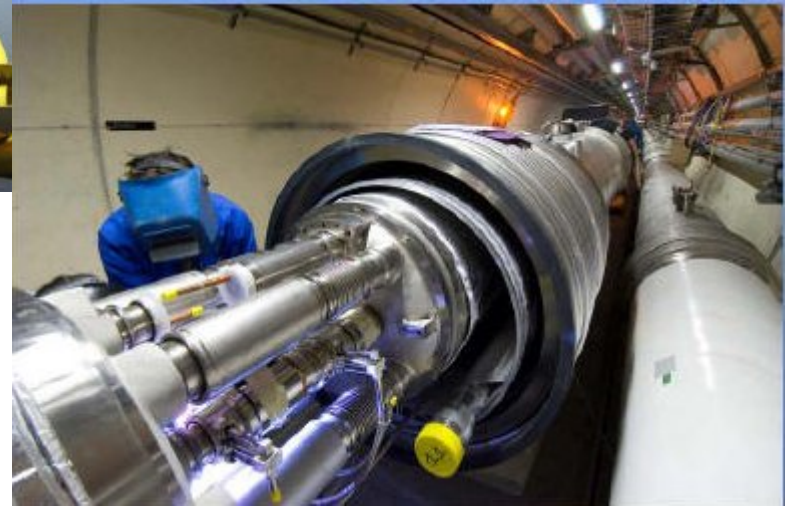


CERN's Large Hadron Collider

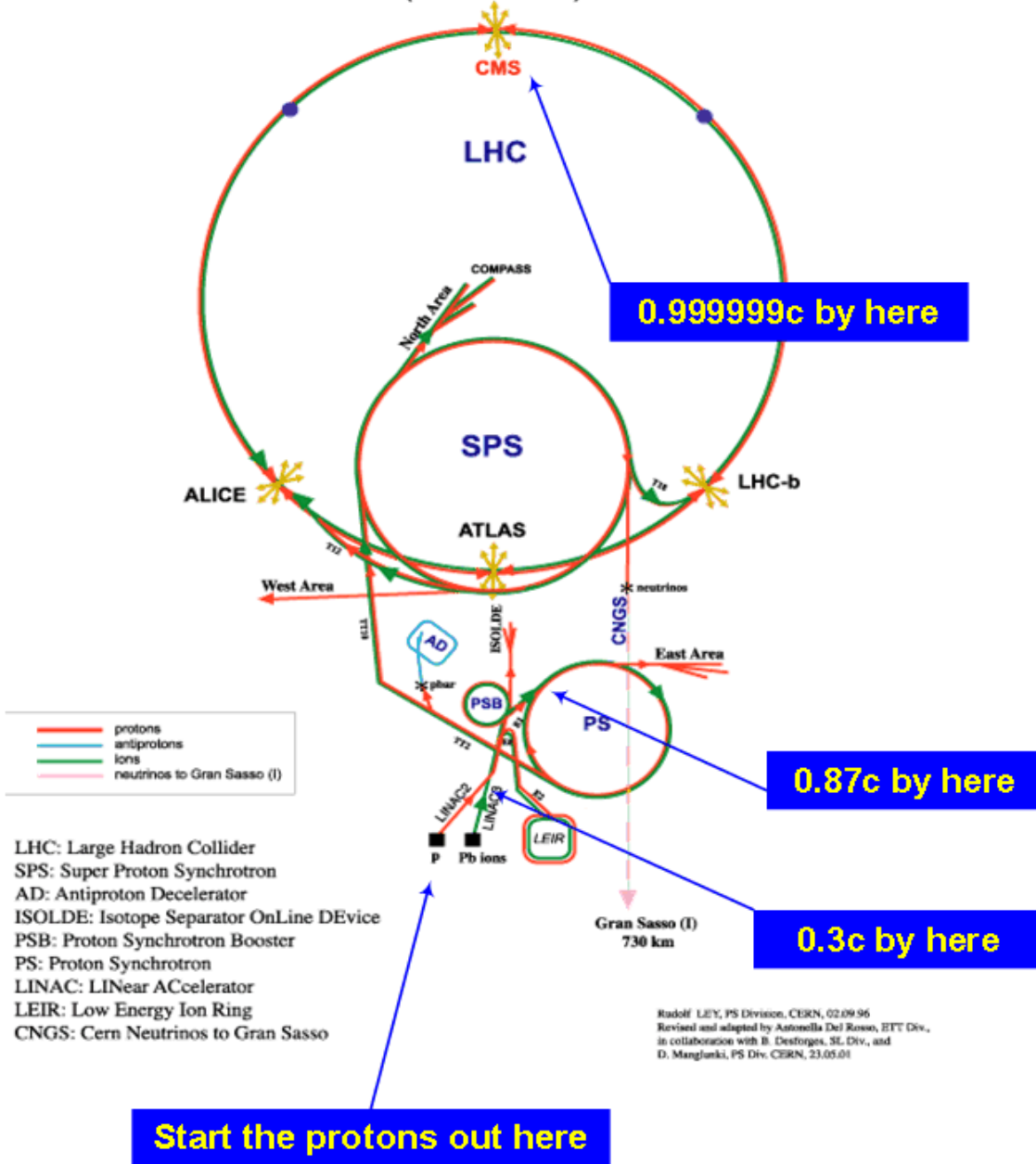


Ref: www.cern.ch



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

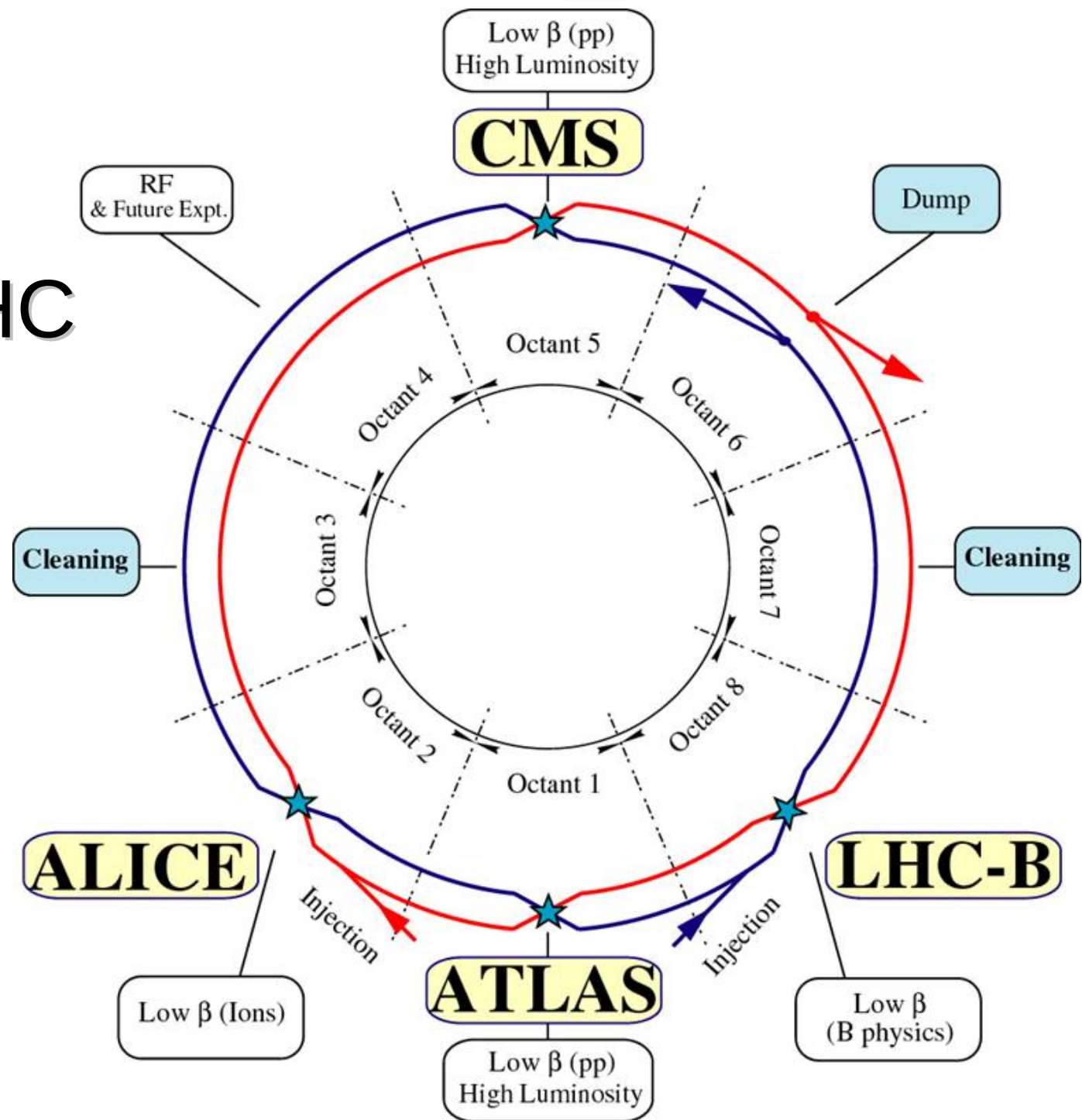


LHCParameters

| | |
|----------------------------------|---|
| 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 | $2.56 \text{ TeV}/n = 6.5 \cdot 82/208$ (Pb-208) |
| no. of protons | $1.2e11$ per bunch |
| no. of bunches | $\leq 2604/2748$ |
| bunch length, 4σ | 1-1.25 ns |
| bunch size, x & y at IP, 1 sigma | 52 x 66 microns |



CERN's LHC





CERN's Large Hadron Collider

The highest energy collider in the world:

- 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 1.2×10^{11} protons
- each beam can 2076 bunches (maybe 2064 collide)
- can collide Pb(+82,208) on Pb ions
- can collide p on Pb ions



Current Status Op Vistar

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

LHC Page 1 Vistar

LHC Page1 Fill: 5981 E: 59 GeV 22-07-17 22:01:01

PROTON PHYSICS: NO BEAM

| | | | | | | | |
|-------------------|----------|----------------|----------|------------|----------|--------|----------|
| BCT TI2: | 0.00e+00 | I(B1): | 0.00e+00 | BCT TI8: | 0.00e+00 | I(B2): | 0.00e+00 |
| TED TI2 position: | BEAM | TDI P2 gaps/mm | up: 8.41 | down: 7.18 | | | |
| TED TI8 position: | BEAM | TDI P8 gaps/mm | up: 8.83 | down: 6.82 | | | |

| | BIS status and SMP flags | | B1 | B2 |
|---|-----------------------------|--|-------|-------|
| Comments (22-Jul-2017 21:04:24) cryo recovery on-going still no beam in SPS more news asap | Link Status of Beam Permits | | true | true |
| | Global Beam Permit | | false | false |
| | Setup Beam | | true | true |
| | Beam Presence | | false | false |
| | Moveable Devices Allowed In | | false | false |
| | Stable Beams | | false | false |

AFS: 50ns_1284b_1272_527_652_72bpi_20inj PM Status B1 **ENABLED** PM Status B2 **ENABLED**

Click Here



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



A recent run on CMS had...

- center-of-mass energy of 13 TeV
- each counter rotating beam proton beam was 6.5 TeV
- each bunch contained 1.1×10^{11} protons
- each beam had 1284 bunches with 1271 colliding
- spaced by 50 ns (not the shorter 25 ns)

CMS Page 1 for status...

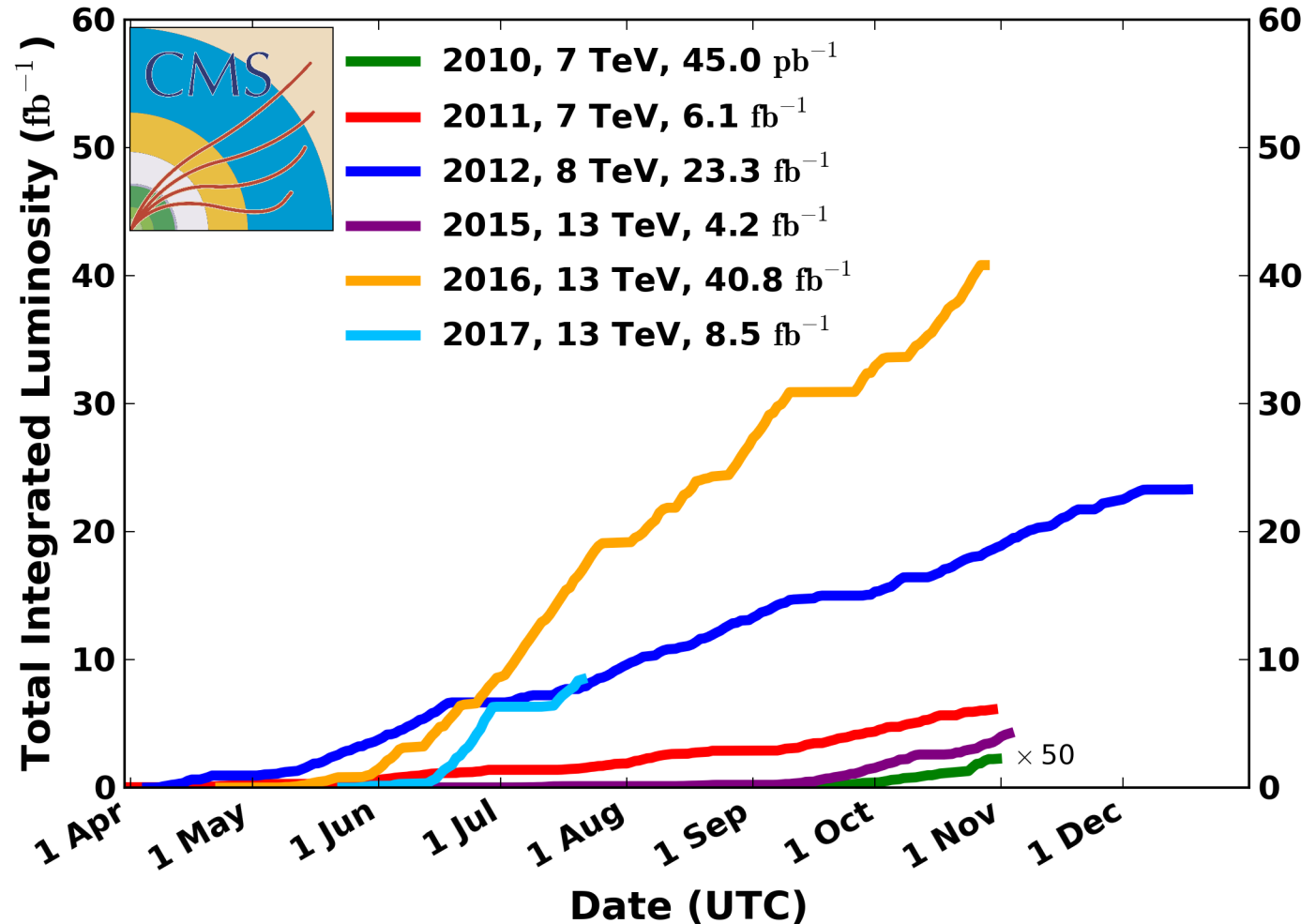
<https://cmswbm.cern.ch/cmsdb/servlet/Page1>



LHC/CMS Integrated Luminosity

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2017-07-21 04:13 UTC



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

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Luminosity_versus_week



Current Plan Approved March 2017 January – June 2017

ML/RS

June 28, 2017
ver. 1.2

LHC Schedule 2017
Approved by the Reseach Board, 8 March 2017

| | Jan | | | | Feb | | | | Mar | | | | | |
|----|-----|---|---|----|-----|----|---|----|-----|----|----|----|----|----|
| Wk | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | |
| Mo | | 2 | 9 | 16 | 23 | 30 | 6 | 13 | 20 | 27 | 6 | 13 | 20 | 27 |
| Tu | | | | | | | | | | | | | | |
| We | | | | | | | | | | | | | | |
| Th | | | | | | | | | | | | | | |
| Fr | | | | | | | | | | | | | | |
| Sa | | | | | | | | | | | | | | |
| Su | | | | | | | | | | | | | | |

Controls interventions: Jan 2-9, Mar 10-11
 Start powering tests phase 1: Mar 12, 13
 Technical stop (EYETS): Mar 7-8

| | Apr | | | May | | | | June | | | | | |
|----|-----|----|---------------|-----|-----------|----|----|------|----|--------|----|----|----|
| Wk | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| Mo | 3 | 10 | Easter Mon 17 | 24 | 1st May 1 | 8 | 15 | 22 | 29 | Whit 5 | 12 | 19 | 26 |
| Tu | | | | | | | | | | | | | |
| We | | | | | | | | | | | | | |
| Th | | | | | | | | | | | | | |
| Fr | | | | | | | | | | | | | |
| Sa | | | | | | | | | | | | | |
| Su | | | | | | | | | | | | | |

LHC to OP: Apr 15
 1st stable beams: May 21
 Machine checkout: Apr 17-18
 Recommissioning with beam: May 1-8
 Ascension: May 21
 Interleaved commissioning and intensity ramp-up: May 22-29
 G. Friday: Apr 15
 MD 1: June 26



Current Plan Approved March 2017 July – December 2017

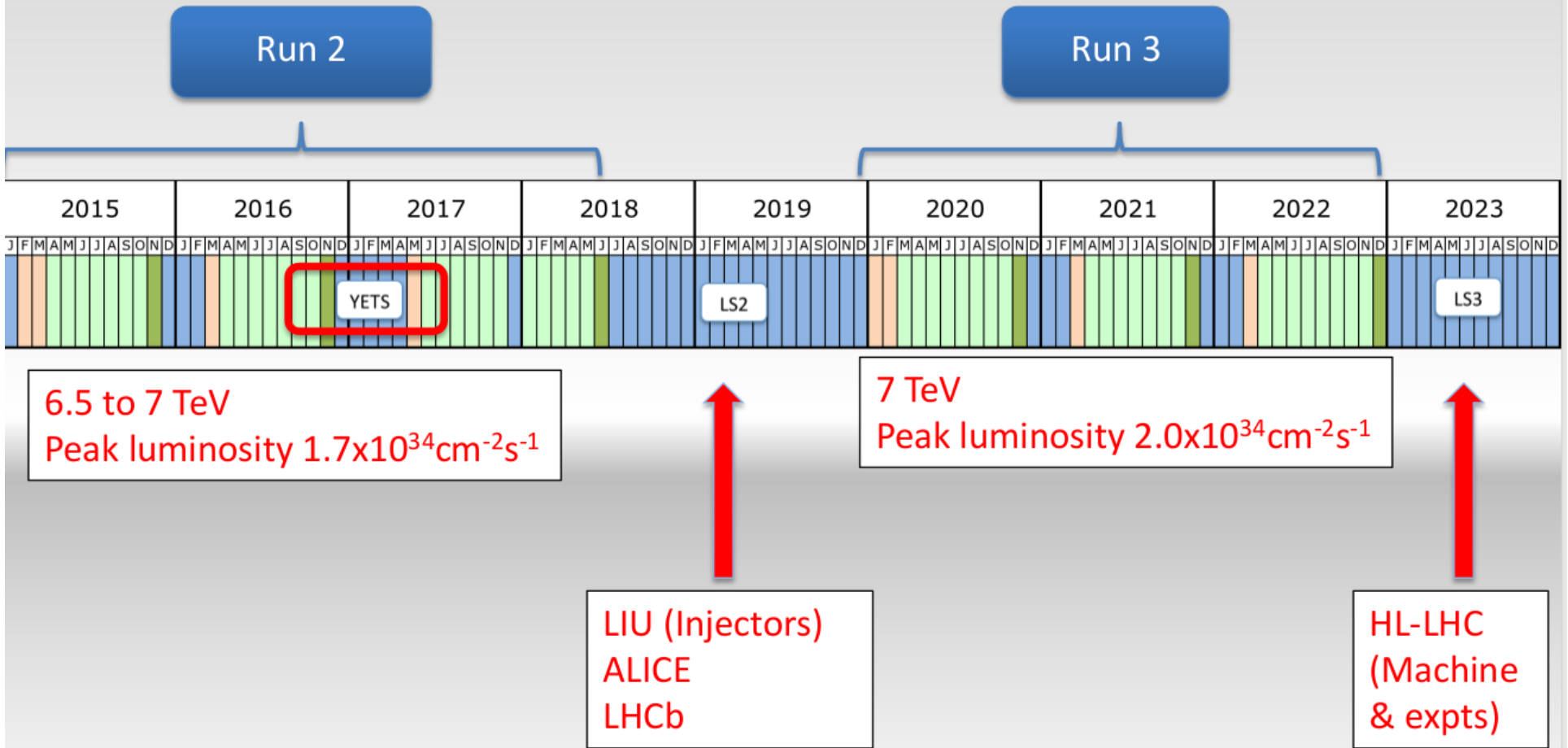
| | July | | | Aug | | | | Sep | | | | | |
|----|------|----|----|---------|----|----|----|--------------------|----|---------|------|-----|----|
| Wk | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| Mo | 3 | 10 | 17 | 24 | 31 | 7 | 14 | 21 | 28 | 4 | 11 | 18 | 25 |
| Tu | | | | MD 2 | | | | Special physic run | | | | | |
| We | TS1 | | | VdM run | | | | | | | | 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 | 2 | 9 | 16 | 23 | 30 | 6 | 13 | 20 | 27 | 4 | 11 | 18 | Xmas 25 |
| Tu | | | | | | Special physic run | | | | | | | |
| We | | | | MD 4 | | | | | | | | | |
| Th | | | | | | | | | | | | | |
| Fr | | | | | | | | | | | | | |
| Sa | | | | | | | | | | | | | |
| Su | | | | | | | | | | | | | |

End of run
[06:00]

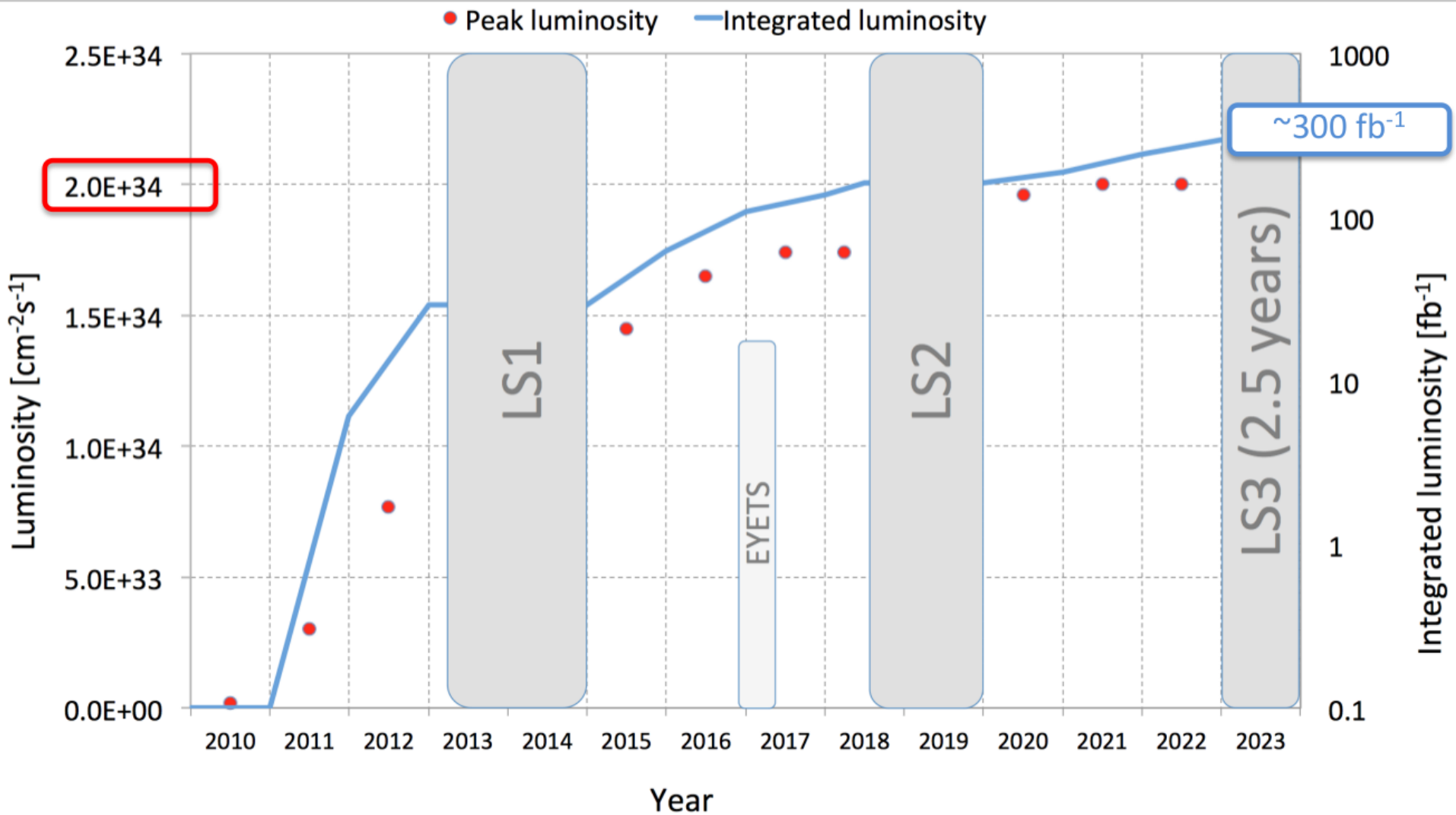
- Technical Stop
- Machine development
- Recommissioning with beam
- Special physics runs (indicative - schedule to be established)
- Scrubbing (indicative - dates to be established)

Next 10 years



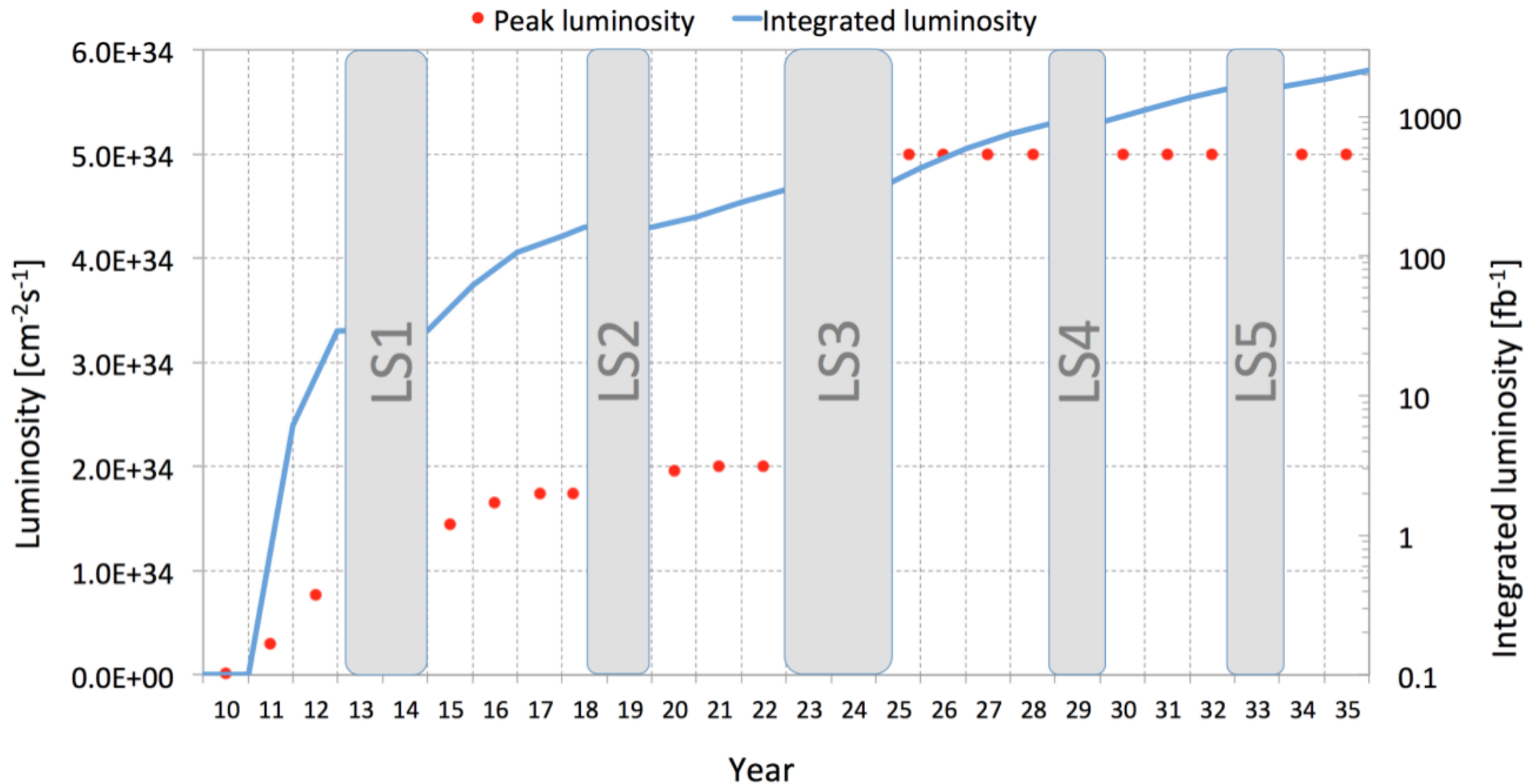


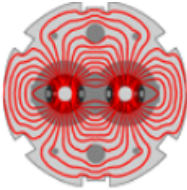
Luminosity evolution



Usual caveats apply

2010 - 2035





| | 50 ns | 25 ns |
|------|--|---|
| GOOD | <ul style="list-style-type: none">• Lower total beam current• Higher bunch intensity• Lower emittance | <ul style="list-style-type: none">• Lower pile-up |
| BAD | <ul style="list-style-type: none">• High pile-up• Need to level• Pile-up stays high• High bunch intensity – instabilities... | <ul style="list-style-type: none">• 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...



What has the LHC done?

Energies & Modes:

Proton-Proton

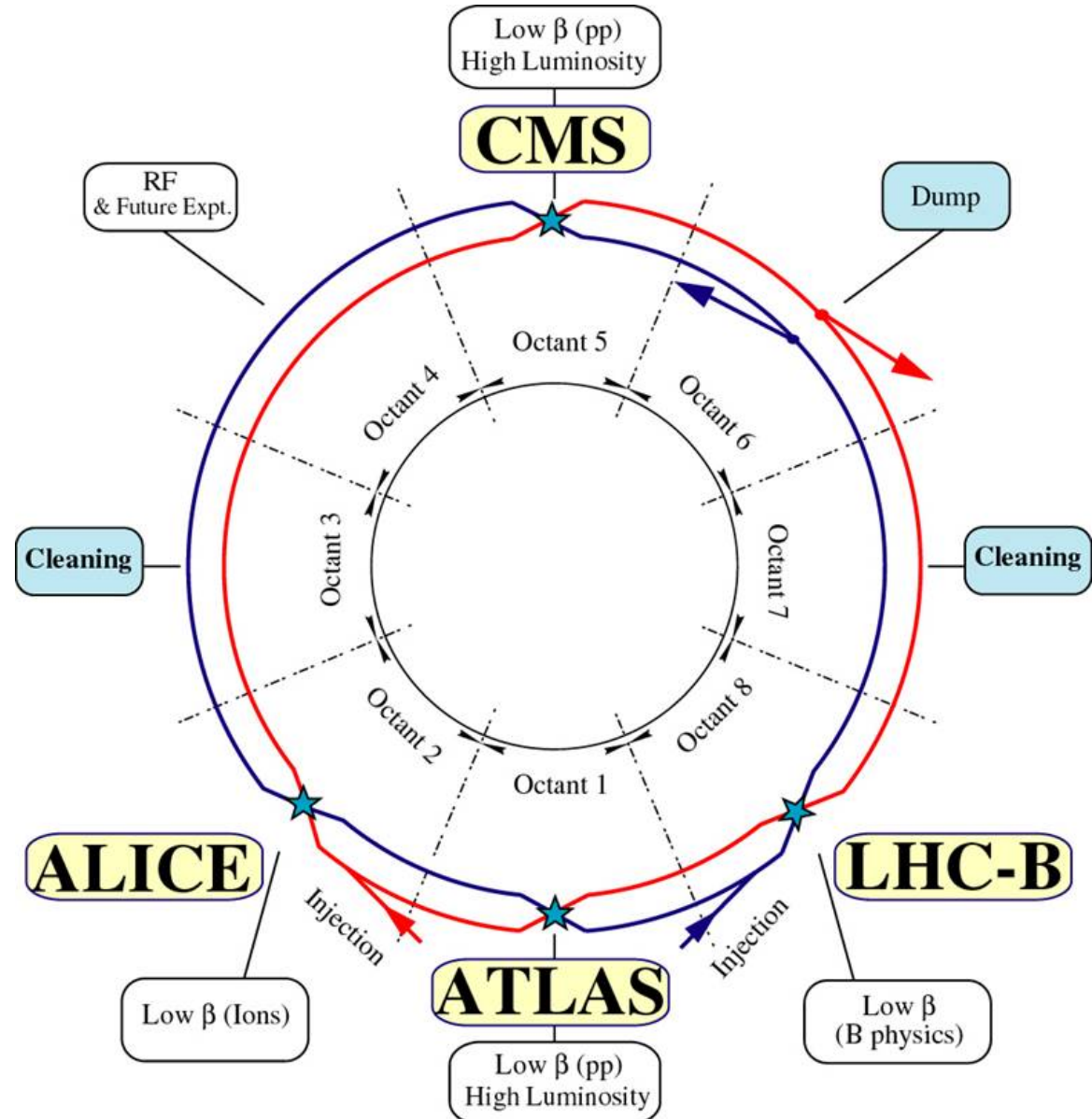
- 2011 3.5+3.5 TeV
- 2012 4+4 TeV
- 1380 on 1380 bunches
- 2013 Long Shutdown 1
- 2015-7 6.5+6.5 TeV

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





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.”

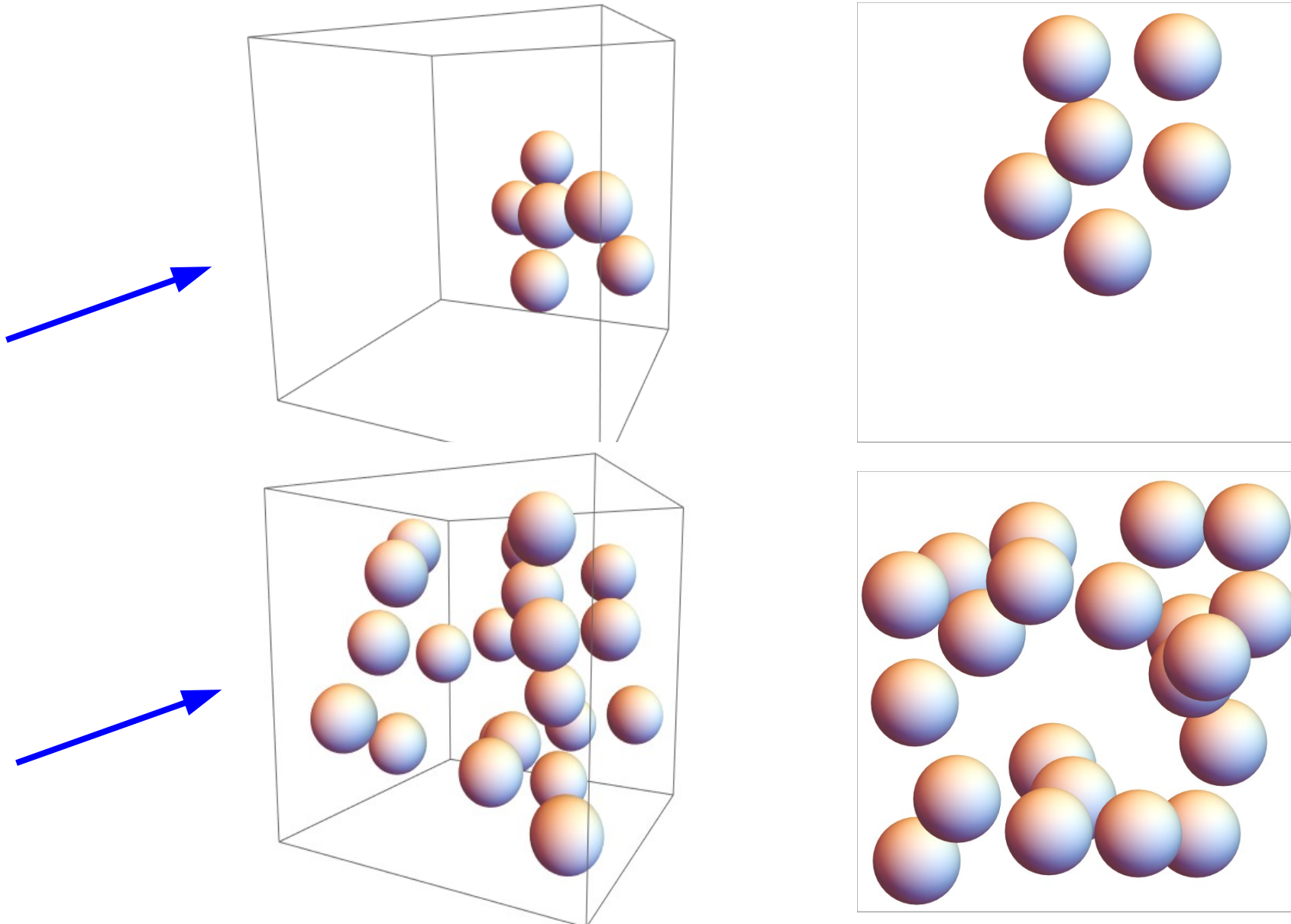
Jan 2013 – Proton-Lead collisions and Proton-Proton at 1.38 TeV.

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.

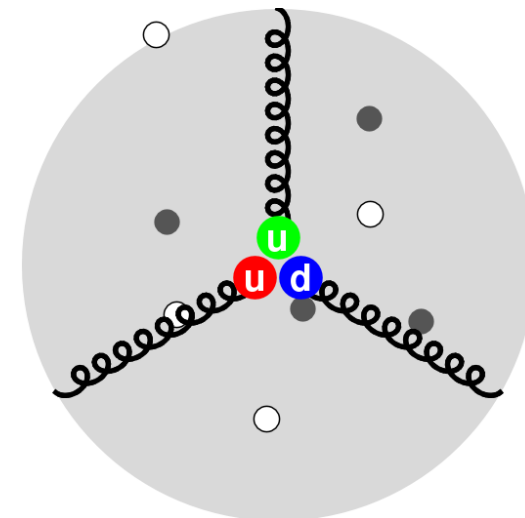
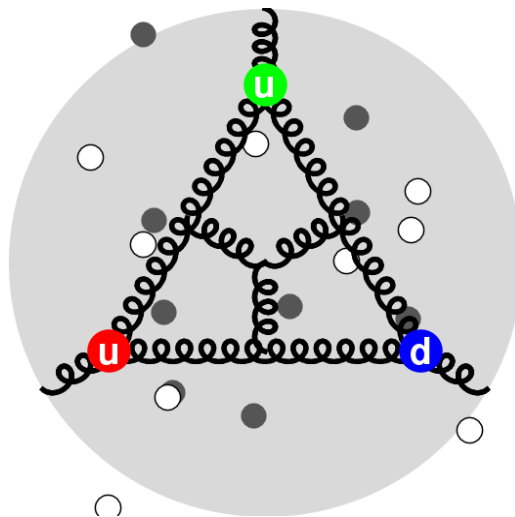
Cross-Section for Interactions



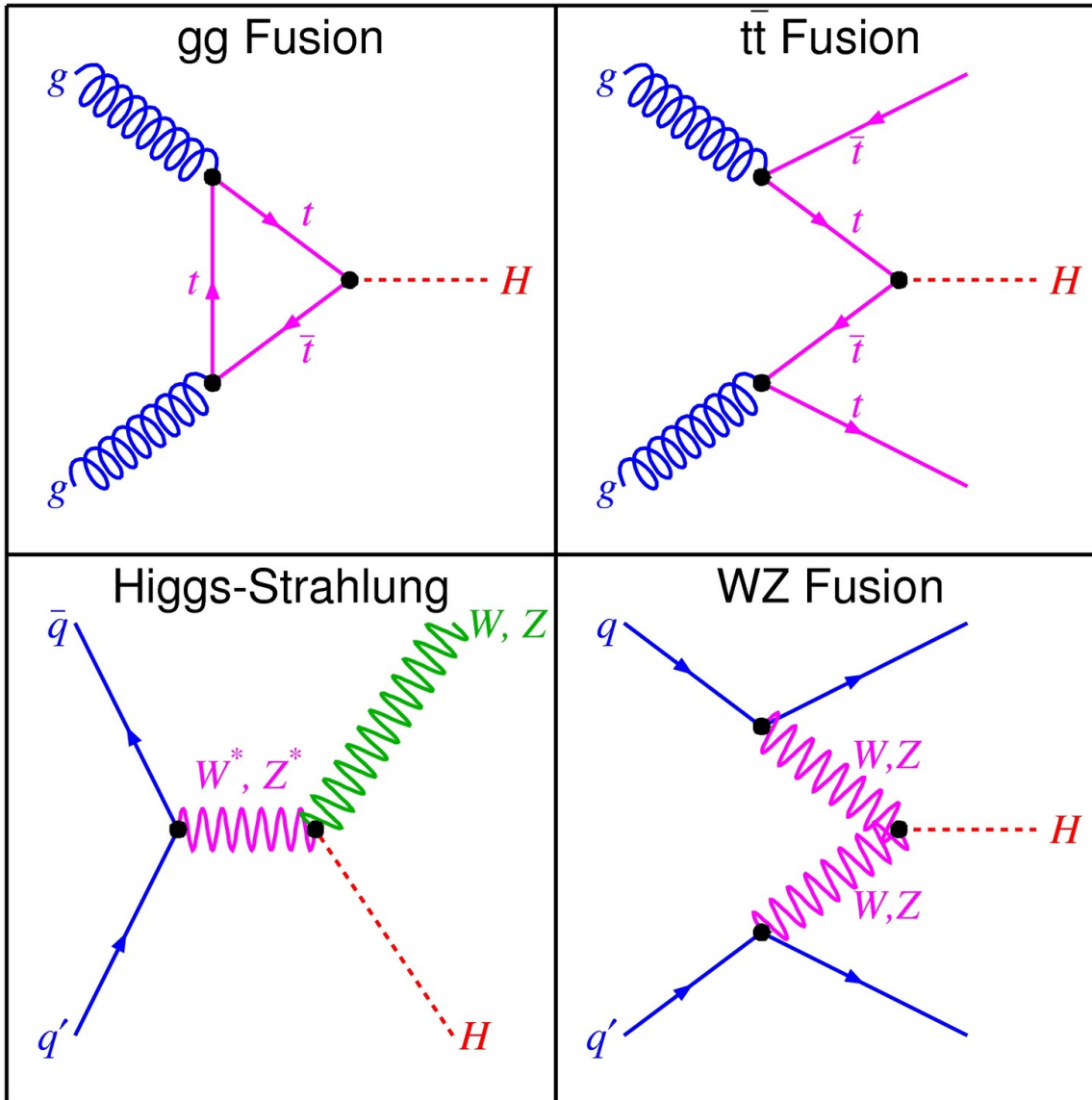
Physical or Effective size and density decide how many times you will interact for each crossing of the box.

Proton is not a simple object.

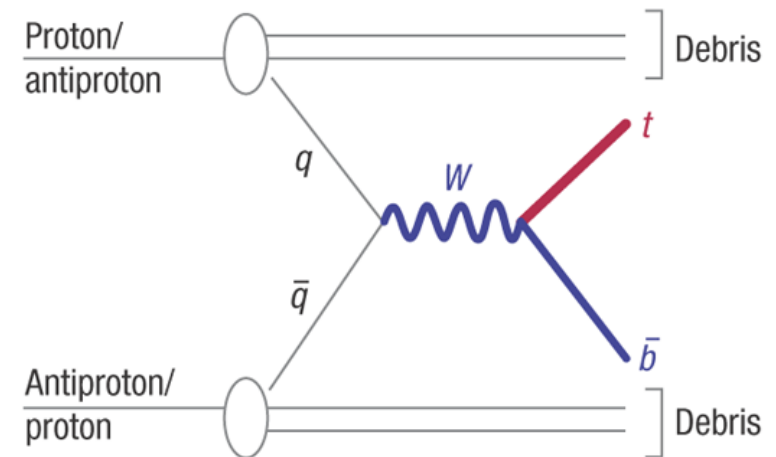
Protons are bags of valence quarks, gluons, and virtual quarks. Proton is a u-u-d valence quark combination, the “intrinsic mass” of the u is $1.9 \text{ MeV}/c^2$ and the d is $4.6 \text{ MeV}/c^2$ (an electron’s rest mass is $0.511 \text{ MeV}/c^2$). Yet the mass of the proton is $940 \text{ MeV}/c^2$!



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



VS





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 $50,350 \text{ fb} * 2 \text{ fb}^{-1}$ 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/>
- <http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-schedule-update.pdf>



Backup

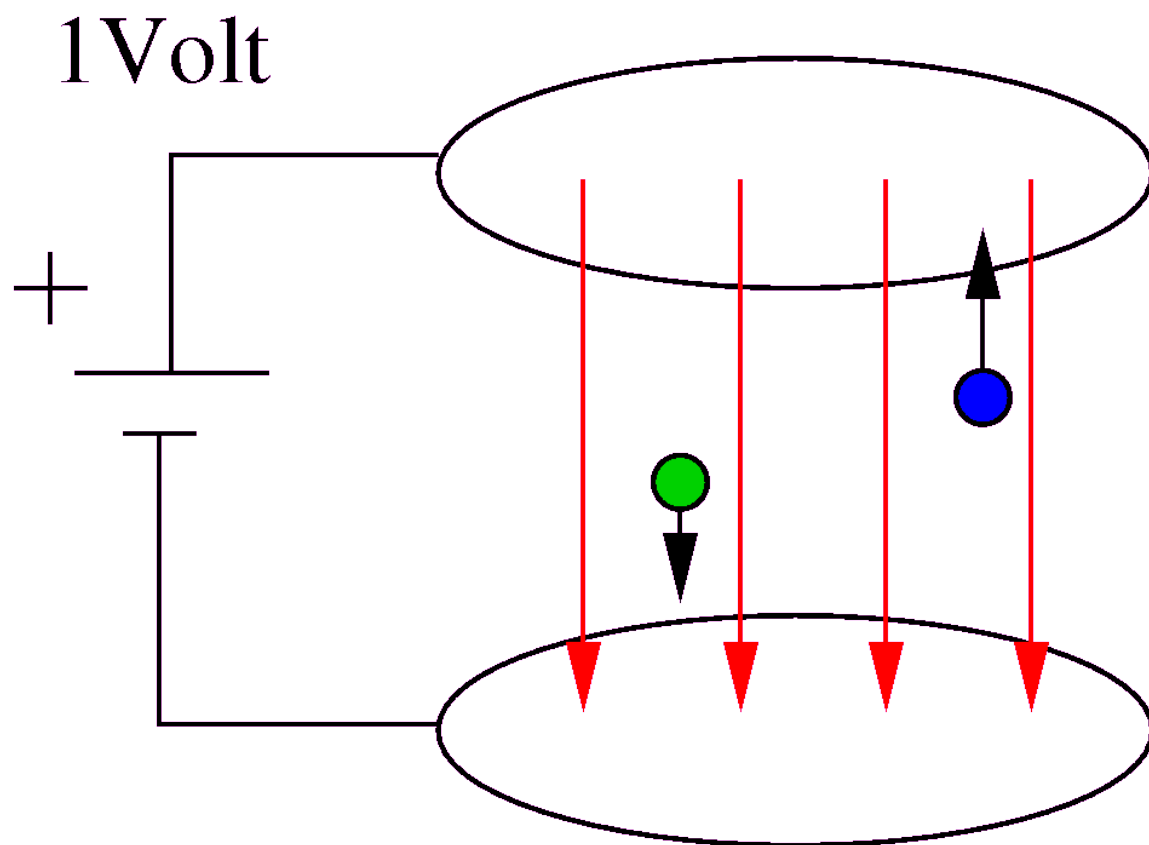


SI Prefixes

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 cm/ns

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

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