A Glimpse of the Future of Particle Physics

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CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
NTU, Singapore

March 30th- April 2nd Muscat

Europe Strategy Group

European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

European Strategy Update

CERN

Europe Strategy Group

….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

d) *CERN should undertake design studies for accelerator projects in a global context,*

- *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****.*
- *These design studies should be coupled to a vigorous accelerator* ***R&D programme, including high-field magnets and high-gradient accelerating structures****,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

Similar recommendation from the Snowmass studies in the US

=> The CERN Roadmap

F. Bodry , March 2015

The CERN Medium Term Plan approved by June'14 Council, implements the **European Strategy** including a long-term outlook.

The scientific programme is concentrated around four priorities:

1. **Full LHC exploitation** – the highest priority - including the construction of the High Luminosity Upgrade until 2025
2. **High Energy Frontier** – CERN's role and preparation for the next large scale facility
3. **Neutrino Platform** – allow for to contribute to a future long baseline facility in the US and for detector R&D for neutrino experiments
4. **Fixed-target programme** – maintain the diversity of the field and honour ongoing obligations by exploiting the unique facilities at CERN

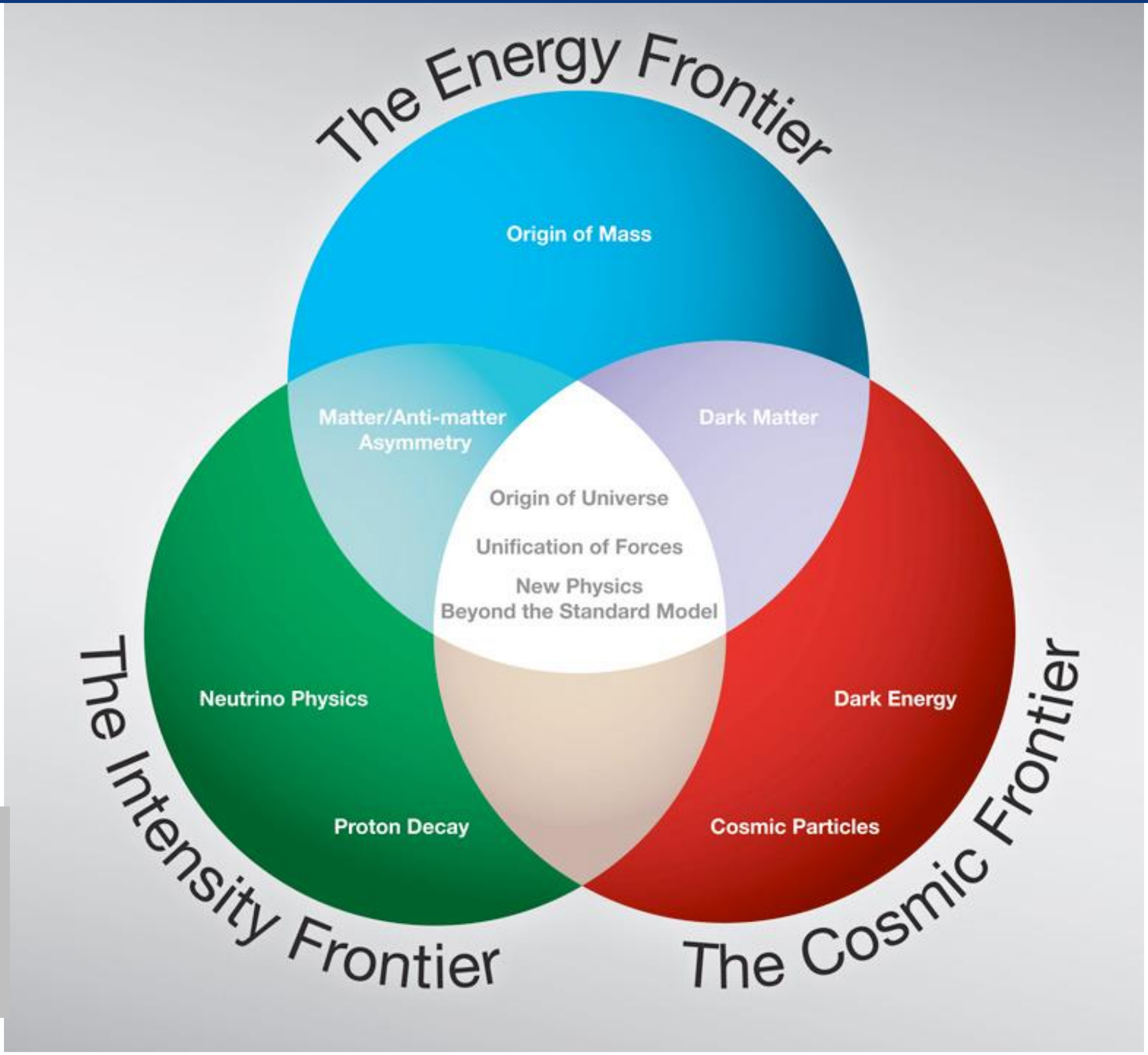
Future HEP: The Three Frontiers

After the Higgs discovery

2012-2014

Evaluation in all regions: Europe Asia, the Americas

- European strategy group
- Snowmass study and IP5
- Japan strategy group



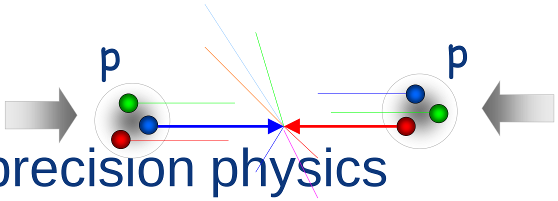
Will concentrate here on the Energy Frontier

FCC General Yearly Meeting May 2017

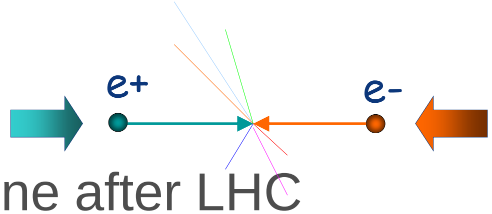
Slides from M. Benedikt, M. Mangano, W. Riegler, Y. Wang, F.Zimmerman, A Blondel

Collider Characteristics

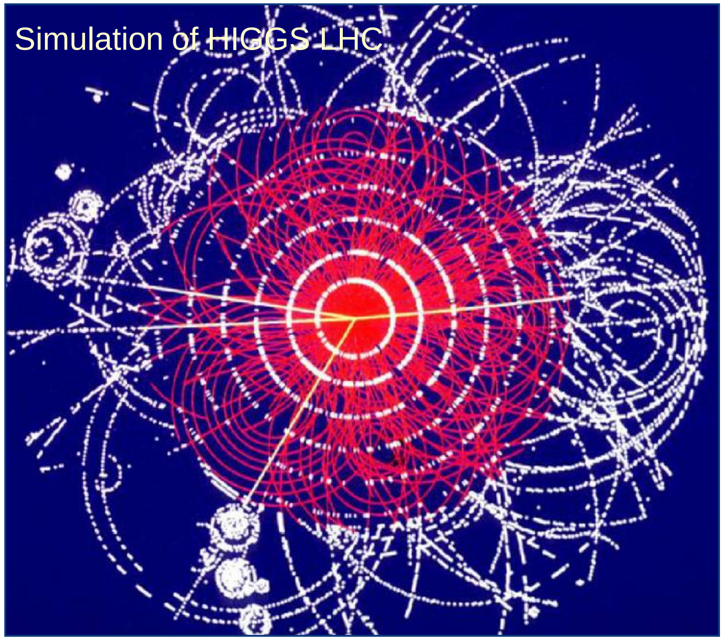
- Hadron collider at the frontier of physics
  - huge QCD background
  - not all nucleon energy available in collision

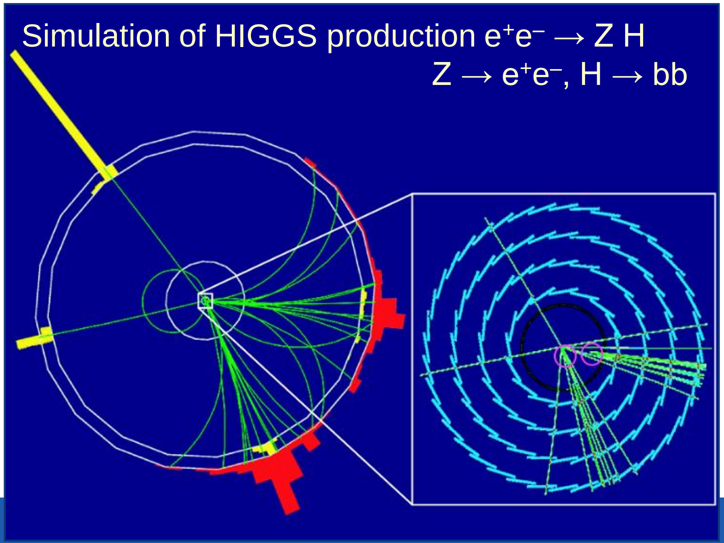


- Lepton collider for precision physics
  - well defined initial energy for reaction
  - Colliding point like particles

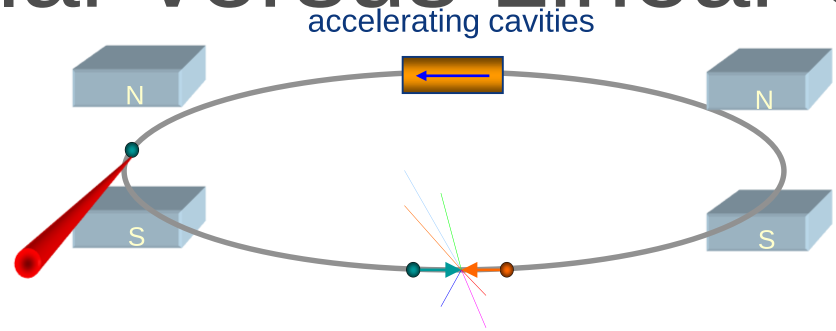


- Candidate next machine after LHC
  - pp, e^+e^-, he collider
  - energy determined by LHC discoveries
  - study in detail the properties of the new physics that the LHC finds and search for new physics BSM.





Circular versus Linear Collider

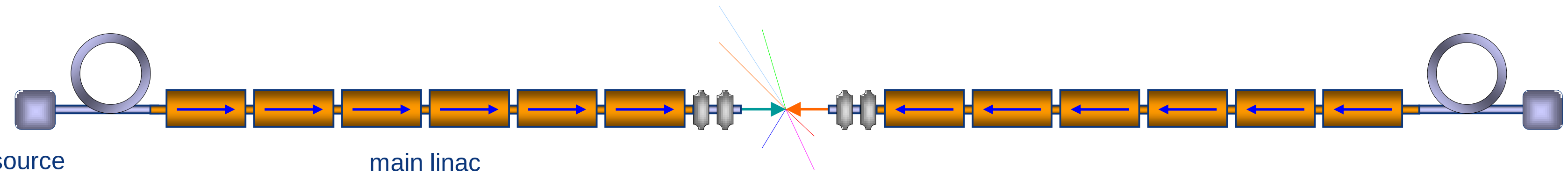


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



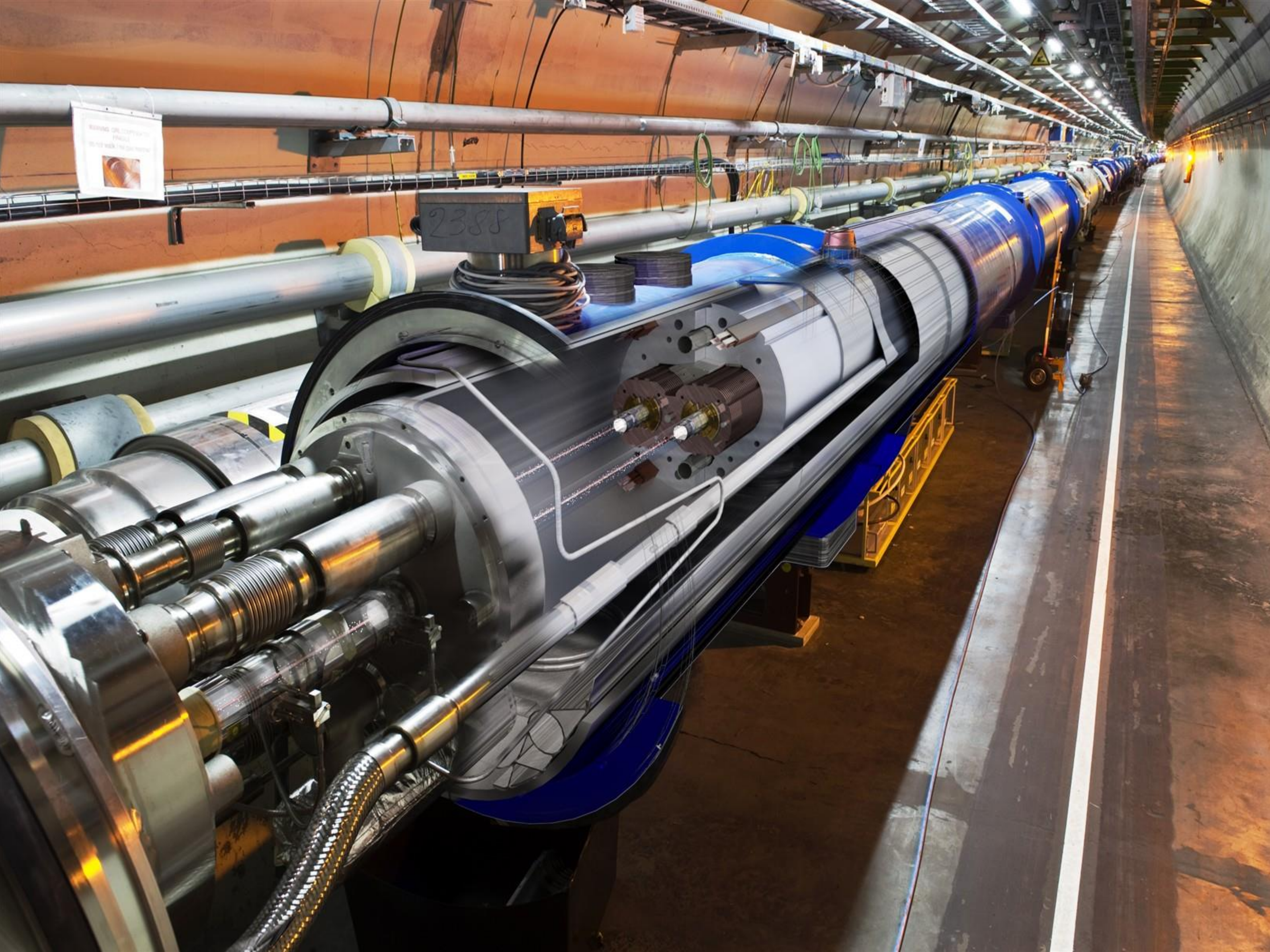
Linear Collider

few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

The LHC Upgrade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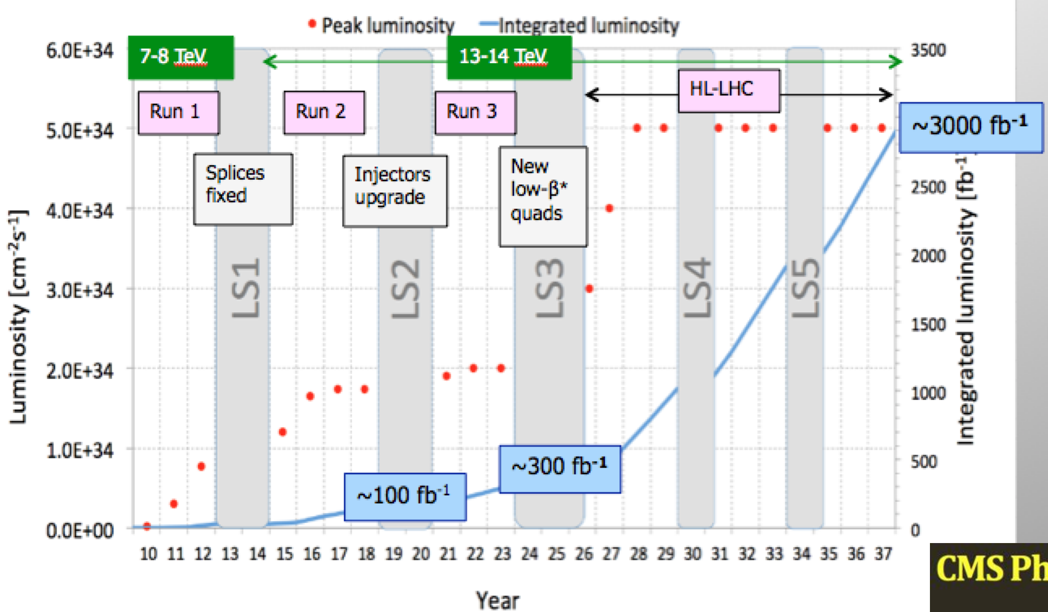
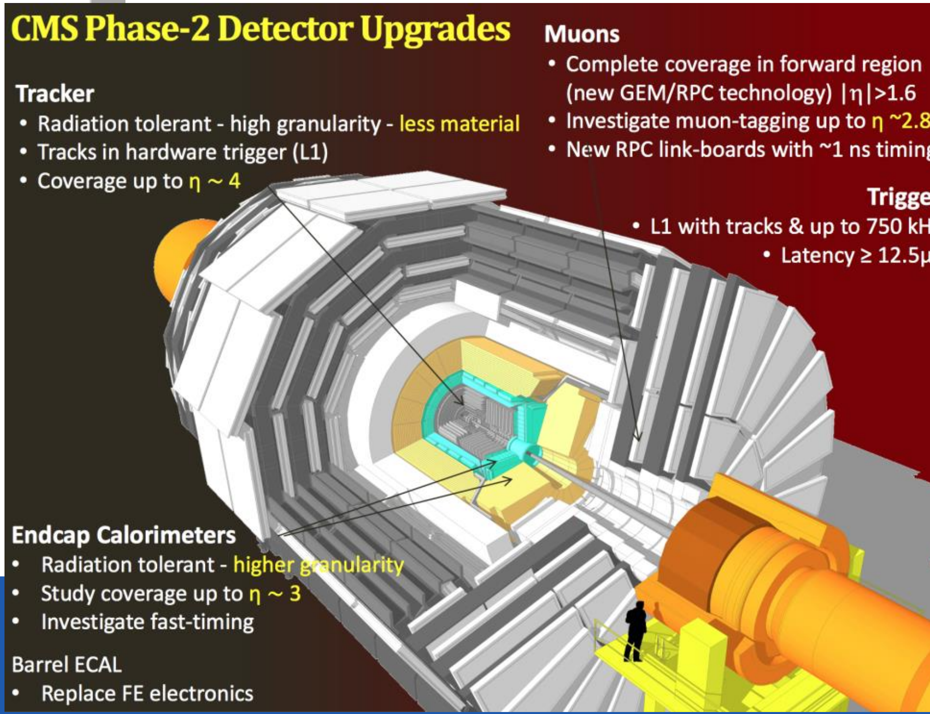
LHC Outlook and Plans



All LHC experiments plan upgrades for either 2019-2020 or 2024-2026 for the High Luminosity LHC upgrade (ATLAS and CMS)

Approved LHC program to collect 3000 fb^{-1}
In total with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (eg Higgs)

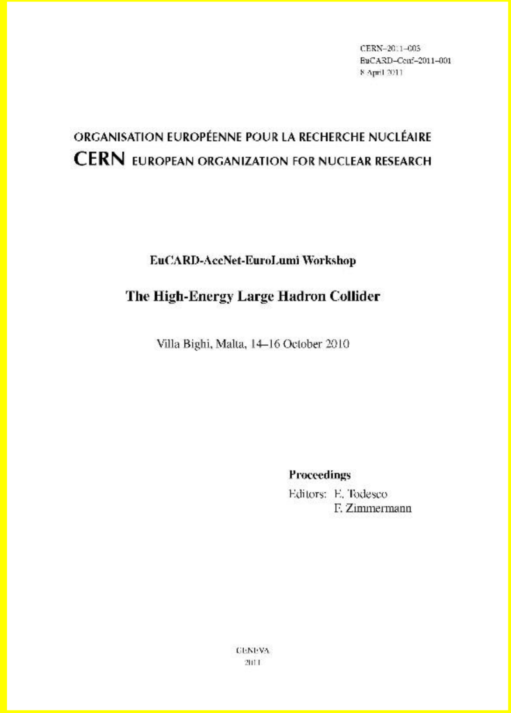


LHC will run till ~2037
Only 2% of the collisions delivered so far…
Then a high energy LHC (28 TeV)?

High-Energy LHC??

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1



CERN-2011-003
EuCARD-Conf-2011-001
8 April 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EuCARD-AccNet-EuroLumi Workshop

The High-Energy Large Hadron Collider

Villa Bighi, Malta, 14–16 October 2010

Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

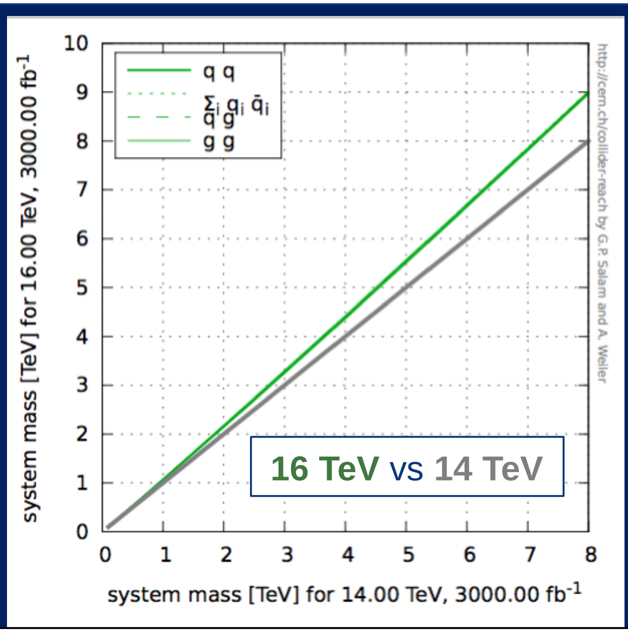
EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

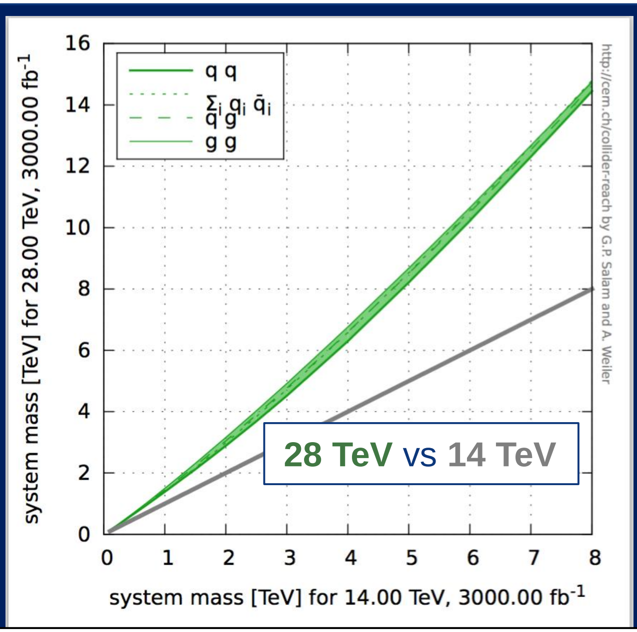
- based on 16-T dipoles developed for FCC-hh
- extrapolation of other parts from the present (HL-)LHC and from FCC developments

CM Energy 25-28 TeV

High-Energy LHC

F. Gianotti
FCC meeting
Rome April 2016





Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb_3Sn magnets)
→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
→ Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ $\sqrt{s}$~ 30 TeV)
- ❑ uses existing tunnel and infrastructure; can be built at fixed budget
- ❑ strong physics case if new physics from LHC/HL-LHC
- ❑ powerful demonstration of the FCC-hh magnet technology

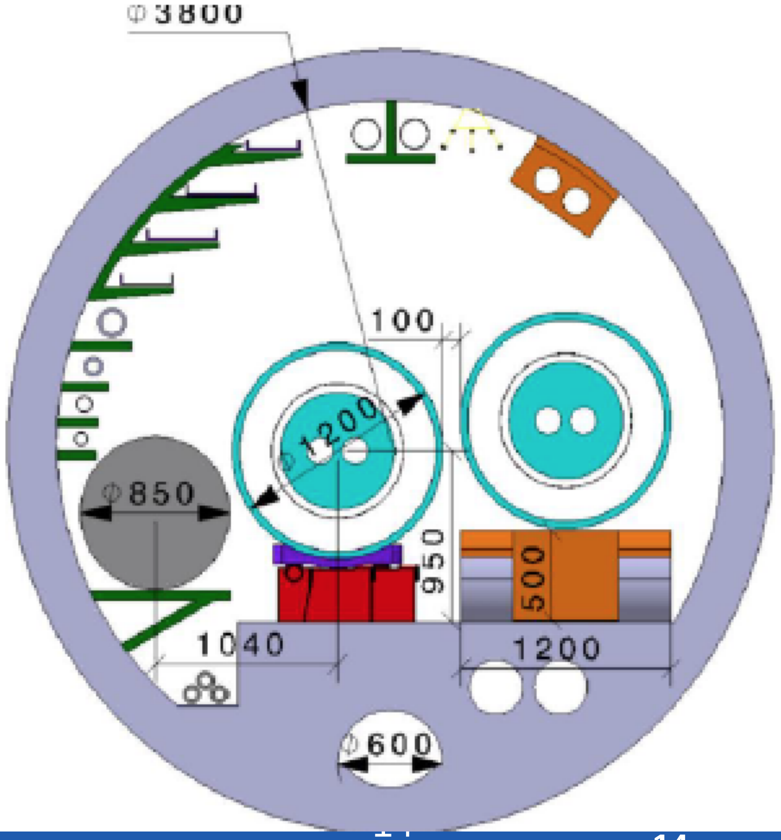
High-Energy LHC

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$;

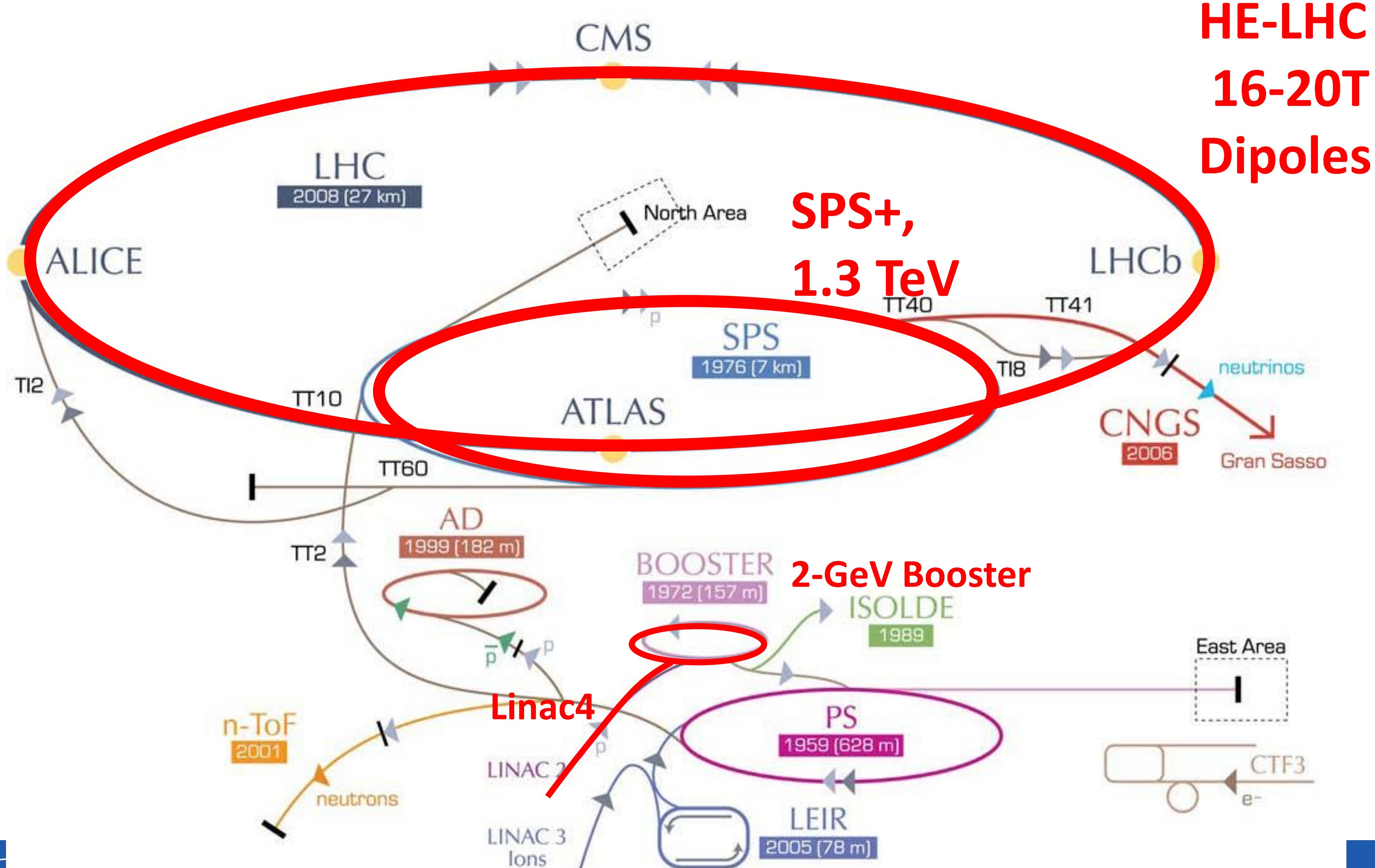
Present working hypothesis for HE LHC design:

No major CE modification on machine tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- Due to 16 T dipole field and increased cryogenic load, magnet cryostat and cryo distribution line (QRL) larger than for LHC.
- Challenges for tunnel integration and QRL & 16 T cryostat design.
- **Maximum magnet cryostat external diameter compatible with LHC tunnel: 1200 -1250 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**



High-Energy LHC (HE-LHC)



Beyond the LHC

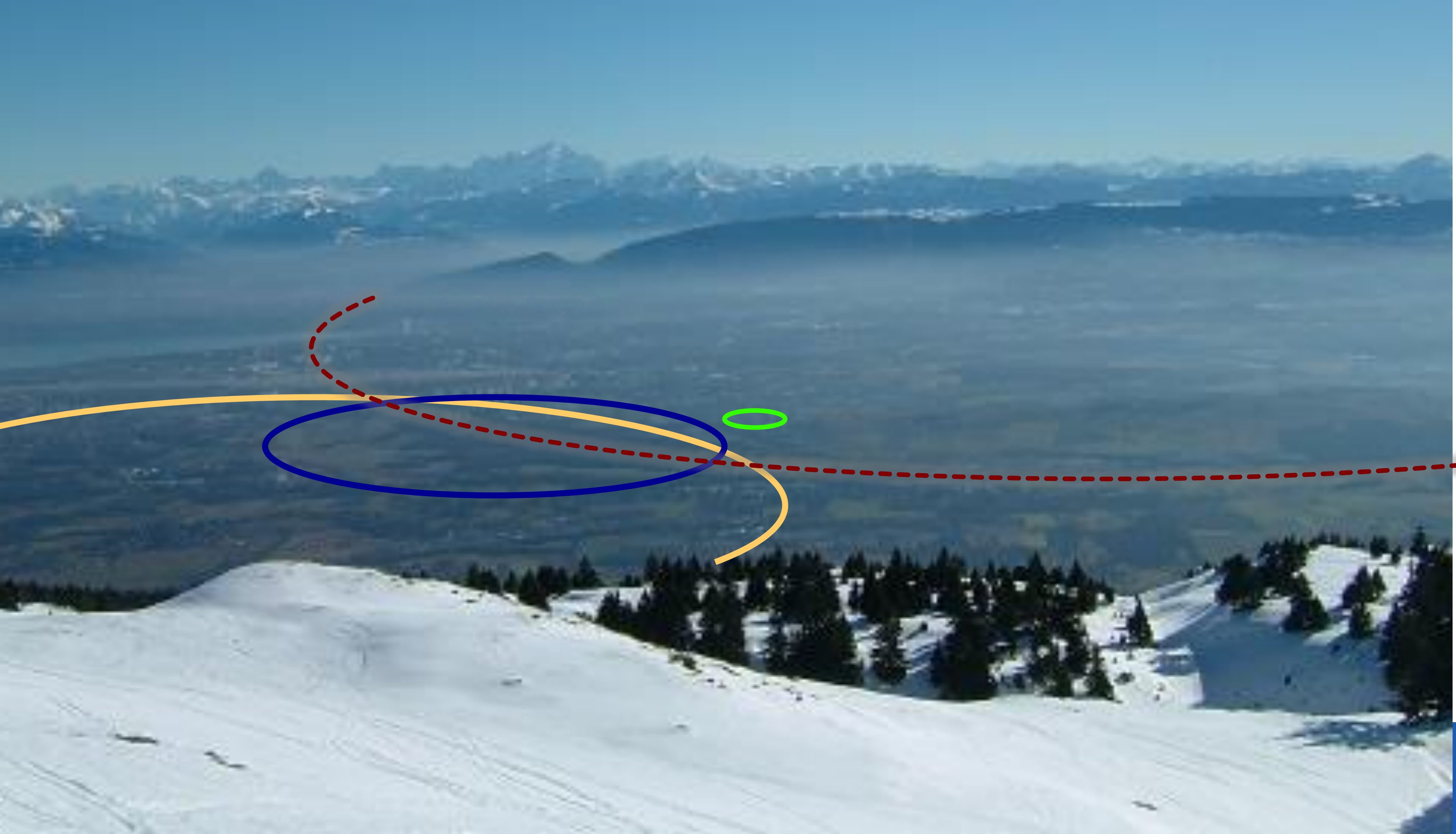
- Proton-proton machines at higher energy…

- Electron-positron machines for high precision…

- Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

Future Circular Colliders



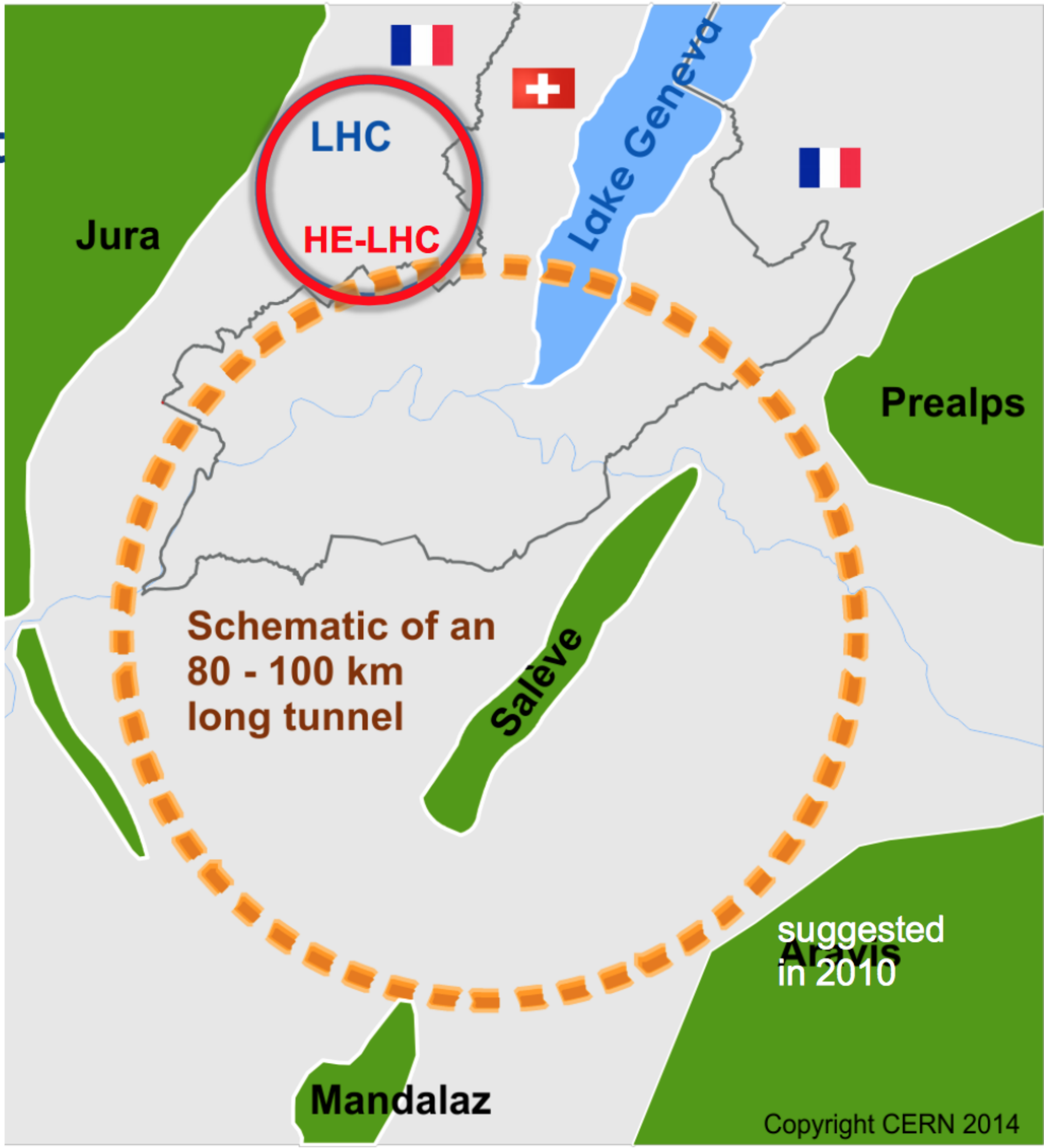
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to design:

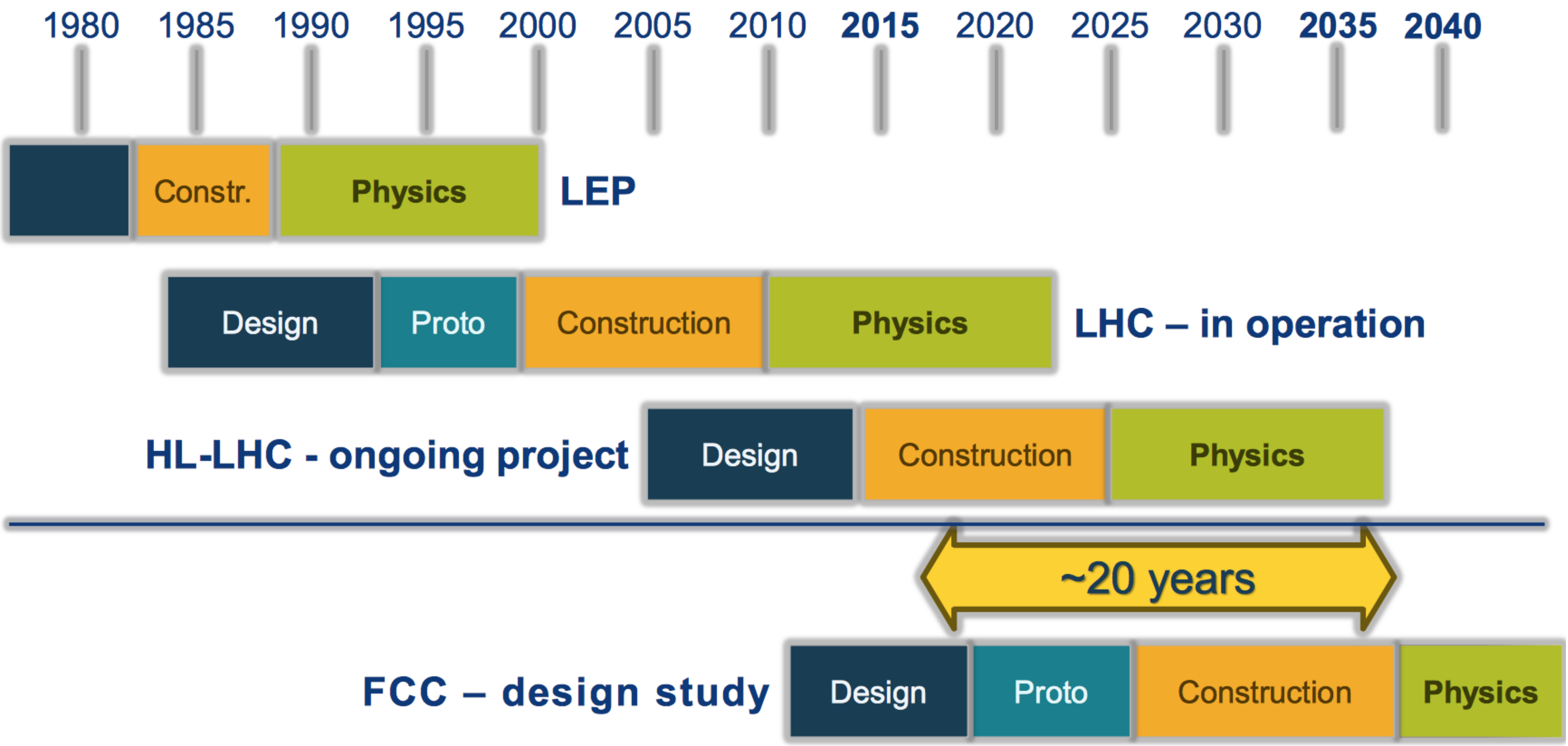
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology

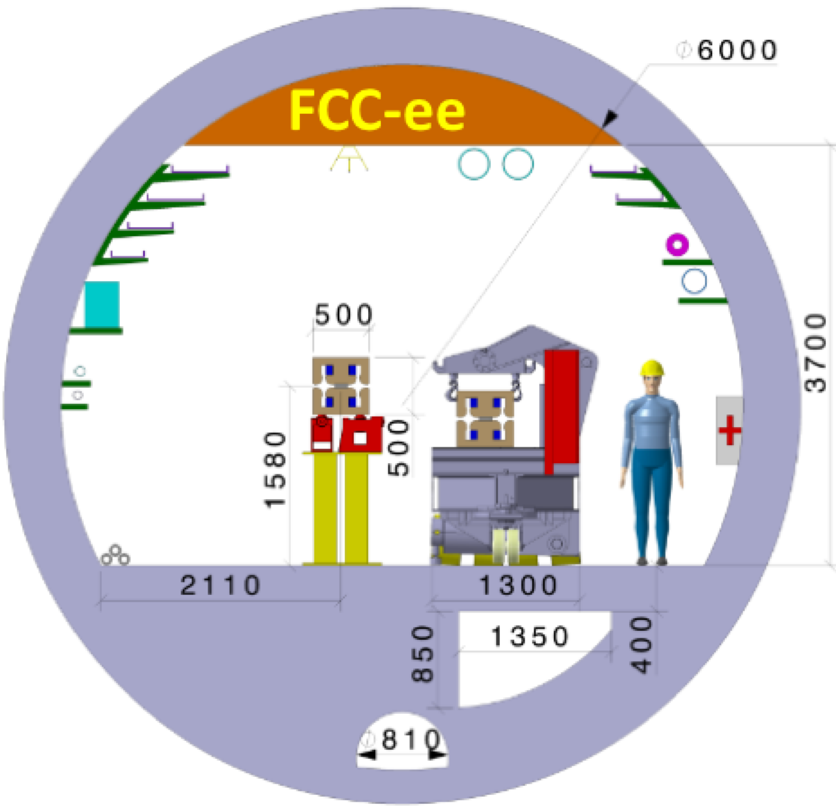


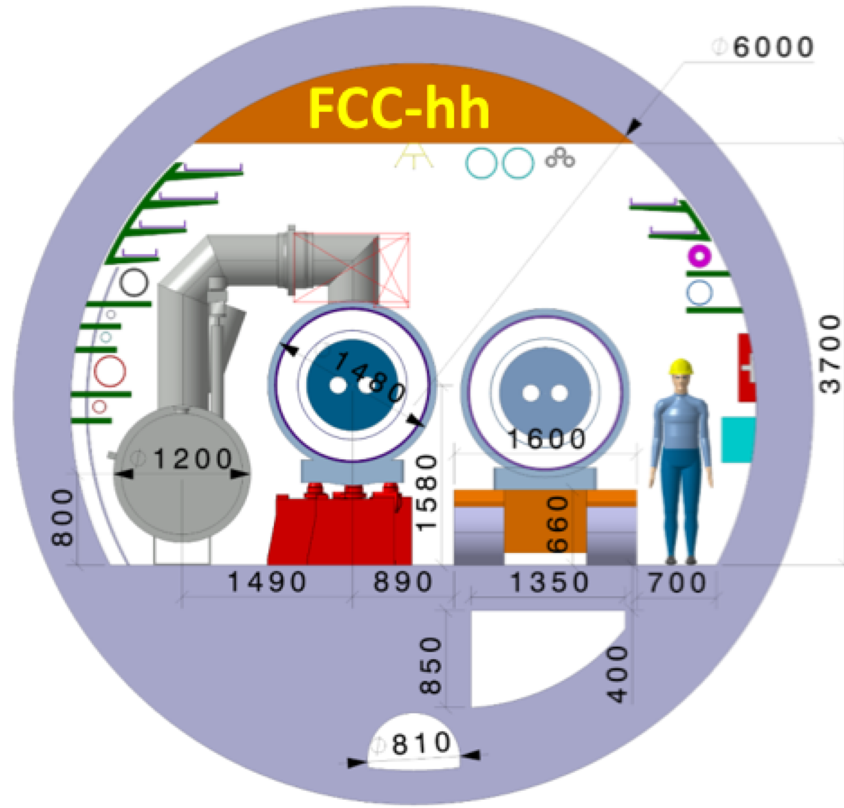
CERN Circular Colliders & FCC



must advance fast now to be ready for the period 2035 – 2040

milestone: CDR by end 2018 for next update of European Strategy

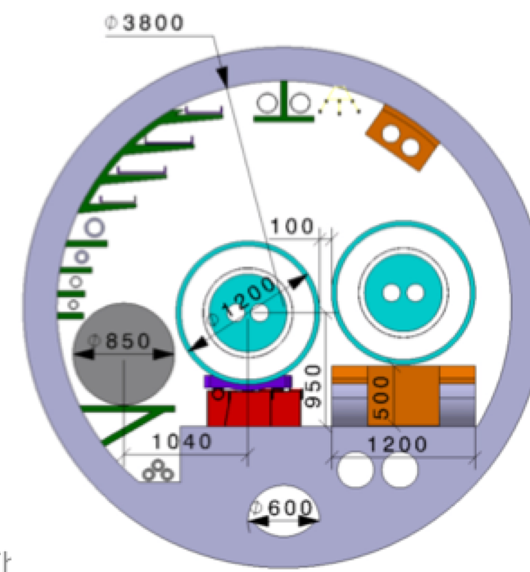




HE-LHC :
constraints:
No civil engineering, same beam height as LHC
→ Magnets OD ca. 1200 m max
QRL (shorter than FCC) OD ca. 850 mm (all included)

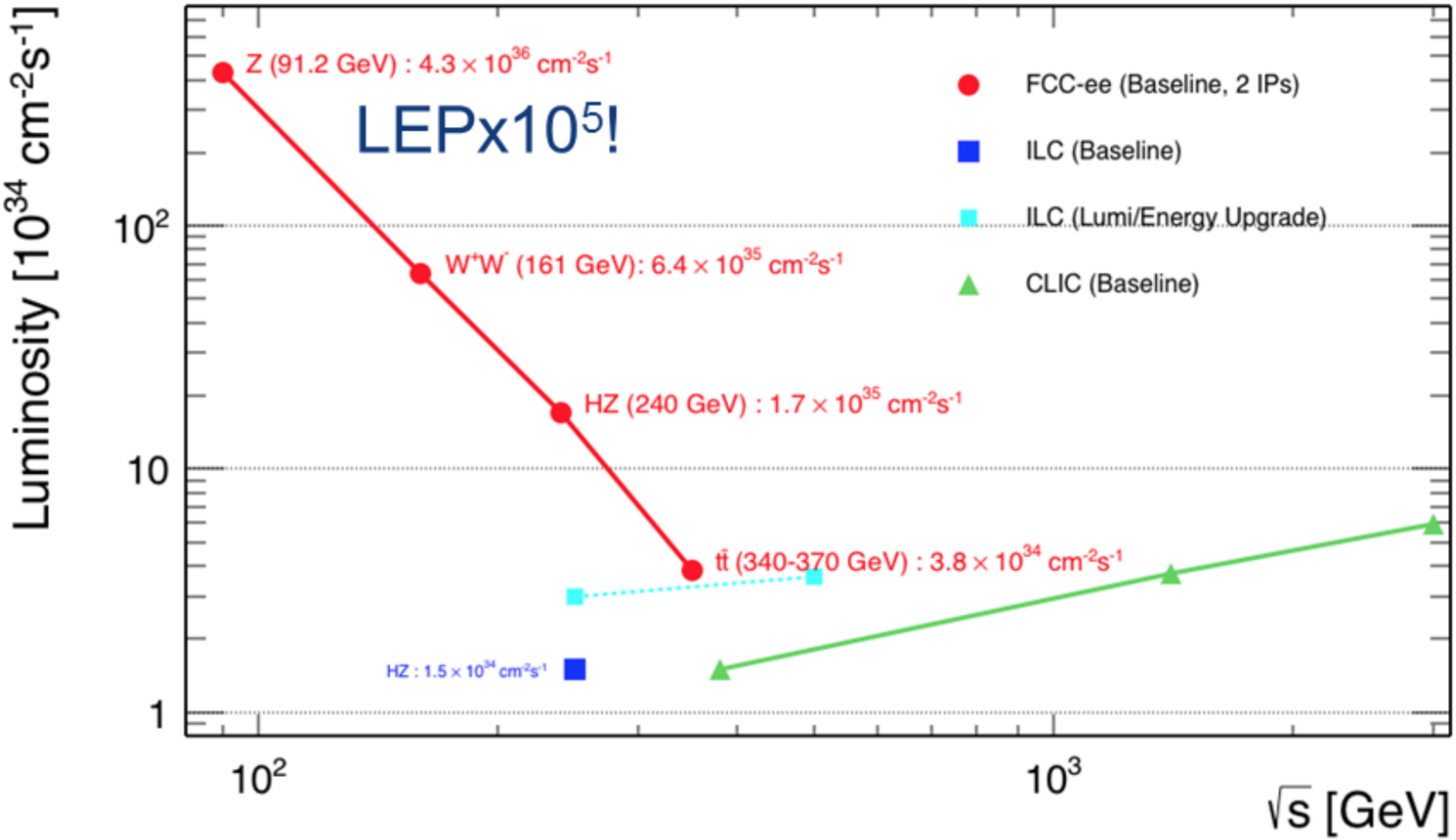
Magnet suspended during „handover“
from transport vehicle to installation transfer table

Compliant 16T magnet design ongoing
+ still many items to study!



If HE-LHC can work in 3.8m ∅ ... it will feed-back to FCC tunnel design!

Luminosities for Future ee colliders



A. Blondel, Lepton-Photon 2017

FCC-ee Physics Runs

A. Blondel LP17

- **FCC-ee physics goals (sum of two IPs):**
  - 150 ab^{-1} at and around the Z pole (88, 91, 94 GeV)
  - 10 ab^{-1} at the WW threshold (~161 GeV with a +/- few GeV scan)
  - 5 ab^{-1} at the HZ maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the ttbar threshold (a few 100 fb^{-1} with a scan from 340 to 350 GeV, and the rest at 365-370 GeV)
- **Assumptions:**
  - 200 scheduled physics days per year, i.e. 7 months – 13 days of MD/stops.
  - "Hübner factor" H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  - Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)
  - Machine configuration between WPs is changed during winter shutdowns (effective time of about 3 months/year)

FCC-ee Detectors

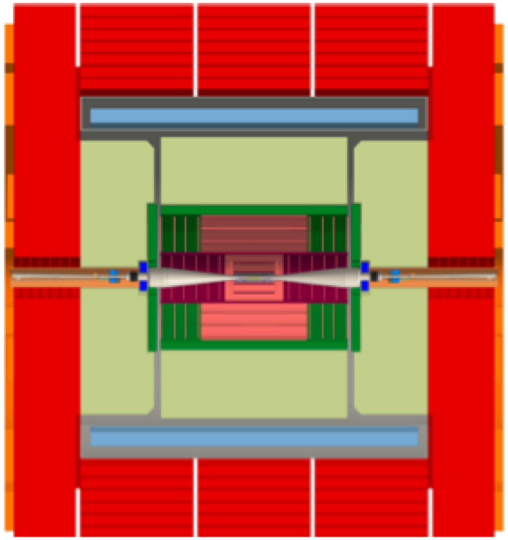
A. Blondel LP17

Two integration, performance and cost estimates ongoing:

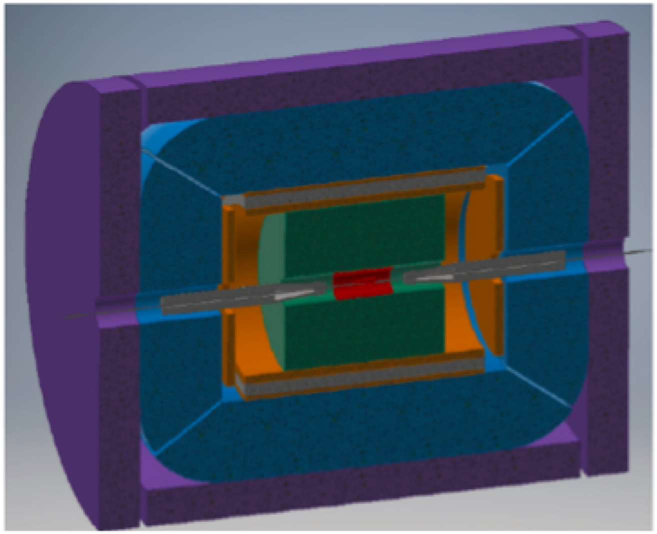
-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



"IDEA"



- Vertex detector: ALICE MAPS
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

FCC-ee Discovery Potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

A. Blondel LP17

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
m_Z, m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality
-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.
+ flavour physics (10^{12} bb events) (B→s τ τ etc..)

DISCOVER dark matter as «invisible decay» of H or Z or in LHC loopholes.

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

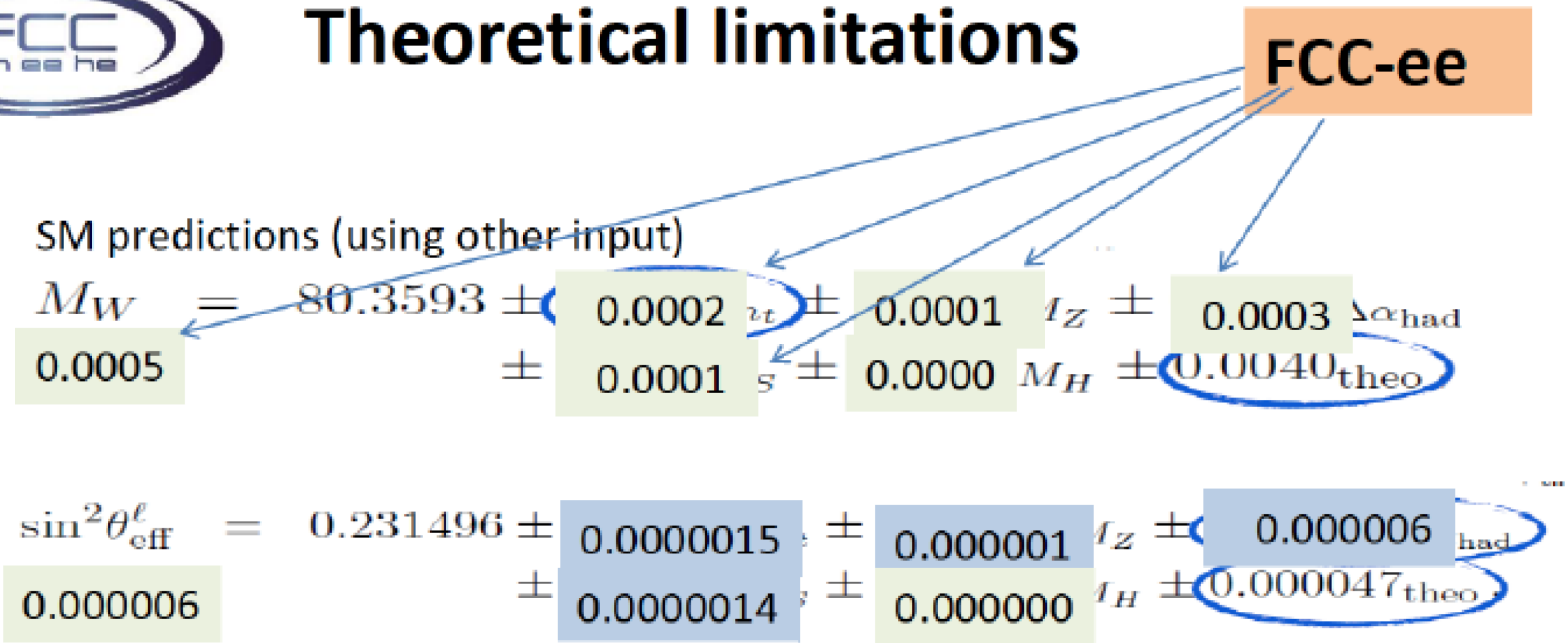
+ an enormous amount of clean, unambiguous work on QCD etc….

NB the «Z factory» plays an important role in the 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164,

FCC-ee: Need for Precise Theory

Theoretical limitations



Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
<u>Will require significant theoretical effort and additional measurements!</u>
the above explains why we want the top running – and high Z statistics.
Freitas, Heinemeyer, Jadach, Gluza … need for 3 loop calculations for the future!
<u>Suggest including manpower for theoretical calculations in the project cost.</u>

Hadron Colliders (*pp*)

Parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		**27**	14
dipole field [T]	16		**16**	8.3
circumference [km]	100		**27**	27
beam current [A]	0.5		**1.12**	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		**2.2**	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		**25 (12.5)**	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (2.2)		**2.5 (1.25)**	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	**25**	(5) 1
peak #events / bunch Xing	170	1000 (500)	**800** (400)	(135) 27
stored energy / beam [GJ]	8.4		**1.4**	(0.7) 0.36
SR power / beam [kW]	2400		**100**	(7.3) 3.6
transv. emit. damping time [h]	1.1		**3.6**	25.8
initial proton burn off time [h]	17.0	3.4	**3.0**	(15) 40

16 Tesla Magnets

FCC goal is 16 T operating field
- Requires to use Nb_3Sn technology
- At 11 T used for HL-LHC

⇒ Strong synergy with HL-LHC

R&D on cables in test stand at CERN

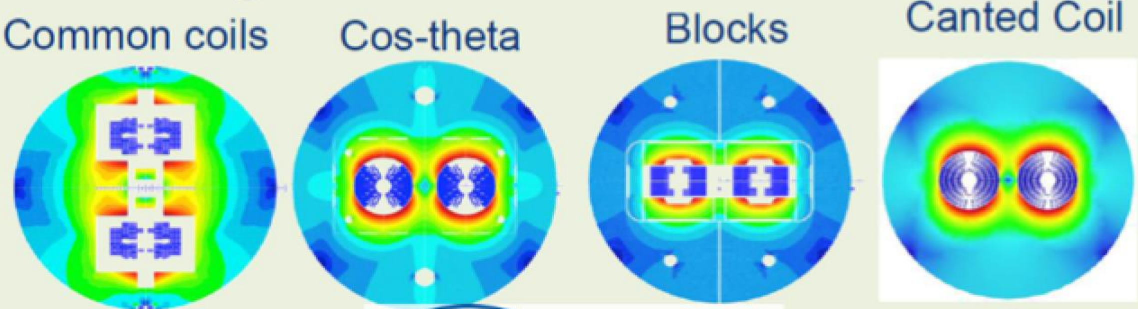
Target: $J_C > 2300$ A/mm² at 1.9 K and 16 T (**50% above HL-LHC**)

Industrial fabrication:
Target cost: 3.4Euro/kAm

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

Magnet design to **minimise material** use and limit margins to essential level

D. Tommasini at al.



CIEMAT, CEA, INFN

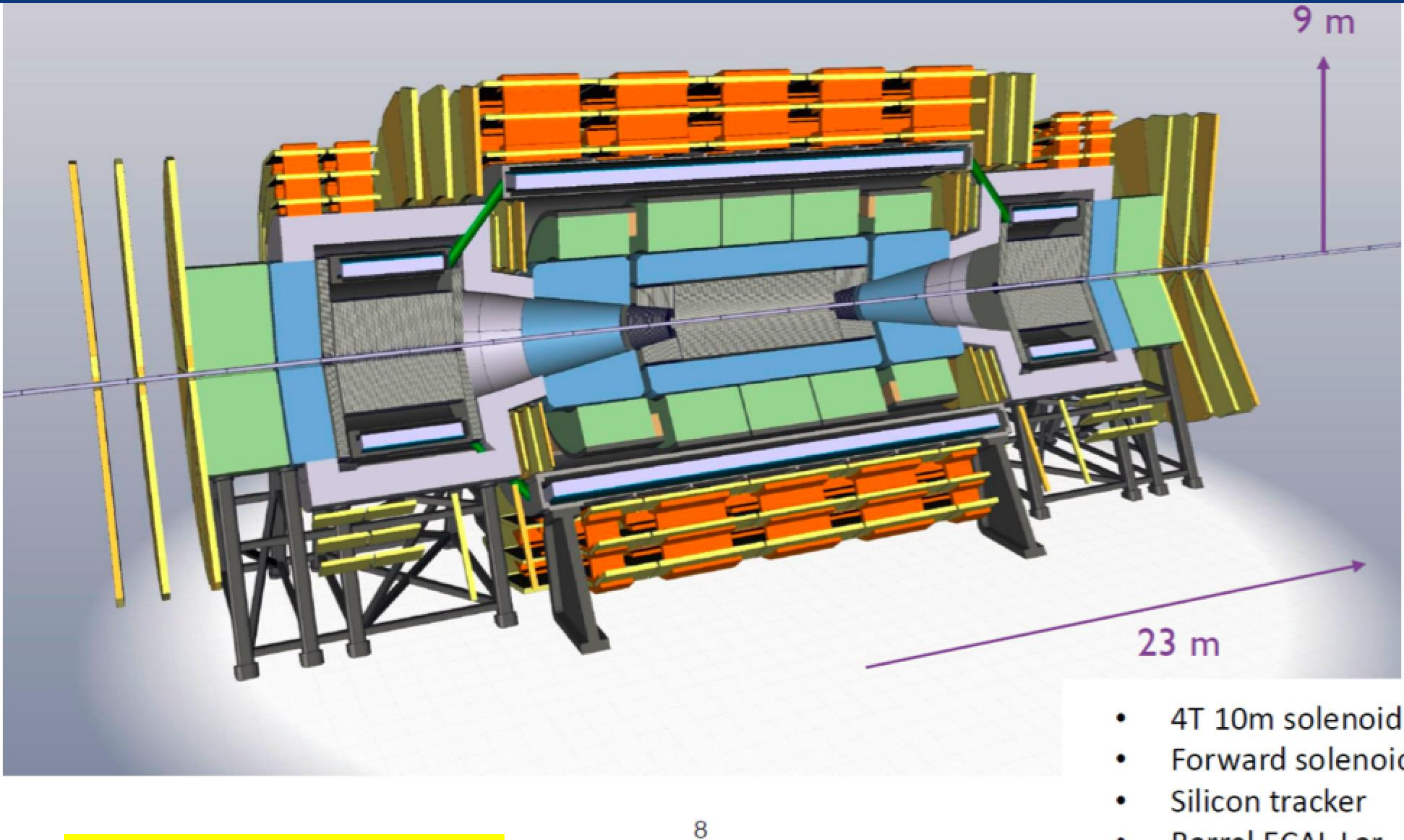
EuroCirCol
A key to New Physics

Swiss contribution
via PSI

D. Schulte, EPS'17

-- possible shorter term application SCSPS or HE-LHC
-- For longer timescale HTS is also studied → 20T

FCC-hh Reference Detector 2017



- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

New Design 2017

Solenoids in Central *and* forward areas no flux return.

FCC-hh Discovery Highlights

FCC-hh is a HUGE discovery machine (if nature ...), but not only.

FCC-hh physics is dominated by three features:

-- **Highest center of mass energy** –> a big step in high mass reach!

ex: strongly coupled new particle up to 50 TeV

Excited quarks, Z', W', up to ~tens of TeV

Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV

Sensitivity to high energy phenomena in e.g. WW scattering

-- **HUGE production rates** for single and multiple production of SM bosons (H,W,Z) and quarks

-- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, ttH/ttZ @% level

-- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling

-- detection of rare decays $H \rightarrow V\gamma$ ($V = \rho, \varphi, J/\psi, \Upsilon, Z$...)

-- search for invisibles (DM searches, RH neutrinos in W decays)

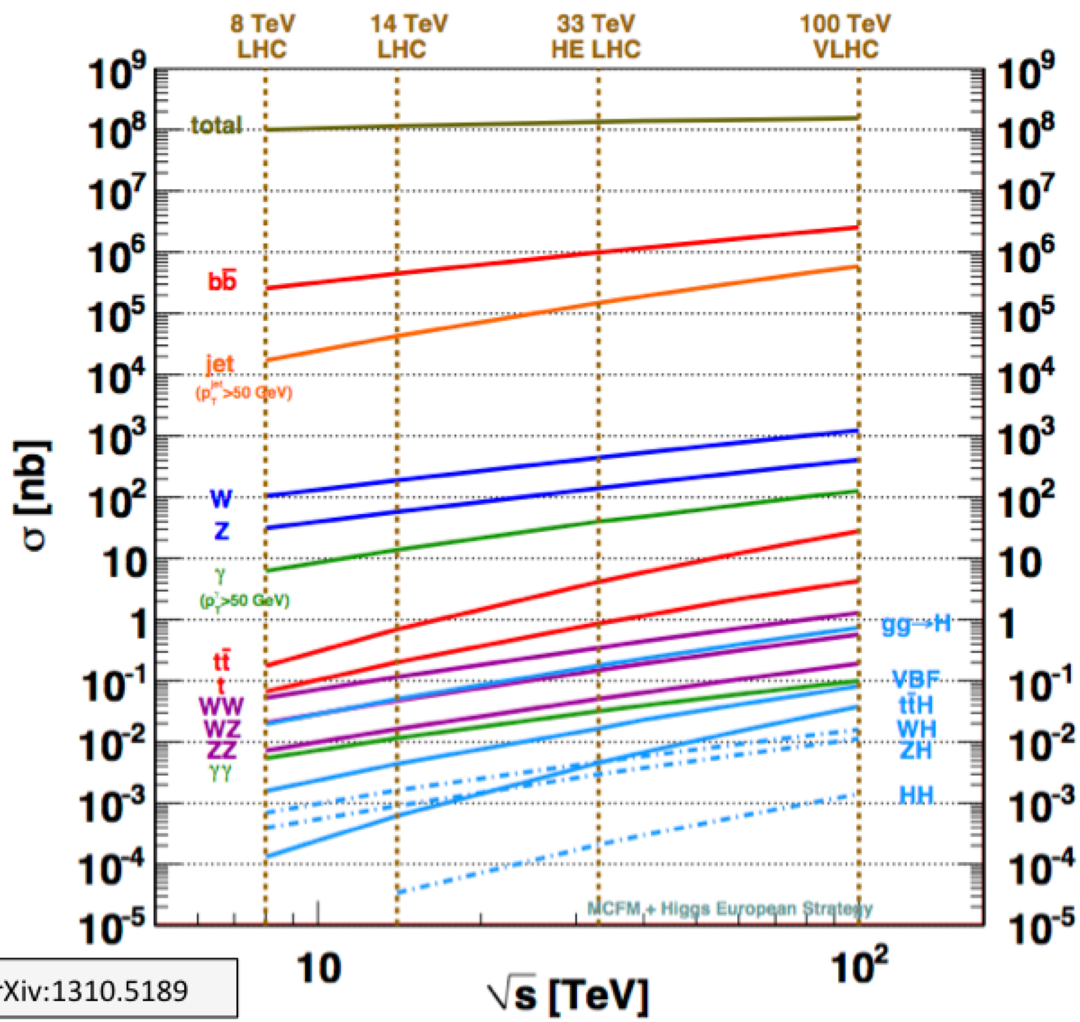
-- renewed interest for long lived (very weakly coupled) particles.

-- rich top and HF physics program

-- **Cleaner signals for high Pt physics**

-- allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)

Hadron colliders: direct exploration of the "energy frontier"



arXiv:1310.5189

Gianotti

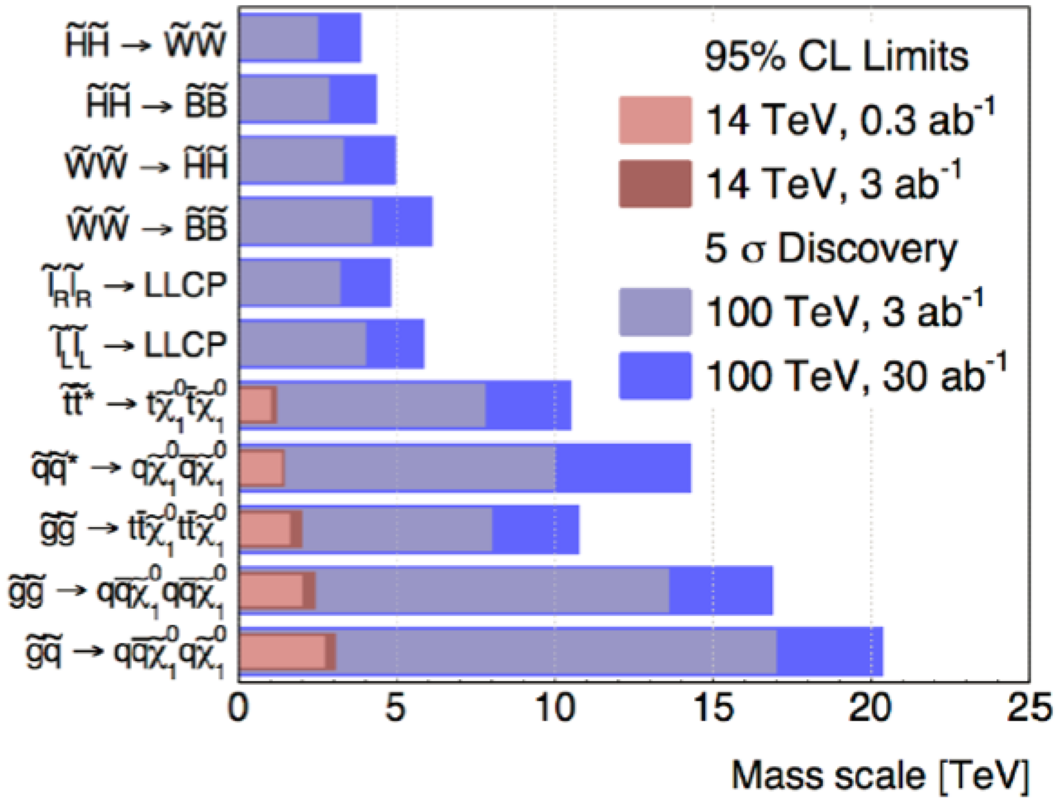
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	$\sim 10^3$

With 40/ab at √s=100 TeV expect: $\sim 10^{12}$ top, 10^{10} H bosons, 10^5 m=8 TeV gluino pairs, …

If new (heavy) physics discovered at the LHC → completion of spectrum is a "no-lose" argument for future ~ 100 TeV pp collider: extend discovery potential up to m~50 TeV

Supersymmetry

Summary from FCC Report:



The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume SM or ee measurements

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
γγ	1.5%	**<1%**	
Zγ	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
ττ	**0.5%**		
cc	**0.7%**		1.8%
μμ	6.2%	**2%**	
uu,dd	H→ ργ?	H→ ργ?	
ss	H→ φγ ?	H→ φγ ?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%

Science

China unveils plans for super-giant particle collider – the biggest and most powerful on Earth

By Hannah Osborne
October 29, 2015 10:06 GMT

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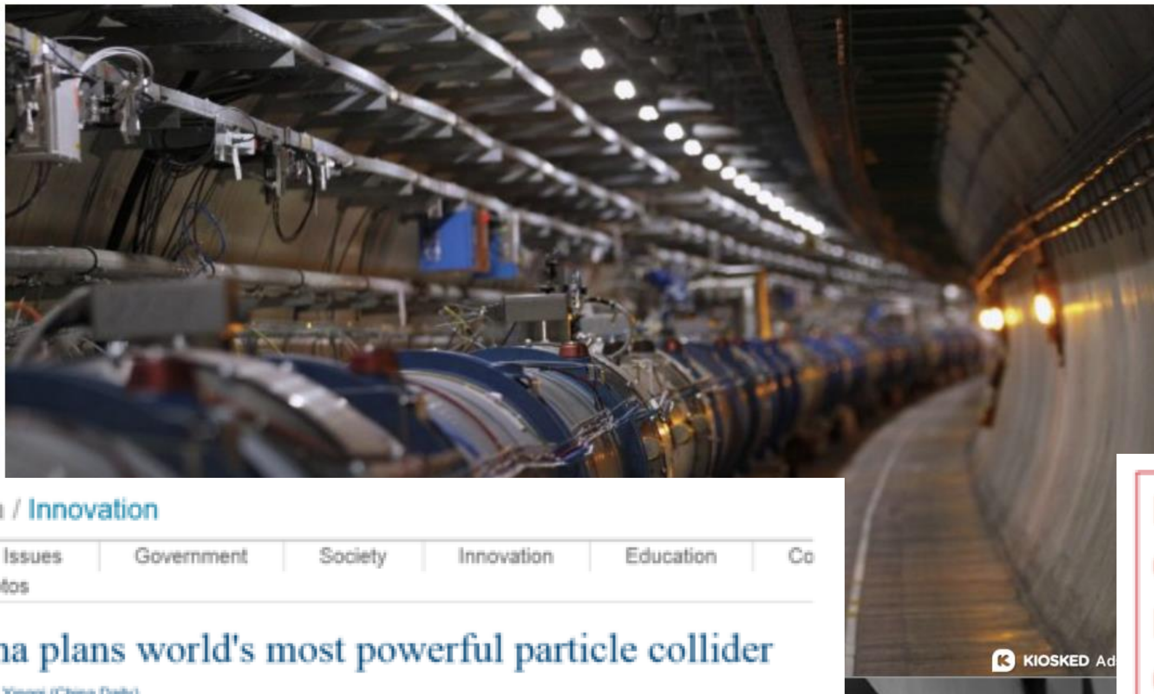

China is set to build the biggest and most powerful particle collider on Earth, dwarfing the Large Hadron Collider at Cern. The super-giant particle collider will measure between 50 and 100km in circumference – double or quadruple that of the

China / Innovation

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Photos

China plans world's most powerful particle collider

By Cheng Yingqi (China Daily)
Updated: 2015-10-29 07:49

Comments Print Mail Large Medium Small

The first phase of the project's construction is scheduled to begin between 2020 and 2025

This hit the news end if 2015!

What is all about??

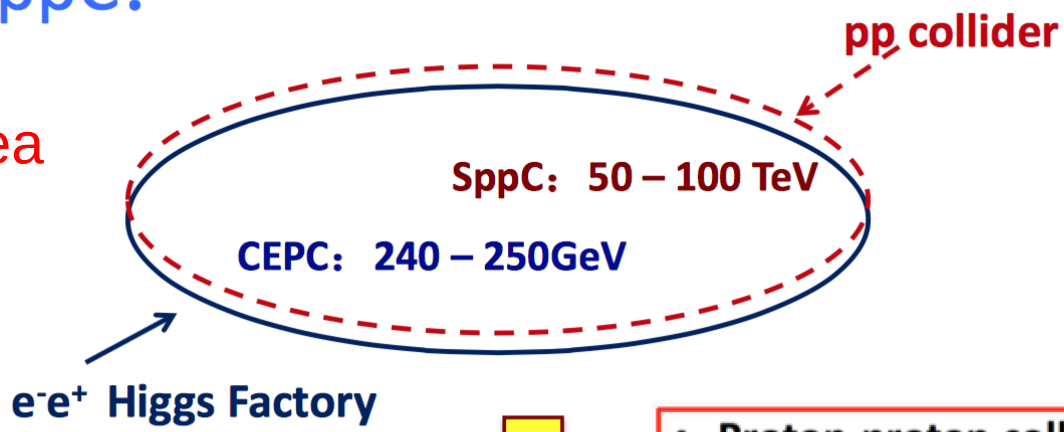
Media is media
Chinese media is also media
Don't get too excited, nor panic
CEPC will not be easy and quick
R&D will come gradually

Y. Wang

The CEPC/SppC Design (China)

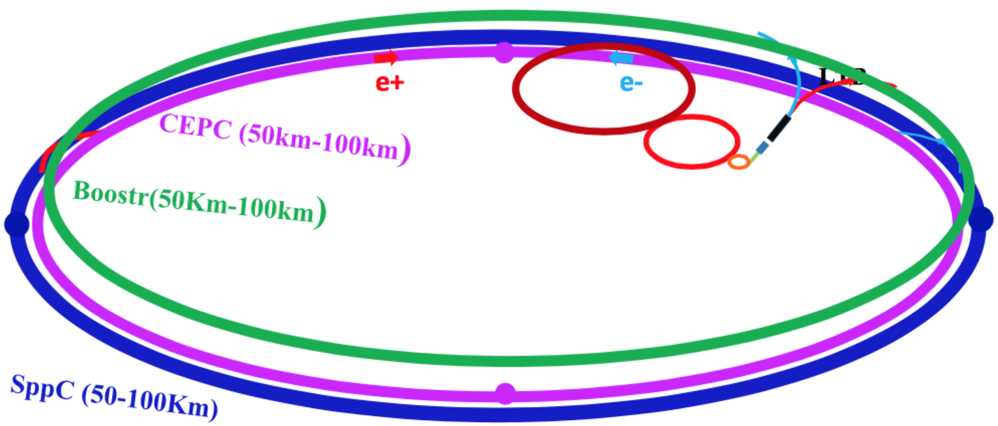
CEPC+SppC：

2012-2014: idea

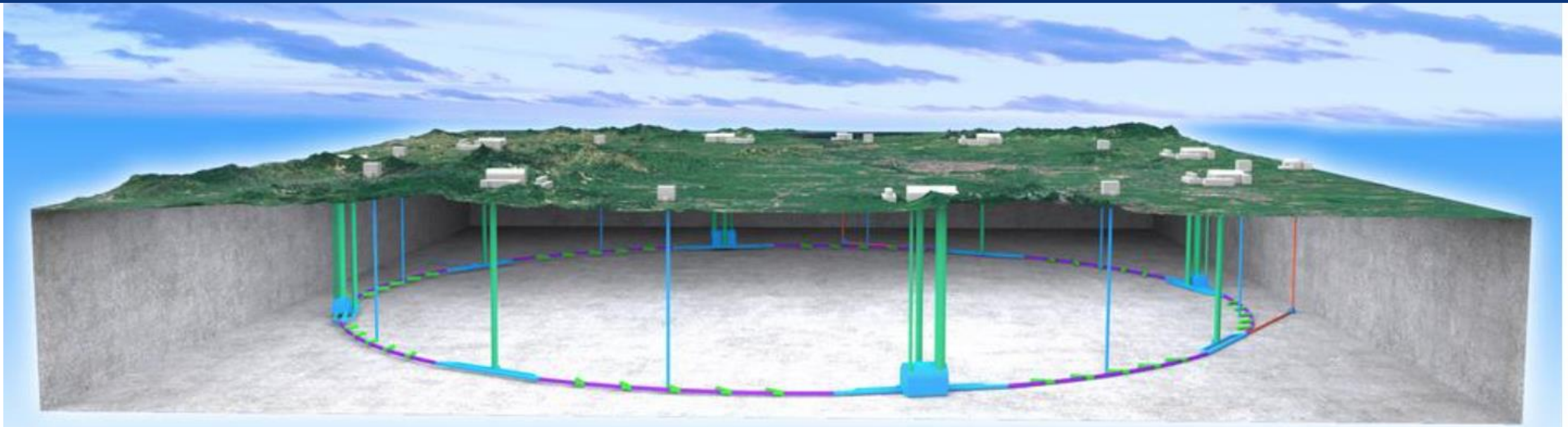


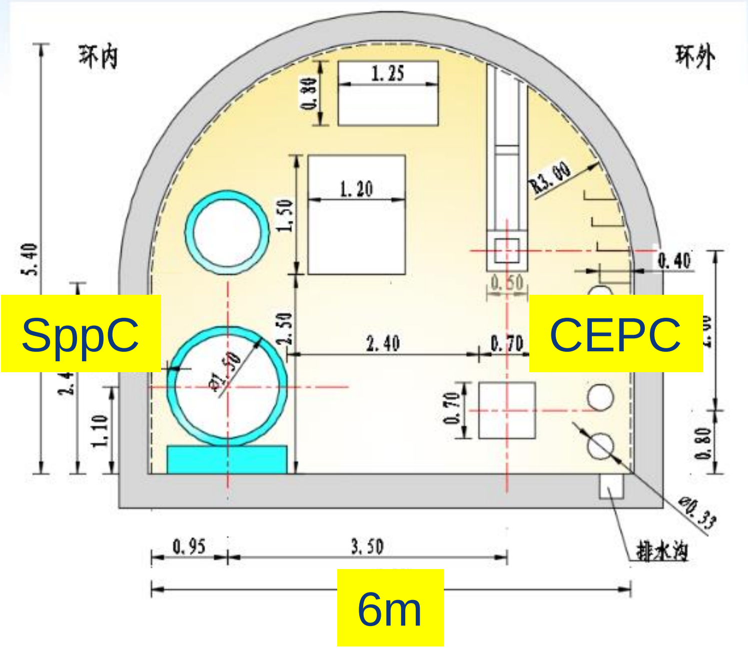
- Proton-proton collider(~100 TeV)
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

2015 pre-CDR



The CEPC/SppC Civil Construction

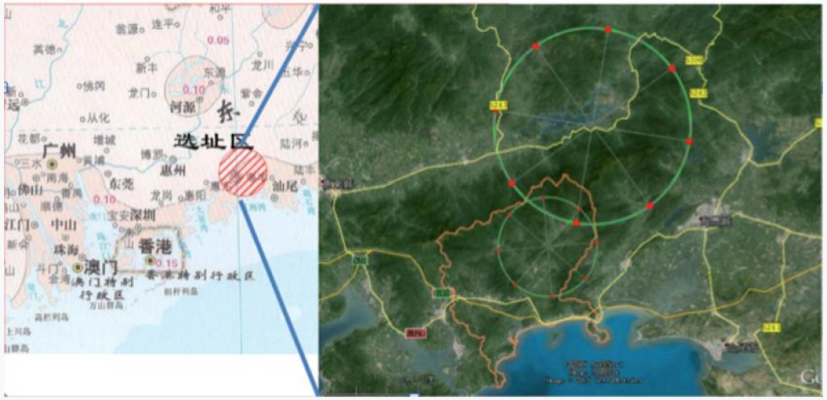




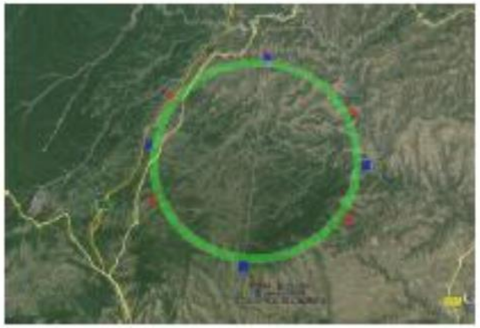
Site selection ongoing

Possibilities among others..

- Qinhuangdao (1 hr by train from Beijing)
- Close to Hong-Kong?...



Alternative CEPC Sites



1) Qinhuangdao

   (site technical exloring done)

2) Shanxi Province

   (under site technical exploring, started from Jan. 2017)

3) Near Shenzhen and Hongkong

   (site technical exloring done)

M. Koratzinos, HongKong

CEPC Schedule (Ideal)

X. Lou LP17

design issues
R&D items
preCDR

design, funding
R&D program
Intl. collabration
site study

seek approval, site decision
construction during 14th 5- year plan
commissioning

- **CEPC data-taking starts before the LHC program ends**
- **Possibly con-current with the ILC program**

FCC WEEK 2018

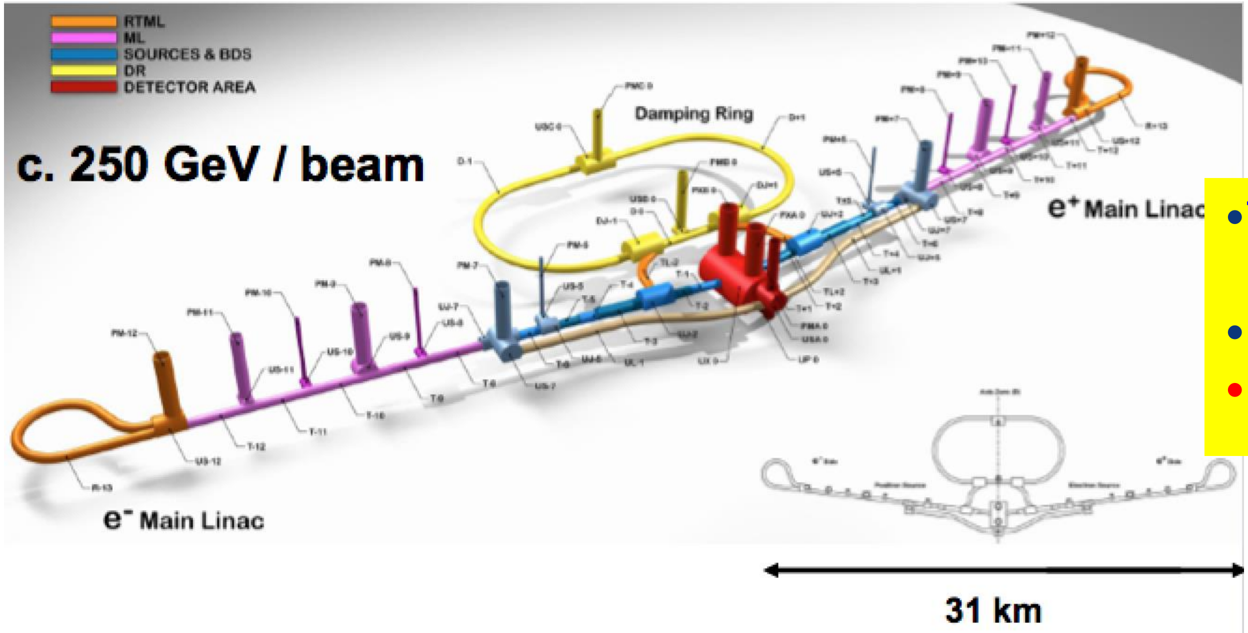
AMSTERDAM, 9-13 April 2018

also: 2018 FCC Physics Workshop, 15-19 January 2018, CERN

Future Circular Colliders: Summary

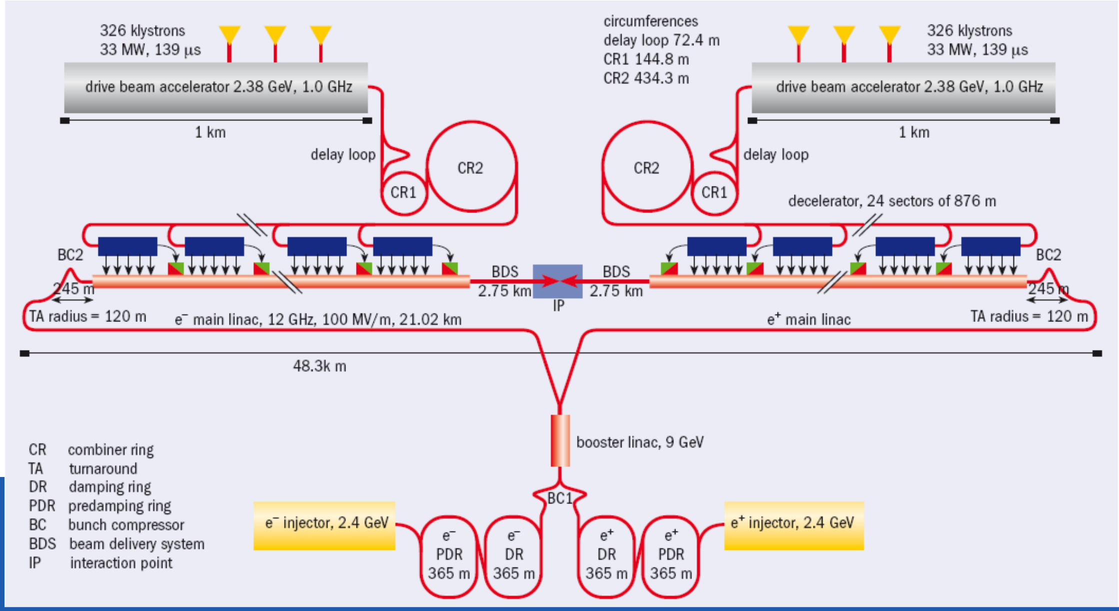
- FCC collider design is being developed as option for future flagship project at CERN for the world-wide high energy physics community. It includes hh-ee-eh options
  - Goal is to have CDR ready by end 2018 for European strategy update. No show stoppers so far
  - **https://indico.cern.ch/category/5153/**
- A High Energy LHC scenario is also being studied (again)
- SppC//CEPC in China is moving to a CDR phase
  - Detailed magnet R&D program ramping up for hh-mode
- Detailed physics studies for pp at 100 TeV, e+e- and ep at FCC in progress. Interested people are very welcome to join!

Linear e+e- Colliders



- The international linear collider (ILC)
- Max CM energy 0.5-1 TeV
- Discussed in Japan!

- The compact linear collider (CLIC)
- Max CM energy ~3 TeV
- R&D project

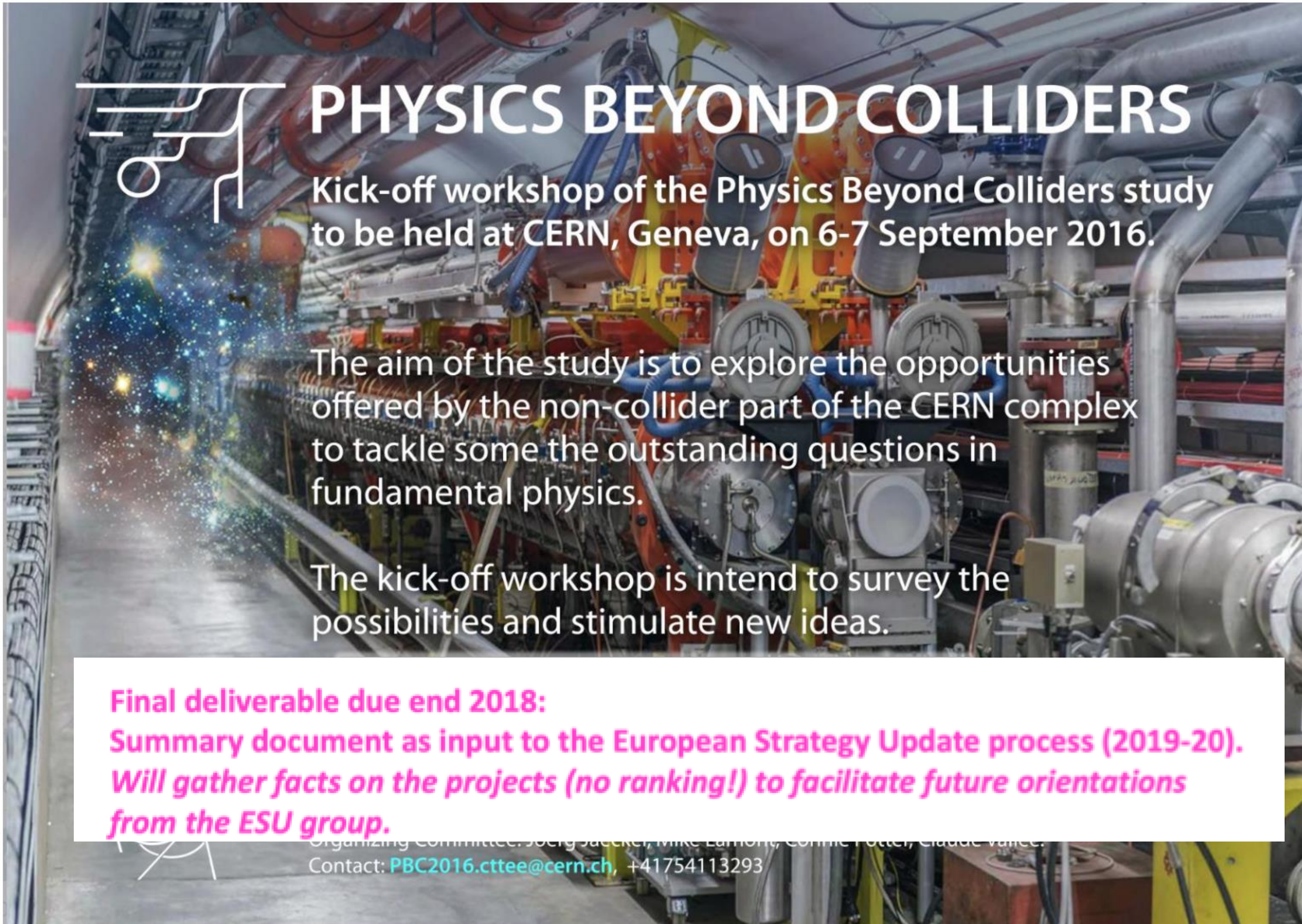


State of the art accelerating cavities

ILC goal: 35 MV / m

CLIC goal: 100 MV / m

6-7 September 2016: kick-off meeting



Final deliverable due end 2018:
Summary document as input to the European Strategy Update process (2019-20).
Will gather facts on the projects (no ranking!) to facilitate future orientations from the ESU group.

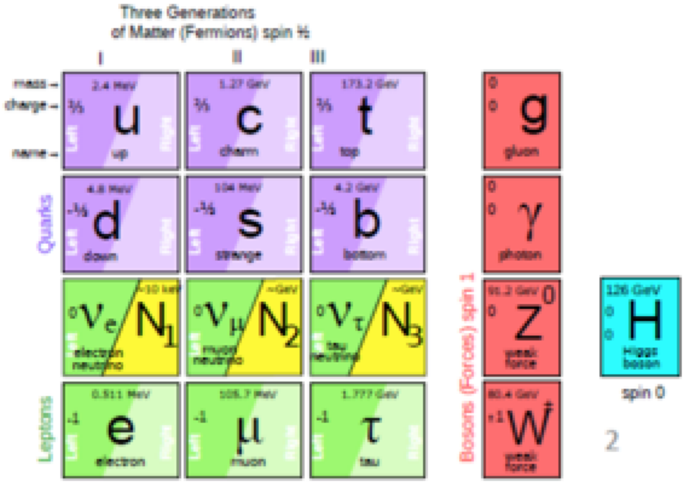
Other Experiments: The SHiP Proposal

SHiP is a proposed new general purpose fixed target facility at the CERN SPS for exploring the domain of hidden particles

Hidden particles: low mass particles (O(1-10) GeV) with very weak interactions

Example: heavy neutral leptons

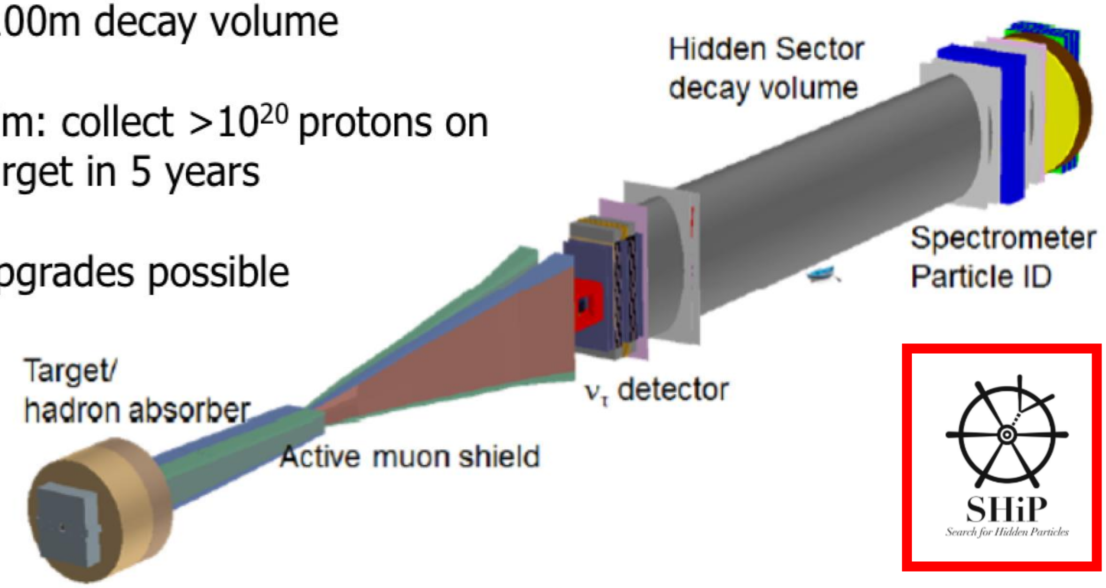
νMSM: neutrino minimal standard model



Approx 200m long experiment
-100m decay volume

Aim: collect >10^{20} protons on target in 5 years

Upgrades possible



Can explain dark matter and baryon asymmetry in the Universe

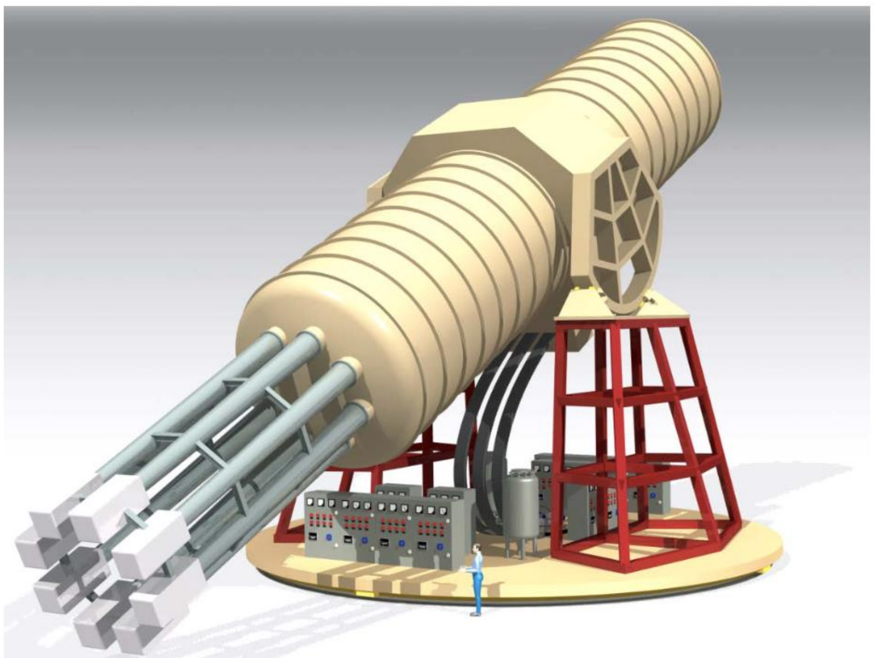
An experiment at the CERN SPS

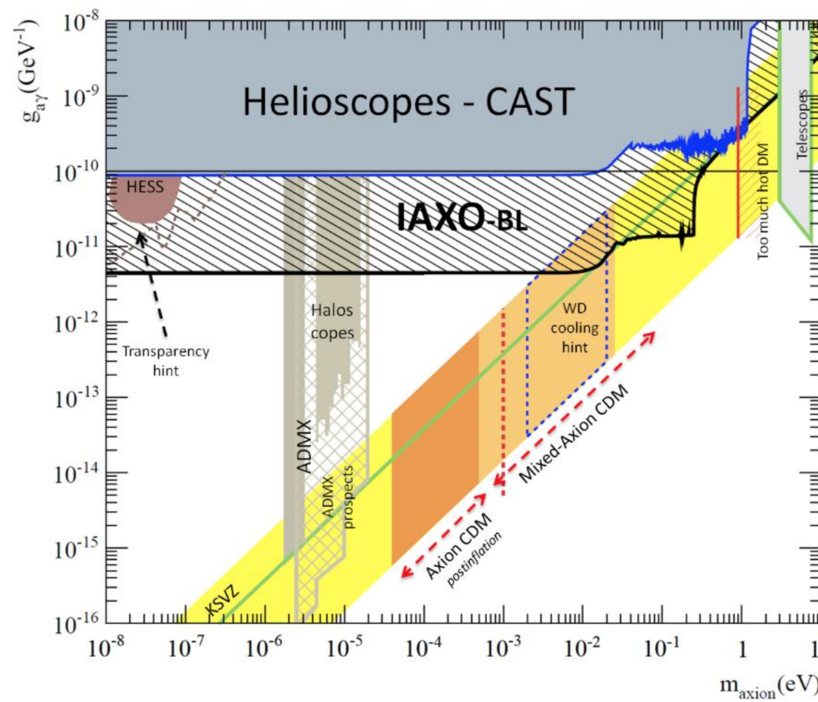
Starting ~ 2027?

Axion Search

New idea: IAXO

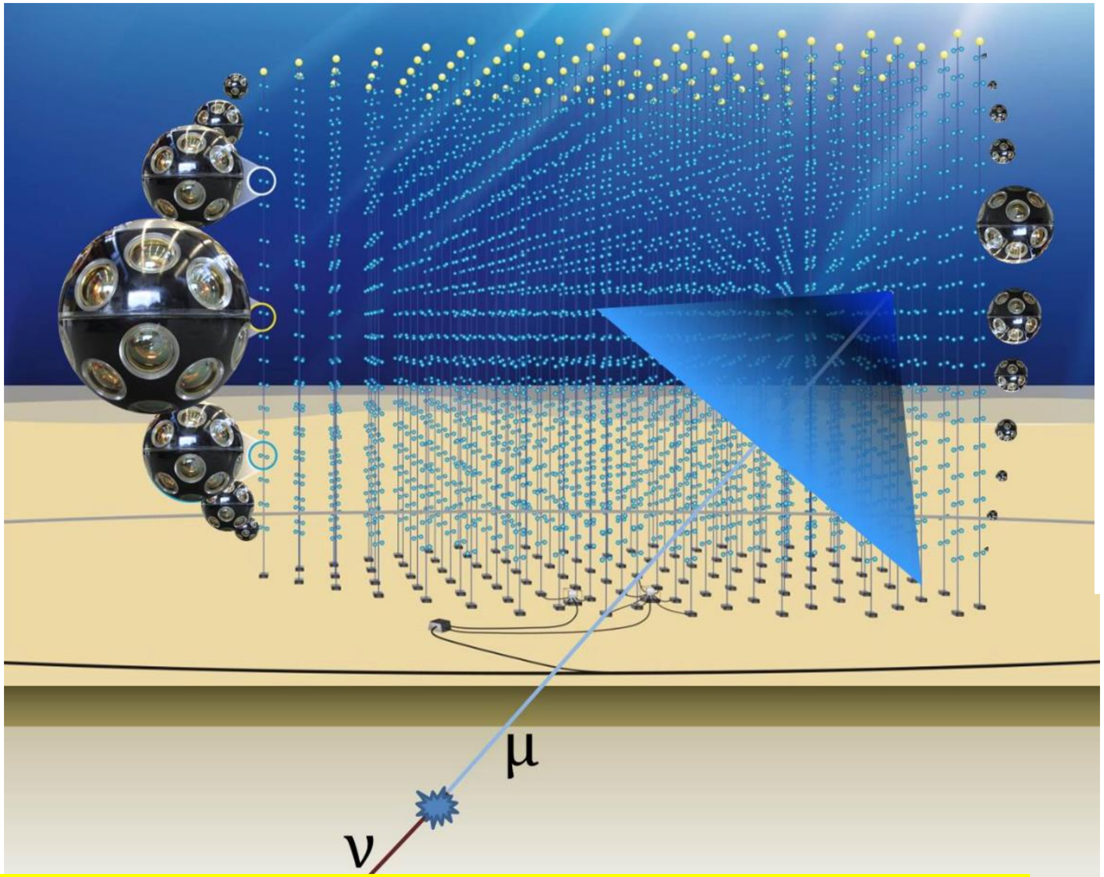
Next generation Axion Helioscope beyond CAST





Wish to profit from CERN magnet expertise (ATLAS-like large bore toroid)

KM3NET



KM3NeT is a large distributed research infrastructure that comprises a network of deep-sea neutrino telescopes in the Mediterranean Sea with user ports for Earth and Sea sciences. The main objectives of KM3NeT are the discovery and subsequent observation of high-energy neutrino sources in the Universe (ARCA) and the determination of the mass ordering of neutrinos (ORCA).

An array of thousands of optical sensors will detect the faint light in the deep sea that arises from charged particles originating from collisions of neutrinos and the Earth.

Wikipedia: 5 km3 distributed over the mediterranian
In Toulon, Sicily, Pylos

Club Med

1. Discovery and subsequent observation of high-energy neutrino sources in Universe
2. Measurement of neutrino mass hierarchy
3. Synergy with Earth & Sea sciences

First physics results in 2020?

Design

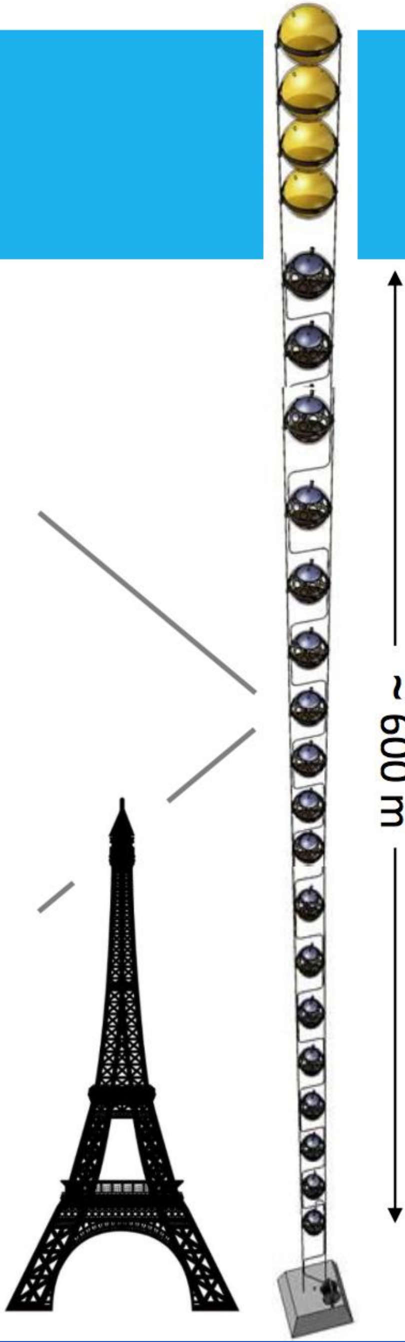
Launcher vehicle

- *rapid deployment*
- *autonomous unfurling*
- *recoverable*

Optical module

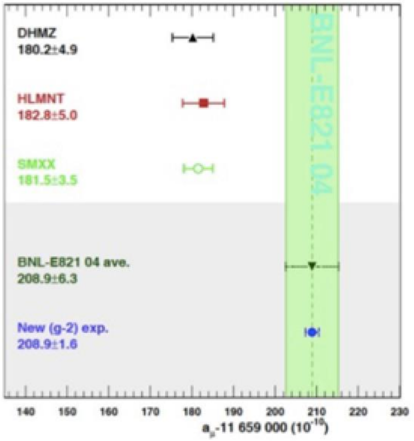
17”

- *31 x 3” PMTs*
- *low-power HV*
- *LED & piezo sensor*
- *FPGA readout*
- *White Rabbit*
- *DWDM*

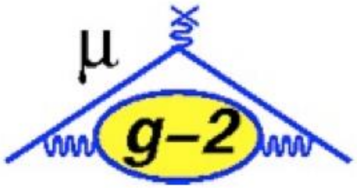


Other Experiments: Examples

- A new g-2 measurement experiment at FNAL
- Solve the 3σ discrepancy seen by the BNL exp.
- Starting taking data soon; in progress



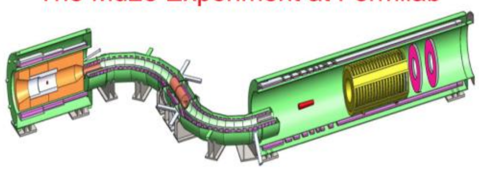
Intensity frontier!



- An improved μ-> e measurement experiment at FNAL
  neutrinoless muon-to-electron conversion lepton-flavor violation) process

- Discover μ to e conversion or set limit
  - $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL.
  - 10,000 × better than previous best limit.
  - Mass scales to O(10,000 TeV) are within reach.

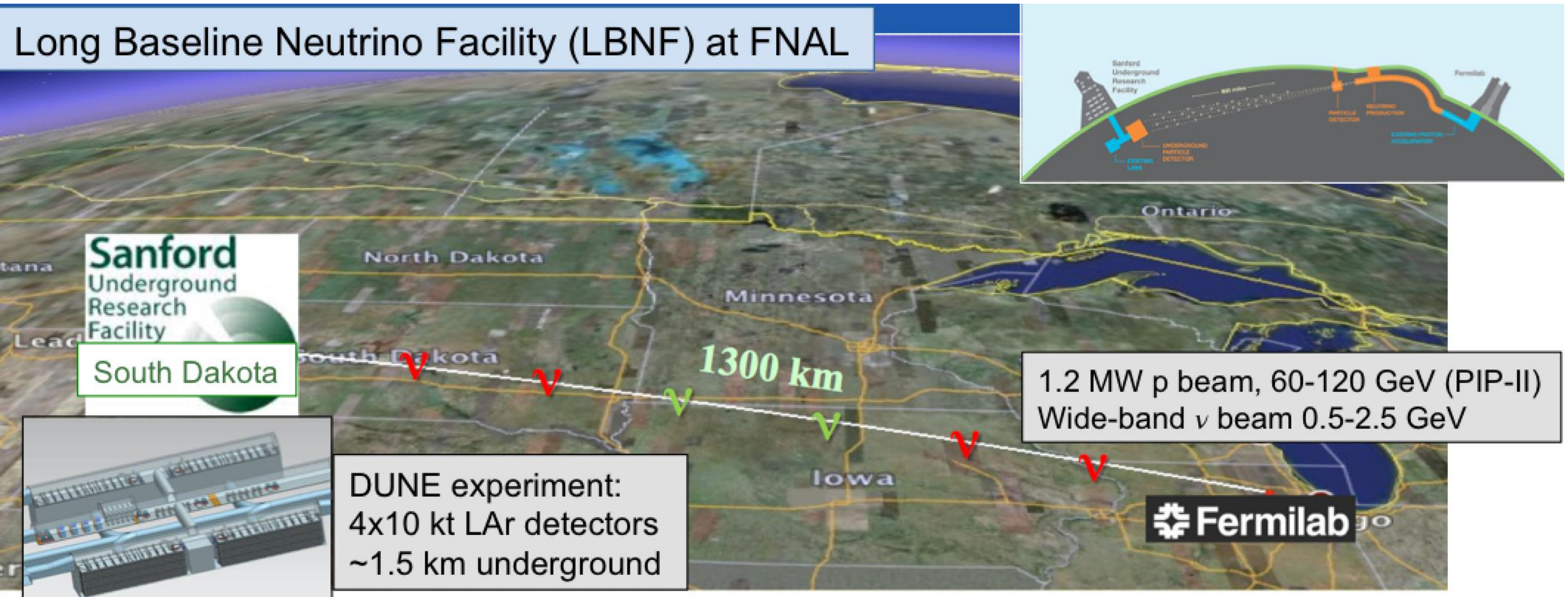
The Mu2e Experiment at Fermilab



- begin construction in 2015. Start taking data in 2019, first results in 2020

Neutrino Program in the US/Japan

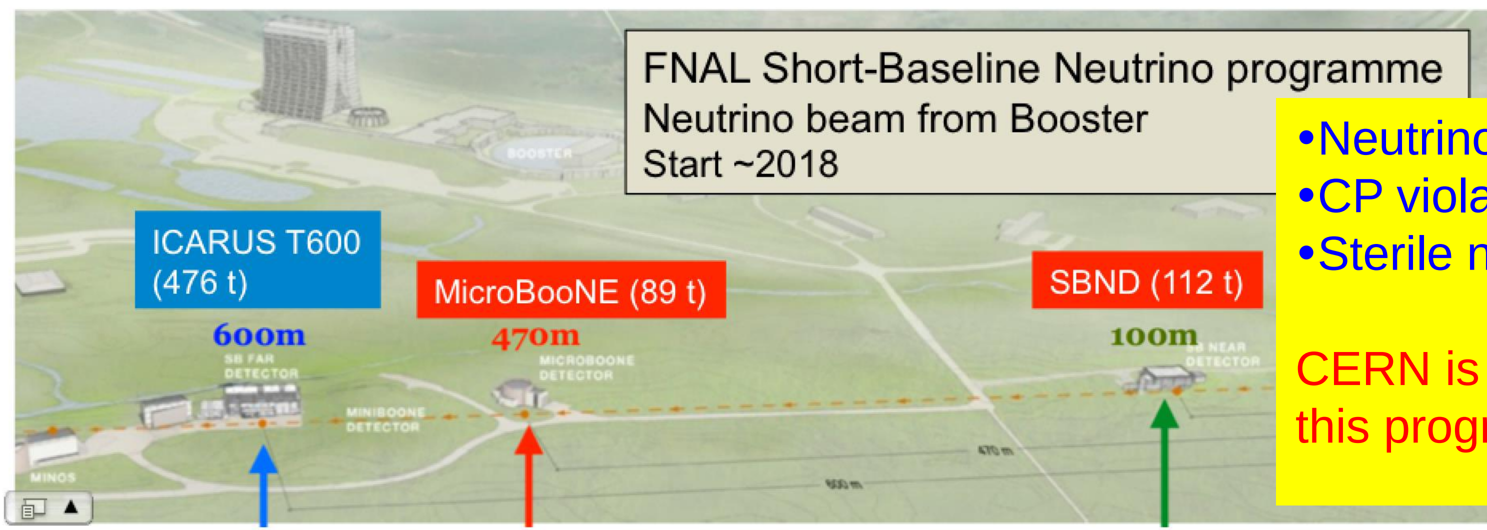
Long Baseline Neutrino Facility (LBNF) at FNAL



1.2 MW p beam, 60-120 GeV (PIP-II)
Wide-band ν beam 0.5-2.5 GeV

DUNE experiment:
4x10 kt LAr detectors
~1.5 km underground

Far site construction starts ~2017, 1st detector installed ~2022, beam from FNAL ~ 2026



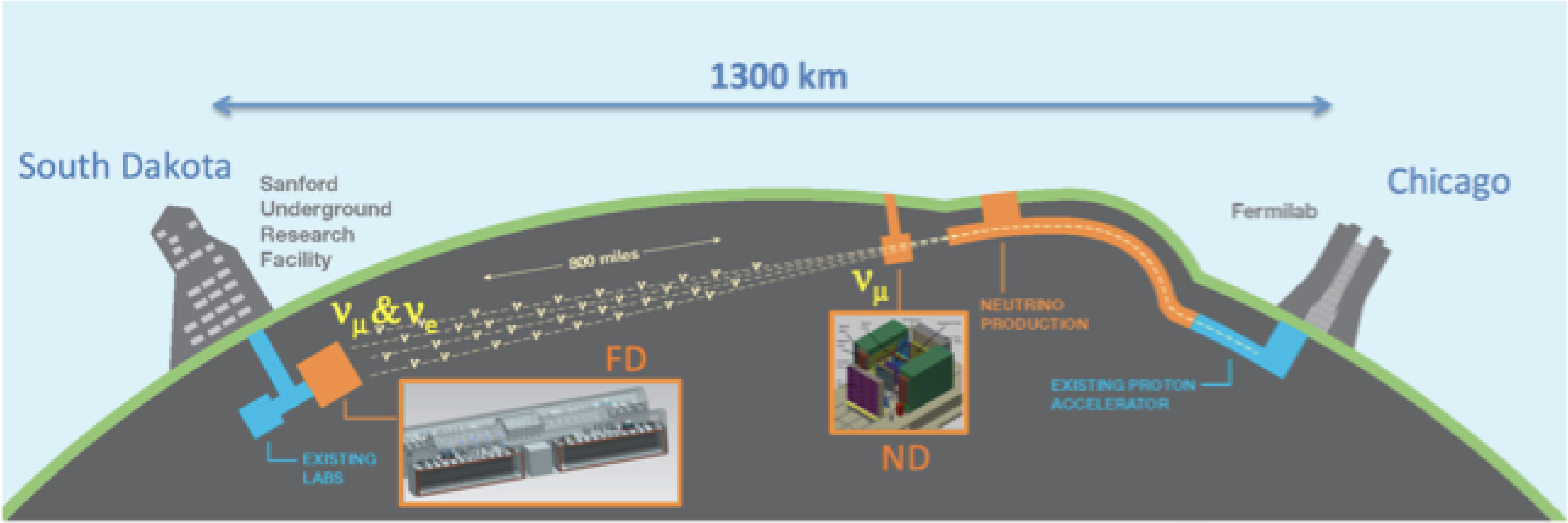
FNAL Short-Baseline Neutrino programme
Neutrino beam from Booster
Start ~2018

- Neutrino mass hierarchy
- CP violation?
- Sterile neutrinos?

CERN is participating in this program

LBNF/ DUNE Overview

- Muon neutrinos/antineutrinos from high-power proton beam
  - **1.2 MW** from day one; upgradeable to 2.4 MW
- Massive underground Liquid Argon Time Projection Chambers
  - **4 x 17 kton** fiducial mass of > 40 kton
- Near detector to characterize the beam (100s of millions of neutrino interactions)



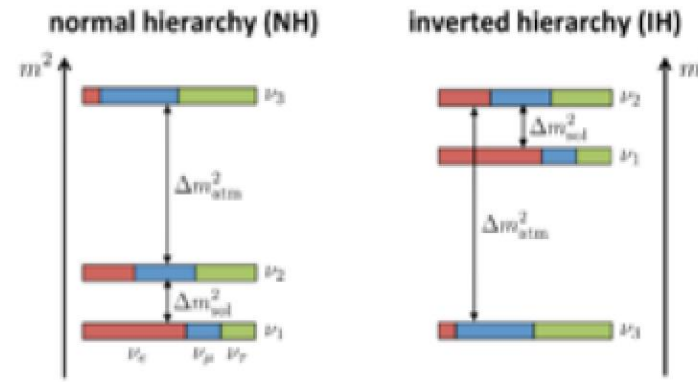
The DUNE Science Program

- Neutrino Oscillation Physics
  - **Search for leptonic (neutrino) CP Violation**
  - Resolve the mass hierarchy ($m_3 > m_{1,2}$ or $m_{1,2} > m_3$)
  - Precision oscillation physics
    - Parameter measurements, θ_{23} octant
    - **Testing the current 3-neutrino model, non-standard interactions, …**
- Nucleon Decay
  - Particularly sensitive to $p \rightarrow K^+ \overline{\nu}$
- Supernova burst physics and astrophysics
  - 3000 ν_e events in 10 sec from SN at 10 kpc

+ many other topics (ν interaction physics with near detector, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.)

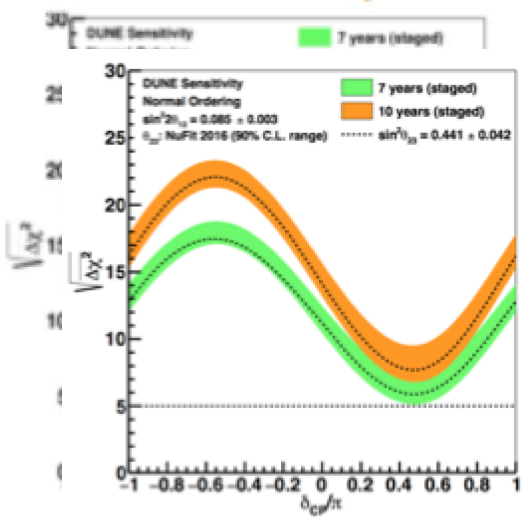
Neutrino Oscillation Physics and More…

Short- and long-baseline oscillation experiments probe several of the essential questions

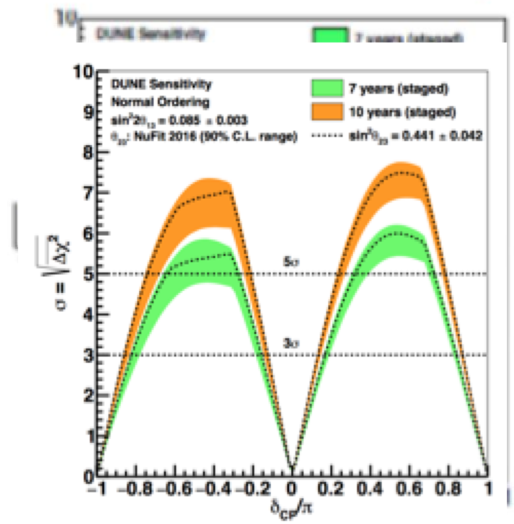


- How are the neutrinos masses ordered?
- Do neutrinos and antineutrinos oscillate differently?
- Are there additional neutrino types & interactions?

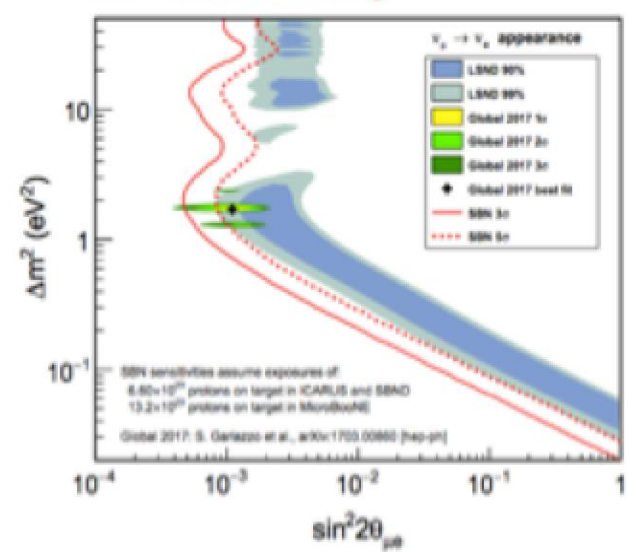
DUNE Mass Hierarchy Sensitivity



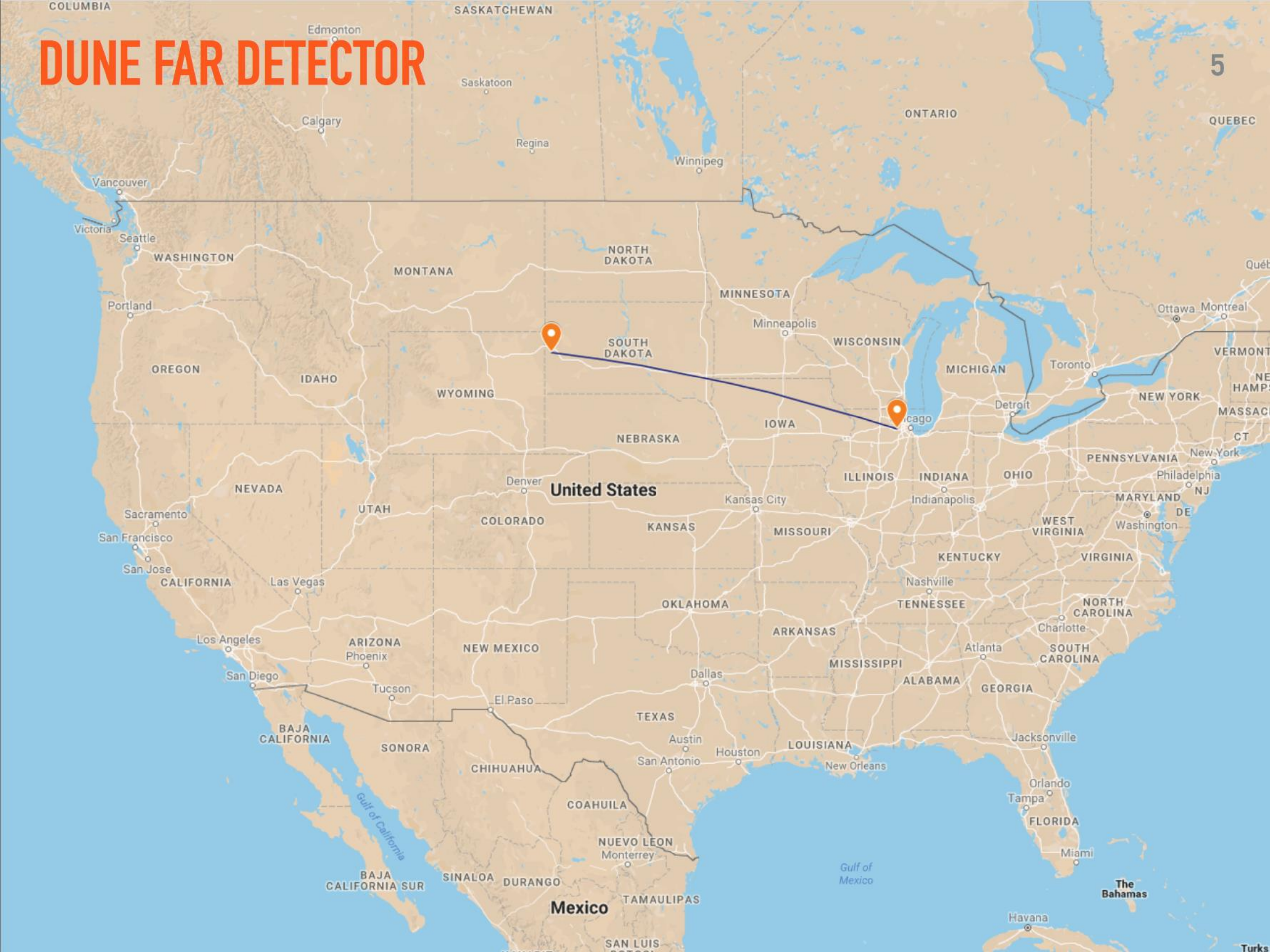
CP Violation Sensitivity



SBN Sensitivity



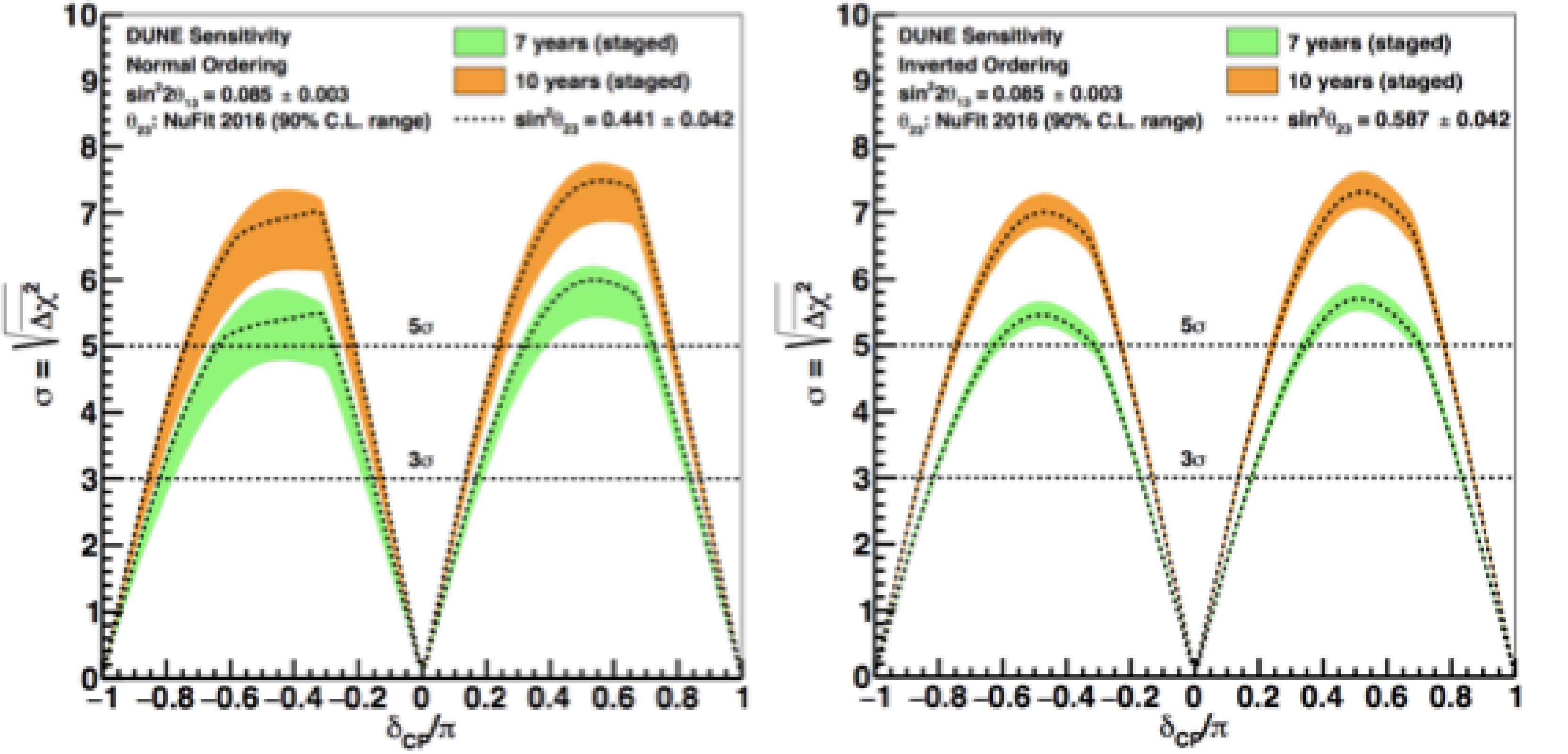
DUNE FAR DETECTOR



DUNE FAR DETECTOR

DUNE FAR DETECTOR

Sensitivity to CP violation



- Width of the bands represents the range of sensitivities for the 90% CL region in the θ_{23} values range.
- Sensitivity increases with increasing θ_{23}

LBNF/ DUNE Far Site

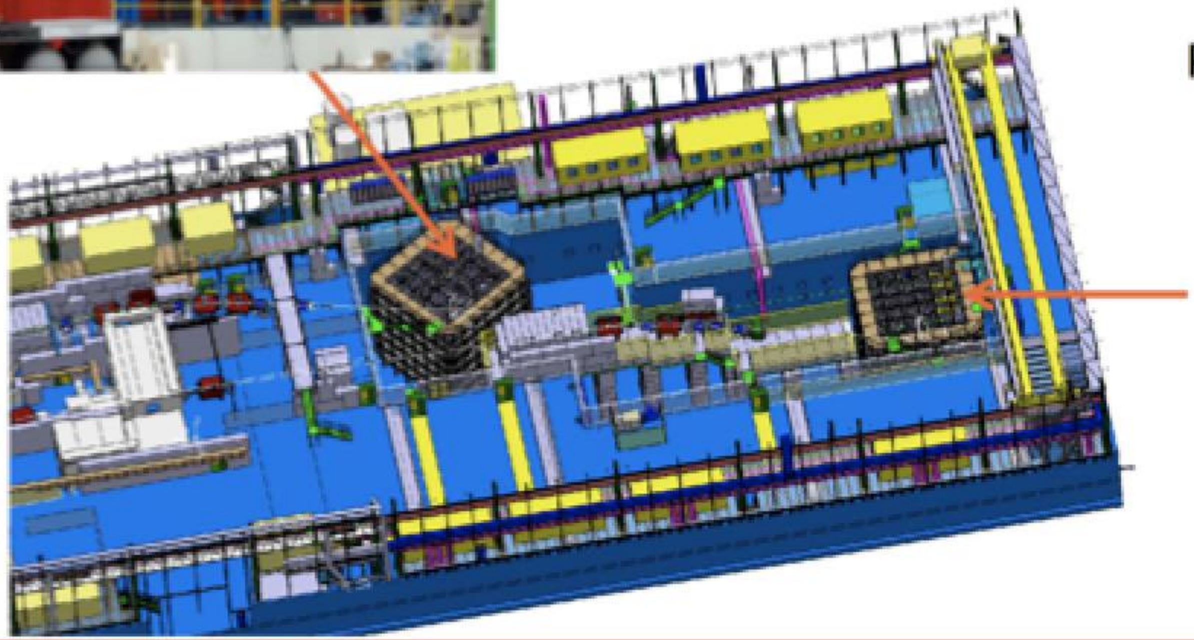
2017: start excavation at the far site (Sanford Underground Research Facility SURF)

Prototypes at CERN Neutrino Platform

ProtoDUNE Dual Phase

Both ProtoDUNEs aim to begin data taking in mid 2018.

EHN1 Webcams:
http://cenf-ehn1-np.web.cern.ch/images/np04-webcam-neutrino-platform-hall-ehn1



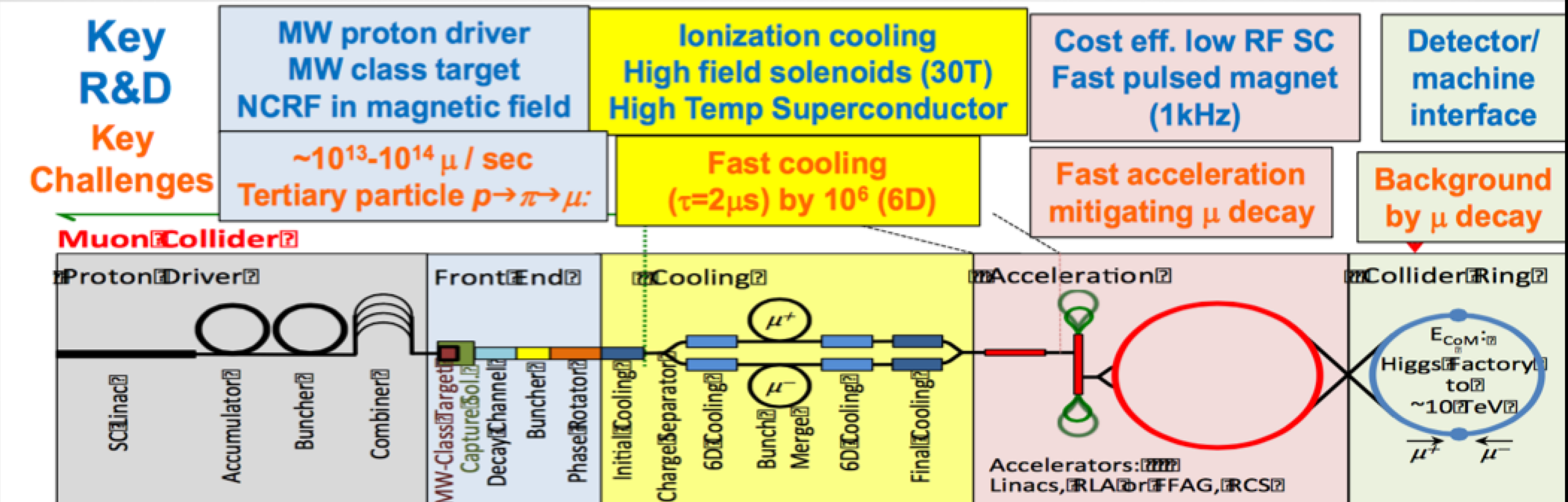
ProtoDUNE Single Phase

A Muon Collider?

Limit of proton machines: Strength of dipole magnets
massive proton needs strong field to keep it in the ring
Limit of electron machines: Synchrotron radiation
light electron radiates when bent by ring magnets

What about muons? More compact machine than pp, less energy loss per turn
Small problem: Muons are not stable particles!!

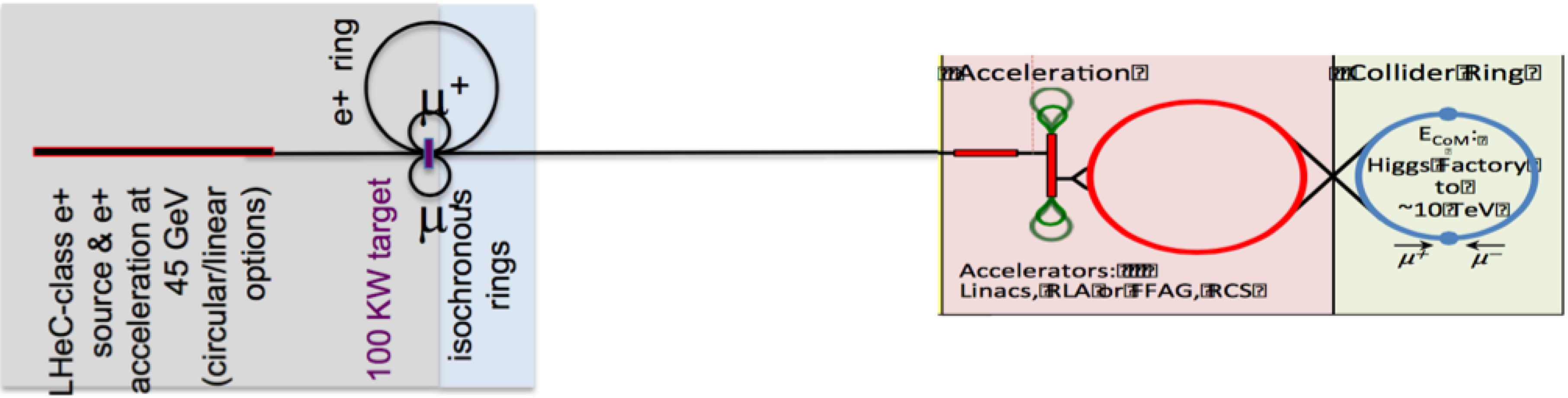
Muon Collider: Traditional Design



- Muons as tertiary from high intensity proton beam on target
  - Issue with target to sustain required intensity
- Large momentum transverse to the beam direction => huge emittance => need cooling
  - Major issue to be solved

New Idea

Don't use a proton beam but create muon pair "at rest" in e+e-



- Asymmetric $e^+e^- \rightarrow \mu^+\mu^-$ with $\sqrt{s}$ at threshold
- Muons at rest in CoM frame, boosted by large (p_{e+}- p_{e-}) => automatically getting low emittance

e+e- Driven Muon Collider

Pros:

- Low emittance: can be very small close to the μ+μ- threshold ($2xm_{\mu}$ ~0.21 GeV)
- Low background: smaller number of muons → reduced background/radiation from decay products
- More time to accelerate: large boost from asymmetric e^+e^- collisions
- Energy spread: muon energy spread also small at threshold gets (further reduced with shorter bunches)

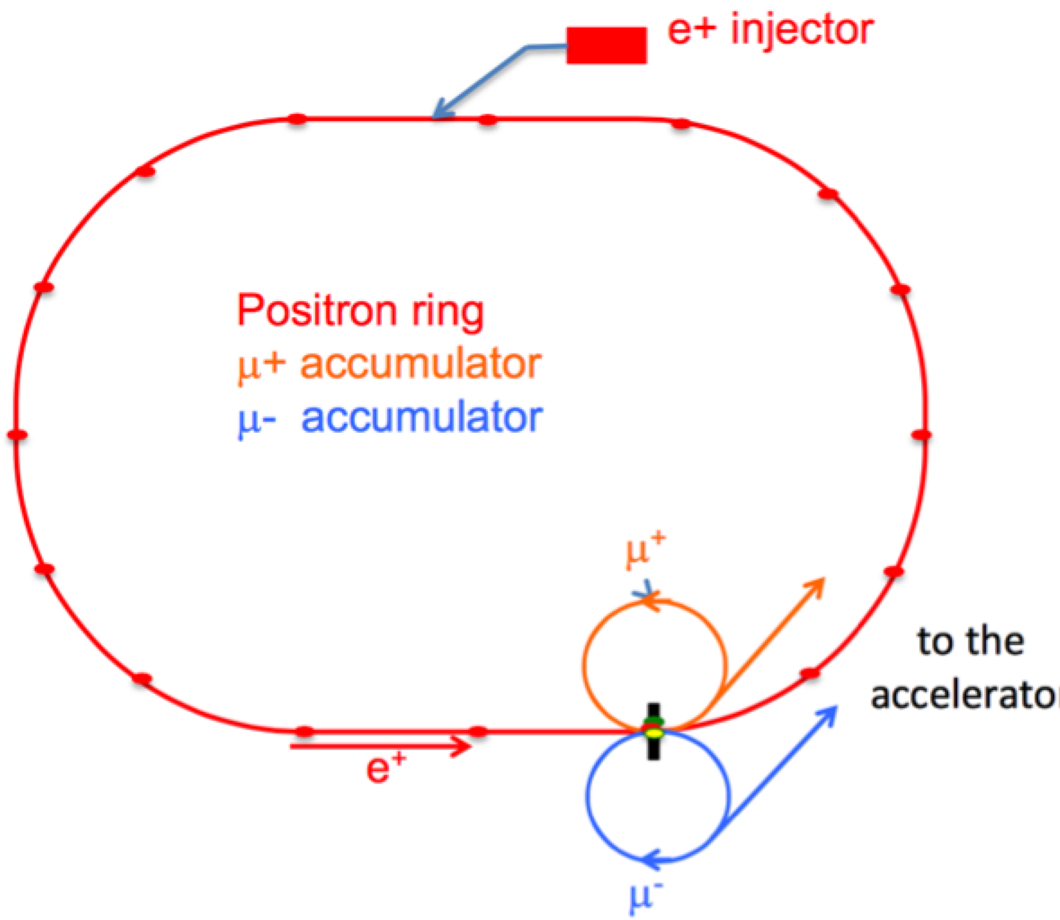
Cons:

- Rate: much smaller cross section wrt protons: $\sigma(e^+e \rightarrow \mu^+\mu^-)$ ~ 1 μb at most:
  - Need $L=10^{40}$ cm^{-2} s^{-1} for 10^{10} Hz μ rate..

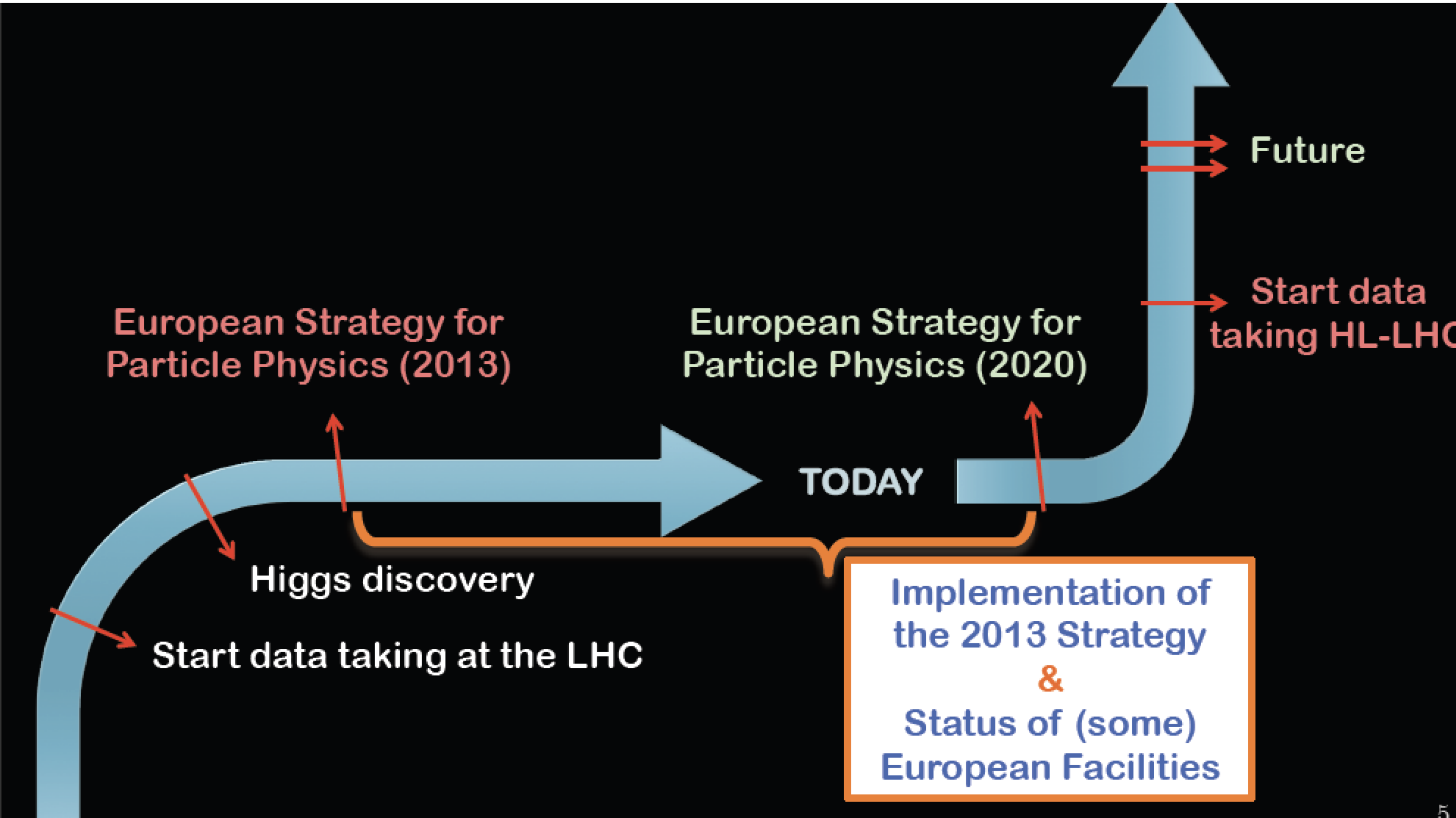
Use a fixed target with an 45 GeV e+ beam

Layout for muon source

	LEMMA*
e+ bunch spacing	200 ns
e+/bunch	$3 \cdot 10^{11}$
Beam current	240 mA
Rate e+ on target	$1.5 \cdot 10^{18}$ e^+/s



European Strategy Upgradse



Particle Physics at the eve of a European Strategy Update

- The timing of the Strategy Update is dictated by physics considerations, for the coming Update this are mainly the results of the experiments at the LHC Run2.
- Other key considerations will be the ongoing design studies and updated plans for future colliders (ILC, CLIC, FCC), exploration of opportunities for non-collider projects at CERN and elsewhere, and R&D work on accelerator technologies.
- The results from other running experiments and facilities and the status of the various neutrino physics projects across the world will be further important factors.
- By the end of 2018, significant input from all the above activities should be available.
- Taking into account inputs from scientists and institutions worldwide is essential to deliver a proper Update of the European Strategy for Particle Physics.

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Summary

- Accelerators are used worldwide for many applications. A small fraction of that is used in particle physics
- The Large Hadron Collider is a technologically challenging machine. It is the highest energy collider in the world for a long time to come.
- The LHC now produces collisions at 13 TeV, and will deliver a luminosity of ~ 100 fb^{-1} by 2018.
- New accelerator projects are being studied. Which one will be stated in the next 10 years?
- New accelerator techniques are being studies as well, in order to reach higher energies with smaller machines. The future for >2050?
- Accelerators is not enough: now we need experiments!