NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

European Particle Physics Strategy - Overview of collider physics Programmes

Mogens Dam, Niels Bohr Institute, Copenhagen

Spaatind 2020 – Nordic Conference on Particle Physics

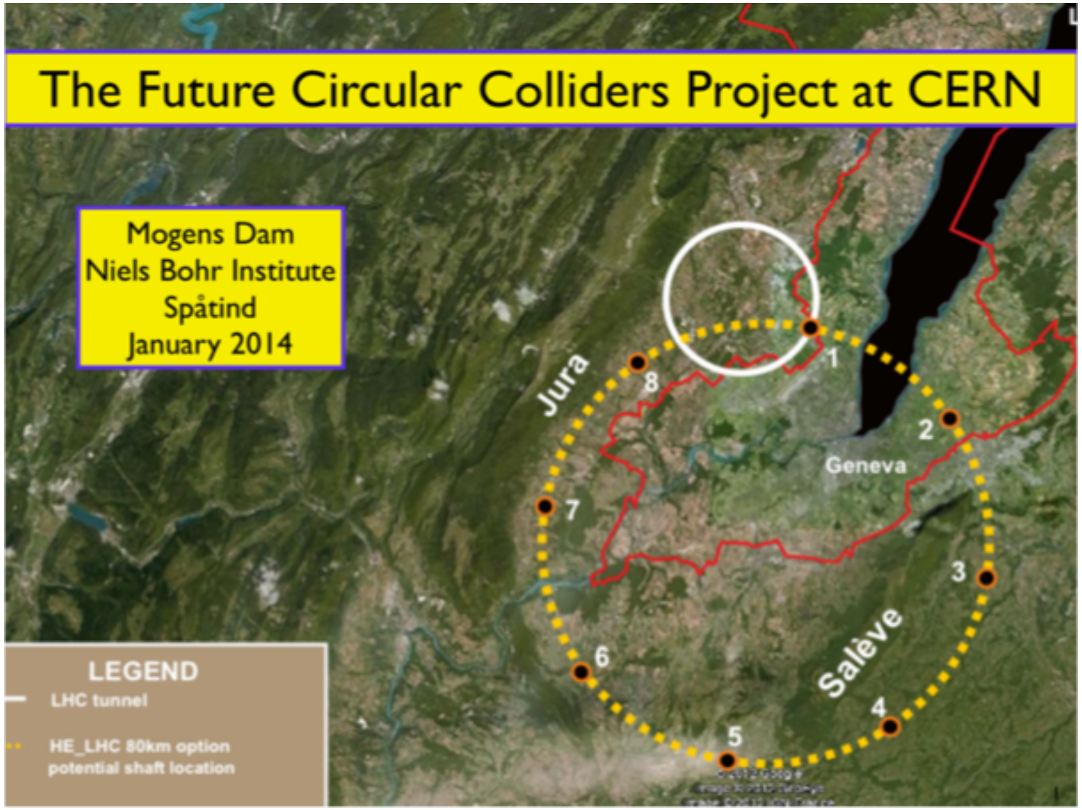
"No doubt that future high energy colliders are extremely challenging projects.

However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

Fabiola Gianotti, DG CERN

Disclaimer

- I am not personally involved in the ongoing ESPP process; I have no inside information
  - There may easily be people in the audience being better informed than me
- The talk is based only on publicly available information that I have been able to collect
- I have been involved in the FCC project since 2013
  - This of course reflects my personal preference towards a future collider



Outline

a. European Strategy for Particle Physics
b. e^+e^- Colliders & Higgs Factories
c. FCC-hh
d. ESPP Scenarios
e. Next generation Colliders
f. Outlook

European Strategy for Particle Physics- Overview

- The ESPP is the process by which every ~7 years the European particle physics community updates the priorities and strategy of the field
  - 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
  - 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.
- ESPP produces the European roadmap in the worldwide context of the field
  - 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 European Particle Physics Strategy 2013

Main recommendations:

1) **Europe's top priority should be the exploitation of the full potential of the LHC, including the high- luminosity upgrade** of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

→ HL-LHC approved by Council 2016

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

→ FCC Study started 2014

3) Europe **looks forward to a [ILC] proposal from Japan** to discuss a possible participation.

4) 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

European Strategy Update

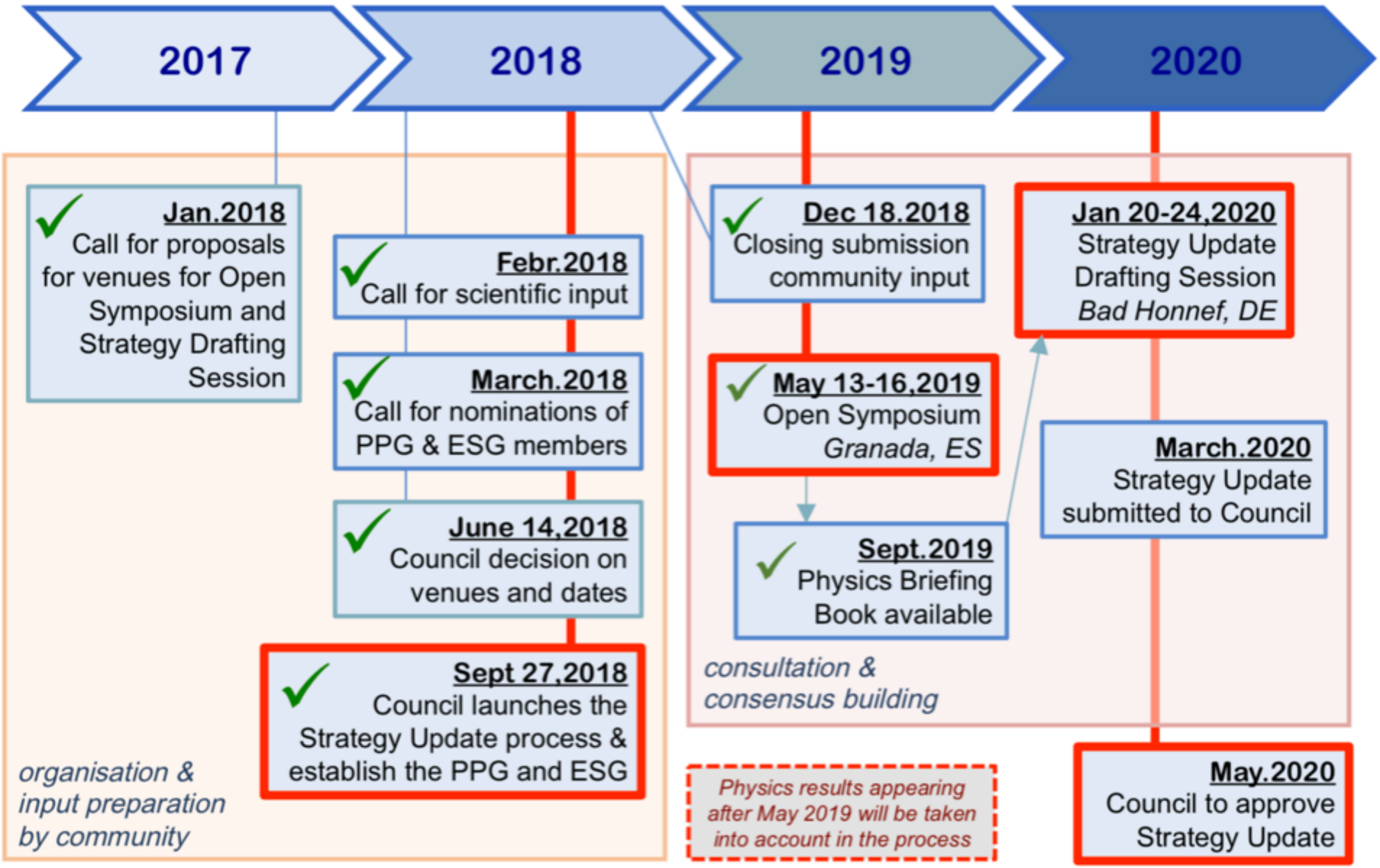
EUROPEAN STRATEGY FOR PARTICLE PHYSICS

The European Strategy for Particle Physics is the cornerstone of Europe's decision-making process for the long-term future of the field. Mandated by the CERN Council, it is formed through a broad consultation of the grass-roots particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the US and Japan in order to ensure coordination between regions and optimal use of resources globally.

STRATEGY SECRETARIAT

Scientific Secretary (Chair)	Prof. Halina Abramowicz (IL)
SPC Chair	Prof. Keith Ellis (UK)
ECFA Chair	Prof. Jorgen D'Hondt (BE)
Chair EU Lab. Directors' Mtg	Prof. Lenny Rivkin (CH)

2020 ESPP Timeline



Input to the European Particle Physics Strategy Update 2018-2020

European Strategy Update

1 November 2018 to 19 December 2018
Europe/Zurich timezone

- Overview
- Guidelines
- Submit Input
- Submitted Input
- Open Symposium

Submitted Input

160 / 160 Enter #id or search string

5. A European Data Science Institute for Fundamental Physics
Instrumentation and com...

In order to facilitate the deployment of modern data science technologies (e.g., Deep Learning) into theoretical and experimental research in high energy physics, we suggest that the creation of a **European Data Science Institute for**

112. A European Strategy Towards Finding Axions and Other WISPs
Dark matter and dark sec...

Since the last update of the European strategy on particle physics (ESPP) the interest in hypothetical very weakly interacting slim particles, dubbed WISPs,

57. A high precision neutrino beam for a new generation of short baseline experiments
Neutrino physics (acceler...

The current generation of short baseline neutrino experiments is approaching intrinsic source limitations in the knowledge of flux,

70. A memorandum by the Global Neutrino Network as input to the update of the European Strategy for Particle Physics
Neutrino physics (acceler...

The Global Neutrino Network is an association of the neutrino telescope projects targeting the investigation of cosmic and atmospheric neutrinos in the energy range from GeV to beyond PeV. The main scientific objectives are the

CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

European Strategy Update

13-16 May 2019 - Granada, Spain

Physics Preparatory Group

Halina Abramowicz (Chair)
Shoji Asai
Stan Bentvelsen
Caterina Biscari
Marcela Carena
Jorgen D'Hondt
Keith Ellis
Belen Gavela
Gian Giudice
Beate Heinemann
Xinchou Lou
Krzysztof Redlich
Leonid Rivkin
Paris Sphicas
Brigitte Vachon
Marco Zito
Antonio Zoccoli

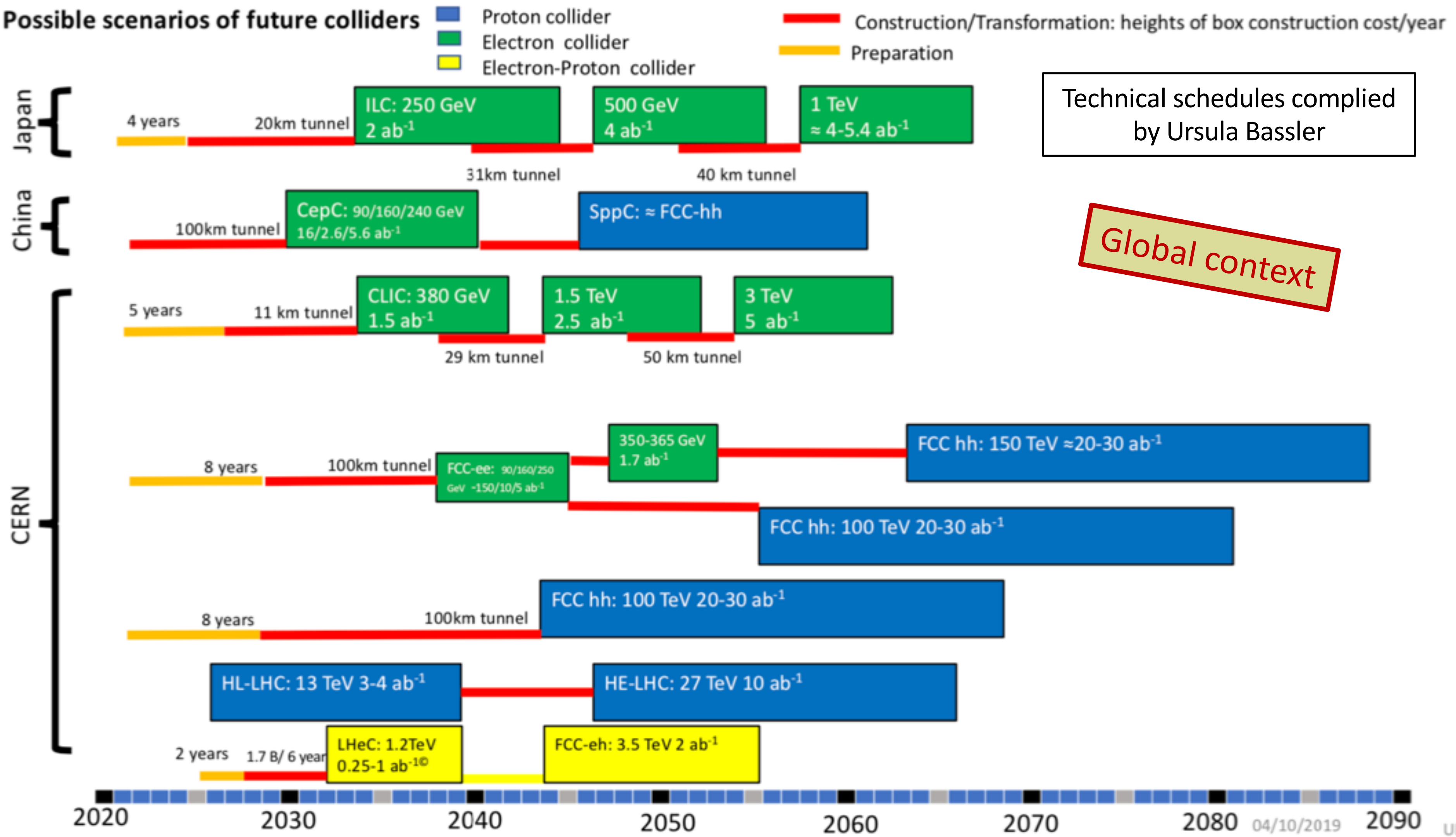
Local Organizing Committee

Francisco del Águila
Antonio Bueno (Chair)
Alberto Casas
Nicanor Colino
Javier Cuevas
Elvira Gámiz
María José García Borge
Igor García Irastorza
Eugeni Graugés
Juan José Hernández
Mario Martínez
Carlos Salgado
Benjamín Sánchez Gimeno
José Santiago

Granada Symposium Organisation

Topic	Conveners
Accelerator Science and Technology	Caterina Biscari, Lenny Rivkin
Instrumentation and Computing	Xinchou Lou, Brigitte Vachon
Electroweak Physics	Keith Ellis, Beate Heinemann
Strong interactions	Jorgen D'Hondt, Krzysztof Redlich
Neutrino Physics	Stan Bentvelsen, Marco Zito
BSM at colliders	Gian Giudice, Paris Sphicas
Dark Matter and Dark Sector	Shoji Asai, Marcela Carena
Flavour Physics and CP violation	Belen Gavela, Antonio Zoccoli

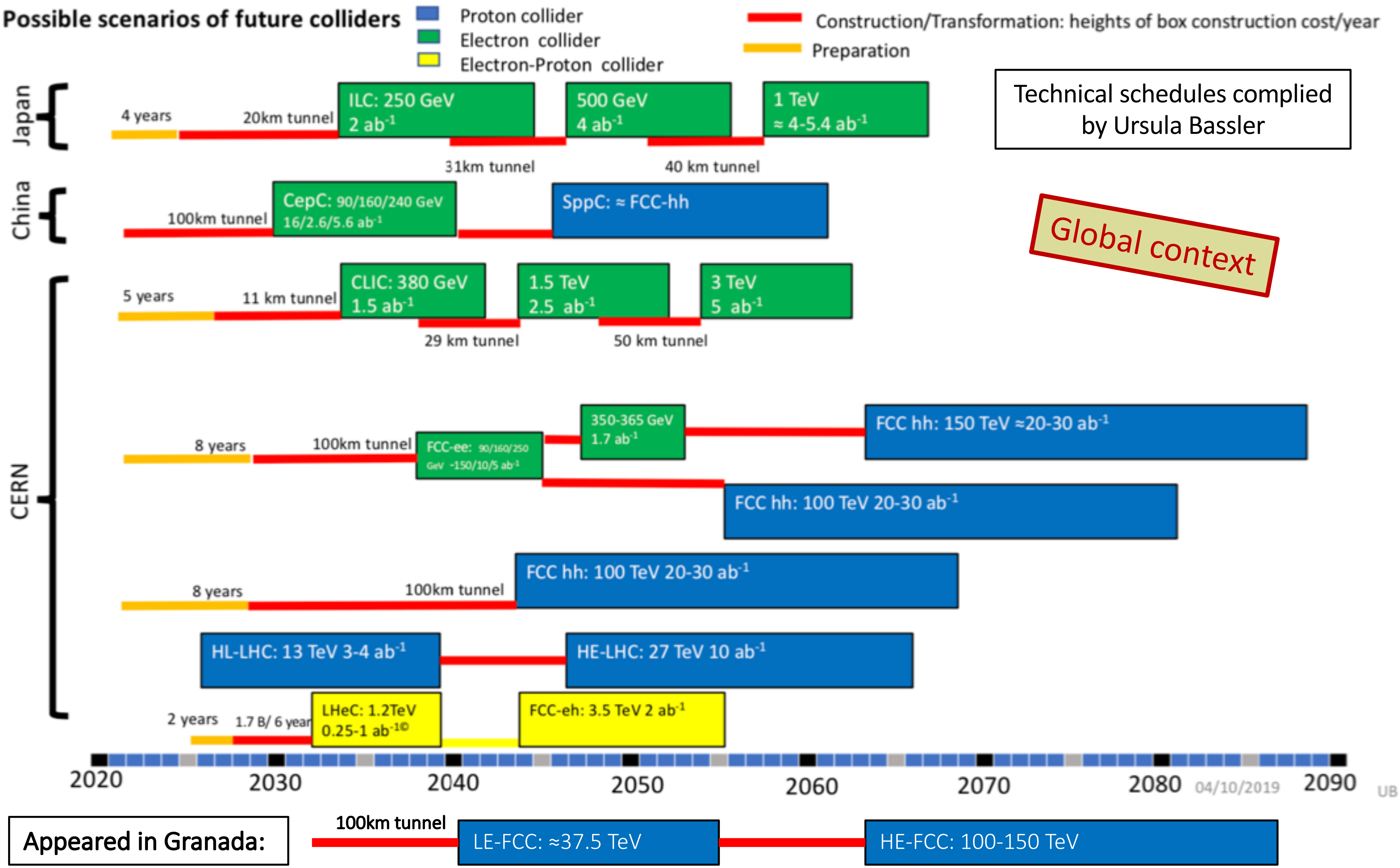
Landscape of proposed colliders



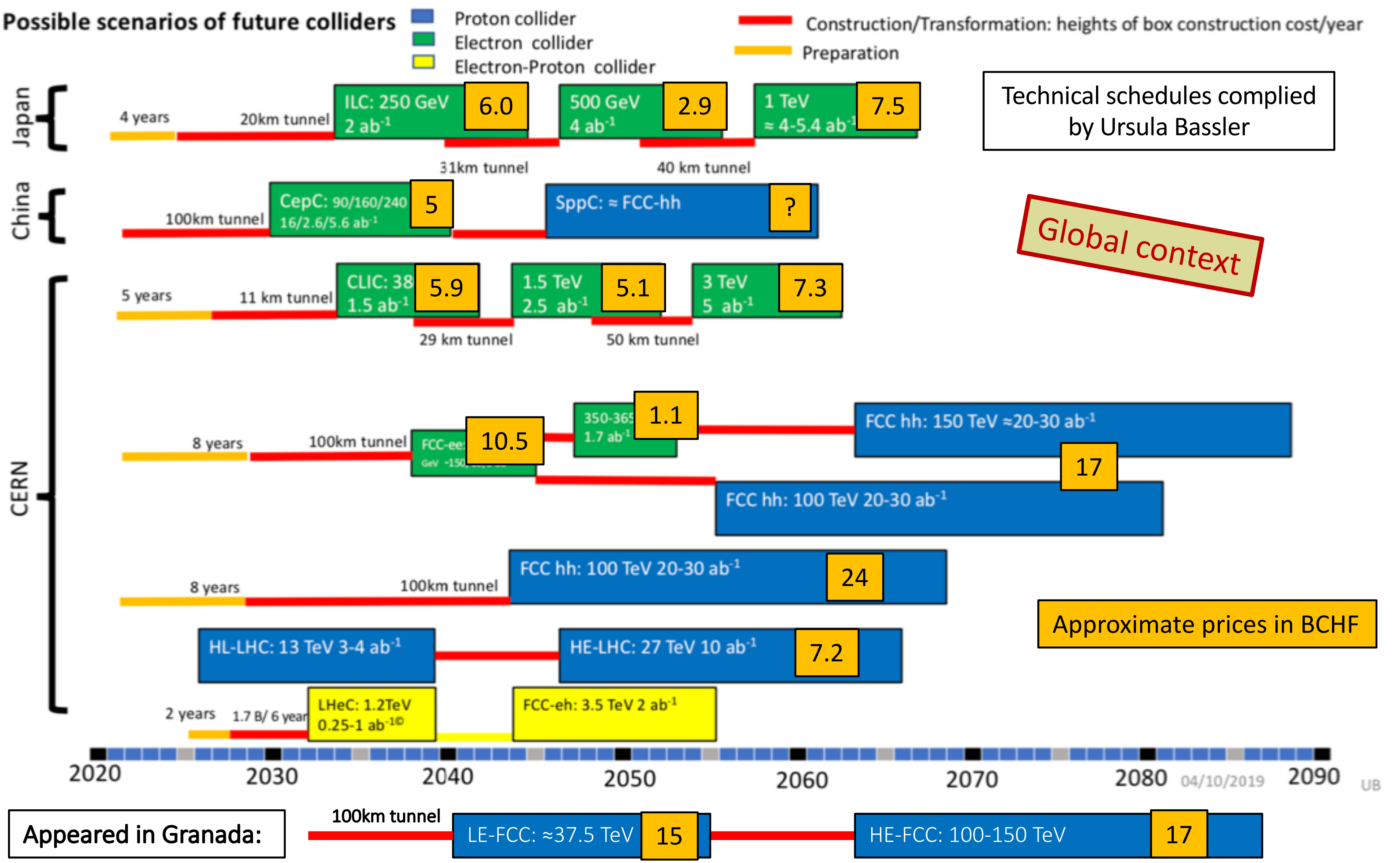
Technical schedules complied by Ursula Bassler

Global context

Landscape of proposed colliders



Landscape of proposed colliders



Granada Conclusions ?

No official conclusions.
But I believe the conclusions of the CERN Director are widely shared

Fabiola Gianotti,
SPC, 23 Sep 2019

My conclusions of the discussions at the Granada's Symposium

Strong support for:

- e+e- Higgs factory somewhere in the world: potential of ILC@250, CLIC@380, CepC and FCC-ee for Higgs measurements considered to be similar, to first order
- accelerator R&D (including muon colliders)
- scientific diversity programme
- energy-frontier proton-proton collider

No clear consensus on the next collider at CERN: CLIC vs FCC
But broad consensus there should be one.

More from the CERN DG

CERN's Future

Fabiola Gianotti,
SPC, 23 Sep 2019

I think it would be good for CERN if the 2020 Strategy update recommended:

- ❑ the direction for a future collider at CERN: linear or circular
  → so that its technical and financial feasibility can be assessed by next Strategy update in ~2026 → pre-requisite for project approval by the Council
- ❑ a compelling scientific diversity programme at the injectors, complementary to high-E colliders for physics reach and size/type of projects (→ attract a diverse community). Based on input from Physics Beyond Colliders (PBC) study group.
- ❑ a vigorous and transformational accelerator R&D programme at CERN and other European laboratories and institutions: high-field magnets (including High-Temperature Superconductors), high-efficiency klystrons, high-gradient accelerating structures, plasma wakefield, feasibility of muon colliders, etc.

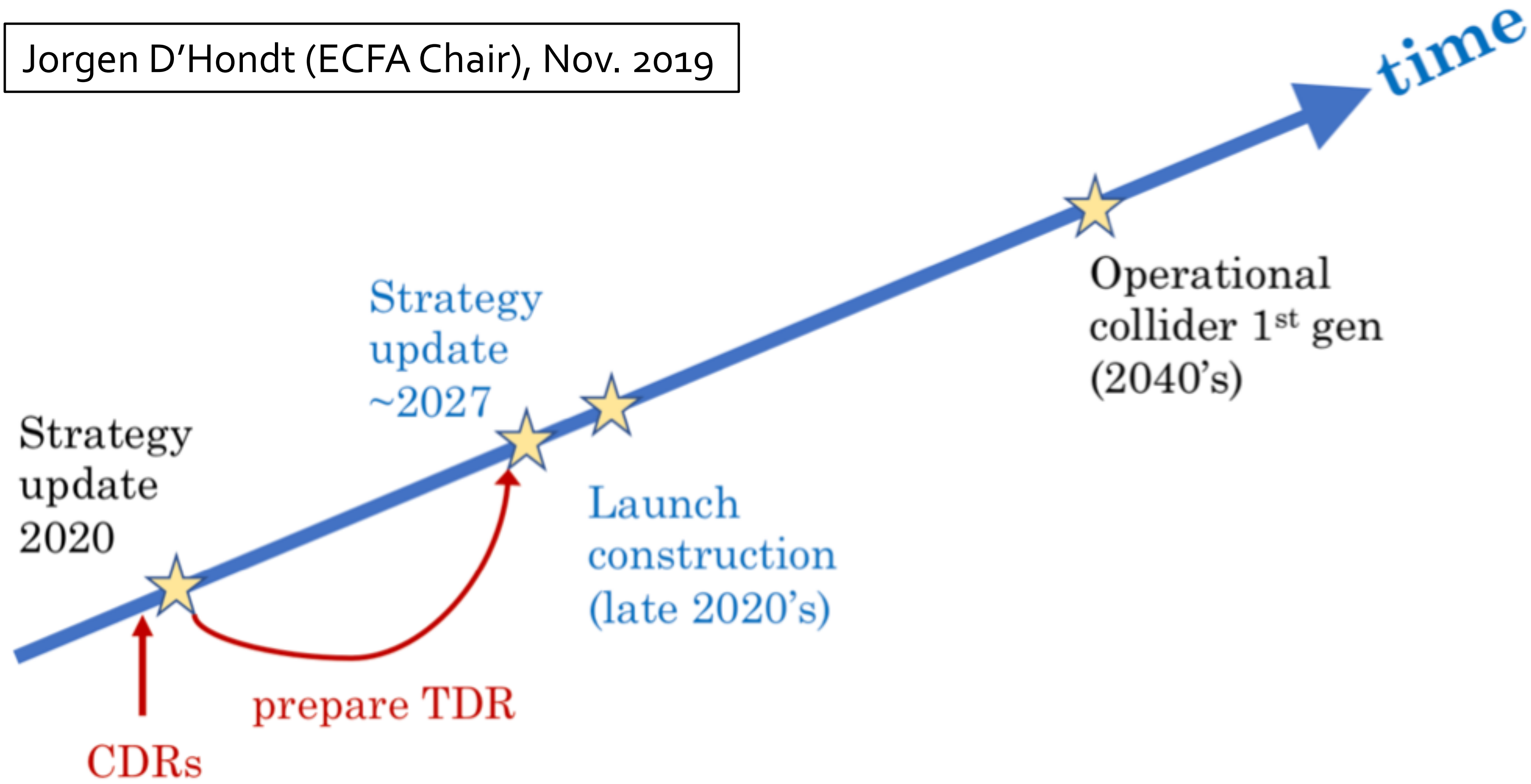
Timeline

Several years will be needed to assess the technical and financial feasibility of a future collider before the project can be approved by the Council, in particular to work through the administrative, political, legal and environmental procedures related to the tunnel excavation
→ a clear direction (linear or circular) in 2020 would allow much of this work to be accomplished by the ~ 2026 update of the ESPP

CERN's financial constraints over 2021-2025
do not allow CLIC and FCC to be both supported at the level needed for the next significant step: Technical Design Report by Strategy update in ~2026

Strategy towards a new CERN Collider

Jorgen D'Hondt (ECFA Chair), Nov. 2019



Landscape for future colliders in Europe

CERN/ESG/05b
29 September 2019

Post-Granada strawman scenarios:

	2020-2040	2040-2060 1st gen technology	2060-2080 2nd gen technology
CLIC-all	HL-LHC	**CLIC380-1500**	CLIC3000 / other tech
CLIC-FCC	HL-LHC	**CLIC380**	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC	**FCC-ee (90-365)**	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC	**LE-FCC-h/e/A (low-field magnets)**	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC **+ LHeC**	**LHeC**	FCC-h/e/A (Adv HF magnets) / other tech

Jorgen D'Hondt, ECFA Chair, November 15, 2010:

"Nothing is written in stone at this stage for new colliders in Europe, the European Strategy Group will discuss at least these strawman scenarios with a focus on the 1st generation collider"

Overall future collider timeline

	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
technology	SCRF ~ 30 MV/m B ~ 11 T	SCRF ~ 50 MV/m B ~ 14 T plasma demo muon demo	SCRF ~ 70 MV/m B > 16 T (HTS?) plasma collider muon collider

CERN-ESU-004
1 October 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
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Elisabeth Petit[11], Riccardo Rattazzi[12], Wouter Verkerke[13] *(Contributors)*

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Nestor Armesto[18], Daniël Boer[19], David d'Enterria[20], Tetyana Galatyuk[21], Thomas Gehrmann [22],
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Gudrun Hiller[39], Gino Isidori[22], Yoshikata Kuno[40], Alberto Lusiani[41], Yosef Nir[36],
Marie-Helene Schune[42], Marco Sozzi[43], Stephan Paul[44], Carlos Pena[31] *(Contributors)*

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Roger Jones[67], Emilia Leogrande[20] *(Scientific Secretaries)*
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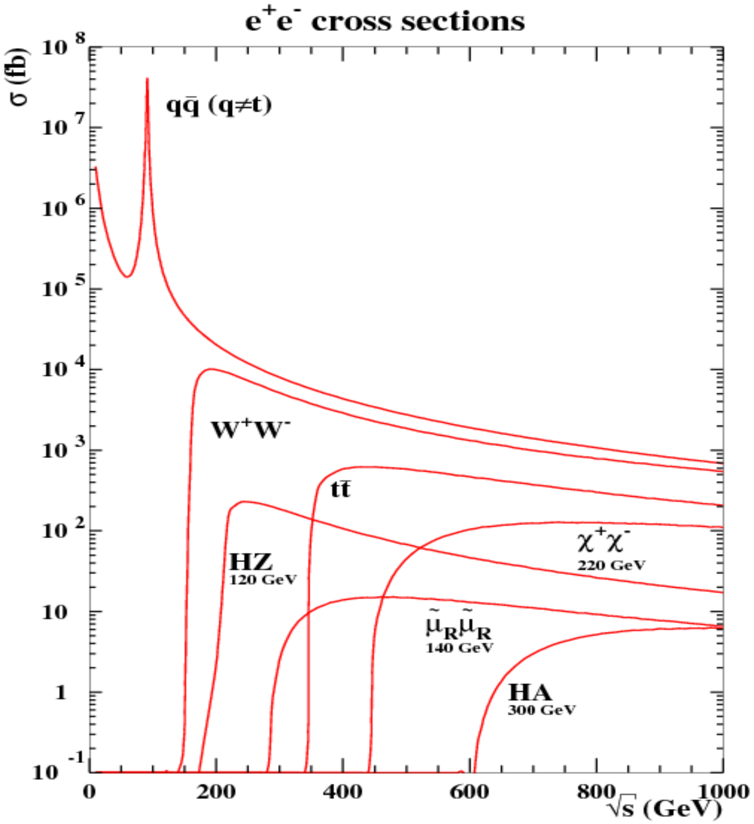
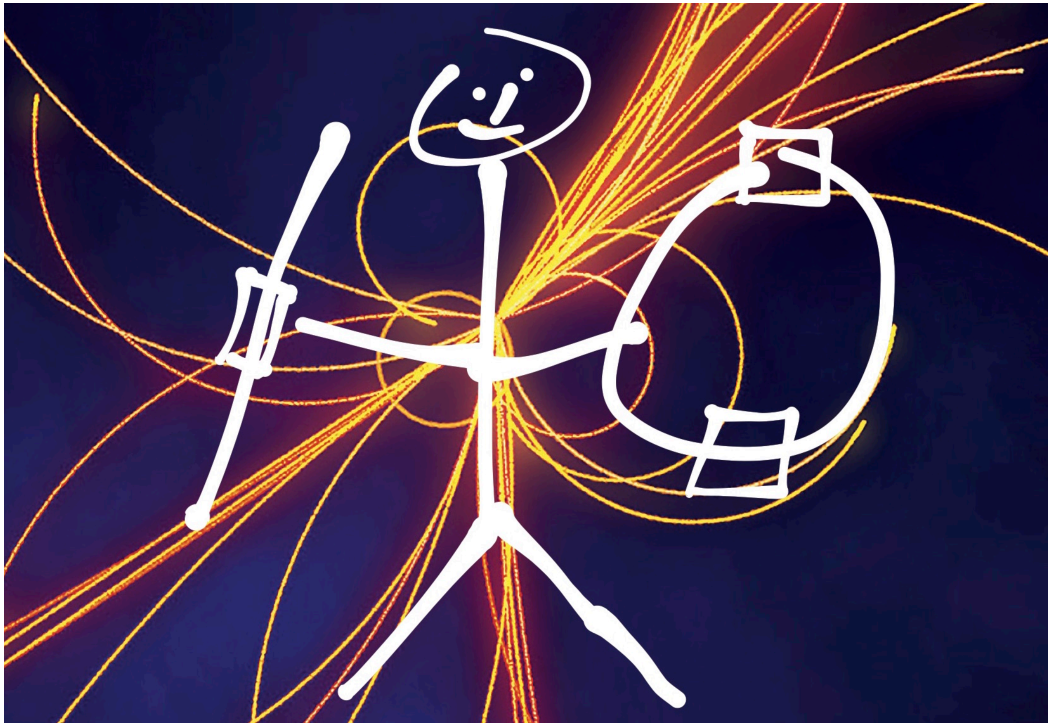
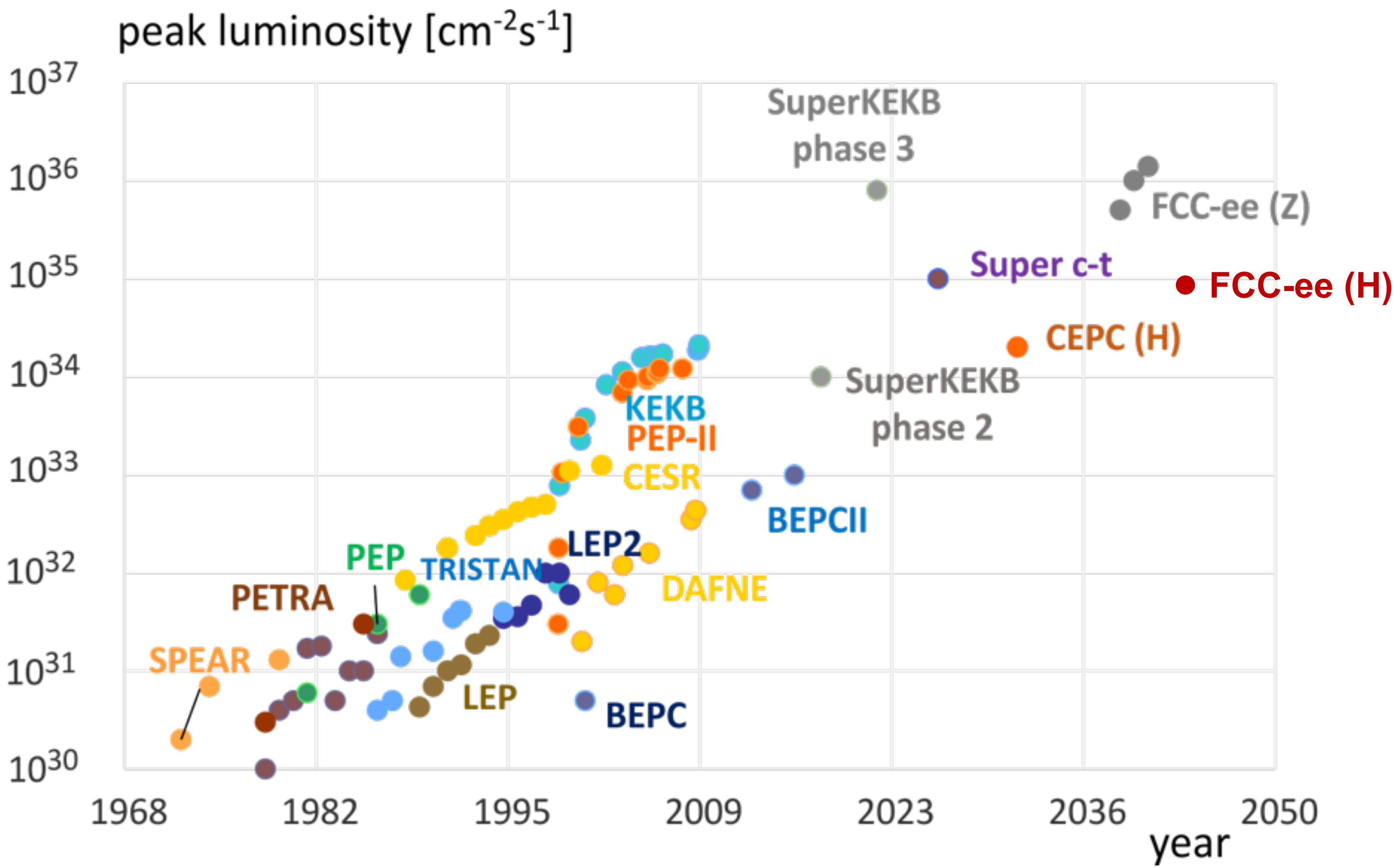
254 pages

e^+e^- Colliders & *Higgs Factories*



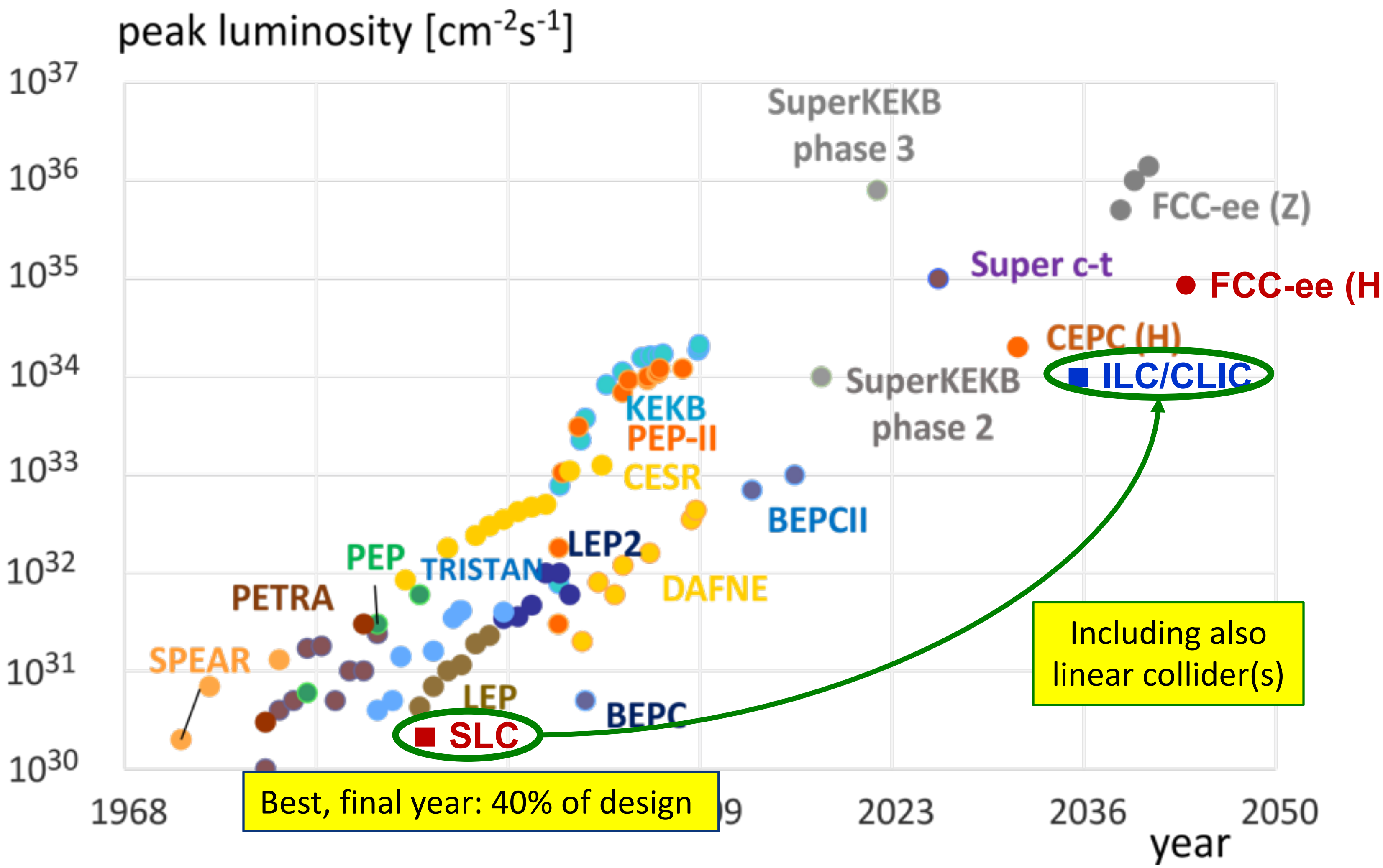


e⁺e⁻ luminosity performence



Peak luminosity of **circular** e^+e^- colliders as a function of year – for past, operating, and proposed facilities including the FCC-ee

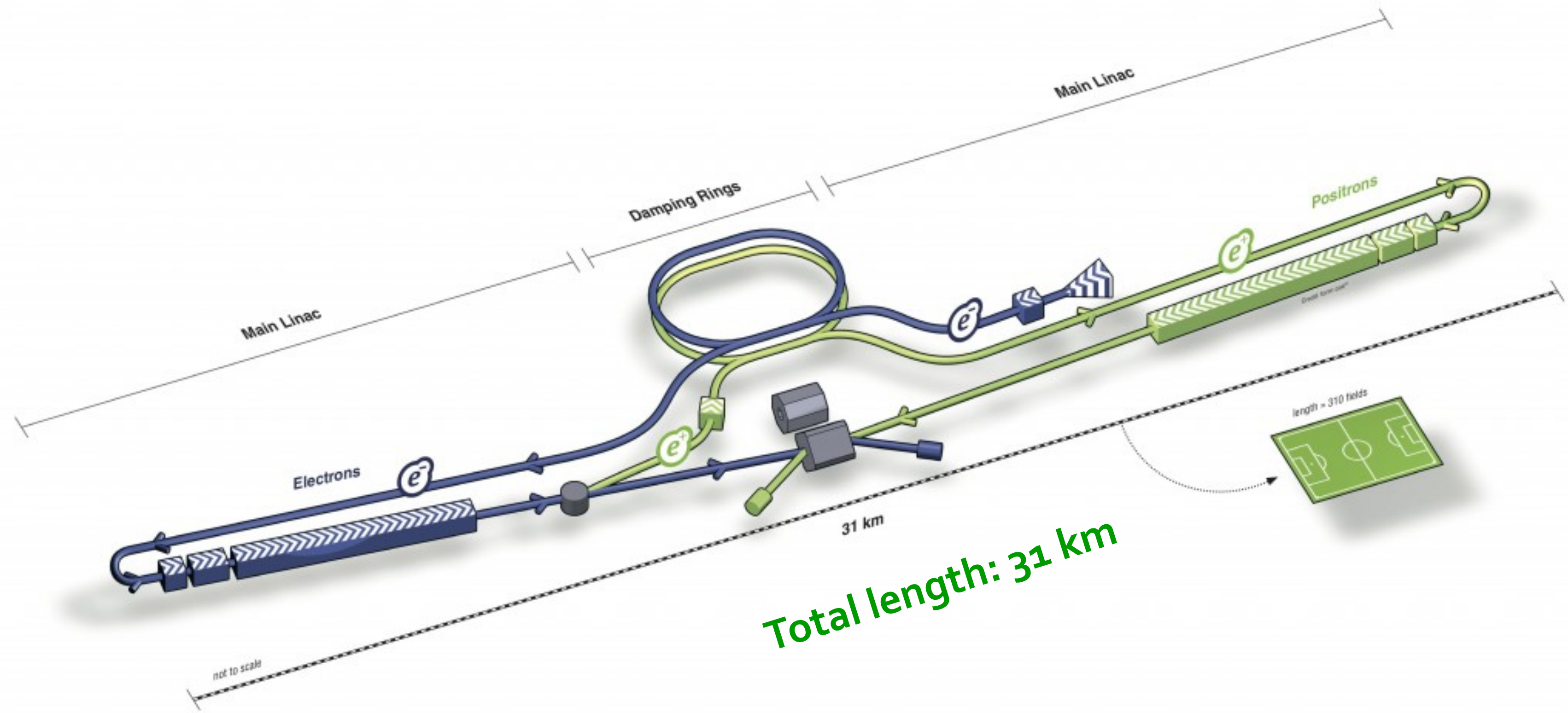
e^+e^- luminosity performence



Peak luminosity of **circular** e^+e^- colliders as a function of year –
for past, operating, and proposed facilities including the FCC-ee

Linear or Circular ? (1)

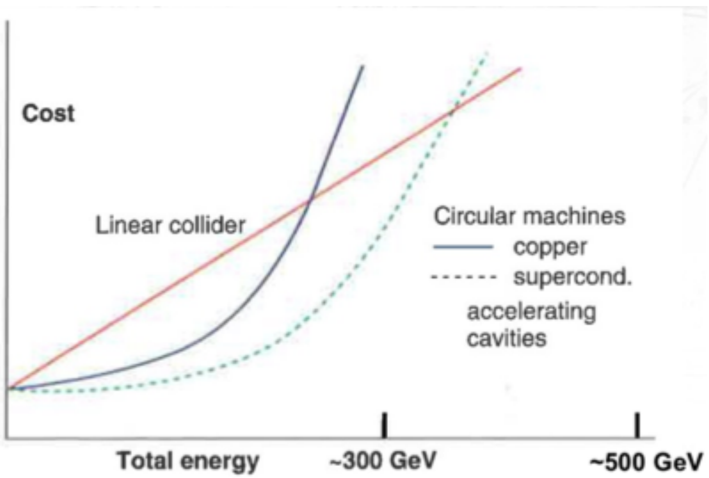
- For 20 years, there was only one future e^+e^- collider project on the market
  - A 500 GeV e^+e^- linear collider, now called "ILC", proposed in the early 1990's

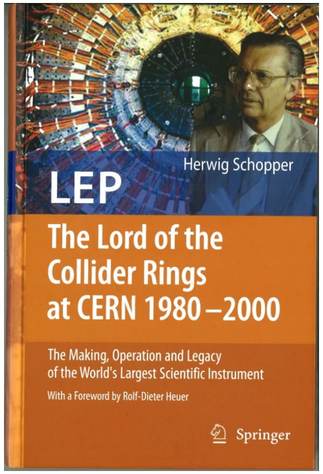


  - Why not a 500 GeV circular collider ?

Linear or Circular ? (2)

- Why not a 500 GeV circular collider ?
  - Synchrotron radiation in circular machines
    - Energy lost per turn grows like $\boxed{\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4}$, e.g., 3.5 GeV per turn at LEP2
      - Must compensate with *R* and accelerating cavities $\longrightarrow$ Cost grows like E^4 too

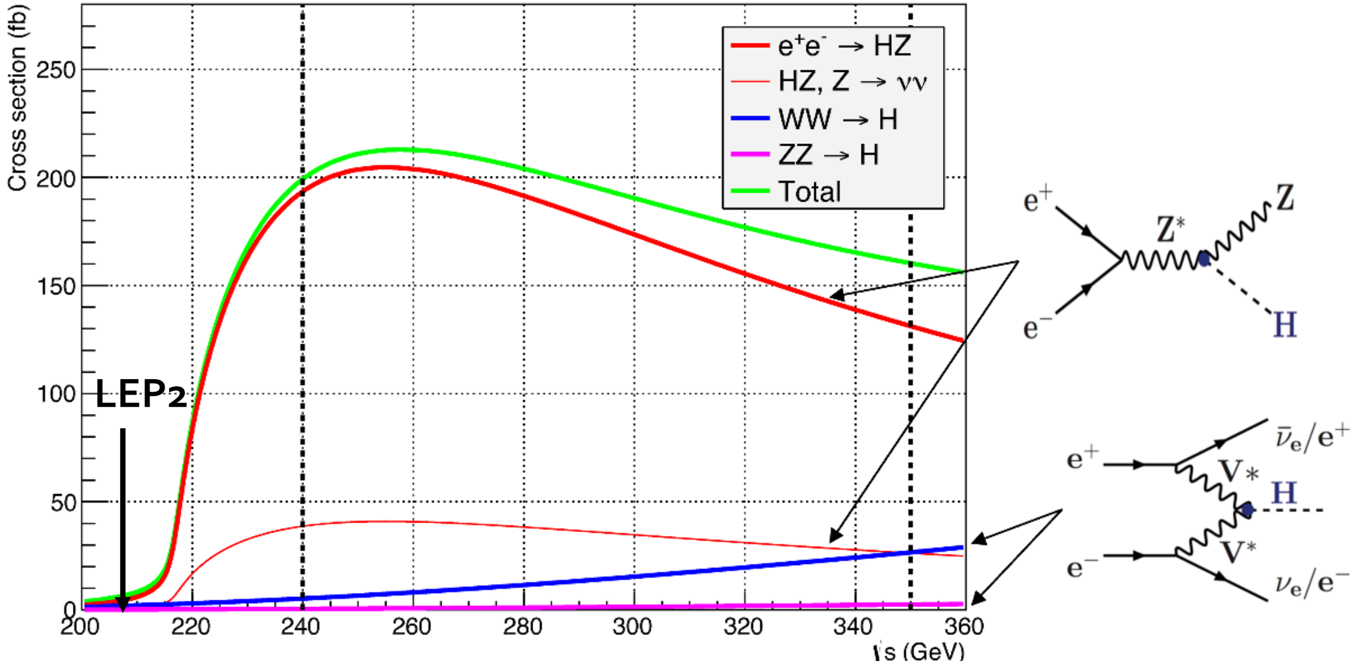




- *"Up to a centre-of-mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option"*, Herwig Schopper
- At and above 500 GeV, a e^+e^- collider can only be linear

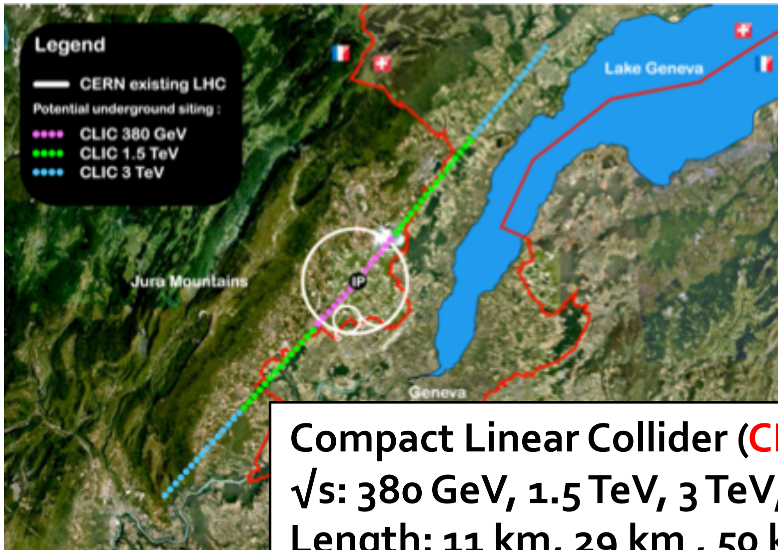
The Revival of Circular e^+e^- Colliders

- Interest for circular collider projects grew up again after first LHC results
  - The Higgs boson is light – LEP2 almost made it: only moderate √s increase needed

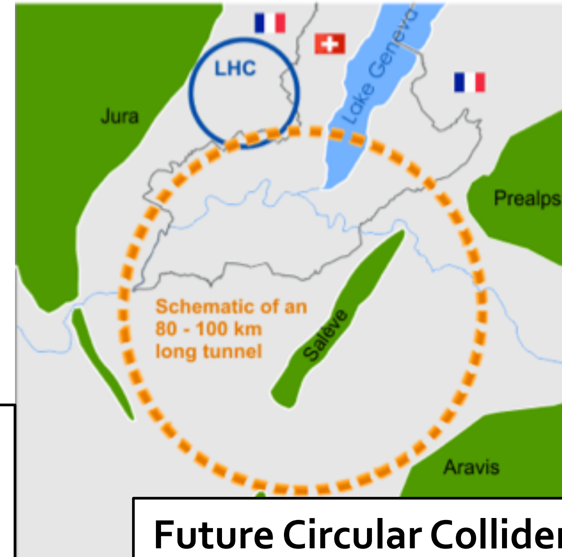


  - From LHC, we have (so far) seen no signs of heavy new physics below 500 GeV
  - One way out: study with unprecedented precision Z, W, H bosons and the top quark
    - Need to go up to the top-pair threshold (350+ GeV) anyway to study the top quark
    - Aim for highest possible luminosities at 91, 160, 240 and 350+ GeV

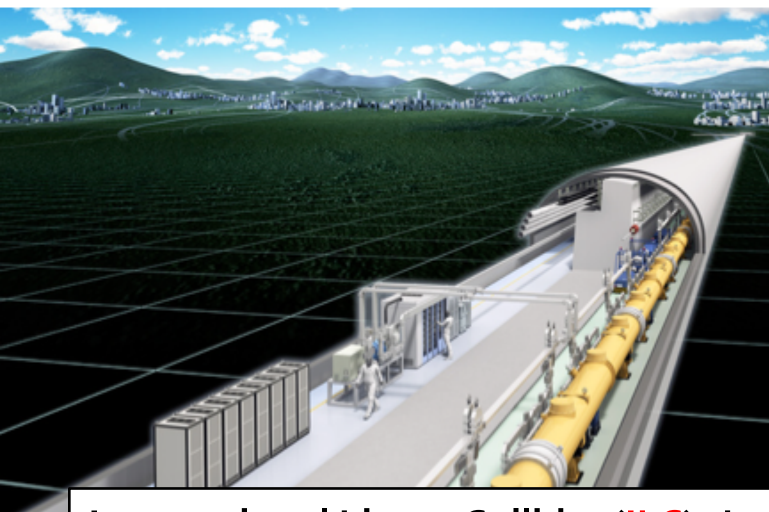
Proposed High-energy e^+e^- Colliders



Compact Linear Collider (CLIC): CERN
√s: 380 GeV, 1.5 TeV, 3 TeV;
Length: 11 km, 29 km , 50 km

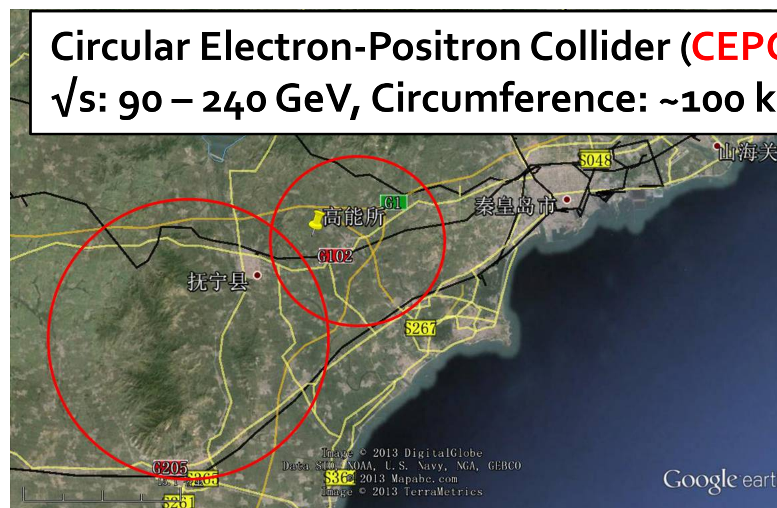


Future Circular Collider (FCC): CERN
e^+e^-, √s: 90 - 350 GeV; pp, √s: 100 TeV;
Circumference: 97.5 km



International Linear Collider (ILC): Japan
√s: 250 – 1000 GeV,
Now concentrating on √s = 250 GeV,
Length: 21 km (250 GeV)

Circular Electron-Positron Collider (CEPC): China
√s: 90 – 240 GeV, Circumference: ~100 km



ILC

- Originally designed for $\sqrt{s}$ = 500 GeV, recently re-optimized for 250 GeV
  - Supported by 25 years of R&D and innovation
    - Complete technical design report delivered in 2013
      - In principle, ready for construction as soon as decision is taken
  - Many technological challenges
    - ~10 km-long, high-gradient (31 MV/m), RF system
    - Very low β^* optics delivering small beam spot size at high intensity
    - Positron source with no precedent
      - 30 x world record (SLC)
    - Green-field project
  - Can deliver data to only one detector at a time
  - In principle upgradeable to $\sqrt{s}$ = 1 TeV
    - And possibly more : CLIC or *plasma acceleration* later in the same tunnel (?)
  - Longitudinally polarized beams available: $P_- / P_+ = \pm 0.8 / \pm 0.3$
  - "GigaZ" option to run at the Z pole has been dormant – now being revived

arXiv:1908.08212

ILC postponed decision

MEXT's view in regard to the ILC project Executive Summary

March 7, 2019
Research Promotion Bureau, MEXT

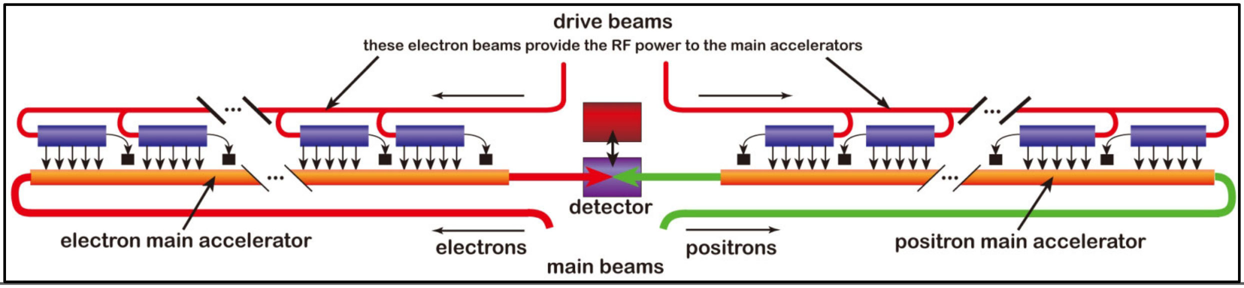
○ Following the opinion of the SCJ, MEXT has not yet reached declaration for hosting the ILC in Japan at this moment. The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain understanding and support from the domestic academic community.

○ MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.

○ The ILC project has certain scientific significance in particle physics particularly in the precision measurements of the Higgs boson, and also has possibility in the technological advancement and in its effect on the local community, although the SCJ pointed out some concerns with the ILC project. Therefore, considering the above points, MEXT will continue to discuss the ILC project with other governments while having an interest in the ILC project.

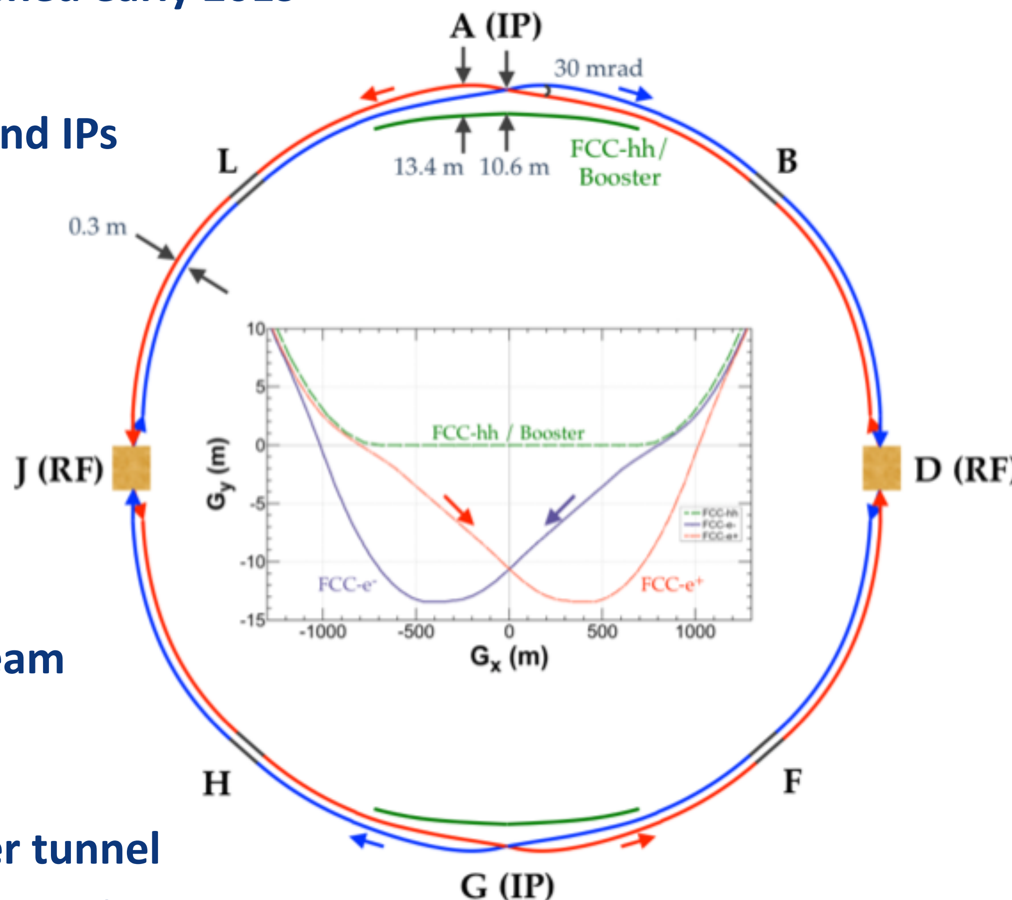
CLIC

- Designed to reach the highest possible energies in e^+e^- collision
  - In staging scenario, foreseen to cover 3 energy points: $\sqrt{s}$ = 380, 1500, 3000 GeV
  - More than 30 years of innovation and R&D
    - Very high acceleration gradient, 100 MV/m, from a 2-beam acceleration scheme
      - demonstrated via CLIC Test Facilities
    - Conceptual Design Report delivered in 2012
  - A number of technological challenges common with ILC
    - Very low β^* optics delivering small beam spot sizes at high intensity
    - Positron source with no precedent
  - Longitudinally polarized beams available: $P_- / P_+ = \pm 0.8 / 0$
  - Can deliver data to only one detector at a time
  - No design to run at the Z pole



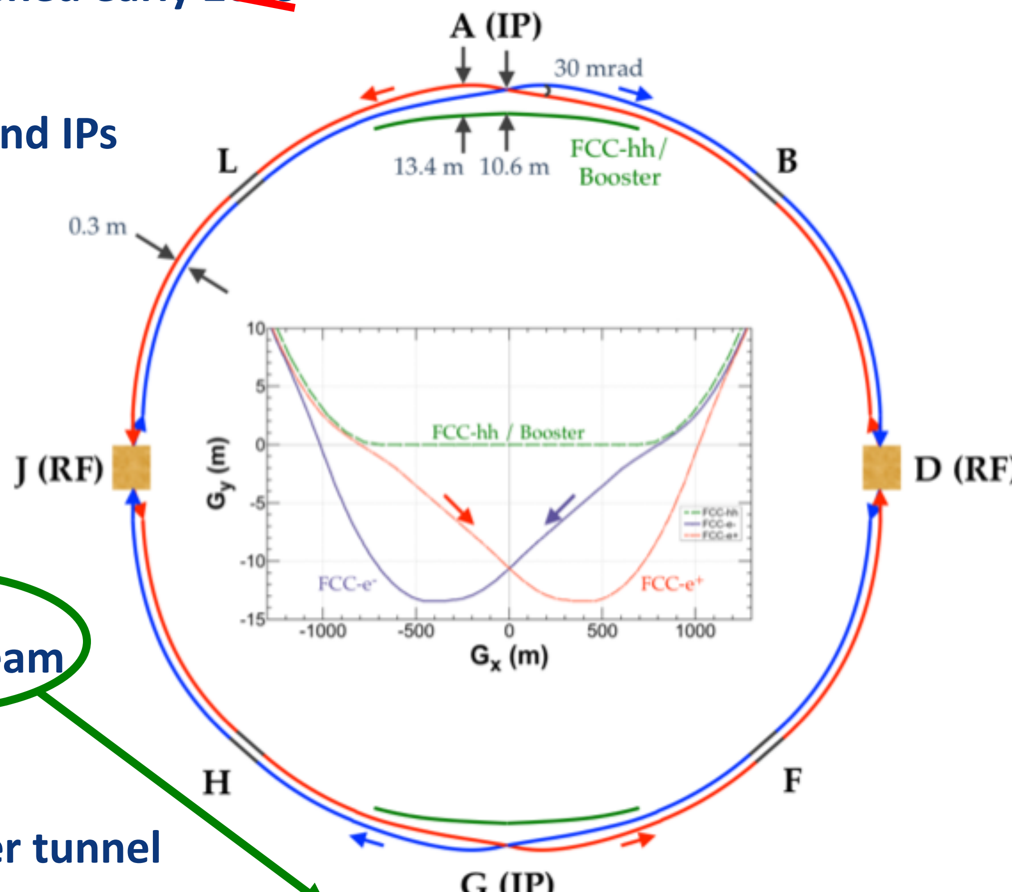
FCC-ee

- relatively young project; ~8 years
  strong progress, first as "TLEP", from 2014 as part of FCC project
  Conceptual Design Report (CDR) published early 2019
- double ring e^+e^- collider ~100 km
- follows footprint of FCC-hh, except around IPs
  first step towards 100 TeV pp collider
- asymmetric IR layout & optics
  to limit synchrotron radiation
  towards the detector
- 2 IPs (layout with 4 IPs under study)
- large horizontal crossing angle 30 mrad,
  crab-waist optics; very low β^*
- synchrotron radiation power 50 MW/beam
  at all beam energies
- top-up injection scheme;
  requires booster synchrotron in collider tunnel
- high-power (200 MW), high-gradient (10 MV/m),
  2 km-long, RF system
- transverse polarization for beam-energy measurement



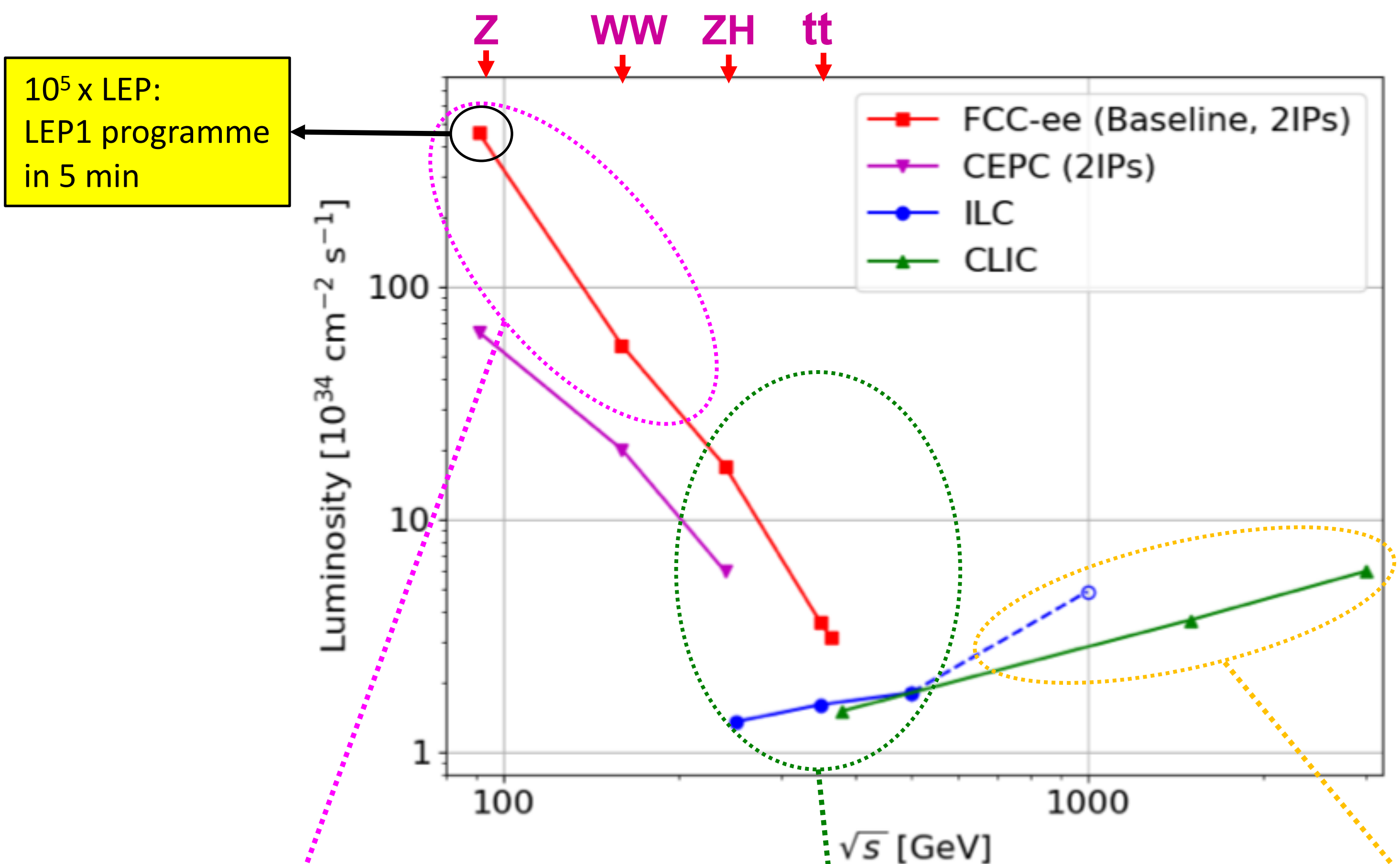
FCC-ee → CEPC

- relatively young project; ~8 years
  strong progress
  Conceptual Design Report (CDR) published ~~early 2019~~ 2018
- double ring e^+e^- collider ~100 km
- follows footprint of ~~FCC-hh~~ SppS, except around IPs
  first step towards 100 TeV pp collider
- asymmetric IR layout & optics
  to limit synchrotron radiation
  towards the detector
- 2 IPs ~~(layout with 4 IPs under study)~~
- large horizontal crossing angle ~~30~~ 33 mrad,
  crab-waist optics; very low β^*
- synchrotron radiation power ~~50 MW~~ 30 MW/beam
  at all beam energies
- top-up injection scheme;
  requires booster synchrotron in collider tunnel
- high-power (200 MW), high-gradient (10 MV/m),
  2 km-long, RF system
- transverse polarization for beam-energy measurement



Main difference between FCC-ee and CEPC is the lower SR power resulting in a somewhat lower luminosity

Projected luminosities of e^+e^- accelerators

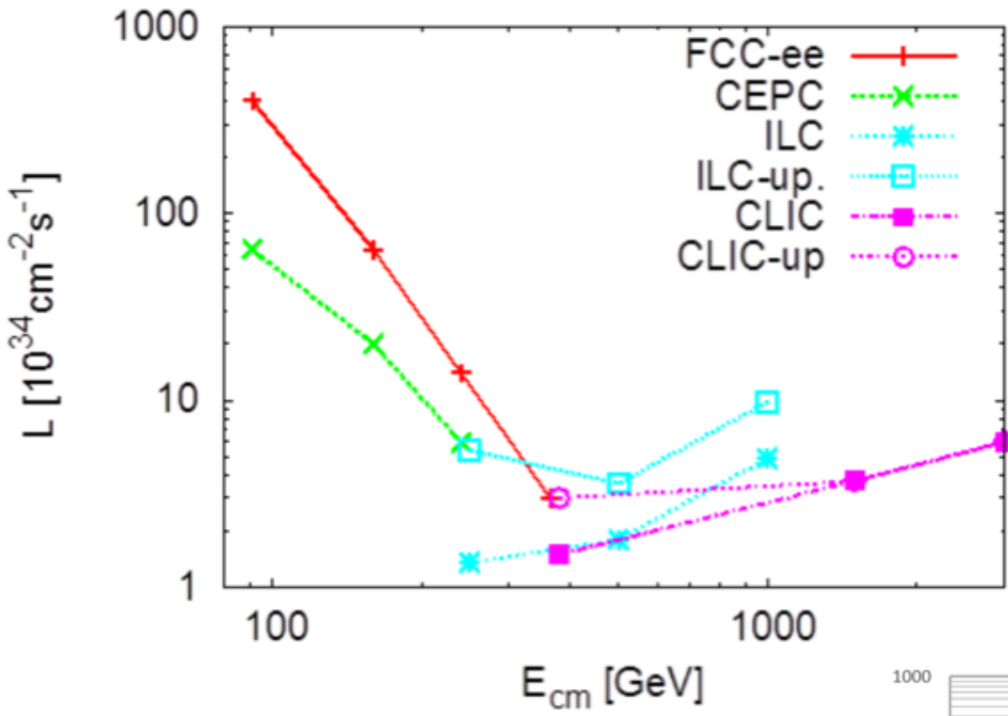


Circular colliders:
Extremely high luminosities at lower energies:
"Z, WW, and flavour factories"

Overlap region, 240-380 GeV:
"Higgs Factories"

Linear colliders:
High centre-of-mass energies

Luminosity upgrade plans



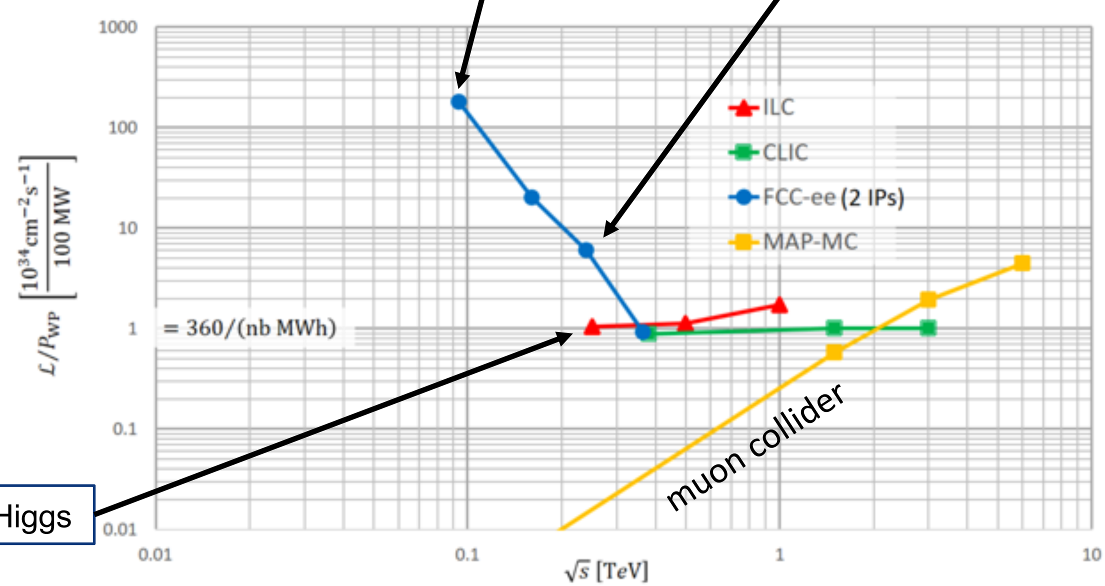
Plots from *Briefing Book*

Recent ILC and CLIC lumi upgrade plans
- Positive effect of FCC-ee competition

FCC-ee would receive × 1.7 lumi improvement from 2IP → 4IP

0.1 kWh per Z

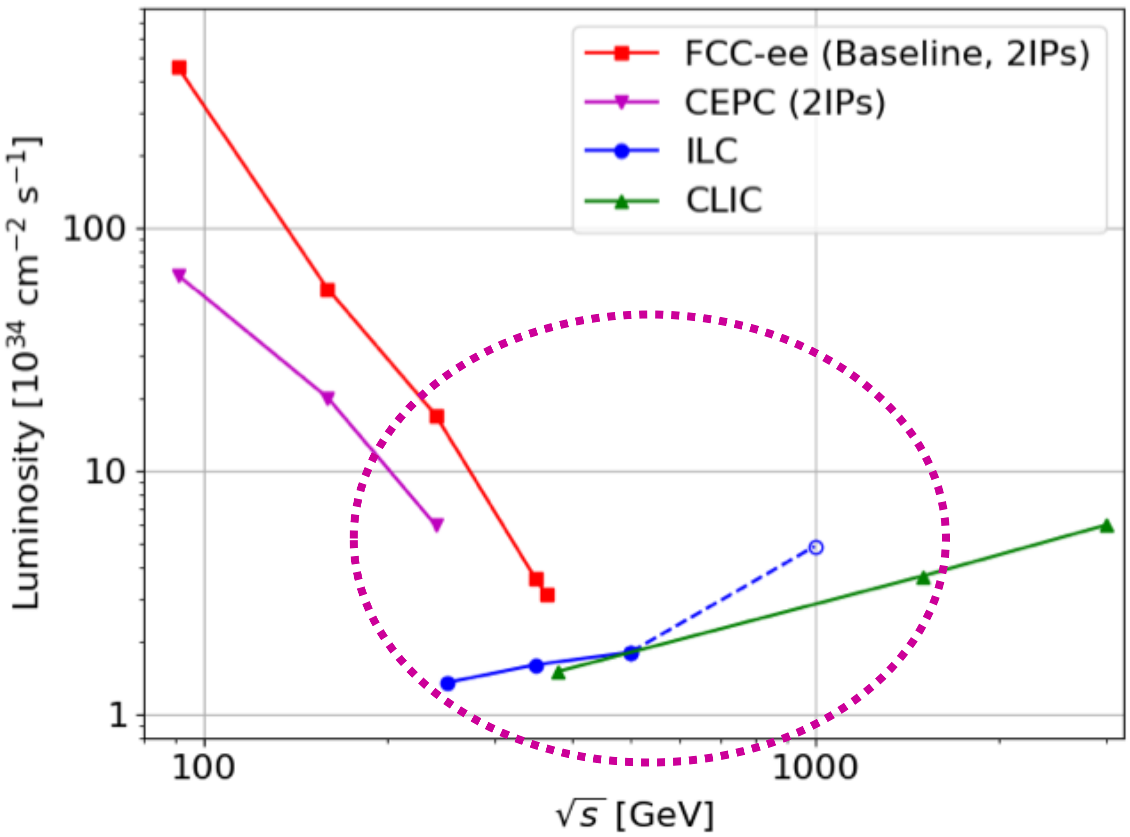
2.5 MWh per Higgs



Another way to picture collider performance:
➢ luminosity per wall plug power

13 MWh per Higgs

e^+e^- Higgs Factories



Higgs Boson studies at future particle colliders

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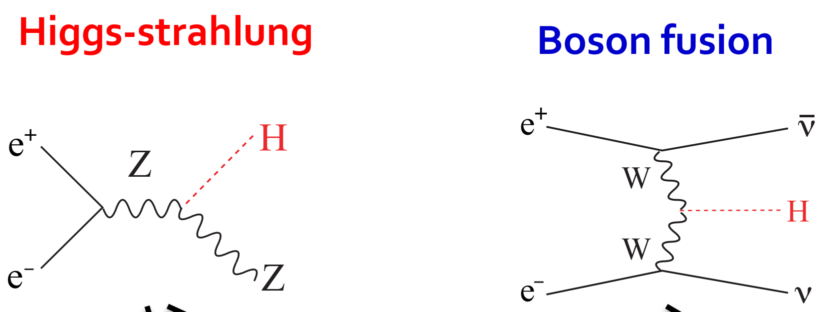
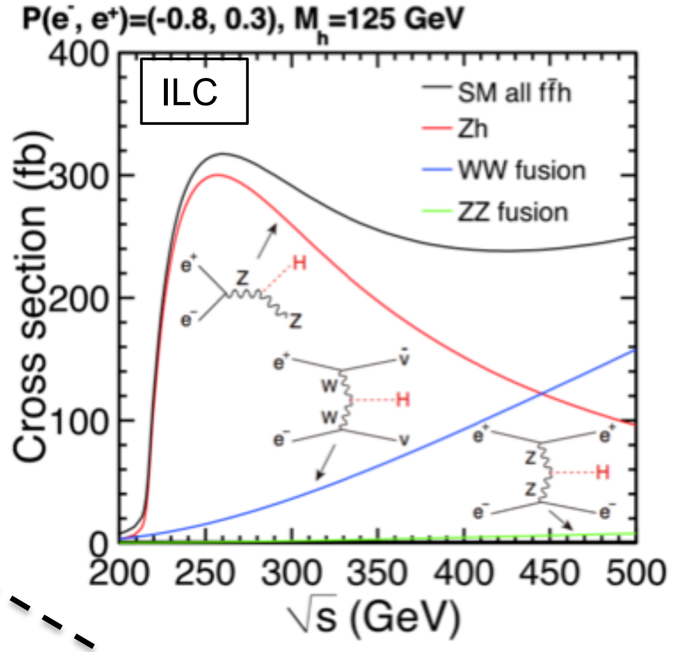
ABSTRACT

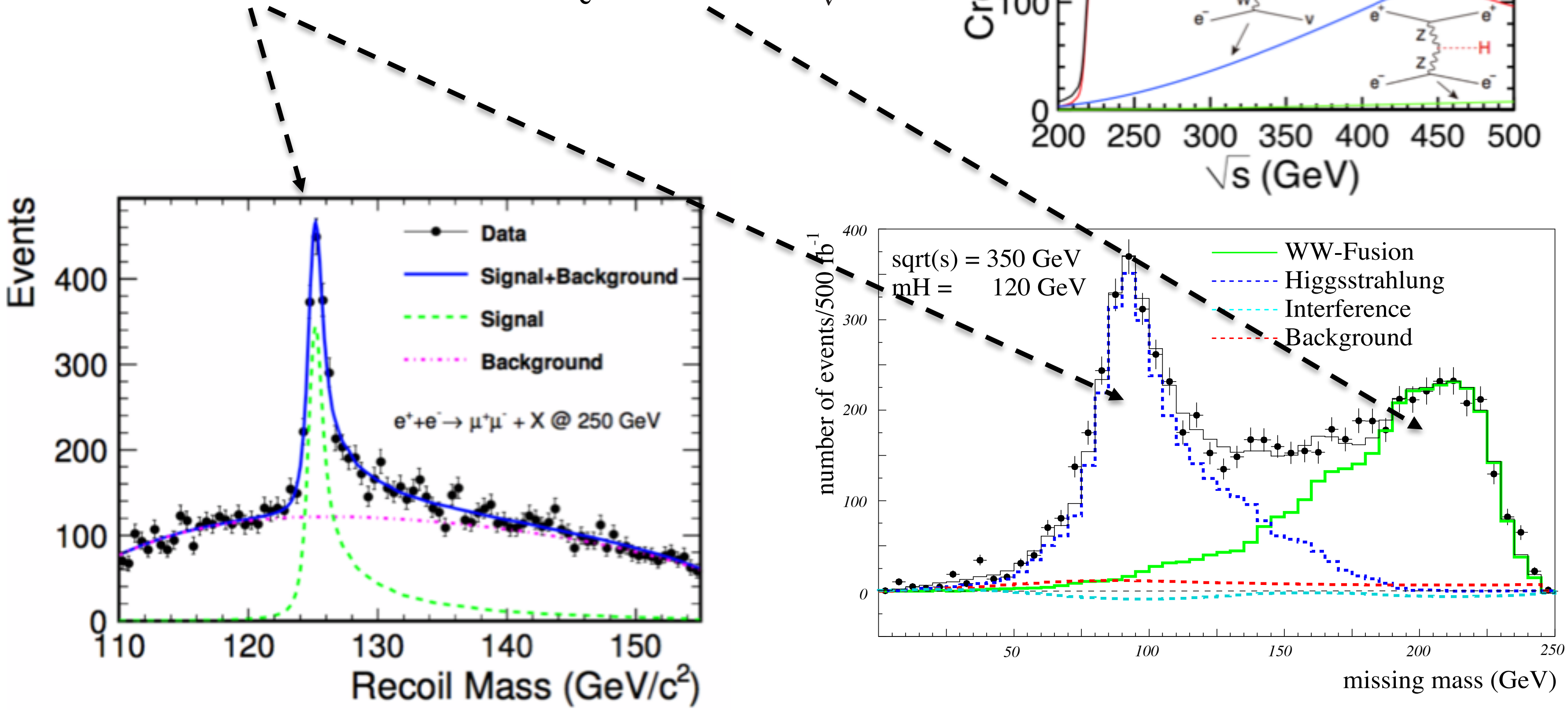
This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects of sufficient maturity using uniform methodologies. A first version of this report was prepared for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019). Comments and feedback received led to the consideration of additional run scenarios as well as a refined analysis of the impact of electroweak measurements on the Higgs coupling extraction.

75 pages

Higgs Production

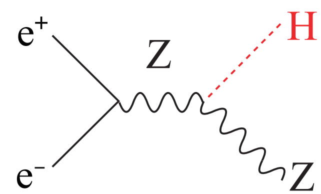


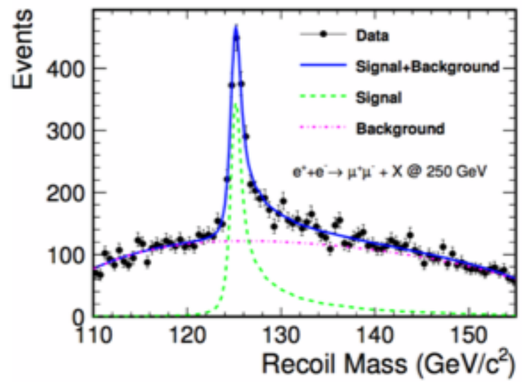


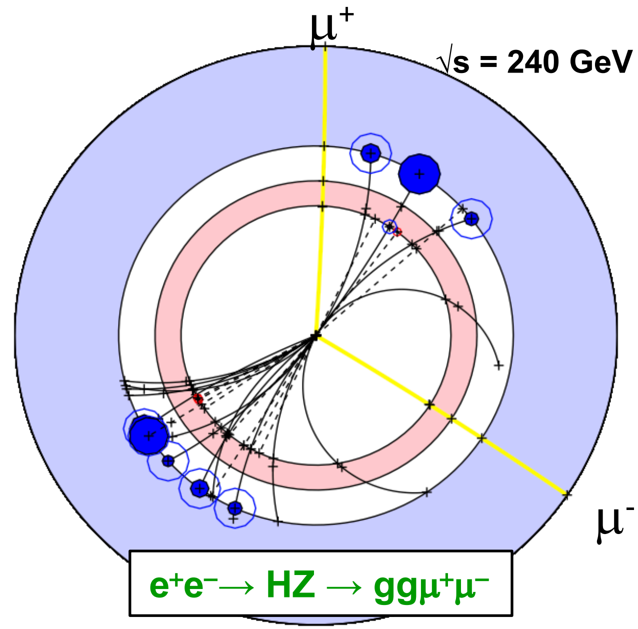


Precision Higgs Physics

- Example of a Higgs boson event
  - Tagged with a Z boson
  - Very clean signature







- Run at √s = 240-250 GeV (and 350-500 GeV) in order to
  - Determine all Higgs couplings in a model-independent way
  - Infer the Higgs total decay width
  - Evaluate (or set limits on) the Higgs invisible or exotic decays
    - Through the measurements of

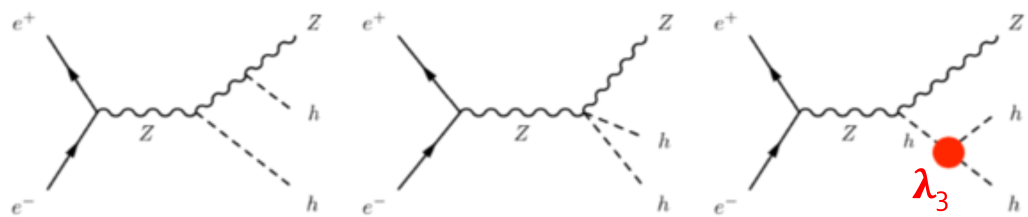
$$\sigma(e^+e^- \to H + X) \times BR(H \to YY)$$

with Y = b, c, g, W, Z, γ, τ, μ , *invisible*

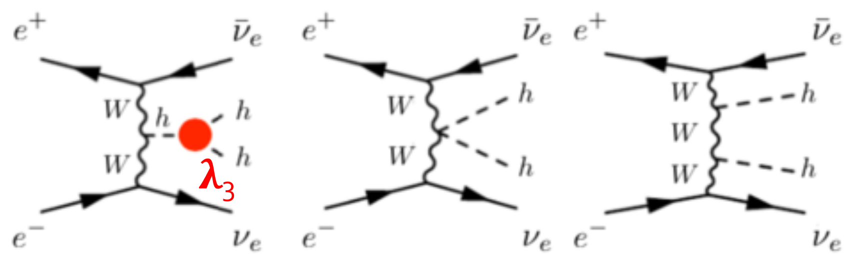
Higgs Self Coupling, λ_3

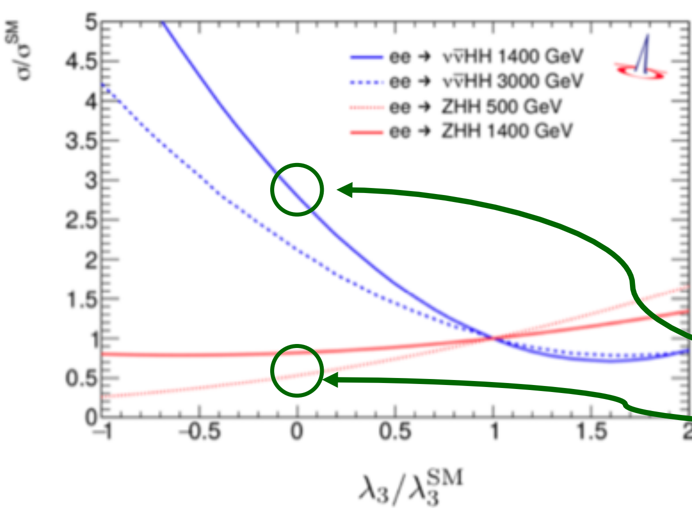
- Higgs self-coupling, λ_3, is a fundamental parameter of the SM who's value should be checked against prediction
  - Essentially dictates the shape of the Higgs potential
- For √s ≳ 500 GeV, access to di-Higgs production

From 500 GeV



From ≈800 GeV

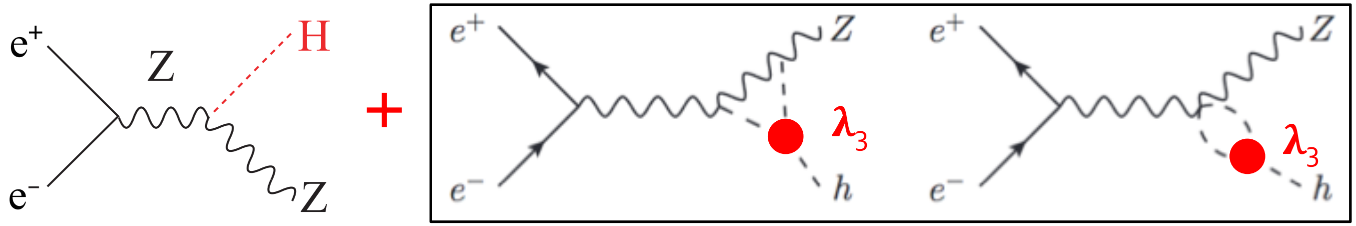




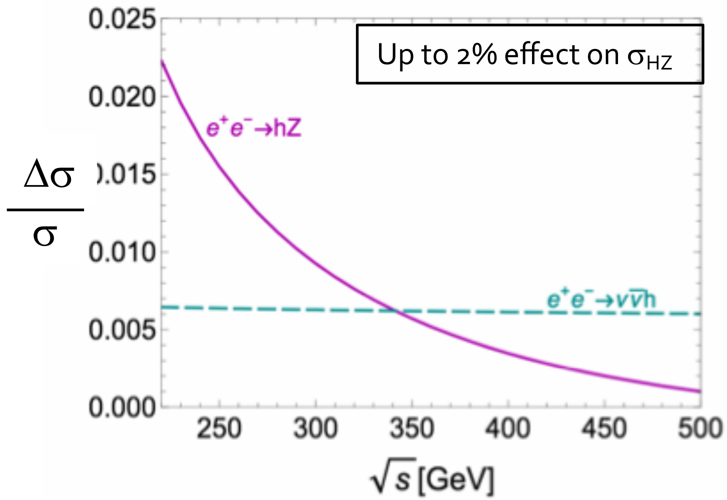
- In both cases, three interfering diagrams
  - Higgs self coupling, λ_3, extracted from fit to production cross section
    - At 1400 GeV: relatively strong dependence
    - At 500 GeV: weak(er) dependence

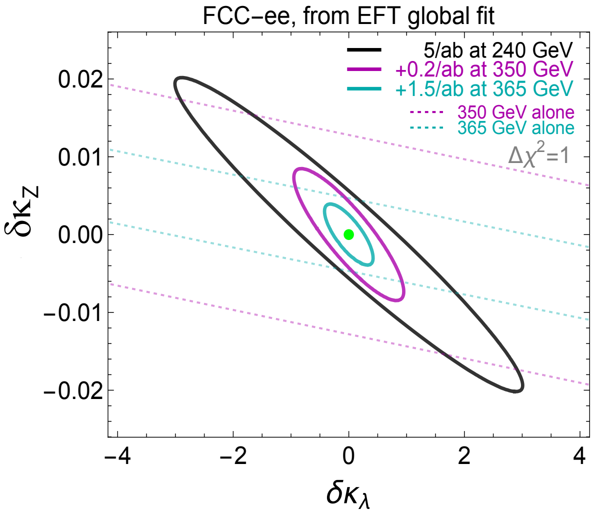
Higgs Self Coupling, λ_3

- At lower energies, no production of Higgs pairs
- But, loops including Higgs self coupling contribute to Higgs production



- Effect on σ_{ZH} and $\sigma_{\nu\nu H}$ of Higgs self coupling (λ_3 and hence $\kappa_\lambda=\lambda_3/\lambda_3^{SM}$) depends on $\sqrt{s}$





- Two energy points (240 and 365 GeV) lift the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_\lambda$
  - Precision on λ_3 with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : ±34% (3σ) ; in the SM : ±12%

All e+e- Higgs Factories similar?

F. Gianotti:

Strong support for:

- e+e- Higgs factory somewhere in the world: potential of ILC@250, CLIC@380, CepC and FCC-ee for Higgs measurements considered to be similar, to first order

Well yes, perhaps to first order…

Collider	HL-LHC	ILC_{250}	CLIC_{380}	CEPC_{240}	$\mathrm{FCC\text{-}ee}_{240\to 365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{\mathrm{HZ}\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 27./24.
Γ_{H} (%)	SM	2.2	2.5	1.7	1.1
$\mathrm{BR}_{\mathrm{inv}}$ (%)	1.9	0.26	0.65	0.28	0.19
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	1.1

arXiv:1912.11871

Scenarios I have chosen to compare

Facility	$CEPC_{240}$	$FCC\text{-}ee_{365}$	ILC_{500}	$CLIC_{1500}$
$\sqrt{s}$ [GeV]	240	240 / 365	250 / 350 / 500	380 / 1500
$\mathcal{L}$ [ab^{-1}]	5.6	5 / 1.5	2.0 / 0.2 / 4.0	1.0 / 2.5
# years	7	9	22	17
Polarisation	no	no	yes	yes
# Higgs ($\times 10^3$)	1100	1000 / 240	500 / 40 / 800	150 / 600

- The landscape is complicated; not easy to make a ”fair” comparison:
  - CEPC: no *current* plans to go beyond $\sqrt{s}$ = 240 GeV
    - However, clearly technically feasible
  - FCC-ee: Both $\sqrt{s}$ = 240 and 365 GeV included in baseline project
    - The energy upgrade of FCC is the FCC-hh, which will bring ultimate precisions
  - ILC: Current baseline is 250 GeV only; but clearly an upgrade to 500 GeV is understood/hoped for
    - However, approximately a factor two on price, and long time scale (Σ = 22 years)
  - CLIC: Have included the two first stages (380 & 1500 GeV) leaving out the the 3 TeV run
    - The 3 TeV run is the ”energy upgrade”

Summary of Higgs Measurement Precisons

Coupling	HL-LHC	$CEPC_{240}$	ILC_{500}	$FCCee_{365}$	$CLIC_{1500}$
κ_Z [%]	1.5	0.14	0.23	0.17	0.26
κ_W [%]	1.7	1.3	0.29	0.43	0.16
κ_c [%]	SM	2.2	1.3	1.3	1.8
κ_t [%]	3.3	-	6.9	-	n.a.
κ_b [%]	3.6	1.2	0.58	0.67	0.46
κ_μ [%]	4.6	8.9	9.4	8.9	13
κ_τ [%]	1.9	1.3	0.7	0.73	1.3
κ_γ [%]	1.9	3.7	3.4	3.9	5.0
κ_g [%]	2.3	1.5	0.97	1.0	1.3
$\kappa_{Z\gamma}$ [%]	10	8.2	-	-	15
Γ_H [%]	~50	2.8	1.6	1.3	2.6
BR_{inv} [%]	$\lesssim 2$	< 0.27	< 0.23	< 0.19	< 0.62
BR_{EXO} [%]	SM	< 1.1	< 1.4	< 1.0	< 2.4
λ_3 (sngl-H/di-H)	- / 50	17 / -	27 / 27	19 / -	41 / 36

Model-independent results

Sensitive to new physics at tree level
Expected effects < 5% / Λ^2_{NP}
1% precision needed for Λ_{NP} ~ 1TeV
Sub-percent needed for Λ_{NP} > 1TeV

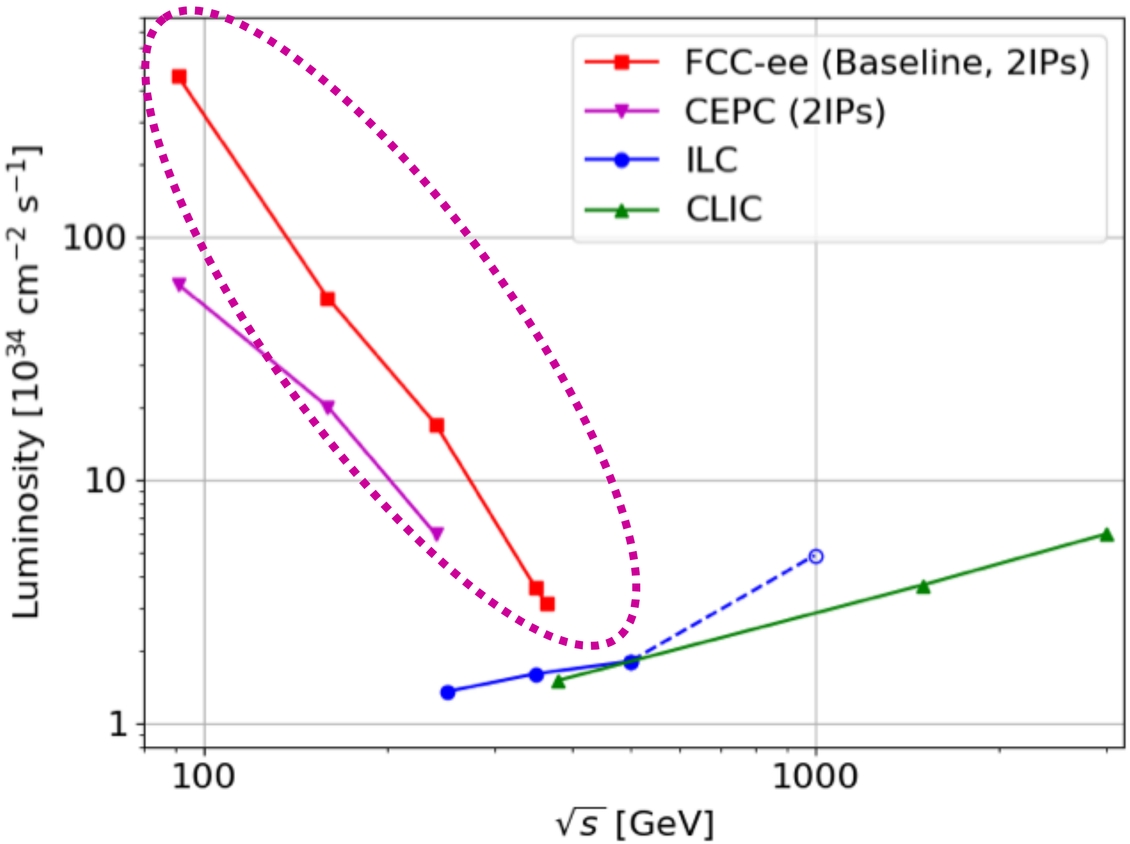
Sensitive to new physics in loops

Sensitive to light dark matter particles (sterile ν, χ, …) and to other exotic decays

Higgs self-coupling

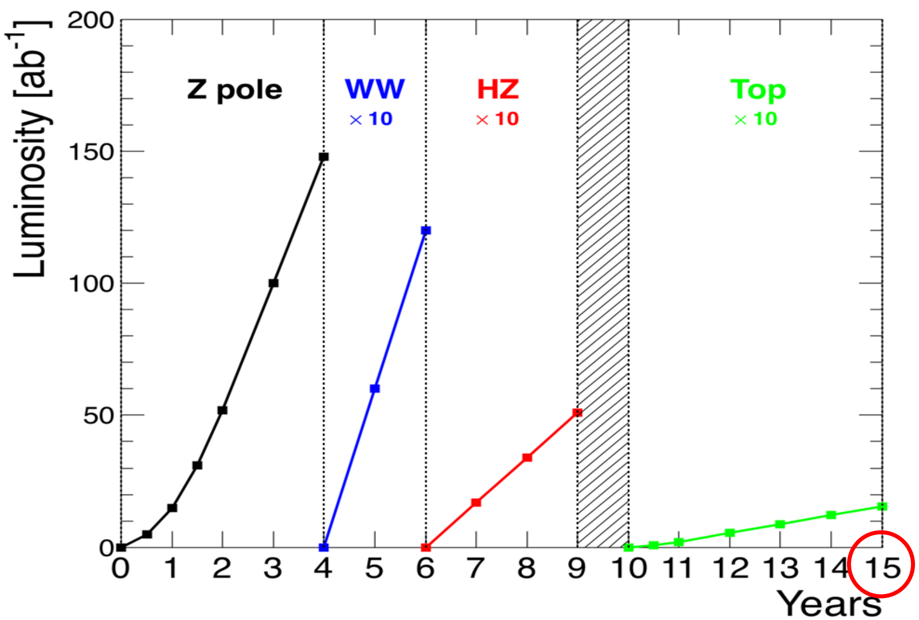
Generally, a factors of 2–10 better than HL-LHC
Plus model independence

Electroweak Precision Measurements – FCC-ee



Electroweak Precision Physics: FCC-ee Statistics

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold…	… and above
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4



Total : 15 years

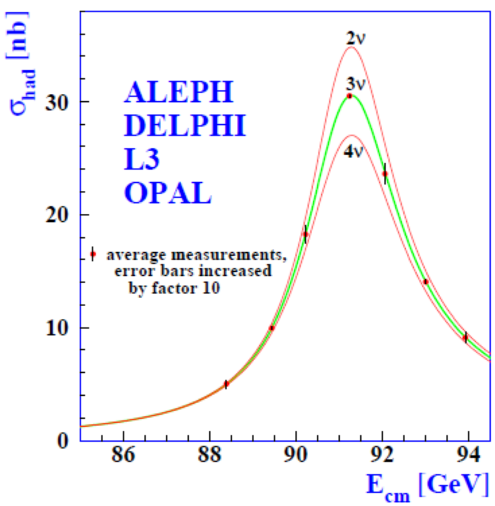
Event statistics	$\sqrt{s}$ precision
5×10^{12} $e^+e^- \rightarrow Z$	100 keV
10^8 $e^+e^- \rightarrow W^+W^-$	300 keV
10^6 $e^+e^- \rightarrow HZ$	1 MeV
10^6 $e^+e^- \rightarrow t\bar{t}$	2 MeV

(Conservative) assumptions: 185 physics days / year, 75% efficiency, 10% margin on luminosity

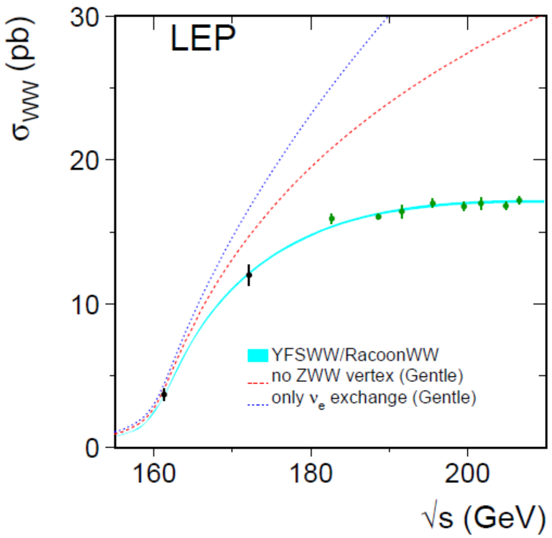
FCC-ee Precision EW Physics Measurements

- EW precision measurements at FCC-ee (see arXiv:1308.6176 and FCC CDR)

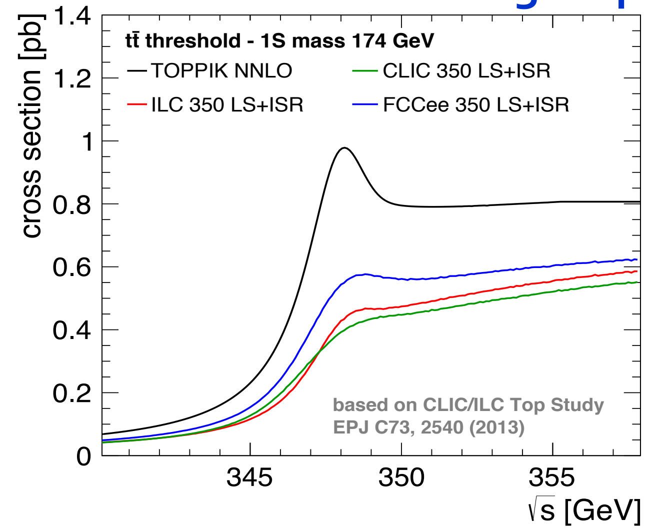
Z reconance: TeraZ



WW threshold scan: OkuW



$t\bar{t}$ threshold scan: MegaTop



Lineshape

- Exquisite E_{beam} (unique!)
- m_Z, Γ_Z to < 100 keV (2.2 MeV)

Asymmetries

- $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
- $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

Threshold scan

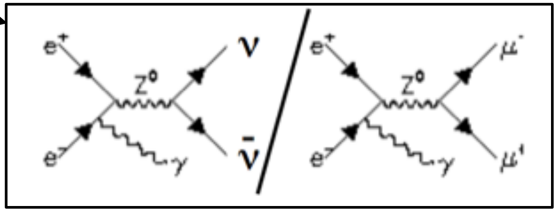
- m_W to 0.6 MeV (12 MeV)

Branching ratios R_l, R_b

- $\alpha_S(m_W)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.001 (0.008)



Threshold scan

- m_{top} to 20 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 2%

Sample of EW observables, experimental precisions

Observable	Measurement	Current precision	FCC-ee stat.	FCC-ee syst.	Challenge
m_Z (keV)	Z lineshape	91186700 ± 2200	5	100	Beam energy calib
Γ_Z (keV)	Z lineshape	2495200 ± 2300	8	100	Beam energy calib
R_l ($\times 10^3$)	Ratio of hadrons to leptons	20767 ± 25	0.01	0.2−1	Acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	From R_ℓ	1196 ± 30	0.1	0.4−1.6	ditto
R_b ($\times 10^6$)	Ratio of bb to hadrons	216290 ± 660	0.3	< 60	$g \to bb$
N_ν ($\times 10^3$)	Peak hadronic cross section	2991 ± 7	0.005	< 1	Lumi meast
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	From $A_{FB}^{\mu\mu}$ at Z peak	231480 ± 160	3	2−5	Beam energy calib
$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	From $A_{FB}^{\mu\mu}$ off-peak	128952 ± 14	4	small	QED corr.
$A_{FB}^{pol,\tau}$ (10^4)	τ polarization charge assym	1498 ± 49	0.15	< 2	τ decay physics
m_W (MeV)	WW threshold scan	80385000 ± 15000	600	300	Beam energy calib
N_ν	$e^+e^- \to \gamma Z, Z \to \nu\nu, \ell\ell$	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$ ($\times 10^4$)	From R_ℓ^W	1170 ± 420	3	small	Lepton acceptance
m_{top} (MeV)	tt threshold scan	172740 ± 500	20	small	QCD corr
Γ_{top} (MeV)	tt threshold scan	1410± 190	40	small	QCD corr
$\lambda_{top} / \lambda_{top}^{SM}$	tt threshold scan	1.2 ± 0.3	0.08	small	QCD corr

Sample of EW observables, experimental precisions

Observable	Measurement	Current precision	FCC-ee **stat.**	**FCC-ee syst.**	Challenge
m_Z (keV)	Z lineshape	91186700 **± 2200**	**5**	**100**	Beam energy calib
Γ_Z (keV)	Z lineshape	2495200 **± 2300**	**8**	**100**	Beam energy calib
R_l ($\times 10^3$)	Ratio of hadrons to leptons	20767 **± 25**	**0.01**	**0.2−1**	Acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	From R_l	1196 **± 30**	**0.1**	**0.4−1.6**	ditto
R_b ($\times 10^6$)	Rati			**< 60**	$g \to bb$
N_ν ($\times 10^3$)	Peak h			**< 1**	Lumi meast
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	Fro			**2−5**	Beam energy calib
$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	From $A_{FB}^{\mu\mu}$ off-peak	128952 **± 14**	**4**	**small**	QED corr.
$A_{FB}^{pol,\tau}$ (10^4)	τ polarization charge assym	1498 **± 49**	**0.15**	**< 2**	τ decay physics
m_W (MeV)	WW threshold scan	80385000 **± 15000**	**600**	**300**	Beam energy calib
N_ν	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, $\ell\ell$	2.92 **± 0.05**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$ ($\times 10^4$)	From R_ℓ^W	1170 **± 420**	**3**	**small**	Lepton acceptance
m_{top} (MeV)	tt threshold scan	172740 **± 500**	**20**	**small**	QCD corr
Γ_{top} (MeV)	tt threshold scan	1410**± 190**	**40**	**small**	QCD corr
$\lambda_{top} / \lambda_{top}^{SM}$	tt threshold scan	1.2 **± 0.3**	**0.08**	**small**	QCD corr

Very precise (100 keV – 1 ppm) √s calibration via transverse beam polaristion and resonant depolarisation. Measurement of √s spread

Sample of EW observables, experimental precisions

Observable	Measurement	Current precision	FCC-ee **stat.**	**FCC-ee syst.**	Challenge
m_Z (keV)	Z lineshape	91186700 ± **2200**	**5**	**100**	Beam energy calib
Γ_Z (keV)	Z lineshape	2495200 ± **2300**	**8**	**100**	Beam energy calib
R_l (×10³)	Ratio of hadrons to leptons	20767 ± **25**	**0.01**	**0.2−1**	Acceptance for leptons
$\alpha_s(m_Z)$ (×10⁴)	From R[illegible]	[illegible]	**[illegible].1**	**0.4−1.6**	ditto
R_b (×10⁶)	Rati[illegible]	[illegible]	**[illegible].3**	**< 60**	$g \rightarrow bb$
N_ν (×10³)	Peak h[illegible]	[illegible]	**[illegible]005**	**< 1**	Lumi meast
$\sin^2\theta_W^{eff}$ (×10⁶)	From $A_{FB}^{\mu\mu}$ at Z peak	231480 ± **160**	**3**	**2−5**	Beam energy calib
$1/\alpha_{QED}(m_Z)$ (×10³)	From $A_{FB}^{\mu\mu}$ off-peak	128952 ± **14**	**4**	**small**	QED corr.
$A_{FB}^{pol,\tau}$ (10⁴)	τ polarization charge assym	1498 ± **49**	**0.15**	**< 2**	τ decay physics
m_W (MeV)	WW threshold scan	80385000 ± **15000**	**600**	**300**	Beam energy calib
N_ν	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, \ell\ell$	2.92 ± **0.05**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$ (×10⁴)	From R_ℓ^W	1170 ± **420**	**3**	**small**	Lepton acceptance
m_{top} (MeV)	tt threshold scan	172740 ± **500**	**20**	**small**	QCD corr
Γ_{top} (MeV)	tt threshold scan	1410± **190**	**40**	**small**	QCD corr
$\lambda_{top} / \lambda_{top}^{SM}$	tt threshold scan	1.2 ± **0.3**	**0.08**	**small**	QCD corr

Precise luminosity measurement:
- Absolute to 10^{-4}
- Relative (energy to point) to 10^{-5}

Sample of EW observables, experimental precisions

Observable	Measurement	Current precision	FCC-ee **stat.**	**FCC-ee syst.**	Challenge
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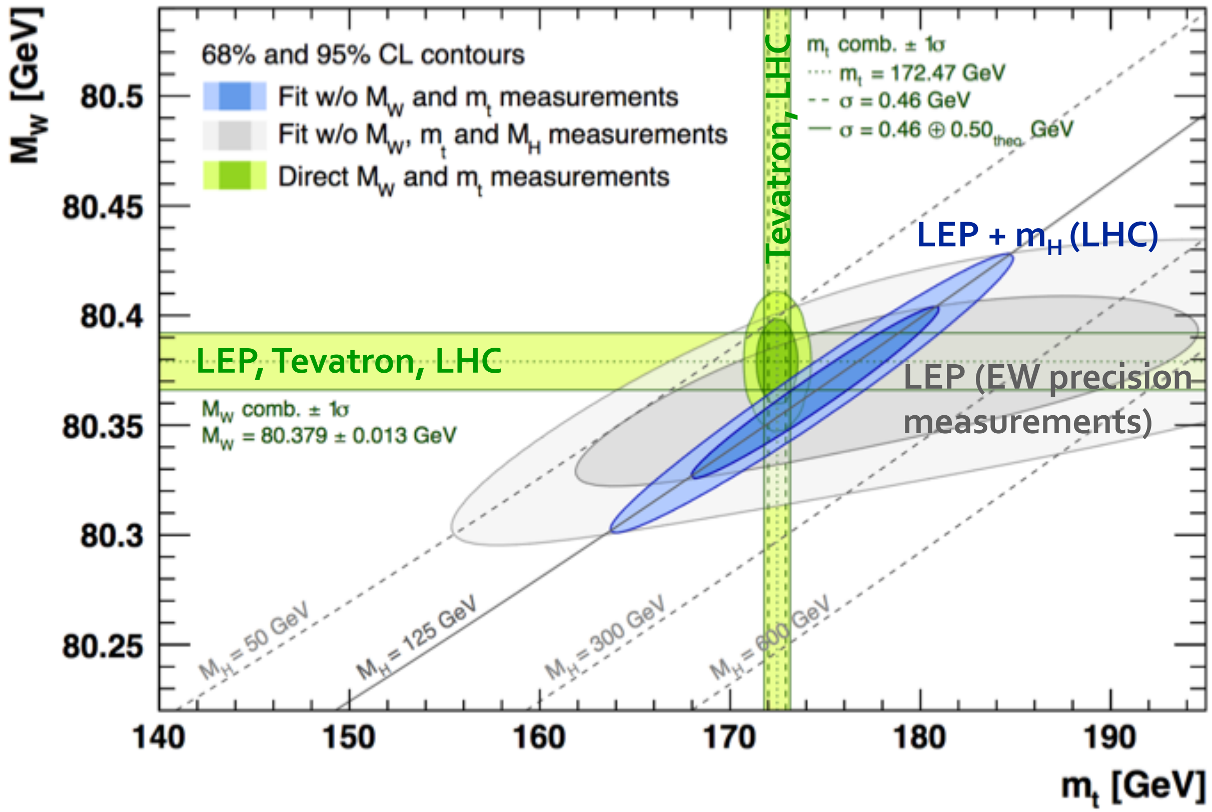
$\alpha_s(m_Z)$ ($\times 10^4$)	From R_l	1196 **± 30**	**0.1**	**0.4−1.6**	ditto
R_b ($\times 10^6$)	Rati		**0.3**	**< 60**	$g \rightarrow bb$
N_ν ($\times 10^3$)	Peak hadronic cross section	2991 **± 7**	**0.005**	**< 1**	Lumi meast
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	From $A_{FB}^{\mu\mu}$ at Z peak	231480 **± 160**	**3**	**2−5**	Beam energy calib
$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	From $A_{FB}^{\mu\mu}$ off-peak	128952 **± 14**	**4**	**small**	QED corr.
$A_{FB}^{pol,\tau}$ (10^4)	τ polarization charge assym	1498 **± 49**	**0.15**	**< 2**	τ decay physics
m_W (MeV)	WW threshold scan	80385000 **± 15000**	**600**	**300**	Beam energy calib
N_ν	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, \ell\ell$	2.92 **± 0.05**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$ ($\times 10^4$)	From R_ℓ^W	1170 **± 420**	**3**	**small**	Lepton acceptance
m_{top} (MeV)	tt threshold scan	172740 **± 500**	**20**	**small**	QCD corr
Γ_{top} (MeV)	tt threshold scan	1410**± 190**	**40**	**small**	QCD corr
$\lambda_{top} / \lambda_{top}^{SM}$	tt threshold scan	1.2 **± 0.3**	**0.08**	**small**	QCD corr

Excellent flavour tagging:
- 15 mm beam pipe radius

Electroweak precison measurements – Current status

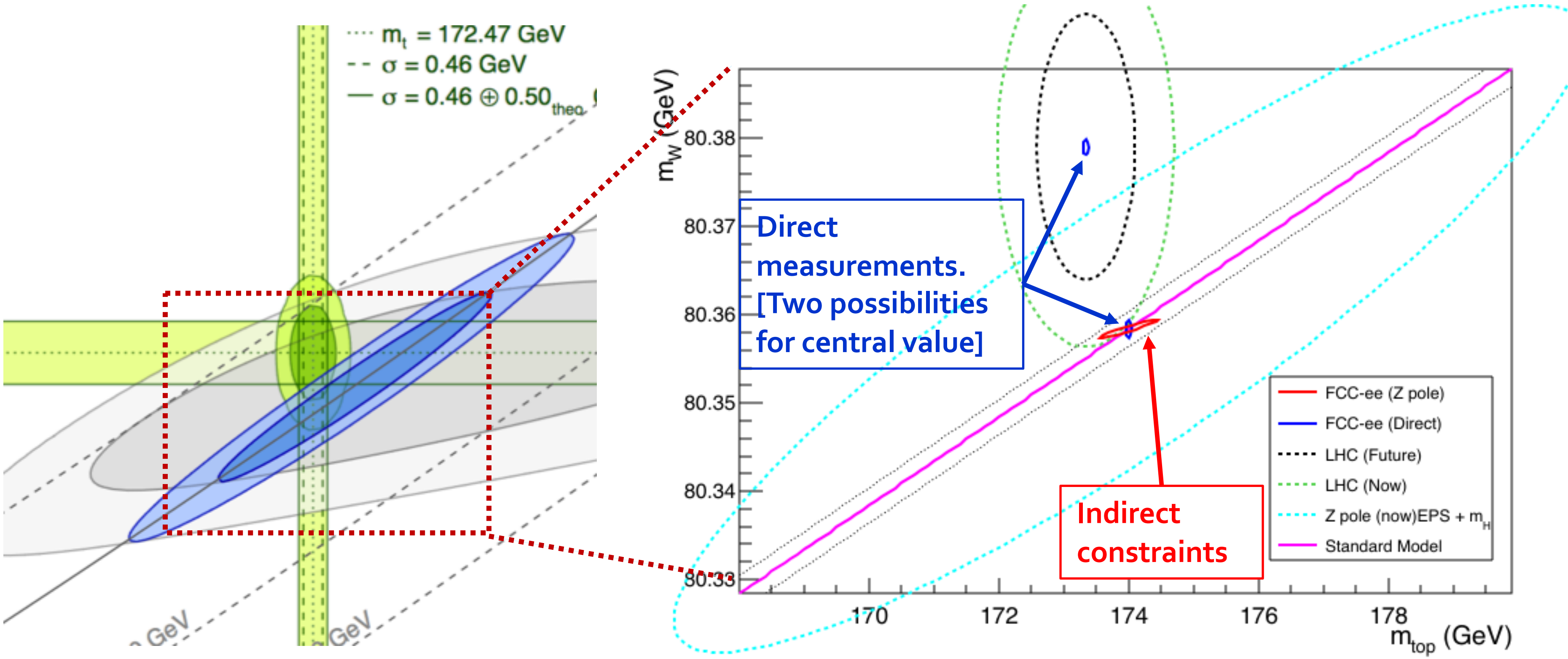
- With m_{top}, m_W and m_H known, the Standard Model has nowhere to go



- Within current precision direct and indirect constraints are consistent
  - No evidence for the need for BSM physics
- But what if measurements precisions were improved ?
  - Strong incentive to significantly improve the precision of all measurement

Electroweak precision measuremetns – post FCC-ee

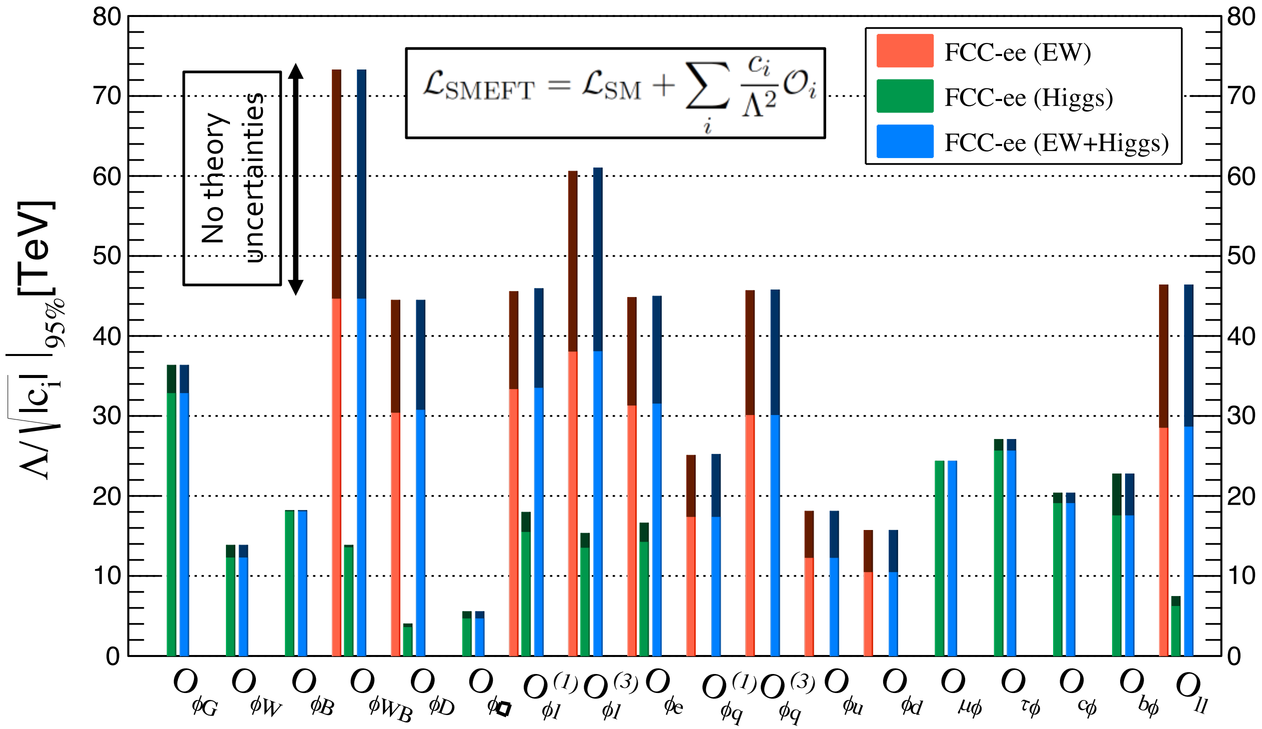
- Combination of all precision electroweak measurements
  - FCC-ee precision allows m_{top}, m_W, $\sin^2\theta_W$ to be predicted within the SM
    - … and to be compared to the direct measurements



- New Physics ?
  - Direct meast (blue ellipse) and indirect constraints (red ellipse) may or may not overlap

Precision ⇔ Discovery ?

- Combining precision Higgs and EW measurements in SMEFT



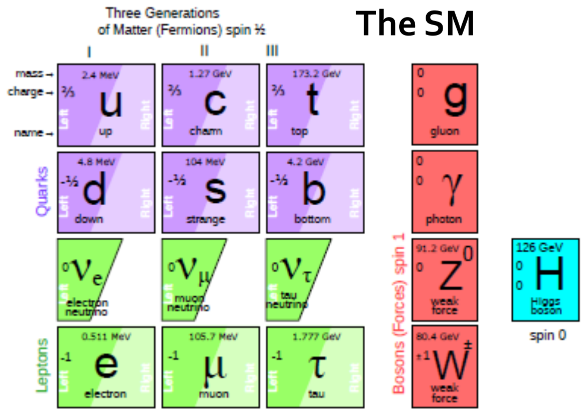
(Pattern of) deviating operators may point to the new physics to be looked for at tFCC-hh

- Higgs and EWPO measurements are rather complementary (b,c,τ PO to be added)
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
  - Sensitivity at the level of up to ~5 TeV at LEP
- Larger statistics pays off for Higgs measurements (4 IPs ?)
- *Further improvement in theory predictions pays off for EWPO measurements*

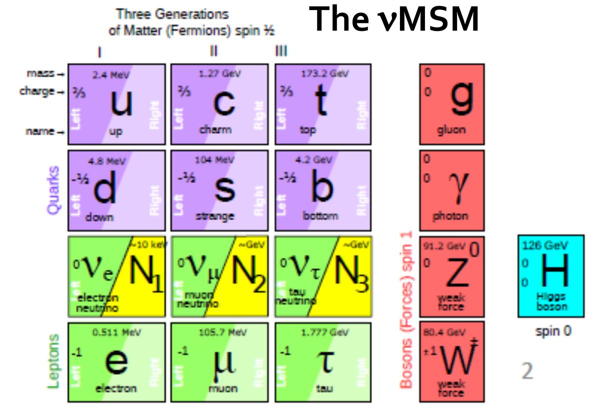
Direct discoveries – Example

- Discover right-handed neutrinos
  - νMSM : Complete particle spectrum with the missing three right-handed neutrinos

The SM

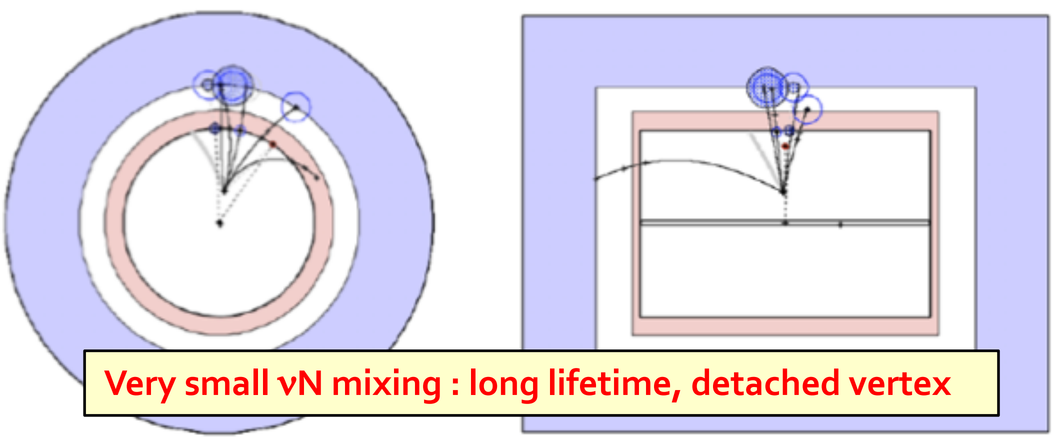


The νMSM

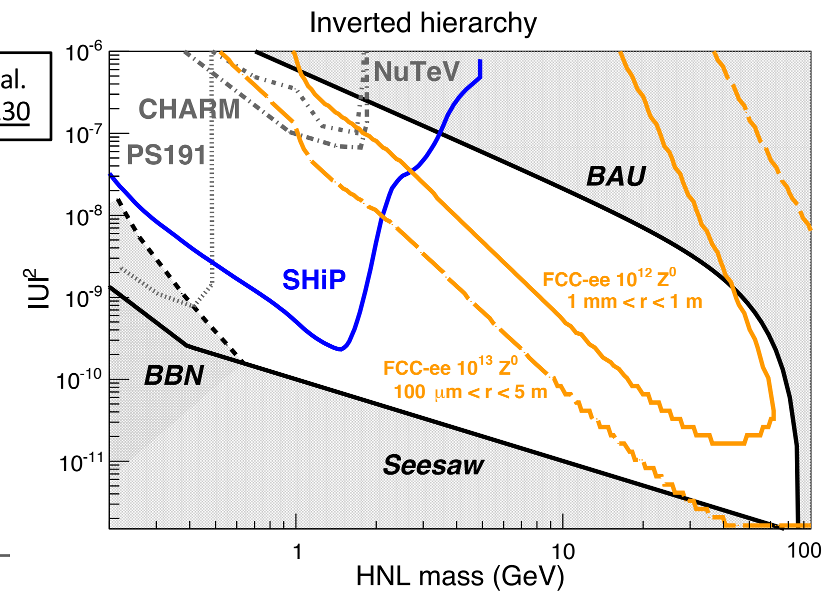


- Could explain everything: Dark matter (N_1), Baryon asymmetry, Neutrino masses
- Searched for in very rare $Z \rightarrow nN_{2,3}$ decays
  - Followed by $N_{2,3} \rightarrow W^*\ell$ or Z^*n

A. Blondel et al.
arXiv:1411.5230



Very small νN mixing : long lifetime, detached vertex

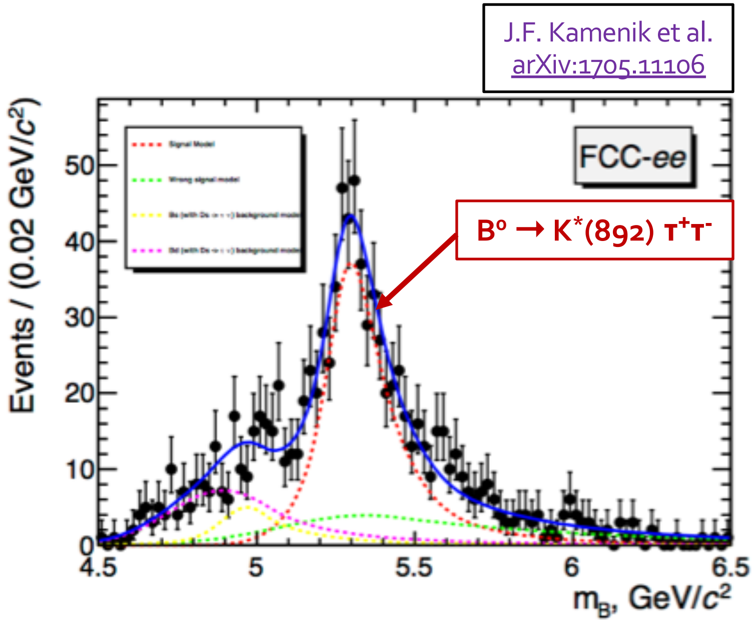


FCC-ee is also powerful Heavy Flavour Factory

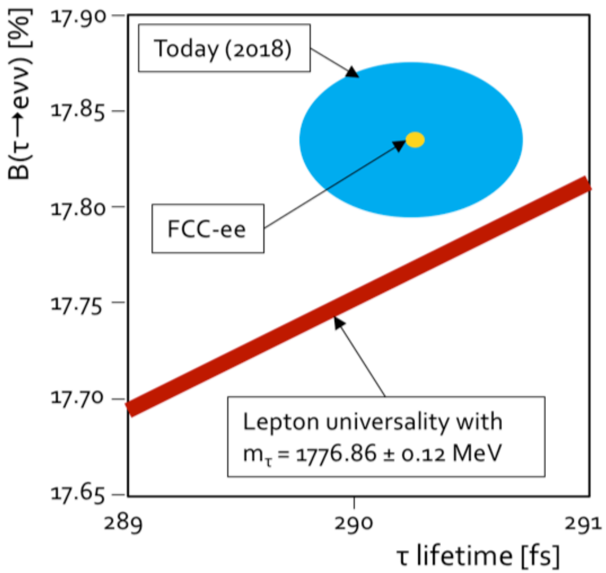
10^{12} bb events, 1.7×10^{11} $\tau^+\tau^-$ events

Examples:

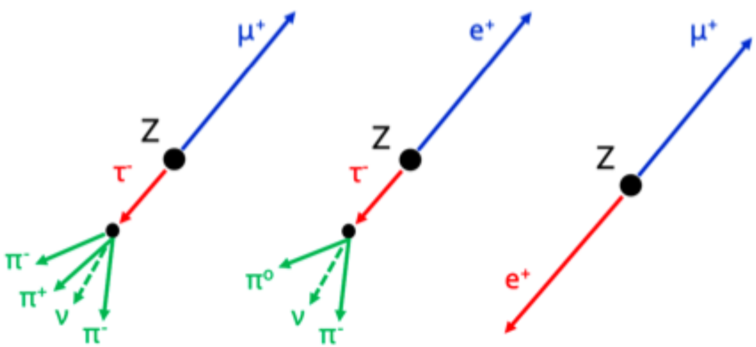
B decays and test of flavour universality



Improve lepton universality tests by > $\mathcal{O}(10)$



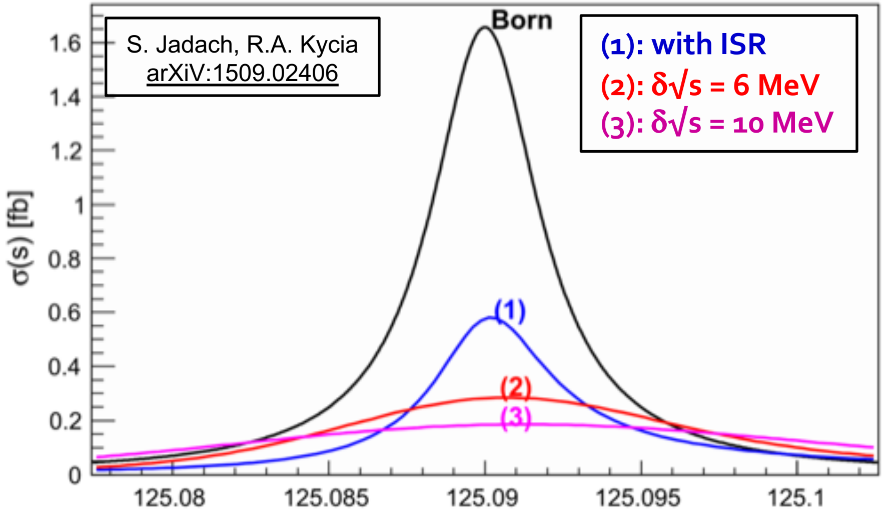
- Improve sensitivity of lepton flavour violation Z decays by **4 orders of magnitude**



$e^+e^- \to H$ possibility

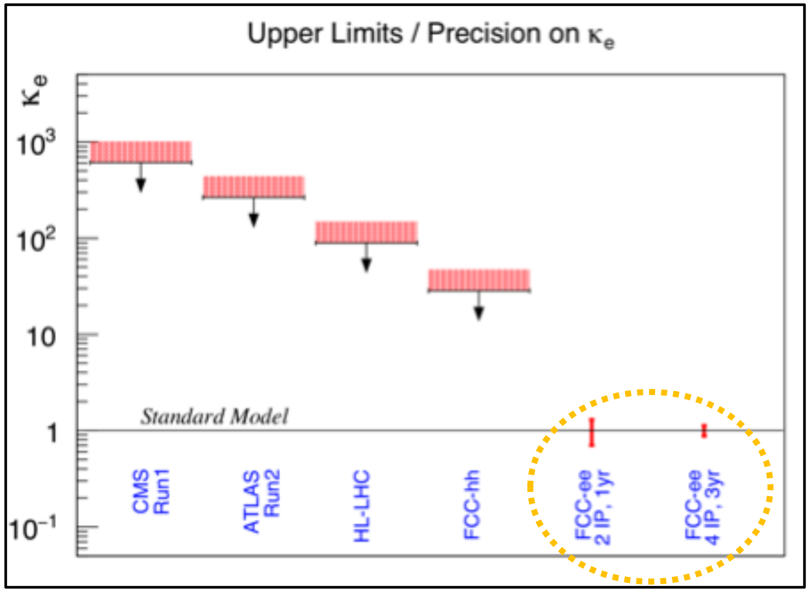
- If there is time, spend few years at $\sqrt{s}$ = 125.09 GeV with high luminosity
  - For s-channel production $e^+e^- \to H$ (a la muon collider, with 10^4 higher lumi)

D. d'Enterria
arXiV:1701.02663

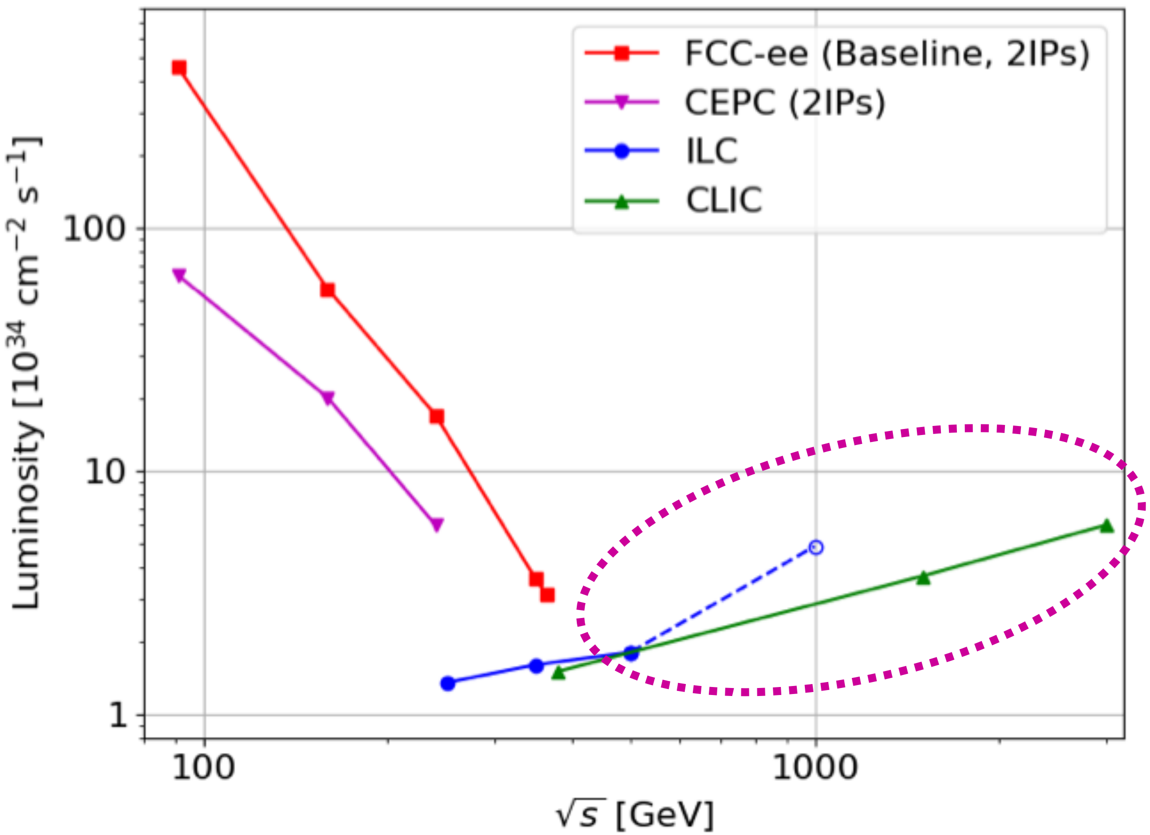


- FCC-ee **monochromatization** setups
  - Default: $\delta\sqrt{s}$ = 100 MeV, 25 ab^{-1} / year
    - No visible resonance
  - **Option 1**: $\delta\sqrt{s}$ = 10 MeV, 7 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 100$ ab
  - **Option 2**: $\delta\sqrt{s}$ = 6 MeV, 2 ab^{-1} / year
    - $\sigma(e^+e^- \to H) \sim 250$ ab

- Backgrounds much larger than signal
  - $e^+e^- \to q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$
- Expected signal significance of ~0.4σ / √year
- Unique opportunity to constrain electron Yukawa

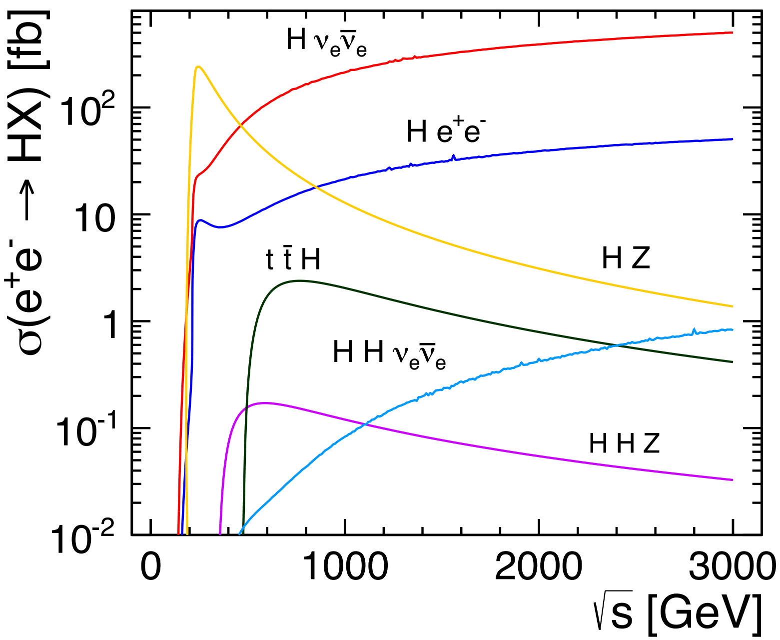


High Energy e⁺e⁻ - CLIC



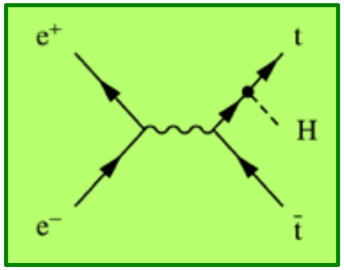
Precision: Higgs properties at high energy (1)

- Why do precision Higgs physics at high √s ?
  - Precision achieved with e^+e^- colliders at √s=240-500 GeV : 0.1% - 1%
    - Superior to what can be done at higher energy
      - σ_{HZ} decreases, kinematics less favourable, backgrounds increase, …
- However …
  - Some production processes are not directly accessible at low-energy e^+e^- colliders
    - Hence more couplings might become measurable at larger energy
      - Htt, HHH, HHHH, …



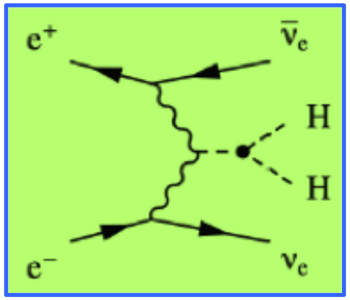
Htt

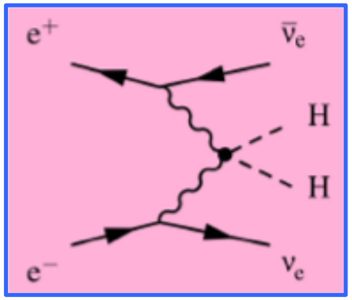
√s > 500 GeV



HHH

√s > 1 TeV





Background

Precision: Higgs properties at high energy (2)

- Achievable precisions

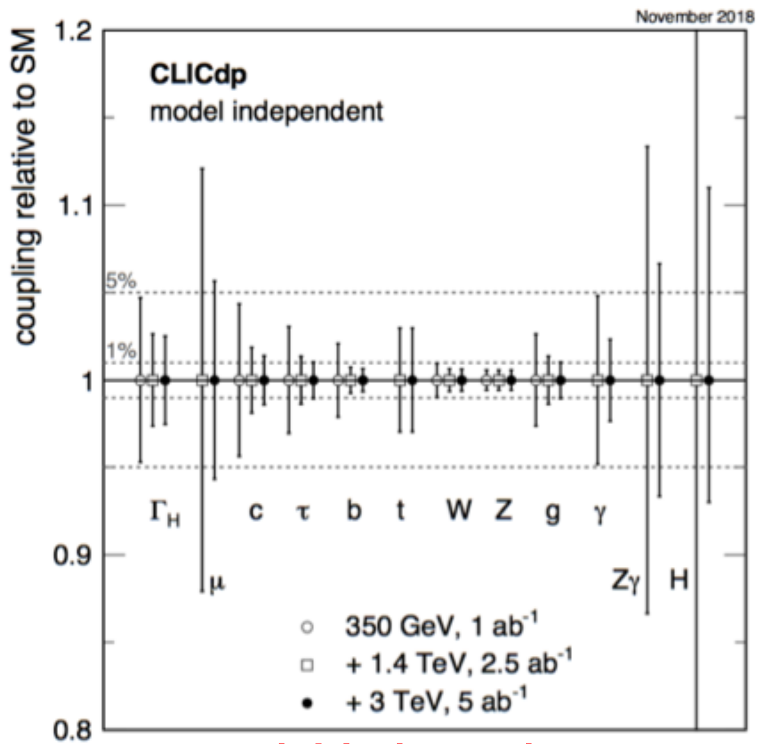
Collider	HL-LHC	$CLIC_{3000}$	FCC-ee	FCC-ee+hh
$\Delta g_{Htt}/g_{Htt}$	3%	2.6%	10% (*)	1.5%
$\Delta g_{HHH}/g_{HHH}$	50%	$^{+11}_{-7}$ %	19%	5%

(*) indirect

- Combined CLIC Higgs results
  - 380 GeV; 1.5 TeV, 3.0 TeV

Full CLIC program, ~27 yrs of running in total

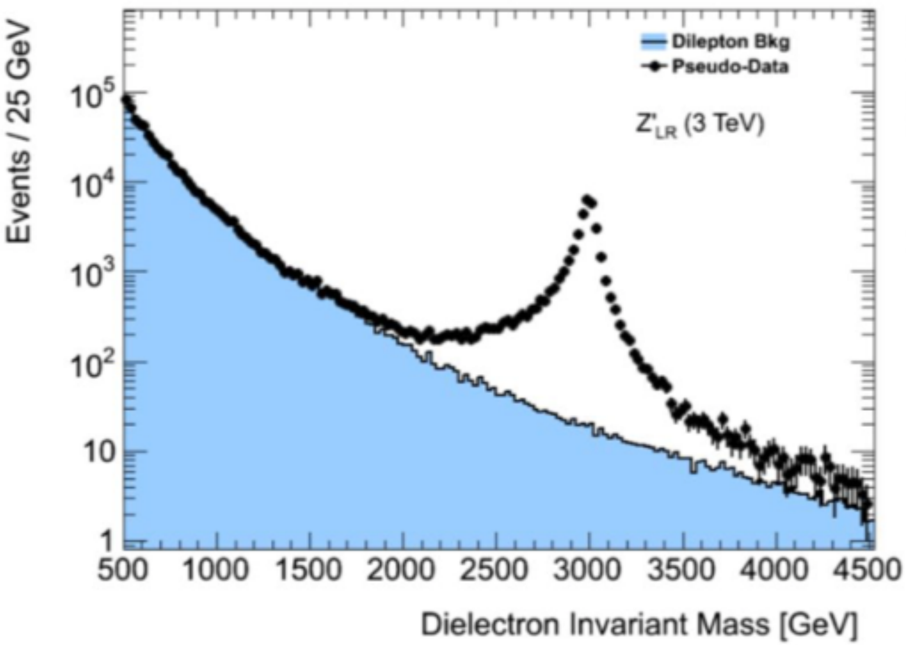
- **Large gain from CLIC380 to full programme**
- **Precision of $\mathcal{O}(1\%)$ for most couplings**
- **Accuracy on Higgs width: ±1.6%**



Model-independent

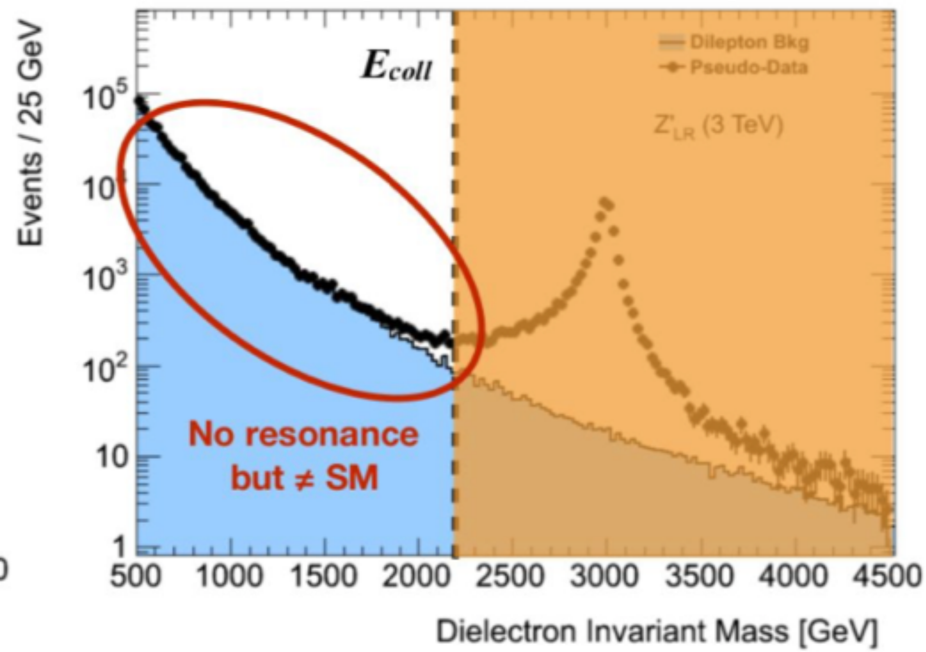
High-mass searches: peak vs. mass tails

Example: Z′ at 3 TeV



- Seeing the "peak". Mass reach:
  - mass < √s for lepton colliders
  - mass ≲ 0.3–0.5 √s at hadron for couplings ~ weak couplings

accelerator only goes to √s = 2.2 TeV



- **Deviations in high-mass tails:**
  - **Very well suited for lepton colliders; sentitive to [mass/couplings] ≫ √s**

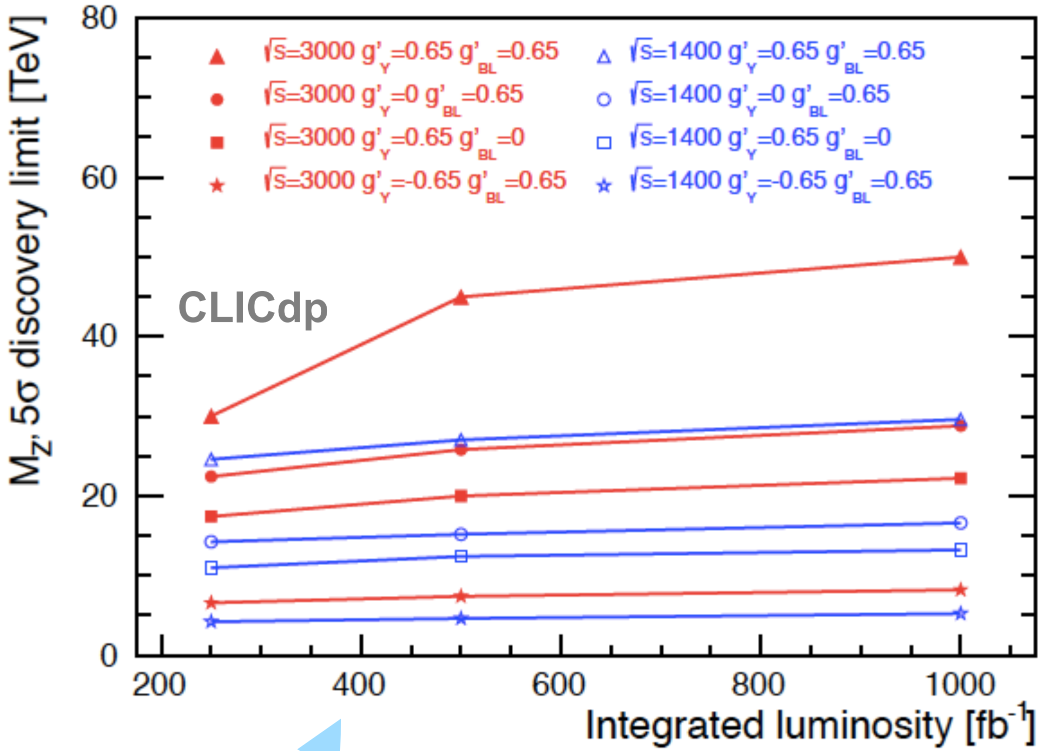
BSM example: Z' sensitivity

Minimal anomaly-free Z' model

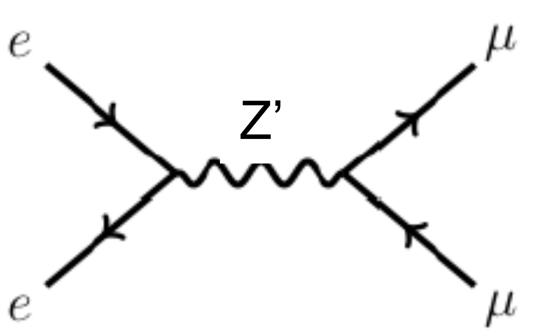
$$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$$

Observables:
- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry

(with ±80% e^- polarisation)



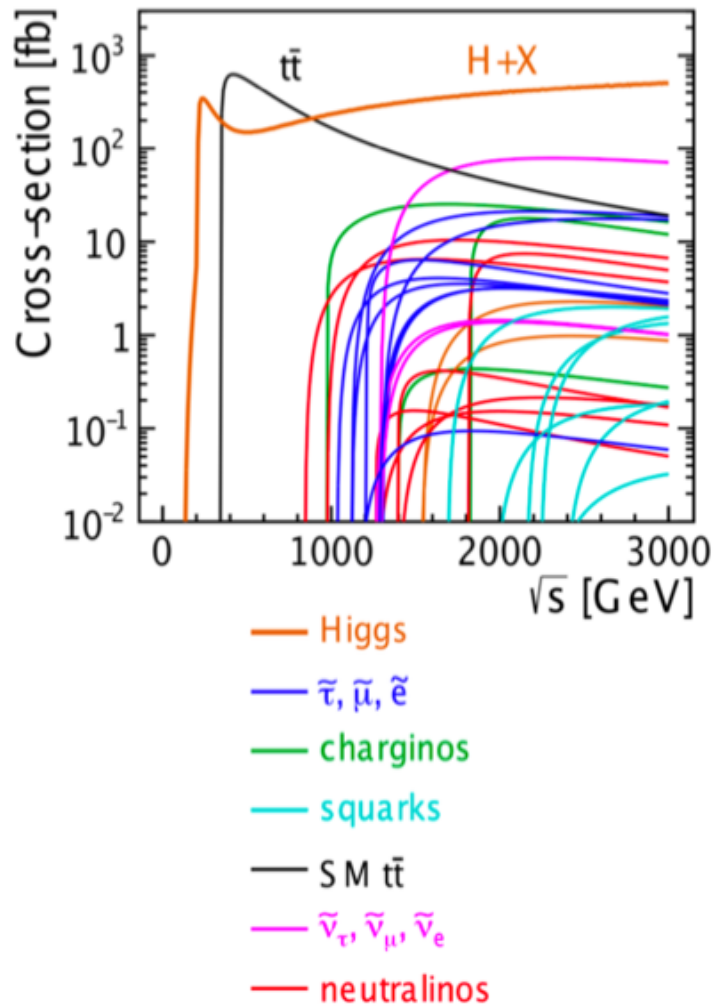
- If LHC discovers Z' (e.g. for $M_{Z'}$ = 5 TeV)
  - CLIC precision measurement of effective couplings
- Otherwise:
  - CLIC discovery reach up to tens of TeV (depending on the couplings)



Direct BSM sensitivity – Example SUSY

- Unique opportunity to directly probe new particles with masses up to 1.5 TeV
- Direct observation of particles coupling to $\gamma^*/Z/W$
  - precision measurement, $\mathcal{O}(1\%)$, of new particle masses and couplings
- Wider capability than only SUSY: reconstructed particles can be interpreted as "states of given mass, spin and quantum numbers"
- Very rare processes accessible due to low backgrounds
  - CLIC especially suited for electroweak states
- Polarised electron beam and threshold scans may be useful to constrain the underlying theory

"model III"
- smuons, selectrons, staus, gauginos



CLIC Global Sensitivity to BSM Effects

Standard Model

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

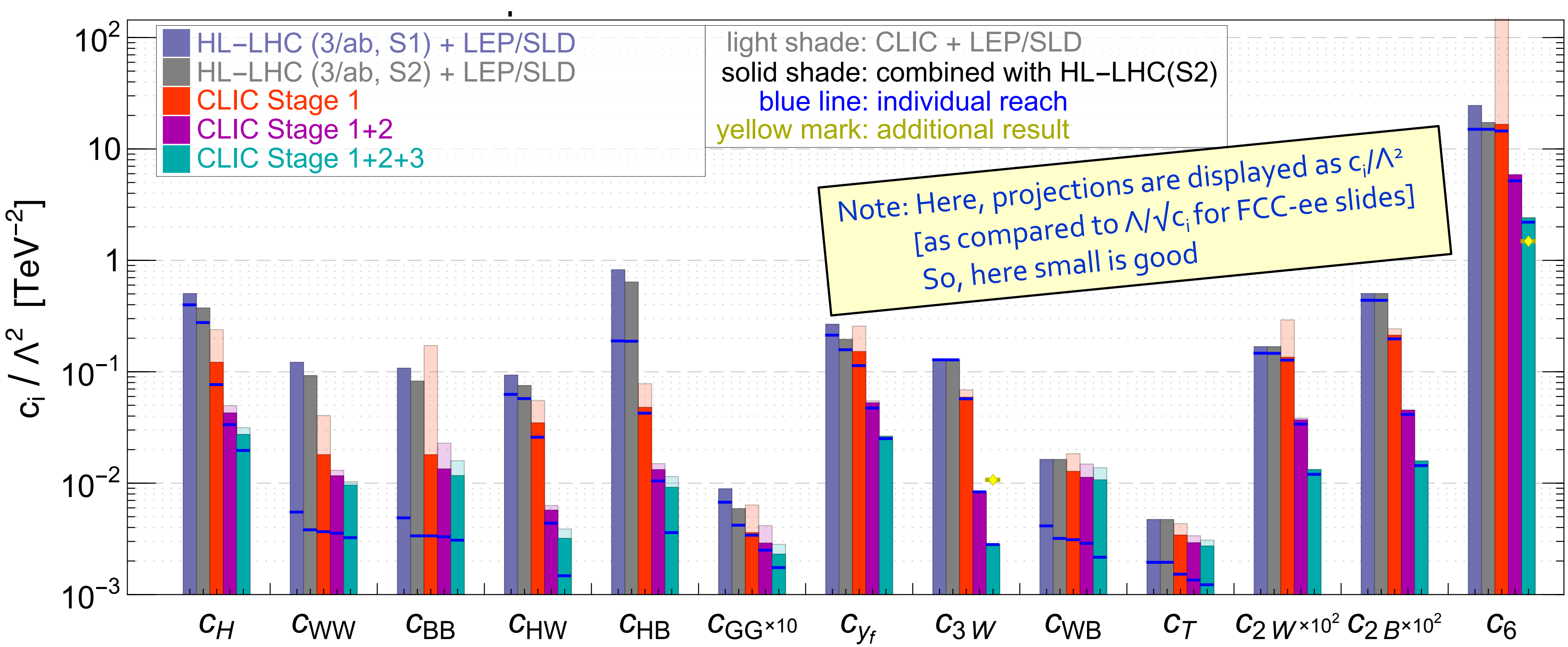
Scale of new decoupled physics

Dimension-6 operators

Universal EFT fit

Includes CLIC measurements of:
- Higgs
- Top
- WW
- $e^+e^- \rightarrow f\bar{f}$

Strong benefits from high-energy running



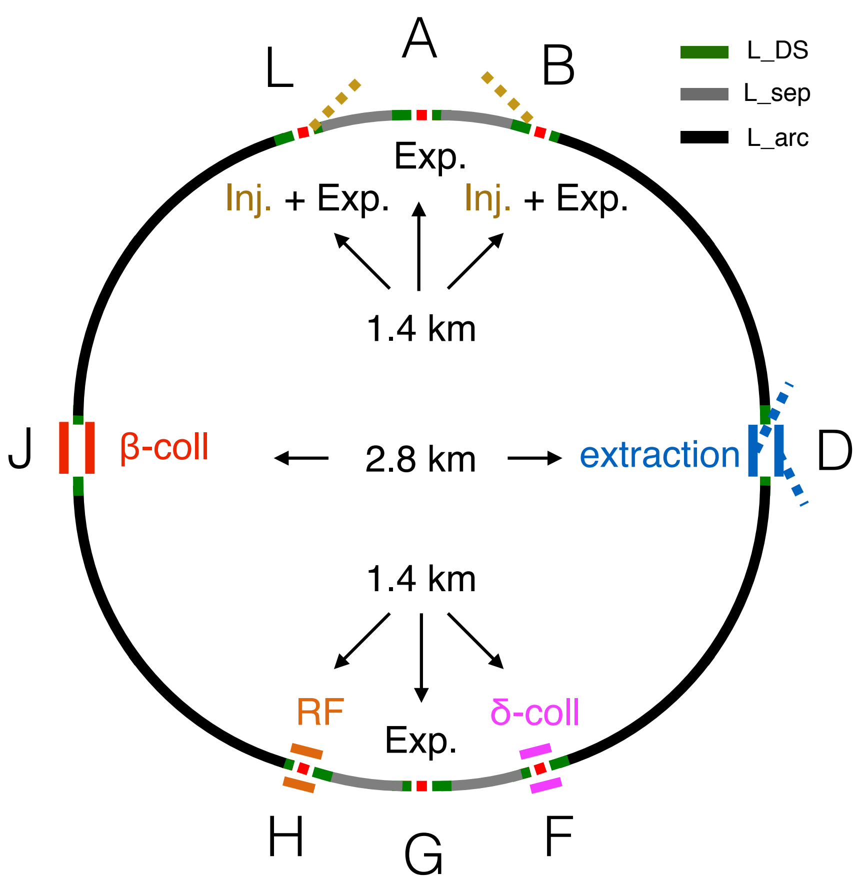
Circular / linear e^+e^- collider complementarity

Table 3: Summary of complementary qualities of the proposed circular and linear colliders FCC-ee and ILC. Notes: [1] single-parameter sensitivity, full program; [2] multi-parameter sensitivity up to 365/500 GeV; LFUV: Lepton Flavour Universality Violation; LNV: Lepton Number Violation.

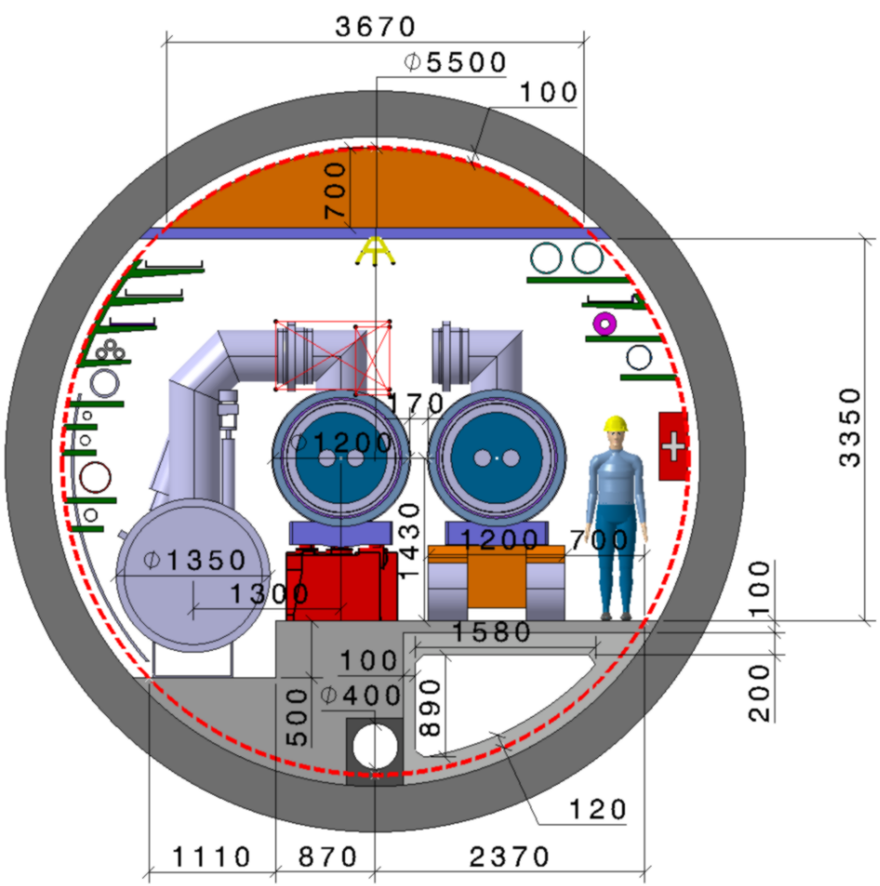
Quality	FCC-ee	ILC
Energy Range (GeV)	88 to 240, up 365	(91) 240 up 500, 1000
Interaction points	2–4	1
Luminosity Main statistics Z WW HZ $t\bar{t}$ and above	$\propto E_{\mathrm{beam}}^{-3.5} \times$ Radius $\times$ Power $\times$ #IP 5.10^{12} Z 3.10^{8} WW 10^{6} H 10^{6} $t\bar{t}$ at 365 GeV	$\propto E_{\mathrm{beam}} \times$ Power 5.10^{9} Z 10^{7} WW 4.10^{5} H 3.10^{6} $t\bar{t}$ at 500 GeV
Beam Polarisation For Beam Energies Use	Transverse $e^+$and e^- up to WW threshold $\sqrt{s}$ ppm calibration	Longitudinal $e^-(\pm 80\%)$, $e^+(\pm 30\%)$ all energies helicity cross-sections
Monochromatisation Use	$\sigma_{\sqrt{s}} = 4 - 10$ MeV s-channel H production	no
Higgs Physics Hee Coupling HHH Coupling: from $\sigma(e^+e^- \to ZH)$ from HH production	 SM $(m_e) \pm$ 15-50% $\pm 14^1 - 33^2\%$ –	 – $\pm 25^1 - 38^2\%$ $\pm$ 27% (500 GeV), $\pm$ 10% (1 TeV)
Electroweak	m_Z, Γ_Z, m_W (100, 25, 600 keV) $\sin^2\theta_W^{\mathrm{eff}}(3.10^{-6})$ $\Delta\alpha_{\mathrm{QED}}(3.10^{-5})$ LFUV g_A (10^{-5}), g_V (10^{-5}) EFT operators up to 70 TeV	High-energy polarised Cross sections and asymmetries for leptons, quarks and bosons contact interactions up to 100 TeV
Flavour Physics	$e/\mu/\tau$ LNV 10^{-10} LFUV $< 10^{-5}$ b and c hadrons properties rare decays and CPV	
QCD	30-365 GeV jet systems hadronisation α_s in Z,W,τ (10^{-4})	240-1000 GeV jet systems hadronisation
New particle search	in Z decays: Feebly coupled particles RH neutrinos, ALPs etc.	up to 500 GeV pair production searches in gaps left by hadron collider

Blondel, Janot, arXiv:1912.11871

FCC-hh

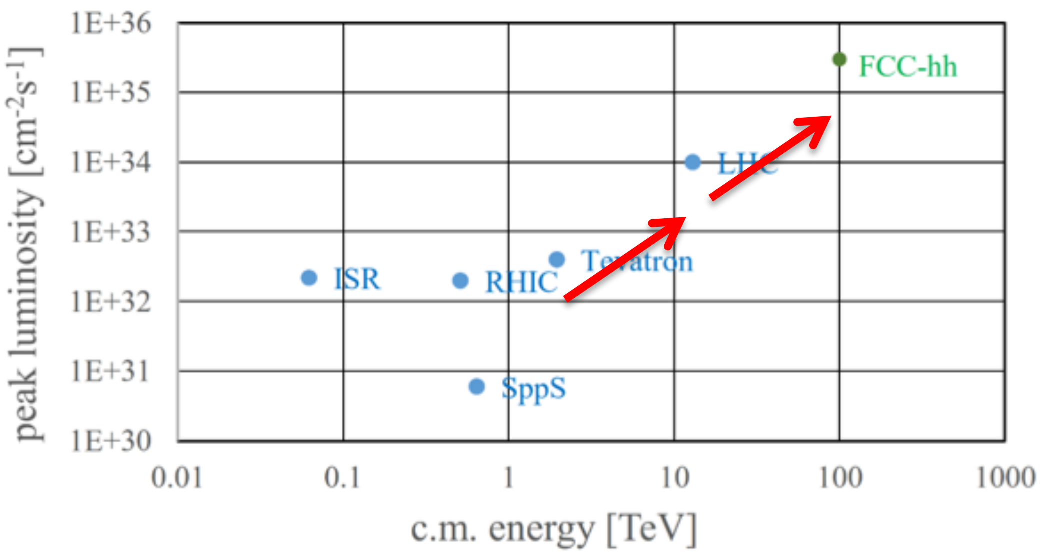


A
L
B
L_DS
L_sep
L_arc
Exp.
Inj. + Exp.
Inj. + Exp.
1.4 km
J
β-coll
2.8 km
extraction
D
1.4 km
RF
δ-coll
Exp.
H
G
F



3670
Φ5500
100
700
3350
170
Φ1200
1430
1200
700
Φ1350
1300
1580
100
Φ400
500
890
100
200
120
1110
870
2370

FCC-hh Performance

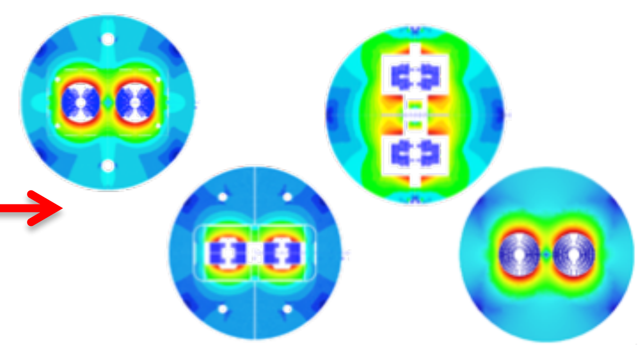


- Aim at **~one order of magnitude performance increase** in both **energy and luminosity w.r.t LHC**
- **100+ TeV cm collision energy**
  - vs 14 TeV for LHC
- **20 ab^{-1} per experiment collected over 25 years** of operation
  - vs 3 ab^{-1} for LHC.
- Similar performance increase as from Tevatron to LHC.
- **Key technology: High-field magnets**

From LHC technology
8.3 T NbTi

via HL-LHC technology
11 T Nb_3Sn

to 16 T Nb_3Sn
EuroCirCol, Chart, US MDP



FCC-hh: Higgs Production

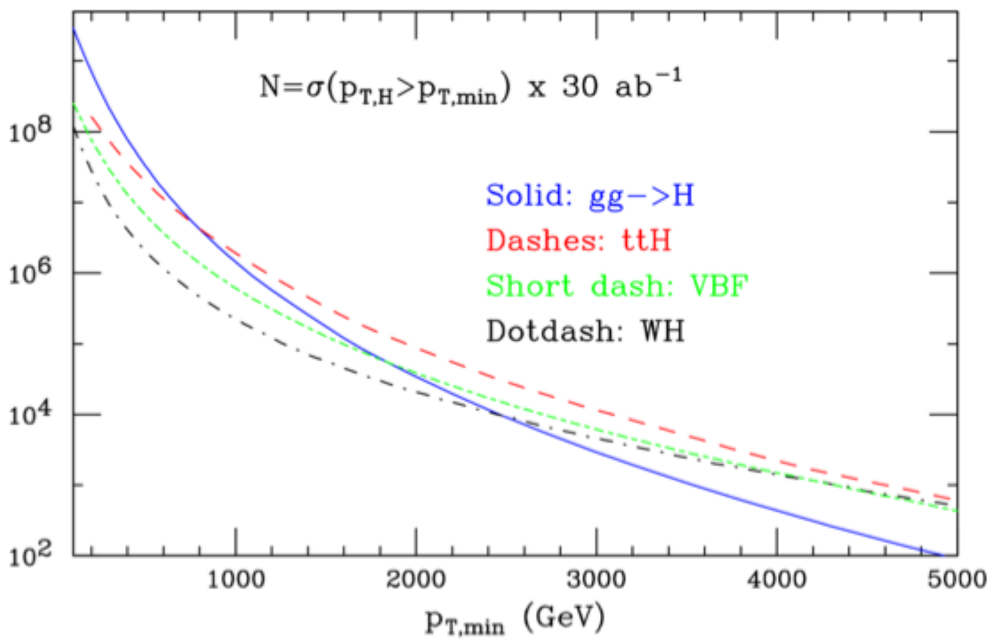
Huge production rates

	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24 x 10^9	2.1 x 10^9	4.6 x 10^8	3.3 x 10^8	9.6 x 10^8	3.6 x 10^7
N_{100}/N_{14}	180	170	100	110	530	390

FCC-hh 100 TeV
30 ab^{-1}

LHC 14 TeV
3 ab^{-1}

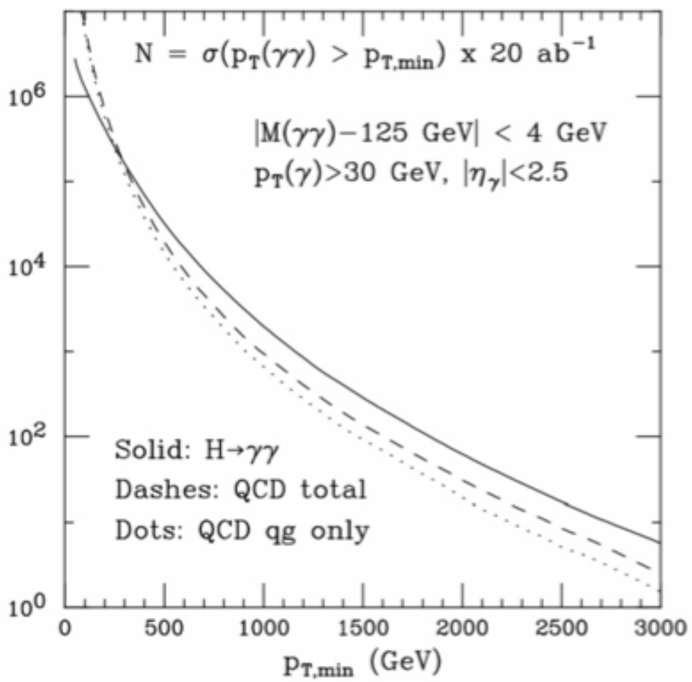
Large p_T

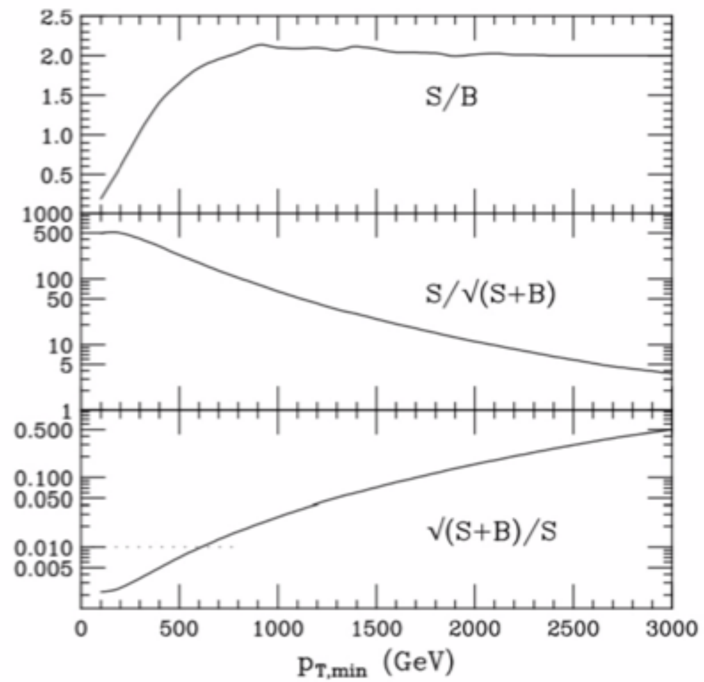


Production hierarchy of channels changes at large p_T

FCC-hh: Clean Higgs Samples at high p_T

Example: $gg \rightarrow H \rightarrow \gamma\gamma$ at large p_T





$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

- At LHC, S/B in $H \rightarrow \gamma\gamma$ channel is $\mathcal{O}$(few %)
- At FCC, for $p_T > 300$ GeV, S/B ~ 1
- Potentially accurate probe of H p_T spectrum up to large p_T

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**6.5**
BR_{exo} (95%CL)	BR_{inv} < 2.5%	**< 1%**	**BR_{inv} < 0.025%**

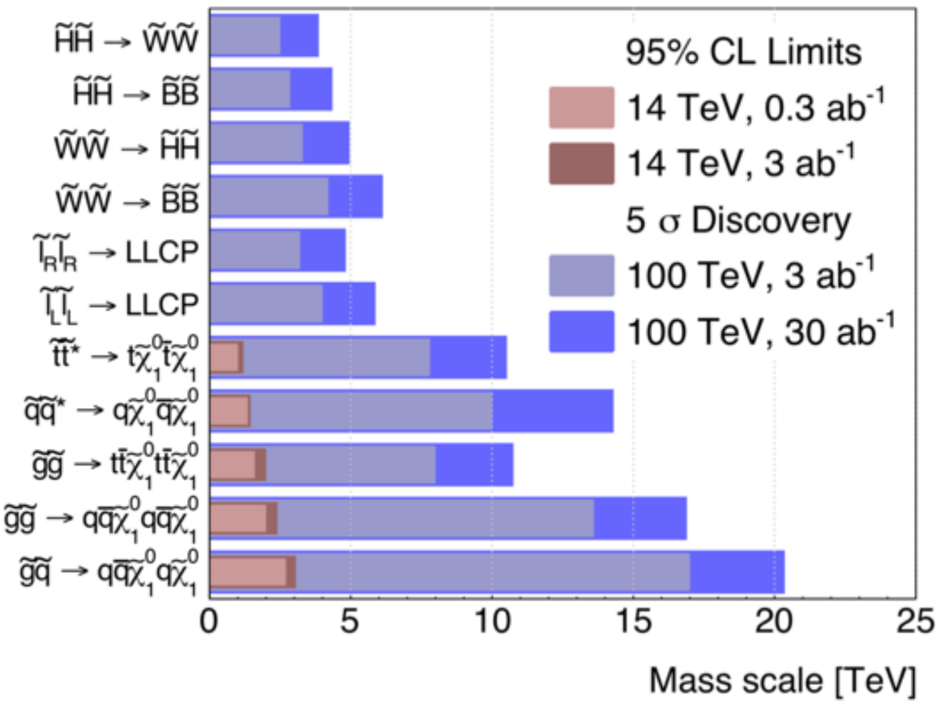
* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

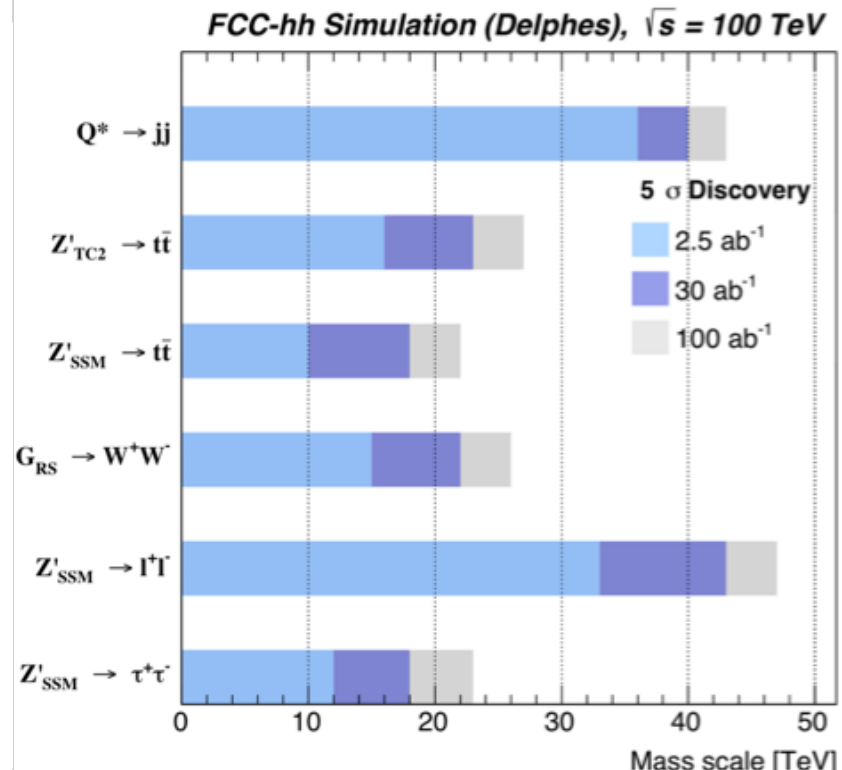
Absolute coupling measurements facilitated by width measurement from FCC-ee

FCC-hh Examples of New Physics Reach

SUSY



s-channel resonances



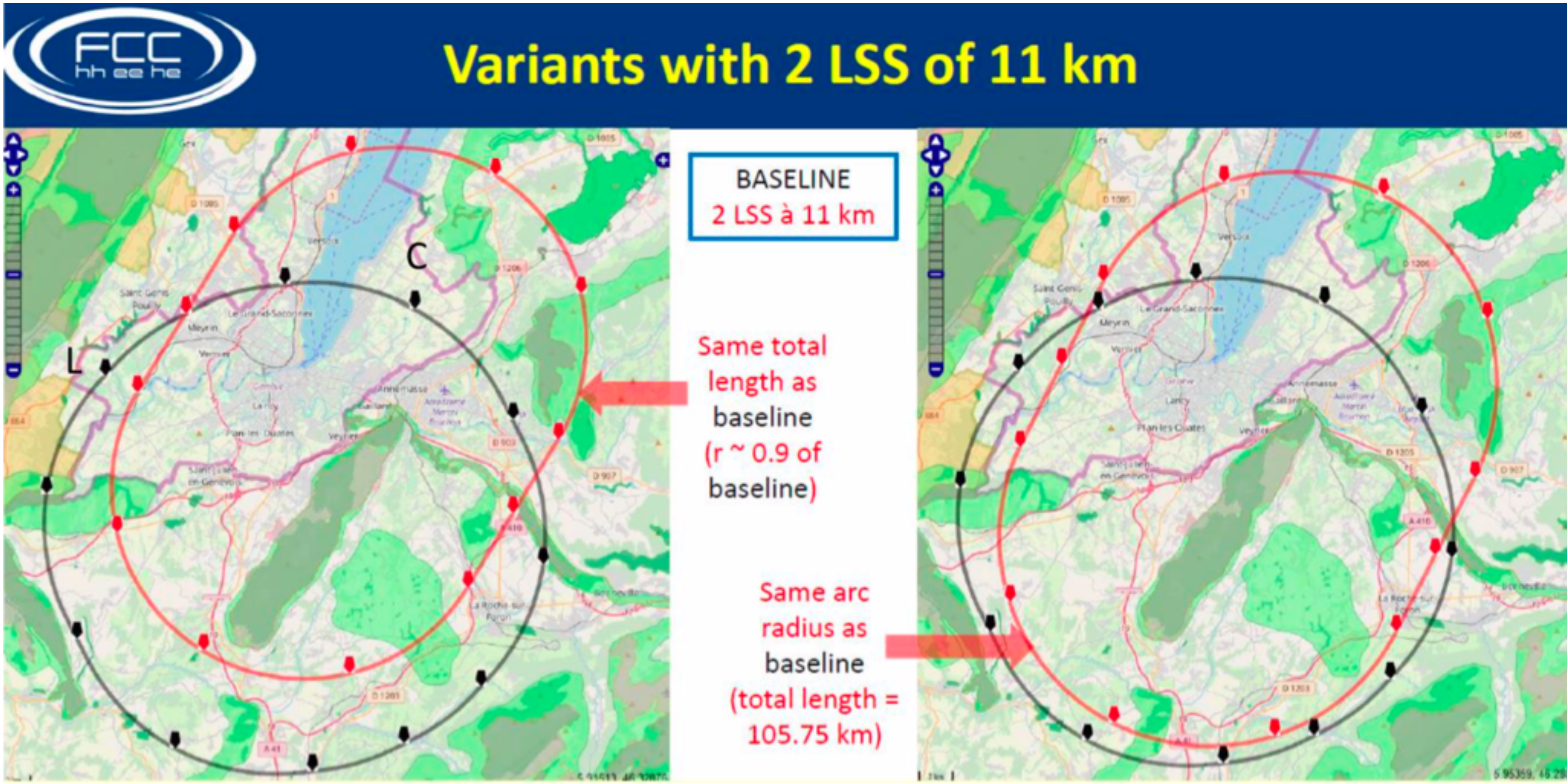
~ 6 × HL-LHC reach

Scenarios

	2020-2040		2040-2060	2060-2080
			1st gen technology	2nd gen technology
CLIC-all	HL-LHC		**CLIC380-1500**	CLIC3000 / other tech
CLIC-FCC	HL-LHC		**CLIC380**	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC		**FCC-ee (90-365)**	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC		**LE-FCC-h/e/A (low-field magnets)**	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC	**+ LHeC**	**LHeC**	FCC-h/e/A (Adv HF magnets) / other tech

CLIC 380 then FCC-hh (i)

5 years | 11 km tunnel | CLIC: 380 GeV 1.5 ab^{-1} | **?** | 100km tunnel | FCC hh: 100 TeV 20-30 ab^{-1}



CLIC-380 in (one of) 11 km straight sections

CLIC-380 then FCC-hh (ii)

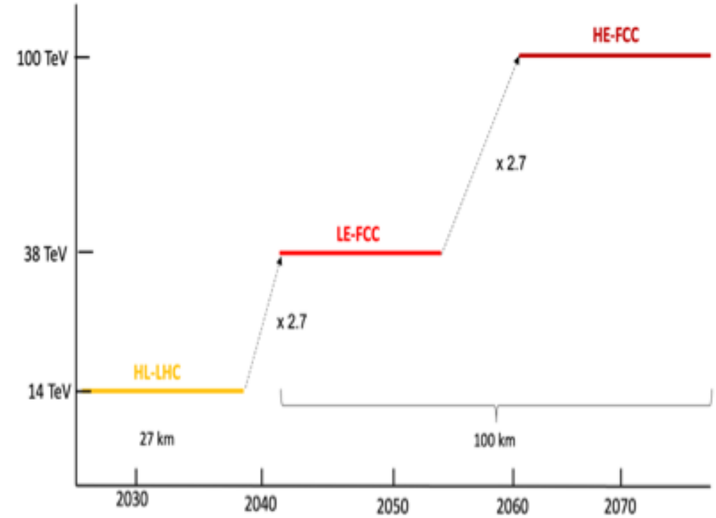
- CLIC serves only ONE experiment
- CLIC-380 Higgs + top physics programme similar to FCC-ee-365
- Overall Higgs measurements less precise than FCC-ee
  - Only 160,000 Higgs boson (vs 1.3×10^6)
  - m_H precision ~80 MeV (vs. 6 MeV)
  - Γ_H precision ~2.6% (vs. 0.19%)
- Possible CLIC GigaZ option
  - Lack of precision of EW measurements (stats, poor E_{beam} determination)
  - $\lll 5 \times 10^{12}$ Z
    - no ALPs, no RH νs, no flavour physics, ...
  - No ee → H possibility

CLIC-all

- ONE experiment only
- Higgs programme short of statistics compared to FCC-hh
  - Higgs rare decays, invisible decays, g_{HHH}, …
- Possible CLIC GigaZ option
  - Lack of precision of EW measurements (stats, poor E_{beam} determination)
  - ⋘ 5×10^{12} Z
    - no ALPs, no RH νs, no flavour physics, …
- Limited high energy exploration
- Cost (~FCC-hh) and efforts will likely preclude Europe from pursuing future hadron collider physics

LE-FCC / HE-FCC

- Not complementary nor synergetic with FCC-hh
  - Brings no additional measurement wrt FCC-hh
  - Weakens the physics case of FCC-hh
    - Reduces the CM energy increment
  - No more guidance from FCC-ee
- Reduces CERN attractiveness (only pp physics)
- More expensive than FCC-INT



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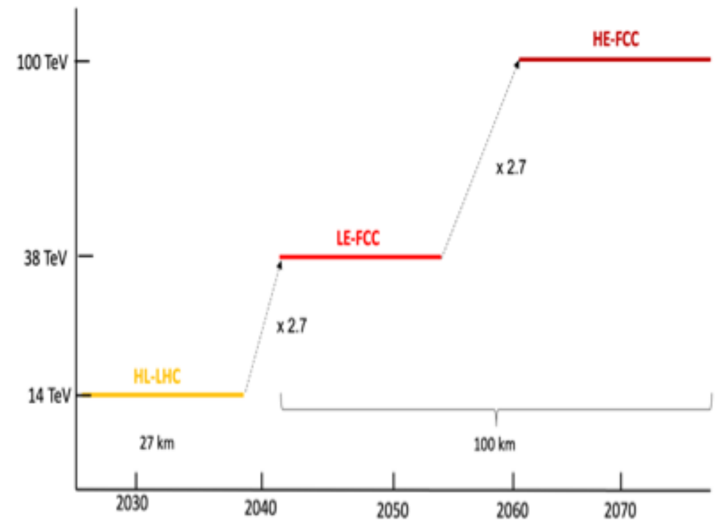
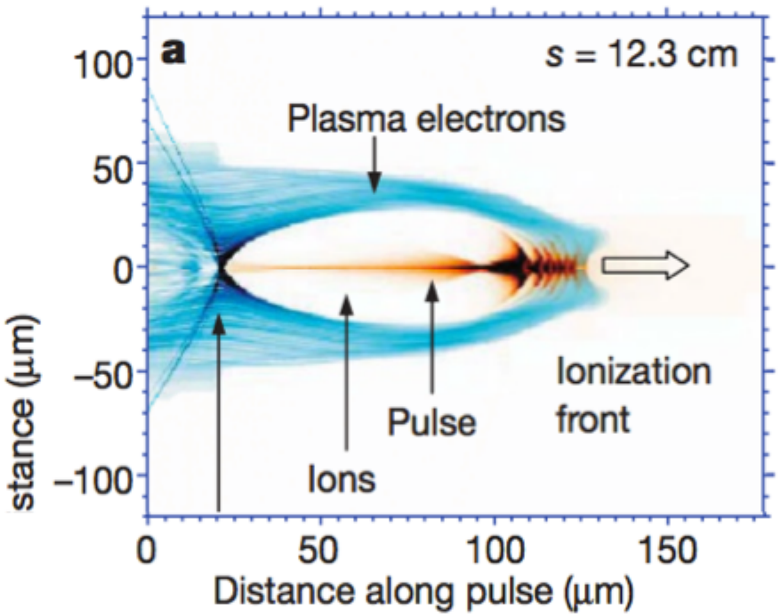


FCC International Advisory Committee, Oct. 2019:

"The available cost estimate [of the LE-FCC option] is still high, especially in the view of the limited physics reach. In a staging scenario, it is not attractive to replace the FCC-ee option by a low energy proton version"

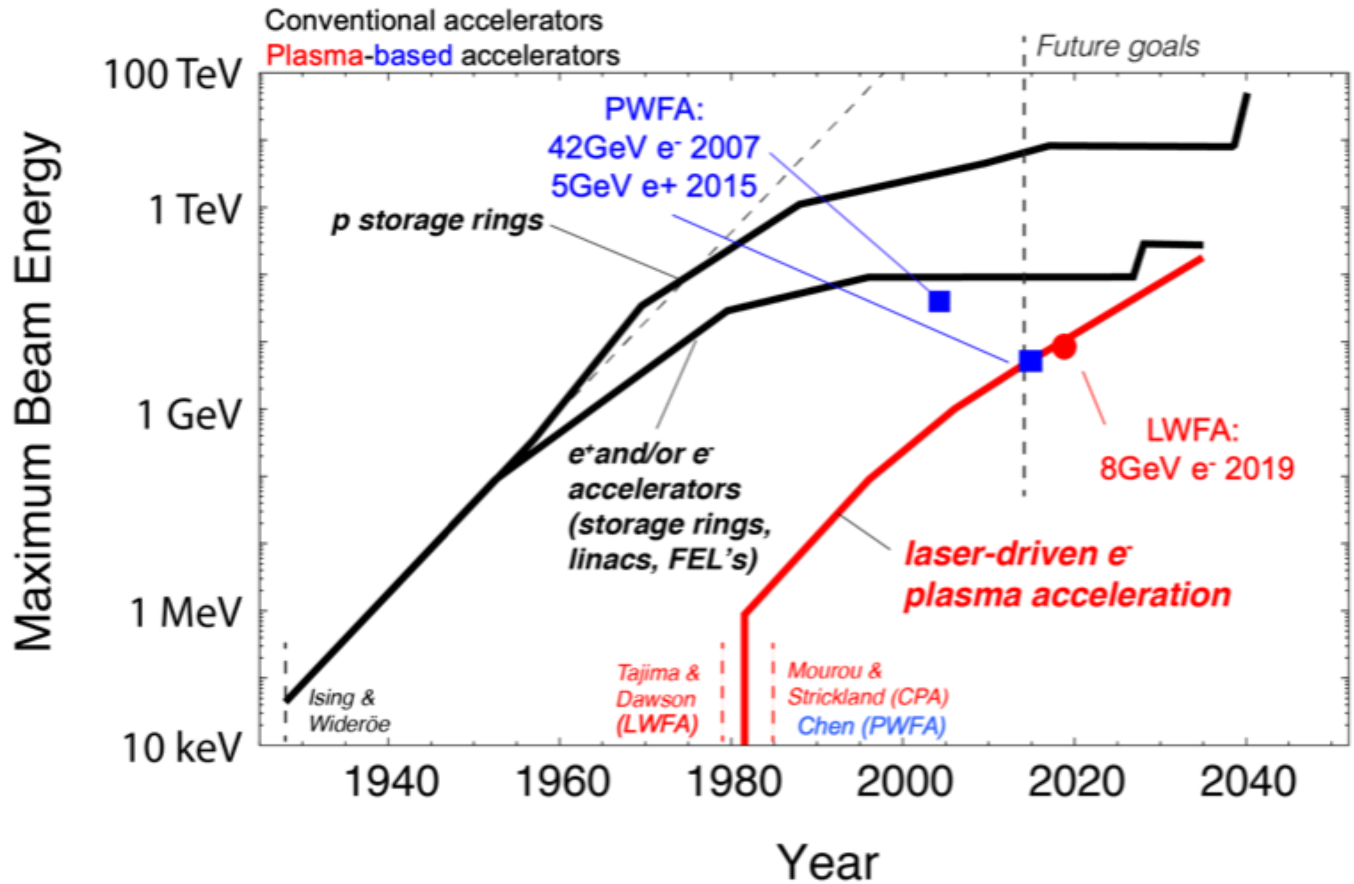
Next Generation Colliders



PLASMA-BASED ACCELERATOR (PBA) YOUNG FIELD

P. Muggli,
105th ECFA Plenary
Nov. 15, 2019

- Livingston plot



- Energy plotted, not beam quality/luminosity

Towards PWFA-based colliders ?

J. Osterhoff,
105th ECFA Plenary
Nov. 15, 2019

Colliders pose ultimate challenge

Ballpark requirements illustrate complexity of the task

	Current	FEL	Collider
Charge (nC)	0.1	0.1	**1**
Energy (GeV)	0.1 - 10	0.1 - 10	**1000**
Energy spread (%)	2	**0.1**	**0.1**
Emittance (µm)	0.5	0.5	**0.01**
Wall-plug efficiency (%)	<0.1	<0.1 - 1	**10**
Rep. rate (Hz)	10	10^1 - 10^6	**10^3-10^5**
Continuous run	24	24/1 - 24/7	**24/365**
Parameter stability	2%	**0.1%**	**0.1%**

gulf of collider requirements

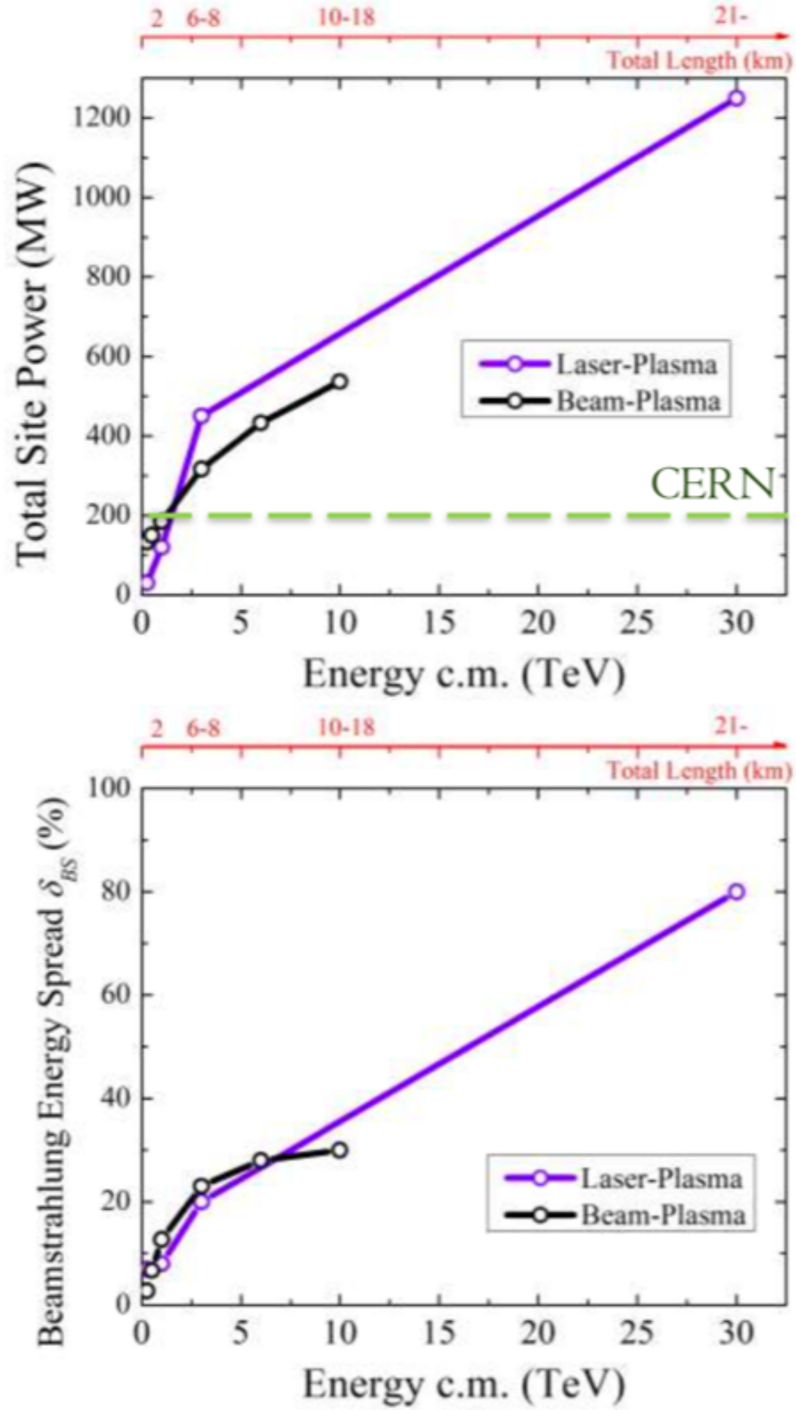
Advance near-term applications → **Develop solutions specifically for particle colliders**

Colliders require exclusive solutions and concepts

- *high energy:* staging of plasma modules
- *low emittance:* novel compact injector concepts and precision beam and plasma control
- *efficiency:* high-charge beam-loading (and energy recovery), high-efficiency laser technology
- *rep. rate and avg. power:* kW/cm thermal management, high average and peak-power laser technology
- *positron acceleration with exquisite quality*
- *beam polarization maintenance*
- *computing capabilities for optimization*

Needs a coordinated worldwide effort (and dedicated funding)

DESY. | Jens Osterhoff | Plenary ECFA Meeting, Geneva | November 14, 2019 Page 4



Input #7

arXiv:1308.1145

Plasma Colliders :

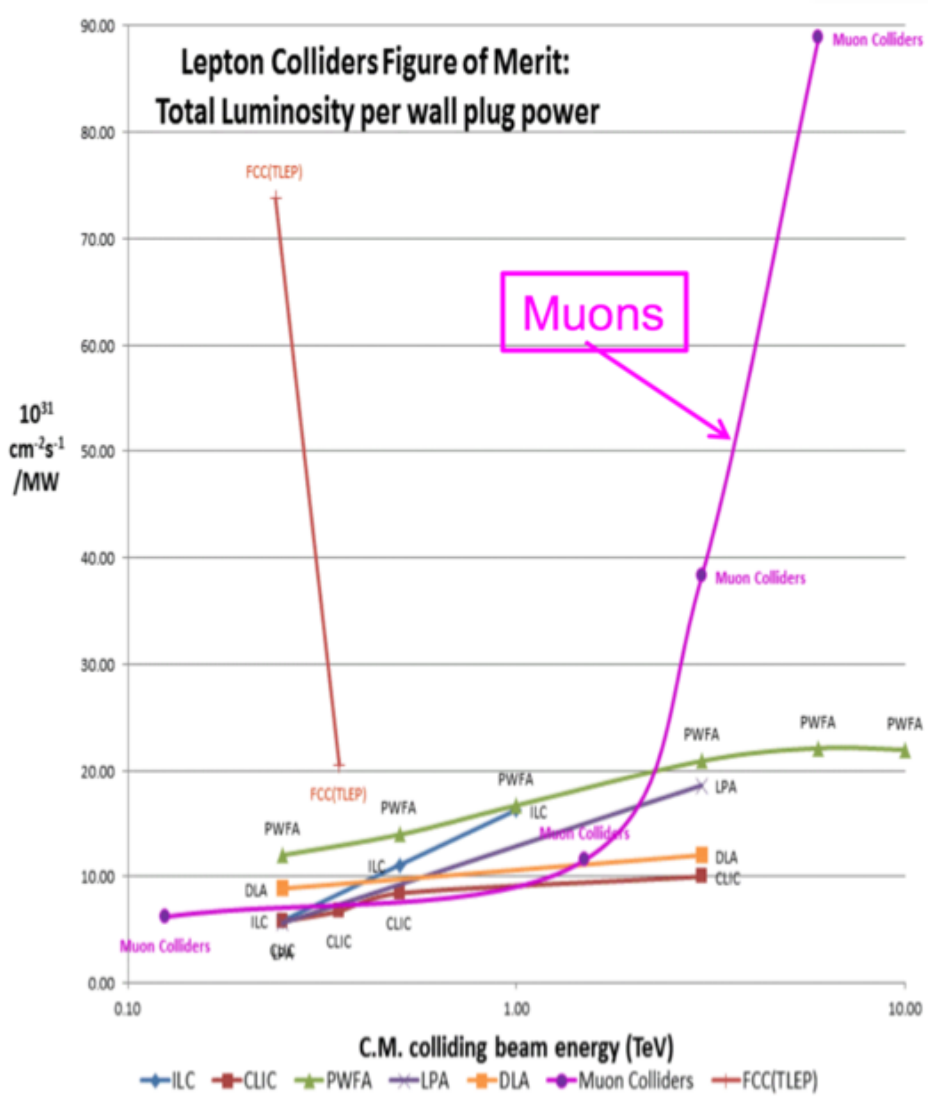
Shiltsev, EPPS Symp, Granada May. 13, '19

- **Key Issues to Study:**
  - acceleration of positron
  - Staging efficiency
  - emittance control vs scatter
  - beamstrahlung
  - HP lasers / HP operation
  - power efficiency

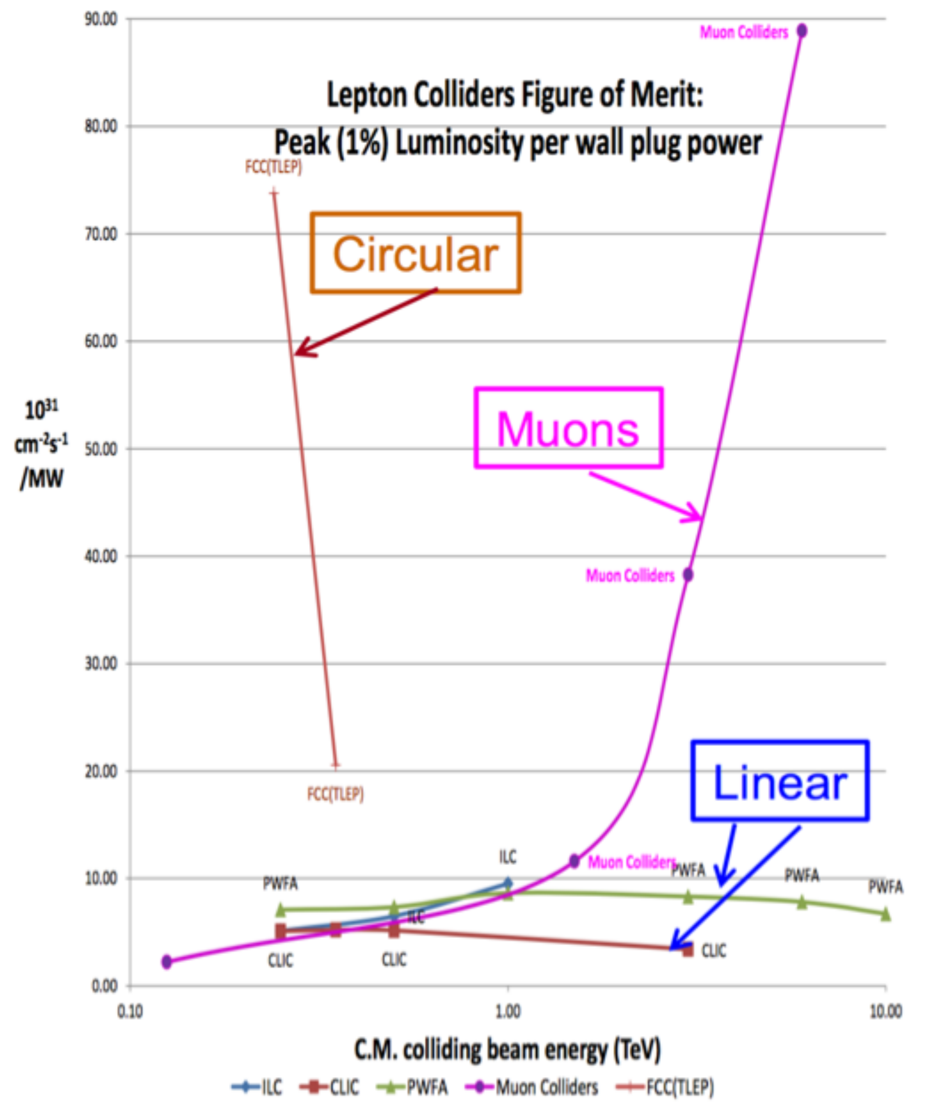
  * the first four can be addressed by using μ's in 10^{22} cm^{-3} crystals – up to 1 PeV

- **Plenty of interest and opportunities:**
  - **Collaborations:** *EuPRAXIA, ALEGRO study, ATHENA*
  - **Facilities:** *PWASC, ELBE/HZDR, AWAKE, CILEX, CLARA and SCAPA, EuPRAXIA @ SPARC_LAB at INFN-LNF, Lund, JuSPARC at FZJ and FLASHFor-ward and SINBAD at DESY; also in Japan (ImPACT), China (SECUF) and in the US (FACET-II BELLA)*
  - Advanced Acceleration Concepts **US roadmap** : **CDR by 2035**
  - Proposals of plasma *e*- injectors:
    - 100 MeV to IOTA (FNAL)
    - 700 MeV to PETRA-IV booster (DESY)

Muons, maybe ?



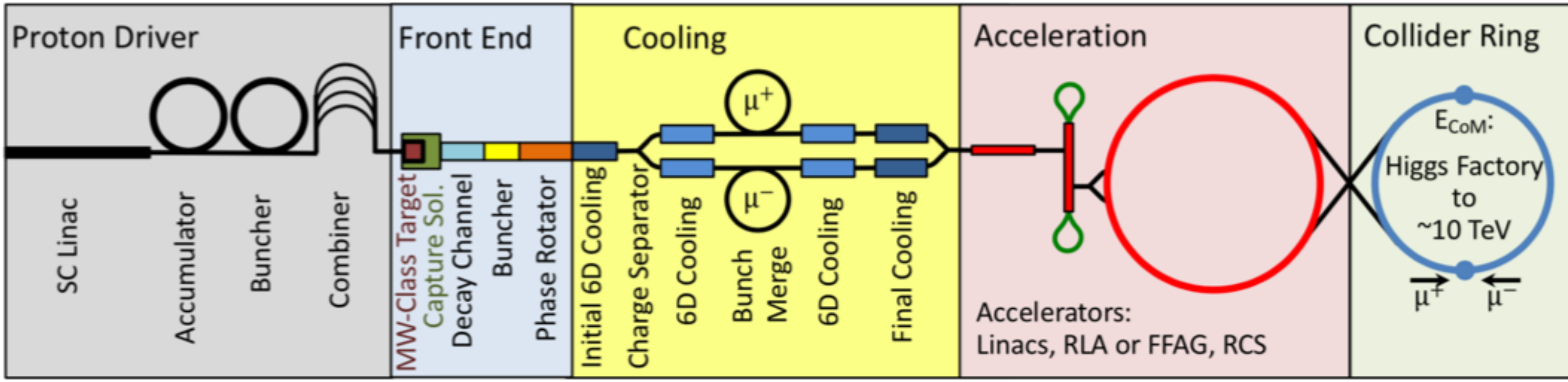
Lepton Colliders Figure of Merit:
Total Luminosity per wall plug power
Muons
Muon Colliders
FCC(TLEP)
PWFA
ILC
CLIC
LPA
DLA
10^{31} $cm^{-2}s^{-1}$ /MW
C.M. colliding beam energy (TeV)
ILC CLIC PWFA LPA DLA Muon Colliders FCC(TLEP)



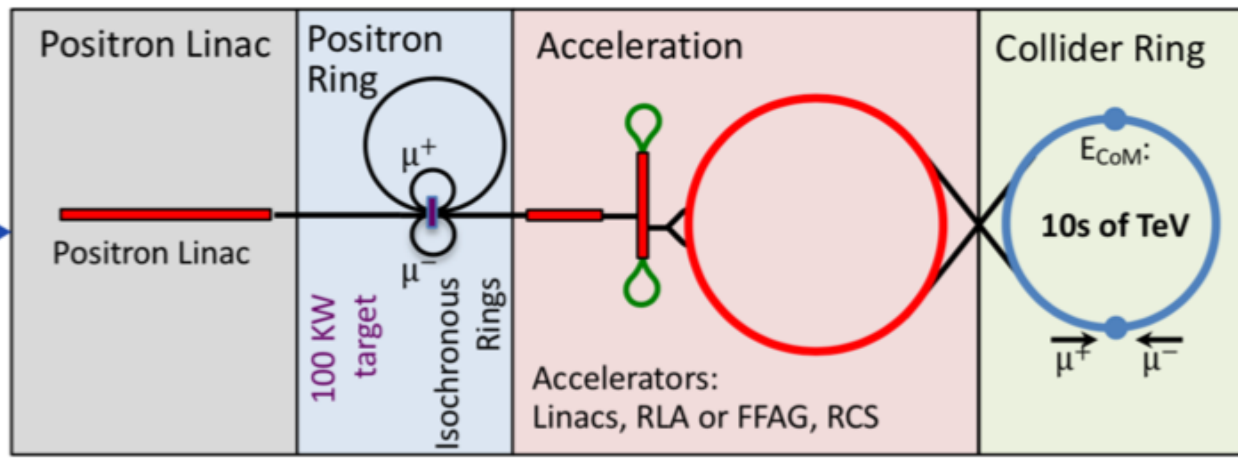
Lepton Colliders Figure of Merit:
Peak (1%) Luminosity per wall plug power
Circular
Muons
Linear
Muon Colliders
FCC(TLEP)
PWFA
ILC
CLIC
10^{31} $cm^{-2}s^{-1}$ /MW
C.M. colliding beam energy (TeV)
ILC CLIC PWFA Muon Colliders FCC(TLEP)

Muon collider options

MAP: π decays



Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



LEMMA: $e^+e^- \rightarrow \mu^+\mu^-$ at thteshold

Muon Collider Possibilities

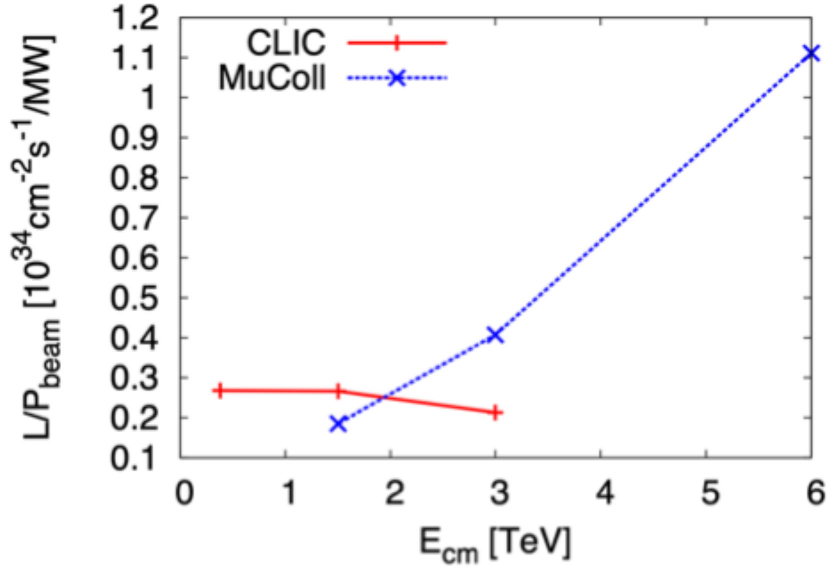
Target Parameter Examples

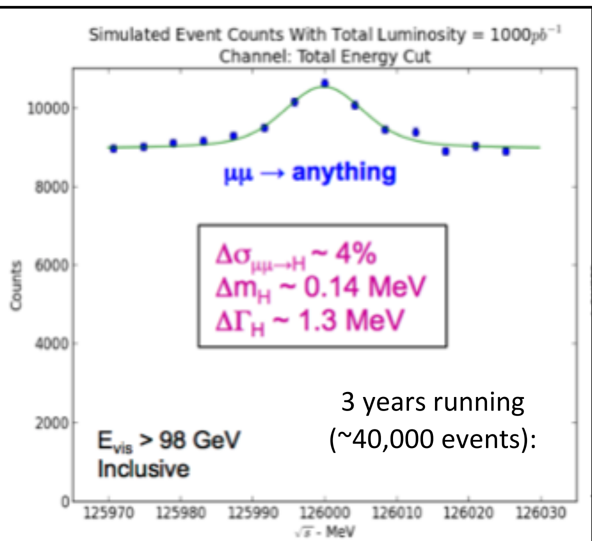
D. Schulte,
Muon Collider, ECFA, CERN, Nov. 2019

From the MAP collaboration:
Proton source (M. Palmer et al.)

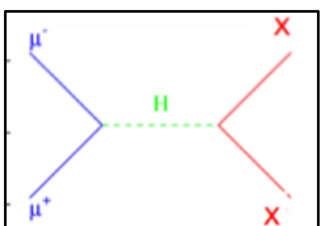
Muon Collider Parameters

Parameter	Units	Higgs: *Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270



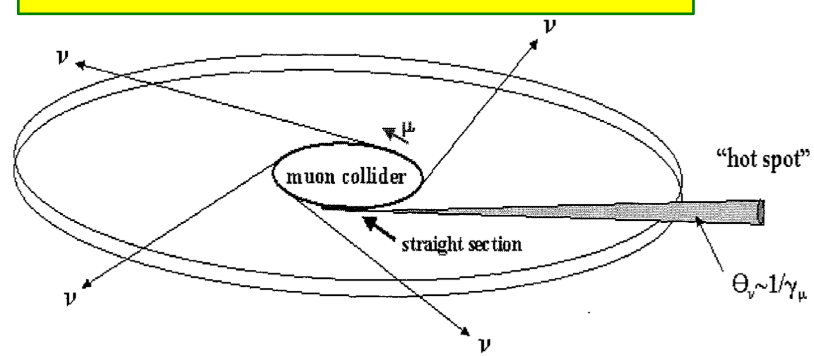


A muon collider is not (currently) a competitive Higgs factory …



… but it may be the best way to get lepton collisions at $\sqrt{s} \geq 3$ TeV

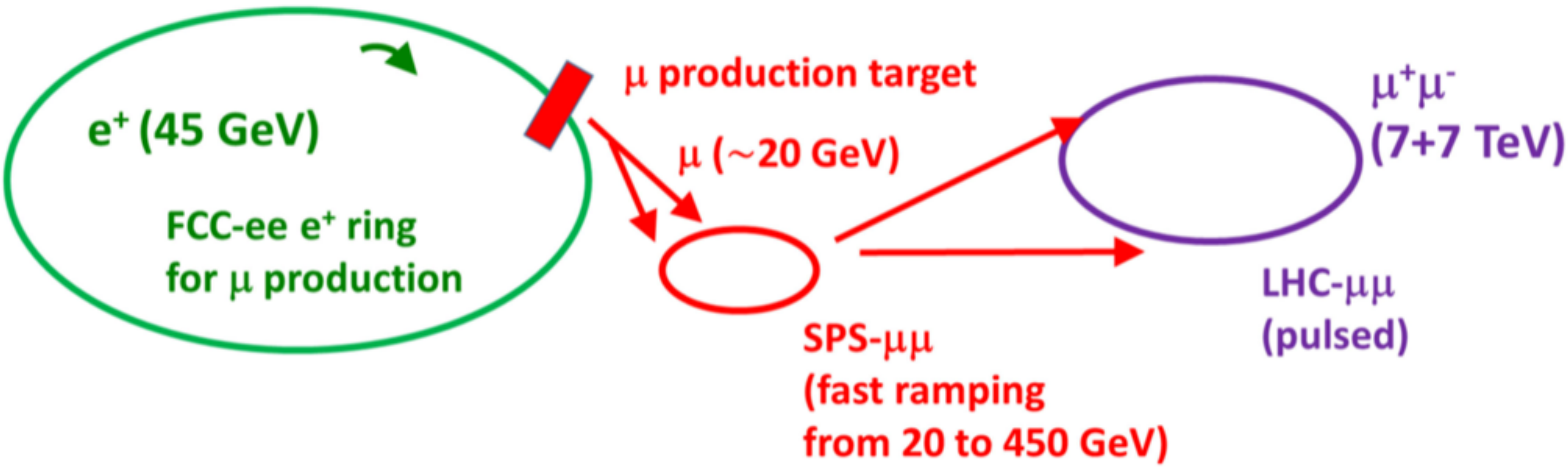
However, Neutrino Radiation Hazard



A possible (?) muon collider scenario

F.Zimmerman, arXiv:1801.03170

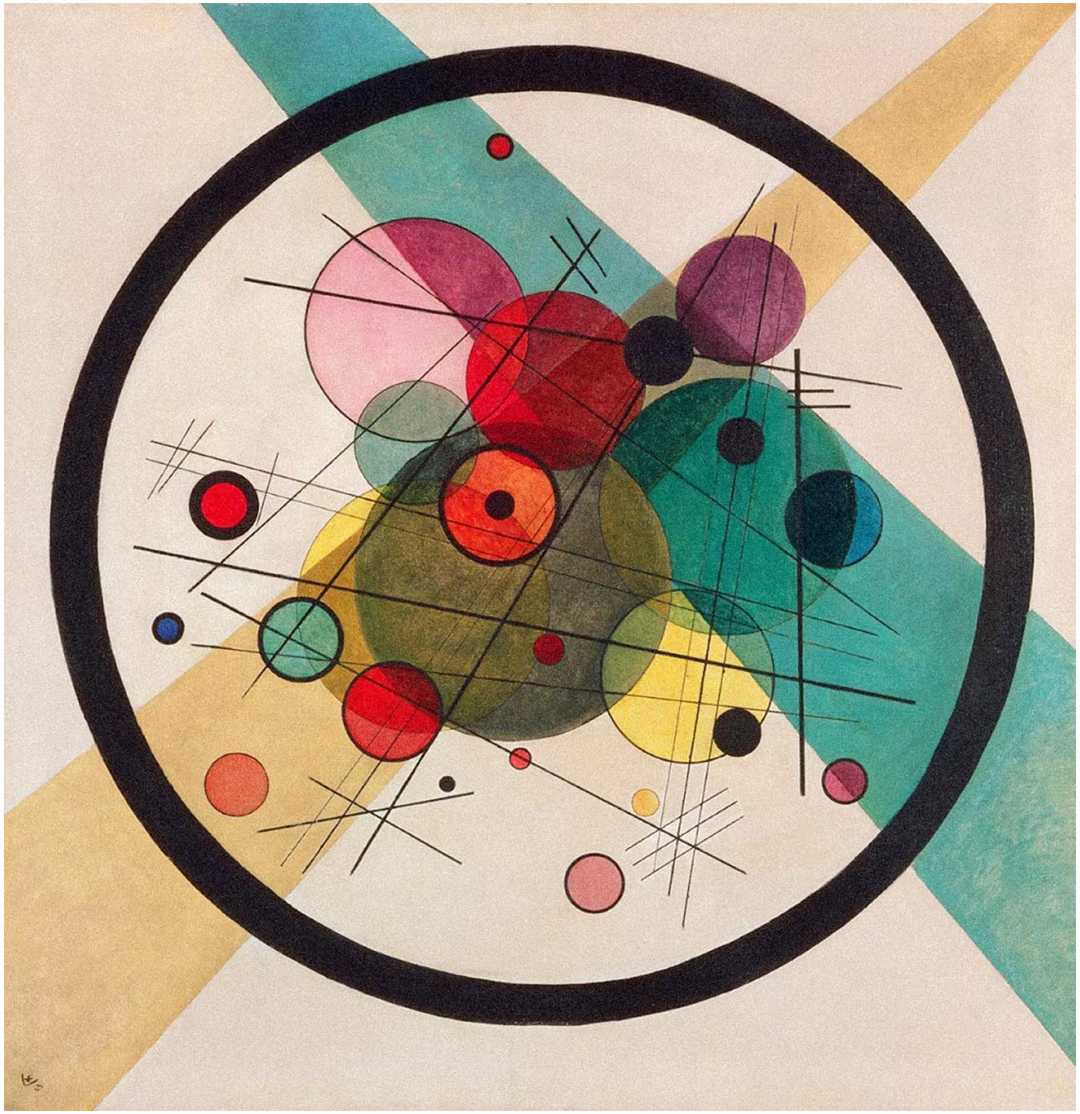
14 TeV μ collider LHC-$\mu\mu$ with FCC-ee $\mu^{\pm}$ production



Outlook

ESPP Outlook

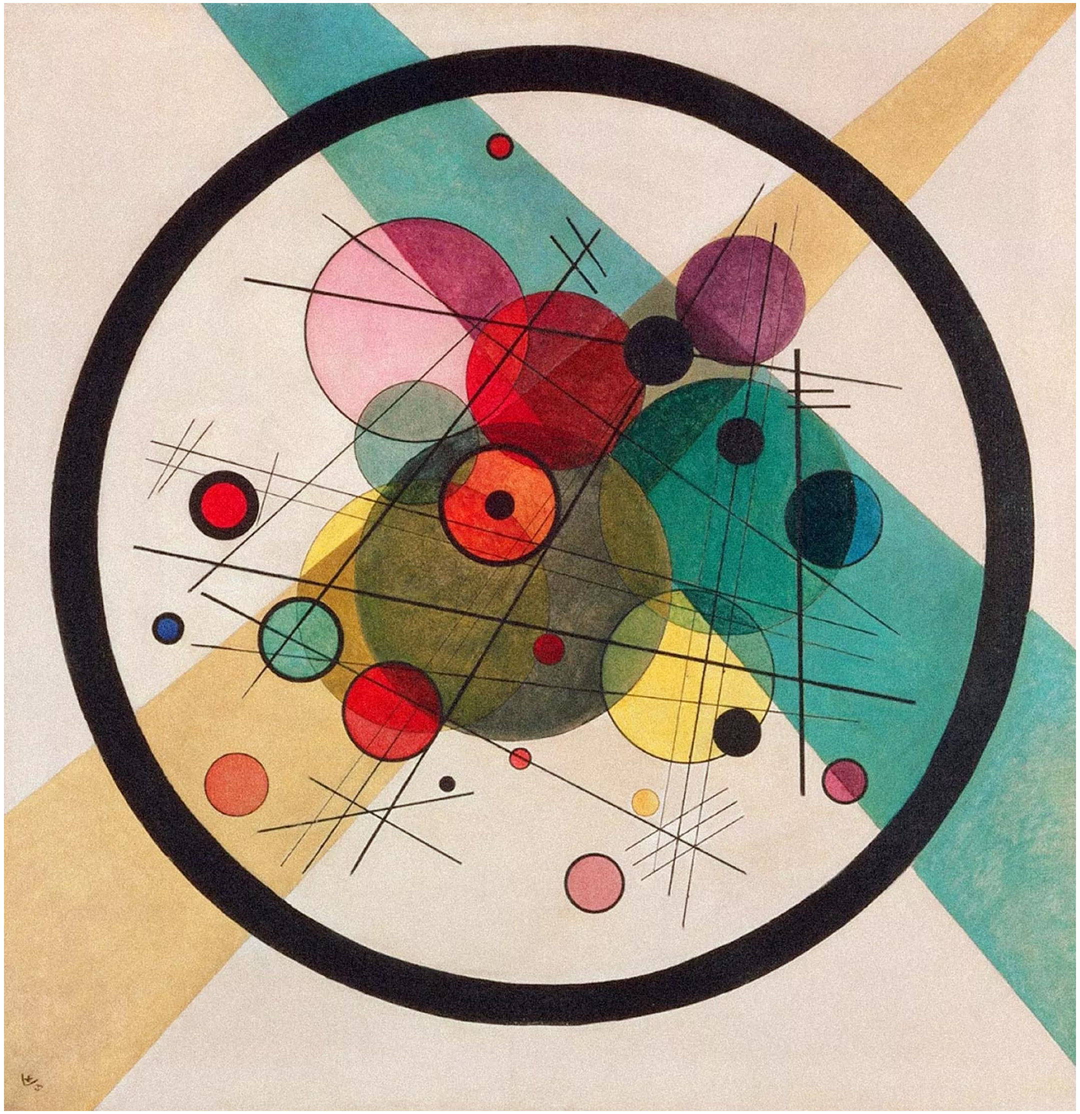
Soon, we will know a lot more ...



V. Kandinsky

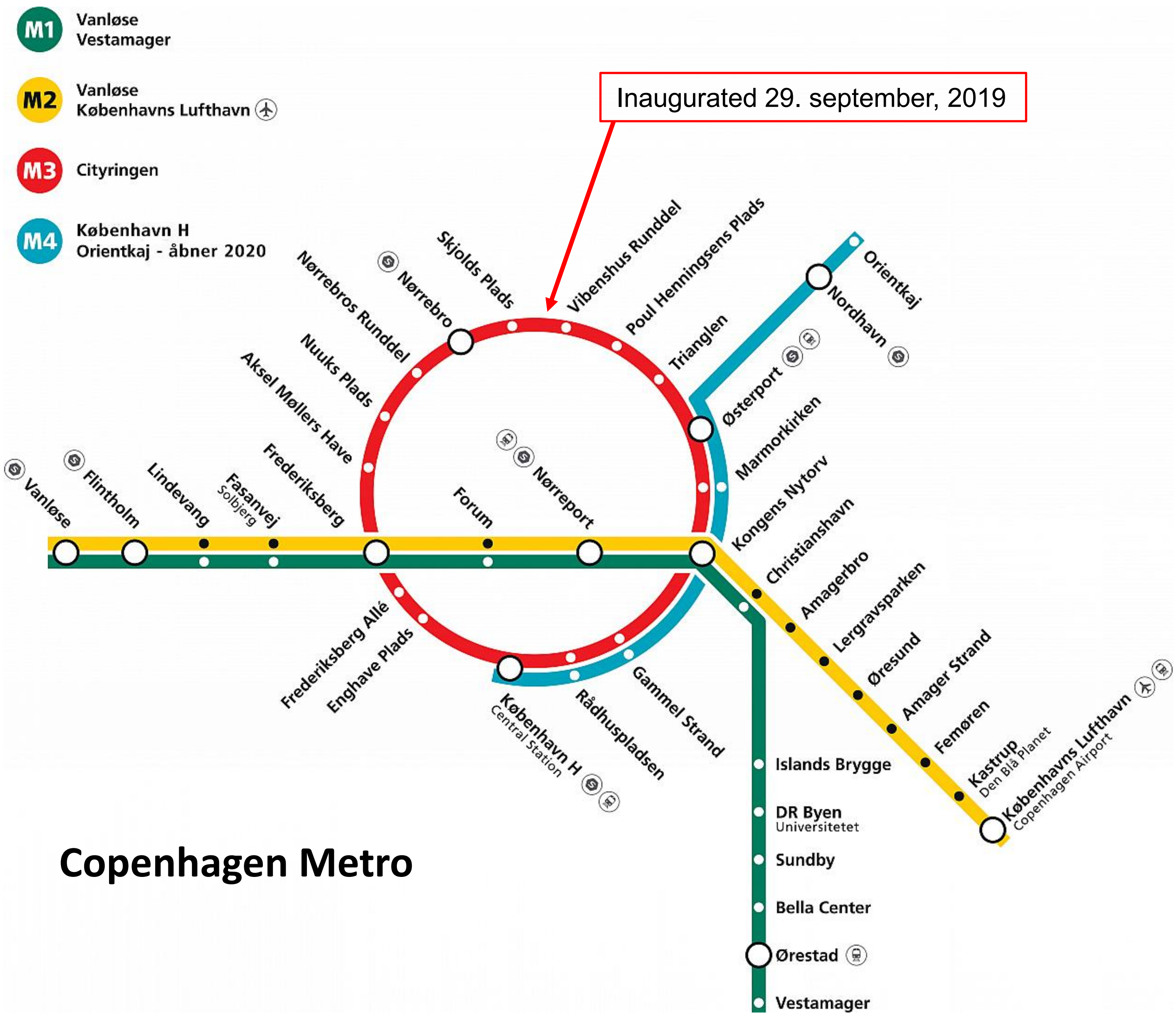
ESPP Outlook

Soon, we will know a lot more ...



V. Kandinsky
Circles in a Circle

Lines and a Circle



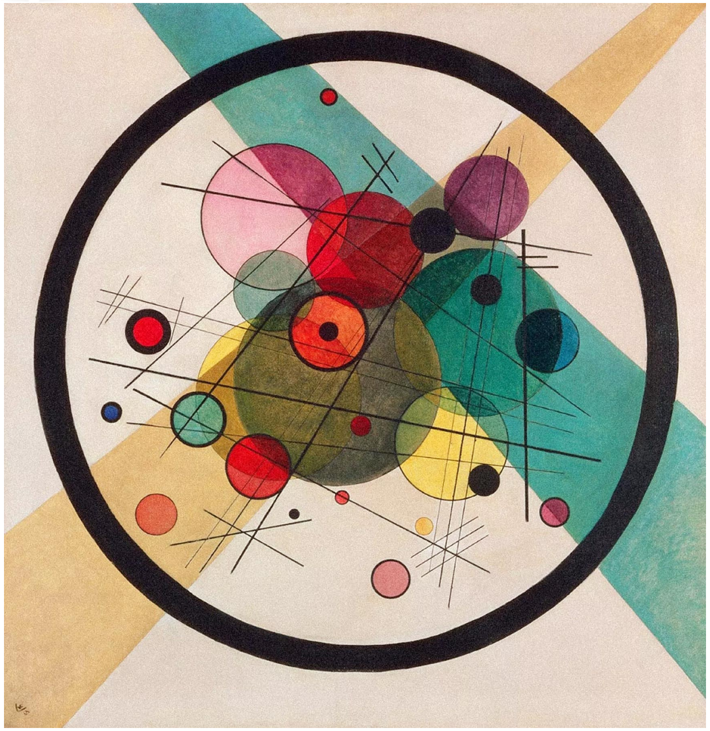
Extra Slides

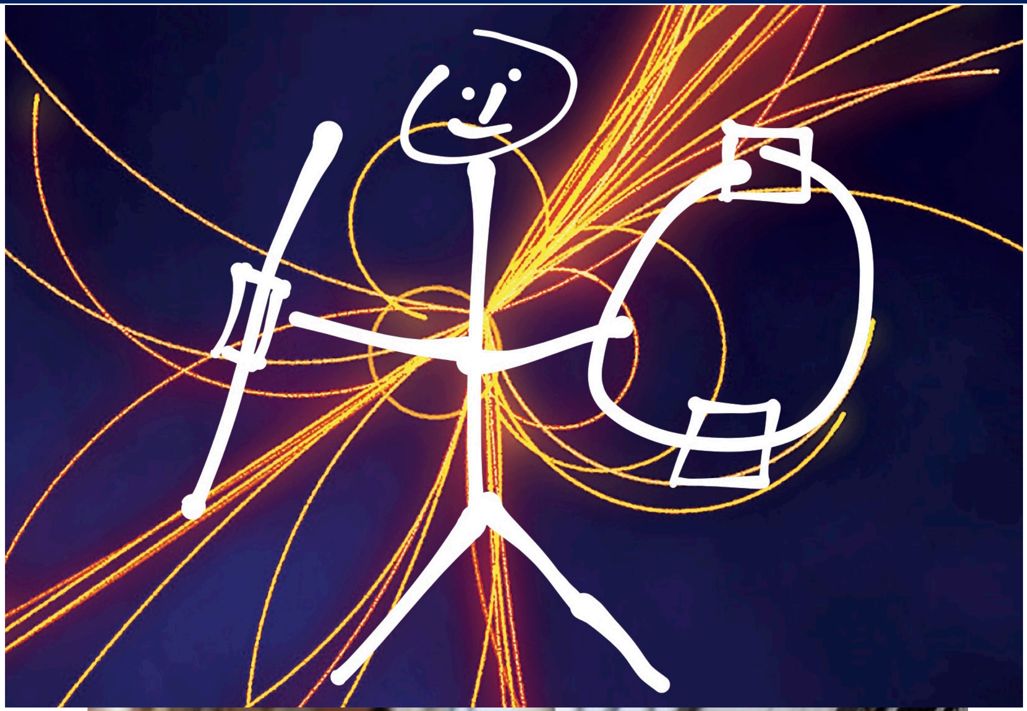
FCC-ee Baseline Parameters

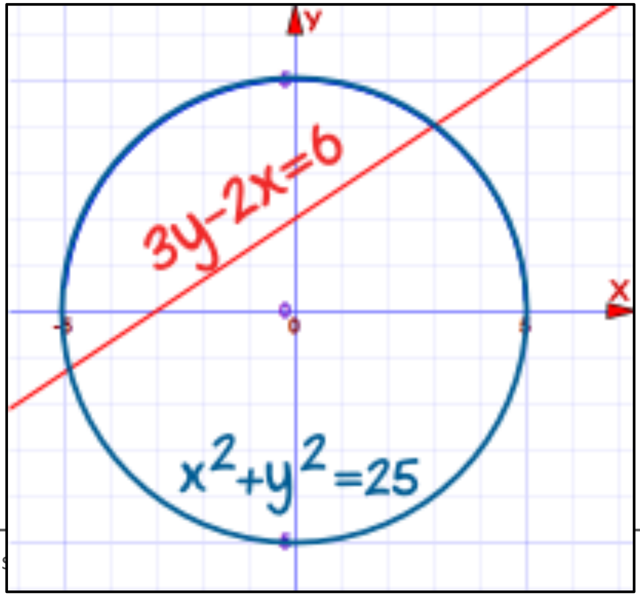
parameter	FCC-ee				LEP2
energy/beam [GeV]	**45**	**80**	**120**	**182.5**	105
bunches/beam	16640	2000	328	48	4
beam current [mA]	1390	147	29	5.4	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**230**	**28**	**8.5**	**1.5**	0.0012
energy loss/turn [GeV]	0.036	0.34	1.72	9.2	3.34
total synchrotron power [MW]	100				22
RF voltage [GV]	0.1	0.75	2.0	4+6.9	3.5
rms bunch length (SR,+BS) [mm]	3.5, 12	3.0, 6,0	3.2, 5.3	2.0, 2.5	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.3, 1.0	0.8, 1.7	0.6, 1.3	1.5, 2.9	22, 250
longit. damping time [turns]	1273	236	70	20	31
crossing angle [mrad]	30				0
beam lifetime (rad.B+BS) [min]	68	48	12	12	434

FCC-ee: 2 separate rings LEP: Single beam pipe

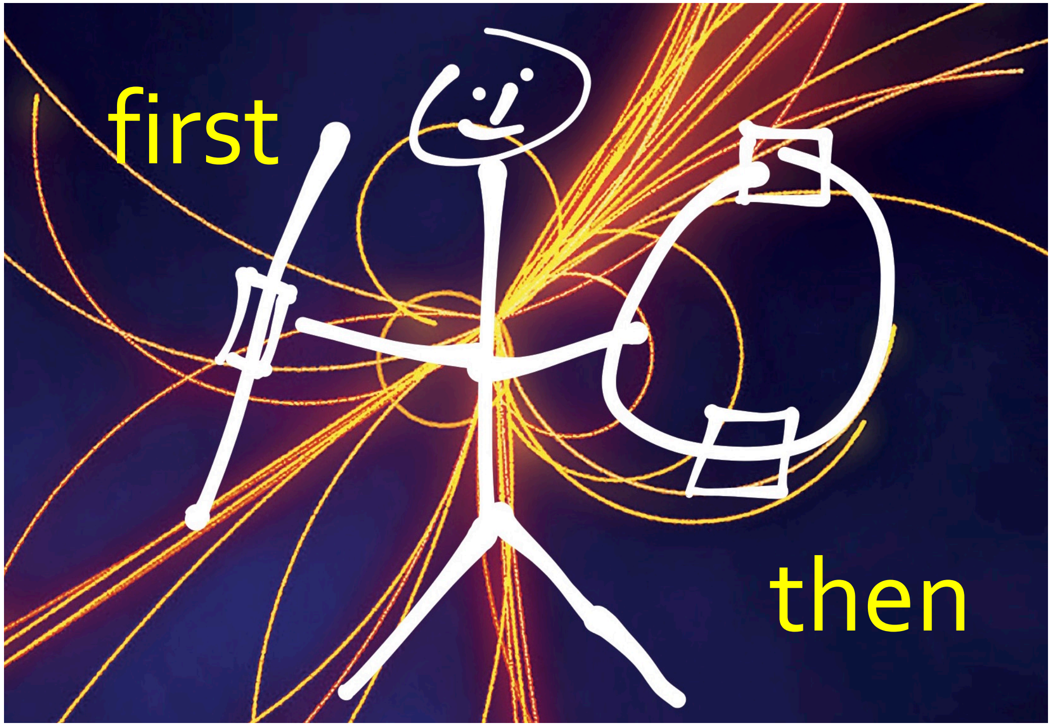
Outlook… Circular or Linear ?



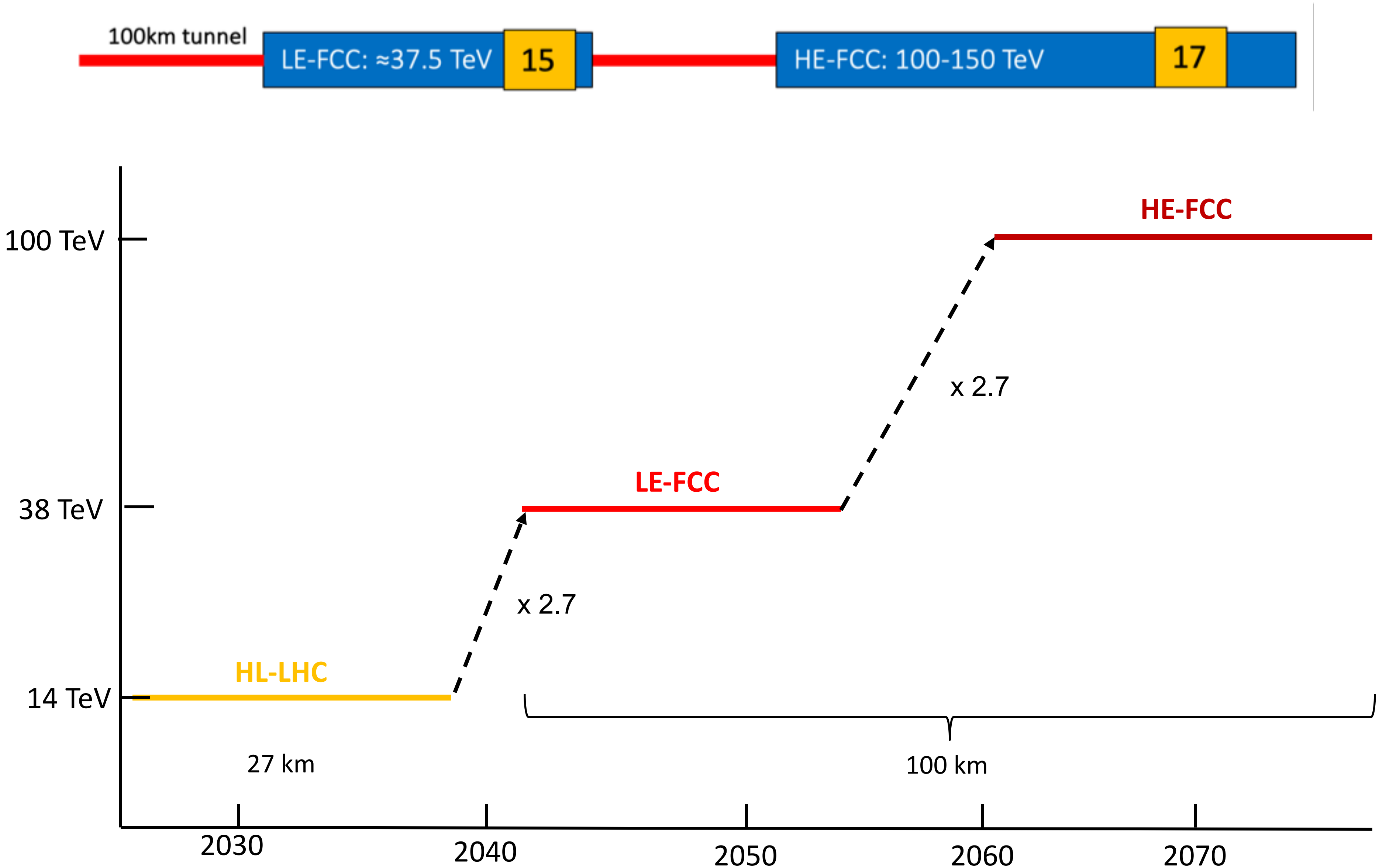




Scenarios



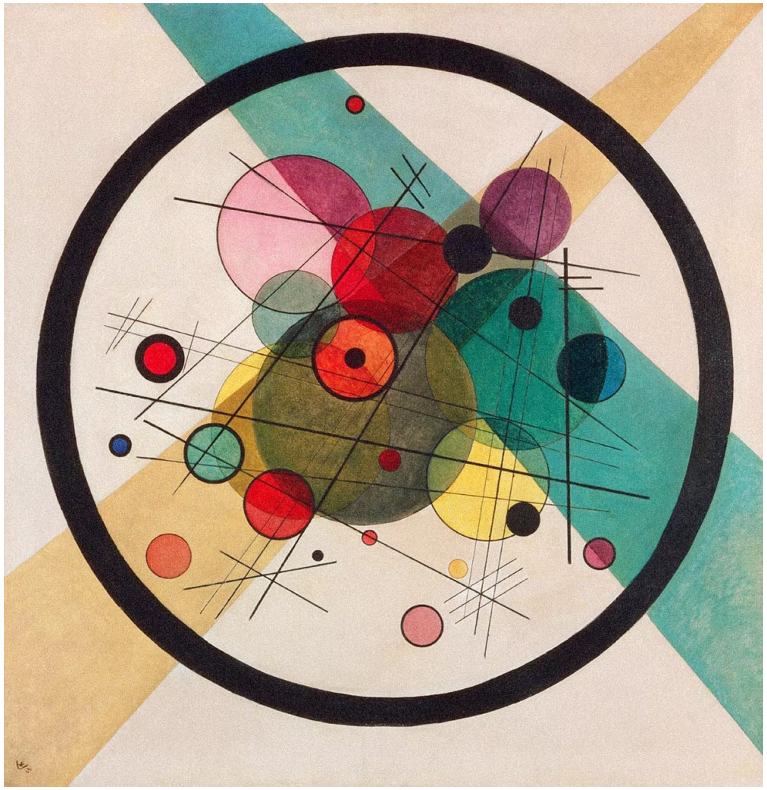
LE-FCC / HE-FCC


100km tunnel
LE-FCC: ≈37.5 TeV
15
HE-FCC: 100-150 TeV
17
100 TeV
38 TeV
14 TeV
HE-FCC
LE-FCC
HL-LHC
x 2.7
x 2.7
27 km
100 km
2030
2040
2050
2060
2070

Conclusions

From the ESPP process, two elements of consensus seem to have emerged:

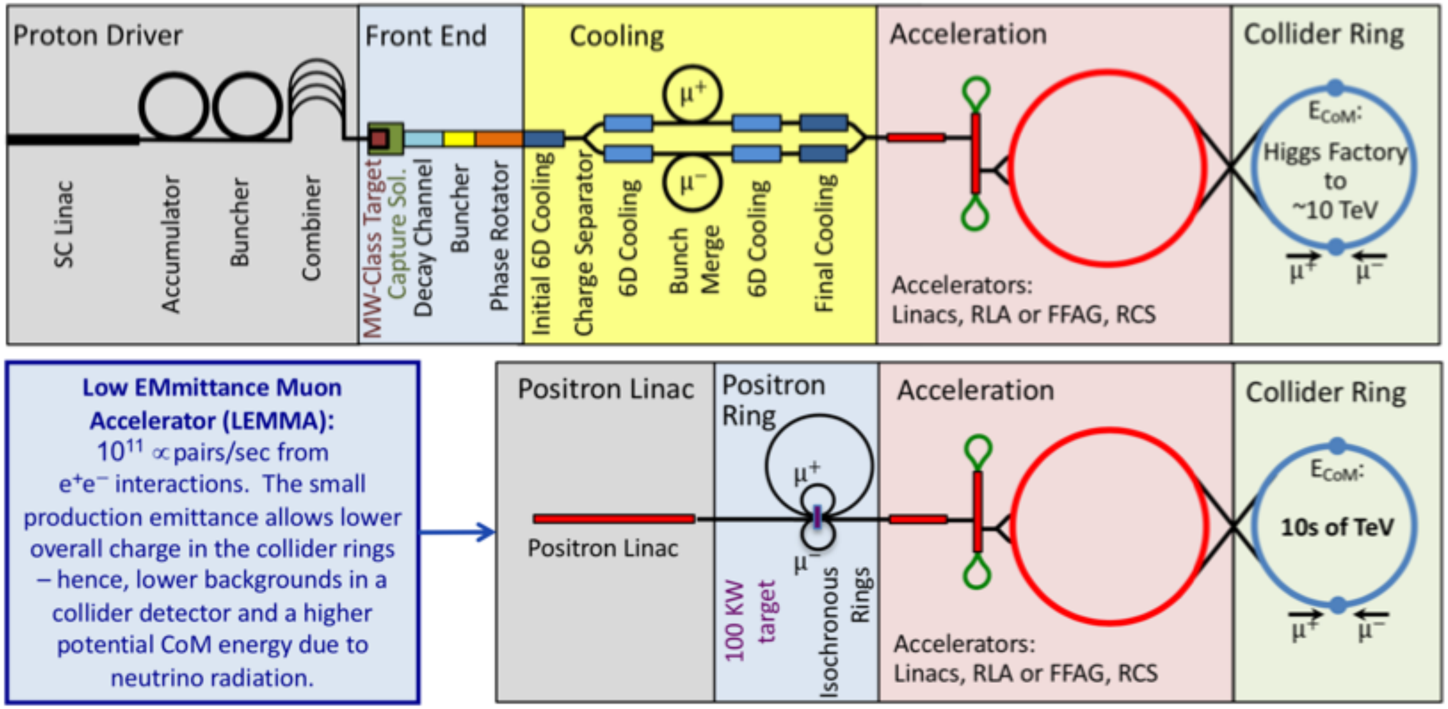
1. There is a strong physics case for an e^+e^- collider to measure Higgs and other particle properties
2. The highest elementary parton-parton collision energy can be achieved, in the foreseeable future, with a high-energy proton-proton collider, for which a circular geometry is the only available option



Muon collider options

MAP:
π decays

LEMMA



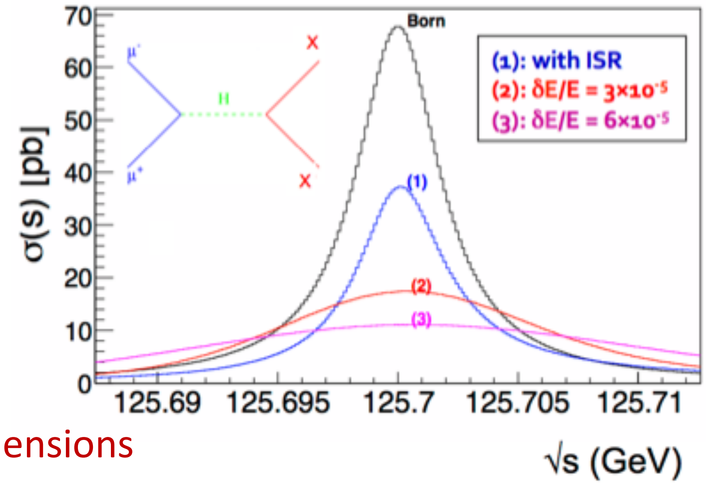
With 14 T state-of-the-art dipoles

$\sqrt{s}$	91 GeV	125 GeV	161 GeV	350 GeV	6 TeV	24 TeV
$t = \gamma\tau_m$	0.94 ms	1.30 ms	1.67 ms	3.64 ms	62.3 ms	249 ms
$L = \gamma\beta c\tau_m$	283 km	389 km	501 km	1090 km	18700 km	74000 km
Ring	100 m	140 m	180 m	390 m	6.6 km	27 km
N_{turns}	~2800 turns					

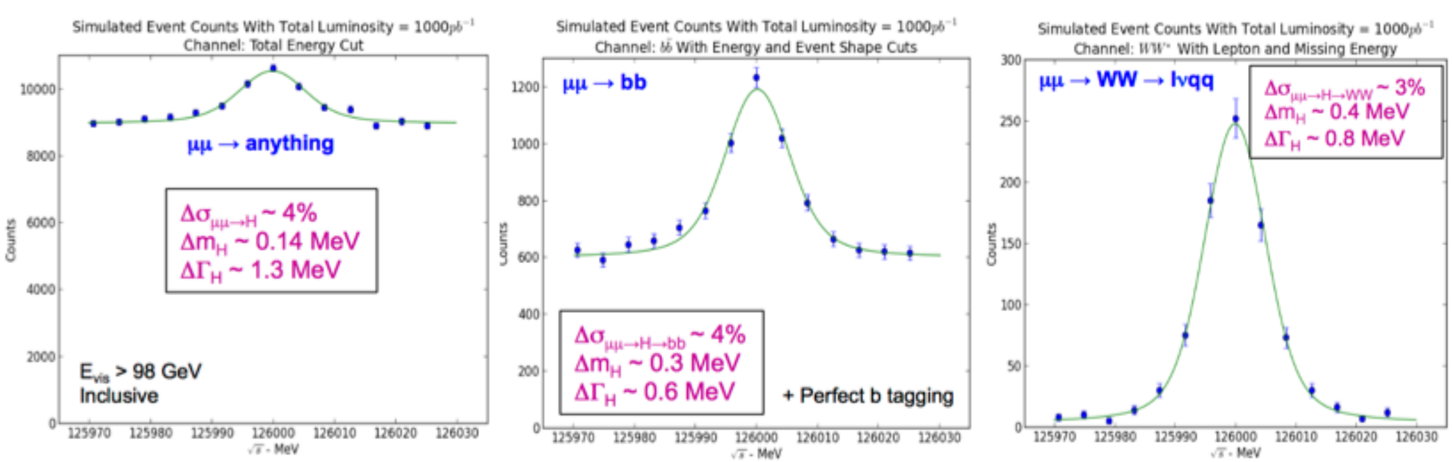
A muon collider may be the best way to get lepton collisions at $\sqrt{s} \geq 3$ TeV

Muon collider as a Higgs factory

- Challenges for the Higgs factory
  - Γ_H is small (4.2 MeV)
    - Fast longitudinal cooling required to reduce beam energy spread to 3×10^{-5}
  - $\sigma(\mu^+\mu^- \rightarrow H)$ is about 20 pb
    - Luminosity must be at the 1.6×10^{32} $cm^{-2}s^{-1}$ level for the same number of Higgs bosons as ILC …
      - Fast transverse cooling to reduce beam spot dimensions
  - Problem: Longitudinal and transverse cooling are antagonistic
    - Luminosity is limited (as of today's knowledge) to a few 10^{31} $cm^{-2}s^{-1}$



10 years running (~40,000 events):



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