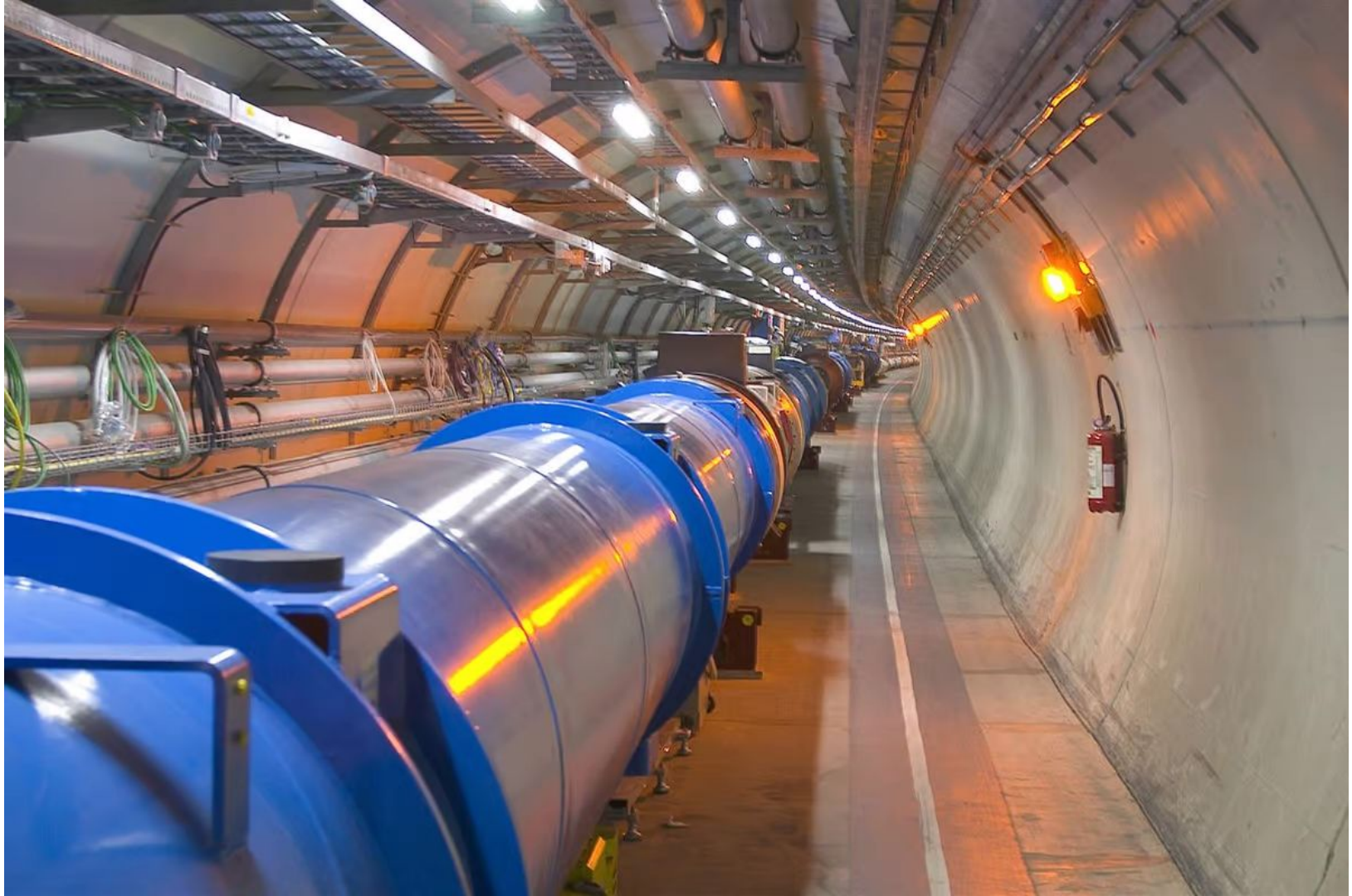
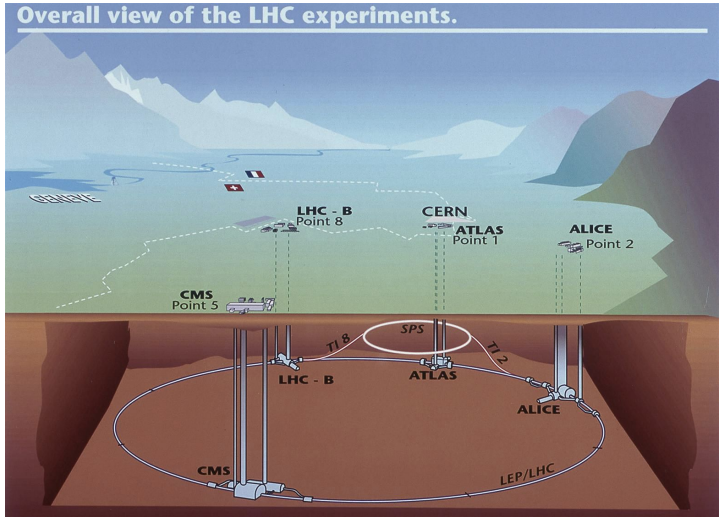
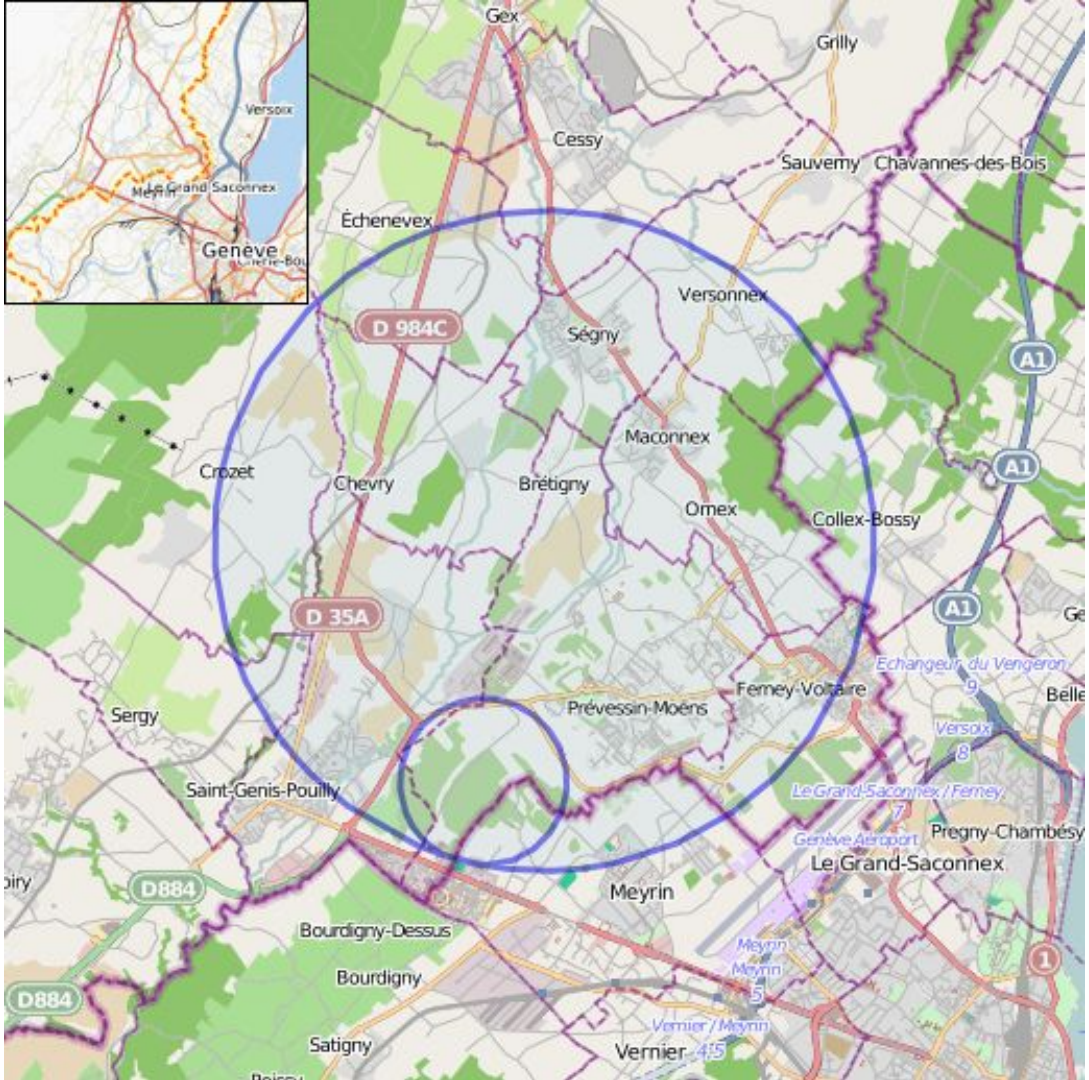
LHC



LHC Overview

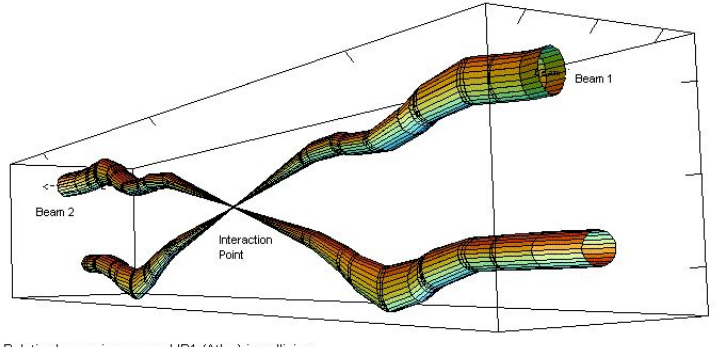
- The Large Hadron Collider (LHC) is the leading accelerator in the world
- Capable of accelerating protons and heavy ions
  - Proton beams at 6.8 TeV
  - Lead ion beams at 522 TeV (2.3 TeV per nucleon)
- 17 mile (27 km) long synchrotron
  - Up to 574 ft (170 m) underground
  - Tilted at a 14 mrad angle due to geological conditions
  - Built in pre-existing LEP tunnel
- Located underneath Switzerland and France
- Hadron beams circulate in opposite directions
- Collisions occur at 4 interaction points




Gex
Grilly
Cessy
Sauverny
Chavannes-des-Bois
Échenevex
Versonnex
Ségny
D 984C
A1
Maconnex
Crozet
Chevry
Brétigny
Ornex
Collex-Bossy
D 35A
Echangeur du Vengeron
9
Ferney-Voltaire
Prévessin-Moëns
Sergy
Versoix
8
Saint-Genis-Pouilly
Le Grand-Saconnex / Ferney
7
Genève Aéroport
Pregny-Chambésy
Le Grand-Saconnex
D884
Meyrin
Bourdigny-Dessus
Meyrin
Meyrin
5
Bourdigny
Satigny
Vernier / Meyrin
Vernier
415
Versoix
Le Grand Saconnex
Meyrin
Genève

LHC magnets

- Complex system of magnets used to steer and control beams
- 1232 main dipoles keep beam along ring
  - Superconducting magnets generate a field strength of 8.3 T
  - 15 m long and weighs 15 tons
- Sextupole, octupole and decapole magnets help to maintain beam integrity
- Sets of quadrupole magnets guide beams to collision points
  - Compress beams to increase proton density (0.2 mm diameter to 20 μm)
  - Precisely steer beams into interaction point volume (20 μm x 20 μm x 8 cm)

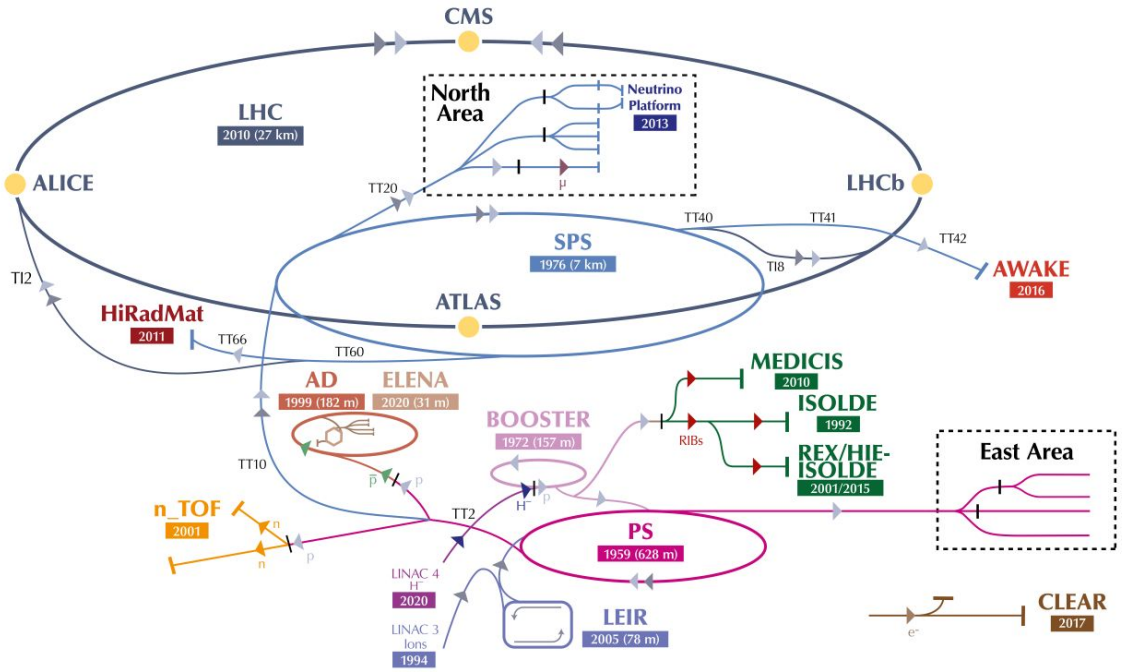


Relative beam sizes around IP1 (Atlas) in collision

Accelerating protons

- Protons are sourced from Hydrogen gas
  - Electrons are stripped, leaving protons
- Initially accelerated using a linac
- Passed through a series of synchrotrons
  - Increasing energy at each stage
  - Previous colliders make up acceleration chain
- Heavy ion acceleration is similar

The CERN accelerator complex
Complexe des accélérateurs du CERN



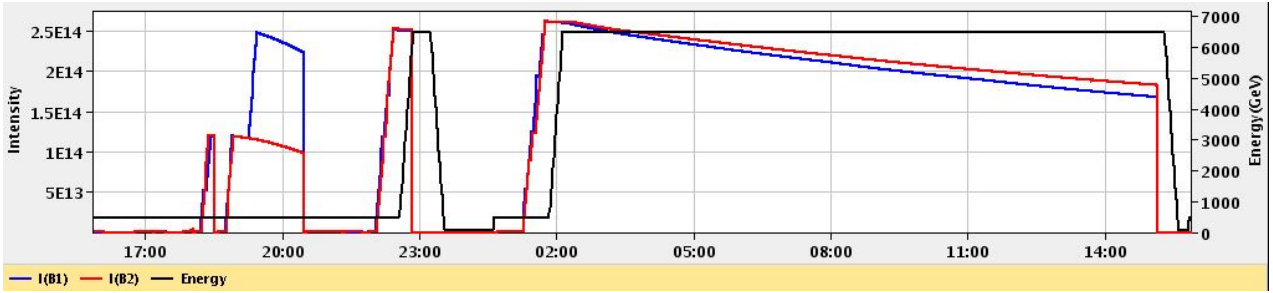
H⁻ (hydrogen anions) · p (protons) · ions · RIBs (Radioactive Ion Beams) · n (neutrons) · p̄ (antiprotons) · e⁻ (electrons) · μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

January 2022

LHC proton beams

- LHC collisions occur in “fills”
  - Number of protons decreases throughout a fill
  - A fill lasts several hours until the beam is dumped and a new fill is started
- Each beam consists of 2835 “bunches” of protons
  - Each bunch begins with ~10^{11} protons
  - Each interaction point has one bunch crossing every 25 ns
  - Most protons in a bunch pass without interacting, but a few interact at each crossing
- 600 million collisions per second
- Protons lost continually lost during run

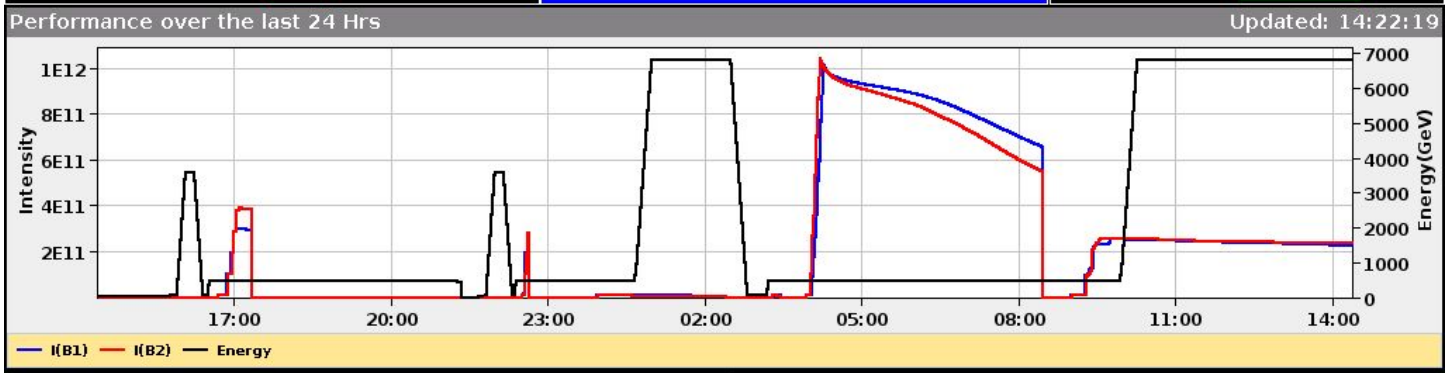


https://op-webtools.web.cern.ch/vistar/vistars.php

13-Apr-2023 14:22:38 Fill #: 8582 Energy: 6800 GeV I(B1): 2.25e+11 I(B2): 2.35e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	CALIBRATION	STANDBY	STANDBY
Instantaneous Lumi [(ub.s)^-1]	2.712	0.151	3.365	1.019
BRAN Luminosity [(ub.s)^-1]	2.8	0.0	82.3	0.2
Fill Luminosity (nb)^-1	0.000	0.000	0.000	0.000
Beam 1 BKGD	0.000	0.002	0.139	0.000
Beam 2 BKGD	0.000	0.000	0.000	0.002
Beta*	0.30 m	10.00 m	0.30 m	2.00 m
Crossing Angle (urad)	-160(V)	200(V)	160(H)	0(H)

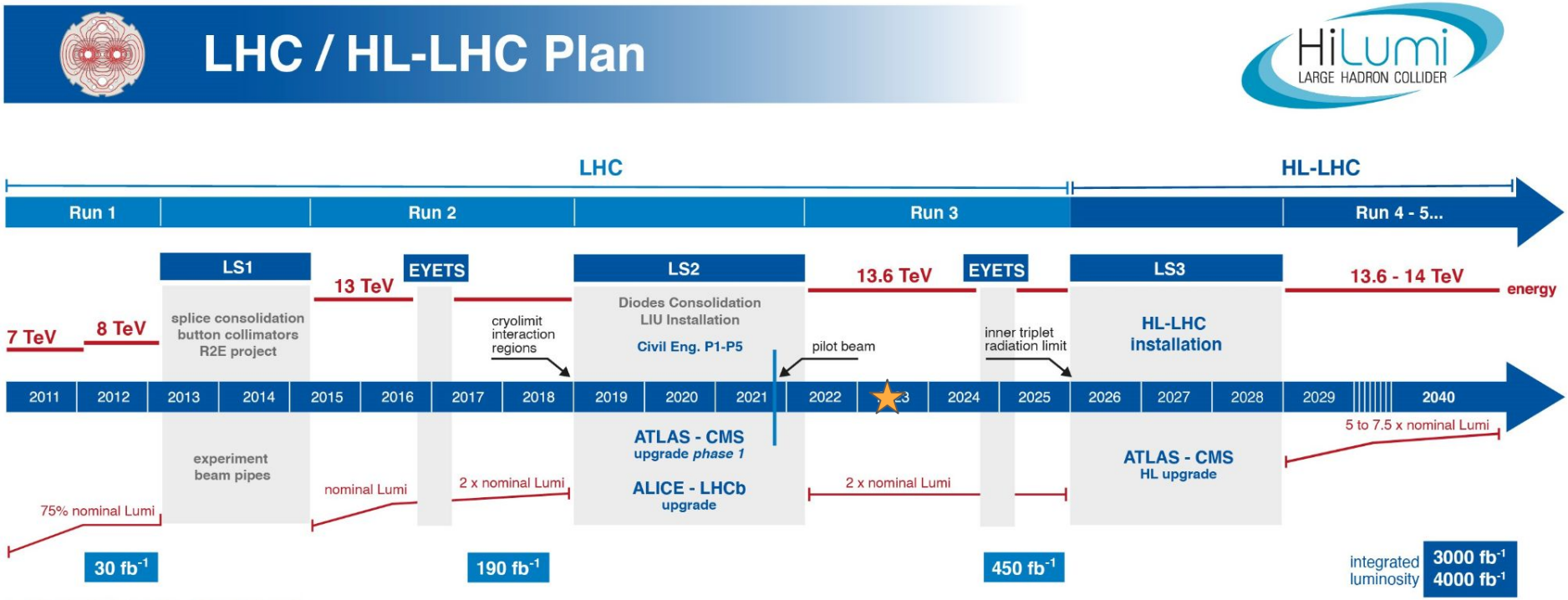
LHCb VELO Position OUT Gap: 59.6 mm TOTEM: STANDBY



Best laid plans

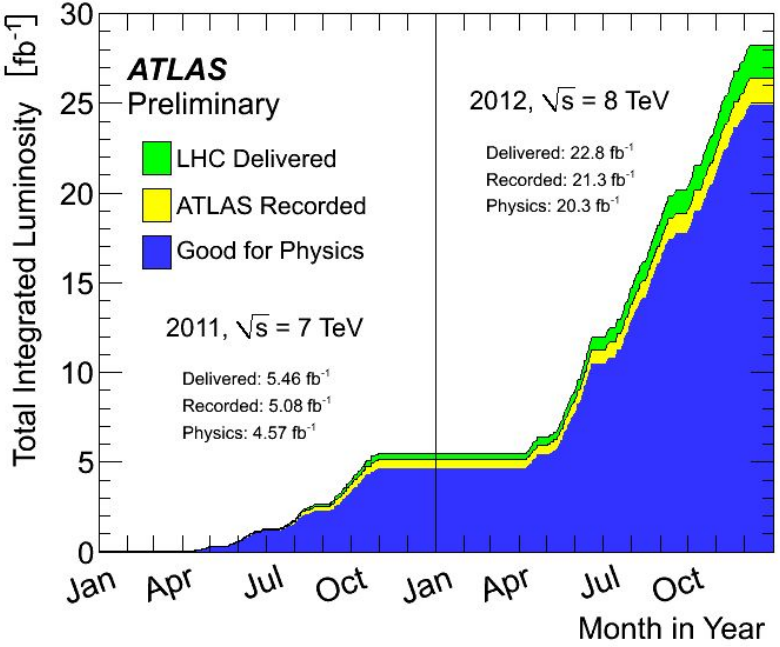
- Originally planned to start running at 14 TeV in 2005
- Budgetary constraints and technical delays pushed start date to 2008
- Initial testing led to quenching and severe damage
- Operations began in 2009 at 2.36 TeV
- Data collected in 2010-211 at 7 TeV
- Currently producing collisions at 13.6 TeV

LHC Run Schedule

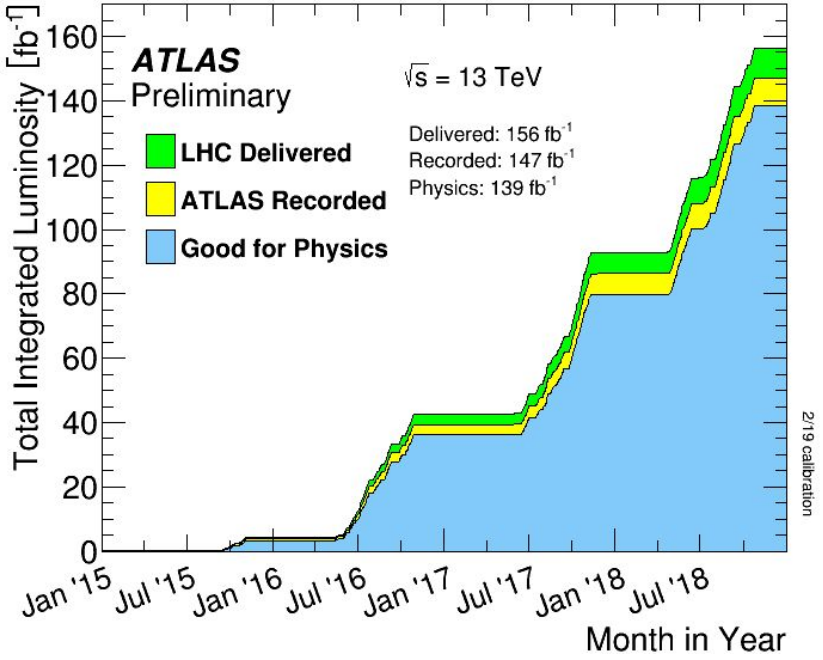


Luminosity

Run 1

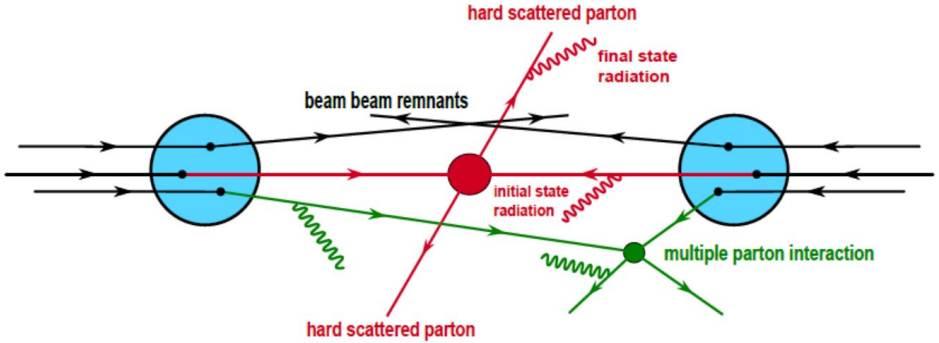


Run 2



Closer look at hadron collisions

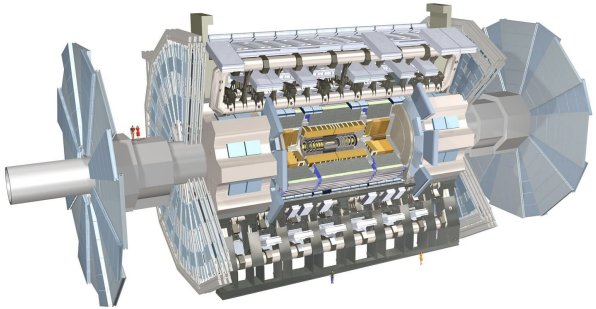
- Hadron collisions are much more complex than lepton collisions
- Two partons can interact in a “hard scatter” event
  - Occurs at a primary vertex (PV)
- Initial state radiation and final state radiation
  - Typically gluon radiation but can also be photons
- Multiple parton interaction (MPI) hard scatter event can happen
- Remaining partons can scatter elastically into detector



Pileup

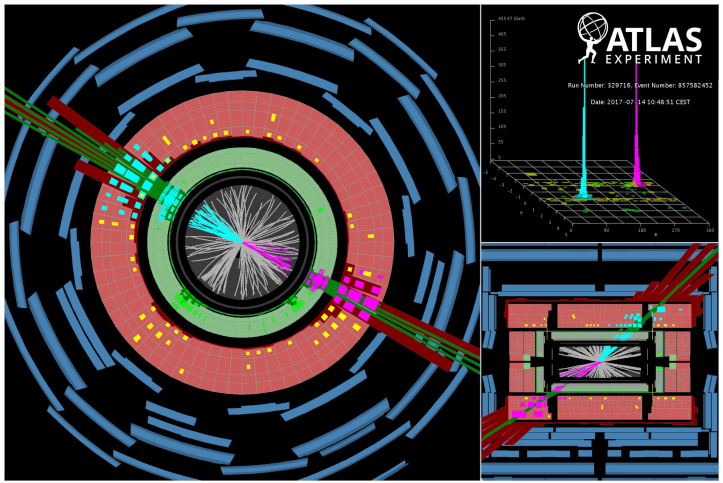
- Proton bunch crossings have multiple collisions
  - Referred to as in-time pileup
- Quantified using number of primary interaction vertices (N_{PV}) and average number of interaction per bunch crossing ($<\mu>$)
- Out-of-time pileup also occurs
  - Primarily due to collisions in preceding or subsequent bunch crossings
  - Additional effects from collisions with beam collimators and stray gas molecules
  - Detector latency (read-out time) is generally longer than 25 ns, so additional interactions in that time can result in overlapping detector signals
- Many techniques used to mitigate effects of pileup
  - Precise tracking to associate reconstructed particles to interaction vertices
  - Other techniques to disentangle pileup calorimeter energy deposits

ATLAS event displays



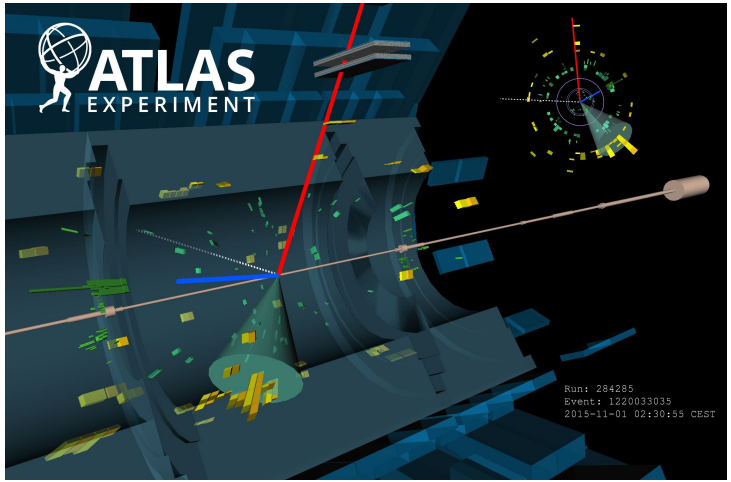
- Collisions (events) are highly complex
- Can be fully described only as non-human-readable data
- Event displays visually depict reconstructed particles in a collision
- Perspective and transparency optimized for each event

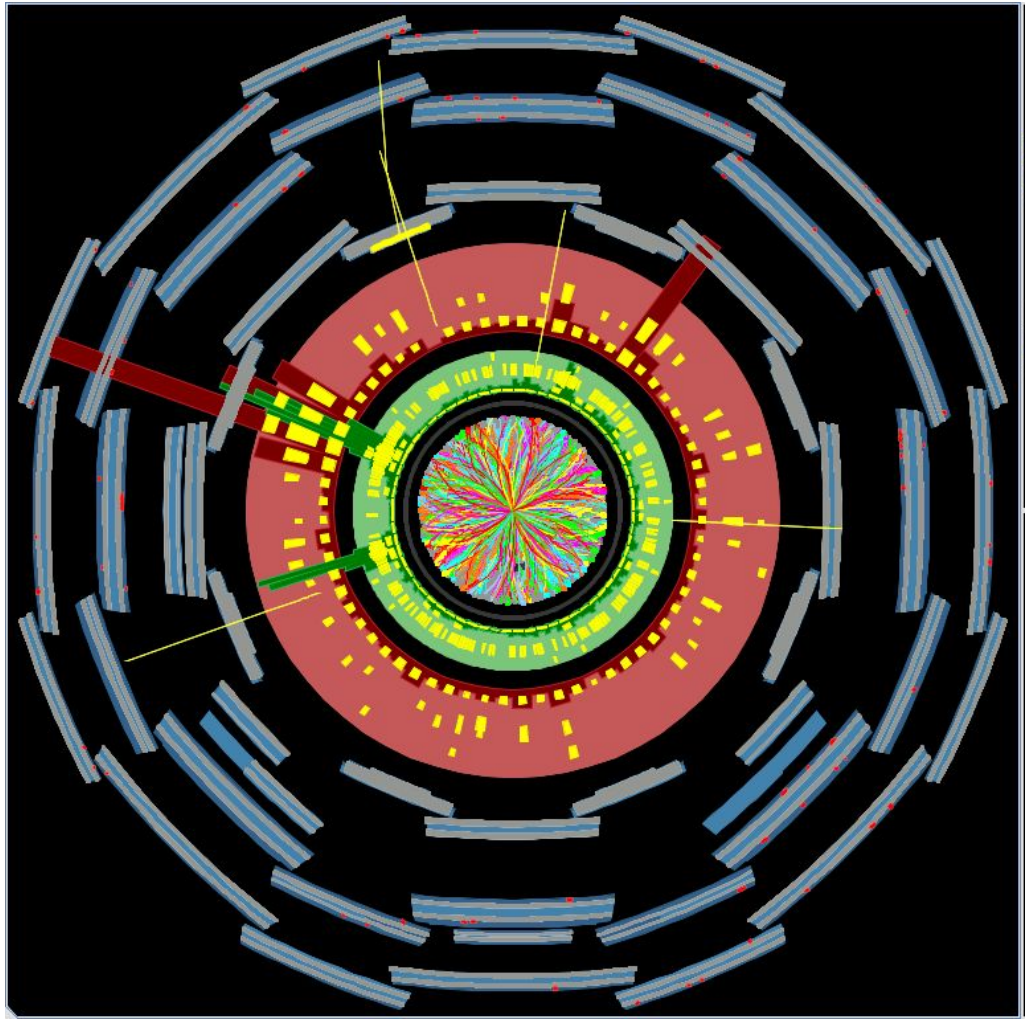
End view

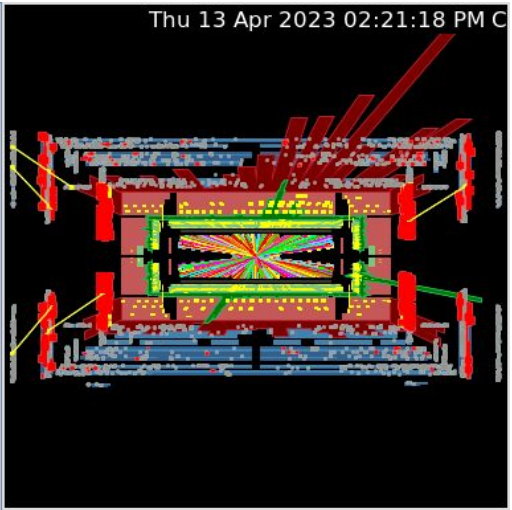


"Unrolled" view

Side view







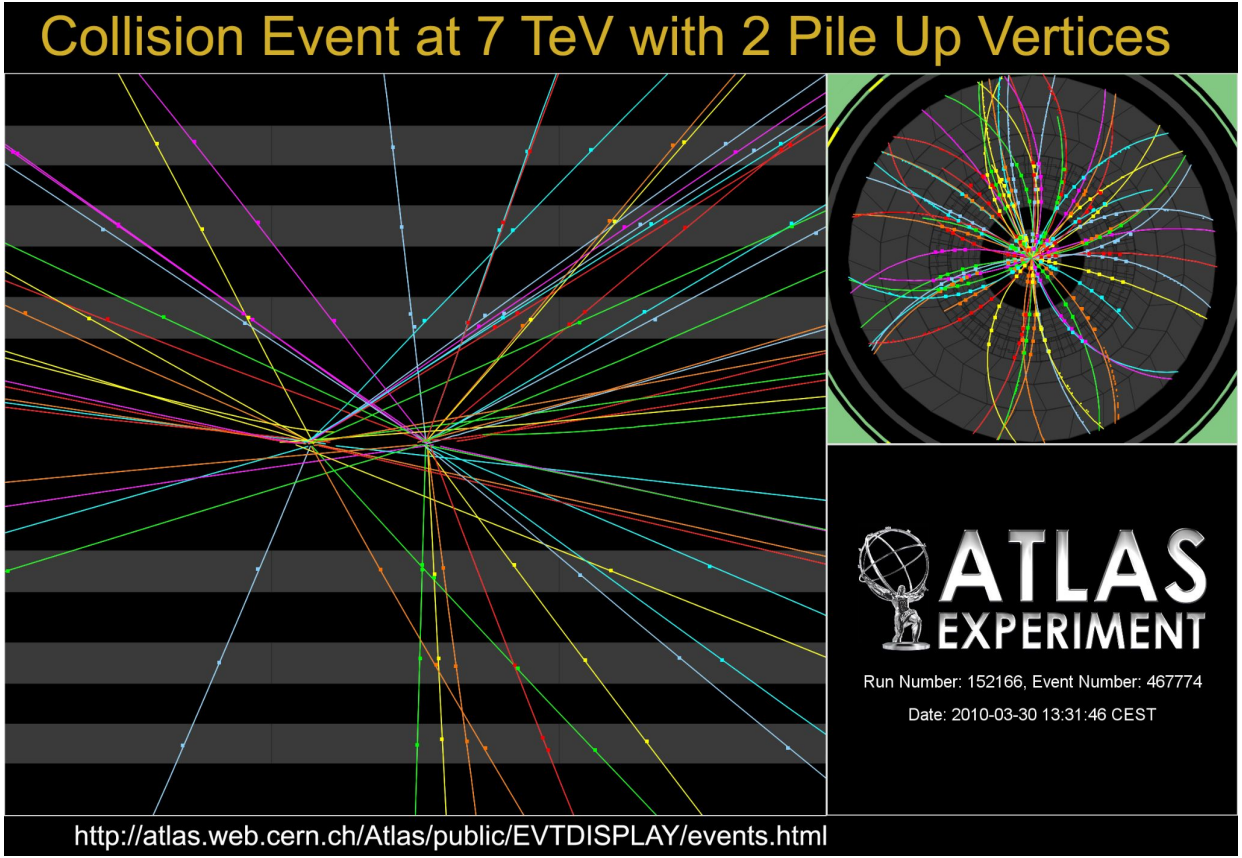
ATLAS EXPERIMENT

Run Number: 440613, Event Number: 4050954636

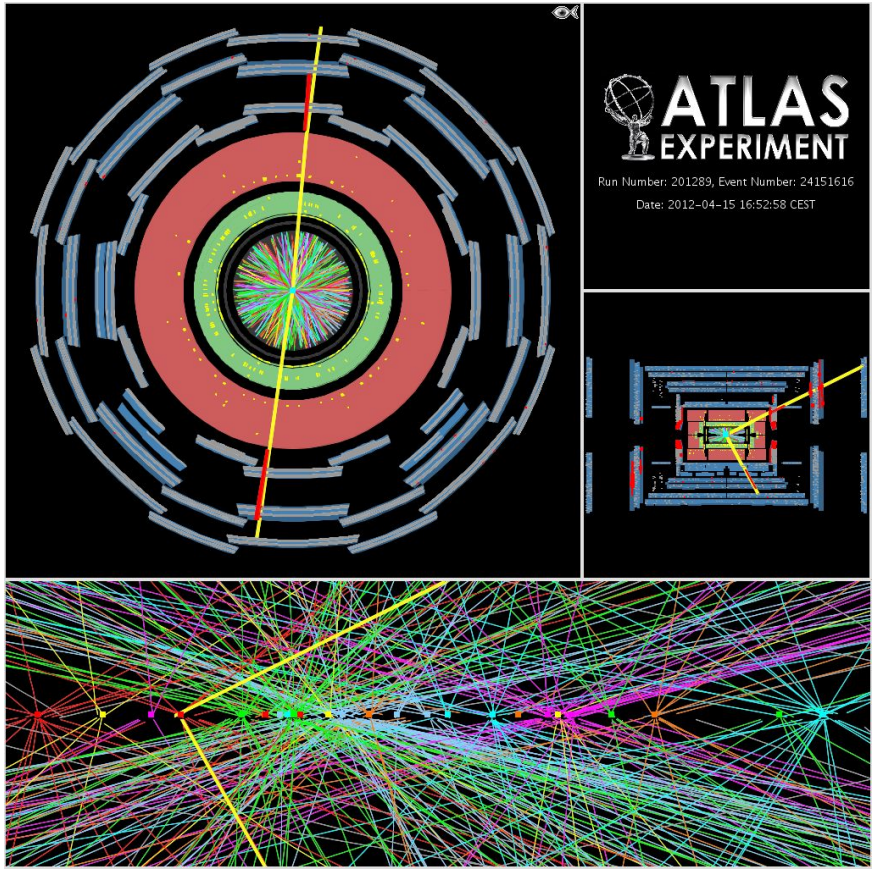
Date: 2022-11-28 05:55:51 CET

Snapshot of a proton collision
directly from the ATLAS experiment

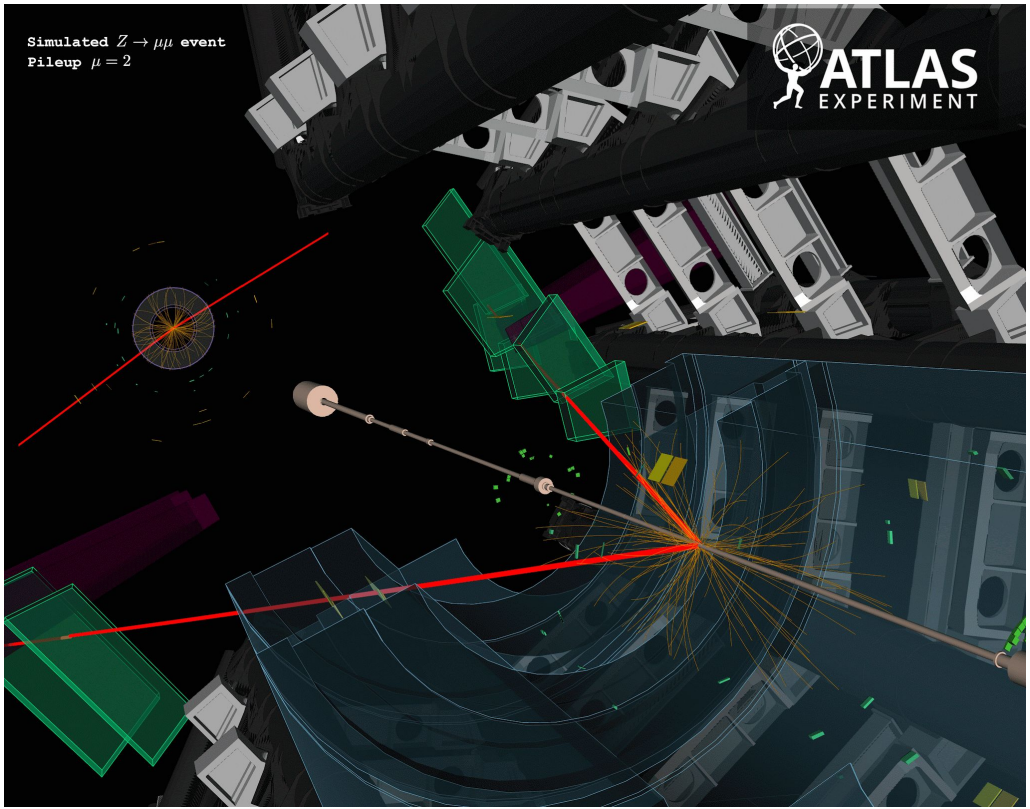
Pileup - 2 vertices



Pileup - 25 vertices

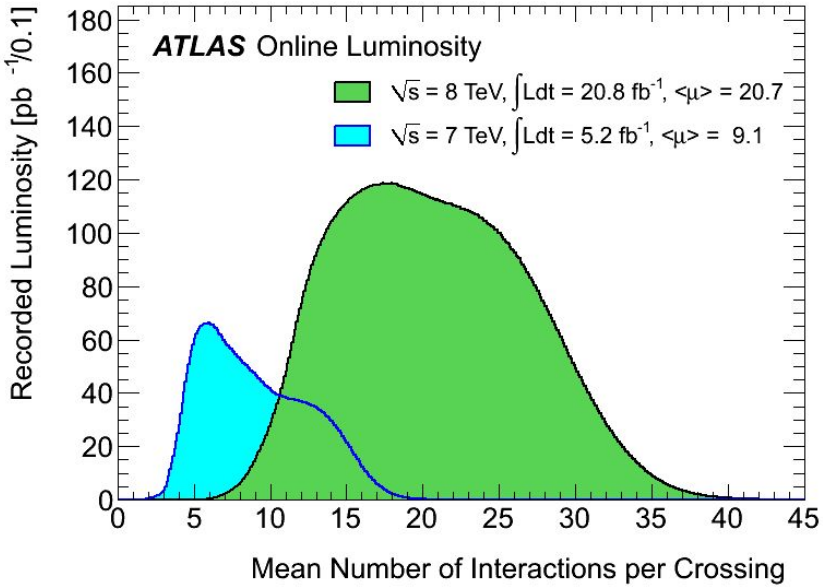


Pileup - 2, 50, 140 vertices

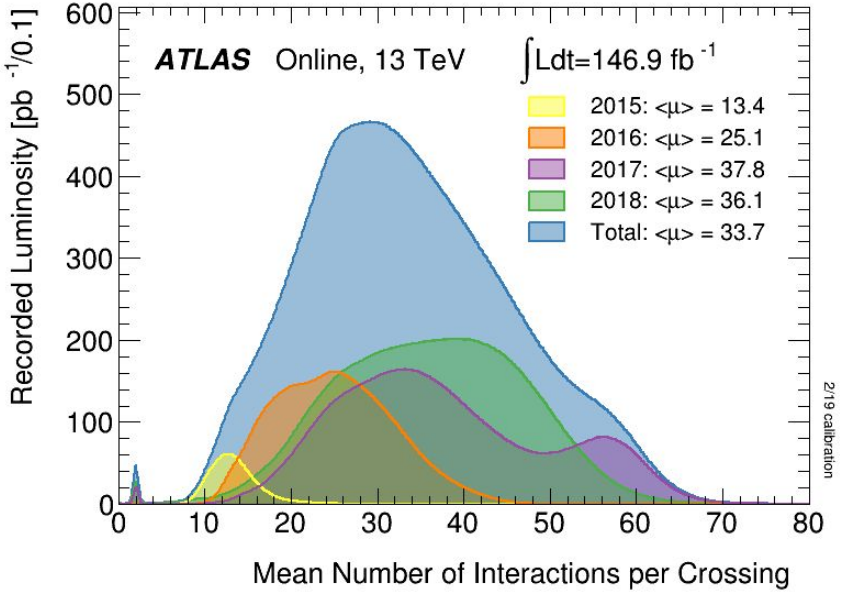


Pileup profiles

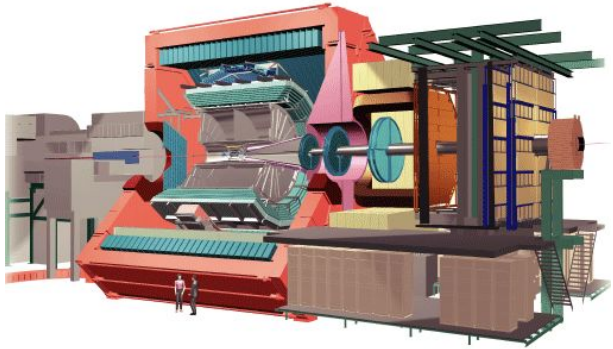
Run 1



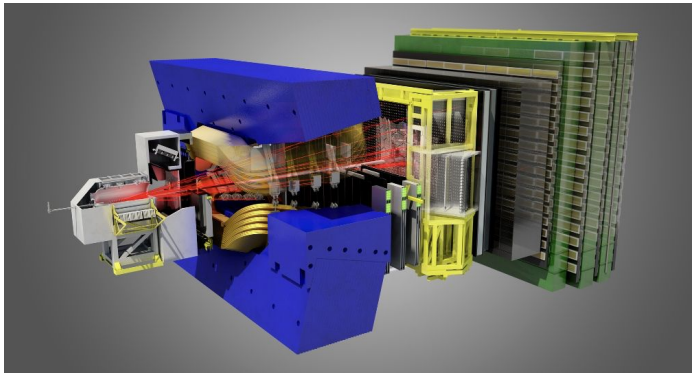
Run 2



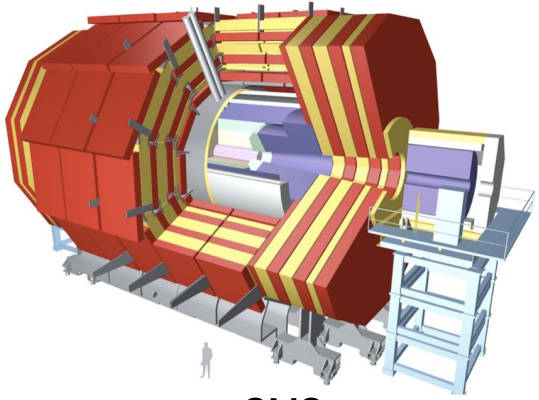
Main LHC Experiments



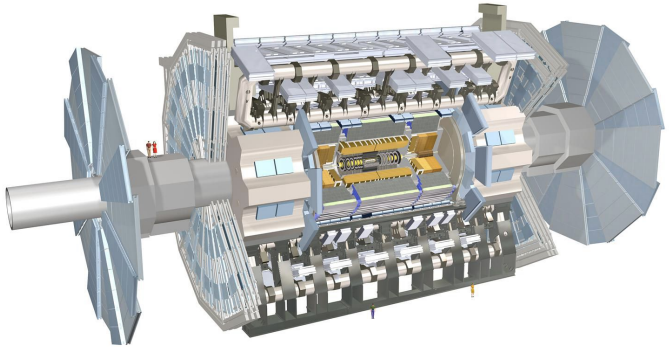
ALICE



LHCb



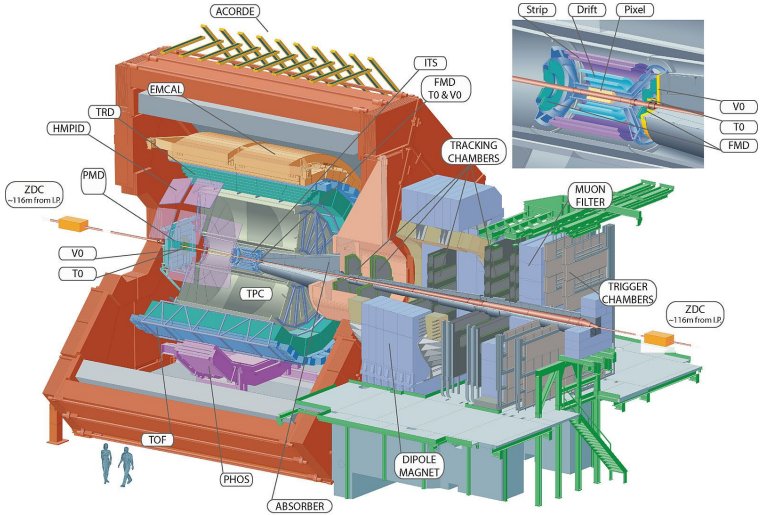
CMS

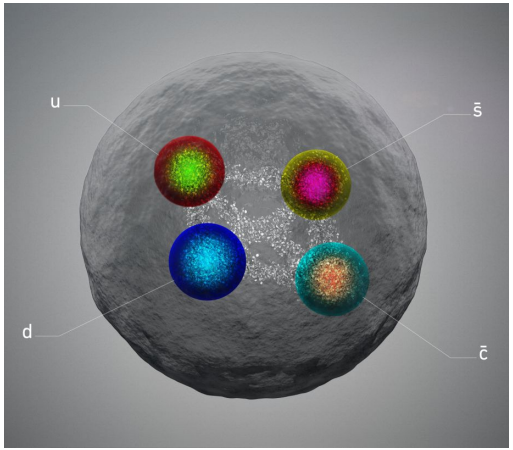


ATLAS

ALICE

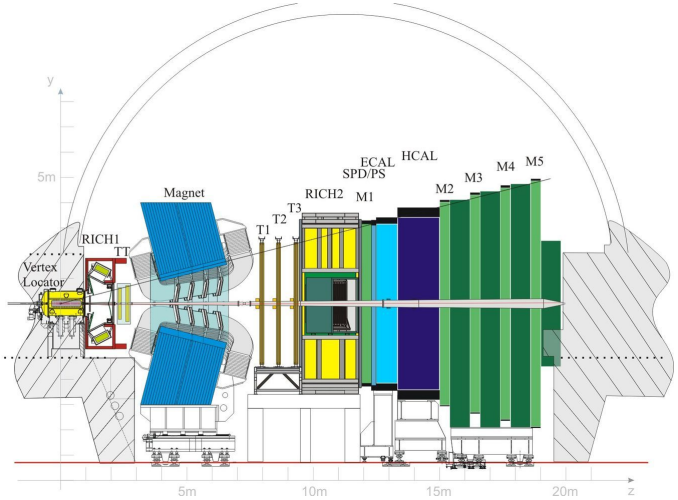
- A Large Ion Collider Experiment
- Specialized for Pb-Pb collisions
  - Also uses p-Pb collisions
- Goals are to improve understanding of QCD
  - Quark-gluon plasma
    - State of matter in which free color charges exist
  - Quark deconfinement
    - Existence of quarks outside of bound states
- Many discoveries including new tetraquarks and pentaquarks





LHCb

- Large Hadron Collider beauty experiment
- Focused on studying properties of B-hadrons
  - Hadrons containing a b quark
- Numerous measurement goals
  - B-hadron branching ratios
  - Asymmetries in flavor-changing neutral currents
  - CP violation in B-hadron decays
    - Could explain matter/anti-matter asymmetry
  - Other B-hadron decays



ATLAS and CMS

- A Toroidal LHC ApparatuS and Compact Muon Solenoid
- General purpose experiments
- Designed to search for generic particle discovery and measurements
- Similar designs and physics goals
- Primarily focused on pp collisions, but also make use of heavy ion collisions
- Friendly competition for discoveries
  - Simultaneous observation of the Higgs boson
  - Agreement to inform each other of major discoveries in advance of public announcement
  - Harmonization of some techniques to enable comparisons and combinations
- More details next week

Other LHC experiments

- LHCf
  - Measurement of particles traveling close to beamline
- MATHUSLA and FASER
  - Search for long-lived particles and neutrinos
  - Recent detection of neutrinos
- MilliQan
  - Search for milli-charged particles
- MOEDAL
  - Search for magnetic monopoles and other exotic particles
- TOTEM
  - Total cross-section measurements

Future Circular Collider

- Ongoing work towards the Future Circular Collider (FCC) at CERN
- 90-100 km long
  - Limited by geography
- ~100 TeV collision energy
- LHC will be in acceleration chain
- At least 30 years expected for design and construction