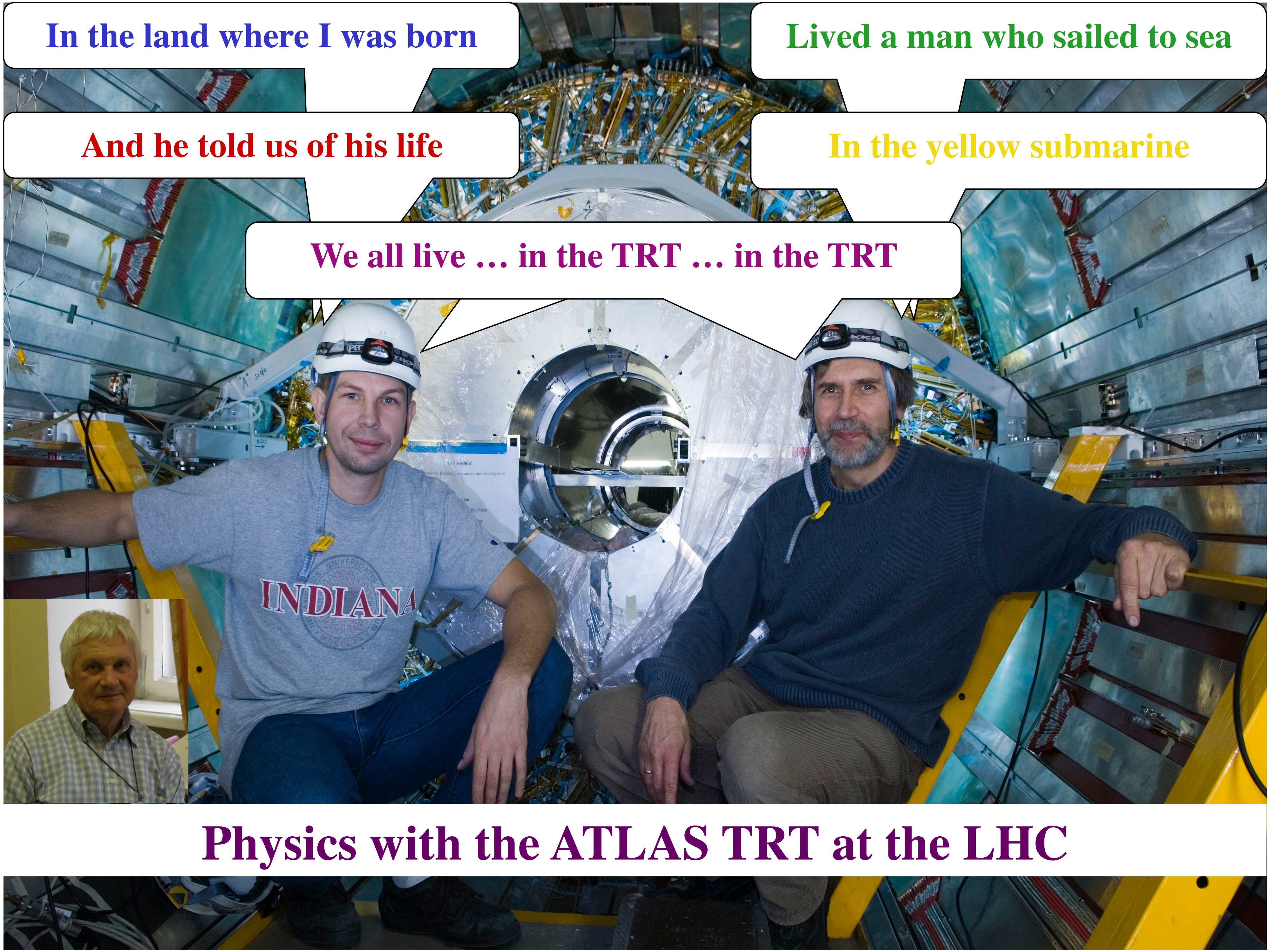
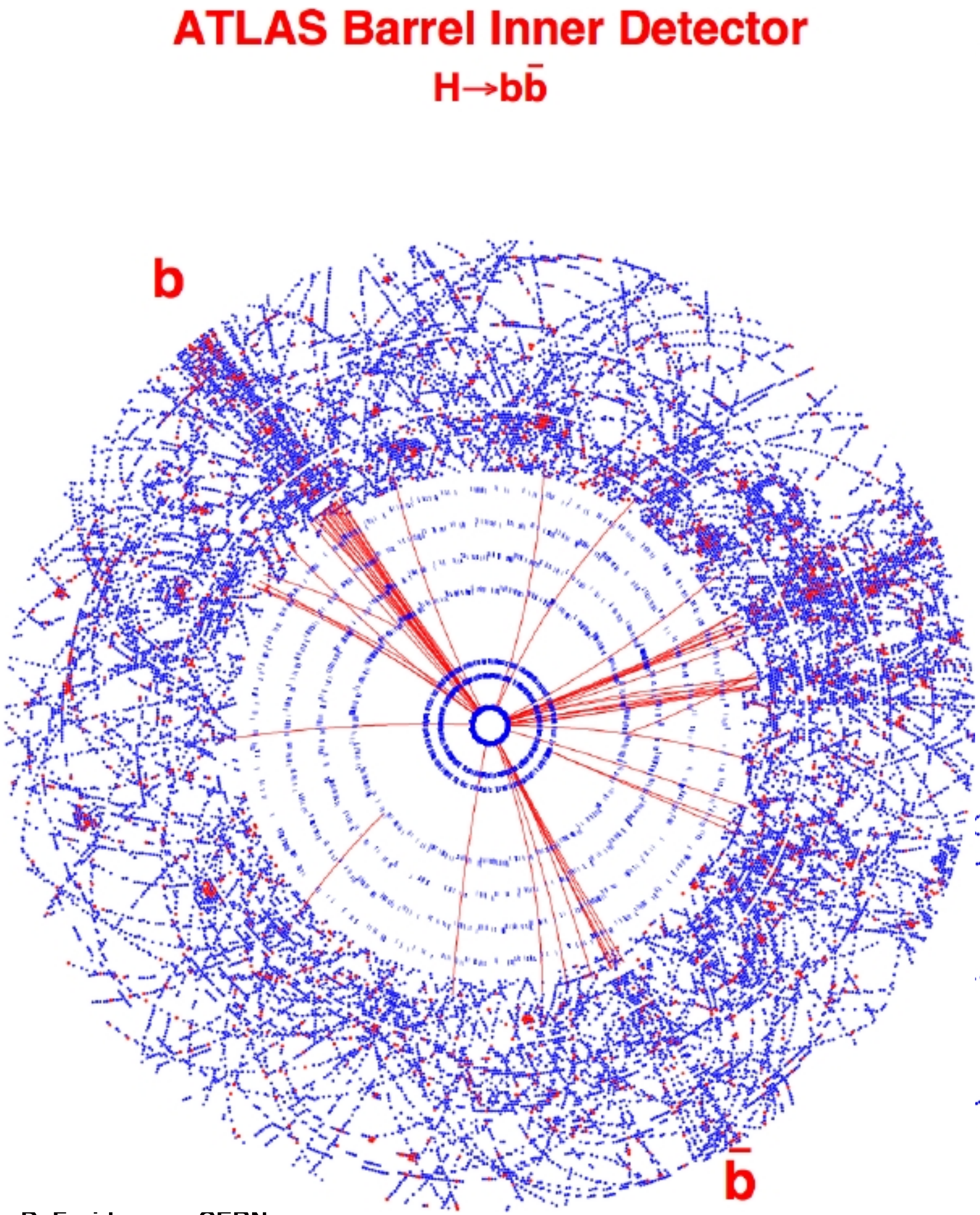


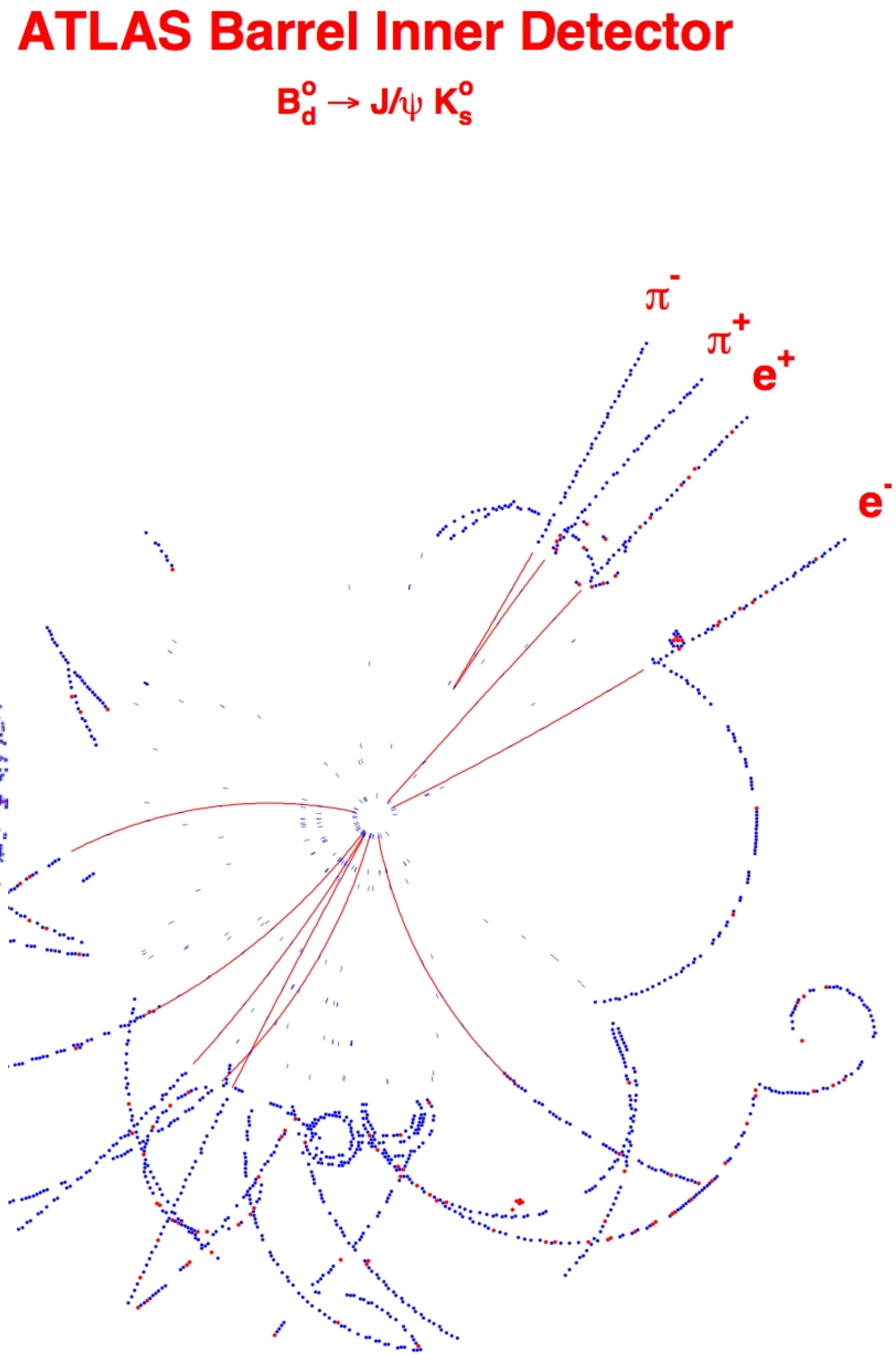
Physics with the ATLAS TRT at the LHC

Serious conceptual design started in RD6 in early 90s

- Electrical modelling of straw response (including measurement of straw response without amplifier, leading to much better understanding of long ion tails, of behaviour different from expected $1/(t+t_0)$, etc)
- Careful study of straw behaviour at high repetition rate (up to 20 MHz for the innermost long barrel straws with significant contributions from photons/neutrons)
- Occupancy calculations, time and time again!
  - Occ = $1 - e^{-\langle n \rangle}$ with $\langle n \rangle$ defined as rate at which straw crossed by particles
  - Need to define over which time interval: 75 ns, 25 ns, 12 ns or 10 ns (going from crude calculation for readout to refined calculation for drift-time measurements)
  - Average occ of e.g. 20% leads to $0.2^{35} \sim 10^{-25}$, less than overall silicon prob.

Serious conceptual design started in RD6 in early 90s



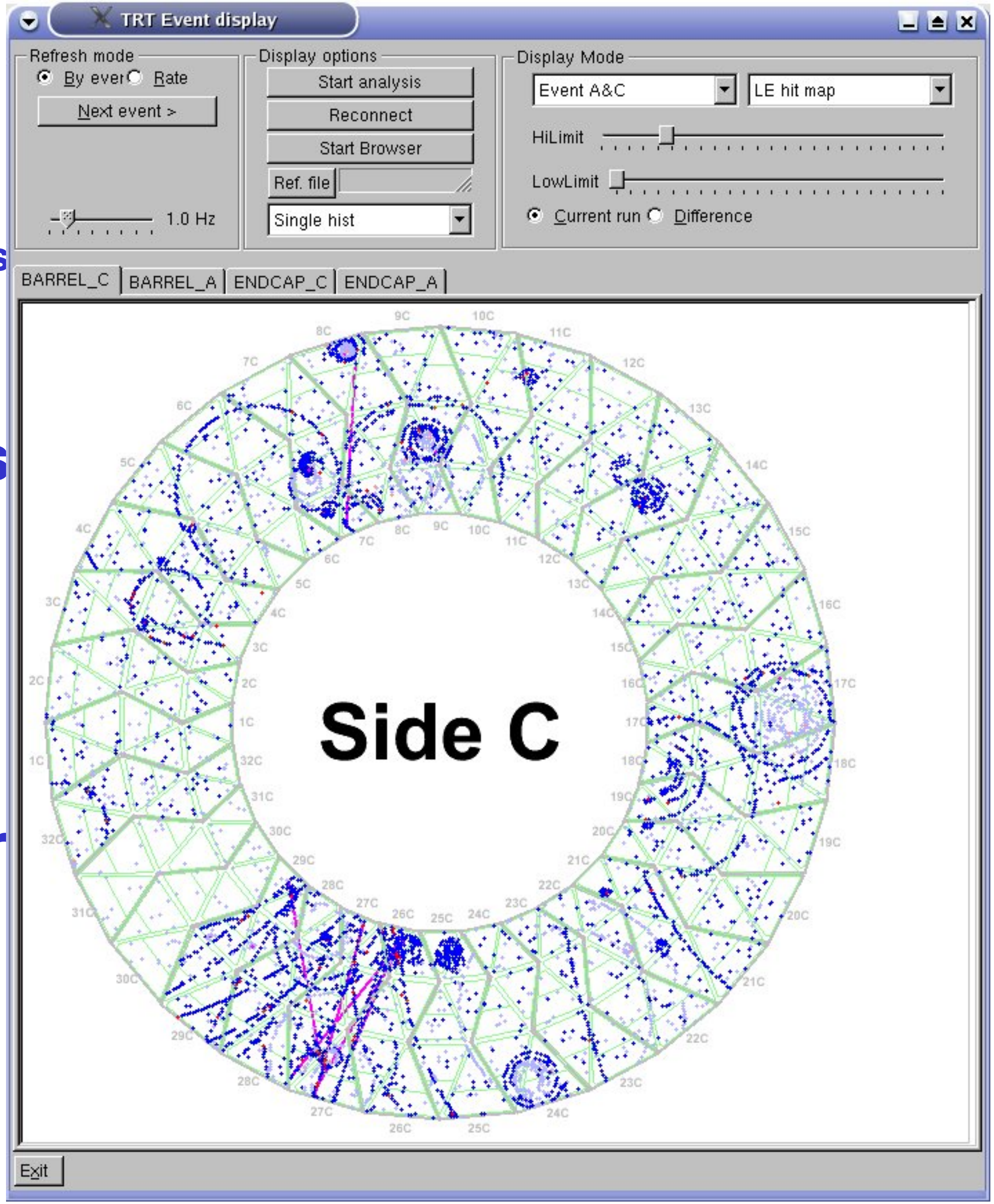


D. Froidevaux, CERN

A TRT Event (23.8.08)

With ATLAS Solenoid on: TRT is working as expected

- **Example: cosmic particles seen with the TRT Barrel**
- **Events remind viewer of bubble-chamber photos…**



Serious conceptual design started in RD6 in early 90s

Occupancy calculations, time and time again!

- But large correlations from straw to straw (low-energy loopers from photon conversions, etc), so need to study realistically fake rates vers R_{min} and R_{max} of TRT
- Thanks in particular to I. Gavrilenko and P. Nevski, TRT survived real estate battle reasonably well and got $\Delta R \sim$ 40-50 cm, which is what is required for a performant detector at the LHC
- One often hears: previous TRD detectors have not worked, especially at hadron colliders. This is simply not true: they have worked for what they were meant for but they were not useful for physics because MC studies were not done to predict the real backgrounds to be faced.
- ATLAS TRT is a greatly improved TRD + tracking concept and has no such excuses with 20 years of detailed simulation behind it
- TRT will provide L2 robustness and also pattern recognition and momentum measurements. In addition, it will help us identify electrons in an environment worse by ~ factor 100 than Tevatron

Physics with the ATLAS TRT at the LHC

- Electrons in cosmic rays
- Electrons in photon conversions
- First high-p_T electrons from W to eν and Z to ee
- Electrons everywhere in physics: role of TRT
- Measurement of inclusive electron spectrum
- What next?

Electrons in cosmic rays: why bother?

• Remember? There was an accident in the LHC machine in 2008. One benefit from this delay of one year for pp collisions was that ATLAS/CMS and LHC were much more ready for operation in late 2009 than in late 2008

• Excitement was huge after so many years of construction and software preparations: let's use our software (for cosmics, some adaptation was required, especially for the inner-detector tracking) and analyse the data beyond just looking for the muon track(s)!

• ATLAS has ~ 1000 students: even in these huge experiments, the training of a student cannot be only through MC simulations.

• Finally, we were curious. There were no predictions of what to expect and we were surprised in the end.

Electrons in cosmic rays: which sources?

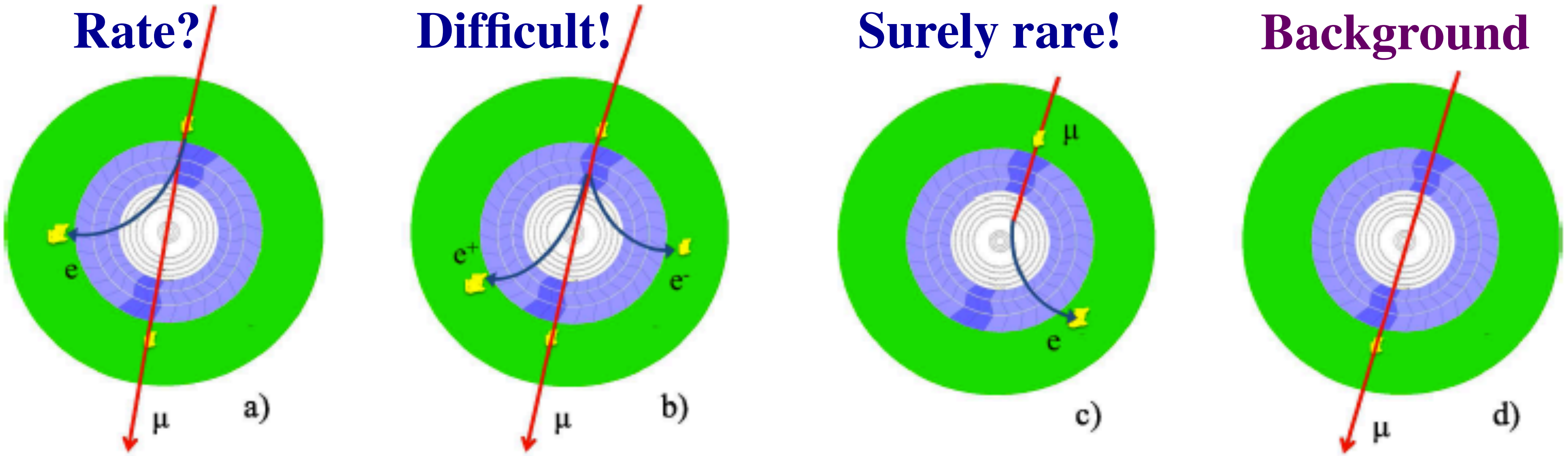
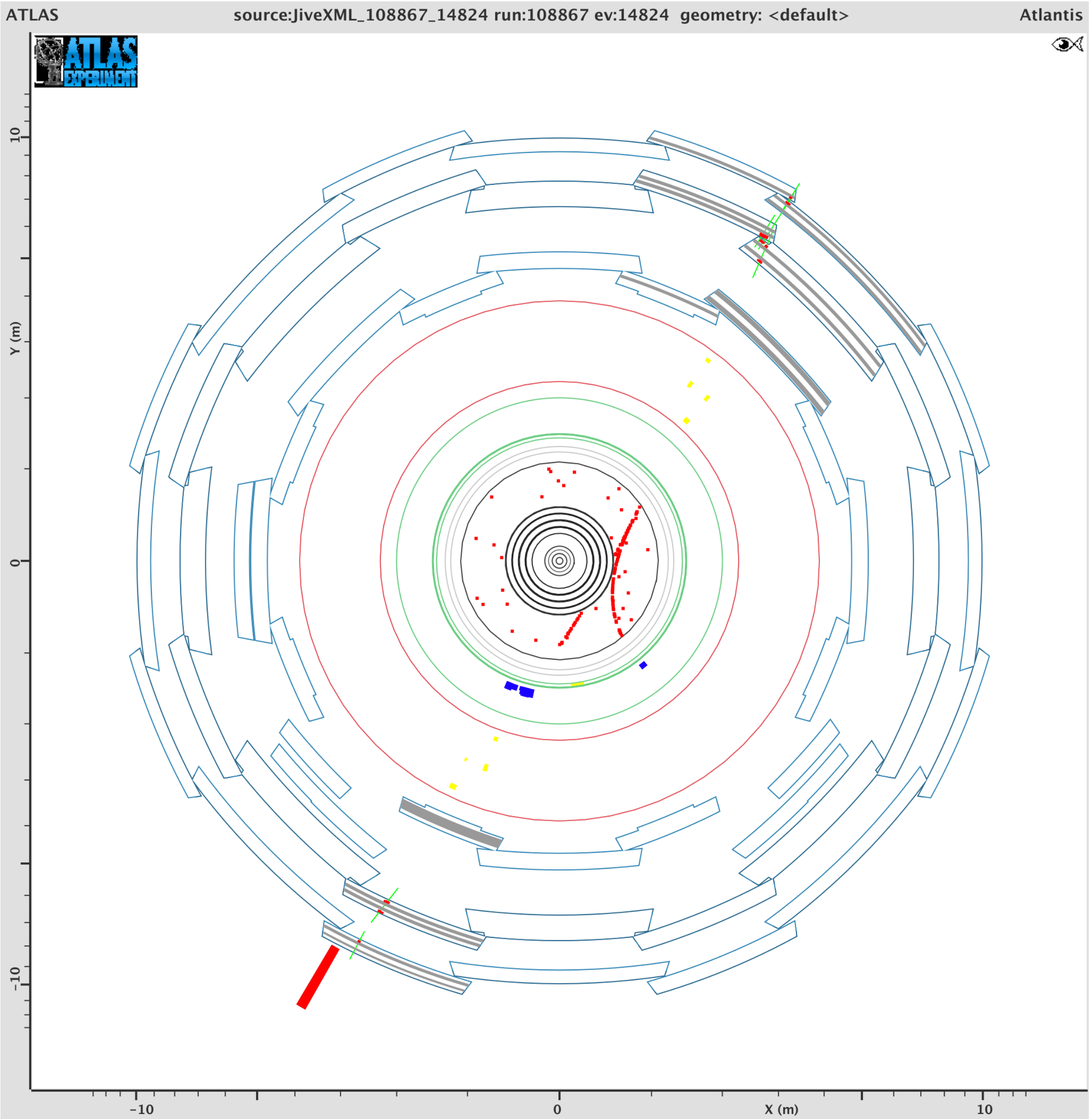


Figure 4.17: A schematic illustration of the three possible scenarios for an electron to be produced in cosmic ray data as well as the background process. From left to right: a) A δ-electron produced by direct muon ionization in the detector material. b) Muon bremsstrahlung, where the photon converts to an electron-positron pair in the Inner Detector. c) Muon decay in flight within the ID. d) Background process where the muon emits bremsstrahlung, which leaves a proper cluster in the calorimeter that is matched to the muon track.

Electrons in cosmic rays



An event display of an electron produced by muon ionisation. The TRT hits, visible in red, are made by the muon track (left) and the electron track (right). The blue dots are the EMTopoClusters in the EM calorimeter.

The electron in this particular event has a p_T = 650 MeV, 68 TRT hits and no hits in the silicon detectors. The muon has a p_T of 185 GeV.

Electrons in cosmic rays

The selection cuts are very specialised: non-pointing tracks without silicon hits in most cases, low-energy clusters in the EM calorimeter. Non-standard software had to be used. Limited to barrel region (low stats)

1. **Tracking cuts**

- Events with > 1 track are considered (events with only one track are used as a control sample to estimate the background)
- Number of TRT hits ≥ 25
- TR ratio > 0.10 (standard electron id cut for TRT)

2. **Topocluster moment cuts**

- The tracks are then matched to an EMTopoCluster430 with $|\Delta\phi| < 0.3$
- Second moment in lambda: $\lambda^2 < 21000$ mm^2
- Second lateral moment: $lat_2 > 0.6$
- The distance to the shower center along the shower axis: $\lambda_{center} < 220$ mm
- The energy fraction in the most energetic cell: $f_{max} < 0.36$

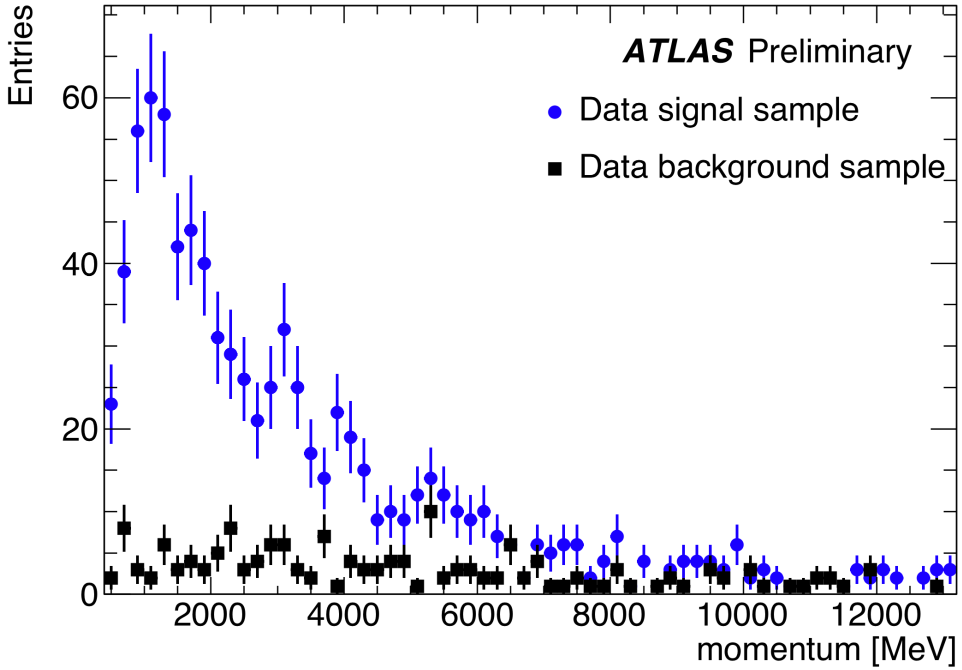
3. **Final cut: E/p > 0.5 (p from track and E from cluster)**

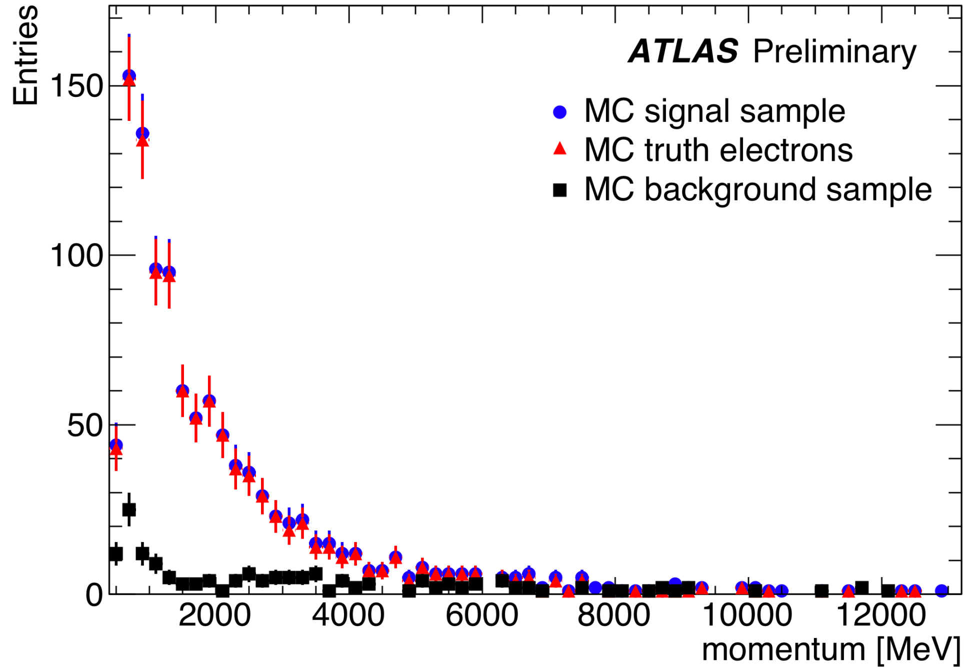
Electrons in cosmic rays

The table shows the remaining electron candidates after each selection requirement. The red numbers in brackets are the MC tracks matched to true electrons.

Selection cuts	**Signal sample** Data 08/09	Monte Carlo	**Background sample** Data 08/09	Monte Carlo
# of ID barrel tracks	385 k	358 k (6619)	4.75 M	2.72 M (685)
TRT hits > 25	293 k	300 k (4383)	4.52 M	2.66 M (449)
TR ratio > 0.10	89 k	53 k (2940)	809 k	239 k (262)
Track – cluster match	15 k	16 k (1667)	115 k	87.6 k (151)
Cluster moment cuts	1930	2466 (1242)	6461	11276 (104)
E/p > 0.5	882	1091 (1058)	195	170 (84)
Resulting electron candidates	**882**	**1091** (1058 = 97%)		

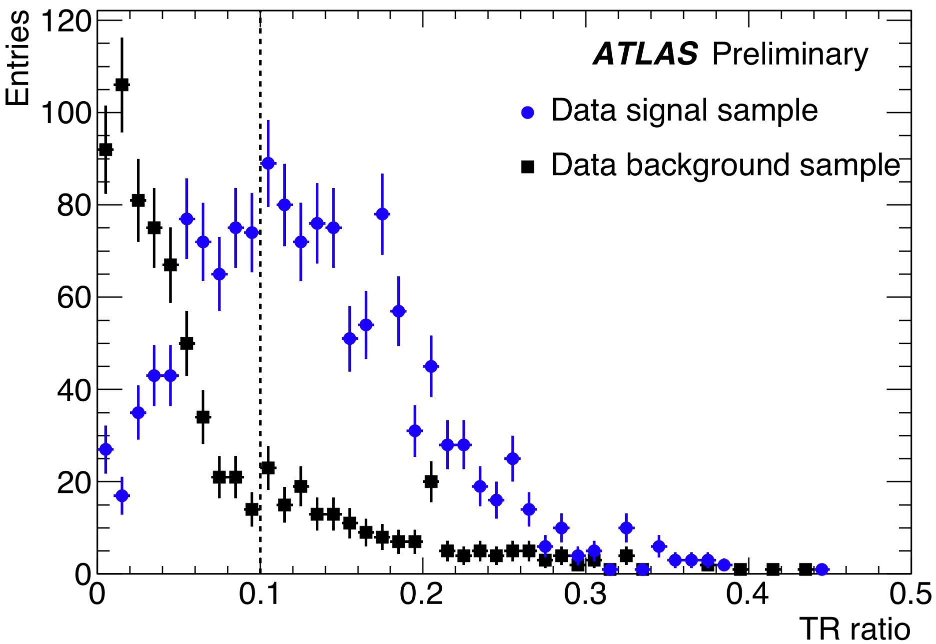
Electrons in cosmic rays

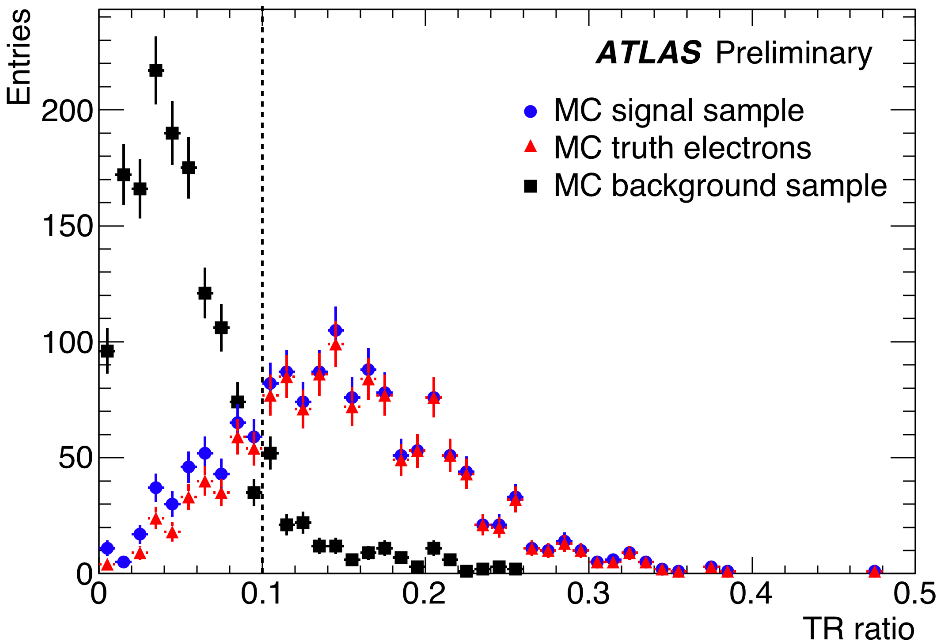




Resulting momentum distribution of the final isolated sample of electron candidates . The distribution of the real electrons peaks at low values (around 1 GeV), while the background sample is flatter (triggered cosmic muons are more energetic in general).

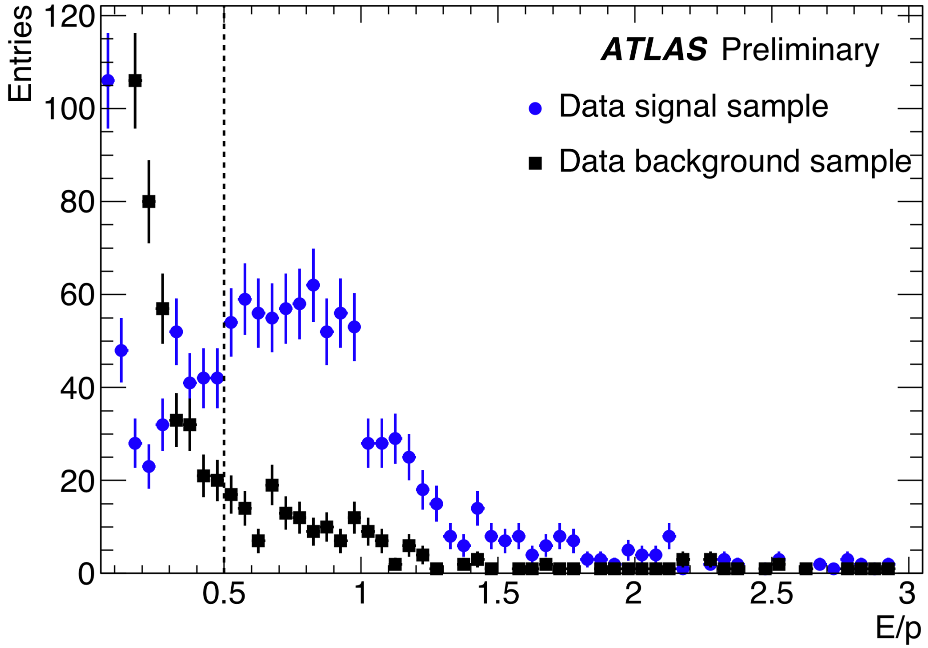
Electrons in cosmic rays

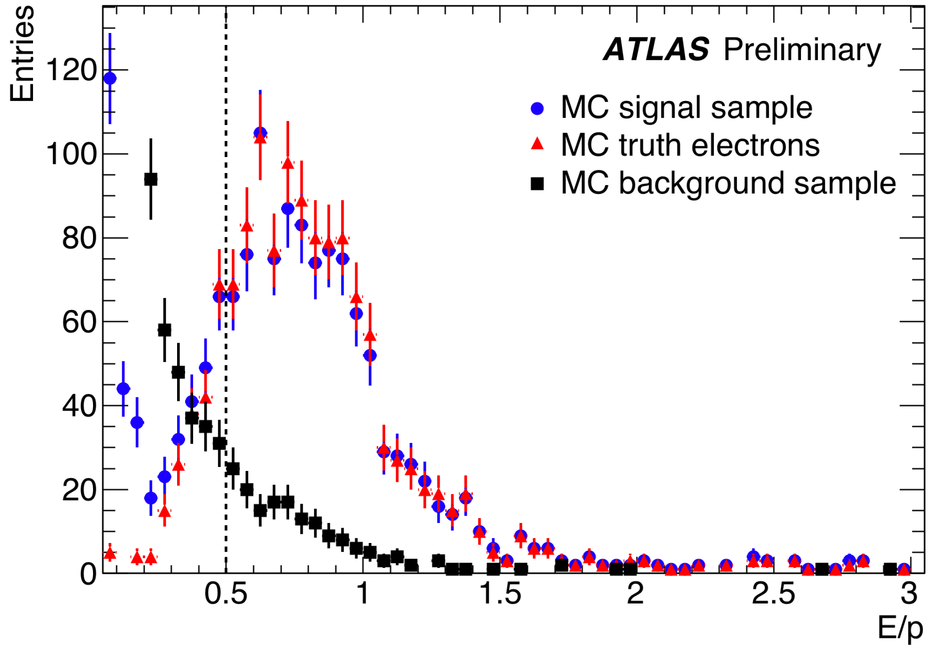




TR ratio of resulting electron candidates. The dotted lines indicate the final cut at TR ratio > 0.10. It is clear that little background remains in the signal sample after the E/p cut has been applied for both MC and data. The TR ratio of the data signal sample does contain more events at low values indicating somewhat more background contamination than in MC.

Electrons in cosmic rays





E/p of resulting electron candidates in the signal and background samples. The dotted lines indicate the final cut at E/p > 0.5.

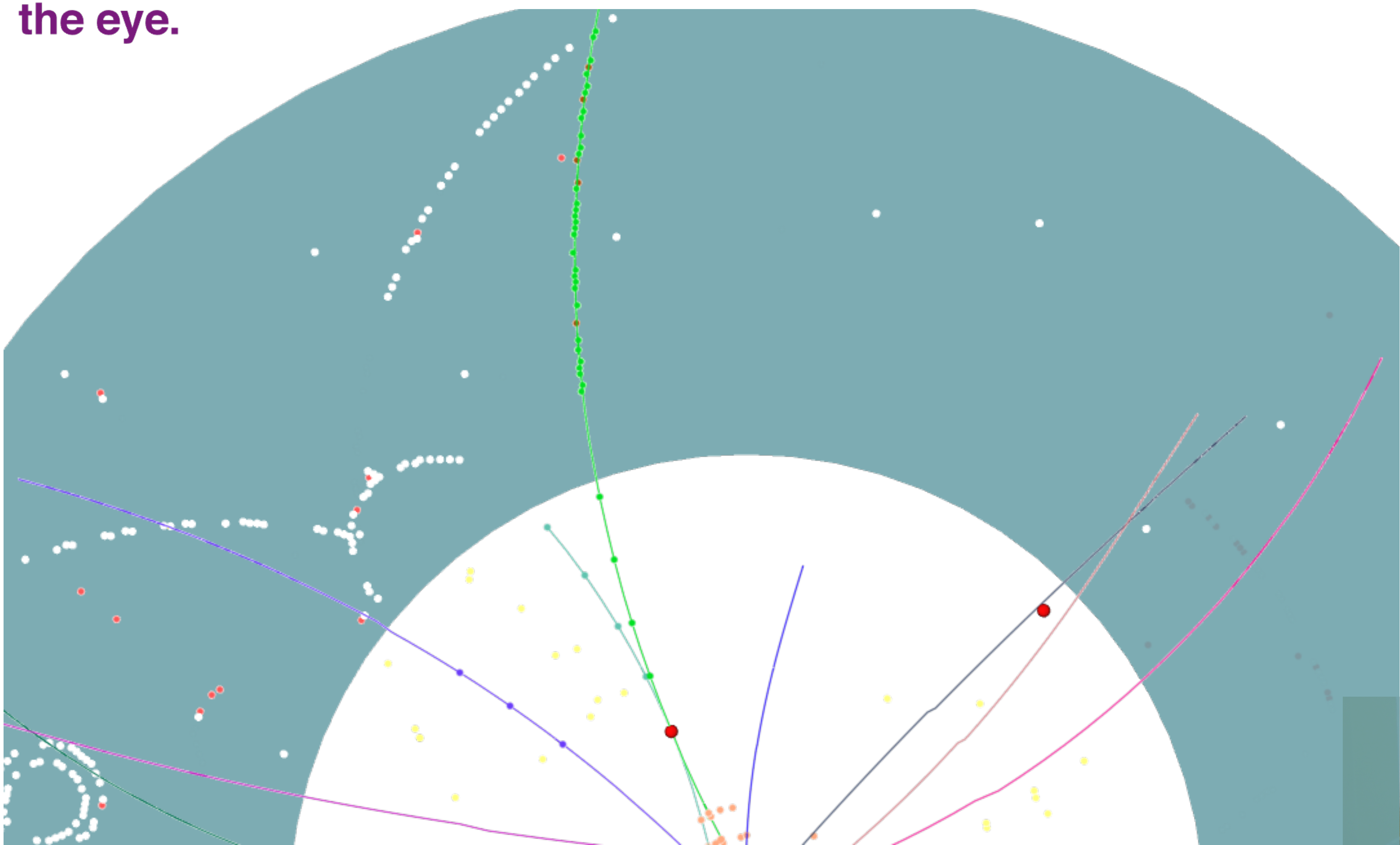
Electrons in cosmic rays: conclusions

- A clear signal has been observed (only in ATLAS), in great part thanks to TRT performance, both for tracking and electron identification!
- This signal is dominated by d-rays, but very energetic ones (could not find any sign in literature of measurements done in this range, so we had with Anatoli to extrapolate published measurements from 100 keV to above 500 MeV!). Rate seems plausible.
- Photon brem + conversion rate is smaller and muon decay rate is negligible.
- **Amazing that required electron identification performance is very similar to the design performance of ATLAS (albeit at much lower energies)!**

	2008/2009 cosmic data		Simulated cosmic data	
Total nbr of events	13.2 million		10.6 million	
Electron candidates	882		1091 (true: 1058)	
Background	**percent**	**muons**	**percent**	**muons**
MC truth	-	-	3.0	33
TFractionFitter	5.5 ± 1.9%	48 ± 17	1.0 ± 1.6%	11 ± 17

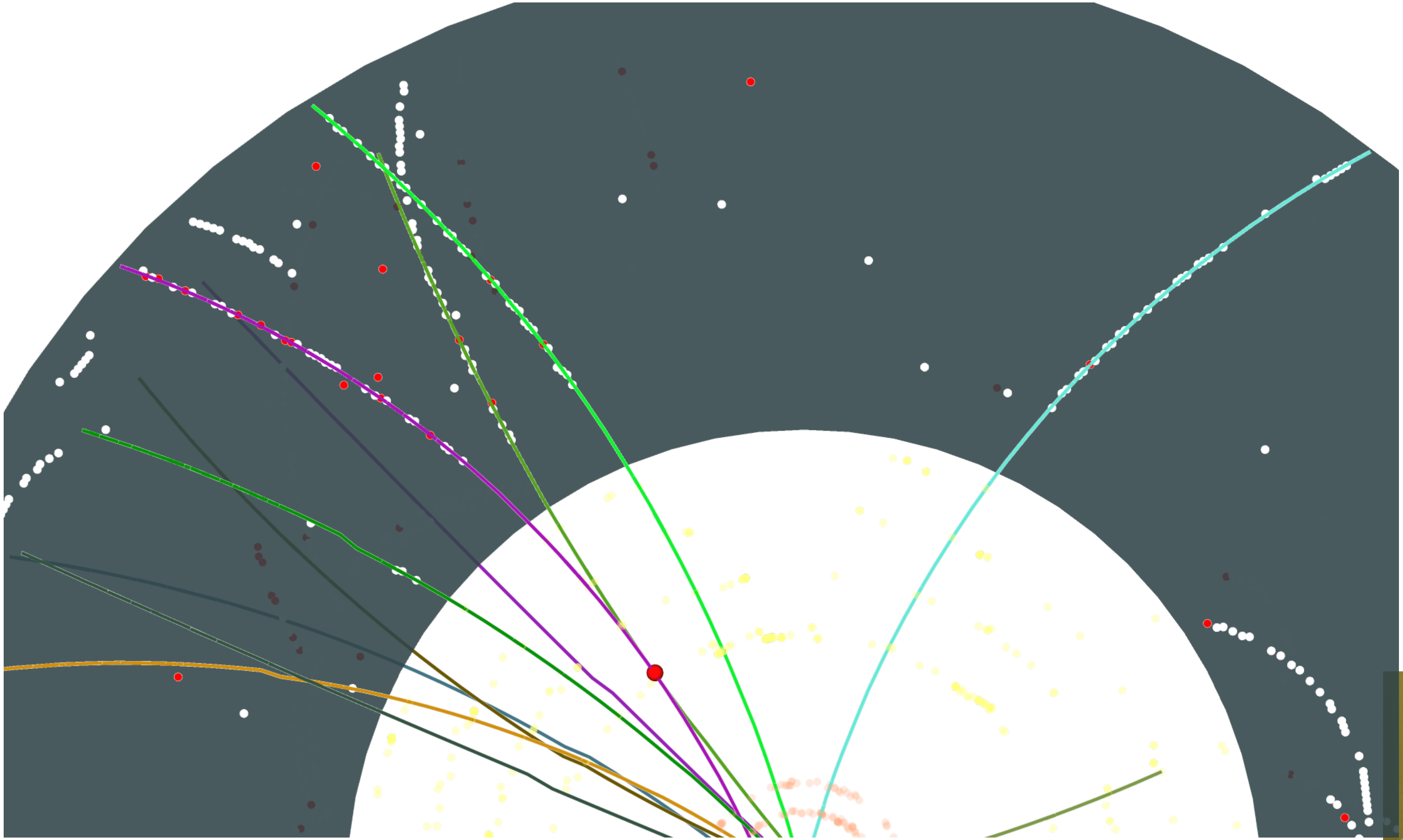
Electrons from photon conversions

- TRT very powerful to track secondaries and then identify which ones are conversions. A few beautiful examples shown here for the pleasure of the eye.



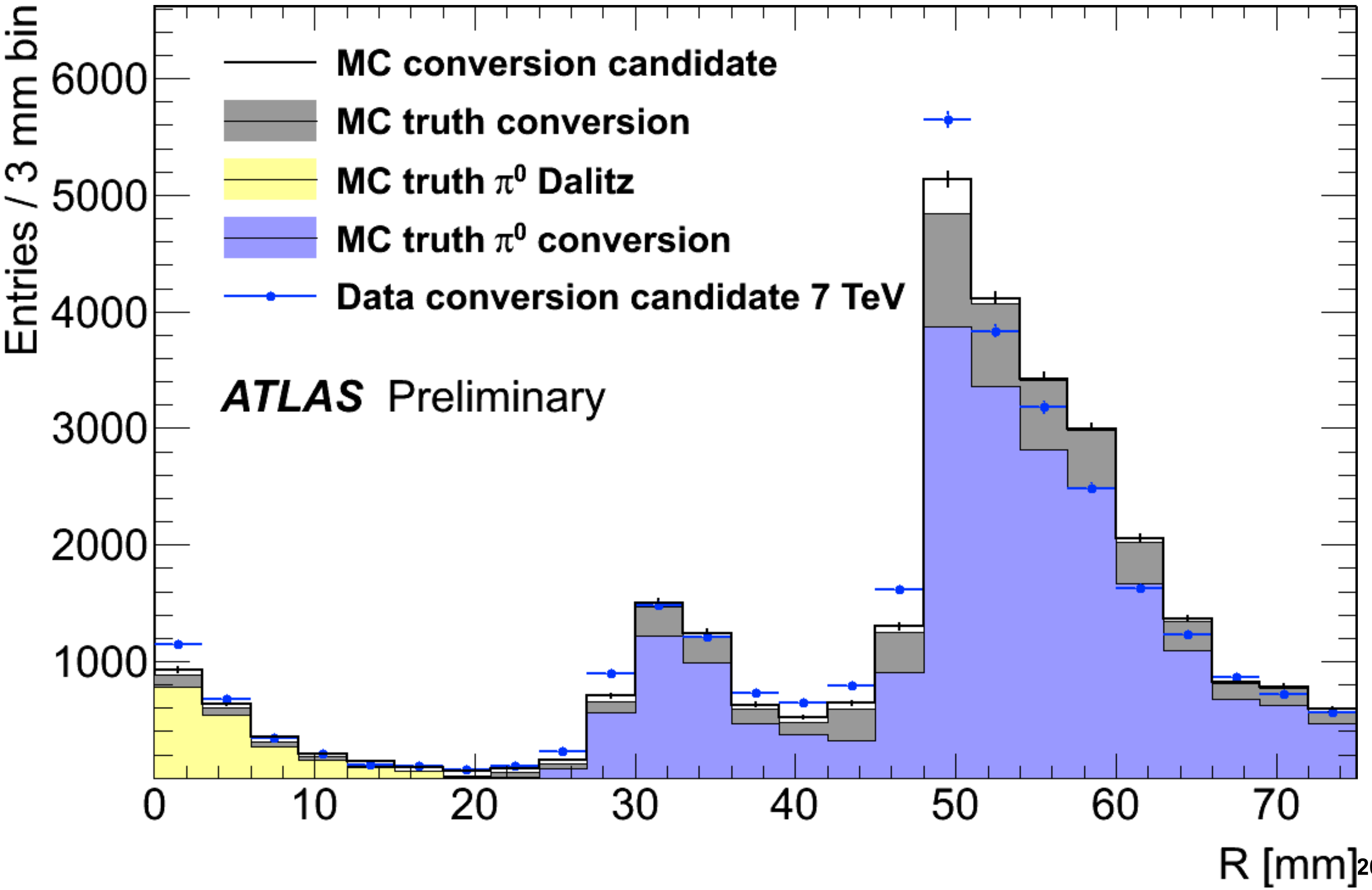
Electrons from photon conversions

- TRT very powerful to track secondaries and then identify which ones are conversions. A few beautiful examples shown here for the pleasure of the eye.



Electrons from photon conversions

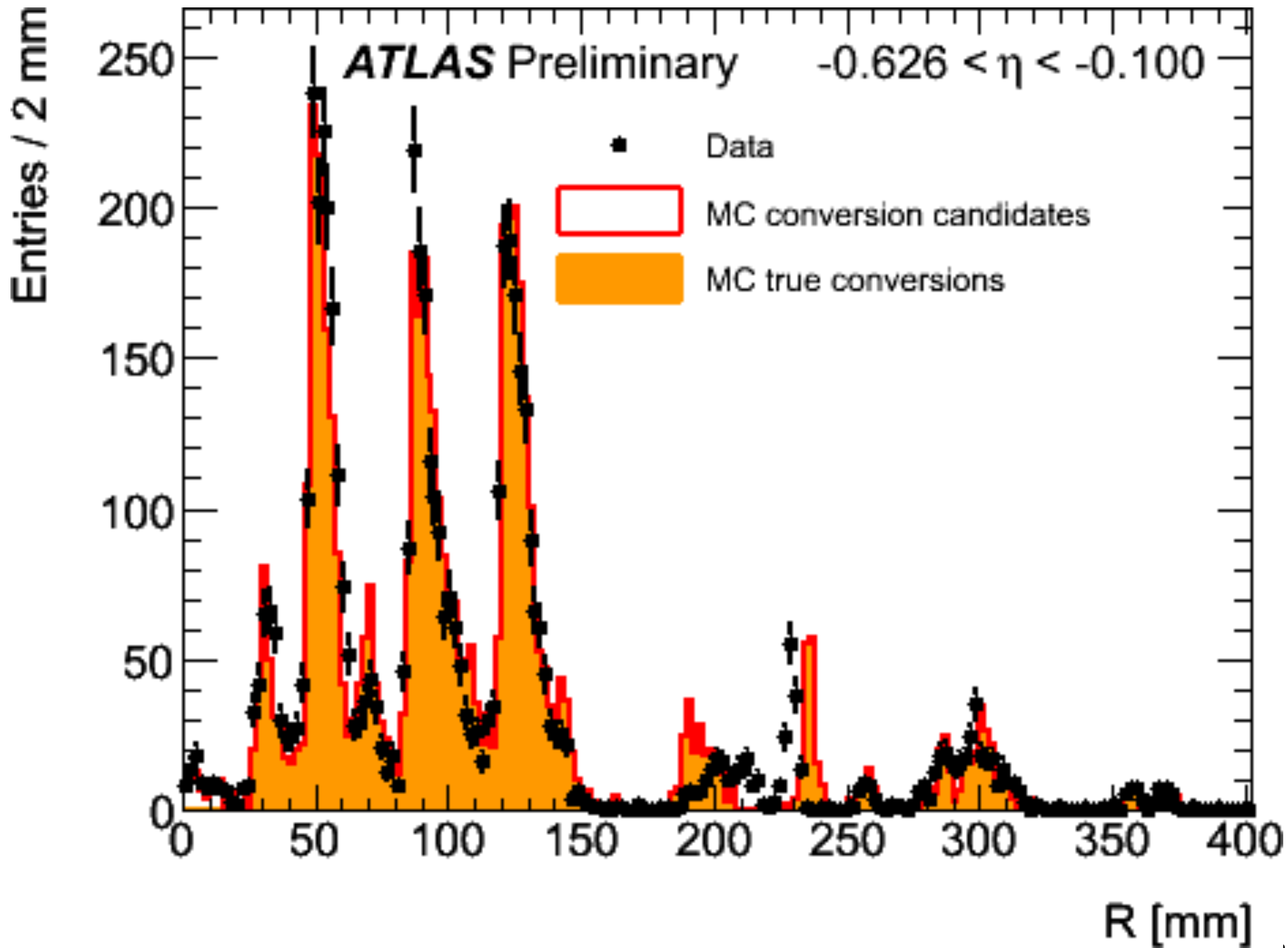
- Proceed to commission analysis to determine amount of material in the ATLAS inner detector: one example is the observation of a clean signal of Dalitz decays from p0’s. Without TR signature, background from fakes from primary vertex would be overwhelming



2011

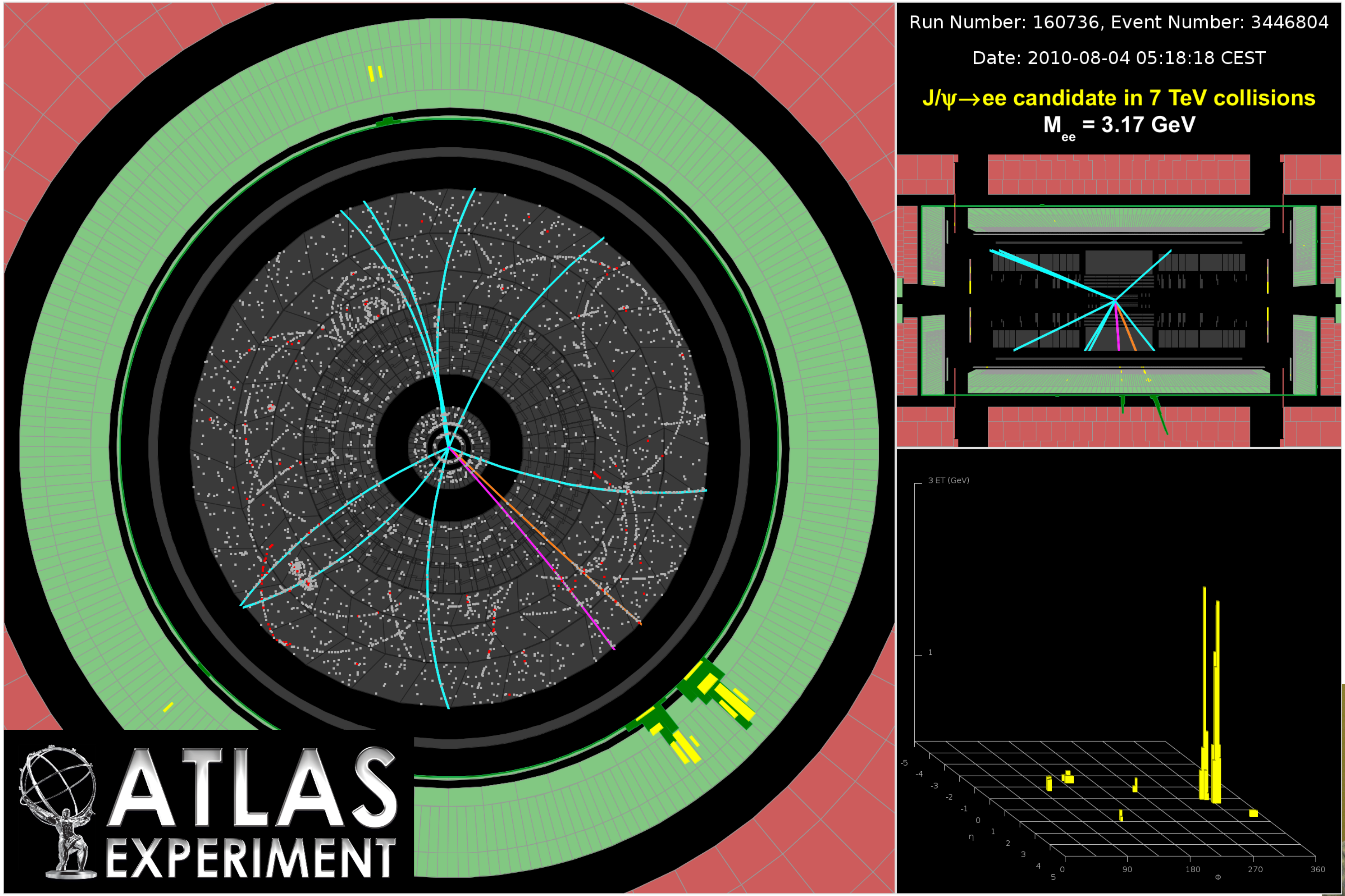
Electrons from photon conversions

- Proceed to commission analysis to determine amount of material in the ATLAS inner detector: second example has been to identify misplaced supports, etc.



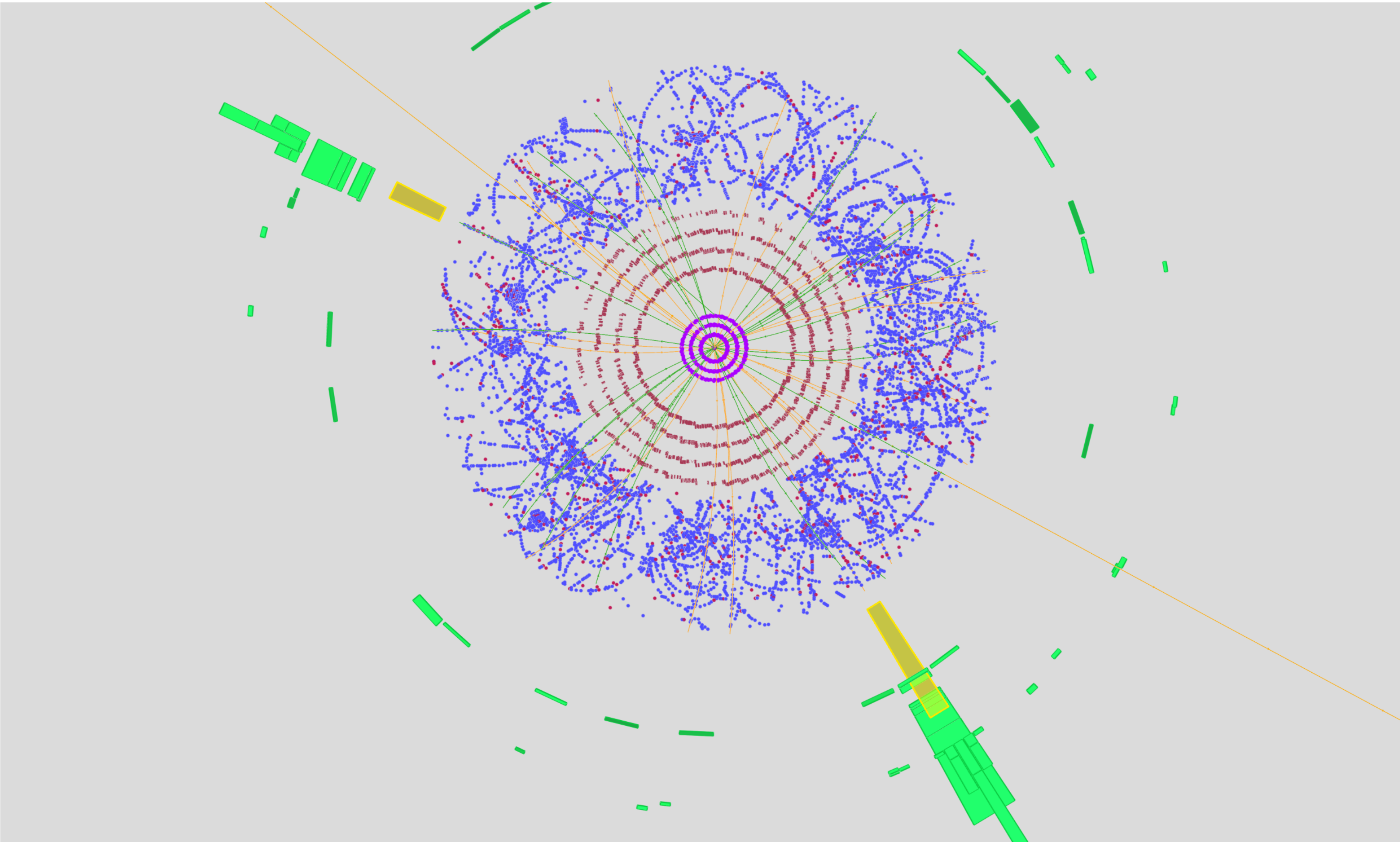
Electrons from J/ψ decay

- Thanks to TRT, ATLAS has a J/ψ tag-and-probe trigger even at 3 10^{33} luminosity. This is crucial to understand low-p_T electrons for H to 4e



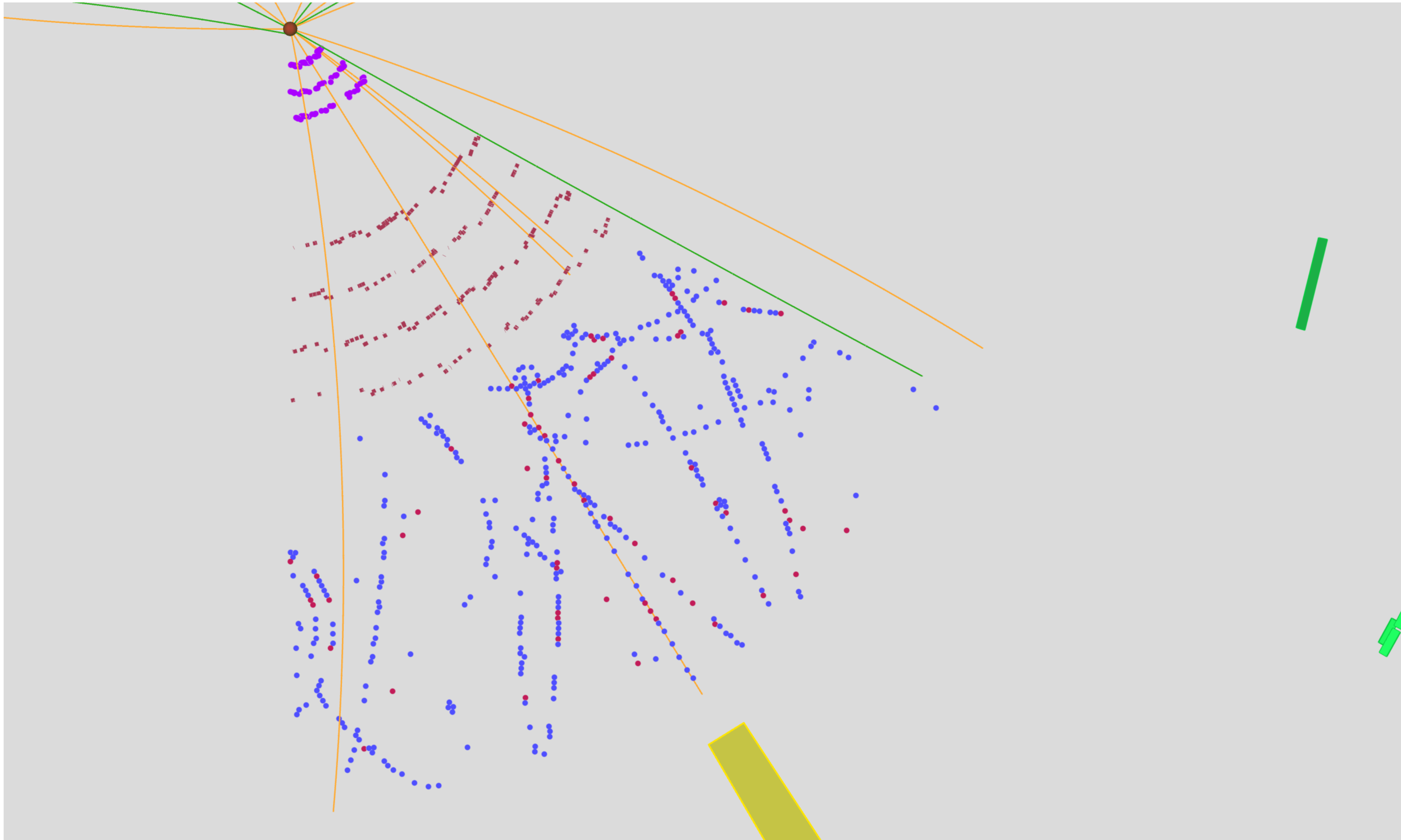
Electrons from ZZ production

- It's still fun to look at these one by one in the latest events found from rare processes. ATLAS is so powerful a detector that even complex final states can be identified almost unambiguously event per event!

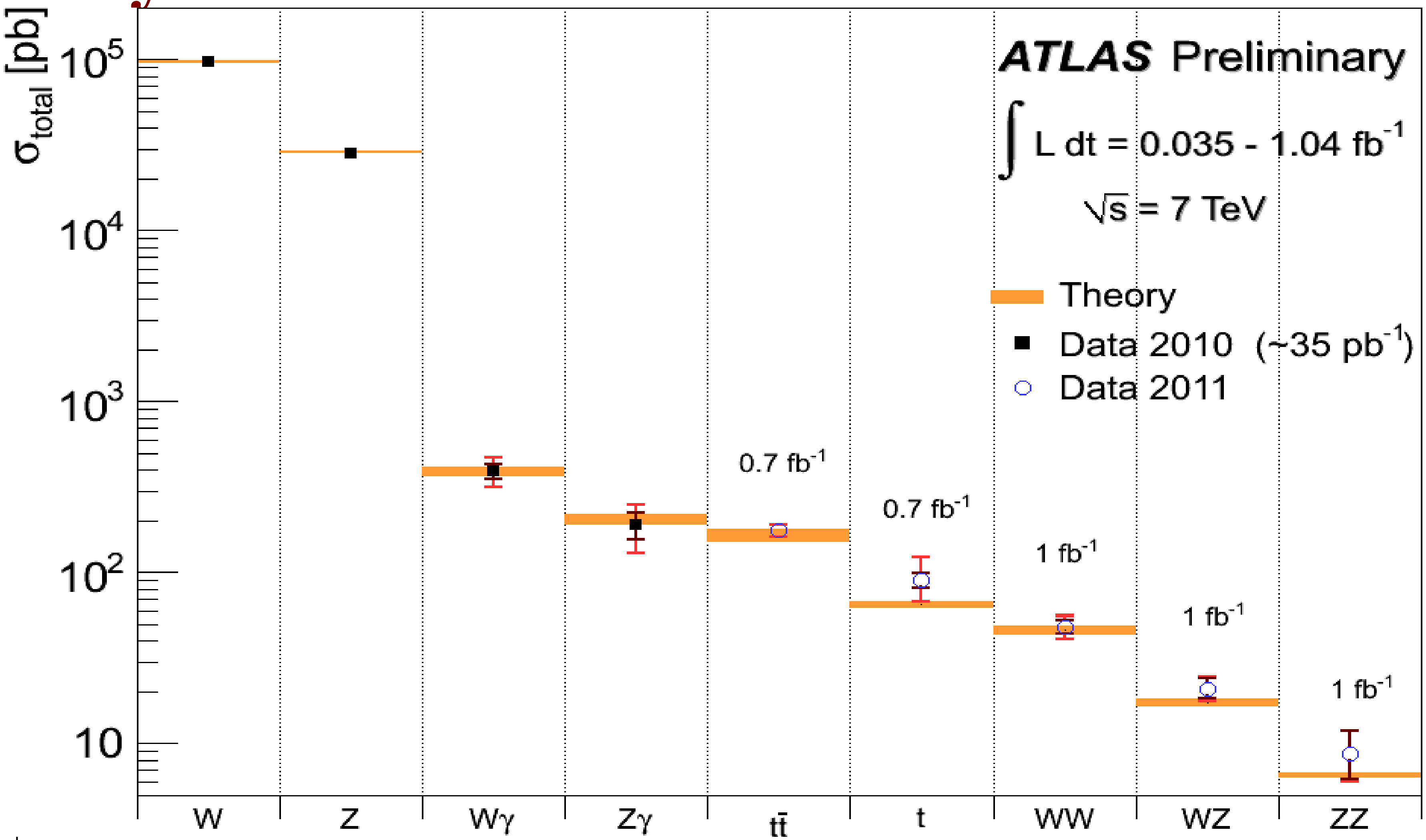


Electrons from ZZ production

- It's still fun to look at these one by one in the latest events found from rare processes. ATLAS is so powerful a detector that even complex final states can be identified almost unambiguously event per event!



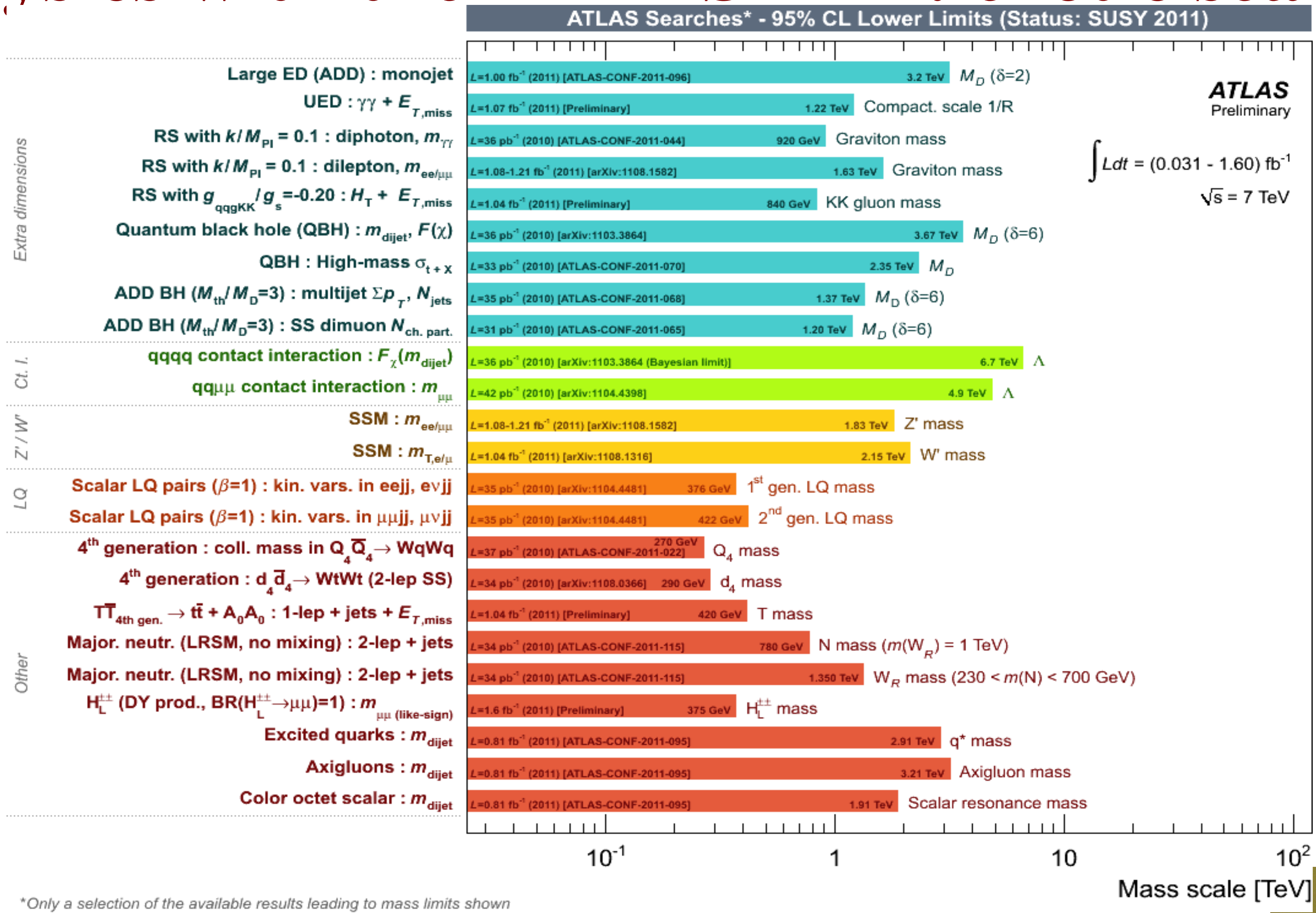
Physics with the ATLAS TRT: SM EW meas.



Is TR(T) used?

- Yes, almost everywhere to minimise background from fake electrons
- Exception is Z to ee and ZZ to 4 leptons where background is low
- Recent exception is W inclusive for precision measurements since scale factors for efficiency due to TR are large (although well known)
- For W+jet measurements, TR is used because of even larger fake rates

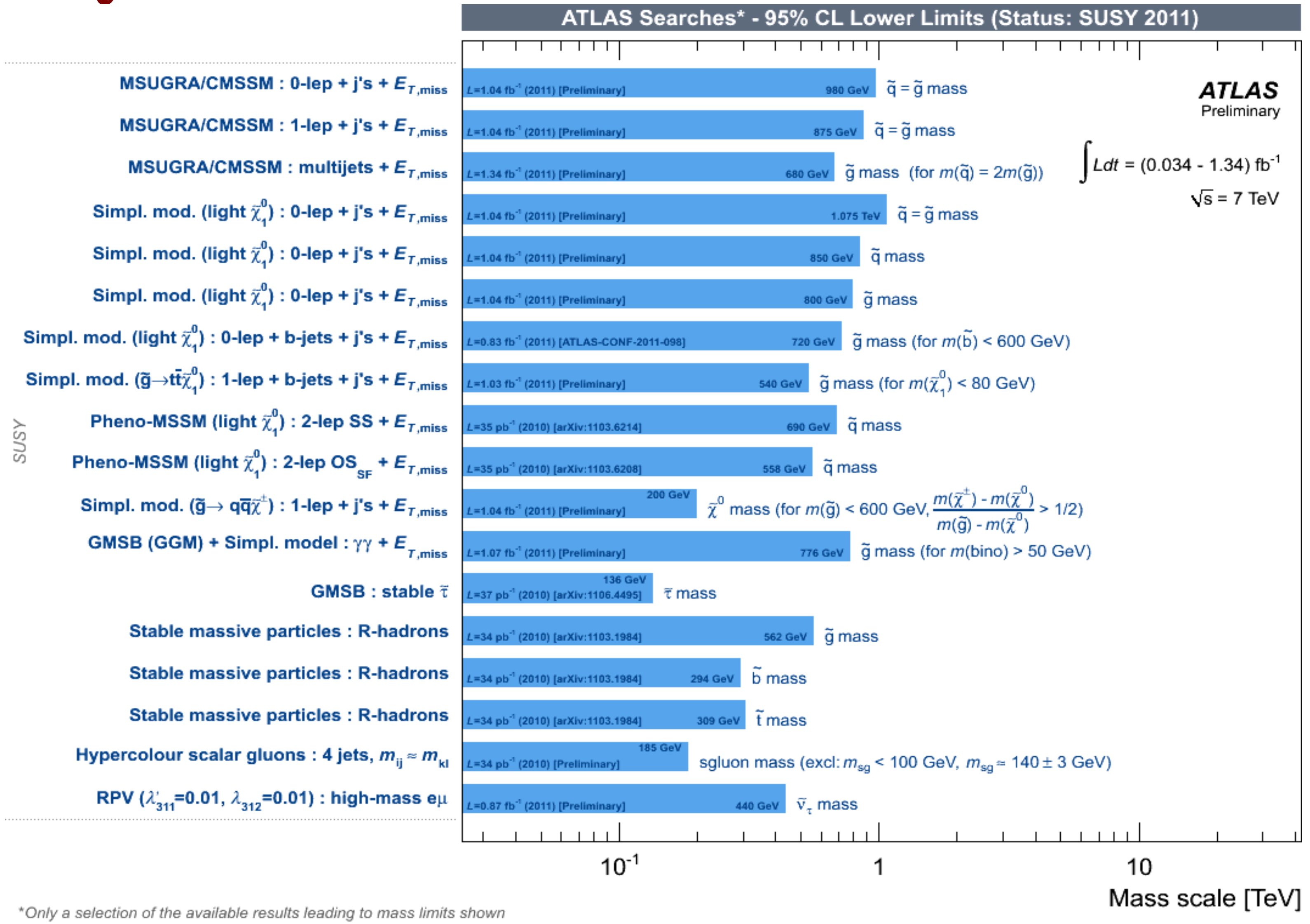
Physics with the ATLAS TRT: exotic searches

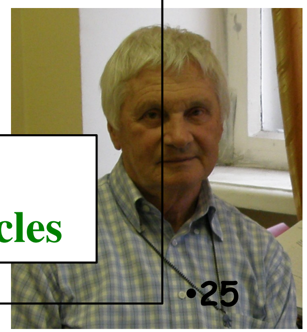


Is TR(T) used?

- In general, no because backgrounds at high pT are not so much a concern
- For specific cases, such as same-sign leptons, leptoquarks, may be used

Physics with the ATLAS TRT: SUSY searches

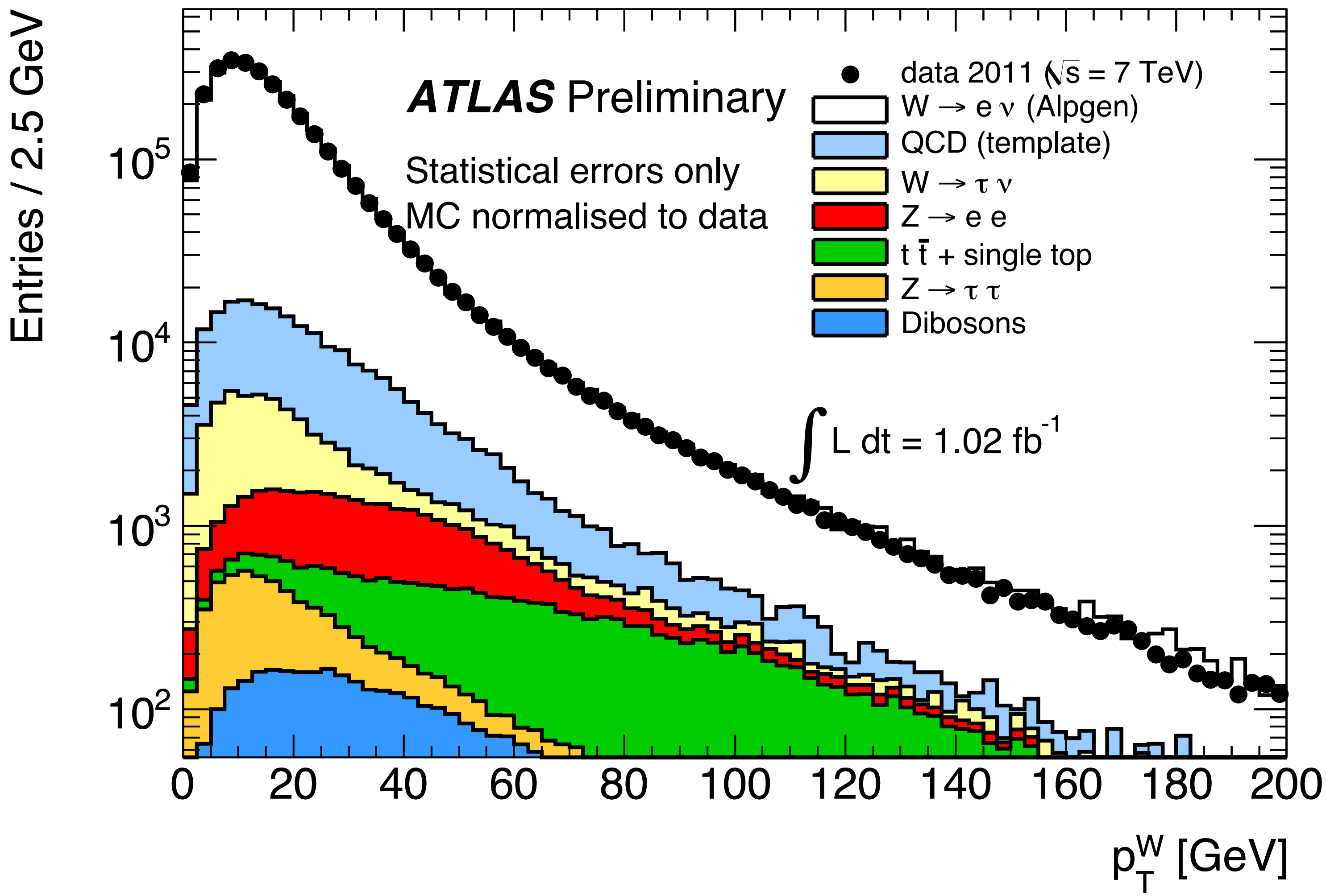


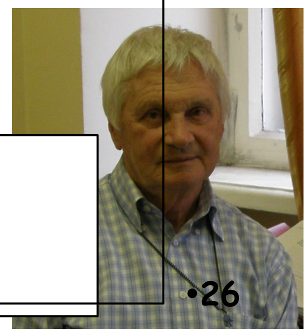


Is TR(T) used?

- In general, yes for searches including leptons
- Also useful for exotic stable heavy particles, or “transsexual” particles

Physics with the ATLAS TRT: SUSY searches

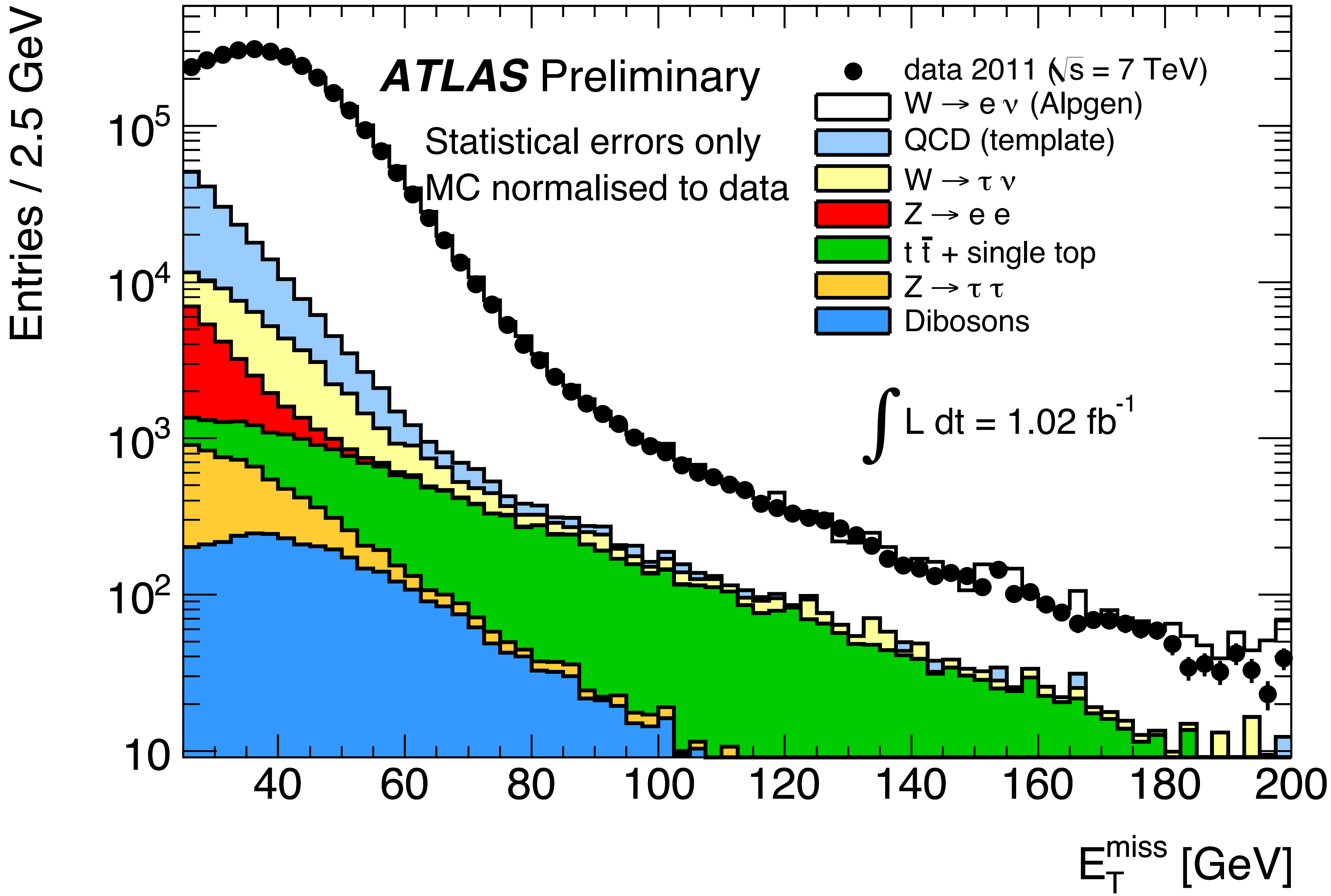




Is TR(T) used?

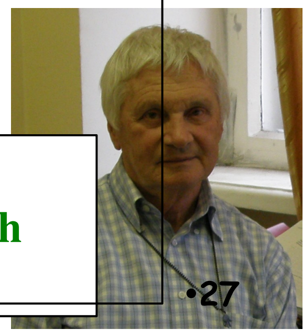
- Let's look at inclusive spectrum of electrons for 1 fb^{-1} of data
- Background from fakes and heavy flavour electrons is largest component of all backgrounds

Physics with the ATLAS TRT: SUSY searches

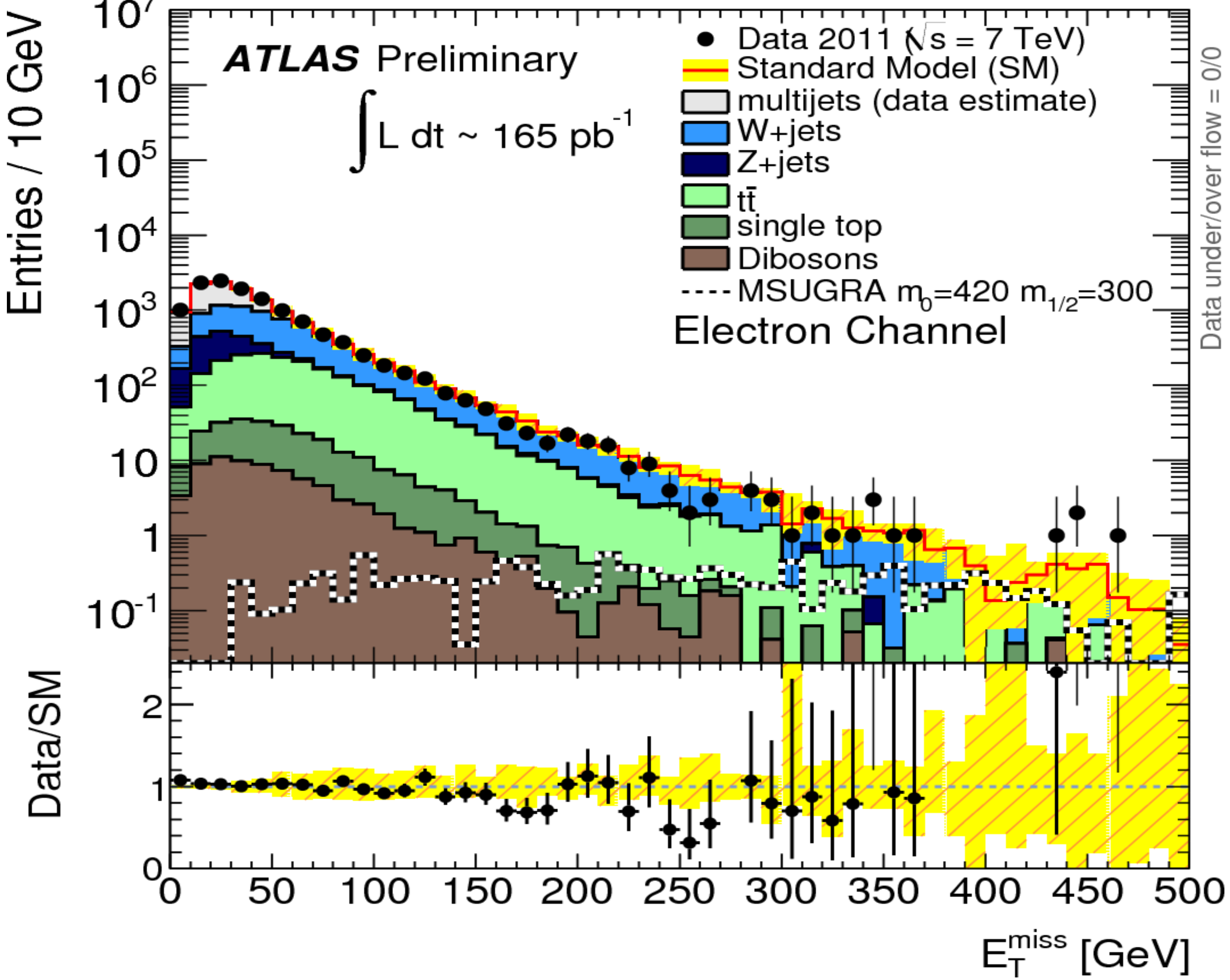


Is TR(T) used?

- **If we look at E_T^{miss} spectrum, background has mostly small E_T^{miss}**
- **Background from heavy flavour cannot easily have high E_T for both the electron and the neutrino**



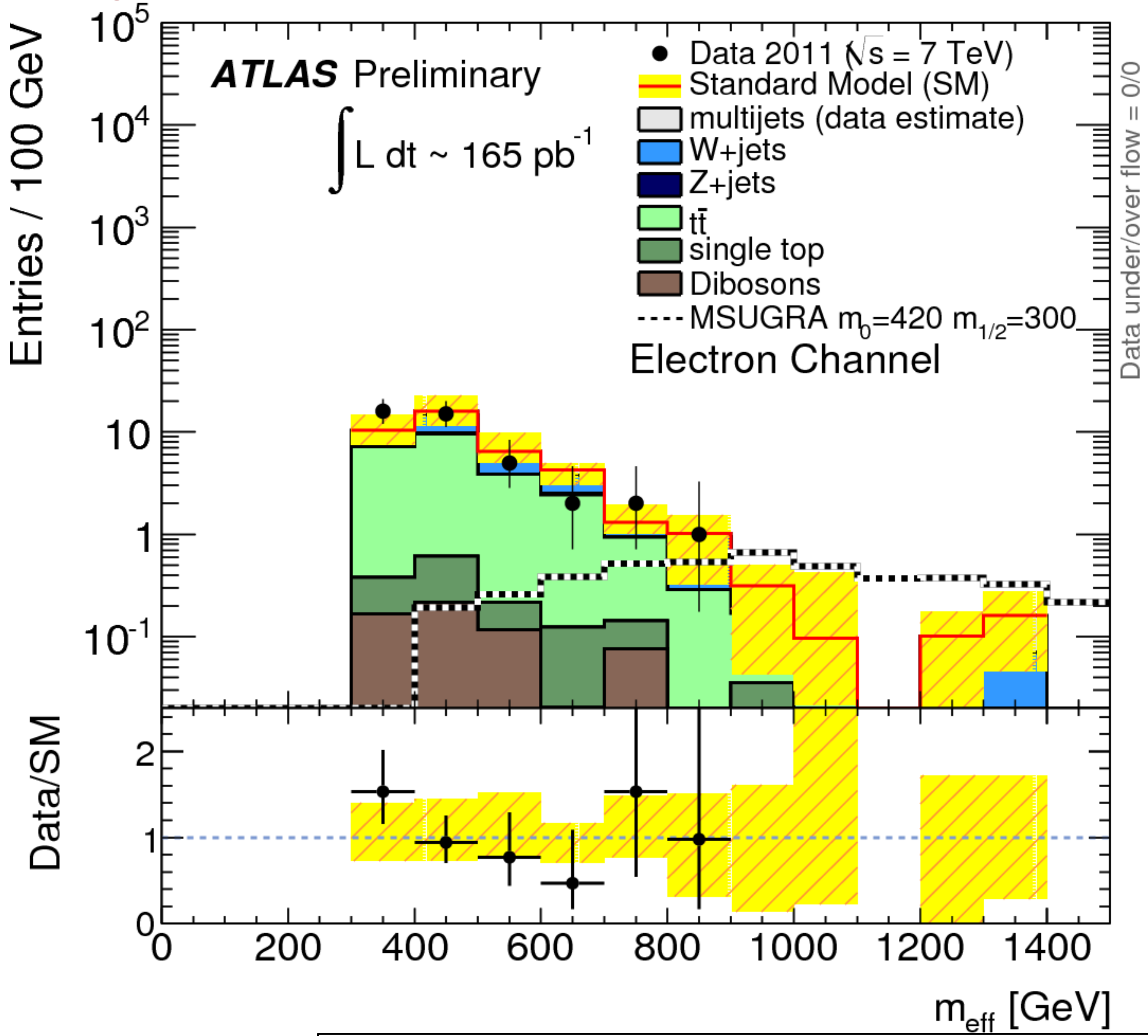
Physics with the ATLAS TRT: SUSY searches

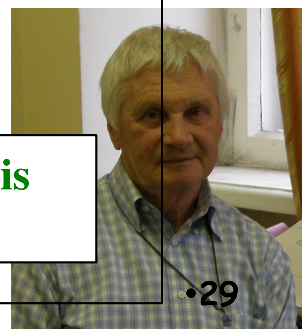


Is TR(T) used?

• Similar picture when looking at E_T^{miss} spectrum for SUSY preselection (several additional jets required). Background from fakes only in first bins on this scale

Physics with the ATLAS TRT: SUSY searches

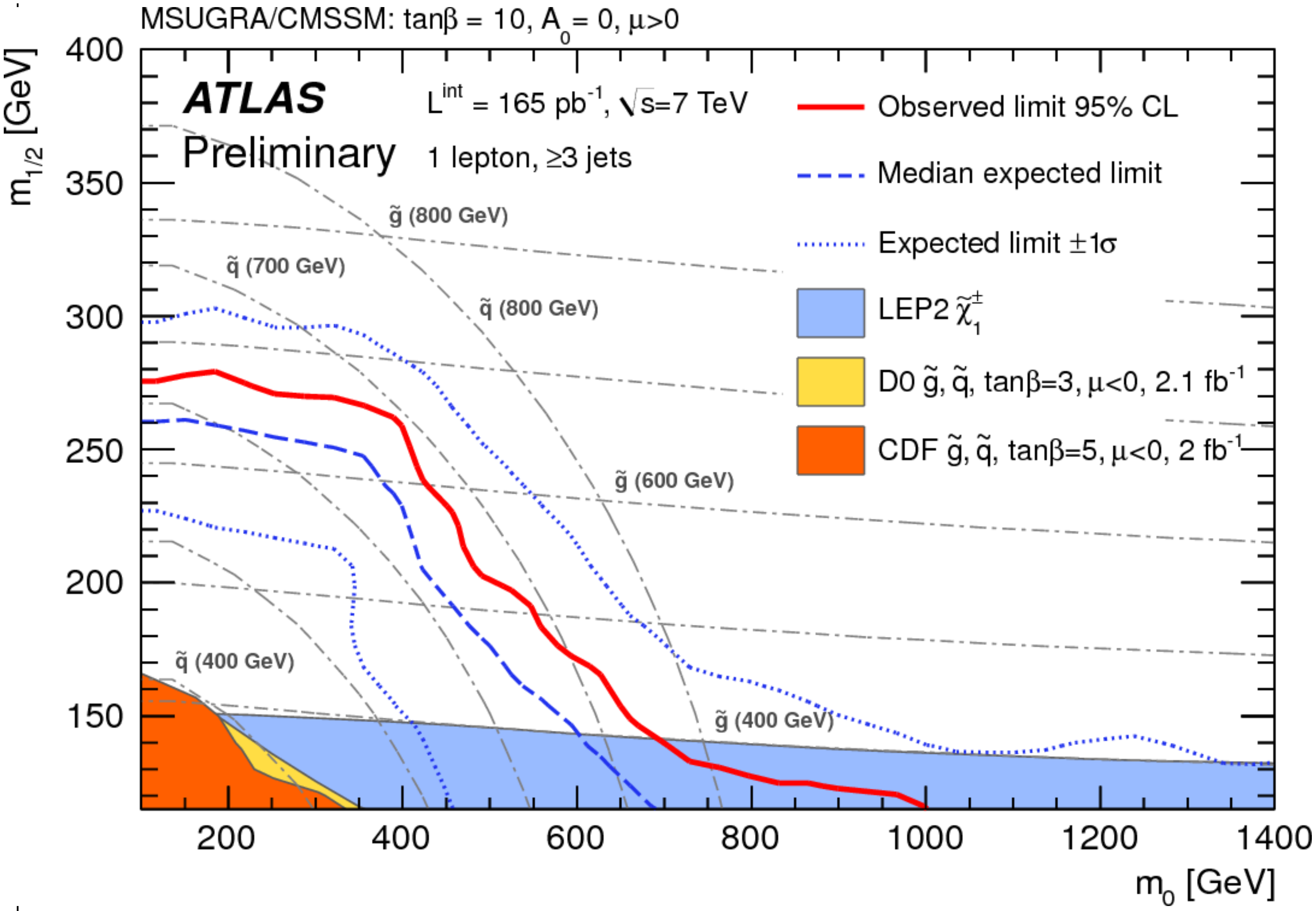


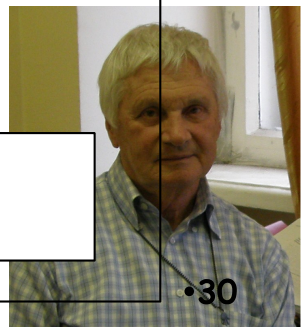


Is TR(T) used?

• After final selection cuts on E_T^{miss} and $m_T^{e\nu}$, dominant background is from top production

Physics with the ATLAS TRT: SUSY searches

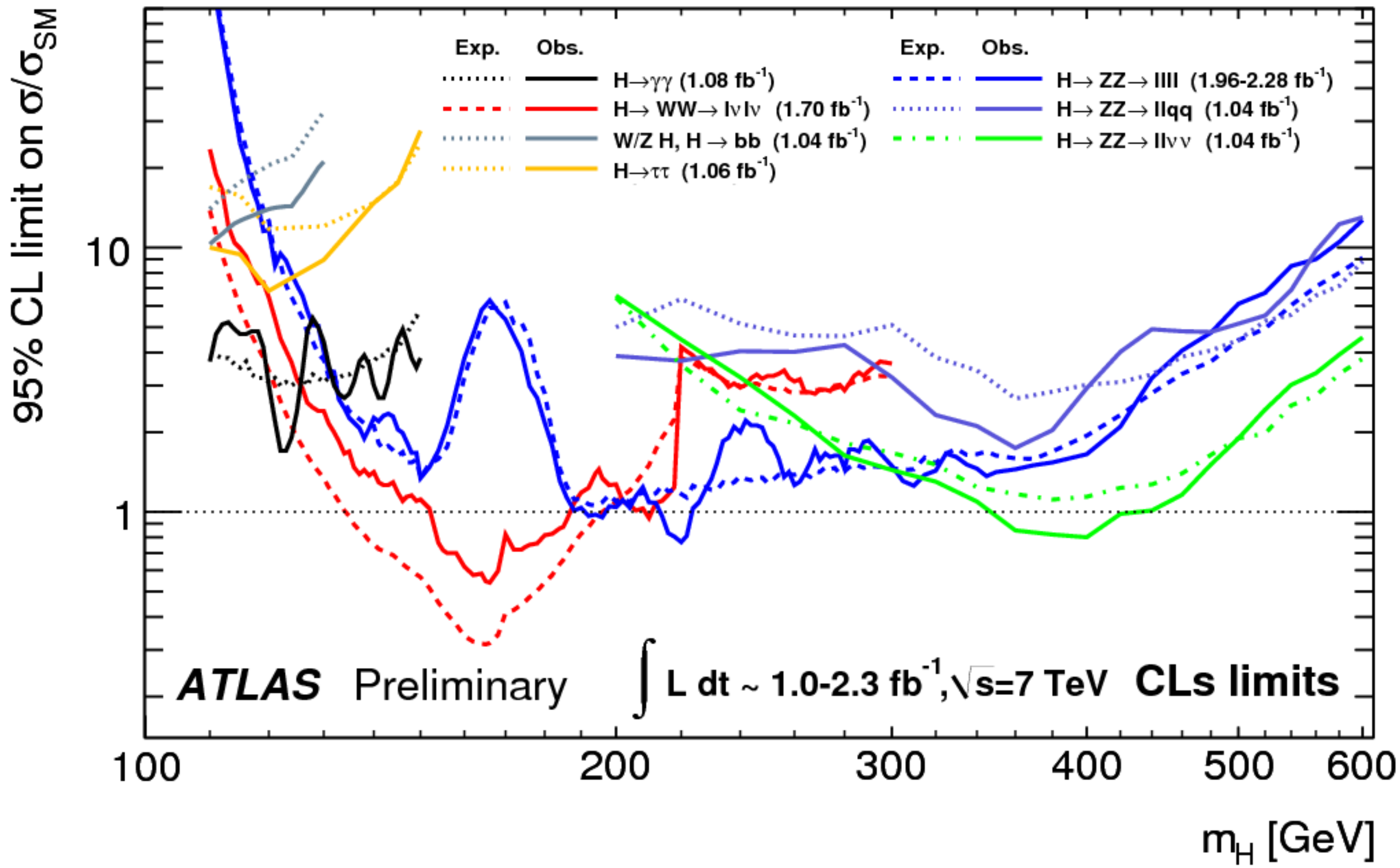




Is TR(T) used?

• **Yes, it plays its own modest role in the global picture. But here one cannot claim that it is vital**

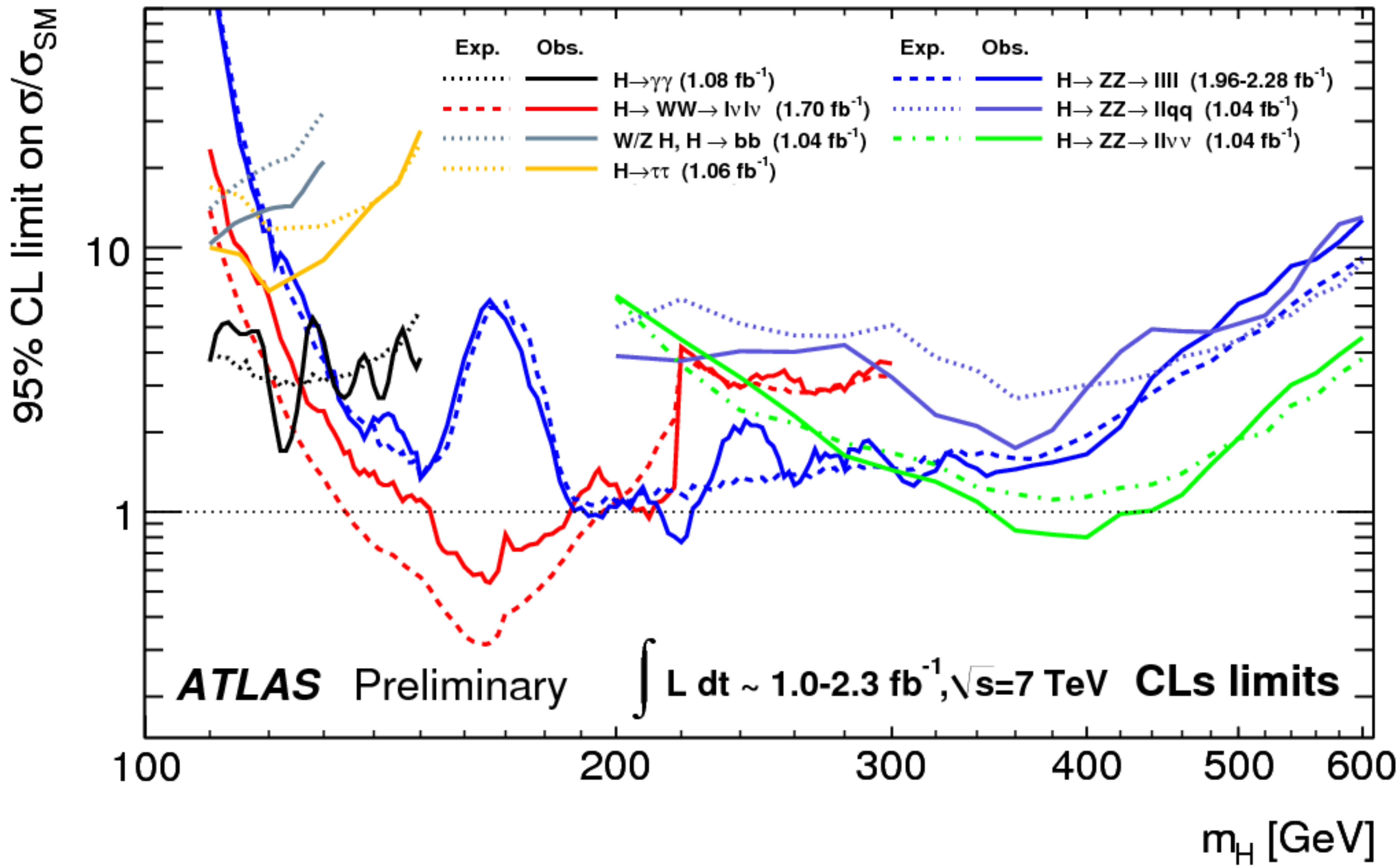
Physics with the ATLAS TRT: Higgs searches



Comments:

- $H \rightarrow \gamma\gamma$: most sensitive channel $m_H \leq 120$ GeV
- $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$: most sensitive channel $130 \leq m_H < 180$ GeV
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$: most sensitive channel $180 \leq m_H \leq 300$ Gev
- and most convincing channel down to ~ 130 GeV
- $H \rightarrow ZZ \rightarrow ll\nu\nu$: most sensitive channel $300 < m_H \leq 600$ GeV

Physics with the ATLAS TRT: Higgs searches



Is TR(T) used?

- H→ γγ : yes! for photon conversions, $f_{\gamma \rightarrow ee} \sim 40\%$
- H→ WW(*)→ lνlν : yes, background from fakes (W+jets)
- H→ ZZ(*)→ 4l : no, low rate and low backgrounds from fakes
- H→ ZZ→ llνν : no, same as above
- H to ττ : yes! for electron veto in single-prong decays

Inclusive electrons at the LHC: a real challenge!

- This is another measurement unique to ATLAS at the moment. It has never been done at the Tevatron, namely publish in the same paper and on the same footing the measured inclusive spectra for electrons and muons from heavy-flavour hadron decay.

- It is of course much more challenging for electrons than for muons.

- The interest from theorists is genuine: state-of-the-art calculations are reasonably accurate and they can be tested in an area where such tests have never been done before, namely the really high-pT muons above the Jacobean peak from W/Z decay.

- To succeed in the measurement for electrons, the TRT has been an essential component: without it, it is unlikely that such a measurement could have been performed without relying heavily on the MC.

Inclusive electrons at the LHC: a real challenge!

- What does one see if one selects single electrons (left) and electron pairs (right) after applying the tightest selection criteria to reduce the background from hadrons (initially dominant) and photon conversions?
- Inclusive electrons at low ET are ~50% pure (mostly from b,c decays)
- Electron pairs have a more complicated spectrum and exact composition of background not measured yet.

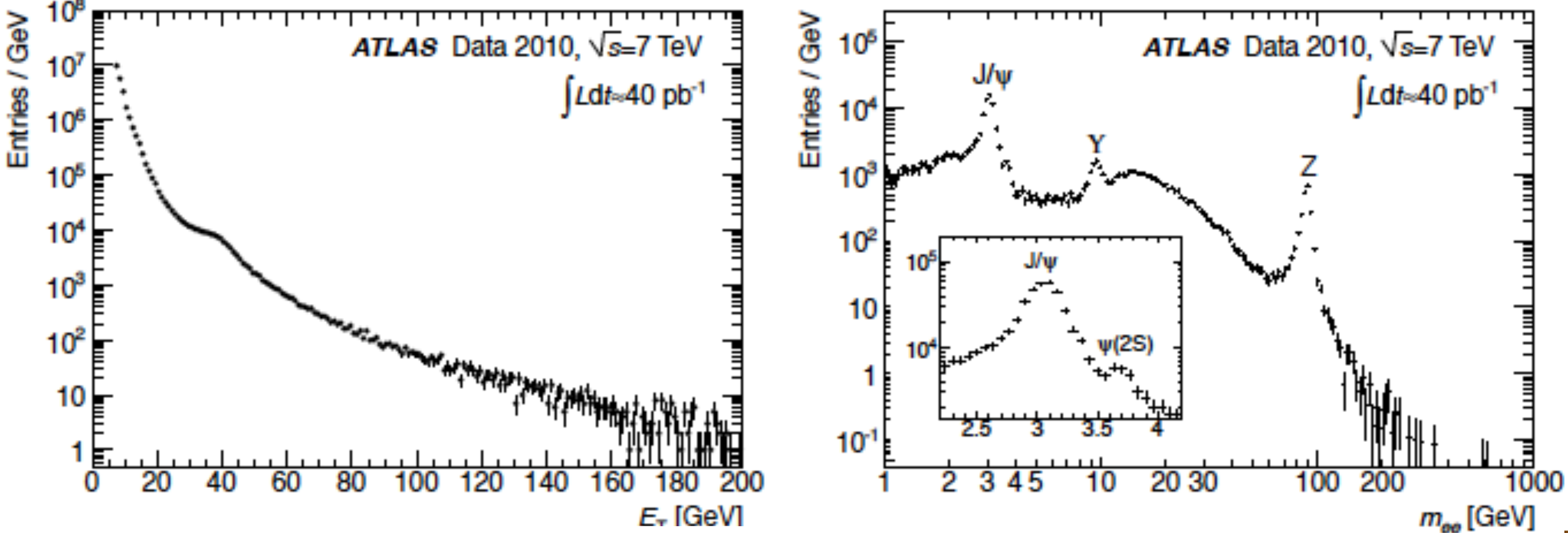


Fig. 2. (left) E_T distribution of electron candidates passing the *tight* identification cuts for events selected by single electron triggers with varying E_T thresholds. Data with $E_T < 20$ GeV correspond to lower integrated luminosity values and were rescaled to the full luminosity. (right) Reconstructed dielectron mass distribution of electron candidate pairs passing the *tight* identification cuts for events selected by low E_T threshold dielectron triggers. The number of events is normalised by the bin width. Errors are statistical only.

Inclusive muons at the LHC: an easier challenge!

For muons, for which the reconstruction and identification is only weakly coupled to the isolation properties, it makes sense to measure the whole spectrum of heavy flavour decays (which means W/Z have to be subtracted out).

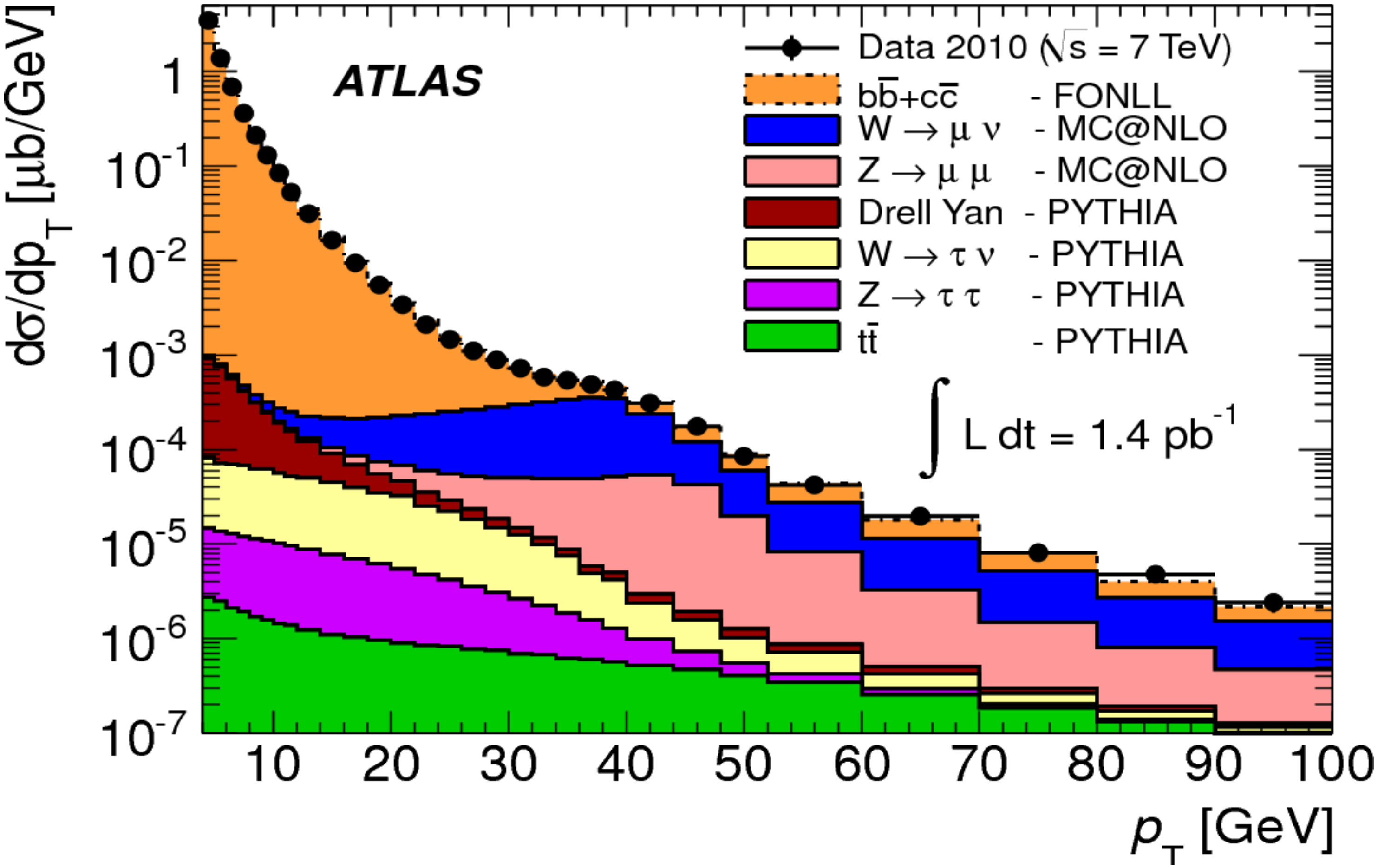


Figure 3: *Muon differential cross-section as a function of the muon transverse momentum for $|\eta| < 2.5$ compared to theoretical predictions. The Drell-Yan component corresponds to the Z/γ^* for $M_{\mu^+\mu^-} < 60$ GeV.*

Inclusive electrons at the LHC: a real challenge!

To improve the efficiency for electrons from heavy flavour, but above all to preserve best discriminating variables to measure the composition of the background before rejecting it, apply less stringent identification cuts leading to an expected signal contribution of ~ 10% for E_T < 20 GeV

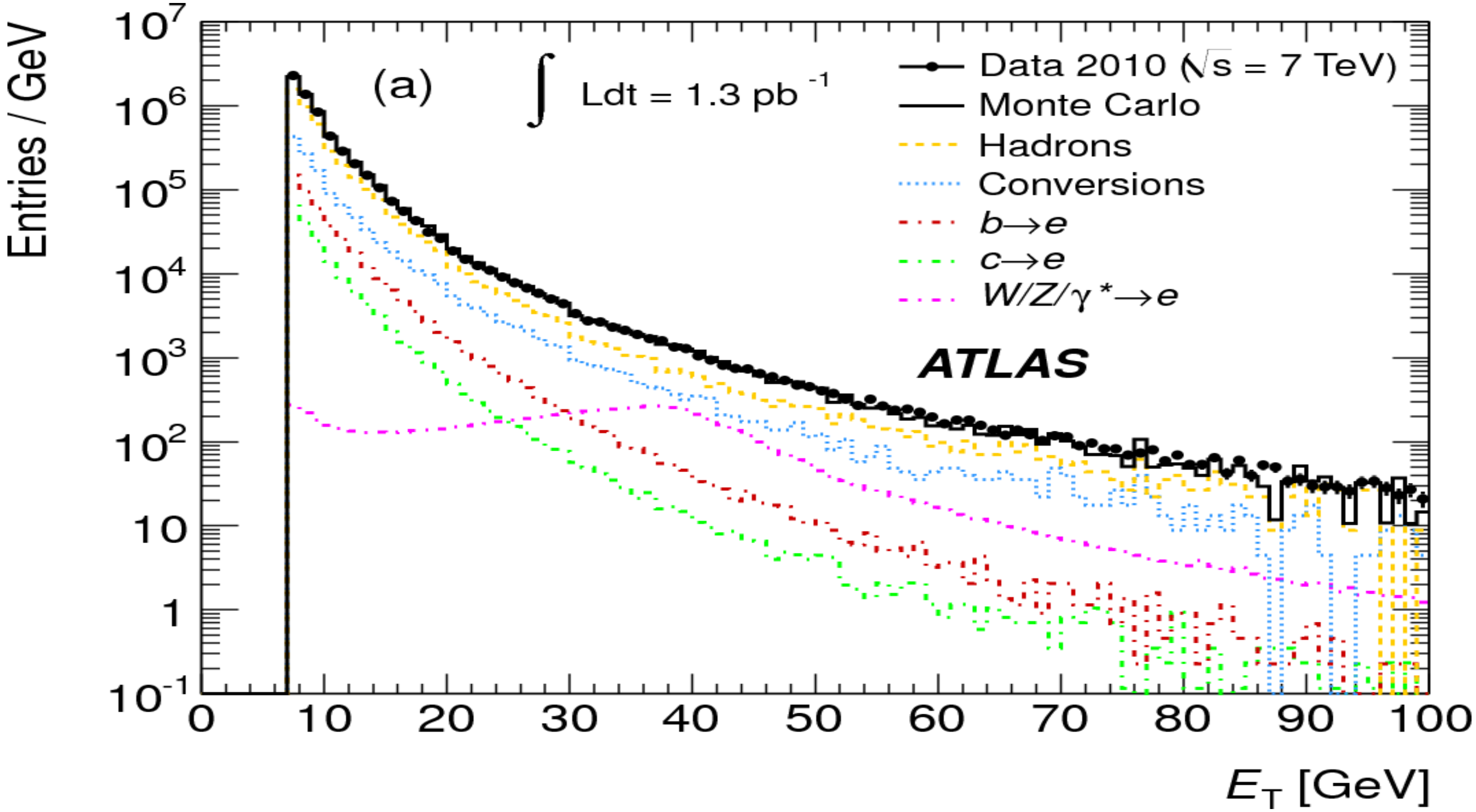
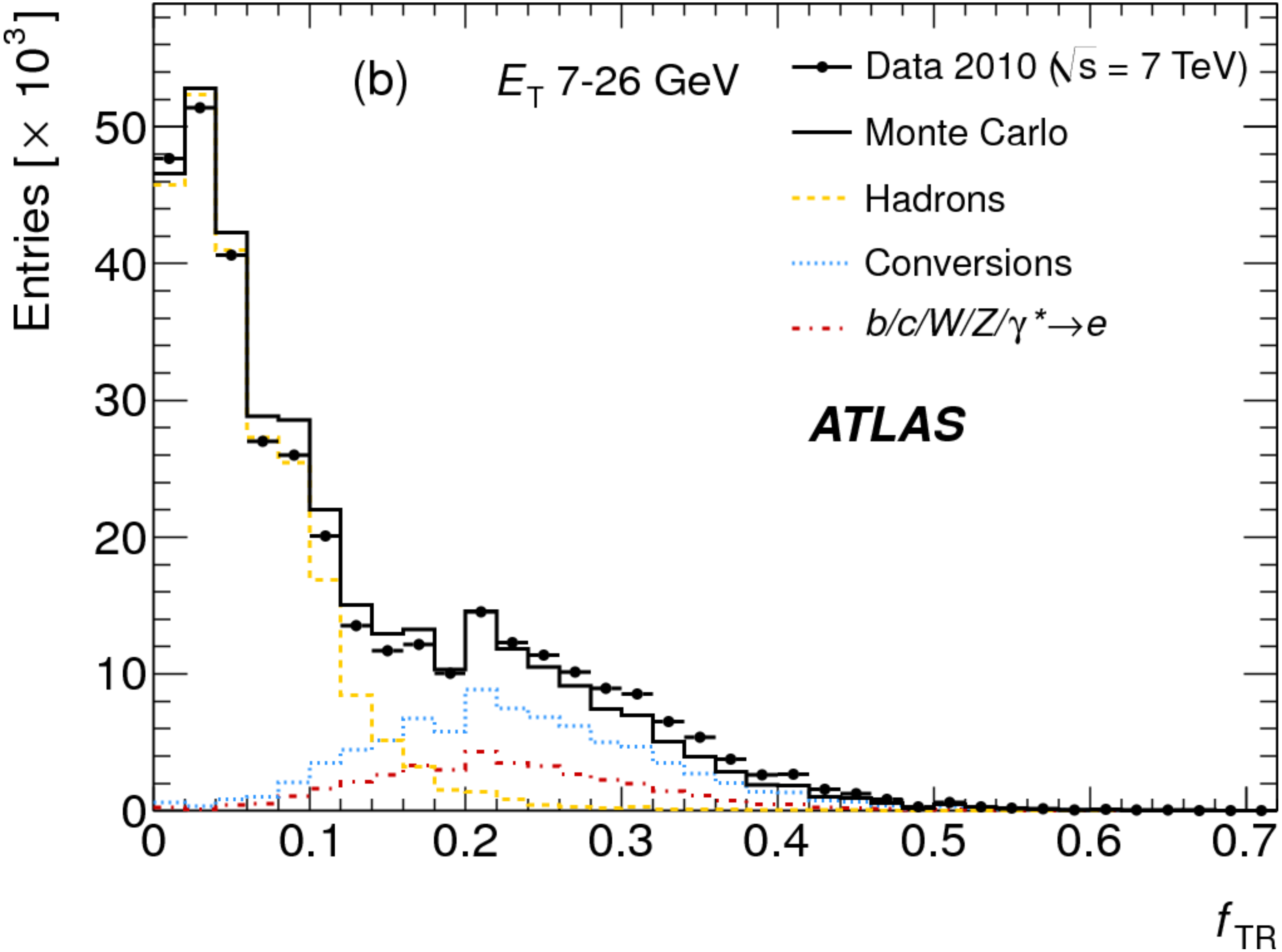


Figure 1: *(a) Distribution of cluster transverse energy, E_T, for the electron candidates. The simulation uses* PYTHIA *with the W and Z/γ^* components normalised to their NNLO total cross-sections and the heavy-flavour, conversion and hadronic components then normalised to the total expectation from the data. Data with $p_T < 18$ GeV are rescaled to 1.3 pb^{-1} from lower integrated luminosities. (b-d)*

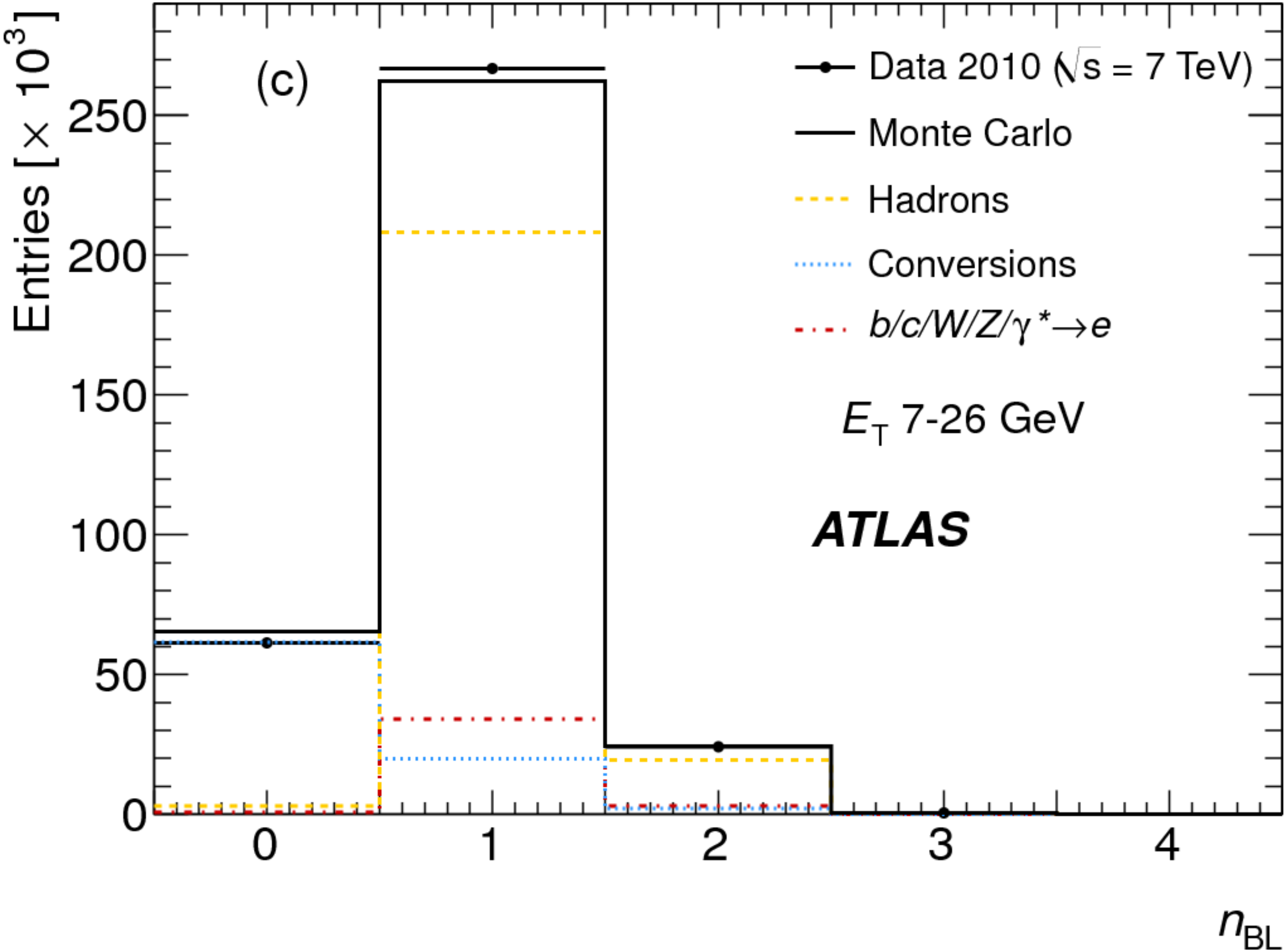
Inclusive electrons at the LHC: a real challenge!

TR ratio provides excellent discrimination between hadrons and electrons of any type. But it varies depending on how much jet activity is around.



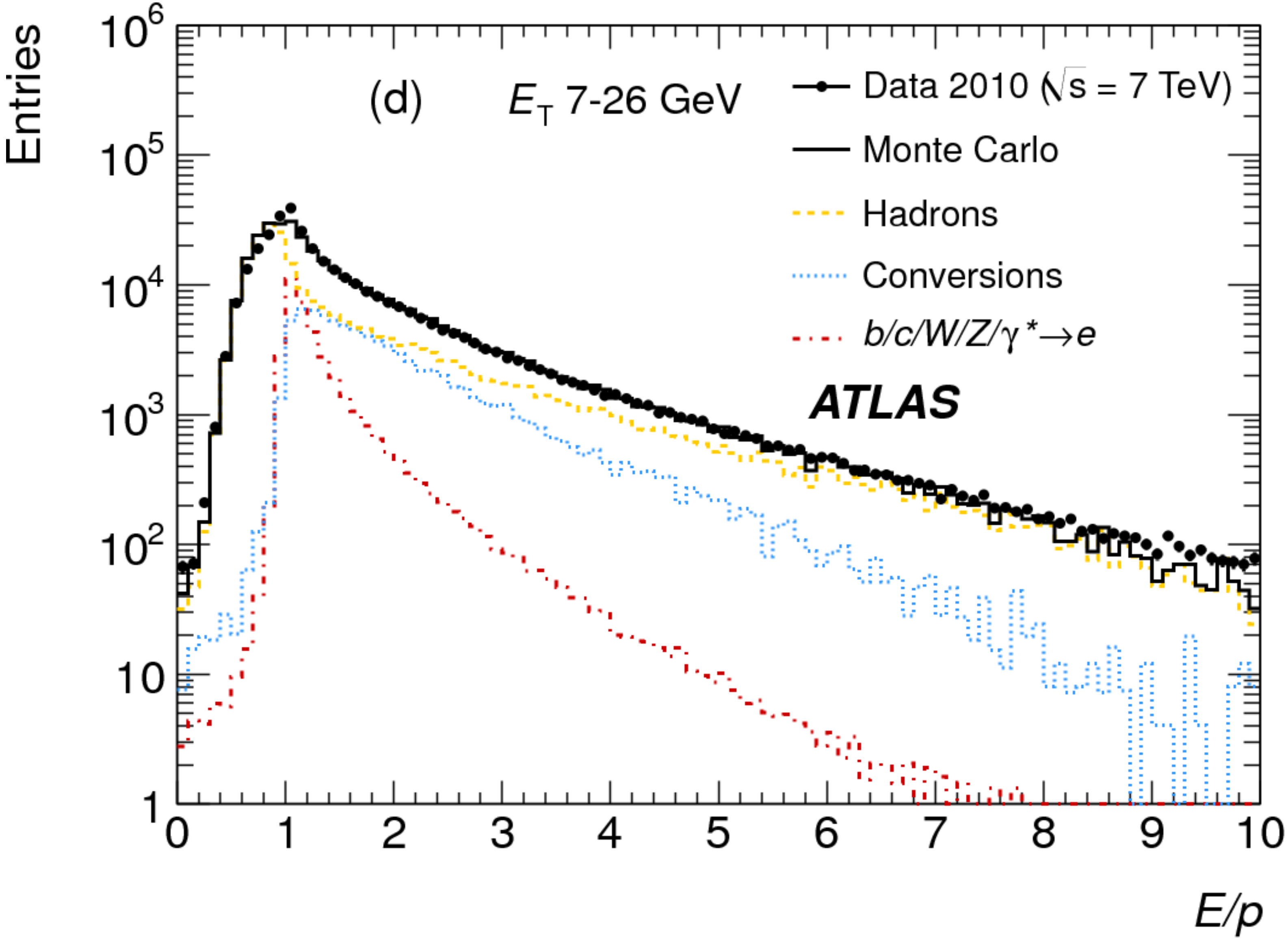
Inclusive electrons at the LHC: a real challenge!

Presence of hit in B-layer provides excellent discrimination between electrons from conversions and any other charged particle track



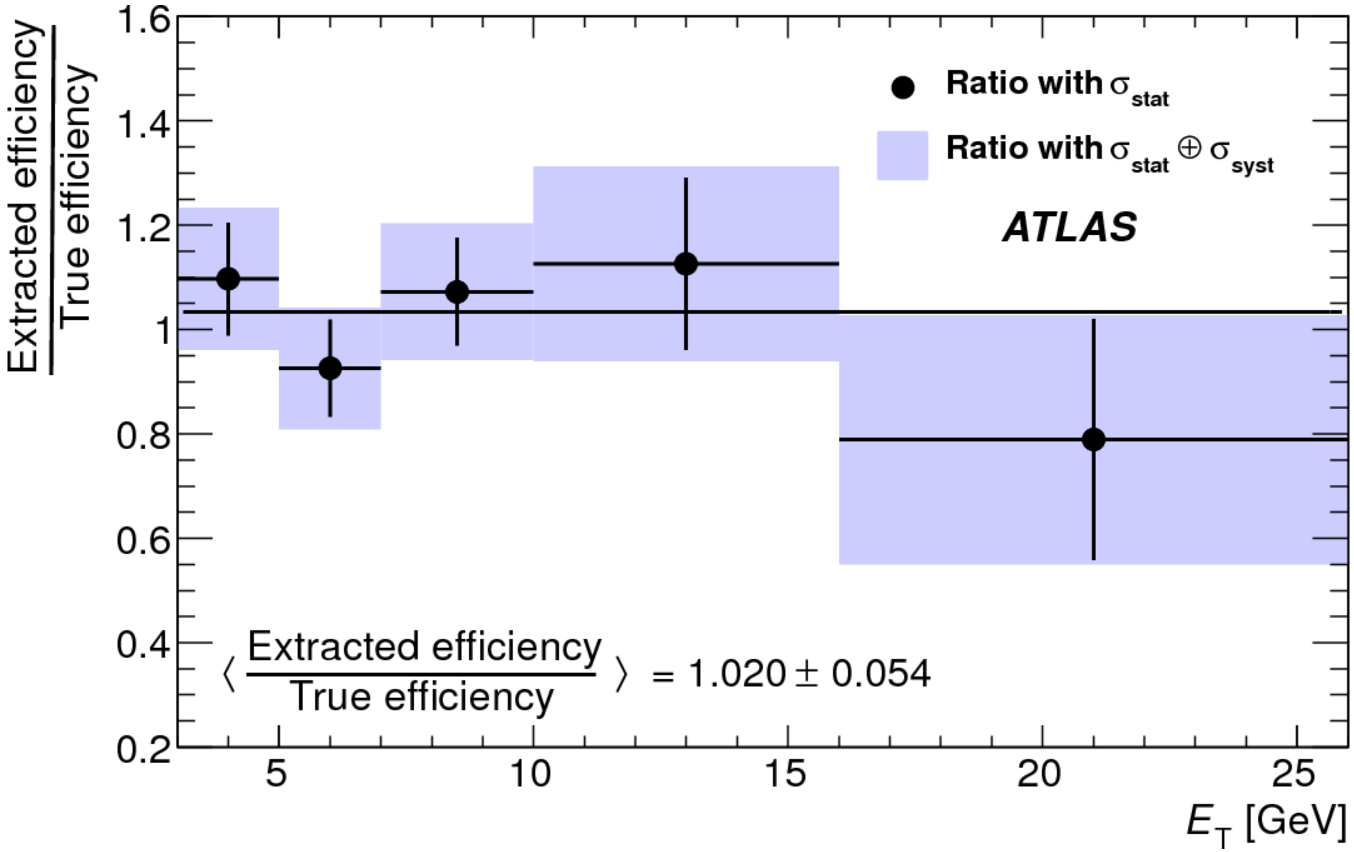
Inclusive electrons at the LHC: a real challenge!

E/p is a useful discriminating variable also, but brem losses and jet activity around the electron limit its power.



Inclusive electrons at the LHC: a real challenge!

The biggest challenge for the electrons has been to measure the efficiency for non-isolated electrons from data: use tag-and-probe technique where the tag is a tight electron candidate, which enriches the QCD dijet background in heavy-flavour dijets with one jet producing a real electron. The probe is then selected with minimal cuts and the fraction of signal is large enough to apply the same method as in the normal analysis to measure the signal component before and after cuts.



Inclusive electrons at the LHC: a real challenge!

For the first time in a hadron collider, fiducial heavy-flavour cross-sections for inclusive leptons are produced in a coherent analysis!

State-of-the-art theoretical calculations can predict these fiducial cross-sections (once the measurements are unfolded for resolution and efficiency of course)

We obtain a fiducial heavy-flavour electron cross-section in the range $7 < p_T < 26$ GeV and within $|\eta| < 2.0$, excluding $1.37 < |\eta| < 1.52$, of

$$\sigma^{e}_{\mathrm{HF}} = 0.946 \pm 0.020(\mathrm{stat.}) \pm 0.146(\mathrm{syst.}) \pm 0.032(\mathrm{lumi.})\ \mu\mathrm{b}.$$

In order to compare to the results of the electron analysis, the muon cross-section has been studied in the same acceptance region ($7 < p_T < 26$ GeV and $|\eta| < 2.0$, excluding $1.37 < |\eta| < 1.52$) and with the subtraction of the $W/Z/\gamma^*$ contribution, giving a fiducial heavy-flavour muon cross-section of

$$\sigma^{\mu}_{\mathrm{HF}} = 0.818 \pm 0.003(\mathrm{stat.}) \pm 0.036(\mathrm{syst.}) \pm 0.028(\mathrm{lumi.})\ \mu\mathrm{b}.$$

Inclusive electrons at the LHC: final result

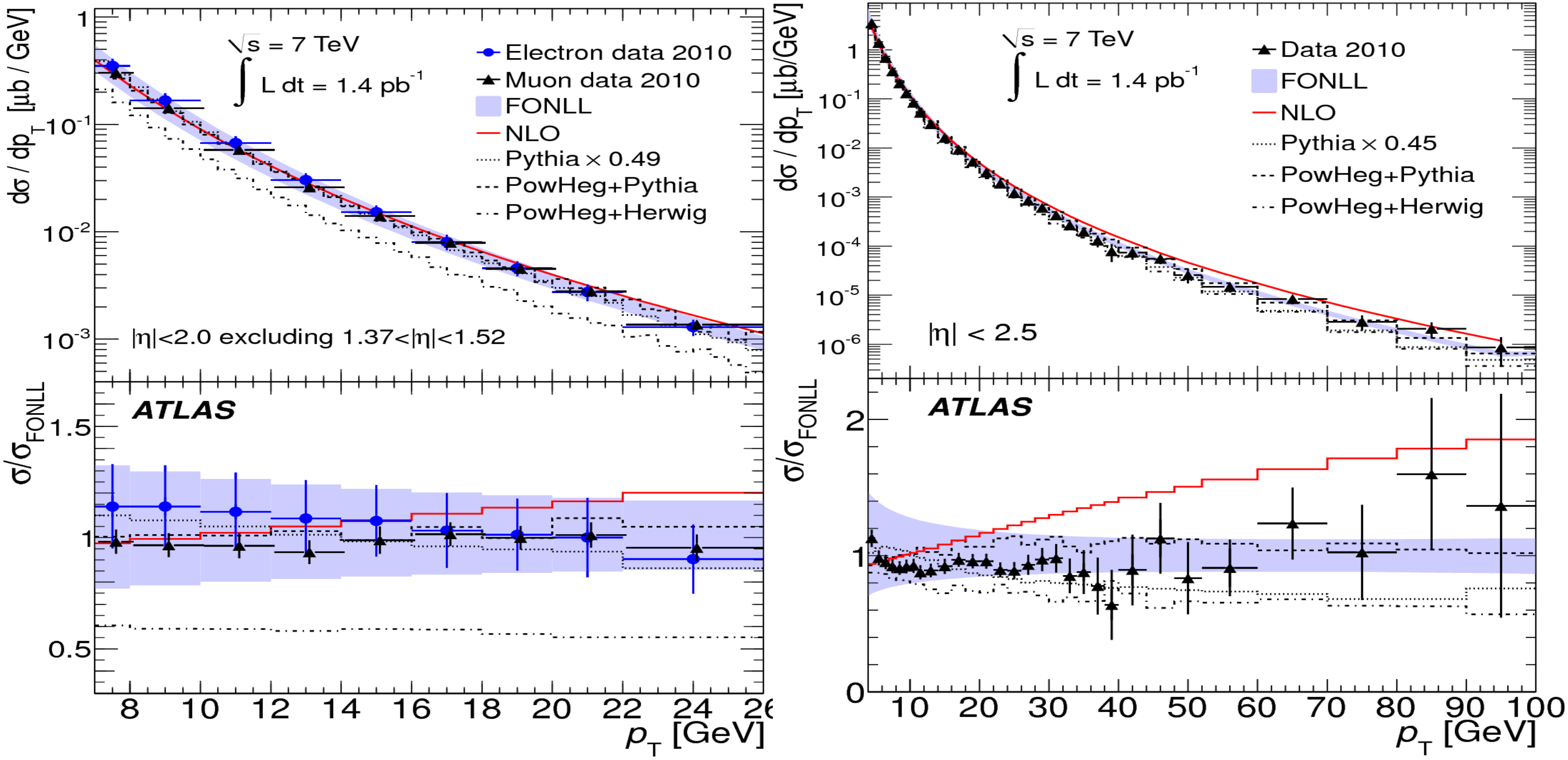


Figure 4: *(Left) Electron and muon differential cross-sections as a function of the charged lepton transverse momentum for* $|\eta| < 2.0$ *excluding the* $1.37 < |\eta| < 1.52$ *region. (Right) Muon differential cross-section as a function of the muon transverse momentum for* $|\eta| < 2.5$. *The ratio of the measured cross-section and the other predicted cross-sections to the FONLL calculation is given in the bottom of each plot. The* PYTHIA *(LO) cross-sections are normalised to the data in order to compare the shape of the spectra.*

Physics with the ATLAS TRT: concluding remarks

- ATLAS and its TRT are still babies learning about proton-proton physics at 7 TeV

- As expected, electron identification is more than one order of magnitude harder than at the TeVatron

- As designed, the TRT operates to specifications (and even beyond) for track reconstruction, momentum resolution and especially electron identification (one of the significant differences between ATLAS and CMS)

- With time, precision measurements will require even more from this wonderful detector. Boris would have been very proud!