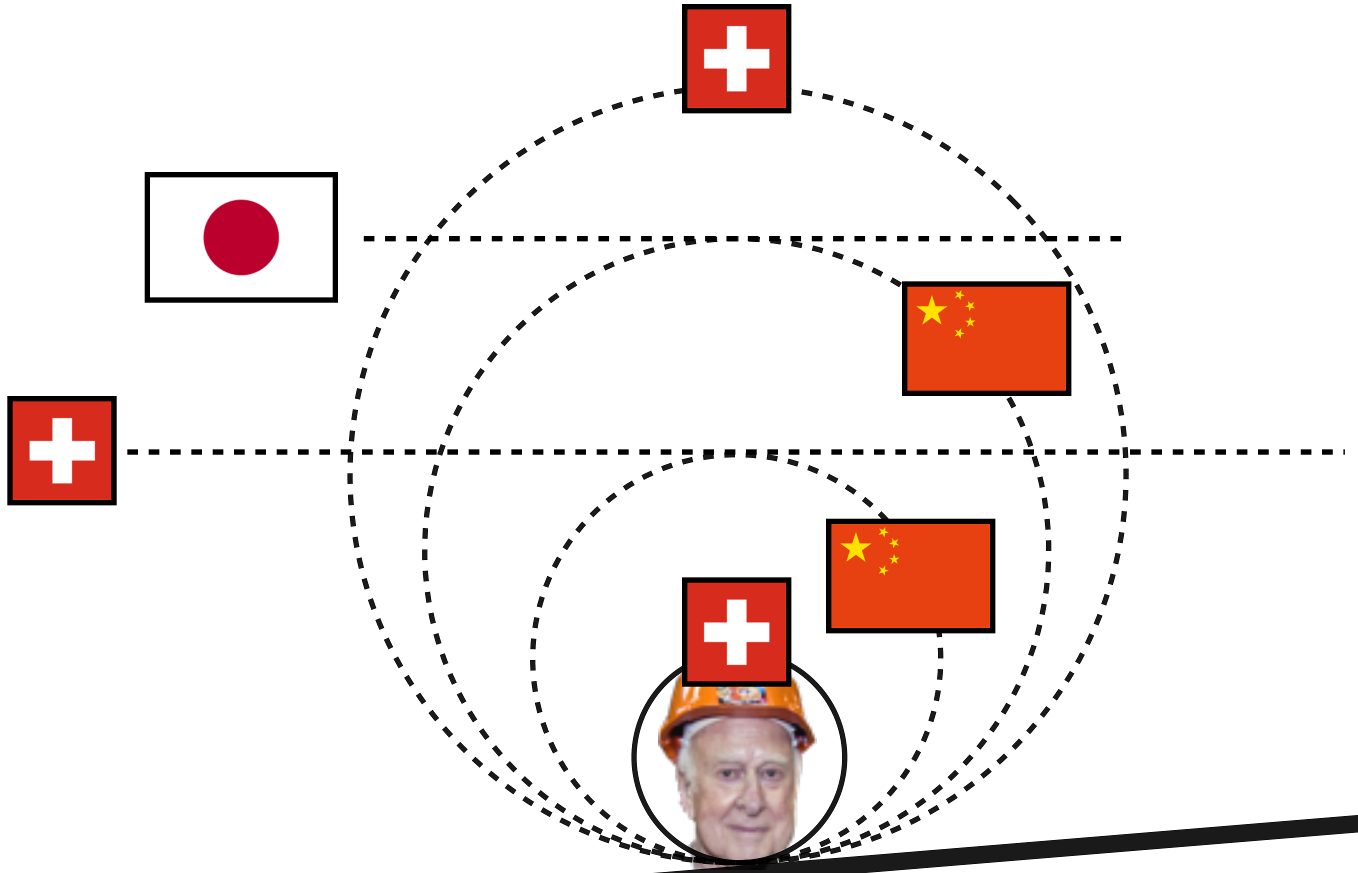
Prospectives
Future Accélérateurs

Ecole de Gif 2023

Annecy, France



Lecture 2/2

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Outline

Lecture #1: A few theoretical considerations on EFTs

- Importance of selection rules/symmetries
- Swampland vs landscape of EFTs
- EFTs for Higgs data
- Beyond inclusive analyses
- Higgs self-couplings
- EFTs for composite Higgs models
- CP violation in (SM)EFT
- EFT validity discussion

Lecture #2: Physics at future colliders

- Higgs factories
- FCC-ee: a great Higgs factory, and so much more
- FCC-hh: the energy-frontier collider with the broadest exploration potential

Which Machine(s)?

Hadrons

- ○ large mass reach ⇛ exploration?
- ▹ S/B ~ 10^{-10} (w/o trigger)
- ○ S/B ~ 0.1 (w/ trigger)
- ○ requires multiple detectors
  (w/ optimized design)
- ▹ only pdf access to $\sqrt{\hat{s}}$
- ○ ⇛ couplings to quarks and gluons

Leptons

- ○ S/B ~ 1 ⇛ measurement?
- ○ polarized beams
  (handle to chose the dominant process)
- ○ limited (direct) mass reach
- ○ identifiable final states
- ○ ⇛ EW couplings

Circular

- ○ higher luminosity
- ○ several interaction points
- ○ precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- ▹ √s limited by synchroton radiation

Linear

- ○ easier to upgrade in energy
- ○ easier to polarize beams
- ○ "greener": less power consumption*
- ▹ large beamsthralung
- ▹ one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Which Machine(s)?

The challenges of big colliders:

- **energy**: 10^{13} larger than everyday life batteries
- **magnetic field**: 10^4 larger than everyday life magnets

Cannot use permanent magnets:
currents needed in 16T magnets ~ intramolecular fields (100 MV/m).
Going higher will imply a reorganisation of matter!
→ Plasma wakefield acceleration

Exercise: with 2 magnets of 1T, can you build a magnet of 2T?

Which Machine(s)?

Choice between different options: delicate balance between
physics return, technological challenges and feasibility,
time scales for completion and exploitation, financial and political realities

Exploration machines are at the heart of HEP
Current consensus towards European Strategy Update:
the best way to go to energy frontier is to start with a **e^+e^- Higgs factory**

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

Three relevant questions to address to help taking a decision:
1) Impact of Z pole measurements?
2) Benefit of beam polarisation?
3) Is low energy a limitation?

Future colliders as BSM probes

in order to address the physics questions outside the SM boundaries
the physics program of the future colliders is built around four key goals

1. Measurement of the properties of the newly-discovered **Higgs** boson with very high precision.
⇛ Is it elementary? Does it have siblings/relatives? What keeps it light? Why does it freeze in?

2. Measurement of the properties of the **top** quark with very high precision to indirectly constrain new physics

3. Precision measurements of the EW observable: the **Z** boson will be the atomic clock of HEP

4. Direct searches for and studies of (uncoloured) **new particles** expected in models of physics at the TeV energy scale. Complementary to LHC searches.

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Guaranteed deliverables
machine than can achieve
landmark textbook measurements

Exploration potential
HEP remains a frontier science

The way forward

- increased energy
- increased statistics

↓ ↓

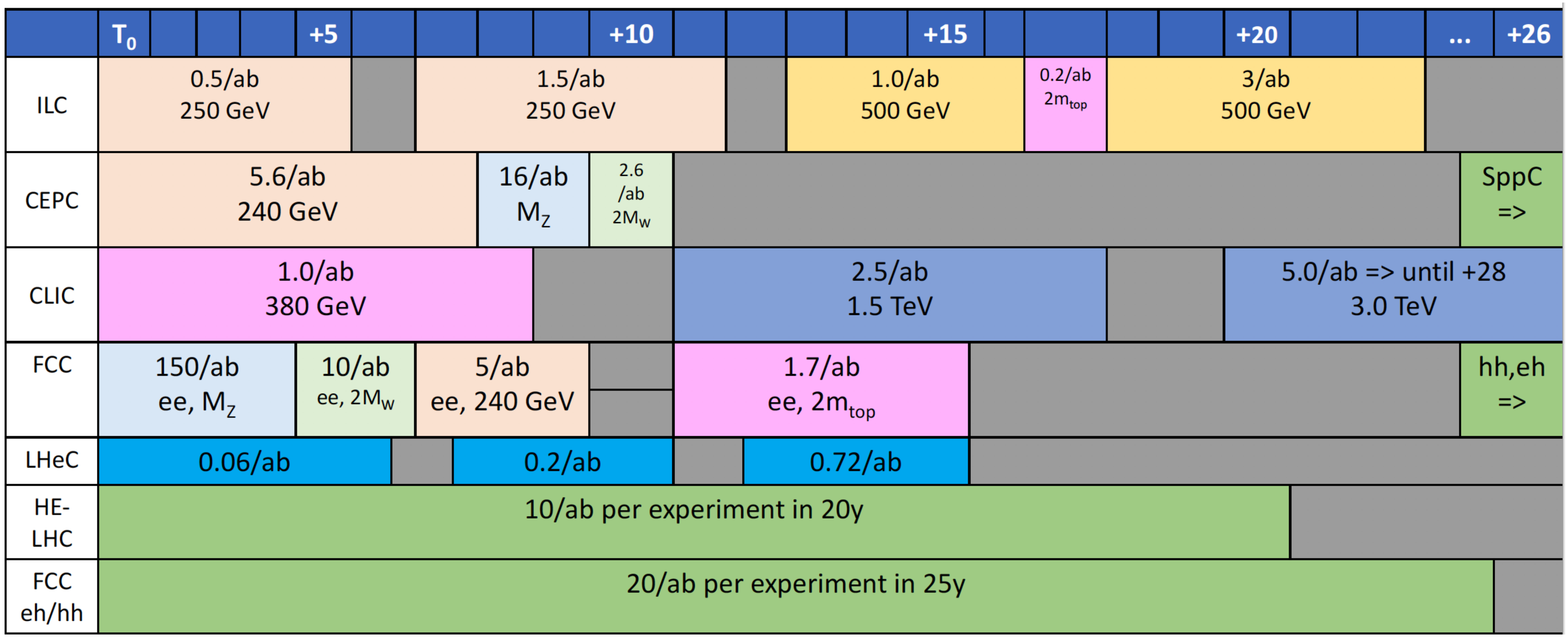
- increased precision
- increased sensitivity

- High rates allow the exploration of rare phenomena and extreme phase space configurations
- High rates also shift the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the “systematic wall” of low statistic measurements

Future of HEP

ECFA Higgs study group '19

Subject to large uncertainty
1) need a scientific consensus
2) political approval



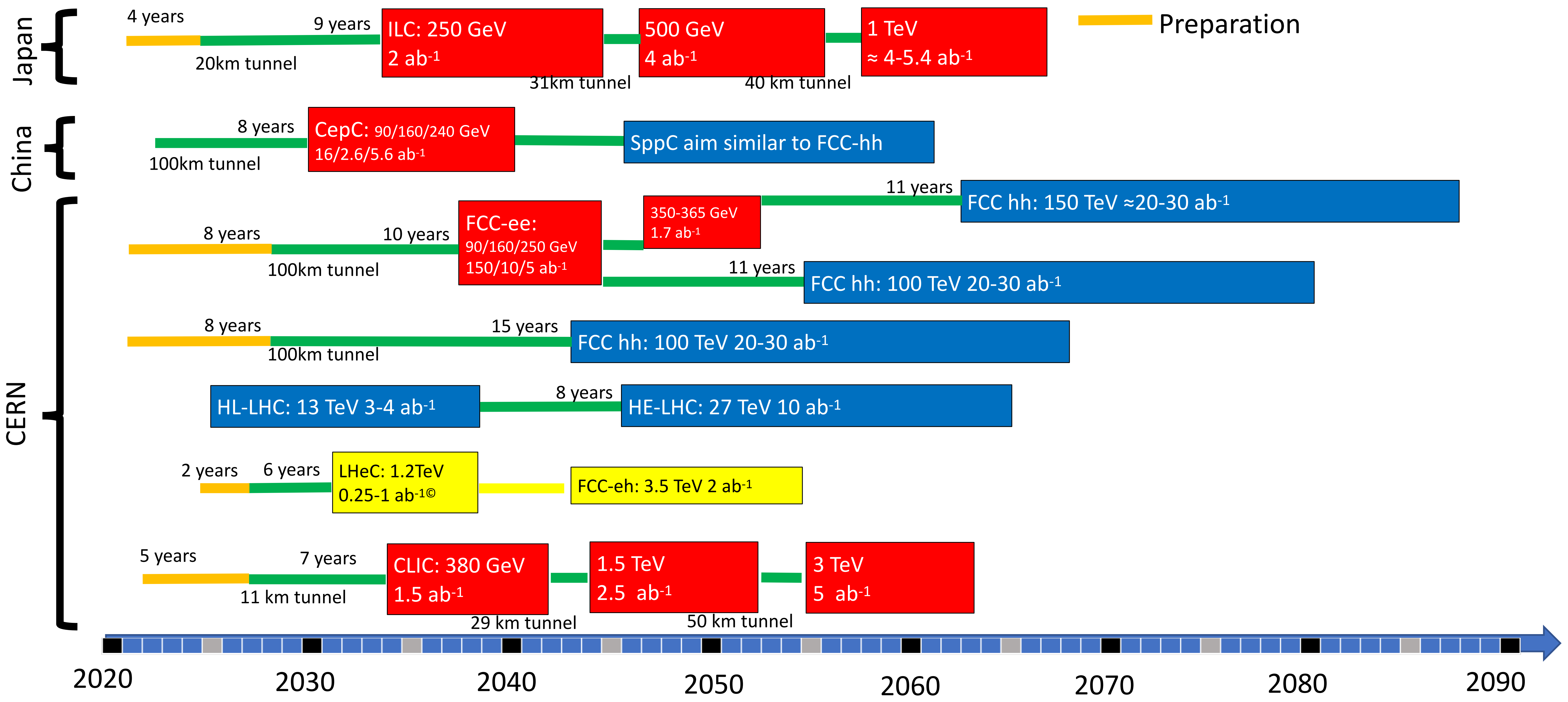
	T_0 … +5 … +10 … +15 … +20 … +26								T_0
ILC	0.5/ab 250 GeV		1.5/ab 250 GeV		1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV		2032
CEPC	5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$		SppC =>				2030
CLIC	1.0/ab 380 GeV		2.5/ab 1.5 TeV		5.0/ab => until +28 3.0 TeV				2035
FCC	150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV		1.7/ab ee, $2m_{top}$		hh,eh =>		2037
LHeC	0.06/ab		0.2/ab		0.72/ab				2030
HE-LHC	10/ab per experiment in 20y								2040
FCC eh/hh	20/ab per experiment in 25y								2045

+ muon-collider + gamma-gamma collider + …

Future of HEP

Possible scenarios of future colliders

🟦 Proton collider
🟥 Electron collider
🟨 Electron-Proton collider
🟩 Construction/Transformation
🟧 Preparation



Japan
4 years
9 years
20km tunnel
ILC: 250 GeV
2 ab^{-1}
31km tunnel
500 GeV
4 ab^{-1}
40 km tunnel
1 TeV
≈ 4-5.4 ab^{-1}

China
8 years
100km tunnel
CepC: 90/160/240 GeV
16/2.6/5.6 ab^{-1}
SppC aim similar to FCC-hh

CERN
8 years
10 years
100km tunnel
FCC-ee:
90/160/250 GeV
150/10/5 ab^{-1}
350-365 GeV
1.7 ab^{-1}
11 years
FCC hh: 150 TeV ≈20-30 ab^{-1}
11 years
FCC hh: 100 TeV 20-30 ab^{-1}

8 years
15 years
100km tunnel
FCC hh: 100 TeV 20-30 ab^{-1}

HL-LHC: 13 TeV 3-4 ab^{-1}
8 years
HE-LHC: 27 TeV 10 ab^{-1}

2 years
6 years
LHeC: 1.2TeV
0.25-1 ab^{-1}©
FCC-eh: 3.5 TeV 2 ab^{-1}

5 years
7 years
11 km tunnel
CLIC: 380 GeV
1.5 ab^{-1}
29 km tunnel
1.5 TeV
2.5 ab^{-1}
50 km tunnel
3 TeV
5 ab^{-1}

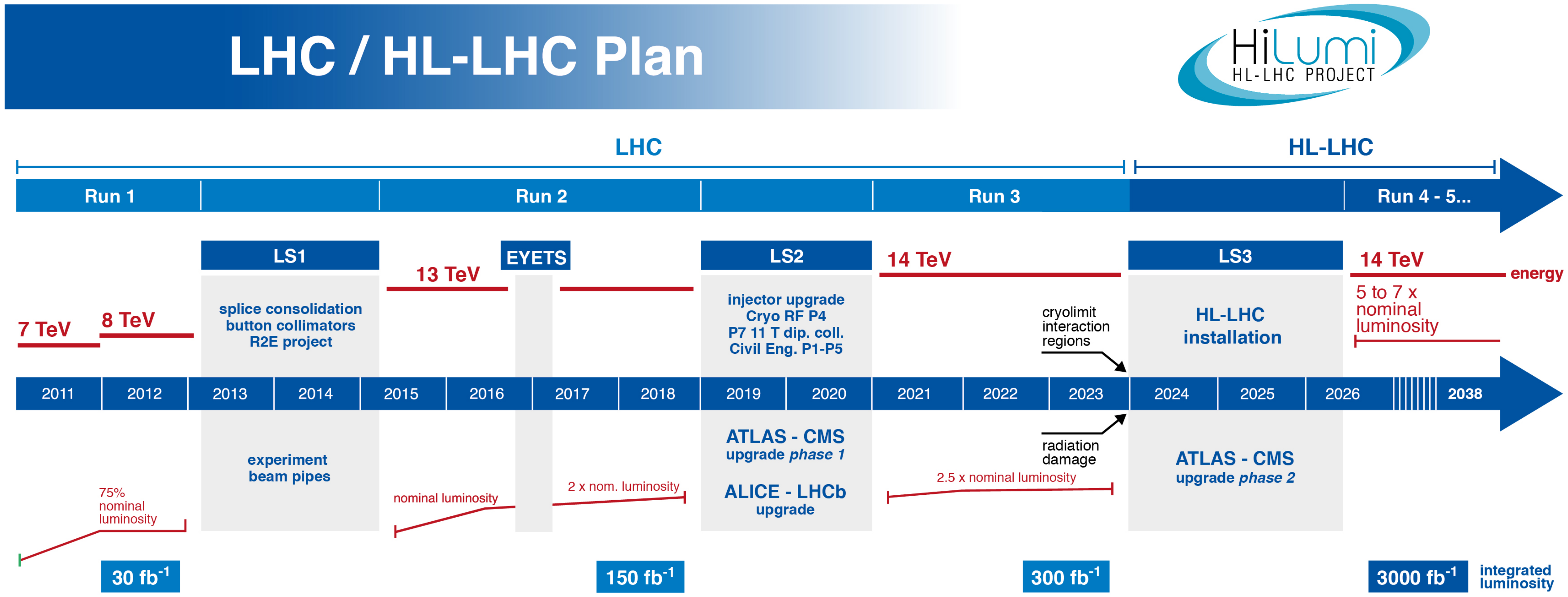
2020 2030 2040 2050 2060 2070 2080 2090

Ursula Baesler, Granada 13.05.2019

HL-LHC (2023-2041)

14 TeV - 3/ab

2018 timeline



A Higgs factory
on its own

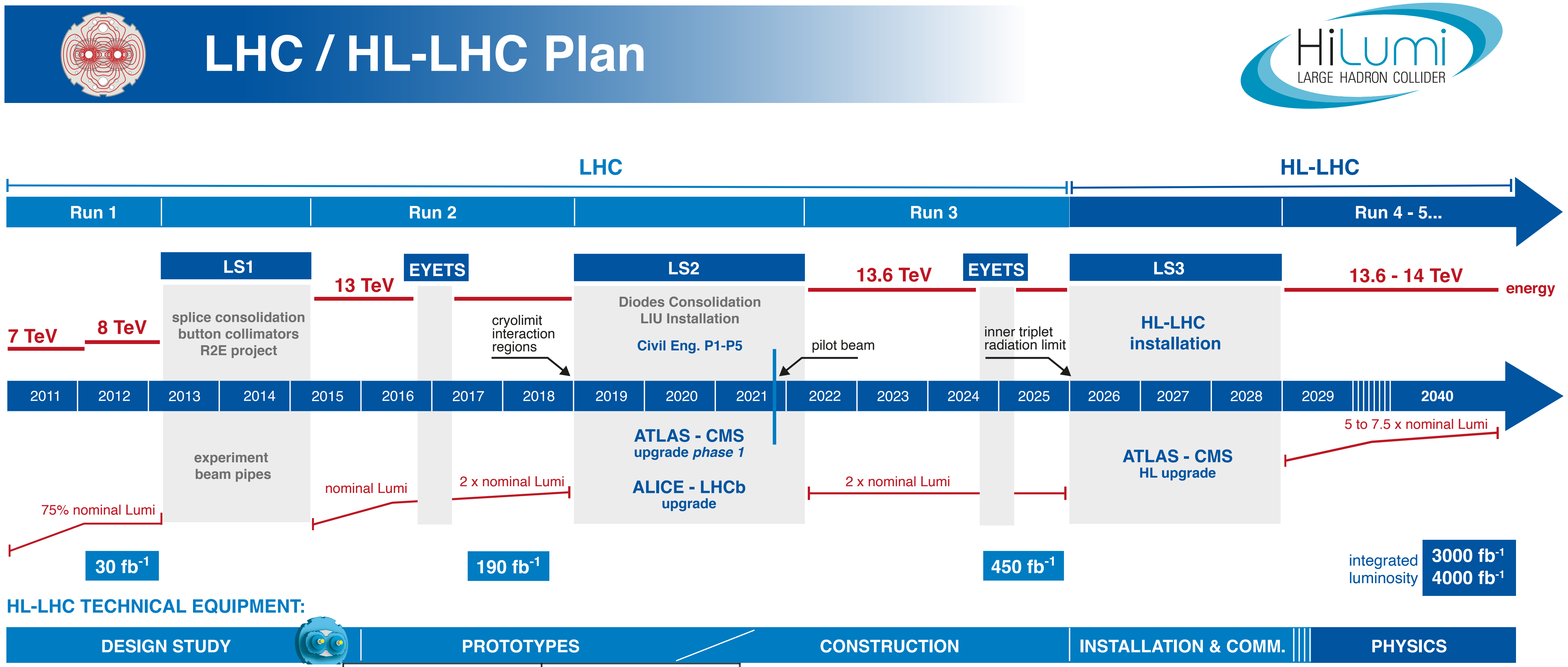
	Higgs bosons at $\sqrt{s}$=14TeV
HL-LHC, 3000fb^{-1}	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
H->Zγ	230k
H->μμ	37k
HH (all)	121k

Main issue: how to cope with pile-up?

HL-LHC (2023-2041)

14 TeV - 3/ab

2022 timeline



A Higgs factory on its own

	Higgs bosons at √s=14TeV
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Higgs @ HL-LHC

2013 projections

HL-LHC WS, Aix-les-Bains ‘13

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	N/a	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

Snowmass ’13 Higgs report

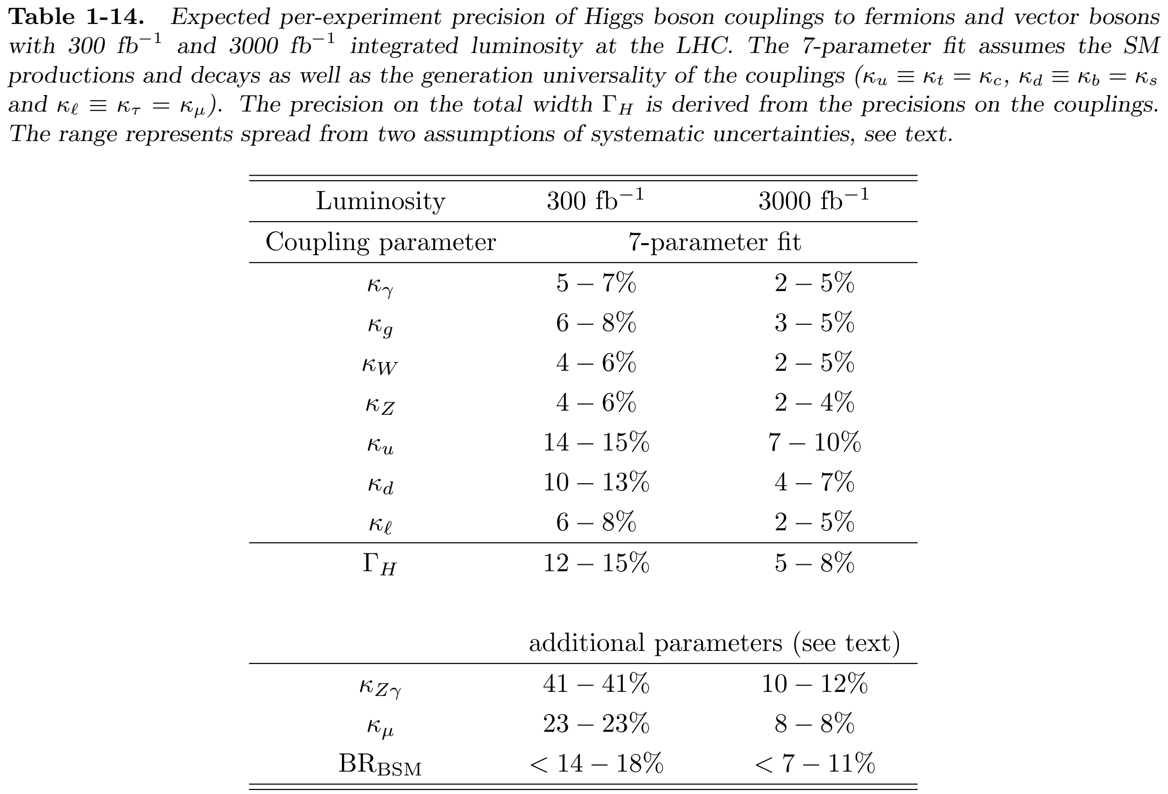


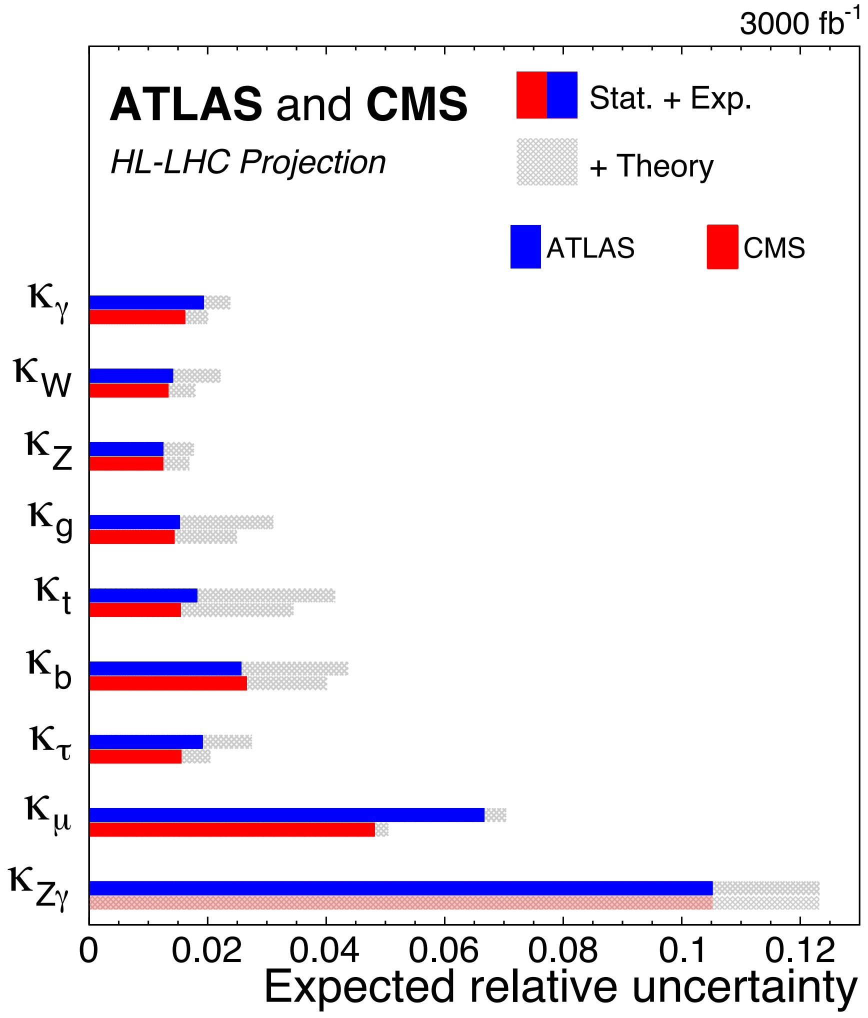
Table 1-14. *Expected per-experiment precision of Higgs boson couplings to fermions and vector bosons with 300 fb^{-1} and 3000 fb^{-1} integrated luminosity at the LHC. The 7-parameter fit assumes the SM productions and decays as well as the generation universality of the couplings ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$ and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The precision on the total width Γ_H is derived from the precisions on the couplings. The range represents spread from two assumptions of systematic uncertainties, see text.*

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	5 – 7%	2 – 5%
κ_g	6 – 8%	3 – 5%
κ_W	4 – 6%	2 – 5%
κ_Z	4 – 6%	2 – 4%
κ_u	14 – 15%	7 – 10%
κ_d	10 – 13%	4 – 7%
κ_ℓ	6 – 8%	2 – 5%
Γ_H	12 – 15%	5 – 8%
	additional parameters (see text)	
$\kappa_{Z\gamma}$	41 – 41%	10 – 12%
κ_μ	23 – 23%	8 – 8%
BR$_{\mathrm{BSM}}$	< 14 – 18%	< 7 – 11%

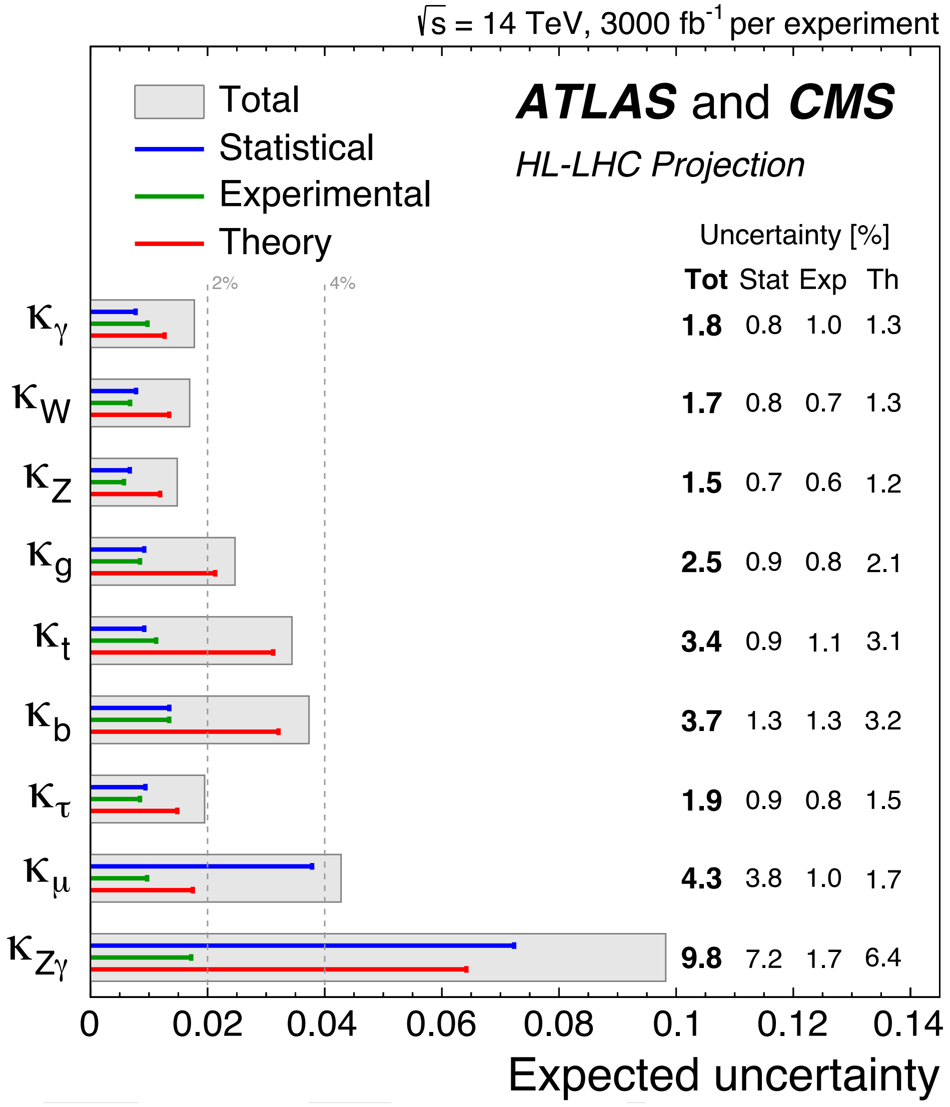
2018-2019 projections

HL/HE-LHC Higgs WG report

Individual



Combined



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

$Z\gamma$ and $\mu\mu$ are statistically limited but otherwise O(2-3%) precision

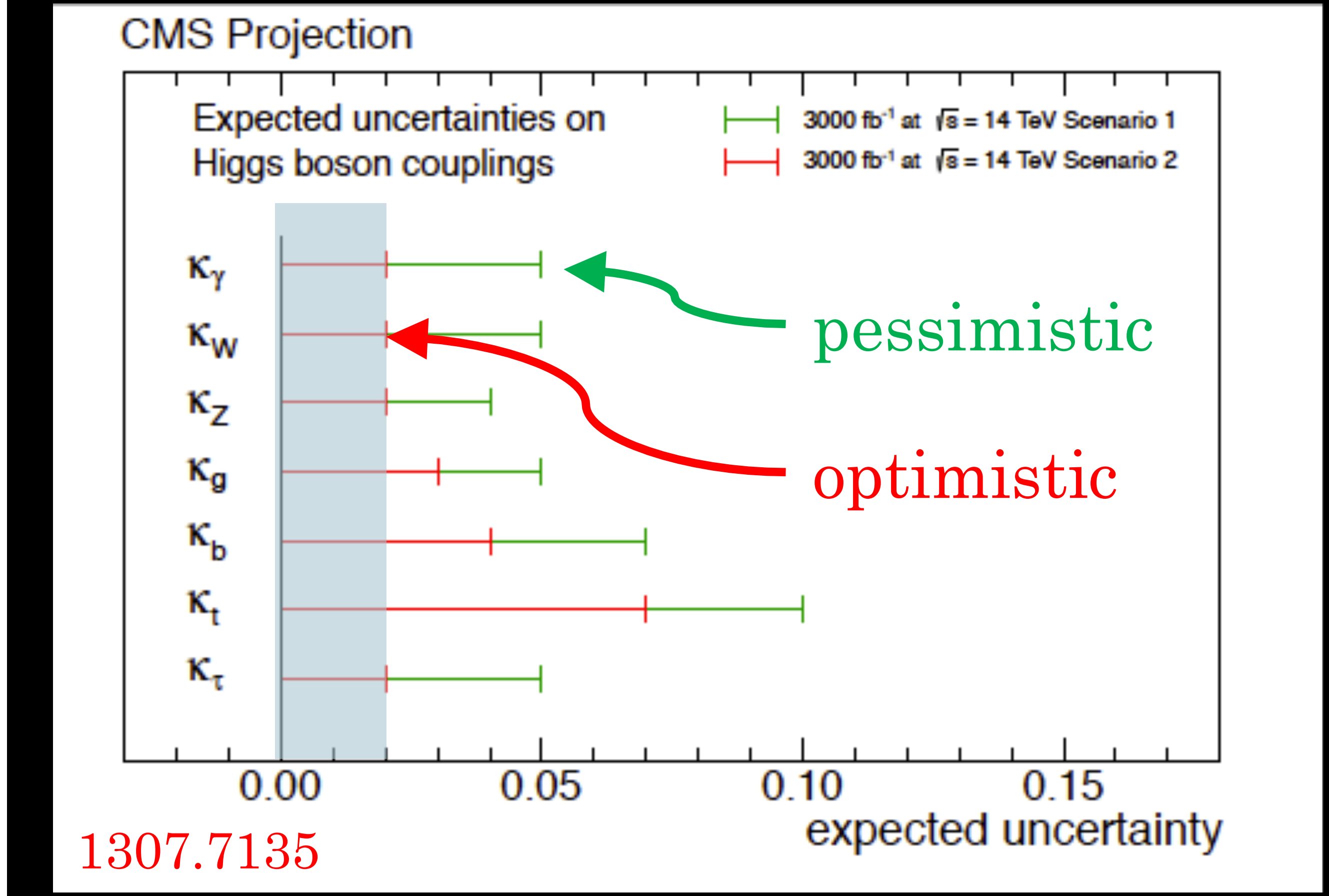
Higgs @ HL-LHC

2013 projections

2018-2019 projections

J. D'Hondt @ Higgs Hunting 2019

Potential HL-LHC performance in Higgs couplings
anno 2013 versus anno 2019



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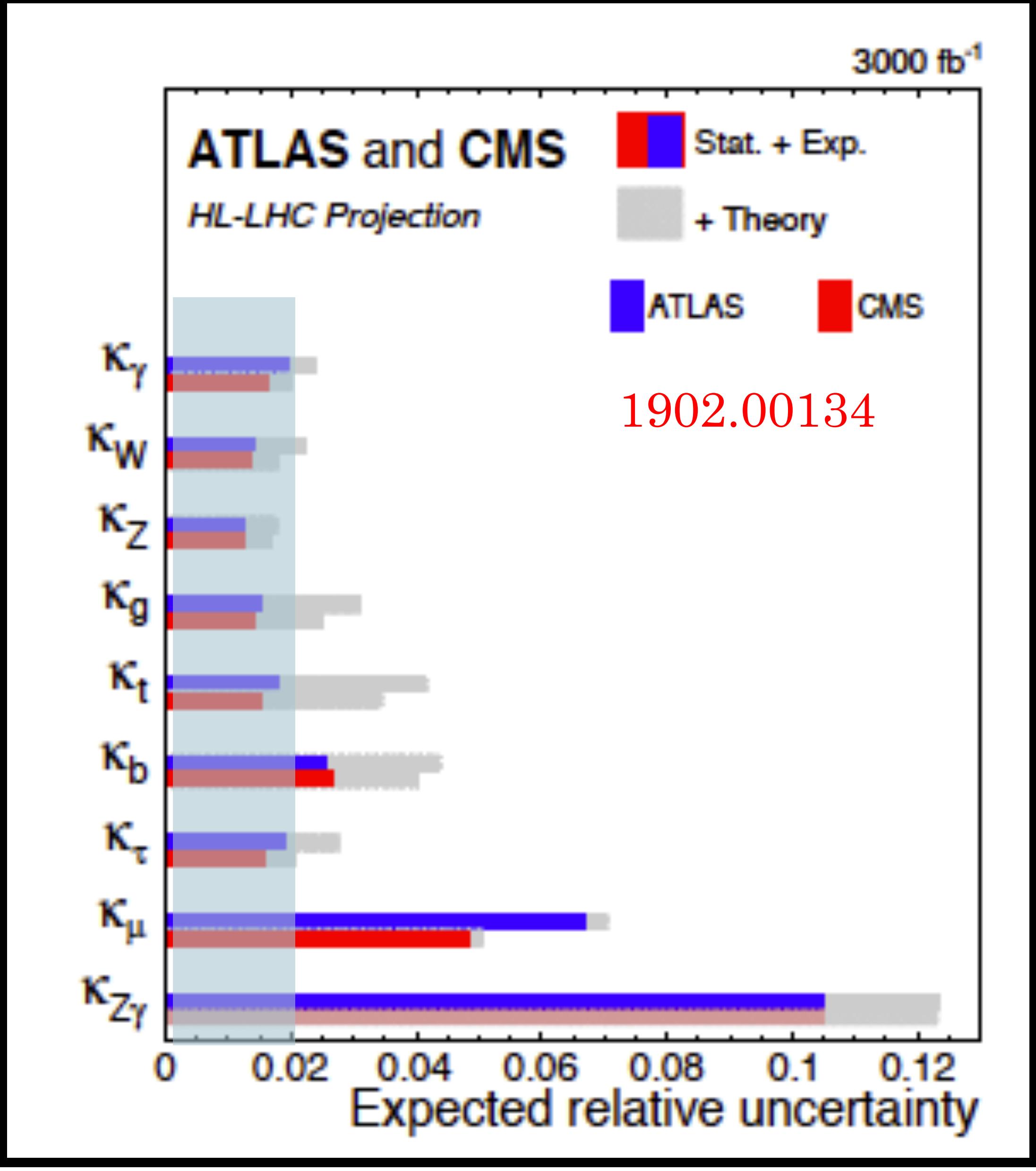


1902.00134

Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

HE-LHC (TBD)

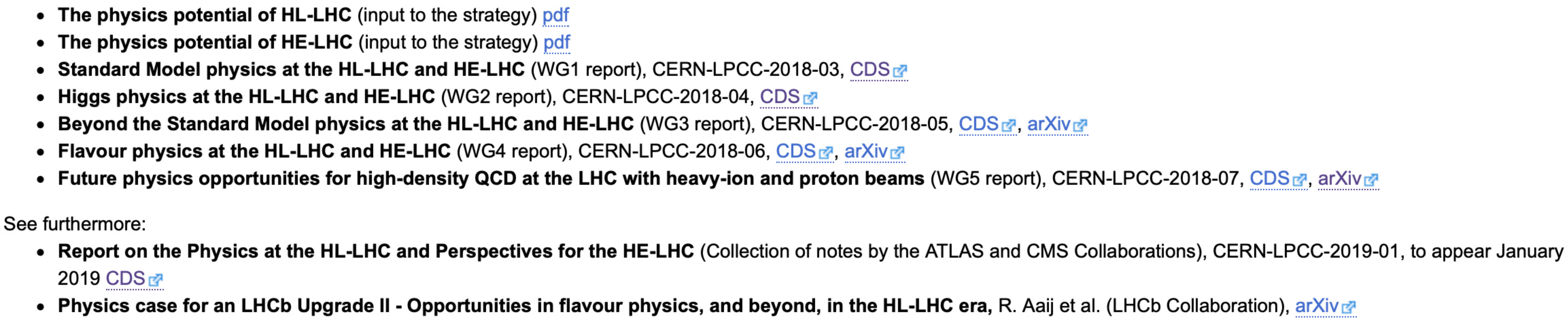
27 TeV - O(20)/ab

Main **technical** issue: 16T magnets (same magnets as in FCC-hh)
But also: SPS upgrade, detectors upgrade…

One **theoretical** issue: EW large Sudakov logs

Kick-off meeting Nov. 2017: indico.cern.ch/e/647676/

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

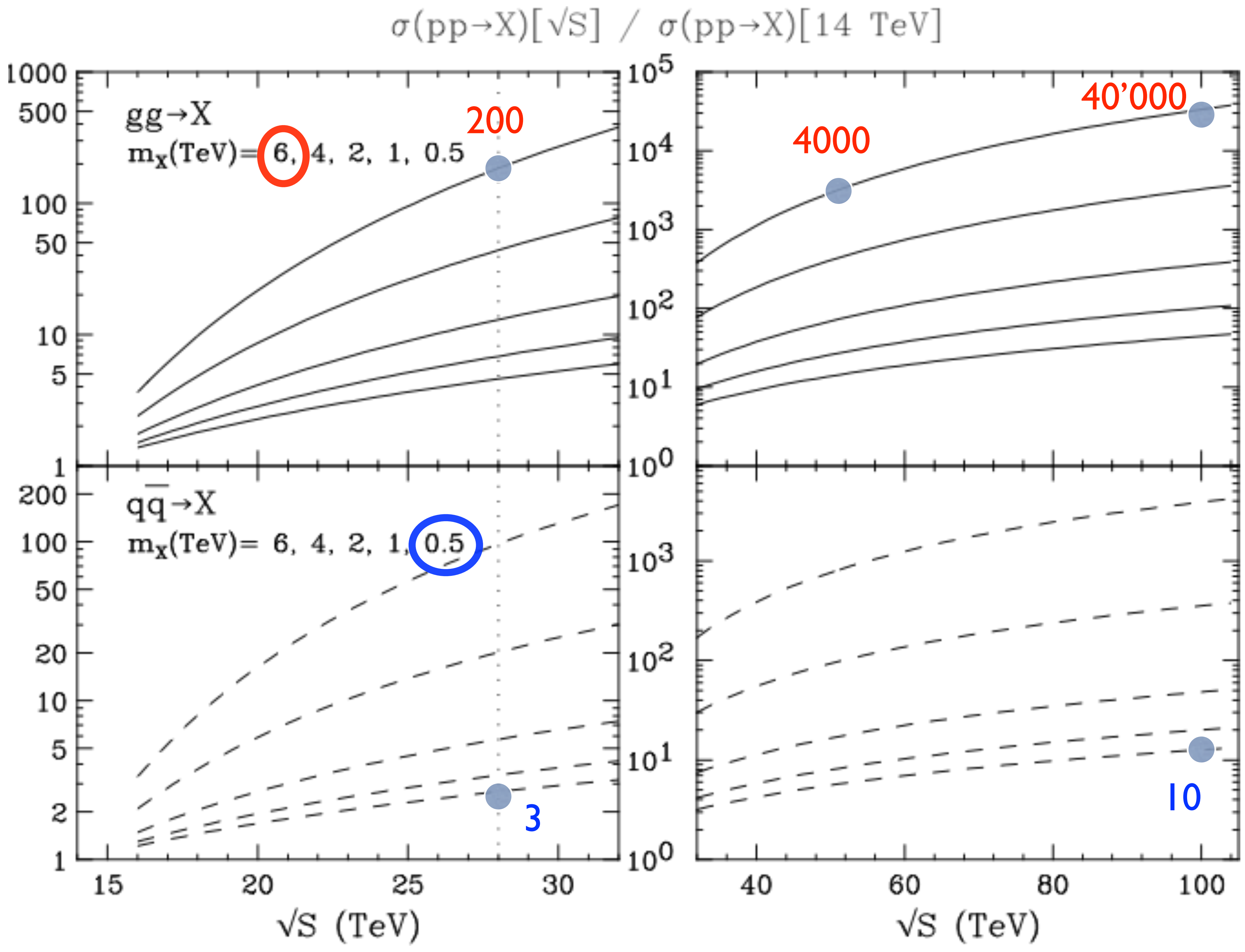


- **The physics potential of HL-LHC** (input to the strategy) pdf
- **The physics potential of HE-LHC** (input to the strategy) pdf
- **Standard Model physics at the HL-LHC and HE-LHC** (WG1 report), CERN-LPCC-2018-03, CDS
- **Higgs physics at the HL-LHC and HE-LHC** (WG2 report), CERN-LPCC-2018-04, CDS
- **Beyond the Standard Model physics at the HL-LHC and HE-LHC** (WG3 report), CERN-LPCC-2018-05, CDS, arXiv
- **Flavour physics at the HL-LHC and HE-LHC** (WG4 report), CERN-LPCC-2018-06, CDS, arXiv
- **Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams** (WG5 report), CERN-LPCC-2018-07, CDS, arXiv

See furthermore:

- **Report on the Physics at the HL-LHC and Perspectives for the HE-LHC** (Collection of notes by the ATLAS and CMS Collaborations), CERN-LPCC-2019-01, to appear January 2019 CDS
- **Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era,** R. Aaij et al. (LHCb Collaboration), arXiv

HE-LHC (TBD)



- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough (σ_{100}/σ_{14}~$4 \cdot 10^4$, σ_{50}/σ_{14}~$4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses ≳ $2m_X$ (⇒ *28 TeV would be insufficient ....*)
- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 ∫L at LHC?
  - Do we build CLIC?

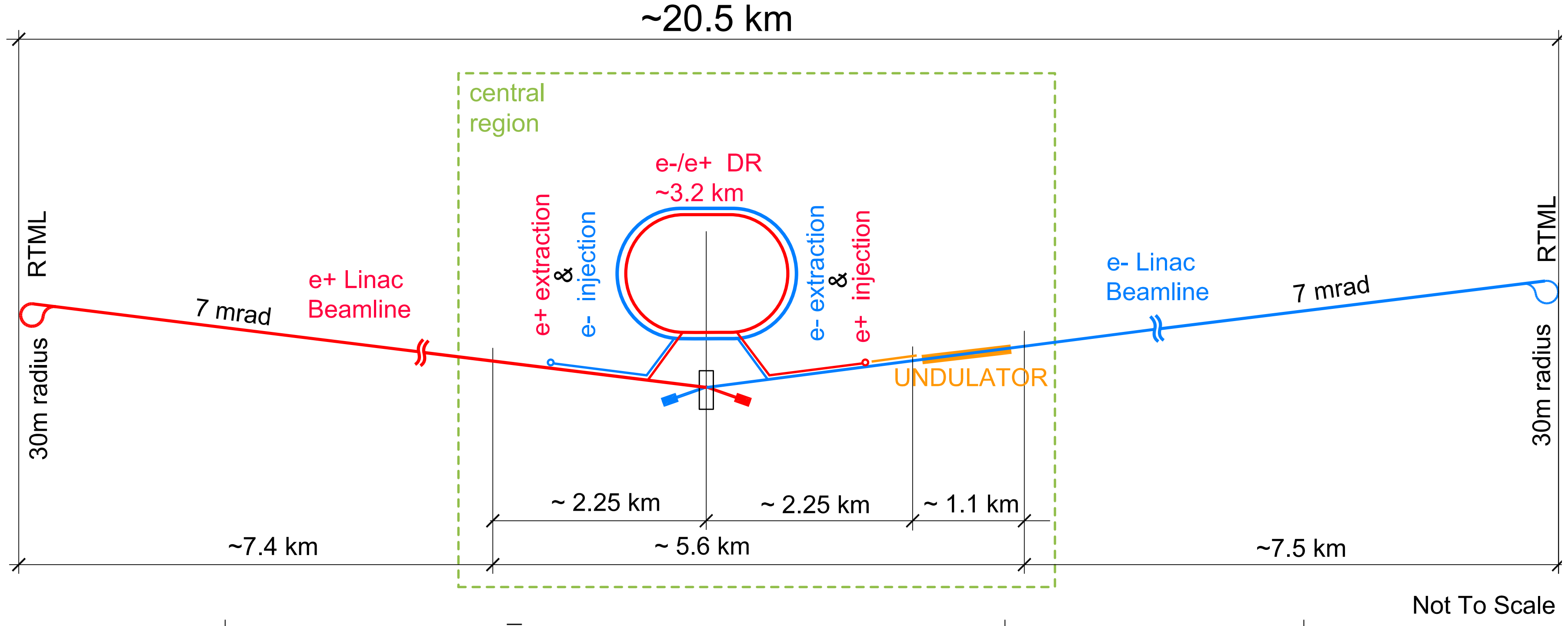
Mangano @ HK'18

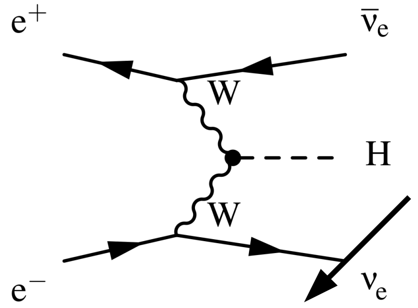
ILC (construction starts in XX*, operation: XX+7-XX+27)

*ready for construction once approved

250/350/500/1000 GeV - 5/ab

First stage 250 GeV

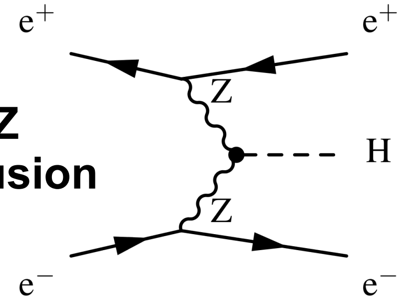




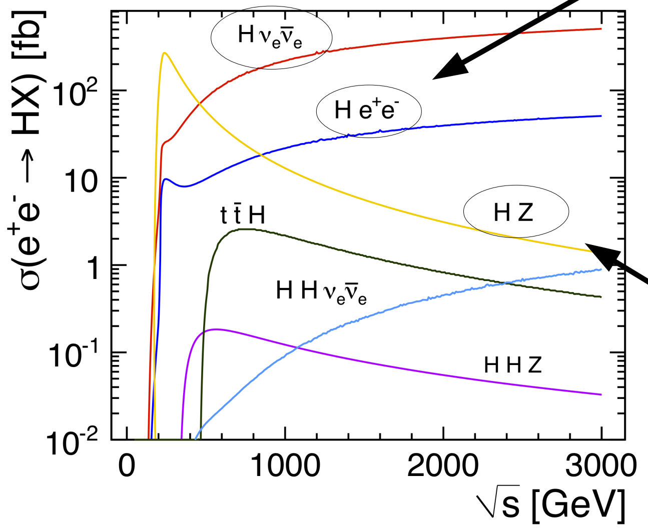
$\sigma \sim \log(s)$

WW fusion

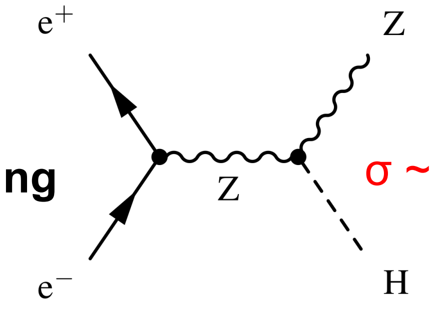
ZZ fusion



O(10⁶) Higgs bosons produced and reconstructed



Higgs-strahlung



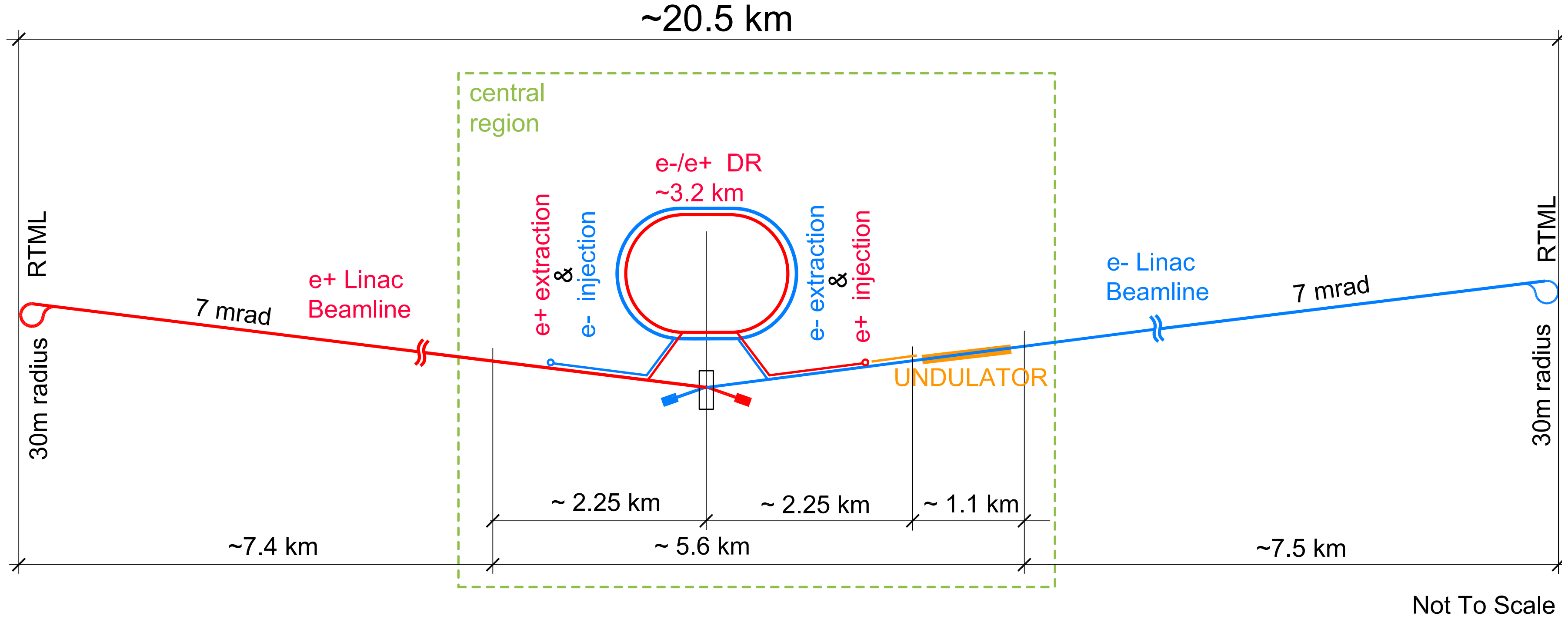
$\sigma \sim 1/s$

ILC (construction starts in XX*, operation: XX+7-XX+27)

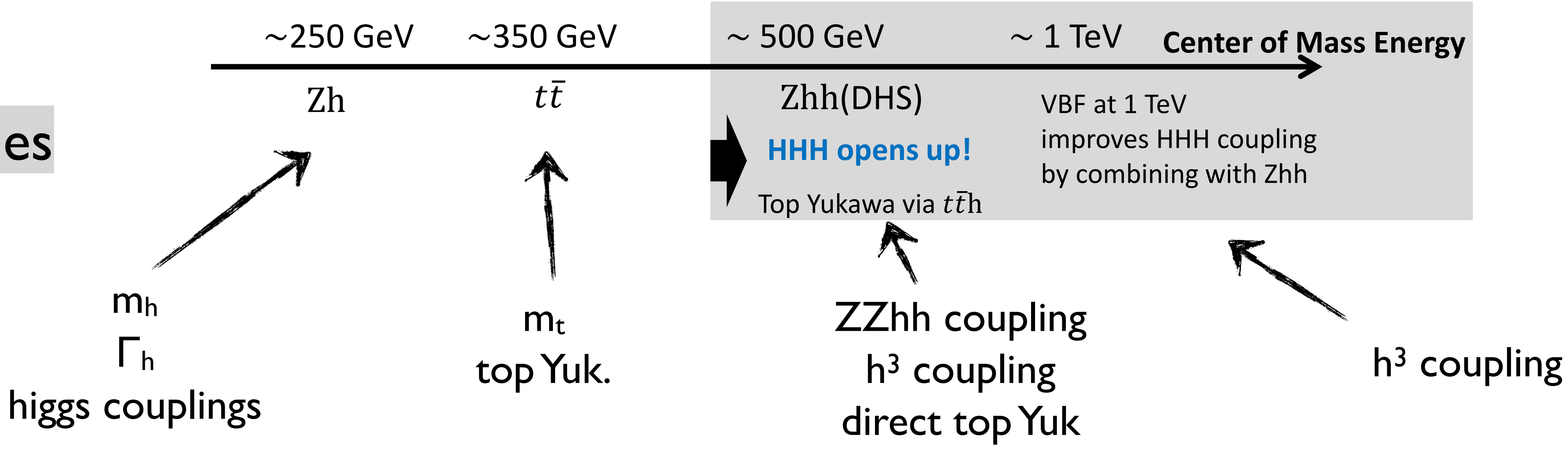
*ready for construction once approved

250/350/500/1000 GeV - 5/ab

First stage 250 GeV



Energy upgrades



~250 GeV

Zh

~350 GeV

$t\bar{t}$

~ 500 GeV

Zhh(DHS)

HHH opens up!

Top Yukawa via $t\bar{t}h$

~ 1 TeV

Center of Mass Energy

VBF at 1 TeV
improves HHH coupling
by combining with Zhh

m_h
Γ_h
higgs couplings

m_t
top Yuk.

ZZhh coupling
h^3 coupling
direct top Yuk

h^3 coupling

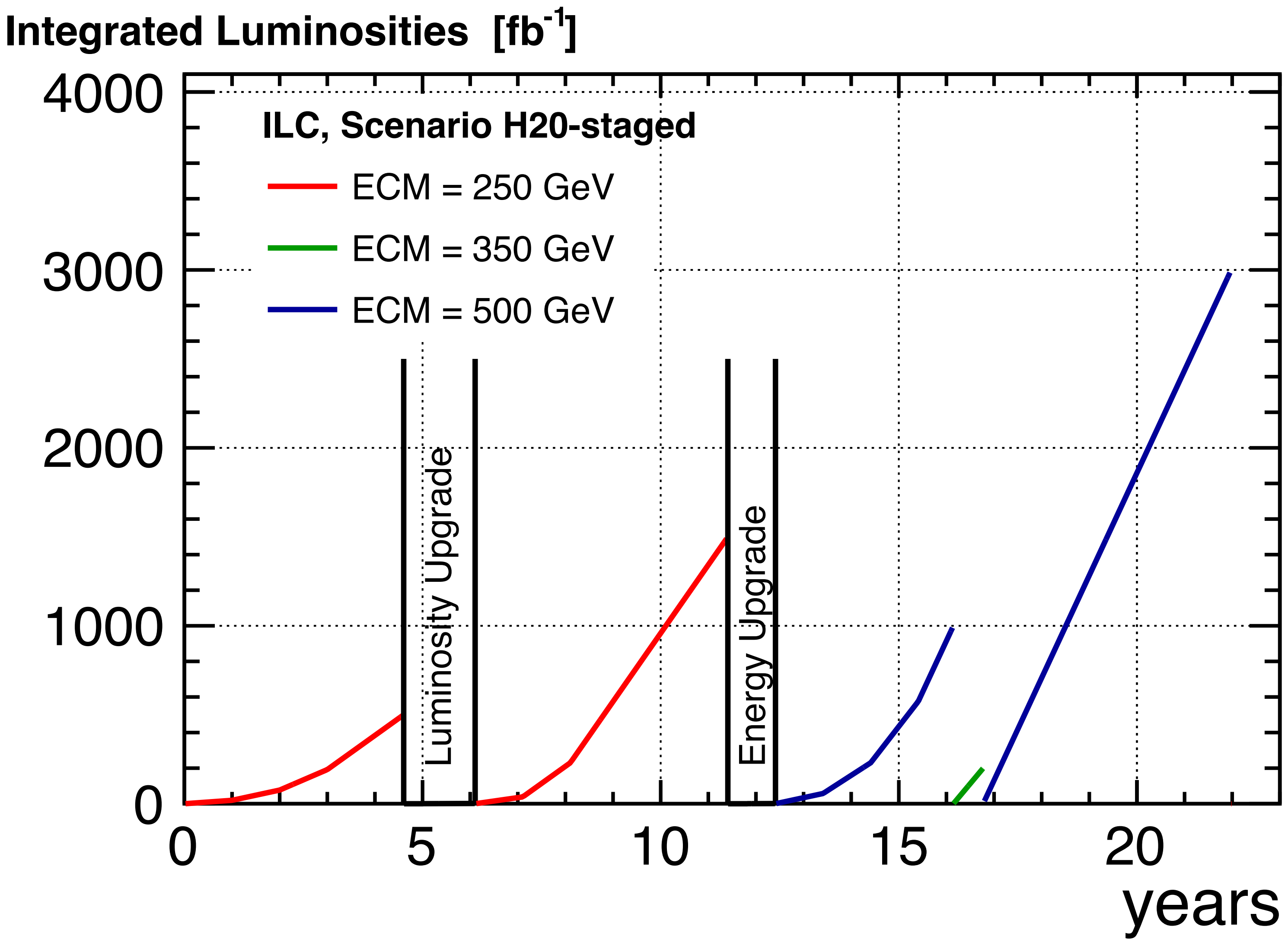
ILC Run Plan in brief

Material from ILC contribution to ESU

		$\int \mathcal{L}dt$ [fb^{-1}]		
$\sqrt{s}$	G-20	H-20	I-20	Snow
250 GeV	500	2000	500	1150
350 GeV	200	200	1700	200
500 GeV	5000	4000	4000	1600

	fraction with sgn($P(e^-), P(e^+)$) =			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV (2015)	67.5	22.5	5	5
250 GeV (update)	**45**	**45**	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10

$\sqrt{s}$	1 TeV	90 GeV	160 GeV
$\int \mathcal{L}dt$ [fb^{-1}]	8000	100	500

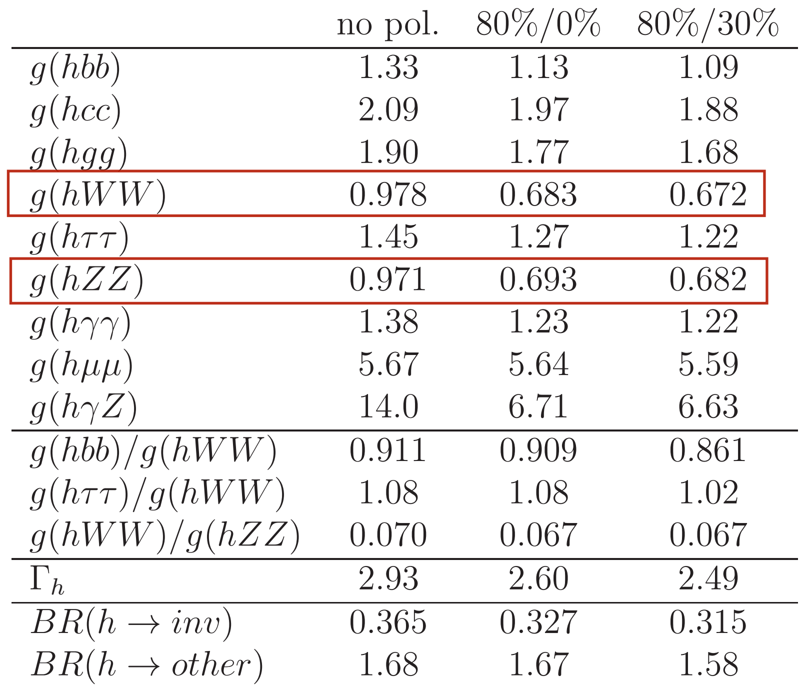


Polarised beams @ ILC$_{250}$

G. Moortgat-Pick et al '08 LCC Physics WG '18

Various benefits of polarised beams:

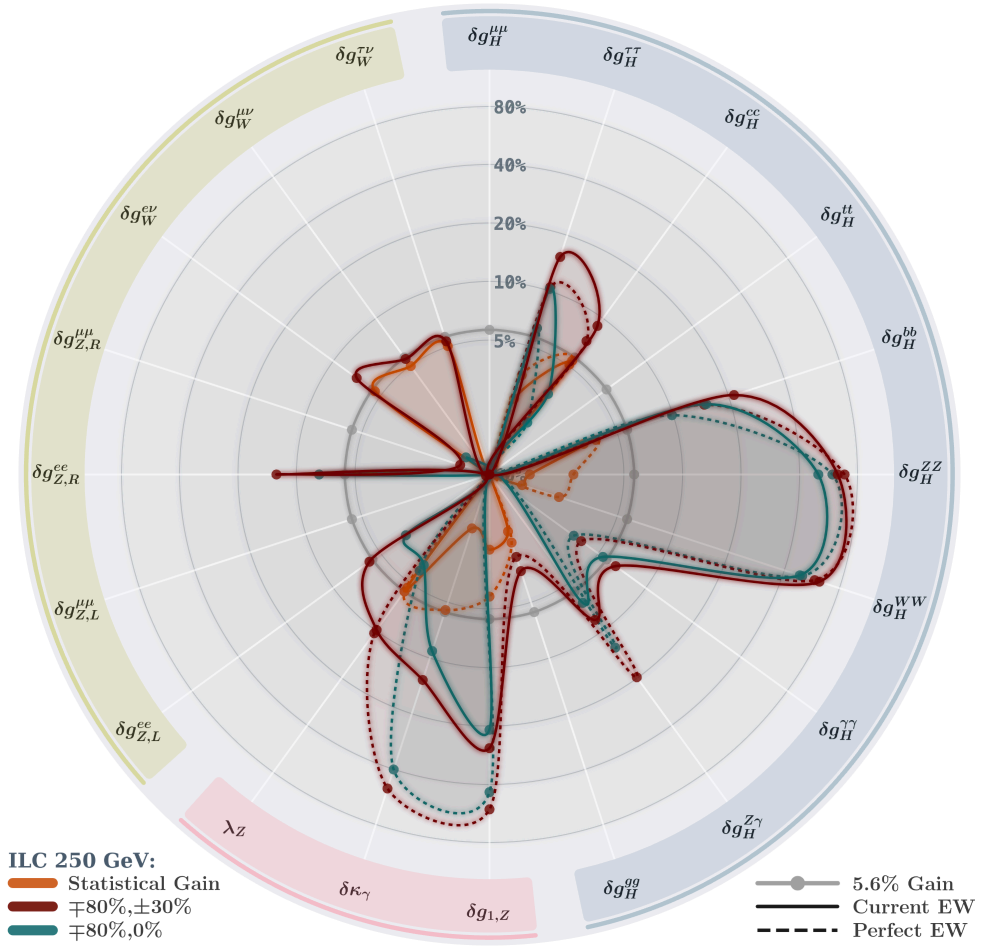
- Higher signal rates and lower background rates (equivalent to 40% higher L)
- Different data sets → helps resolving degeneracies → gain is much more than increased rates (see later)
- Better control of systematics (thanks to exp. redundancy)



	no pol.	80%/0%	80%/30%
$g(hbb)$	1.33	1.13	1.09
$g(hcc)$	2.09	1.97	1.88
$g(hgg)$	1.90	1.77	1.68
$g(hWW)$	0.978	0.683	0.672
$g(h\tau\tau)$	1.45	1.27	1.22
$g(hZZ)$	0.971	0.693	0.682
$g(h\gamma\gamma)$	1.38	1.23	1.22
$g(h\mu\mu)$	5.67	5.64	5.59
$g(h\gamma Z)$	14.0	6.71	6.63
$g(hbb)/g(hWW)$	0.911	0.909	0.861
$g(h\tau\tau)/g(hWW)$	1.08	1.08	1.02
$g(hWW)/g(hZZ)$	0.070	0.067	0.067
Γ_h	2.93	2.60	2.49
$BR(h \to inv)$	0.365	0.327	0.315
$BR(h \to other)$	1.68	1.67	1.58

Table 1: Projected relative errors for Higgs boson couplings and other Higgs observables at 250 GeV, in %, comparing three cases of beam polarization: 2 ab^{-1} with $\mathcal{P}_{e^-} = \mathcal{P}_{e^+} = 0\%$, as well as the $\mathcal{P}_{e^+}$=0 and $\mathcal{P}_{e^+}$=30% scenarios defined in the Introduction.

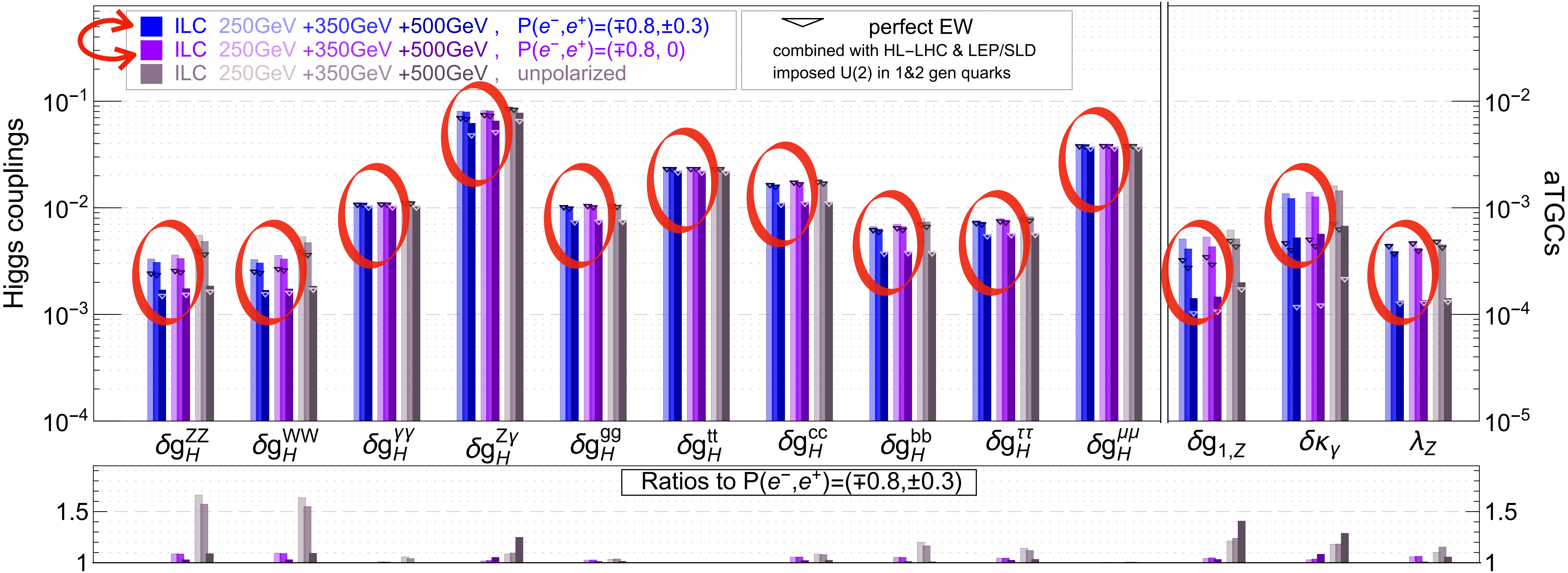
LCC Physics WG '18



J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Impact of Beam Polarisation

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- Positron polarisation doesn't play a big role (for Higgs couplings determination)

Impact of Beam Polarisation

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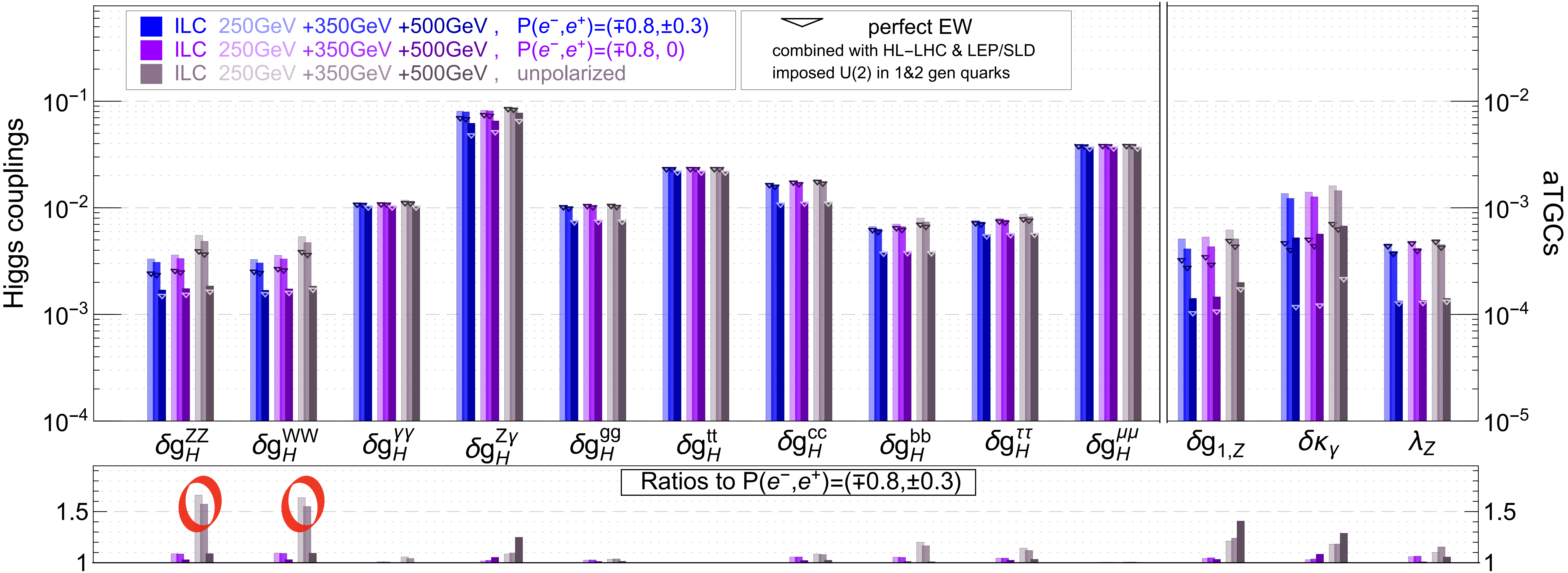

- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination

Impact of Beam Polarisation

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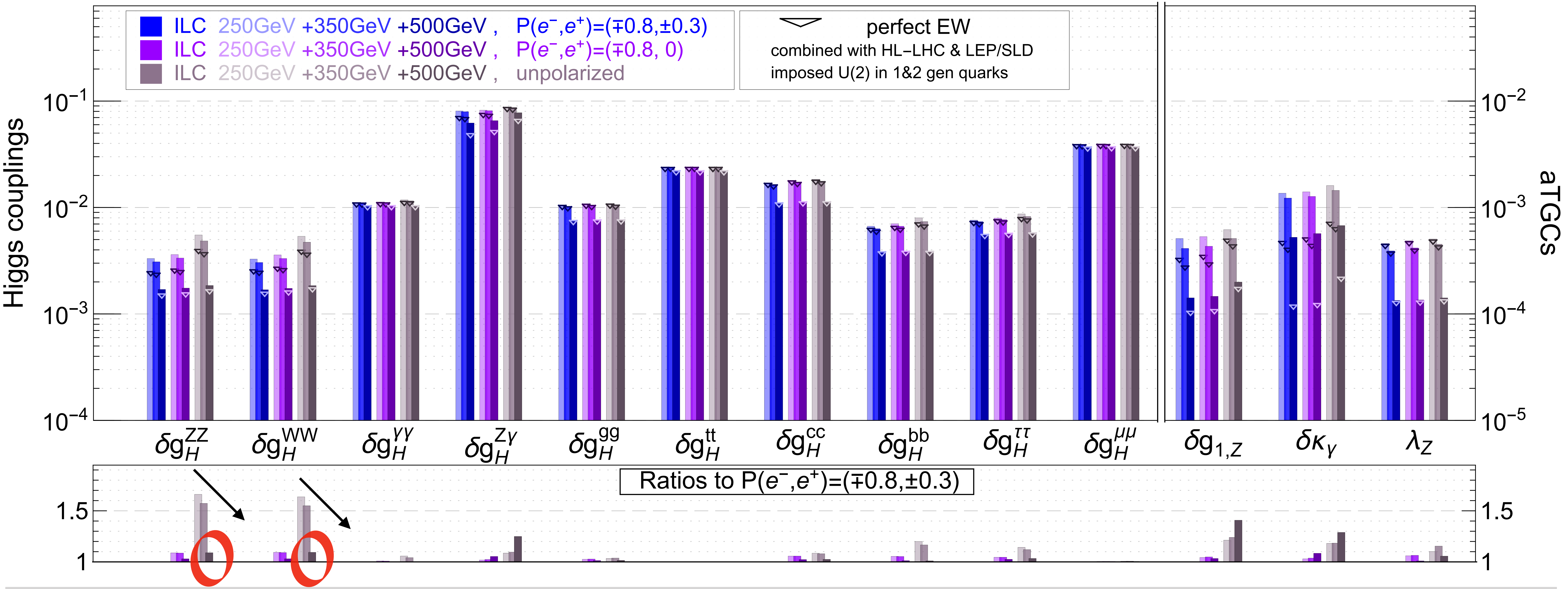
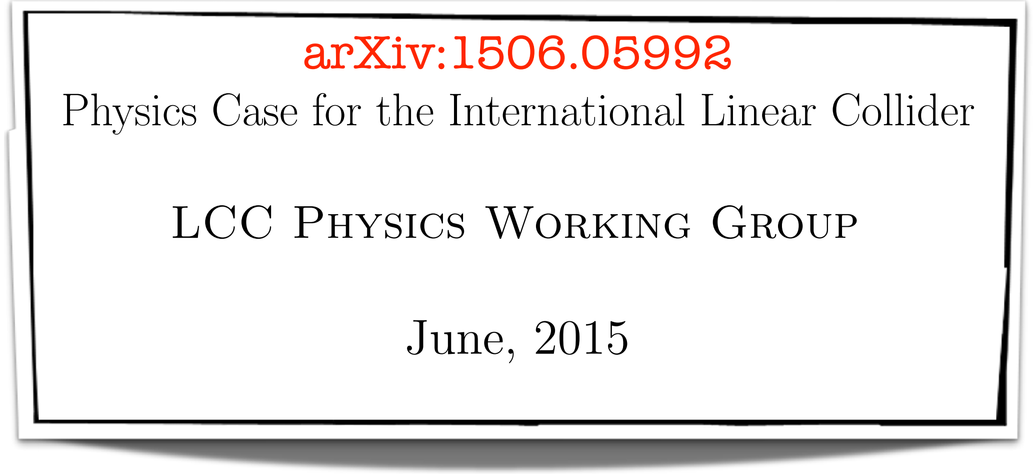


- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination
- Polarisation-benefit diminishes (in relative and absolute terms) when other runs at higher energies are added

Literature on ILC

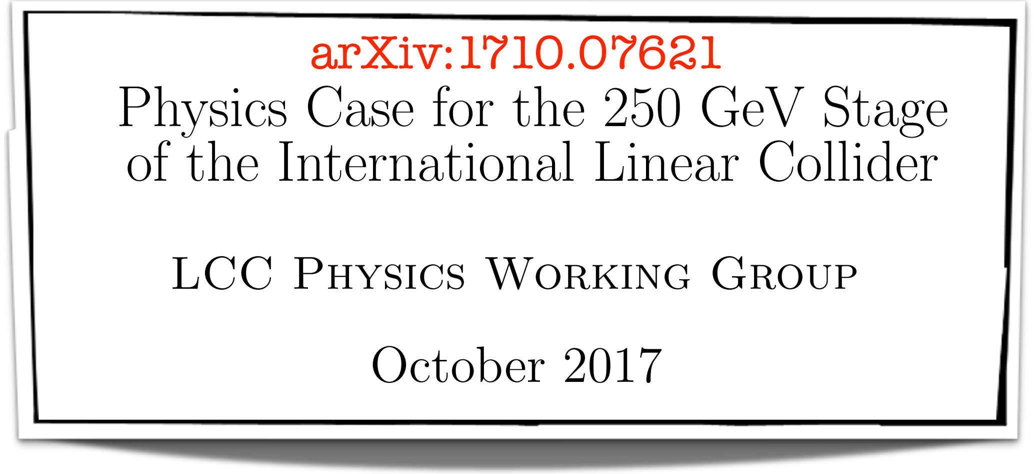
https://ilchome.web.cern.ch


arXiv:1506.05992

Physics Case for the International Linear Collider

LCC Physics Working Group

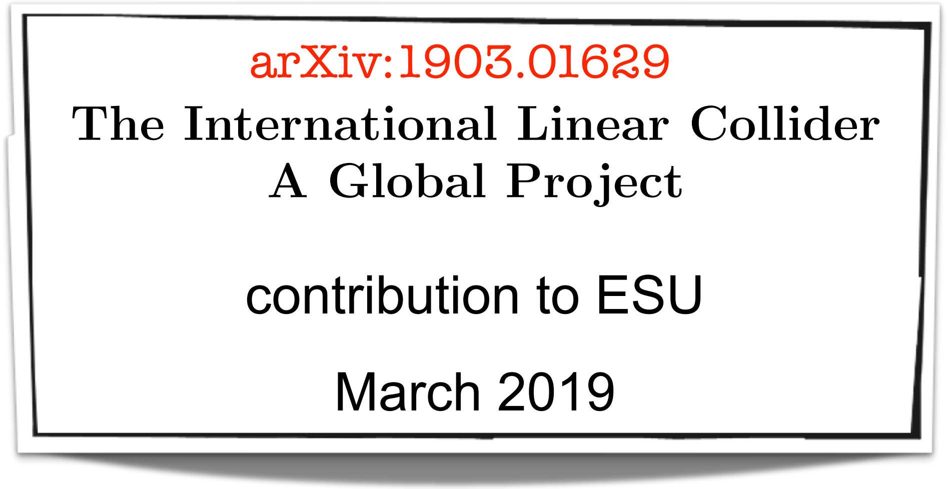
June, 2015


arXiv:1710.07621

Physics Case for the 250 GeV Stage of the International Linear Collider

LCC Physics Working Group

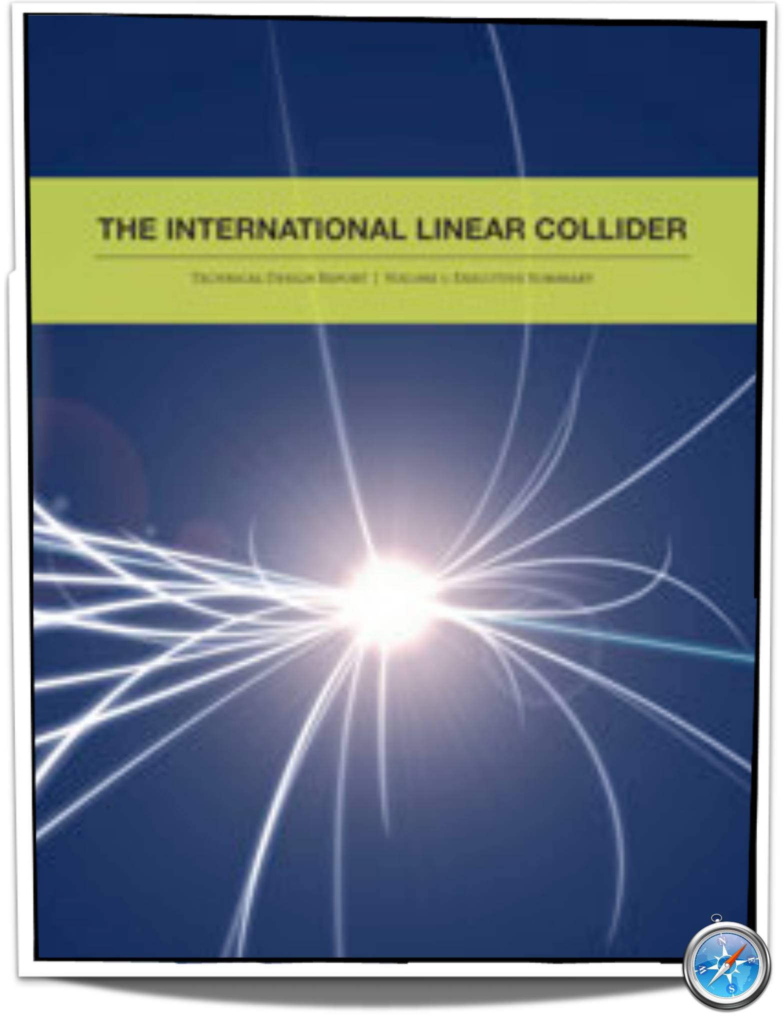
October 2017


arXiv:1903.01629

The International Linear Collider
A Global Project

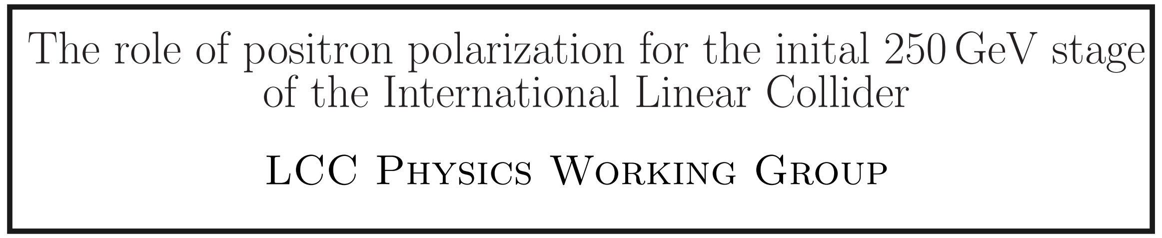
contribution to ESU

March 2019

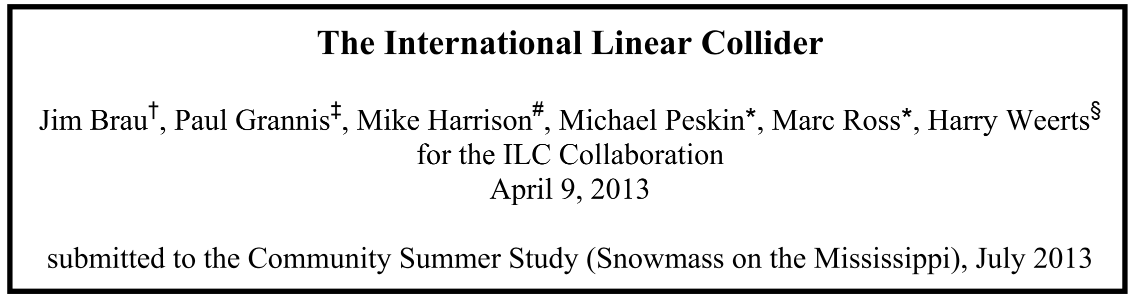

THE INTERNATIONAL LINEAR COLLIDER


The Potential of the ILC for Discovering New Particles

Document Supporting the ICFA Response Letter to the ILC Advisory Panel

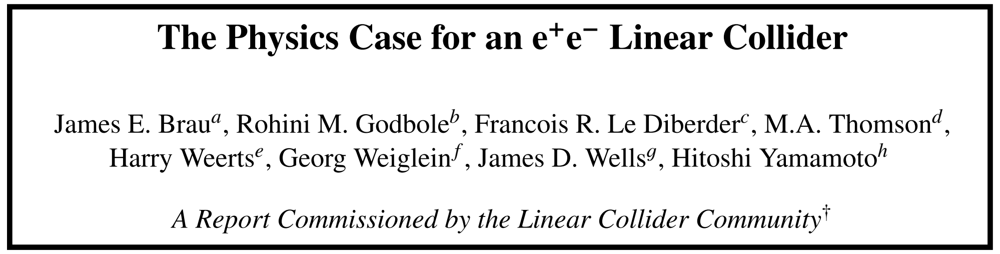

The role of positron polarization for the inital 250 GeV stage of the International Linear Collider

LCC Physics Working Group


The International Linear Collider

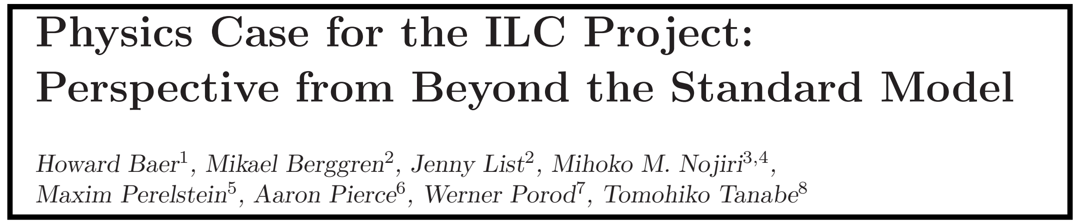
Jim Brau[†], Paul Grannis[‡], Mike Harrison[#], Michael Peskin[*], Marc Ross[*], Harry Weerts[§]
for the ILC Collaboration
April 9, 2013

submitted to the Community Summer Study (Snowmass on the Mississippi), July 2013


The Physics Case for an e^+e^- Linear Collider

James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d], Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]

A Report Commissioned by the Linear Collider Community[†]

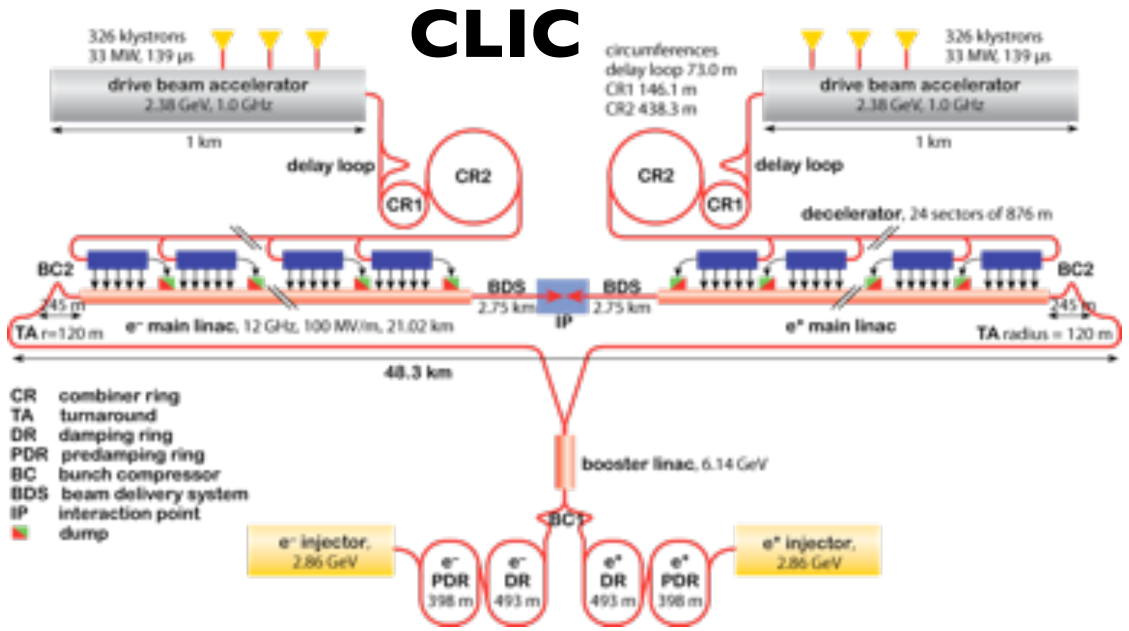

Physics Case for the ILC Project: Perspective from Beyond the Standard Model

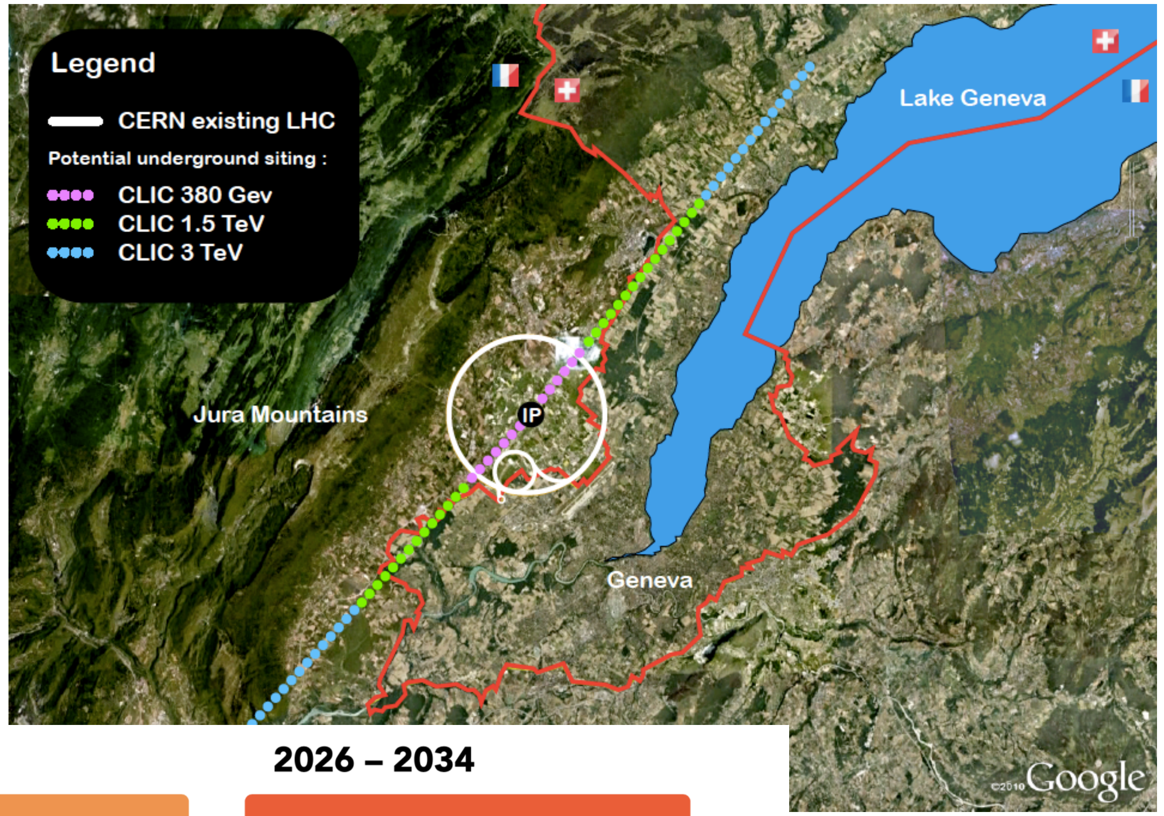
Howard Baer[1], Mikael Berggren[2], Jenny List[2], Mihoko M. Nojiri[3,4], Maxim Perelstein[5], Aaron Pierce[6], Werner Porod[7], Tomohiko Tanabe[8]


Physics at the e^+e^- Linear Collider

CLIC (2035-2060??)

380/1000/3000 GeV - 5/ab





2013 – 2019

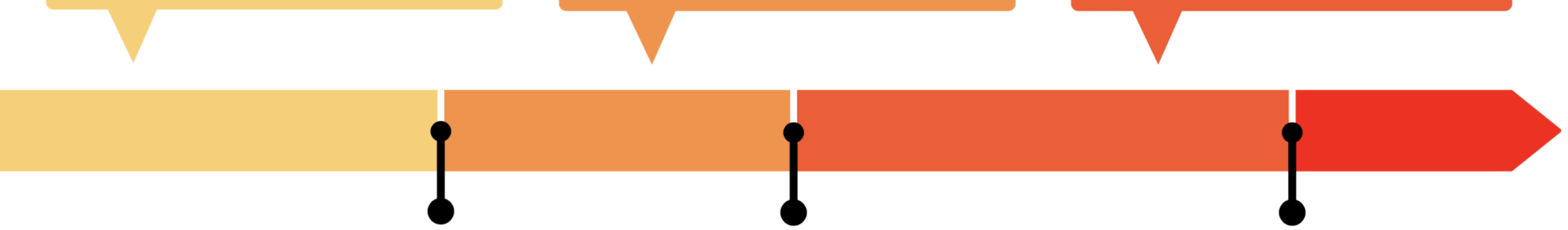
Development Phase
Development of a project plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 – 2025

Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, pre-series and system optimisation studies, technical proposal of the experiment, site authorisation

2026 – 2034

Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning



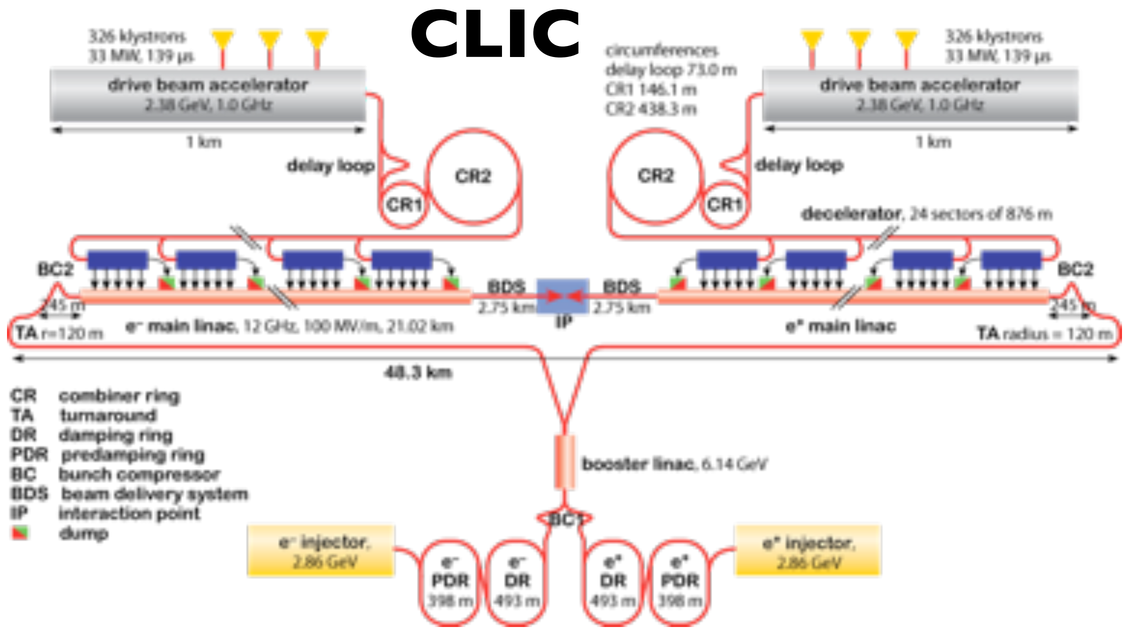
2020
Update of the European Strategy for Particle Physics

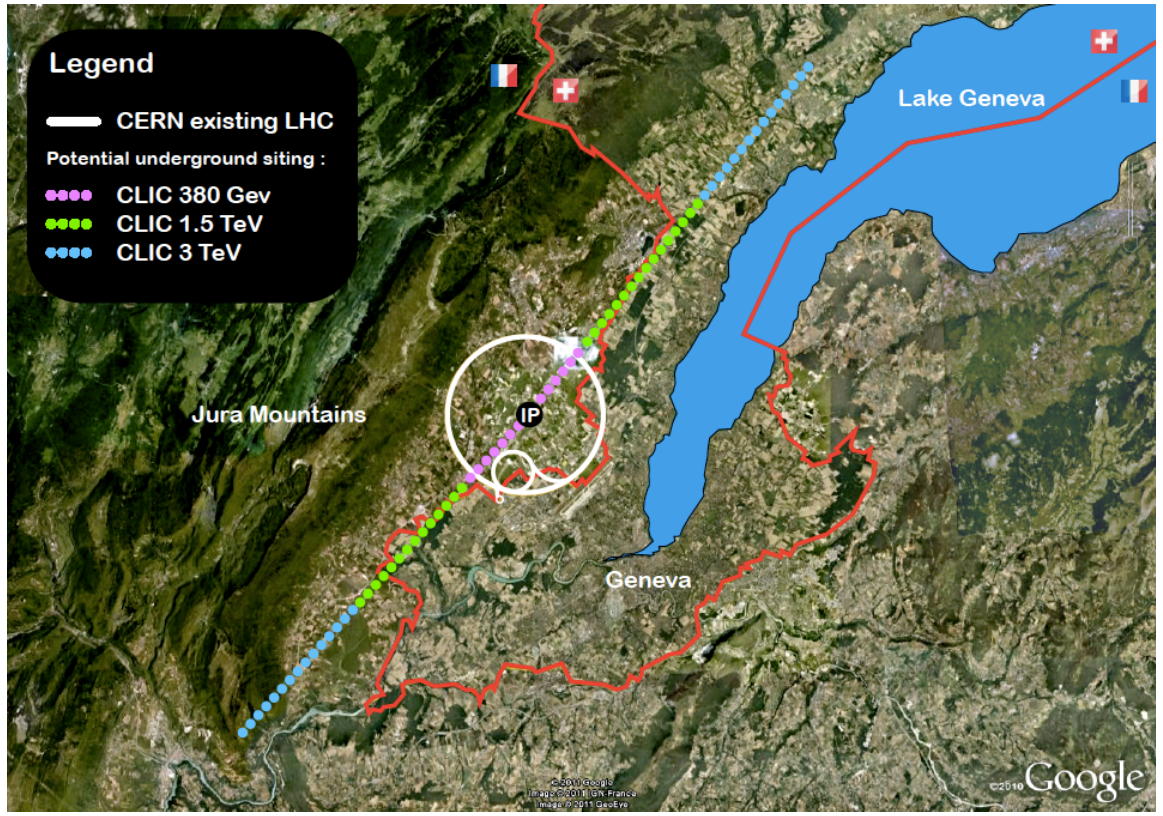
2026
Ready for construction

2035
First collisions

CLIC (2035-2060??)

380/1000/3000 GeV - 5/ab



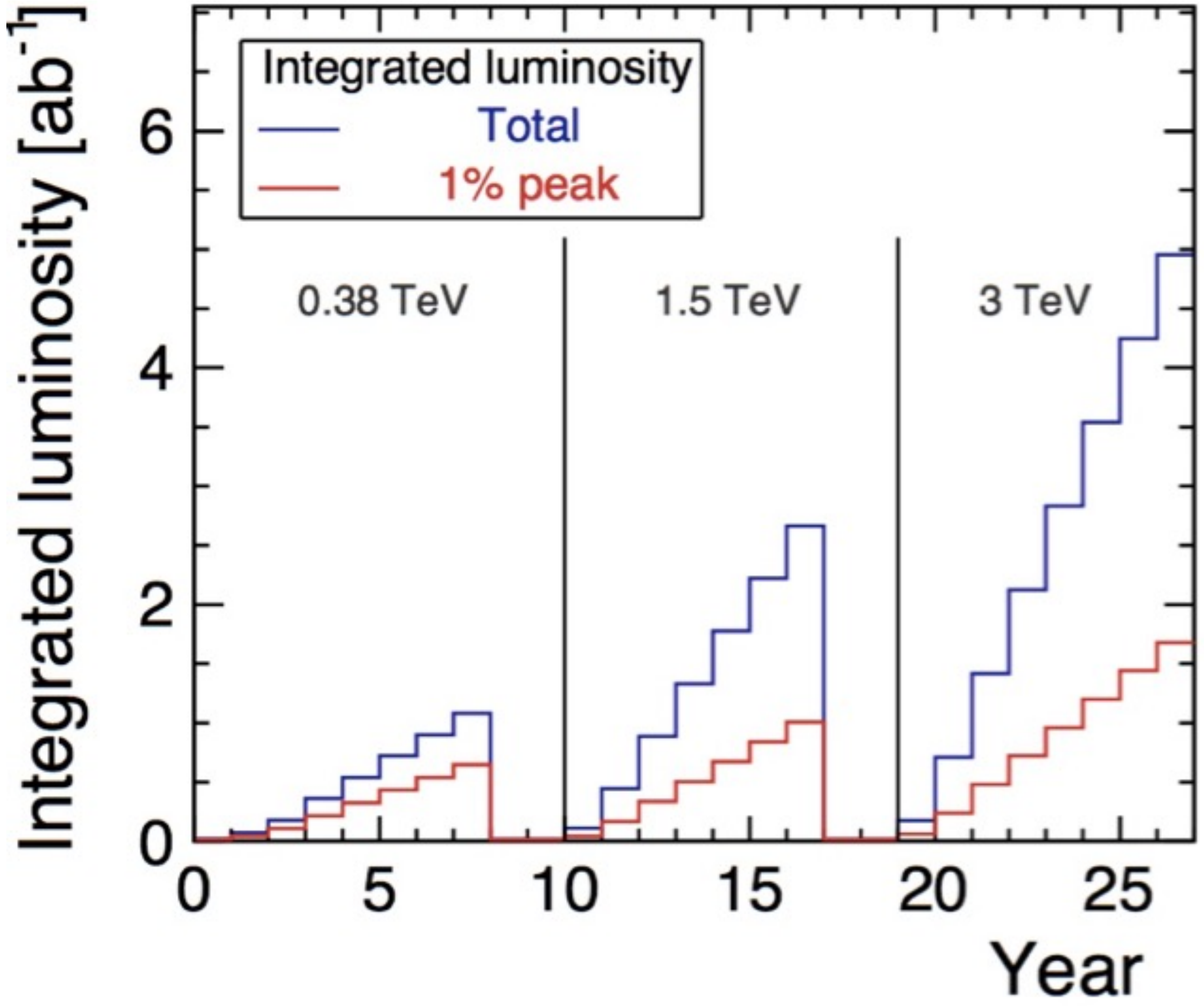


Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

- sub-percent Higgs coupling measurements
- few percents Higgs width
- top mass, top EW couplings
- direct BSM sensitivity in the multi-TeV region (direct and indirectly via precision)

CLIC Run Plan

Material from A. Robson



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	increased from
1	0.38 (and 0.35)	1.0	0.5+0.1ab^{-1}
2	1.5	2.5	1.5ab^{-1}
3	3.0	5.0	3ab^{-1}

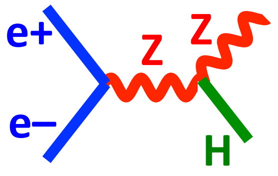
Electron polarisation enhances Higgs production at high-energy stages and provides additional observables

Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio (50:50) at $\sqrt{s}$=380GeV ; (80:20) at $\sqrt{s}$=1.5 and 3TeV

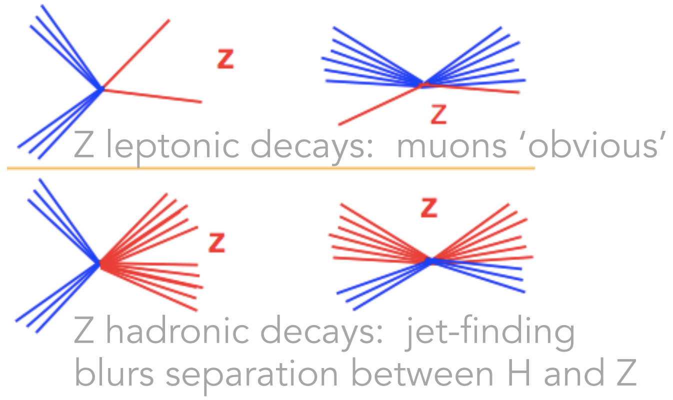
CLIC: Why 380 GeV?

Material from A. Robson

- Precise determination of g_{HZZ} from ZH recoil measurement at initial stage crucial for Higgs couplings at all energy stages



- ZH cross-section peak is at 250GeV
- At 380 GeV, Z hadronic decays provide the best sensitivity

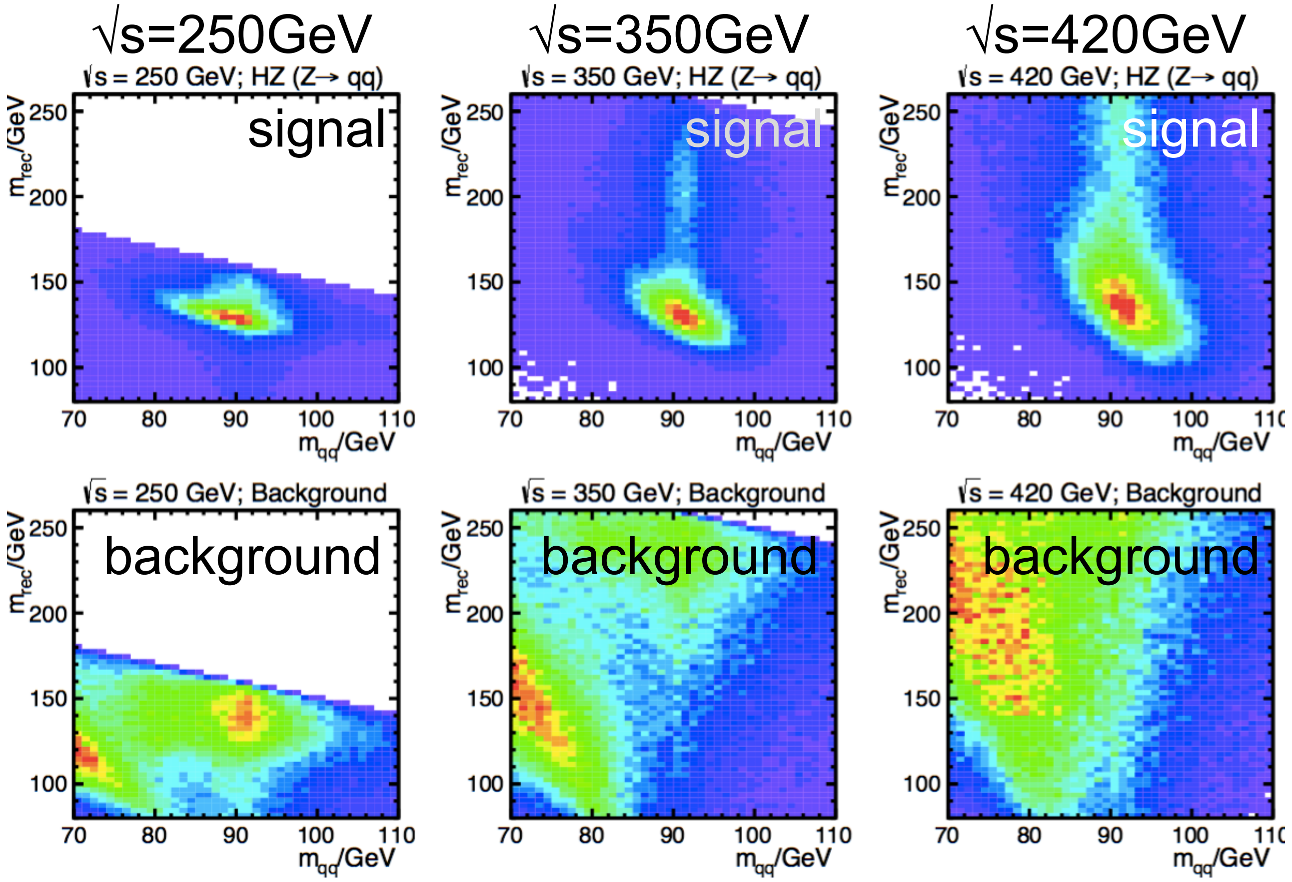


Z leptonic decays: muons 'obvious'

Z hadronic decays: jet-finding blurs separation between H and Z

- At 250GeV the background to Z hadronic is more signal-like
- At 420GeV the cross-section is lower and jet energy resolution worse

$\sqrt{s}$	$L_{int}[ab^{-1}]$	$\sigma(ZH)$[fb]	$\Delta\sigma(ZH)$
250	1	136	±2.6%
350	1	93	±1.3%
420	1	68	±1.9%



Eur. Phys. J. C 76 (2016) 72

- Overall, 380GeV allows best precision on g_{HZZ}
- 380GeV also gives access to top quark

–> 380GeV is optimal initial energy for e^+e^-

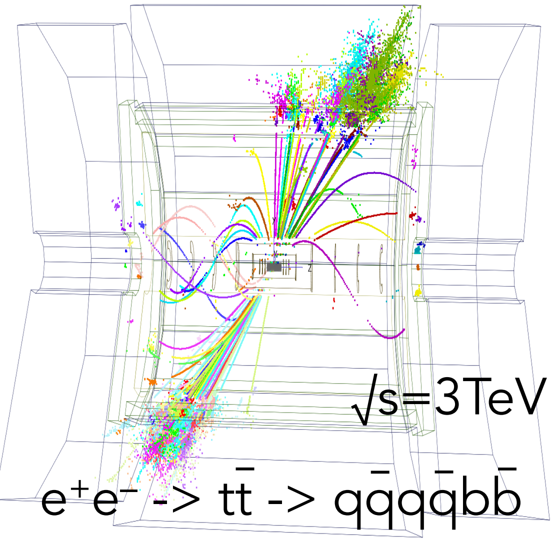
CLIC: What Do Higher Energies Buy You?

Material from A. Robson

- Precision Higgs physics:
  - Increases VBF single-Higgs production
  - Adds ttH and HH production
  - Allows precise measurement of g_{HHH}
- Precision top-quark physics:
  - Cross-sections, asymmetries and optimal observables at all energies (necessary to disentangle effects), including boosted regime, study of ttH
- Precision two-fermion and multi-boson measurements
- BSM physics reach via precision measurements:

- Can probe CP-odd component of ttH coupling to $0.02<\Delta\sin^2\phi<0.08$ for full range of $\sin^2\phi$

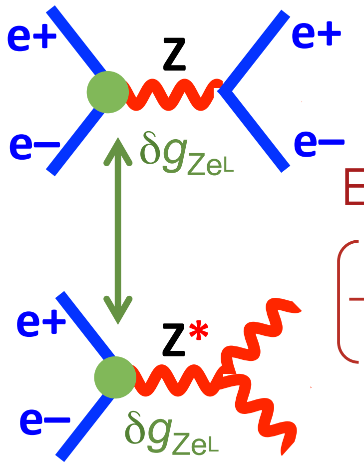
First study of boosted top production in e^+e^-



$\sqrt{s}$=3TeV

e^+e^- -> $t\bar{t}$ -> $q\bar{q}q\bar{q}b\bar{b}$

At low energy ($\sqrt{s}=m_Z$)



Effect grows as *s*

$\left(\frac{3000}{91.2}\right)^2 \sim 1000$

At high energy ($\sqrt{s}$=3TeV)

Imagine measuring $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$ => $\delta g_{Ze_L} \sim 10^{-4}$

same precision!

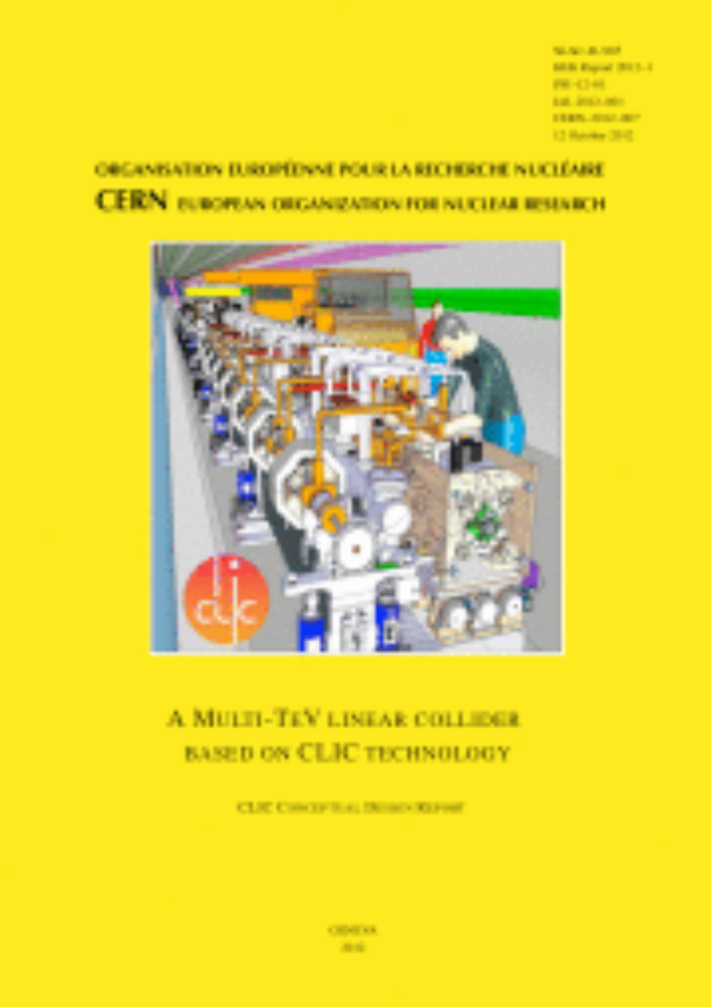
...equivalent to $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3\text{TeV}} \sim 10\%$ => $\delta g_{Ze_L} \sim 10^{-4}$

–> strongly benefit from high energies

Literature on CLIC

https://clic.cern

2012



ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

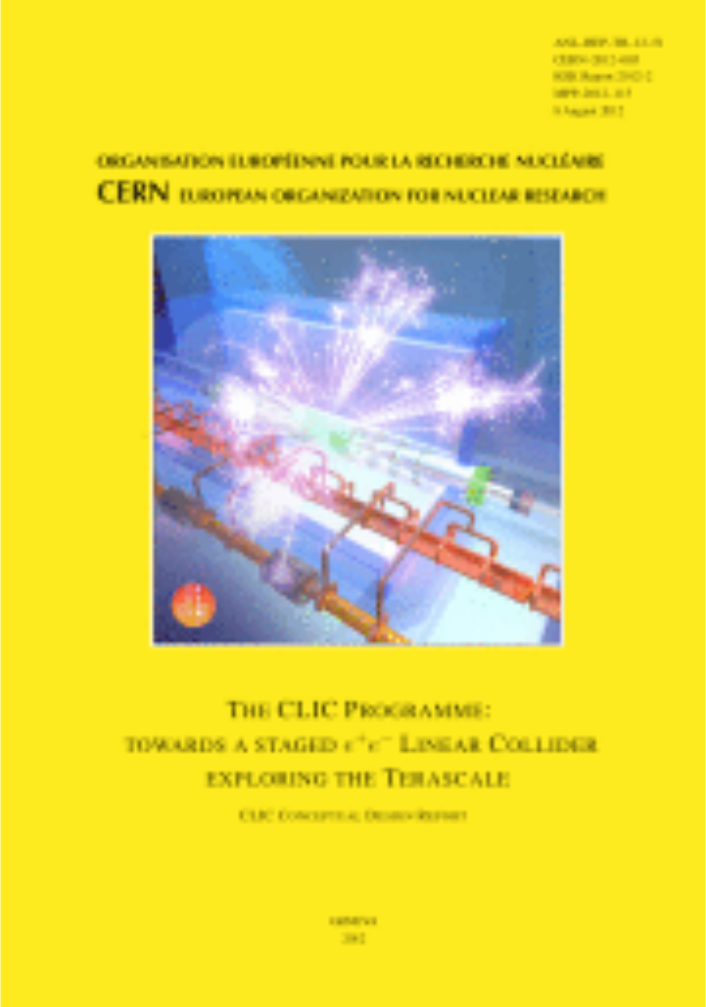
A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT



ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE CLIC PROGRAMME:
TOWARDS A STAGED e^+e^- LINEAR COLLIDER
EXPLORING THE TERASCALE

CLIC CONCEPTUAL DESIGN REPORT

2018

The CLIC Potential for New Physics

Editors: *J. de Blas* [1,2], *R. Franceschini* [3,4], *F. Riva* [5], *P. Roloff* [6], *U. Schnoor* [6], *M. Spannowsky* [7], *J. D. Wells* [8], *A. Wulzer* [1,6,9] *and J. Zupan* [10]

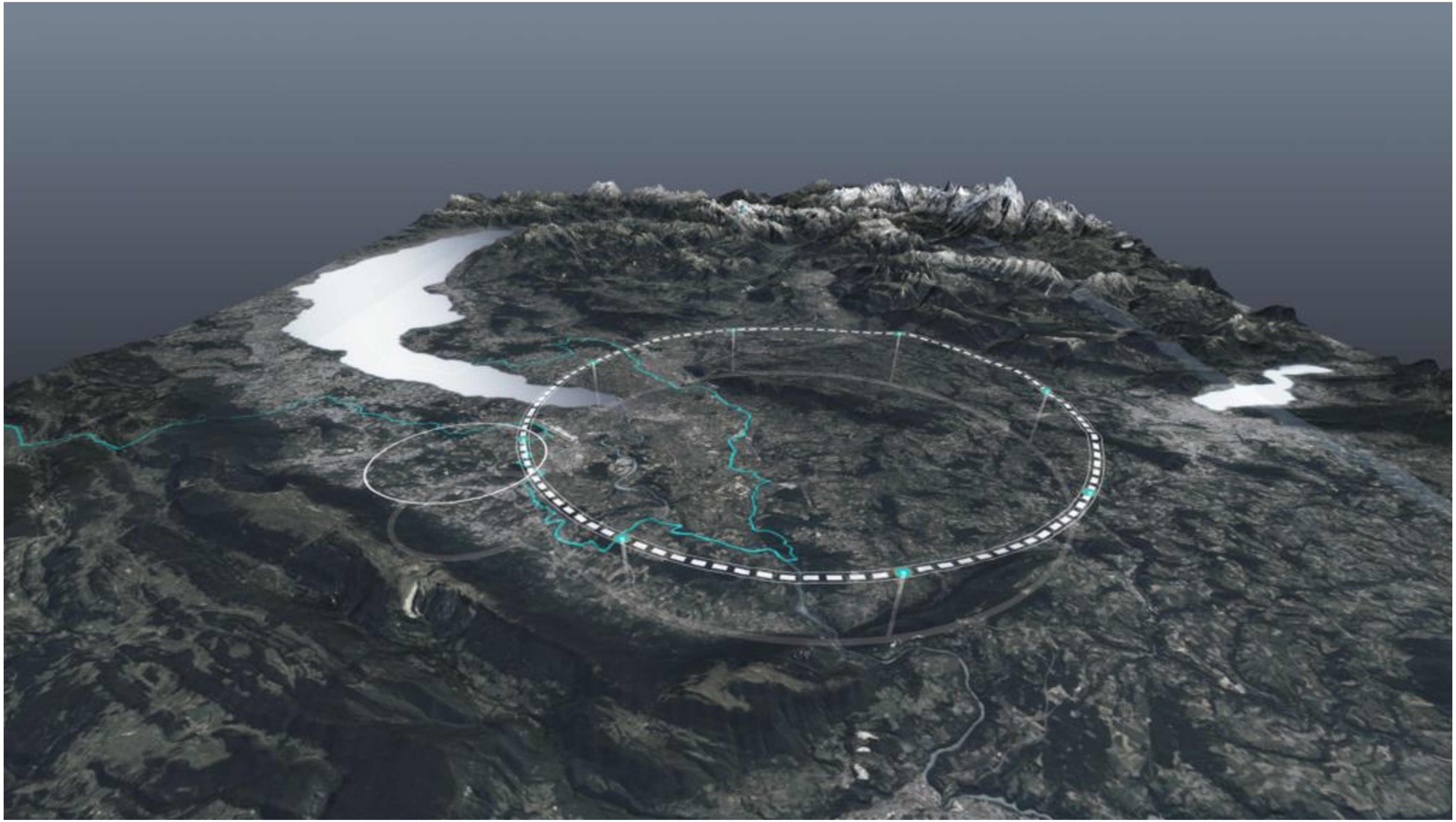
arXiv:1812.02093

THE COMPACT LINEAR COLLIDER (CLIC)
2018 SUMMARY REPORT

arXiv:1812.06018

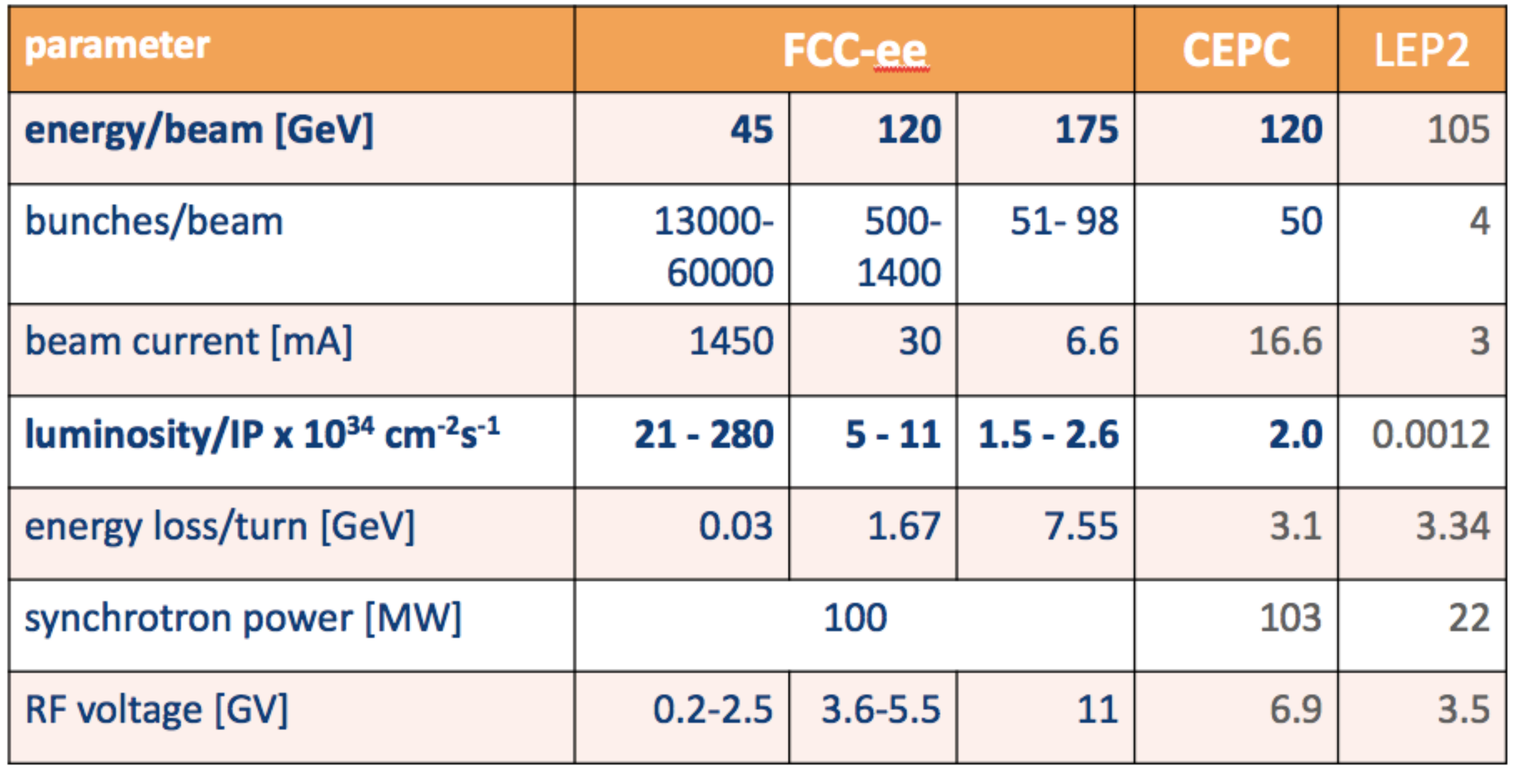
FCC-ee (x=2045 - 2060)/CEPC (2030??-2040??)

90/240/350/(500) - O(10/ab)

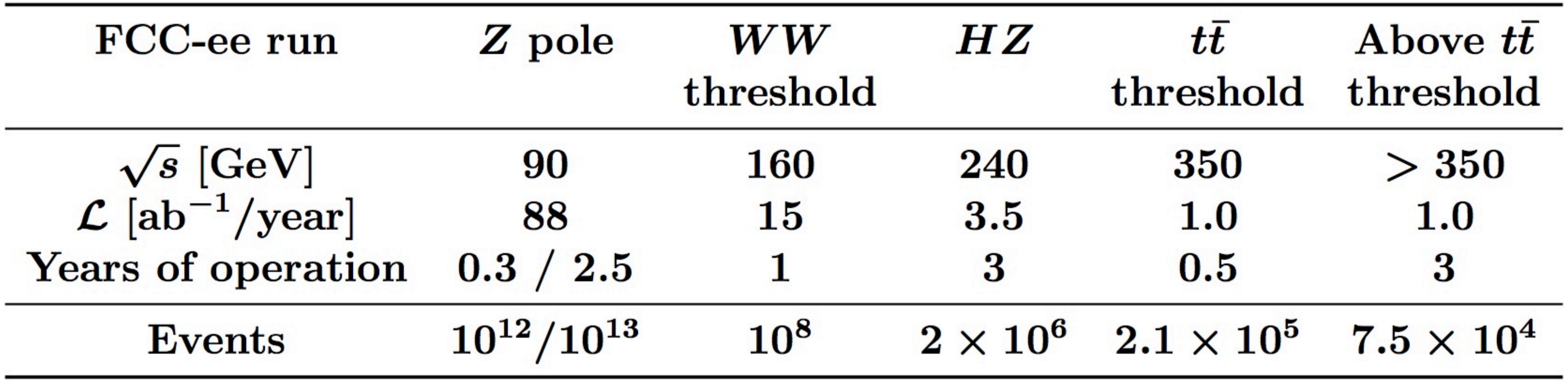


FCC-ee (x=2045 - 2060)/CEPC (2030??-2040??)

90/240/350/(500) - O(10/ab)



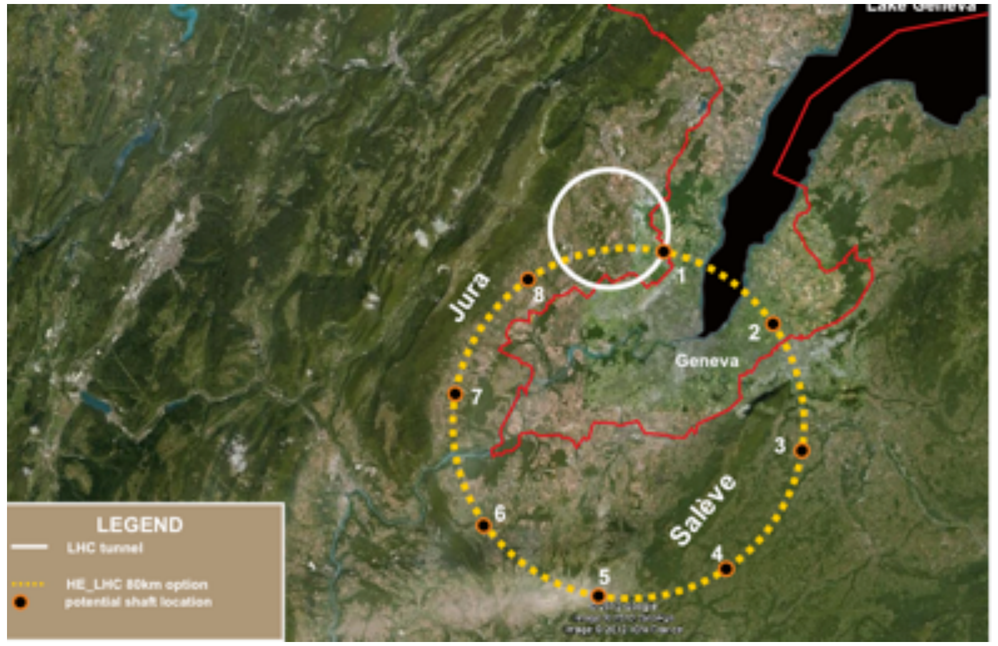
parameter	**FCC-ee**			**CEPC**	**LEP2**
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	13000-60000	500-1400	51- 98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	6.9	3.5

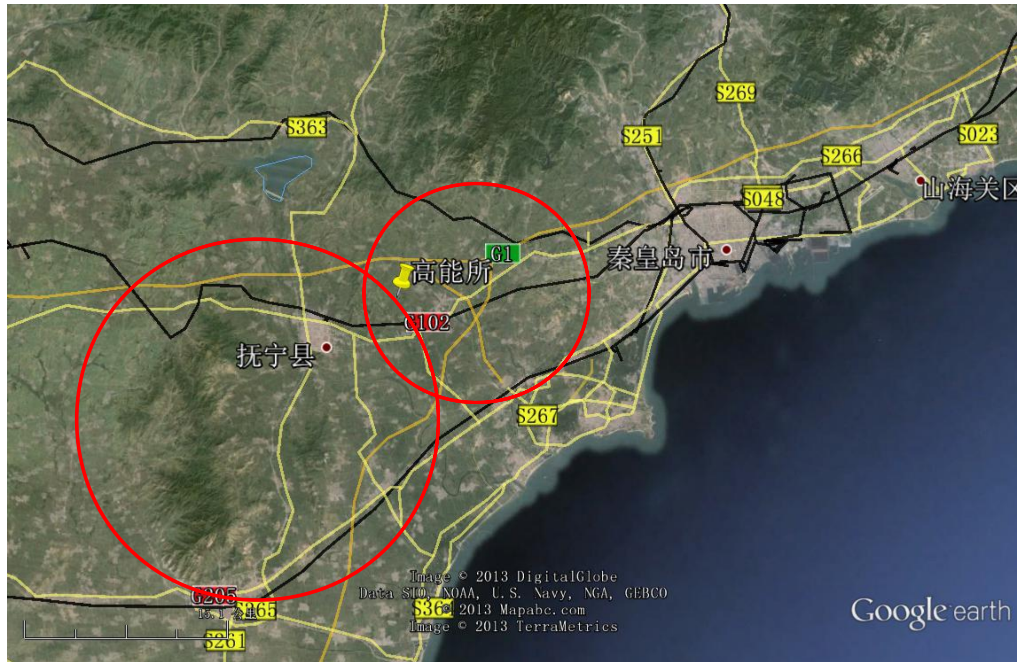


FCC-ee run	Z pole	WW threshold	HZ	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/year]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^8	2×10^6	2.1×10^5	7.5×10^4

FCC-ee (x=2045 - 2060)/CEPC (2030??-2040??)

90/240/350/(500) - O(10/ab)

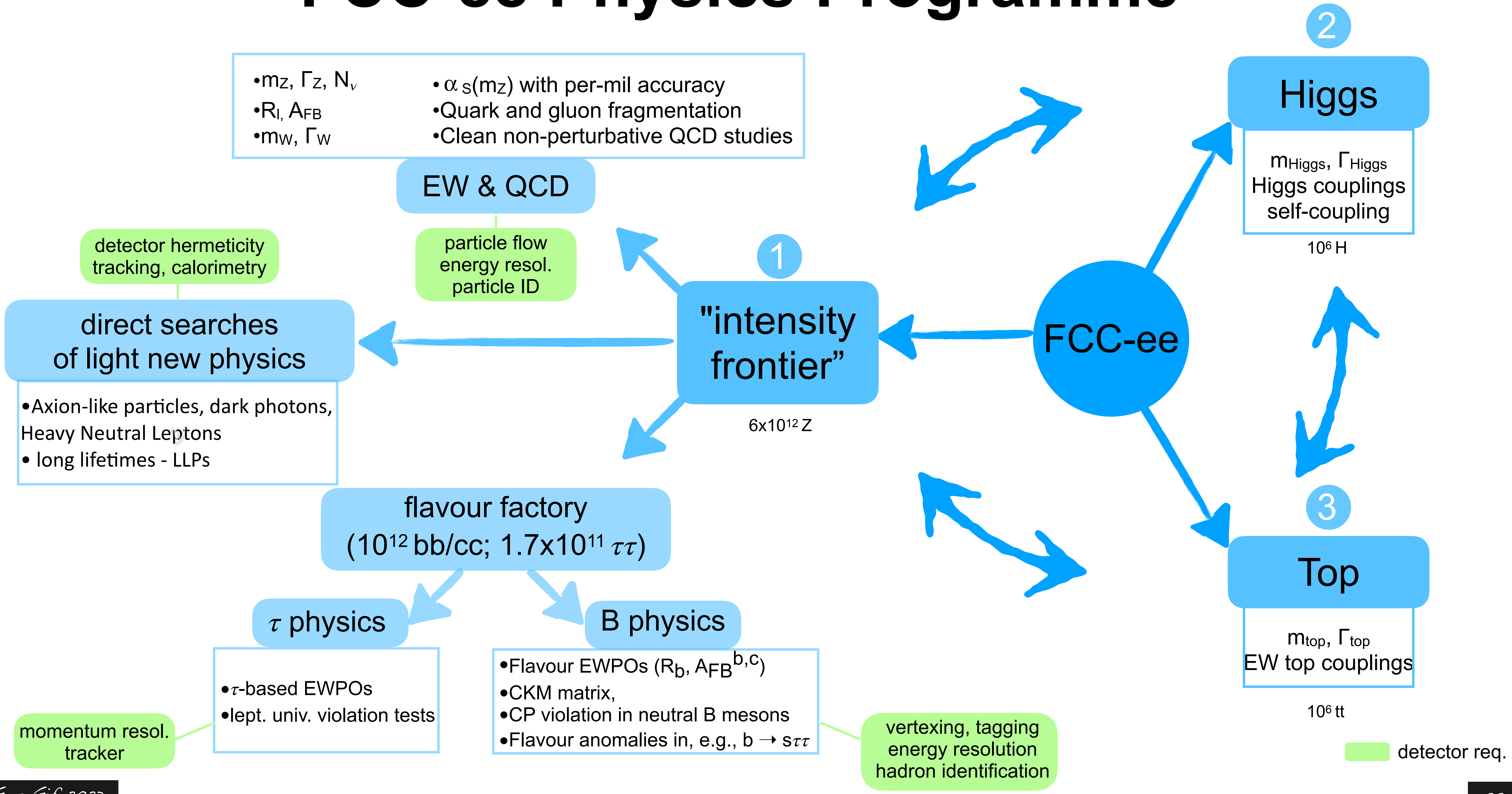




@FCC-ee

- 10^6 H
- 10^{12} Z possible upgrade to 10^{13} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^8 W (mass)
- $3\mathrm{x}10^{10}$ tau/muon pairs
- $2\mathrm{x}10^{11}$ b/c quarks ⇒ >20'000 $B_s \to \tau^+\tau^-$
- TLEP@340/500: 10^6 top pairs (pole mass, probe FCNC decays, top Yukawa)

FCC-ee Physics Programme



FCC-ee

① "intensity frontier"

6×10^{12} Z

EW & QCD

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

particle flow
energy resol.
particle ID

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

detector hermeticity
tracking, calorimetry

flavour factory
(10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}{}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \rightarrow s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

② Higgs

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

10^6 H

③ Top

m_{top}, Γ_{top}
EW top couplings

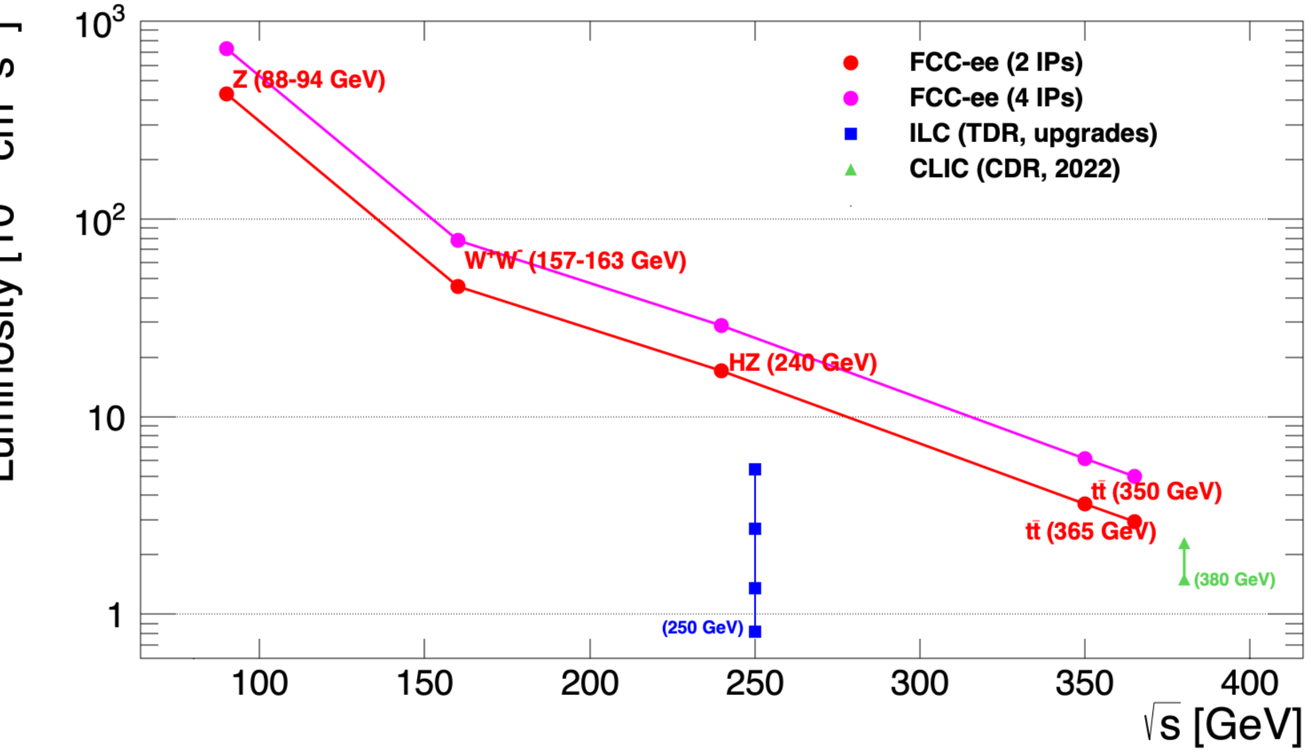
10^6 tt

🟩 detector req.

FCC-ee Run Plan

LEP1 data accumulated in **every 2 mn**. Then exciting & diverse programme with different priorities every few years.

(order of the different stages still subject to discussion/optimisation)



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

— Superb statistics achieved in only 15 years —

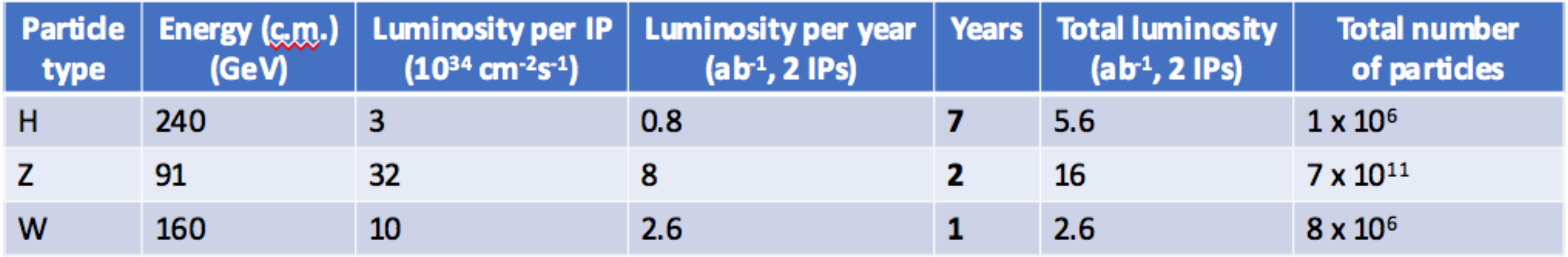
in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

Event statistics (with 2 IPs, x1.7 for 4 IPs now official baseline)

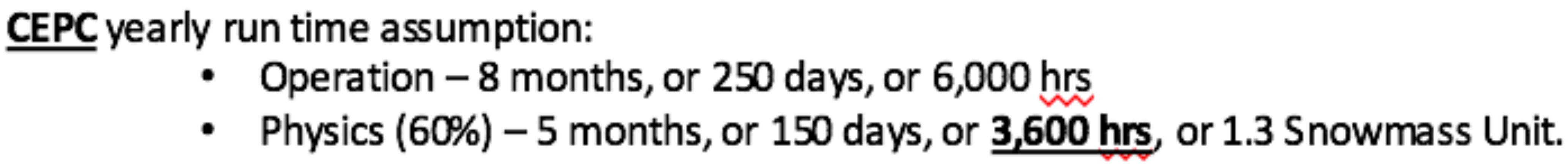
						$\sqrt{s}$ uncertainty
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \rightarrow ZH$	Never done	2 MeV
$\bar{t}t$ threshold	$\sqrt{s}$ ~ 365 GeV	5 years	10^6	$e^+e^- \rightarrow \bar{t}t$	Never done	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \rightarrow Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \rightarrow W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s}$ = 125 GeV	5? years	~5000	$e^+e^- \rightarrow H_{125}$]	Never done	< 100 keV

CEPC Run Plan

Material from J. Guimarães da Costa, L.T. Wang et al.



Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} cm^{-2}s^{-1})	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^6
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^6



CEPC yearly run time assumption:

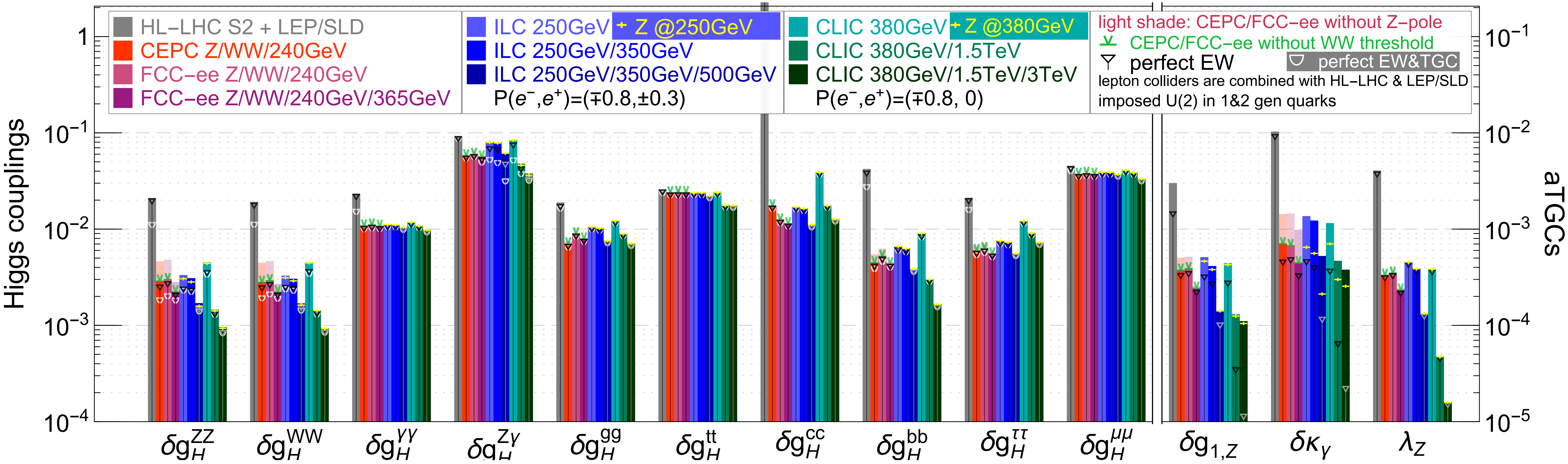
- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.

No run above 240/250 GeV planned for the moment

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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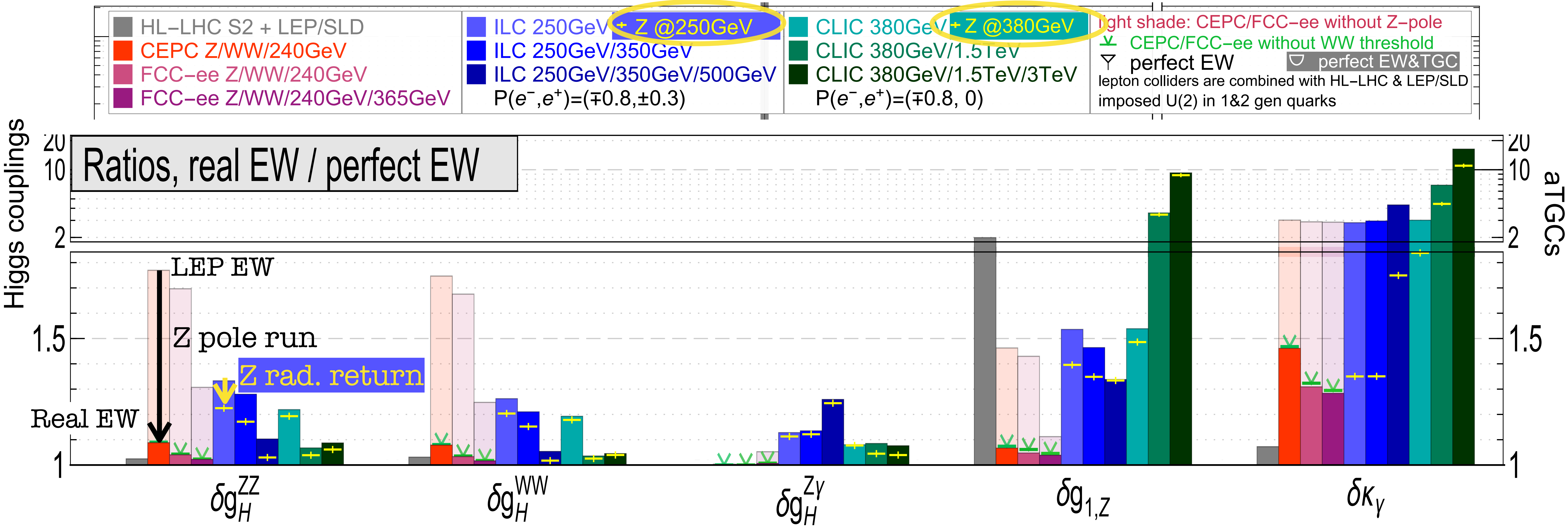
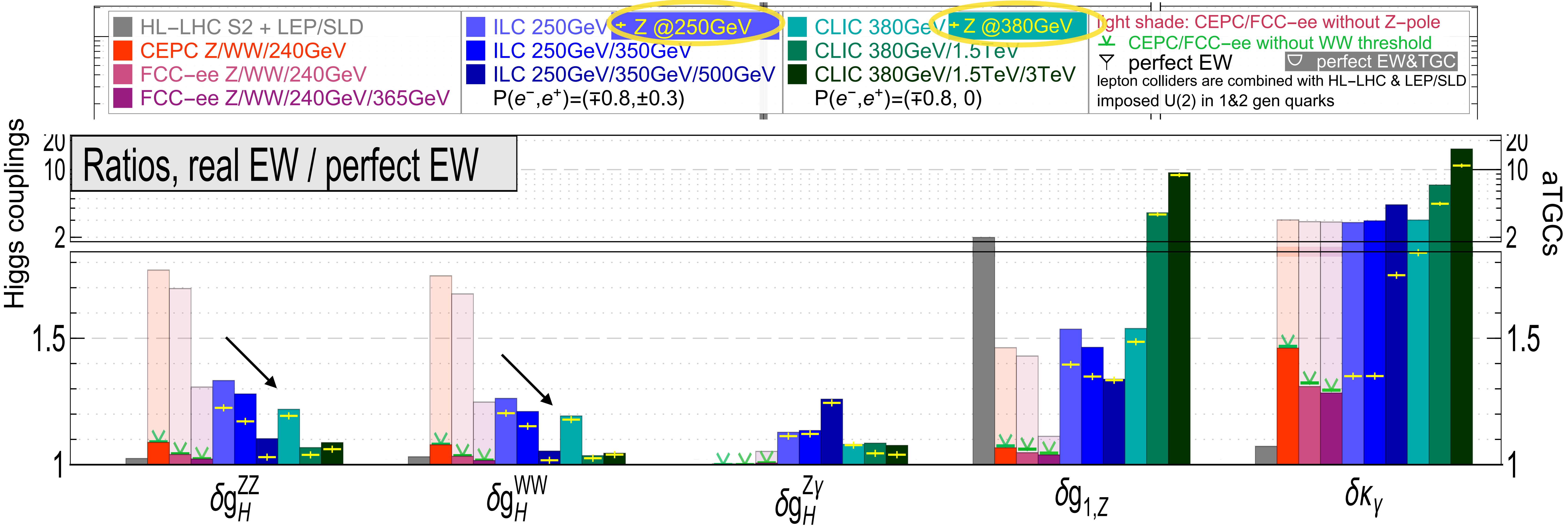


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
  But EW measurements at high energy (via Z-radiative return) help mitigating this issue

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

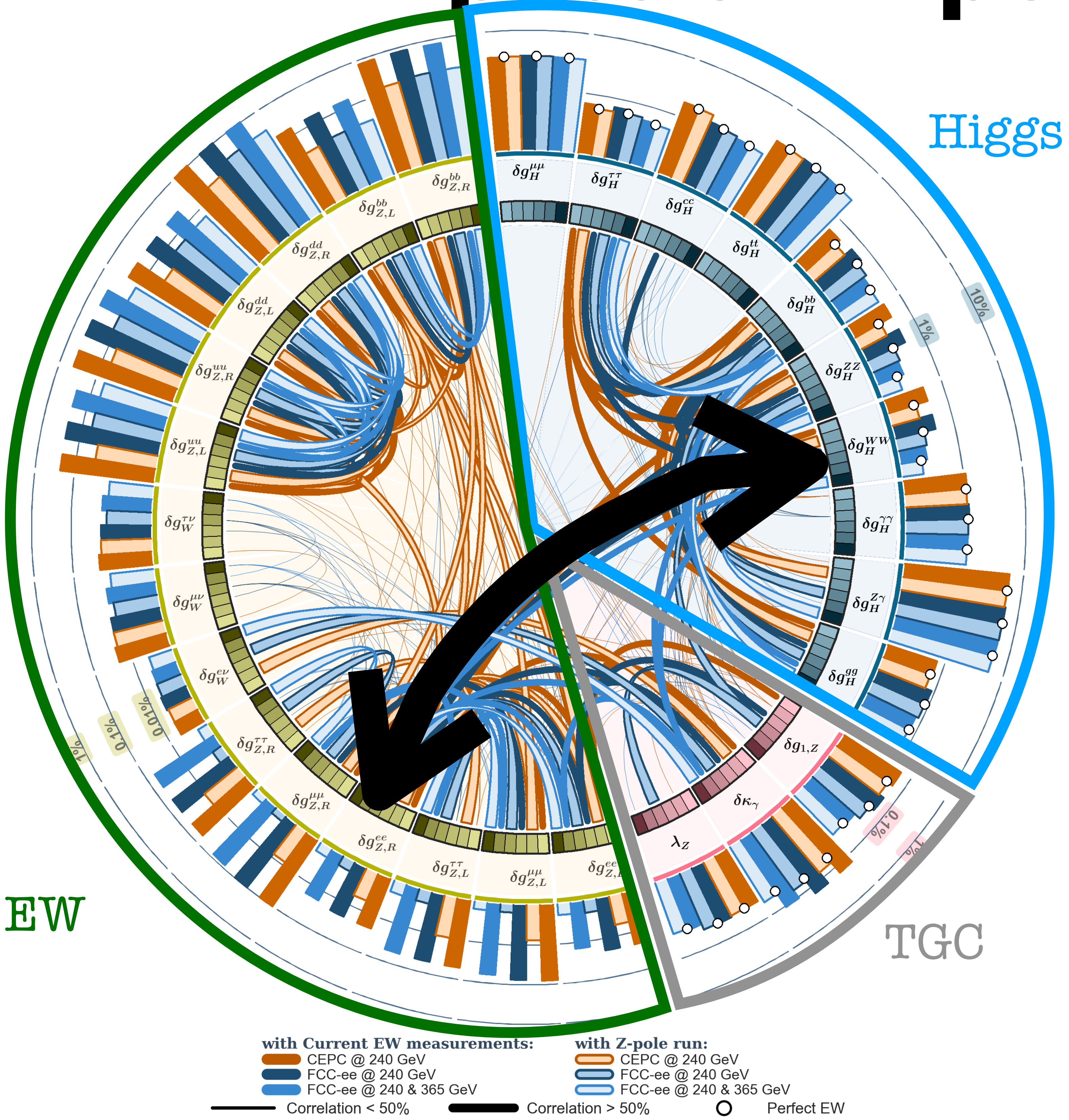
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



- Higher energy runs reduce the EW contamination in Higgs coupling extraction

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

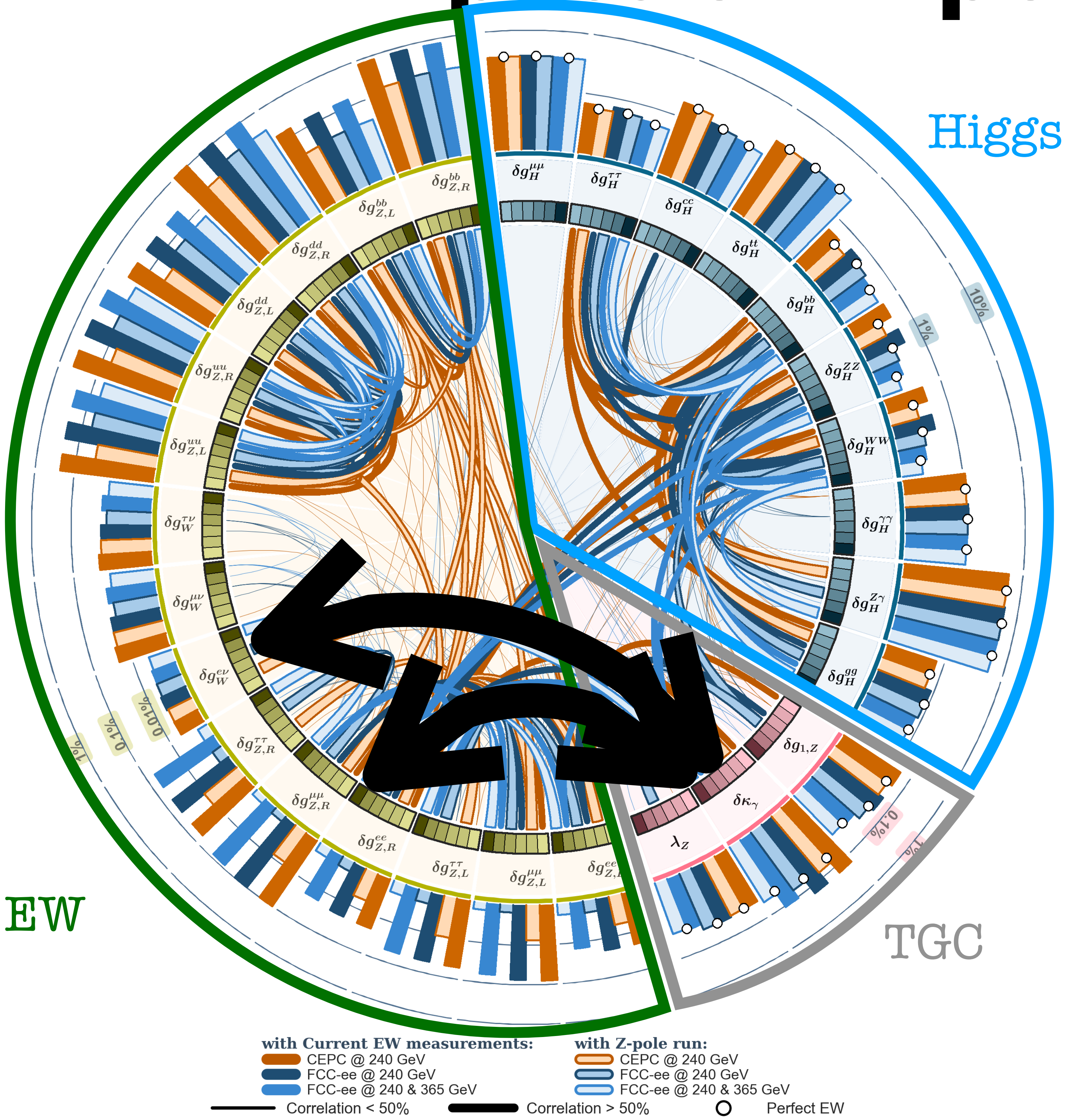


Contamination EW/TGC/Higgs can be understood by looking at correlations

Without Z-pole runs, there are large correlations between EW and Higgs

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



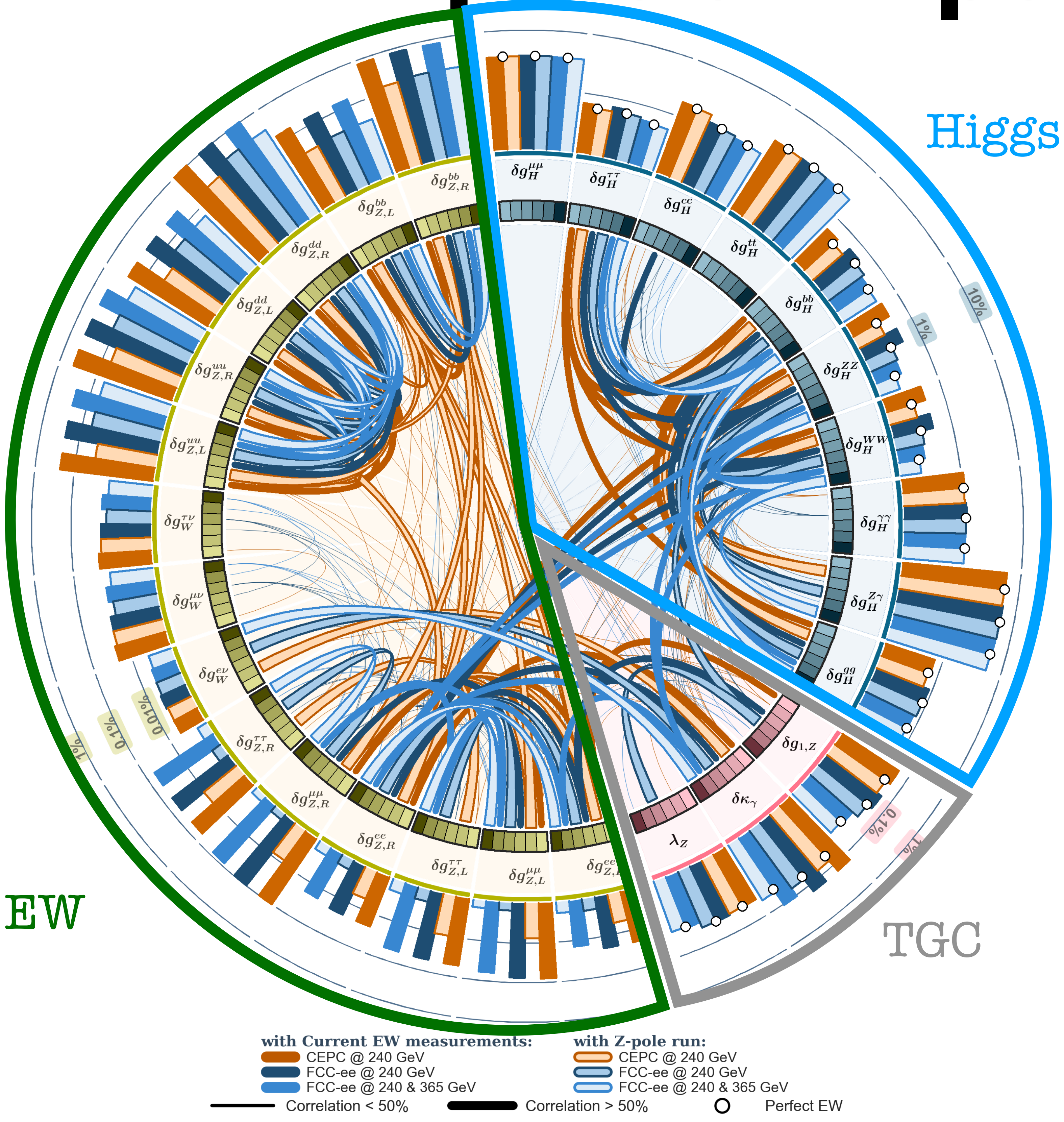
Contamination EW/TGC/Higgs can be understood by looking at correlations

With Z-pole runs, only correlations between EW and TGC remain

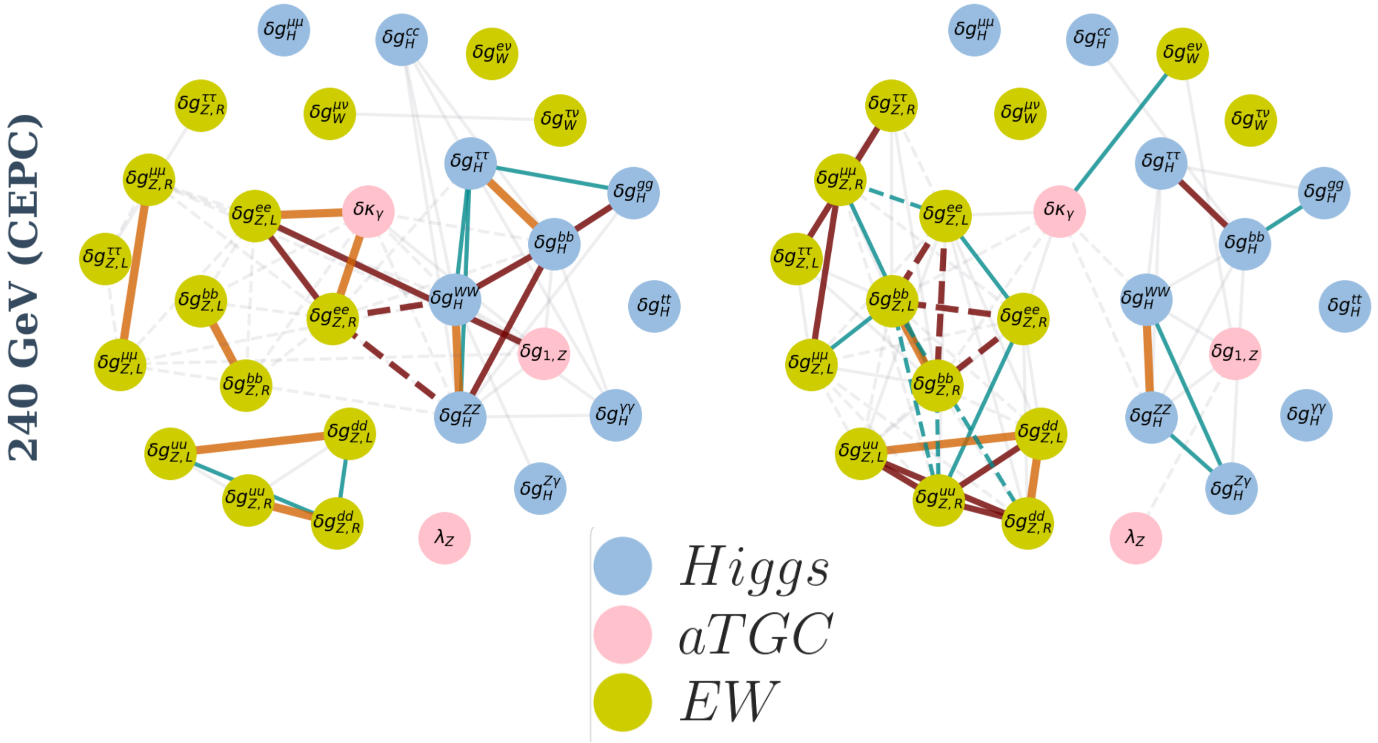
Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

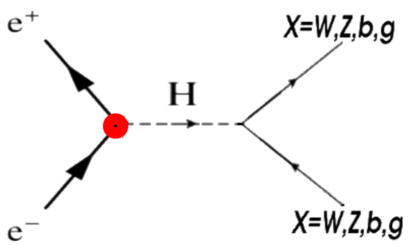
Contamination EW/TGC/Higgs can be understood by looking at correlations



Z-pole runs at circular colliders isolate EW and Higgs sectors from each others



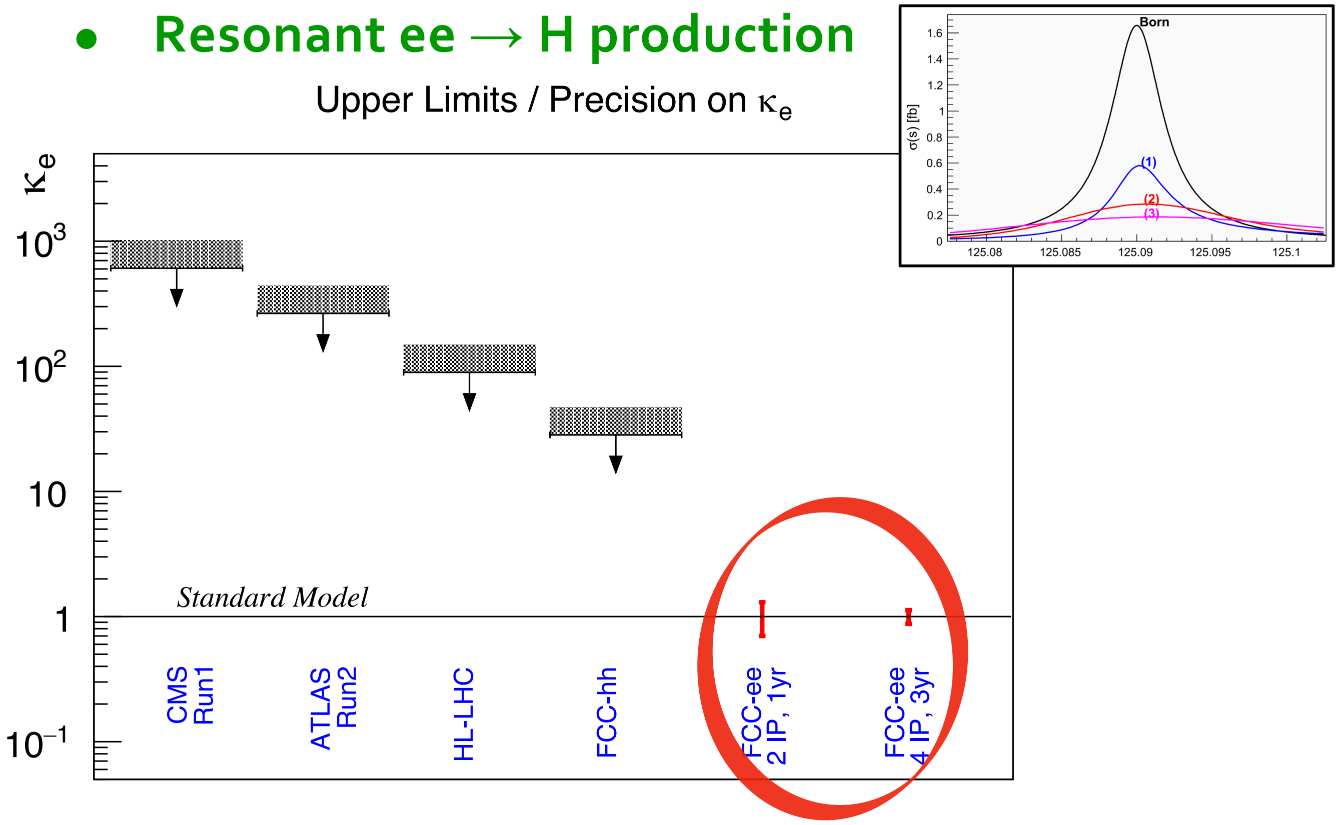
Access to e⁻ Yukawa



$\sigma(e^+e^- \to H)$ = 1.64 fb

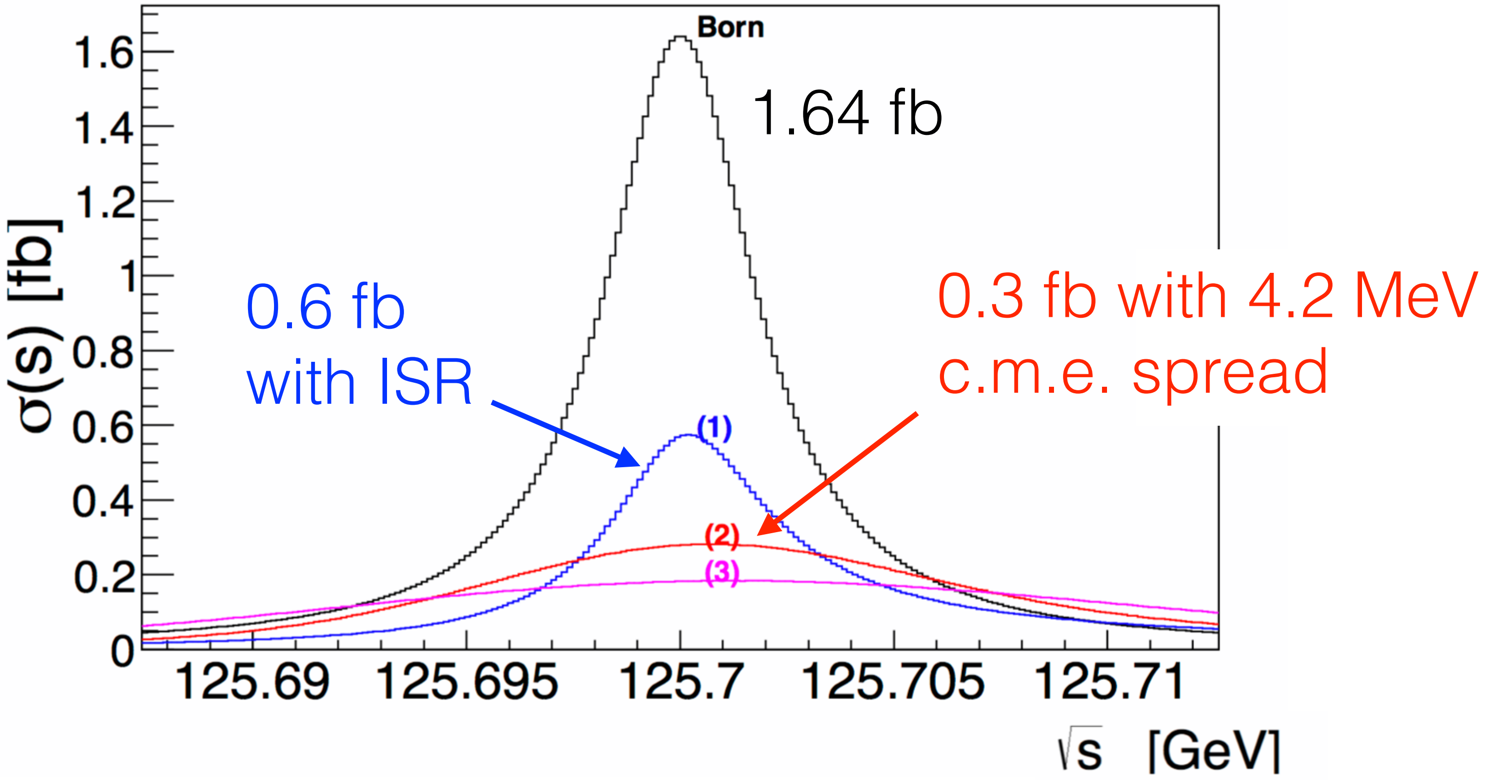
$\sigma_{\text{spread+ISR}}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H) = 290$ ab

- **20 ab⁻¹ / year at √s = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim 1\text{-}2 \times \Gamma_H \sim 6$ to 10 MeV**
  - **Resonant ee → H production**



  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406



d'Enterria+, arXiv: 2107.02686

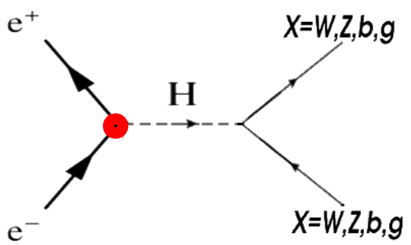
Higgs decay channel	$\mathcal{B}$	$\sigma \times \mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \to H \to b\bar{b}$	58.2%	164 ab	$e^+e^- \to b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \to H \to gg$	8.2%	23 ab	$e^+e^- \to q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to \tau\tau$	6.3%	18 ab	$e^+e^- \to \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \to H \to c\bar{c}$	2.9%	8.2 ab	$e^+e^- \to c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \to H \to WW^* \to \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^- \to WW^* \to \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^- \to WW^* \to 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^- \to WW^* \to 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to ZZ^* \to 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^- \to ZZ^* \to 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to \gamma\gamma$	0.23%	0.65 ab	$e^+e^- \to \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

w. 10/ab

$H \to gg$	$H \to WW^* \to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$	$H \to ZZ^* \to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$	$H \to b\bar{b}$	$H \to \tau_{\text{had}}\tau_{\text{had}};\ c\bar{c};\ \gamma\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

w/ 10/ab: S~55, B~2400 → 1.1σ

Access to e^- Yukawa



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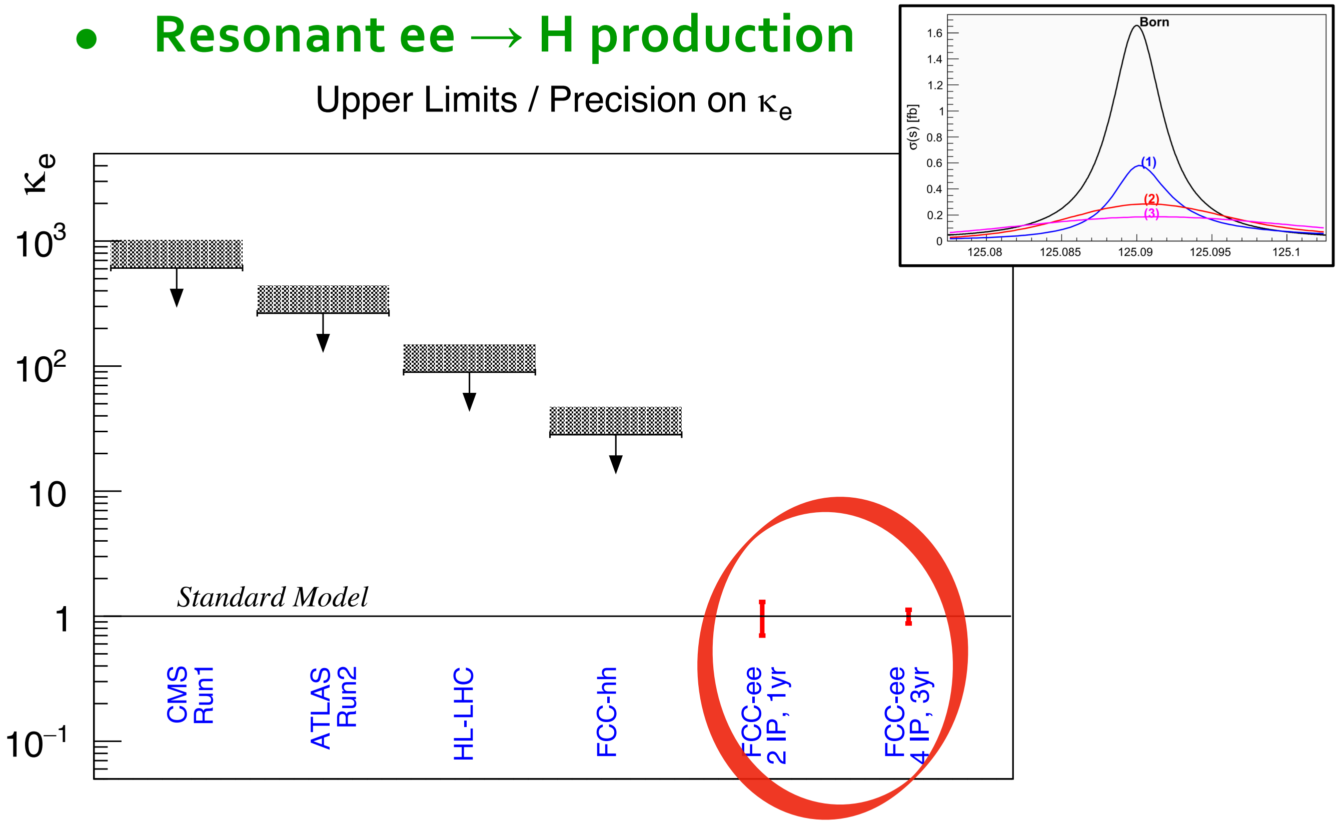
  - **Resonant ee → H production**

Upper Limits / Precision on κ_e



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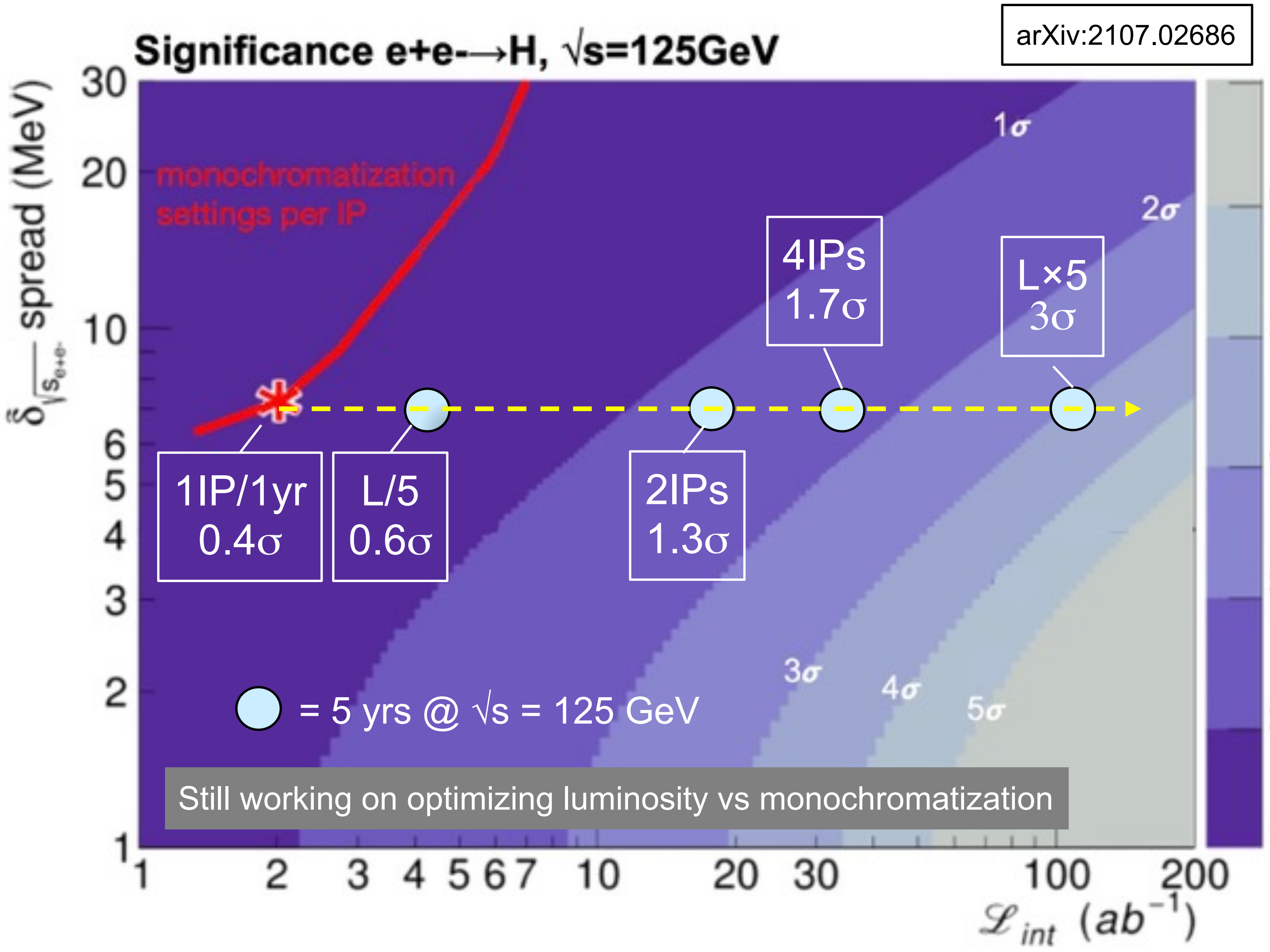
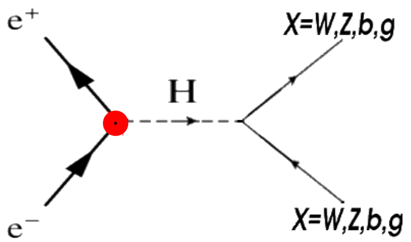


arXiv:2107.02686

Still working on optimizing luminosity vs monochromatization

Access to e⁻ Yukawa



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- ◆ **Monochromatization $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**
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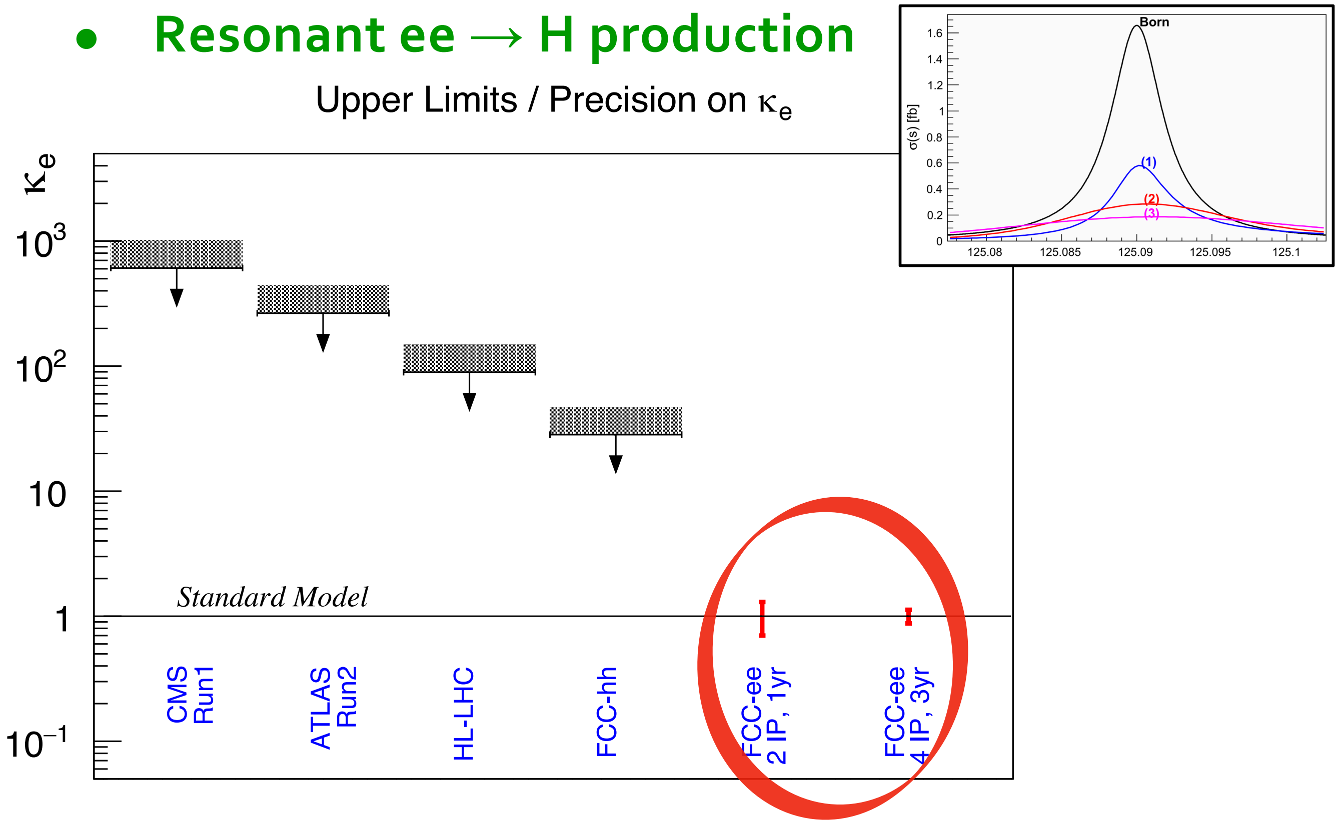

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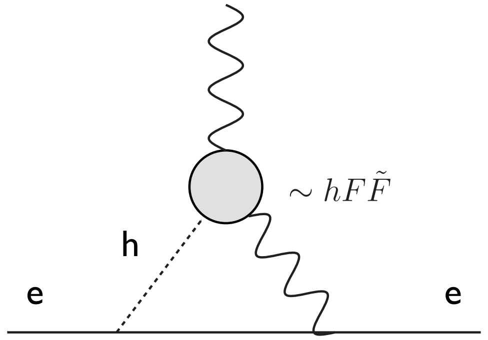
Why this measurement is important?

Constraints on CPV from EDM measurements

would vanish if hee is zero!

operators with γ

McKeen+ '12

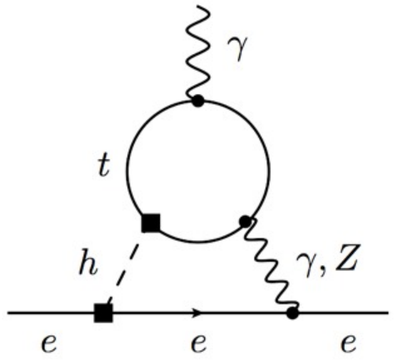


$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$

Λ_{CPV} > 25 TeV

operators with top

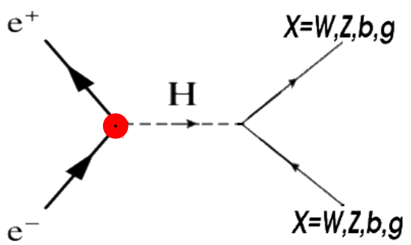
Brod+ '13



$\delta\tilde{g}_{htt} \leq 0.01$

Λ_{CPV} > 2.5 TeV

Access to e- Yukawa



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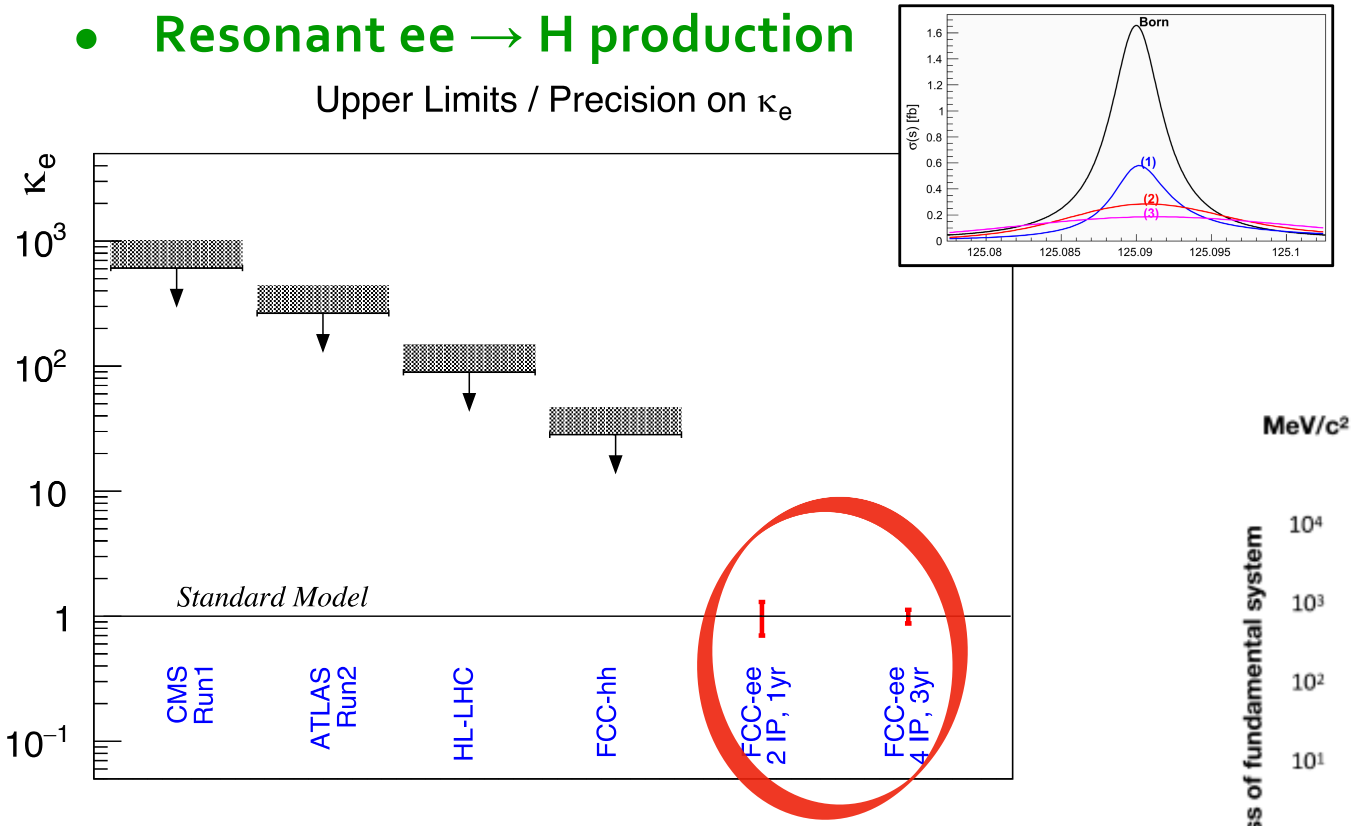

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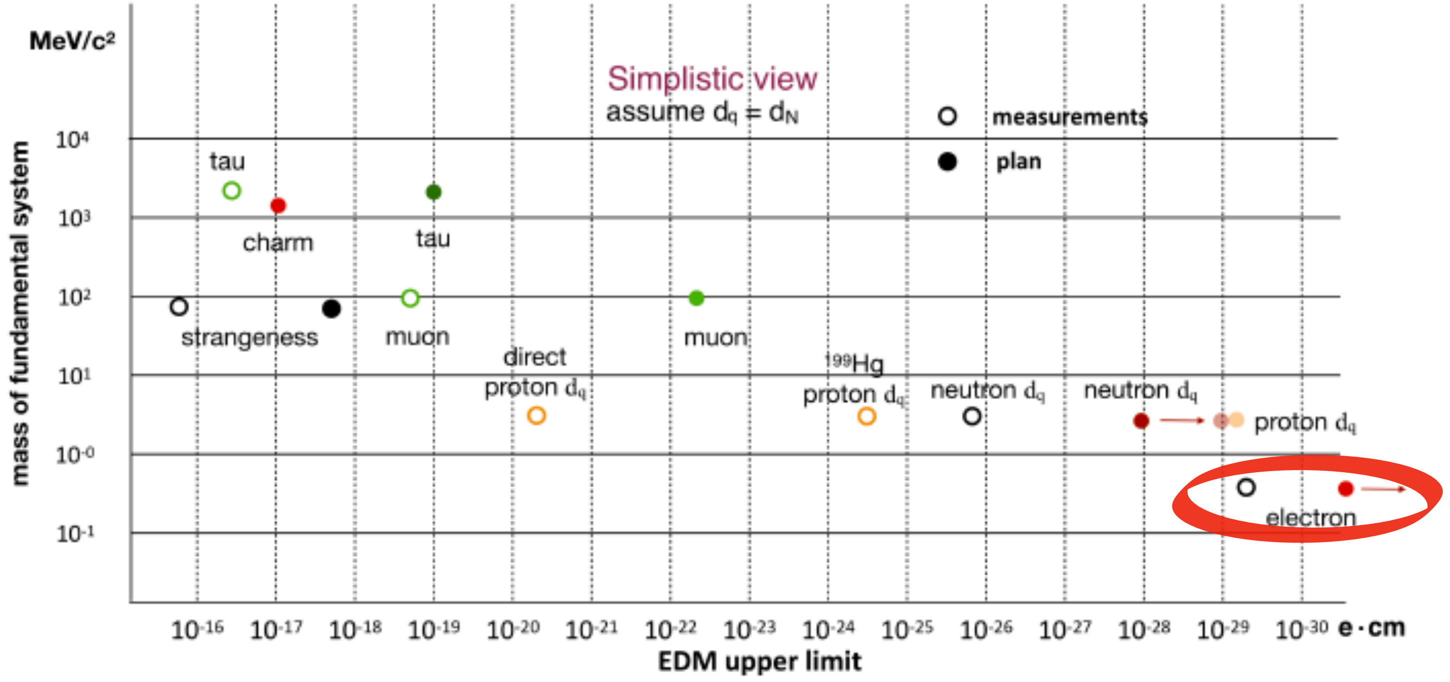
current ACME 90%CL bound on e EDM

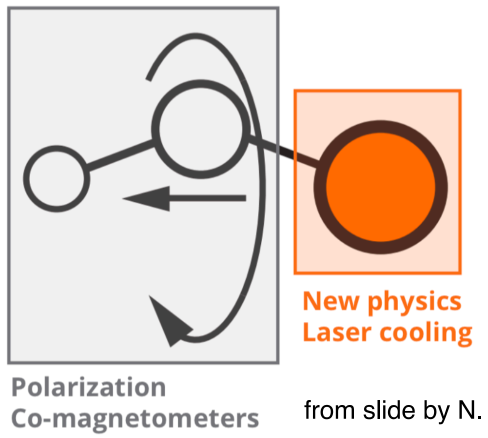
$$|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}.$$

(SM4 value : 10^{-37}-10^{-44} *e* cm)

ESU, arXiv:1910.11775



Polyatomic EDM



from slide by N. Hutz

Time scale of 5-10 years:

$$|d_e| \lesssim 10^{-32}\, e\,\mathrm{cm}$$

1-loop, PeV scale sensitivity

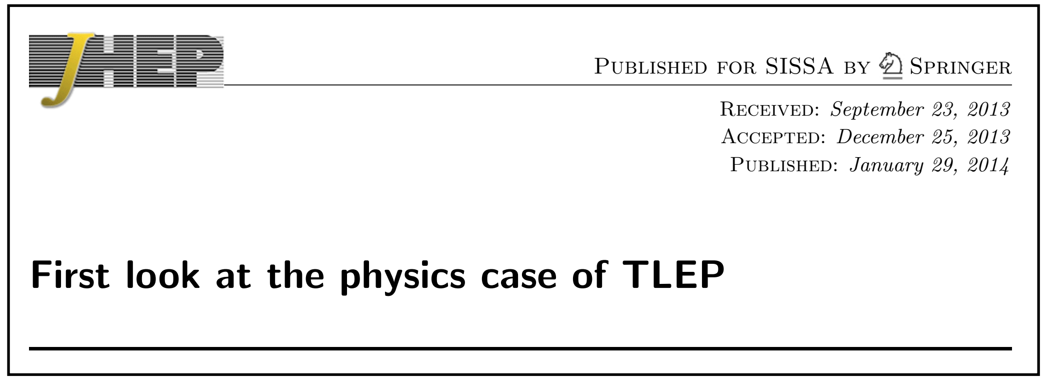
M. Reece @ Pheno2020
Snowmass LOI

Literature on FCCee/CEPC

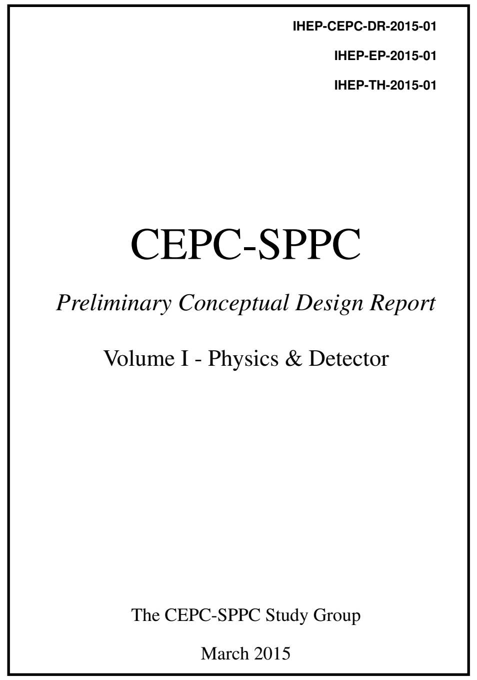
2013-2015

- physics case: JHEP01(2014)164 arXiv:1308.6176

pre-CDR:

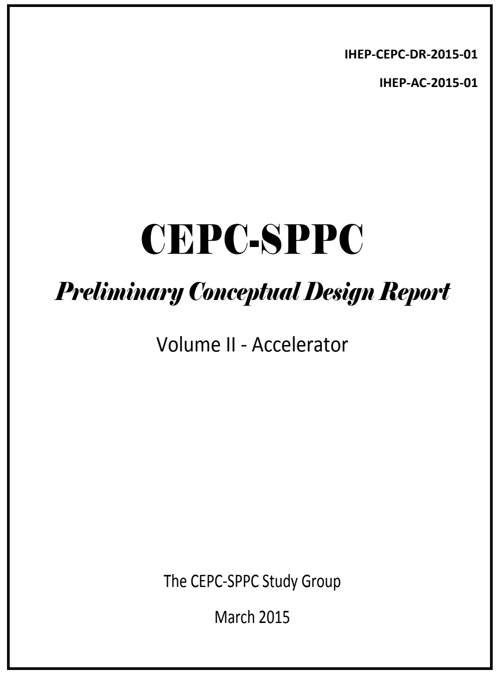

JHEP
PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: *September 23, 2013*
ACCEPTED: *December 25, 2013*
PUBLISHED: *January 29, 2014*

First look at the physics case of TLEP


IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC
Preliminary Conceptual Design Report
Volume I - Physics & Detector

The CEPC-SPPC Study Group
March 2015


IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC
Preliminary Conceptual Design Report
Volume II - Accelerator

The CEPC-SPPC Study Group
March 2015

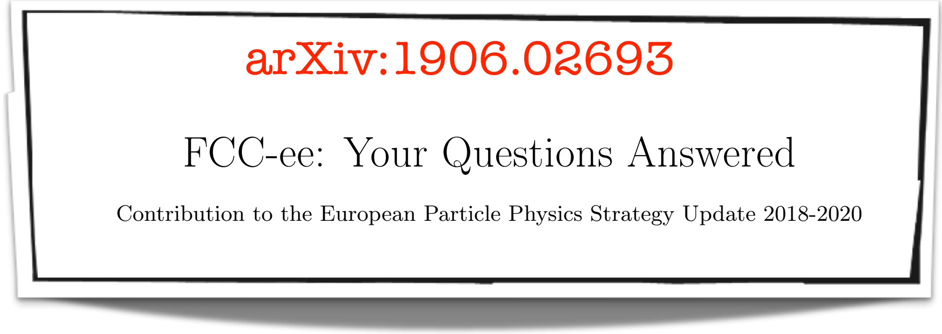
The FCC and CepC are essentially equivalent proposals with different emphasis; FCC – hadrons via e+e-, CepC – e+e- then hadrons

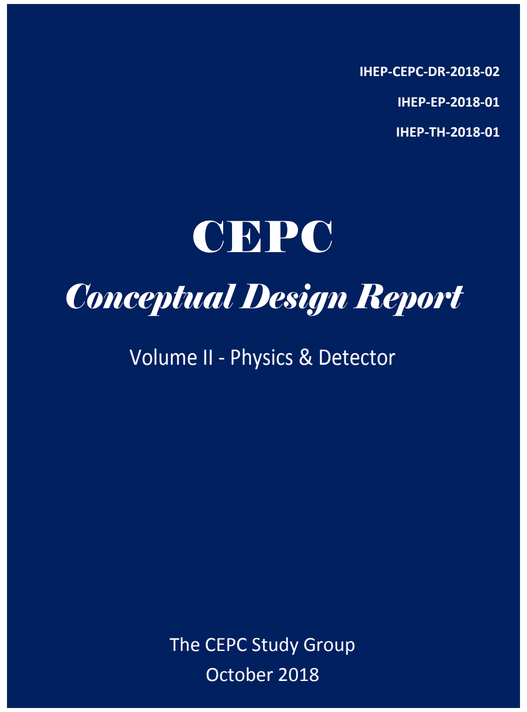
Mike Harrison , SPC meeting Sept. 2015

2018-2019

FUTURE CIRCULAR COLLIDER
CONCEPTUAL DESIGN REPORT
THE FUTURE CIRCULAR COLLIDER (FCC) STUDY IS SET TO PUBLISH ITS CONCEPTUAL DESIGN REPORT IN JANUARY 2019, DESCRIBING TANTALIZINGLY MORE POWERFUL PARTICLE COLLIDERS FOR THE POST-LHC ERA IN PARTICLE PHYSICS.

arXiv:1906.02693


FCC-ee: Your Questions Answered
Contribution to the European Particle Physics Strategy Update 2018-2020

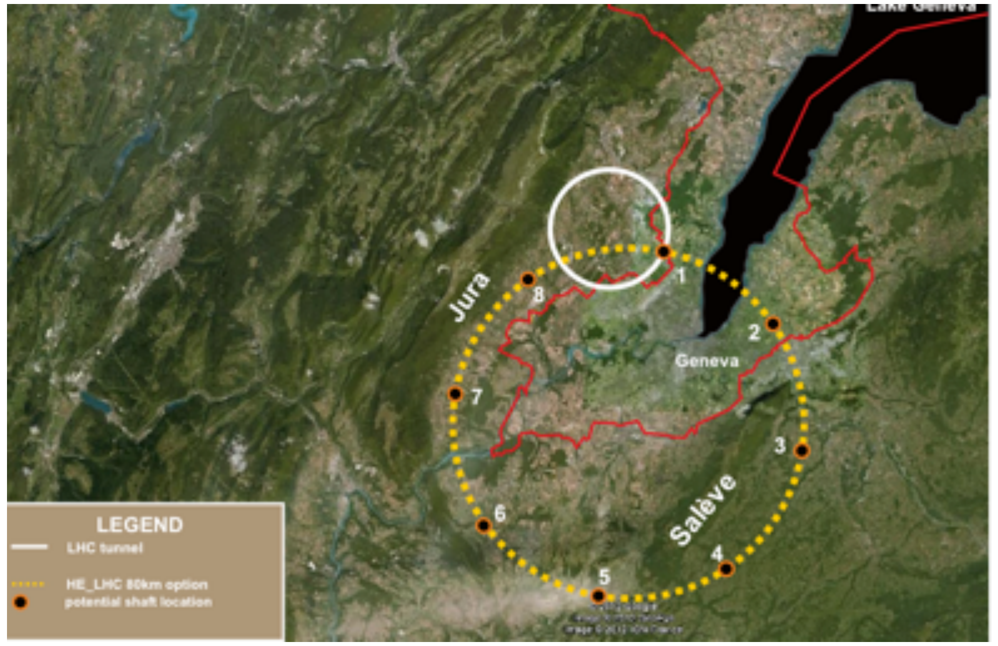

IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

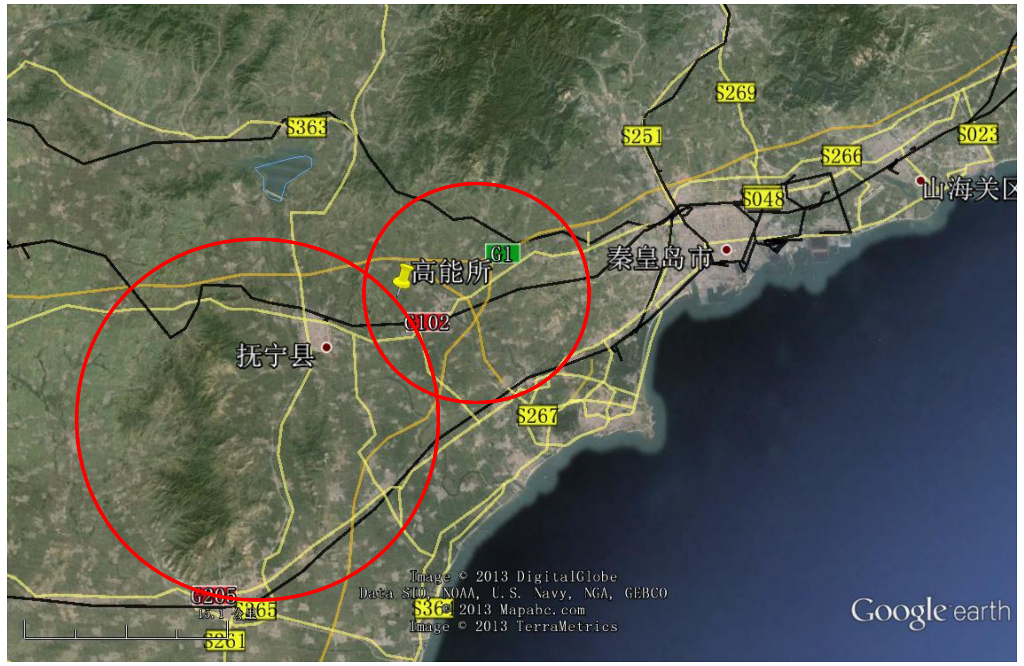
CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
October 2018

FCC-hh (2065?-2085?)/SppC (??-??)

80/100 TeV - 20/ab





SppC

2020 2030 2040

R&D
(2014-2030)

Engineering Design
(2030-2035)

Construction
(3035-2042)

Data taking
(2042-2055)

FCC-hh (2065?-2085?)/SppC (??-??)

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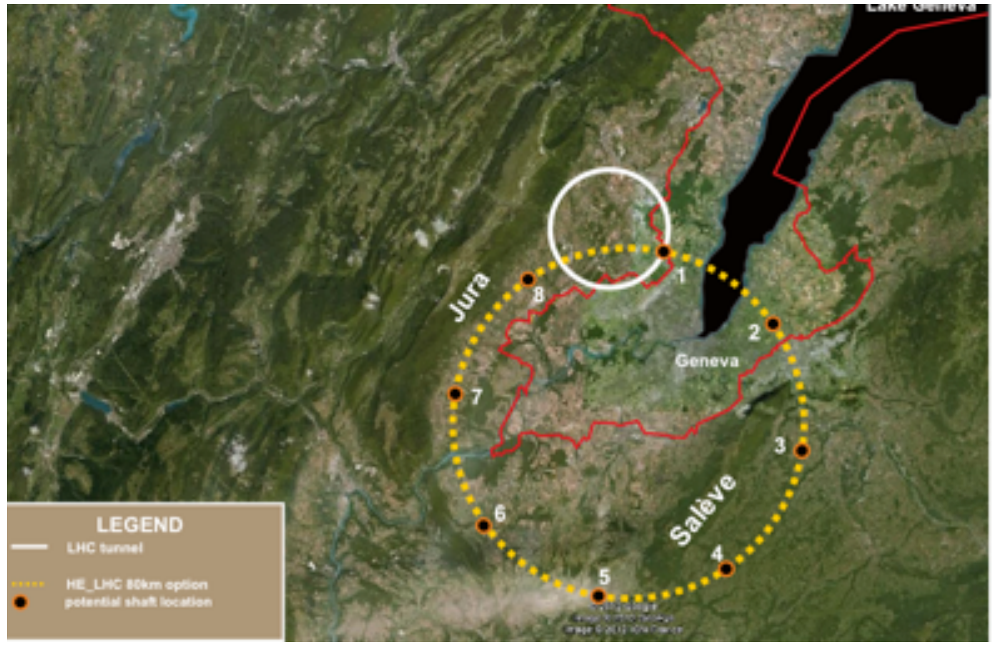
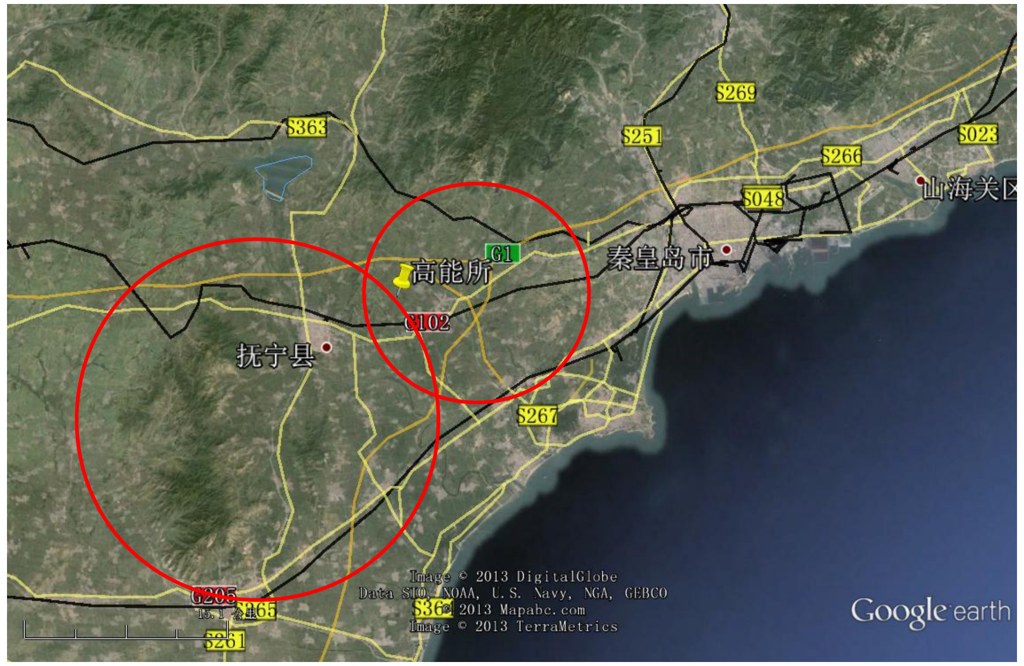




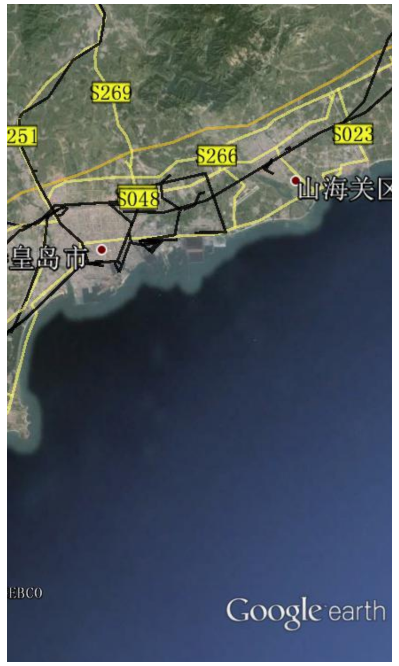
Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	**100**		**71.2**	14	
dipole field [T]	**16**		**20**	8.3	
# IP	**2 main & 2**		**2**	2 main & 2	
bunch intensity [10^{11}]	**1**	**1 (0.2)**	**2**	1.1	2.2
bunch spacing [ns]	**25**	**25 (5)**	**25**	25	25
luminosity/Ip [10^{34} cm^{-2}s^{-1}]	**5**	**25**	**12**	1	5
events/bx	**170**	**850 (170)**	**400**	27	135
stored energy/beam [GJ]	**8.4**		**6.6**	0.36	0.7
synchr. rad. [W/m/apert.]	**30**		**58**	0.2	0.35

FCC-hh (2065?-2085?)/SppC (??-??)

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages) arXiv:1607.01831
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages) arXiv:1606.09408
- **Volume 3: beyond the Standard Model phenomena** (189 pages) arXiv:1606.00947
- **Volume 4: physics with heavy ions** (56 pages) arXiv:1605.01389
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)



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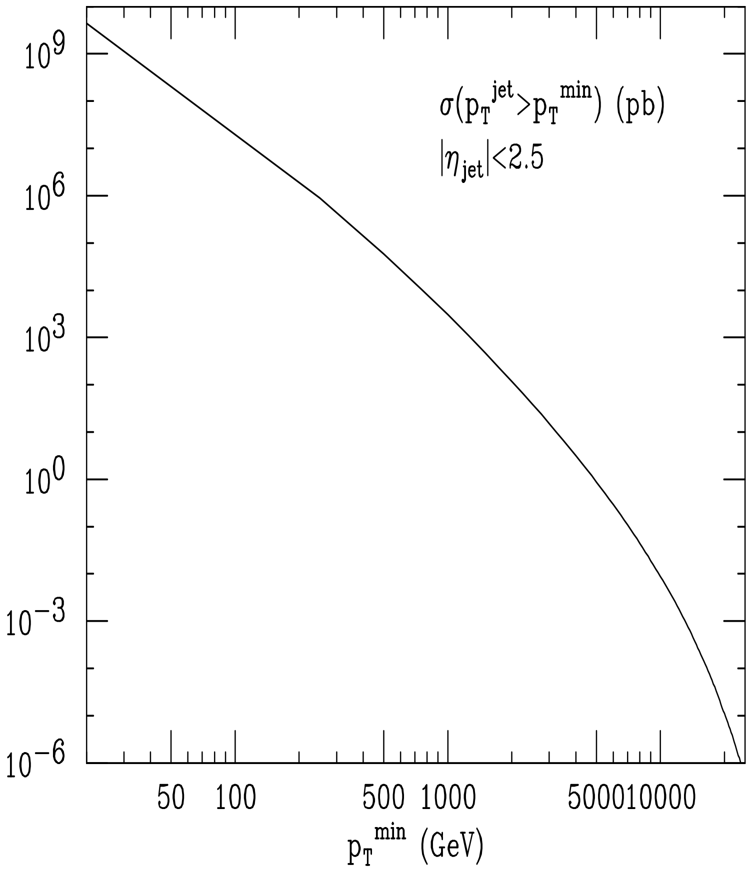
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

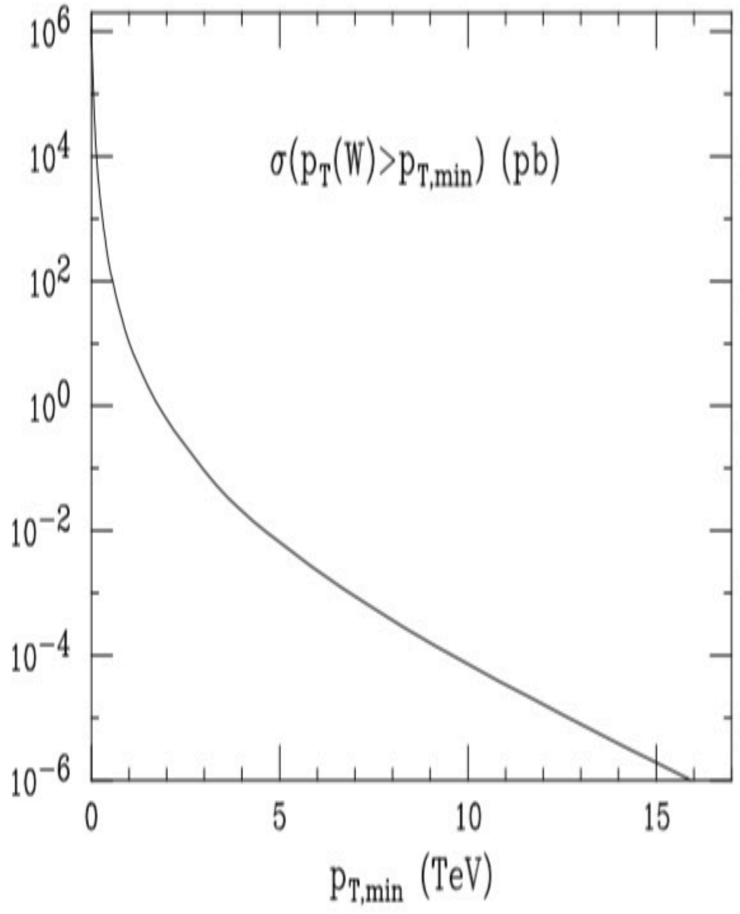
FCC-hh/SppC

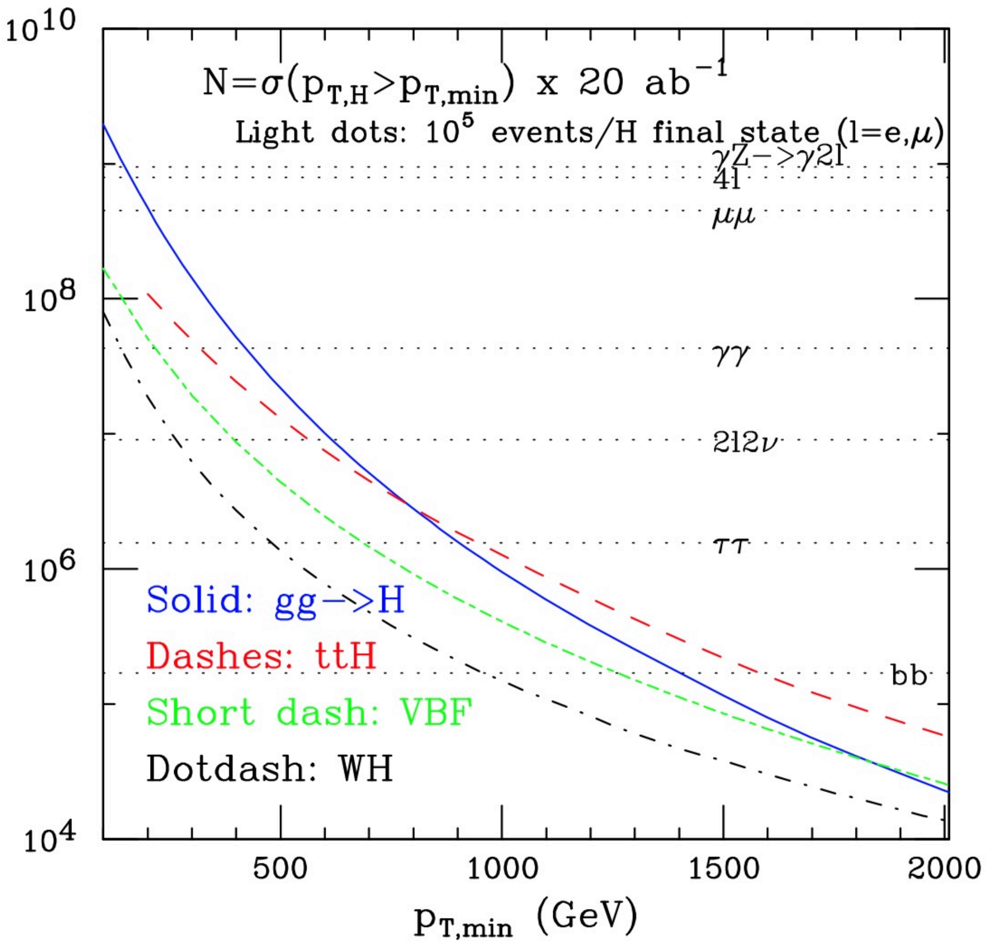
80/100 TeV - O(20/ab)

@FCC-hh

- 10^5 jet with p_T>10TeV
- 10^{11} Z in DY
- 10^{12} W in DY
- 10^{10} H in gg, 10^9 H in VBF, vH, ttH
- 10^{12} top pairs (rare/forbidden top decays, inclusive W decays triggerable by the other W)



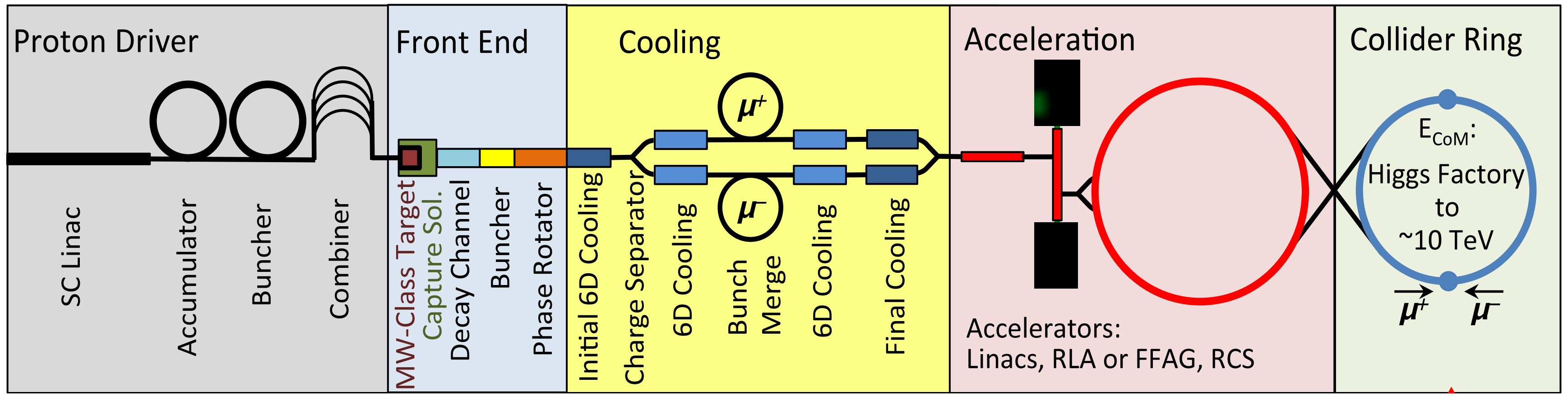




μ-collider aka project X (TBD: ?-?)

Input to ESU arXiv:1901.06150

125/1’000/15’000 GeV - O(1-100)/ab



M. Palmer, CERN ‘15

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

$$\triangleleft \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times 10^4$$

Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

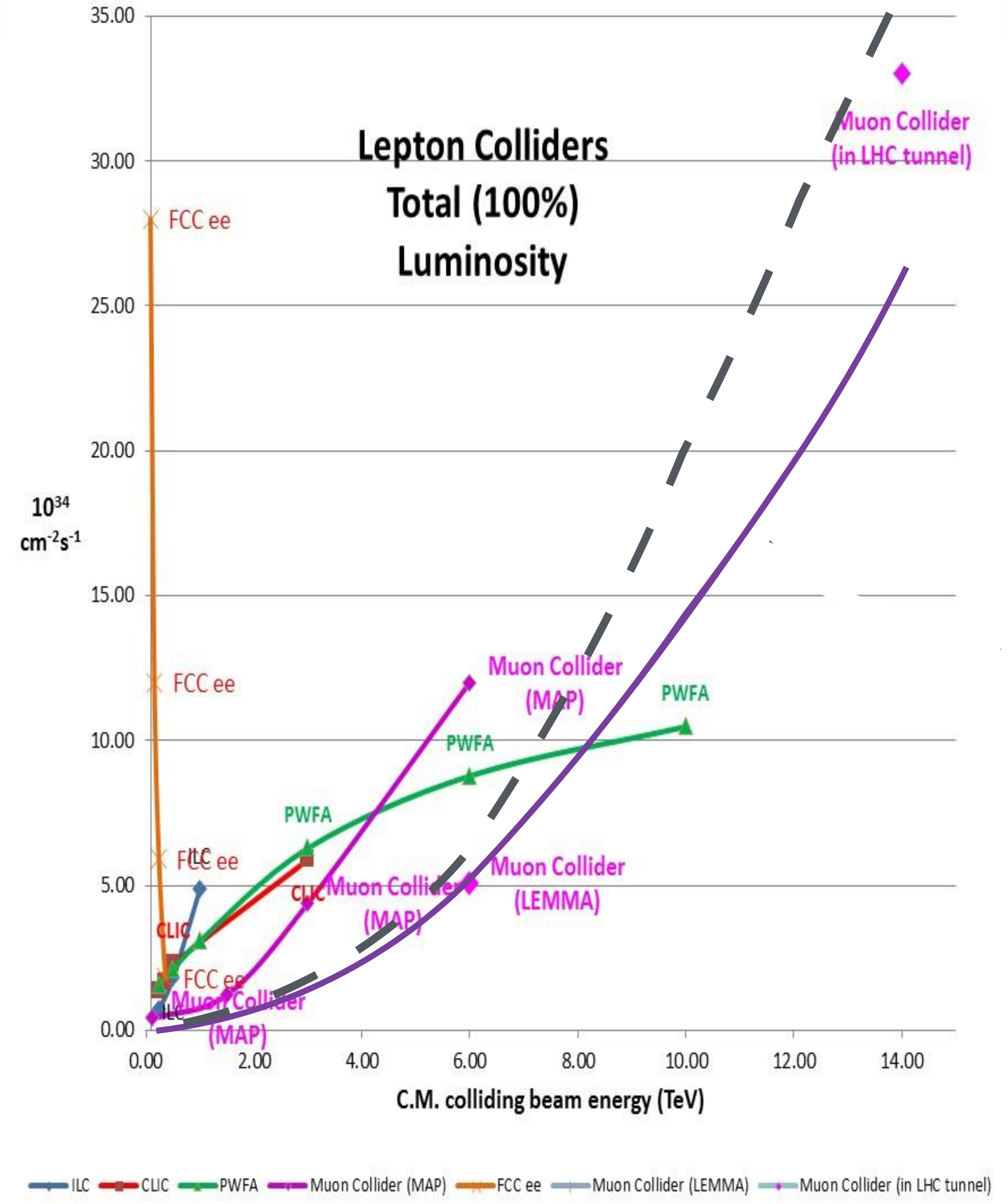
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

μ-collider in brief

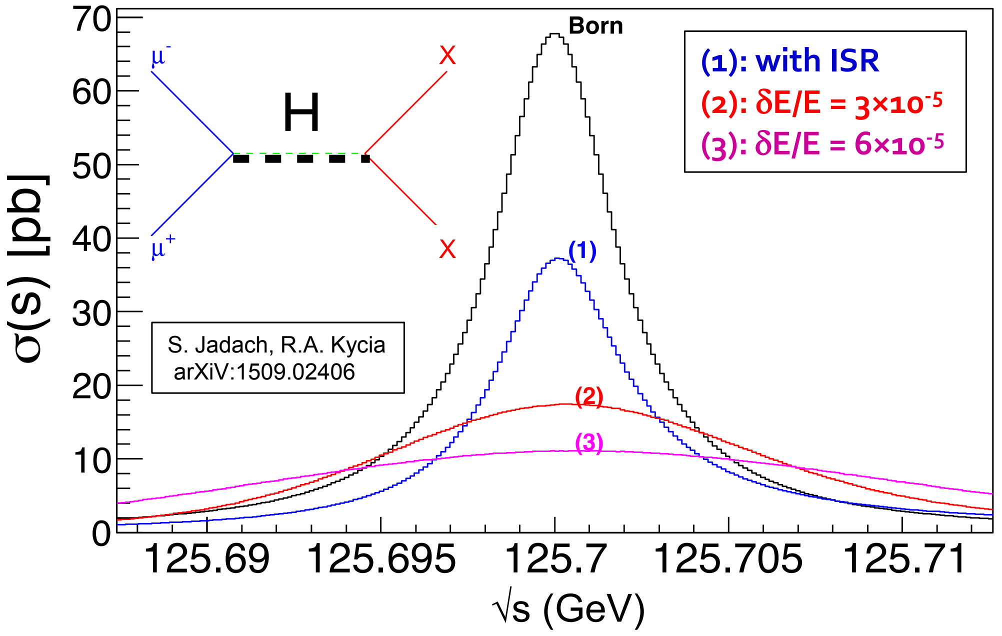
Material from A. Wulzer

No definite plan yet

Two milestones: 1) s-channel Higgs production and 2) highest energy possible



1)



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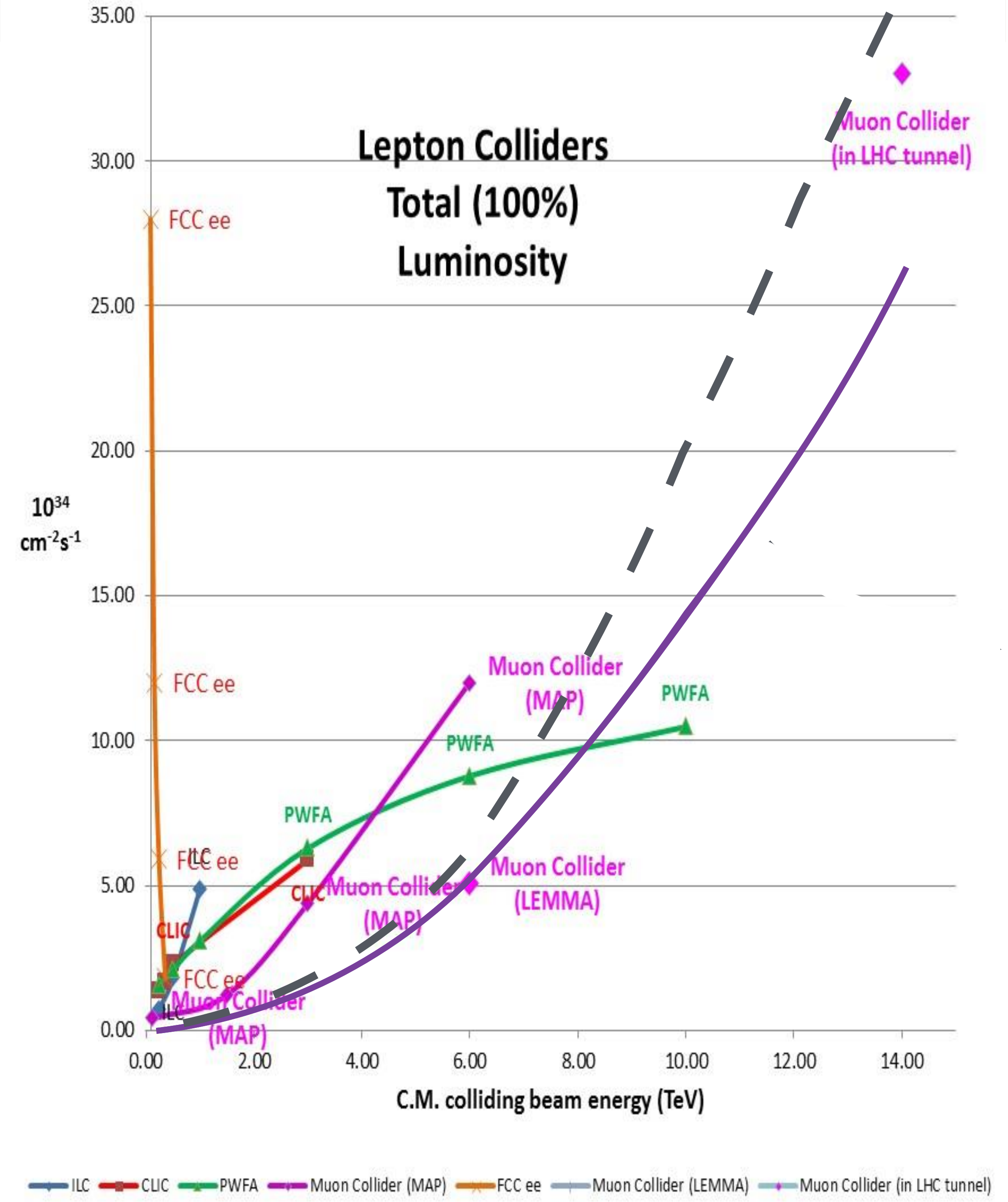
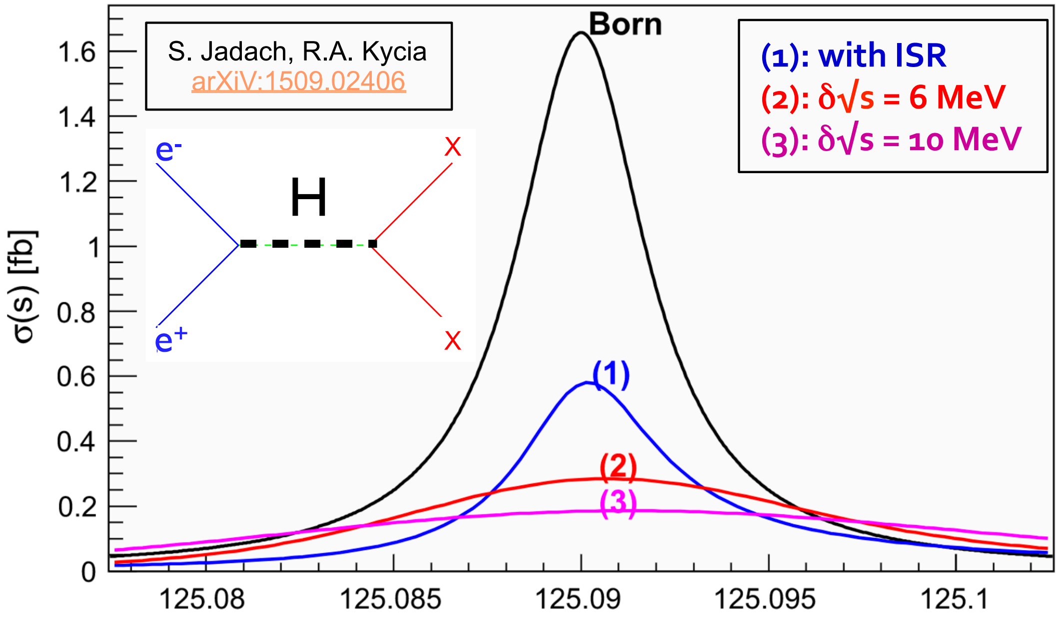


1)



μμ

40'000 better

than ee

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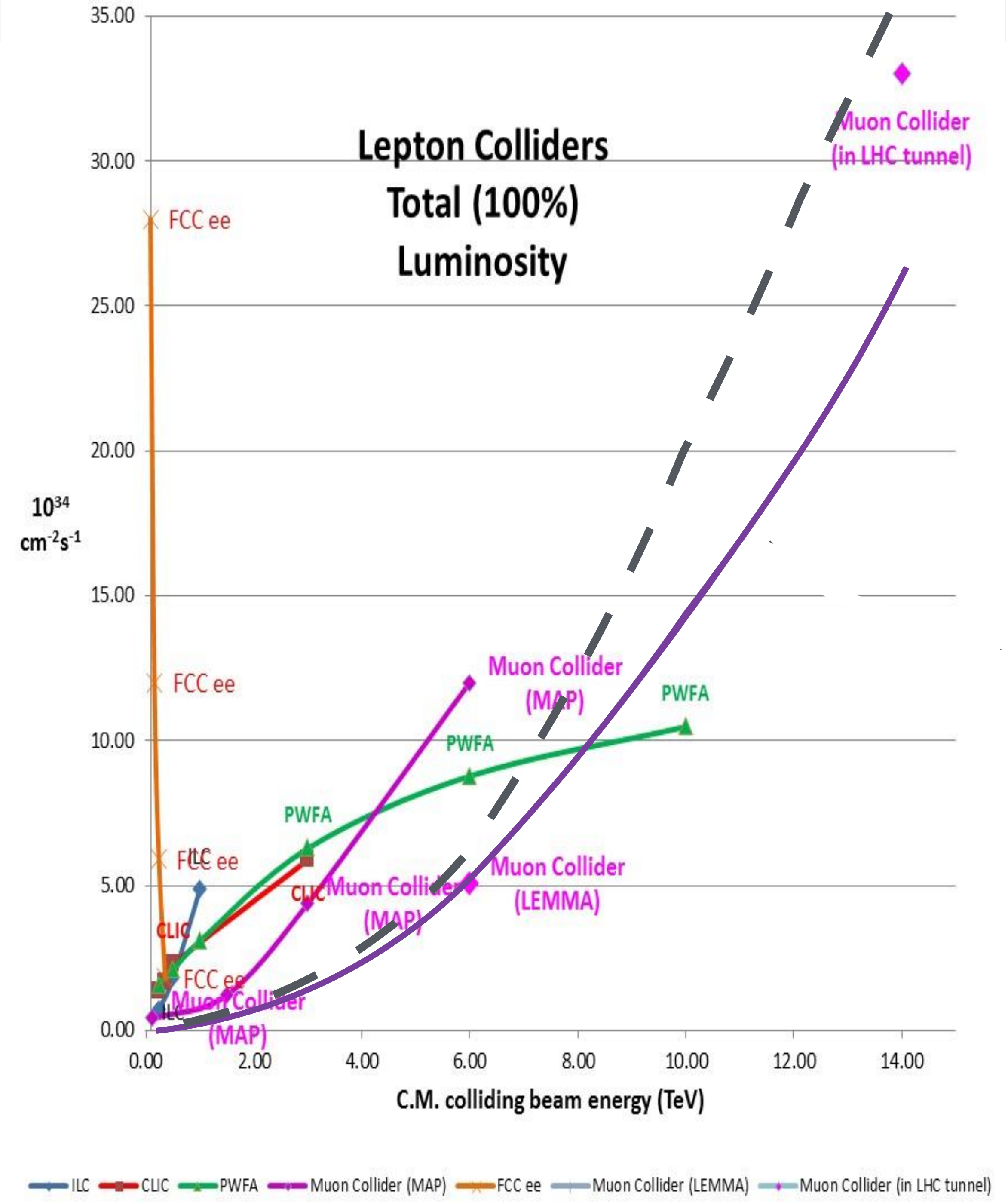

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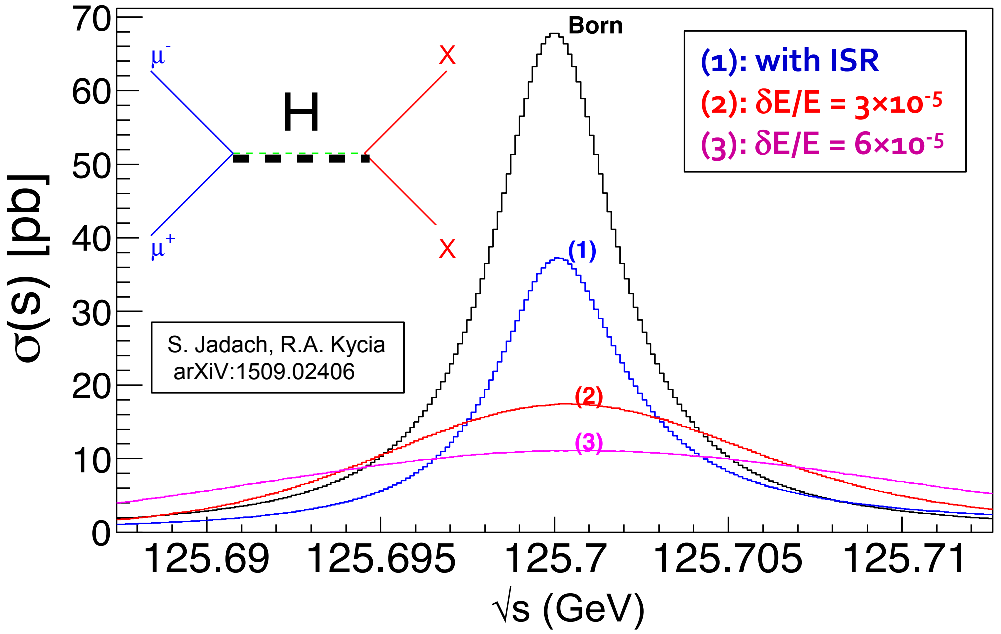
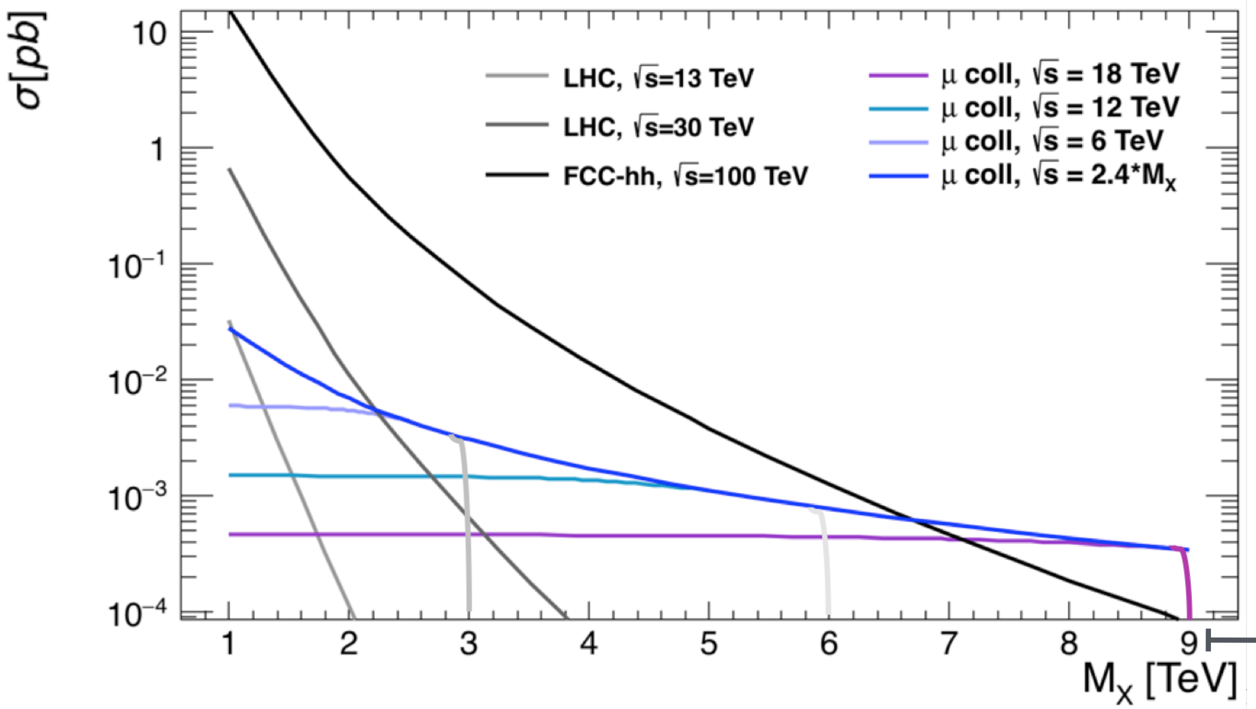


2)

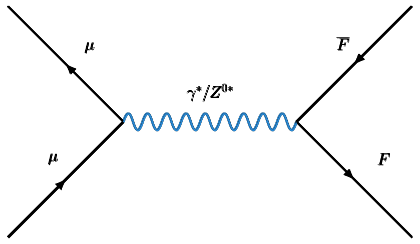
Fermionic top partners in Composite Higgs:



Estimated reach of the FCC-hh

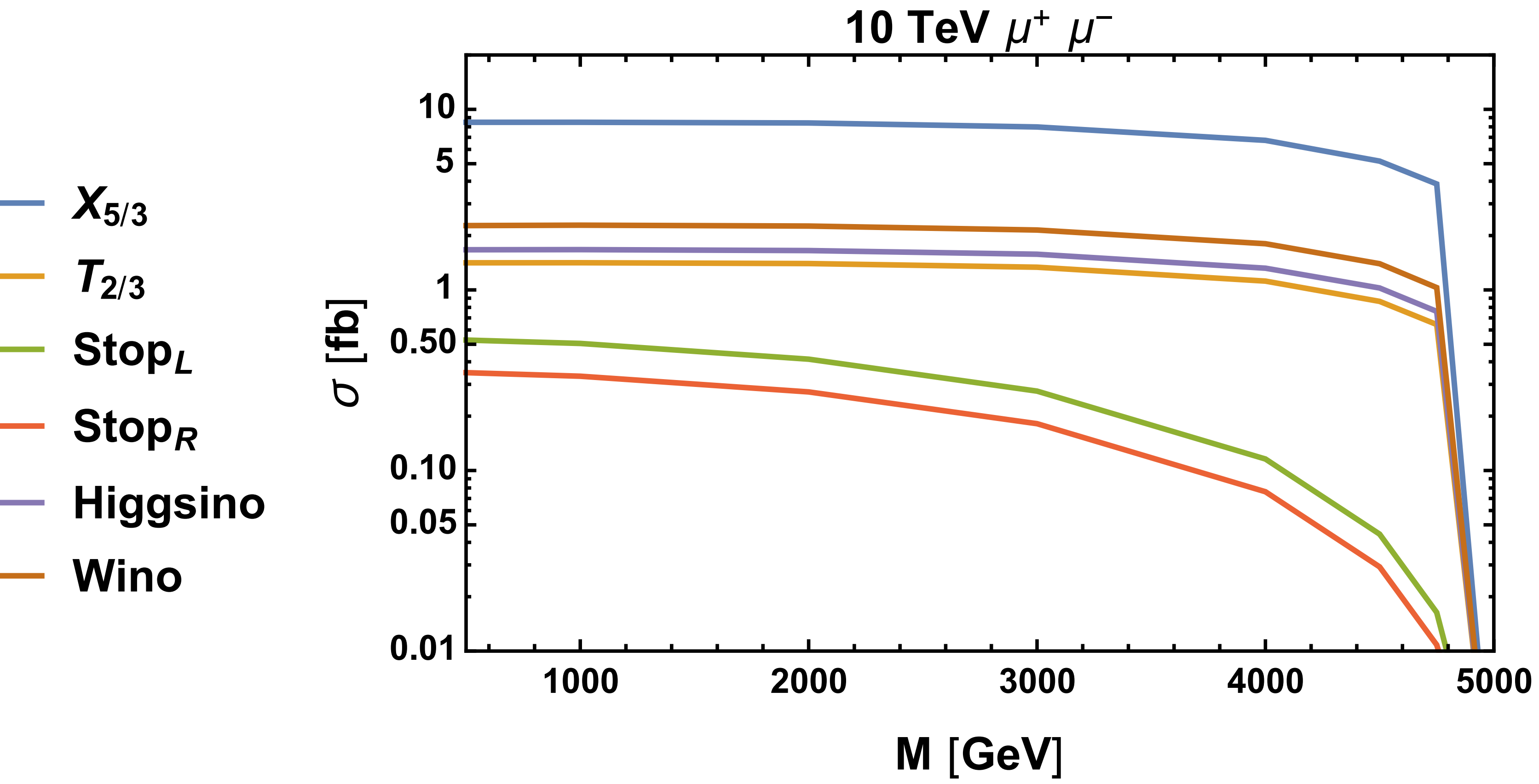
μ-collider in brief

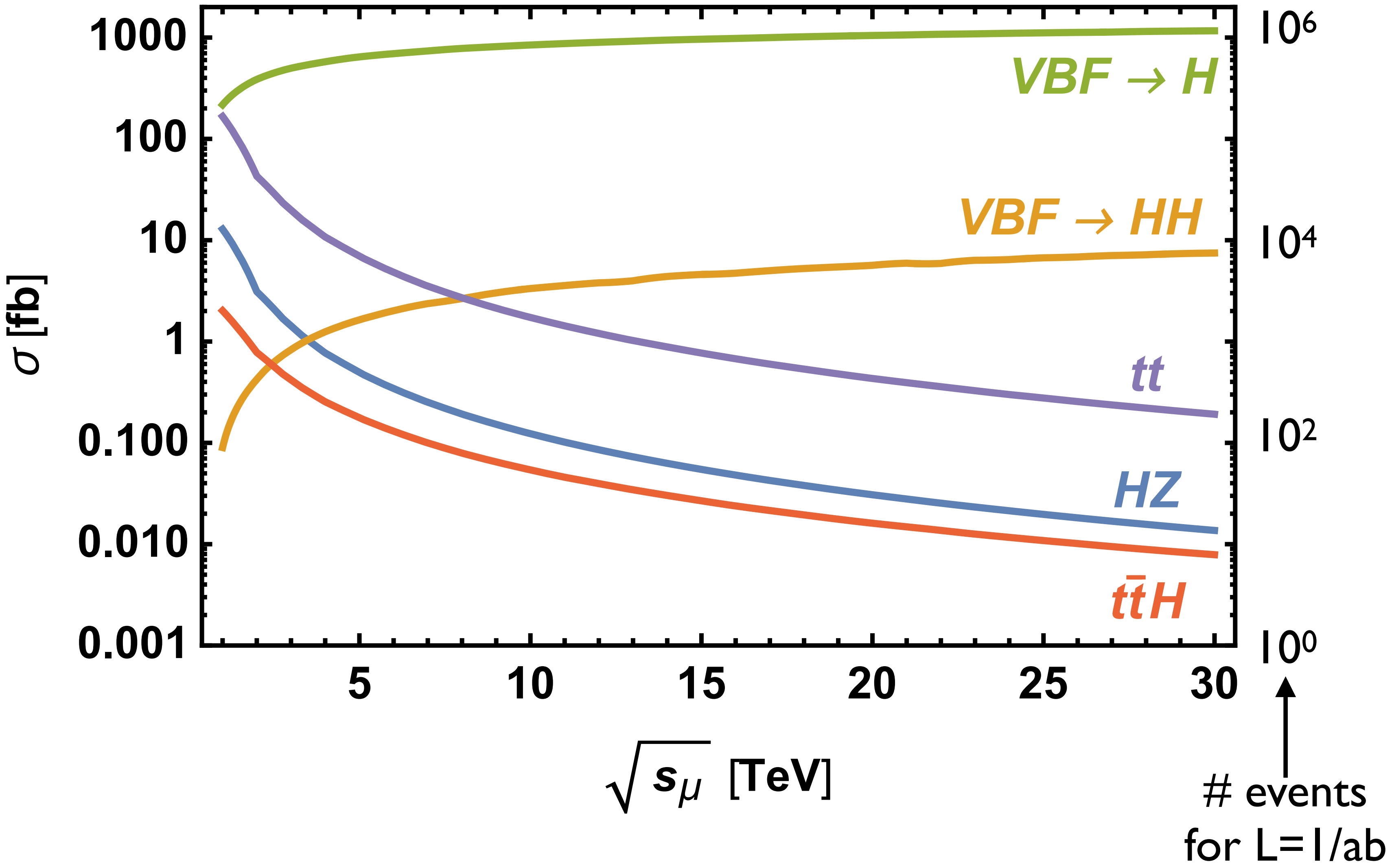
Input to ESU arXiv:1901.06150



up to $m_F<\sqrt{s}/2$

$$\sigma \sim \left(\frac{10\,\mathrm{TeV}}{\sqrt{s_{\mu\mu}}}\right)^2 \cdot 1\,\mathrm{fb}$$



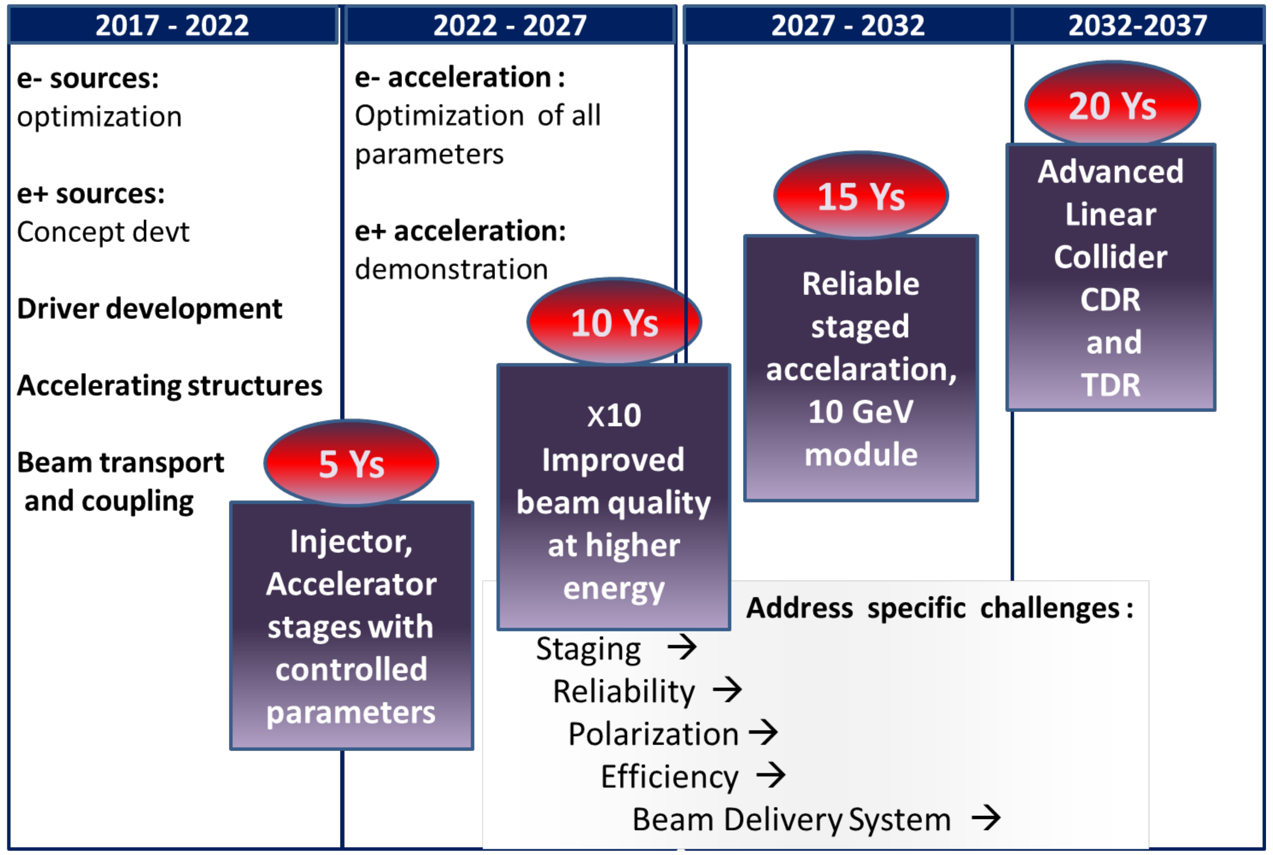


events for L=1/ab

Alegro/Advanced Linear Collider (ALIC)

Input to ESU arXiv:1901.00370

No definite plan yet
R&D for new accelerating techniques (laser or plasma wakefield)
ee and γγ colliders from 100 GeV to 100 TeV



could be done at CepC, FCCee, ILC, CLIC

1. High-precision study of the Z resonance and high-precision measurement of the W mass, resolving current tensions among the precision electroweak measurements and testing the SM at the 10^{-4} level.
2. Model-independent measurement of the Higgs boson couplings to 1% precision. This accesses deviations from SM model predictions at the level at which effects of beyond-SM interactions would be visible.
3. Search for invisible or exotic decays of the Higgs boson to the parts-per-mil level of branching fraction.
4. Measurement of the top quark electroweak form factors to parts per mil precision. This accesses deviations from SM model predictions at the level at which effects of beyond-SM interactions would be visible.
5. Search for invisible particles pair-produced in e^-/e^+ collisions. An important objective is the pure Higgsino dark matter candidate, which would have a mass of 1 TeV.
6. Search for additional electroweak gauge bosons and signals of lepton and quark compositeness. A 3 TeV e^-/e^+ collider would be sensitive to new bosons at 15 TeV and compositeness scales of 60-80 TeV, far beyond the LHC capabilities.

need multi-TeV collider

7. Search for pair-production of any new particles with multi-TeV masses that couple to the electroweak interactions.
8. Search for "thermalization" of Higgs boson production, the production of events with hundreds of W, Z, and Higgs bosons at center of mass energies above 10 TeV.
9. Exploration of the resonances of the new strong interactions associated with composite Higgs boson models. These resonances are expected to appear above 10 TeV in the center of mass.
10. Determination of the geometry of extra space dimensions from the systematics of observed Kaluza-Klein resonances. Given current constraints, e^-/e^+ or $\gamma\gamma$ experiments above 20 TeV would be needed to draw firm conclusions.
11. Characterization of leptoquark bosons proposed to explain suggested anomalies in flavor physics, or other new particles that could be involved in explaining the systematics of flavor interactions.

Time to wrap up…

The Higgs Boson is Special

The Higgs discovery in 2012 has been an important milestone for HEP.
Many of us are still excited about it. Others should be too.

Higgs = **new forces** of different nature than the interactions known so far

- No underlying local symmetry
- No quantised charges
- Deeply connected to the space-time vacuum structure

The knowledge of the values of the **Higgs couplings** is essential
to understand the deep structure of matter/Universe

m_W, m_Z ↔ Higgs couplings ✓

↑

lifetime of stars

(why $t_{Sun} \sim t_{life\ evolution}$?)

m_e, m_u, m_d ↔ Higgs couplings ?

size of atoms — nuclei stability

EWSB @ $t \sim 10^{-10}$s ↔ Higgs self-coupling ?

matter/anti-matter ↔ CPV in Higgs sector ?

The Higgs Boson is Special

LHC will make remarkable progress
but it won’t be enough
A new collider will be needed!

The knowledge of the values of the **Higgs couplings** is essential
to understand the deep structure of matter/Universe

m_W, m_Z ↔ Higgs couplings
✓
↑
lifetime of stars
(why $t_{\text{Sun}} \sim t_{\text{life evolution}}$?)

m_e, m_u, m_d ↔ Higgs couplings
?
size of atoms
nuclei stability

EWSB @ $t \sim 10^{-10}$s ↔ Higgs self-coupling
?

matter/anti-matter ↔ CPV in Higgs sector
?

Executive summary

BAD NEWS

Experimentalists haven't found (yet)
what theorists told them they will find

GOOD NEWS

There are rich opportunities
for mind-boggling signatures
@ colliders and beyond

Breaking the HEP frontiers

new machines much wanted to

— open new horizons beyond LHC —

no lack of theoretical motivations

& plenty of physics issues outside the SM frame

from deep QFT questions — to pressing phenomenological puzzles

* no BSM major discovery without a thorough understanding of SM background

* challenge: control theoretical uncertainty to the level of experimental sensitivity

* complementarity and synergy of electron and hadron machines

When thinking about any future big projects:

— 2 human characteristics to balance —

finite lifetime
(and awareness of it)

capacity of dreaming

Thank you for your attention.
Good luck for your future career!

And thanks a lot to the organisers for setting up this nice event!

if you have question/want to know more

do not hesitate to send me an email

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