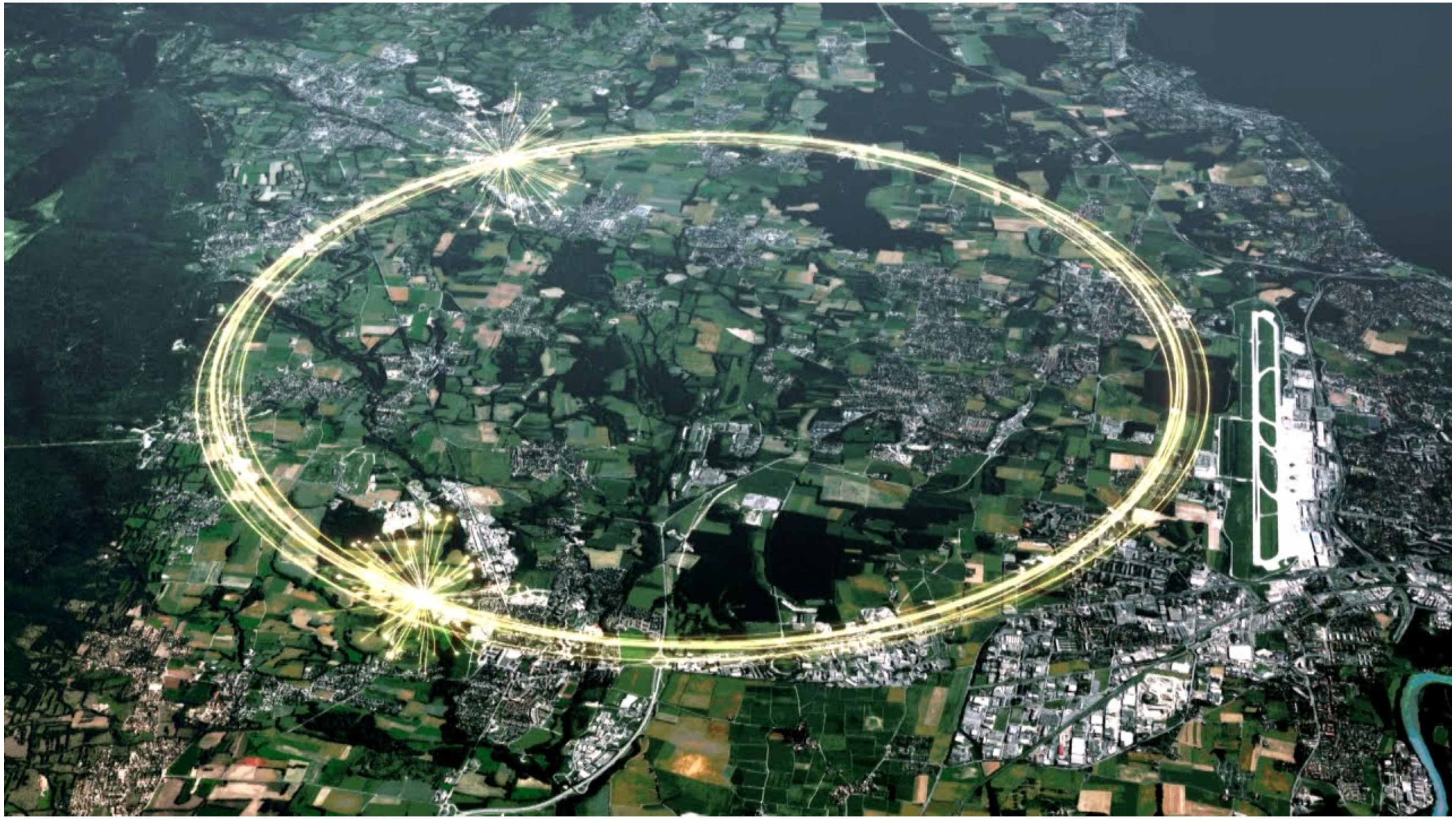
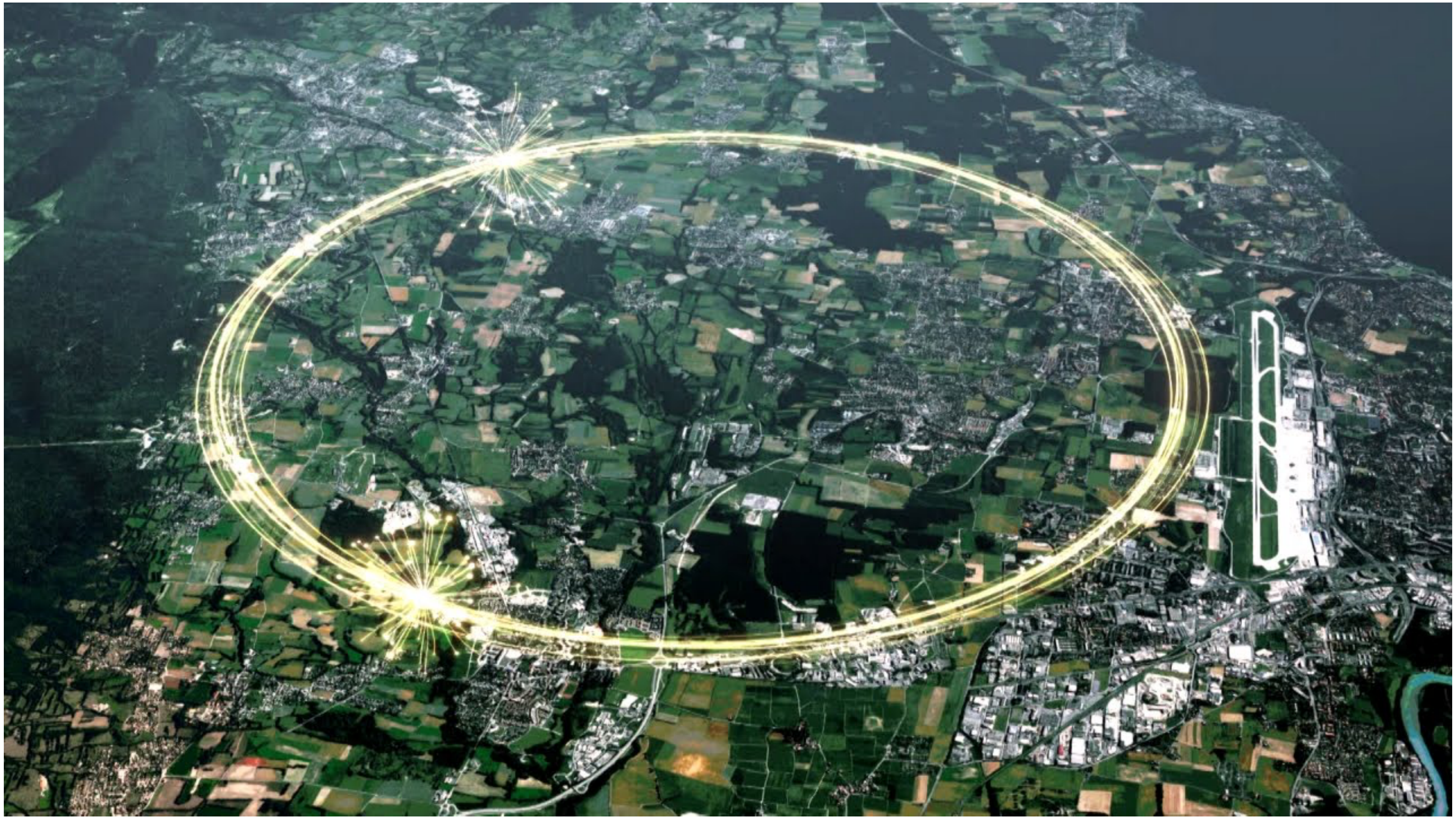
Future colliders: where, how, why



Gabriella Gaudio

INFN - Pavia

Future colliders: where, how, why

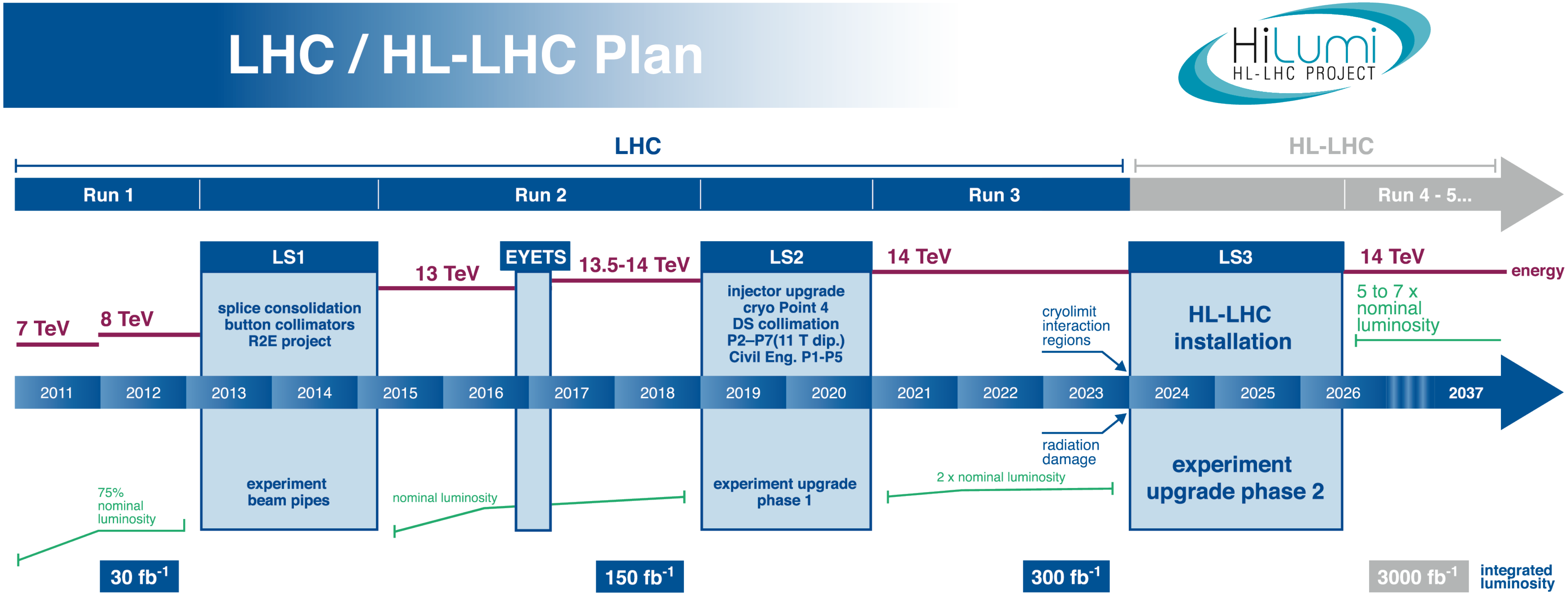


In my understanding

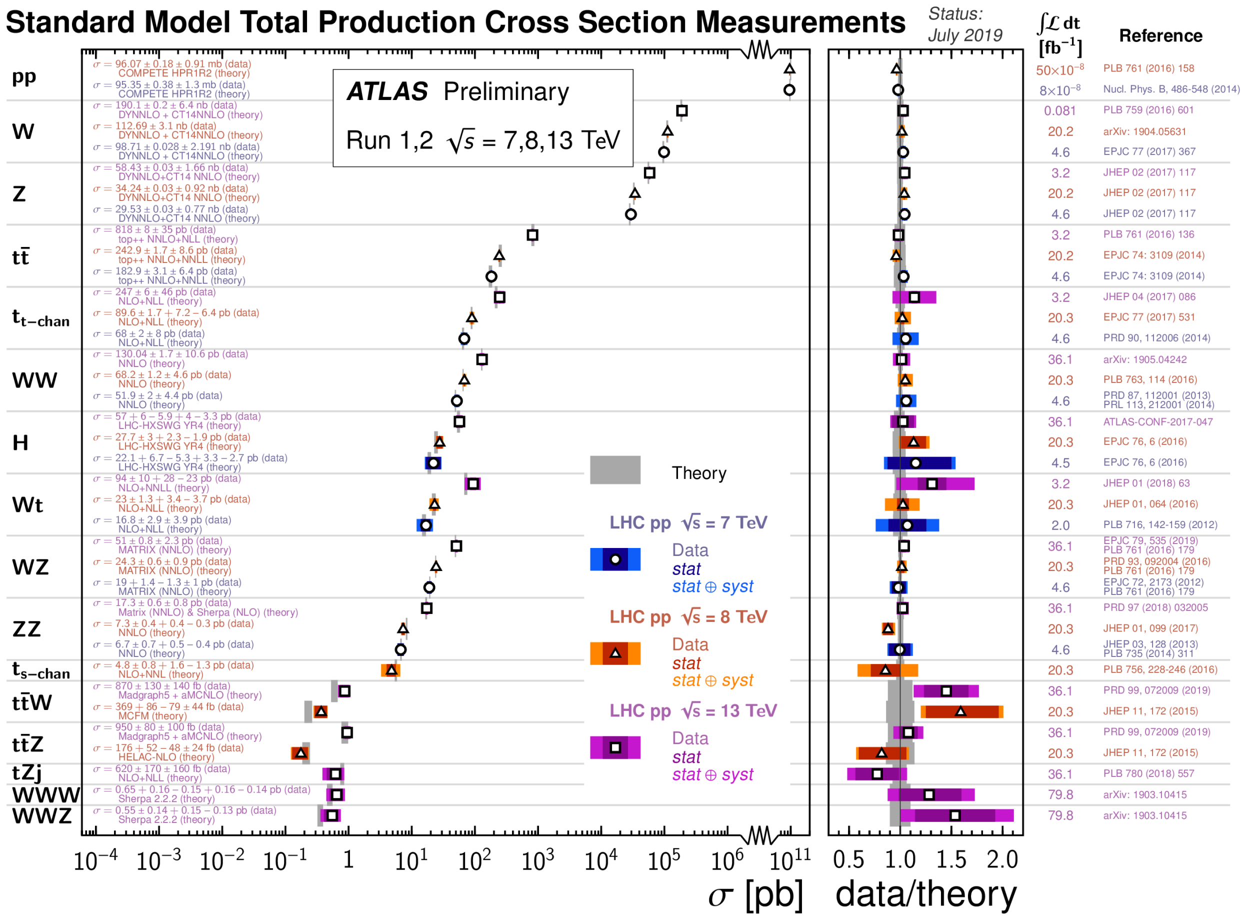
Gabriella Gaudio

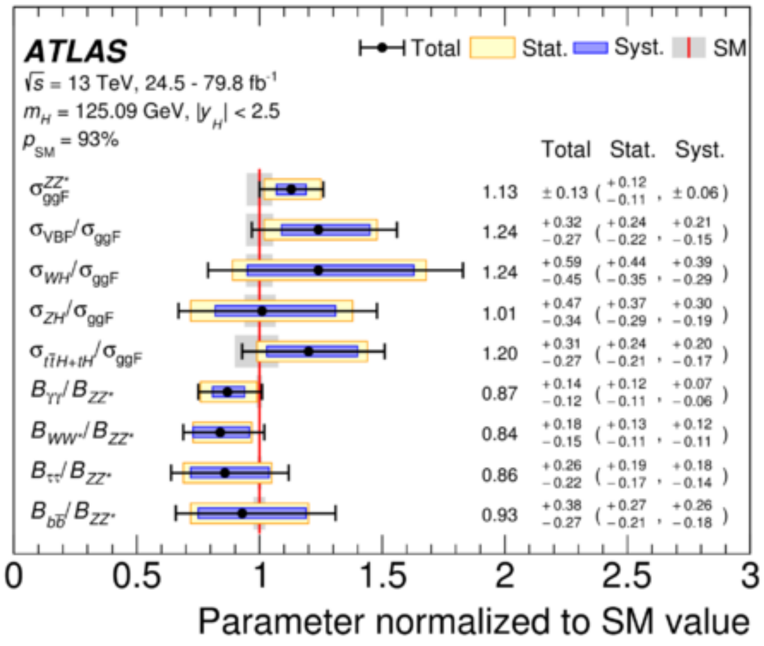
INFN - Pavia

LHC schedule

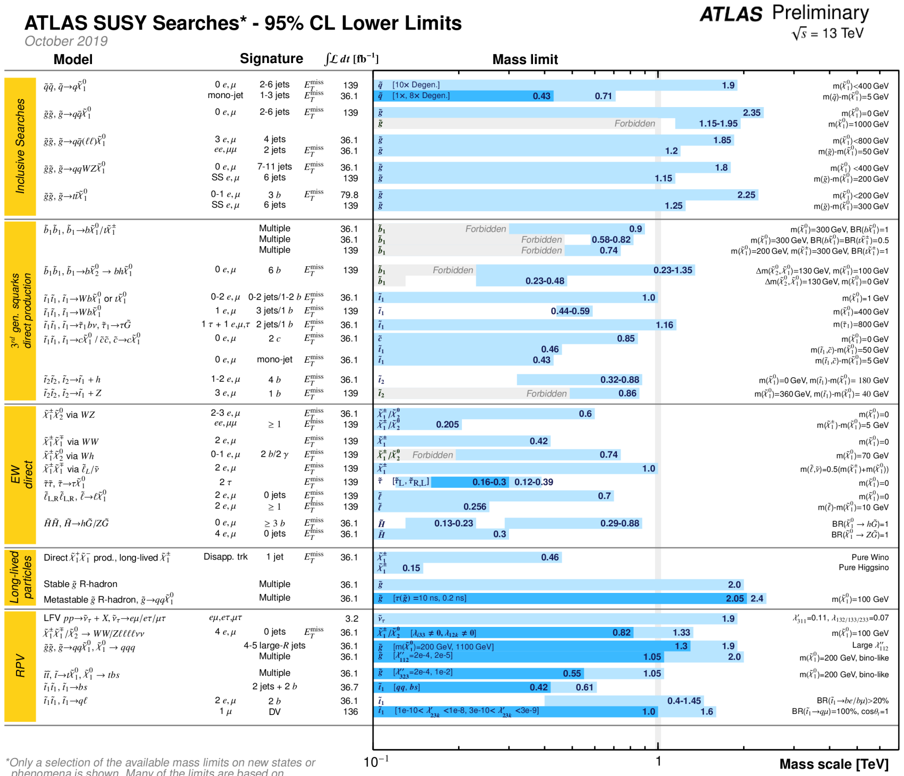


Stubbornly Standard Model

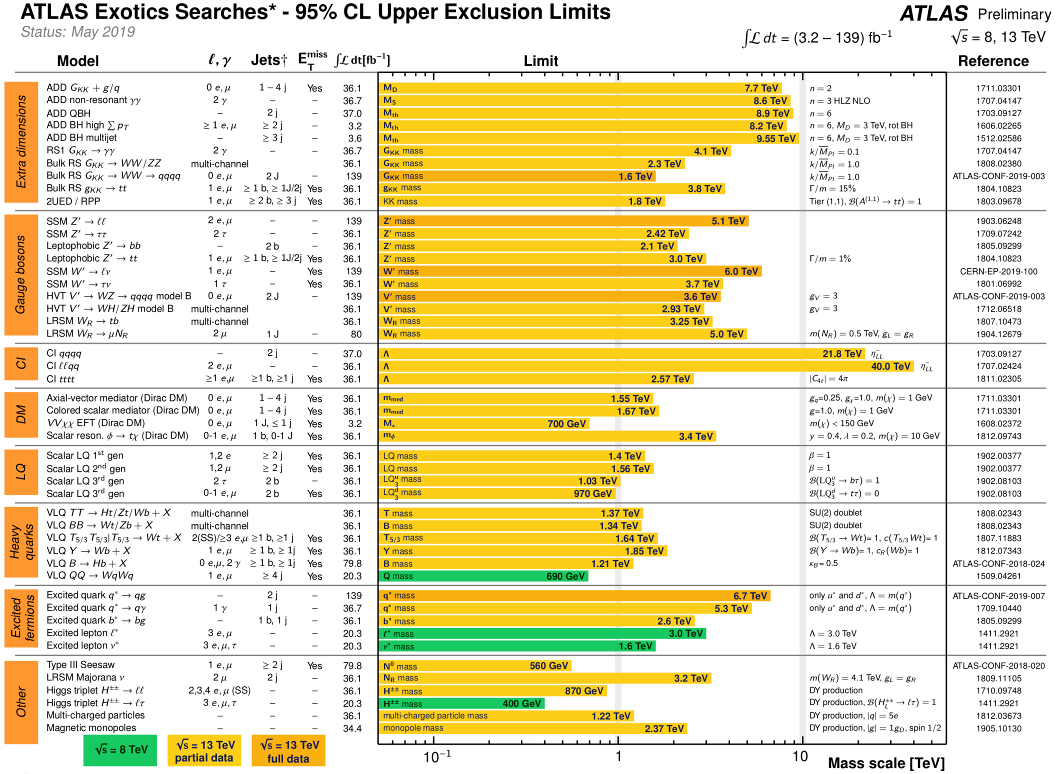




Stubbornly Standard Model



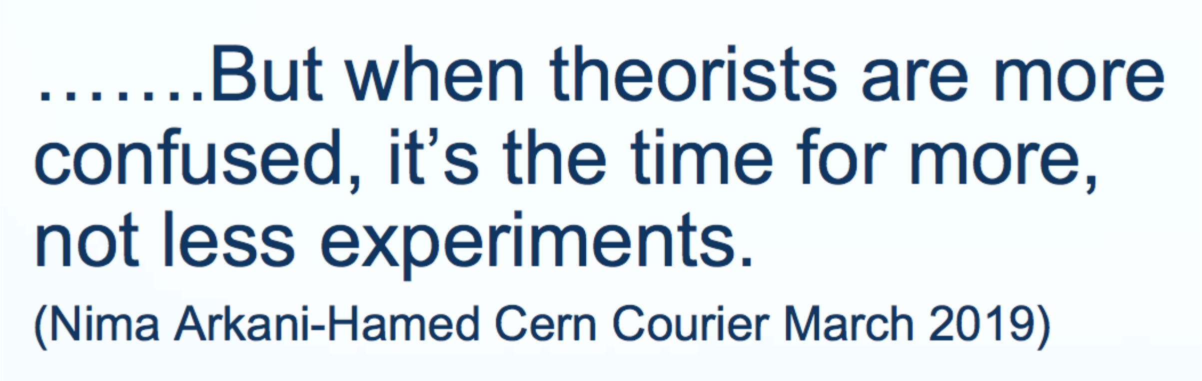
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



*Only a selection of the available mass limits on new states or phenomena is shown.

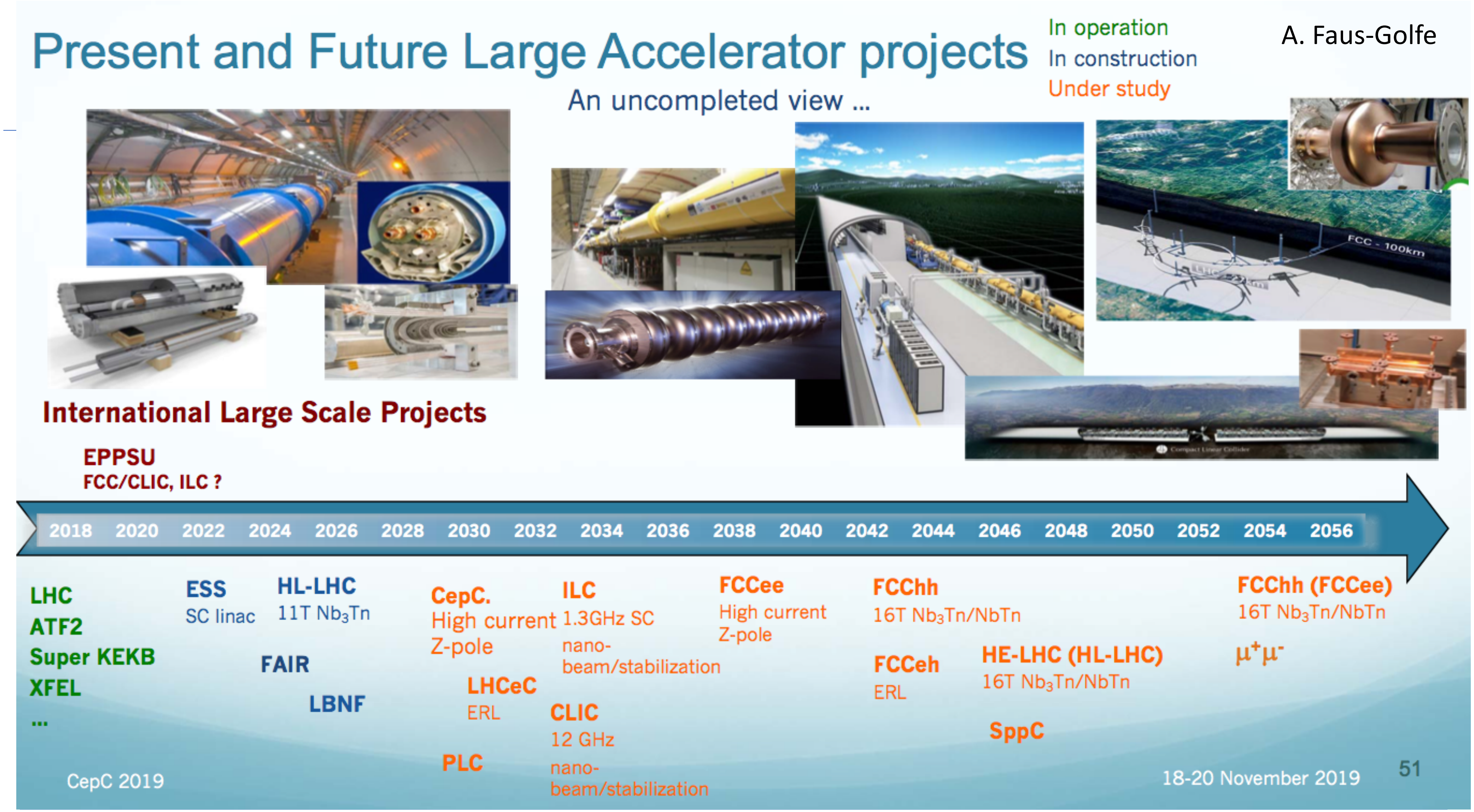
†Small-radius (large-radius) jets are denoted by the letter j (J).

No new physics scenario



…….But when theorists are more confused, it's the time for more, not less experiments.

(Nima Arkani-Hamed Cern Courier March 2019)



Present and Future Large Accelerator projects

In operation
In construction
Under study

A. Faus-Golfe

An uncompleted view …

International Large Scale Projects

EPPSU
FCC/CLIC, ILC ?

2018 2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056

LHC
ATF2
Super KEKB
XFEL
…

ESS
SC linac

HL-LHC
11T Nb_3Tn

FAIR

LBNF

CepC.
High current
Z-pole

LHCeC
ERL

PLC

ILC
1.3GHz SC
nano-beam/stabilization

CLIC
12 GHz
nano-beam/stabilization

FCCee
High current
Z-pole

FCChh
16T Nb_3Tn/NbTn

FCCeh
ERL

HE-LHC (HL-LHC)
16T Nb_3Tn/NbTn

SppC

FCChh (FCCee)
16T Nb_3Tn/NbTn

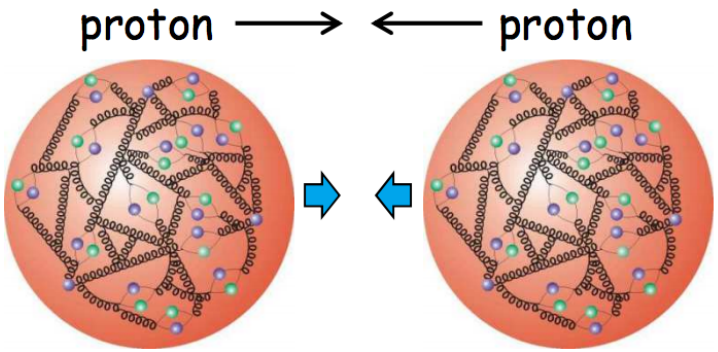
$\mu^+\mu^-$

CepC 2019

18-20 November 2019

51

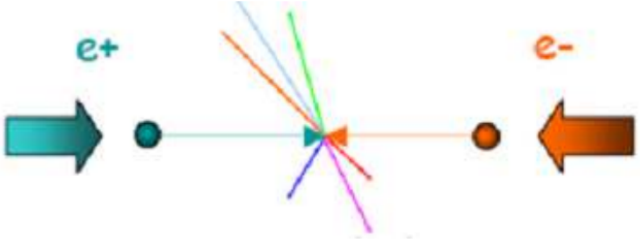
Hadron vs lepton accelerator machine



collision of two composite particles
(with different initial constituents
and energies)

$$\sqrt{s} = \sqrt{x_1 \ x_2 \ s}$$

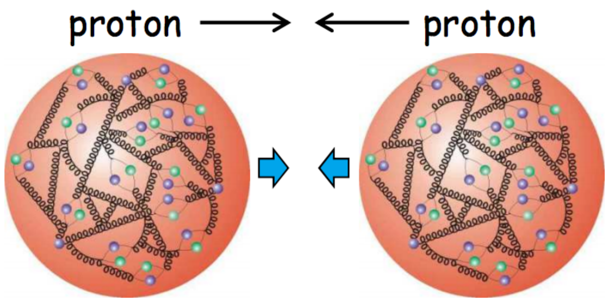
electroweak interactions
+ strong interactions

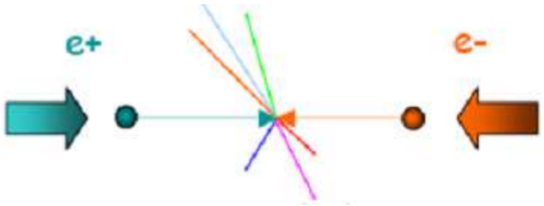


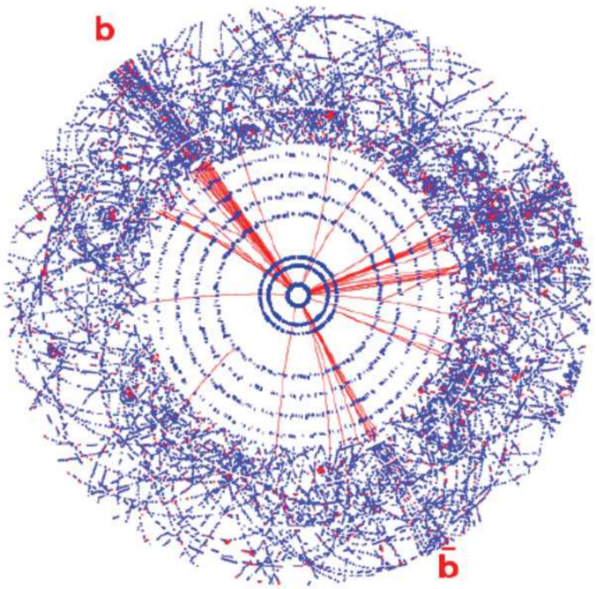
collision of two point-like particles
(with exactly defined initial state,
quantum numbers and energies)

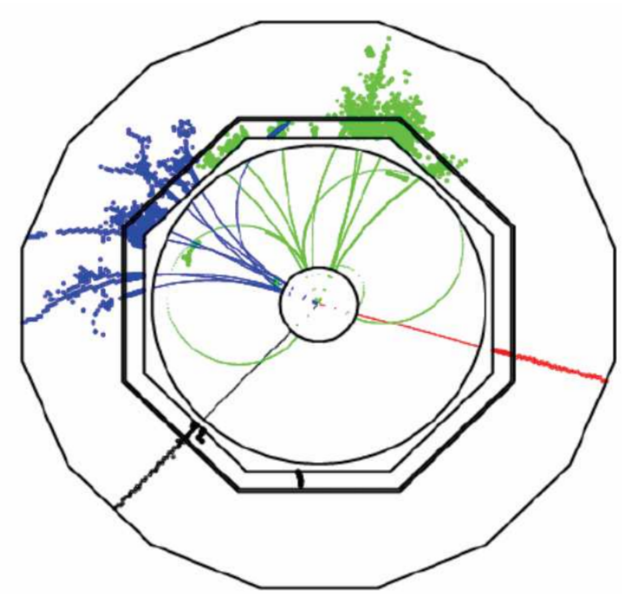
electroweak interactions

Hadron vs lepton accelerator machine









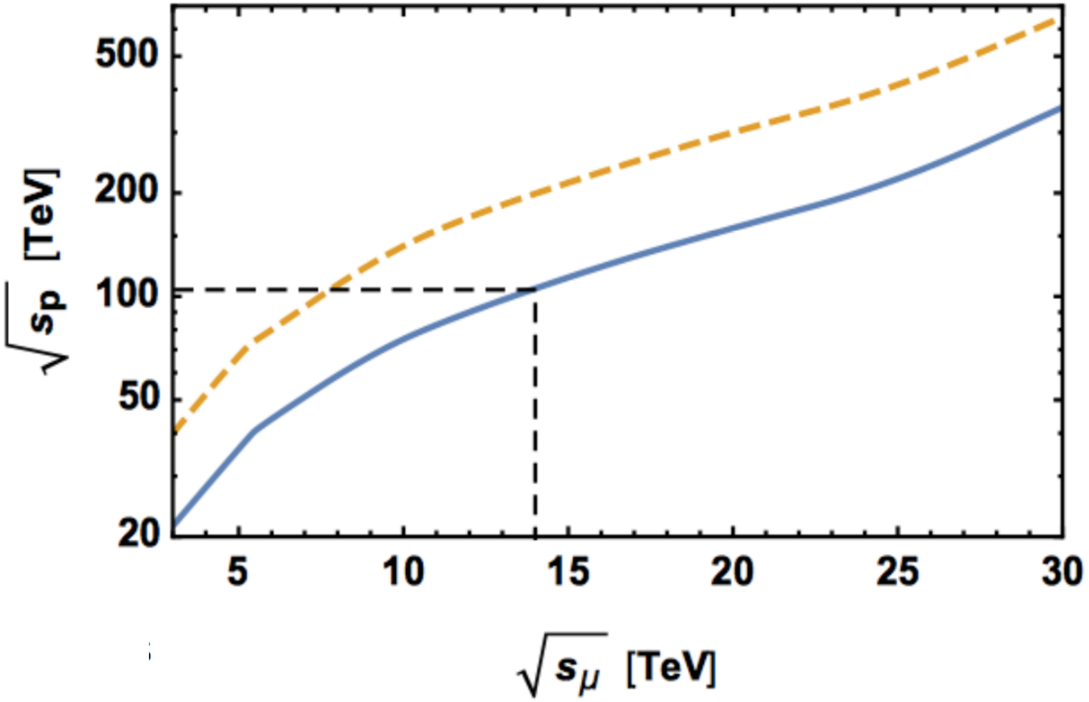
Lepton collider motivation

Lepton colliders offer the potential of precision measurements

- Well defined initial conditions
- Low background levels
- …

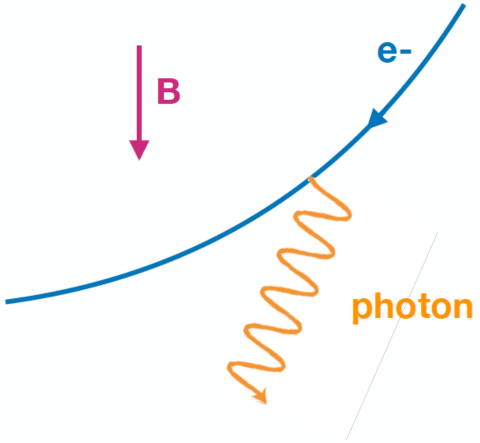
At high energies they are efficient discovery machines

- Full collision energy available for particle production
- But sufficient luminosity is required



14 TeV lepton collisions are comparable to 100 TeV proton collisions

Accelerating electrons (positrons)



Energy loss by synchrotron radiation of charged particles bent by a magnetic field

$$\Delta E \simeq \left(\frac{E}{m}\right)^4 \times \frac{1}{R}$$

Electron mass m_e: 0.5 MeV

2.75 GeV/turn lost at LEP for E = 105 GeV

Proton mass ~2000 m_e

Energy loss reduced by a factor

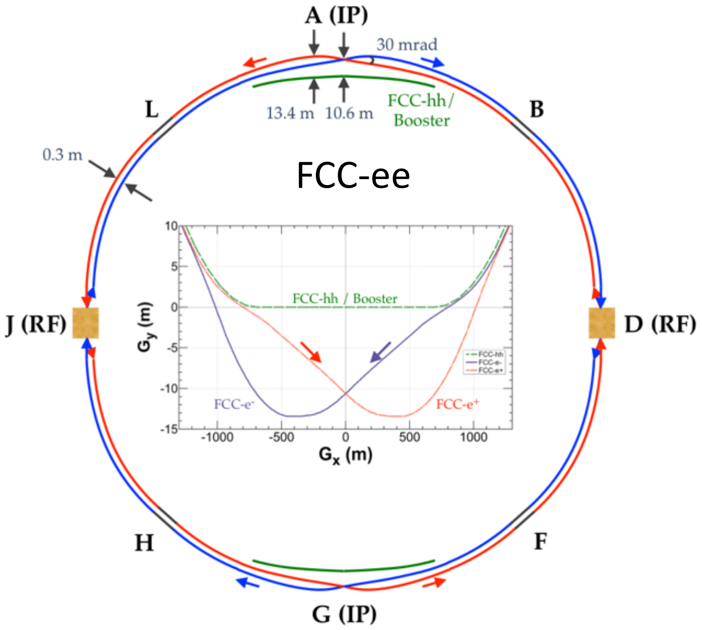
$$\left(\frac{1}{2000}\right)^4 \approx 6 \cdot 10^{-14}$$

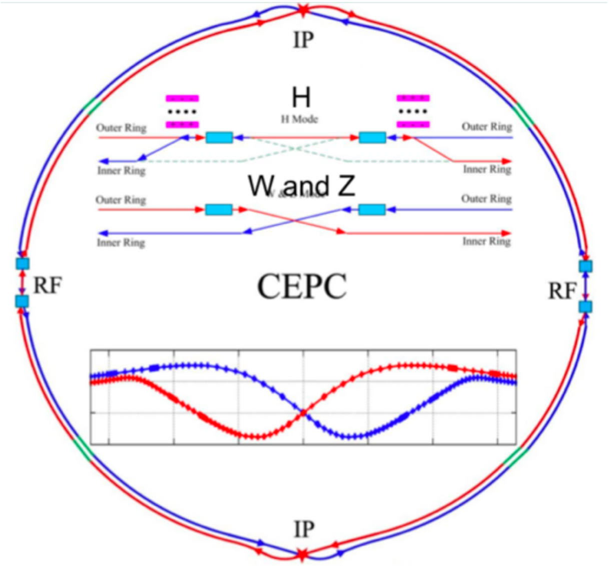
Muon mass ~200 m_e

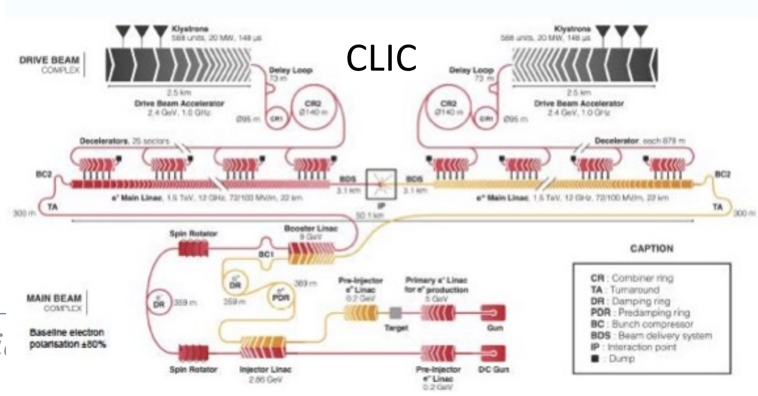
Energy loss reduced by a factor

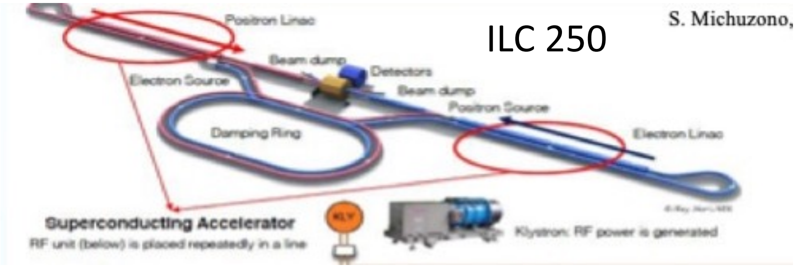
$$\left(\frac{1}{200}\right)^4 \approx 6 \cdot 10^{-10}$$

e^+e^- competing projects









S. Michuzono,

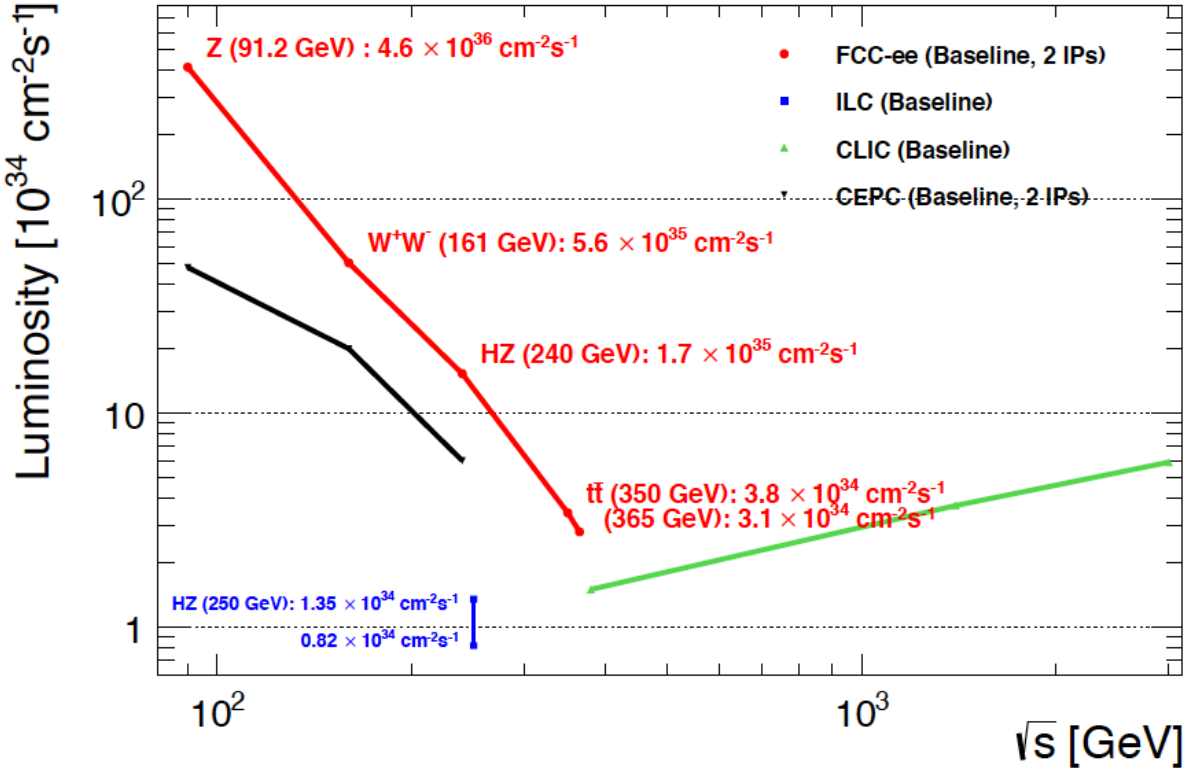
Luminosity per facility

The collider luminosity is the proportionality factor between the number of events per second and the cross section

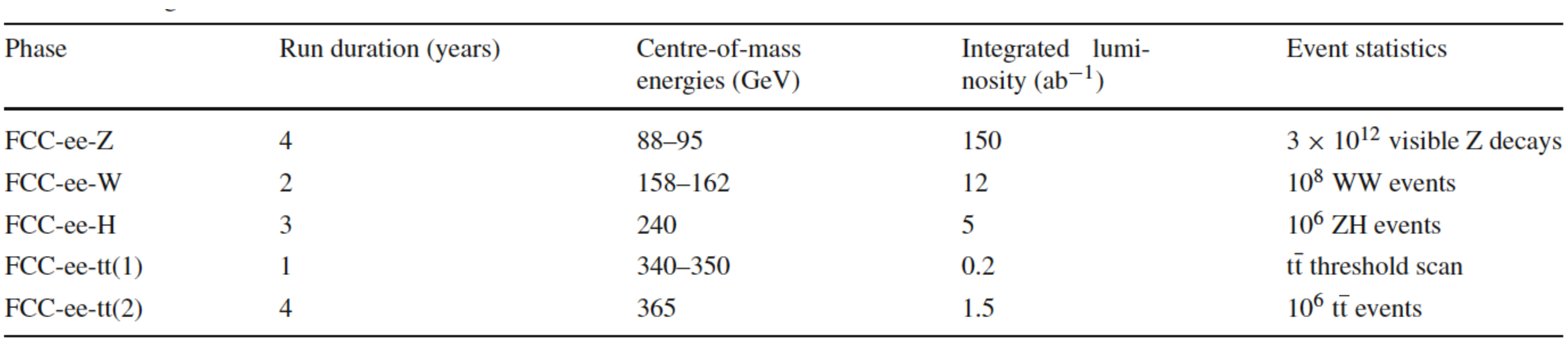
$$\frac{dN}{dt} = \mathscr{L}\,\sigma$$

Given by physics

Given by the machine

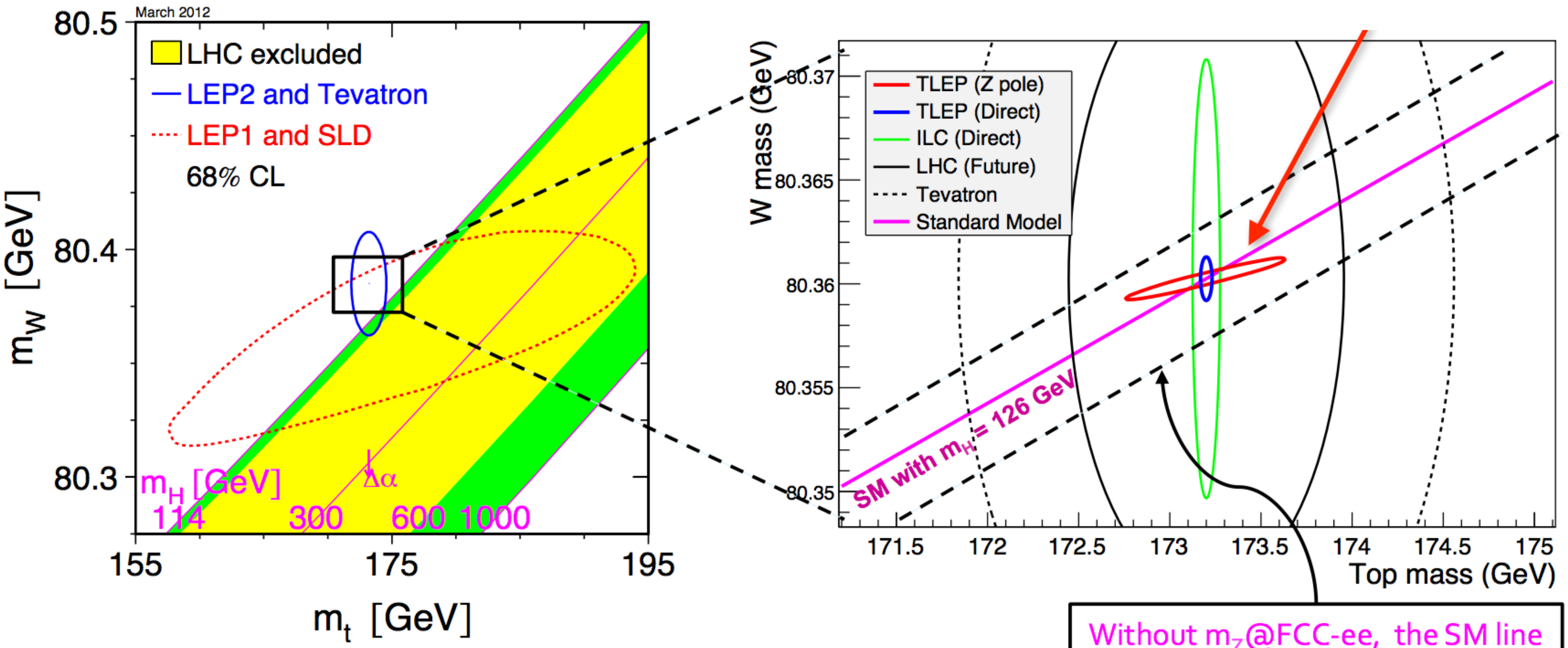


Running phase (FCC as example)



Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340–350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10^6 $t\bar{t}$ events

Precision is the way …



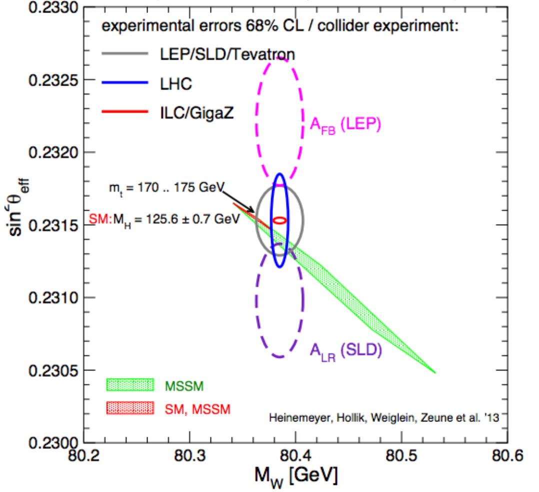
- **Constraints on new physics ?**

Without m_Z@FCC-ee, the SM line would have a 2.2 MeV width

The importance of precision measurements

A.Vicini

Baak et al., arXiv:1310.6708, Snowmass 2013, EW WG

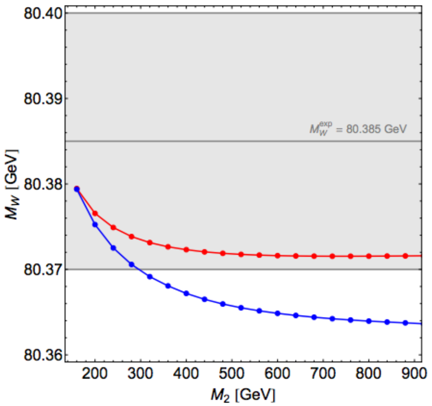


The precision measurement of MW and $\sin^2\theta_{\mathrm{eff}}$
with an error of 0.7 MeV and 0.000004
(5 MeV and 0.000100 at a hadron collider)
(formidable challenges!)
would offer a very stringent test of the SM likelihood

In the case a BSM particle had been discovered
a very precise MW value would offer
a strongly discriminating tool about the mass spectra
in BSM models

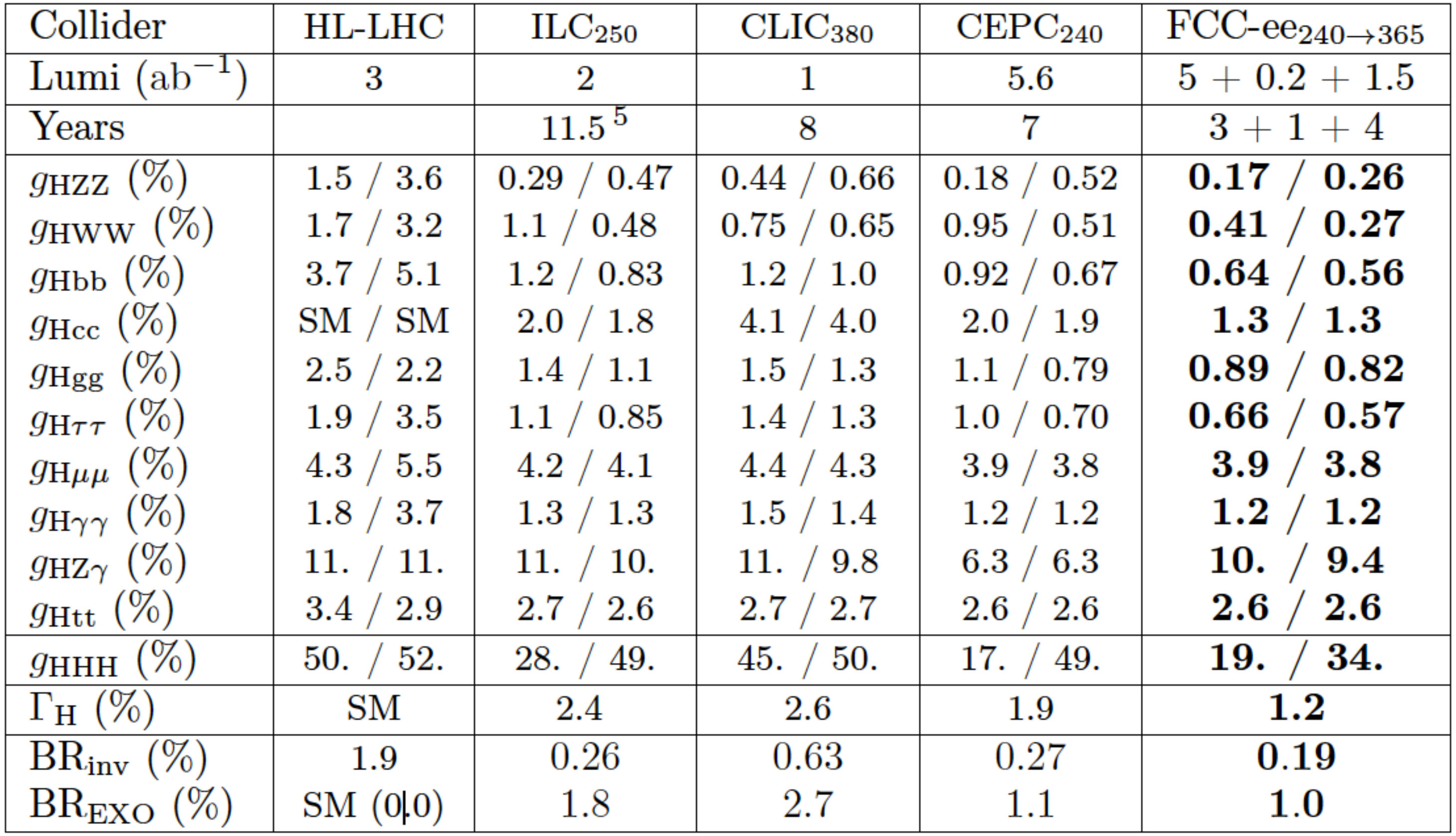
different dependence on the neutralino mass M_2
of the MW prediction in the MSSM and NMSSM

O. Stål, G.Weiglein, L. Zeune, arXiv:1506.07465



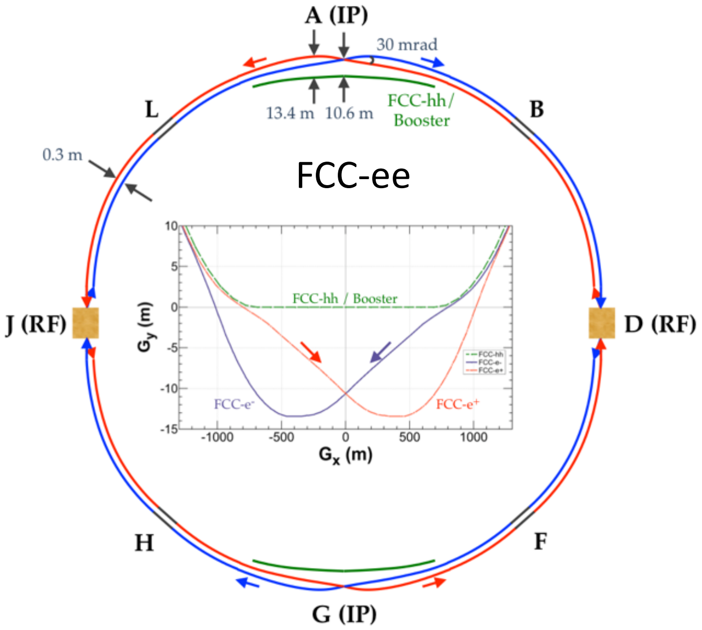
12

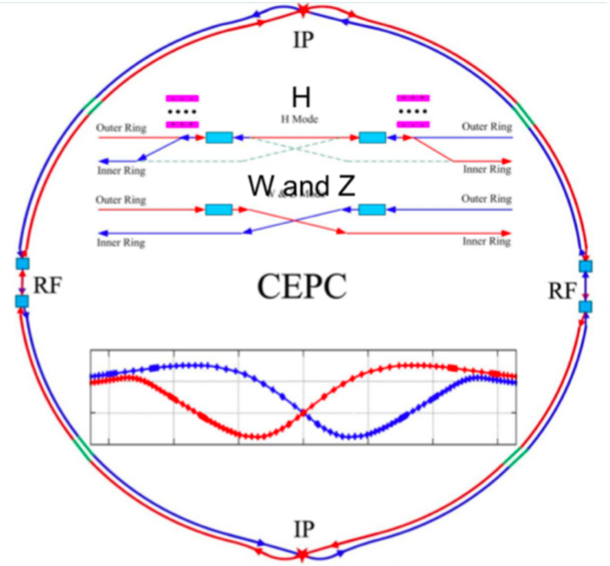
Precision on the Higgs boson coupling

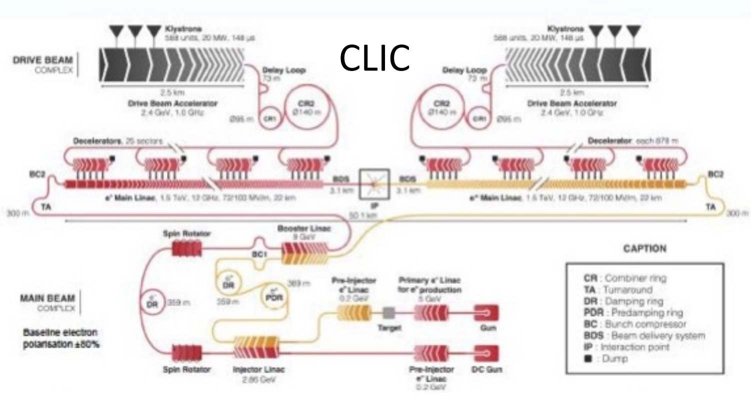


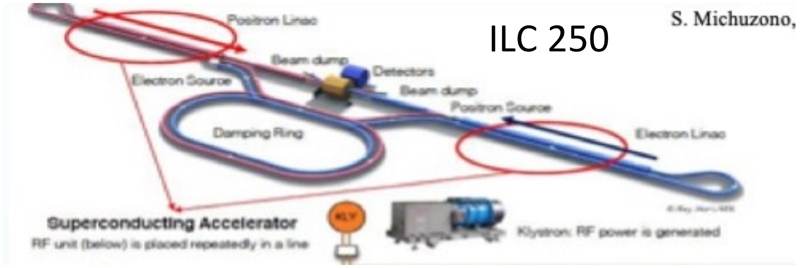
Collider	HL-LHC	ILC_{250}	CLIC_{380}	CEPC_{240}	$\mathrm{FCC\text{-}ee}_{240\rightarrow365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{\mathrm{H}\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{\mathrm{H}\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{\mathrm{HZ}\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_{H} (%)	SM	2.4	2.6	1.9	**1.2**
$\mathrm{BR}_{\mathrm{inv}}$ (%)	1.9	0.26	0.63	0.27	**0.19**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

e^+e^- competing projects



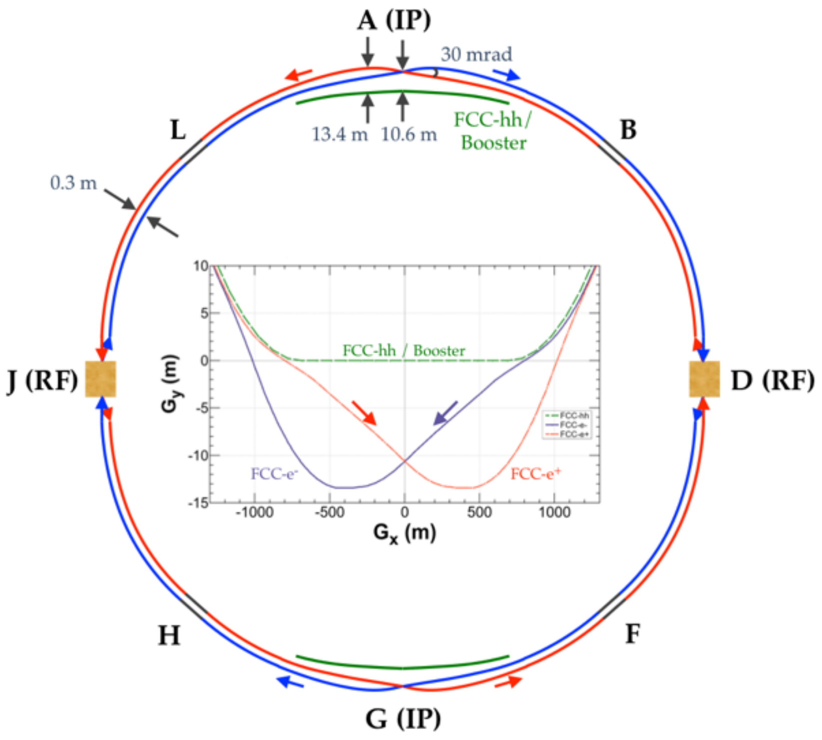




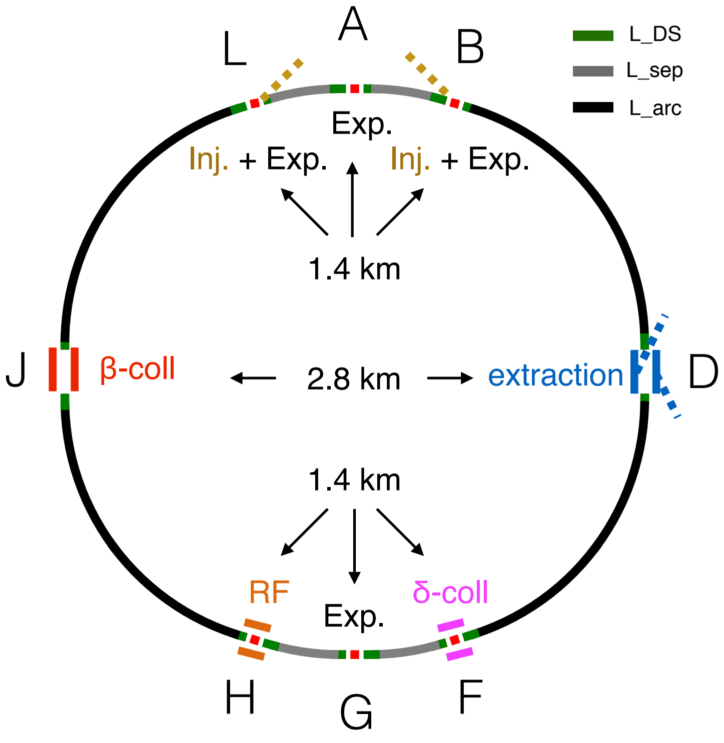


S. Michuzono,

FCC ee and hh



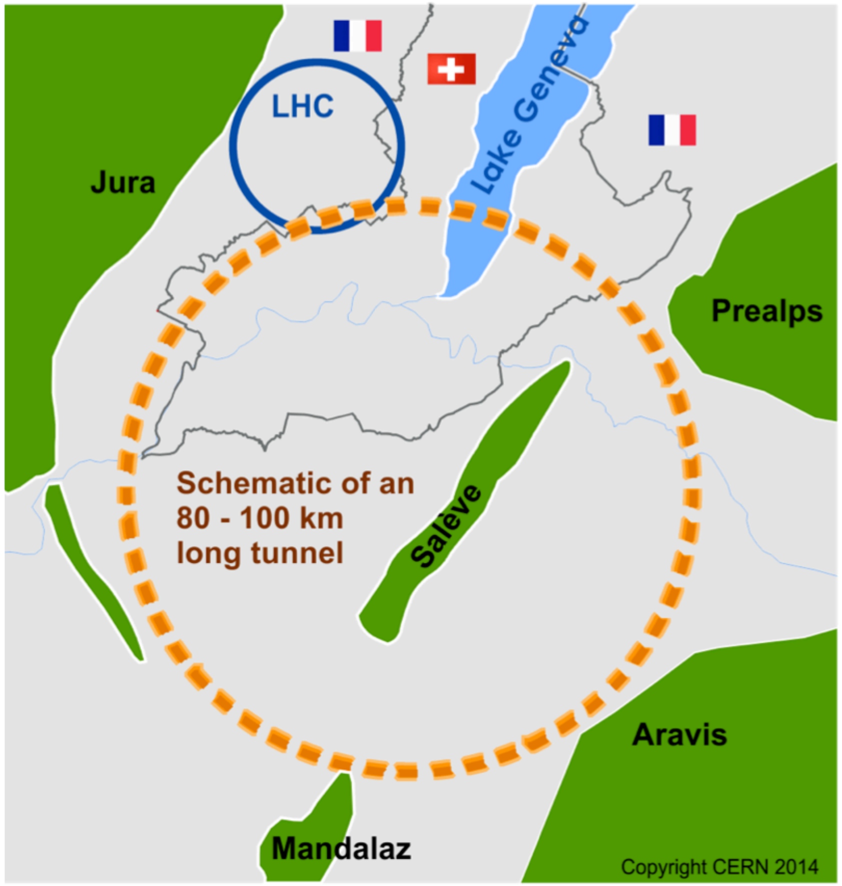
FCC-ee



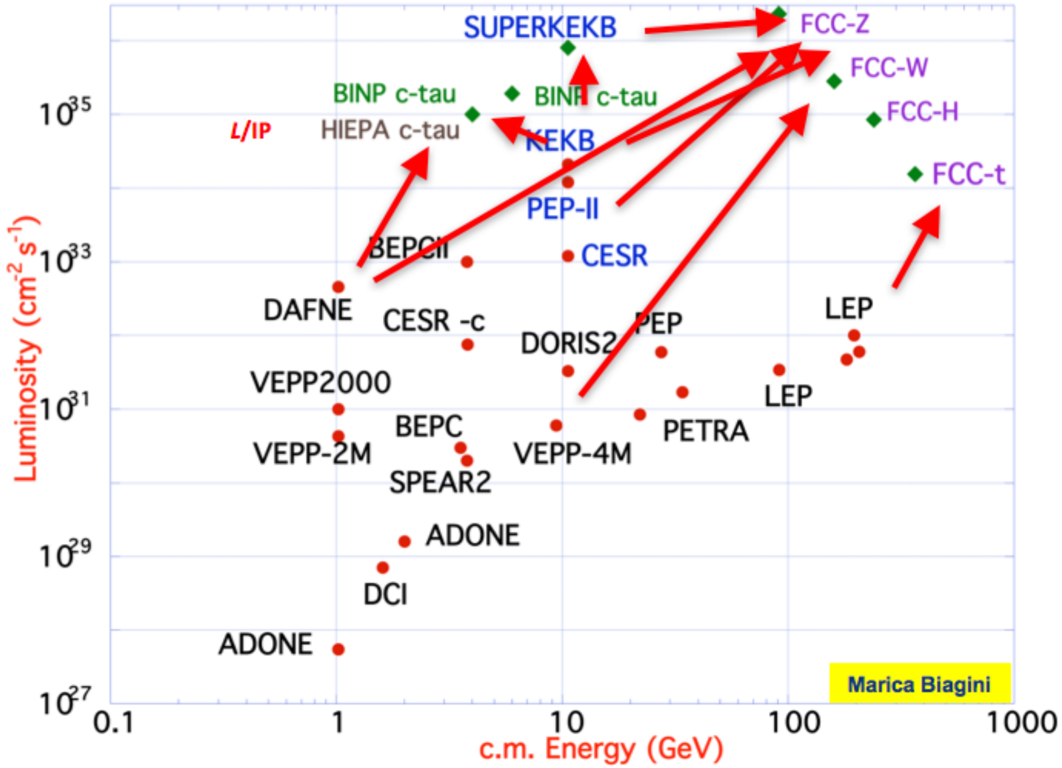
FCC-hh

Common layout for ee and hh phases

FCC tunnel proposal



FCC-ee design



B-factories: KEKB & PEP-II: double-ring lepton colliders, high beam currents, top-up injection

DAFNE: crab waist, double ring

SuperB-factories, S-KEKB: low β_y^*

LEP: high energy, SR effects

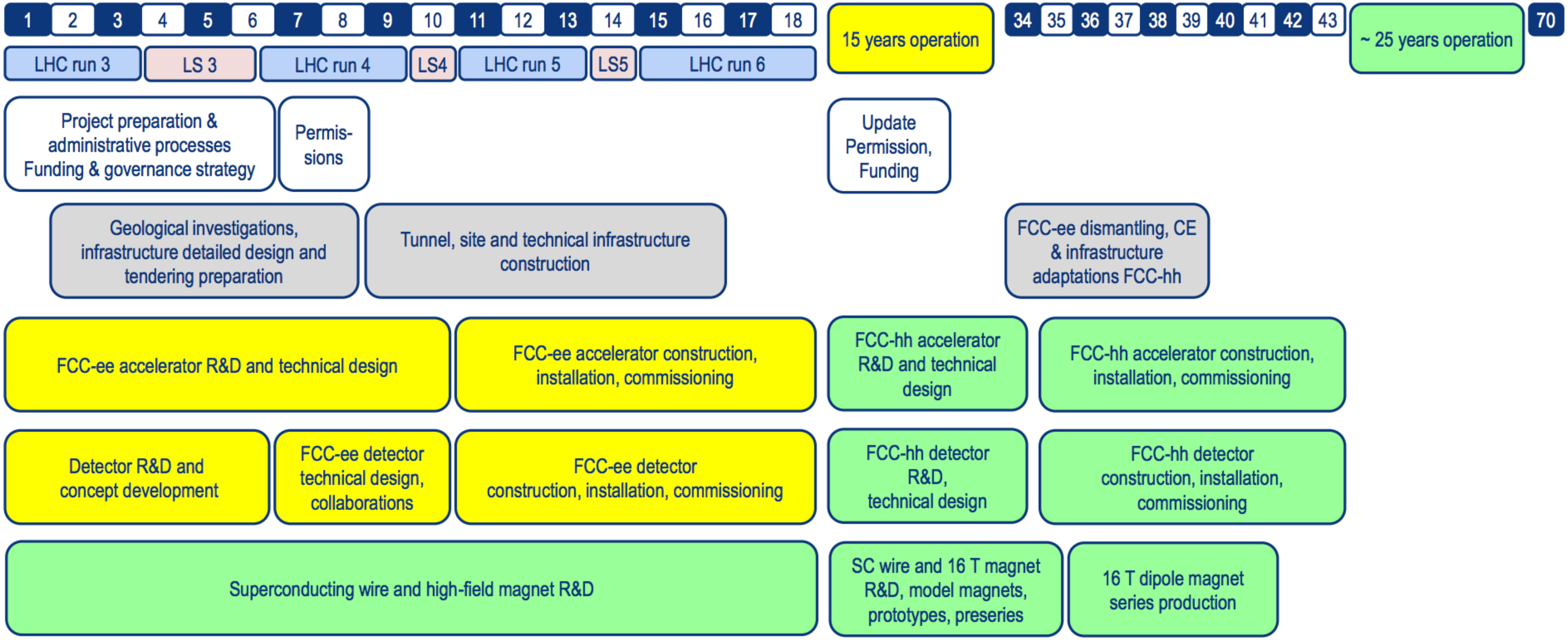
VEPP-4M, LEP: precision energy calibration w. res. depolarisation

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

FCC integrated project schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

LHC run 3

LS 3

LHC run 4

LS4

LHC run 5

LS5

LHC run 6

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

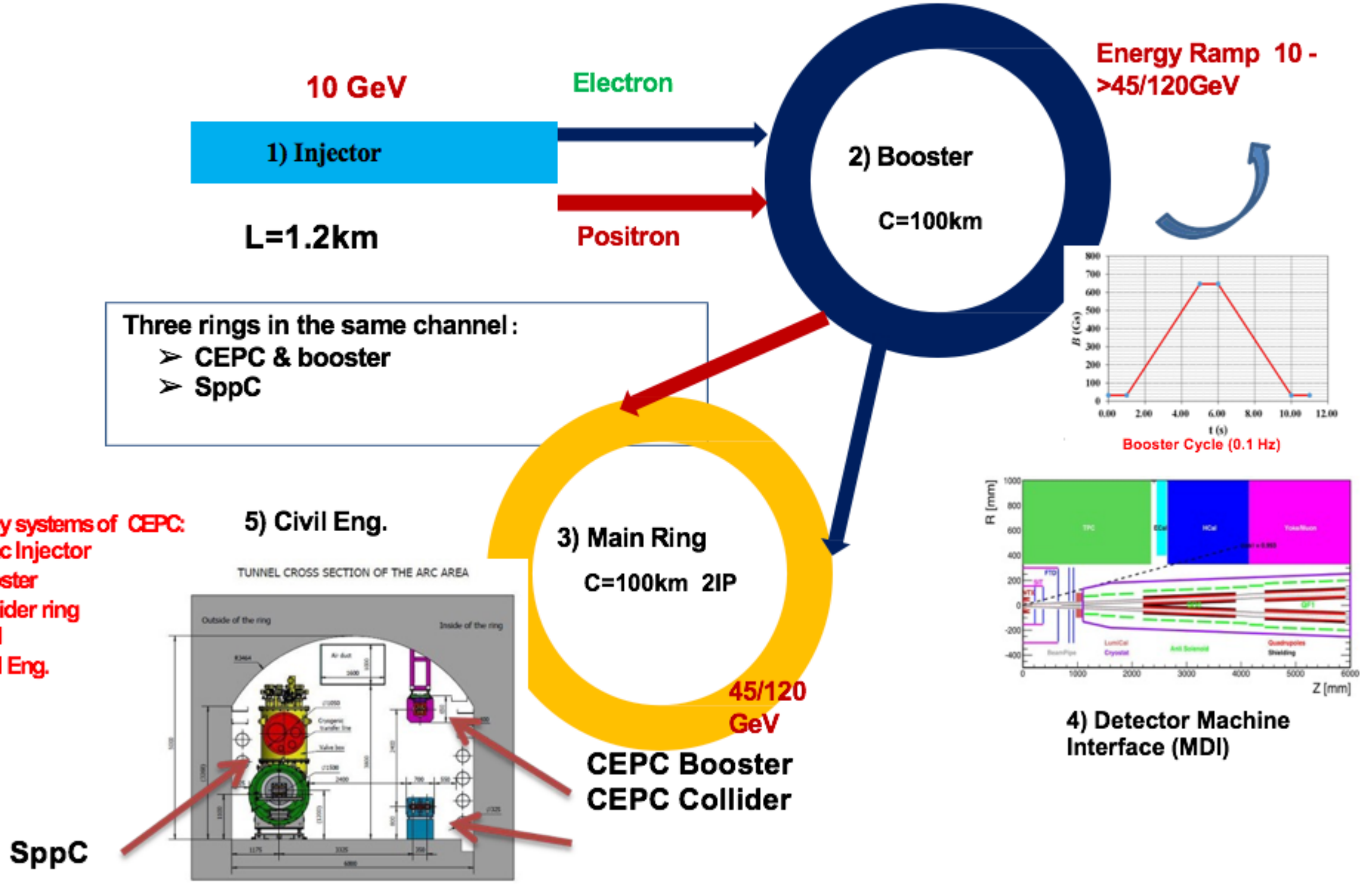
FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

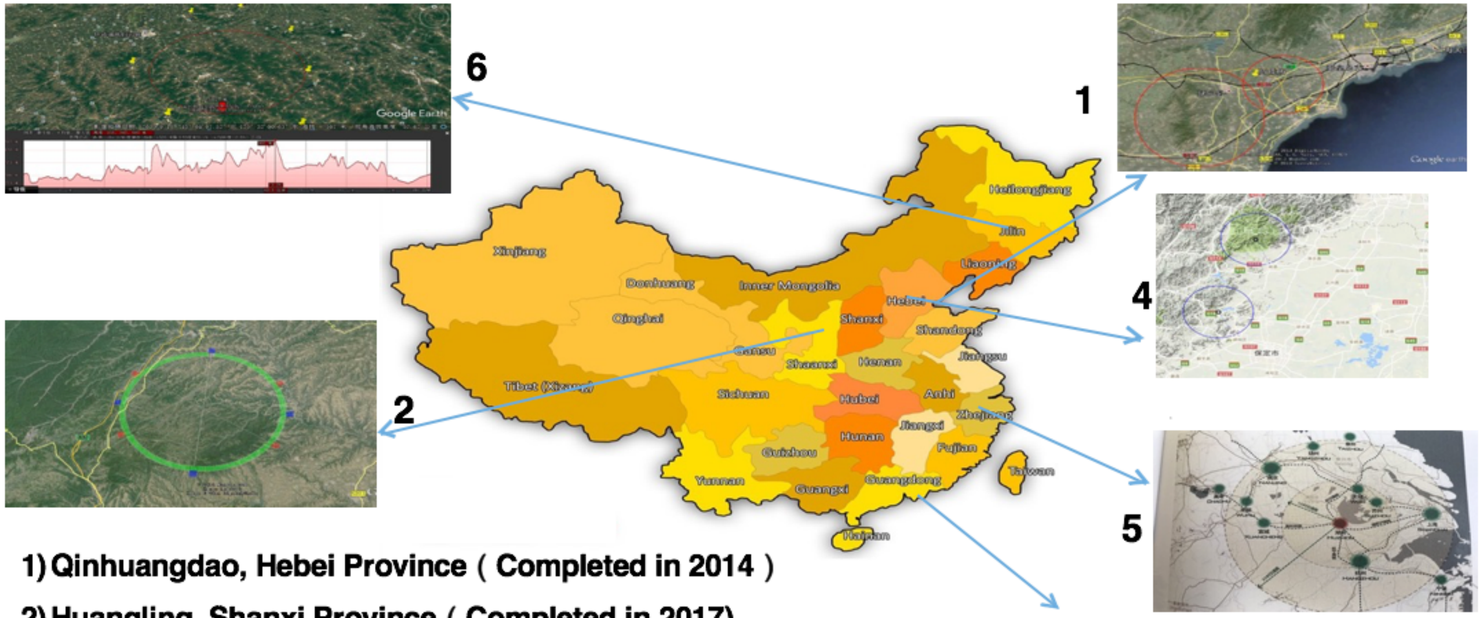
CEPC Accelerator Chain



Three rings in the same channel:
- CEPC & booster
- SppC

The key systems of CEPC:
1) Linac Injector
2) Booster
3) Collider ring
4) MDI
5) Civil Eng.

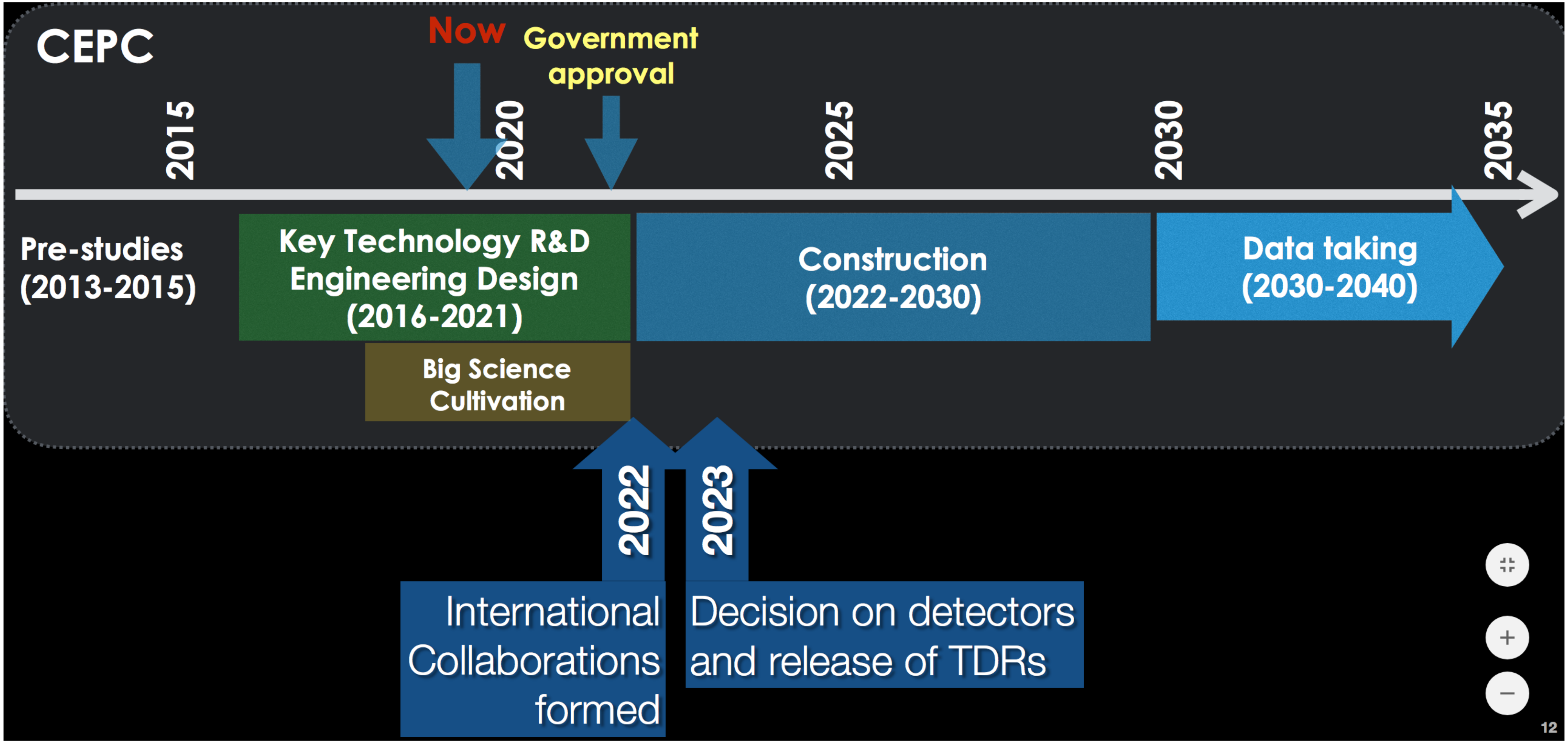
CEPC site selection



1) Qinhuangdao, Hebei Province (Completed in 2014)
2) Huangling, Shanxi Province (Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Changchun, Jilin Province (Started in May 2018)

3

CEPC timeline



CEPC

Now

Government approval

Pre-studies (2013-2015)

Key Technology R&D Engineering Design (2016-2021)

Big Science Cultivation

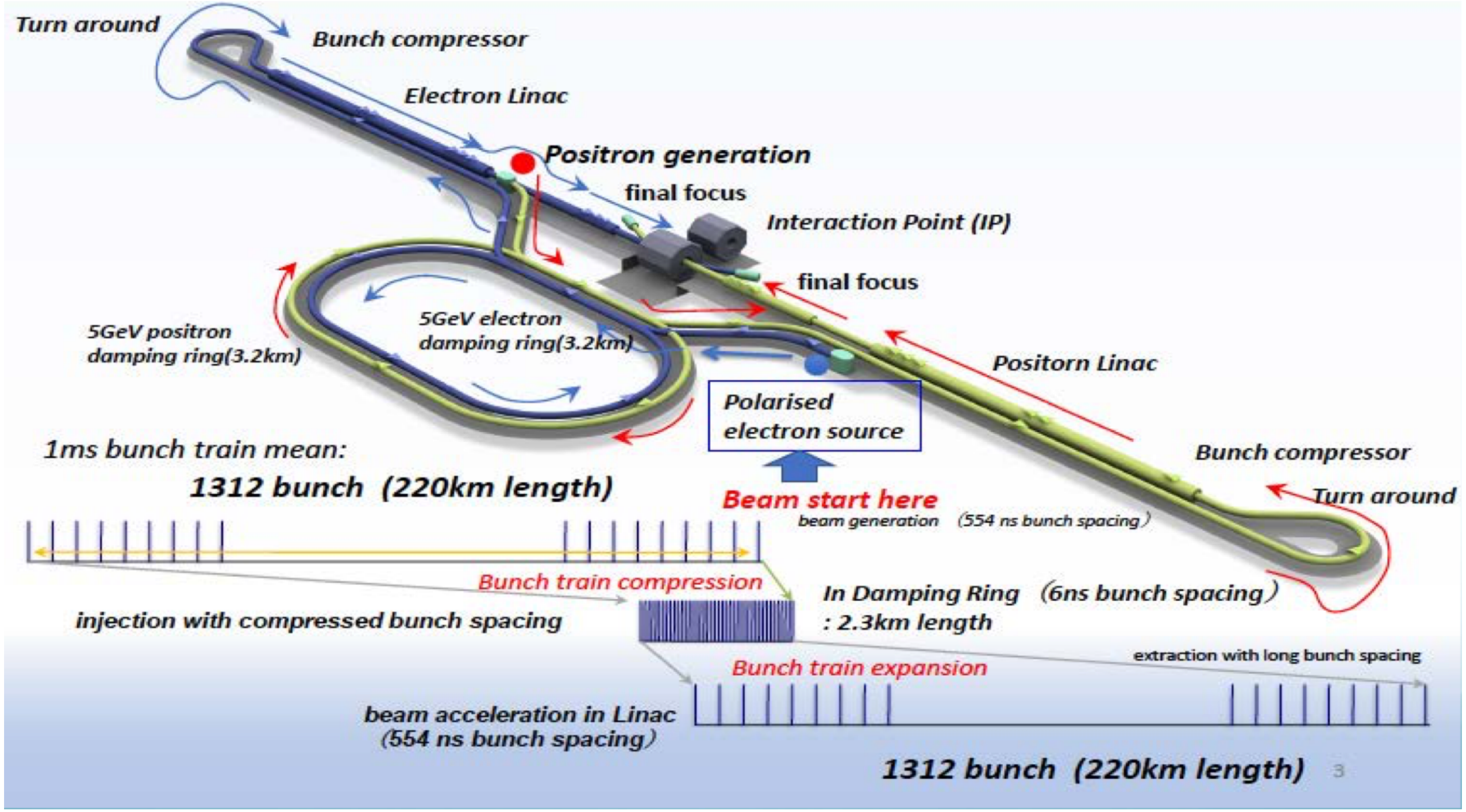
Construction (2022-2030)

Data taking (2030-2040)

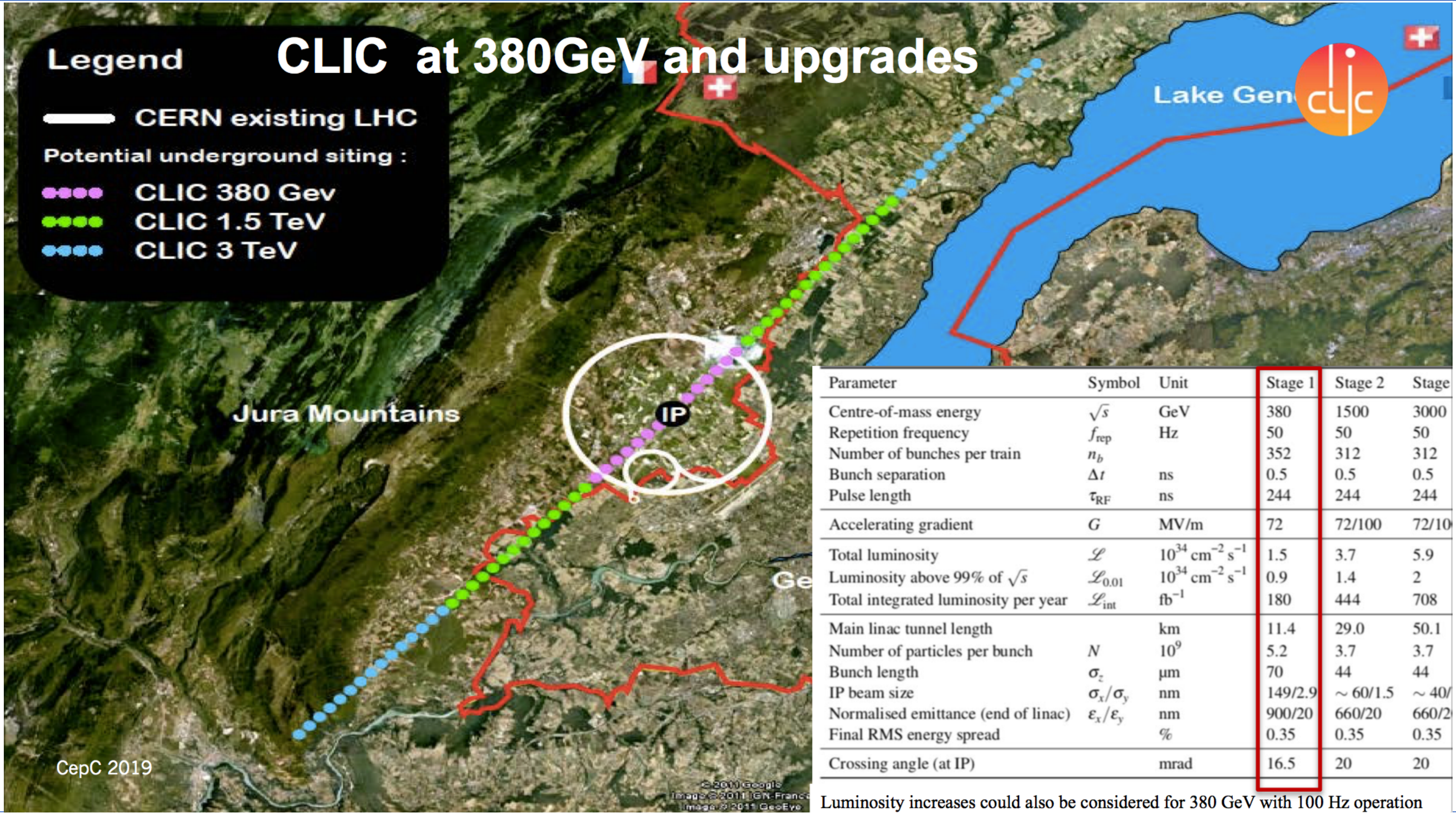
2022: International Collaborations formed

2023: Decision on detectors and release of TDRs

ILC beam accelerator



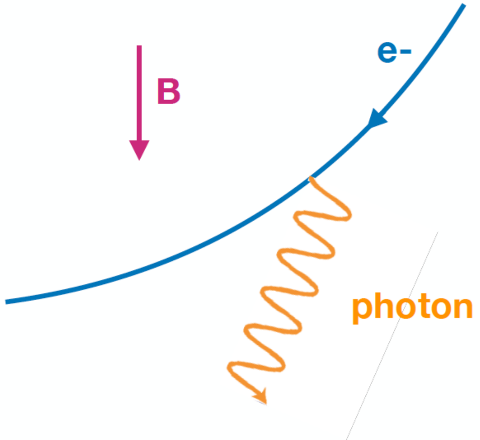
CLIC tunnels



Parameter	Symbol	Unit	Stage 1	Stage 2	Stage
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/10
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-1}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	~ 60/1.5	~ 40/
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	900/20	660/20	660/2
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

Luminosity increases could also be considered for 380 GeV with 100 Hz operation

Accelerating electrons (positrons)



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Proton mass ~2000 m_e

Energy loss reduced by a factor

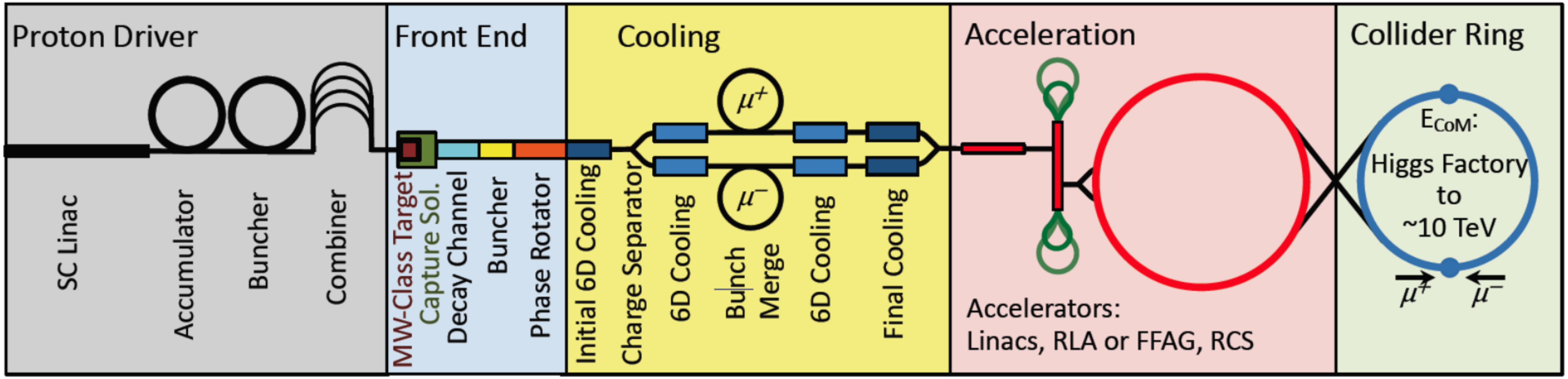
$$\left(\frac{1}{2000}\right)^4 \approx 6 \cdot 10^{-14}$$

Muon mass ~200 m_e

Energy loss reduced by a factor

$$\left(\frac{1}{200}\right)^4 \approx 6 \cdot 10^{-10}$$

Muon colliders – proton driver



Short, intense proton bunches to produce hadronic showers

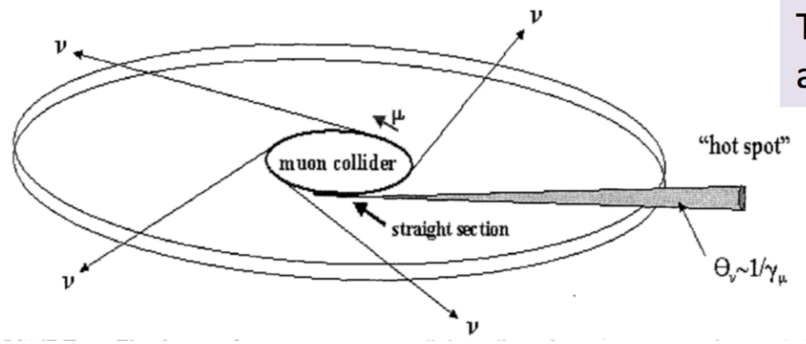
Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

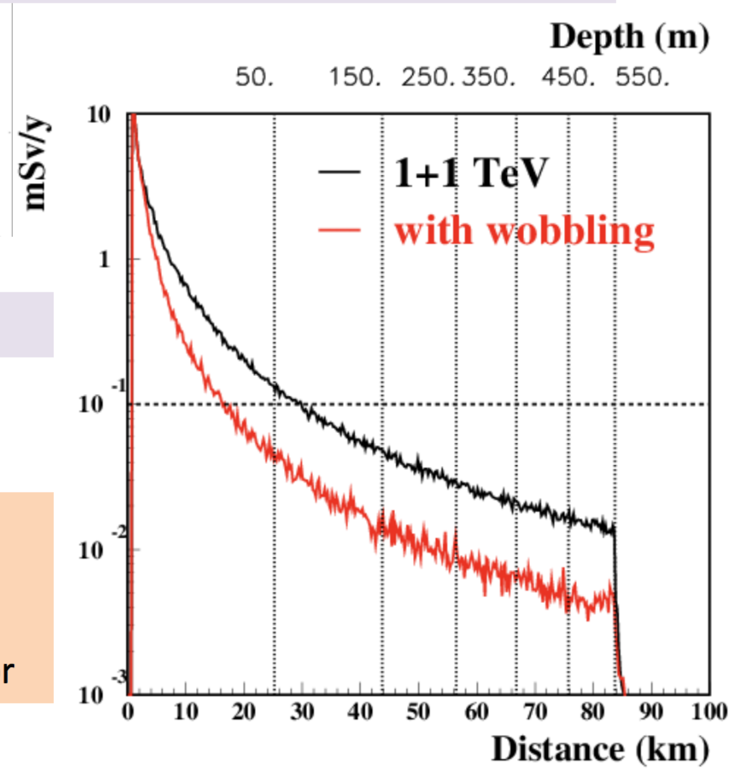
Acceleration to collision energy

Collision

Beam induced background – neutrino radiation hazard



The source, ring or section, is placed at the fixed depth of 550 m.



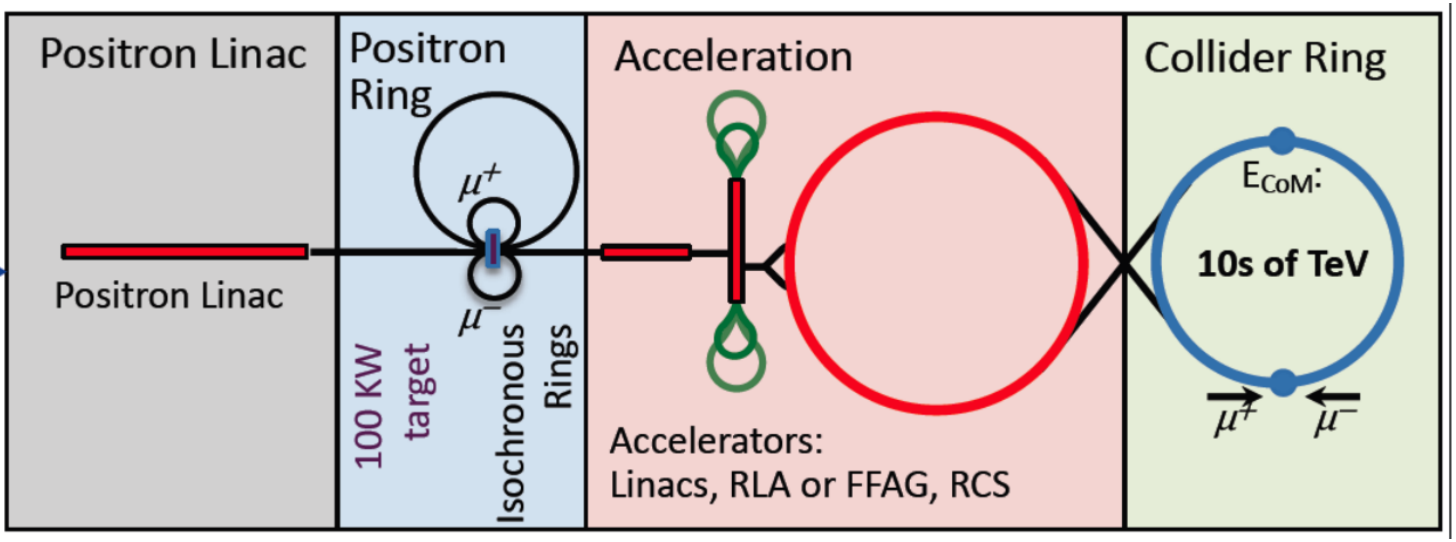
Ambient dose assuming 1.2 × 10^{21} decays/year

Need to study for higher energies (scaling E^3)

Straights in LHC might increase problem
⇒ Another reason to consider this as accelerator

LEMMA schema

Low EMmittance Muon Accelerator (LEMMA): 10^{11} μ 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.



In the LEMMA schema 45 GeV positrons annihilate with the electrons of a beryllium target: a beam of muons and antimuons with collimated energy and emission angle can be obtained.

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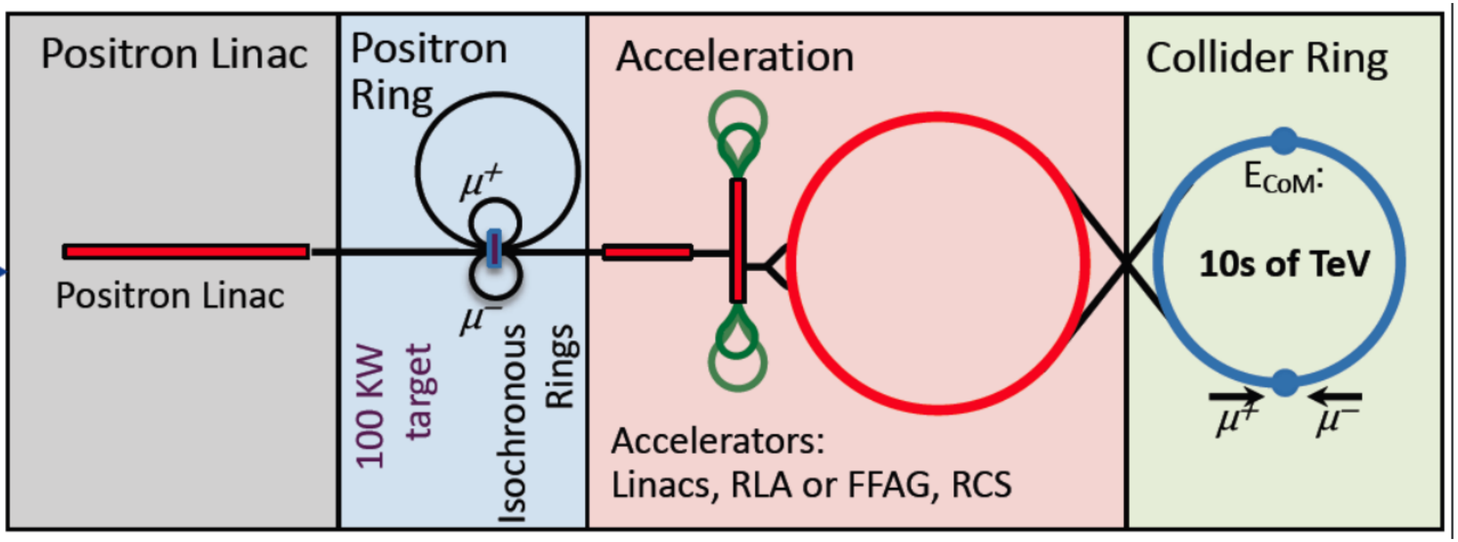


Accelerators:
Linacs, RLA or FFAG, RCS

Small efficiency of converting positrons to muon pairs

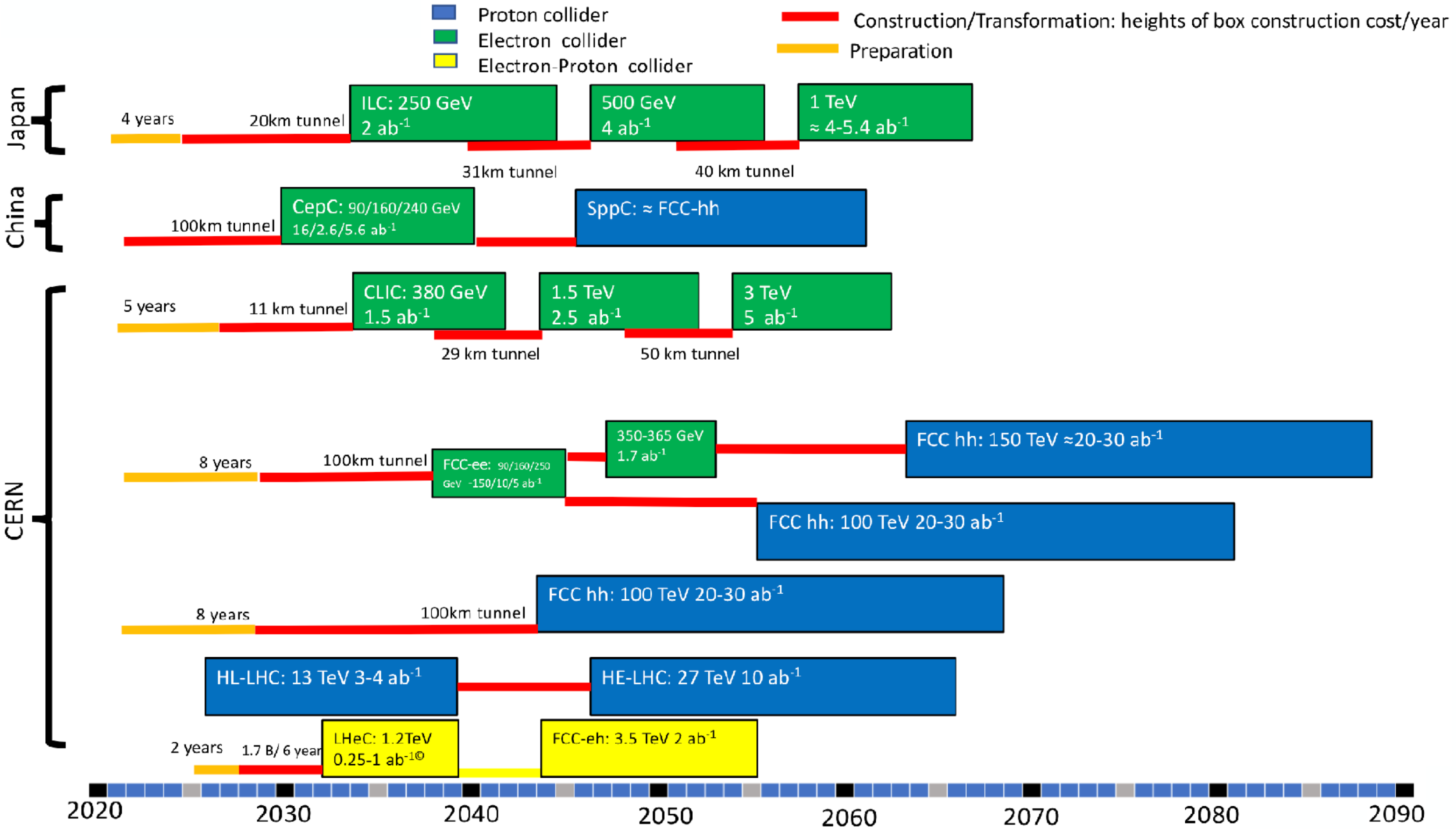
- Muon pair production is only small fraction of overall cross section (O(10-5))
- Most positrons lost with no muon produced
- Have to produce many positrons (difficult)
- O(100MW) synchrotron radiation
- High heat load and stress in target (also difficult)

$e^+e^- \to \mu^+\mu^-$ O(1μb)

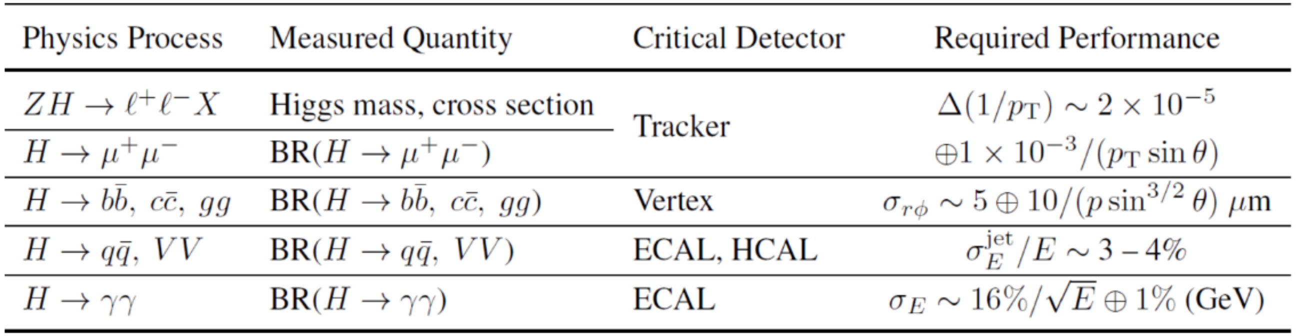
$e^+e^- \to e^+e^-\gamma$

O(100mb), $E_\gamma \geq 0.01\ E_p$

Proposed Schedule

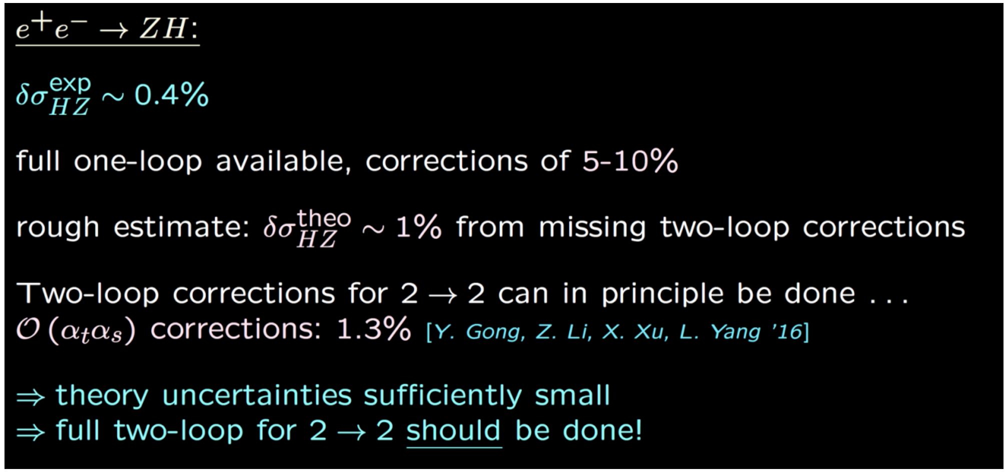


The others ingredients



Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_\mathrm{T}) \sim 2\times 10^{-5} \oplus 1\times 10^{-3}/(p_\mathrm{T}\sin\theta)$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p\sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^\mathrm{jet}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

Detector capability to exploit physic potential



$e^+e^- \to ZH$:

$\delta\sigma_{HZ}^{\mathrm{exp}} \sim 0.4\%$

full one-loop available, corrections of 5-10%

rough estimate: $\delta\sigma_{HZ}^{\mathrm{theo}} \sim 1\%$ from missing two-loop corrections

Two-loop corrections for $2 \to 2$ can in principle be done . . .
$\mathcal{O}(\alpha_t\alpha_s)$ corrections: 1.3% [Y. Gong, Z. Li, X. Xu, L. Yang '16]

⇒ theory uncertainties sufficiently small
⇒ full two-loop for $2 \to 2$ should be done!

Availability of large statistics will bring the measurements quickly systematic-limited

HVALA