CPPM
Particle Physics Seminar
02/25/2011

Electromagnetic signatures in ATLAS: First steps towards a longer goal

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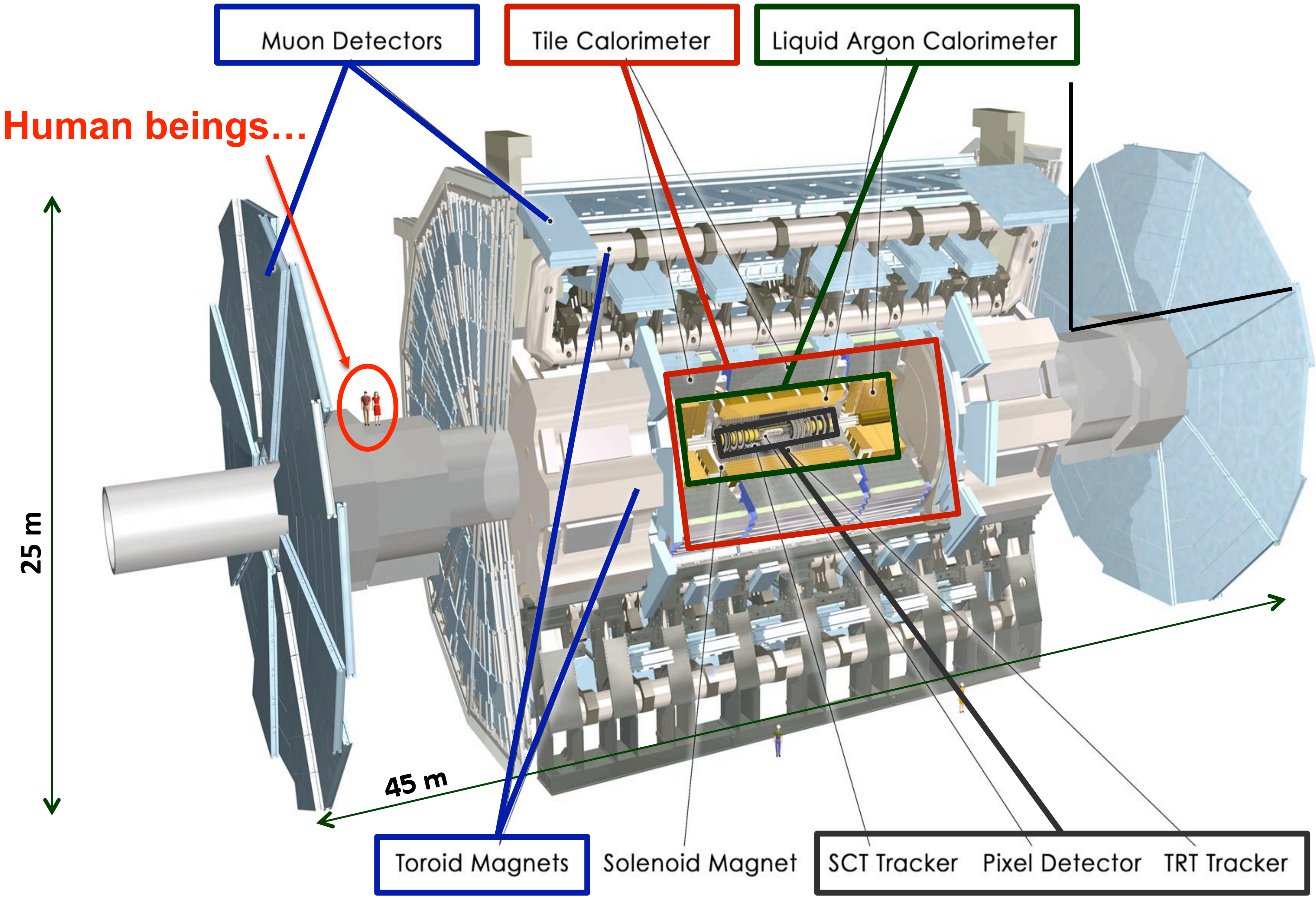
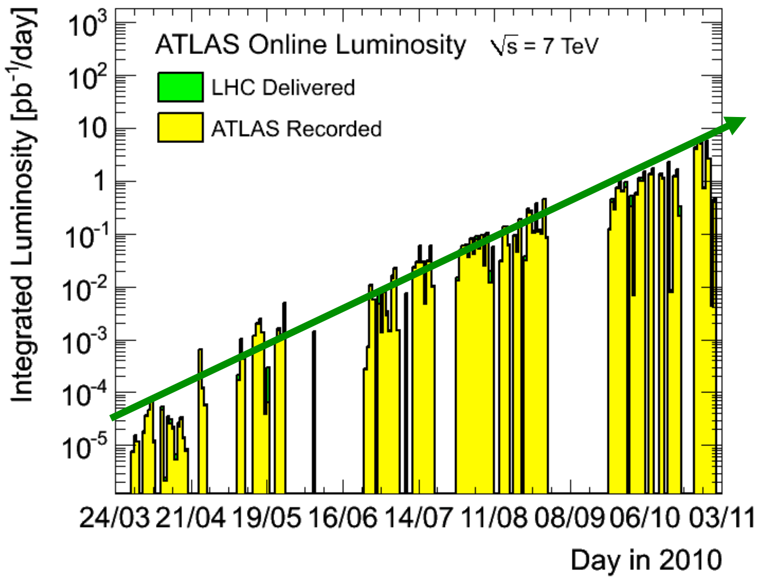
A Toroidal LHC ApparatuS



LHC and ATLAS Performance

Life in a new accelerator is very exciting:

- Integrated luminosity increased almost exponentially during 2010!

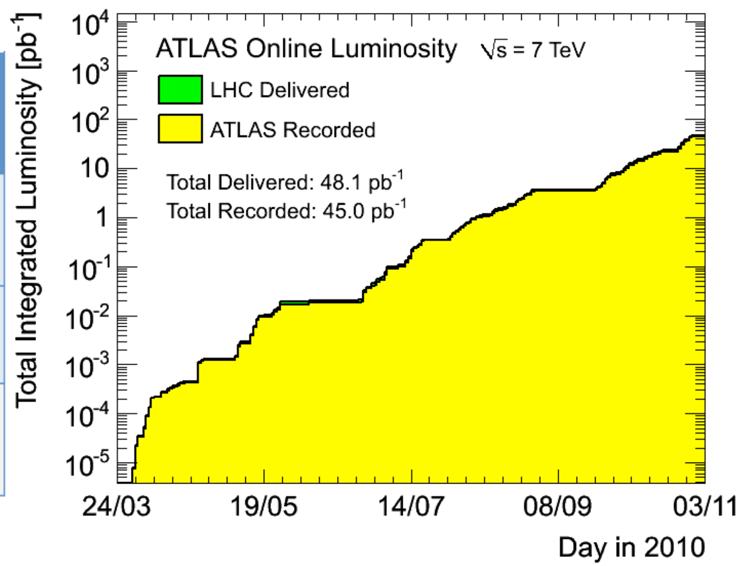


ATLAS operated very well:

- Recorded almost all delivered luminosity
- Sub-systems operational ~100% of time

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at $\sqrt{s}$=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.



The ATLAS Tracker

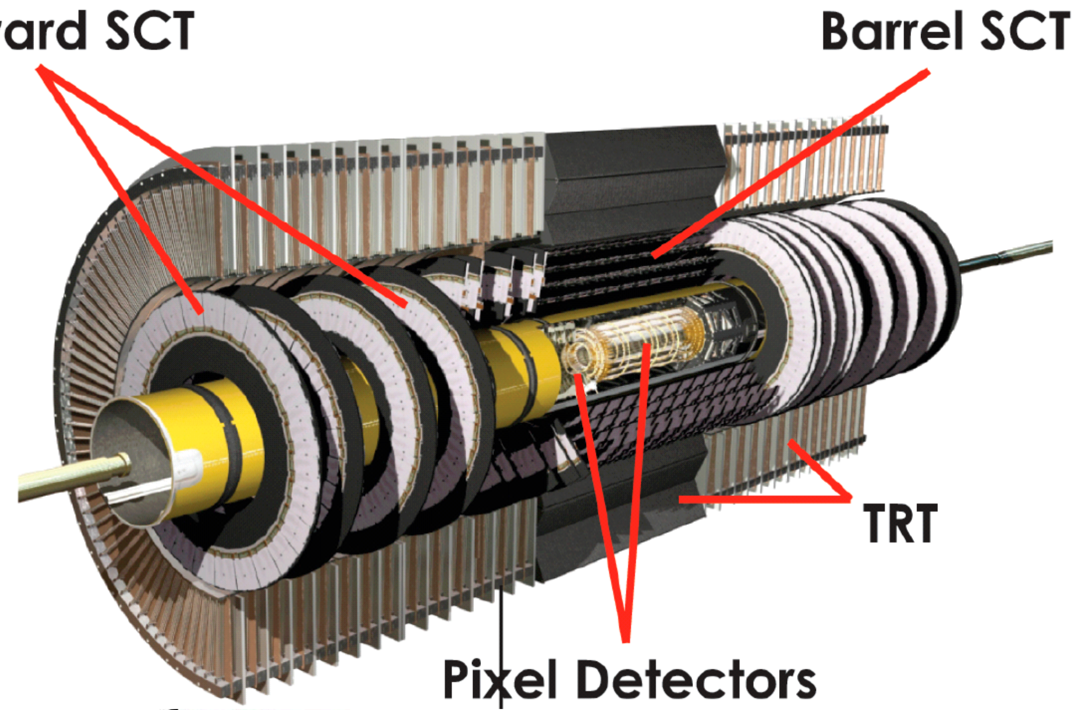
The Inner Detector (ID) is organized into three sub-systems:

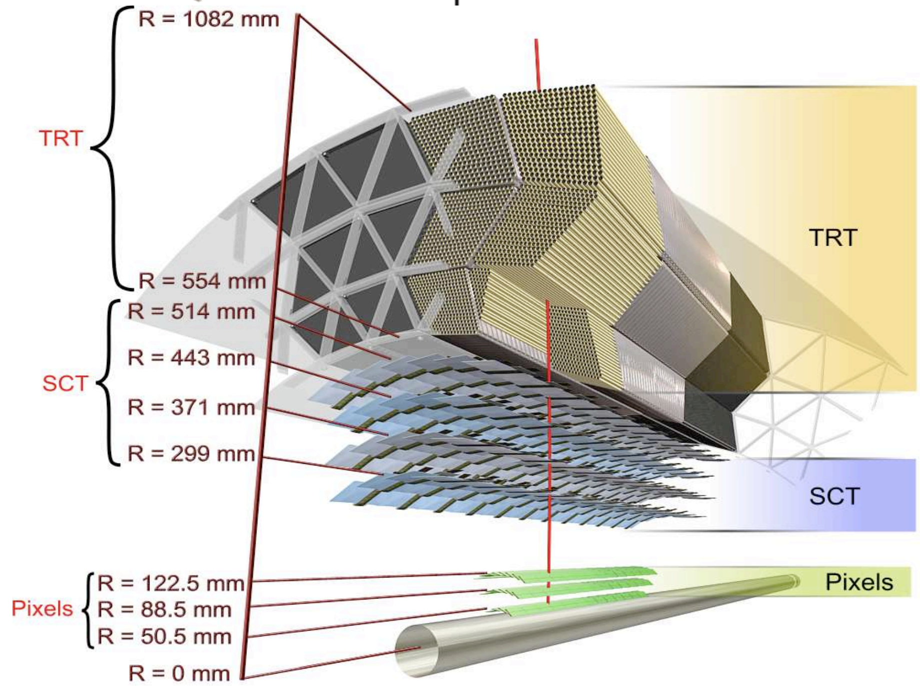
Pixels
- high resolution space points
- 1 removable barrel layer
- 2 barrel layers
- 4 end-cap disks on each side
- ($0.8\ 10^8$ channels)

Silicon Tracker (SCT)
- silicon microstrips
- 4 barrel layers
- 9 end-cap wheels on each side
- ($6\ 10^6$ channels)

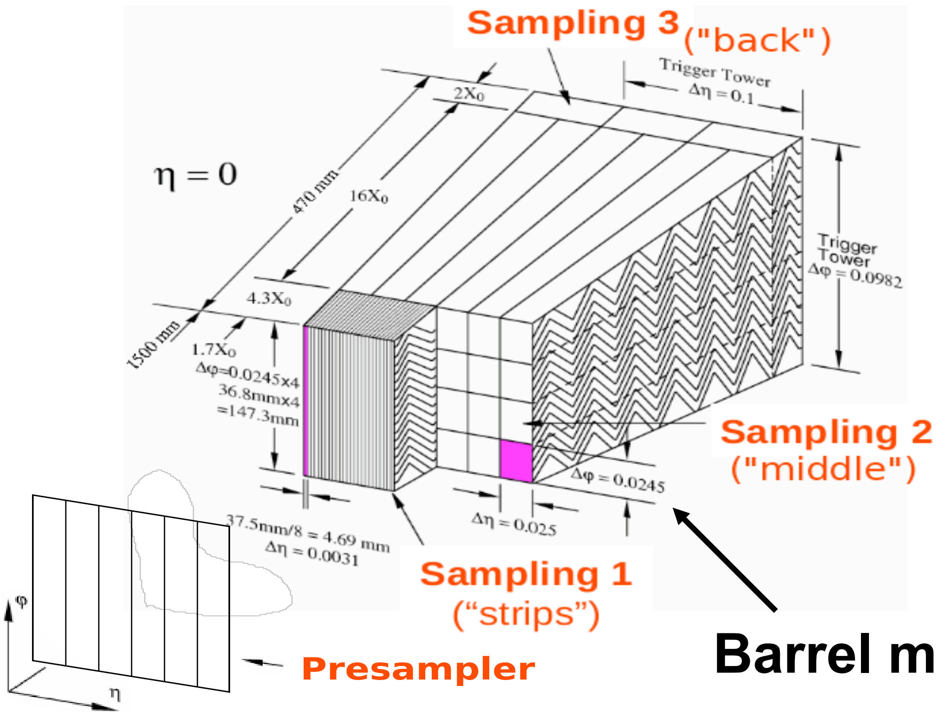
Transition Radiation Tracker (TRT)
- Axial barrel straws
- Radial end-cap straws
- Interleaved with polypropylene radiator
- ~35 straws per track
- ($4\ 10^5$ channels)
- electron PID capability

Total coverage $|\eta| < 2.5$

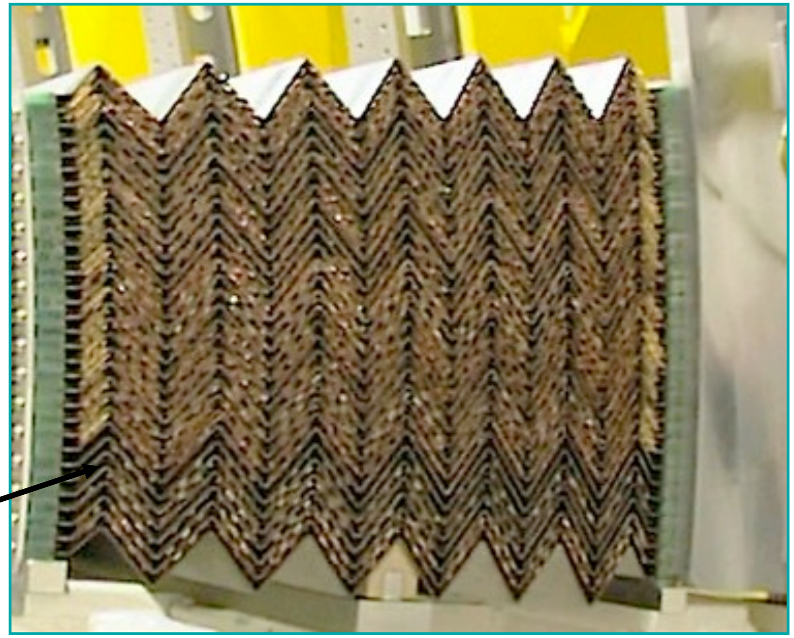




LAr EM Calorimeter description



Barrel module



EM Calo (Presampler + 3 layers):

- Presampler 0.025×0.1 (η×φ)
  ⇒ Energy lost in upstream material
- Strips 0.003×0.1 (η×φ)
  ⇒ optimal separation of showers in non-bending plane, pointing
- Middle 0.025×0.025 (η×φ)
  ⇒ Cluster seeds
- Back 0.05×0.025 (η×φ)
  ⇒ Longitudinal leakage

- LAr-Pb sampling calorimeter
- Accordion shaped electrodes
- Fine longitudinal and transverse segmentation
- EM showers (for $e^{\pm}$ and photons) are reconstructed using calorimeter cell-clustering
- Totla coverage |η|<3.2(precision <2.5)

Overview of the ATLAS Track Reconstruction

- The combination of precision trackers at small radii with the TRT at a larger radius allows for a robust pattern recognition and high precision measurements at both the R-ϕ and R-z planes

- Charged particles with p_T>0.1 GeV and $|\eta|$<2.5 are reconstructed

- A three-step reconstruction sequence is in place:
    - Inside-out tracking seeded by precision hits and developing outwards towards the larger radii
        - Efficient reconstruction of charged particles originating at the primary vertex
        - Precision hits ensure high efficiency in reconstructing tracks in dense environments, e.g. jets
    - Outside-in tracking seeded by TRT straw hits and moving inwards towards the precision layers
        - Efficient reconstruction of charged particles from long lived particle decays (V0s, conversions)
        - Second-pass sequence for improving the efficiency of the inside-out tracking
    - Stand-alone TRT tracking for charged particles created at larger radii in the tracker
        - Reconstruct all charged particle tracks that do not have Si hits assigned to them
        - Common seeding with the outside-in track reconstruction

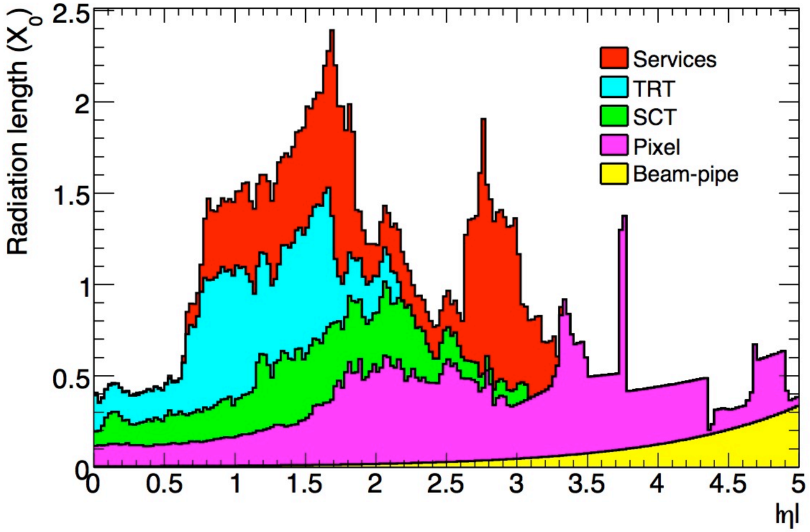
- A dedicated low-p_T tracking option is in place for charged particles with 100 MeV < p_T < 500 MeV
    - Pattern recognition within the pixel and Si-strip detectors, no TRT counterpart

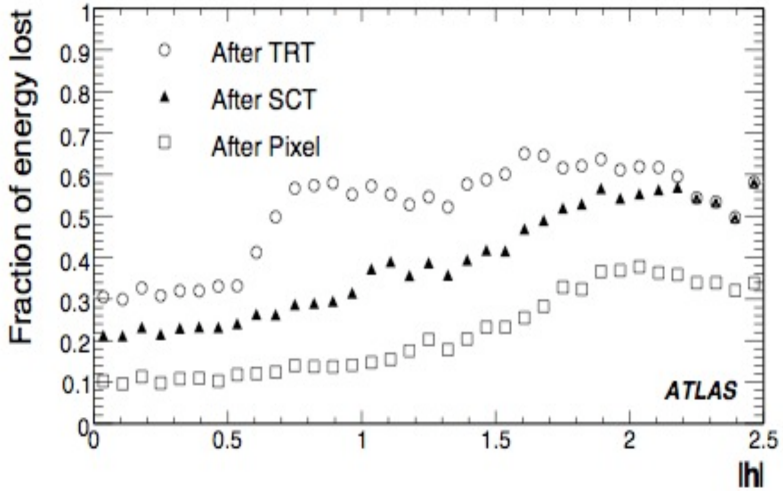
- The above algorithms are applied sequentially in the order listed here

- All tracks reconstructed by the algorithms described above are stored in one container
    - Common event model (EDM) allows for that
    - Author label can provide the method used for reconstructing the track in question

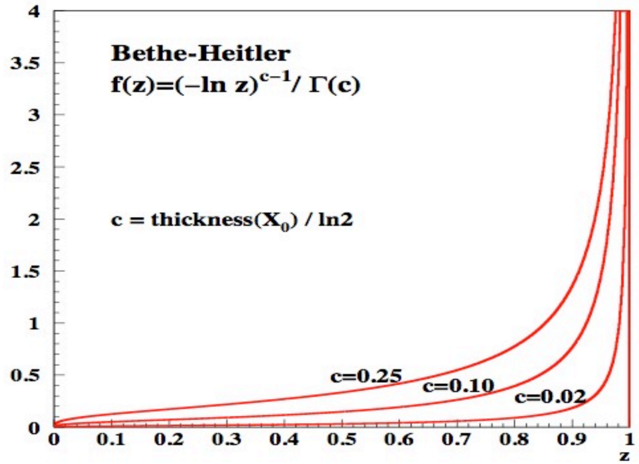
Electron Track Reconstruction

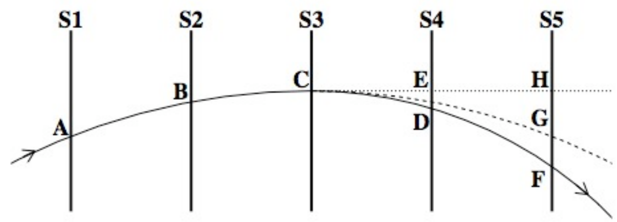
- Reconstruction of electrons (and converted photons) a particular challenge in ATLAS
  - Unprecedented amount of material in tracker traversed by electrons





- Transition Radiation Tracker (TRT) provides particle identification capabilities
  - Separation of electrons from pions or muons possible
- Track or calorimeter based bremsstrahlung recovery algorithms improve track parameters
- Energy loss due to bremsstrahlung described by Bethe-Heitler





Electron retains its direction of propagation

Bremsstrahlung Corrections

- Dynamic Noise Adjustor (DNA)
  - If bremsstrahlung activity retained energy is estimated
  - Used to calculate effective system noise

$$\sigma_{DNA}(z) = \frac{\Delta z}{\Delta x}$$

  - Added as additional noise during track fit

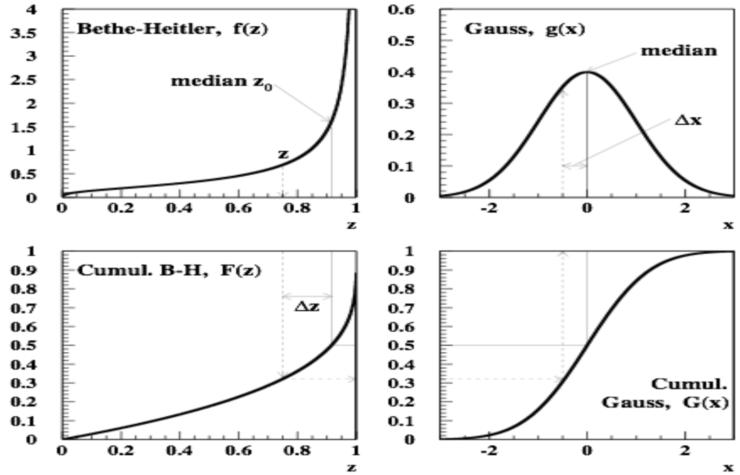
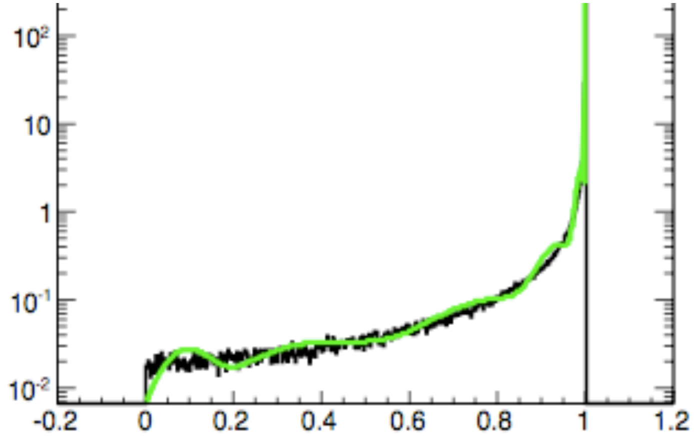
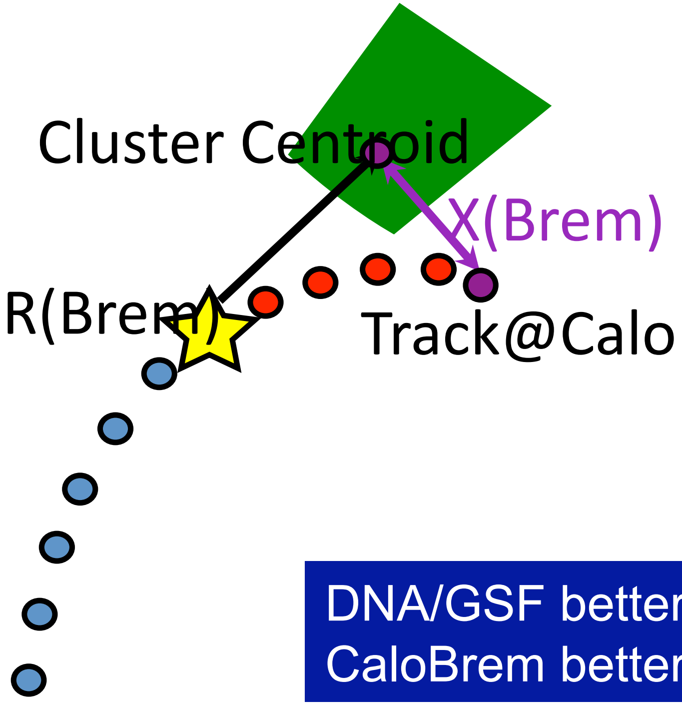


Figure 4. *Mapping of probability distributions used to calculate the variance of the effective noise term.*

- Gaussian Sum Filter (GSF)
  - Bethe-Heitler distribution approximated by Gaussians
  - Track parameters convolved with PDF for material effects



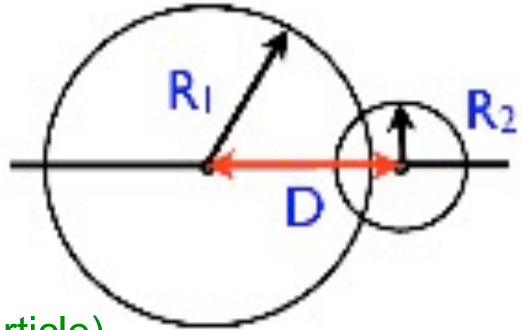


- Calo Brem
  - Track fit incorporates calorimeter cluster
  - Requires good calorimeter-tracker alignment

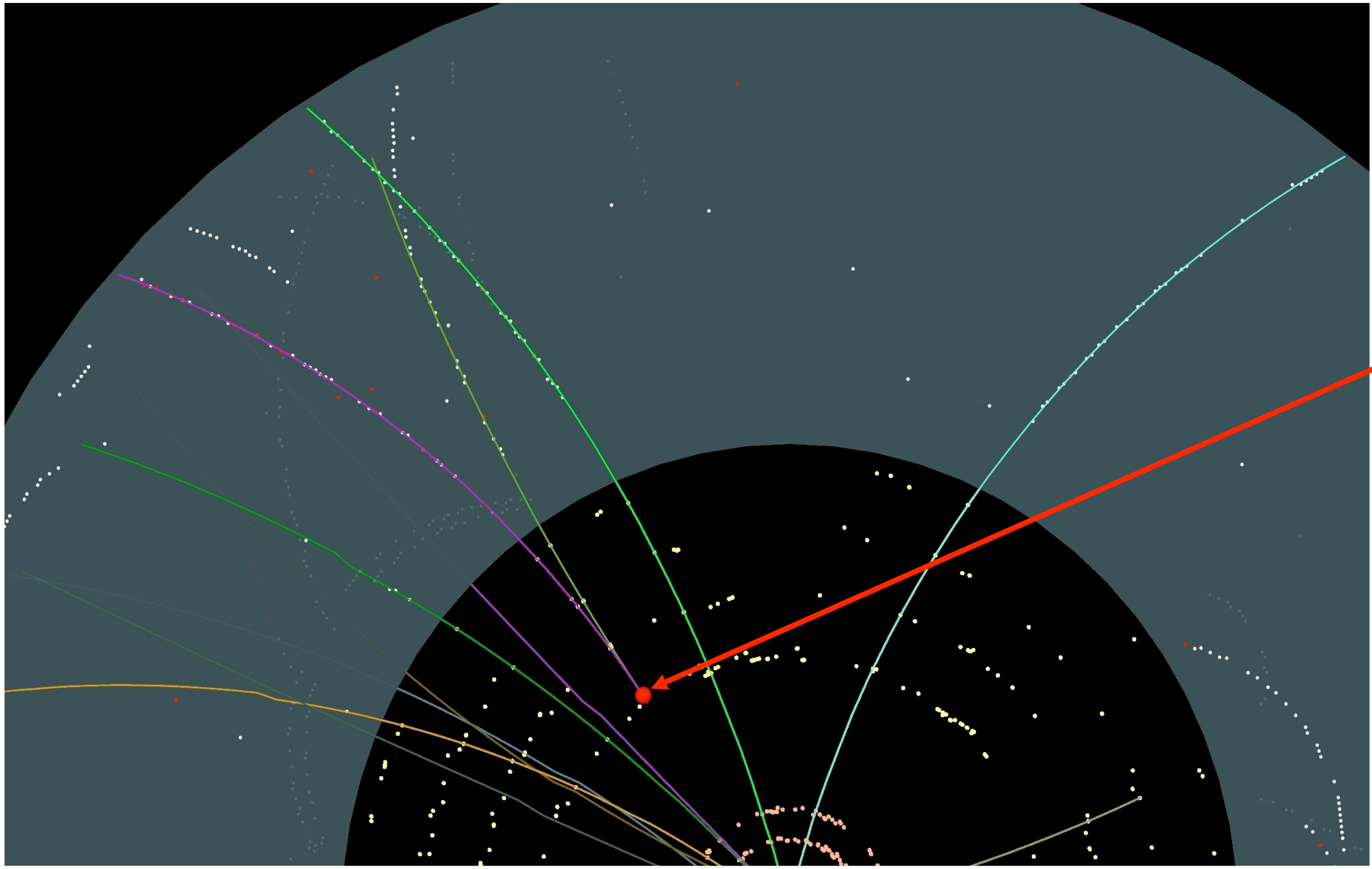
DNA/GSF better performing for low-p_T tracks (<10 GeV)
CaloBrem better performing for high-p_T tracks (> 20 GeV)

Converted Photon Reconstruction

- Tracks are selected based on their particle identification probability for being electrons
- Pairs are formed using opposite charge tracks
- Track pairs are selected according to the following criteria:
    - Distance of minimum approach between the two tracks in the pair
    - Opening angles in θ and ϕ
    - D-R1-R2 as shown in the figure



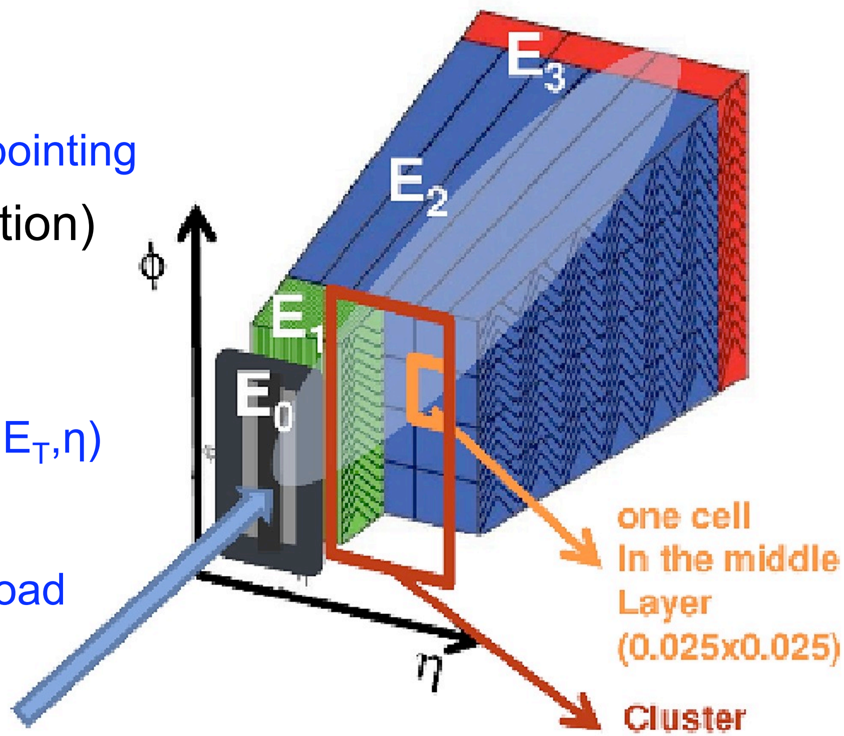
- Selected pairs are passed to the vertex fitter:
    - Constrained fit where Δθ=Δϕ=0 is required (equivalent to massless particle)
    - Additional selection using the fit χ^2



Converted photon event display from a 900 GeV data run

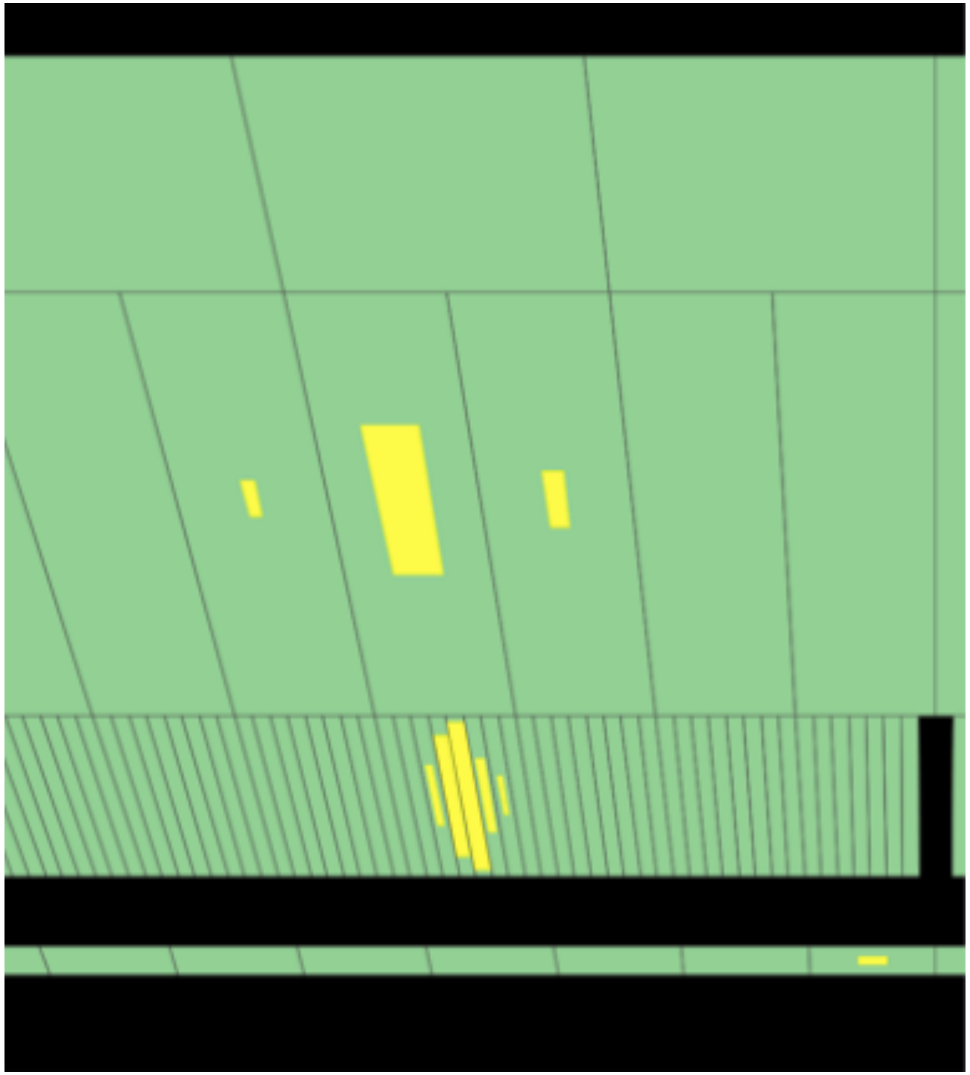
Combined Electron/Photon Reconstruction

- Search for seed energy clusters in the EM calorimeter with significant energy
  - Seed clusters either rectangular window or result of nearest-neighbor clustering algorithm
- Match cluster with tracks/vertices. Classify as electron, unconverted/converted photon
  - Electron tracks corrected for bremsstrahlung losses
  - Photon conversion vertices formed by opposite charged electron tracks
- Form cluster from cells in a rectangular region around seed
  - Size depends on location and classification
- Calculate energy and direction
  - Energy weighted sum of layer energies
  - Corrected for detector effects
  - Direction provided by track information or cluster pointing
- Particle identification (hadronic background rejection)
  - Discriminating variables based on information from EM calorimeter, tracker, track-to-cluster matching (when applicable)
  - Define reference sets of cuts (optimized in bins of E_T,η)
    - Loose, medium, tight for electrons
    - Loose, tight for converted/unconverted photons
  - EM calorimeter shower shapes carry most of the load
  - Tight cuts result in highest signal purity
    - TRT particularly important at this stage

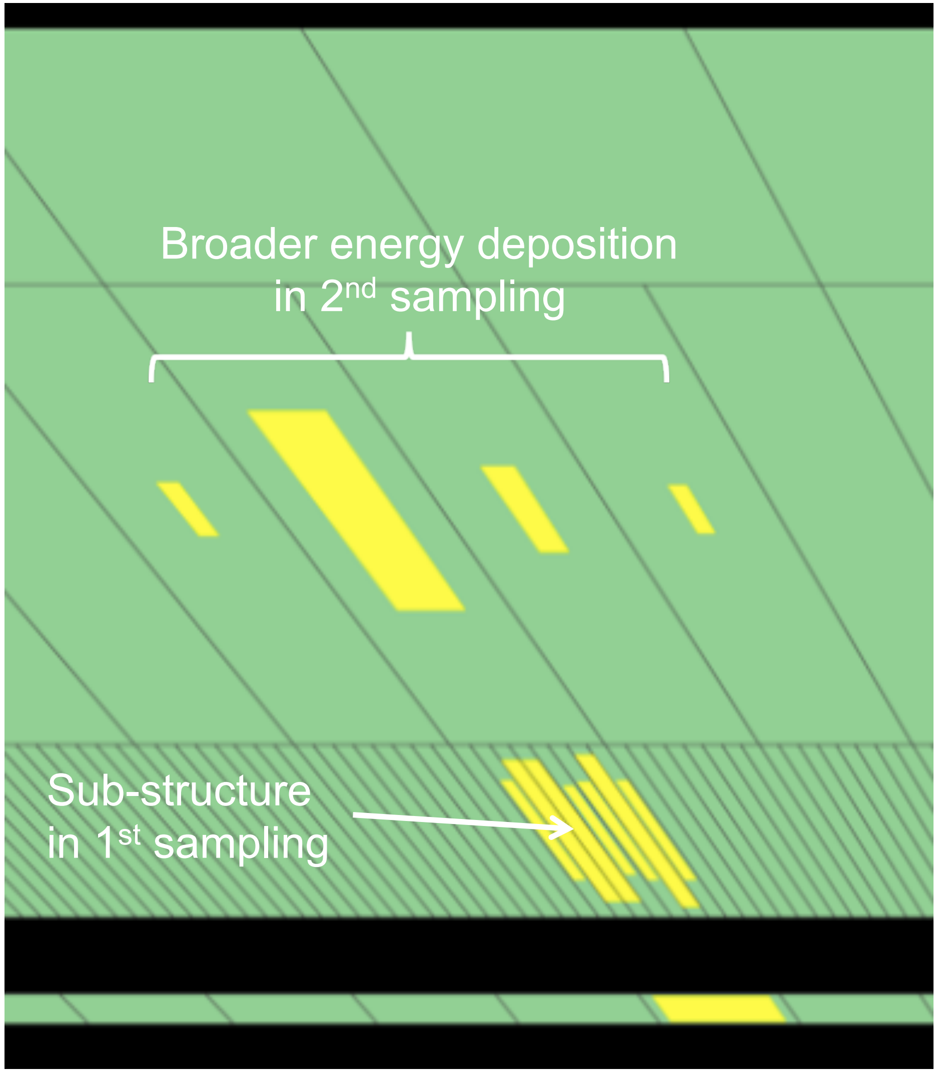


Photon Identification with the EM Calorimeter

Aim: reject jets with one or more π^0 which decay into two photons



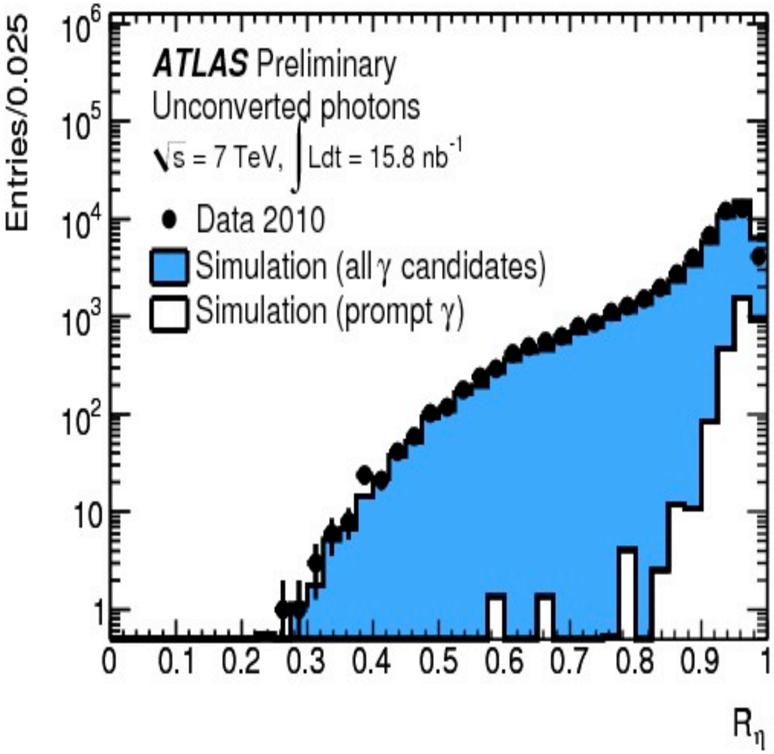
Signal photon candidate E_T=32 GeV

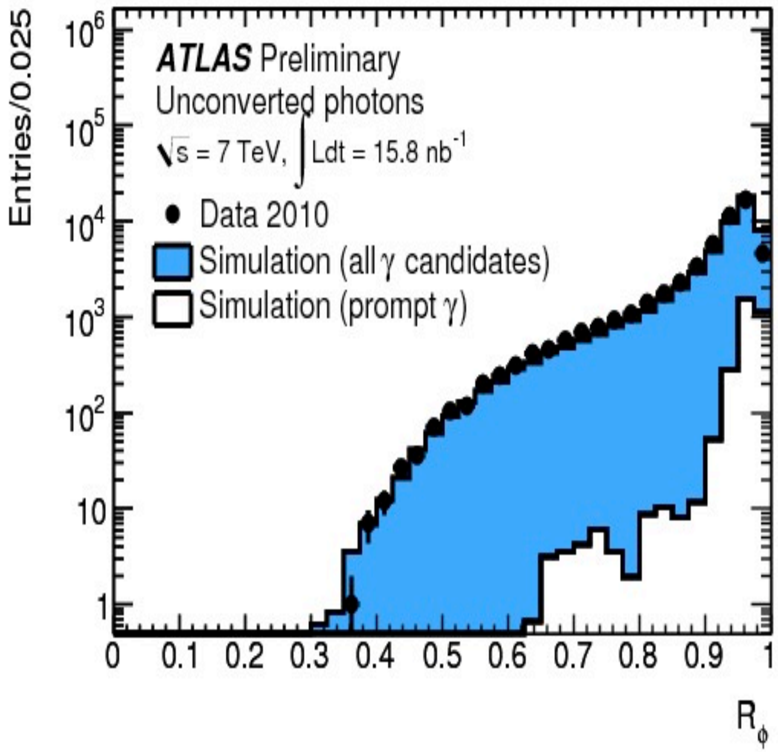


π^0 candidate E_T=21 GeV

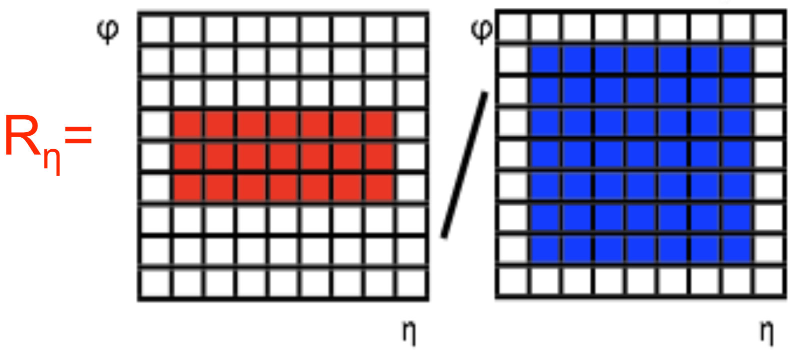
Photon Identification with the EM Calorimeter

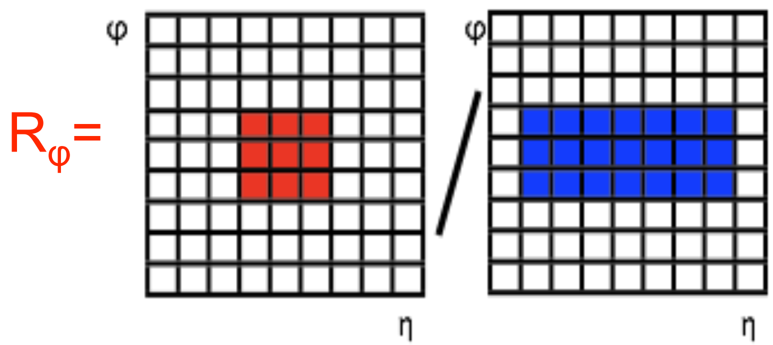
Use first the 2nd sampling





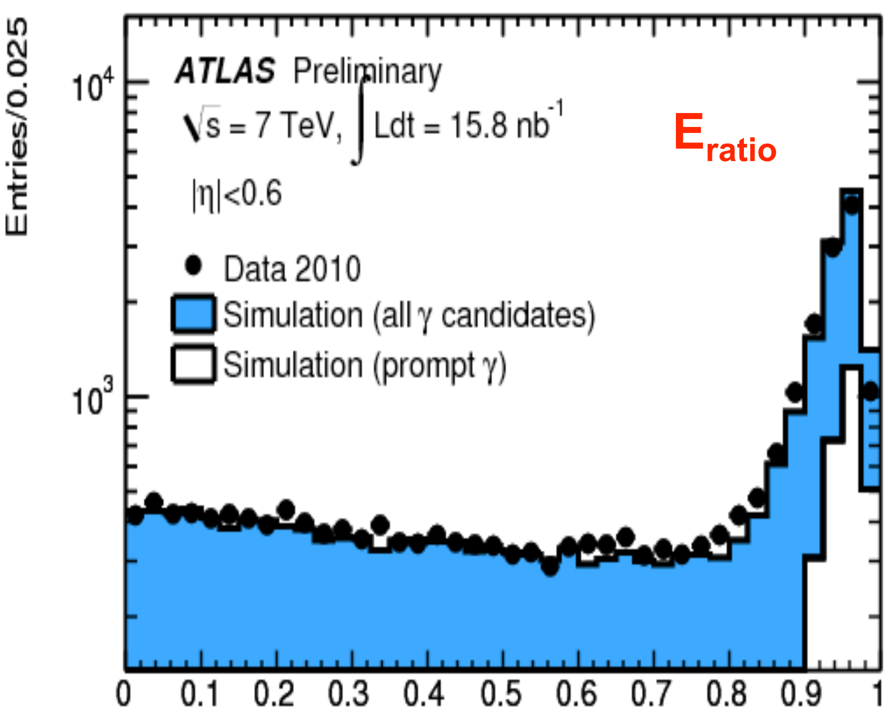
Unconverted photons

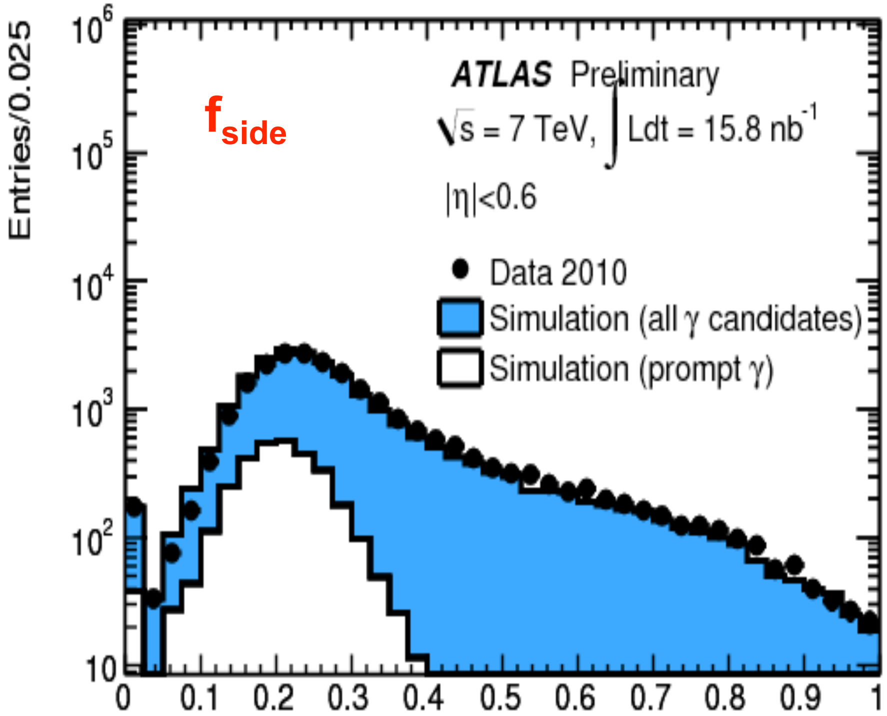


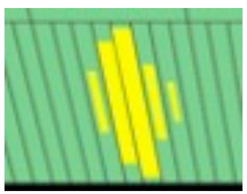


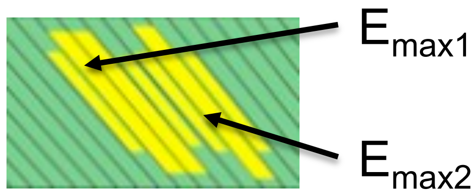
Photon Identification with the EM Calorimeter

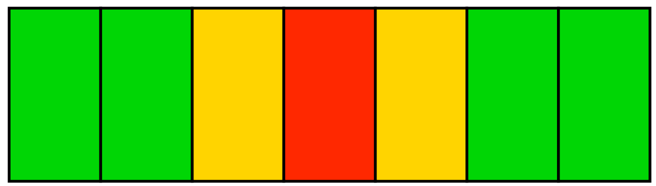
Improve rejection by using shower shapes in 1st sampling











Single Photon

π^0 Photon

Hottest cell

$E_{ratio}= (E_{max1}-E_{max2})/(E_{max1}+E_{max2})$

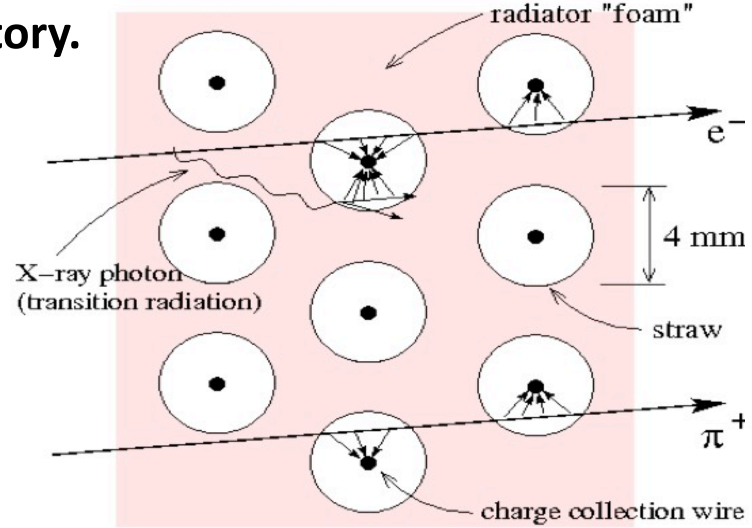
$f_{side} =(E_{\pm3} -E_{\pm1})/E_{\pm1}$

Asymmetry of two energy maxima

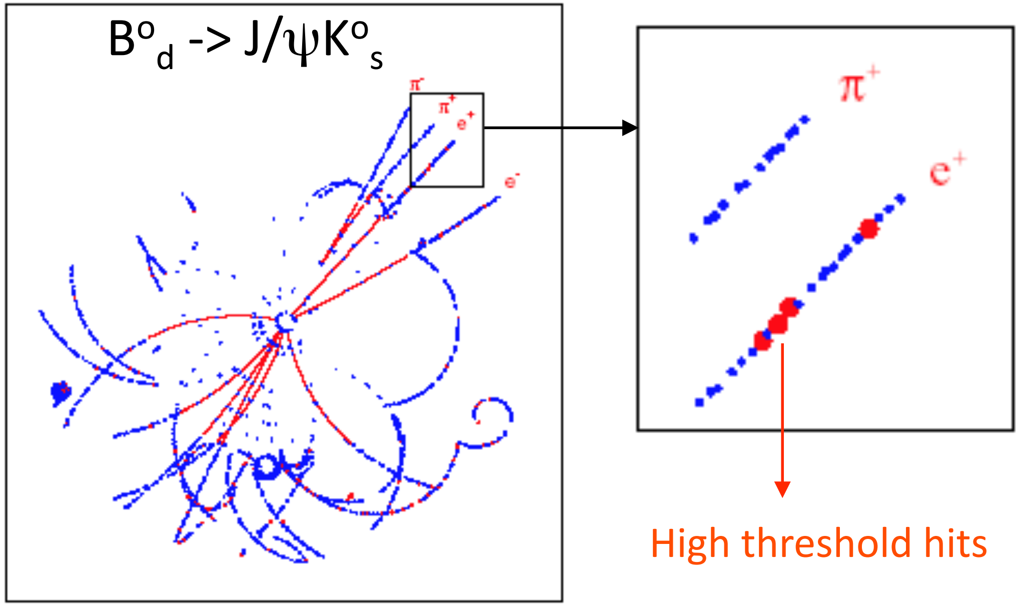
Cluster energy outside core cells

Electron Identification with the TRT

Transition radiation is produced when a charged ultra-relativistic particle crosses the interface between different media, PP (fibres or foils) & air for the TRT. TR photons are emitted at very small angle with respect to the parent-particle trajectory.



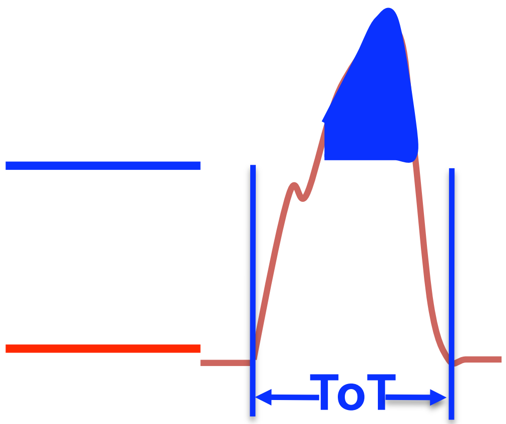
Transition Radiation



Two threshold analysis

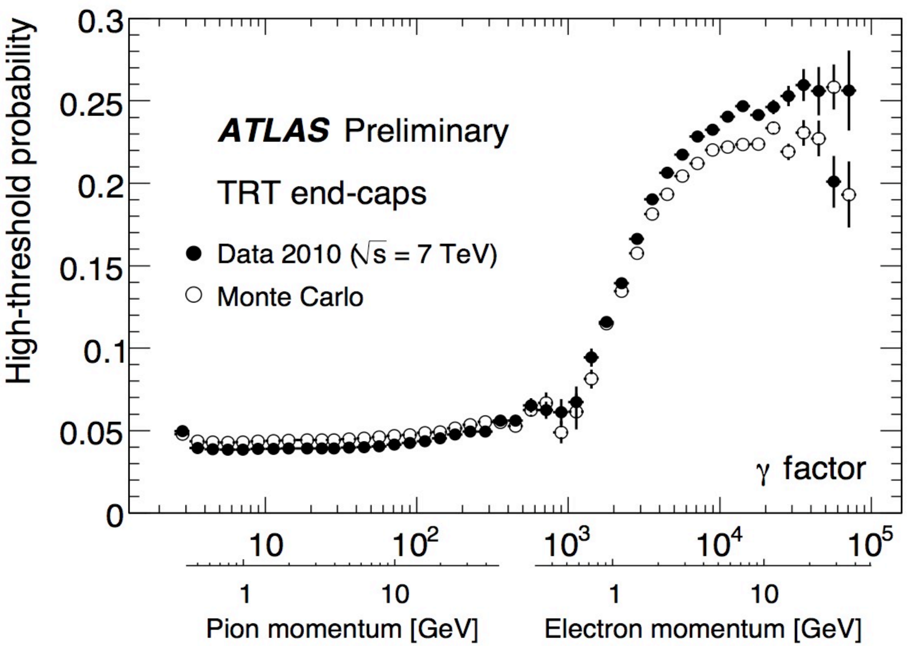
TR threshold – electron/pion separation **5.5 keV**

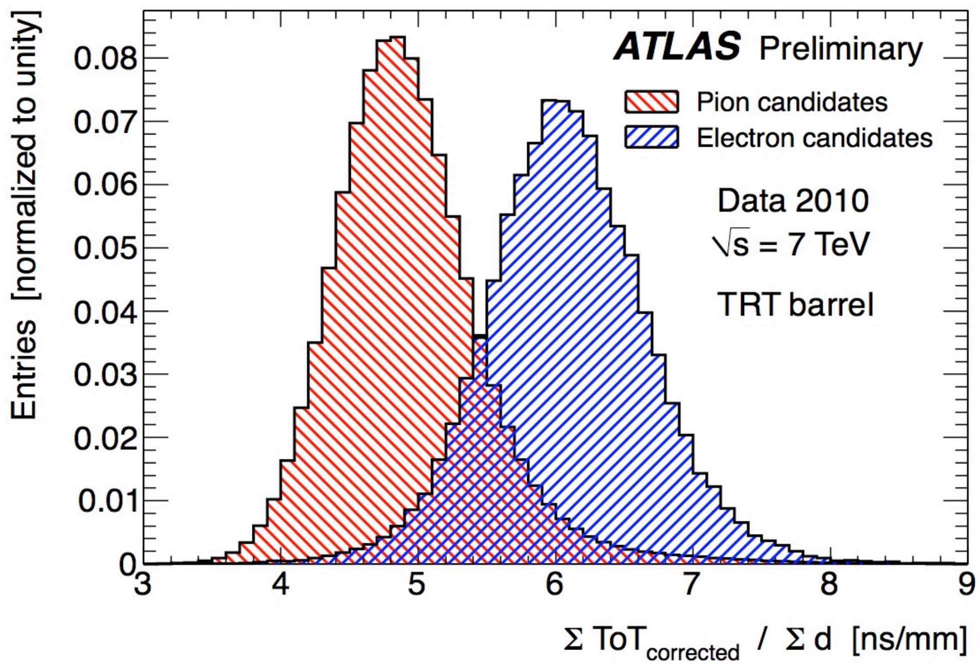
MIP threshold – precise tracking/drift time determination **0.2 keV**



Electron Identification with TRT

- Transition radiation X-rays contribute significantly to the number of high threshold hits
  - True for electrons with energies above 2 GeV
  - Saturation sets in at electron energies above 10 GeV
- Including the Time over Threshold (ToT) could improve the rejection
  - Signal duration above threshold longer for electrons



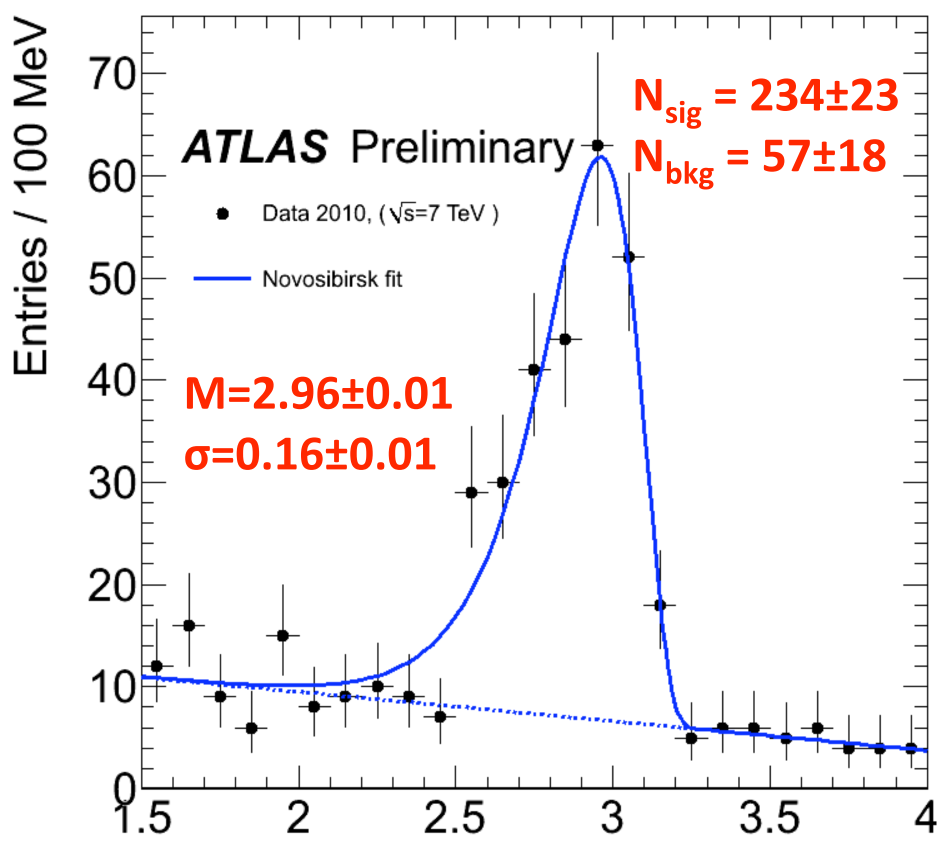


- Set up a likelihood evaluation based on information above (individual or combined)
- At higher energies pions become relativistic and start to emit transition radiation
  - TRT particle identification capabilities are reduced (minimal for pions above ~ 50GeV)
- Transition radiation performance in endcap TRT better than in the barrel

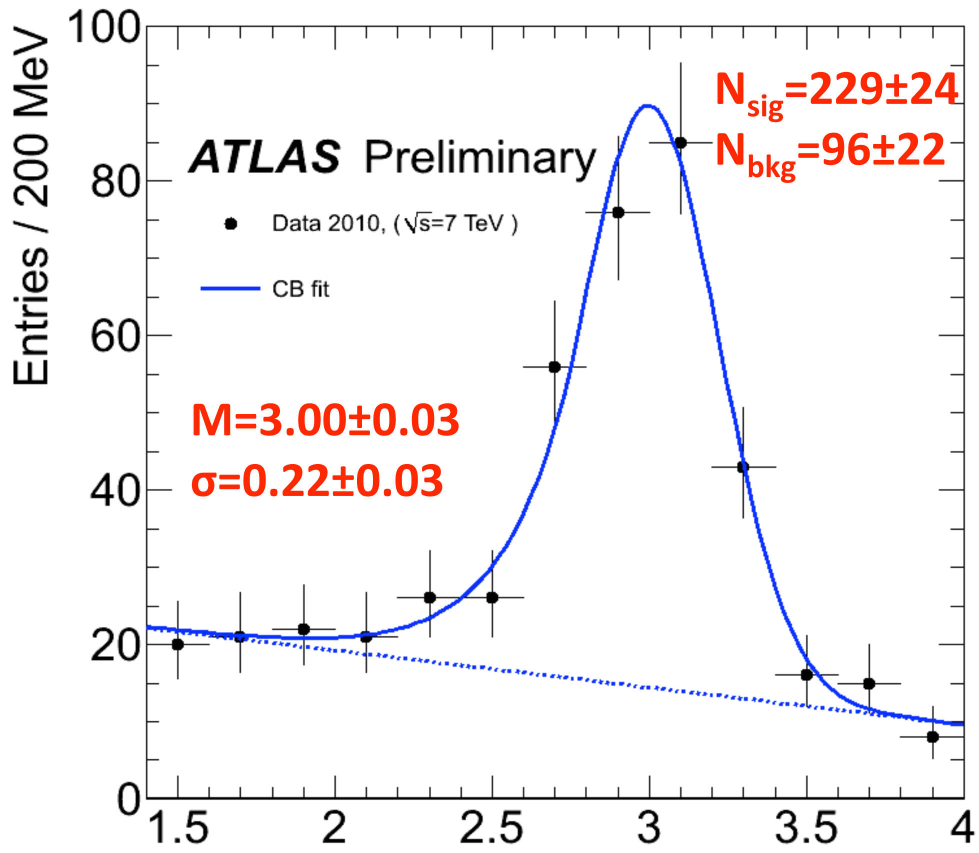
$J/\psi \rightarrow e^+e^-$ Invariant Mass Reconstruction

- Select electron pairs with p_T>4 GeV and p_T>2 GeV respectively
- Reconstruct the invariant mass using tracking information only
  - Mean smaller than known J/ψ mass due to bremsstrahlung tail
- Repeat using energy from EM clusters, direction from tracking
  - Mean smaller than known J/ψ mass due to imperfect calorimeter calibration at low p_T

~78 nb^{-1} data



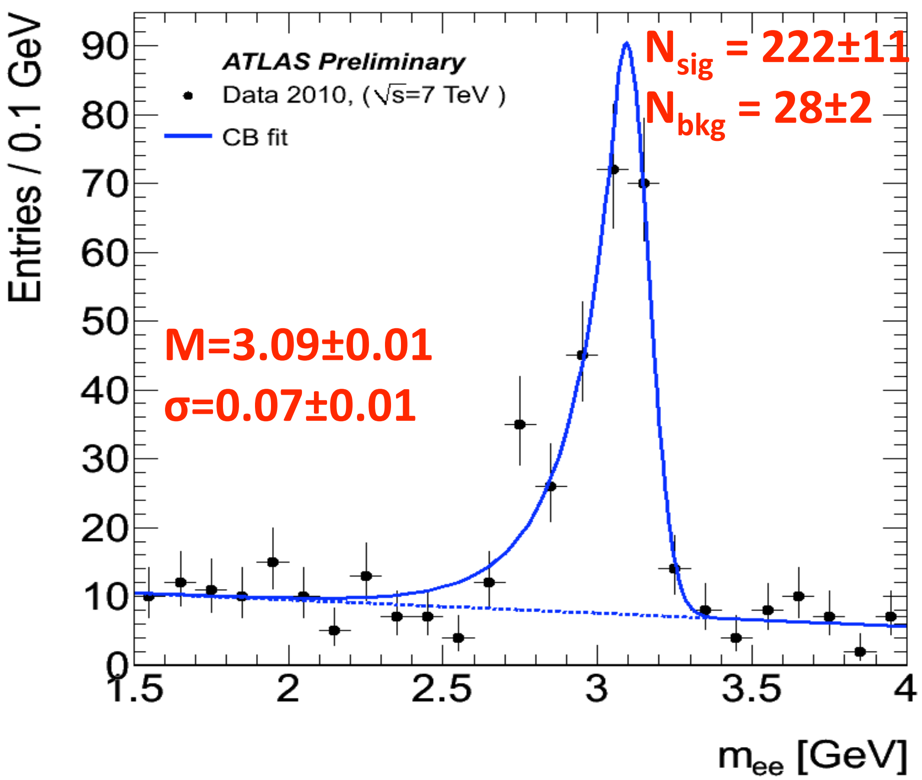
Track information only

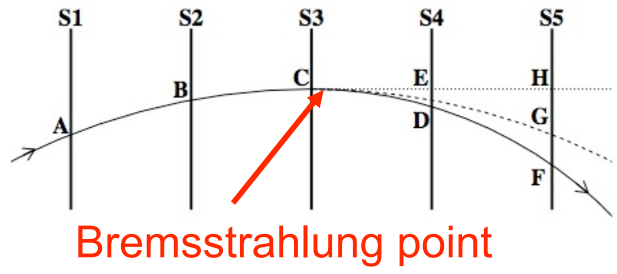


Energy from calorimeter

Bremsstrahlung Correction

- Use track information only after refitting tracks to account for bremsstrahlung losses:
  - Search for kinks along the identified electron trajectory trajectory
  - Energy loss described by Bethe-Heitler distribution
  - Use Gaussian Sum Filter[1] to approximate it with sum of Gaussian distributions
  - Mass resolution improves by more than a factor of 2





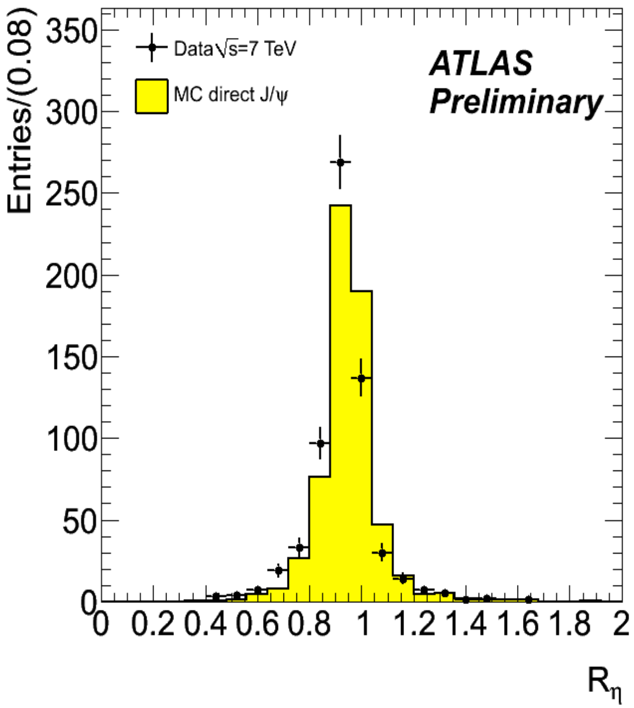
- Up to now only track information utilized
  - Appropriate for soft J/ψ electrons
- In future should be applied to W/Z electrons
  - Harder electrons need CaloBrem
  - Requires good tracker/calorimeter alignment
  - Recently alignment better for it to be tried

PDG average m(J/ψ) = 3.097 GeV

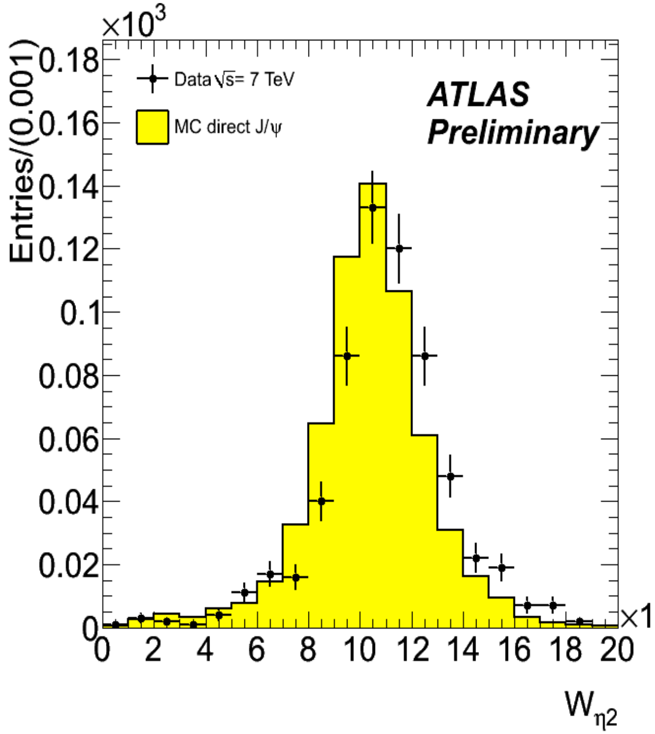
[1] R. Frühwirth, Comp. Phys. Comm. **100** (97); T. Atkinson, PhD Thesis, U. Melbourne (06)

Shower Shapes of J/ψ Electrons

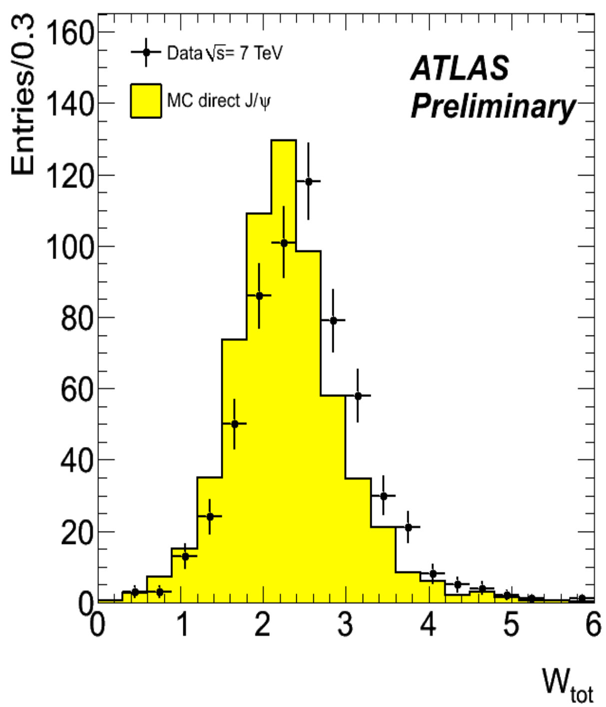
- The J/ψ signal provides a sample of real electrons that can be used to check the modeling of electron discriminating variables by the detector simulation
  - Important for evaluating systematic uncertainties on electron identification
- Use a tag&probe approach:
  - Maintain tight selection on the tag electron (p_T>4 GeV, cluster E_T>2.5 GeV, f_{TR}>0.18)
  - Remove shower shape selection criteria from the other probe electron
- Select electron pair candidates with 2.7 GeV < m_{ee} < 3.2 GeV
- Differences between data and MC are visible



R_η=E(3×7)/E(7×7)



Cluster η width: Layer 2

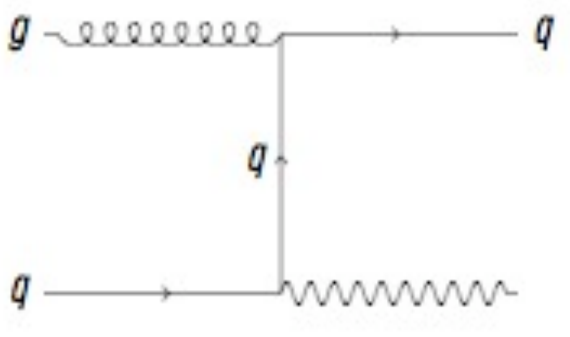


Cluster η width: Layer 1

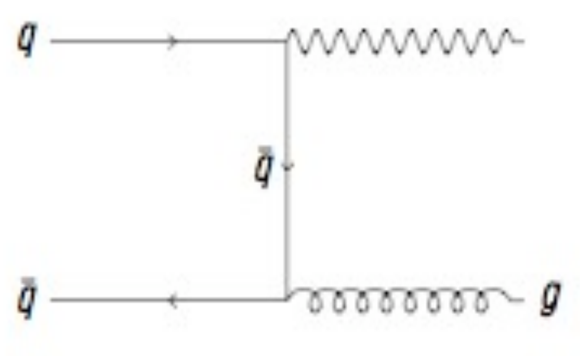
Direct Photon Production

Why direct photons?

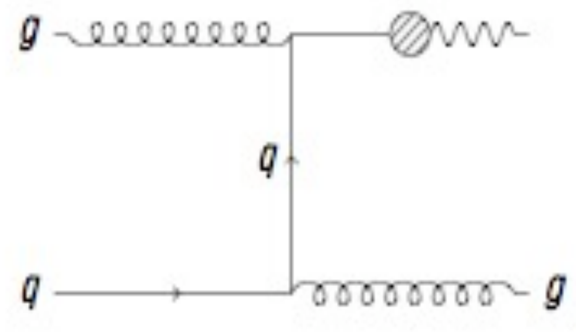
- One of the first measurements in ATLAS that identifies/uses photons
  - Learn about the photon reconstruction
- Provide a clean probe of the gluon composition of the proton
- Single- and di-photons are important components of some SM/BSM analyses:
  - $H \longrightarrow \gamma\gamma$ will be important for low mass Higgs
  - GMSB in SUSY
  - Graviton searches, high-mass di-photon resonances



Compton scattering



Quark annihilation



Fragmentation

- Signal is composed of “direct” and “fragmentation” processes:
  - Direct part is dominated by Compton process at LHC
  - Fragmentation part more significant at low E_T
  - Reduce QCD background by imposing isolation requirement
- Primary background is from real photons (e.g. $\pi^0 \longrightarrow \gamma\gamma$)

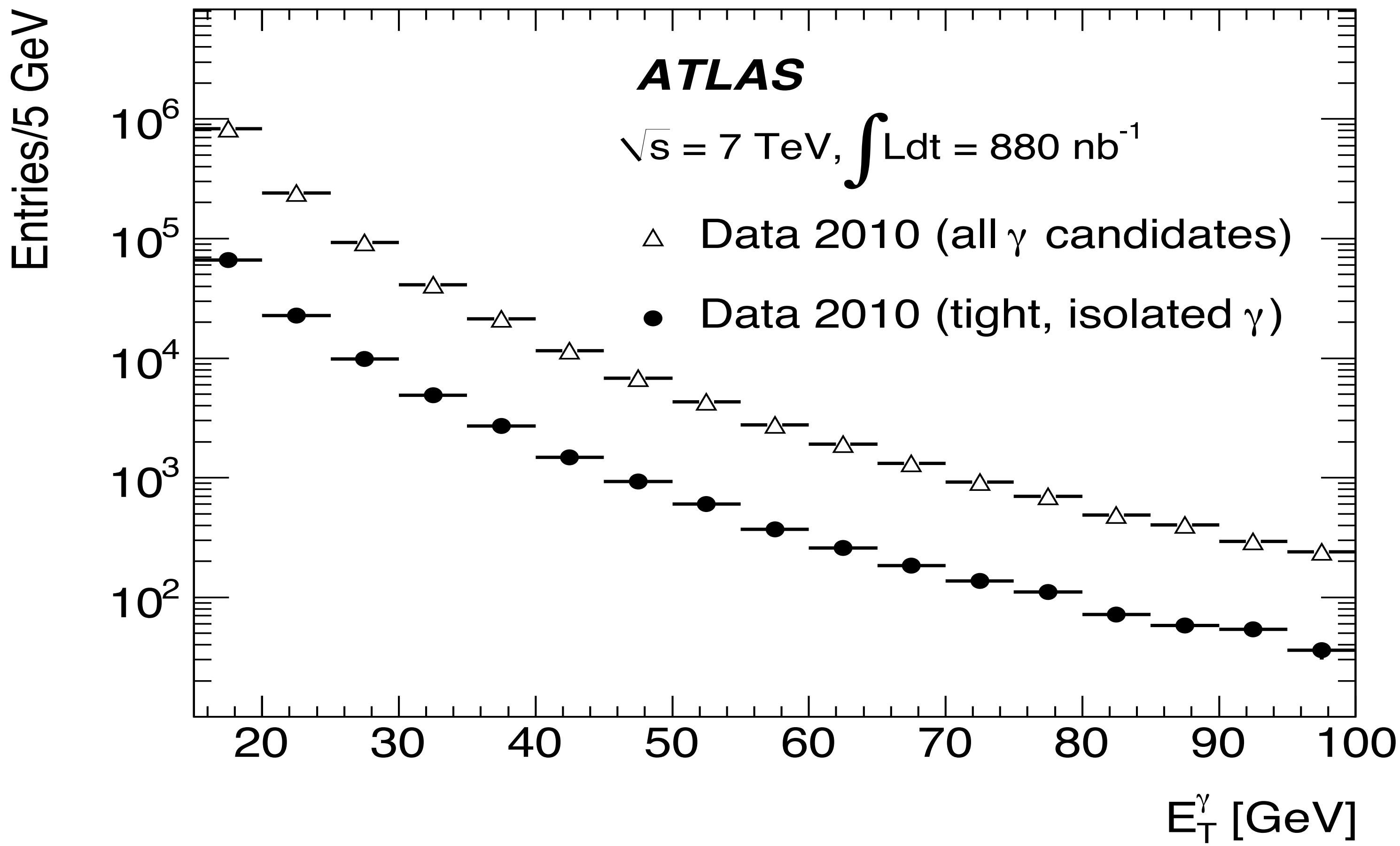
Direct Photon Spectrum

Initial selection:

- Photon cluster E_T>10GeV
- Remove reconstructed photons in problematic regions in calorimeter

Tight selection:

- Additional selection criteria using shower shower shapes in 1st sampling of the EM calorimeter.



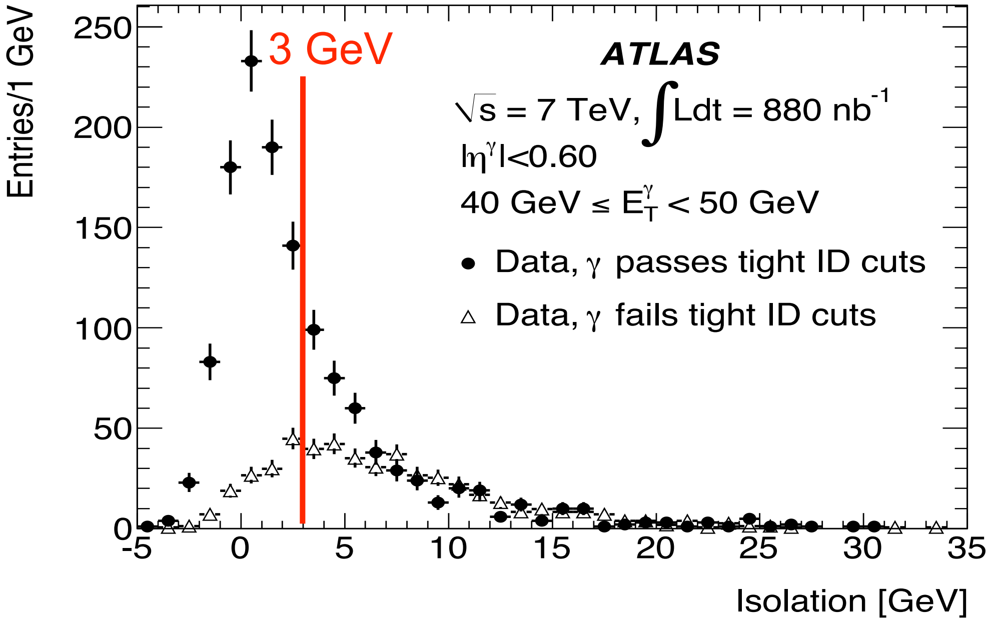
Calorimeter Cluster Isolation

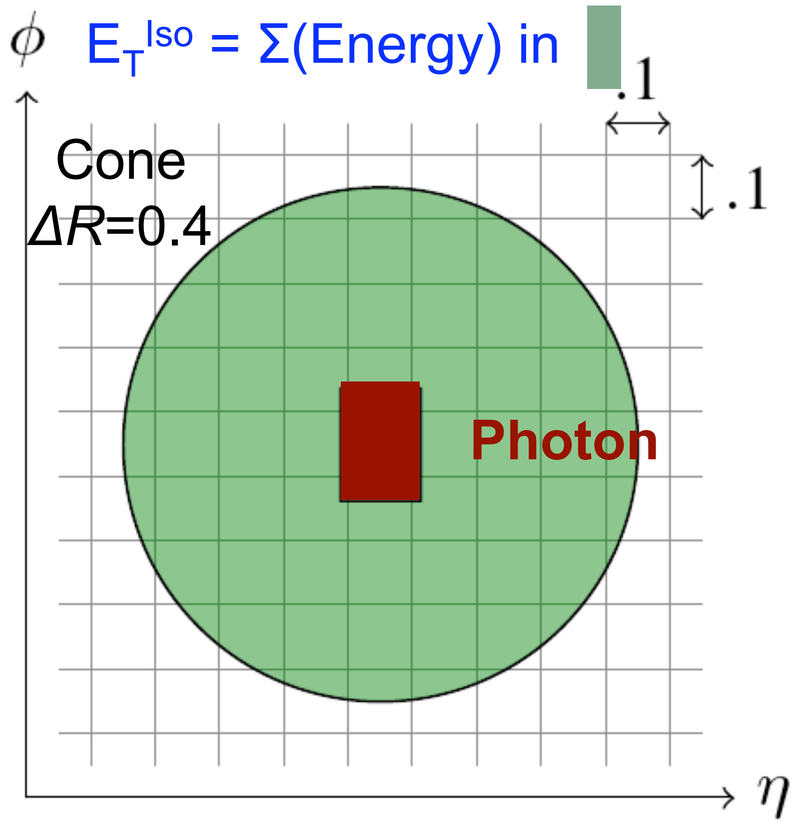
- Direct photon signal more isolated from hadronic activity than background from π^0
- Cluster isolation defined as energy deposited in a cone ΔR defined as:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$$

where the photon candidate energy itself is not included in the computation

- To better model it corrections are applied:
  - Photon E_T corrections to account for energy leakage outside the cone of interest
  - Corrections to remove residual activity from underlying events, pileup etc.[1]
- Signal region: $E_T^{Iso} < 3$GeV





~110k photons after "tight" photon selection and cluster isolation cut in 880 nb^{-1} data

Direct Photon Identification Efficiency

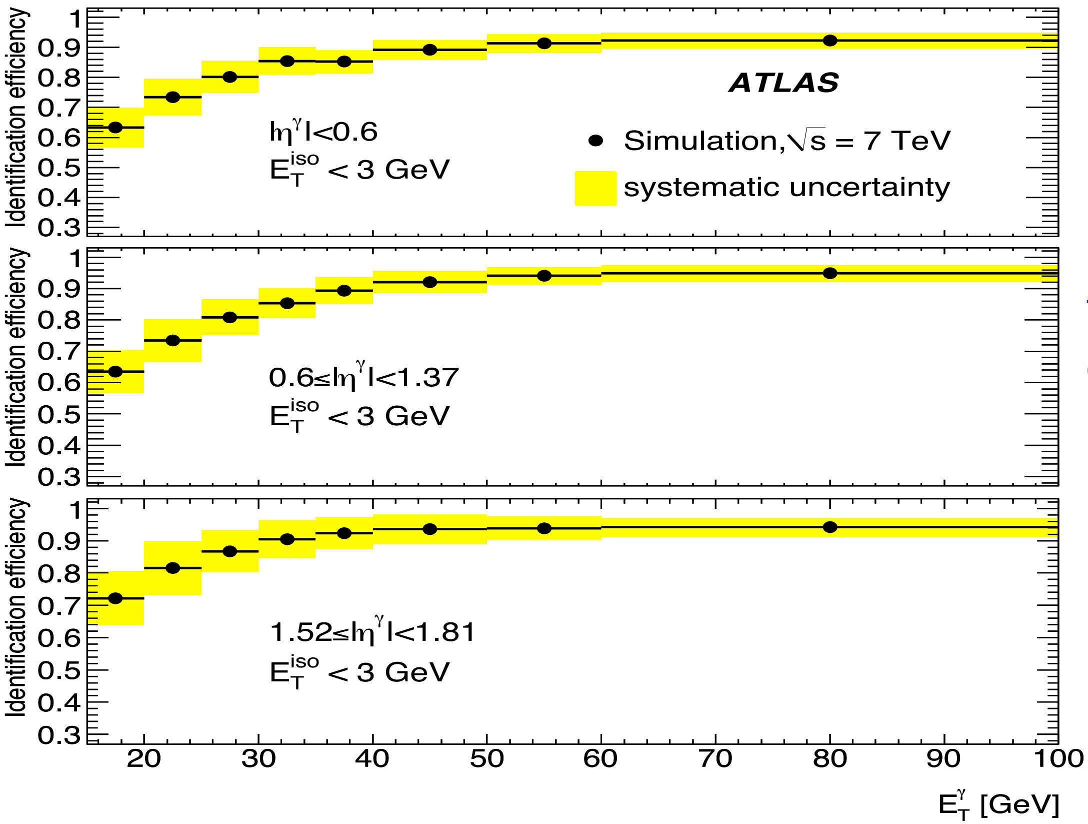
Photon identification efficiency (ε) determined from simulation after:

- "Tight" selection
- Cluster isolation at < 3 GeV

Consists of 3 individual efficiencies:

1. Trigger ε_{Trig} : Need to trigger in order to reconstruct a photon-high ~100% at E_T>15GeV
2. Reconstruction ε_{Rec} : Need to reconstruct a photon before identification-stable ~82%
3. Prompt photon identification ε_{ID}-varies with photon pseudorapidity η

Therefore $\varepsilon = \varepsilon_{Trig} \times \varepsilon_{Rec}\, \varepsilon_{ID}$

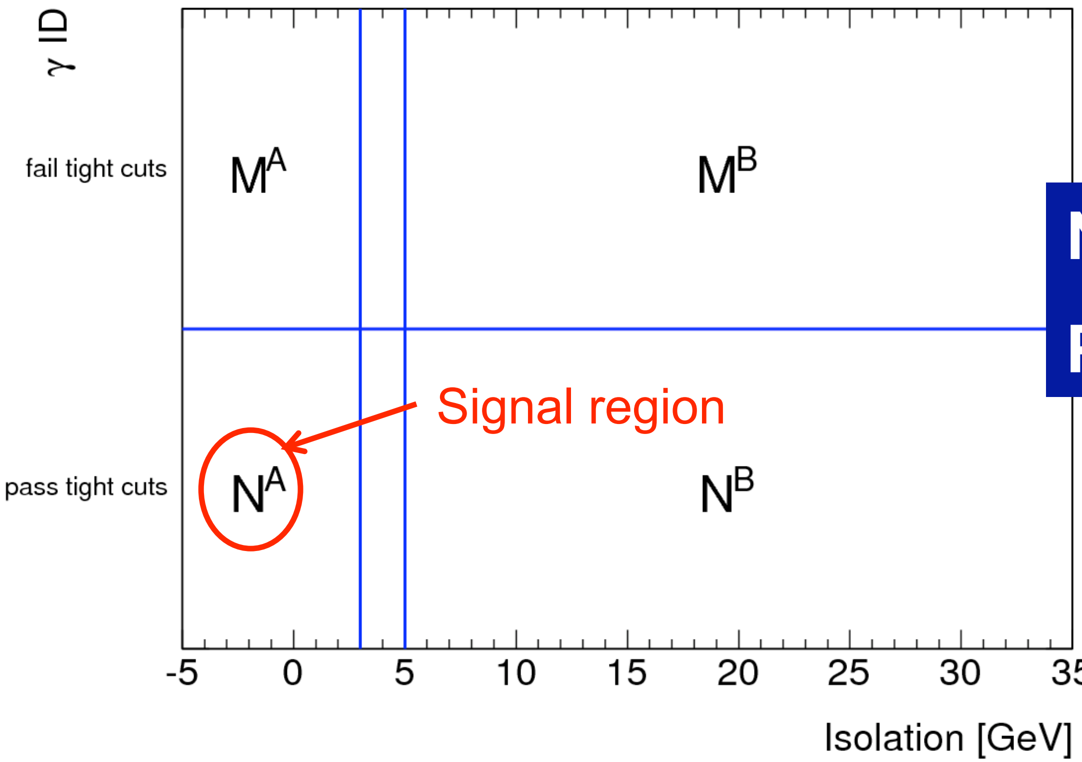


Main source of uncertainty (systematic) the accuracy with which the simulation describes the experimental conditions:

- Direct vs. fragmentation photons
- Calorimeter response
  - Shower shape development
- Amount of material in front of calorimeter

Purity Estimation: 2D Sidebands

- Simulation cannot be trusted to accurately predict the fake rate
- Use the cluster isolation and shower shapes in 1st layer
- Define as signal, photons that pass the 1st layer shower shape and isolation criteria
- Define as background, photons that fail any of the two
- Assumptions:
  - Signal contribution to background regions negligible
  - For background, isolation independent of shower shapes in first calorimeter layer



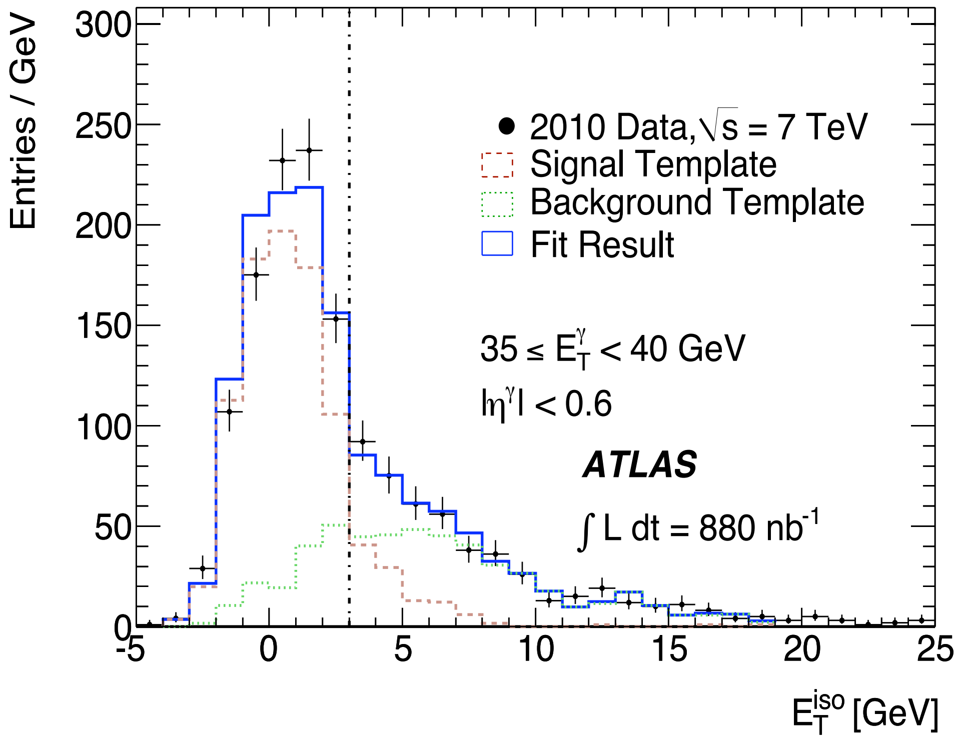
$$N^A_{Sig} = N^A - N^B\, M^A/M^B$$

$$P = 1 - (N^B/N^A_{Sig})\,(M^A/M^B)$$

Assumptions above don't hold exactly; corrections are applied, uncertainties part of the error estimation

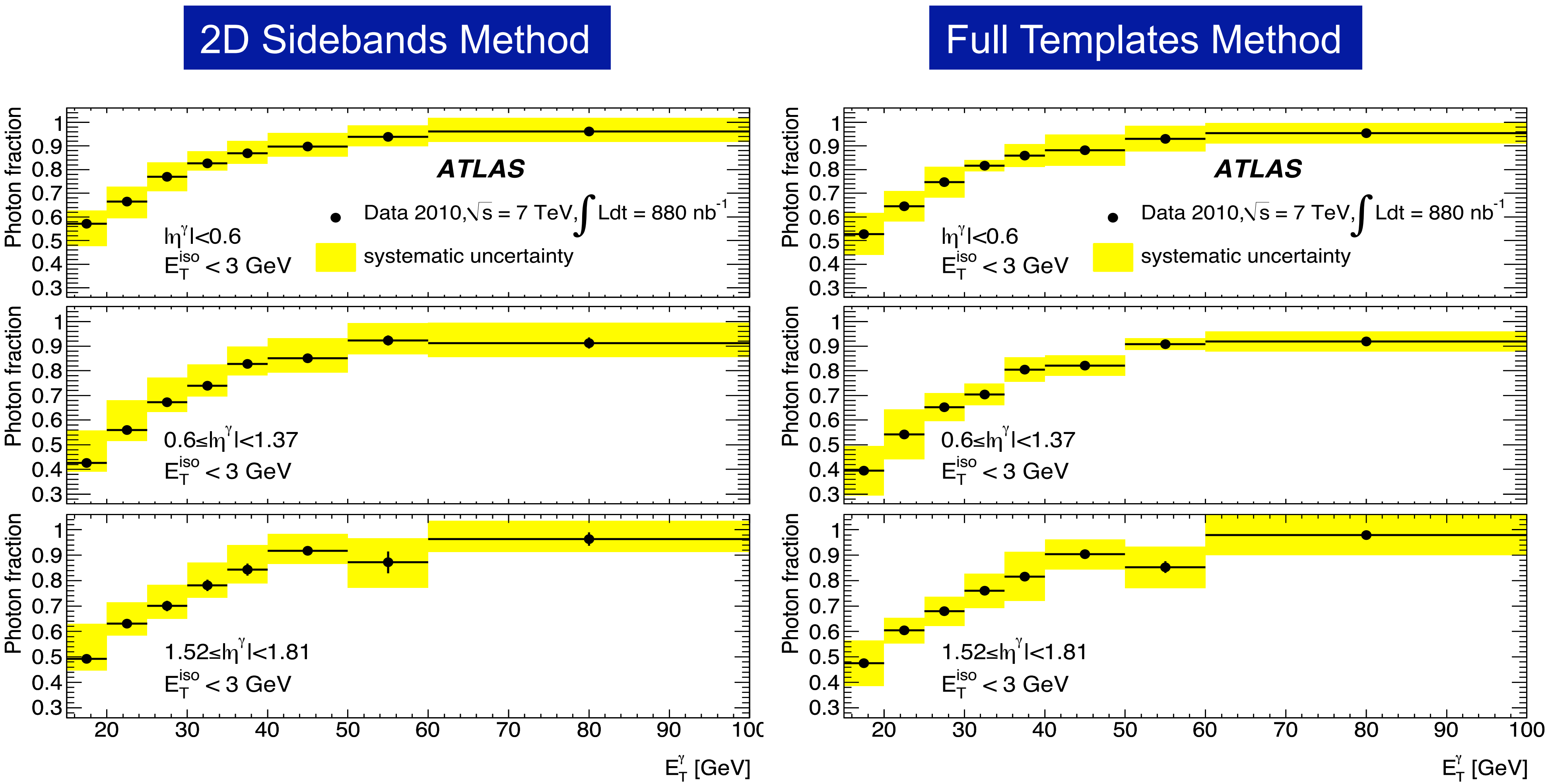
Purity Estimation: Full Templates

- Select data signal photons that pass "tight" PID cut and cluster isolation
  - Cluster isolation defined as energy in cone ΔR<0.4 in addition to that of photon itself
- Construct signal/background templates using the cluster isolation
  - Construct signal template using pure electron sample from W/Z decays
  - Construct background template from data photons after reversing some 'tight" PID cuts
- For converted photons signal/background templates also by using p_T/E_T
- Use signal/background templates to extract data sample composition



Potential limitation:
Isolation template not identical between electrons and photons

Purity Estimation



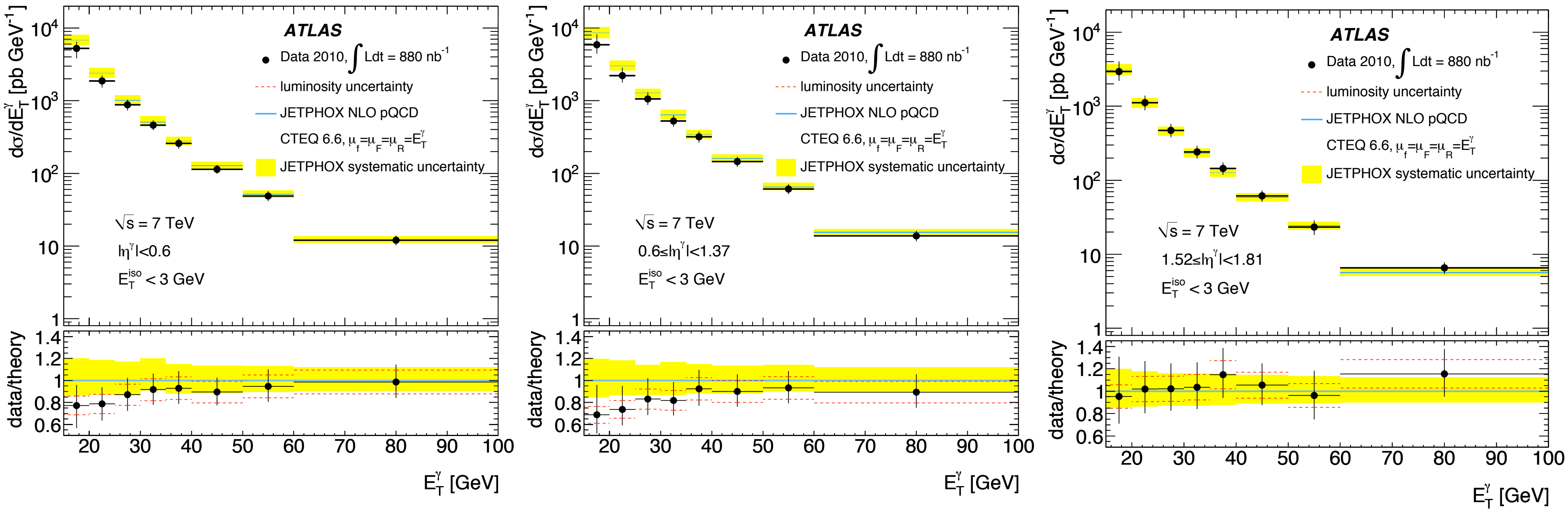
- Two methods give compatible results within the estimated uncertainties
- Purity increasing with photon transverse energy

Additional impurities due to electrons (e.g. from W/Z boson decays) misidentified as photons are ~0.5% reaching a maximum of ~2.5% in the 40-50 GeV E_T region

Cross-section Measurement

$$\frac{d\sigma}{dE_{T\gamma}} = \frac{N_{\text{yield}} U}{\Delta E_{T\gamma} \times \varepsilon_{Trig} \times \varepsilon_{\text{Re}c} \times \varepsilon_{ID} \int \mathcal{L}\, dt}$$

where N_{yield} the number of photons after correcting for purity
and U correction factors due to energy resolution effects (unfolding)

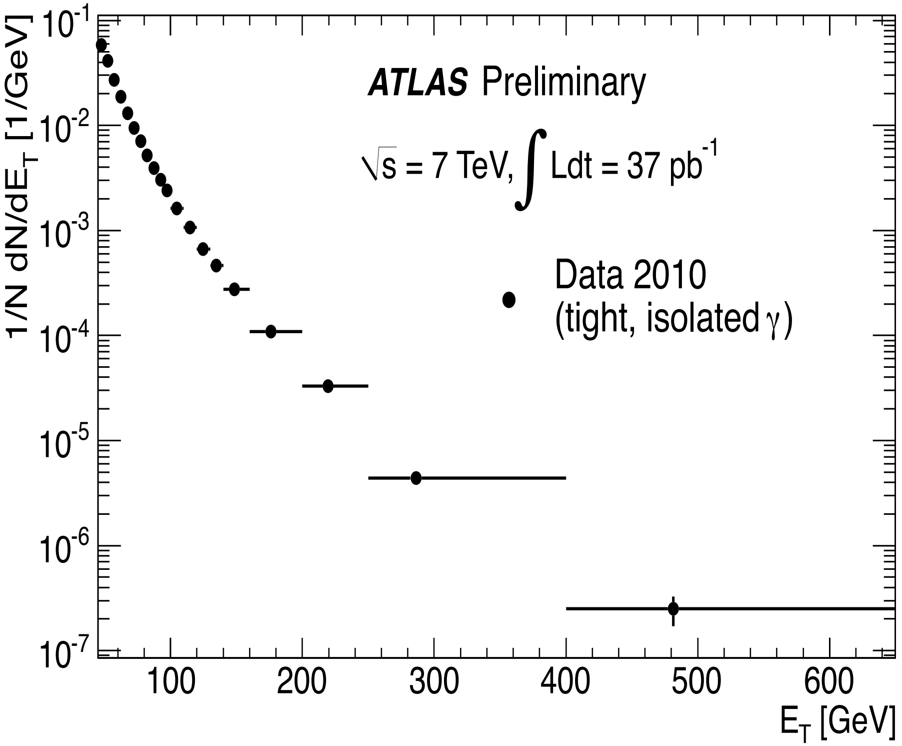


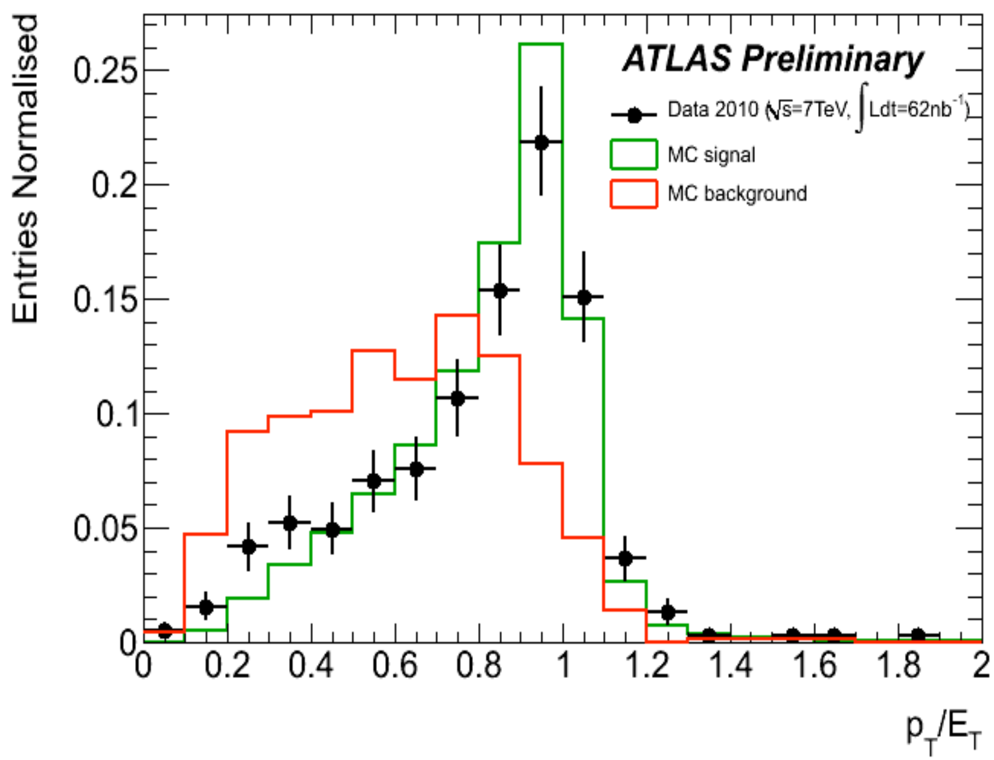
Theoretical cross-section larger than that measured in data at E_T<25 GeV

- Region where theoretical predictions less accurate
- Uncertainties on the theoretical predictions likely to be underestimated

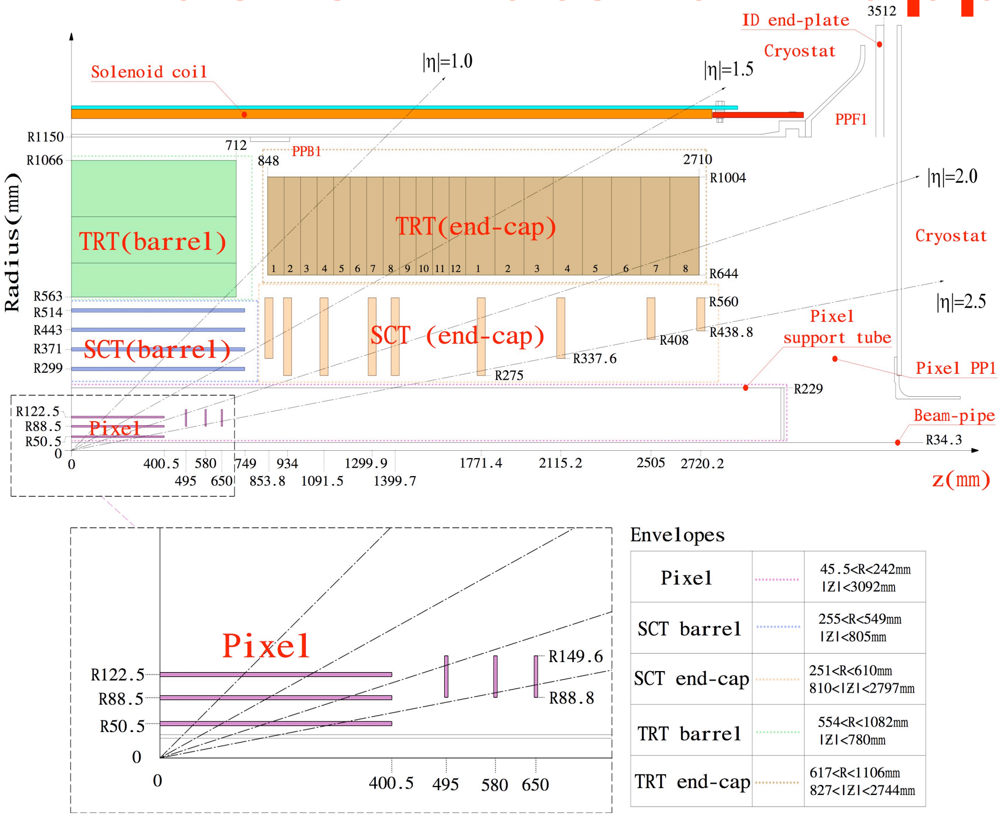
Outlook on Cross-section Measurement

- Measurement of the cross-section will be repeated with full statistics of 2010 LHC data
- Move to data-driven methods for estimating photon identification efficiency
- Focus on extending the energy spectrum at higher transverse energies
  - At >100 GeV theoretical predictions are much more reliable
- Improve on the determination of the cluster isolation
  - Should reduce contamination from fragmentation photons (already small at higher E_T)
- Separate between converted/unconverted photons
  - Additional discriminating variables for estimating the purity (p_T/E_T)



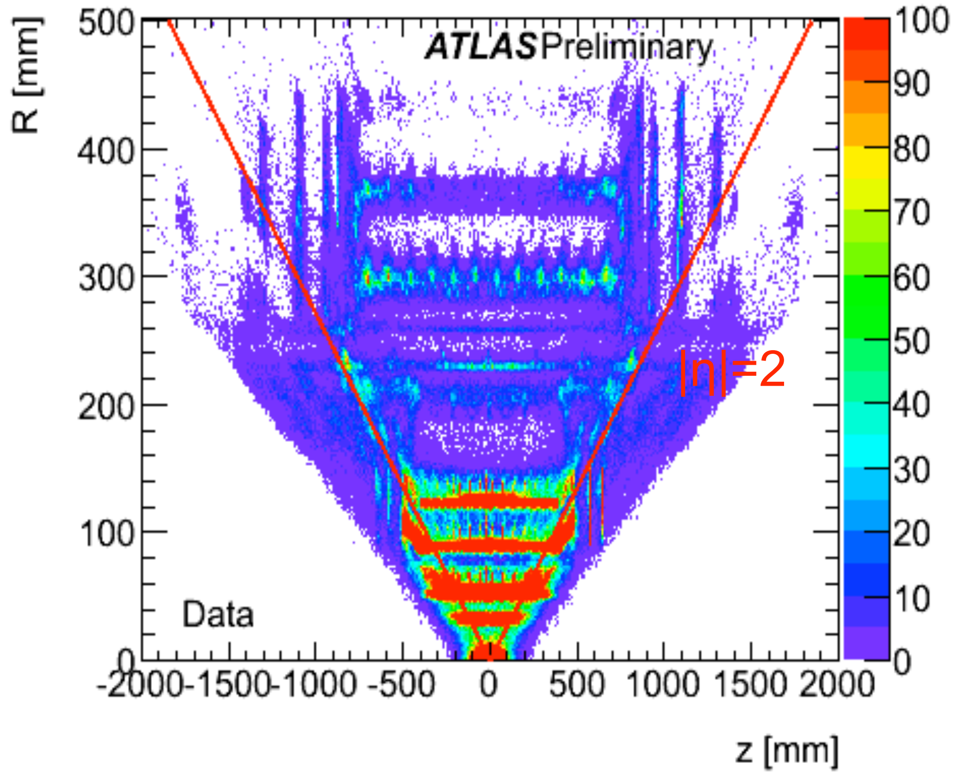


Tracker Material Mapping: (R,z) Distributions



Envelopes

Pixel	....	45.5<R<242mm |Z|<3092mm
SCT barrel	....	255<R<549mm |Z|<805mm
SCT end-cap	....	251<R<610mm 810<|Z|<2797mm
TRT barrel	....	554<R<1082mm |Z|<780mm
TRT end-cap	....	617<R<1106mm 827<|Z|<2744mm



Can use the reconstructed conversion vertex radial position to map the material in the ATLAS tracker

- Data-driven procedure for comparing to and correcting the tracker description in MC

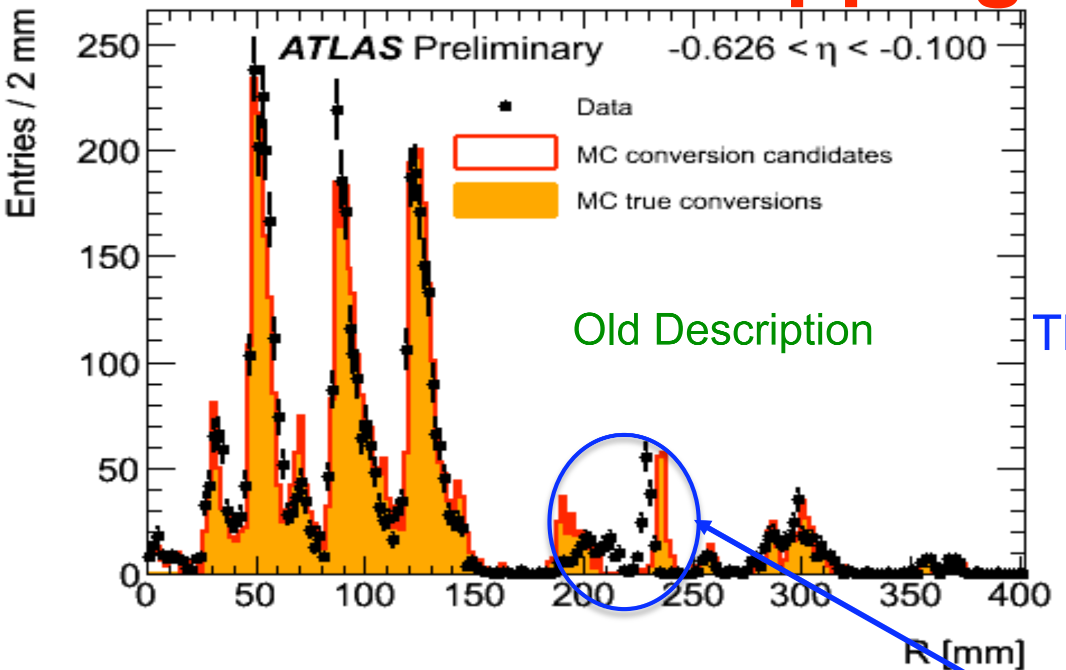
ATLAS tracker radiogram using converted photons:

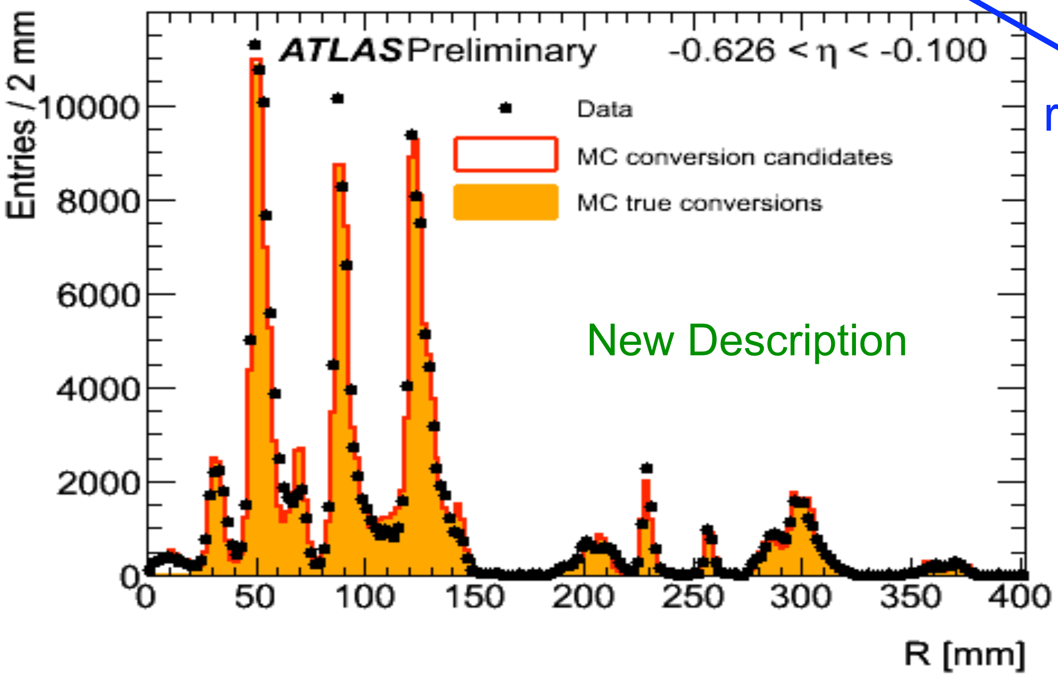
- Three barrel (|η|<1) pixel layers are visible
- The first two barrel SCT layers and the first end-cap disks are also visible
- Red line corresponds to |η|=2 above which conversion reconstruction is inefficient

Conversion reconstructed radial position resolution of ~3mm in pixel tracker

Statistical precision already at <5% level with ~14 nb^{-1} integrated luminosity

Tracker Material Mapping: Radial Distributions





Si-tracker barrel slice

The beam pipe, pixel and SCT structures are clearly visible

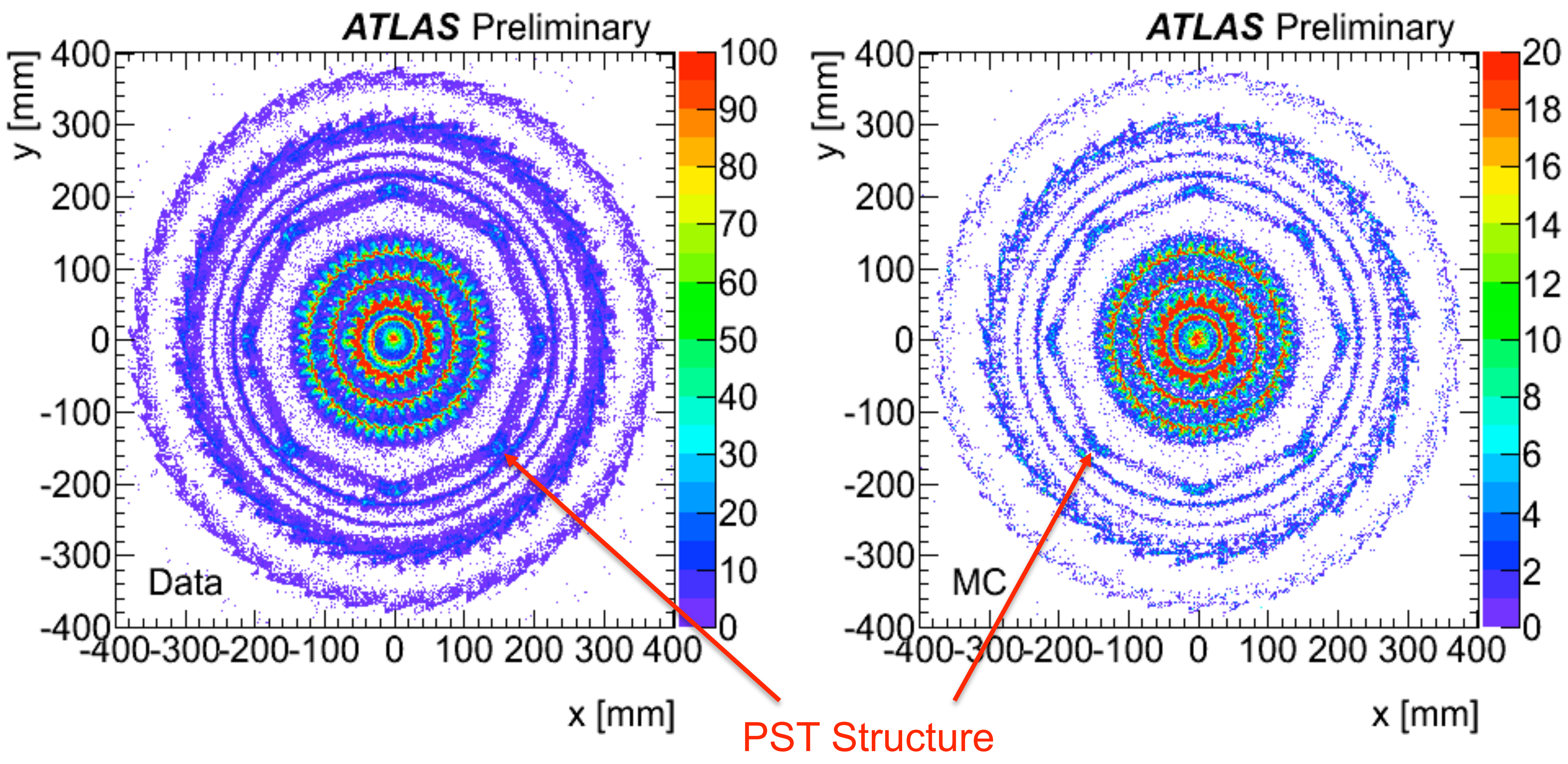
Overall good agreement between data and simulation

Discrepancies between data and the simulation, e.g. in the pixel support region, can be identified and eventually corrected

Purity of reconstructed conversions very high (>90%)

Tracker Material Mapping: (x,y) Distributions

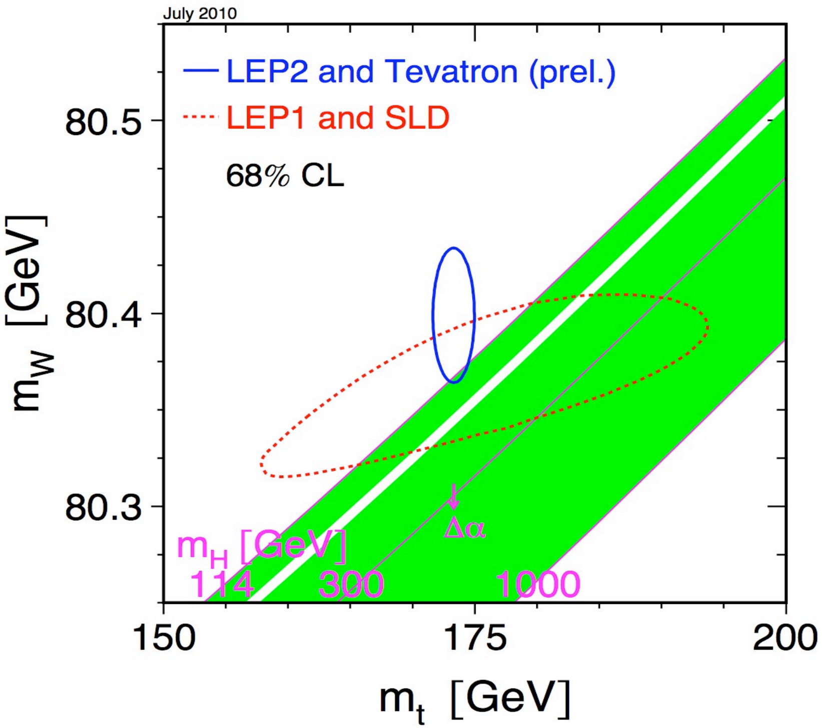
Results have already been used towards providing a much more realistic ATLAS tracker description

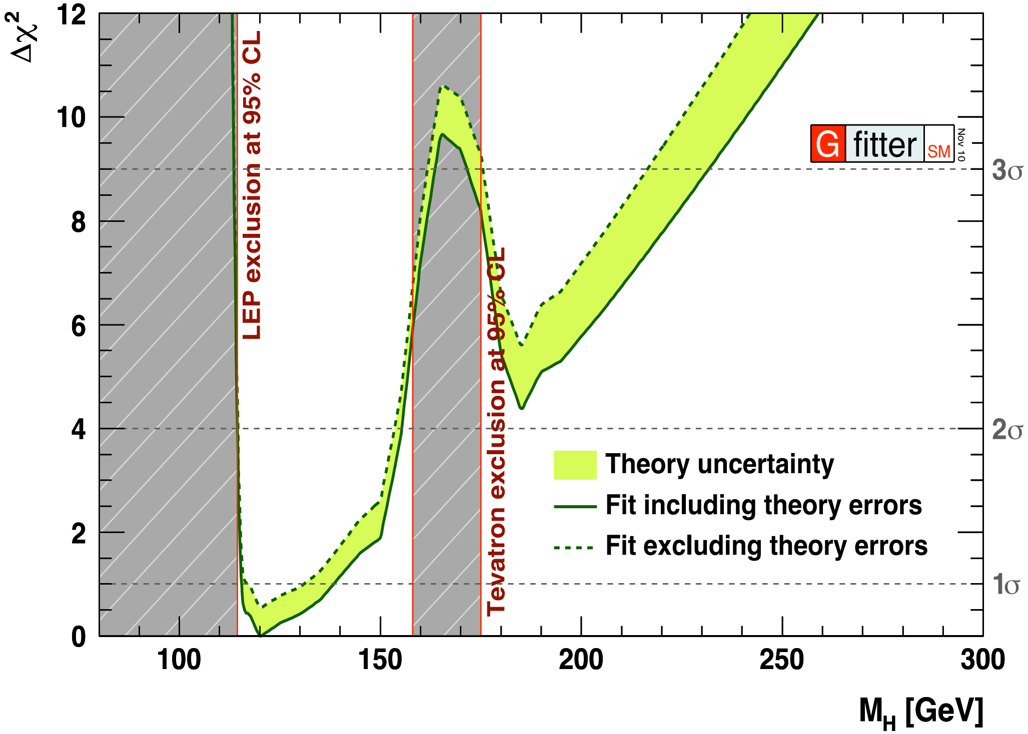


Reconstructed conversion vertices locations on the bending plane (x,y):

- Projection over Si-tracker barrel pseudorapidity range (|η|<1.0)

What do we know about the SM Higgs?





From theory: m_H< 1 TeV

Lower mass bound from direct searches at LEP: 114.4 GeV @ 95%CL

From direct searches at Tevatron:
158<m_H<175 GeV excluded @ 95%CL

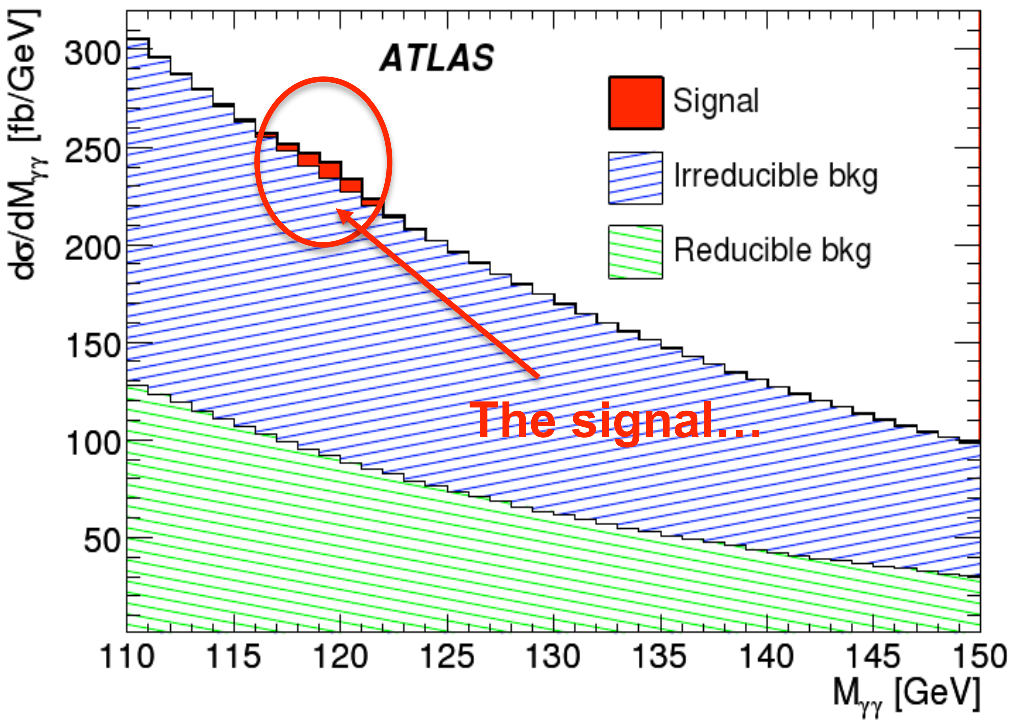
Indirect constraints on the Higgs boson mass from global EW fits:

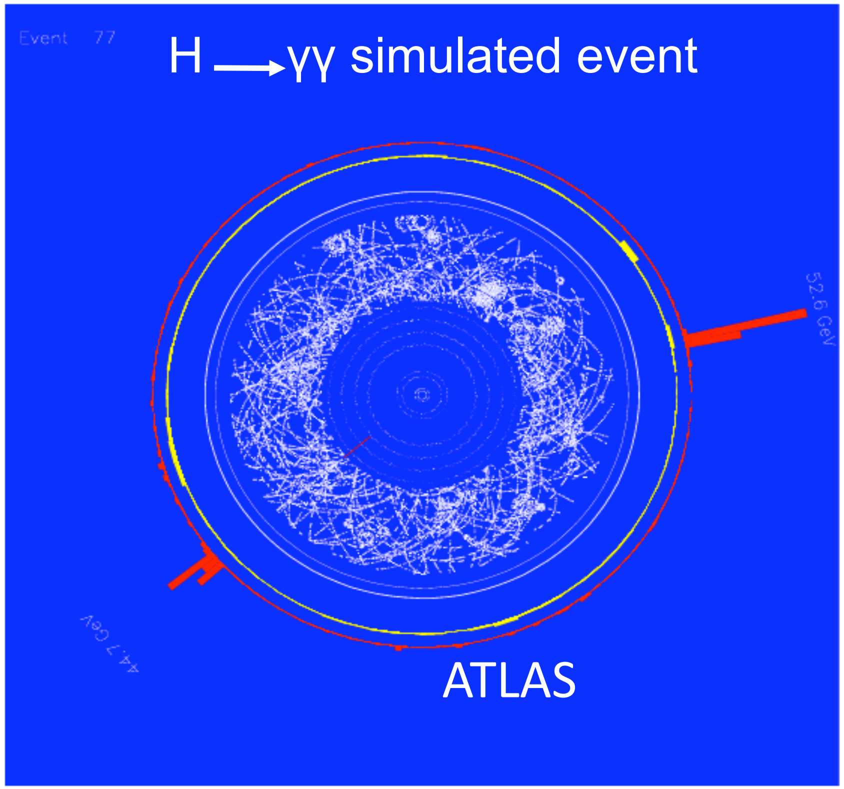
m_H < 186 GeV @ 95%CL
(including the direct limit from LEP)

EW data (interpreted in SM) prefer a rather light Higgs boson:
- If m_H < 140GeV, a favorite search mode is via $H \longrightarrow \gamma\gamma$

Search of Higgs Boson Decaying into Photons

- One of channels of choice for low-mass Higgs boson observation
  - Most efficient for $m_H < 140$ GeV
- Signal in the form of a narrow peak over a “smooth” background.
- Key points:
  - Good mass resolution ⇒Energy resolution of e.m. calorimeter + photon direction.
  - Good photon identification: To reduce jet background below true photon one.
  - Efficient photon conversion recovery (~30% of photons convert in tracker).



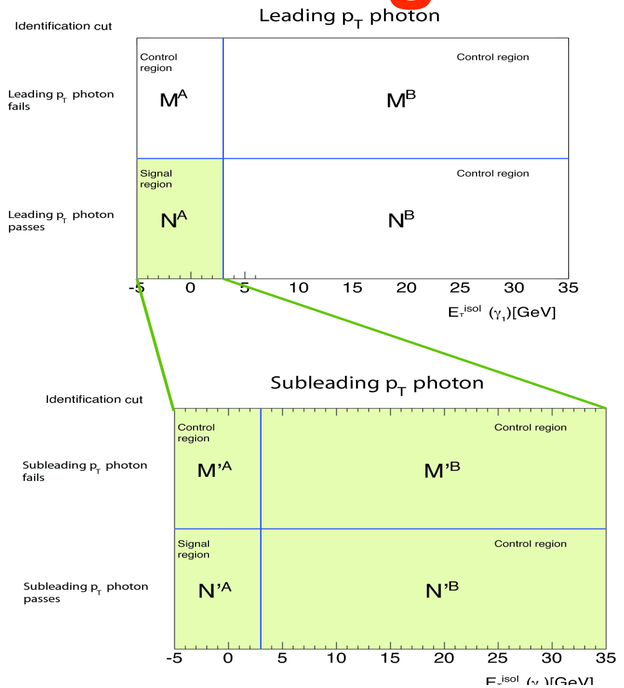


Background considerations for $H \rightarrow \gamma\gamma$

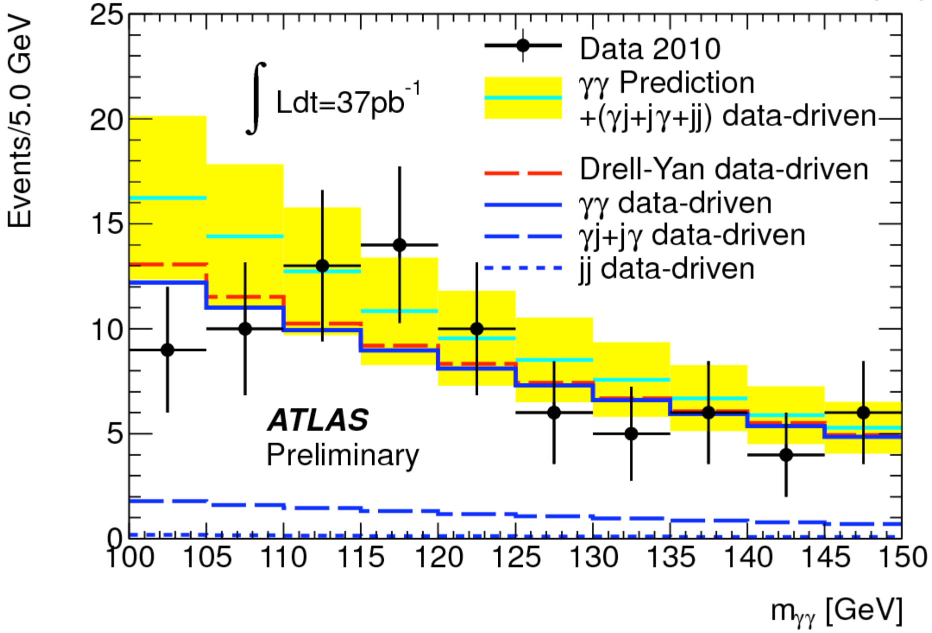
- Irreducible background consists of genuine photon pair continuum:
  - DIPHOX & ResBos; Background computation @ NLO⇒47% incr.
  - Computation agrees well with Tevatron data.
  - ~125fb/GeV @ m_H=120 GeV (after cuts and photon efficiency).

- Reducible background comes from jet-jet and γ-jet events in which one or both jets are misidentified as photons (Reducible / irreducible cross section ratio (LO-TDR) ~$2x10^6$ (jj) and ~ $8x10^2$ (γj)):
  - Jet-jet events dominated by gluon initiated jets (easier to reject), while γ-jet events dominated by quark initiated jets.
  - Total contribution @ LO dominated by γ-jet events: ~20fb/GeV.
  - A rejection factor of ~10^3 is needed to bring these backgrounds below the 20% level of the irreducible one.

Background considerations for H→γγ



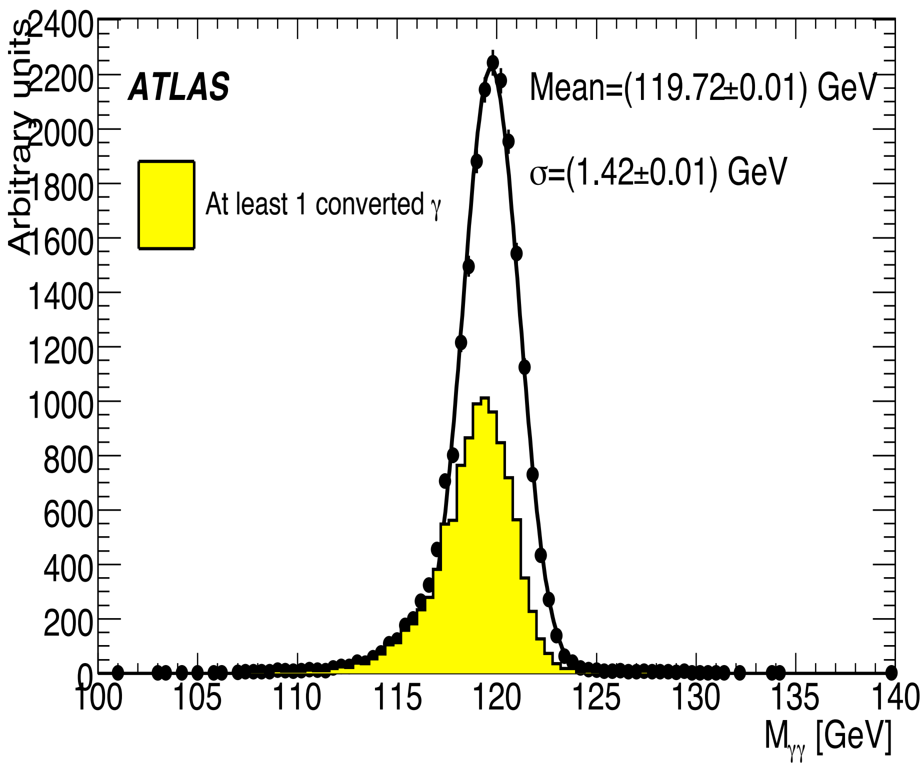
- Events with 1 γ in the electromagnetic calorimeter cracks excluded (bad energy resolution):
  - $|\eta|<0.05$, $1.4<|\eta|<1.55$ and $|\eta|>2.45$
- Transverse momentum cuts (background rejection):
  - $p_T(1)>40$ GeV, $p_T(2)>25$ GeV
- Tight photon identification cuts applied.
- Isolation criteria as in inclusive photons
- The direction of both photons is corrected for the primary vertex position.

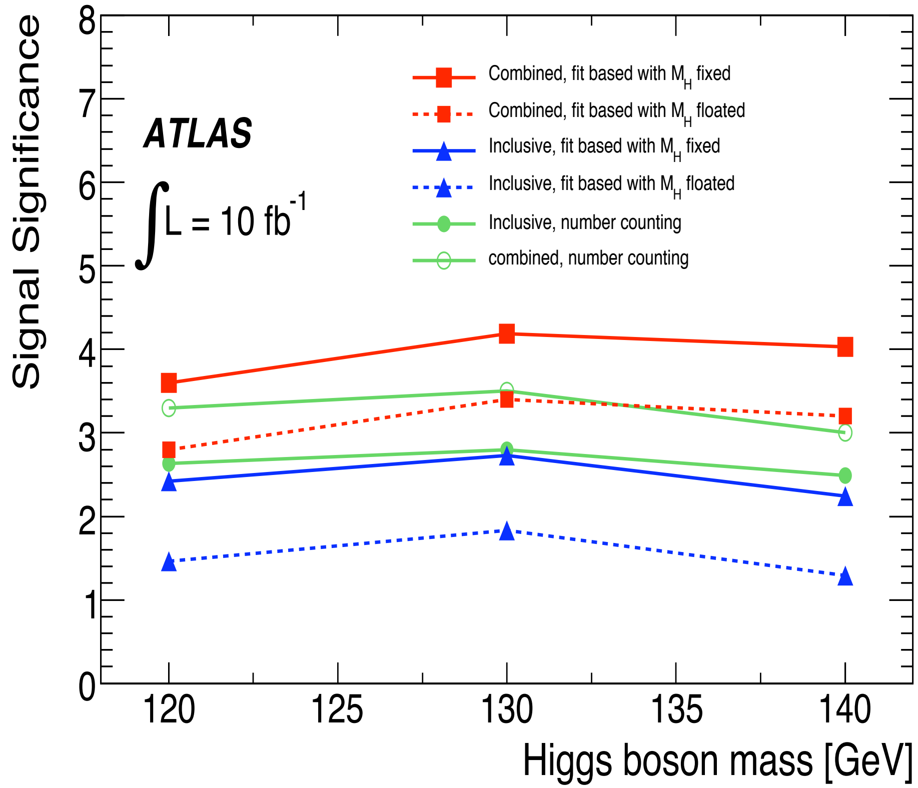


83 events passing the above criteria reconstructed in 100-150 GeV mass window using the 2010 data (37 pb^{-1})

Sensitivity to H ⟶ γγ

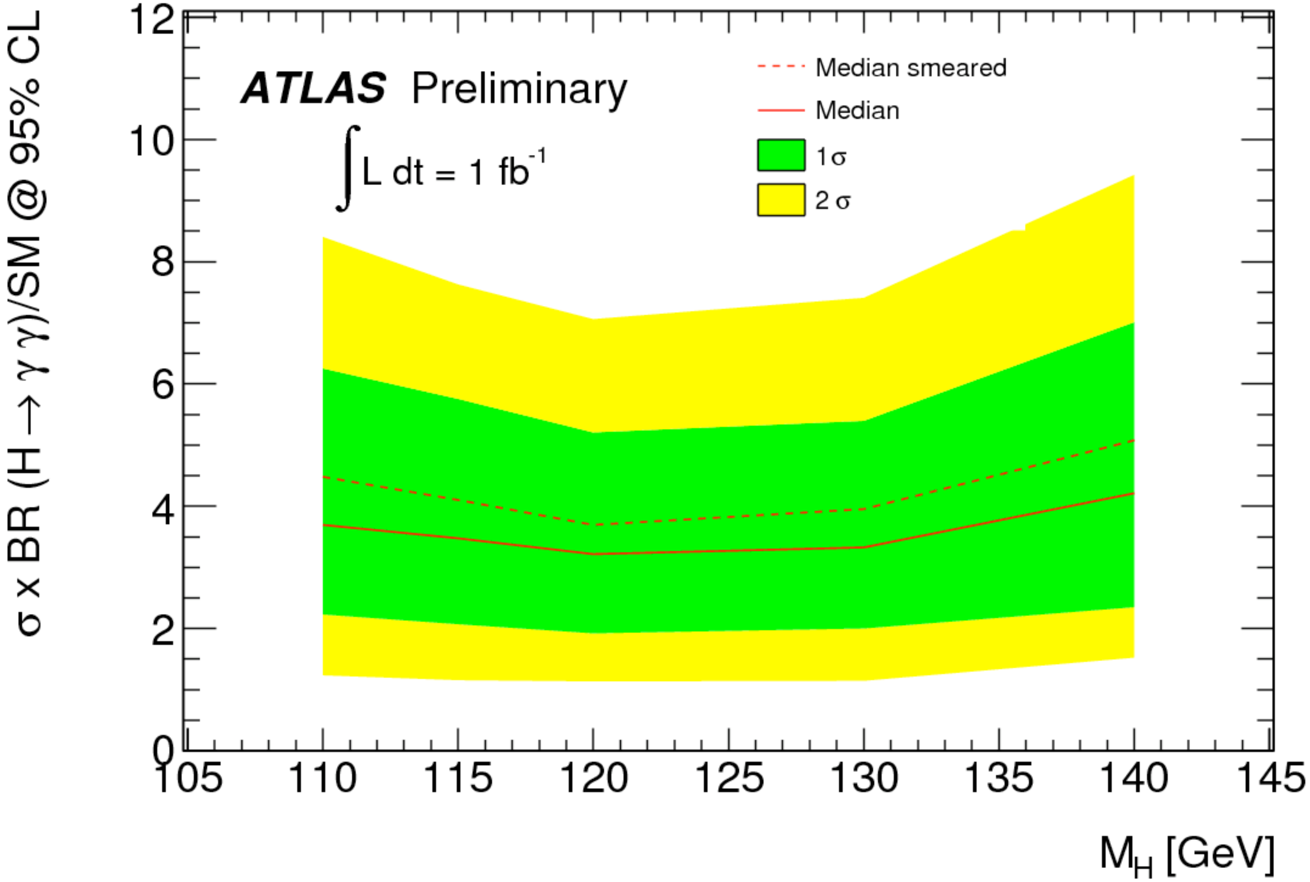
- Based on simulated samples equivalent to 10 fb^{-1} of LHC data (<3 years of running)
- Combined mode includes Higgs boson produced together with ≥1 jets
- Fit based analysis includes statistical methods:
  - Involve construction of discriminating variable templates e.g. $m_{\gamma\gamma}$
  - Used to fit the composition of data sample (fraction of signal + background)
    - With and without using a specific mass of the Higgs boson as an input
- Search to start in earnest after ~ 0.25 fb^{-1} worth of data (sometime in 2011)





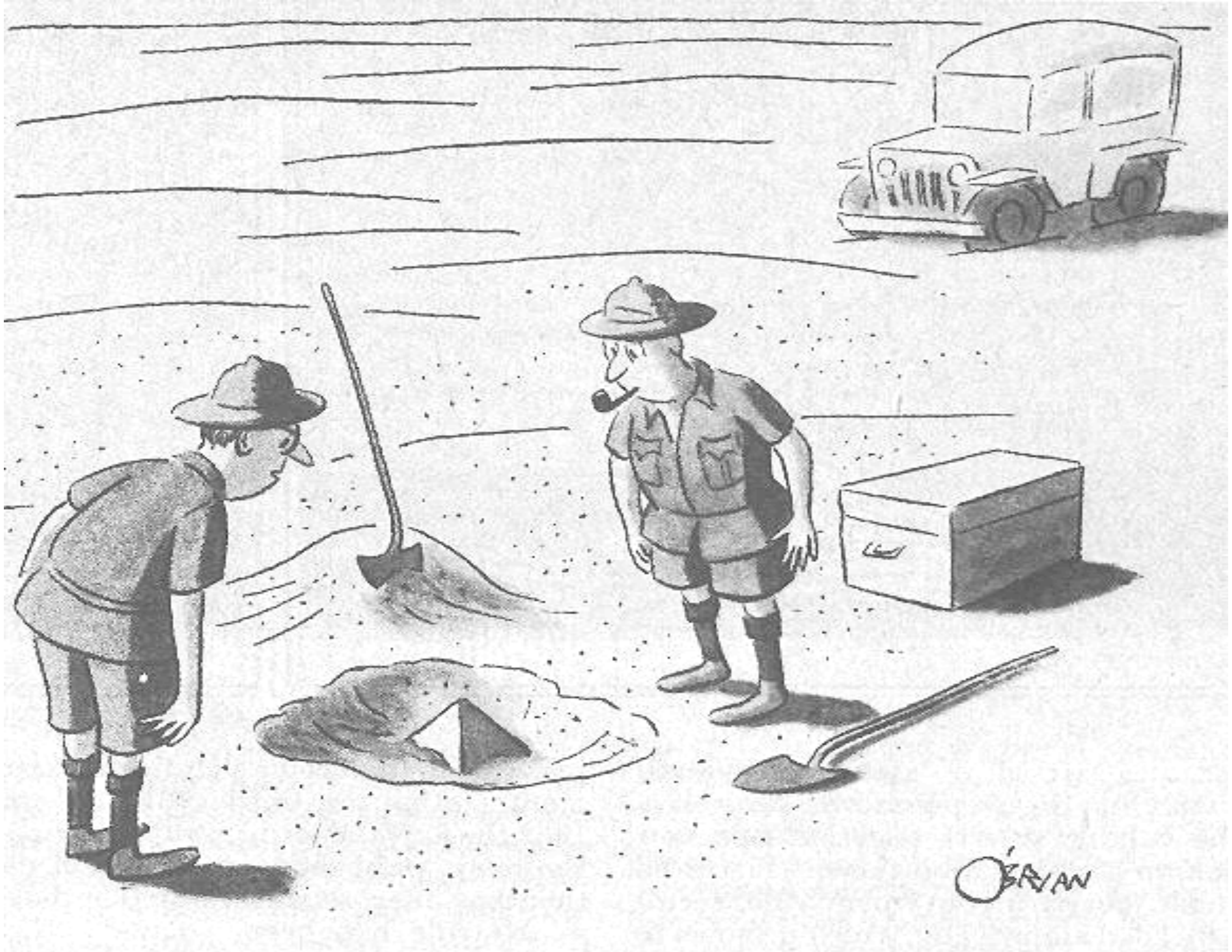
Exclusion Limit to H ⟶ $\gamma\gamma$ at 1 fb^{-1}

- Rescale observed event rates at 37 pb^{-1} to those expected at 1 fb^{-1}
  - Take into account improved detector acceptance in 2011
  - Take into account the foreseen pileup conditions in 2011 running
- Perform maximum likelihood fit
  - Signal is modeled by CB, combined with small, wider Gaussian
  - Background is modeled by an exponential function



The journey has only begun; we have just set sail…

Be positive: LHC will be a success & we will make many discoveries !



"This could be the discovery of the century. Depending, of course, on how far down it goes."