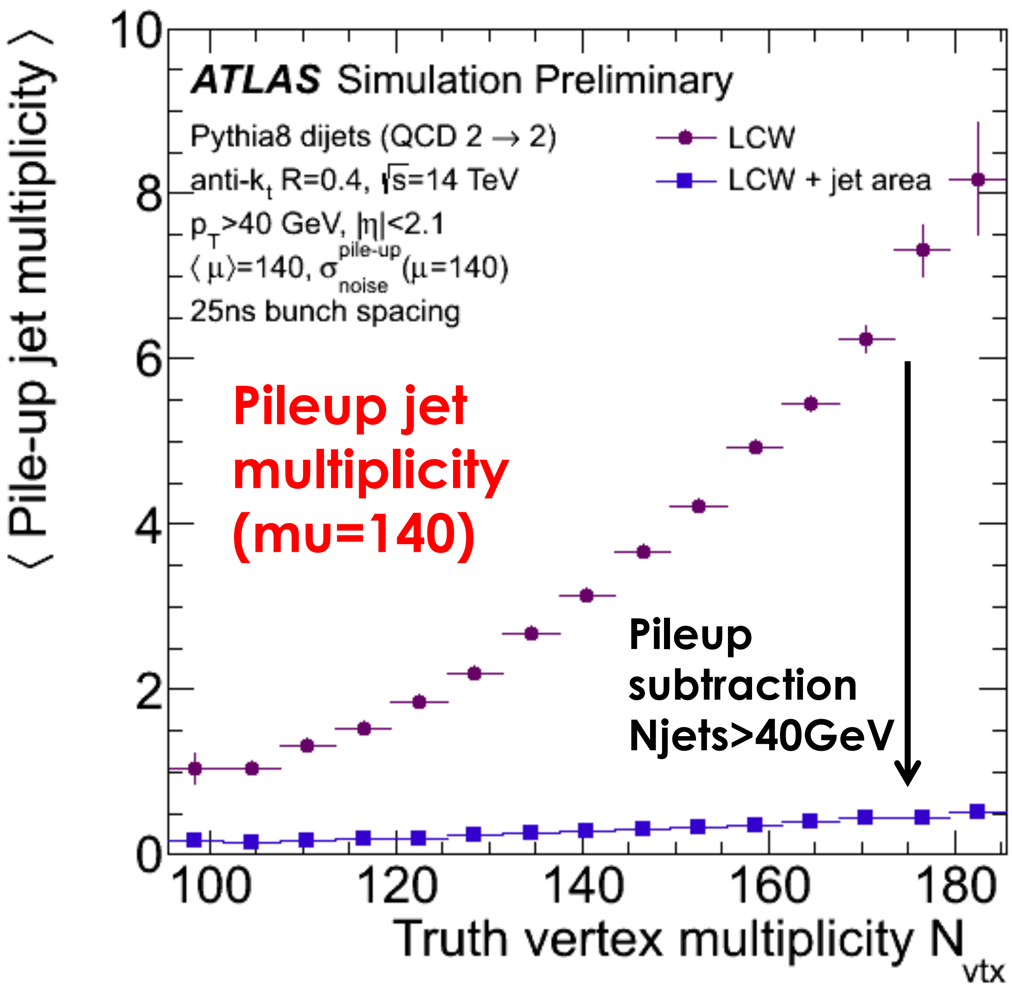
Jet energy resolution





- **Fractional jet energy resolution degrades at low p_T due to increased (pileup) noise term:**
  - Local pileup fluctuations within events, not captured by the global event-by-event median p_T density (rho) used in the calibration
- **Noise term increases as sqrt(mu)**
  - **Linear behavior of topo-clustering, pileup subtraction, and jet calibration up to very high luminosity**
- **Expect improvements using tracks**
  - Reduce local pileup fluctuations

Pileup jets

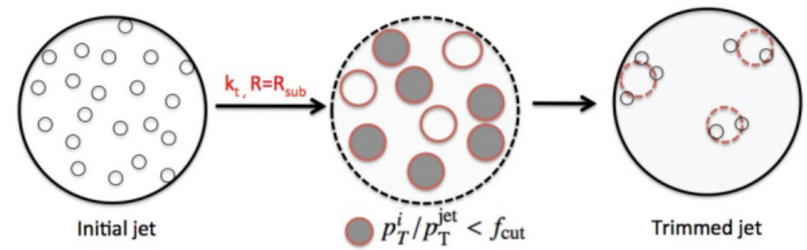


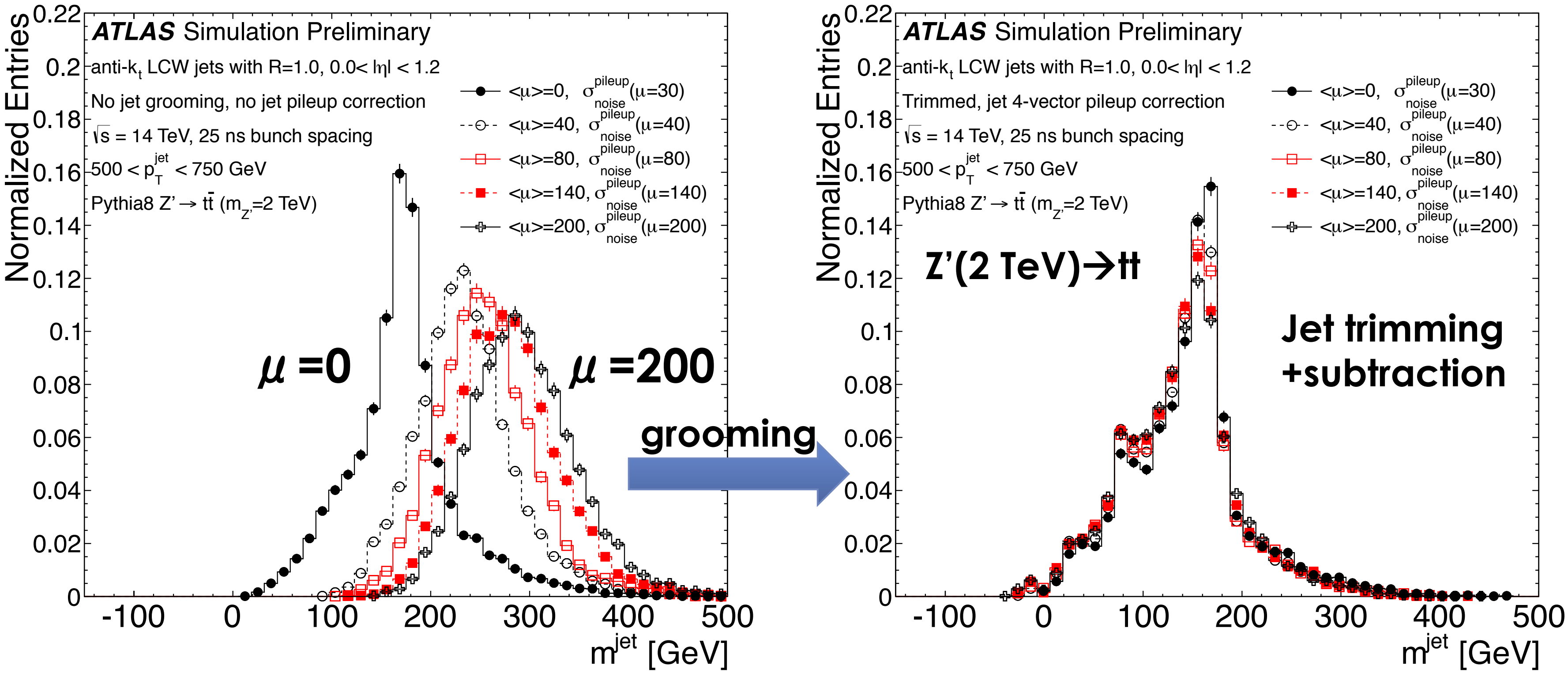
- **Pileup subtraction significantly reduces the mean number of pileup jets per event**
  - About 3 (0.5) pileup jets with p_T>20 (40) GeV per event at N_{PV} = 140
- **Further improvements expected using tracking and vertexing information**

Jet substructure

- **Test performance of grooming algorithms using 2012 based optimization:**
    - Trimming R_{kt}=0.3, f=5%

Jet trimming

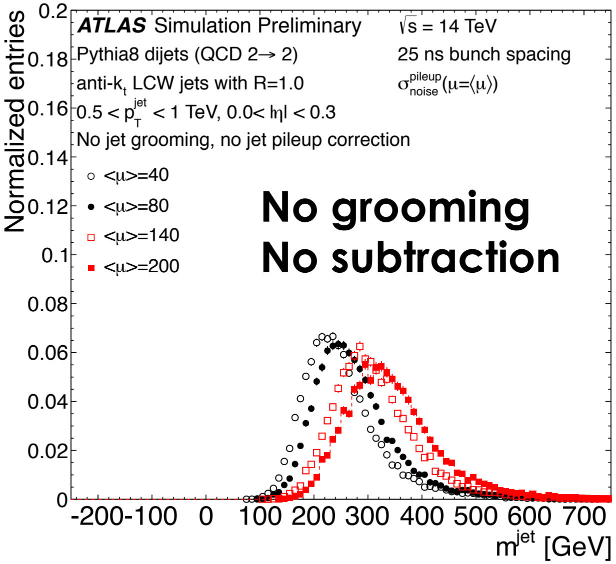




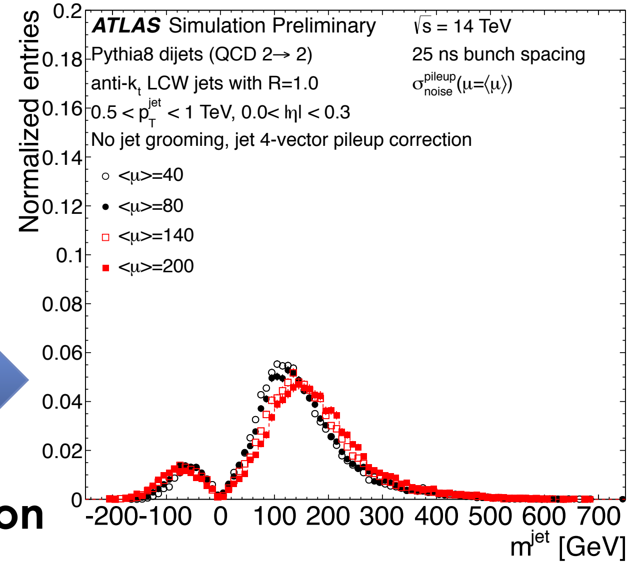
- **Trimming with 2012 parameter optimization works at μ =200**
    - Jet mass distribution stable with μ up to very high luminosity

Jet grooming performance

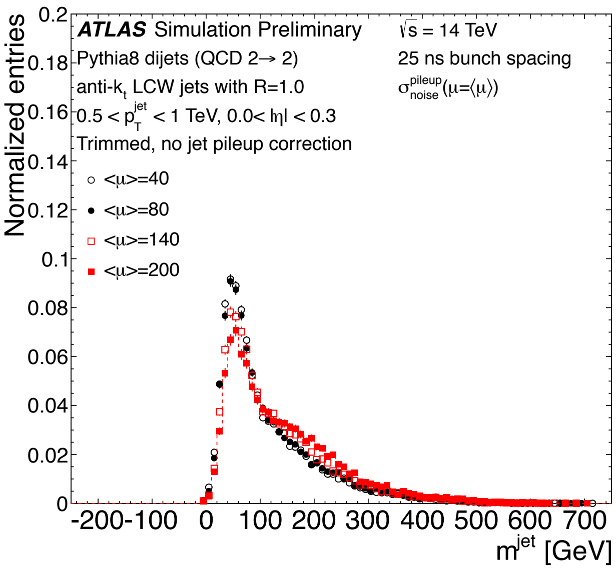
Dijet events

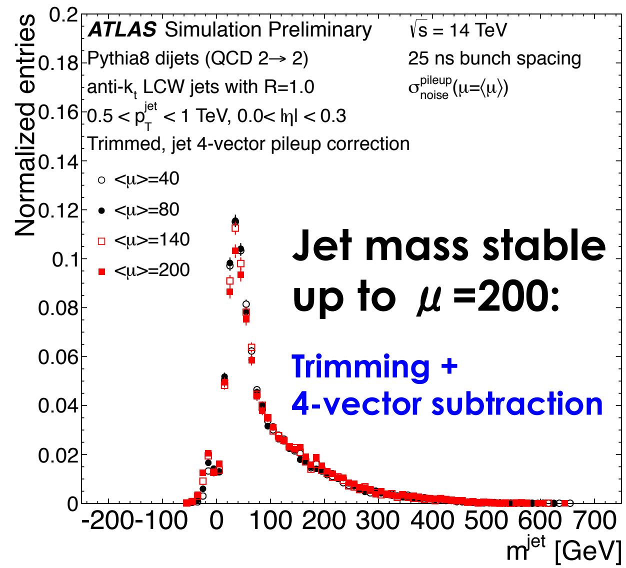


4-vector subtraction



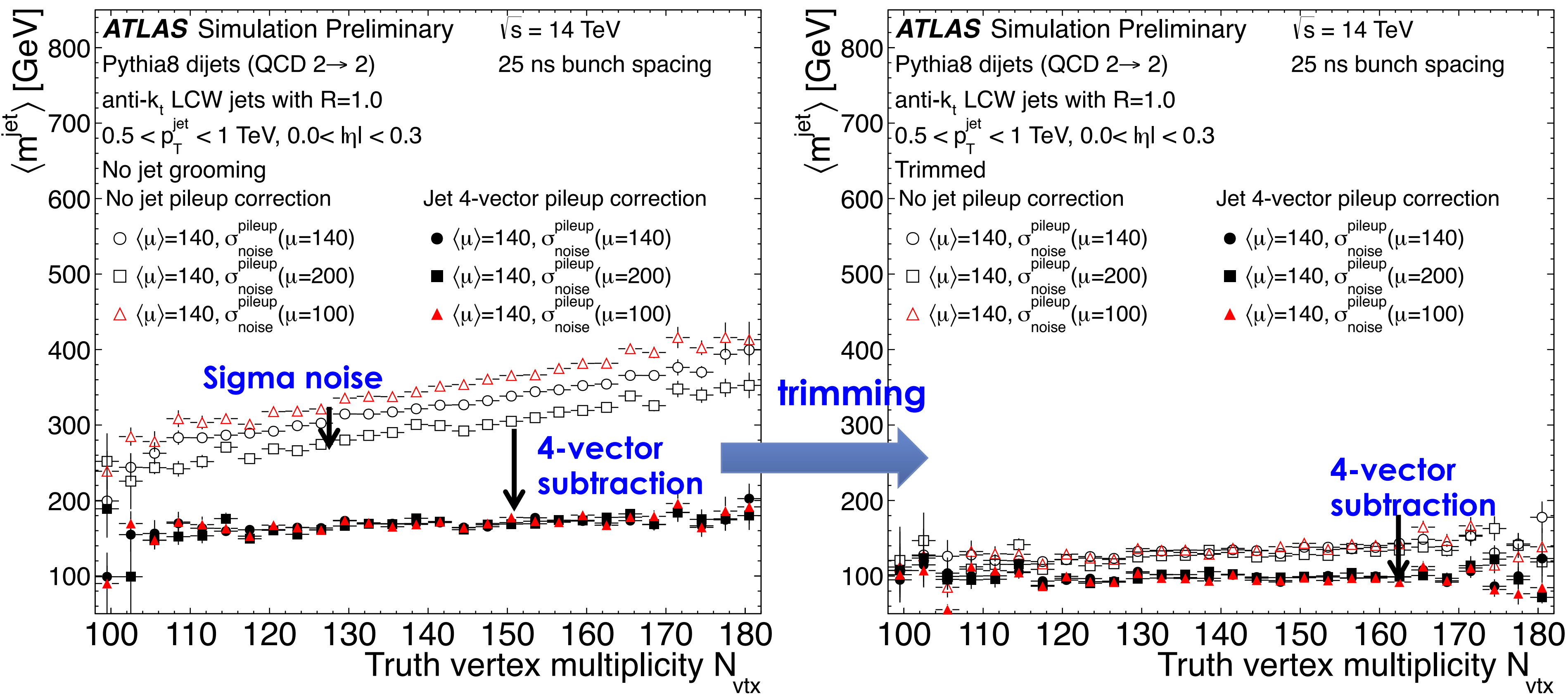
trimming





Jet grooming performance

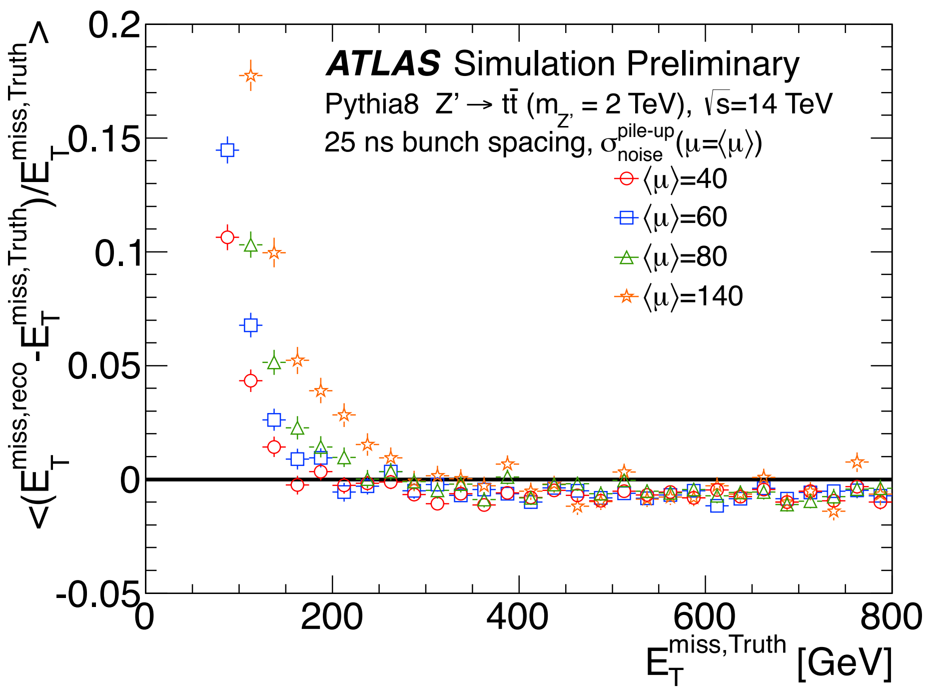
Dijet events

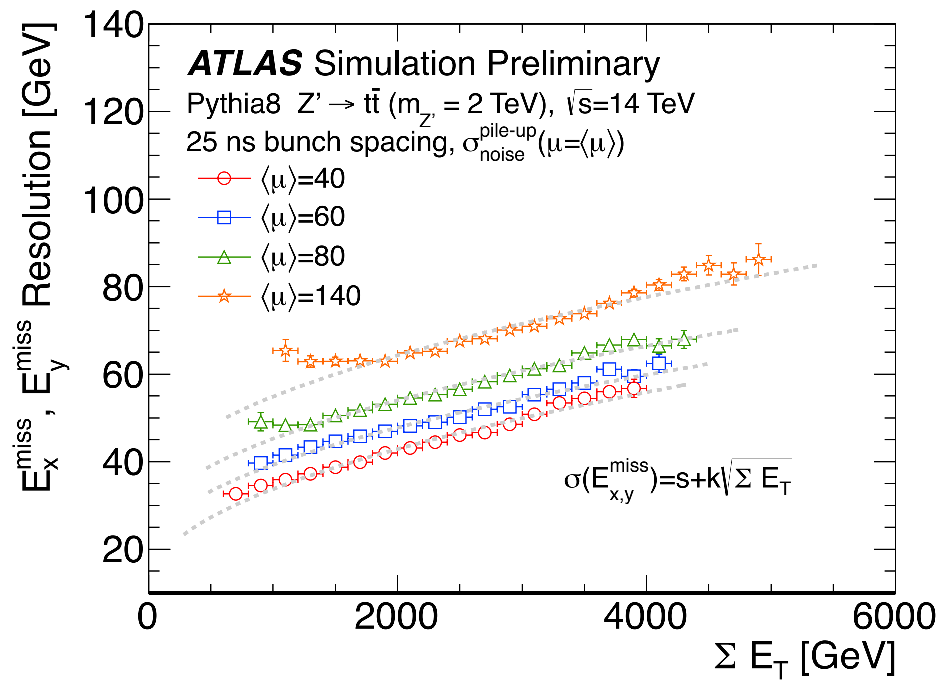


- Raising pileup noise values reduces the mean mass, but does not affect the dependence on pileup
- 4-vector subtraction successfully suppresses pileup, even without grooming
- **Trimming with subtraction further reduces pileup contributions to the jet mass**

Missing ET

- **Linearity of the response is within 1% up to mu=140**
  - Achieve a correct missing ET scale
  - Positive bias at low missing ET is due to the finite resolution of the missing ET, and is highly dependent on the event topology
- **Missing ET resolution shifts upwards with pileup, but it does not change the slope with mu**
  - Pileup affects the s-term of the resolution, but the k-term remains approximately constant
- **Large room for improvements using tracks to suppress pileup**





Detector upgrades

ATLAS Phase-0

- 4^{th} pixel layer (IBL)
- Complete muon coverage

ATLAS Phase-1

- Fast Track Trigger (FTK)
- Muon new small wheel
- LAr calorimeter electronics

ATLAS Phase-2:

- New pixel and strip tracker
- Calorimeter
- Trigger system

CMS Phase-0

- Complete muon coverage
- Partial replacements of photodectors in HCAL

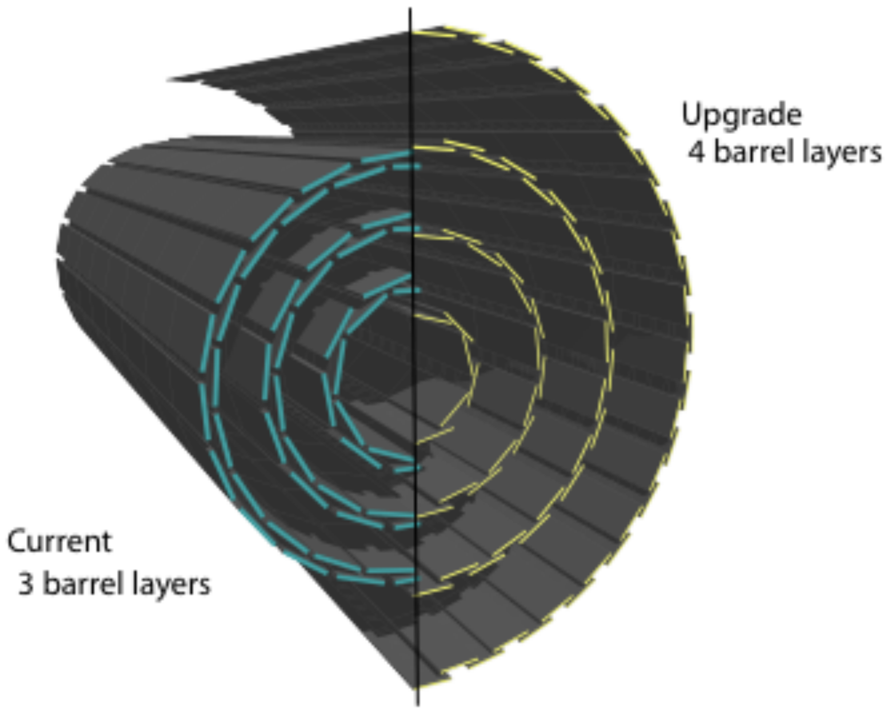
CMS Phase-1

- New pixel tracker
- Trigger upgrade
- HCAL upgrade (longitudinal segmentation)

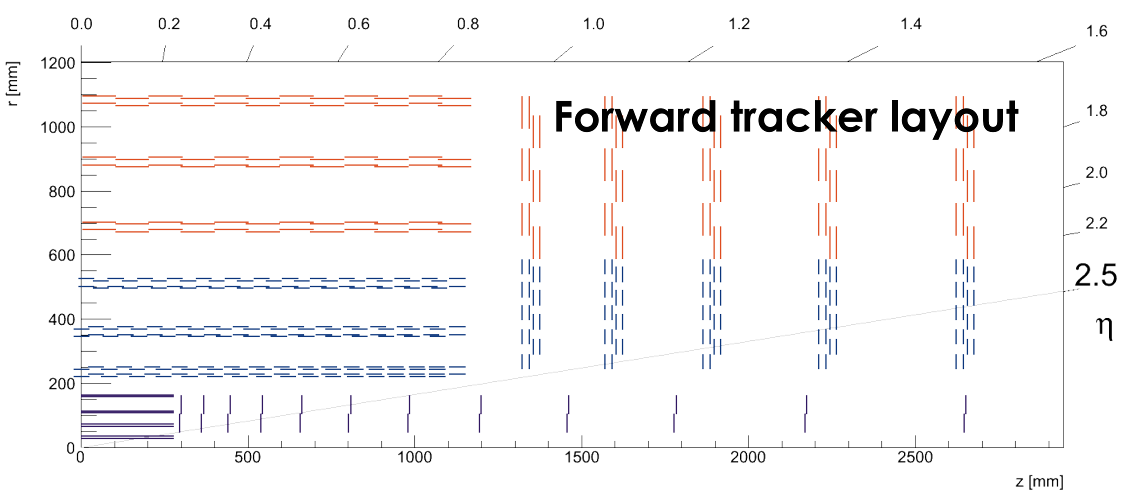
CMS Phase-2:

- New tracker
- Calorimeter electronics and forward detectors
- Trigger system

CMS pixel upgrade



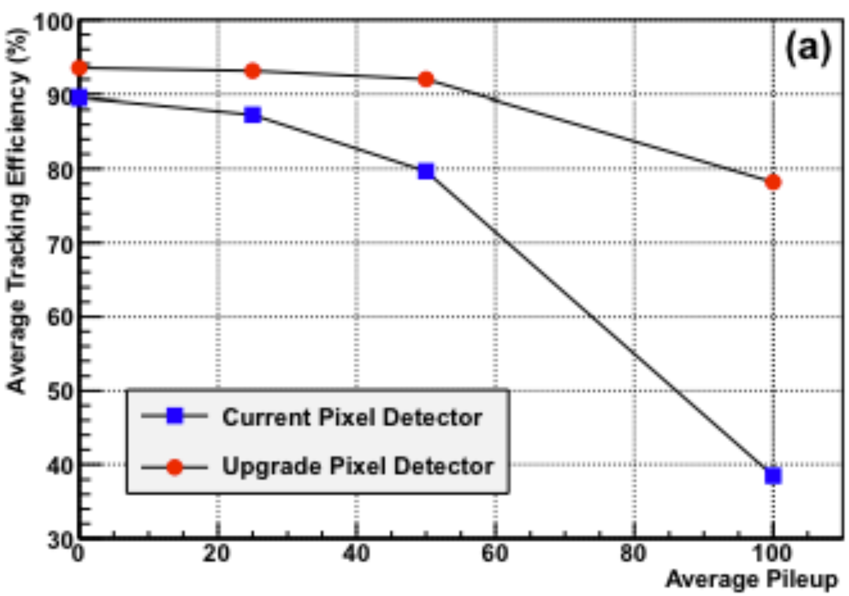
- **Increase number of layers (4) and disks (3)**
  - 4th layer is key to improve tracking pattern recognition at high pileup
  - **<u>Crucial for particle flow</u> and b-tagging**
- Smaller inner radius
- Reduced material
- **forward pixel layout under study for phase 2**
  - <u>improved pileup suppression and particle flow</u>, VBF jet tagging, b-tagging forward jets)

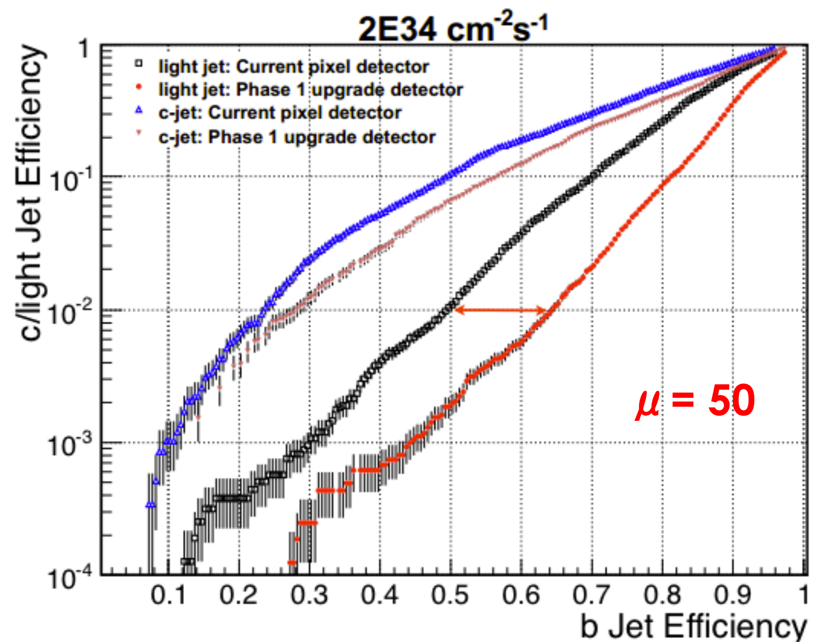


- **Recovers (or improves) the low pileup performance at high luminosity**

CMS pixel performance

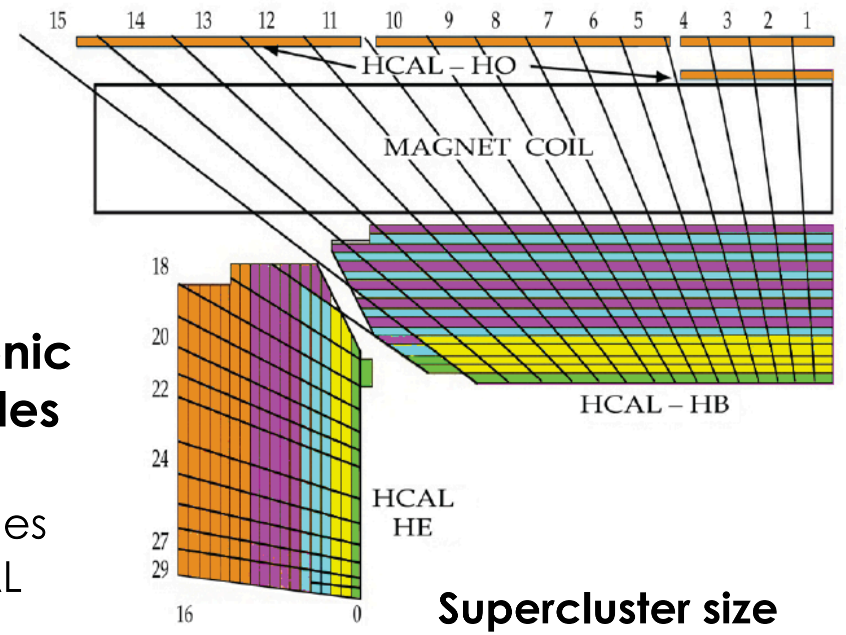
- **Improved tracking efficiency in jets, stable with pileup**
- **Significantly improved b-tagging:**
  - At μ =50, 15% absolute gain in efficiency for 1% fake rate
  - Maintain current (8 TeV) b-tagging performance at μ =100
- **Room for optimization of tracking and b-tagging algorithms**
  - expect better performance

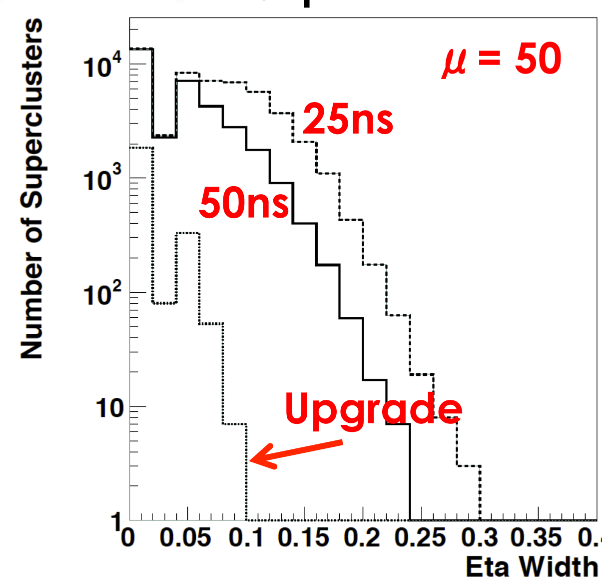




CMS HCAL upgrade

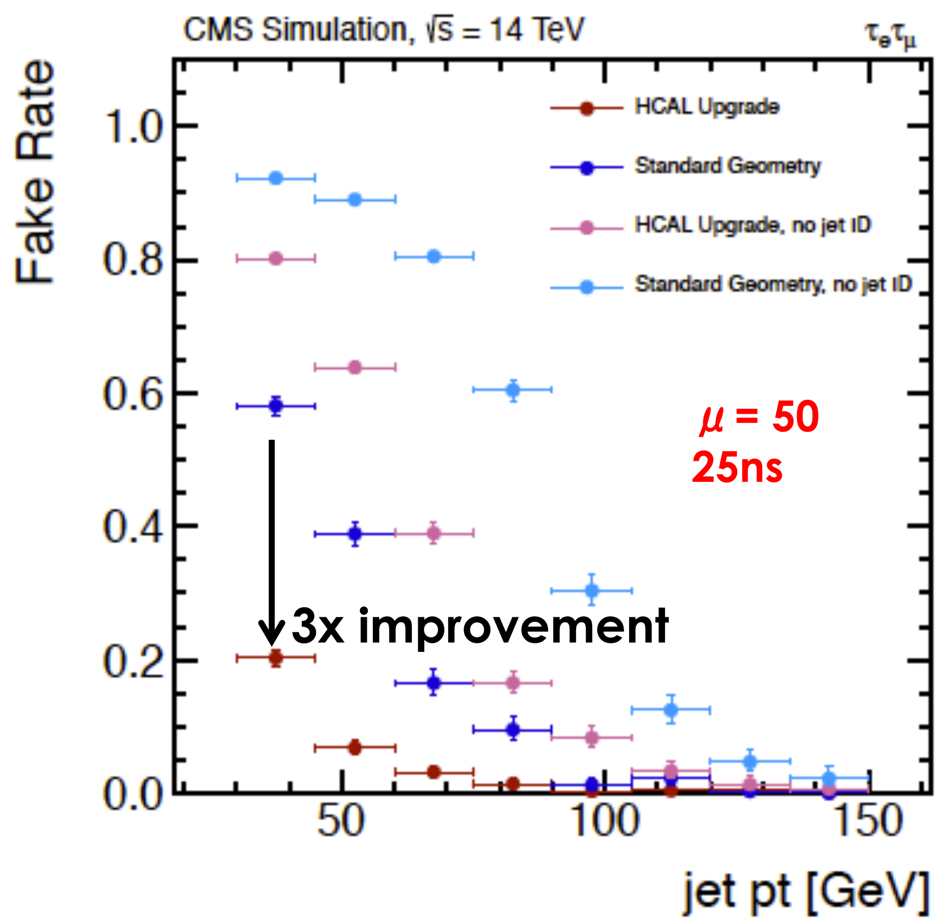
- **<u>Longitudinal segmentation</u>**
  - Enabled with new SiPM detectors (improved S/N and higher gain)
  - 3 (4) depths in barrel (endcap)
  - **Increased ability to separate hadronic showers and suppress pileup particles**
    - Use longitudinal shower profile information to identify pileup particles contributing to the first layer of HCAL
- **Improved cell timing information**
  - reduce out-of-time pileup contributions at 25ns running
- **<u>Significantly improved particle flow performance</u>**
  - Superclusters: transverse clusters from each depth associated longitudinally + tracks + timing





CMS pileup suppression

- **Multivariate discriminator to separate jets from the hard interaction from jets originating from pileup**
  - Track-vertex association
  - Jet shape variables
  - Multiplicities of neutral and charged components of the jet
- **Significant improvement for the upgraded HCAL detector and particle flow algorithm**
- **<u>Lots of room for optimization</u>**
  - Improved clustering algorithms
  - Cluster-level pileup suppression
  - Particle flow optimization

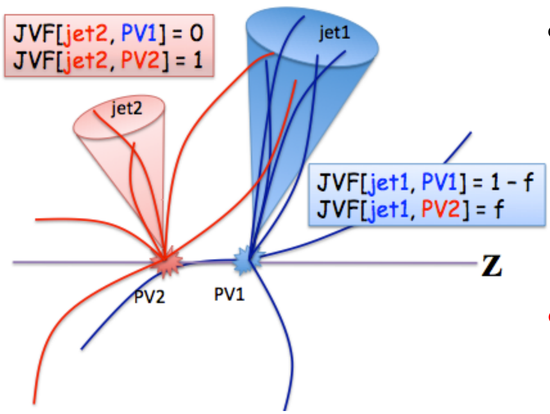


Conclusions

- **Extremely exciting future physics program at the LHC**
  - Extend the discovery potential for new particles beyond the Standard Model to the multi-TeV range
  - Precision Higgs physics
  - **Jet substructure techniques, well established in Run1, will become a major element in the LHC physics program beyond 2015**
- **Pileup will be a major challenge for the experiments**
  - Radiation, triggering, object reconstruction, computing
- **Detector upgrades are expected to maintain or exceed the current performance of ATLAS and CMS in the much higher pileup environment**
  - **CMS upgrade HCAL and pixel detectors will significantly improve particle flow and pileup suppression**
  - **ATLAS Initial studies show that jet, missing ET, and jet substructure techniques work well up to very high luminosity**
    - Resolution is degraded in some cases, but there is significant room for improvements (use of tracks and vertices to reduce local pileup fluctuations and further suppress pileup jets, Improved topoclustering, advanced subtraction techniques using more local information, optimization of grooming parameters at high luminosity

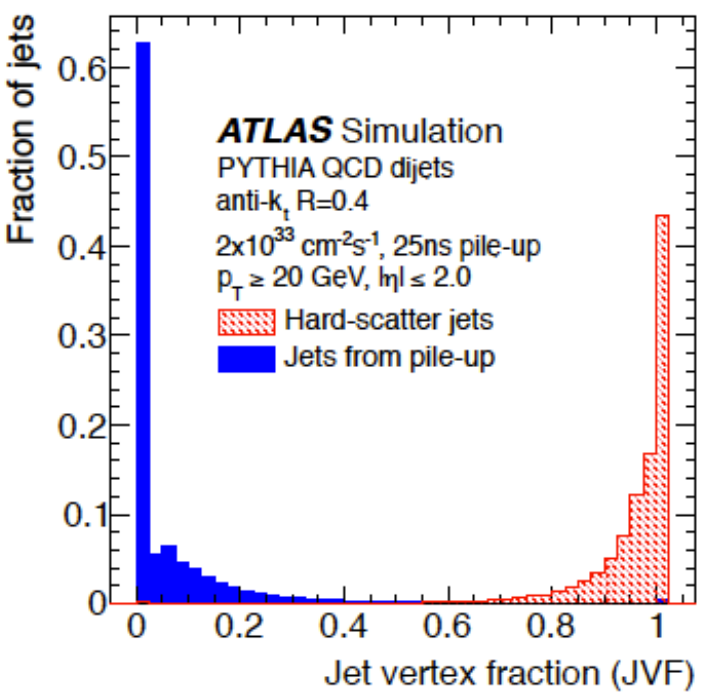
Backup slides

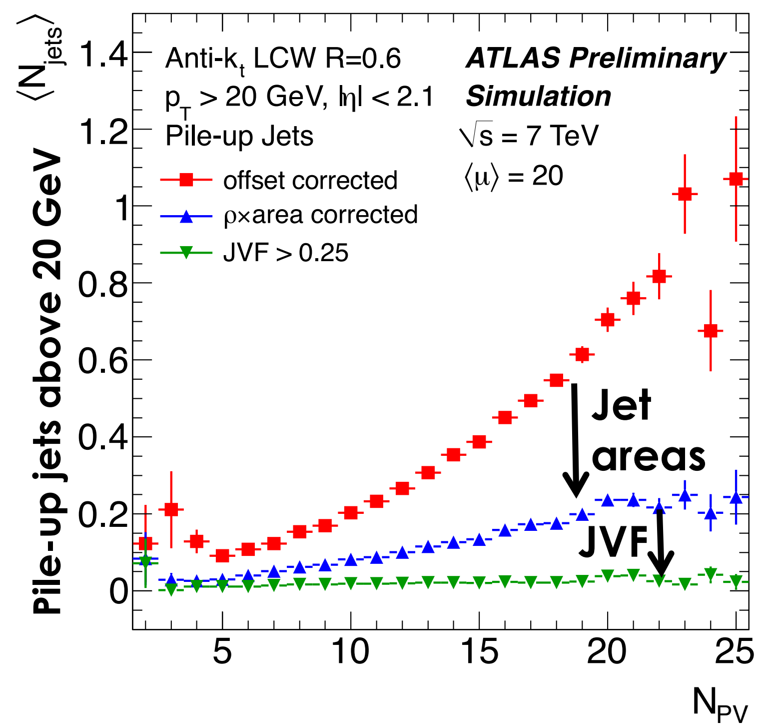
Pileup suppression (2012)



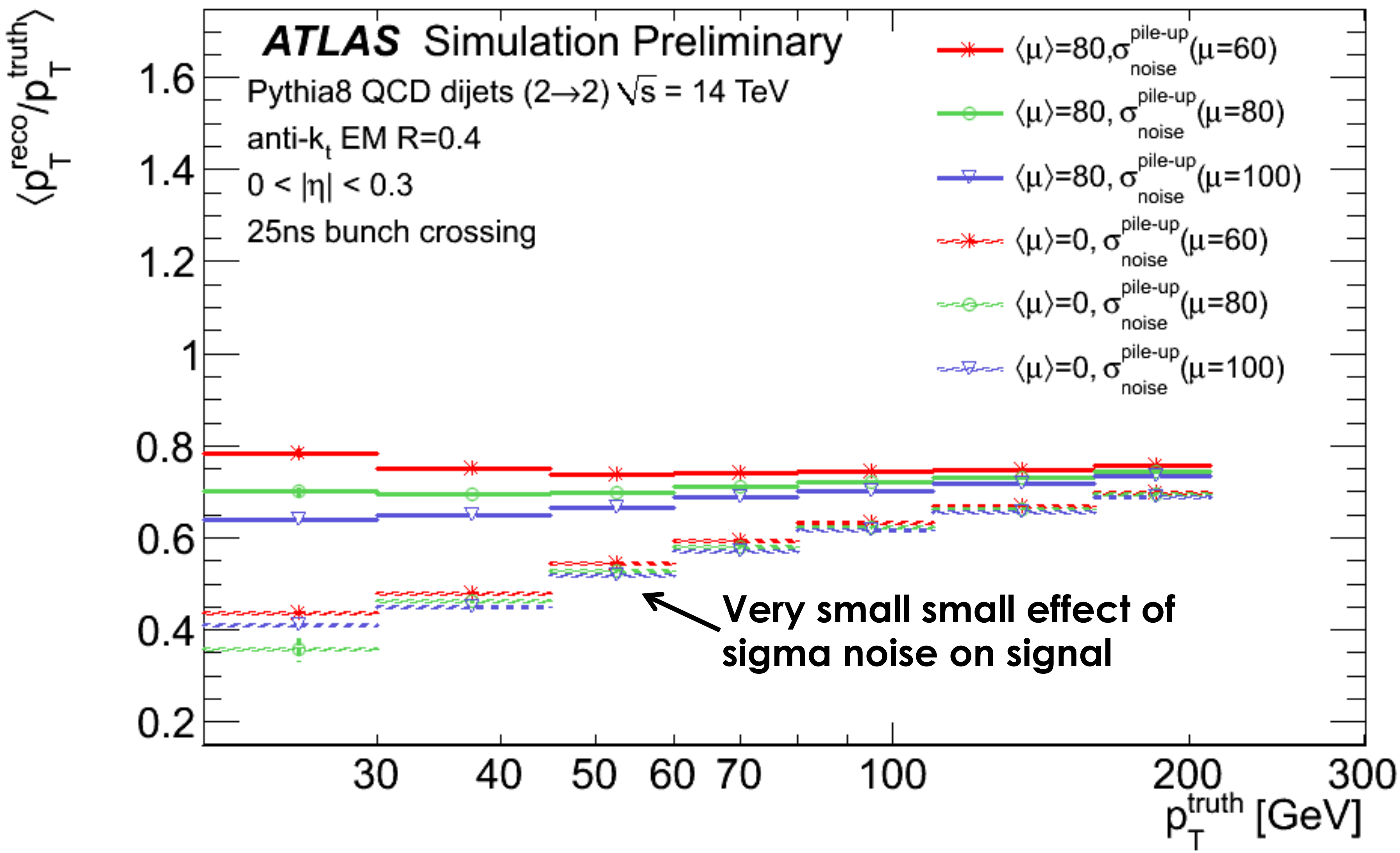
- **Pileup local fluctuations within a same event can lead to (fake) pileup jets:**
  - Mix of QCD jets from additional interactions and random combination of particles from pileup interactions
- **Jet vertex fraction algorithm**
  - Reject fake pile-up jets using tracking and vertexing information

Jet Vertex Fraction (JVF)

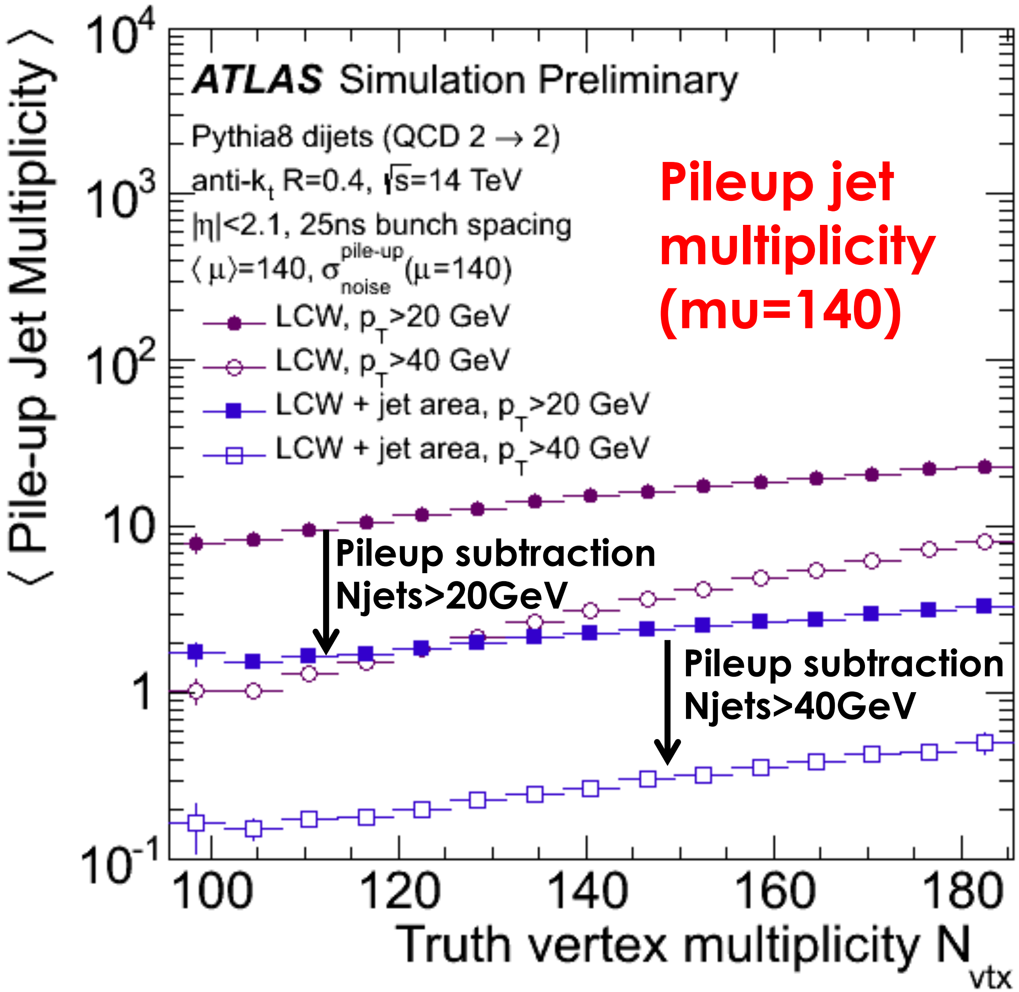




Jet response

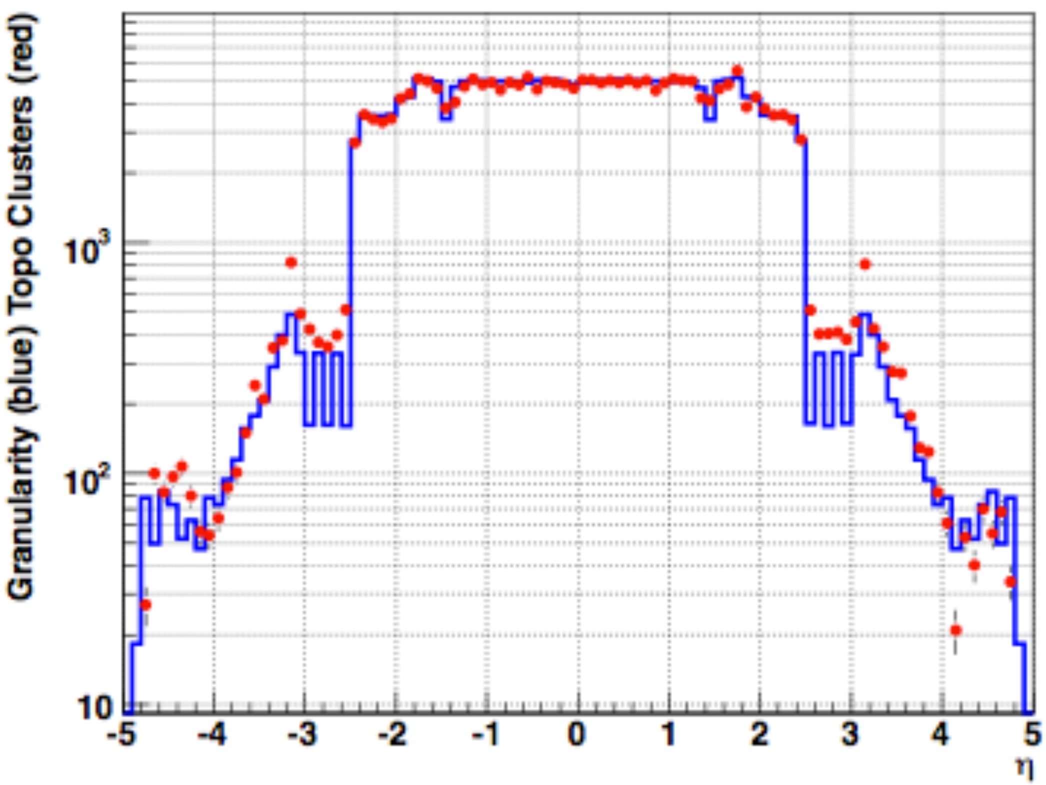


Pileup jets



- **Pileup subtraction significantly reduces the mean number of pileup jets per event**
  - About 3 (0.5) pileup jets with p_T>20 (40) GeV per event at N_{PV} = 140
- **Further improvements expected using tracking and vertexing information**

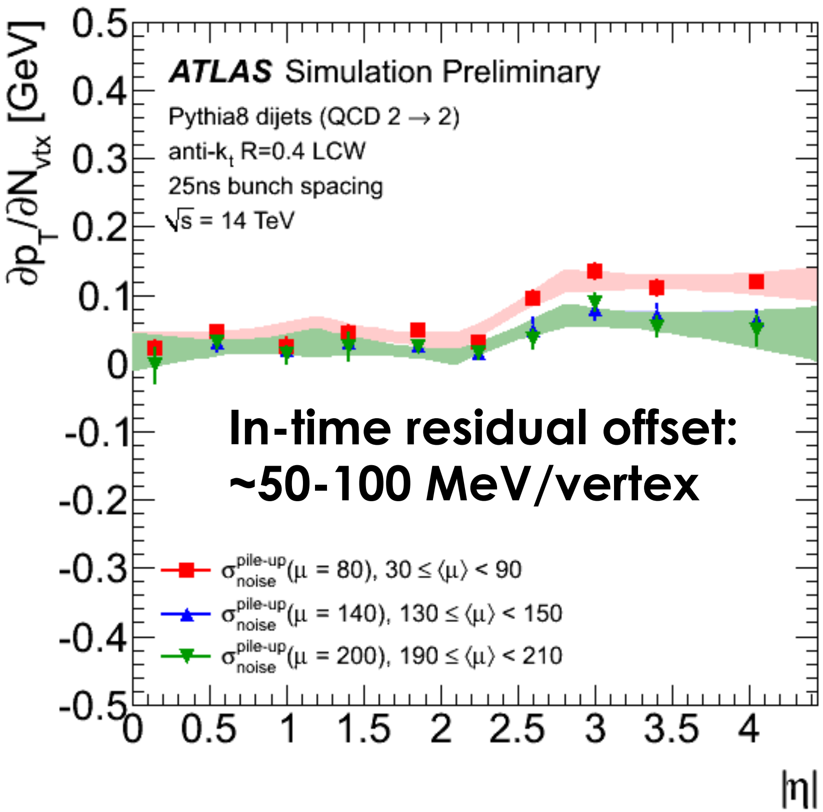
Experimental issues

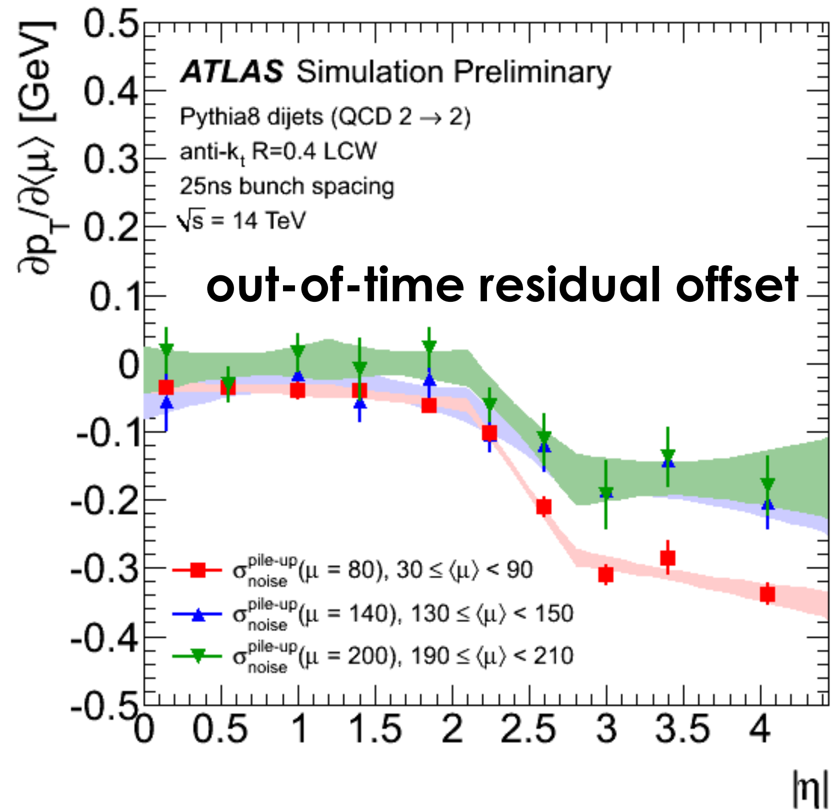


- **Noise thresholds** (topoclusters) **have a different effect inside and outside the core of jets** (pileup particles outside jets are more suppressed than inside jets, where signals are more likely to be above threshold)
- **Coarser calorimeter granularity above |eta|>2:**
  - Few clusters from pileup (noise) only above threshold
  - Need to restrict the calculation of rho to the central eta region
  - Leads to a reduction in the power of the jet areas technique to correct for pile-up effects in the forward region

Pileup subtraction (HL)

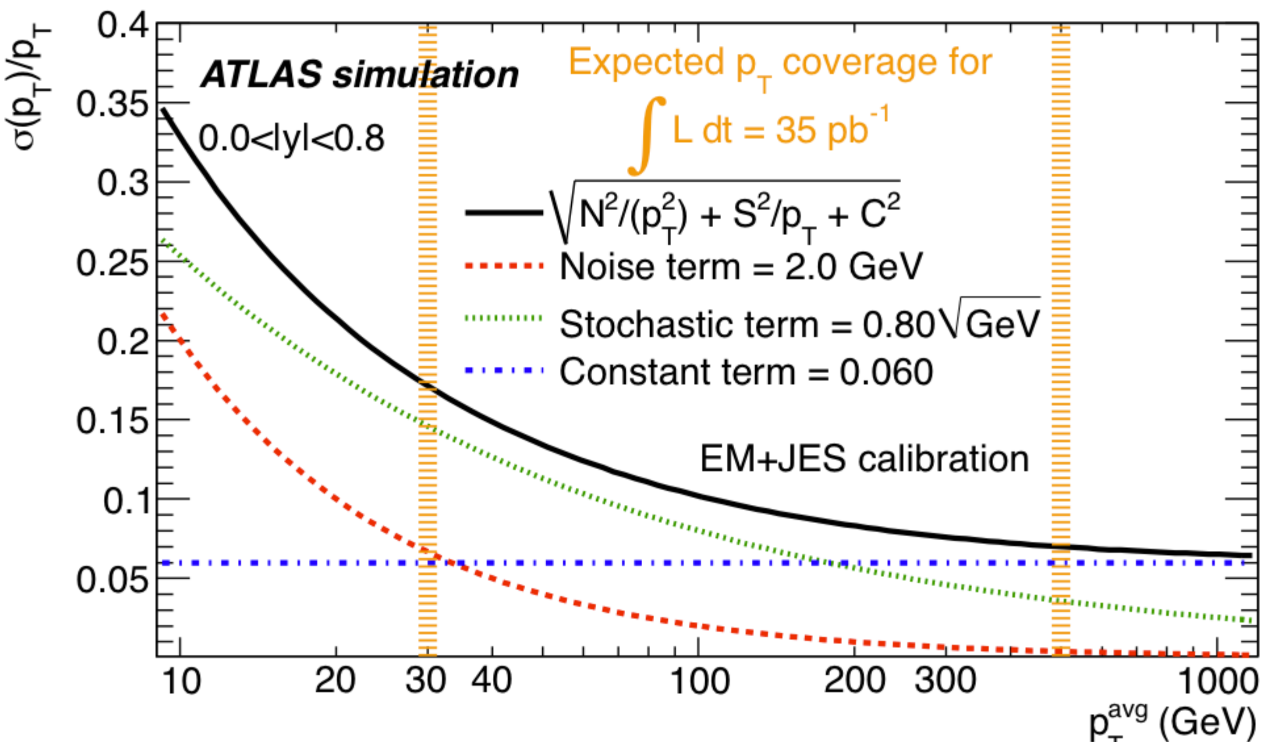
- Residual offset after subtraction is mostly pileup independent
- **Jet areas subtraction, topo-clustering, and local cluster weighting work well at high luminosity**





Jet energy resolution

- Jet resolution is described by three parameters: noise (N), stochastic (S) and constant (C) terms.
- **Pile-up determines the noise term:** $1/p_T$ dependence in the fractional resolution means a constant (p_T-independent) smearing of the absolute p_T from pile-up (noise) fluctuations
  - Constant term is not affected by pile-up
  - Noise term determines the jet resolution at low p_T
  - **The key to improve jet energy at low p_T is to reduce the pile-up fluctuations!**



Out-of-time pileup

- **ATLAS LAr calorimeter has a large integration time relative to bunch spacing:**
  - **Out-of-time** pile-up contributions
  - bi-polar shape compensates, on average, for both in-time and out-of-time pile-up, but out-of-time effects vary significantly within sub-detectors (eta-dependence)
  - ATLAS needs both in-time and out-of-time pile-up corrections
- **CMS is mostly insensitive to out-of-time pile-up:**
  - 2 time-slices (TS) for integration