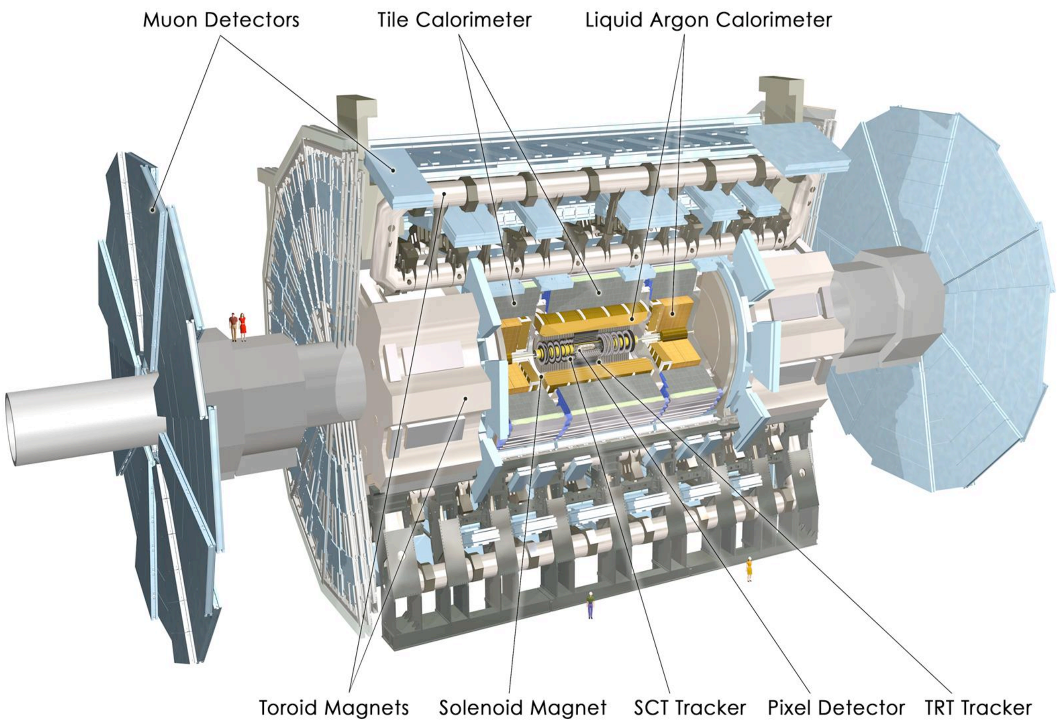
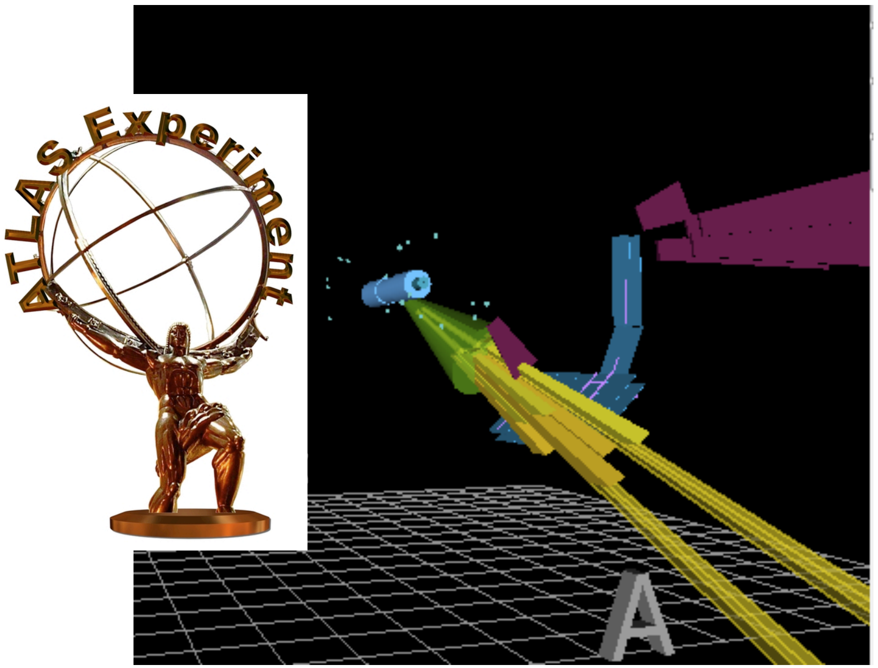
Stable Massive Particles in ATLAS





Paul D. Jackson

(SLAC)

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Presented at LPNHE
March 2nd, 2010

Overview

- A brief description of the CERN Large Hadron Collider and ATLAS detector
- Try to convey some of the excitement of the turn-on and early results from the 2009 run
- Mention the physics ATLAS was built for, and the physics it was not built for, but we're trying to do anyway!
- Motivate searches of heavy stable charged particles
- Analysis challenges throughout the detector
- Outlook for 2010 and beyond

The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC)

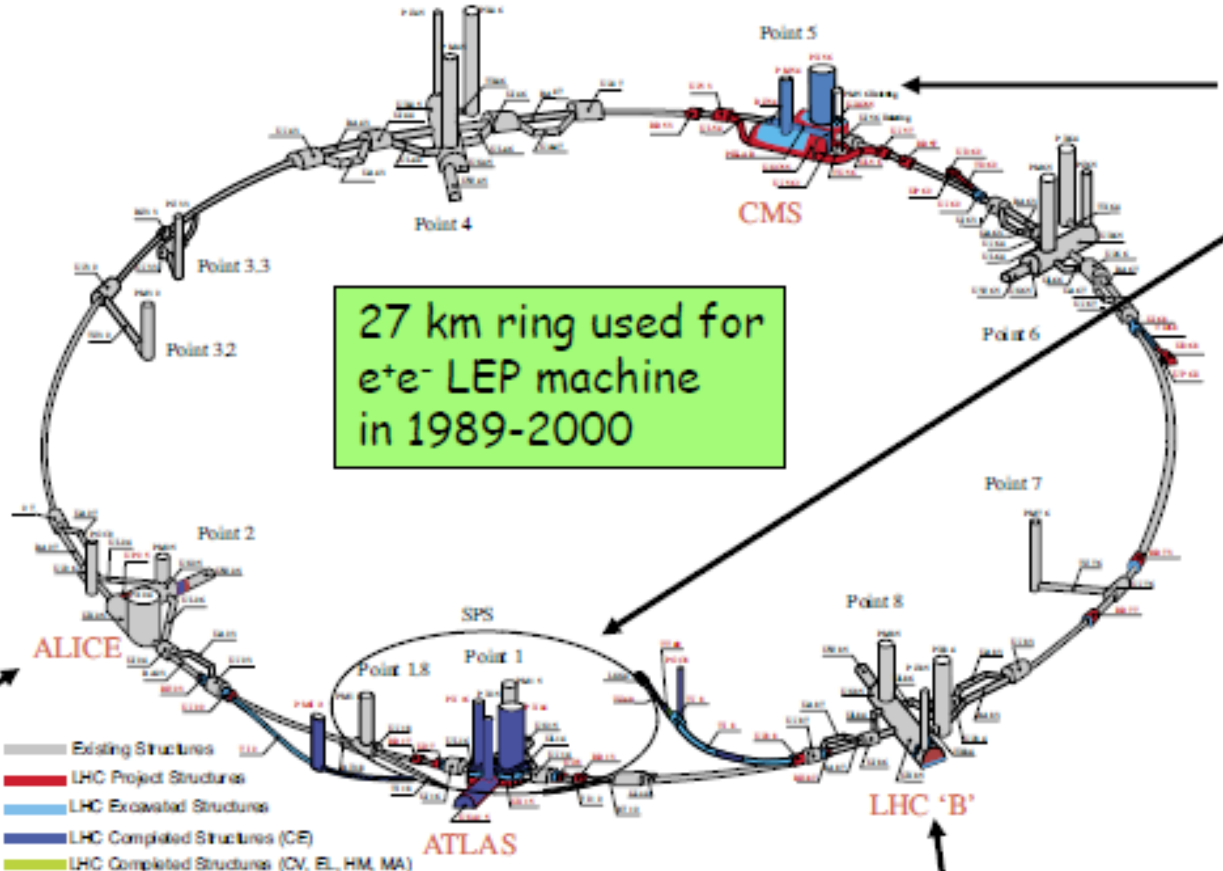
LHC

pp

- $\sqrt{s}$ = 14 TeV (7 times higher than Tevatron/Fermilab)
  → search for new massive particles up to m ~ 5 TeV

- $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (>10^2 higher than Tevatron/Fermilab)
  → search for rare processes with small σ (N = Lσ)

ATLAS and CMS : pp, general purpose



ALICE : heavy ions

LHCb : pp, B-physics

The LHC Accelerator

LHC Machine is a marvel of technology

Protons are accelerated by powerful electric fields

And are guided around their circular orbits by powerful superconducting dipole magnets

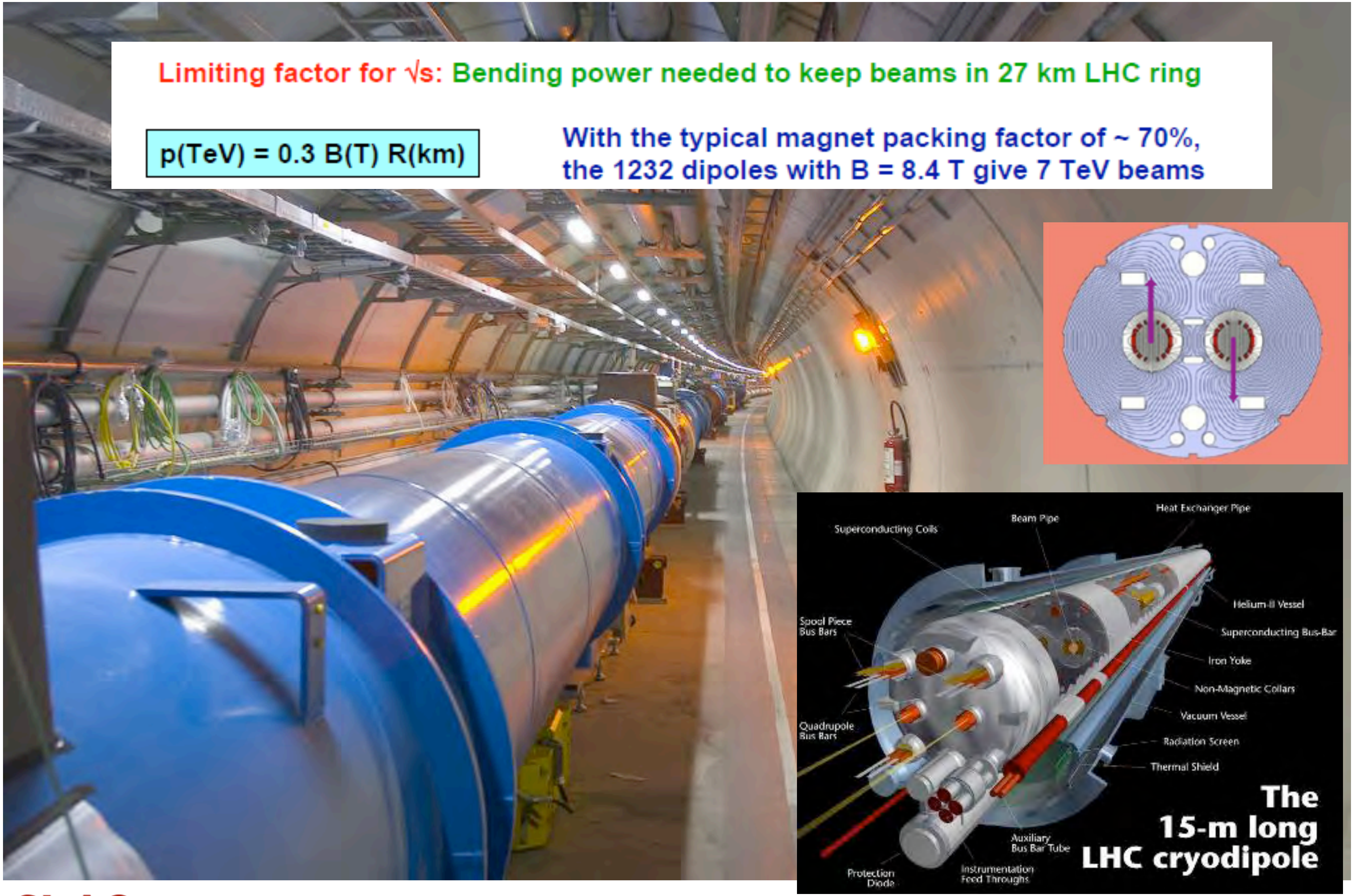
To reach the required energy in the existing tunnel, the s.c. dipoles operate at 8.4 T (200'000 x Earth's magnetic field) & 1.9 K (-271°C) in superfluid helium.

Protons travel in a tube with better vacuum and colder than inter-planetary space.

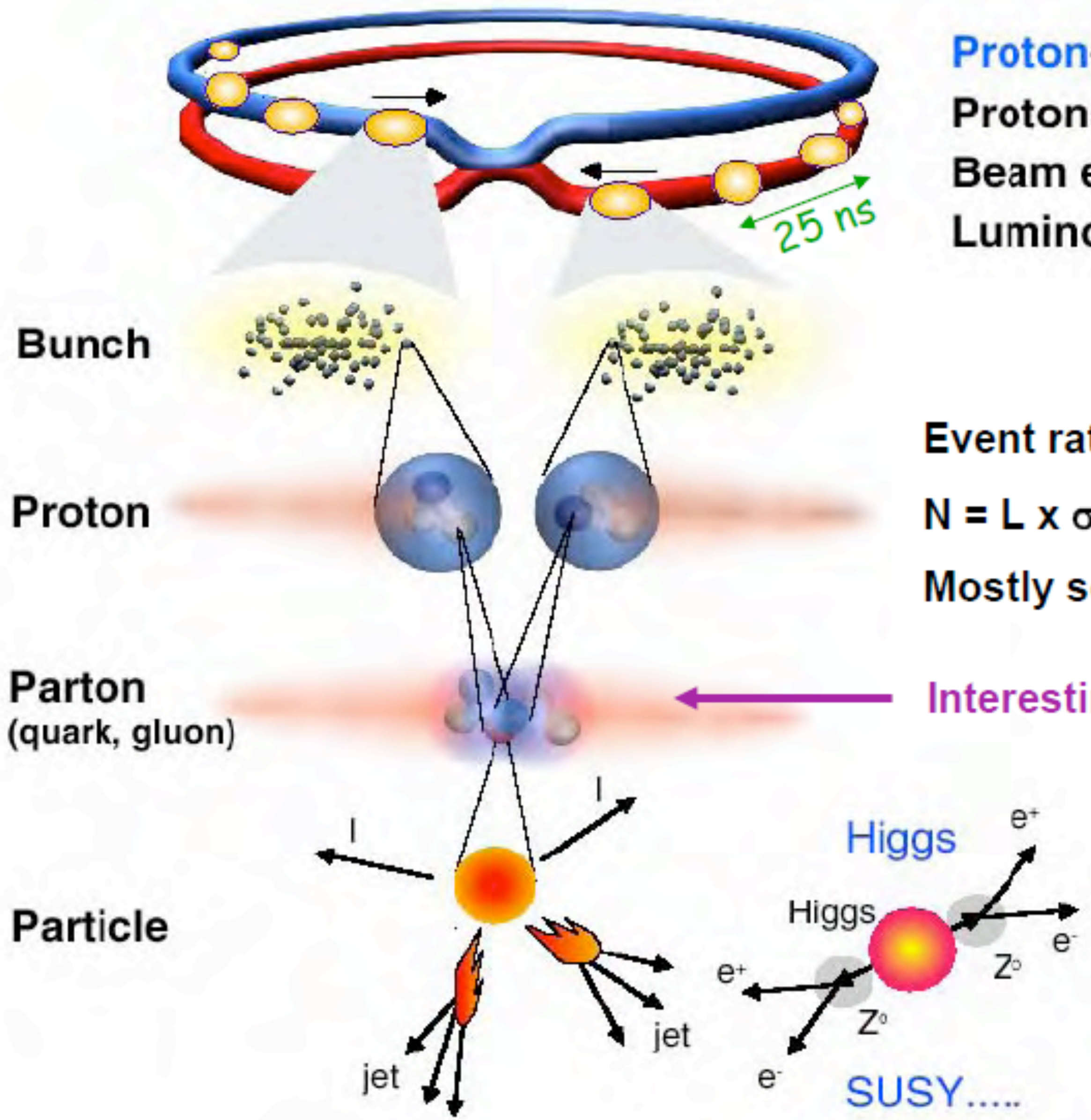
Limiting factor for √s: Bending power needed to keep beams in 27 km LHC ring

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

With the typical magnet packing factor of ~ 70%, the 1232 dipoles with B = 8.4 T give 7 TeV beams



Collisions at LHC



Proton-Proton

Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate in ATLAS :

$N = L \times \sigma\ (pp) \approx$ **10^9 interactions/s**

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

Selection of 1 in 10,000,000,000,000

Fun Facts about the LHC

Uses ~700 GWh of electricity / year, ~10% of Geneva

7 TeV proton moves at 0.999999991 c

... energy of a mosquito flying ~few km/h

Beam has rest mass of ~1 ng, energy at 7 TeV is ~400 MJ

... 400 ton TGV train at 150 km/h, 80 kg of TNT

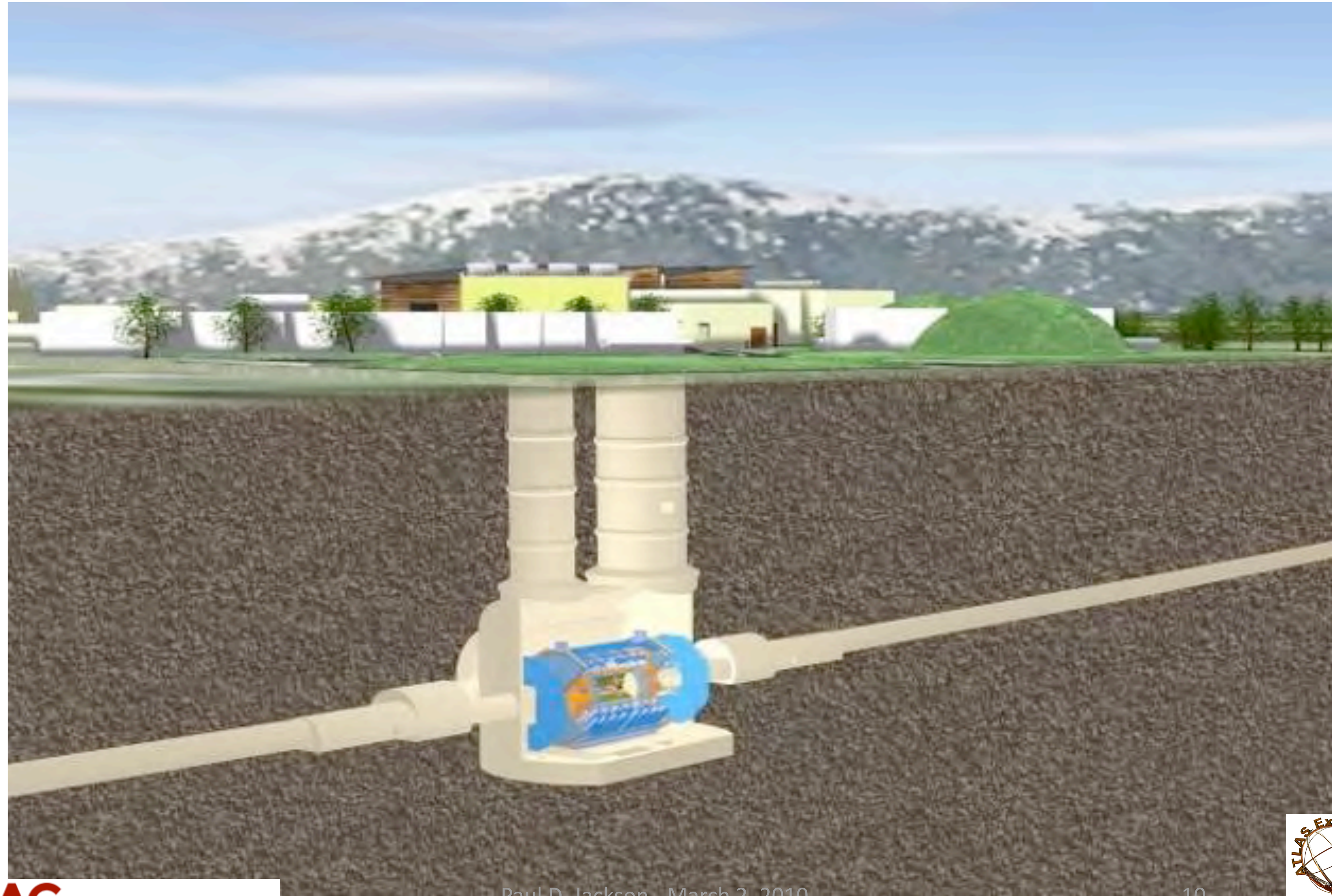
Energy stored in (dipole) magnets: 11,000 MJ

Superconducting filament length >10 times distance to Sun

Vacuum in beampipe is 10^{-10} Torr (~3 million molecules/cm^3)

Atmosphere at ~1000 km altitude

(ATLAS) A Toroidal LHC ApparatuS



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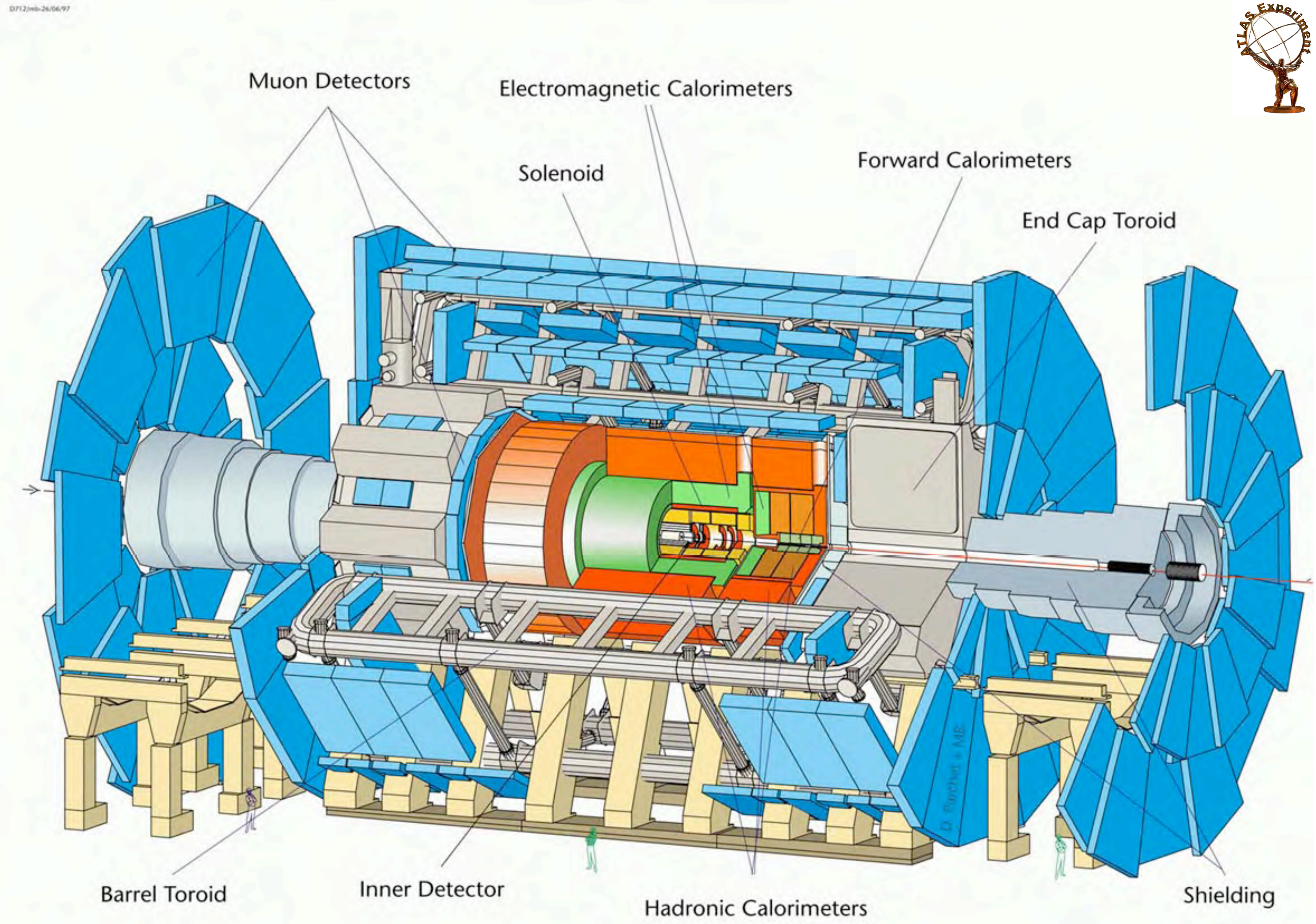
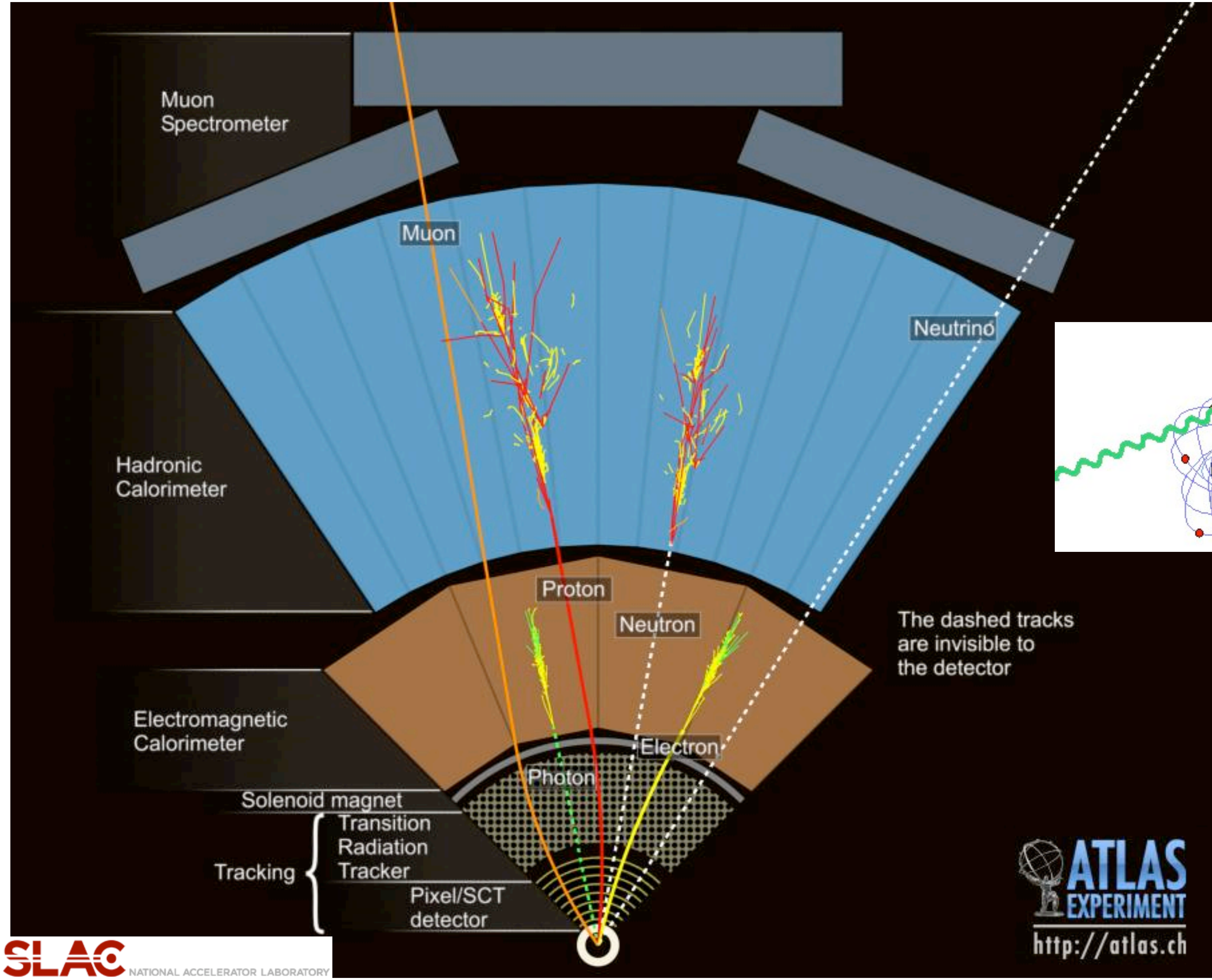
ATLAS Experiment


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch
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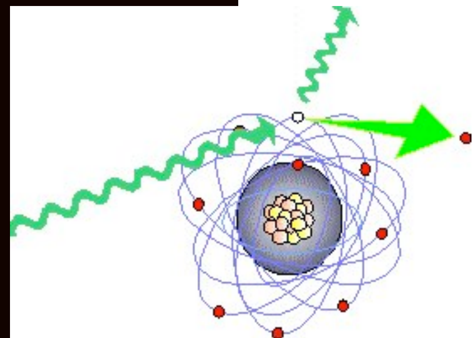


Ionization

Worldwide Scientific Collaboration !

ATLAS

37 Countries

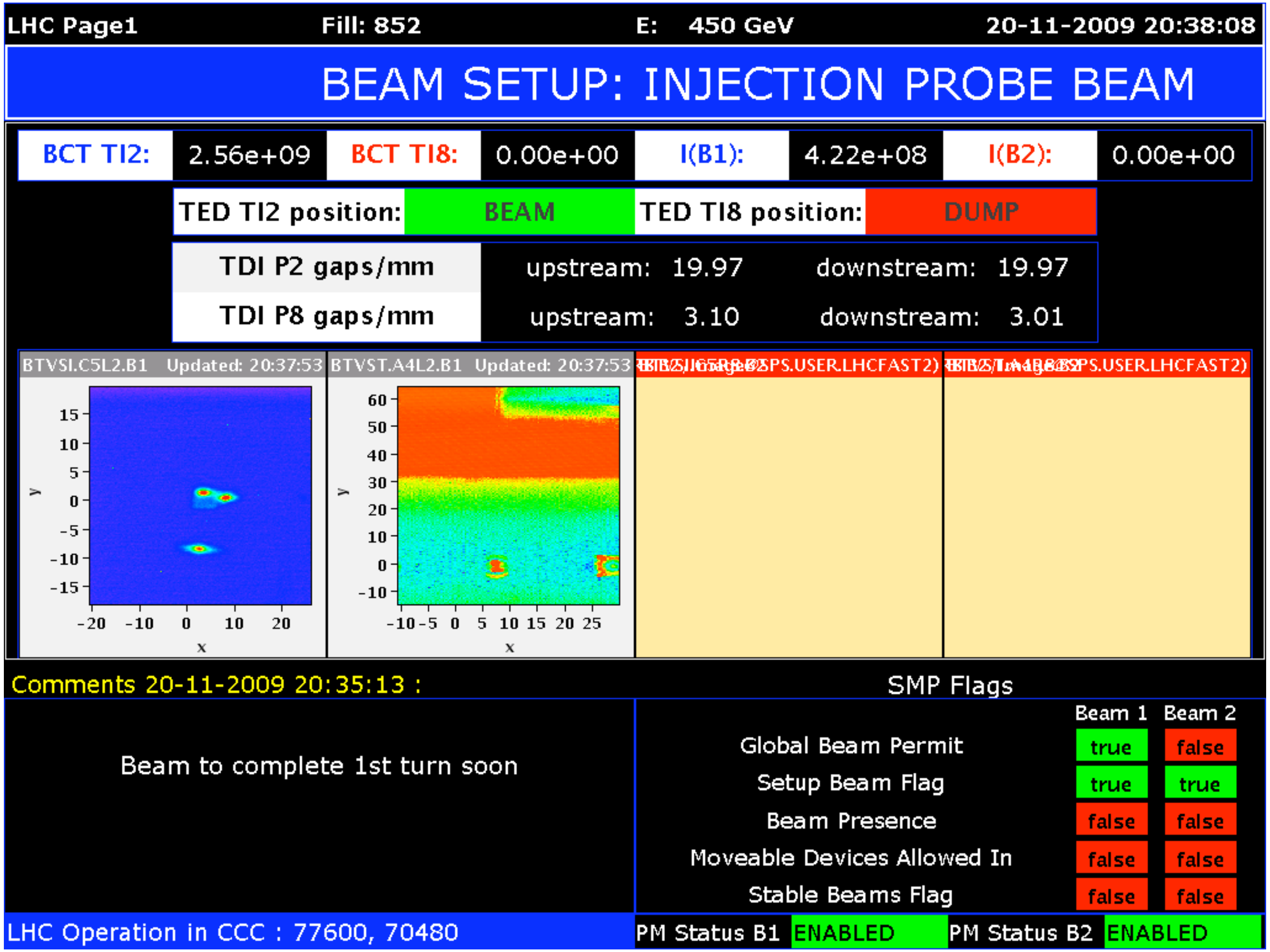
169 Institutions

2500 Scientific Authors

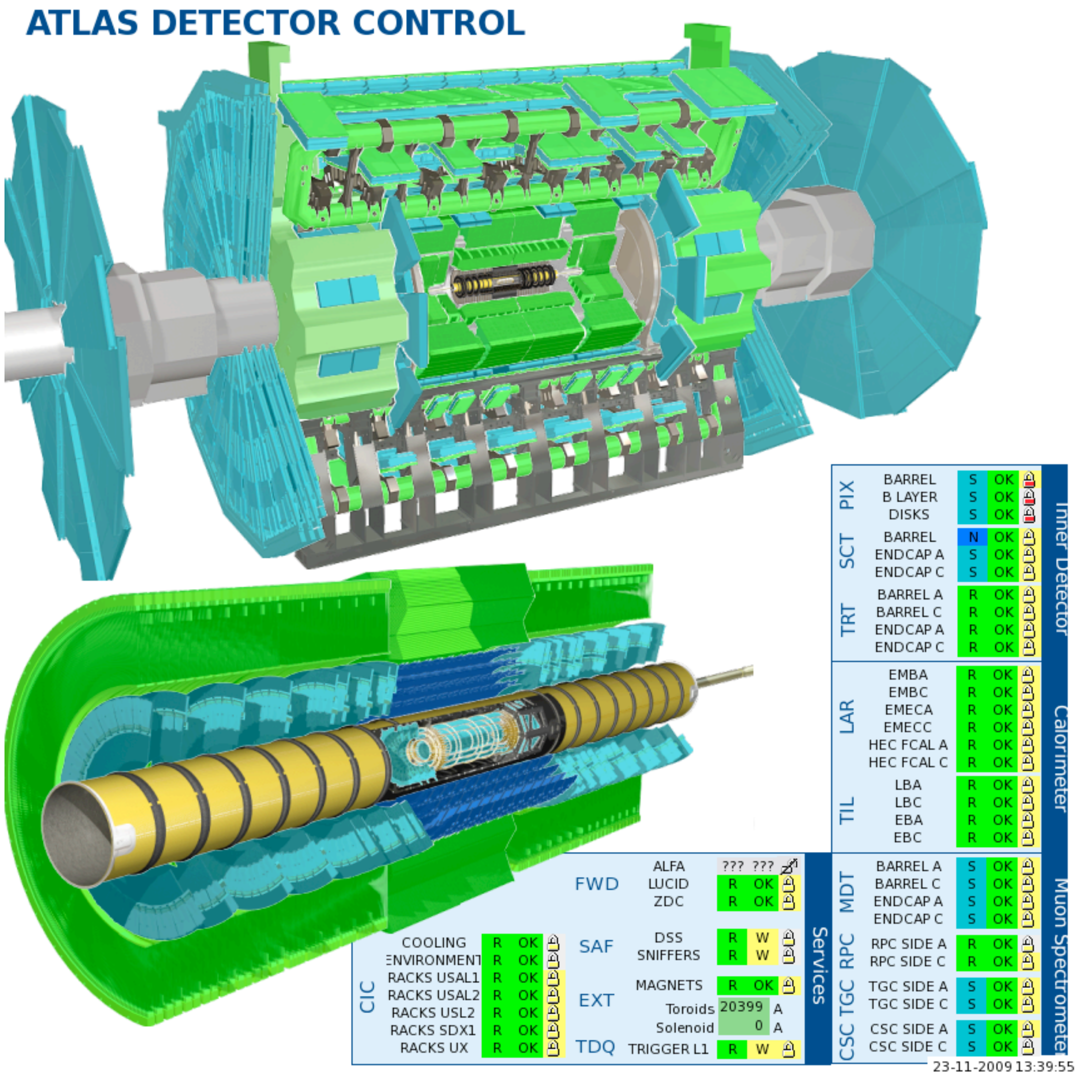
November 2009

FIRST HOURS OF THE LHC

The LHC came online in record time



The first hours of ATLAS: *READY!*



Setup for first LHC beams

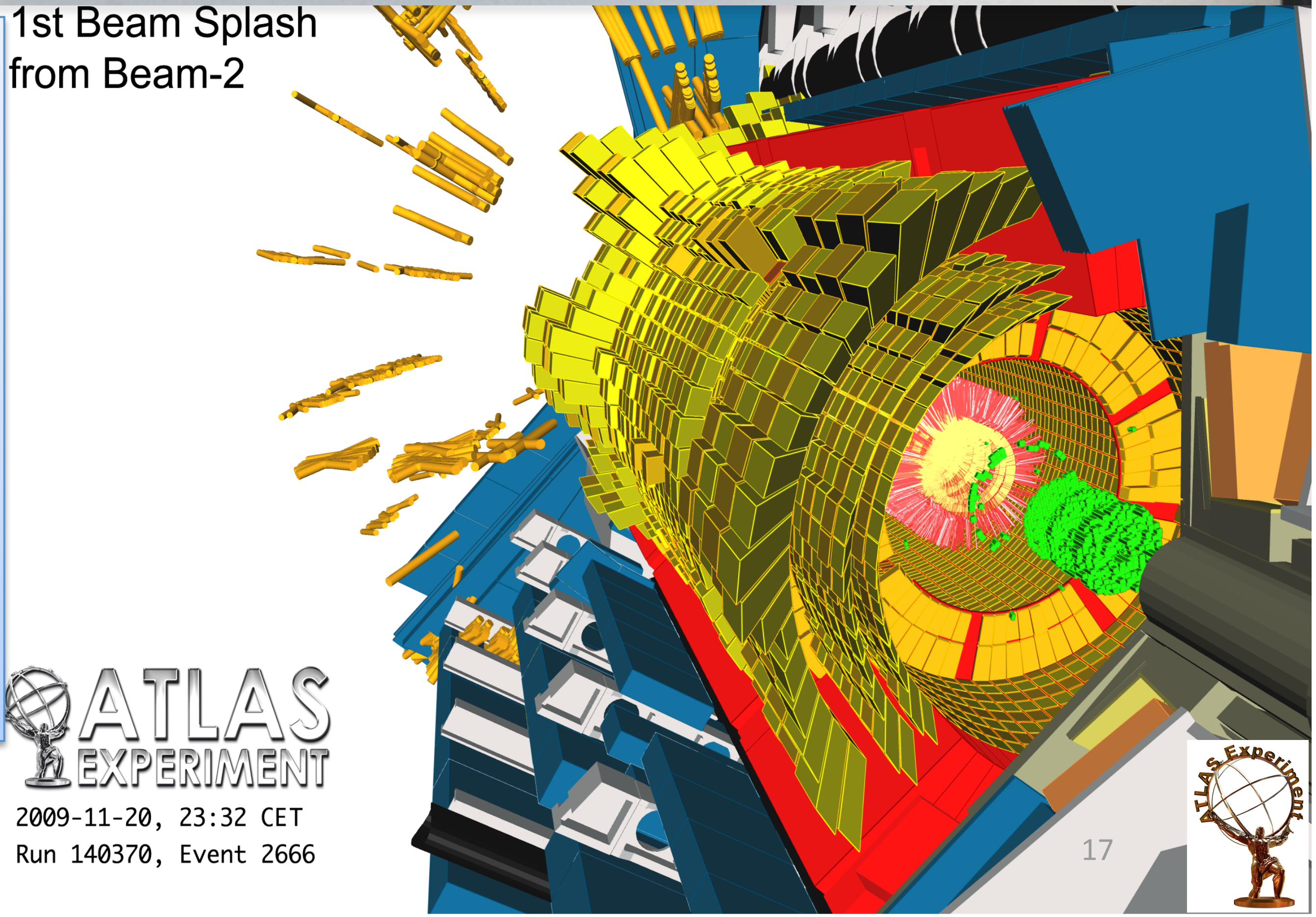
- Pixel off for safety
- SCT in "STANDBY" state
  - Reduced voltage, 50% eff.
- All other systems ON
- **No solenoid field, toroids ON**

CSC running in separate DAQ partition for rate tests

a few days of (single) beam commissioning for the machine, timing tests for ATLAS

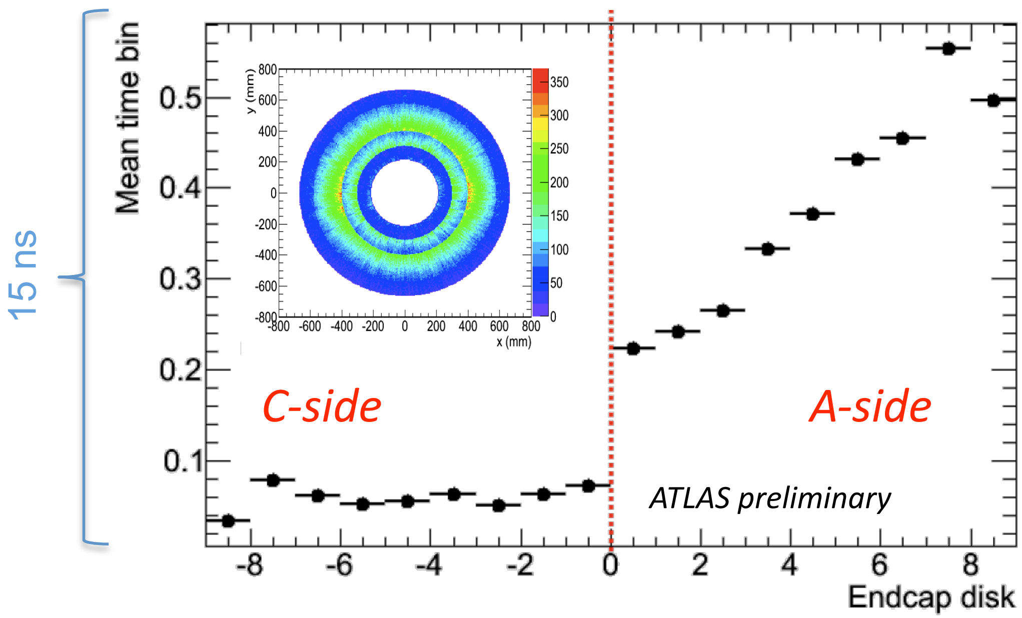
Beam "splash" events

- The LHC closed the collimators closest to ATLAS
- Several "shots" were provided onto the collimators, resulting in a huge spray of particles
- Uniformly illuminated the ATLAS detector, allowing for much needed timing studies
- Sensitive detectors like the silicon and some muon chambers were (of course) off

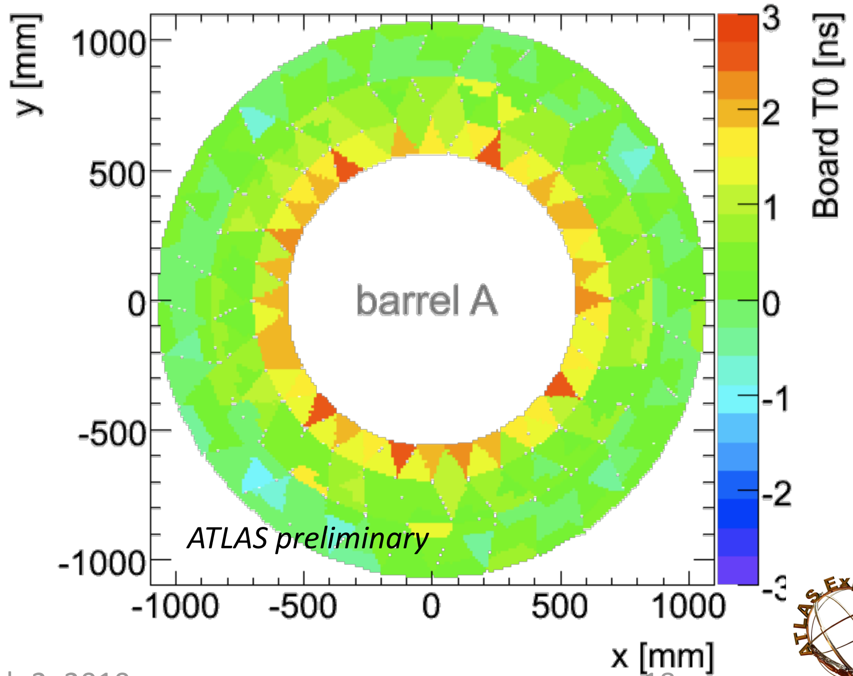


a few days of (single) beam commissioning for the machine, timing tests for ATLAS

Beam-1 arriving from A-side: timing as collisions for C-side, but wrong for A-side



TRT Barrel: plot made with collision timing → sensitive to ToF effect on Inner Boards !

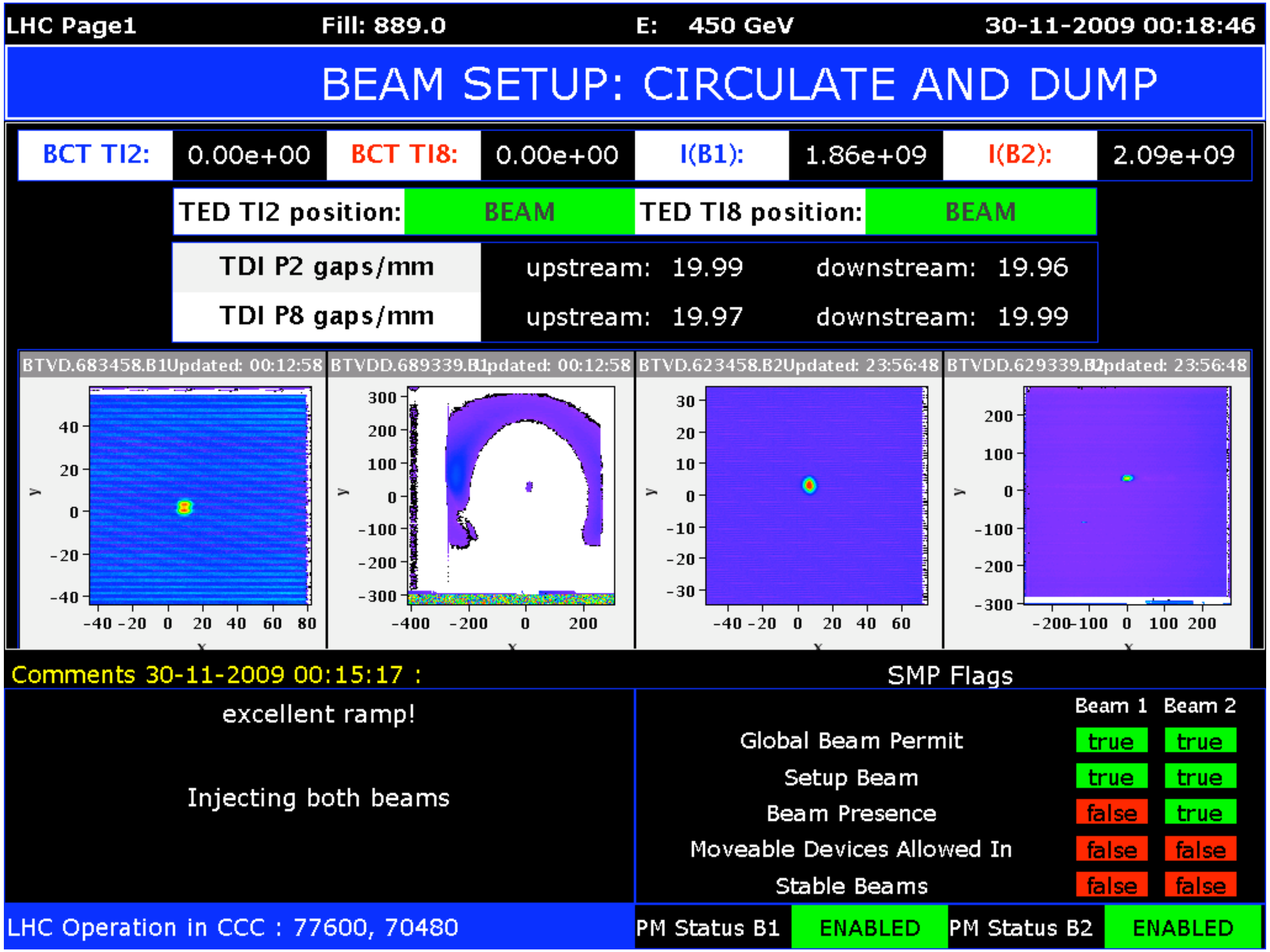


We were very excited…

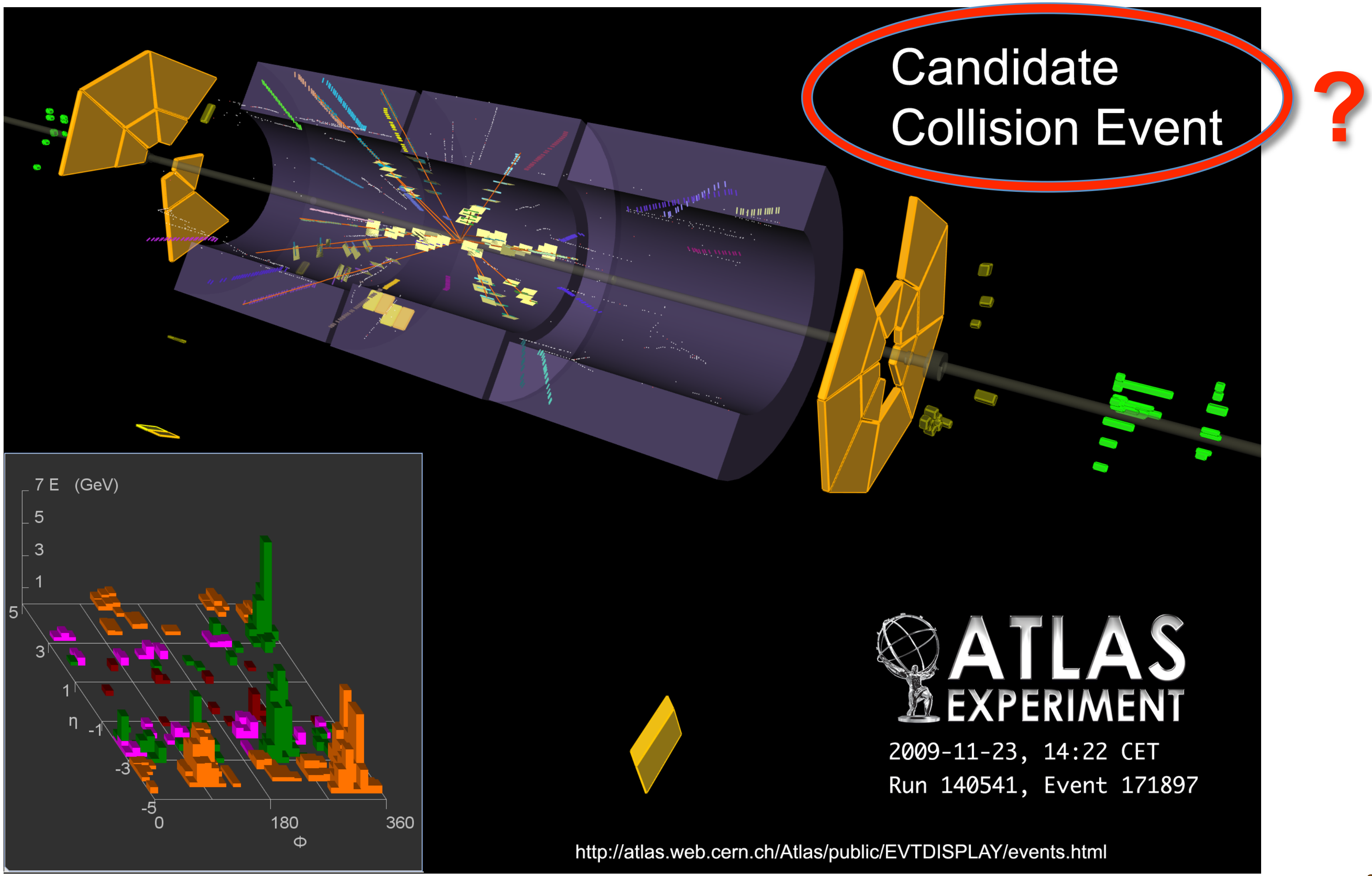
November-December 2009

COLLISIONS

LHC operations decided to go for collisions early



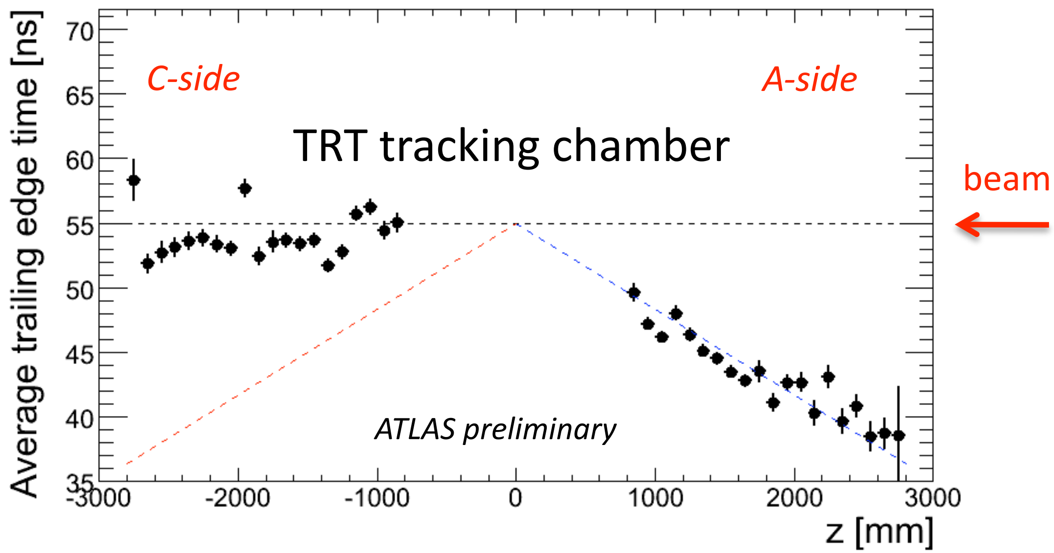
The first "collision" event display

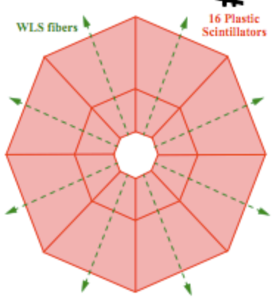


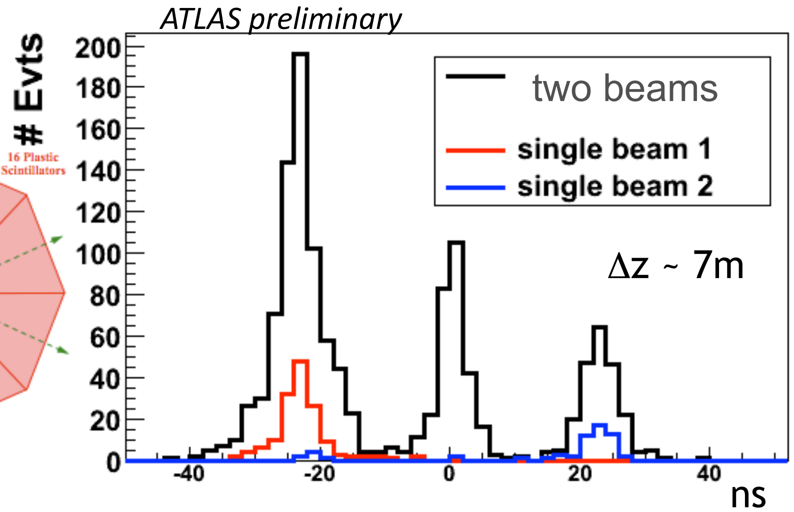
Hints of collisions: time of flight

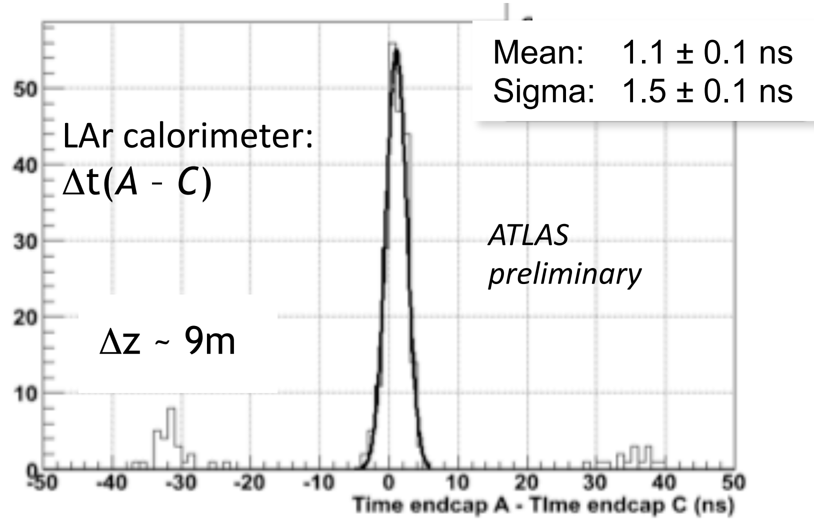
Using the timing from different detectors, we were able to convince ourselves that we were seeing collisions…***can we prove it though?***

A beam-related background event →
coming from beam-1 (A-side) →
timing is "wrong" for A-side →

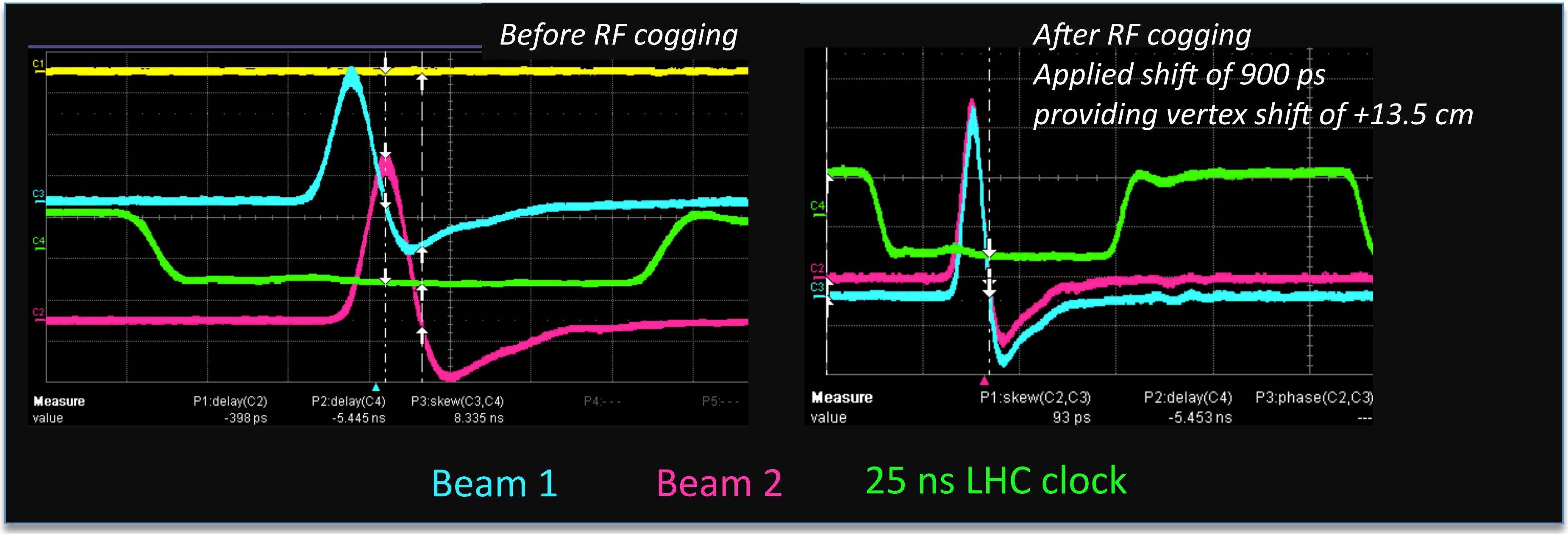








RF cogging: proof of first collisions

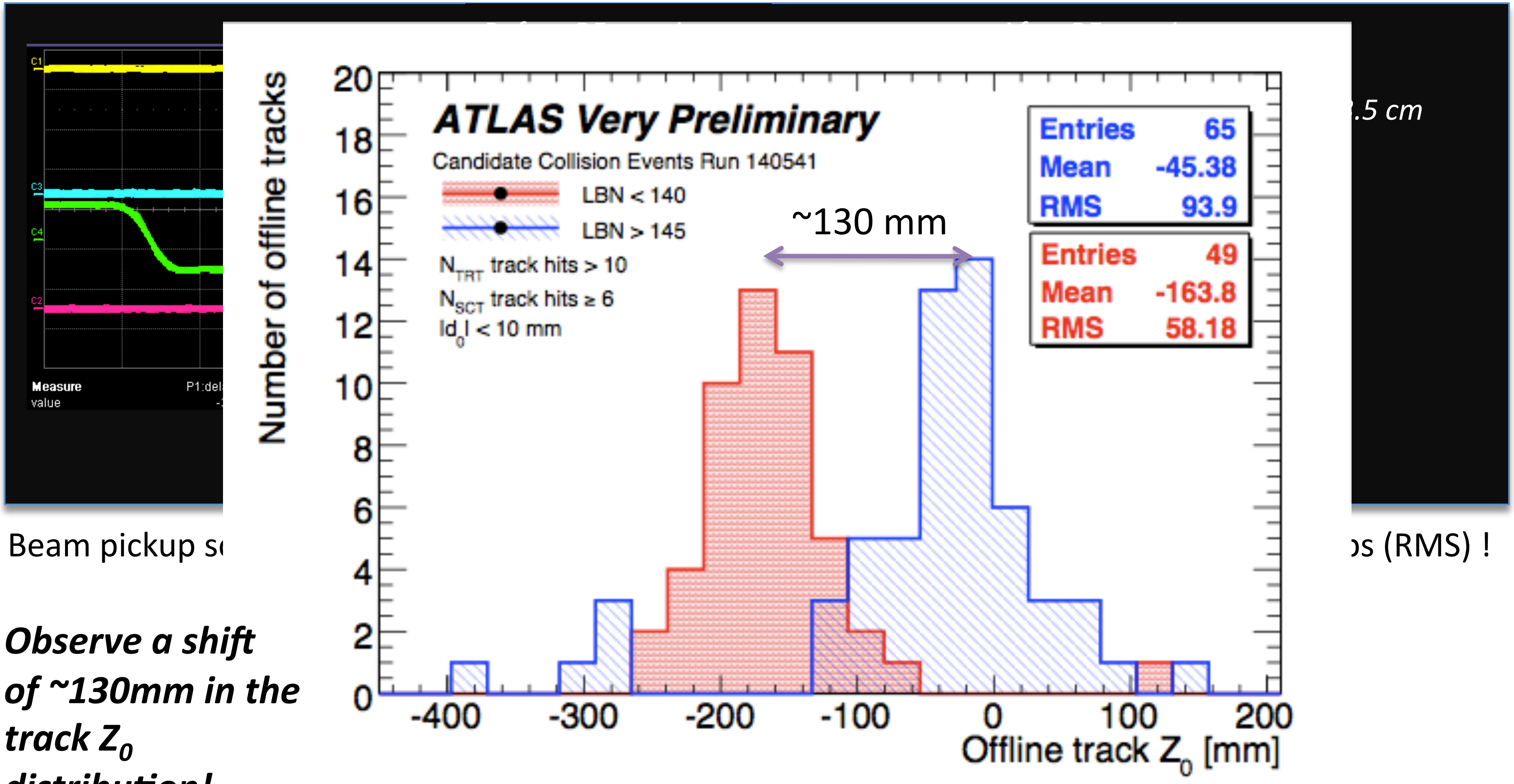


Beam pickup scope shots, beam 1 & 2

Bunches stable within 20 ps (RMS) !

- In the middle of one of the first runs, the RF group at the LHC decided to shift the beam, after discussions with the level-1 trigger crew on ATLAS
- A shift of 900ps was applied → ***expect a shift of 134 mm***

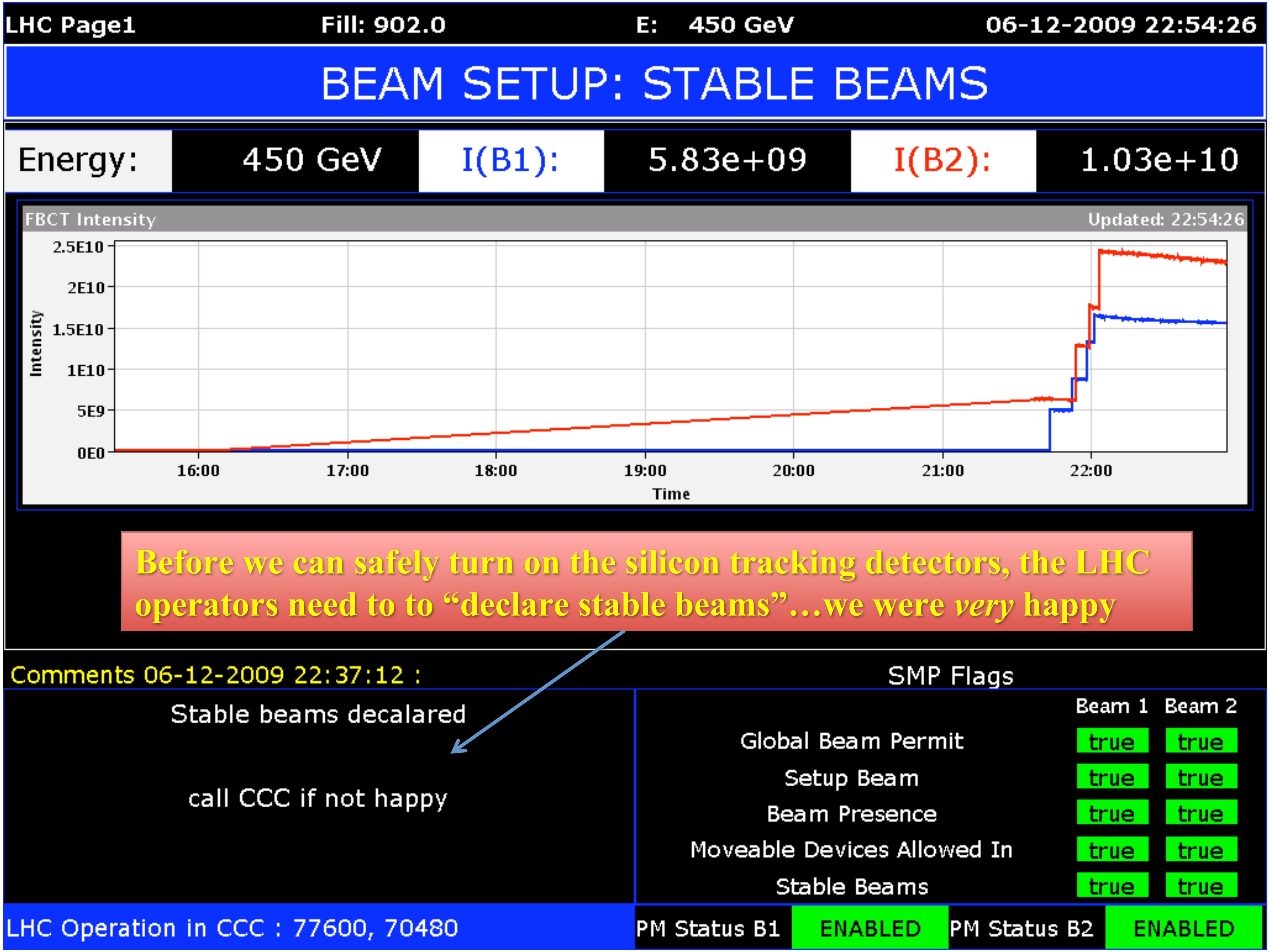
RF cogging: proof of first collisions



Beam pickup s ... s (RMS) !

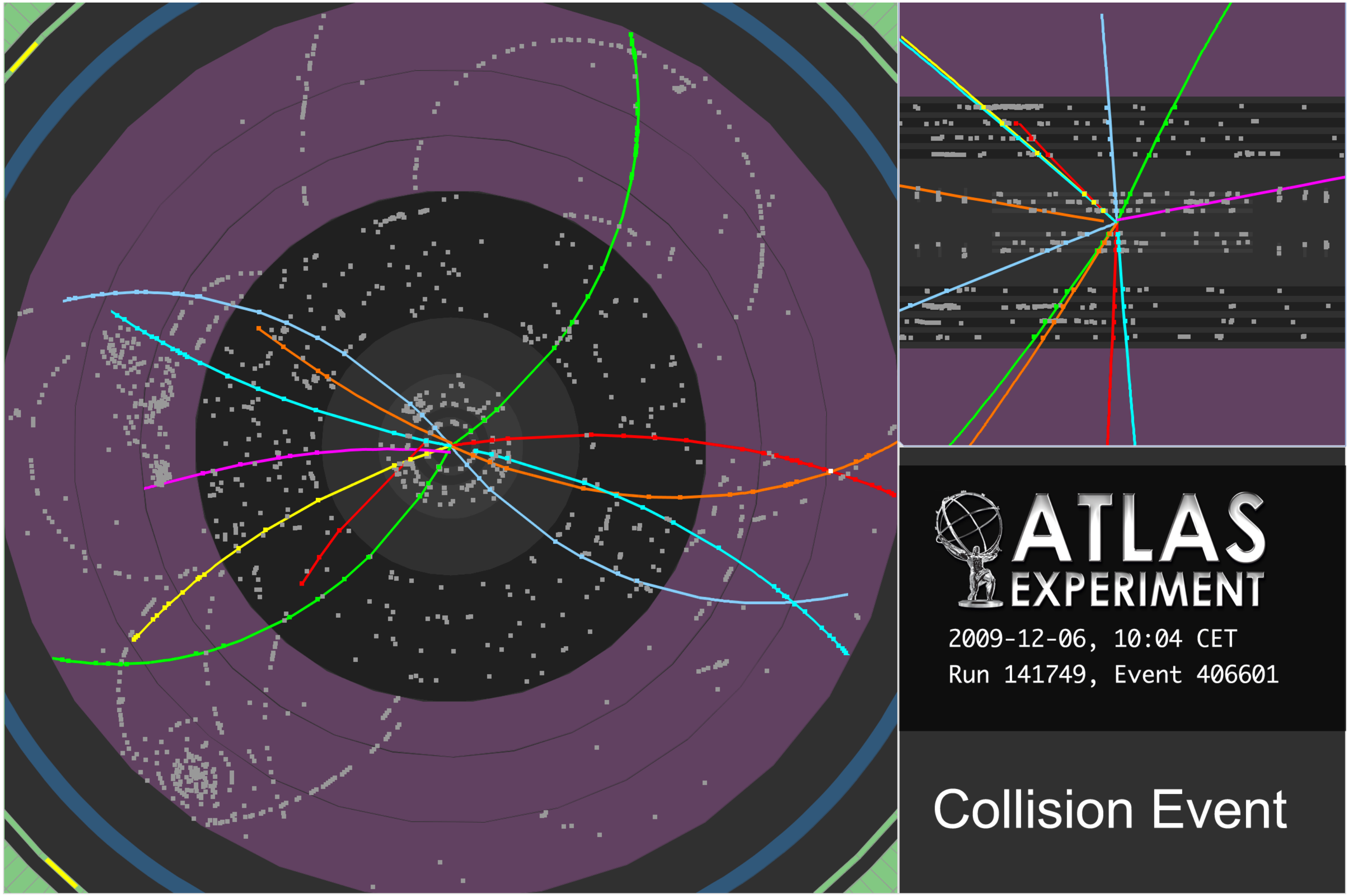
Observe a shift of ~130mm in the track Z_0 distribution!

Collisions!



Before we can safely turn on the silicon tracking detectors, the LHC operators need to to "declare stable beams"…we were *very* happy

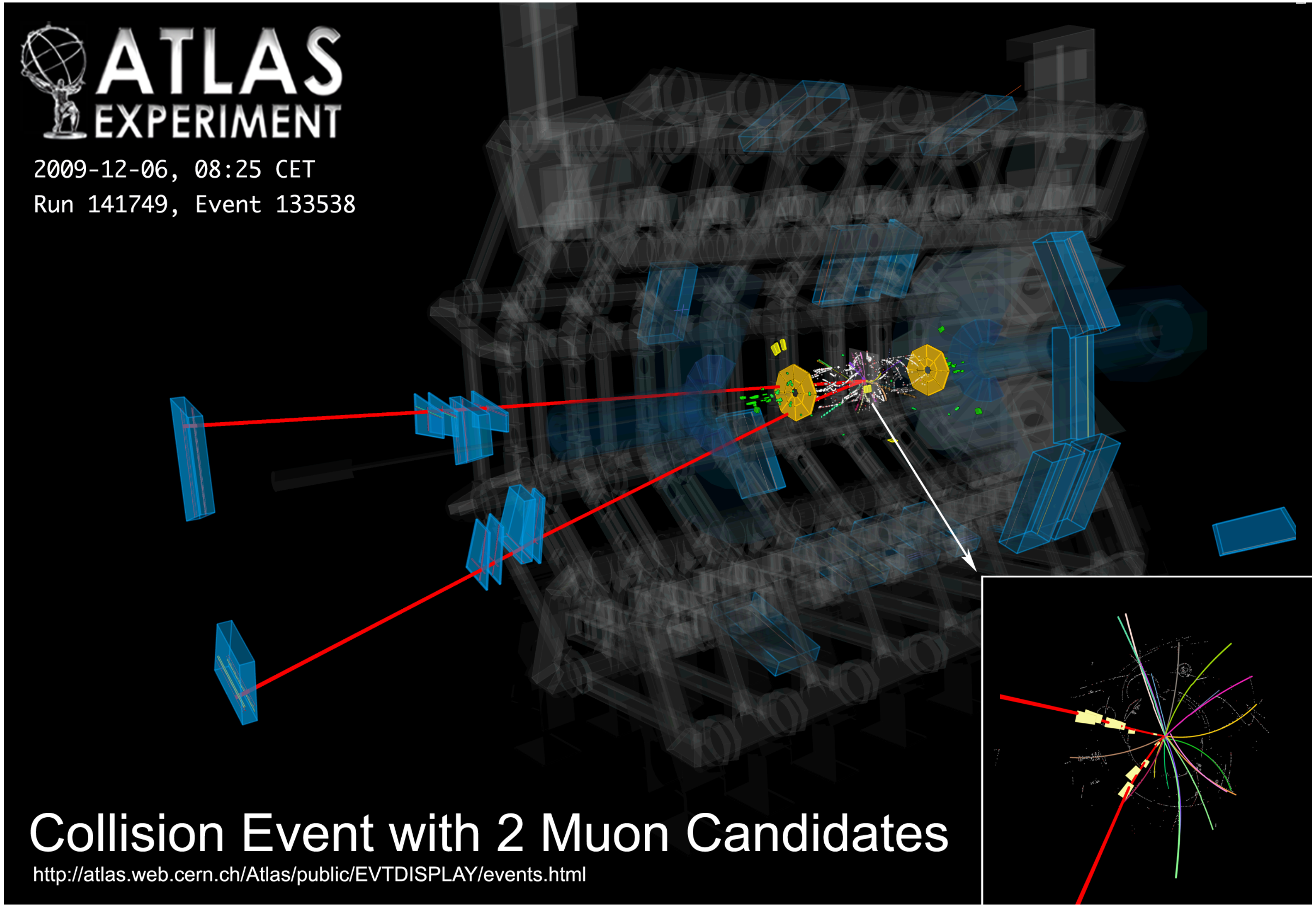
With collisions, comes the start of physics



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

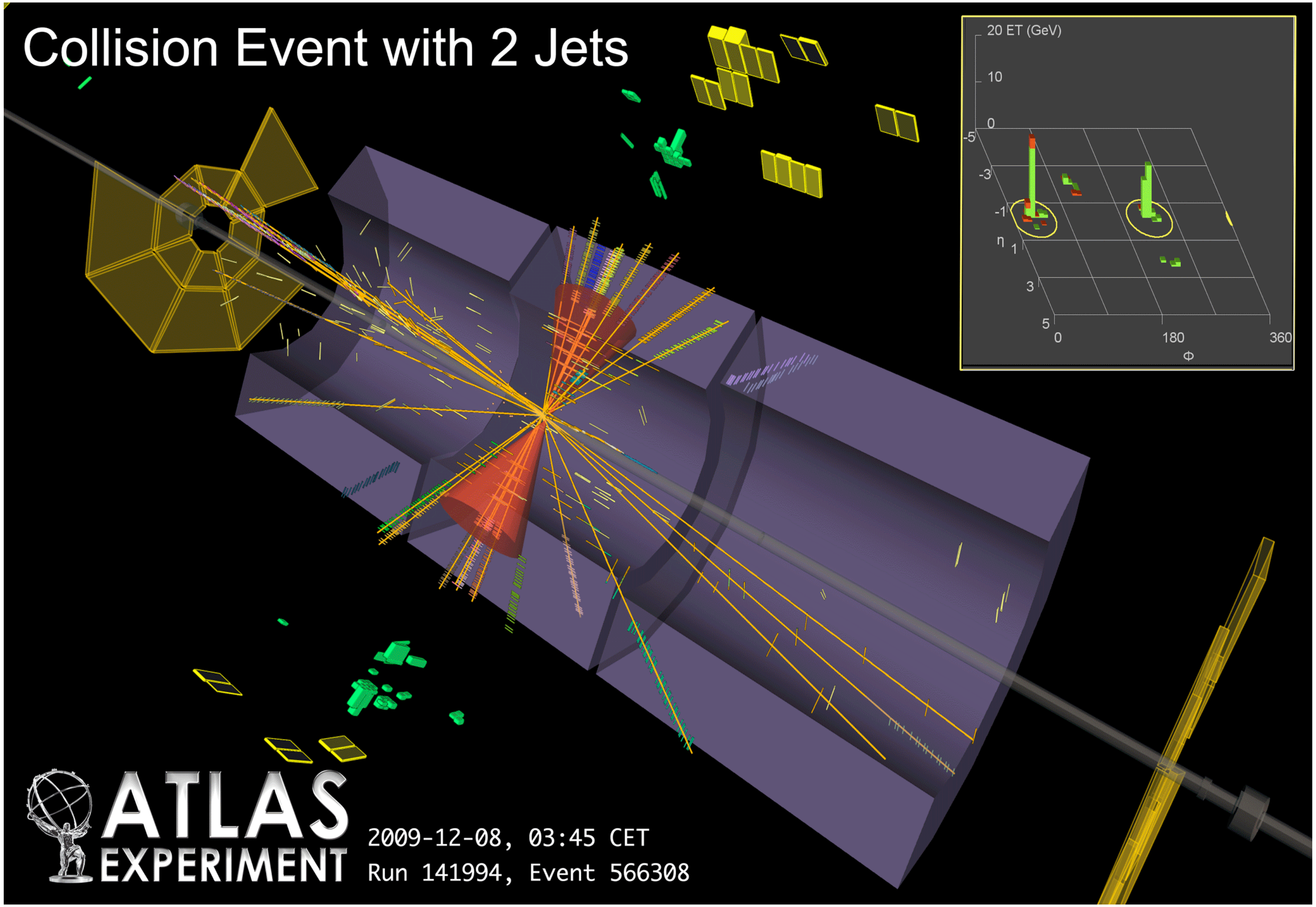
The inner detector observes tracks with the first stable beams

With collisions, comes the start of physics



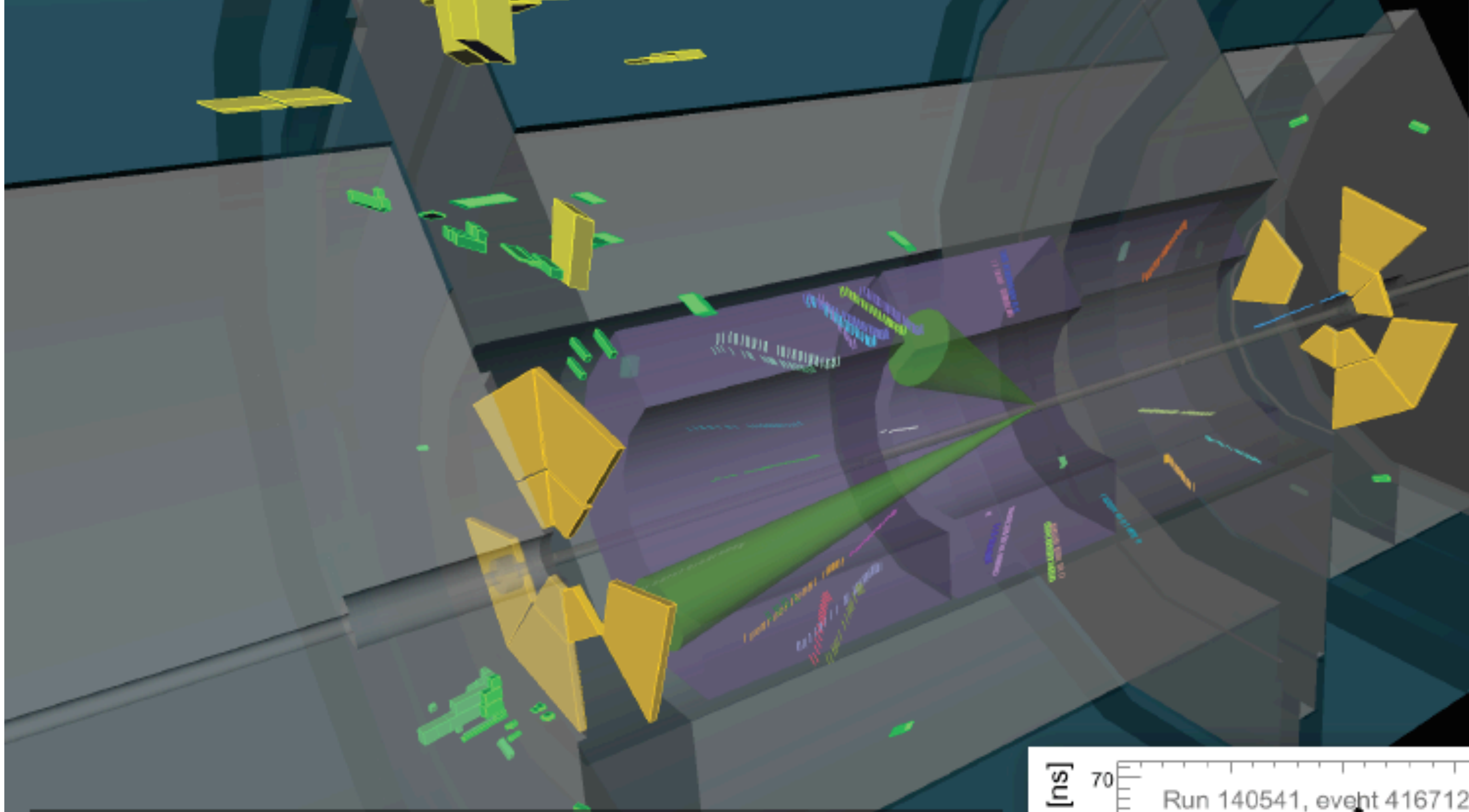
The muon system observes di-muon candidate events

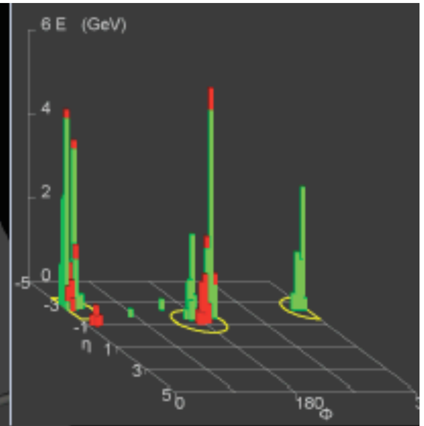
With collisions, comes the start of physics

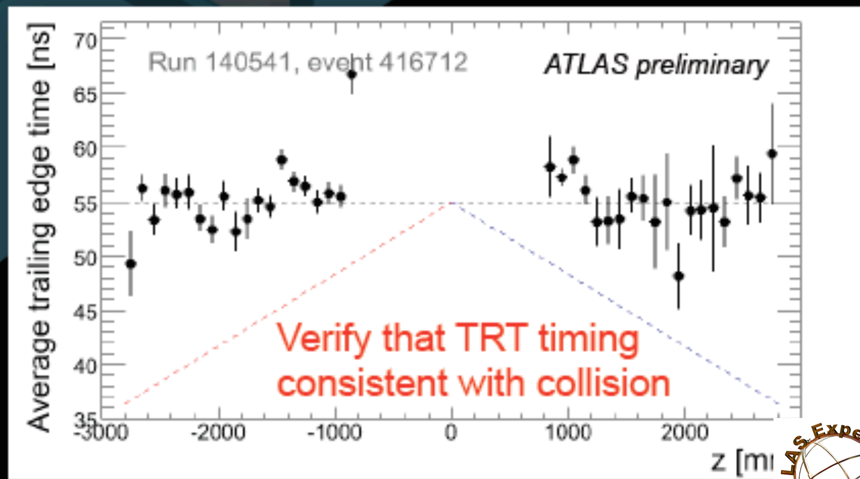


The calorimeter observes di-jet candidate events

A di-jet candidate



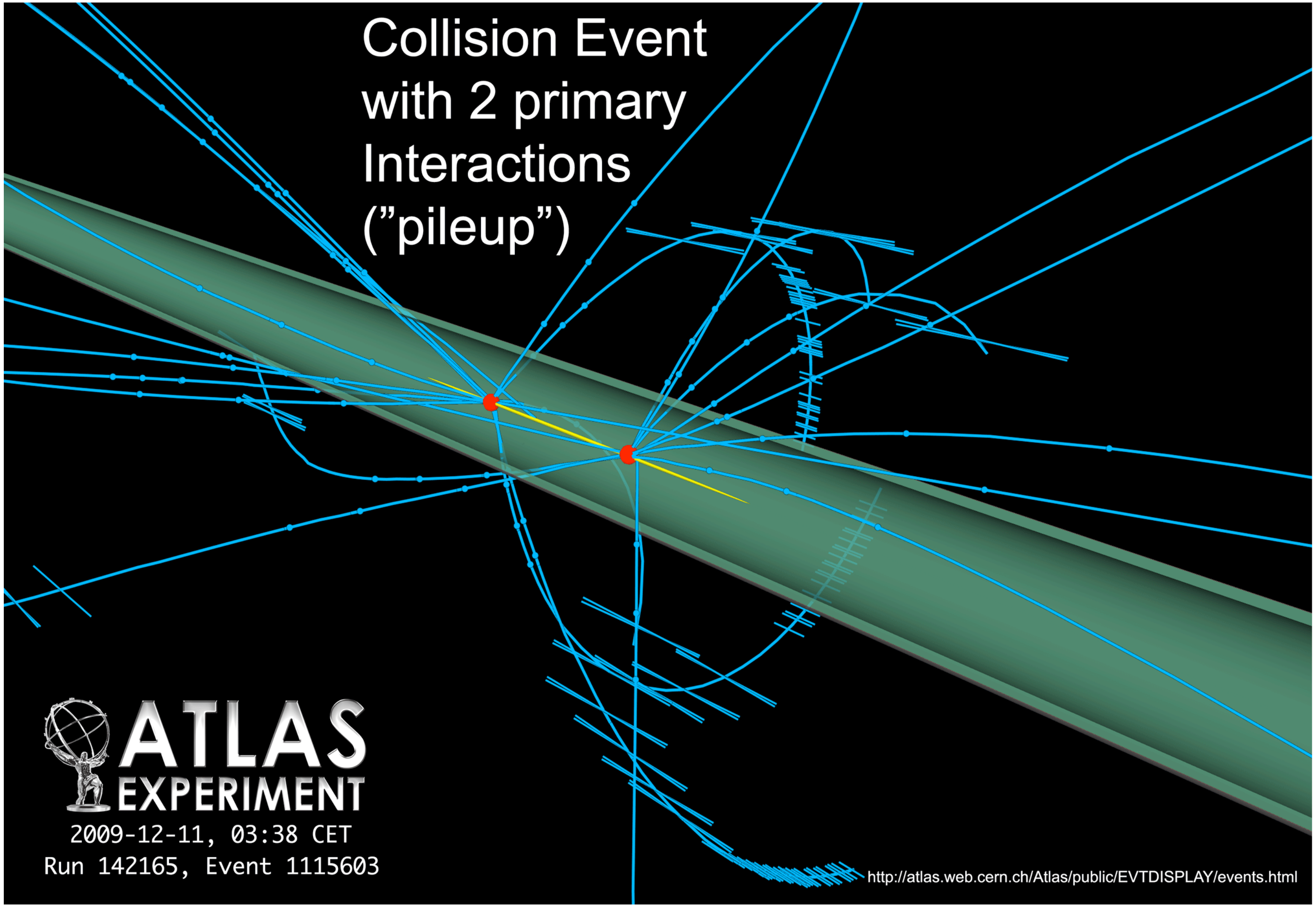




Two jets back-to-back in ϕ, both with (uncalibrated) E_T ~ 10 GeV, η of −1.3 and −2.5, ~ no missing E_T

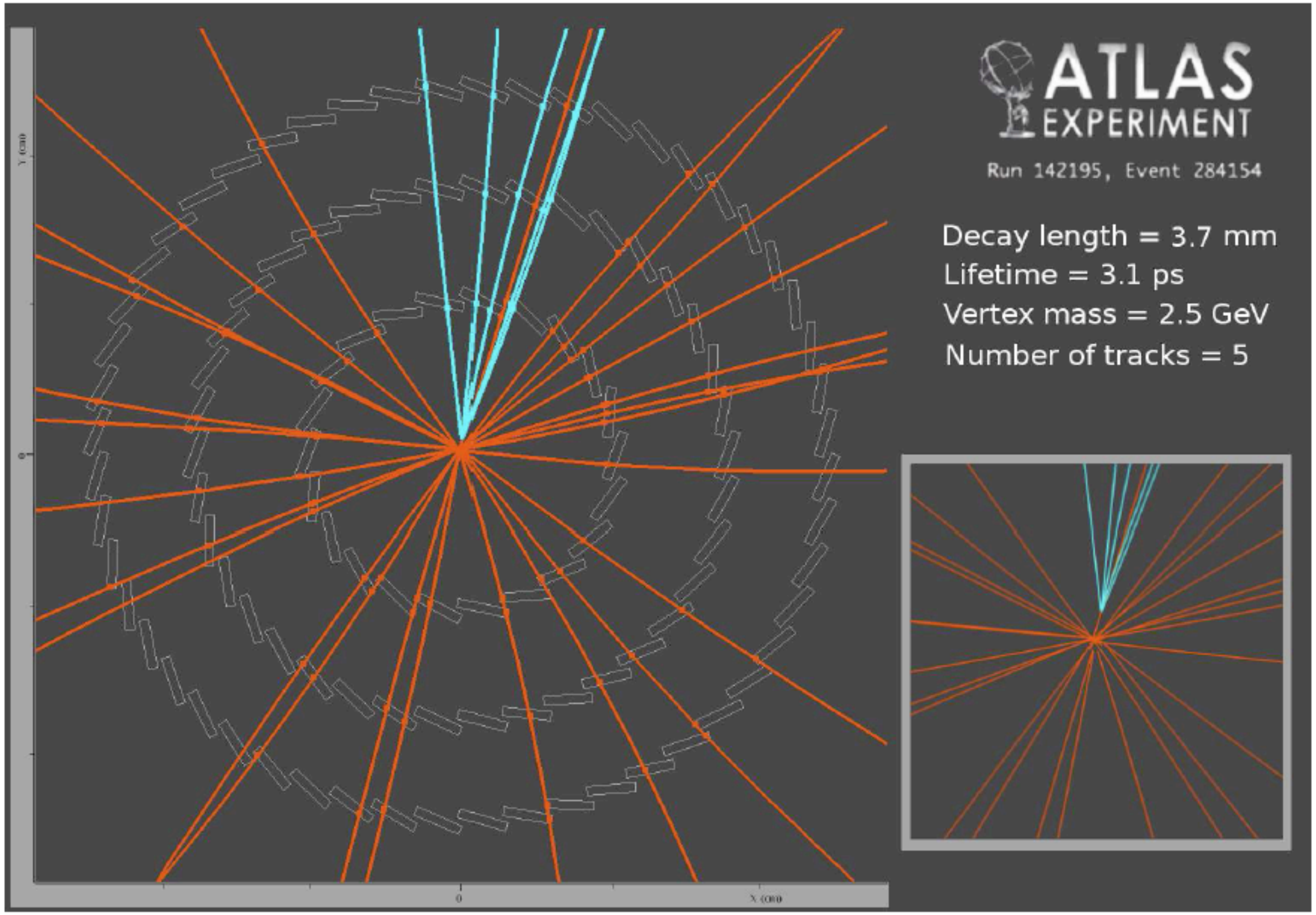
Triggered by MBTS A/B in time, several hits
Also triggered by L1Calo EM3

With collisions, comes the start of physics

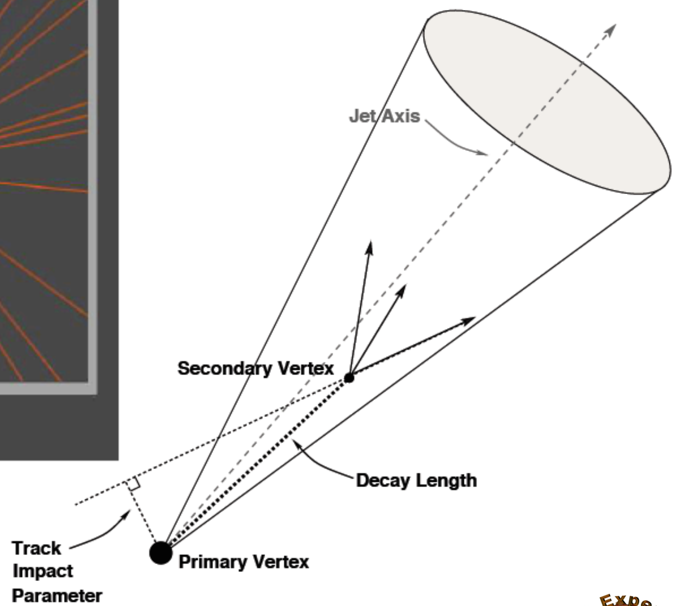


…maybe we even start to see pile-up

With collisions, comes the start of physics

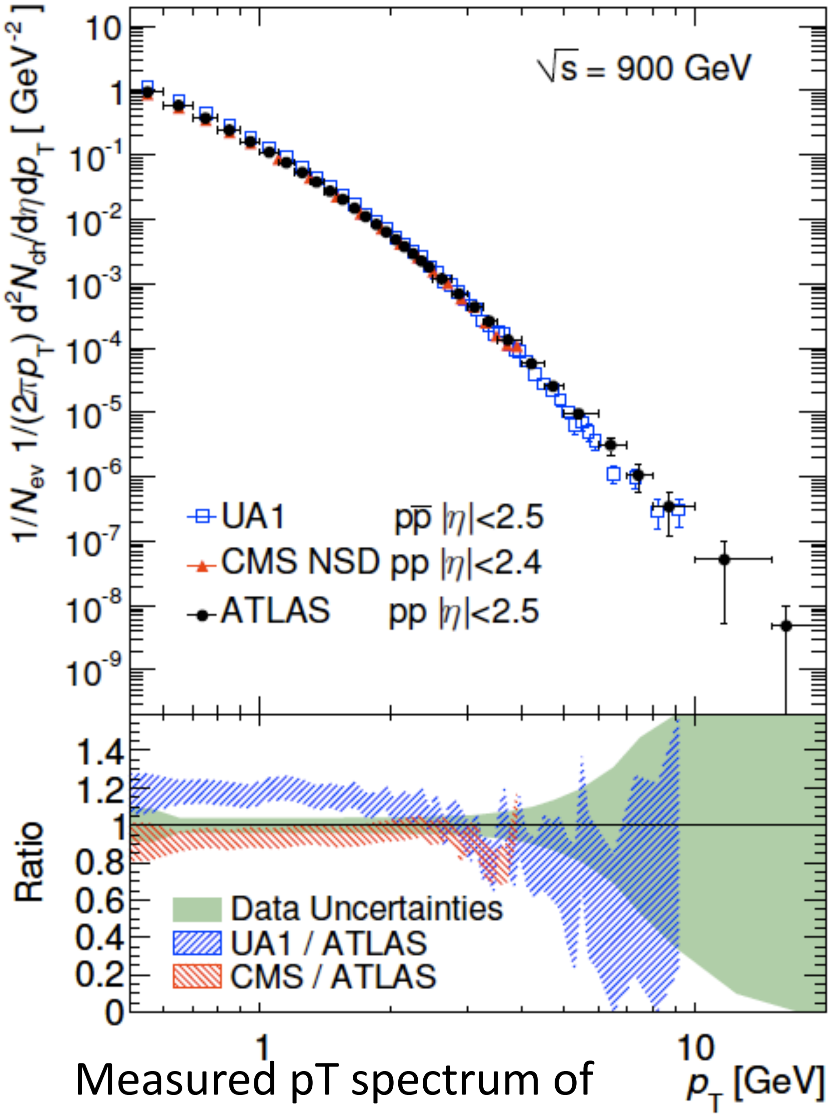


SV0 tagger using signed decay length significance.
Only tracks in jets considered.



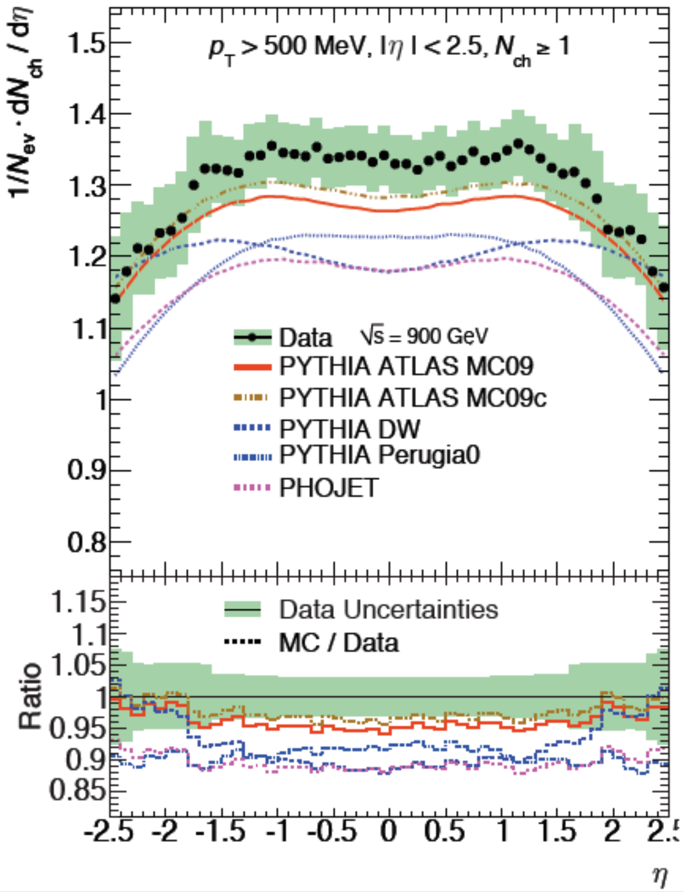
…perhaps even an event consistent with heavy flavour production

The first ATLAS physics result/paper



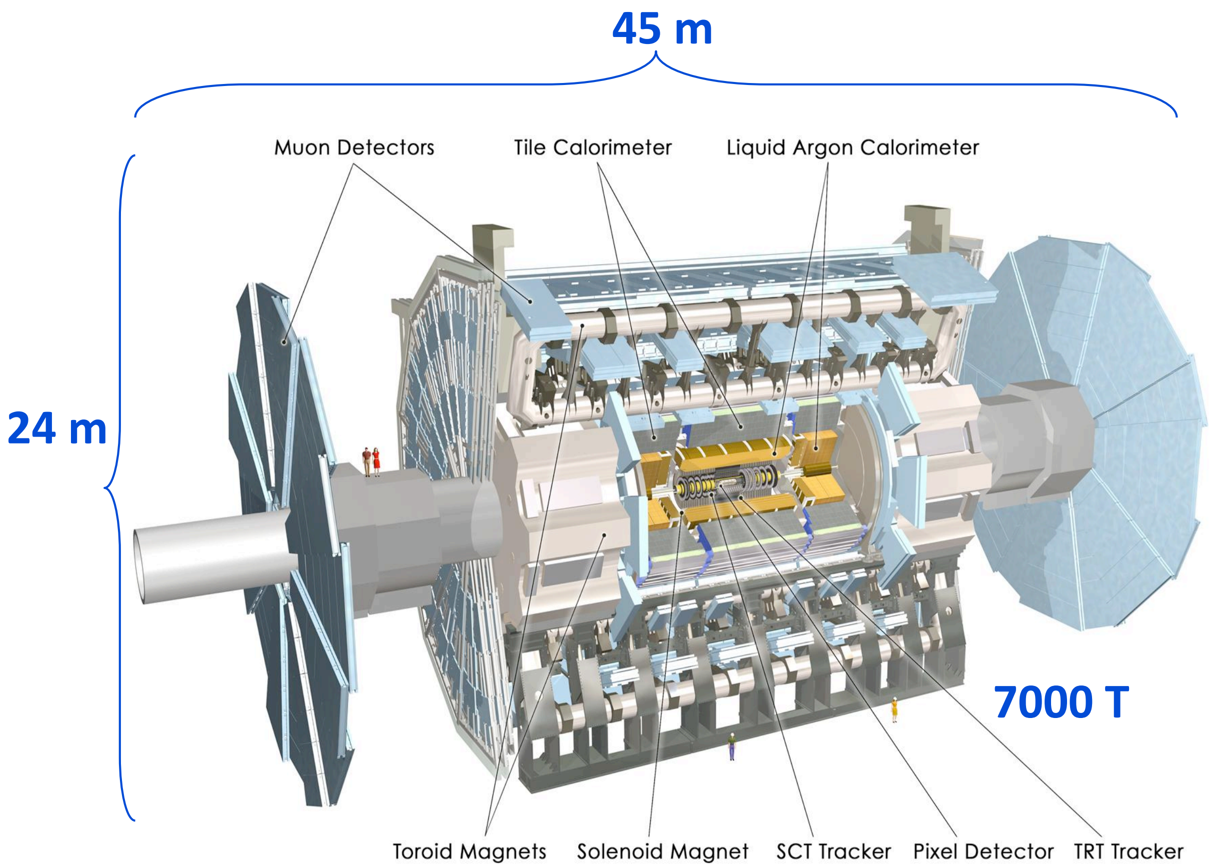
Measured pT spectrum of charged particle multiplicities

Charged-particle multiplicities in pp interactions at $\sqrt{s} = 900$ GeV measured with the ATLAS detector at the LHC



Track density as a function of η

Searching for Stable Massive Particles



- With an understood and commissioned detector we can start to search for exotic new phenomena
- Stable massive particles can be searched for in each subdetector of ATLAS
- I'll give a flavour of this by highlighting examples from the tracker, the calorimeter and the muon system
- But I'll focus mostly on the calorimeters

Motivation for SMP searches

- Host of SUSY scenarios (RPC & RPV)
- Universal Extra dimensions
- Leptoquarks
- Heavy leptons
- R-hadrons from stable gluino or squark
- Generic dE/dx
- “slow” muon like objects ~ns delays

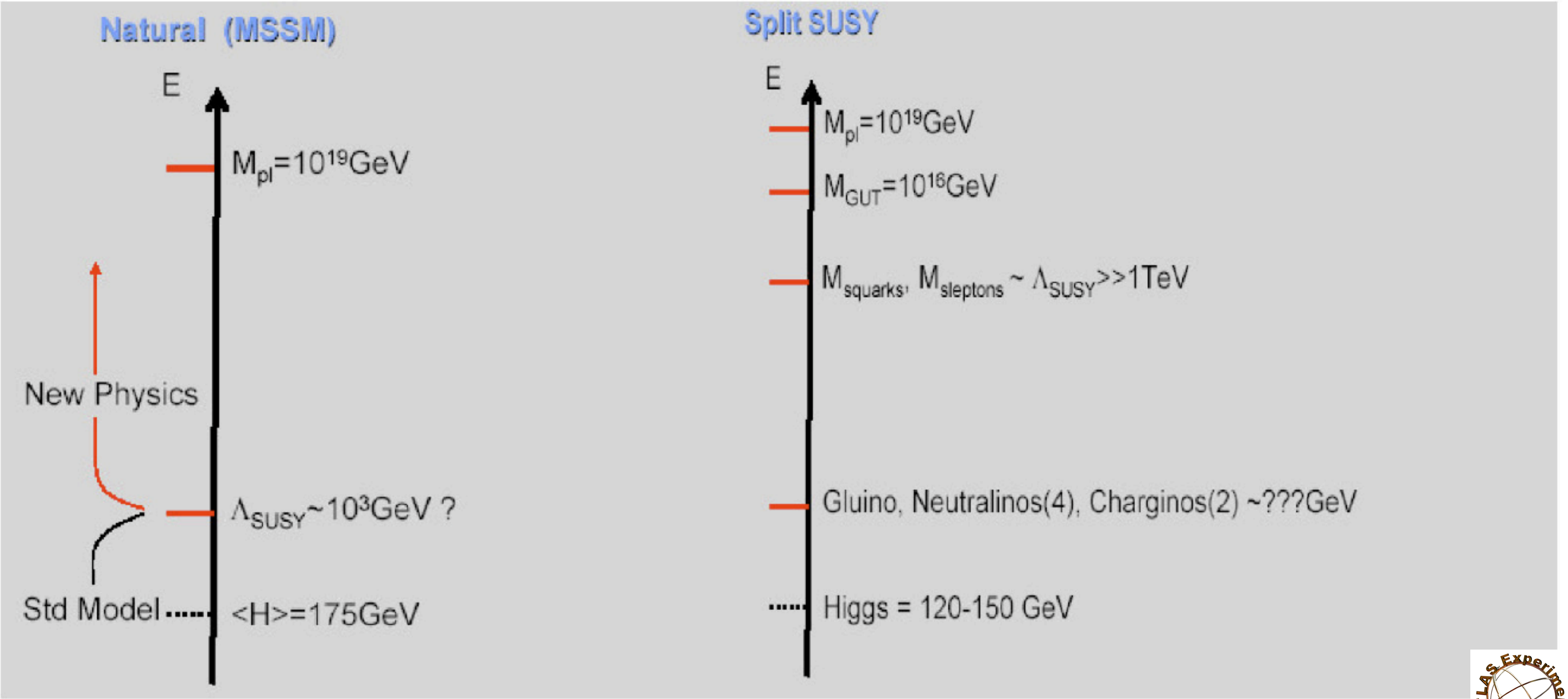
SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

hep-ph/0611040v2

Split SUSY

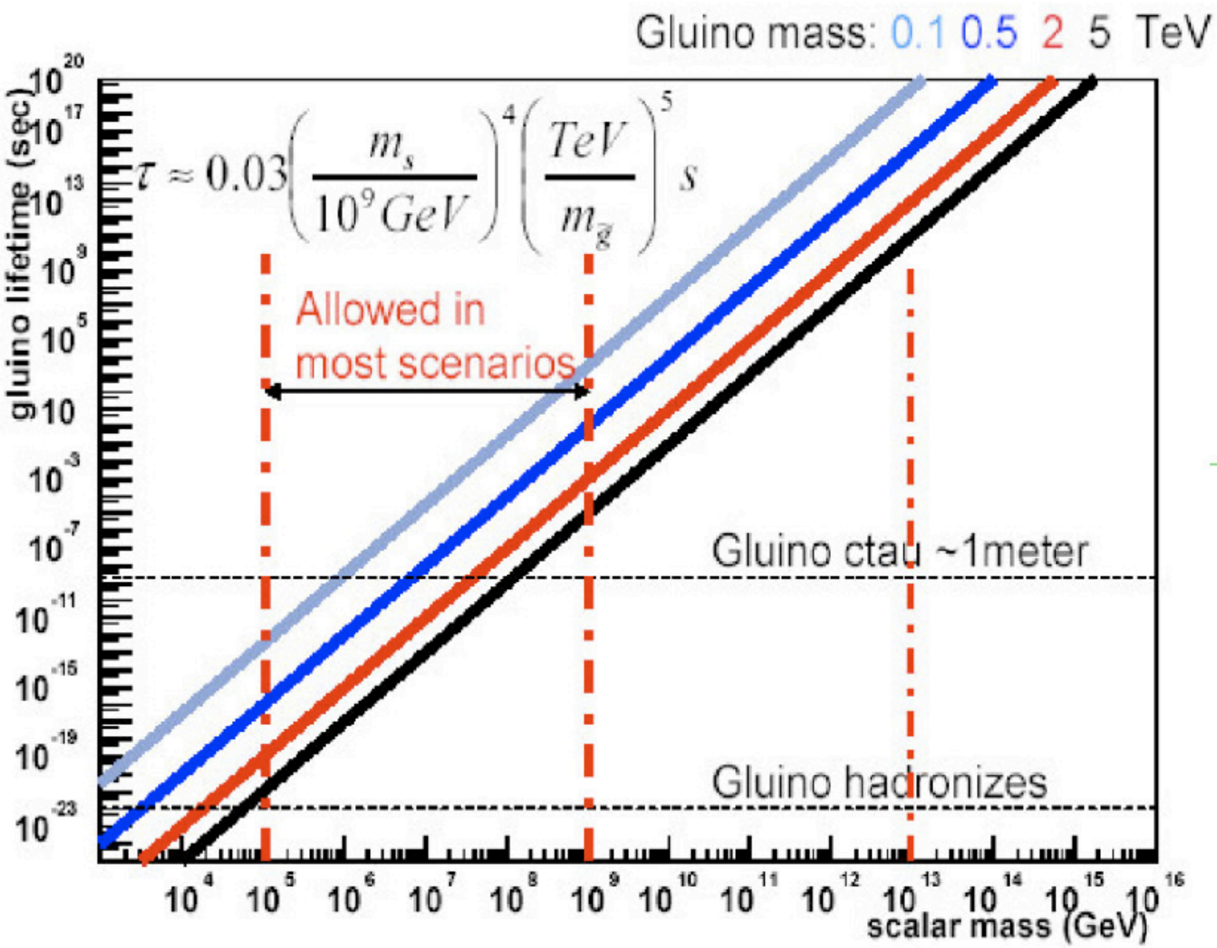
Arkani-Hamed et. al.
hep-ph/0409232

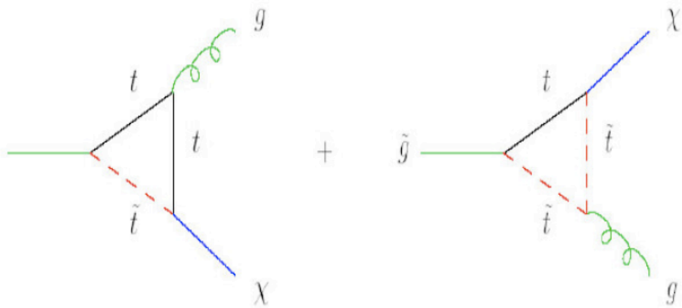
- Abandon the hierarchy problem!
- SUSY breaking occurs at high scale Ms>> 1TeV
- Scalars have masses at this scale –Higgs light. Fermions are light



Gluino in Split SUSY

Heavy squark leads to a light gluino ➔ (meta)stable gluino





Can decay into a WIMP candidate

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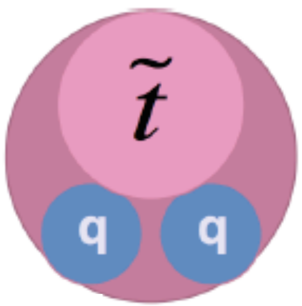
SMPs and their interactions

R-hadrons - what are they?

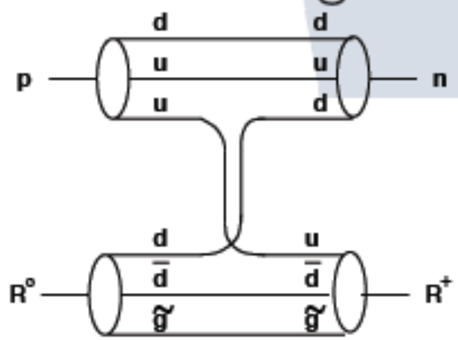
A stable color charged object will hadronize and form R-hadrons

- current mass limits on R-hadrons $\lesssim 250\,\text{GeV}$
- R-hadron is a heavy hadron with
  - one heavy parton that carries most of the hadron's momentum
  - a light quark system (LQS)

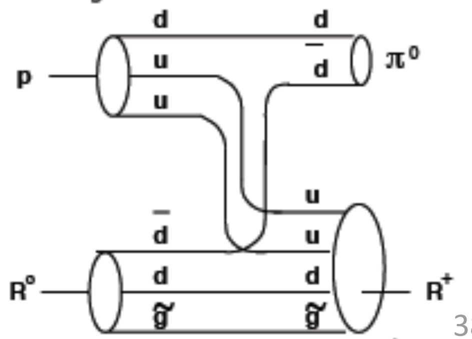


How do they interact?

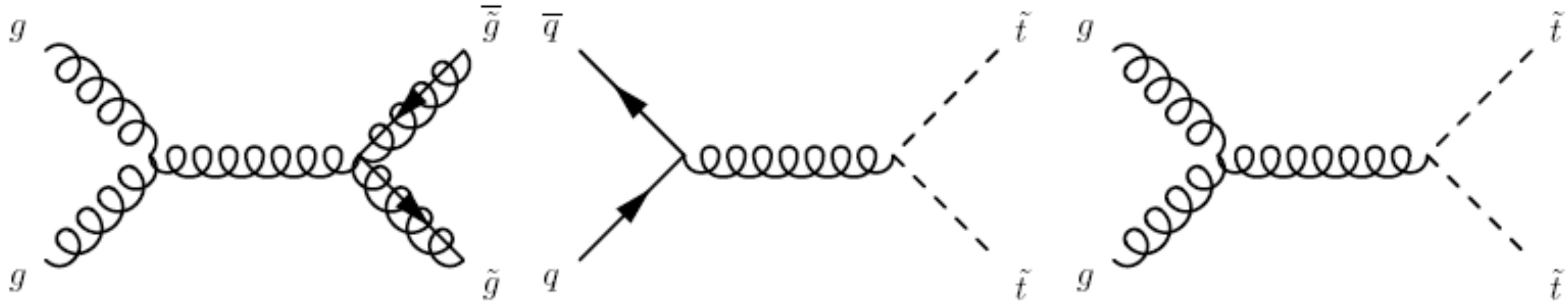
- Heavy parton unlikely to interact (cross section suppressed by $1/m^2$)
- LQS interacting with detector material can cause exchange of
  - electric charge



  - baryon number

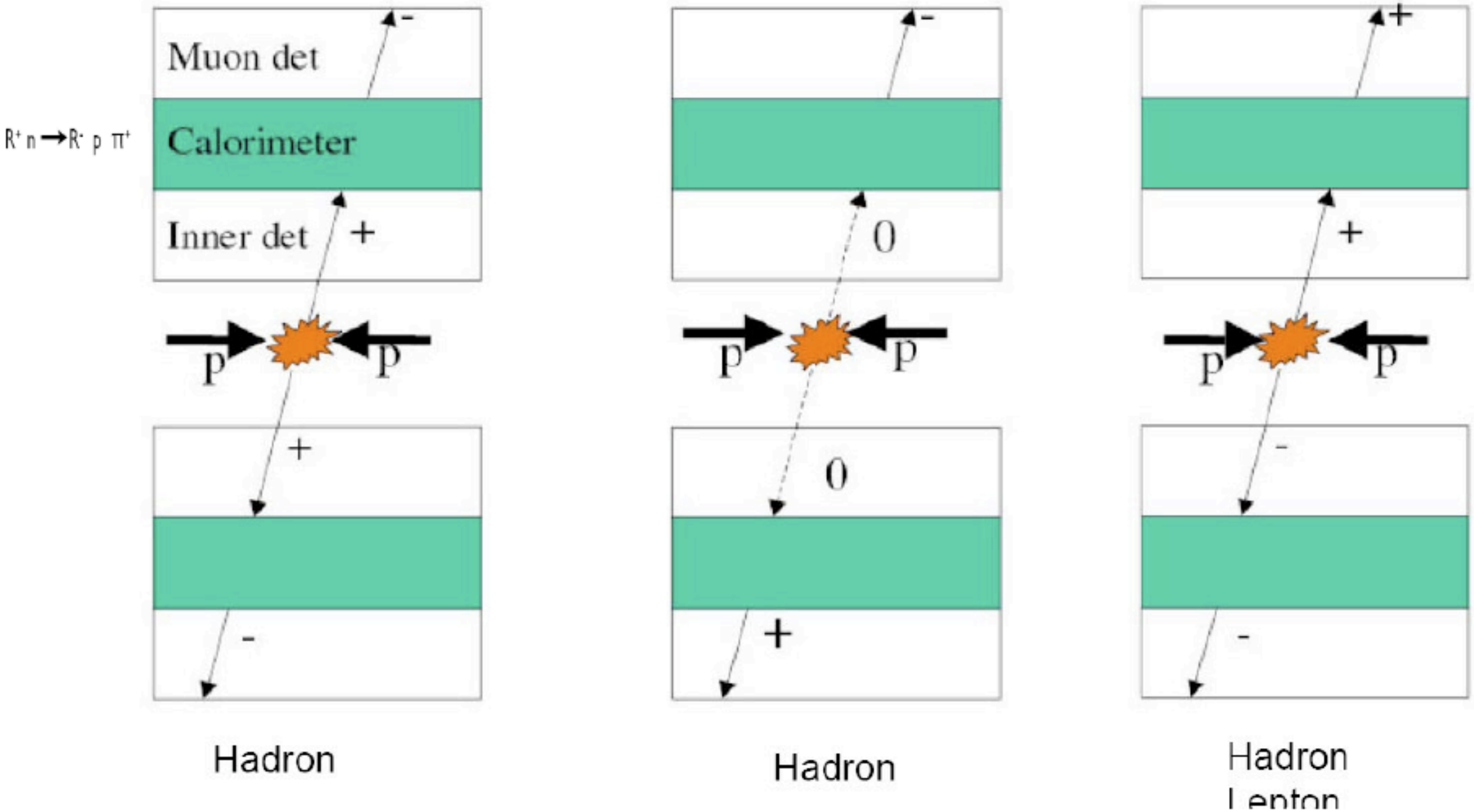


R-hadrons

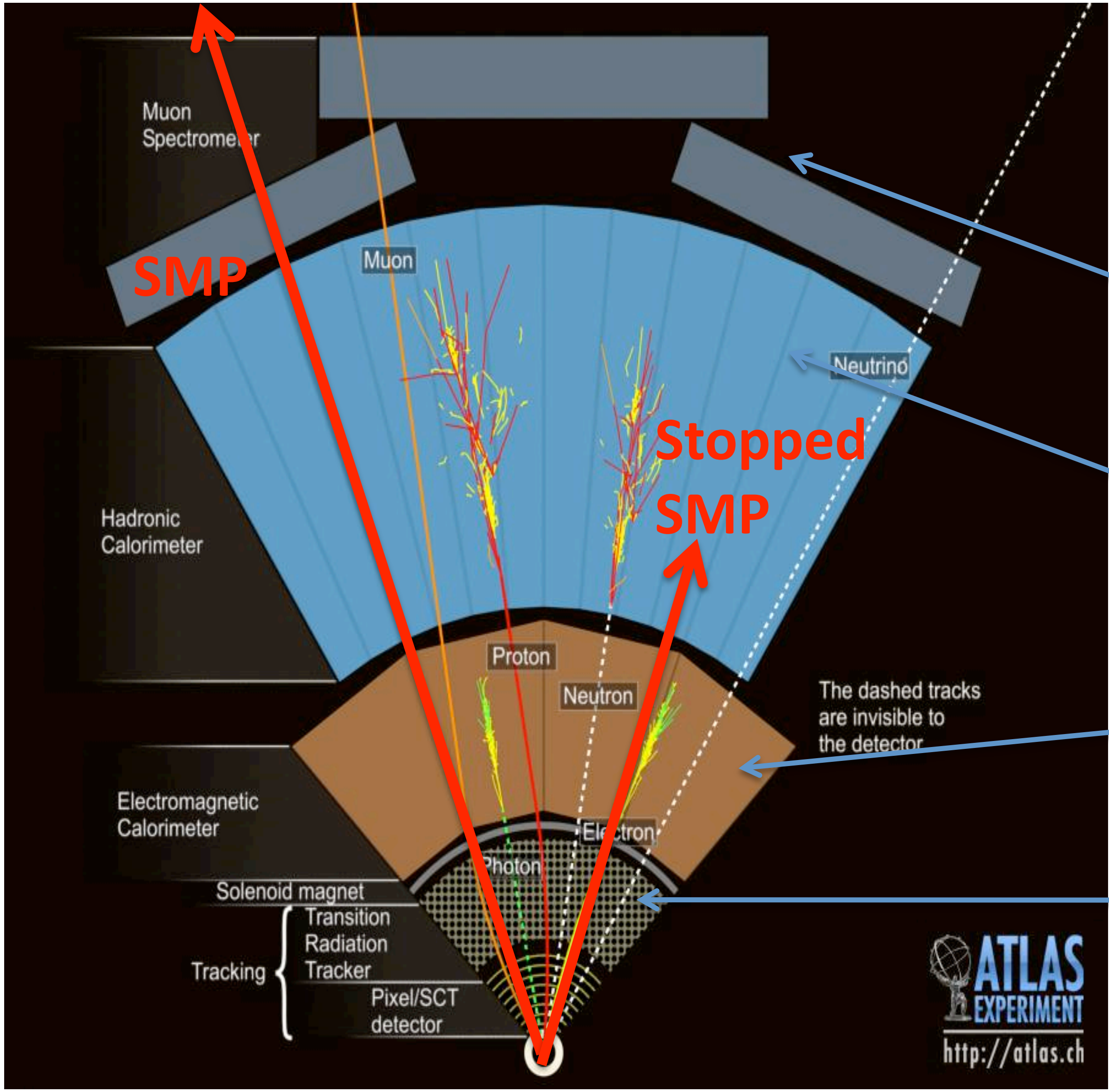


Leading order production mechanisms for gluino and stop squarks

Some event topologies



Understanding hadronisation and scattering in material is crucial

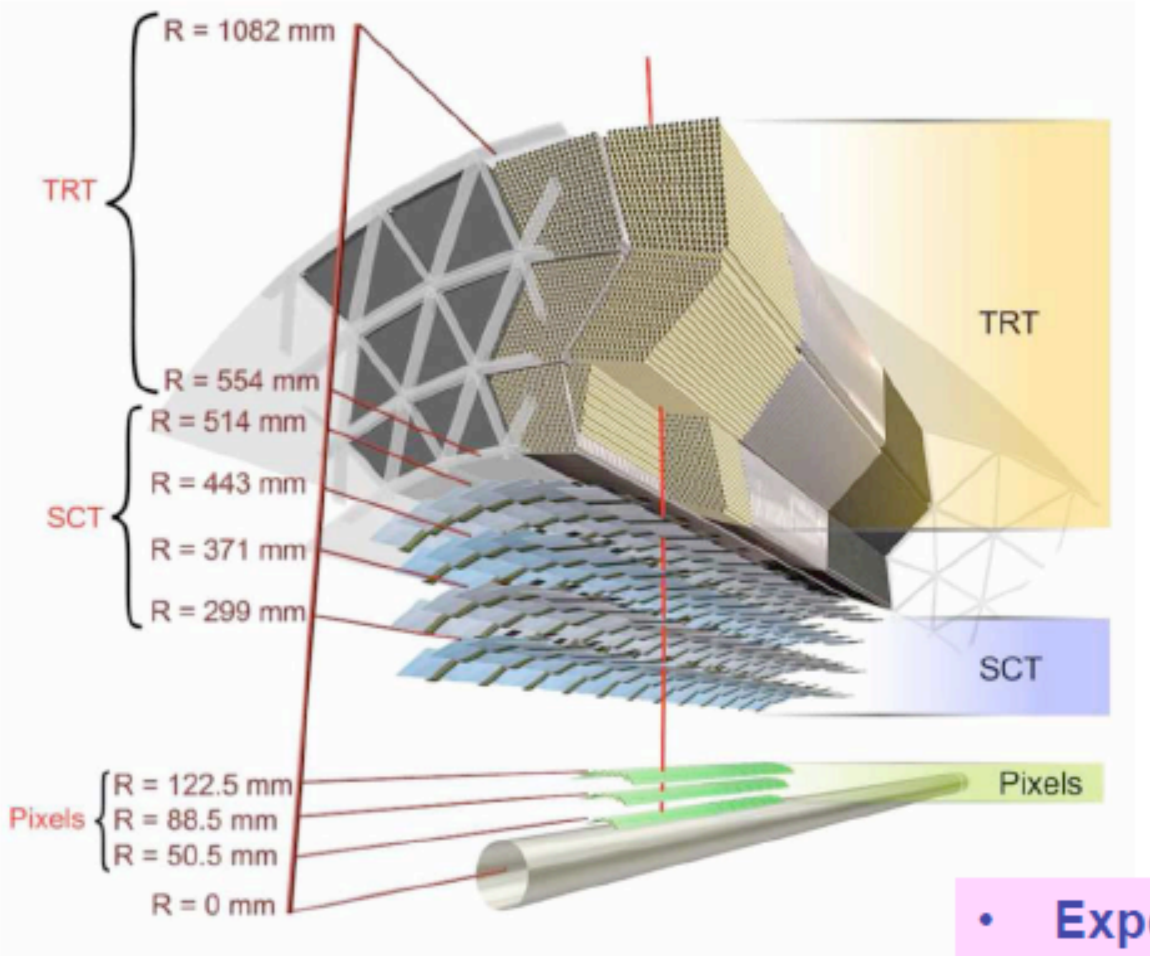


Muon spectrometer: Time of Flight (ToF)

Calorimeters: ToF, dE/dx and stopped particles

Transition Radiation Tracker: ToF and dE/dx

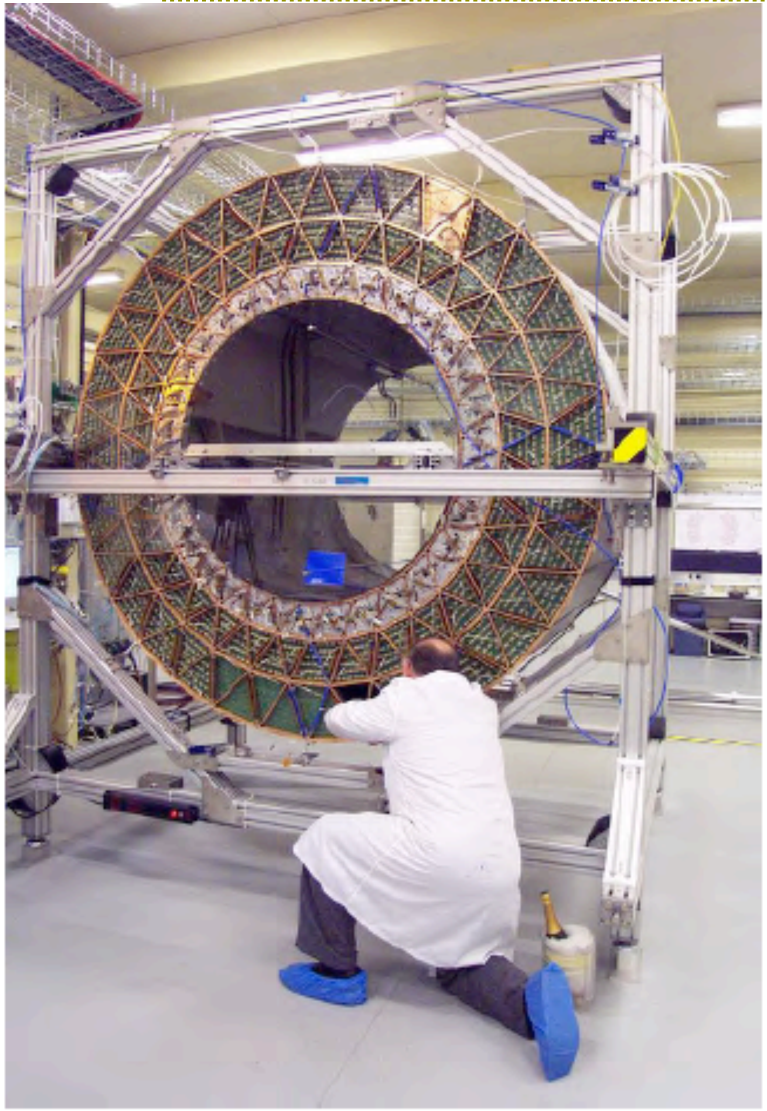
Inner Detector Tracking



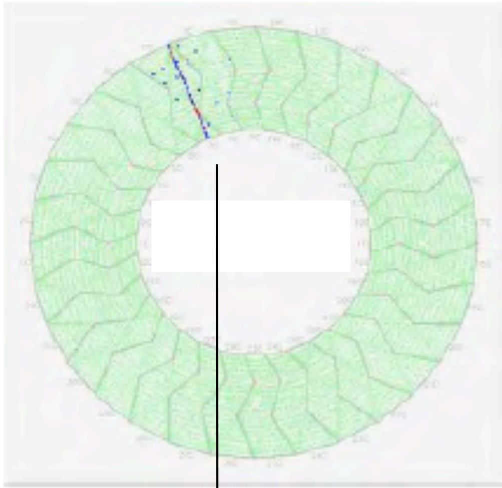
- Tracking in $|\eta|<2.5$, B=2T
- A track in barrel passes:
  - 36 TRT straws
  - 4x2 silicon strips
  - 3 pixels layers

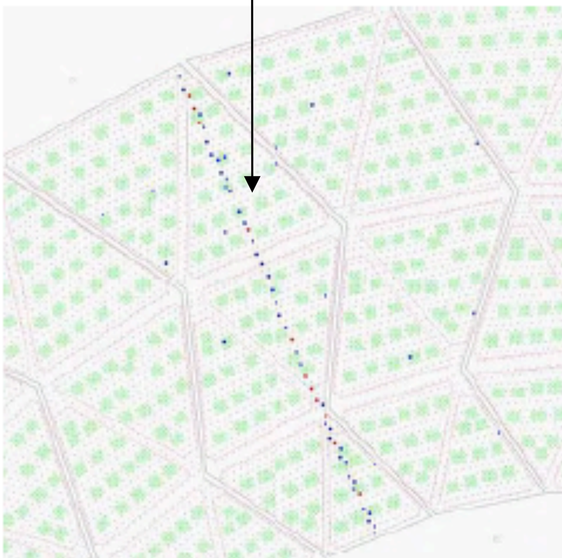
- Expected performance:
  - $\sigma/p_T \sim 3.4\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$
  - $\sigma_{d0} \sim 10 \oplus 140/p_T\,(\mathrm{GeV})\ \mu\mathrm{m}$

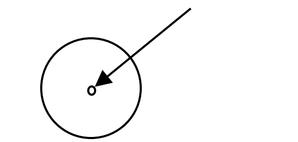
Transition Radiation Tracker



Barrel TRT during insertion of the last modules (February 2005)







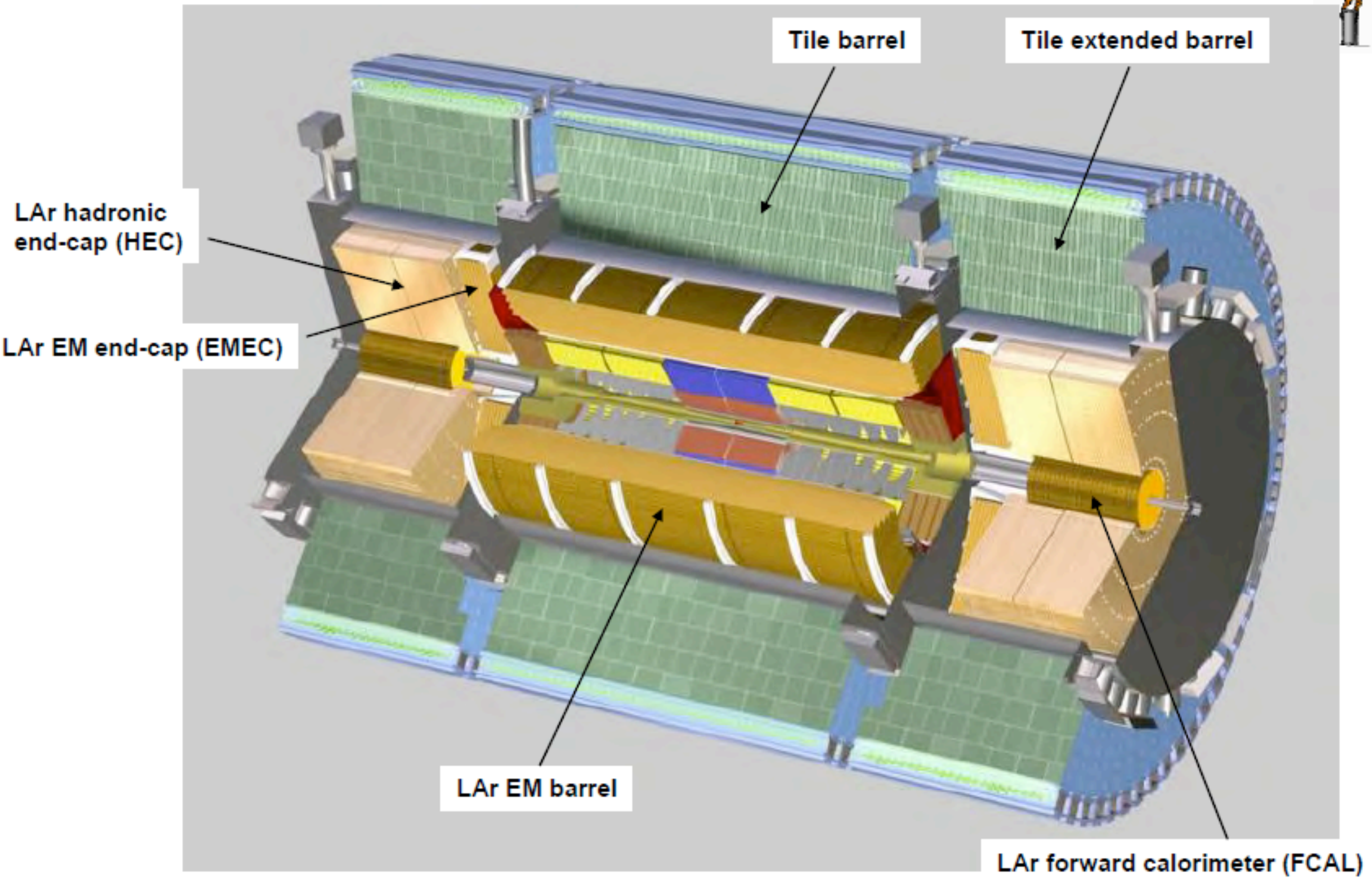
readout at both ends (in barrel)

420,000 channels

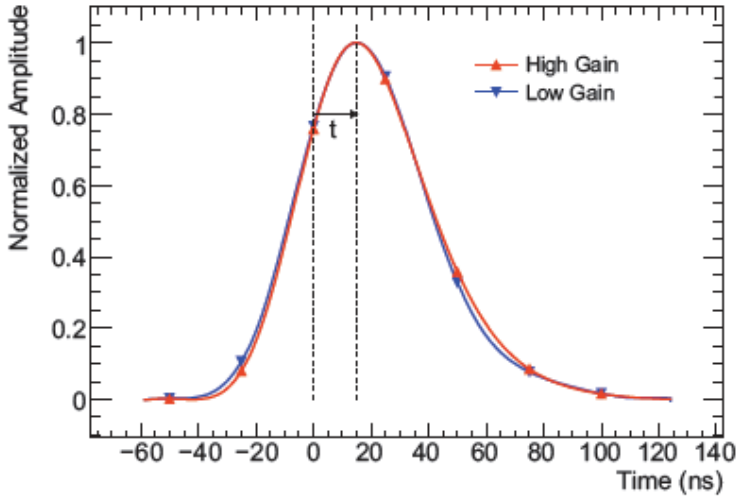
Situated close to IP
➔Degraded β resolution

Sensitive primarily to low β particles (β<=0.5)

LAr and Tile Calorimeters



Measuring β with the ATLAS Calorimeters



Calorimeter readout

- Sample every 25ns
- Upon L1 trigger, 7 samples are read out
- Optimal Filter algorithm (or offline fit) ➔ *E,t*

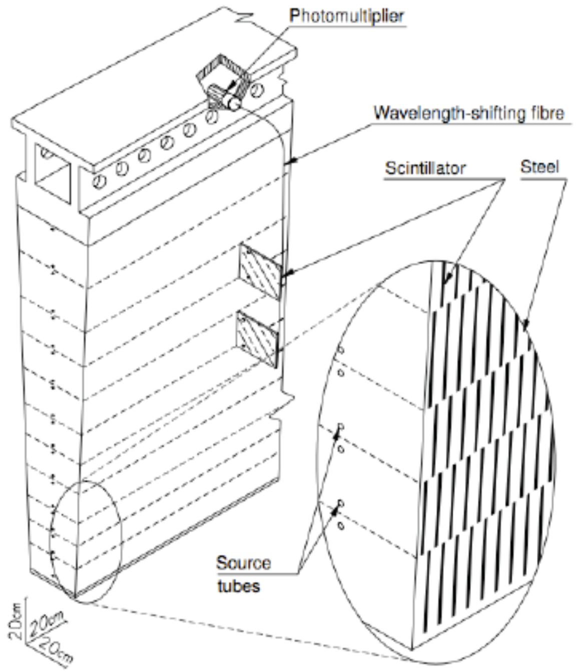
SMPs are likely to have $\beta < 1 \Rightarrow$ late arrival to the calorimeters. Large fraction of e.g. $R_{\tilde{g}}$-hadrons ($m_{\tilde{g}} > 300\,GeV$) will have $\beta < 0.7$.
Back-of-envelope calculation for TileCal:

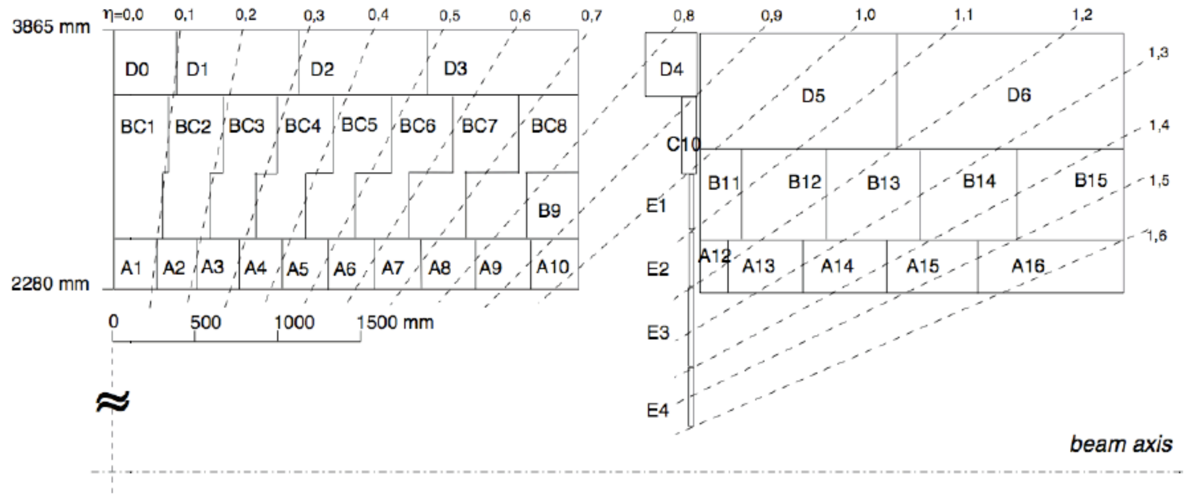
$$\Delta t = t_{SMP} - t_{ref} = \frac{d}{c}\left(\frac{1}{\beta} - 1\right) \qquad (1)$$

In TileCal for example, with $\beta = 0.7$ we get $3.2 < \Delta t_{min} < 9.3$ ns.

Measuring β with the ATLAS Calorimeters

How can cell timing be used to measure β?





- Each cell gives a beta measurement $\beta_{cell} = \frac{d_{cell}}{t_{reco}c + d_{cell}}$
- Combining the cells along the trajectory improves the resolution, e.g. $\beta = \bar{\beta} = \frac{\Sigma\beta_i}{n_{cells}}$

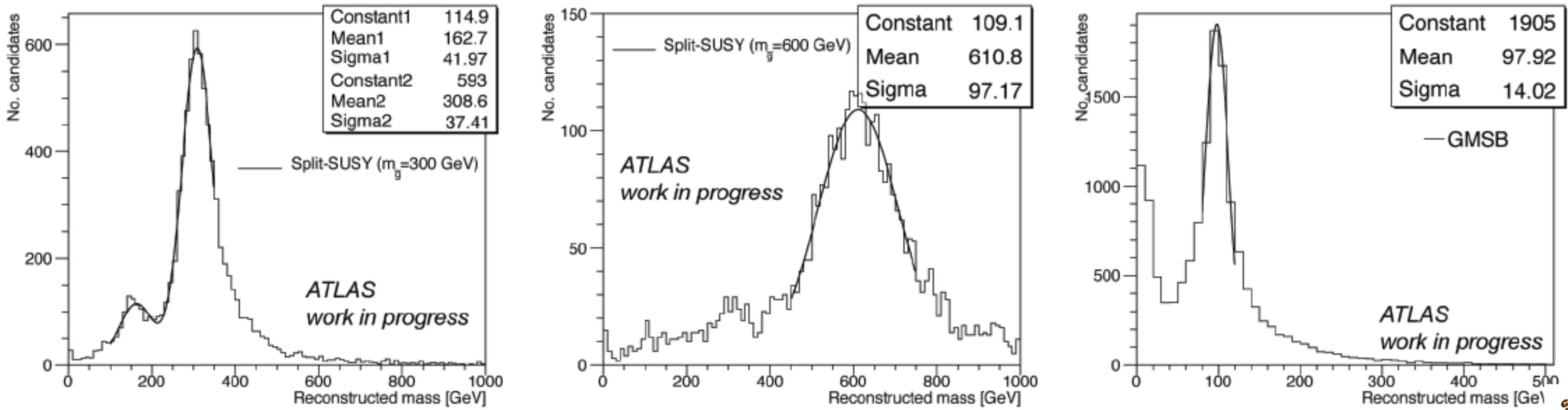
Measuring the mass through β and p

Resolution of mass measurement

By combining the β measurement with a momentum measurement, either from a track in the inner detector or muon spectrometer, the mass of the particle can be calculated

$$m = p\frac{\sqrt{1-\beta^2}}{\beta}$$

From left to right: stable gluino of 300GeV and 600GeV mass in Split-SUSY scenario, and stable slepton of mass 100GeV in Gauge-Mediated SUSY Breaking scenario



Study performed for 10TeV CM

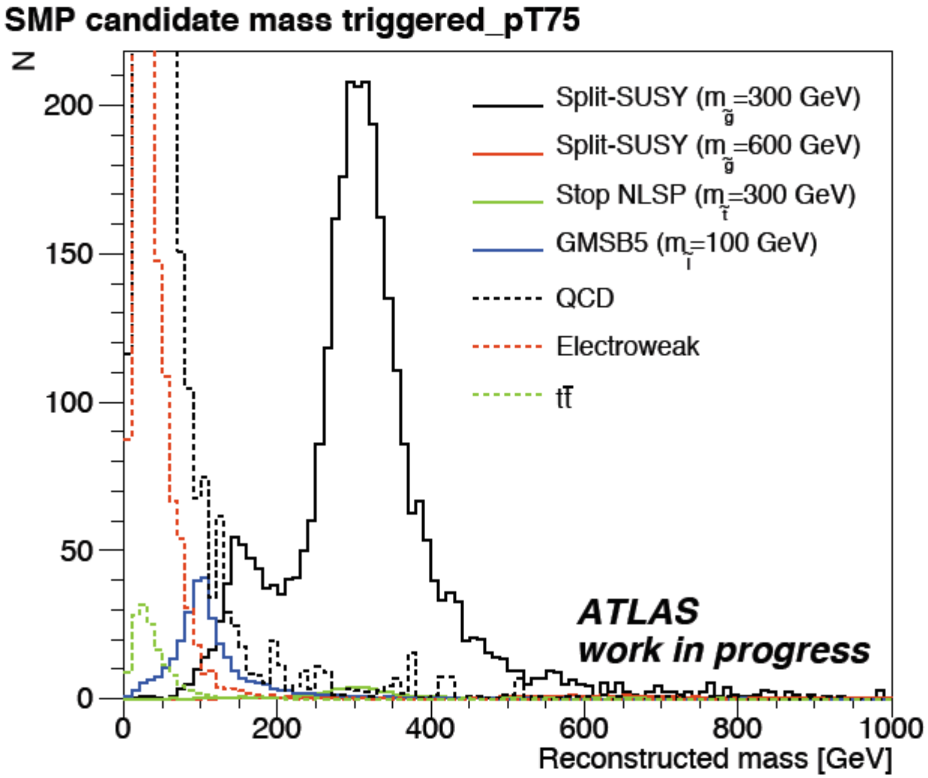
Low Luminosity Search

What can be done with $50pb^{-1}$?

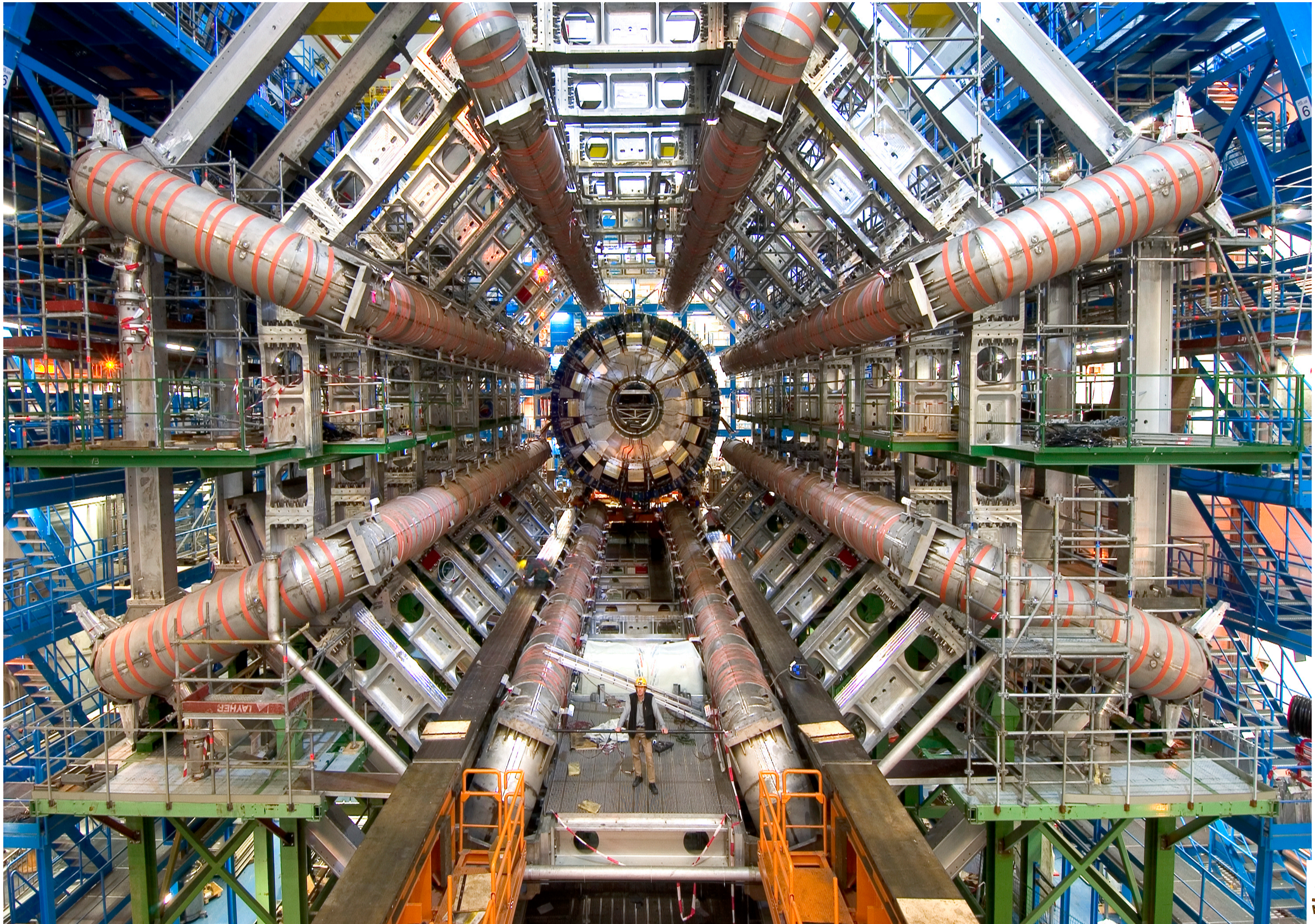
Using the method described here, and a few simple cuts

- Trigger: one of
  - 40 GeV muon trigger
  - 120 GeV jet trigger
  - 70 GeV jet + 30 GeV E_T^{miss} trigger
- Consider all reconstructed muons with $p_T > 75$ GeV as SMP candidates

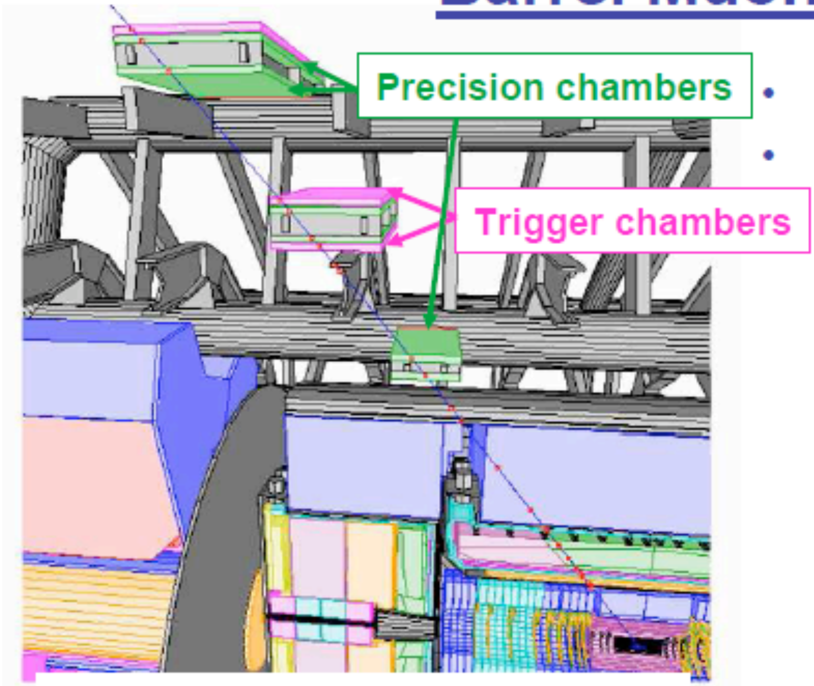
$\Rightarrow$ 300 GeV stable $\tilde{g}$ should definitely be possible to find with first-year data, but work to be done for stable $\tilde{\ell}$ and higher mass color charged stable particles



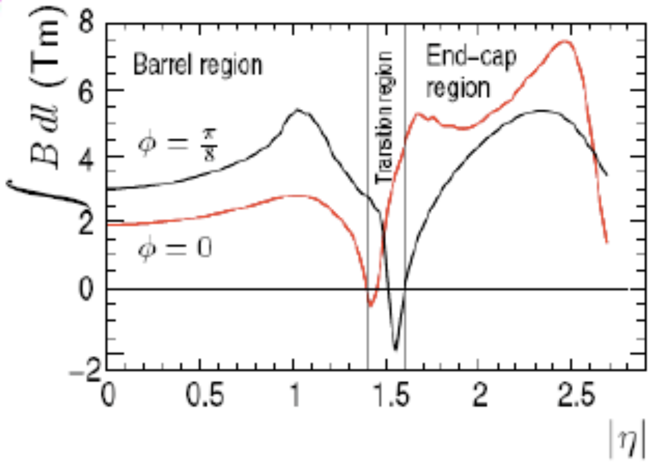
The Toroidal System of Magnets of ATLAS

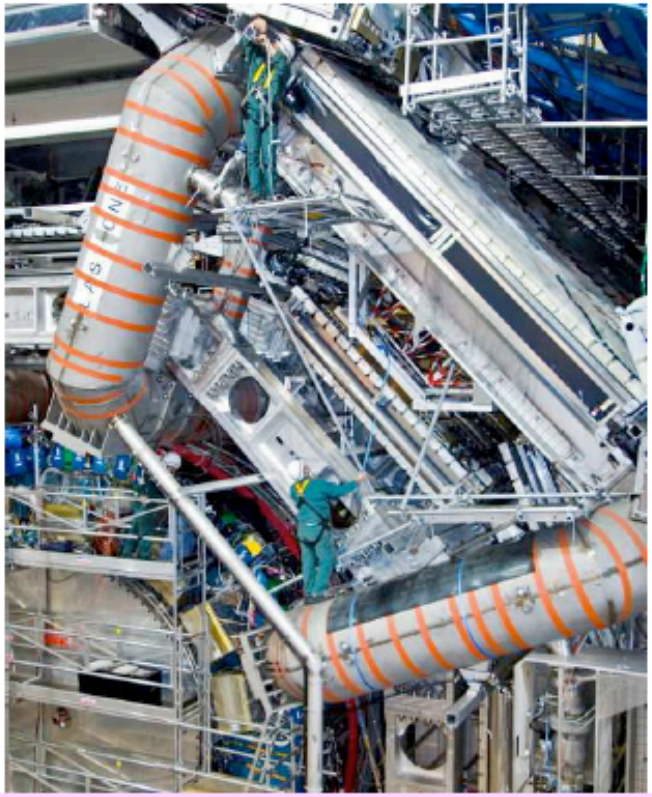


Barrel Muon Spectrometer



- 700 barrel precision chambers (MDT)
- 600 barrel trigger chambers (RPC, |η|<1.05)





Momentum resolution: <10% up to ~1 TeV

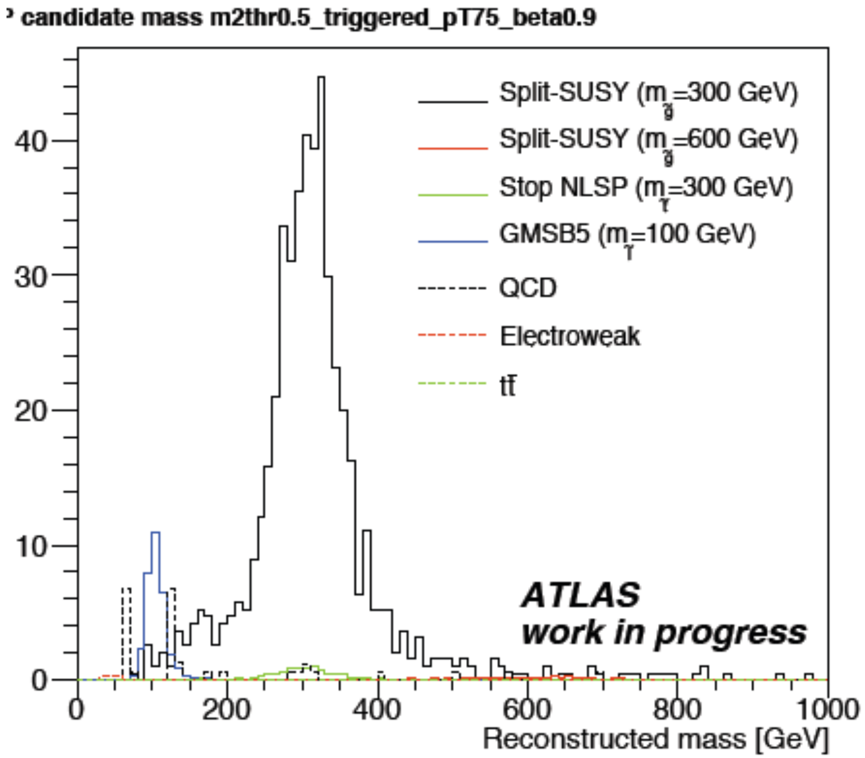
Field integral: 2-6 Tm |η|<1.3, 4-8 Tm 1.6<|η|<2.7

Study performed for 10TeV CM

Low Luminosity Search

What can be done with 50pb^{-1}?

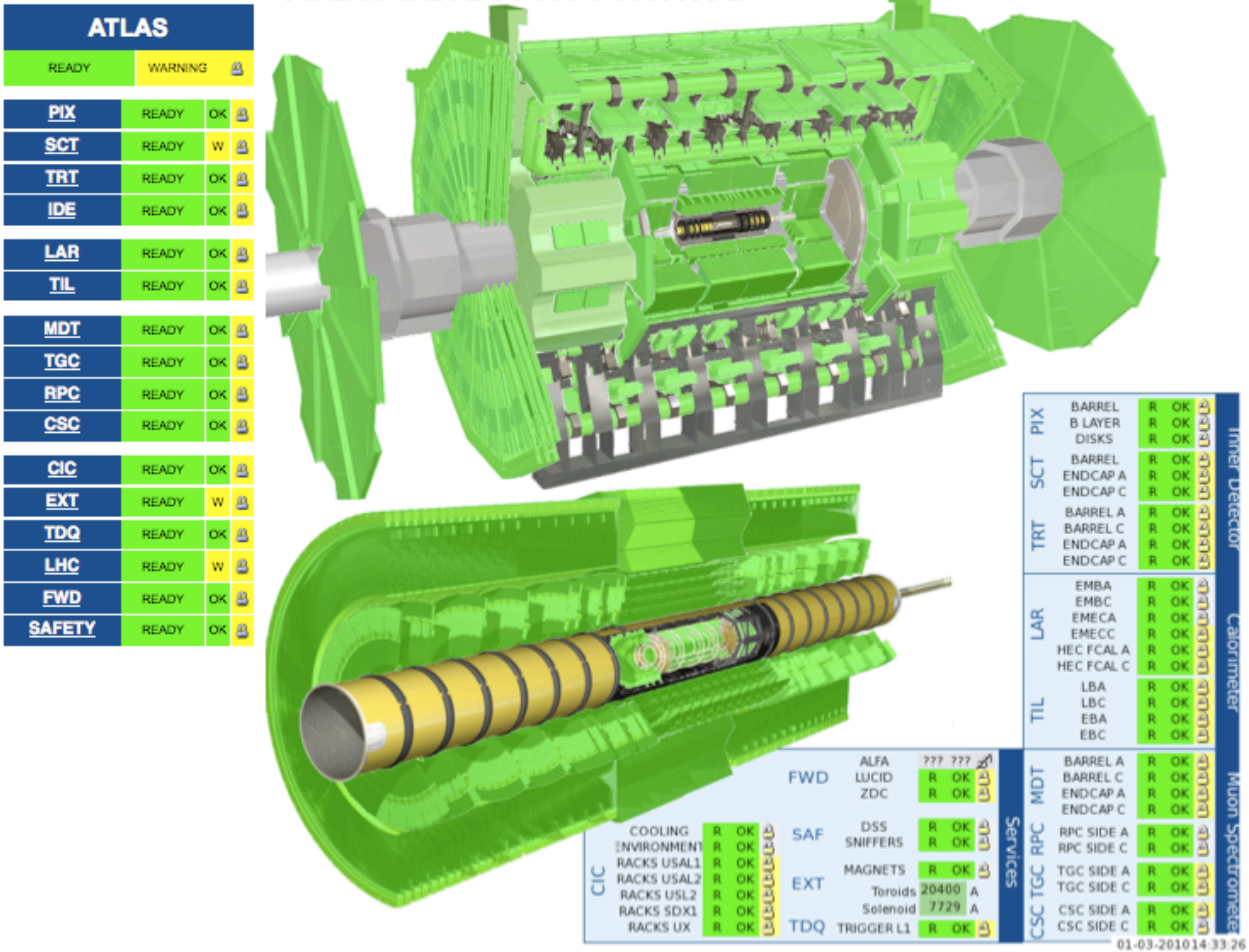
- β spectrum will have tails, causing background muons to populate mass bins up to $\sim$100 GeV
  $\Rightarrow$ require $\beta < 0.9$ in both calorimeter and muon spectrometer (independent measurements)
- Efficient background rejection, but lose 75-80% of signal...



Outlook for 2010

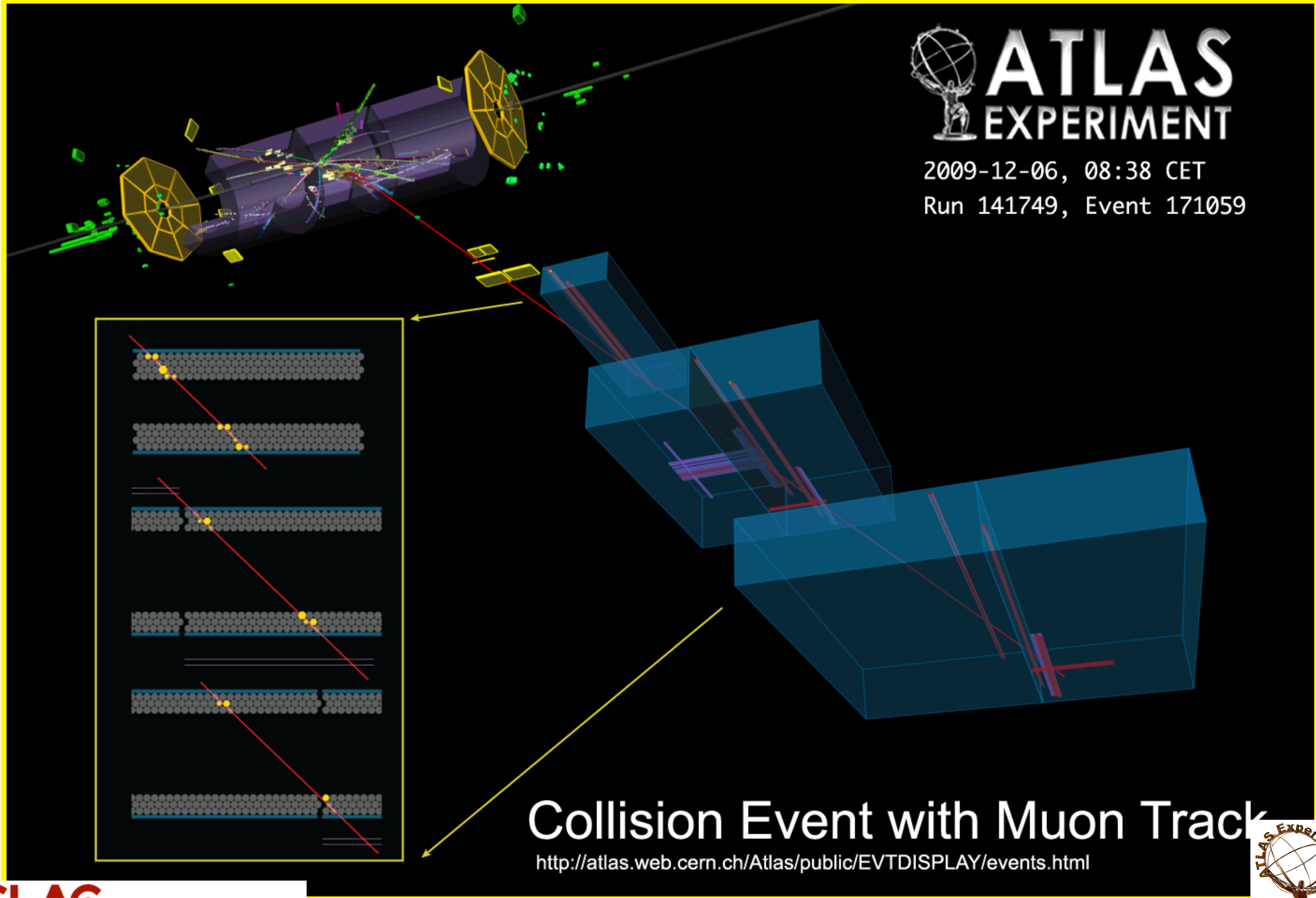
- The LHC will begin back online and begin commissioning to 7 TeV CoM
  - A few shifts at 900 GeV
  - Move to 7 TeV ASAP
  - Turn on a crossing angle within a few weeks
  - Start increasing # bunches: 2→43→156 within ~weeks/months
  - Move to 50ns bunch spacing within a few months
  - Expect 100pb^{-1} per month by end of 2010
    - Several suggestions for bunch structure, etc
  - Chamonix Workshop Agenda:
    - http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=67839
- After 2011 a major shutdown will start to prepare the machine to move to 14 TeV

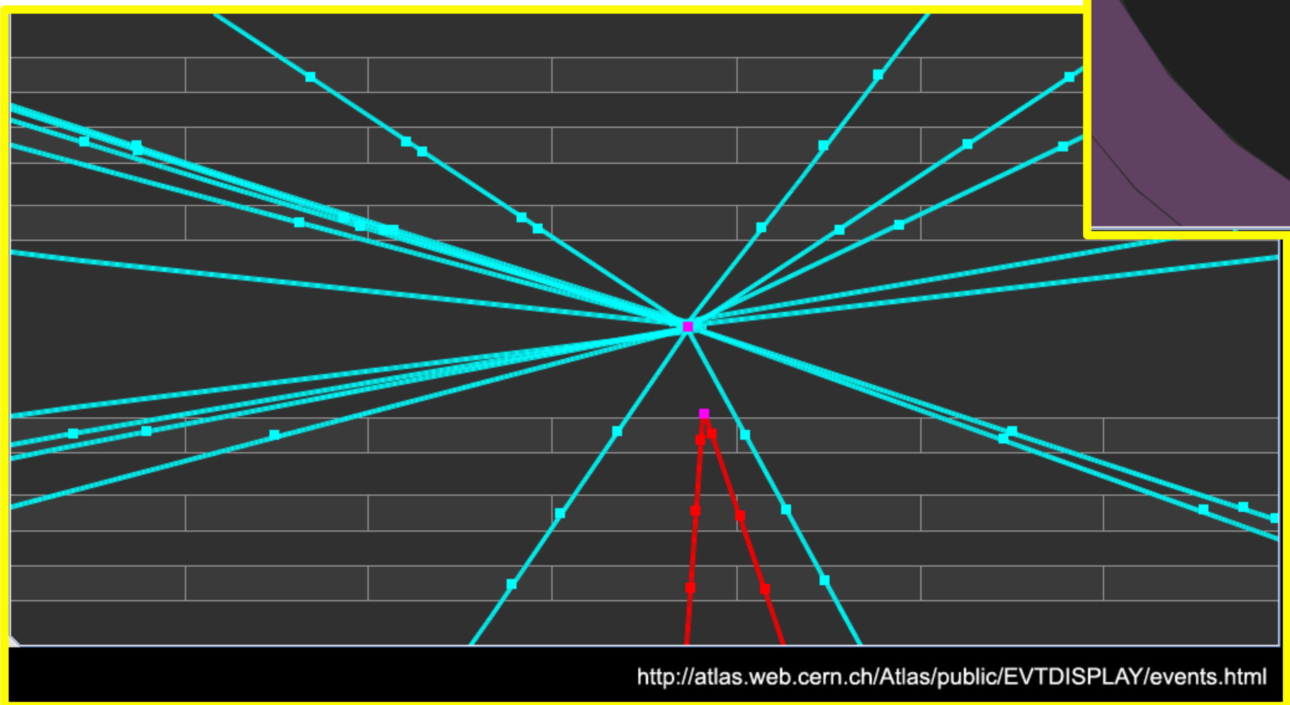
ATLAS DETECTOR CONTROL

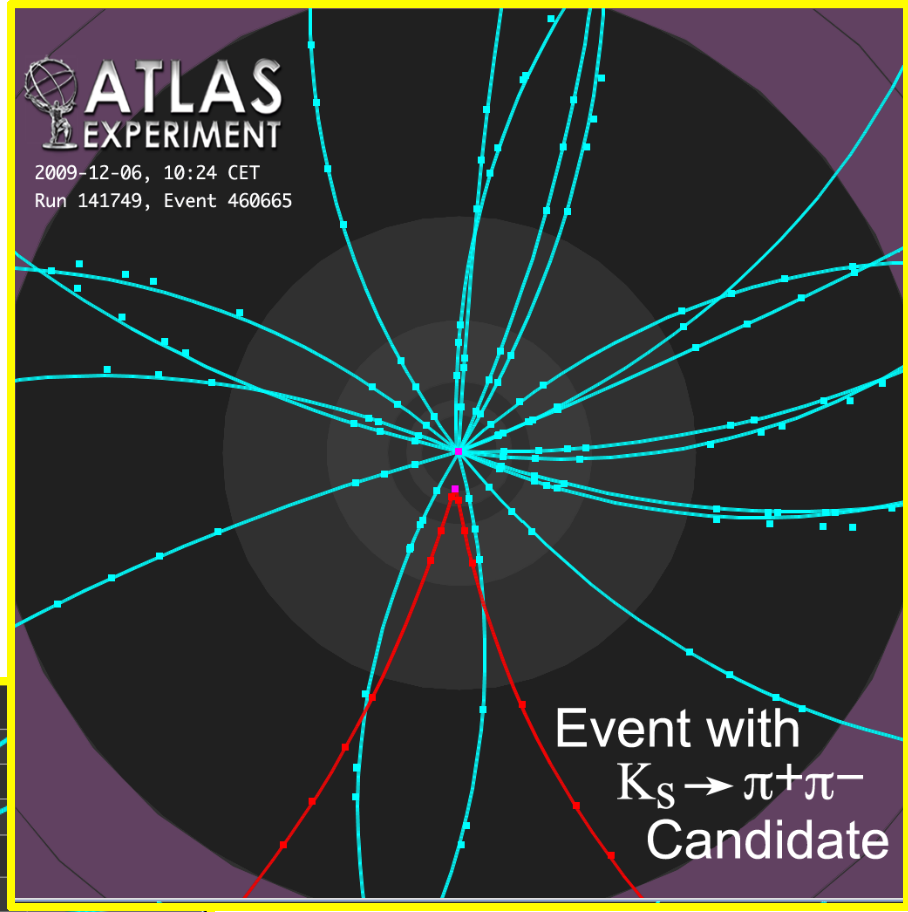


- ATLAS is taking data right now!
- With the first year of data-taking we are sensitive to measurements of SMPs, which are predicted in a variety of new physics scenarios
- Can cross-check signals among various sub-detectors and with multiple analysis methods
- We are in for an exciting few years!!!

BONUS MATERIAL

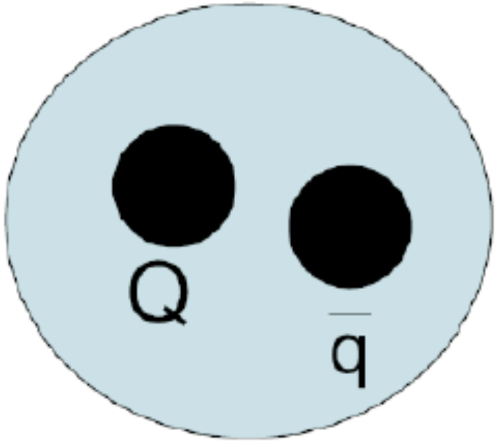

ATLAS EXPERIMENT
2009-12-06, 08:38 CET
Run 141749, Event 171059
Collision Event with Muon Track
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html


ATLAS
EXPERIMENT
2009-12-06, 10:24 CET
Run 141749, Event 460665
Event with
$K_S \rightarrow \pi^+\pi^-$
Candidate

R-hadrons

Heavy hadron scattering



Heavy exotic meson from massive exotic colour triplet Q and SM quark $\bar{q}$.

$M_Q \approx M_H = 200$ GeV $\quad E = 1$ TeV

$\Rightarrow \gamma = E/M = 5$

$M_q \approx 0.2$ GeV $\Rightarrow \mathrm{KE}_q = (\gamma - 1) M_q \approx$ GeV

Heavy quark doesn't interact

Low energy collision between SM quark in material.

Summary of SMP search status in ATLAS

- Stable Massive Particles can signal new physics, searches for them are important with early data at LHC
- Simulation studies indicate time-of-flight can be measured with the ATLAS hadronic calorimeter (~5% resolution, 95% efficiency)
- Using the ToF method, as little as 20pb^{-1} may be required for SMP discovery, good prospects for early limit setting
- Careful timing calibration is crucial for calorimeter ToF measurements ➔efforts already underway on precision timing of the calorimeters