The European Strategy Update Priorities for Future Facilities

Albert De Roeck
CERN
16 January 2019

Introduction

The European Strategy for Particle Physics (ESPP) is the process by which every ~ 7 years the European particle physics community updates the priorities and strategy of the field.
It also makes recommendations on related activities: education, communications and outreach, technology transfer, organisational aspects, etc.

First ESPP in 2006; first update in 2013; next update 2020.

Bottom-up process involving the community. Driven by physics*, with awareness of financial and technical feasibility.

ESPP produces the European roadmap in the worldwide context of the field.
Note: particle physics requires global coordination, given the number, size and complexity of the projects → "alignment" of the European, US and Japanese roadmaps in recent years to optimise the use of resources

The Strategy is adopted by the CERN Council.
Individual (major) projects require dedicated approval: e.g. HL-LHC

* The scientific input includes: physics results from current facilities from all over the world; physics motivations, design studies and technical feasibility of future projects; results of R&D work, etc.

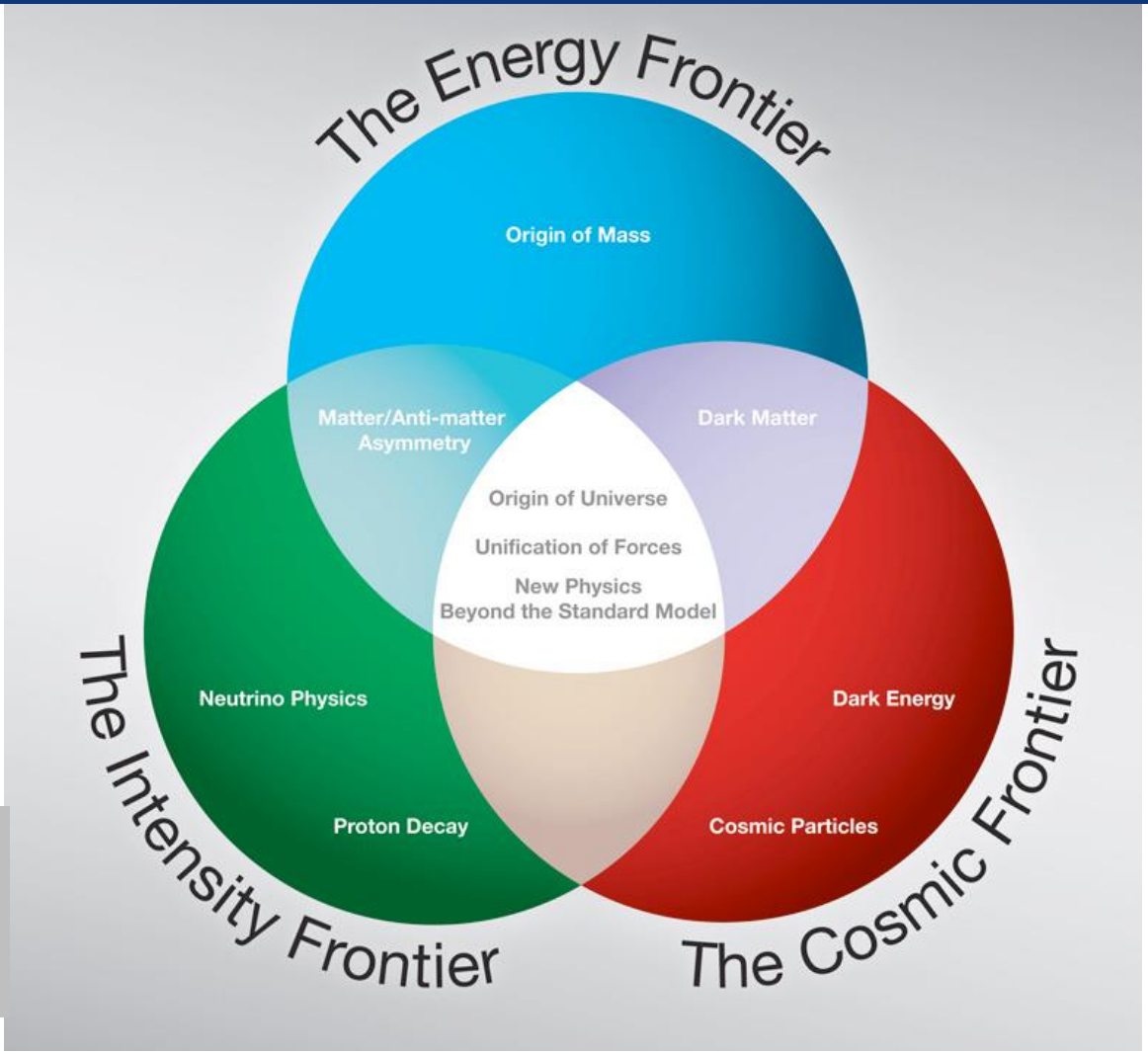
Future HEP: The Three Frontiers

After the Higgs discovery

Previous Strategy Update: 2012-2013

Evaluation in all regions: Europe Asia, the Americas

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



Examples of recommendations from 2013 ESPP

The success of the LHC is proof of effectiveness of the European organisational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN. *Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.*

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.

→ HL-LHC approved by Council 2016

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 …

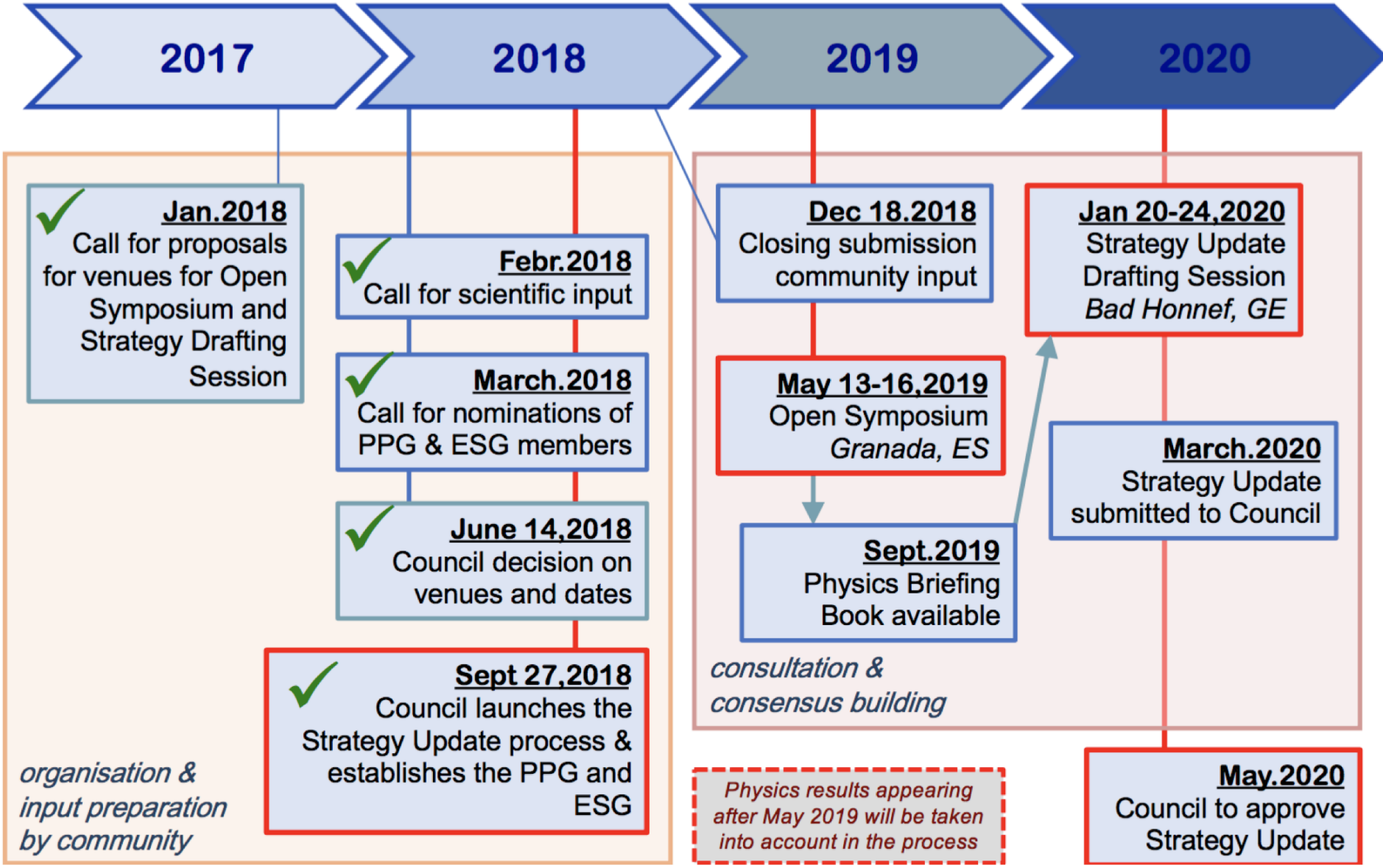
→ Continuation of CLIC, FCC started 2014

CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

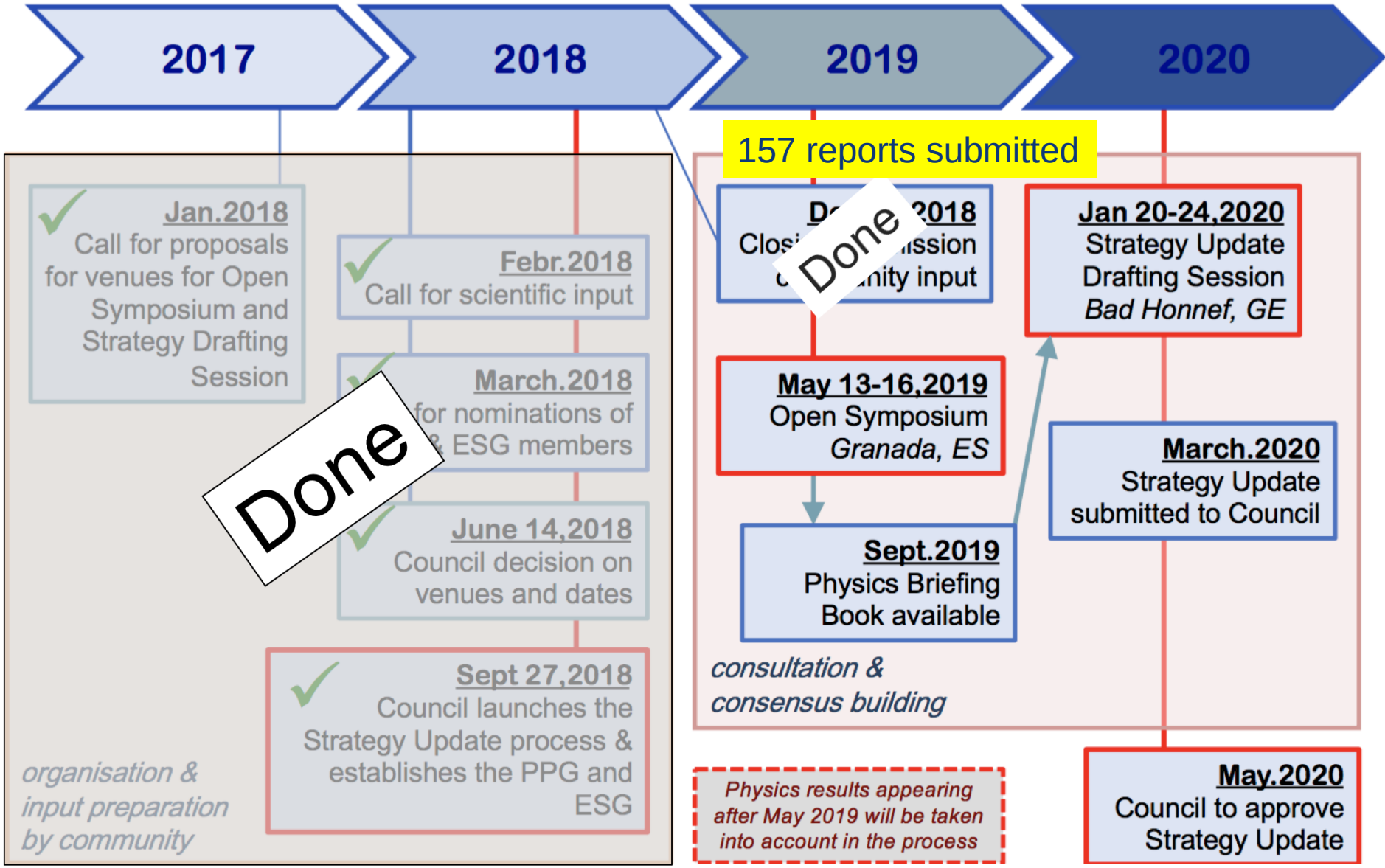
→ Neutrino Platform started 2014

CERN, together with national funding agencies, institutes, laboratories and universities, should continue supporting and further develop coordinated programmes of education and training.

2020 ESPP update: timeline and committees



2020 ESPP update: timeline and committees



2020 ESPP update: timeline and committees

- **Strategy Secretariat**
  Organizes the ESPP process
  H. Abramowicz (Chair; also chair of PPG and ESG), J. D'Hondt (ECFA Chair), K. Ellis (SPC Chair), L. Rivkin (Chair of LDG=Laboratory Directors Group)

- **Physics Preparatory Group (PPG)**
  Collects community's input, organises Open Symposium, prepares briefing book
  Strategy Secretariat
  4 members appointed by Council on recommendation of SPC
  4 members appointed by Council on recommendation of ECFA
  1 CERN representative
  2 representatives from Asia and 2 from Americas (appointed by respective ICFA representatives)

- **European Strategy Group (ESG)**
  Drafts the final strategy document
  Strategy Secretariat, 1 representative per CERN Member State, LDG, CERN DG,
  Invited: Council President, 1 representative per Associate Member State and Observer State, PPG, EC representative, JINR/Dubna representative, Chairs of ApPEC, NuPECC, FALC, ESFRI

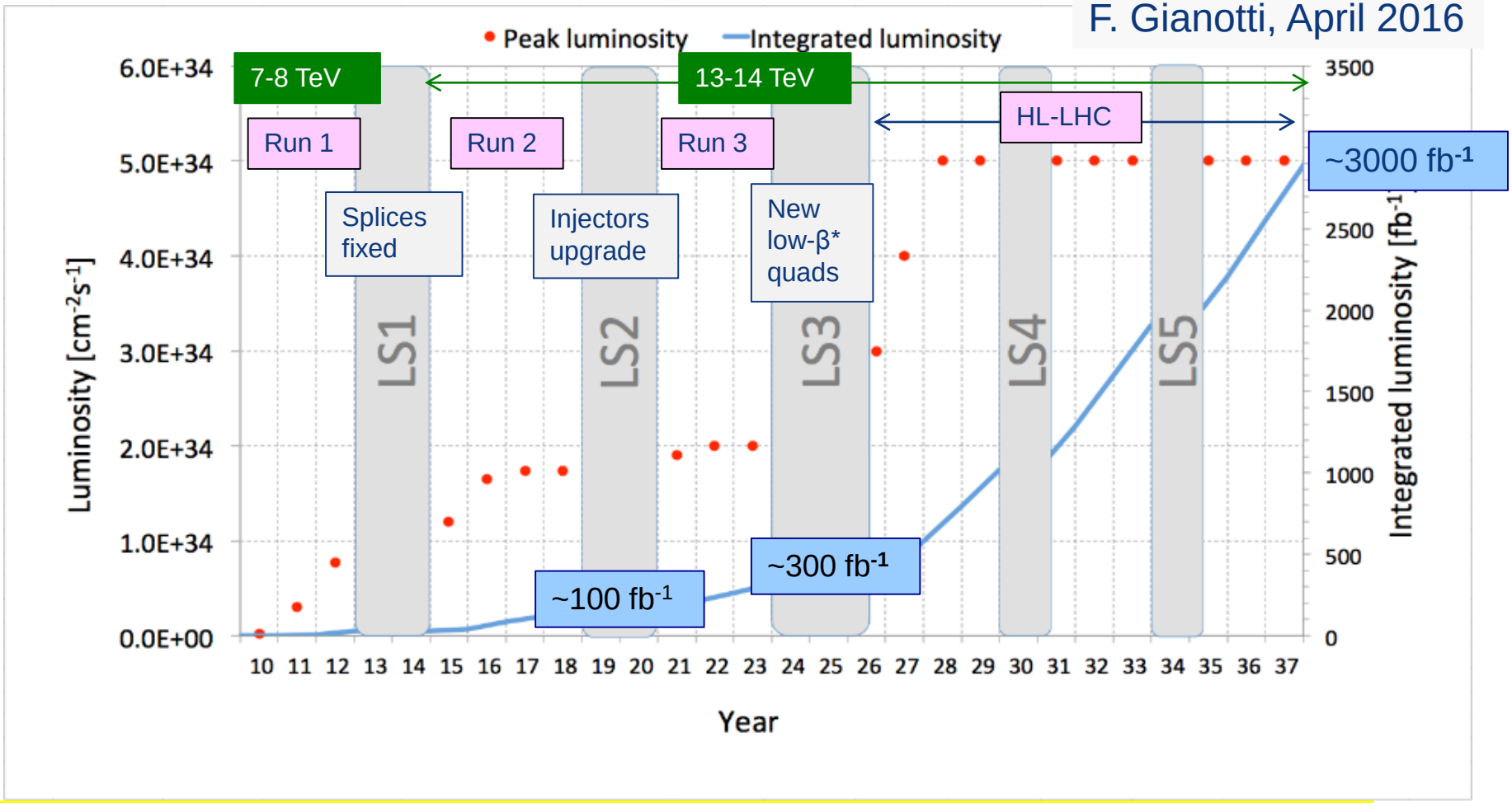
For more information see:
https://indico.cern.ch/event/754792/contributions/3127781/attachments/1715899/2768187/spc-e-1115-c-e-3389_ESPP-update-composition_of_PPG_and_ESG.pdf

Focus on large facilities

The LHC Upgrade

The Approved LHC Roadmap

F. Gianotti, April 2016

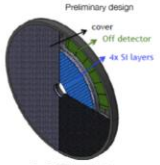


Approved program at CERN to collect 3-4 ab^{-1} with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (eg Higgs)

ATLAS PHASE 2 UPGRADE

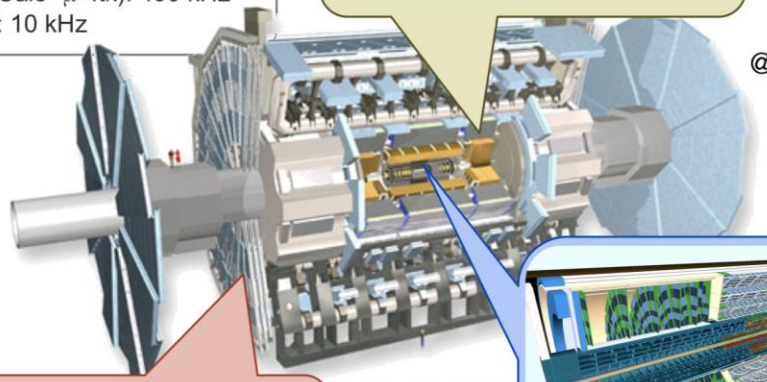
Trigger and DAQ
- L0 (Calo+μ): 1 MHz
- L1 (Calo+μ+Itk): 400 kHz
- HLT: 10 kHz

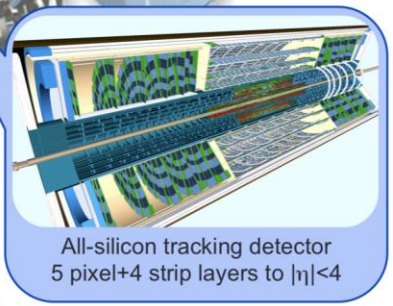
Calorimeters
- New readout electronics compatible with L0 1 MHz rate
- High granularity timing detector (under discussion)



HGTD

@z~3500mm





All-silicon tracking detector
5 pixel+4 strip layers to |η|<4

Muon systems
- New readout and trigger electronics
- Additional chambers for inner barrel layer improves acceptance
- Muon tagger for 2.7<|η|<4.0

INFN PADOVA

8

Experiments need upgrades for the HL-LHC as well

Upgrade program under way

CMS PHASE 2 UPGRADE

MUON SYSTEMS
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in 1.5<|η|<2.4
- Muon-tagging in 2.4|η|<3.0

BARREL CALORIMETERS
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

ENDCAP CALORIMETERS
- high granularity calorimeter
- Radiation tolerant scintillator
- 3D capability and timing

TRACKER
- radiation tolerant, high granularity, low material budget
- coverage up to |η|=3.8
- track trigger at l1

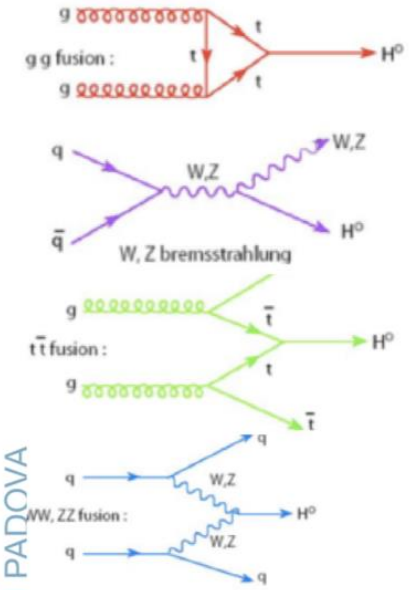
TRIGGER & DAQ
- Track-trigger @L1
- L1 rate ~750kHz
- HLT output ~7.5kHz

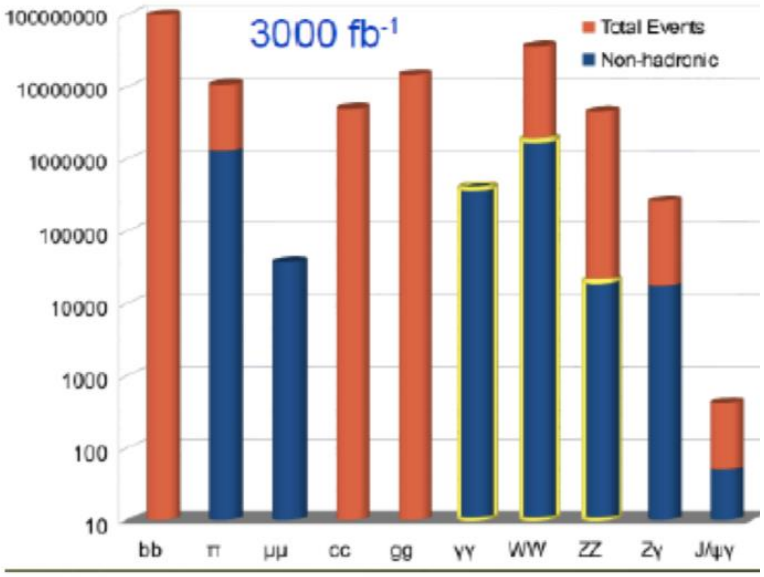
PADOVA

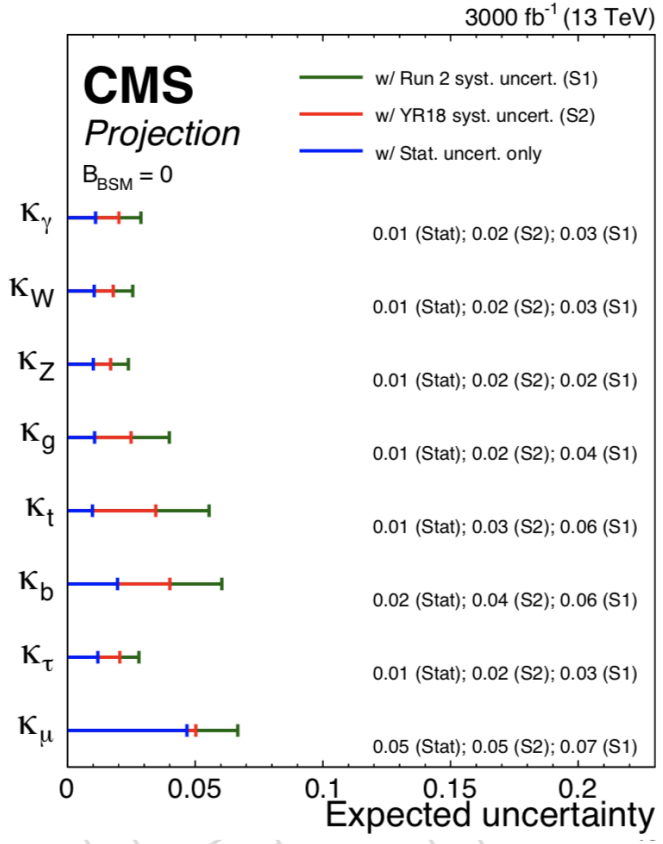
INFN

HL-LHC IS A HIGGS FACTORY

- At HL-LHC, we expect to produce ~170M Higgs Bosons, including ~120k of pair produced events
- Over 1Million for each of the main production mechanisms, spread over many decay modes





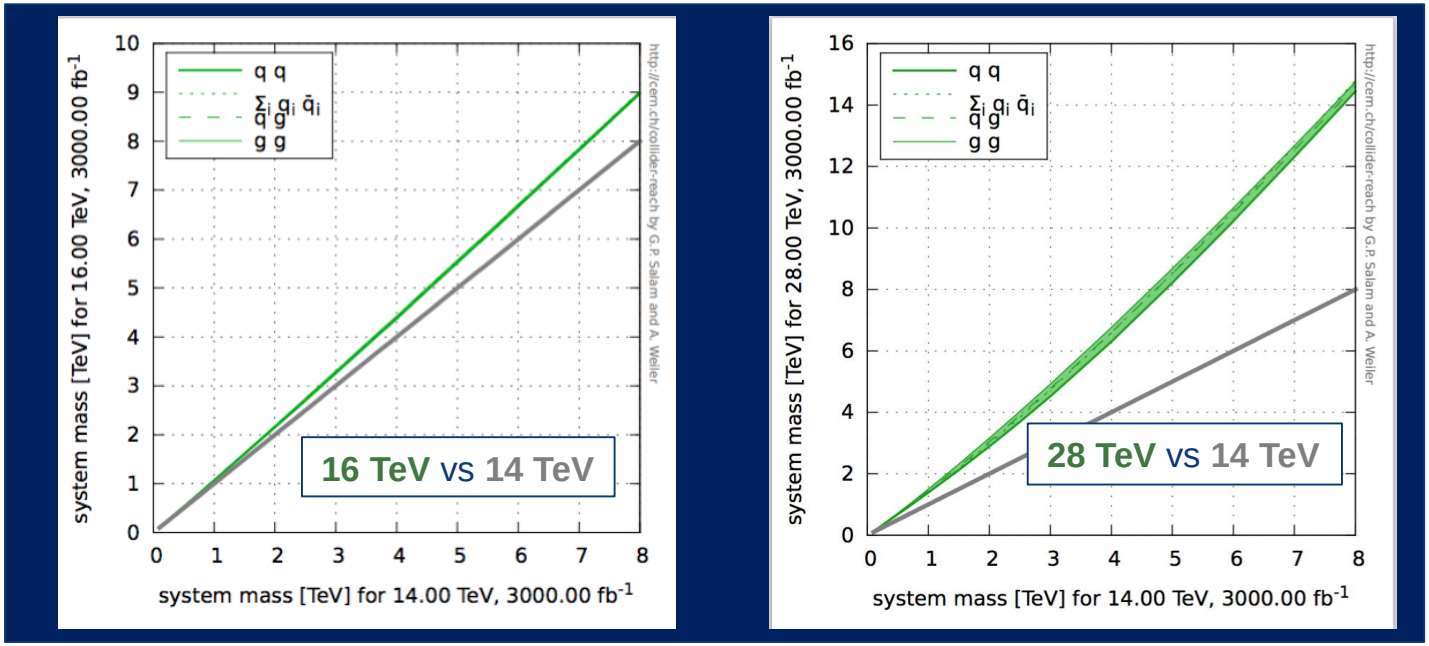


- Enables a broad program:
  - Precision O(few%) measurements of couplings acros
  - Exploration of Higgs potential (hh production)
  - Sensitivity to rare decays involving new physics
  - extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)

Higher Energy LHC??

F. Gianotti
FCC meeting
April 2016

HE-LHC part of the FCC study



WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV (8.3T magnet fields)
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

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ √s~ 27 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

CERN

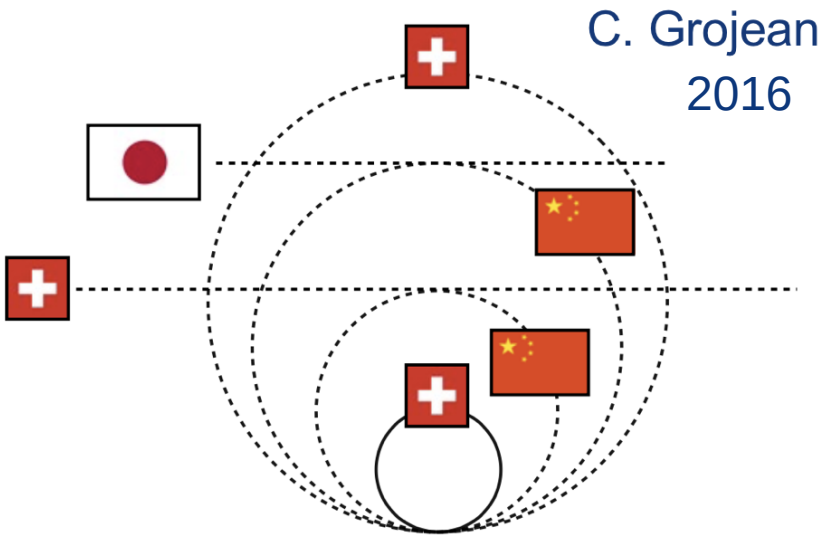
Beyond the LHC

- Proton-proton machines at higher energy…
- Electron-positron machines for high precision…
- Both? And allowing for electron-proton collisions..?

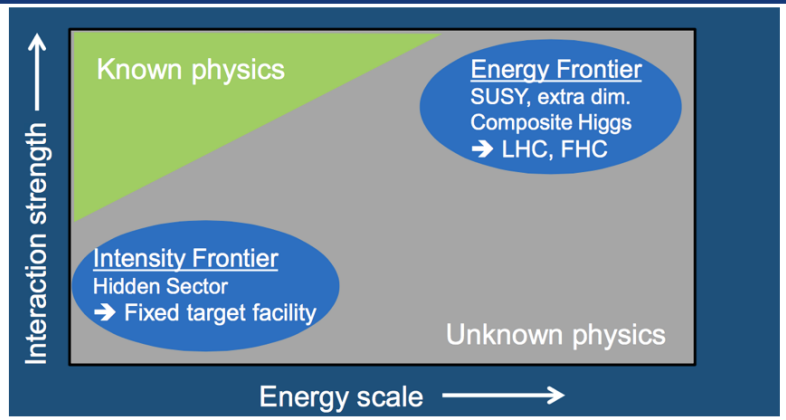
New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

Based on the PECFA meeting @CERN November 2018

Future Colliders



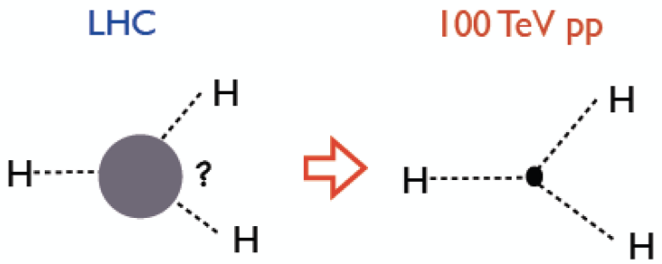
Theorist view on future colliders



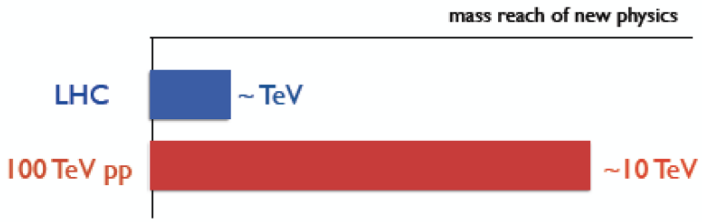
FCC-hh: THE machine for direct search at the higher energy scale.

Hadron colliders main themes:

The study of the Higgs Boson(s)



The search for massive new physics



Precision measurements

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

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** ≥16 T magnets
  ≥100 TeV pp-collider (FCC-hh)

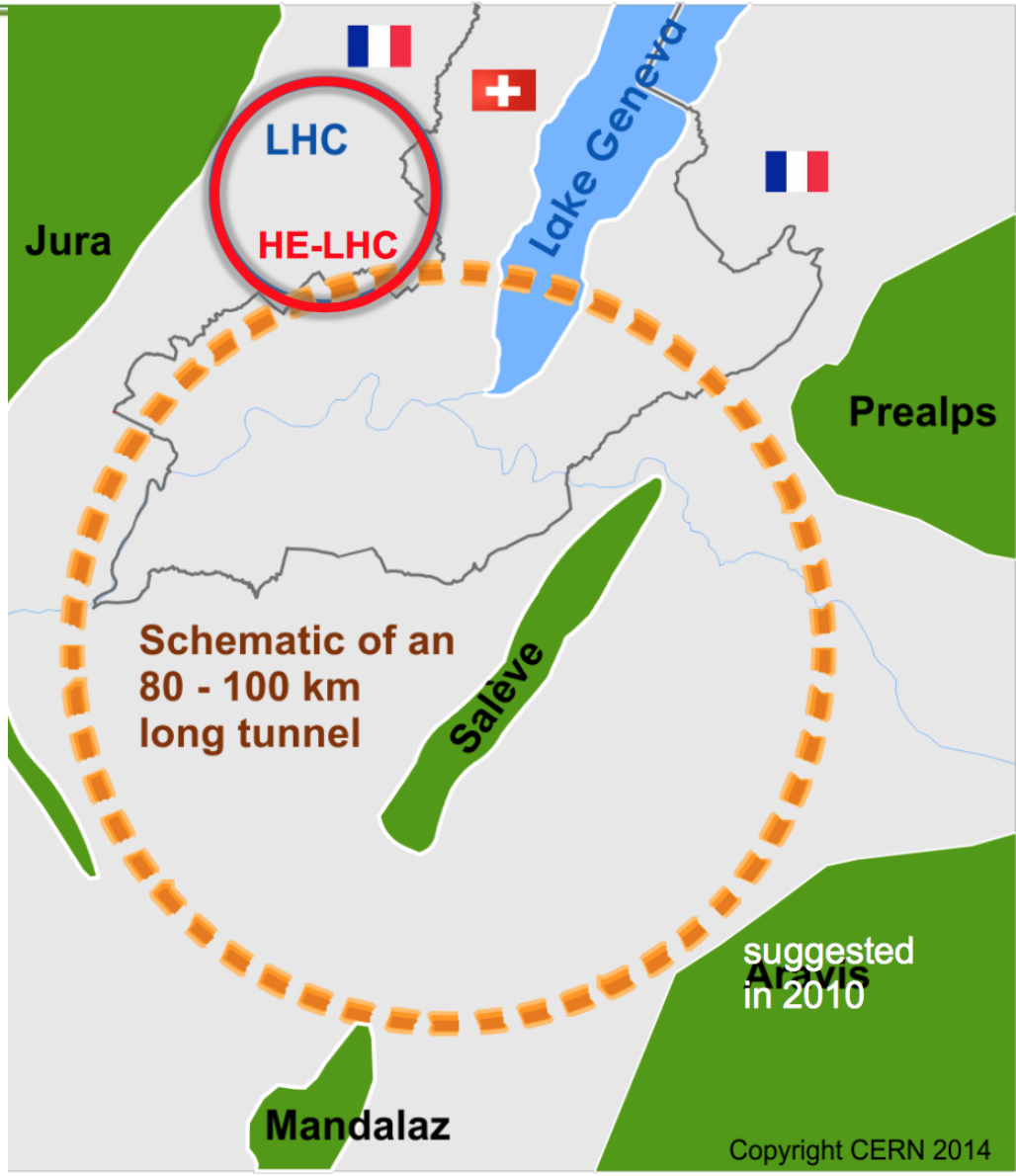
→ defining infrastructure requirements

Two possible first steps:

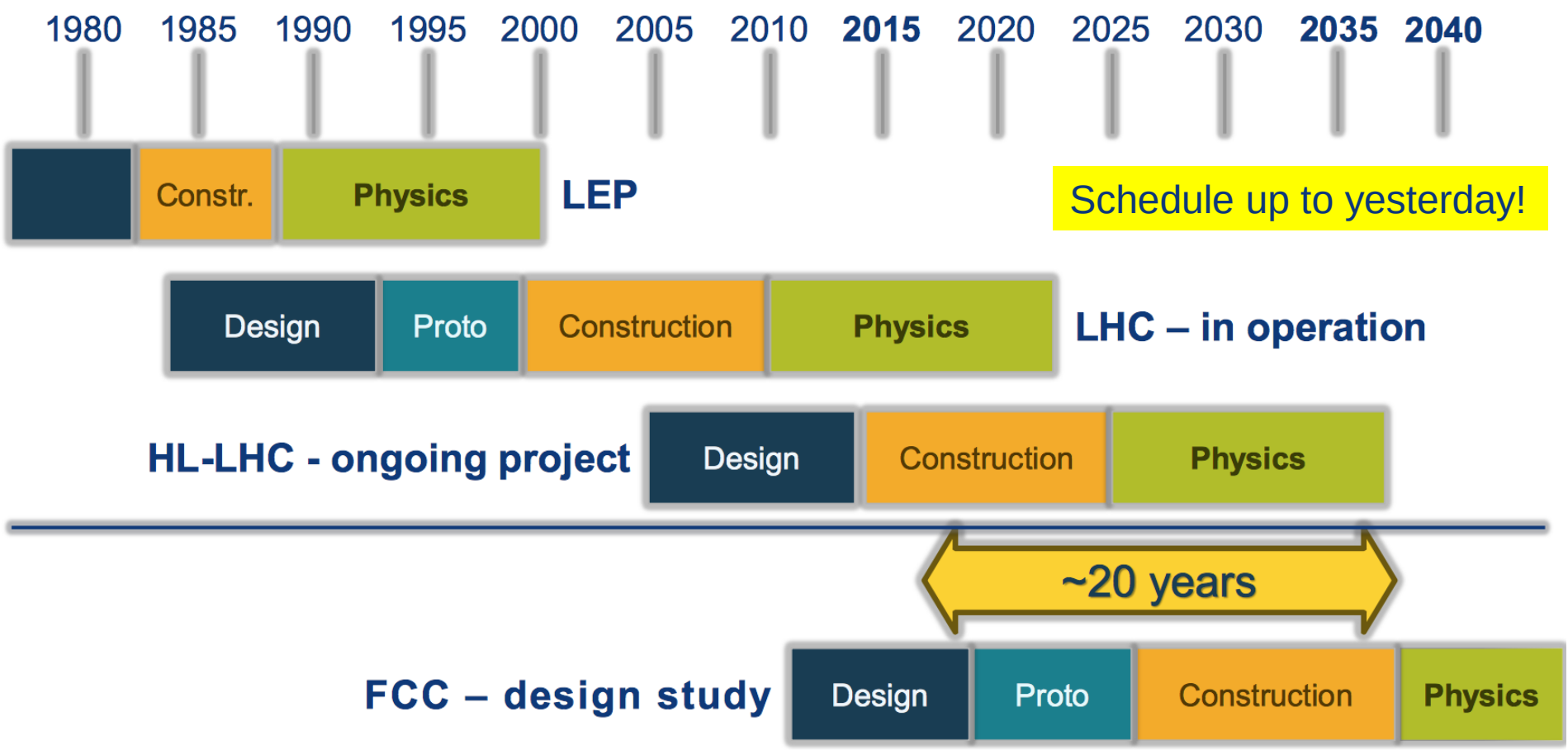
- e^+e^- collider (***FCC-ee***)
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC*** 16T ⇒ 27 TeV
  in LEP/LHC tunnel

Possible addition:

- *p-e* (***FCC-he***) option



CERN Circular Colliders & FCC



schedule constrained by 16 T magnets & CE

→ **earliest possible physics starting dates**

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 /**

CERN Circular Colliders & FCC

International collaboration publishes concept design for a post-LHC future circular collider at CERN

Date Issued
January 15th, 2019

Source
CERN

The proposed layout of the future circular collider (Image: CERN)

Geneva, 15 January 2019. Today, the Future Circular Collider (FCC) collaboration submitted its Conceptual Design Report (CDR) for publication, a four-volume document that presents the different options for a large circular collider of the future. It showcases the great physics opportunities offered by machines of unprecedented energy and intensity and describes the technical challenges, cost and schedule for realisation.

Breaking News: 15/01/2019 (press release)

Yesterday the Conceptual Design Reports have been released with an updated time schedule and approx. cost estimate

Tunnel:	5000 MCHF
e+e- machine in tunnel:	4000 MCHF
hh machine in tunnel:	15000 MCHF
Possible e+e- starting date	~ 2040
Possible hh starting date	~ late 2050's

e+e- Colliders

- Circular colliders
  FCC-ee (CERN), CEPC China)

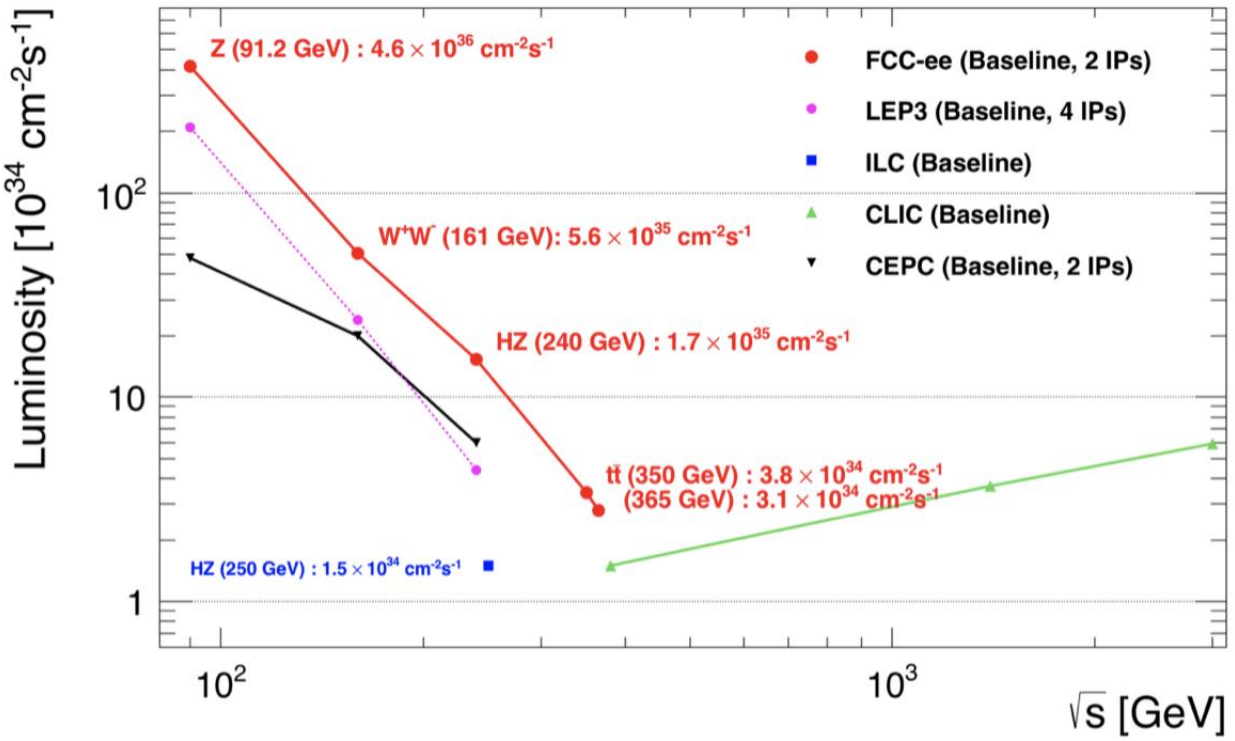
- Linear Colliders
  ILC (Japan?), CLIC (CERN)

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee

Z WW HZ tt



Event statistics

- **Z peak**
- **WW threshold**
- **ZH threshold**
- **$t\bar{t}$ threshold**

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

E_{CM} errors:

- 100 keV
- 300 keV
- 1 MeV
- 2 MeV

Great energy range for the heavy particles of the Standard Model.

s://cosmosmagazine.com/physics/de 80% CEPC next supercollider
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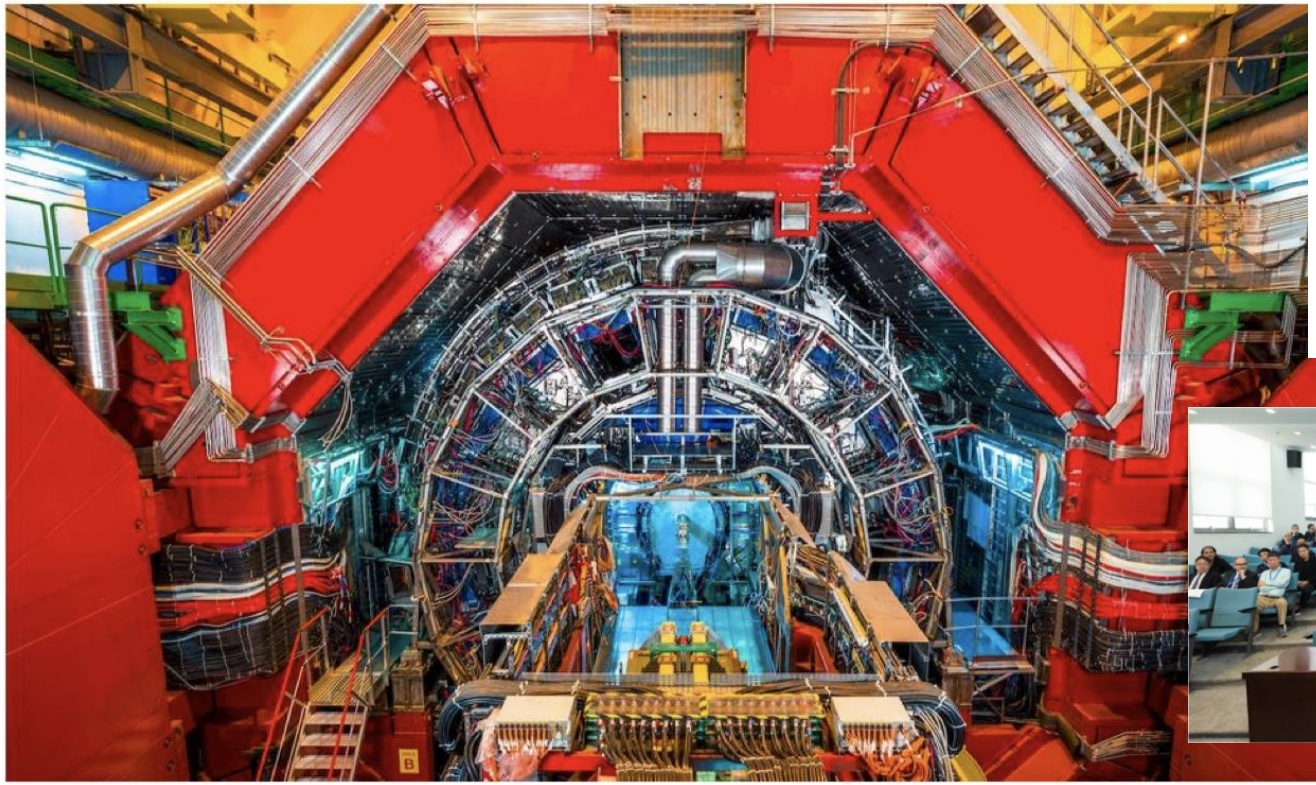
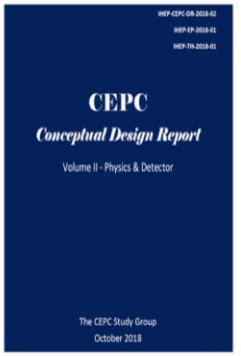
Design reports released for proposed China supercollider

Ifff the funding bid is successful at first round
-> physics start may be in 2030

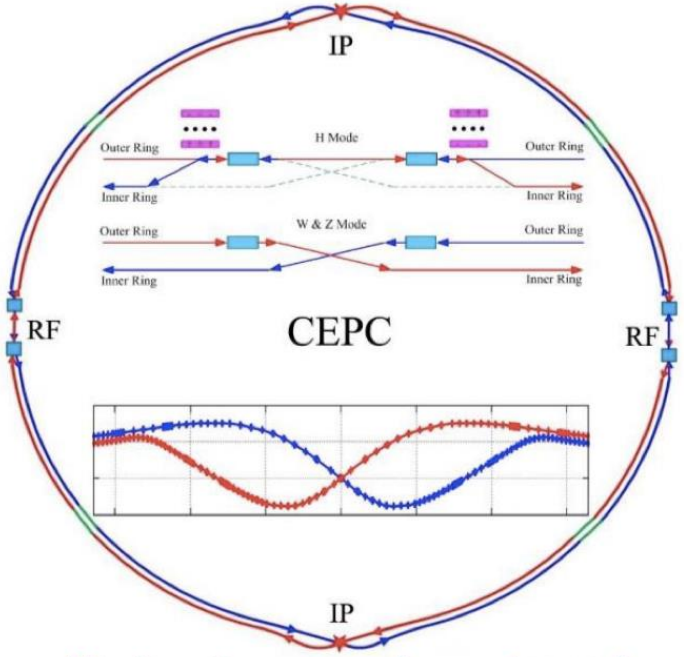
The biggest particle collider in the world moves one step closer to reality. Nick Carne reports.

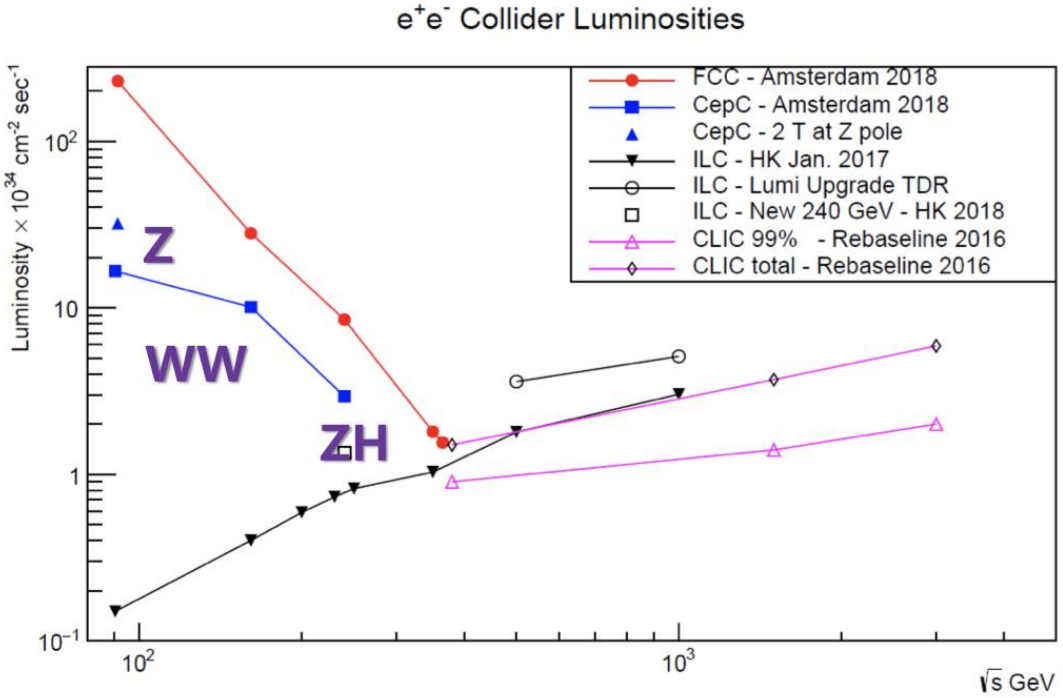




China: CEPC Project

- CEPC is Higgs Factory (E_{cms}=240GeV , 10^6 Higgs)
- CEPC is Z factory(E_{cms}~91GeV) ,electroweak precision physics at Z pole.
  - **baseline** L=1.6 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =2T, 3X10^{11} Z boson
  - L= 3.2 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =3T , 6X10^{11} Z boson
  - **Assuming Z cross section with ISR correction : 32 nb**
- WW threshold scan runs (~160GeV) are also expected.
  - Total luminosity 2.5 ab^{-1} ,**14M WW events**





https://indico.ihep.ac.cn/event/7389/

FCC-ee discovery potential

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

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

-- ~20-50 *(stat 400…)* fold improved precision on many EW quantities (eq. x 5-7 in mass)

m_Z, m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, top quark couplings

~ Model-independent Higgs width and couplings measurements at percent-permil level.

~3σ, possibly 5 discovery of effect of Higgs self-coupling from Vertex corrections

possible investigation of Hee coupling at $\sqrt{s} = m_H$

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}

-- ex FCNC ($Z \rightarrow \mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} $Z \rightarrow \tau\,\tau$

+ flavour physics (10^{12} bb events) ($B \rightarrow s\,\tau\,\tau$ etc..)

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

DIRECT DISCOVERY of very weakly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons etc…

+ and many opportunities in – e.g. QCD ($H \rightarrow gg$) etc….

NB Not only a «Higgs Factory», «Z factory» and «top» are important for 'discovery potential'

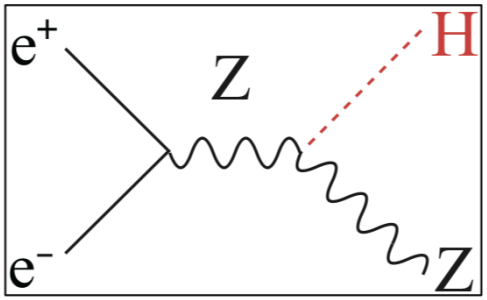
"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164

A sample of precision observables.

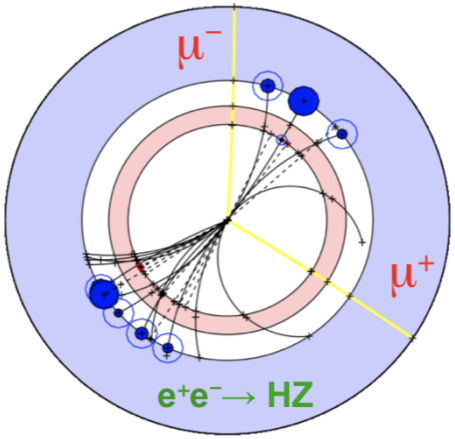
	Observable	Measurement	Current precision	FCC-ee **stat.**	FCC-ee **syst.**	Dominant exp. error
Z pole	m_Z (keV)	Z Lineshape	91187500 ± 2100	5	< 100	Beam energy
	Γ_Z (MeV)	Z Lineshape	2495200 ± 2300	8	< 100	Beam energy
	R_l ($\times 10^3$)	Z Peak ($\Gamma_{had}/\Gamma_{lep}$)	20767 ± 25	0.06	0.2 – 1	Detector acceptance
	R_b ($\times 10^6$)	Z Peak (Γ_{bb}/Γ_{had})	216290 ± 660	0.3	< 60	g → bb
	N_ν ($\times 10^3$)	Z Peak (σ_{had})	2984 ± 8	0.005	1	Lumi measurement
	$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$A_{FB}^{\mu\mu}$ (peak)	231480 ± 160	3	2 – 5	Beam energy
	$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	$A_{FB}^{\mu\mu}$ (off-peak)	128952 ± 14	4	< 1	Beam energy
	$\alpha_s(m_Z)$ ($\times 10^4$)	R_l	1196 ± 30	0.1	0.4 – 1.6	Same as R_l
WW thresh.	m_W (MeV)	WW Threshold scan	80385 ± 15	0.6	0.3	Beam energy
	Γ_W (MeV)	WW Threshold scan	2085 ± 42	1.5	0.3	Beam energy
	N_ν ($\times 10^3$)	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2920 ± 50	0.8	small	?
	$\alpha_s(m_W)$ ($\times 10^4$)	$B_l = (\Gamma_{had}/\Gamma_{lep})_W$	1170 ± 420	2	small	CKM Matrix
$t\bar{t}$ thresh.	m_{top} (MeV)	Top Threshold scan	173340 ± 760 ± 500	17	< 40	QCD corr.
	Γ_{top} (MeV)	Top Threshold scan	?	45	< 40	QCD corr.
	λ_{top}	Top Threshold scan	μ = 1.28 ± 0.25	0.10	< 0.05	QCD corr.
	ttZ couplings	$\sqrt{s}$ = 365 GeV	± 30%	0.5 – 1.5%	< 2%	QCD corr

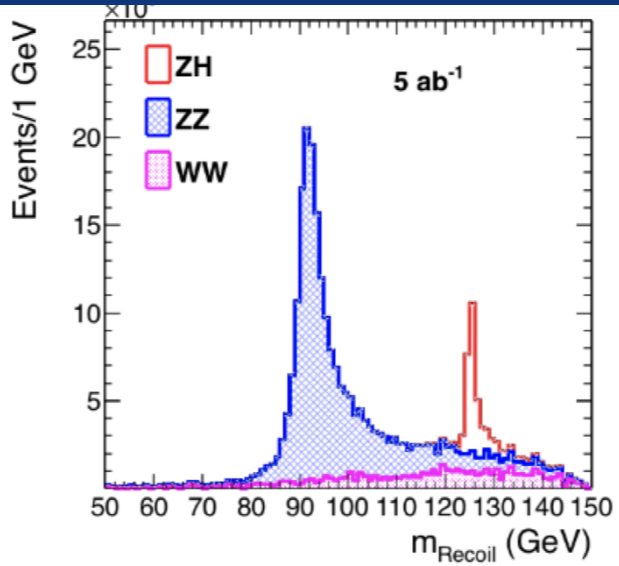
Higgs Factory

- Higgs tagged by a Z, Higgs mass from Z recoil



$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





- Total rate ∝ g_{HZZ}^2 → measure g_{HZZ} to 0.2%
- ZH → ZZZ final state ∝ g_{HZZ}^4 / Γ_H → measure Γ_H to a couple %
- ZH → ZXX final state ∝ $g_{HXX}^2\, g_{HZZ}^2 / \Gamma_H$ → measure g_{HXX} to a few per-mil / per-cent
- Empty recoil = invisible Higgs width; Funny recoil

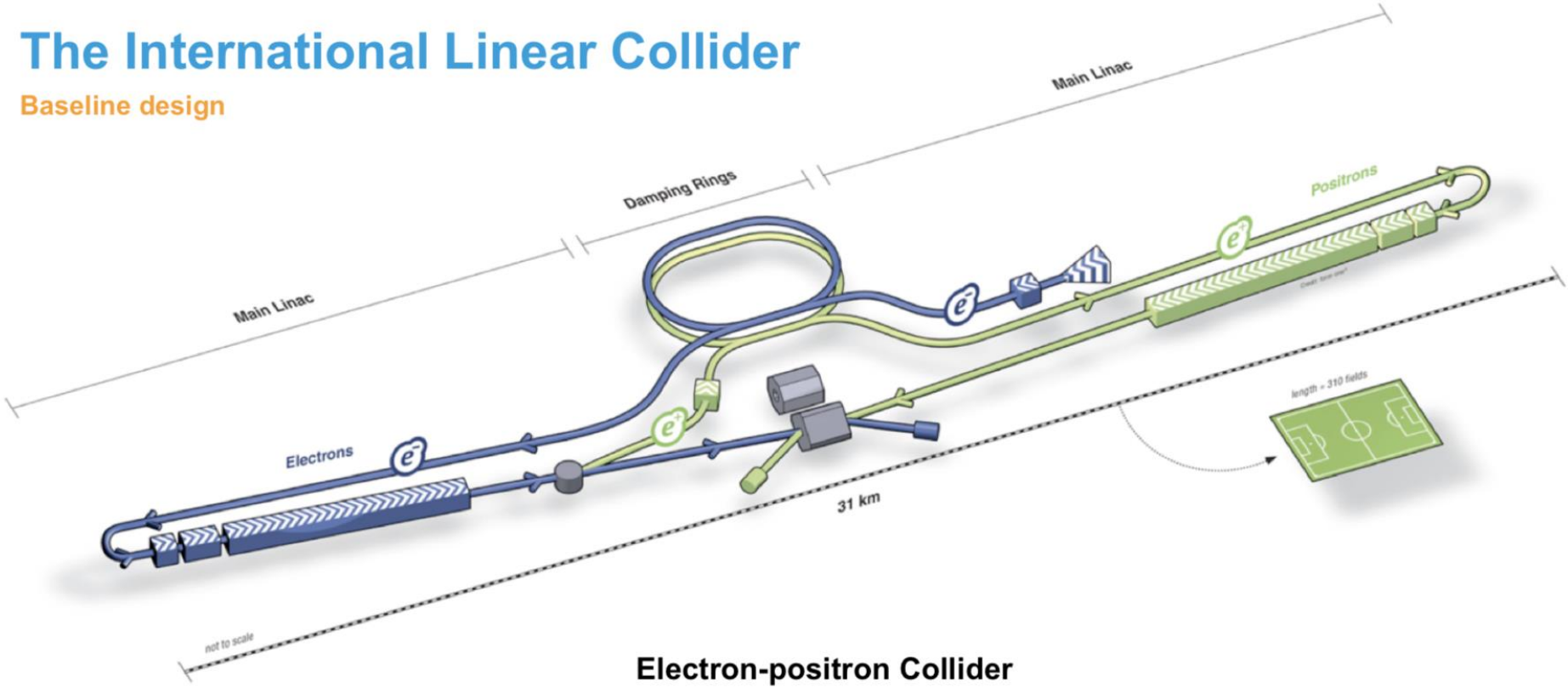
- Note: The HL-LHC is a great Higgs factory (10⁹ Hi

- $\sigma_{i\to f}^{(\text{observed})} \propto \sigma_{prod}\, (g_{Hi})^2\, (g_{Hf})^2 / \Gamma_H$
  - Difficult to extract the couplings : σ_{prod} is uncer
    - Must do physics with ratios or with additi

Collider *	HL-LHC	FCC-ee		
Lumi (ab^{-1})	3	5_{240}	$\oplus 1.5_{365}$	$\oplus$ HL-LHC
$\delta\Gamma_H/\Gamma_H$ (%)	50	2.8	1.6	**1.5**
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	0.25	0.22	**0.22**
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	1.3	0.47	**0.46**
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	1.4	0.68	**0.67**
$\delta g_{Hcc}/g_{Hcc}$ (%)	**SM**	1.8	1.23	**1.20**
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	1.7	1.03	**0.89**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	1.4	0.80	**0.78**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	9.6	8.6	**3.4**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	4.7	3.8	**1.4**
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	–	–	**3.3**
BR_{EXO} (%)	**SM**	< 1.2	< 1.1	< **1.0**
BR_{invis} (%)	< 3.0	< 0.3	< 0.25	< **0.25**

The International Linear Collider

Baseline design



Electron-positron Collider

- Center-of-mass energy 250 GeV (Higgs factory)
  Extendable to higher energies (1 TeV)
- Based on superconducting RF niobium cavities
- Polarized beams
- One interaction region, two detectors

Page 3

Expected:

by fall 2018

Discussion in Science Council of Japan

by the end of Dec. 2018

Expression of Interest from Japanese government

Then a 4 years preparatory phase and 8 years construction

…and then came December 19 2018

Plans for world's next major particle collider dealt big blow

nature
International journal of science

Japanese science committee questions the project's multi-billion-dollar price tag — but

Plans to build a particle smasher in Japan to succeed the Large Hadron Collider have suffered a significant setback. An influential report by Japanese scientists concluded that they could not support plans to build the International Linear Collider (ILC) in the country. The facility has been decades in design and would study the Higgs boson, which was discovered in 2012 and is the last puzzle piece in particle physicists' 'standard model'.

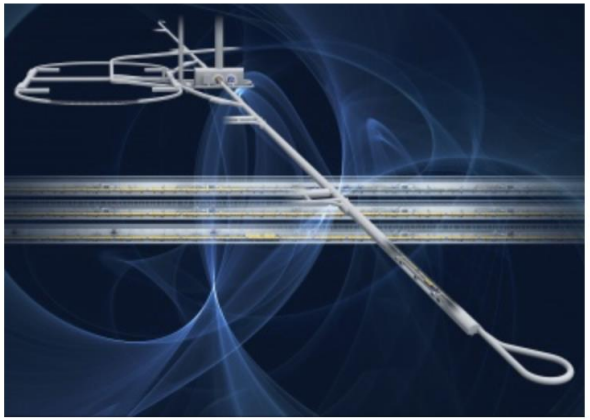
The discoveries predicted to come out of the ILC would not fully warrant its nearly US$7-billion cost, said a committee of the Science Council of Japan in a report released on 19 December, according to press reports. As host, Japan might be expected to pay as much as half of the total. The committee, which advises the government, added that uncertainty about whether international partners would share the project's costs increased its concerns.

The proposed accelerator — which would be more than 20 kilometres long — would enable physicists to detect the products of precise collisions between electrons and their antimatter counterparts, positrons.

Government advice

The government will now use the report, which reflects the views of the academic community in Japan and not just those of high-energy physicists, to guide its decision on whether to host the facility. A decision is expected by 7 March, when the international group overseeing the ILC's development, the Linear Collider Board, meets in Tokyo.

Clarifications on the report from the Science Council of Japan regarding the ILC

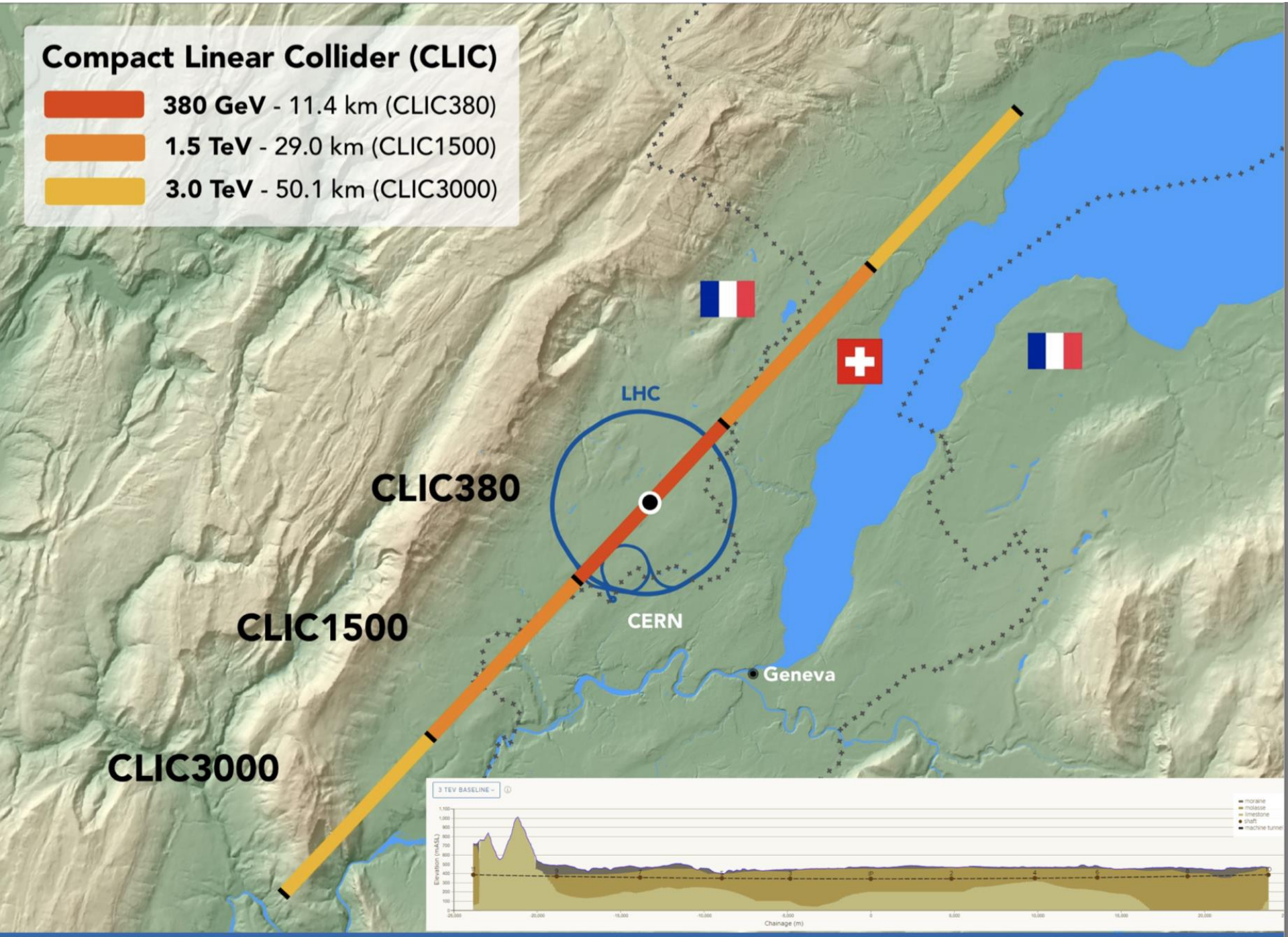


The report released by the Science Council of Japan on 19 December on the realisation of the ILC raised many questions within the linear collider community. The ILC Planning Office at KEK asks for continuing support.

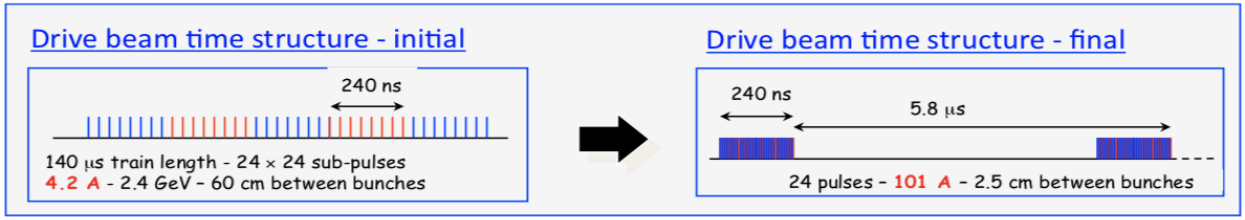
Final decision with government of Japan, expected in spring 2019

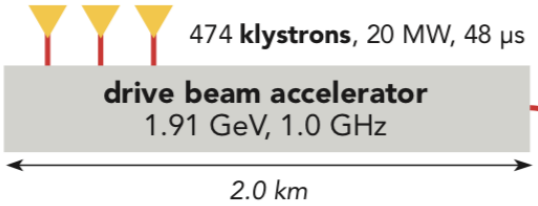
But negative advice of science council is a set-back

Story still to be continued

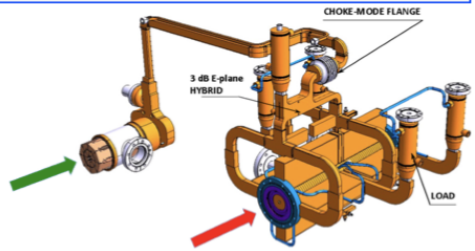

Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CERN
CLIC1500
Geneva
CLIC3000
3 TEV BASELINE
Elevation (mASL)
Chainage (m)
moraine
molasse
limestone
shaft
machine tunnel

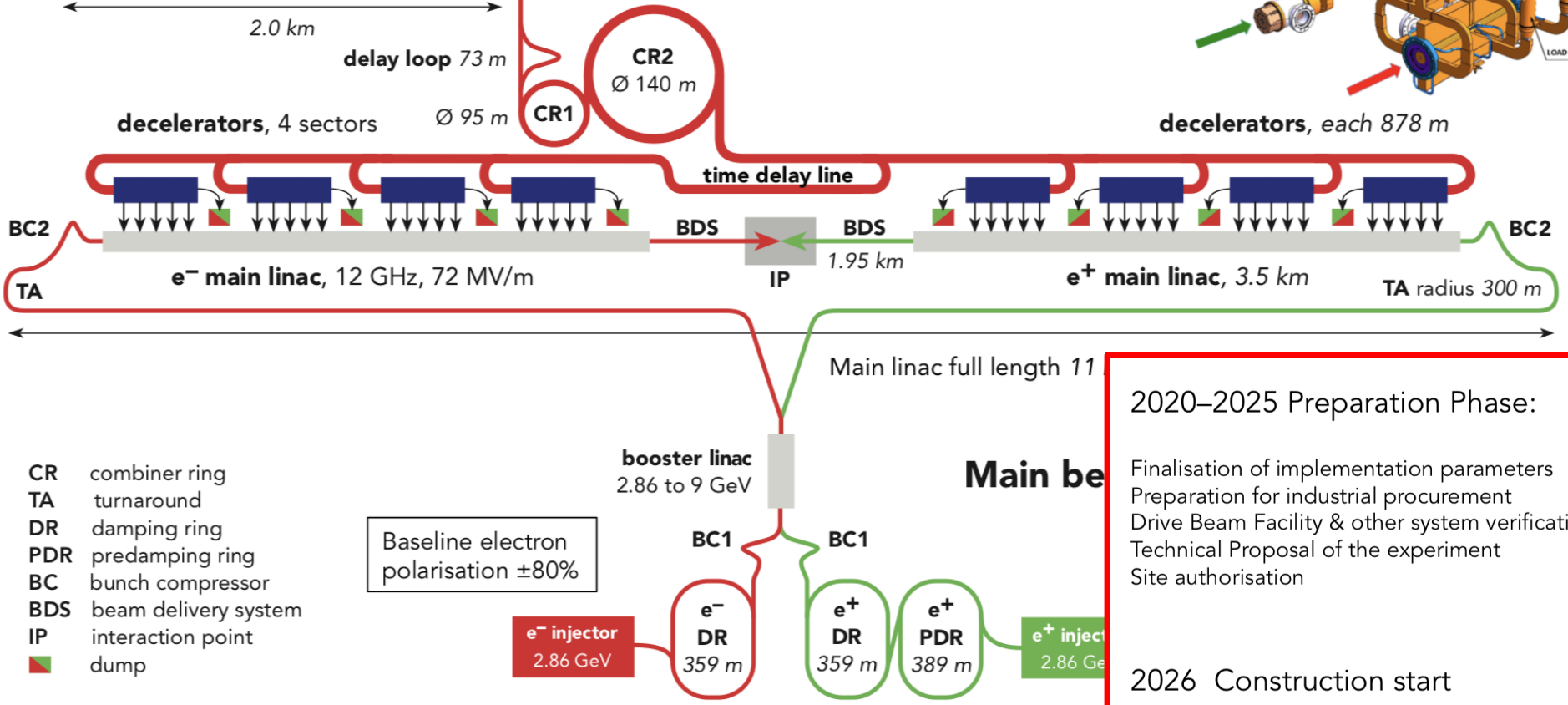
CLIC layout and power generation





Drive beam complex





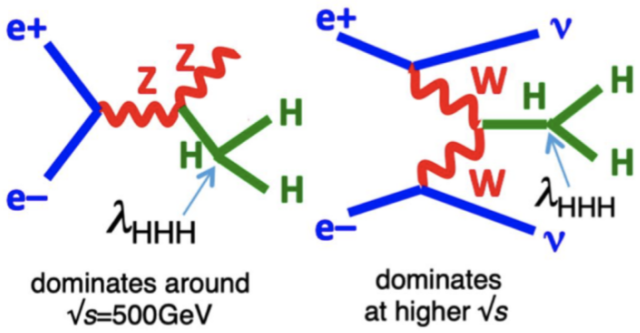
2020–2025 Preparation Phase:

Finalisation of implementation parameters
Preparation for industrial procurement
Drive Beam Facility & other system verificatio
Technical Proposal of the experiment
Site authorisation

2026 Construction start

Higgs self-coupling at CLIC

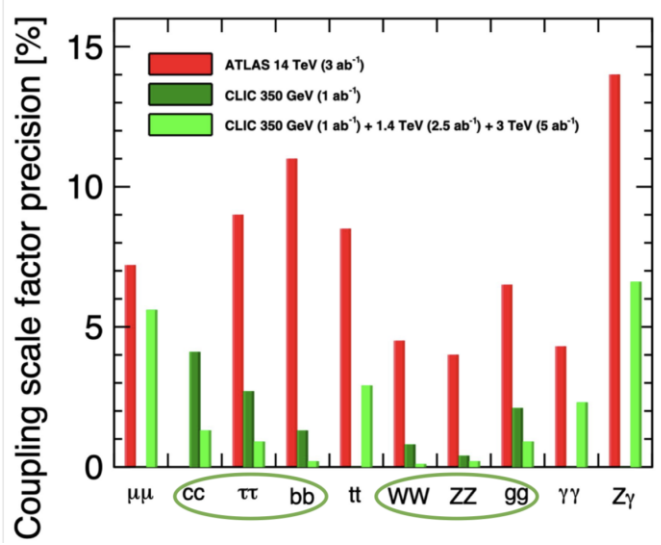
Higgs self-coupling at CLIC, 3 TeV, 5 ab^{-1}
-80%/+80% electron polarisation, sharing 80%/20%
Main contribution from VBS, with HH → bbbb (58%)
HZZ production at 1.4 TeV, helps to resolve ambiguities



Improved analysis, includes use of angular distributions

Trilinear Higgs self-coupling $\Delta\lambda/\lambda = -7\ \%, +11\ \%$ at 68 % C.L. ⇐ *new result*

assuming SM and setting the quartic HHWW coupling to the SM value.



First CLIC stage is already significantly more sensitive than HL-LHC for several couplings

The full CLIC programme further enhances the precision

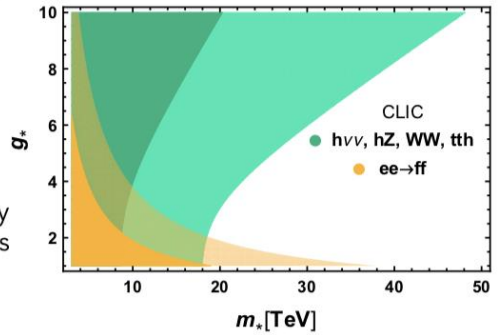
Higgs couplings

Based on: Eur. Phys. J. C 77 475 (2017)
ATLAS-PHYS-PUB-2014-016

Can interpret in concrete BSM scenarios
e.g. Higgs & top-quark compositeness

Sensitivity via EFTs

5-σ discovery regions



CLIC can ***discover*** compositeness up to 8TeV compositeness scale (~30TeV in favourable conditions) – above what LHC can ***exclude***

Hadron Colliders

- FCC-hh (CERN)
- SppC (China)

FCC-pp collider parameters

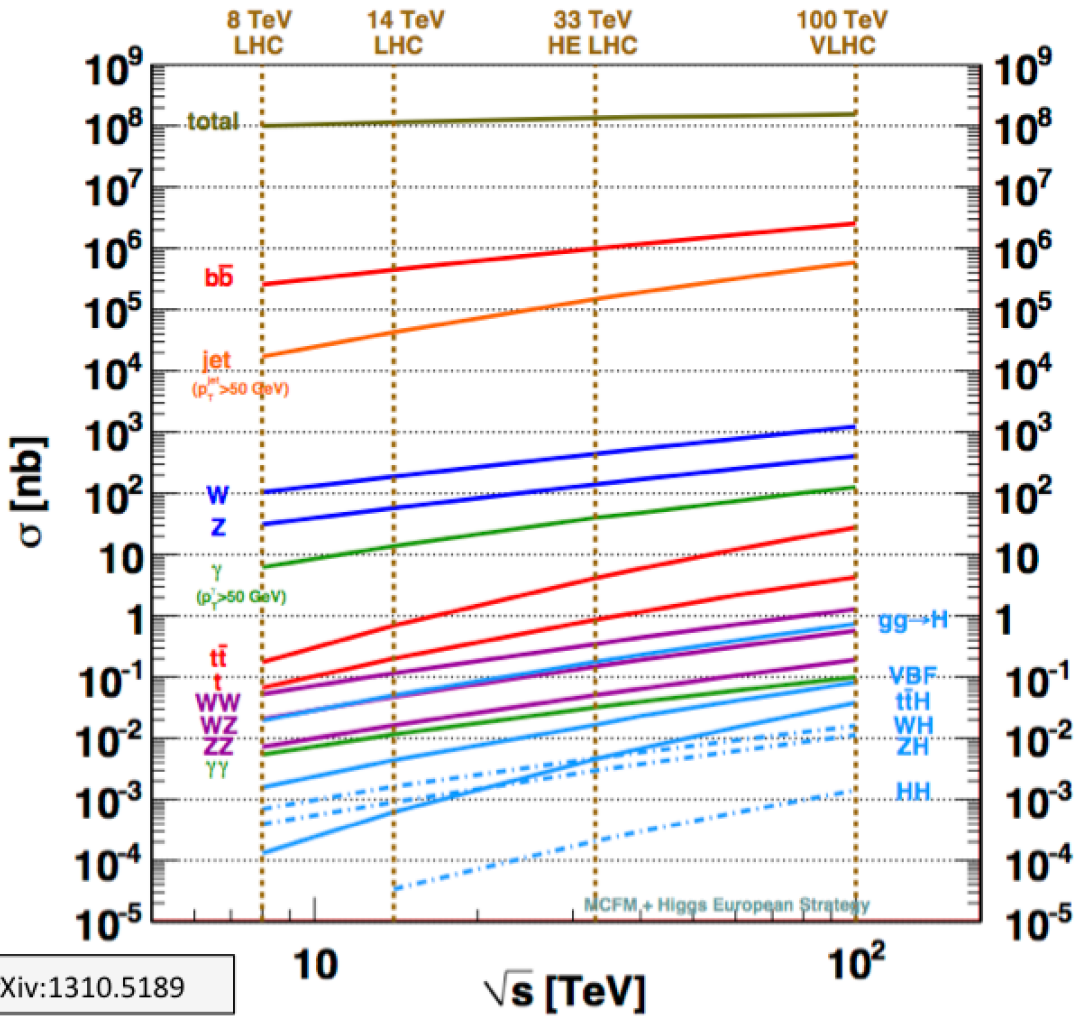
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.1	1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

China: Hadron Collider

- **SppC Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, using full iron-based HTS technology
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV
  - Relatively lower luminosity for the first phase, higher for the second phase
- **Energy upgrading phase**
  - Dipole magnet field: 20 -24T, full iron-based HTS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (e.g., adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)
- **Development of high-field superconducting magnet technology**
  - Starting to develop required HTS magnet technology; before applicable iron-based HTS wire are available, models by YBCO and LTS wires can be used for specific studies (magnet structure, coil winding, stress, quench protection method etc.)

Make use the CEPC Tunnel

Hadron colliders: direct exploration of the "energy frontier"



arXiv:1310.5189

Gianotti

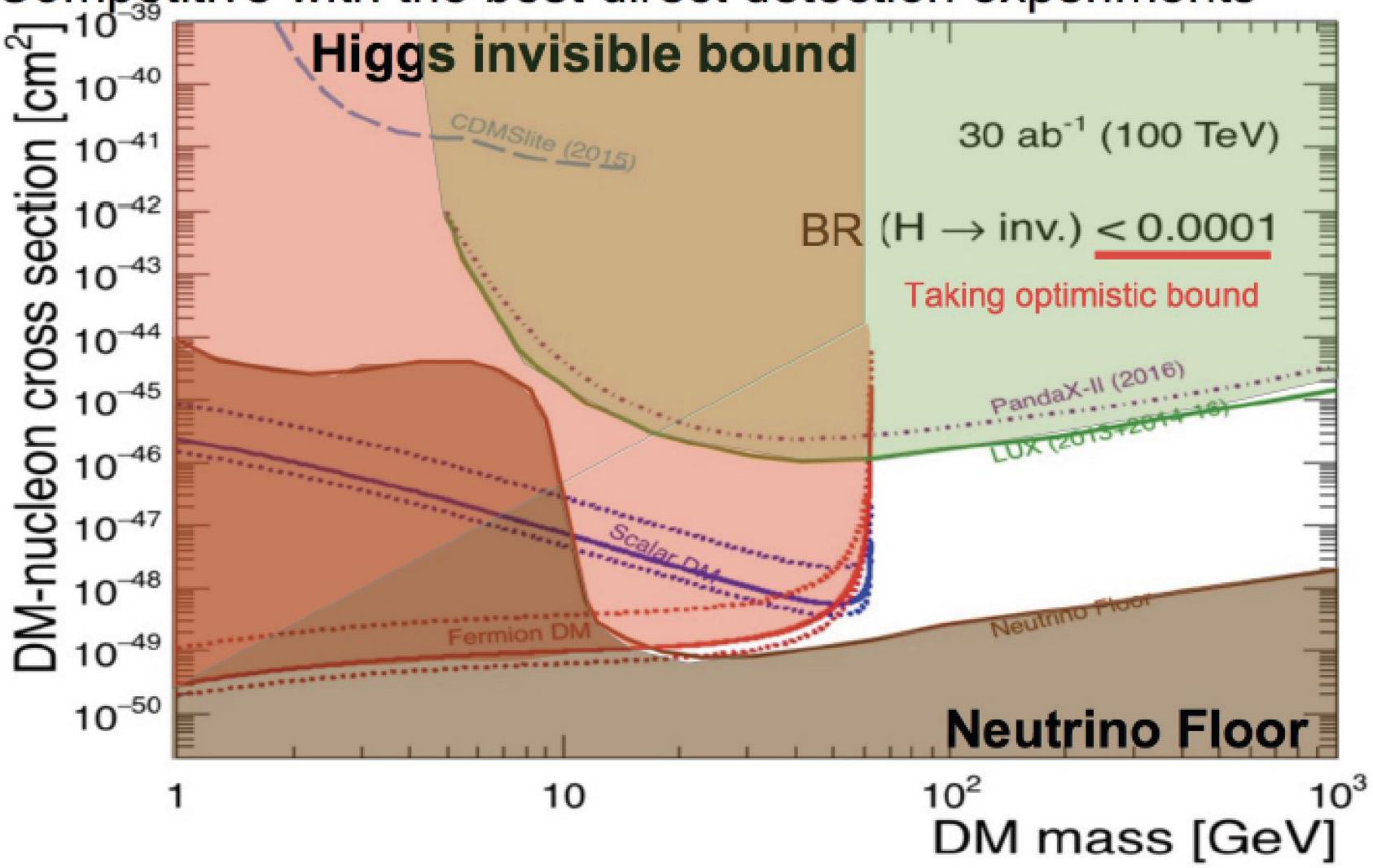
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

With 40/ab at √s=100 TeV expect: ~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

Impact on DM bounds

Competitive with the best direct detection experiments



Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

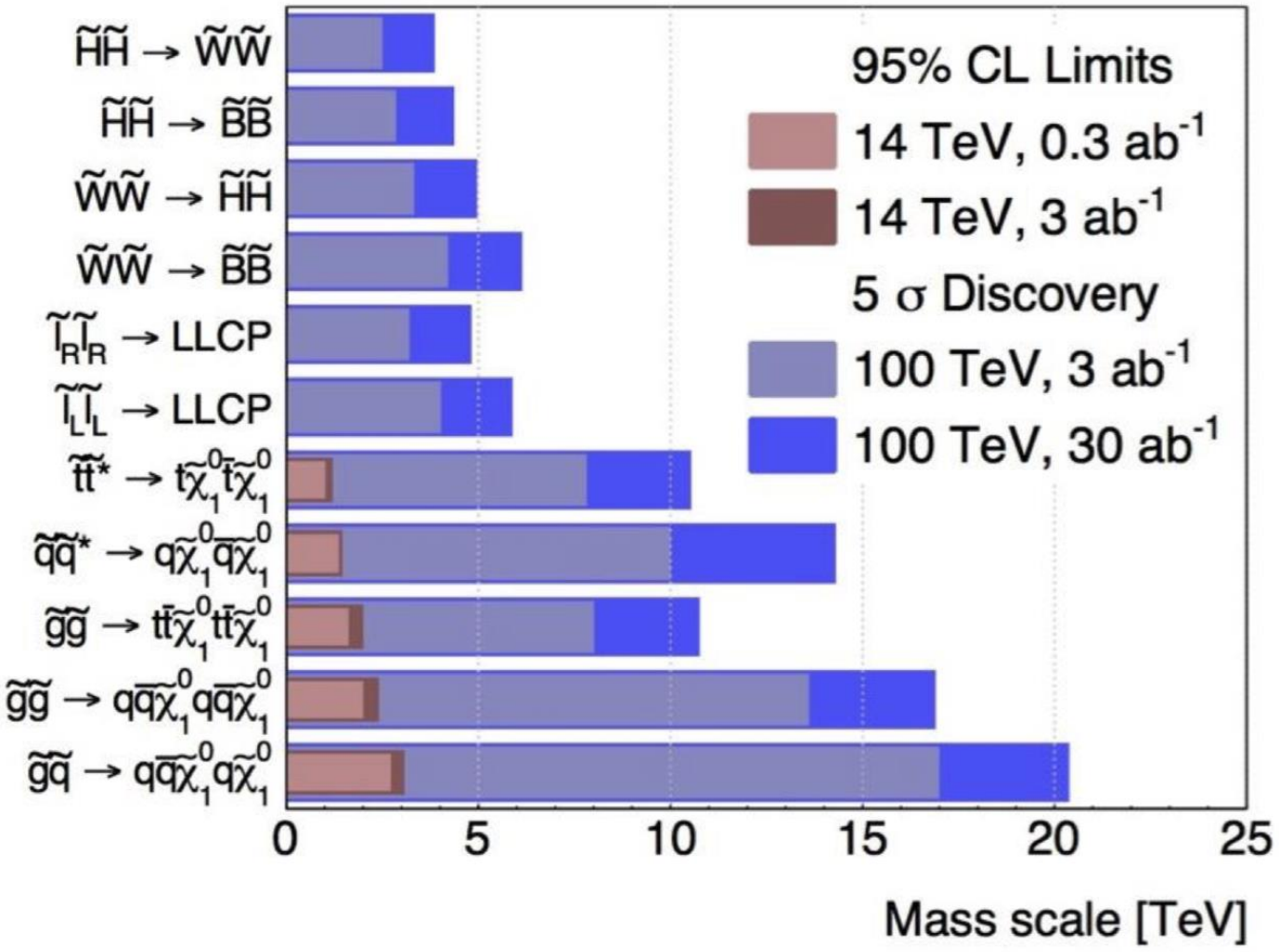
hh, eh precisions assume SM or ee measurements
FCC-hh : H→ ZZ to serve as cross-normalization

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.22 %**	**< 1%** *	
WW	**0.47%**		
Γ_H	**1.6%**		
γγ	4.2%	**<1%**	
Zγ	--	**1%**	
ttH	13%	**1%**	
bb	**0.7%**		0.5%
ττ	**0.8%**		
cc	**0.7%**		1.8%
gg	**1.0%**		
μμ	8.6%	**1-2%**	
uu,dd	H→ ργ?	H→ ργ?	
ss	H→ φγ ?	H→ φγ ?	
ee	**ee → H**		
HH	40%	**~3-5%**	20%
inv, exo	<0.55%	**10^{-3}**	5%

for ttH, combination of ±4% (model dependent)HL-LHC with FCC-ee will lead to ttH coupling to ± 3%...
model independent!

for g_{HHH} investigating now : the possibility of reaching 5σ obsservation at FCC-ee:
4 detectors
+ recast of running scenario

Supersymmetry

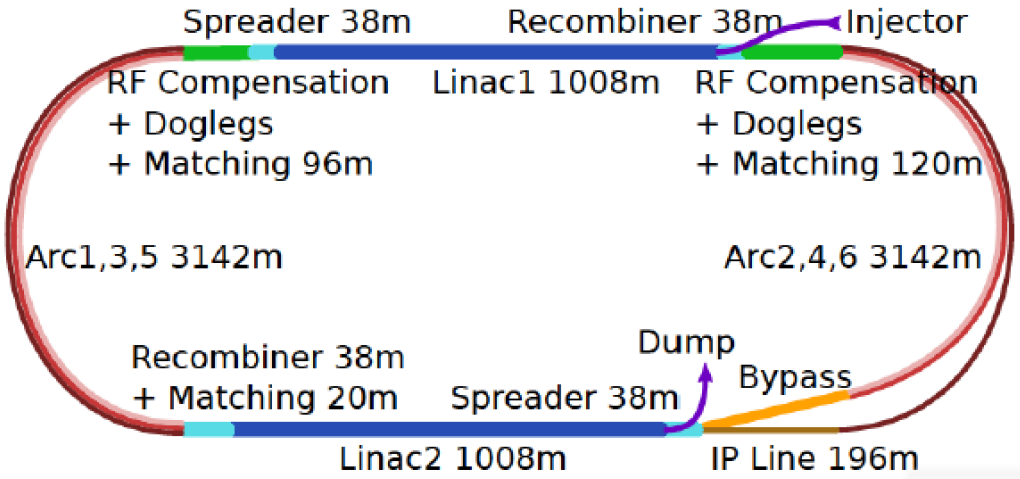


FCC-eh

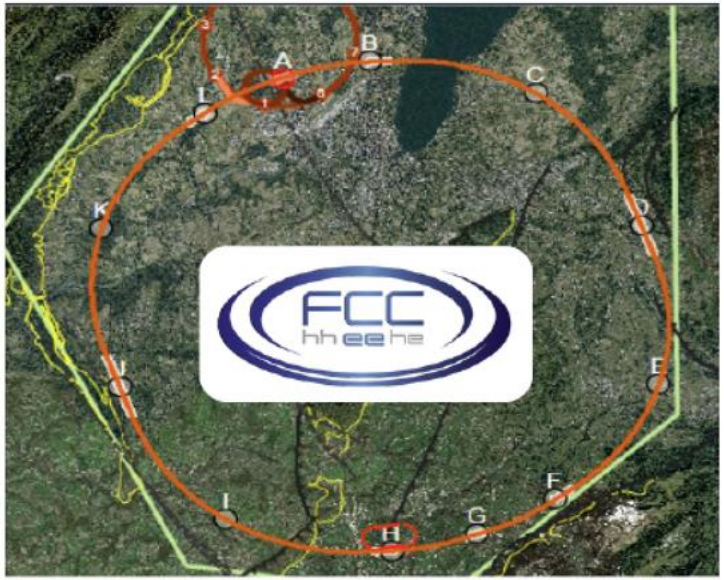
Using a 60 Gev Electron Energy recovery linac As an electron beam (PERLE Project)

Electron beam

60GeV acceleration with Recirculating Linacs



A. Bogaz (JLab) @ ERL '15



Center-of-mass energies

- LHeC: $\sqrt{s} \sim 1.3$ TeV
- FCC-eh: $\sqrt{s} \sim 3.5$ TeV
- Up to 1 ab^{-1} integrated luminosity

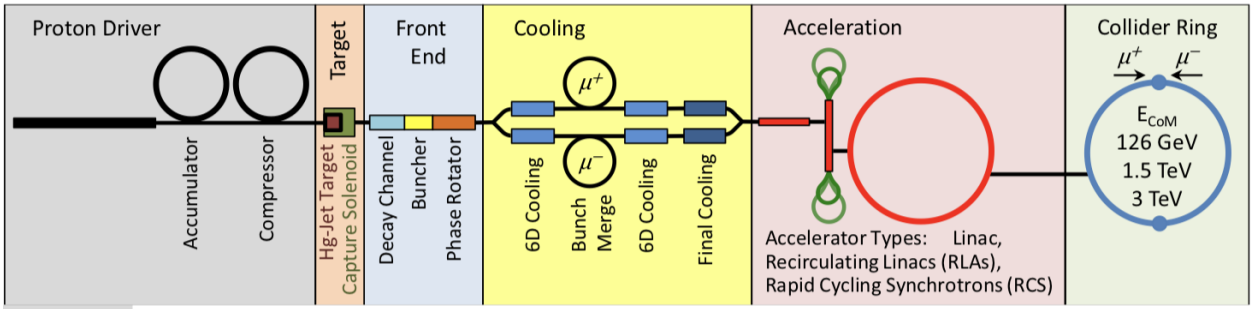
Concurrent operation to pp. Power limit: 100 MW, 10^{34} cm^{-2} s^{-1} luminosity

- LHeC/FCCeh: 1000 times HERA luminosity. It therefore extends up to x~1.

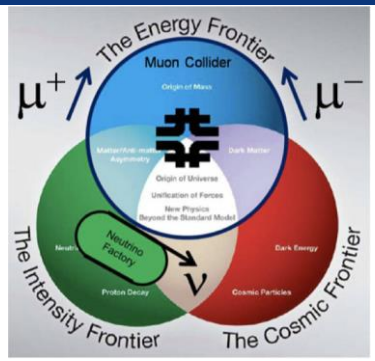
$\mu^+\mu^-$ Colliders

- Proton generated muon beams
  MAP Scheme
- Electron generated muon collider
  LEMMA Scheme

Muon Colliders

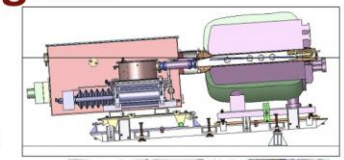


MAP scheme

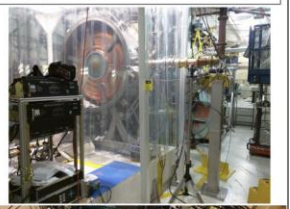


International R&D program

MERIT - CERN
Demonstrated principle of liquid Mercury jet target



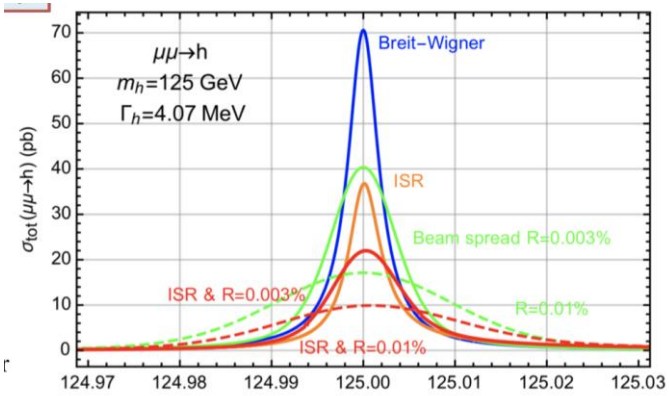
MuCool Test Area - FNAL
Demonstrated operation of RF cavities in strong B fields



EMMA - STFC Daresbury Laboratory
Showed rapid acceleration in non-scaling FFA

MICE - RAL
Demonstrate ionization cooling principle
Increase inherent beam brightness
→ number of particles in the beam core
"Amplitude"

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier



Muon Colliders

Low EMittance Muon Accelerator

Snowmass 2013 - M. Antonelli e P. Raimondi

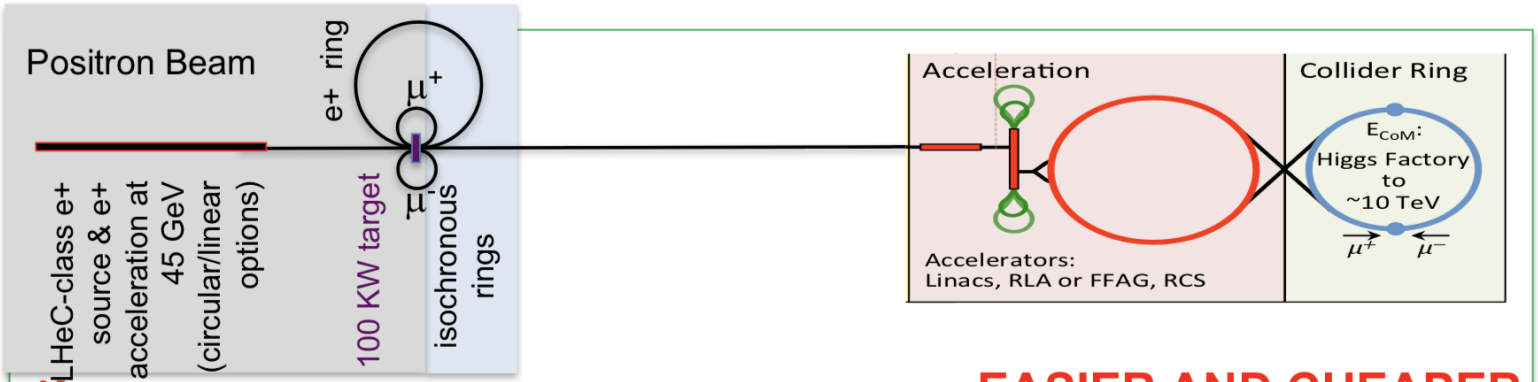
Direct μ pair production: muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at √s around the $\mu^+\mu^-$ threshold **(√s~0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

Potential of this idea, but key challenges need to be demonstrated to prove its feasibility ➔ a new proposal for machine studies and measurements

Advantages: Low emittance possible — Low background

Reduced losses from decay — Energy spread

Disadvantages: **Rate:** $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b$ at most



Key Challenges

~10^{11} μ / sec from $e^+e^- \rightarrow \mu^+\mu^-$

Key R&D

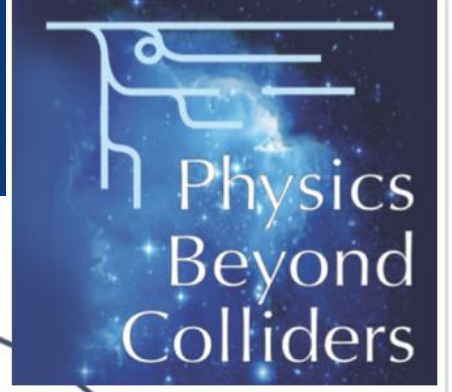
10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

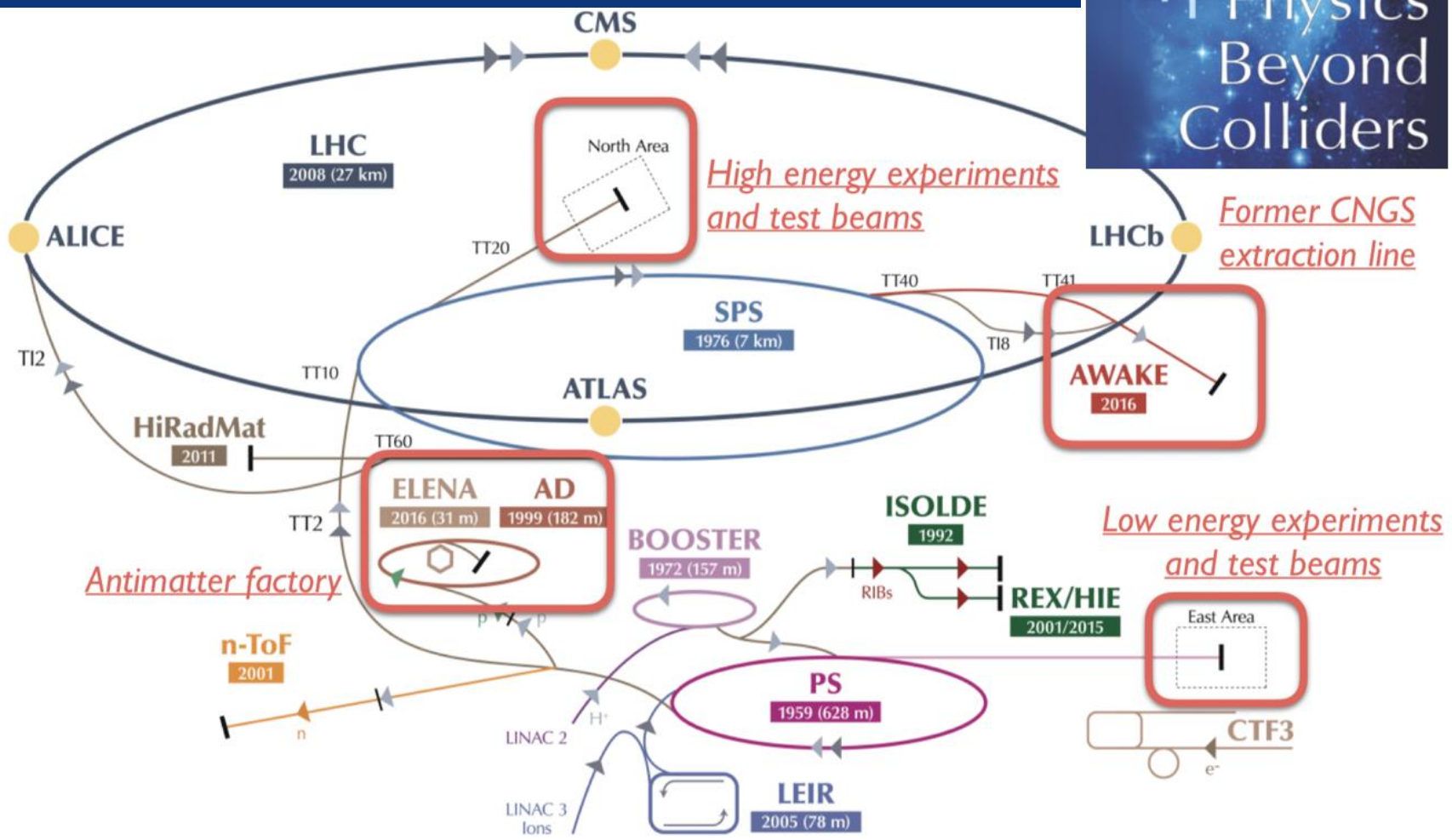
EASIER AND CHEAPER DESIGN, IF FEASIBLE

Other Projects

- Electron-Ion Collider (US)
- Intensity Frontier (CERN)
- Accelerator based Neutrino Projects

CERN: Intensity Frontier



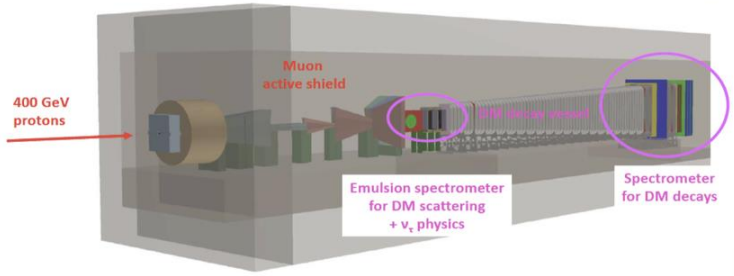


Excerpt from the PBC mandate: "*Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world.*"
(Time scale of opportunities: next 2 decades)

SHiP

Flagship programme for a comprehensive investigation of the Hidden Sector in the few GeV domain

Similar layout as NA62, with larger acceptance to reach the c / b mass range

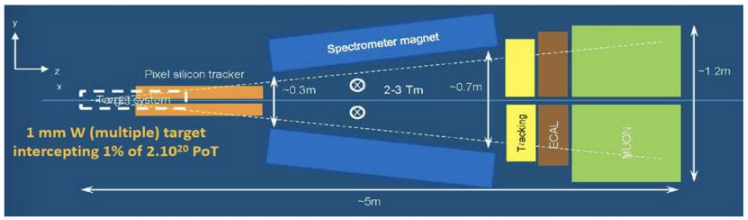


NB: NA62 plans to pave the way with short runs in beam dump mode after LS2

TauFV

Recently revived idea to intercept small BDF beam fraction to look for $\tau \rightarrow 3\mu$ decays

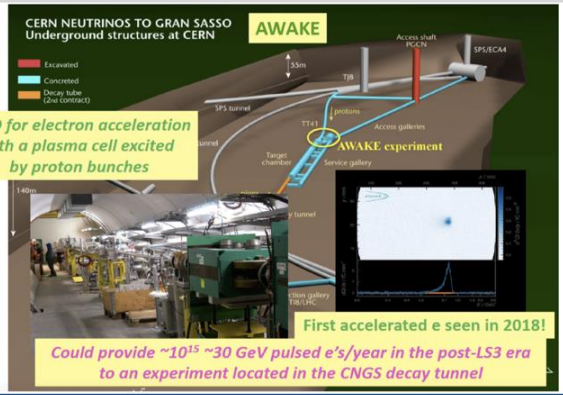
Could set limits on branching ratio better than 10^{-10} level (> BELLE-II reach)



Implementation layout upstream of BDF target under study

A promising option to maximize the physics reach of the Beam Dump Facility

AWAKE

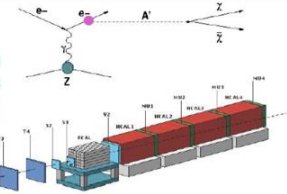


Examples of Beyond Collider Studies

More than 20 proposed projects

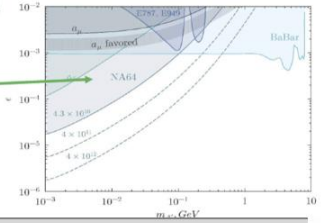
NA64

Hidden sector search from invisible decays with missing energy



Implemented in 2016 on e test beam

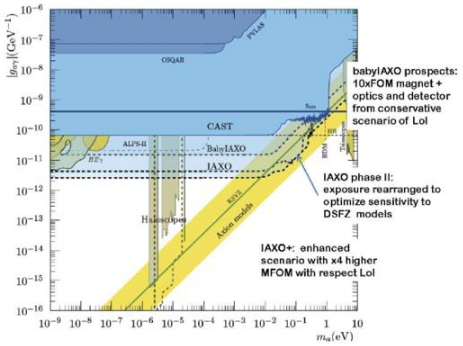
Fast analysis excluding $(g-2)_\mu$ interpretation confirms the potential of the method



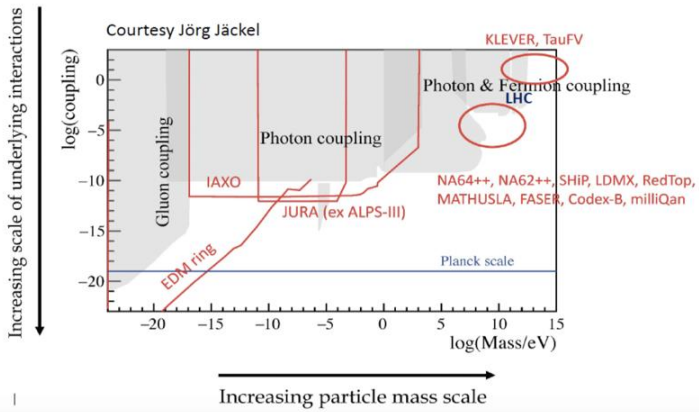
AFTER LS2:

Wish to extend the method to higher e intensity and μ / π / K / p beams

IAXO - next generation Axion helioscope beyond CAST



Support from CERN for magnet design within PBC



Intensity Frontier: Neutrinos

Neutrino oscillations (e.g. $\nu_\mu \rightarrow \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos → imply neutrinos have masses and mix

Since then: great progress in understanding ν properties at various facilities all over the world

Nevertheless, several open questions:

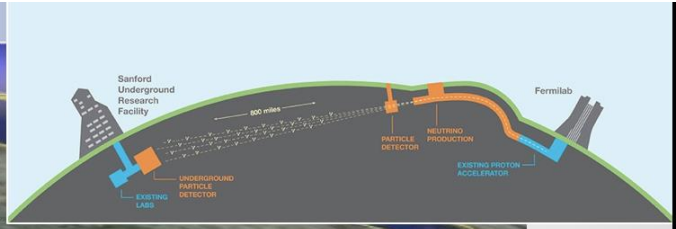
- Origin of ν masses (e.g. why so light compared to other fermions ?)
- Mass hierarchy: normal (ν_3 is heaviest) or inverted (ν_3 is lightest) ?
- Why mixing much larger than for quarks ?
- CP violation (observed in quark sector): do ν and anti-ν behave in the same way?
- Are there additional (sterile) ν (hints from observed anomalies)?

Accelerator experiments can address the of above questions studying neutrino oscillations

Need high-intensity p sources (> 1MW) and massive detectors, as ν are elusive particles and the searched-for effects tiny → Next-generation facilities planned in US and Japan.

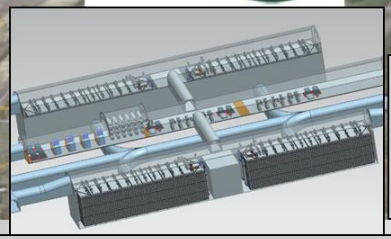
Europe (& CERN) participate in world-wide neutrino accelerator projects such as DUNE at FNAL/US and T2K/T2HK in Japan

Long Baseline Neutrino Facility (LBNF) at FNAL



Sanford Underground Research Facility
South Dakota

North Dakota
Minnesota
Ontario
Iowa
1300 km
Fermilab



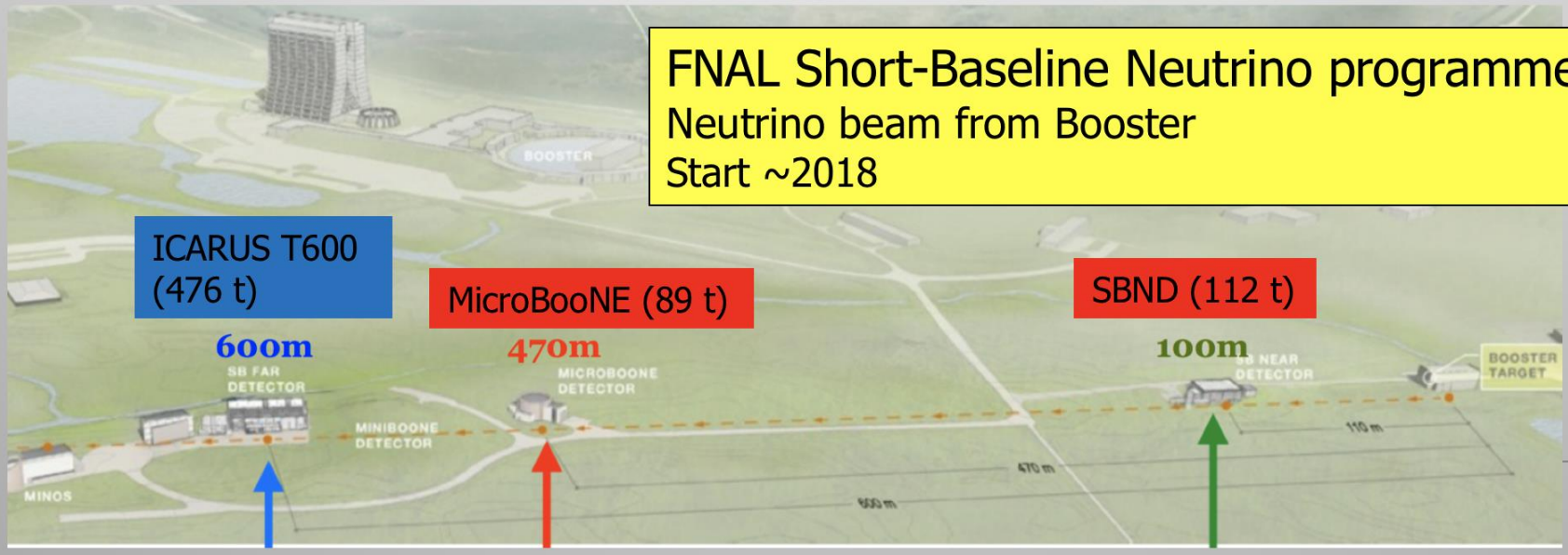
DUNE experiment:
4x10 kt LAr detectors
~1.5 km underground

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

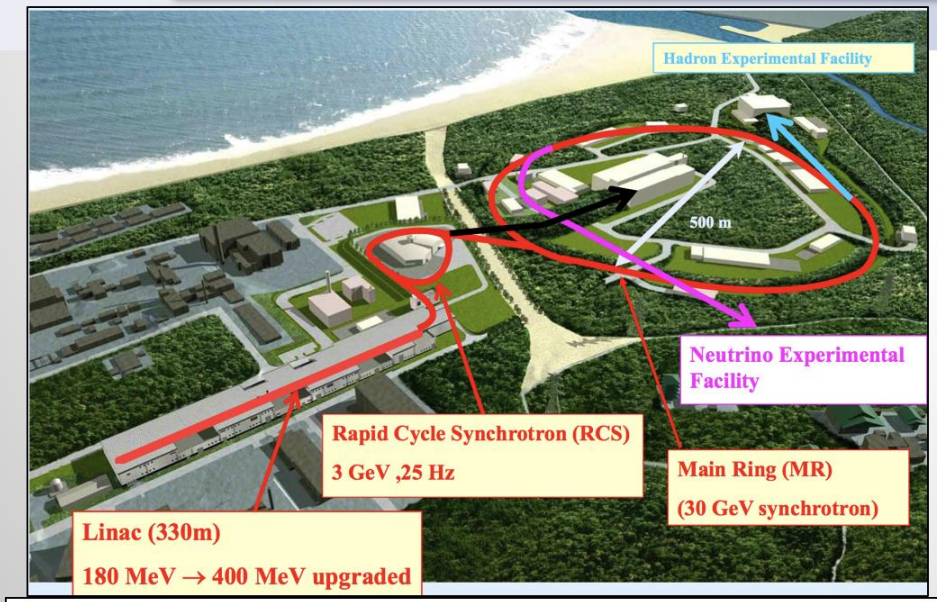
Far site construction starts ~2017, 1st detector installed ~2022, beam from FNAL ~ 2026

FNAL Short-Baseline Neutrino programme

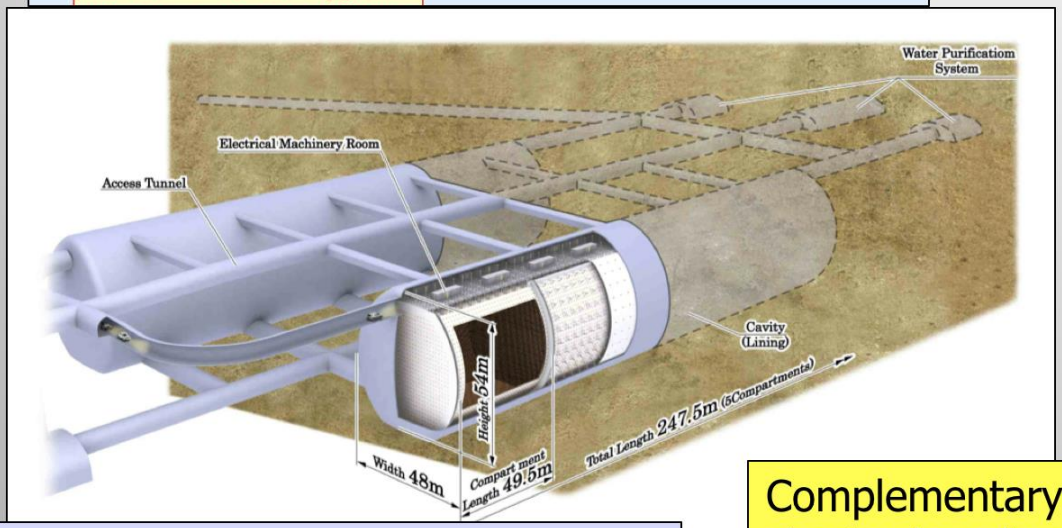
Neutrino beam from Booster
Start ~2018



Hyper-Kamiokande, JPARC: construction to start in 2019



0.38 → 0.75 → > 1 MW p source
E_p = 30 GeV → E_ν~ 0.6 GeV
Narrow-band ν beam
→ high intensity at oscillation peak



~0.5 Mton Water Cerenkov detector (~20 x Super-K)
~ 1 km underground
~ 2.5^0 off-axis → narrow-band beam

Complementary to LBNE: different detector technology, shorter baseline (→ less sensitive to mass hierarchy), narrow-band beam (→ high statistics of ν/anti-ν at oscillation peak but limited measurement of oscillation spectrum)

Summary

European Strategy Update launched

- Input by December 18 2018 concluded
- Working groups are at work now
- Open meeting in Granada 13-16 May
- Conclusion of the ‘update’ by May 2020

This is done in a worldwide context (US, China, Japan)

A lot of activity in preparing proposals at the energy and intensity frontier. FCC CDR released yesterday!

Outcome will affect all of future particle physics!

The European Strategy for Particle Physics

2006 European Strategy for Particle Physics approved by CERN Council
Contains 17 statements on scientific and organizational matters

2013 Update of the European Strategy for Particle Physics
- Open Symposium – Krakow, 10-12 Sept. 2012
- Book of Abstracts submitted to the Open Symposium
http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/abstractBook.pdf

- Physics Briefing Book compiled by the Preparatory Group (200 p)
http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/Briefing_book.pdf

- Strategy Group Meeting to draft the Update of the Strategy – Erice – January 2013: Document: CERN-Council-S-0106
https://cds.cern.ch/record/1567258/files/esc-e-106.pdf

- Approved by CERN Council in a special European Strategy Session of the Council in Brussels (May 30)
Contains 17 points, labeled a – q, numbers were avoided on purpose, not to give the impression of a pure priority list.

2018-2020 Next Update