Experimental particle physics at the LHC (1)

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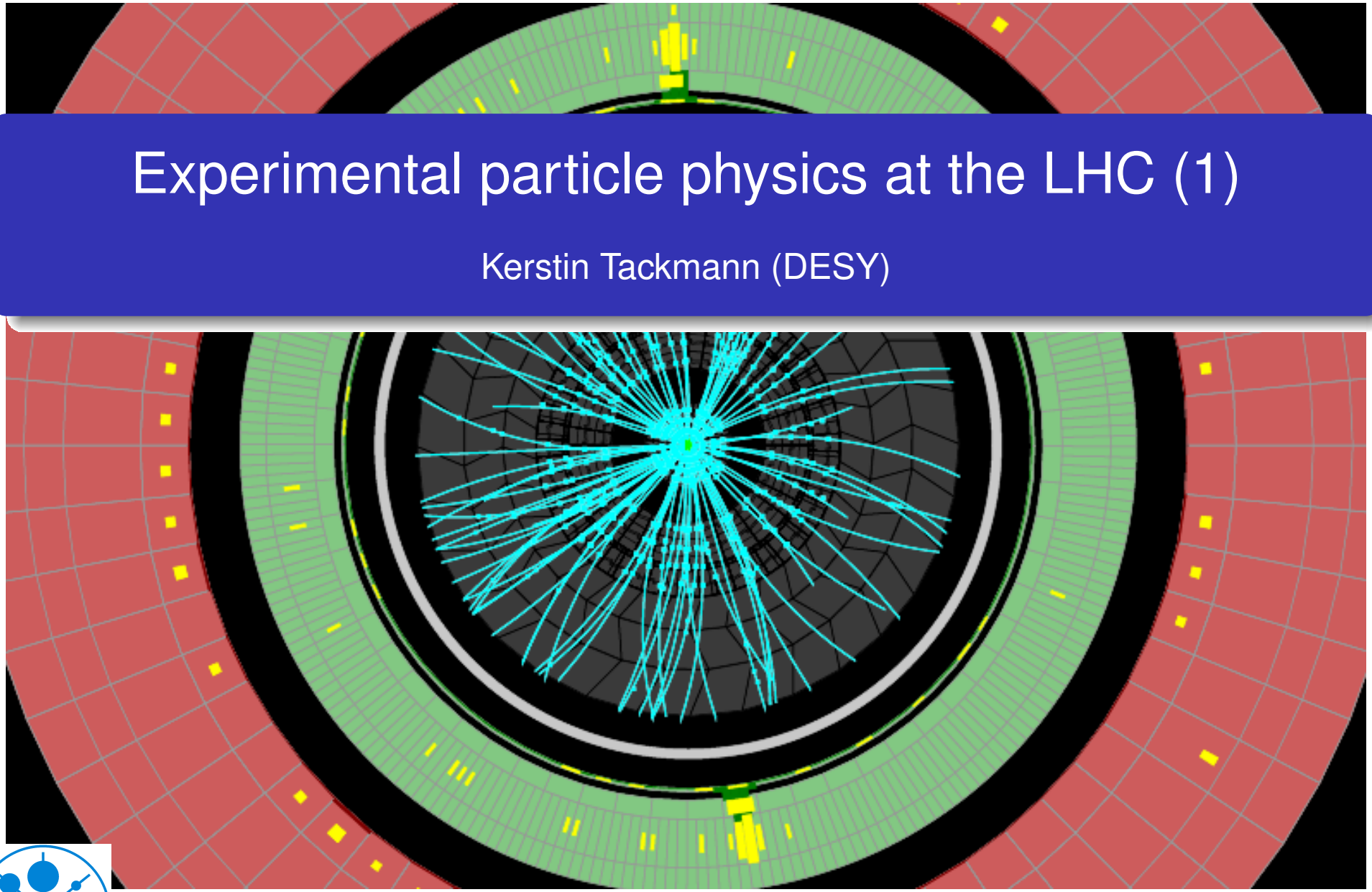


GRK1504/2: Autumn Block Course 2016

Particle physics and the Large Hadron Collider

The Standard Model very successfully describes (laboratory-based) measurements

- Sometimes to amazing accuracy: the limit on the electron dipole moment has been verified to $\mathcal{O}(10^{-27})$

...but we also have hints that it may not be the end of the story...

- What is the origin of the matter/antimatter asymmetry in the universe?
- What is dark matter?
- How do neutrinos acquire mass?

...and would like to understand more...

- Are the forces unified at high energies?
- What did the early universe look like?
- Do we (really) understand why elementary particles have mass?
- ...

The LHC is studying physics at high energies (and high luminosities), trying to answer (some of) these questions

Experimental particle physics at the LHC – menu

Topics of the lectures

- Overview LHC, proton collisions, and the experiments
- A close look at the $H \to \gamma\gamma$ analysis: analysis techniques
- Overview of Higgs measurements and searches in other decay channels and combined results
- Overview of non-Higgs results (if time allows)

General remarks

- Please interrupt to ask questions!
- In most cases I will use ATLAS examples

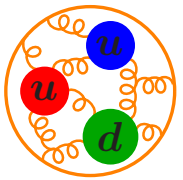
Many thanks to Peter Jenni, Andreas Hoecker, Sandra Kortner, Manuella Vincter, Markus Elsing, Heather Gray, and Witold Kozanecki for material used in these slides.

Why a hadron collider?

Energy loss from synchrotron radiation in a circular collider (per turn)

$$\Delta E = \frac{q^2}{3R\epsilon_0}\left(\frac{E}{mc^2}\right)^4 \qquad \frac{\Delta E_e}{\Delta E_p} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

$\rightarrow$ Higher energies much easier to reach with proton collisions



But protons also have disadvantages ...

- ...only part of the protons' energies is available for the partonic collision
- ...unkown boost along the beam direction (incomplete kinematic information)
- ...large probability for low-energy processes
- ...strong interaction makes theoretical predictions more complicated

Large Hadron Collider (@CERN, Geneva)

LHC uses LEP tunnel

- Circumference $\sim$ 26.7 km
- $\sim$ 100 m below the surface

Design: pp collisions at $\sqrt{s} = 14$ TeV

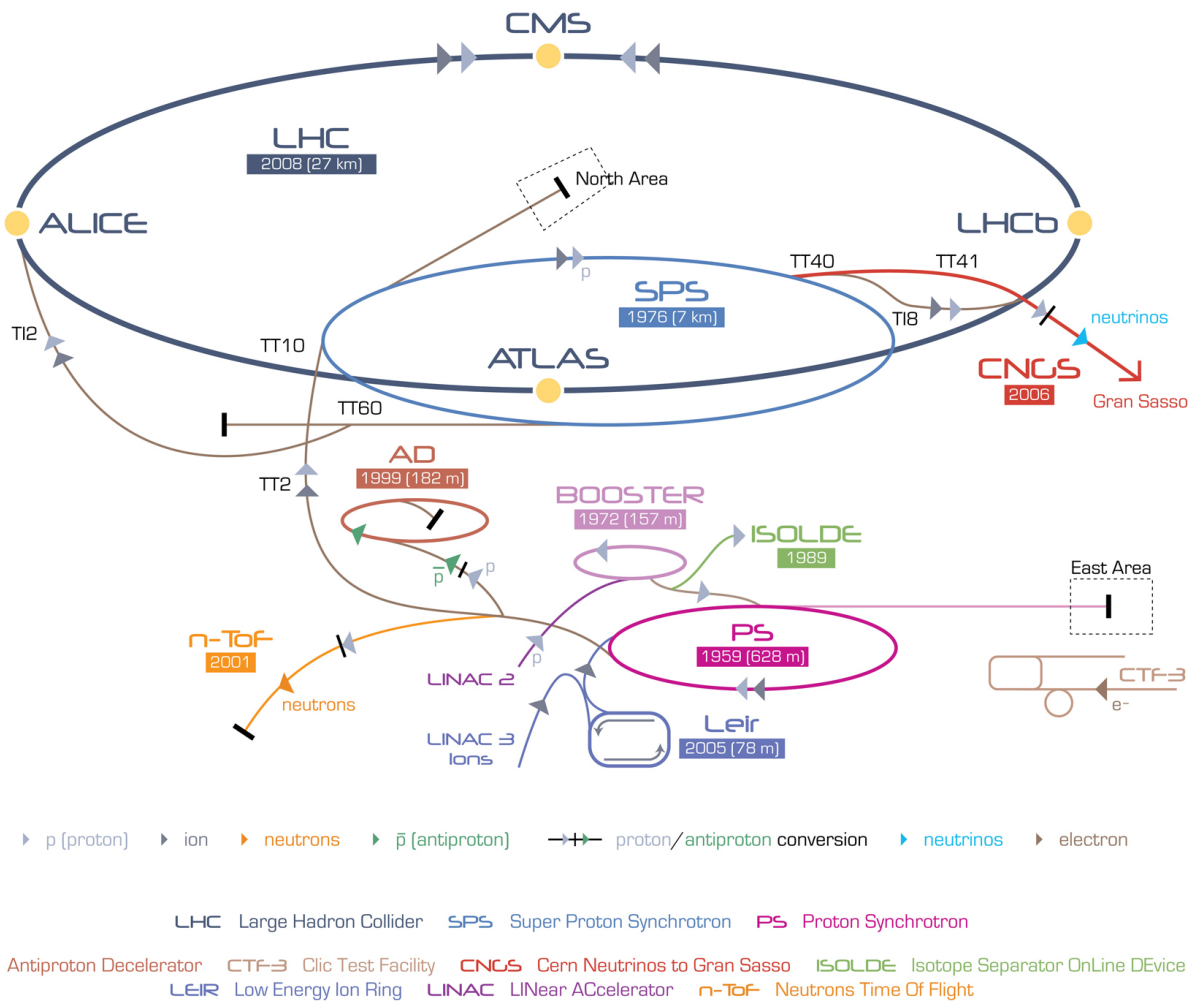
pp collisions at

- 2009 $\sqrt{s} = 900$ GeV
- 2010/11 $\sqrt{s} = 7$ TeV
- 2012 $\sqrt{s} = 8$ TeV
- 2015/16 $\sqrt{s} = 13$ TeV

- 2013/14 shutdown: machine and detector consolidation

in addition p-lead and lead-lead collisions

The LHC (pre-)accelerator chain



Linac 60 MeV

Booster 1.4 GeV

PS 25 GeV

SPS 450 GeV

LHC 3.5-7 TeV

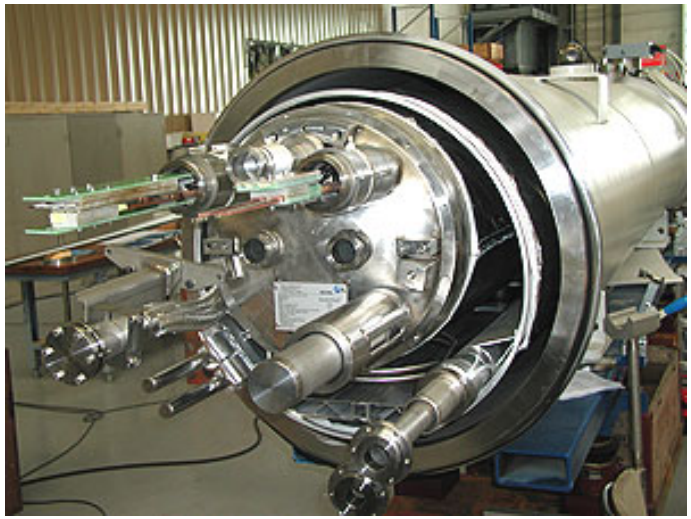
>50 years of CERN history still operational

Previous main accelerator turns into pre-accelerator for the next step

LHC magnets

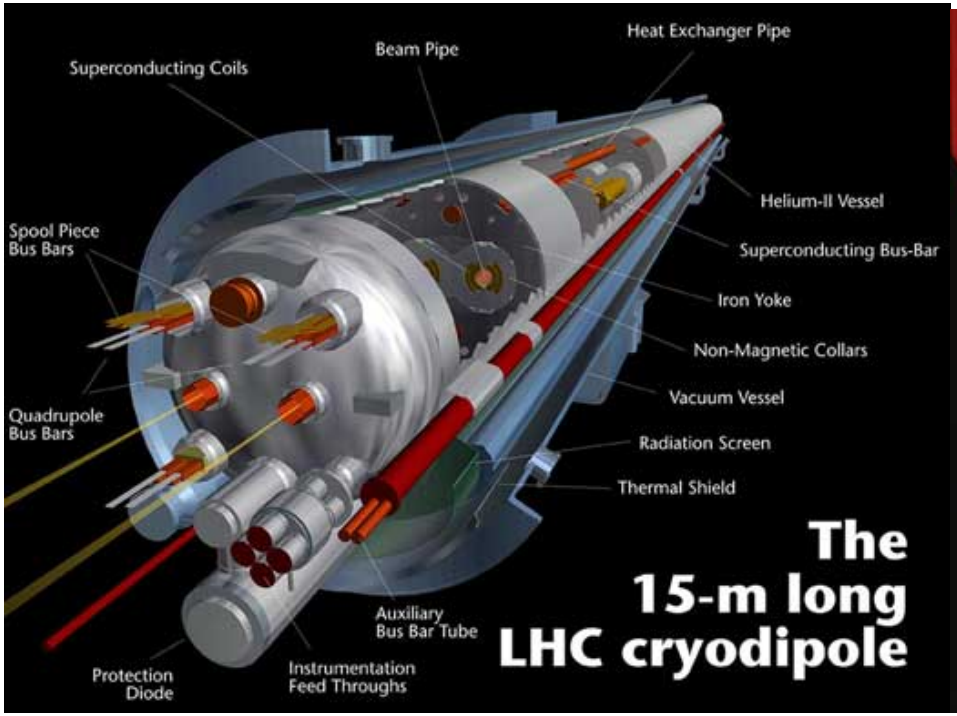
$\sim$ 6700 magnets controlling the beams

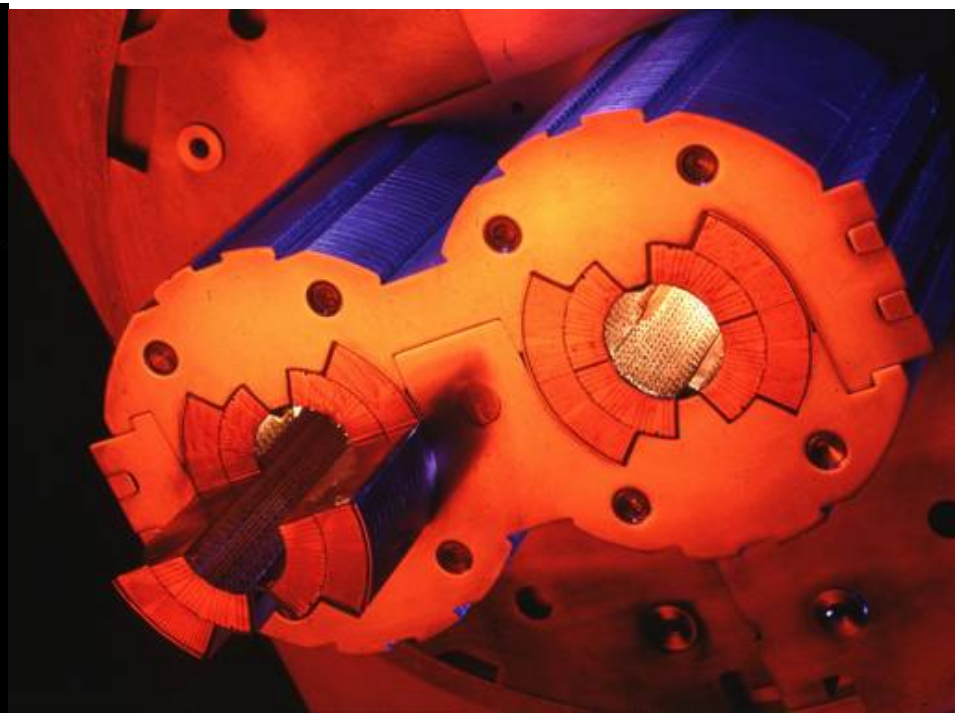
Dipoles	bending	1232
Quadrupoles	focusing	400
Sextupoles		2464
Octupoles/decapoles		1568
Orbit correctors		642
Others		376



Quadrupoles (inner triplet)

Technical challenge: dipole magnets





Keeping a proton with momentum p on circular orbit

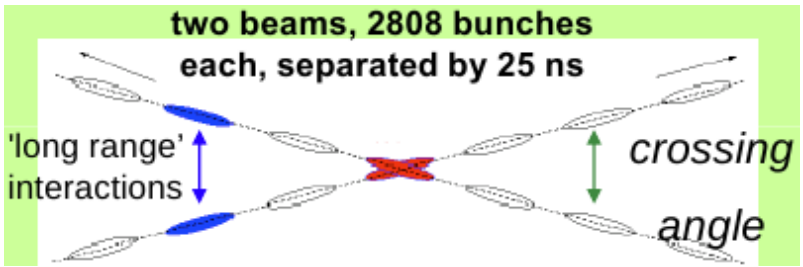
$$p(\mathrm{TeV}) = 0.3B(\mathrm{T})R(\mathrm{km})$$

For $p = 7$ TeV and $R = 4.3$ km need $B = 8.4$ T $\rightarrow$ 12 kA

$\rightarrow$ need superconducting magnets (normal conducting magnet would melt): Nb-Ti cooled to 1.9 K with pressurized superfluid Helium

LHC design parameters

beam energy	7	TeV
instantaneous luminosity	10^{34}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
integrated luminosity/year	$\sim$ 100	fb^{-1}
dipole field	8.4	T
dipole current	11700	A
circulating current/beam	0.53	A
number of bunches	2808	
bunch spacing	25	ns
protons per bunch	10^{11}	
rms beam radius at IP1/5	16	μm
rms bunch length	7.5	cm
stored beam energy	360	MJ
crossing angle	300	μrad
number of events per crossing	20	
luminosity lifetime	10	h



...but this is not how LHC has been operating so far

Beam energy stored in each LHC beam 360 MJ

Equivalent to

- Kinetic energy: 450 cars at 100 km/h
- Chemical energy: 70 kg of chocolate

LHC design parameters

beam energy	7	TeV
instantaneous luminosity	10^{34}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
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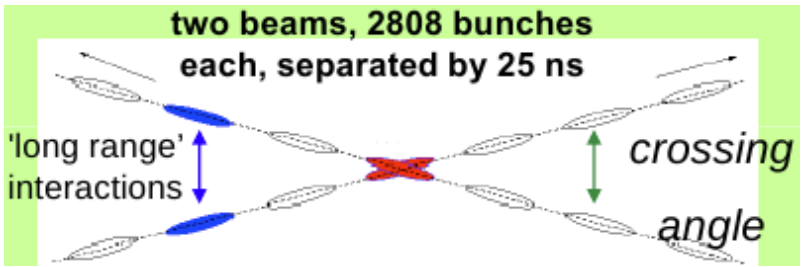

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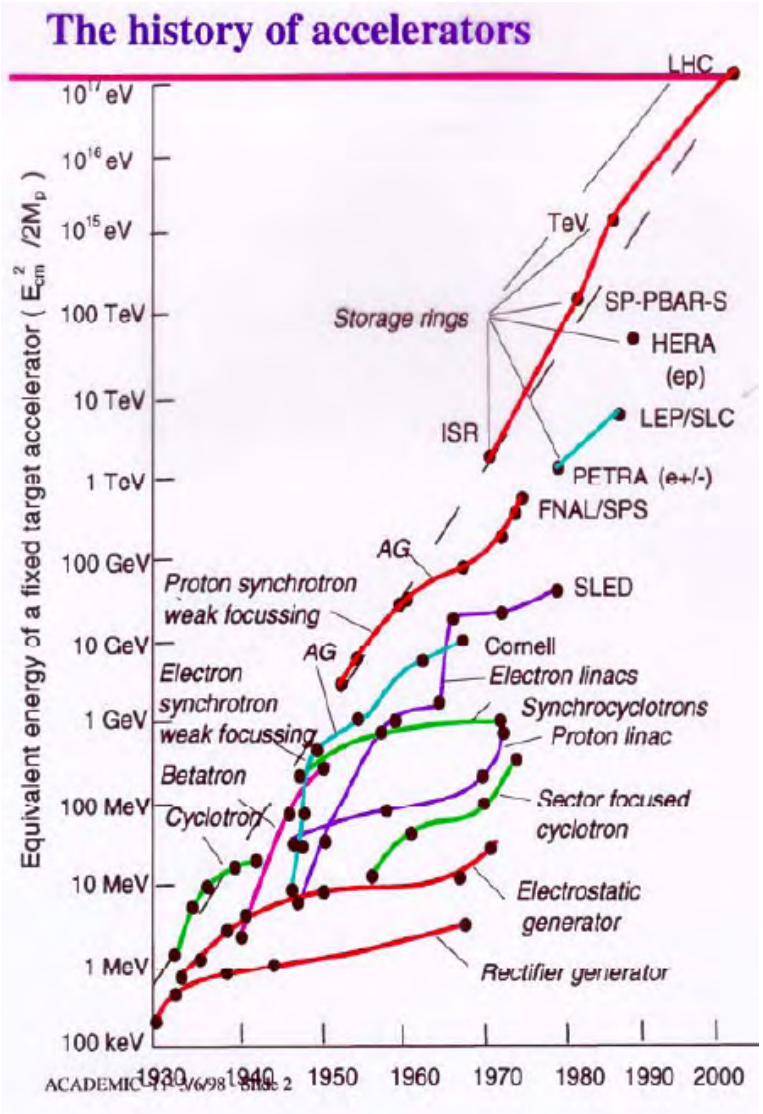
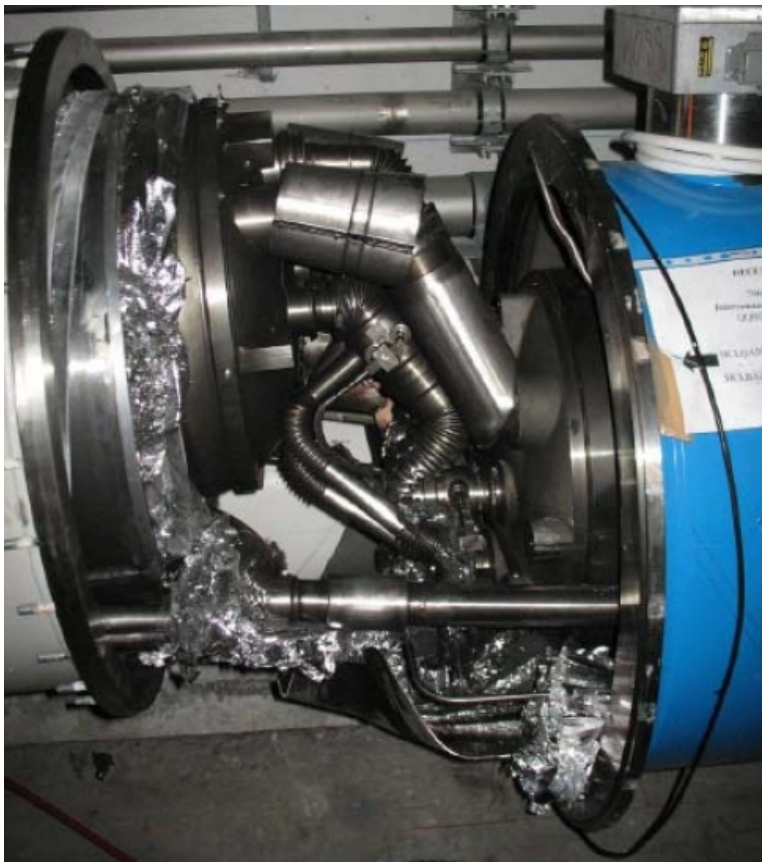


exponential development

LHC operations



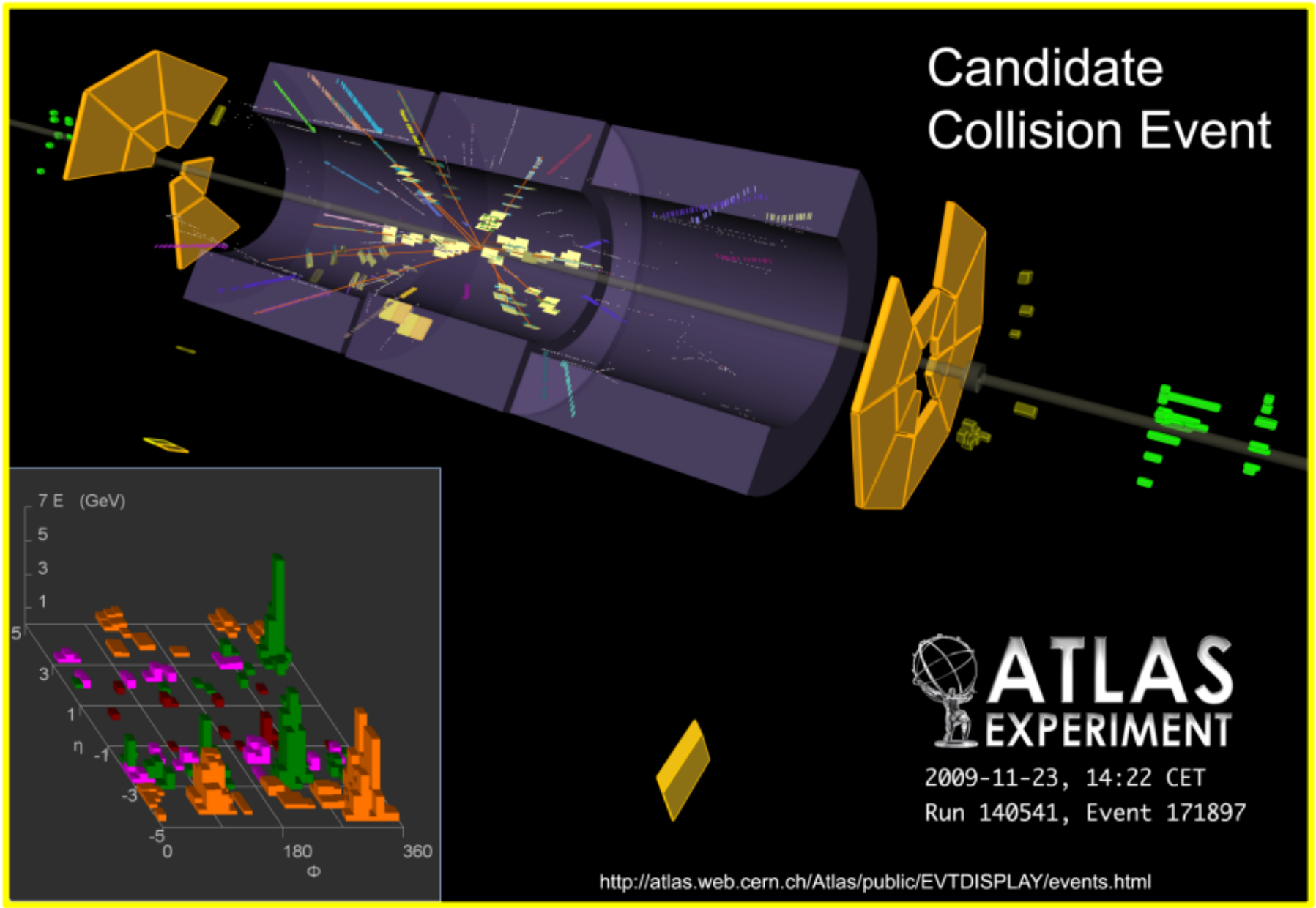
On September 19, 2008 one superconductor joint failed, damaged the vaccum enclosure, caused a catastrophic release of Helium and collatoral damage (up to 50 cm displacement of several quadrupoles, beam pipe contaminated with soot, ...)

$\sim$ 1 year of repairs and improvements

Highest safe energy for operation was determined to be 3.5 TeV per beam (given measured resistance in joints)

- Operation with 1400 bunches, i.e. 50 ns bunch spacing

First collisions at 900 GeV (end of 2009)



Luminosity and event rate

Rate of events N produced for a process with cross section σ

$$dN/dt = \mathcal{L}\sigma$$

Luminosity depends on the beam parameters

$$\mathcal{L} = \frac{N_p^2 n_{\mathrm{bunch}} f}{A}$$

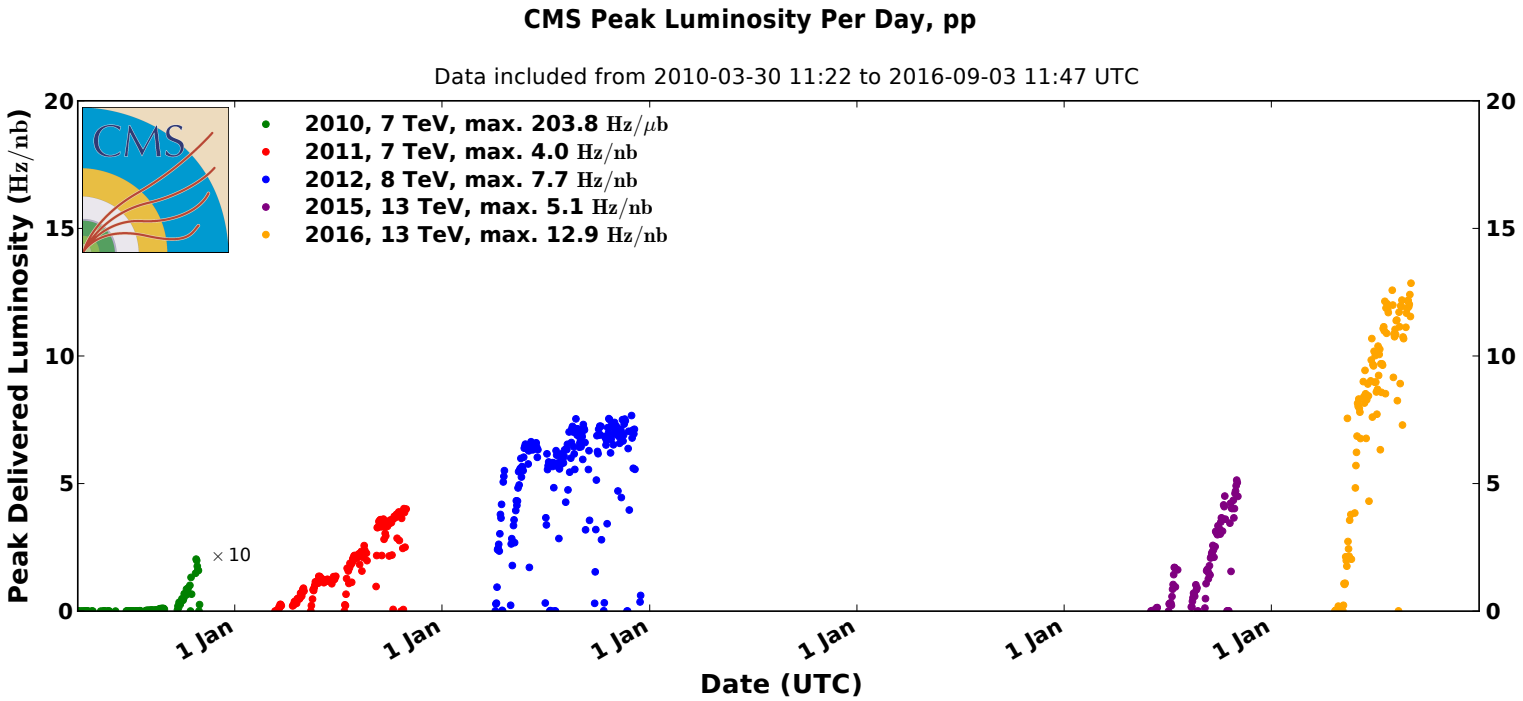
with

- N_p number of protons/bunch (10^{11})
- n_{bunch} number of bunches (2808)
- f revolving frequency (11245 Hz)
- A effective cross section area of beams

Integrated luminosity

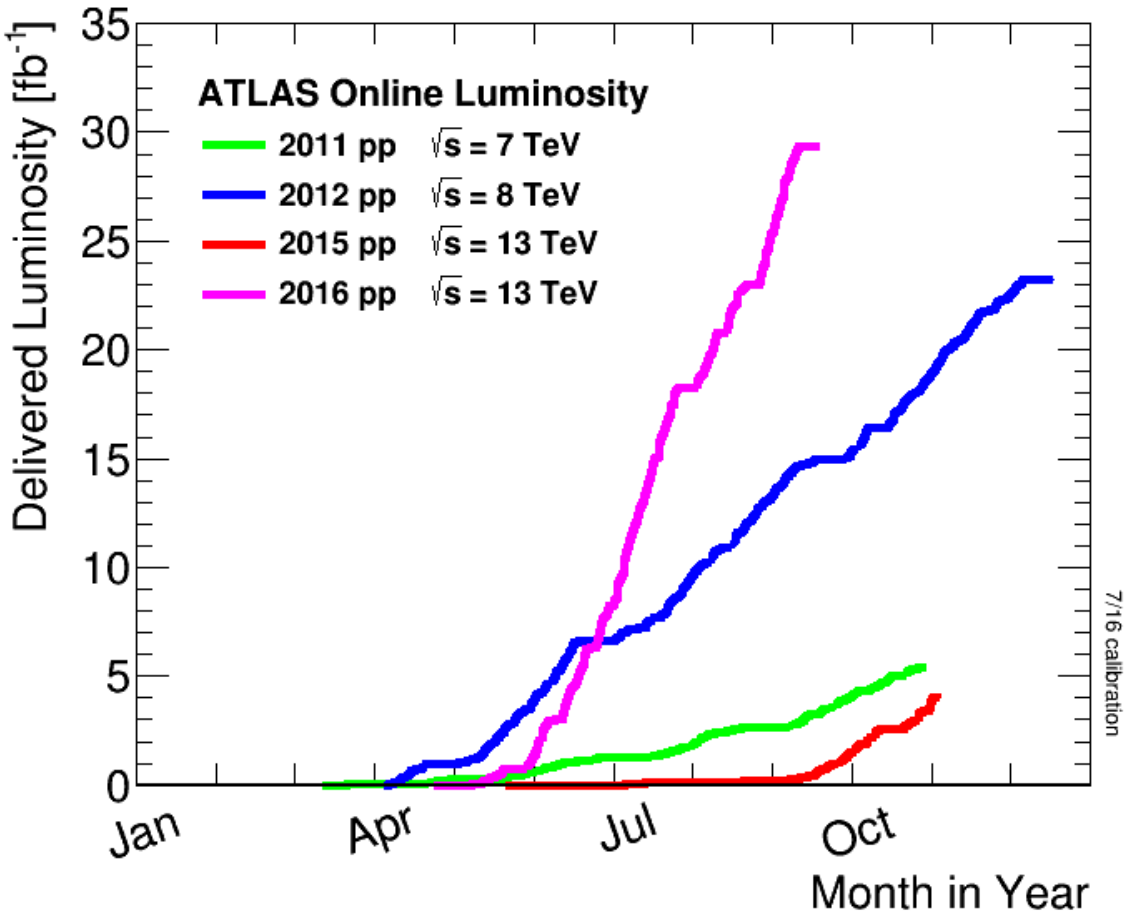
$$L = \int \mathcal{L} dt$$

Instantaneous luminosity at LHC



- Significant increase of instantaneous luminosity over time
  - ⋆ Increase of number of bunches, protons per bunch, more tightly focused beam
  - ⋆ Operation with 25 ns bunch spacing since summer 2015
- Design instantaneous of $1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ surpassed this summer

Integrated luminosity



2016 29.3 fb^{-1}

2012 23.3 fb^{-1}

2011 5.6 fb^{-1}

2015 4.2 fb^{-1}

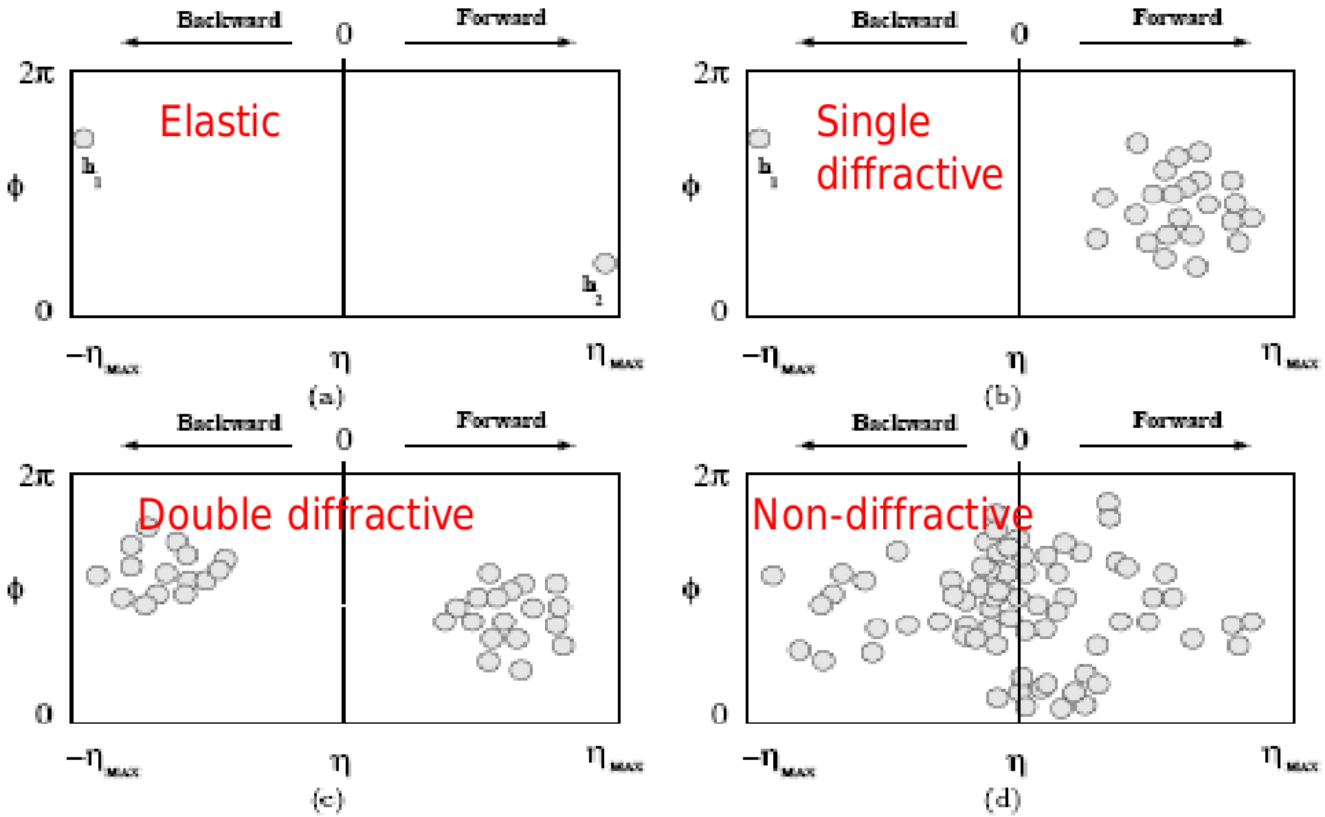
2010 0.048 fb^{-1}

- In most years LHC has outperformed expectations
  - ⋆ E.g. at the beginning of 2011, we were hoping for $\sim$1 fb^{-1}
- Efficiency (delivered by LHC $\rightarrow$ analyzed) $\sim$90%

Total pp cross section

- Total pp cross section $\sigma_{\mathrm{tot}} = \sigma_{\mathrm{elastic}} + \sigma_{\mathrm{inelastic}}$
- Inelastic term can be decomposed as
  $\sigma_{\mathrm{inelastic}} = \sigma_{\mathrm{single\,diffractive}} + \sigma_{\mathrm{double\,diffractive}} + \sigma_{\mathrm{non-diffractive}}$

- Single (double) diffractive: $pp \to pX(XX)$, clear gap
- Non-diffractive: $pp \to X$, gaps filled by particles



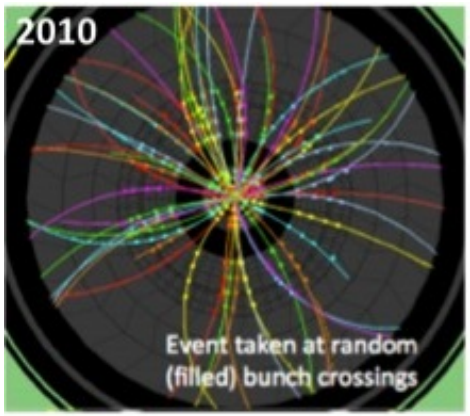
Inelastic collisions per bunch crossing

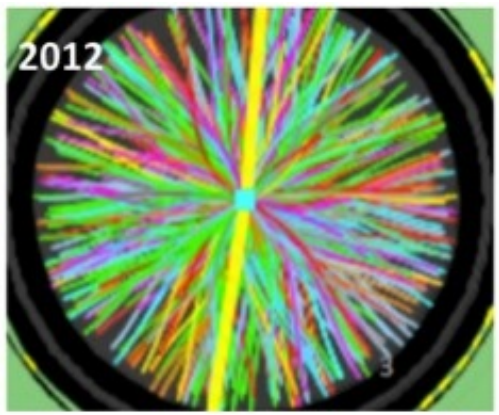
- Number of inelastic collisions per bunch crossing

$$< \mu >= \sigma_{\mathrm{inel}} \, \mathcal{L} \, \Delta t \; / \; \epsilon_{\mathrm{bunch}}^{\mathrm{occupancy}}$$

- LHC $< \mu >=\sim 80\,\mathrm{mb}\; 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\; 25\,\mathrm{ns} \; / \; 0.8 = 20 - 25$
  - ⋆ On average, >20 simultaneous pp collisions per bunch crossing
- Much more than at recent machines
  - ⋆ LEP $\Delta t = 22\,\mathrm{ms}$ and $< \mu > << 1$
  - ⋆ SppS $\Delta t = 3.3\,\mathrm{ms}$ and $< \mu > \approx 3$
  - ⋆ HERA $\Delta t = 96\,\mathrm{ns}$ and $< \mu > << 1$
  - ⋆ Tevatron $\Delta t = 0.4\,\mathrm{ms}$ and $< \mu > \approx 2$

The price of high luminosity: many events overlayed in the detector





ATLAS was designed to operate with 23 interactions overlayed

Measurement of the luminosity (I)

$$\mathcal{L} = \frac{\mu n_{\text{bunch}} f}{\sigma_{\text{inel}}} = \frac{\mu_{\text{eff}} n_{\text{bunch}} f}{\sigma_{\text{eff}}}$$

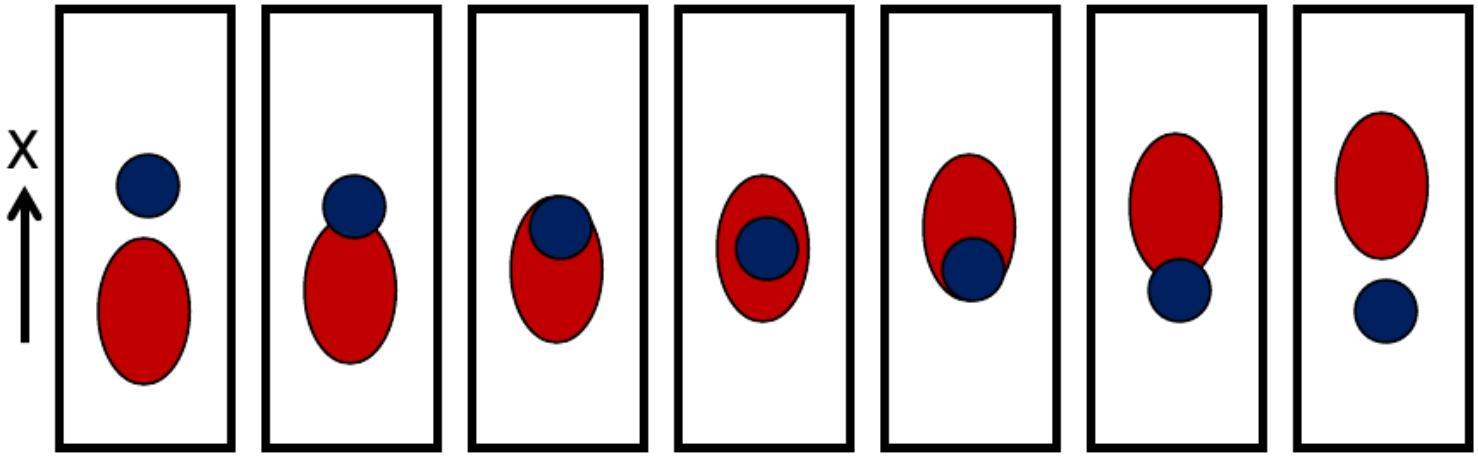
- μ inelastic interactions per bunch crossing
- μ_{eff} measured number of interactions per bunch crossing
- σ_{eff} effective cross section, needs to be calibrated

Luminosity monitoring algorithms

- Event counting: dedicated lumi monitor (LUCID), beam conditions monitor (BCM) ("How many bunch crossings see an event?")
  - ⋆ Count fraction of bunch crossings without events
  - ⋆ $\mathcal{L}$ is monotonic (non-linear) function of the event rate
- Track (+primary vertex) counting: tracking detectors
- Flux counting: currents in the calorimeters

Measurement of the luminosity (II)

- Measure visible interaction rate μ_{eff} as a function of beam separation δ in beam profile scans



Measurement of the luminosity (II)

- Measure visible interaction rate μ_{eff} as a function of beam separation δ in beam profile scans

- Measured reference luminosity

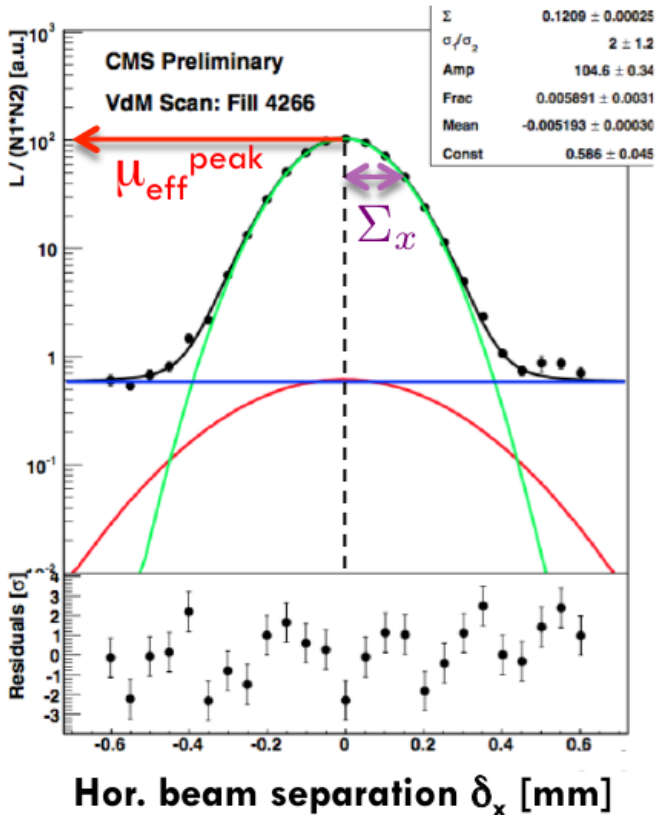
$$\mathcal{L} = \frac{N_p^2 n_{\mathrm{bunch}} f}{2\pi \Sigma_x \Sigma_y}$$

with $\Sigma_{x,y}$ from the scan curve

- Allows direct calibration of the effective cross section σ_{eff} (for each luminosity detector/algorithm)

$$\sigma_{\mathrm{eff}} = \mu_{\mathrm{eff}}^{\mathrm{peak}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

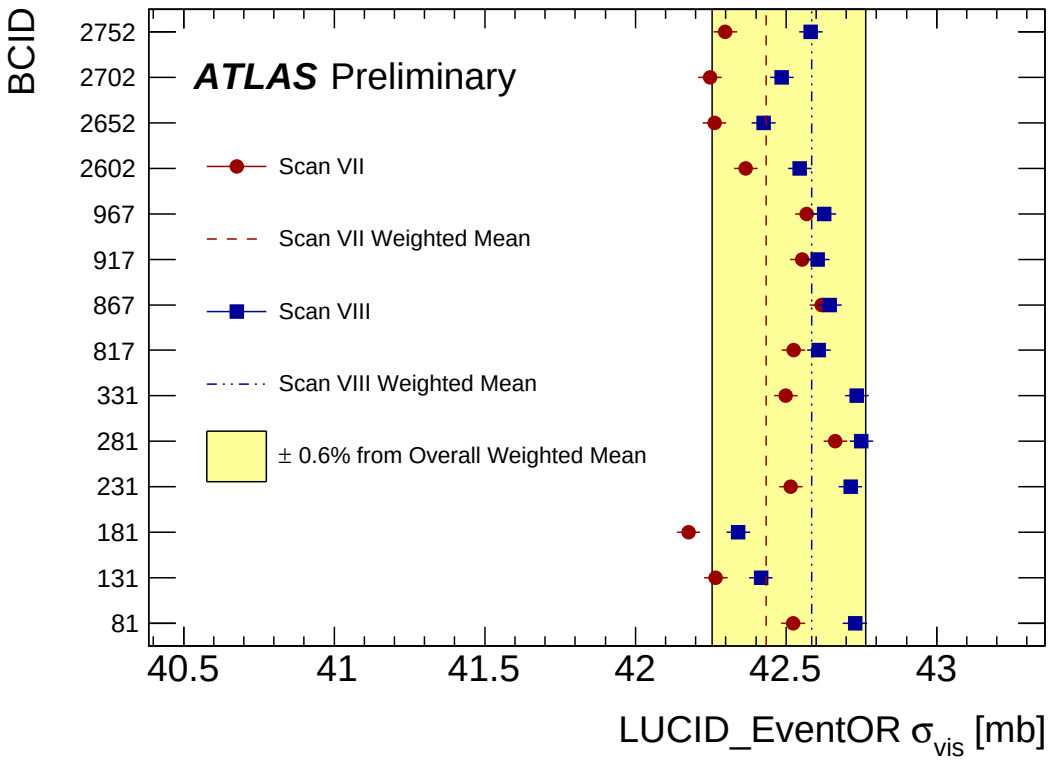
effective cross-section; peak rate; scan widths; bunch populations



- Assumption: can factorize into scan in x and y (not completely true)

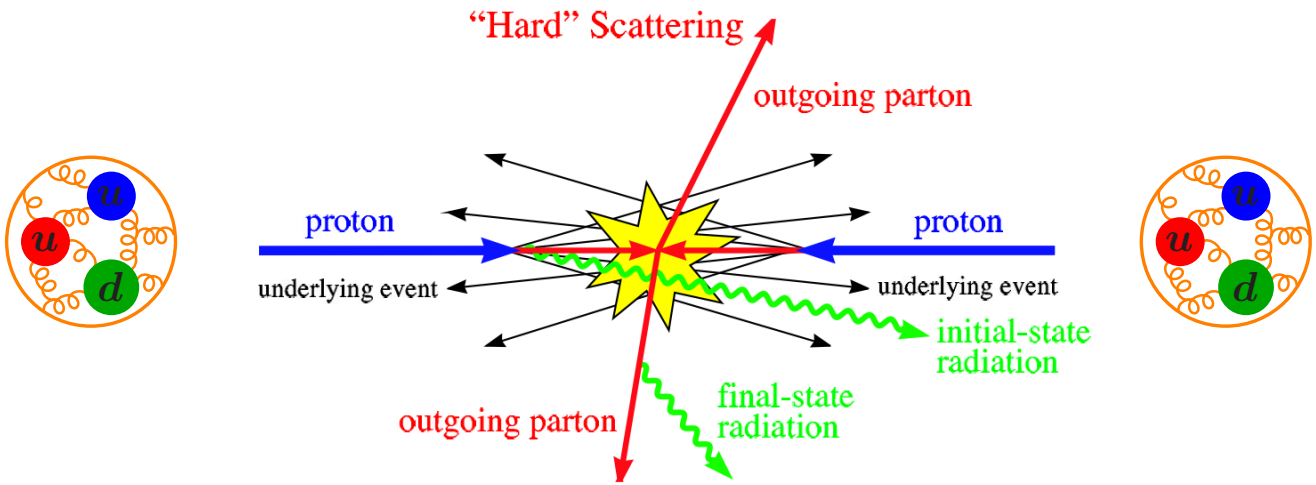
Measurement of the luminosity (II)

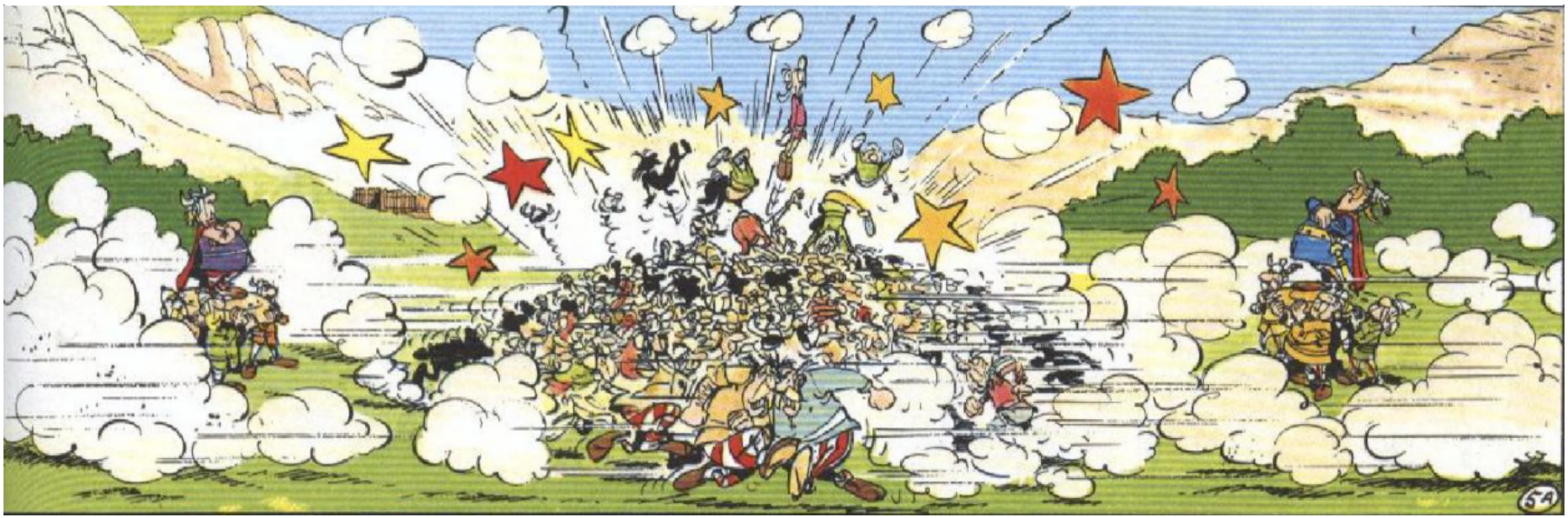
σ_{eff} measured in 2011 in LUCID (two different scans)



- Yellow band: uncertainty assigned from variations between scans and BCID
- Typical uncertainty on luminosity measurement 2-3%

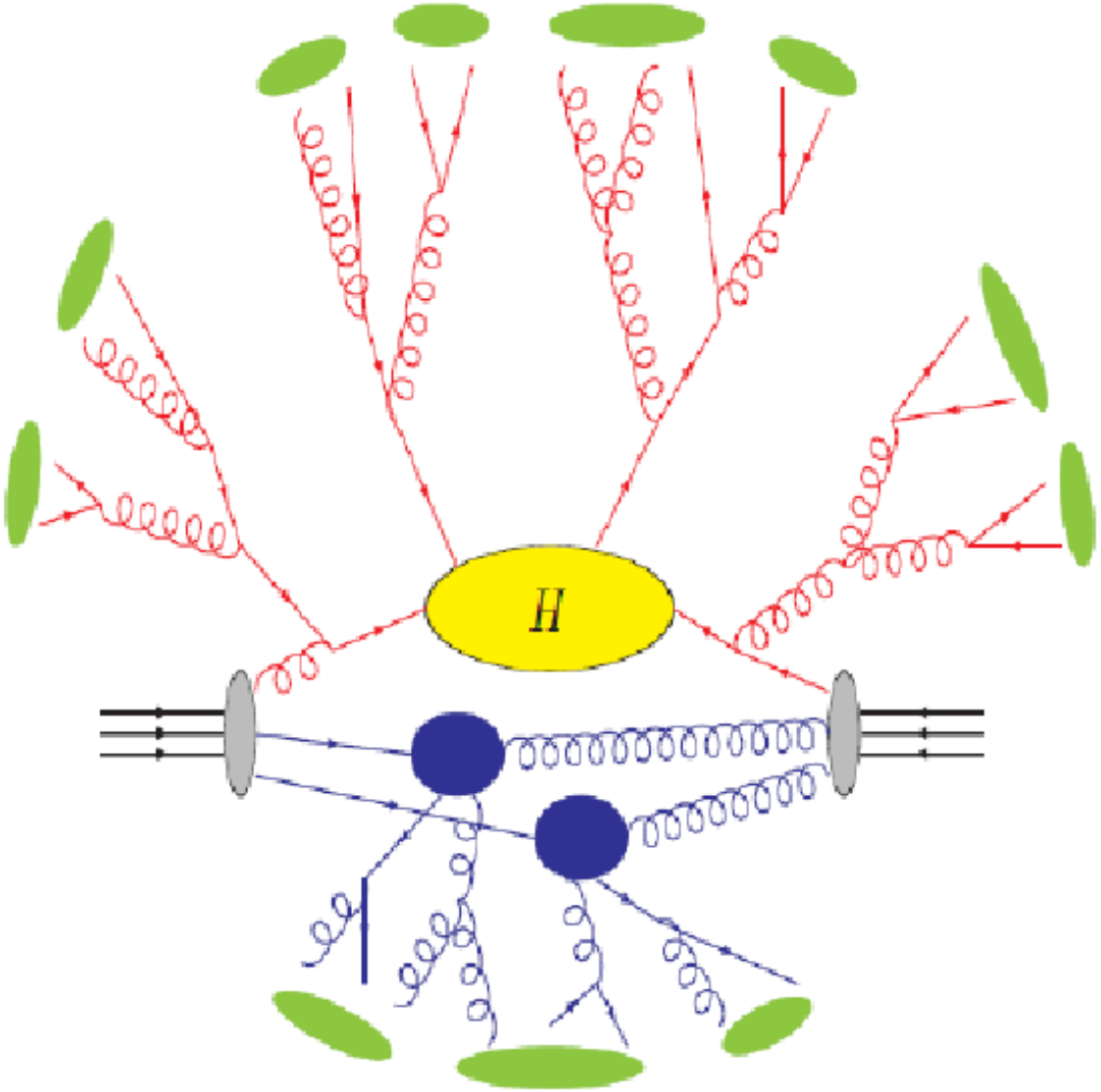
Proton collisions are a bit messy...





Proton collisions in detail...

...or rather, how we simulate them...



+ Decay

Hadronization of partons to hadrons, nonperturbative model

Parton shower: splitting of partons $\rightarrow$ modeling initial and final state radiation

Hard scatter described by matrix element (perturbative)

Proton structure: partons inside the proton

Multiple parton interactions: interactions of remaining partons in protons

Cross sections

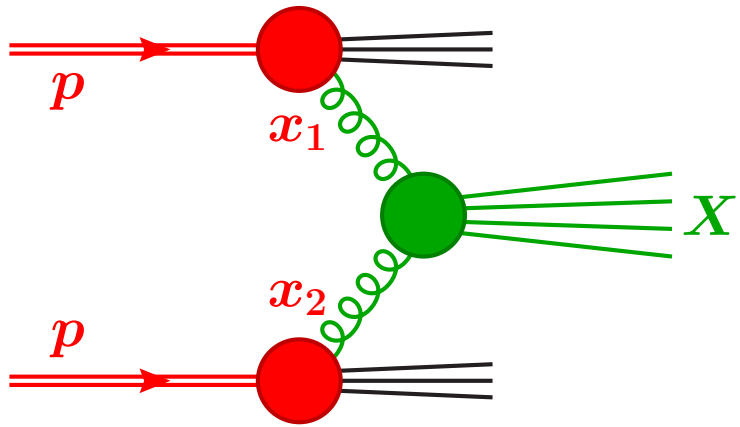
Cross section (σ) is the probability that a process $a + b \to X$ occurs when a and b collide

- Differential cross section $\mathrm{d}\sigma/\mathrm{d}y$ is the probability for final state with given $\mathrm{d}y$
  - ⋆ Example: jet transverse momentum spectrum $\mathrm{d}\sigma/\mathrm{d}p_T$

Proton collisions: For inclusive processes $\sigma(pp \to X)$ can be computed via factorization theorem, separating the short distance and long distance

$$\sigma_{pp\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{ab\to X}(x_1, x_2, Q^2)$$

- ⋆ Hard scattering: production of W, Z, top, Higgs, ..., computed in perturbative QCD at scale Q^2
- ⋆ Parton distribution functions → nonperturbative structure of the proton



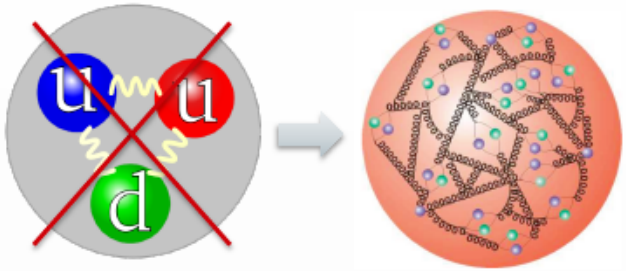
Note: strictly speaking only proven for inclusive processes

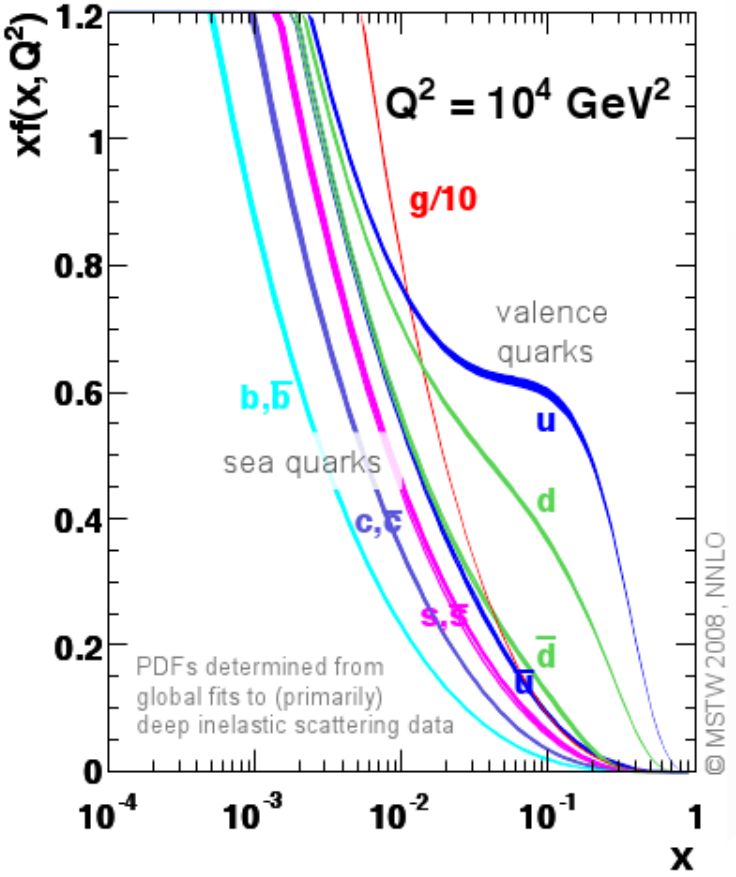
Parton distribution functions (pdfs)

- Proton content: valence quarks, sea quarks, gluons
- Momentum distribution of partons described by pdfs, function of
  - ⋆ Momentum fraction (of proton momentum) x
  - ⋆ Q^2 (scale of hard process)
- CM energy for parton collision $\hat{s} = x_1 x_2 s (= m_X^2)$
- For $m_X = 100\,\mathrm{GeV}$
  - ⋆ Tevatron ($\sqrt{s} = 2\,\mathrm{TeV}$) $x = 0.22$ (if $x_1 = x_2$)
  - ⋆ LHC ($\sqrt{s} = 14\,\mathrm{TeV}$) $x = 0.08$ (if $x_1 = x_2$)

→ Larger cross sections at LHC

→ LHC: cross section dominated by gg





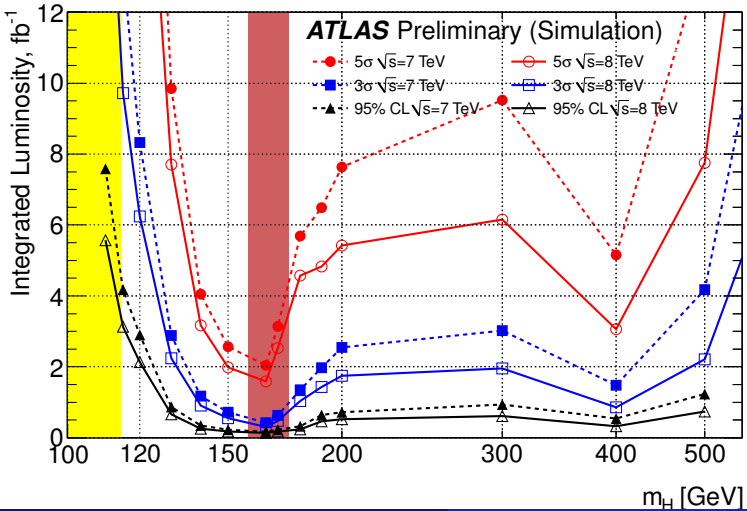
Aside: implication of running at lower $\sqrt{s}$ in 2010-2012

- Lower $\sqrt{s} \rightarrow$ need larger x to have the same available energy

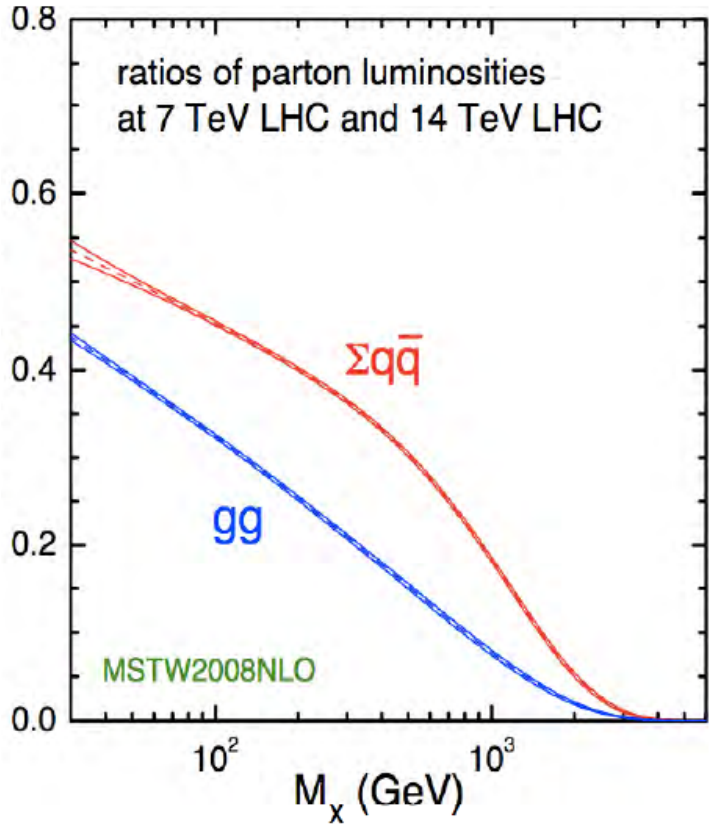
$\rightarrow$ Production of high-mass objects more difficult at lower $\sqrt{s}$

$\rightarrow$ More luminosity needed for discovery of new particles

  - ⋆ In particular for gg induced processes (like Higgs production)
  - ⋆ Relative behavior of signal and background processes also important

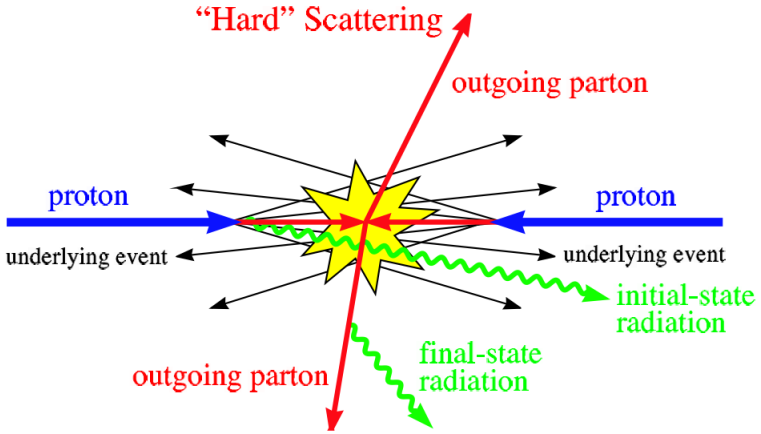


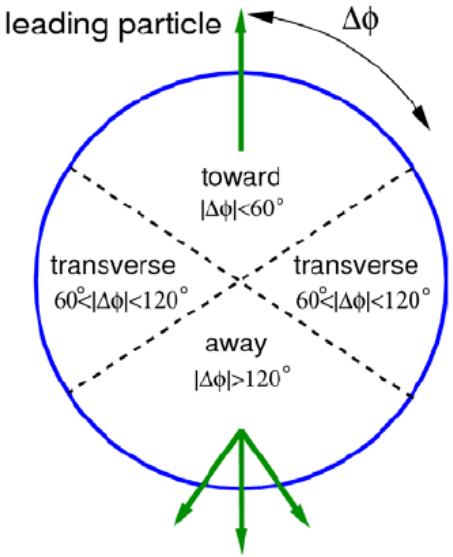
Ratio of parton luminosities at 7/14 TeV (from James Stirling)



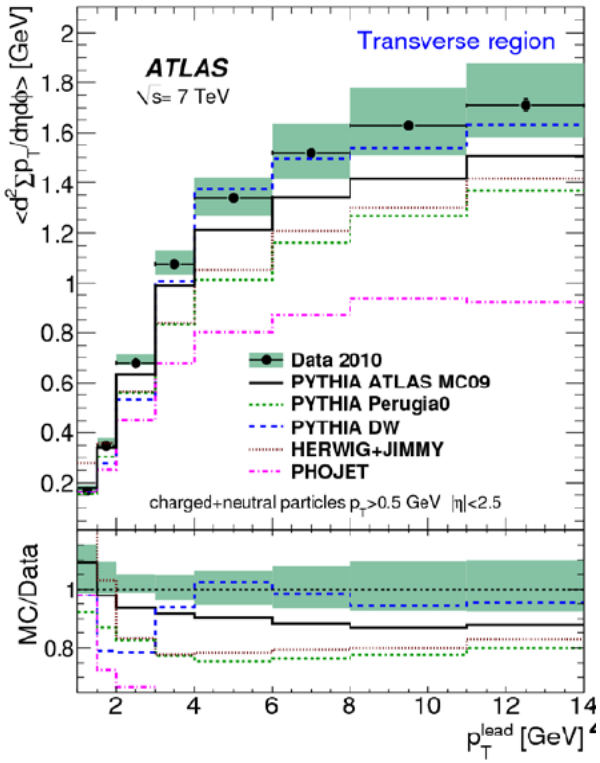
Underlying event

- Soft hadronic activity, produced in addition to the hard scattering
- Includes initial and final state radiation, multiple particle interactions and other soft effects
- Description in MC traditionally tuned using observables measured in the region transverse to the hard scatter axis

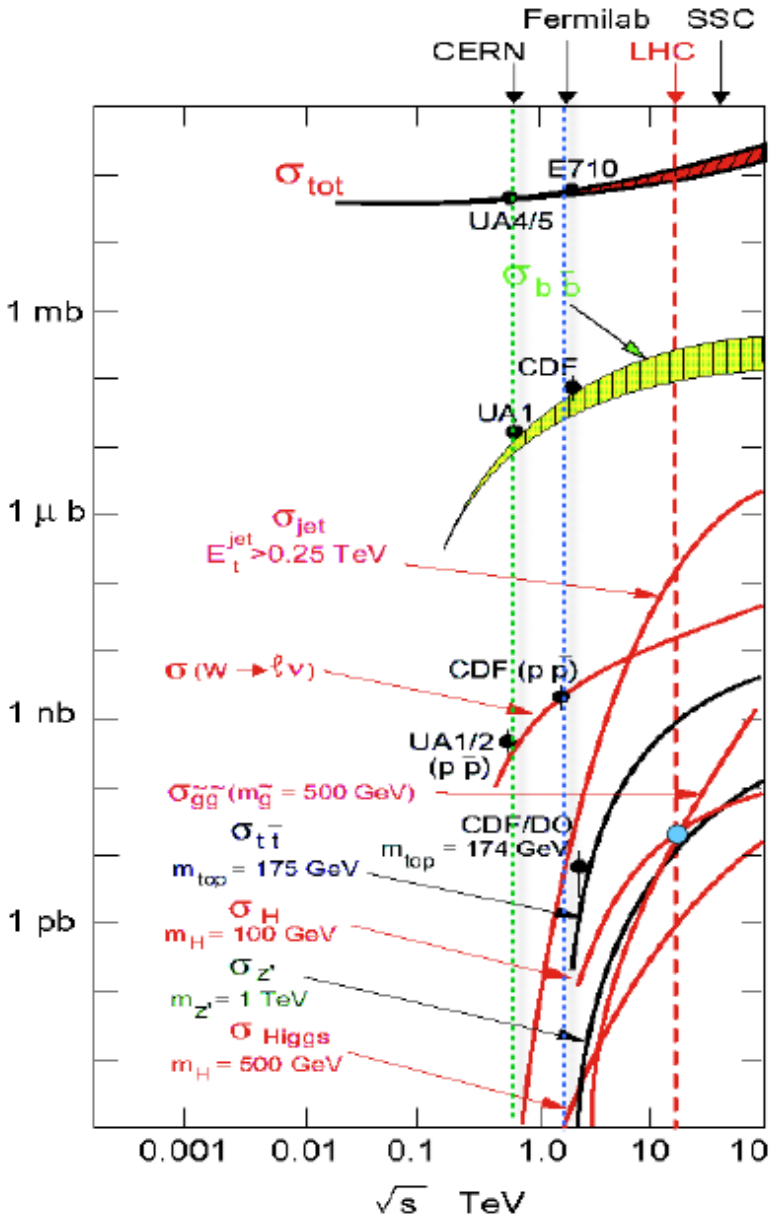




average Σp_T for stable particles per unit area in $\eta - \phi$ in transverse region as a function of p_T^{lead}



Production cross sections at hadron colliders

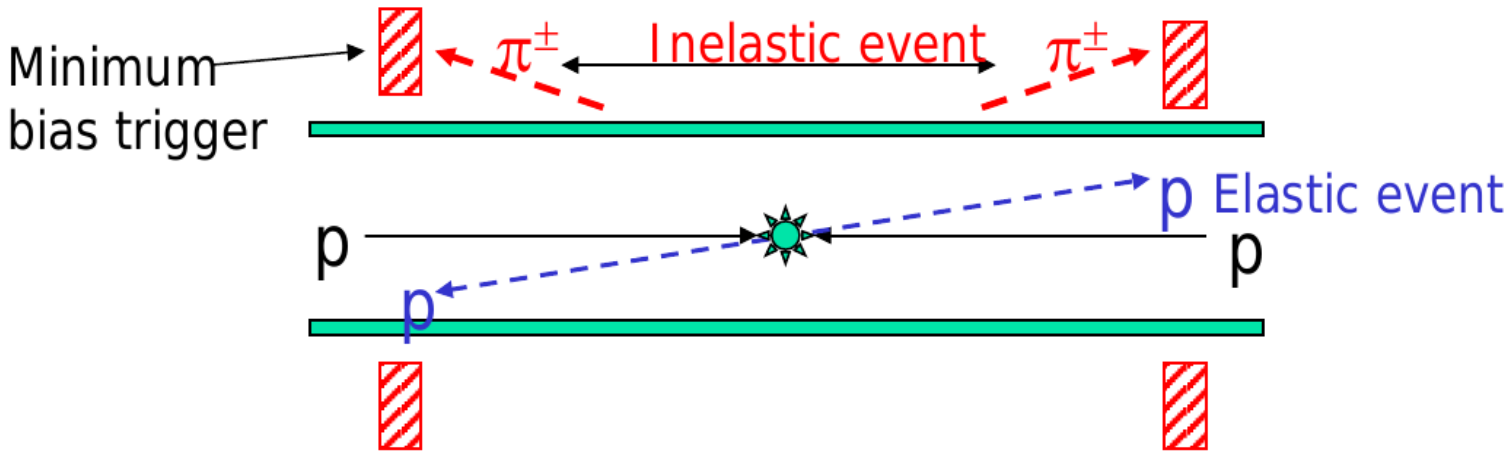


Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34}$ cm^{-2}s^{-2}
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	150
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

Many orders of magnitude between Higgs/New Physics and QCD backgrounds

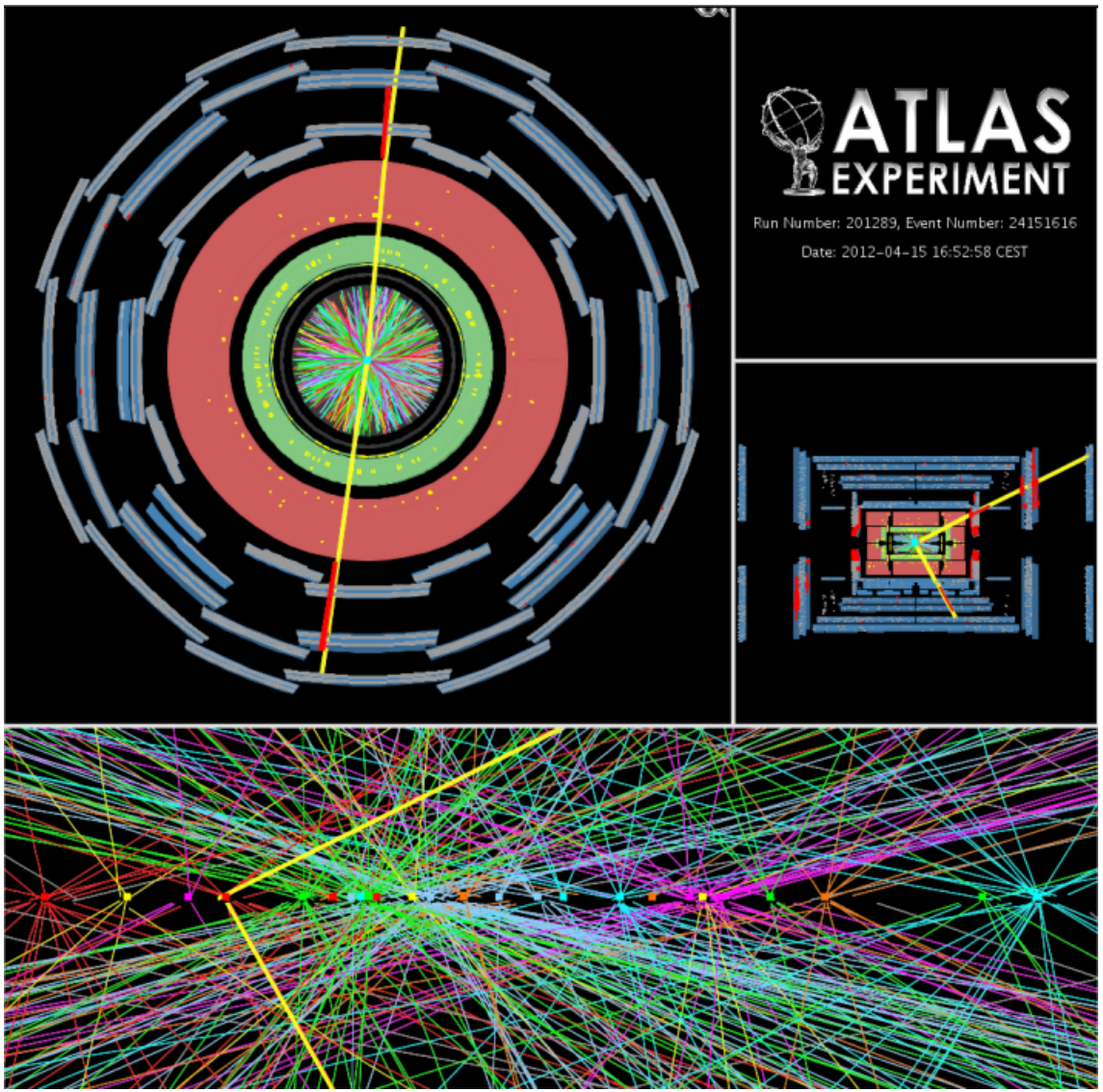
Minimum bias events

- "Any inelastic non-diffractive event" or "A generic pp inelastic non-diffractive event"
- Experimentally "anything that triggers the minimum bias trigger"
  - ⋆ This is effectively any non-single diffracive (nsd) inelastic event



- Minimum bias cross section fills almost the total inelastic cross section ($\sigma_{\mathrm{inel}} = 80 - 85\,\mathrm{mb}$, $\sigma_{\mathrm{nsd}} = 65 - 70\,\mathrm{mb}$)
- Mainly soft, nonperturbative, QCD interactions
- (Almost) all (additional) pp interactions in a recorded pp event are minimum bias events

Pileup

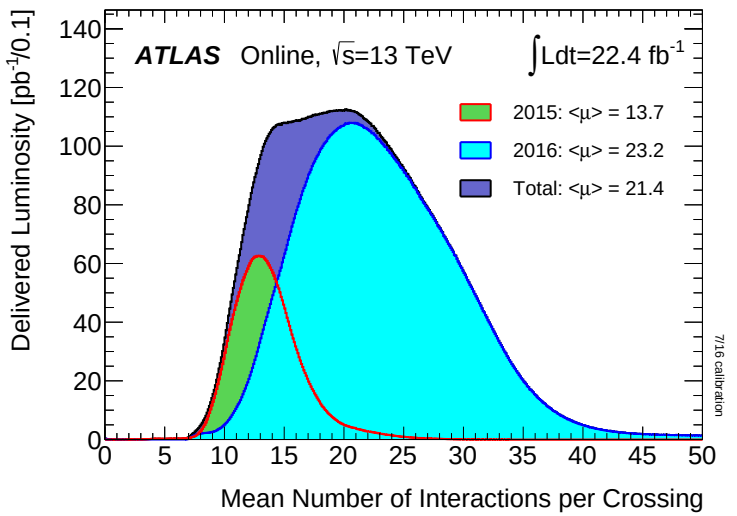


$Z \to \mu\mu$ with 25 interaction vertices

Challenge to trigger, software and analyses

- → Large amount of data to process and store
- → Identification and measurement of the "interesting" objects

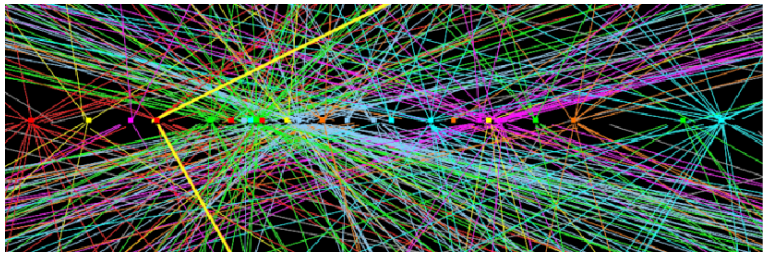
Especially for jets, $\boldsymbol{E_T^{\mathrm{miss}}}$ and $\boldsymbol{\tau}$



In-time and out-of-time pileup

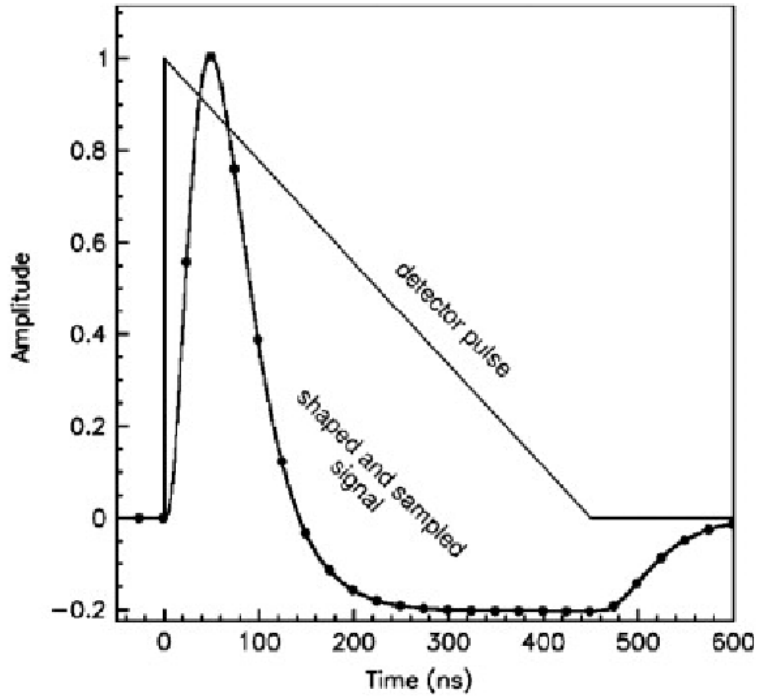
In-time

- Additional pp collisions occuring in the same bunch crossing as the collision of interest
- Can be suppressed by identifying pp collision vertex of interest



Out-of-time

- Additional pp collisions occuring in bunch crossings (just) before and after the collision of interest
- Typically corrected for on average
- E.g. ATLAS LAr calorimeter detector pulse $\sim$450 ns
- Shaped by electronics such that average net contribution of in- and out-of-time pileup cancel for design running conditions



Kinematic variables

Transverse momentum p_T and missing transverse momentum "E_T^{miss}"

- Transverse momentum is conserved $\sum \vec{p}_T^{\,i} = 0$
- Large missing transverse momentum $E_T^{\text{miss}} = |\vec{p}_T^{\,\text{miss}}| \rightarrow$ invisible particle escaped detection (e.g. neutrino)

Longitudinal momentum p_z and (visible) energy E

- Boost of partonic CM unknown $\rightarrow$ cannot use p_z and E conservation

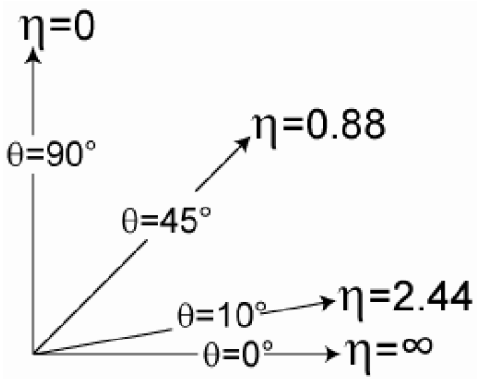
Polar angle θ

- Not Lorentz invariant

Pseudorapidity η and rapidity y

$$\eta = \frac{1}{2}\ln\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} = -\ln\left(\tan\frac{\theta}{2}\right) \; (= y \text{ if } m = 0)$$

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z} = \frac{1}{2}\ln\frac{x_1}{x_2}$$



- Δy and p_T are invariant under longitudinal boosts
- Particle production in hadron colliders is roughly constant in y

The World of LHC...

CMS
multipurpose
3000 physicists
184 institutions
38 countries

+ smaller earldoms: LHCf, TOTEM, Moedal

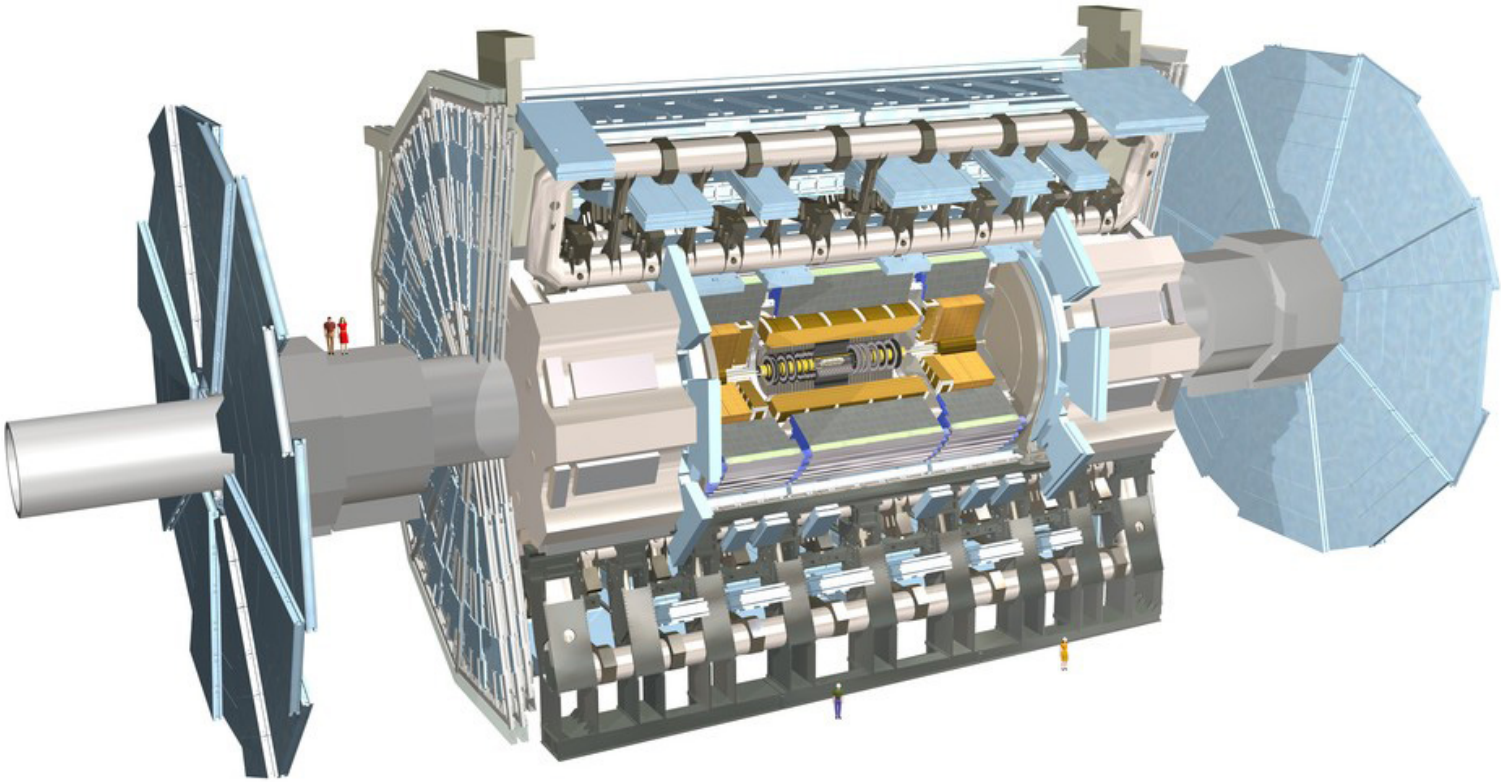
LHCb
b physics
730 physicists
54 institutions
15 countries

ATLAS
multipurpose
3000 physicists
177 institutions
38 countries

Alice
heavy ion physics
1300 physicists
130 institutions
35 countries

ATLAS

- 2 T solenoid magnet
- Tracking: Si pixel, microstrip, straw tubes
- Transition radiation for $e^{\pm}$ id
- Pb/LAr and steel/scint, Cu/LAr calos
- μ chambers in $\sim$0.4 T toroid field



24 m$\times$45 m
7 ktons

ATLAS inner detector ($|\eta| < 2.5$)

Pixel detector

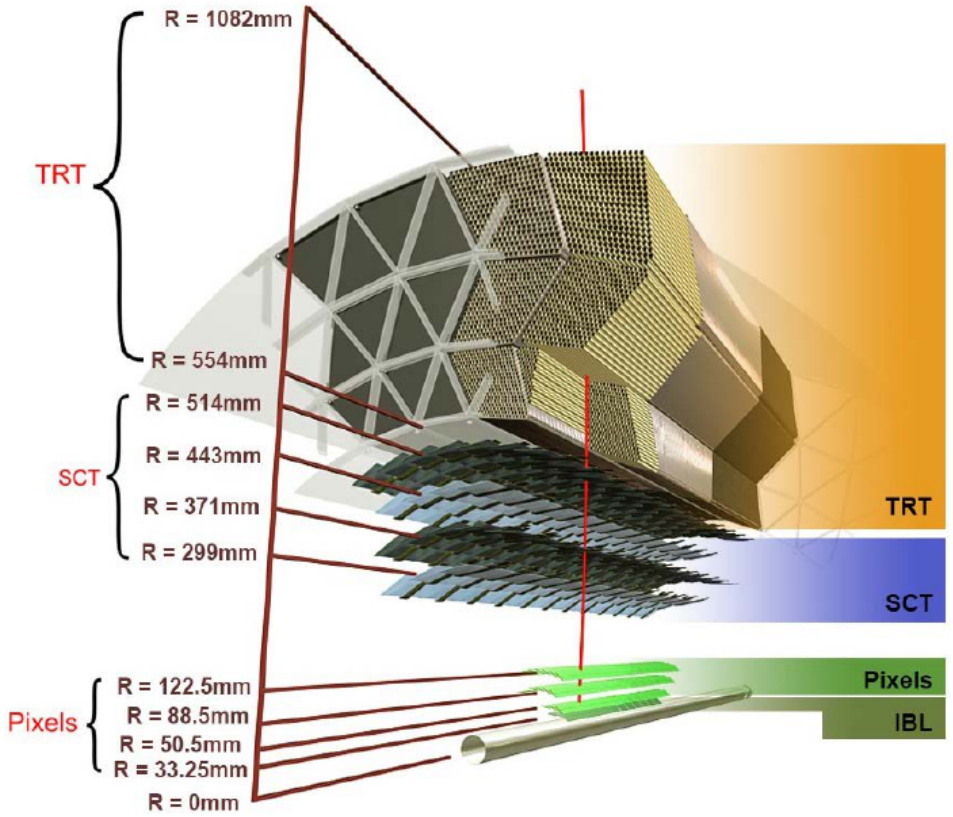
- 4 barrel layers, 2×3 endcap disks
- Innermost layer (IBL) installed for Run2 (33 mm radius)
- Pitch 50 μm × 400 μm (250 μm for IBL)

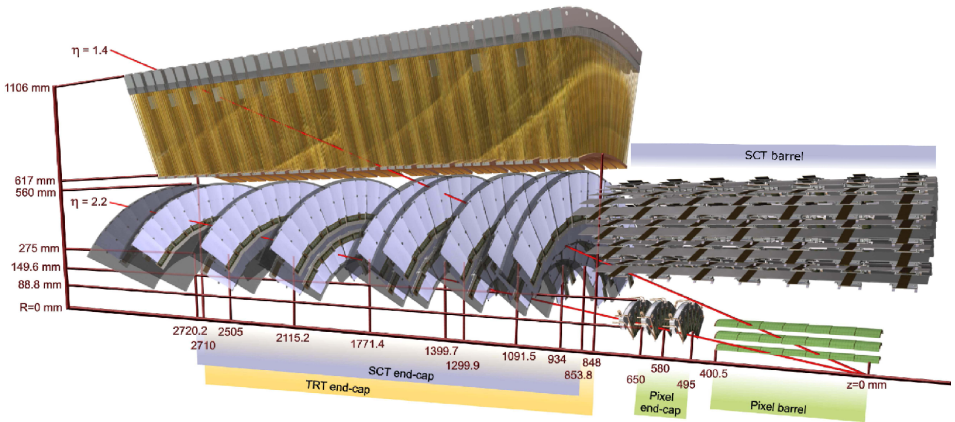
Silicon microstrip detector (SCT)

- 4 barrel layers, 2×9 endcap disks
- Pitch 80 μm, 40 mrad stereo angle

Transition radiation tracker

- Typically 36 straw-tube hits per track
- Transition radiation in scintillators to identify electrons





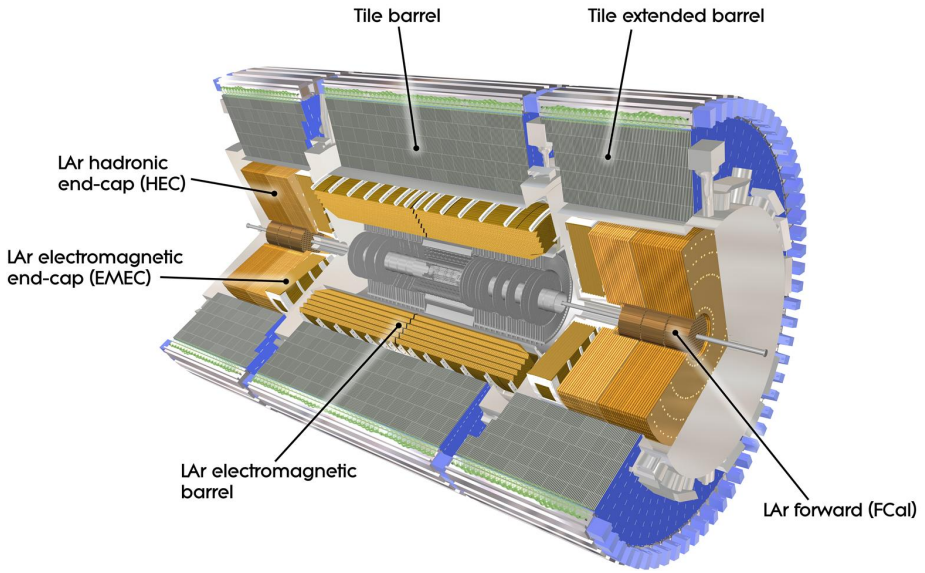
ATLAS calorimeters

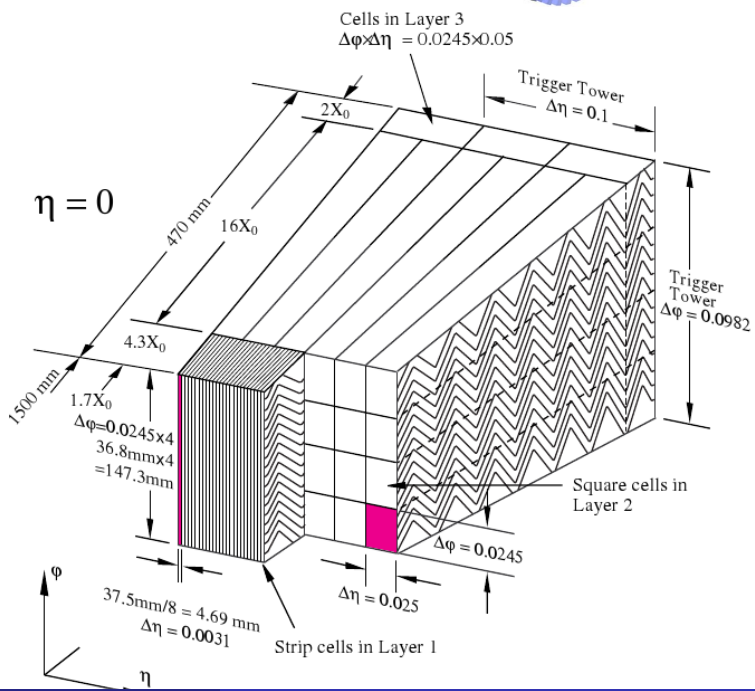
Electromagnetic calo ($|\eta| < 3.2$)

- Pb/LAr sampling calorimeter
- Radiation hard
- 3 longitudinal layers with accordion geometry and presampler inside of cryostat
- Fine lateral segmentation $\rightarrow$ measure shower shape

Hadronic calo

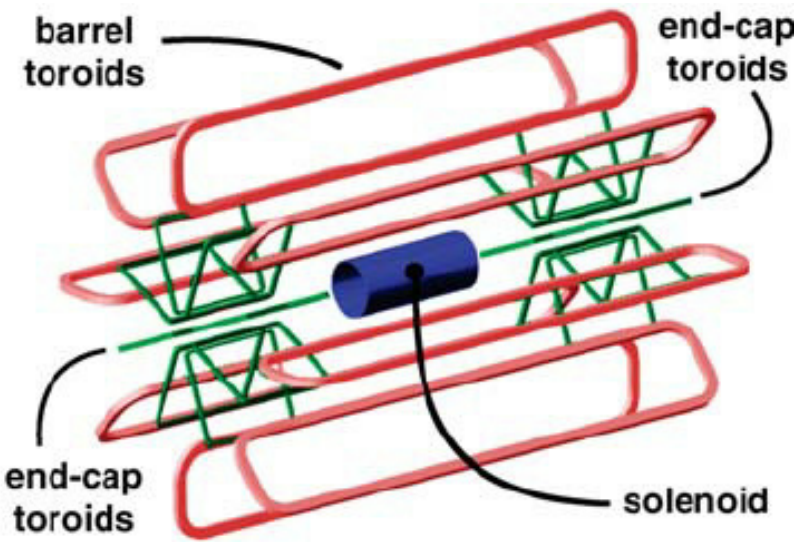
- Iron/plastic scintillator tiles sampling calorimeter ($|\eta| <$1.7)
- Copper (EC) and tungsten (FCal)/LAr sampling calorimeter ($|\eta| <$4.9)

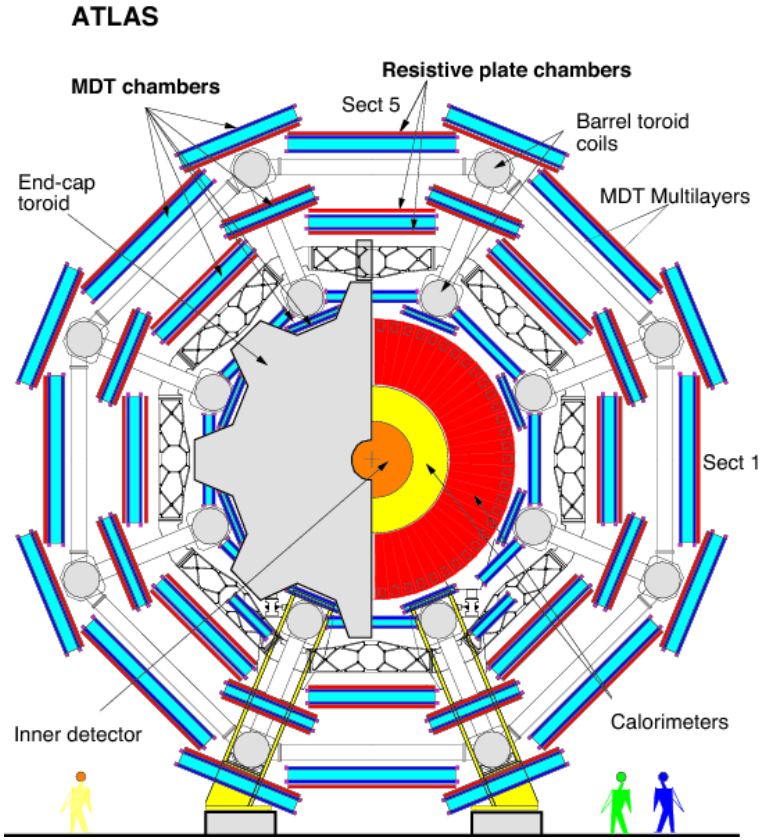


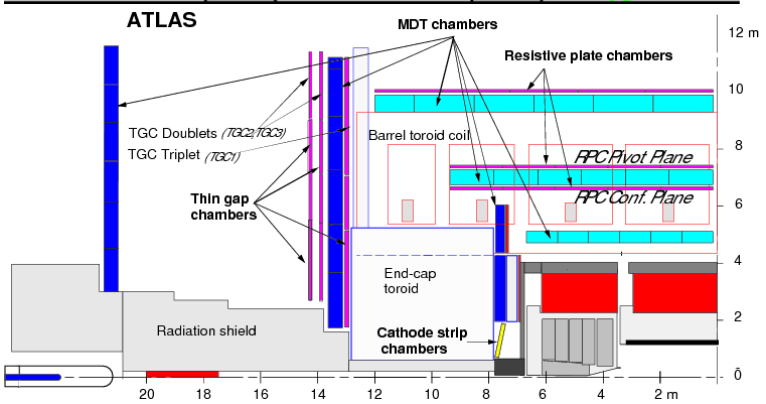


ATLAS muon spectrometer ($|\eta| < 2.7$)

- 3 barrel layers, 2×3 endcap wheels
- Fast trigger chambers: TGC (thin gap chambers), RPC (resistive plate chambers)
- High resolution tracking: MDT (monitored drift tubes), CSC (cathode strip chambers)
- Air-core toroids ($< B >= 0.4\,\mathrm{T}$)
  - ⋆ Large field variations in toroid, close to 4 T near coil

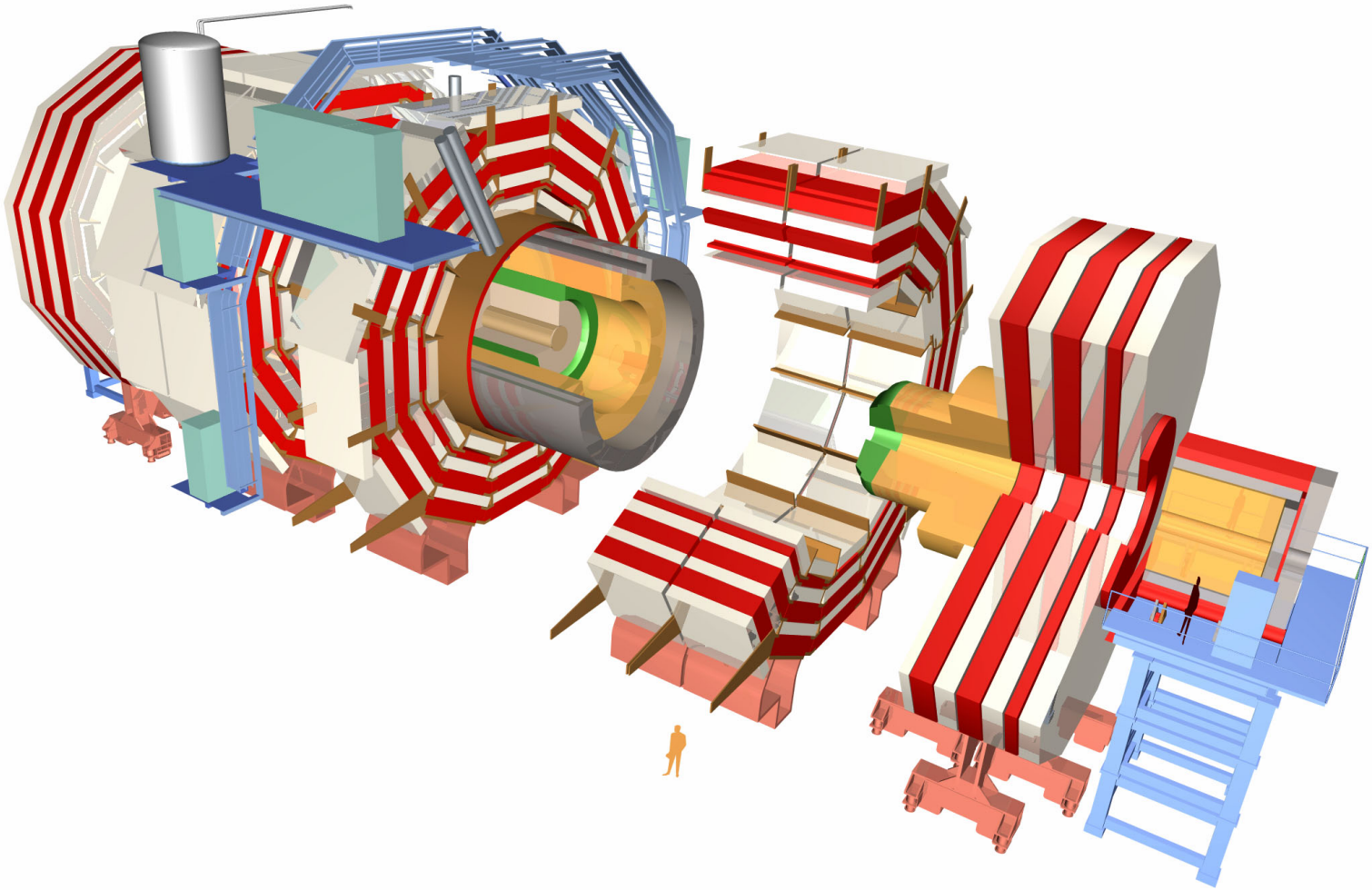






CMS

- 4 T solenoid magnet
- Tracking: Si pixel, microstrip
- $PbWO_4$ crystals and Fe/scint calos
- μ chambers in return yoke

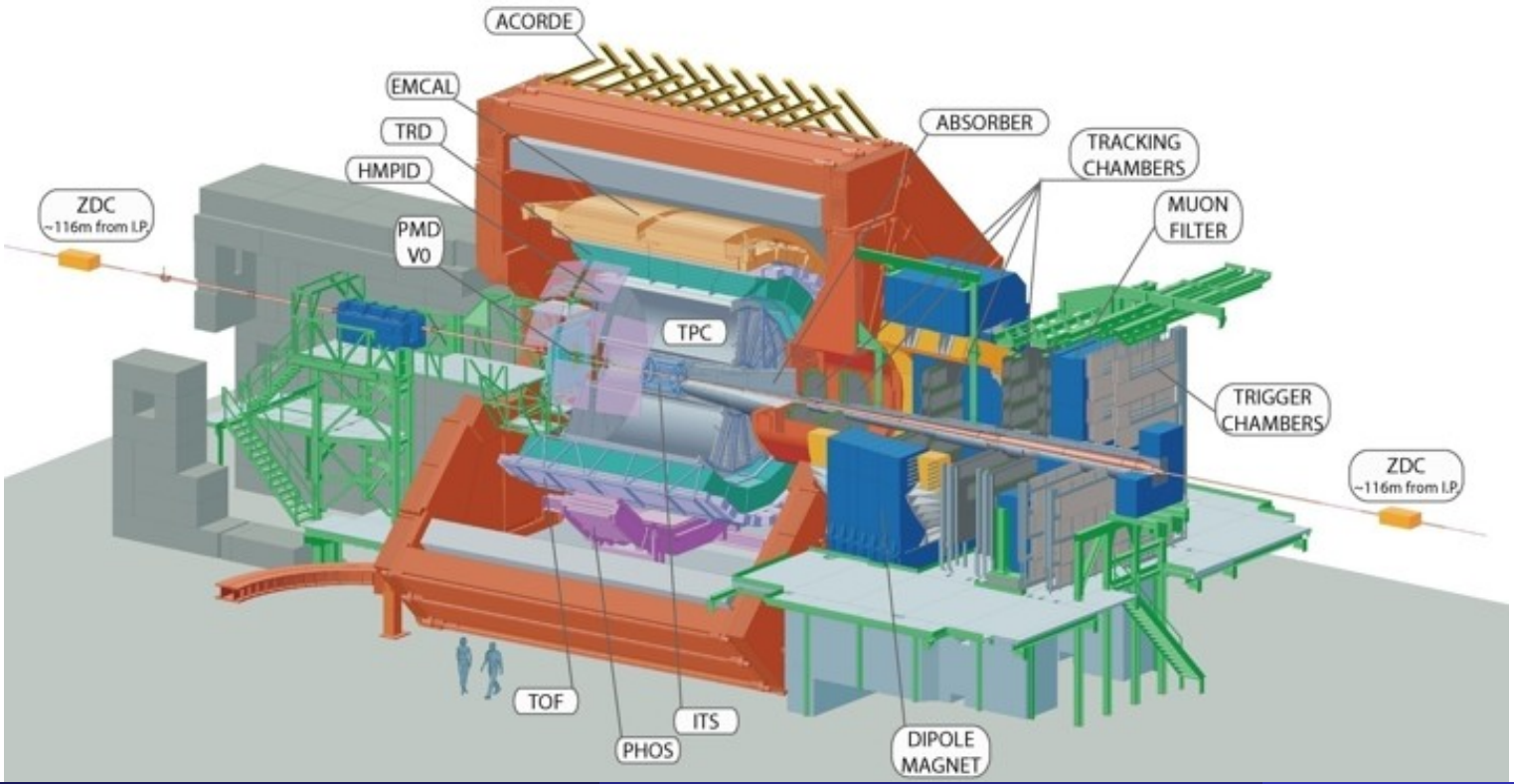


15 m$\times$22 m
12.5 ktons

Alice

Dedicated to heavy ion collisions (quark-gluon plasma), but also taking data during pp collisions

- L3 solenoid
- Tracking: Large TPC, Si pixel, drift and microstrip detectors
- $PbWO_4$ crystal and Pb/scint calo
- Particle id: RICH, TRD and TOF

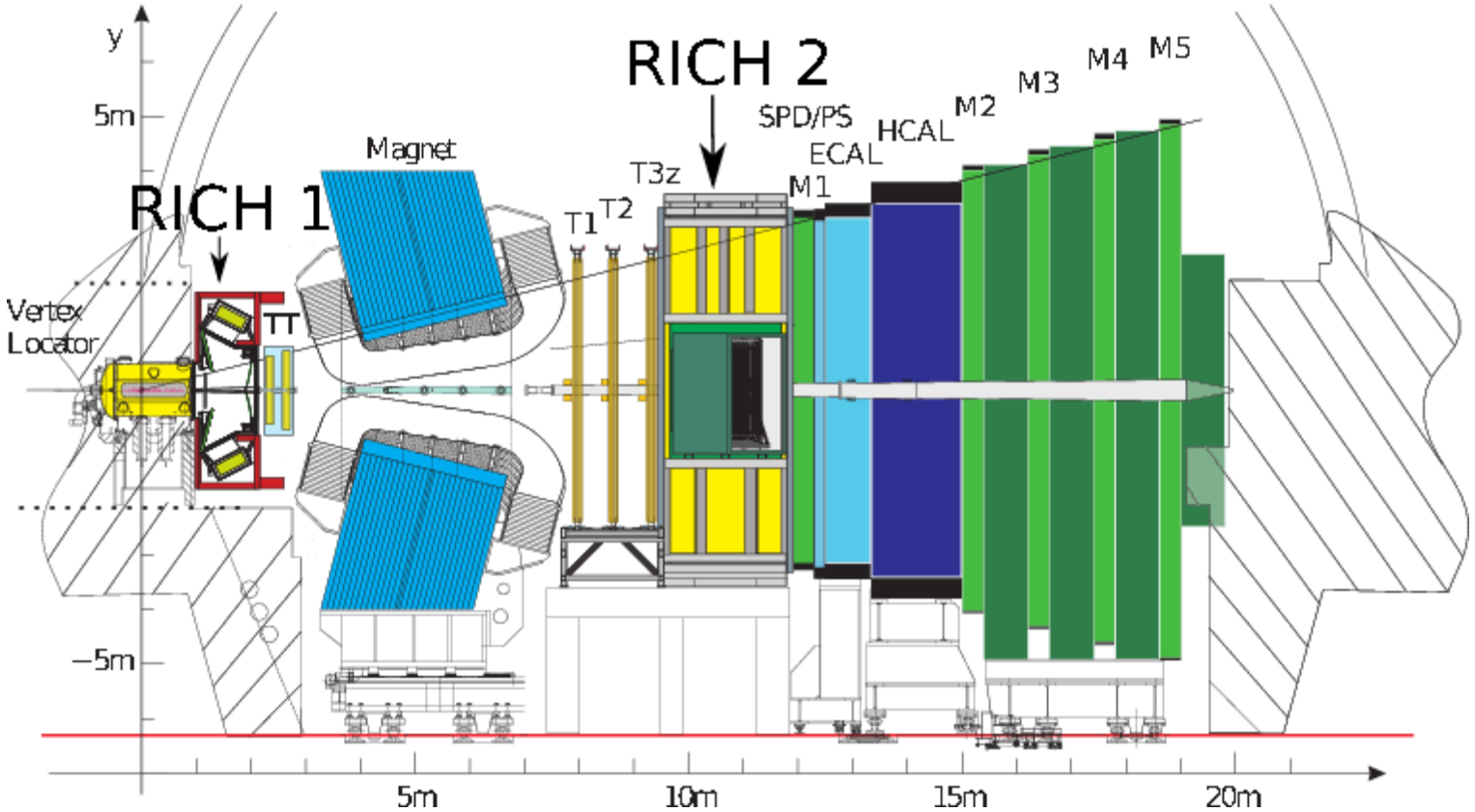


16 m×26 m
10 ktons

LHCb

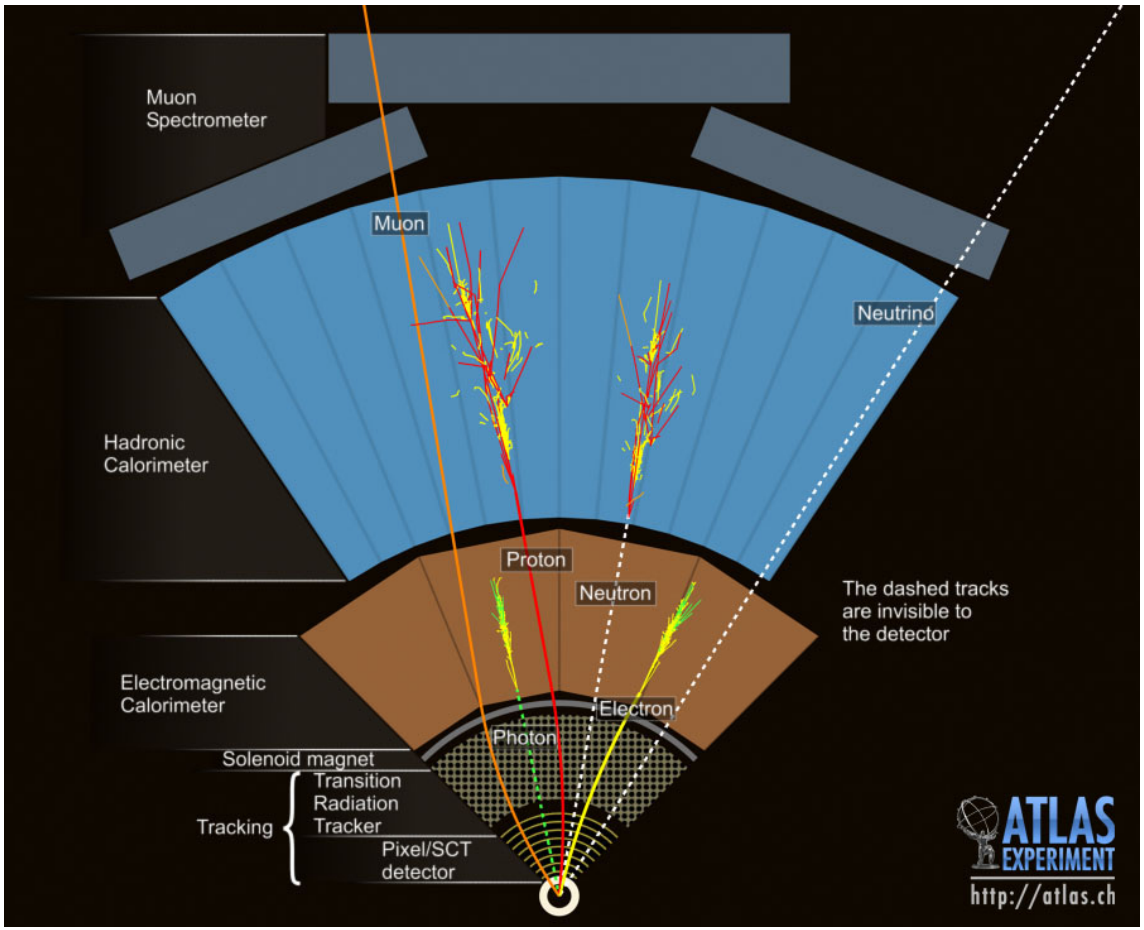
b physics and CP violation (indirect search for new physics)

- forward spectrometer
- dipole magnet
- Tracking: 21-layer Si microstrip, straw tubes
- Pb/scint and Fe/scint calorimeters
- Particle id: 2 RICH systems
- multiwire proportional chamber μ system



10 m×13 m ×21 m
5.6 ktons

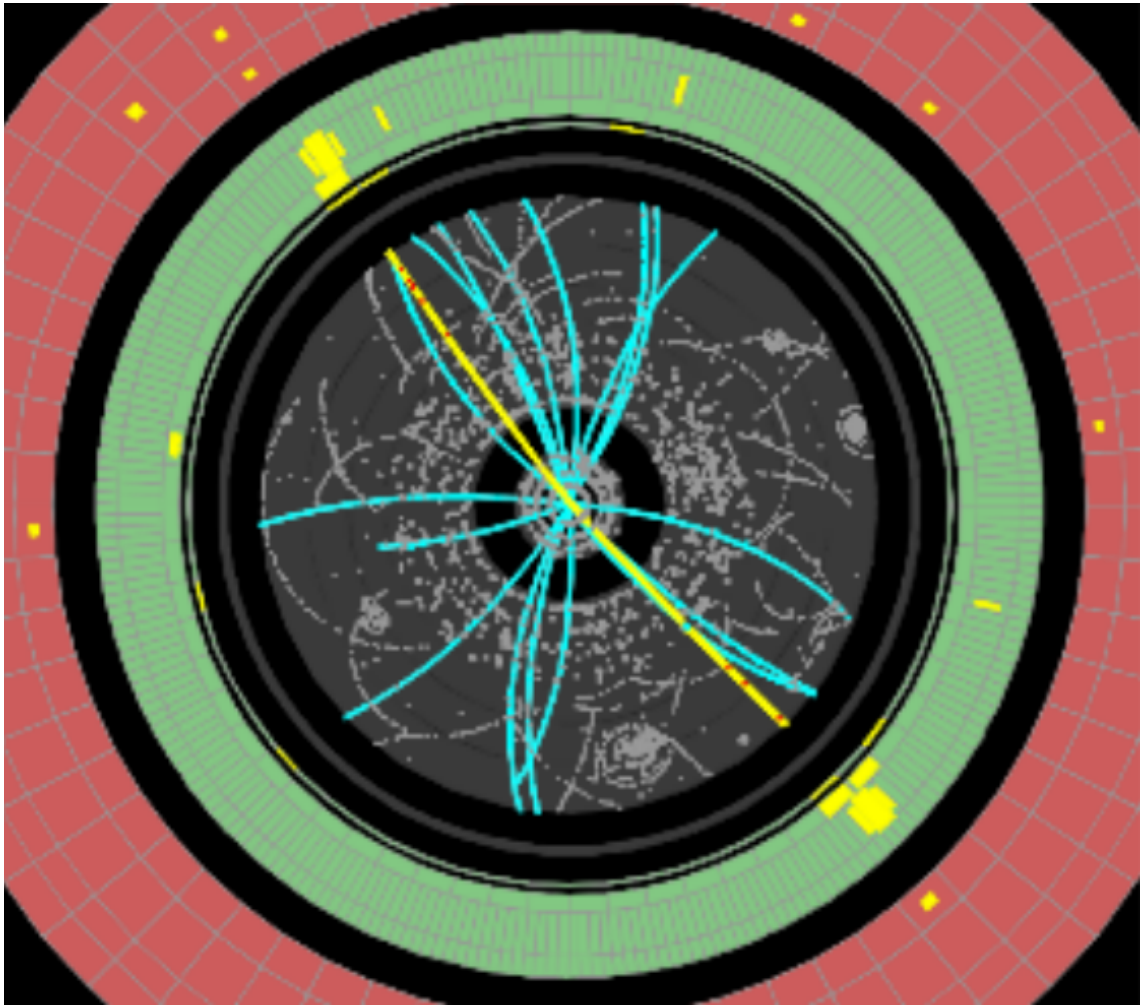
Object reconstruction (at ATLAS and CMS)



Electron

- Track in tracking system
- Shower in electromagnetic calorimeter
- No (or little) energy in hadronic calorimeter

Object reconstruction (at ATLAS and CMS)



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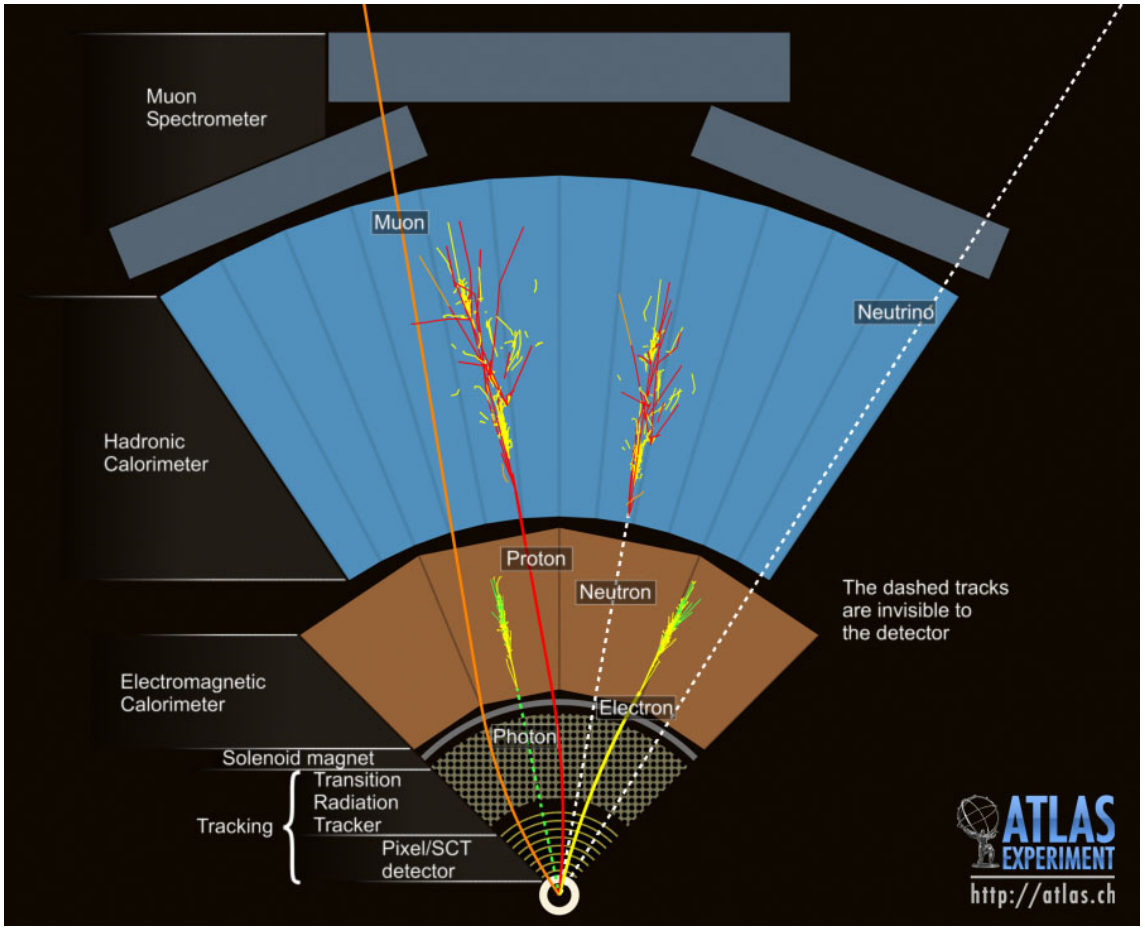
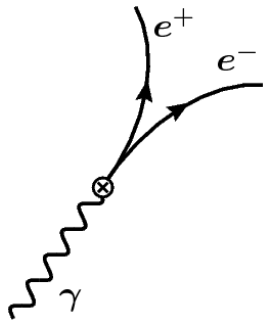


Photon

- No track or conversion vertex in tracking system
  - ⋆ ∼40% of photons convert into e^+e^- due to high material budget
- Shower in electromagnetic calorimeter
- No (or little) energy in hadronic calorimeter



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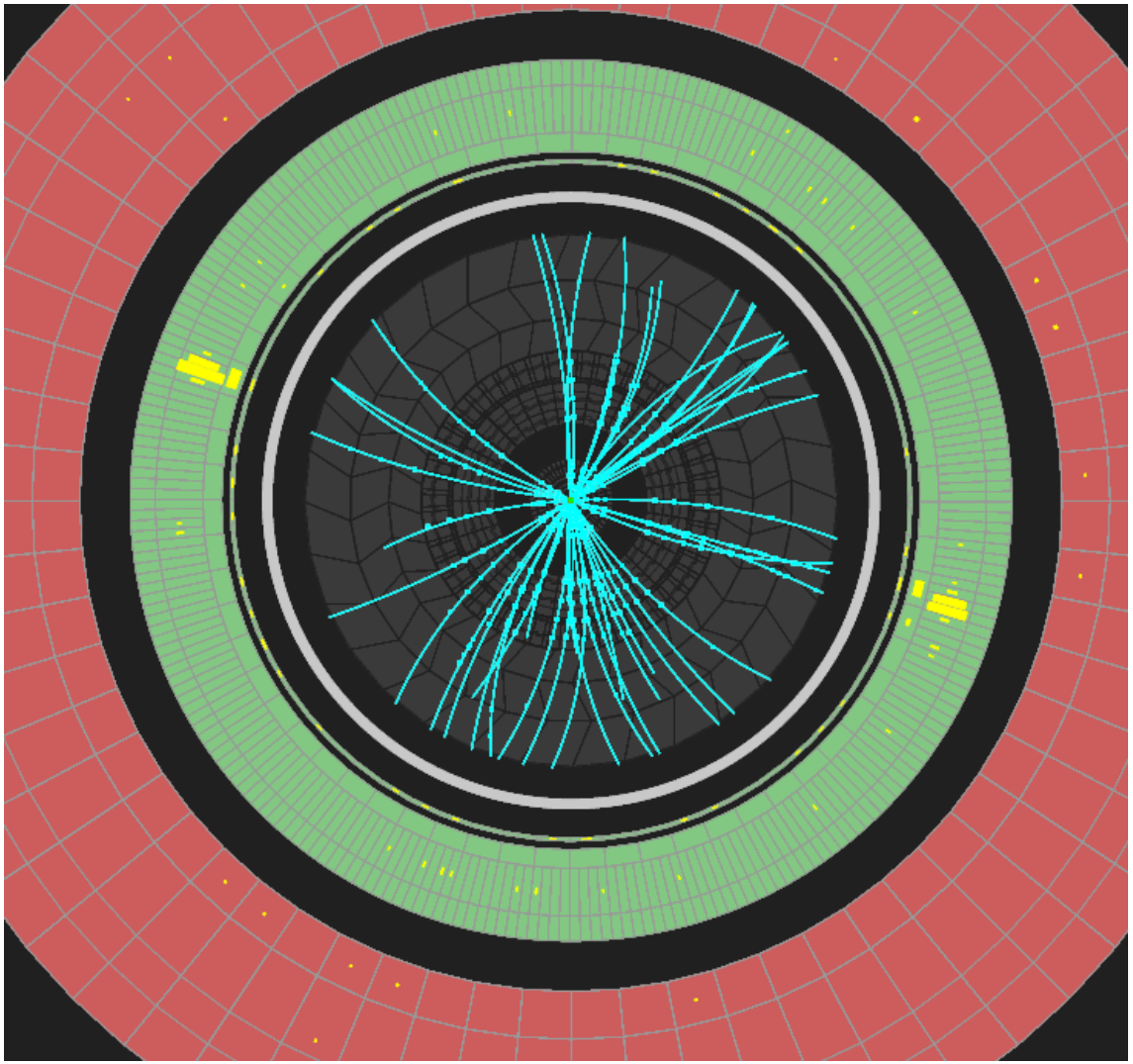

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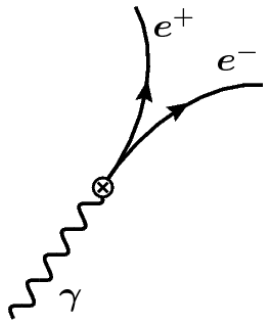
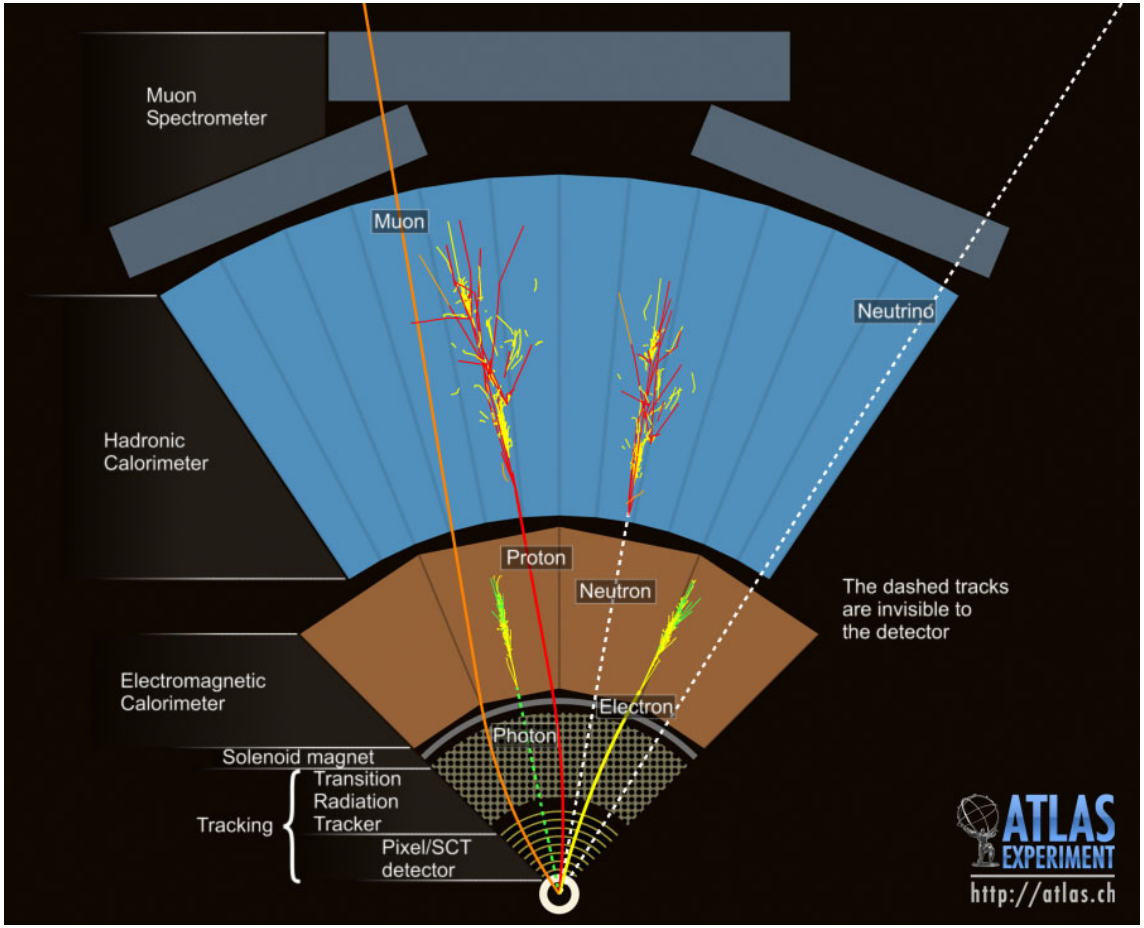


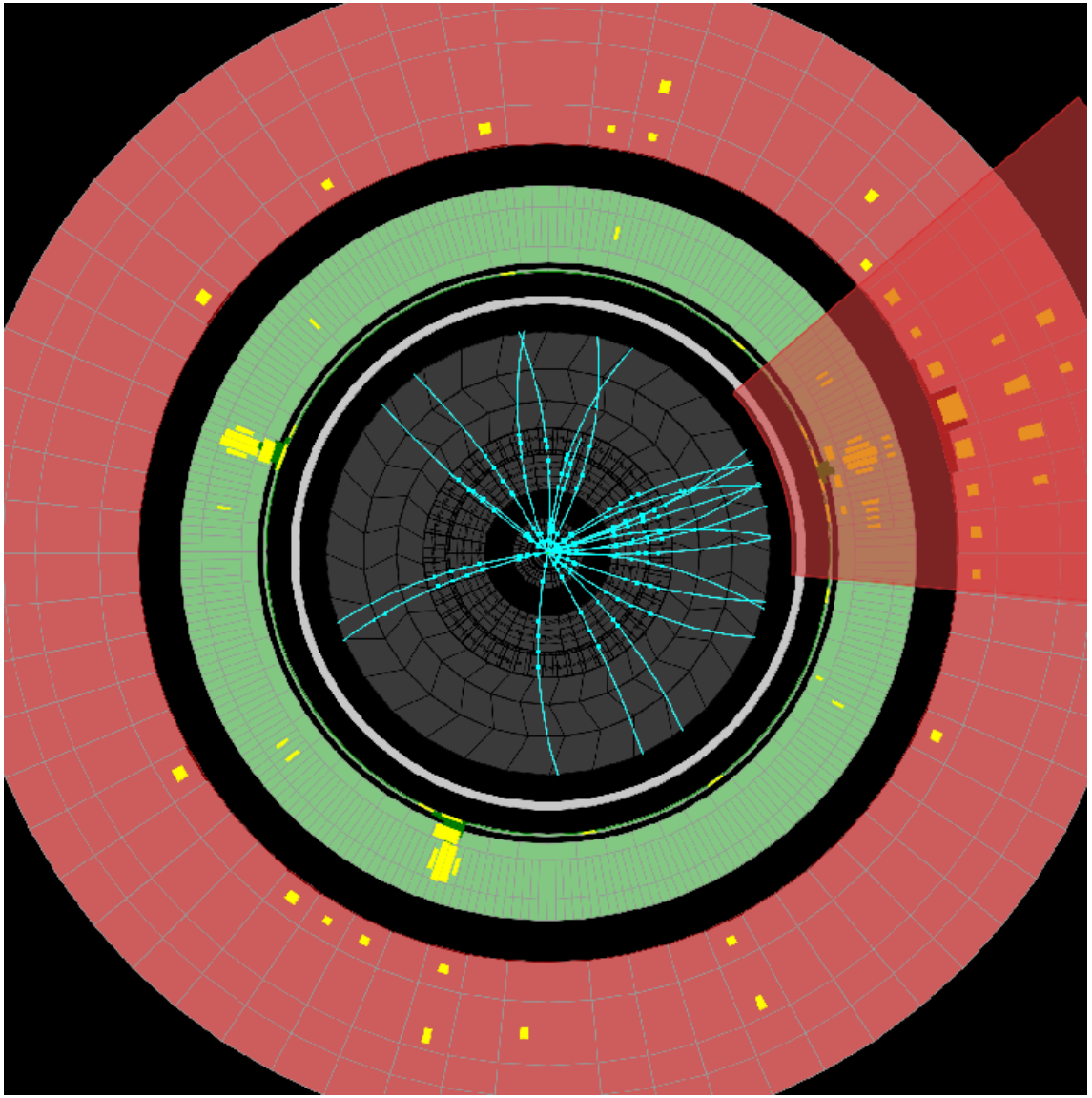
Object reconstruction (at ATLAS and CMS)



Hadron (Jet = hadronic shower)

- Tracks in tracking system (from charged component)
- Shower in hadronic and electromagnetic calorimeter

Object reconstruction (at ATLAS and CMS)



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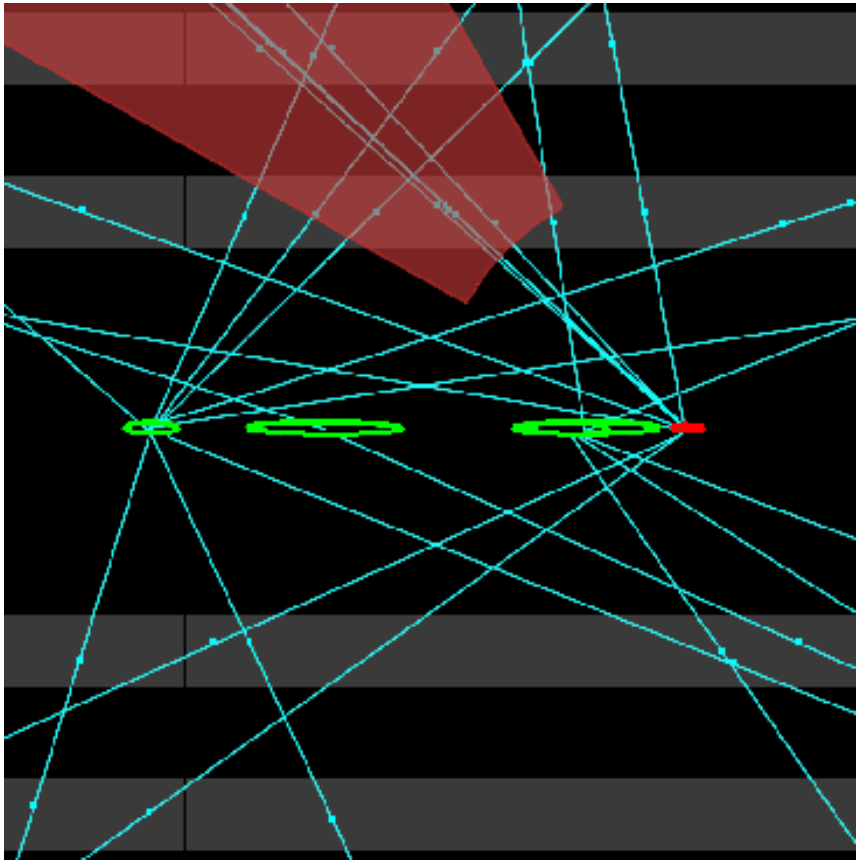

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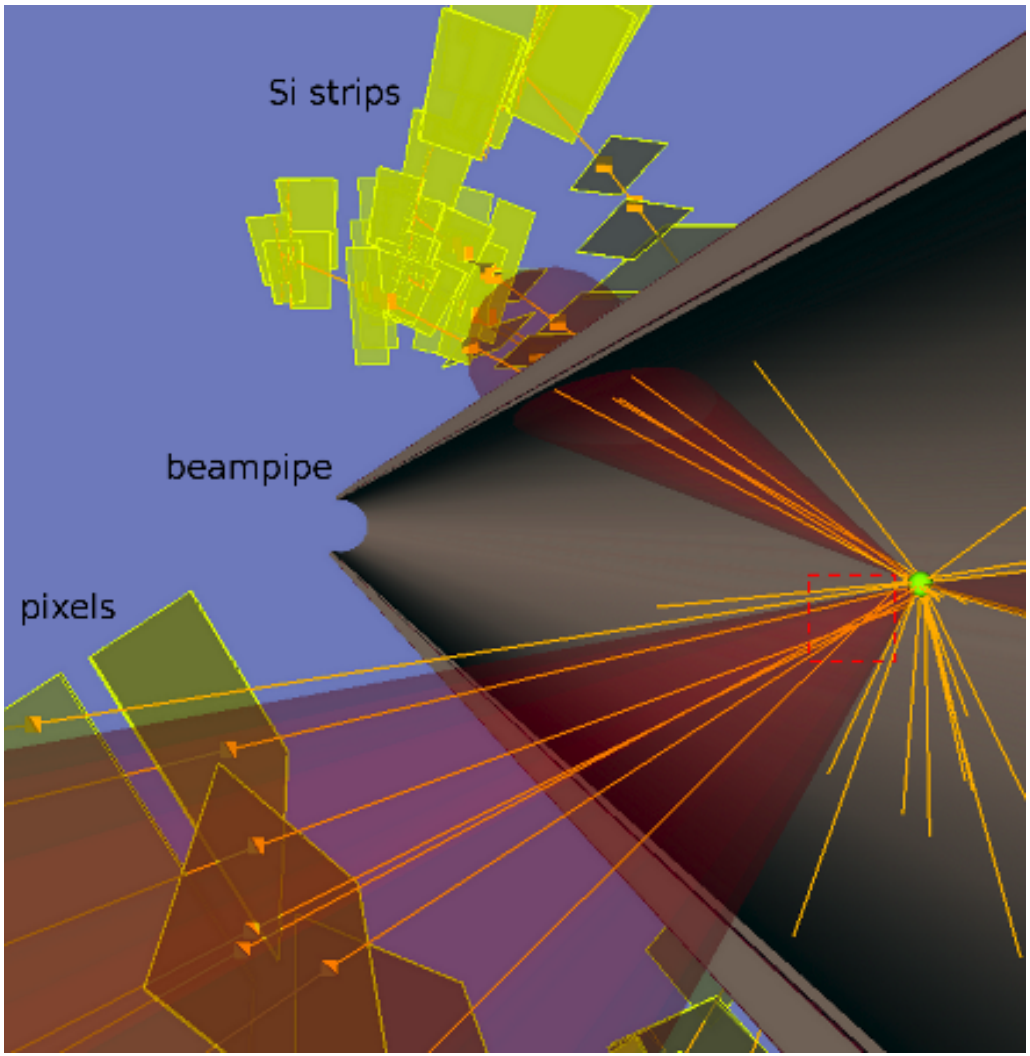


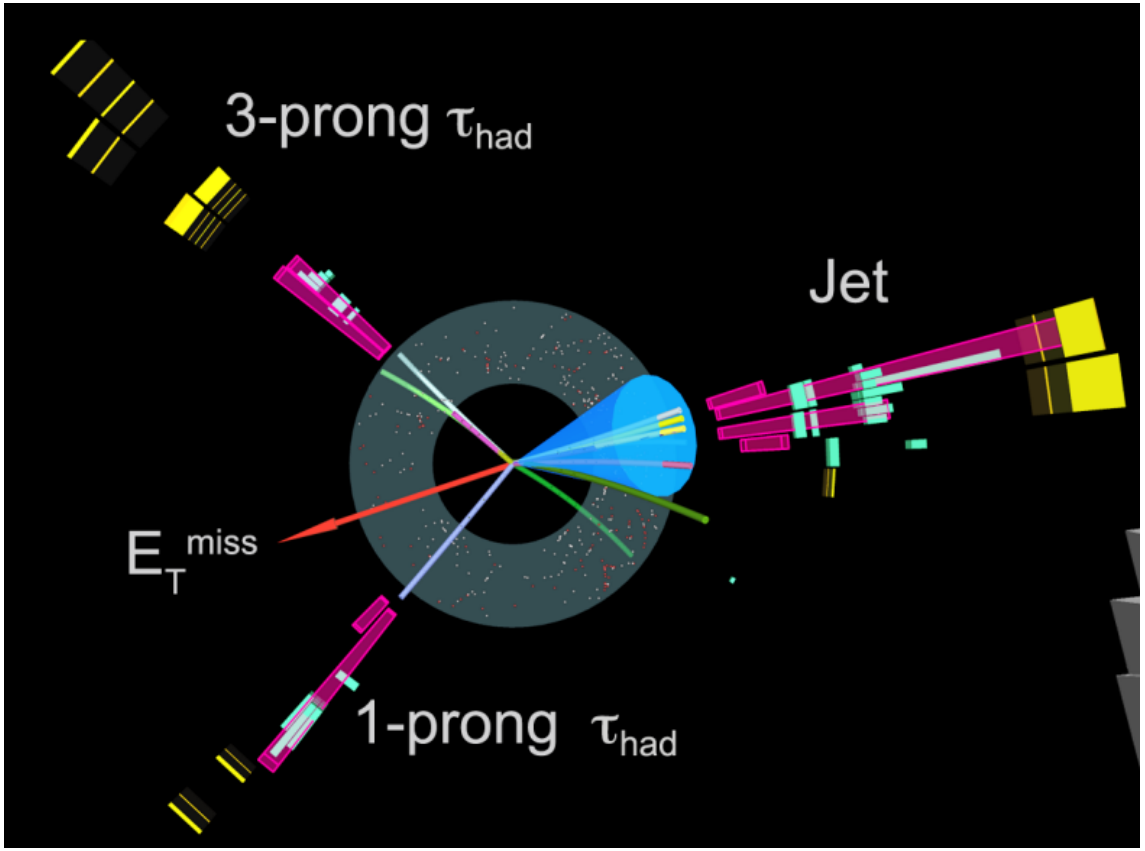
Hadron (Jet = hadronic shower)

- Tracks in tracking system (from charged component)
- Shower in hadronic and electromagnetic calorimeter

b-jet

- Origin of tracks offset with respect to pp interaction vertex

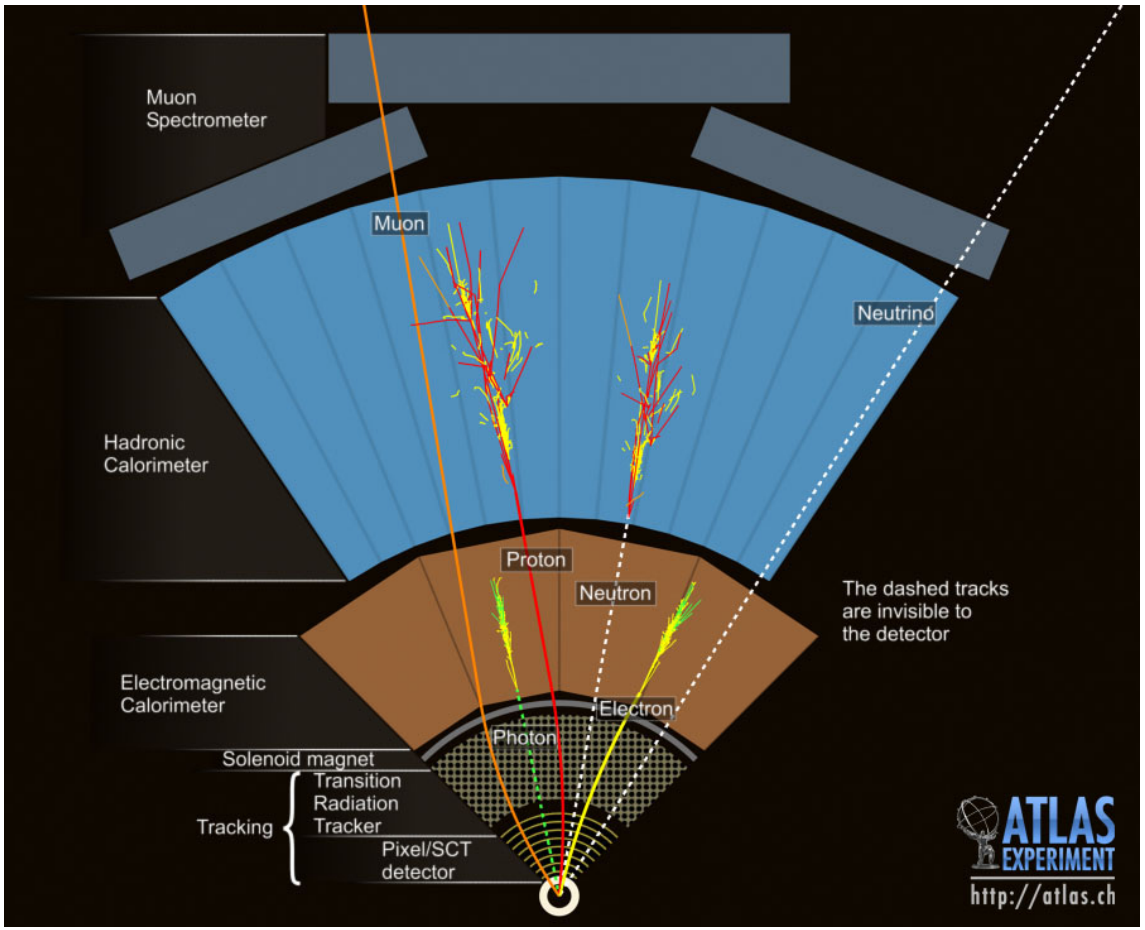
Object reconstruction (at ATLAS and CMS)



τ

- Hadronic (τ-jet):
  Collimated, 1 or 3 tracks in tracking system
- Leptonic ($\tau \rightarrow e(\mu)\nu\nu$):
  1 track: electron or muon

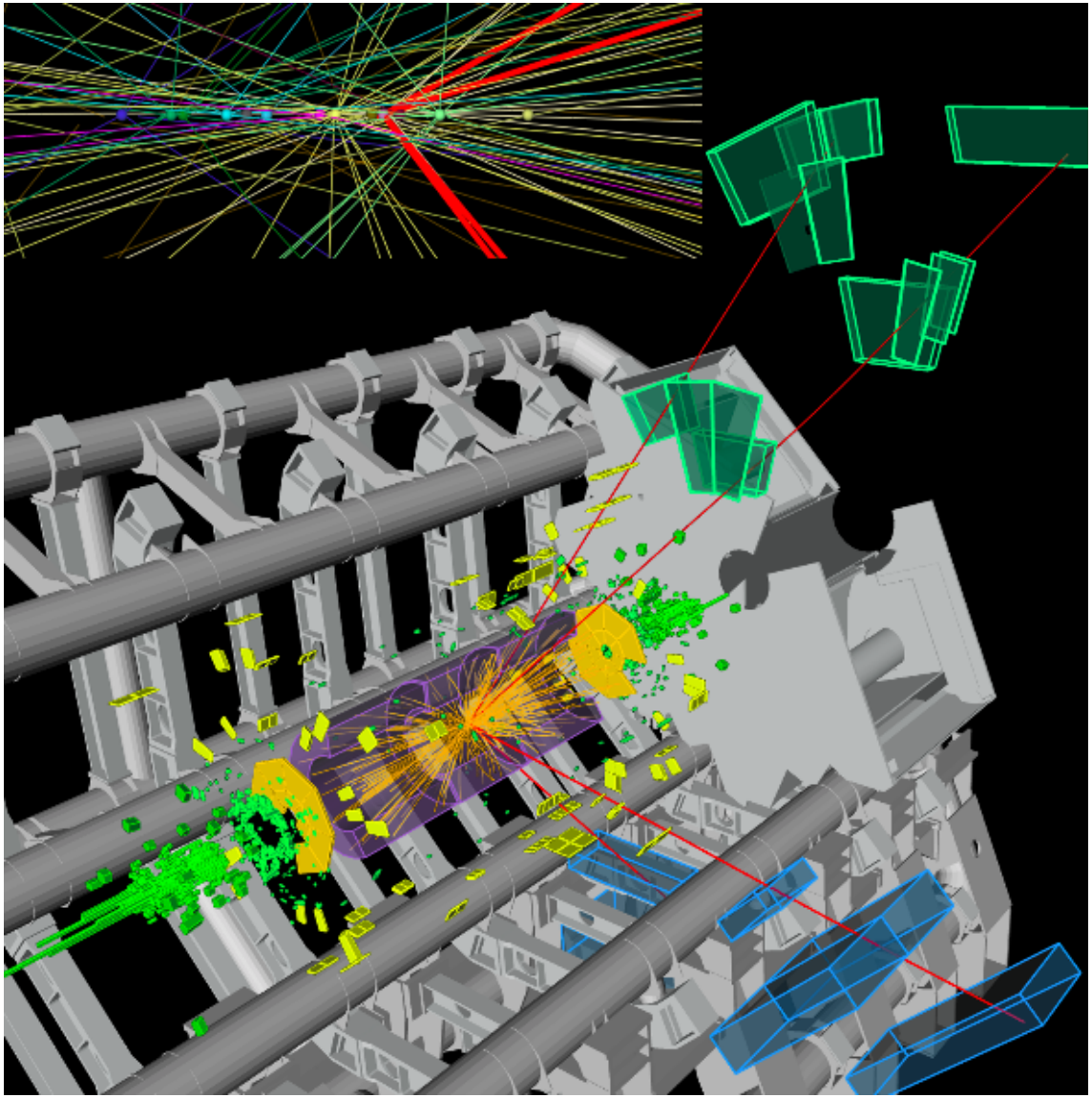
Object reconstruction (at ATLAS and CMS)



Muon

- Track in tracking system
- Little energy deposited in electromagnetic calorimeter
- Track in muon system

Object reconstruction (at ATLAS and CMS)



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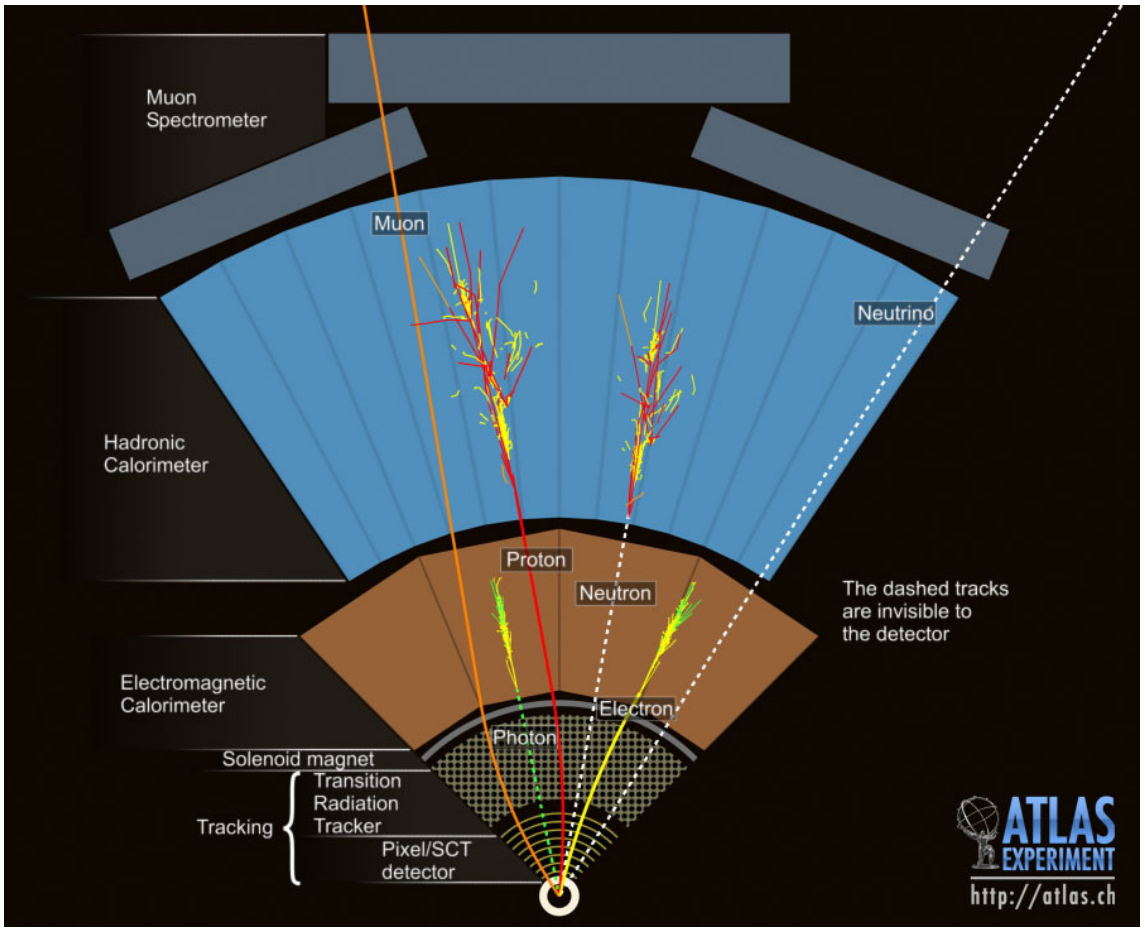
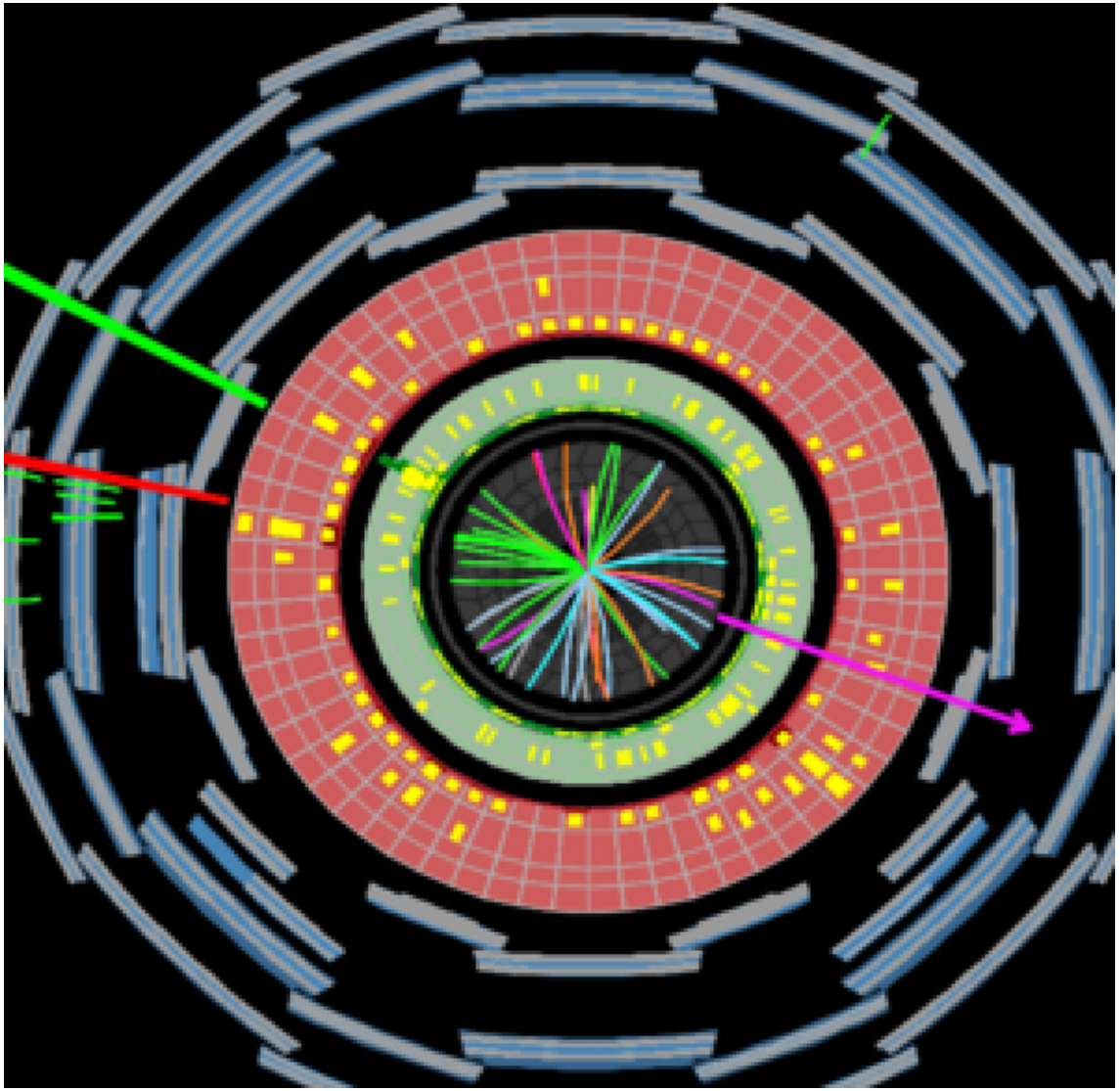


Neutrino (E_T^{miss})

- No signal in any subdetector
- Transverse energy imbalance in the event

Object reconstruction (at ATLAS and CMS)



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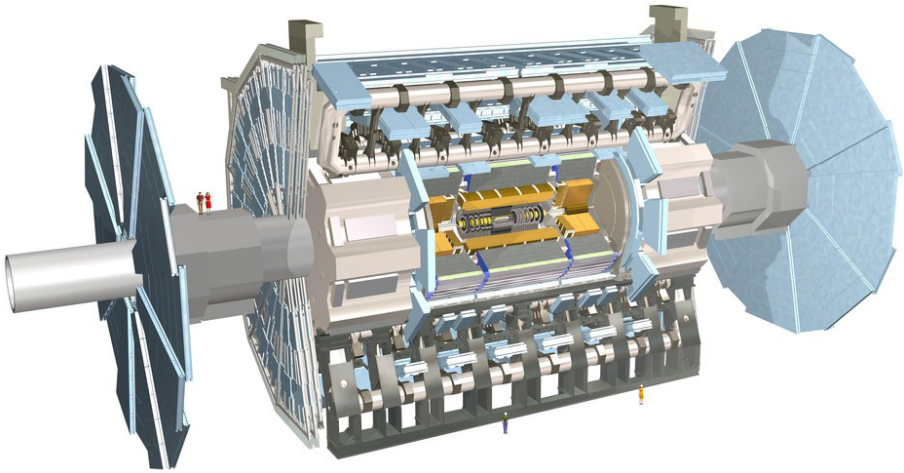
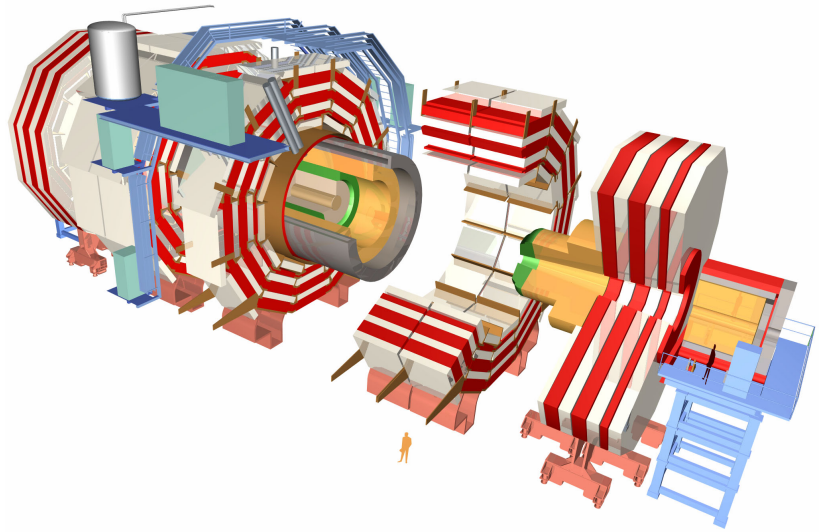
The ATLAS and CMS experiments – comparison





ATLAS Emphasis on jet and missing E_T resolution, particle identification and standalone muon measurement

CMS Emphasis on electron/photon and tracking (muon) resolution

Both: excellent hermeticity and forward acceptance