Particle Physics & the Energy Frontier Beyond HL-LHC

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PPAP 2018
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RAL

OUTLINE

What are the important questions to consider at the Energy Frontier in preparing the UK input to the European Strategy Update?

Particle Physics circa 2018

Opportunities for *great discoveries*
@ the energy frontier

Will present information that will be relevant to considering this recommendation

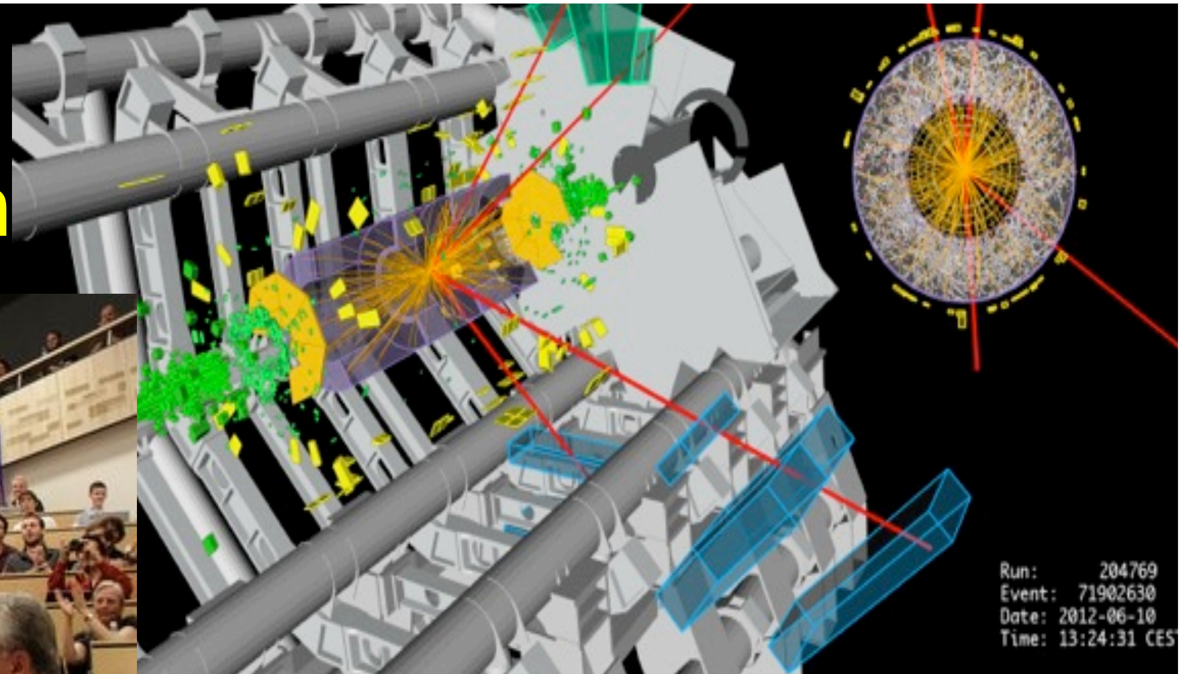
European Strategy Workshop, IPPP 16-18th April 2018: Meeting Summary

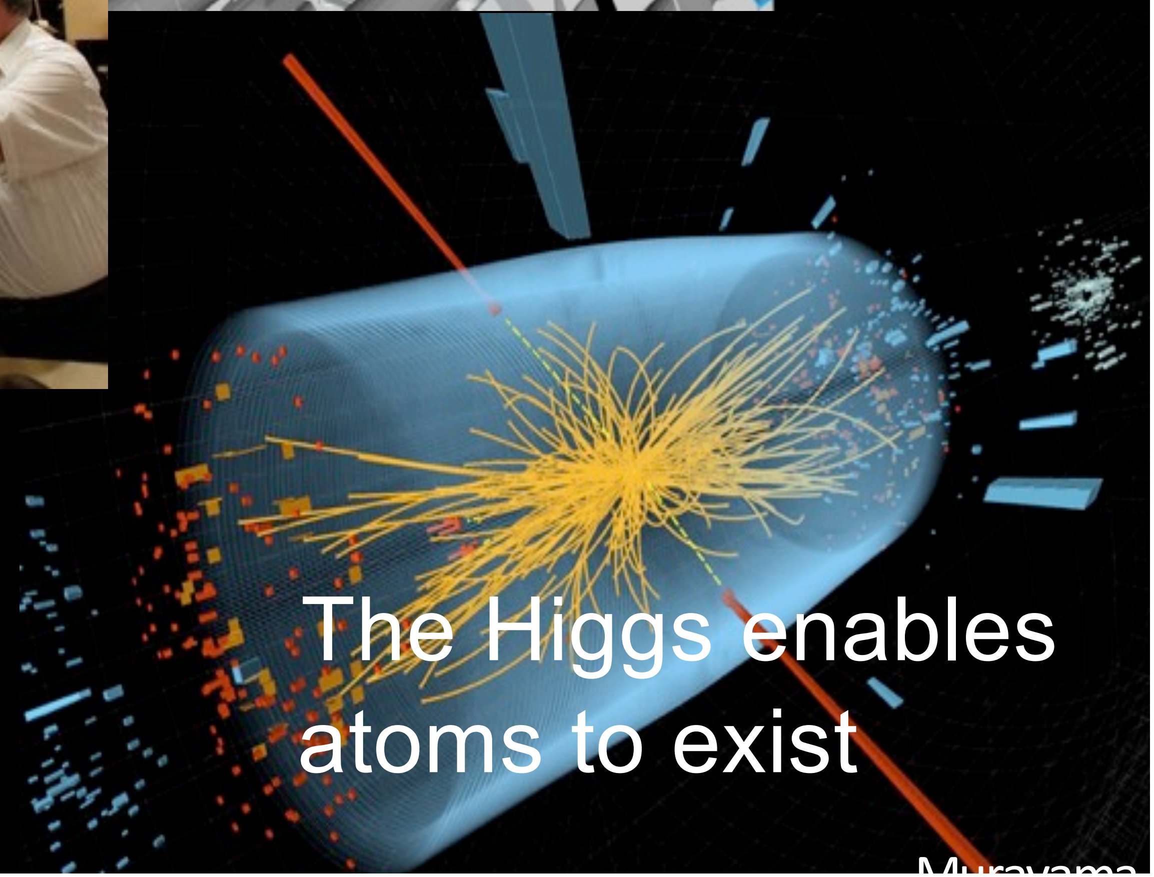
<u>Overview</u> (J. Evans, S. Farrington, E. Goudzovski, M. Patel, M. Spannowsky)

4) The physics cases for FCC and CLIC are clearly both strong but there are resource implications in pushing both R&D programs forward during the 2020s. The last UK ES submission said that *"a timely decision should be taken on optimal next-generation collider facilities for exploitation of LHC discoveries"*. The final 2013 ES update document said *"to stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available".* It is the recommendation of the organisers of this workshop that it should be considered, in a UK community meeting, whether a decision can now be made on a definitive UK recommendation. If a consensus cannot be reached, then it could be debated in the community meeting whether to put forward to the ES process that its committee makes a definitive recommendation by 2020.

2012.7.4

discovery of Higgs boson





theory : 1964

design : 1984

construction : 1998

The Higgs enables atoms to exist

Murayama

Outstanding Questions in Particle Physics *circa* 2011

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

EWSB
- ❑ Does the Higgs boson exist?

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Outstanding Questions in Particle Physics *circa* 2018

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

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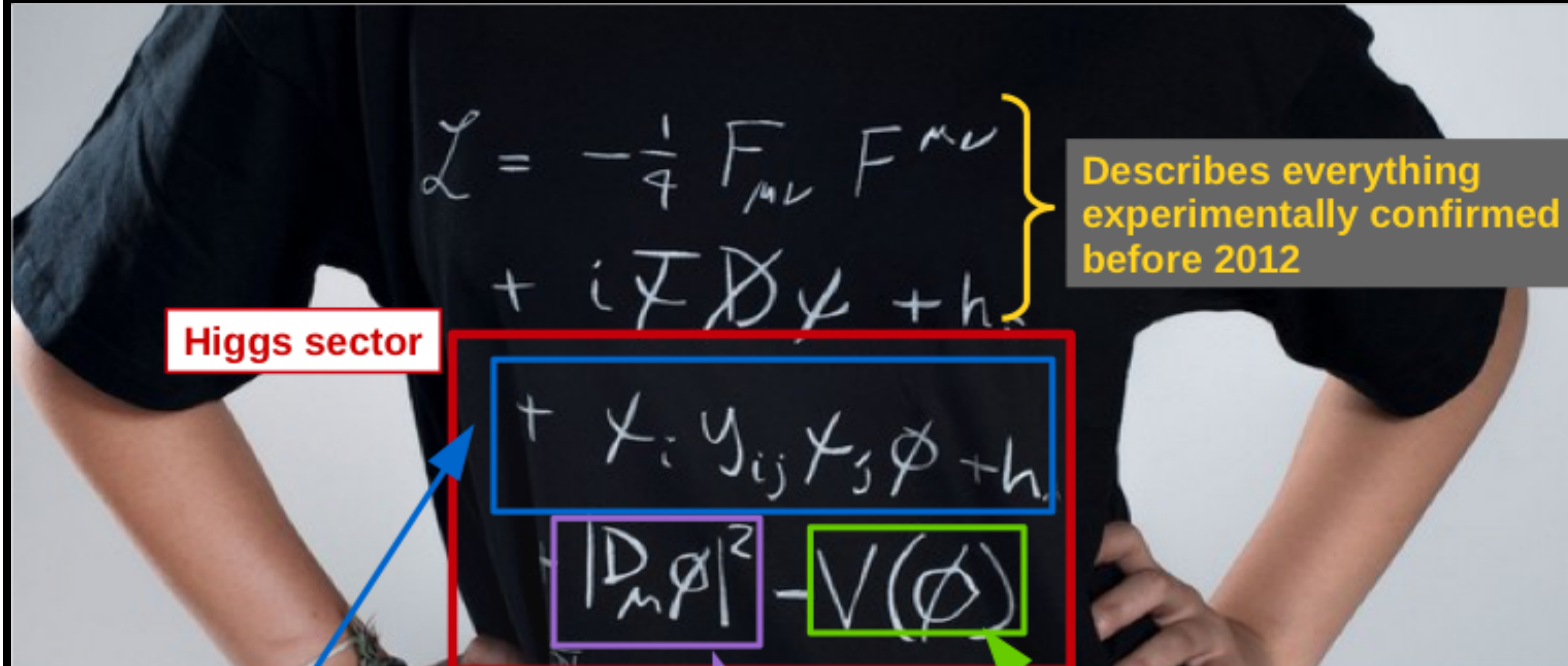
These questions are compelling, difficult and intertwined → require multiple approaches high-E colliders, neutrino experiments (solar, short/long baseline, reactors $0\nu\beta\beta$ decays), cosmic surveys (CMB, optical/IR spectroscopic and photometric), dark matter direct, indirect and astrophysical detection, precision measurements of quark and lepton rare decays and phenomena, dedicated searches (axions, dark-sector particles), ...

Main questions and main approaches to address them

	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos			x	x	x
Dark Matter	x			x	x
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

These complementary approaches are ALL needed: their combination is crucial to explore the largest range of E scales, properly interpret signs of new physics, and build a coherent picture of the underlying theory.

Standard Model Langrangian

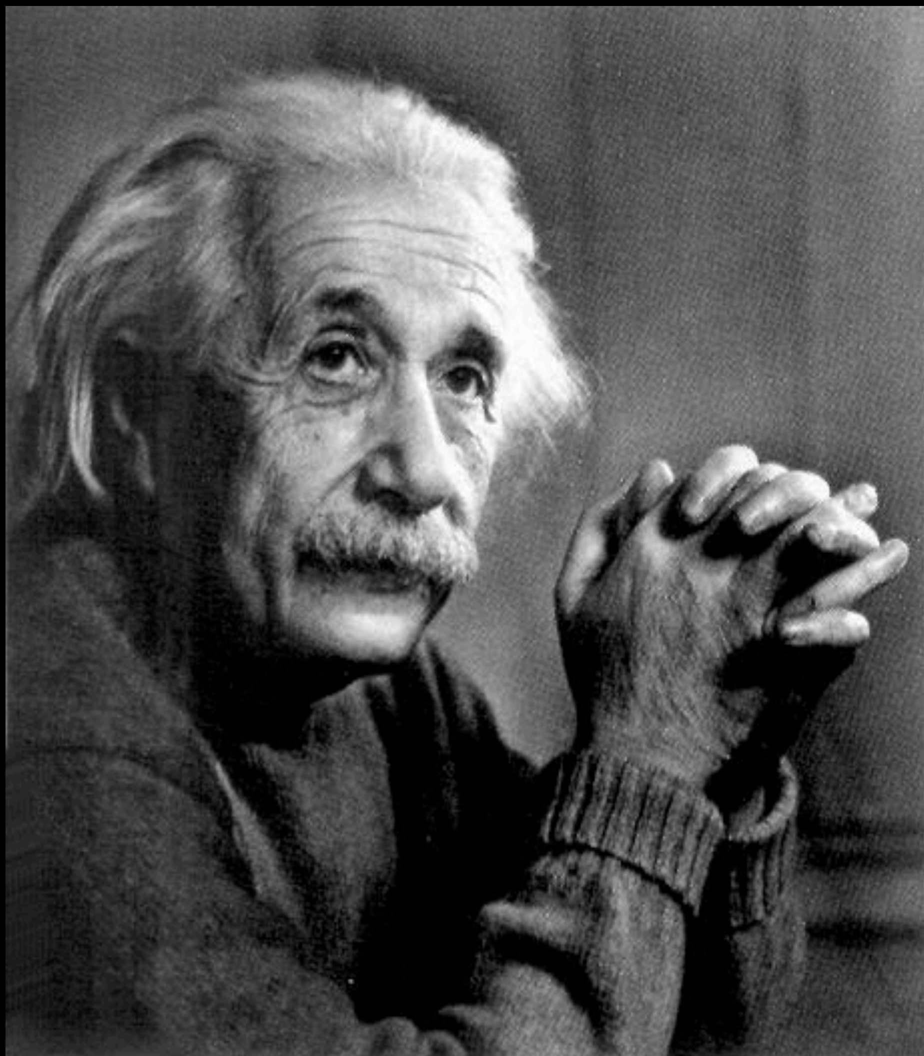


Yukawa coupling with new scalar
(completely new interaction type)
ttH, H→bb and H→ ττ are important !

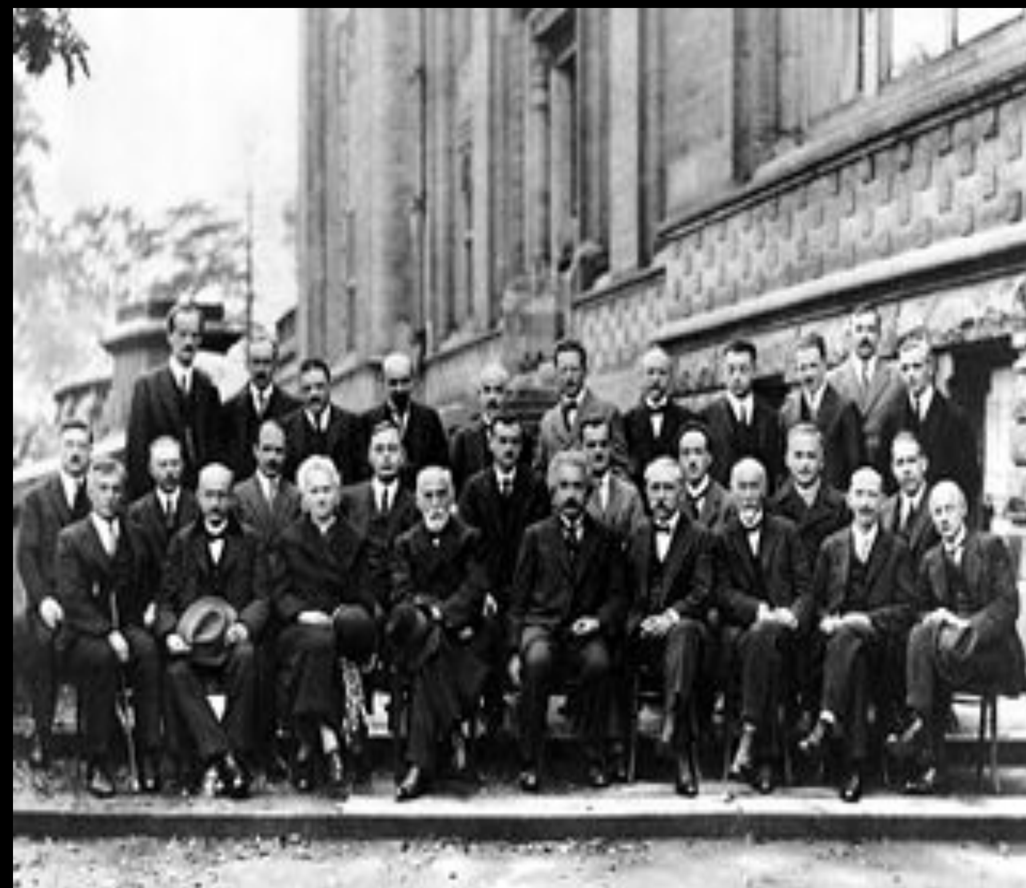
Higgs potential ($\mu^2 \phi^2 + \lambda \phi^4$)

Gauge boson interaction with new scalar
(new for scalar, but known for fermions)

Our work has the potential to lead to a reconciliation of the two great edifices of physics



General Relativity



Quantum Mechanics

No-lose completion of the Standard Model

Guaranteed discoveries

W & Z	CERN SppS	(1983)
Top quark	Tevatron	(1995)
Higgs	LHC	(2012)

No-lose completion of the Standard Model

Now that the Standard Model is complete, there are no further no-lose theorems
In principle, the Standard Model could be valid to the Planck scale

No guaranteed discoveries

There are no guaranteed discoveries

Higgs is central to SM & BSM
& a guaranteed deliverable
@ any future collider

Direct
High E
pp (later)

Precision
Lower E
ee (sooner)

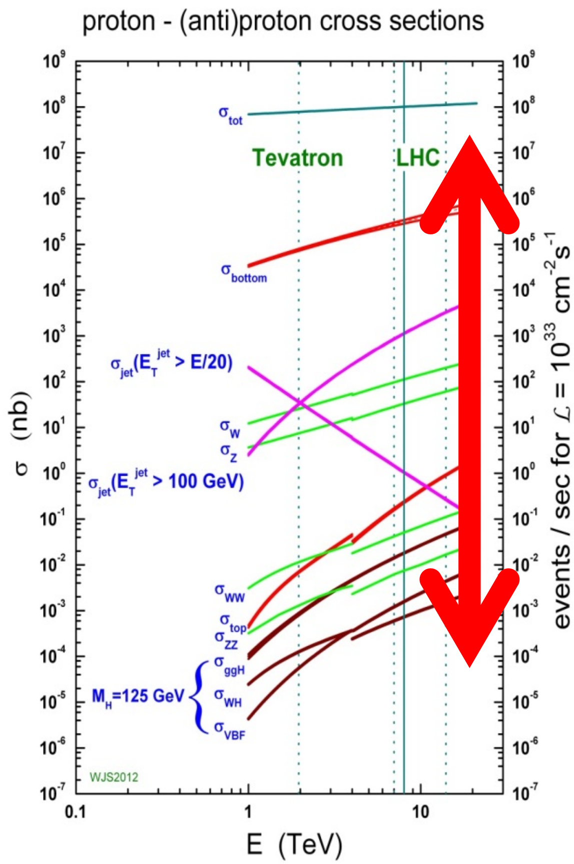
Focus on Higgs @ ee
& in particular the couplings

IMPACT of 125 GeV on Energy Frontier

The low mass of the Higgs makes e+e- Higgs factories both linear and circular tractable & has consequently modified & simplified the landscape of accelerator options at the energy frontier since 2012

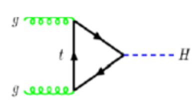
Higgs Factories (also Z, W, t)	ILC 250 CLIC 380 CEPC FCC-ee LHeC	Energy Frontier	ILC CLIC SPPC FCC-pp FCC-eh

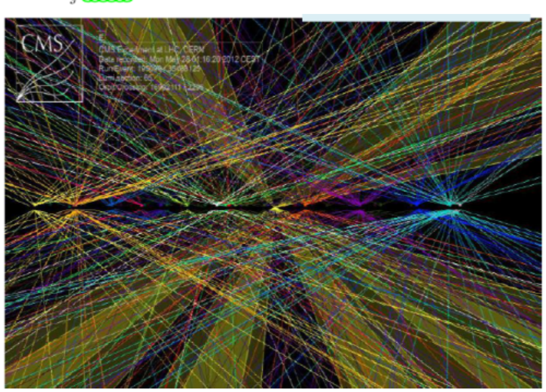
Higgs @ a pp colldier



LHC –
- large Higgs cross section
- 150M Higgs per exp.
- dominated by QCD events
- **S**(H)/**B**(All) 10^{-10}
- Pile-up and jet overlap
- Not knowing

$(P_H, E_H)_{initial}$

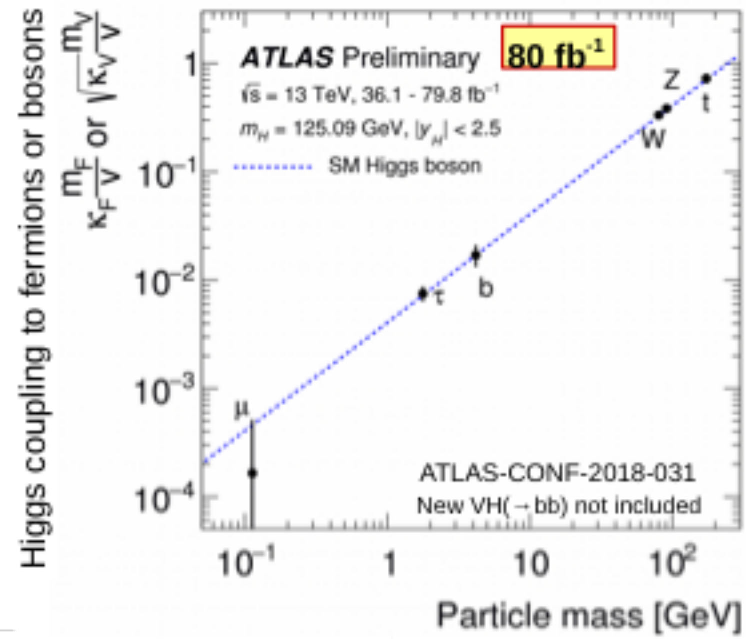


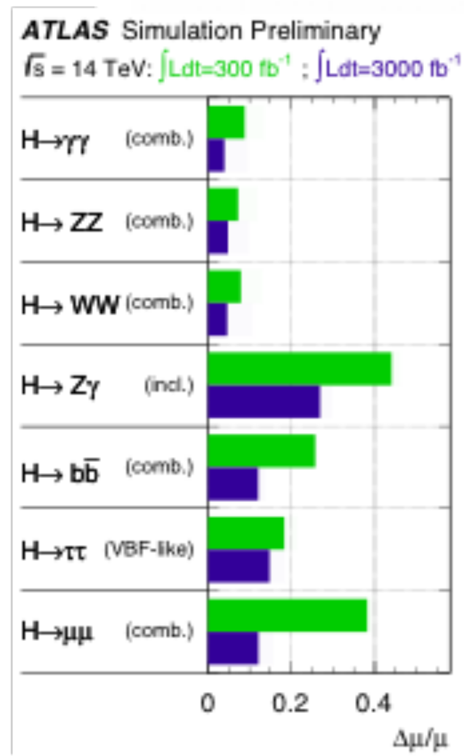


Precisions on H couplings

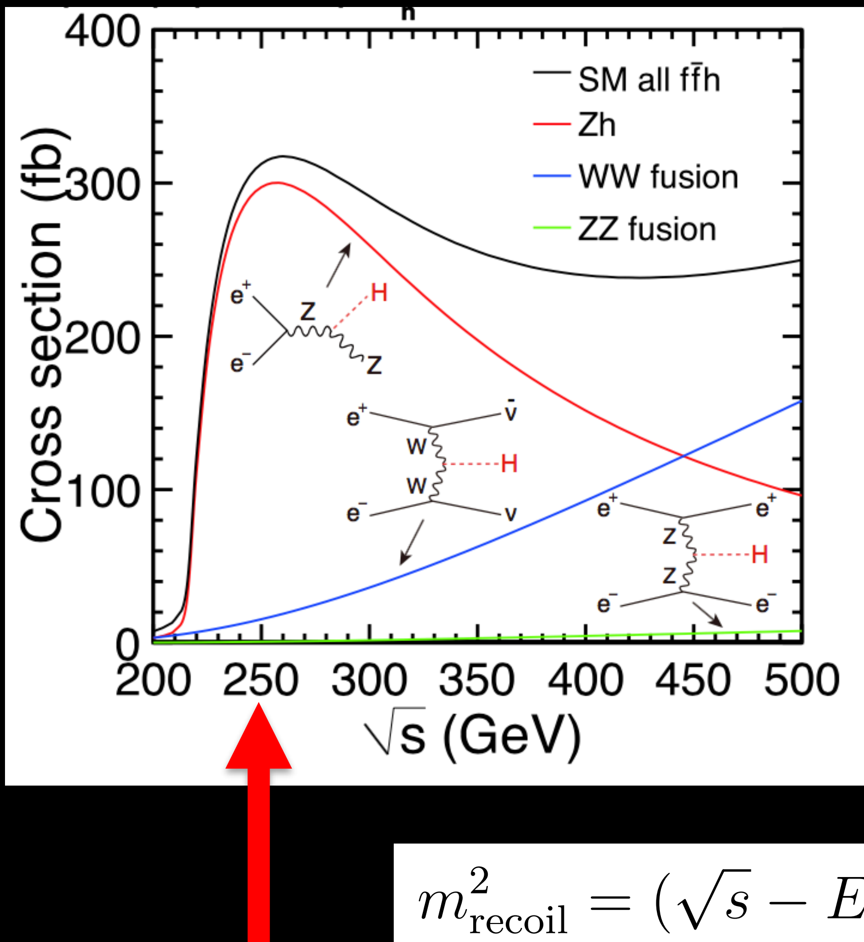
~(5-10)% expected

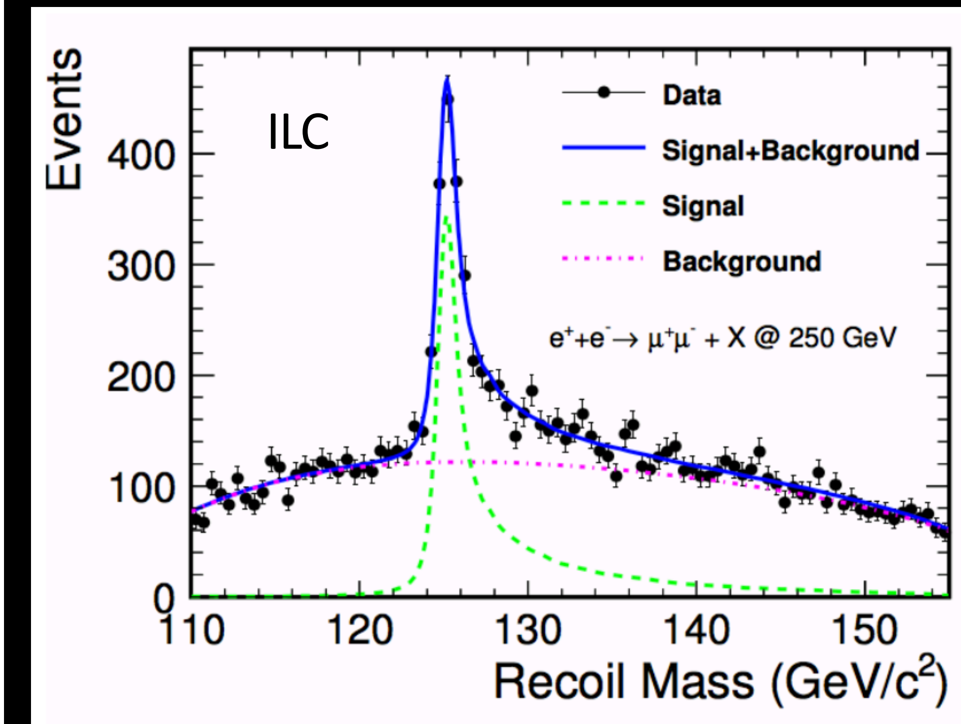
Key feature:
Higgs coupling depends on the particle mass





e^+e^- Higgs production @ 250 GeV





$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{f\bar{f}})^2 - p_{f\bar{f}}^2 = s - 2E_{f\bar{f}}\sqrt{s} + m_{f\bar{f}}^2$$

The tagging of $e_+e_- \rightarrow ZH$ events through the recoil mass method is independent of the Higgs boson decay.

e^+e^- Higgs production @ 250 GeV

Higgs events are readily isolated from background.
All standard Higgs decay modes are visible.

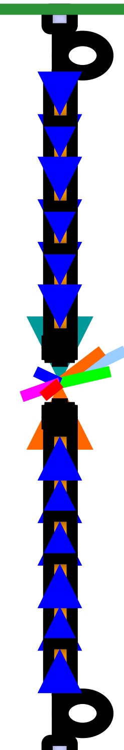
Measurement accuracies are such that 1% coupling measurements are feasible.

The absolute cross section for $e^+e^- \to Zh$ can be measured.

At 250 GeV, to first approximation, any Z boson with $E_{lab} = 110\ \text{GeV}$ is recoiling against a Higgs boson.

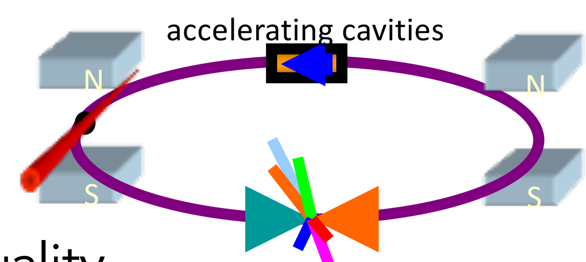
ILC/CLIC and CEPC/FCC(ee)

Linear accelerator can reach high energies ~multi-TeV with high luminosity



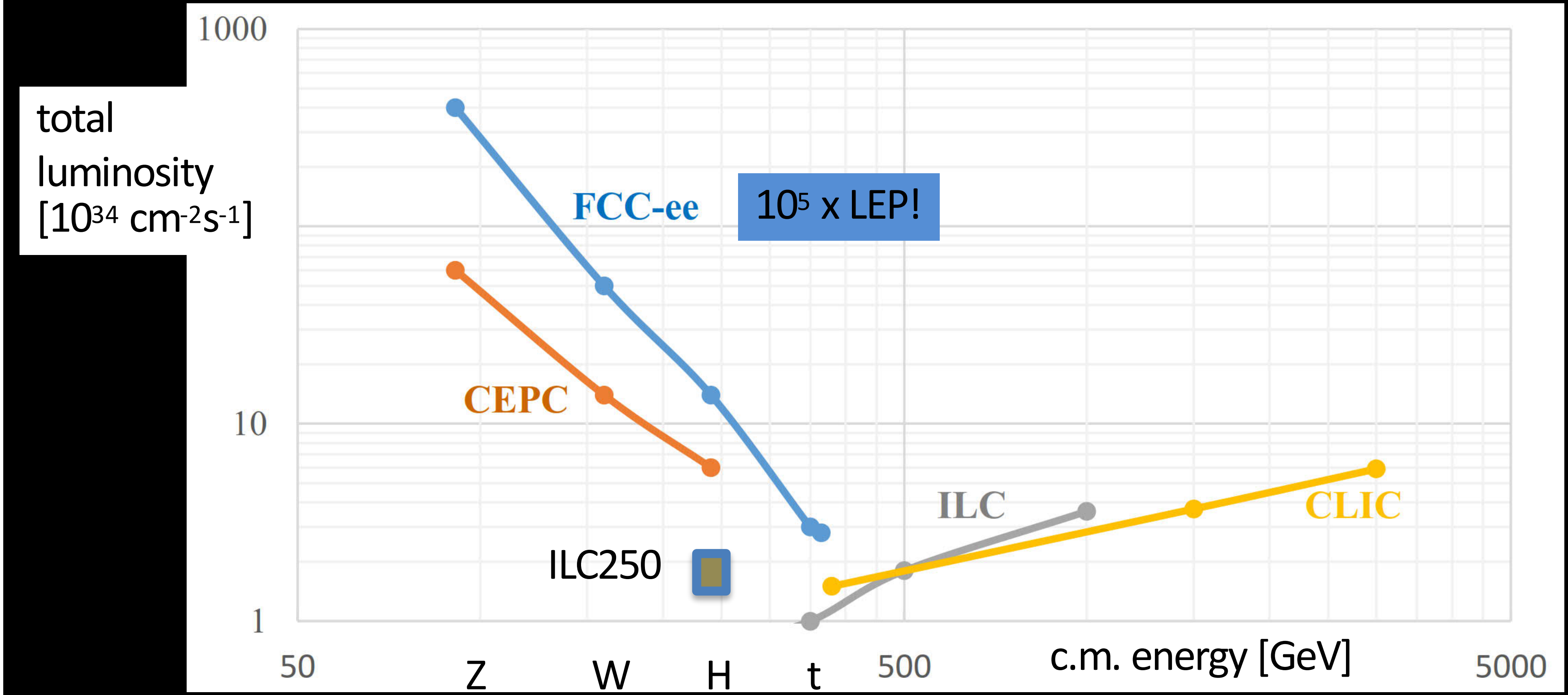
- Can avoid synchrotron radiation
- High accelerating field to achieve high energy
  - ✓ Normal conducting accelerating structures (CLIC)
- High beam current and quality to achieve the luminosity
  - ✓ High quality of components
  - ✓ Nano beams

Circular accelerator can reach high luminosity at lower energies



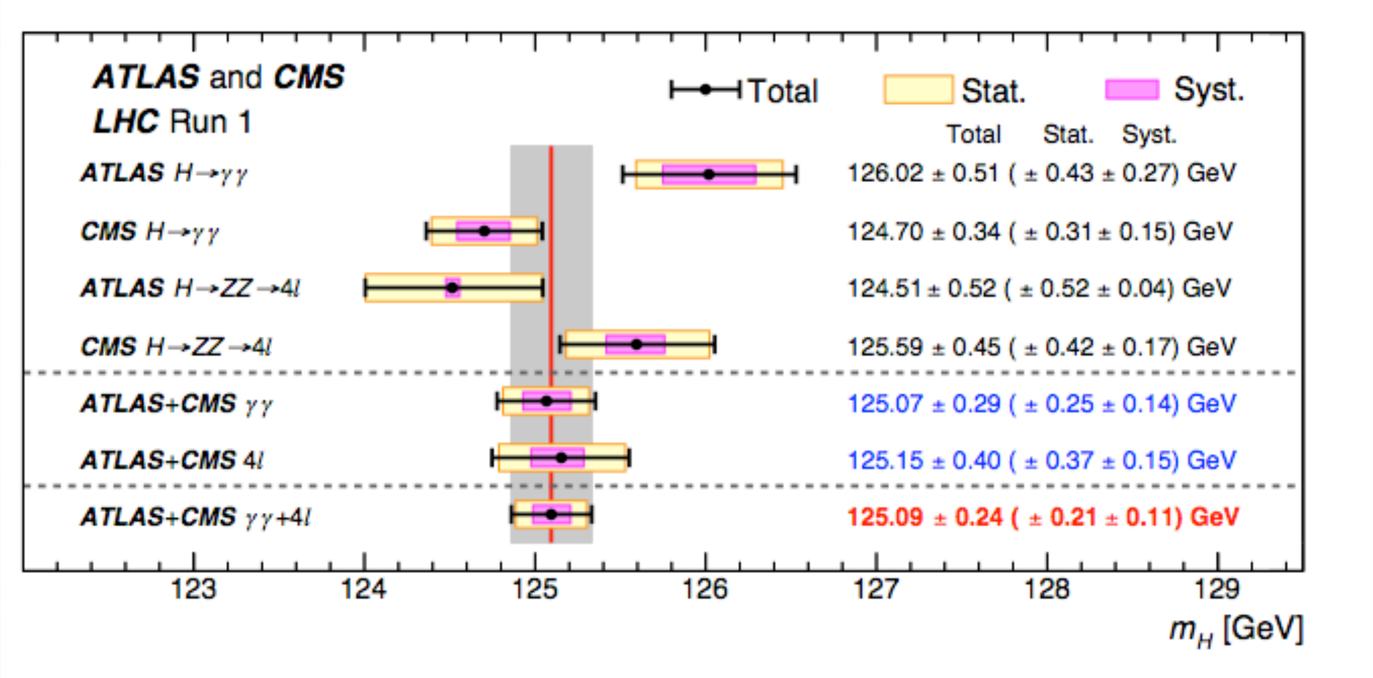
- Can store and re-collide the beams
- Experience
- Synchrotron radiation limits the energy and beam quality

future lepton collider luminosities



→ **earliest possible physics starting dates**
- **ILC250: 2032**
- **CLIC350: 2035**
- **FCC-ee: 2039**
- **CEPC: 2030**

Higgs mass



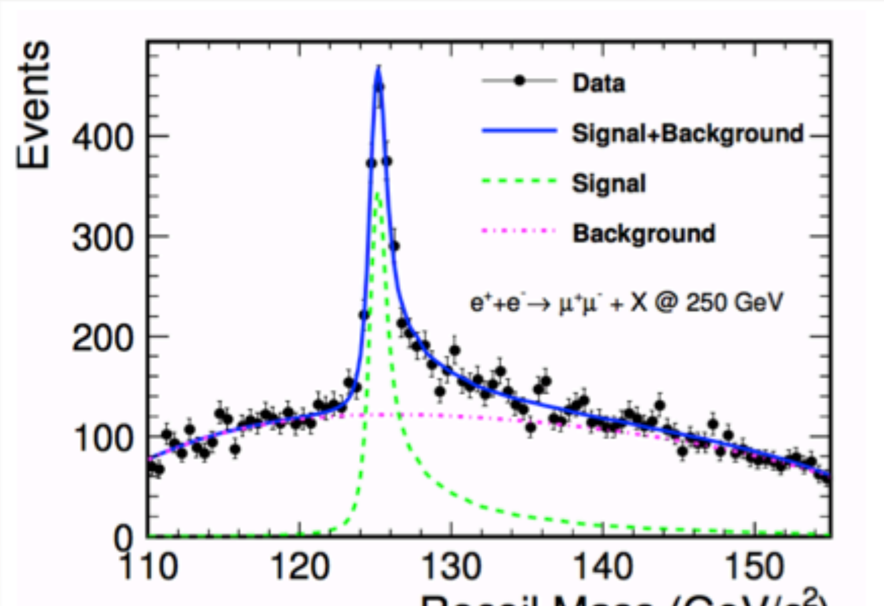
δm_h ~300 MeV

- Higgs mass precision can be limitation of coupling fit precision

$$\delta_W = 6.9 \cdot \delta m_h, \qquad \delta_Z = 7.7 \cdot \delta m_h$$

[Almeida, Lee, Pokorski, Wells `13]

- through leptonic recoil in $Z \to \mu^+\mu^-$ the Higgs mass can be constrained to 14 MeV [LCC Physics Working Group `18]



[Yan et al. `16]

- impact on Z/W couplings ~0.1%

Higgs Branching Fraction Measurements

With both σZh and σZh · BR measured, the absolute branching ratios can be determined independently

Decay mode	$\sigma(ZH) \times$ BR	BR
$H \to b\bar{b}$	0.28%	0.57%
$H \to c\bar{c}$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to$ inv	–	0.28%

Relative error (%) CEPC Pre-CDR

Most precise: BR_{bb} and $BR_{\tau\tau}$, ILC (CEPC) 0.89% (0.57%) and 1.4% (1.3%) respectively.

If there are O(1%) or larger exotic decay modes, a first hint would be provided by observing the resulting deviations in BR_{bb} and $BR_{\tau\tau}$.

Measuring the Higgs width

$$BR(h \to A\overline{A}) = \Gamma(h \to A\overline{A})/\Gamma_h$$

Γ(H125) SM = 4.1 MeV, too small to be measured directly determine indirectly;
requires a formalism.
Traditionally width is determined using the κ parametrization.
Assumes Higgs coupling to A is modified from SM value by a mutiplicative factor κ_A

$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \ , \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

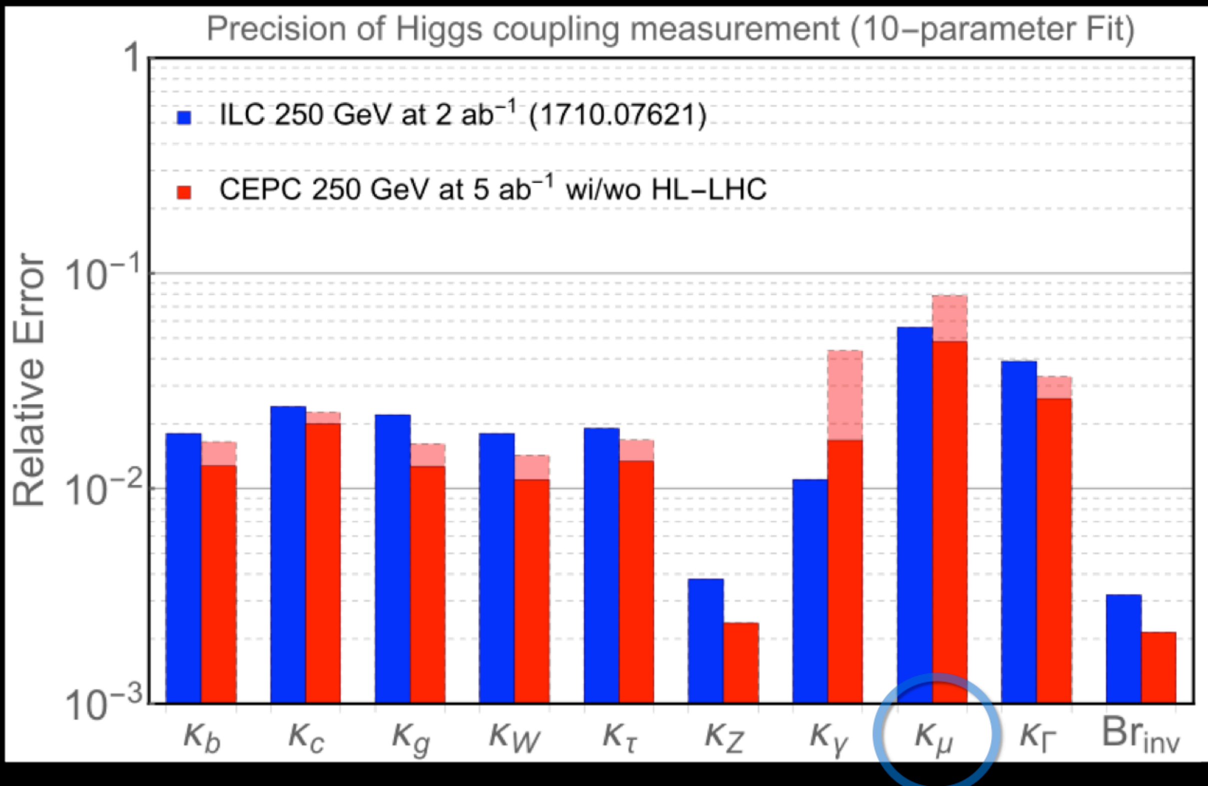
$$\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}.$$

(CEPC)

Γ_H	$\sigma(ZH)$
3.3%	0.50%

(LHC limits ~ x3 SM ATLAS 14.4 MeV new ICHEP 18)

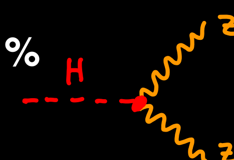
Higgs Coupling Measurements comparison ILC & CEPC



$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2$$

ILC
CEPC
~1% uncertainty

K_Z ~ 0.2 %



δ Γ ~ 3% (12 KeV) c.f. Current LHC limit ~x3 Γ(SM)

ILC and CepC achieve similar precision

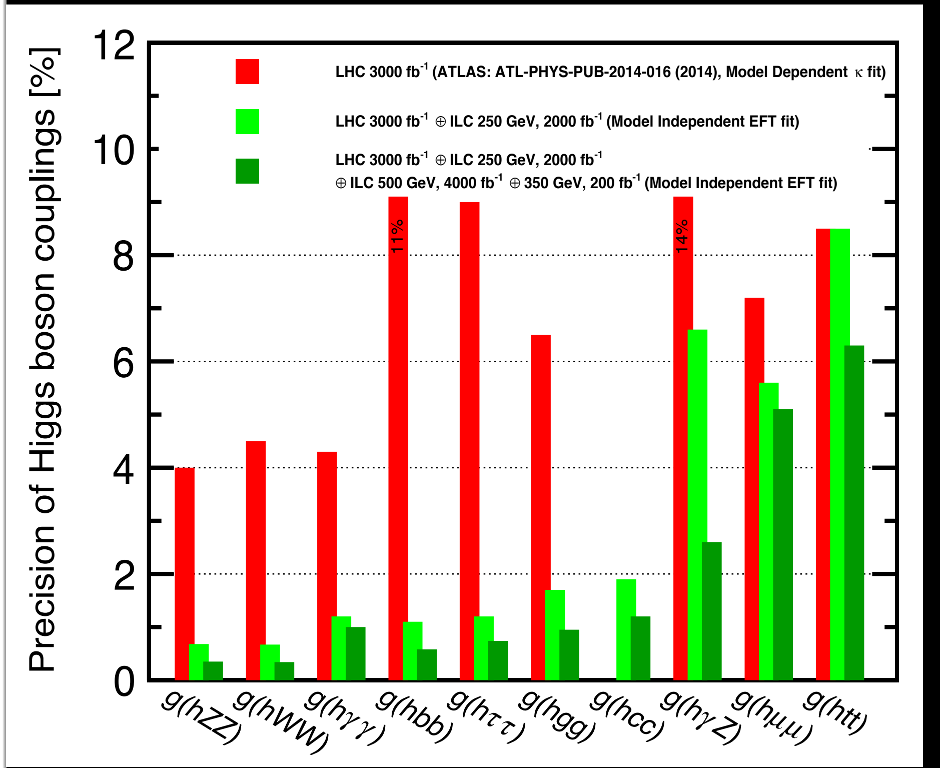
Higgs Coupling Measurements @ ILC & HL-LHC

	ILC250 2 ab^{-1} w. pol.	ILC250+500 full ILC 250+500 GeV
$g(hb\bar{b})$	1.1	0.58
$g(hc\bar{c})$	1.9	1.2
$g(hgg)$	1.7	0.95
$g(hWW)$	0.67	0.34
$g(h\tau\tau)$	1.2	0.74
$g(hZZ)$	0.68	0.35
$g(h\gamma\gamma)$	1.2	1.0
$g(h\mu\mu)$	5.6	5.1
$g(hbb)/g(hWW)$	0.88	0.46
$g(hWW)/g(hZZ)$	0.07	0.05
Γ_h	2.5	1.6
$BR(h \to inv)$	0.32	0.29
$BR(h \to other)$	1.6	1.2

Physics Case for the 250 GeV Stage of the ILC, arXiv:1710.07621

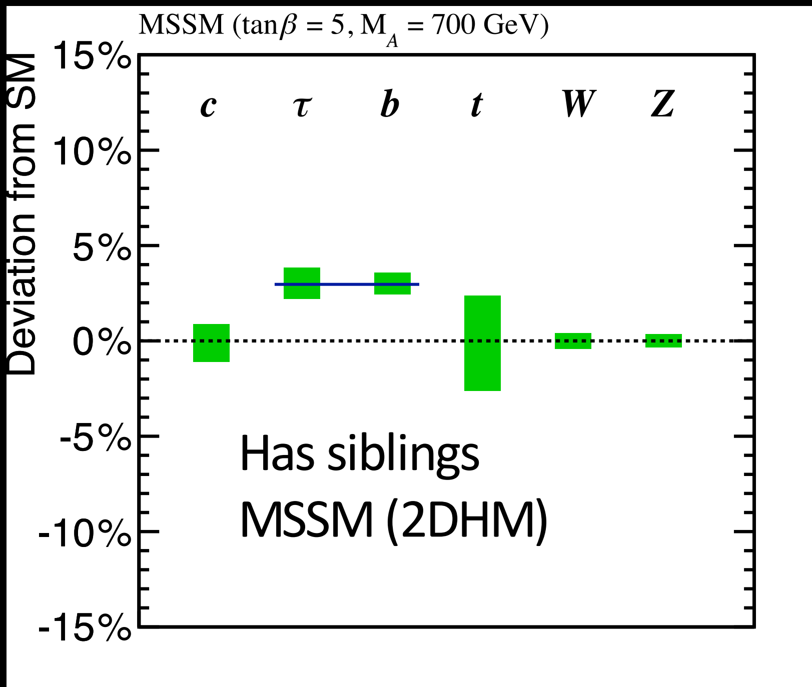
Effective Field Theory

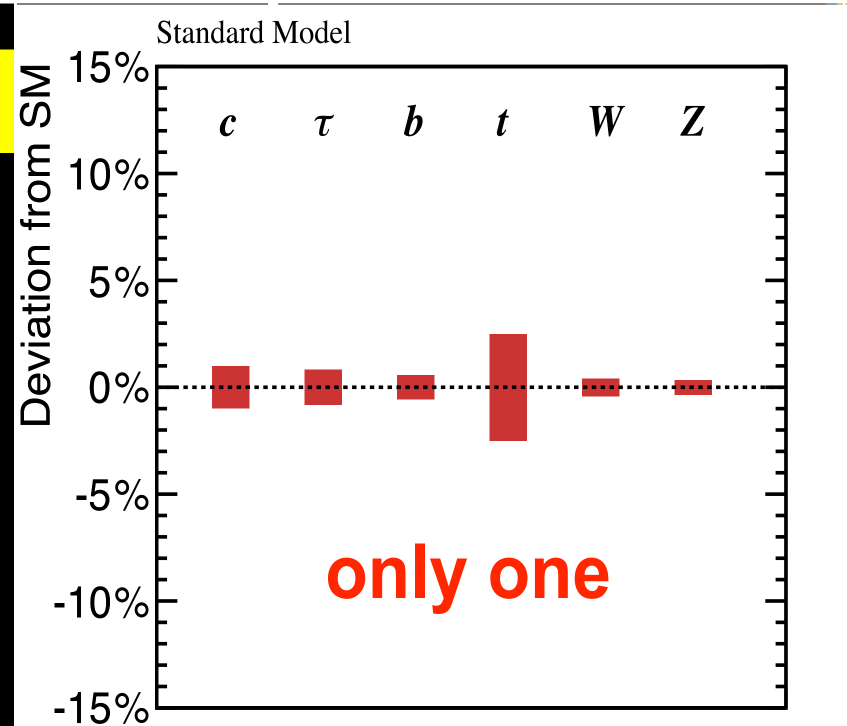
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

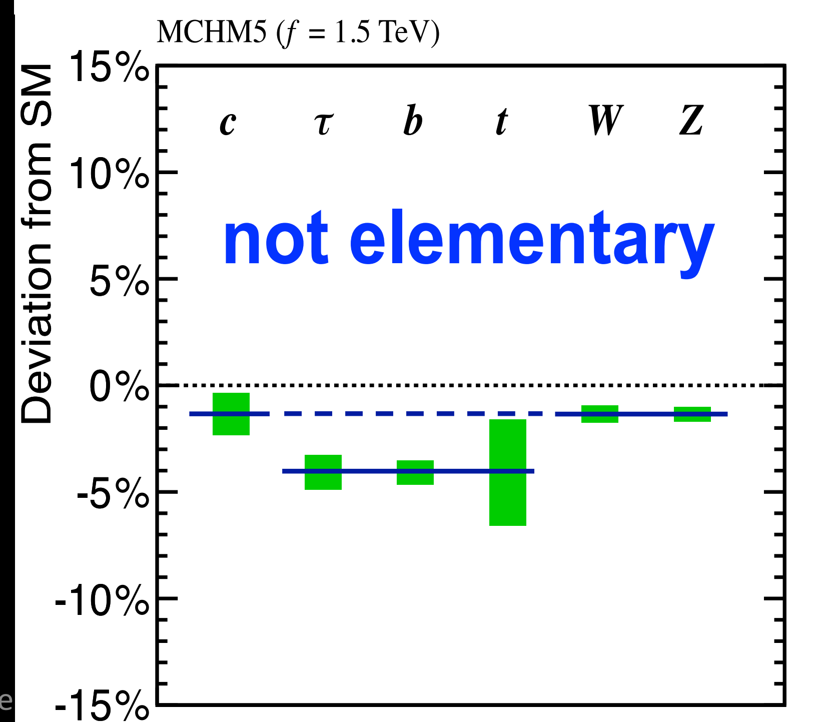


(Standard Model Effective Field Theory (EFT) formalism.)

Higgs couplings sensitivity to new physics







Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and model-independent percent (or better) measurement of the couplings

ILC shown

Similar considerations apply to a circular e+e- colider

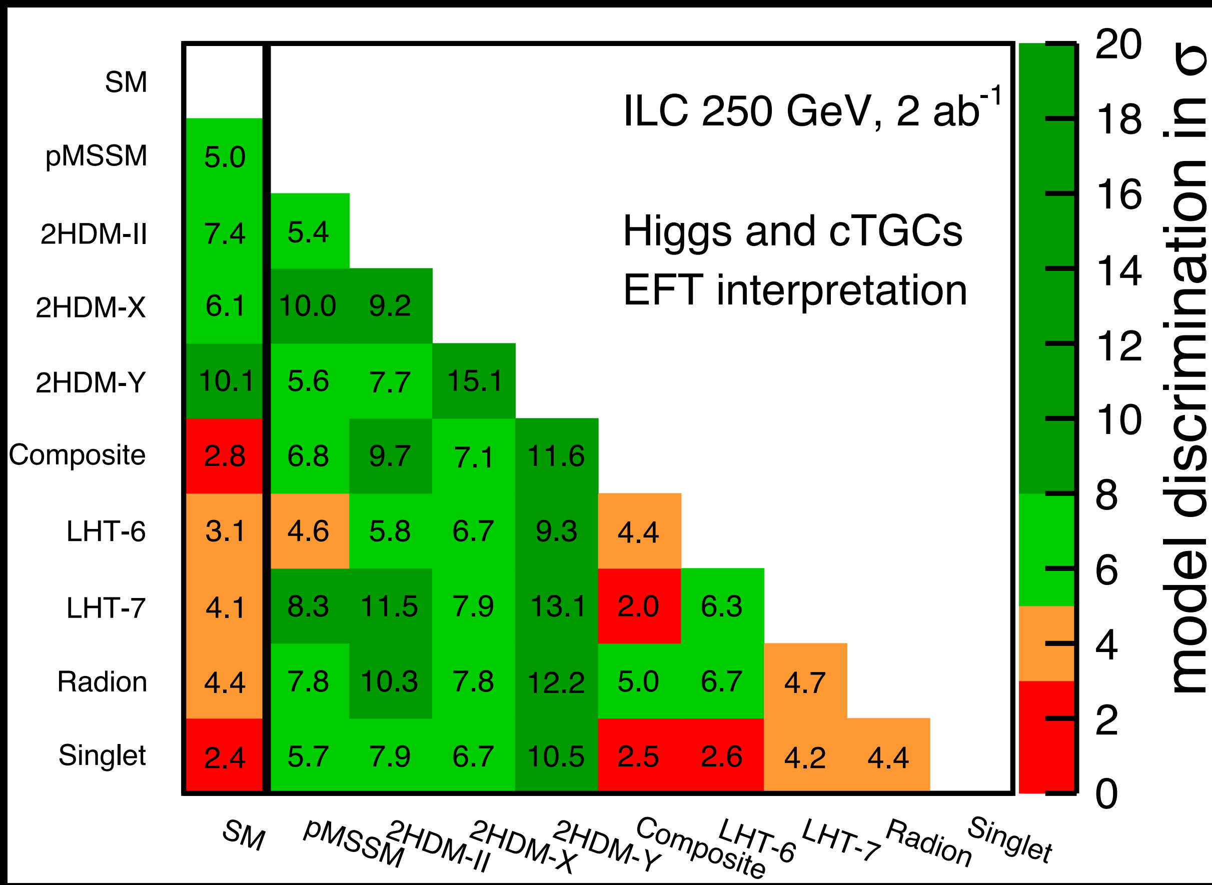
Many BSM models impact Higgs couplings at percent level

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [38]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [41]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [42]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [43]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [44]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

For the models shown above LHC not likely sensitive with full HL-LHC dataset

ILC250 Physics Case arXiv 1710.07621

Many BSM models impact Higgs couplings at percent level



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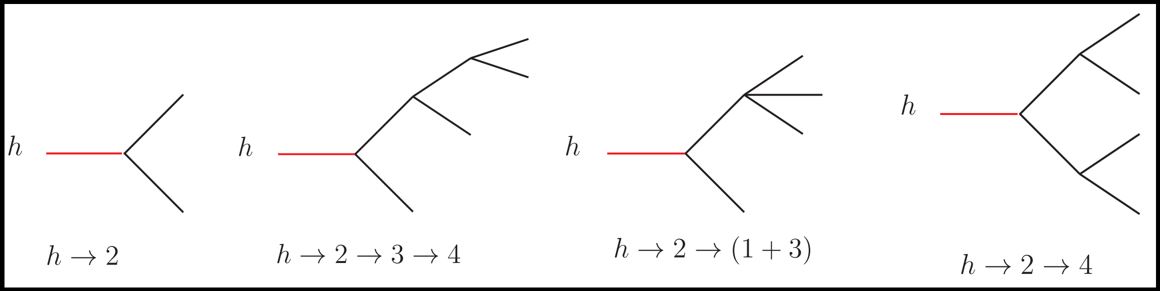
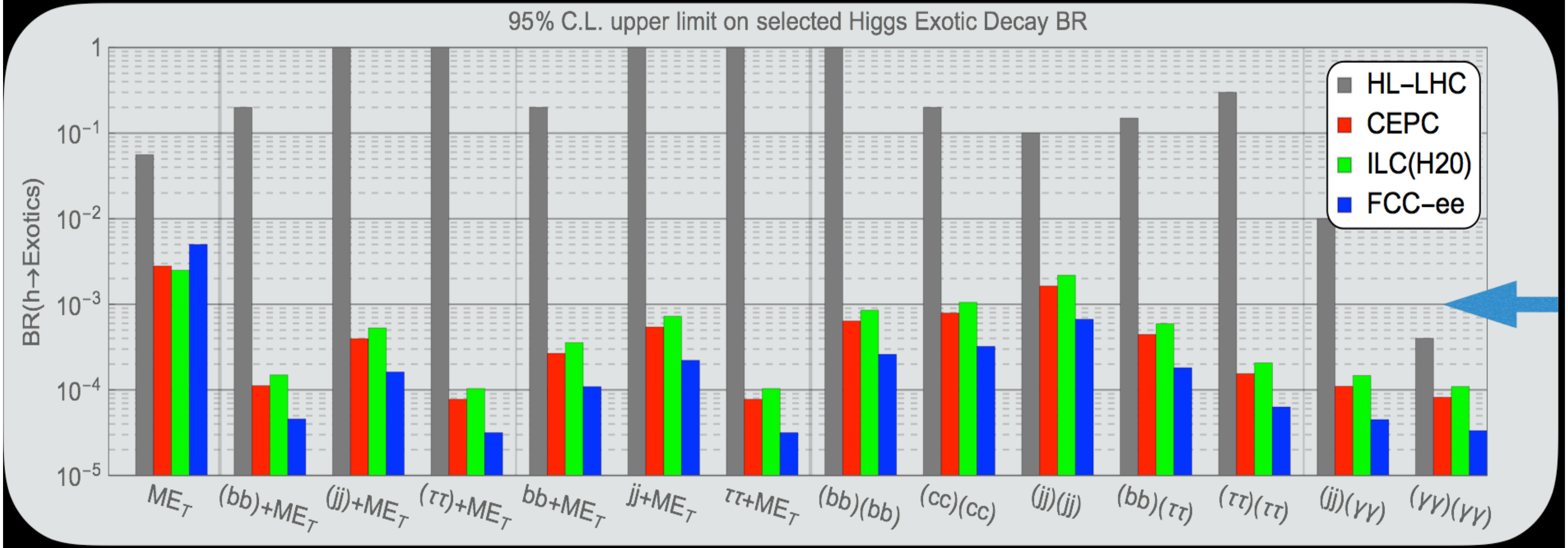
ILC250 Physics Case arXiv 1710.07621

BSM physics through exotic Higgs decays





Uses ILC250 Physics Case arXiv 1710.07621

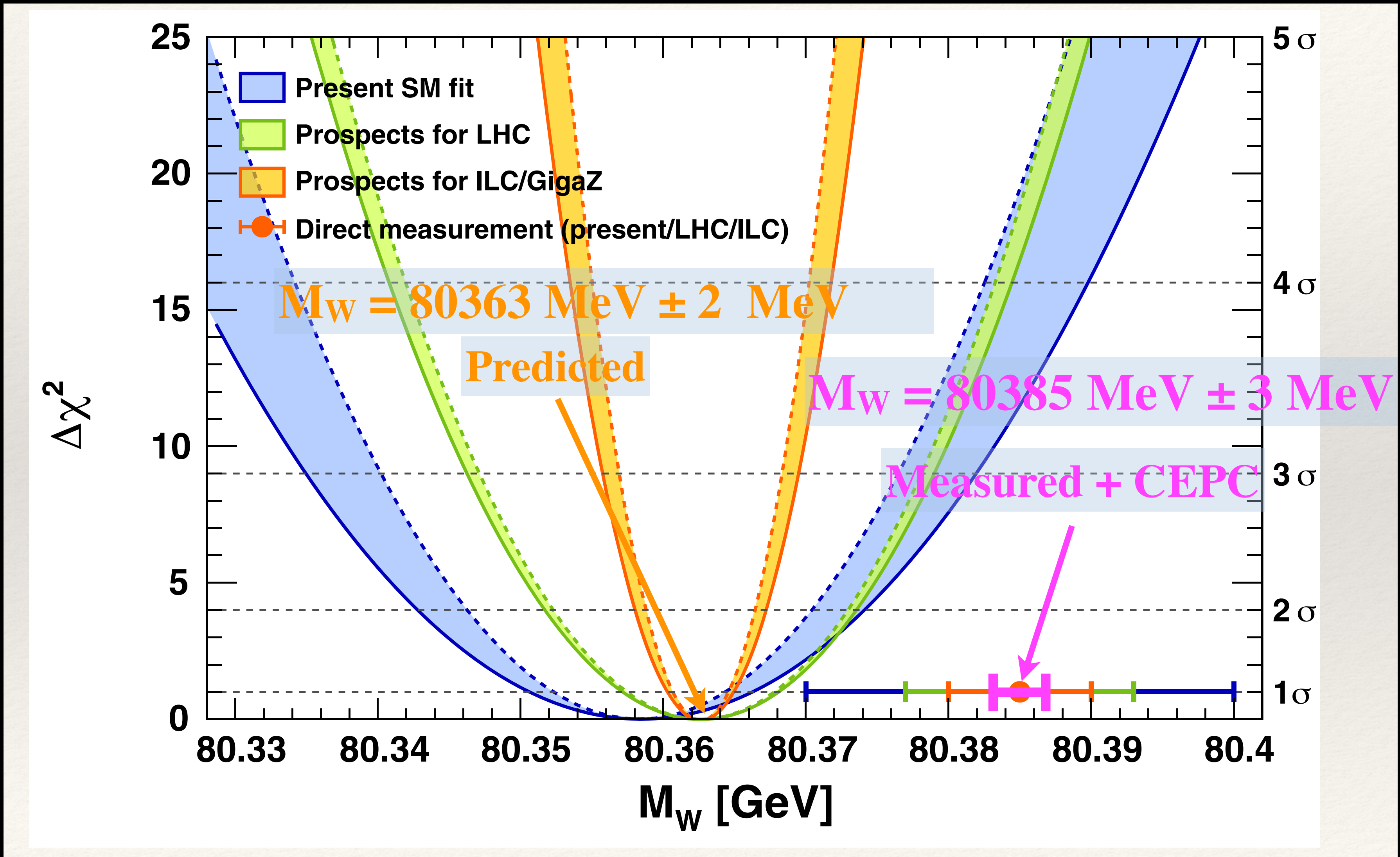
Z. Liu, H. Zhang, LT Wang, 1612.09284

Electroweak programme (W, Z) FCC-ee & CEPC (revisiting LEP with 100,000 times the Luminosity)

FCC-ee @ Z-pole 3 x 10^{12} Z bosons in 2 years
CEPC @ Z-pole 10^{12} Z bosons in 2 years

Observable	LEP precision	CEPC precision	CEPC runs
m_Z	2 MeV	0.5 MeV	Z threshold scan
A_{FB}^b	1.7%	0.1%	Z threshold scan
$\sin^2\theta_W^{\text{eff}}$	0.07%	0.002%	Z threshold scan
R_b	0.3%	0.02%	Z pole
R_μ	0.2%	0.01%	Z pole
N_ν	1.7%	0.05%	ZH runs
m_W	33 MeV	2-3 MeV	ZH runs
m_W	33 MeV	1 MeV	WW threshold

Electroweak programme (W, Z) FCC-ee & CEPC

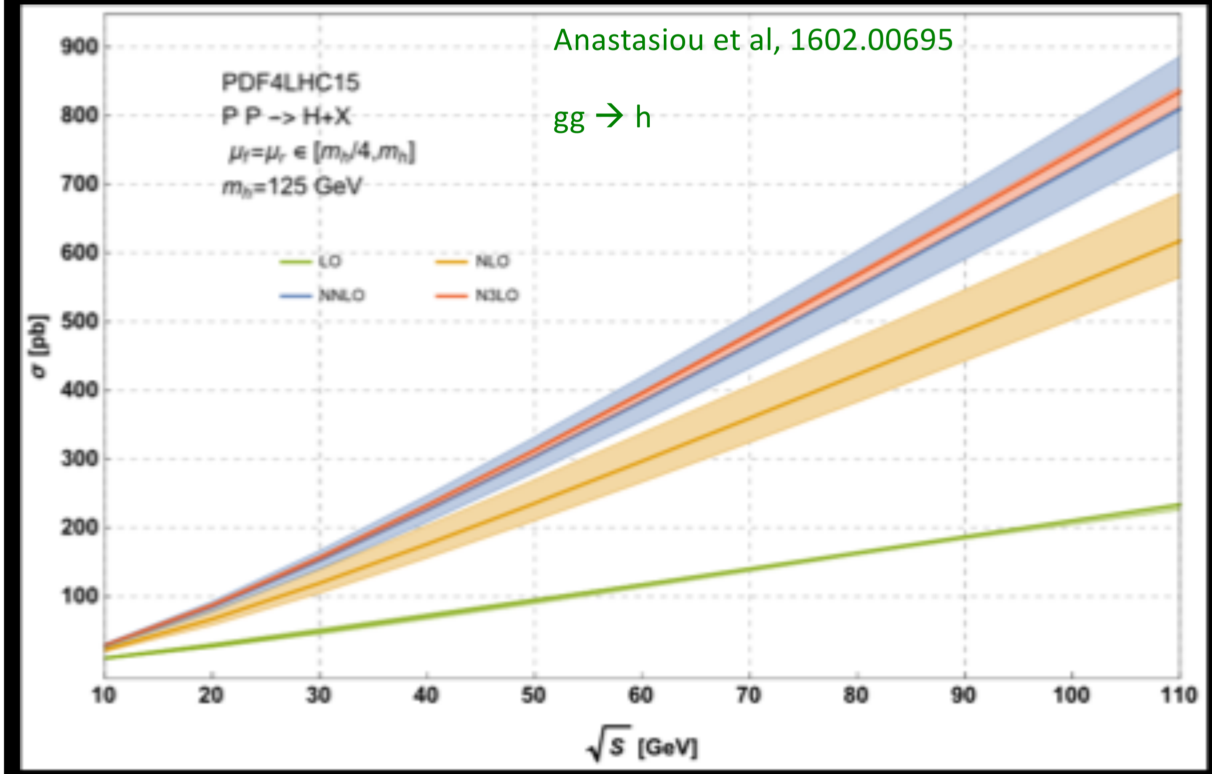


Current values δMW :16 MeV Tevatron (comb.) 19 MeV ATLAS, SM Fit 4 MeV

Future Circular Collider (FCC) – proton collider

Higgs production

Compared to LHC at 14 TeV the cross section increases with a factor of about 16 at NNNLO. Together with a larger luminosity, one can expect 60-400x more events.



Top Yukawa coupling

Measurement to 1% precision

Higgs self-coupling

Measurement to 3-5% precision

Higgs invisible decay Branching Ratio

Sensitivity down to 3-5 x 10^{-4}

Top quark production

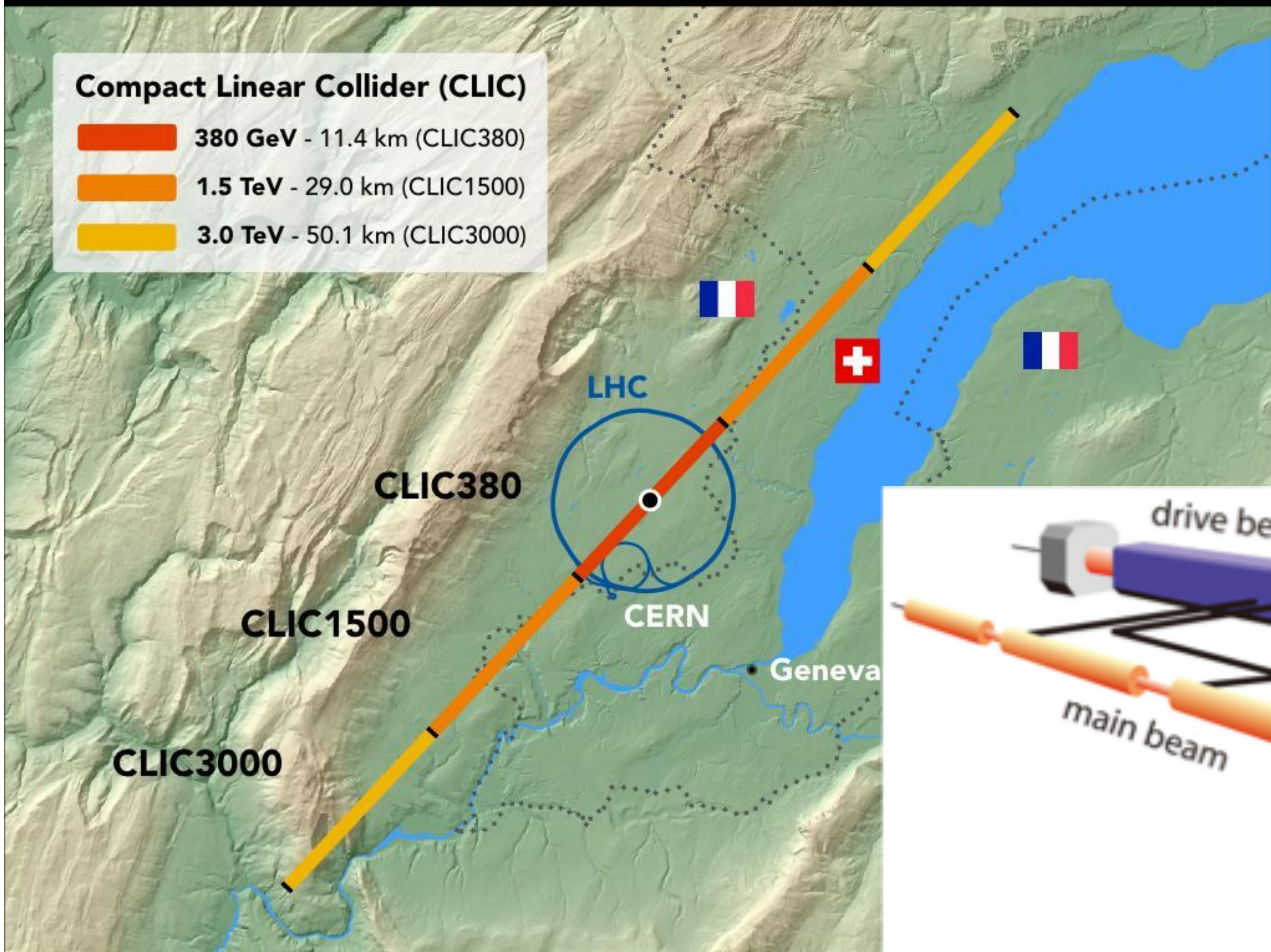
Cross section increases x35 compared to LHC at 14 TeV, and might collect up to 10^{12} top quarks

New physics phenomena

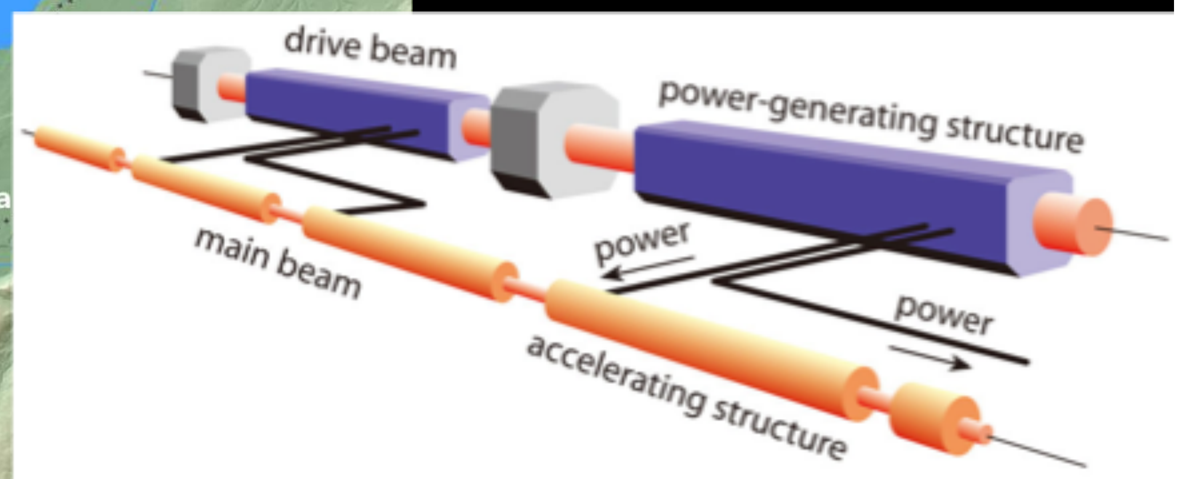
In general direct sensitivity to processes with mass scales up to 10-40 TeV.

Compact Linear Collider (CLIC)

CERN-2016-004
arXiv:1608.07537

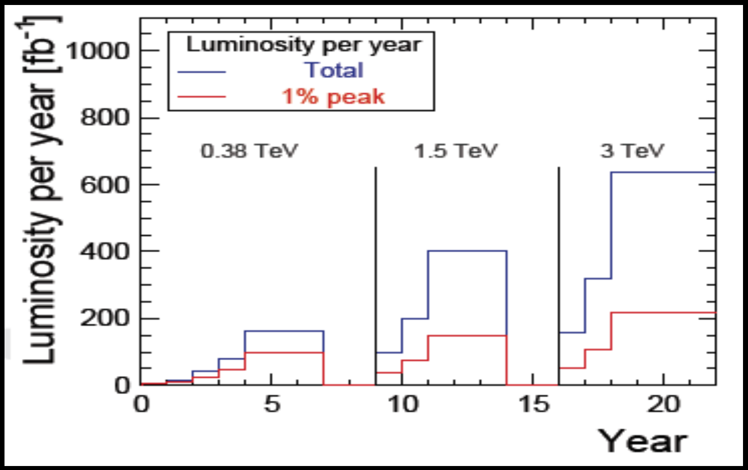


CLIC aims at an acceleration gradient of 100 MV/m. A drive beam is decelerated in dedicated Power Extraction and Transfer Structures (PETS), and the generated RF power is transferred to the main beam.



CLIC – some physics highlights

P. Burrows @ ICFA Seminar 2017



Higgs & top quark characterization

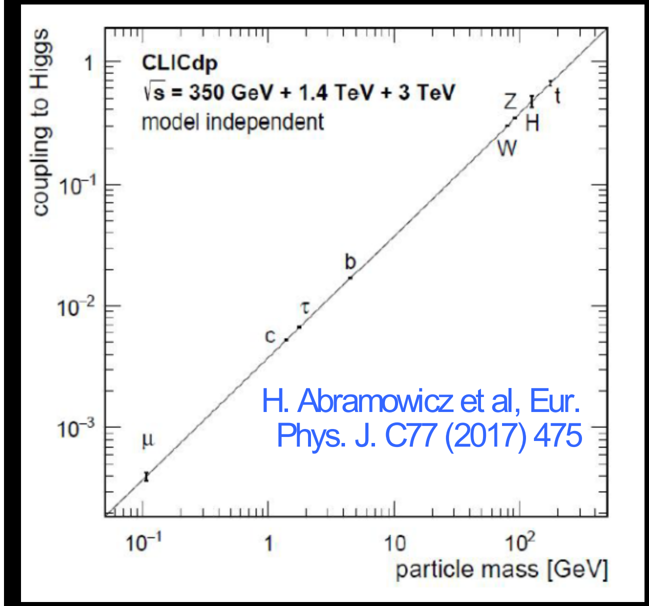
Precision on top quark Yukawa of ~4%, m(top) to 100 MeV (x5 better than HL-LHC) and Higgs self-coupling of ~20%.

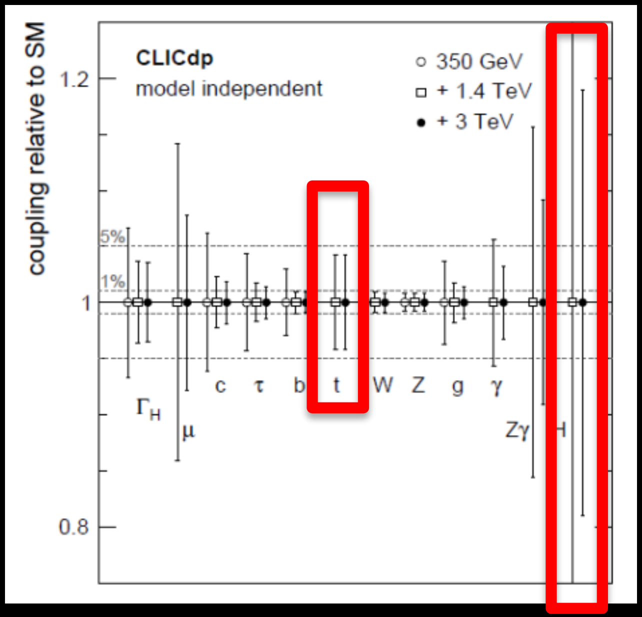
Staged approach

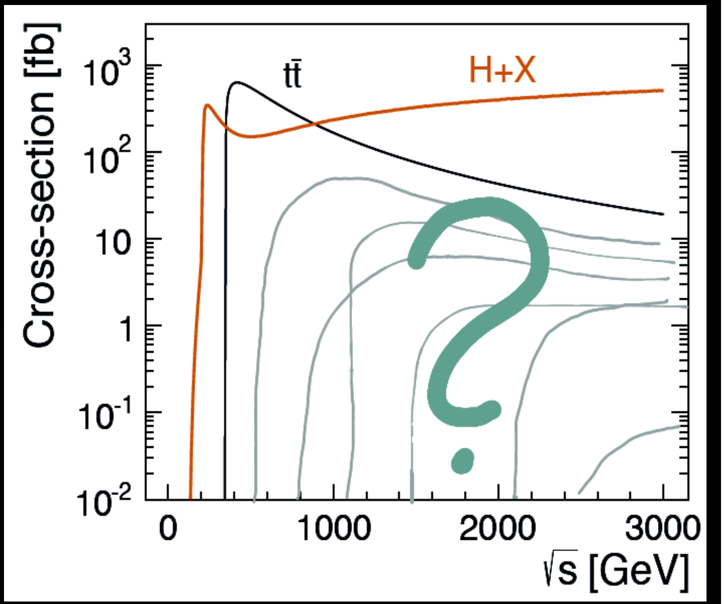
First period as a Higgs/top factory, including a run at top quark pair threshold, thereafter operate at higher energies (upto 3TeV) which give access to:

- tth and HHH couplings, as well as
- study any accessible new particles discovered @LHC
- searches for new phenomena

500 fb^{-1} 380 GeV, 1.5 ab^{-1} 1.5 TeV \and 3 ab^{-1} at 3 TeV.

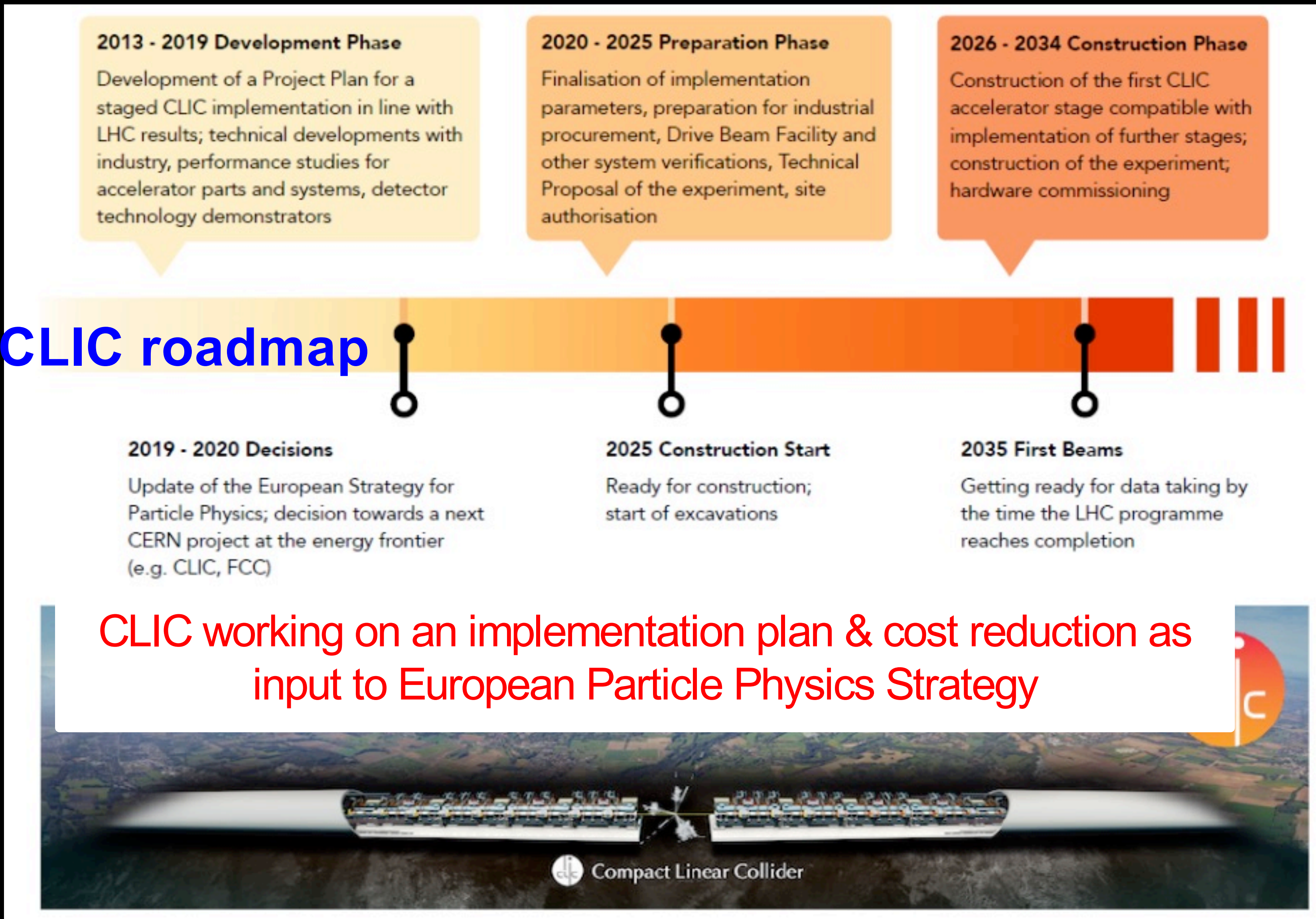






Total: 3 x10^{6} Higgs

CLIC roadmap



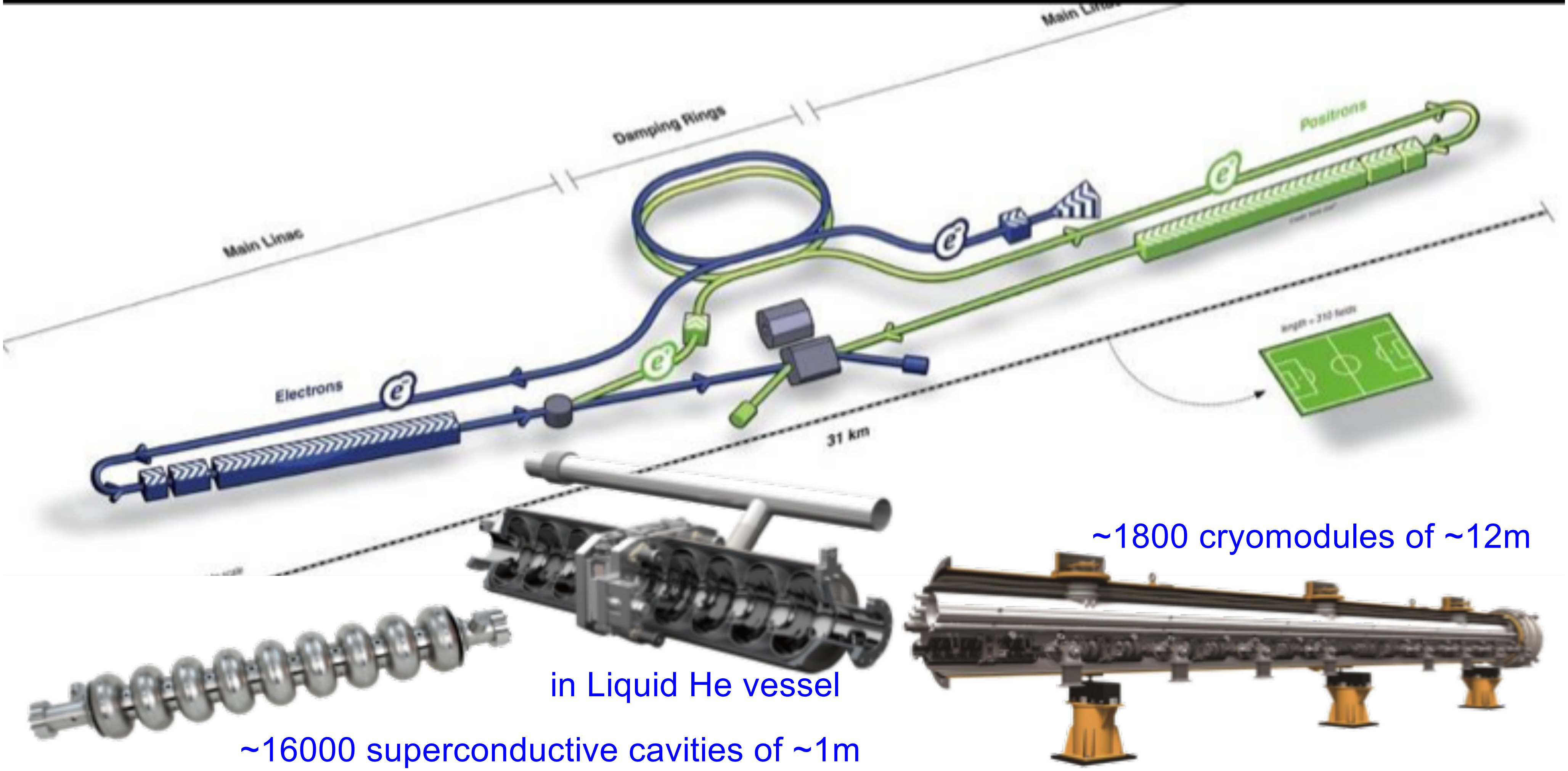
CLIC working on an implementation plan & cost reduction as input to European Particle Physics Strategy

The 2013 European Particle Physics Strategy

"There is a strong scientific case for an electron-positron collider, … Europe looks forward to a proposal from Japan to discuss a possible participation."

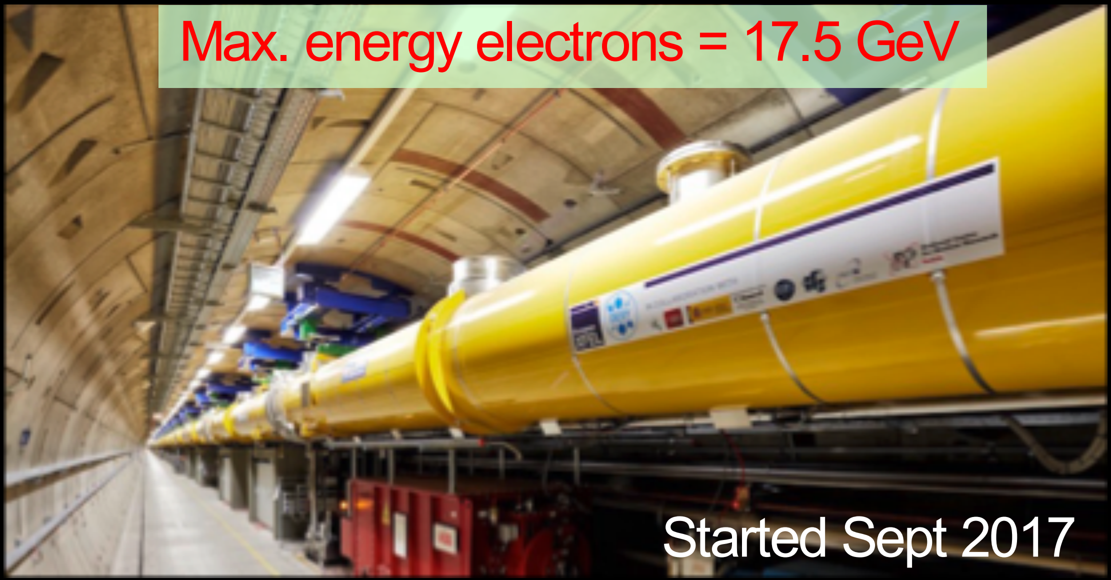
Waiting for a statement from the Japanese Government for their willingness to host ILC before end of 2018

International Linear Collider (ILC)



Technology connection with the European XFEL at DESY

The 3.4 km long European XFEL generates extremely intense X-ray flashes to be used by researchers from all over the world.



First mass production in industry of SC radio frequency TESLA technology (from about 100 accelerator modules at the XFEL to about 2000 at ILC).

XFEL : 80% of the cavities reach a gradient of 33 MV/m
ILC : 90% of the cavities need a gradient of 35 MV/m

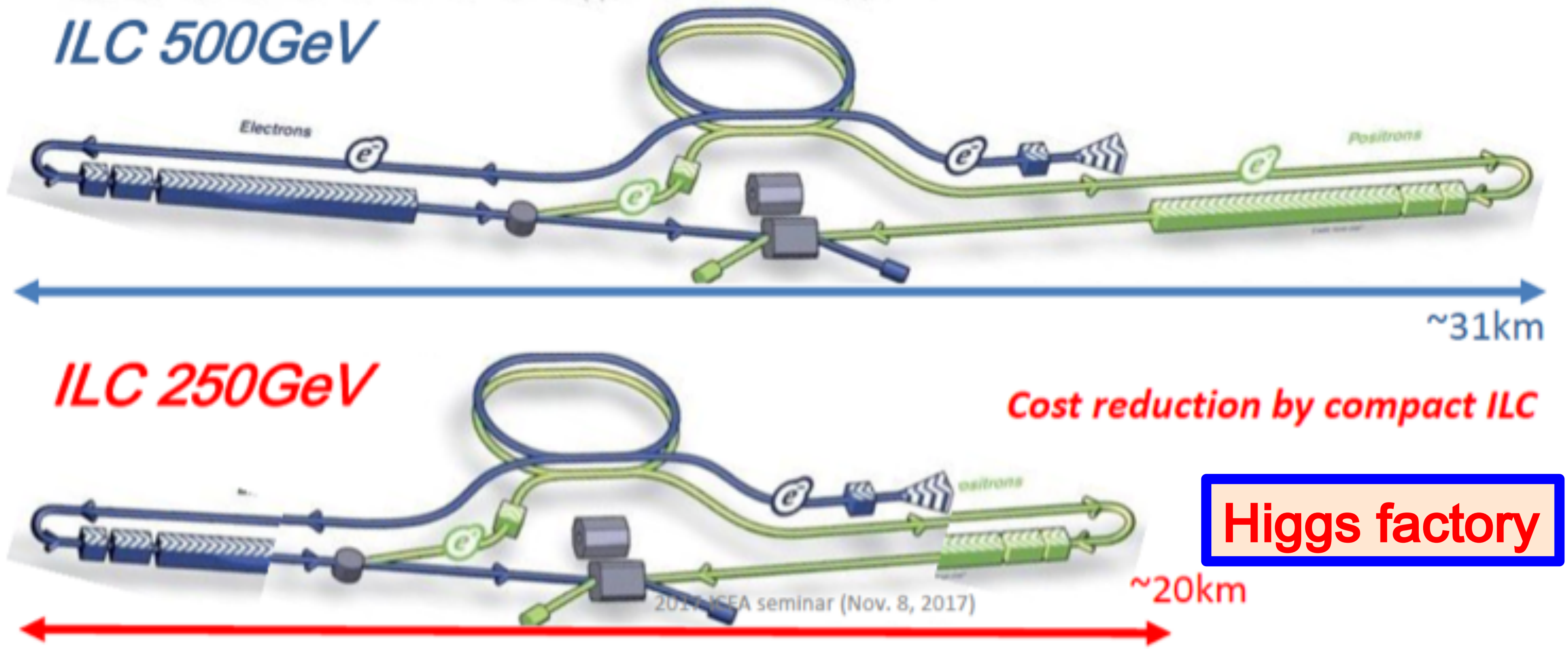
Denis Kostin @ LCWS2017, Oct 24

This demonstrates the goal for the ILC is within reach.

International Linear Collider (ILC) – 500 GeV → 250 GeV

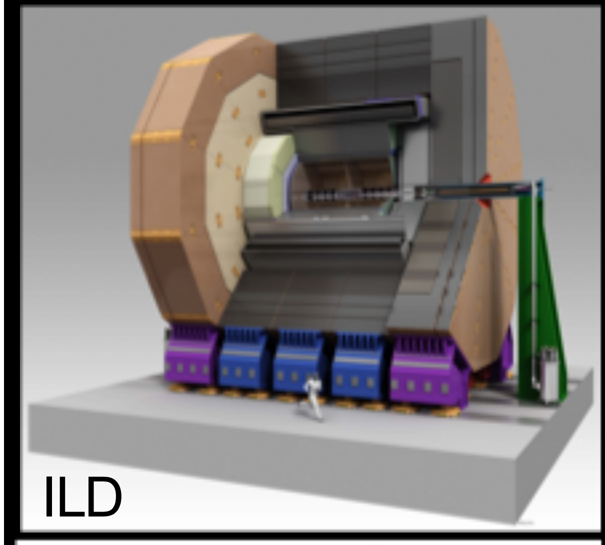
Cost reduction both by scaling from 500 GeV to 250 GeV with a focus on Higgs physics, and by technological innovations on the superconducting materials (Nb) and cavity construction (surface process).

Physics Case for the 250 GeV Stage of the ILC, arXiv:1710.07621



ILC would be on a site surveyed for capability to reach 1 TeV – once ILC250 constructed extensions to at least 375 GeV would be almost guaranteed since we know that tt physics is very interesting and the enormous infrastructure/people investment for ILC250 would hardly be written off by Japan after 10 years.

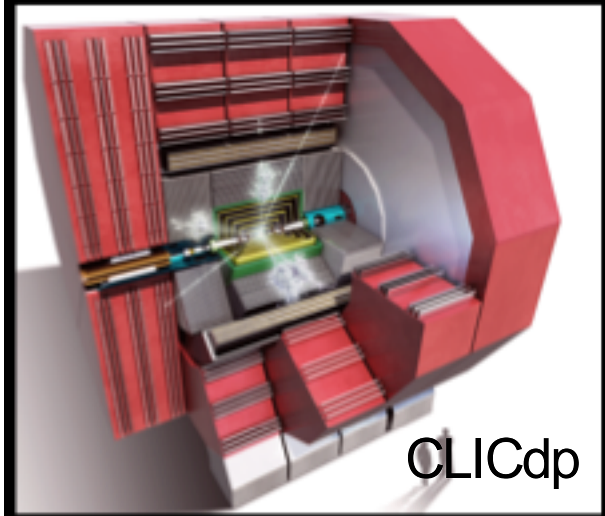
Linear Collider detector & physics studies: Europe engaged

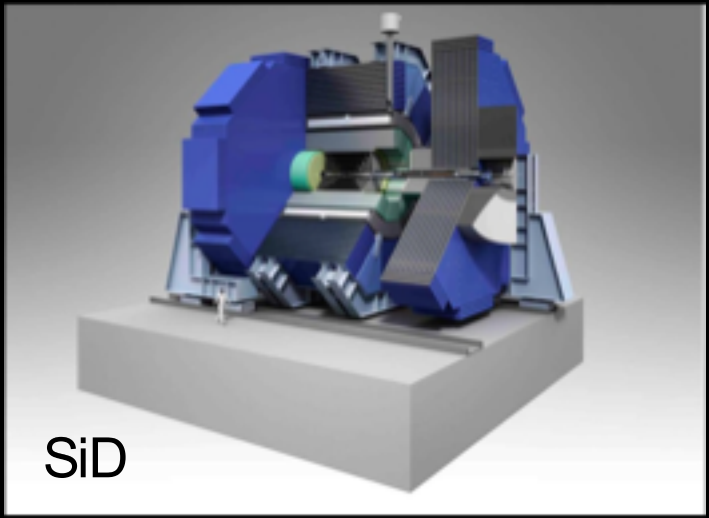


The LCC physics & detector directorate is responsible for activities that advance the physics and detectors of the linear collider.

Three detector concepts:

- ILD: 71 institutions mostly from the European Region
- SiD: 24 institutions many from the European Region
- CLICdp: 29 institutions mostly from the European Region





Three detector R&D groups:

- CALICE: 57 institutions mostly from the European Region
- LCTPC: 32 institutions many from the European Region
- FCAL: 14 institutions mostly from the European Region

UK groups' interests in ILC/CLIC

All UK PP groups are represented in LCUK

~75 faculty have expressed interest in physics / detector / accelerator

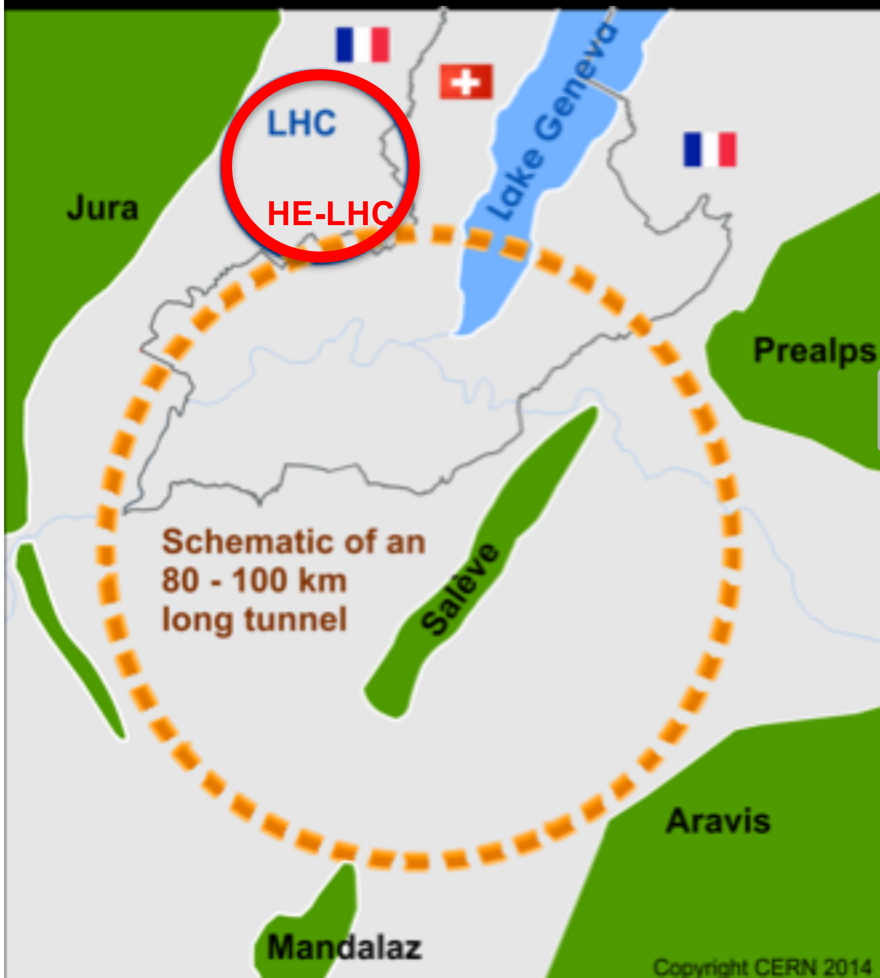
UK expertise puts us in a strong position to play leading roles

P. Burrows (LCUK)

Technical system Institute	Accelerator					Detector			Physics
	BDS/MDI	DR	Beam dumps	e+ source	RF	Si tracker	Calorimetry	DAQ	
Birmingham	X					X	X		X
Bristol						X		X	X
Cambridge							X		X
STFC – Daresbury Laboratory	X			X	X				
Durham IPPP									X
Edinburgh						X			X
Glasgow						X			X
Imperial College							X	X	X
Lancaster				X	X	X			X
Liverpool		X				X			X
Manchester	X				X	X			X
Open University						X			
Oxford	X	X			X	X		X	X
QMUL						X			X
STFC – RAL			X			X			X
RHUL	X							X	X
Sheffield						X			X
Southampton									X
Sussex								X	X
UCL	X						X	X	X
Warwick						X			X

Many of these capabilities would also be of relevance to a future circular electron-positron collider should plans for either CEPC or FCCee proceed

Future Circular Collider (FCC) Study



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

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

~16 T ⇒ 100 TeV *pp* 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***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

FCC : physics and performance targets

FCC-ee:

- Exploration of 10 to 100 TeV energy scale via couplings 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)

➢ Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks

➢ Machine design for 100 TeV c.m. energy & integrated luminosity ~ 20ab^{-1} within 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC

➢ Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies 10 ab^{-1} over 20 years.

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 operation model

working point	luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	25	7 ab^{-1}/year	**10 ab^{-1}**	**1-2**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	0.36 ab^{-1}/year	**1.5 ab^{-1}**	**4**

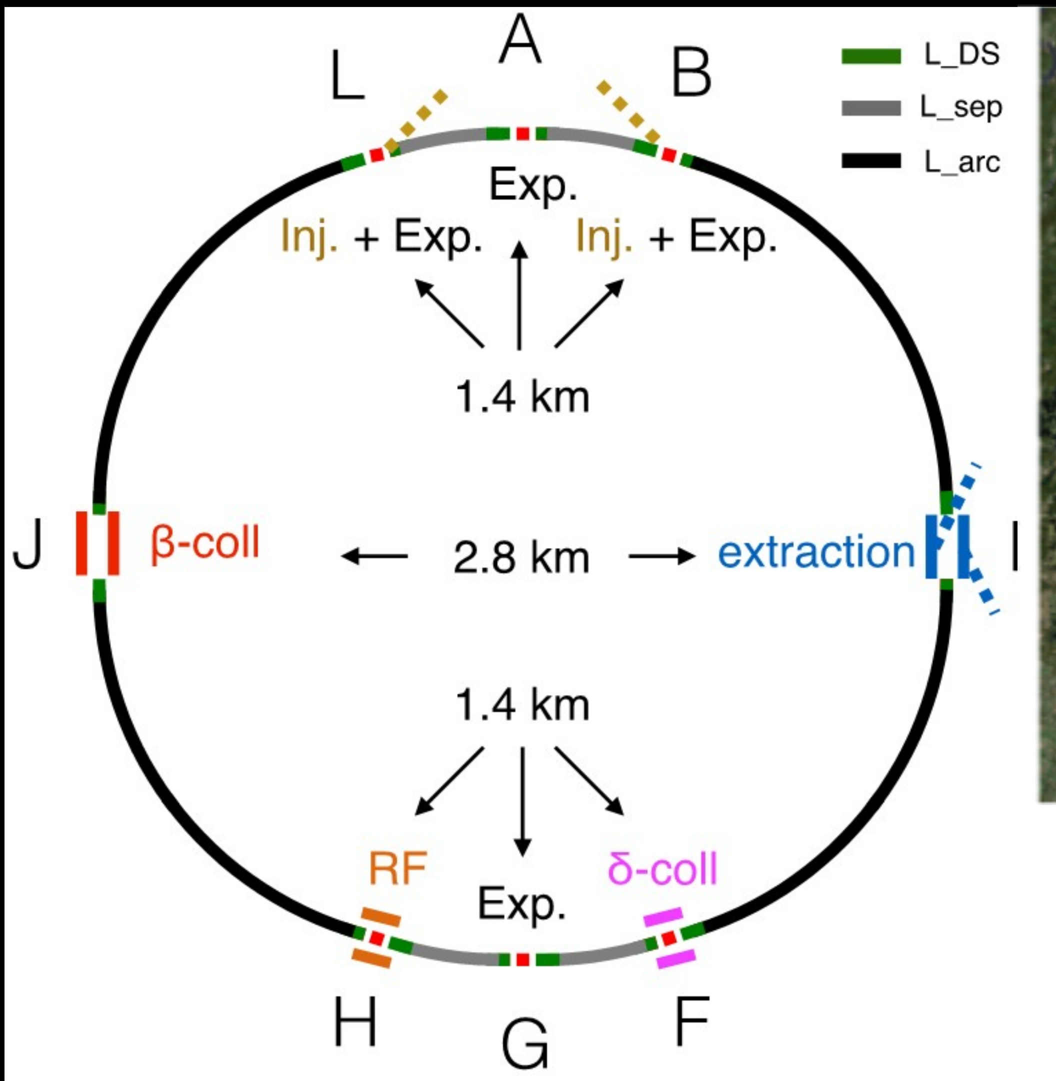
total program duration: 14-15 years ***- including machine modifications***

phase 1 (*Z, W, H*): 8-9 years, phase 2 (top): 6 years

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	0.45	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	16	5 (lev.)	1
events/bunch crossing	170	1000	460	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

FCC-pp layout

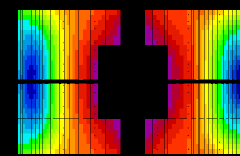


Worldwide FCC Nb_3Sn program

Main development goal is wire performance increase:

- **J_c (16T, 4.2K) > 1500 A/mm^2 →50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**

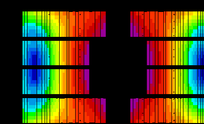
5400 mm^2



~10% margin
HL-LHC

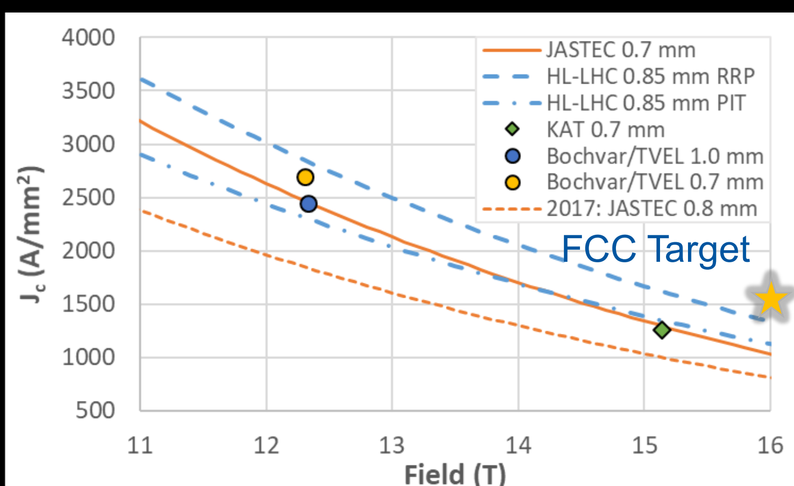
~1.7 times
SC

3150 mm^2



~10% margin
FCC ultimate

After only one year of development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC performance**



Conductor activities for FCC started in 2017:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT, Korea**
- **Columbus, Italy**
- **University of Geneva, Switzerland**
- **Technical University of Vienna, Austria**
- **SPIN, Italy**
- **University of Freiberg, Germany**

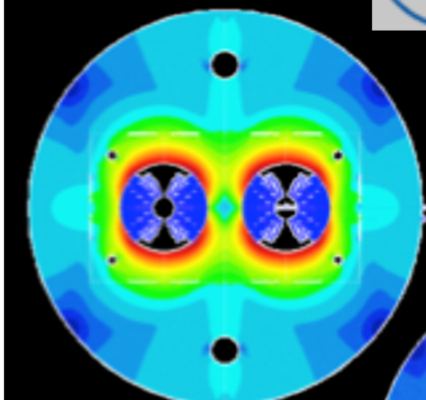
In addition, agreements under preparation:

- **Bruker, Germany**
- **Luvata Pori, Finland**

16 T dipole design activities and options

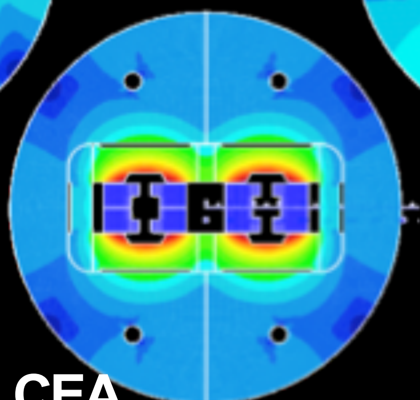
H2020

Cos-theta



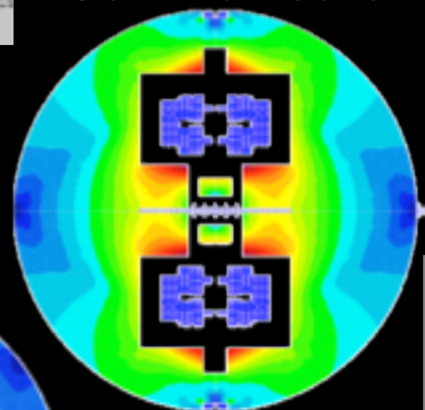
INFN

Blocks



CEA

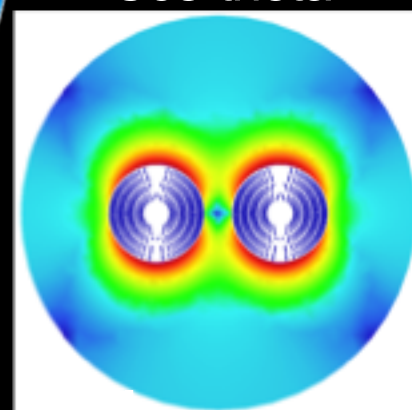
Common coils

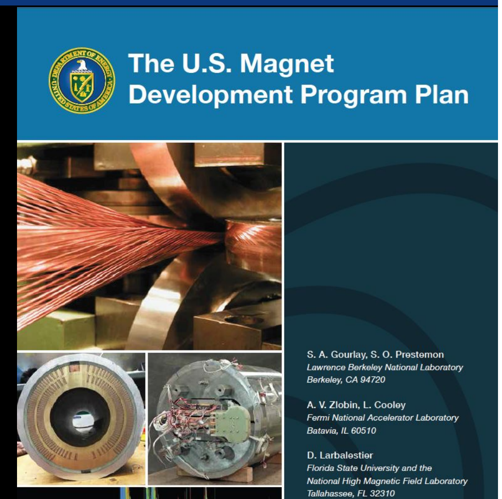


CIEMAT

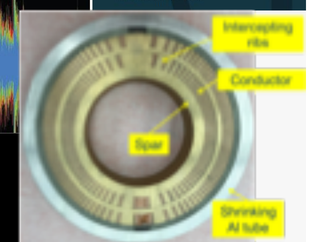
Swiss contribution

Canted Cos-theta

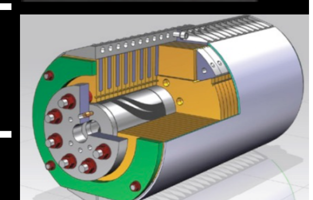




LBNL

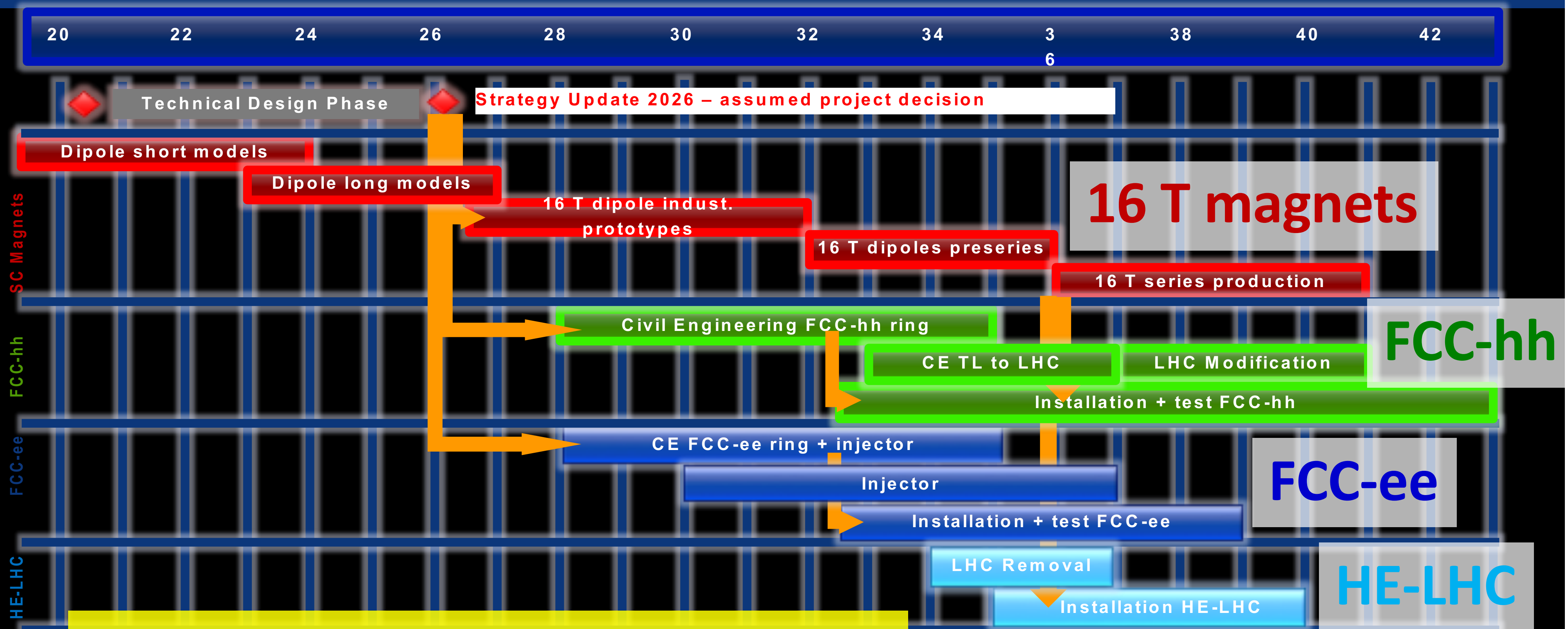


FNAL



Short model magnets (1.5 m lengths) will be built from 2018 – 2022
Russian 16 T magnet program launched by BINP recently.

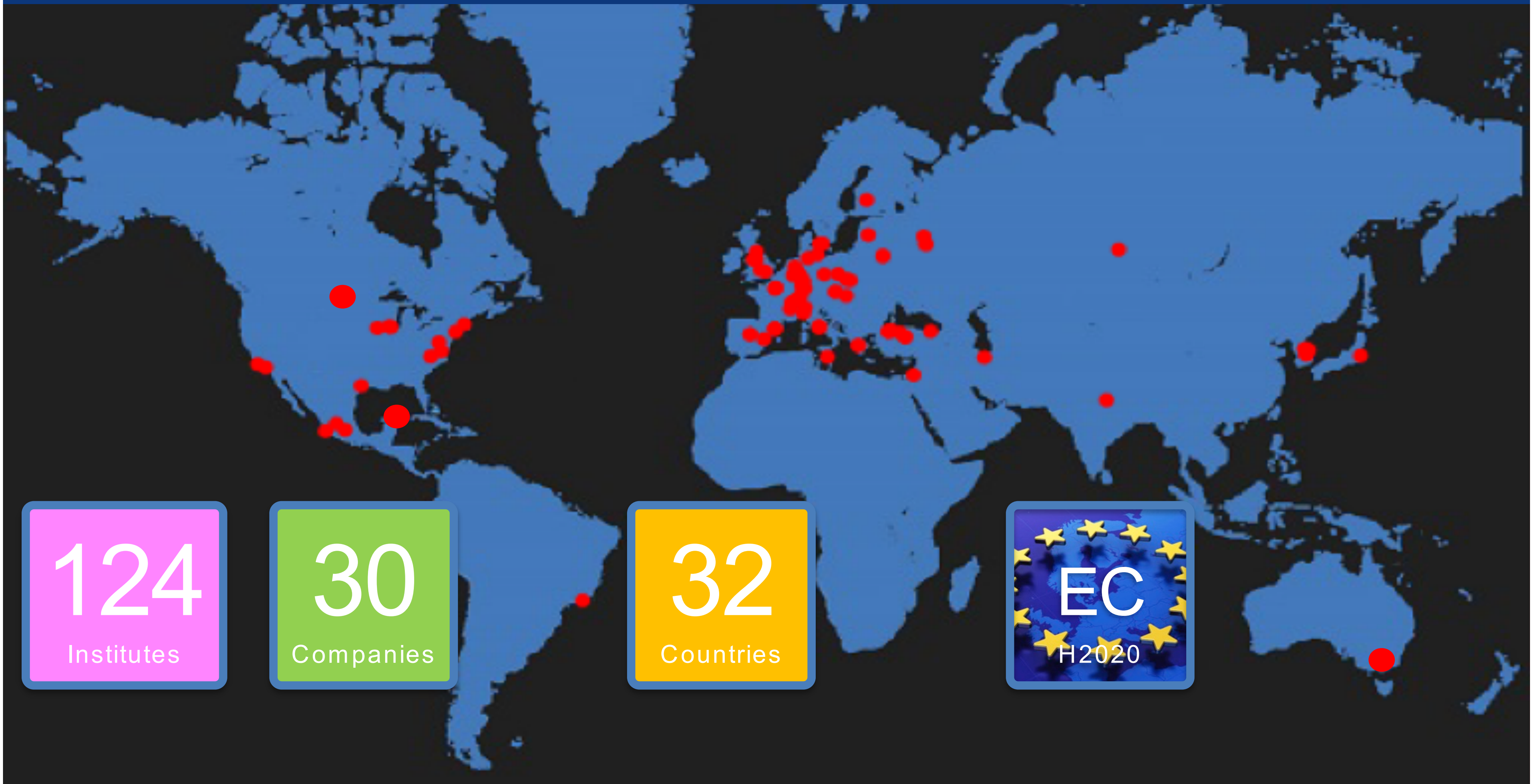
Technical Schedule for each of the 3 options



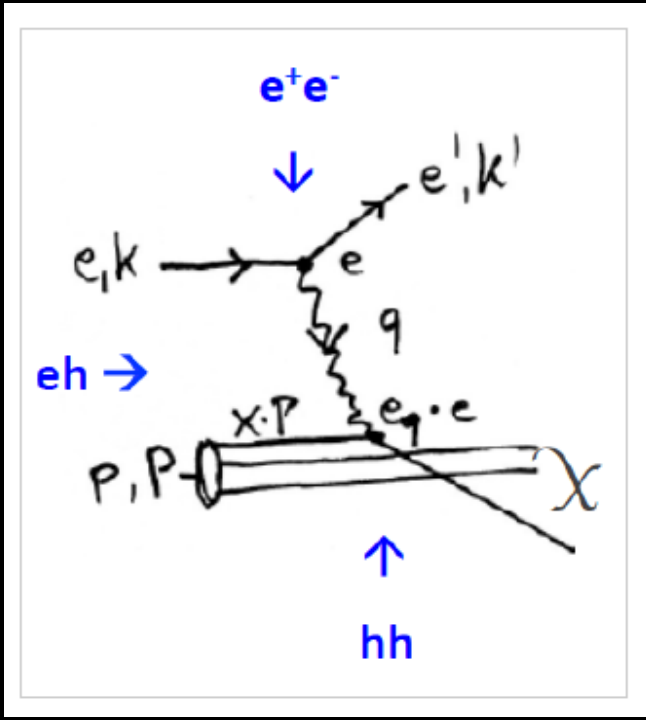
schedule constrained by 16 T magnets & CE
→ earliest possible beam operation dates

- **FCC-ee: 2039**
- **FCC-hh: 2043**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

Global FCC Collaboration

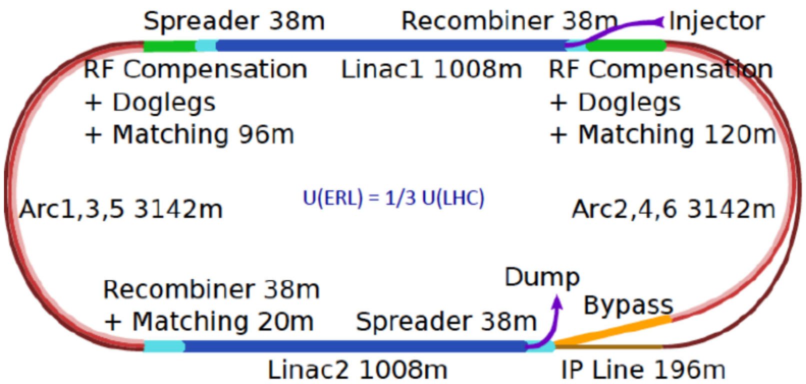


LHeC



W Kandinsky, Circles in a Circle, 1923, Philadelphia Art Museum

Slides from Max Klein for LHeC UK



Three Raisons d'etre of the LHeC

Physics

- **Microscope**: World's Cleanest High Resolution
- **Maximises** the LHC Physics Programme
- **Creation** of a high precision, novel Higgs facility
- **Discovery** Beyond the Standard Model
- **Revolution** of Nuclear Particle Physics

Sustainability and Cost

LHC:
- see: SM, Higgs and no BSM
- use: Investment of O(5) BSF
- run: HL LHC until ~2040

LHeC [1206.2913, update 2/19]
- 1.2 TeV ep/A for O(1)BSF

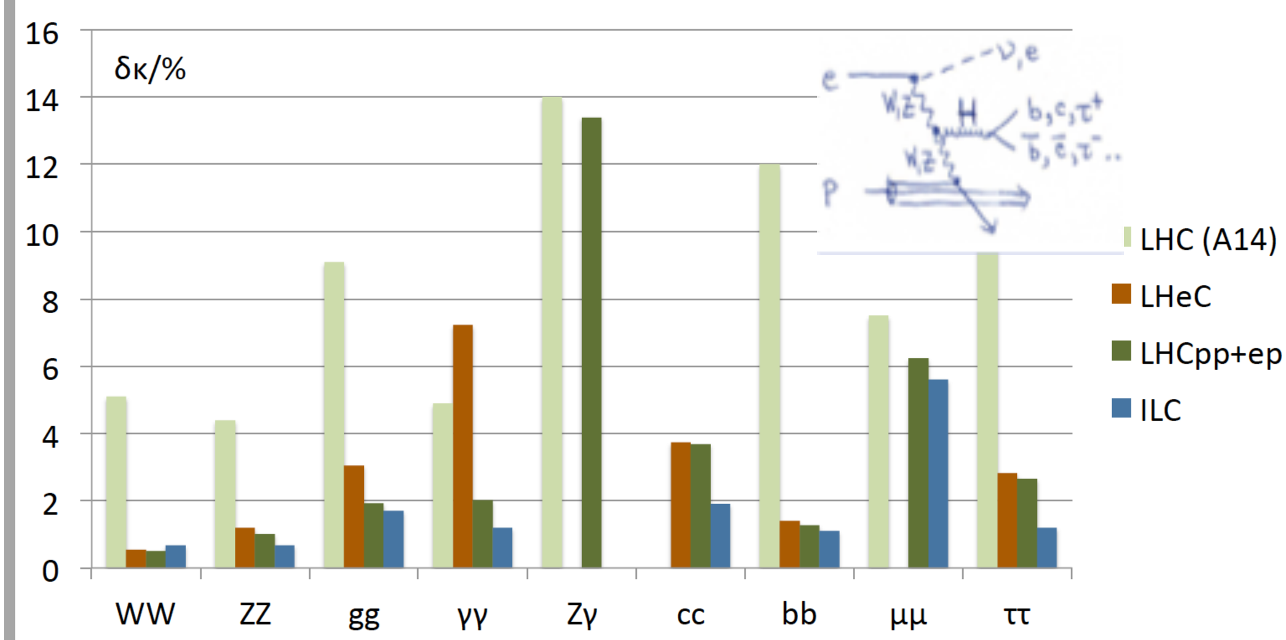
→ Establish novel ep+pp Twin Collider Facility at CERN: sustains HL LHC and bridges to CERN's long term future
For installation during LS4 (2030+) and long term use (HE LHC, FCCeh)

Technology

Accelerator: Novel SRF ERL, green power facility
Detector: Novel high tech (CMOS..) apparatus

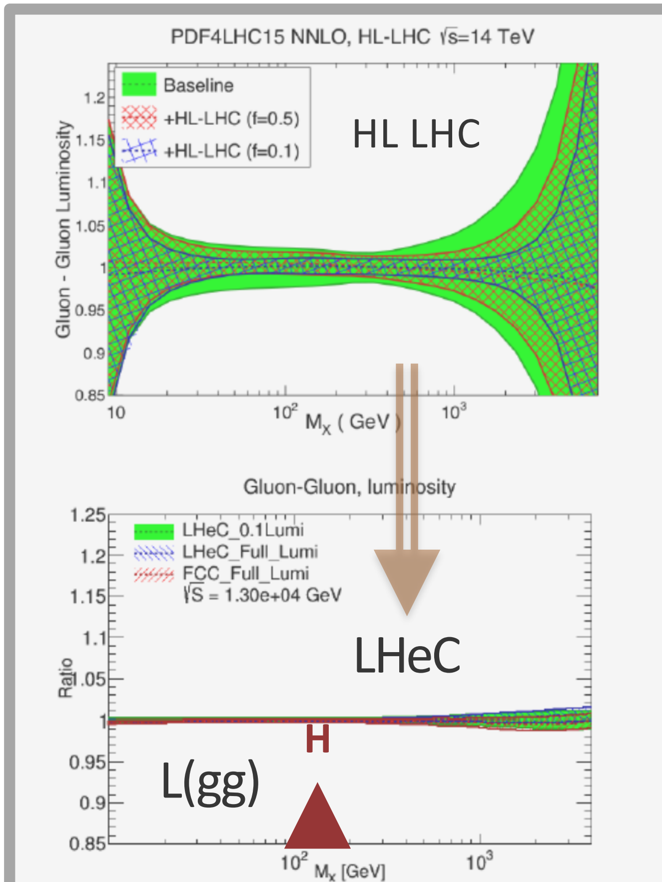
→ Keep accelerator and detector base uptodate while preparing for colliders that cost O(10)BSF

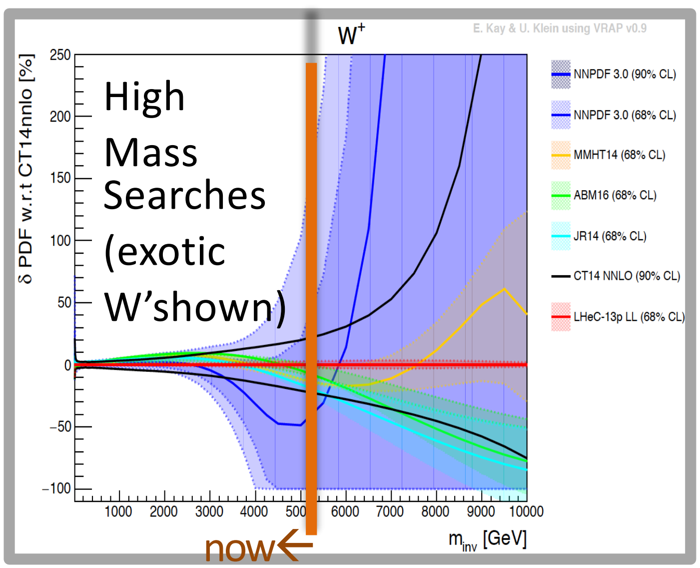
Prospects for Higgs Couplings: LHC, LHeC, ep+pp, ILC



HL-LHC ATLAS2014. LHeC: $1ab^{-1}$, in progress ep+A14 ILC: $2ab^{-1}$: 1710.0761

HL LHC WS to come, ep: J de Blas, M+U Klein ep+pp: J de Blas, prel. e^+e^- provides Γ_{tot}





Physics

1802.04317

α_s to 0.1%

V_{tb} to 1%...

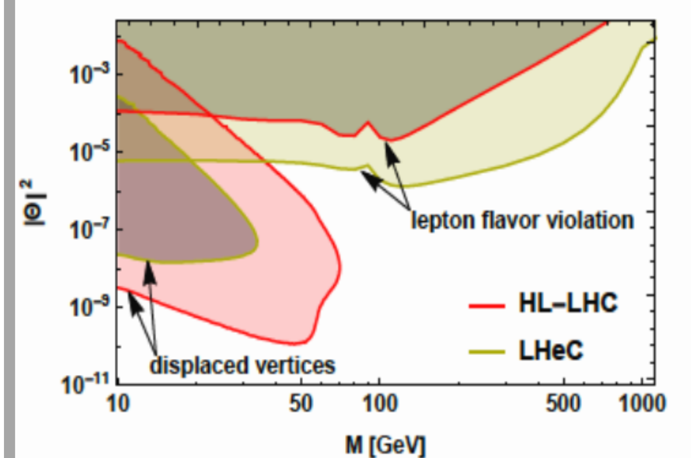
$\sin^2\theta_W$ better than LEP

M_W [pp+ep]: 0.007%

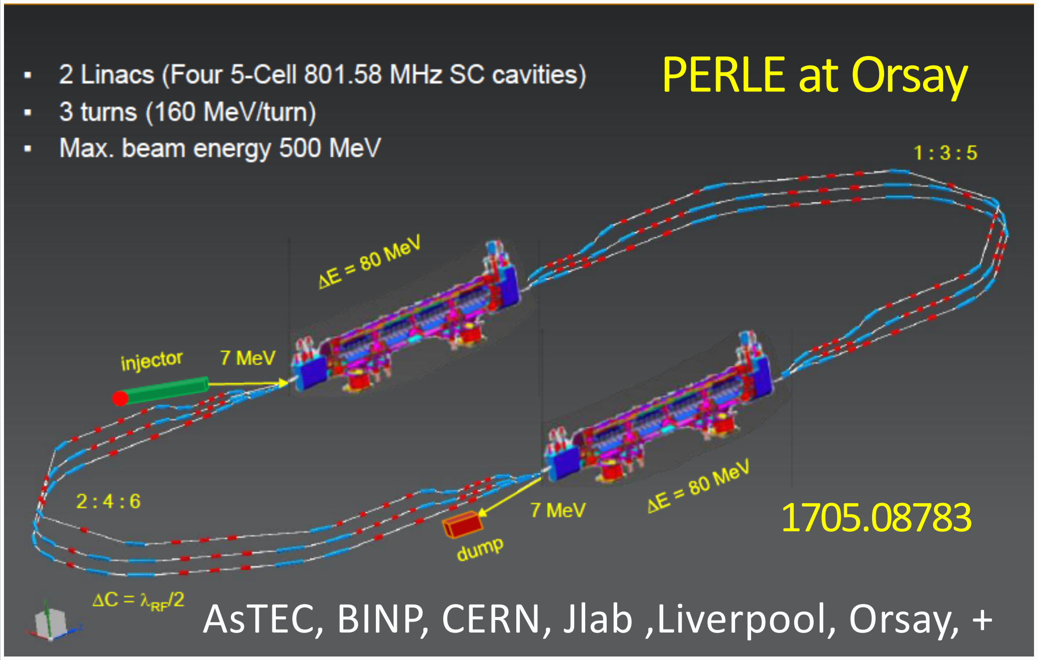
...

HIGH precision leads to Discovery BSM

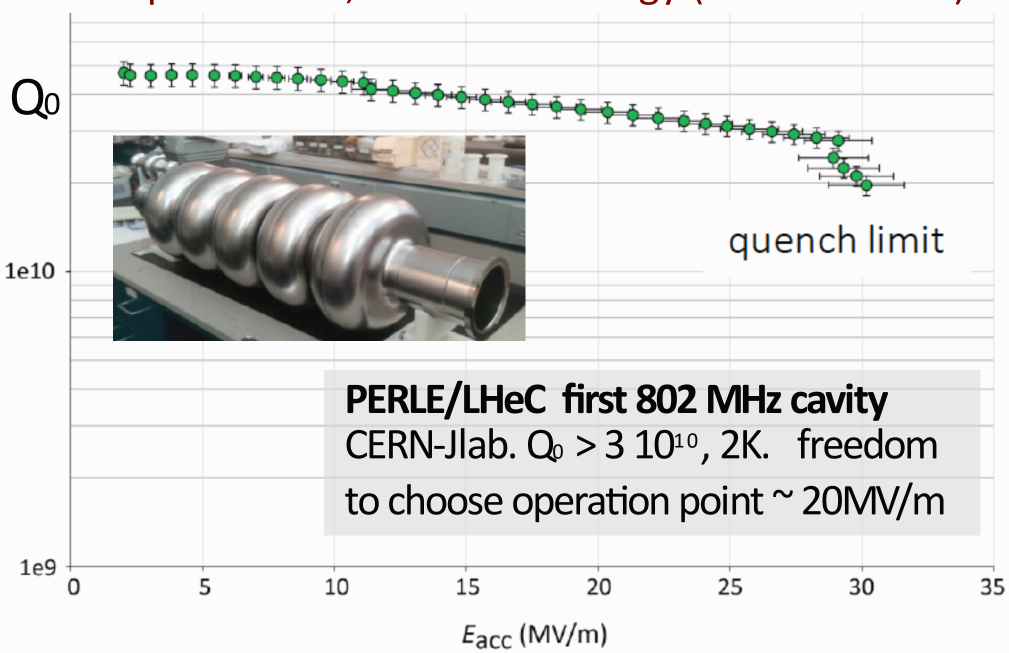
Search for Heavy Neutrinos

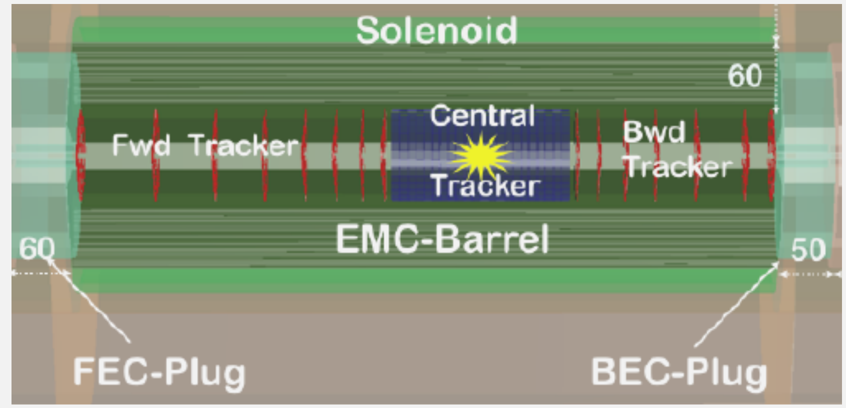


Acc & Det Technology



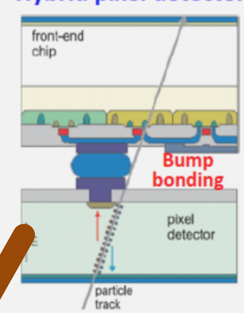
Challenge: demonstrate multi-turn ERL (cbeta, 2019)
Develop 802 MHz, LHeC Technology (PERLE > 2022)



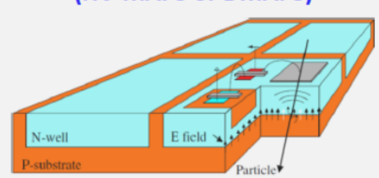


Zoom LHeC detector [15.6 x 10.4m^2 HE LHC]

Hybrid pixel detector



Fully monolithic HV-CMOS
(HV-MAPS or DMAPS)



UK Institutes

Accelerator
AsTEC, Cockcroft (Lancaster, Manchester, Liverpool, Srathclyde), JAI (Oxford)

Detector+Physics
Birmingham, Liverpool, Manchester, Oxford, QMW

HERA+LHC have also Bristol, Glasgow, Imperial, Lancaster, RAL, UCL.

Detector: a new task post HL LHC design
Challenge for Acc+Det: 3 beam-IR design

Most up-to-date Information: https://indico.cern.ch/event/698368/

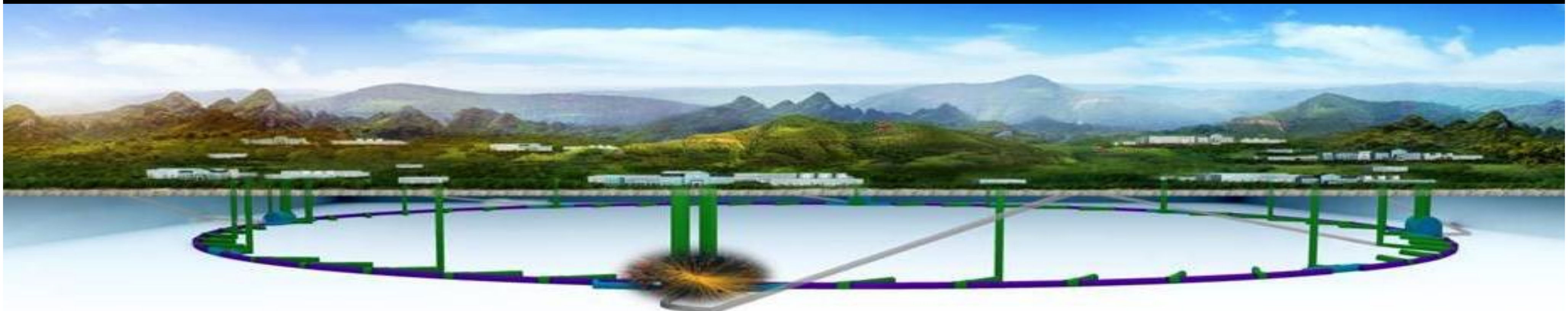
Workshop: LHeC/FCCeh and PERLE
Two week ago at Orsay near Paris

http://lhec.web.cern.ch

New and Updates on

Physics: PDFs, QCD, H, t, BSM, eA + Relation eh-hh..
Accelerator: IR, Optics, Lattice, Cost-Energy, CE..
Detector: the GPD and its fwd and bwd detectors
PERLE: Source, Injector, Cavity, Cryomodule,.. Physics
Project Development towards the ES2020:
LHeC + FCCeh+ PERLE input 12/18. **PERLE TDR in 2019.**

Circular electron positron Collider (CEPC)



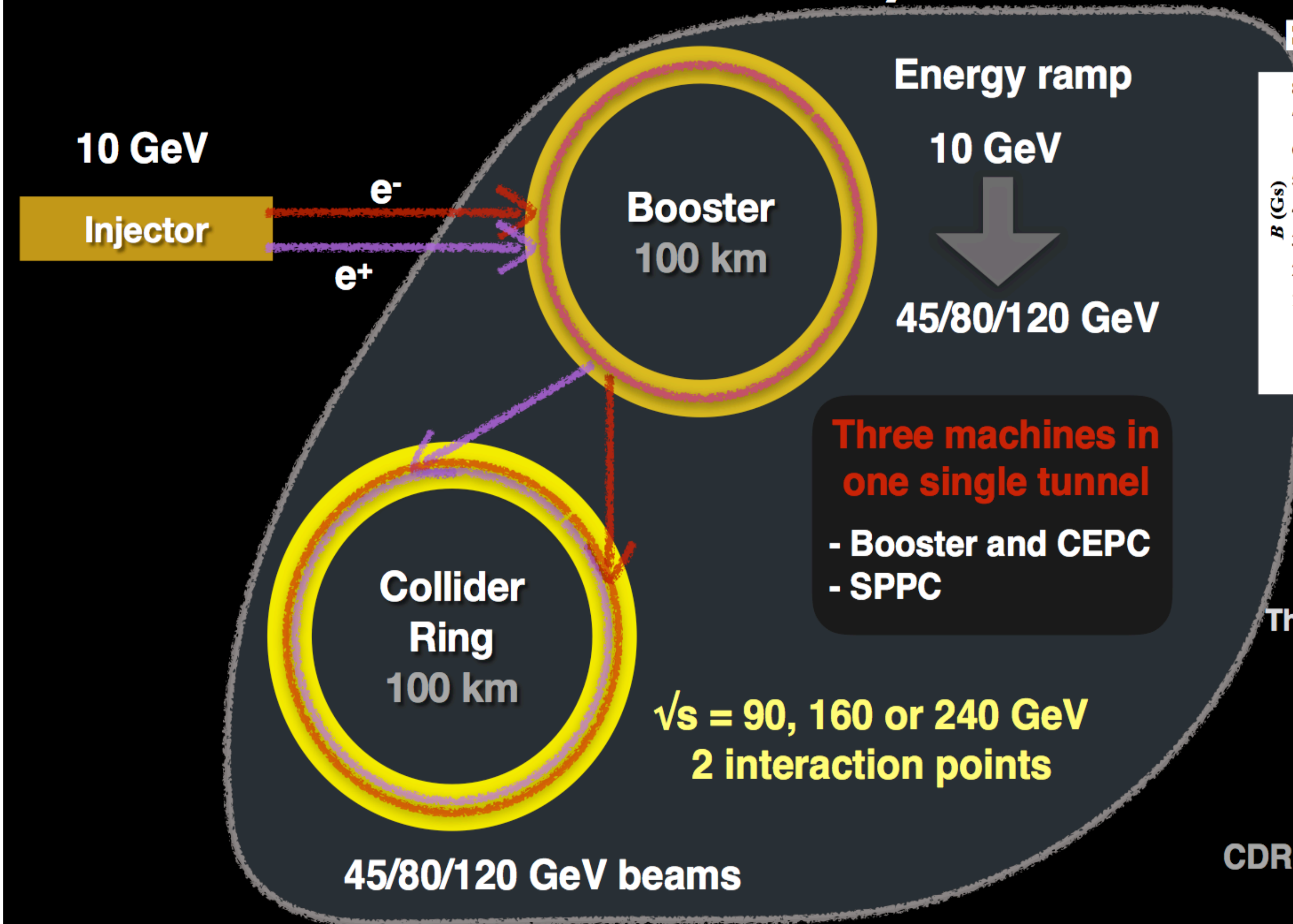
April 2017 June 2018

Lumi.	Higgs	W	Z	Z(2T)
$\times 10^{34}$	2.93	11.5	16.6	32.1

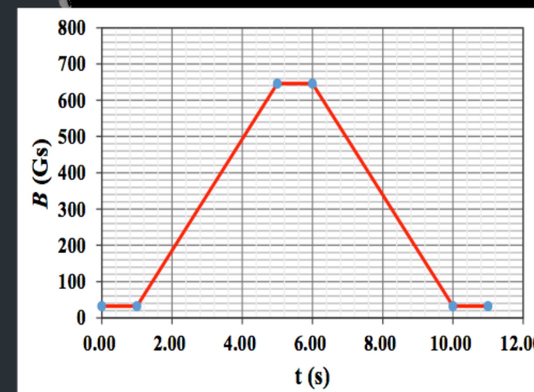
- ✓ double ring baseline design
- ✓ switchable between H and Z/W w/o hardware change (magnet switch)
- ✓ use half SRF for Z and W
- ✓ can be optimized for Z with 2T detector (~3200× LEP luminosity)

Intl. review - June 28-30 at IHEP
Release of CDR: July (accelerator), September (detector)

CEPC Accelerator Chain and Systems



Booster Cycle (0.1 Hz)

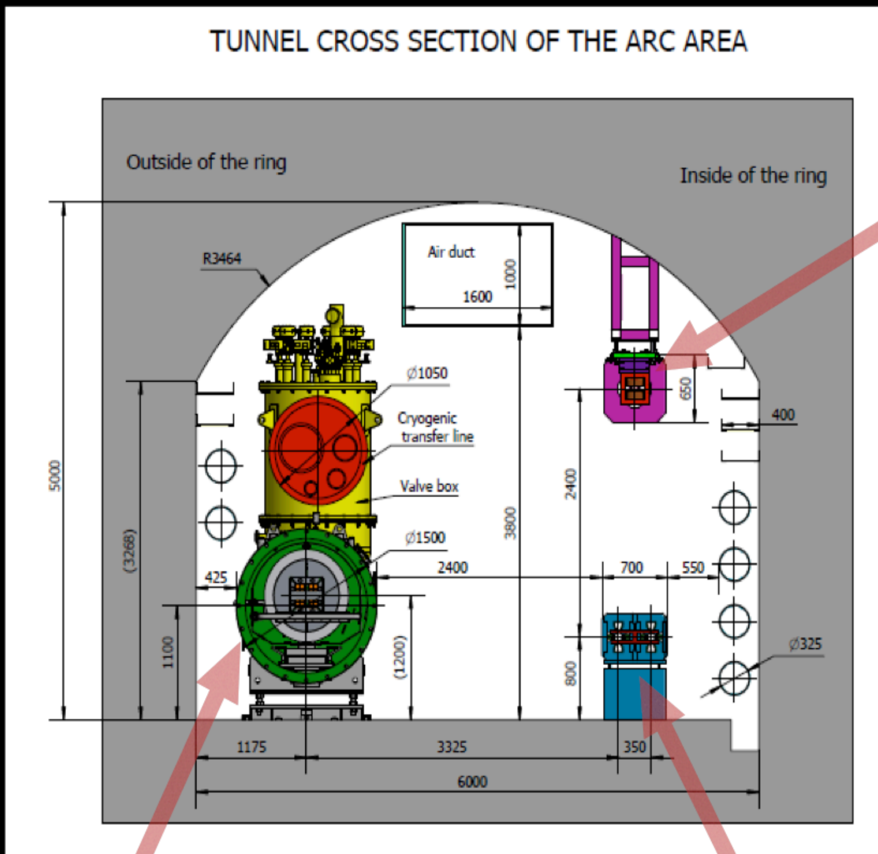


The key systems of CEPC:

1) Linac Injector
2) Booster
3) Collider ring
4) Machine Detector Interface
5) Civil Engineering

CDR provides details of all systems

The 100k tunnel cross section

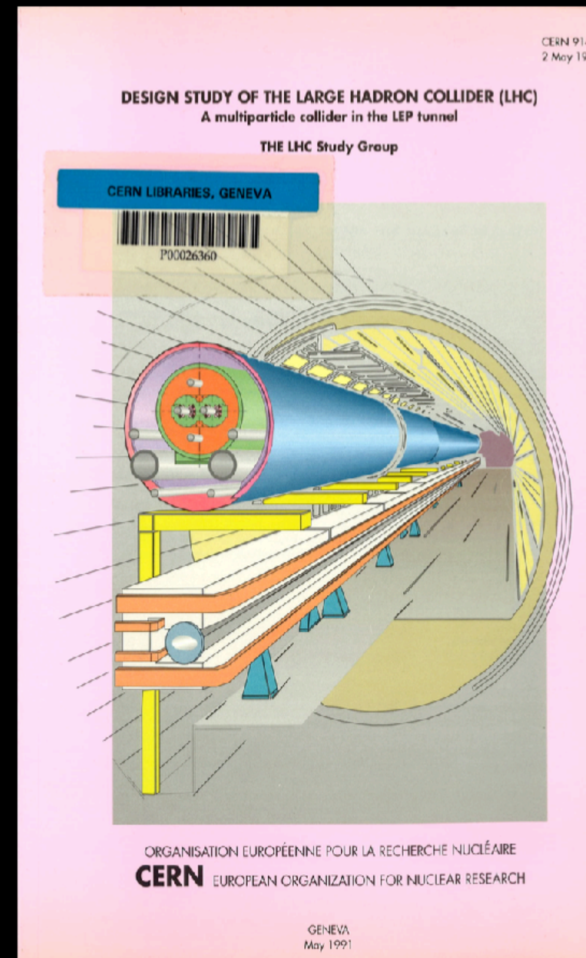


CEPC Booster

SPPC collider

CEPC collider

Proposed in Lausanne Workshop in 1984

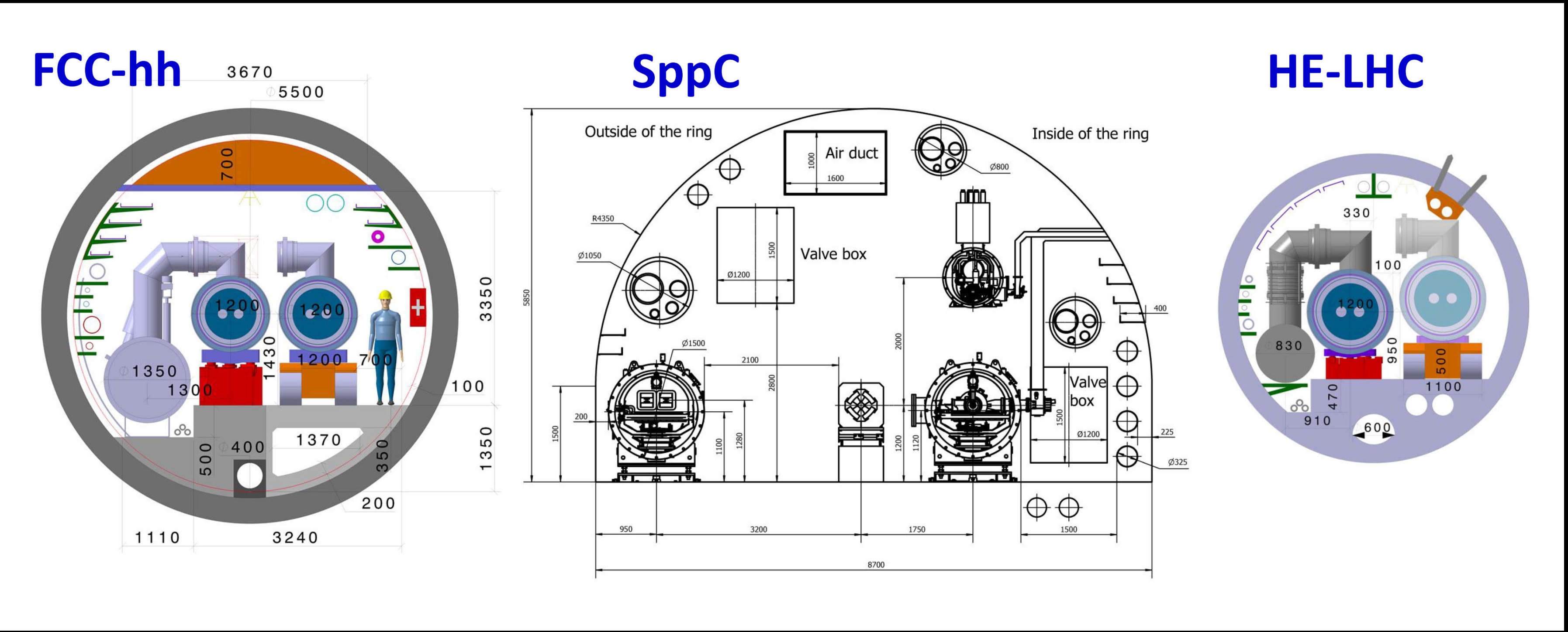


CEPC Civil Engineering Design very advanced

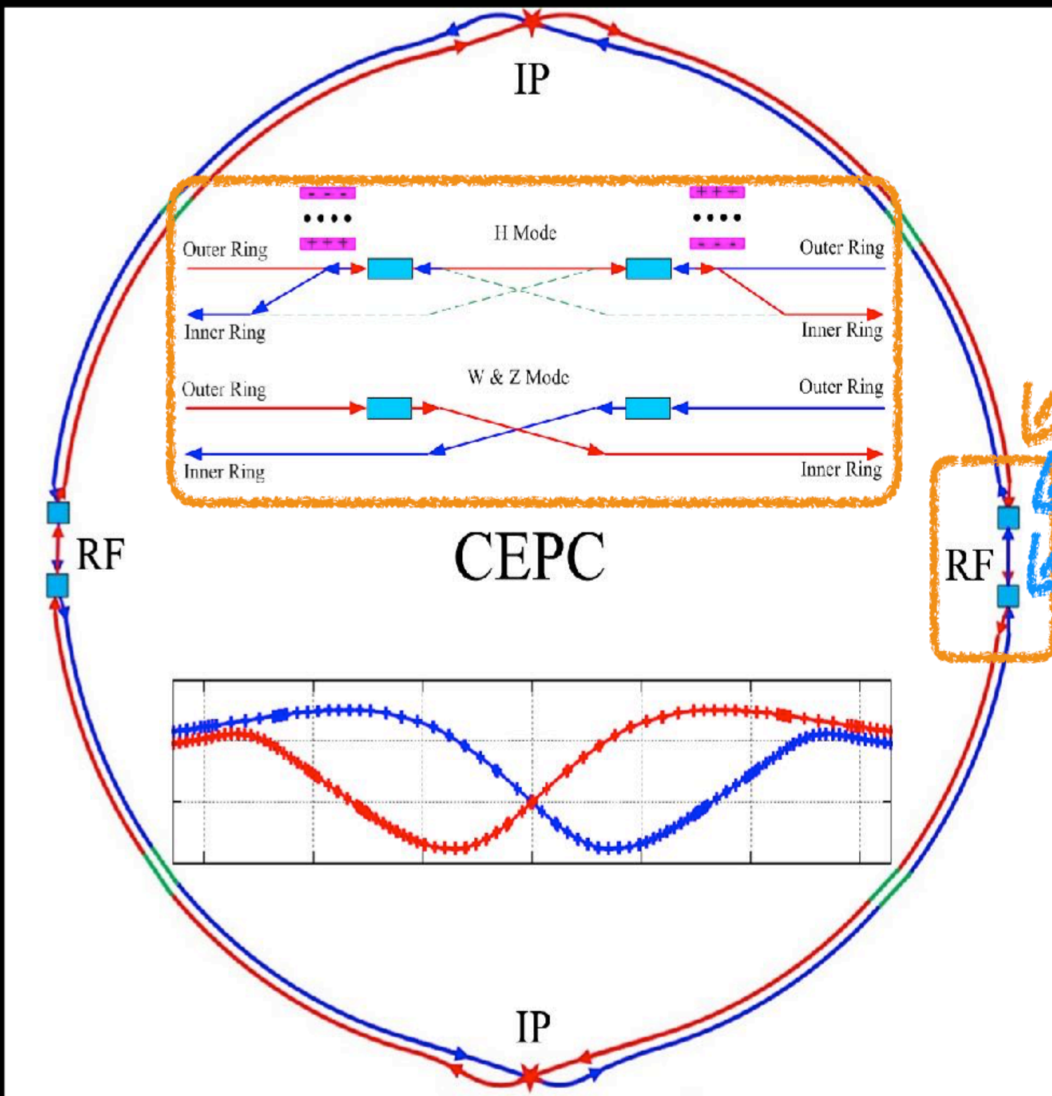
LEP tunnel internal diameter is 3.8 metres in the arcs

4.4 or 5.5 metres in the straight sections

Tunnel cross sections for HE-LHC, SppC and FCC-hh



The CEPC Baseline Collider Design



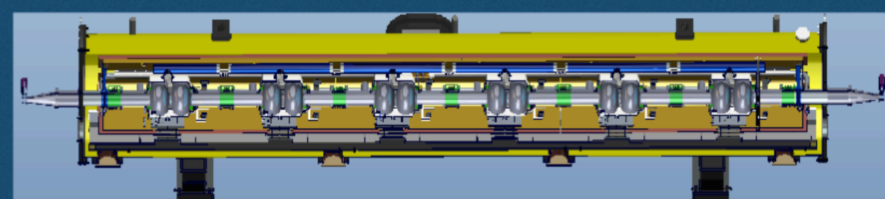
Double ring

Common RF cavities for Higgs

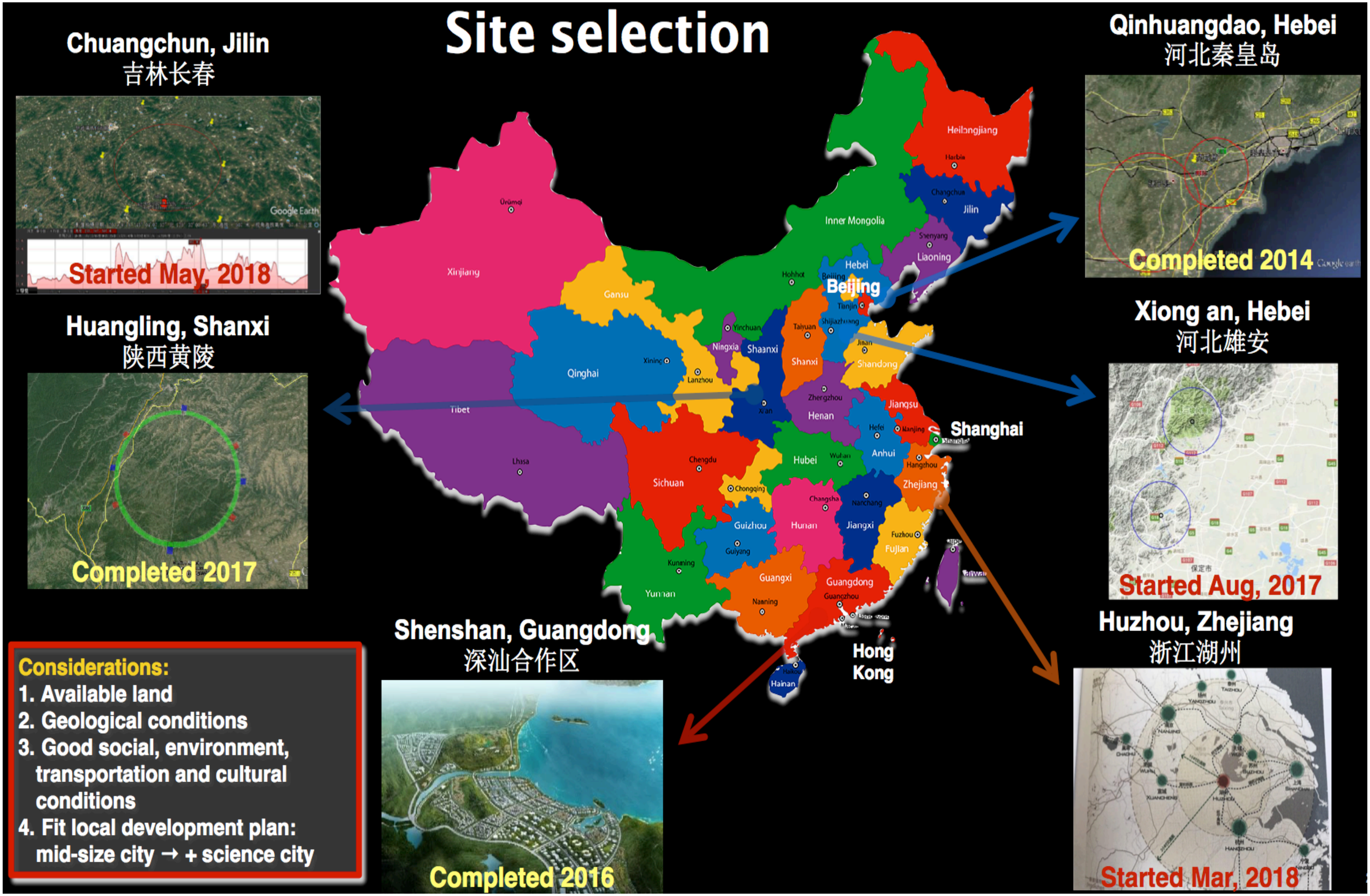
Two RF sections in total

Two RF stations per RF section

10 x 2 = 20 cryomodules

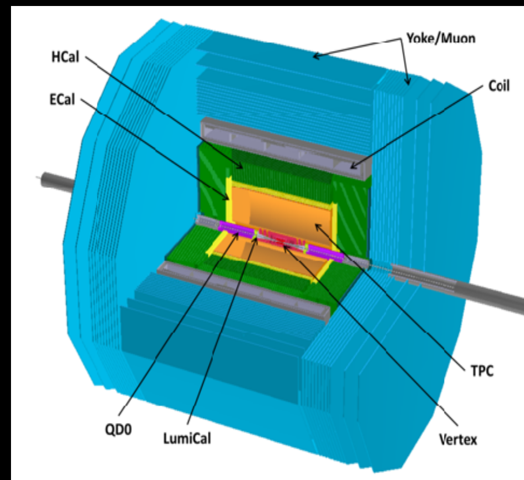


6 2-cell cavities per cryomodule

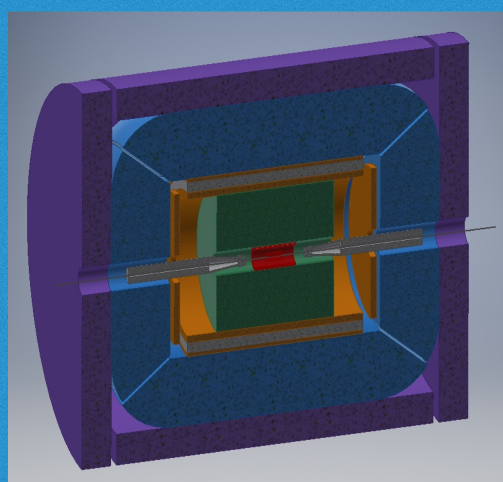

Site selection
Chuangchun, Jilin
吉林长春
Started May, 2018
Huangling, Shanxi
陕西黄陵
Completed 2017
Qinhuangdao, Hebei
河北秦皇岛
Completed 2014
Xiong an, Hebei
河北雄安
Started Aug, 2017
Huzhou, Zhejiang
浙江湖州
Started Mar, 2018
Shenshan, Guangdong
深汕合作区
Completed 2016
Beijing
Shanghai
Hong Kong
Heilongjiang
Jilin
Liaoning
Inner Mongolia
Hebei
Xinjiang
Gansu
Qinghai
Tibet
Ningxia
Shaanxi
Shanxi
Shandong
Henan
Jiangsu
Anhui
Hubei
Sichuan
Zhejiang
Hunan
Jiangxi
Guizhou
Fujian
Yunnan
Guangxi
Guangdong
Hainan
Considerations:
1. Available land
2. Geological conditions
3. Good social, environment, transportation and cultural conditions
4. Fit local development plan: mid-size city → + science city

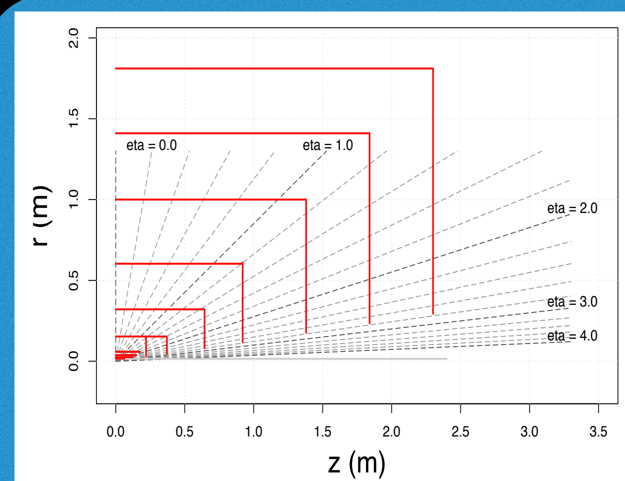
Detector Conceptual Designs (CDR)

Baseline detector (3 Tesla)
ILD-like
(similar to pre-CDR)



Low magnetic field concept (2 Tesla)





Full silicon tracker concept

Final two detectors likely to be a mix and match of different options

CEPC Accelerator CDR Completed

CEPC accelerator CDR completed in June 2018 (to be printed in July 2018)

- Executive Summary

1. Introduction
2. Machine Layout and Performance
3. Operation Scenarios
4. CEPC Booster
5. CEPC Linac
6. Systems Common to the CEPC Linac, Booster and Collider
7. Super Proton Proton Collider
8. Conventional Facilities
9. Environment, Health and Safety
10. R&D Program
11. Project Plan, Cost and Schedule

Appendix 1: CEPC Parameter List

Appendix 2: CEPC Technical Component List

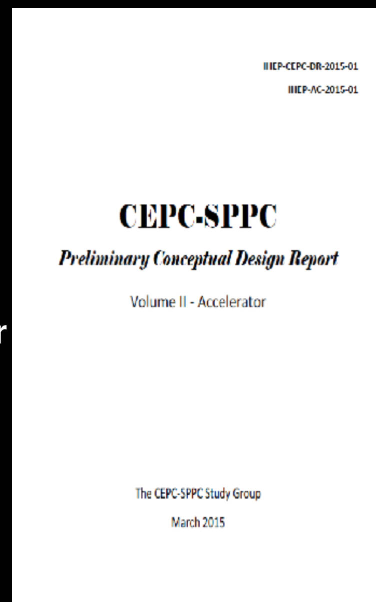
Appendix 3: CEPC Electric Power Requirement

Appendix 4: Operation for High Intensity γ-ray Source

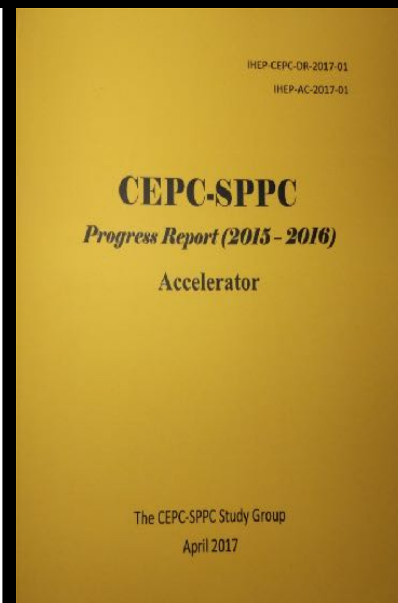
Appendix 5: Advanced Partial Double Ring

Appendix 6: CEPC Injector Based on Plasma Wakefield Accelerator

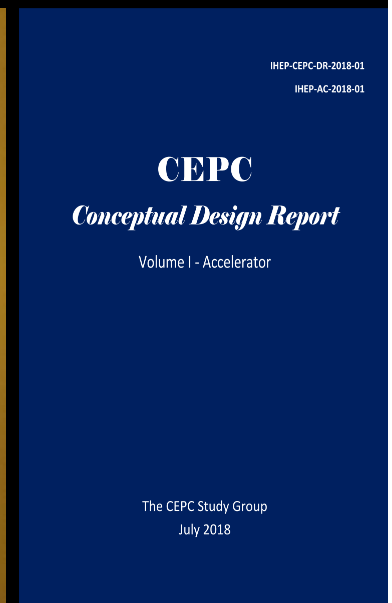
Appendix 7: International Review Report



March 2015



April 2017

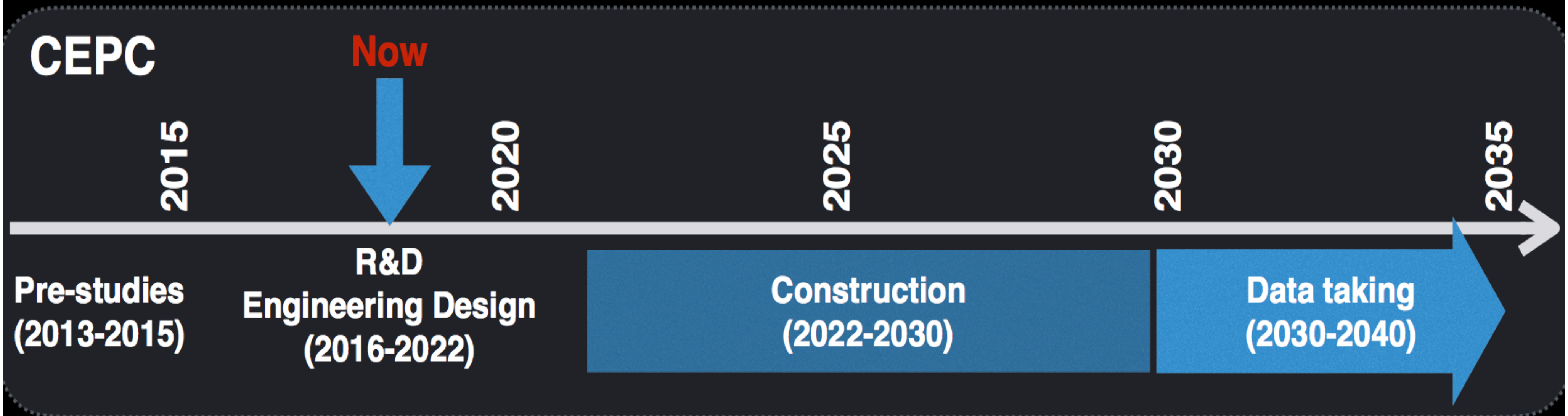


July 2018

Physics and Detector CDR to follow soon afterwards

(Need to adapt to recent modifications)

CEPC "optimistic" Schedule



- Design issues
- R&D items
- preCDR

- Design, funding
- R&D program
- Intl. collaboration
- Site study

- Seek approval, site decision
- Construction during 14th 5-year plan
- Commissioning

- CEPC data-taking starts before the LHC program ends
- Possibly concurrent with the ILC program

Current CEPC Organization

Since Sept. 2013

Institutional Board
YN GAO
J. GAO

→ **Steering Committee**
Y.F. WANG (IHEP),….

↓ **Project Director**
XC LOU
Q. QIN
N. XU

↓

Theory	**Accelerator**	**Detector**
HJ HE(TH)	J. GAO (IHEP)	Joao Costa (IHEP)
JP MA(ITP)	CY Long (IHEP)	S. JIN (NJU)
XG HE(SJTU)	SN FU (IHEP)	YN GAO (TH)

International Advisory Committee (→ Steering Committee)

Young-Kee Kim, U. Chicago (Chair)
Barry Barish, Caltech
Hesheng Chen, IHEP
Michael Davier, LAL
Brian Foster, Oxford
Rohini Godbole, CHEP, Indian Institute of Science
David Gross, UC Santa Barbara
George Hou, Taiwan U.
Peter Jenni, CERN
Eugene Levichev, BINP
Lucie Linssen, CERN
Joe Lykken, Fermilab
Luciano Maiani, Sapienza University of Rome
Michelangelo Mangano, CERN
Hitoshi Murayama, UC Berkeley/IPMU
Katsunobu Oide, KEK
Robert Palmer, BNL
John Seeman, SLAC
Ian Shipsey, Oxford
Steinar Stapnes, CERN
Geoffrey Taylor, U. Melbourne
Henry Tye, IAS, HKUST
Yifang Wang, IHEP
Harry Weerts, ANL

CEPC meetings and international impact

Many international events have been hosted to discuss CEPC physics and carry out collaboration on key-technology research

260 attendees

30% from foreign institutions

55% attendance from abroad

Next workshop
April 2019 in Oxford

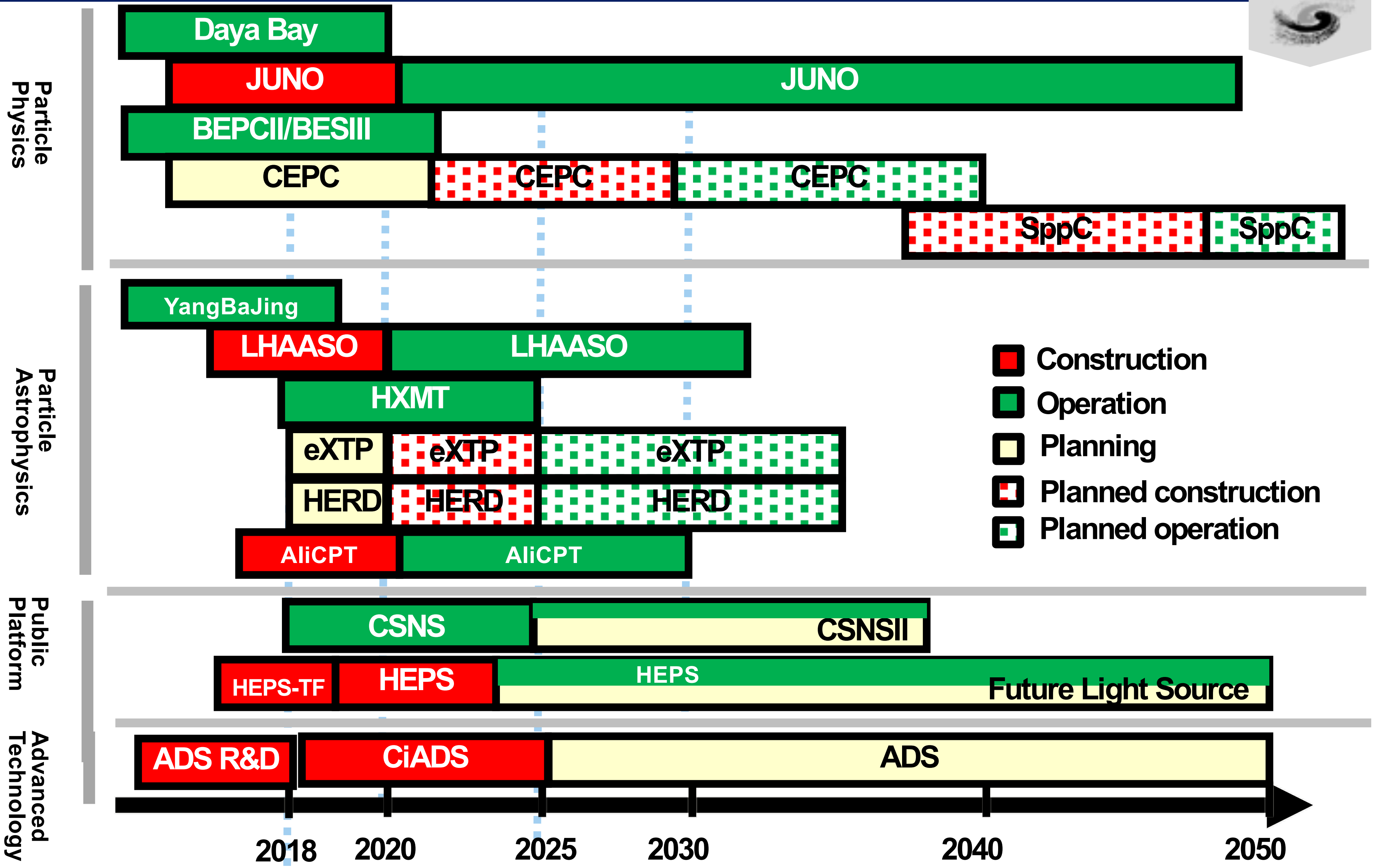
- The accelerator CDR has been completed satisfying the luminosity requirements both as a Higgs and Z factory
  - Detector CDR will follow soon

- Key technologies are under R&D and put to prototyping:
  - Accelerator: SC cavity, high efficiency klystron, low field precision magnet, copper vacuum chamber, HTS, …
  - Detector: Pixel detector, TPC, PFA-based electromagnetic and hadronic calorimeters, magnet, …

- CEPC civil engineering design and site selection going well
- CEPC funding adequate for required R&D program
- CEPC interest abroad is steadily increasing
- From 2018-2022, CEPC TDR will be finished with accelerator key hardware R&D completed and industrialization ready for construction start in 2022

Future Plan of IHEP

Part 3



IHEP Large Science Facilities

Part 1

In operation (6)

1. Beijing Electron Positron Collider (BEPCII) / (BESIII)
2. Beijing Synchrotron Radiation Facility (BSRF)
3. Yangbajing Cosmic Ray Observatory (YBJ)
4. Daya Bay Reactor Neutrino Experiment
5. Hard X-ray Modulation Telescope (HXMT)
6. China Spallation Neutron Source (CSNS)

Under construction (4)

1. Jiangmen Underground Neutrino Observatory (JUNO)
2. Large High-Altitude Air Shower Observatory (LHAASO)
3. Ali CMB Polarization Telescope (AliCPT-1)
4. High Energy Photon Source (HEPS/HEPS-TF)

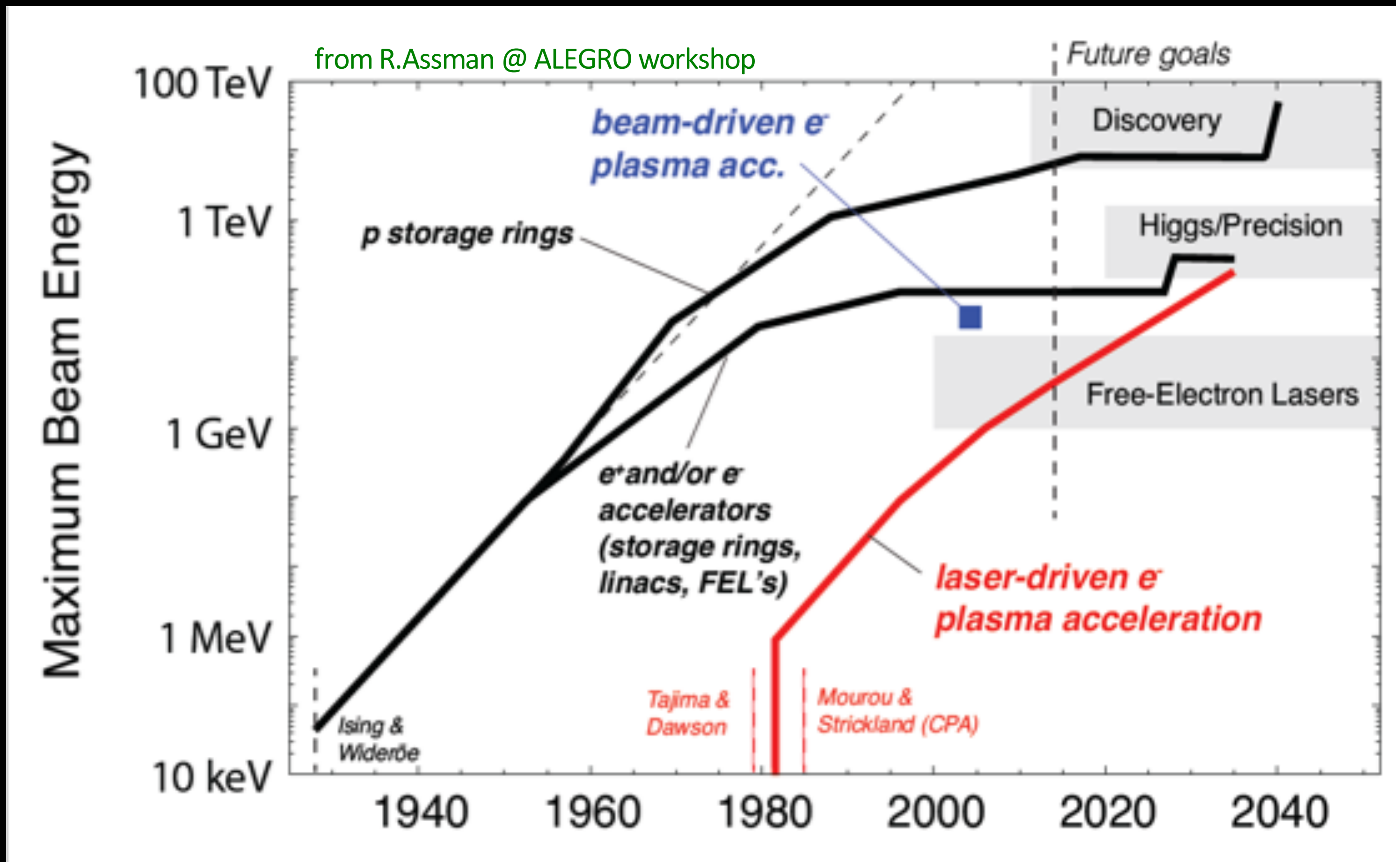
Under planning (6)

1. China Initiative Accelerator Driven System (CiADS)
2. China Spallation Neutron Source II (CSNSII)
3. Enhanced X-ray Timing and Polarimetry mission (eXTP)
4. High Energy cosmic-Radiation Detection (HERD)
5. Circular Electron Positron Collider-Super proton-proton collider (CEPC-SppC)
6. Other Light Source Projects： Southern Photon Source 、 SCLS……

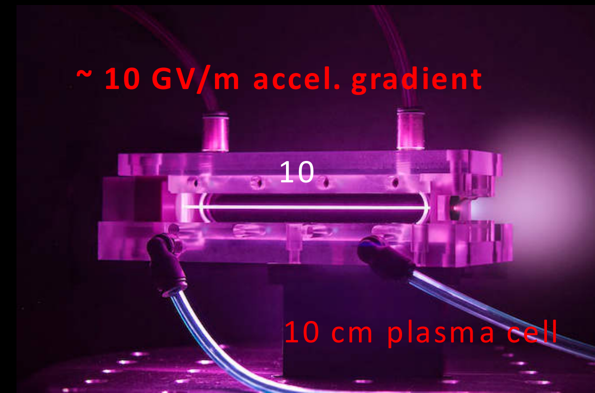
Accelerator R&D – Advanced Novel Accelerators (ICFA Panel)

ALEGRO (Advanced LinEar collider study GROup, for a multi-TeV Advanced Linear Collider) Workshop (March 2018 in Oxford): http://www.physics.ox.ac.uk/confs/alegro2018/index.asp

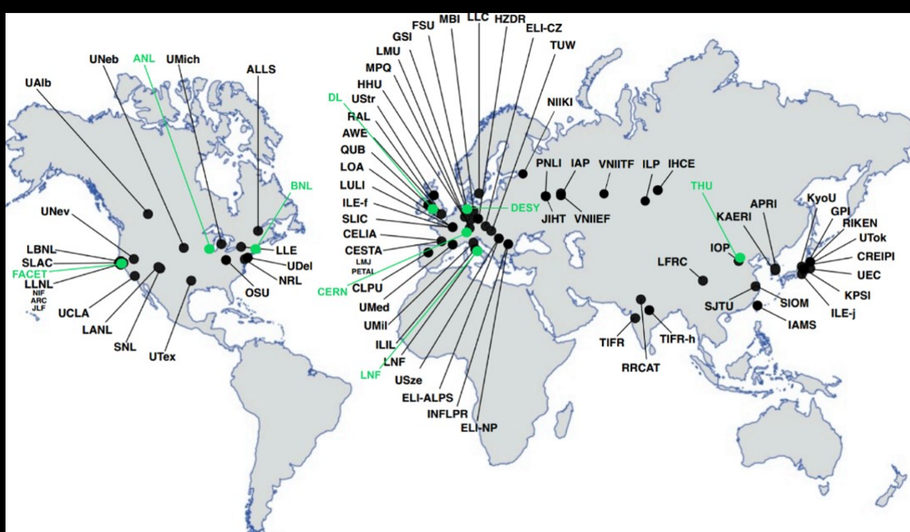
The objective of this first ALEGRO workshop was to prepare and deliver, by the end of 2018, a document detailing the international roadmap and strategy of Advanced Novel Accelerators (ANAs) with clear priorities as input for the European Particle Physics Strategy Update.



Current UK advanced accelerator technique work



Technique/beam	Groups/facilities
Laser driven (LWFA) electrons	CI (Lan, Liv, Man, Str) – CLF/SCAPA JAI (Imp, Oxf) - CLF
Laser driven (LWFA) positrons	QUB - CLF
Laser driven (LWFA) protons/ions	Imp, Str, QUB, York – CLF/SCAPA
Electron driven (PWFA) electrons	CI (Lan, Liv, Man, Str) – CLARA/FACET
Proton driven (PWFA) electrons	Lan, Liv, Man, UCL – AWAKE



PWFA

UK Plasma Wakefield Accelerator Roadmap 2018

UK roadmap for plasma acceleration research

"Although, having an electron-positron linear collider as an ultimate aim for plasma wakefield acceleration and working towards achieving a number of its parameters is very valuable, it is prudent to consider other first applications.

One should however distinguish between the first plasma acceleration application to a stand-alone all plasma acceleration collider, and an upgrade of conventional collider with plasma acceleration. While it is at this moment inconceivable to suggest an all-plasma electron-positron collider, it is reasonable to consider plasma acceleration upgrade for either ILC or CLIC colliders, in case if construction of the first Higgs-Factory or Top-Factory stage of either of them will be approved. Given the rate of the progress of plasma acceleration technology, it is entirely possible to consider their upgrades to TeV energy using plasma acceleration."

http://pwasc.org.uk/uk-roadmap-development

European Strategy Workshop, IPPP 16-18th April 2018: Meeting Summary

<u>Overview</u> (J. Evans, S. Farrington, E. Goudzovski, M. Patel, M. Spannowsky)

4) The physics cases for FCC and CLIC are clearly both strong but there are resource implications in pushing both R&D programs forward during the 2020s. The last UK ES submission said that *“a timely decision should be taken on optimal next-generation collider facilities for exploitation of LHC discoveries”*. The final 2013 ES update document said *"to stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available".* It is the recommendation of the organisers of this workshop that it should be considered, in a UK community meeting, whether a decision can now be made on a definitive UK recommendation. If a consensus cannot be reached, then it could be debated in the community meeting whether to put forward to the ES process that its committee makes a definitive recommendation by 2020.

Observations and Conclusions

It is good to have different regions of the world that are interested in fundamental physics and consider that the outstanding questions today in particle physics are worth building the next generation particle collider.

While competition can be energizing global cooperation across all three regions maximizes our resources and should be the aim. This is something the ESU, Asian and P5 processes can jointly accomplish.

The science case for e+e-- is mature. The science case for 100 TeV is not mature.

In Europe there is development work to do. It is not possible now to proceed with either CLIC or FCC. Any decision will wait for the the next ESU ~2026. One possible ESU outcome is a decision to proceed with continued development of both CLIC & FCC placing great demand on CERN resources at a time when the HL-LHC must be delivered

Europe's Strategy depends on another region hence pressure for Japan to decide before end of December 2018 on ILC250.

ILC/CLIC is a mature community that recognizes it is unlikely both will be built. The community collaborate and would work on either. Should ILC250 go ahead, CLIC will not proceed changing the resource picture at CERN. FCC-ee also becomes less attractive even though it offers the highest luminosity of the four e+e- options

Observations and Conclusions

There is no possibility to know if CEPC goes head before 2020 (source: Yifang Wang).

It is possible CEPC would go ahead even if ILC250 goes ahead. But clearly the degree of international support (financial and participation) for either project would be modified if both proceeded.

If ILC250 does not proceed but CEPC does or the ILC250 decision is later than planned it would be prudent for the ESU to allow for this possibility and advise on how CERN should proceed in that eventuality. For example making continued support of CLIC development contingent on no other e+e- Higgs factory receiving the green light.

By 2026 we will have the full benefit of Run 3 data from LHC. We will know all that can be known at 14TeV (before the upgrade to the LHC itself). The high field magnet program would also be much further along and we will have a refined idea of the cost and time to build HE-LHC or FCC-pp. A decision at that time could be made to proceed with one or the other. While HE-LHC may be affordable in the CERN budget over twenty years, FCC-pp will not be. (300 MCHF/year for development or 6BillionCHF/20 years).

Observations and Conclusions

There is no possibility to know if CEPC goes head before 2020 (source: Yifang Wang).

It is possible CEPC would go ahead even if ILC250 goes ahead. But clearly the degree of international support (financial and participation) for either project would be modified if both proceeded.

The science case for FCC-pp and SppC is not yet mature. But we have to continue to develop these machines with high priority. If we do not do all the work we can now (and argue together as a community to keep all our options) we will surely not get it.

FCC affordability. I am not aware that there is an "official CERN answer" but it is clear that such a project will require real buy-in from politicians as the LHC did originally.

Only obvious path: allow (eg) EU money to be used on CERN projects – an FCC is conceivable over three cycles of H2020 successor programmes. There has been much work (by CERN and the EU) in recent years to try to understand how/if funding for CERN from the EU might work. I do not know if there are any answers as yet, but it certainly will require major support from politicians and support from across the sciences and medicine and engineering & the public

It is important to invest in advanced accelerator techniques in parallel.

The LHeC is a low cost intriguing option that should be fully explored.

Electron Summary

Four future higher energy electron colliders are presently under study worldwide ILC is shovel ready, CLIC is far along, FCC-ee has made impressive progress and CEPC is gaining extraordinary momentum – no known show stoppers

Proton Summary

Three future higher energy hadron colliders are presently under study worldwide, with c.m. energies ranging from 27 to 100 TeV.

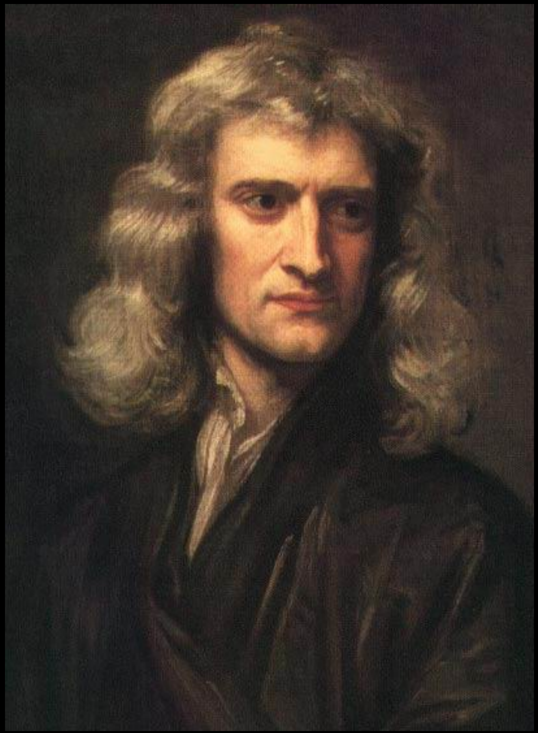
R&D on cost-effective high-field magnets is the key to their realization. Each of the three proposed colliders could start operation around 2040–2045

Proton–electron Summary

FCC-he testifies to the versatility and richness of the FCC facility

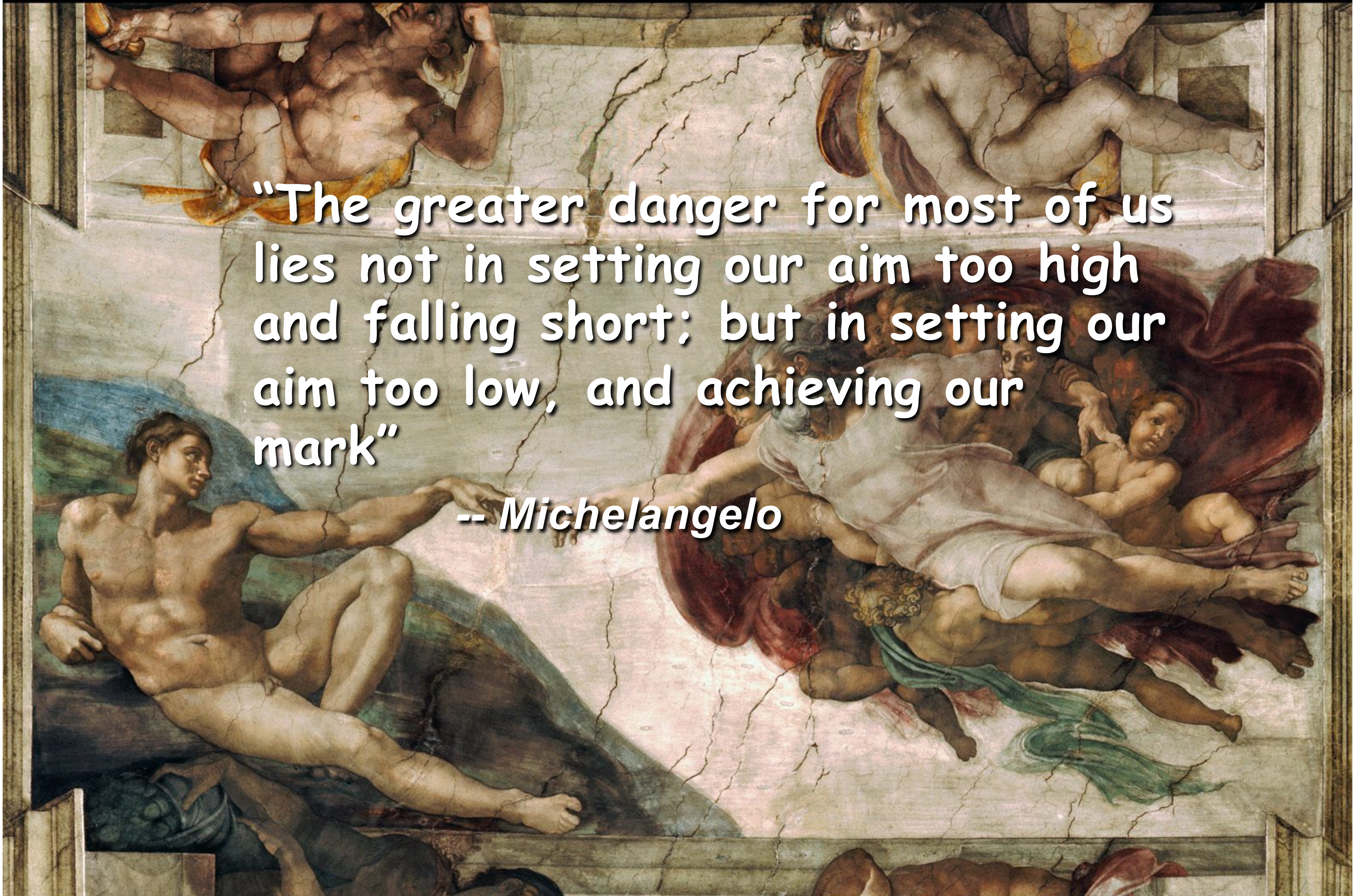
Muon Colliders and advanced acceleration techniques

Muon colliders and plasma accelerators both a gain of about a factor 200 in energy reach for the same size as traditional accelerator. Not ready today they might be ready in 20 years or significantly before the end of the 21st century if R&D is advanced properly. The offers a lower cost to access the highest energies → prudent to invest



"What we know is a droplet, what we don't know is an Ocean"

Sir Isaac Newton (1643-1727)


"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark"
-- Michelangelo