CERN's Large Hadron Collider

Ref: www.cern.ch

CERN's Large Hadron Collider

The highest energy collider:

- proton on proton collider
- center-of-mass energy is now 13 TeV
- each counter rotating beam proton beam is 6.5 TeV
- each bunch contains 1.2e11 protons
- each beam has 2076 bunches (maybe 2064 collide)

Ref: www.cern.ch

Upgrades during LS1, 2013-14

Ref: L. Ponce Annecy 2013

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

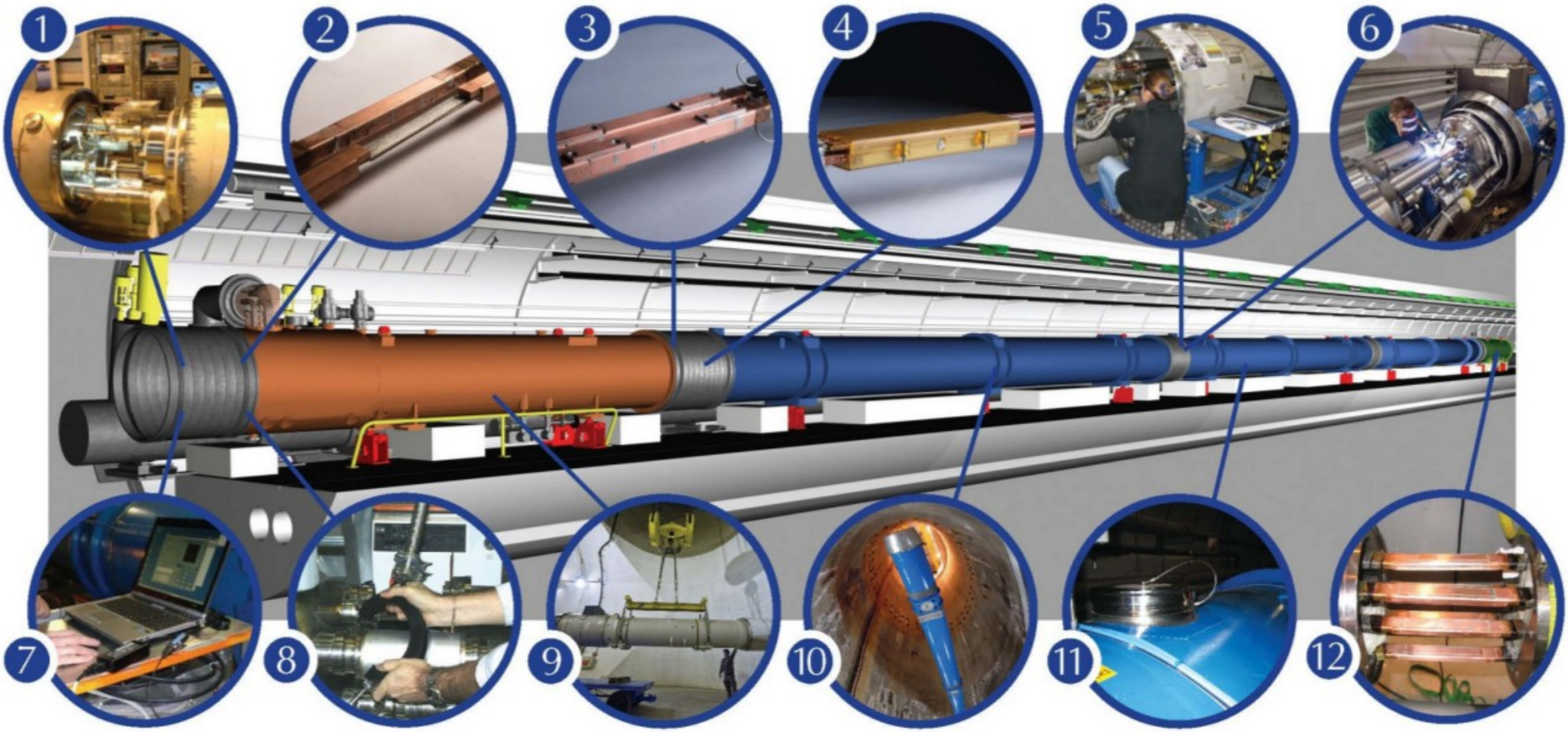
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

4 quadrupole magnets to be replaced

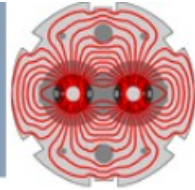
15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

Ref: L. Ponce Annecy 2013

50 versus 25 ns

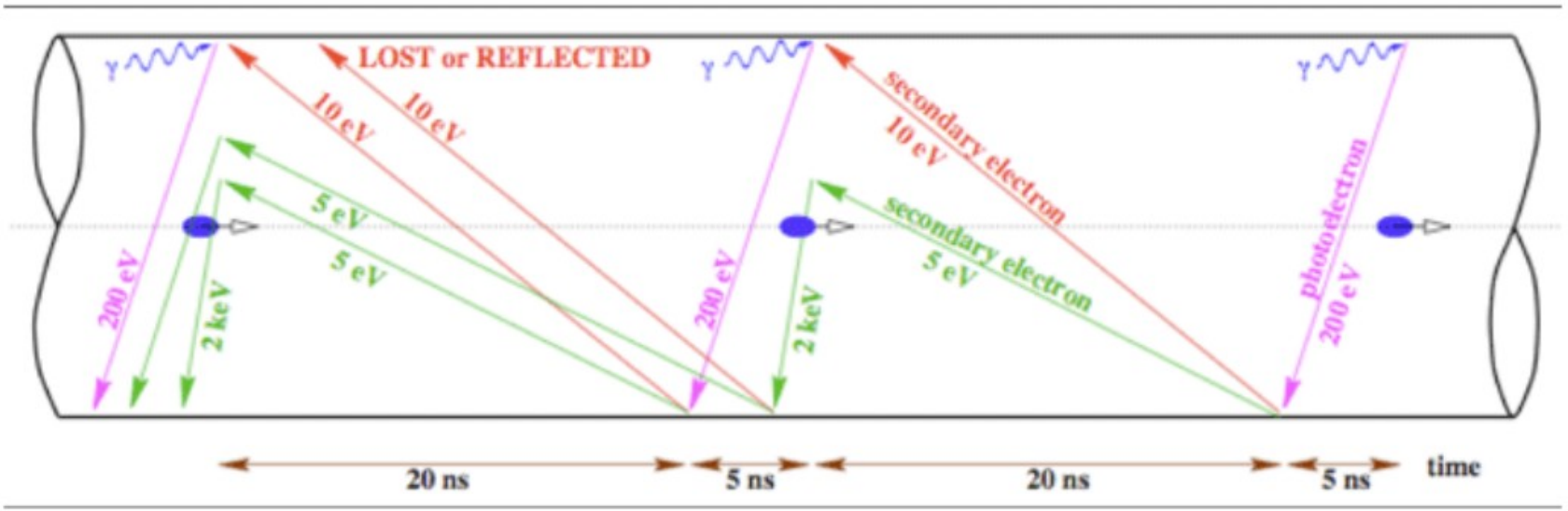


	50 ns	25 ns
GOOD	• Lower total beam current • Higher bunch intensity • Lower emittance	• **Lower pile-up**
BAD	• **High pile-up** • Need to level • Pile-up stays high • High bunch intensity – instabilities…	• More long range collisions: larger crossing angle; higher beta* • Higher emittance • Electron cloud: need for scrubbing; emittance blow-up; • Higher UFO rate • Higher injected bunch train intensity • Higher total beam current

Expect to move to 25 ns because of pile up…

Ref: L. Ponce Annecy 2013

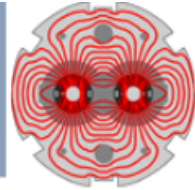
25 ns & electron cloud



- Typical e^- densities: $n_e = 10^{10}$–10^{12} m^{-3} (~a few nC/m)
- Typical e^- energies: <~ 200 eV (with significant fluctuations)

Ref: L. Ponce Annecy 2013

Electron cloud: possible consequences



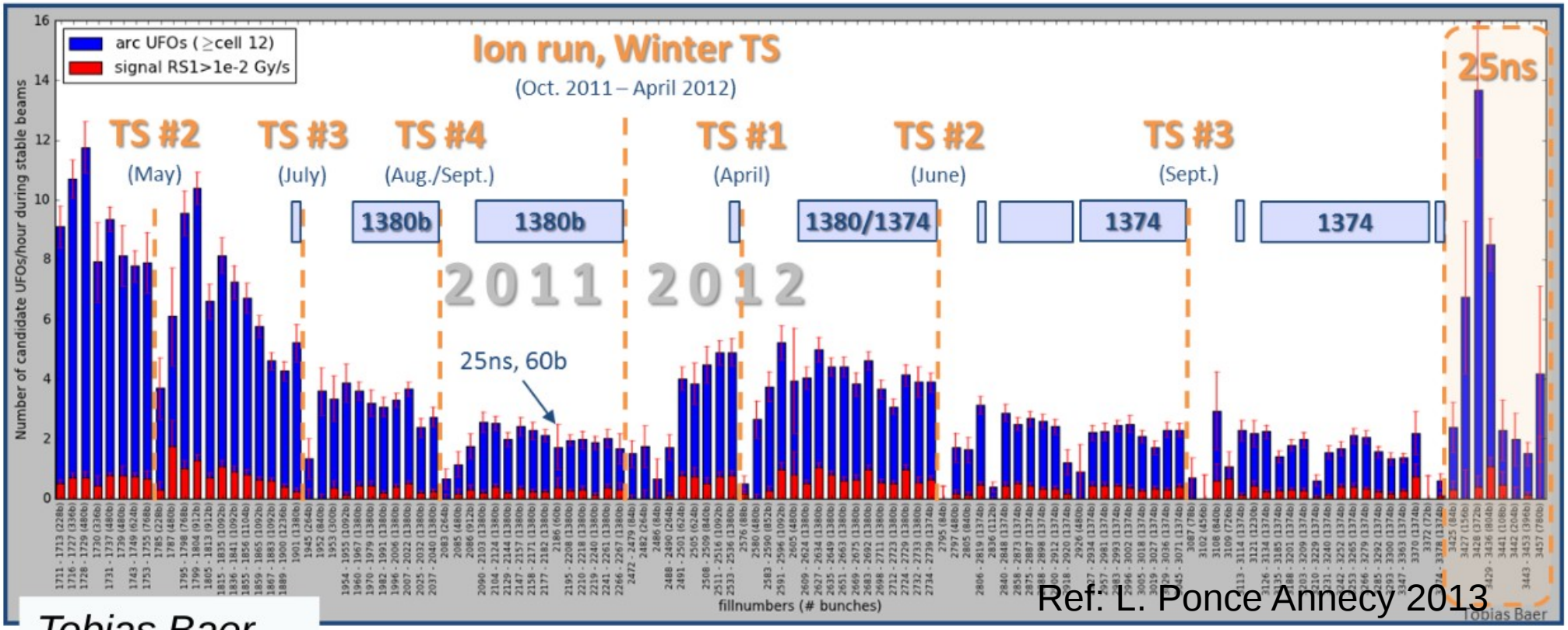
- **single-bunch instability**
- **multi-bunch instability**
- **emittance growth**
- **gas desorption from chamber walls**
- **excessive energy deposition on the chamber walls (heat load)** - important for the LHC in the cold sectors
- **particle losses, interference with diagnostics**,…

Electron bombardment of a surface has been proven to reduce drastically the secondary electron yield of a material.
This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up and its undesired effects

Ref: L. Ponce Annecy 2013

UFOs (Unidentified Falling Objects)

- **UFOs: showstopper for 25 ns and 6.5 TeV?**
  - 10x increase in rate and harder UFOs
- UFO “scrubbing”: does it work? What parameters?
- Deconditioning expected after LS1
- Operational scenario to be developed:
  - start with lower energy and/or 50 ns beam…
  - Adjust beam loss monitor thresholds based on quench tests



Ref: L. Ponce Annecy 2013

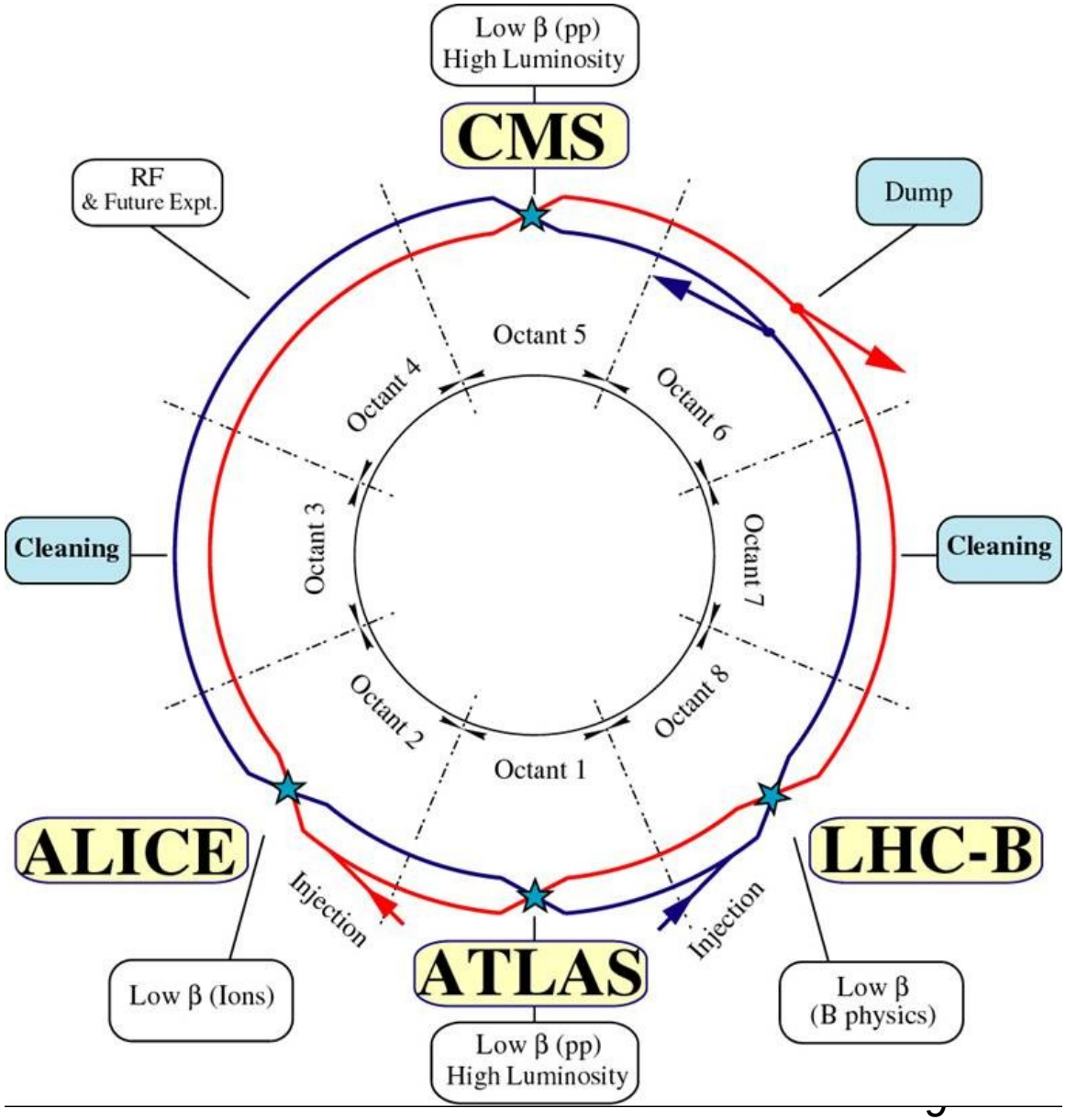
What has the LHC done?

Energies & Modes:

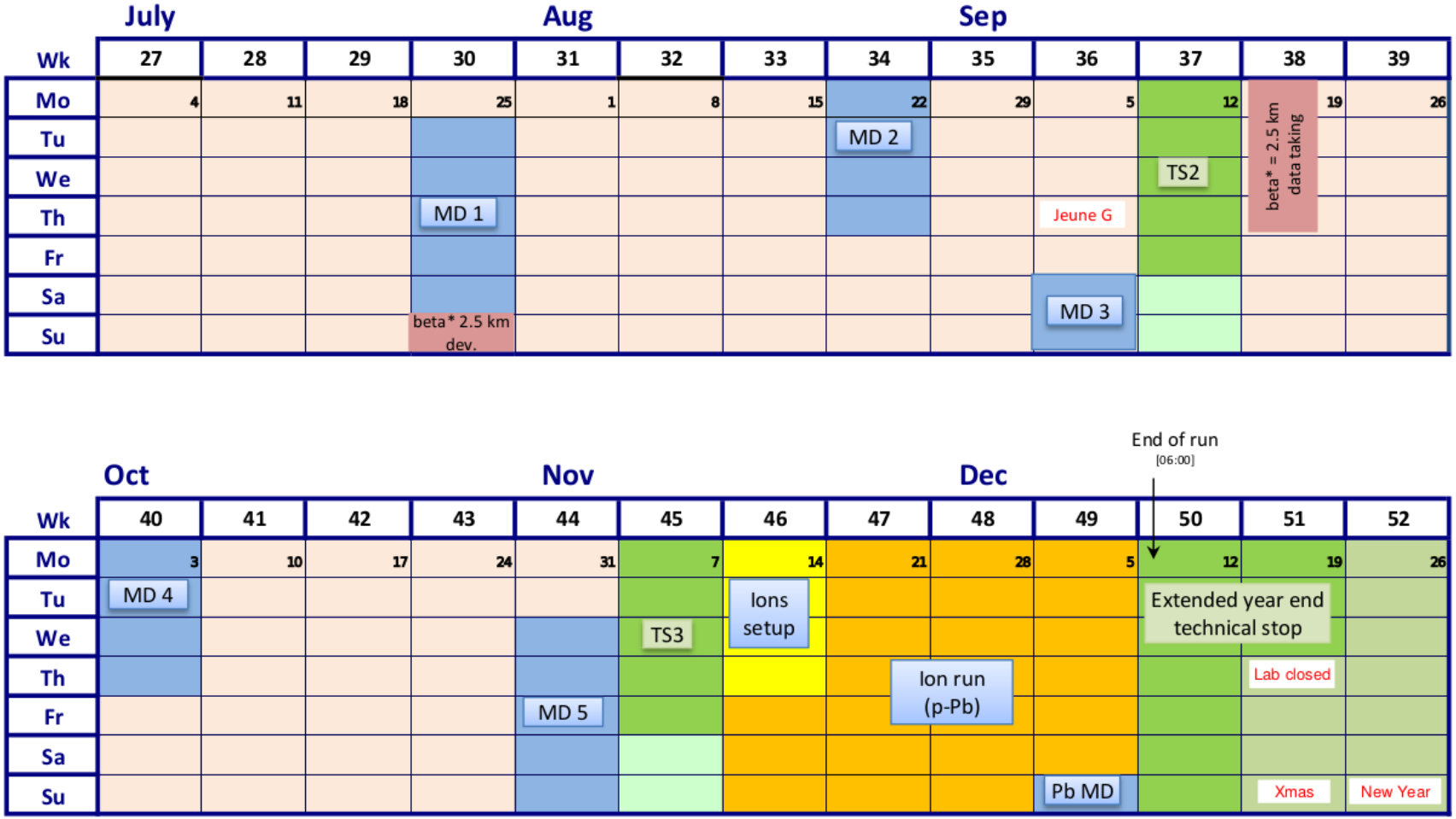
Proton-Proton
2011 3.5+3.5 TeV
2012 4+4 TeV
1380 on 1380 bunches
2013 Long Shutdown 1
2015 6.5+6.5 TeV

Lead-208 (82+)-Lead
2011 1.38+1.38 TeV/u
2012 none (?)
358 on 358 bunches

Proton-Lead
2013 4.0+1.577TeV/u
338 on 338 bunches

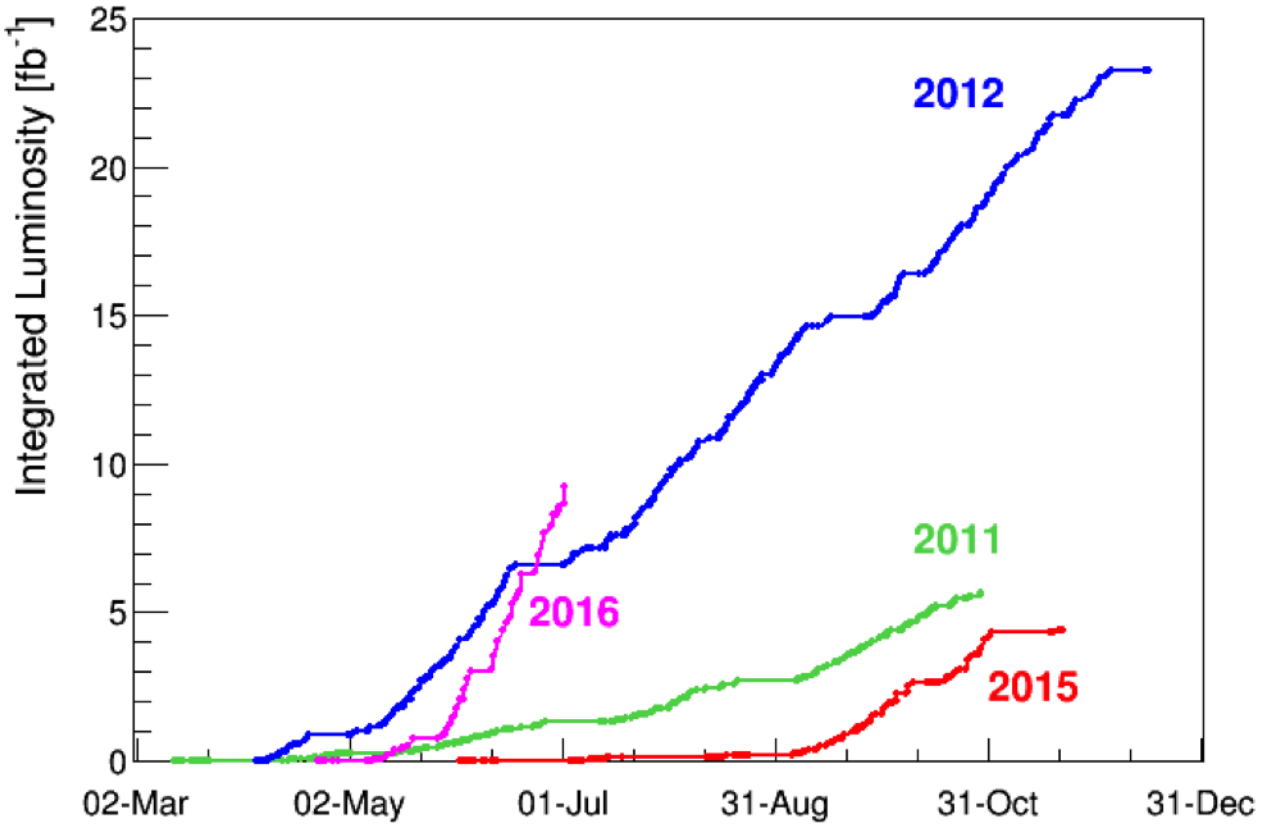


LHC Schedule, July-December 2016



July 2, 2016 v1.9

LHC Integrated Luminosity



This graph shows the integrated luminosity delivered by the LHC to the ATLAS and CMS experiments in 2011, 2012, 2015 and 2016. The integrated luminosity indicates the amount of data delivered to the experiments and is measured in inverse femtobarns. One inverse femtobarn corresponds to around **80 million million collisions**.

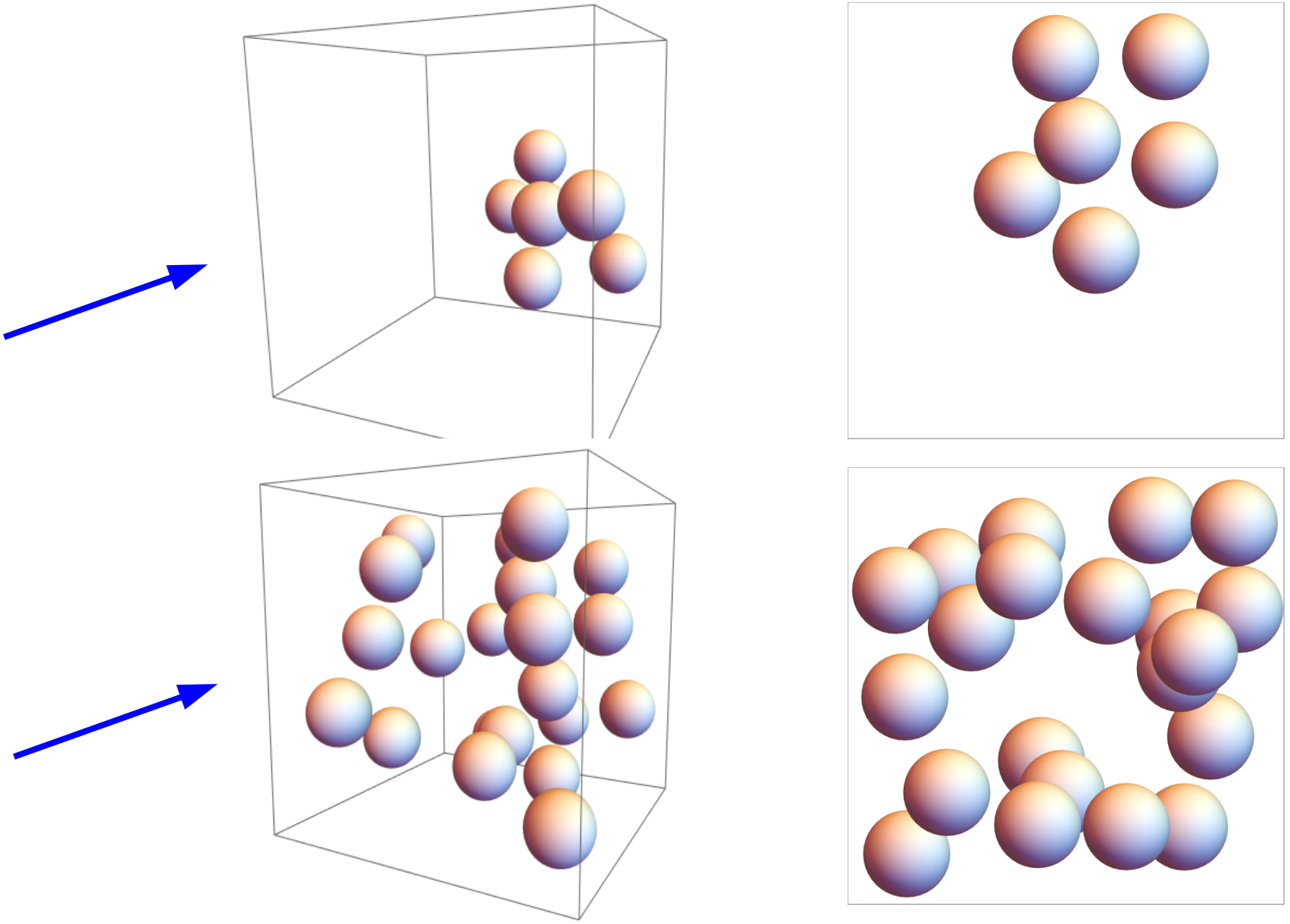
8e13 collisions

Ref: lhc-performance-reaches-new-highs

Some dates from the LHC timeline:

27 April 2007- Last LHC dipole magnet lowered underground.
29 Feb 2008 – Final large detector piece lowered, ATLAS.
10 Sep 2008 – LHC starts up.
19 Sep 2008 – Incident at the LHC.
30 April 2009 – Final repaired magnet goes underground. 53 magnets repaired.
20 Nov 2009 – Beams back in the LHC. 2.36 TeV collisions in December. Highest energy at that time.
30 Mar 2010 – First collisions at 7 TeV.
18 Oct 2011 – End of the 2011 Proton collision run.
5 April 2012 – Highest energy collisions at 8 TeV.
4 July 2012 – CMS and ATLAS announce “particle consistent with Higgs boson.”
Jan 2013 – Proton-Lead collisions and Proton-Proton at 1.38 TeV.
16 Feb 2013 – End of LHC Run 1. Start Long Shutdown 1.
8 Oct 2013 – Nobel prize for Englert and Higgs for Higgs boson.
3 June 2015 – Proton collisions at 13 TeV start.

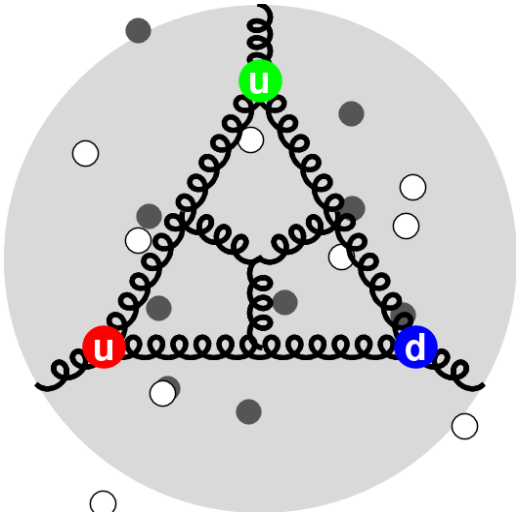
Cross-Section for Interactions

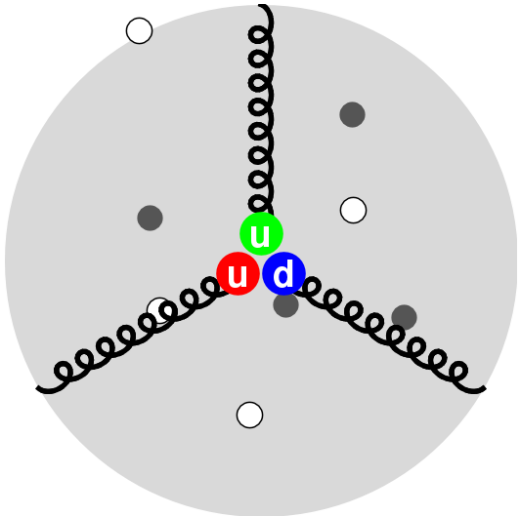


Physical or Effective size and density decide how many times you will interact for each crossing of the box.

Proton is not a simple object.

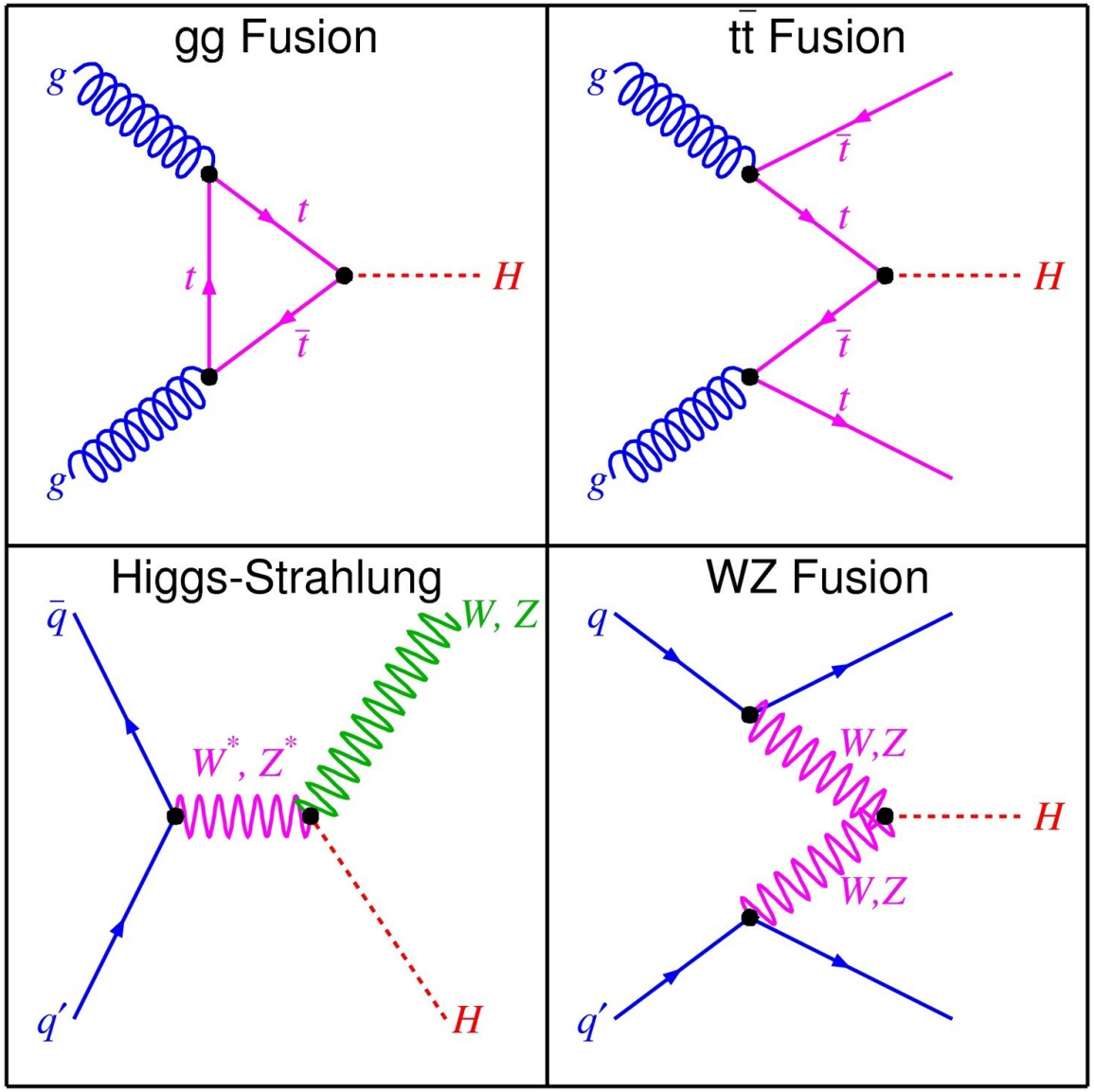
Protons are bags of valence quarks, gluons, and virtual quarks. Proton is a u-u-d valence quark combination, the “intrinsic mass” of the u is 1.9 MeV/c^2 and the d is 4.6 MeV/c^2 (an electron’s rest mass is 0.511 MeV/c^2). Yet the mass of the proton is 940 MeV/c^2 !



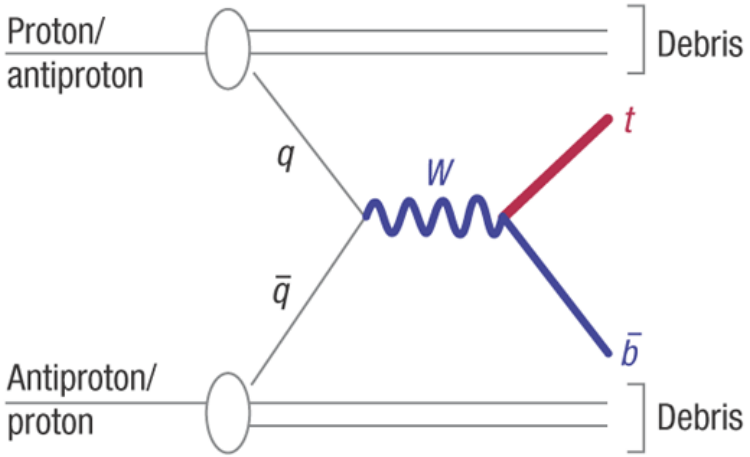


Ref: www.cern.ch

Not so much matter-antimatter but (Vector-Boson) Fusion!



VS



Interaction Rate and Cross-section

At 14 TeV and using Higgs mass 125 GeV.

ggF (gluon-gluon fusion)	50.35 pb (picobarns)
VBF (vector boson fusion)	4.172 pb
WH	1.504 pb
ZH	0.8830 pb
ttH	0.6113 pb
bbH	0.5805 pb

Ref: HiggsEuropeanStrategy

Previous slide, making about 2 fb^-1 (inverse femtobarns) of luminosity every week, get the units right, then making Higgs by ggF is 50,350 fb * 2 fb^-1 or 100,700 Higgs via that channel every two weeks!

Barn is an (effective area) of 10^-28 m^2 about the physical size of a nucleus. Depending on energy and details, nuclear effects have cross-sections of 1 to 10^6 barns.

Links

- https://home.cern/topics/large-hadron-collider
- https://timeline.web.cern.ch/timelines/The-Large-Hadron-Collider
- https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1
- http://demonstrations.wolfram.com/HowTheProtonAndNeutronGotTheirMasses/
- http://pdg.lbl.gov/
- aa

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Backup

LHCParameters

Circumference	26659 m
Dipole operating temp	1.9 deg K
Main RF frequency	400.8 MHz
“Bucket,” 1/frequency	2.5 ns
Energy per beam	6.5 TeV, operating
Dipole Magnetic Field	7.7 T
Ions Energy per nucleon	2.56 TeV/n = 6.5*82/208 (Pb-208)
no. of protons	1.2e11 per bunch
no. of bunches	<= 2604/2748
bunch length, 4sigma	1-1.25 ns
bunch size, x & y at IP, 1 sigma	52 x 66 microns

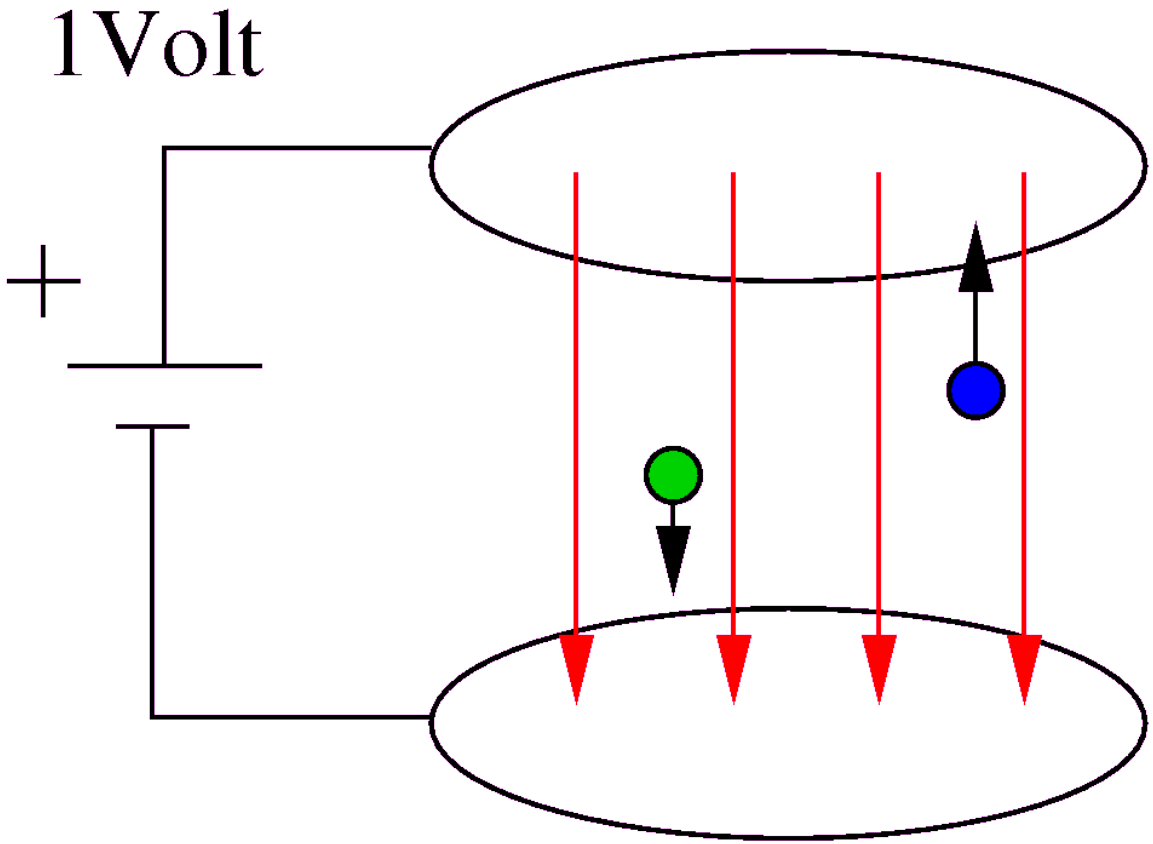
Ref: www.cern.ch

SI Prefixes

Table 5. SI prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Units?



- Proton, heavy, +e
- Electron, light, –e

Speed of Light

Fastest possible speed is the speed of light in vacuum.

Defined as $299792458\,\mathrm{m/s}$

$3.0 \times 10^8\,\mathrm{m/s}$

$30\,cm/ns$

$300\,m/\mu s$

$300\,\mu m/ps$