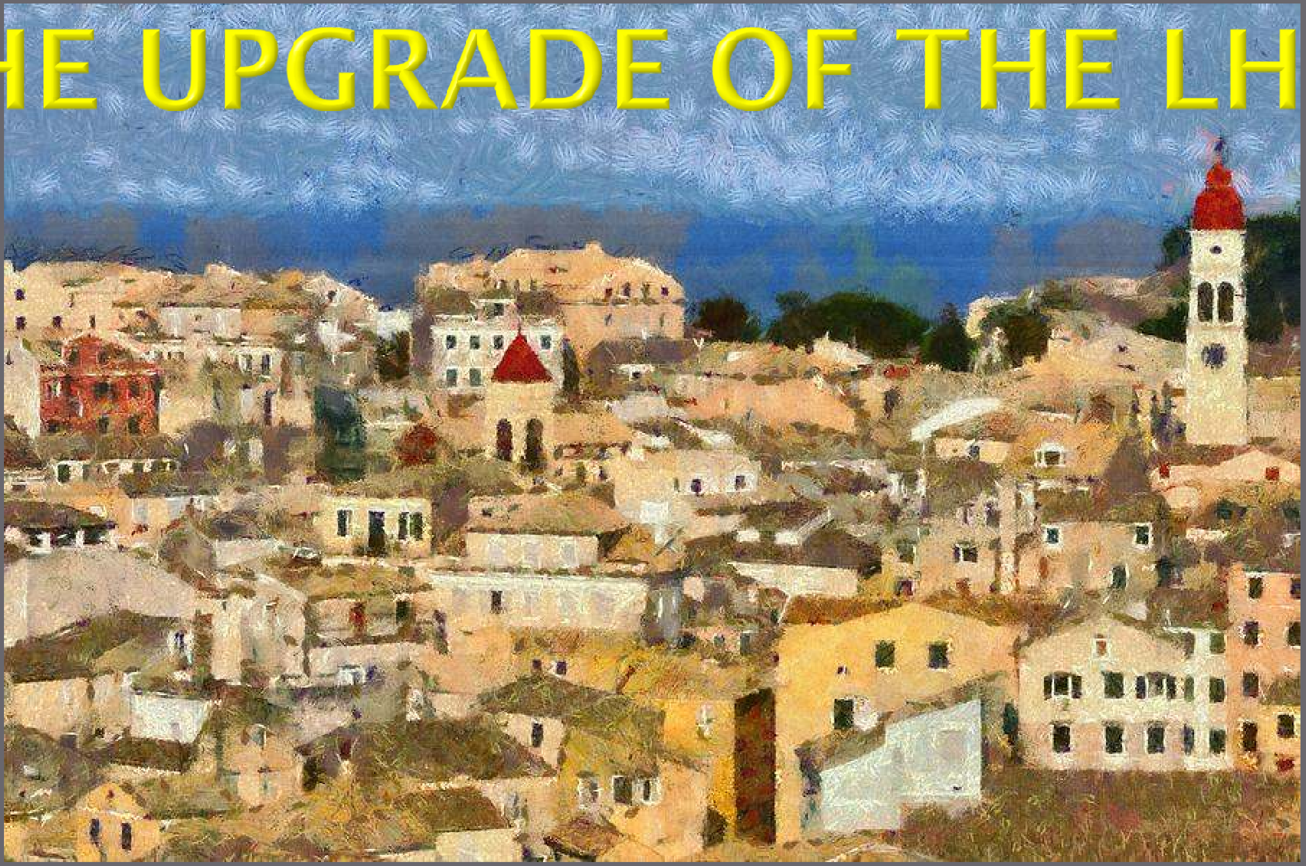
THE UPGRADE OF THE LHC



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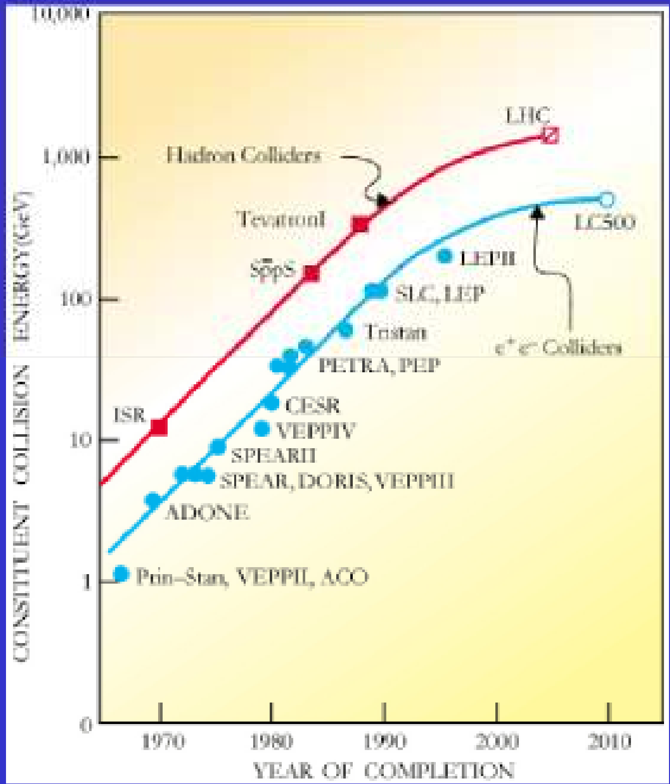
Corfu Summer Institute on Elementary Particles Physics & Gravity
14 September 2012

INTRODUCTION

Introduction - Accelerators

- Historically, HEP has depended on advances in accelerator design to make scientific progress
  - linear accelerators → cyclotron → synchrocyclotron → synchrotron → collider (circular, linear)
- Advances in accelerator design and performance require corresponding advances in accelerator technologies
  - Magnets, vacuum systems, RF systems, diagnostics,...
- Costs & time span of today's accelerator projects are high
  - International co-operation/collaboration are obligatory

Colliders – Energy vs. Time



M. Tigner: “Does Accelerator-Based Particle Physics have a Future?” Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!

Not enough: Project cost increased by factor 200!

New technology needed…

Next Decades

Road beyond Standard Model

LHC results will guide the way at the energy frontier

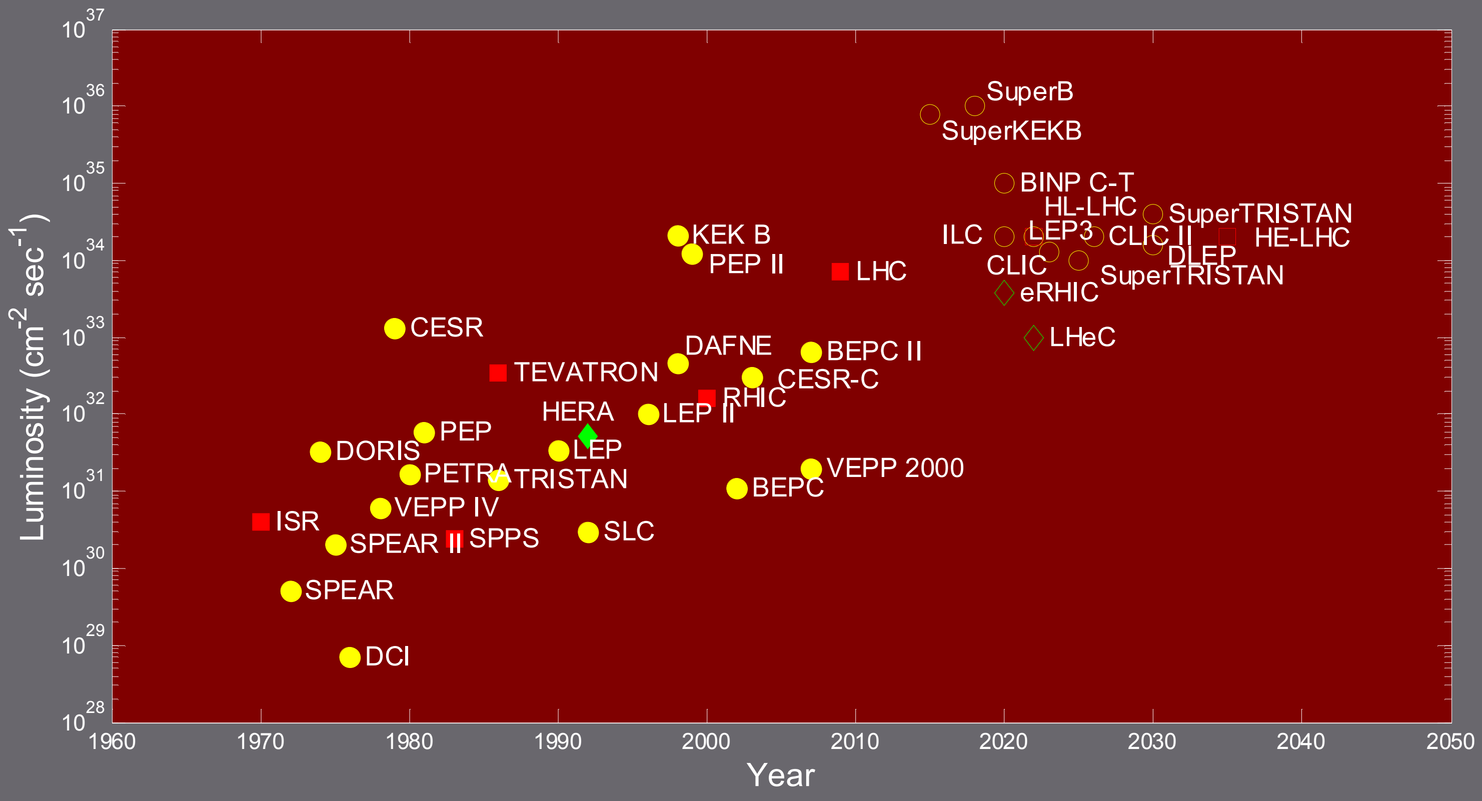
through synergy of

hadron - hadron colliders (LHC,HL-LHC,HE-LHC?)

lepton - hadron colliders (LHeC ??)

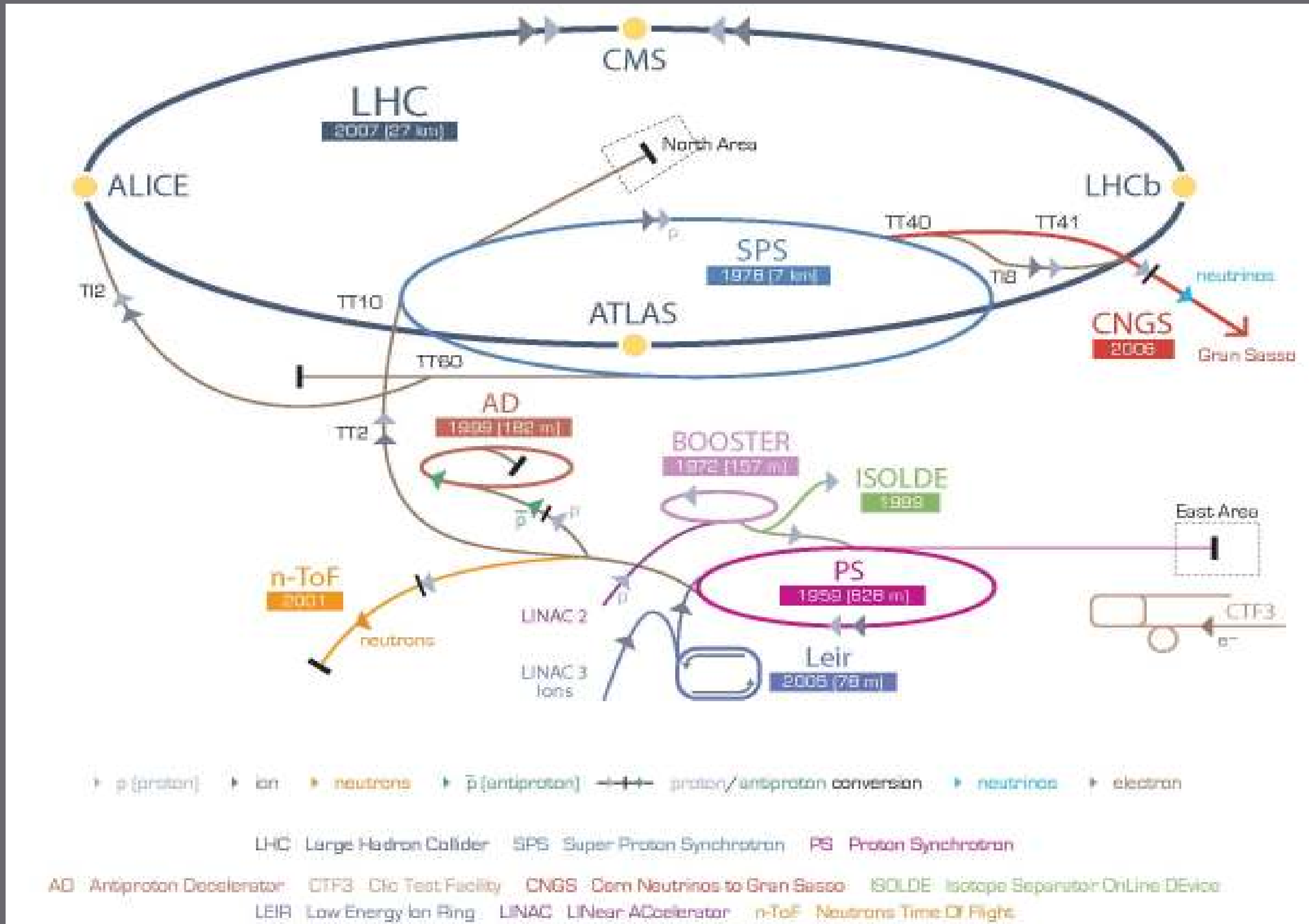
lepton - lepton colliders (LC (ILC or CLIC) ?)

Evolution of Accelerators

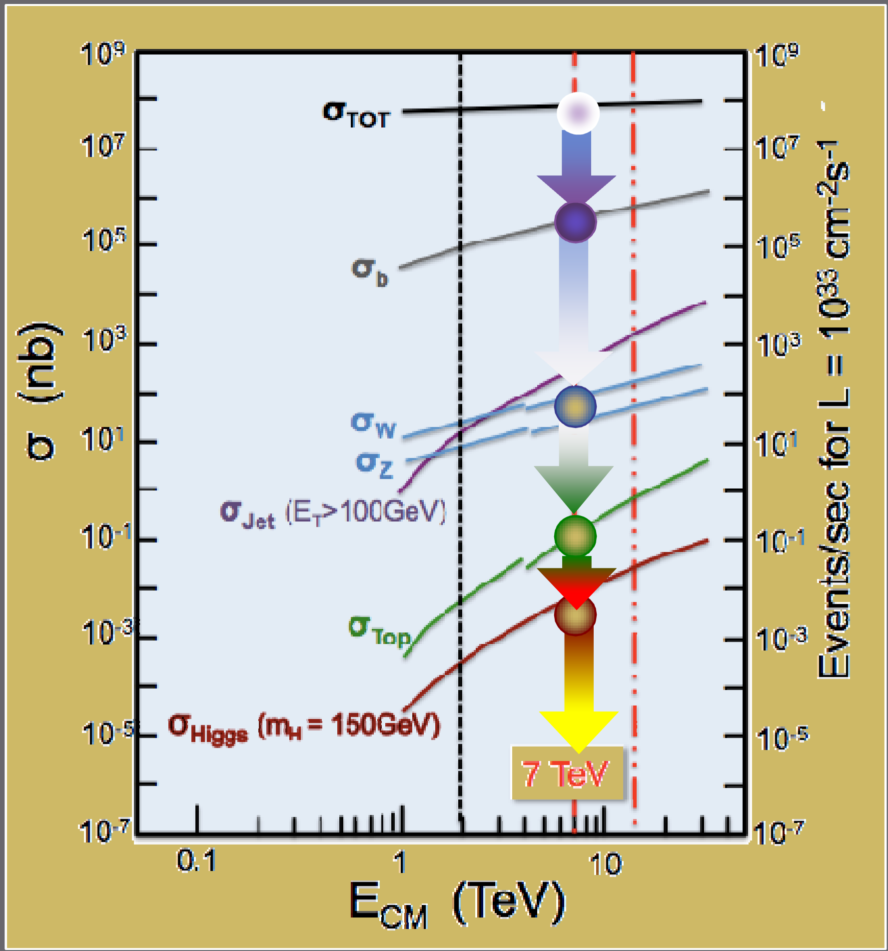


LHC OPERATIONS

CERN Accelerator Complex



The 2011 and 2012 runs …



Search for physics within & beyond SM

- ❑ Discovering new particles (Higgs, SUSY…)
- ❑ Making precise measurements of properties of known particles/forces: e.g. $B_s \rightarrow \mu^+\mu^-$

….in 2012 already
about 15 fb^{-1} delivered

→ entered new territory !

2012 LHC Strategy

4 TeV

$\beta^*=0.6m \rightarrow 0.7m \rightarrow 0.9m$

50 ns

$\int Ldt = 5\ fb^{-1}$ in June?

$\int Ldt = 15\text{-}19\ fb^{-1}$

SEE dumps=30-50

Pile-Up=26-35

LHCb $\int Ldt=1.5\ fb^{-1}$

$L_{peak}=5\text{-}6.8\ 10^{33}\ cm^{-2}s^{-1}$

TCP gap=2.2mm

SPS ε= 2 μm

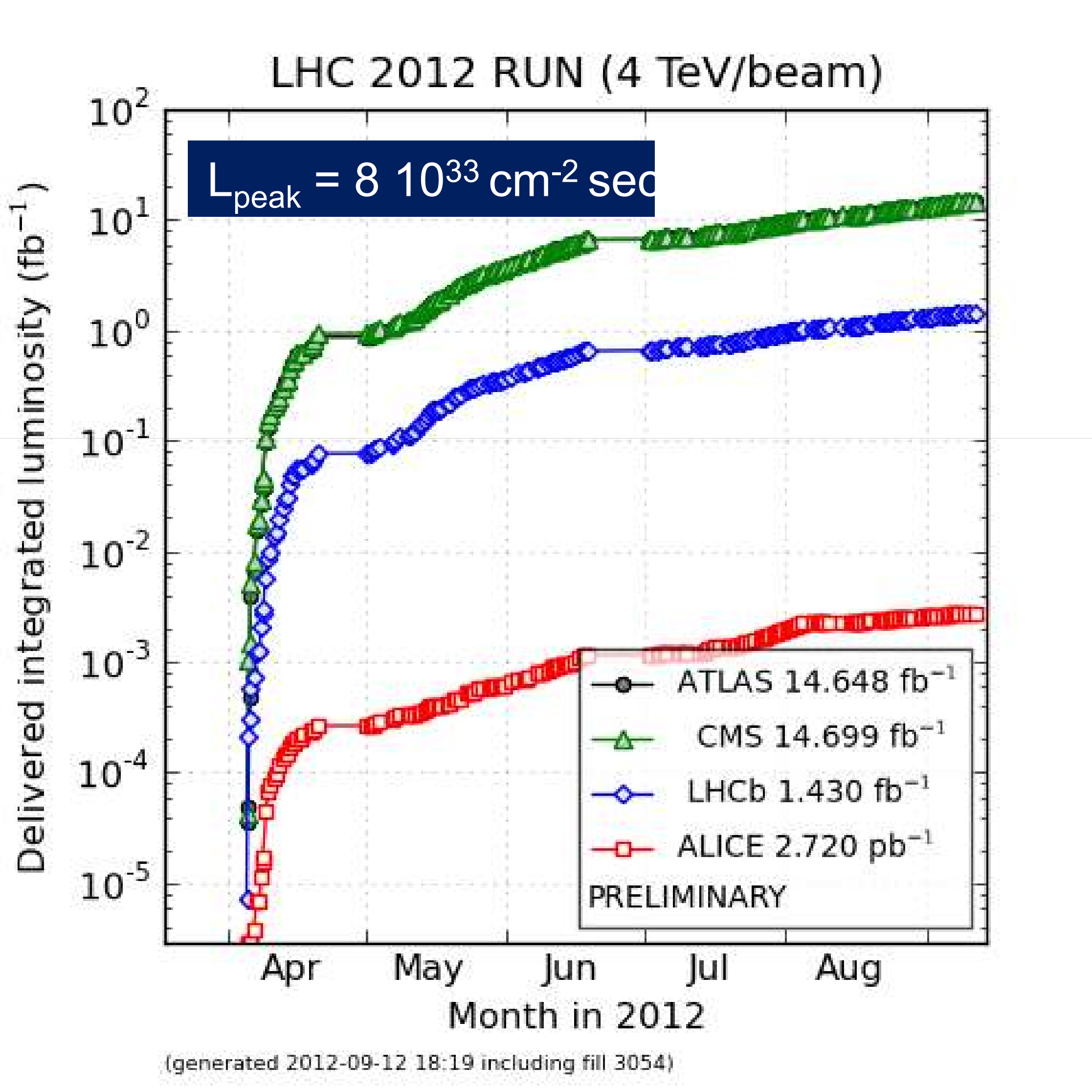
SPS $N_p= 1.6\ 10^{11}$

p-Pb: 3.5 TeV or 4 TeV

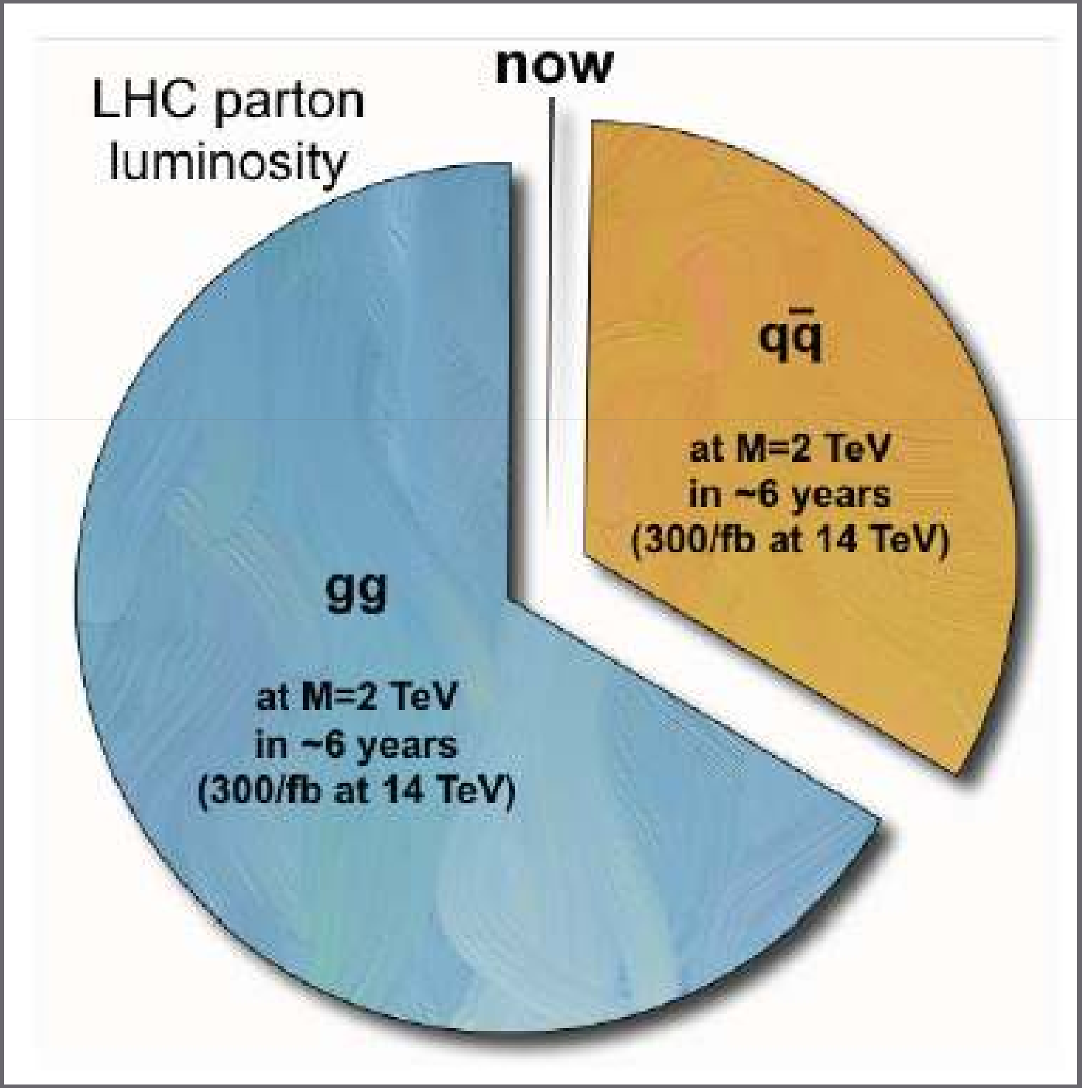
$\int Ldt = 15\text{-}23\ nb^{-1}$

$\beta^*=(0.6,0.6,0.6,3)m$

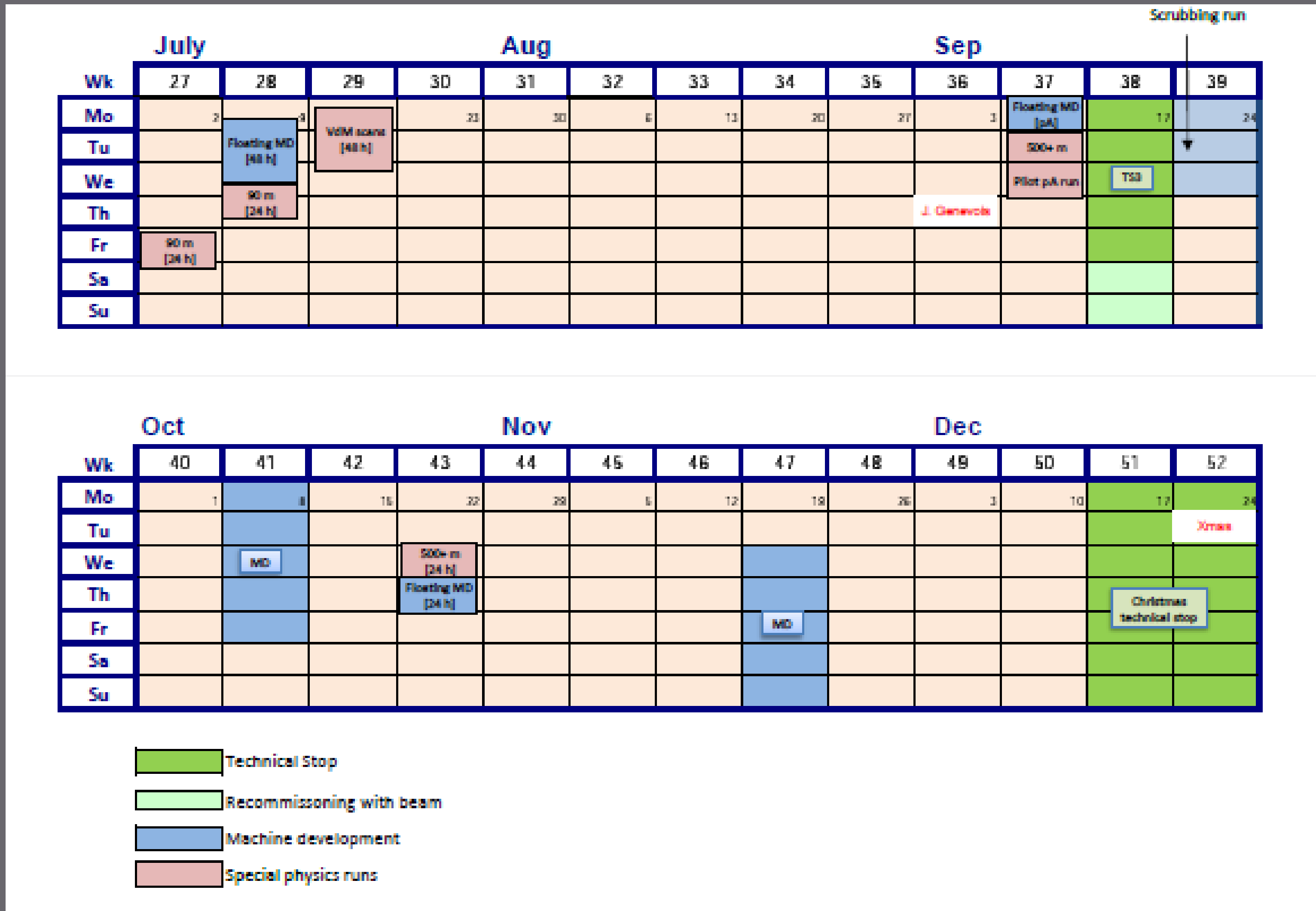
LHC Performance 2012



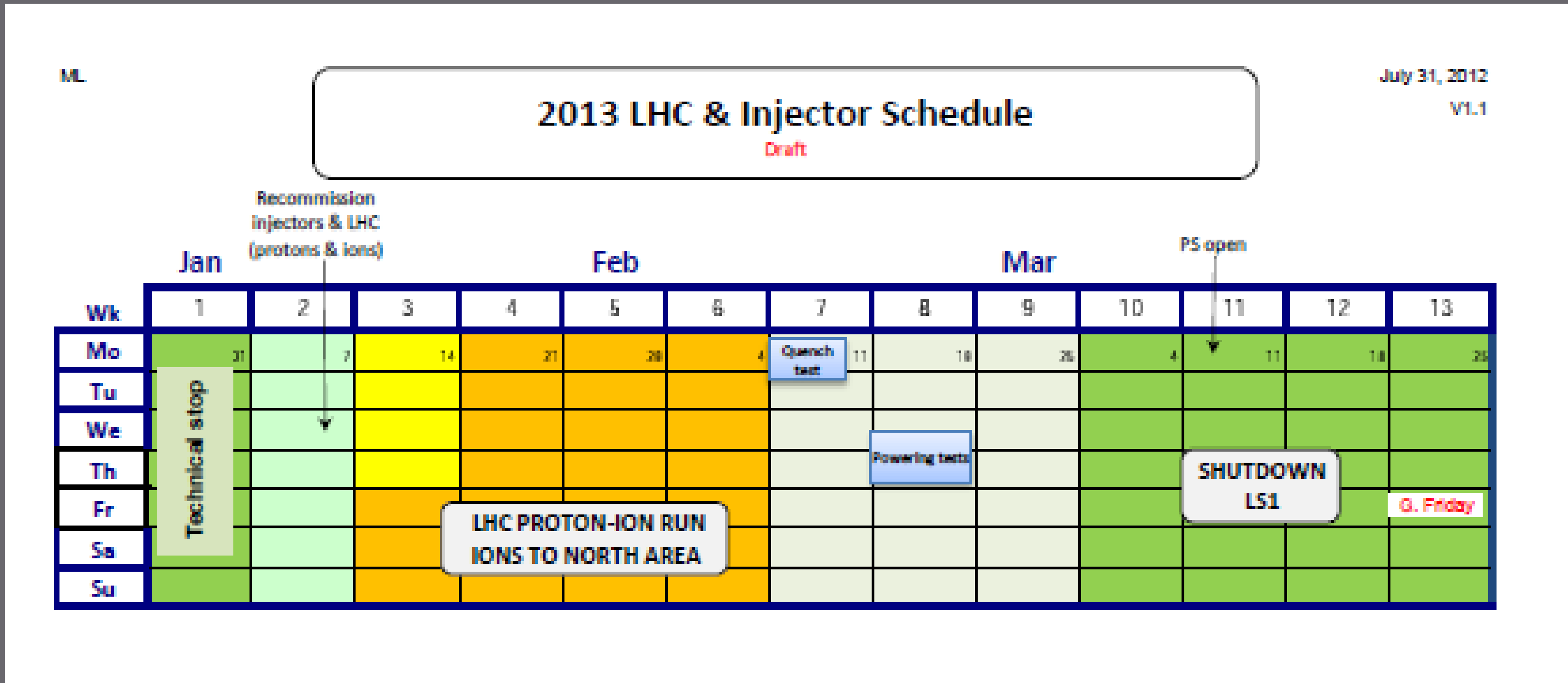
LHC Luminosity Pie Chart



2012 LHC schedule Q3/Q4



2013 LHC Schedule Q1



LHC re-start after LS1 scheduled for end 2014

ACCELERATOR PLANS AT THE ENERGY FRONTIER

CERN Scientific Strategy

- Full exploitation of LHC physics potential
  - LHC Injector Upgrade (LIU) for the injection complex
    - Reliable operation (including consolidation & LINAC4).
    - Remove bottlenecks to benefit from nominal luminosity for both machine & experiments.
  - Focused R&D and prototyping for High-Luminosity LHC (HL-LHC).
  - Re-establish standards for technical and general infrastructure.
- Preparation for the long-term future
  - Energy frontier
    - CLIC/ILC collaboration and R&D (machine & experiments)
    - Generic R&D for High-Energy LHC (HE-LHC), e.g. high-field magnets.
    - Studies for future Large Hadron-electron Collider (LHeC)
    - R&D for high-power proton sources (HP-SPL), e.g. for neutrino physics.

Project Organization

- **Two projects have been created for studying and implementing the luminosity upgrade of the LHC:**

1. “HL-LHC” for the LHC itself

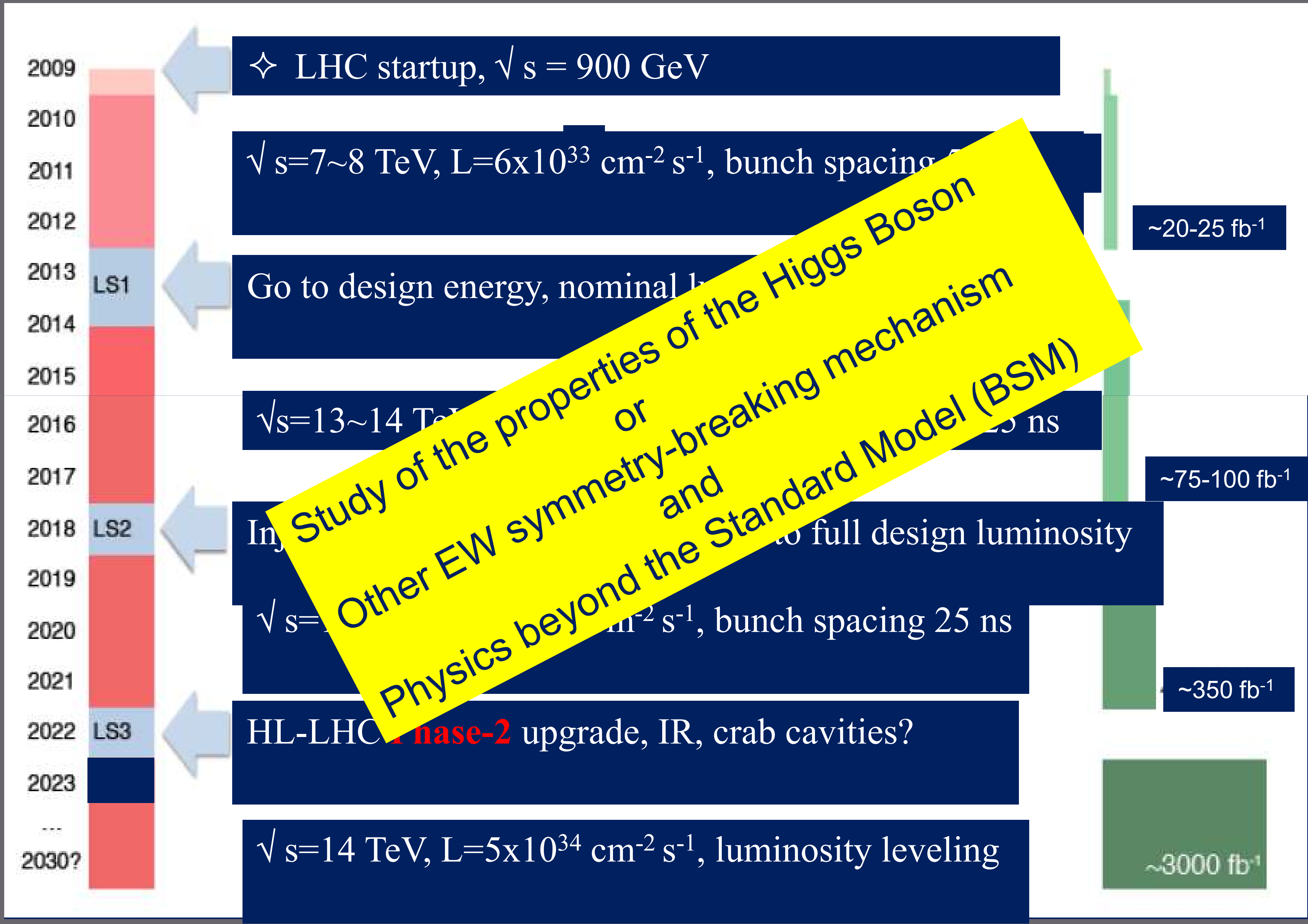
This study combines all work related to the provision of a peak luminosity of five times the design luminosity of the LHC (i.e. $5x10^{34}$ $cm^{-2}s^{-1}$) and with an enhanced luminosity lifetime by “luminosity leveling”.

2. “LHC Injector Upgrade” (LIU) for the LHC injector complex

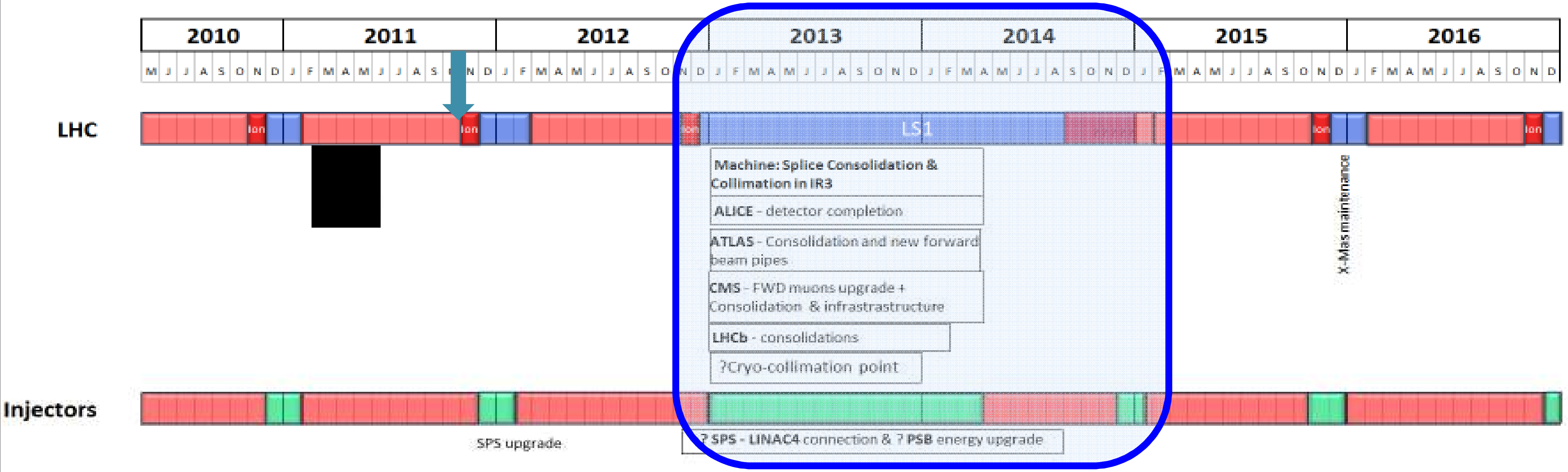
The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC. This includes LINAC4, the PS Booster, the PS, the SPS, as well as the heavy-ion chain.

R&D for a Superconducting Proton Linac (SPL) is pursued as an option for future.

LHC Schedule Assumptions



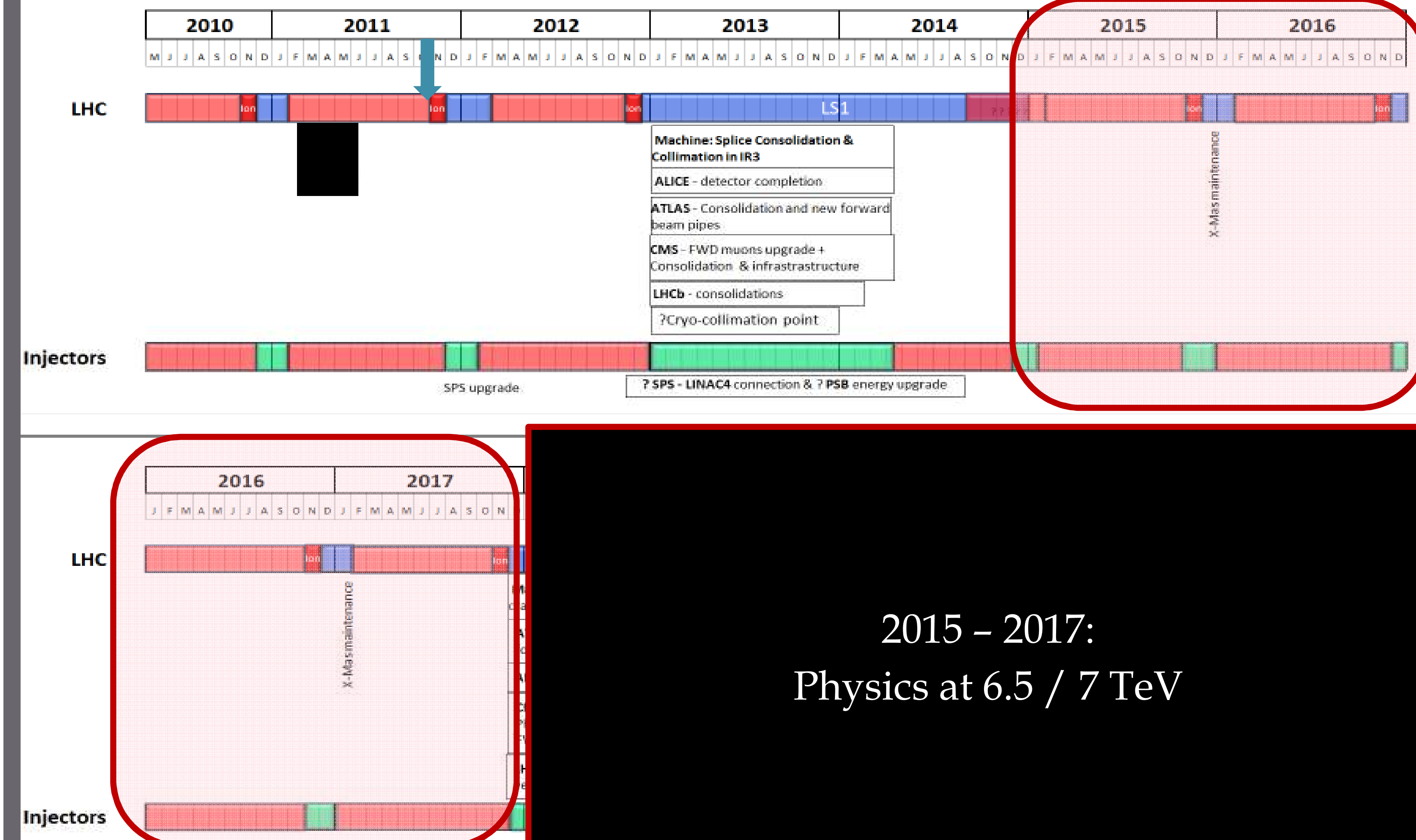
New rough draft 10 year plan



2013 – 2014: Long Shutdown 1 (LS1) consolidate for 6.5 / 7 TeV

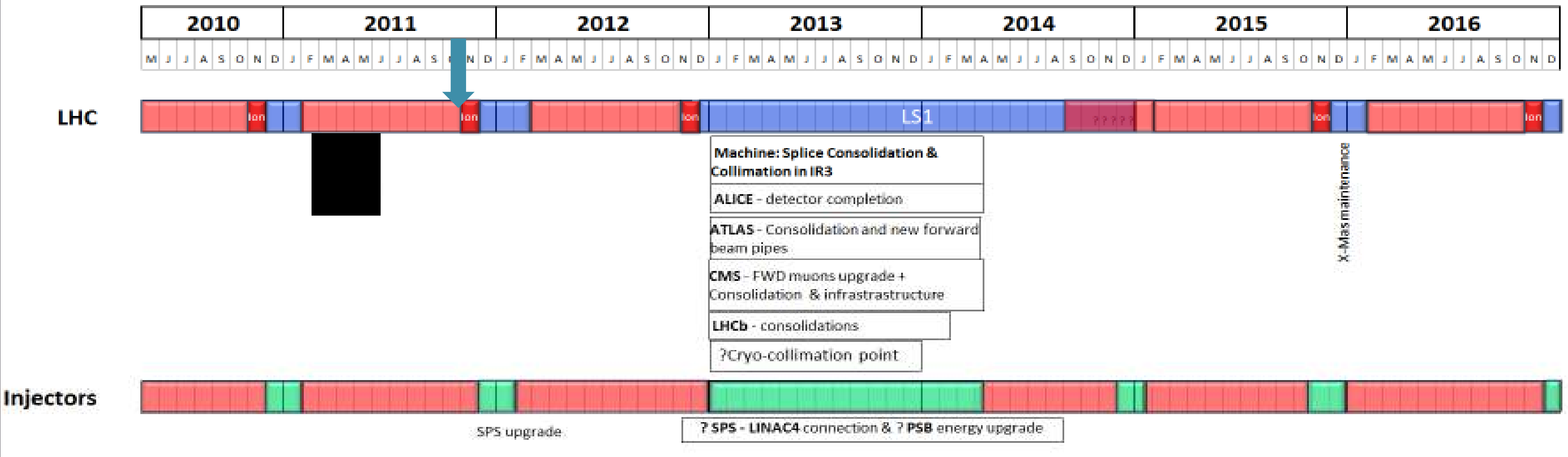
- Measure all splices and repair the defective
- Consolidate interconnects with new design (clamp, shunt)
- Finish installation of pressure release valves (DN200)
- Magnet consolidation
- Measures to further reduce SEE (R2E): relocation, redesign, …
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)
- Experiments consolidation/upgrades

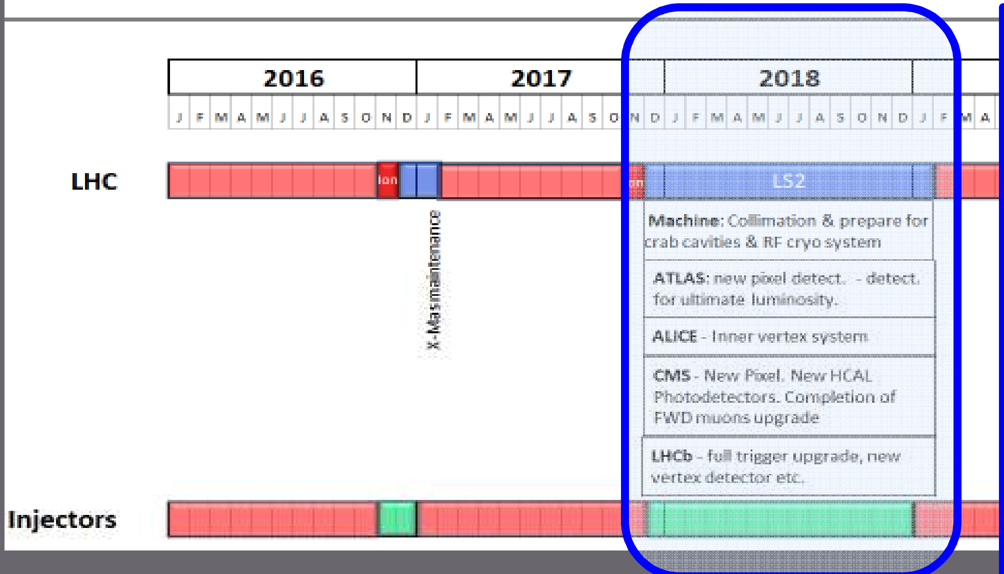
New rough draft 10 year plan



2015 – 2017:
Physics at 6.5 / 7 TeV

New rough draft 10 year plan



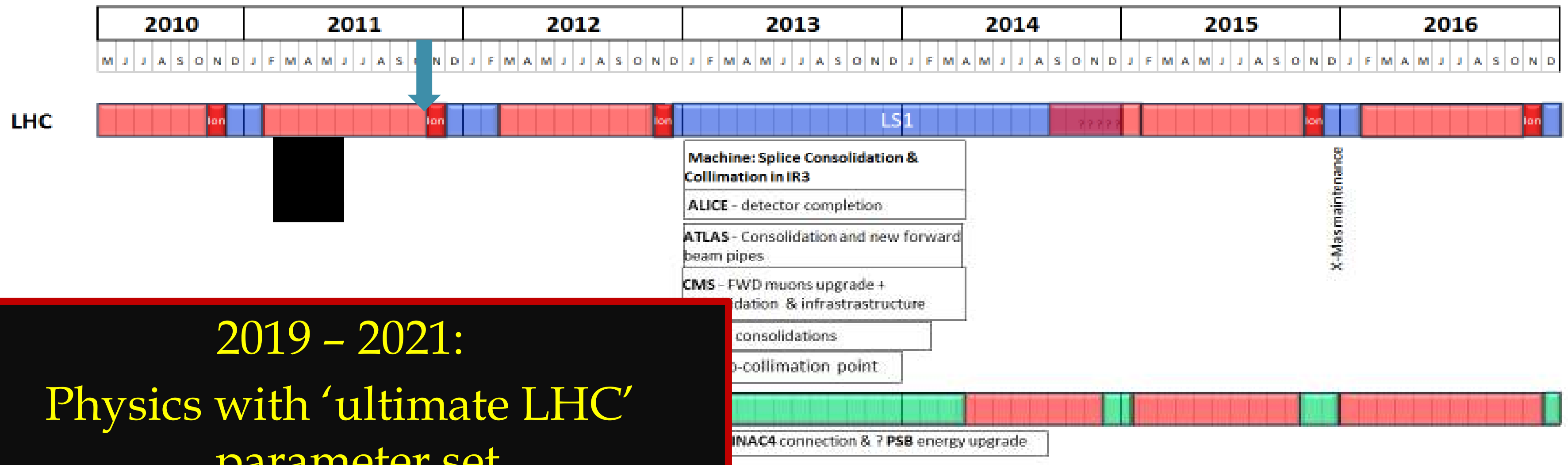


2018: LS2 to prepare for 'ultimate LHC' parameter set:

- Phase II collimation upgrade
- Major injectors upgrade (LINAC4, 2GeV PS Booster, SPS coating, …)
- Prepare for crab cavities (for HL-LHC)

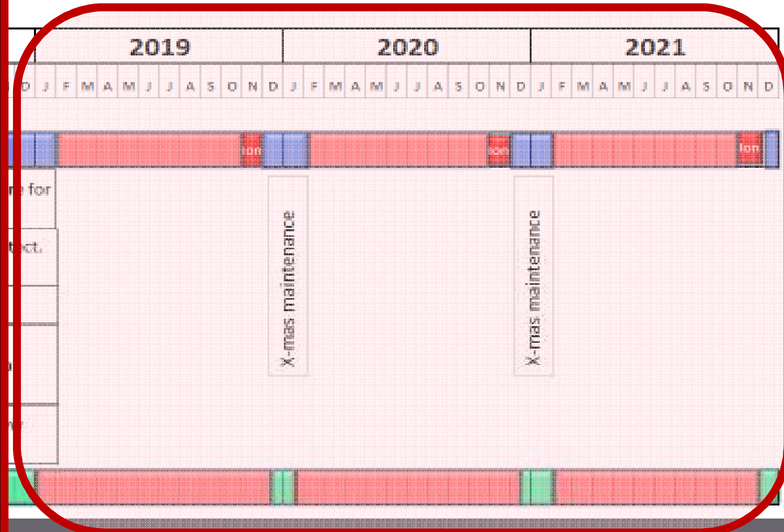
New rough draft 10 year plan

Not yet approved!



2019 – 2021:
Physics with 'ultimate LHC' parameter set

Parameters	'Ultimate'
k (# of bunches)	2808
N (bunch intensity)	1.7×10^{11} p
β^*	0.5 m
Luminosity [$cm^{-2}s^{-1}$]	2.4×10^{34}
E[TeV]	7
E[MJ]	541

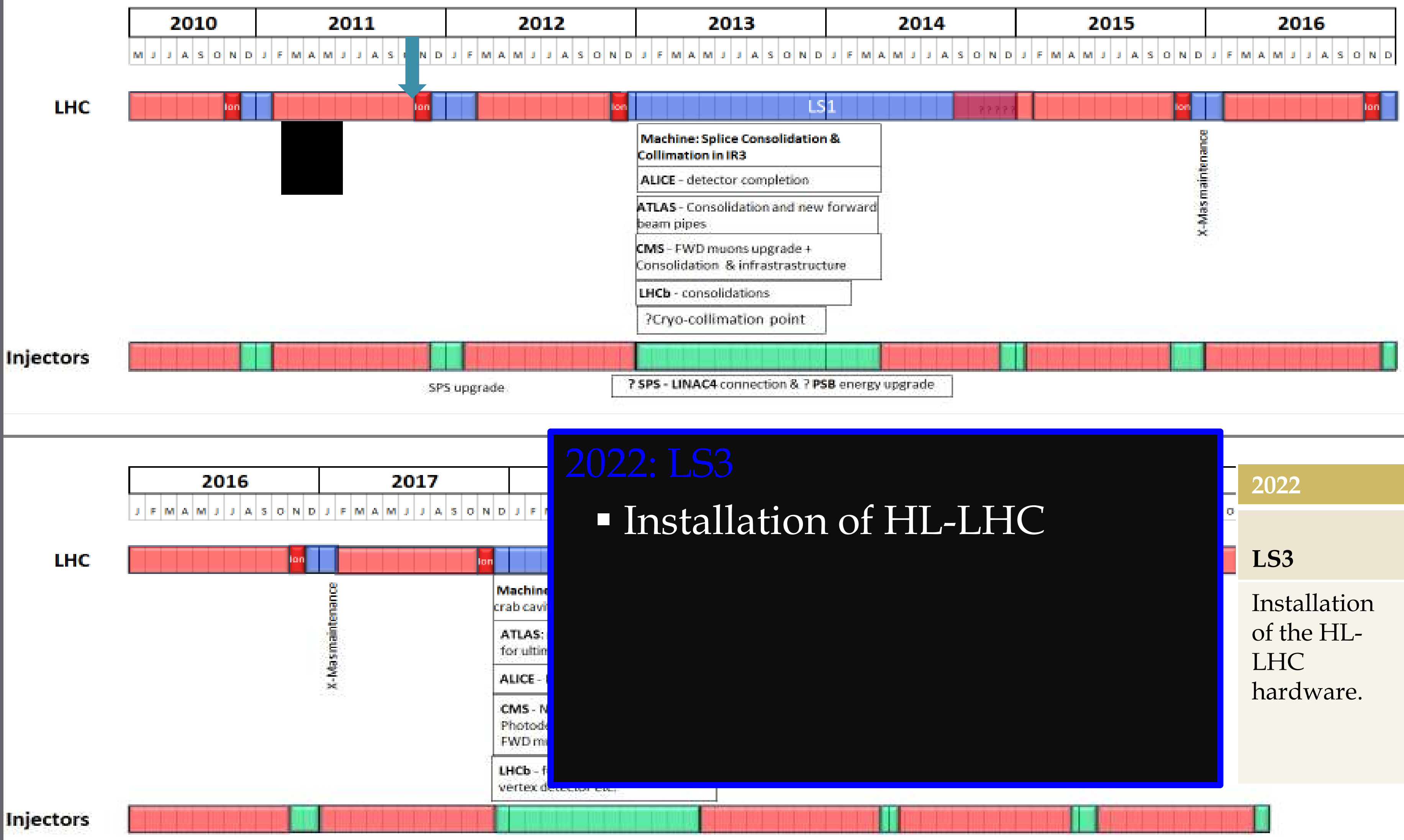


2022

LS3

Installation of the HL-LHC hardware.

New rough draft 10 year plan



2022: LS3

- Installation of HL-LHC

2022

LS3

Installation of the HL-LHC hardware.

Why Upgrade the Injectors ?

- Need for reliability
  - Accelerators are old [LINAC2 (1978), PSB (1975), PS (1959), SPS (1976)].
  - They operate far from their design parameters and close to hardware limits.
  - The infrastructure has suffered from the concentration of resources on LHC during its construction phase.
- Need for better beam characteristics

Goals & Means

To increase performance (increase brightness):

⇒ Increase injection energy in the PSB from 50 to 160 MeV
  ⇒ Linac4 (160 MeV H^-) to replace Linac2 (50 MeV H^+).

⇒ Increase injection energy in the PS from 1.4 to 2.0 GeV
  ⇒ Increasing the field in the PSB magnets, replacing power supply and changing transfer equipment.

⇒ Upgrade the PSB , PS and SPS to make them capable to accelerate and manipulate a higher brightness beam.
  ⇒ Feedbacks, cures against electron clouds, hardware modifications to reduce impedance…)

Intensity Limits

- Present & Future Peak Performance

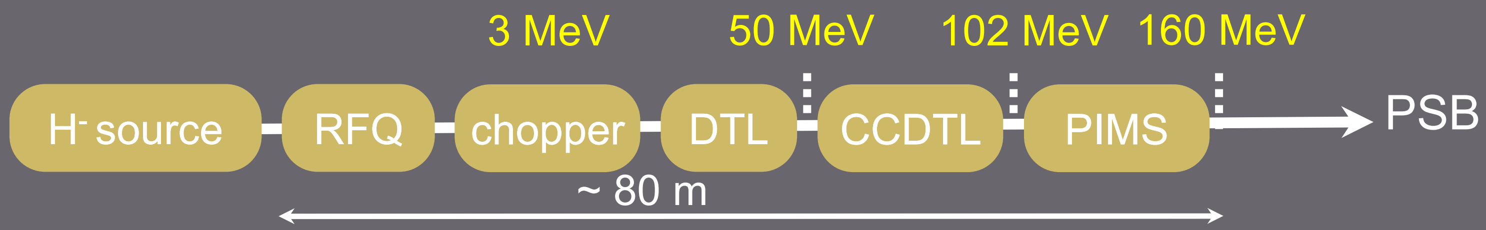
Intensity Limitations (10^{11} protons per bunch)

Reminder: design = 1.15 (for 10^{34}); Ultimate = 1.7 (for 2.3×10^{34})

	Present	2GeV in PS
LINAC2/LINAC4	4.0	4.0
PSB	3.6	3.6
PS	1.7	3.0
SPS	1.2	>1.7?
LHC	1.1	1.7-2.3?

Conclusion:
SPS is bottleneck for ultimate.
PSB energy upgrade removes this bottleneck.

LINAC4 - Introduction



Ion species		**H^-**	
Output Energy	**160**	**MeV**	
Bunch Frequency	**352.2**	**MHz**	
Max. Rep. Rate	**2**	**Hz**	
Max. Beam Pulse Length	**1.2**	**ms**	
Max. Beam Duty Cycle		**0.24**	**%**
Chopper Beam-on Factor	**65**	**%**	
Chopping scheme: 222 transmitted /133 empty buckets			
Source current	**80**	**mA**	
RFQ output current	**70**	**mA**	
Linac pulse current	**40**	**mA**	
N. particles per pulse	**1.0**	**$\times 10^{14}$**	
Transverse emittance	**0.4**	**π mm mrad**	

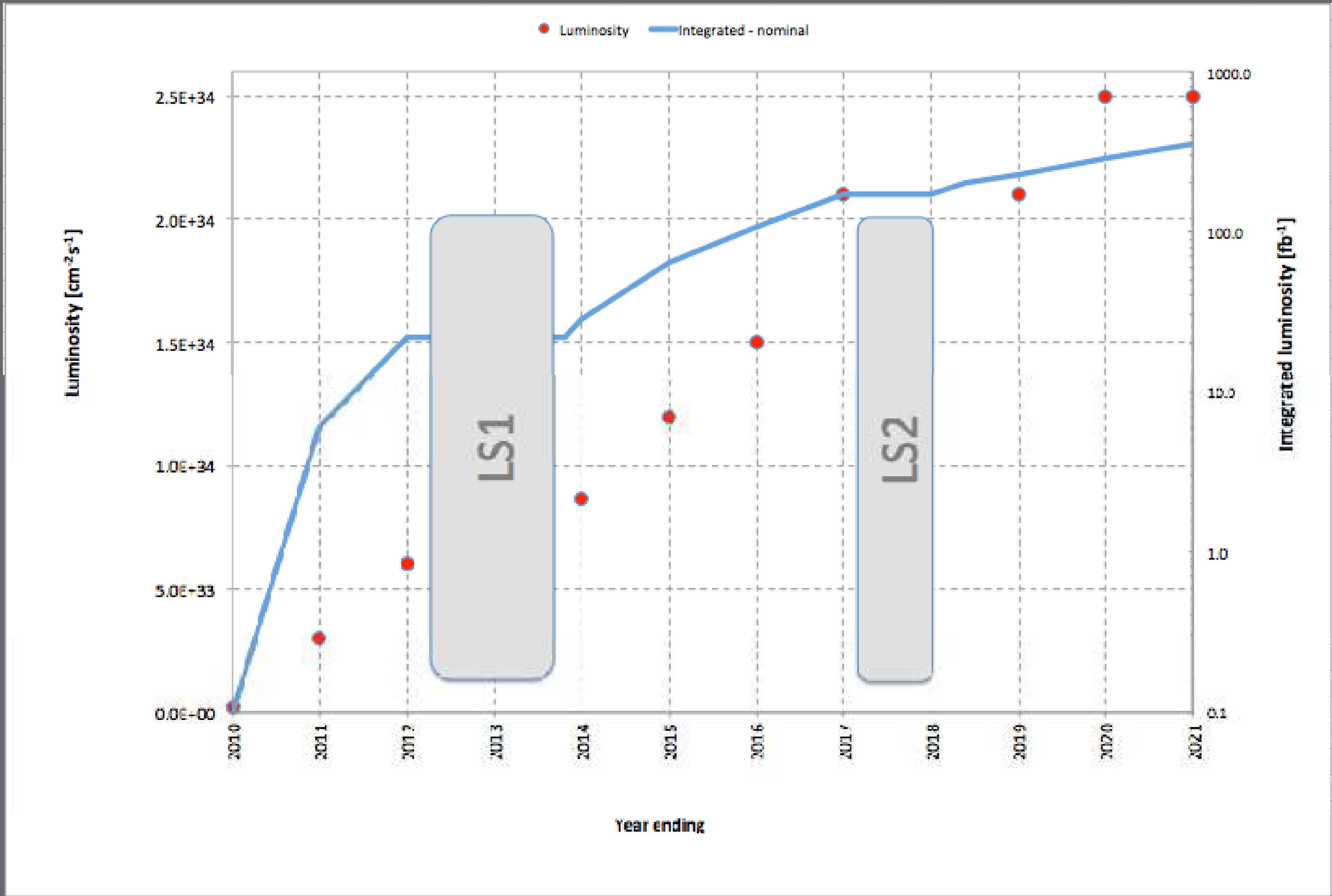
H^- charge exchange injection in the PSB

160/50 MeV $\Rightarrow$ factor 2 in $\beta\gamma^2$) $\rightarrow$ doubled brightness in the PSB

Chopping at low energy to ease longitudinal capture and reduce beam loss in PSB.

LINAC4 – Civil Engineering

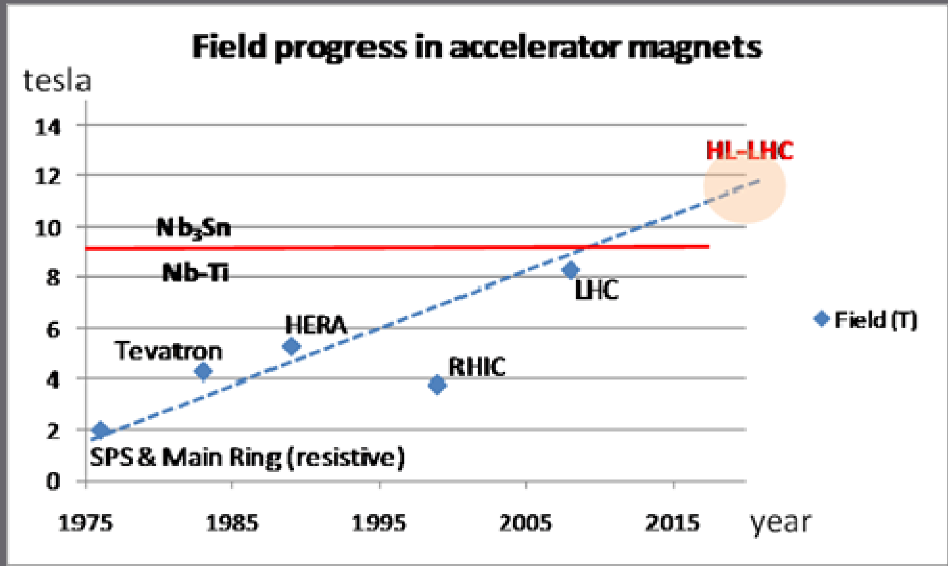
LHC Projection



THE LHC
LUMINOSITY UPGRADE
HL-LHC

Beam Focusing
High-Field SC Magnets

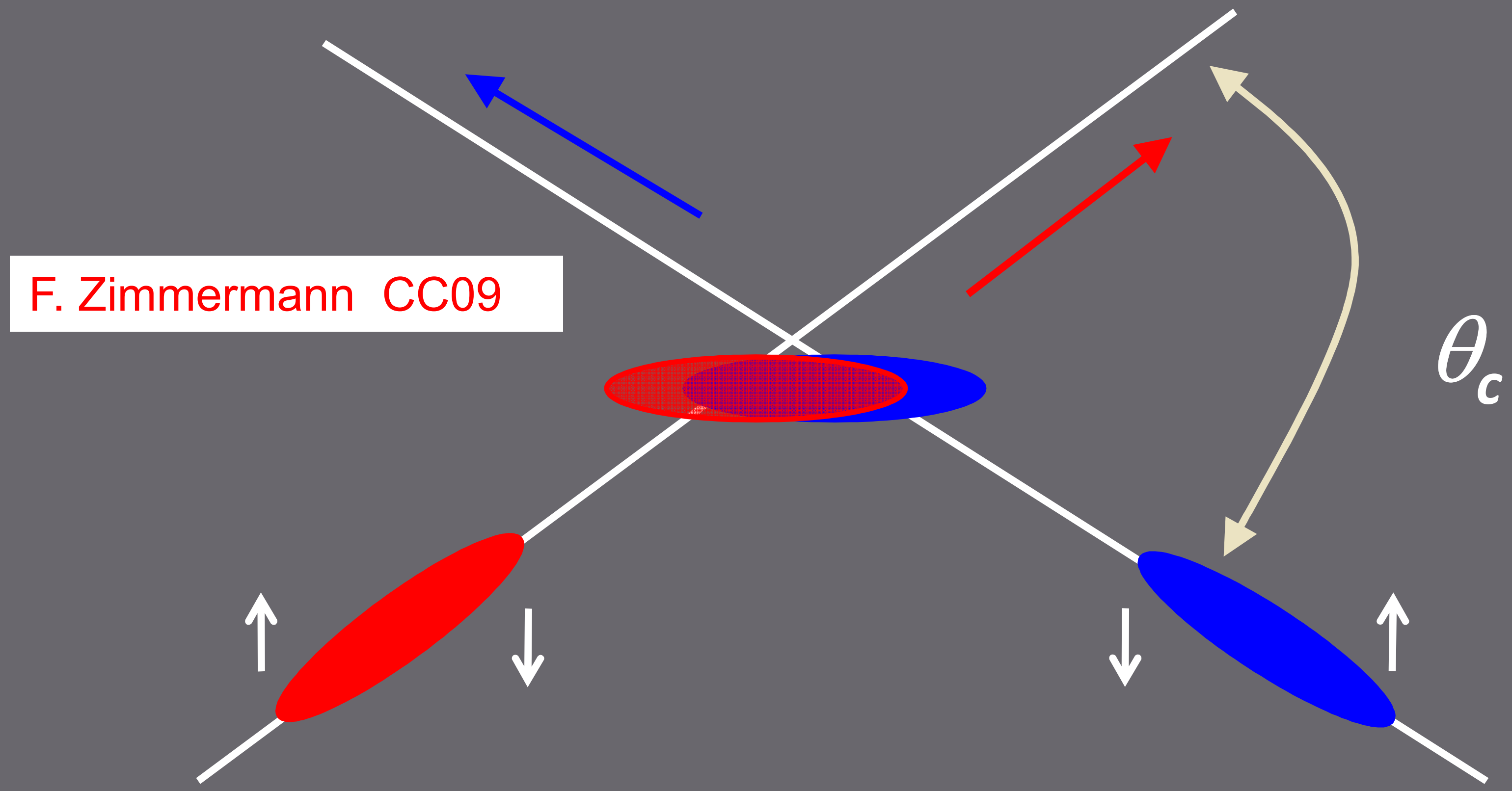
- 13 T, 150 mm aperture quadrupoles for the inner triplet:
  - LHC: 8 T, 70 mm.
- More focus strength, β* as low as 15 cm (55 cm in LHC).
  - In same scheme even β* down to 7.5 cm considered
- Dipole separators capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)



Goal:

Enable focusing of the beams to β^*=0.15 m in IP1 and IP5.

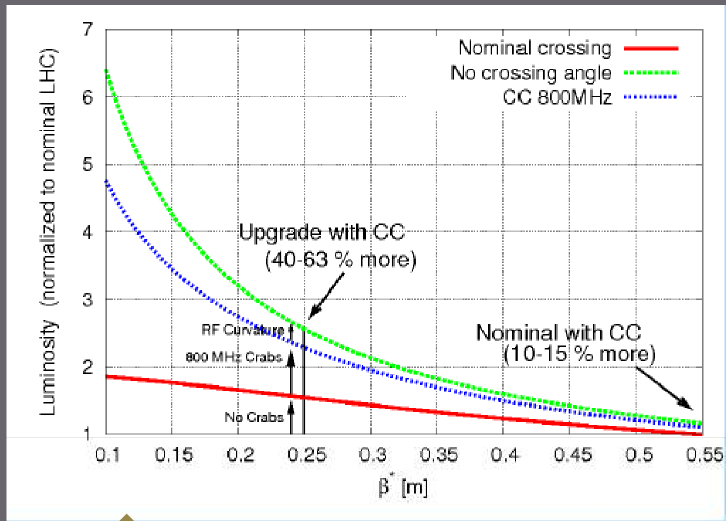
Crab-crossing Restores Bunch Overlap

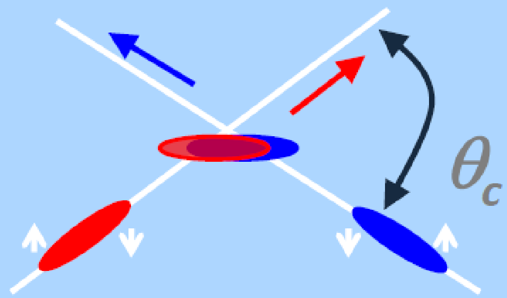


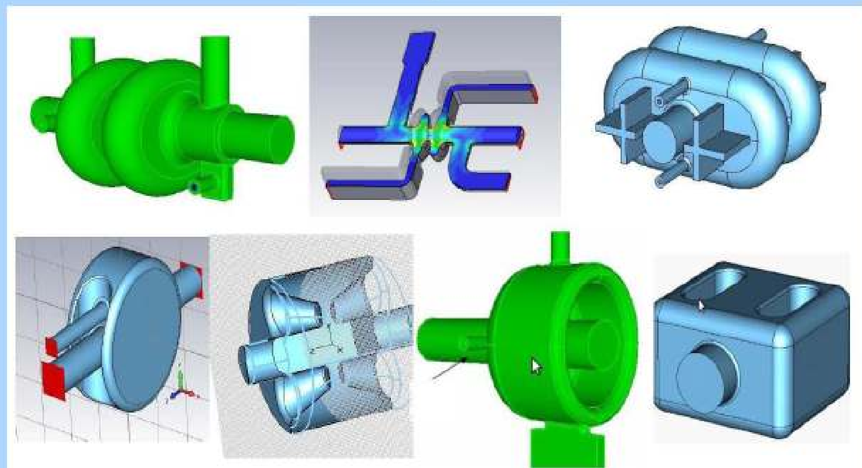
- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- Bunch centroids still cross at an angle (easy separation)
- First proposed in 1988, in operation at KEKB since 2007

$\longrightarrow$ *world record luminosity!*

Crab Cavities for Low β*







Compact 400 MHz crab cavities

Example HL-LHC Parameters

Parameter	Symbol	Nom.	Nom.*	HL Crab
protons per bunch	N_b [10^{11}]	**1.15**	1.7	**1.78**
bunch spacing	Δt [ns]	**25**	50	**25**
beam current	I [A]	**0.58**	0.43	**0.91**
longitudinal profile		**Gauss**	Gauss	**Gauss**
rms bunch length	σ_z [cm]	**7.55**	7.55	**7.55**
beta* at IP1&5	$\beta*$ [m]	**0.55**	0.55	**0.15**
full crossing angle	θ_c [μrad]	**285**	285	**(508-622)**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	**0.65**	0.65	**0.0**
tune shift	ΔQ_{tot}	**0.009**	0.0136	**0.011**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**10.6**
events per #ing		**19**	40	**95**
effective lifetime	τ_{eff} [h]	**44.9**	30	**13.9**
run or level time	$t_{run,level}$ [h]	**15.2**	12.2	**4.35**
e-c heat SEY=1.2	P [W/m]	**0.2**	0.1	**0.4**
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	**0.32**	0.30	**0.62**
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	**59, 102**	40, 69	**38, 66**
annual luminosity	L_{int}[fb^{-1}]	**57**	58	**300**

Luminosity Levelling

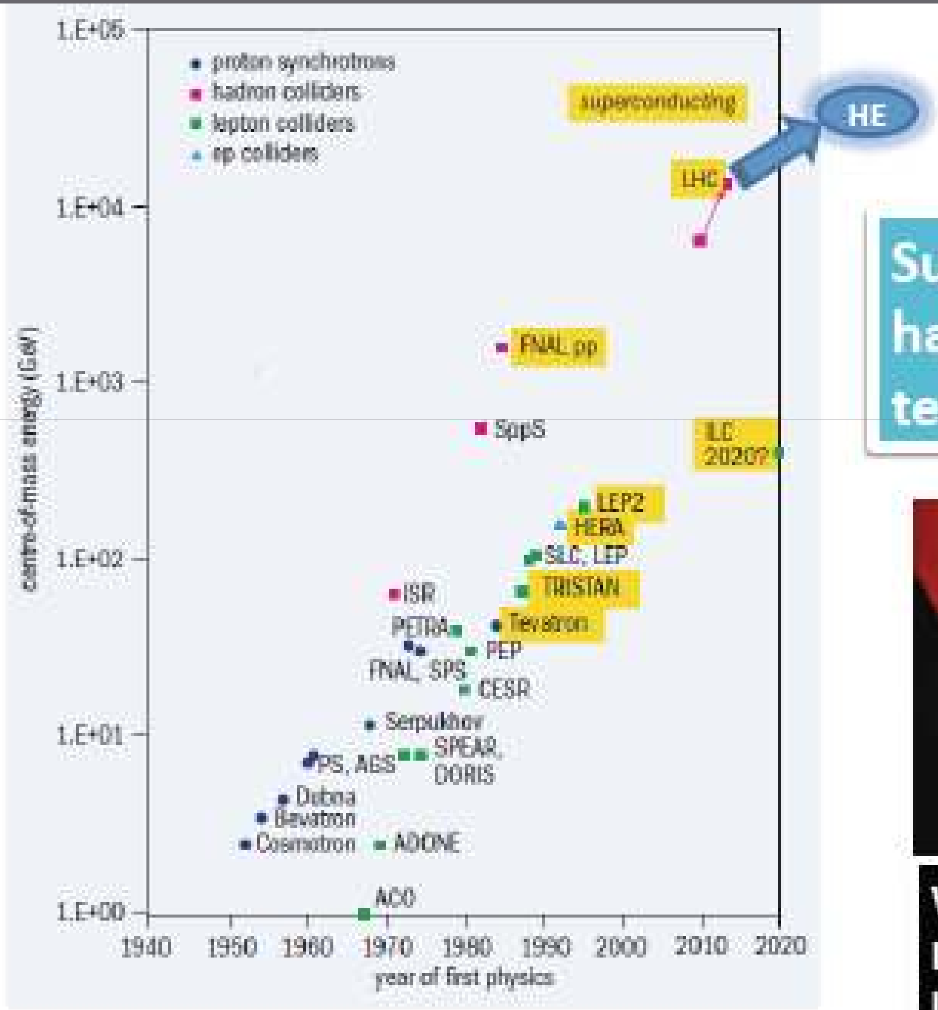
- For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time ⇒ low efficiency.
- Estimates show that the useful integrated luminosity is greater with a peak luminosity of 5×10^{34} cm^{-2} s^{-1} and luminosity levelling than with 10^{35} cm^{-2} s^{-1} and a luminosity lifetime of a few hours.
- Luminosity Levelling by
  - Beta*, crossing angle, crab cavities, and bunch length

Particle detector upgrade would become more complicated and expensive for a peak luminosity of 10^{35} due to

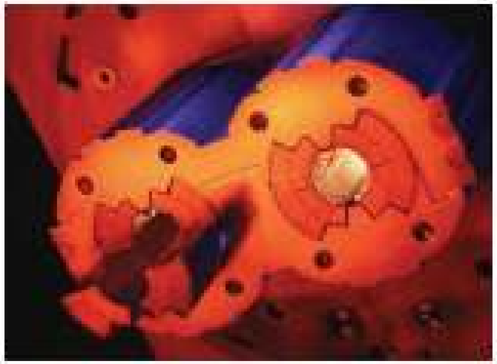
- Pile up events
- Radiation effects

THE LHC
ENERGY UPGRADE
HE-LHC

Thirty Years of SC Accelerators

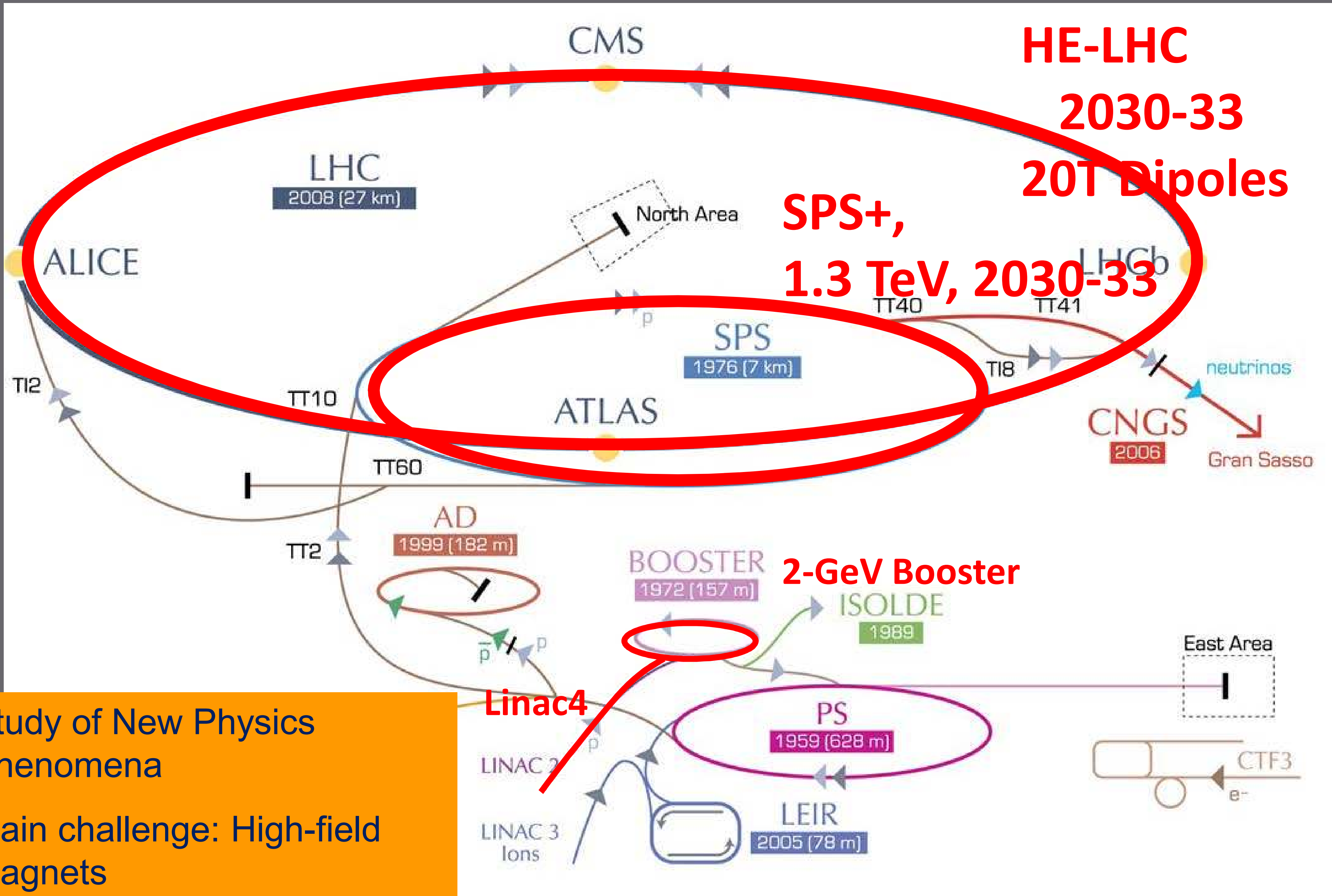


Superconductivity has been an enabling technology



Without SC technology LHC would be 100 km long and 900 MW !

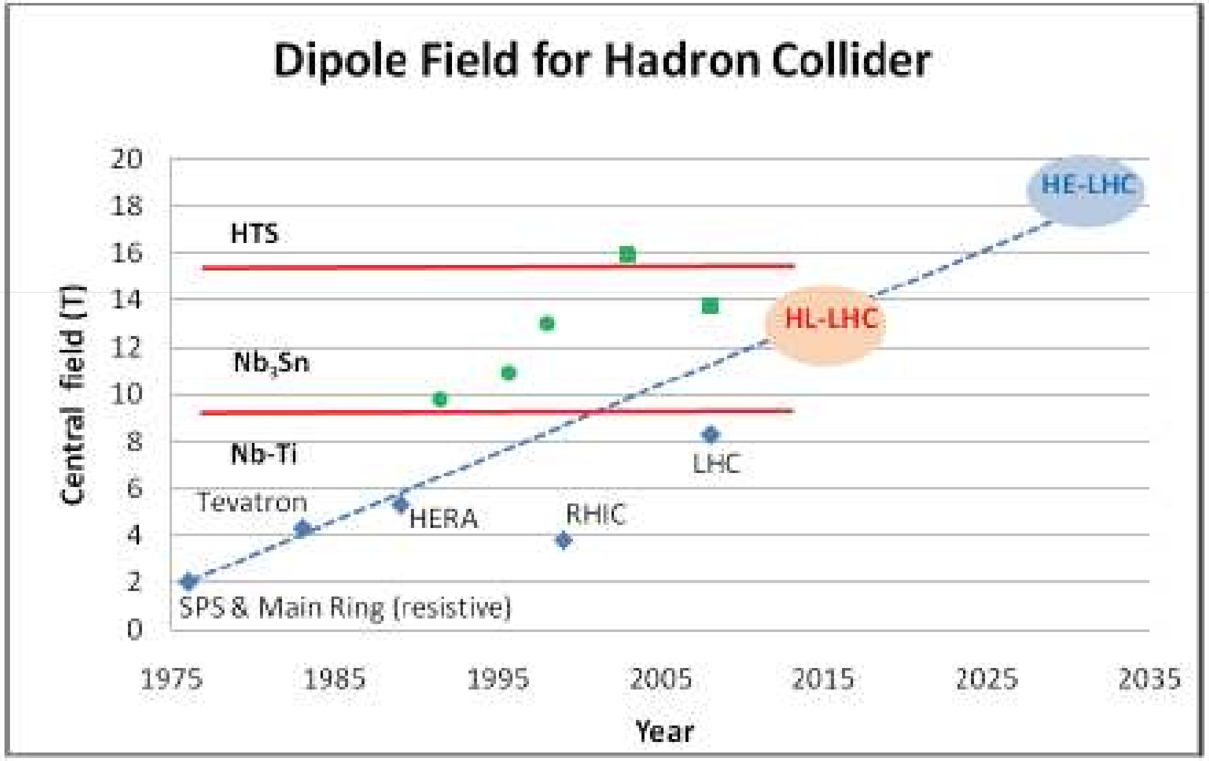
High-Energy LHC (HE-LHC)



Study of New Physics Phenomena

Main challenge: High-field Magnets

Main Dipoles – Is it Possible?



Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) **the practical limits is around 20 T.** Such a challenge is similar to a 40 T solenoid (μ-C)

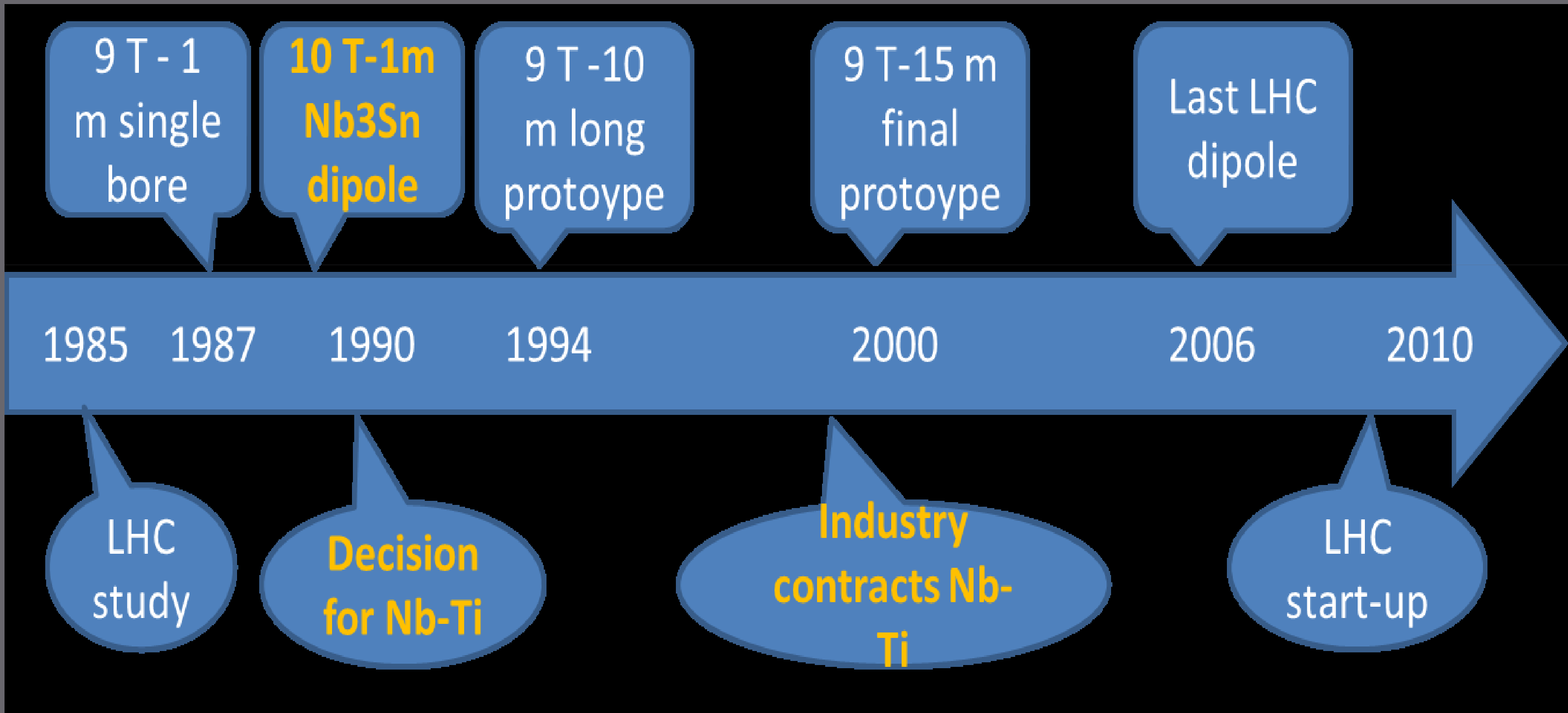
◆ **Nb-Ti operating dipoles;** ● **Nb3Sn cosθ test dipoles** ■ **Nb3Sn block test dipoles**

R&D on High-field SC Magnets

R&D started in view of VLHC and ITER - Multi Labs and Industrial Collaborations
examples: LARP - bnl - fnal- lbnl – slac (prototype for 2012)
FRESCA - EuCARD WP7 – 12 Institutes - main involvement from CERN, FERMILAB, LBNL, BNL, KEK

NbTi	• Robust, ductile, well extablished techology • B < 10 T
Nb_3Sn	• Heat treatment, brittleness • B < 15 T • US-LARp, Bruker - Prototyping
Nb_3AL	• KEK, Hitachi • Subscale Magnet for demonstration (B = 13 T)
HTS	• B up to 45 T • R&D on wires , still long road for High fields magnets • Mechanical weakness

LHC – 25-year Project



HE-LHC Performance Targets

- Proton beam energy 16.5 TeV in LHC tunnel
- Peak luminosity $2x10^{34}$ $cm^{-2}s^{-1}$
- Also heavy-ion collisions at equivalent energy
- Eventually high-energy ep collisions?

HE-LHC Activities

Beam: energy 16.5 TeV; 20-T magnets
Cryogenics: **synchrotron-radiation heat, radiation damping & emittance control**
Vacuum system: synchrotron radiation
New injector: energy > 1 TeV

	LHC	**HE-LHC**
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.0
events per crossing	19	76

HE-LHC Challenges

- 20-T dipole magnets
  - cost & feasibility uncertainties
    - Nb_3Sn 4x more expensive than Nb-Ti
    - HTS 4x more expensive than Nb_3Sn; price for 1200 magnets: **5-6B$**
    - 20 T or 15 T (available today)?
  - stored energy and magnet protection
- Injector
  - S-SPS w 5-6 T dipole or 2-T superferric ring in LHC tunnel
  - LHC injector complex still working in 2030-40?
- Synchrotron radiation handling & heat load
  - beam screen 6x more heat load than LHC (40-60 K?)
  - cold mass 50% higher; h-l near limit of LHC cryo capacity

LARP Magnets

Big Leaps – V-LHC
New 80 km Tunnel

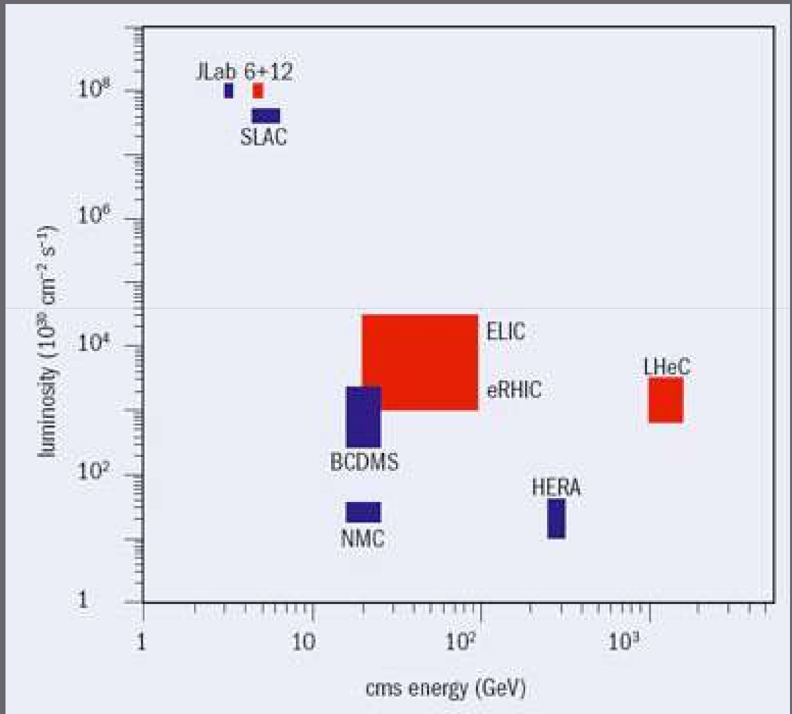
Option 1 (preferred)

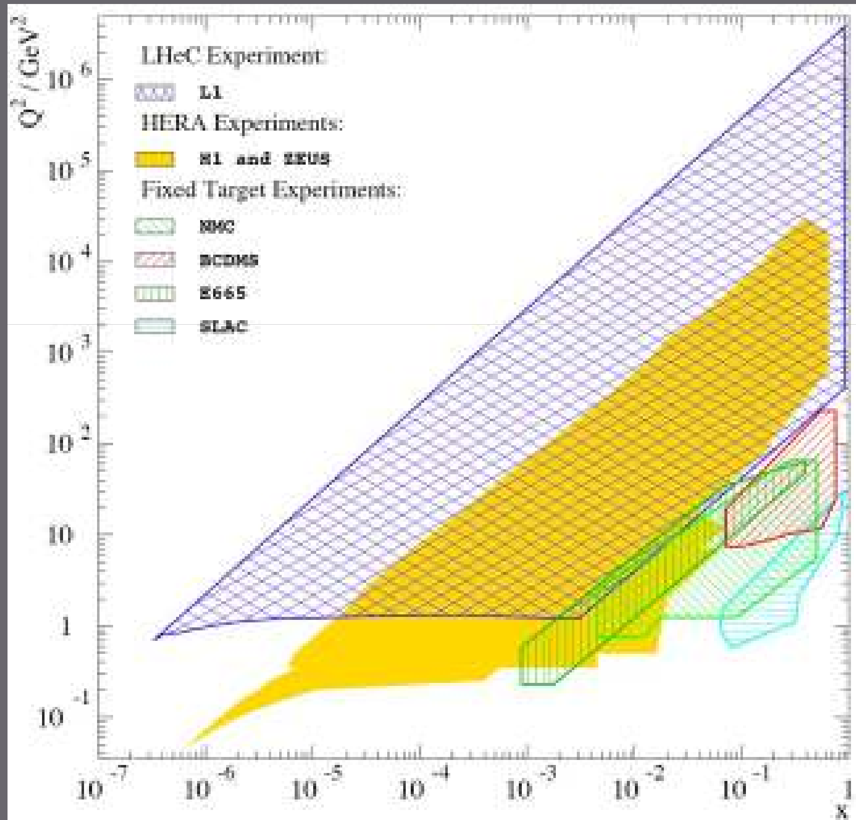
For LEP3, then for HE-LHC
Optimitation could be at 16 T field level:
collision **energy 80 TeV c.o.m.**
Much better new infrastructure.
However many costs go linearly, or more, with length. Magnet stored energy, beam energy also a concern

Whatever solution, a vigorous Magnet R&D will enable to go beyond LHC energy

HADRON-ELECTRON COLLIDERS

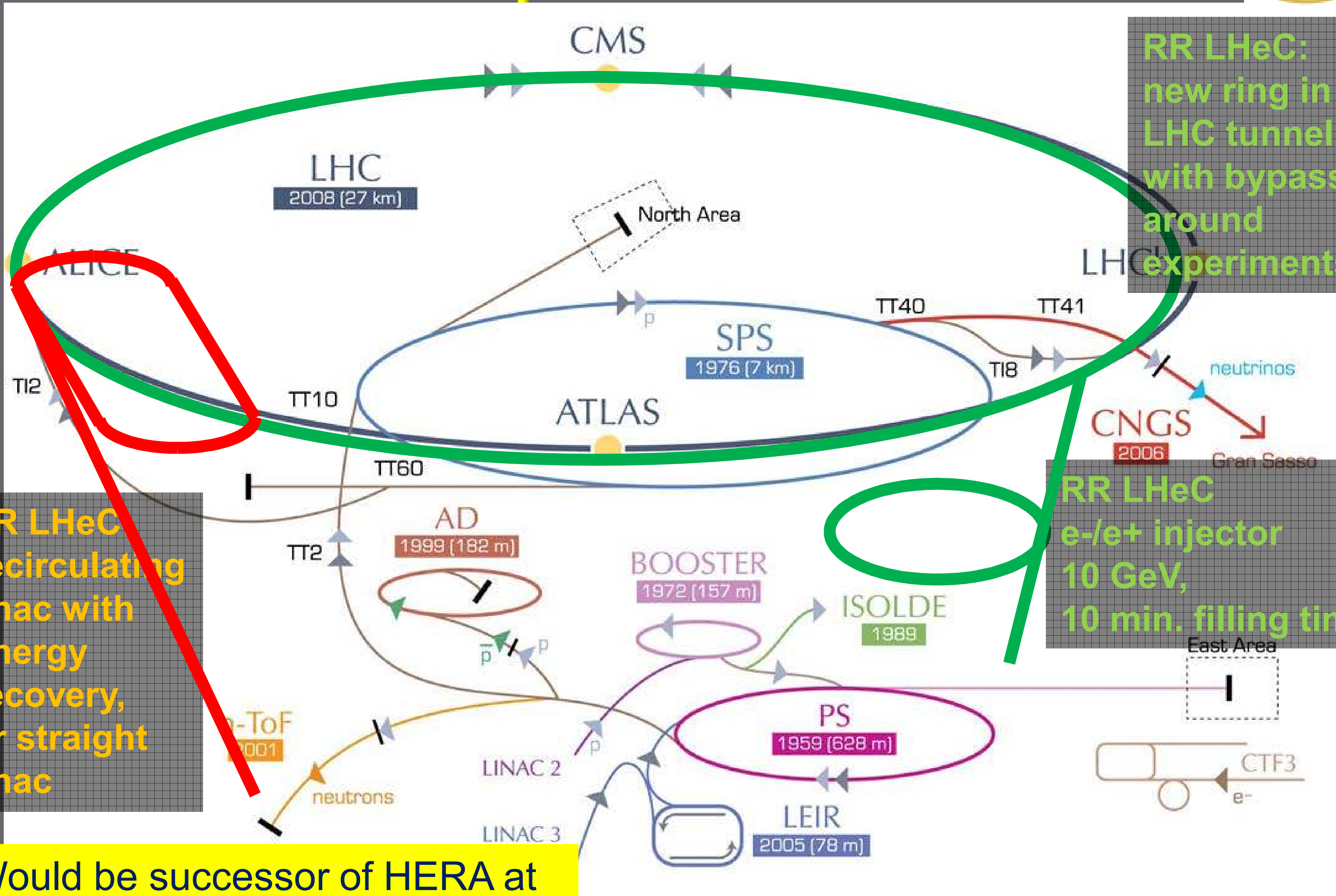
Projected Physics Reach of LHeC





QCD, Leptoquarks?

LHeC options: RR and LR



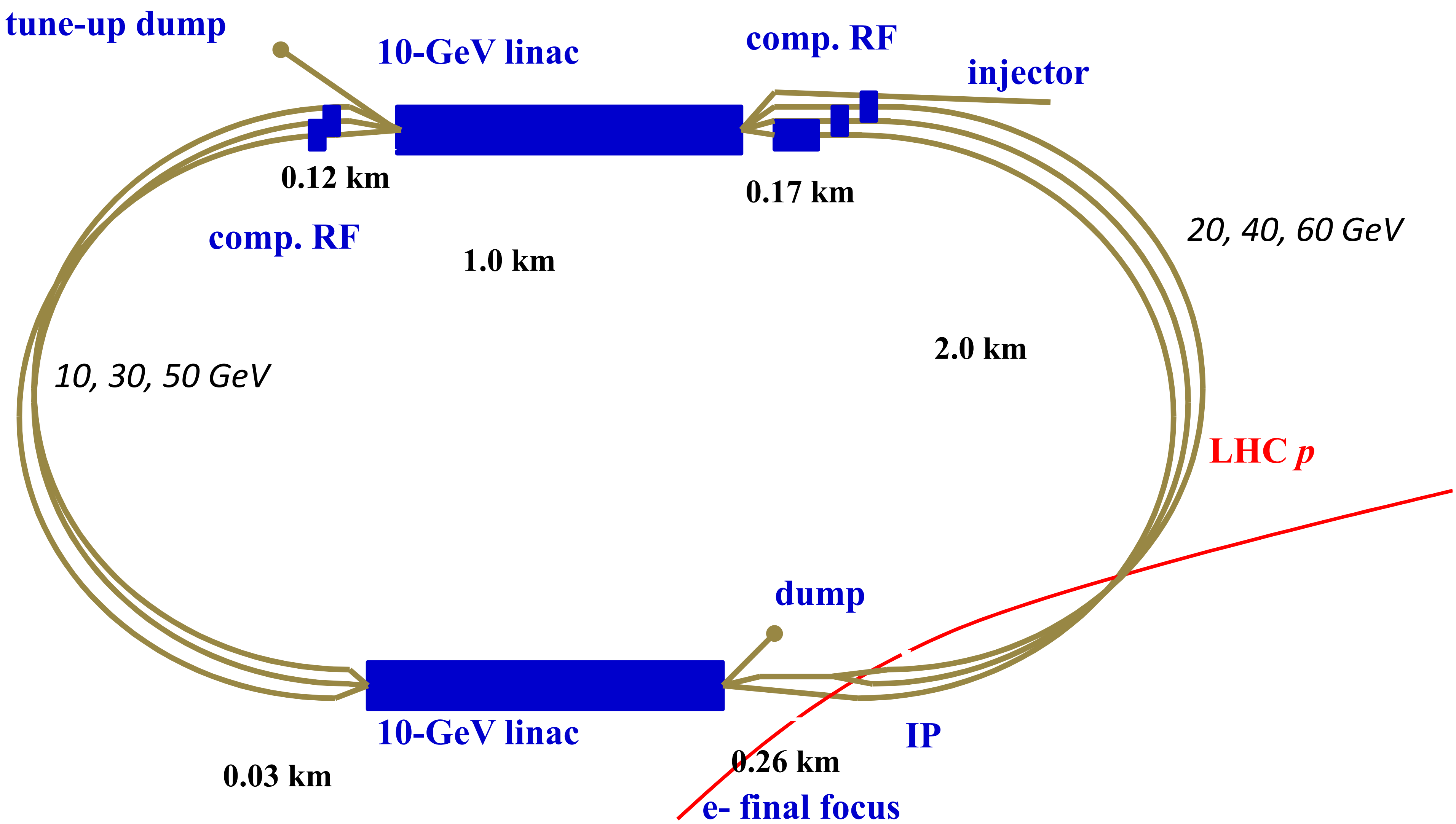
RR LHeC: new ring in LHC tunnel, with bypasses around experiments

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time

LR LHeC: recirculating linac with energy recovery, or straight linac

Would be successor of HERA at higher centre-of-mass energy

ERL Configuration



total circumference ~ 8.9 km

LHeC Design Parameters

electron beam	RR	LR	LR*
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

*) pulsed, but high energy ERL not impossible

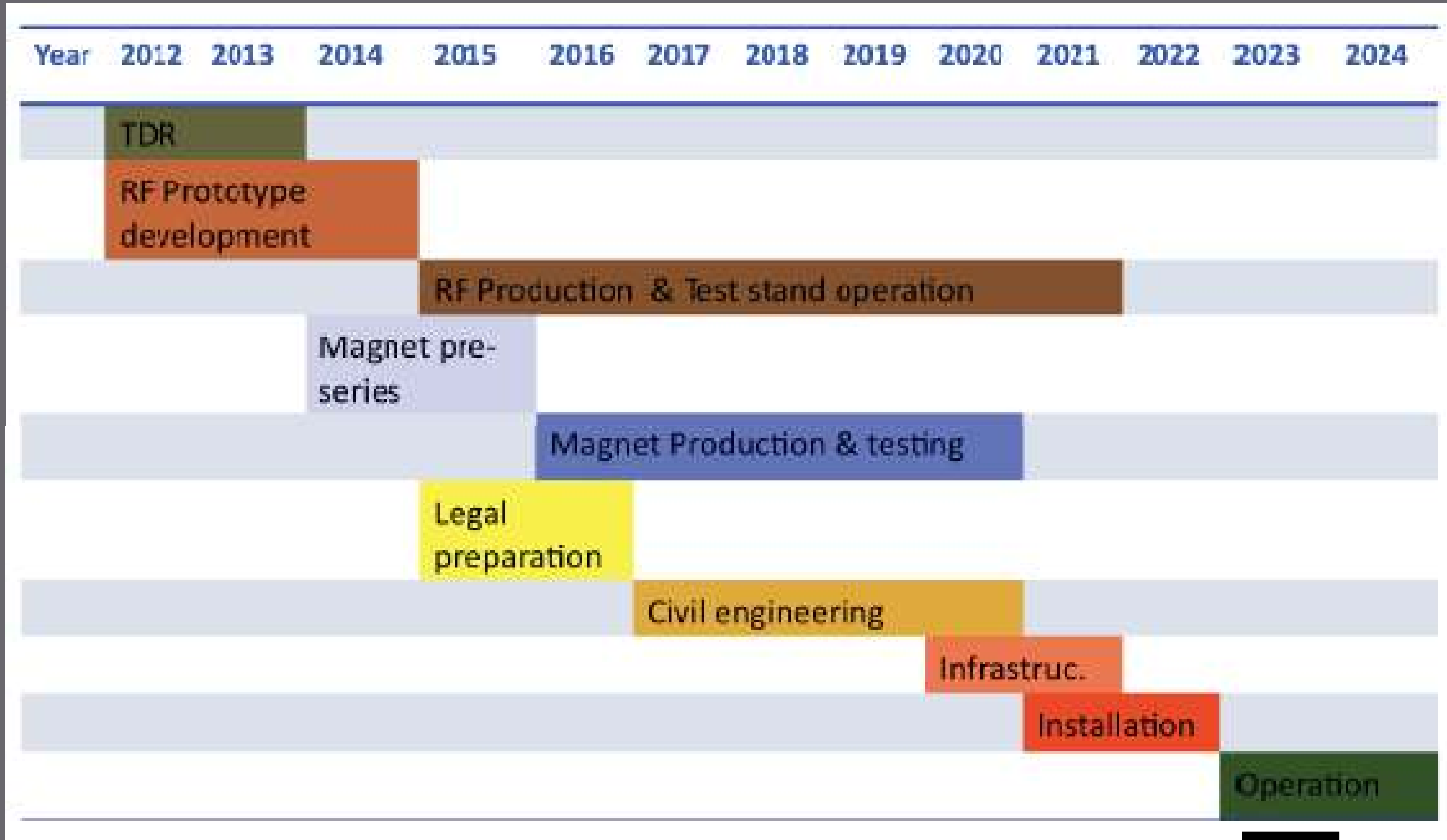
proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

50 ns & N_b=1.7x10^{11} probably conservative

design also for deuterons (new) and lead (exists)

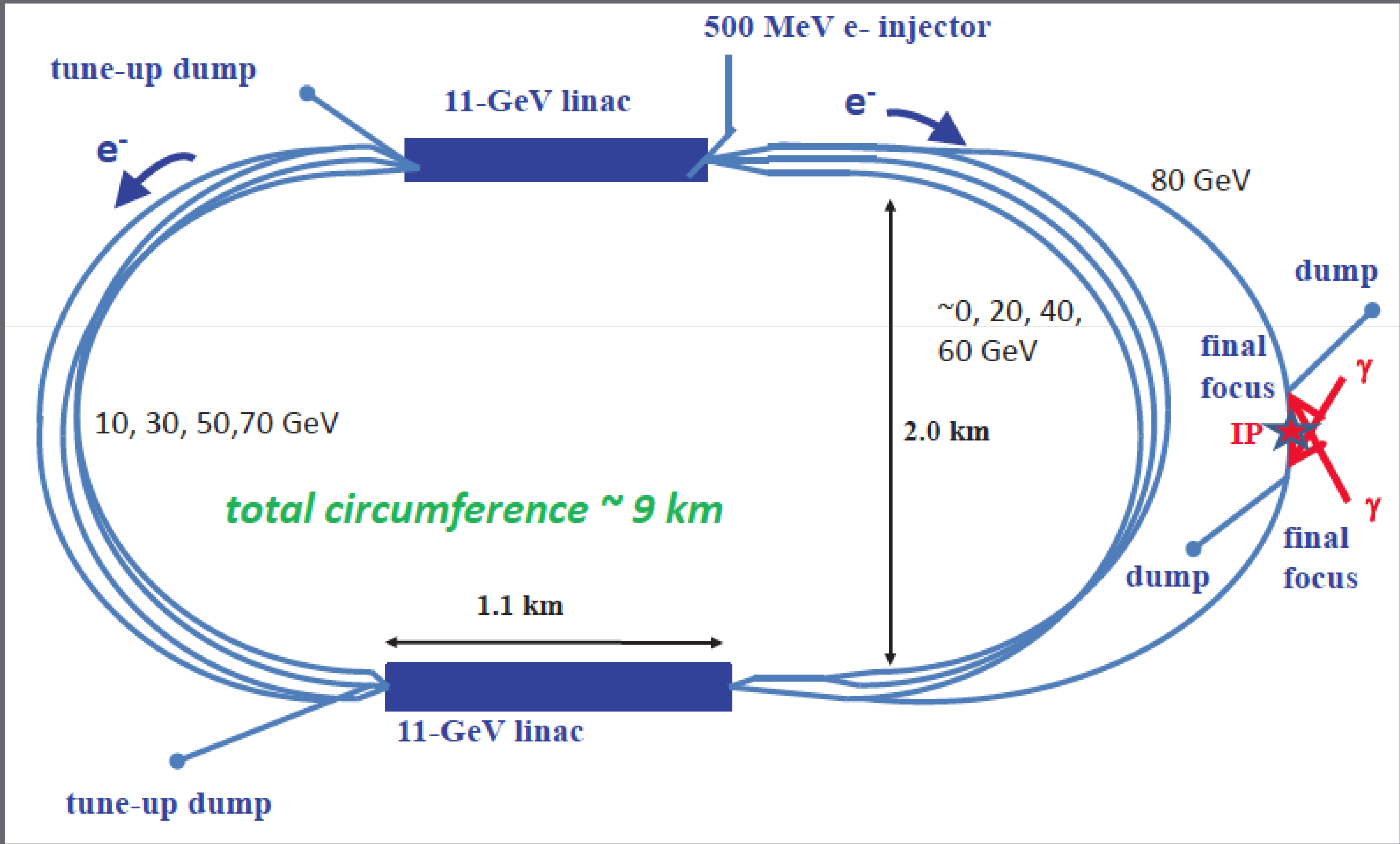
RR= Ring – Ring
LR =Linac –Ring

Baseline LHeC Time Schedule



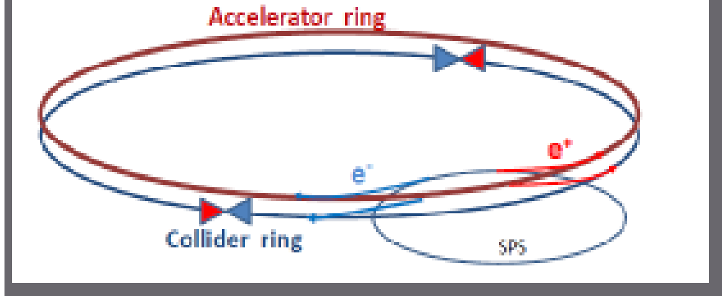
LS3 --- HL LHC

γγ Collider


500 MeV e- injector
tune-up dump
11-GeV linac
e-
e-
80 GeV
dump
~0, 20, 40, 60 GeV
final focus
IP
γ
γ
10, 30, 50,70 GeV
2.0 km
total circumference ~ 9 km
final focus
dump
1.1 km
11-GeV linac
tune-up dump

LEP3 Higgs Factory

- e^+e^- collider in LHC tunnel, few bunches / beam
- 50 MW SR power per beam; ex. *LHeC optics*
- $>10^{34}$ $cm^{-2}s^{-1}$ in ATLAS & CMS, τ_{beam}~few minutes
- $>10^4$ Z-H events per year



two ring scheme with top-up injection into collider ring

Alain Blondel, Frank Zimmermann, *A High Luminosity e+e- Collider in the LHC tunnel to study the Higgs Boson*, CERN-OPEN-2011-047, arXiv:1112.2518v1 [hep-ex]

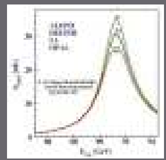
	LEP	LHeC ring design	LEP3
E_b beam energy	104.5 GeV	60 GeV	120 GeV
beam current	4 mA (4 bunches)	100 mA (2808 bunches)	7.2 mA (3 bunches)
total #e- / beam	2.3e12	5.6e13	4.0e12
horizontal emittance	48 nm	5 nm	20 nm
momentum compaction	1.85×10^{-4}	8.1×10^{-5}	8.1×10^{-5}
SR power / beam	11 MW	44 MW	50 MW
$\beta_{x,y}$*	1.5, 0.05 m	0.18, 0.10 m	0.15 0.0012 m
rms IP beam size	270, 3.5 micron	30, 16 micron	55, 0.4 micron
hourglass loss factor	0.98	0.99	0.65
energy loss per turn	3.408 GeV	0.44 GeV	6.99 GeV
total RF voltage	3641 MV	500 MV	9000 MV
beam-beam tune shift (/IP)	0.025, 0.065	N/A	0.126, 0.130
average acc.field	7.5 MV/m	11.9 MV/m	18 MV/m
effective RF length	485 m	42 m	505 m
RF frequency	352 MHz	721 MHz	1300 MHz
rms bunch length	1.61 cm	0.688 cm	0.30 cm
peak luminosity / IP	1.25×10^{32} $cm^{-2}s^{-1}$	N/A	1.33×10^{34} $cm^{-2}s^{-1}$
beam lifetime	6.0 h	N/A	12 minutes

SUMMARY & CONCLUSIONS

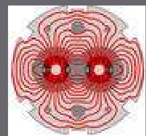
Timeline of CERN HEP Projects

1980 | 1990 | 2000 | 2010 | 2020 | 2030 | 2040

LEP: Constr. | Physics | Upgr.



LHC: Design, R&D | Proto. | Constr. | Physics



HL-LHC: Design, R&D | Constr. | Physics

High Luminosity LHC

runs in parallel to HL-LHC; tight R&D schedule

LHeC: Design R&D | Constr. | Physics

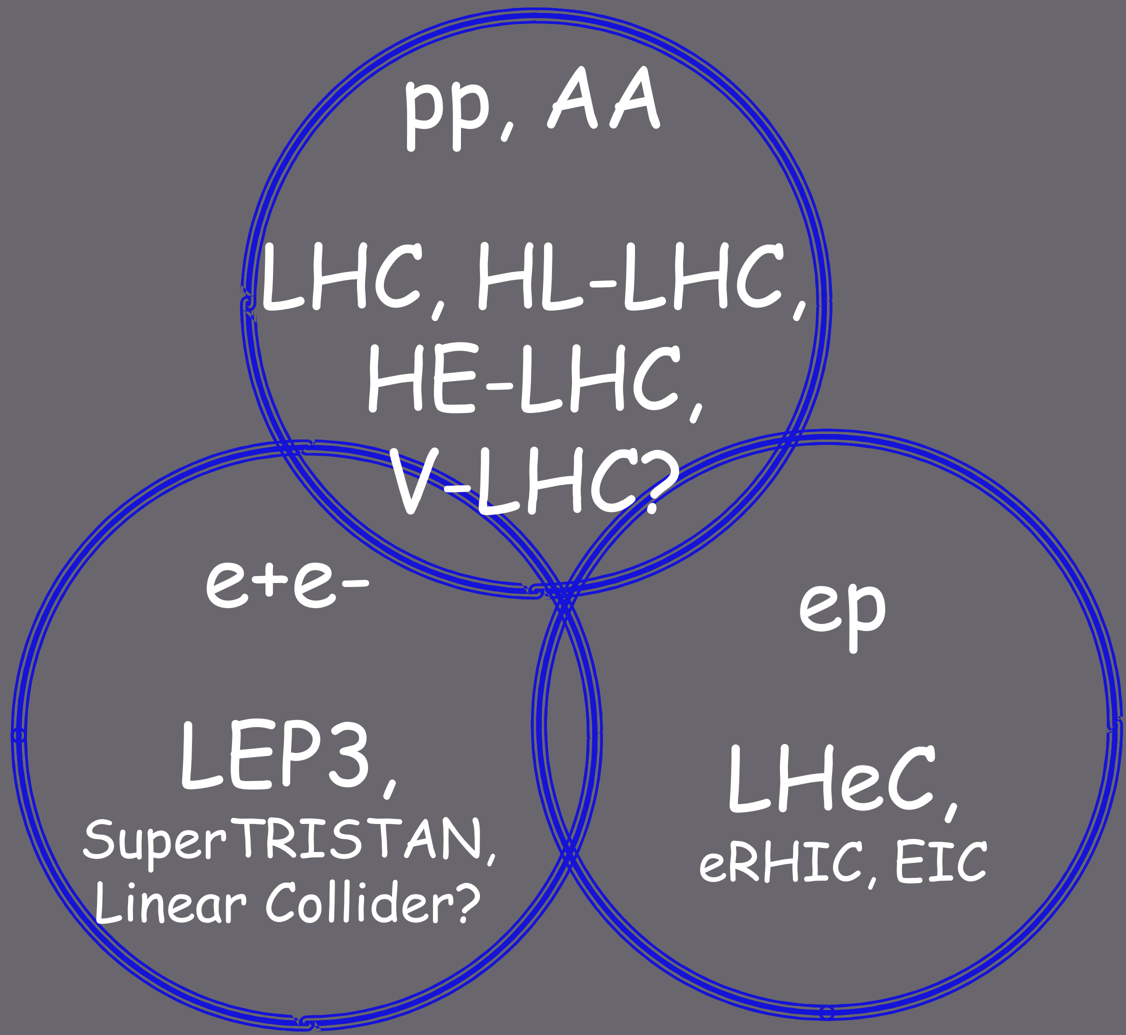
LHeC

follows HL-LHC; R&D & prototype time < for LHC

HE-LHC: Design, R&D | Constr. | Physics

High Energy LHC

THE SUB-FERMI SCALE (2010-2040)?



all can be done with LHC "upgrades"!

Key Messages

- All projects need continuing accelerator and detector R&D.
- All projects need continuing attention concerning a convincing physics case.
  - Close collaboration experiment and theory is mandatory.
- So that community is ready to make right decision when the time comes to identify the next energy frontier accelerator (collider).

Today, we need to keep our choices open. The way forward –

- **Physics results from the LHC.**
- **Update of the European Strategy for Particle Physics (2012-2013).**

Summary

- Highest priority of the particle physics community is to fully exploit the physics potential of the LHC.
- The current European Strategy for Particle Physics incorporates a number of new accelerator projects for the future. (Update in progress)
  - Need to renovate LHC injectors recognised; relevant projects/studies started.
  - Main motivation to upgrade luminosity (HL-LHC) & energy (HE-LHC) of LHC is to explore further the physics beyond the SM while at the same time completing SM physics started at LHC.
- Further down the line, many open questions from LHC could also be addressed by:
  - Hadron-electron collider LHeC is also under design.
  - New studies for circular machines – V-LHC, LEP3, $\gamma\gamma$ collider.
  - An electron-positron linear collider (ILC or CLIC).
  - CERN participation in a European neutrino physics.

- ***These new initiatives will lead particle physics well into next decades of fundamental research.***