LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

[Future Collider Projects]

P. Conde Muíño

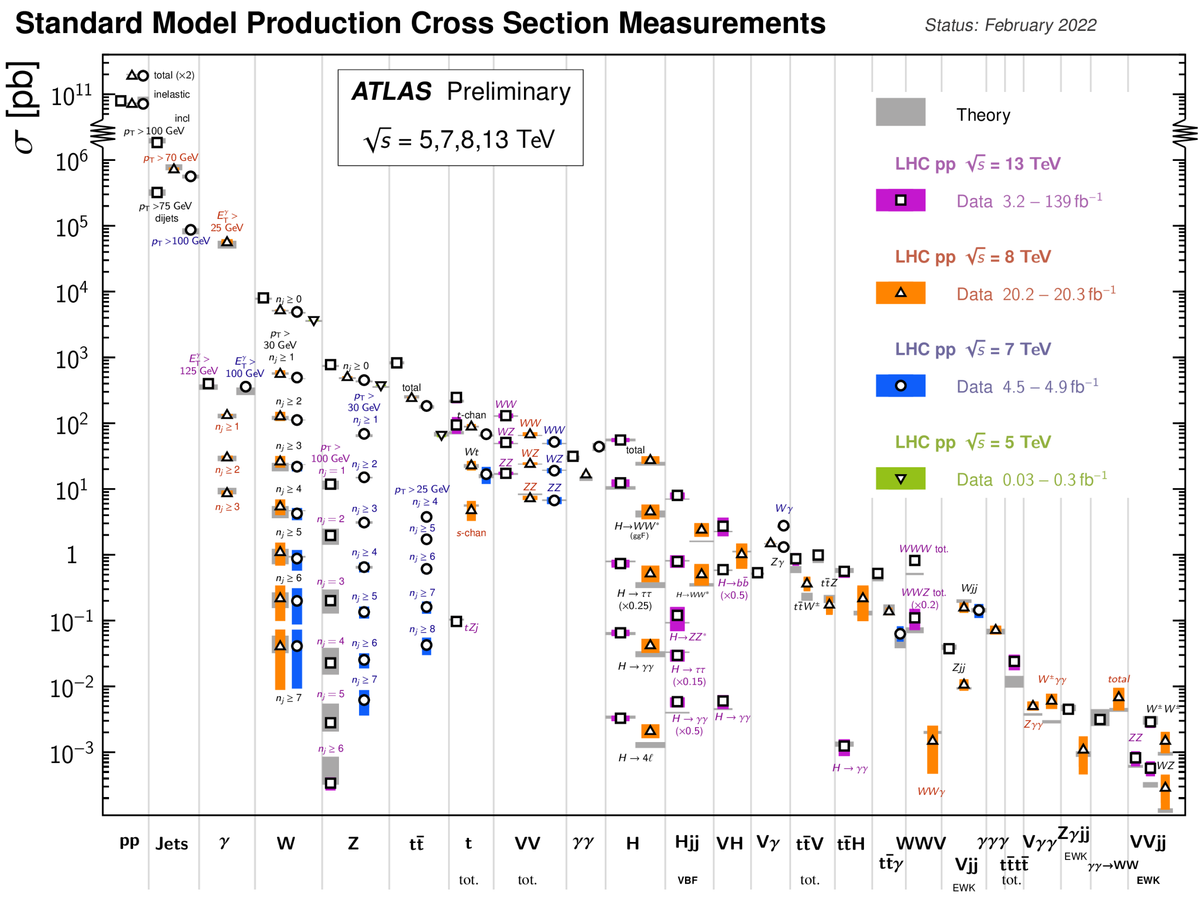
Disclamer

- I've been given the draconian task of summarising a wealth of colliders/physics measurements in 15 min
  - Many possible future colliders
  - Many different physics studies
  - Very few up to date comparisons
  - A lot of developments in the last months

I will try my best to offer an unbiased discussion about the different options

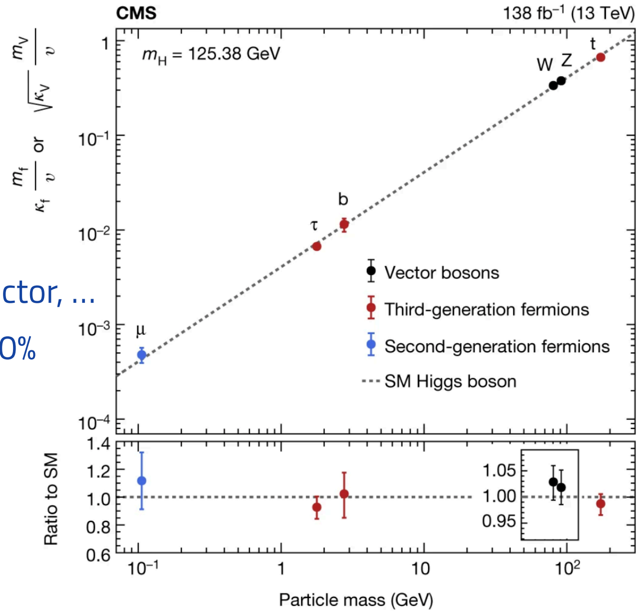
Standard Model Measurements

14 years of SM measurements @ LHC

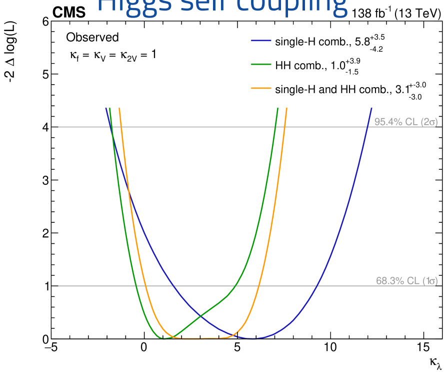


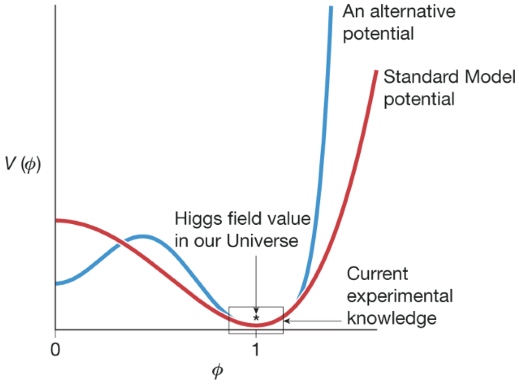
12 years of Higgs boson measurements

- Discovery of the Higgs boson
- Measured
  - its interactions with W, Z, t, b, τ, μ
  - Spin/CP properties
- Searched for new physics: exotic decays, CP-violation in the Higgs sector, …
- Overall, results show good agreement with the SM expectations 3-20%
- Limited sensitivity to the Higgs self interaction

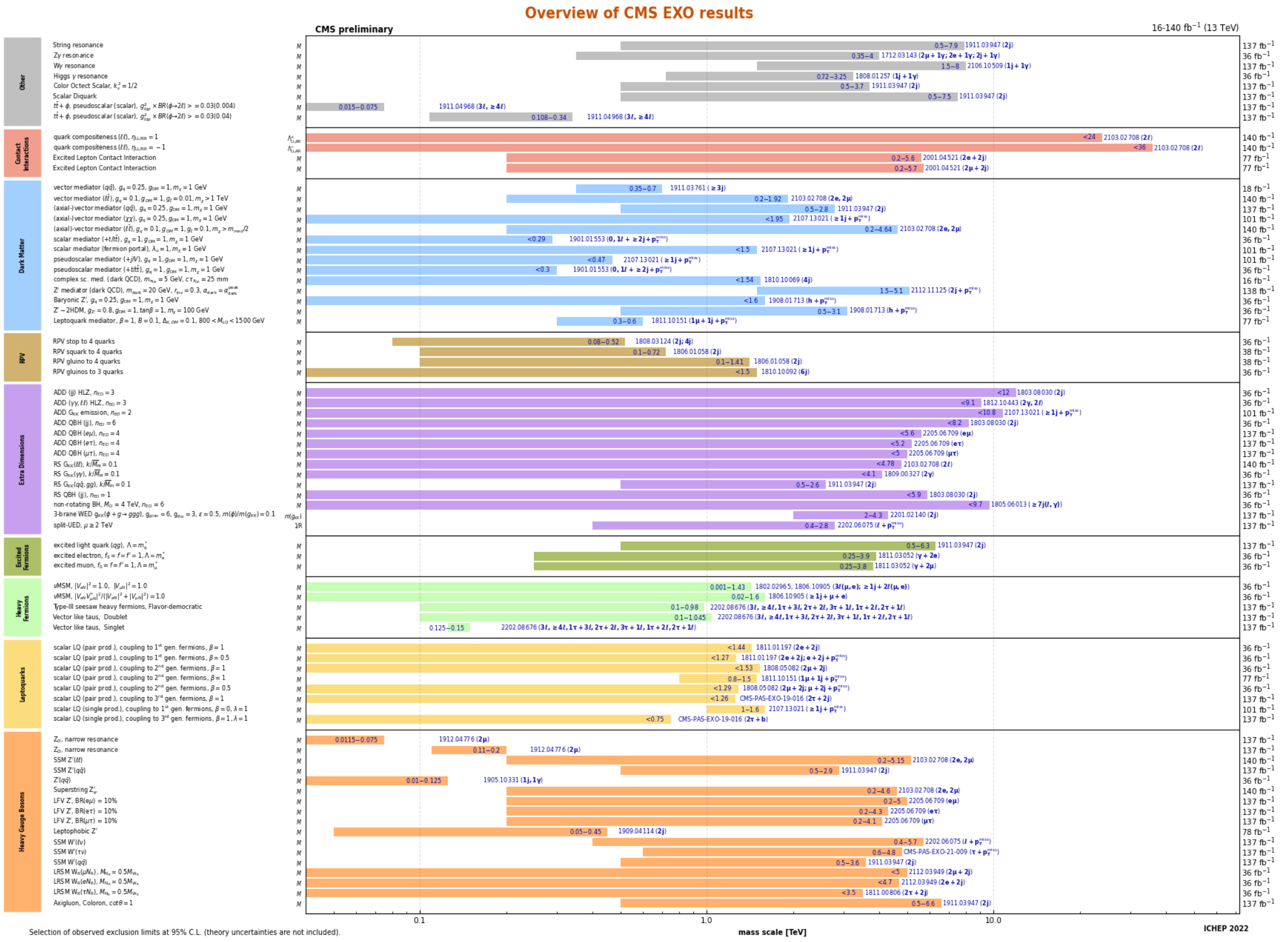


Higgs self coupling





Searches for new exotic particles at the LHC



*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).

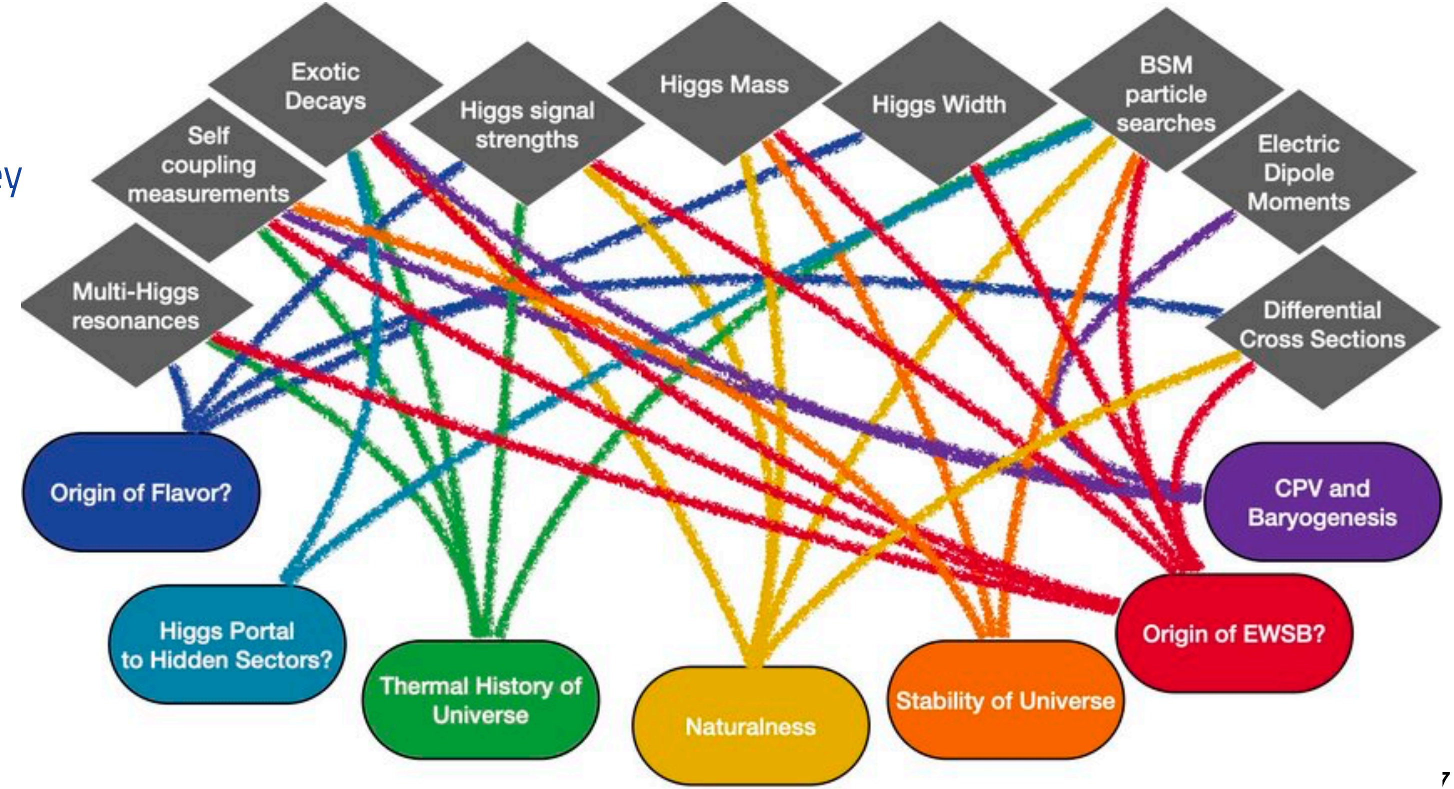
Many unanswered questions remain…

- Why is there a matter-antimatter asymmetry in the Universe?
- What are dark matter and dark energy?
- Why is gravity so weak?
- Why is the Higgs boson so light (naturalness/hierarchy problem)?
- What is the origin of flavour?
- What is the origin of neutrino masses and oscillations?
- Is the Universe stable?
- …

Measuring the Higgs boson properties precisely

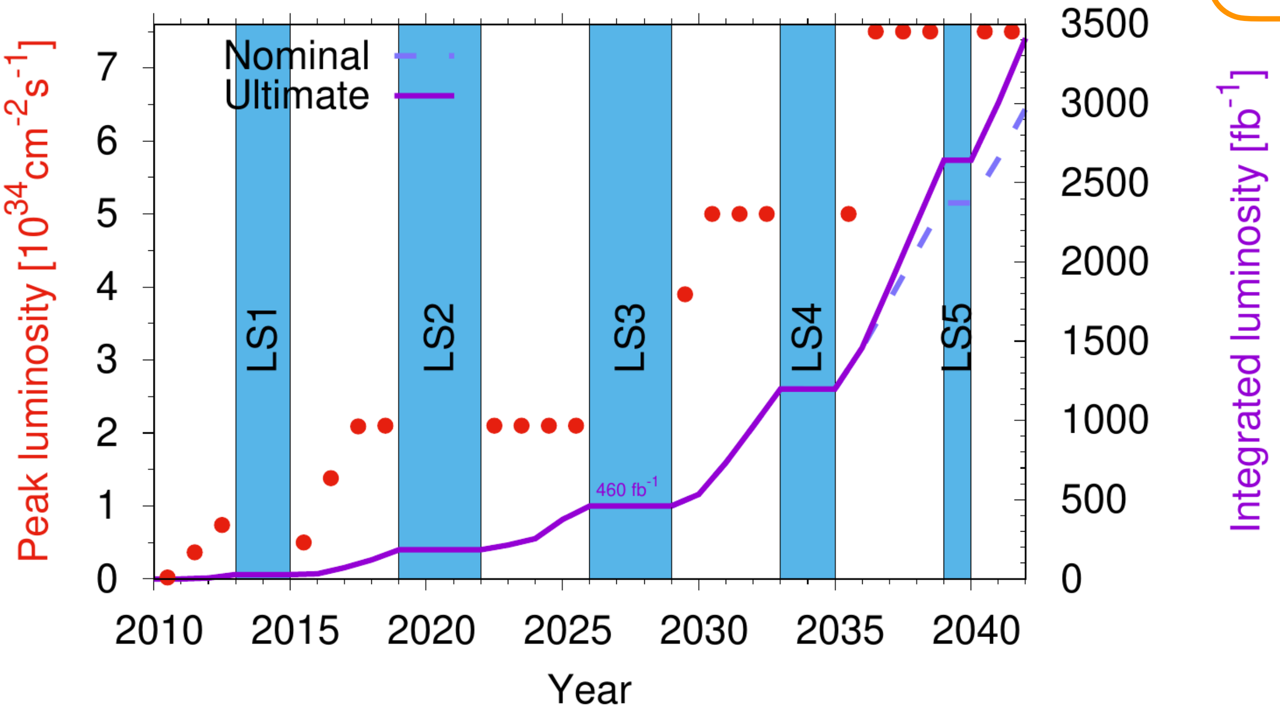
- The Higgs Boson may provide the key to answer some of these questions

- Precision measurements of the Higgs properties are a must

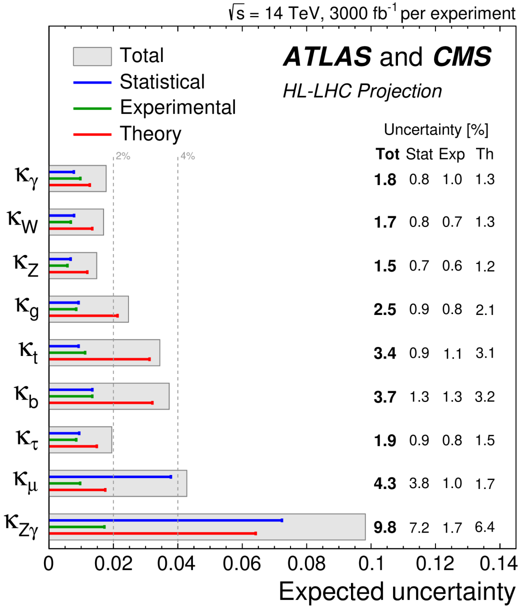


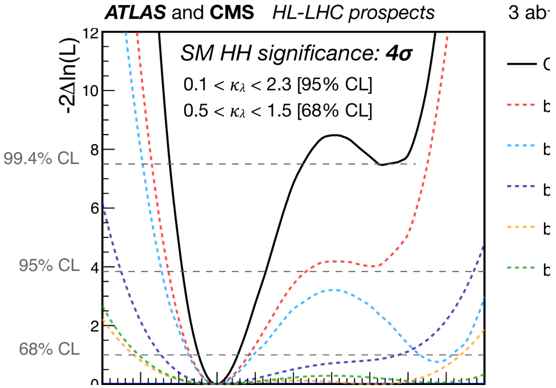
HL-LHC: the next Future Collider!

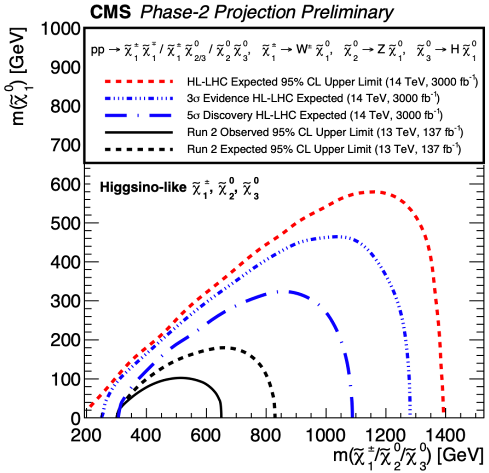
10 times higher integrated luminosity up to 2040!

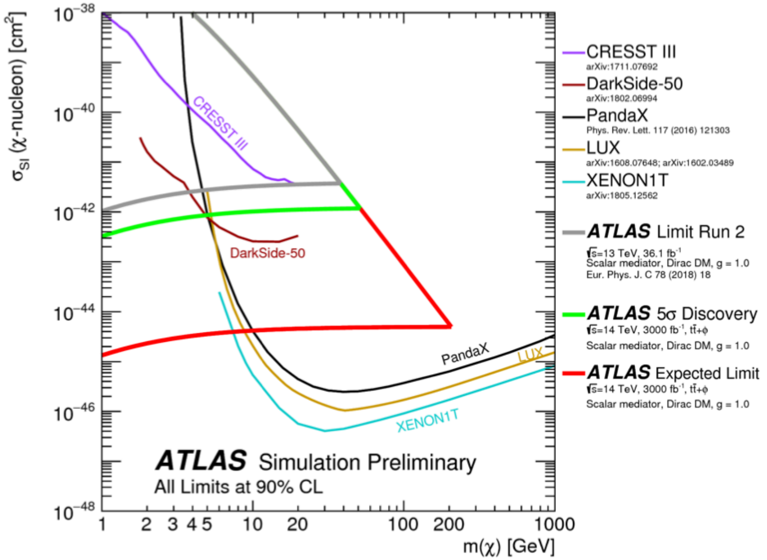


High Luminosity LHC expectations- Examples









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ATL-PHYS-PUB-2022-018

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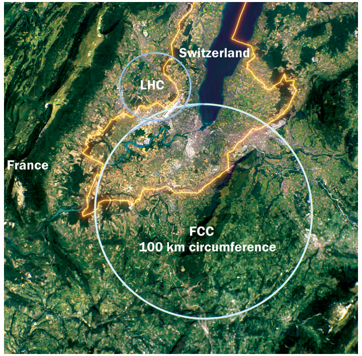
The LHC is and should continue to be the highest priority!

?

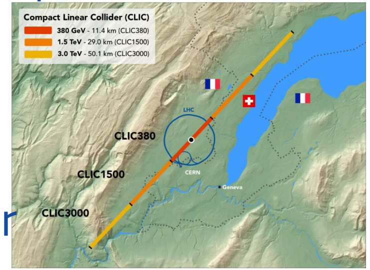
What’s next?



Future Circular Collider

International Linear Collider

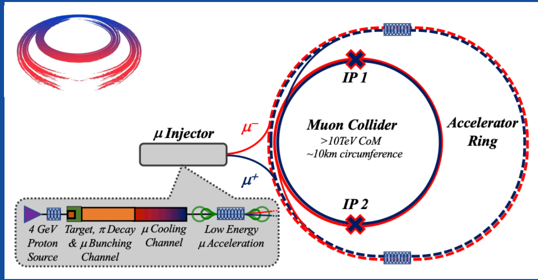
Compact Linear Collider



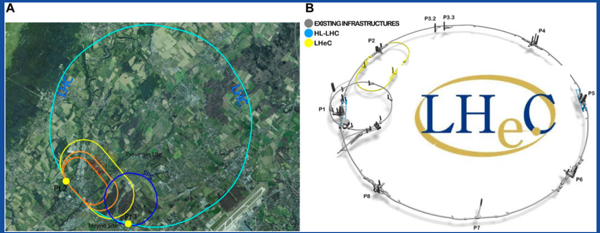
Circular Electron Positron Collider

Future Colliders

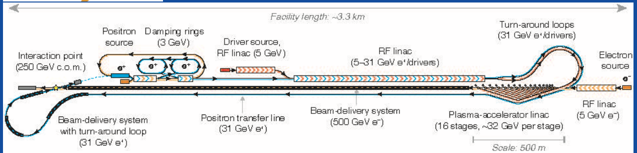
International Muon Collider



Energy Recovery LINACs



HALHF Plasma accelerators

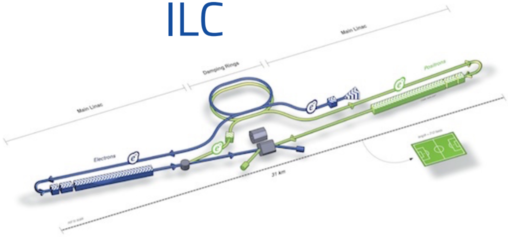


e^+e^- colliders — operation goals

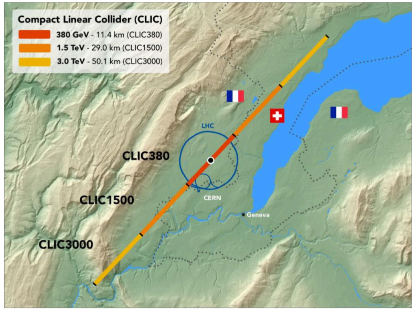
Linear

Circular

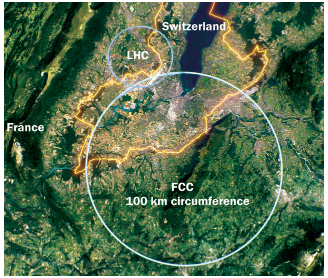
ILC



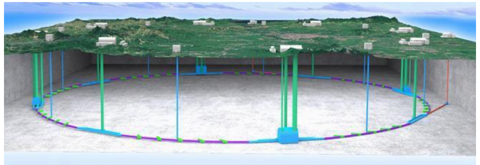
CLIC



FCC



CEPC



ILC, Japan*

- 250 GeV- 300 GeV - 500 GeV- 1000 GeV
- Polarisation: $\pm 80, \pm 30$

*A similar option has been proposed @CERN! (LCV2025)

CLIC, CERN

- 380 GeV, 1500 GeV, 3000 GeV
- Polarisation: ± 80

FCC-ee, CERN

- Energy: $m_Z, 2 \times m_W$, 240 GeV, $2 \times m_t$
- No polarisation
- 4 interaction points

CEPC, China

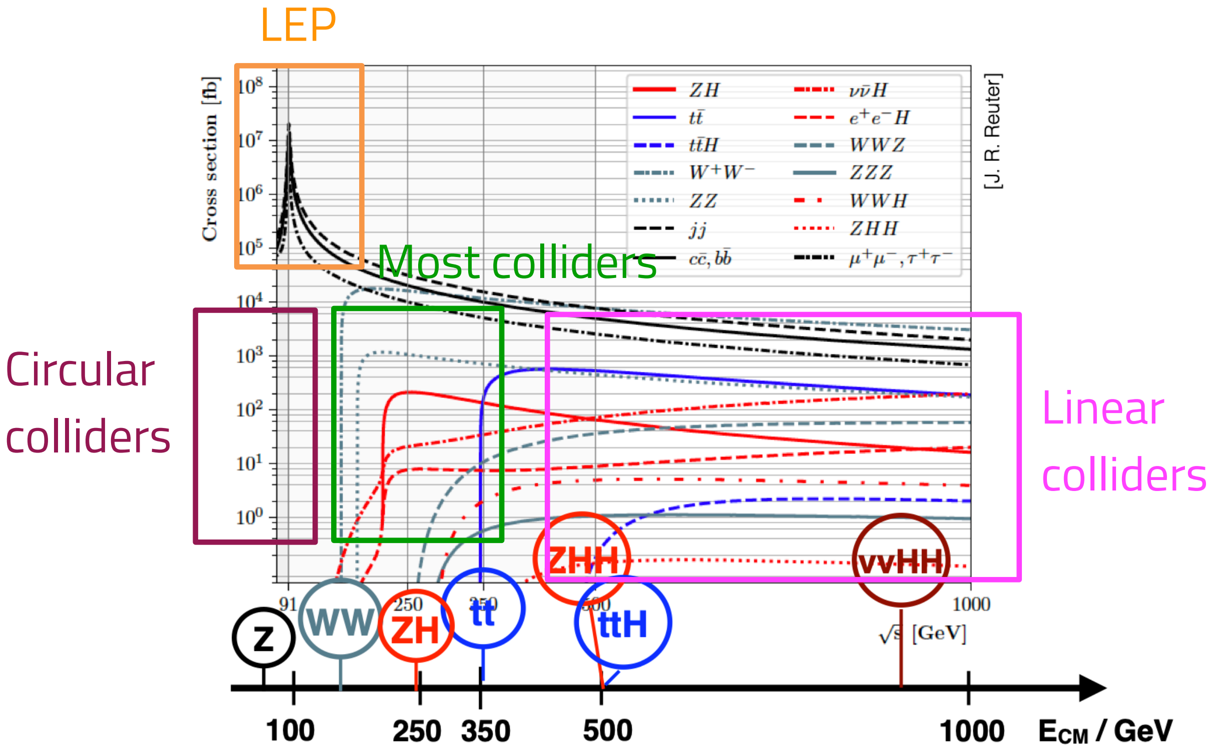
- $m_Z, 2 \times m_W$, 240 GeV, upgrade: $2 \times m_t$
- No polarisation
- 2 interaction points (could be 4)

Same tunnel can hold a hh collider @ ~100 TeV

Linear versus circular

	Linear	Circular
Energy	$E = eGL$ With e = electric charge, G = gradient, L = length	$E \propto B\rho$ With B = magnetic field, ρ = average bending radius
Advantages:	Can go up to higher energies Polarised beams	Can reach higher instantaneous luminosities More than 1 interaction point possible
Limitations:	Cost ∝ Energy	Energy limited by synchrotron radiation $\propto \frac{E^4}{m^4\rho}$

e^+e^- physics menu



Adapted from J. List, LCW2024

e^+e^- physics menu

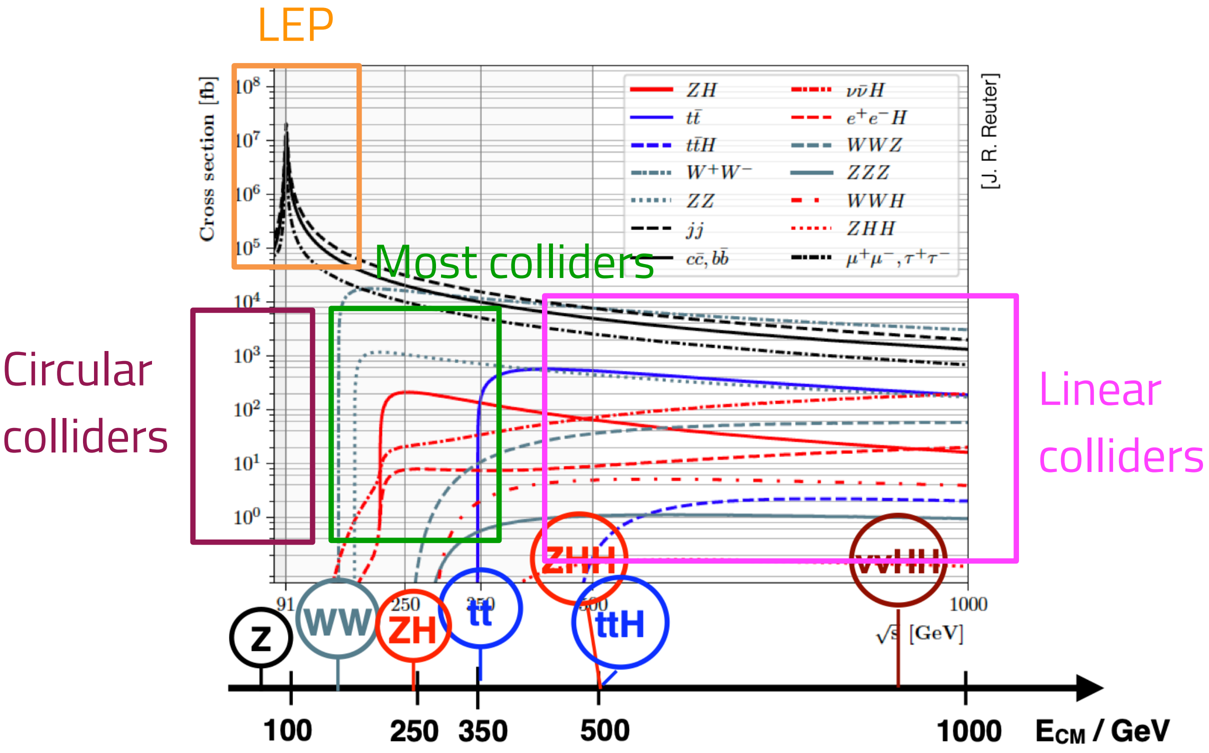
High energy opens new possibilities

500…600 GeV, 4 ab-1:

- Higgs self-coupling in ZHH
- Top quark EW couplings
- Top Yukawa coupling (incl CP structure)
- improved Higgs, WW and ffbar
- probe Higgsinos up to ~300 GeV
- probe Heavy Neutral Leptons up to ~600 GeV

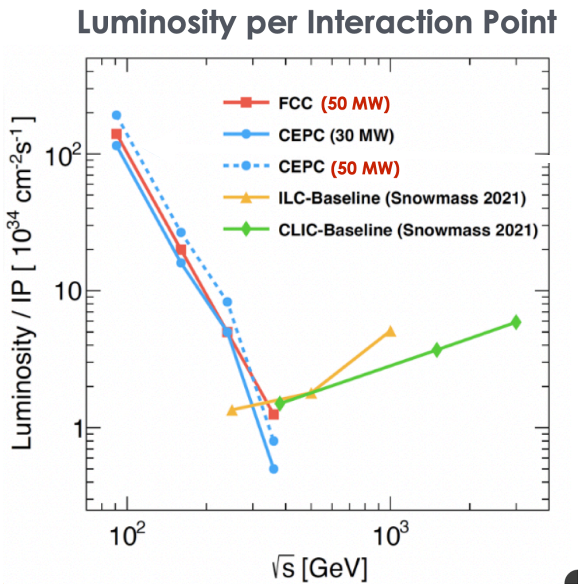
800…1000 GeV, 8 ab-1:

- Higgs self-coupling in VBF
- further improvements in tt, ff, WW, ….
- probe Higgsinos up to ~500 GeV
- probe Heavy Neutral Leptons up to ~1000 GeV
- searches, searches, searches,



Adapted from J. List, LCW2024

e^+e^- colliders — energies and luminosities



J. Guimarães, Seminar@LIP

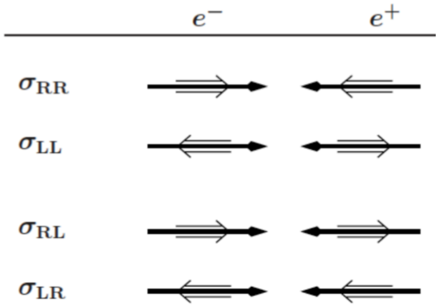
Proposal	CEPC		FCC-ee		CLIC	ILC‡
Lum./IP [10^{34} cm^{-2}s^{-1}]	5.0	0.8	7.7	1.3	2.3	2.7
Number of IPs	2	2	4 (2)	4 (2)	1	1
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	276	430
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.2	1.6
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.6	0.82

S. Stapnes, CEPC Workshop, Edinburg, July 2023

Default scenarios:

- FCC-ee: 50 MW, with 4 interaction points
- CEPC: 30 MW (if fully paid by China) with 2 interaction points
  - 4 will be possible
  - 50 MW scenario possible with international contributions

Polarisation



Longitudinal polarisation expected at linear colliders

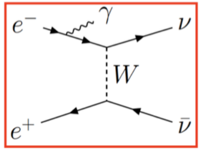
- Cross sections can be enhanced/reduced
- Background control
- Improves as well efective operators fits (tuning of the cross sections)

Table 3.2: The dependence of the event rates for the s-channel $e^+e^- \to ZH$ process and the pure t-channel $e^+e^- \to H\nu_e\nu_e$ and $e^+e^- \to He^+e^-$ processes for several example beam polarisations [24].

Polarisation	Scaling factor		
$P(e^-):P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
$-80\,\%$: $0\,\%$	1.12	1.80	1.12
$-80\,\%$: $+30\,\%$	1.40	2.34	1.17
$-80\,\%$: $-30\,\%$	0.83	1.26	1.07
$+80\,\%$: $0\,\%$	0.88	0.20	0.88
$+80\,\%$: $+30\,\%$	0.69	0.26	0.92
$+80\,\%$: $-30\,\%$	1.08	0.14	0.84

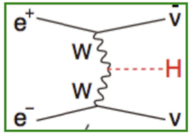
background suppression:

- $e^+e^- \to WW$ / $\nu\nu$ strongly P-dependent since t-channel only for $e^-_L e^+_R$



signal enhancement:

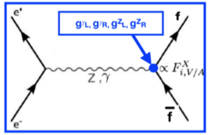
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions
- BSM: chiral structure unknown, needs to be determined!



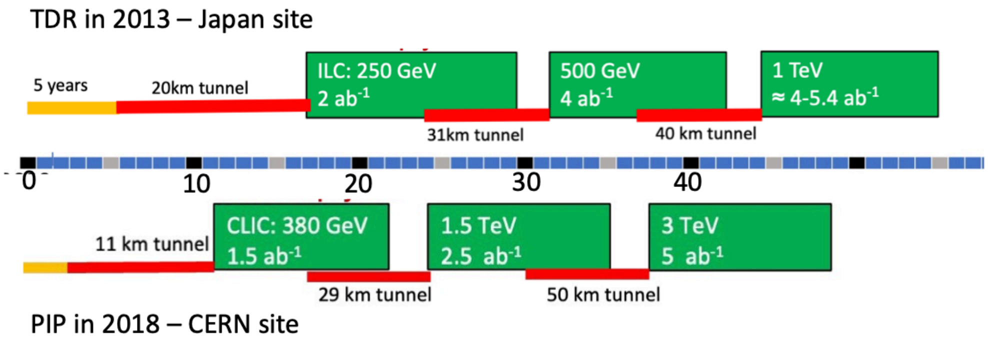
redundancy & control of systematics:

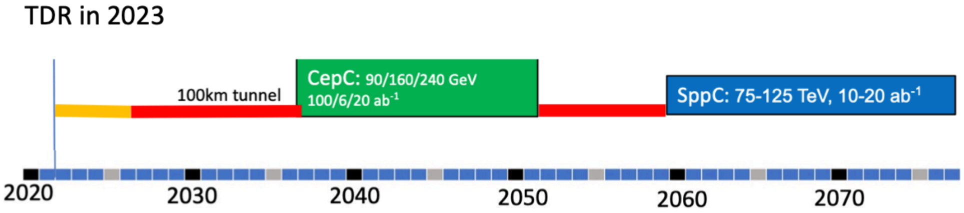
- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

J. List, arXiv:2012.11267v2

Schedules

Dates of possible approval still to be defined





From P. Campana, LCW2024

Cost of the projects

Other relevant figures to take into account

- Time and cost of operations
- Sustainability issues

(See A. Blondel et al.)

From P. Campana, LCW2024

HERA cost 0.7 G$
~20% non-german contributions
LEP cost 1.4 G$

LHC cost 5 G$
benefitting of LEP tunnel + 15% NMS contributions

FCCee cost 12 G$

CEPC cost 5 G$

ILC cost 7 G$

However, CEPC baseline cost can be covered by China!

Alternative Projects

Muon Collider

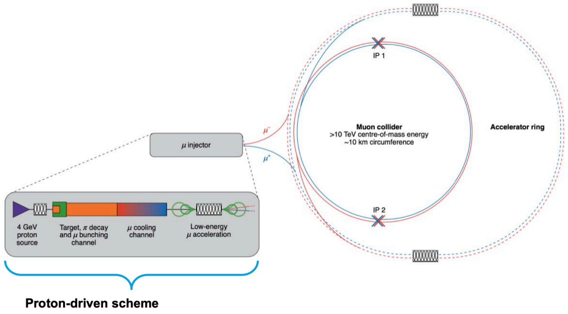
HALPH

Asymmetric e^+e^- collider
C.o.M. energy: 250 GeV
Plasma Wakefield acceleration

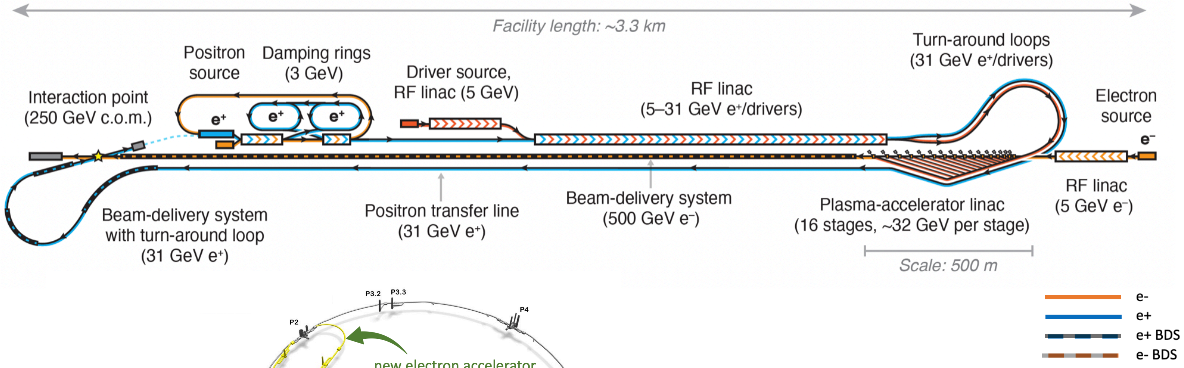
LHeC

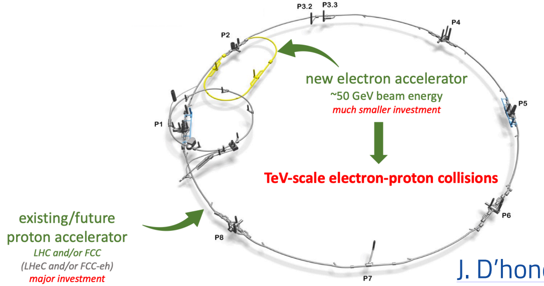
Energy-recovery LINAC
>1 TeV ep collisions

Less mature but… very interesting!



Smaller synchrotron radiation allows higher C.o.M. energy (10 TeV!)



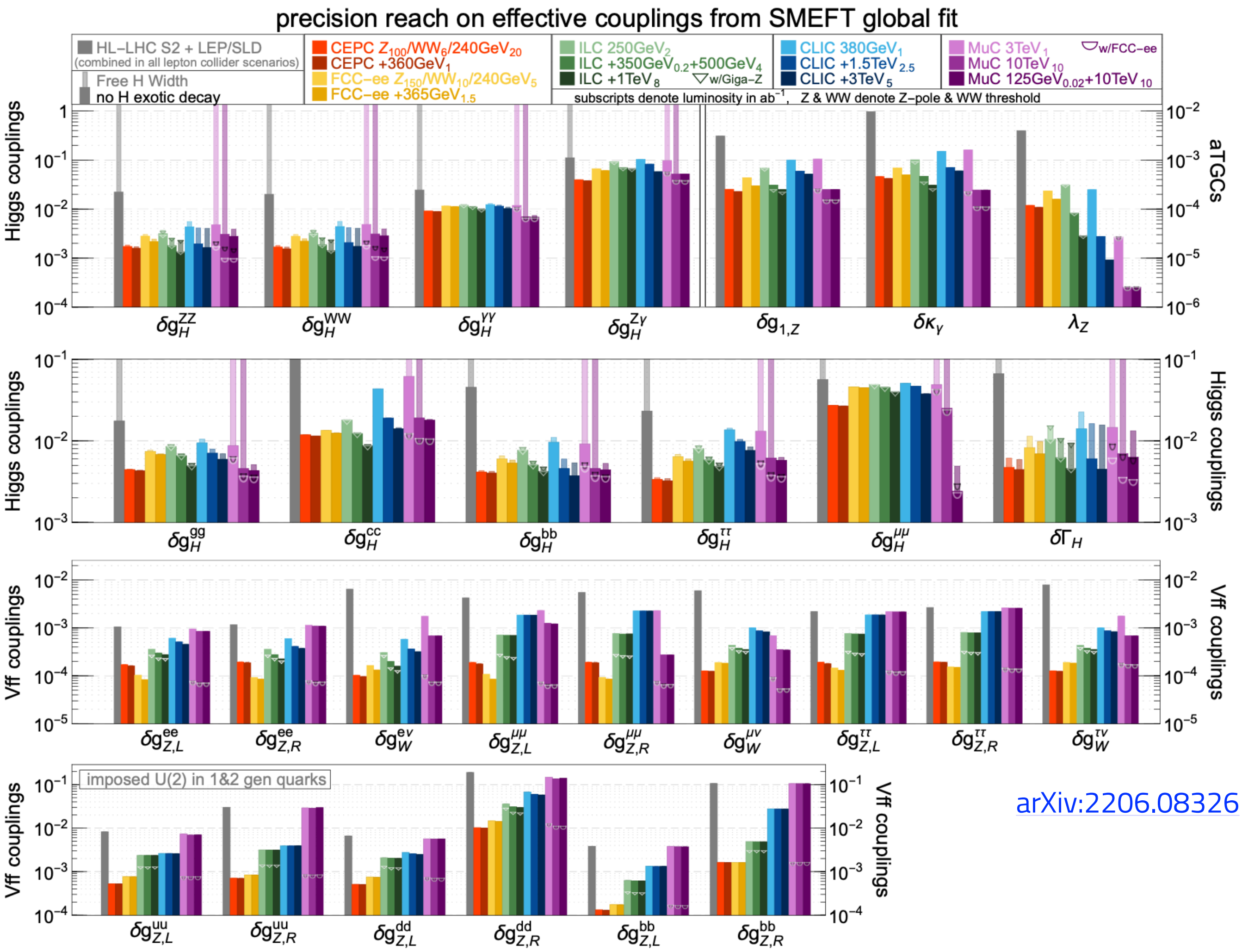


Opens the possibility of additional physics topics

J. D'hondt, ICHEP 2024

Physics Reach

- Combined EFT Fit
- HL-LHC combined with all collider hypothesis
- Circular colliders provide better sensitivity for more parameters



arXiv:2206.08326

Higgs self-coupling

M. Mühlleitner

Precision on Trilinear Higgs Self-Coupling

Collider / Observable	LHC	HL-LHC	FCC-ee365	CEPC	ILC	CLIC	Muon Collider	HE-LHC 27TeV, 15ab^{-1}	FCC-hh
Single Higgs $\lvert\delta_{h^3}^{exp}\rvert$			FCC-ee w/HL-LHC **33%** [55] FCCee4IP w/HL-LHC **24%** [55]	CEPC240 + HL-LHC **35%** [82]	ILC250/ $C^3$250 **49%** [51,52]	CLIC380 **50%** [54]			
Di- Higgs $\lvert\delta_{h^3}^{exp}\rvert$	**-1.4-7.5** [3,4]	**50%** [5,6]			ILC500/ $C^3$550 **20%** [10,51,52] ILC1000 **10%** [7]	CLIC1500 **36%** [54] CLIC3000 **~9%** [9,54]	Muon3TeV **15-30%** [64] Muon10TeV **4%** [64]	95%CL **~30%** [11] 68%CL **~15%** [11]	30 ab^{-1} **3.4-7.8%** [79]

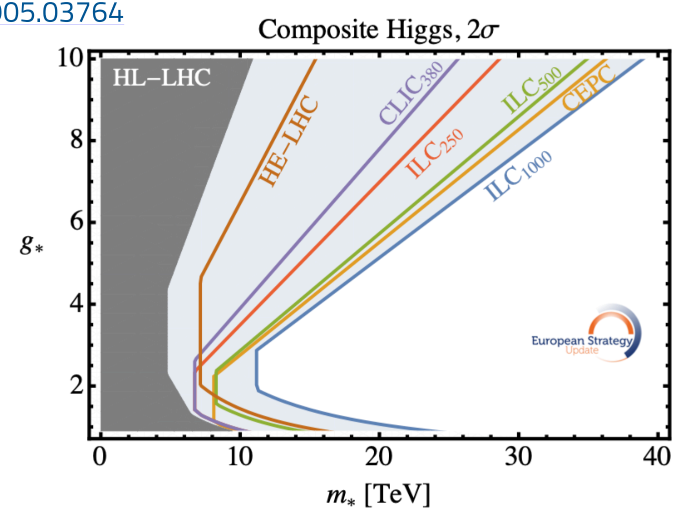
arXiv:1905.03764

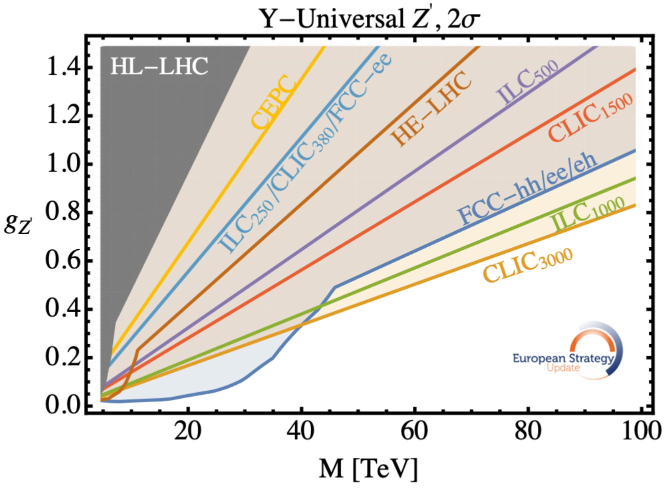
New Physics Exclusion Reach

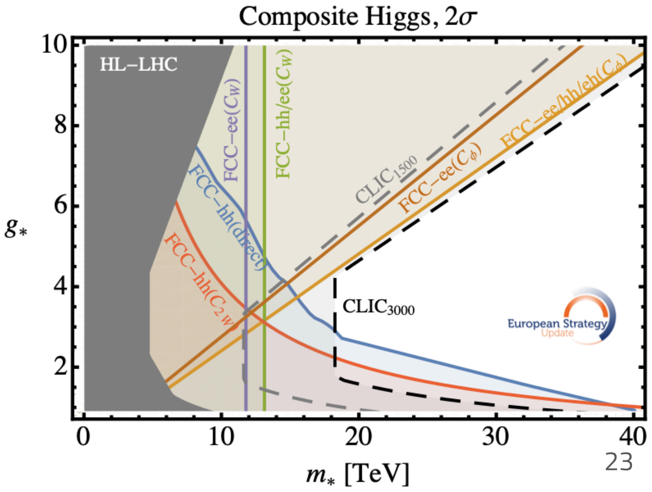
Examples of exclusion limits from ESUPP 2020

- Numbers are likely outdated!

Complementarity between linear and circular colliders!







arXiv:1905.03764

Complementarity of colliders

Ultimate precision (1-4‰) obtained with a combination of all colliders

- Numbers are likely outdated! (Many studies ongoing)

Circular e^+e^- +hh + eh

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

FCC-ee (or CEPC)

eh+hh

FCC-hh (CEPC-hh?)

Which collider is better?

- Which project will cover the widest physics programme?
- Which one will have the best precision?
- Which one should it be the next big project at CERN?
- Do we want Europe leading collider physics?
- Shall we support an e^+e^- collider outside Europe?
- Shall we bet on new technologies?
- ...

Thanks!

Acknowledgments

REPÚBLICA PORTUGUESA

FCT Fundação para a Ciência e a Tecnologia

Backup

A. Blondel, C. Grojean, P. Janot, G. Wilkinson, arXiv: 2412.13130

Table 1: Scenarios for future collider options considered in this note for the measurement of Higgs properties. The changes with respect to Ref. [11] are highlighted in bold and explained in the text.

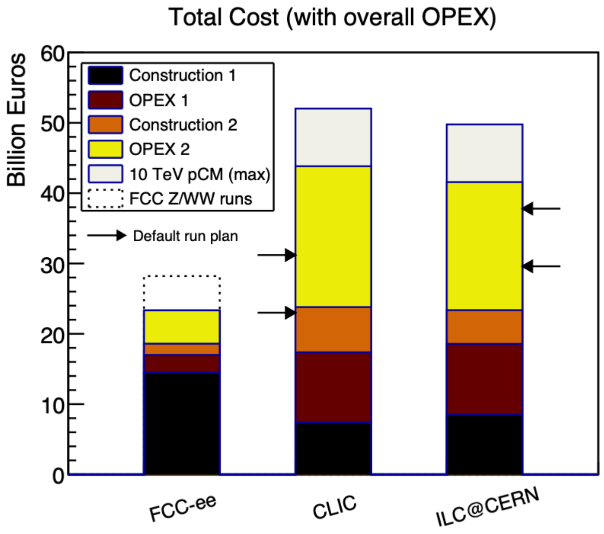
Collider	Longitudinal Polarisation (e^-, e^+) (%)	$\sqrt{s}$ (GeV)	Integrated Luminosity (ab^{-1})	Time (Years)	Ref.
FCC-ee	$0, 0$	240	**10.8**	3	[15]
		350	**0.42**	1	
		365	**2.70**	4	
CLIC	$\pm 80, 0$	380	**1.5**	8	[6]
		1500	2.5	7	
ILC	$\pm 80, \pm 30$	250	2	**15**	[8]
		350	0.1	**1.5**	
		500	4	**11.5**	
	$\pm 80, \pm 20$	1000	8	**13**	

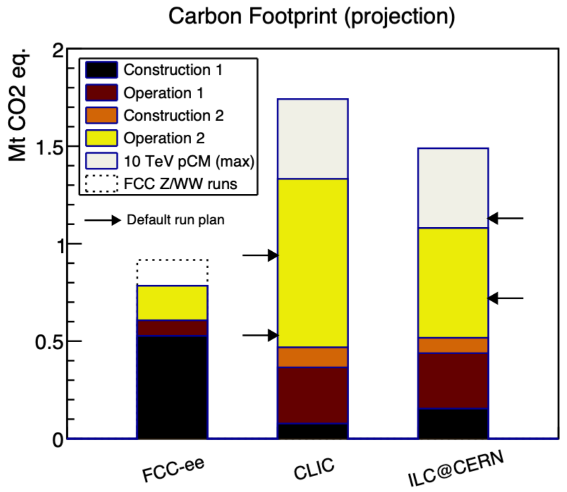
Precision Vs cost/carbon footprint

Table 5: Precision reach (in percentage) on effective couplings from a SMEFT global fit of the Higgs measurements after the planned second stages of FCC-ee (365 GeV), CLIC (1.5 TeV) and ILC (500 GeV), i.e., after 8, 15 and 28 years of operation, respectively. The results from the free-Γ_H fit, scaled from Ref. [11], are shown.

Precision (%) on coupling to	$\text{FCC-ee}_{240+365}$	$\text{CLIC}_{380+1500}$	$\text{ILC}_{250+500}$
b	0.40	0.56	0.56
c	0.89	1.81	1.2
τ	0.42	0.89	0.63
Z	0.17	0.36	0.26
W	0.17	0.37	0.26

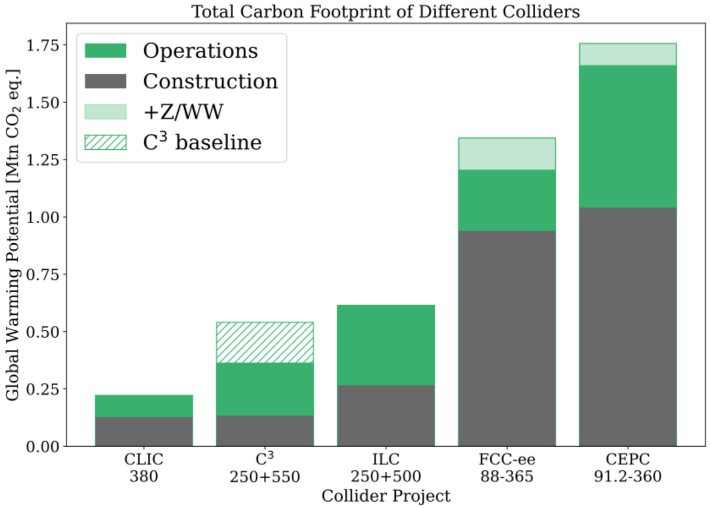
A. Blondel, C. Grojean, P. Janot, G. Wilkinson, arXiv: 2412.13130





Precision versus sustainability

https://arxiv.org/pdf/2307.04084



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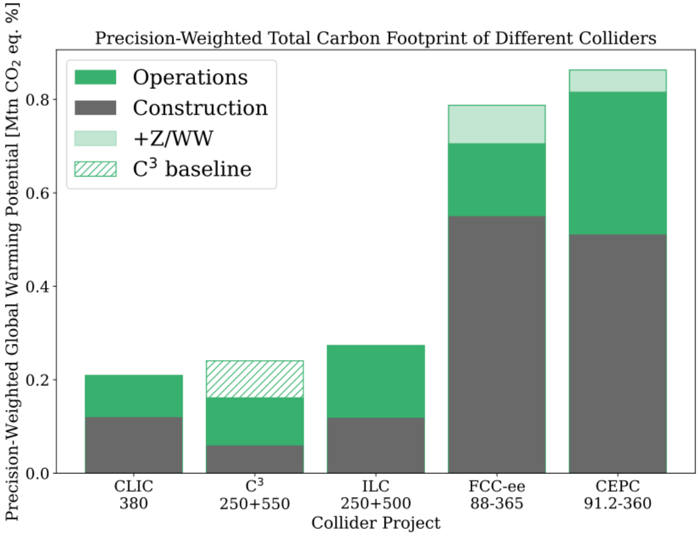
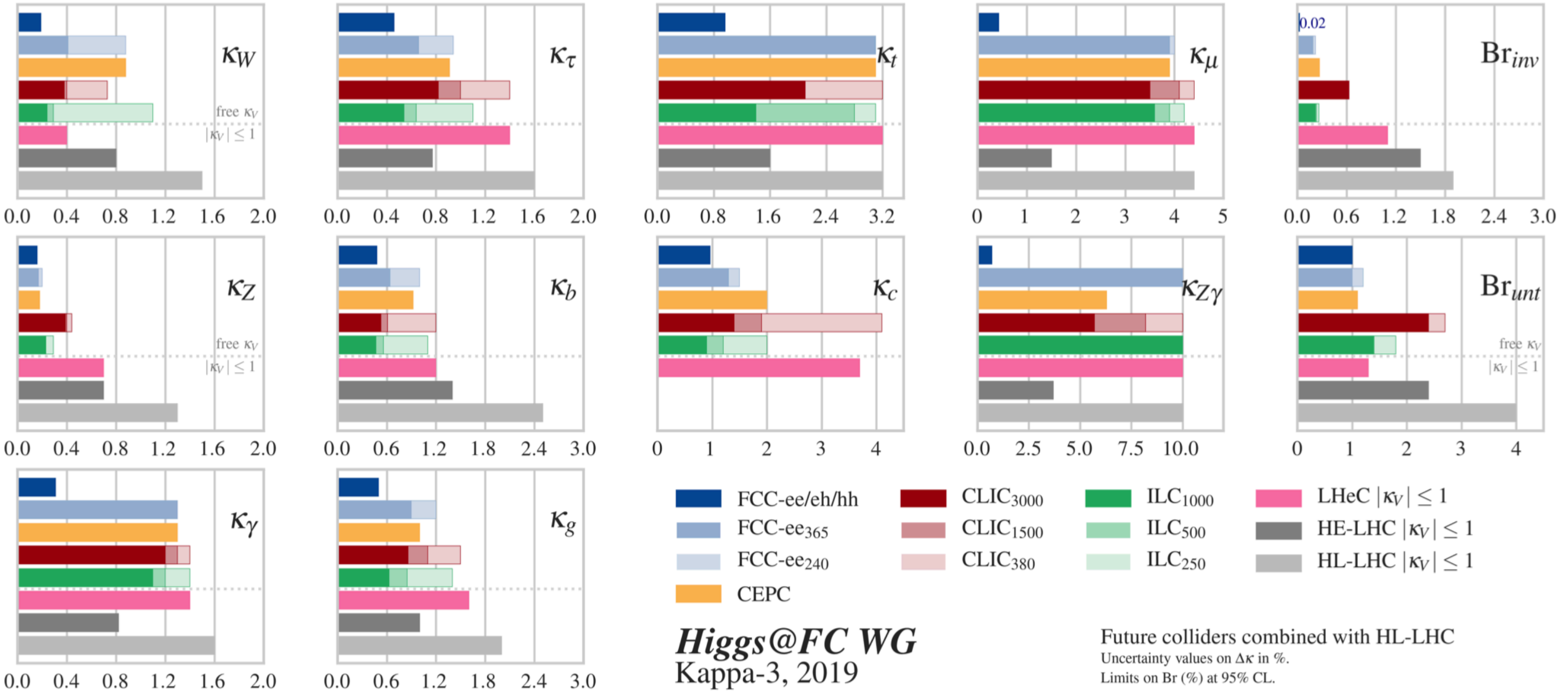


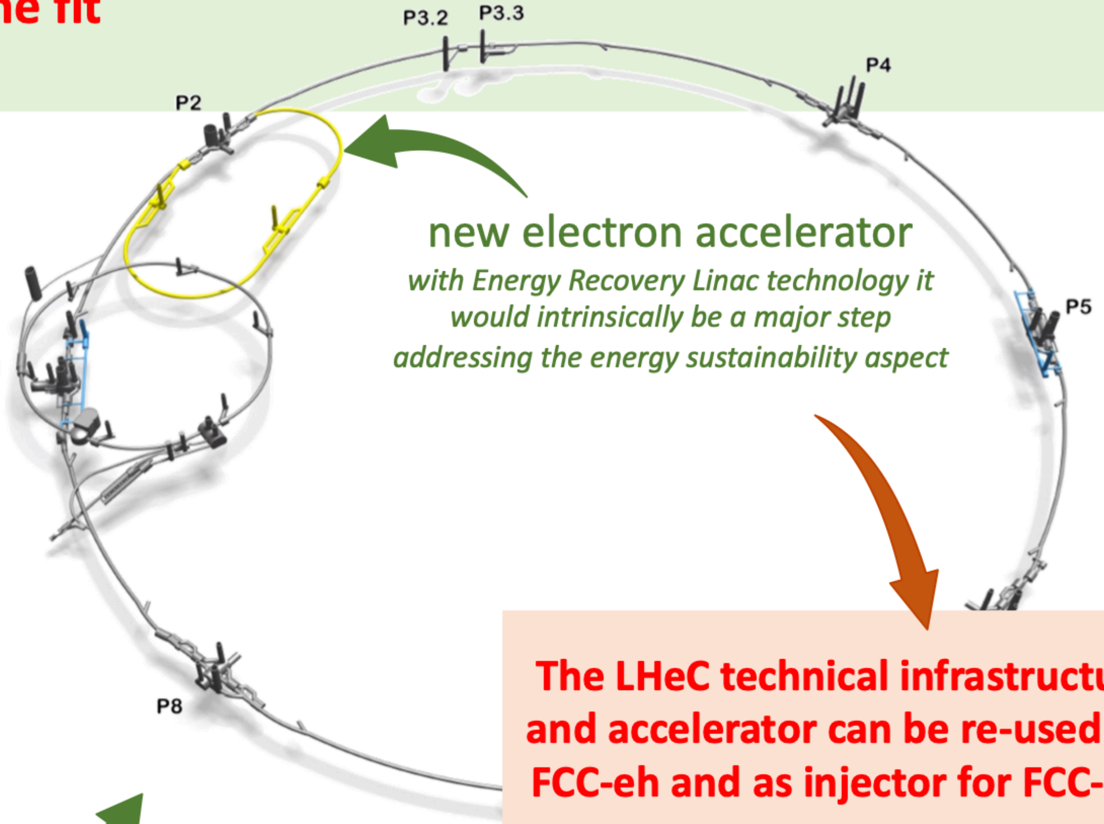
(b)


κ_W
κ_τ
κ_t
κ_μ
Br_inv
0.02
κ_Z
κ_b
κ_c
κ_Zγ
Br_unt
κ_γ
κ_g
free κ_V
|κ_V| ≤ 1
FCC-ee/eh/hh
FCC-ee365
FCC-ee240
CEPC
CLIC3000
CLIC1500
CLIC380
ILC1000
ILC500
ILC250
LHeC |κ_V| ≤ 1
HE-LHC |κ_V| ≤ 1
HL-LHC |κ_V| ≤ 1
Higgs@FC WG
Kappa-3, 2019
Future colliders combined with HL-LHC
Uncertainty values on Δκ in %.
Limits on Br (%) at 95% CL.

How does the LHeC progamme fit into the collider landscape?

The LHeC (and/or FCC-eh) is not *"the"* major new collider for CERN, but enables an ultimate upgrade of the existing LHC (and/or future FCC) programme.

However, the LHeC is the first affordable collider at CERN that can significantly go beyond the HL-LHC physics reach and complete its physics programme in the 2040'ies.



new electron accelerator

with Energy Recovery Linac technology it would intrinsically be a major step addressing the energy sustainability aspect

The LHeC technical infrastructure and accelerator can be re-used for FCC-eh and as injector for FCC-ee.

existing/future proton accelerator

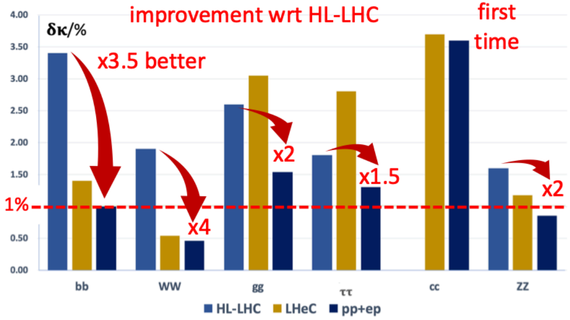
J. D'hondt, ICHEP 2024

Some physics highlights of the LHeC (ep/eA@LHC)

J. D'hondt, ICHEP 2024

on several fronts comparable improvements between LHC → HL-LHC as for HL-LHC → LHeC

Higgs physics - pp+ep comb



DIS scattering cross sections - ep 1y

- complete unfolding of PDFs extended in (Q^2,x) by orders of magnitude

EW physics – pp & ep

- Δm_W to 2 MeV (today at ~10 MeV) pp with ep input
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP + scale dep) ep only

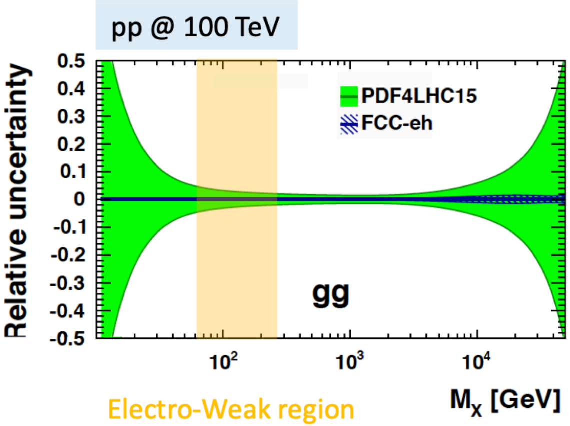
Top quark physics – ep only

- $|V_{tb}|$ precision better than 1% (today ~5%)
- top quark FCNC and γ, W, Z couplings

Strong interaction physics - ep 1y

- α_s precision of 0.2%
- low-x: a new discovery frontier

3 (2021) 110501, 364p (updated CDR)



The Large Hadron-Electron Collider at the HL-LHC, J. Phys. G 48 (2021) 110501, 364p (updated CDR)

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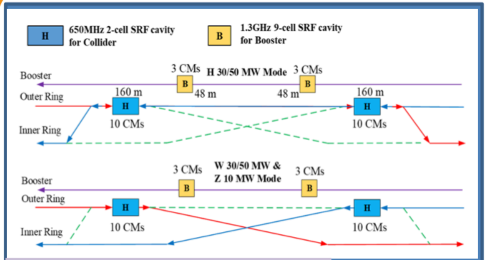
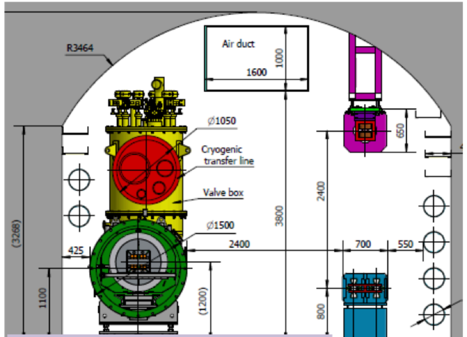
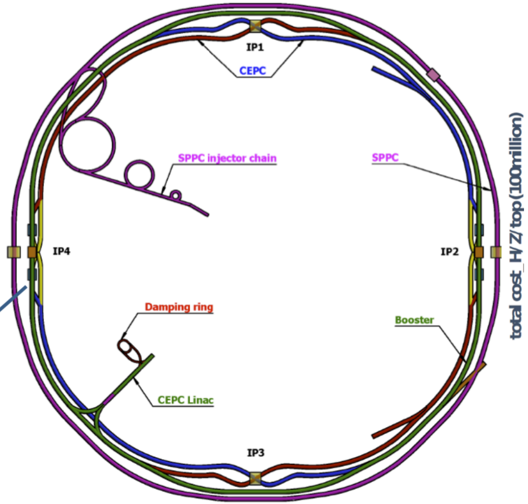
CEPC Higgs Factory and SppC in Accelerator TDR



Switchable operation for Higgs W and Z



Common tunnel for booster/collider & SppC



Three sites considered:

- **Circular collider**: Higher luminosity with crabwaist collision of double ring
- **100km circumference**: Optimum total cost
- **Shared tunnel**: Compatible design for CEPC and SppC
- **Switchable operation**: Higgs, W/Z, ttbar

Baseline: 100 km, 30 MW; Upgradeable to 50 MW, High Lumi Z, ttbar

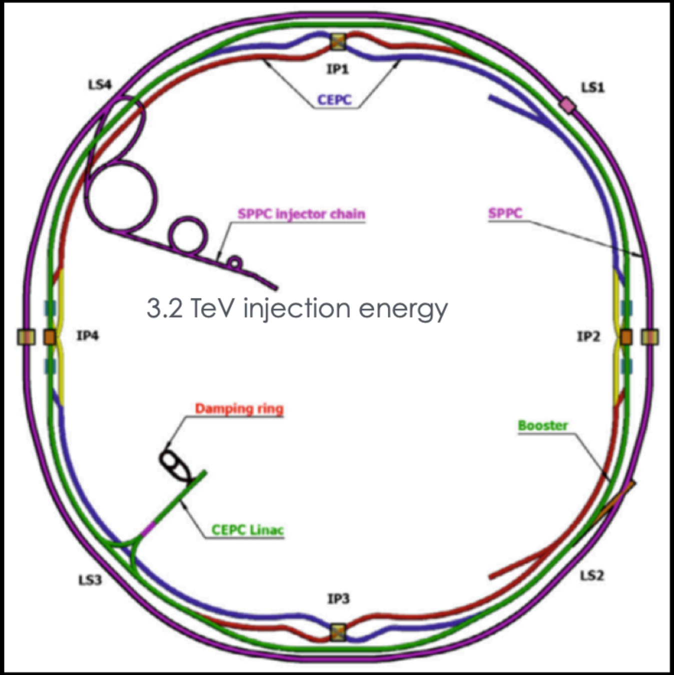
Super proton-proton Collider (SppC)

Compatible with CEPC and in same tunnel

- E_{cm} 100-150 TeV with 100 km ring
- 2 IPs, 10^{35} $cm^{-2}s^{-1}$ per IP
- Can extend to heavy ion collisions
- Retaining the CEPC collider add possible ep option

Current consideration for SppC:

- 20-24T B field, twin-aperture magnets
- New HTS (IBS?) magnets (in 20-30 years)



Stainless-steel stabilized IBS tape

Significantly reduced cost and raised mechanical properties

achieved the highest J_e in 2022

IBS coils reached 49 A at 4.2 Kelvin and 35 T

FCC- Feasibility Study