Charged track reconstruction and b-tagging performance in ATLAS

Andrea Favareto
Università degli Studi di Milano & INFN
On behalf of ATLAS collaboration

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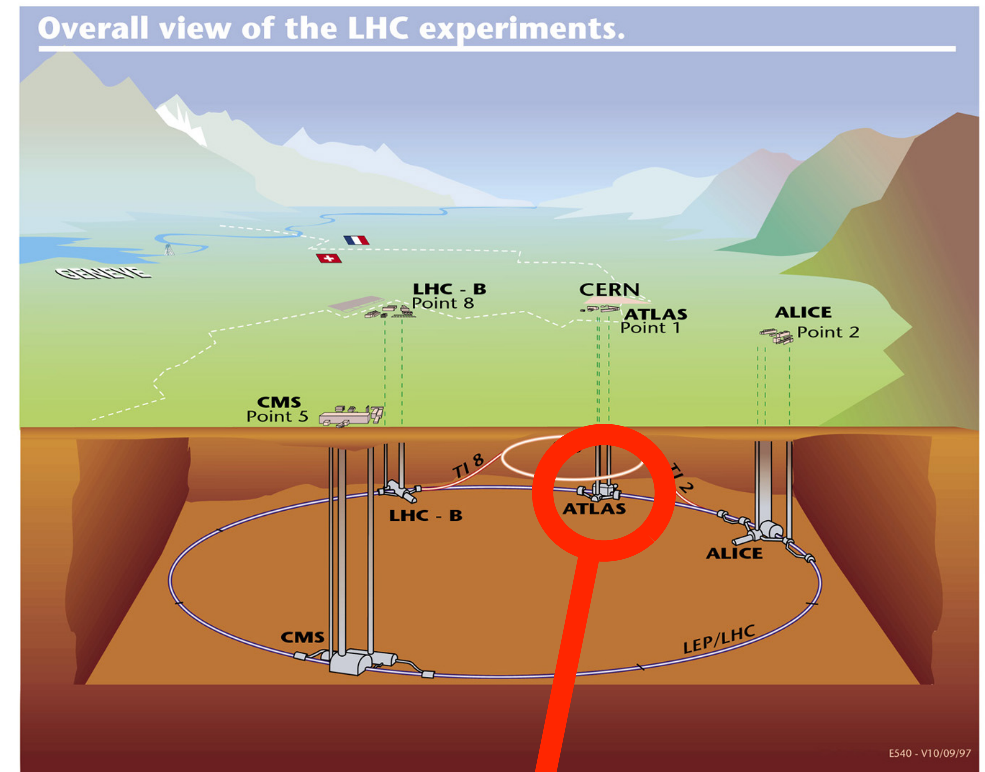
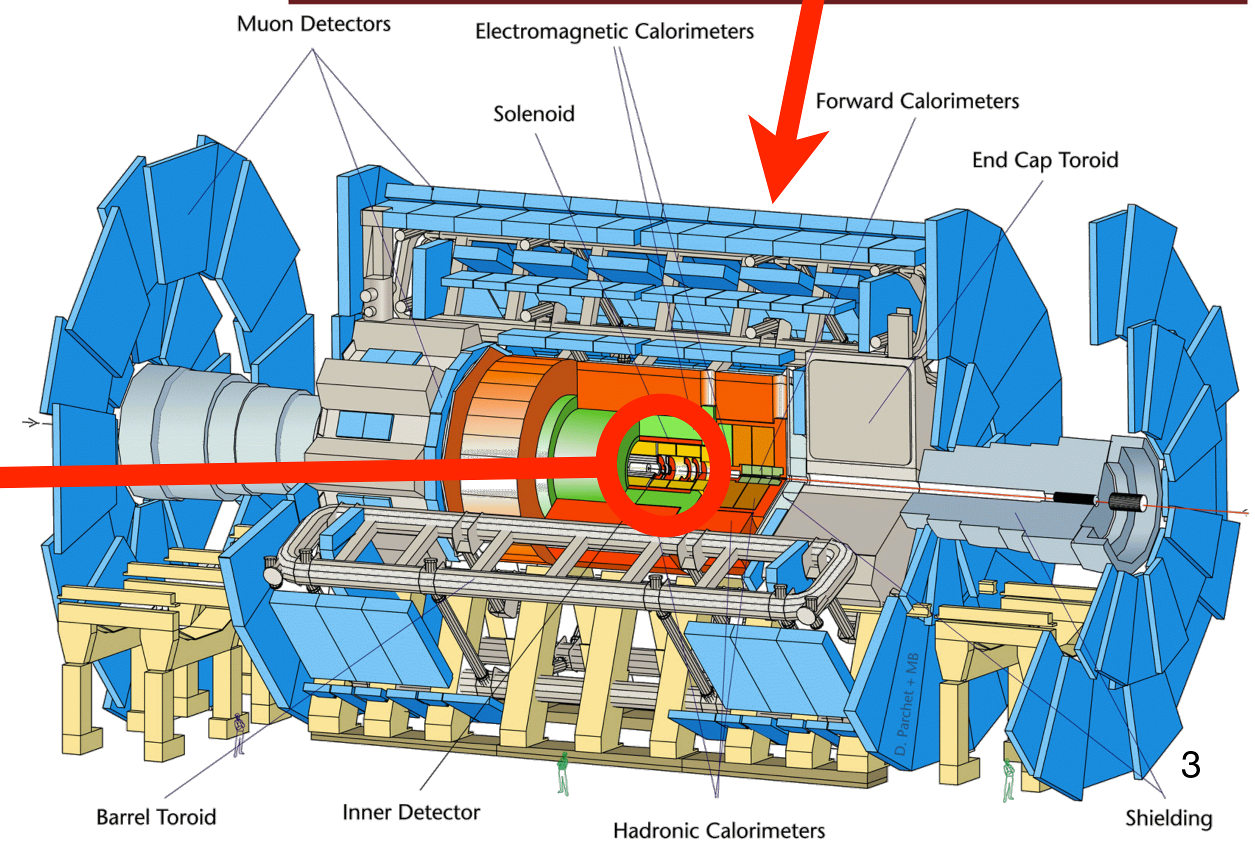
Introduction and Outline

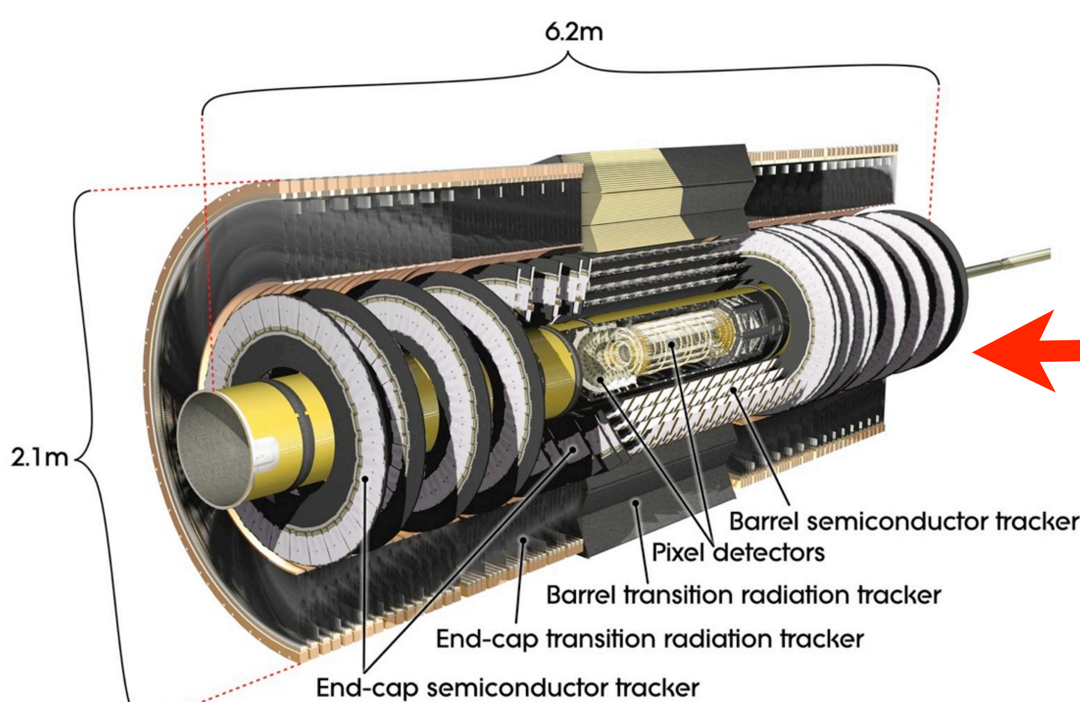
- tracking and b-tagging are extremely important for many physics analyses from the precision top quark measurements to the searches of the Higgs boson and physics beyond the Standard Model
- evaluating the performance of the Inner Detector (ID) and the tracking algorithms is a major ingredient for most of the physics analyses
- In this talk I will summarize
  - ATLAS experiment and Inner Detector operation
  - pattern recognition
  - material studies
  - vertexing
  - alignment
  - track resolution
  - b-tagging performances

The ATLAS experiment at LHC

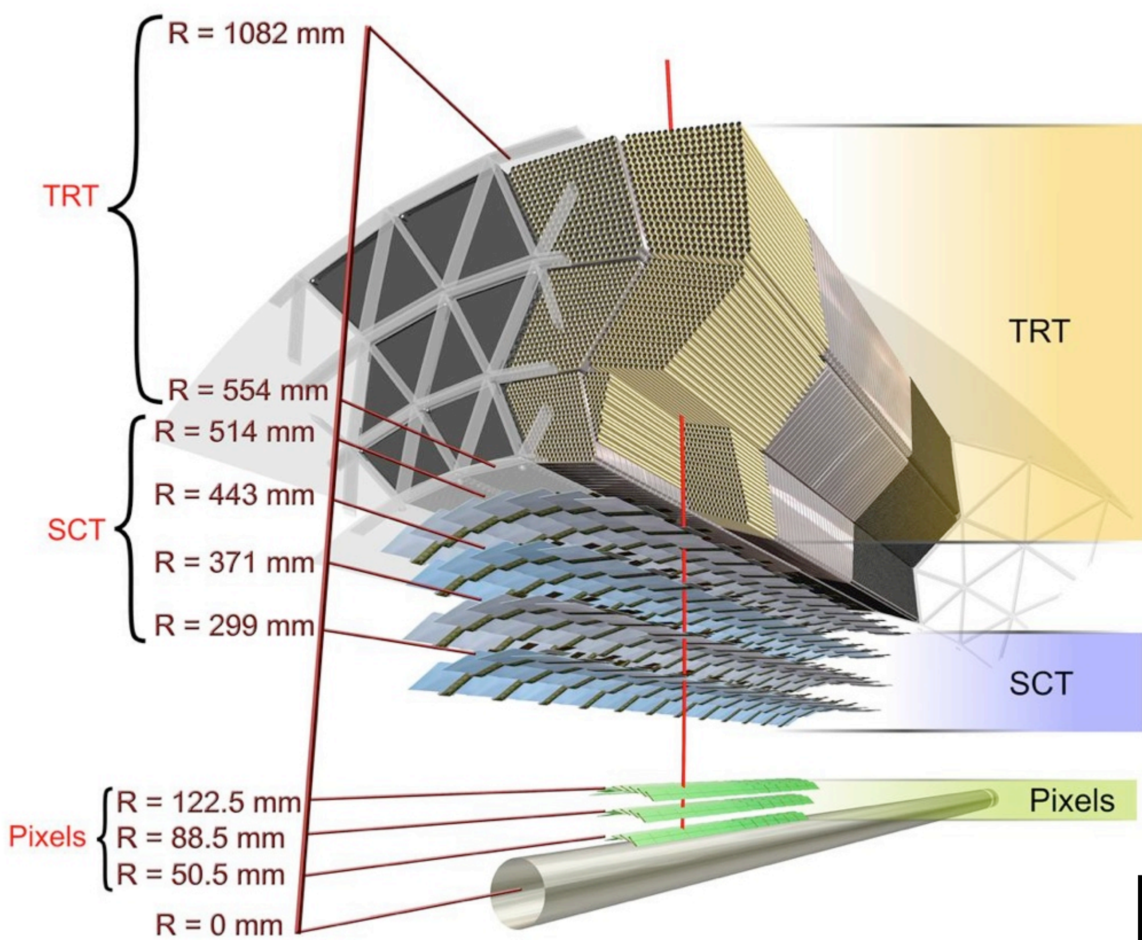
- ***ATLAS***: general purpose experiment
  - Length ~45 m
  - Diameter ~24 m
  - Weight ~7000 ton
  - Electronic channels ~10^8
- ***Inner Detector***: efficient and accurate charged particle reconstruction
  - Length ~6.2 m
  - Diameter ~2.1 m
  - Acceptance $|\eta|<2.5$

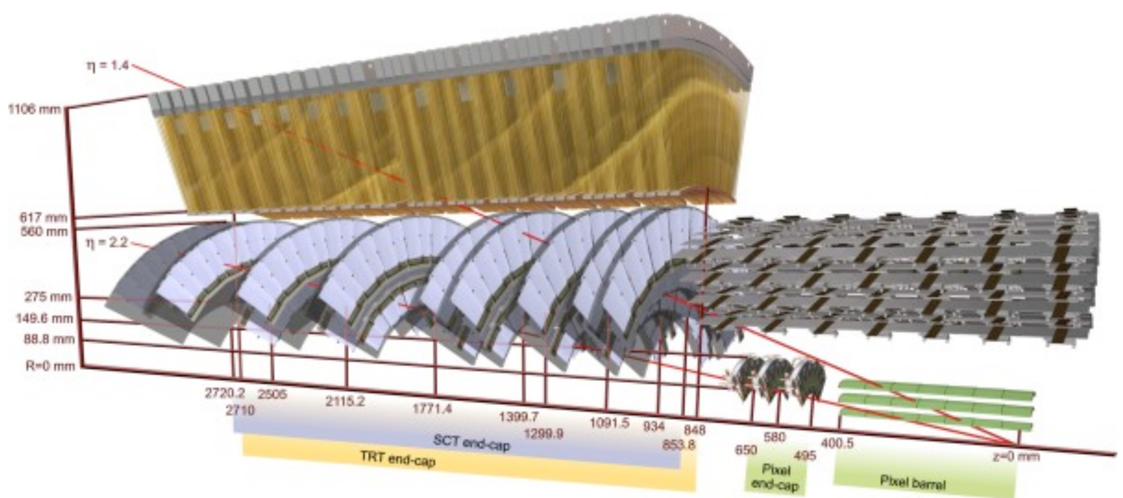






The ATLAS tracking system



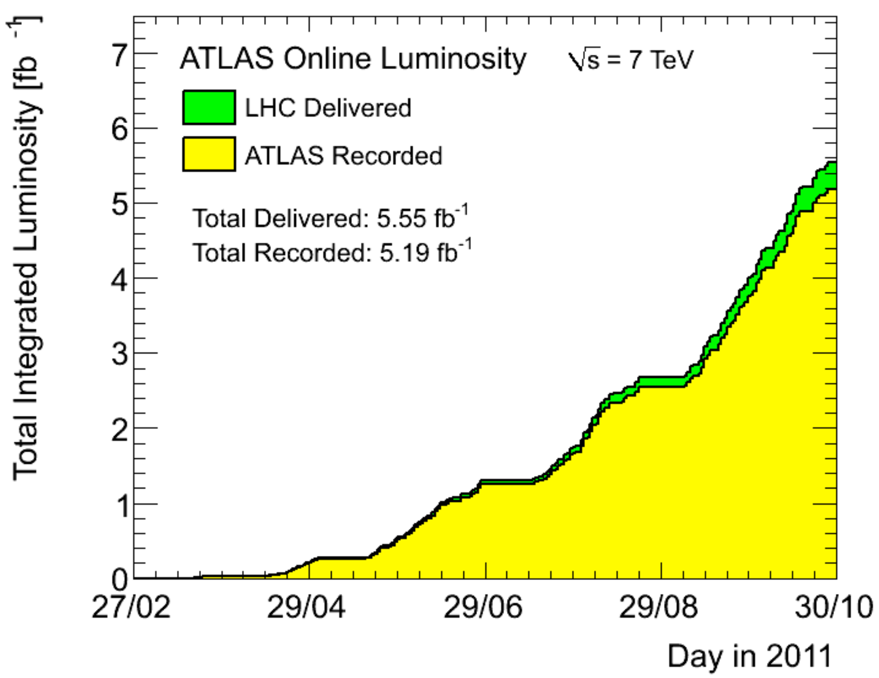


- the Inner Detector (ID) comprises 3 different subsystems embedded in a 2T axial field
  - *Pixel Detector* (silicon pixels)
  - ***S**emi-**C**onductor **T**racker* (SCT; silicon micro-strips)
  - ***T**ransition **R**adiation **T**racker* (TRT; gaseous proportional drift tube with transition radiation detection)
- each subsystem divided into
  - Barrel (B)
  - 2 End-cap regions (A,C)

	Channels	Resolution (X x Y) μm	<hits>/ track	Approx. Operational
Pixel	80 x 10^6	10 x 115	~3	96.4%
SCT	6.3 x 10^6	17 x 580	~8	99.2%
TRT	3.5 x 10^5	130	~36	97.5%

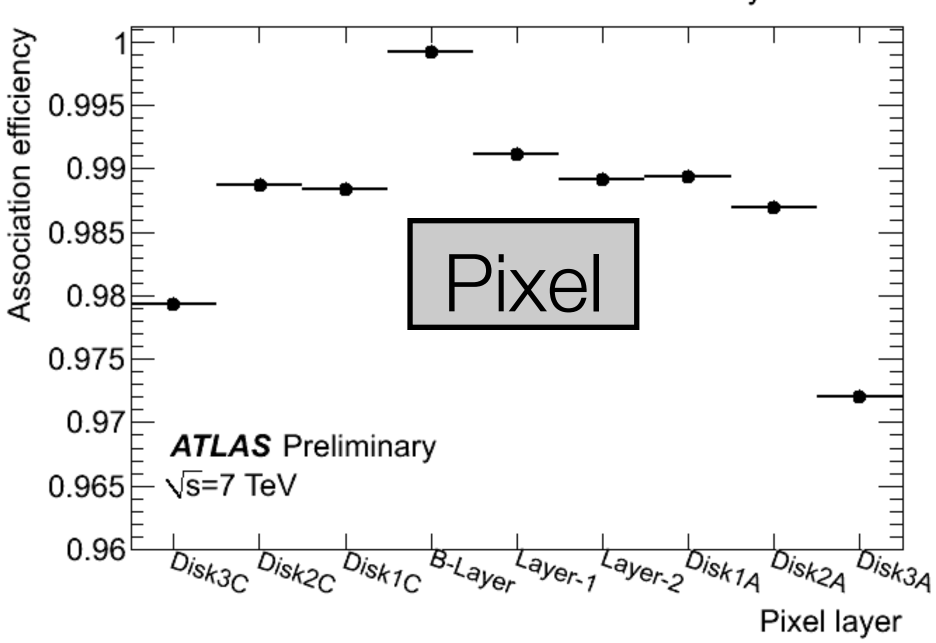
The ATLAS tracking system

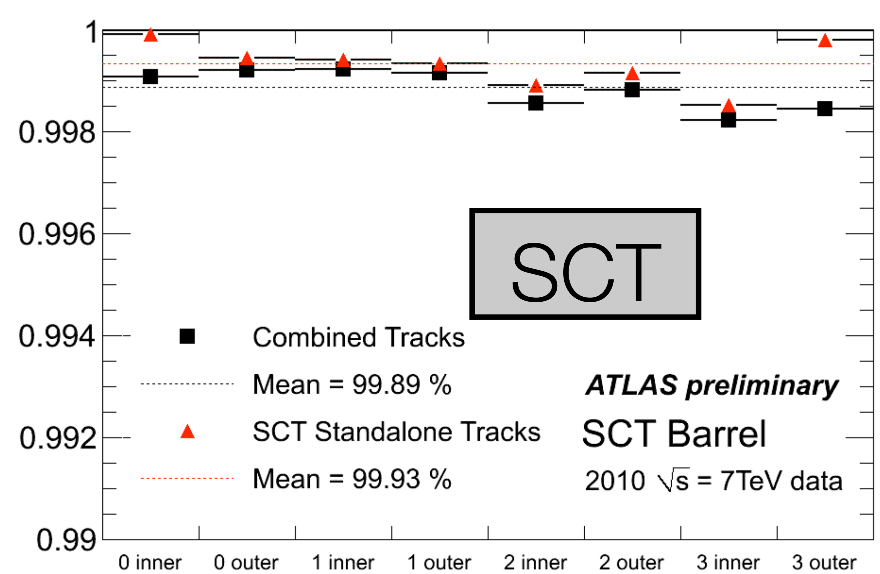
Integrated luminosity up to now

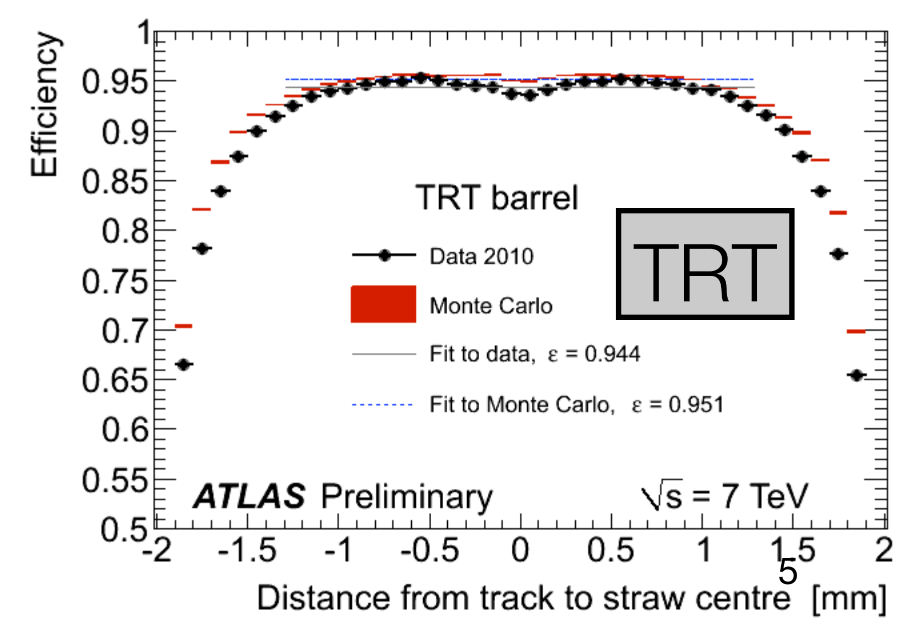


- requirements to cover ATLAS physics program
  - precision tracking at LHC luminosities with a hermetic silicon tracker covering over 5 units in η
  - Pixel detector for precise primary vertex reconstruction and to provide excellent b-tagging
  - reconstruct electrons and converted photons, including transition radiation in TRT for electron identification
  - tracking of muons combined with toroid Muon Spectrometer
  - fast tracking for high-level trigger
  - enable tau reconstruction
  - V0, b- and c-hadron reconstruction

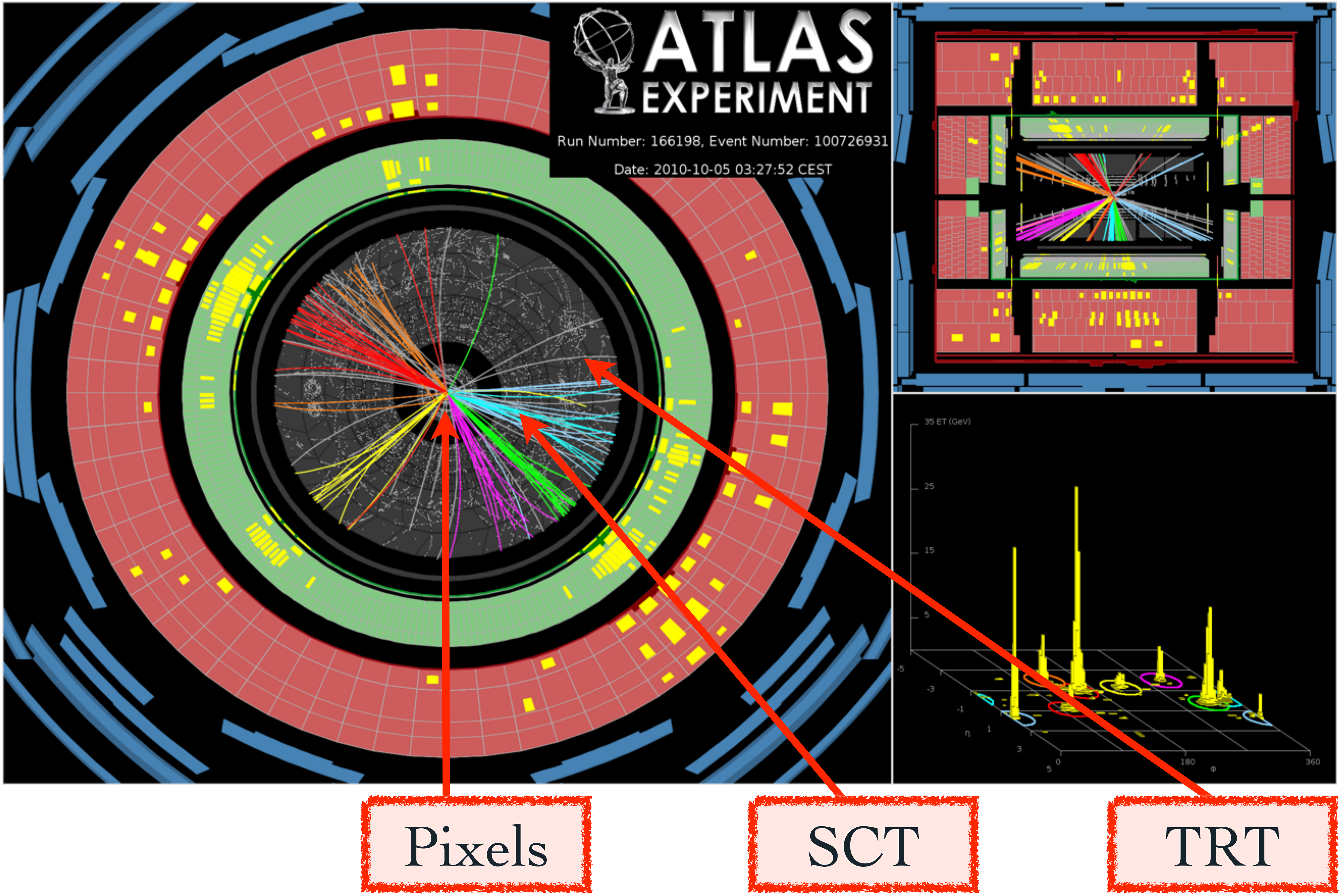
hit efficiency





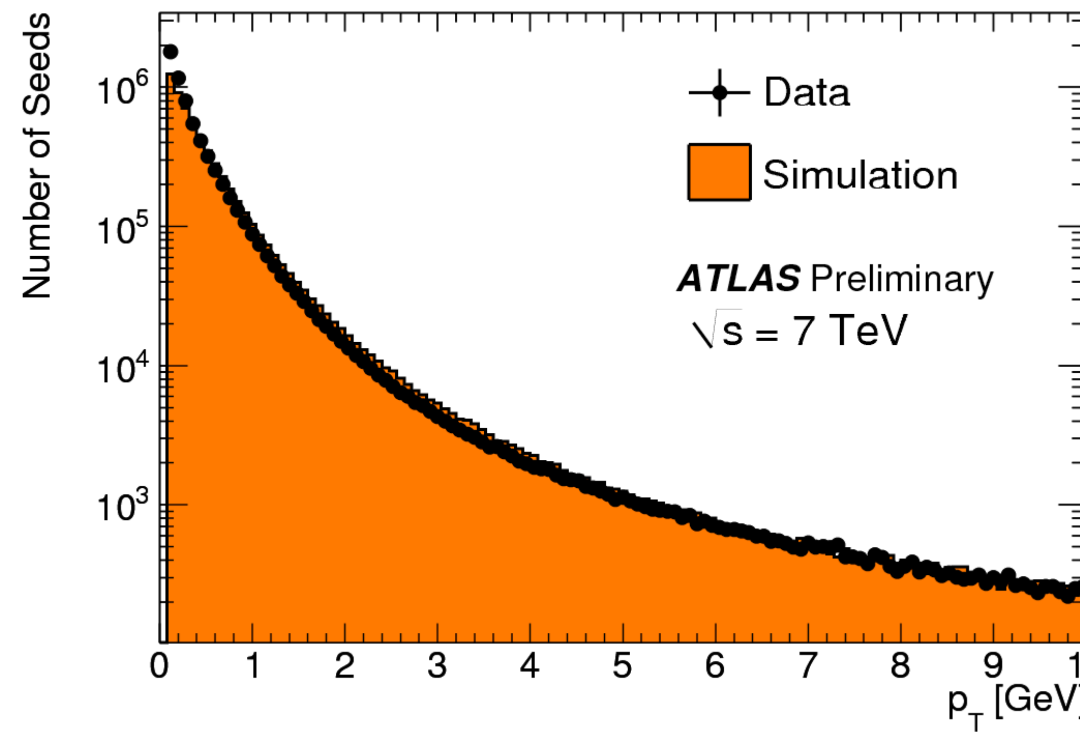


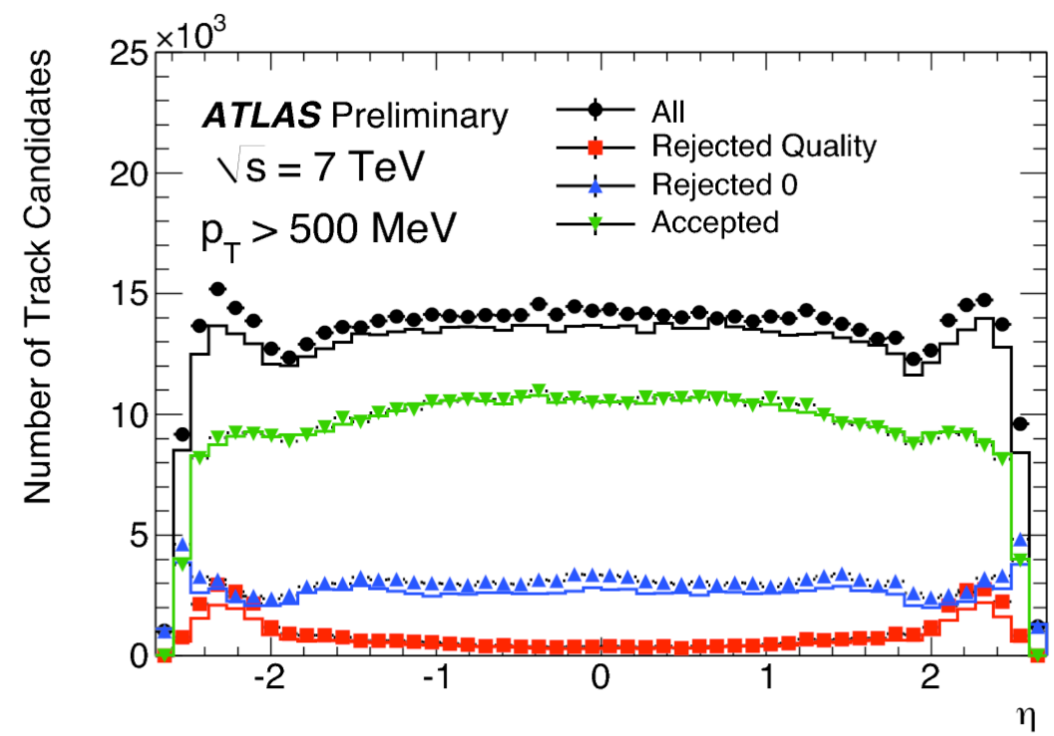
A nice ATLAS event display



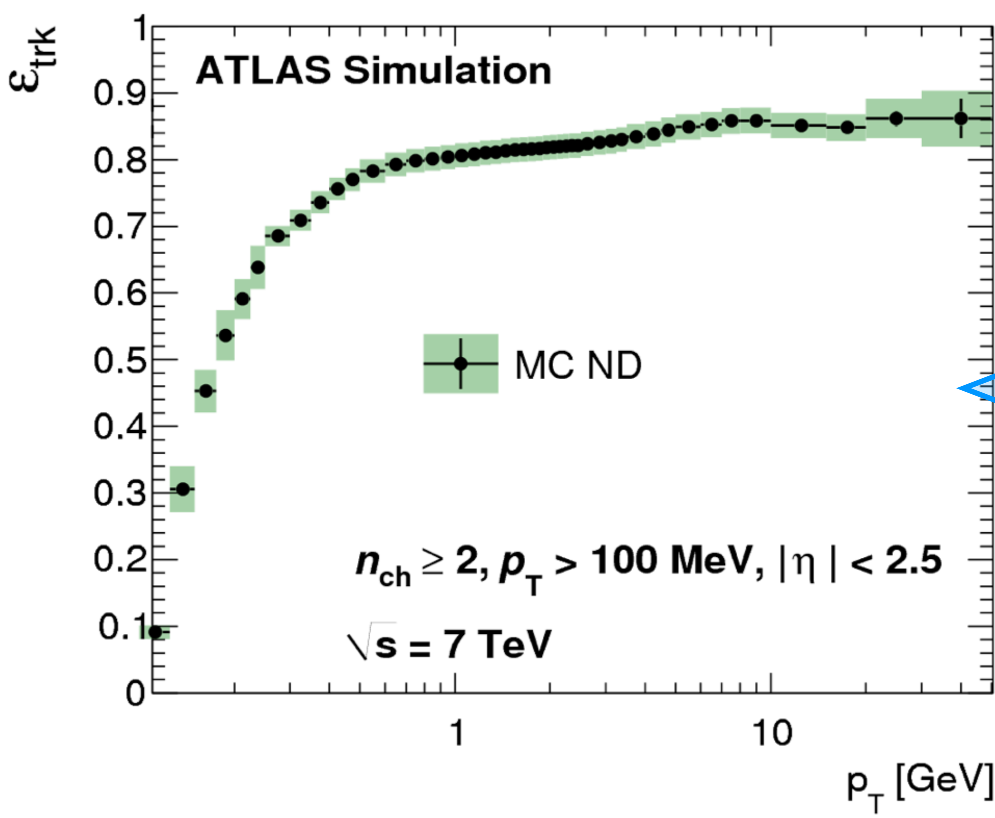
Pattern recognition

- two-stage pattern recognition
  - inside-out: pixel seeding + outward extension
  - outside-in: TRT track segment seed + inward extension
- study performance at different levels in reconstruction process
  - seeding, track candidate fitting, solving ambiguities
- a robust pattern recognition is a key ingredient for good tracking
  - changing conditions of noisy/dead modules
  - varying detector calibrations and alignment
- ***excellent performance!***

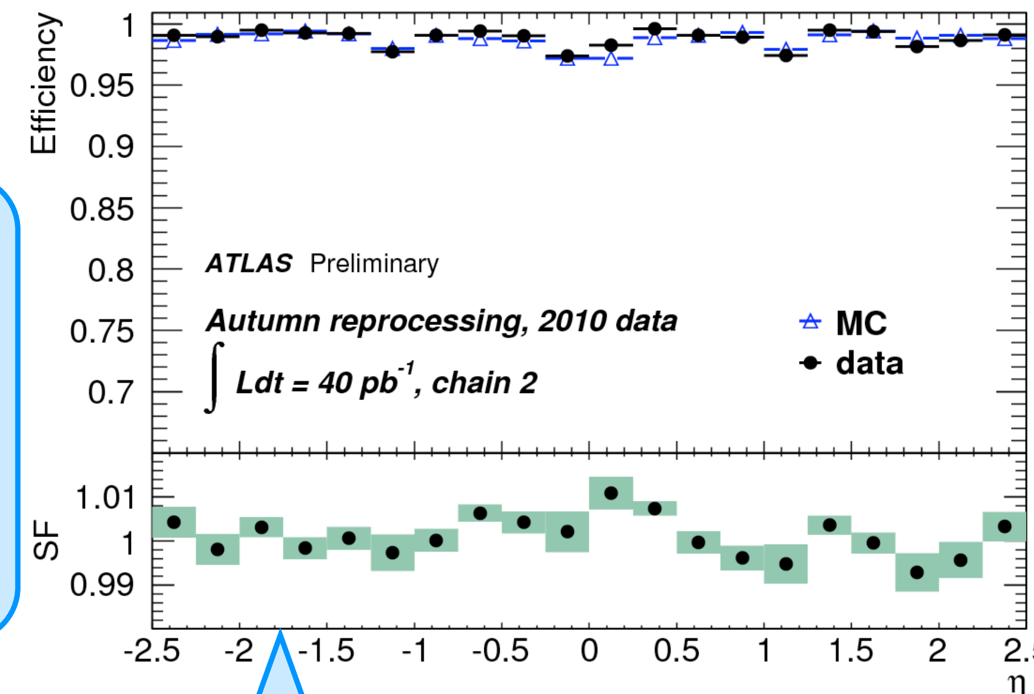




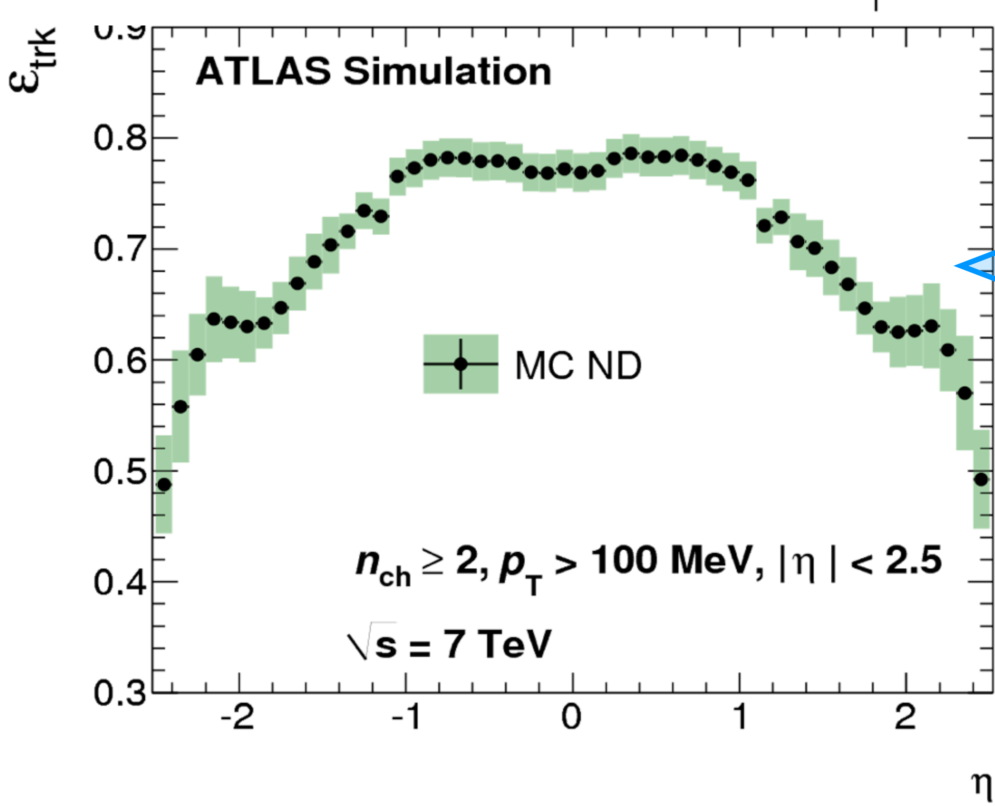
Track reconstruction efficiency



Track reconstruction efficiency vs p_T derived from non-diffractive MC



Comparison of the measured ID muon reconstruction efficiency as a function of |η| with MC prediction

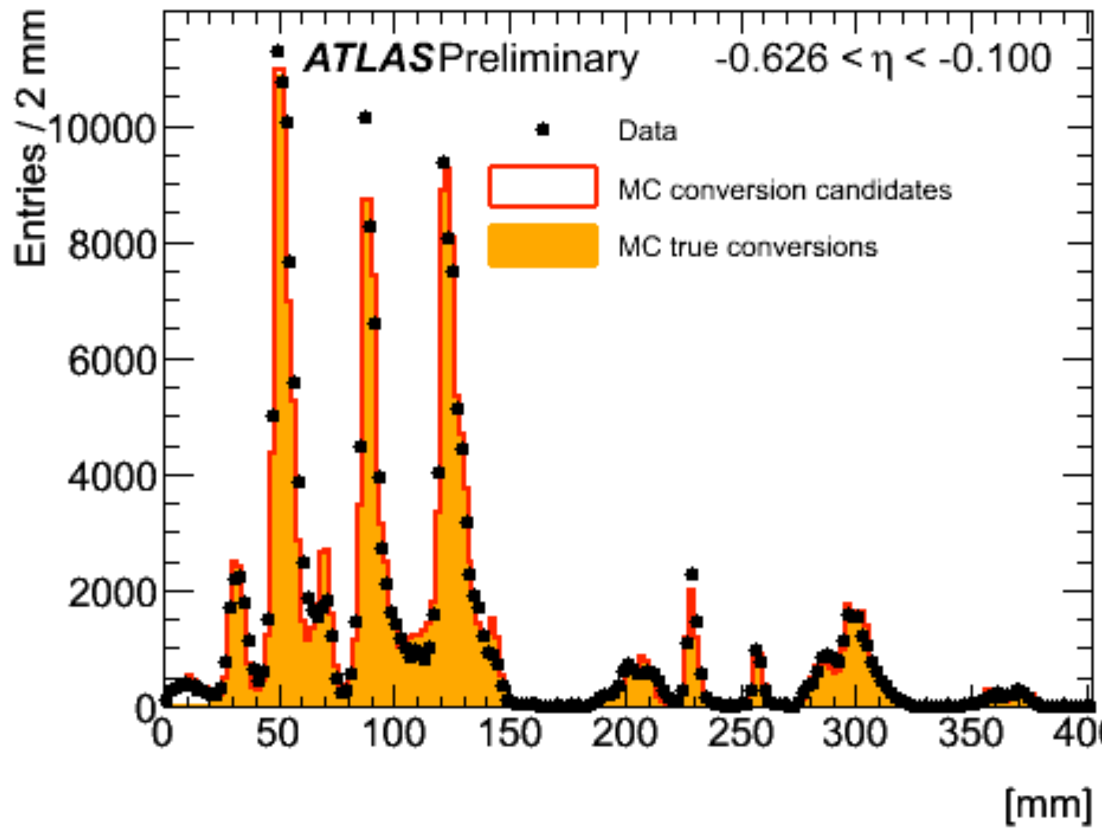


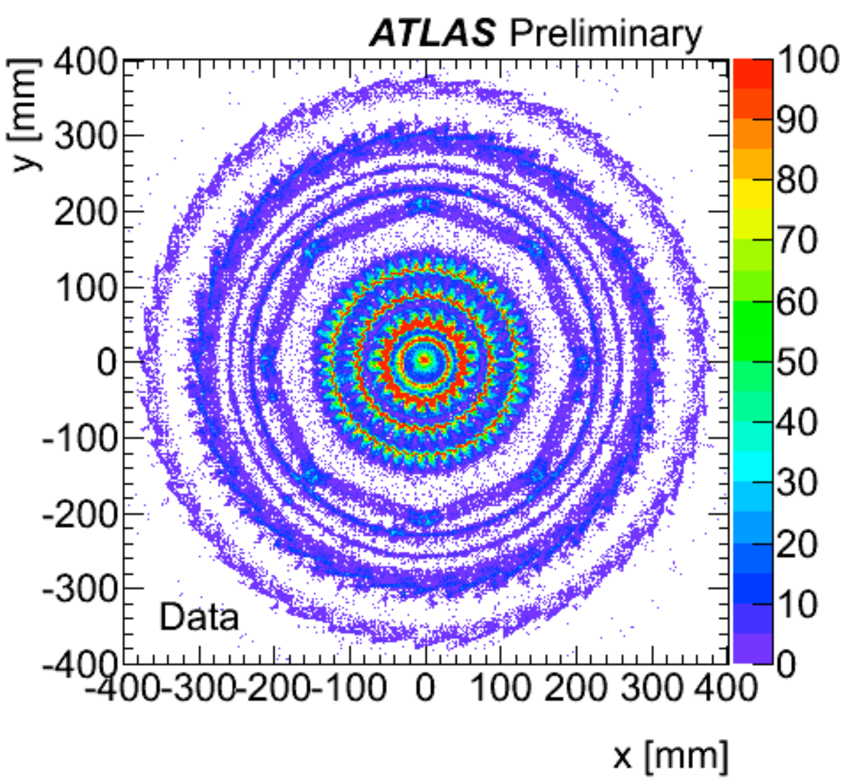
Track reconstruction efficiency vs |η| derived from non-diffractive MC

- tracking efficiency for muon measured data and near to 100%
- tracking efficiency for hadron derived from MC
  - inefficiency dependent on material distribution in the ID

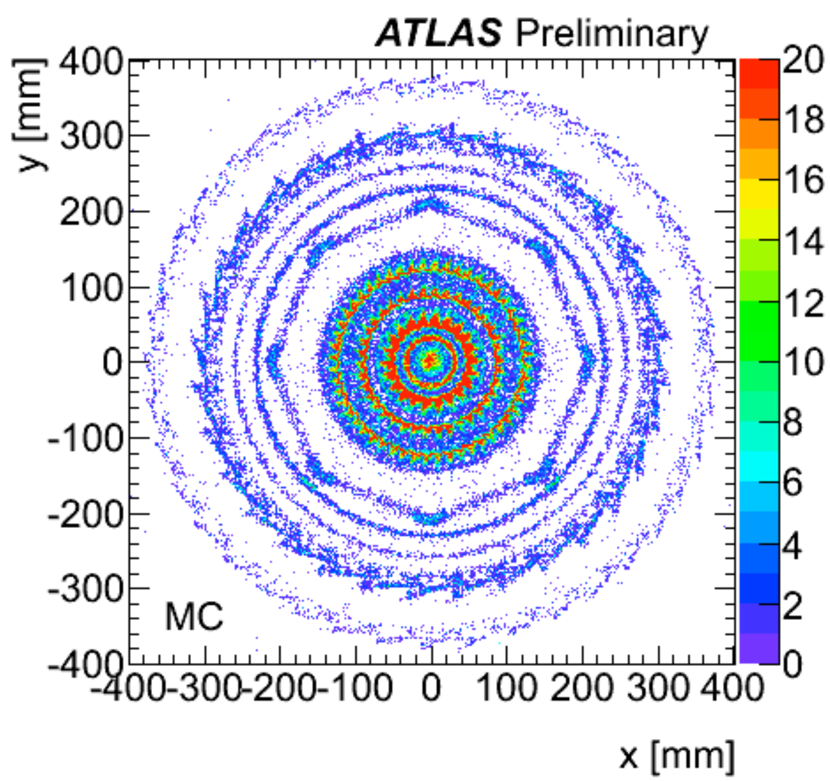
Material studies: photon conversions

- the precise knowledge of the material budget within the tracking volume is a crucial input for an excellent track reconstruction
  - photon conversions & hadronic interactions allow to study the material
- photon conversions mandatory for
  - very precise estimate of the material
    - calibrate w.r.t. known reference objects (e.g. beam pipe)
  - understand geometrical data/MC differences
    - supporting structures, cooling pipes, power cables, etc.

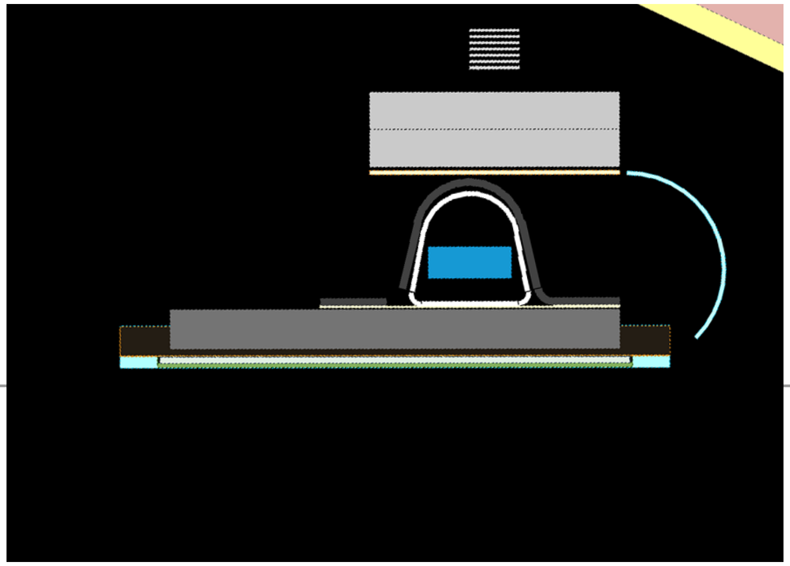




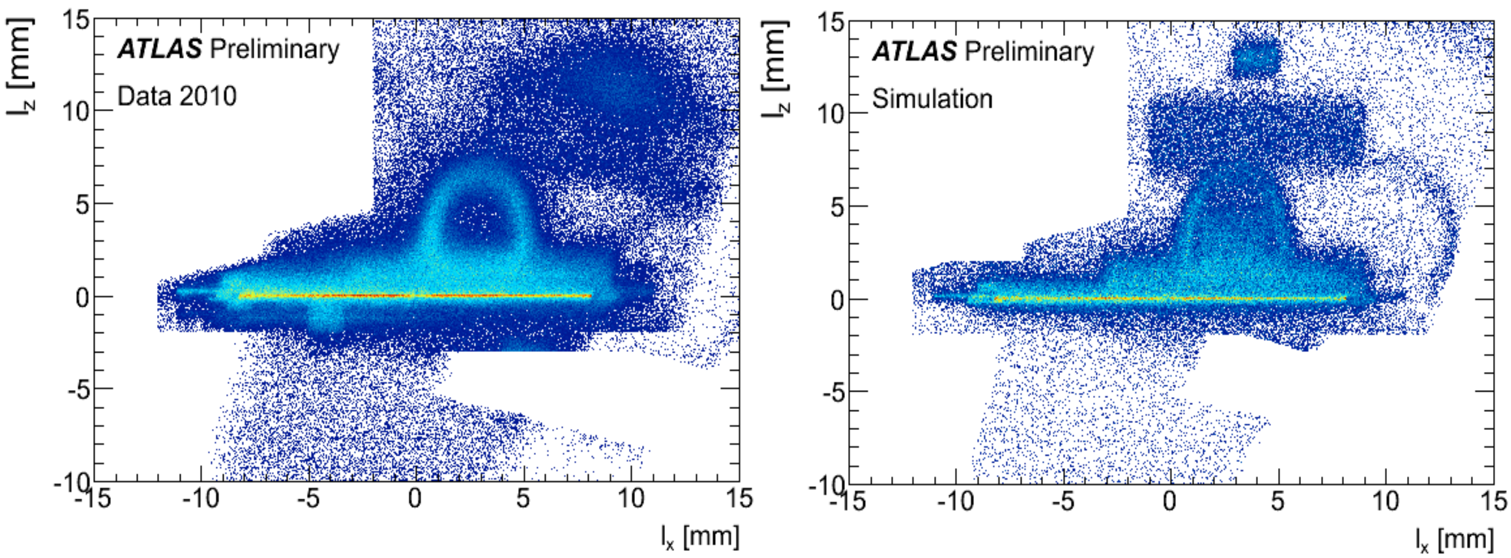
DATA VS **MC**

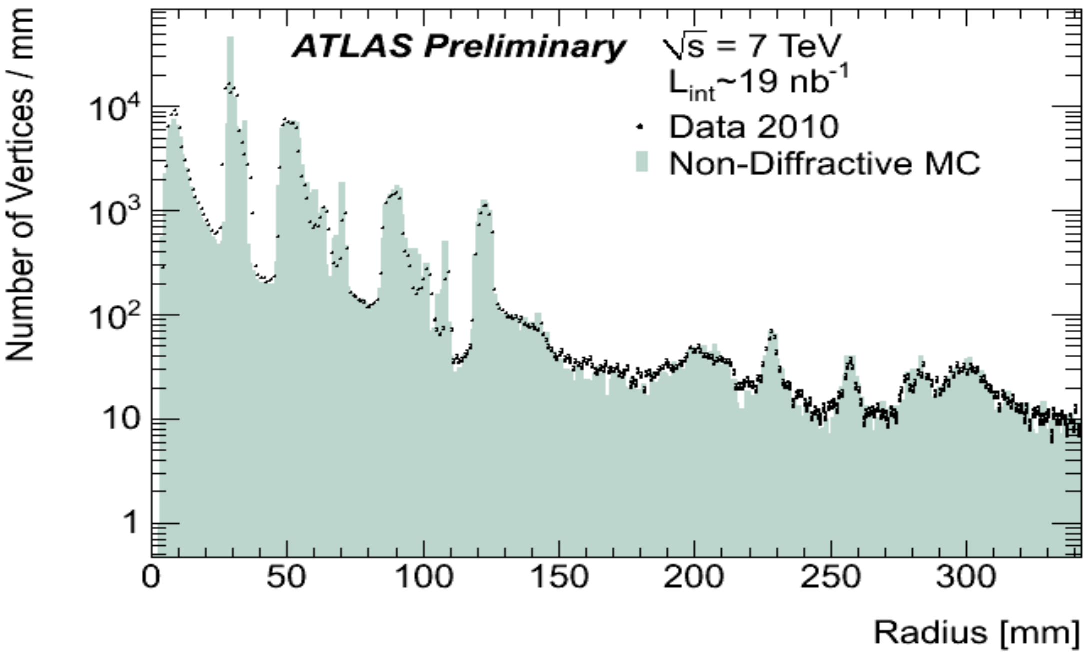


Material studies: hadronic interactions



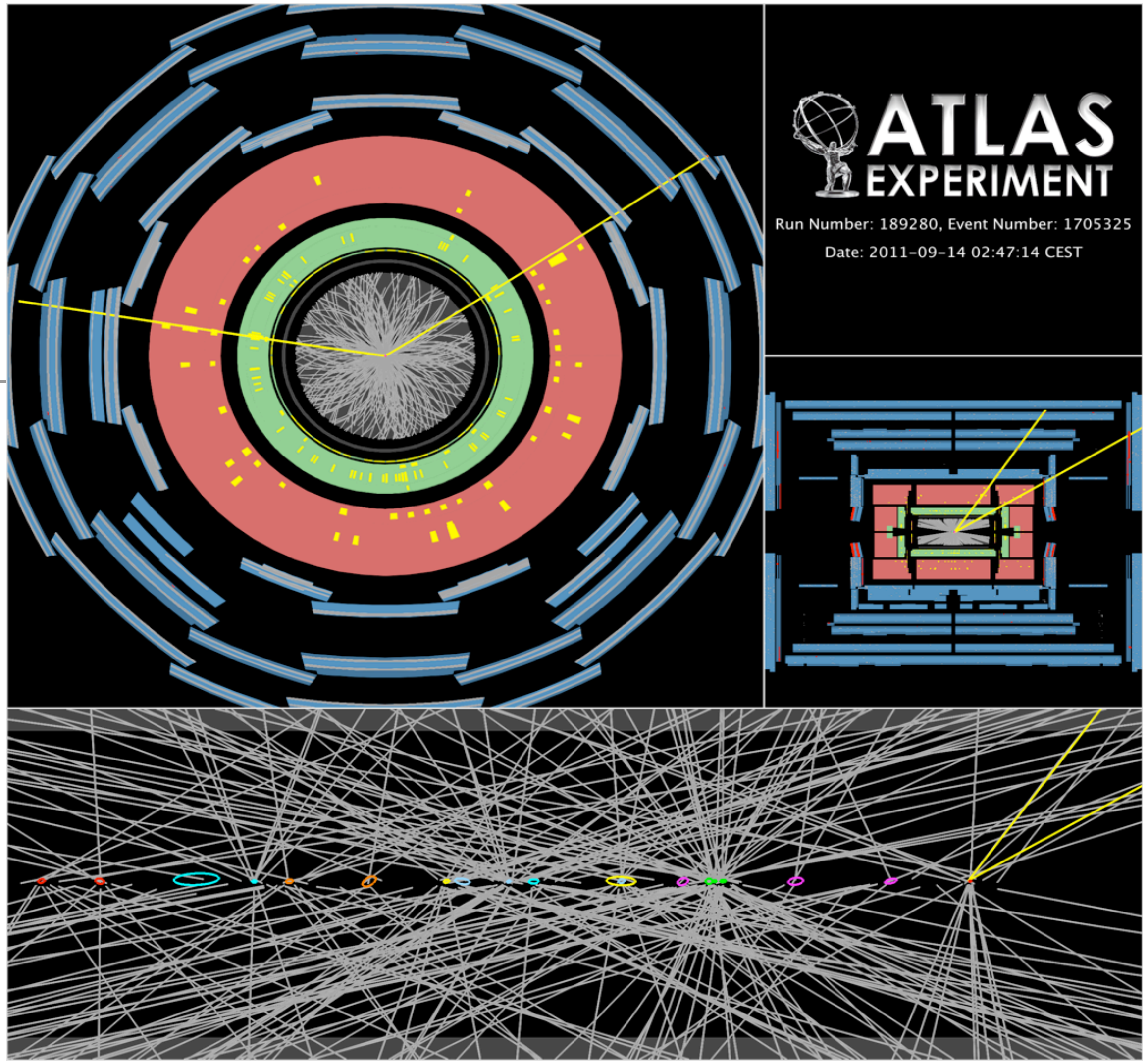
- reconstruction of hadron interaction vertices is a precise method for a detector tomography
  - reveal the true material
  - excellent vertex resolution: hadronic interaction, 200-300 μm in both R and z for vertices with R≤100 mm and ~1 mm for vertices at larger radii
- material uncertainty in simulation
  - constrained by sum of different techniques
    - conversions and hadronic interactions
    - study K^0 and other mass signals
    - stopping tracks, SCT extension efficiency
    - study of multiple scattering resolution term
  - estimated uncertainty
    - better than ~5% in the central region
    - at the level of ~10% in most of the end-caps



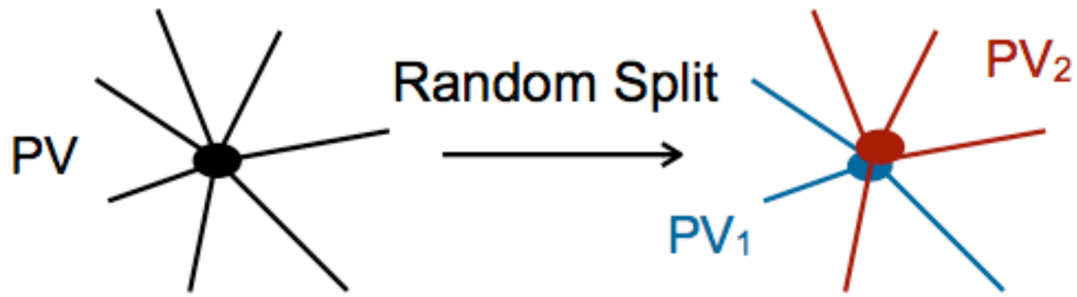


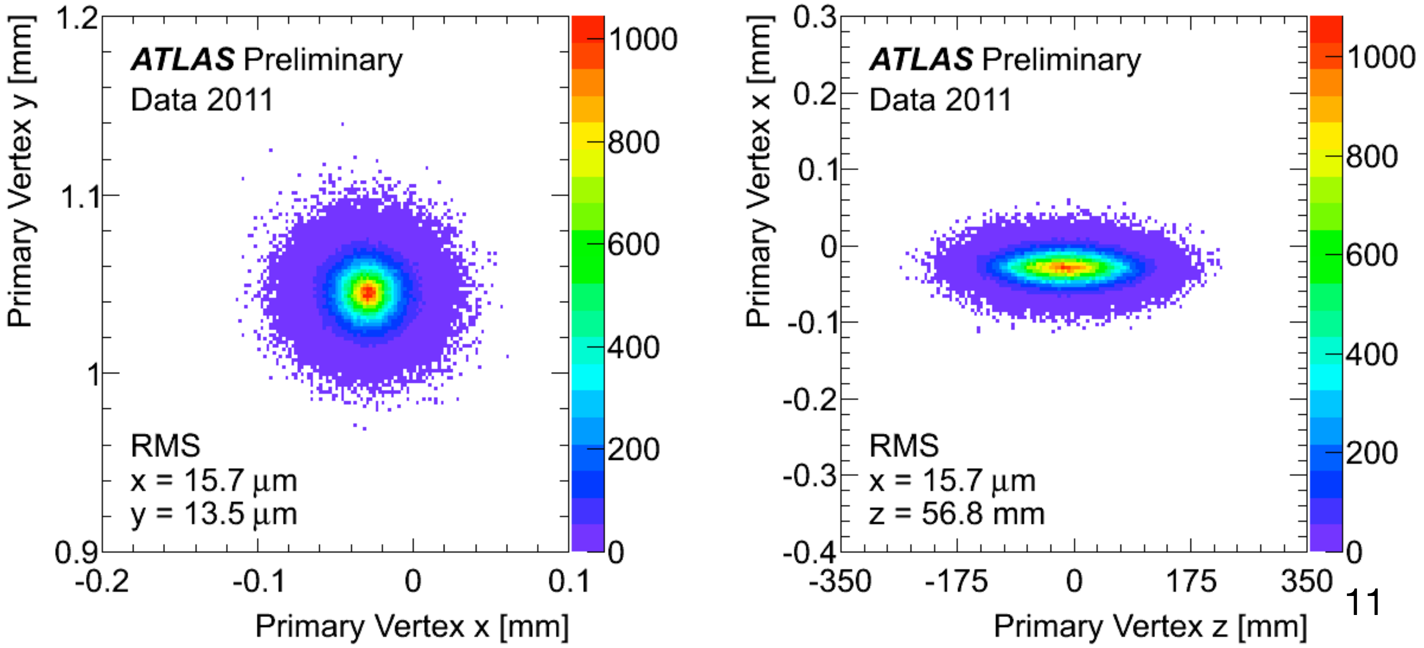
Vertex reconstruction

- an excellent vertex reconstruction is mandatory for many applications
  - primary vertex counting (luminosity), Jet-vertex fraction (pile-up), b-tagging, ...
- iterative vertex finder and adaptive fitter
  - find primary and pile-up vertices
- beam spot is routinely computed: online and offline
  - input to vertexing
- vertex resolution extracted from data
  - split vertex technique

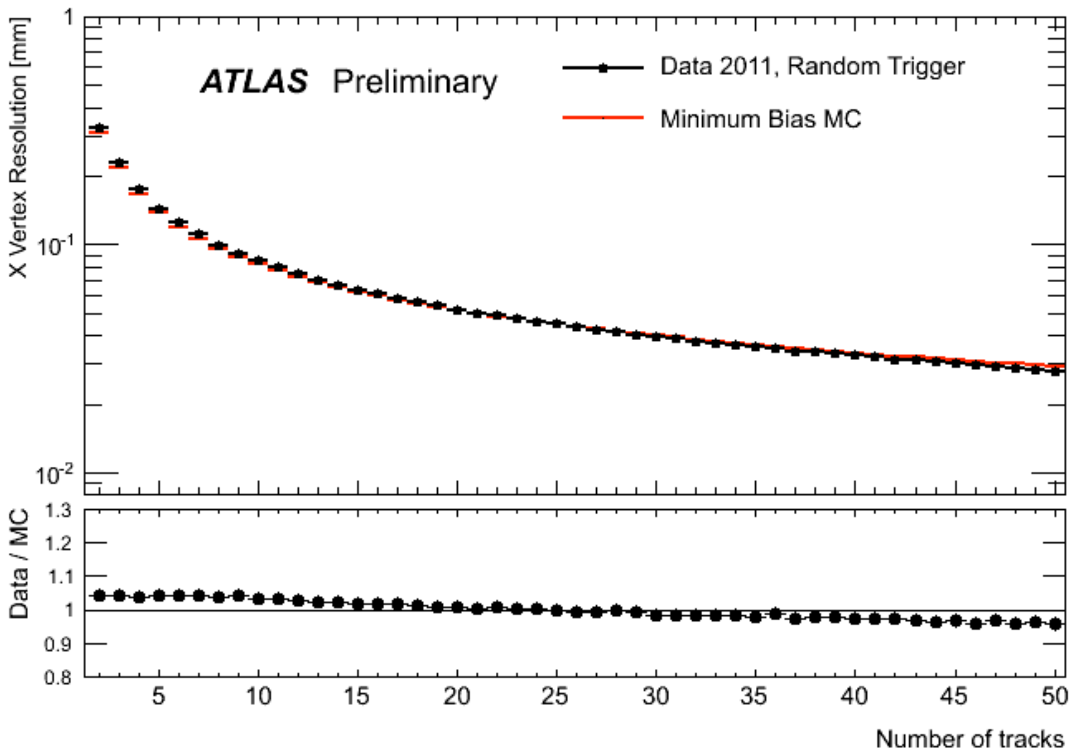


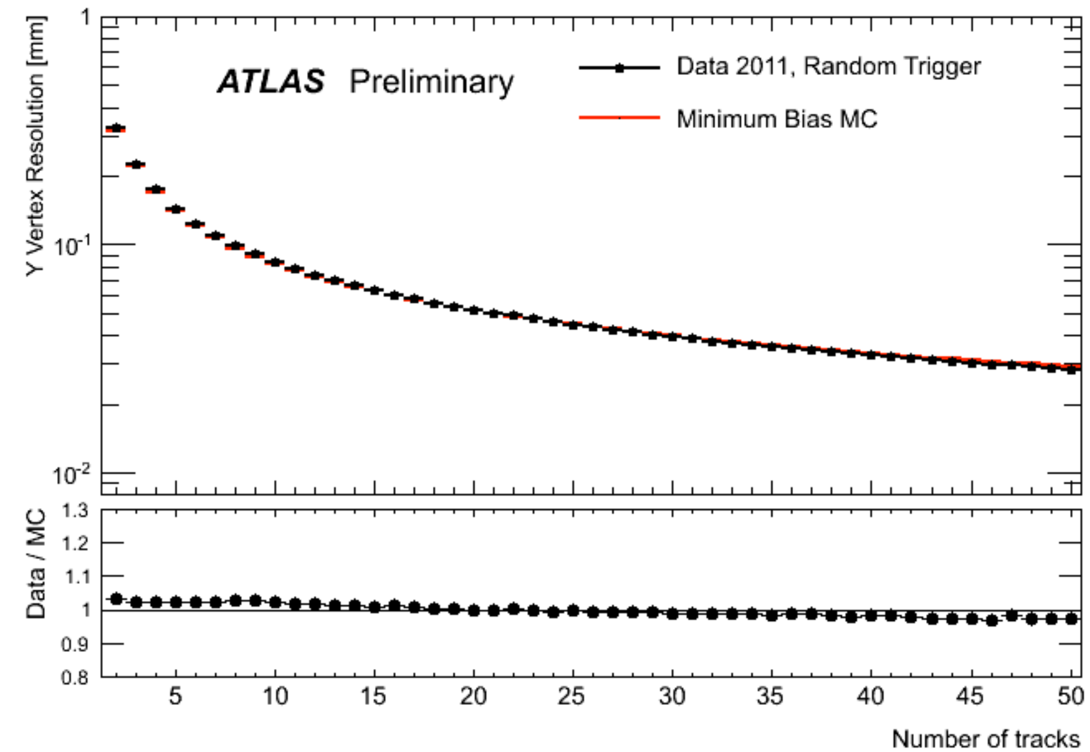
Z->μμ candidate with 20 reconstructed vertices

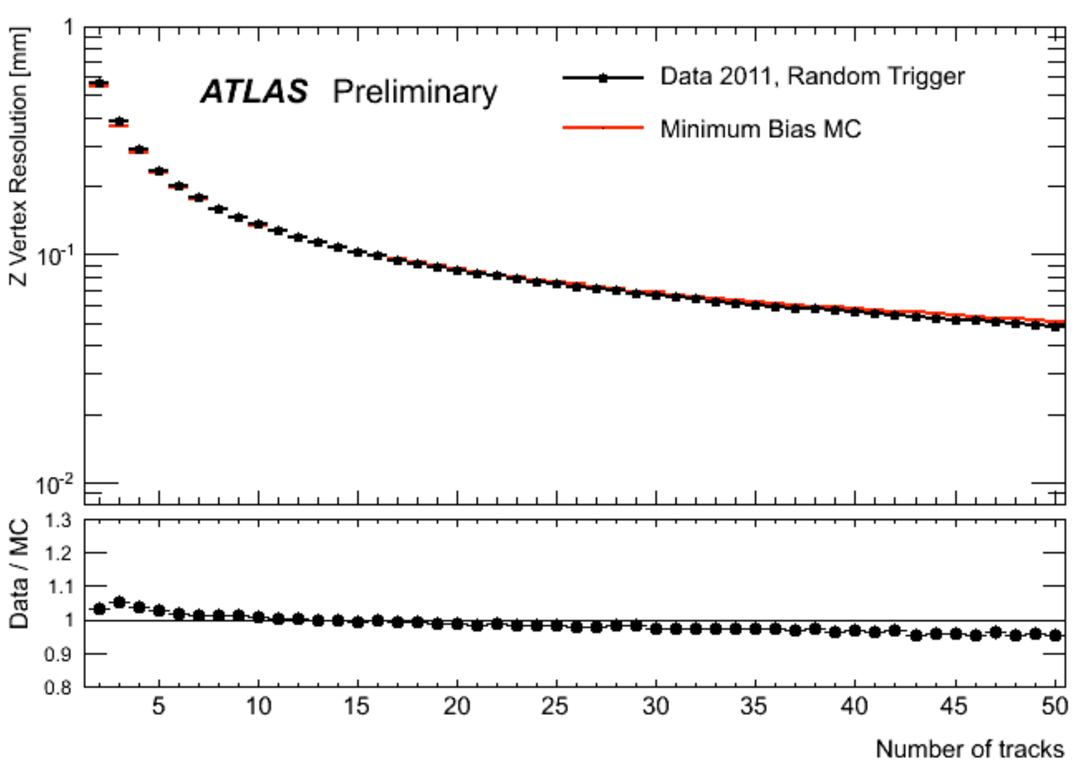




Vertex reconstruction



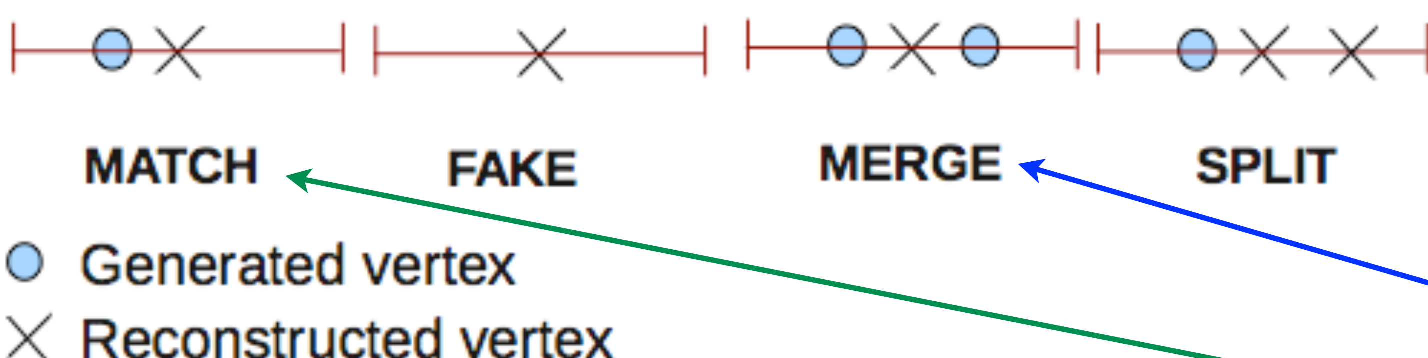




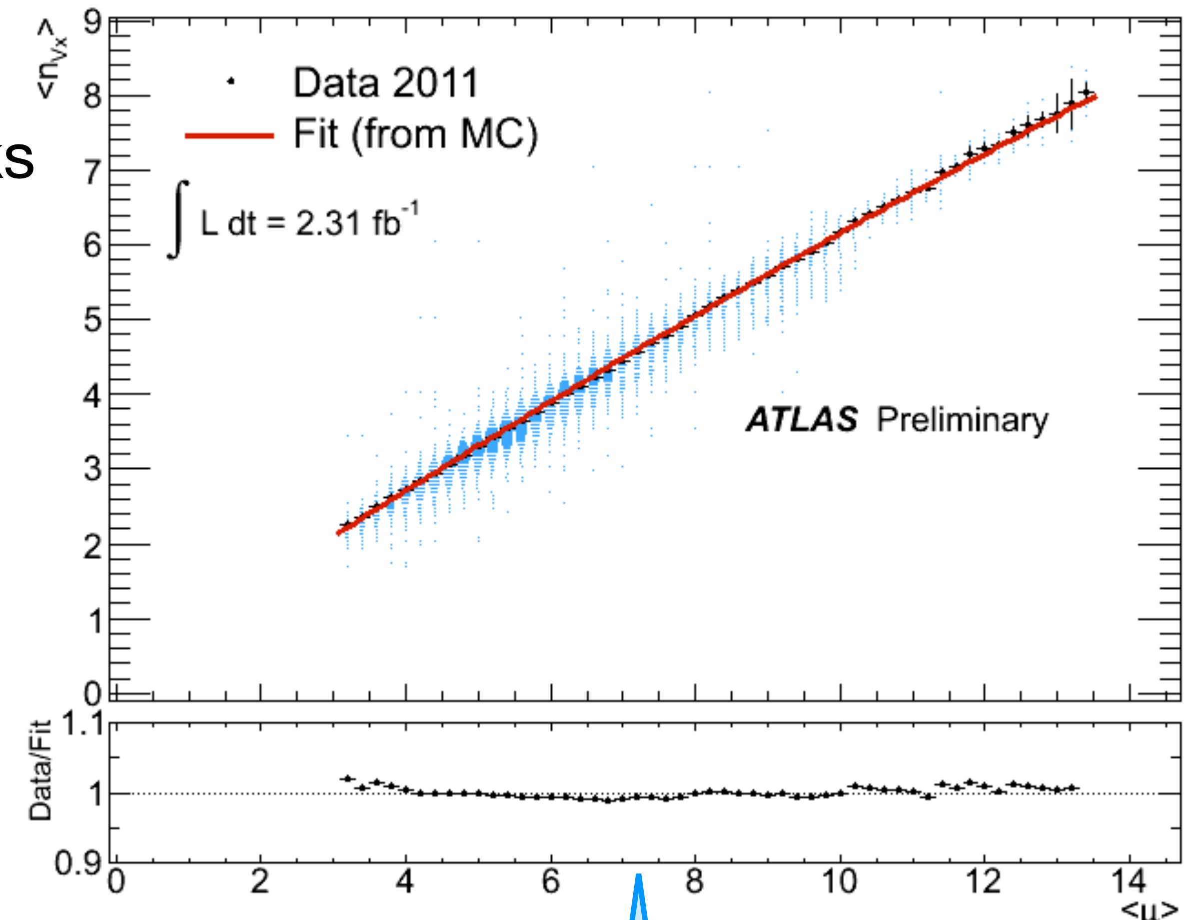
- vertex resolution shown as a function of track multiplicity
  - general good agreement
  - small trend of underestimated resolution for low number and overestimated for high number

Vertex reconstruction with high pile-up

- use simulation to study higher pile-up scenarios
- the reconstruction efficiency (= most of the tracks from correct interaction) is sample dependent
  - nearby vertices can “shadow” a clean reconstruction
  - fake-rate will become important for μ~40
- these effects have been studied in simulation



- vertex multiplicity in data well agrees with expectation
- expected vertex reconstruction efficiency: ~95% for non-diffractive events and ~10% for diffractive ones

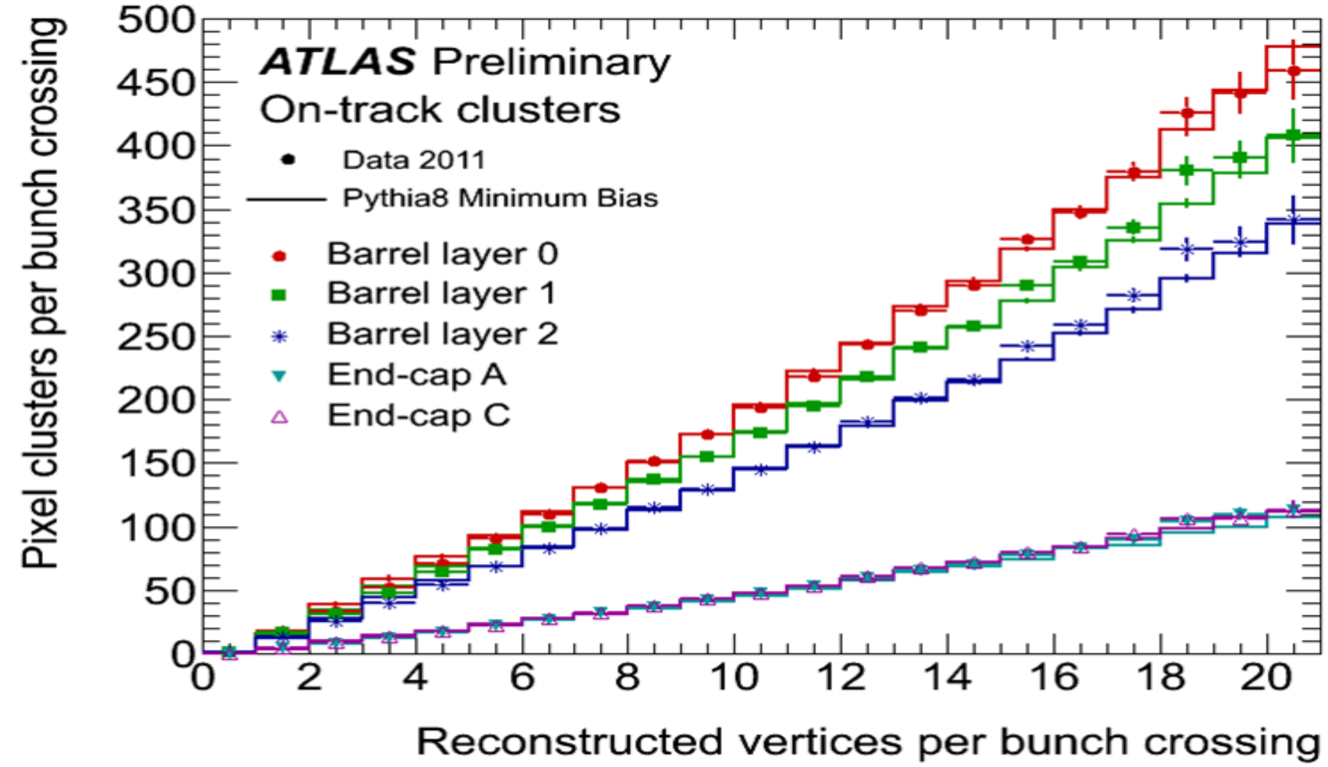


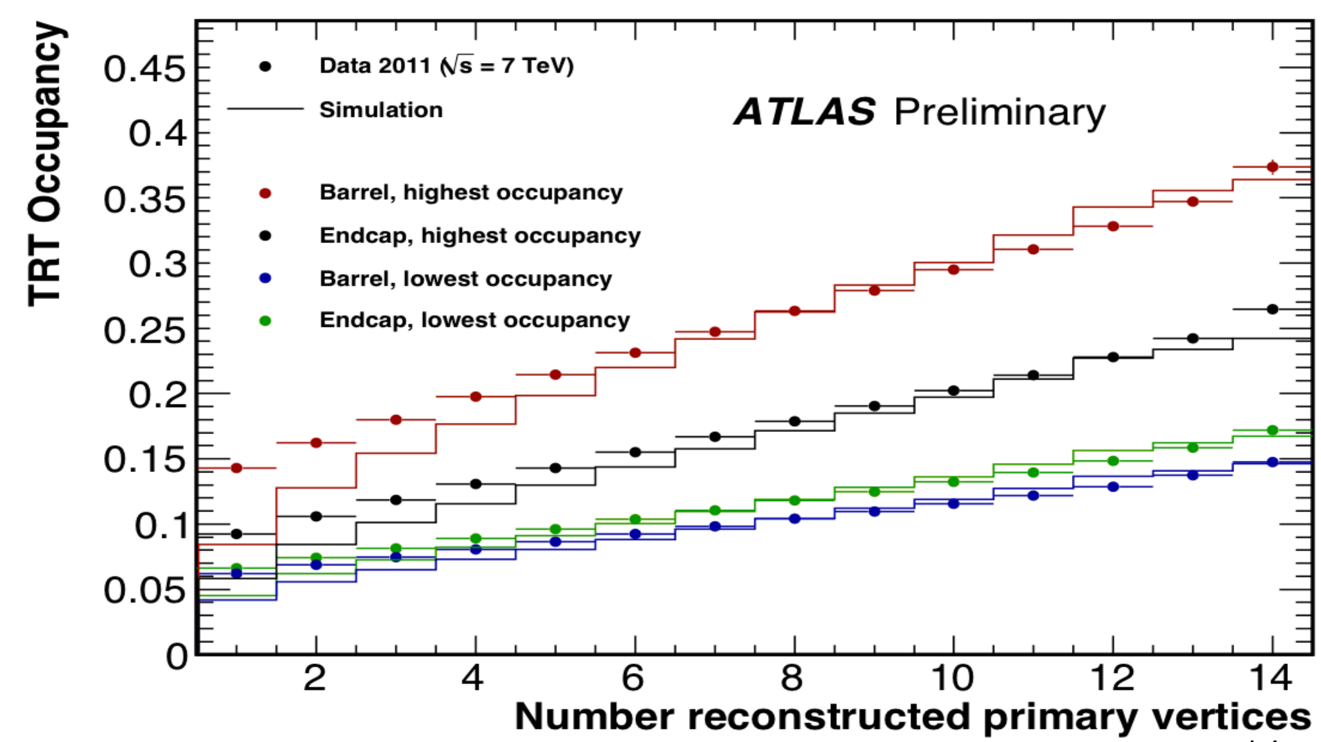
Fit function

$$\langle n_{Vx} \rangle = p_0 + p_1\mu + p_2\mu^2$$

Inner Detector with high pile-up

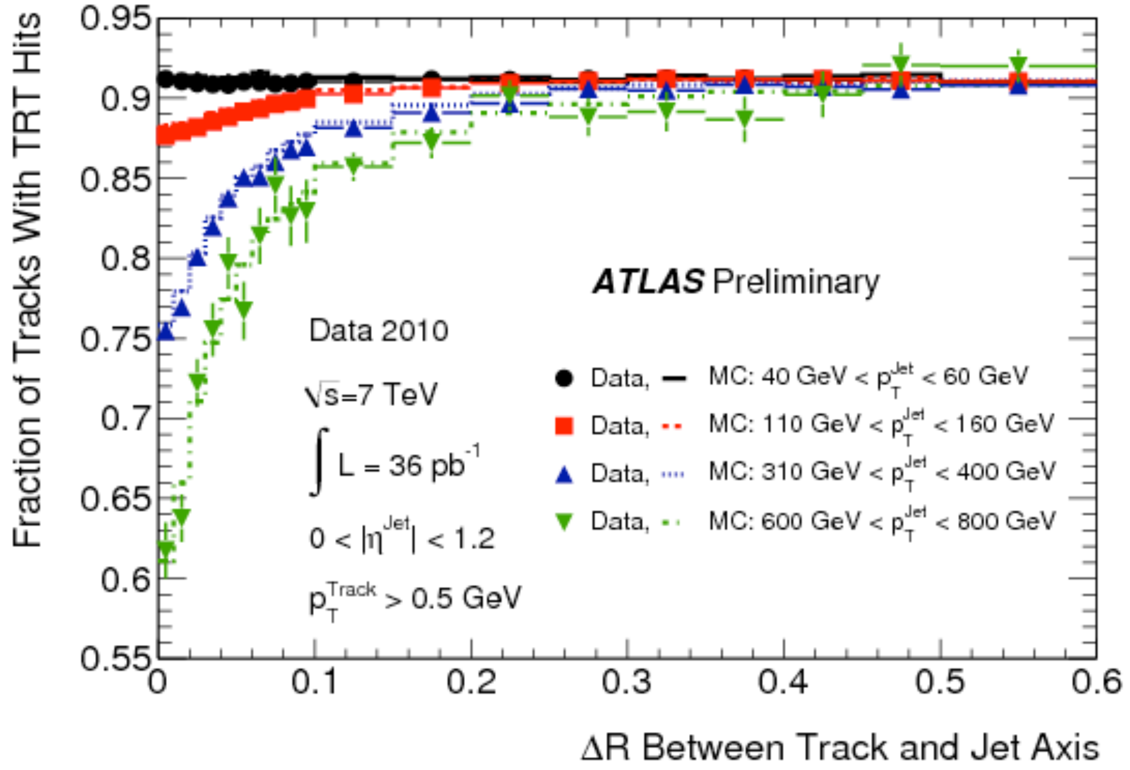
- event pile-up is a reality
  - in 2011 we reached 50% of design levels, but at 50 ns bunch spacing
  - may expect 2-3 times increase in 2012
- tracking performance depends on isolation of tracks/hits
- for higher occupancy not possible to have a unique association of hits
- important to understand how the number of hits is growing with increasing number of additional pile-up interactions
- ID tracking mostly sensitive to in-time pile-up
  - out-of-time pile-up affects TRT performance

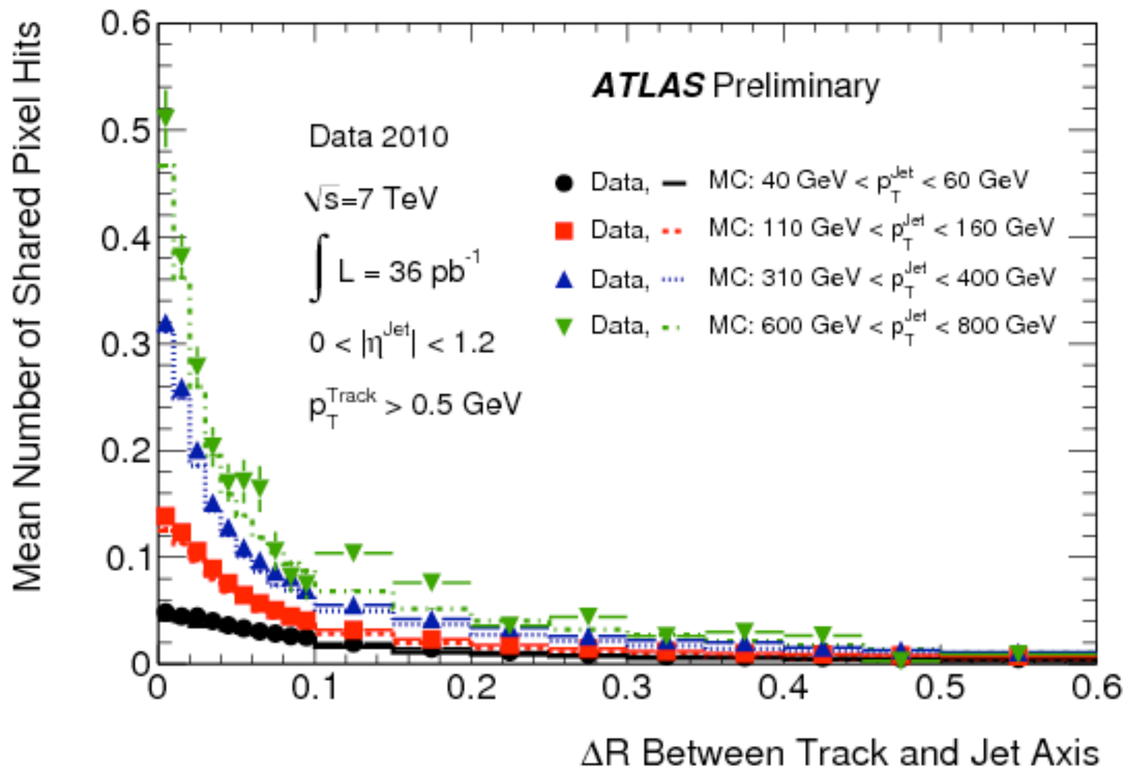




Core of jets

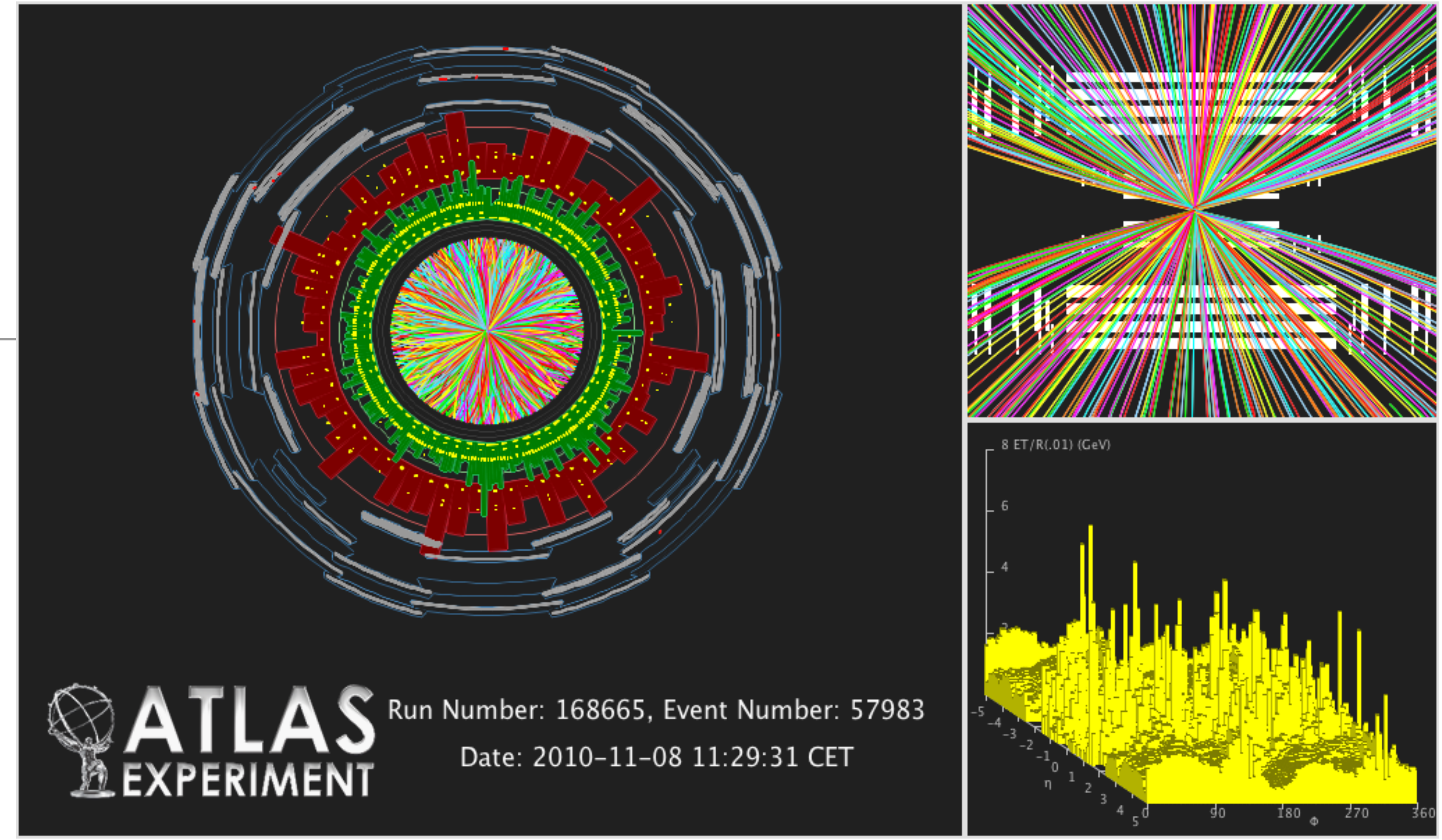
- unique hit-to-track association is more complicated in dense region,leading to a higher probability of shared hits
  - need improved cluster algorithms to reduce the fraction of shared hits
  - at the same time the fraction of tracks with TRT association is reduced
  - the effect is shown for four different jet momentum regions
  - MC reproduce well the behavior of the data

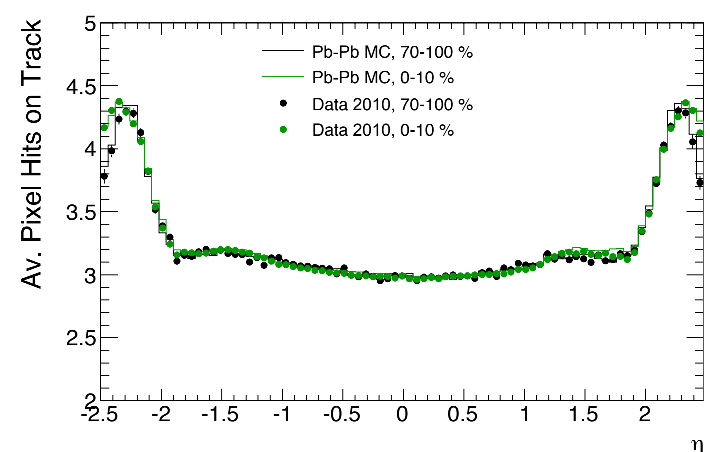


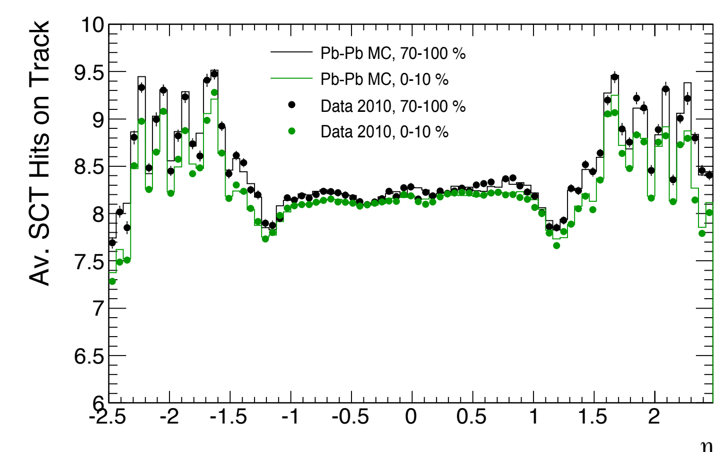


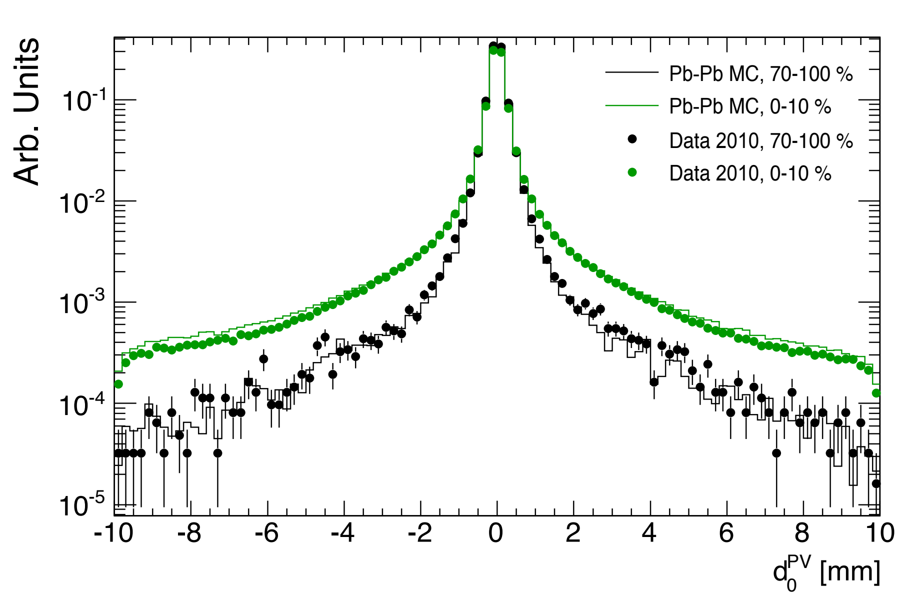
Heavy ion tracking

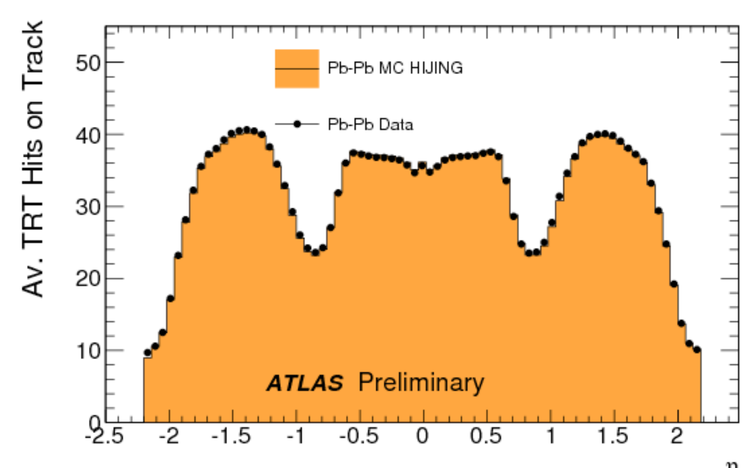
- heavy ion conditions give also the opportunity to study tracking under high occupancy conditions
- tracking in heavy ion conditions is quite challenging
  - very high track multiplicity
  - test bench for studying tracking performance in future very high pile-up p-p runs
  - tighten hit requirements in order to keep the fake rate low
- overall tracking performance is excellent!





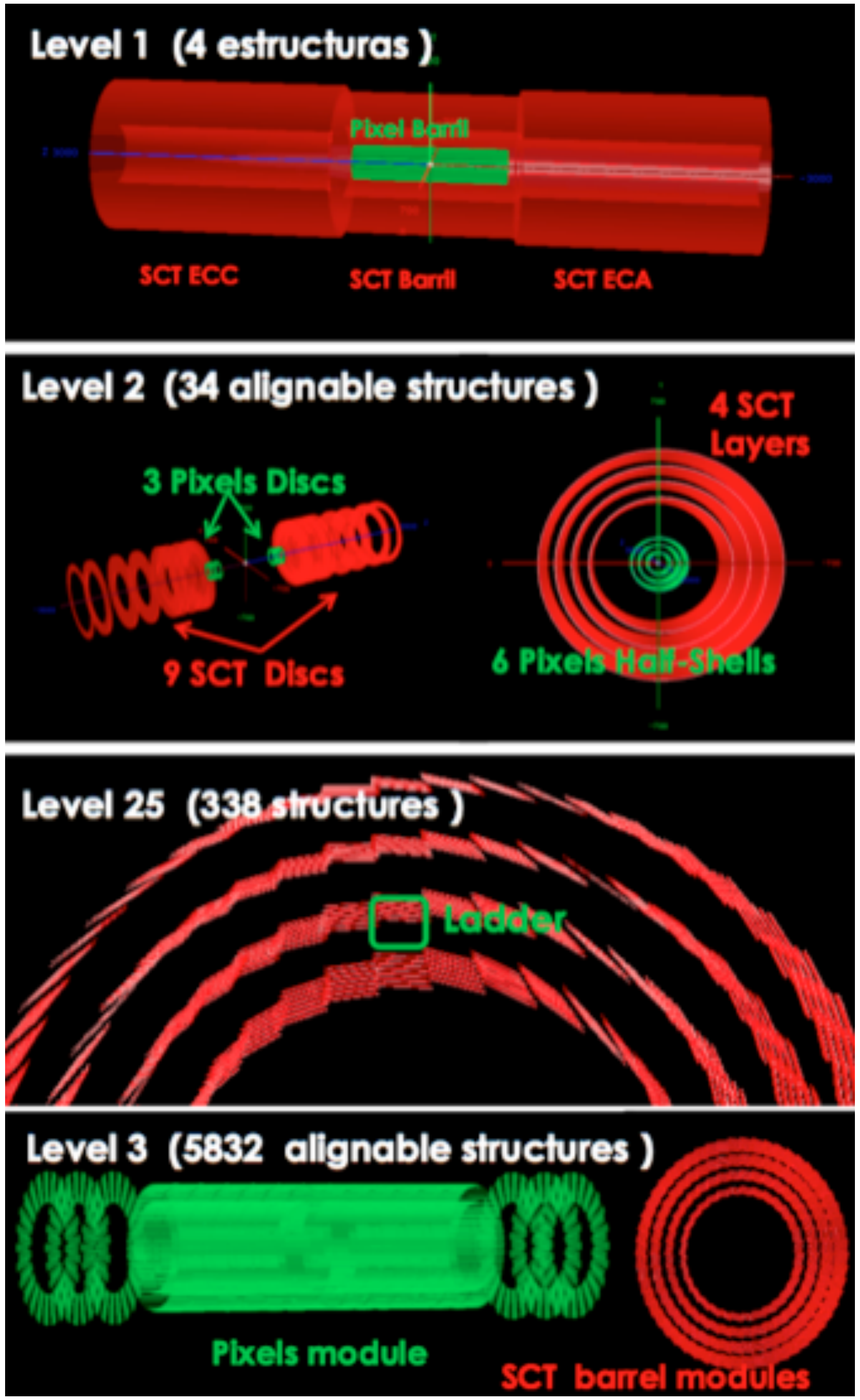






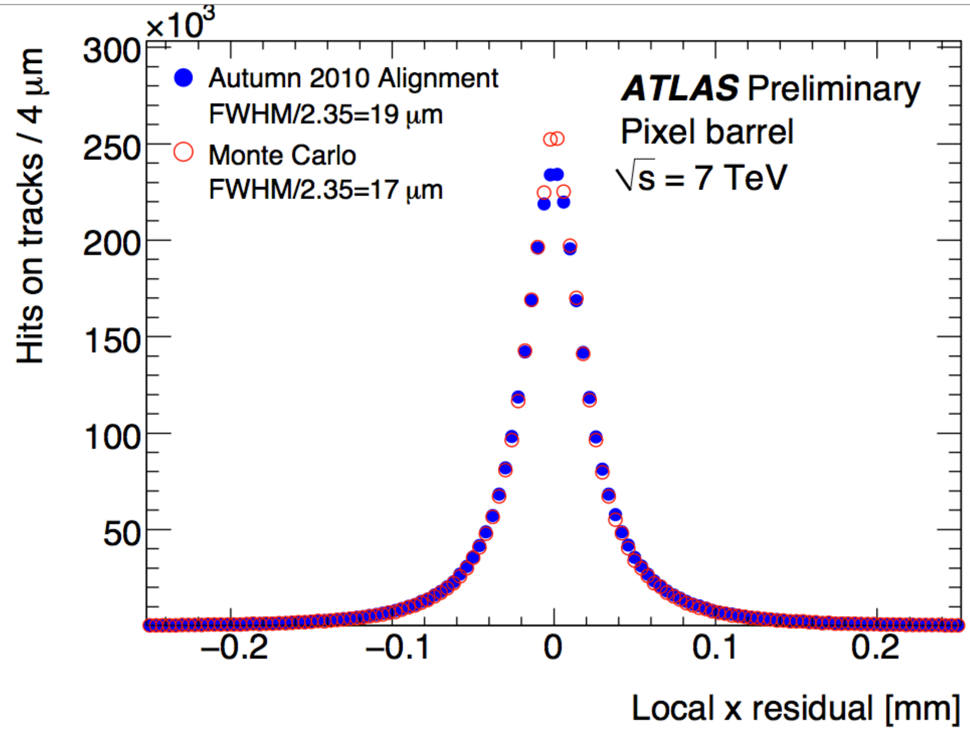
Alignment

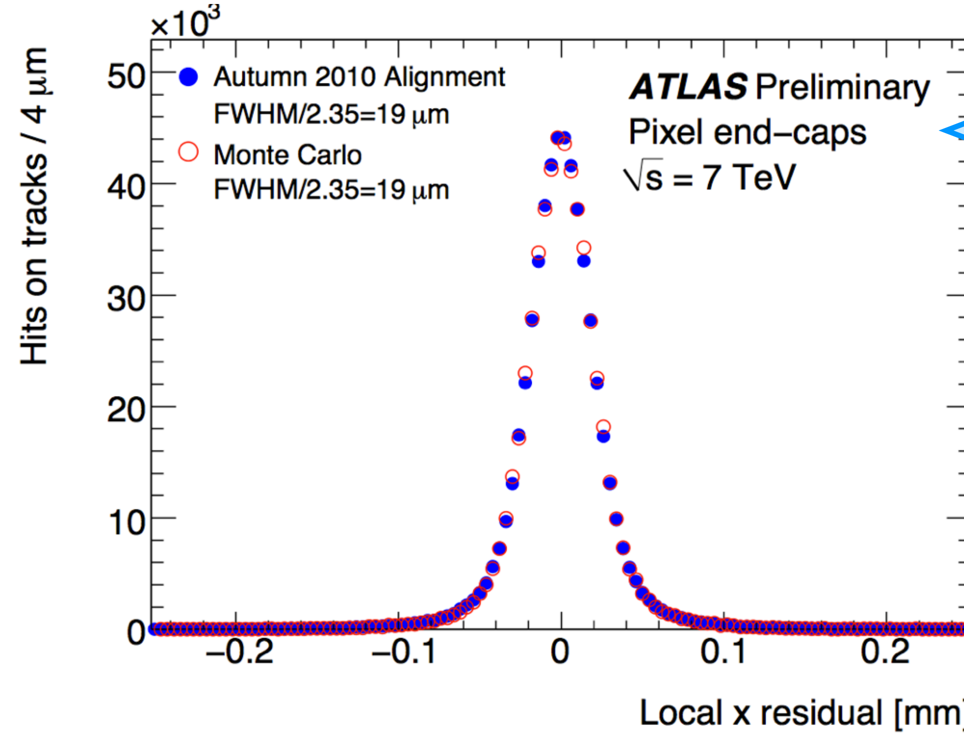
- the limited knowledge of the relative position of detector pieces should not lead to a significant degradation of the track parameter beyond the intrinsic tracker resolution, nor introduce biases
- high accuracy needed for precision physics measurement
  - e.g. a 10-15 MeV precision in W mass requires a ~1 μm alignment
- using calibration stream (isolated tracks with p_T>9 GeV) and cosmic events during empty proton bunches
- Alignment parameters are determined iteratively in three steps with increasing number of aligned substructures
  - proceed from large structures to module level with increasing granularity of structures and degrees of freedom
    - barrel and/or end-caps
    - barrel layers and end-cap disks/wheels
    - silicon modules and TRT wires



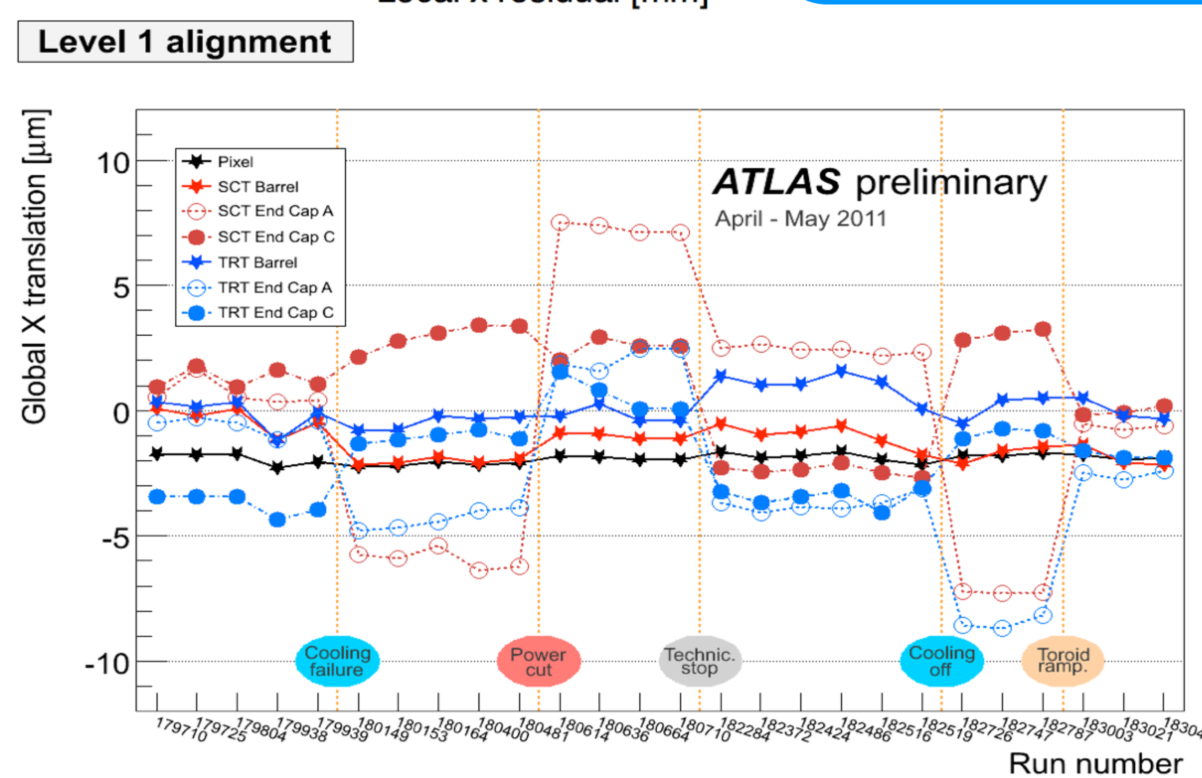
Alignment results

- Residuals (global χ^2 minimization)





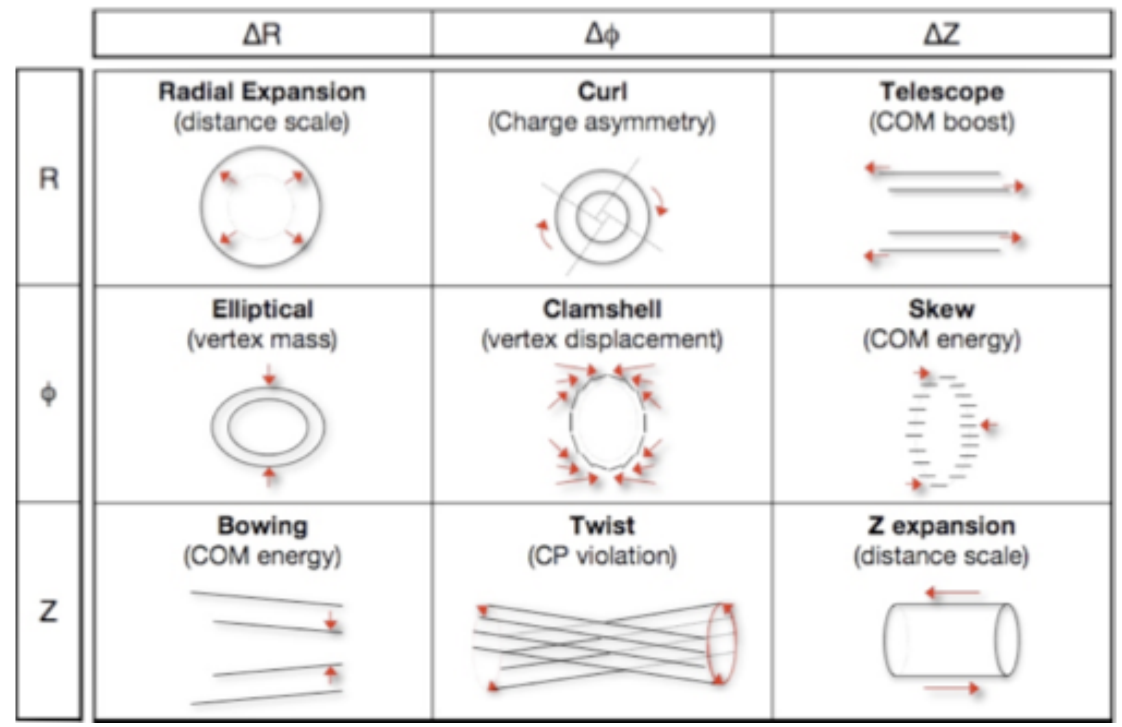
distribution of local x residuals of the pixel modules. Used isolated tracks with p_T>2 GeV. The local x coordinate of the pixels is along the most precise pixel direction

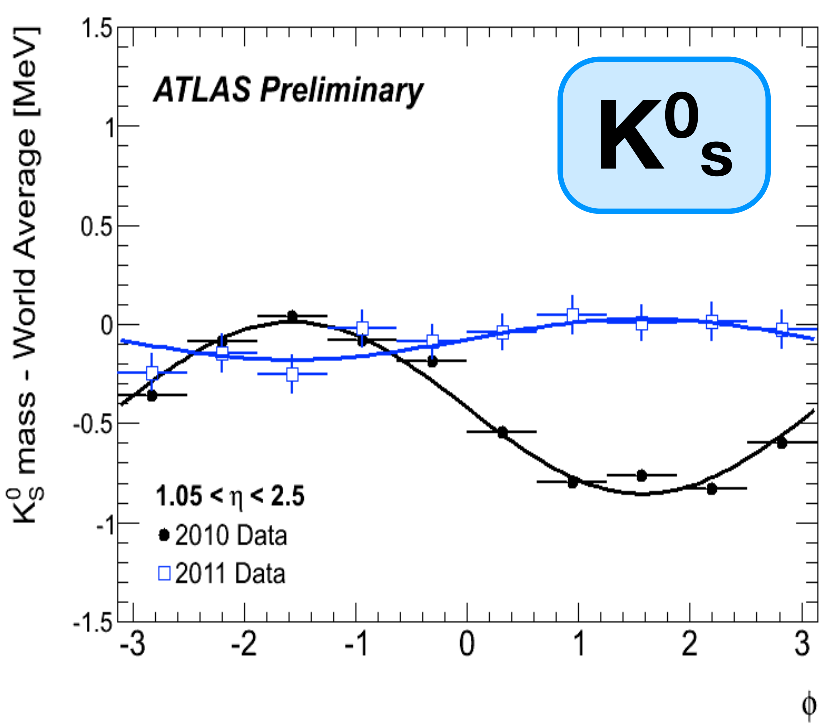


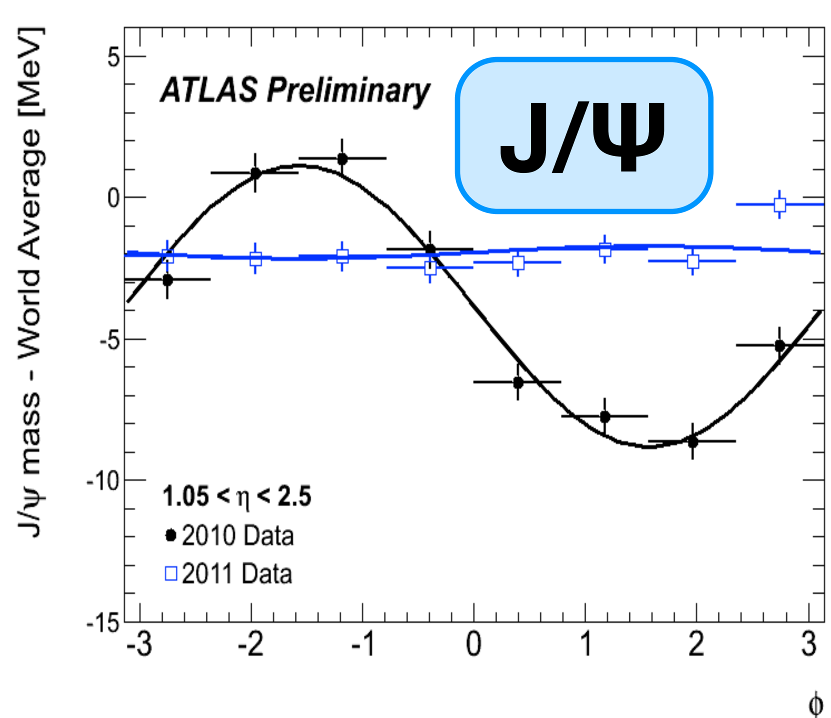
- Detector stability
  - movements due to changes in operational conditions (typical size < 10 µm)
  - otherwise the detector is stable

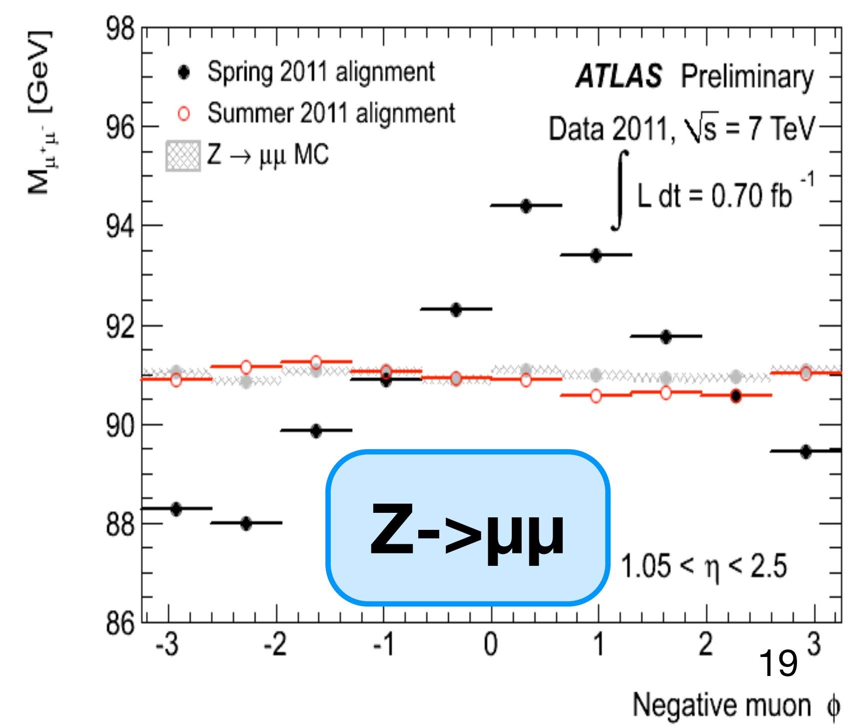
Alignment validation using physics observables: ***weak modes***

- weak modes are global deformations
  - affect momentum scale, e.g. Z-mass resolution
  - several techniques to control weak modes
    - TRT to constrain silicon alignment
    - electron E/p using calorimeter
    - muon momentum in ID vs Muon spectrometer
- systematics studies with K^0_s, J/ψ and Z->μμ
  - detected a relative rotation of the solenoid and ID axis
    - corrected by 0.55 mrad field rotation around y axis (end-cap C shown)



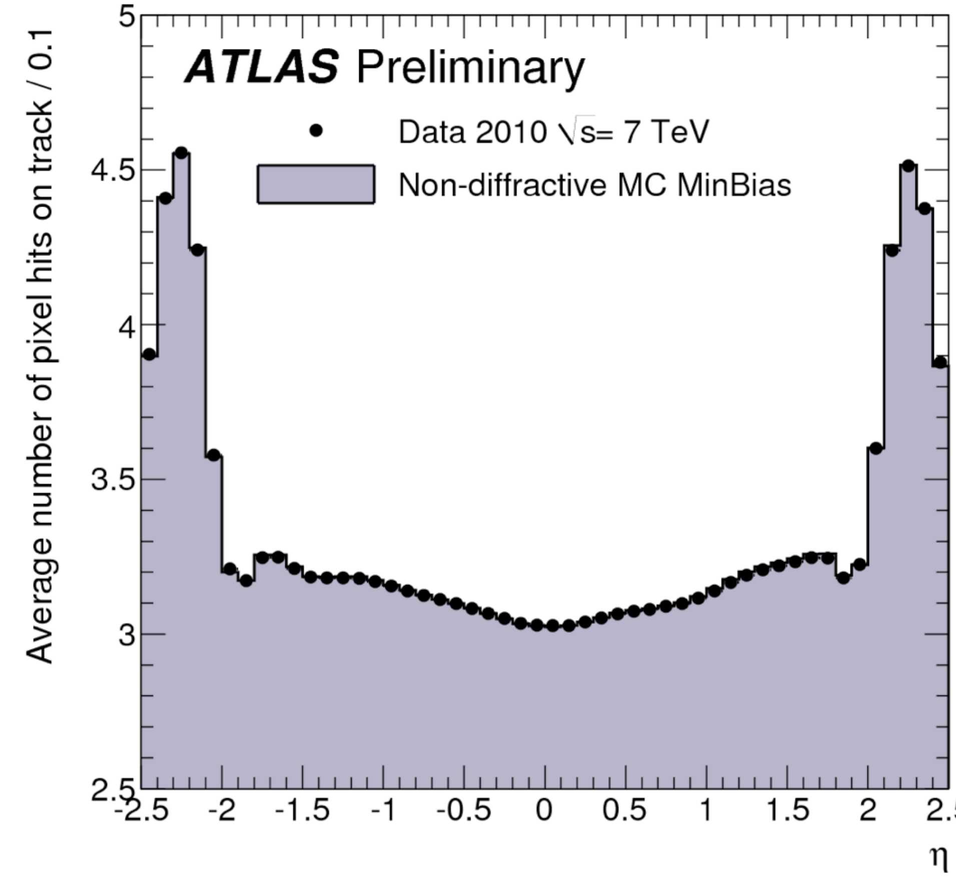


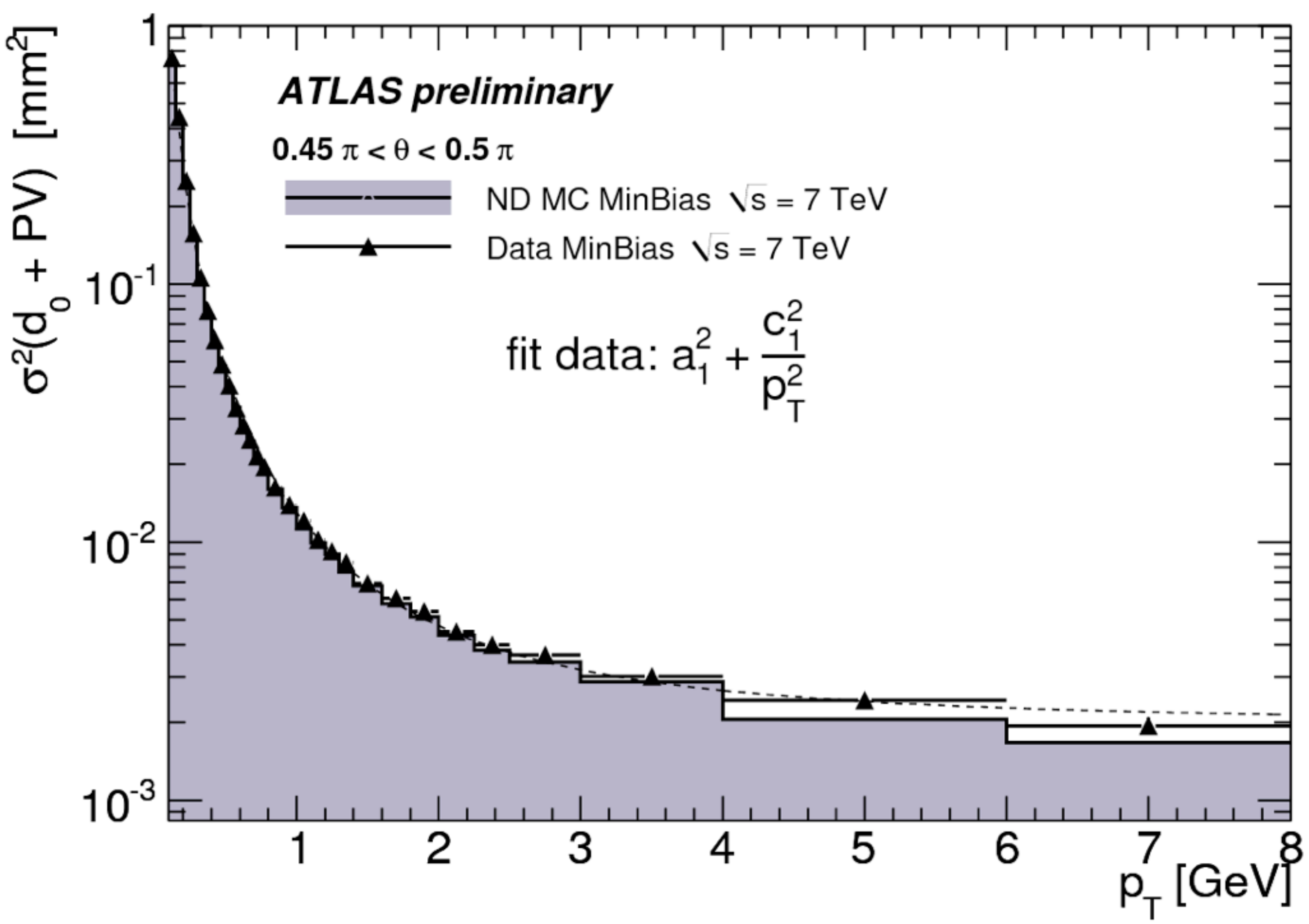


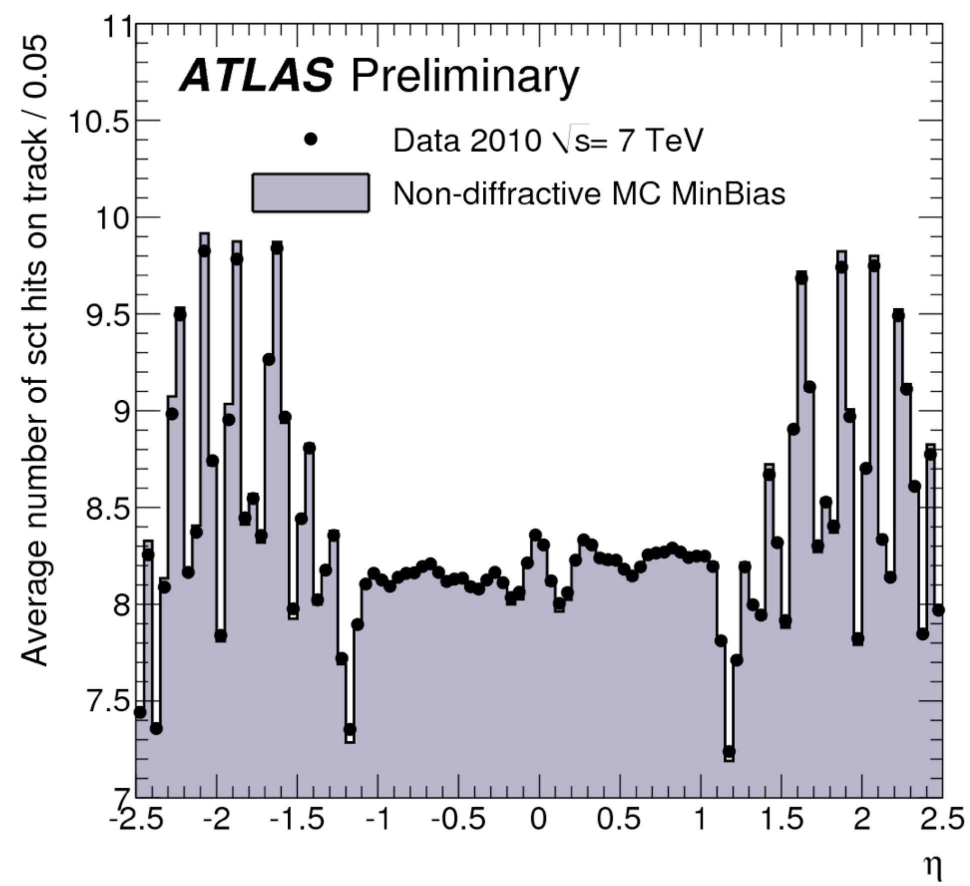


Track properties

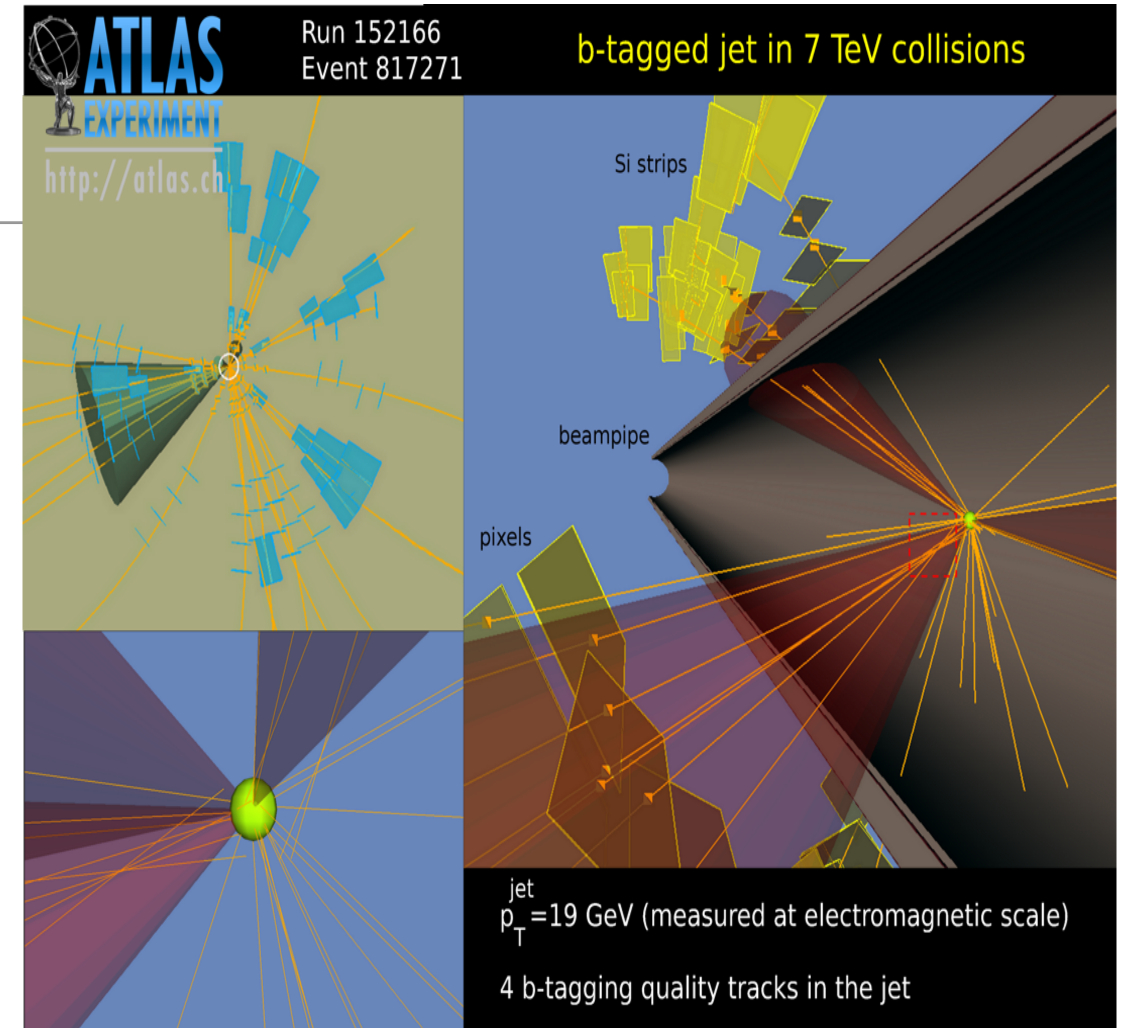
- general good agreement of track properties
  - number of hits and geometrical structure well reproduced
  - track impact parameter resolution also well reproduced





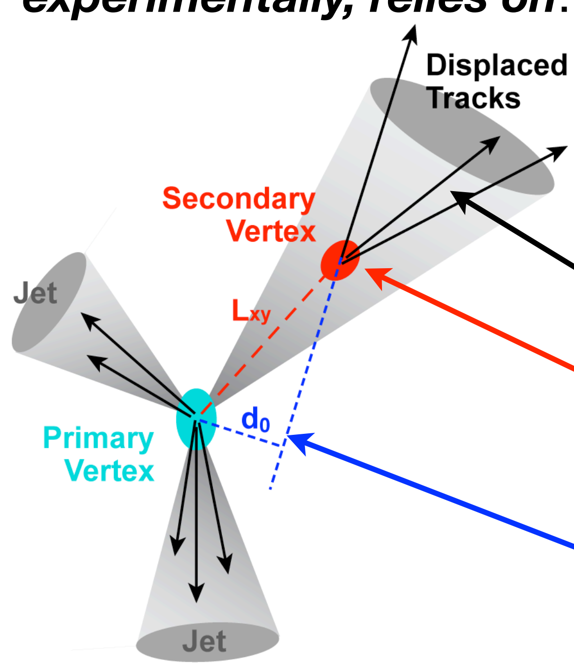


B-tagging



b-tagged jet in 7 TeV collision

- ***physics motivation***: the ability to detect jets stemming from the hadronization of b-quarks is extremely important for many analyses
  - SM measurement (σ_{bbar}, top physics, ...)
  - searches for Higgs boson
  - searches for Physics beyond SM (SUSY, ...)
- ***b-tagging overview***: identification of b-jets exploits the properties of b-hadrons
  - high mass (~5 GeV): many particles in decay
  - long lifetime (~1.5 ps, cτ ~450 μm): a b-hadron in a jet (p_T ~50 GeV) flies on average ~3 mm before decaying!
  - semi-leptonic decay with BR ~21%
- ***experimentally, relies on***:



detecting soft leptons in jets

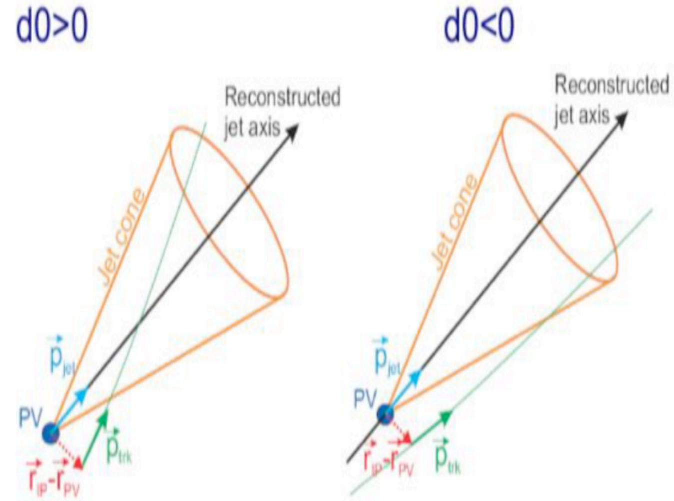
reconstructing secondary vertices (SV) displaced from the primary vertex (PV)

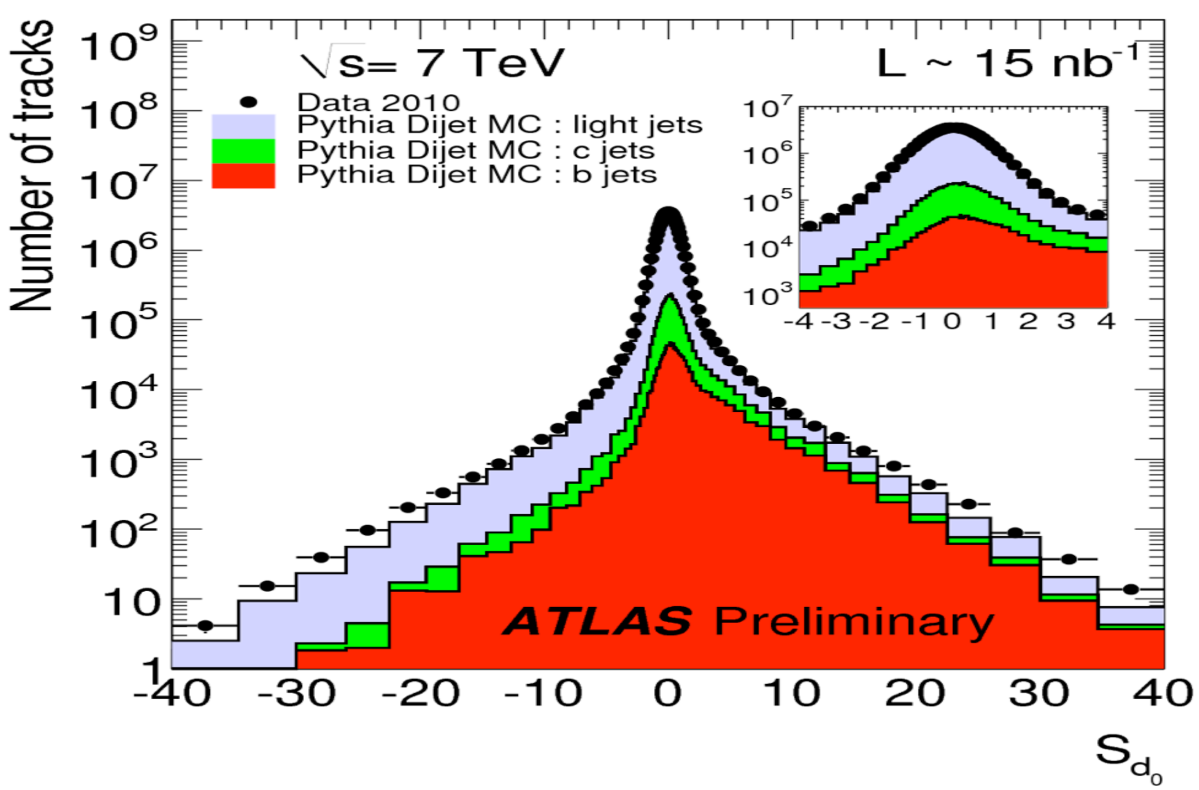
measuring large impact parameter (IP) of tracks in jets

B-tagging algorithms

JetProb
IP-based

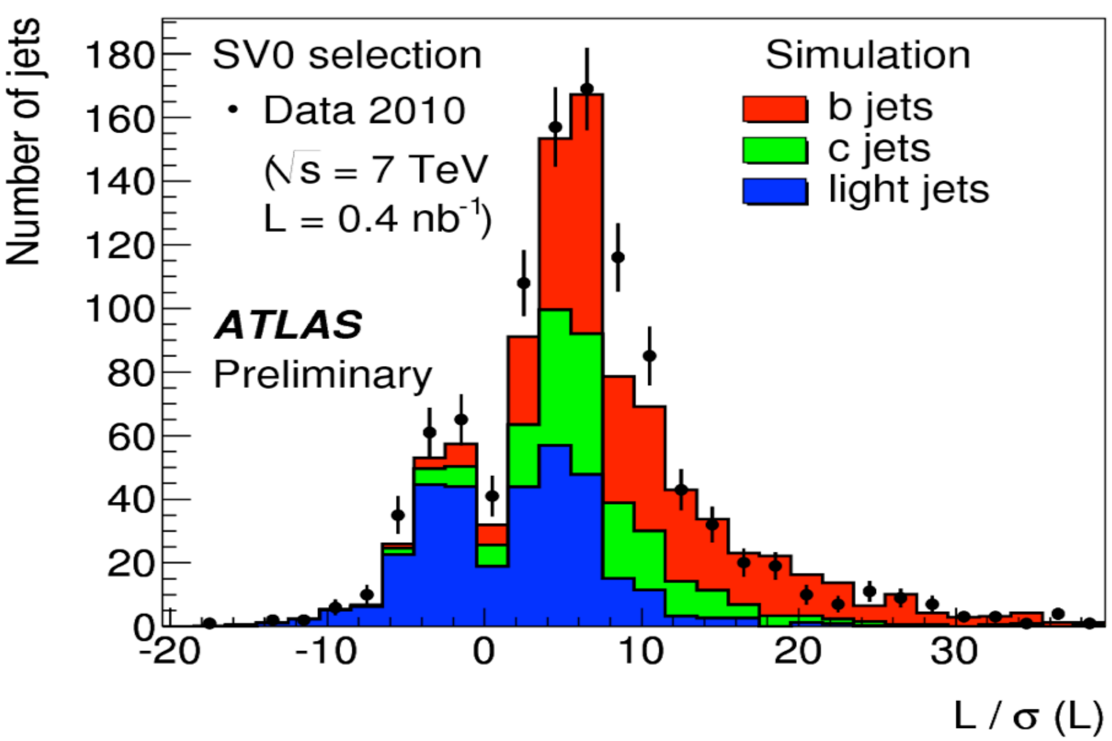
- ***principle***: it signs the transverse and longitudinal impact parameters of tracks with respect to the primary vertex. It also build a probability that the tracks in the jet originate from the primary vertex





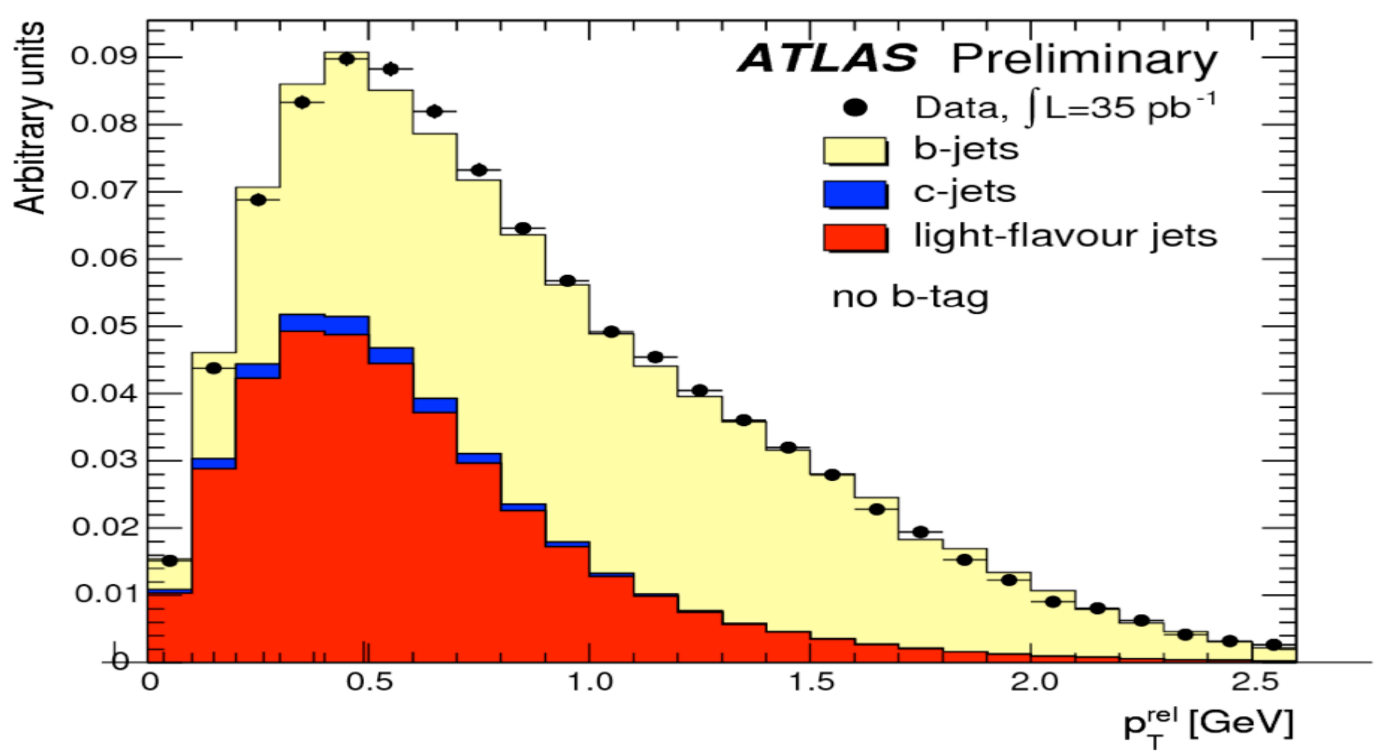
SV0
SV-based

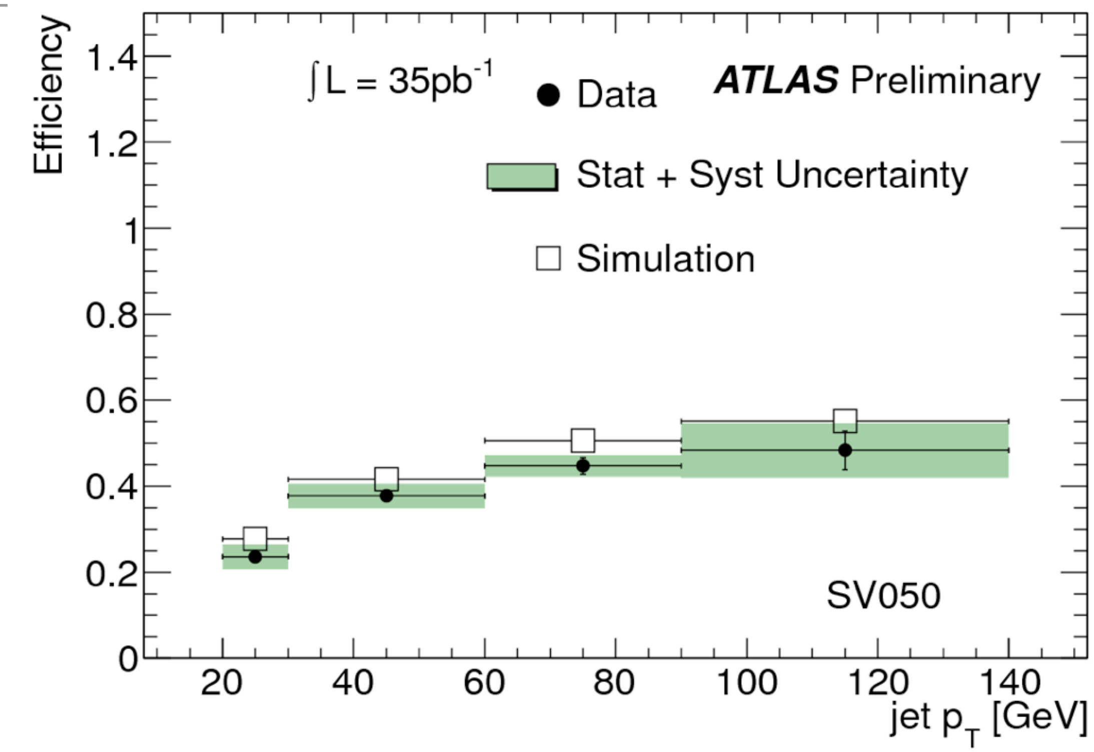
- ***principle***: it reconstruct the inclusive vertex formed by the decay products of the b-hadron, including products of the eventual subsequent c-hadron decay

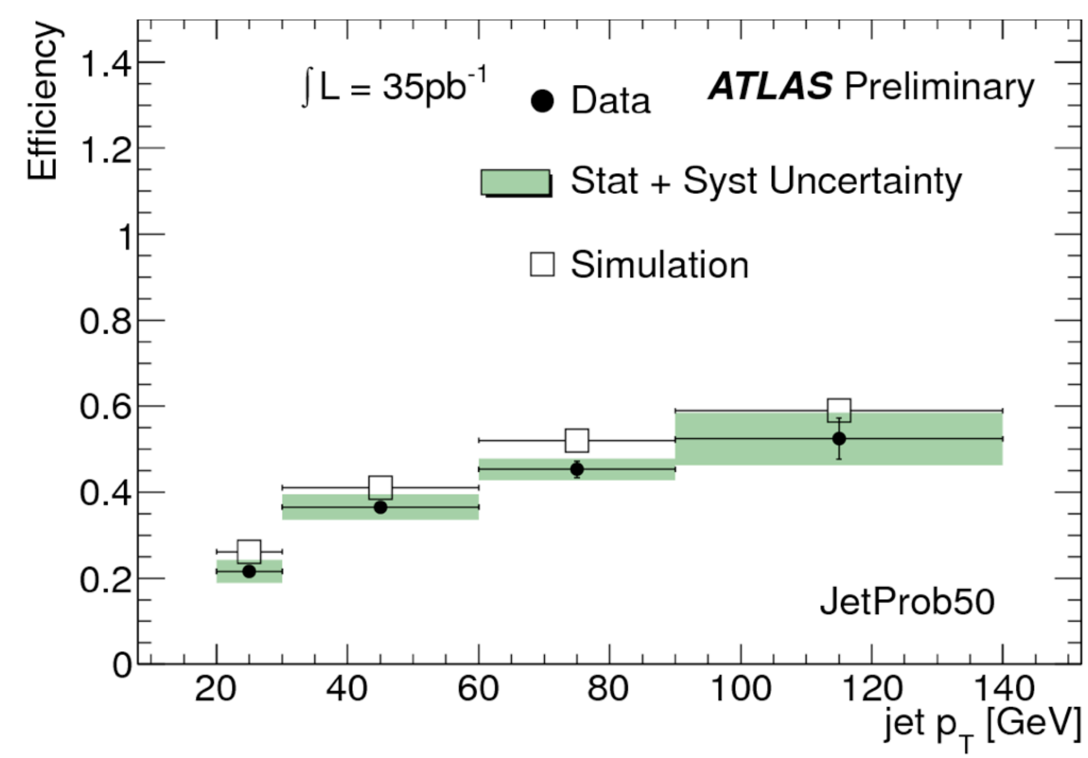


B-tagging efficiency measurements: ***pTrel***

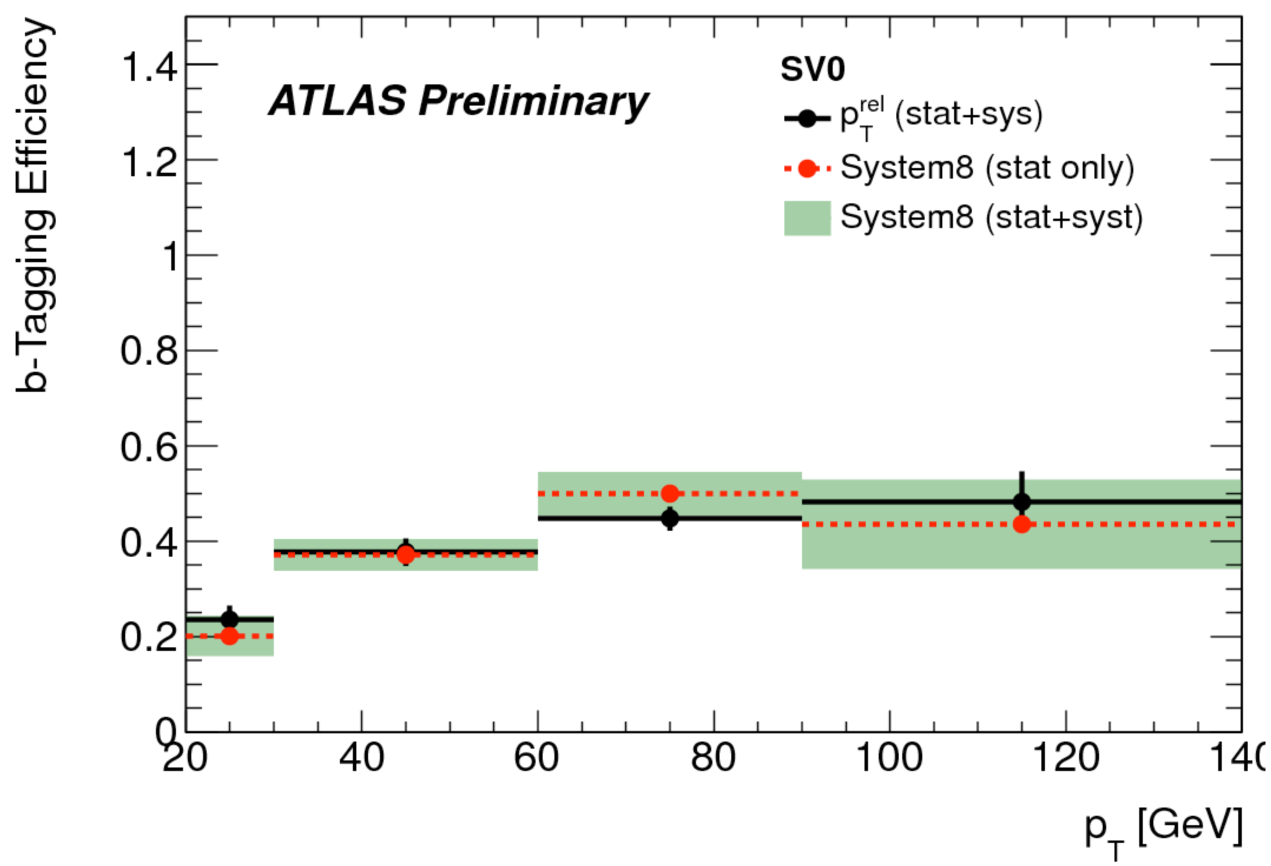
- Leptonic decays of b-quarks offer uncorrelated ways of measuring the efficiency of lifetime based tagging algorithms
- in the pTrel measurement the momentum of a muon orthogonal to the flight axis of the jet it is associated to is used to measure the b-jet content of a given sample
- templates of pTrel for b-, c- and light-flavor jets are fit to the data before and after b-tagging and the efficiency is calculated as $\varepsilon = N_{b,tag}/N_b$

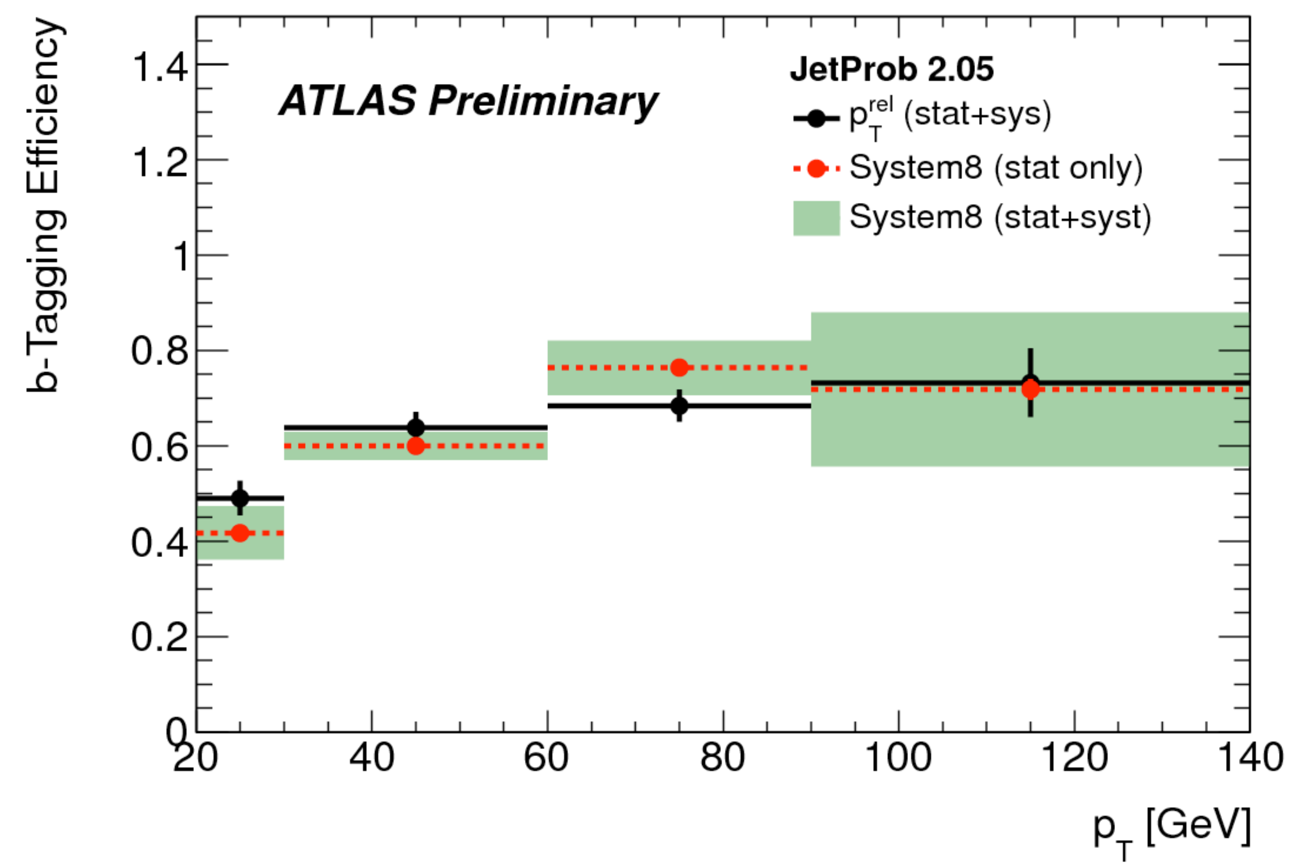






B-tagging efficiency measurements: ***System8***





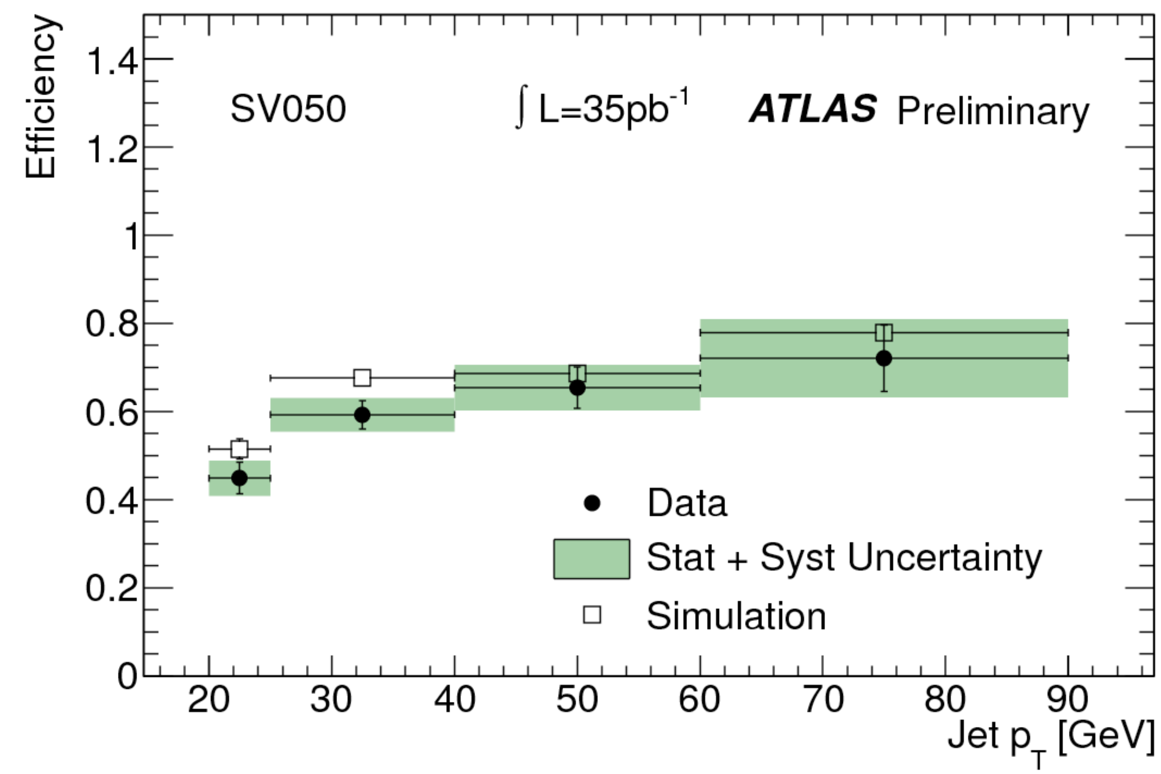
- System8 is a very promising method that will be used in future b-tagging calibration results (ATLAS-CONF-2011-143)
  - uses uncorrelated taggers to numerically calculate the b-tagging efficiency from a set of 8 equations
  - method designed to minimize the dependence on simulation
  - measurement done with the full 2010 dataset

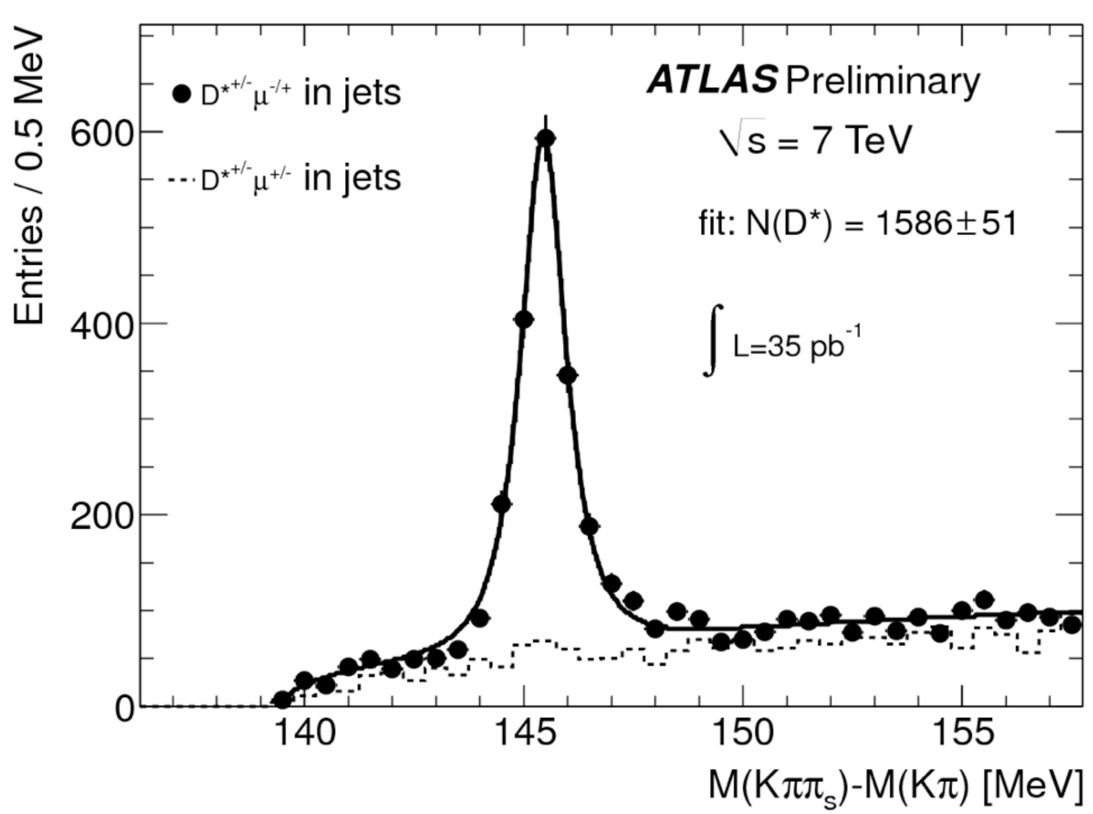
B-tagging efficiency measurements: ***D* decay***

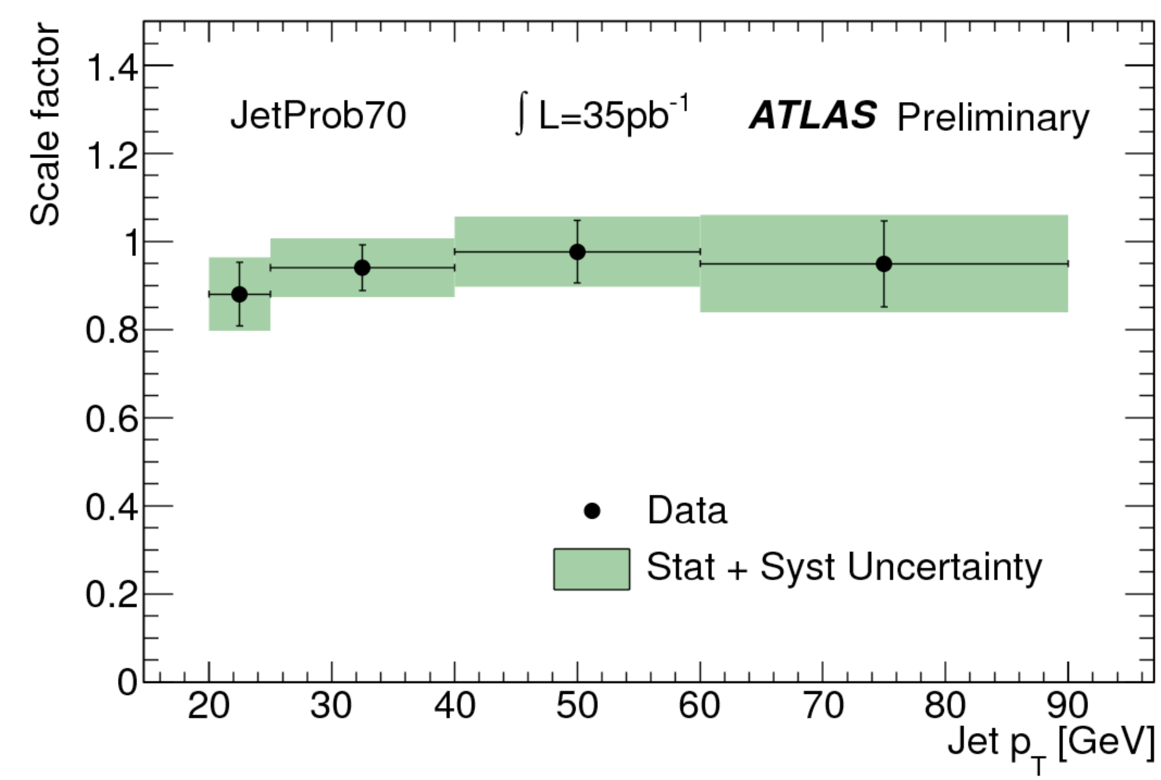
- it is possible to measure the efficiency using the semi-leptonic decay chain

$$b \to D^* \mu X \to D^0(\to K\pi)\pi\mu X$$

- the mass reconstruction combined with the muon requirement yields a high b-jet purity and therefore gives direct access to the b-tagging efficiency $\varepsilon = N_{b,tag}/N_b$

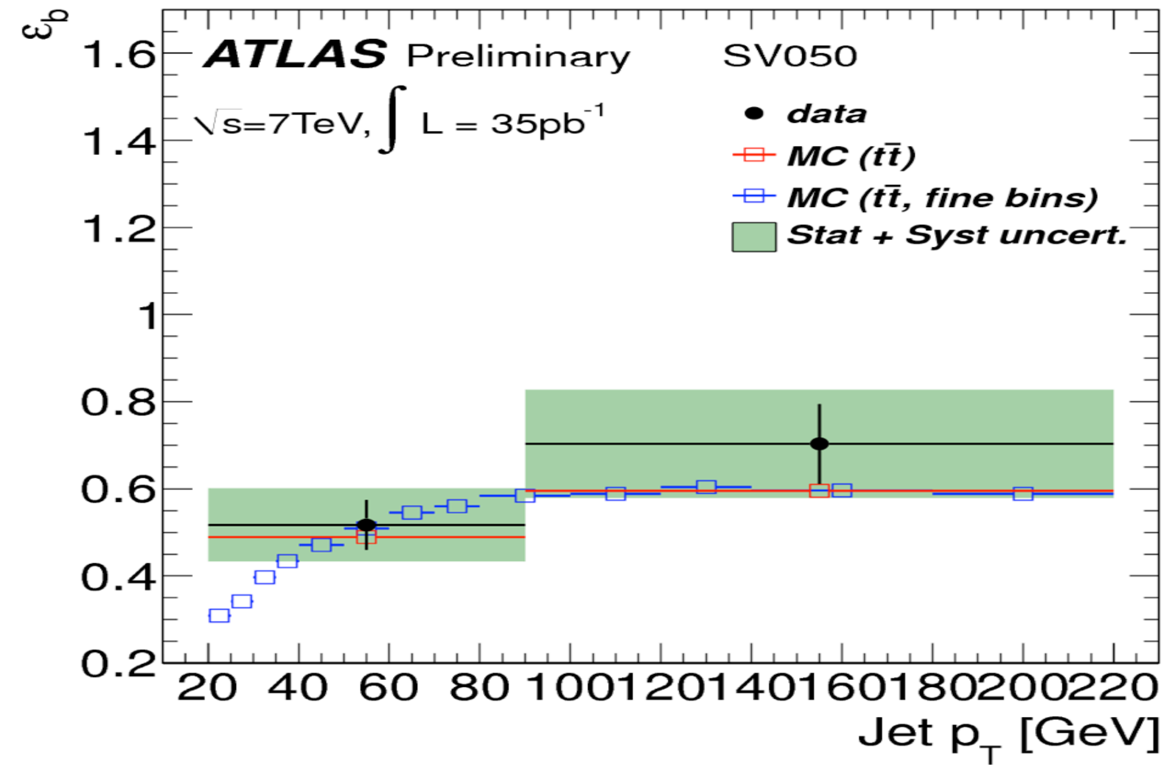


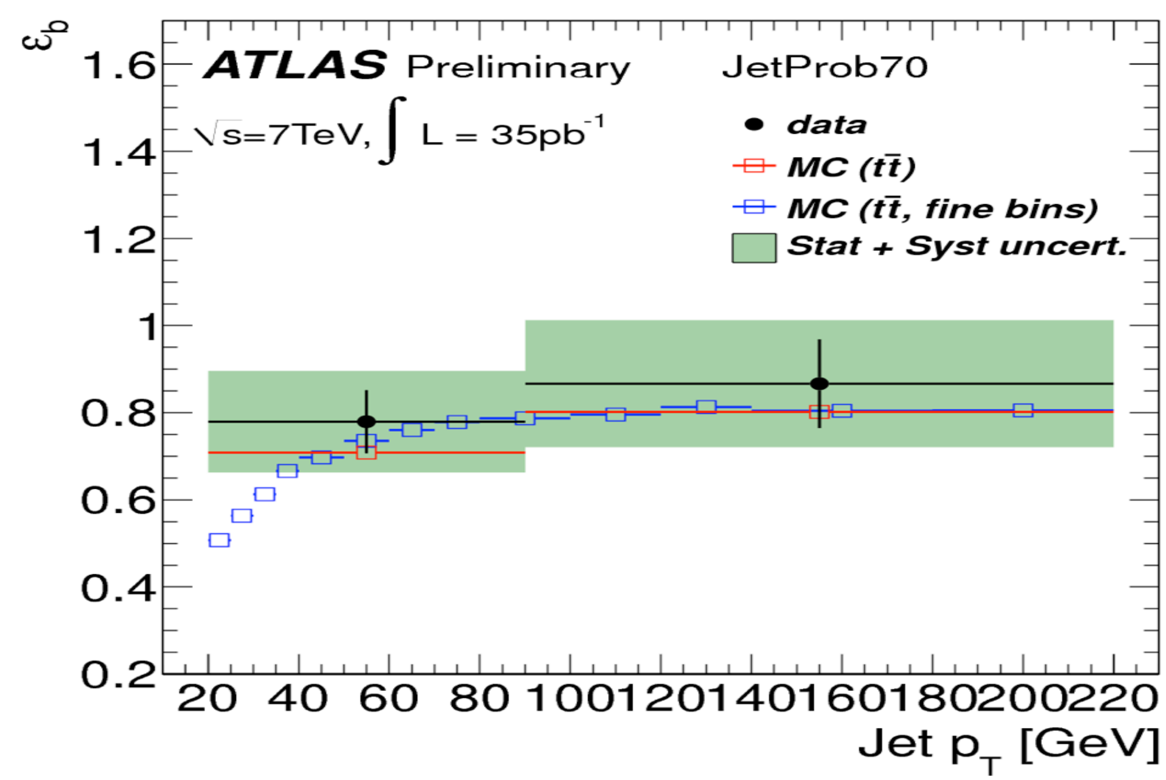


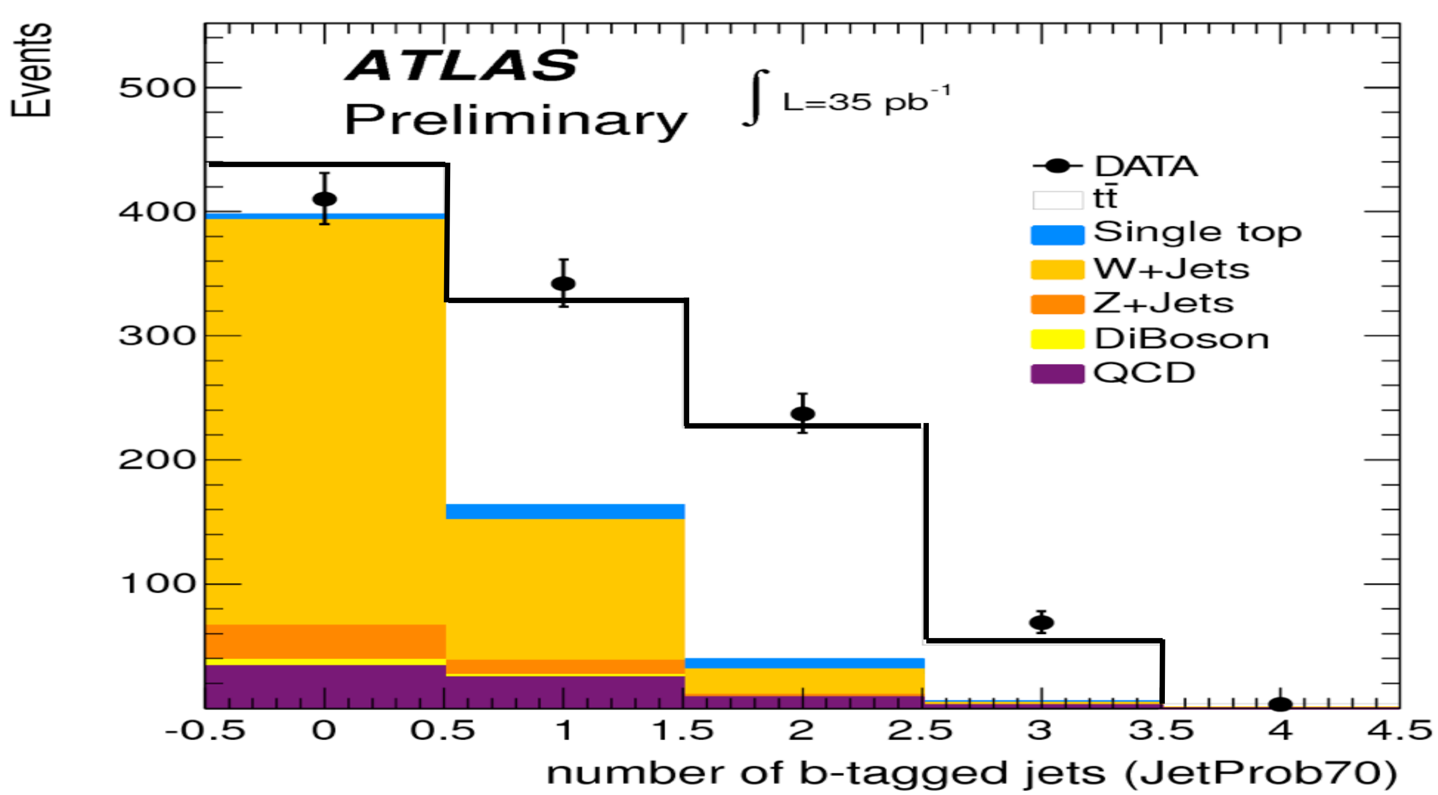


B-tagging efficiency measurements: ***Top-quark pairs***

- an enriched b-jets sample can be obtained selecting top quark pairs, because a top quark almost exclusively decay into a W-boson and a b-quark
  - used semi-leptonic and di-leptonic ttbar decay channels, selected requiring isolated leptons, high p_T jets and significative missing transverse energy
- developed different methods to measure the b-tagging efficiency in a ttbar-enriched sample yielding promising results that are becoming especially important as the integrated luminosity increases



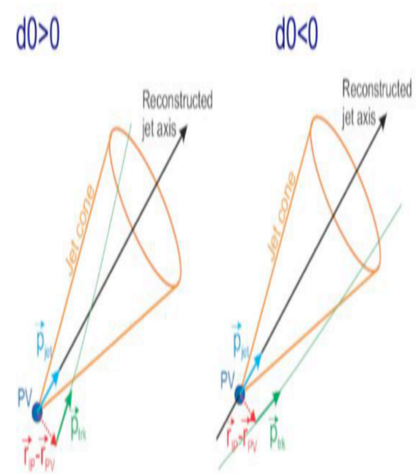




High performance b-tagging algorithms

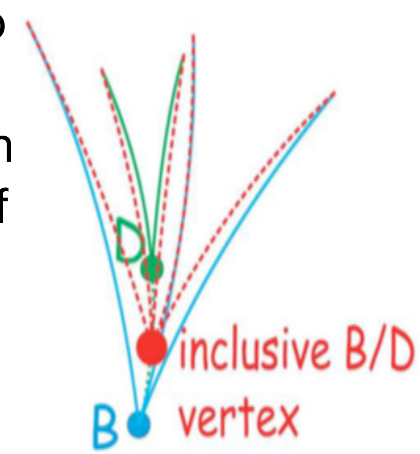
IP3D
IP-based

- likelihood ratio using transverse and longitudinal IP distributions



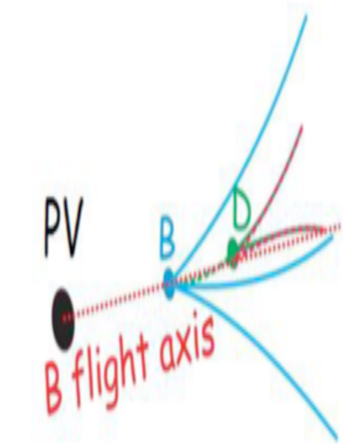
SV1
SV-based

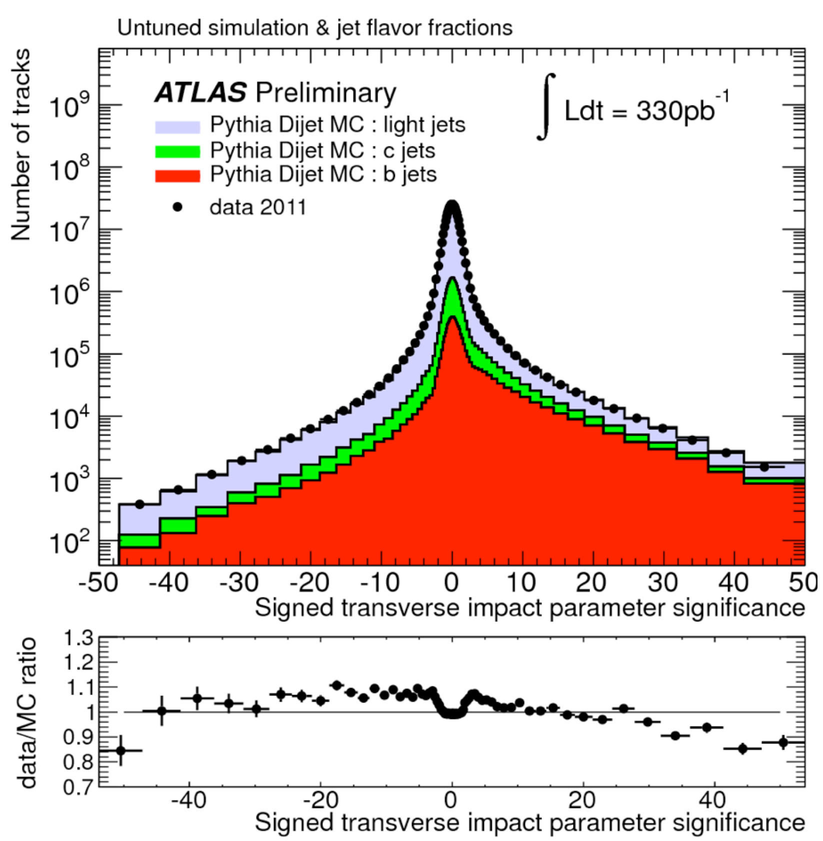
- likelihood ratio using mass, energy fraction and number of two-tracks vertices in secondary vertex

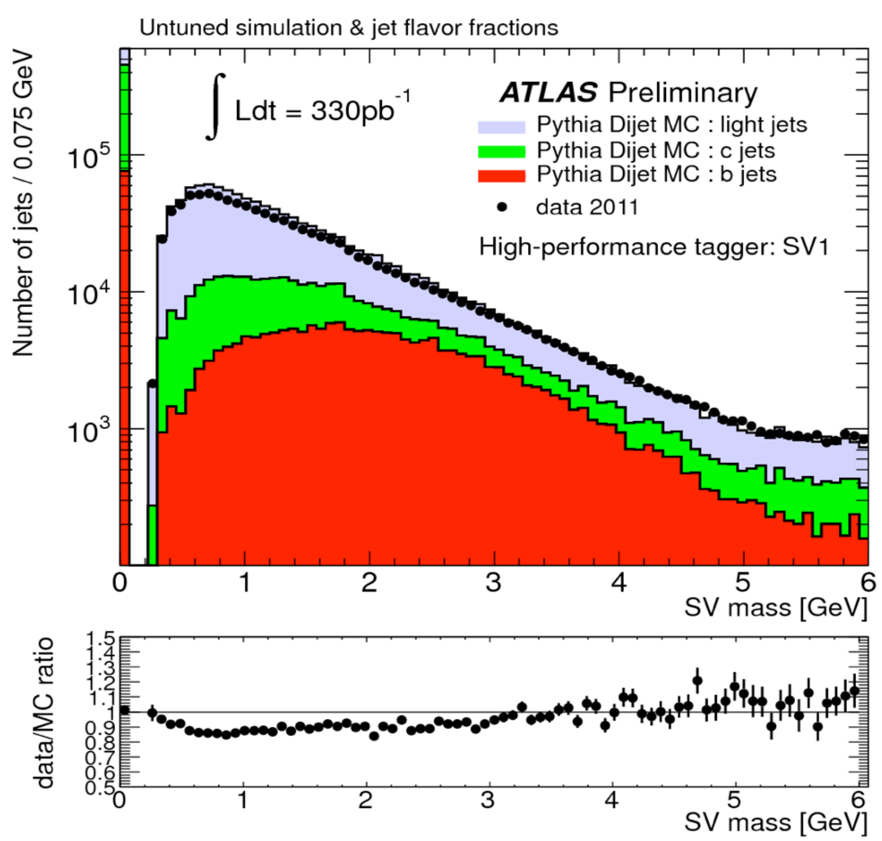


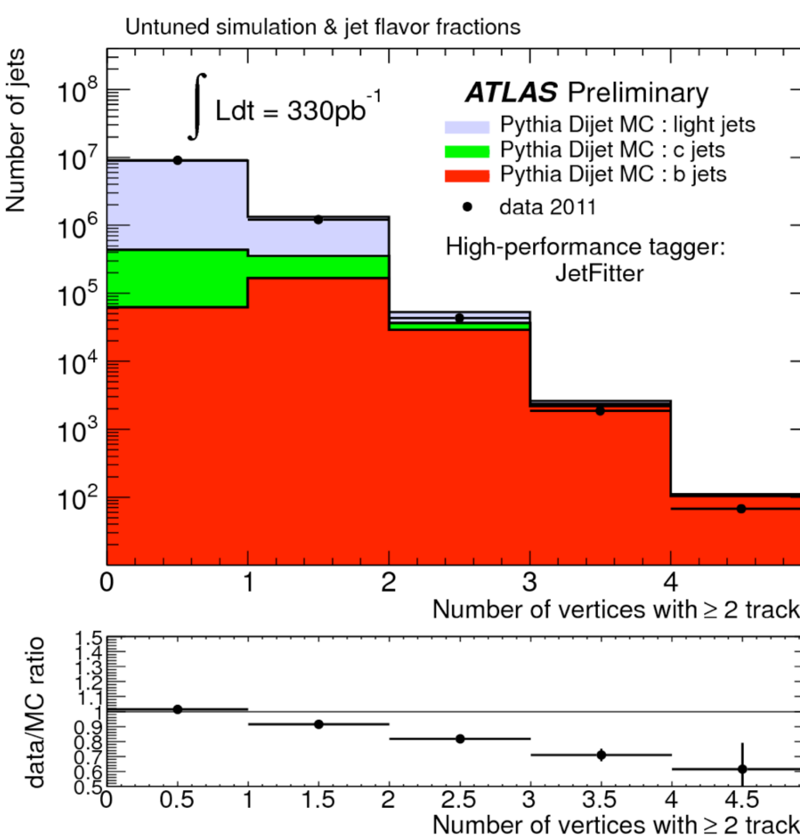
JetFitter
Multi-vertex fit

- neural network aiming at reconstucting both B and D decay vertices





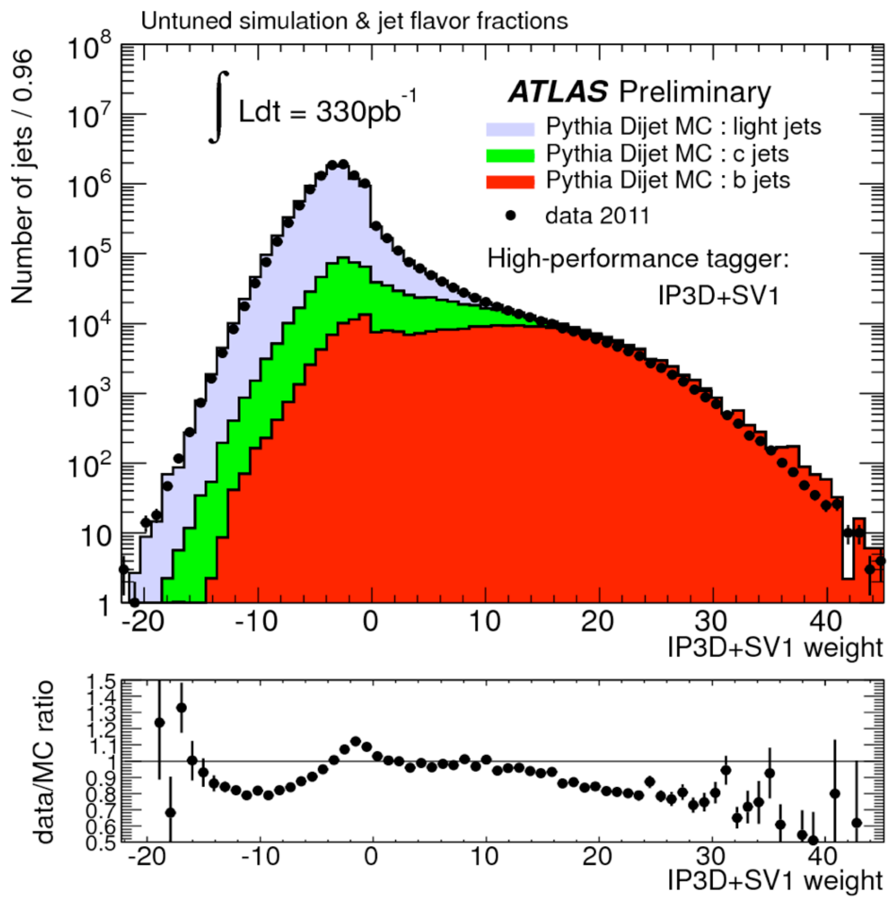




High performance b-tagging algorithms:
Combined taggers

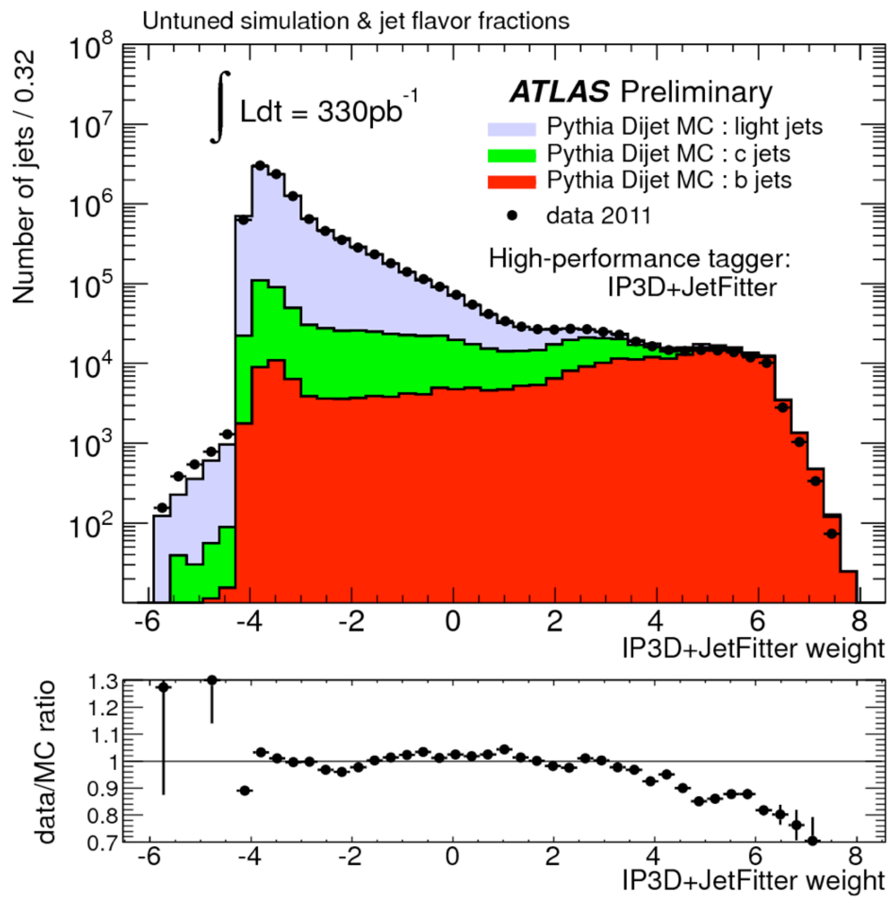
IP3D + SV1

- thanks to the likelihood ratio method used for IP3D and SV1, the algorithms can be easily combined: the weights of the individual tagging algorithms are simply summed up



IP3D + JetFitter

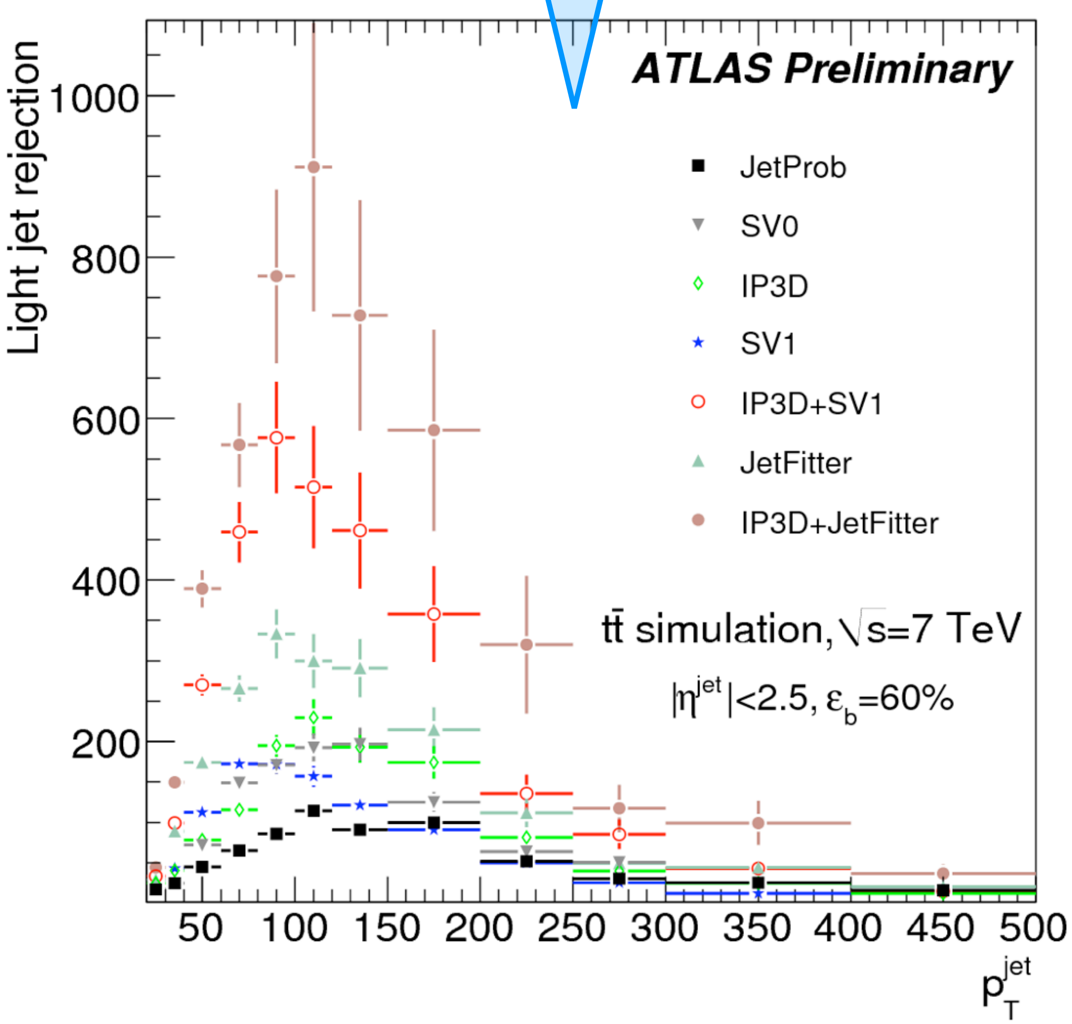
- the combination IP3D+JetFitter is based on artificial neural network techniques with Monte Carlo simulated training samples and additional variables describing the topology of the decay chain



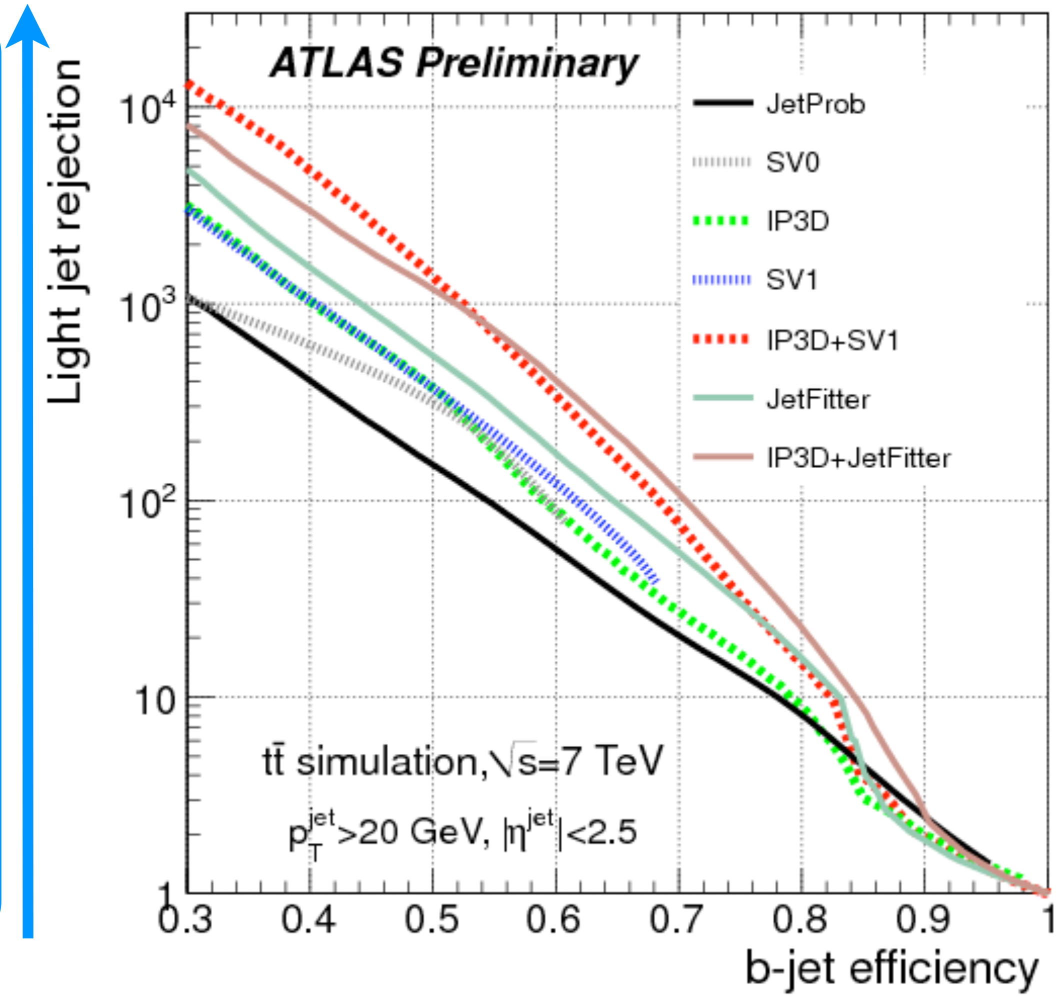
High performance VS “early” b-tagging algorithms

ttbar simulation

light jet rejection at ε_b=60%: new taggers greatly improve tagging also of high-p_T jets



- at same b-jet efficiency, the light jet rejection can be increased by a factor of 2 to 5 with new taggers
  - allow better background rejection



- for same rejection, can work at higher efficiency
  - promising for searches with low production cross section

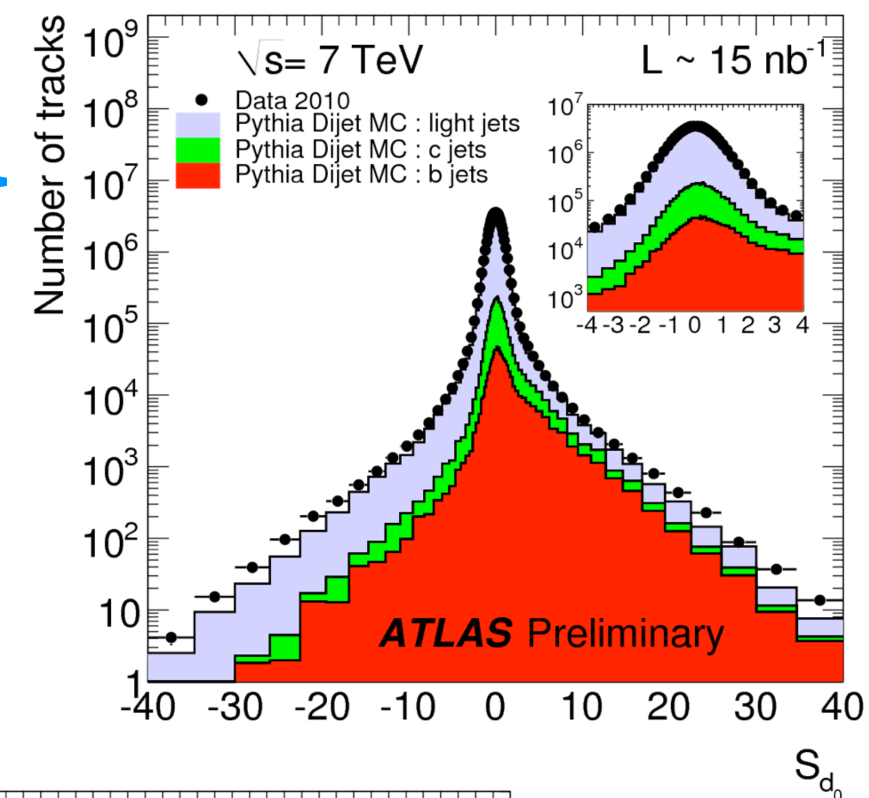
Conclusions

- the ATLAS Inner Detector is operating very efficiently
  - Pixel 96.4%; SCT 99.2%; TRT 97.5%
- ***excellent performance of ATLAS track reconstruction and b-tagging***
  - they satisfy the stringent requirements on Inner Detector track reconstruction to cover ATLAS physics program
  - detailed studies of detector, tracking, material, alignment, ...
    - after years of preparation based on simulation and test beam and after the commissioning phase with cosmics and early beams
    - generally good agreement between data and MC
  - heavy ion running as well gives good insights into tracking at high occupancy
- several b-tagging algorithms have been developed and used in physics analyses
  - JetProb and SV0 algorithms were studied in detail an show good performance
  - high performance algorithms, providing a greatly improved light-jet rejection at a fixed b-tagging efficiency, have been commissioned and are already heavily used in ATLAS physics analyses (*see e.g. M.I. Besana's talk on "top physics in ATLAS"*)
- look forward to great physics results and discoveries!

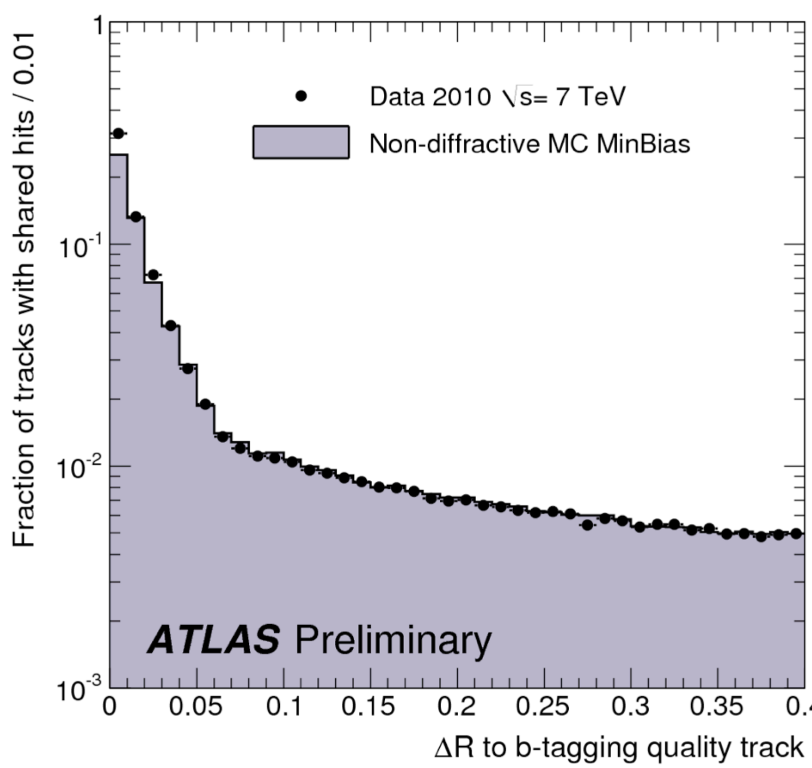
Backup

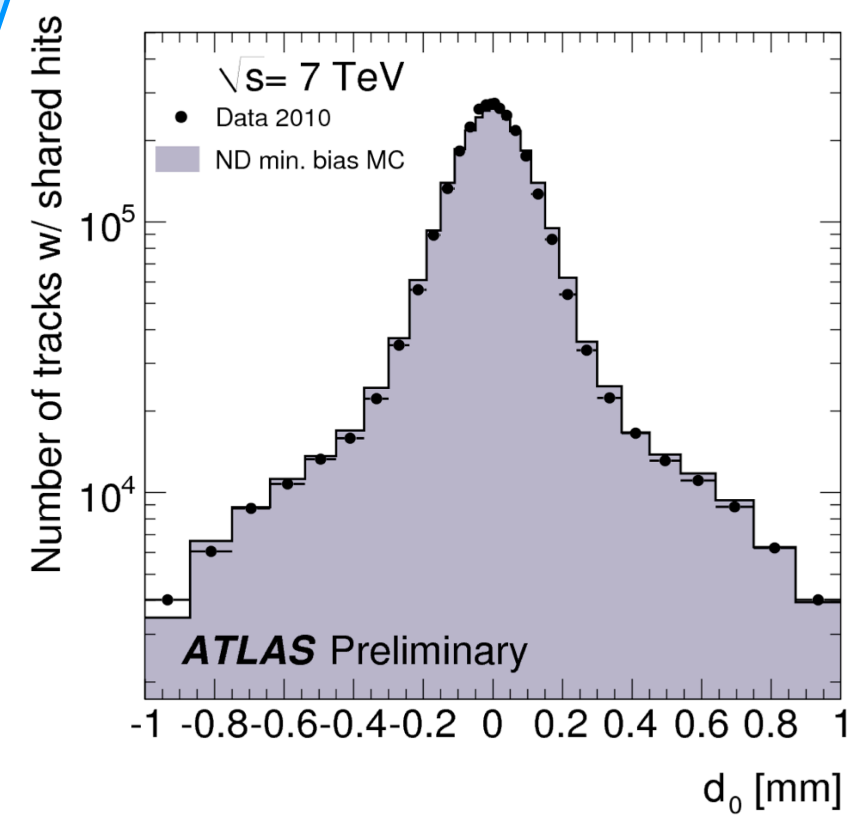
Track properties (important for b-tagging)

Transverse impact parameter significance d_0/σ_{d0}: very important for most b-tagging algorithms. IP significance used instead of pure IP in order to give more weights to tracks well measured

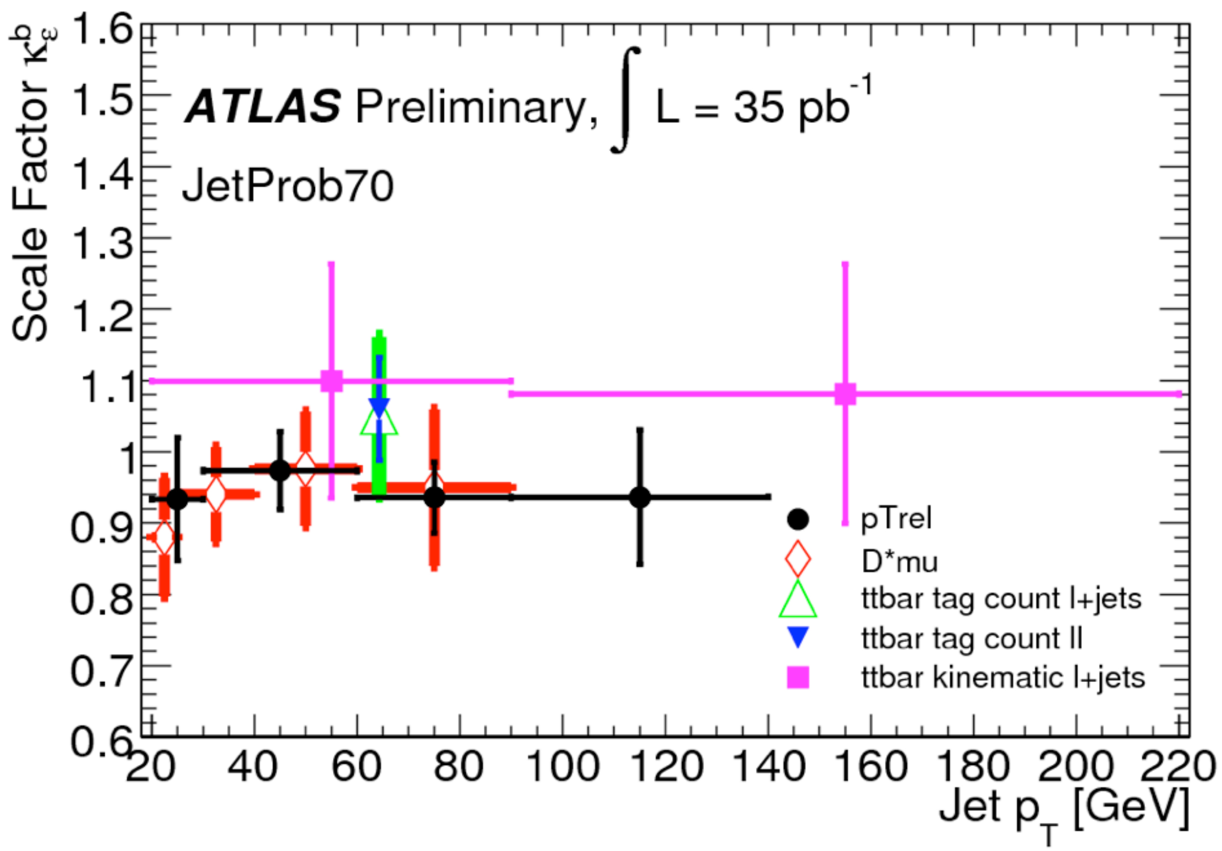


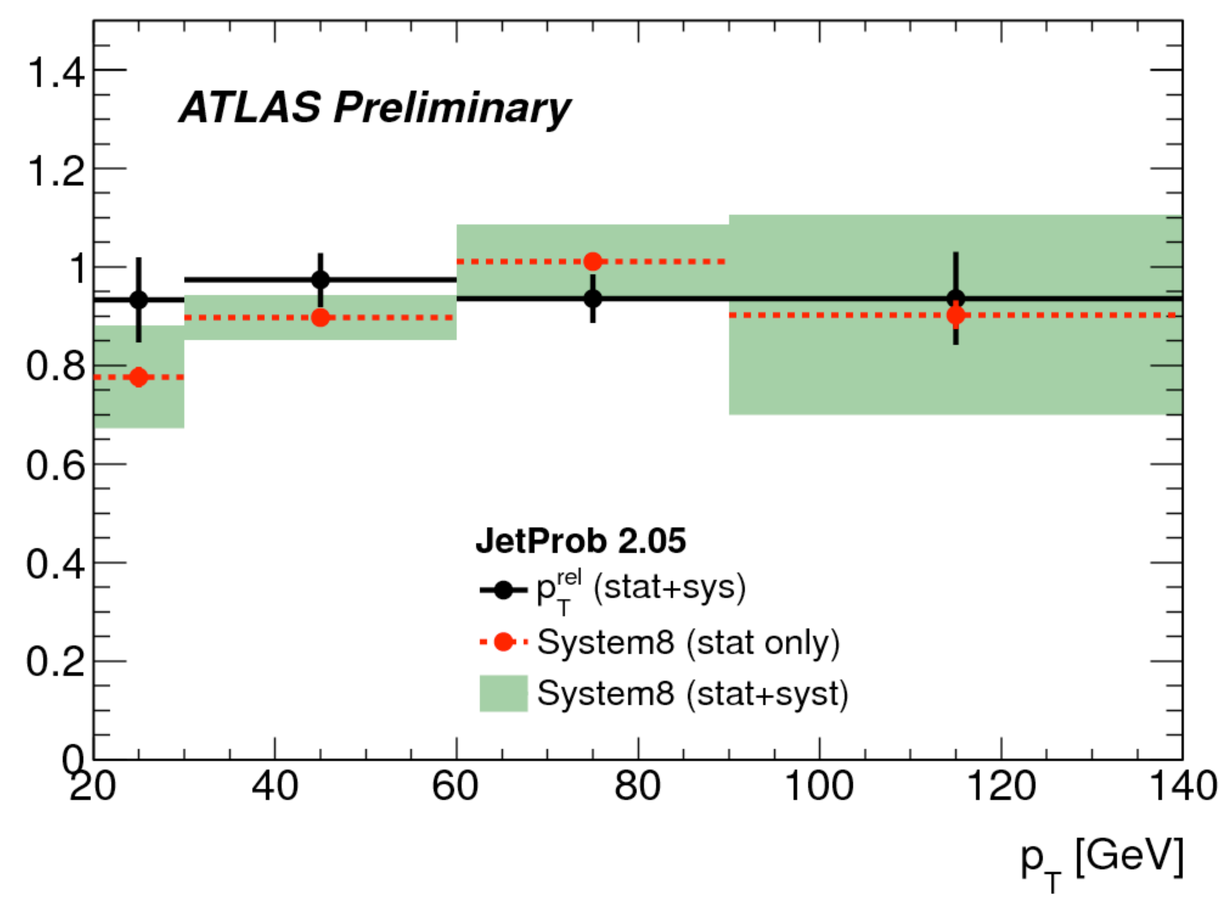
tracks with shared hits: biased impact parameter resolution -> larger tails





B-tagging efficiency measurements: ***Scale Factors***



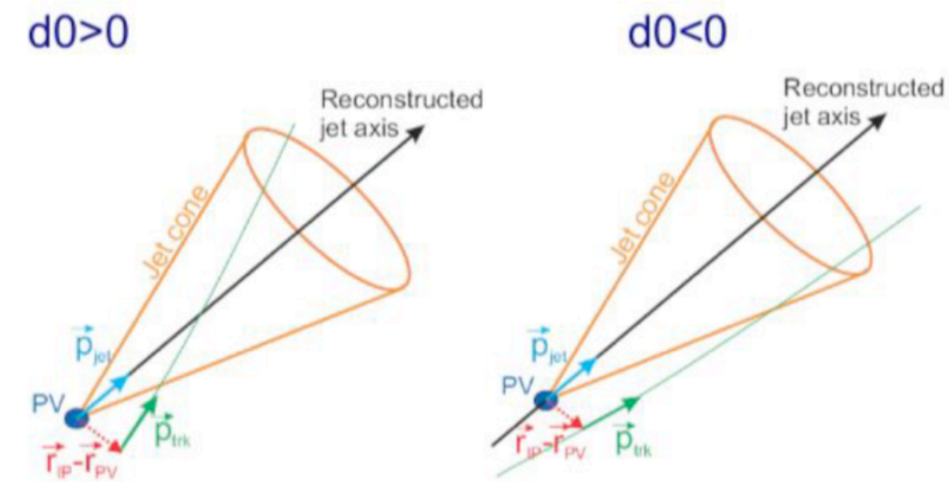


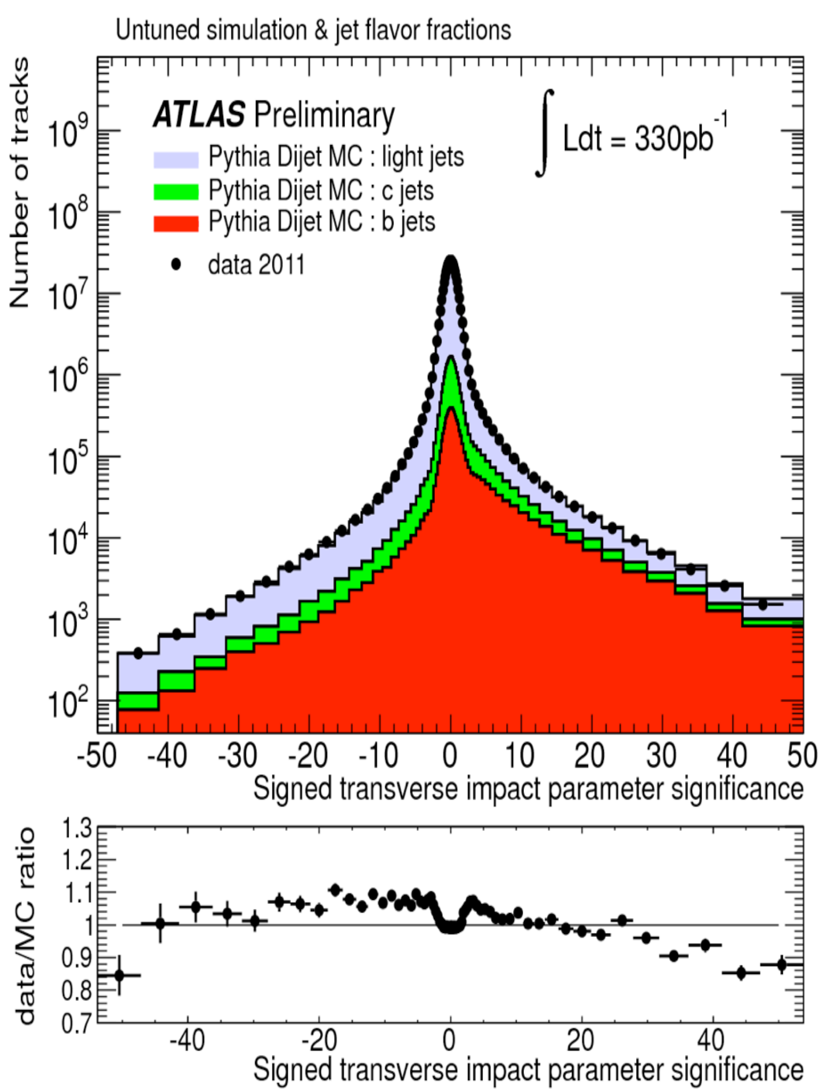
- very good agreement data/mc in b-tagging efficiency measurements
  - data-to-simulation scale factors ($\kappa_{\epsilon b}^{data/sim}$) compatible with one
  - the measured scale factors agree with each other within uncertainties

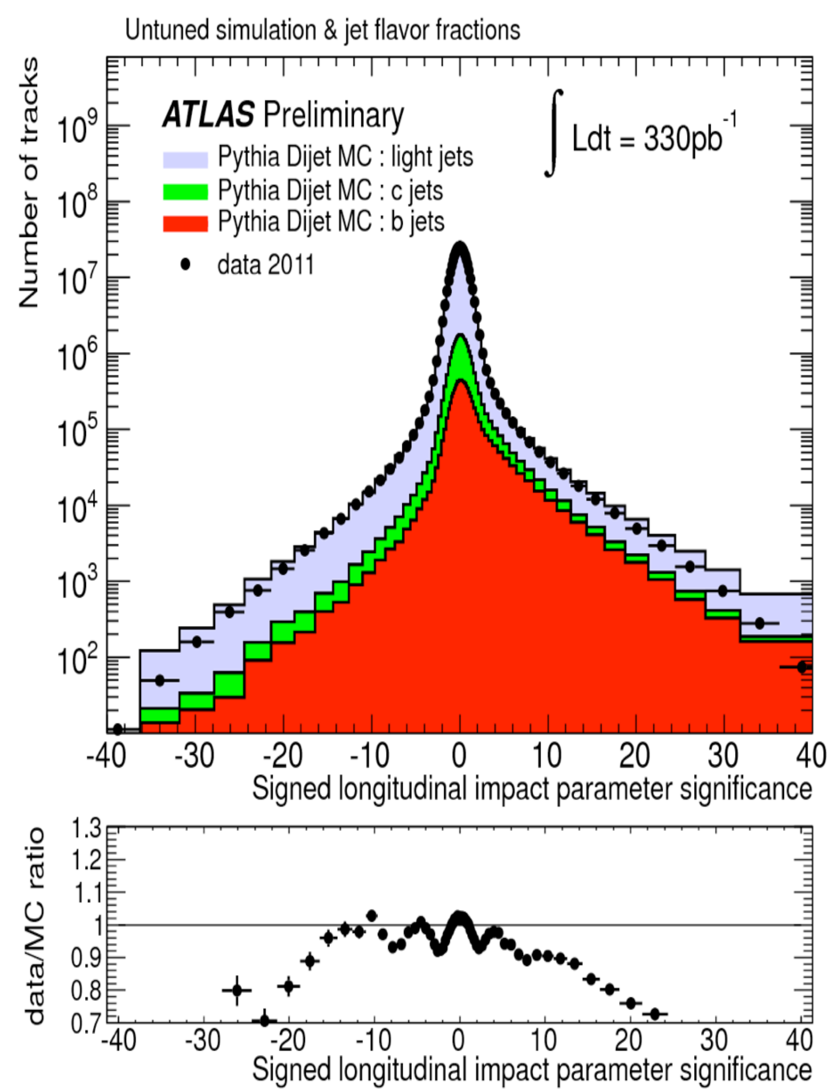
IP-based

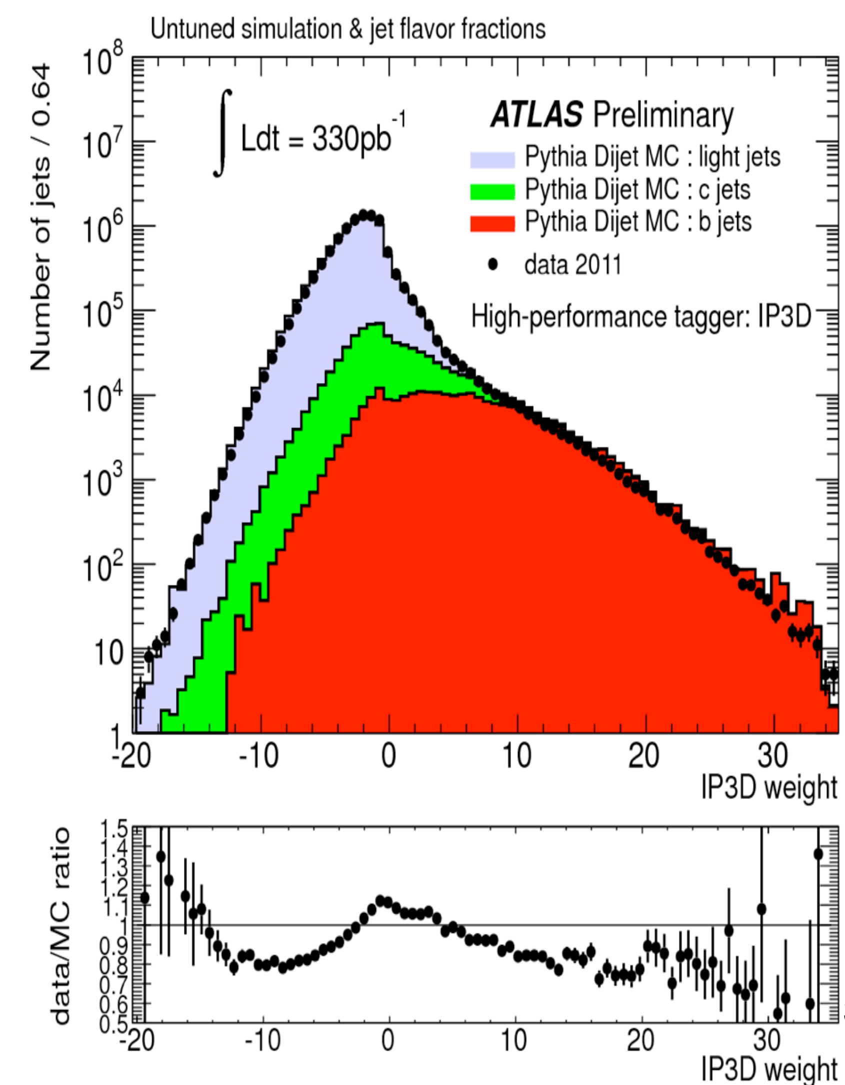
High performance b-tagging algorithms: ***IP3D***

- ***principle***: it signs the transverse and longitudinal impact parameters of tracks with respect to the primary vertex
  - it uses the IP significances IP/σ_{IP} to give more weights to well measured tracks
  - combine longitudinal and transverse significance with a likelihood ratio technique





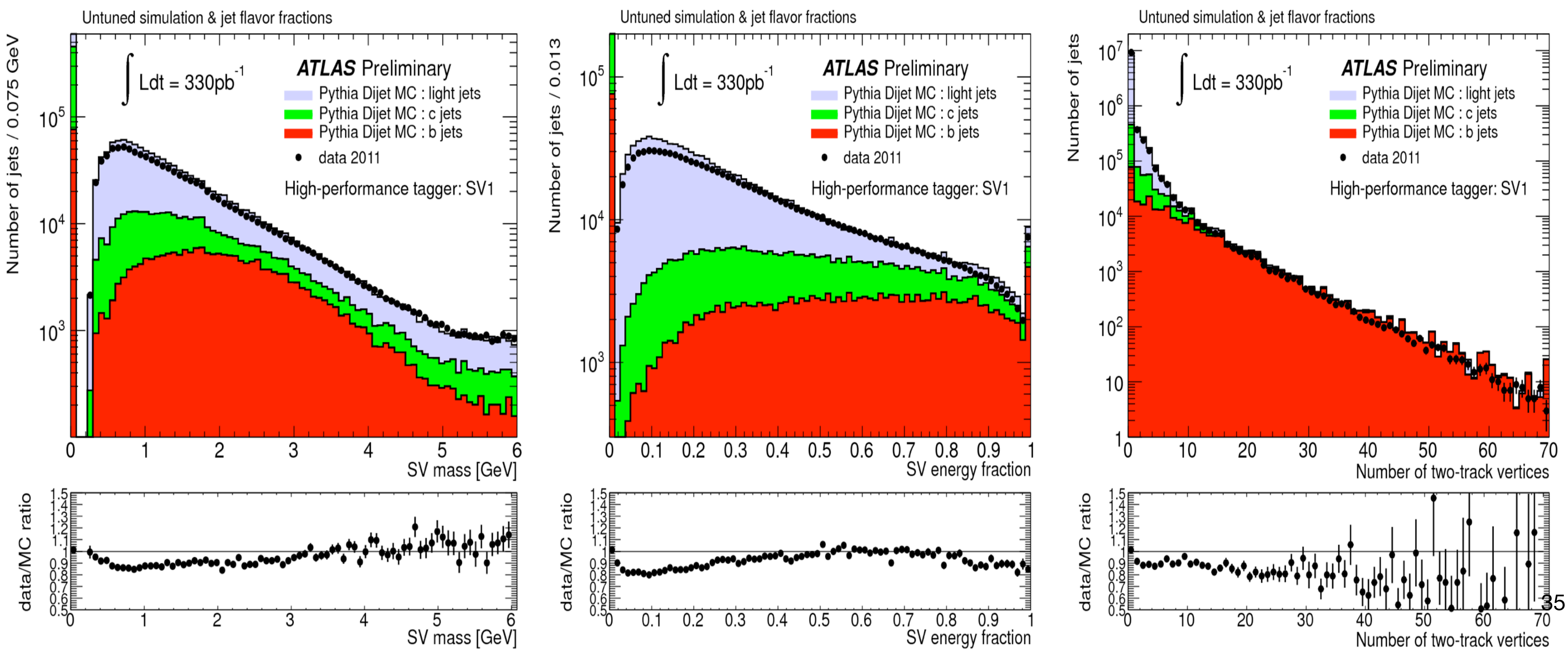




SV-based

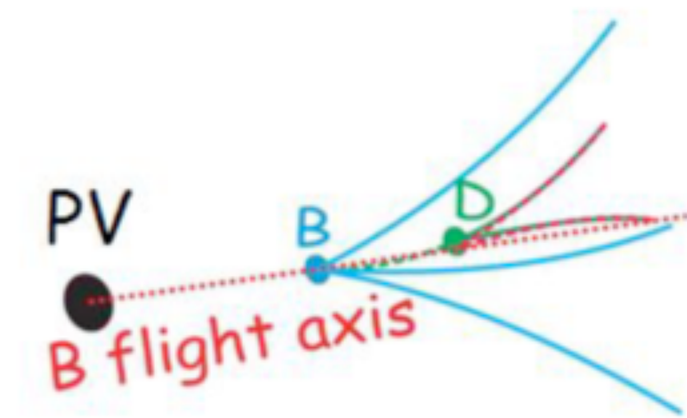
High performance b-tagging algorithms: ***SV1***

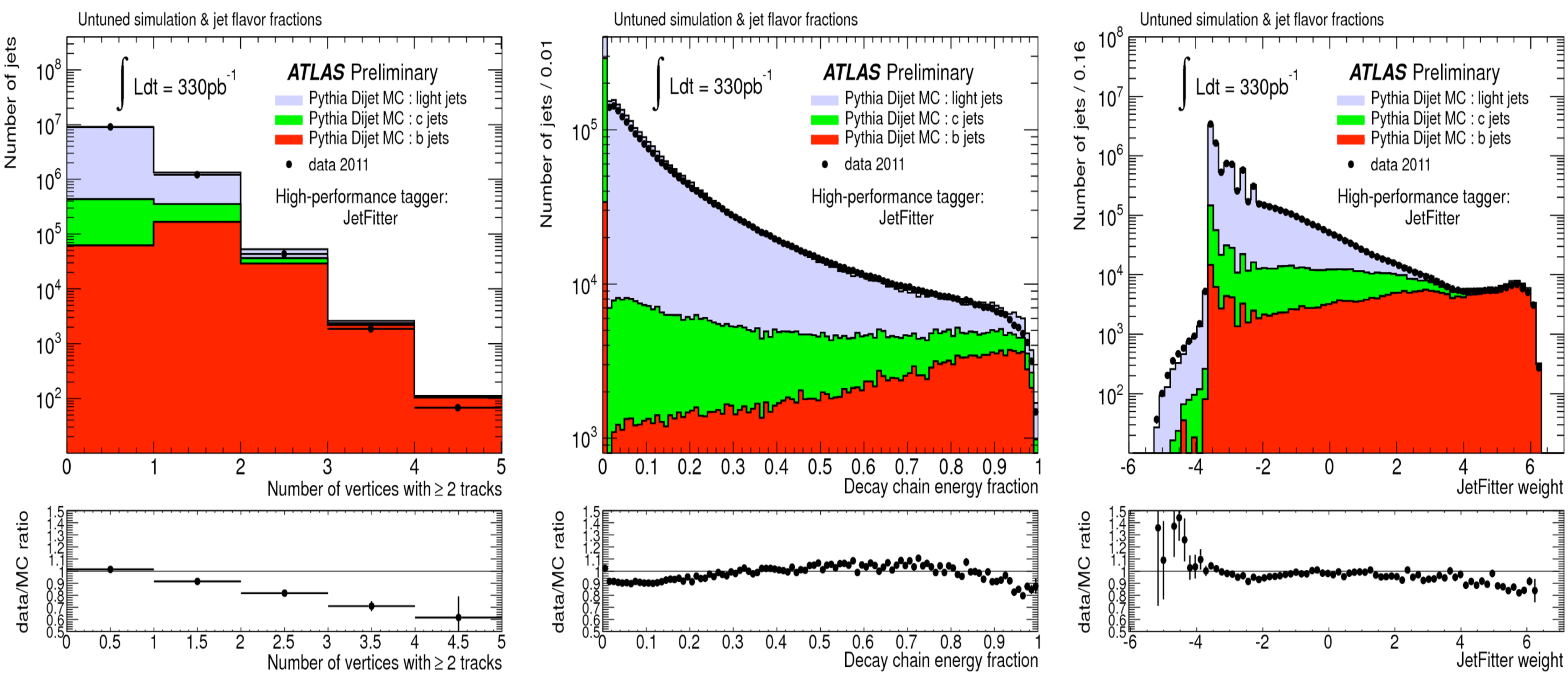
- ***principle***: it reconstructs the inclusive vertex formed by the decay products of the b-hadron, including products of the eventual subsequent c-hadron decay
  - it takes advantage of different properties of the SV
  - combine variables related to SV properties with a likelihood ratio technique



High performance b-tagging algorithms: ***JetFitter***

- ***principle***: it tries to reconstruct the full b-hadron decay chain under the hypothesis that b- and c-hadrons decays lie on the same line
  - it takes advantage of the different properties of these vertices
  - neutral network using several variables from simulation for b-jet, c-jet and light-jet hypothesis





High performance VS “early” b-tagging algorithms

QCD jet events: data and simulation

- for similar b-tagging efficiency
  - the fraction of light jets incorrectly tagged as b-jets is substantially reduced with new taggers

ε_b=50%

ε_b=70%