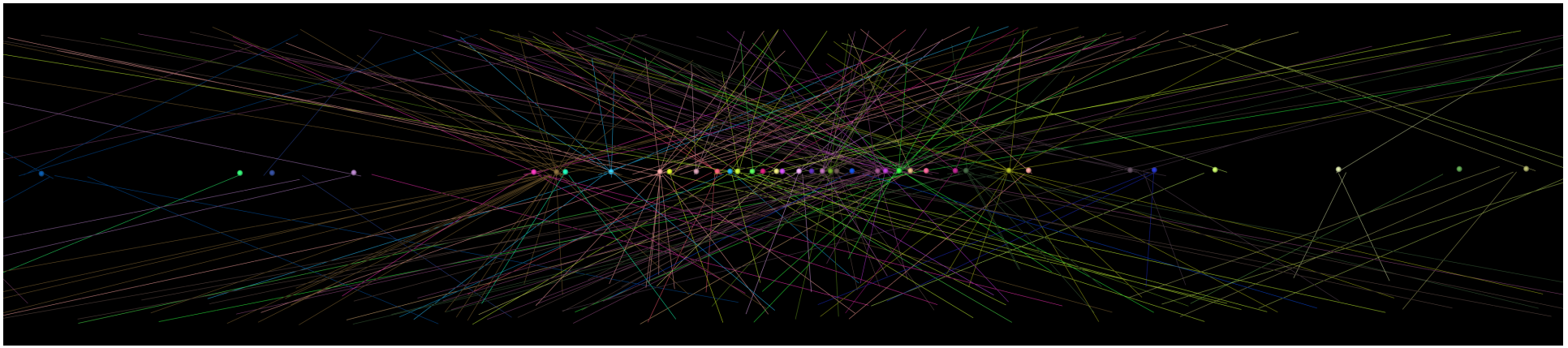
Performance of the ATLAS Inner Detector in the high pile-up environment

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Outline

- ATLAS and ATLAS Inner Detector
- Operation: 2010, 2011, 2012
- Reconstruction of tracks in high pile-up
- Primary vertex reconstruction
- Collective effects
- Monte Carlo and data-driven studies
- Summary and Conclusions



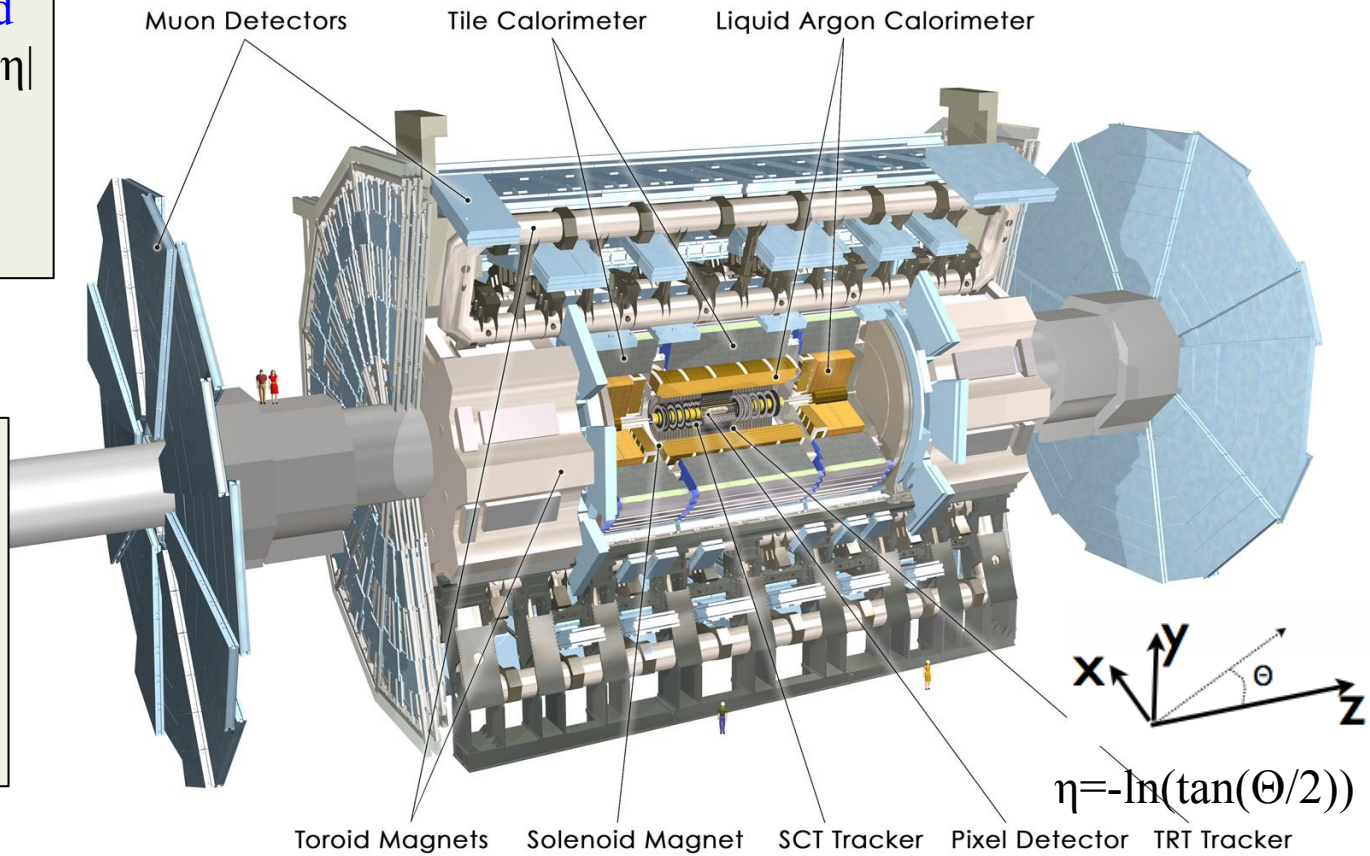
ATLAS detector overview

EM Calorimeter: (|η|<4.9) Pb-LAr accordion structure provides e/γ trigger, identification, measurement **σ/E ~10%√E**

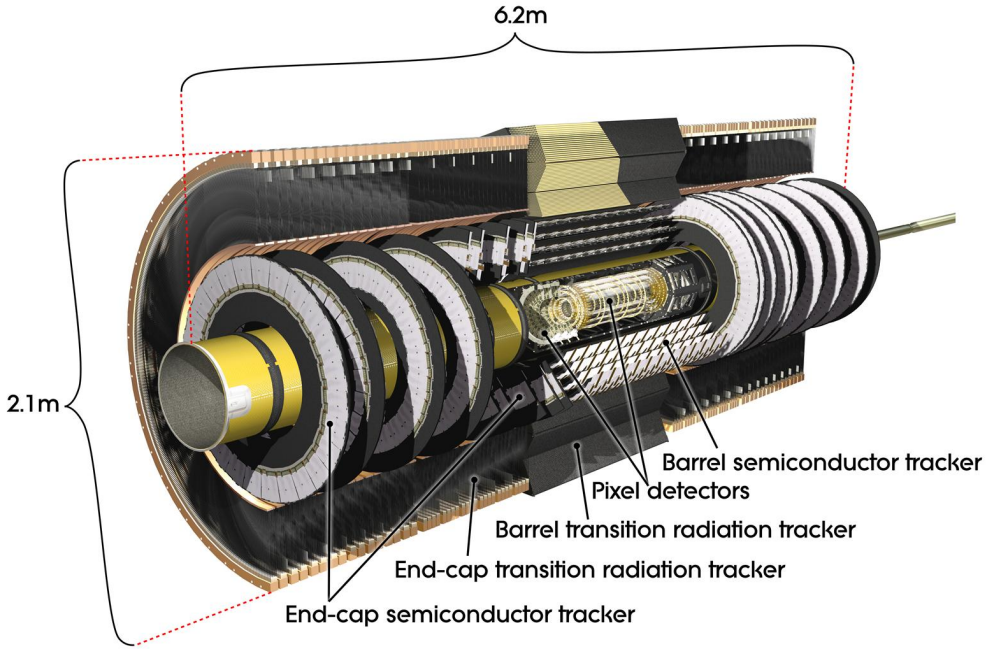
Hadronic (Tile): provides trigger, jet measurement, E_T^{miss} **σ/E ~50%√E ⊕ 0.03.** (|η|<1.7)

The Inner Detector provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at η = 0. Coverage: |η| < 2.5 (2.0 for TRT)
Resolution goal: σ_{pT}/p_T = 0.05% p_T ⊕1%

Muon spectrometer: high precision tracking and trigger chambers. |η| coverage up to 2.7. Magnetic field produced by 3x8 air-core toroids.

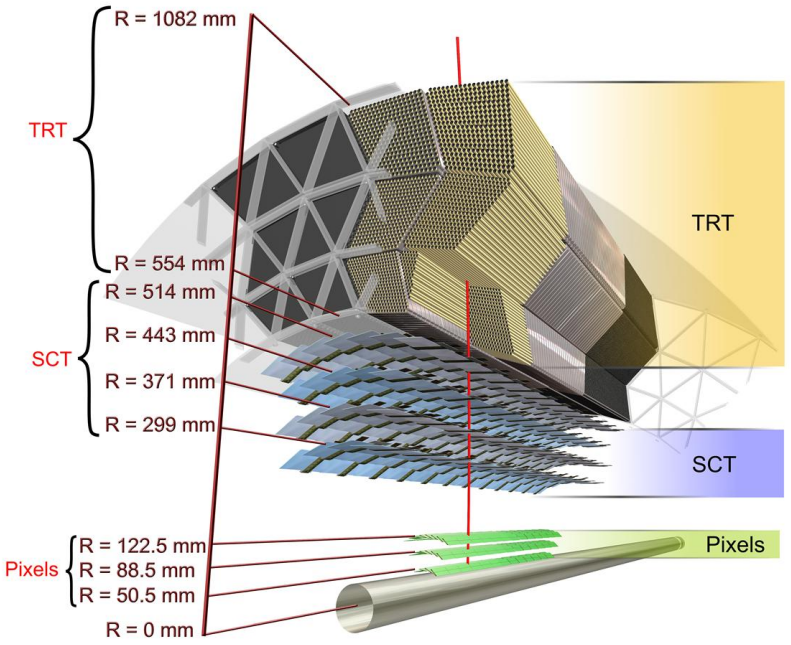


ATLAS Inner Detector

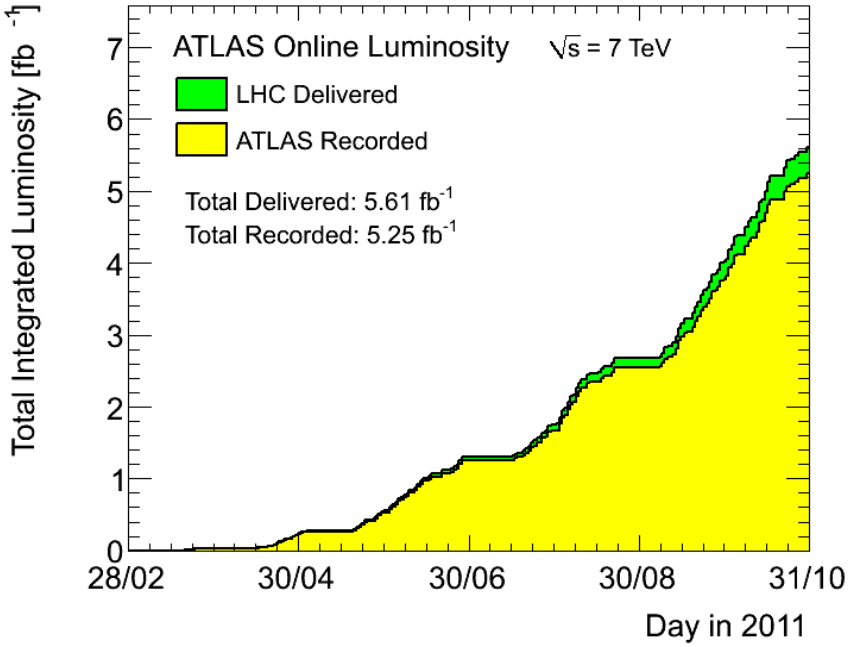


Tracking detector with
2 Tesla solenoid field.
3 sub-detectors: (resolution)
Pixel: 10/115 μm in Rϕ/z
Silicon strip (SCT): 17/580 μm
Transition radiation tracker (TRT):
130μm in Rϕ

The ID provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at $\eta = 0$.
Coverage: $|\eta| < 2.5$ (2.0 for TRT)
Allows for accurate track and vertex reconstruction.
Resolution goal: $\sigma_{pT}/p_T = 0.05\%\ p_T \oplus 1\%$



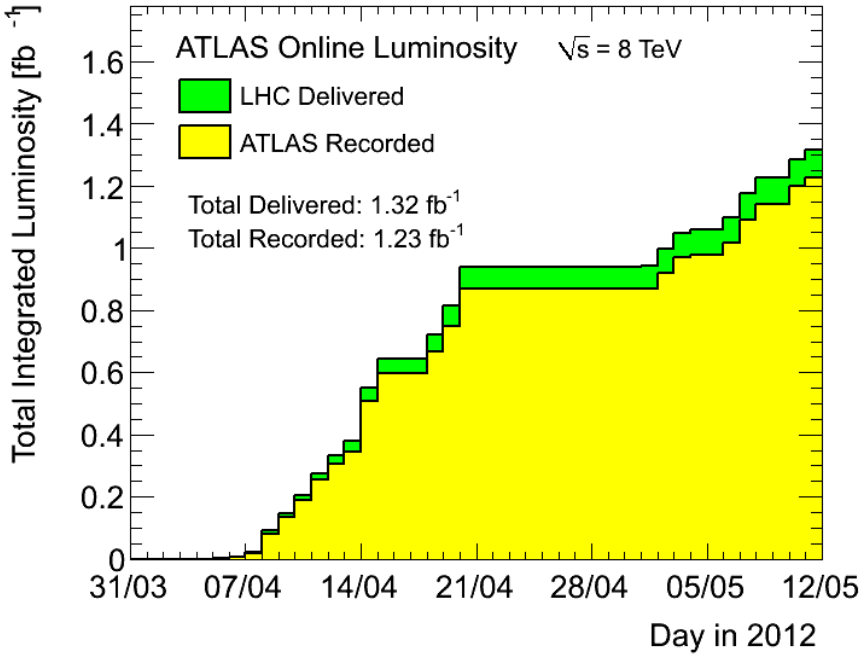
Data taking in 2010, 2011 and 2012



		Delivered	Recorded
pp	2010	**48.1 pb^{-1}**	**45.0 pb^{-1}**
pp	2011	**5.61 fb^{-1}**	**5.25 pb^{-1}**
pp	2012	**1.32 fb^{-1}**	**1.23 fb^{-1}**

ATLAS luminosity detectors calibrated with van der Meer beam separation scans

- 5 different luminosity detectors
- In 2010 $d\mathcal{L}/\mathcal{L}$ ~3.4%; In 2011 $d\mathcal{L}/\mathcal{L}$ ~3.7%

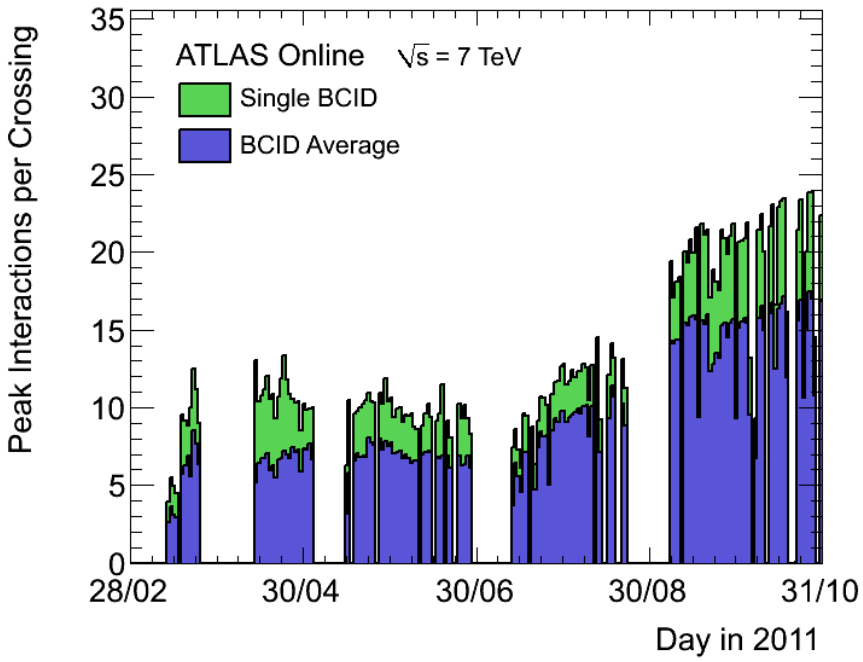


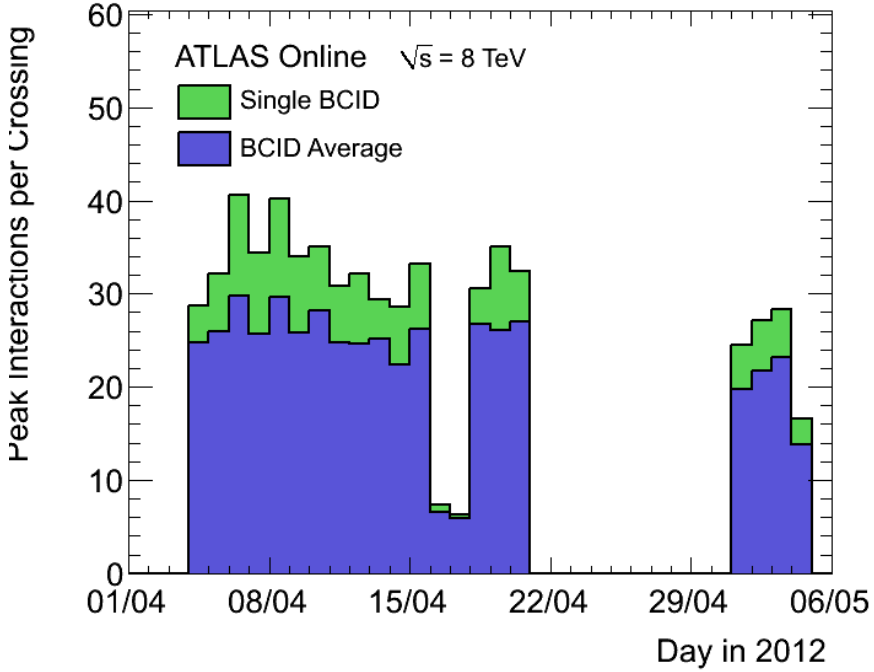
arXiv::11012185v1

ATLAS-CONF-2011-116

Data taking in 2010, 2011 and 2012

ATLAS has a very narrow and long beam-spot: σ≈15μm in the transverse plane and σ≈5.6cm in the longitudinal projection. The Inner Detector is only sensitive to the in-time pile-up: superposition of many interactions in the same bunch crossing.





Number of interactions per bunch crossing at the peak of the fill for each day in 2011 and 2012 for data used in physics analysis. Blue: average over the bunch crossings. Green: bunch crossing with the maximal rate.

Pile – up effects in the Physics Analysis

In the presence of high pile-up, each signal hard-scatter interaction is reconstructed together with several 10s of minimum bias pile-up collisions.

Understanding of the pile-up effects is important for physics analysis:

- Understanding of the event multiplicity and correct modeling of the pile-up contribution by Monte Carlo (pile-up re-weighting).
- Understanding of reconstruction efficiency of tracks and vertices.
- Understanding of the properties physics objects (isolation of reconstructed and other properties related to the event multiplicity.)
- Understanding of identification efficiency of the hard-scatter primary vertex among pile-up collisions.
- Study of the primary vertex multiplicity is also a measure of the luminosity.

Pile – up effects in the Inner Detector Reconstruction

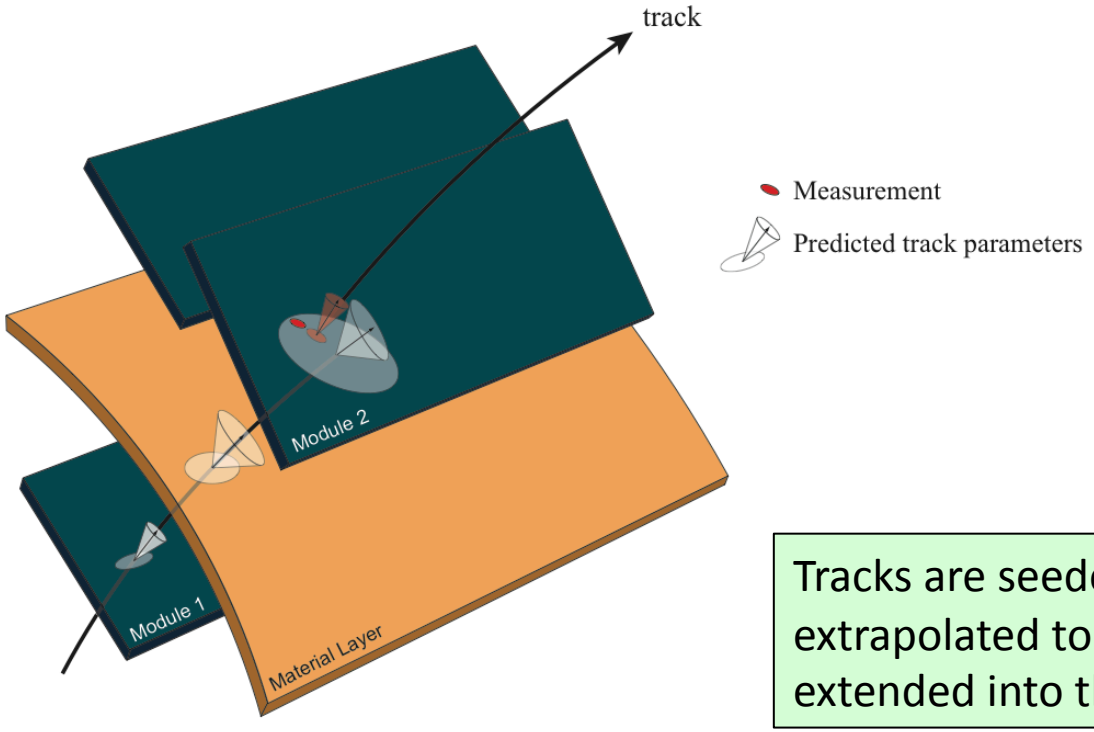
The Inner Detector is particularly sensitive to the pile up effects. The presence of multiple interactions in bunch crossing affect both reconstruction of tracks and vertices. The efficiency of track and vertex reconstruction suffers from the reduced pattern recognition.

- Pixel detector: closest to the interaction point, highest flux but lowest occupancy due to the high granularity. SCT: highest occupancy in the first layer due to the large size of strips. TRT: highest occupancy.

- Degradation of track reconstruction quality:
  - Track quality degradation due to the wrong hit assignment.
  - Reconstruction of fake tracks: random combinations of tracks/hits.

- Degradation of the vertex reconstruction.
  - Both position resolution and reconstruction efficiency can be affected.

Track Reconstruction



A sequence of track reconstruction algorithms is used in ATLAS Inner Detector.

Inside-out tracking: Reconstruction of primary charged tracks. (Particles produced in the primary *pp* collisions)

Tracks are seeded in the Pixel detector (3 point seeds), extrapolated to the outer layers of the SCT and then extended into the TRT detector.

Back tracking: reconstruction of secondary charged tracks. (Photon conversions, decays of long-lived particles, material interactions).

Seeding the tracks from TRT segments and extending them into the SCT.

In the current presentation we will only discuss primary tracking and vertex reconstruction.

Data and Monte Carlo samples

Dedicated runs at the end of 2011 data taking.

- Low integrated luminosity: 4.7 to 480 μb^{-1}.
- Large bunch spacing (mostly single-bunch data): no out-of-time pile-up.
- Average multiplicities (<μ>): 15, 32, 29.
- Collected with random trigger.

Minimum bias Monte Carlo for exactly one and average of 1, 21 and 41 interactions per bunch crossing. Pythia 6 with AMBT2B tune.

Single inelastic collision overlayed with a Poisson distribution of average 20 or 40.

For the vertex reconstruction studies, the data runs of different multiplicity, collected in 2011 using random trigger are used.

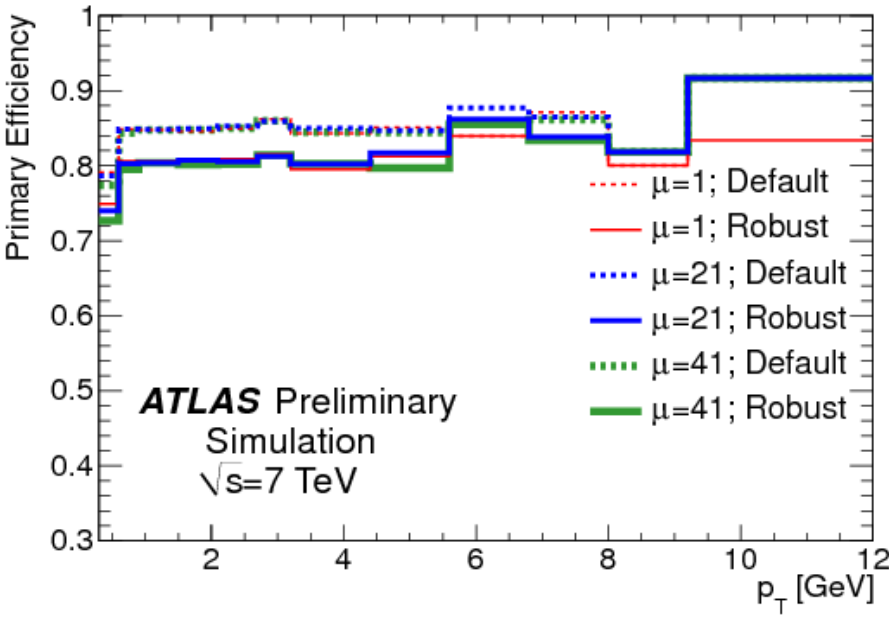
Track Reconstruction Efficiency

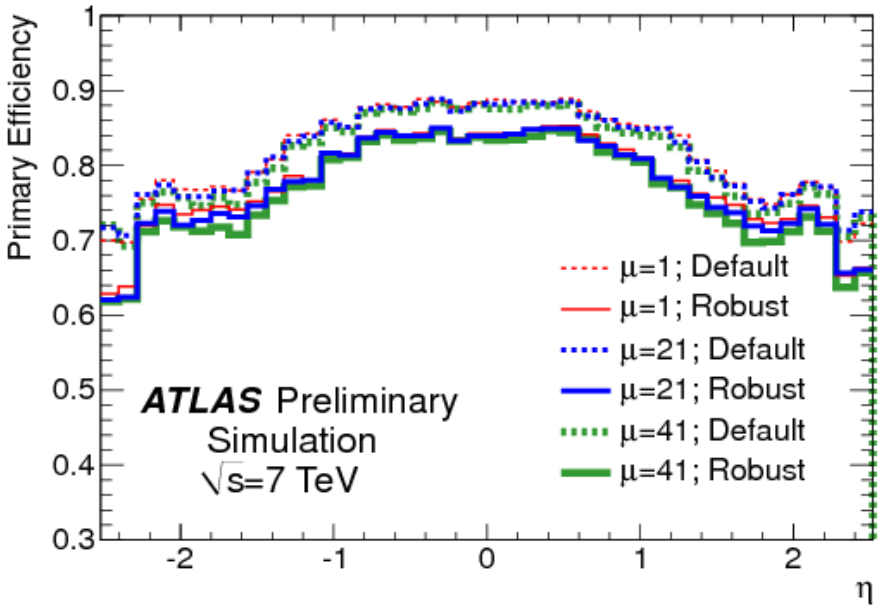
Reconstruction efficiency for primary (produced in decays with $\tau < 3 \times 10^{-11}$s) tracks in different pile up conditions. p_T>400 MeV. Hit-based truth matching.

Default (2011): At least 7 hits in the Si detectors, at most two holes in the pixel.

Robust (proposed for high pile up): At least 9 hits in the Si detectors, 0 holes in the pixel.

Minimum bias Monte Carlo for exactly one and average of 21 and 41 interactions per bunch crossing.

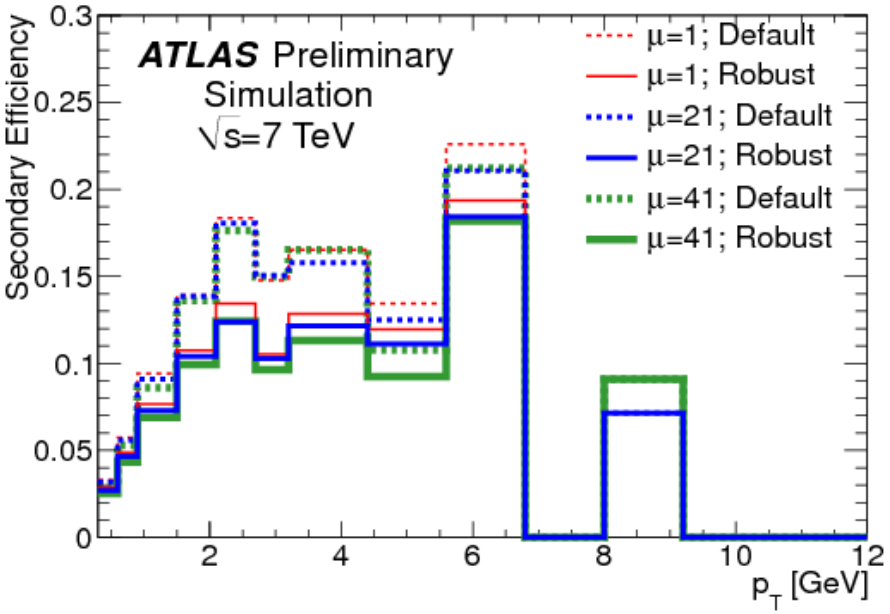


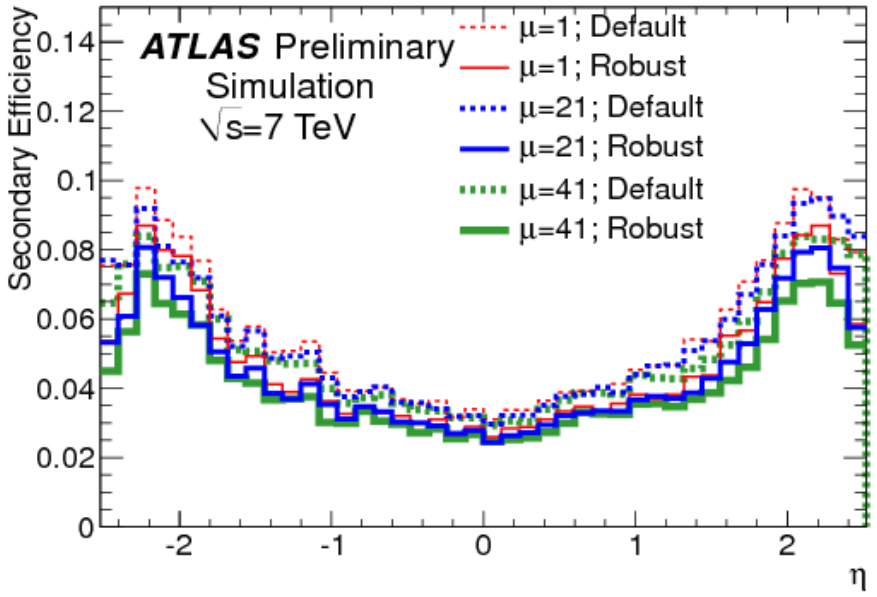


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Secondary tracks

Reconstruction efficiency for secondary tracks: produced in decays of primary (or other secondary) particles.

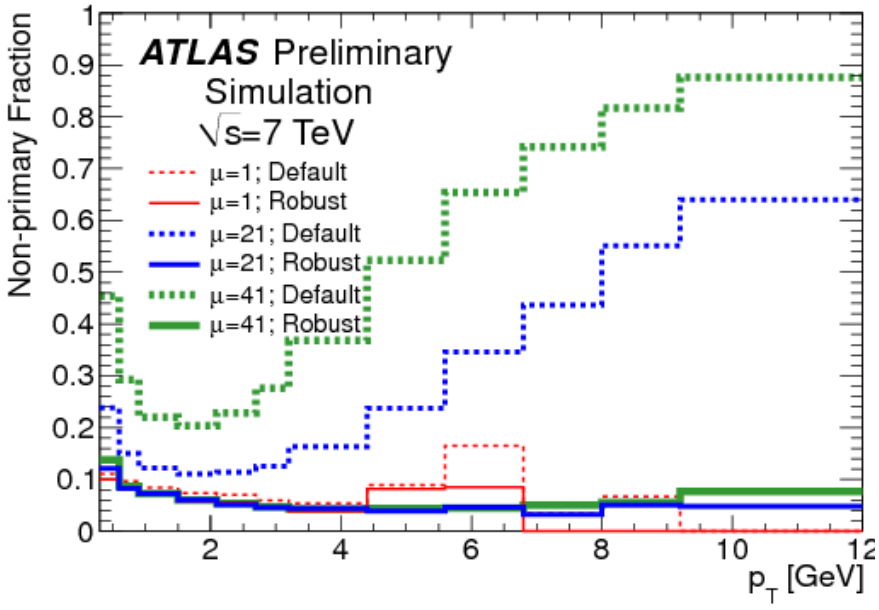


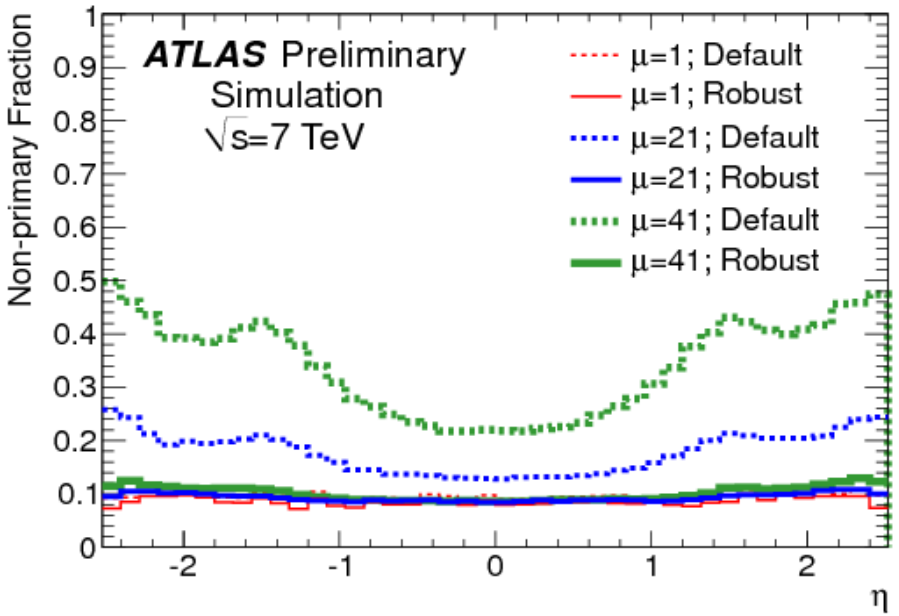


The reconstruction efficiency for both primary and secondary tracks degrade slightly with pile-up. The application of robust cuts decreases the efficiency for few percent for both primary and secondary particles.

Non-primary tracks

Non-primary tracks: combination of secondary tracks and combinatorial fakes. At μ=1 – only secondaries.



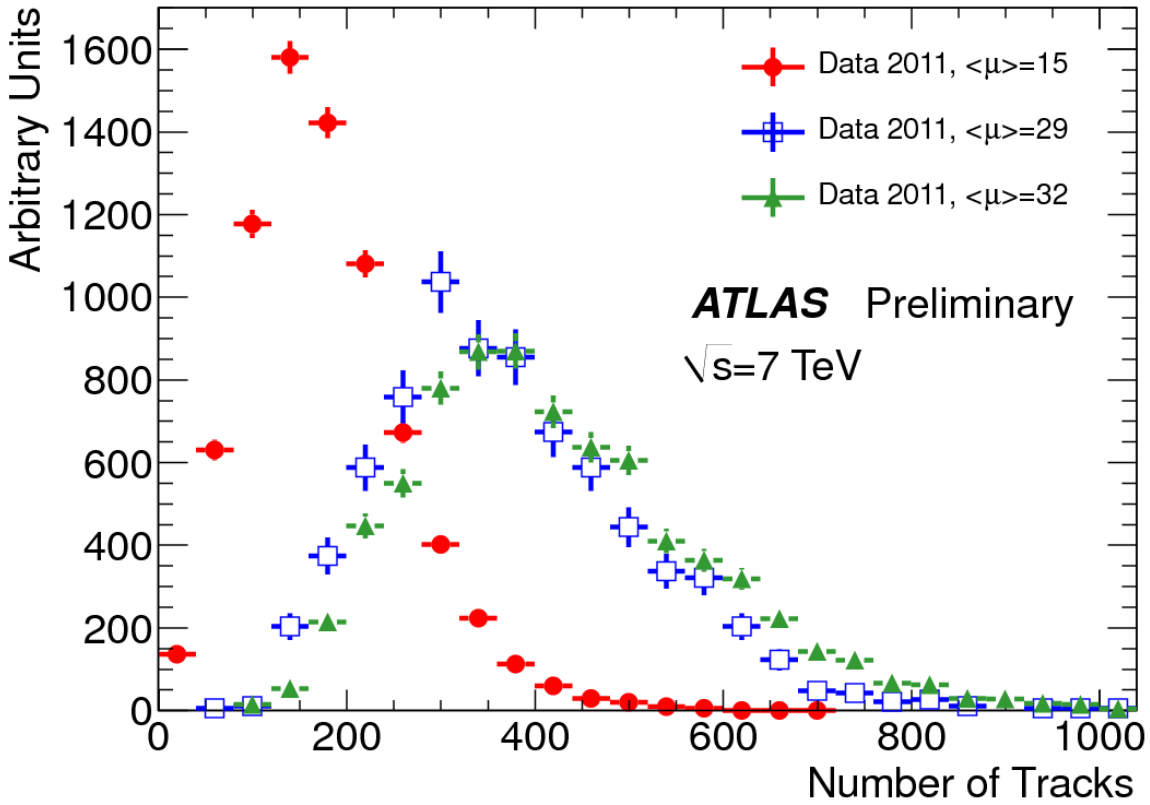


As the fraction of secondaries stay stable with pile up, the amount of fakes grows. Can be suppressed efficiently with the robust cuts.

Reconstructed Tracks in data

Number of reconstructed tracks per interaction for data containing different amount of pile-up. The robust requirements keep the average number of the reconstructed tracks constant with increasing pile up. Rejected by these cuts are mostly fake tracks.

Minimum bias events collected with random trigger during special high intensity fills in October 2011.

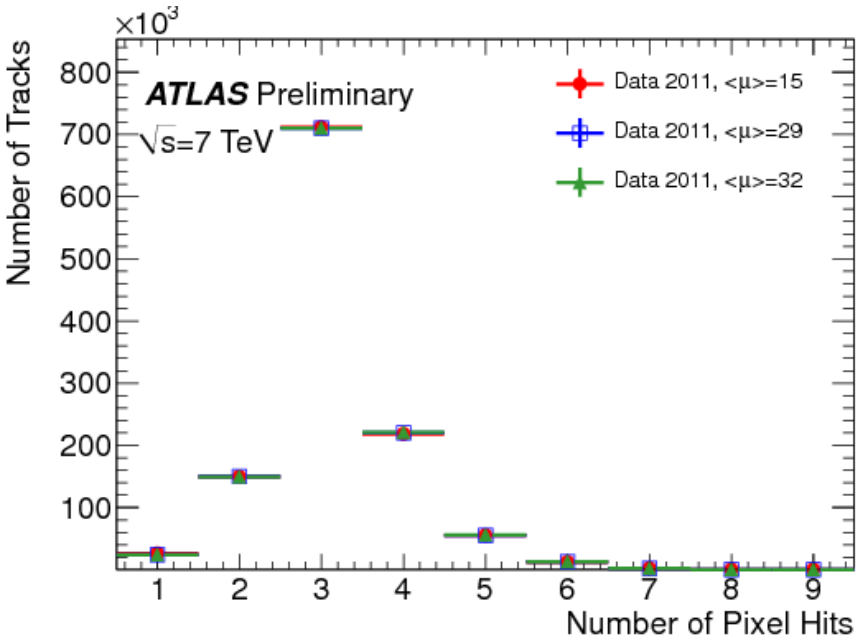


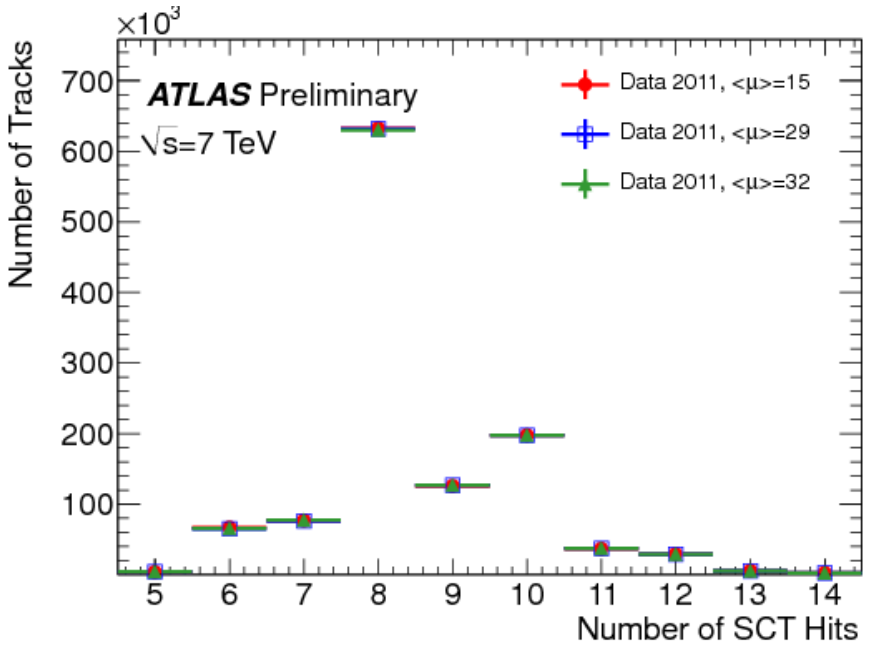
Average number of reconstructed tracks per interaction

<μ>	Default	Robust
15	11.8	10.3
29	12.8	10.2
32	13.2	10.3

Quality of Tracks

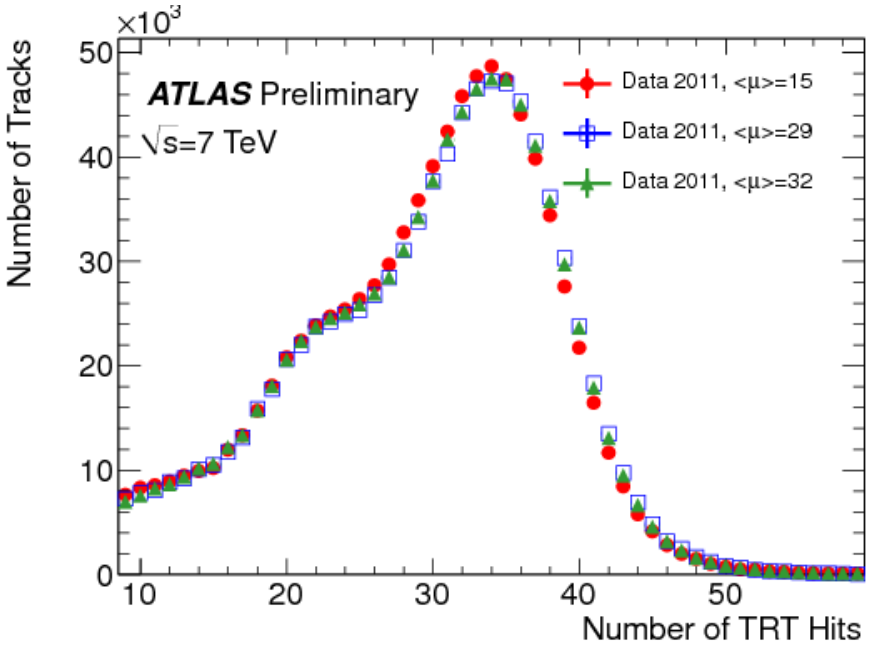
Number of pixel and SCT hits per track using robust requirements for different values of pile up with robust requirements. No dependence on the event occupancy observed.

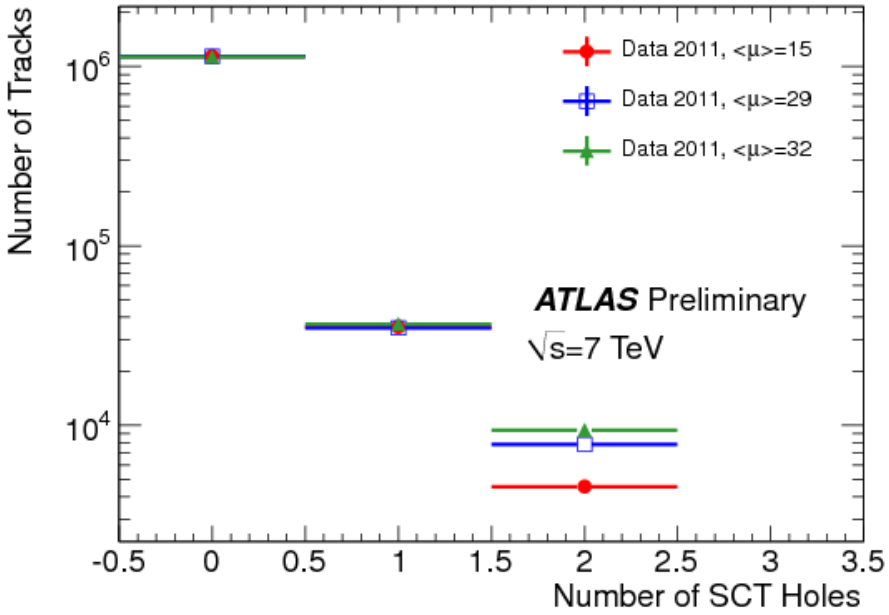




Quality of Tracks

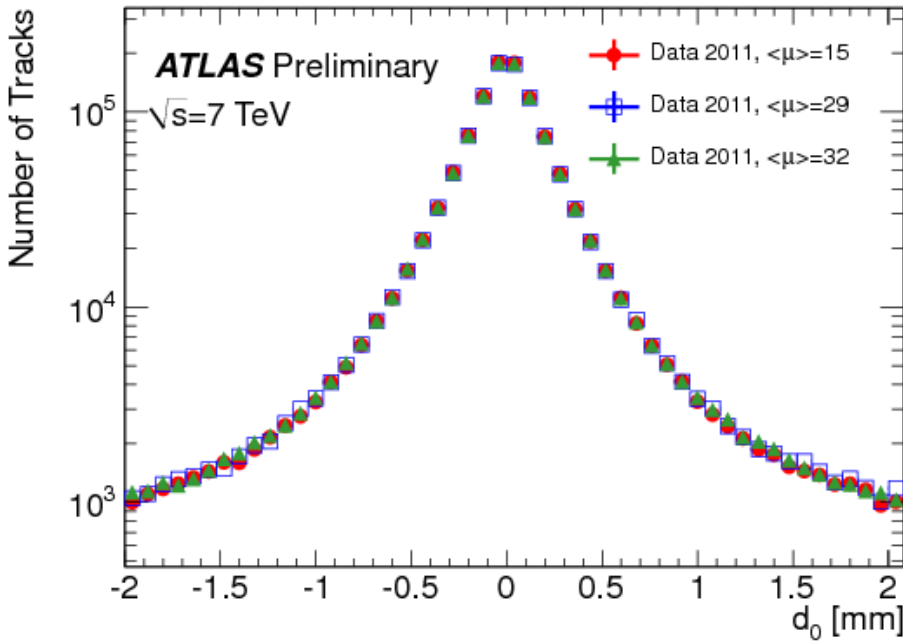
Number of TRT hits and SCT holes per track using robust requirements for different values of pile up reconstructed with robust requirements. A little dependence is observed. The number of SCT holes start increasing due to the high occupancy (sub-percent) effect.

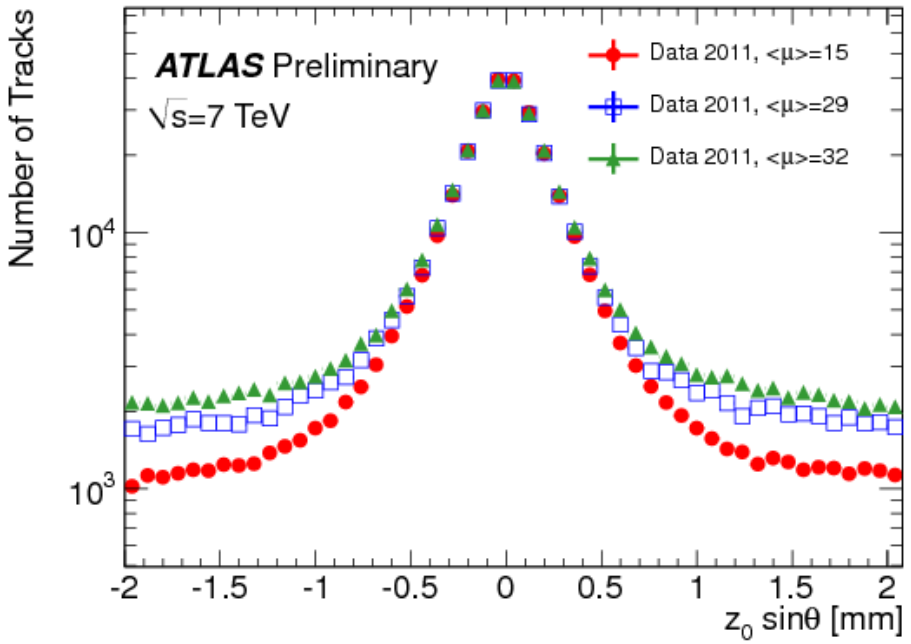




Impact Parameters

Impact parameters of tracks meeting robust requirements for different levels of pile up. Tracks reconstructed with robust requirements. Pile up effects are clearly visible for the longitudinal impact parameters.





Primary vertex reconstruction

- Pre-selection of input tracks
  - Track reconstruction cuts + compatibility with the beam region.

- Iterative Primary Vertex Finder
  - Out of the track pre-selected for the primary vertex search creates a single seed.
  - Fits it to a single vertex candidate using the Adaptive Vertex Fitter.
  - Uses rejected and outlier tracks (>7σ) to look for more vertex seeds.
  - Repeats the procedure until no more outliers left (no more seeds can be created).

- Adaptive Vertex Fitter (Deterministic Annealing Filter)
  - Based on the iterative χ^2 minimization approach (Kalman filter)
  - Track parameters are treated as "virtual measurements", position and covariance matrix of their joint vertex are reconstructed.
  - During fit iterations, tracks are down-weighted with respect to vertex estimate.
  - At the end of the fitting procedure close-by tracks have weights close to 1 and outliers – close to 0.

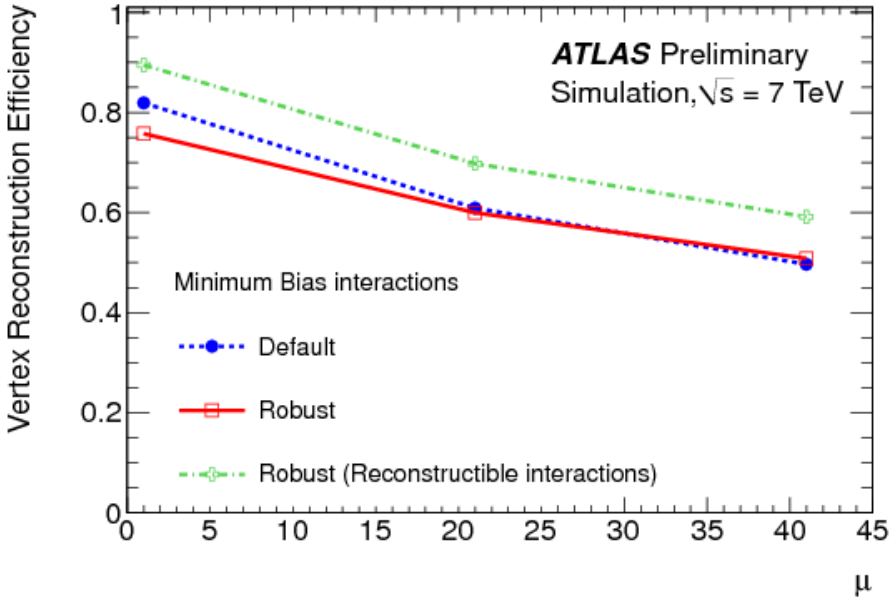
Minimum Bias reconstruction efficiency

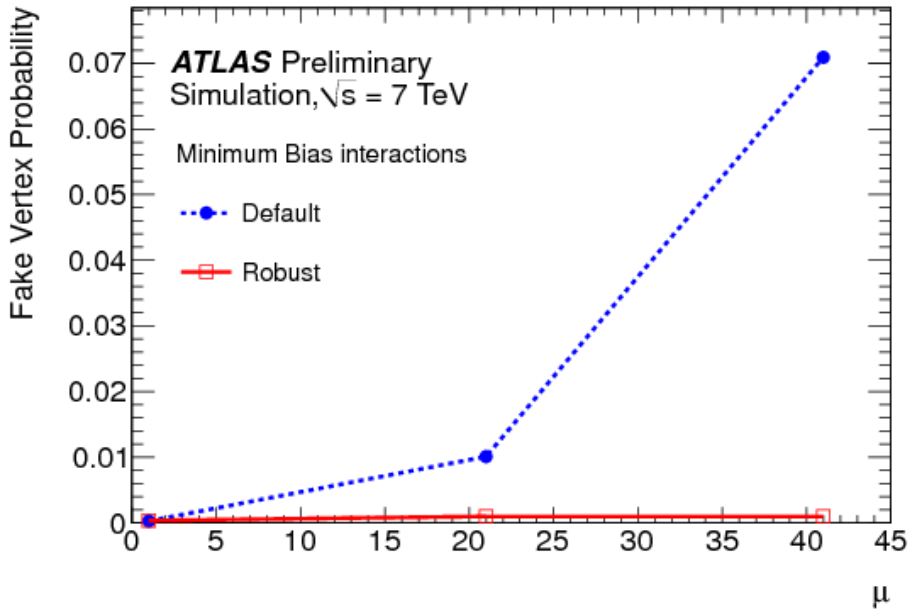
Reconstruction efficiency: Vertices are considered as reconstructed if the sum of weights of truth-matched tracks coming from the same interaction is >50%. Single- and Double-diffractive contributions are included.

Fake probability: leading contribution comes from the fake tracks.

At least two tracks per vertex and beam constraint.

Minimum bias Monte Carlo for exactly one and average of 21 and 41 interactions per bunch crossing.





Collective effects

The presence of many pile up interactions in the bunch crossing give raise to several collective effects previously rarely observed in the collider experiments.

- Production of fake primary vertices: Primary vertices composed mostly of fake tracks (random combinations of detector hits).

- Split of the primary vertices: The *pp* interaction reconstructed as several distinct primary vertices due to the resolution of the detector, secondary interactions, presence of jets etc.

- Merge and shadowing of primary vertices:
  - several *pp* interactions contributing to a single reconstructed primary vertex.

  - The trajectories produced in a hard-scatter *pp* interaction are divided between close-by pile-up vertices or merged with one of them, preventing the efficient reconstruction and identification of the primary vertex in question.

Collective effects

The collective effects can be modeled by the Monte Carlo simulation and also observed in data. One can try to quantify them by composing a probability density function of observing N reconstructed vertices given G truth (generated) collisions.

$$P(N \mid G) = \sum \rho(N_1 \mid G) \cdot \varphi(N_2) \cdot \sigma(N_3 \mid \rho(N_1 \mid G)) \cdot \mu(N_4 \mid \rho(N_1 \mid G))$$

where the sum runs over all possible combinations (N_1, N_2, N_3, N_4), such that: $N_1+N_2+N_3-N_4=N$. The individual contributions are defined as follows:

$\rho(N_1 \mid G)$

Probability of to reconstruct independently N_1 vertices given G truth collisions. It includes the acceptance of the detector and reconstruction efficiency.

$\varphi(N_2)$

Is the probability to reconstruct N_2 fake vertices. It depends on pile up level through the detector occupancy. Can be efficiently suppressed by track-level cuts.

Collective effects

$$P(N \mid G) = \sum \rho(N_1 \mid G) \cdot \varphi(N_2) \cdot \sigma(N_3 \mid \rho(N_1 \mid G)) \cdot \mu(N_4 \mid \rho(N_1 \mid G))$$

$\sigma(N_3 \mid \rho(N_1 \mid G))$

Probability that N_3 out of reconstructed vertices are subject to splitting.

$\mu(N_4 \mid \rho(N_1 \mid G))$

Probability that N_4 out of reconstructed vertices are subject to merging and shadowing.

An average number of reconstructed vertices given G true interactions:

$$E(N) = E(\rho) + E(\varphi) + E(\sigma) - E(\mu)$$

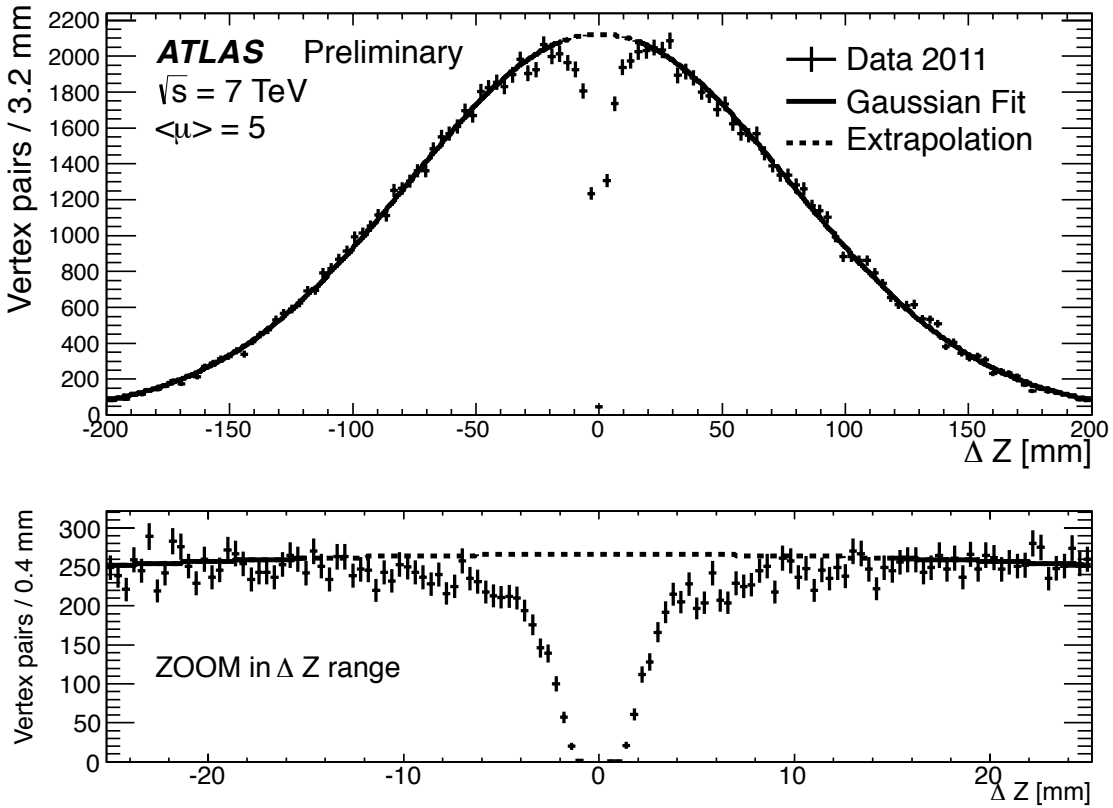
Provided a correct description of collective effects, one can obtain the true distribution of the number of interactions given the measured distribution of the number of primary vertices. This might help significantly in understanding the influence of the pile-up conditions on physics analyses.

The measurement of the number of reconstructed is also a direct measure of the amount of the pile-up on event by event basis.

Collective effects

Longitudinal separation between the reconstructed primary vertices in the minimum bias events with exactly 2 reconstructed vertices. Data 2011 selected with random trigger.

Since the distribution of density of protons in bunches is Gaussian, here the Gaussian distribution is expected.

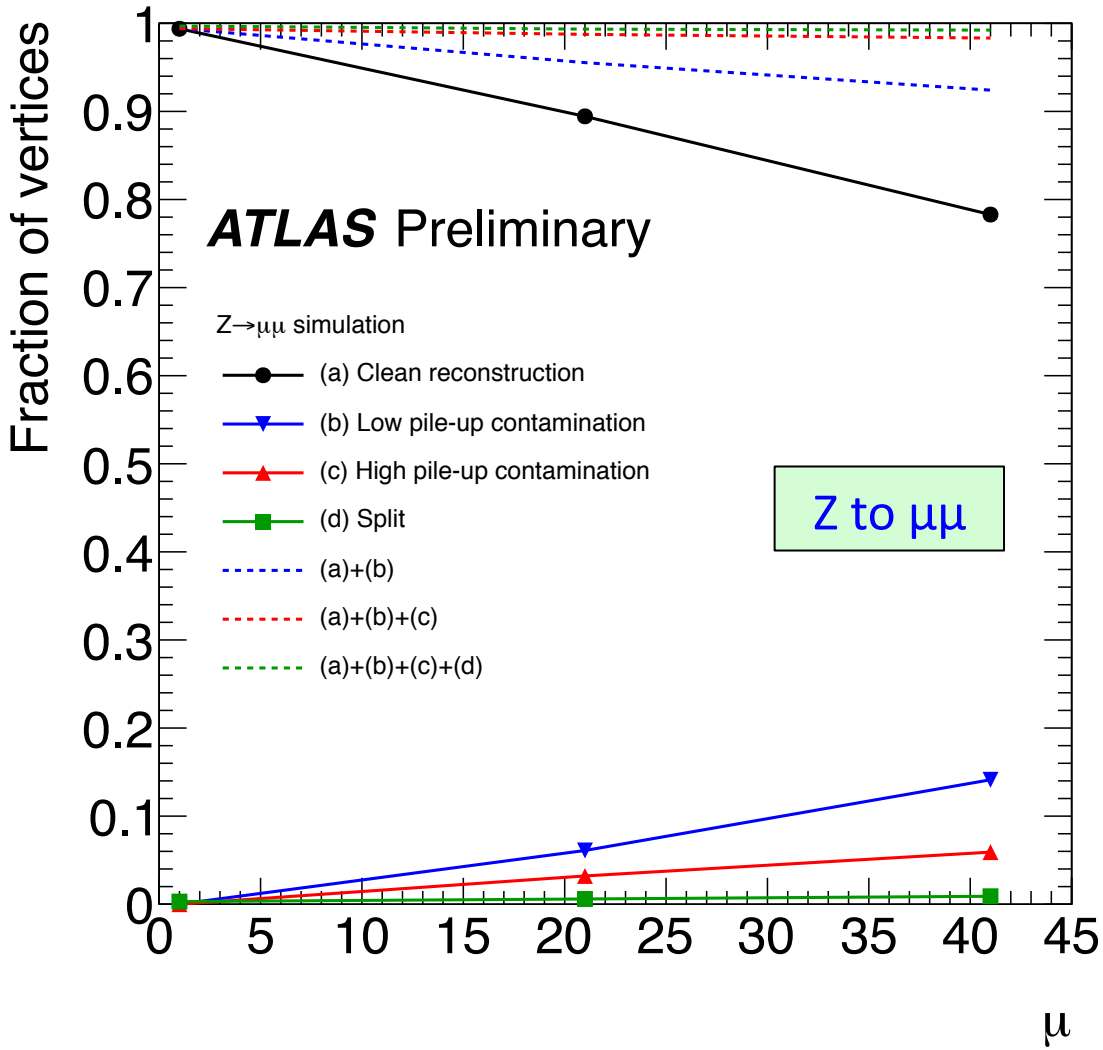


Additional distortion of the turn-on shape comes from the splitting of primary vertices.

Missing fraction is due to the merging primary vertices.

Efficiency of Primary Vertex Reconstruction

Monte-Carlo truth-matched efficiency for reconstructing hard-scatter (Z->μμ) primary vertex in pile-up conditions.



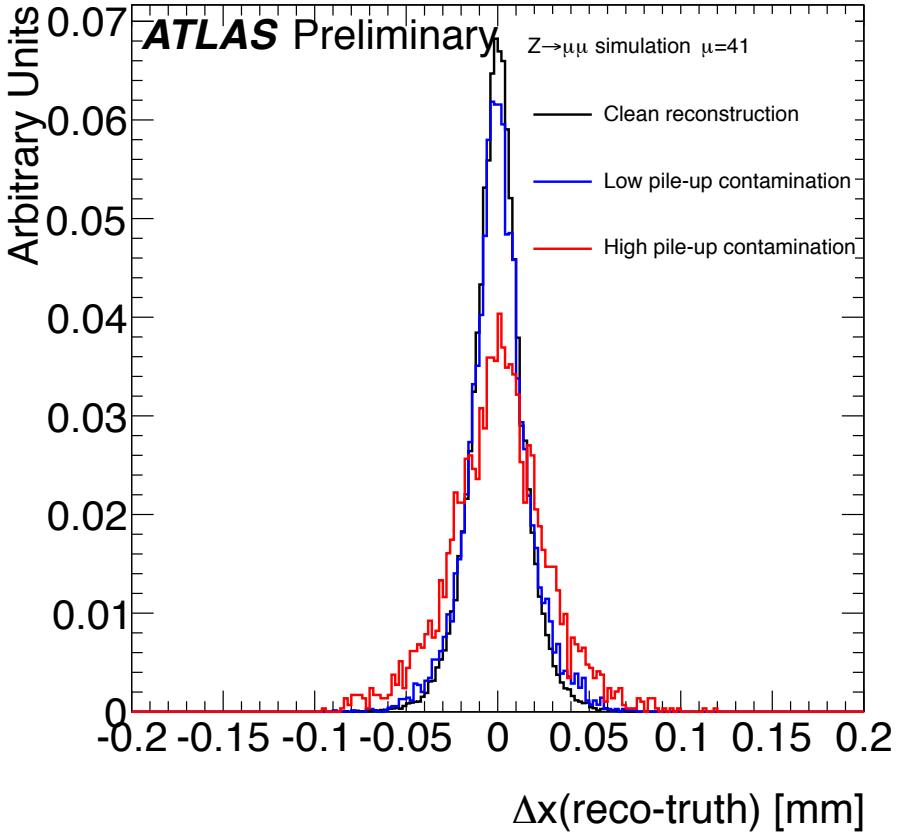
High pile-up contamination: reconstructed hard-scatter primary vertices with >50% contributions from pile-up tracks.
Low pile-up contamination: 30-50% contributions from pile-up tracks.

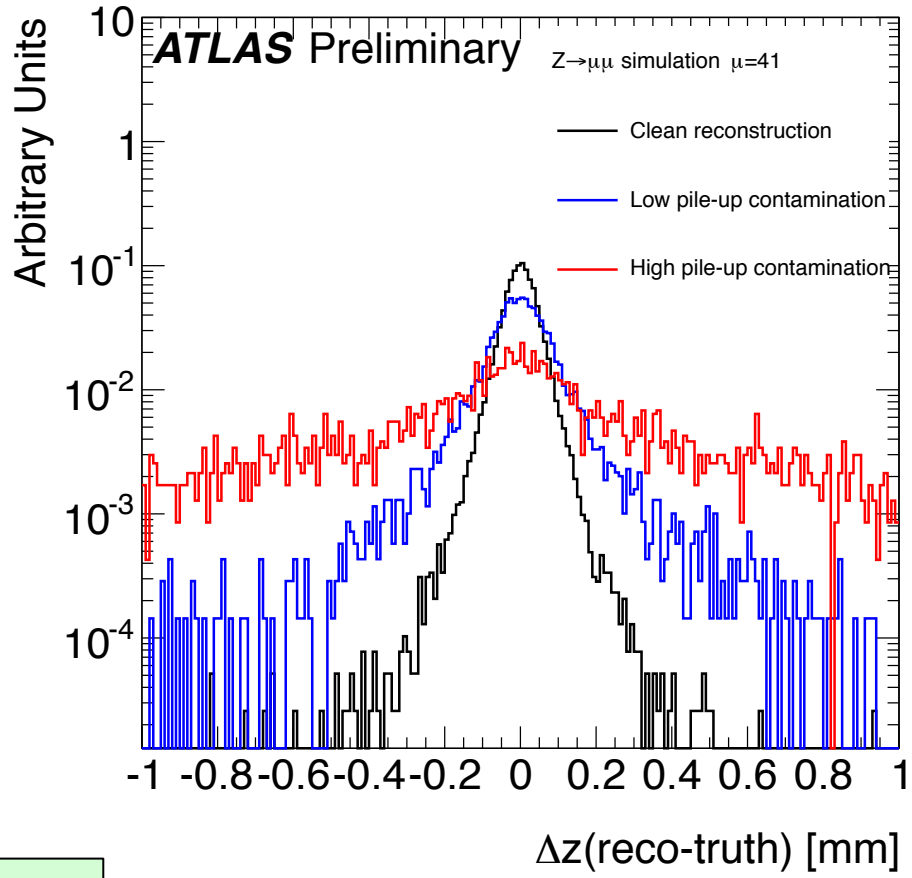
Clean reconstruction: hard-scatter primary vertices with >70% contribution from tracks produced in the hard-scatter.

Default tracking cuts

Changes in the resolution

Degradation of the position resolution of primary vertices due to the pile up contamination (Z->μμ). The transverse resolution is dominated by the size of the beam spot (σ~15μm); therefore no significant degradation observed. The longitudinal size of the beam spot is about 5.6 cm.



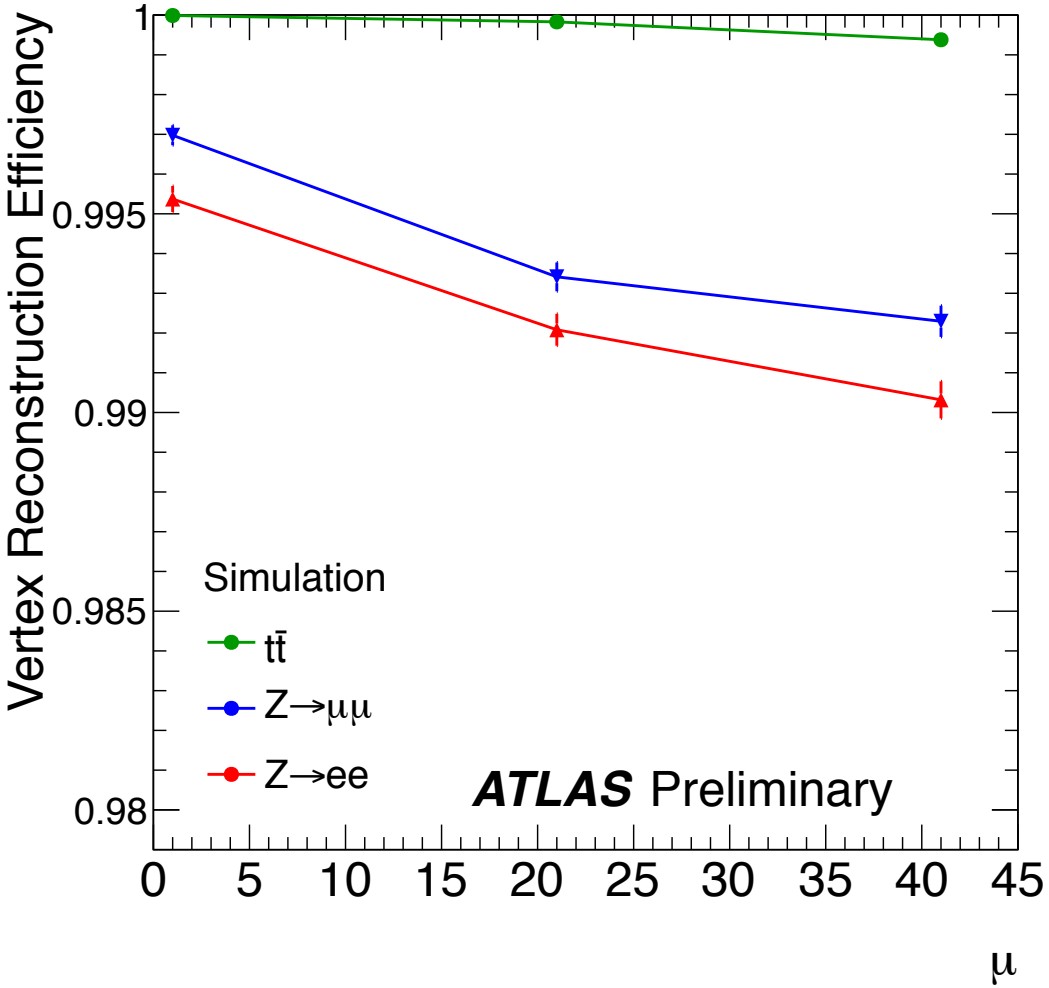


Default tracking cuts

Z to μμ

Efficiency of Primary Vertex Reconstruction

Monte-Carlo truth-matched efficiency for reconstructing hard-scatter primary vertex in pile-up conditions. The efficiency corrected for the high- and low- pile-up contamination and primary vertex split.



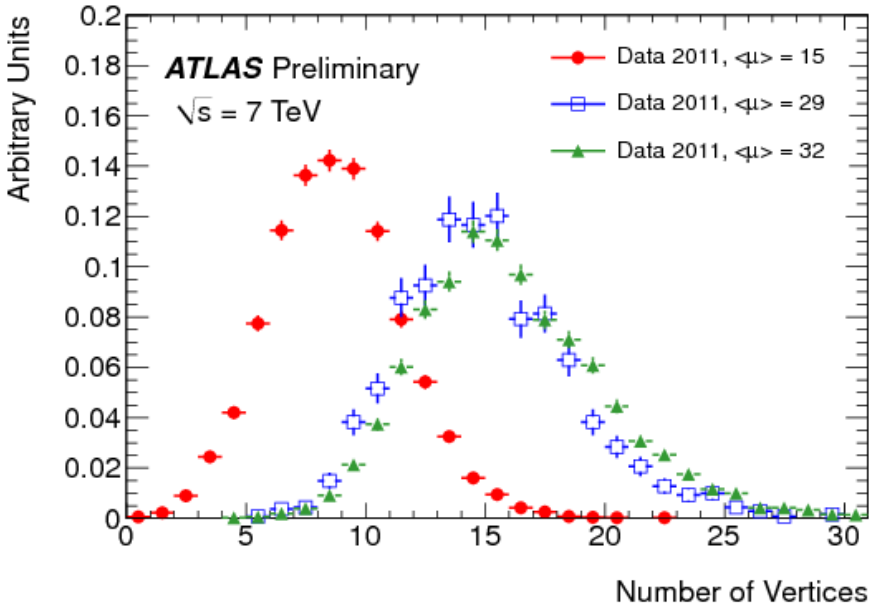
The remaining degradation of efficiency with pile up is negligible: <1%. It can be presumably attributed to the very heavy shadowing effects.

Default tracking cuts

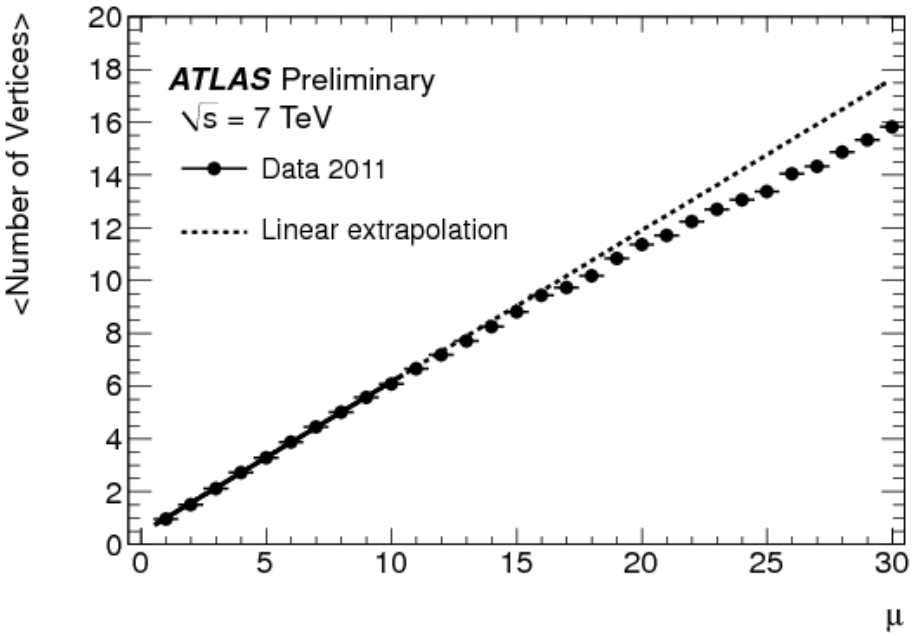
Reconstruction efficiency in data

Minimum bias data collected with random trigger. Number of primary vertices reconstructed in data as a function of the average number of interactions per bunch crossing. The dependence is non-linear due to the merging and shadowing effects.

Robust cuts, special high intensity fills collected in October 2011.

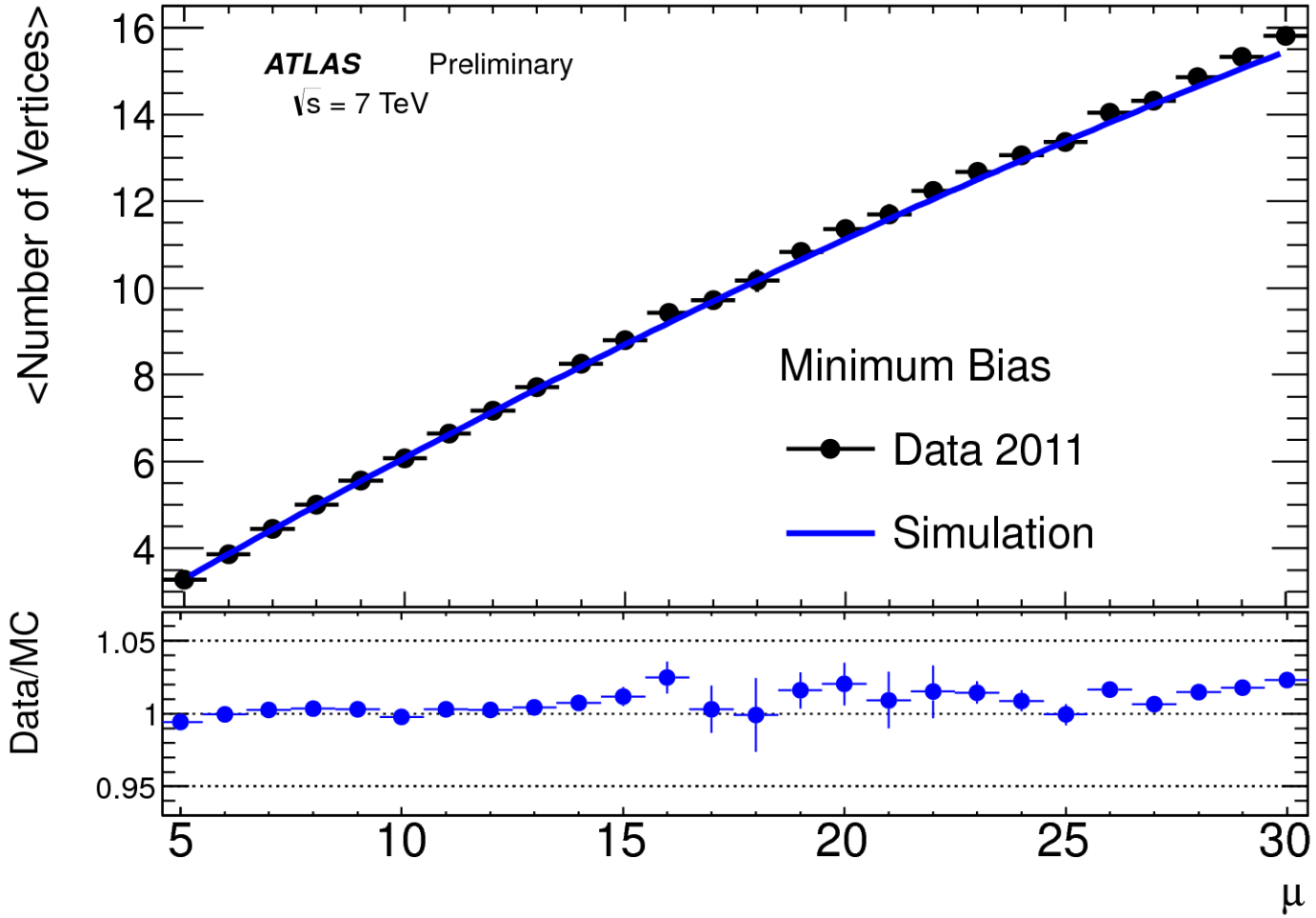


Default cuts, data 2011



Reconstruction efficiency in data

Minimum bias data collected with random trigger. Number of primary vertices reconstructed in data as a function of the average number of interactions per bunch crossing. Comparison to the Pythia 6 AMBT2 tune.

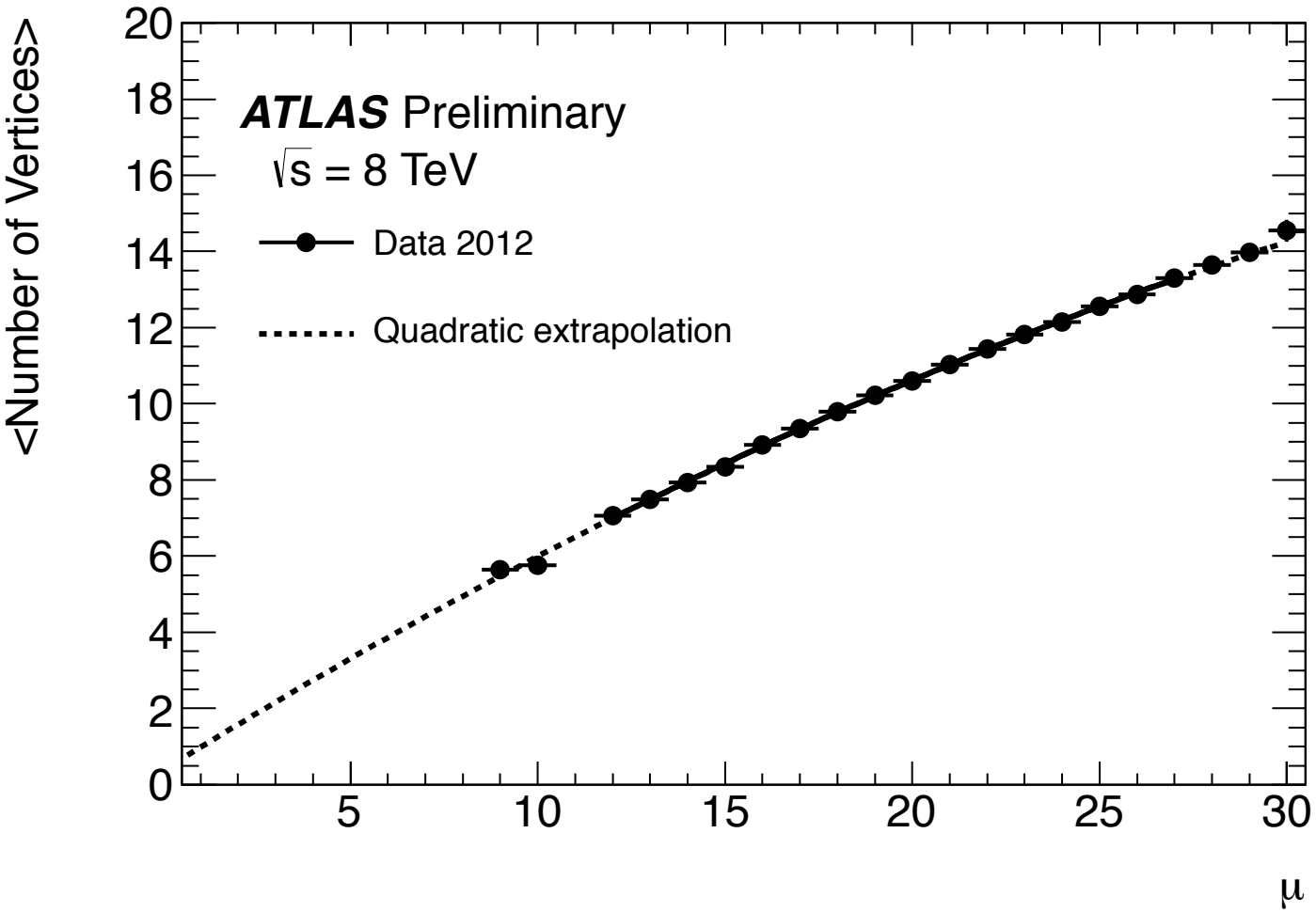


Very good agreement.

Default tracking cuts

First look at data 2012

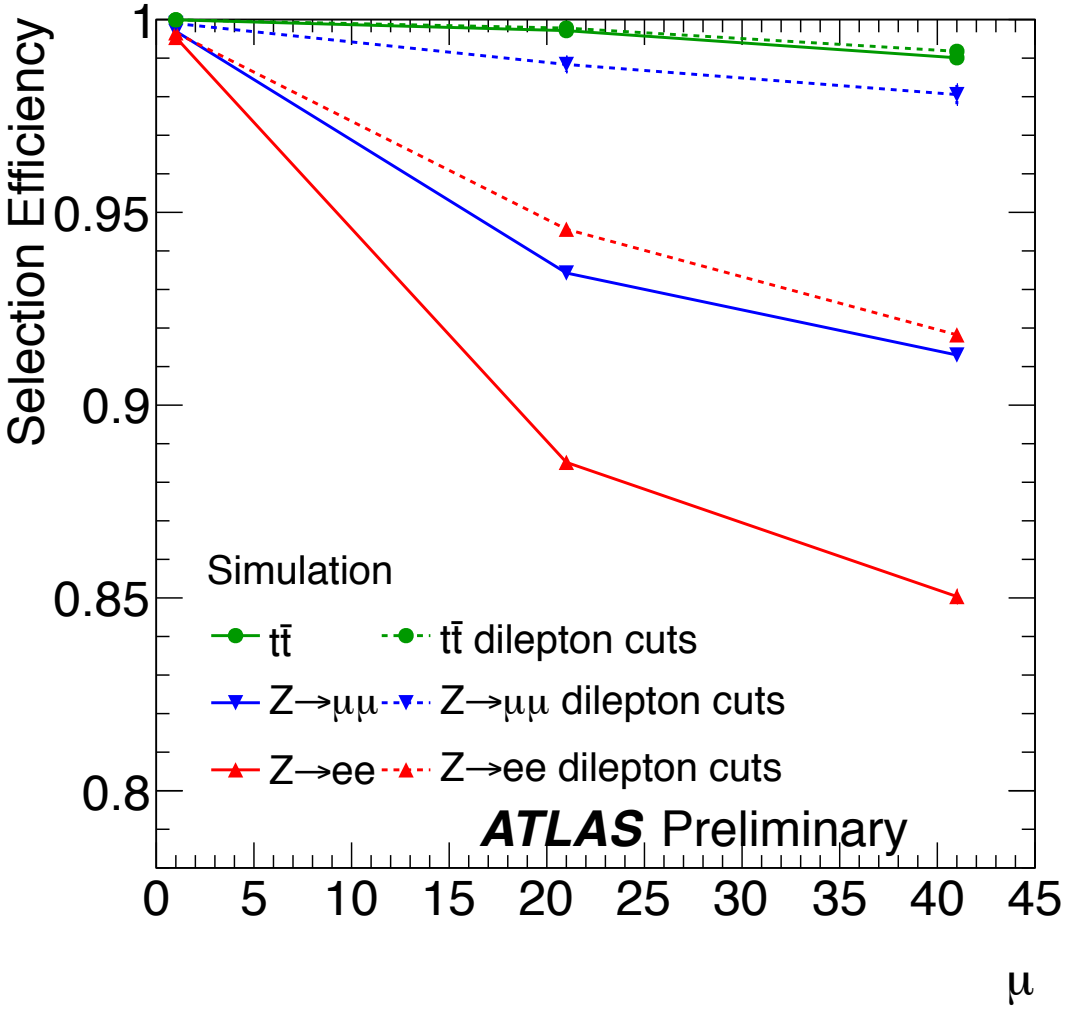
Minimum bias data collected with random trigger. Number of primary vertices reconstructed in data as a function of the average number of interactions per bunch crossing. The dependence is not linear due to shadowing and merging effects.



Robust tracking cuts

Identification of the Hard Scatter

Monte-Carlo truth-matched efficiency to reconstruct and correctly identify hard-scatter primary vertex in pile-up conditions. The efficiency corrected for the high- and low- pile-up contamination and primary vertex split.



Presently, the hard scatter vertex is identified as the primary vertex having the biggest Σp_T^2 of all fitted tracks.

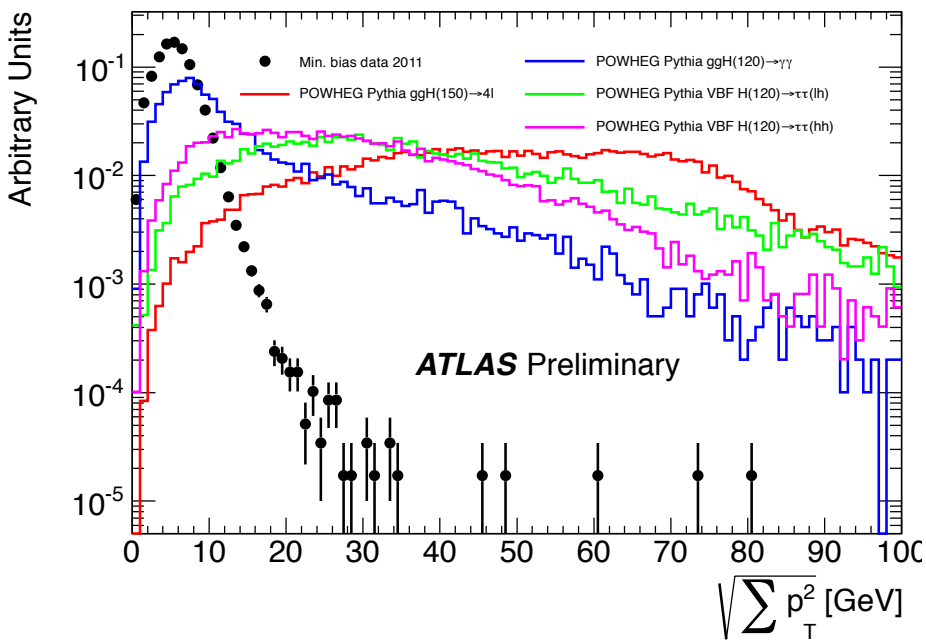
This is not the best criterion for every given physics channel. To improve the vertex reconstruction efficiency in physics analyses, the final state objects (leptons, photons, jets etc..) should be used to identify the hard scatter vertex.

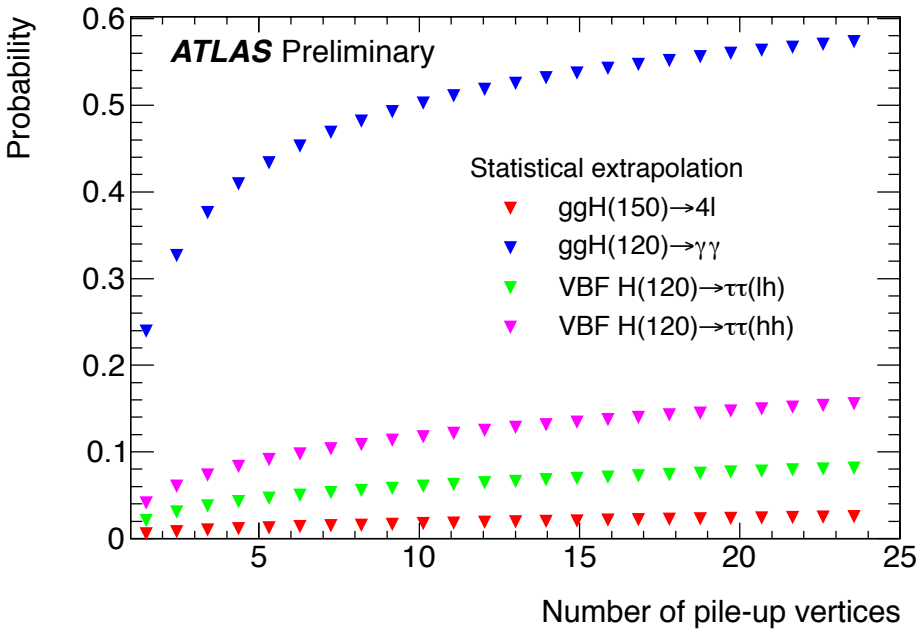
Default tracking cuts

Identification of the Hard Scatter

Statistical extrapolation showing the probability of the hard-scatter vertex to have the Σp_T^2 of all fitted tracks inferior to the one of the minimum bias interaction as a function of number of pile up vertices.

The p.d.f. for the minimum bias interactions is measured from the special single collision Sample collected with the random trigger during low luminosity runs.

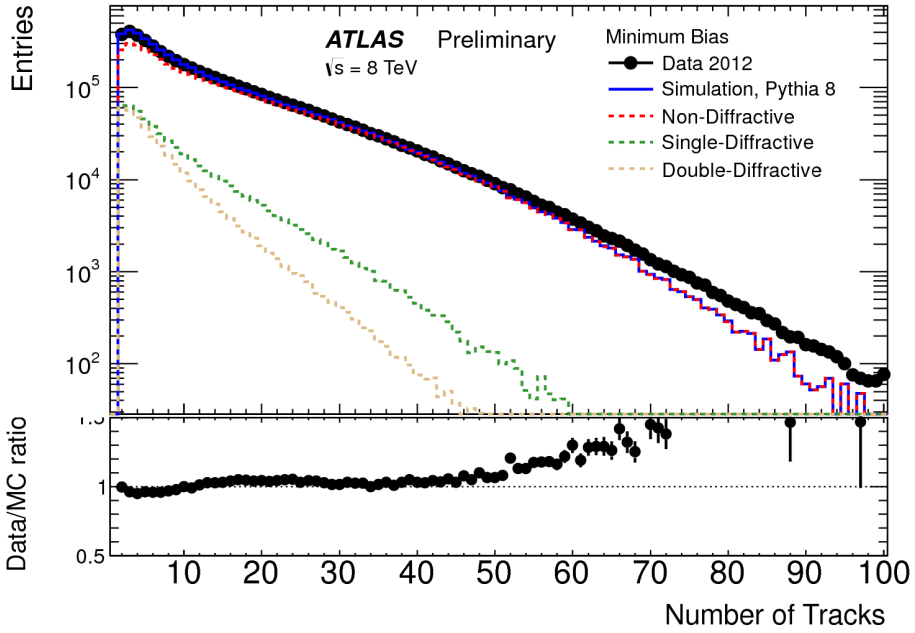


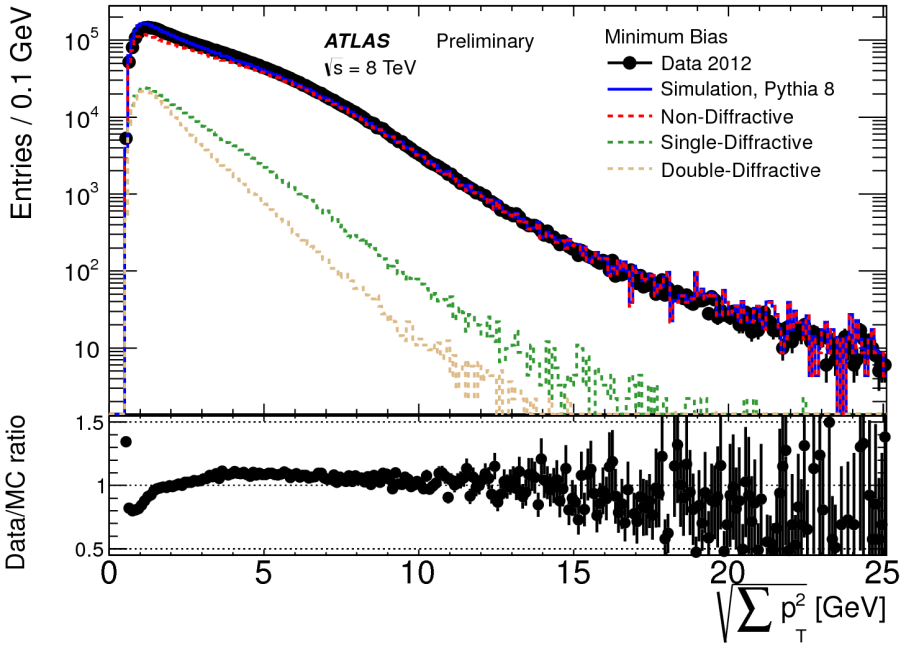


Conclusion

- Presented are the first results illustrating the performance of the ATLAS Inner Detector in the high pile-up environment of the LHC.
- The reconstruction algorithms are found to be robust against high multiplicity environment. The fraction of the fake tracks can be kept under control by applying robust quality requirements.
- There is no degradation in track quality, however a few % loss of the efficiency can be expected independently of μ.
- The efficiency of primary vertex reconstruction stays high, while the effects of splitting, merging and shadowing of the primary vertices are observed. The amount of fake vertices can be controlled using robust track cuts.
- The vertex-related pile-up effects are correctly described by the Monte-Carlo simulation.
- The selection of the hard-scatter primary vertex in high pile-up conditions may show a considerable loss of efficiency depending on the final state. To identify the hard-scatter primary vertex correctly, the final state objects should be employed.

Backup


ATLAS Preliminary
√s = 8 TeV
Minimum Bias
Data 2012
Simulation, Pythia 8
Non-Diffractive
Single-Diffractive
Double-Diffractive
Entries
Data/MC ratio
Number of Tracks


ATLAS Preliminary
√s = 8 TeV
Minimum Bias
Data 2012
Simulation, Pythia 8
Non-Diffractive
Single-Diffractive
Double-Diffractive
Entries / 0.1 GeV
Data/MC ratio
√Σ p²T [GeV]

Backup (Lumi Calibration)

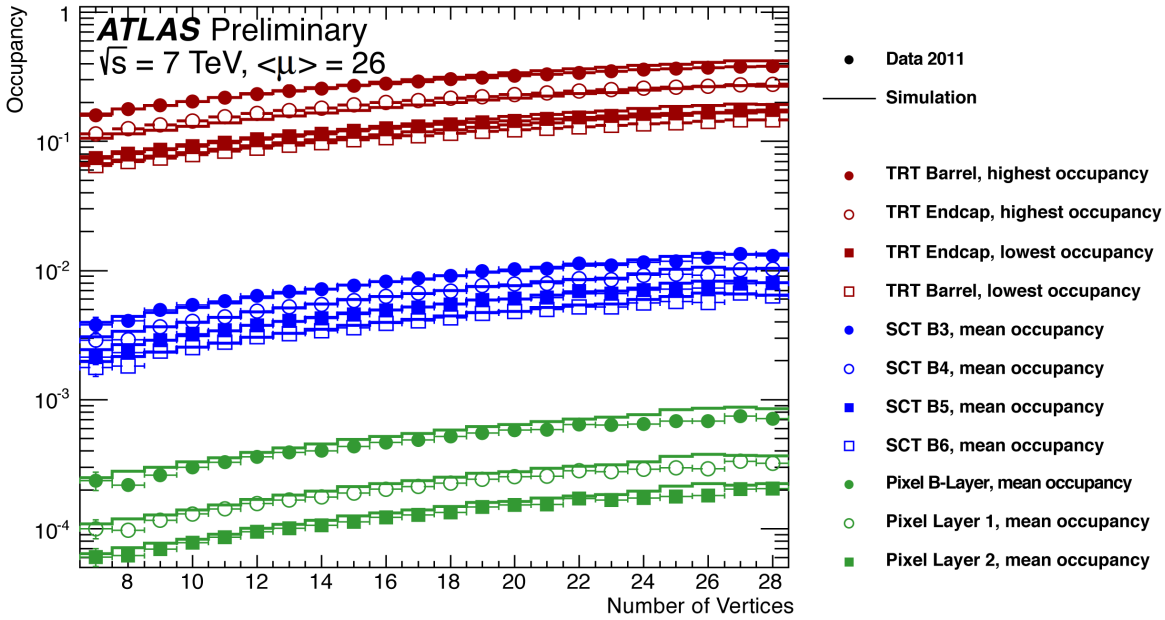
$$\mu = \frac{L\sigma_{inel}}{n_b f_r} \qquad L = \frac{\mu n_b f_r}{\sigma_{inel}}$$

$$\sigma_{inel} = 71{,}5 mb(Pythia);$$

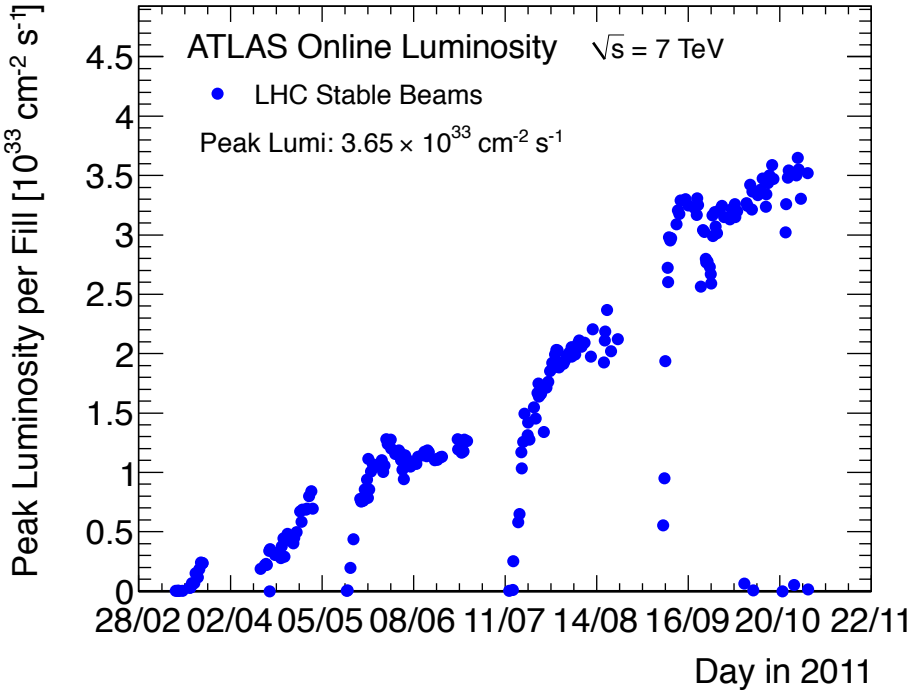
$$\sigma_{inel} = 69{,}1 \pm 2.4(\exp.) \pm 6.9(extr.) mb(ATLAS);$$

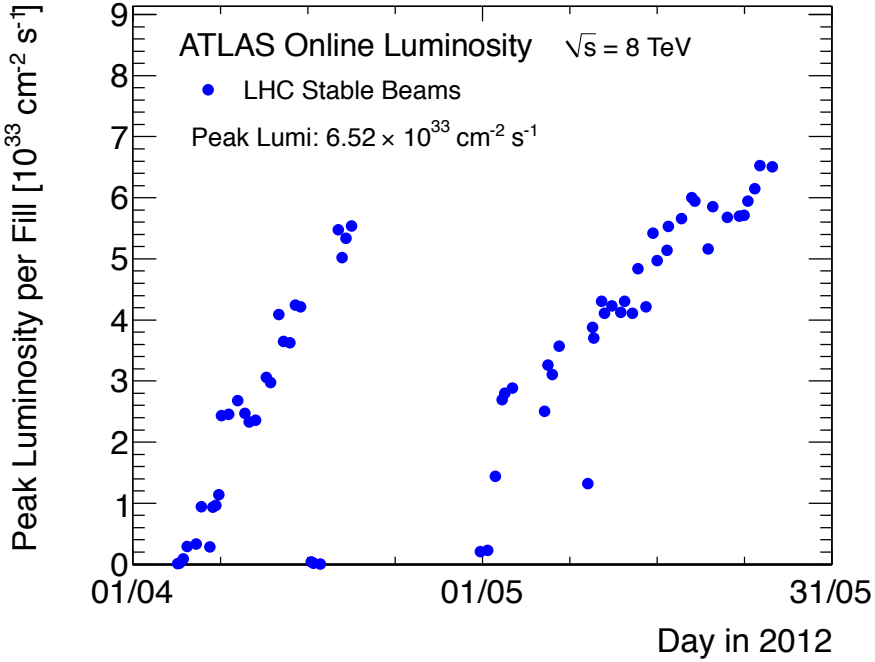
$$\sigma_{inel} = 73.5 \pm 1.9 mb(TOTEM);$$

Backup (Occupancy)

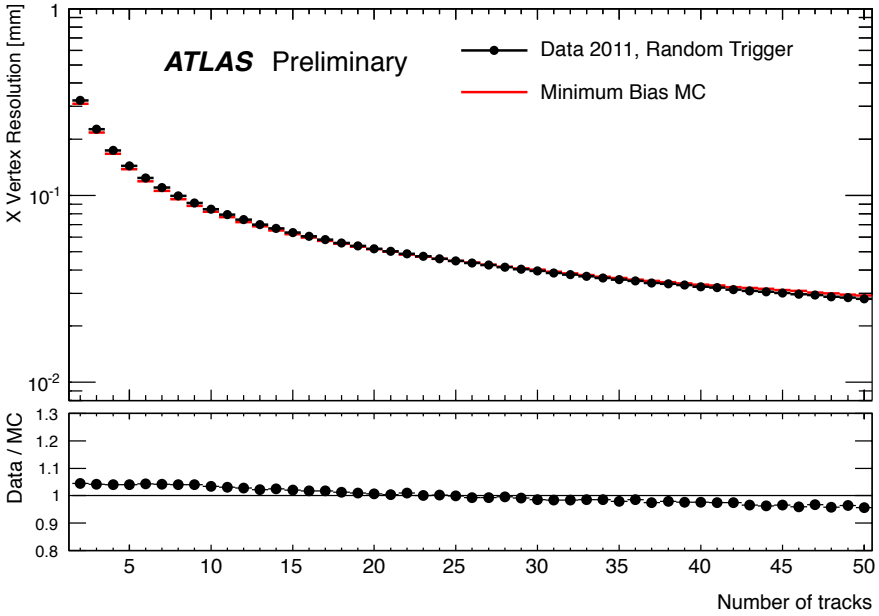


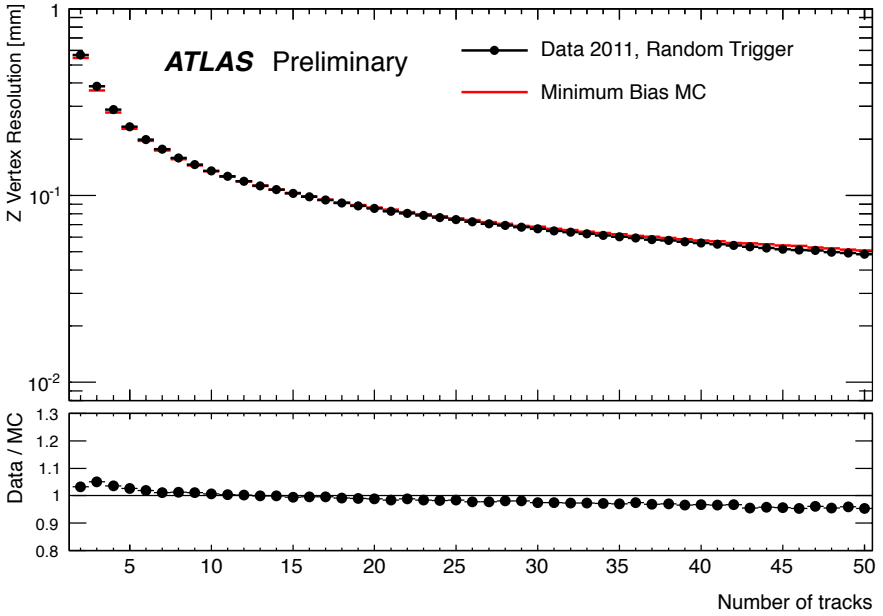
Backup (Luminosity)

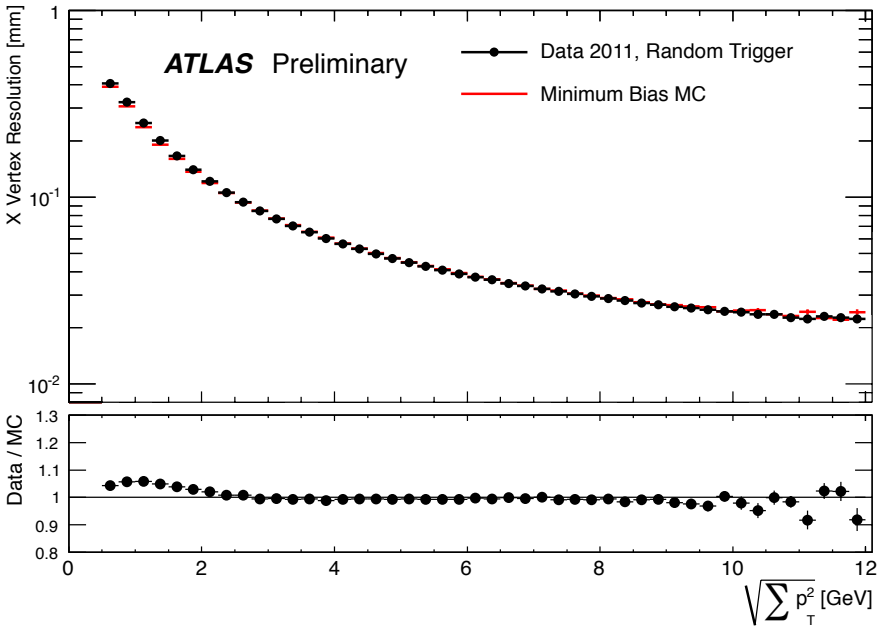


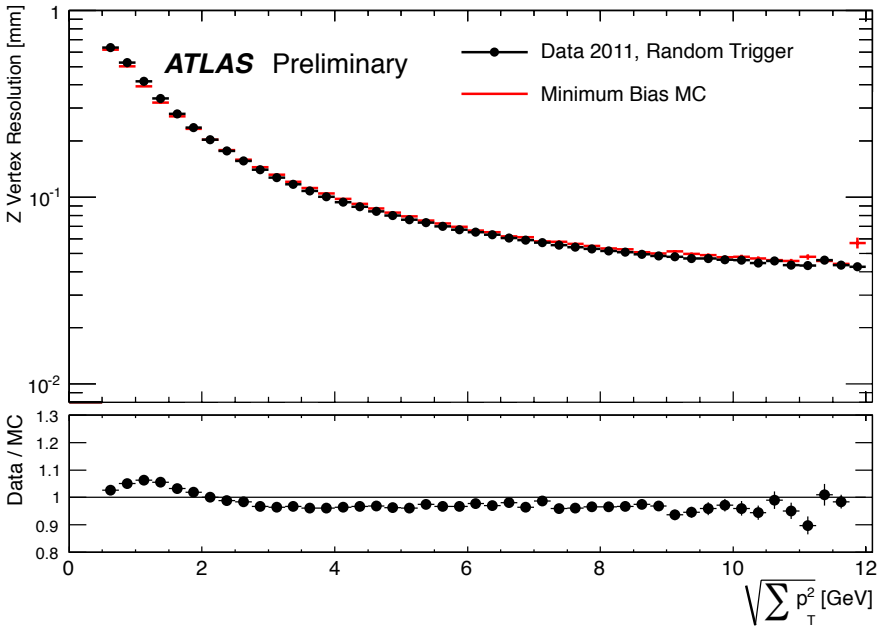


Backup (Resolutions)









Backup (Resolutions)

