Title: Collider Experiment

Speakers: Manuella Vincter

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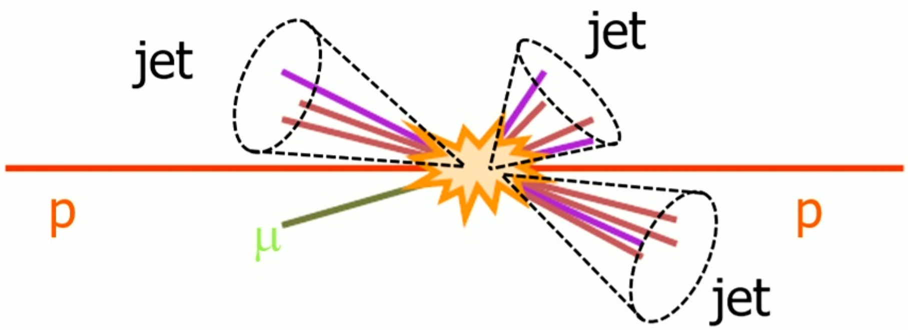
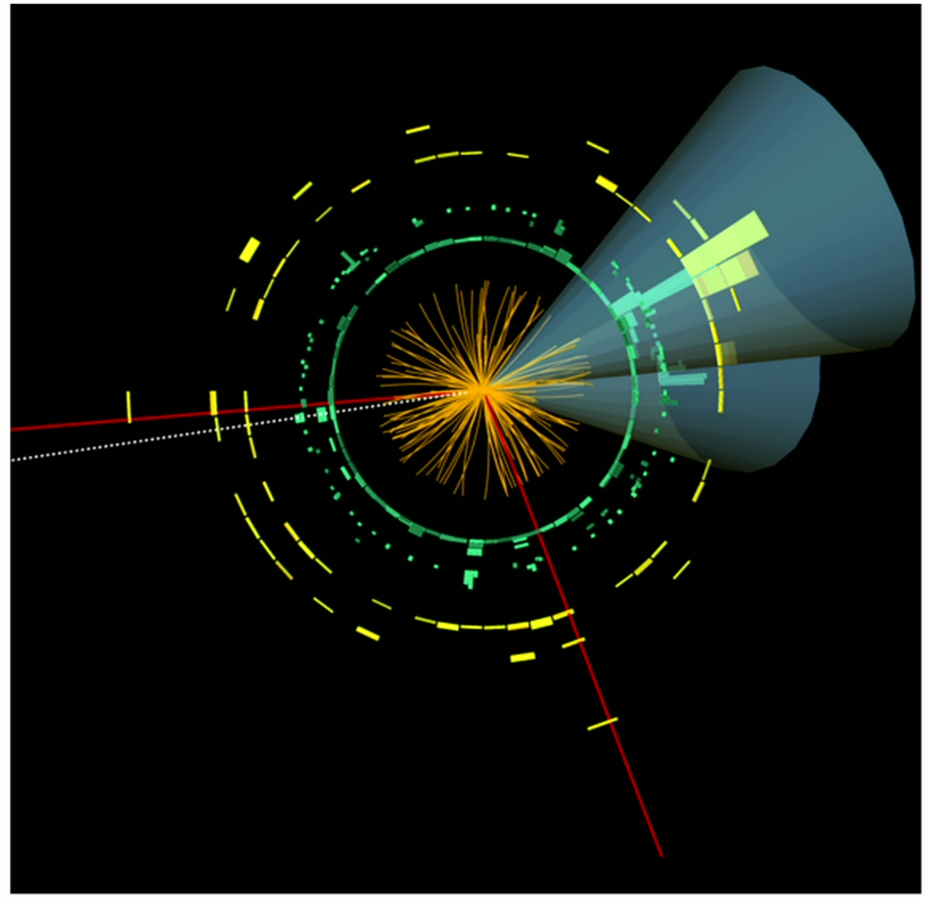
URL: https://pirsa.org/23060058

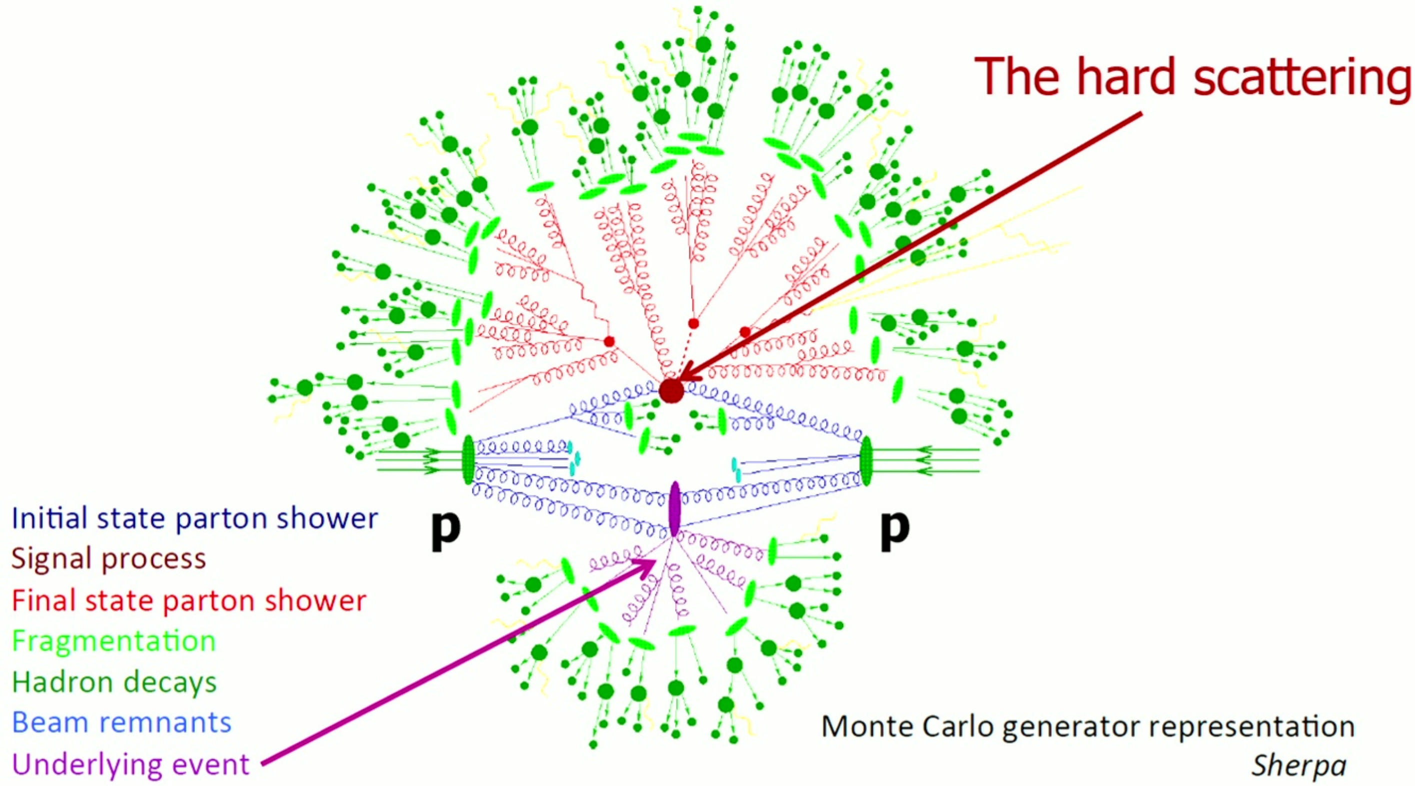
A proton-proton collision event (cartoon)





A proton-proton collision event (full glory)

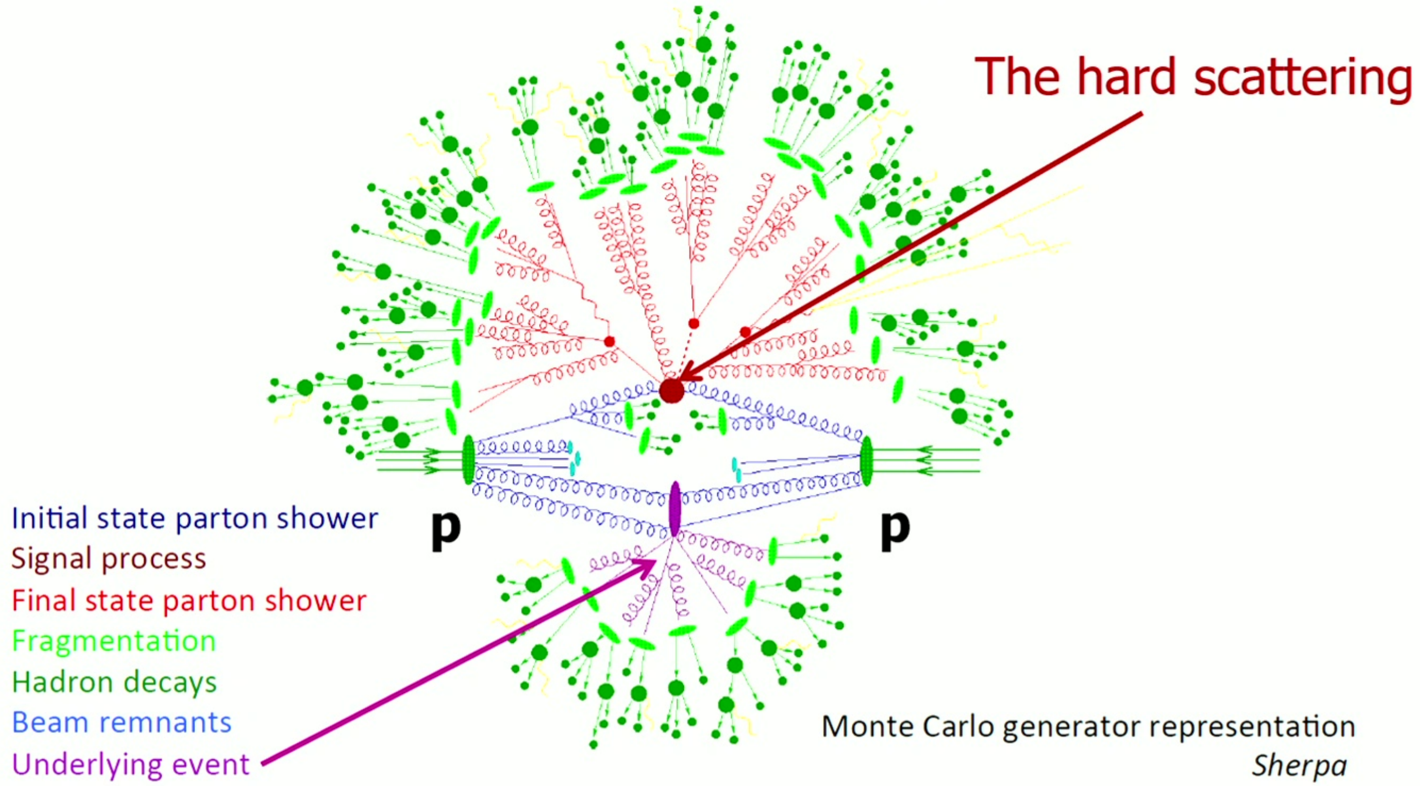
A proton-proton collision



47

A proton-proton collision event (full glory)

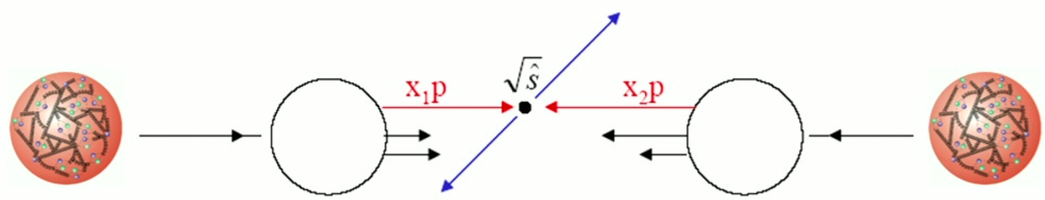
A proton-proton collision



Monte Carlo generator representation
Sherpa

Hard scattering

- Inelastic collisions are dominated by soft interactions. Occasionally, we get a hard scatter:



$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$$

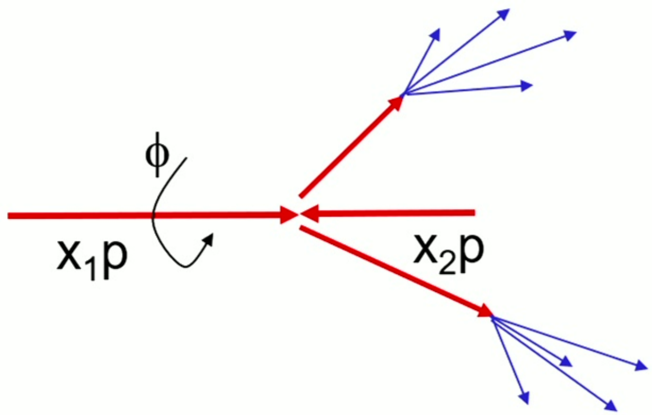
- x_1, x_2 = momentum fraction of partons in protons
- Since the partons only carry a fraction of their parent hadron's momentum, the available centre-of-mass energy squared $\sqrt{\hat{s}}$ is less than the overall hadron-hadron collision energy $\sqrt{s}$
- The hard interaction can be described by perturbative QCD:

$$\sigma = \sum_{a,b,k} \int dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}^{k}_{a,b}(x_a, x_b)$$

- Hard scattering cross section for k^{th} sub-process between partons a and b
- $f_{a,b}$ are the parton distribution functions of partons a,b

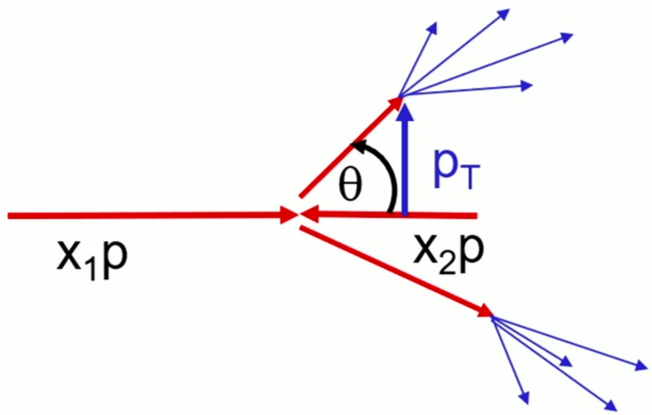
Hard scattering to jets

- The hard scattering can produce e.g. leptons or hadrons produced from the fragmentation of partons
  - The blue part are the jets: collimated set of hadrons produced from the fragmentation of the partons emerging from the hard interaction → this is what the detector sees
- In general:
  - cross sections are symmetric in azimuthal angle (ϕ)
  - $x_1 \neq x_2$ → The event is boosted along the beam axis
    - Difference from e^+e^- machines



Jet kinematics: p_T

- Use jet p_T (or E_T) to discriminate between hard interaction and soft part
- large momentum transfer = small distances = hard scattering
  - large transverse energies are signal for hard interaction:
    - $E_T = E \sin\theta$, E=energy in calorimeter
- large energies instead do not imply hard scattering: beam remnants have huge energies but have not undergone hard scattering…



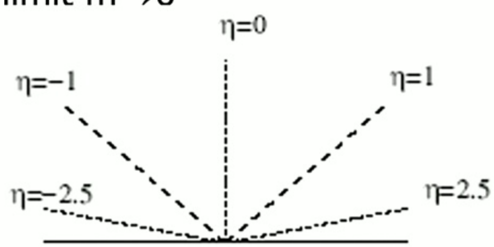
51

Jet kinematics: y and η

- Angular separations in θ are not invariant under longitudinal boosts: a given set of hadrons will appear more collimated depending on the boost. To treat equivalently partons with same p_T but different boost → use rapidity y

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

- y is additive under Lorentz transformation, corresponding to a boost in the z direction: rapidity differences are boost invariant
- In practice, use pseudorapidity variable η, as this is what is measured in the detector. y and η coincide in the limit m→0



$$\eta \equiv -\ln\left(\tan\frac{\theta}{2}\right)$$

$\eta = 0:\ \theta = 90 \qquad \eta = 1:\ \theta \sim 40$

$\eta = 2.5:\ \theta \sim 10 \qquad \eta = 5:\ \theta \sim 0.8$

$$\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

ΔR is invariant → a good variable to assemble jet fragments

Particle and jet kinematics are specified using p_T, η (or y), ϕ

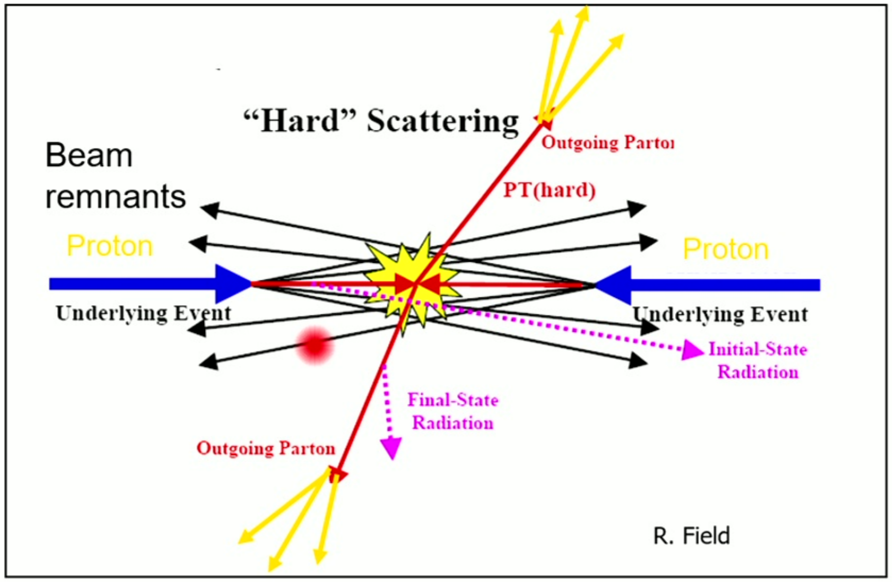
52

Buzz word #5

Underlying event!

The underlying event (UE)

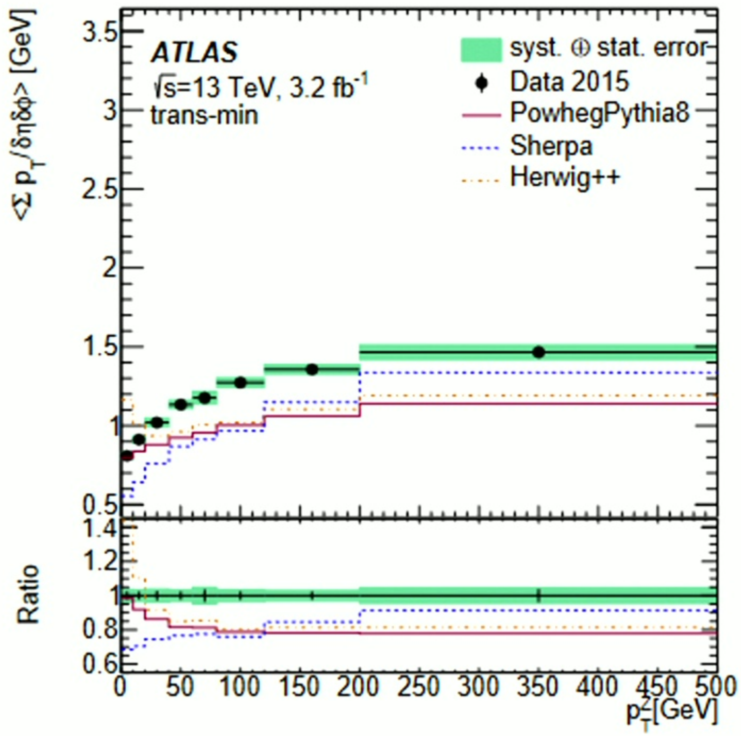
- Underlying event (UE): is the soft part associated with the hard scattering
  - Everything except the two outgoing hard scattered jets but has some correlations with the hard scatter
  - Contains hard components: e.g. initial/final state radiation, additional parton interactions (becomes significant at LHC)
  - Contains soft components: Beam-beam remnants



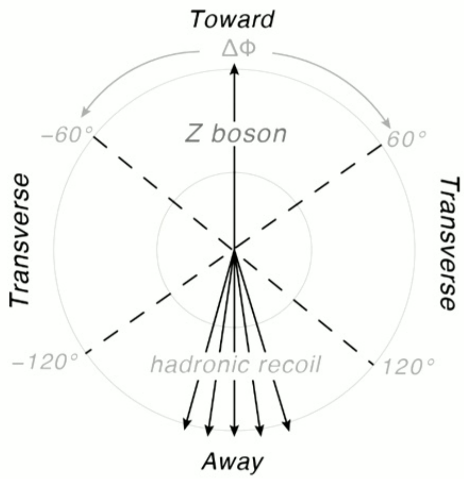
- UE: cannot be described by pQCD
  - Phenomenological models, tuned with LHC data

The underlying event (UE)

- Must understand the UE as it is an important "background" to jets and missing transverse energy E_T^{miss} (= negative of the vector sum of the calorimeter E_T)
  - generates E_T flow around the hard scatter (shifting up the signal)
  - generates fake jets not related to the hard scatter
  - distorts the E_T^{miss} resolution
- Can study UE by looking at region transverse to the hard scatter axis
  - Tune Monte Carlo event generators to data



Distributions sensitive to underlying event in inclusive Z-boson production



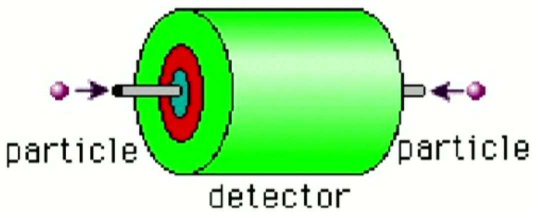
Avg. Σ p_T for charged particles per unit area in η-φ in Trans-min region (region with small scalar sum of charged-particle p_T) as a function of Z boson p_T

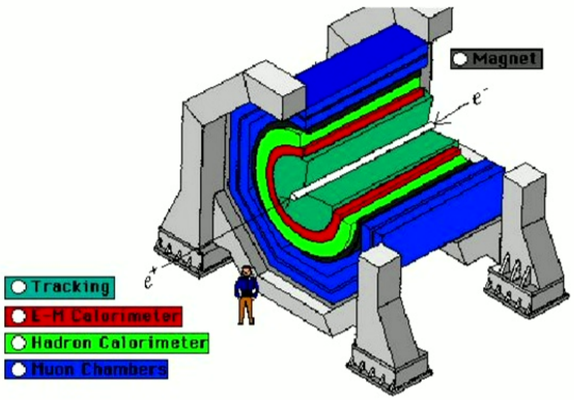
Eur. Phys. J. C 79 (2019) 666

SOME DETECTOR PHYSICS

Particle Detectors: how do they work?

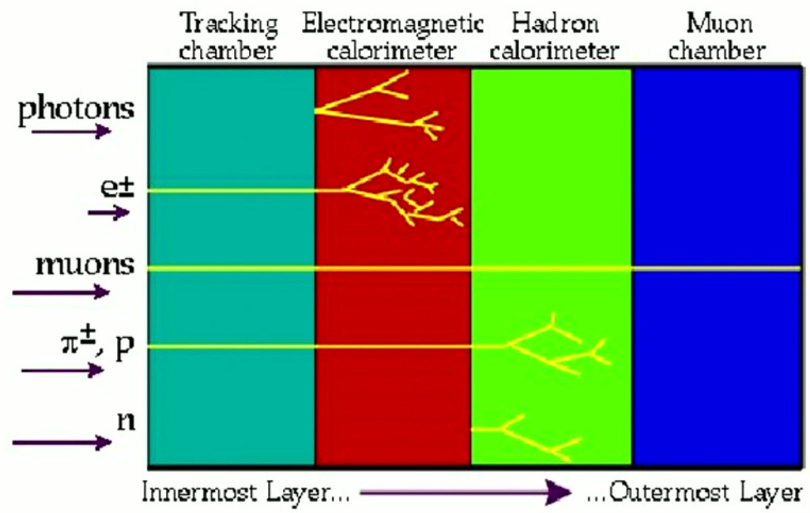
Collider detector:





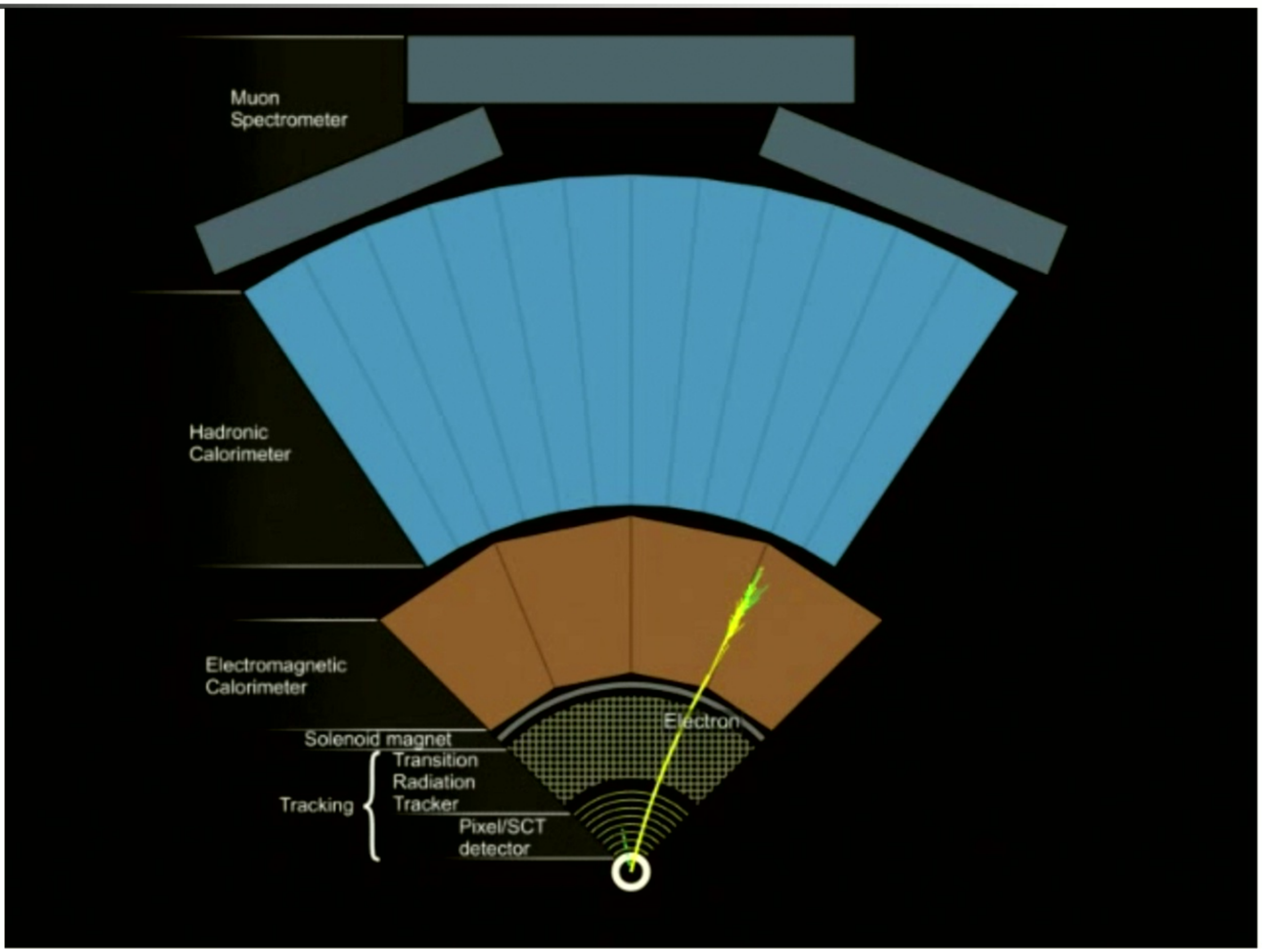
Want to tell the difference between:

- Charged (e.g. e^-) and neutral (e.g. neutrons) particles
- Electromagnetic (e.g. e^-,γ) and hadronic (e.g. protons)
- Is it a muon?



Detector's role: to identify a particle's type, energy/momentum, provenance.

Particle interactions in a detector

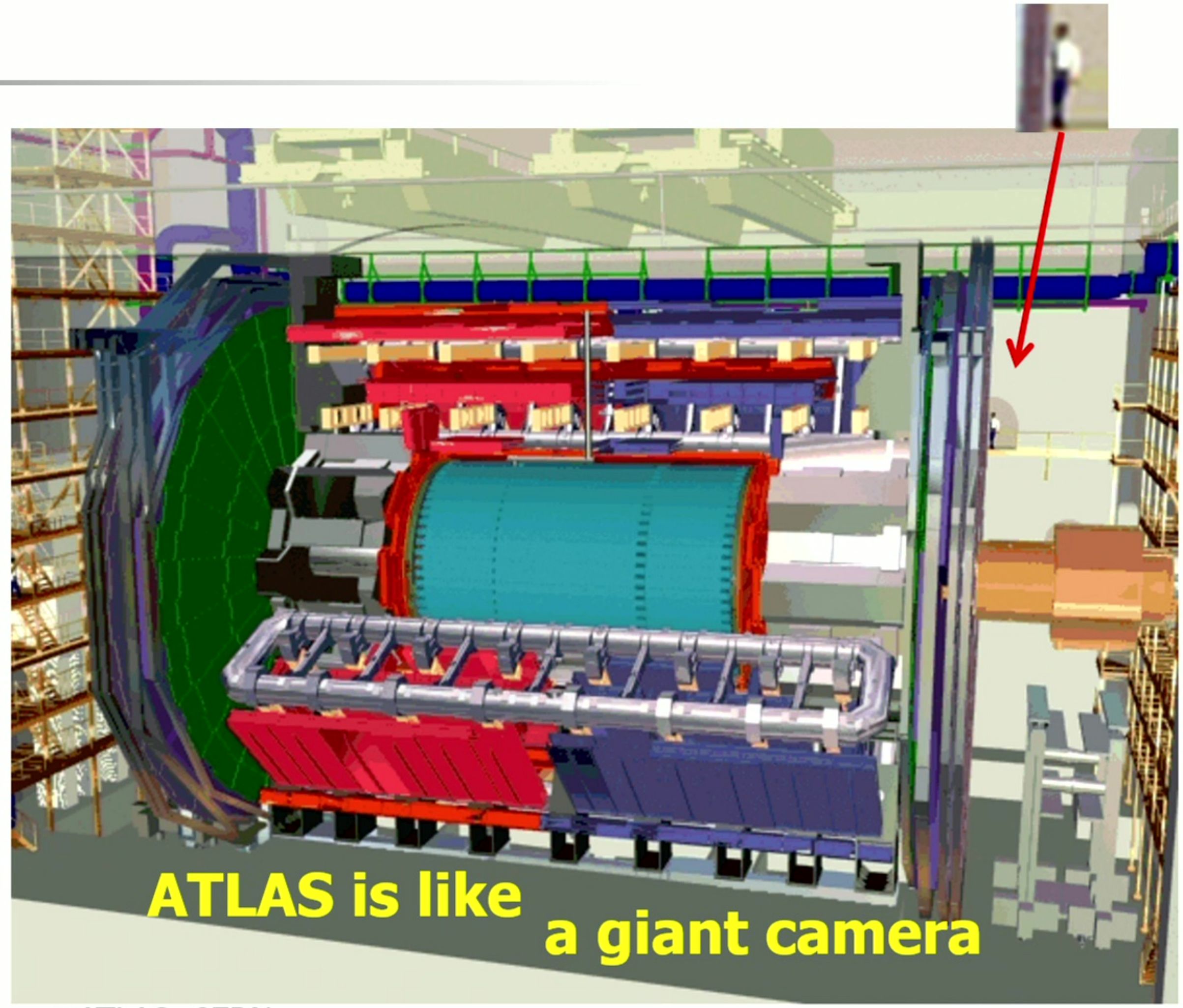


58

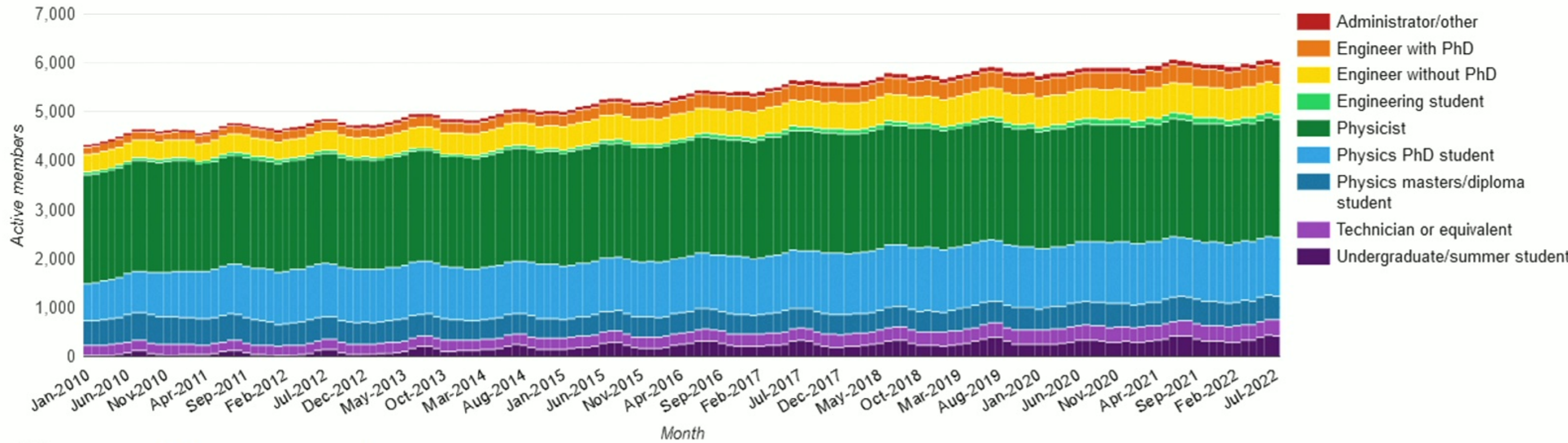
The ATLAS Detector

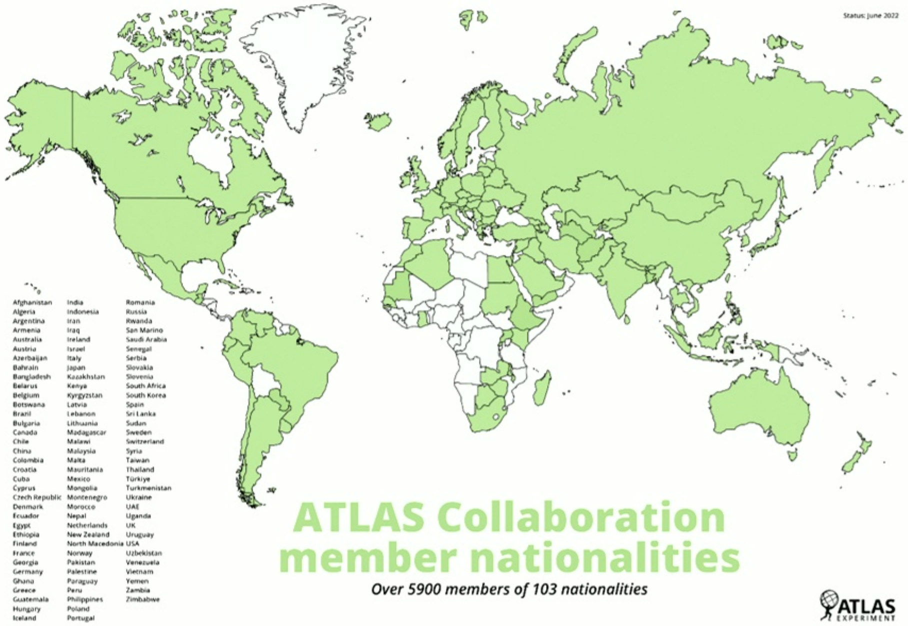
ATLAS is

- … a detector capable of identifying the particles produced in pp collisions
  - ~80 m underground
  - As tall as a 7 storey building!
  - 25 m diameter
  - Total length 44 m
  - Weight of 7000 Tons … Same as wrought iron of Eiffel Tower:



©ATLAS, CERN



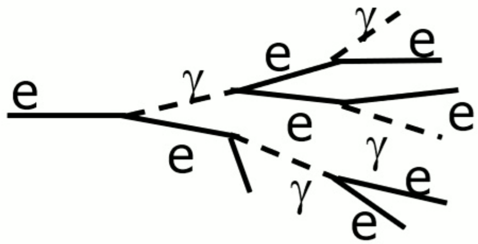


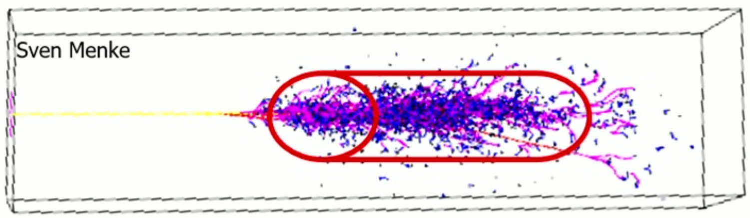
ATLAS is

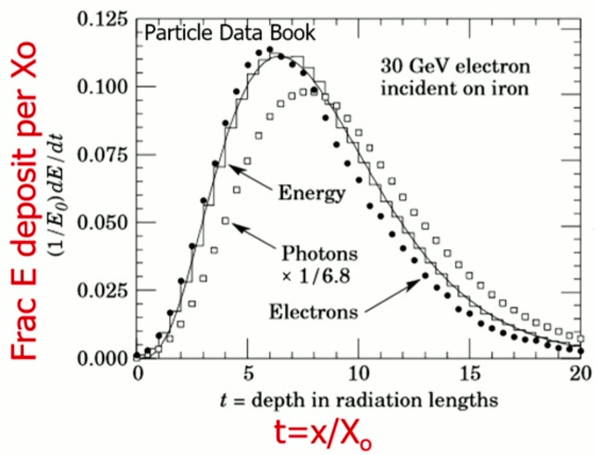
- ... a collaboration of nearly 6000 physicists/students/engineers/technicians working at ~40 different countries and ~100 nationalities (~1200 PhD students!)

60

Electrons: electromagnetic showers in the calorimeter







High-energy electrons lose energy mainly by bremsstrahlung

X_o (radiation length) mean distance over which electron loses all but $1/e$ of its energy due to brem:
$X_o(Pb) = 6.37\ g/cm^2$ or ~0.6 cm

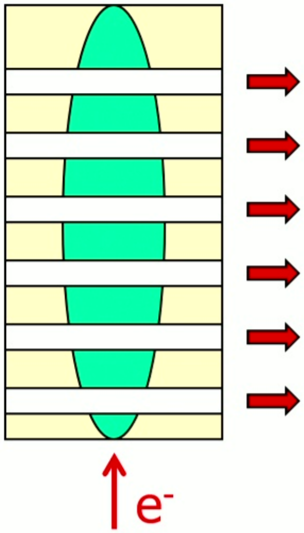
t_{max} (Shower maximum) ~5 X_o for Pb

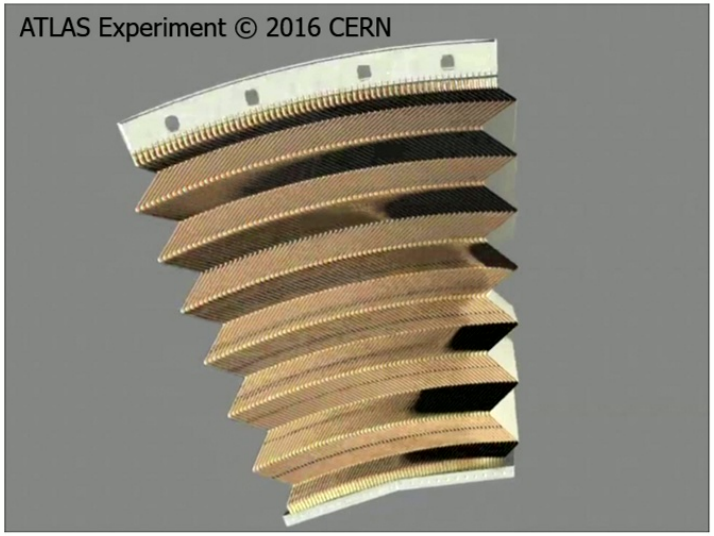
Shower depth scales with X_o:
95% containment
$L_{0.95}(X_o)=t_{max}+0.08\ Z+9.6$
e.g. $L_{0.95}(Pb)$ ~20 X_o

Lateral shower size characterized by
Molière radius $\rho_m = 7A/Z\ g/cm^2$
95% of shower is contained in cylinder of 1 Molière radius
- $\rho_m(Pb) = 17.6\ g/cm^2 \approx 3\ X_0$

EM sampling calorimeter

ATLAS uses a sampling calorimeter: samples the progression of an electromagnetic shower and infers properties from shower width, depth, and where the energy is deposited





Characteristics of electrons and photons in ATLAS

- Narrow showers, well contained in the electromagnetic calorimeter
- Not much variation in the shower properties (lateral, longitudinal) on an event-by-event basis, for an electron/photon of a given energy

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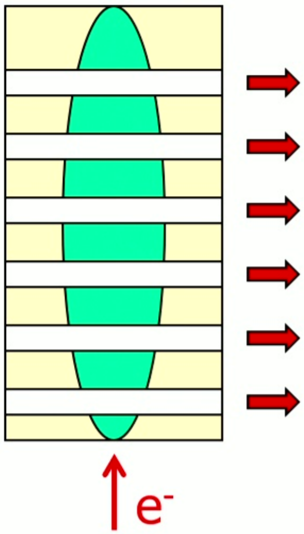

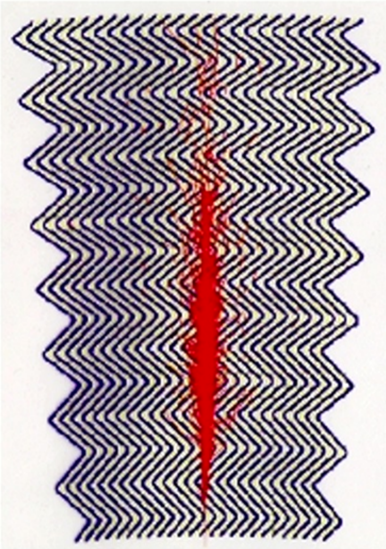

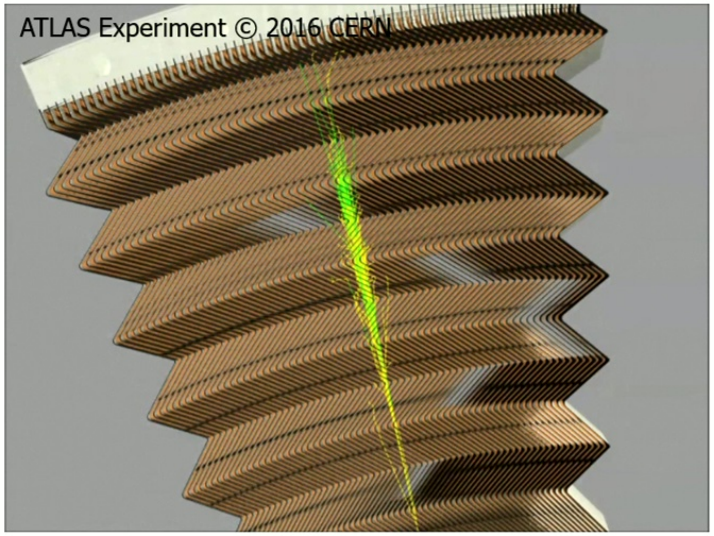

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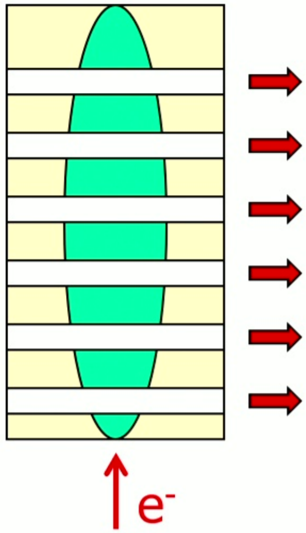

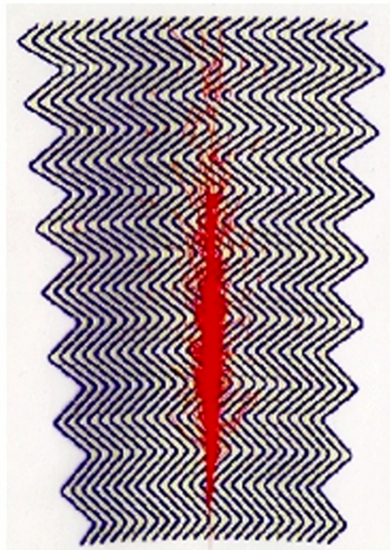

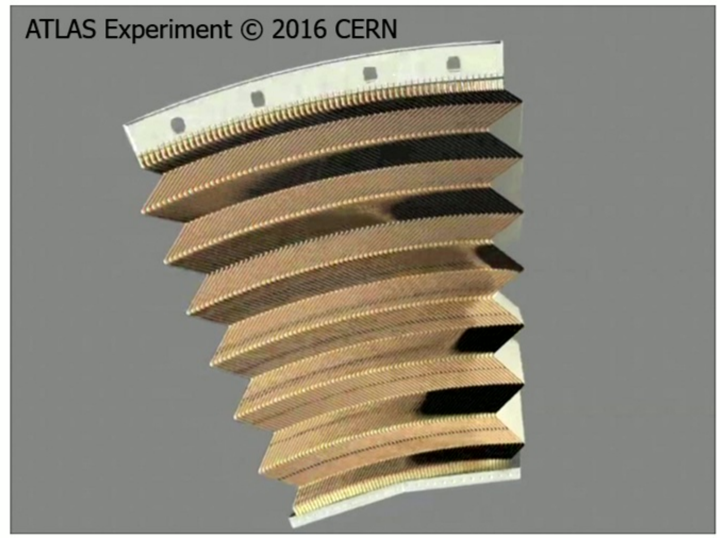

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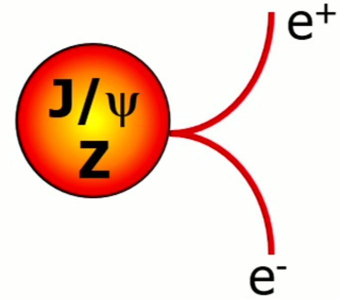
Calibrating the EM calorimeter



- Nature made some very nice resonances that have been measured very precisely!
  - Standard candles!
- Our calorimeters better give consistent values!

Z $J = 1$ pdg.lbl.gov

Z MASS

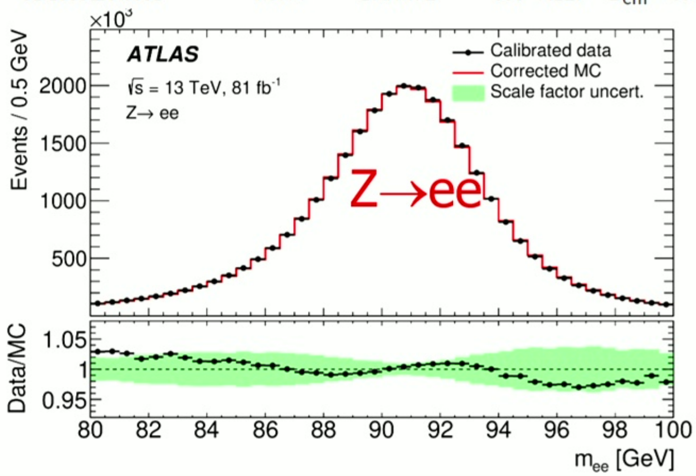
VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
91.1876±0.0021 OUR FIT					
91.1852±0.0030	4.57M	[1] ABBIENDI	01A	OPAL	E^{ee}_{cm}= 88–94 GeV
91.1863±0.0028	4.08M	[2] ABREU	00F	DLPH	E^{ee}_{cm}= 88–94 GeV
91.1898±0.0031	3.96M	[3] ACCIARRI	00C	L3	E^{ee}_{cm}= 88–94 GeV
91.1885±0.0031	4.57M	[4] BARATE	00C	ALEP	E^{ee}_{cm}= 88–94 GeV

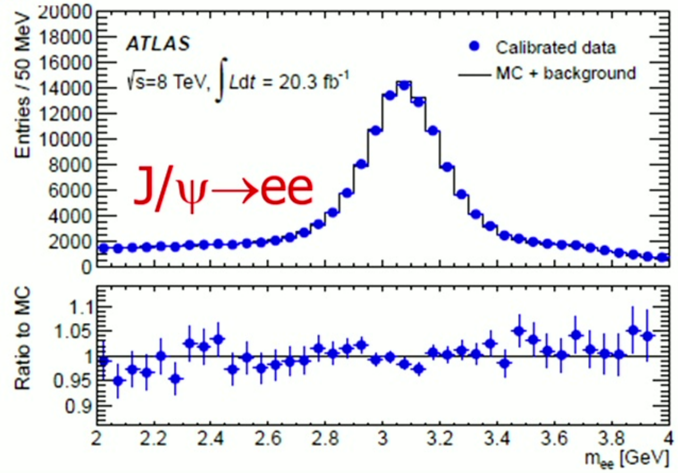
$J/\psi(1S)$ $I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3096.900±0.006 OUR AVERAGE					
3096.900±0.002±0.006		[1] ANASHIN	15	KEDR	$e^+e^- \to$ hadrons
3096.89 ±0.09	502	[2] ARTAMONOV	00	OLYA	$e^+e^- \to$ hadrons
3096.91 ±0.03 ±0.01		[3] ARMSTRONG	93B	E760	$\bar{p}p \to e^+e^-$
3096.95 ±0.1 ±0.3	193	BAGLIN	87	SPEC	$\bar{p}p \to e^+e^-X$

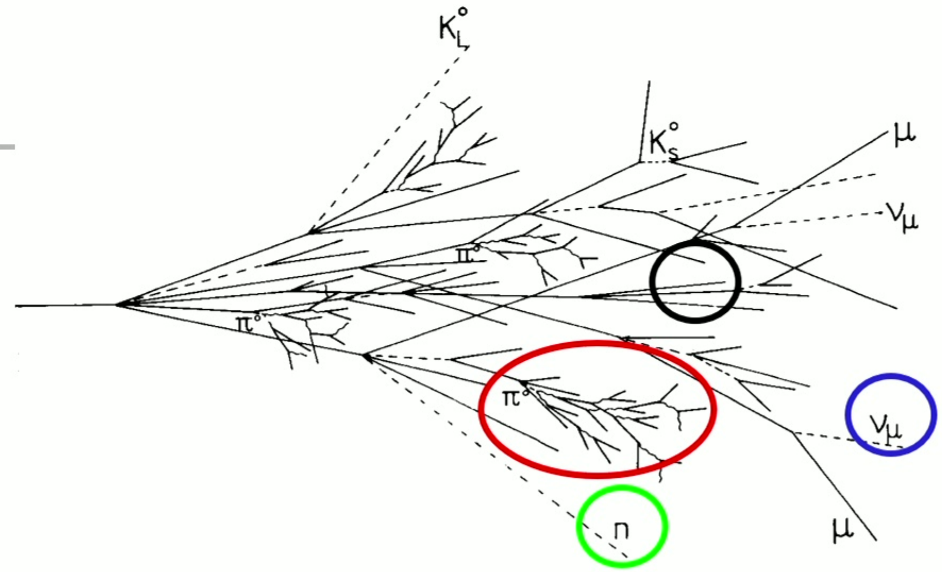
JINST 14 (2019) P12006





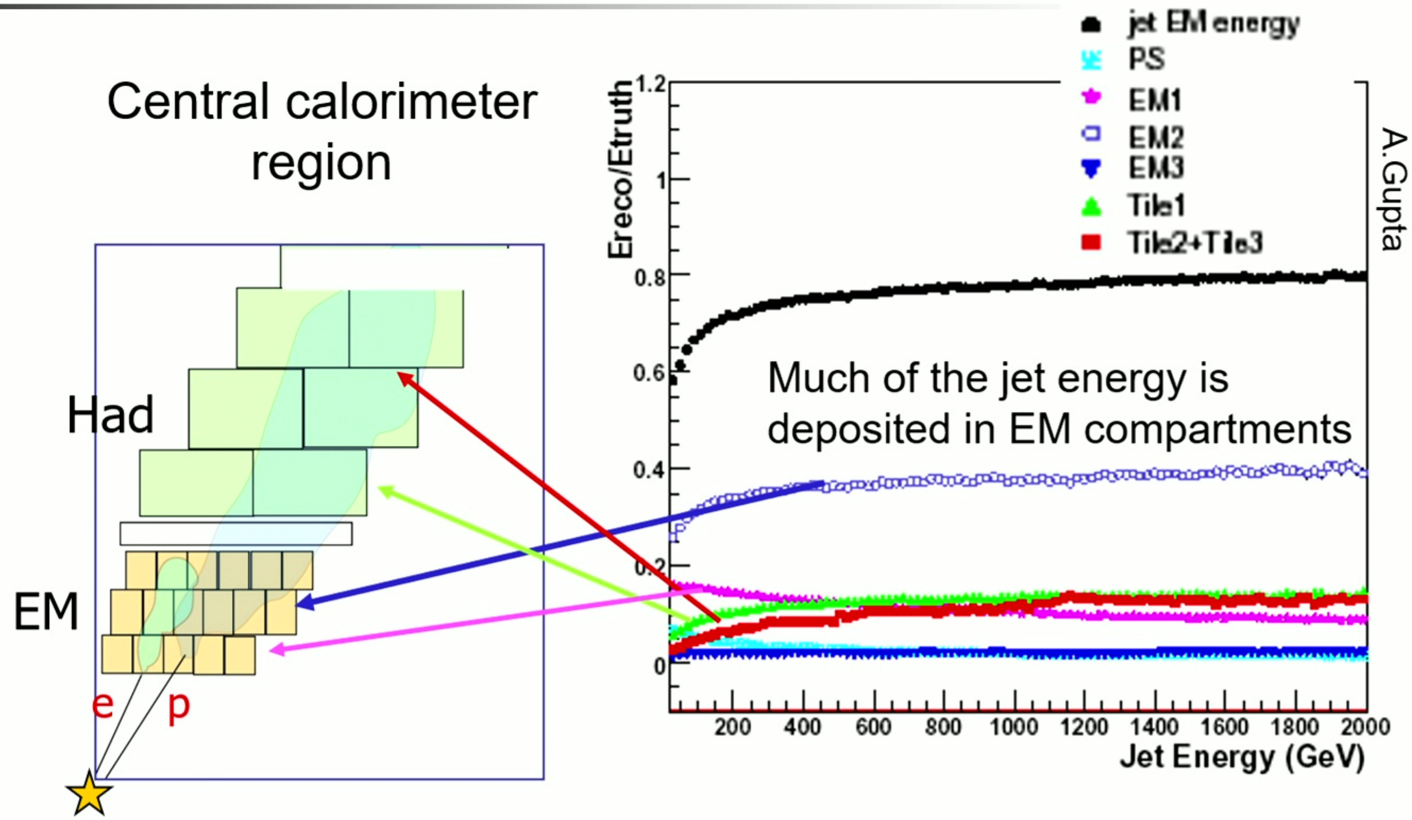
Eur. Phys. J. C 74 (2014) 3071

Jets: hadronic showers



- More complex than EM showers
  - visible EM O(50%)
    - $e^\pm$, γ, $\pi^o \rightarrow \gamma\gamma$
  - visible non-EM O(25%)
    - ionization of $\pi^\pm$, p, $\mu^\pm$
  - invisible O(25%)
    - nuclear break-up & excitation
  - escaped O(2%)
- Only part of visible energy sampled
- Nuclear interaction length is the characteristic distance for hadronic interactions (mean distance travelled by a hadronic particle before undergoing an inelastic nuclear interaction)
  - λ(Fe) = 132g/cm^2 or 17 cm
- Shower maximum $t_{max} \approx 0.6 \ln E(\mathrm{GeV}) - 0.2$
  - t_{max} (100GeV jet) $\approx 2.5\lambda$
- Depth for 95% containment
- $L^{0.95} \approx t_{max} + 4E^{0.15}$ (GeV) $\approx 10\lambda$ for 100 GeV jet
- Radius for 95% containment
  - $R \approx \lambda$
- Hadronic showers are much wider and penetrating than EM showers

Where is the jet energy deposited ?

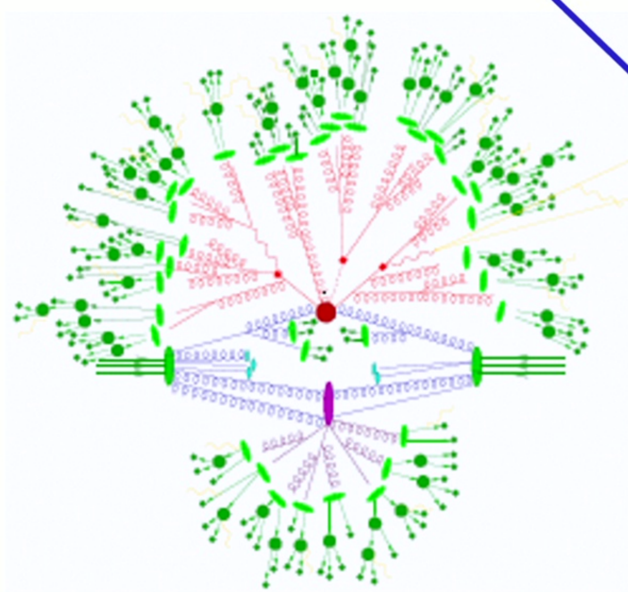


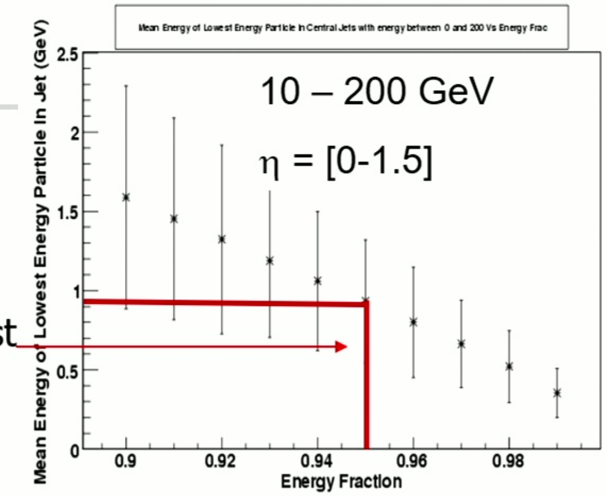
Makes sense since much of the hadronic shower is EM in nature! However, there are enormous fluctuations of an event-by-event basis.

Old simulation for illustration

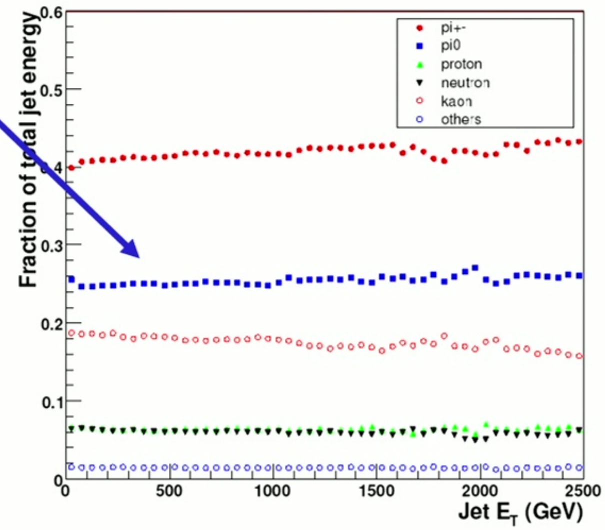
Composition of the jets

- Jets composed of many particles which carry a low percentage of the jet energy
- to collect 95% of the jet energy particles down to GeV must be collected
- 25% of jet energy is from π^0





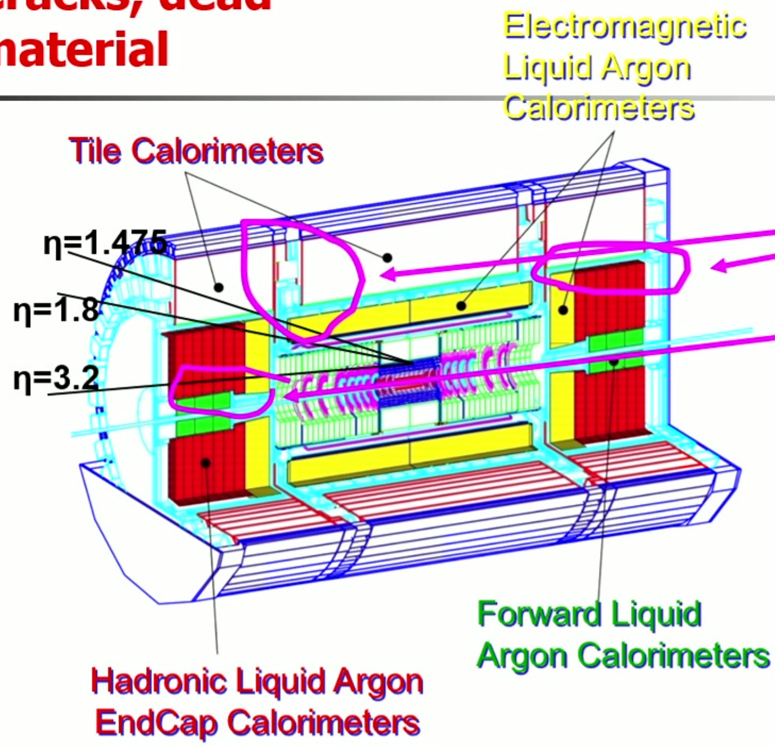
M.Hodgkinson

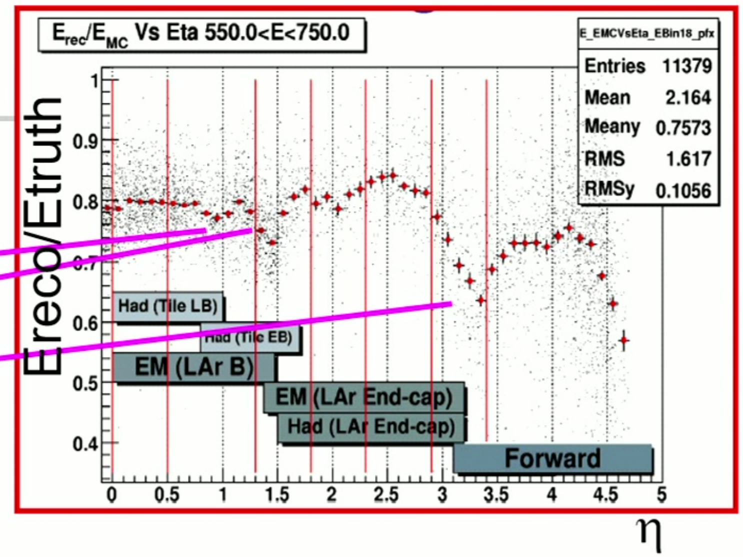


66

Cracks, dead material

Old simulation for illustration





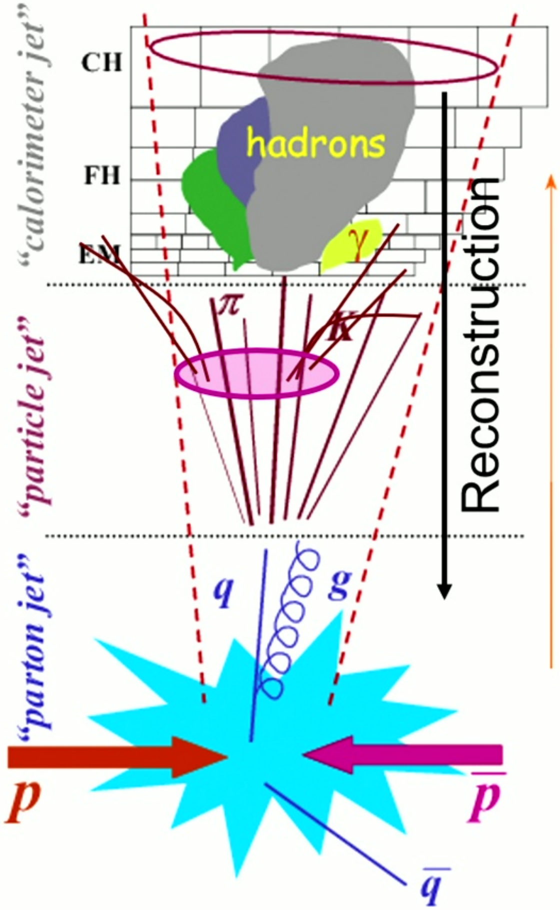
Transition regions

ATLAS analysers need to correct for these losses before data can be useful to outside world. Good simulation of the detector is essential! This is why "raw data" is useless to the outside world!

- ATLAS has a lot of "dead material" and cracks: does not record energy deposit.
  - needed to support the experiment
  - cryostats to contain cryogenic liquids
  - cables to bring voltage to the detector and take signals out of the detector
- Important to know it to reconstruct total energy deposit in detector
- The variation of jet energy response as a function of pseudorapidity is up to 30%

67

Jet reconstruction



- Jet reconstruction: use e.g. the calorimeter signals to determine the kinematics of the particle jet or parton jet (depending on where we want to do theory-data comparison)
- Parton jet, Particle jet, Calorimeter jets obtained running the same jet clustering algorithm on partons, stable particles after fragmentation or calorimeter signal.
- Need to gather clusters of energy in the calorimeters, calibrate them, take into account corrections to go calorimeter jet → particle jet → parton jet

68

Old representation for illustration

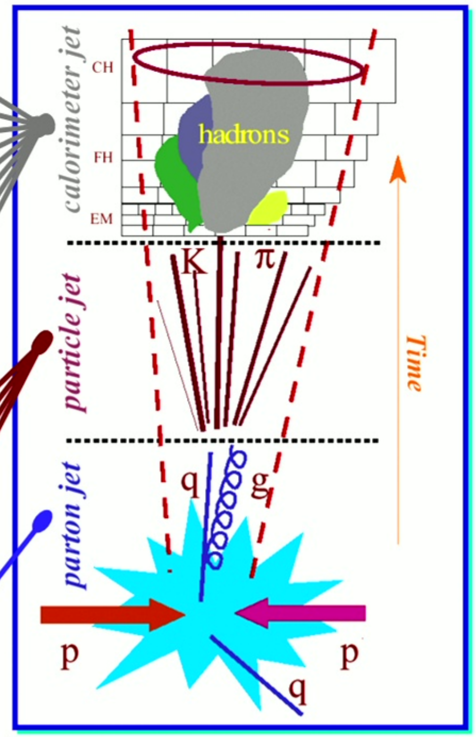
Jet Reconstruction and Calibration

- Examples of contributions to the jet signal:

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV…)
pile-up noise from (off-time) bunch crossings
electronic noise
calo signal definition (clustering, noise suppression ,…)
dead material losses (front, cracks, transitions…)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency

jet reconstruction algorithm efficiency
added tracks from in-time (same trigger) pile-up event
added tracks from underlying event
lost soft tracks due to magnetic field

physics reaction of interest (parton level)

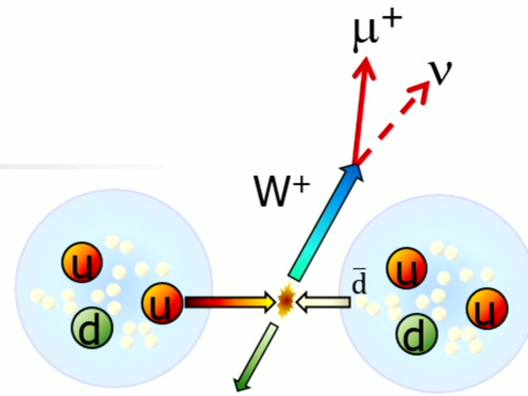


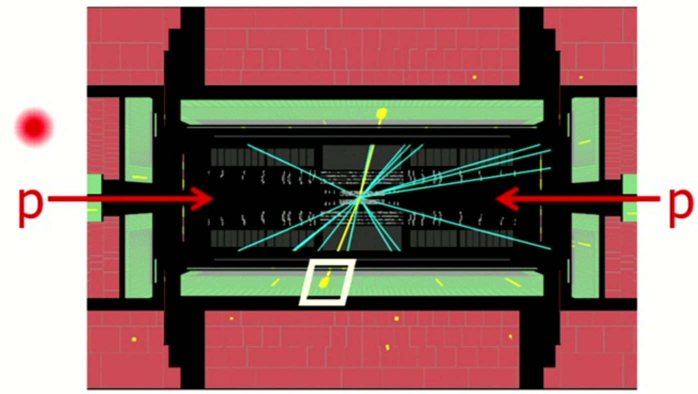
Try to address reconstruction and calibration through different levels of factorisation

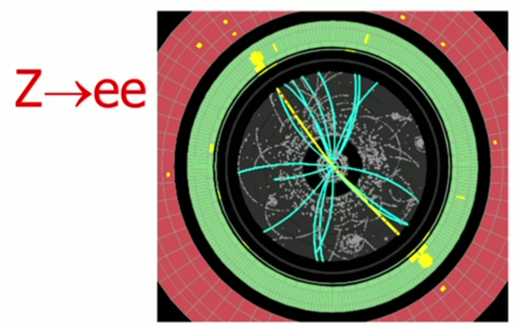
"Invisible" particles

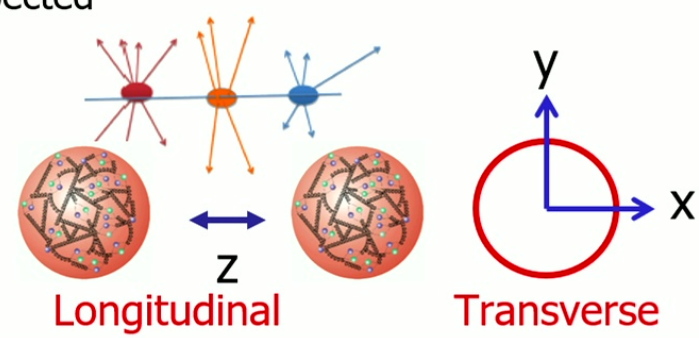
- Real sources of missing energy!
  - Neutrinos!
  - $W \to \mu\nu$, Higgs ($H \to WW$, $H \to \tau\tau$)
  - Understand well your SM processes!
- Fake sources of missing energy!
  - Broken detector components
  - Holes in your detector acceptance
  - Know (simulate) well your detector!

- Look at activity in the transverse plane where no (little) *net* activity expected



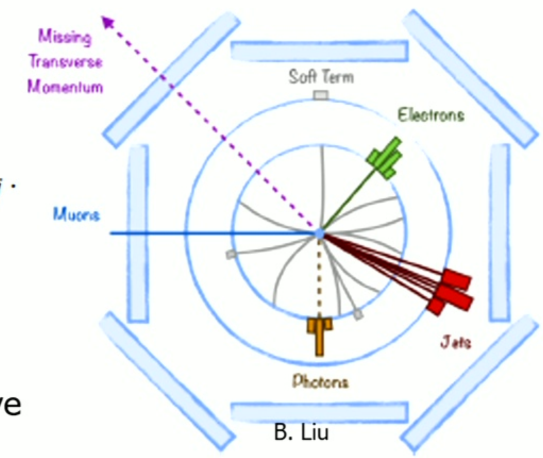






70

Missing transverse energy/momentum E_T^{miss} (MET)



B. Liu

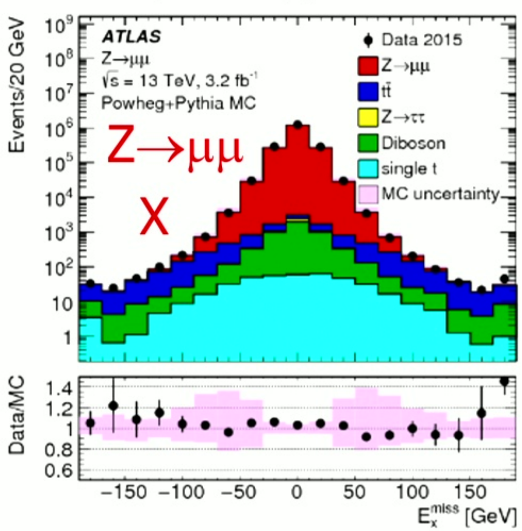
- E_T^{miss}: momentum imbalance in transverse plane
  - Negative vectorial sum of everything detected in event!

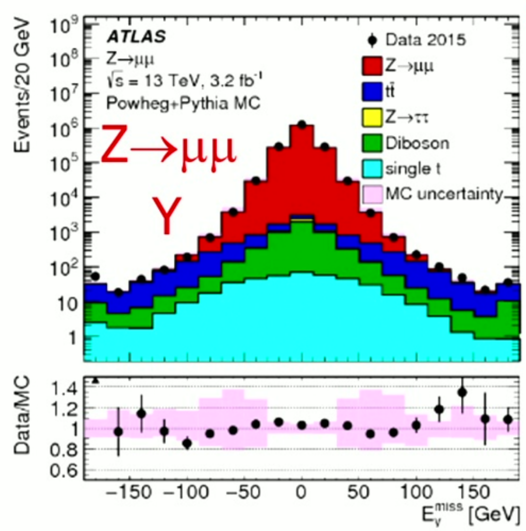
$$E_{x(y)}^{\rm miss} = -\sum_{i\in\{\text{hard objects}\}} p_{x(y),i} - \sum_{j\in\{\text{soft signals}\}} p_{x(y),j}\,.$$

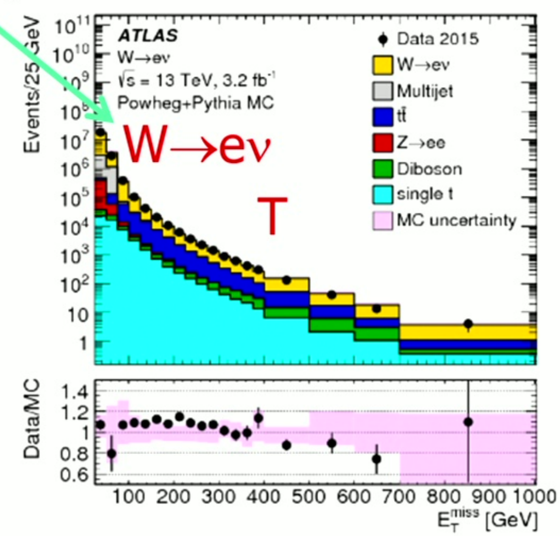
$$E_{x(y)}^{miss} = -(E_{x(y)}^{jets} + E_{x(y)}^{e} + E_{x(y)}^{\gamma} + E_{x(y)}^{\tau} + E_{x(y)}^{\mu} + E_{x(y)}^{soft\,stuff}) \qquad E_T^{\rm miss} = \sqrt{(E_x^{\rm miss})^2 + (E_y^{\rm miss})^2},$$

  - Soft stuff: other objects associated with primary vertex but not to any hard object above
- Performance benchmarked based on different SM samples:
  - No "real" E_T^{miss}: $Z\to\mu\mu$

With "real" E_T^{miss} : $W\to e\nu$



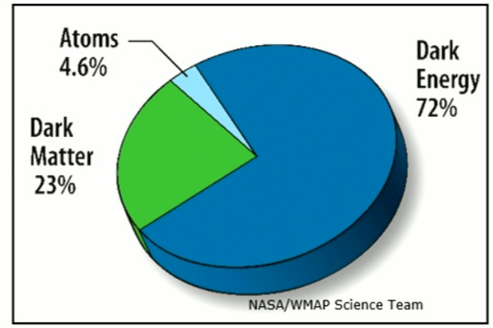




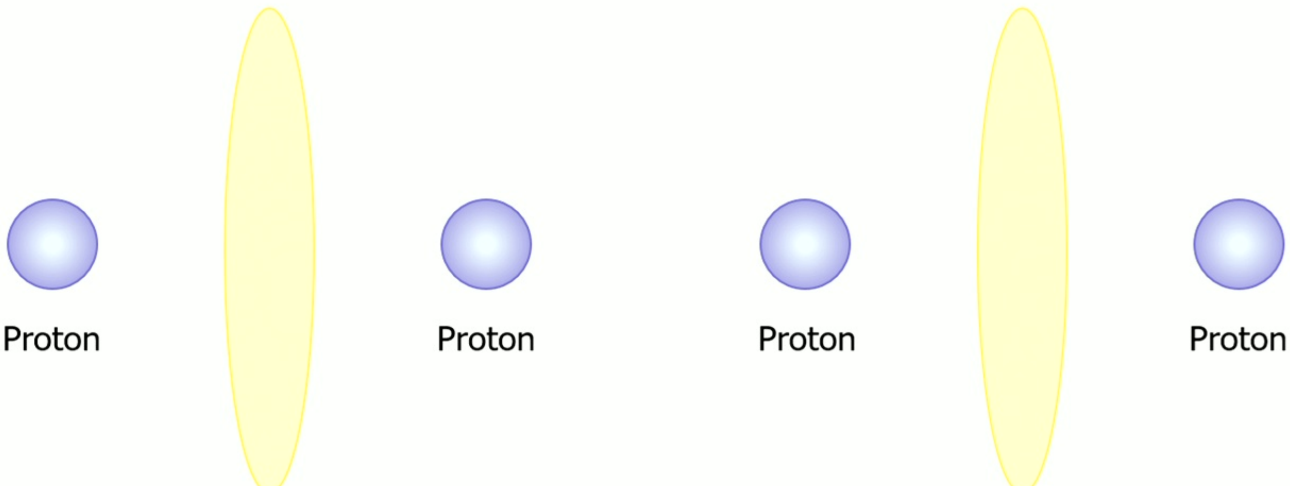
- No "new physics" unless E_T^{miss} well understood!

Eur. Phys. J. C 78 (2018) 903

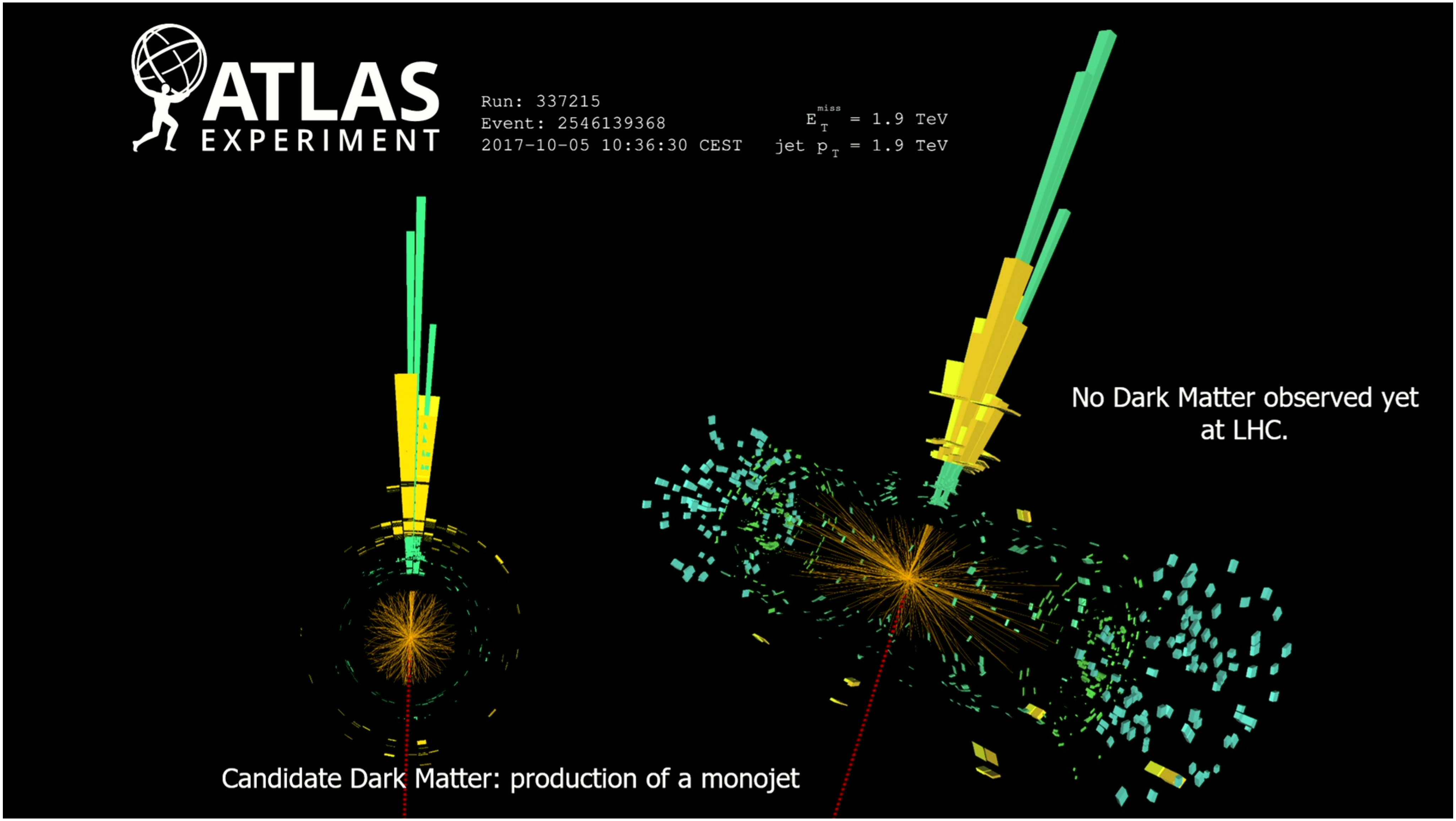
Dark Matter: how can we see something that we can't "see"?



- Dark Matter is thought to be "weakly interacting"
  - Doesn't emit light and doesn't interact with most of the fundamental forces.
- Even if we can't see it, it can have an effect on other particles, through the conservation of fundamental laws of physics like conservation of energy and momentum.

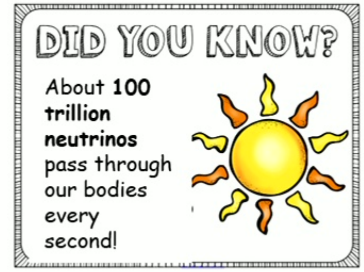


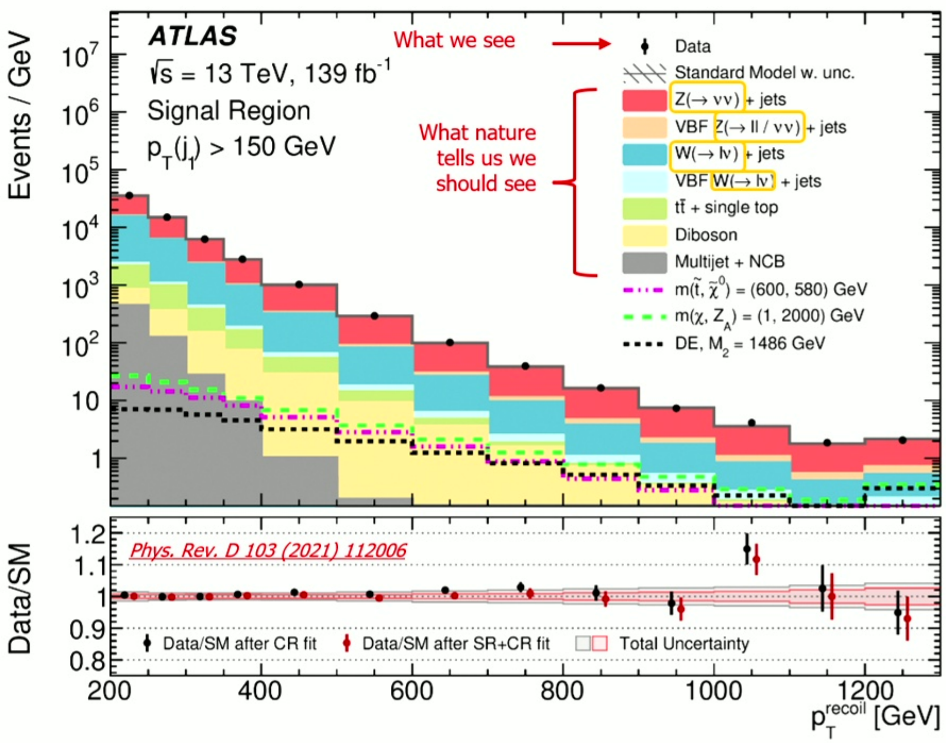
- Can look for particles that seem to recoil against *nothing*
- One example of a search for Dark Matter…

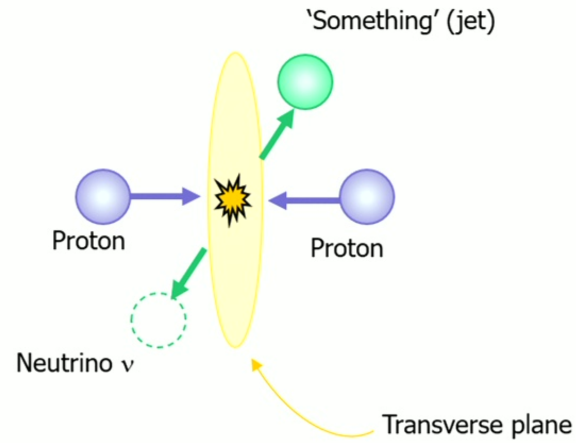

ATLAS
EXPERIMENT
Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST
E_T^{miss} = 1.9 TeV
jet p_T = 1.9 TeV
No Dark Matter observed yet at LHC.
Candidate Dark Matter: production of a monojet

Excluding all plausible causes for such events…

- Nature already produces particles that "we can't see"!
  - Neutrinos ν (e.g. produced in the Sun but also in LHC collisions)
- Momentum in the transverse plane of the recoiling "something"





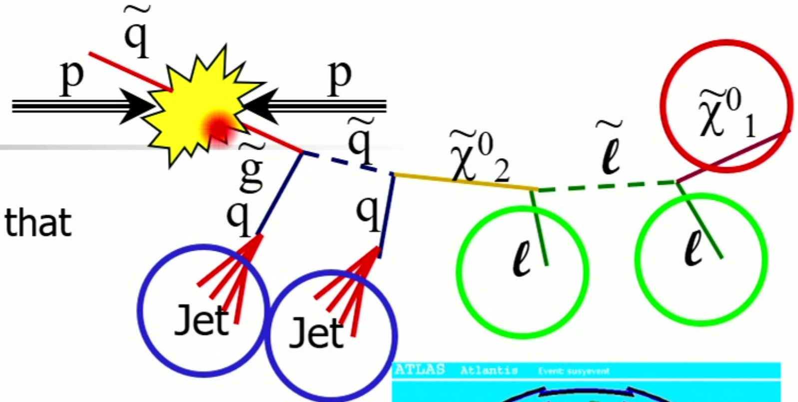


We don't see anything "extra" beyond what our interpretation of Nature ('Standard Model') tells us we should see.

No Dark Matter observed yet at LHC.

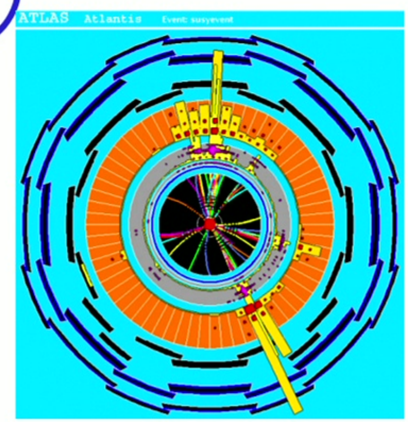
74

Exciting sources of "Invisible" particles…



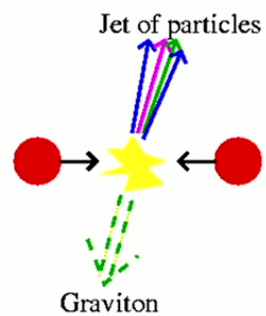
Many exciting beyond SM physics predict new particle that don't interact with the detector

- p-p collision: chain of SUSY & SM particles
  - Signature
    - Jets from quarks
    - Leptons
    - Missing energy from the LSP (neutralino)
- A "typical" SUSY event: six jets, two muons (not visible because they exited the detector in the forward direction), missing energy



- Typical signature for extra dimensions:
  - A single jet recoiling against nothing (escaping graviton)!
    - Jet + lots of missing energy

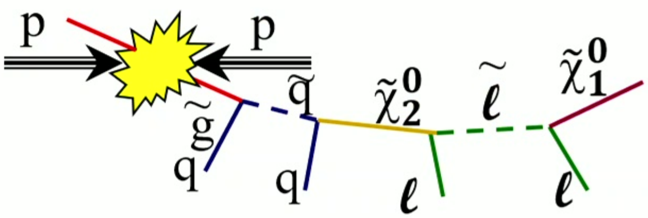
$$q\bar{q} \to gG$$
$$qg \to qG$$
$$gg \to gG$$



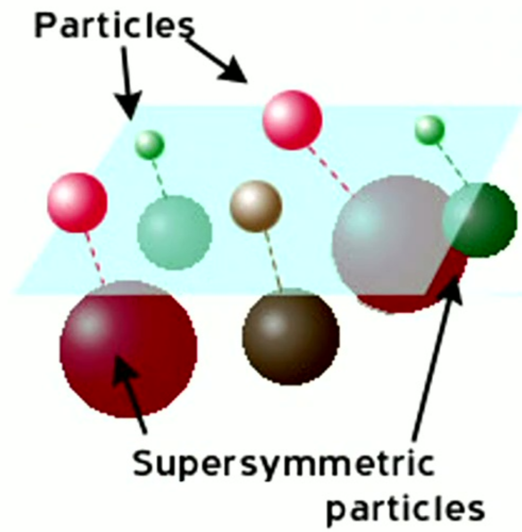
Both cases: something escapes undetected!

Much sought-after: Supersymmetry

- Supersymmetric (SUSY) theory predicts a relationship between matter particles and force carriers. Every fundamental matter particle should have a massive force carrier "super" partner particle, and vice-versa
  - Counterparts to quarks, leptons → squarks, sleptons etc… with different charge, spin…
- In one version of this theory, the lightest member of the SUSY family is the neutralino $\tilde{\chi}_1^0$
  - Neutralinos would have mass (but incredibly difficult to detect). Stable.
  - Could be a candidate for missing dark matter in the universe!



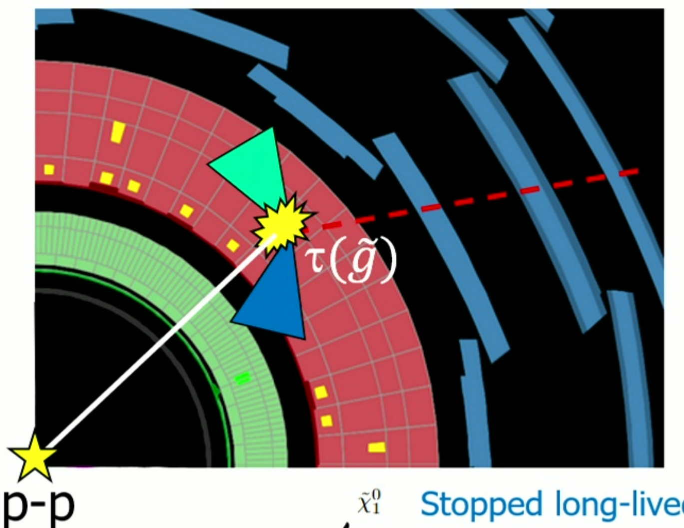
"Democratic" production of SM and SUSY particles in pp collisions

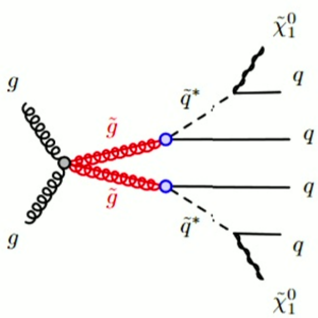


76

Search for long-lived particles: SUSY interpretations

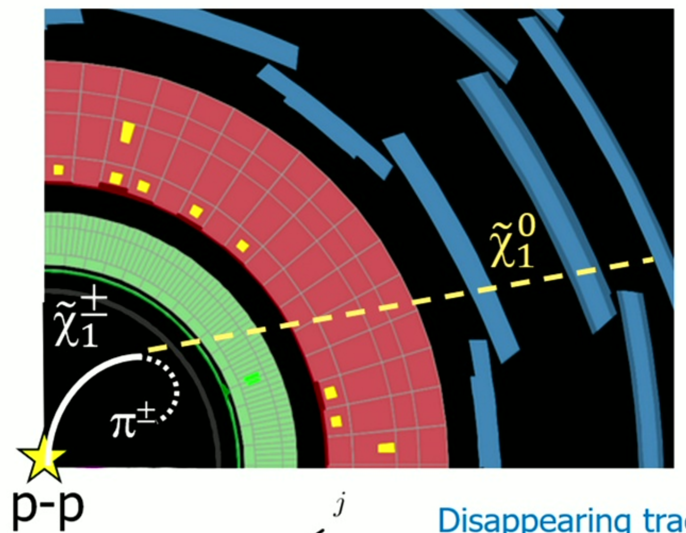
Looking for: stopped gluinos | long-lived charginos

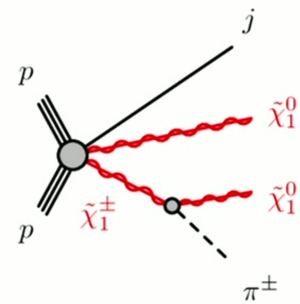




Stopped long-lived particle
Large out-of-time energy deposits

Gluinos forming R-hadrons, $\tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0$



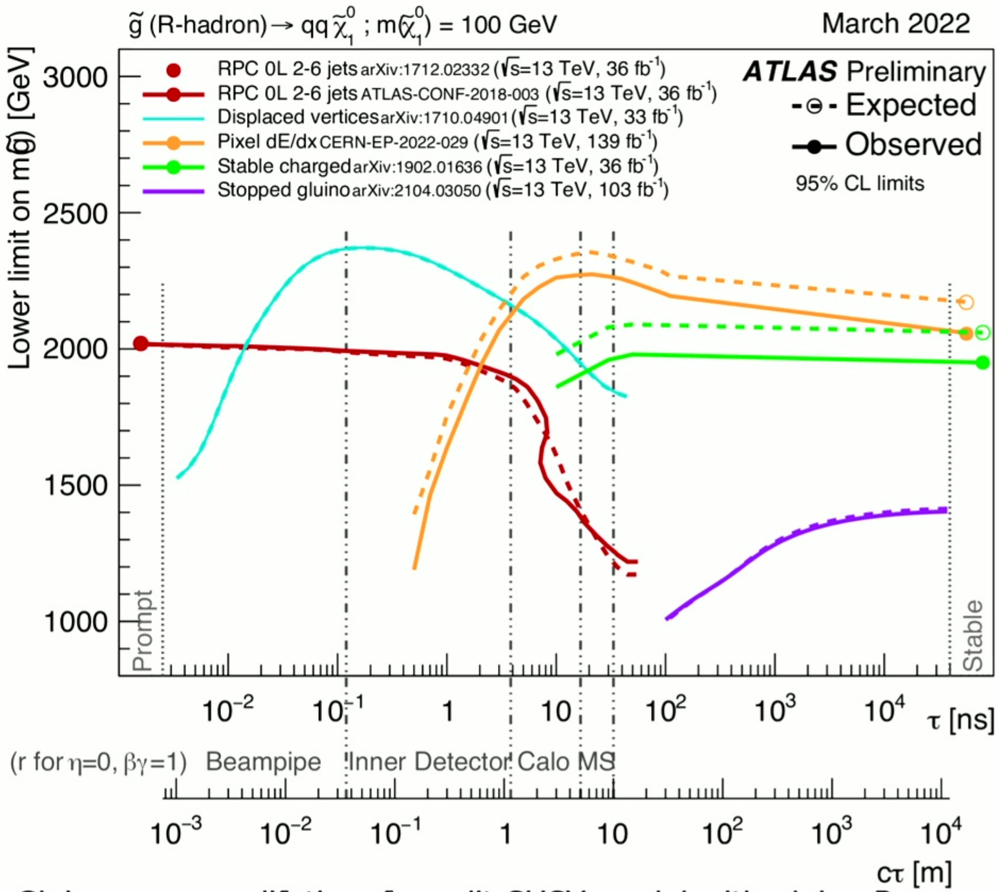


Disappearing track early in inner detector + no calo activity

Chargino $\tilde{\chi}_1^\pm$ decaying to neutralino $\tilde{\chi}_1^0$ + pion

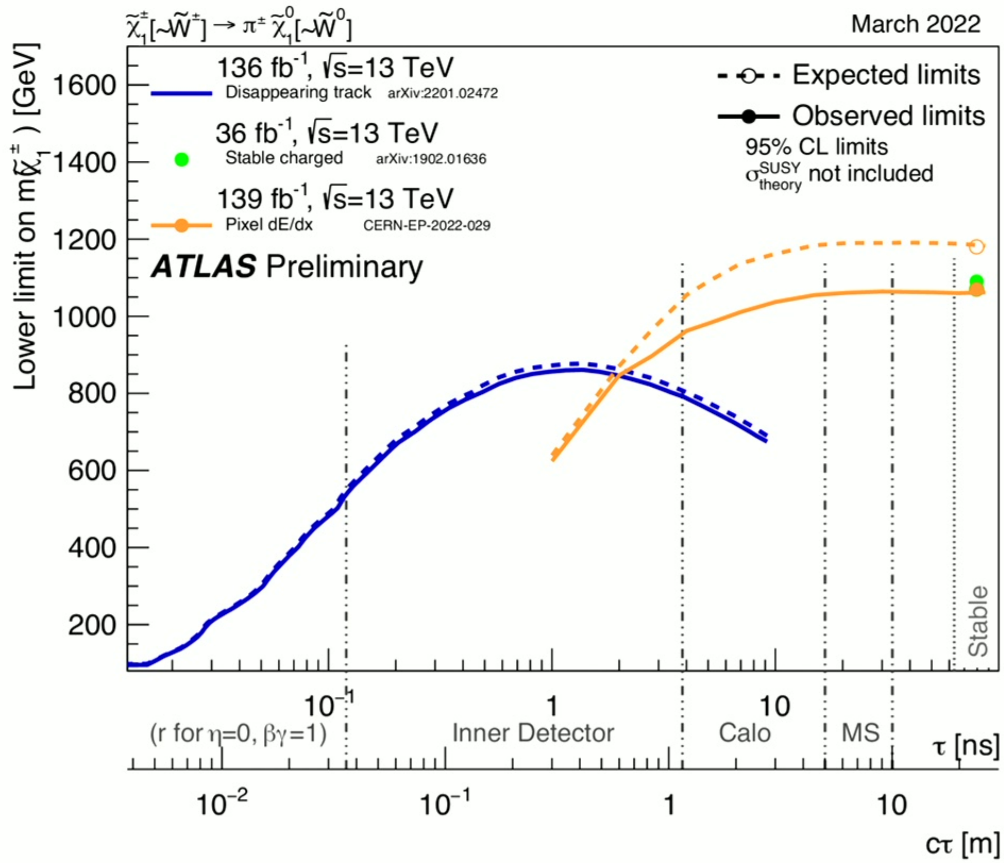
Full long-lived particle programme covers extensive range of possibilities…

Constraints on gluino mass vs. lifetime



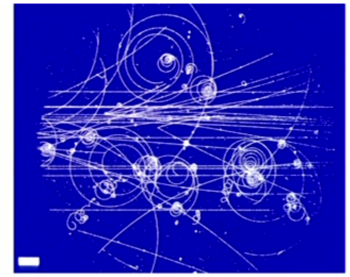
Gluino mass vs. lifetime for split-SUSY model with gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV.

Constraints on chargino mass vs. lifetime



Chargino mass vs. lifetime for AMSB model with tan(β)=5, μ>0. Wino-like chargino is pair-produced and decays to wino-like neutralino and a very soft charged pion.

78

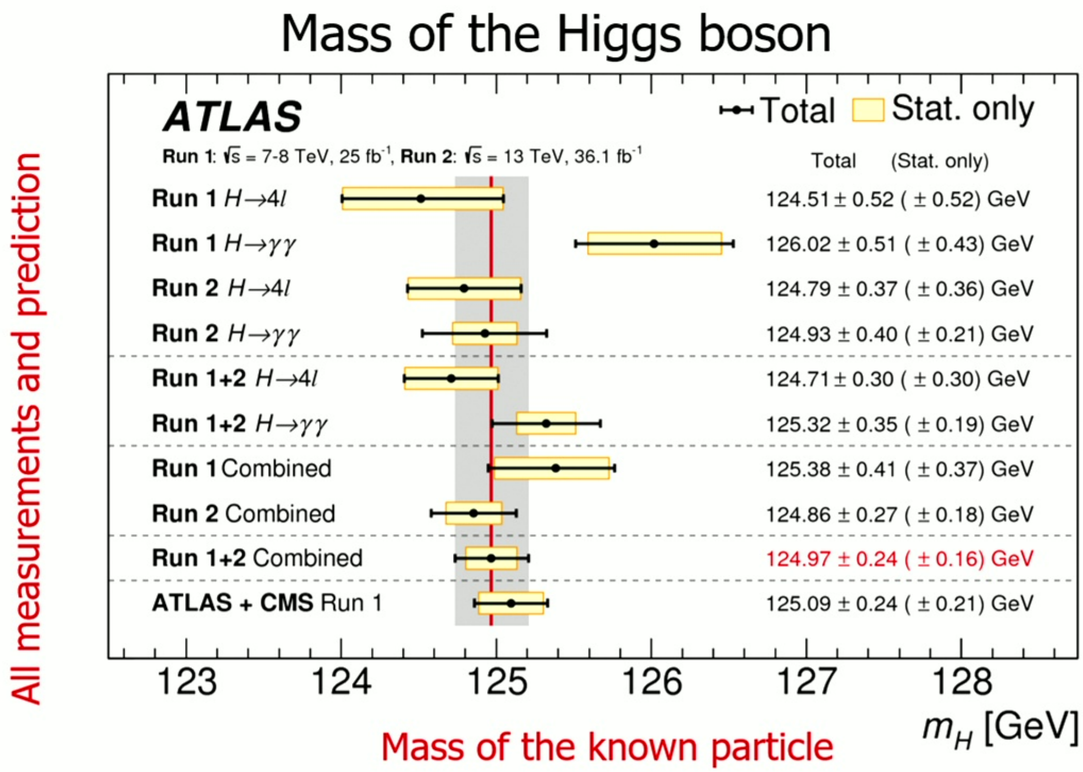


PHYSICS: AT LHC AND OTHER PLACES…

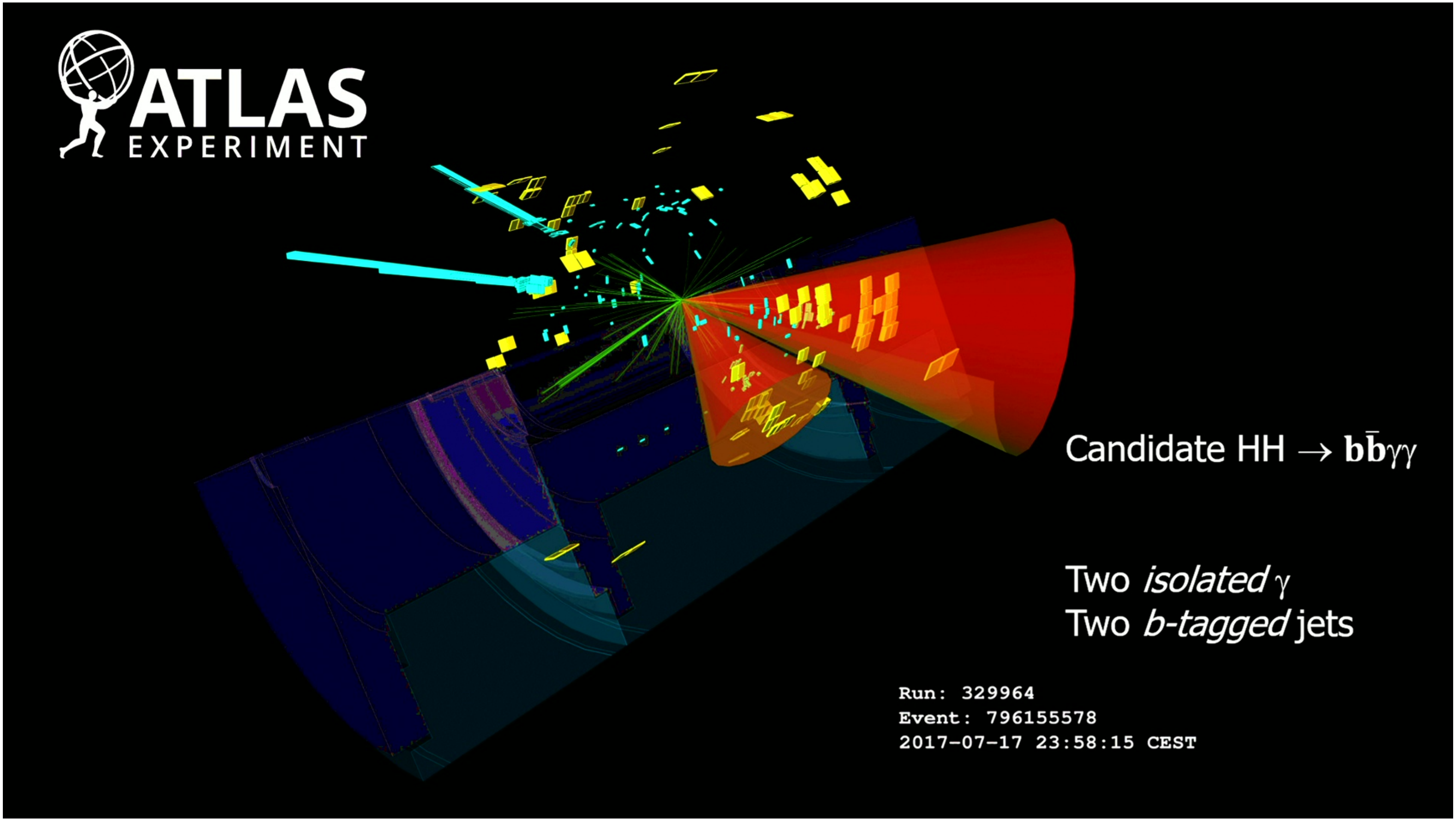
To measure…

[Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with $\sqrt{s}$=13 TeV pp collisions using the ATLAS detector]

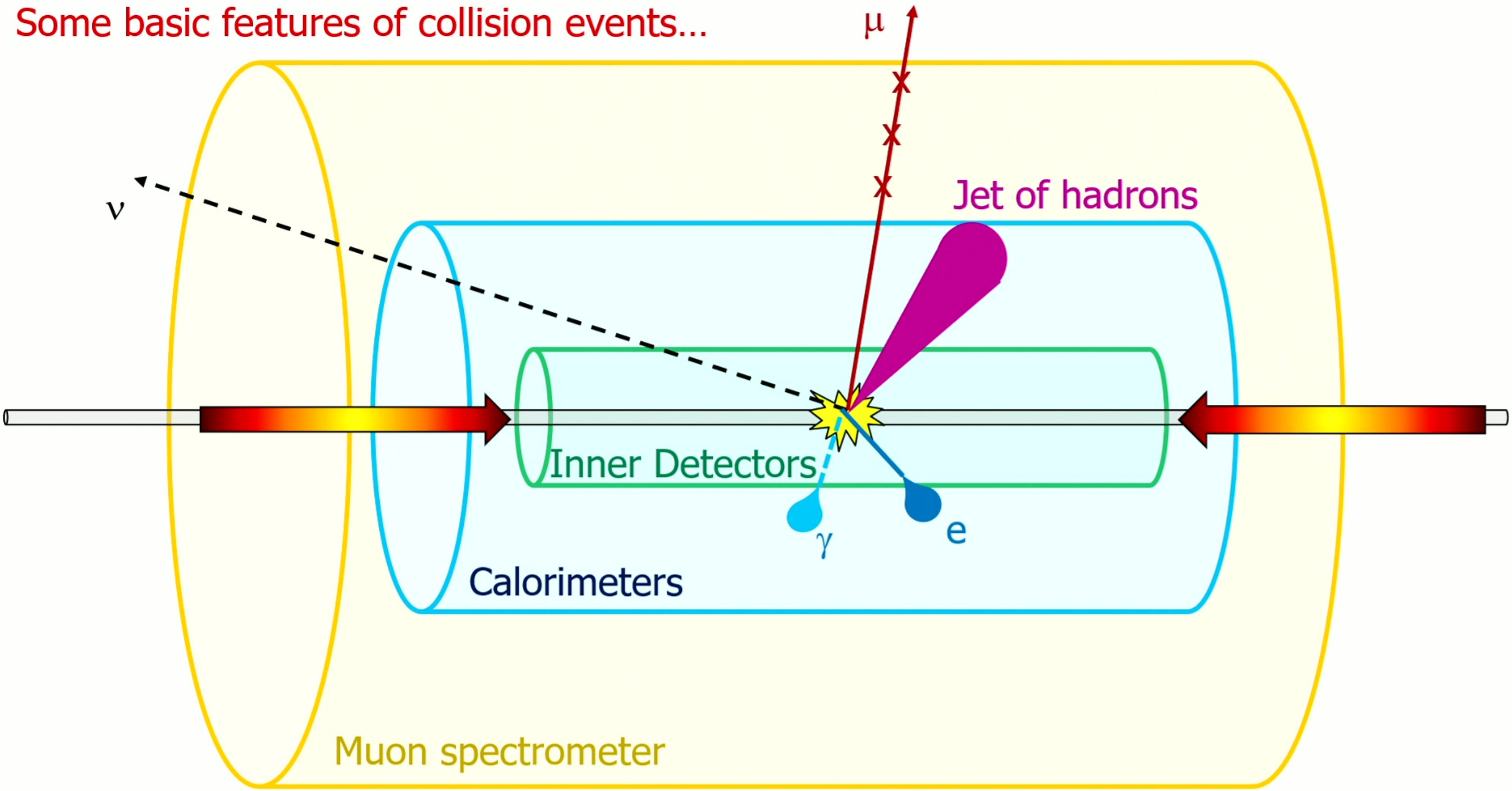
- We study with precision the properties of known particles, to look for deviations from the theoretical predictions.
  - "We measured the properties of this particle with precision, and it agreed with theoretical predictions"



80


ATLAS
EXPERIMENT
Candidate HH → $b\bar{b}\gamma\gamma$
Two *isolated* γ
Two *b-tagged* jets
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

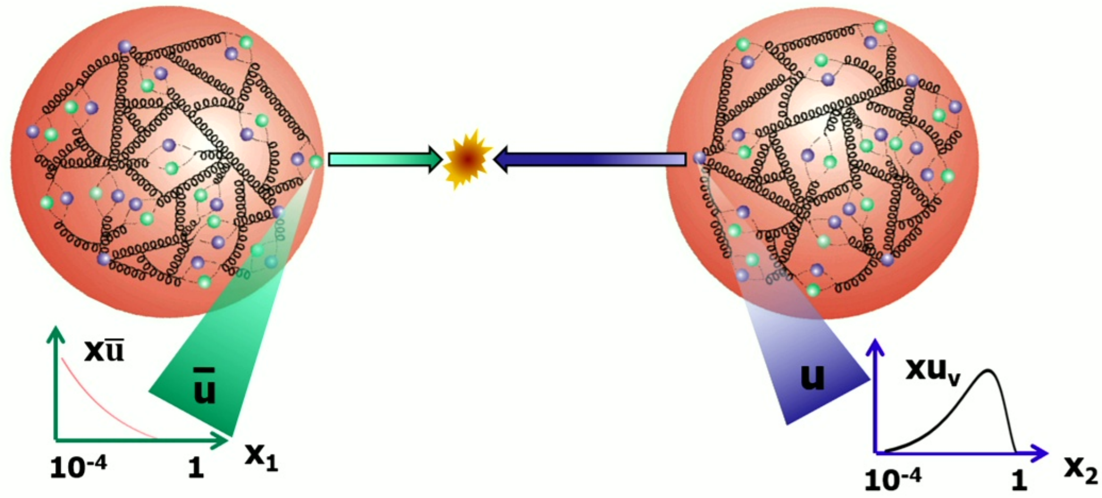
Some basic features of collision events…



And all of this is embedded in magnetic fields for charged-particle bending…

82

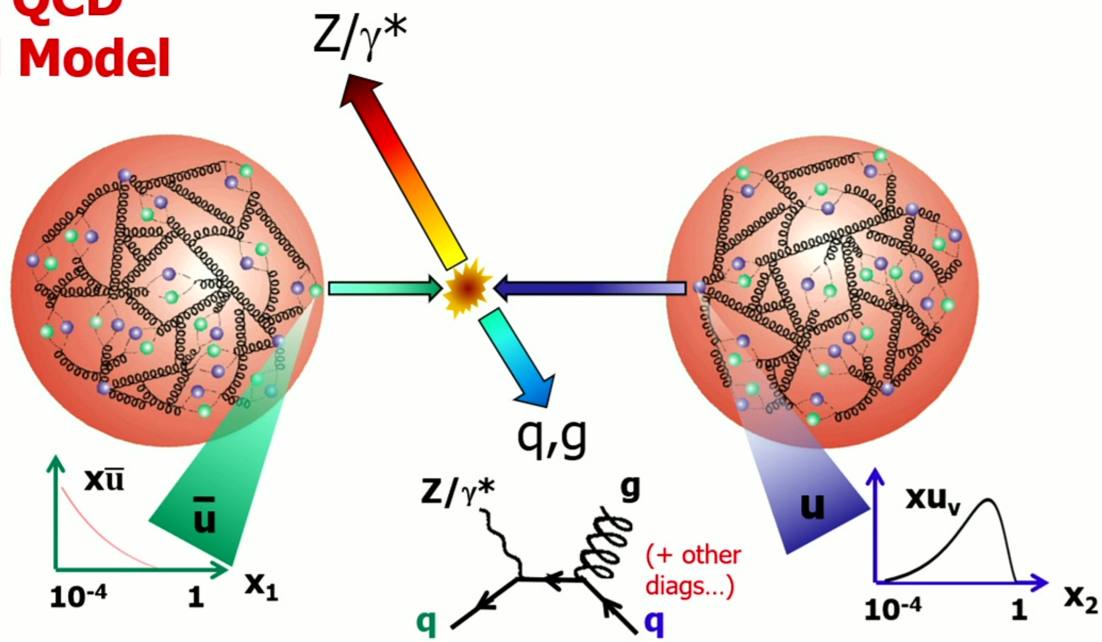
What kind of physics might you see at the LHC?



Parton distribution functions of the proton (pdf)
x_1, x_2 = momentum fraction of partons

Thanks to:
desy.de, hepdata.cedar.ac.uk

Perturbative QCD
i.e. Standard Model



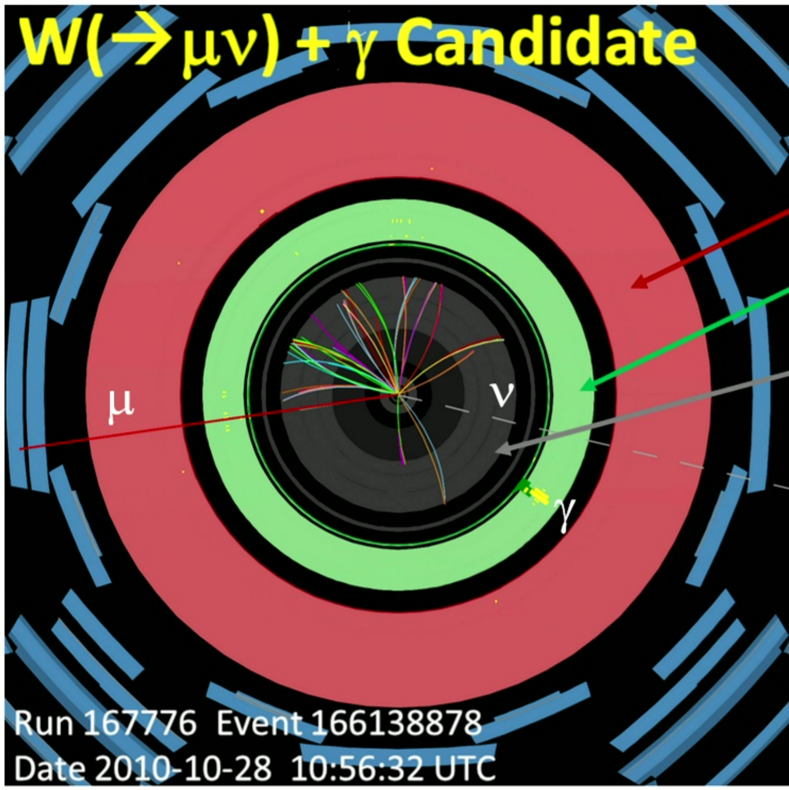
Parton distribution functions of the proton (pdf)
x_1, x_2 = momentum fraction of partons

Hard scattering between partons of flavour q and q

Thanks to:
desy.de, hepdata.cedar.ac.uk

Detecting Standard-Model particles

Massive SM particles decay "immediately" to lighter, more stable particles like electrons, muons, photons



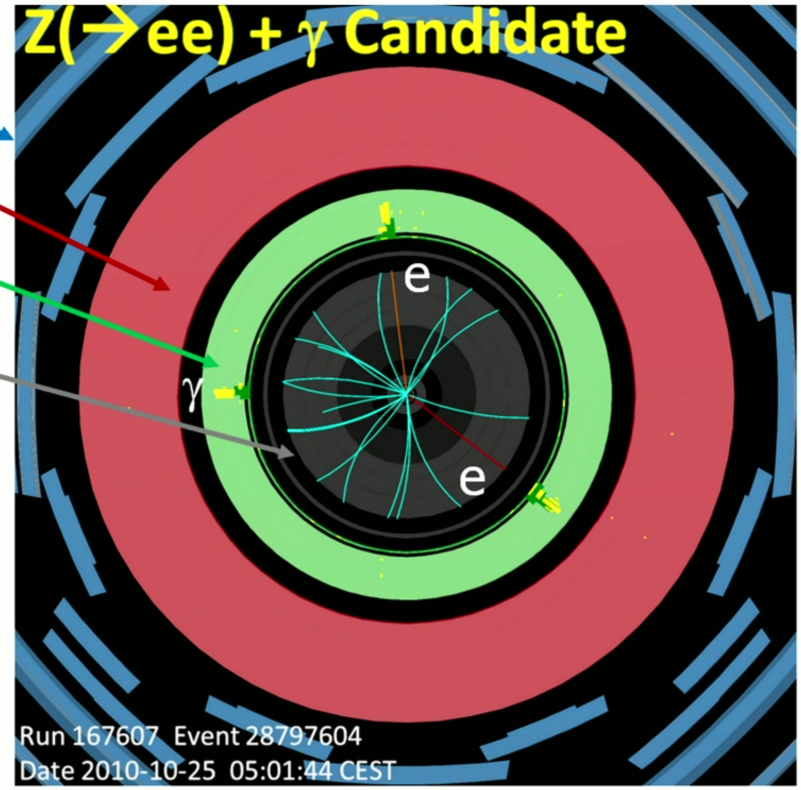
Muon detectors

Hadronic calorimeter

Electromagnetic calo.

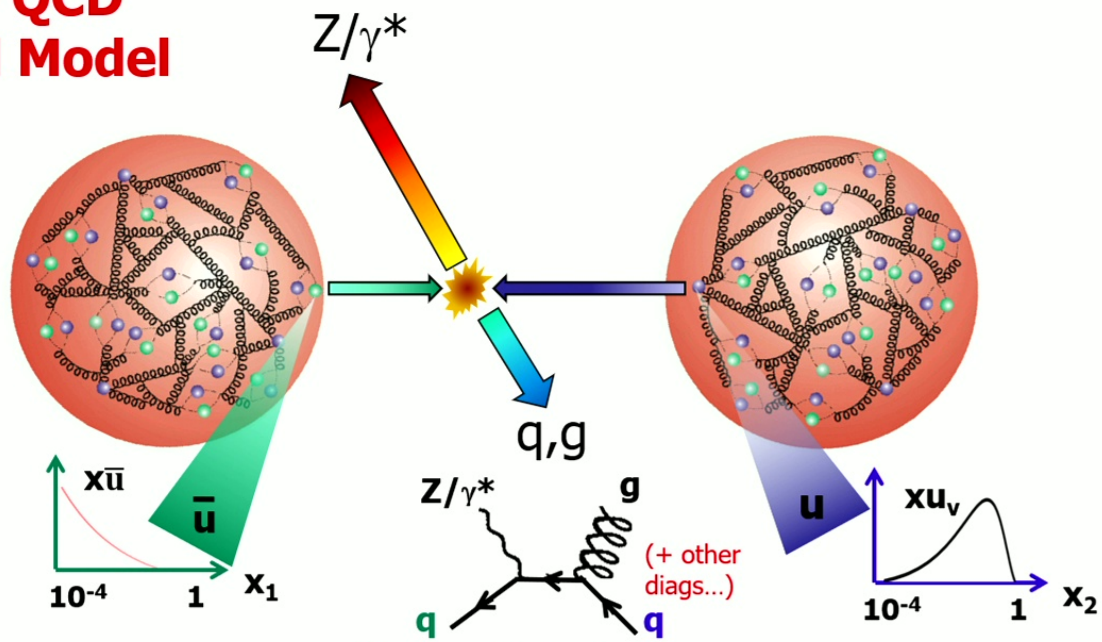
Tracking detectors

W,Z are the carriers of the electroweak force! Half life of ~3×10^{-25} s



proton-proton collision → W (→ μν) or Z (→ ee) + a photon

Perturbative QCD
i.e. Standard Model



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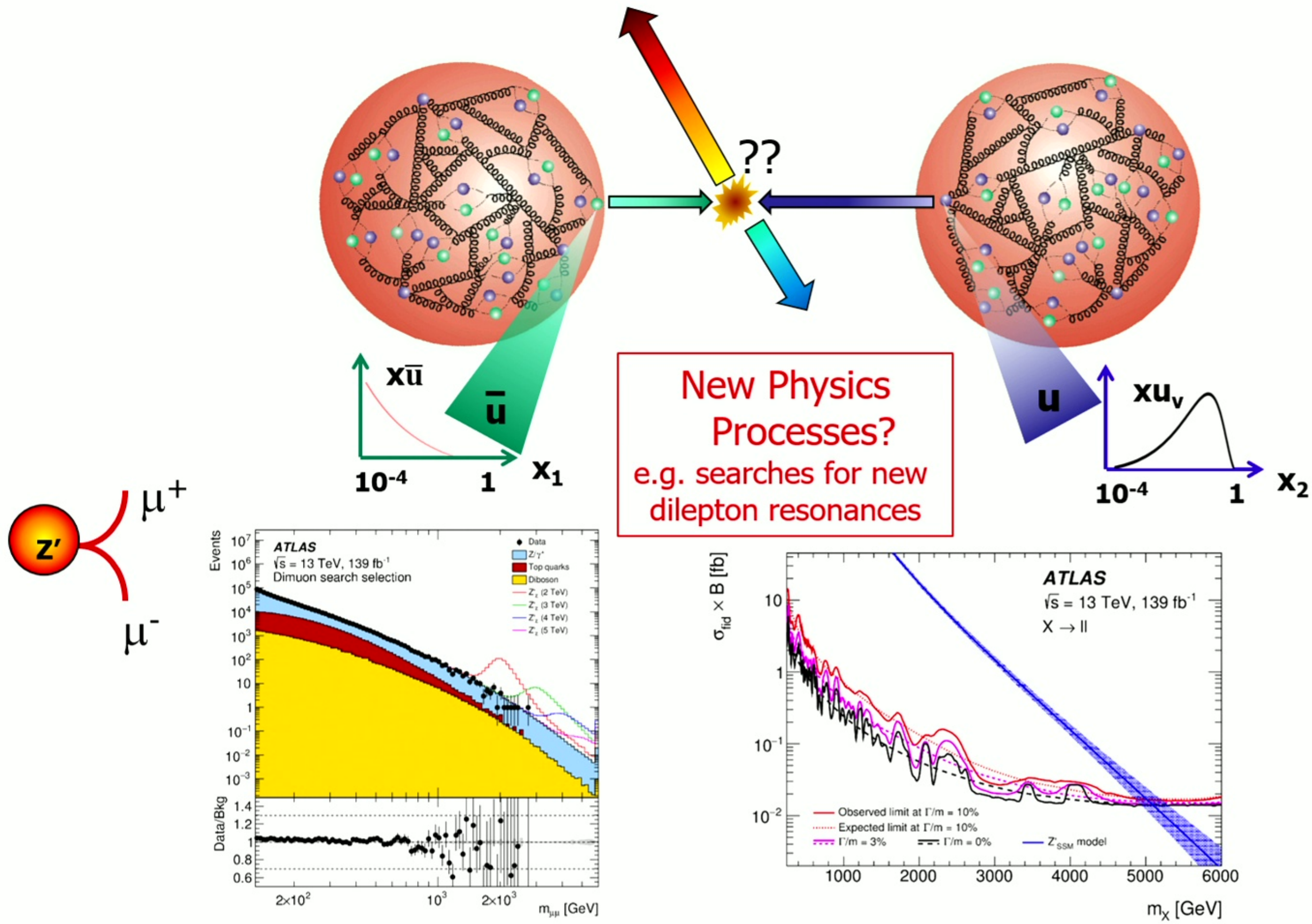
Beyond the SM?

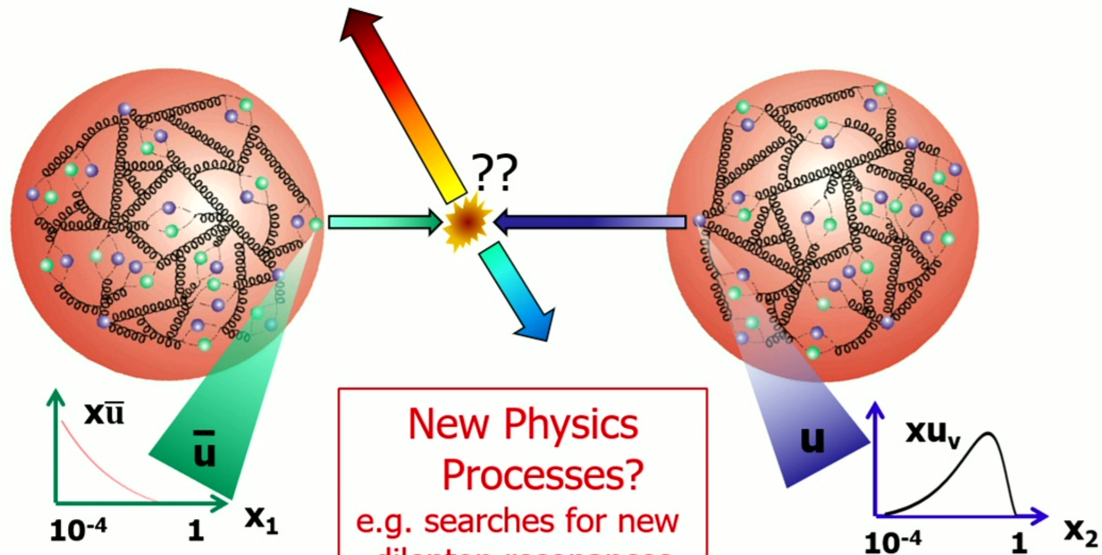
Search for high-mass dilepton resonances using 139fb−1 of *pp* collision data collected at √s=13TeV with the ATLAS detector



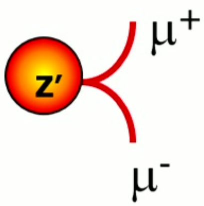
87

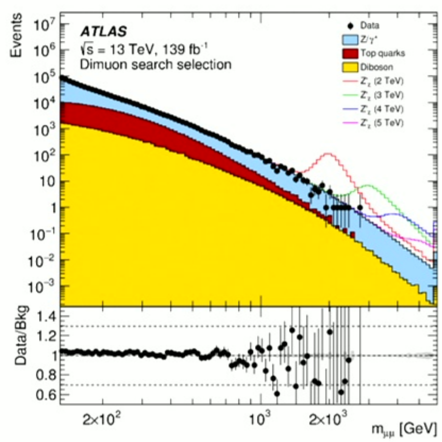
Beyond the SM?

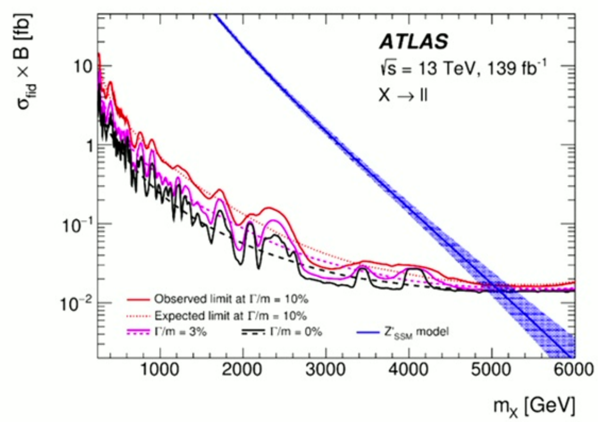
[Search for high-mass dilepton resonances using 139fb−1 of *pp* collision data collected at √s=13TeV with the ATLAS detector]



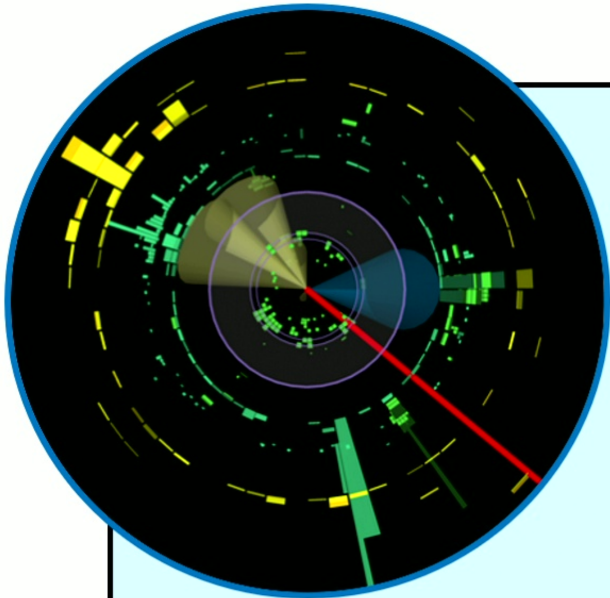
New Physics Processes?
e.g. searches for new dilepton resonances







87



ATLAS EXPERIMENT

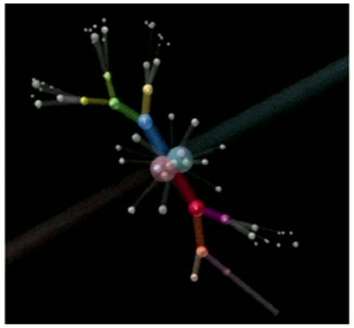
Physics Coordinator

My experience as a woman in science has been extremely positive, which doesn't always mean easy. Women have great deal of resilience and this is a fundamental resource that allows us to succeed through adversities. I am proud of being a woman in science especially when observing and admiring the achievements and success and capabilities of my female colleagues.

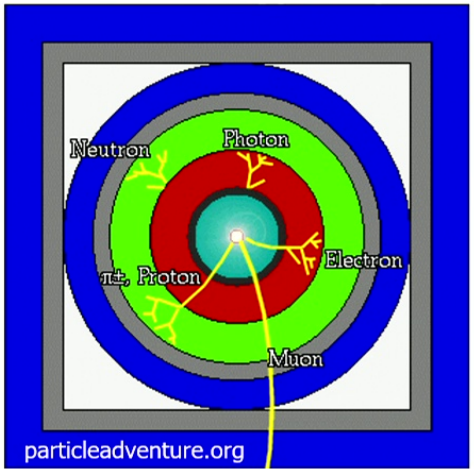
Pamela Ferrari
Chief of Research, Nikhef

88

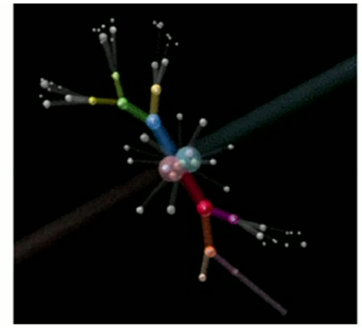
How to interpret the data?



- Particles are created as a result of the proton collisions
- Each layer of our detector provides a piece of the puzzle
- Because colliding "bags of bags of marbles":
  - Interpretation is challenging!
  - Filter out uninteresting part of the "event"
- Most "interesting particles" never make it to detector!
  - Decay so quickly! Only see what that they decay to…
  - Use laws of physics to infer what happened
    - Can deduce the mass of the Higgs



How to interpret the data?



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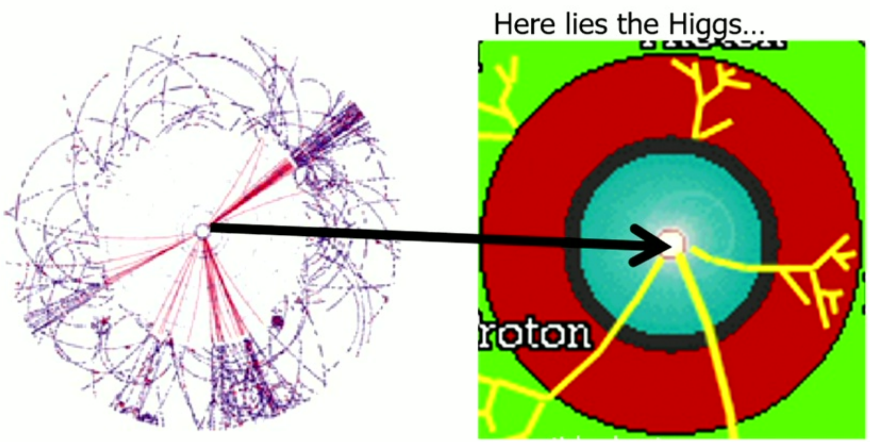
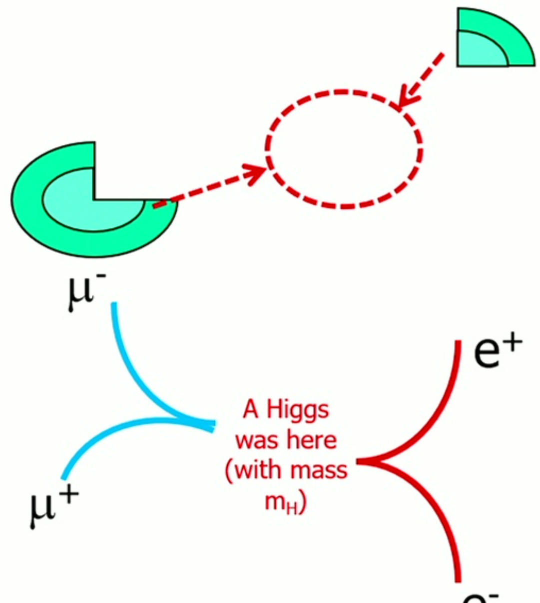
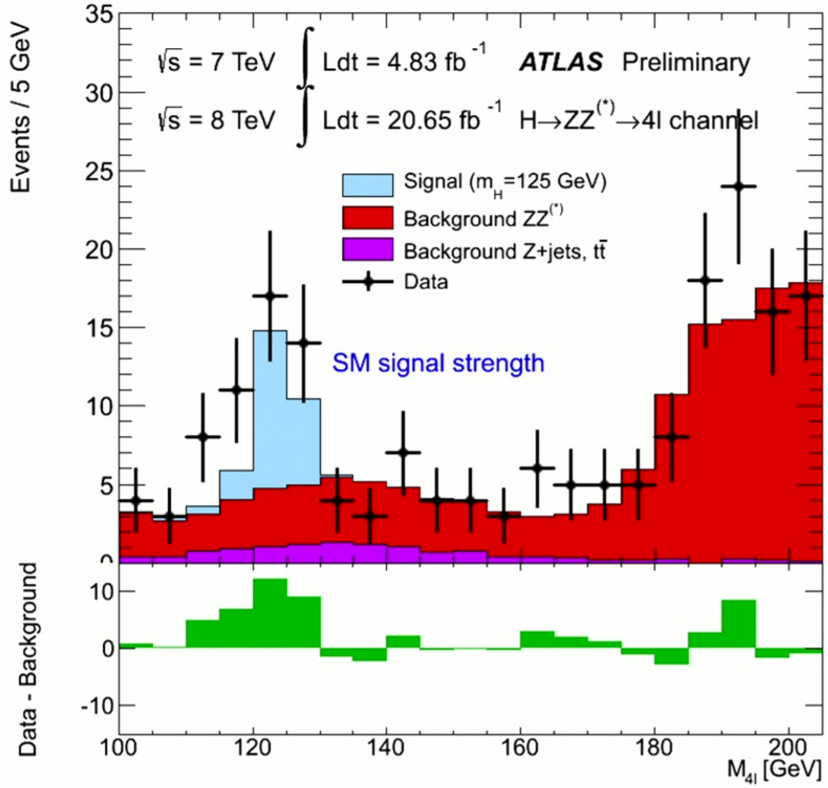




The Higgs signal

H→ZZ→4l



Note the quite clean channel!

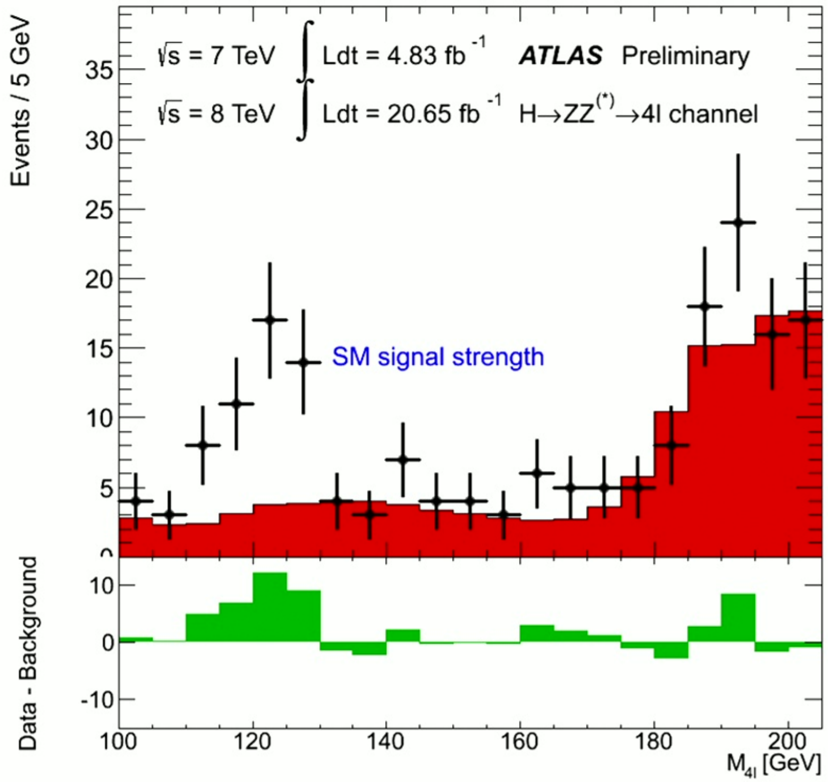
Background under the Higgs peak:

ZZ + Zjet

90

The Higgs signal

H→ZZ→4l



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Background under the Higgs peak:

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