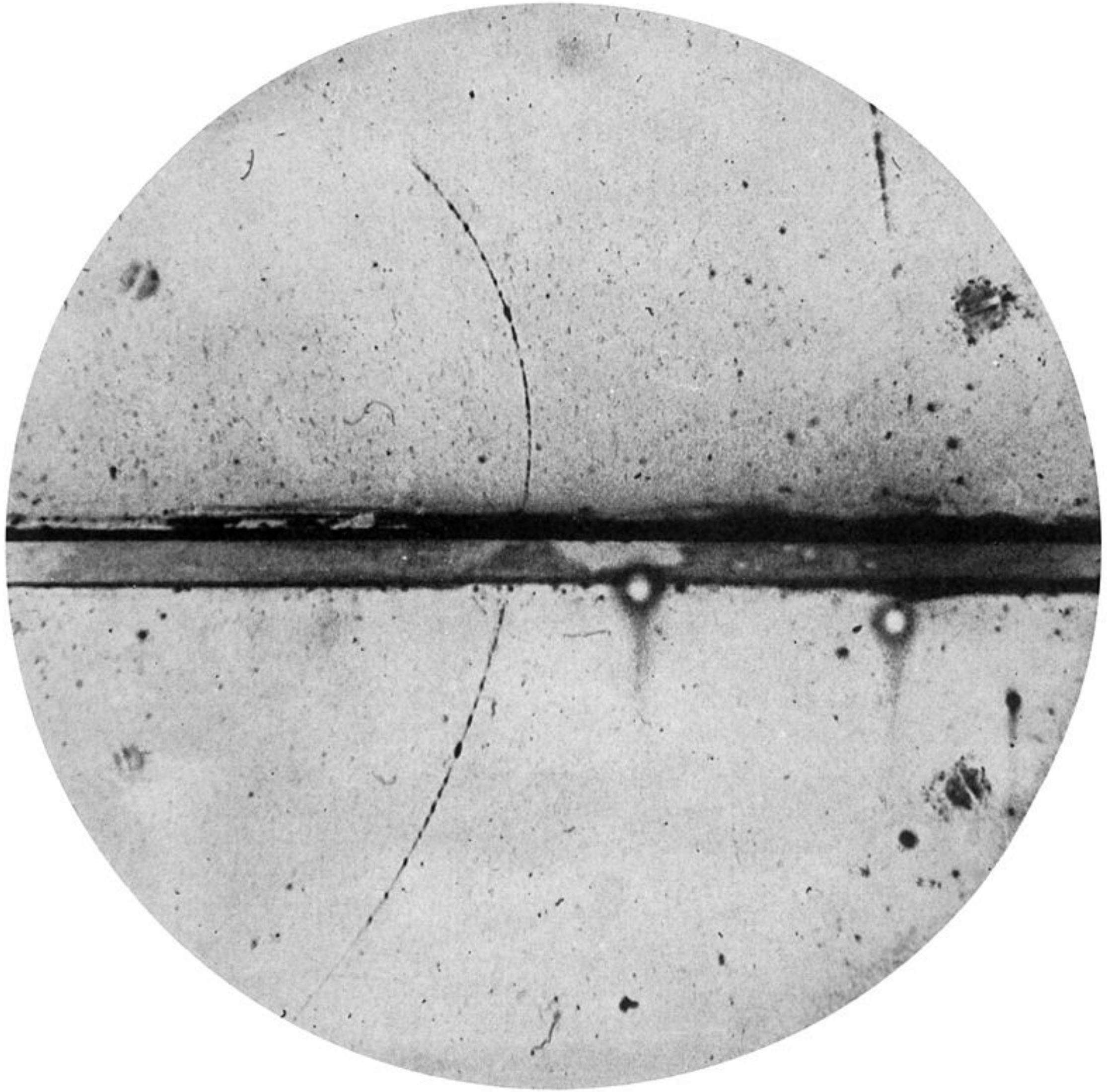
Tracking: ATLAS and (vs?) CMS

Pi-track McCormack

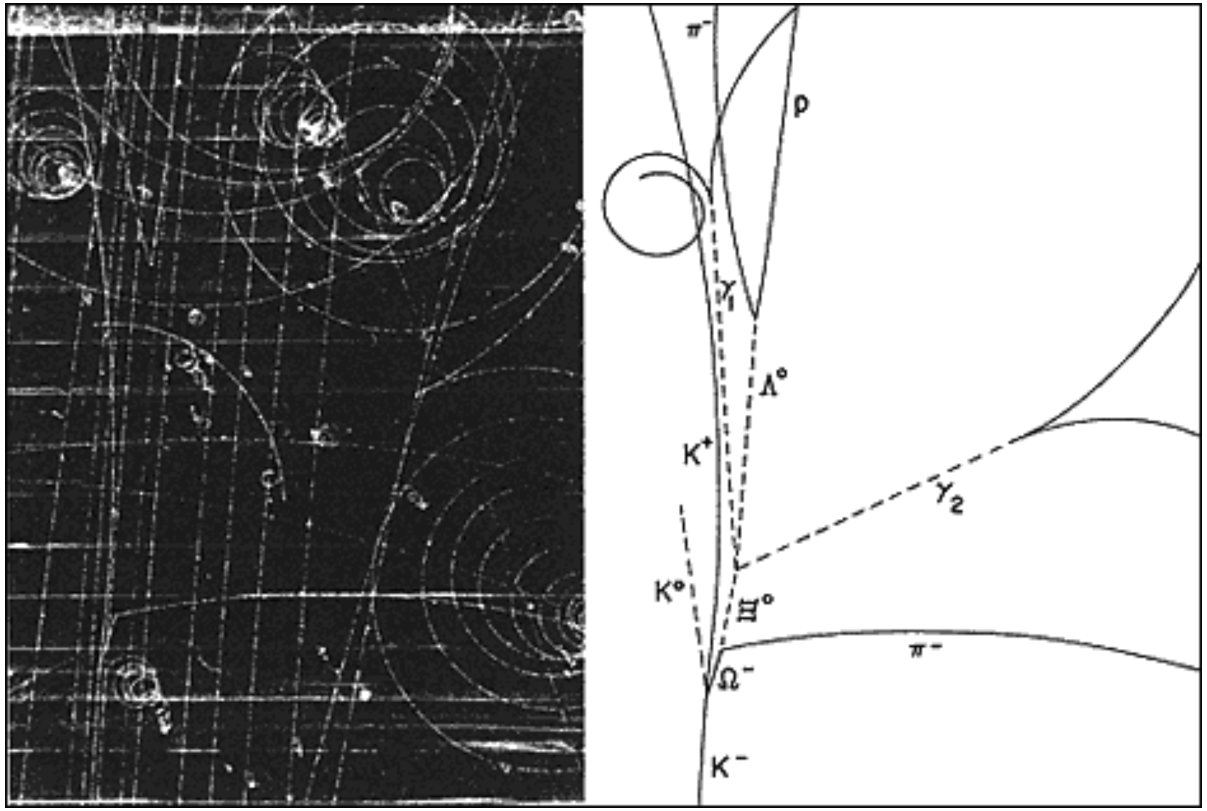
290E

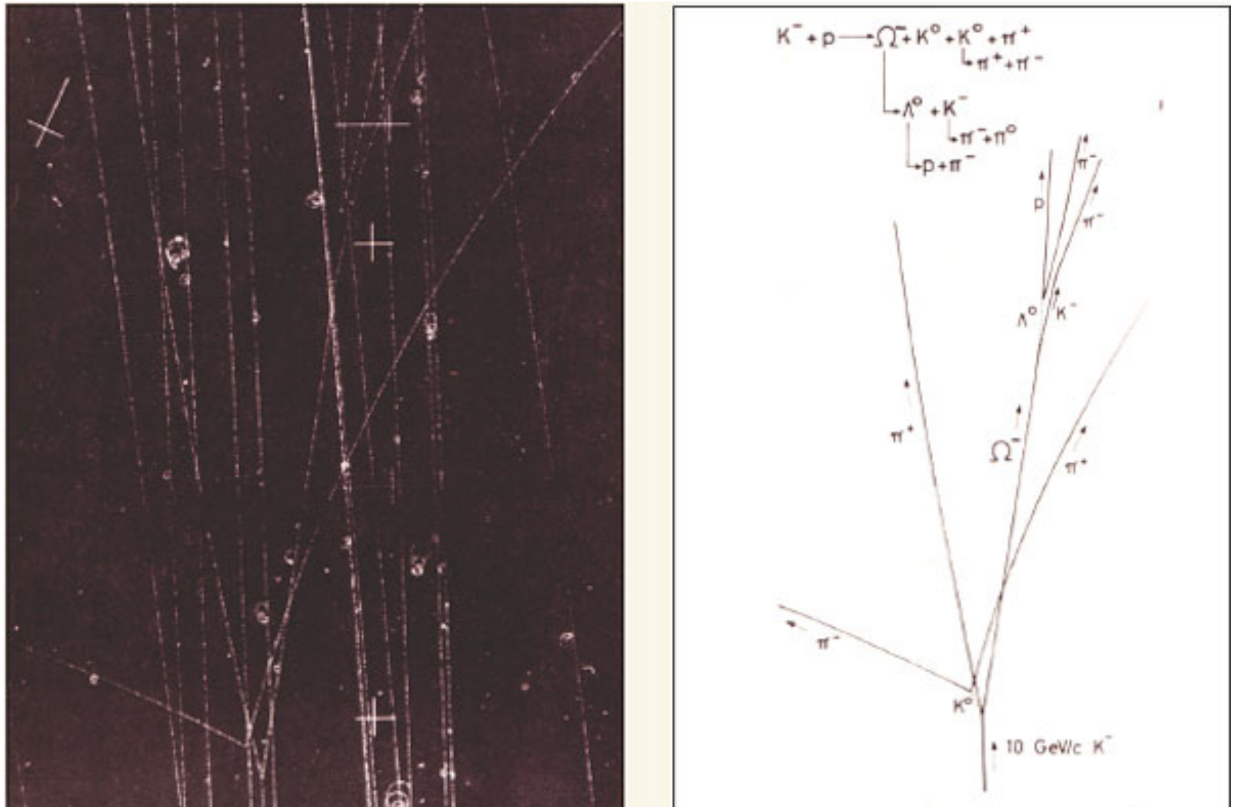
October 25, 2017

Find the track

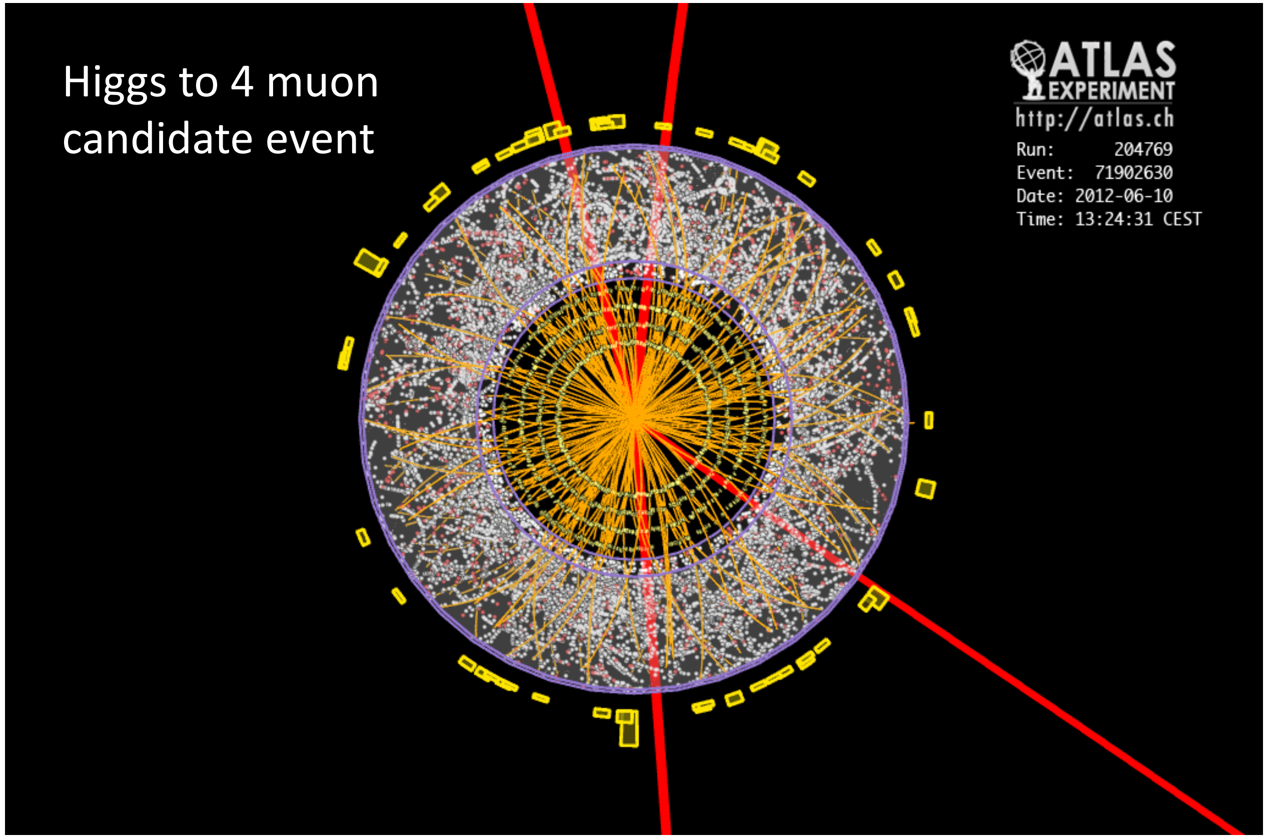


Find the tracks

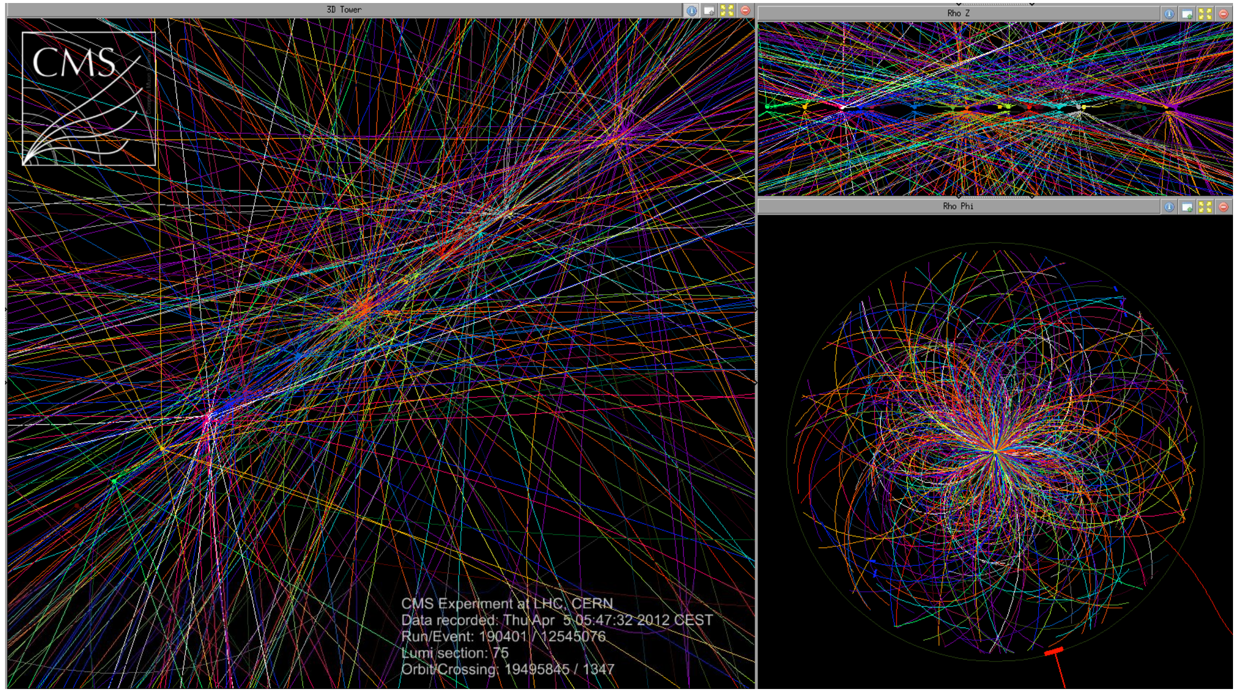




Find the tracks



Bunch crossing with 29 collisions



http://atlasexperiment.org/photos/events-collision-proton.html

http://cms.web.cern.ch/news/new-world-record-first-pp-collisions-8-tev

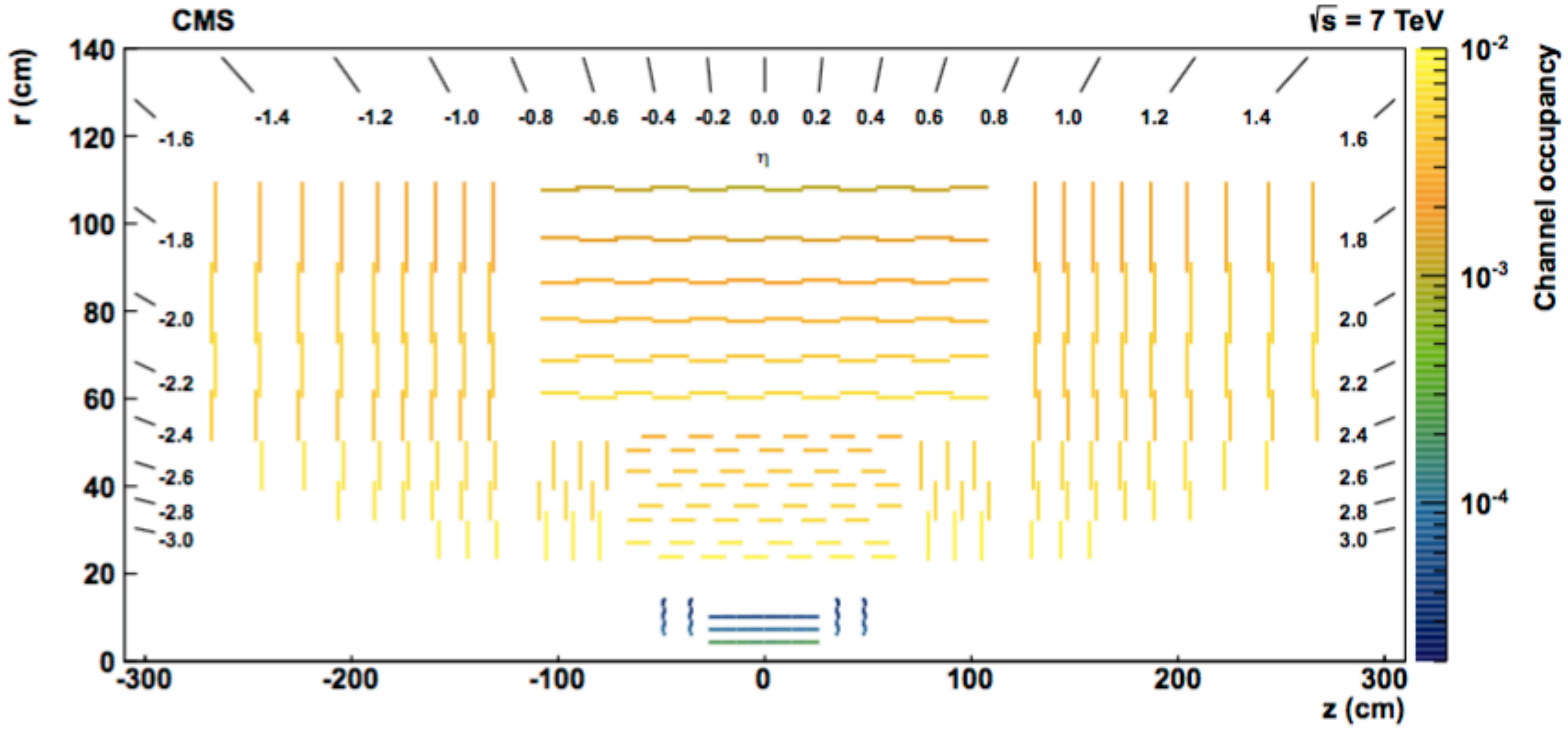
The basics: tracking with silicon

- Charged particles create electron/hole pairs in silicon
- These are read out as electronic signals
- Magnet bends particles based on charge and momentum
- $p_T \approx 0.3BR$
  - p (momentum) in GeV/c, B (magnetic field) in T, and R (bending radius) in m
- σ_p degrades with p

Why do we care about tracking?

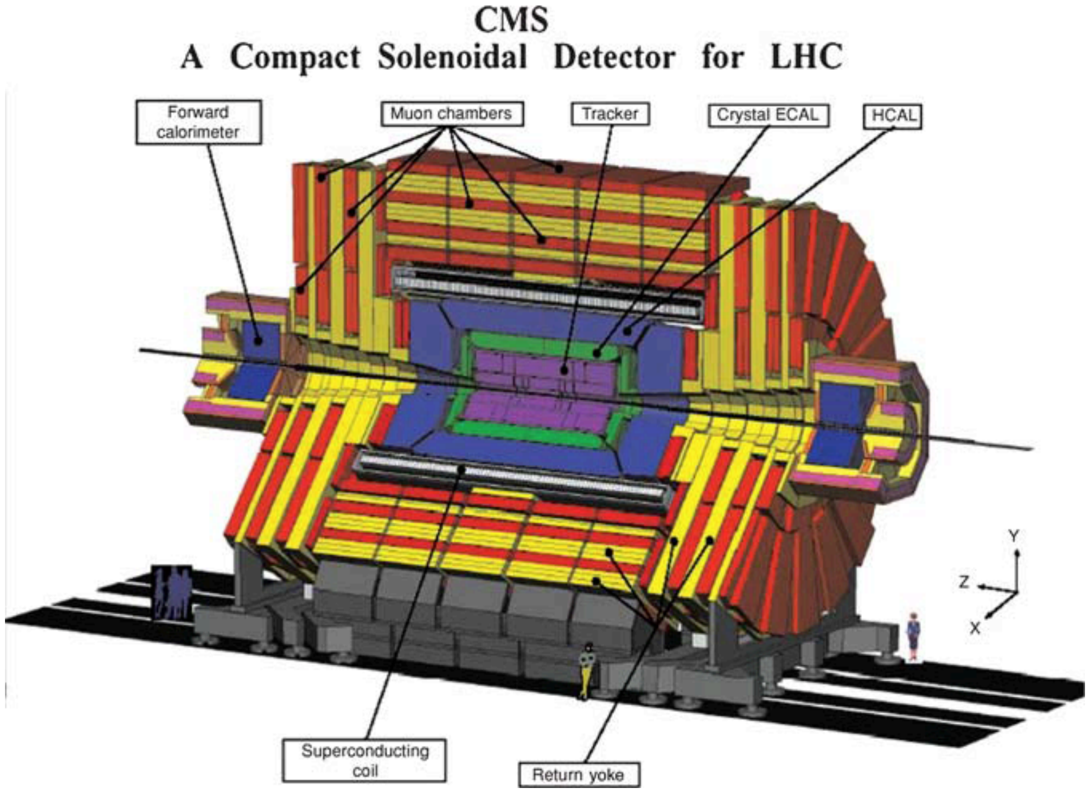
- Provides position and momentum information about charged particles
- Needed for particle ID
- Vertex reconstruction
- Challenges:
  - Should faithfully reproduce a wide range of momenta (p_T ~ 100MeV – 1TeV)
  - Must deal with O(1000) charged particles per bunch crossing (O(20) pp collisions every 25 ns at LHC)
  - Want to maximize ratio of true tracks to fake tracks
  - High density environments (think jets) pose an even greater challenge

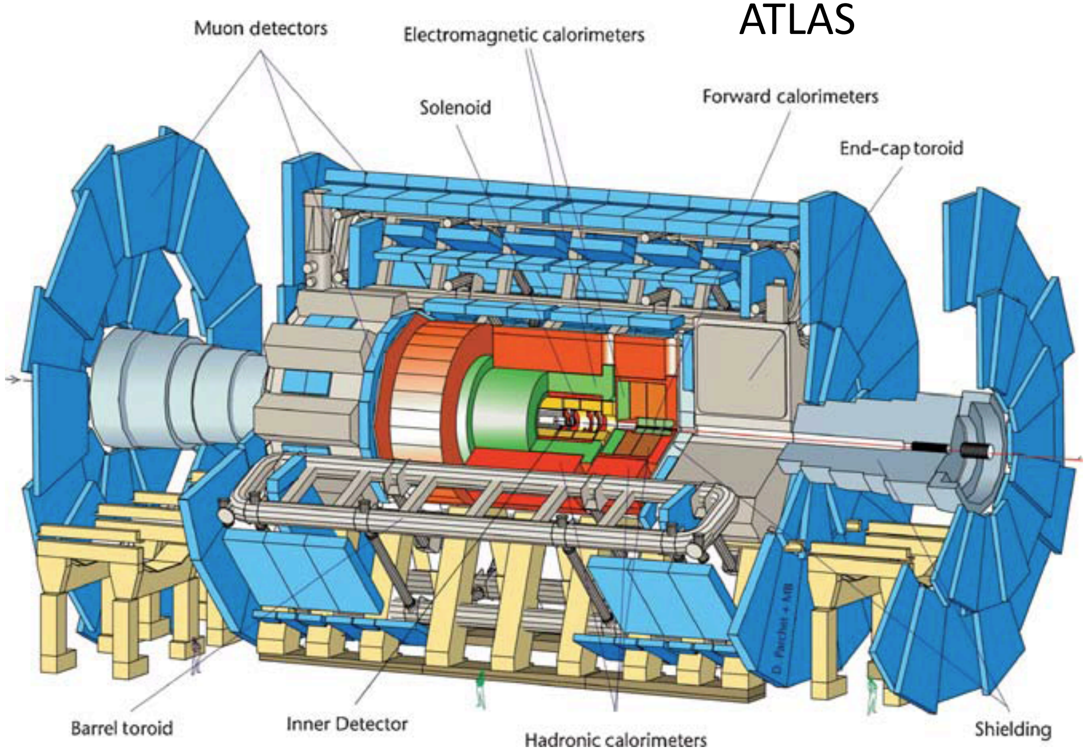
Channel occupancy for 9 collisions/crossing



What kind of activity are we facing? Example channel occupancy for CMS inner detector.

The CMS and ATLAS Detectors



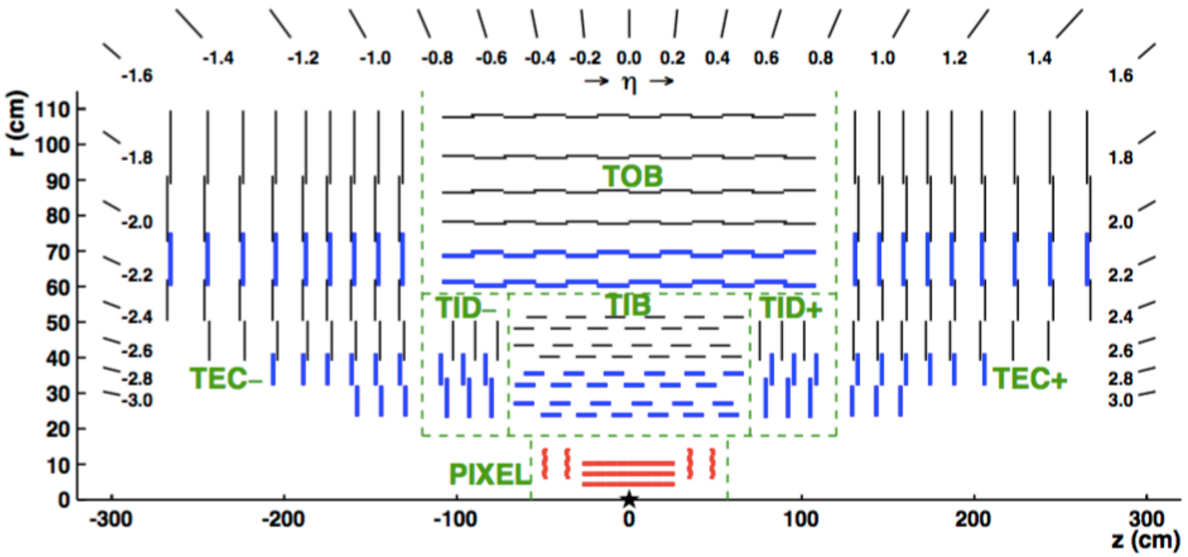


- 12,500 tons
- 15m diameter
- 20m long
- 4T magnet for tracking

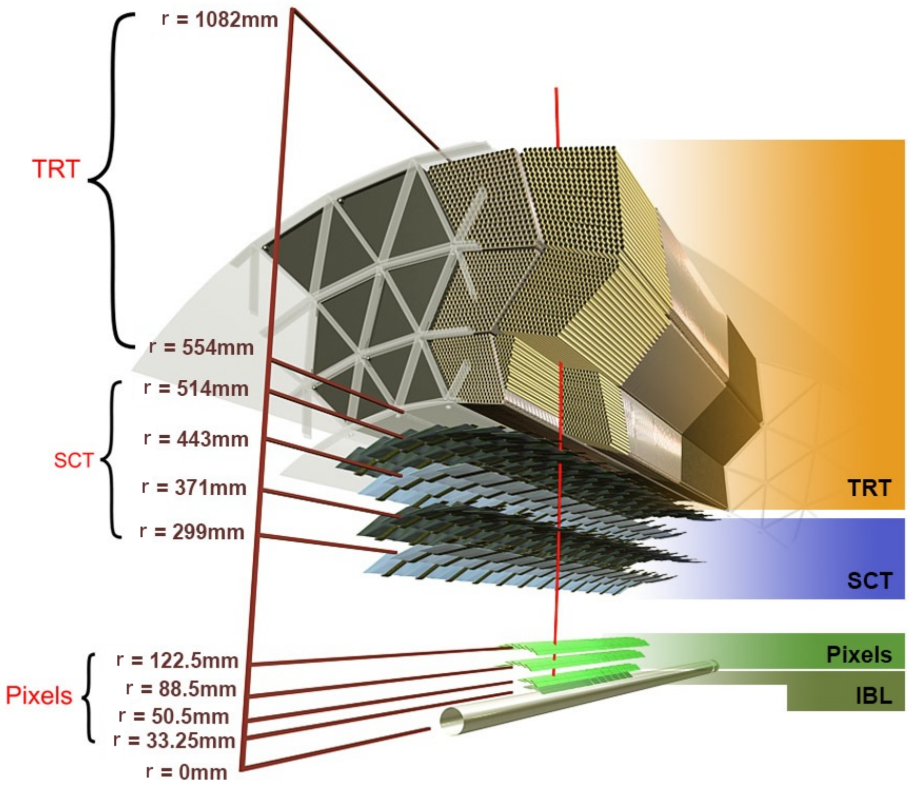
- 7000 tons
- 22m diameter
- 46 m long
- 2T magnet for tracking

The trackers (inner detectors)

CMS



ATLAS

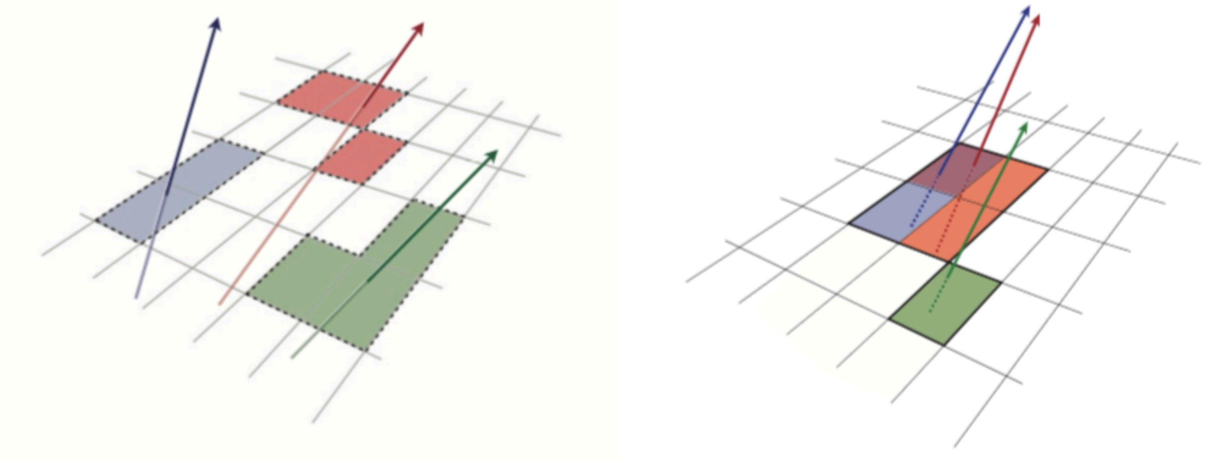


- Pixel and silicon strip components
- Some modules (blue and red) give 3D hit information
- 66 million pixels and ~10 million strips
- Achieves hit resolution of O(10-50μm)
- Immersed in solenoid magnet

- Pixel, silicon strip (SCT), and transition radiation tracker (TRT)
- Pixels give charge deposition information
- 80 million pixels and ~6 million strips
- Achieves hit resolution of O(10-100μm)
- Immersed in solenoid magnet

From particle to hits

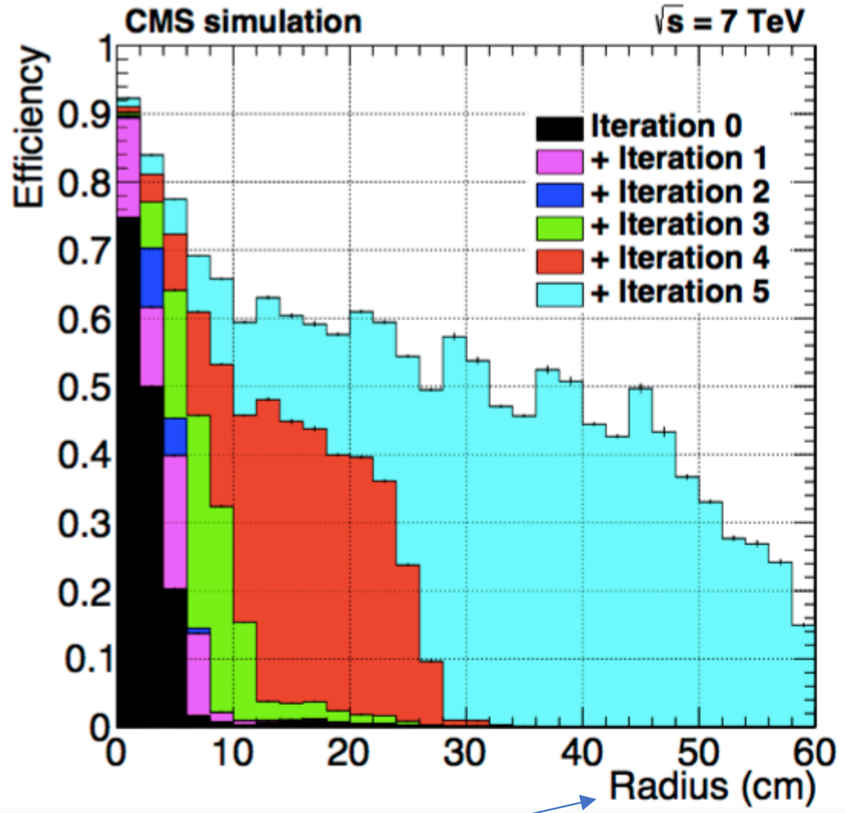
- Charged particle will create O(20000) electron-hole pairs
- Current above a certain threshold is considered a hit
- If charge is collected in multiple adjacent pixel/strips, the hits are grouped together into a cluster
    - Challenge: this can lead to merged clusters in dense environments
- Hit reconstruction efficiency (in working modules) is >99% typically
- Hit must be converted from local position to global position



(a) Single-particle pixel clusters (b) Merged pixel cluster

From hits to tracks in CMS

- Hits converted into 3D space points (accounting for detector deformation)
- CMS uses an Iterative "Combinatorial Track Finder"
  - Hits associated with found tracks are removed after each pass
  - 6 iterations are performed; each looking for the easiest tracks remaining



Transverse radius of particle production relative to beam line

What happens in each iteration?

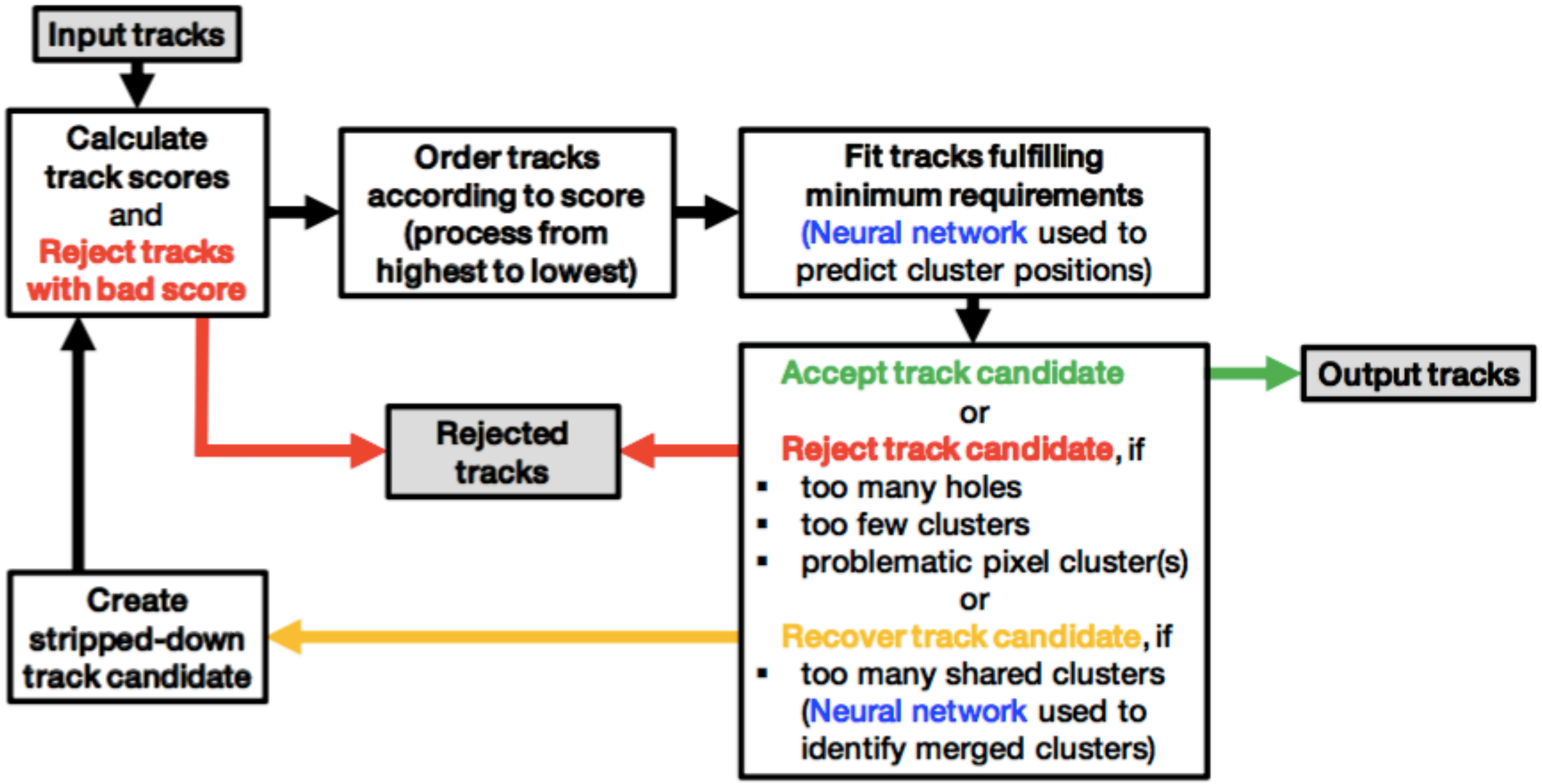
- Helical paths have 5 parameters: we must have at least 3 space points
- Iteration steps
  1. Track "seeds" are generated from 2 or 3 hits (initial estimate of track parameters)
  2. Expected track is extrapolated, looking for hits that would fall on the track
  3. Track parameters are fit to found hits
  4. Track quality flags are implemented and track might be rejected
- Seed and quality requirements are changed from iteration to iteration

Iteration	Seeding layers	p_T (GeV)	d_0 (cm)	$\lvert z_0 \rvert$
0	Pixel triplets	>0.8	<0.2	$<3\sigma$
1	Mixed pairs with vertex	>0.6	<0.2	<0.2 cm*
2	Pixel triplets	>0.075	<0.2	$<3.3\sigma$
3	Mixed triplets	>0.35	<1.2	<10 cm
4	TIB 1+2 & TID/TEC ring 1+2	>0.5	<2.0	<10 cm
5	TOB 1+2 & TEC ring 5	>0.6	<5.0	<30 cm

From hits to tracks in ATLAS

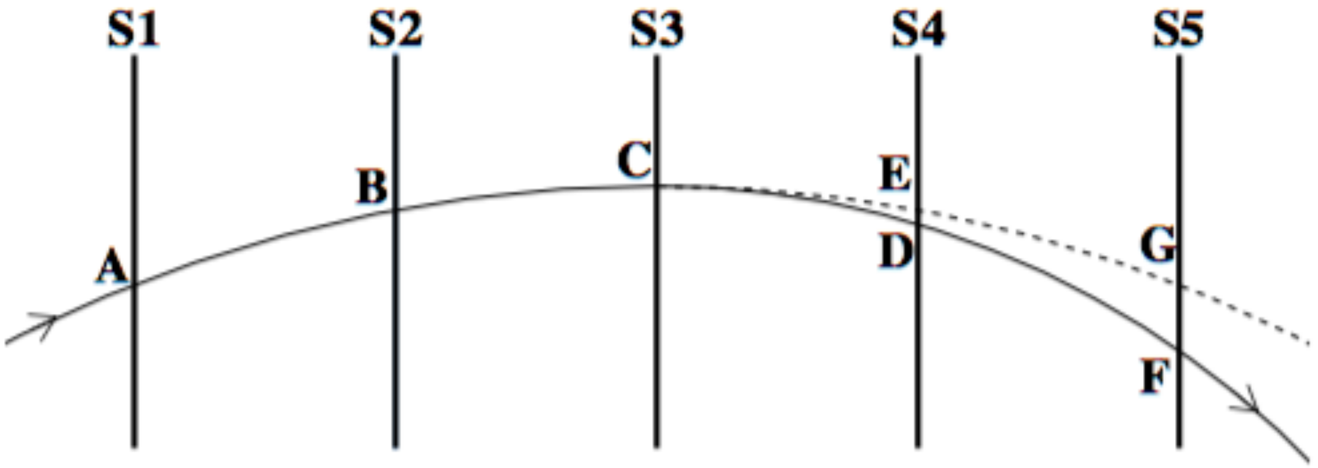
- Track seeds generated from 3 space points (with one additional compatible hit)
  - SCT-based seeds tend to be best, followed by pixel-only, then mixed
- Track candidates constructed from hits in remaining layers
  - Can have multiple candidates per seed
- Ambiguity Solving!
  - Track candidates are assigned a score:
    - clusters increase score based on resolution of component
    - holes decrease score
    - poor χ^2 of fit decreases score
    - high track p_T increases score

Track acceptance flow



Electrons are weird

- Electrons have particularly high probability of losing energy/ deflecting due to Bremsstrahlung
- Additional algorithms are implemented to account for this to recover electron tracks

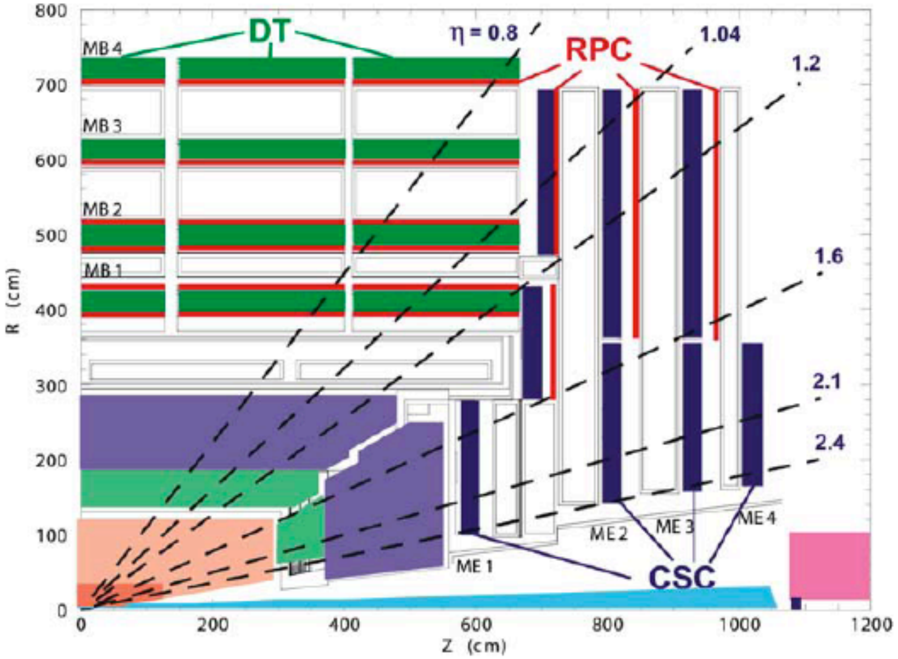


Performance!

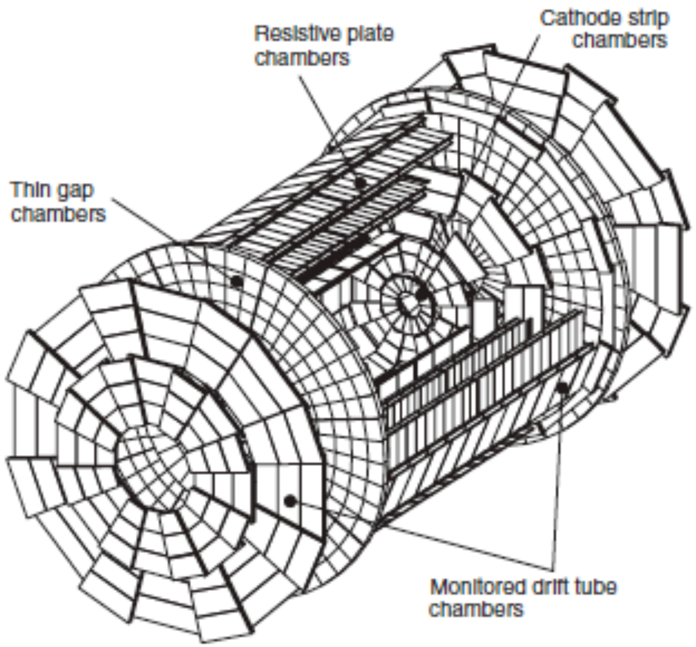
	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (µm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (µm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)	900	1060
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (µm)	90	22–42
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (µm)	190	70

There's something about muons

CMS



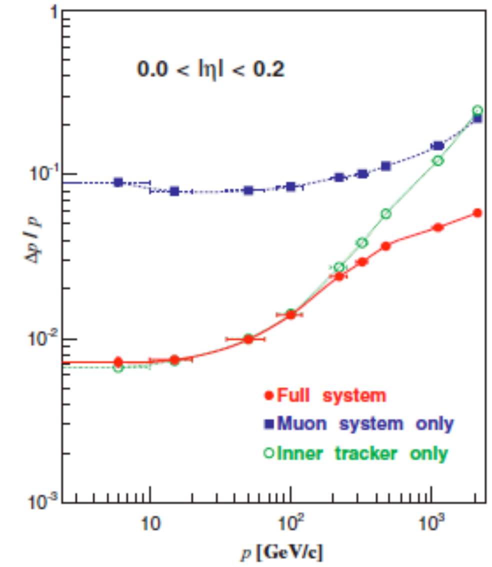
ATLAS

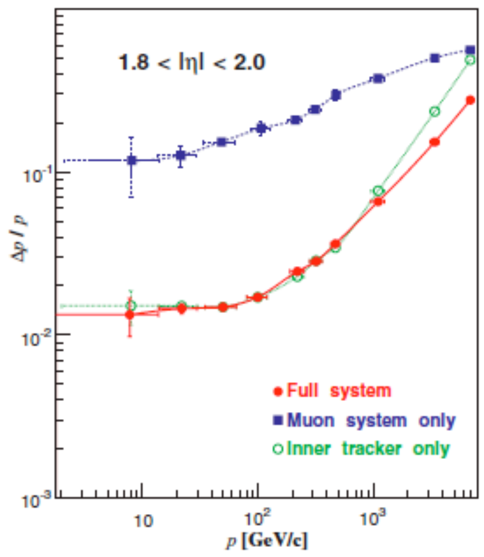


Big difference in the magnet systems. CMS uses return flux from solenoid magnet, while ATLAS uses toroids outside of the calorimeter in its muon spectrometer. Muons are useful for triggering, and muon systems can provide a second momentum measurement.

There's something about muons

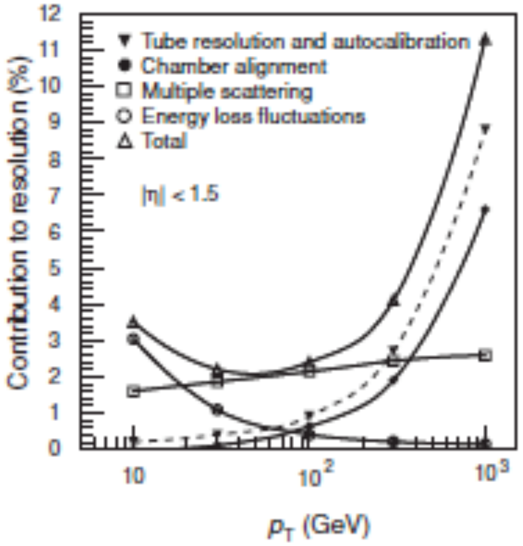
CMS →

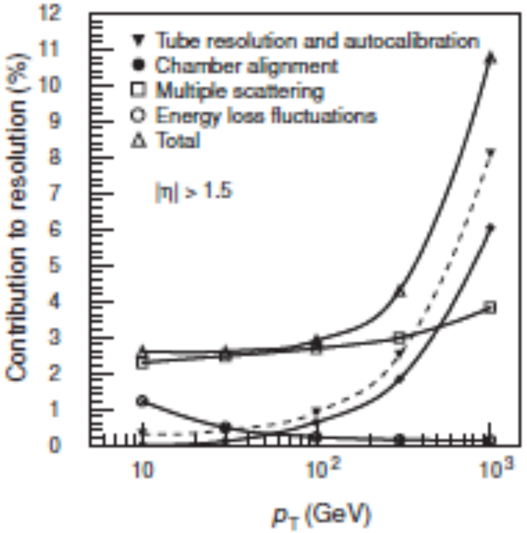


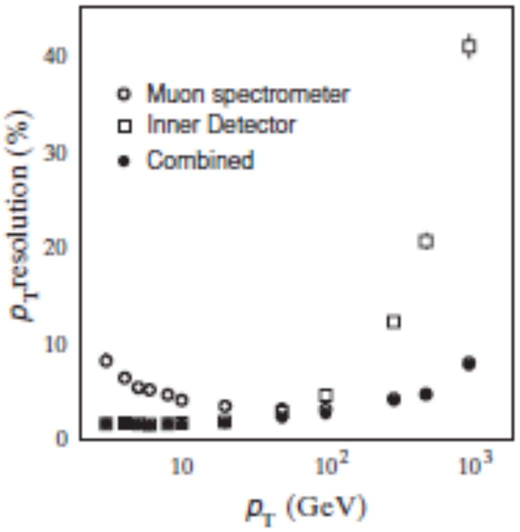


Combined (stand-alone) momentum resolution at	ATLAS	CMS
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

ATLAS →



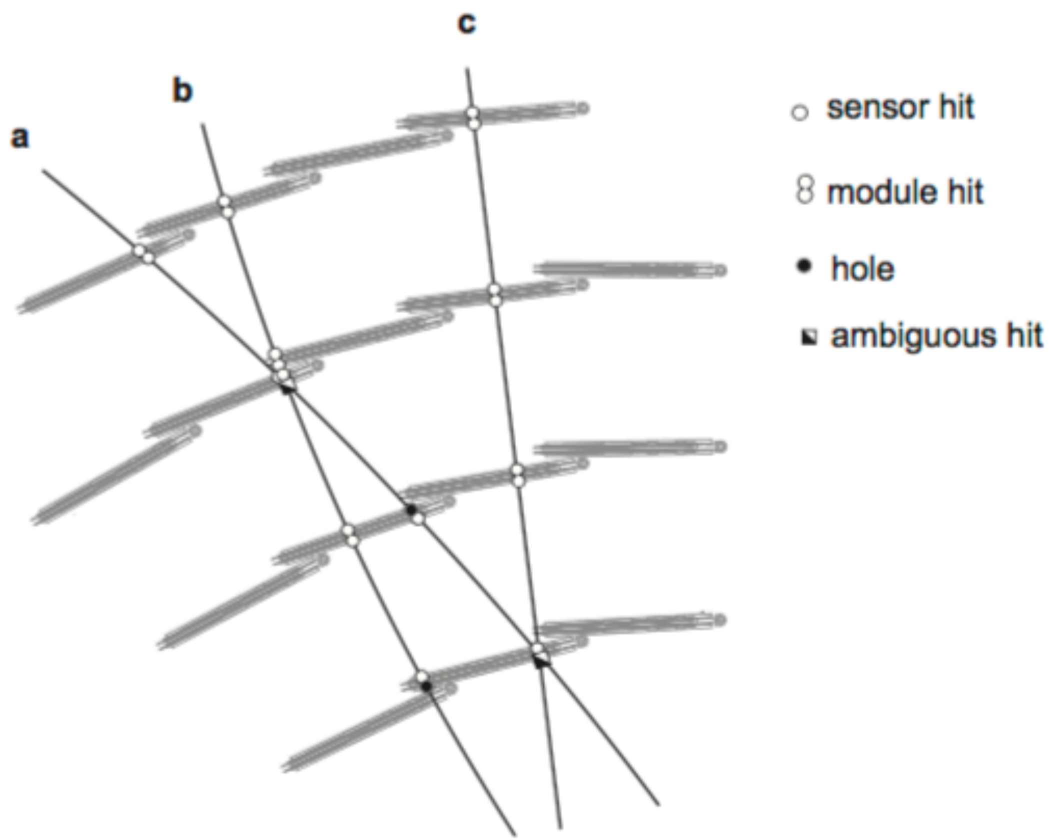




Sources

- CMS Tracking Paper (slightly old)
  - arXiv:1405.6569v2 [physics.ins-det] 28 Oct 2014
- ATLAS Tracking in Dense Environments (relatively current)
  - arXiv:1704.07983v1 [hep-ex] 26 Apr 2017
- ATLAS Track reconstruction (2008, so old)
  - Journal of Physics: Conference Series **119** (2008) 032014 doi:10.1088/1742-6596/119/3/032014 (http://iopscience.iop.org/article/10.1088/1742-6596/119/3/032014/pdf)
- Kalman filters (1987)
  - Nuclear Instruments and Methods in Physics Research A262 (1987) 444-450
- CMS and ATLAS Comparison (2006)
  - Annu. Rev. Nucl. Part. Sci. 2006. 56:375–440. “General-Purpose Detectors for the Large Hadron Collider”
- Comparison Presentation
  - Vorlesung Physik an Hadron-Collidern, Freiburg, SS 2011 (https://portal.uni-freiburg.de/jakobs/dateien/vorlesungsdateien/wpf2hadroncollider/kap2c)

Backup



Hit types in the ATLAS SCT.