Lecture:

High Energy Frontier - Recent Results from the LHC

University of Heidelberg WS 2012/13

Prof. A. Schöning (Uni Heidelberg)

Dr. Ralf Averbeck (GSI Darmstadt)

Dr. Jeroen van Tilburg (Uni Heidelberg)

Goal of this Lecture

Presentation and discussion of **New Results** obtained at the Large Hadron Collider :

- LHC apparatus (A.S.)
- High Energy Frontier at ATLAS & CMS (A.S.)
- Heavy Ion Physics at ALICE (R.A.)
- Heavy Flavor Physics at LHCb (J.v.T.)

Organisation

Prerequisites:

Knowledge: Quantum Mechanics, Electrodynamics, special relativity, particle physics

Lectures: Physics I-V, Particle Physics (MKEP1)

Addressing:

Master Students with specialisation in Particle Physics and graduate students

No tutorial!

More Information on the Web:

http://www.physi.uni-heidelberg.de/~schoning/Vorlesungen/RecentLHC_WS12/

Literature

All results are new and can be found published in various journals or on the arXiv!

Slides of lecture are made available online

Lecture Dates

Dates: Thursday 14:15-16:00

Place: Inf 226, Conference Room 1-3

Dates: Thursday 14:15-16:00 Place: Conference 1-3 , INF 226

Date	Topic Thursday (Link)	Lecturer
18.10.12	LHC Accelerator	A.Schöning
25.10.12	Searches for New Physics I	A.Schöning
01.11.12	Fronleichnam	-
08.11.12	Search for New Physics II	A.Schöning
15.11.12	Higgs Discovery I	A.Schöning
22.11.12	Heavy Ions I	R.Averbeck
29.11.12	Higgs Discovery II	A.Schöning
06.12.12	Heavy Ions II	R.Averbeck
13.12.12	Heavy Ions III	R.Averbeck
20.12.12	Heavy Ions IV	R.Averbeck
10.01.13	Heavy Flavor I	J.Van Tilburg
17.01.13	Heavy Flavor II	J.Van Tilburg
24.01.13	Heavy Flavor III	J.Van Tilburg
31.01.13	Heavy Flavor IV	J.Van Tilburg
07.02.13	examination	-

“Leistungskontrolle”

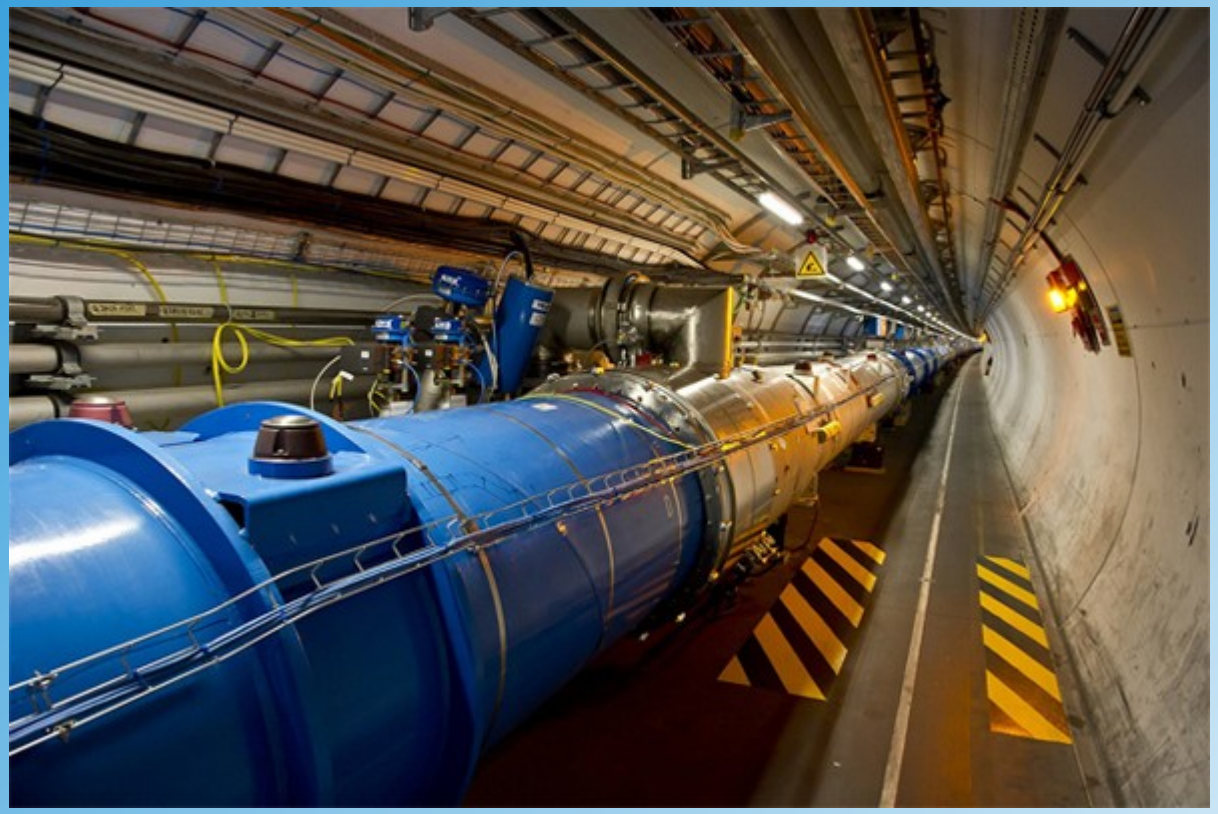
- attendance sheets regularly
- examination (small test) in last week
- number of credit points CP=2
- no grades given (only “pass”)

Feedback!

Questions?

Lecture 1

The LHC-Accelerator



Large Hadron Collider

Motivation for LHC

W,Z-Boson

Super-Proton Synchrotron, CERN

($s^{1/2}$=900 GeV, 6.9 km)

Top Quark

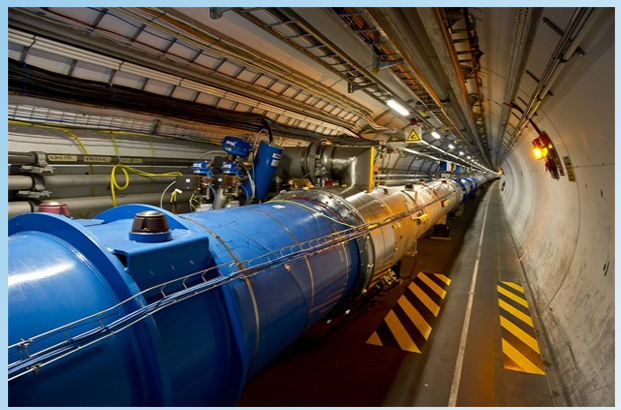
Tevatron, Fermilab 1989-2011

($s^{1/2}$=2 TeV, 6.3 km)

1993

Superconducting Super Collider

($s^{1/2}$=40 TeV, 88 km)



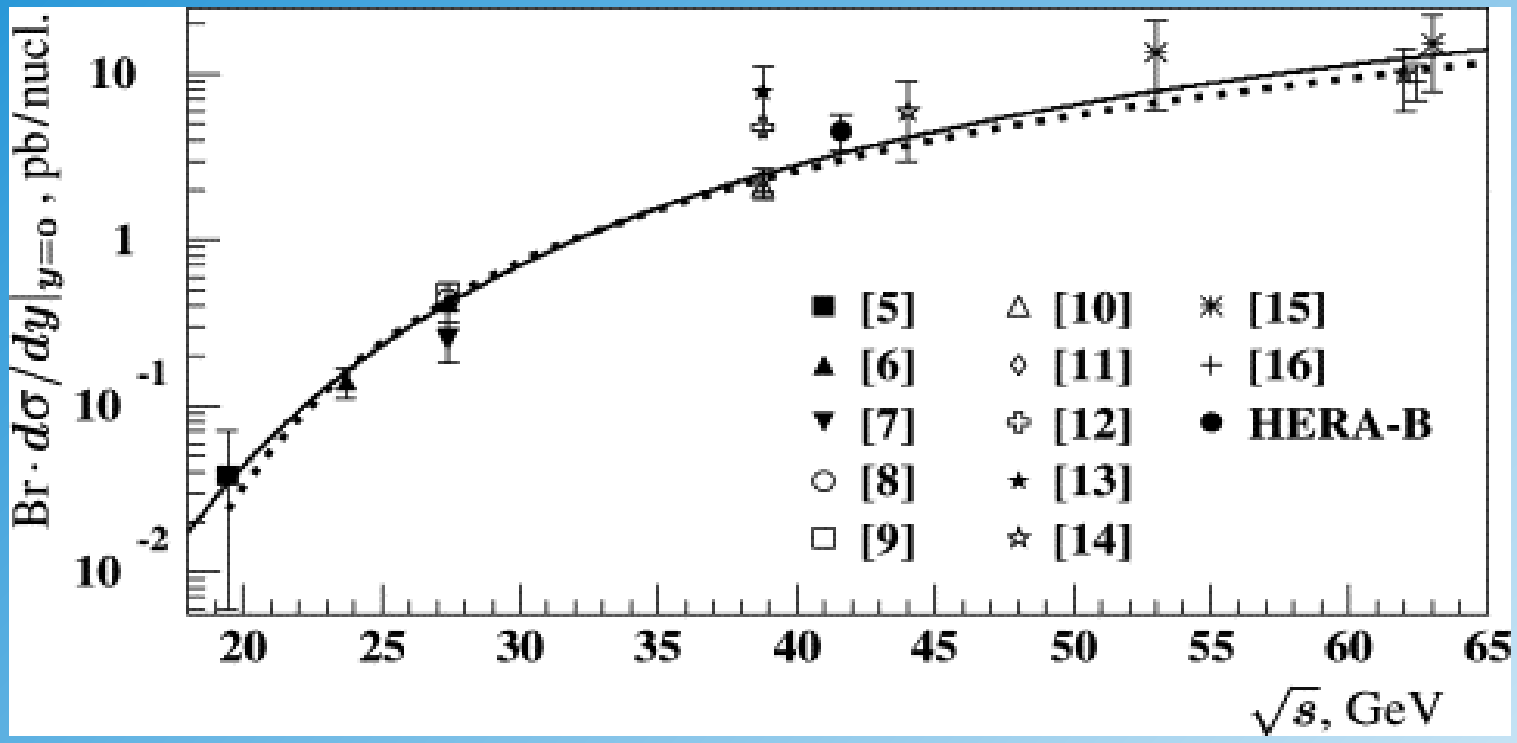
Large Hadron Collider, CERN since 2008

($s^{1/2}$=14 TeV, 30 km)

Physics at LHC

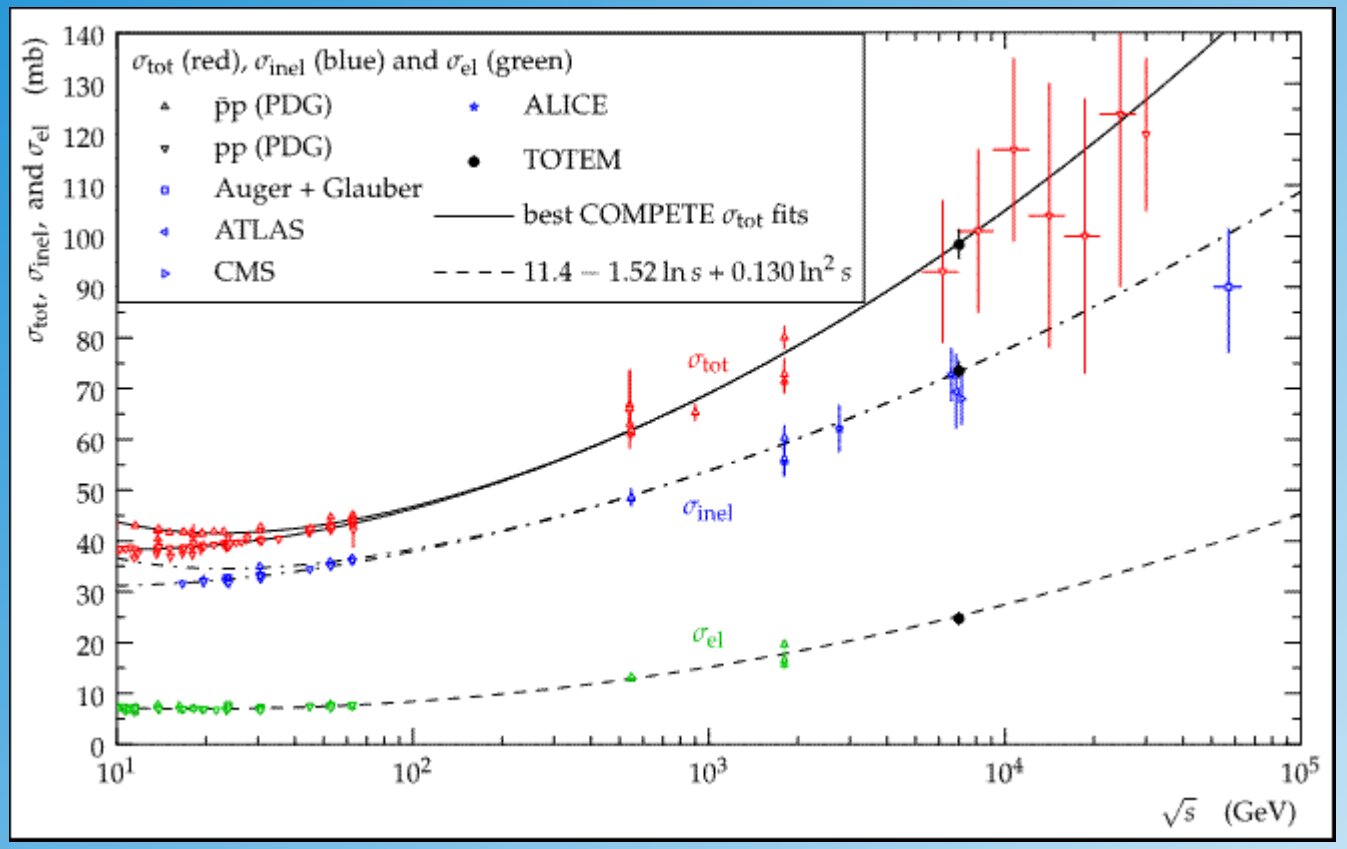
- New Physics Beyond the Standard Model
  (e.g. Supersymmetry)
- Search for the Higgs Boson and Electroweak Symmetry Breaking
  → 2 experiments (ATLAS+CMS)
- LHC is a B-Meson Factory → Plots
  → LHCb experiment
- Collision of Heavy Ions
  → dedicated ALICE experiment

Y-Meson Cross Section



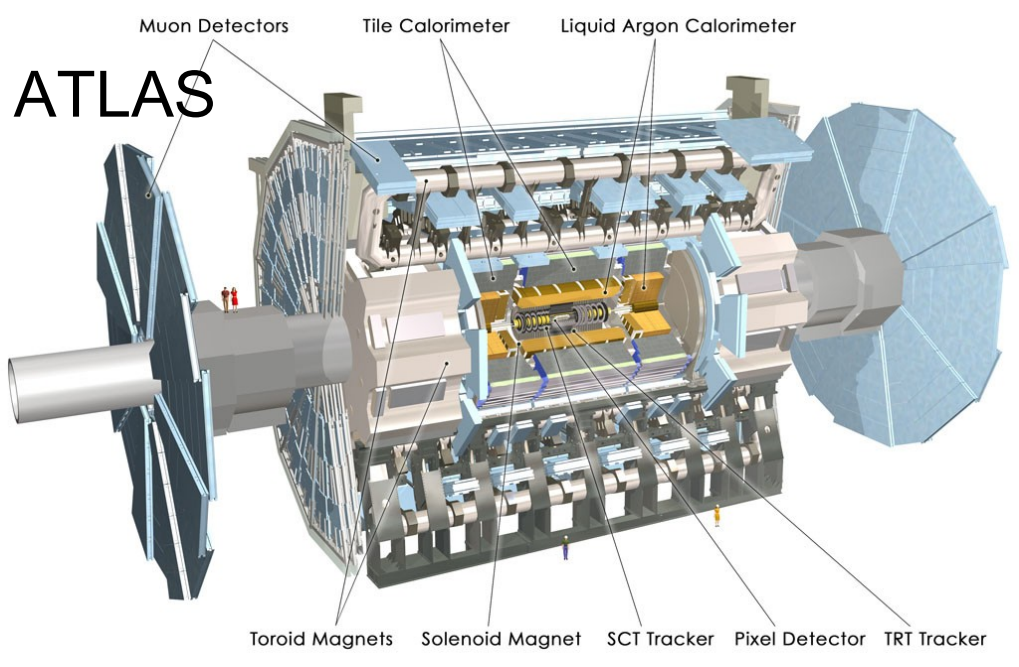
proton-proton cross section of Y-production (b anti-b resonance)

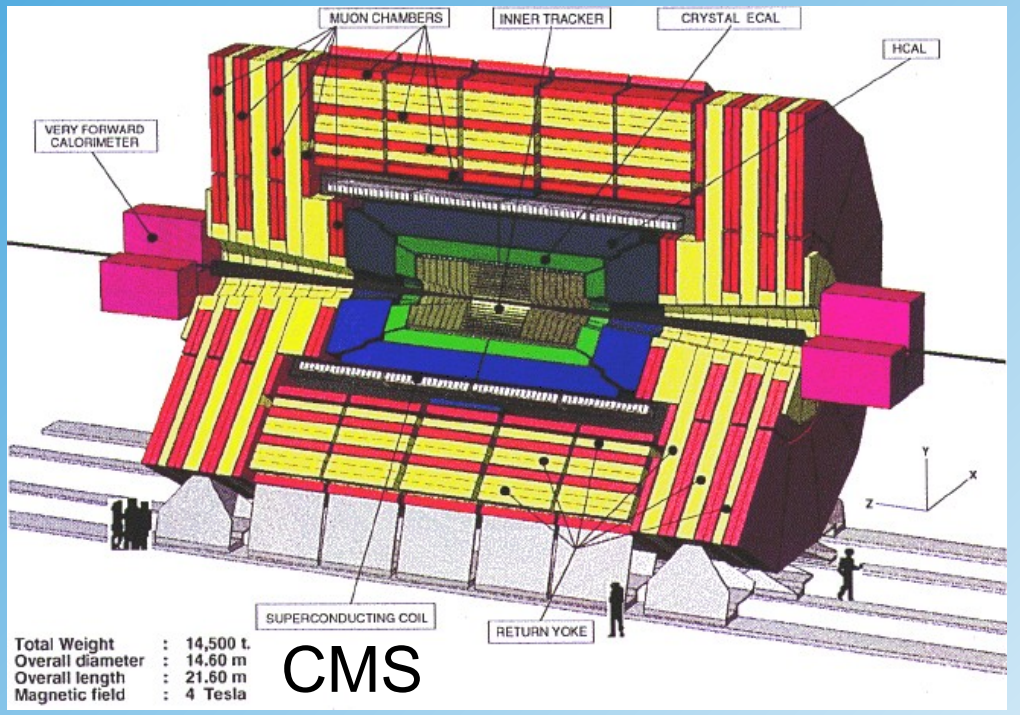
Total pp Cross Section

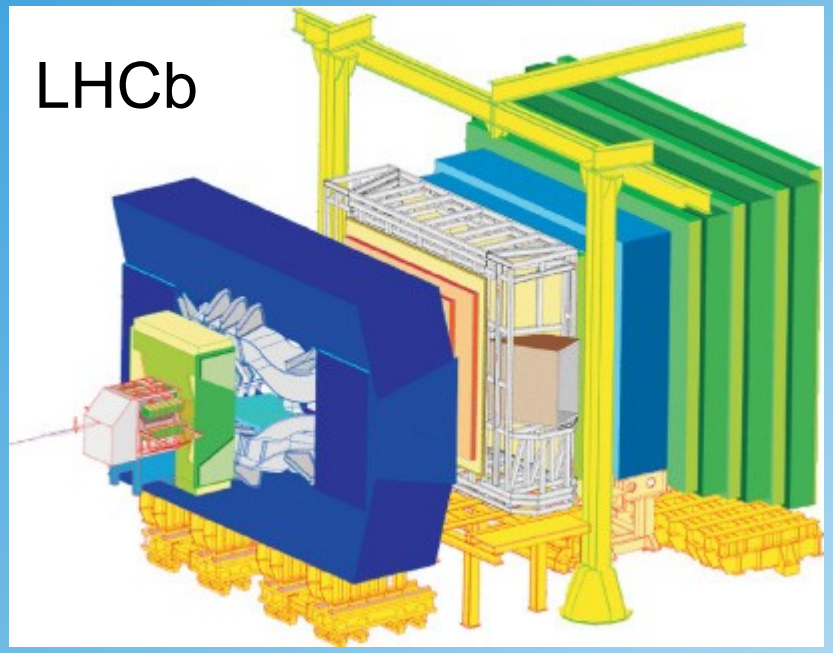


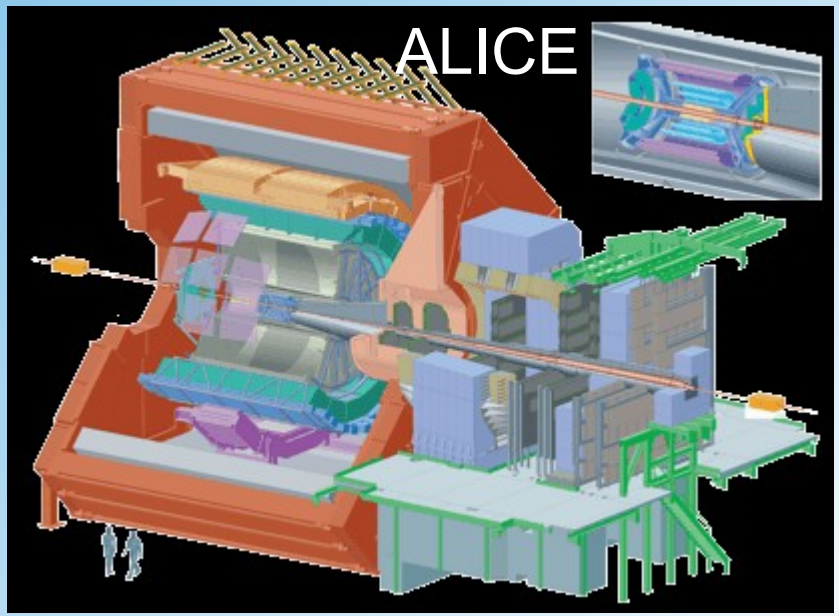
cross section rised logarithmically with cms energy

LHC Experiments









LHC Main Requirements

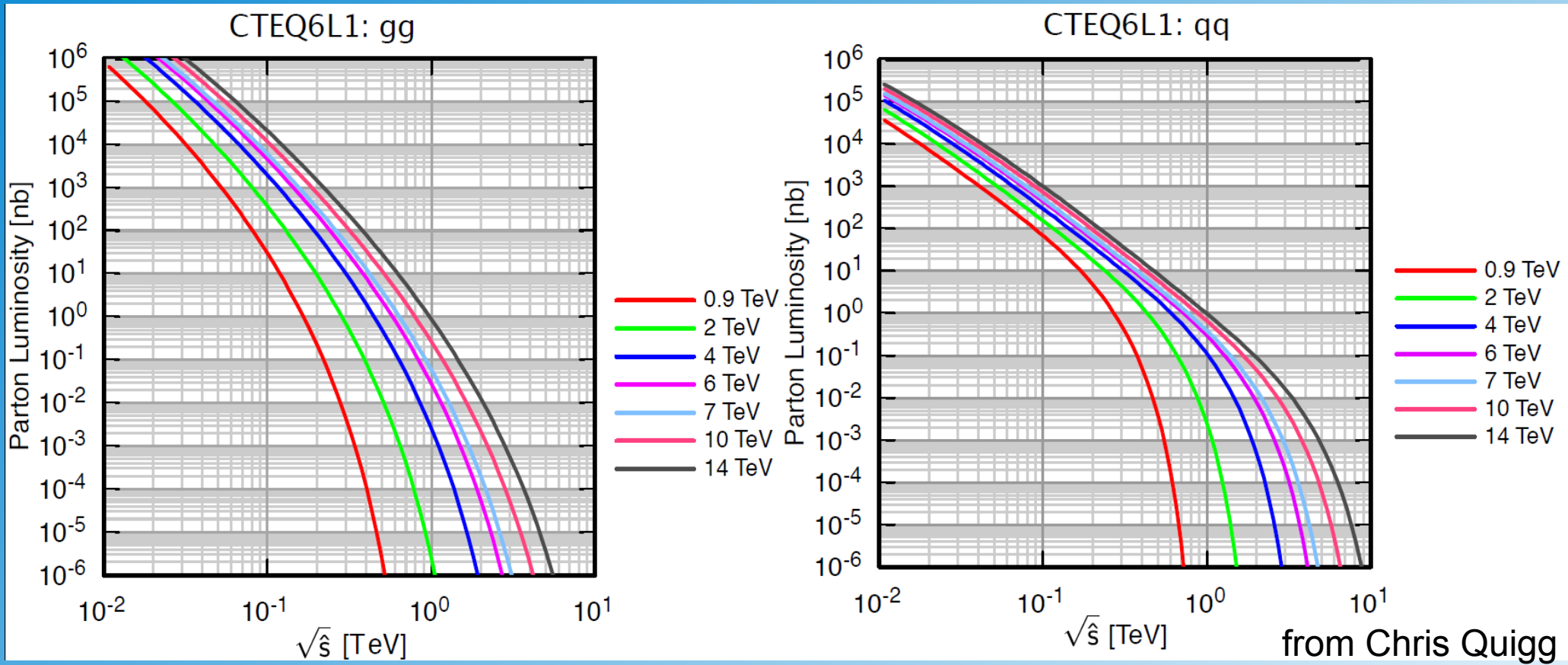
- New Physics (NP) is expected at the electroweak energy scale E_{weak}=246 GeV below 1 TeV
- LHC New Physics reach must cover the range ≤ 1 TeV also for small couplings → **14 TeV** (originally 10 TeV)
- In proton-proton collisions effective center of mass energy reach is determined by so called parton-luminosities → Plots
- The effective mass reach depends also crucially on integrated luminosity!

design luminosity: **$L=10^{34}$ cm^{-2} s^{-1}**

effective year: $t=10^7$ s (shutdown, injection, breaks, technical problems)

integrated luminosity: $L=10^{41}$ cm^{-2} = 100 fb^{-1}

Parton Luminosity



Example: $s^{1/2}$ = **14 TeV**, $\hat{s}^{1/2}$ = 1 TeV

cross section: $\sigma \sim 0.01^2$ parton luminosity ~ 0.1 pb (if couplings ~ 0.01)

luminosity $L=10\ pb^{-1} \rightarrow N_{event} = L\,\sigma = 1$ event

LHC Concept (1986)

(LEP operation 1989-2000)

Re-use 30 km tunnern from Large Electron Positron Collider

Basic Parameters

Lorentz force: $F = e\vec{v} \times \vec{B}$ $\quad p = 0.3\ RB\ (GeV/m/T)$

Magnetic field: B=8.3 T (Niobium titanium superconducter)

Radius: R=2800m (given by LEP tunnel geometry)

Momentum: p=7 TeV (maximum LHC proton energy)

LHC superconducting dipole magnet B=8.3T

Luminosity

Basic formula:

$$L = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

$f = u\, N_b$: collision frequency is given by repetition frequency u and number of bunches N_b

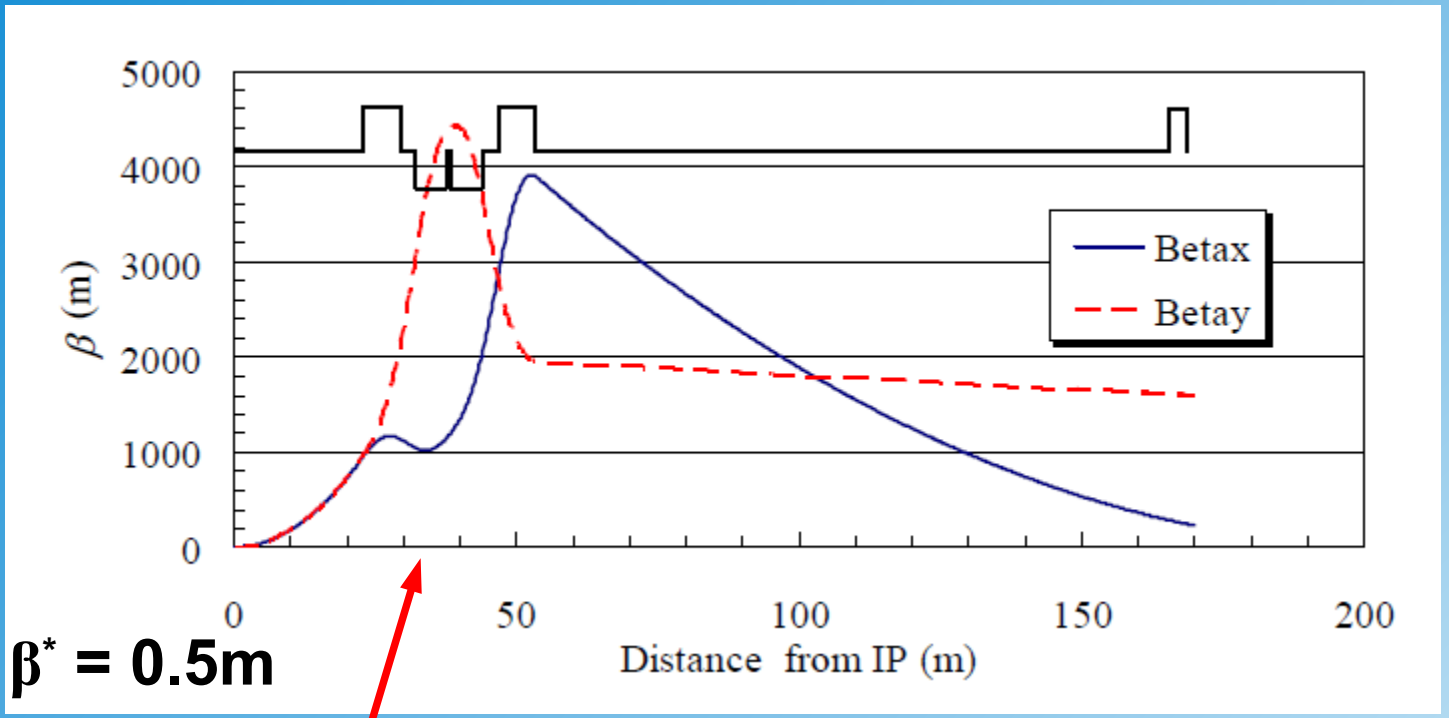
$N_{1,2}$: Number of protons by bunch is given by proton source, pre-accelerators and beam-beam limits

Beam size at interaction point:

The beam size is given by product of the Beta-function (magneto-optics) and the proton beam emittance (given by source, pre-accelerators and beam-beam interactions)

$$\sigma_{x,y} = \varepsilon_{x,y}\beta_{x,y}$$

Beta Function at IP



last quadrupoles (triplet)

- maximum beta given by strength of last focusing magnets
- minimum beta* given by distance of IA point to triplet

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \qquad \text{approximation:} \qquad \beta^* = \frac{s^2}{\beta}$$

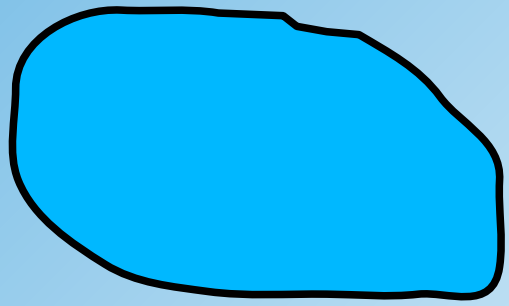
Emittance

The emittance describes the volume of the 6-dimensional phase occupied by the proton bunch

$$\varepsilon_x \varepsilon_y \varepsilon_z = \Delta x \Delta y \Delta z \ \Delta x' \Delta y' \Delta z'$$

$$x' = p_x/p \qquad y' = p_y/p \qquad z' = p_z/p$$

unit: [m mrad]



phase space

Emittance can be reduced in e^+e^- machines due to synchrotron radiation damping, however for protons at LHC: P_{sync}=3.6 kW

$$P_{sync} = \frac{2}{3} r_e m_e c^3 \frac{\gamma^4}{R^2}$$

Note, emittance (beam size) shrinks during acceleration process ("adiabatic damping")

LHC Machine Parameters II

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

LHC Machine Parameters III

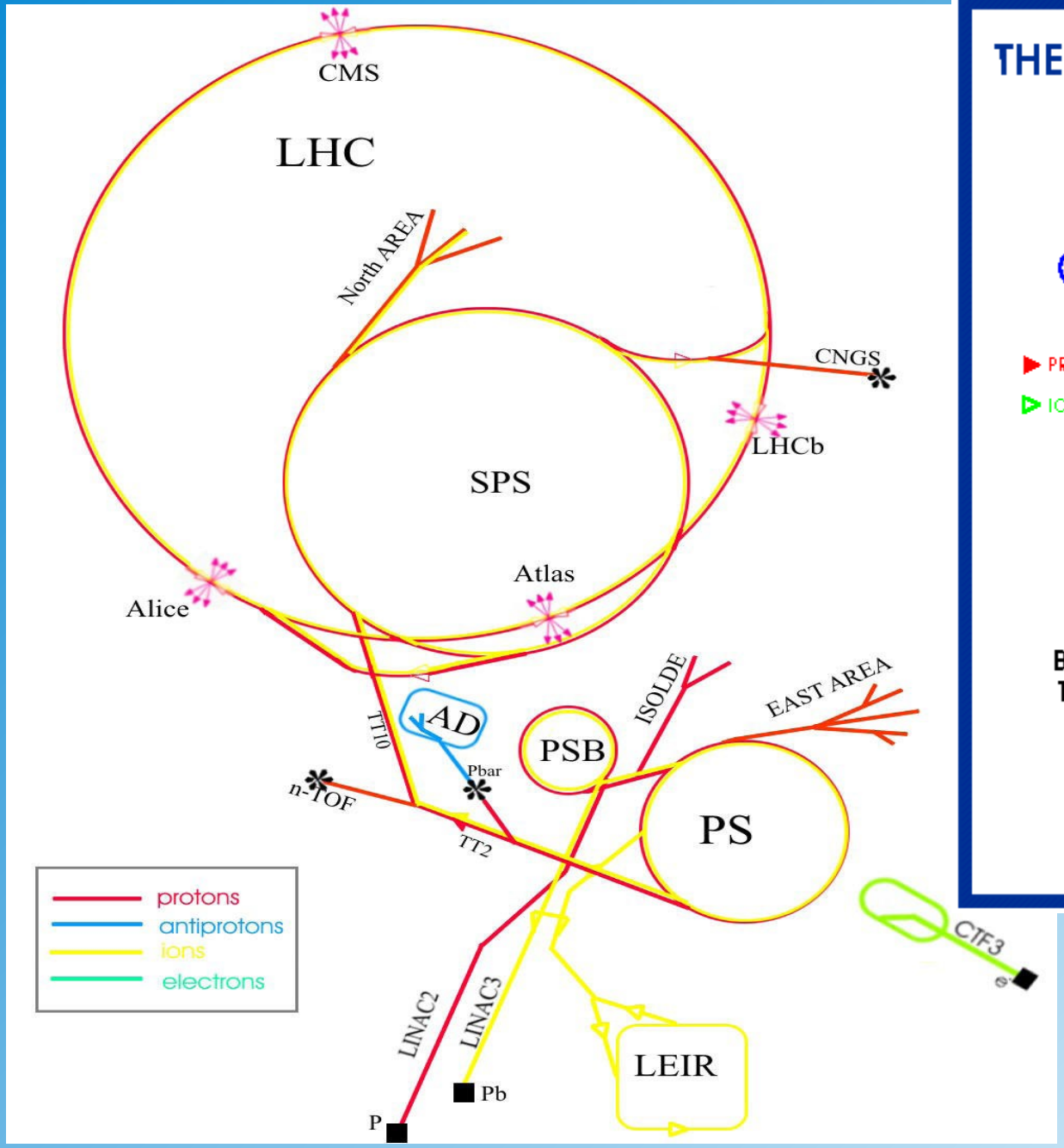
Table 2.3: LHC machine parameter relevant for the peak luminosity

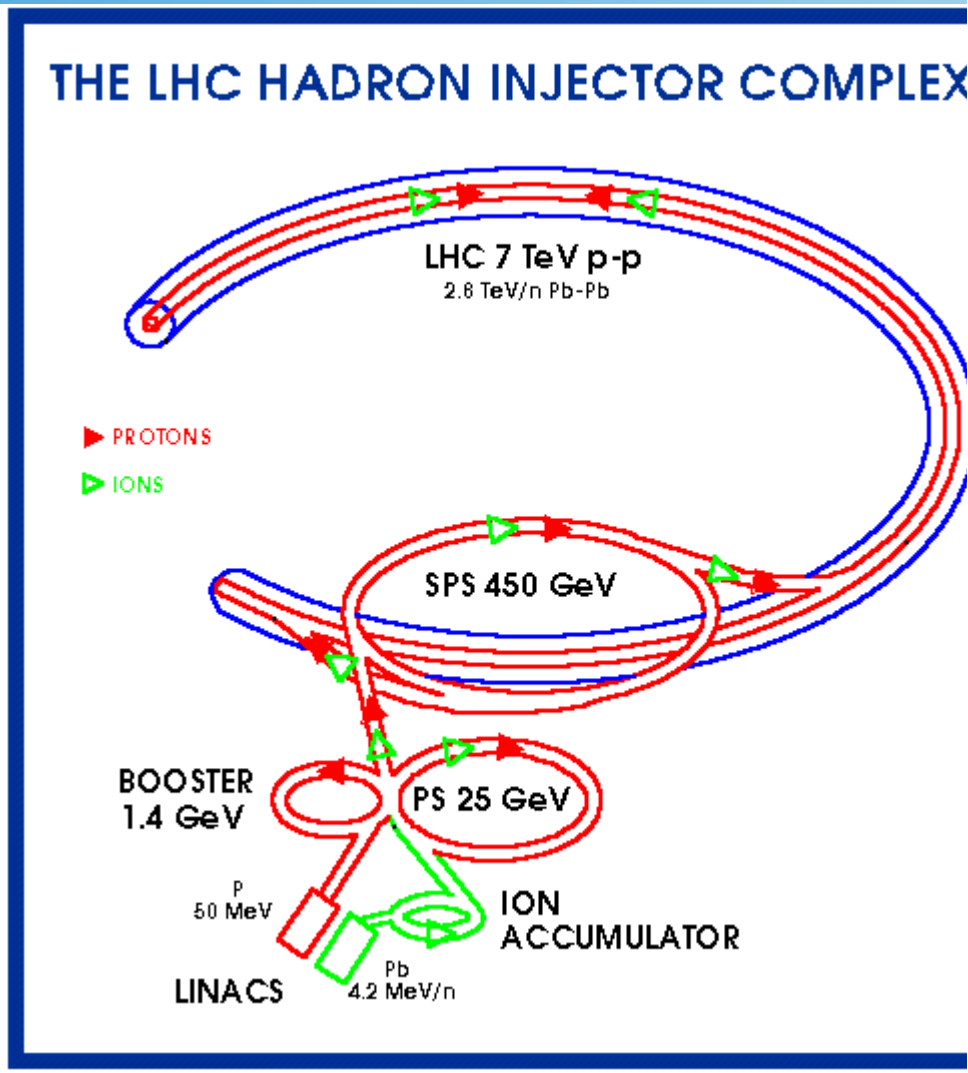
		Injection	Collision
Interaction Data			
Number of collision points		4	
Half crossing angle for ATLAS and CMS (IP1/IP5)	[μrad]	$\pm$160	$\pm$142.5
Half parallel separation at IP for ATLAS and CMS (IP1/IP5)	[mm]	$\pm$2.5	0.0
Half crossing angle at IP [a] for ALICE (IP2)	[μrad]	$\pm$240	$\pm$150
Half parallel separation at IP for ALICE	[mm]	$\pm$2.0	$\pm$0.178 (5 σ total separation)
Half crossing angle at IP [a] for LHCb (IP8)	[μrad]	$\pm$300	$\pm$200
Half parallel separation at IP for LHCb (IP8)	[mm]	$\pm$2.0	0.0
Plane of crossing in IP1		vertical	
Plane of crossing in IP2		vertical	
Plane of crossing in IP5		horizontal	
Plane of crossing in IP8		horizontal	
β at IP1 and IP5	[m]	18	0.55
β at IP2	[m]	10	0.5 for Pb / 10 for p
β at IP8	[m]	10	1.0 $\leftrightarrow$ 50

LHC Machine Parameters I

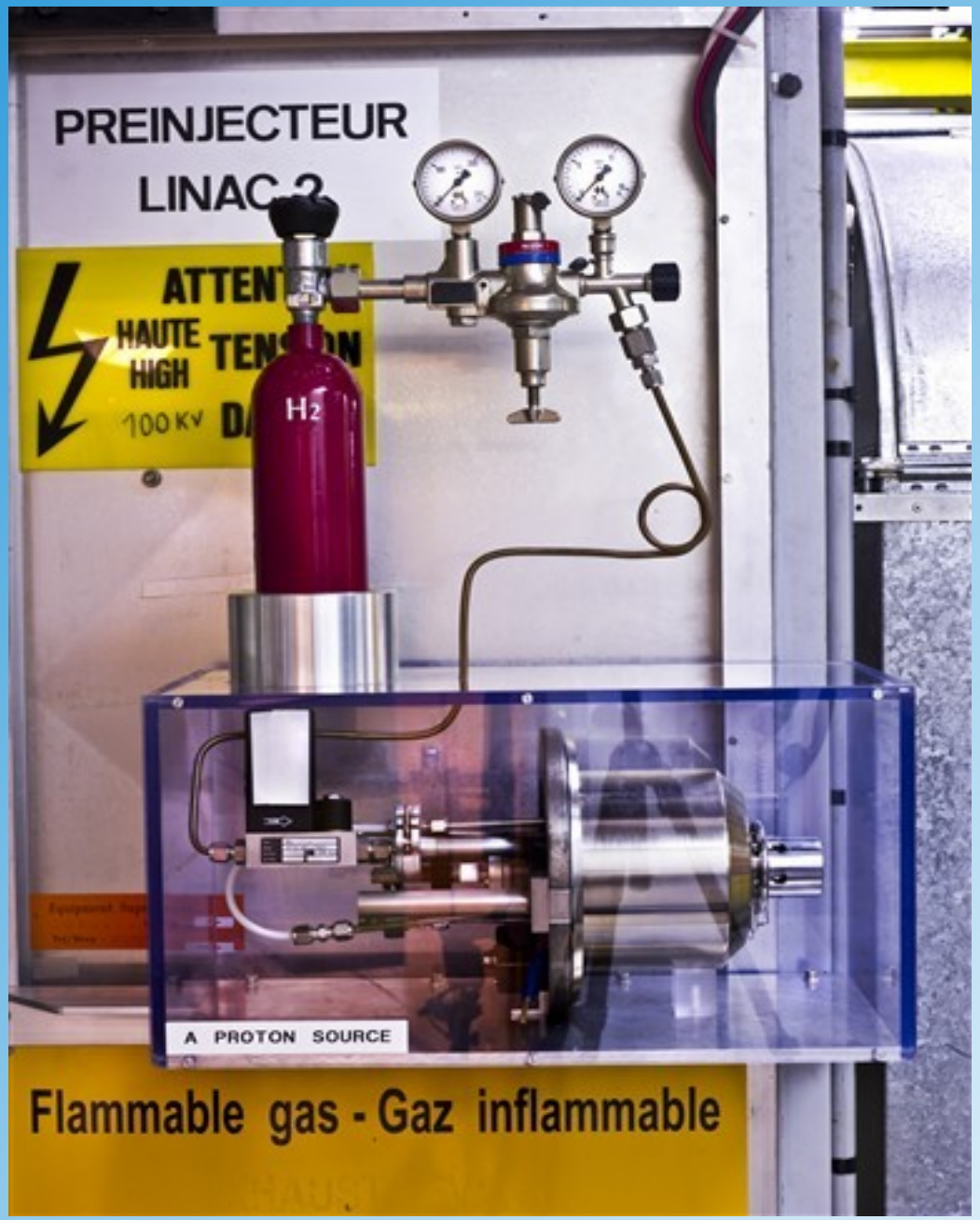
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.06	1.129
RMS bunch length	[cm]	11.24	7.55
Longitudinal emittance growth time	[hours]	30[a]	61
Horizontal emittance growth time	[hours]	38[a]	80
Total beam and luminosity lifetimes[b]			
Luminosity lifetime (due to beam-beam)	[hours]	-	29.1
Beam lifetime (due to rest-gas scattering)[c]	[hours]	100	100
Beam current lifetime (beam-beam, rest-gas)	[hours]	-	18.4
Luminosity lifetime (beam-beam, rest-gas, IBS)	[hours]	-	14.9
Synchrotron Radiation			
Instantaneous power loss per proton	[W]	3.15×10^{-16}	1.84×10^{-11}
Power loss per m in main bends	$[\mathrm{Wm}^{-1}]$	0.0	0.206
Synchrotron radiation power per ring	[W]	6.15×10^{-2}	3.6×10^{3}
Energy loss per turn	[eV]	1.15×10^{-1}	6.71×10^{3}
Critical photon energy	[eV]	0.01	44.14
Longitudinal emittance damping time	[hours]	48489.1	13
Transverse emittance damping time	[hours]	48489.1	26

Overview Accelerator Chain

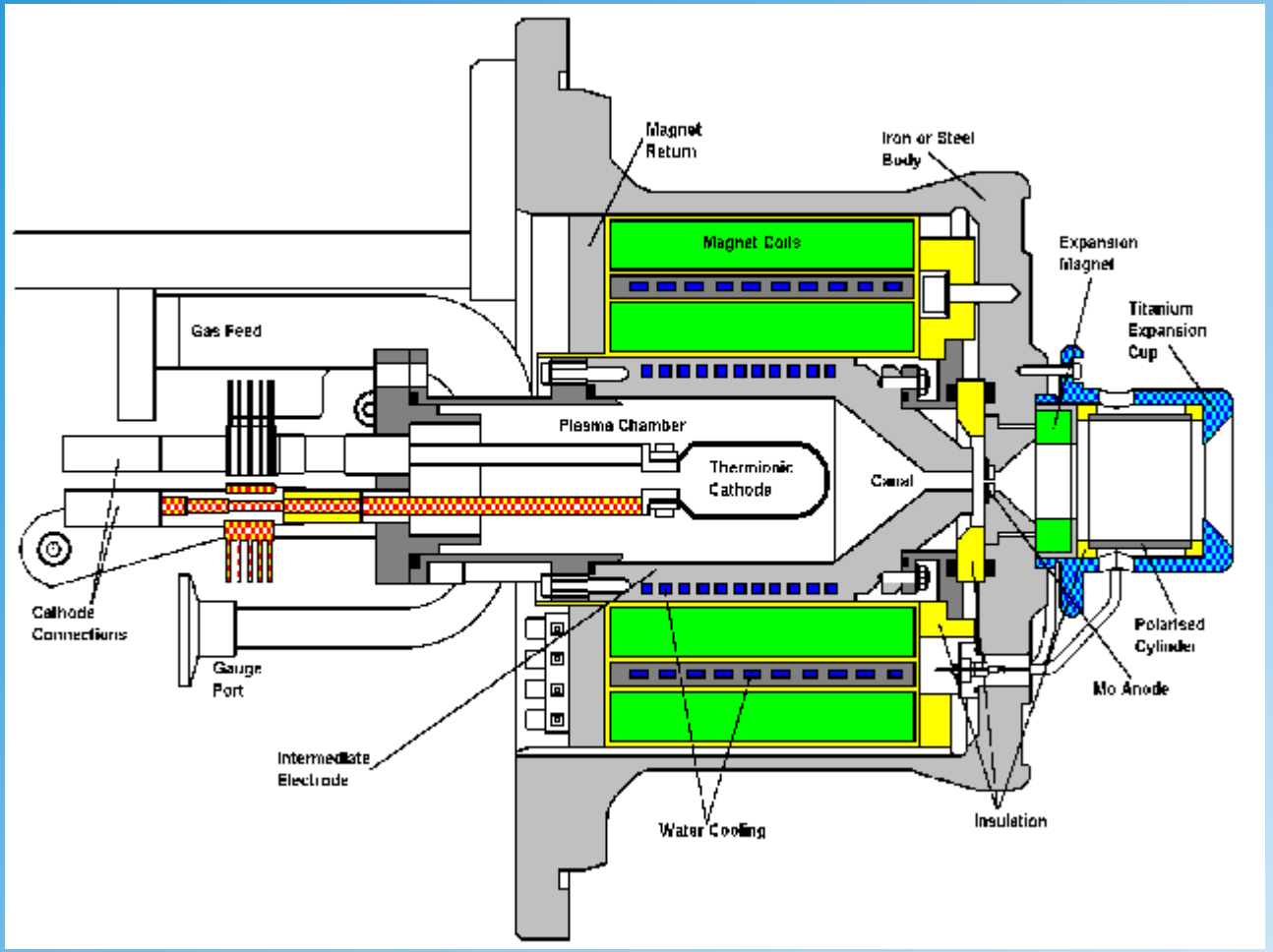




The Proton Source

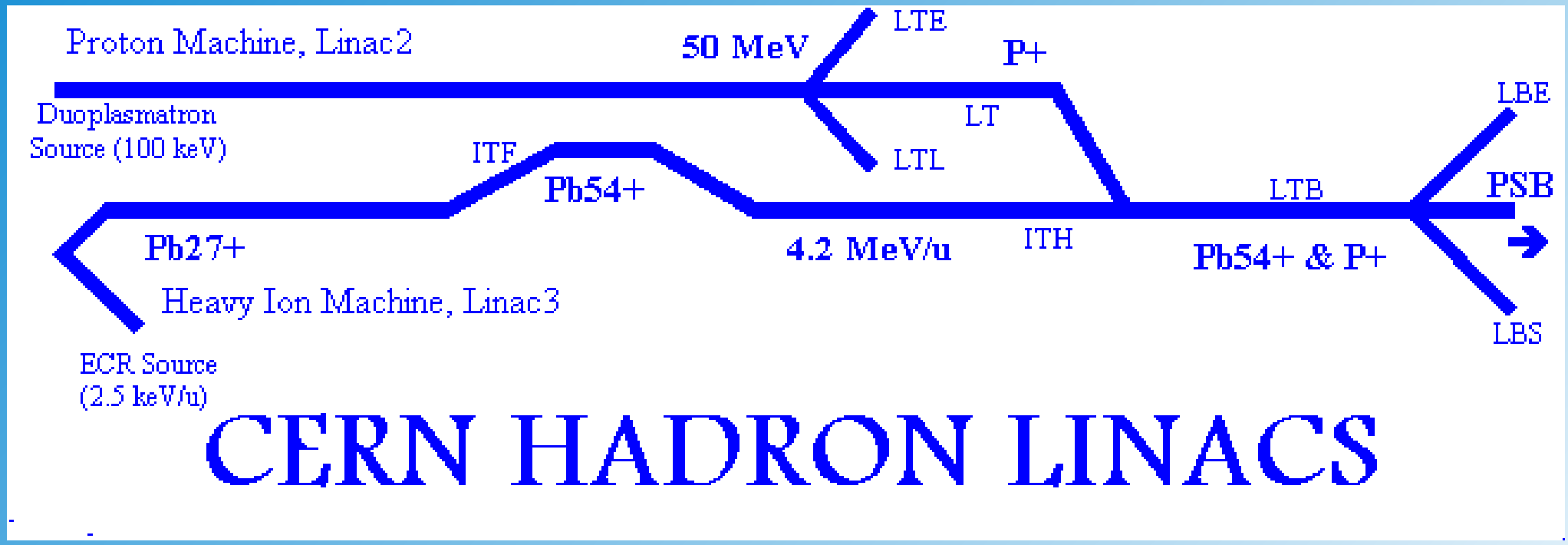


Duo-Plasmotron

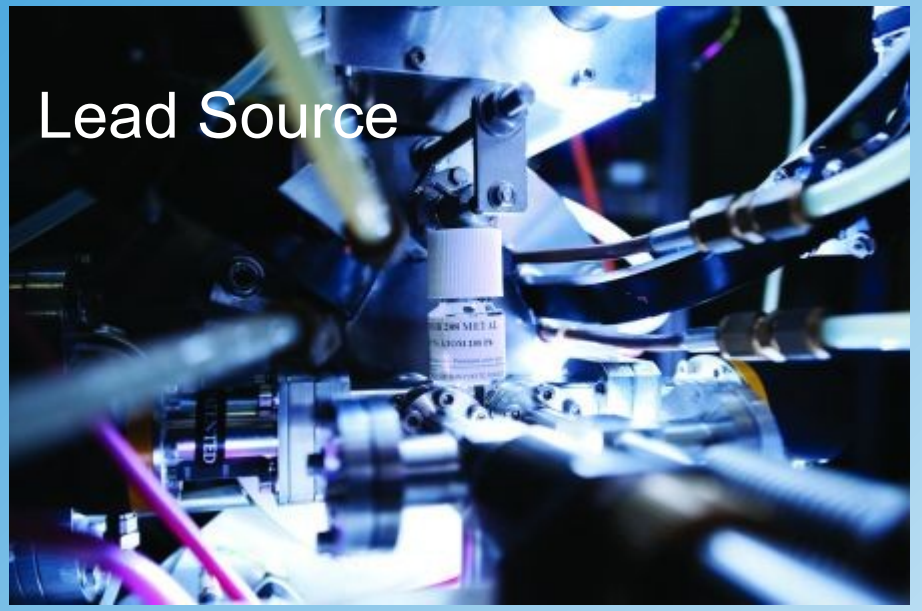


hydrogen (metal) plasma used to create protons (ions)

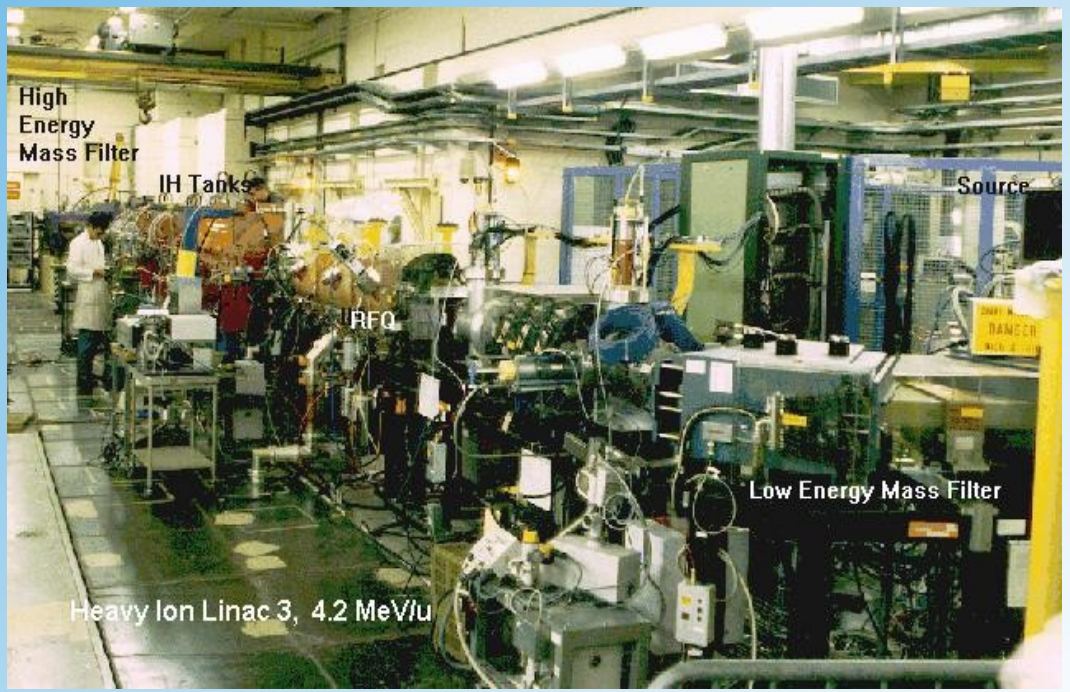
CERN Hadron Linacs



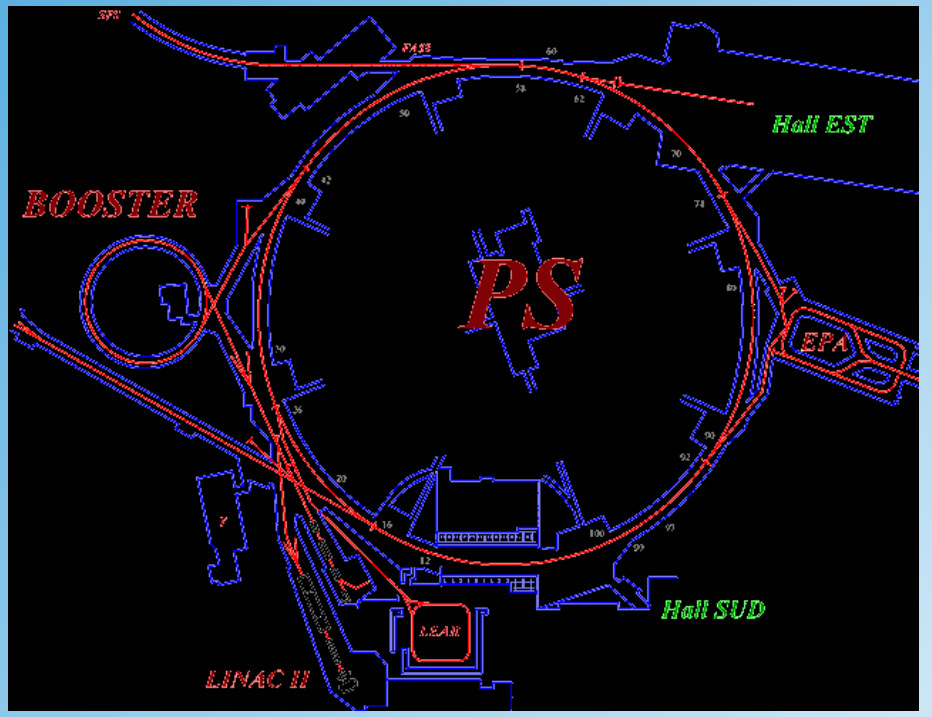

Duo-Plasmotron


Lead Source


LINAC2


High
Energy
Mass Filter
IH Tanks
Source
RFQ
Low Energy Mass Filter
Heavy Ion Linac 3, 4.2 MeV/u

CERN PS (24 GeV)



Parameter name	Unit	Value
Injection kinetic energy	GeV	1.4
Maximum momentum	GeV/c	26
Dipole field at 26 GeV/c	T	1.26
Radius	m	100.000
Curvature radius	m	70.079
g_t		~ 6.1
Pipe half height	cm	3.5
Pipe half width	cm	7.0

CERN SPS 450 GeV (since 1976)

Super Proton Synchrotron, CERN

Note, a proton synchrotron (fixed orbit, varying magnetic dipole fields) have a limited range of operation (magnetic saturation, beam stability)

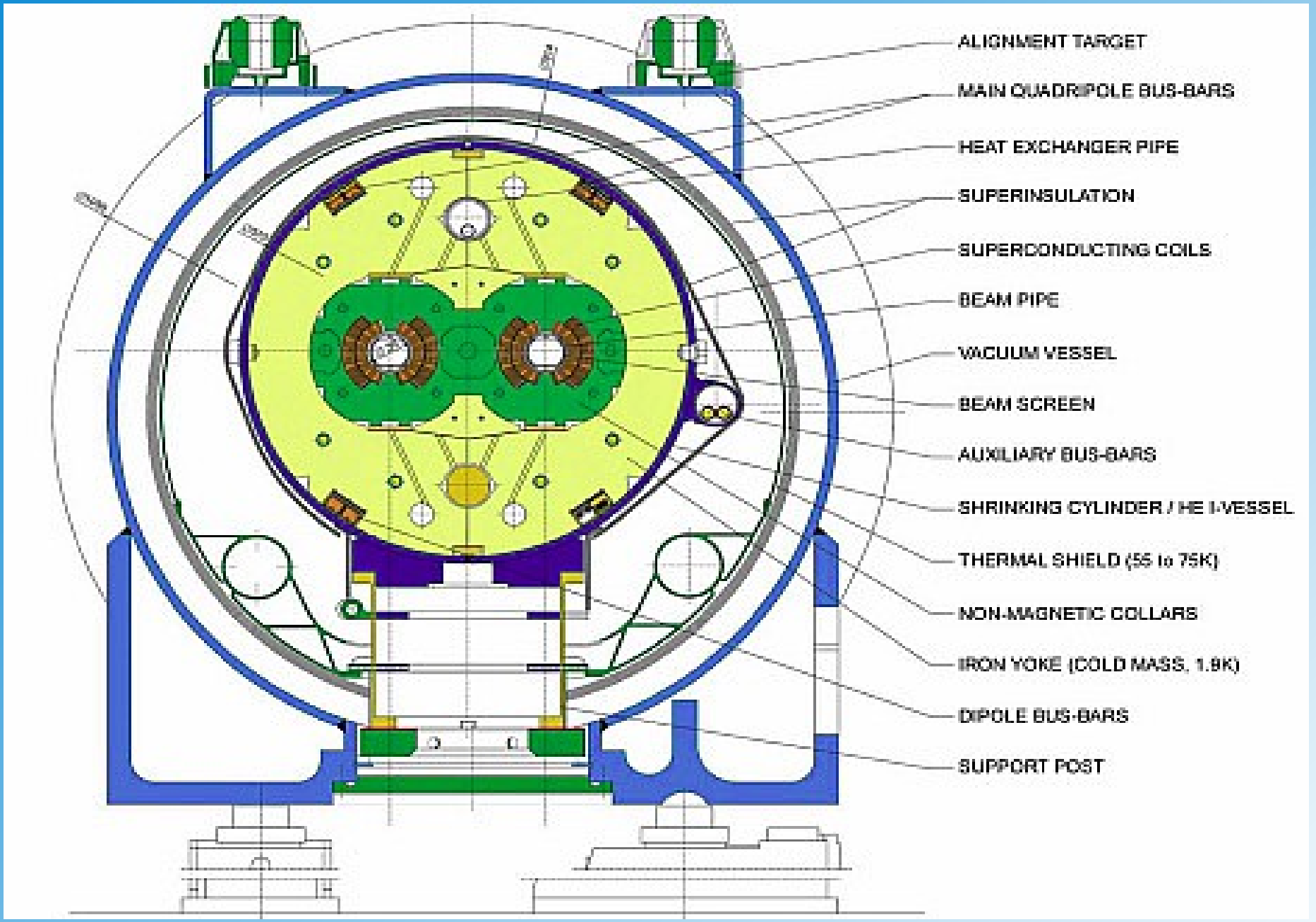
Large Hadron Collider (CERN)

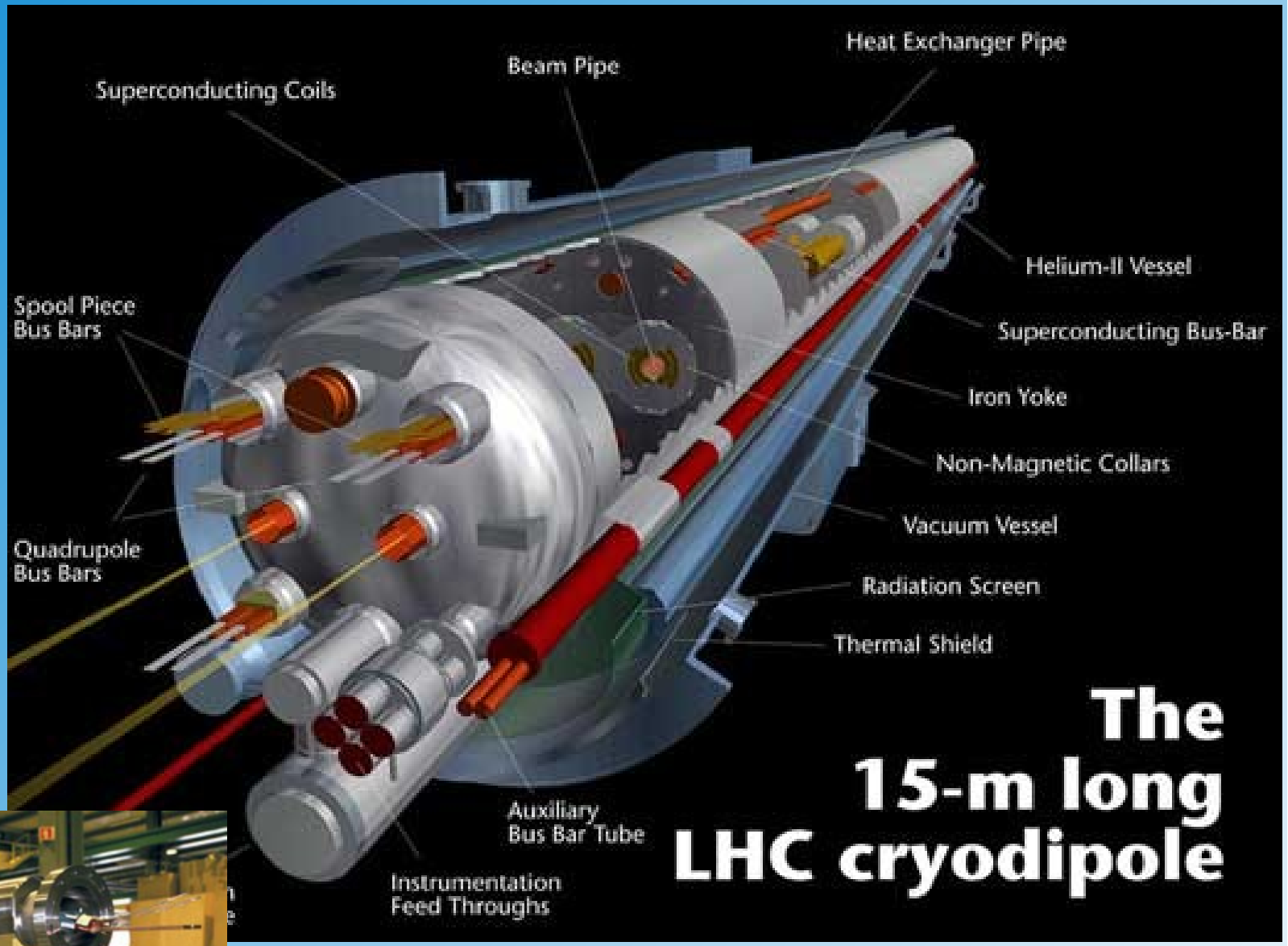
LHC (pp) 7(14) TeV

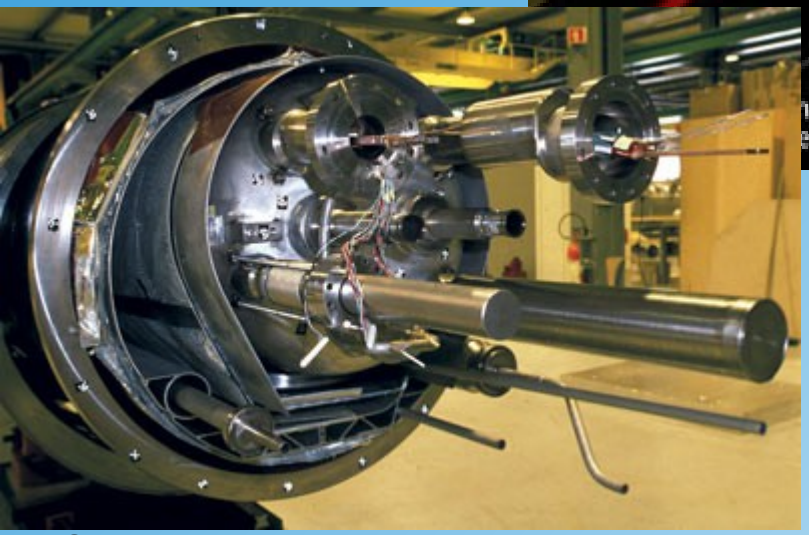
operation started in 2008

26.7 km circumference!

LHC Superconducting Magnet





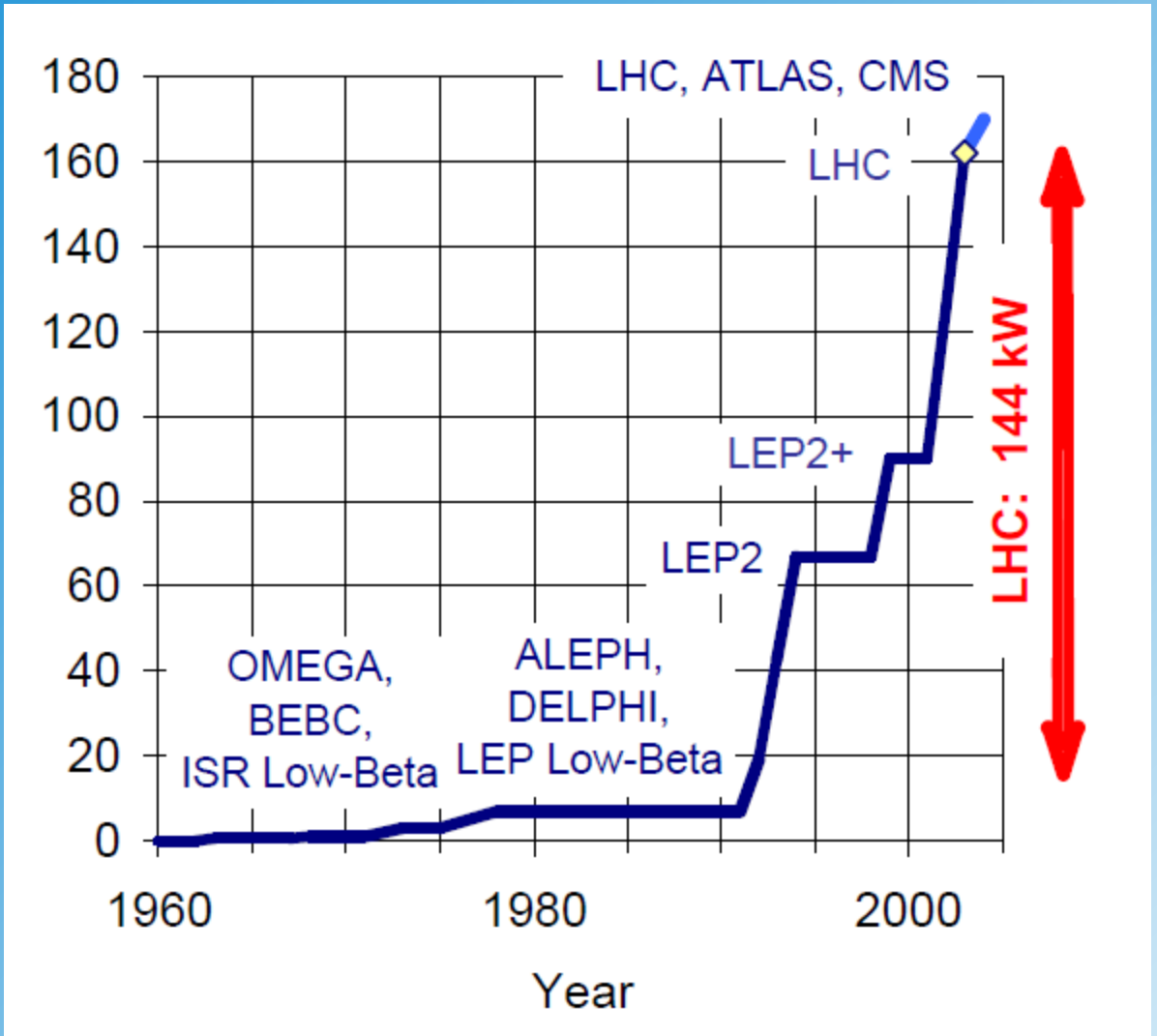


~ 1400 modules

LHC Cryogenic System

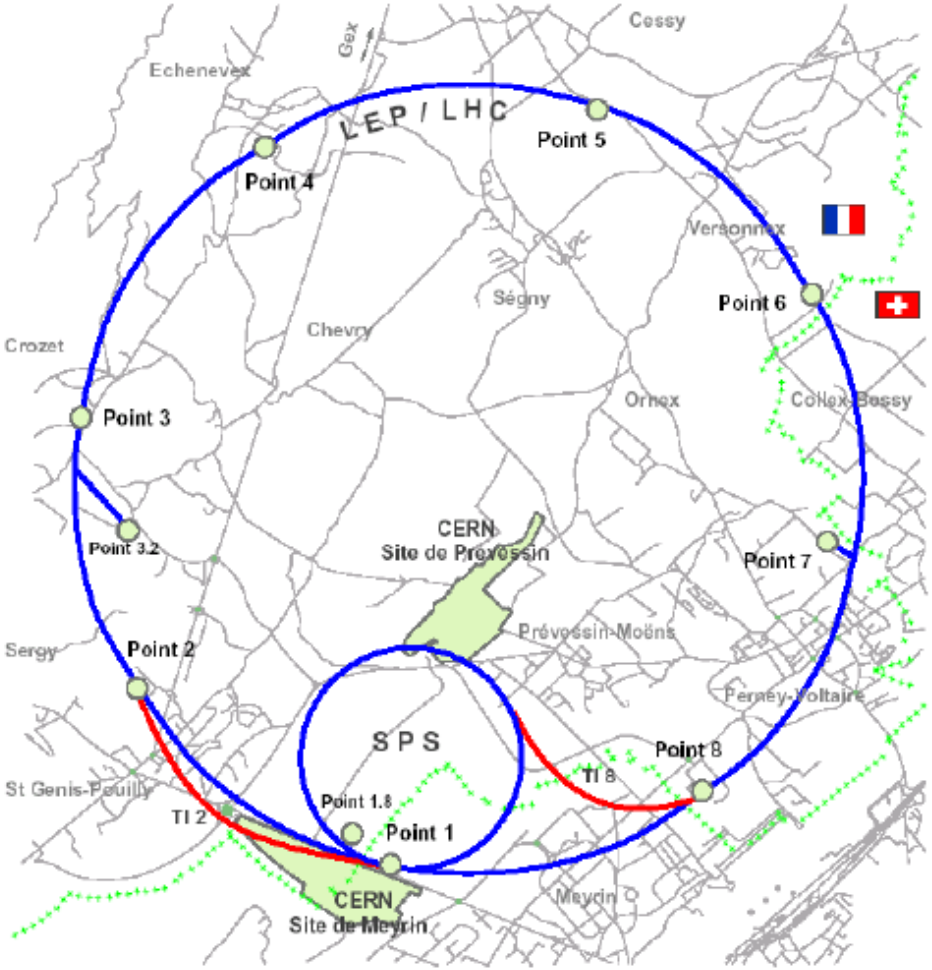
Superfluid Helium (2K)

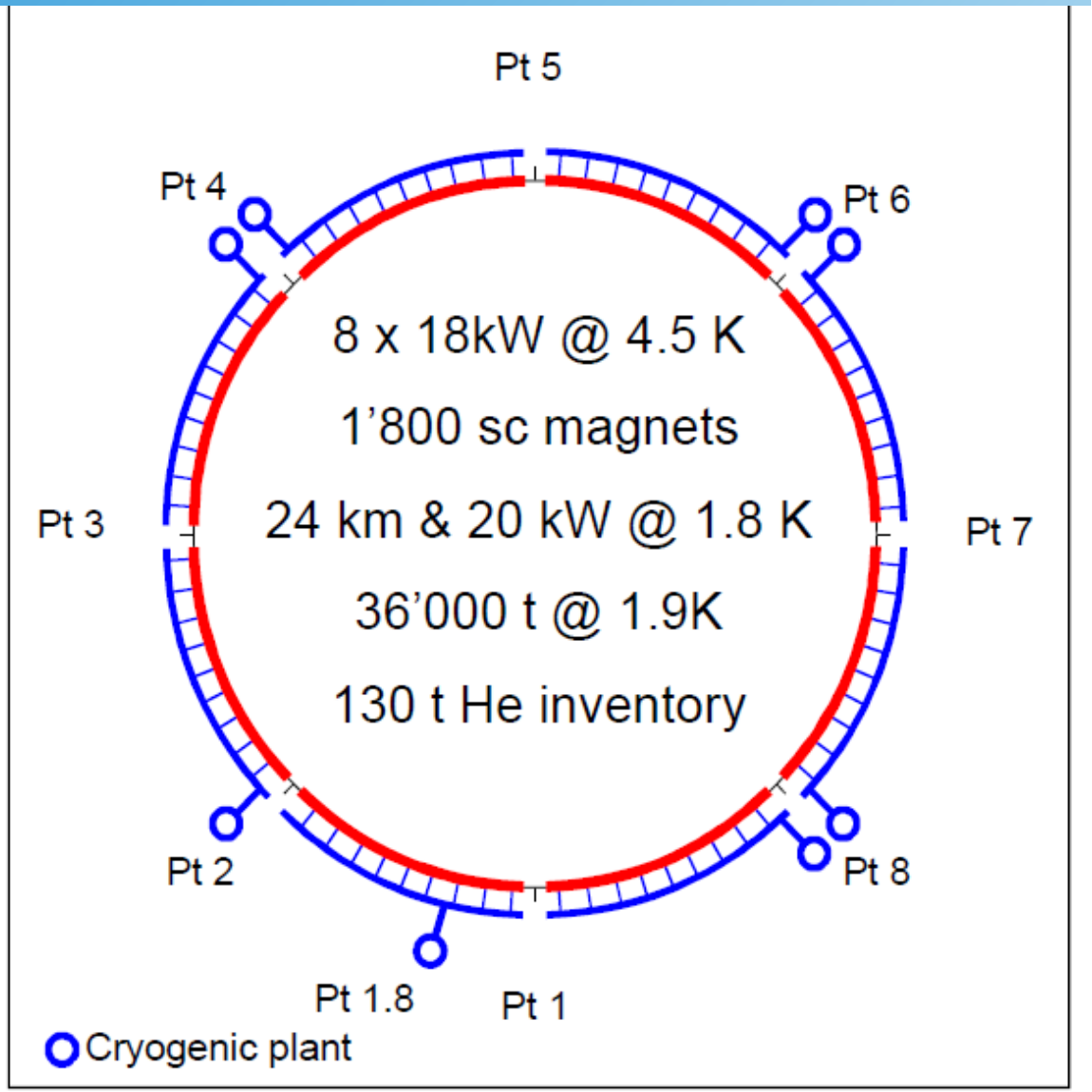
CERN Cryogenic power



from S.Claudet

LHC Cryogenic System

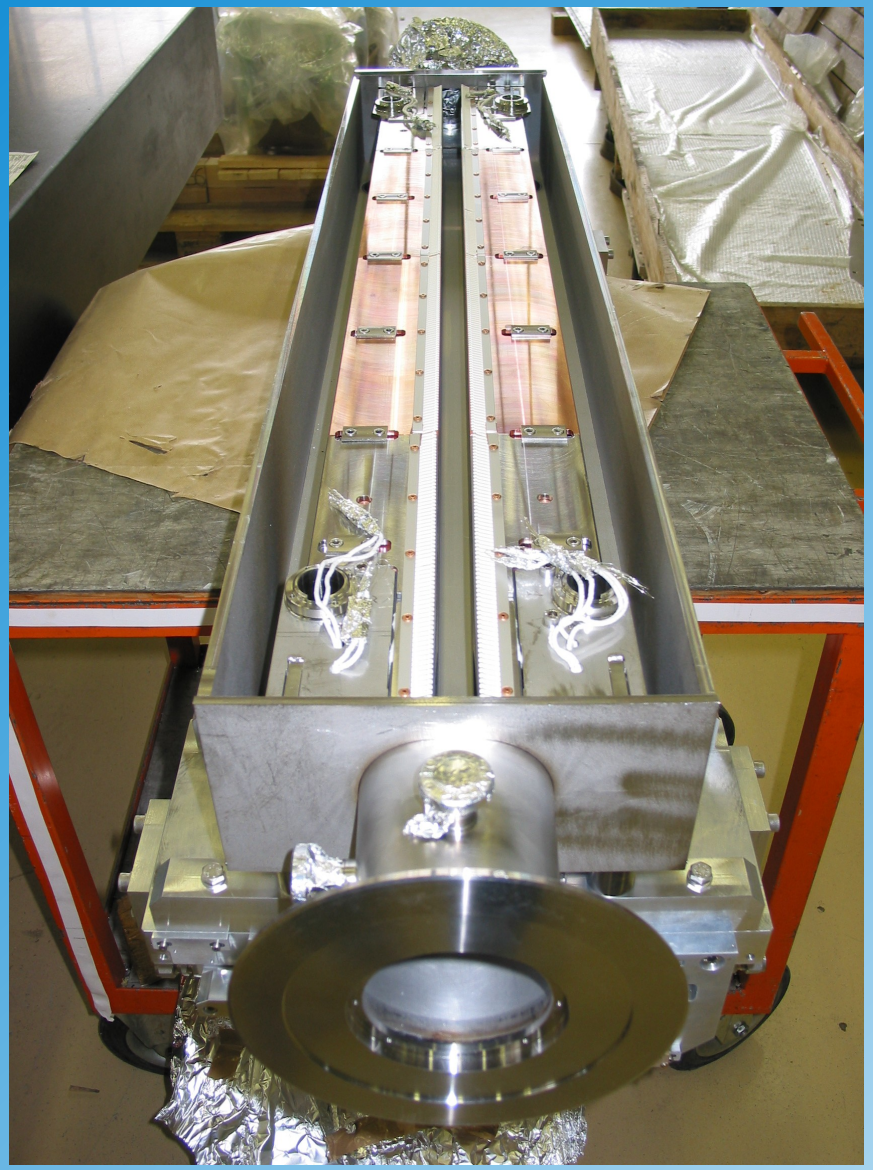


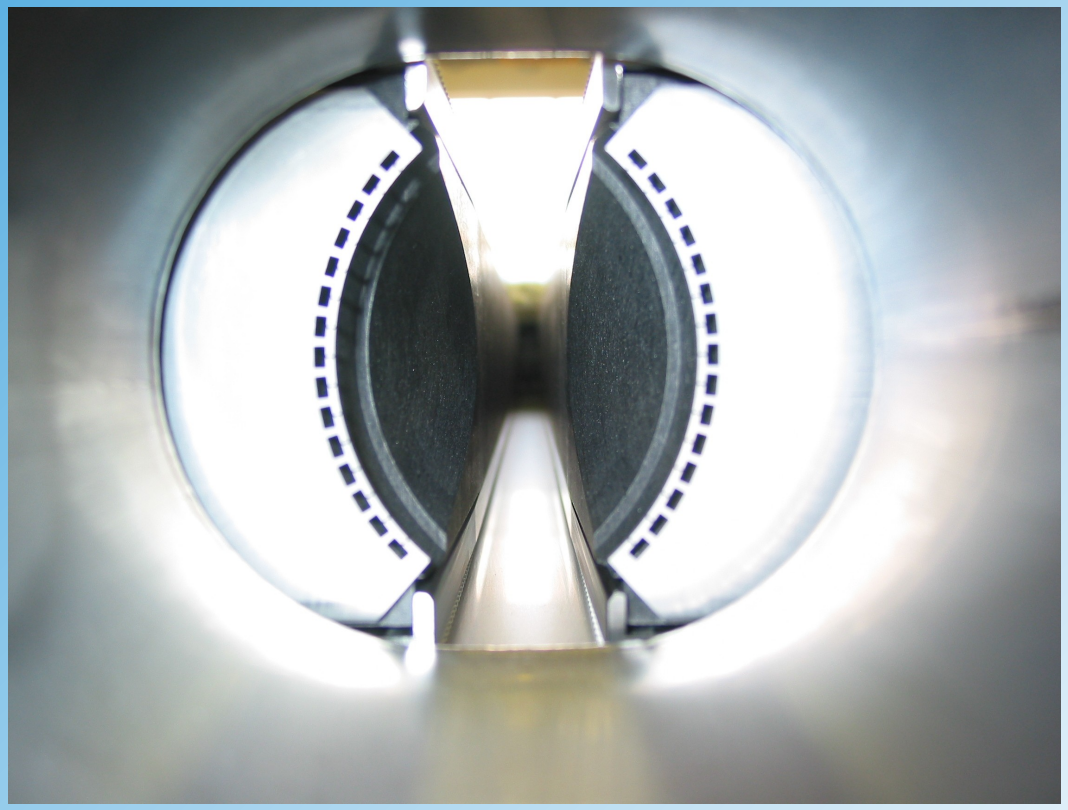


from S.Claudet

LHC Collimator System

Task: absorb halo proton and neutrons straying around the beam

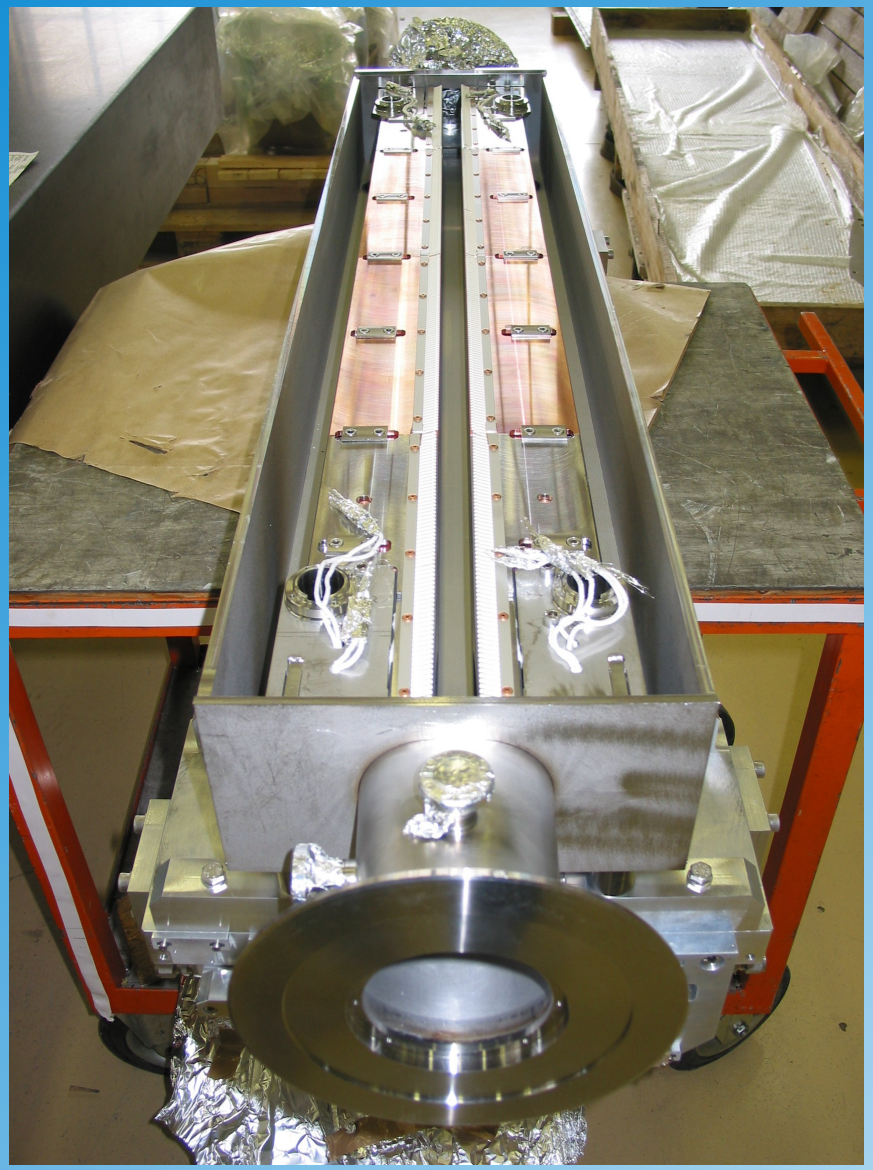


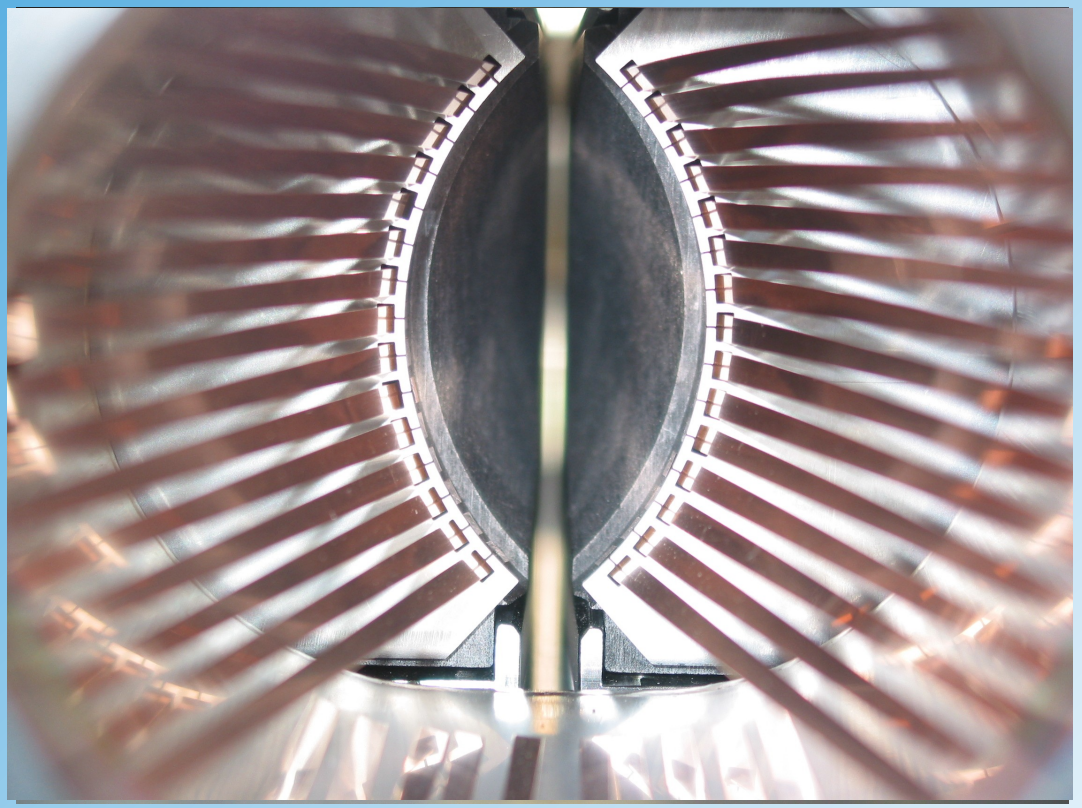


movable jaws

LHC Collimator System

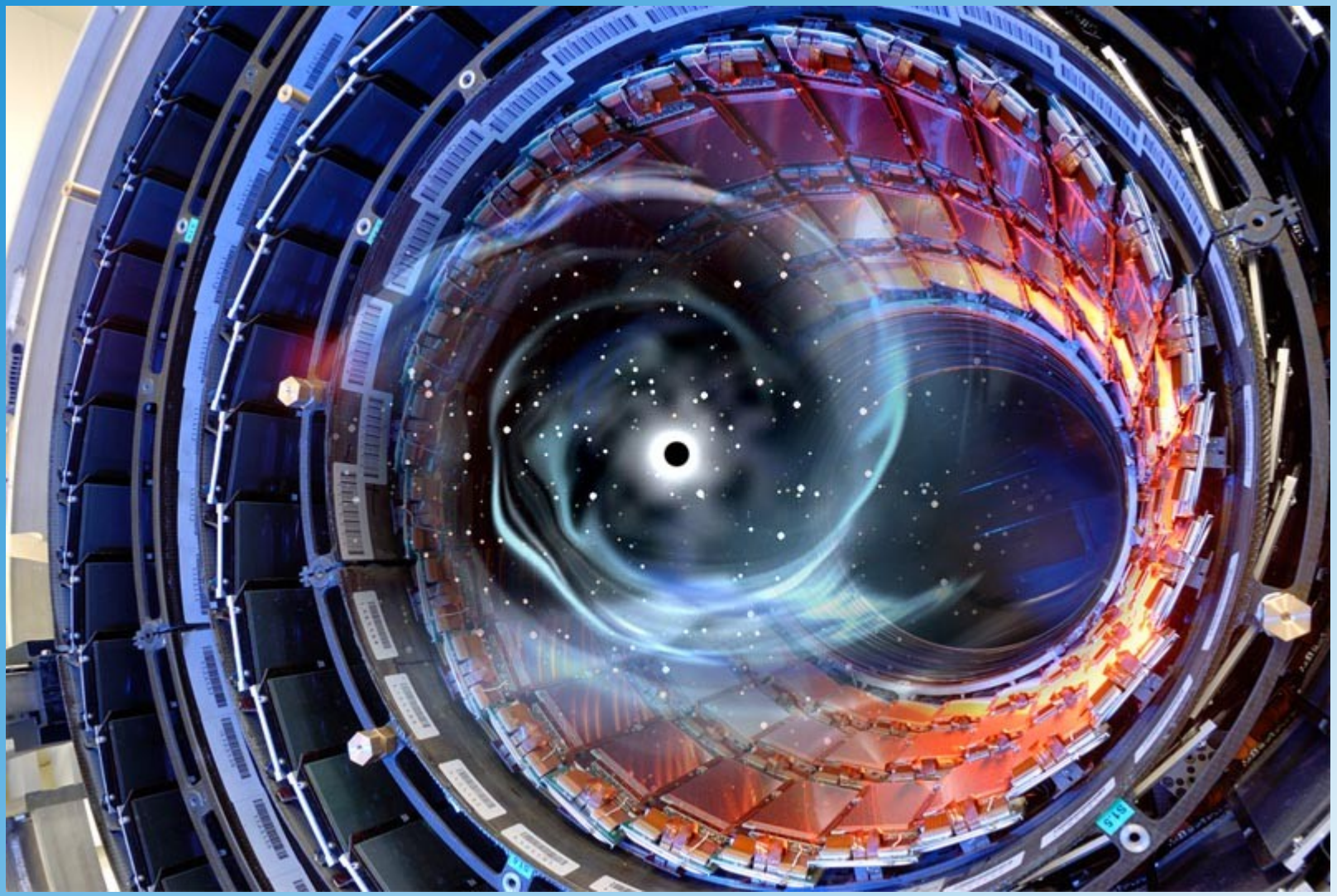
Task: absorb halo proton and neutrons straying around the beam





movable jaws (with RF shield)

LHC creating black holes?



LHC Operation

2008: first non-colliding beam at 450 GeV

2008-2009: 15 month break

2009: first collisions $s^{1/2}$ = 900 GeV, 2.36 TeV (L~20 μb^{-1})

2010: LHC commissioning at $s^{1/2}$ = 2.36 TeV and 7 TeV

end 2010: heavy ion run (Pb-Pb)

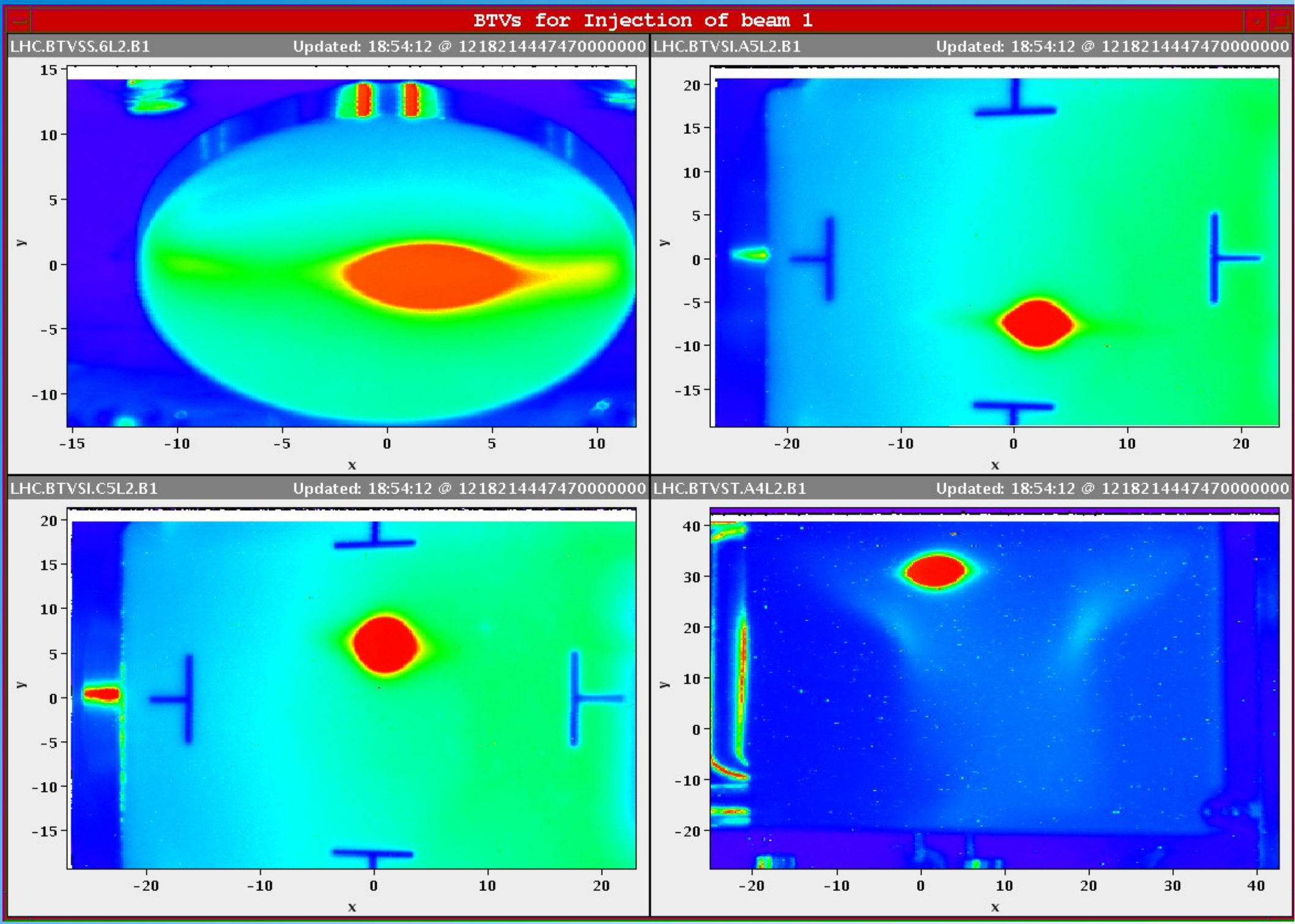
2011: standard running at $s^{1/2}$ = 7 TeV (L~5 fb^{-1})

end 2011: heavy ion run (Pb-Pb)

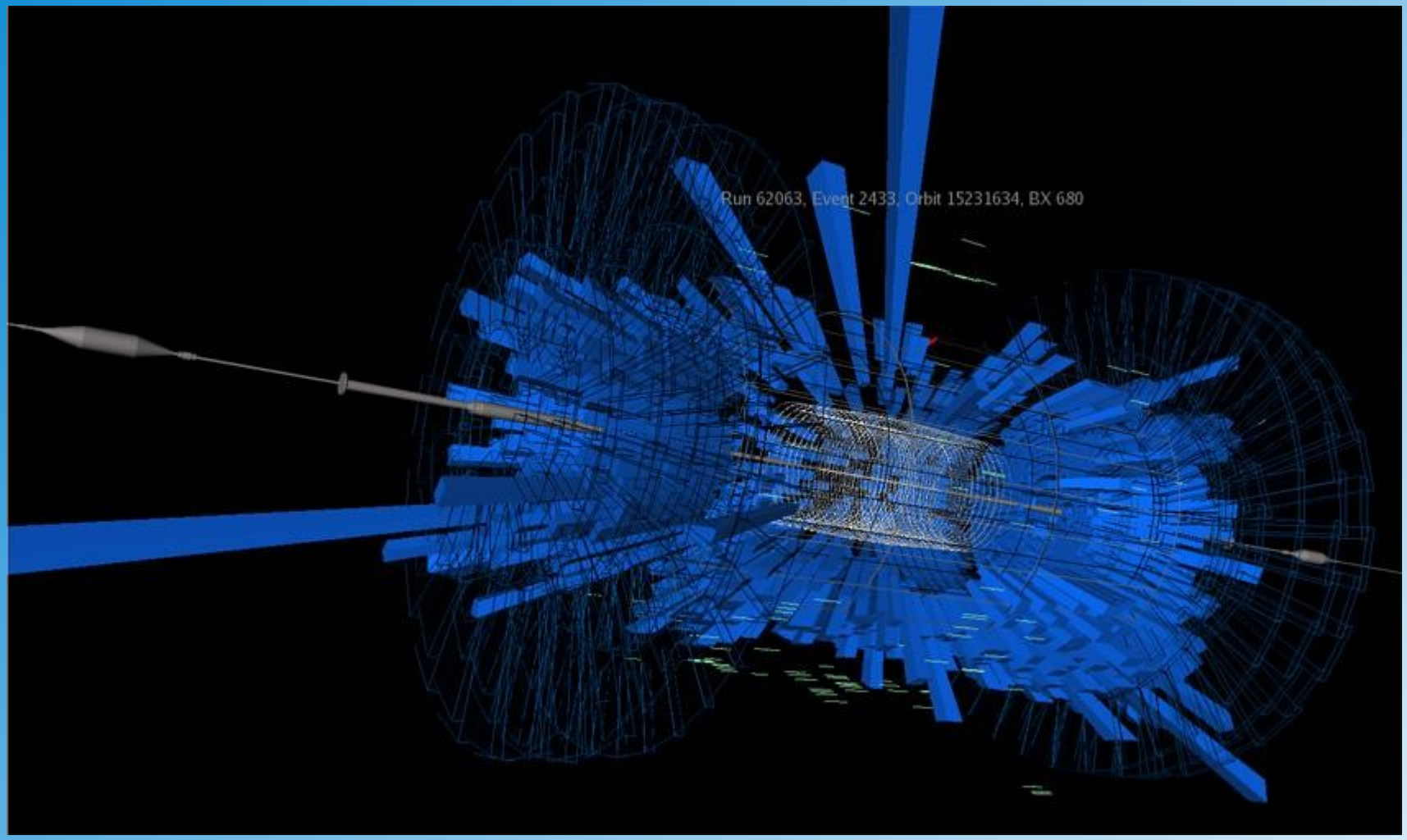
2012: standard running at $s^{1/2}$ = 8TeV (L~25 fb^{-1})

First Beams in September 2008

Big Interest by Press!

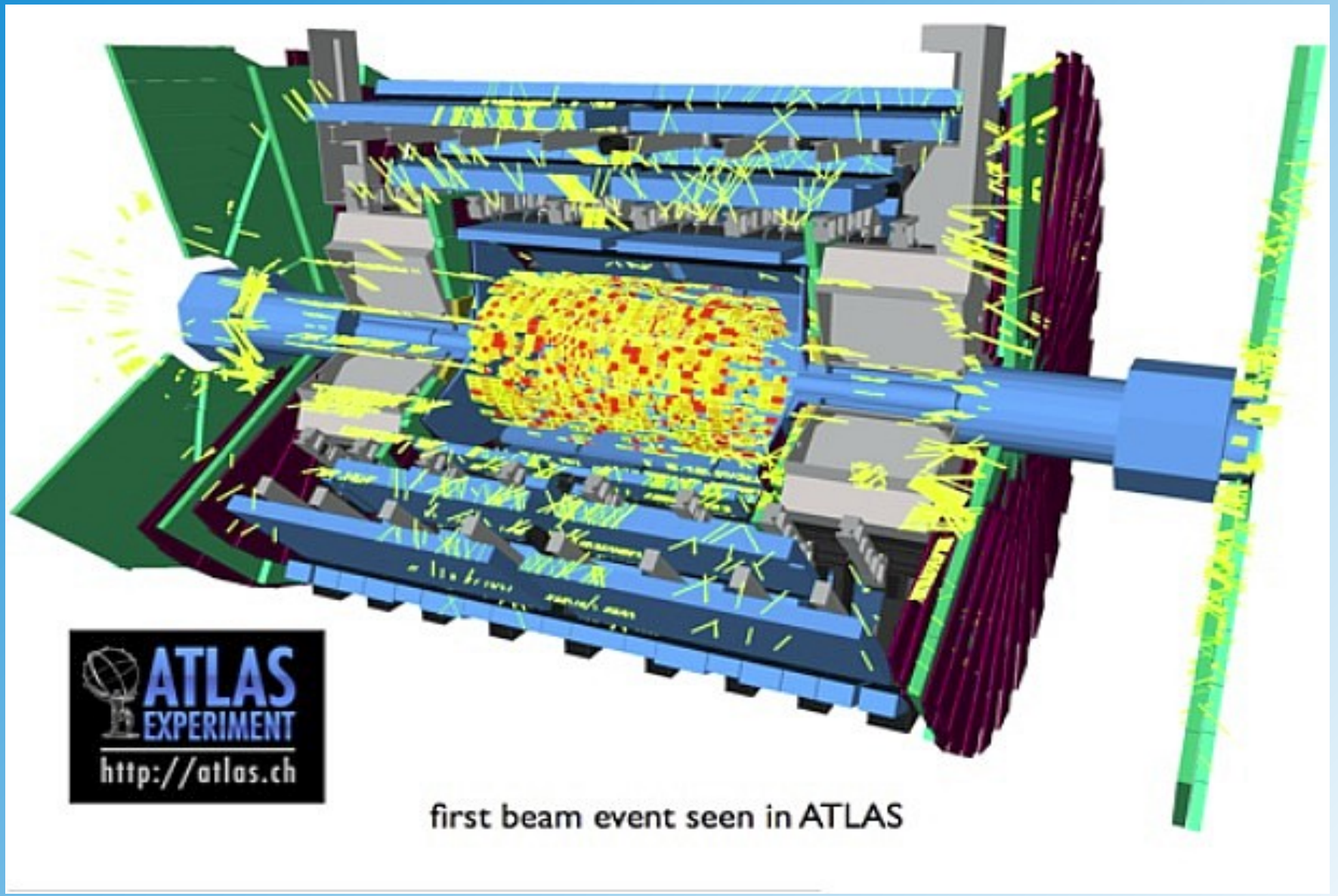

BTVs for Injection of beam 1
LHC.BTVSS.6L2.B1
Updated: 18:54:12 @ 1218214447470000000
LHC.BTVSI.A5L2.B1
Updated: 18:54:12 @ 1218214447470000000
LHC.BTVSI.C5L2.B1
Updated: 18:54:12 @ 1218214447470000000
LHC.BTVST.A4L2.B1
Updated: 18:54:12 @ 1218214447470000000
x
y

First Events in CMS



Beam on tungsten block

First Events in ATLAS

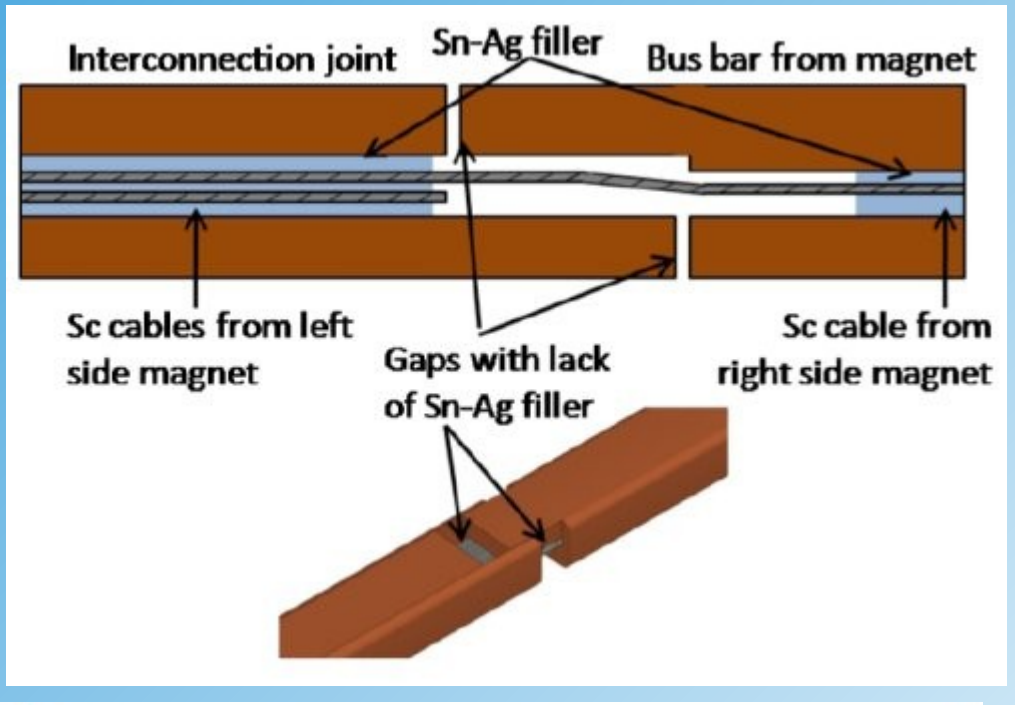


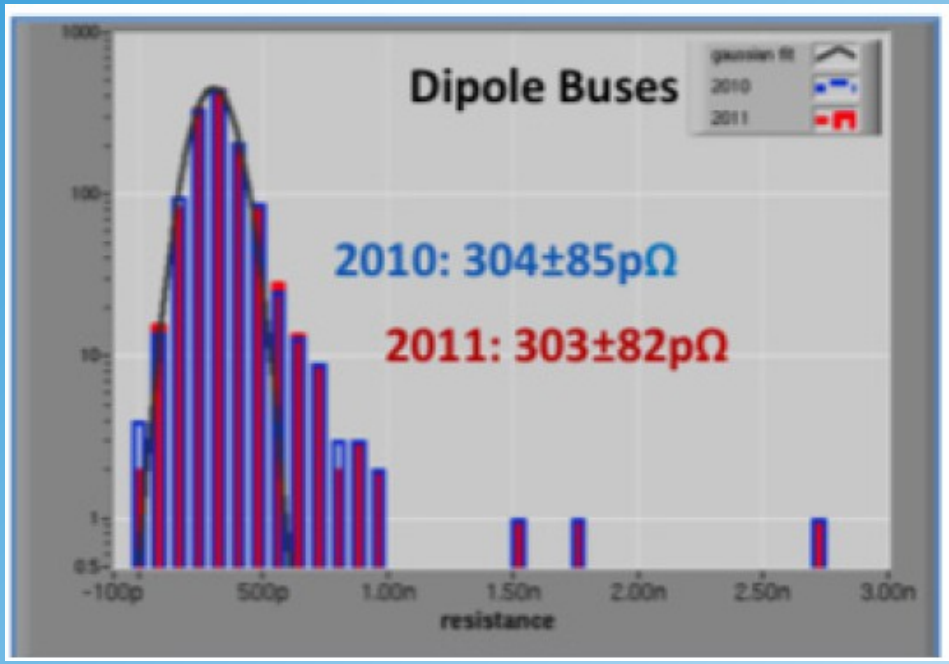
- Movie

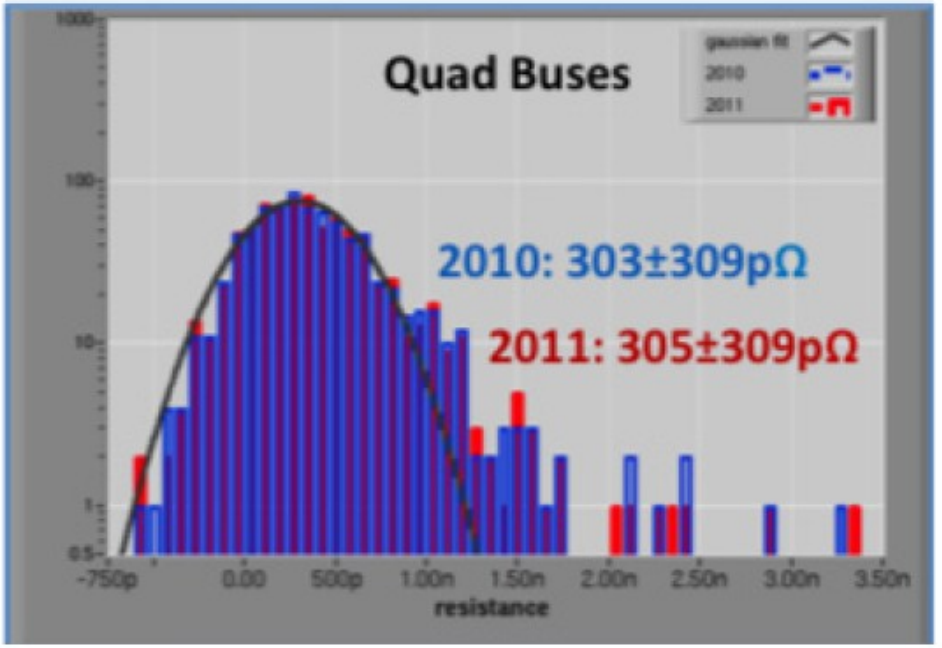
The Accident

Interconnection Joints

Splice Resistance Measurements
(A.Siemko et al)

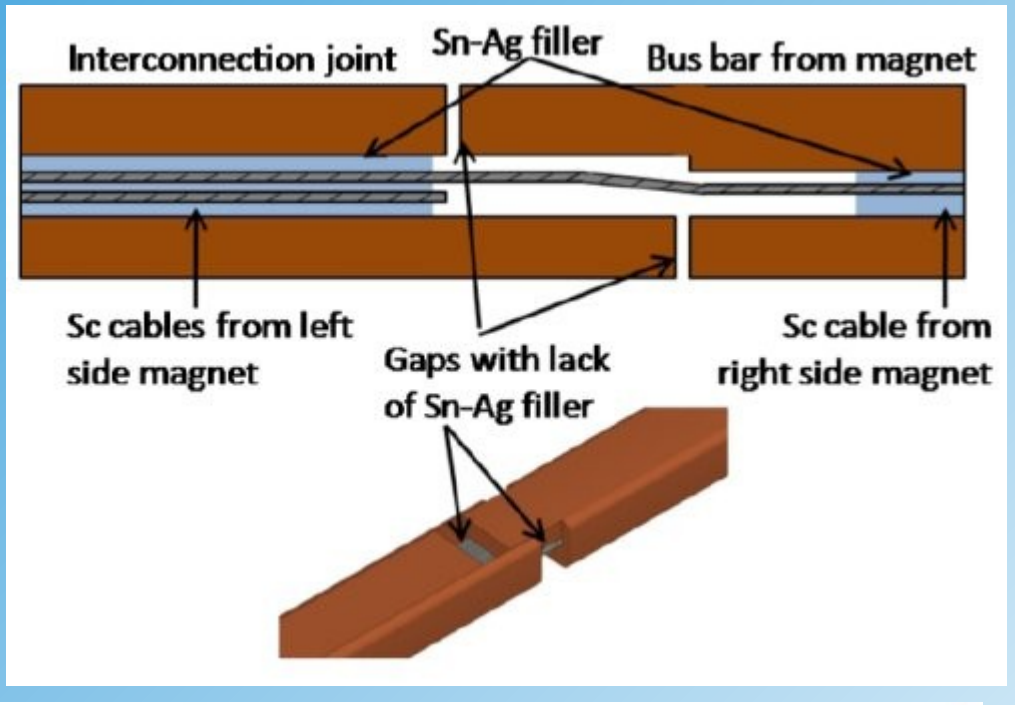


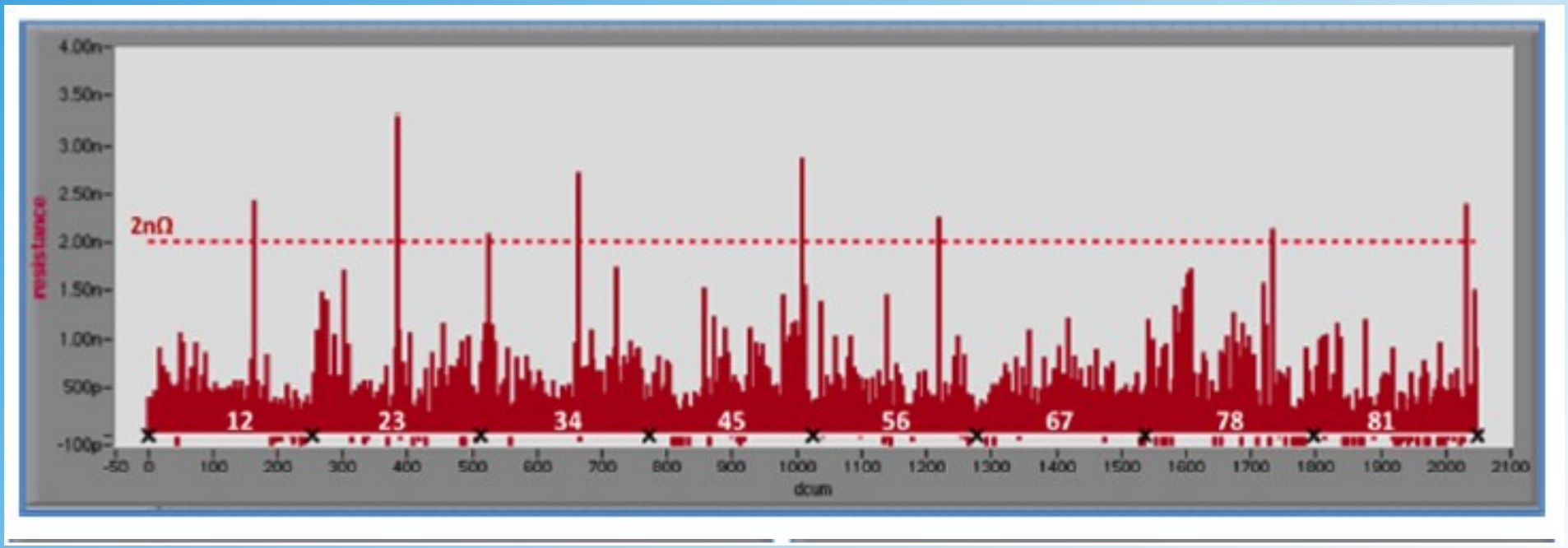




Interconnection Joints

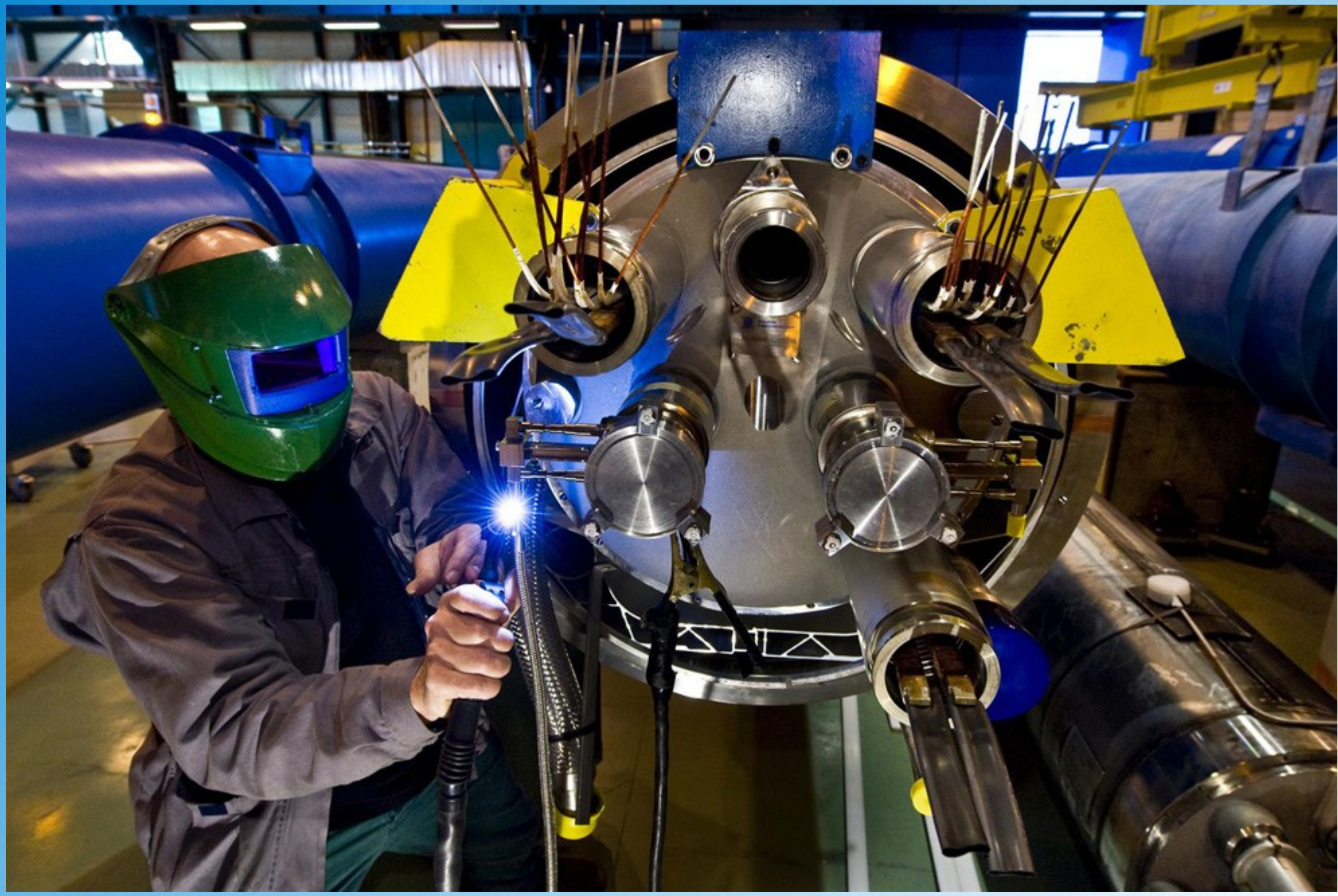
Splice Resistance Measurements
(A.Siemko et al)





LHC Repair

LHC Repair



LHC Operation

2008: first non-colliding beam at 450 GeV

2008-2009: 15 month break

2009: first collisions $s^{1/2}$ = 900 GeV, 2.36 TeV (L~20 μb^{-1})

2010: LHC commissioning at $s^{1/2}$ = 2.36 TeV and 7 TeV

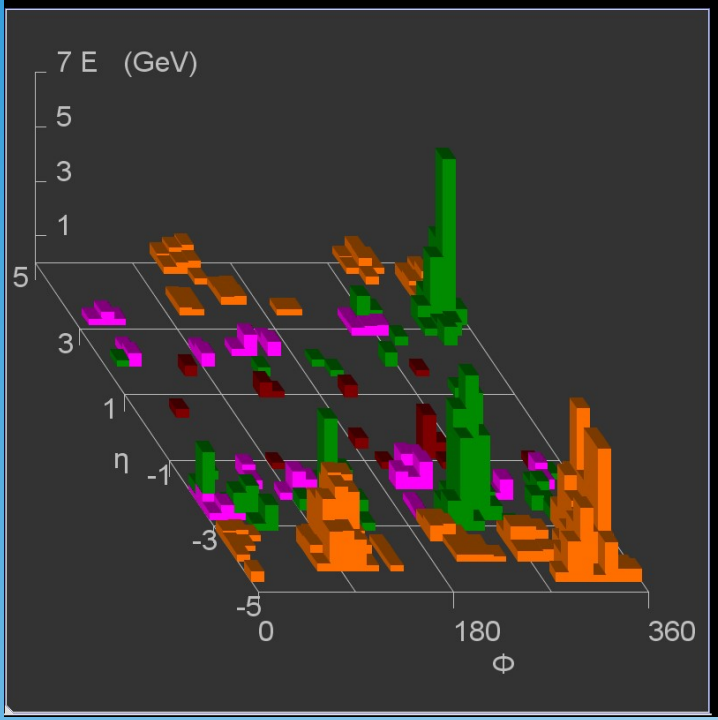
end 2010: heavy ion run (Pb-Pb)

2011: standard running at $s^{1/2}$ = 7 TeV (L~5 fb^{-1})

end 2011: heavy ion run (Pb-Pb)

2012: standard running at $s^{1/2}$ = 8TeV (L~25 fb^{-1})

Candidate Collision Event

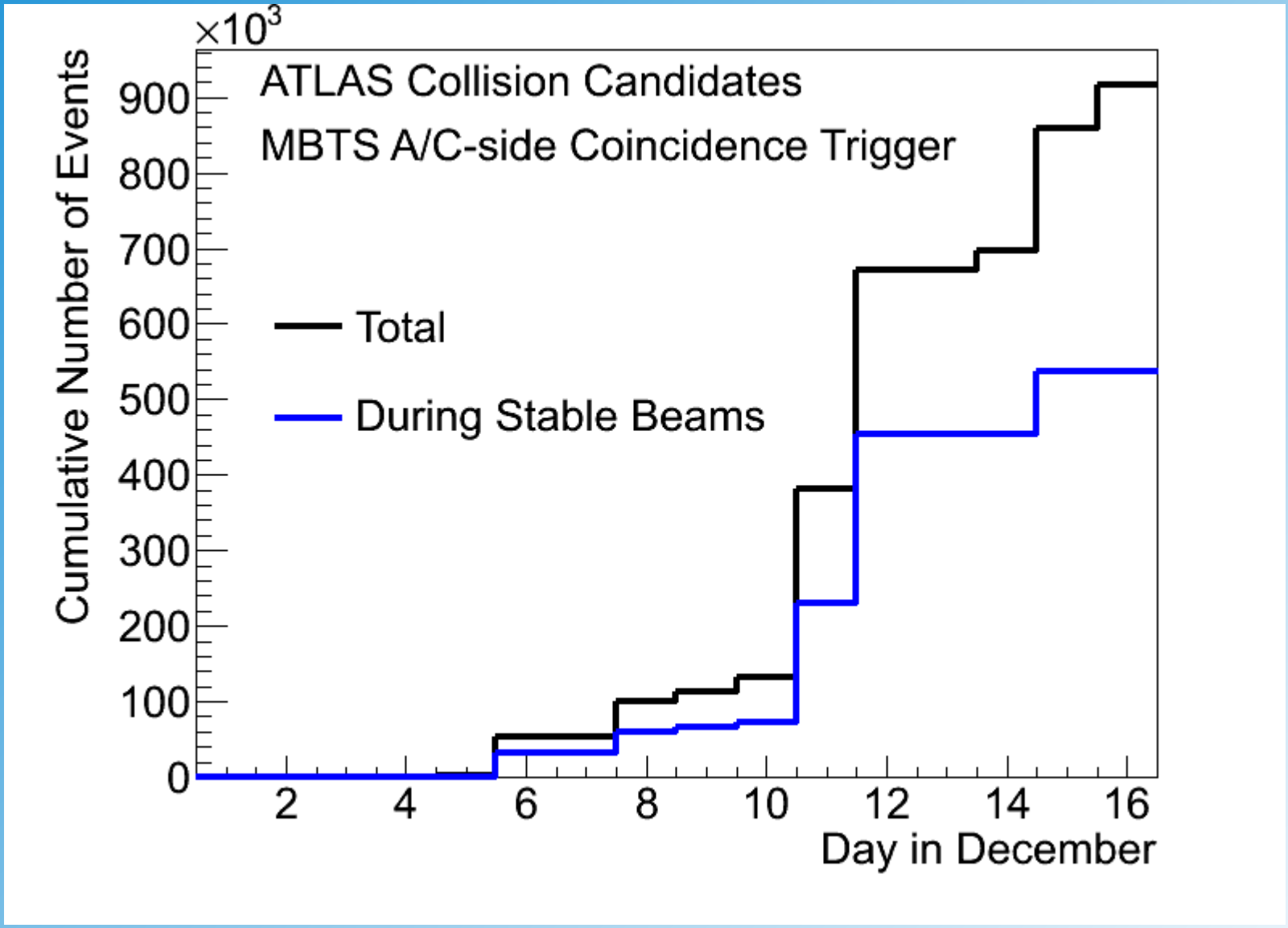


ATLAS EXPERIMENT

2009-11-23, 14:22 CET
Run 140541, Event 171897

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

First Proton-Proton Collisions at LHC



LHC Operation

2008: first non-colliding beam at 450 GeV

2008-2009: 15 month break

2009: first collisions $s^{1/2}$ = 900 GeV, 2.36 TeV (L~20 μb^{-1})

2010: LHC commissioning at $s^{1/2}$ = 2.36 TeV and 7 TeV

end 2010: heavy ion run (Pb-Pb)

2011: standard running at $s^{1/2}$ = 7 TeV (L~5 fb^{-1})

end 2011: heavy ion run (Pb-Pb)

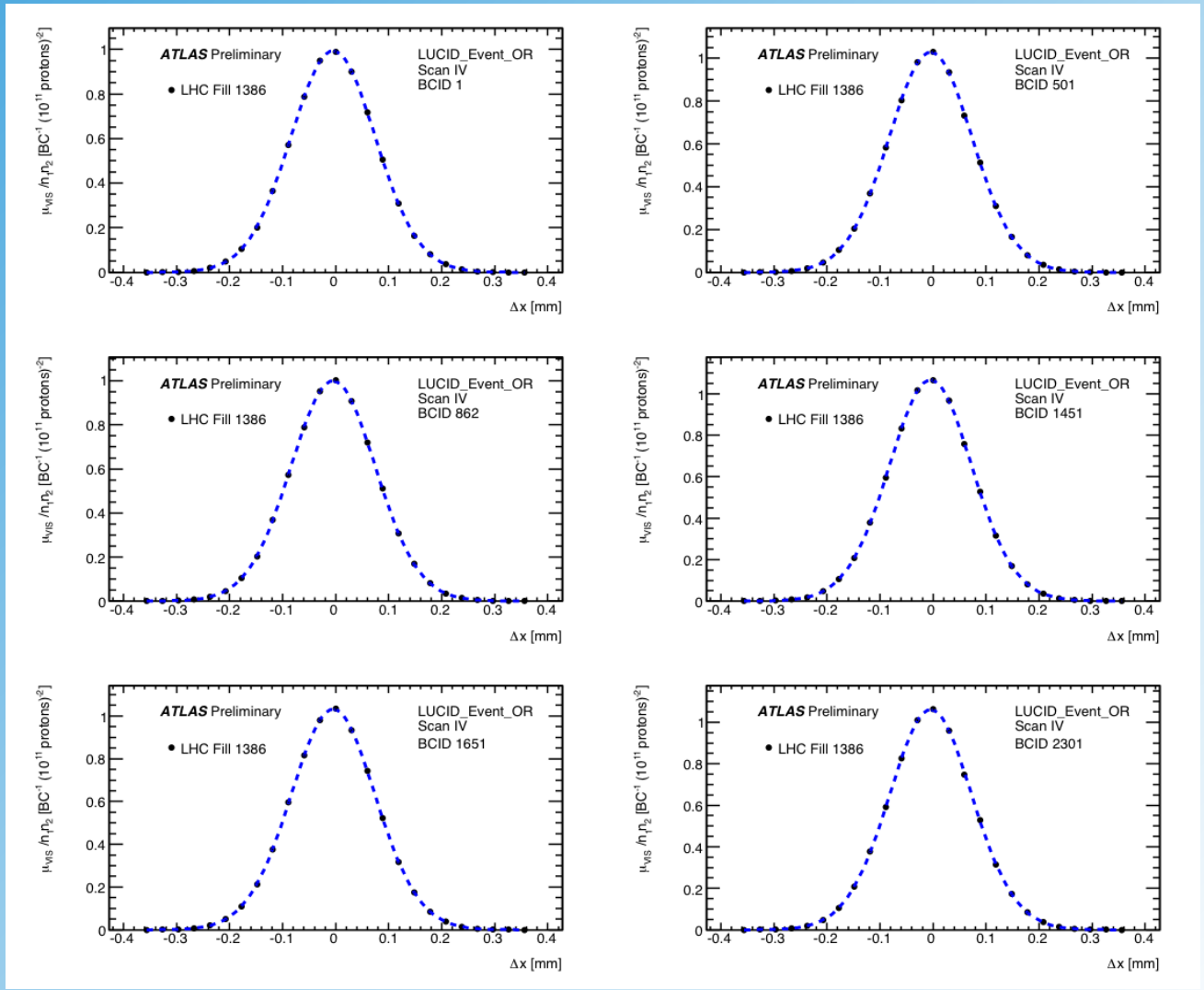
2012: standard running at $s^{1/2}$ = 8TeV (L~25 fb^{-1})

Luminosity Measurements

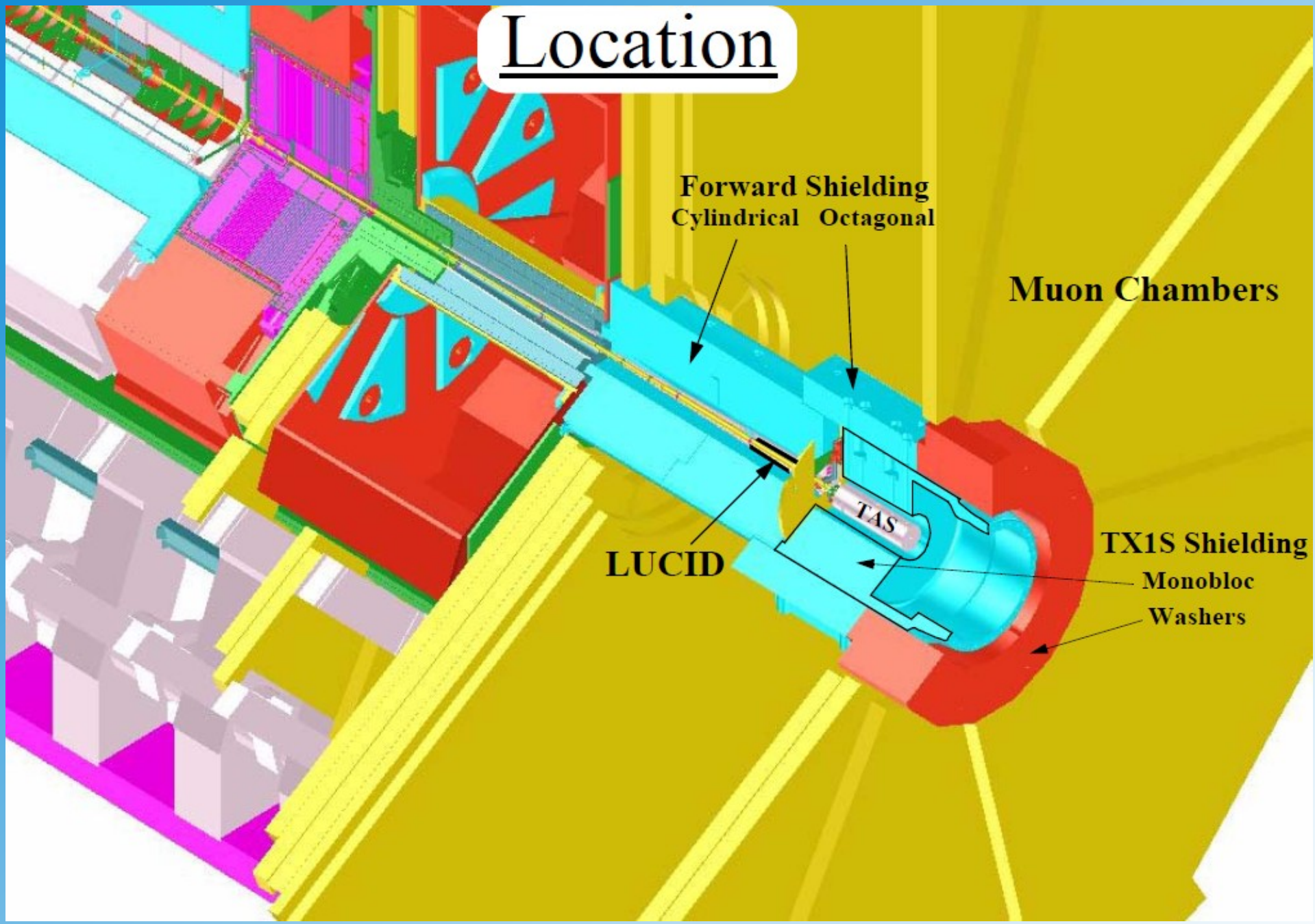
van de Meer Scans:

change orbit positions and measure event rates

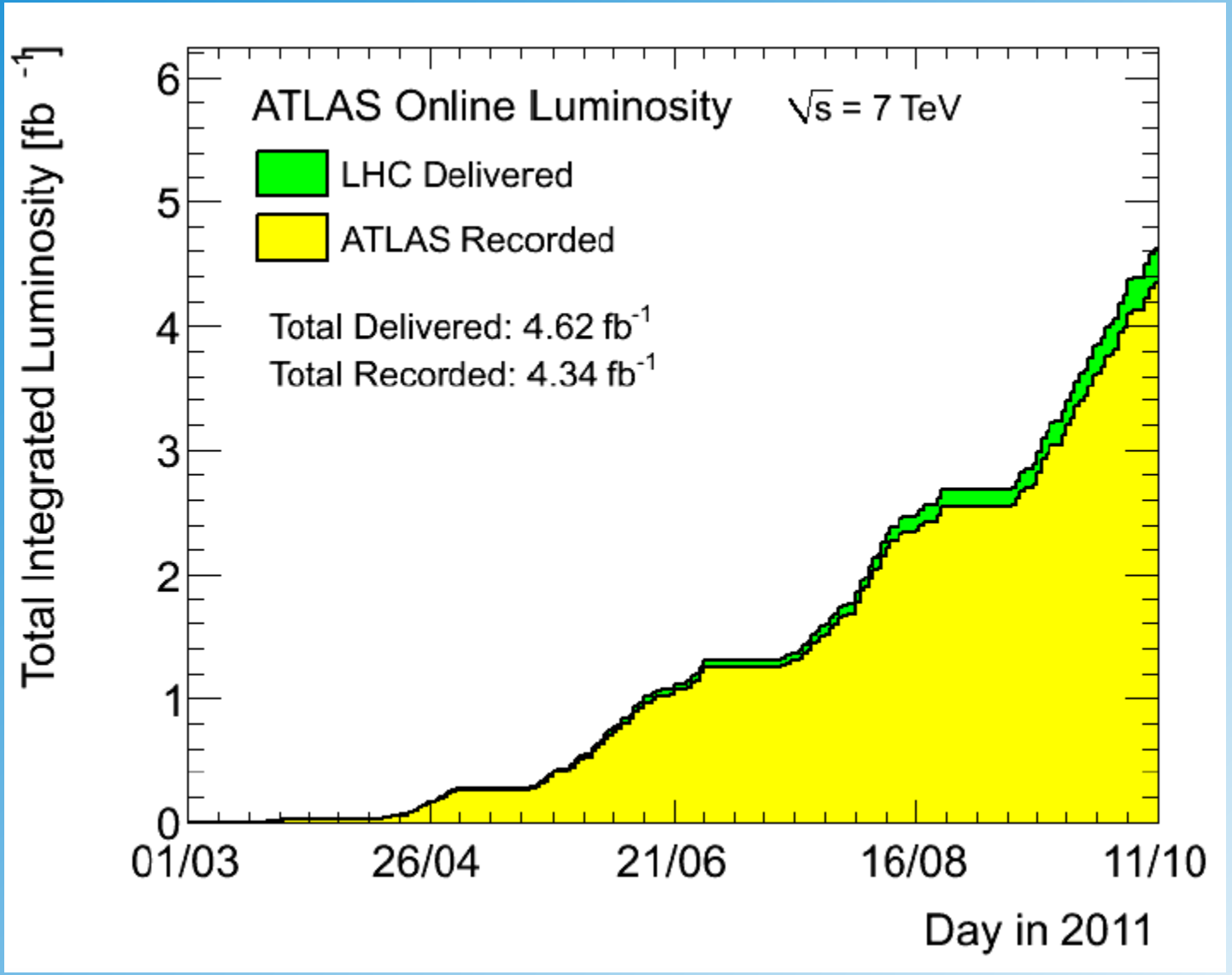
→ beam size



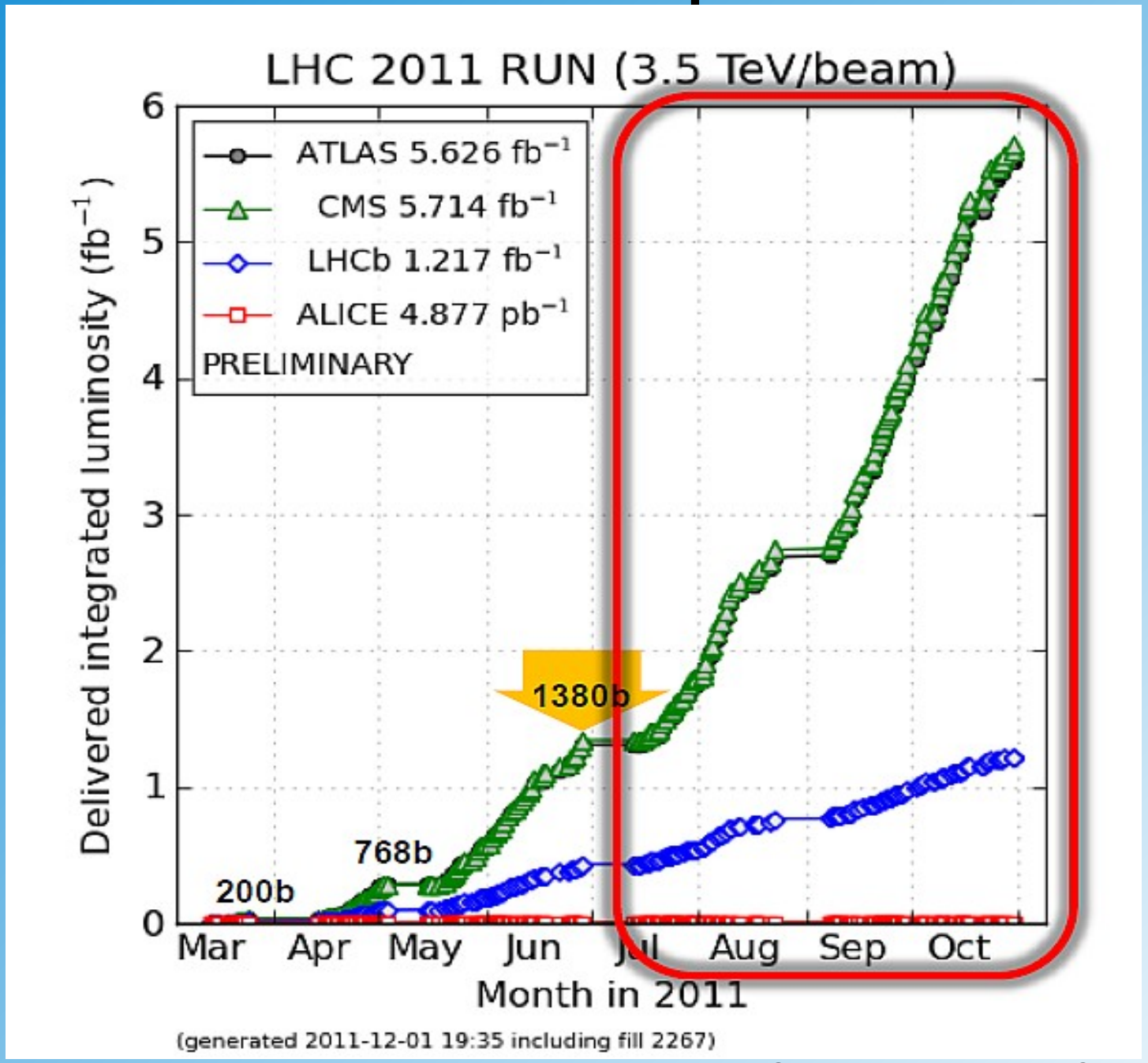
Luminosity Detector LUCID



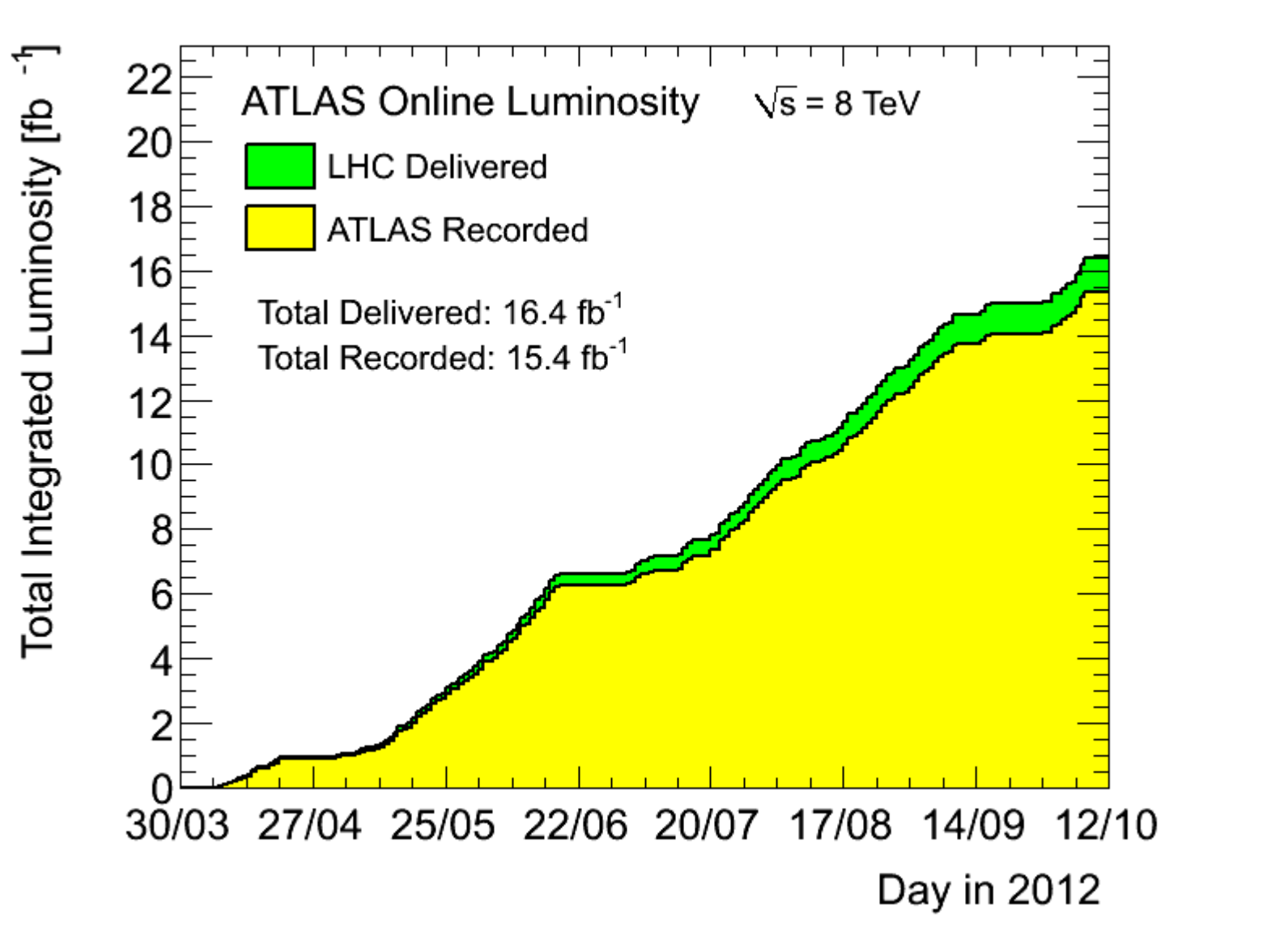
LHC Integrated Luminosity 2011



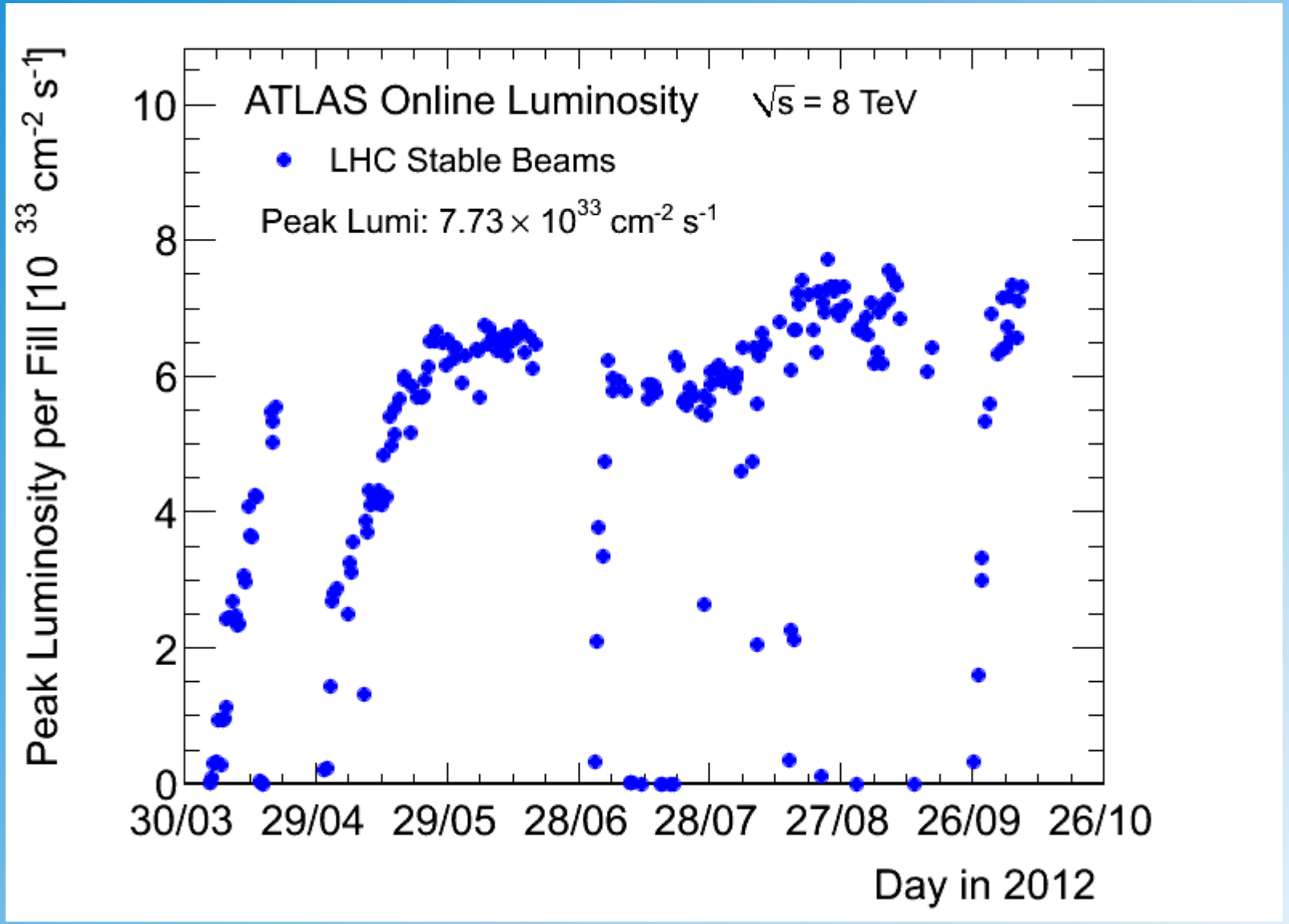
LHC 2011 Operation



LHC Integrated Luminosity 2012



LHC Peak Luminosity



but with half the number of bunches (1380)

LHC Performance and Statistics

Quick search

Fill number :

Overview | Run Details | Fill Summaries | Supertable | Filters: 2012 | 4TeV | proton - proton | Stable Beams | Apply filters

Online Integrated Luminosity

ALICE: 4.35 pb^{-1} ATLAS: 17.08 fb^{-1} CMS: 17.12 fb^{-1} LHCb: 1.65 fb^{-1}

Latest 5 LHC Fills

Fill	Fill Times			Energy [Gev]	Intensity		Bunches		Bunch Collision Scheme [IPI&5/2/8]	Peak Luminosity [Hz/ub] = [10^{30} $cm^{-2}s^{-1}$]				Delivered Luminosity [nb^{-1}] = [10^{33} cm^{-2}]			
	Fill Start	SB Start [hh:mm]	SB Duration [hh:mm]		B1 [10^{12}]	B2 [10^{12}]	Number	Norm Emitt [um]		ATLAS	ALICE	CMS	LHCb	ATLAS	ALICE	CMS	LHCb
3194	18:10 17/10/2012	19:41	12:34	4000	208.9	205.35	1374	2.65	1368/0/1262	6531	16.89	6470	421	164745	217.3	167038	17826
3192	00:50 17/10/2012	03:21	10:39	4000	210.96	205.21	1374	2.74	1368/0/1262	6670	14.52	6765	462	153292	161.34	154359	16330
3191	16:41 16/10/2012	23:57	0:44	4000	210.01	208.56	1374	2.43	1368/0/1262	6500	19.03	6577	404	15938	21.58	16197	980
3188	02:29 16/10/2012	04:02	6:56	4000	210.02	208.64	1374	2.52	1368/0/1262	6722	17.51	6511	436	105404	176.14	104993	9874
3185	08:23 15/10/2012	12:43	7:45	4000	210.47	210.89	1374	2.47	1368/0/1262	6827	18.76	6787	405	122049	190.84	122115	10901

LHC Efficiency and Availability

LHC Run Efficiency

Mode: Proton Physics
Fills: 2469 - 3194 [595 Fills]
SB Time: 56 days 13 hrs 45 mins

Access - No beam : 13.94%
Machine setup : 27.31% Beam in : 14.98%
Ramp + squeeze : 8.14% Stable beams: 35.63%

Run Availability

Based on LHC Physics Schedule

Total Run Time	158 days 19 hrs 1 mins	
Cryo Availability	147 days 14 hrs 12 mins	92.9 %
Fault Downtime	38 days 11 hrs 26 mins	24.2 %

Recent Availability

Total Run Time	5 days 16 hrs 59 mins	
Cryo Availability	5 days 16 hrs 59 mins	100 %
Fault Downtime	0 days 21 hrs 6 mins	15.4 %

Recent Faults: The top 5 list

Fill	Duration	System
3181	3:20	Injection/Hardware
3186	3:17	Power converters/Voltage source
3182	2:54	Experiments/ALICE
3168	2:40	SPS/No beam
3172	1:37	Injection/Hardware

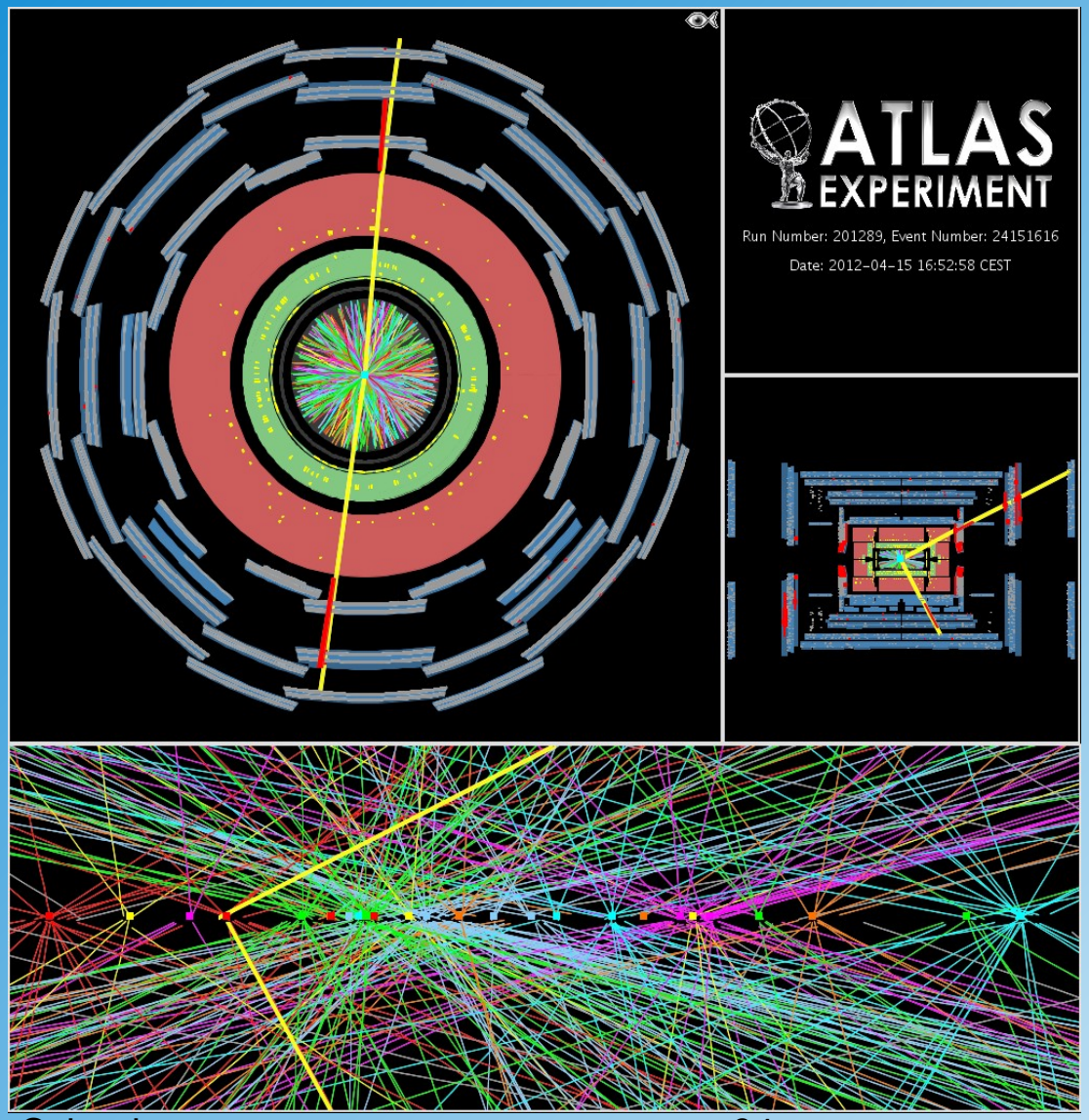
LHC Efficiency in last 7 days

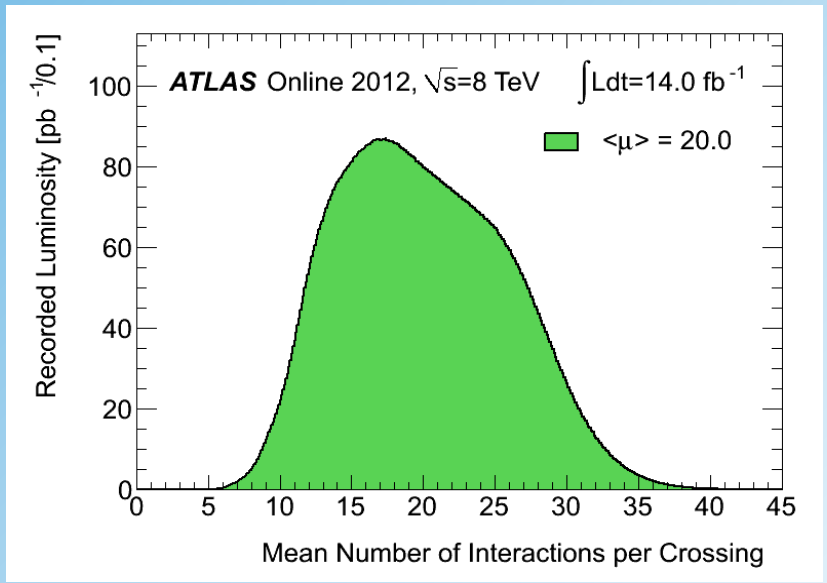
Mode: Proton Physics
Fills: 3158 - 3194 [31 Fills]
SB Time: 2 days 0 hrs 4 mins

Access - No beam : 4.79%
Machine setup : 31.12% Beam in : 18.54%
Ramp + squeeze : 10.46%
Stable beams: 35.09%

Pileup at LHC

- very high luminosity and cross section!
- more than one proton-proton collision per bunch crossing

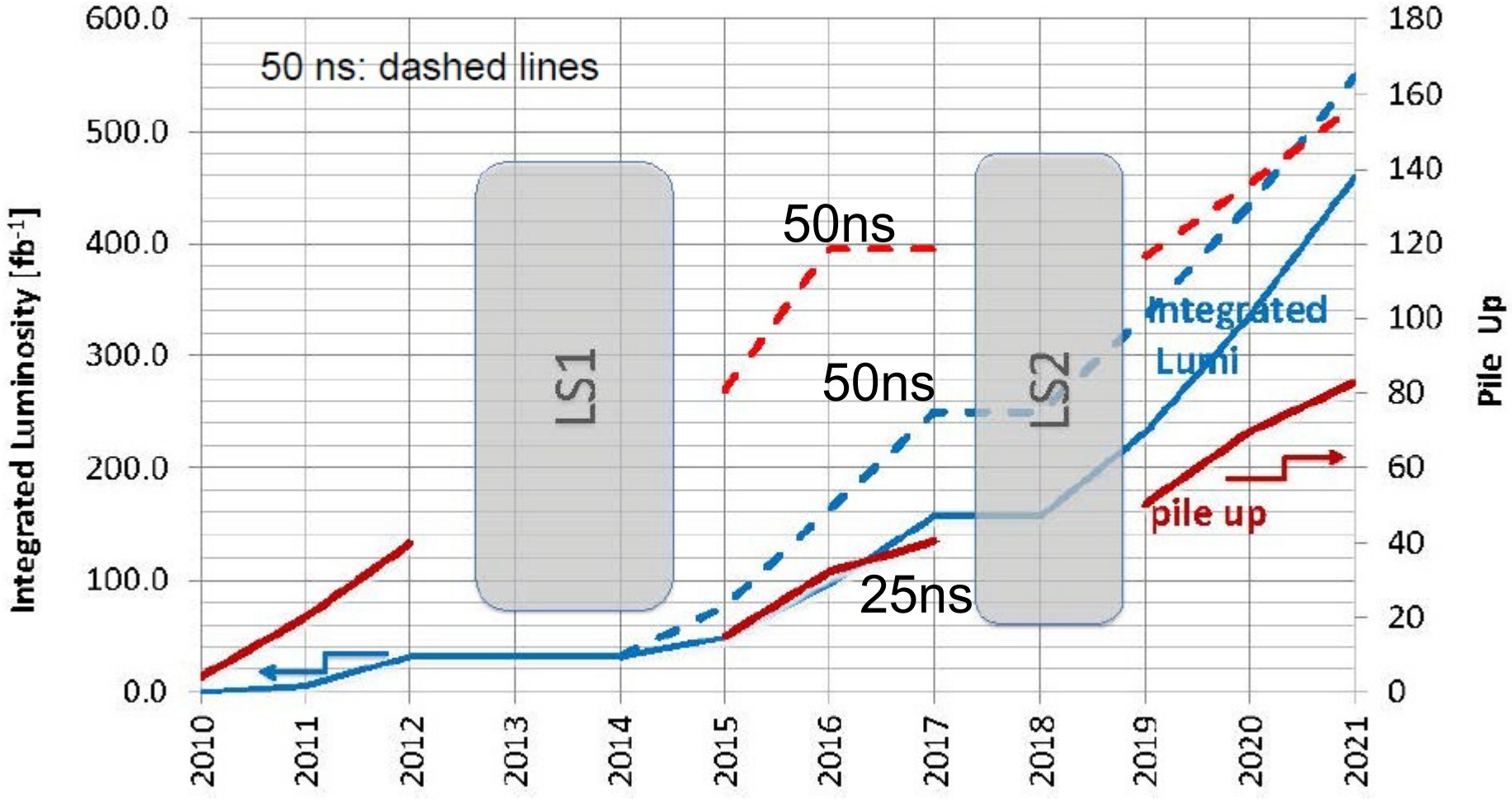




LHC Upgrade

forecast to 2021 (25 & 50 ns)

from Frank Zimmermann (CERN)



- pile up high (80-120) in 2015-2017 with 50 ns spacing
  (50-ns pile up >2x more than for 25 ns spacing)

Upgrade 2021/2

High-Luminosity LHC (HL-LHC)

goals:

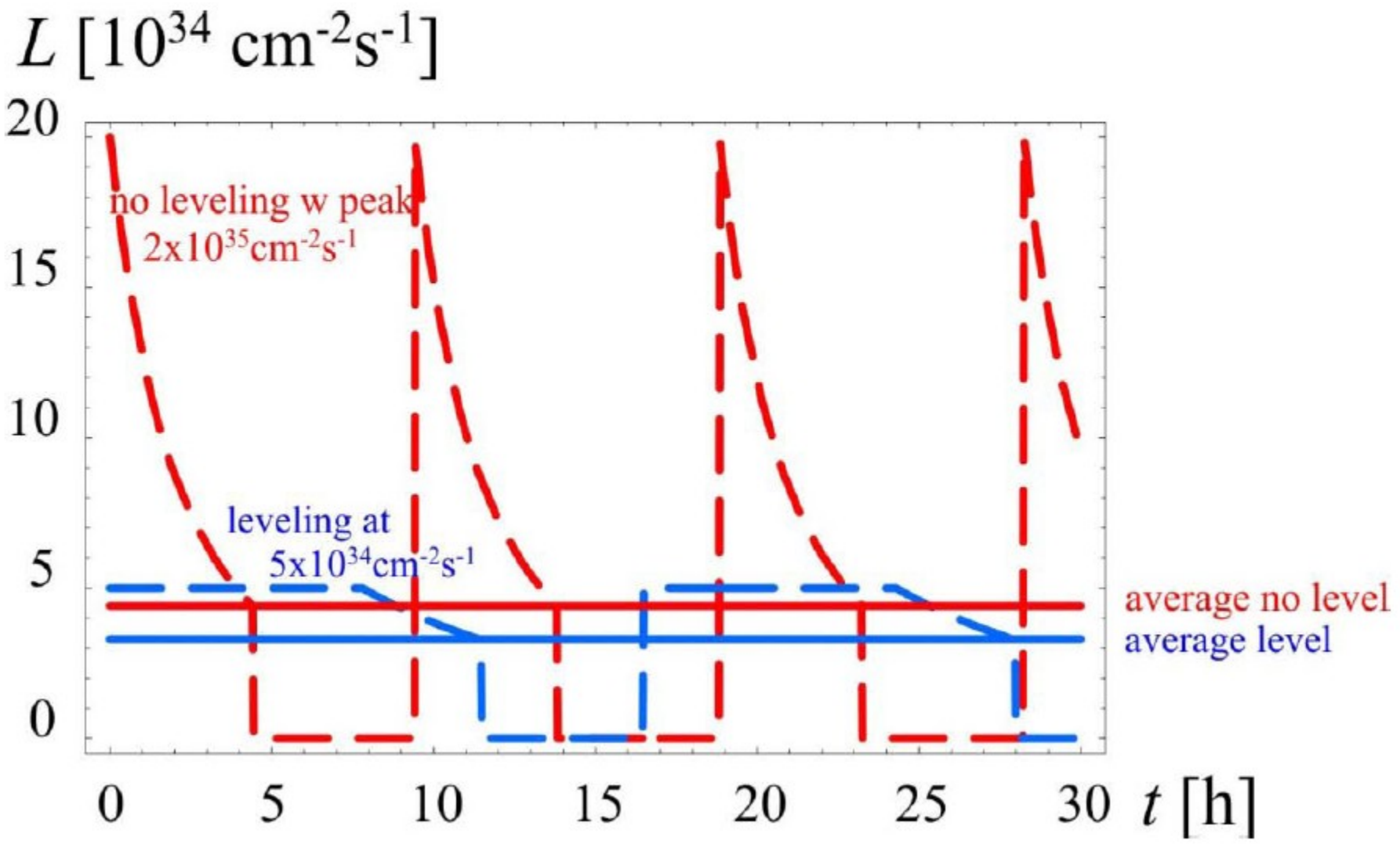
leveled peak luminosity: $L = 5 \times 10^{34}\ cm^{-2}\ s^{-1}$
(detector pile up ~140)

integrated luminosity: 200 - 300 fb^{-1} / yr

total integrated luminosity: ca. 3000 fb^{-1} by ~2030

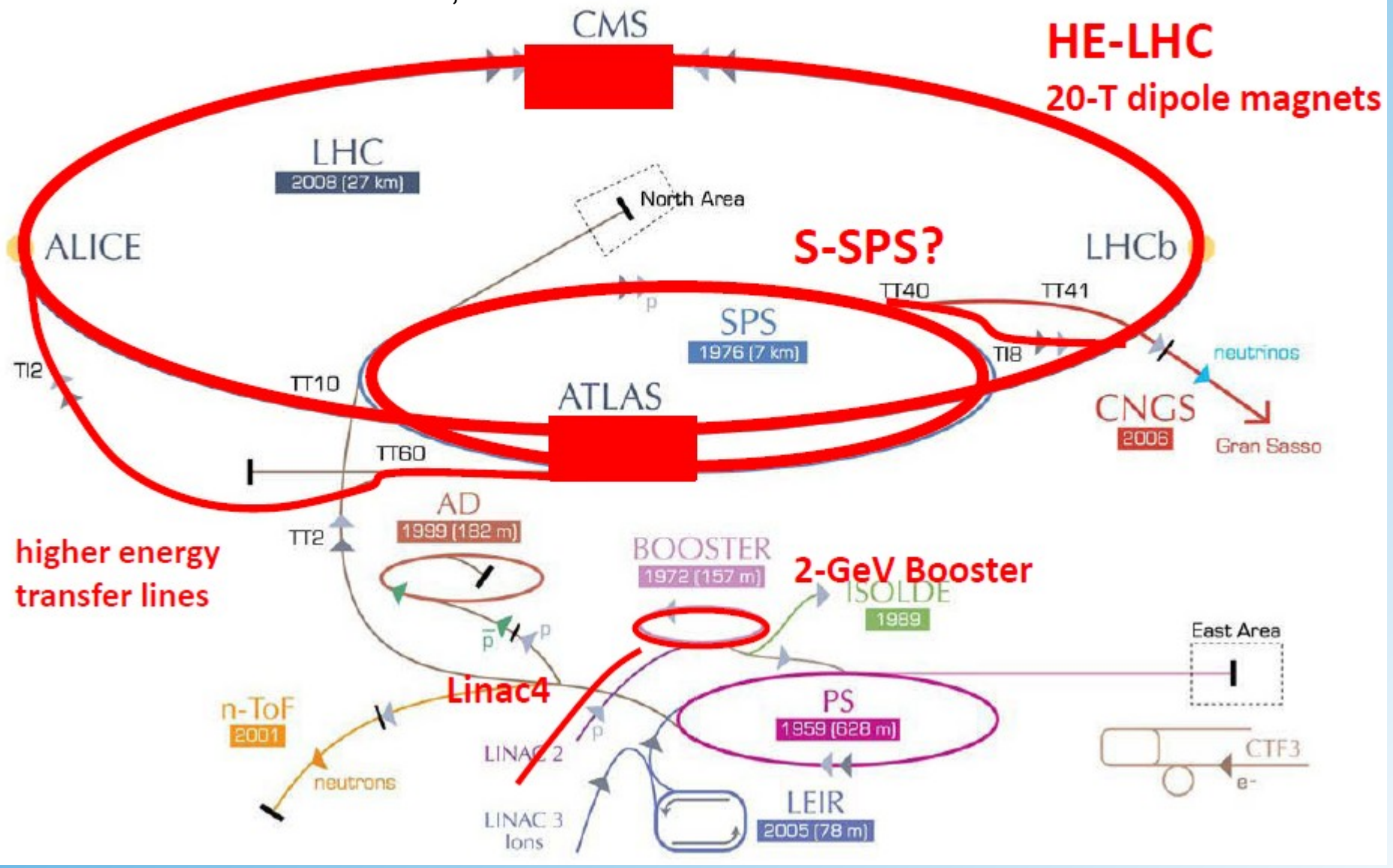
luminosity leveling at the HL-LHC

example: maximum pile up 140



High-Energy LHC ?

from Frank Zimmermann, CERN

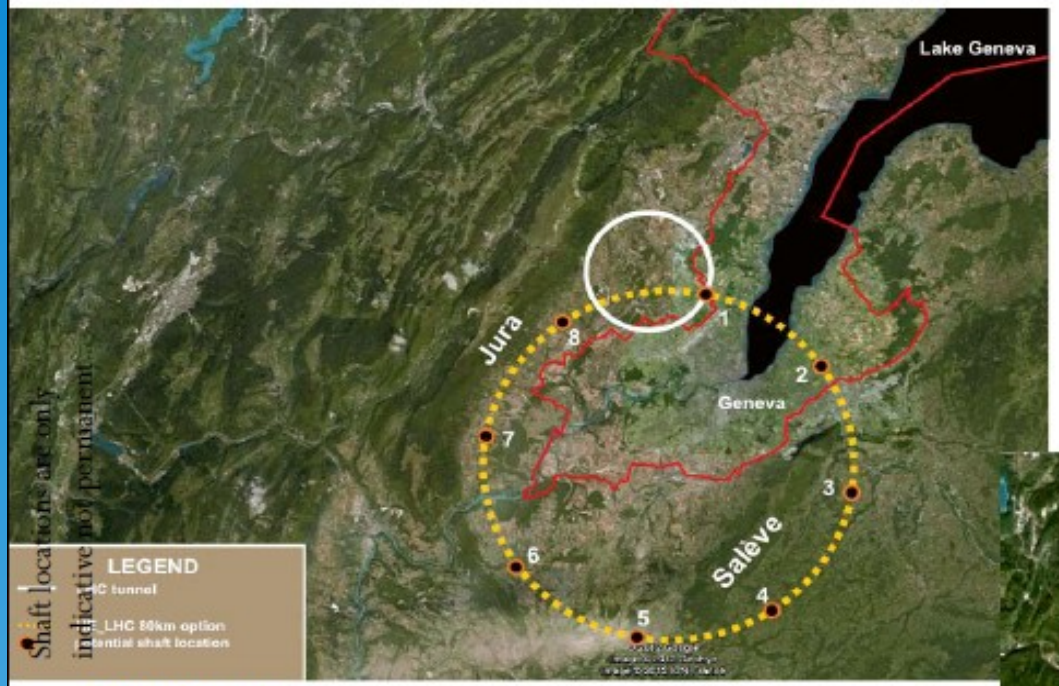


LINAC4 Upgrade

LINAC 4 prototype (Alvarez structure)

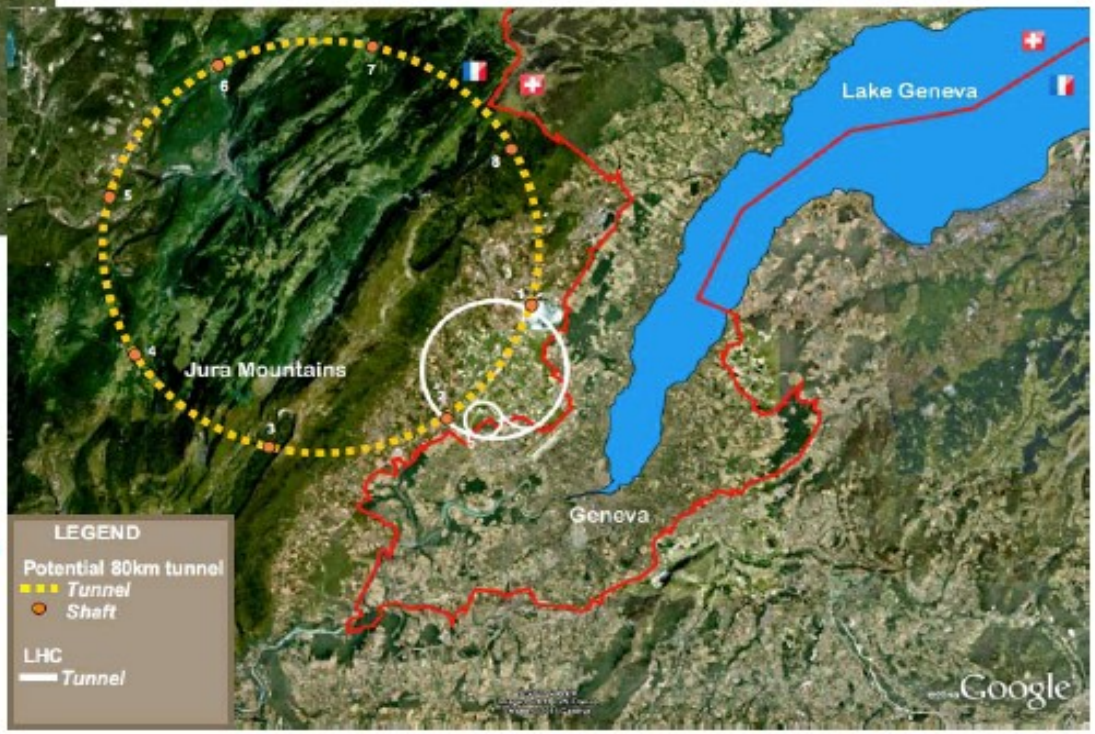
80km tunnel project

Layouts



Option 1

Option 2



John Osborne (CERN),
Caroline Waaijer (CERN)