'Accelerators': UK Input to EU Strategy

Stephen Gibson

John Adams Institute for Accelerator Science

Royal Holloway, University of London

‘Accelerators’ overview

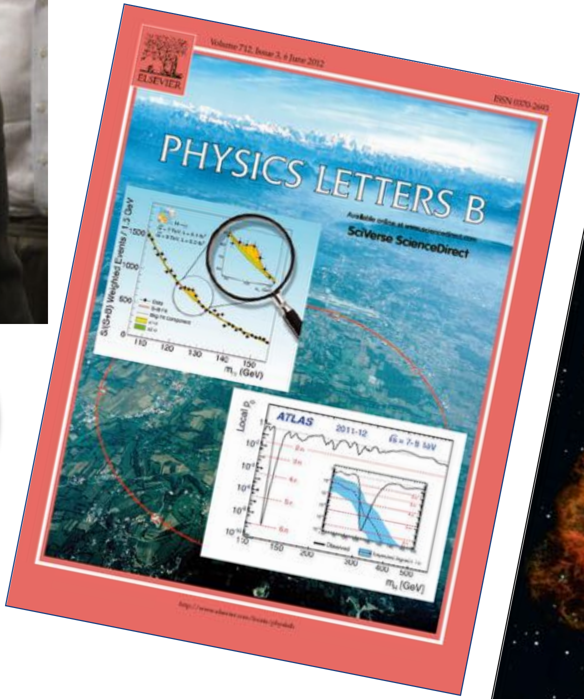
Outline

- ***High energy:*** LHC and HL-LHC
- ***Near Future Colliders***
  - Higgs factories, ILC, CLIC, CEPC
  - FCC (hh ee he), HE-LHC, SppC
  - Strategic build order priorities
- ***Far future***: Novel acceleration
- ***High intensity:*** Beyond Colliders & Neutrino programme, other facilities.
- UK contribution strategy

Disclaimer: focus on accelerators relevant to EU PP (exclude FELs, light sources, medical accelerators, etc…)

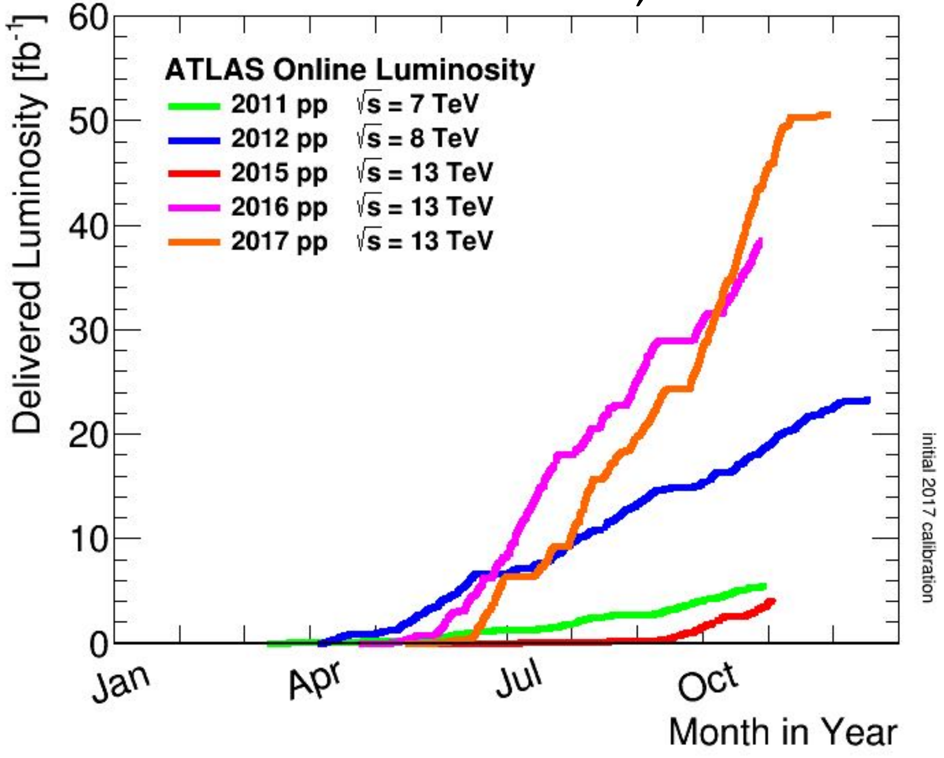
Higgs discovery over 5 years ago…

4 July 2012:
5σ observation of a
Higgs-like boson



LHC performance and future

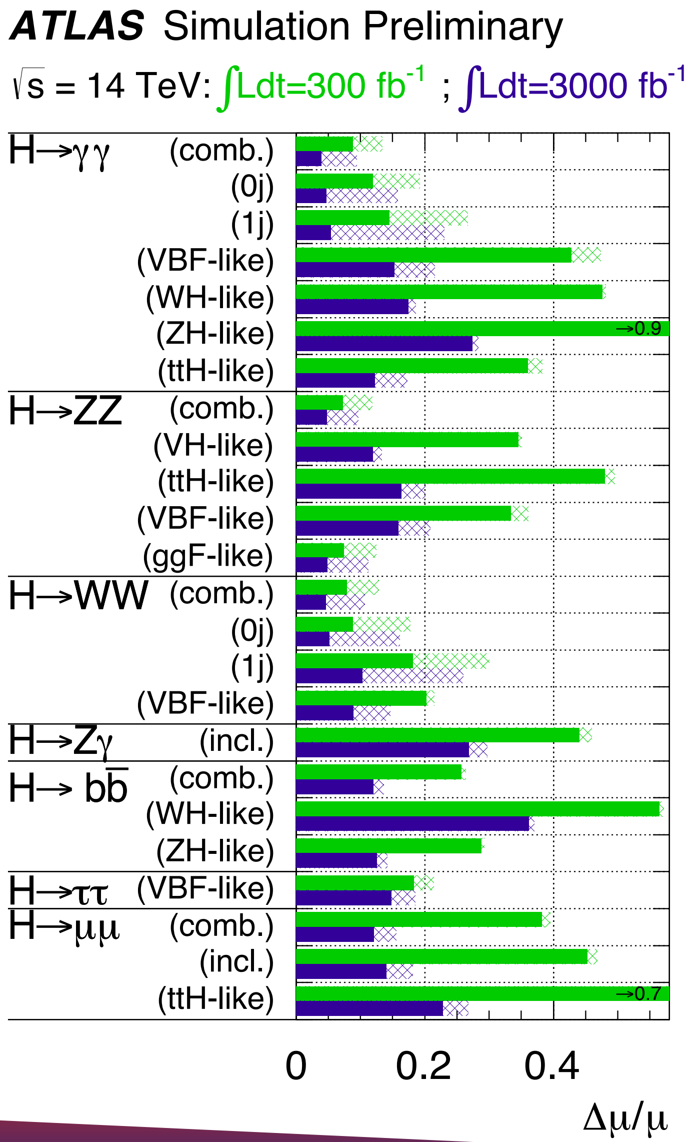
LHC performance exceeding yearly targets in quest to measure Higgs Boson couplings and search for exotic physics:
Dark Matter, Extra Dimensions, Super symmetry, ...



Processes extremely rare, requires many collisions = luminosity!

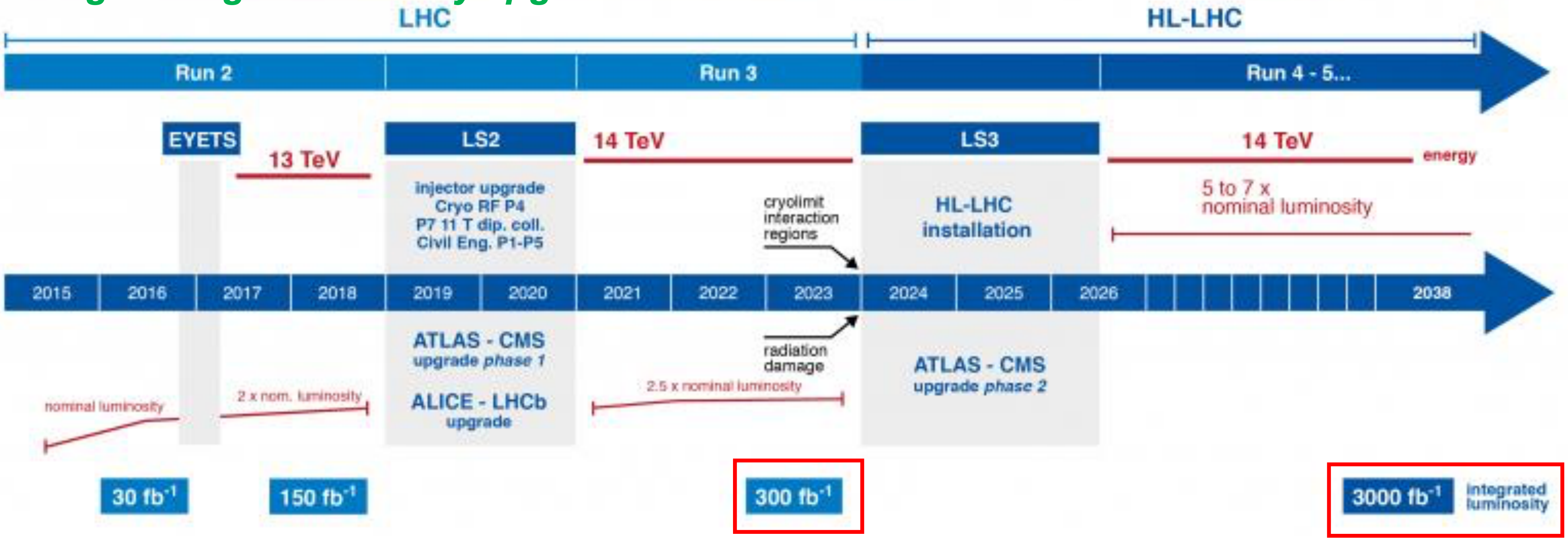
Passed 100 fb^{-1} in October 2017

A test collision recorded by the CMS experiment on 12 April 2018. The CMS collaboration uses these first collisions to prepare for data taking, fine-tuning and powering on various subsystems as needed. (Image: CERN)



The path to High Luminosity LHC

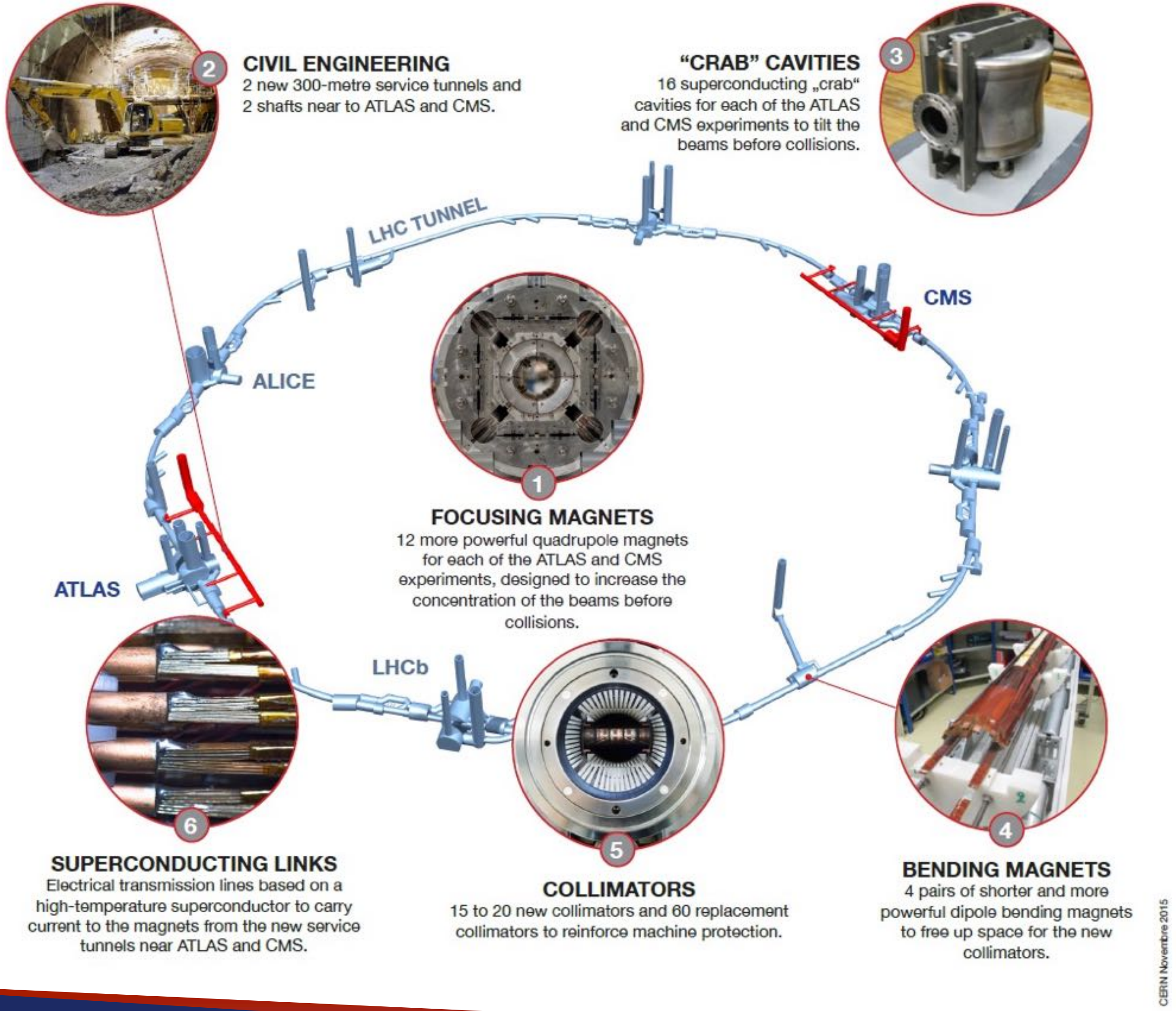
- LHC Run2 currently at 13 TeV, integrated luminosity of >120 fb^{-1} delivered to ATLAS/CMS by end 2017.
- Plan to increase to 14 TeV after Long Shutdown 2.
- After LS3 ending 2026, enter HL-LHC: aim to reach **5 - 7x nominal luminosity**.
- ***EU strategy 2013: Europe's top priority should be exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and detectors.***



Run 3 target

HL-LHC target

High Luminosity LHC – how?

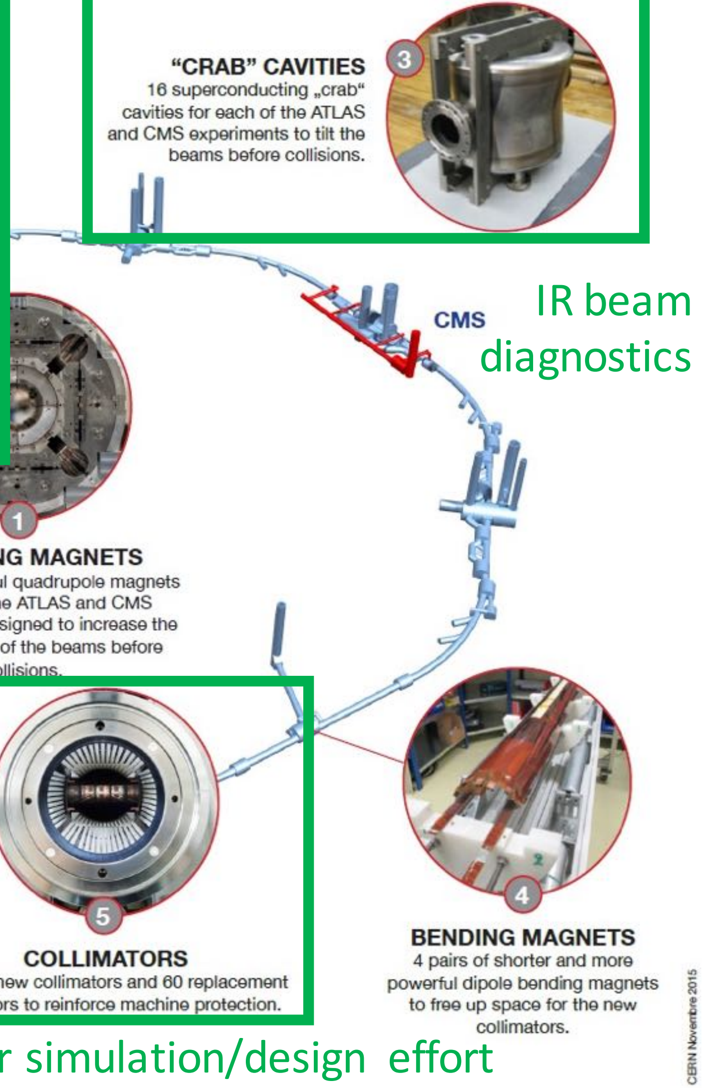


- **Lower beta* (~15 cm)**
  - New inner triplets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam

Major UK contributions to design & build HL-LHC

UK delivered crab cavity prototype to SPS

Complete Crab Cavity Cryomodule installed



IR beam diagnostics

UK built prototypes

Major simulation/design effort

UK institutes on ***HL-LHC-UK***

£8M CERN-STFC investment in UK

HiLumi HL-LHC PROJECT

- The University of Manchester
- The Cockcroft Institute of Accelerator Science and Technology
- Lancaster University
- University of Liverpool
- Royal Holloway University of London
- John Adams Institute for Accelerator Science
- University of Southampton
- University of Huddersfield
- ASTeC

LHC Injectors Upgrade

+ new injector diagnostics

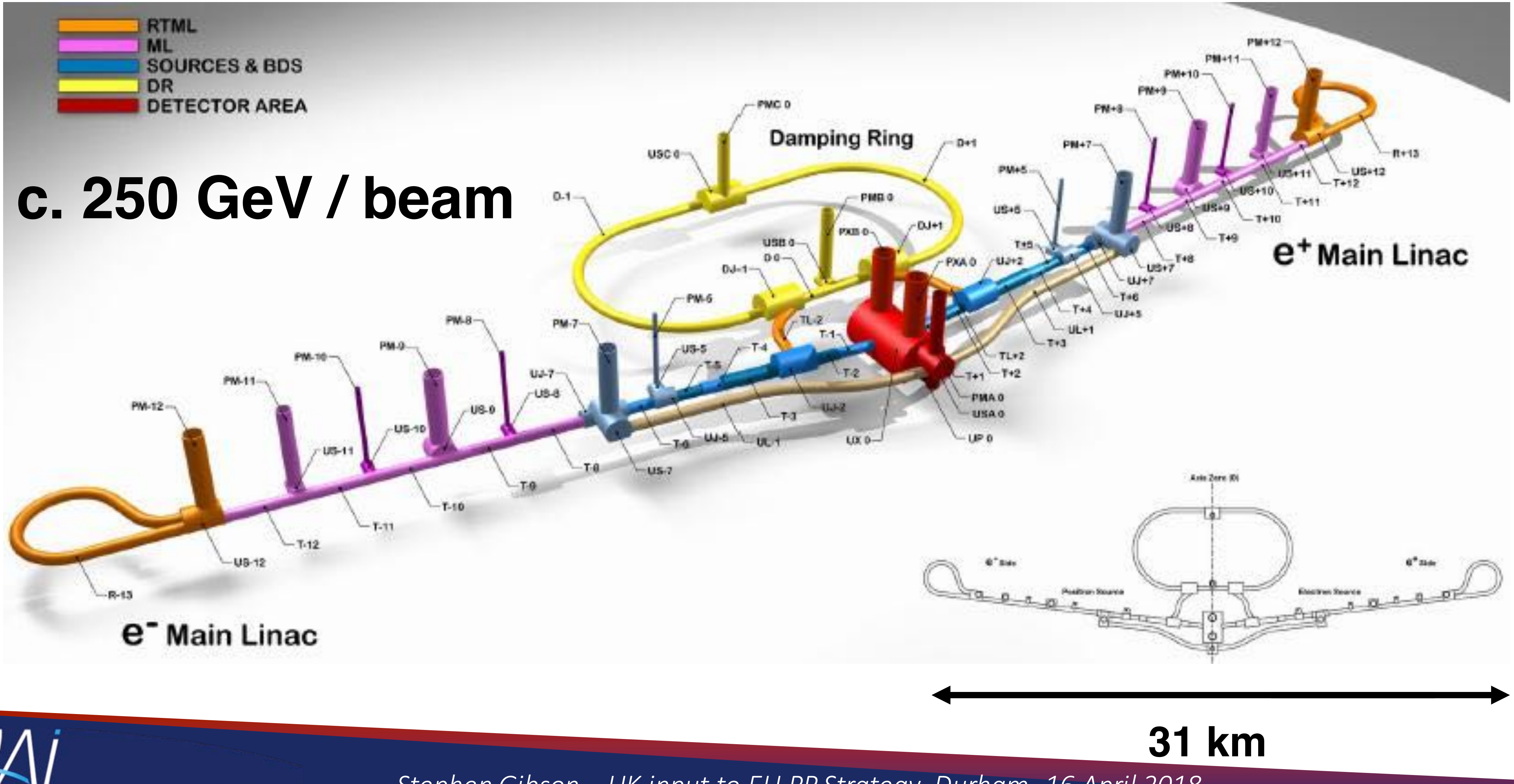
Linac2:
50 MeV protons

Linac4:
160 MeV H- ions
http://home.cern/about/accelerators/linear-accelerator-4

Near Future Colliders

International Linear Collider: ILC

- ***Higgs factory*** e^+e^- collider for precise measurements of Higgs & top ++, complementary to ***LHC***



International Linear Collider: ILC

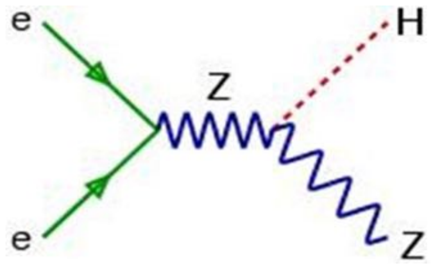
- ***EU strategy 2013:*** *'There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.'*
- ***ILC TDR complete, mature technology.***
- ***XFEL at DESY*** *essentially a 20 GeV prototype:*

e+e- Higgs factory

e+e- annihilations:

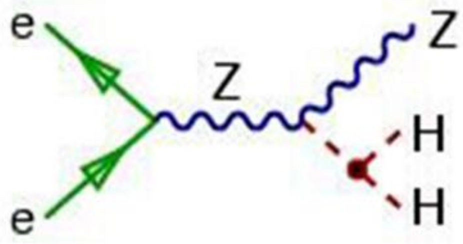
E > 91 + 125 = 216 GeV

E ~ 250 GeV



E > 91 + 250 = 341 GeV

E ~ 500 GeV



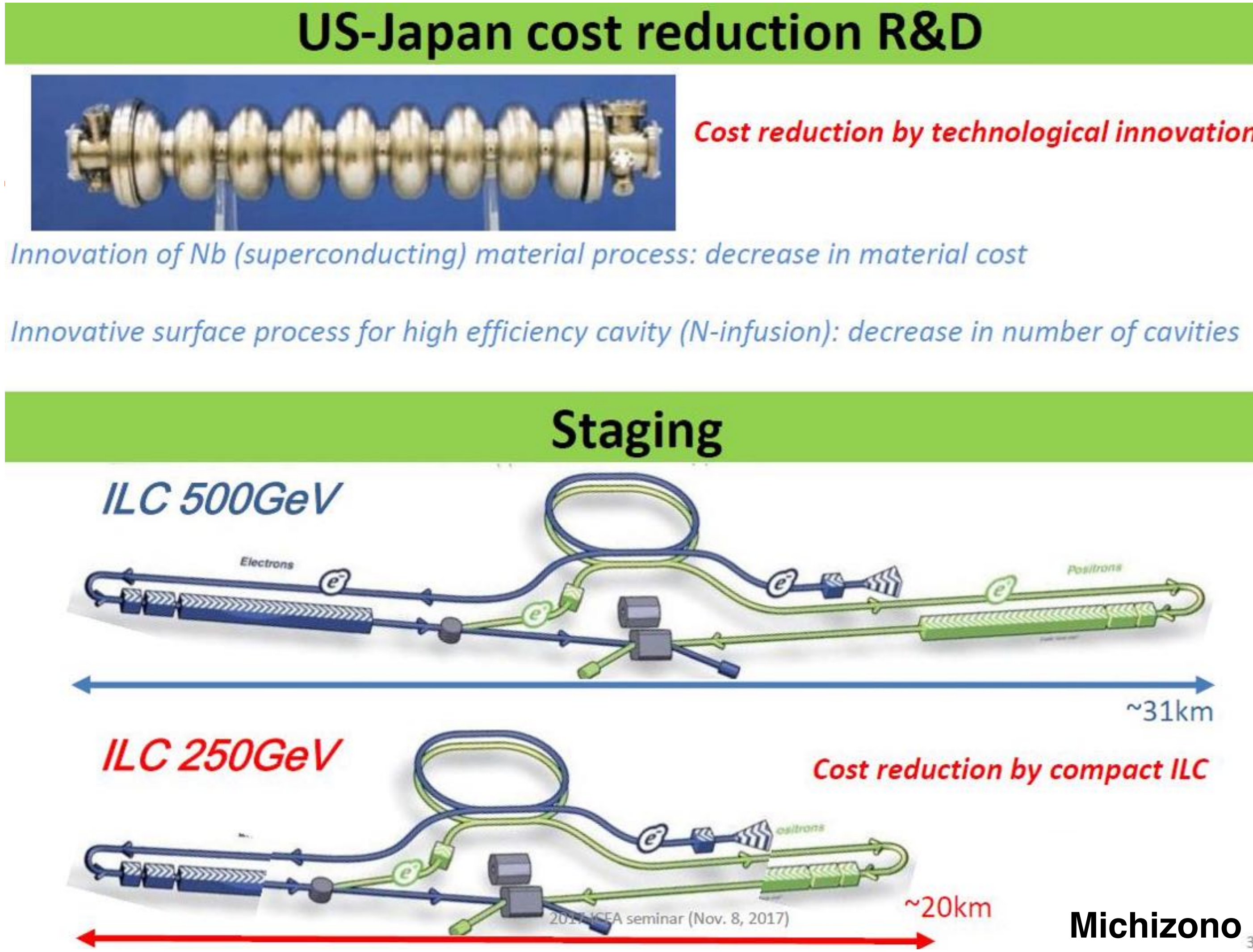
Phil Burrows

International Linear Collider: ILC

ILC in Japan?

meeting of Lyn Evans and Prime Minister Abe, March 27, 2013

- *Early optimism from Japan to host ILC.*
- *Proposed staging of 250 GeV CoM, Higgsstrahlung (saves ~40% cost).*
- *Decision expected by end of 2018.*



Michizono

ICFA STATEMENT ON THE ILC OPERATING AT 250 GEV AS A HIGGS BOSON FACTORY

The discovery of a Higgs boson in 2012 at the Large Hadron Collider (LHC) at CERN is one of the most significant recent breakthroughs in science and marks a major step forward in fundamental physics. Precision studies of the Higgs boson will further deepen our understanding of the most fundamental laws of matter and its interactions.

The International Linear Collider (ILC) operating at 250 GeV center-of-mass energy will provide excellent science from precision studies of the Higgs boson. Therefore, ICFA considers the ILC a key science project complementary to the LHC and its upgrade.

ICFA welcomes the efforts by the Linear Collider Collaboration on cost reductions for the ILC, which indicate that up to 40% cost reduction relative to the 2013 Technical Design Report (500 GeV ILC) is possible for a 250 GeV collider.

ICFA emphasises the extendibility of the ILC to higher energies and notes that there is large discovery potential with important additional measurements accessible at energies beyond 250 GeV.

ICFA thus supports the conclusions of the Linear Collider Board (LCB) in their report presented at this meeting and very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a center-of-mass energy of 250 GeV as an international project[1], led by Japanese initiative.

1 In the LCB report the European XFEL and FAIR are mentioned as recent examples for international projects.

Ottawa, November 2017

Geoffrey Taylor, CoEPP, The University of Melbourne

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

meeting of L

- Early
- Propo Higgs
- Decis

ROYAL HOLLOWAY UNIVERSITY OF LONDON

D

echnological innovation

al cost

e in number of cavities

~31km

tion by compact ILC

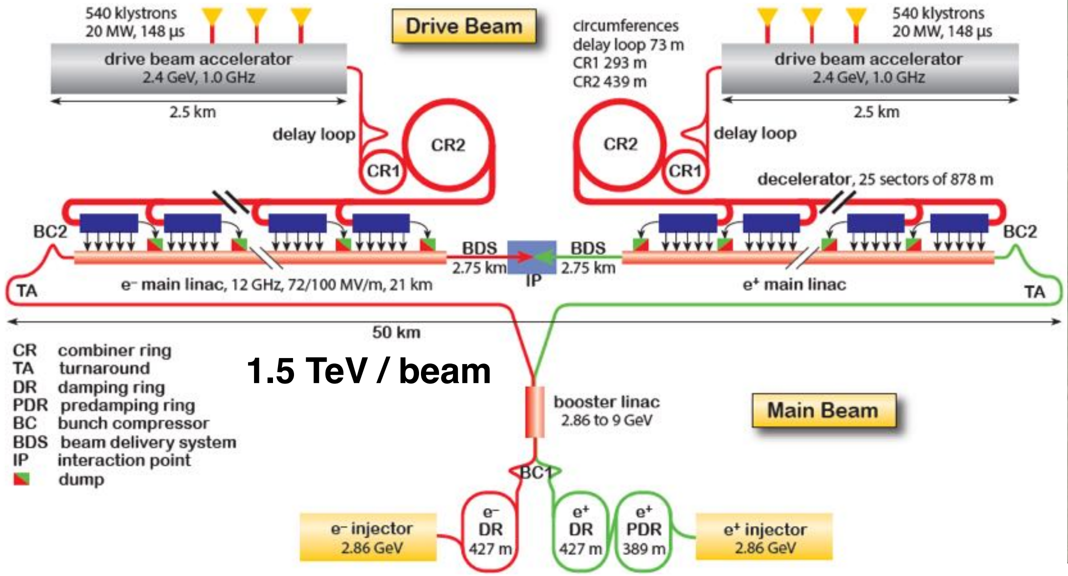
0km

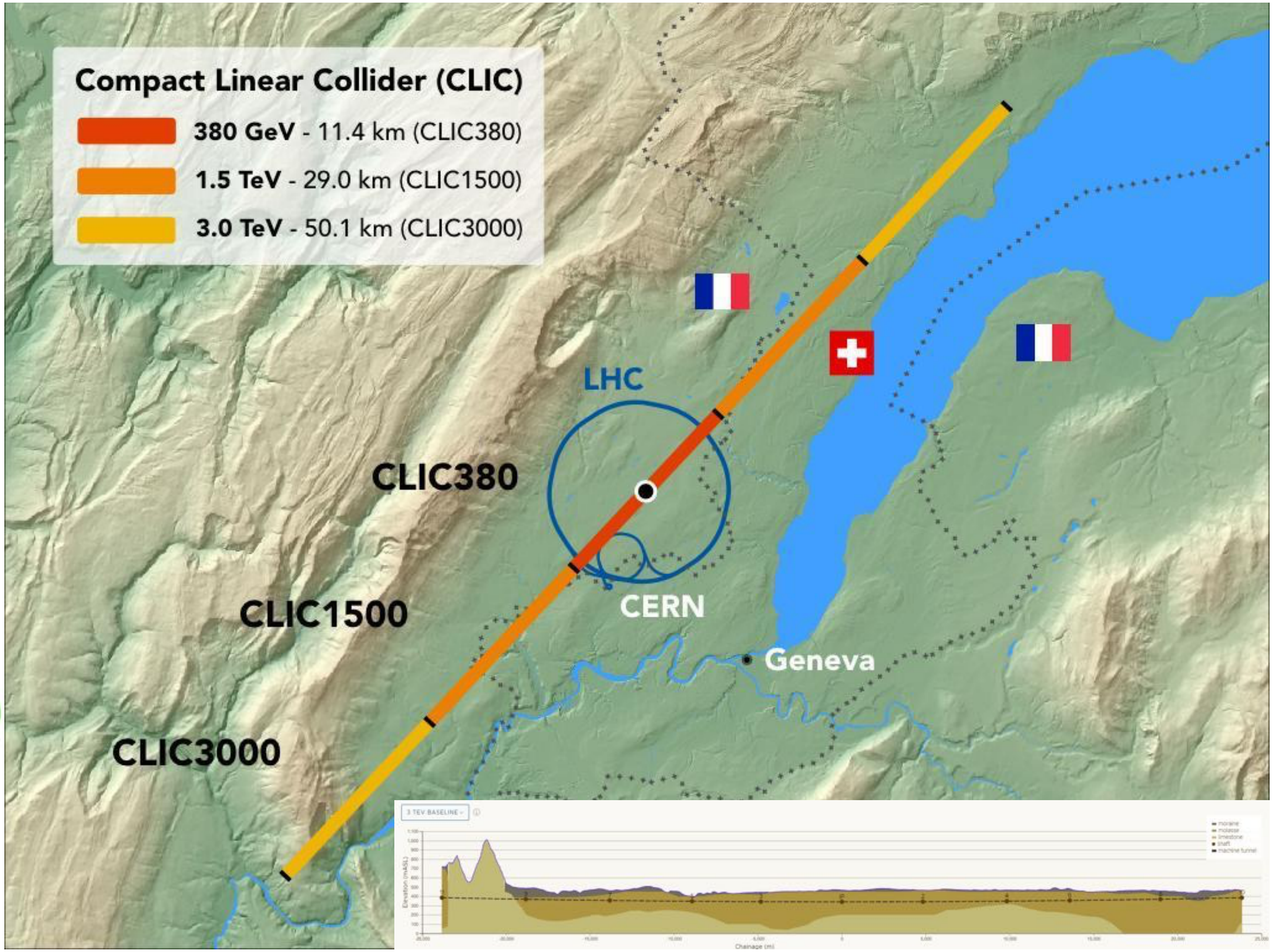
Michizono

John Adams Inst

Compact Linear Collider: CLIC

- ***Drive beam technology demonstrated*** *at CTF3, CERN, acc. gradient upto 150 MV/m.*
- *Operation **100 MV/m**, 135 MW at 12 GHz.*
- Project staging to ***multi-TeV e⁺e⁻***
  - **380 GeV, 1.5 TeV ,3.0 TeV**
- *Design report due in Dec 2018 as input to EU strategy.*



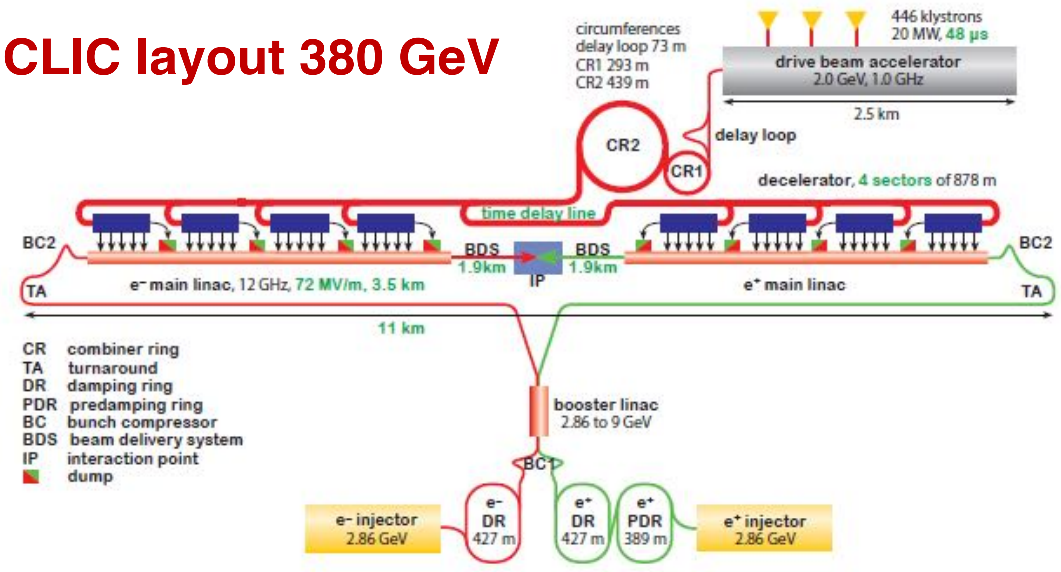


UK institutes contributed to design; Phil Burrows – CLIC spokesperson

Compact Linear Collider: CLIC

- ***Drive beam technology demonstrated** at CTF3, CERN, acc. gradient upto 150 MV/m.*
- *Operation **100 MV/m**, 135 MW at 12 GHz.*
- Project staging to ***multi-TeV e^+e^-***
  - **380 GeV, 1.5 TeV ,3.0 TeV**
- *Design report due in Dec 2018 as input to EU strategy.*

CLIC layout 380 GeV

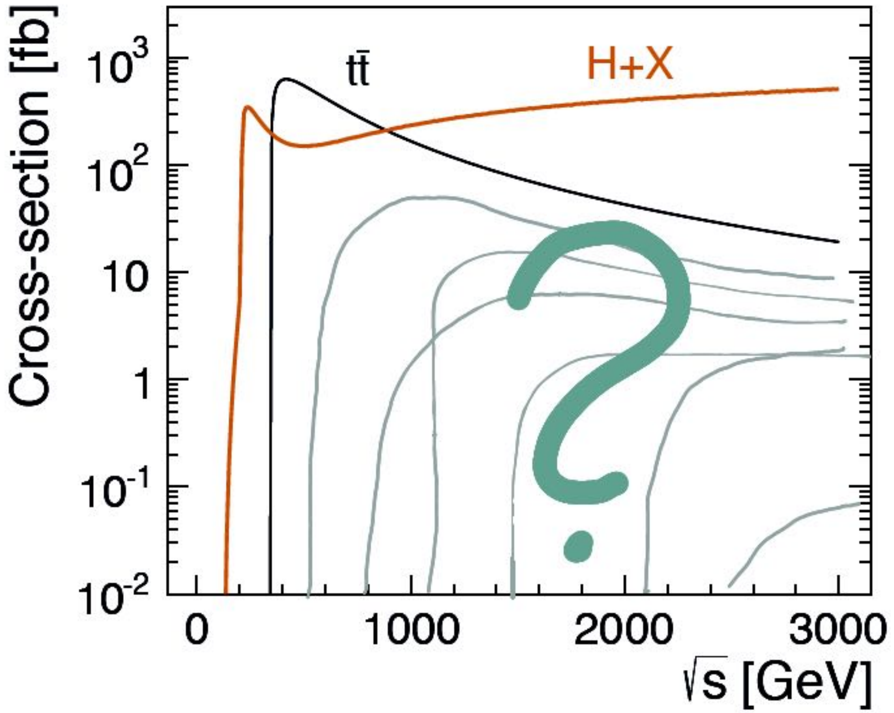


LINEAR COLLIDER COLLABORATION

CLIC physics context

Energy-frontier capability for electron-positron collisions,

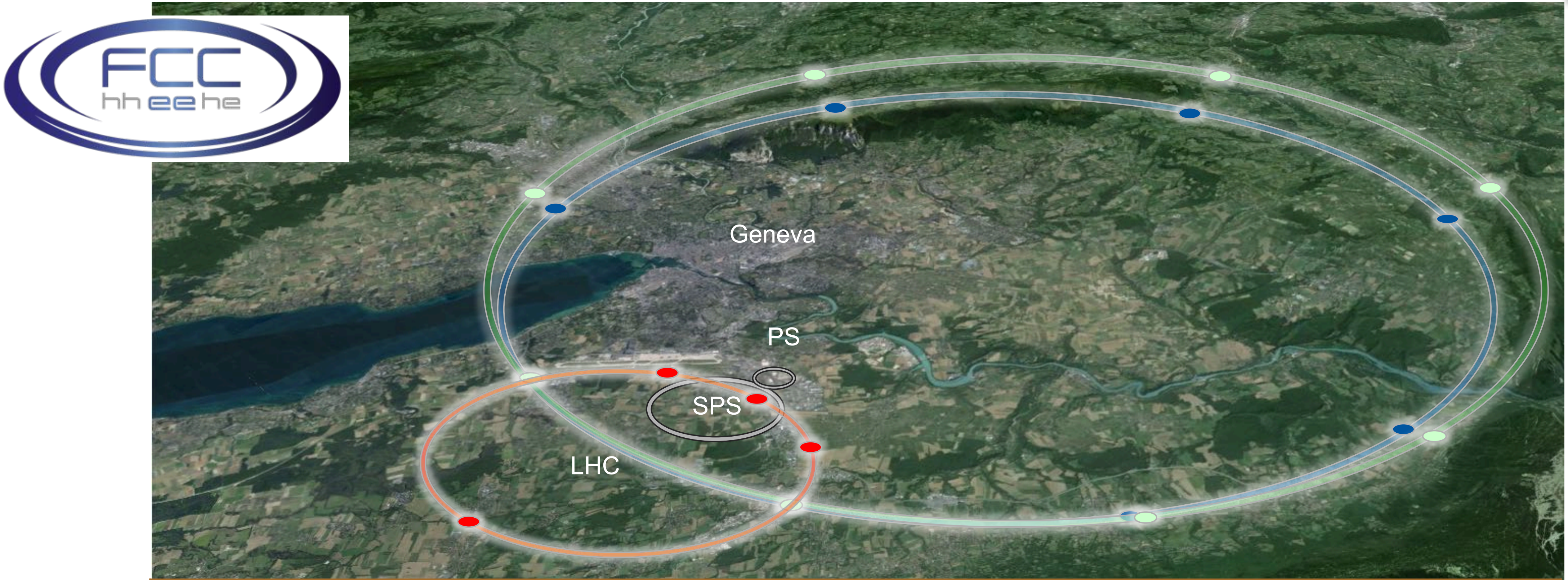
for precision exploration of Higgs + top, as well as potential new physics that may emerge from LHC



UK institutes contributed to design; Phil Burrows – CLIC spokesperson

Proposed Circular Colliders in China

Future Circular Colliders: hadrons

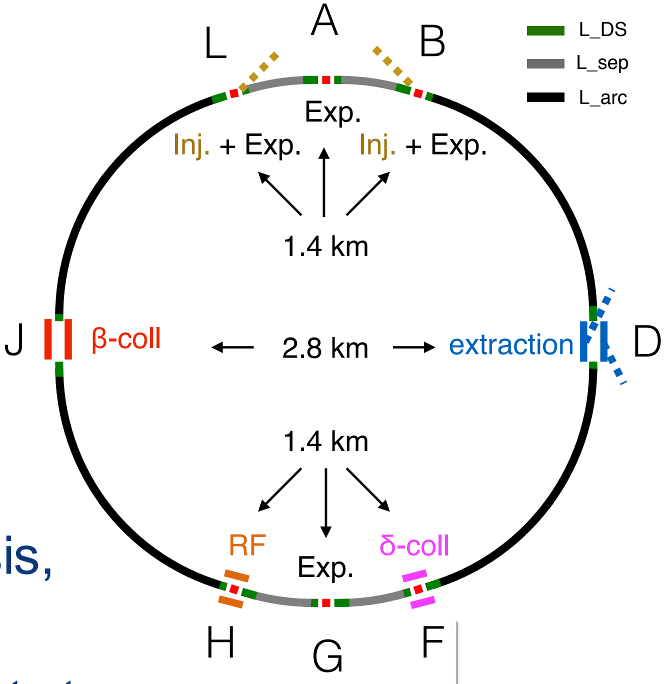


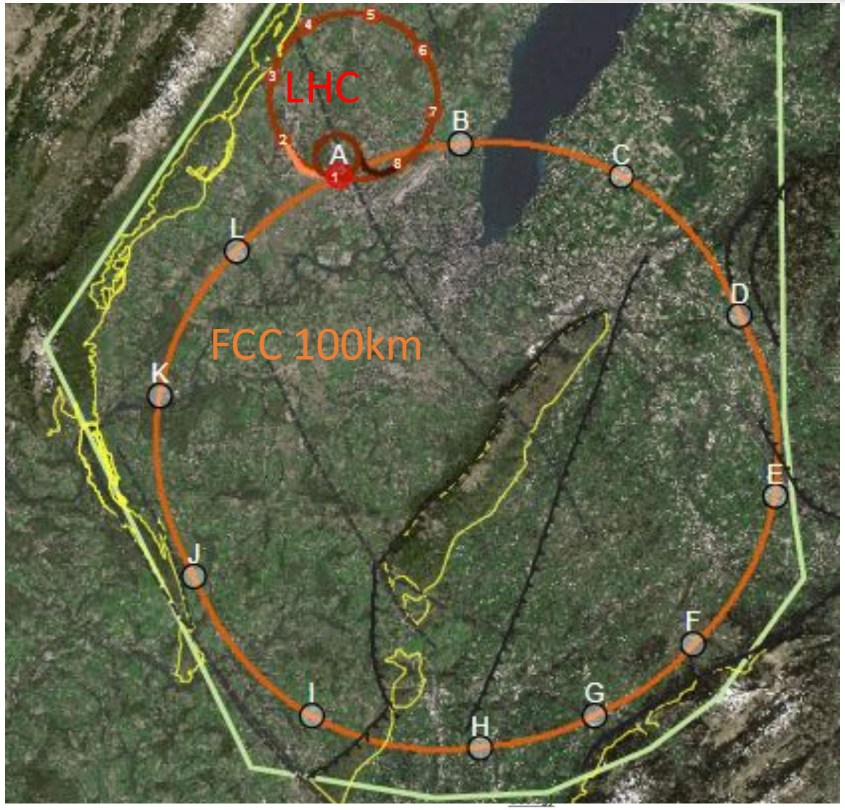
parameter	FCC-hh	SppC	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100	75	27	14	14
dipole field [T]	16	12	16	8.33	8.33
circumference [km]	97.75	100	26.7	26.7	26.7
synchr. rad. power / ring [kW]	2400	1100	101	7.3	3.6
stored energy/beam [GJ]	8.4	9.2	1.3	0.7	0.36

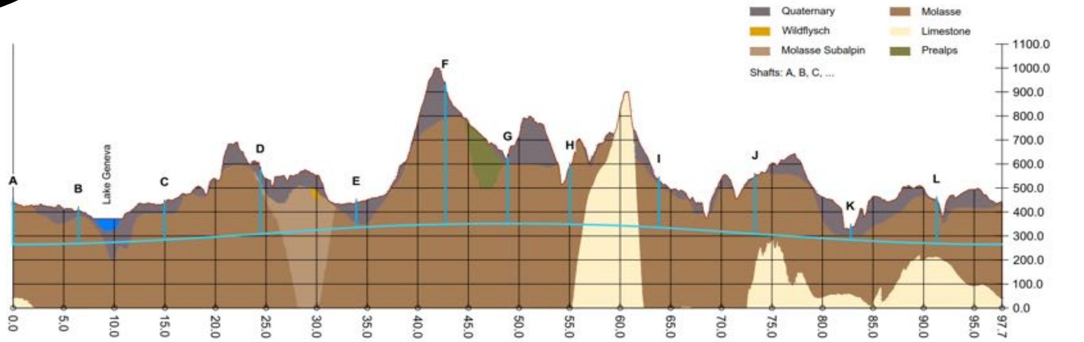
Future Circular Collider: FCC (hh ee he)

- ***Advanced design studies for a 100 km circular collider:***

>470 registered participants







F. Zimmerman J. Osborne & J. Stanyard

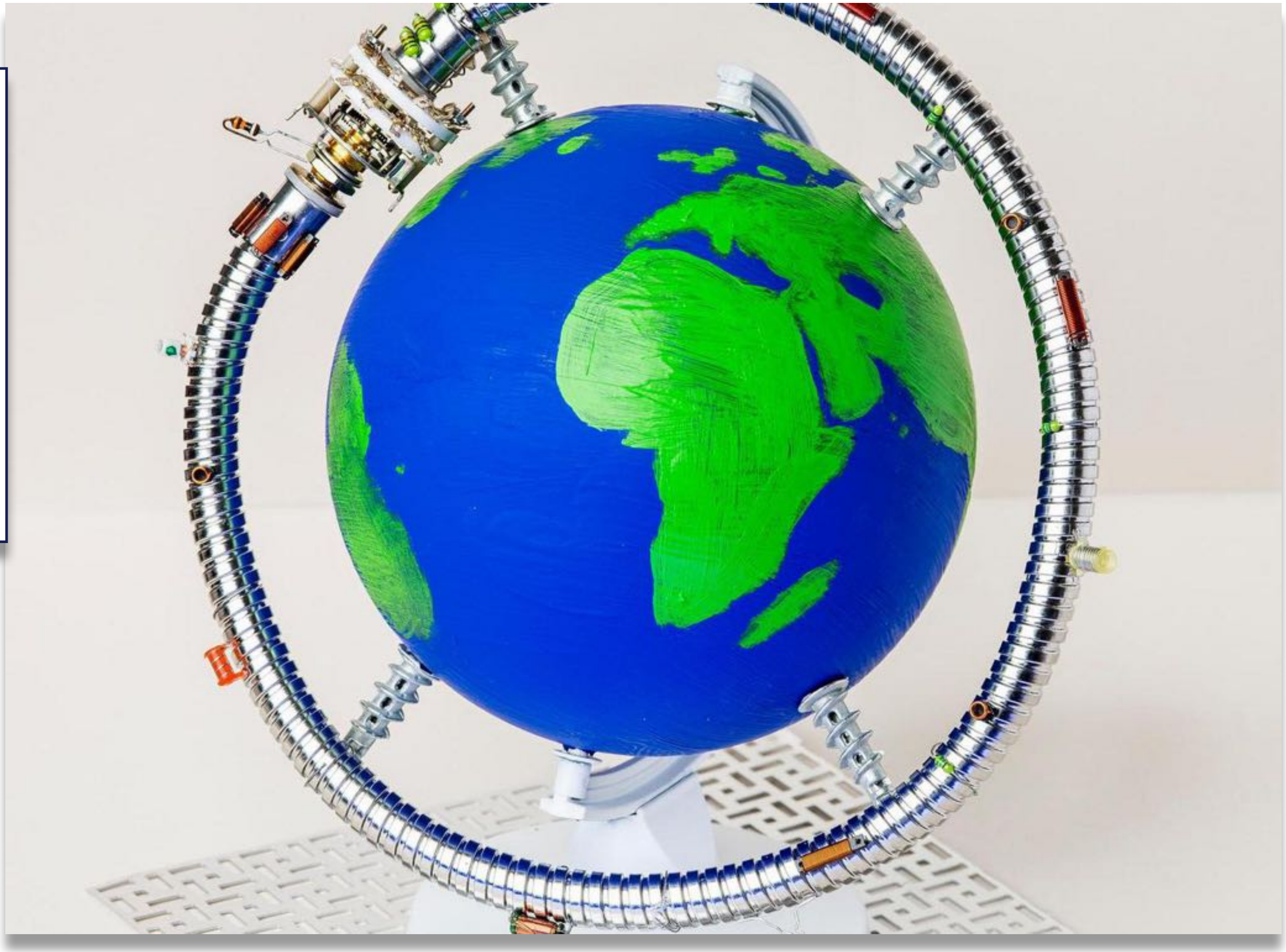
- ***pp*-collider (*FCC-hh*) → main emphasis, defining infrastructure requirements**
- ***e$^+$e$^-$* collider (*FCC-ee*), as potential first step**
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e$^-$ from ERL

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Dutch press last week catch on to Physicists' ambitions:

deVolkskrant

Hoe moet de grootste deeltjesversneller op aarde eruit gaan zien?



"What might the largest particle accelerator on earth look like?"

Considering the options: what to build when?

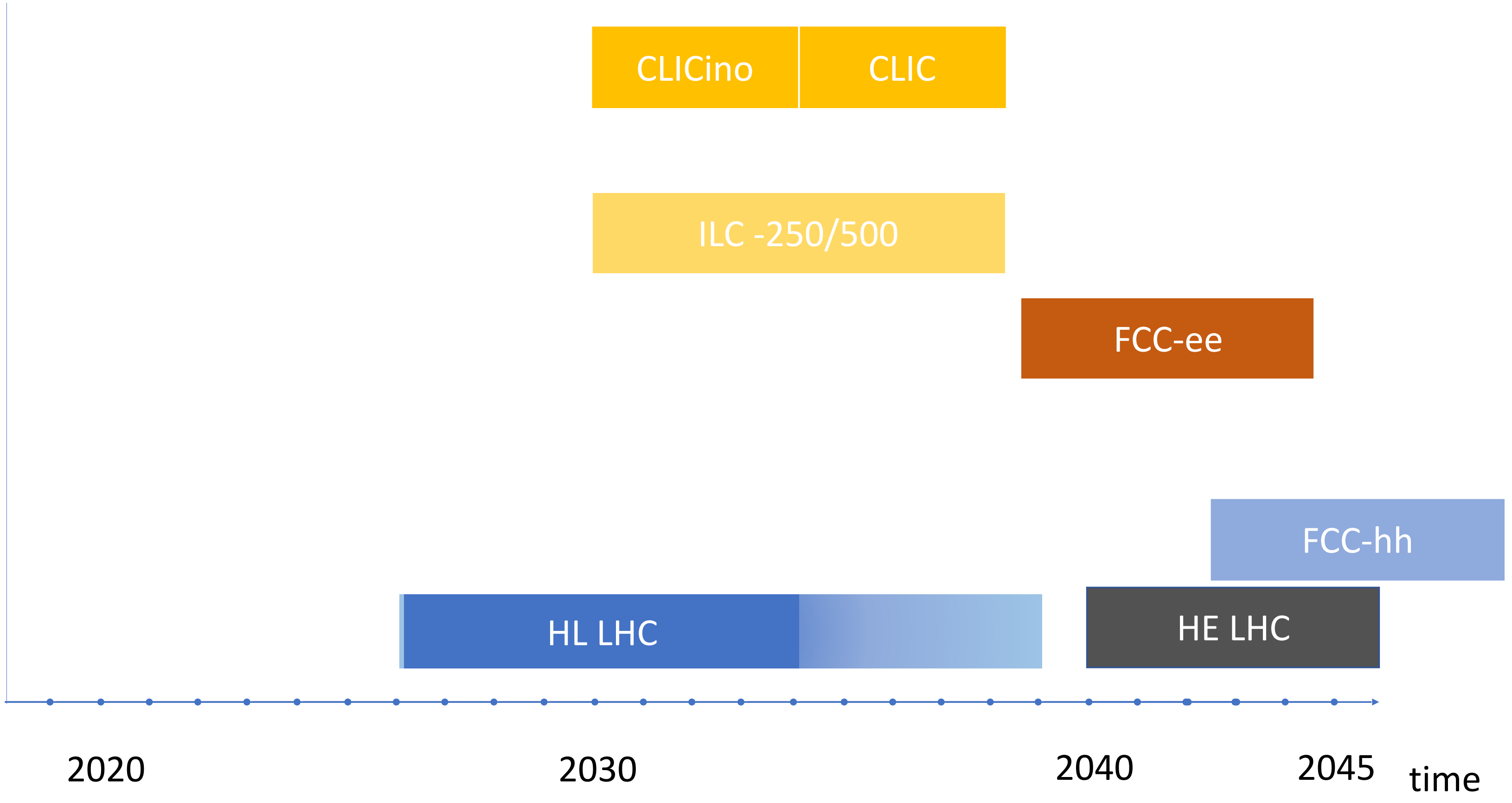
- ***Many options for future accelerators: how to decide which to build and when?***
  - HE-LHC ; FCC-ee, FCC-he, FCC-hh
  - ILC (250 /500 GeV), CLIC (380 GeV CLICino, 1.5, 3.0 TeV)
  - Which combination / sequence of construction?

    HE-LHC —> FCC-hh versus
    HE-LHC —> FCC-ee —> FCC-hh versus
    FCC-ee —> FCC-hh
    CLICino —> HE-LHC —> Muon collider

    G. Dissertori
  - What scenarios are 'realistic', 'feasible', 'dangerous' …?
  - How would construction of ILC in Japan or Chinese colliders impact plans for future collider at CERN?

➢ *Depends on **IPPP:** **I**nnovation, **P**hysics, **P**rice & **P**olitics:*

Considering the options: what to build when?

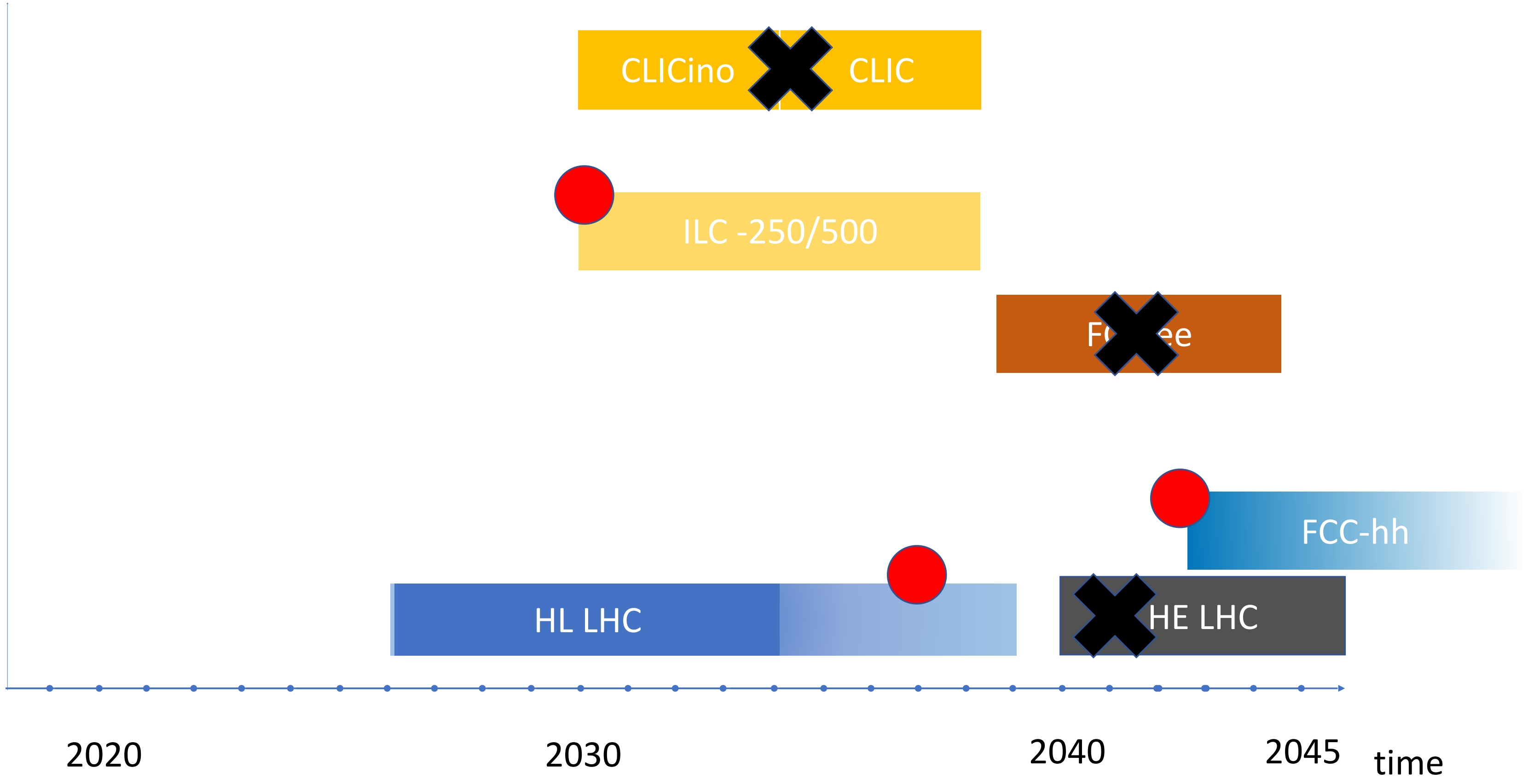


Legend: (red circle) = **built** (black cross) = **killed**

G. Dissertori

Considering the options: what to build when?

Scenario 1a: ILC + FCC-hh

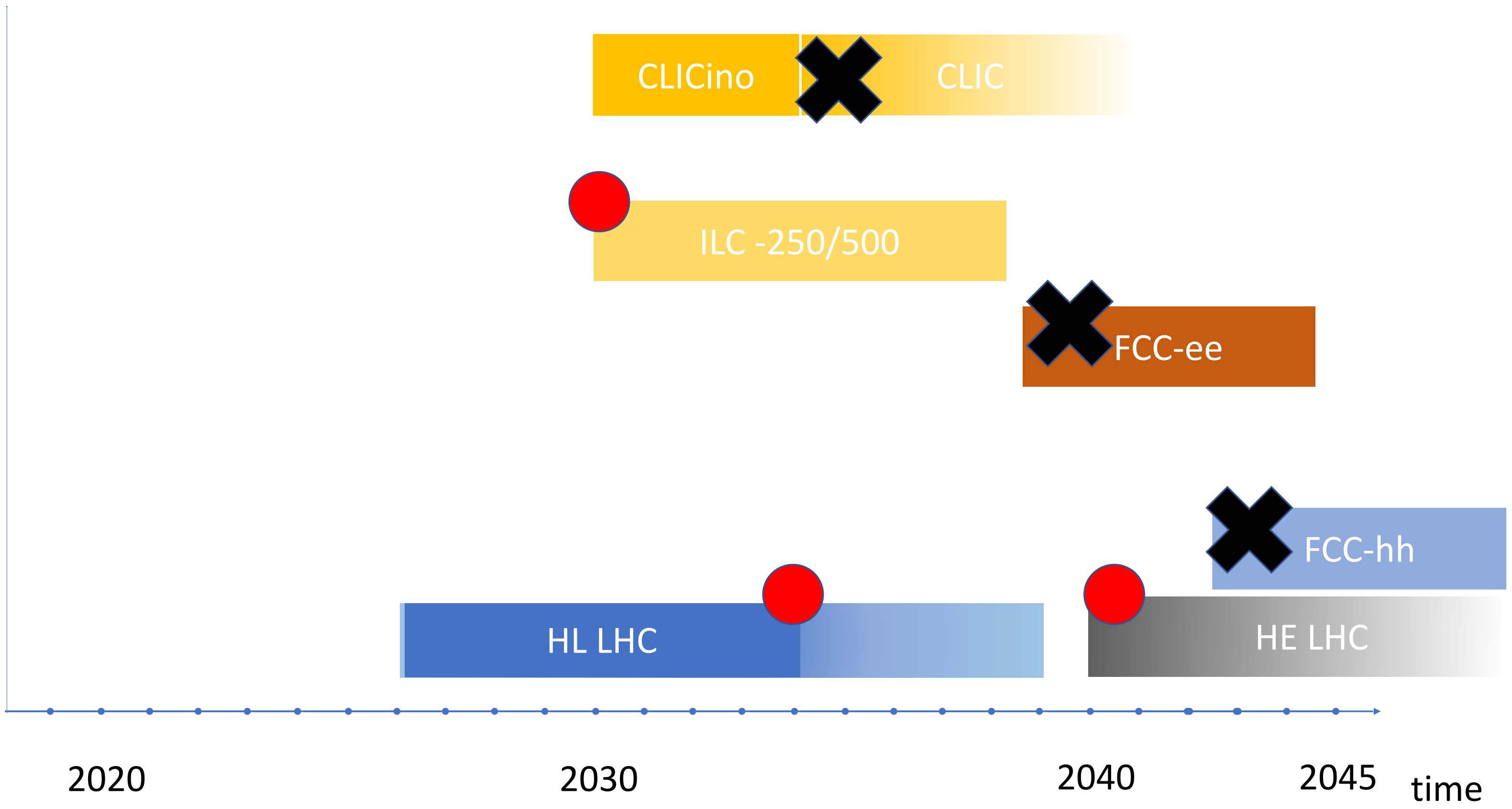


G. Dissertori

Considering the options: what to build when?

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Scenario 1b: ILC + HE-LHC

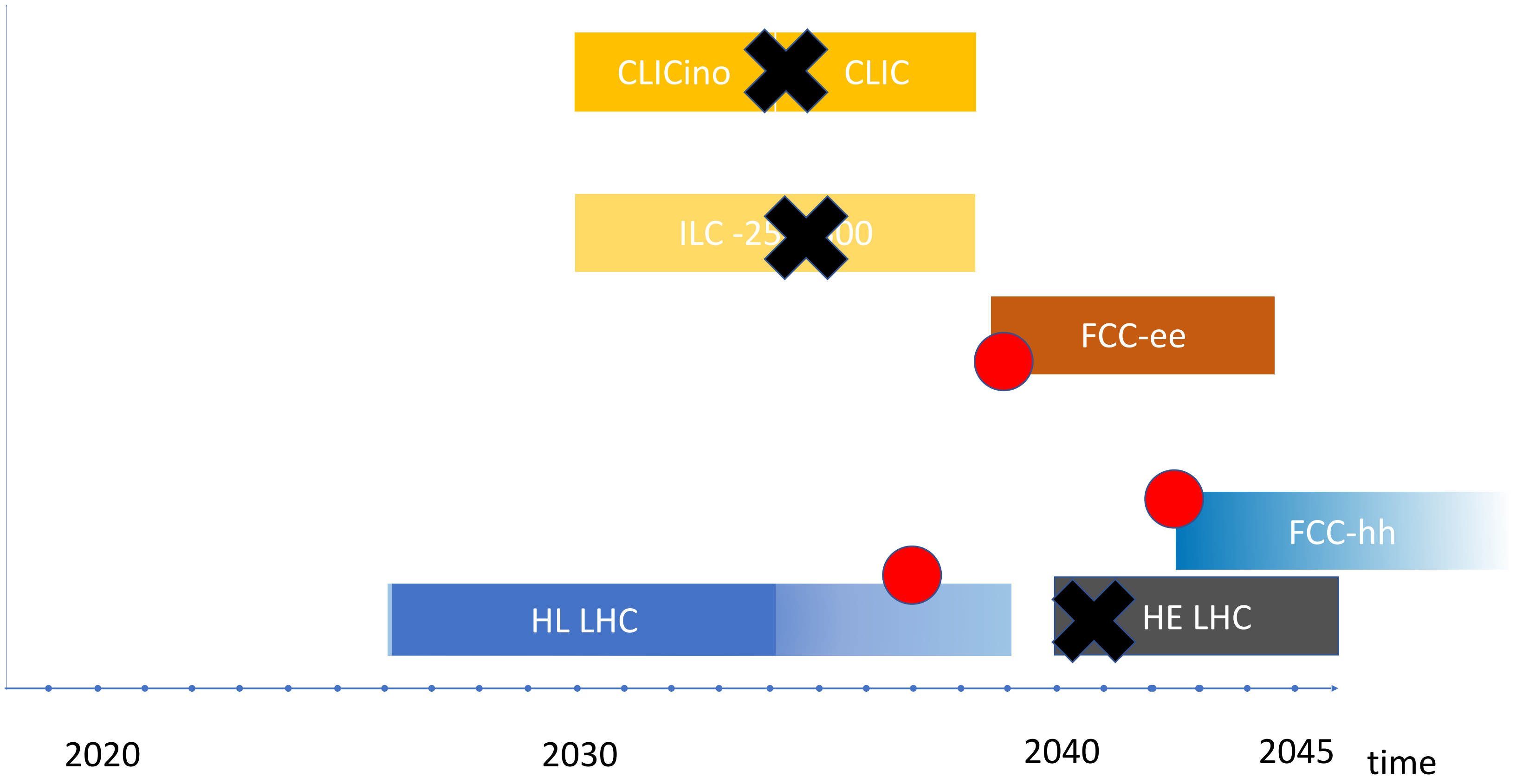


G. Dissertori

Considering the options: what to build when?

ROYAL HOLLOWAY UNIVERSITY OF LONDON

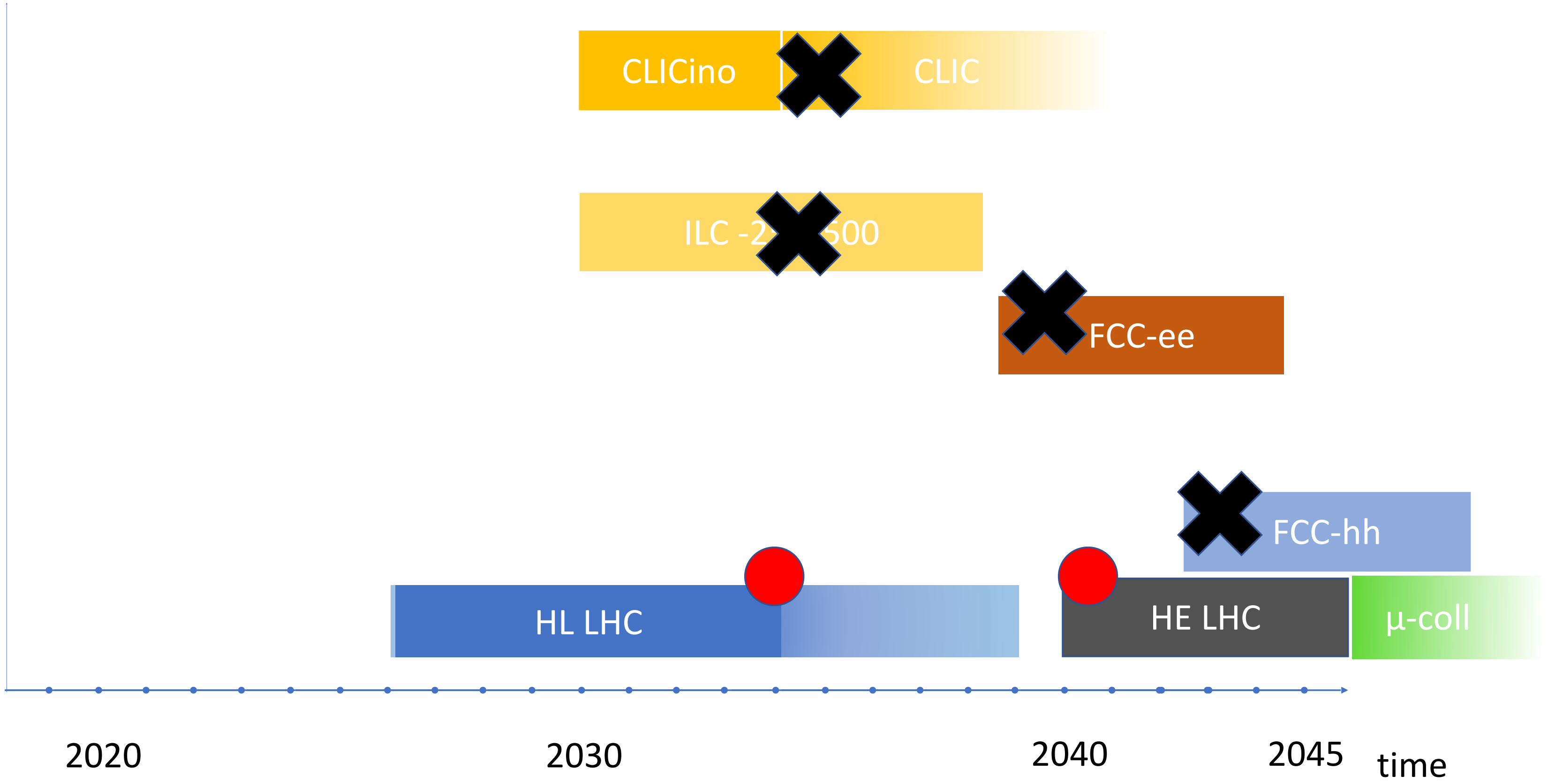
Scenario 2a: FCC-ee + FCC-hh



G. Dissertori

Considering the options: what to build when?

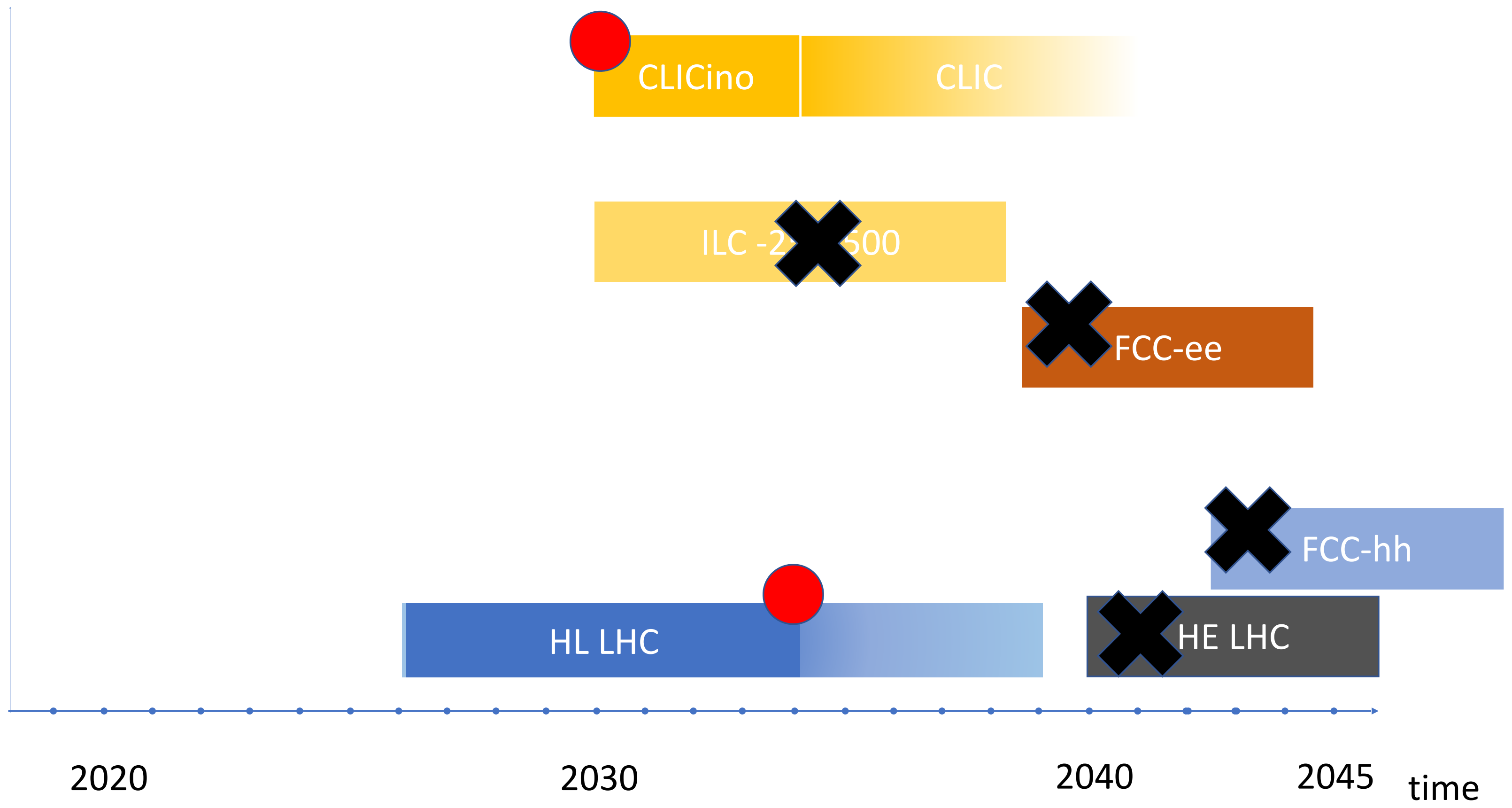
Scenario 2b: HE-LHC + mu-C



G. Dissertori

Considering the options: what to build when?

Scenario 2c: CLIC



G. Dissertori

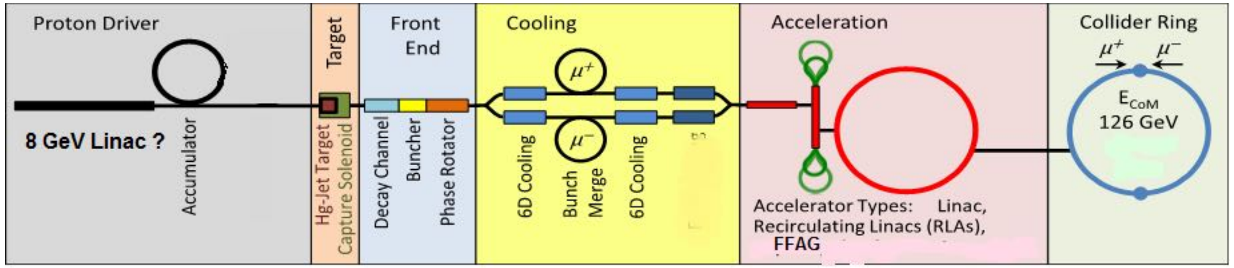
Far Future: Novel Acceleration

Higgs factory: which flavour?

Lenny Rivkin

Muon Collider concepts

- *μ+μ- main advantage over **e+e-** is less synchrotron radiation: TeV collider fits in small ring*

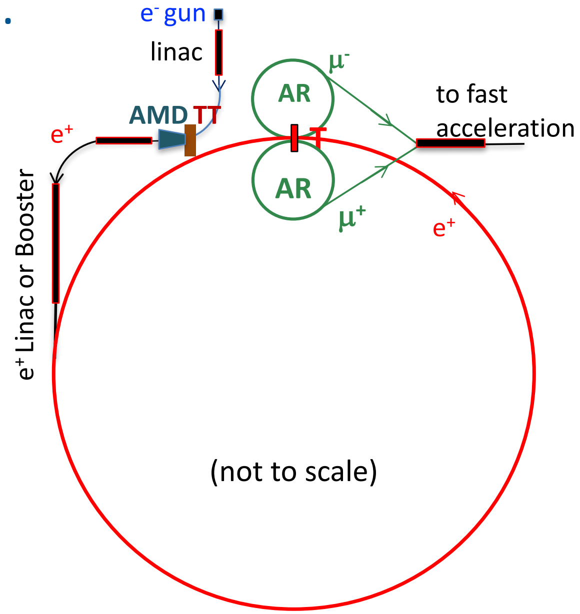


- ***'Traditional' muon collider***
  - High intensity protons on target generate pions which quickly decays:

    - Large 6D emittance beams must be cooled:
    - Muon ionization cooling demonstration by MICE, program ending now…

- **New idea for muon collider** (M. Boscolo)
  - High intensity 45 GeV e+ beam hits thin target (0.01 rad length) collides with e- in target, giving muon pair just above threshold:
  - Small emittance and small energy spread, therefore no need for cooling.
  - 6.2 km storage ring.

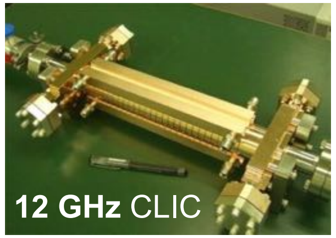
$$e^+e^- \rightarrow \mu^+\mu^-$$

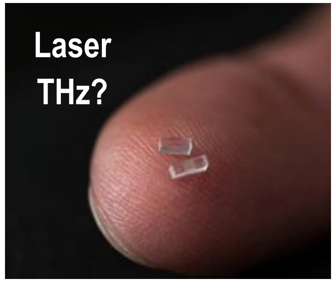


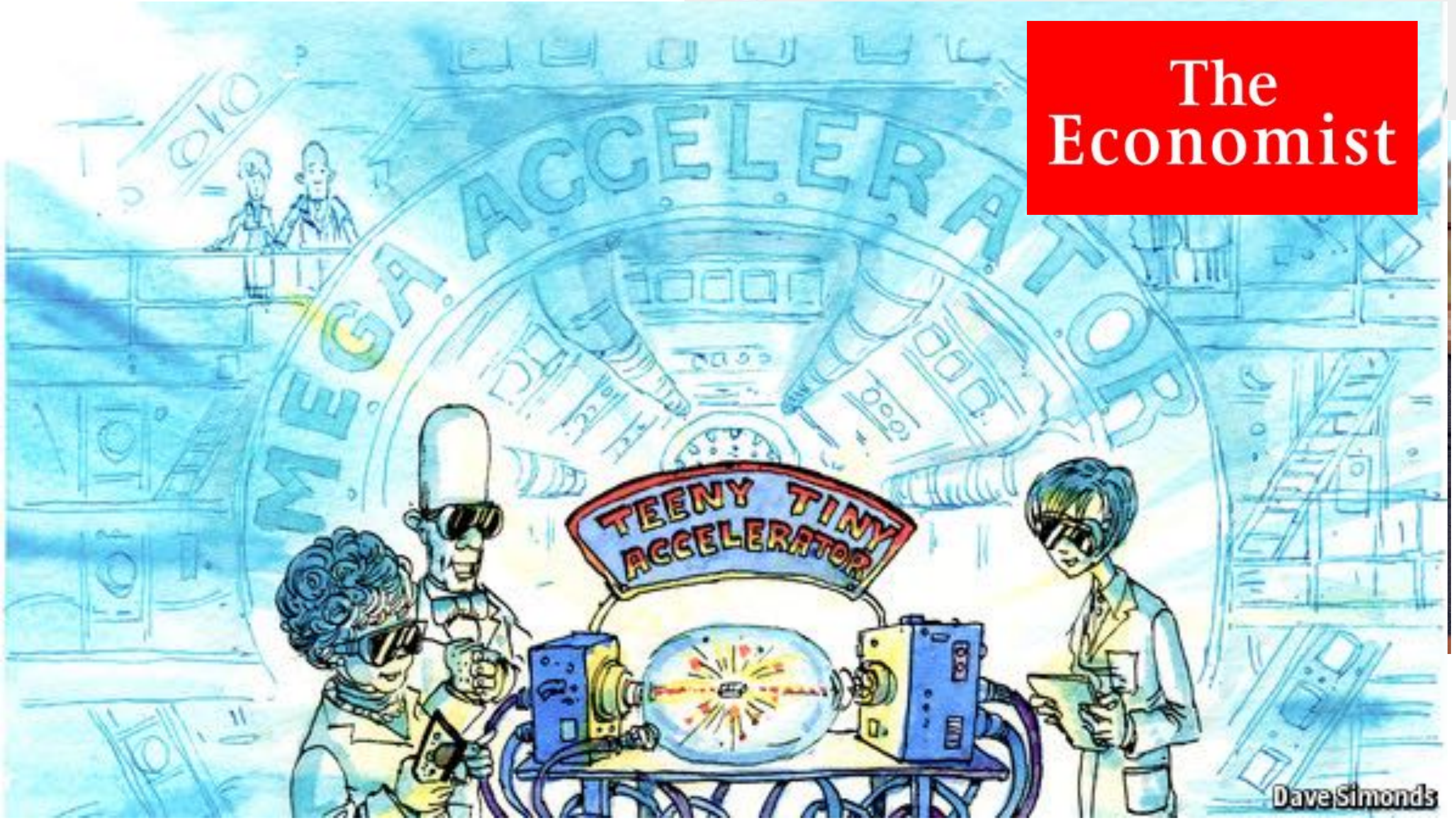
'Table top' accelerators??

- ***How to increase acceleration gradient beyond conventional RF 100 MV/m (CLIC technology)?***

RF Acceleration: scaling with frequency







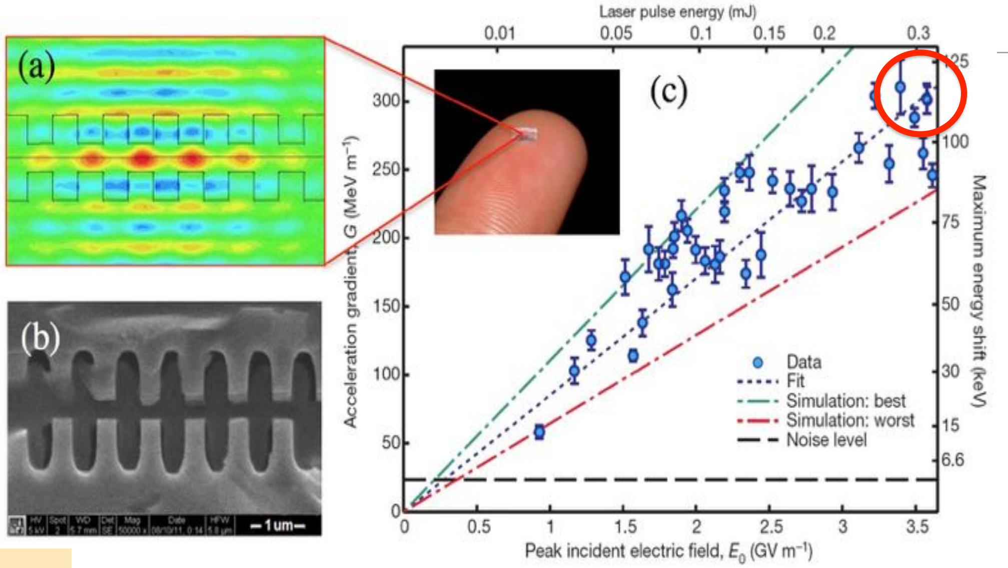
Lenny Rivkin

Laser / THz accelerators

- ***Dielectric Laser Accelerators***
  - High electric field at optical wavelengths:
  - Gradients < 0.3-1 GeV/m
  - Staging rather inefficient, lowers average gradient
  - Laser efficiency -> high power requirements.

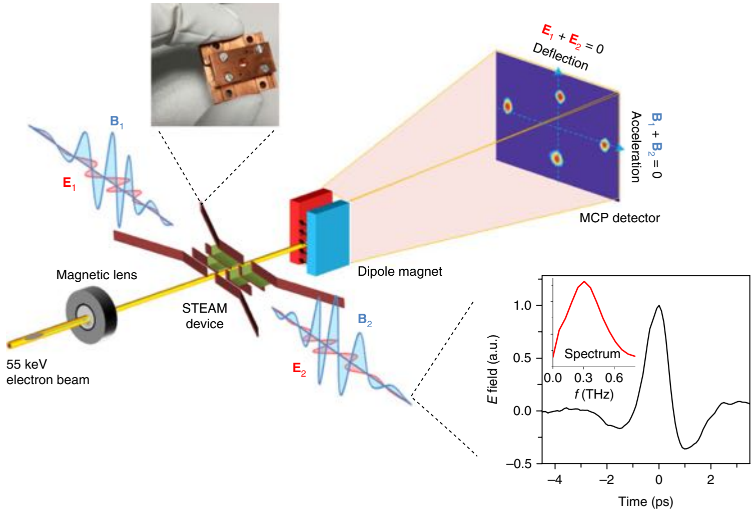
Peak gradient as a function of Laser Field

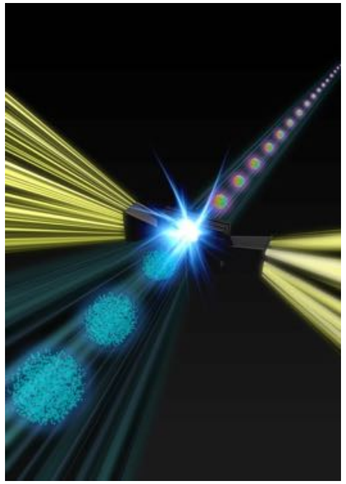
SLAC NATIONAL ACCELERATOR LABORATORY

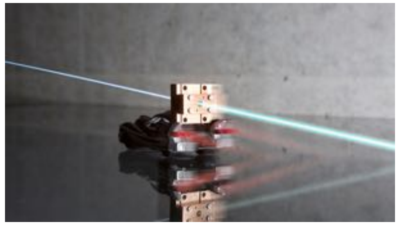


Peralta et al., Nature **503**, 91 (2013)

- ***THz structures***
  - Easier to manufacture / control at THz wavelength.
  - Recent demonstration of THz accelerated beams (>30 keV so far), + new developments in UK.







nature photonics

ARTICLES

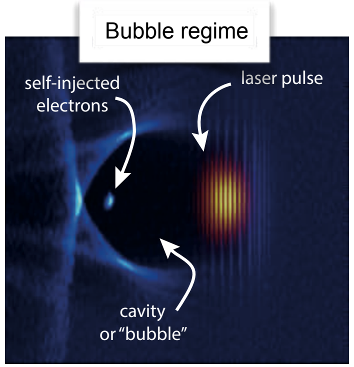
https://doi.org/10.1038/s41566-018-0138-z

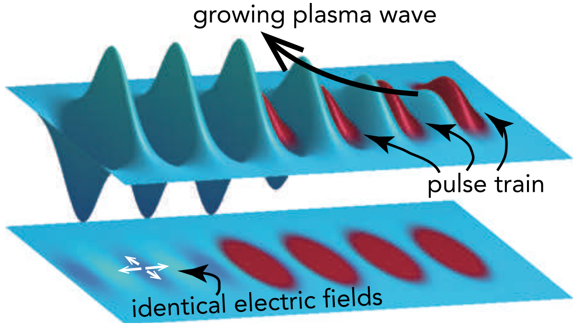
Segmented terahertz electron accelerator and manipulator (STEAM)

Dongfang Zhang[1,2,5*], Arya Fallahi[1,5], Michael Hemmer[1], Xiaojun Wu[1,4], Moein Fakhari[1,2], Yi Hua[1], Huseyin Cankaya[1], Anne-Laure Calendron[1,2], Luis E. Zapata[1], Nicholas H. Matlis[1] and Franz X. Kärtner[1,2,3]

Laser & beam driven plasma wakefield: **100 GV/m**

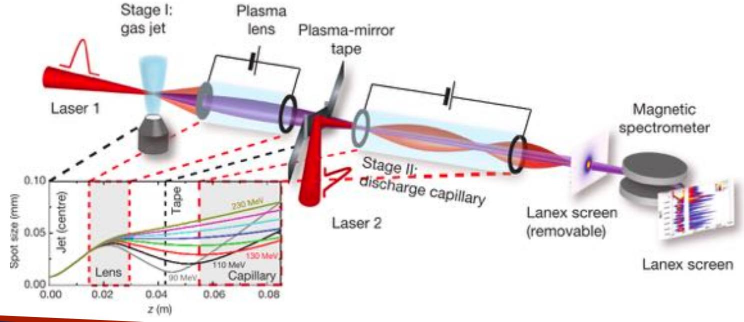
- ***Laser-plasma accelerators*** *(1 GeV demonstrated)*
  - Laser pulse in plasma filled capillary enables electrons to surf a plasma density wave.
  - Recent exciting developments in multi-pulse schemes and staging at low energies.





S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

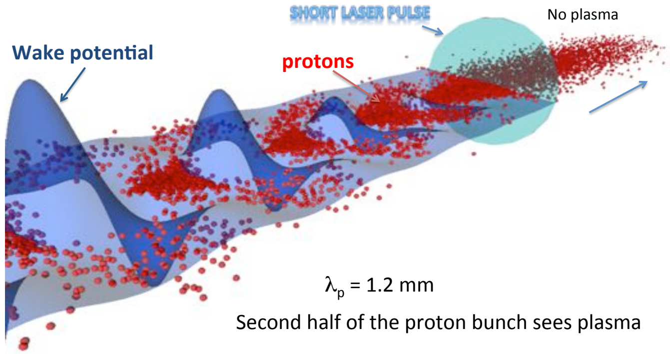
LBNL have demonstrated staging at low energies (~200 MeV increased to ~300 MeV).

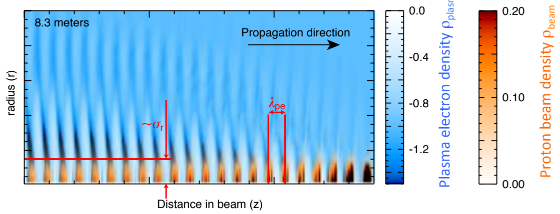


Steinke, S. et al. Multistage coupling of independent laser-plasma accelerators. Nature 530, 190–193 (2016).

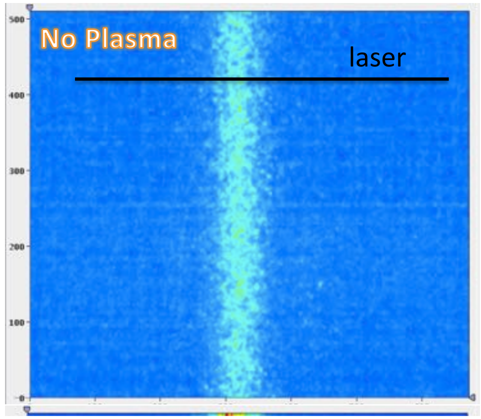
Van Tilborg, J. et al. Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams. Phys. Rev. Lett. 115, 184802 (2015).

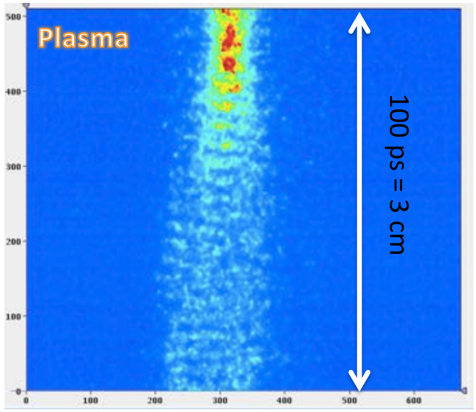
- ***Proton driven plasma wakefield***
  - 12cm, 3x10^{11} proton bunch drives plasma wakefield in cell at SPS.
  - Acceleration of 15 MeV injected e- to >1GeV
  - Successful observation of self-modulation last year:



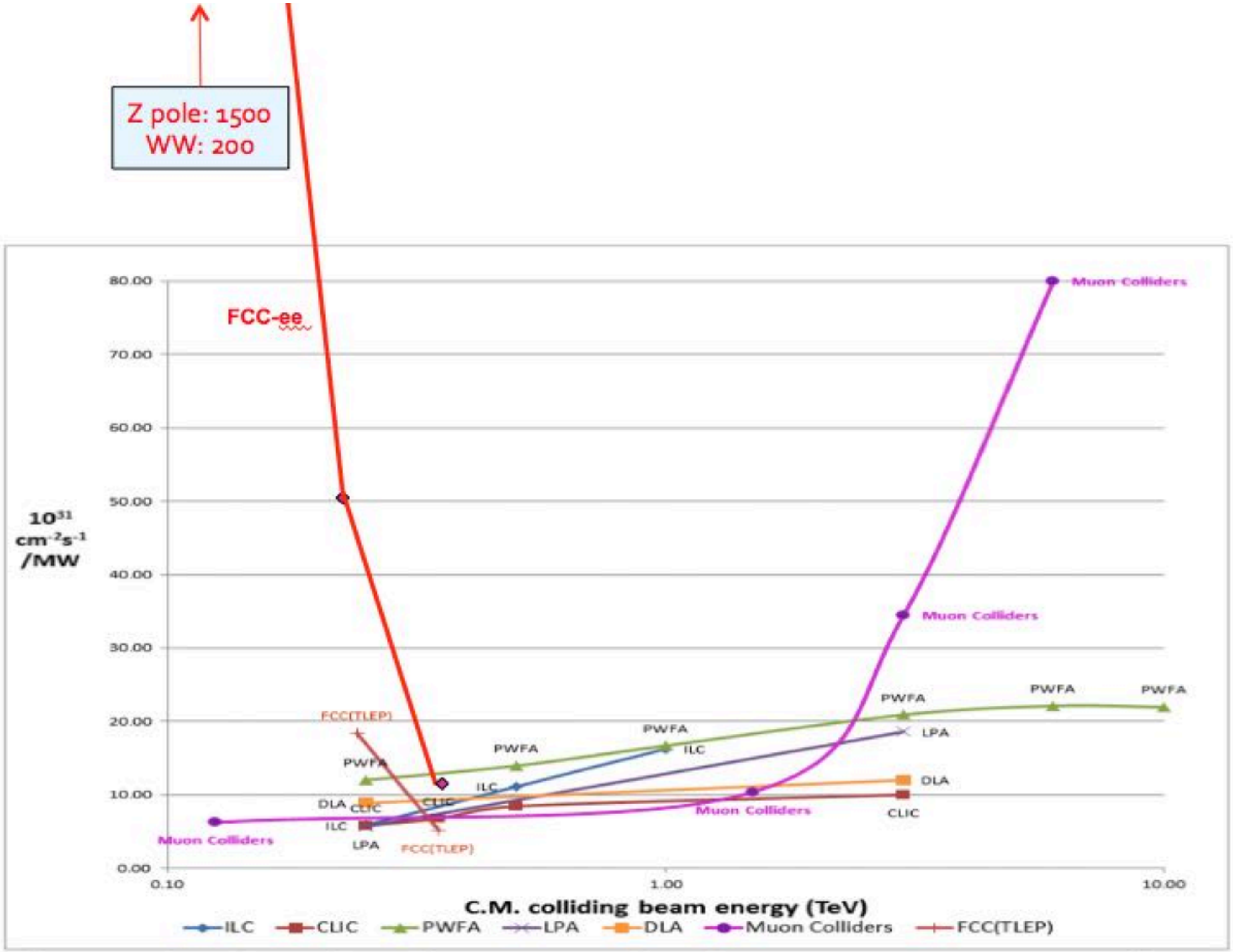


Self-modulated proton bunch resonantly driving plasma wakefields.





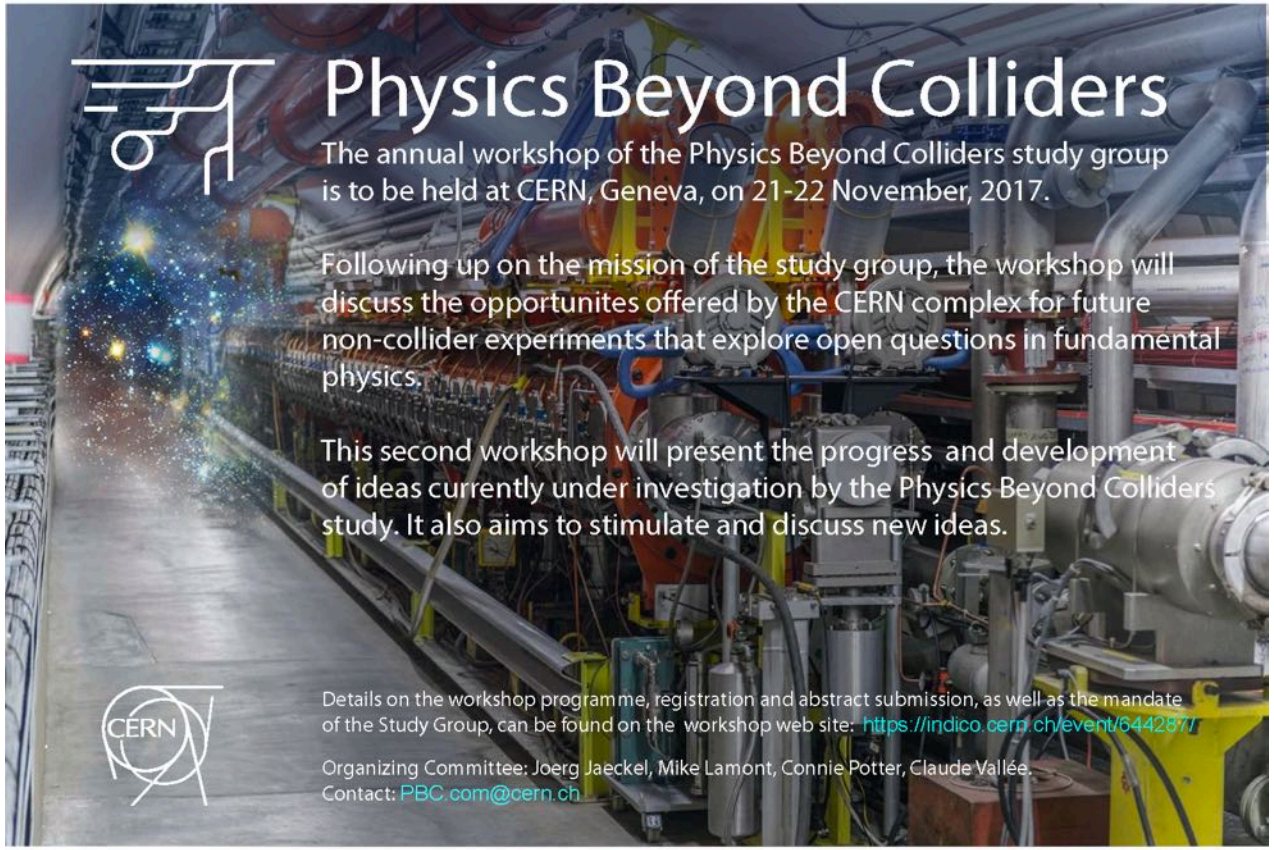
Road to multi-TeV colliders:



G. Dissertori

High intensity beams: physics beyond colliders and neutrino programme

Physics Beyond Colliders at CERN



M. Lamont's slides in 2nd PCB workshop

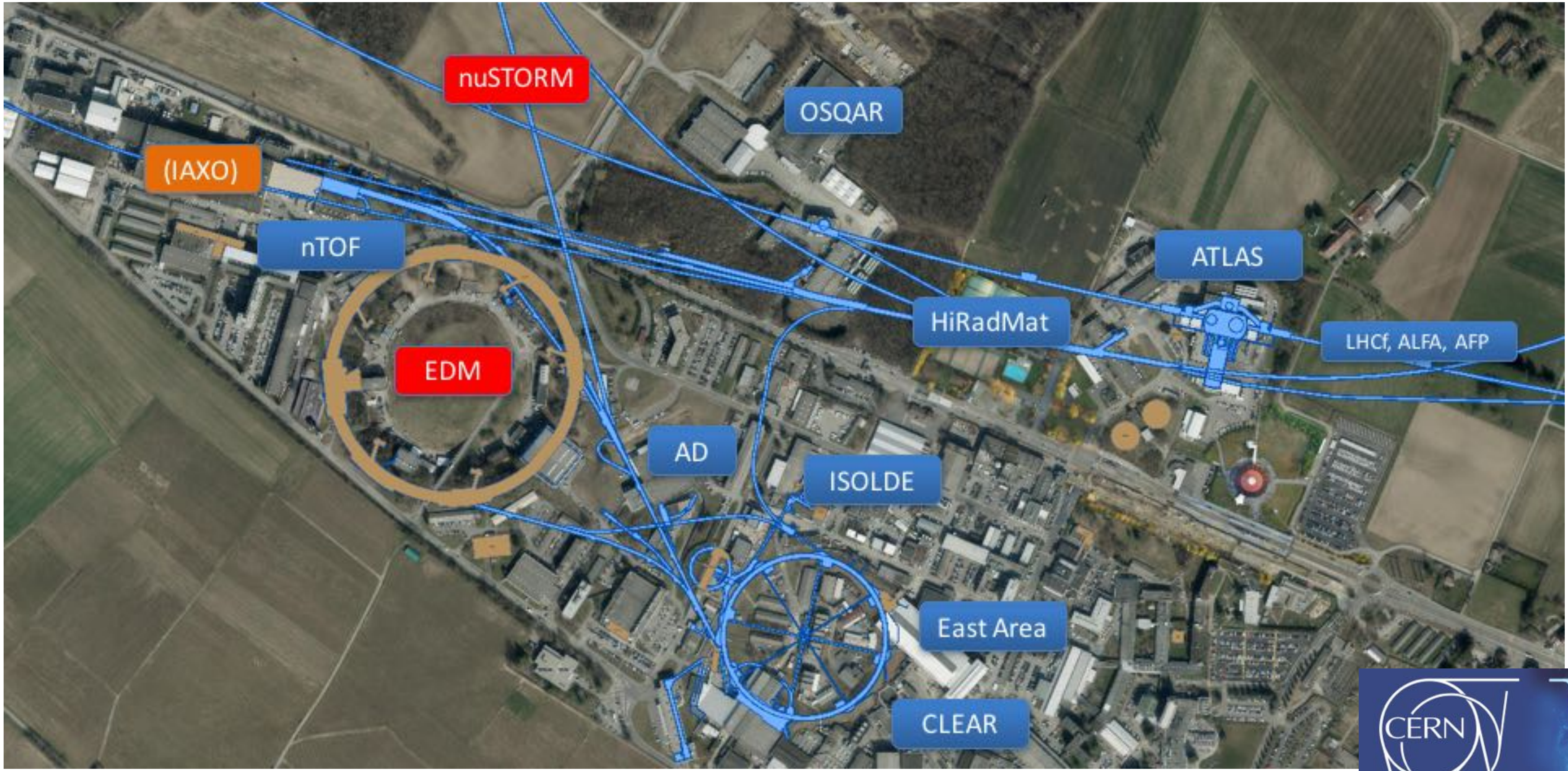
- *PBC launched in 2016 with mandate to explore opportunities offered by the CERN accelerator complex for non-collider physics*
  - *Wide range of beams, intensities, energies*

Input to ESPP update

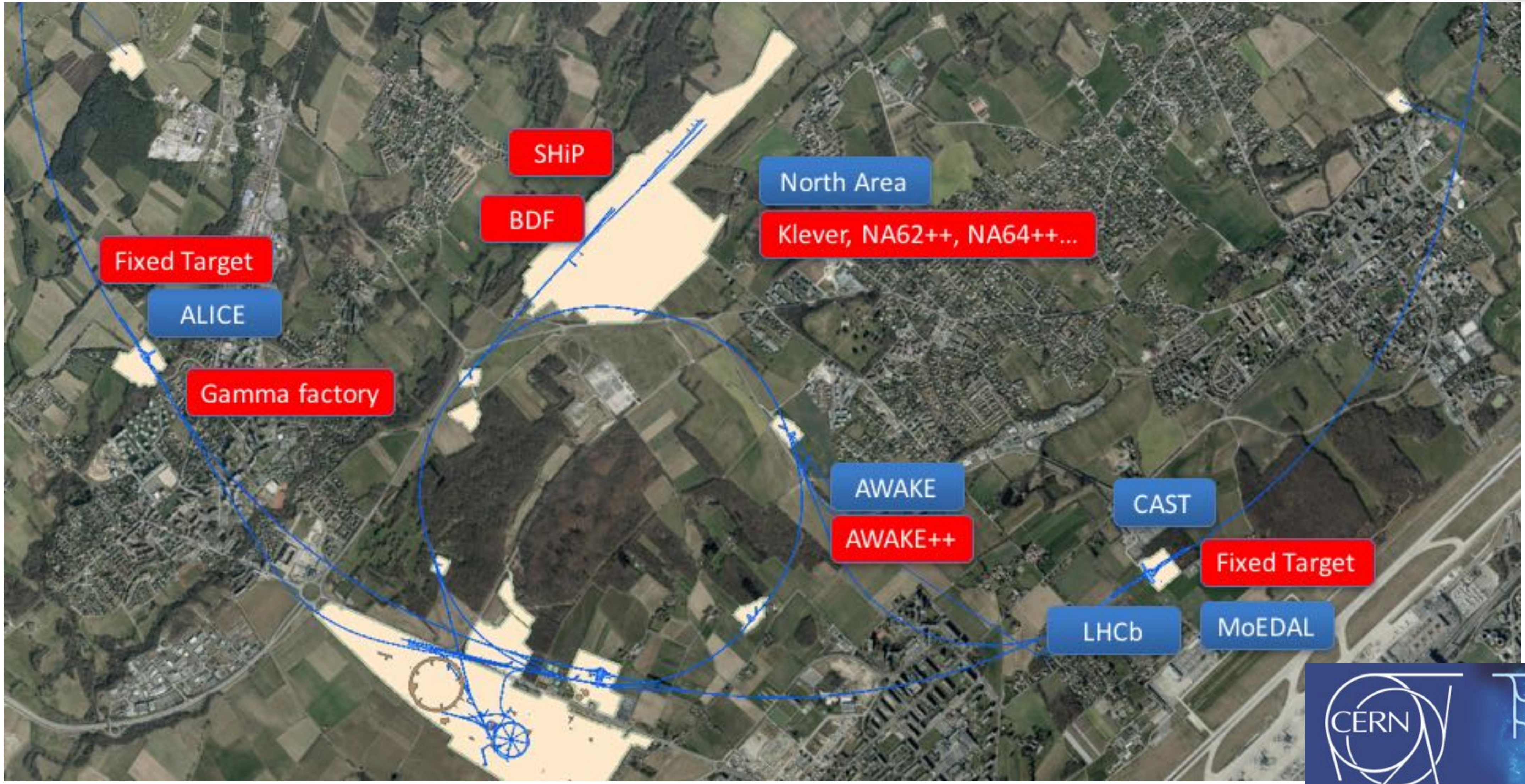
Overall executive summaries plus:

Protons post LIU	Evaluation and proposals
Technology	Evaluation and proposals
BDF	Comprehensive design study
Conventional beams	Case dependent feasibility studies
LHC FT	Preliminary conceptual designs
EDM	Feasibility study
Gamma factory	Exploratory study
AWAKE++	Exploratory study
nuSTORM	Exploratory study

Physics Beyond Colliders at CERN



Physics Beyond Colliders at CERN

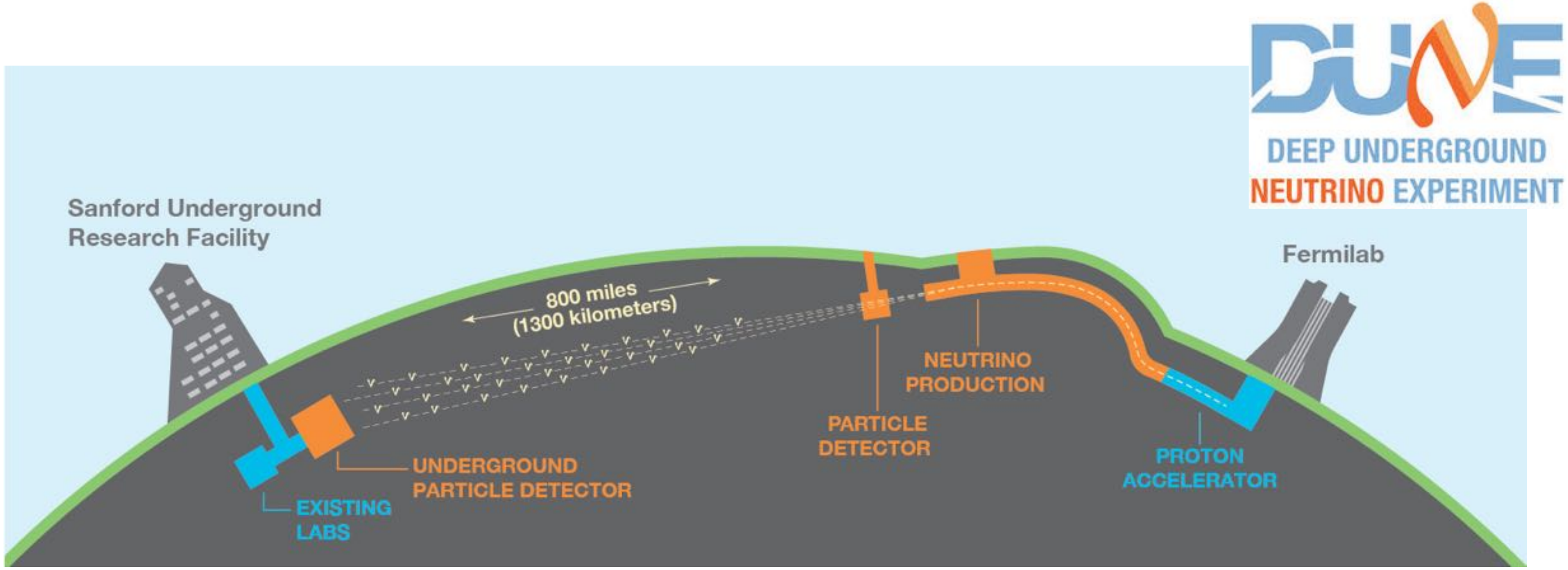


Long Baseline Neutrino programme

- Long Baseline Neutrino programme; see e.g. Asher Kaboth's overview at IOP-HEPP/APP:
  - Current generation: T2K and NOvA
  - Next generation: HK and DUNE
- Accelerator generated high intensity neutrino beam produced via by Proton Improvement Plan at Fermilab:
  - PIP-III high power proton driver 1.2MW -> multi-MW ; (UK: Front End Test Stand development at RAL-ISIS).

- "The US-led DUNE/LBNF project will undertake a game-changing programme of neutrino physics targeting big science challenges
  - STFC is investing £65 million as part of the $500 million international project"

B. Bowsher



Summary & points for discussion

- *Top priority: exploitation of LHC Run III & HL-LHC from 2026 – 2036…*
- *Which collider to build next? Depends on **IPPP**; **I**nnovation, **P**hysics, **P**rice & **P**olitics:*
  - Japan expected to decide whether to build ILC by end of 2018; if not, plenty of options:
  - e^+e^- Higgs factories: ILC, CLIC, CEPC, FCC-ee;
  - Hadron colliders: FCC-hh, HE-LHC.
- Novel acceleration: reaching >100 TeV in feasible size requires new technologies, priorities for development?
  - Laser-plasma, beam-driven plasma wakefield, THz, dielectrics, muon collider…
- Consider many non-collider PP experiments to exploit CERN accelerator infrastructure + UK engagement in high intensity accelerator driven neutrino programme.
- UK strategy for engagement in EU PP; scientific & economic return on investment.

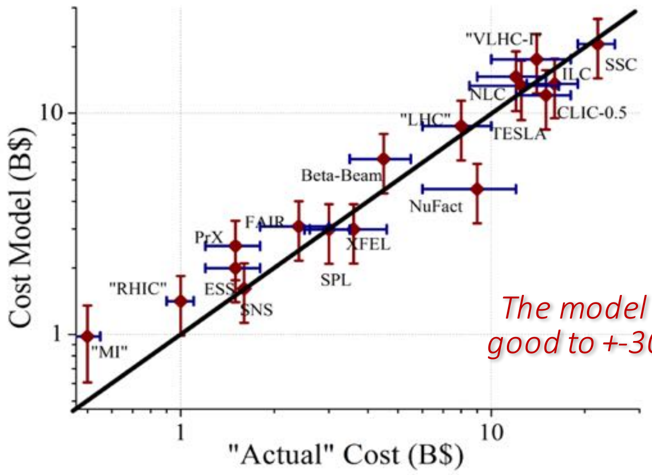
Back up

Future Collider Phenomenological Cost Model

Cost(TPC)= $\alpha\ L^{1/2} + \beta\ E^{1/2} + \gamma\ P^{1/2}$

where α,β,γ – technology dependent constants

- **α≈ 2B$/sqrt(L/10 km)**
- **β≈ 10B$/sqrt(E/TeV)** for RF
- **β≈ 2B$/sqrt(E/ TeV)** for SC magnets
- **β≈ 1B$ /sqrt(E/TeV)** for NC magnets
- **γ≈ 2B$/sqrt(P/100 MW)**



Vladimir Shiltsev

PRESENTED AT

DPF 2015
The Meeting of the American Physical Society
Division of Particles and Fields
Ann Arbor, Michigan, August 4-8, 2015

Table 1: Main parameters (c.o.m. energy E_{cm}, facility size L_f, site power P) of the collider projects and their estimated total project cost *TPC* according to the phenomenological *αβγ*–model [10].

	E_{cm}, TeV	L_f, km	*P*, MW	*Region*	*αβγ–TPC*, $B (est.)
		"Near" Future			
CepC	0.25	54	~500	China	10.2 ±3
FCC-ee	0.25	100	~300	CERN	10.9 ±3
ILC	0.5	36	163	Japan	13.1 ±4
		Future			
CLIC	3	60	589	CERN	27.0 ±8
μμ-Collider	6	~20	230	US ?	14.4 ±5
SppC	~50	54	~300	China	25.5 ±8
FCC-pp	100	100	~400	CERN	30.3 ±9
		"Far" Future			
X-Collider	≤1000	≤10	≤100	?	≤ 10

F. Zimmerman

FCC-ee vs CEPC parameters

parameter	Z FCC-ee	Z CEPC	H (ZH) FCC-ee	H (ZH) CEPC
beam energy [GeV]	45.6	45.5	120	120
beam current [mA]	1390	461	29	17
no. bunches/beam	16640	12000	393	242
bunch intensity [10^{11}]	1.7	0.8	1.5	1.5
SR energy loss / turn [GeV]	0.036	0.036	1.72	1.73
total RF voltage [GV]	0.1	0.1	2.0	2.2
long. damping time [turns]	1281	1280	70	70
horizontal beta* [m]	0.15	0.2	0.3	0.36
vertical beta* [mm]	0.8	1.0	1	1.5
horiz. geometric emittance [nm]	0.27	0.17	0.63	1.21
vert. geom. emittance [pm]	1.0	1.6	1.3	3.1
bunch length with SR / BS [mm]	3.5 / 12.1	2.4 / 8.5	3.3 / 5.3	2.7/ 3.3
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	32	>7	3
beam lifetime rad Bhabha / BS [min]	68 / >200	240 / >300	38 / 18	40 / 100