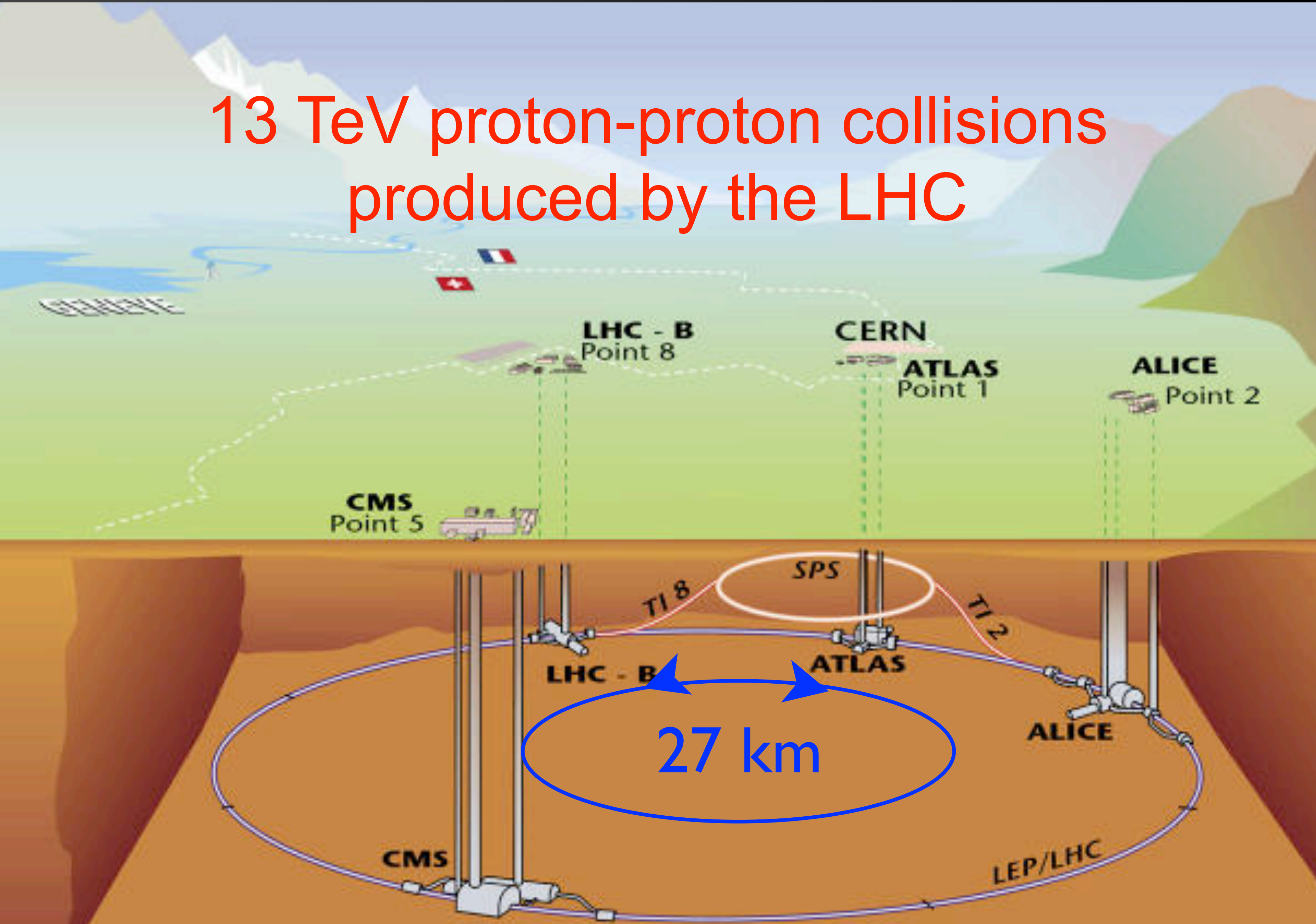
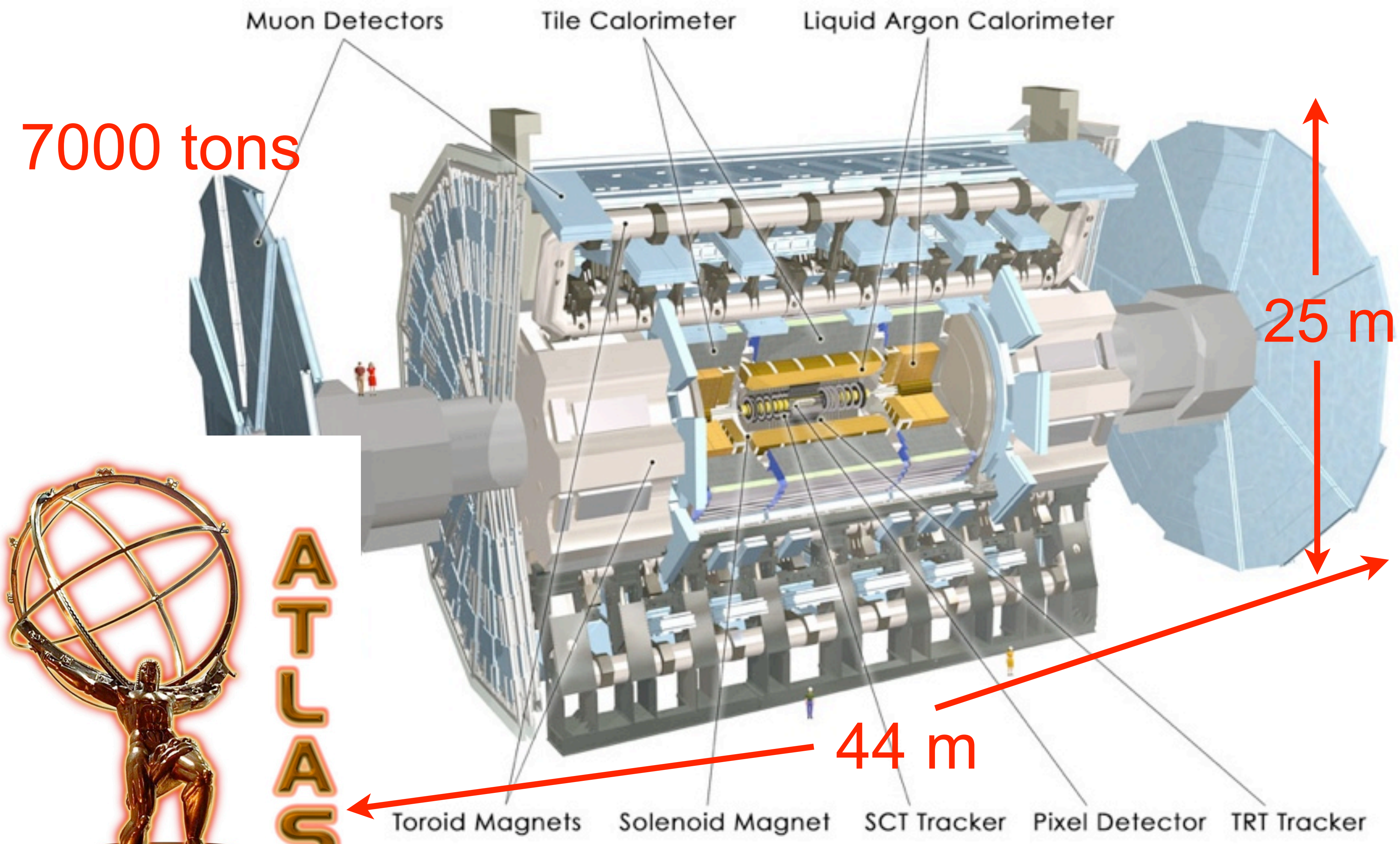
Collisions give us interesting physics (we'll see why)



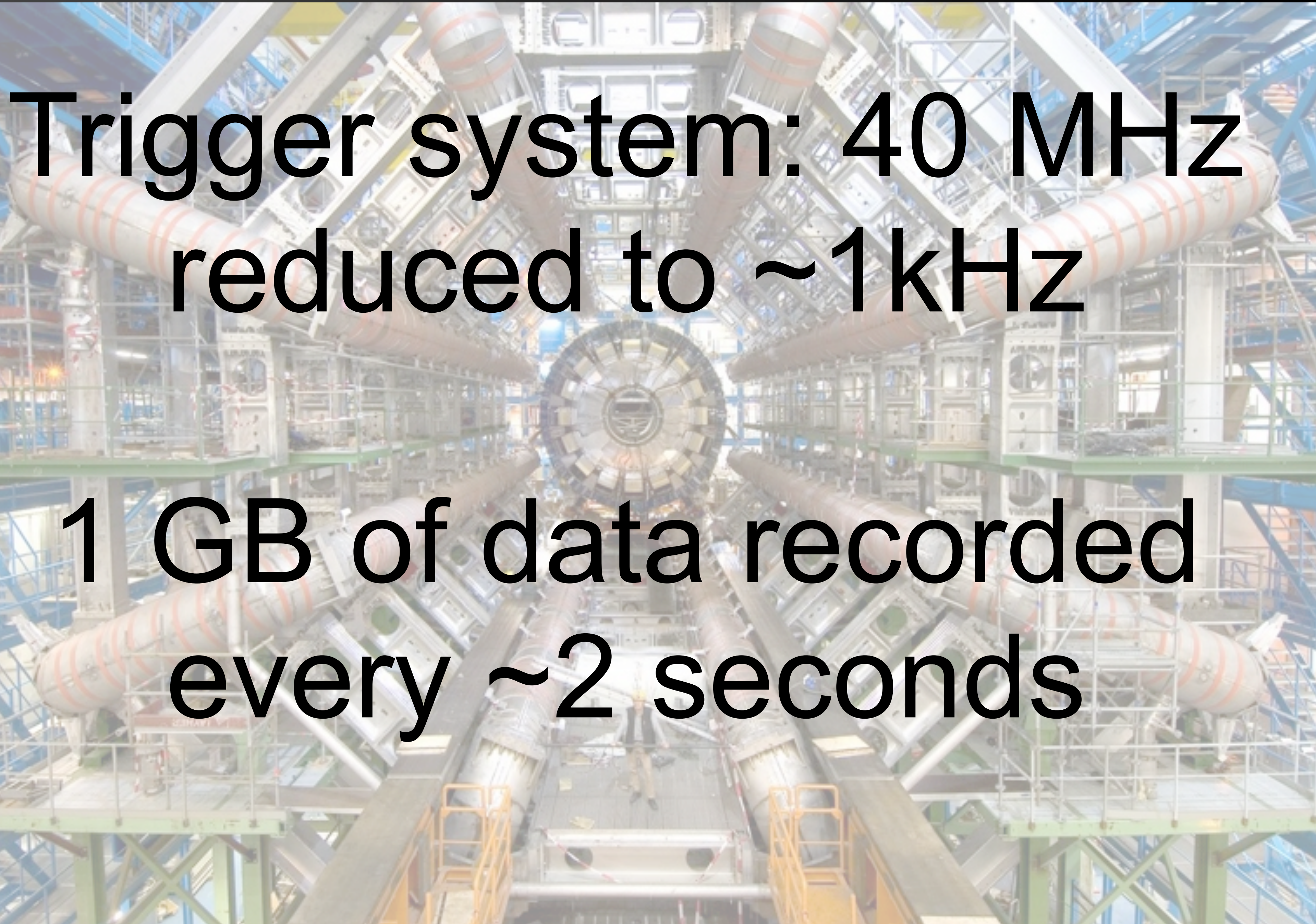
13 TeV proton-proton collisions produced by the LHC

27 km

ATLAS (I can talk about my experiment for.. awhile)



ATLAS

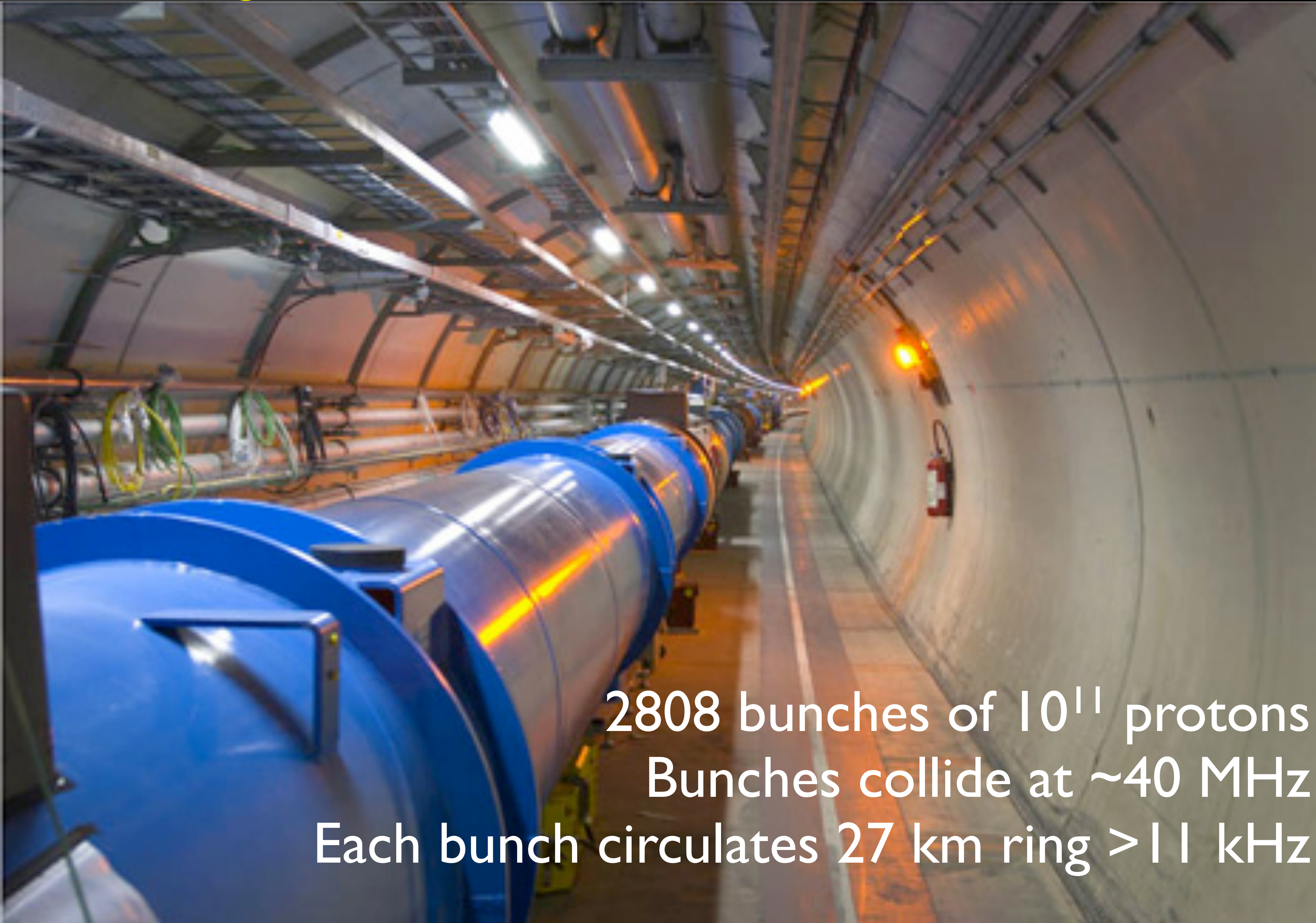


Trigger system: 40 MHz reduced to ~1kHz

1 GB of data recorded every ~2 seconds

Life as a particle physicist

Producing collisions



2808 bunches of 10^{11} protons

Bunches collide at ~40 MHz

Each bunch circulates 27 km ring >11 kHz

Other sorts of modern experiments

g-2
mu2e
neutrino expts (nuclear, solar, accelerator...)
nuclear physics
astroparticle physics
dark matter searches
dark energy surveys
...

Not to mention all the accelerator physics that goes along with much of the above

How do modern particle detectors work?

Want to see the effect of a particle, usually in the form of radiation or energy transfer that we can observe. Goal is to infer as much about the original particle/object as possible.

Problem is of course that we cannot just put things inside of a microscope for careful, lengthy study: typically traveling close to speed of light, often very short-lived, occasionally produced with many other nearby objects, sometimes has no electric charge and can look like other, similar particles

What can we take advantage of?

Charged particles bend in a magnetic field (can measure electric charge and momentum)

Careful timing measurements can give us particle velocity and other information (useful not only for the original particle, but also inside of a detector)

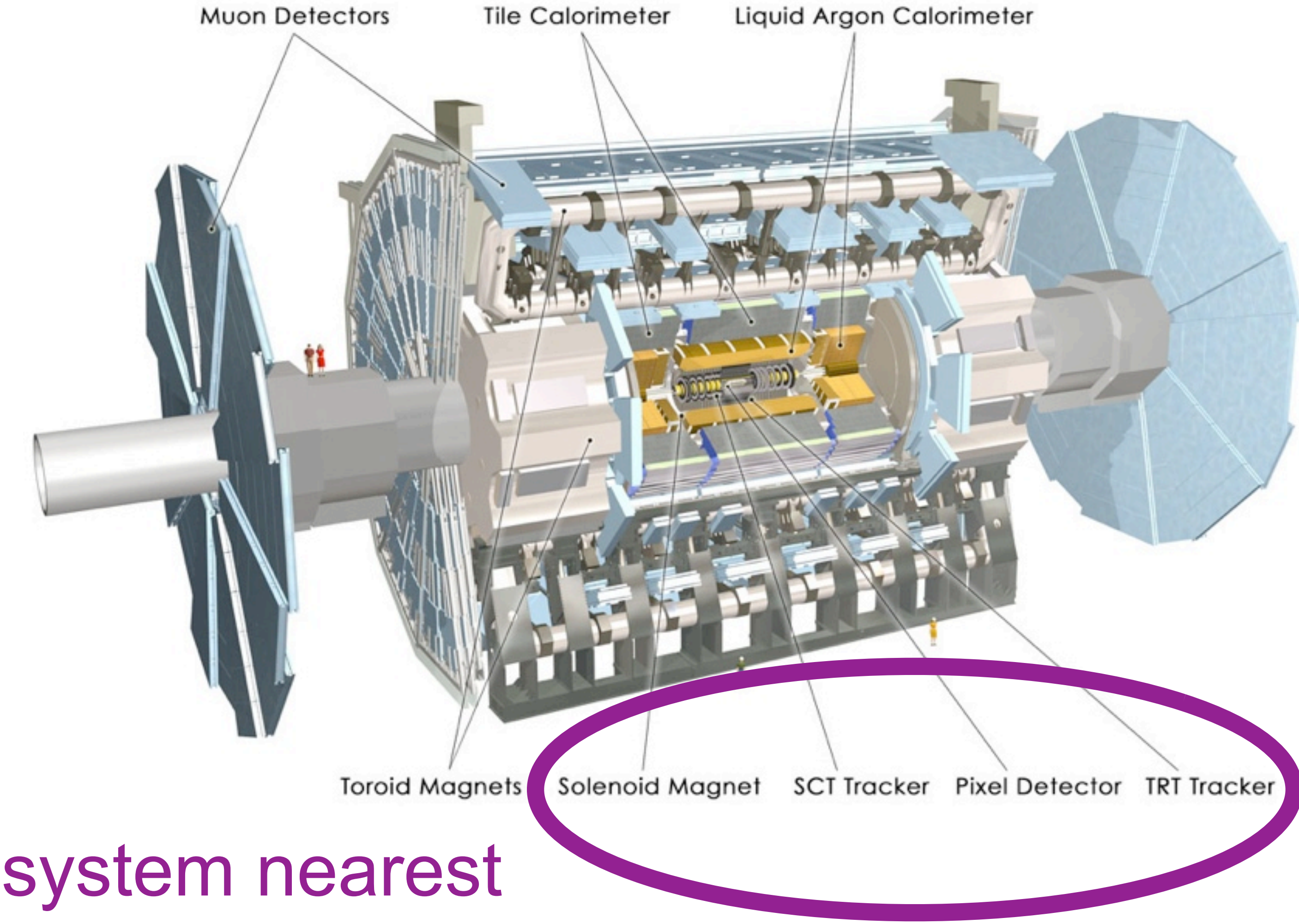
Calorimeter measurements give particle energy (different types of particles deposit energy electromagnetically vs via strong force, and at different rates)

Neutrinos escape ~undetected, leading to imbalance of momentum in detector

Muons are highly penetrating and minimally ionizing

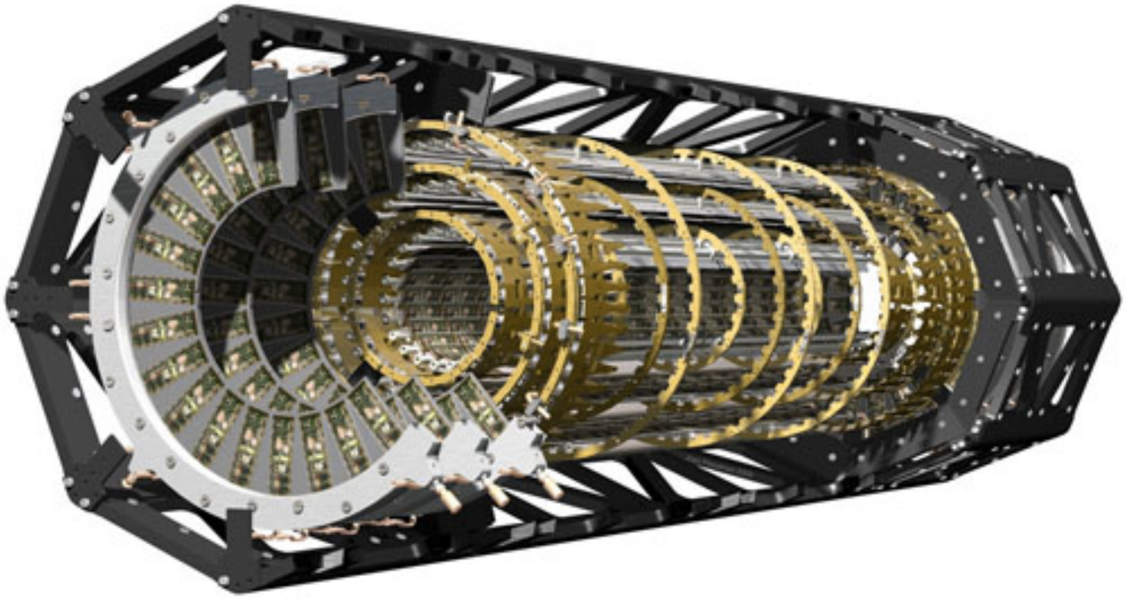
Other tricks like Cherenkov radiation, measurements of dE/dx, looking for transition radiation at material boundaries, ...

Back to ATLAS



Inner tracking system nearest collision point immersed in 2T solenoid magnetic field: measure p and q

ATLAS pixel subsystem



100 million readout channels (recently upgraded for an extra layer during shutdown) to measure precise location of charged particle trajectory

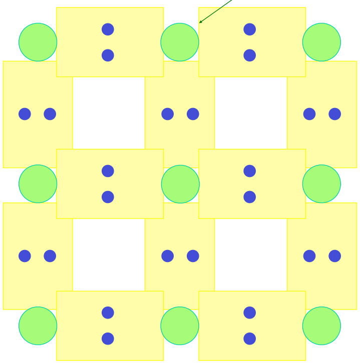
Semiconductors

Slide from Markus Elsing

Semiconductors

Slide from Markus Elsing

- doping of silicon crystal semiconductors:



Si atom with 4 valence electrons

Semiconductors

Slide from Markus Elsing

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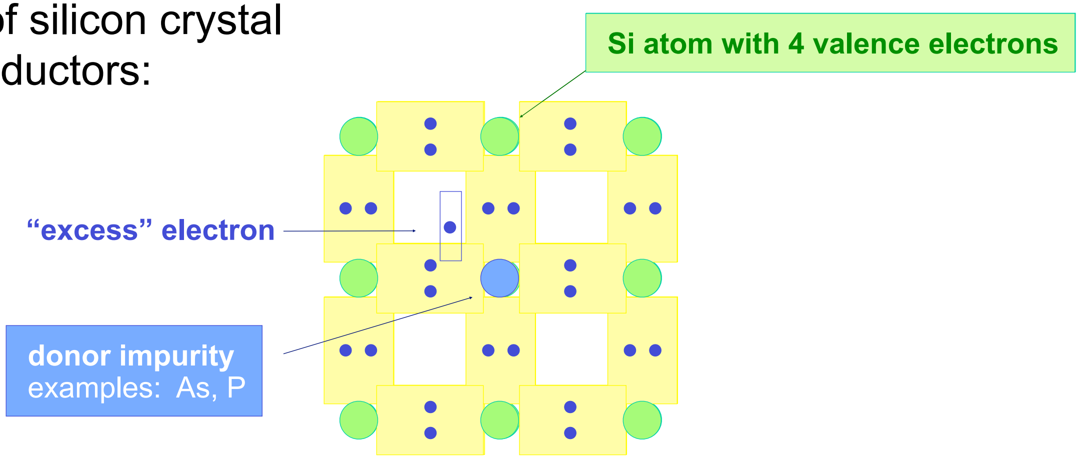

Si atom with 4 valence electrons

"excess" electron

donor impurity
examples: As, P

Semiconductors

Slide from Markus Elsing

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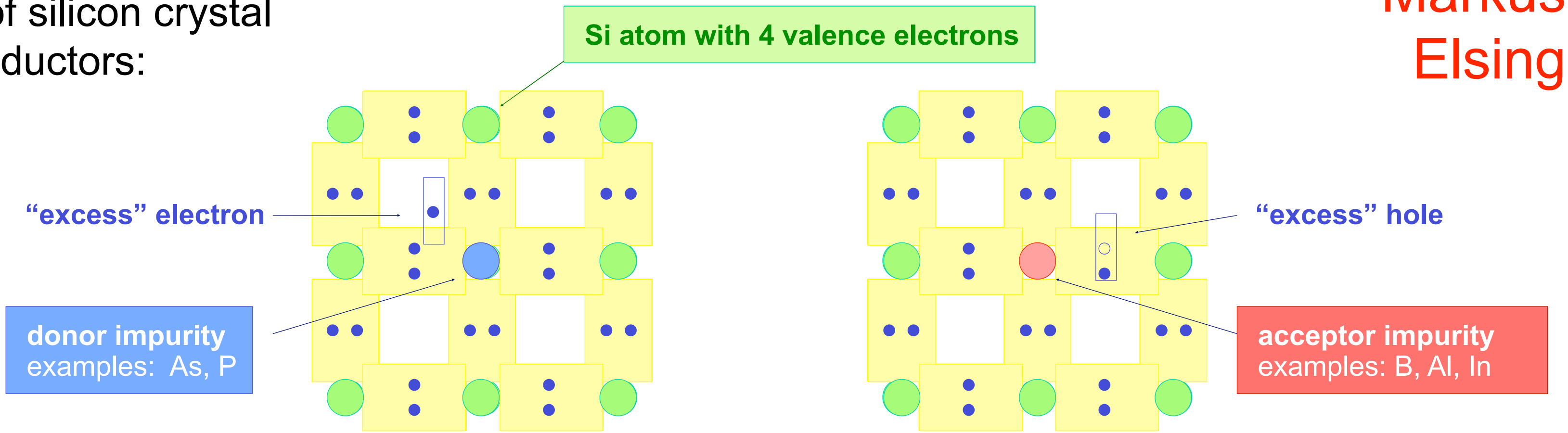


Si atom with 4 valence electrons

“excess” electron

donor impurity
examples: As, P

“excess” hole

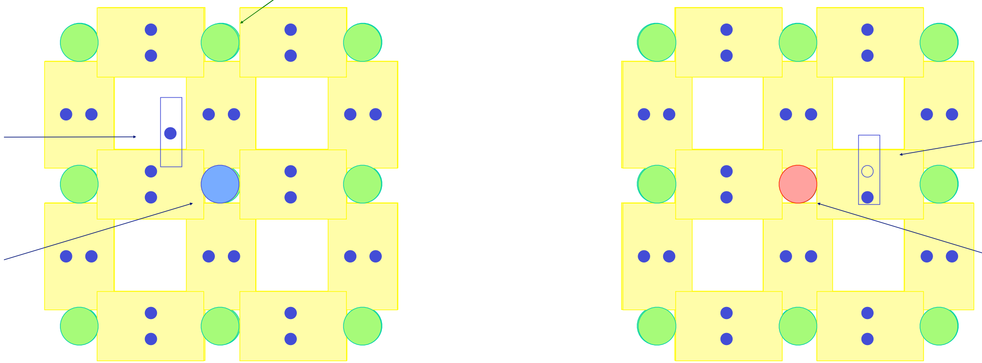
acceptor impurity
examples: B, Al, In

Semiconductors

Slide from Markus Elsing

- doping of silicon crystal semiconductors:

Si atom with 4 valence electrons



“excess” electron

donor impurity
examples: As, P

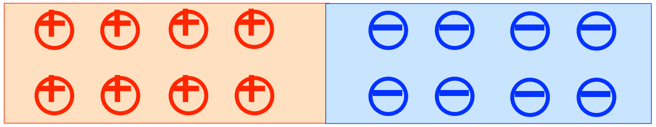
“excess” hole

acceptor impurity
examples: B, Al, In

p–*n* junction

p^+ **hole carrier**

n^- **electron carrier**



e acceptor impurity

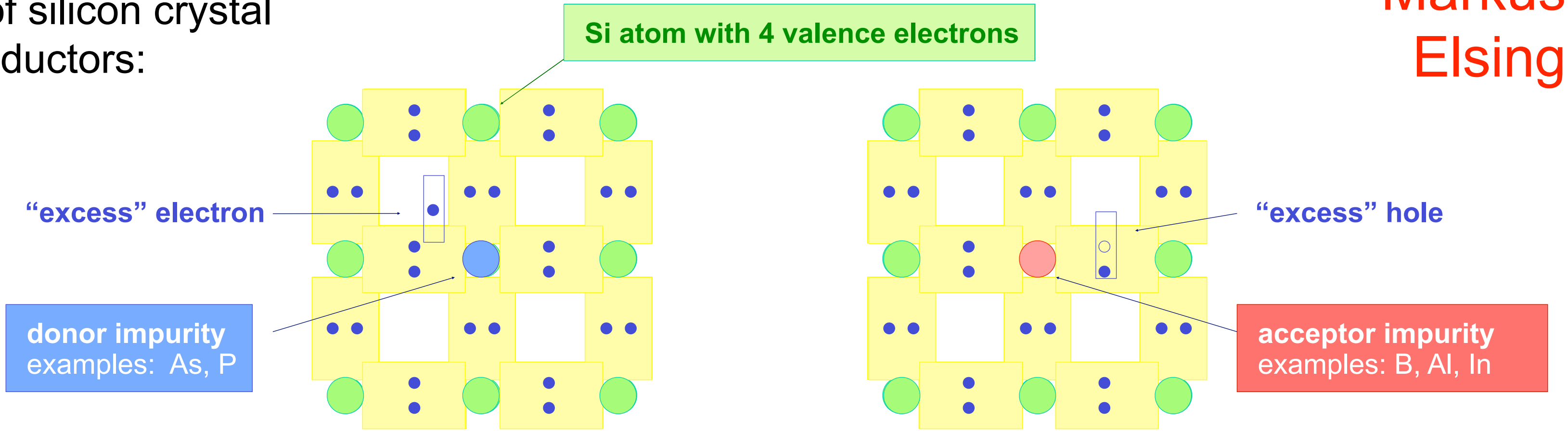
e donor impurity

- *p* doping adds electro-phile atoms
- *n* doping adds electro-phobe atoms

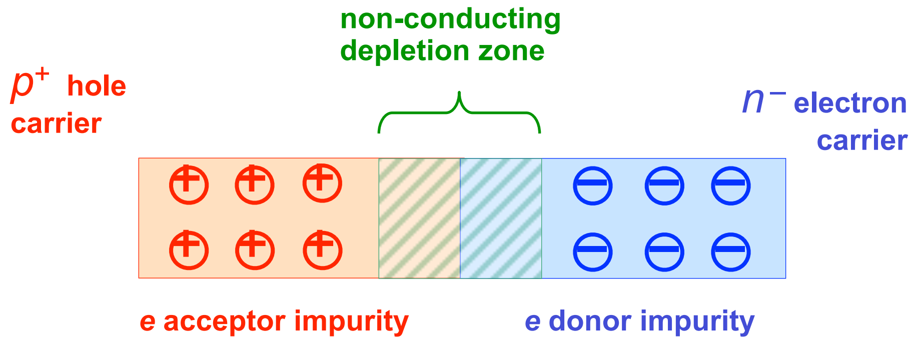
Semiconductors

Slide from Markus Elsing

- doping of silicon crystal semiconductors:



p–*n* junction

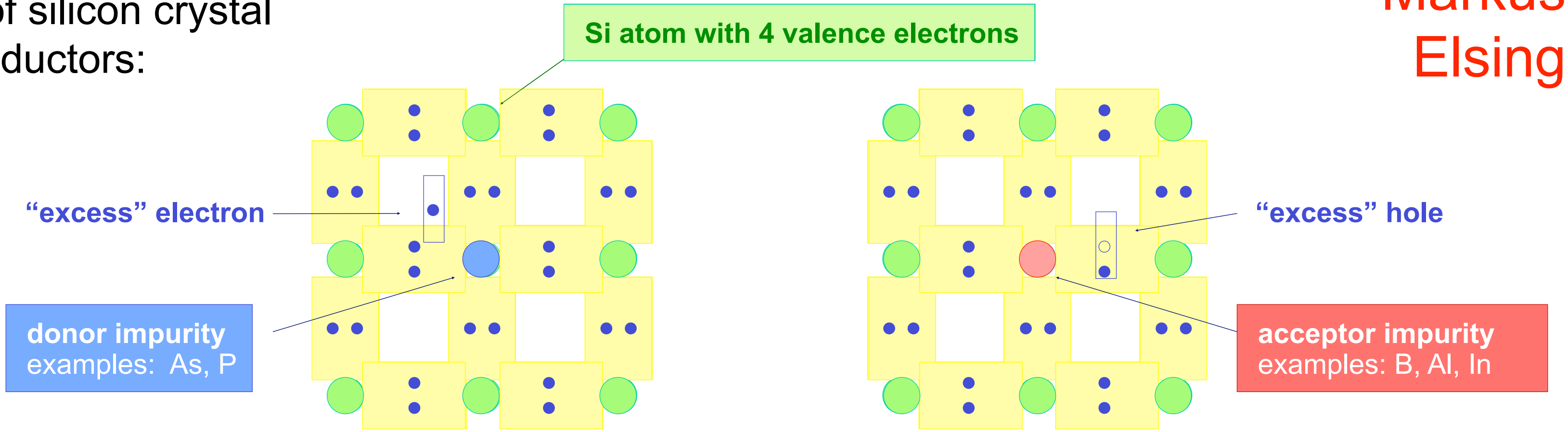


- in the junction zone, electron-hole pairs recombine creating depletion
- the potential barrier in the junction counter-weighs the doping potential

Semiconductors

Slide from Markus Elsing

- doping of silicon crystal semiconductors:



Si atom with 4 valence electrons

“excess” electron

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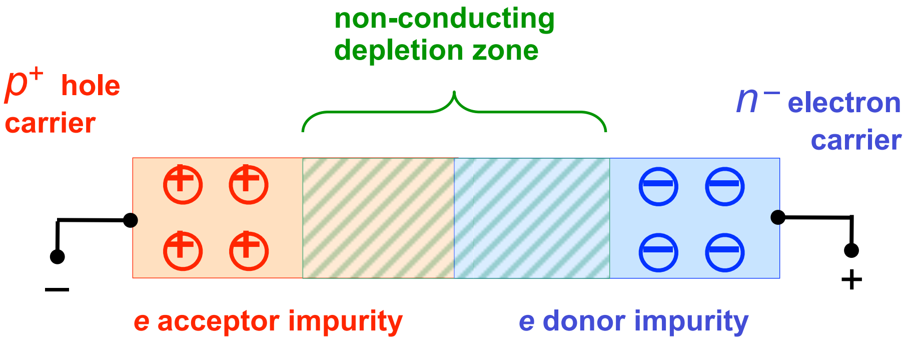
“excess” hole

acceptor impurity
examples: B, Al, In

reverse bias *p*–*n* junction



non-conducting depletion zone

p^+ **hole carrier**

n^- **electron carrier**

−

+

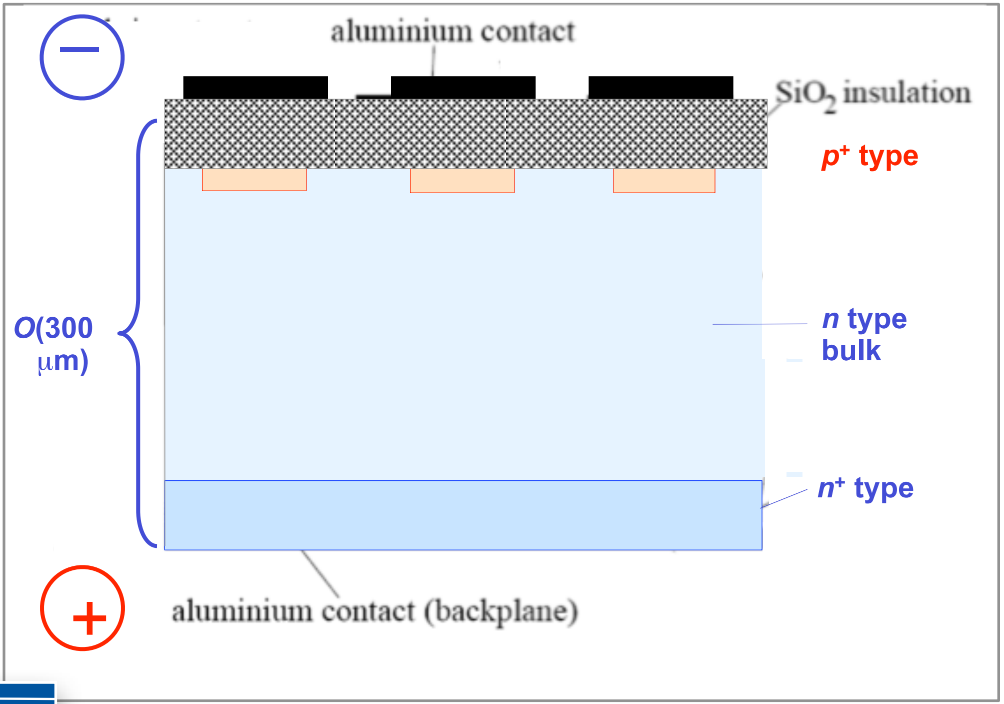
e acceptor impurity

e donor impurity

- the reversed bias voltage increases the potential barrier in the depletion zone, enhancing its resistance
- minimal current across the junction

The *p–n* Junction as a Tracking Detector

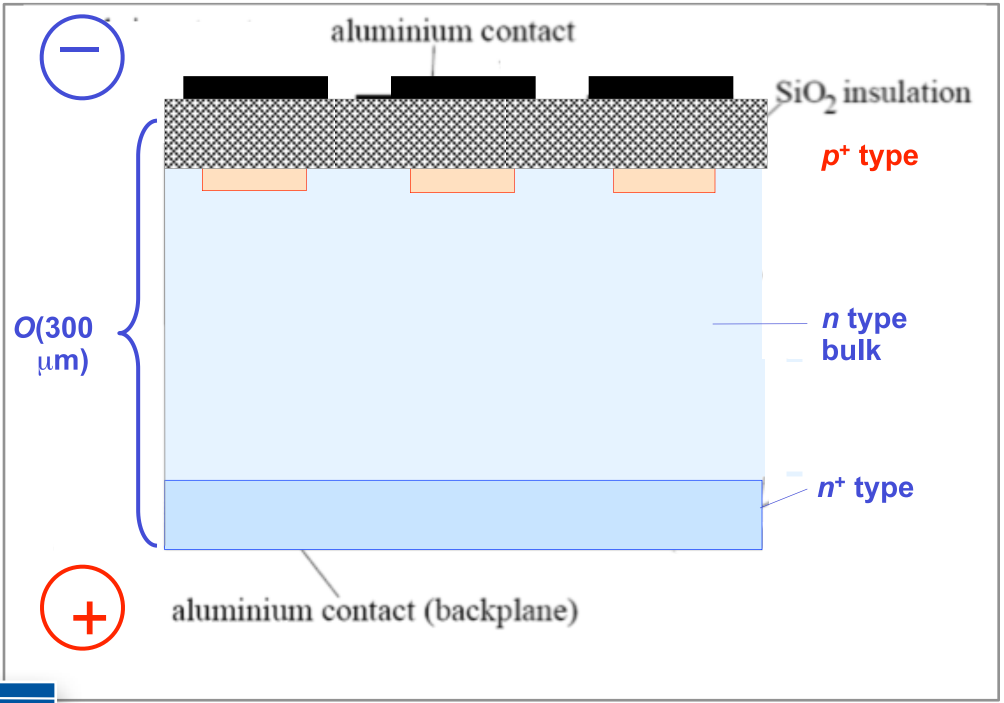
Slide from Markus Elsing



The *p–n* Junction as a Tracking Detector

- thin (~μm), highly doped p^+ (~10^{19} cm^{-3}) layer on lightly doped *n* (~10^{12} cm^{-3}) substrate
- high mobility of charge carriers in Si allows fast charge collection (~5 ns for electron)
- high Si density & low electron–hole creation potential (3.6 eV compared to ~36 eV for gaseous ionization) allows use of very thin detectors with reasonable signal

Slide from Markus Elsing



schema of silicon microstrip sensor

- reverse bias: backplane set to positive voltage (< 500 V)
- a traversing charged particle ionizes silicon, creating conduction electrons and holes that induce a measurable current by drifting to electrodes
- metal-semiconductor transition forms charge (Schottky) barrier similar to *p–n* junction. Highly doped n^+ layer reduces width of potential barrier and hence resistance

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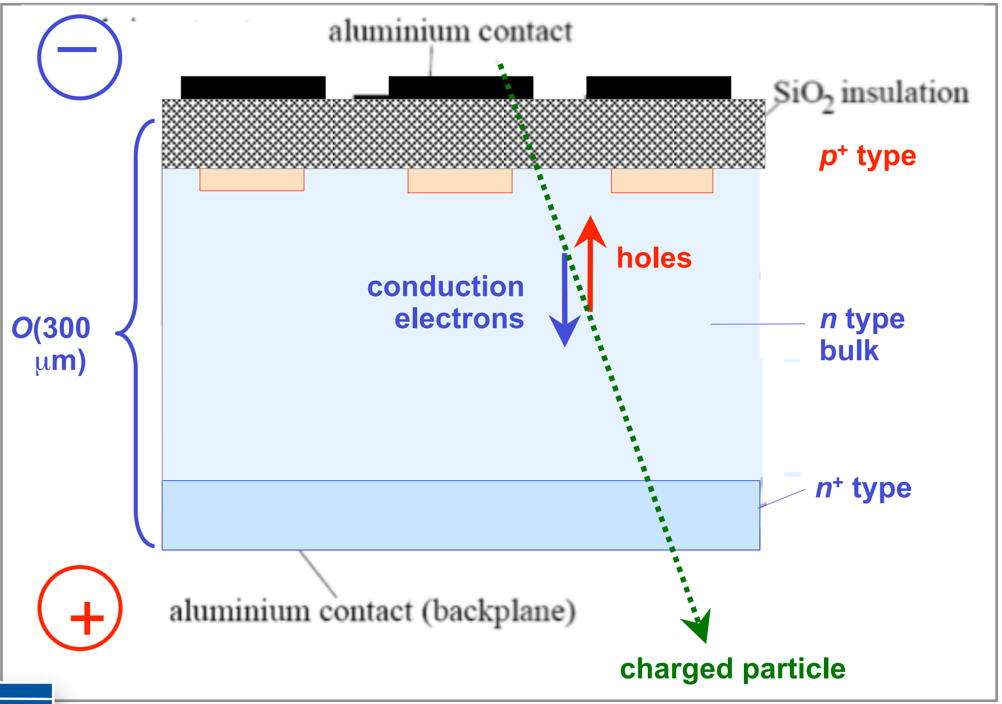

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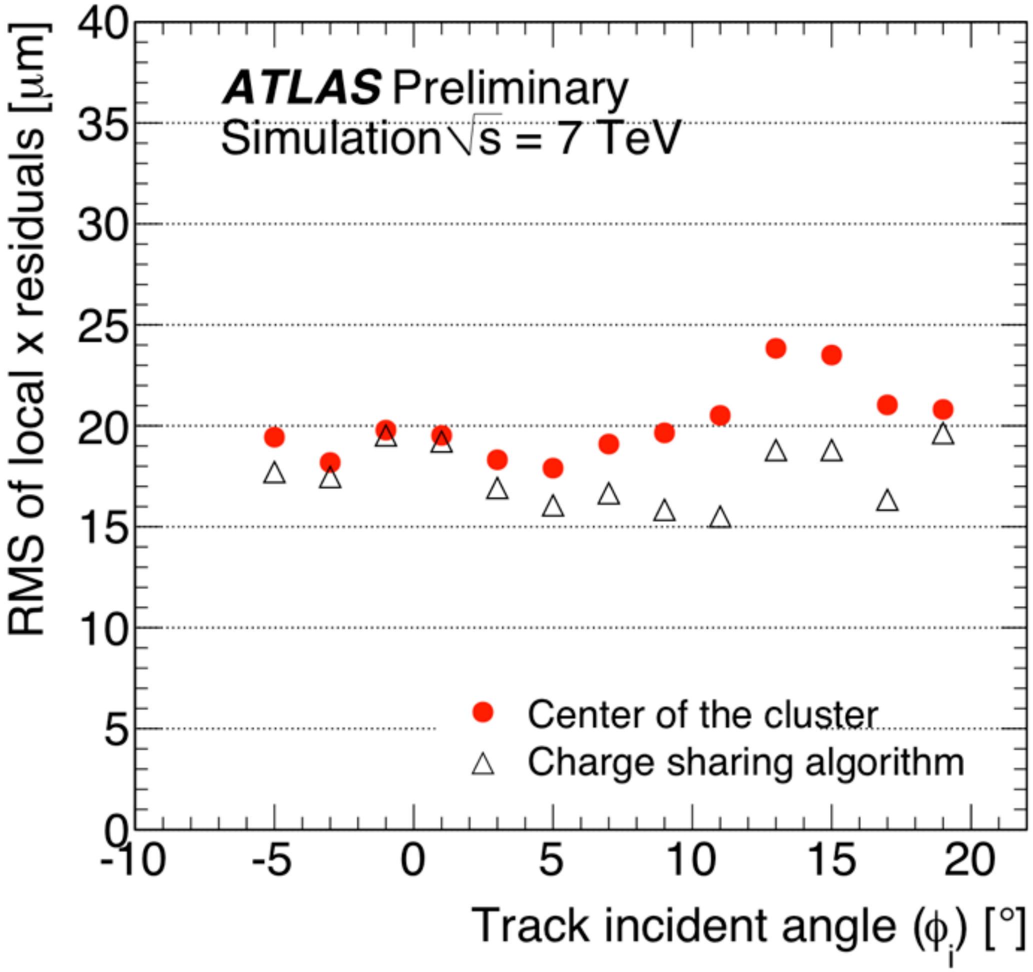
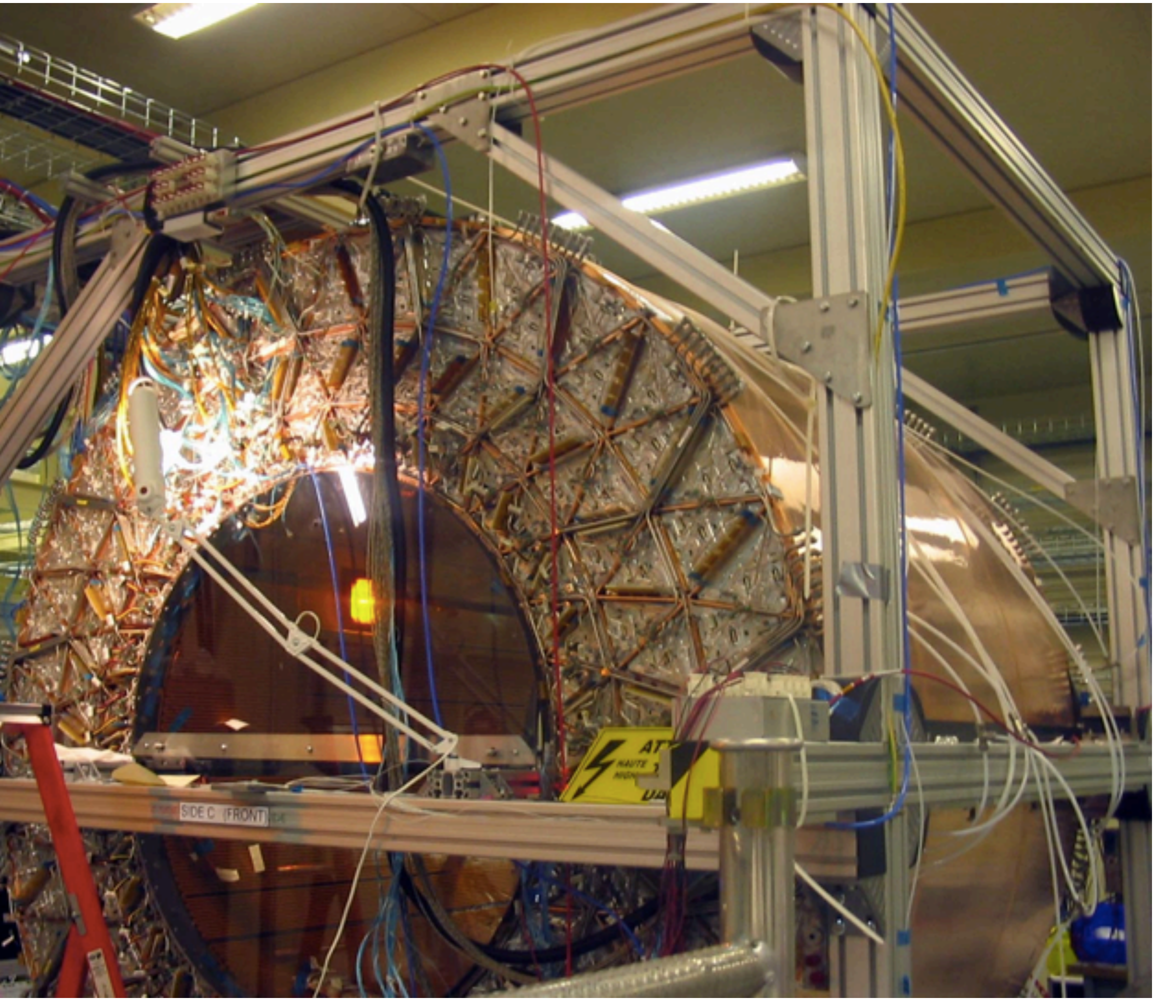
ATLAS pixel system



Tens of micron resolution from single hits! The alignment for all the modules gets quite ... tricky

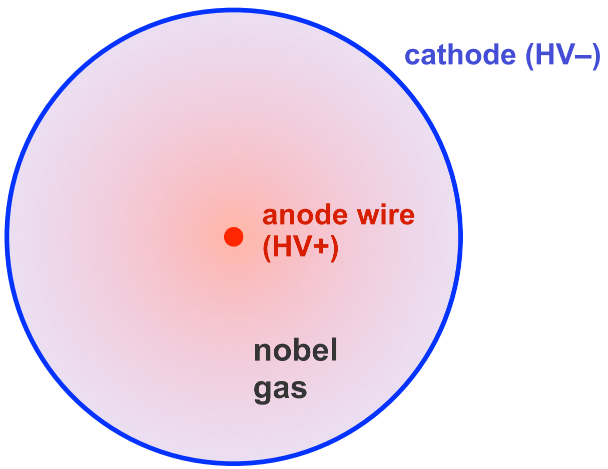
ATLAS TRT (Transition Radiation Tracker)



300,000 straws (4 mm in diameter) at larger track radius, ~35 measurements per track. Also helps with particle identification

Drift Tubes in ATLAS:
Inner Detector and Muon Spectrometer

- classical detection technique for charged particles based on gas ionization and drift time measurement



Slide from Markus Elsing

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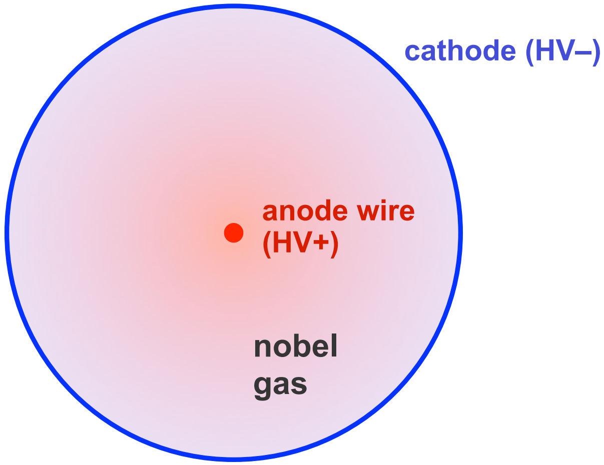


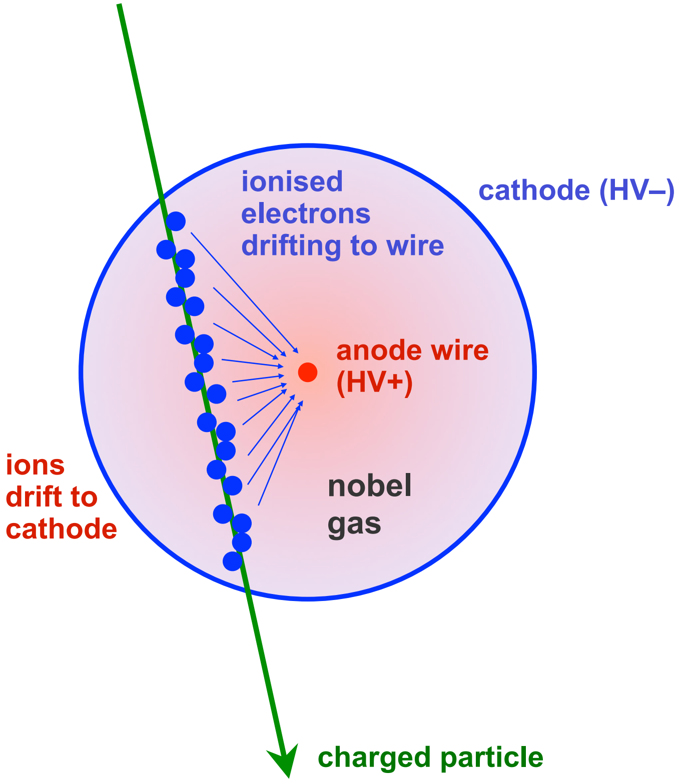
- drift tubes used in muon systems and ATLAS TRT
- primary electrons drift towards thin anode wire
- charge amplification during drift (~10^4) in high E-field in vicinity of wire: $E(r) \sim U_0 / r$
- signal rises with number of primary e's (dE/dx) [signal dominated by ions]
- macroscopic drift time: $v_D / c \sim 10^{-4}$ → ~30 ns/mm
- determine v_D from difference between signal peaking time and expected particle passage
- spatial resolution of $O(100\ \mu\text{m})$

TRT: Kapton tubes, ∅ = 4 mm
MDT: Aluminium tubes, ∅ = 30 mm

Slide from Markus Elsing

Drift Tubes in ATLAS: Inner Detector and Muon Spectrometer

- classical detection technique for charged particles based on gas ionization and drift time measurement



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Drift Tubes in ATLAS: Inner Detector and Muon Spectrometer

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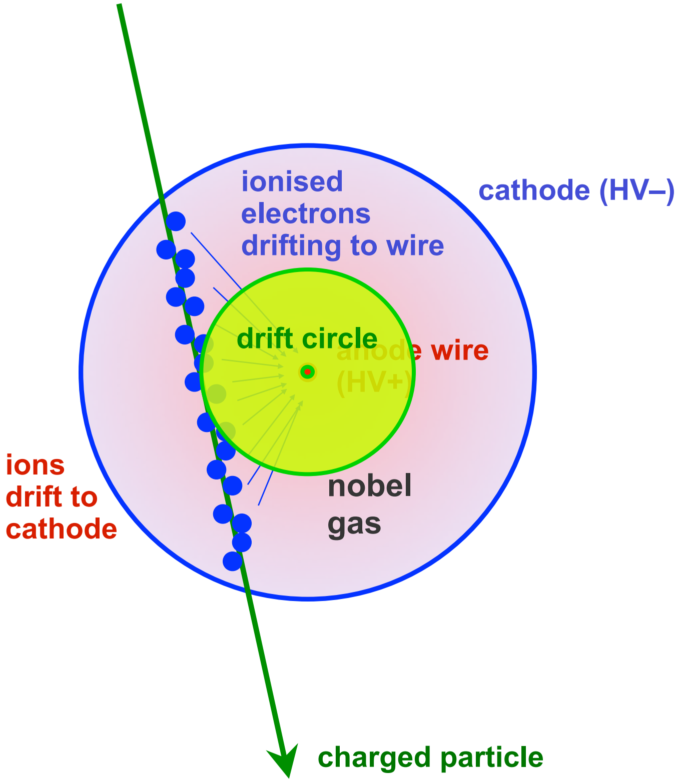
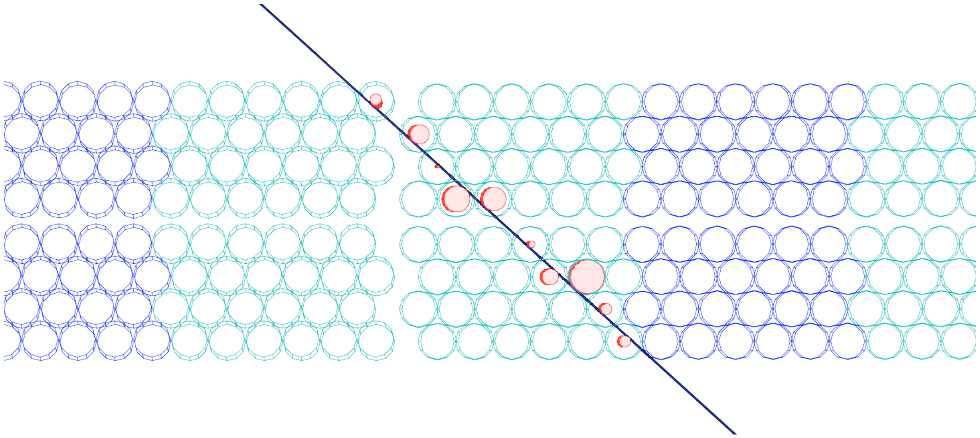


example: segment in muon drift tubes reconstruction from measured drift circles (left-right ambiguity)



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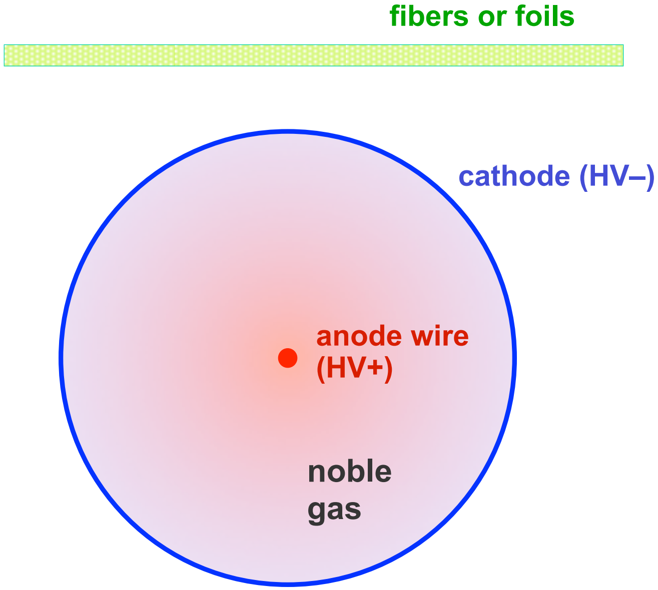
Slide from
Markus Elsing

Combining Tracking with PID: the ATLAS TRT

- *e*/π separation via transition radiation: polymer (PP) fibers/foils interleaved with drift tubes



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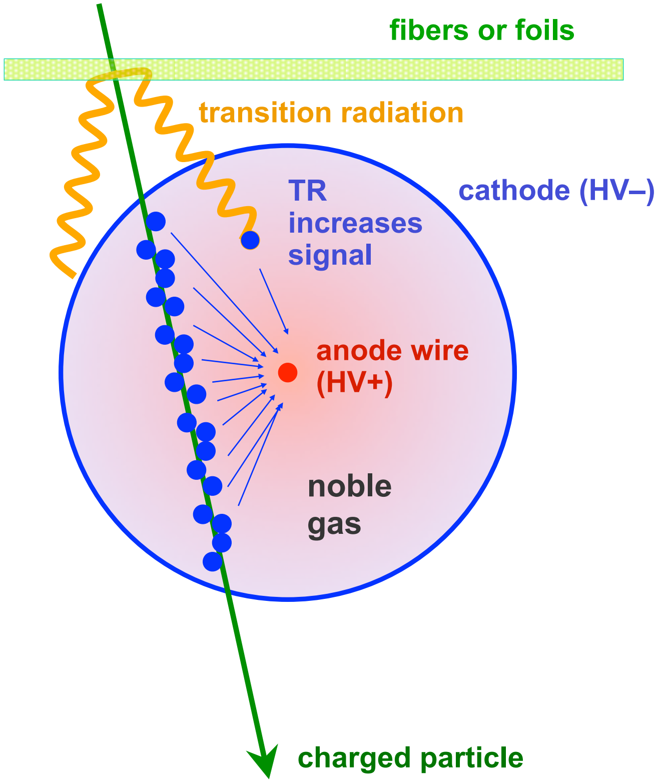

electrons radiate → higher signal
PID info by counting
high-threshold hits

Slide from Markus Elsing

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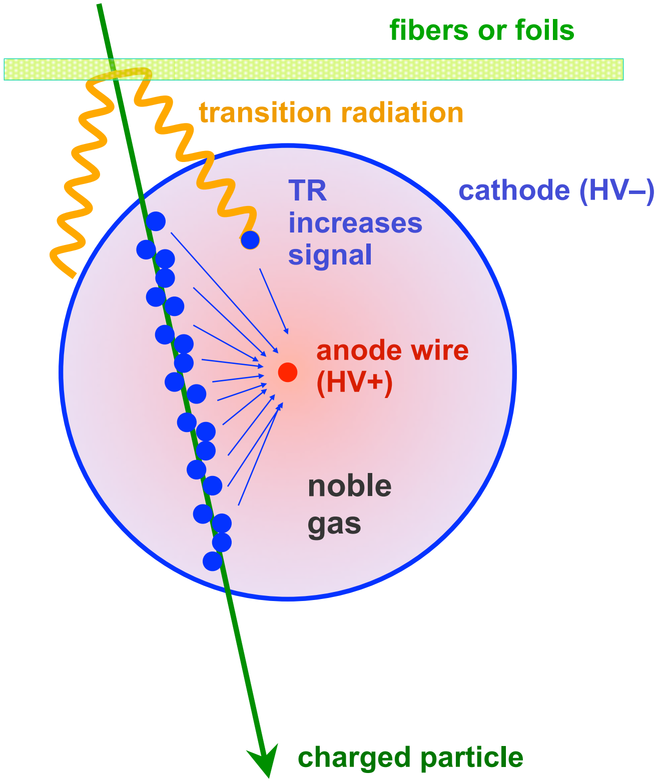

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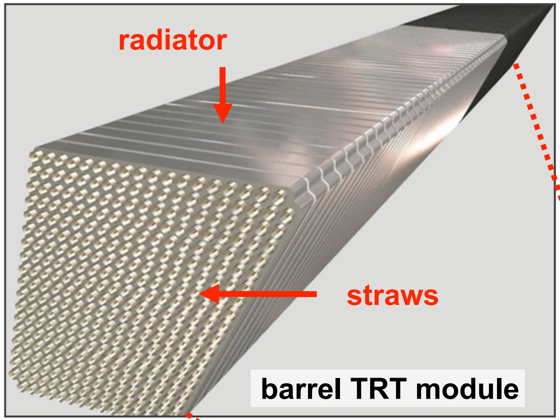
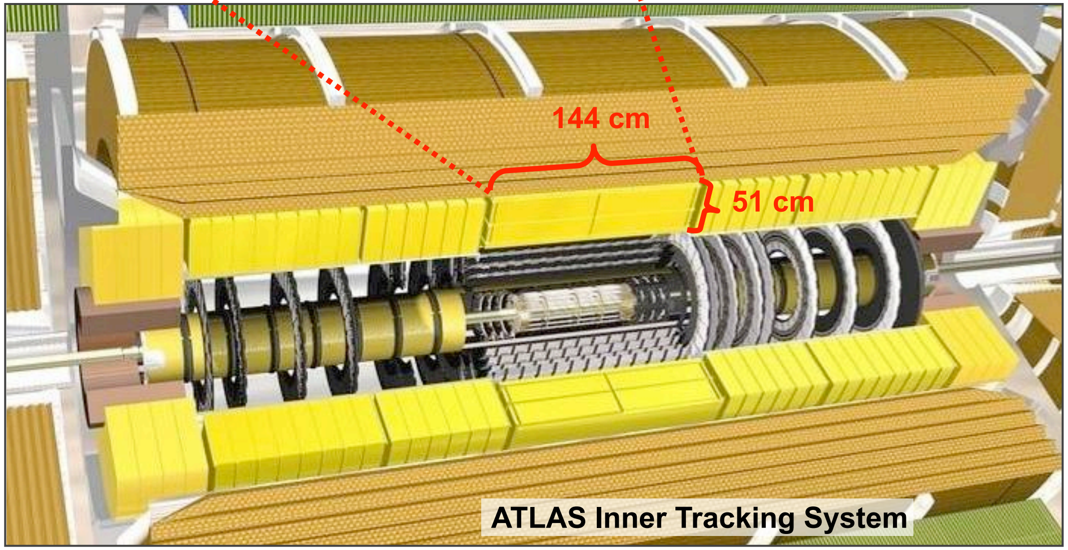


total: 370k straws

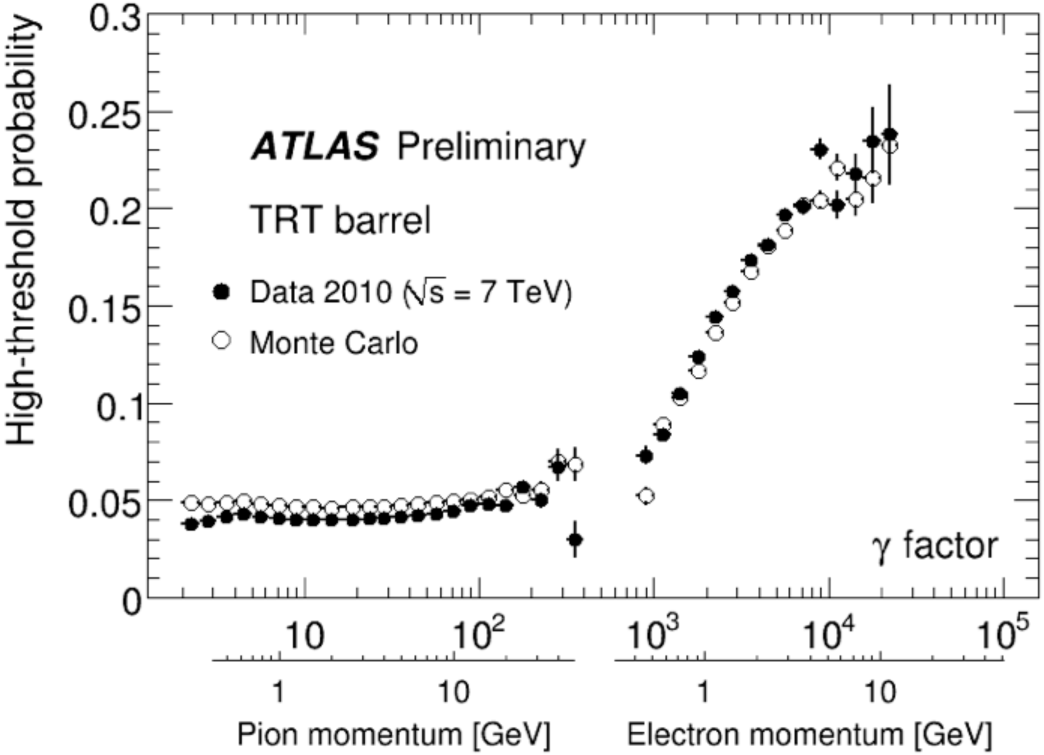
barrel ($|\eta| < 0.7$):
36 r-ϕ measurements / track
resolution ~130 μm / straw

14 end-cap wheels ($|\eta| < 2.1$):
40 or less z-ϕ points



Slide from Markus Elsing

ATLAS TRT (Transition Radiation Tracker) PID



Given ~30 hits per track, small difference in probability to measure hits with a higher threshold can give significant particle identification/ background rejection for electron ID

Charged particle tracking

$$p \propto B \cdot R$$

For precise measurement of p, want precise measurement of radius of curvature. 100 GeV object at ATLAS has R = 166m! A 1 TeV pion will have R close to 1 km... need precision in silicon systems order (~10 microns per measurement)

Stable particles?

Particle travels ~cτ before decaying in its own rest frame but in lab frame, ~γcτ. Typically interested in objects with substantial Lorentz gamma factors, so muons, neutrons and charged pions and kaons travel and decay in the detector

Bethe-Bloche equation

When a relativistic charged particle passes through some material with atomic number Z and electron density n, it ionizes the atoms and thus loses energy. I is the mean excitation energy in the material ~10 Z [eV]

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Not very intuitive :)

Bethe-Bloche equation

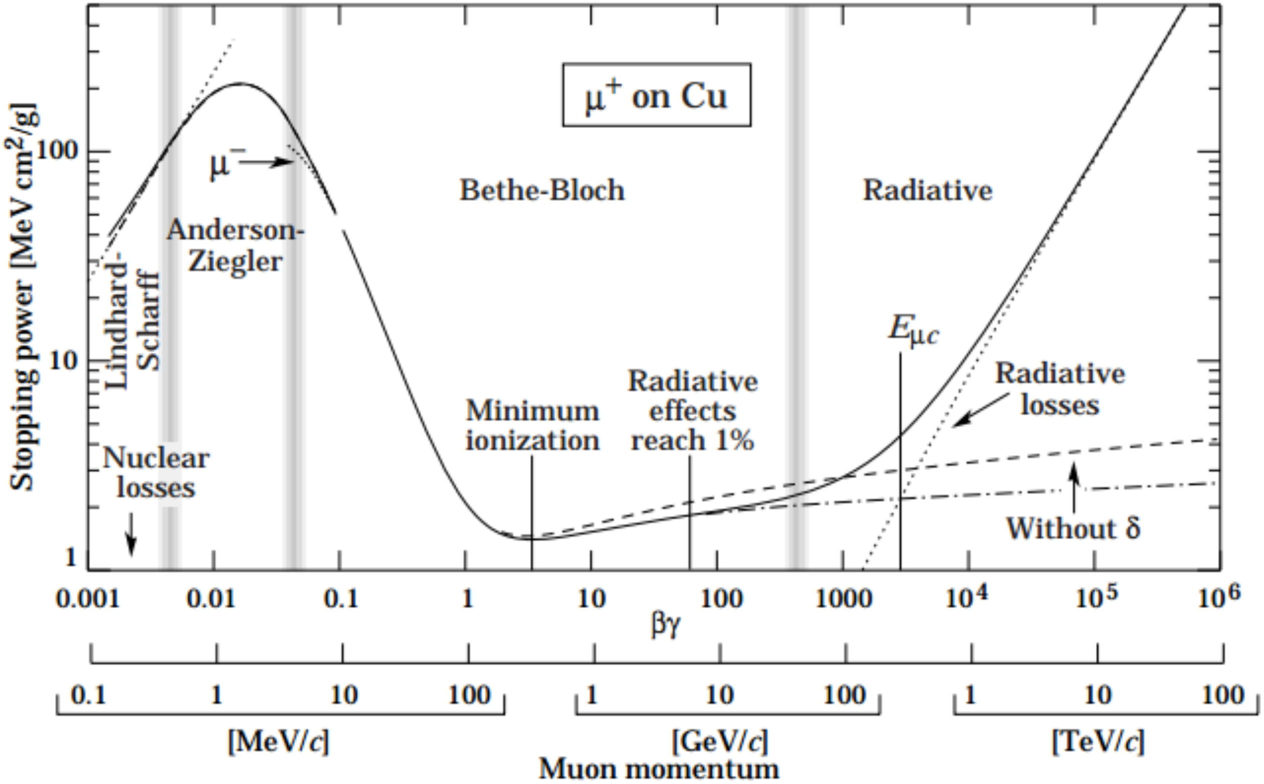
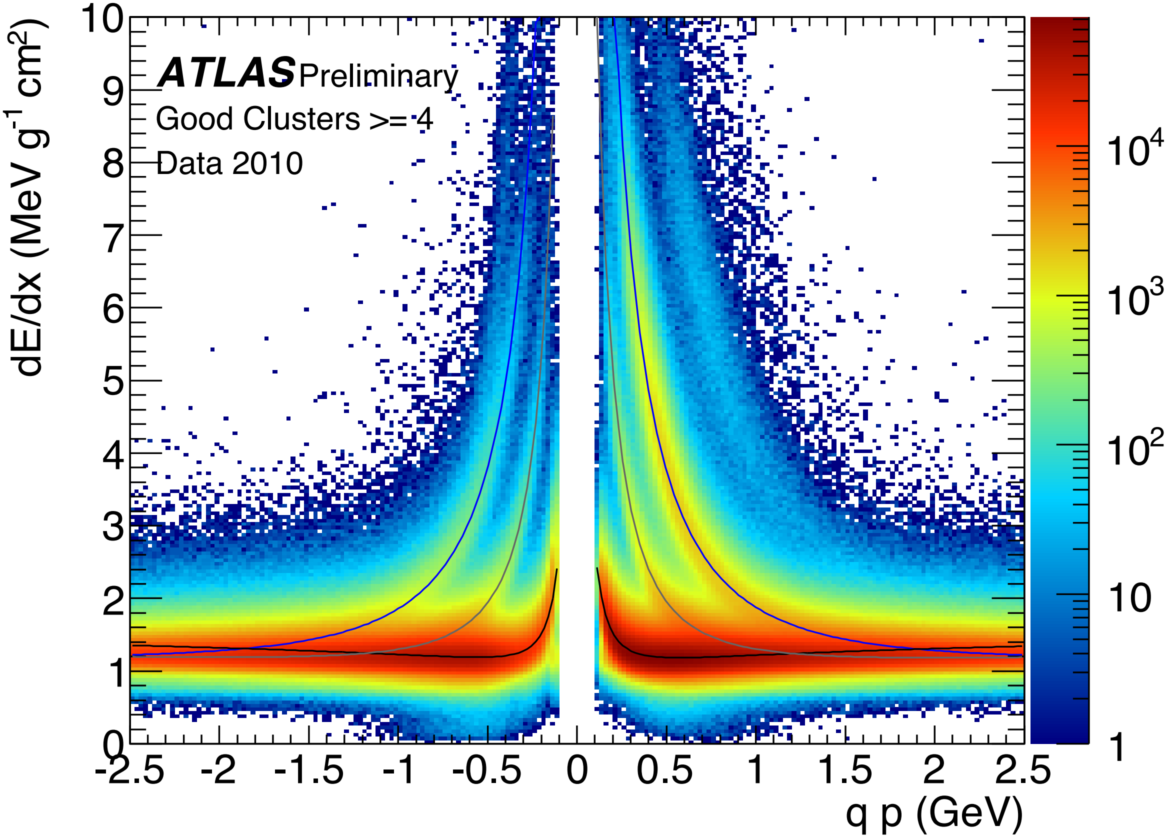


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [4], and data at higher energies are from Ref. 5. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [6].

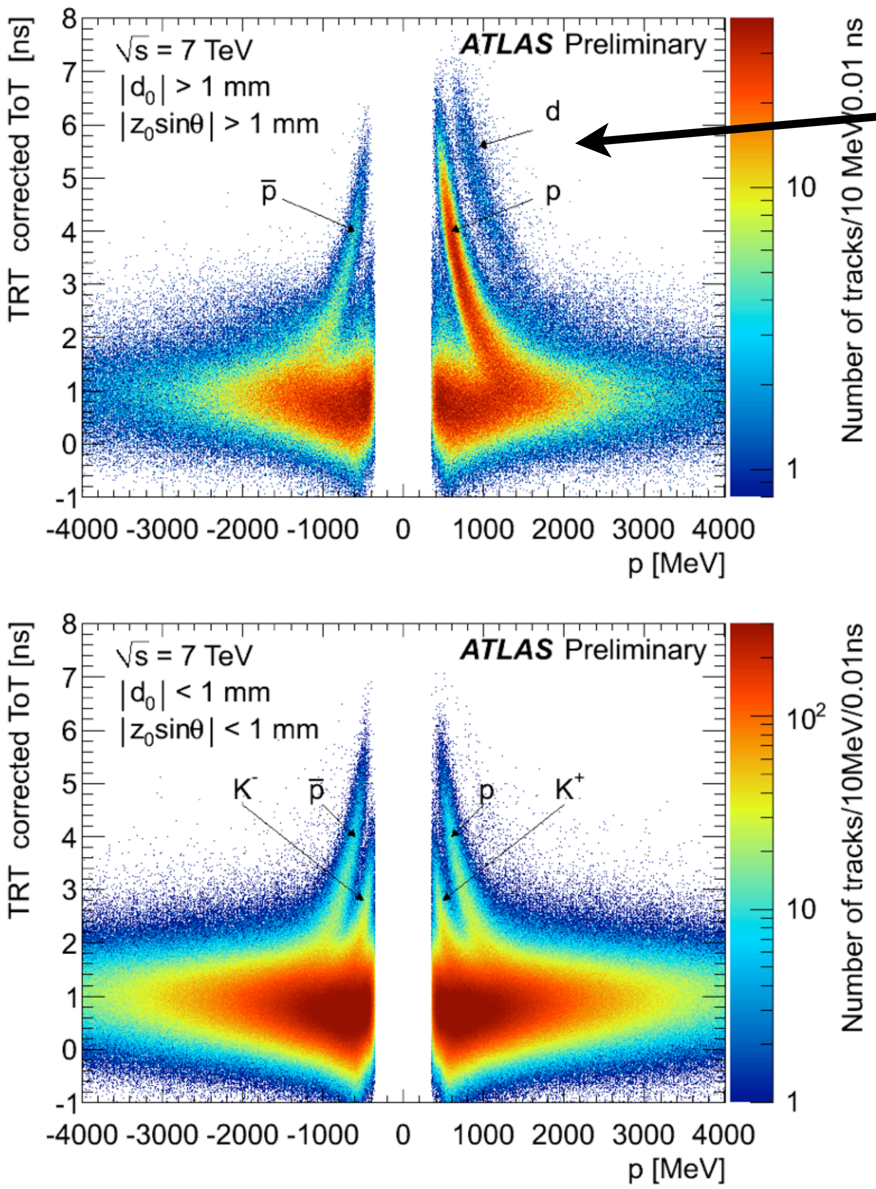
From PDG. Particles with βγ~3 lose the least amount of energy as they travel, and are referred to as "minimum ionizing" particles

Using dE/dx in the pixel system of ATLAS



Can see pions, kaons and protons

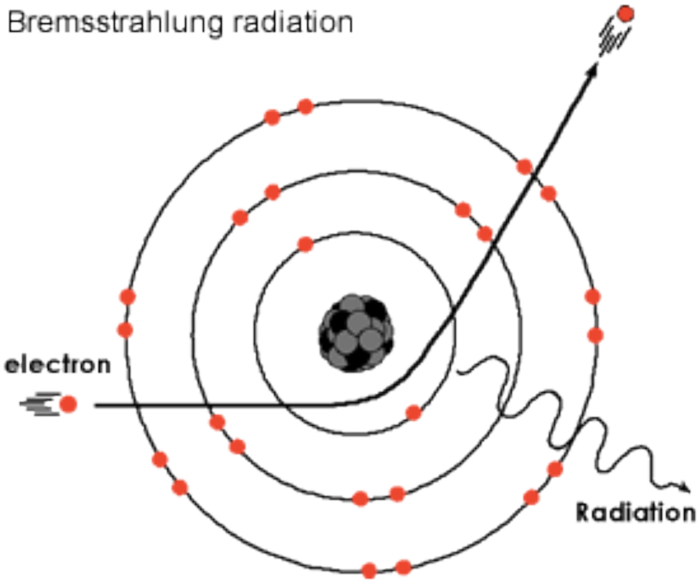
Using dE/dx in the TRT system of ATLAS

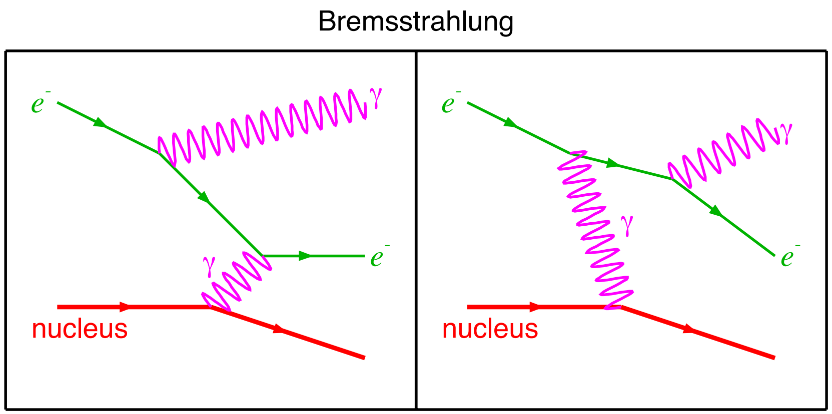


Asymmetry! Why?

Using “time over threshold” can also do particle identification with straw detectors

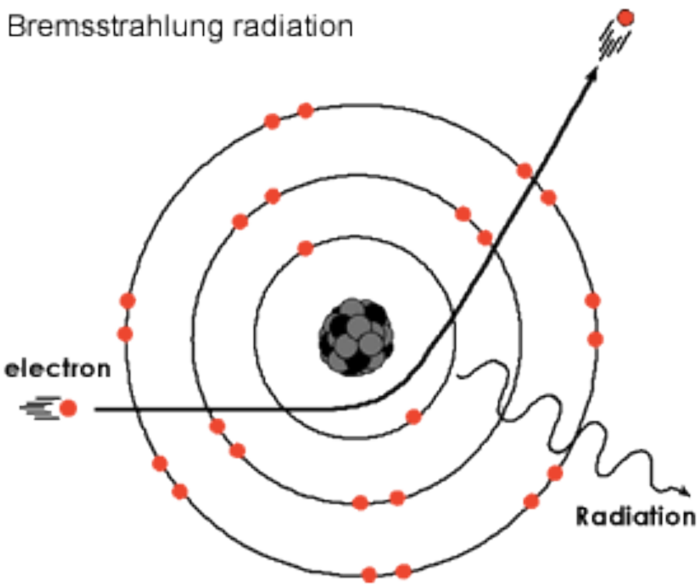
Bremsstrahlung





Literally “braking radiation” in German, bremsstrahlung is the main way that electrons of interest at ATLAS lose energy. In EM you might have seen that the amount of energy radiated away goes as 1/mass^2, which is why one reason why ee accelerators need to be so big, and why muons don’t lose much energy in the detector

Radiation length for high-energy electrons/photons

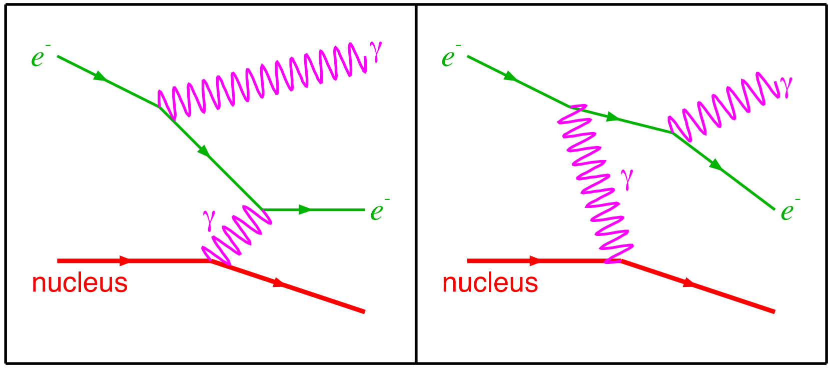


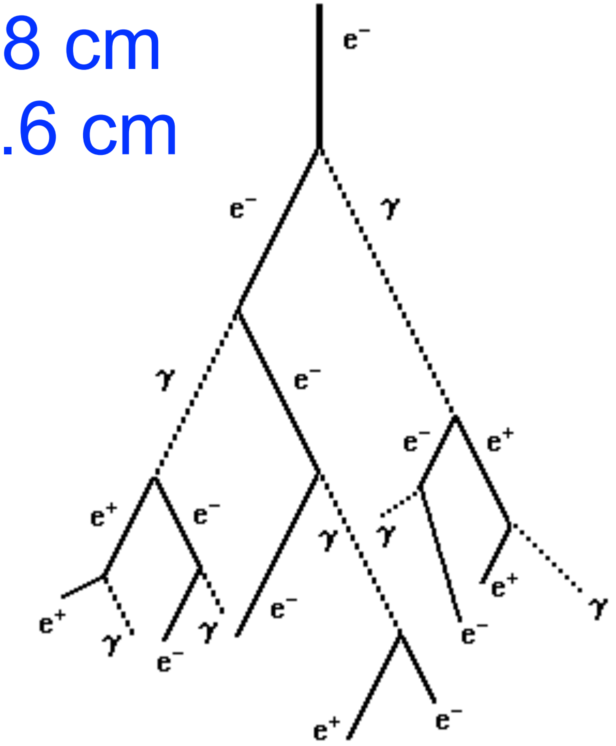
Radiation length X_0 is the average distance over which the energy of an electron is reduced by 1/e (characteristic distance scale for material effects)

X_0(iron) = 1.8 cm

X_0(lead) = 0.6 cm

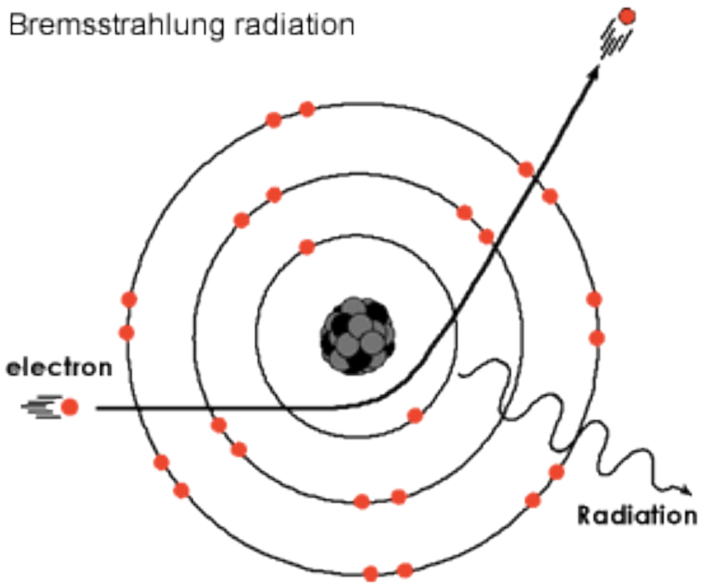
Bremsstrahlung

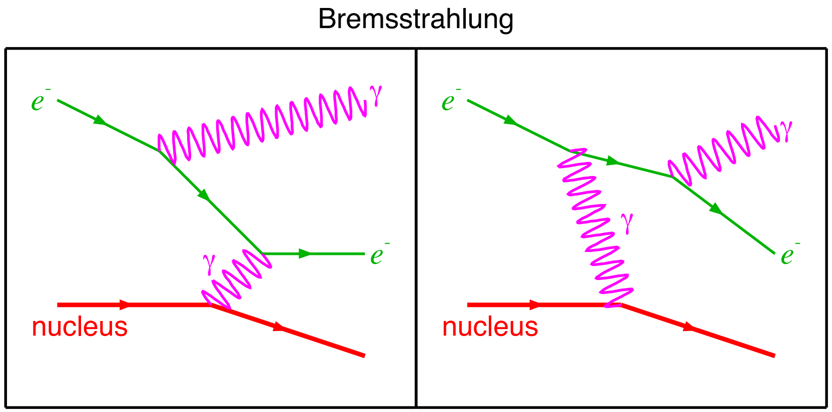




Very similar for photons

Radiation length for high-energy electrons/photons





After 1 X_0 we have roughly twice as many particles, with half the original energy

After 2 X_0, we have ~4x as many particles, with 1/4 the original energy

After n X_0, we have ~2^n as many particles, and the energy of each is ~2^{-n} of the original value

At some critical energy E_c, the Brem process stops

Radiation length for high-energy electrons/photons

$$< E >_n = \frac{E}{2^n} = E_c$$

$$\ln E - \ln 2^n = \ln E_c$$

$$\ln E - n \ln 2 = \ln E_c$$

$$n \ln 2 = \ln(E/E_c)$$

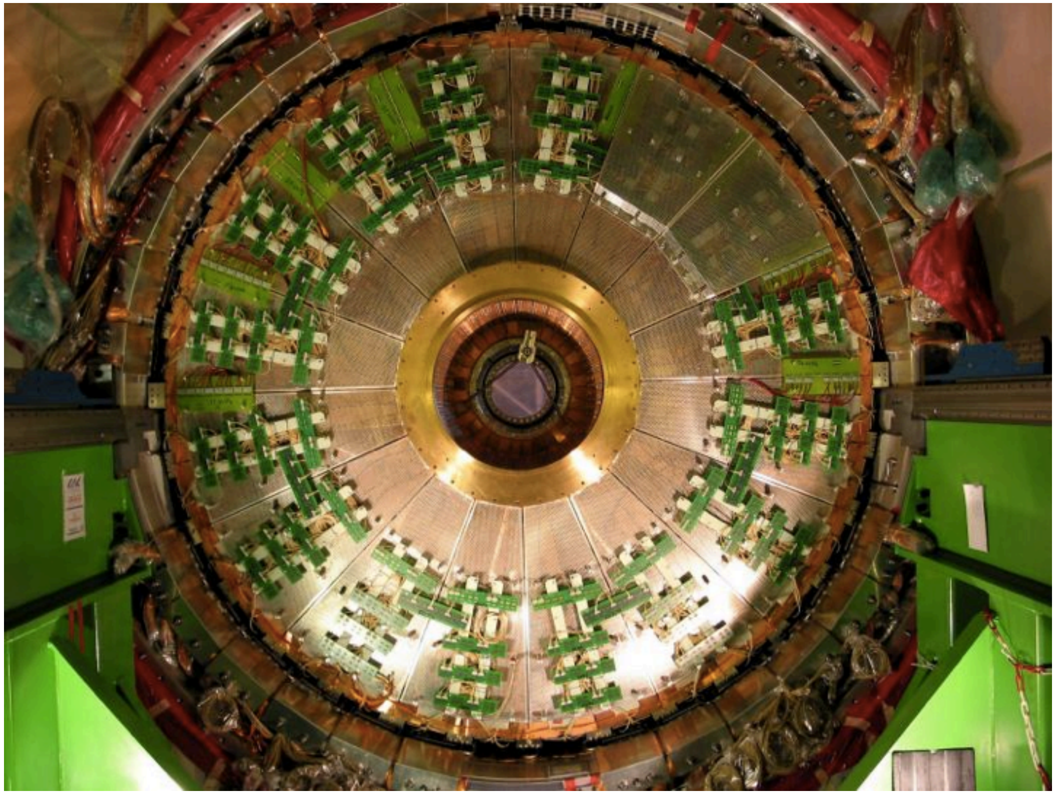
$$n = \frac{\ln(E/E_c)}{\ln 2}$$

Here n is the number of radiation lengths where the maximum number of particles is observed, aka where Brem stops (for lead, 100 GeV electron gives 13 X_0, which is just a few cm)

Calorimeters

Need some dense material to absorb energy, and some active material to notice this and produce an output signal. Can be the same material, often is not. ATLAS EM calorimeter is lead-liquid argon

A view inside the ATLAS LAr calorimeter



Hadronic calorimeters

Trickier, as hadrons can be electrically neutral but even then the constituents (quarks) have electric charge. And sometimes have an overall electric charge

Defined by the nuclear interaction length (λ_I), which is the mean distance between hadronic interactions.

λ_I(lead) = 17 cm (compare with X_0(lead) = 0.6 cm)

Also tricky because neutral pions decay 99% of the time to a pair of photons

ATLAS tile calorimeter

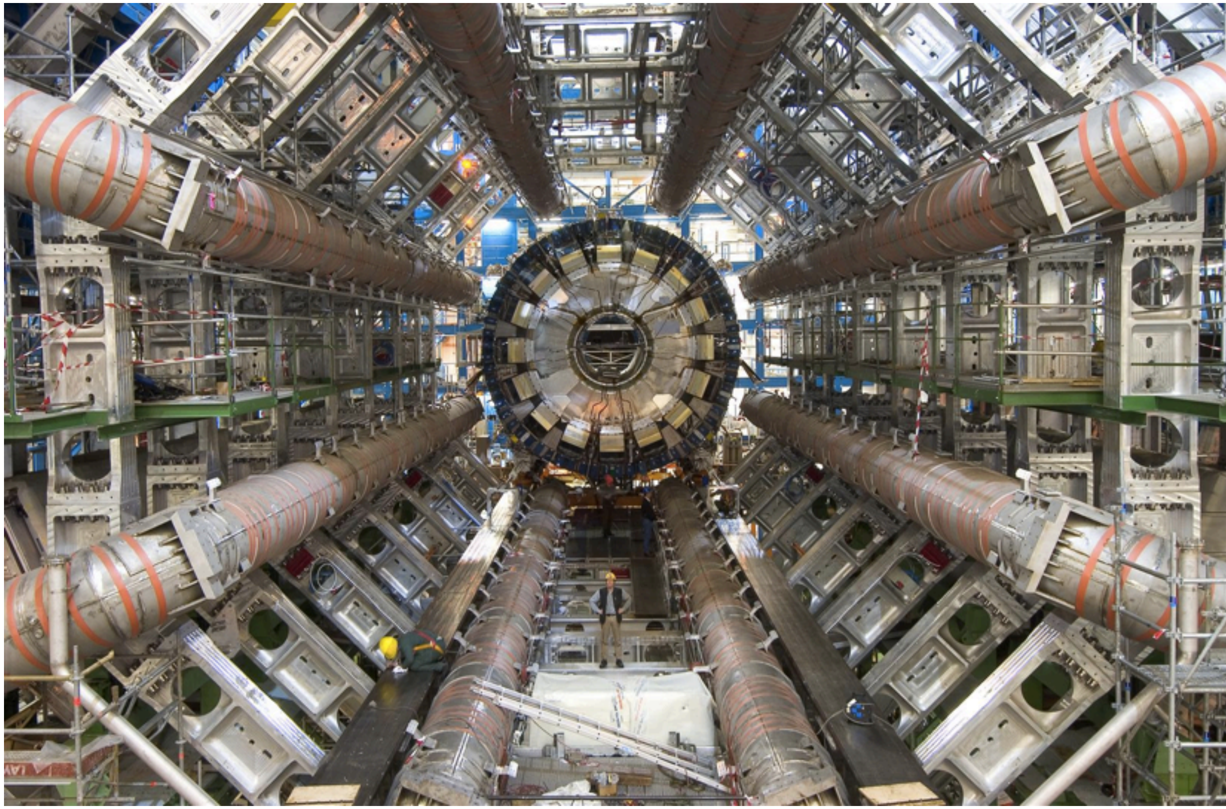
Intersperse steel absorber with plastic scintillator tiles, plastic doped with organic material. When charged secondary particles emerge from the steel, they excite the doped material, and emit UV light that can be re-emitted as one color by a dye

The ATLAS tile calorimeter

What emerges from the calorimeters?

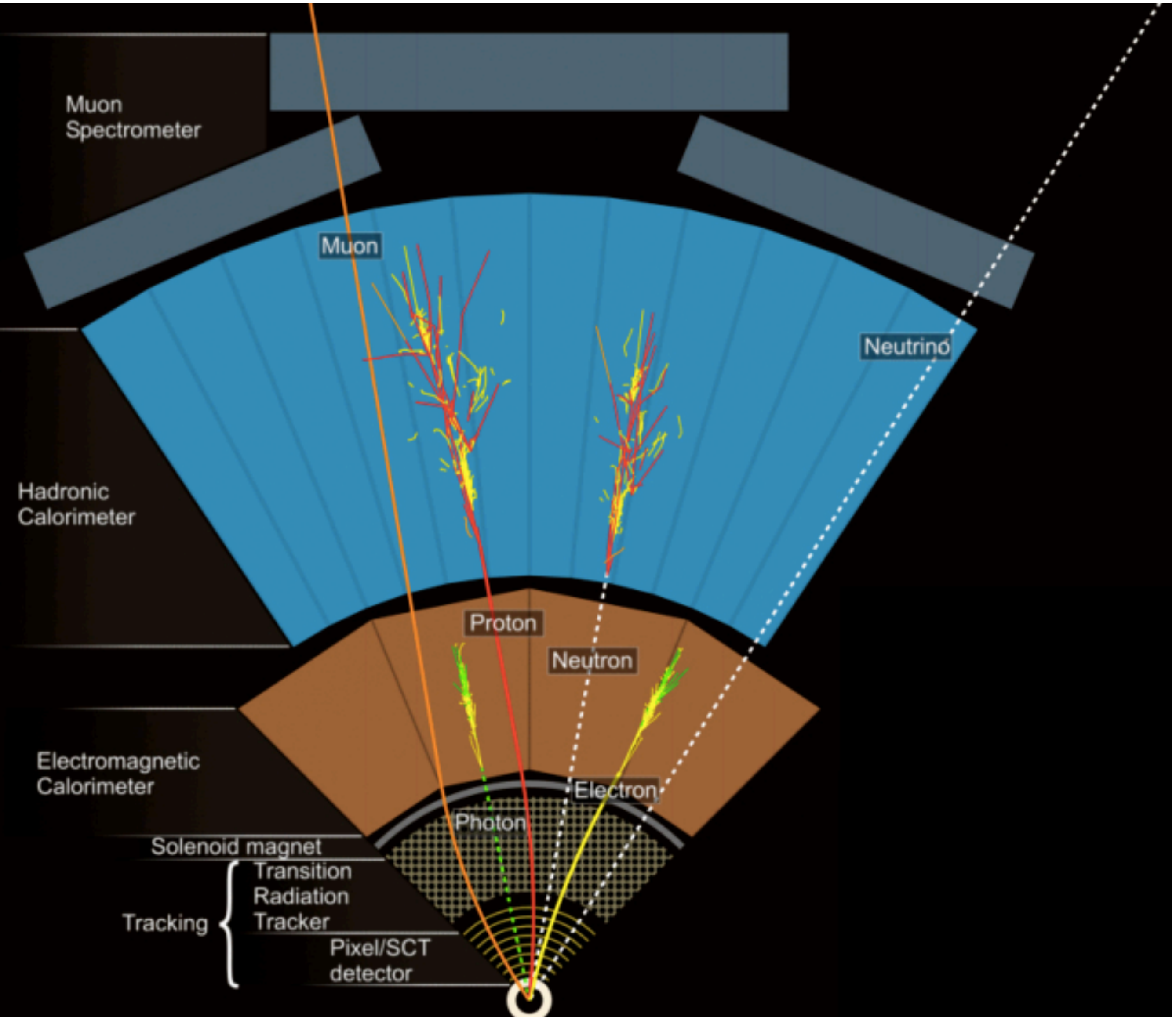
Neutrinos... we "detect" them (indirectly) by applying momentum conservation in the plane perpendicular to the beam

And muons! Have a set of toroidal magnets (giving ATLAS its shape and name) and more muon systems on outside of detector

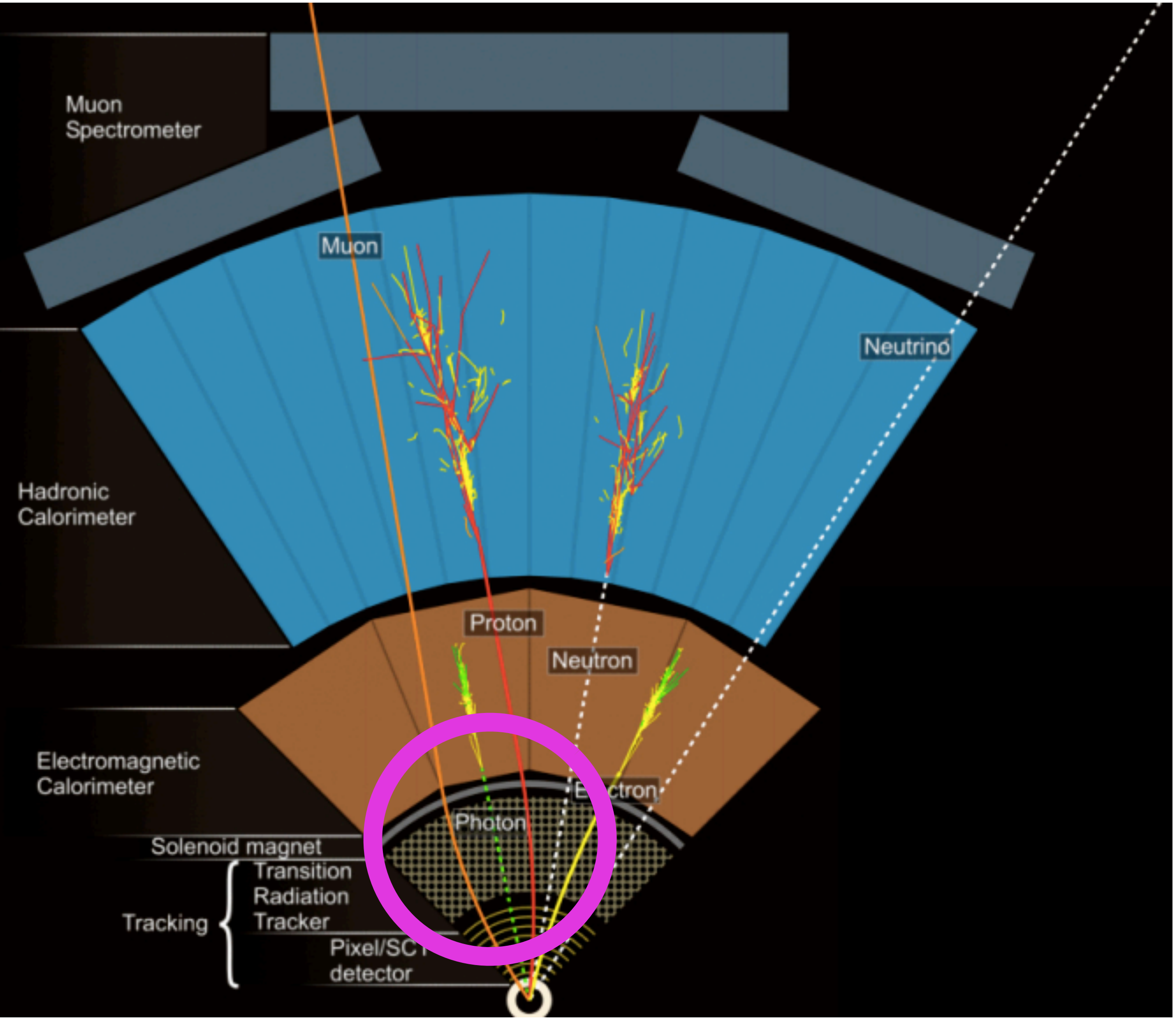


Highly non-trivial B field. Need to monitor not just alignment but also field itself

Putting it all together

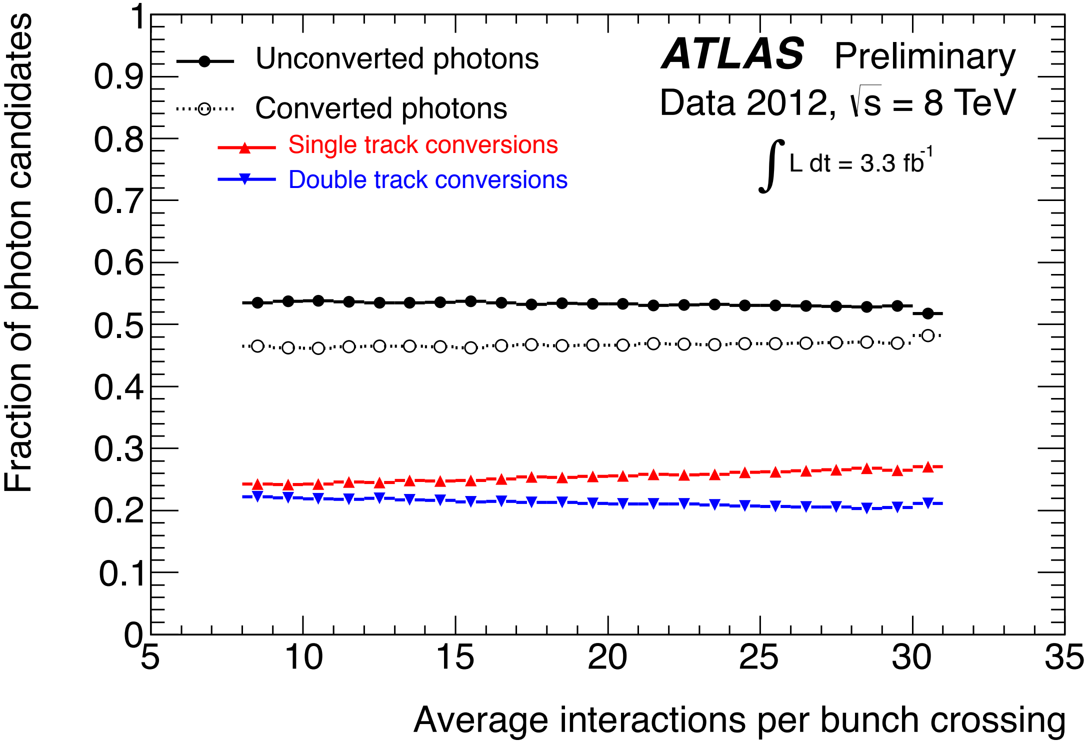


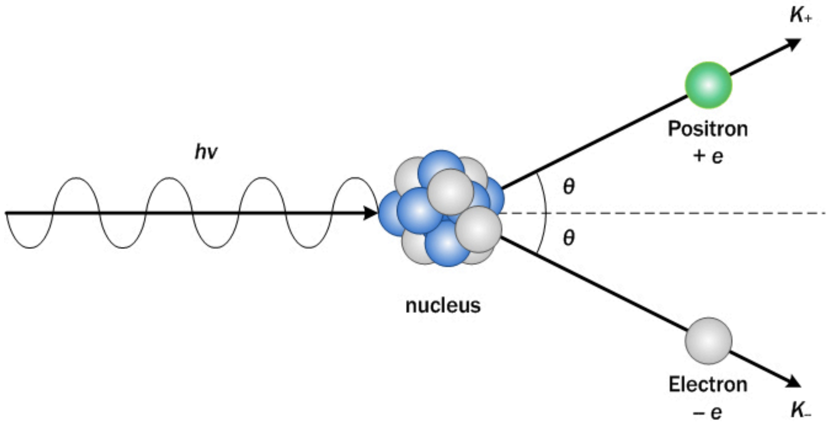
Putting it all together



Photon can appear as isolated cluster in the EM calorimeter with nothing in hadronic calorimeter behind it and nothing else nearby. NO charged track pointing at calorimeter. Careful: lots of neutral pions!

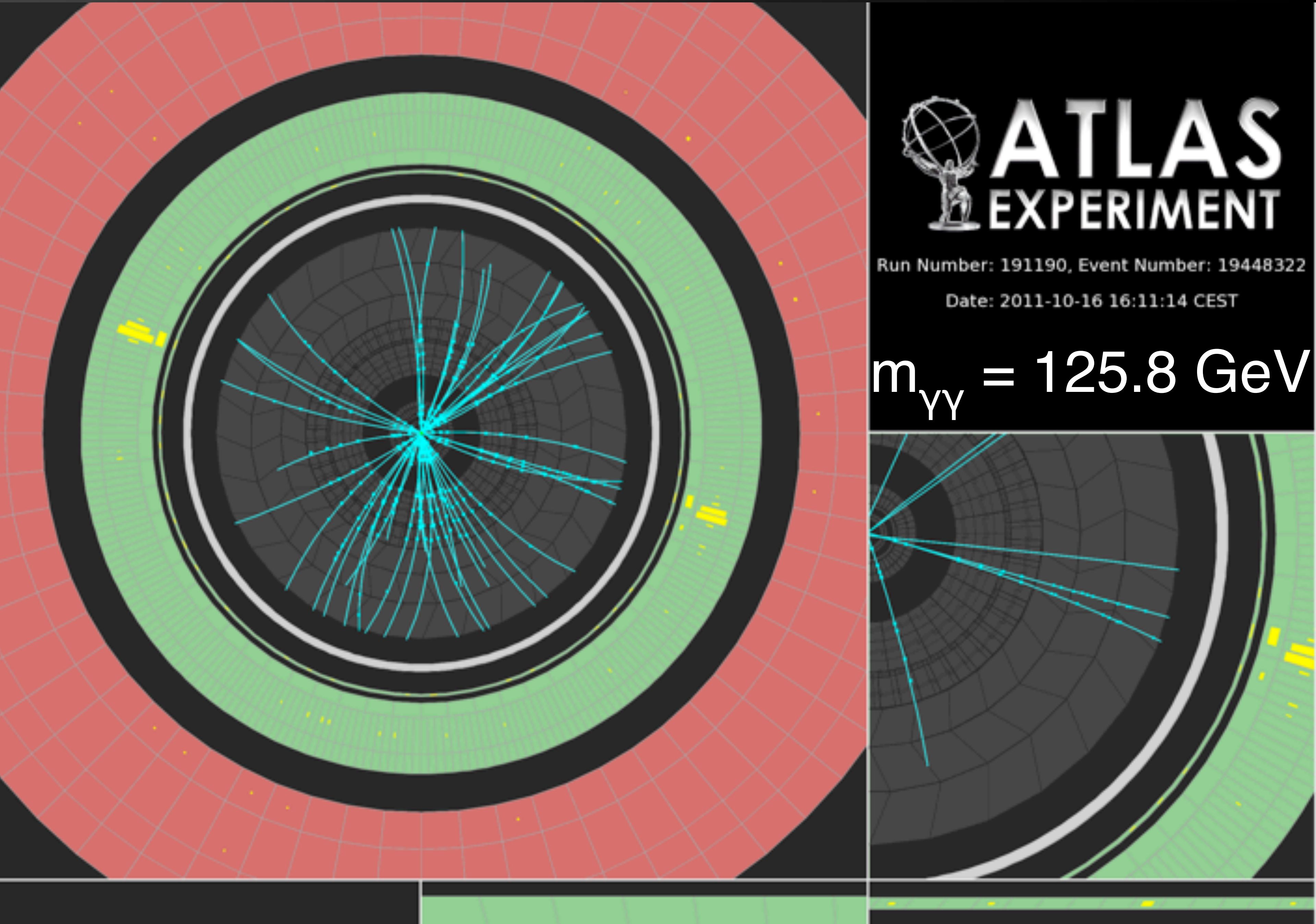
Putting it all together





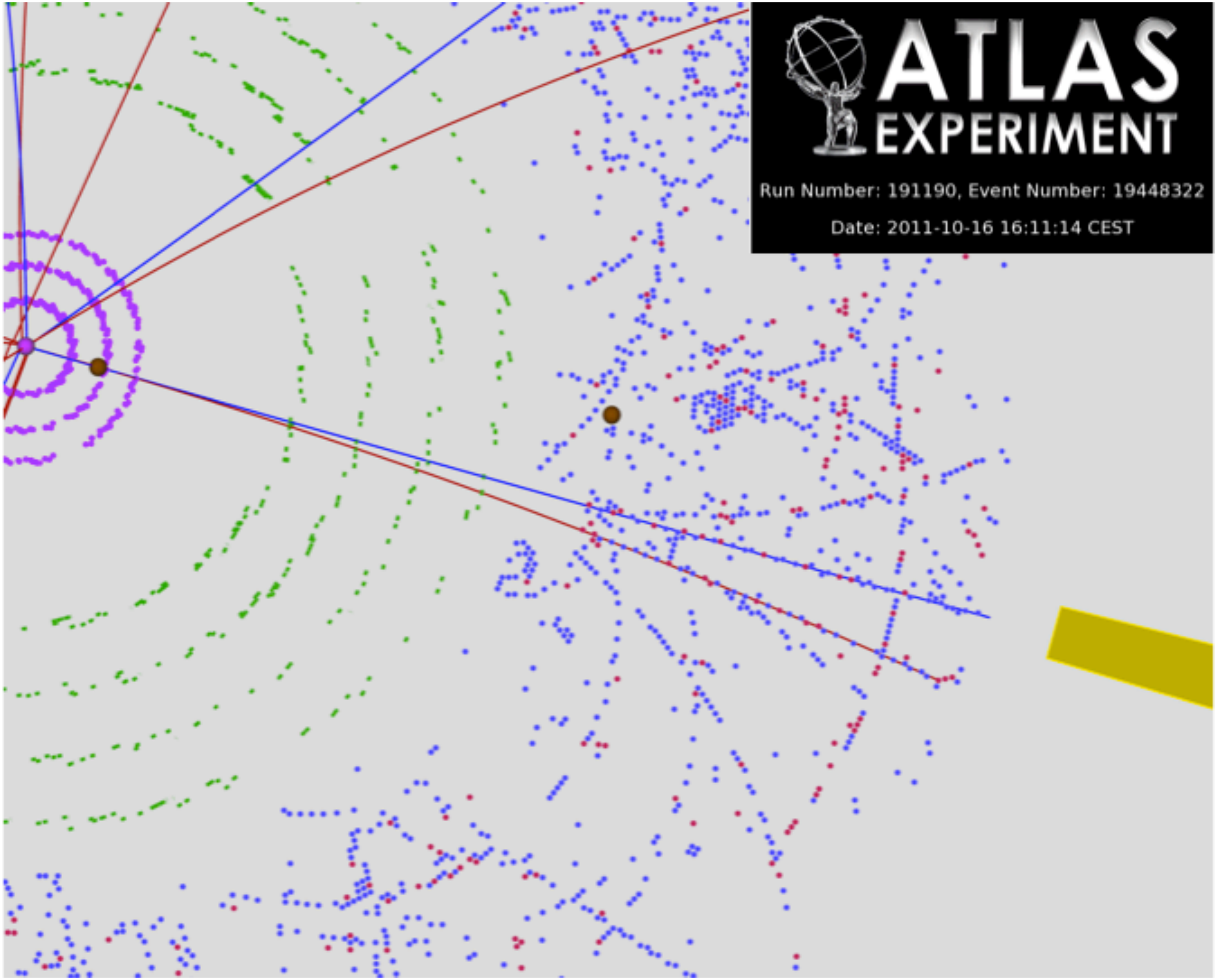
Need to be careful because almost half of the photons at ATLAS interact with material in the detector before reaching the calorimeter! These photons look similar, except there are one or two clusters of energy with charged tracks not coming from the original interaction. How can there be only one track? Other one can be very soft (low momentum)

Higgs boson decaying to two photons

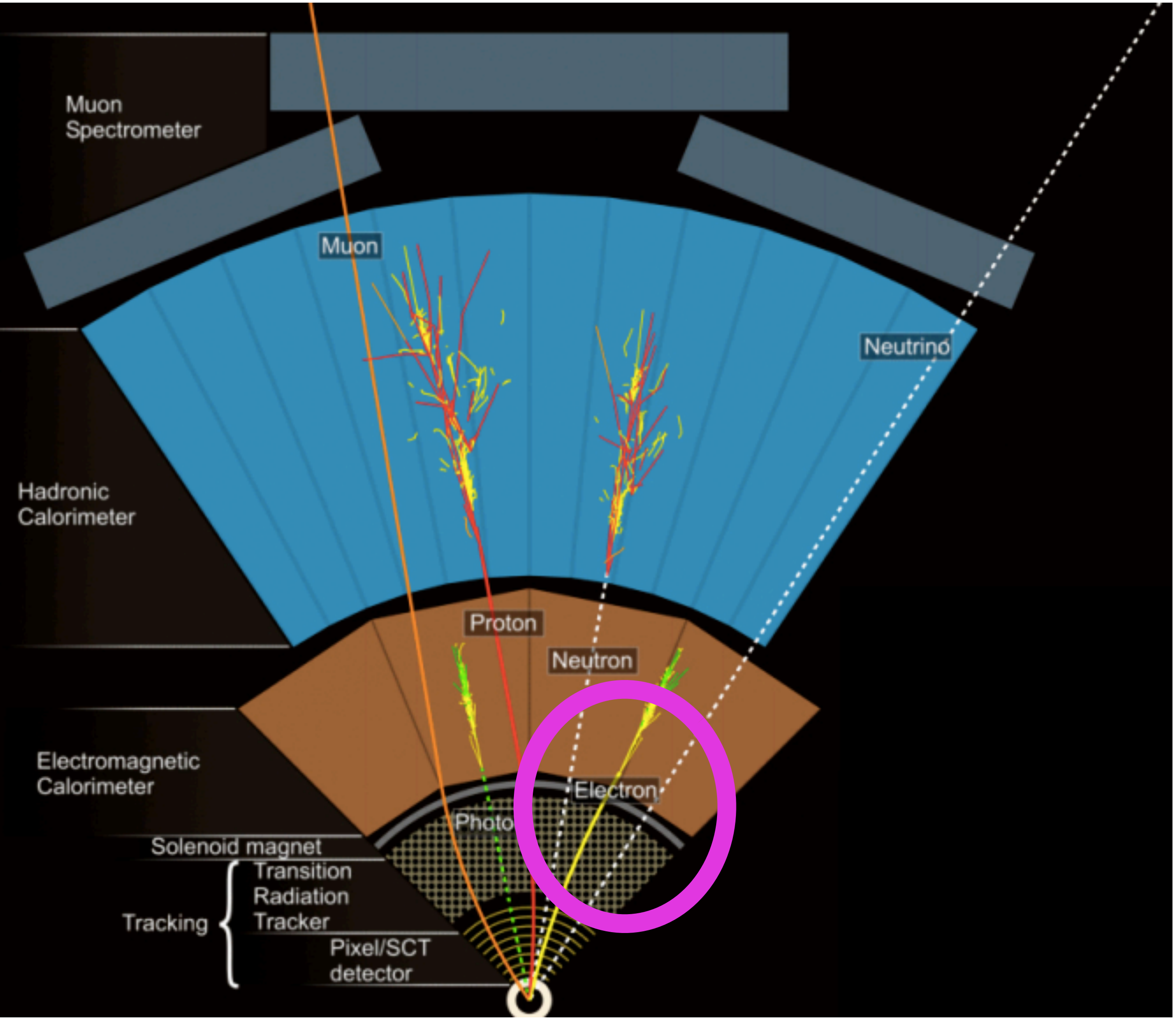


$m_{\gamma\gamma}$ = 125.8 GeV

Zooming in on a converted photon

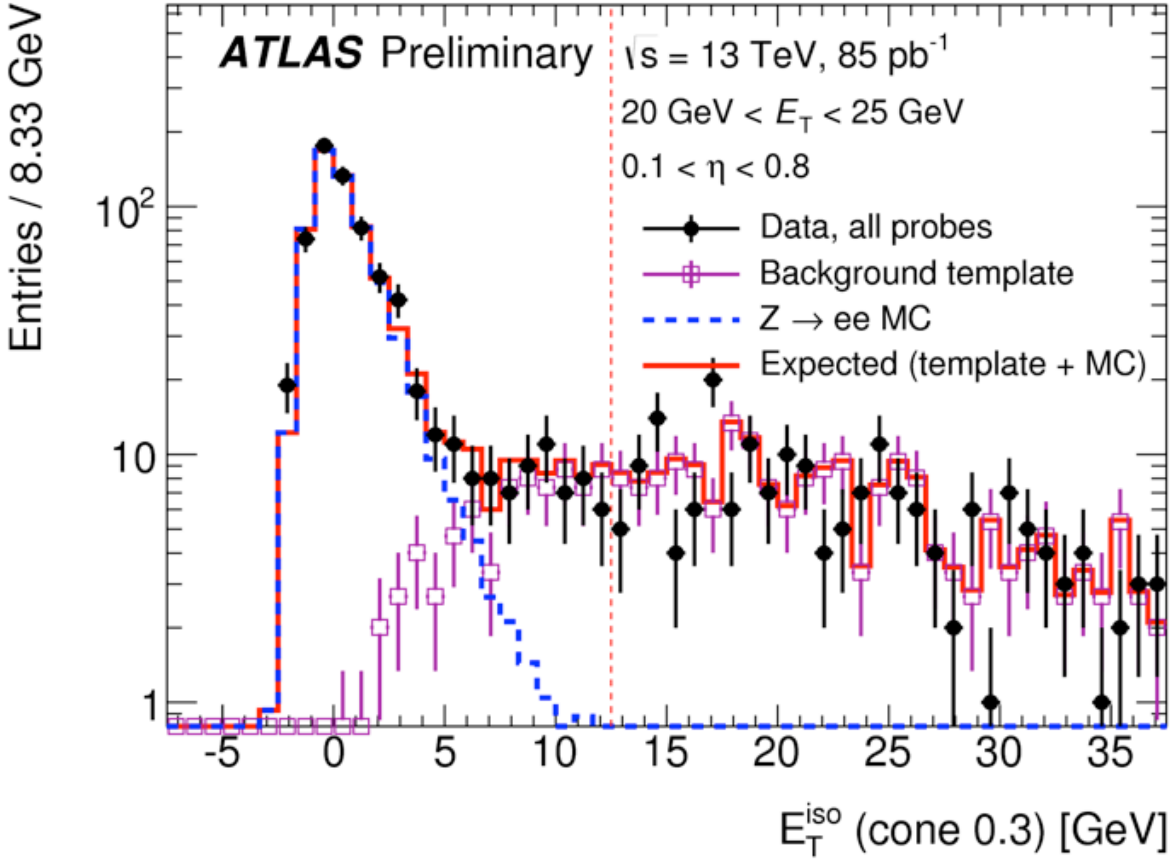


Putting it all together



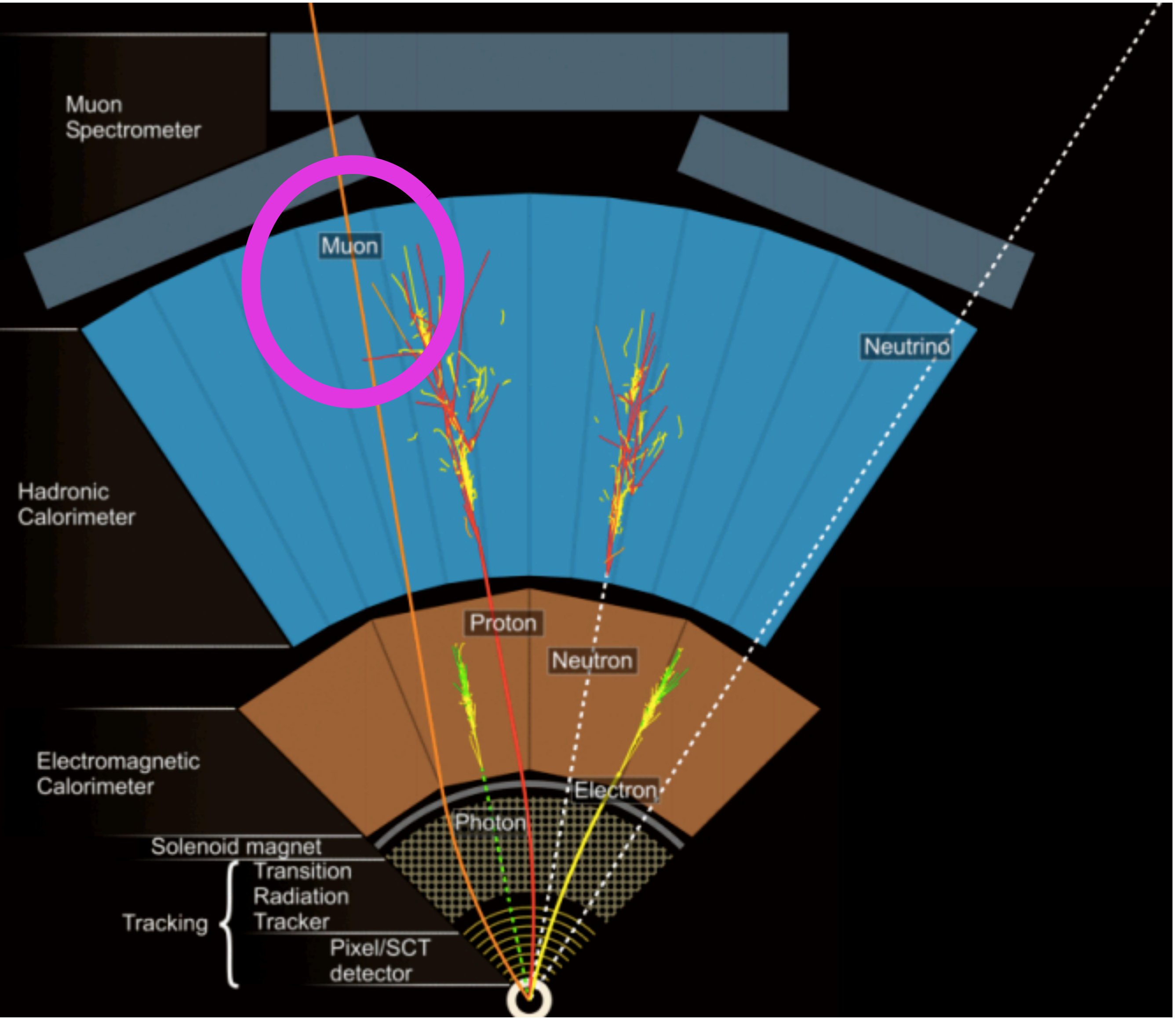
Electron appears as isolated cluster in the EM calorimeter with nothing in hadronic calorimeter behind it and a charged track. Photons and charged hadrons look like this too!

Electron ID at ATLAS



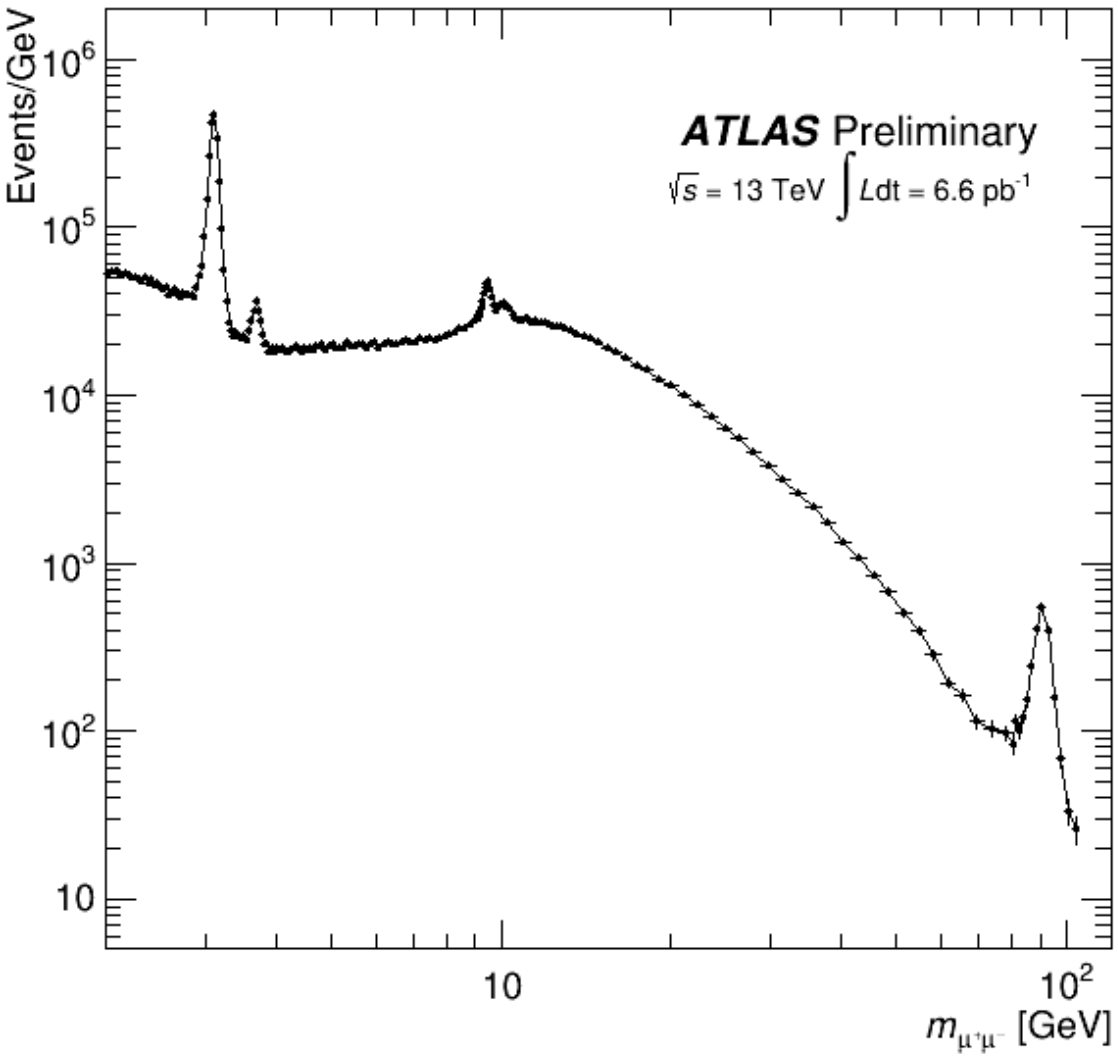
"Isolation" of nearby activity (in calorimeters and also tracking system) can help us to distinguish real electrons from fake electrons

Putting it all together



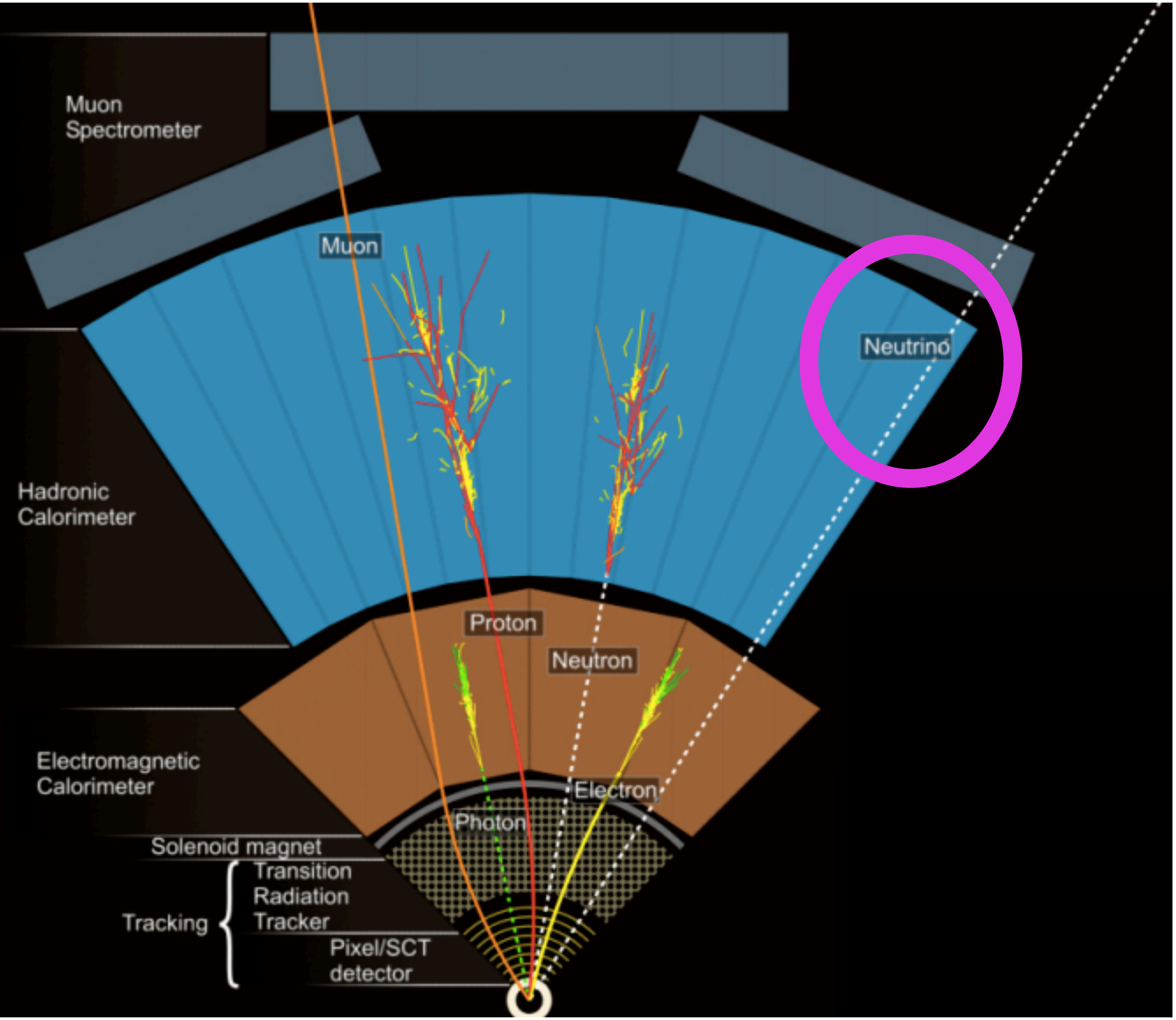
Muons appear as isolated, minimally ionizing particles in the calorimeter, with charged tracks in both the inner detector and also the muon spectrometer. Typically not so many fake muons, but can have muons from hadron decays

Muon ID at ATLAS



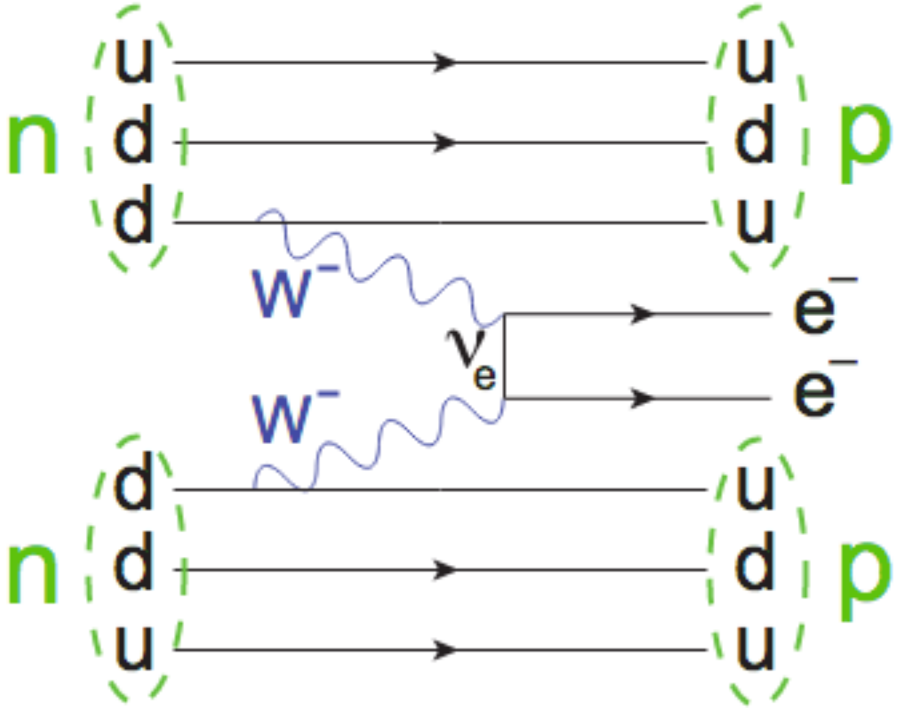
Beautiful invariant mass plot with early Run 2 ATLAS data

Putting it all together



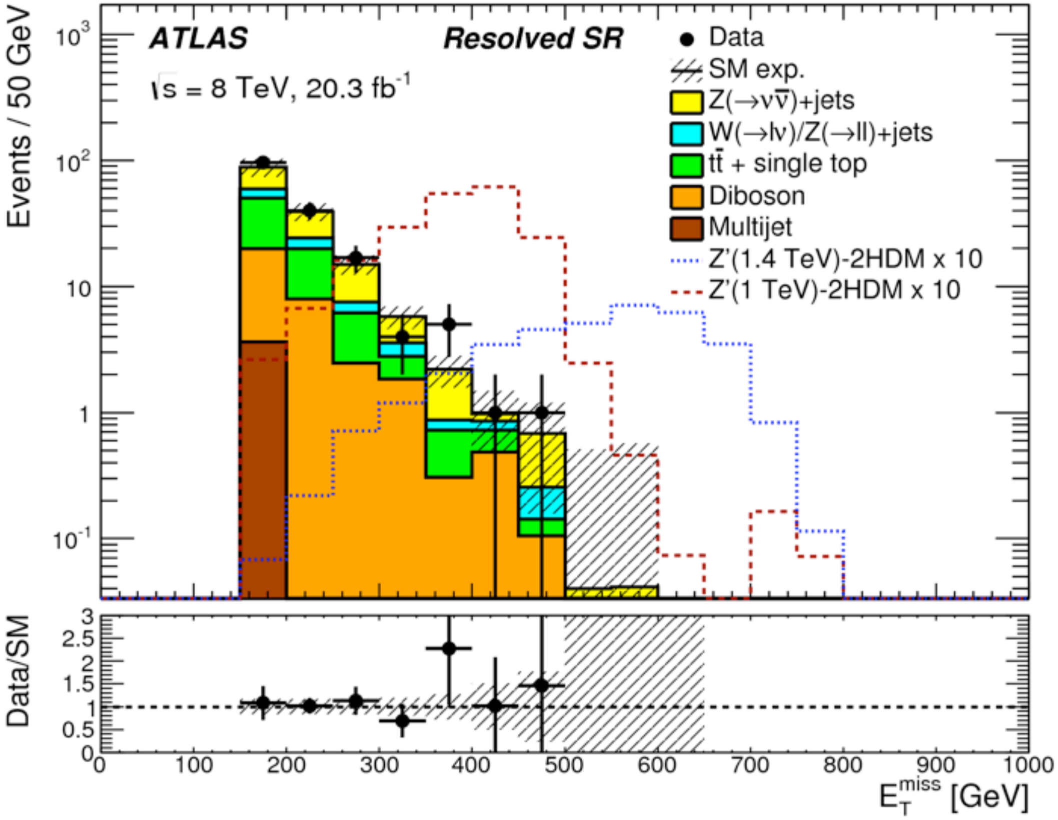
Neutrinos are not measured directly but inferred by applying the conservation of momentum to all measured objects

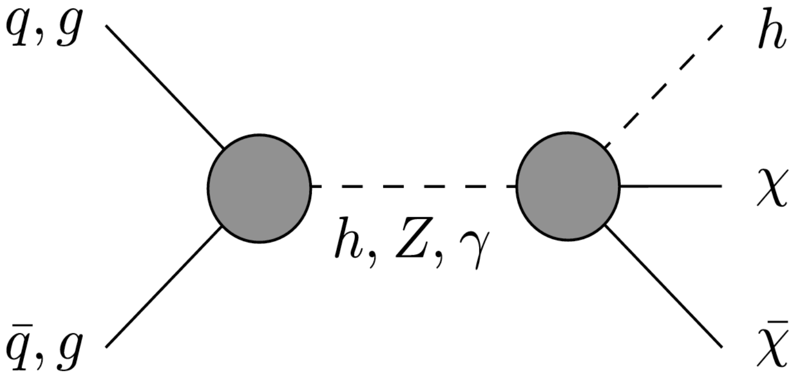
Aside about neutrinos



Are neutrinos Majorana particles (ie their own anti-particles)? Different than Dirac particles (not their own) anti-particles. Would violate electron flavor number! How to observe this?

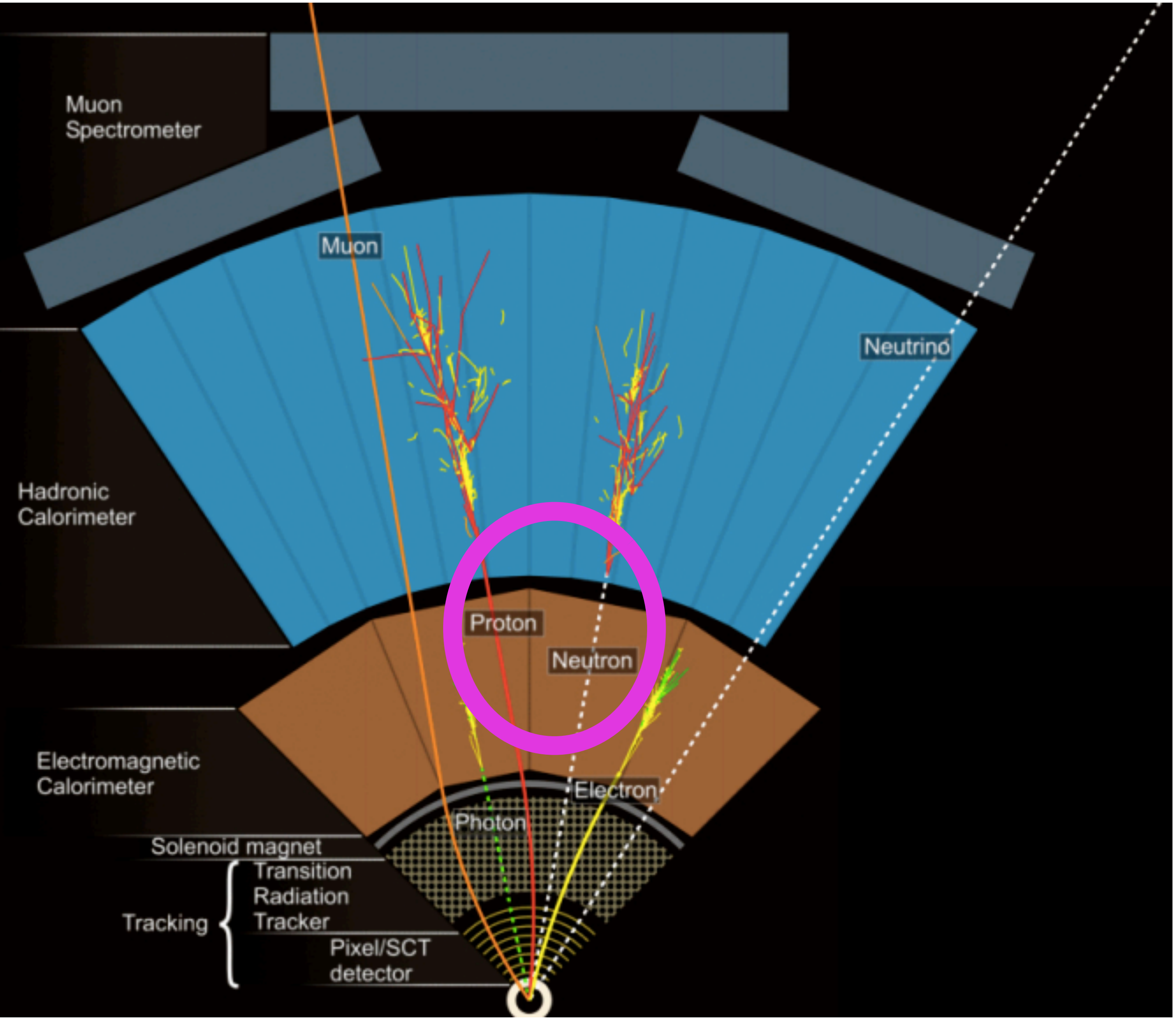
Using MET at ATLAS





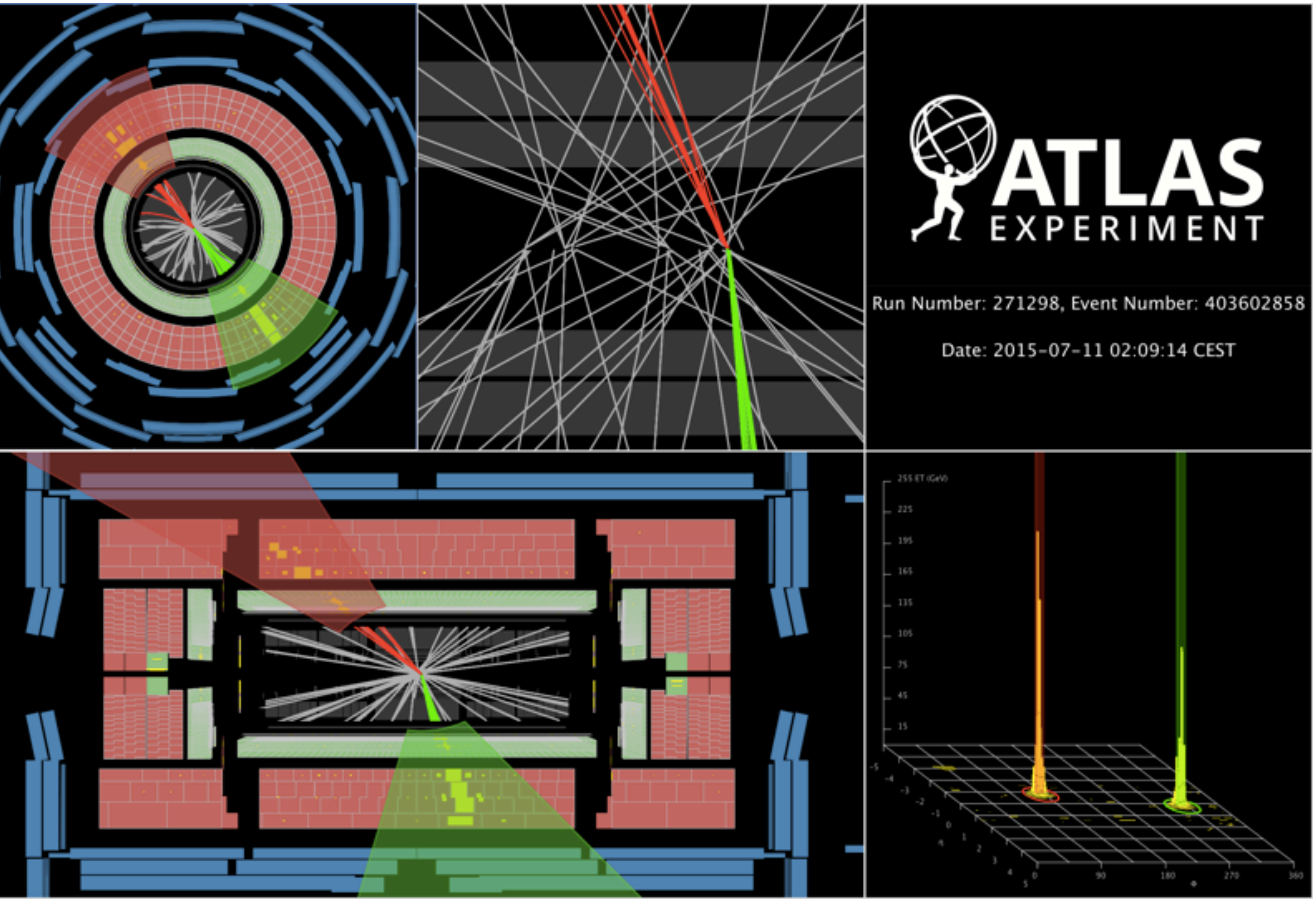
Using momentum imbalance to look for dark matter production

Putting it all together



Protons leave charged tracks, neutrons do not. Both deposit energy in both the electromagnetic and hadronic calorimeters. Both typically not produced on their own but with lots of other particles nearby inside of a jet

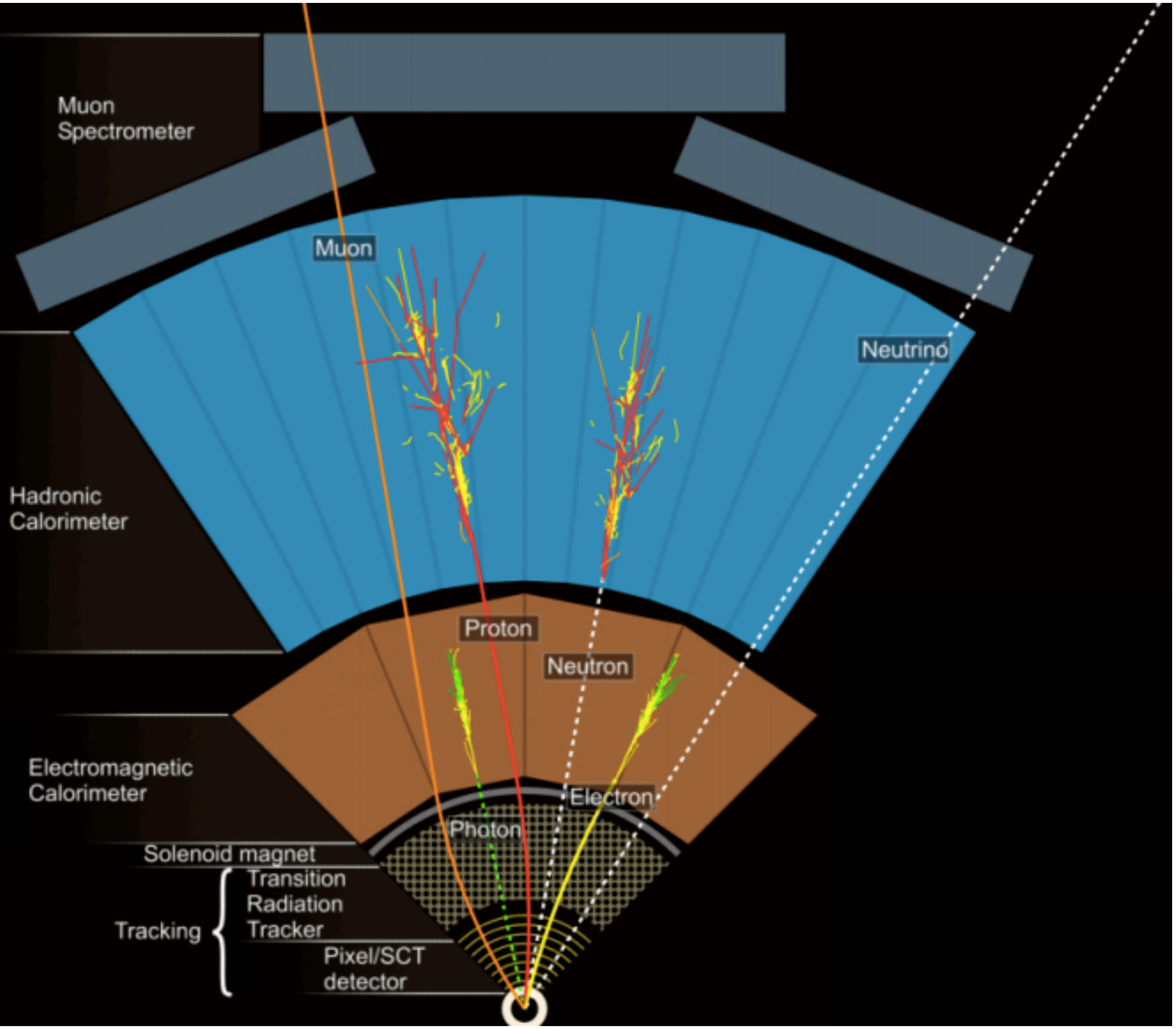
Jets



Typical jet has ~60% of energy in charged particles (mostly pions), ~30% in photons from neutral pion decay, and 10% neutrals. On average, of course

In a process like pp→qqbar, quarks are flying apart in opposite direction. They do not form a bound state together, but the energy pulling them apart leads to radiation of gluons and lots of other quarks, which decay to other objects with QCD color charge, which decay, etc into a collection of particles called a **jet**

Putting it all together



Taus can decay to

an electron (18%);

a muon (17%);

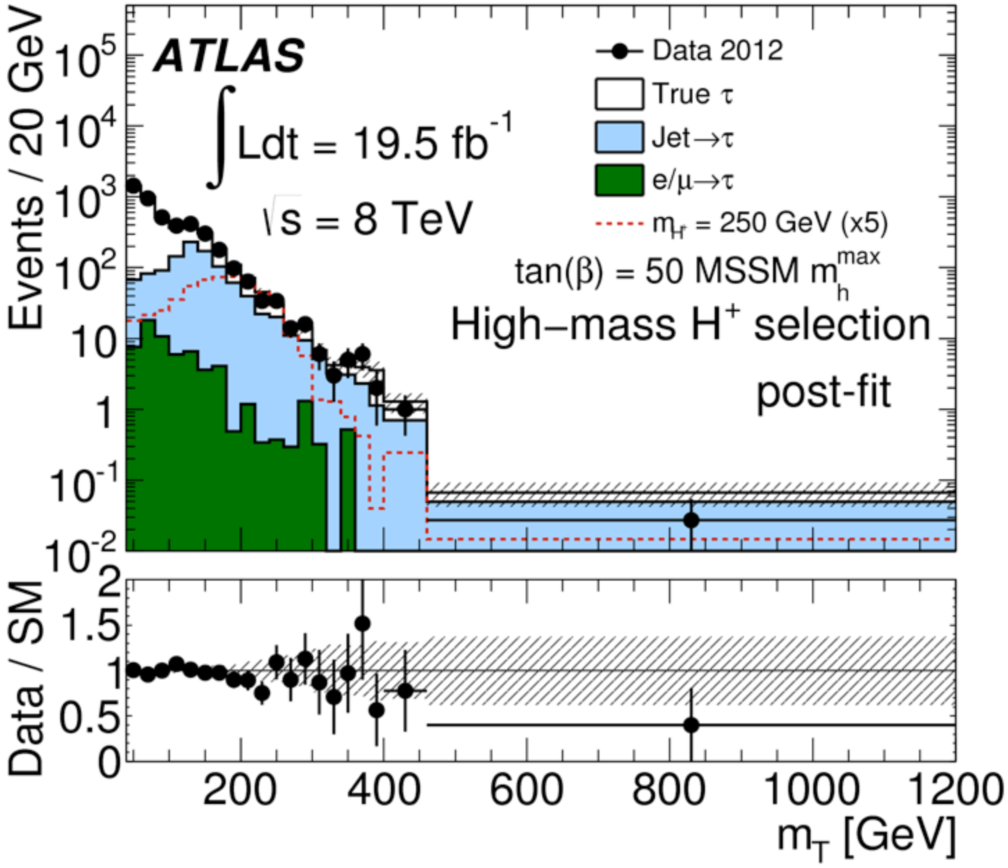
a single charged pion and extra neutral pions decaying to photons (48%);

three charged pions plus extra neutral pions decaying to photons (15%)

Taus thus often reconstructed as a narrow collimated jet of 1 or 3 tracks

(Ignoring neutrinos)

Using taus at ATLAS



In many models of new physics, new Higgs-like particles like to decay to heavy objects. Can have charged Higgs bosons decay to a tau (and a neutrino)