CERN

Status and Plans for the CERN accelerator Complex

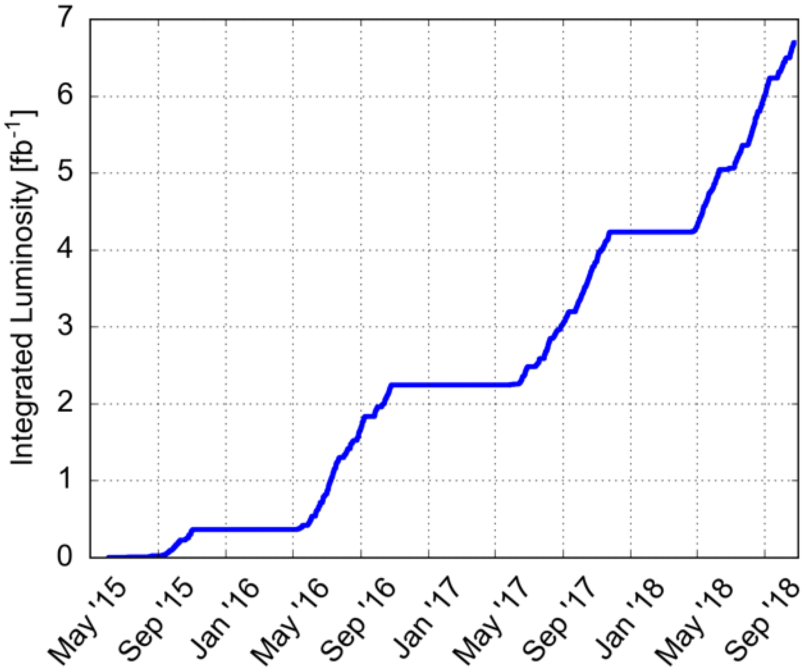
P. Collier, CERN

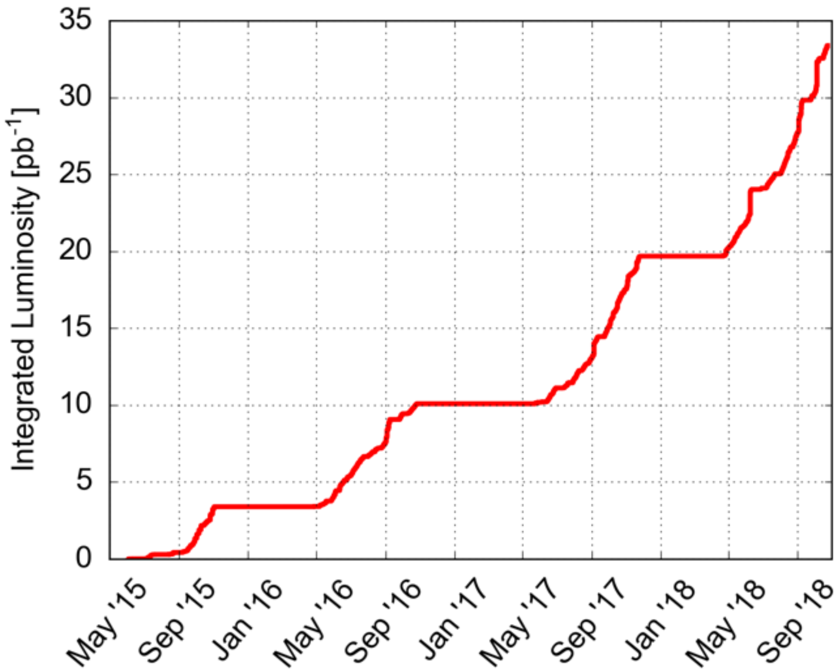
Outline

- A Short history of LHC Run 2
- The Approved Programme: Prospects for Run 3 and beyond
  - The LHC Injector Upgrade Project
  - The HL-LHC upgrade project
  - The Diversity Physics Programme at CERN
- The European Strategy Update and Directions towards the Future
  - Energy Frontier Studies at CERN
  - Science Diversity Options (PBC Study)
  - Constraints & Timelines
- Summary & Conclusions

Run 2: p-p operation

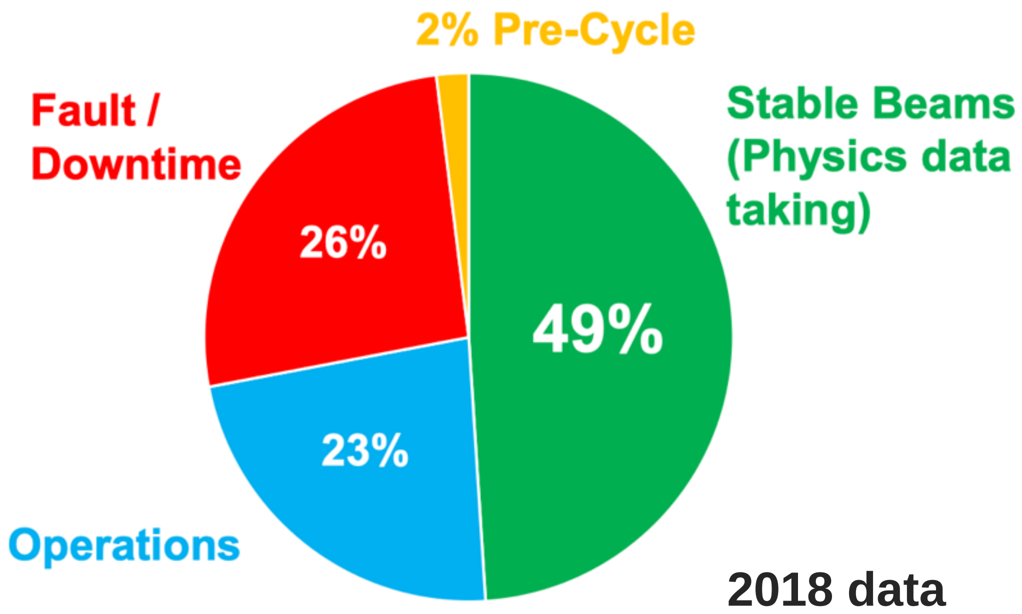
- **Important milestones were set by the LHC during Run 2:**
  - Demonstrated reliable operation with **6.5 TeV beams**
  - Exploited **25 ns** bunch spacing to operate with **>2500 bunches**
  - Reached **design luminosity** $L_{IP1/5} = 10^{34}\ cm^{-2}s^{-1}$ … **and doubled it!**
  - Delivered **6.7 fb^{-1} to LHCb** and **33 pb^{-1} to ALICE**





Operational efficiency

- In spite of their complexity **key systems are very reliable**
- **Robust machine configuration**
- Efficient and optimized **operational procedures and tools**
- **Specialist teams** ready to intervene on short notice in case of problem



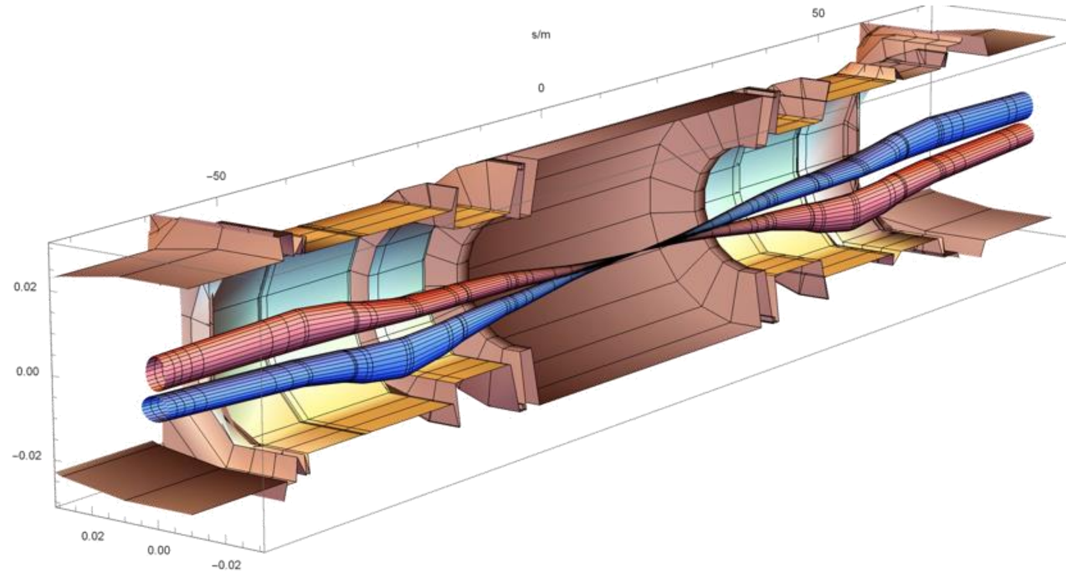
Efficiency very high in spite of the complexity of the machine and the very high stored beam energy (> 300MJ per beam)

Squeezing more luminosity

- The machine was **beautifully designed and built extremely well**
  → no major bad surprises, most systems performing even better than expected!
- Very good **control and reproducibility** of the beams thanks to excellent performance of magnets, power converters, RF, collimation
- **Beam dynamics well under control**
  - Complex and involved combination of orbit, optics, aperture, collimation, stability, coupling, non-linearities, noise, beam-beam, RF settings, feedbacks

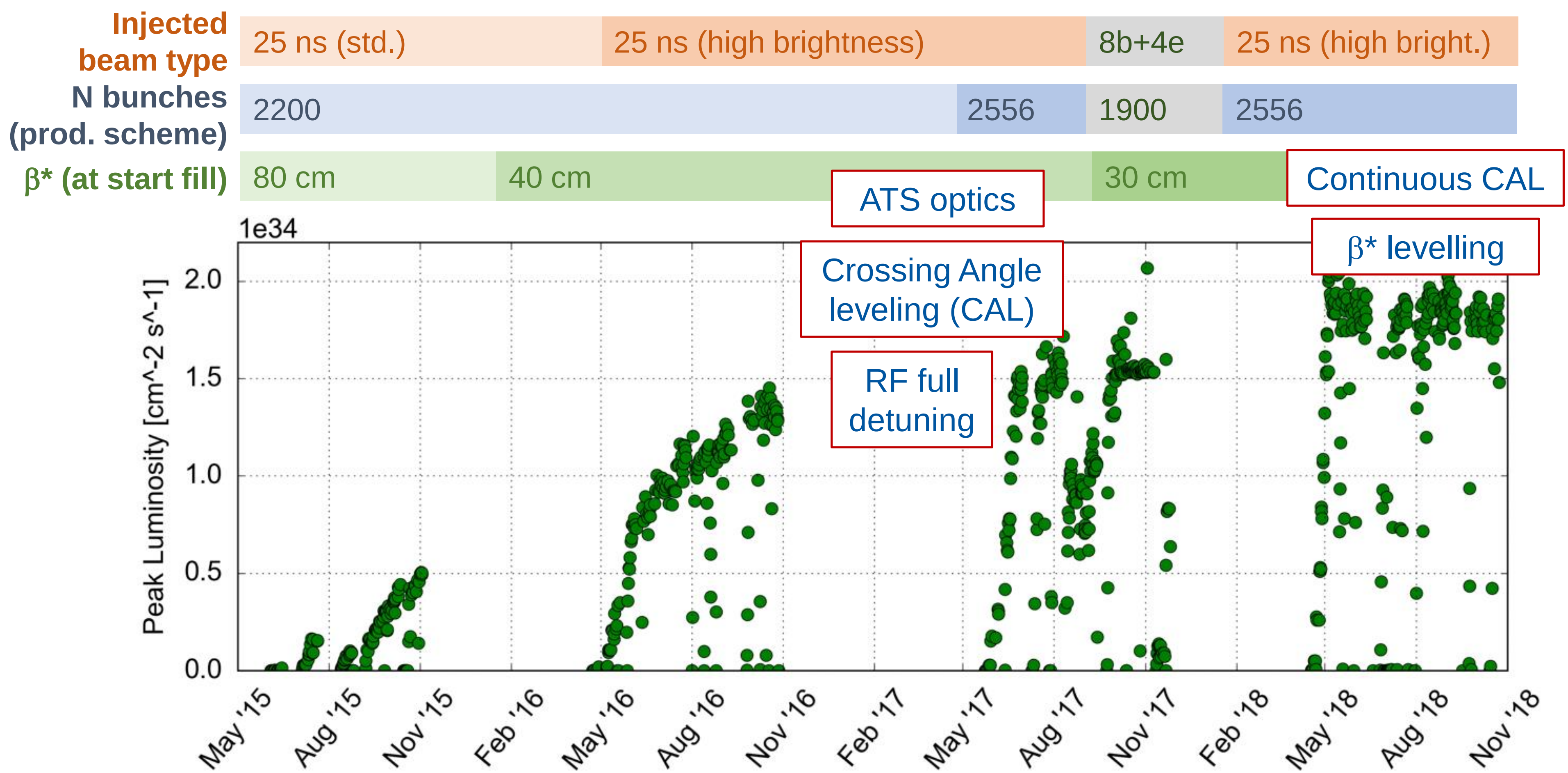
→ Exploited to push the luminosity

- Stronger focusing at the interaction points: **β* down to 30 cm** (design was 55 cm)
- Use of **high-brightness beams** from the injectors (BCMS)
- Operational use of **luminosity levelling** (separation, crossing angle and β* - down to 25 cm!)



Peak luminosity in Run 2

- **Machine and beam configuration progressively pushed over Run 2**
- **Deployment of several optimizations and innovations (testing HL-LHC concepts)**



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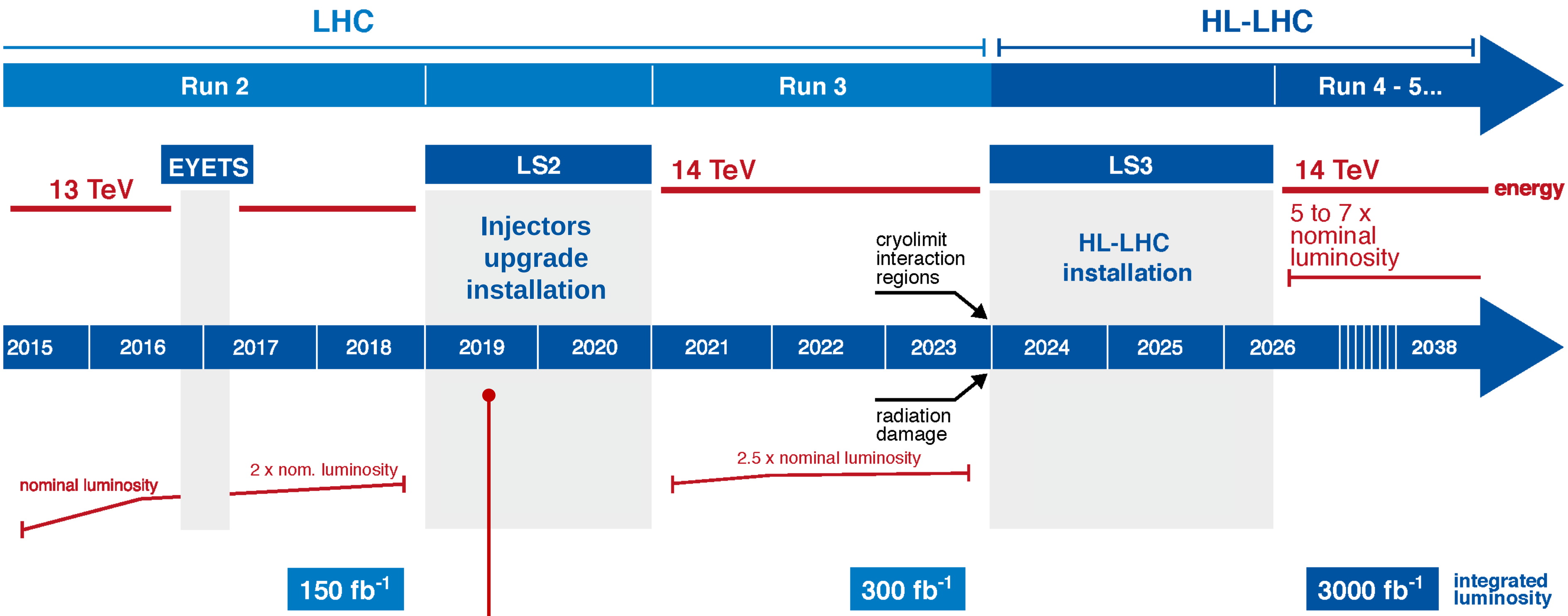
What next?



Long Shutdown 2 (now):

- Maintenance and consolidations works (entire complex)
- Deployment of LHC injectors upgrade
- Preparation for HL-LHC upgrade

grade (LIU project)

Major upgrade works taking place in LS2

→ The goal is to **double the present beam intensity** while

PSB upgrade

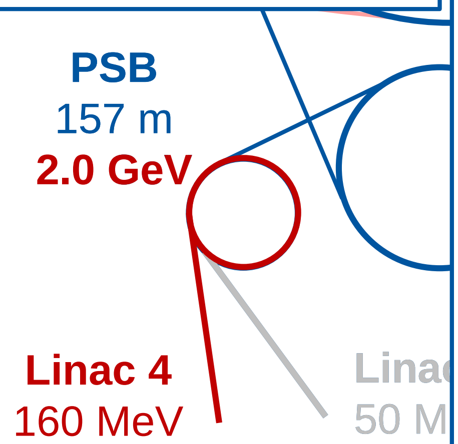
- **H^- charge exchange injection** at 160 MeV → improved beam brightness (weaker space charge forces)
- **Energy: 1.4 GeV → 2 GeV**
  - New main power supply
  - New RF systems

Linac4, has been built to take over.

- Higher energy **160 MeV**
- Acceleration of **H^- ions** (charge exchange injection to the PSB)

Construction **completed in 2017**

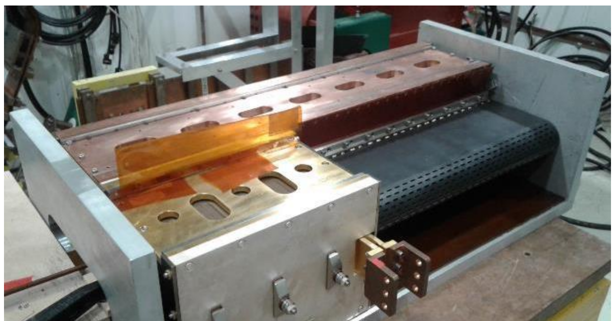
- Extensively tested in 2017-2018
- Connection to the rest of the chain during LS2

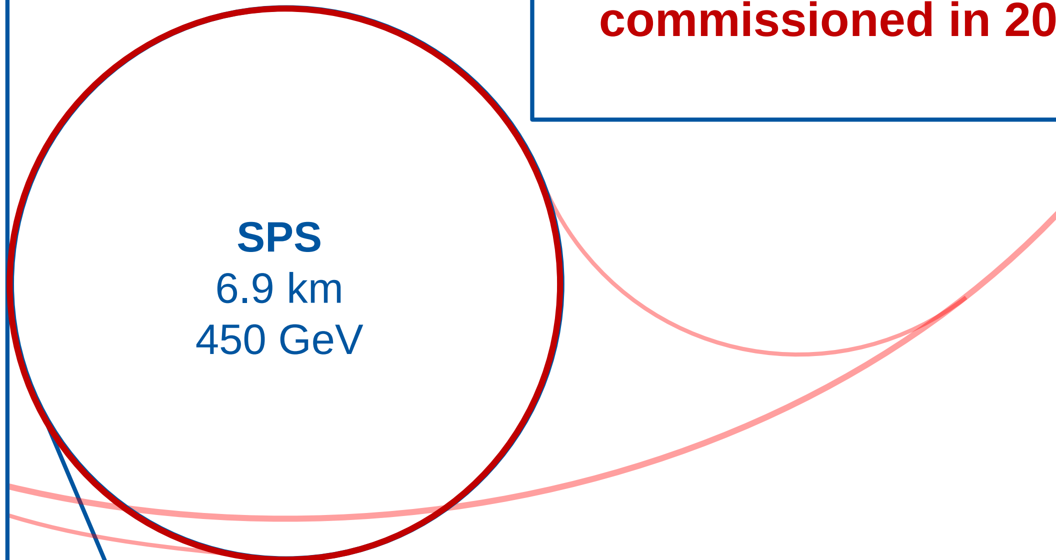


LHC injectors upgrade (LIU project)

PS upgrade

- **Injection at 2 GeV →** improved beam brightness (weaker space charge)
- **RF upgrades** to increase beam intensity



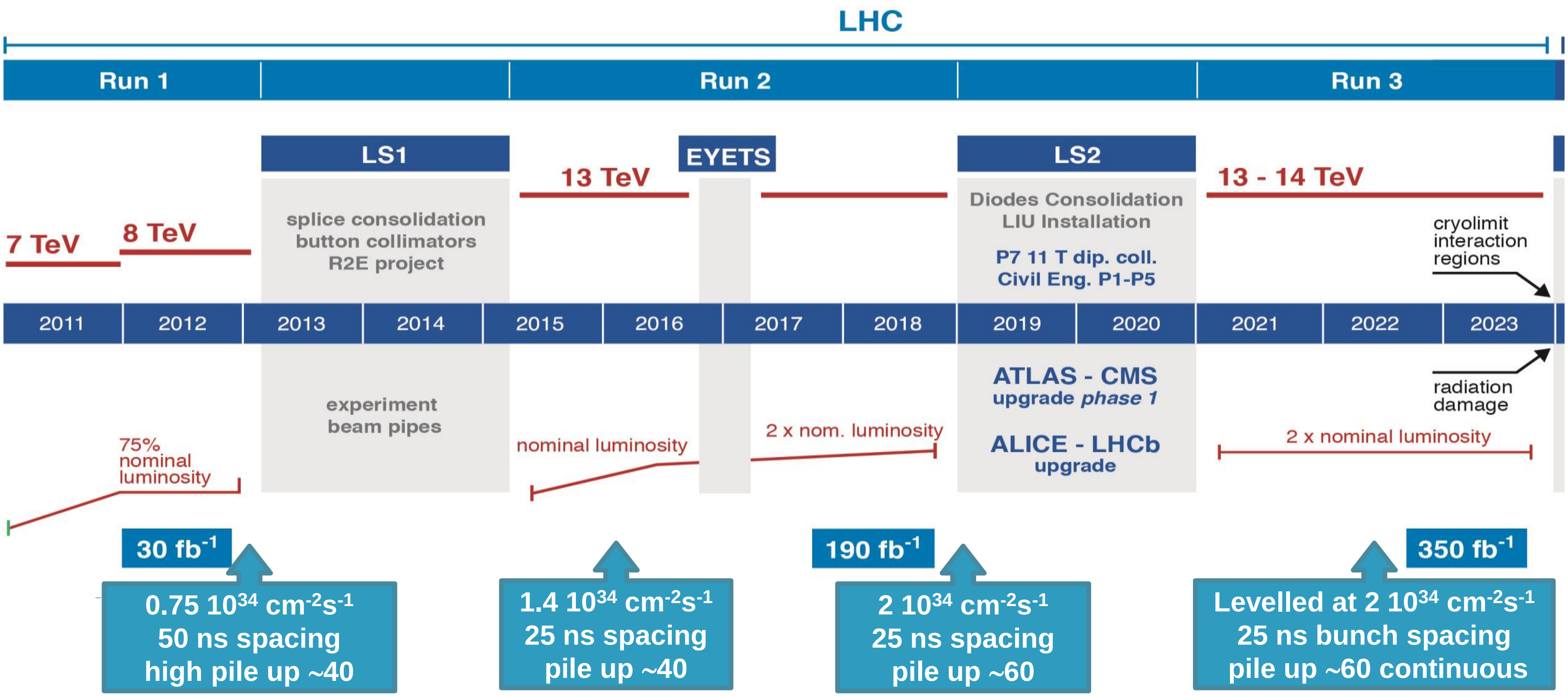


A New Injector Chain to be commissioned in 2020!

SPS upgrade

- **Main RF system upgrade** (new solid state power plants – 2 x 1.6 MW)
- **Impedance mitigation** to improve beam stability
- More robust **beam dump and protection devices**

LHC / HL-LHC Plan



Technical limitation on the Instantaneous Luminosity:

1. **Collider** (cryolimit in the triplet region) at 2×10^{34} $cm^{-2}s^{-1}$ twice the nominal design luminosity)
2. **Experiments** (pile up in the detectors). Designed for peak of 40 they are actually dealing with 60!

Technical limitation on Integrated Luminosity:

1. **Collider** (radiation damage to the IT magnets – correctors and quadrupoles)
2. **Experiments** (radiation damage in the Inner Tracker)

Outlook to LHC Run 3 (2021-2023)

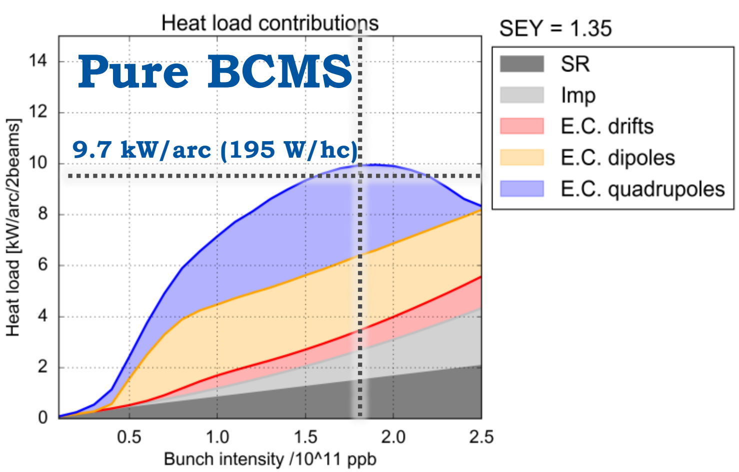
LHC Injectors Upgrade

LIU forecast for beam intensity ramp up for HL: can be used in LHC Run3

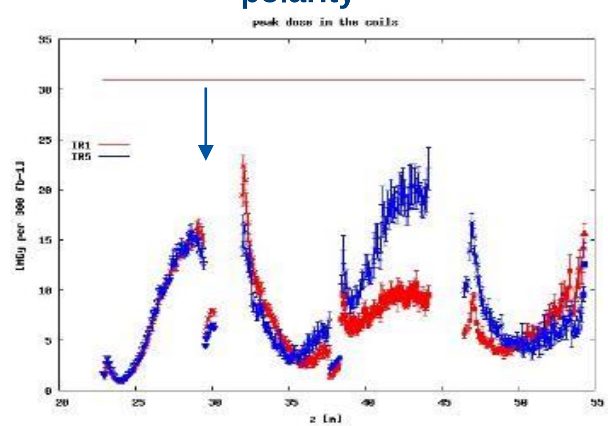
	2021	2022	2023*	Comment
# bunches	Up to 2748 (BCMS)			
ϵ_n $[\mu m]$	1.3	1.3	1.3 → 1.55	Intensity Ramp Up
N_b $[10^{11}\text{p}]$	0 →1.4	1.4 →1.8	1.8 → 2.1	Max bunch population at the end of each year

Pushing the present LHC using HL-LHC studies and early installation of HiLumi equipment in LS2…
Levelling, low-Z collimators and dispersion supressor collimation

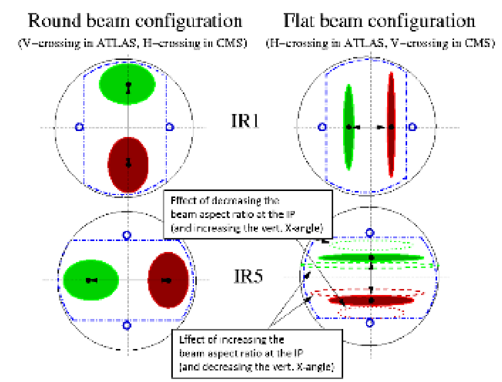
Approaching cryogenic limitations: Different heat load by sector emerged in Run2 and must be understood



Swapping the vertical crossing polarity



r=30% decrease → 40% increase in integrated luminosity



L_{int} 160 fb^{-1} can be reached in Run3 with margins

Goal of HL-LHC

Enable the LHC to deliver **~250 fb^{-1}/year in ATLAS and CMS** reaching **3000 fb^{-1} by ~2037** (leveling at a pile-up of 140 events/crossing)

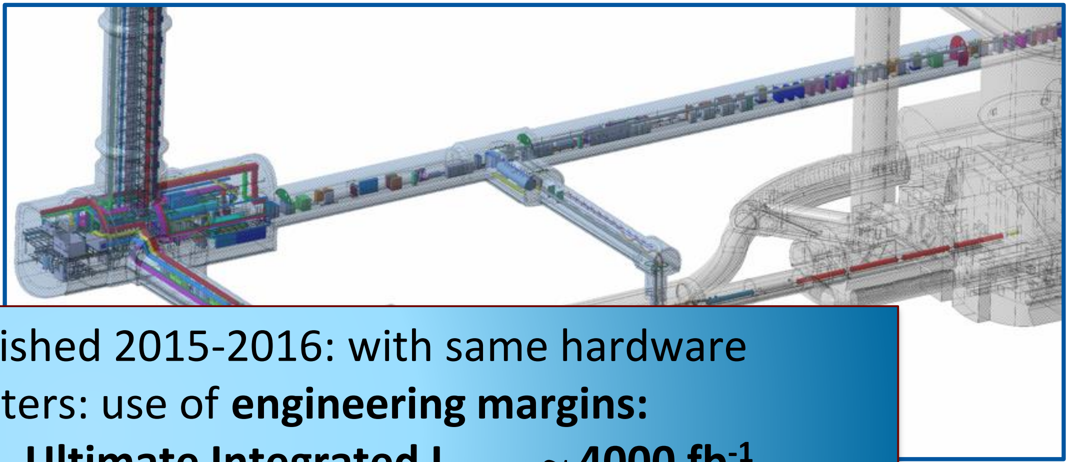
Strategy:

- Complete **redesign of regions next to ATLAS and CMS**, in order to:
  - Achieve smaller beam size and crossing angle at the experiments
  - Withstand radiation from the increased luminosity debris
- Profit from the **increased beam intensity** provided by the injector upgrades
- **Upgrade key LHC systems** to cope with the increased intensity and luminosity (collimation, cryogenics, injection and dump systems)

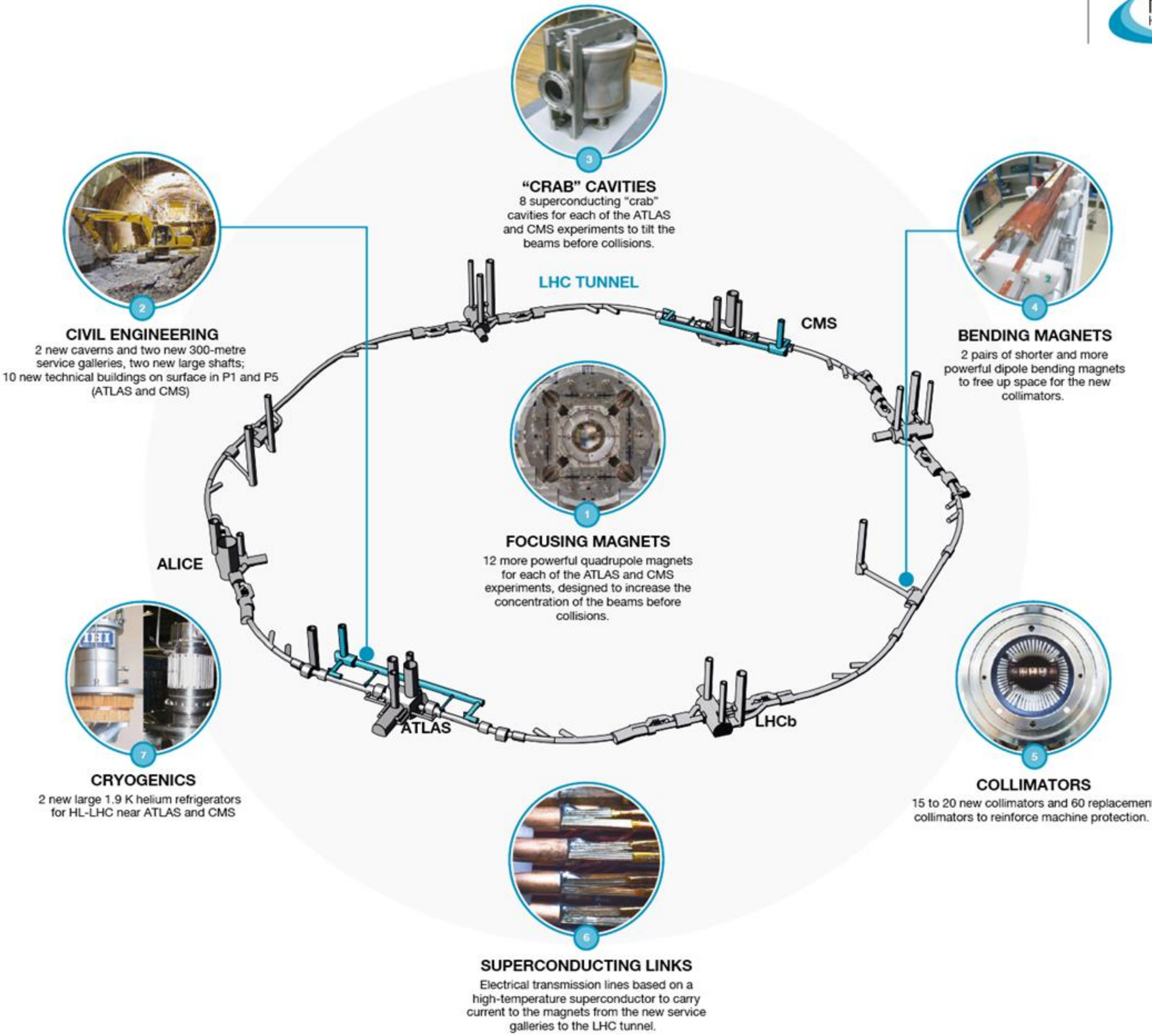
→ Requires **development of new technologies** (magnets, crab cavities, sc. links)

→ Relying on **large international collaborations**

→ Needs **significant new underground and surface infrastructure**



Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**
$L_{peak\ ult} \cong 7.5\ 10^{34}\ cm^{-2}s^{-1}$ and **Ultimate Integrated $L_{int\ ult} \sim 4000\ fb^{-1}$**
LHC should not be the limit, should Physics require more…

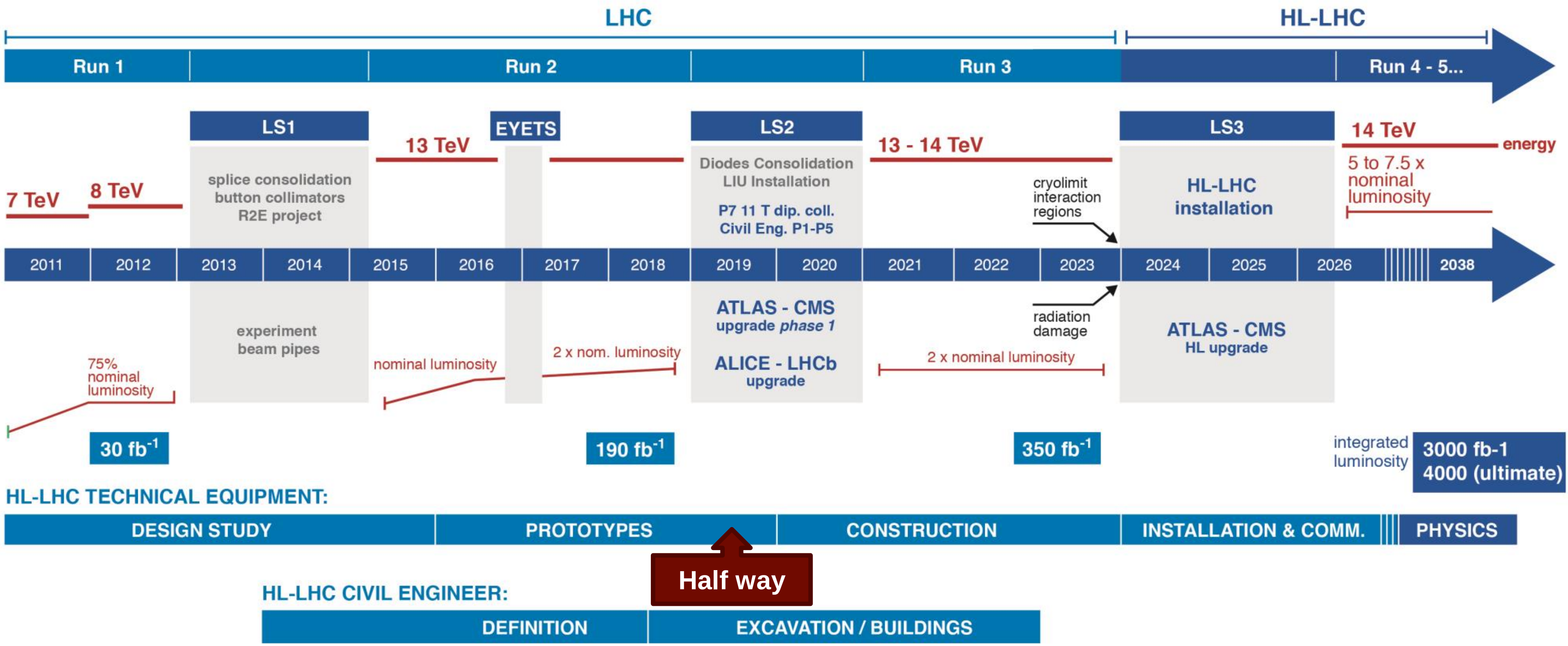


Rebuilding ~1.2km of LHC (the most complicated bit!)

But also touches very many other systems around the machine

- **New IR-quads Nb_3Sn (inner triplets)**
- **New 11 T Nb_3Sn (short) dipoles**
- **Other NbTi magnets in the IR**
- **Collimation upgrade**
- **Cryogenics upgrade**
- **Crab Cavities**
- **Cold powering**
- **Machine protection**
- **…**

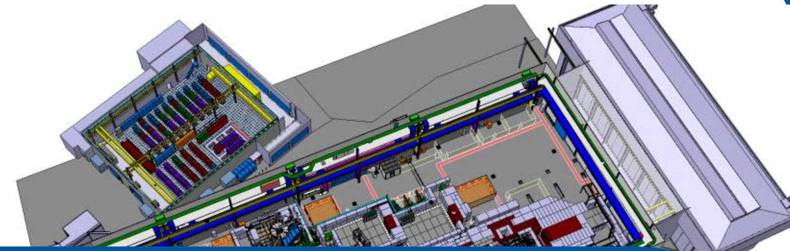
LHC / HL-LHC Plan



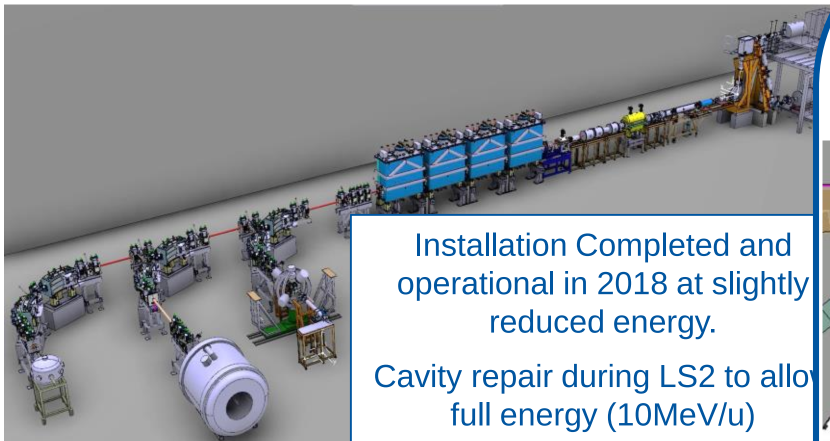
- **Now deep into the construction phase …**
- **Some installations already during LS2 as well as civil engineering works**
- **Main installation work during a 30 month stop (LS3): 2024-2026**

The Diversity Programme at CE

East Area

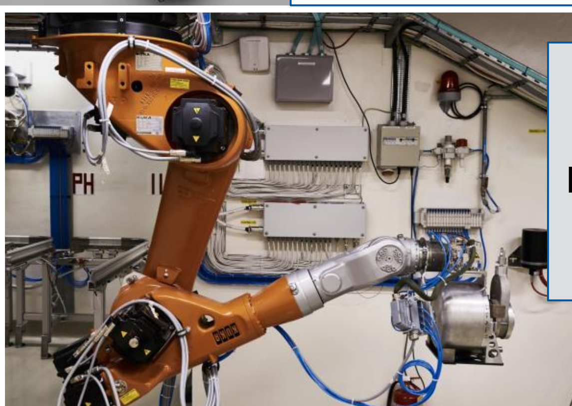


Isolde/HIE-Isolde



Installation Completed and operational in 2018 at slightly reduced energy.

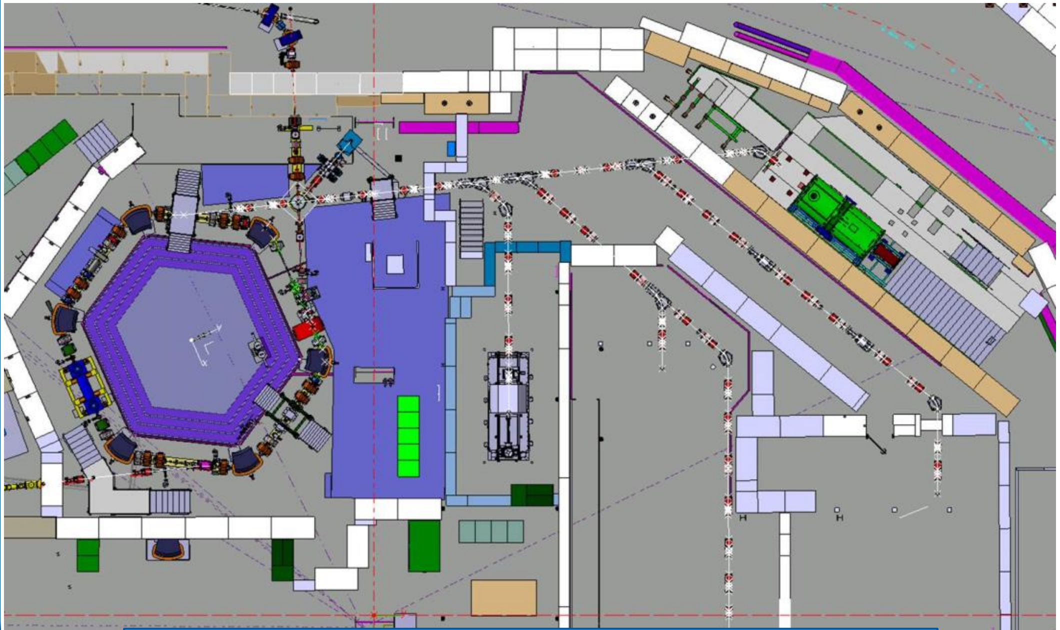
Cavity repair during LS2 to allo full energy (10MeV/u)



CERN-MEDICIS First medic isotopes produced

Antiproton Decelerator (AD)

Construction and initial commissioning of ELENA complete to provide antiprotons at 100keV kinetic
Connection to the existing experimental area during LS2

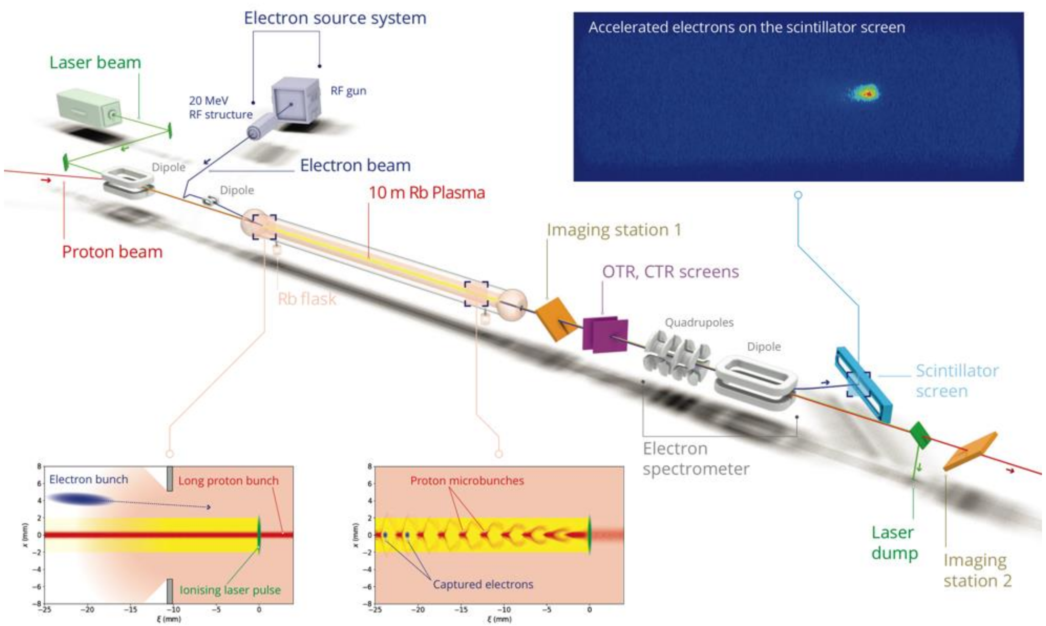


Will allow a substantial increase in the availability of trapped antiprotons (x10 – x100) and serve several experiments simultaneously

The Diversity Programme at CERN (Approved Upgrades)

AWAKE

Proof-of-Principle Accelerator R&D to study Proton Driven Plasma Wakefield acceleration



Demonstrated seeded self-modulation in a the proton bunch and successfully accelerated a witness electron bunch – 200MV/m

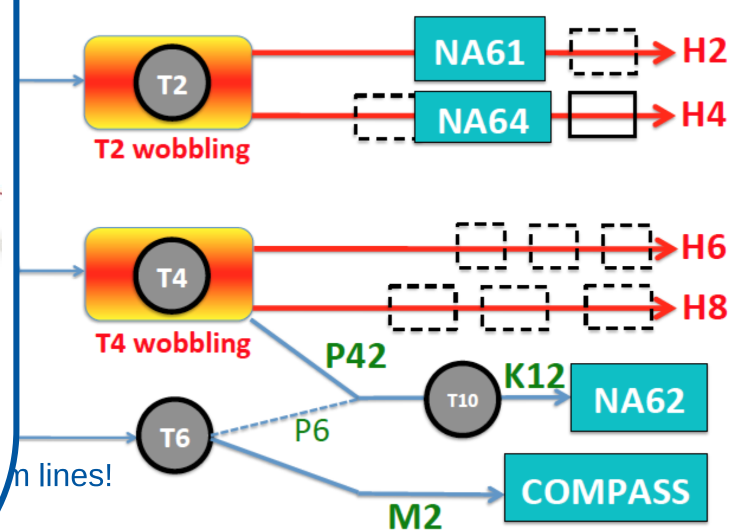
Programme funded to accelerate further and preserve electron beam quality

Single phase already tested with charged bea

North Area Consolidation

Infrastructure dates from the 1970's

ishment of beamlines and Infrastructure planned during LS3 (and beyond)



n lines!

shment to serve not only the present test beams and experiments …

… but also in view of new requests coming out of the Physics Beyond Collider study

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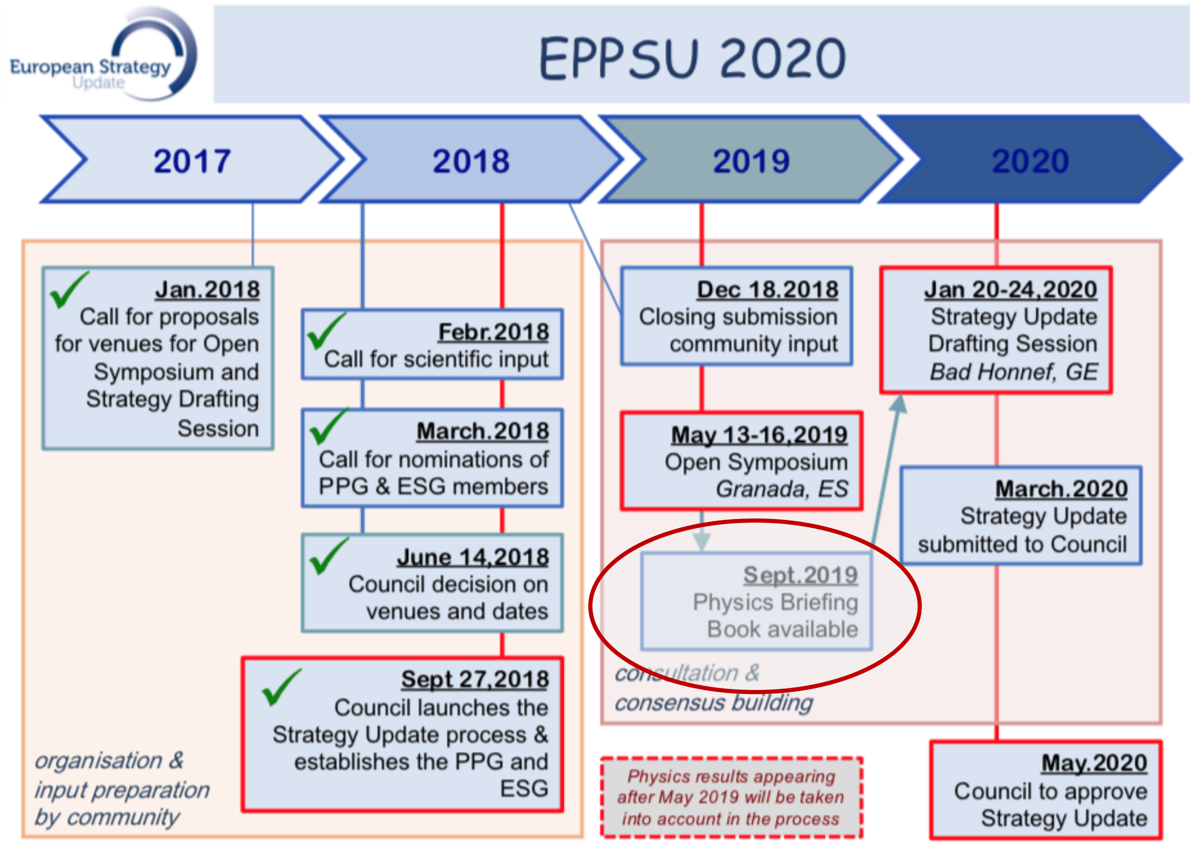
The European Strategy for Particle Physics Update

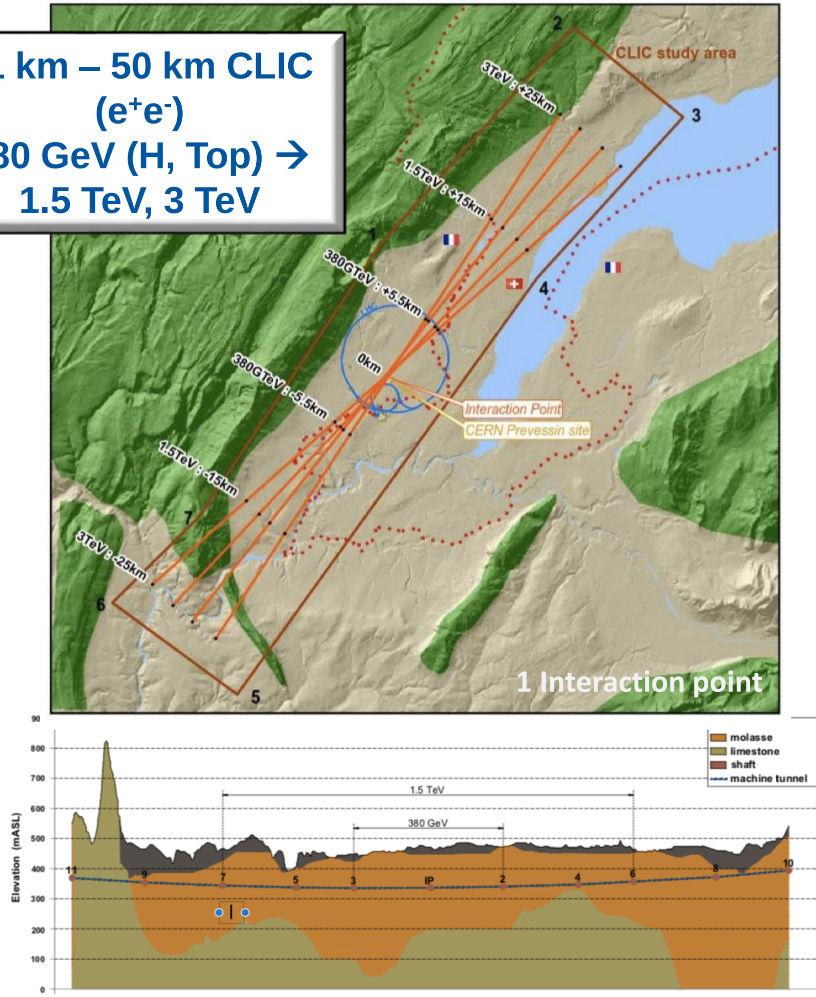


- Very successful Granada Symposium
- Lots of input …
- Lively discussions!
- Some areas of consensus seem to be emerging
- Next milestone will be the publication of the Physics briefing book.

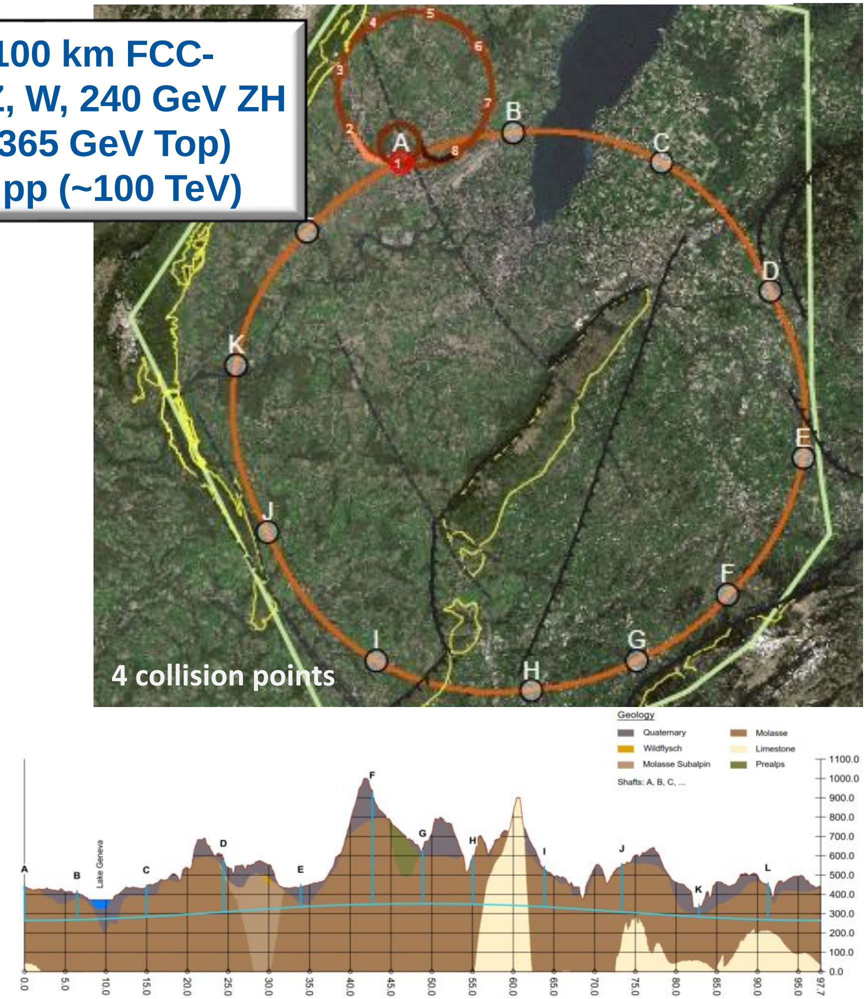
Clearly deliberations are continuing … so any opinions expressed are my own !!

Future Collider Options (focused on CERN)

11 km – 50 km CLIC (e^+e^-)
380 GeV (H, Top) → 1.5 TeV, 3 TeV



~100 km FCC-
e^+e^- (Z, W, 240 GeV ZH → 365 GeV Top)
ep, pp (~100 TeV)



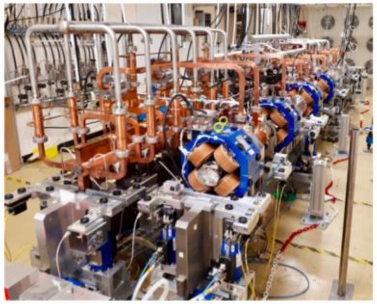
- Consensus seems to be emerging that the next machine should be capable of exploring the Higgs - an e^+e^- Higgs-Factory …
- Much less consensus on what shape it should be !!

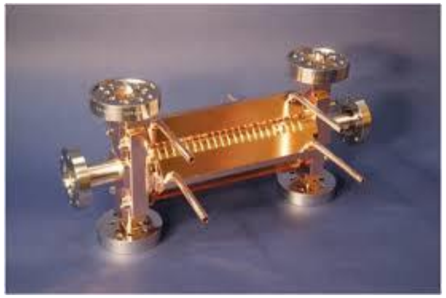
CLIC: multi-TeV e^+e^- Linear Collider

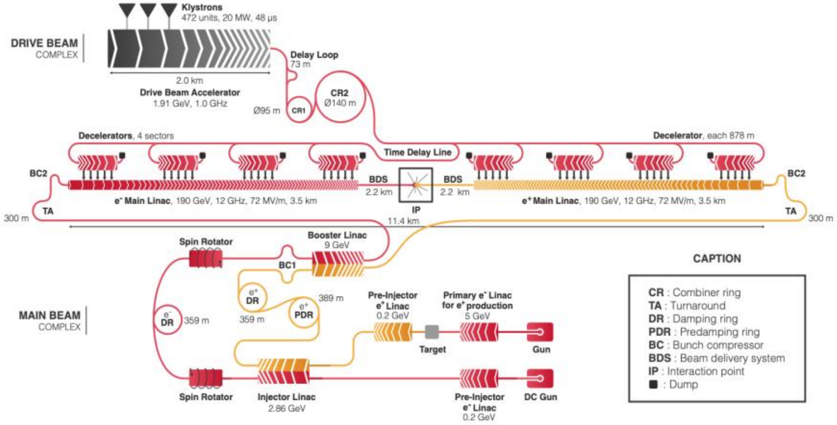
Parameter	Unit	Stage 1	Stage 2	Stage 3
√s	GeV	380	1500	3000
Tunnel length	km	11	29	50
Gradient	MV/m	72	72/100	72/100
Pulse length	ns	244	244	244
Luminosity (above 99% of √s)	10^{34} $cm^{-2}s^{-1}$	1.5 0.9	3.7 1.4	5.9 2
Repetition frequency	Hz	50	50	50
Bunches per train		352	312	312
Bunch spacing	ns	0.5	0.5	0.5
Particles/bunch	10^9	5.2	3.7	3.7
Beam size at IP (σ_y/σ_x)	nm	2.9/149	1.5/60	1/40
Annual energy consumption	TWh	0.8	1.7	2.8
Construction cost	BCH	5.9	+5.1	+7.3

100 MV/m accelerating gradient needed for a compact (~50 km) machine at 3 TeV

based on room temperature, 12 GHz accelerating structures and a two-beam acceleration scheme providing short (244 ns) high-power RF pulses







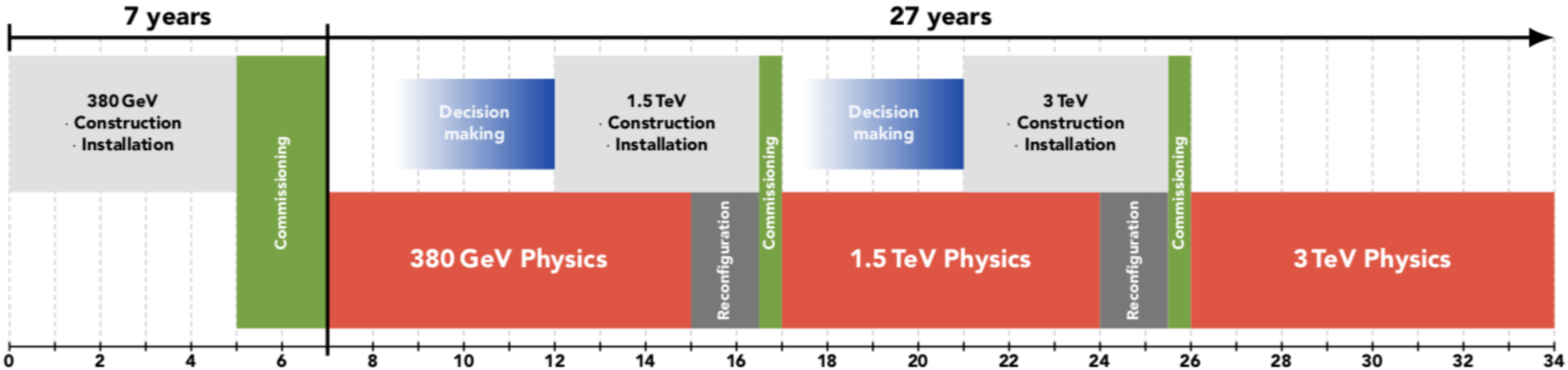
Since 2012 CDR:

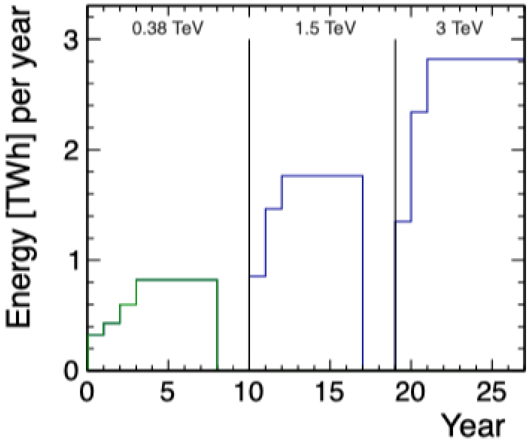
- ✓ 100 MV/m accelerating structures with target low breakdown rate (< 3×10^{-7}/m/pulse)
- ✓ two-beam acceleration scheme demonstrated (CTF3)
- ✓ ~nm vertical emittance achieved by light sources
- ✓ R&D on alignment and vibration stabilization systems
- ✓ reduction of energy consumption (high-efficiency klystrons)
- ✓ cost reduction – optimization continuing
- ✓ Project Implementation Plan published

Profiting from synergies with FEL and light-sources

CLIC: multi-TeV e^+e^- Linear Collider

Technically, construction could start in ~2026 (TDR in 2025) → first collisions at √s=380 GeV in ~2035 → 25-30 years of physics exploitation



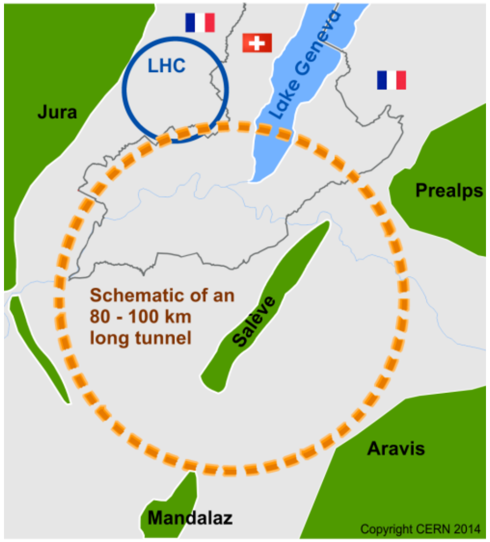


CERN is currently consuming ~1.2TWh/y (~90% in accelerators)

Physics reach:
- Measurements of Higgs couplings, including ttH (to ~3%) and HH (~ 10%) from direct production
- Direct discovery potential and precise measurements of new particles up to the kinematic limit
- Indirect sensitivity to E scales up to Λ ~ 100 TeV; different √s probe E-dependent operators of new physics

FCC: Future Circular Collider(s)

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 ab^{-1} 5 2.5 0.8	2 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 $\times 10^{34}$ 30	2.5 ab^{-1} 15	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb



Also studied: HE-LHC: $\sqrt{s}$=27 TeV using FCC-hh 16 T magnets in LHC tunnel; L~1.6x10^{35} → 15 ab^{-1} for 20 years operation

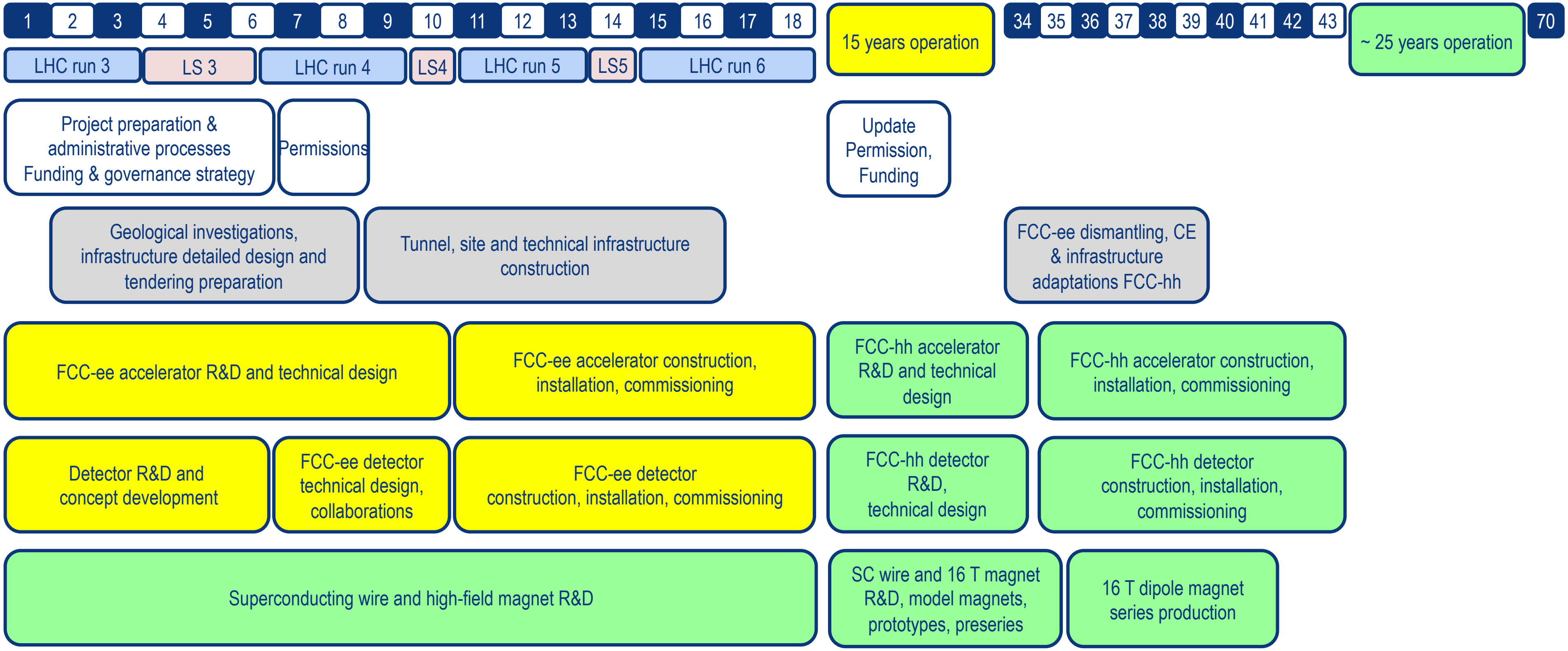
Sequential implementation, FCC-ee followed by FCC-hh, would enable:

- **Variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments**
- **Exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics**
- **Starting with technologically ready machine (FCC-ee); developing in parallel best magnet technology for highest pp energy (100++ TeV!)**
- **Building stepwise at each stage on existing accelerator complex and technical infrastructure**

Additional request after Granada:

Develop an option for an initial FCC-hh using NbTi magnets → 37.5TeV with 6T dipoles.

FCC Integrated Project Technical Schedule



	Cost-estimate /BCHF	AC-Power /MW	Comments
Infrastructure	5.5		100km tunnel and surface infrastructure
FCC-ee	5	260-350	+1.1BCHF for the Top stage (365GeV)
FCC-hh	17	580	

FCC project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

Future of the CERN Scientific Diversity Programme

Pretty Impressive response with lots of ideas for new experiments
– most based around the present CERN infrastructure.
No time to mention these all proposals in any detail … Just a little on some facilities
All submitted as input to the EPPSU

Projects should exploit the uniqueness of CERN accelerator complex and infrastructure.

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, bending crystals) in ALICE and LHCb

Hidden sector with "beam dump"
NA64++ (e,μ)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Rare decays and precise measurements
KLEVER ($K^0_L \rightarrow \pi^0 \nu\nu$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP (η decays)
MUonE (hadronic vacuum polarization for $(g\text{-}2_\mu)$)
Proton EDM

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

Other facilities:
γ-factory from Partially Stripped Ions, nuSTORM

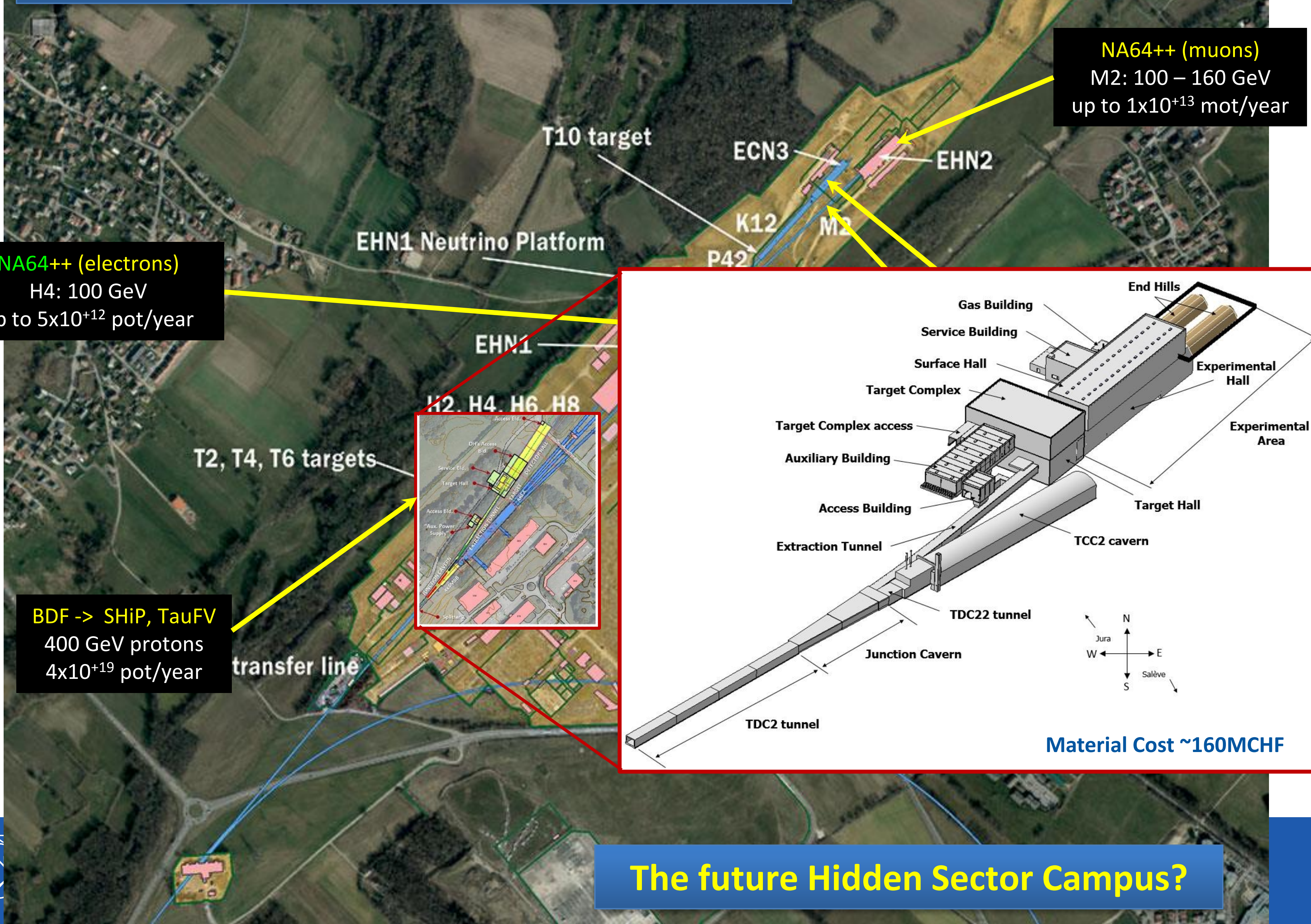
Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

Many Dark Sector proposals are in the SPS North Area

NA64++ (muons)
M2: 100 – 160 GeV
up to $1 \times 10^{+13}$ mot/year

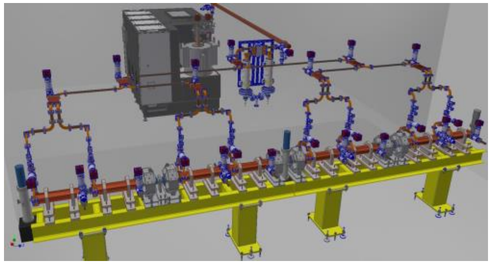
NA64++ (electrons)
H4: 100 GeV
up to $5 \times 10^{+12}$ pot/year

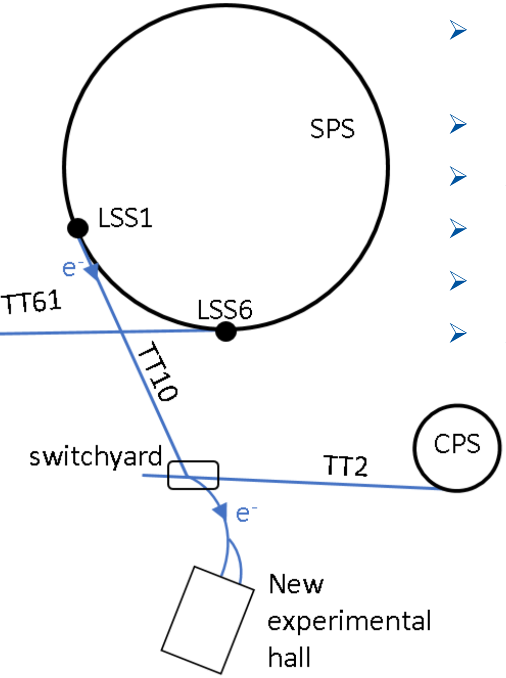
BDF -> SHiP, TauFV
400 GeV protons
$4 \times 10^{+19}$ pot/year



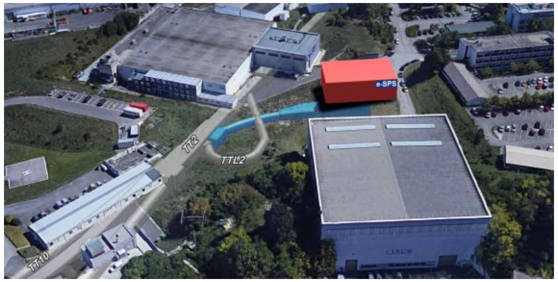
The future Hidden Sector Campus?

eSPS & LDMX



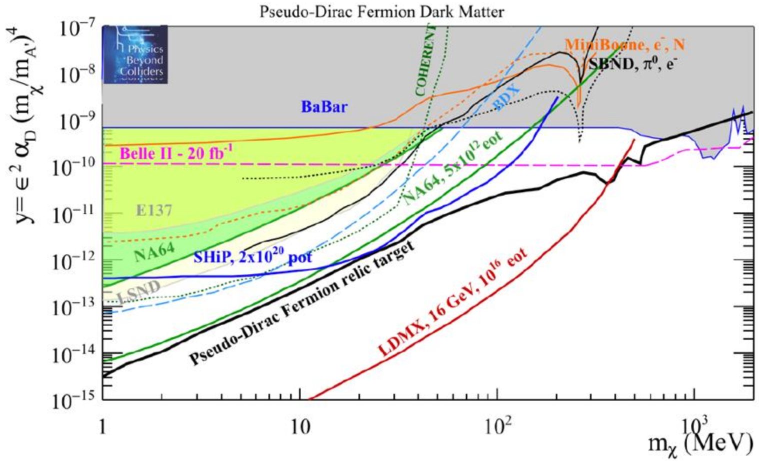


- ~70 m long X-band based linac (CLIC technology) in the old West Area accelerates e- to 3.5 GeV
- SPS filled in 1 to 2 s via TT60
- Acceleration to 16 GeV in the SPS
- Slow resonant extraction in ~10 s
- Beam delivered via the existing TT10 line to the Meyrin site
- A new, short beamline would branch from TT10 to the experimental hall (LDMX)



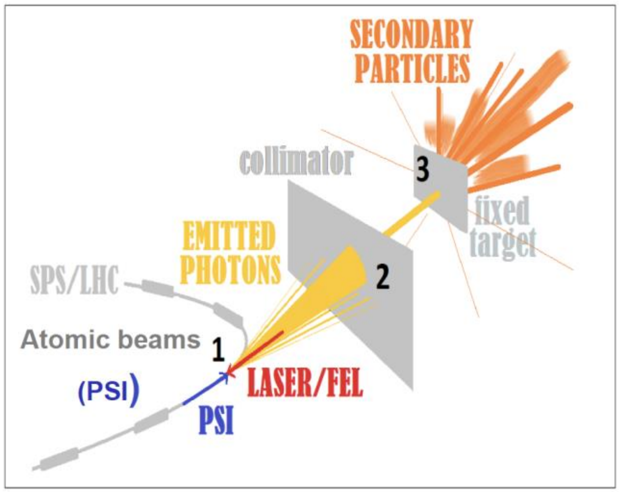
Motivation

- Staged deployment of X-band – return on the significant investment
- Possible deployment of FCC-ee RF cavities and high-efficiency power generation
- Strong case made for accelerator based R&D and other studies at the linac R&D facility
- Physics case - unique LDM search reach
- Material Cost ~80 MCHF



γ- Factory using LHC/SPS

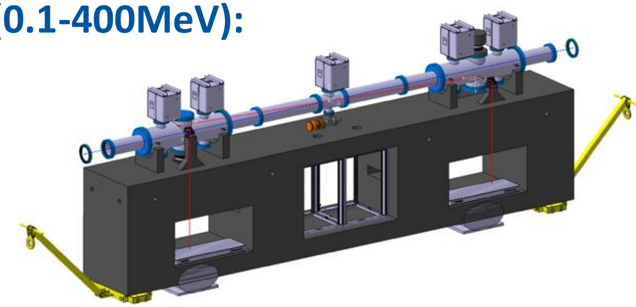
Accelerate and store high energy beams of highly ionized atoms and excite their atomic degrees of freedom by laser photons to produce high energy gamma rays O(0.1-400MeV):

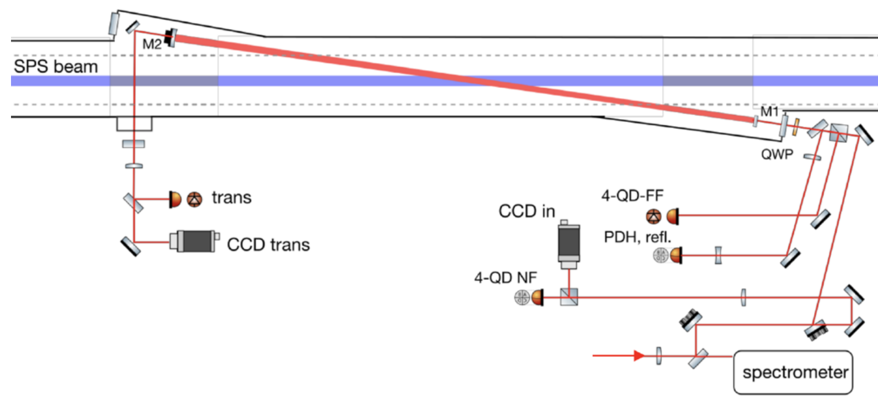


primary beams:
- partially stripped ions
- electron beam (for LHC)
- gamma rays

secondary beam sources:

- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei





- Important milestone reached with the successful acceleration and storage of partially stripped ions in LHC (Pb^{81+})
- Proof of principle experiment with full configuration foreseen in the SPS after LS2
- Physics potential and performance reach to be assessed once all ingredients are better understood

nu-Storm

Well developed proposal for possible siting at FNAL circa 2013

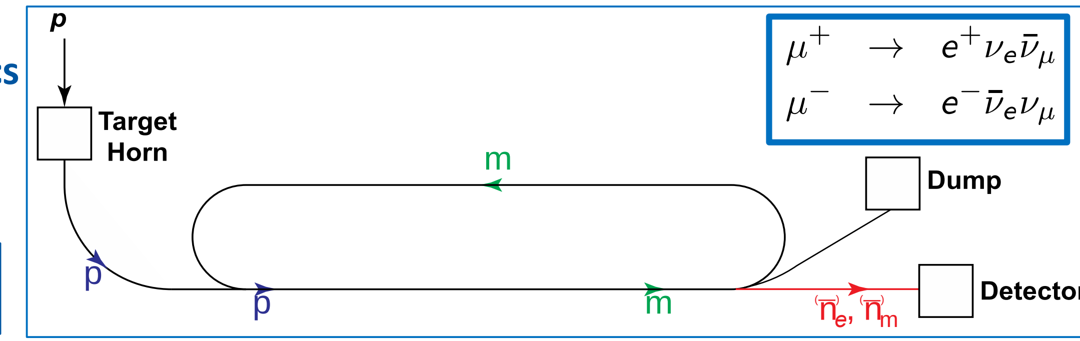
Siting at CERN – Exploratory study:

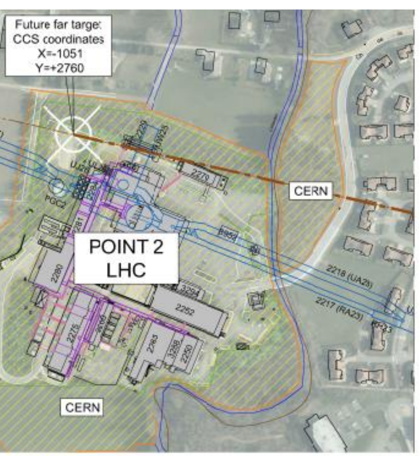
- Via existing SPS fast extraction into a new 600m transfer line
- Graphite target, magnetic horn
- Target complex based on previous CENF design
- Containment & transport of pion beam studied
- Far Detector (2000m) at LHC Point 2
- New design for the decay ring
  - SC Combined function magnets in arcs
  - Central energy 1 – 6 GeV/c
  - Momentum acceptance up to ±16%

Preliminary cost estimate (without far detector)
160 MCHF

Scientific objectives:

1. %-level ($\nu_e N$)cross sections
   - Double differential
2. Sterile neutrino search
   - Beyond Fermilab SBN





Experiment Readiness and Cost

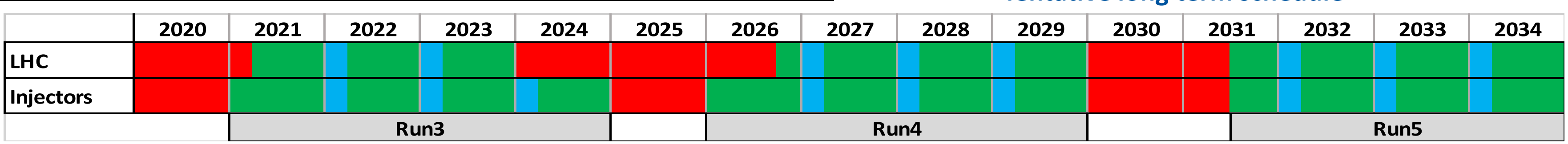
	Physics Highlight	Beam Required	Detector Maturity	Cost	Earliest Operation
SPS Machine					
NA61++	*QGP Charm*	B	B	A	Run3
COMPASS+	R_p *QCD*	A	B	A	Run3
NA62++	*dark sector*	B	A	A	Run3
NA64++	*dark photon*	A	B	A	Run3
MUonE	*HVP(g-2)*$_\propto$	A	B	A	Run3
COMPASS++	*QCD*	B	B	B	Run4
DIRAC++	*Chiral QCD*	C	B	B	Run4
KLEVER	$K^0 \rightarrow p^0$nn- *bar*	B	C	B	Run4
SHiP	*dark sector &* n_t	C	B	C	Run4
eSPS	*dark photon*	C	B	C	Run4
nuStorm	s(n)	C	C	C	Run4
TauFV	t → 3∝	C	C	C	Run5
LHC Machine					
LHC-FT++	*Spin/MM/EDM*	A	C	A	Run3
FASER	*Long lived Particles*	A	A	A	Run3
MATHUSLA	*Long lived Particles*	A	C	B	Run4
Novel					
AWAKE++	*dark photon*	C	B	B	Run4
g- Factory	*High rate* g	C	C		Run5
EDM ring	*p EDM*	C	C	C	Run5
PS Machine					
REDTOP	h *decays*	B	C	B	Run4

Beam Required
A: Ready
B: Needs Upgrade
C: To be Built

Detector Maturity
A: Ready
B: Under Design
C: Needs R&D

Cost
A: <10 MCHF
B: 10-50 MCHF
C: >50 MCHF

Tentative long term schedule



Clearly not everything can be done!
Will need guidance from the EPPSU as well as careful scrutiny of resources availability at CERN

Constraints and Timelines

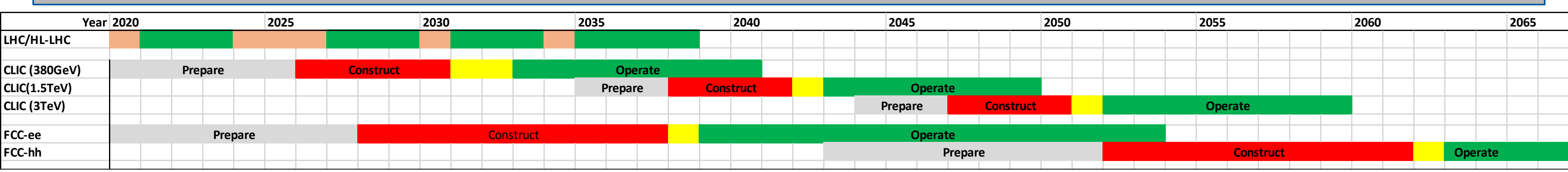
Whatever Path is decided (straight, or circular)

The next 5 years will have to be spent:

- **Continue preparations including detailed site design and administrative actions with the Host State Authorities**
- **Continue high-priority R&D and Prototyping activities – including Energy Efficiency**
- **Advancing towards a full TDR – preparing for approval**
- **Defining the funding model for the necessary resources**
- **Establishing the project as a world-wide facility**

However:

- **Both energy frontier projects require an initial preparation phase of 6-8 years**
- **If we can concentrate on one project, only relatively modest additional resources will be required during the next 5 years**



CERN is hoping for a clear recommendation on which route to take

Summary

CERN is presently in the construction phase of a major upgrade to the LHC and Experiments with a view to collecting 10x the data originally foreseen (~3ab^{-1})

The present Long Shutdown (2019/2020) is being used to upgrade the LHC injector chain as well as undertake the major civil engineering works for HL-LHC

At the same time the diversity physics programme is being enhanced with new facilities and experiments coming on line

For the future CERN has prepared 2 detailed studies for a future energy frontier machine. Both would initially be e^+e^- Higgs-factories, followed by either a hadron collider (100TeV), or a lepton collider (3TeV) the choice should be made based on the physics potential and hopefully consensus will be reached via the EPPSU

In parallel, we have solicited suggestions for new diversity physics experiments and facilities with a very rich and varied set being proposed. Not all can be realized!

CERN has ambitious plans for the future which will help set the direction of the field for decades to come

CERN