

CERN's Large Hadron Collider

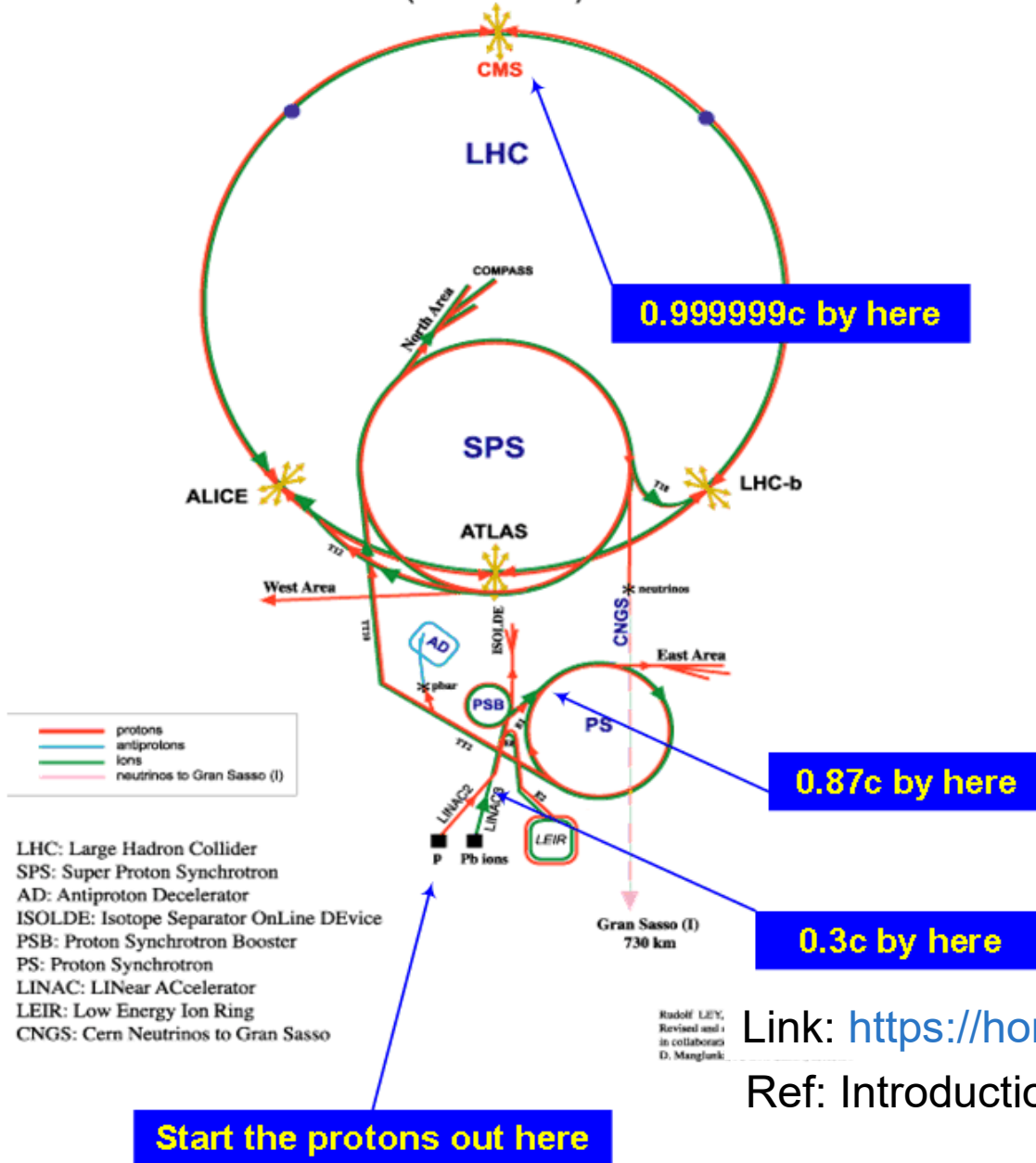


Ref: www.cern.ch



Large Hadron Collider (LHC)

CERN Accelerators
(not to scale)



Energies:

Linac 50 MeV

PSB 1.4 GeV

PS 28 GeV

SPS 450 GeV

LHC 6.5 TeV

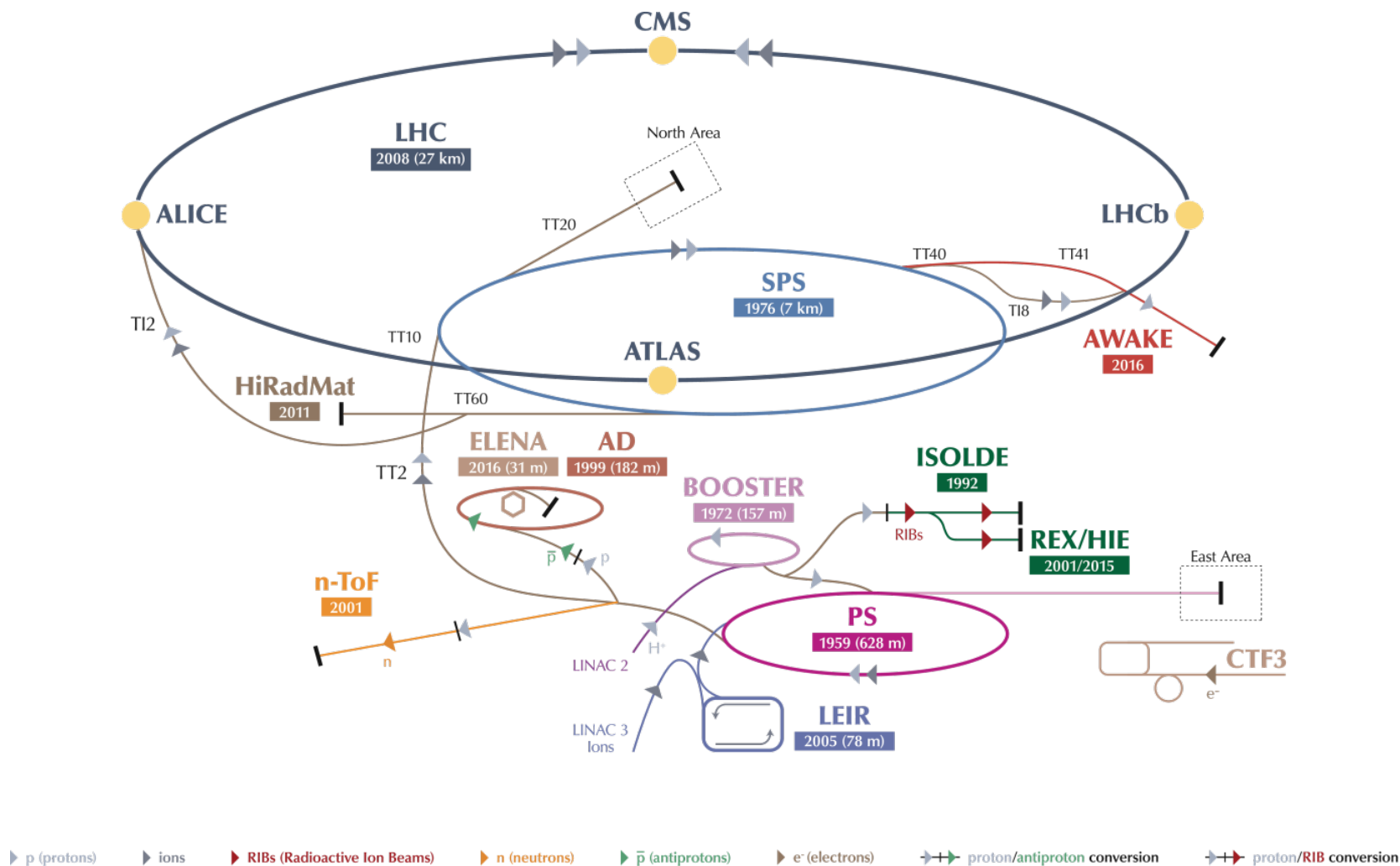
Link: <https://home.cern/topics/large-hadron-collider>

Ref: Introduction to Accelerators, Elena Wildner, CERN

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 = $6.5 \cdot 82 / 208$ (Pb-208)
no. of protons	1.2e11 per bunch
no. of bunches	$\leq 2604 / 2748$
bunch length, 4sigma	1-1.25 ns
bunch size, x & y at IP, 1 sigma	52 x 66 microns

Large Hadron Collider (LHC)



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINEar ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials



LHC Schedule 2018, Jan-June

RS

May 30, 2018

ver. 1.4

LHC Schedule 2018
Approved by Research board on 06.12.2017

	Jan				Feb				Mar				
Wk	1	2	3	4	5	6	7	8	9	10	11	12	13
Mo	1	8	15	22	29	5	12	19	26	5	12	19	26
Tu		Controls Maintenance											
We													
Th													
Fr													
Sa													
Su													

Start powering tests
LHC to OP
LHC, TI2, TI8 closed
Experiments valves open
TI2 & TI8 Beam tests
Start Beam Commissioning

Technical stop (YETS)
DSO test
Machine checkout
G. Fri.

Today, "Special Physics runs"

Proton Collisions Start

	Apr				May				June				
Wk	14	15	16	17	18	19	20	21	22	23	24	25	26
Mo	Easter 2	9	16	Scrubbing 23	30	7	14	Whitsun 21	28	4	11	18	25
Tu					1st May								
We													
Th	Recommissioning with beam												
Fr													
Sa													
Su													

Stable beams
Collisions with 1200 bunches
Interleaved commissioning & intensity ramp up
Ascension
MD 1
VdM program
 $\beta^* = 90$ m run

Link <https://beams.web.cern.ch/content/accelerators-schedules>

Long term schedule

<https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm>



LHC Schedule 2018, July-Dec

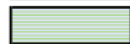
	July			Aug					Sep				
Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	β*= 90 m 2 run	9	16	23	30	6	13	20	27	3	10	17	24
Tu													
We				MD 2								TS2	
Th										Jeune G.			
Fr											MD 3		
Sa													
Su													

	Oct			Nov					Dec				
Wk	40	41	42	43	44	45	46	47	48	49	50	51	52
Mo	1	8	15	22	29	5	12	19	26	3	10	17	Xmas 24
Tu					MD 4	Ion setting up		MD 5					
We		Special physics run											
Th					TS3								
Fr													
Sa													
Su				MD 4									

End of run
[06:00]



Technical Stop



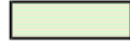
Powering tests



Machine check out



Recomissioning with beam



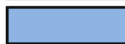
Interleaved commissioning & intensity ramp up



Proton physics run



Special physics runs (indicative - schedule to be established)



Machine development



Scrubbing



Pb - Pb Ion



Pb Ion Sett



LINAC 3 Pb

Long Shutdown 2, from Dec 2018 to Jan 2021, main purpose is LHC Injectors Upgrade

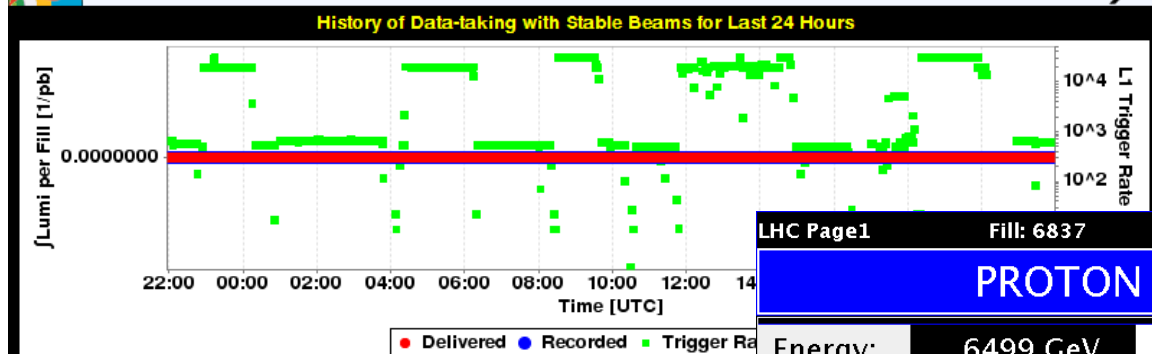
Long Shutdown 2 Goals...

- Upgrade the whole LHC injector chain;
- Energy to 7 TeV? 20% higher luminosity?
- Maintenance on the LHC and the Detectors;
- Start on aspects of the *Accelerator Consolidation Project* and
- the *HL-LHC*, aka the High-Luminosity LHC (even more protons per bunch and/or more bunches.
- LS3 starts (maybe) 2024 and runs 2.5 years until mid-2026.

Current Status Op Vistar

CMS Page1 Fill : 6830 Run : 318448 Sat 23-06-2018 21:57:53 UTC

CMS DAQ Status Running LHC Status SETUP Beam Energy 449 GeV Intensity Beam1: 0.0×10^{10} Beam2: 0.0×10^{10}



CMS Comments Mon 11-06-2018 12:41:23 UTC

Taking cosmics data

LHC Page1 Comments 2018-06-23 20:01:32 UTC

next fill: collimator alignment for 90m B⁺

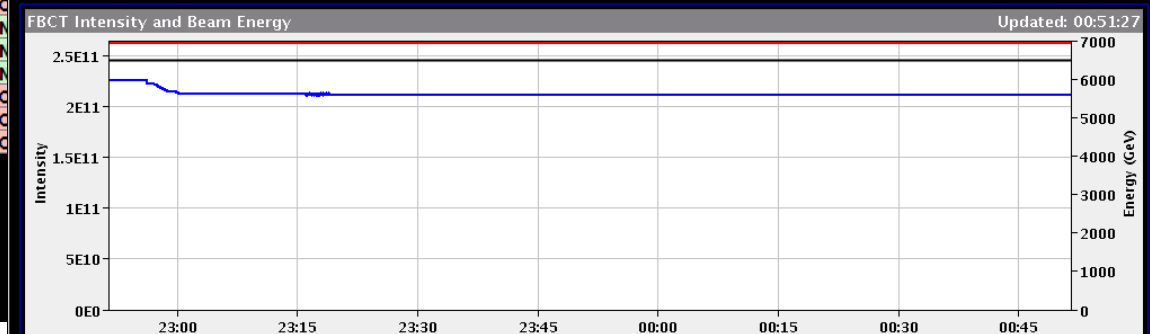
Sub-System	DAQ /	IN	ON
CSC		IN	ON
DT		IN	ON
ECAL		IN	ON
ES		IN	ON
HCAL		IN	ON
PIXEL		IN	ON
RPC		IN	ON
TRACKER		IN	ON
DAQ		IN	
DQM		IN	
SCAL		IN	
TRG		IN	
CTPPS	TOT	OUT	

LHC Page1 Fill: 6837 E: 6499 GeV t(SB): 00:00:00 25-06-18 00:51:29

PROTON PHYSICS: ADJUST

Energy: 6499 GeV I(B1): 2.11×10^{11} I(B2): 2.58×10^{11}

Inst. Lumi [(ub.s)⁻¹] IP1: -0.00 IP2: 0.00 IP5: 0.00 IP8: 0.00



Comments (24-Jun-2018 21:43:13)

fill for TCT and RP alignment @90m

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: 2nominals_10pilots_RomanPot_Alignment PM Status B1 ENABLED PM Status B2 ENABLED

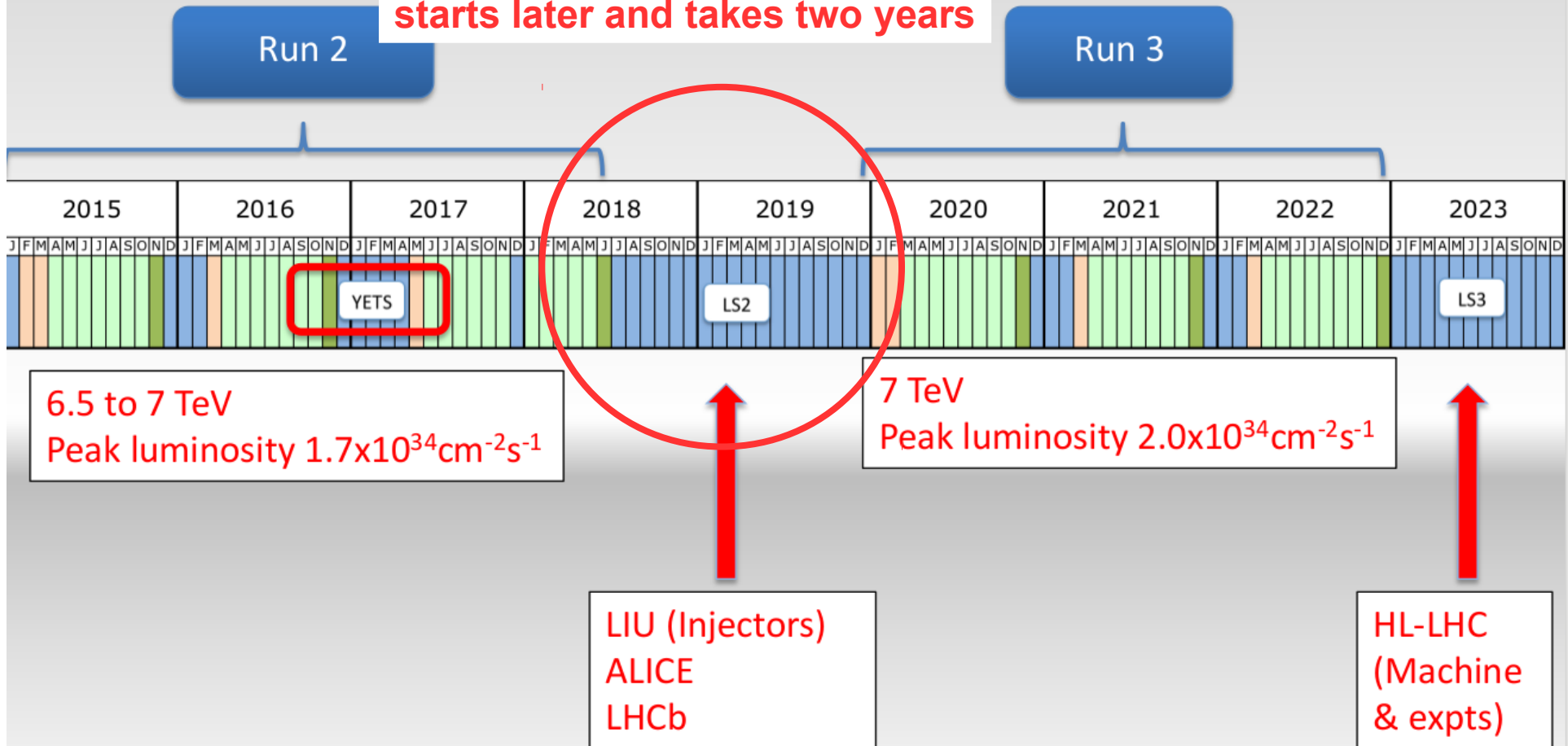
Click Here



<https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1>

Next 10 years

**2015 Plan: LS2 changed,
starts later and takes two years**



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

2015-8 6.5+6.5 TeV

Lead-208 (82+)-

Lead

2011 1.38+1.38 TeV/u

2012 none (?)

358 on 358 bunches

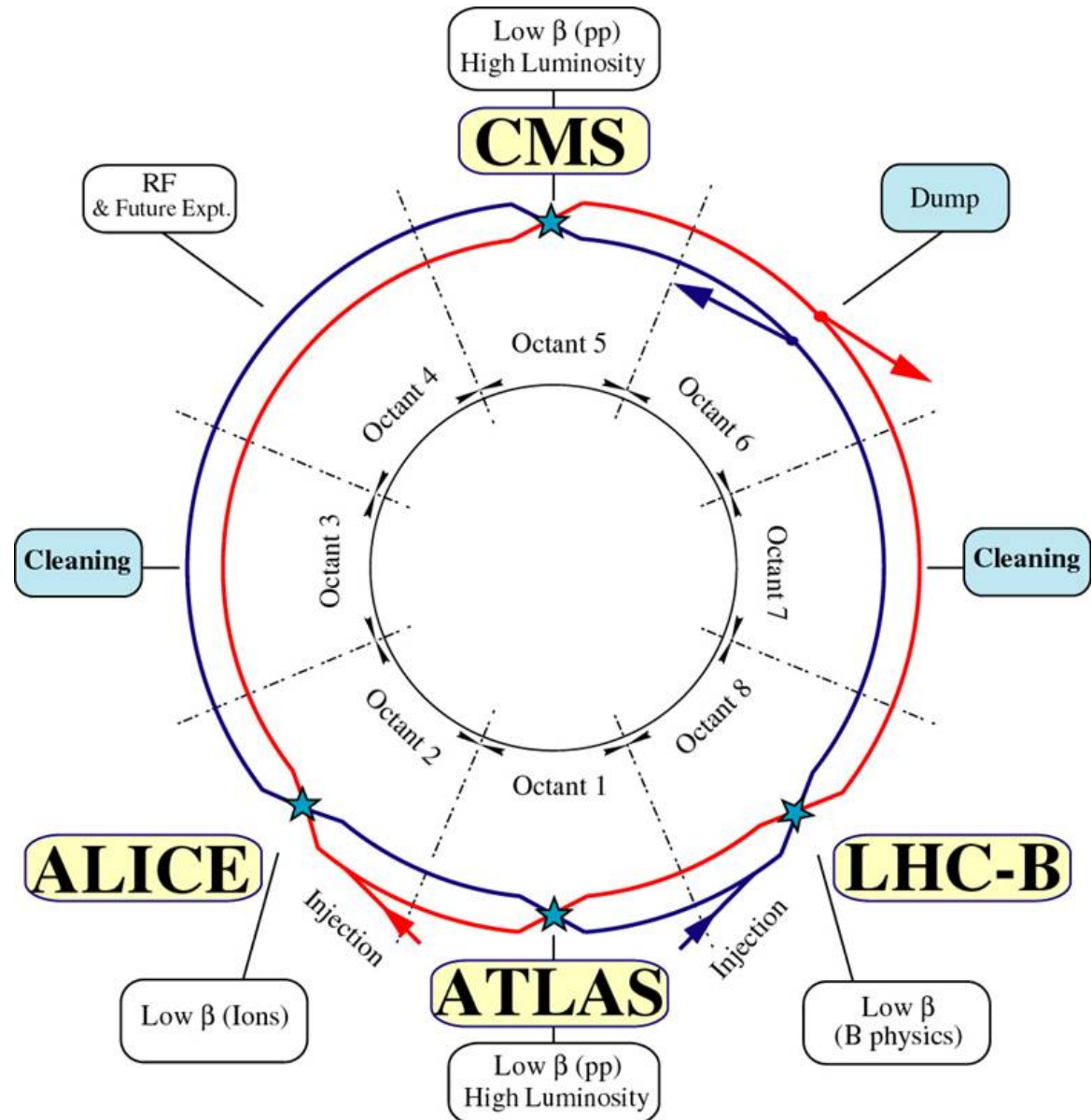
Proton-Lead

2013 5.02 TeV/u

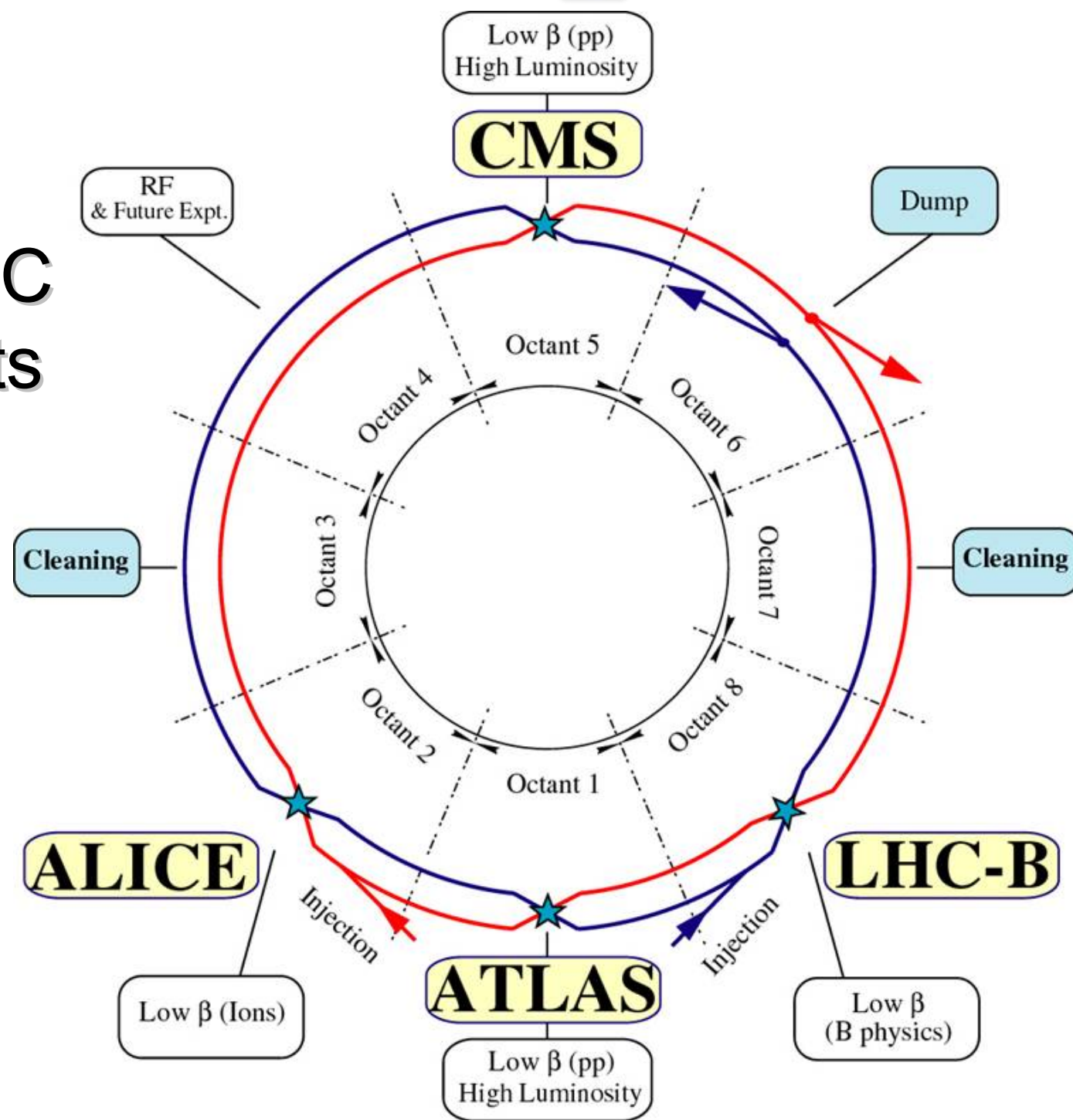
338 on 338 bunches

2016 5.02 TeV/u

2016 8.16 TeV/u



CERN's LHC Experiments



Compact Muon Solenoid (CMS) Detector

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

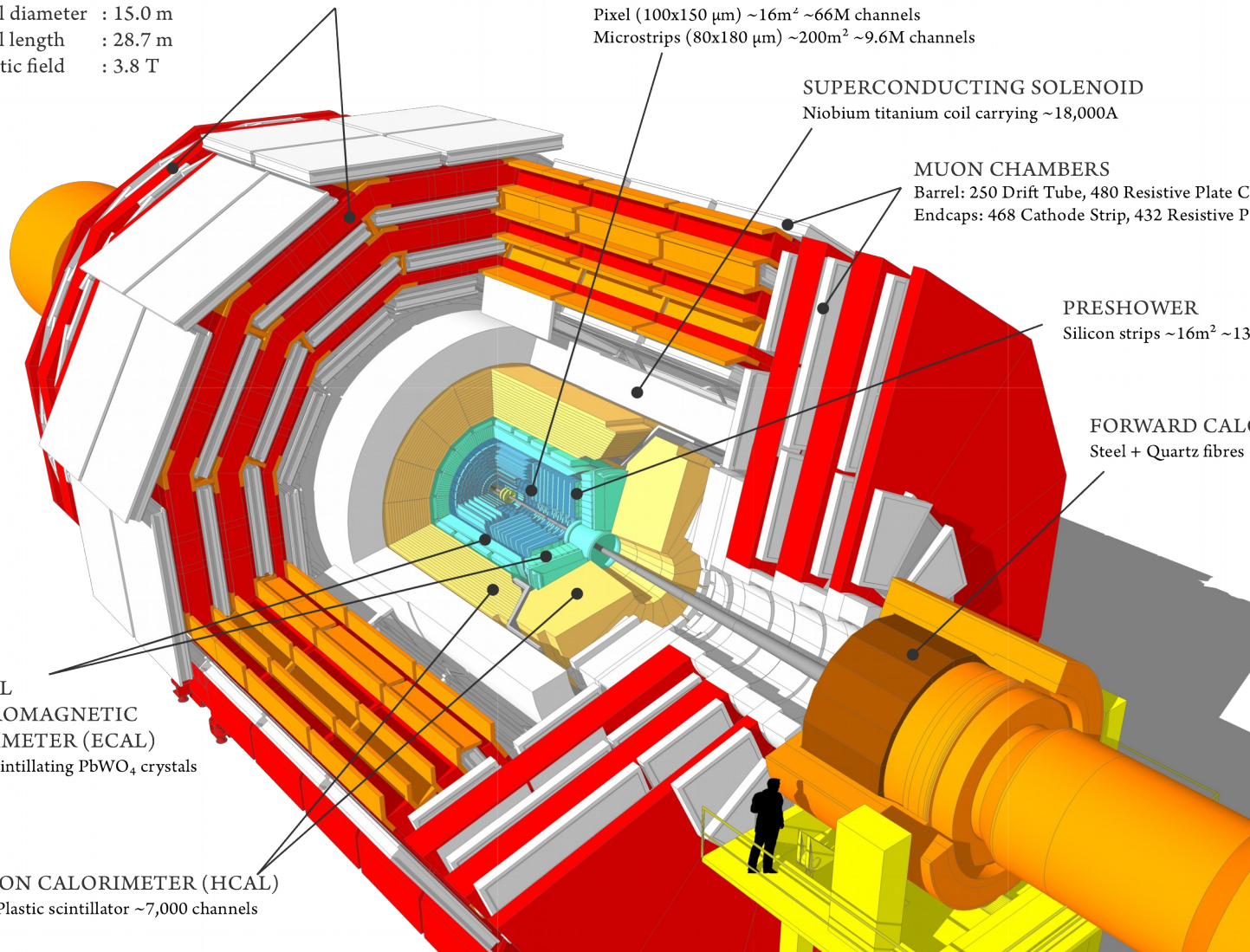
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels





CMS Data Taking Status

CMS Page 1 for status...(login required)

<https://cmswbm.cern.ch/cmsdb/servlet/Page1>

CMS Online Web Based Monitoring...(login required)

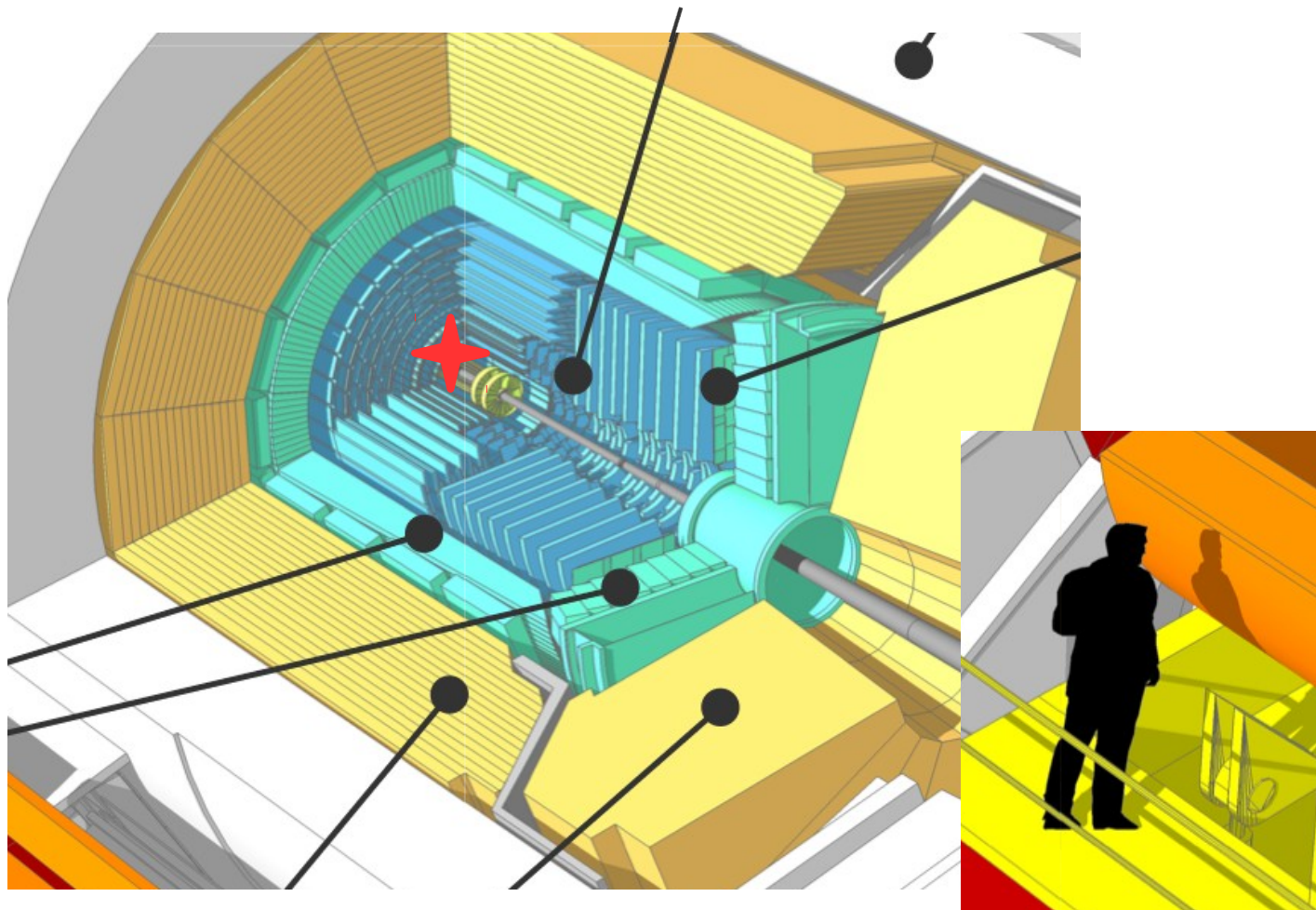
<https://cmswbm.cern.ch/>

Pixel (sub)Detector Wraps around the collision point.

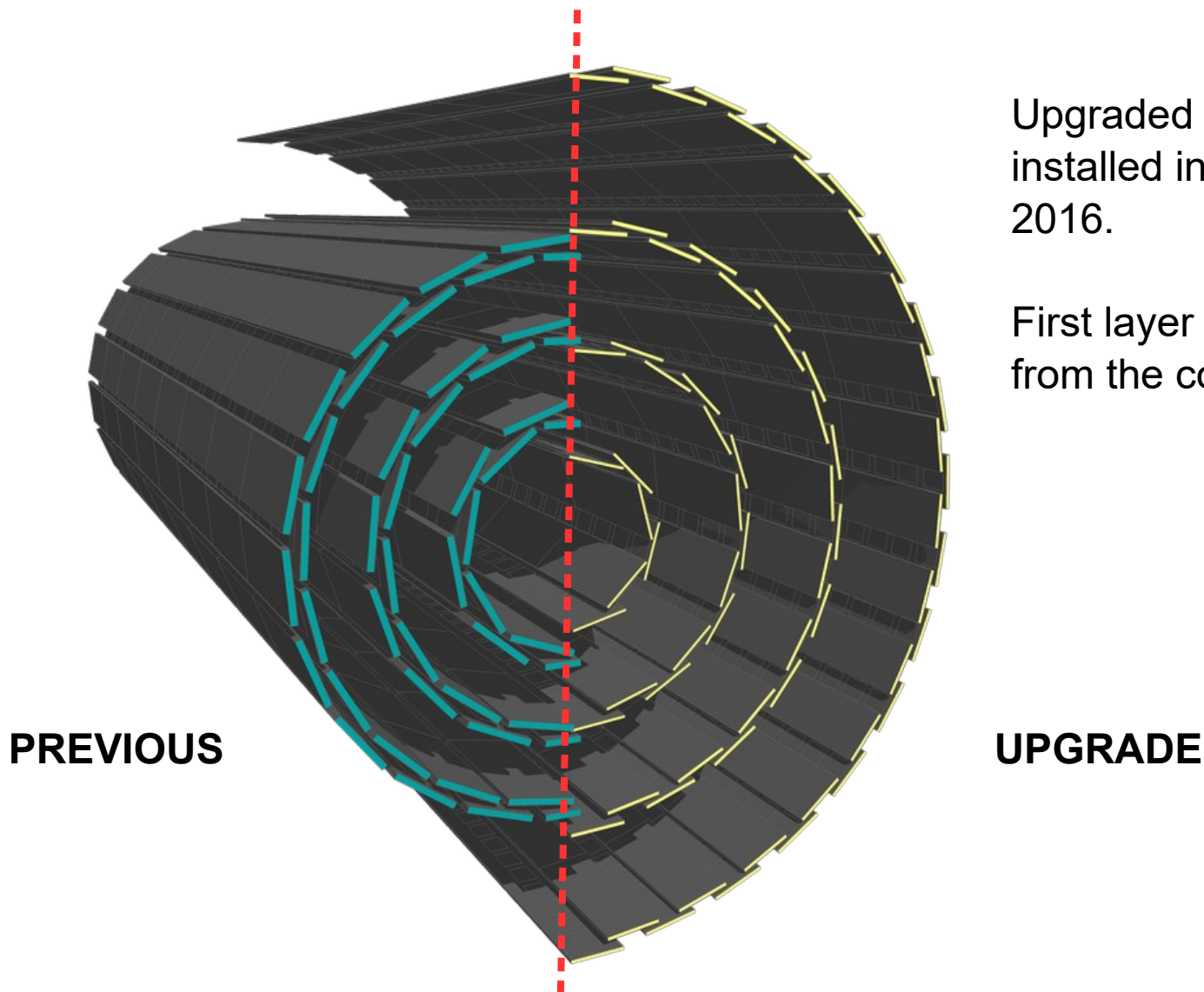
SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2$ $\sim 66\text{M}$ channels

Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2$ $\sim 9.6\text{M}$ channels



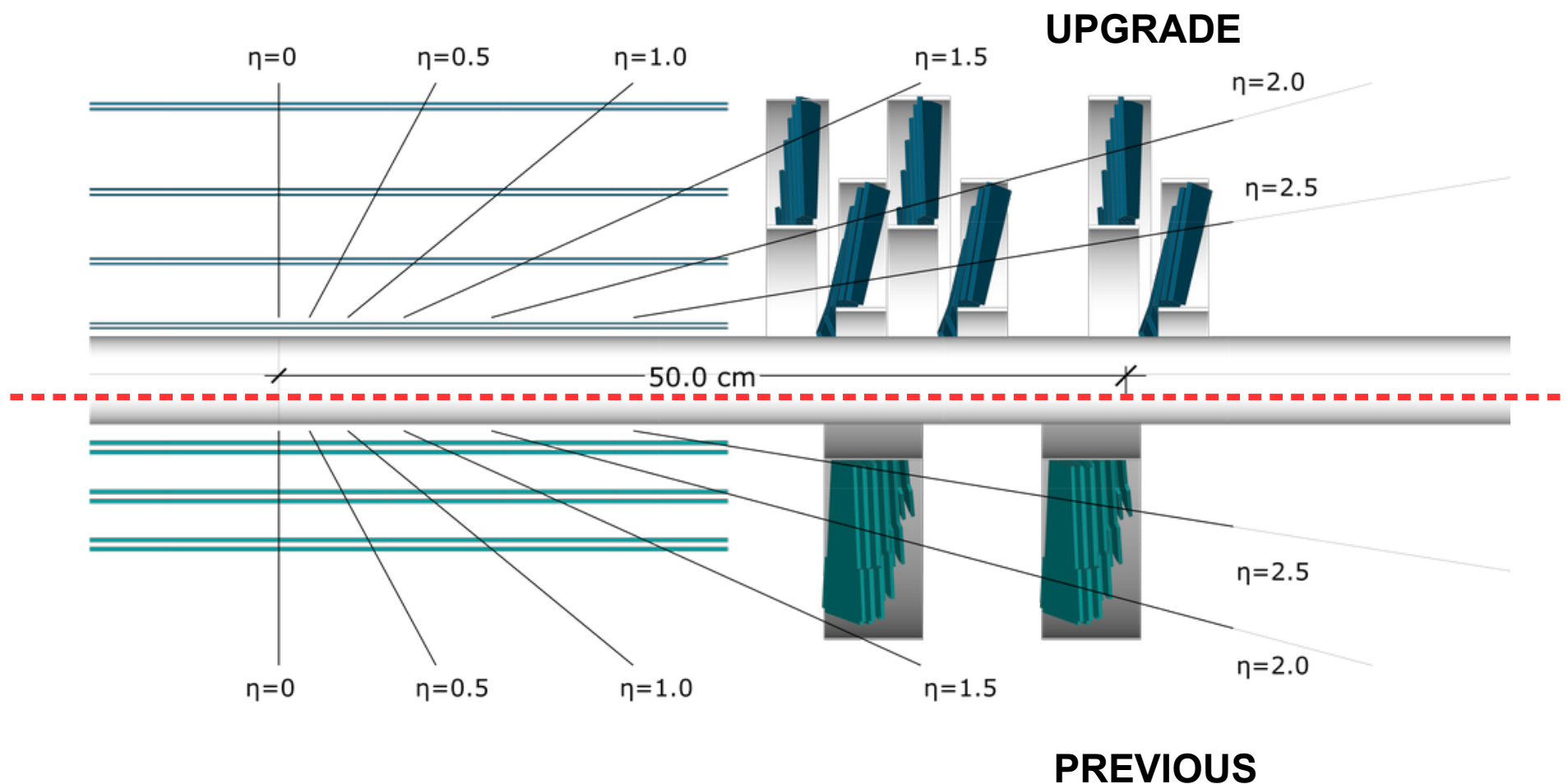
The Pixel is made up of the Barrel and the Forward Pixel



Upgraded to 4 layers,
installed in December
2016.

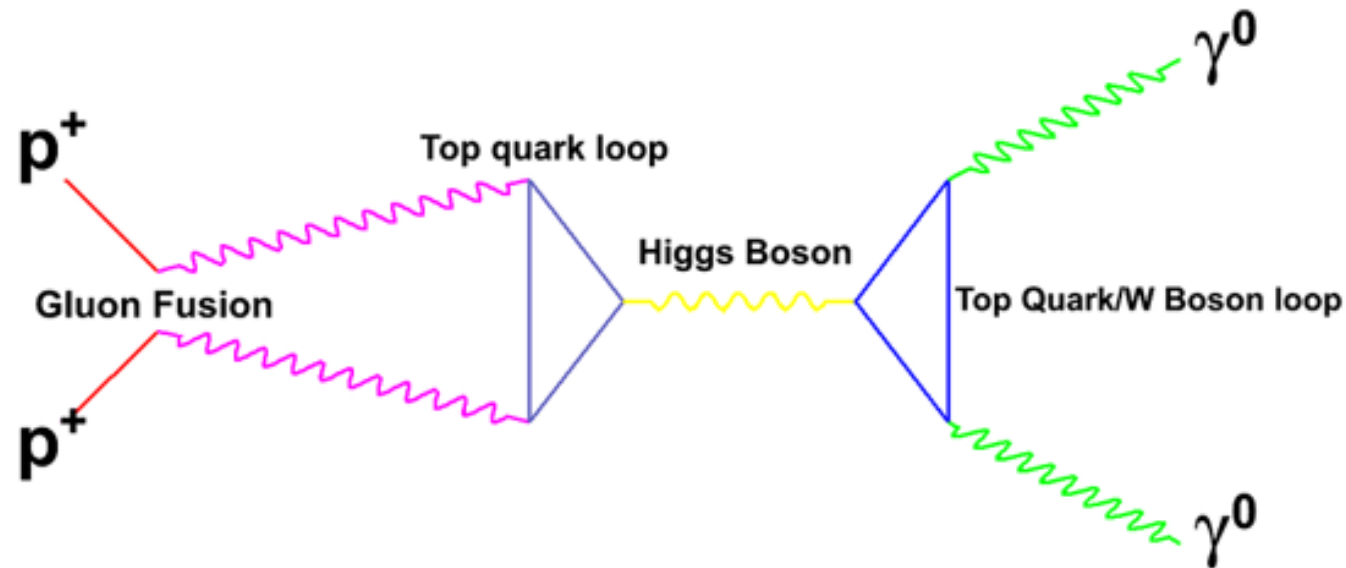
First layer is inches
from the collision point.

Vanderbilt (Will Johns) Supports the Forward Pixel (sub)Detector



CMS and Atlas Discovered the Higgs particle

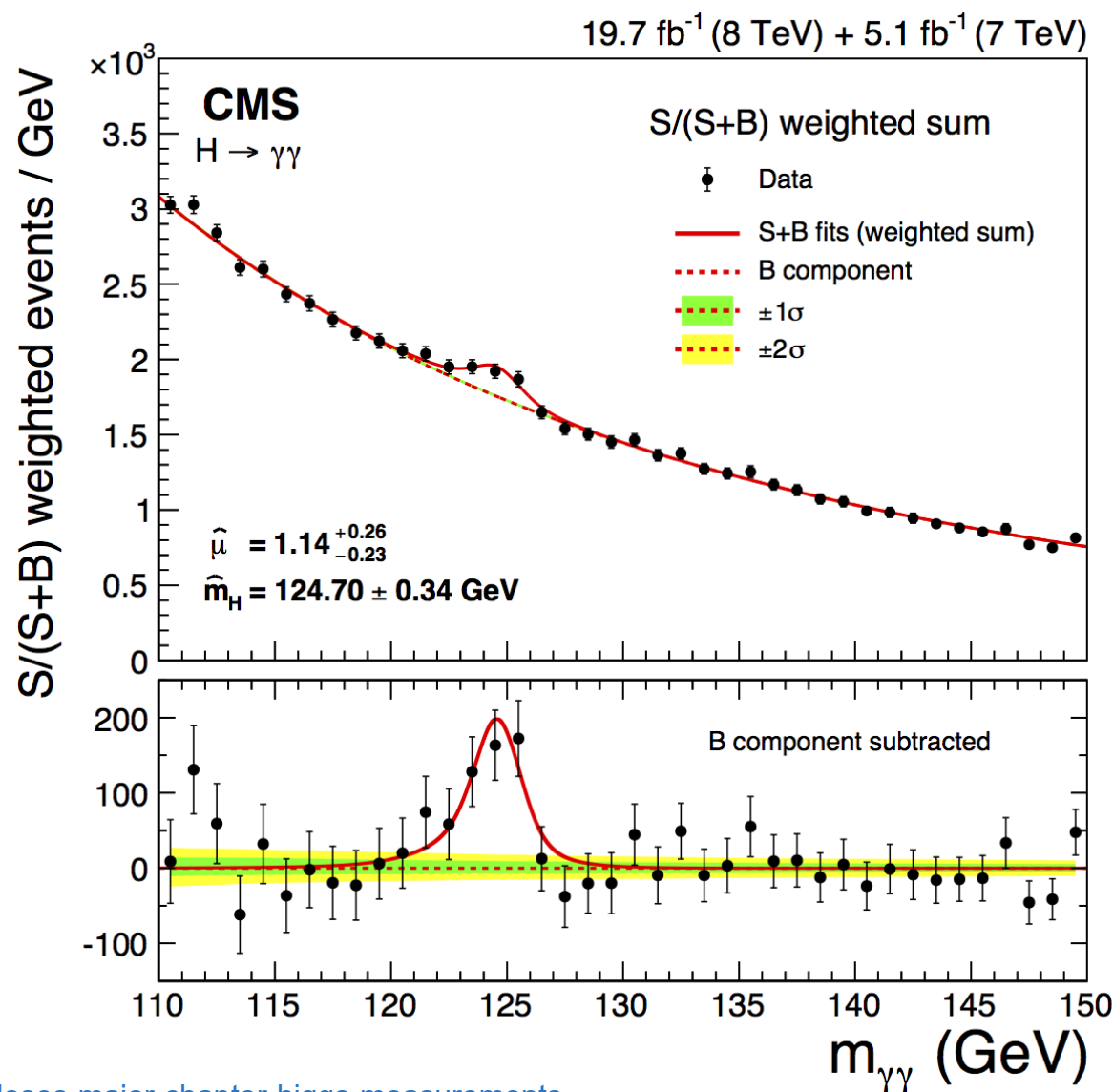
Joint announcement in July 4, 2012, with data from 7 and 8 TeV center of mass energy.



CMS and Atlas Discovered the Higgs particle

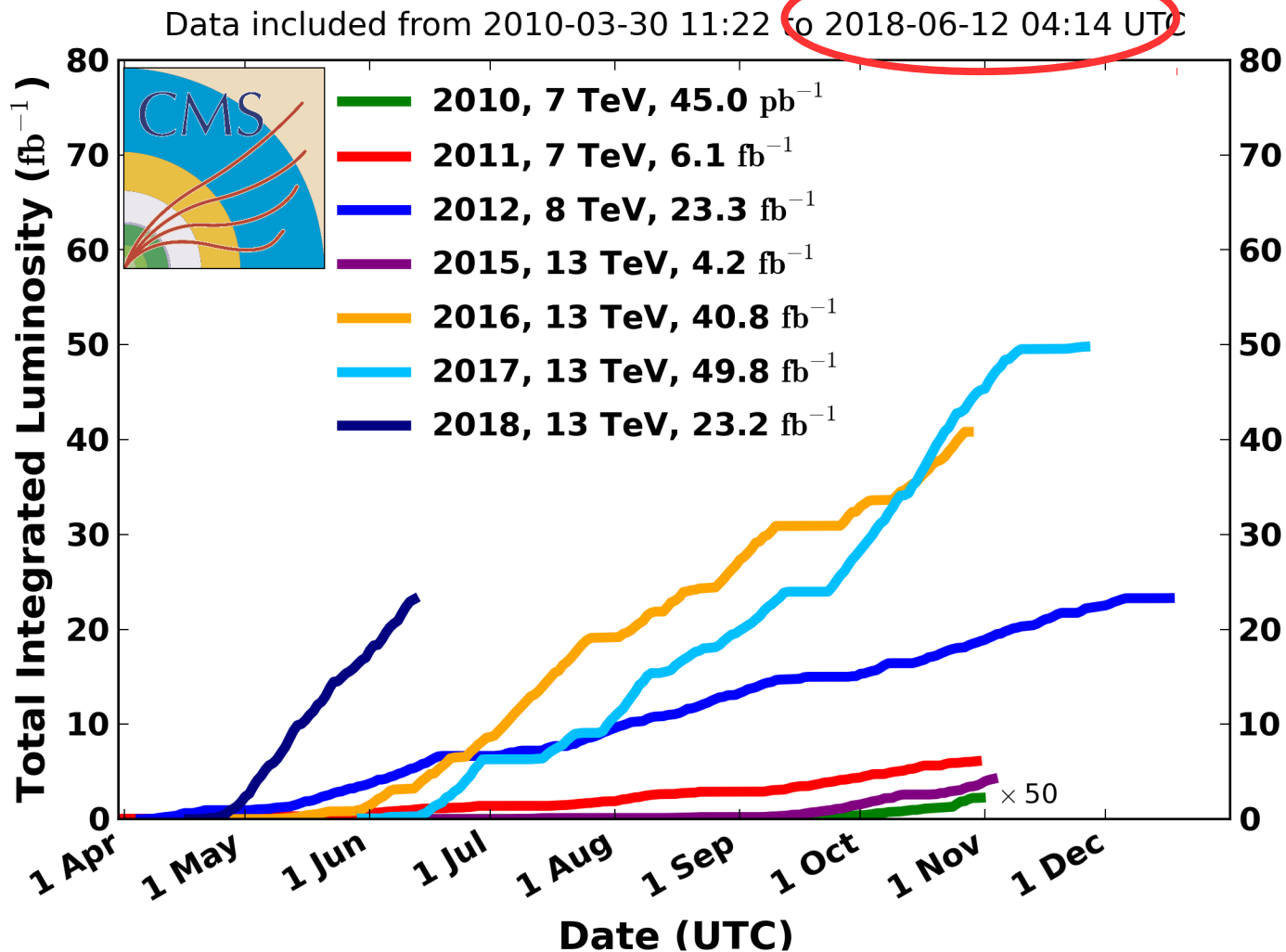
Mass bump,
reconstruct the mass
if a single particle
decayed into the two
photons.

Current mass of the
Higgs, 125.18 ± 0.16
GeV.



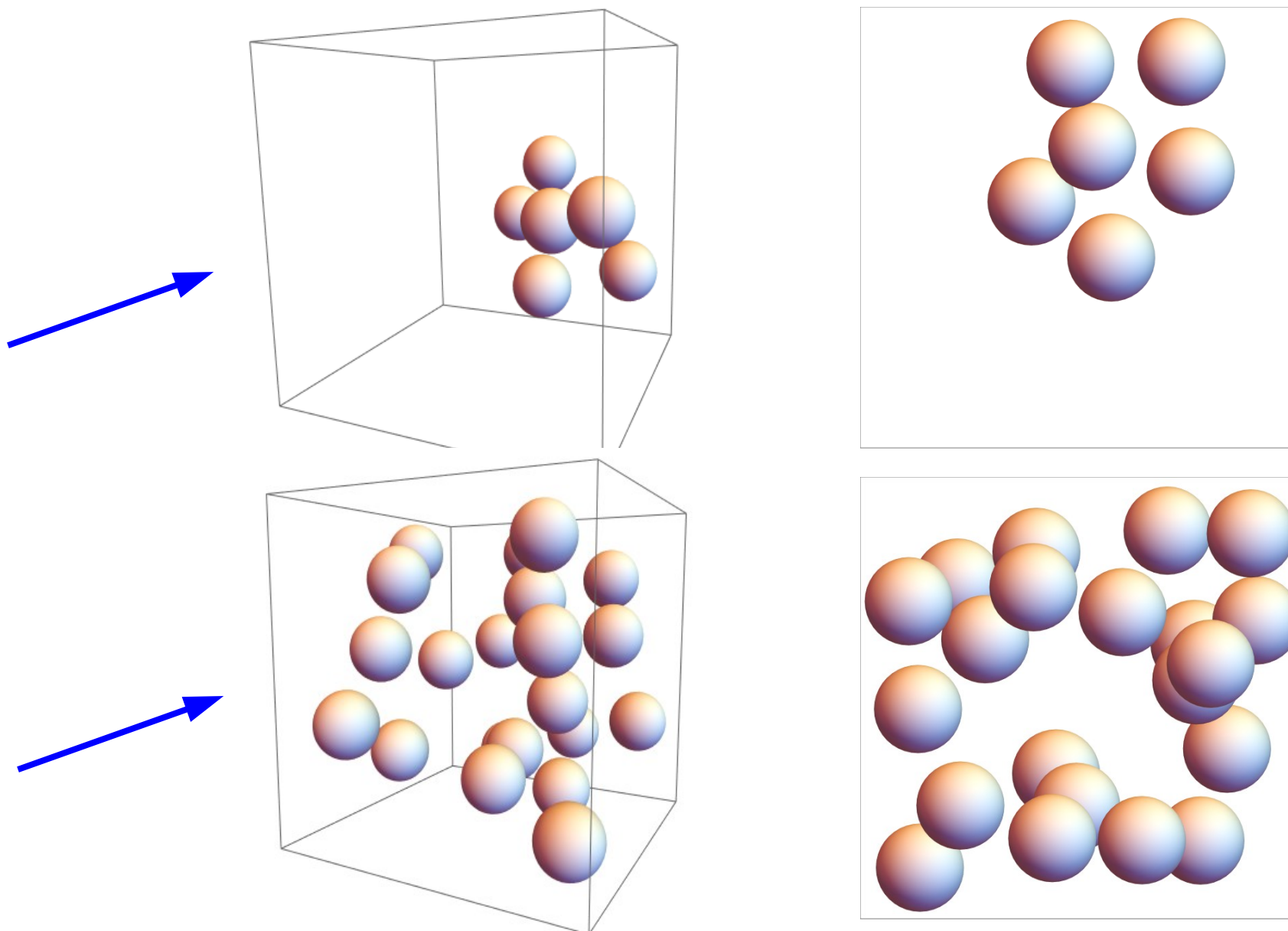
LHC/CMS Integrated Luminosity

CMS Integrated Luminosity, pp



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

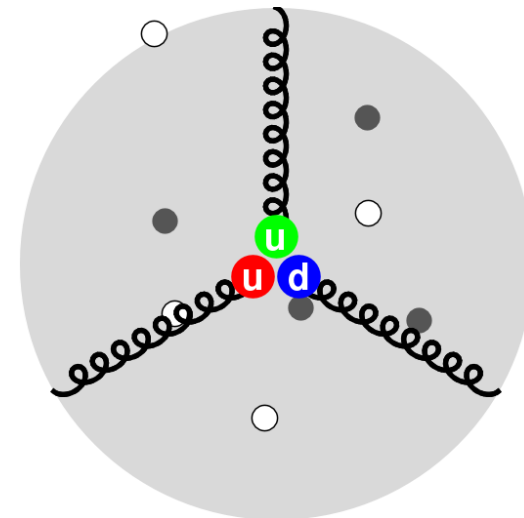
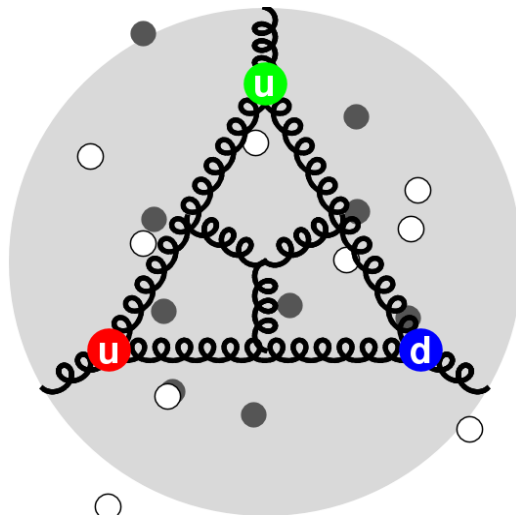
Cross-Section for Interactions



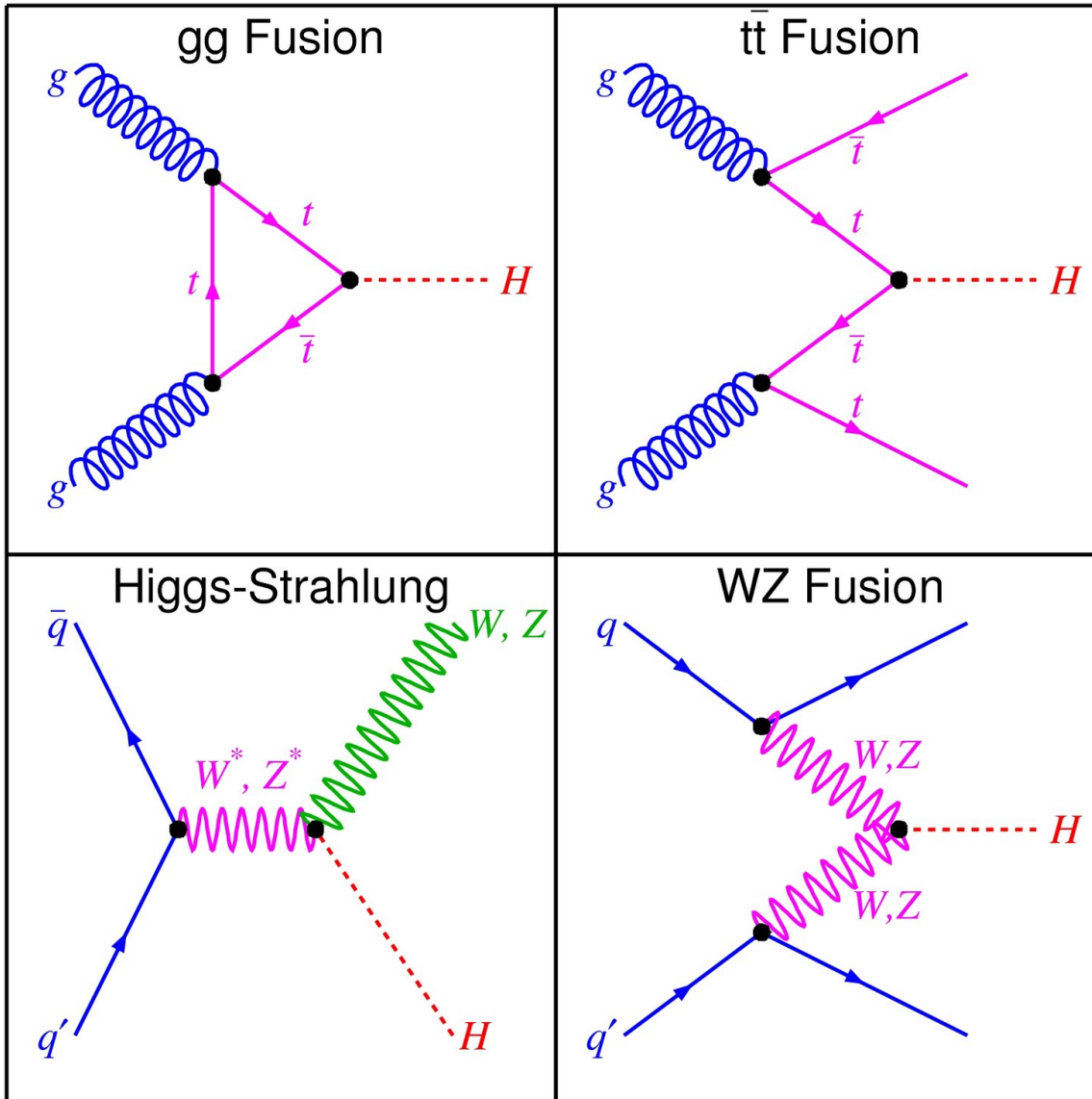
Physical or Effective size and density decide how many times you will interact for each crossing of the box.

Proton is not a simple object.

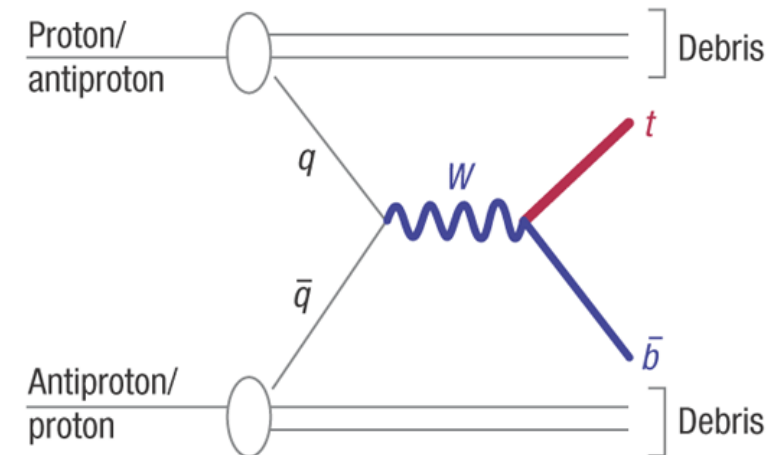
Protons are bags of valence quarks, gluons, and virtual quarks. Proton is a u-u-d valence quark combination, the “intrinsic mass” of the u is $1.9 \text{ MeV}/c^2$ and the d is $4.6 \text{ MeV}/c^2$ (an electron’s rest mass is $0.511 \text{ MeV}/c^2$). Yet the mass of the proton is $940 \text{ MeV}/c^2$!



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



VS



Higgs Production Rate and Cross-section

At 13 TeV and using Higgs mass 125 GeV.

ggF (gluon-gluon fusion)	43.9 pb (picobarns)
VBF (vector boson fusion)	3.75 pb
WH	1.38 pb
ZH	0.870 pb
ttH	0.509 pb
bbH	0.512 pb

Ref: [HiggsEuropeanStrategy](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014)

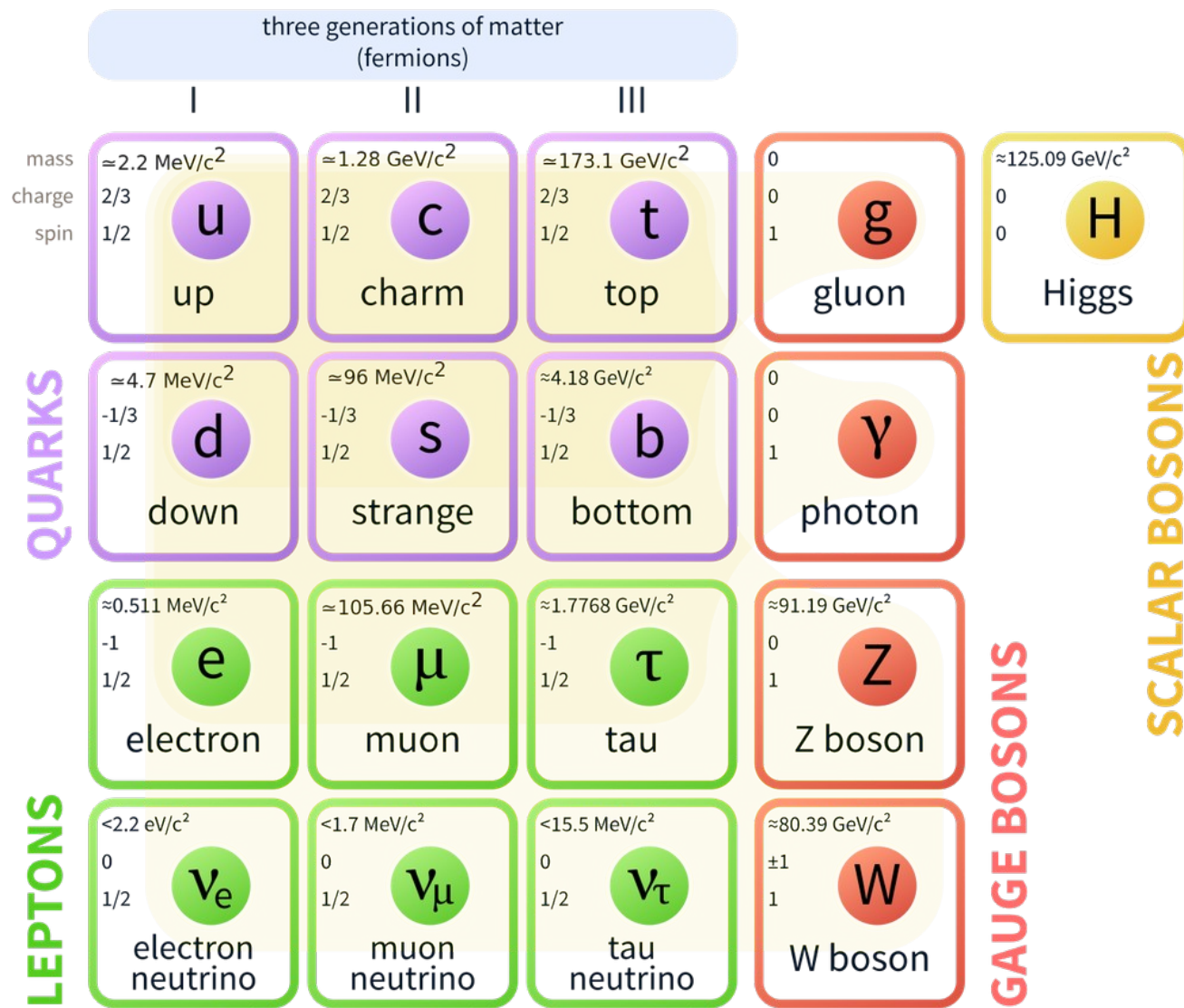
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014>

Previous slide, making about 6 fb^{-1} (inverse femtobarns) of luminosity every week, get the units right, then making Higgs by ggF is $43900 \text{ fb} \times 6 \text{ fb}^{-1} = 263,400$ Higgs via that channel every two weeks! **But cannot detect all of them!**

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 10^{-3} to 10^6 barns.

- Mesons are made up of quark-antiquark pairs;
- Baryons (protons and neutrons) are made of 3 quarks.
- Bosons (spin 0 or 1) carry the force.
- Leptons (electrons, muons, ...) do not have the strong nuclear force.

Standard Model of Elementary Particles



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/>
- <http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-schedule-update.pdf>



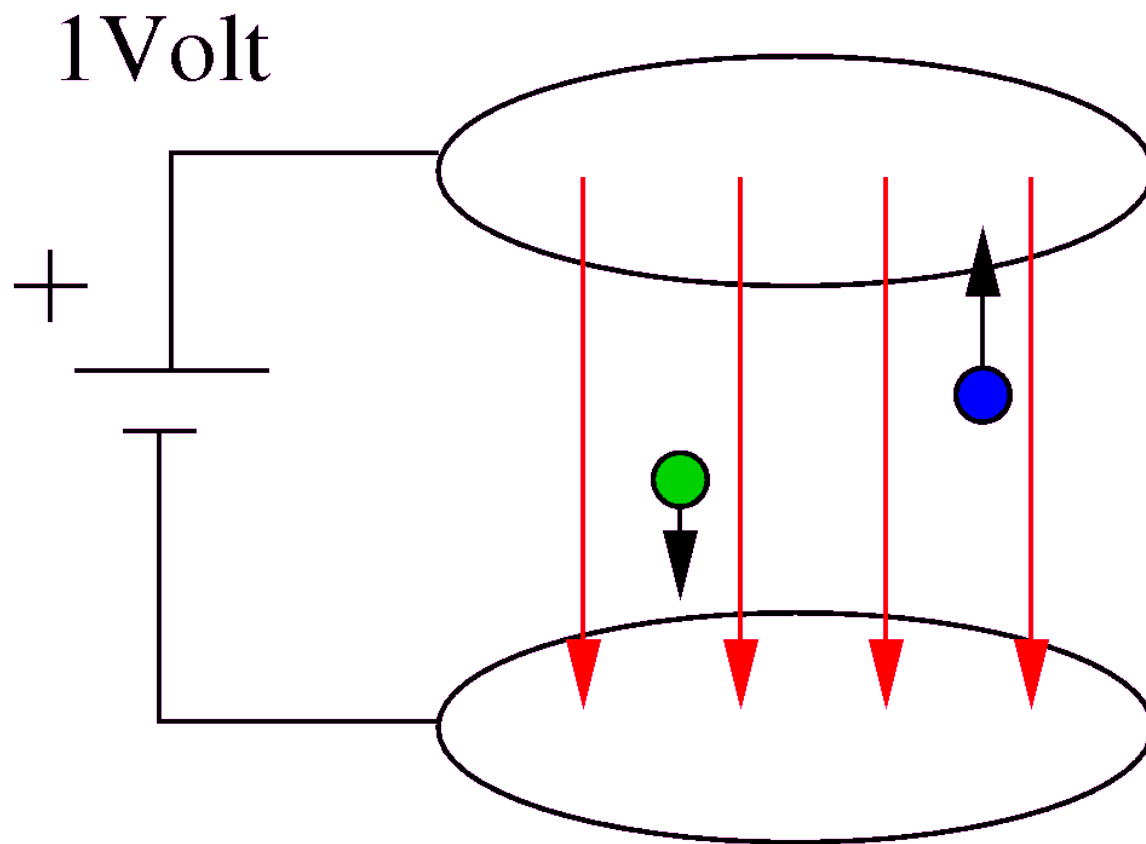
Backup

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 m/s

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

$$30 \text{ cm/ns}$$

$$300 \text{ m}/\mu\text{s}$$

$$300 \mu\text{m}/\text{ps}$$

LHCParameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per direction
Energy, protons*	6.5 TeV
Energy, ions	2.56 TeV/u (**)
Peak magnetic dipole field	7.74 T
Distance between bunches	~7.5 m
Luminosity (protons)	Peak Luminosity: ~ $1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
No. of bunches per proton beam (design value)	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11 245
Number of collisions per second	1 billion

(*) Design value: 7 TeV

(**) Energy per nucleon

Particle Physics in a Page (or two)

- Mesons are made up of quark-antiquark pairs;
- Baryons (protons and neutrons) are made of 3 quarks.
- Bosons (spin 0 or 1) carry the force.

Three Generations
of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] W boson
				Gauge Bosons

Three generations of matter particles and the force carrying particles.