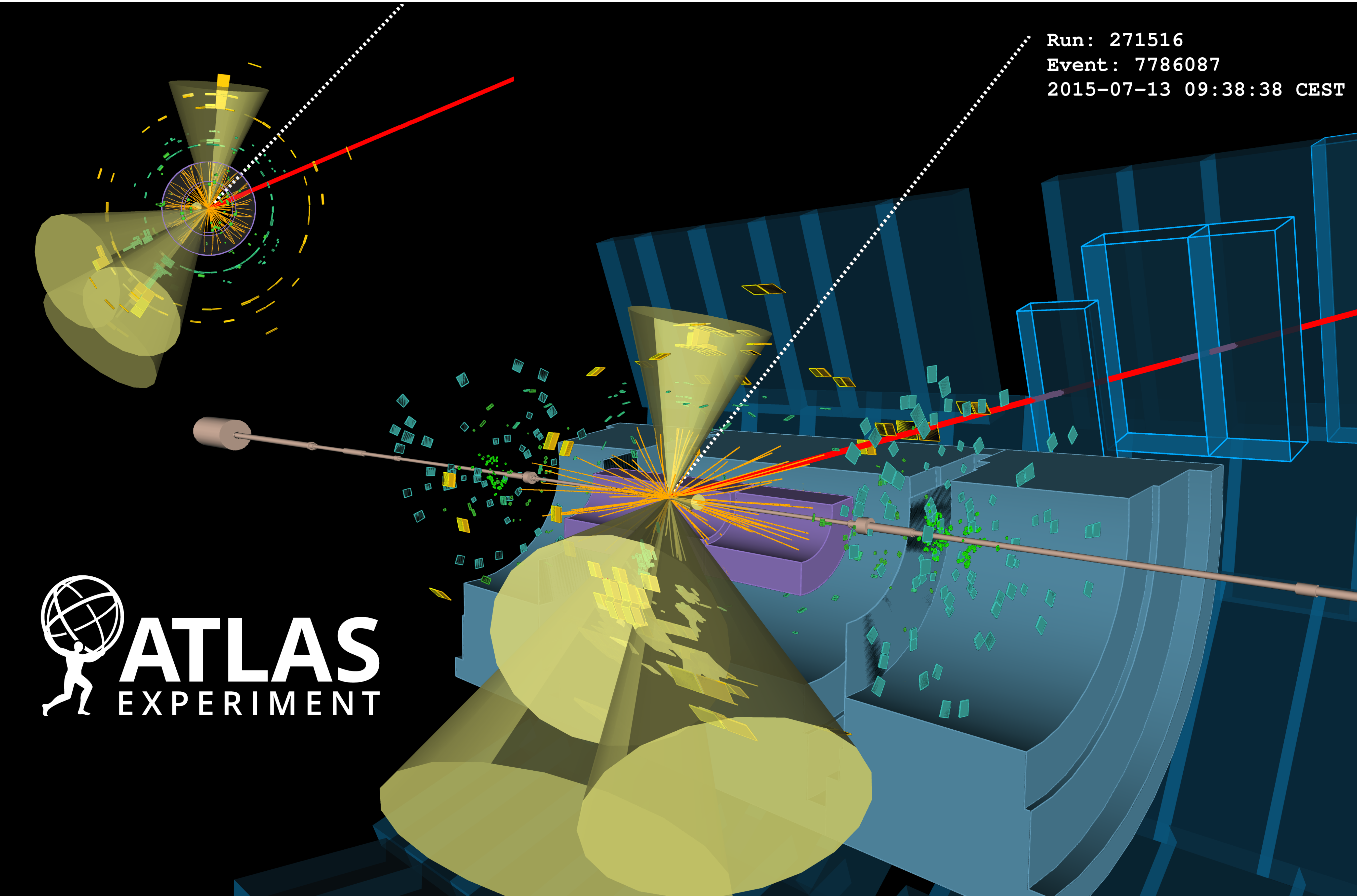
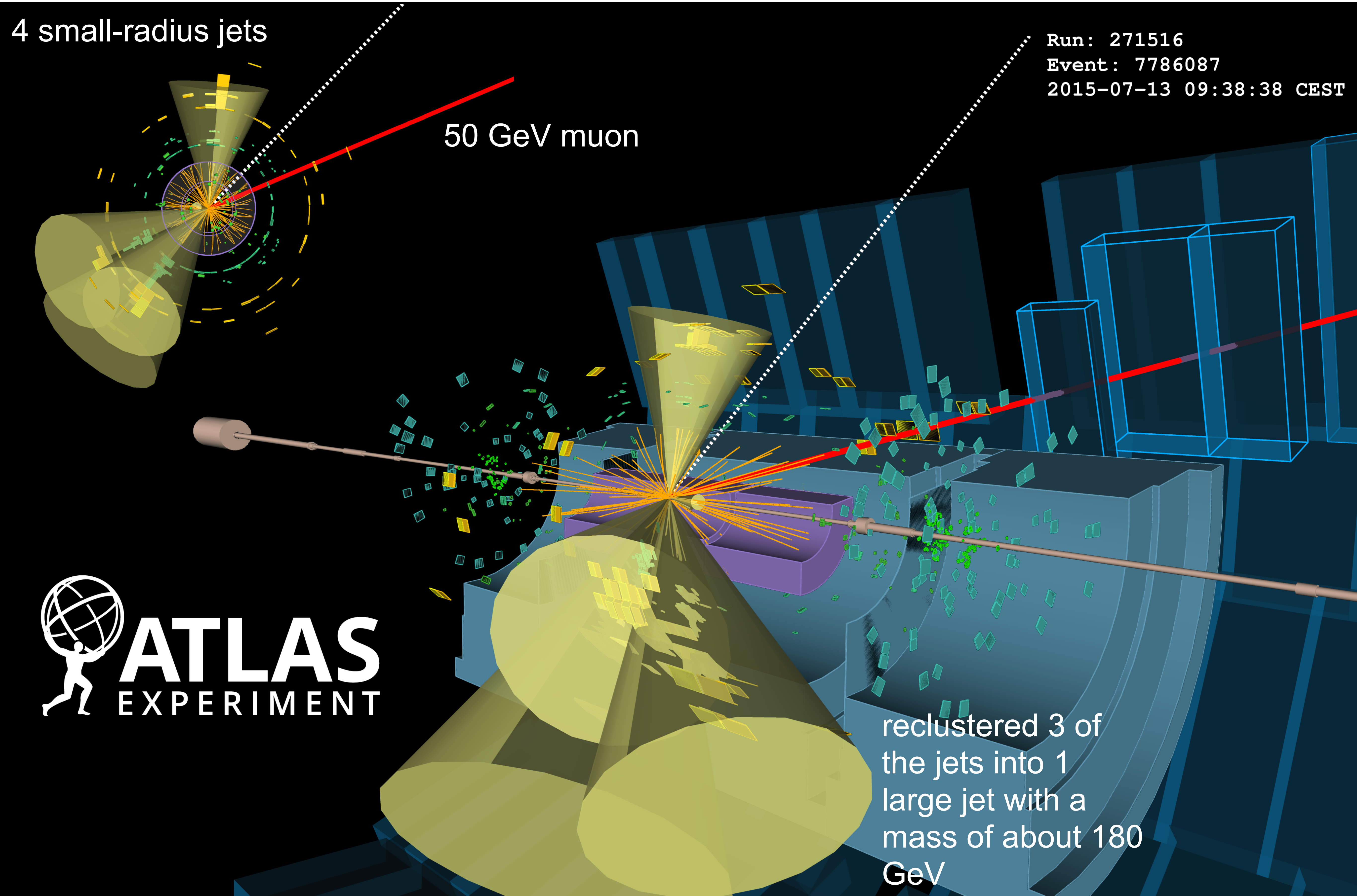
Missing ET and Dark Matter searches in ATLAS
(and some other related stuff too)

Claire Lee, Brookhaven National Laboratory
Tel Aviv University Students CERN visit
October 2015

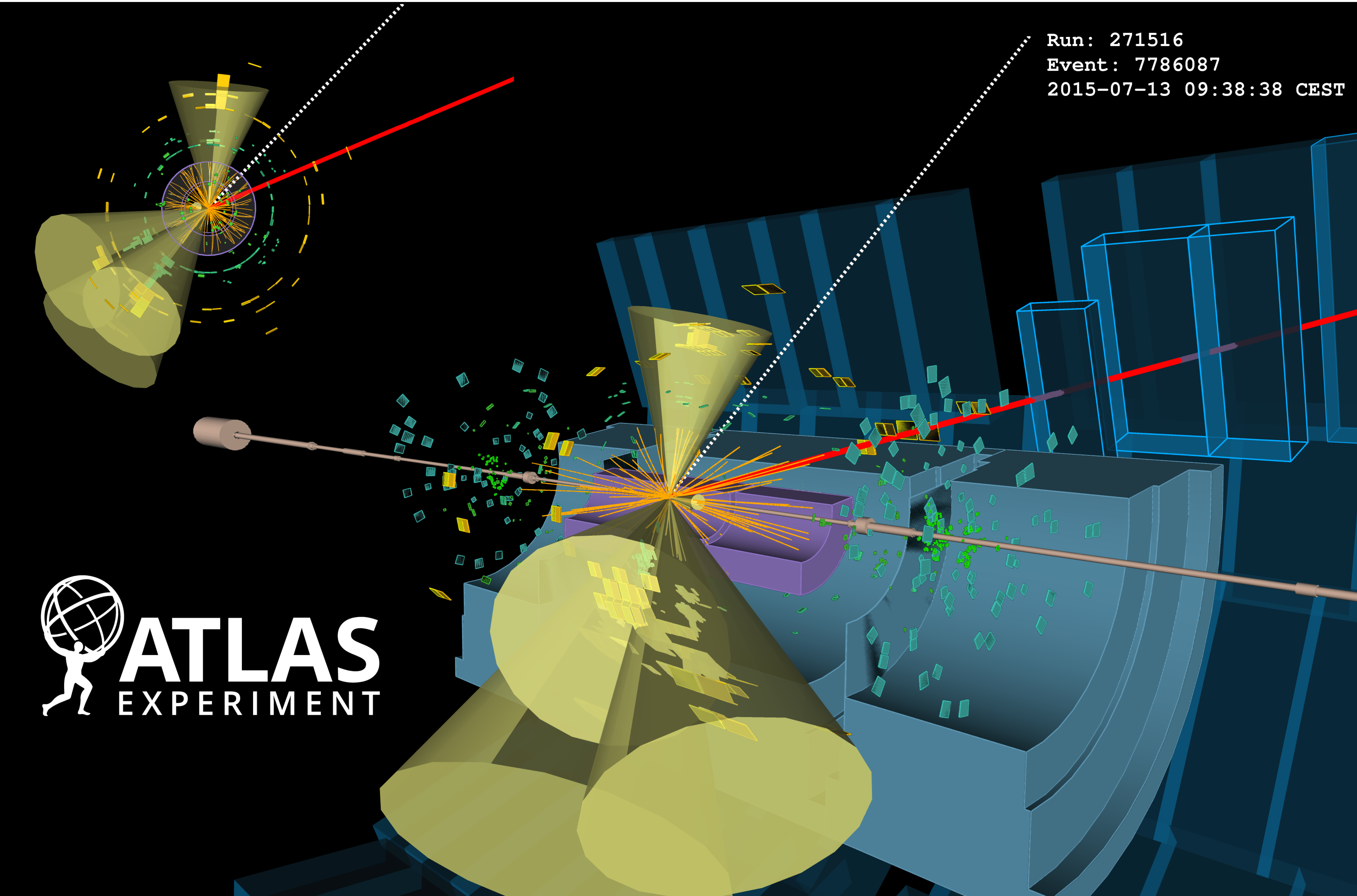
Candidate boosted top quark pair, July 2015



Everything we observe in ATLAS is part of an event



BUT not eveything in an event is seen!



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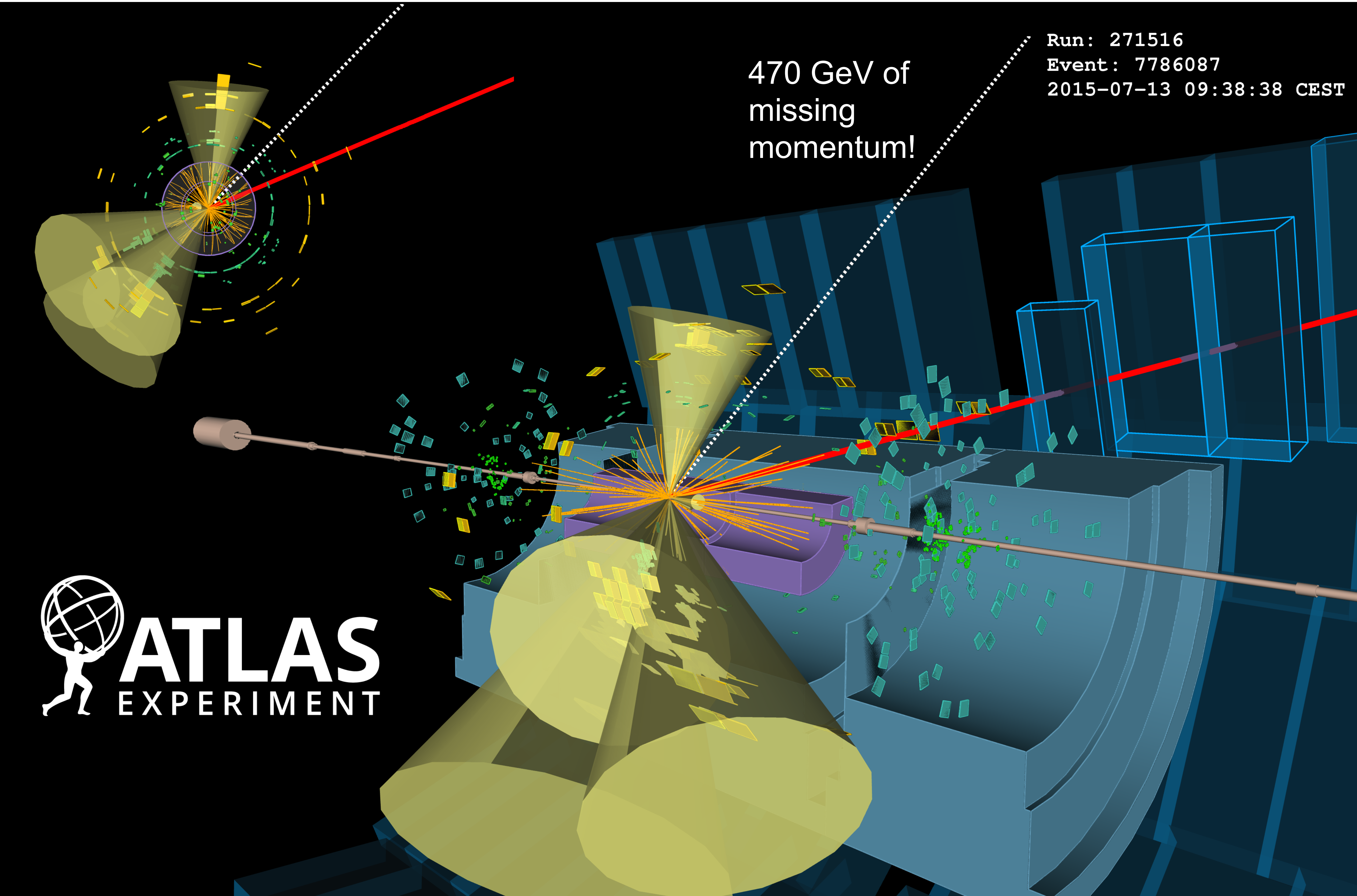

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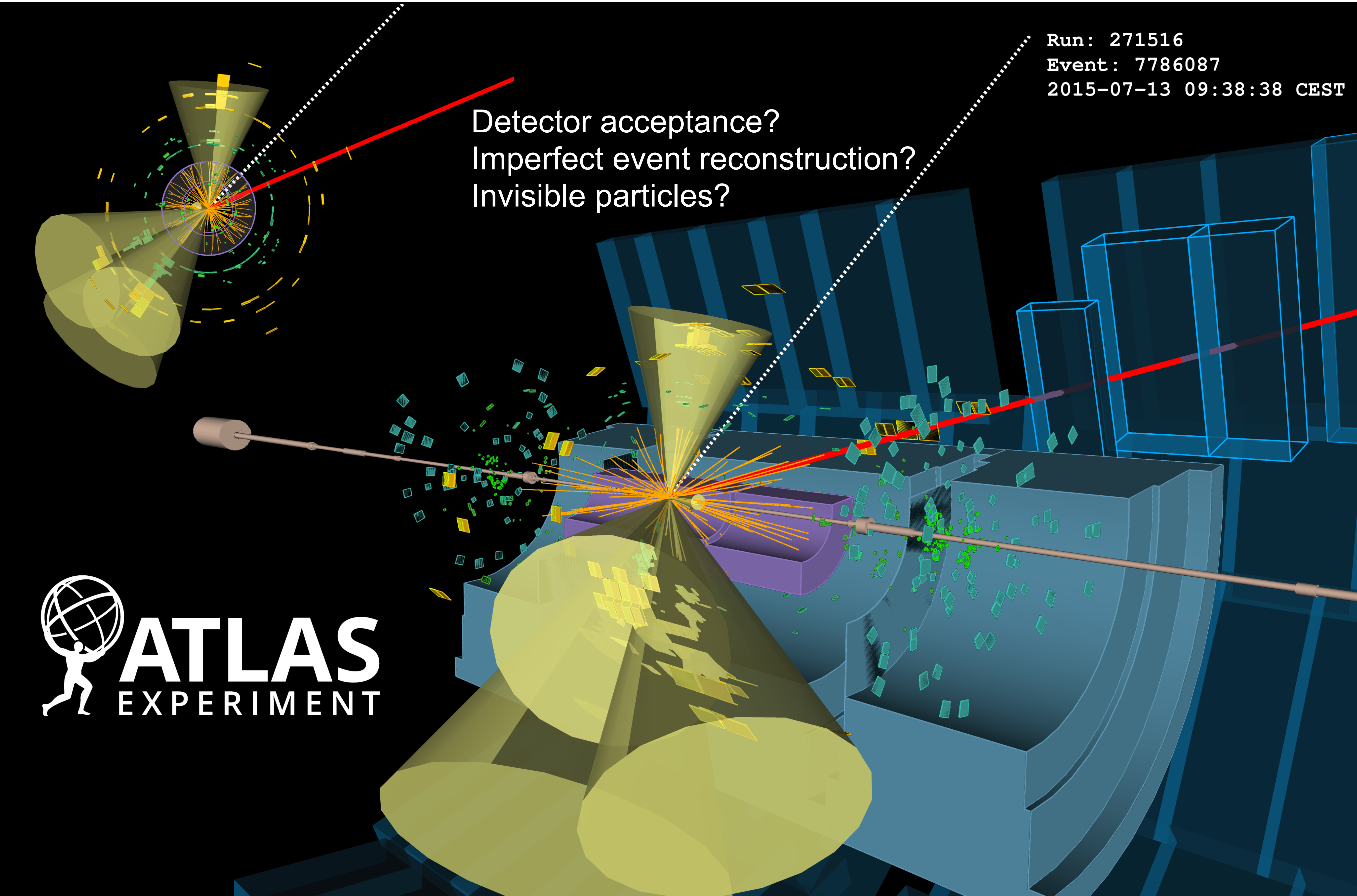
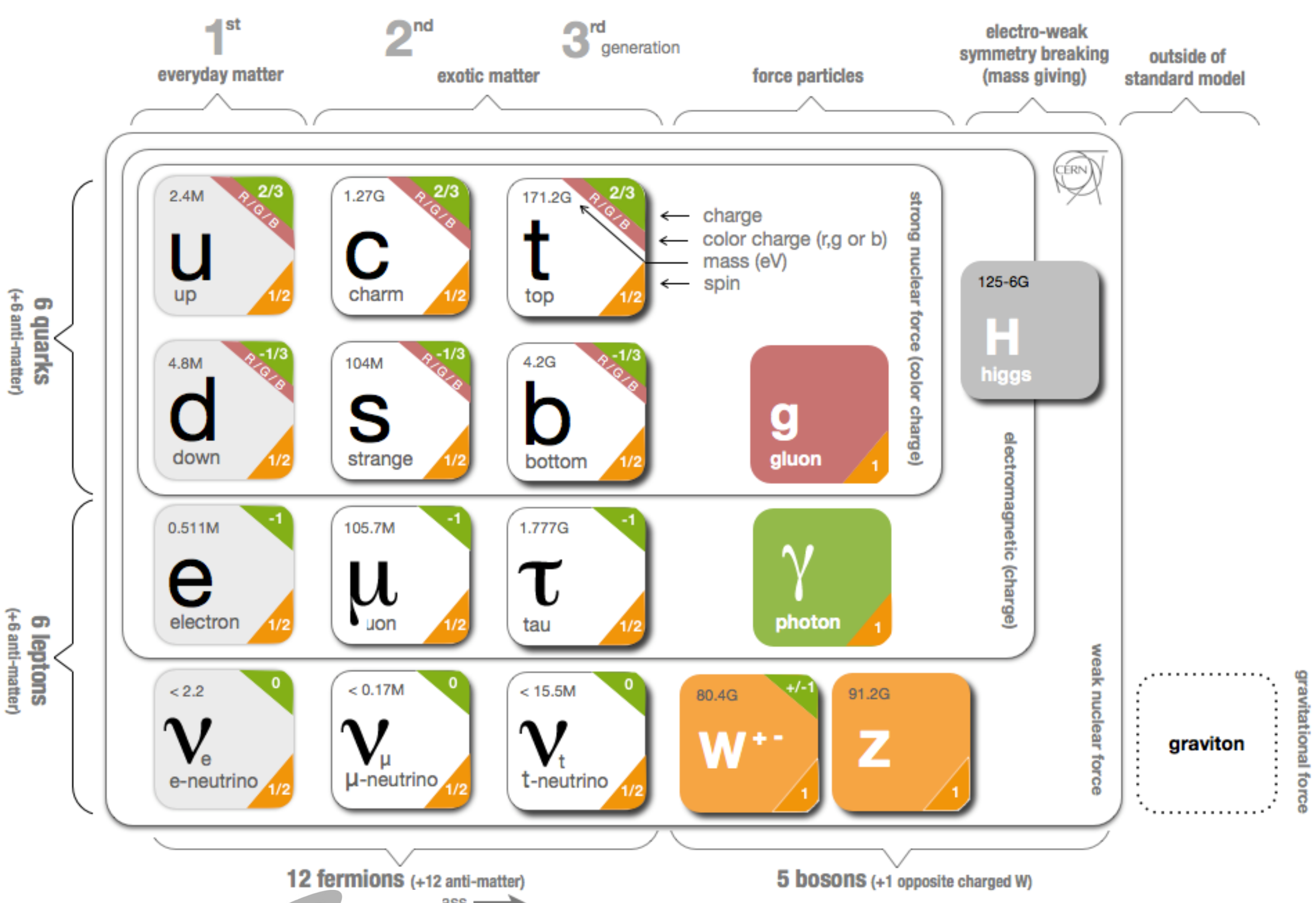


Why do we care about the stuff we can't see?

- Because it can be something we know ought to be there:
  - Standard Model W, Z, B and tau decays all produce neutrinos
- Or it can be something exciting:
  - Supersymmetry (stable LSP)
  - Extra dimensions
  - New exotic particles in general (dark matter, etc)



How do I measure the invisible stuff?

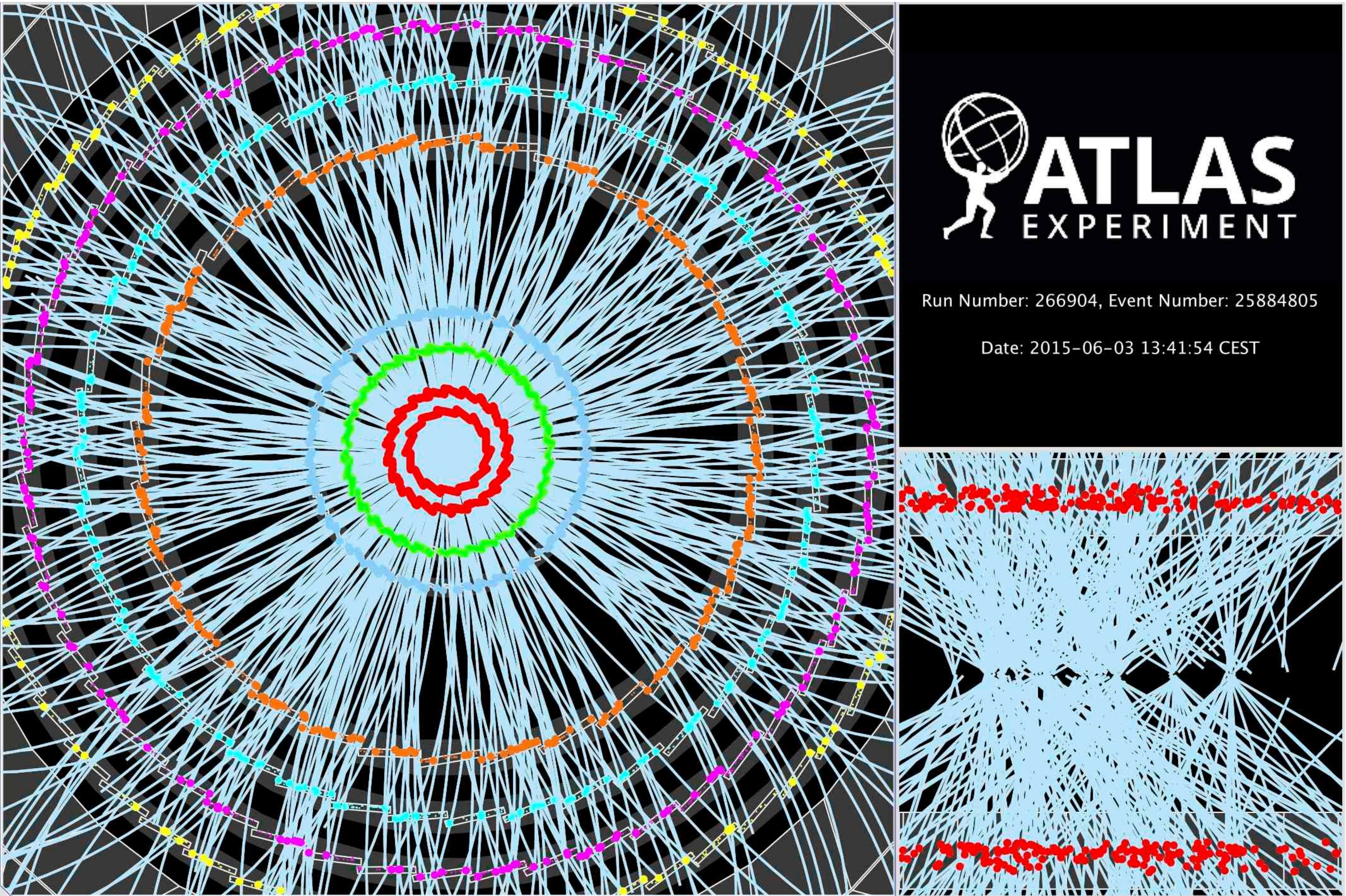
- Protons collide head-on in the LHC, which means that their momentum in the transverse plane is roughly zero

- Thanks to momentum conservation in a proton-proton collision, this means that the (transverse) momenta of all the particles coming out of a collision must sum to zero

- So, what we really want to do is measure everything that comes out of a collision
  - Any net momentum imbalance in the transverse plane could indicate missing (undetected) particles
  - We call this Missing Transverse Momentum (or, Missing ET for short)

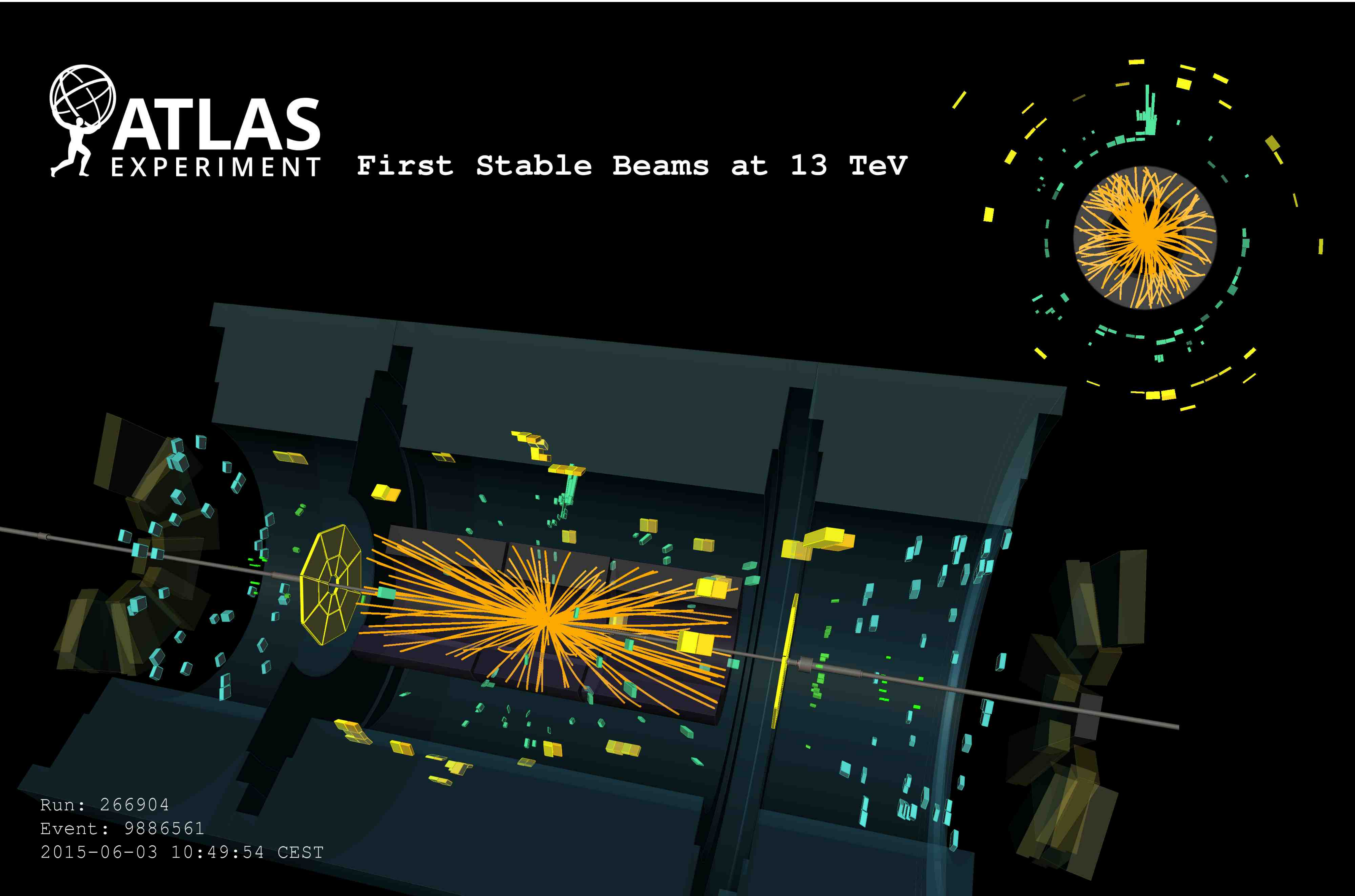
- Wait - what do I mean by "everything"

This.

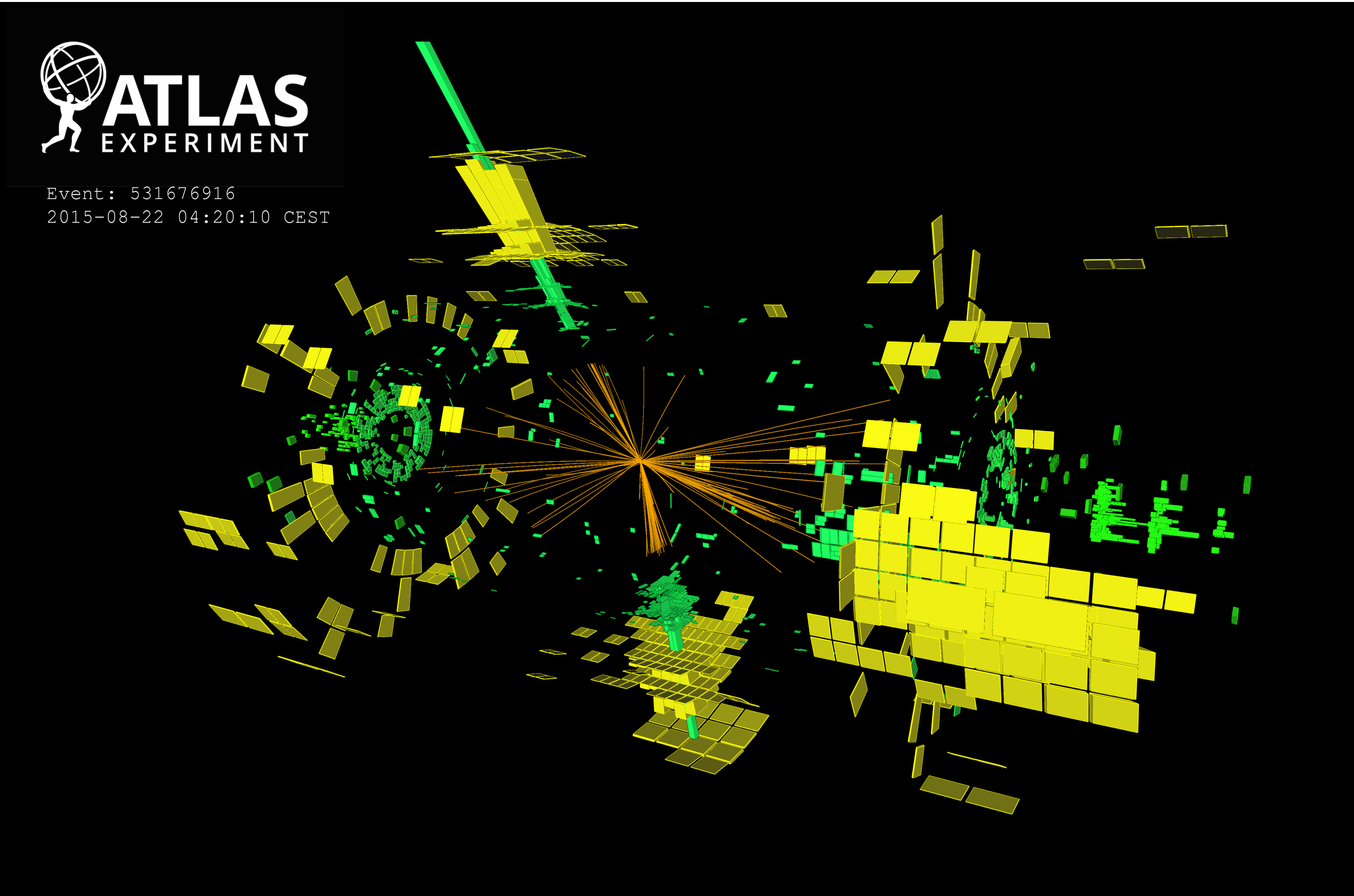


ATLAS
EXPERIMENT
Run Number: 266904, Event Number: 25884805
Date: 2015-06-03 13:41:54 CEST

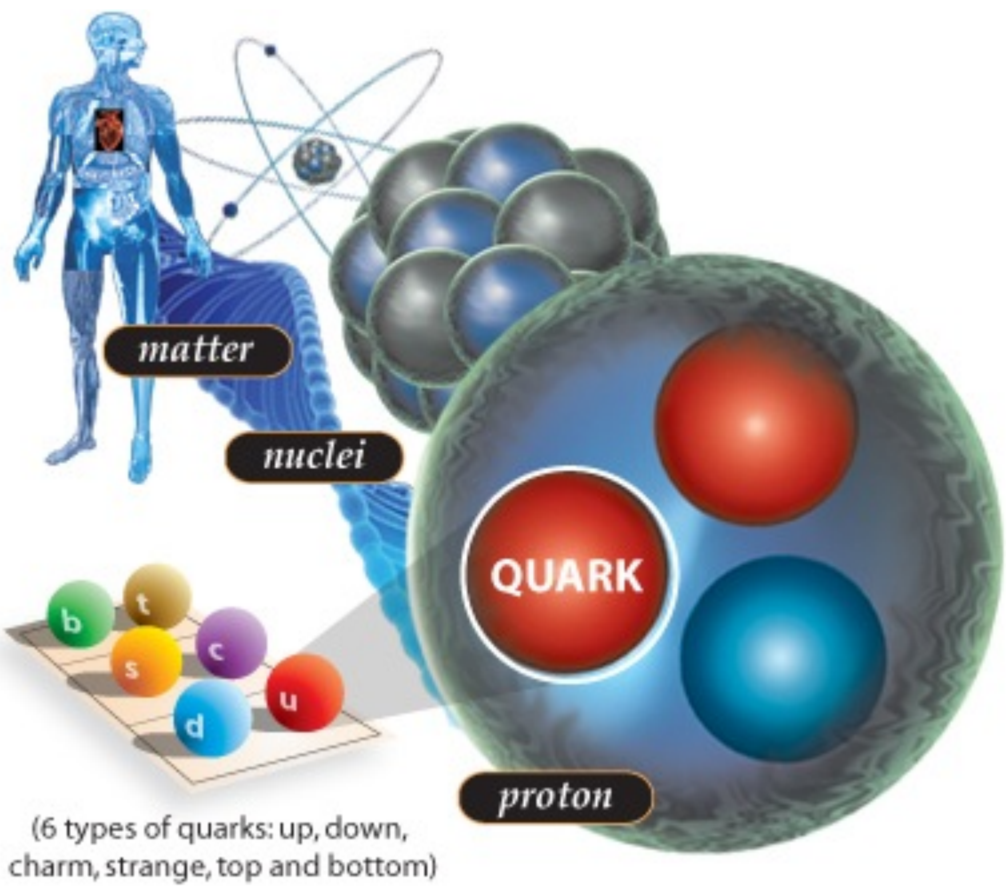
And this.

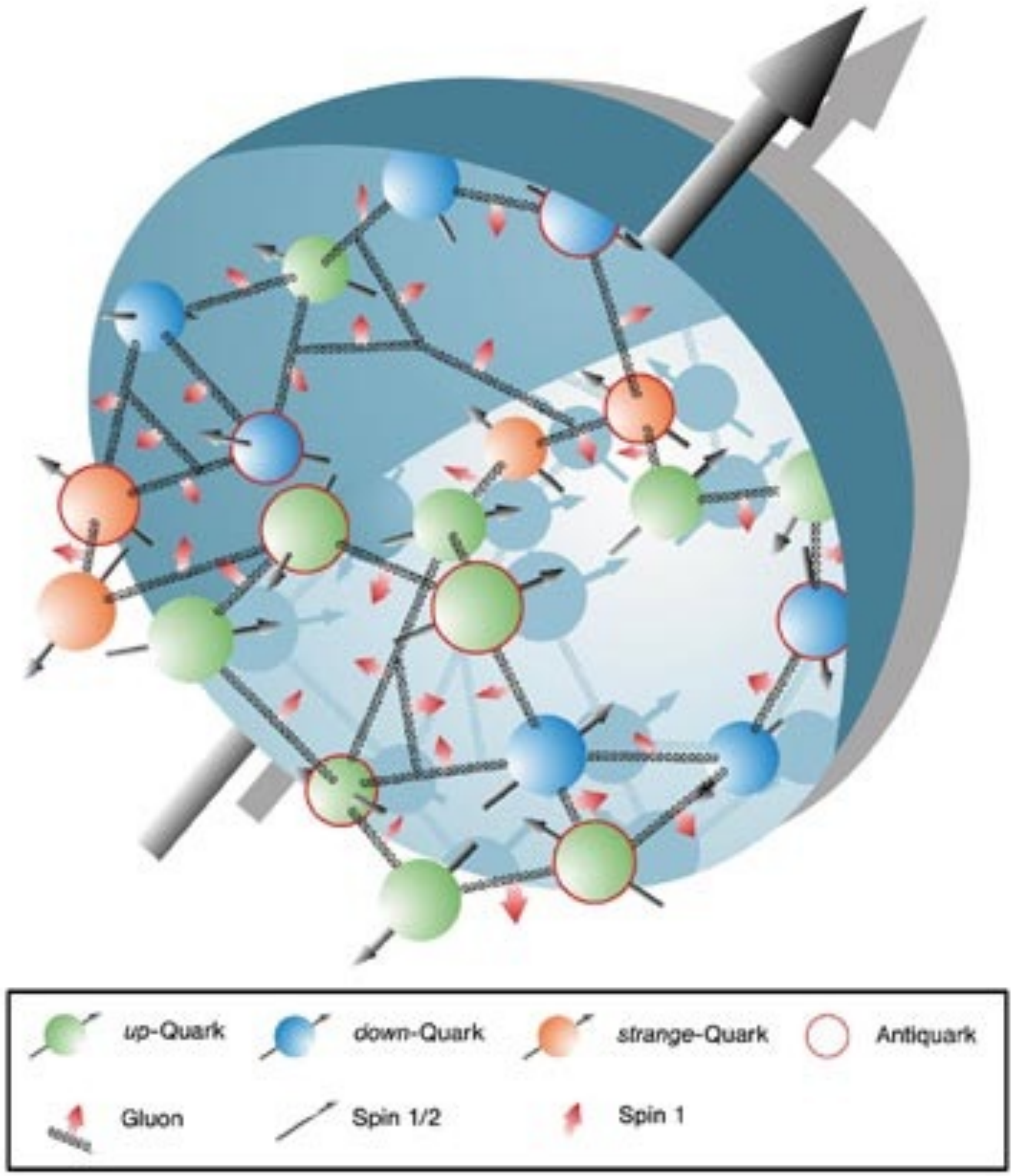

ATLAS
EXPERIMENT
First Stable Beams at 13 TeV
Run: 266904
Event: 9886561
2015-06-03 10:49:54 CEST

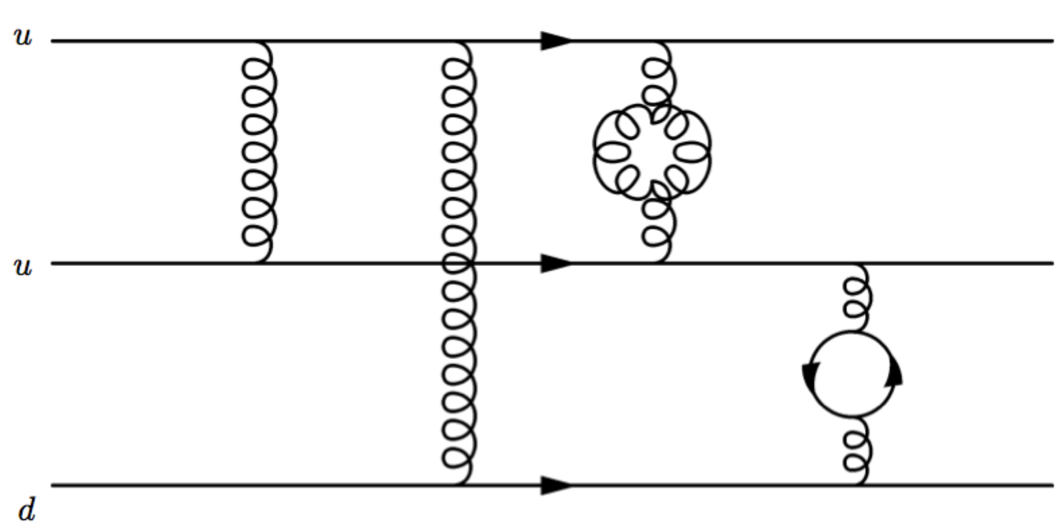
And all of this.



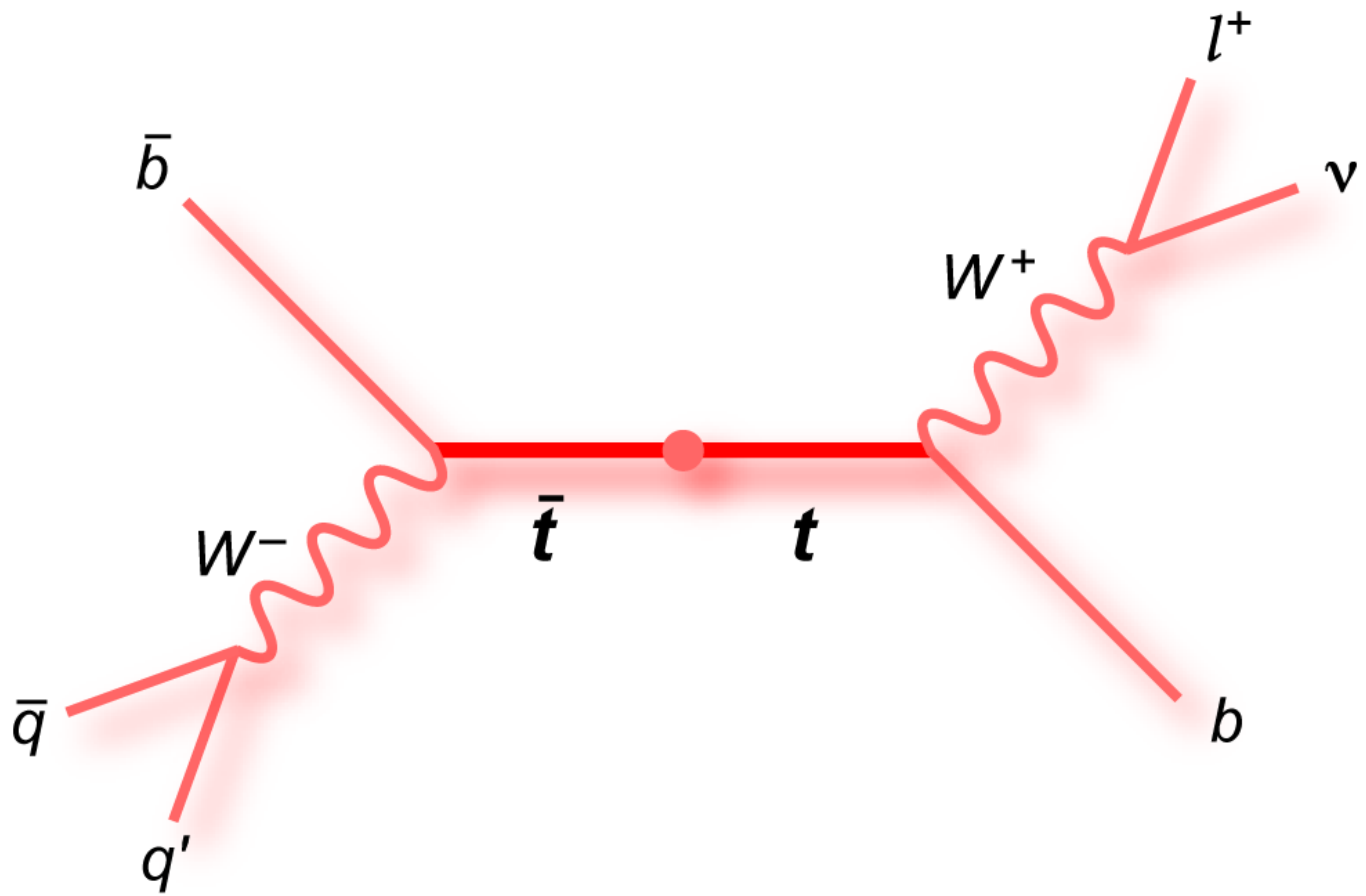
What is all that stuff?





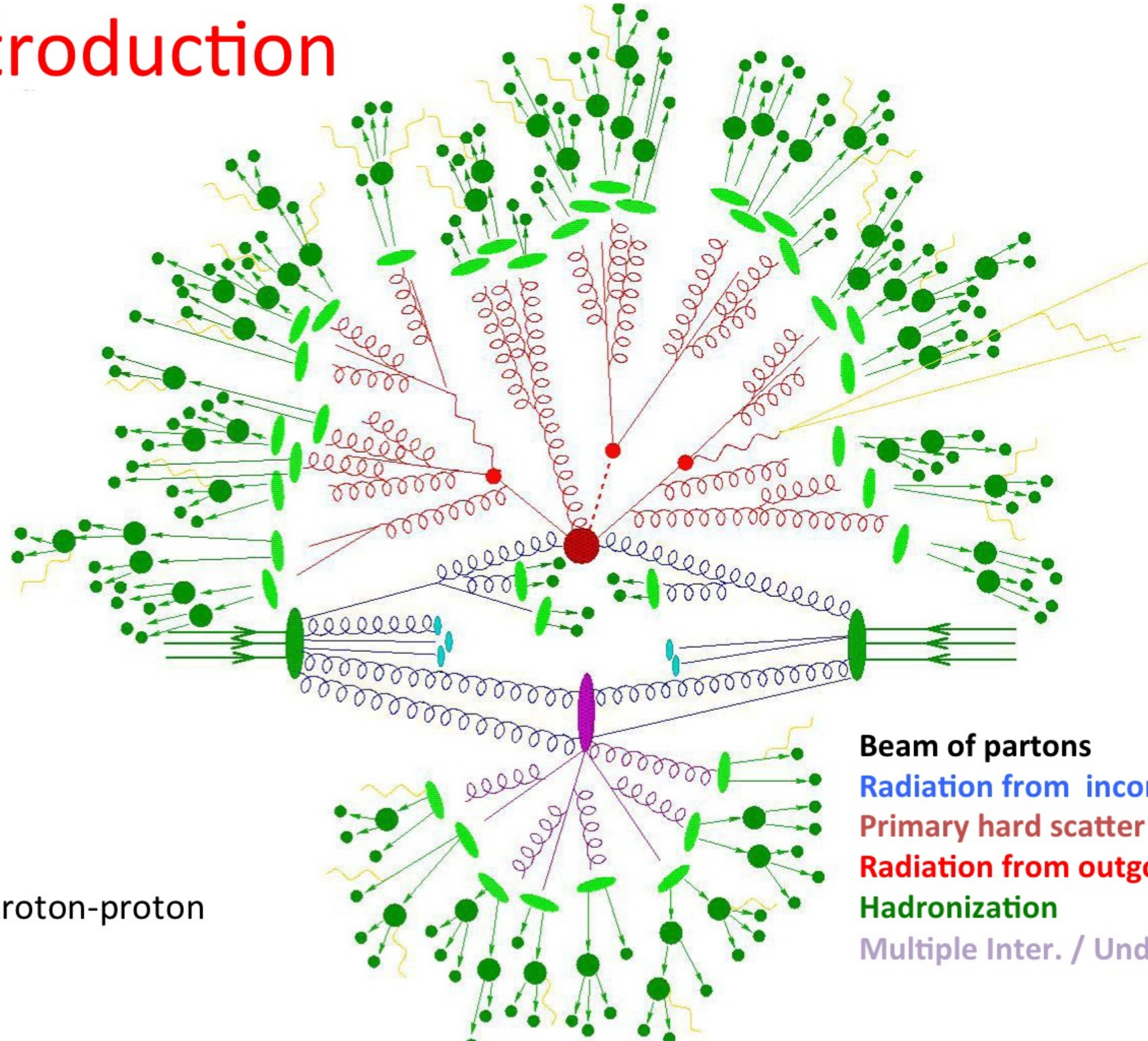


What we like to think about:



What happens in reality: image by Richard Teuscher (University of Toronto)

Introduction



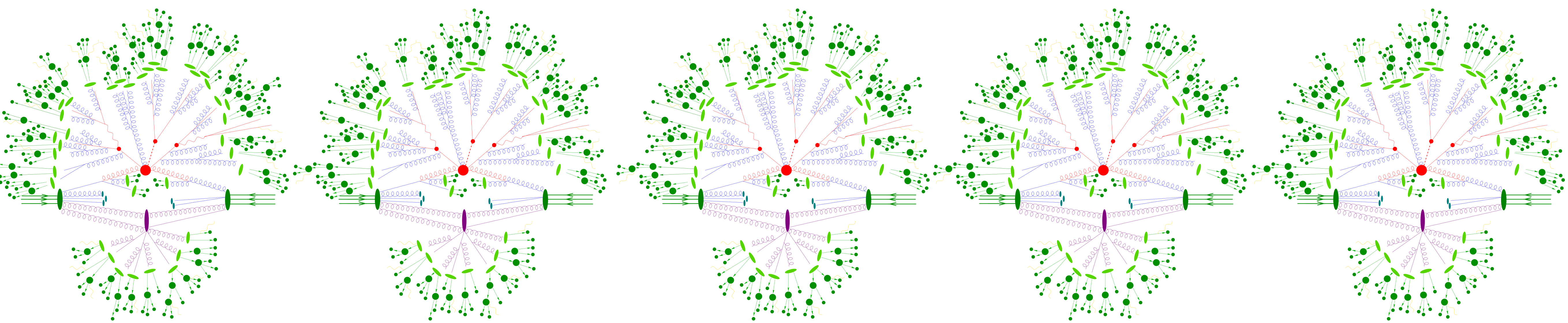
Beam of partons
Radiation from incoming partons
Primary hard scatter
Radiation from outgoing partons
Hadronization
Multiple Inter. / Underlying event

Typical proton-proton collision

8/30/11 PIC 2011, R. Teuscher IPP/Toronto 2

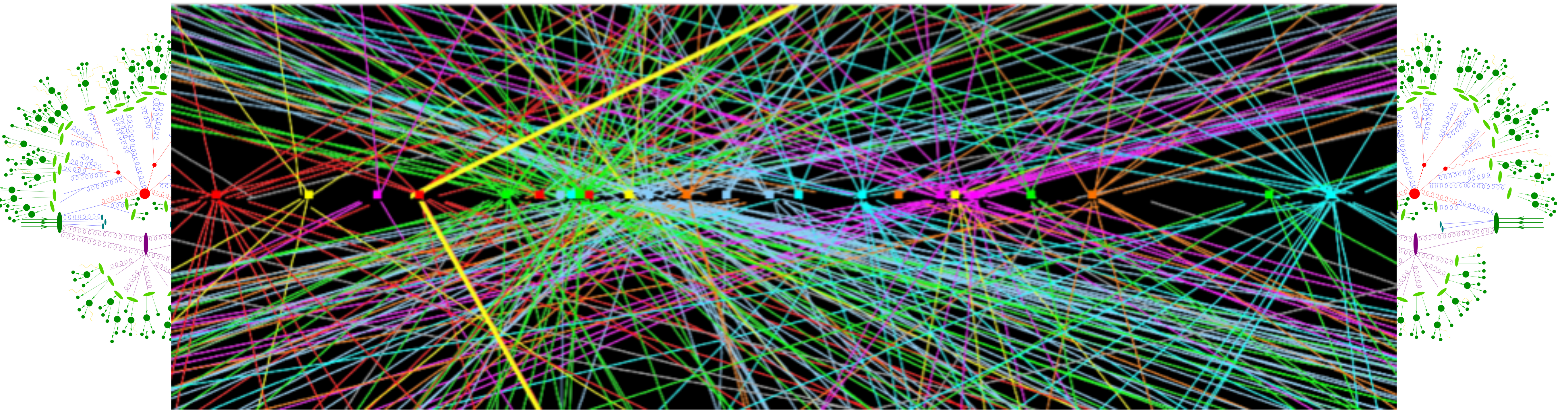
What happens more realistically in reality:

- ~10^{11} protons per bunch



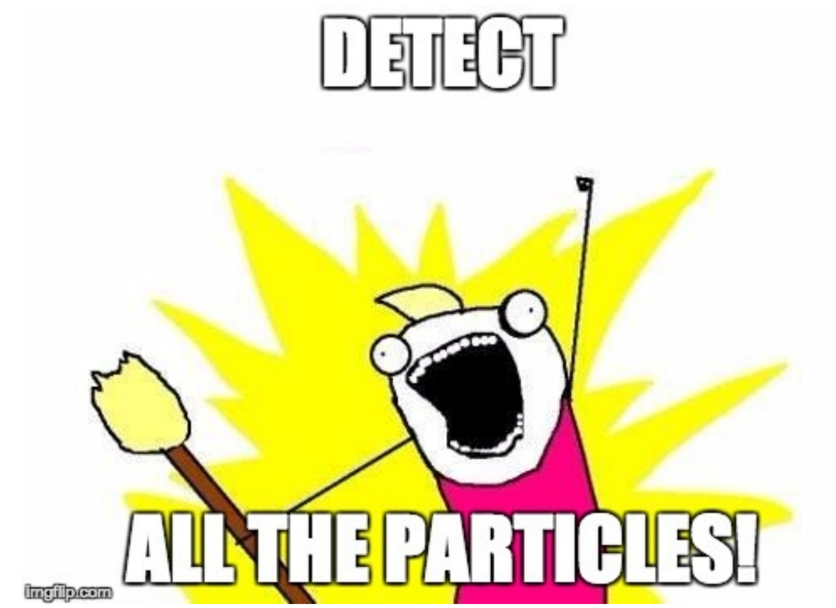
What happens more realistically in reality:

- 30 collisions on average, every 25ns

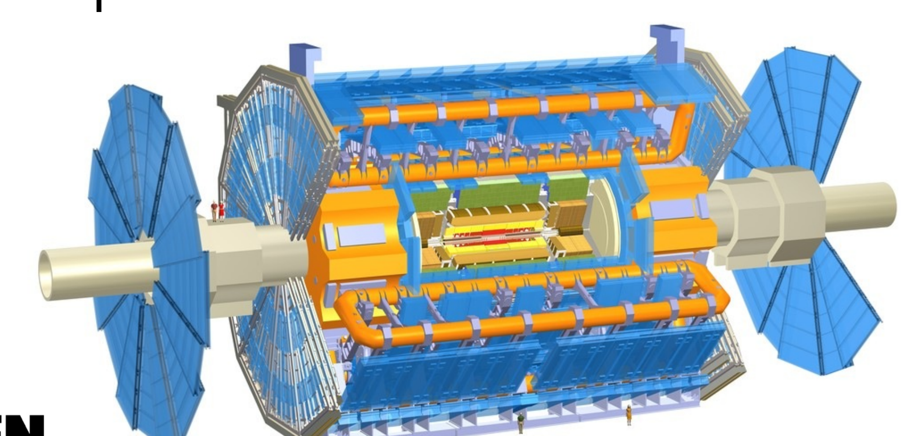


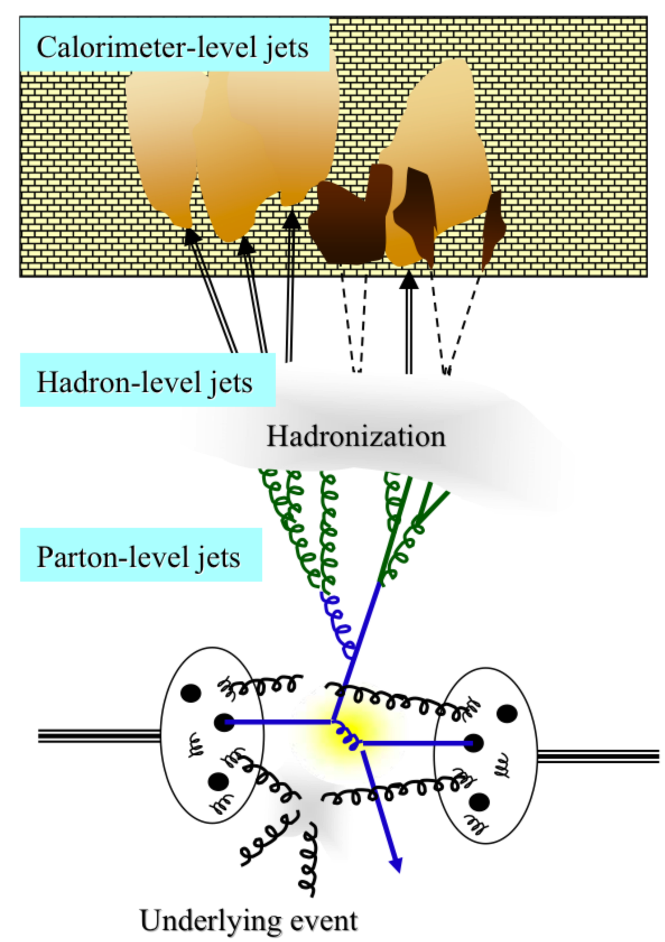
To measure "everything"

- Ideal case:
  - Detect ALL particles:
    - Total spacial coverage of the detector
    - Detect both charged and neutral particles
  - Measure their momenta and energies really well
  - Measure only the event we care about



- Reality:
  - A spherical detector is hard to build - cylindrical + endcaps
  - Use different detectors for different measurements
    - Inner detector: excellent momentum measurement of charged particles
    - Calorimeter: measures energy of charged and neutral particles
    - Muon spectrometer: better muon momentum measurements
  - Particle ID provides us with better measurements





Identifying Particles

- What are the quantities we need to measure to be able to distinguish between the different types of particles?

electrons (and positrons)
photons
muons (and antimuons)
charged hadrons (eg protons)
neutral hadrons (eg neutrons)

Identifying Particles

- What are the quantities we need to measure to be able to distinguish between the different types of particles?
  - Mass
  - Momentum
  - Energy
  - Charge
  - Lifetime*
  - Spin*
  - etc…

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$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

$$\beta = \frac{v}{c}; \quad \gamma = \frac{1}{\sqrt{1 - \beta}}$$

We can identify particles based on a combined measurement of:

$$(E, \vec{p}, Q)$$

$$(\vec{p}, \beta, Q)$$

$$(\vec{p}, m, Q)$$

eV = $1.6\text{x}10^{-19}$ J
c = 299 792 458 m/s
e = $1.602\text{x}10^{-19}$ C

Identifying Particles

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$$E^2 = \vec{p}^{\,2}c^2 + m^2c^4$$

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Okay! So, how do we make these measurements?

We can identify particles based on a combined measurement of:

$$(E, \vec{p}, Q)$$

$$(\vec{p}, \beta, Q)$$

$$(\vec{p}, m, Q)$$

eV = 1.6x10⁻19 J
c = 299 792 458 m/s
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Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

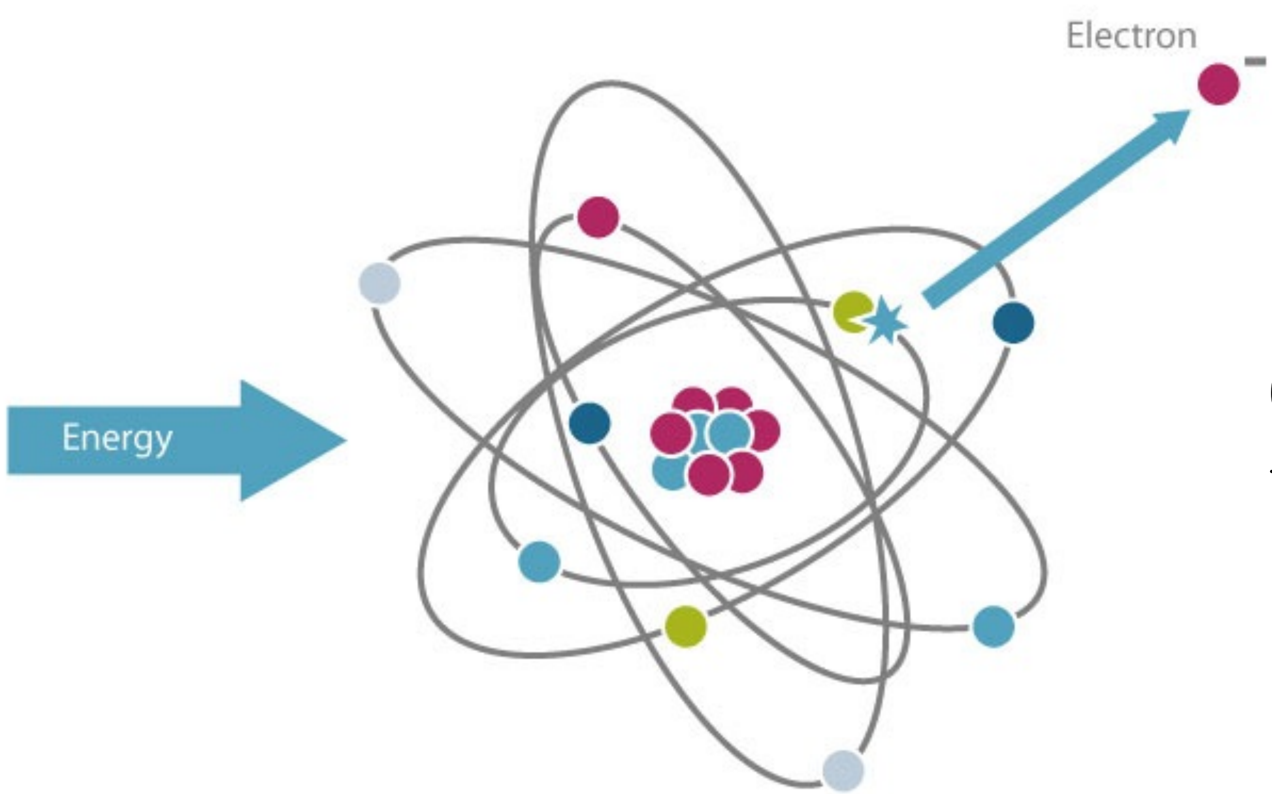
- Some examples of the ways particles interact:

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Ionization

Gives off charge!



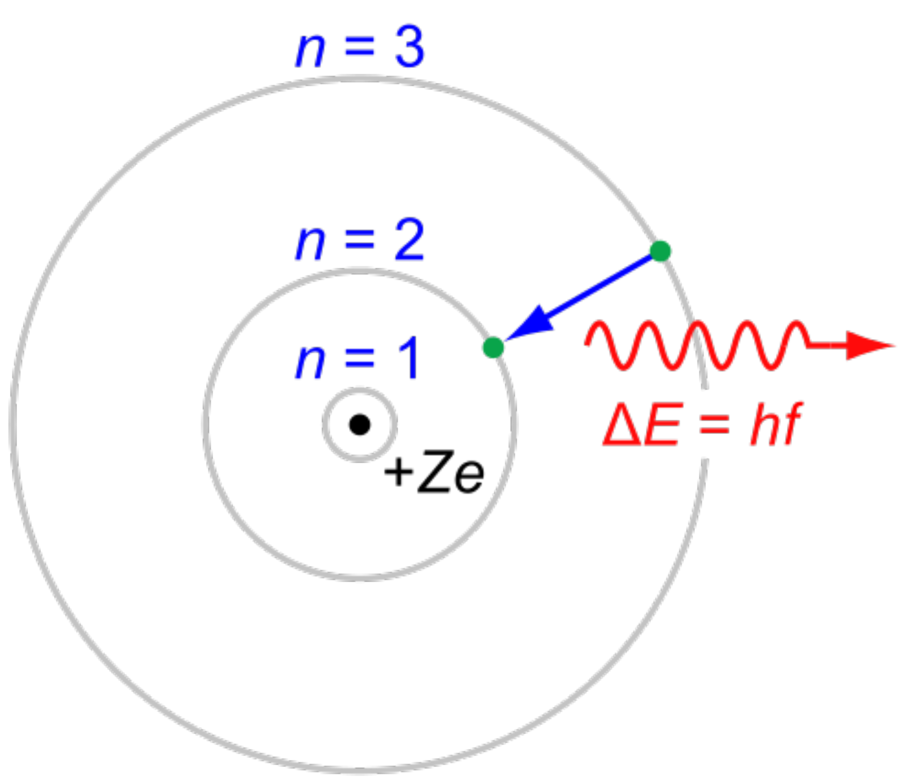
Charged particle "knocks" an electron free, leaving the atom ionised

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact
  - Photoemission

Gives off light!



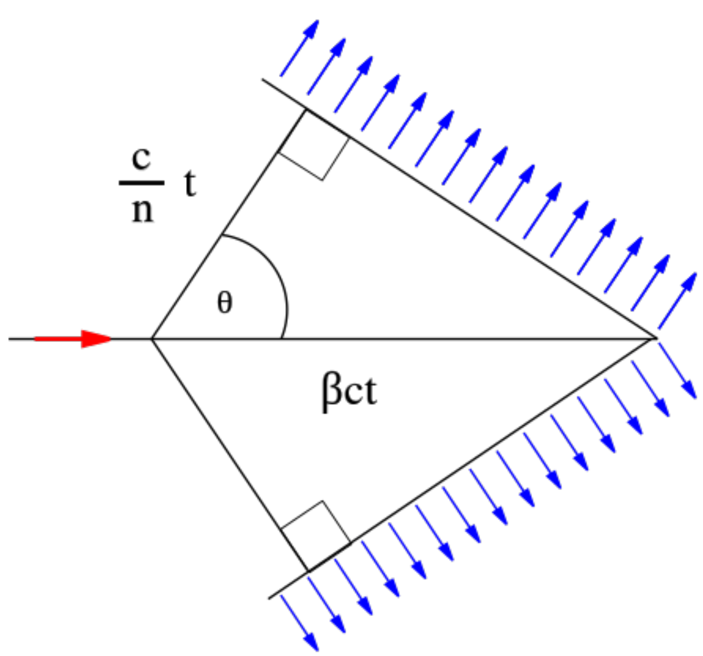
An electron in an atom can gain energy from a particle and be excited into a higher orbit. When it returns to its ground state it emits a photon.

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

Gives off light!

- Some examples of the ways particles interact
  - Cerenkov radiation



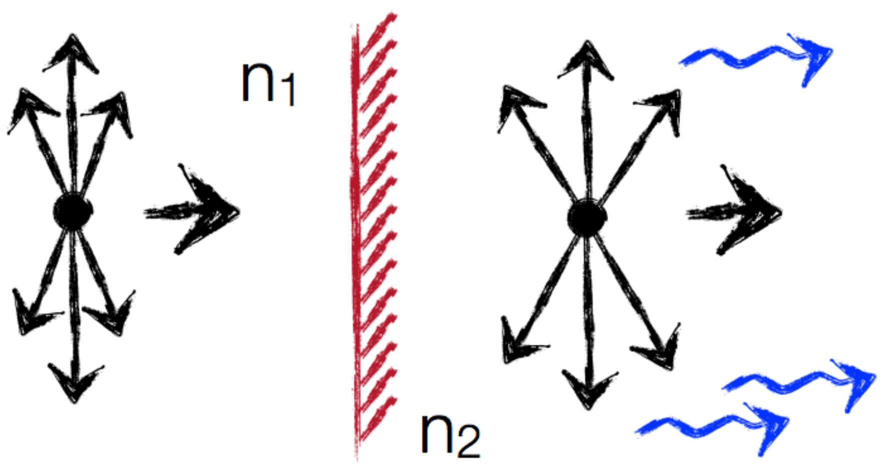
Light slows down in matter, depending on its refractive index. But a particle could move faster than the speed of light, in which case it will give off Cerenkov radiation (much like the sonic boom when breaking the sound barrier)

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Transition Radiation

Gives off light!



Transition radiation occurs if a relativistic particle passes the boundary between two media with different refraction indices

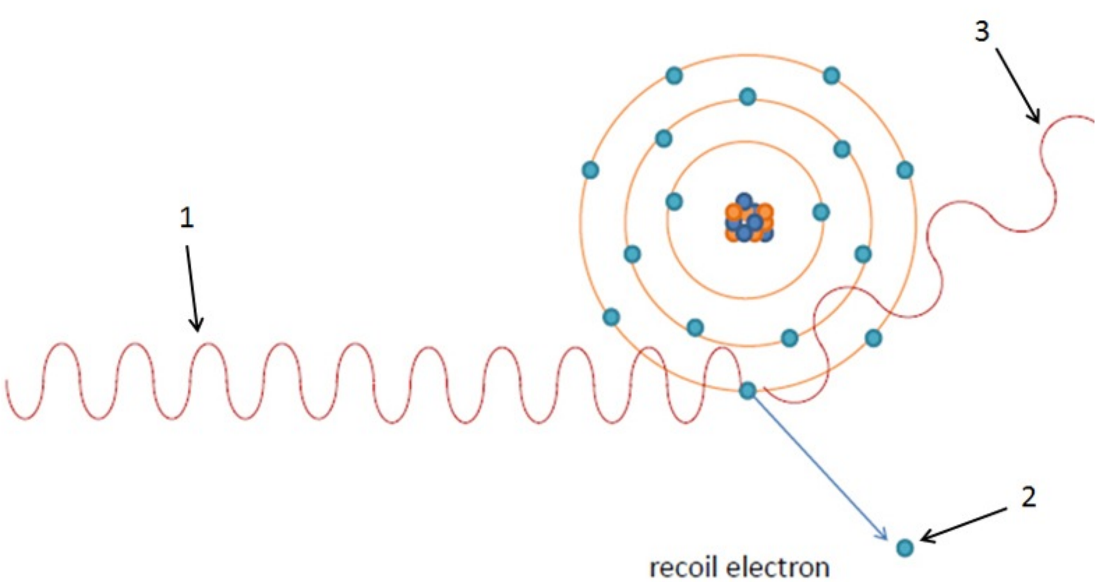
Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Compton Scattering

Gives off charge!

Compton scattering



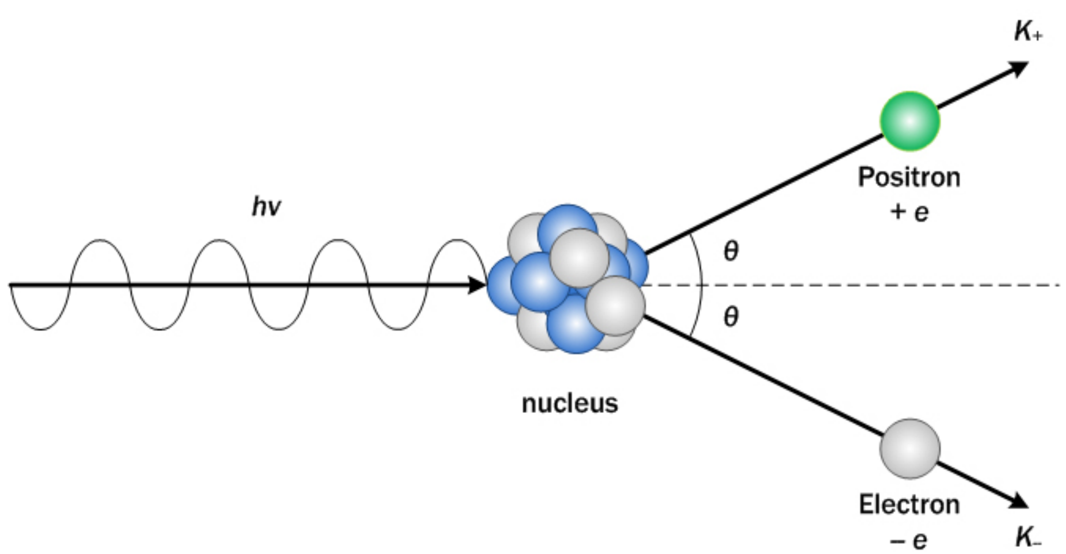
Photon ionises an atom by giving energy to an electron. Photon moves on with reduced energy

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Pair production

Gives off charge!



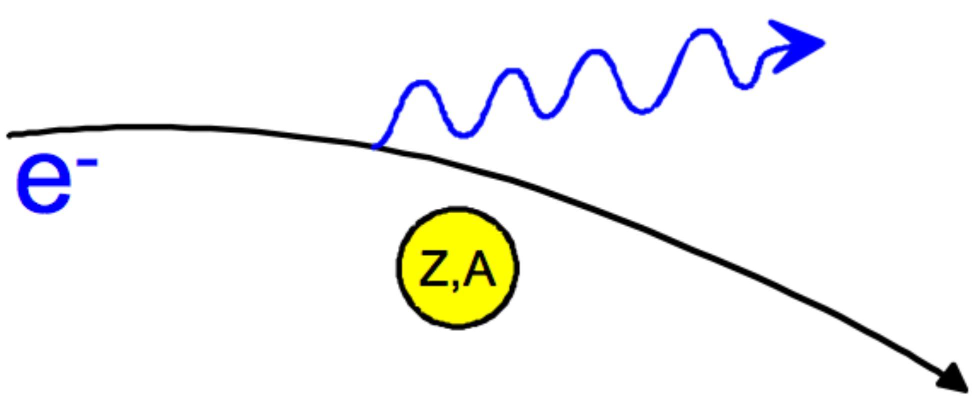
A photon interacting with a nucleus can convert into matter-antimatter pairs

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

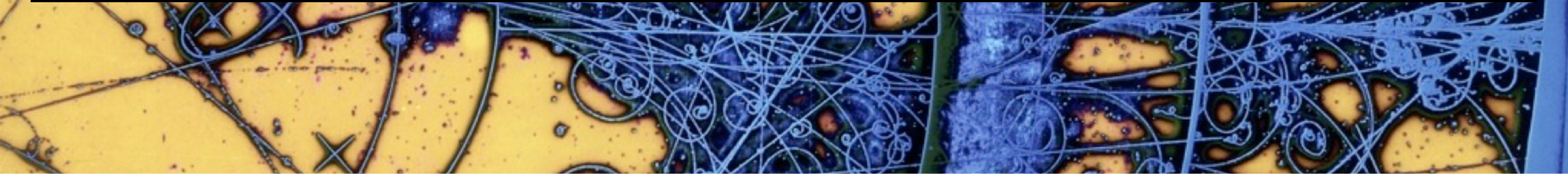
- Some examples of the ways particles interact:
  - Bremsstrahlung

Gives off light!



As an electron gets bent around a nucleus it emits a photon.

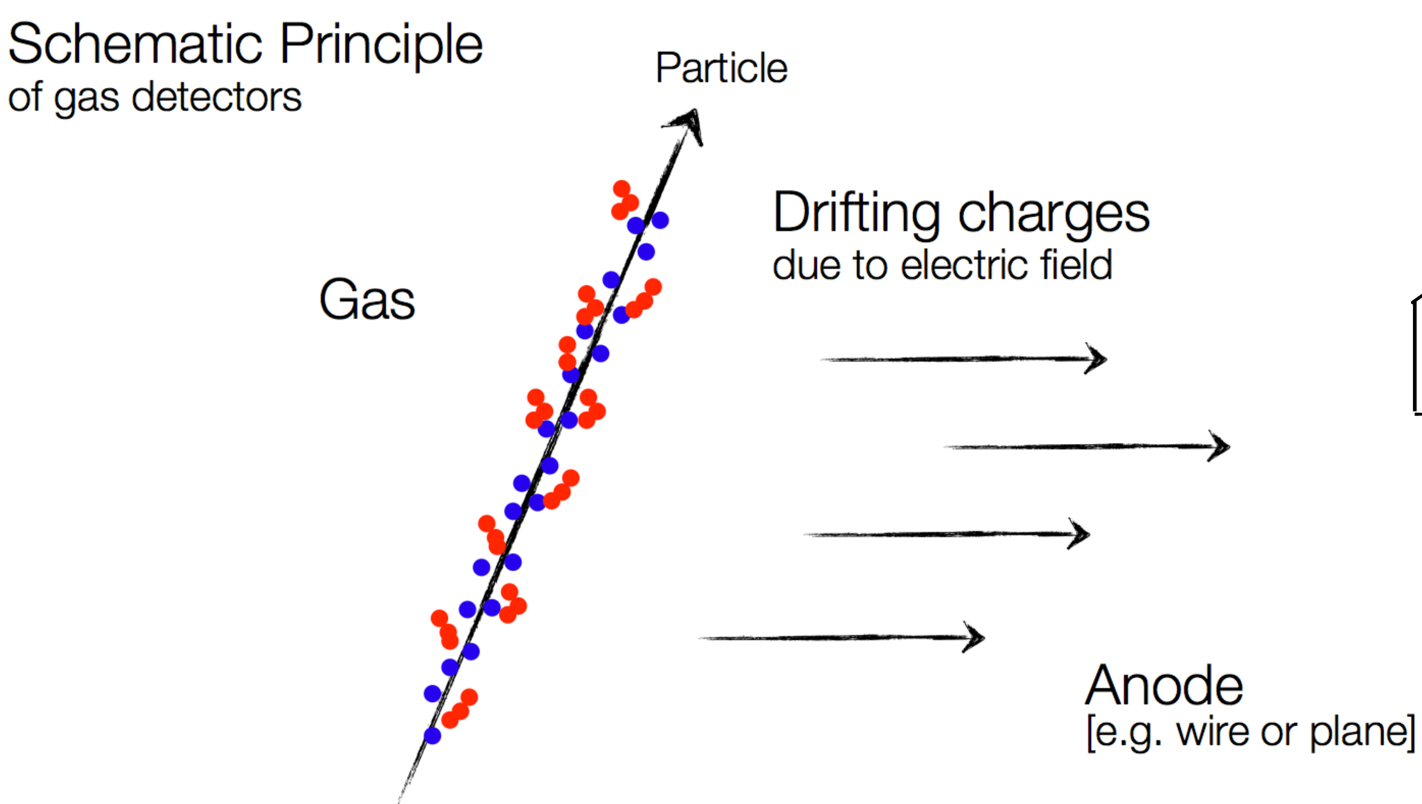
Interactions of Particles with Matter

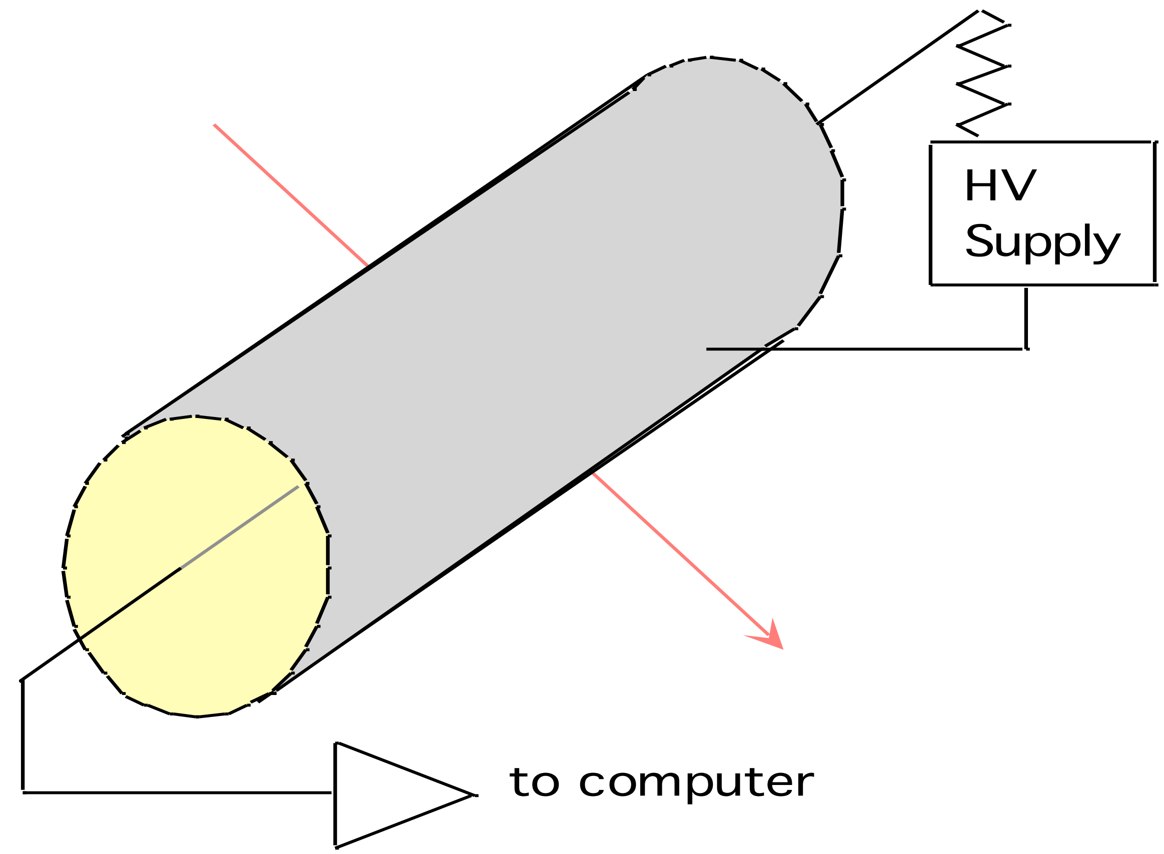


- In order to detect a particle it must interact with the material of the detector.
- Most particle detectors actually detect the light or electric charge the particle leaves behind.
- BUT: The properties of the particle may be different after we have detected it:
  - Lower Energy
  - Different Momentum
  - Completely Stopped
- We can tell what kind of particle it is by how it changes as it goes through the detector, and what it leaves behind (eg. light, electric charge).
  - We can also build our detectors in a particular way, "tuning" them to detect a particular type of particle while ignoring another

Let's Use Ionization to Build a Particle Detector!

- Take a tube
- Fill it with a gas: (noble gases are more likely to ionize than others. Let's use Argon)
- Insert a conducting surface to make an intense electric field: The field at the surface of a small wire gets extremely high, so use tiny wires
- Attach electronics and apply high voltage
- And we're done!

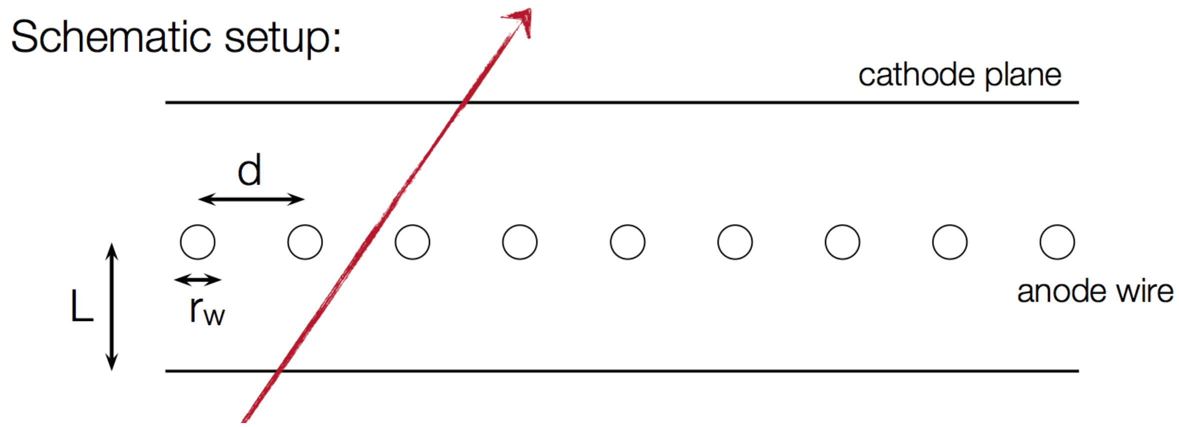


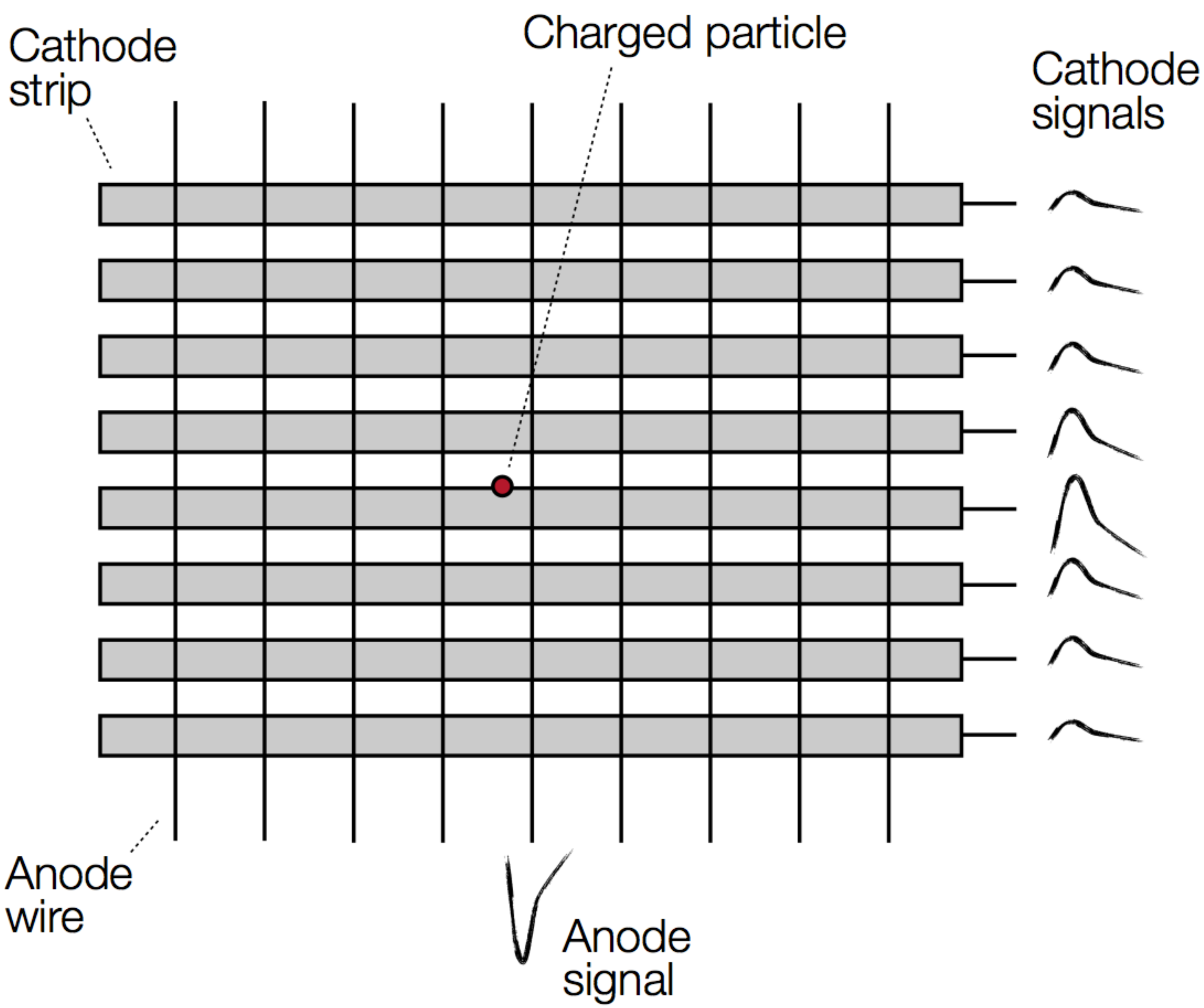


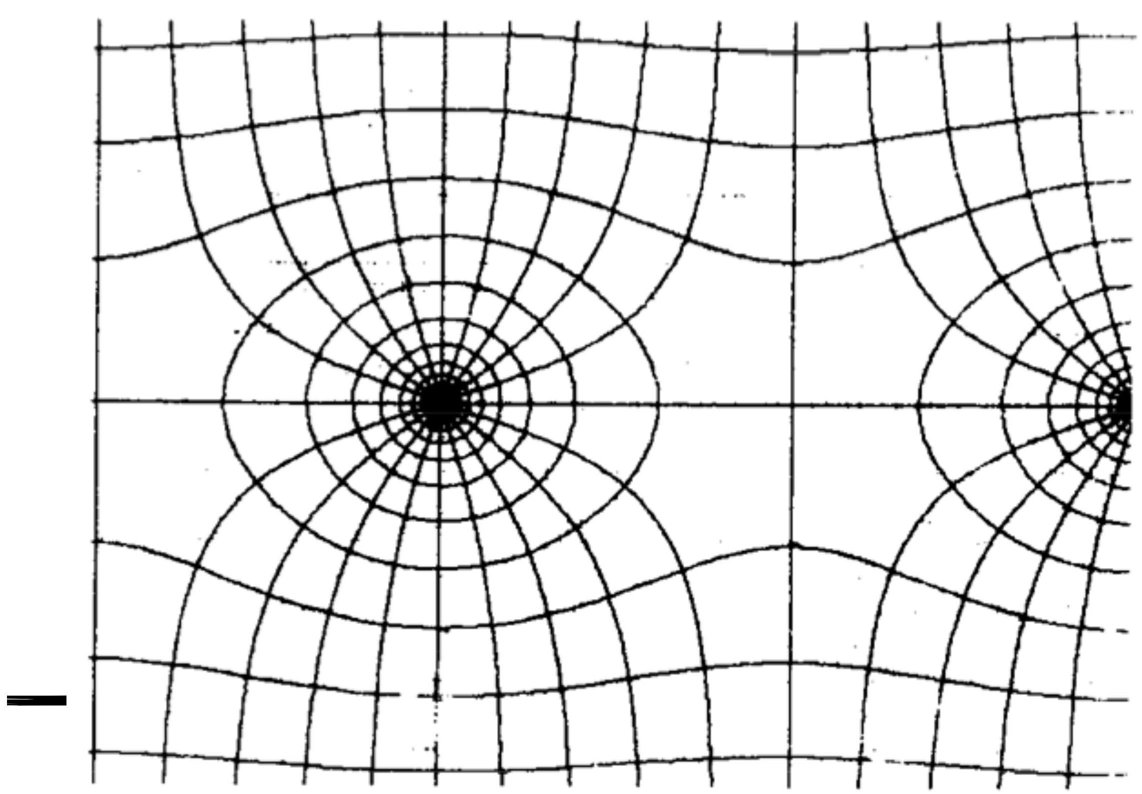
How can I make this more accurate?

Multi Wire Chamber

- We can use many wires to get a more accurate position measurement

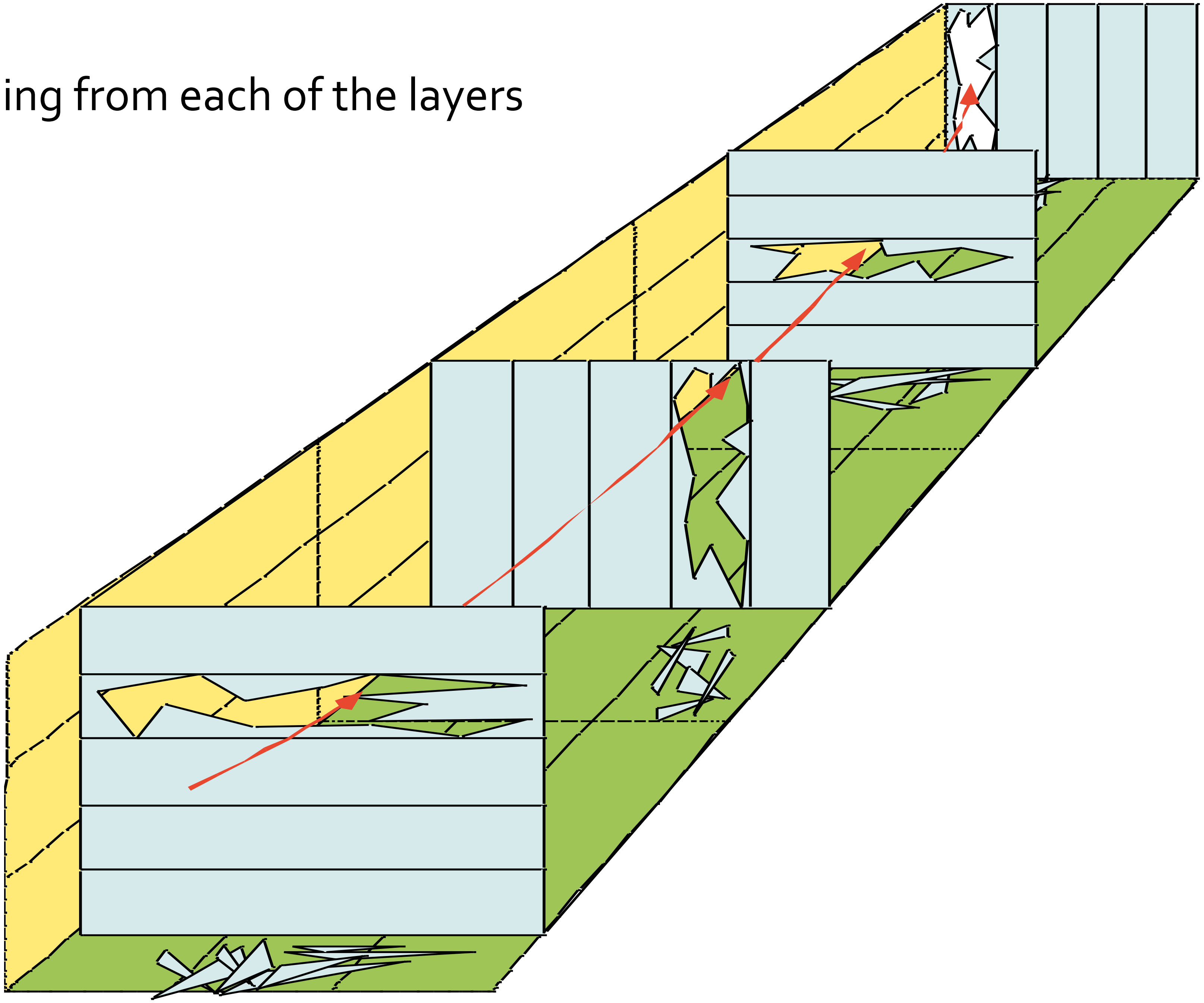






Multi Wire Chamber

- We can also layer the chambers longitudinally along the particle direction
- If we make several measurements of track position along the length of the track, we can figure out the whole trajectory.
  - We can also time the signals coming from each of the layers
- Basic idea of a tracking detector!

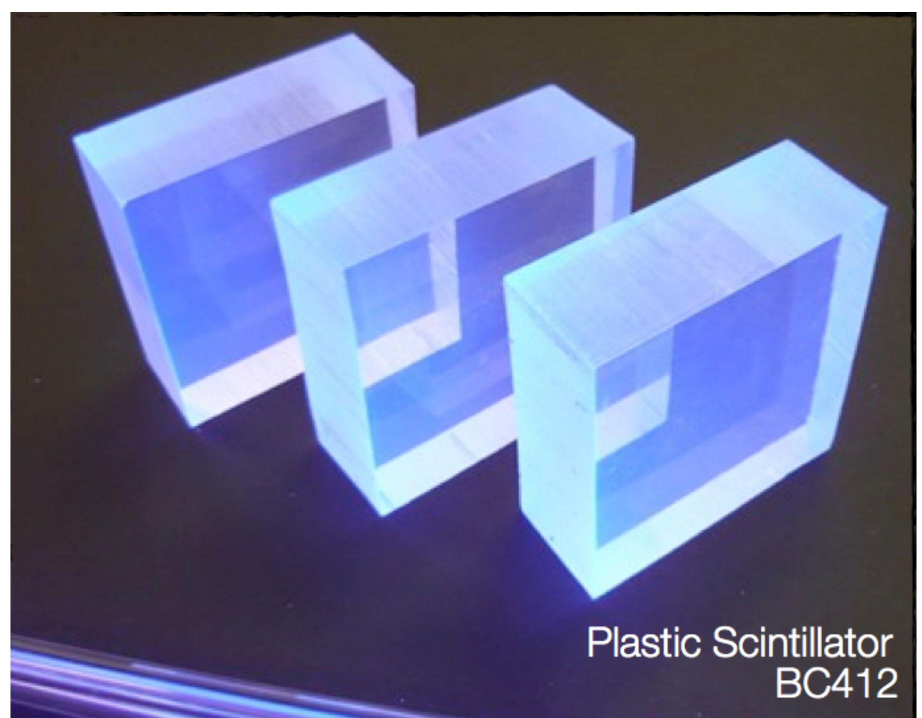


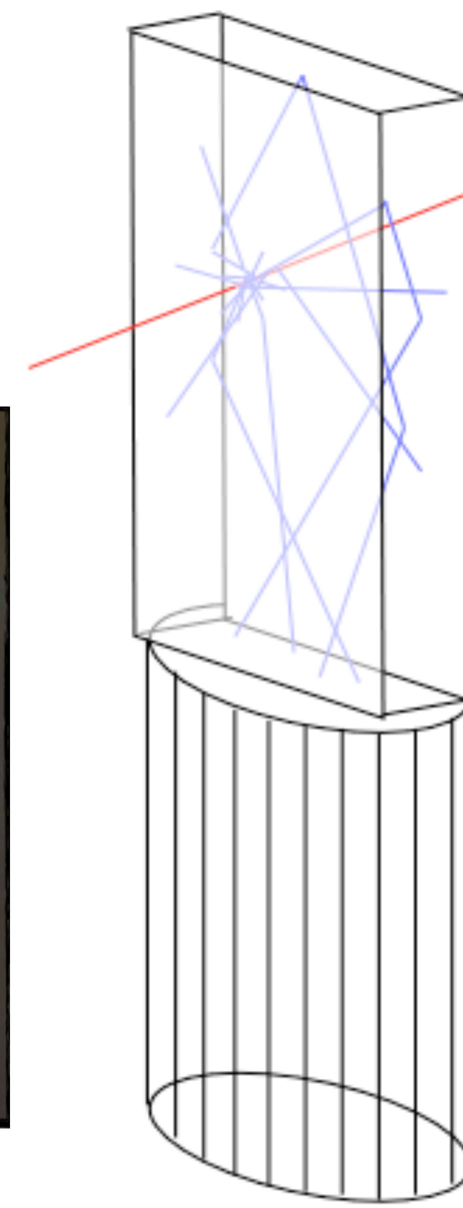
What about using the produced light?

- Many materials radiate light, but most also absorb that light again so that it never gets out.

- However, a type of material called a scintillator produces light that does not get reabsorbed

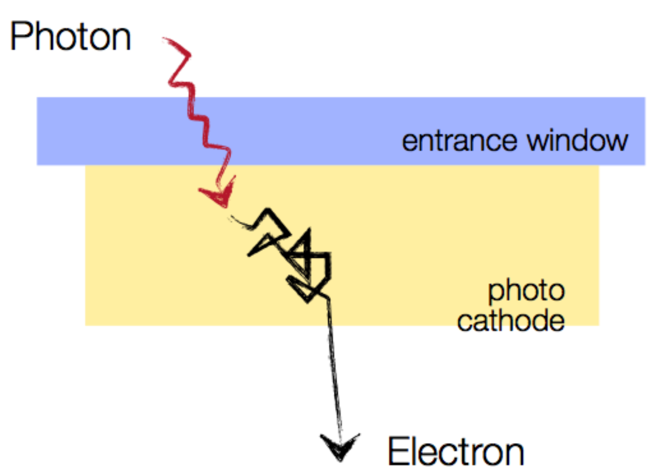
- Scintillators have
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination

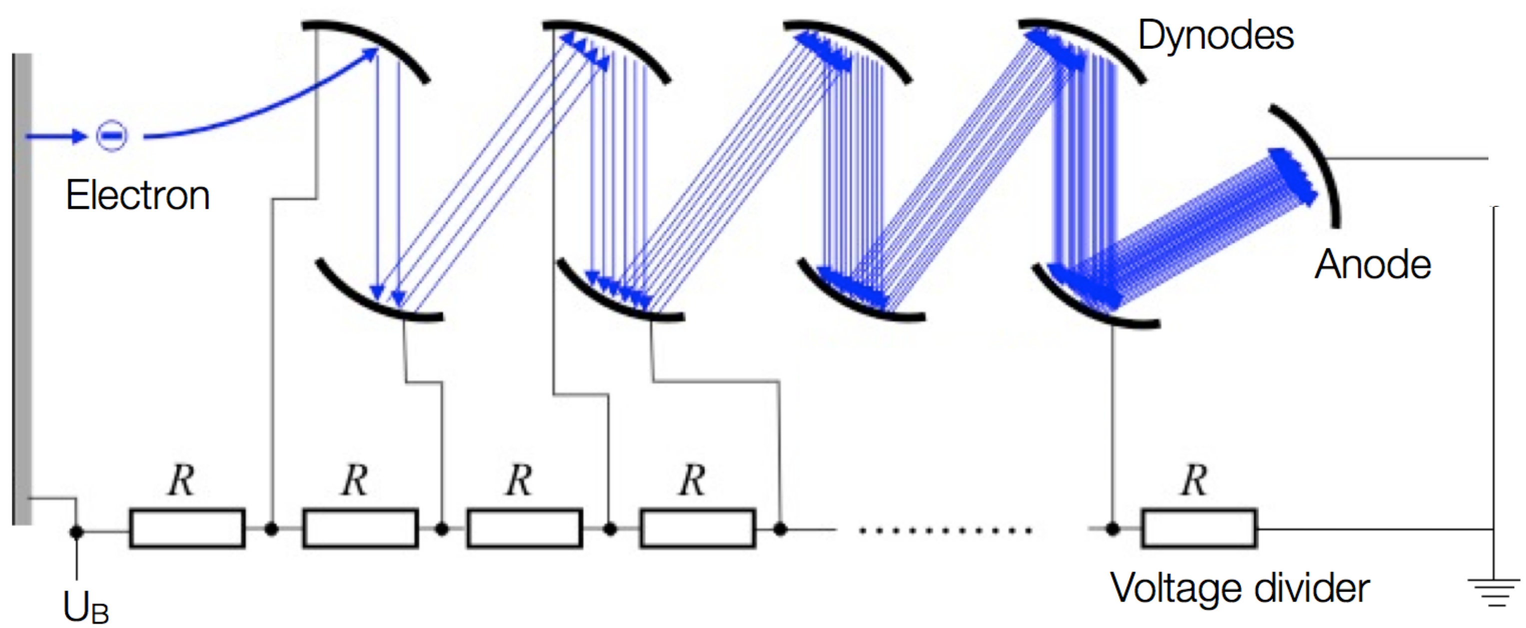


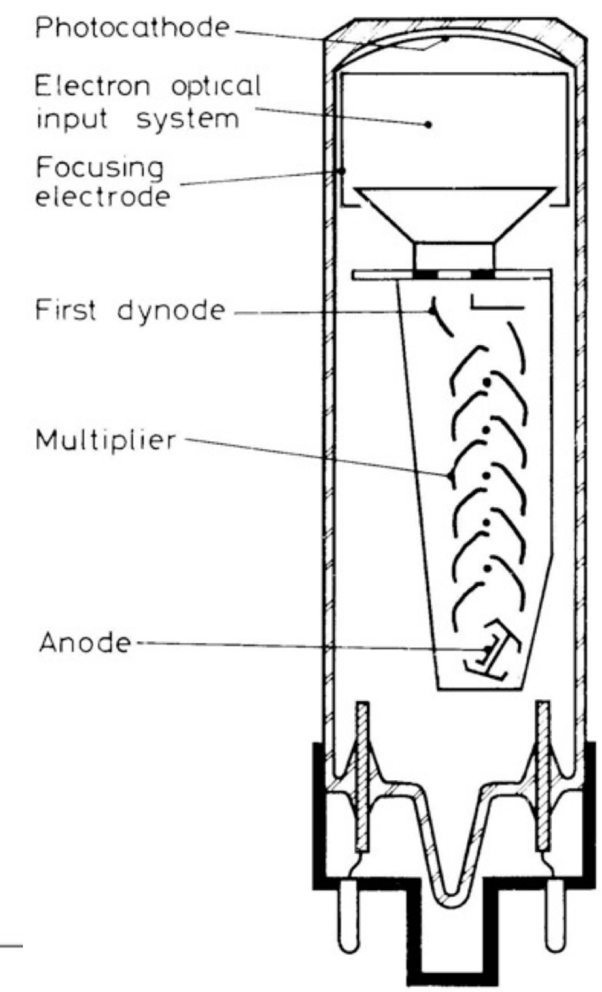


- Photomultipliers convert light into a detectable electronic signal
  - Use photo-electric effect to convert photons to photo-electrons (p.e.)

- Typical PMT Gain: > 10^6
  - PMT can "see" single photons!





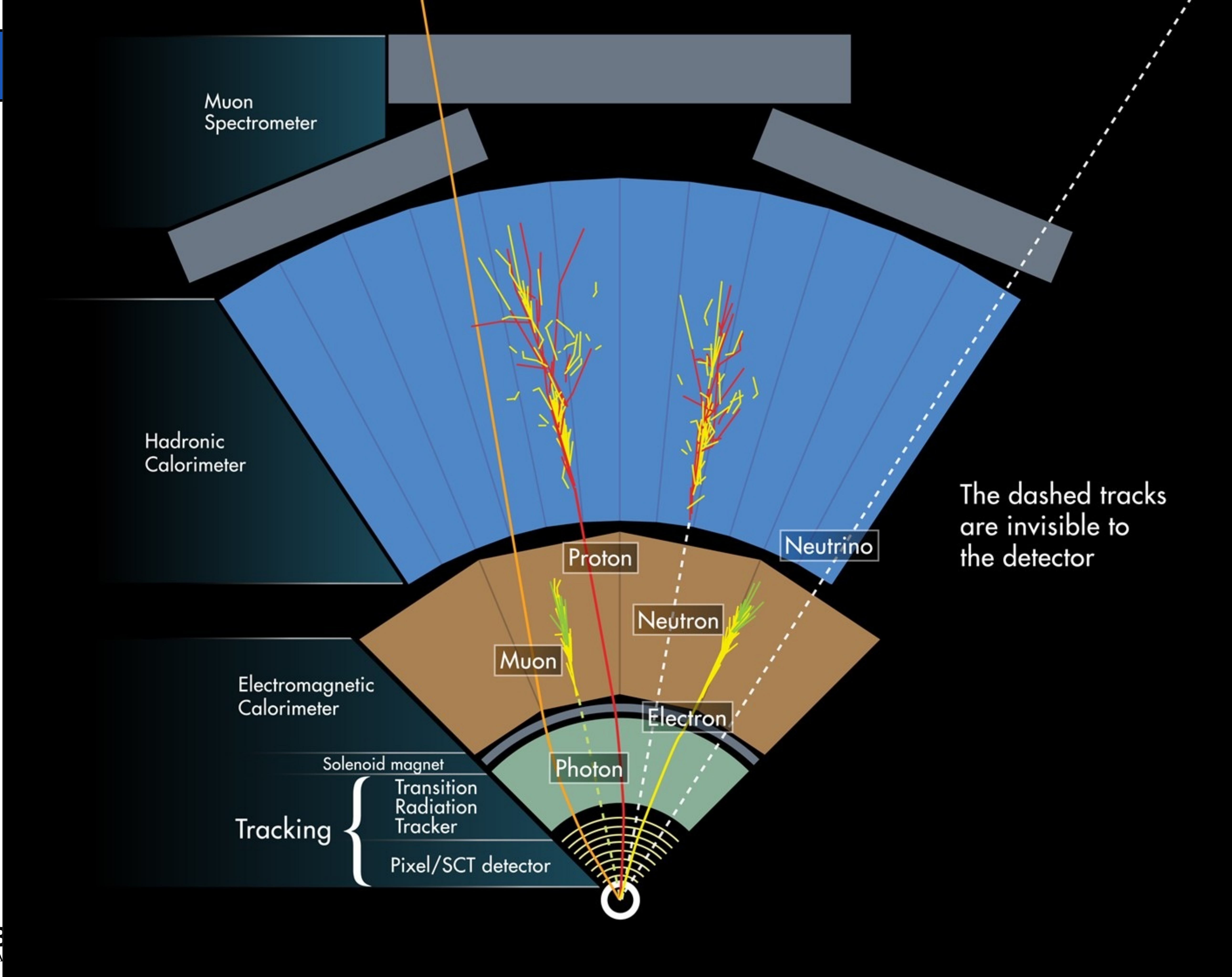


Calorimetry

- If we completely stop a particle (eg in a scintillator) then all of its energy will be transferred into light
  - This is called a calorimeter

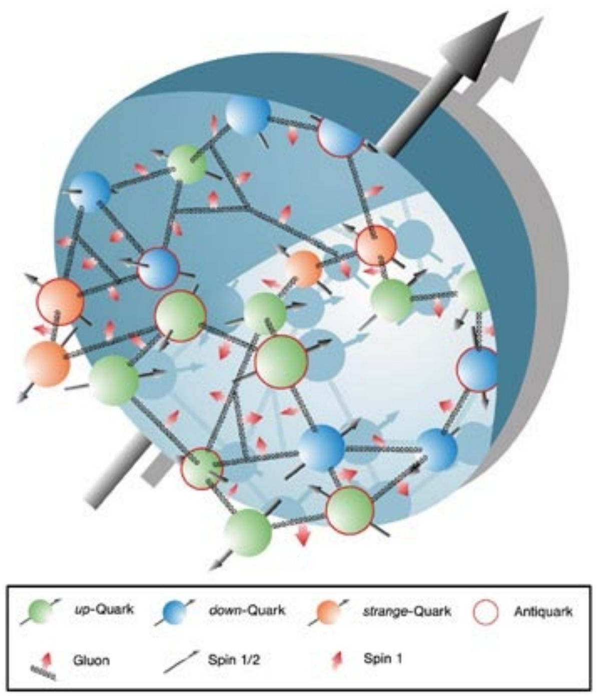
- Operating principle:
    - Incoming particle initiates particle shower …
      Shower Composition and shower dimensions depend on particle type and detector material …
  - Energy deposited in form of: heat, ionization, excitation of atoms, Cherenkov light …

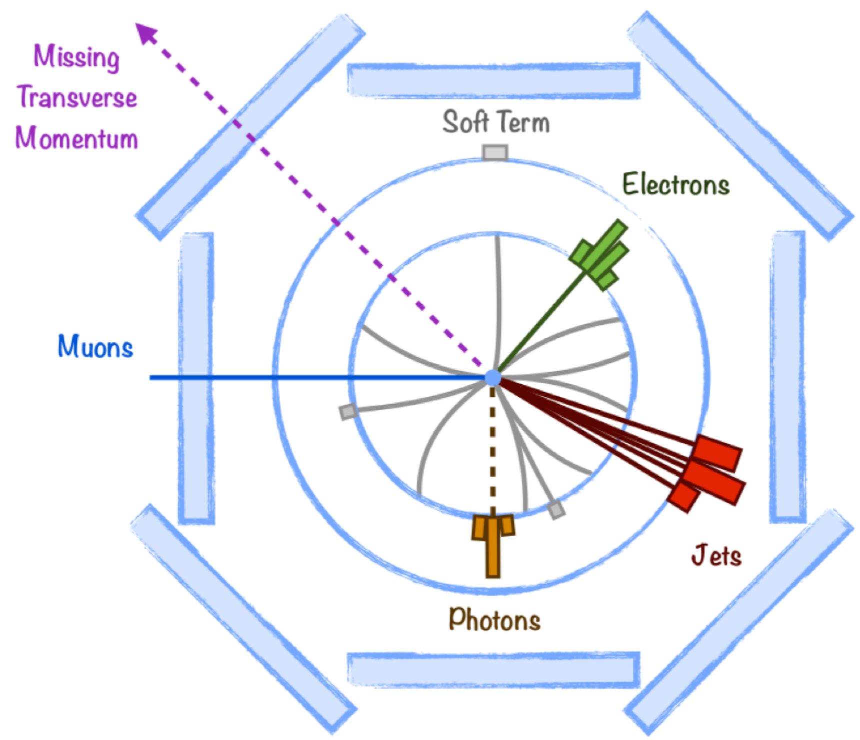
- Calorimeters can measure the energy of both charged and neutral particles, if they interact via either electromagnetic or strong forces
  - different EM and hadronic calorimeters


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

Missing Transverse Momentum in ATLAS (ETmiss)

- ETmiss is defined as the momentum imbalance in the plane transverse to the beam axis
  - Soft term: traditionally all the left over, unassociated energy in the calorimeter



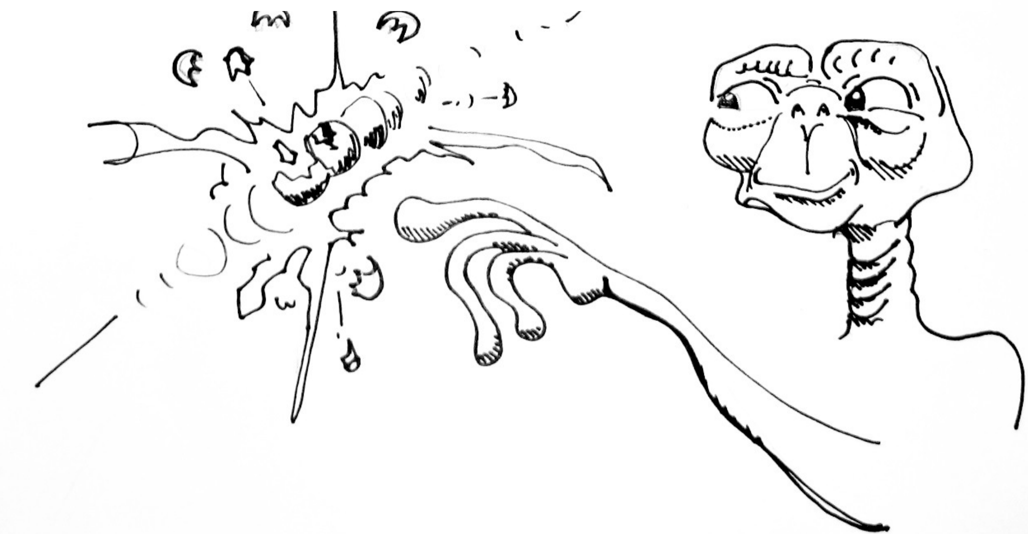


Advantage: provides a complete measurement of the magnitude of the missing energy from all events (vertices)

Disadvantage: sensitive to pileup

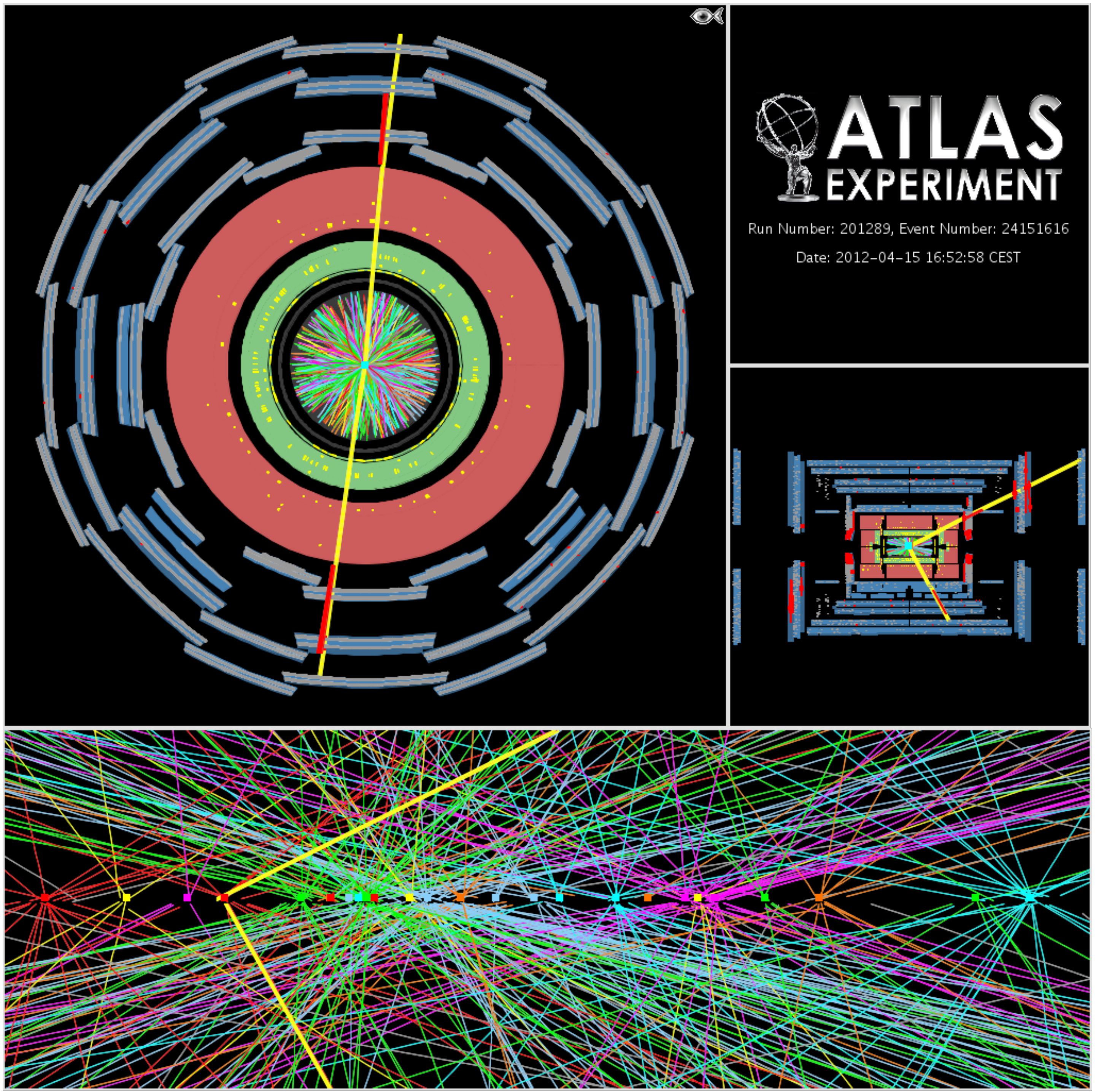
$$E_{\mathbf{x(y)}}^{\mathbf{miss}} = E_{\mathbf{x(y)}}^{\mathbf{miss},e} + E_{\mathbf{x(y)}}^{\mathbf{miss},\gamma} + E_{\mathbf{x(y)}}^{\mathbf{miss},\tau} + E_{\mathbf{x(y)}}^{\mathbf{miss,jet}} + E_{\mathbf{x(y)}}^{\mathbf{miss},\mu} + E_{\mathbf{x(y)}}^{\mathbf{miss,SoftTerm}}$$

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{\left(E_x^{\mathrm{miss}}\right)^2 + \left(E_y^{\mathrm{miss}}\right)^2}$$

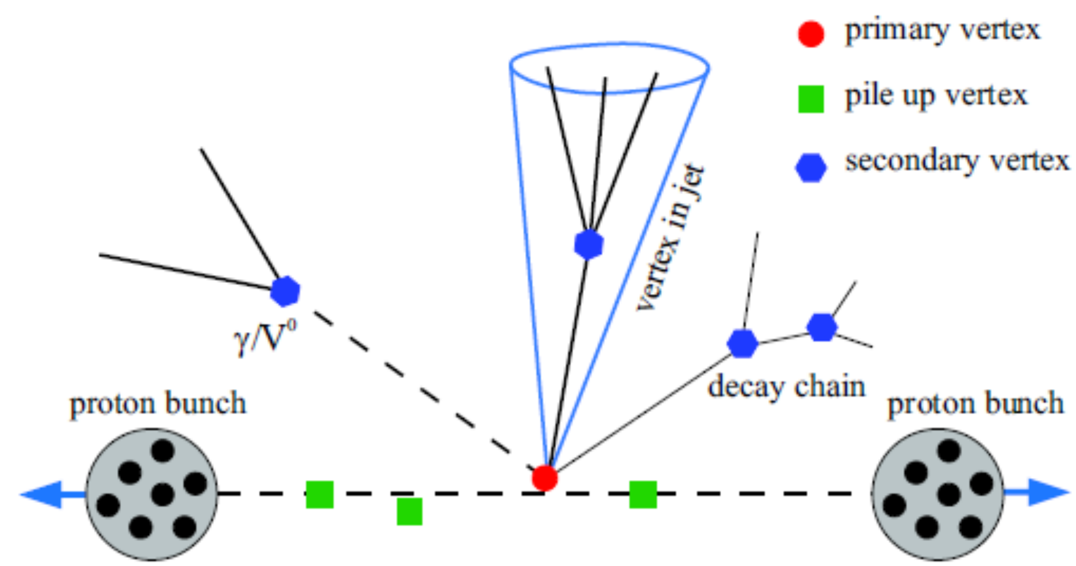


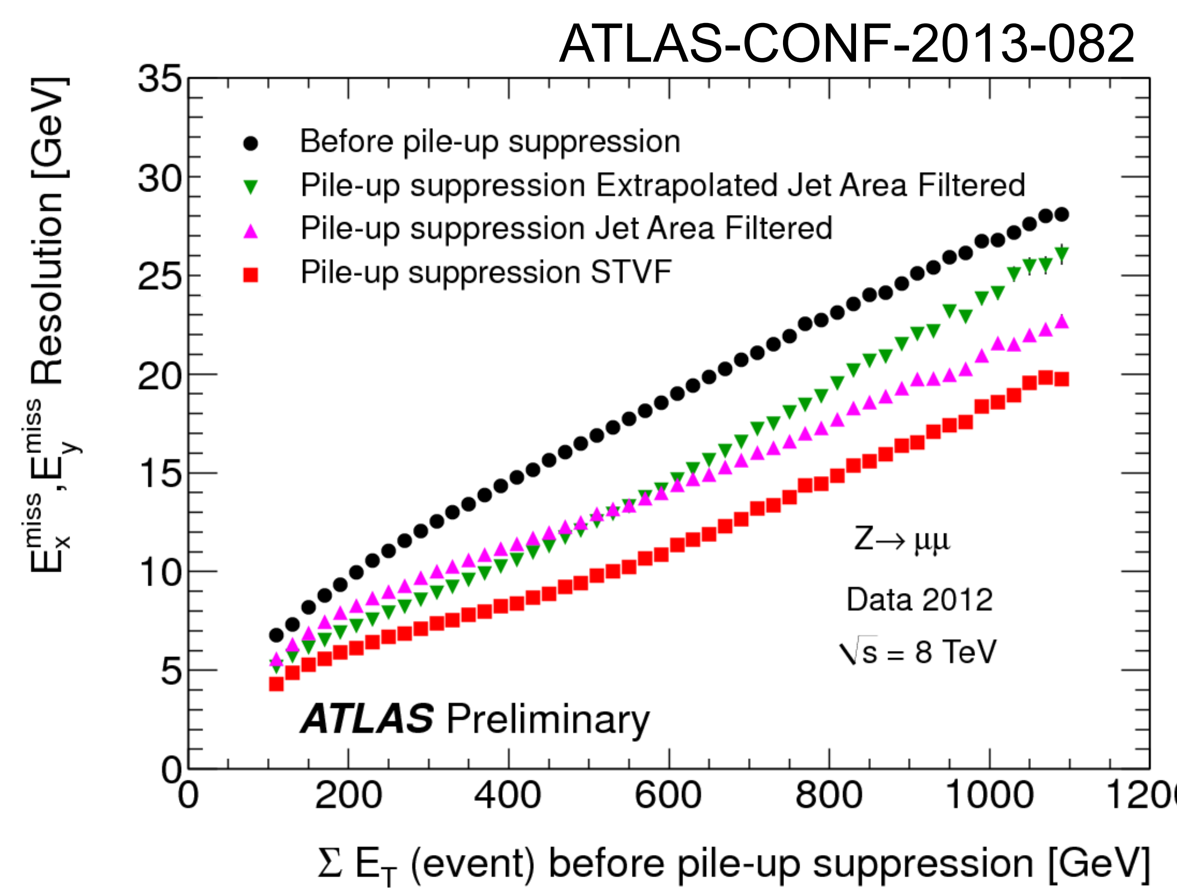
BROOKHAVEN NATIONAL LABORATORY

The problem of pileup



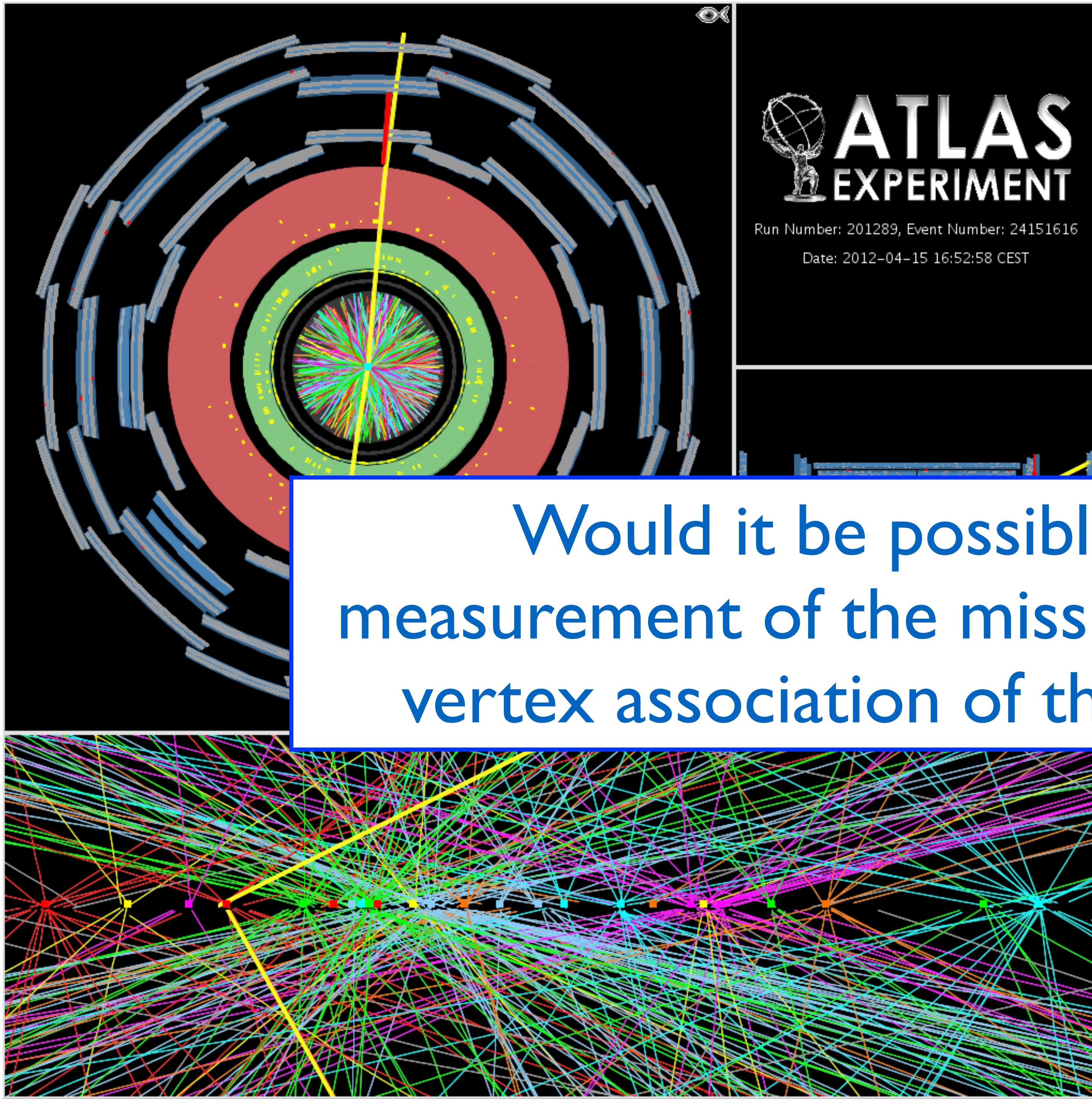
Candidate Z→μμ event from 2012 with 23 pile-up vertices

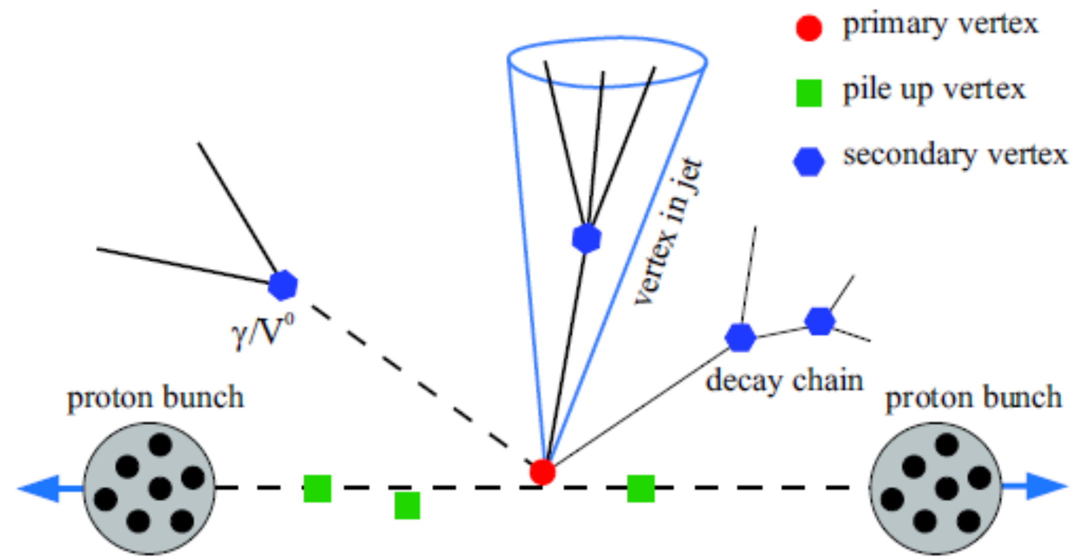


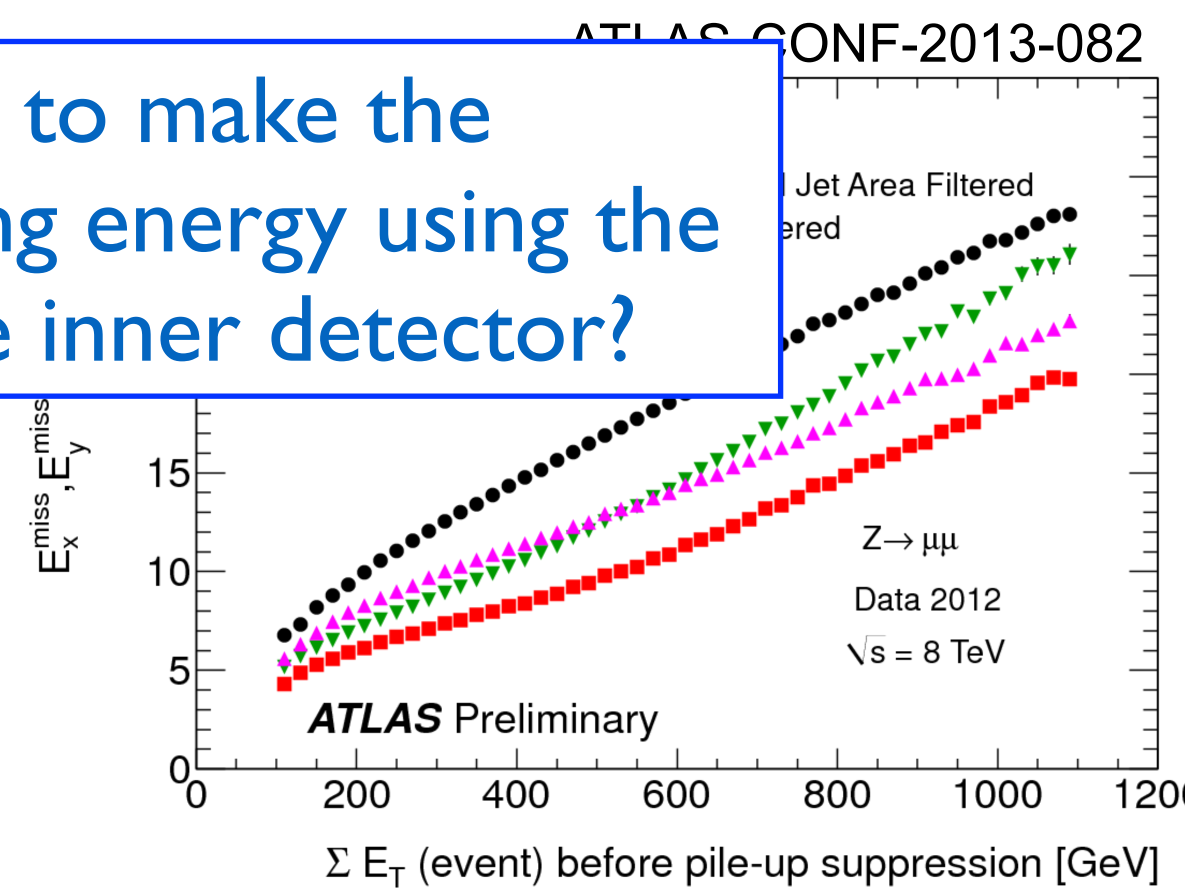


$$\sum E_T = \sum E_T^{e} + \sum E_T^{\gamma} + \sum E_T^{\tau_{had}} + \sum E_T^{jets} + \sum p_T^{\mu} + \sum E_T^{soft\ term}$$

The problem of pileup







Would it be possible to make the measurement of the missing energy using the vertex association of the inner detector?

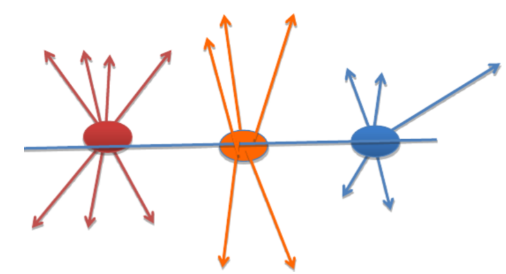
$$\sum E_T = \sum E_T^e + \sum E_T^\gamma + \sum E_T^{\tau had} + \sum E_T^{jets} + \sum p_T^\mu + \sum E_T^{soft\ term}$$

It turns out you can.

- Select general objects such as electrons, muons and jets
  - Find their associated tracks, and group them in separate terms
- For all other tracks in the event, select the ones that pass the following cuts:

pT > 500 MeV	|η| < 2.5
at least 1 pixel hit	|d0_wrtPV| < 1.5mm
at least 6 SCT hits	|z0sinθ_wrtPV| < 1.5mm

These get grouped into a track-based soft term



- Apply extra cuts for "specialised cases"
  - cleaning up tracks around high pT electrons (UE and photon conversions)
  - fake very high pT tracks in dense jets
  - general tracks with very high misreconstructed pT (check q/p and calorimeter deposit)
- The track-based ETmiss (pTmiss) can then be calculated in a similar way to the ETmiss:

$$p_{x,y}^{\mathrm{miss,nominal}} = -\left(\sum_{electron\ tracks} p_{x,y} + \sum_{muon\ tracks} p_{x,y} + \sum_{jet\ tracks} p_{x,y} + \sum_{soft\ tracks} p_{x,y}\right)$$

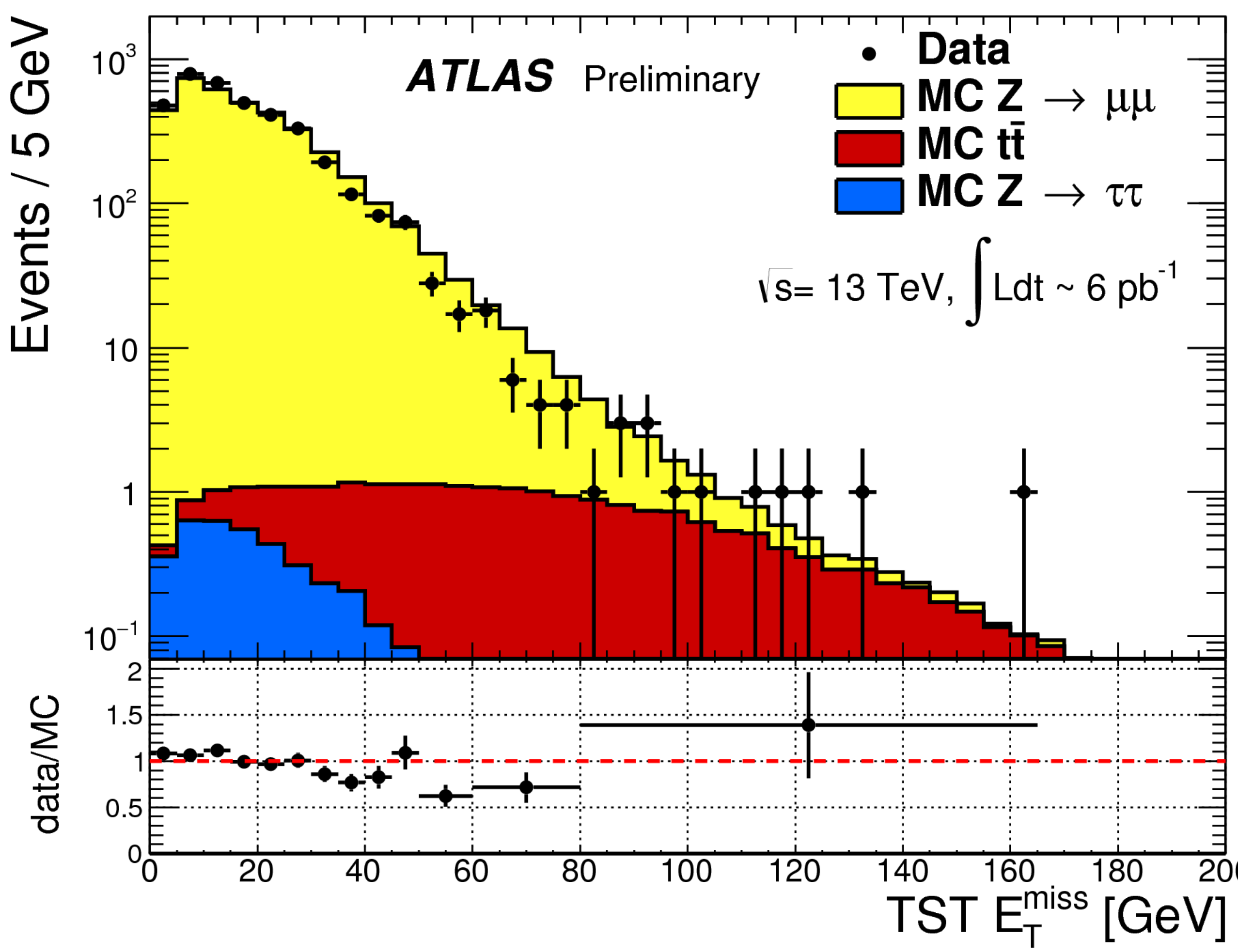
$$\sum p_T^{\mathrm{nominal}} = \sum_{electron\ tracks} p_{\mathrm{T}} + \sum_{muon\ tracks} p_{\mathrm{T}} + \sum_{jet\ tracks} p_{\mathrm{T}} + \sum_{soft\ tracks} p_{\mathrm{T}}$$

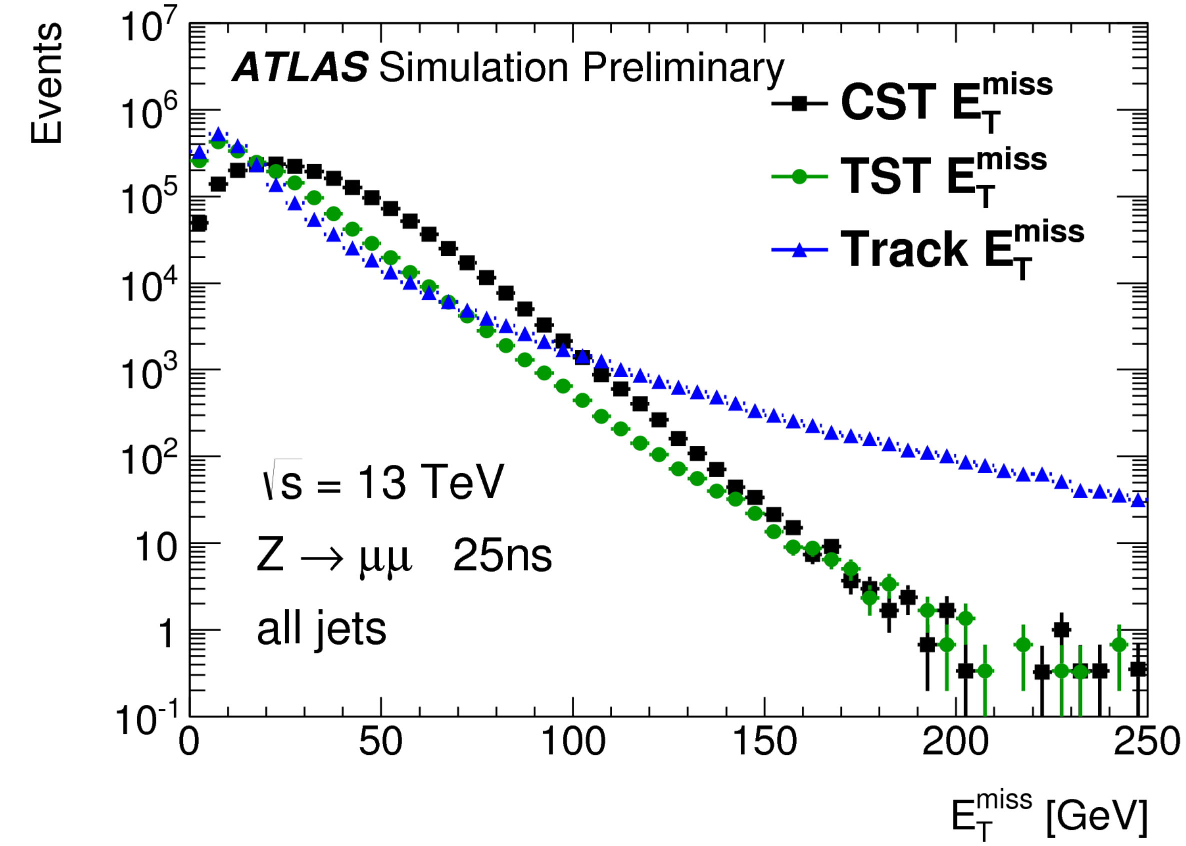
$$p_T^{\mathrm{miss,nominal}} = \sqrt{\left(p_x^{\mathrm{miss,nominal}}\right)^2 + \left(p_y^{\mathrm{miss,nominal}}\right)^2}$$

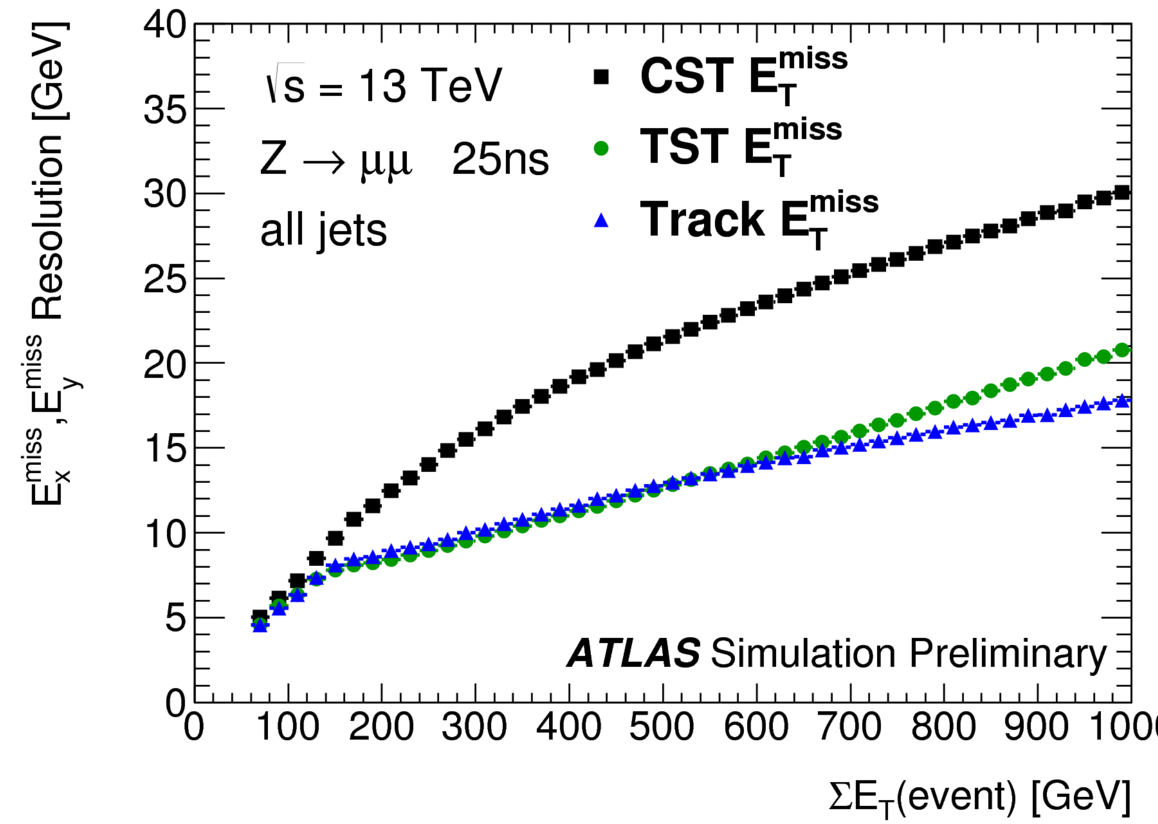
Advantage: provides a measurement of the MET from the signal vertex only

Disadvantage: restricted to charged particles and by ID acceptance

Missing ET with a Track-based Soft Term (TST)

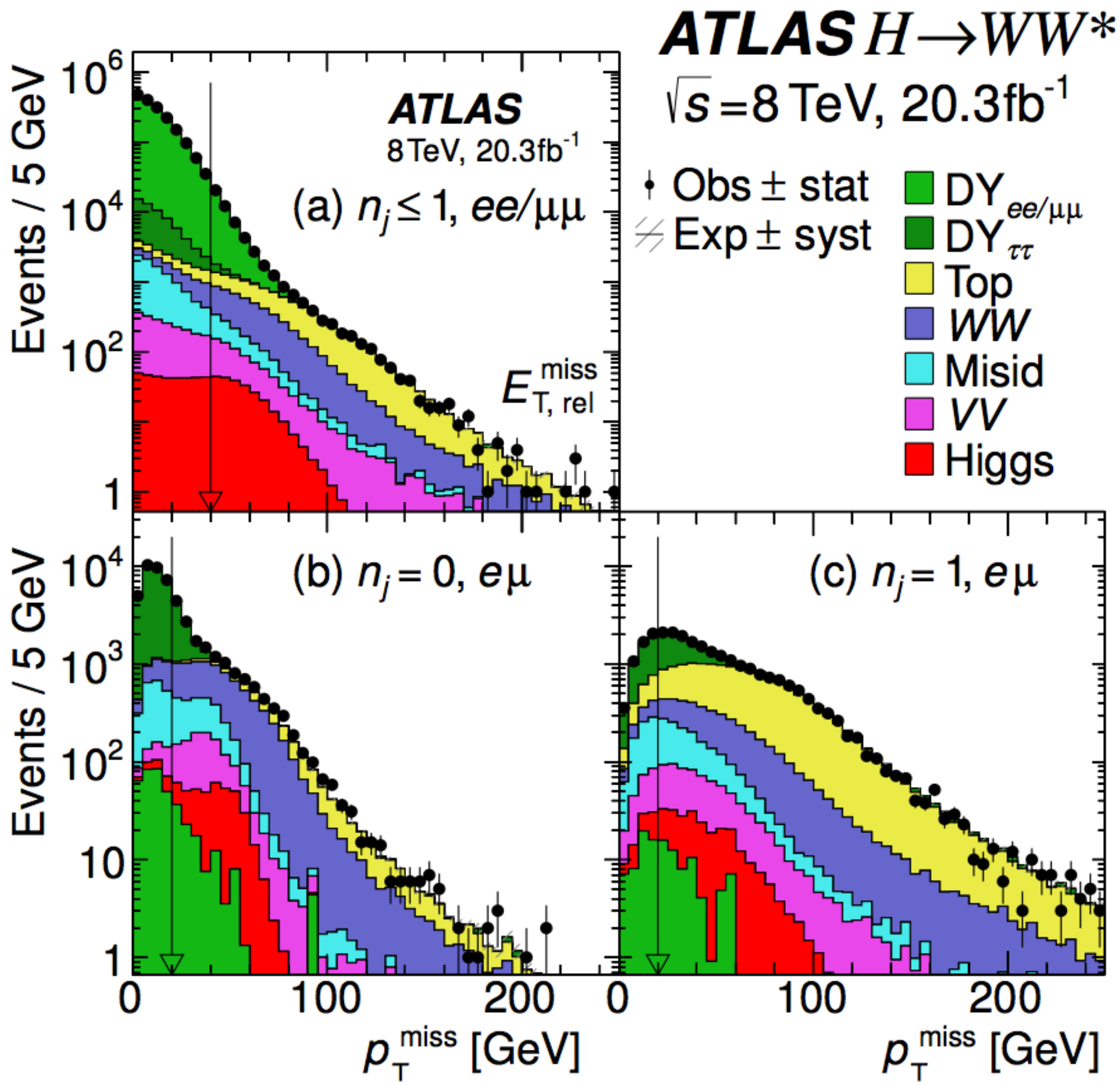






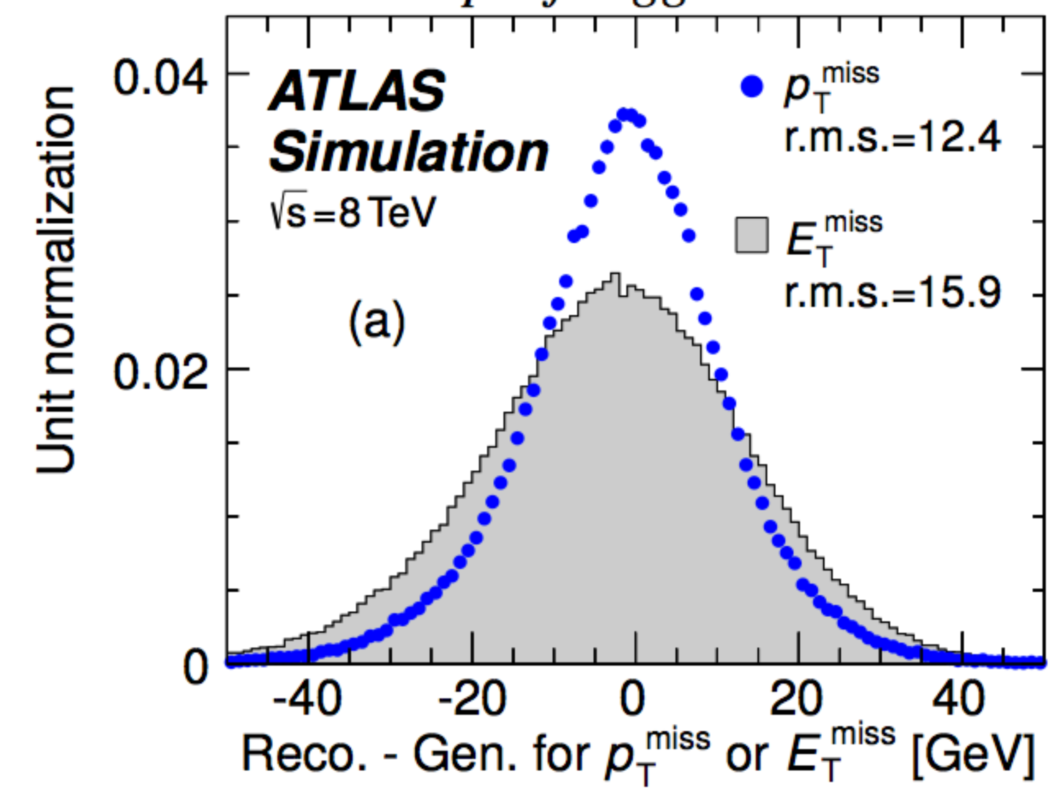
Missing ET used for the SM Higgs measurement

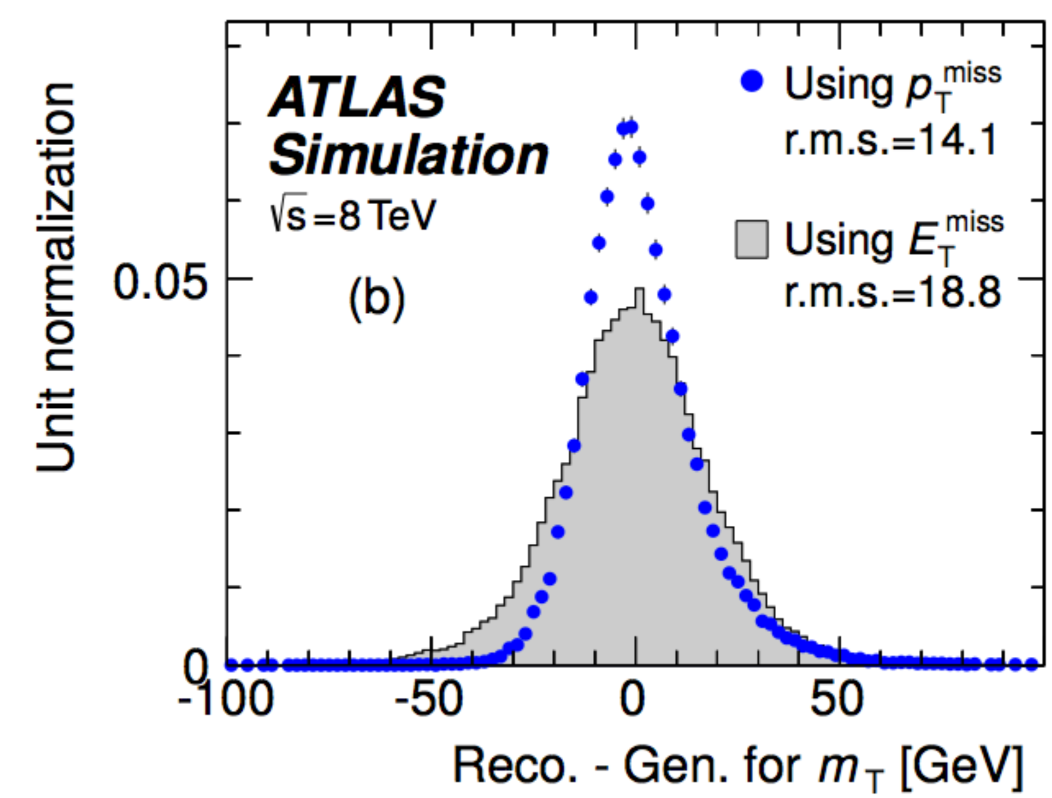
- 2012 Standard Model H→WW analysis



Preselection cuts in 0,1 jet channels to reduce DY

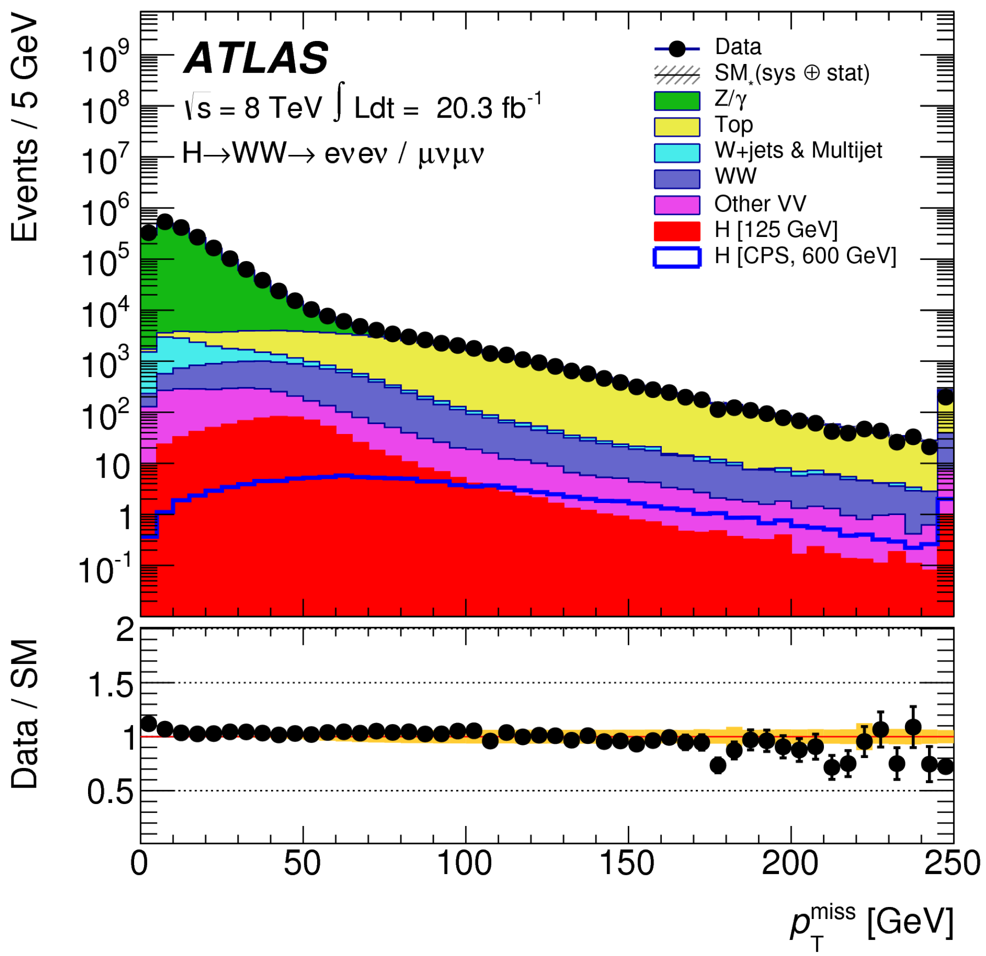
MC sample for ggF $H \rightarrow WW^*$

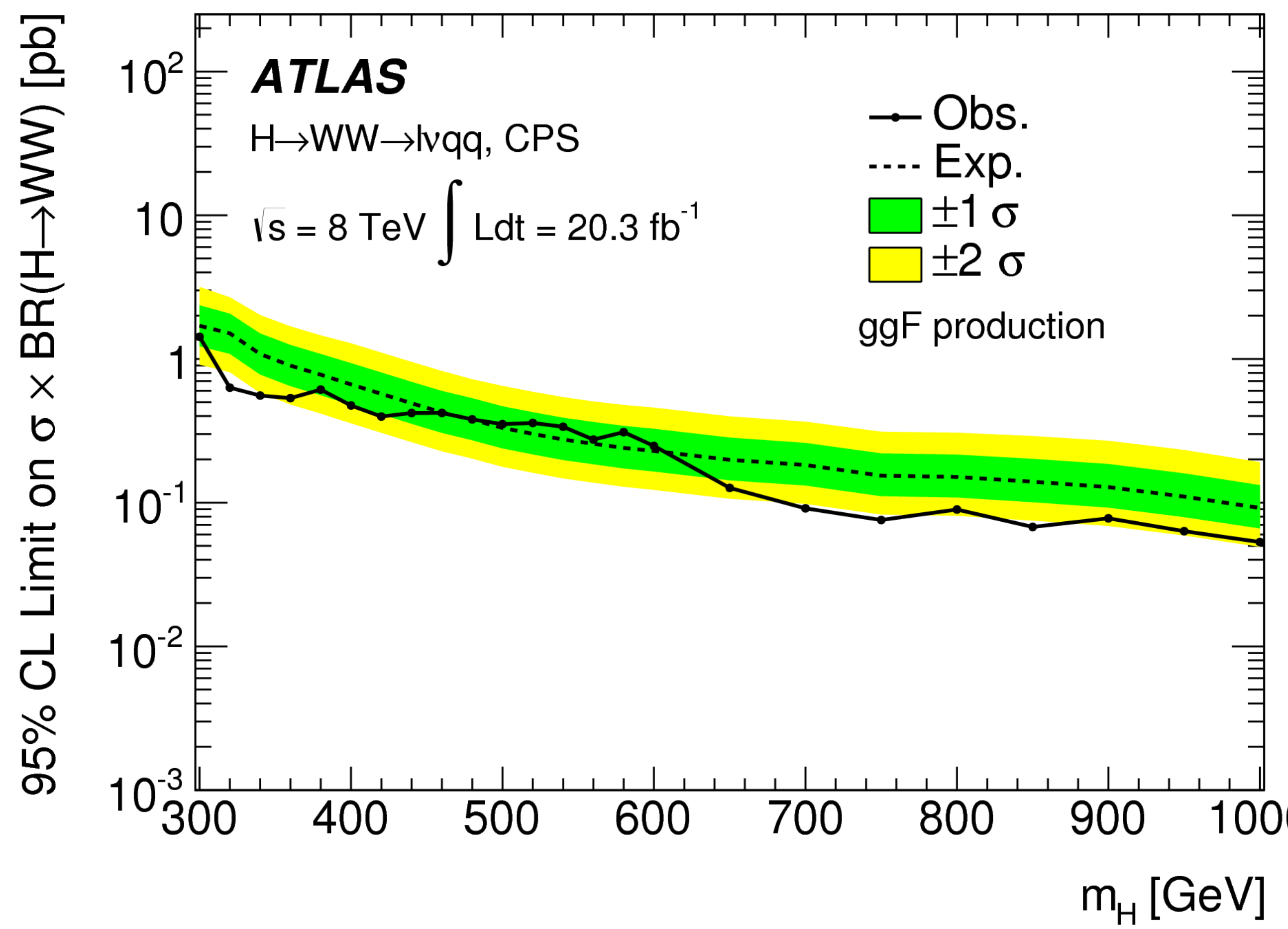




As well as in searches for new, high mass Higgs bosons

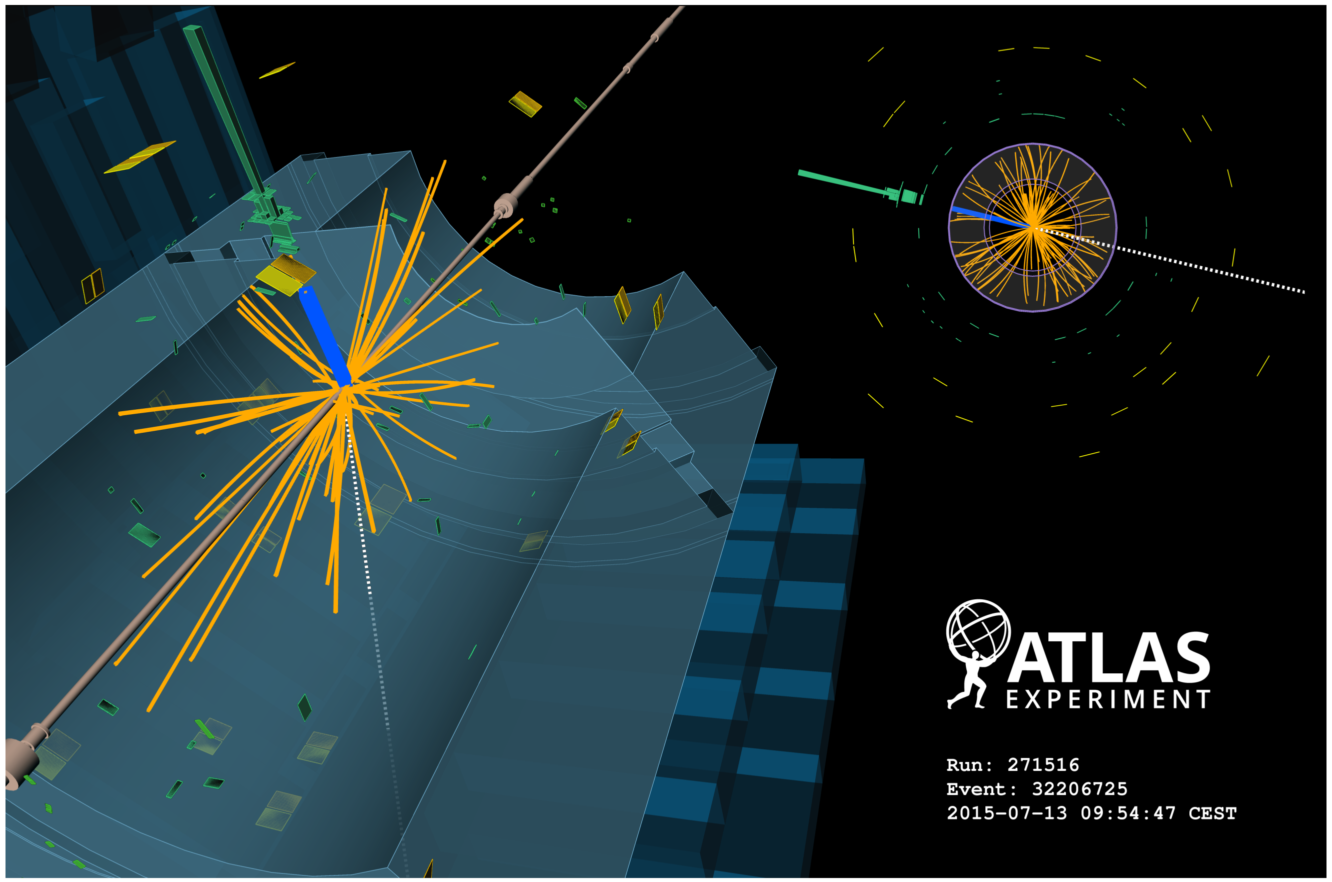
- eagerly awaiting results with 13TeV!

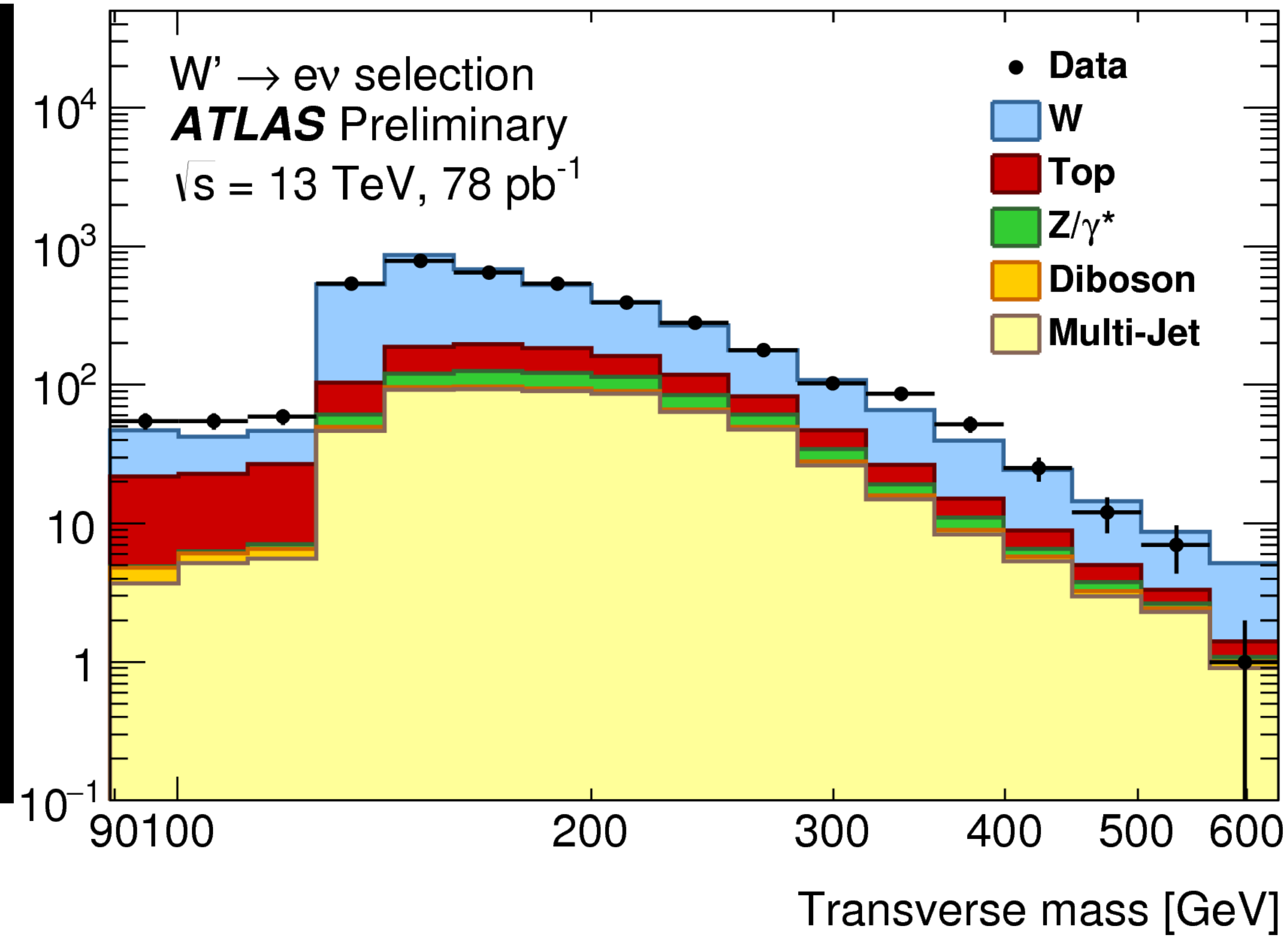




In run 2, the "hot topic" is Beyond the Standard Model Searches

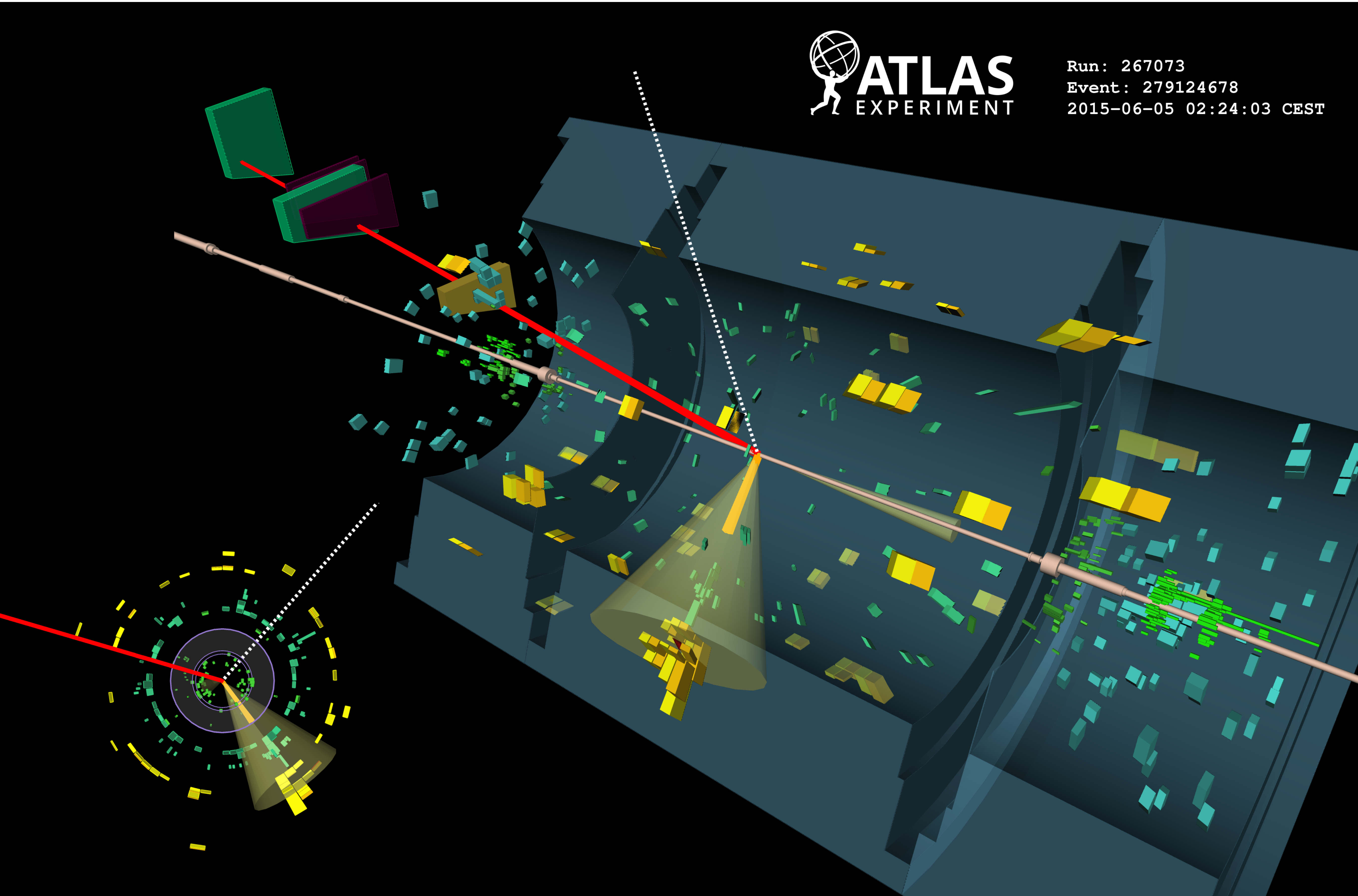
- Search for W' decaying to lepton + Missing ET





One of the highest transverse mass events in the electron channel. The electron has a pT of 525 GeV. The missing transverse momentum is 525 GeV. The transverse mass of the event is 1050 GeV.

LHC Run 2 is happening and we are ready!

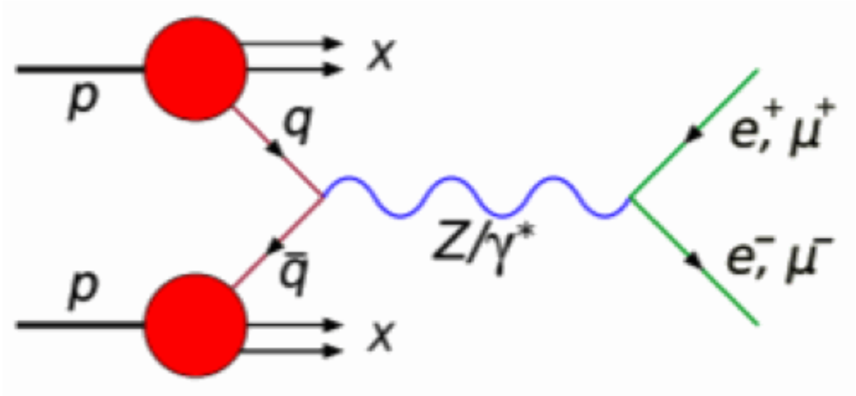


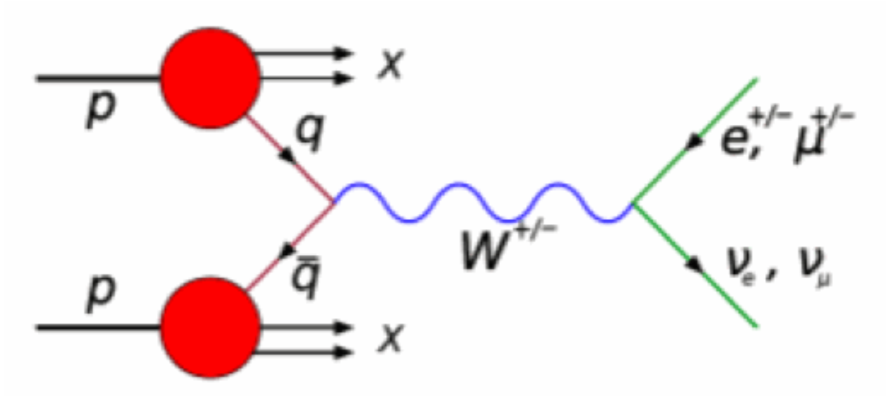
LHC Run 2 is happening and we are ready!

Hope you have had a fantastic time at CERN!

Backup

Zs and Ws as standard candles

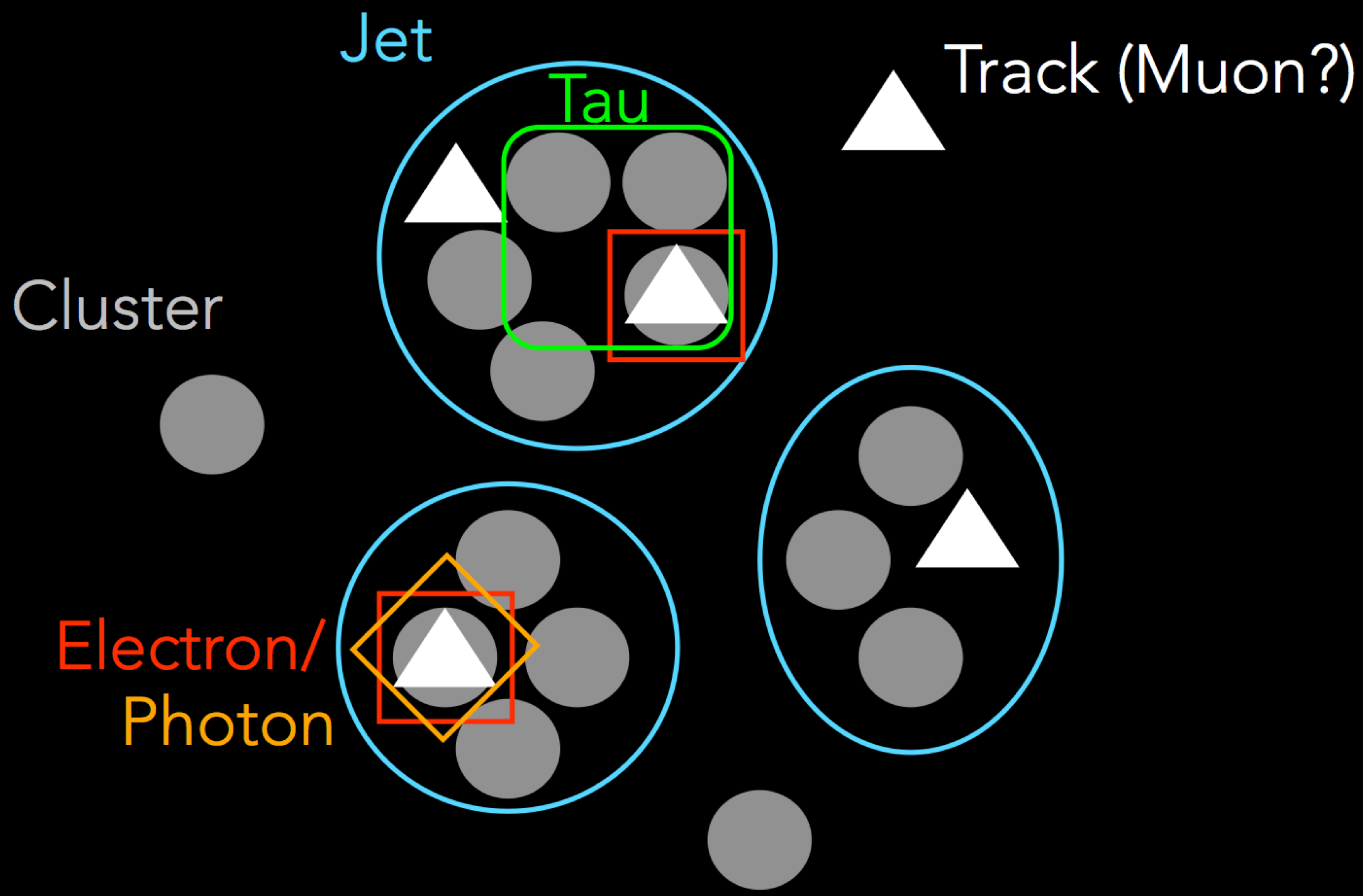




- Z→ℓℓ
  - No real MET in event*, symmetric peak at 0
  - Resolution of peak indicates reconstruction efficiency
  - Scalar projection indicates balance between hard and soft terms
- W→ℓν
  - Real MET in event
  - Scale and directional resolution (not just fluctuations around 0)

*Well, very small amount from heavy-flavour meson decays in jets

METAssociationMap



Energy Loss by Ionisation

- Charged (heavy) particles moving fast through matter ionises the atoms in the material, and leads to energy loss of the traveling particle.

- The energy loss per distance travelled is dominated by the number of collisions with electrons, and can be described by the Bethe-Bloch function:

Charge number of medium

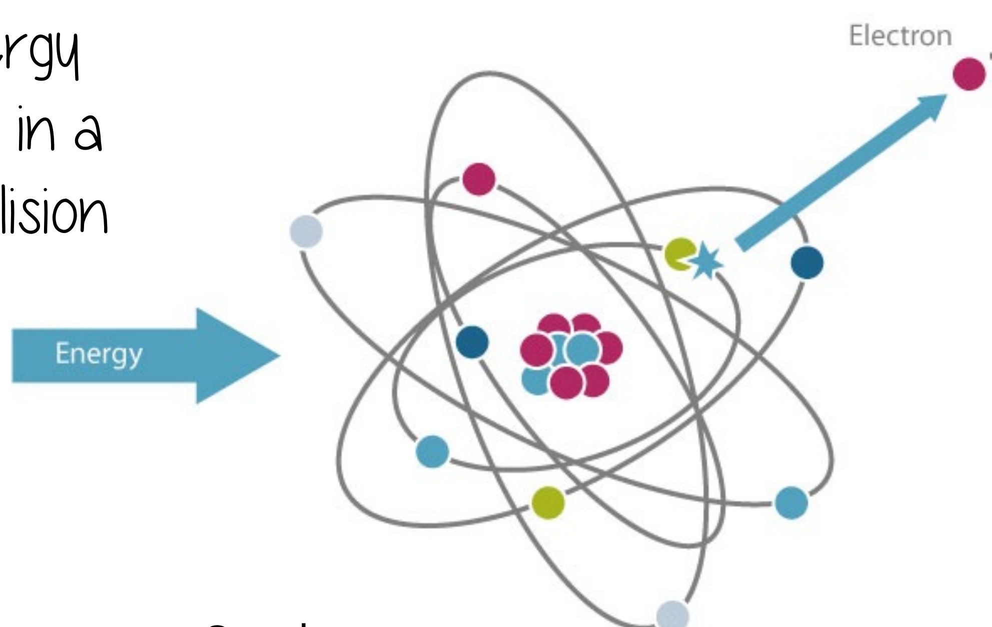
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Constant

Atomic mass of medium

Max. energy transfer in a single collision

Charge of incident (incoming) particle

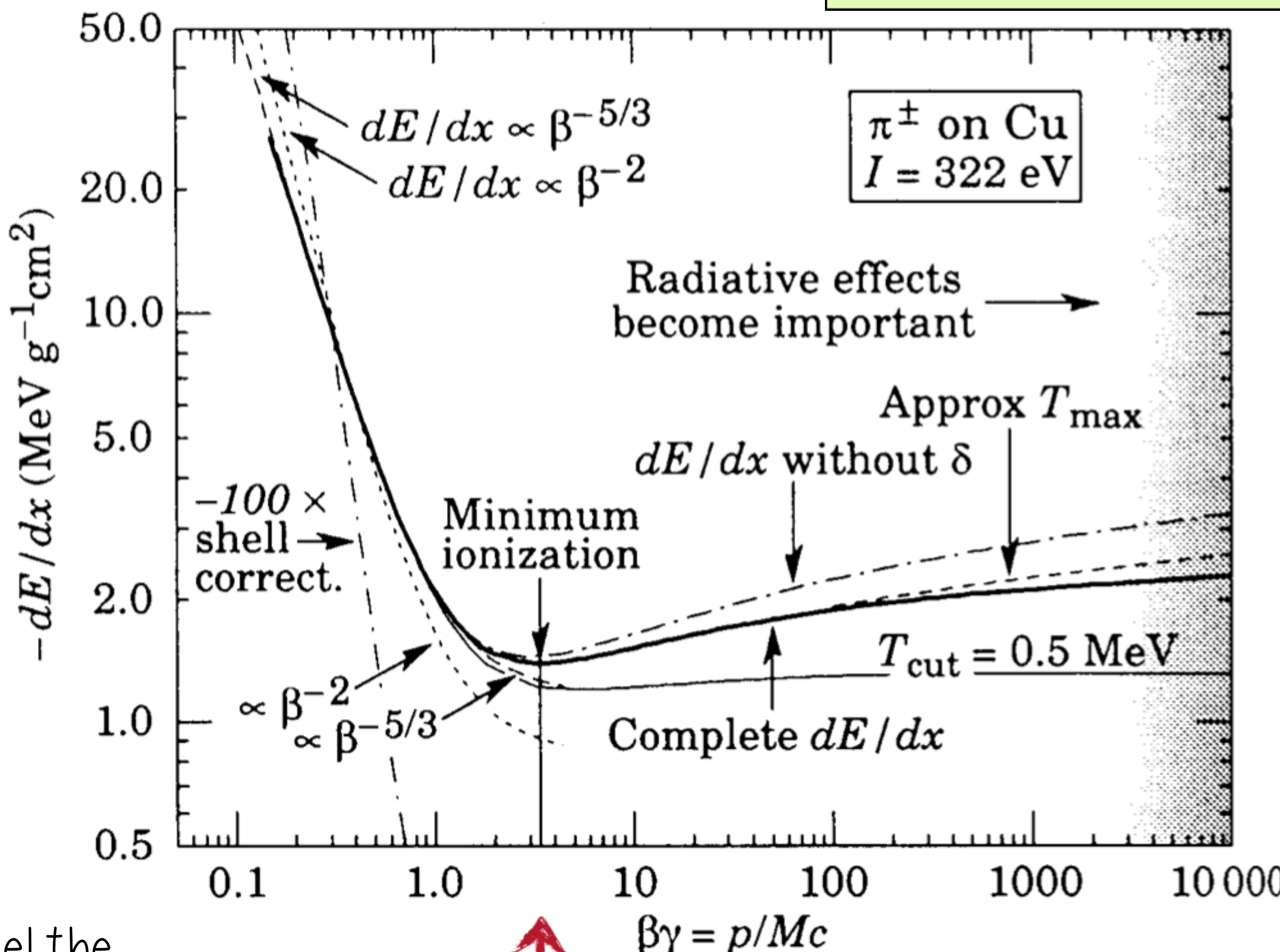


Understanding the Bethe-Bloch Function

- Energy loss of pions in Copper:

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

At low incident particle energies the function has a $1/\beta^2$ dependence



For high energy particles the function has a relativistic rise, as the interaction cross section increases (transverse E field increases due to Lorentz boost)

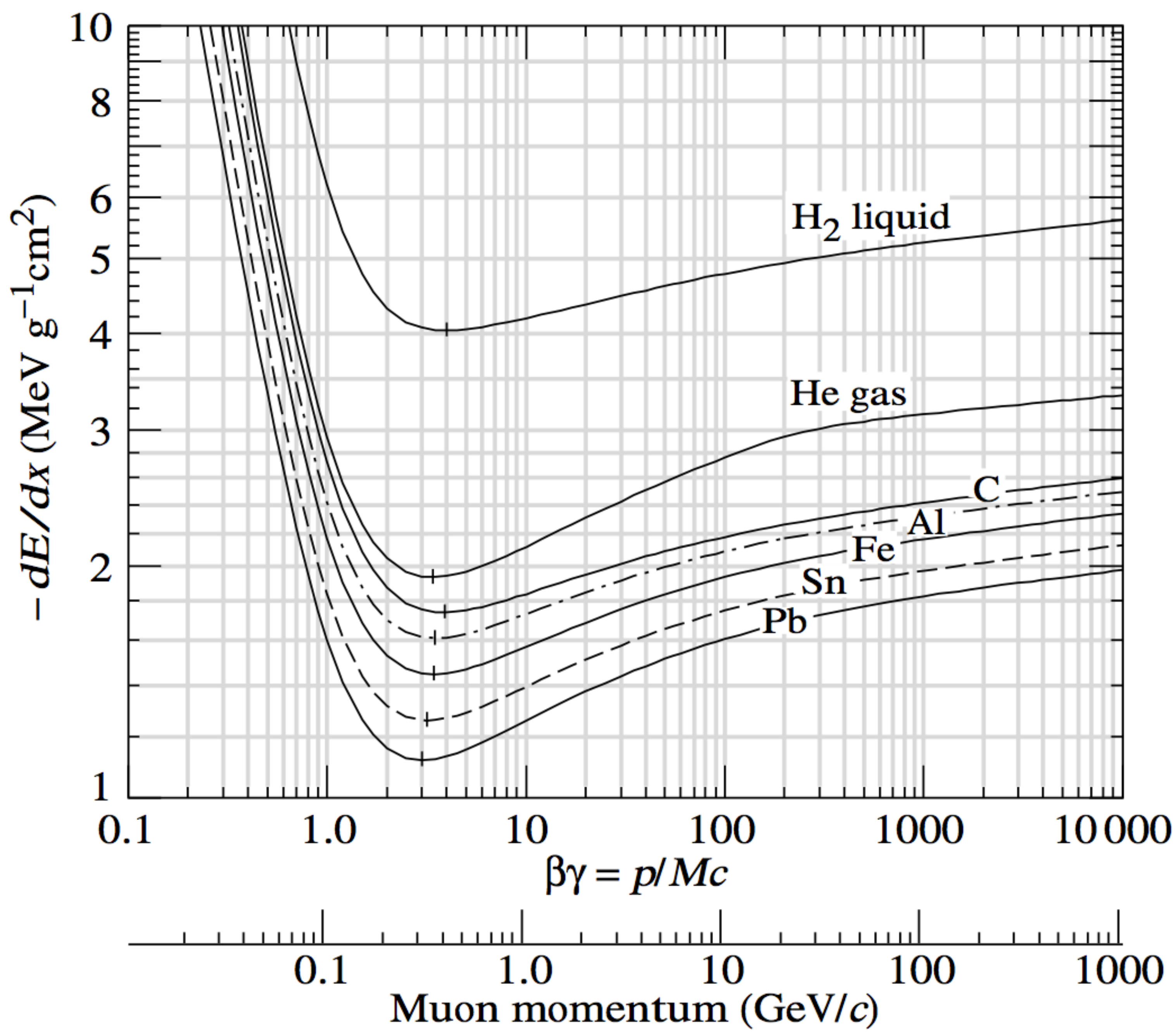
Slower particles feel the electric force of the atomic electron for a longer time, increasing the energy loss

$\beta\gamma = 3\text{-}4$

Bethe-Bloch Function: dependence on medium

- Dependence on mass (A) and charge

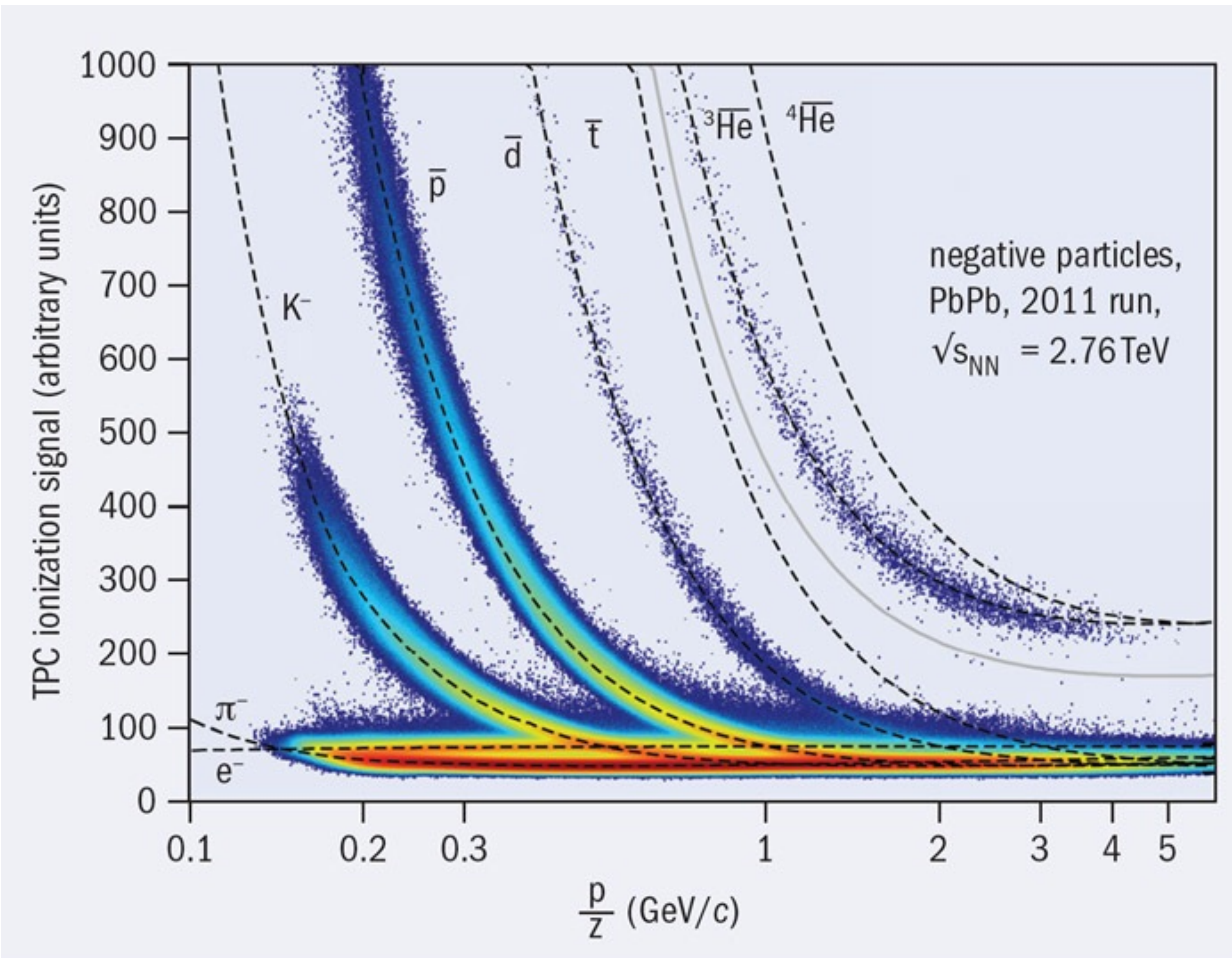
$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Bethe-Bloch Function: dependence on particle type

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$T_{max} = 2m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

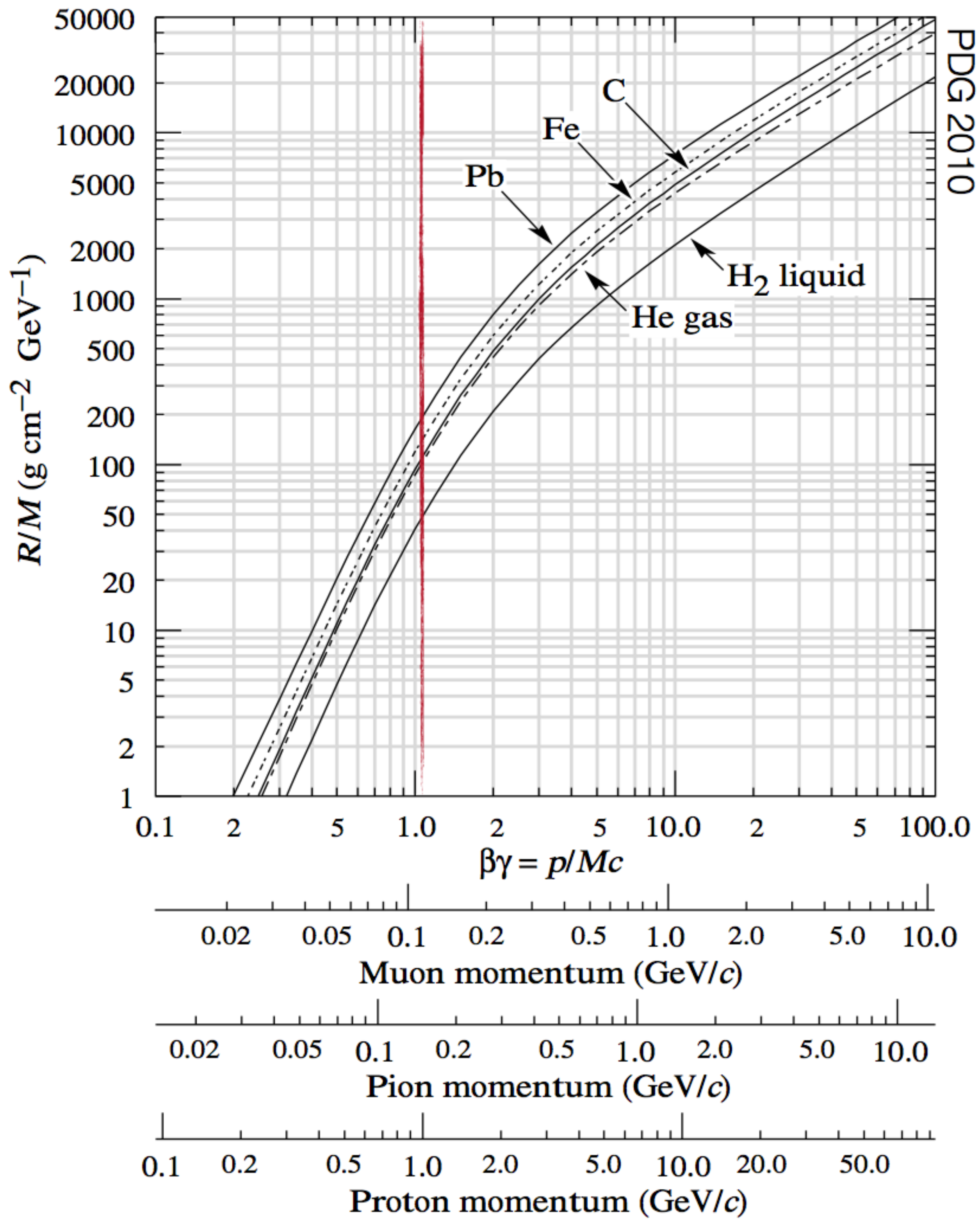


Mean Particle Range

- Since the particle is losing energy, eventually it will stop!

- The range R can be found by integrating ove

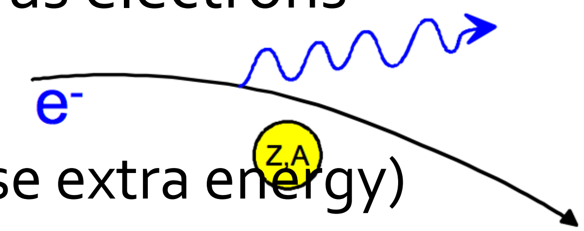
$$R = \int_E^0 \frac{dE}{dE/dx}$$



  - eg: 1 GeV proton on a lead target,
    - R ≈ 20 cm

Bethe-Bloch for Electrons

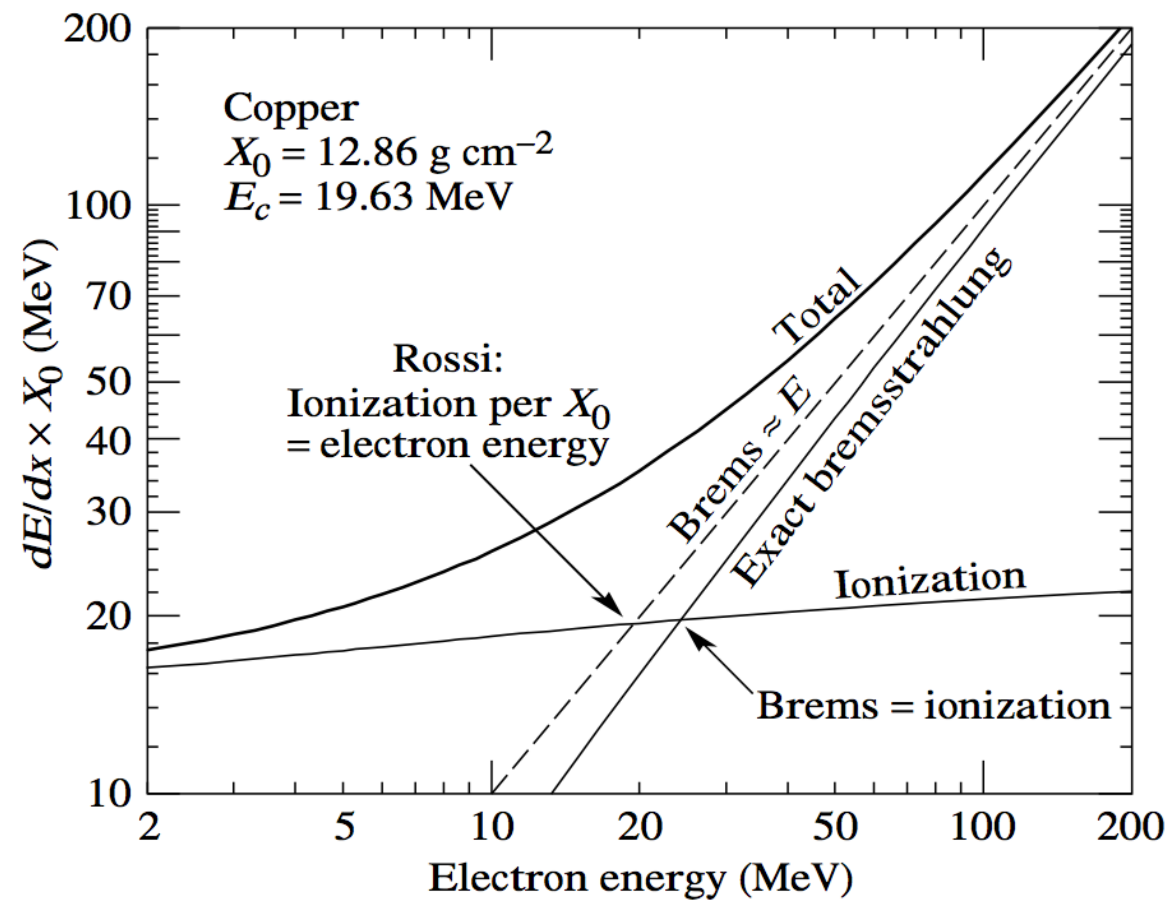
- The Bethe-Bloch function needs a correction for light particles such as electrons
  - Light particles are easily accelerated in the Coulomb field of a nucleus
  - Radiate photons due to conservation of momentum (and therefore lose extra energy)



- The Critical Energy is the energy at which loss from Bremsstrahlung takes over from loss from Ionisation

$$\frac{dE}{dx}(E_c)\bigg|_{\text{Brems}} = \frac{dE}{dx}(E_c)\bigg|_{\text{Ion}}$$

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$



Energy Loss Summary (muons)