Perspectives at Particle Accelerators

F. Bedeschi, INFN

Pisa, November 7, 2019

Outline

- Current physics landscape
- Current directions
- Higgs factories e+e-
  - Current status and comments
- Key measurements and comparisons
- Scenarios under discussion by ESG
  - INFN position

Current physics landscape

- Higgs properties SM-like.
  - After HL-LHC precision level of several %

%

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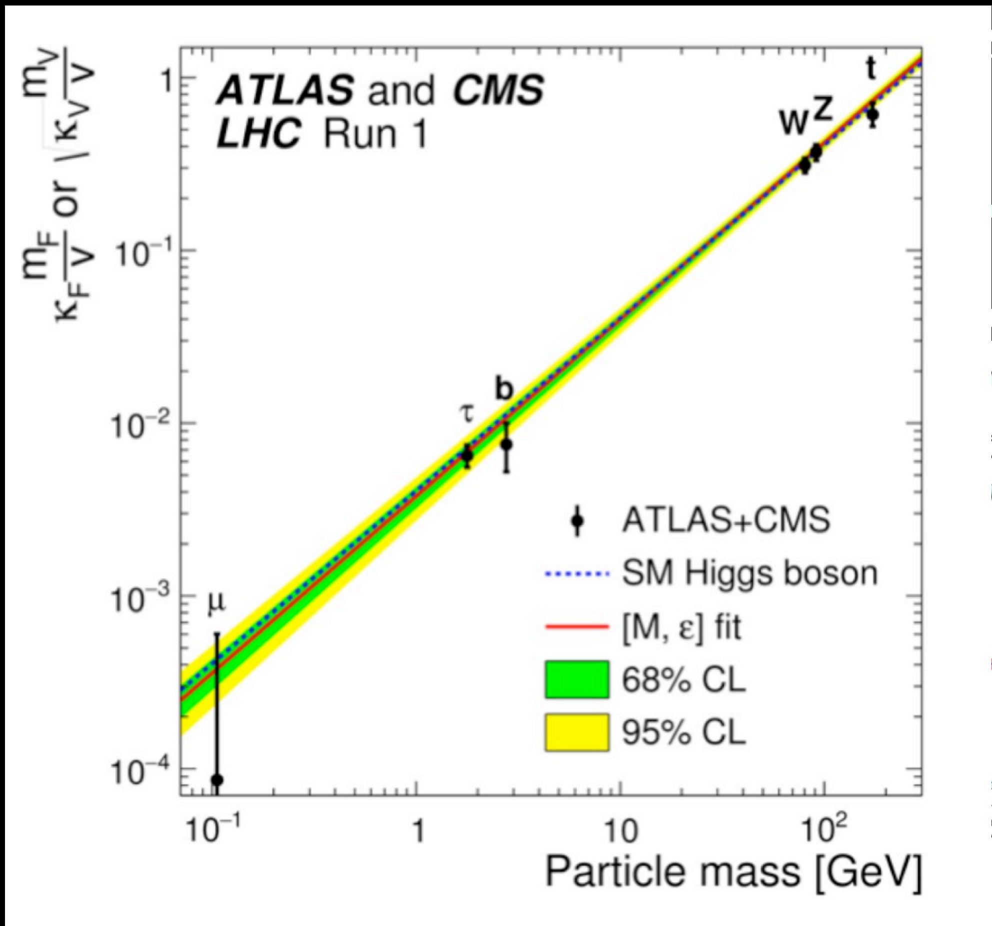
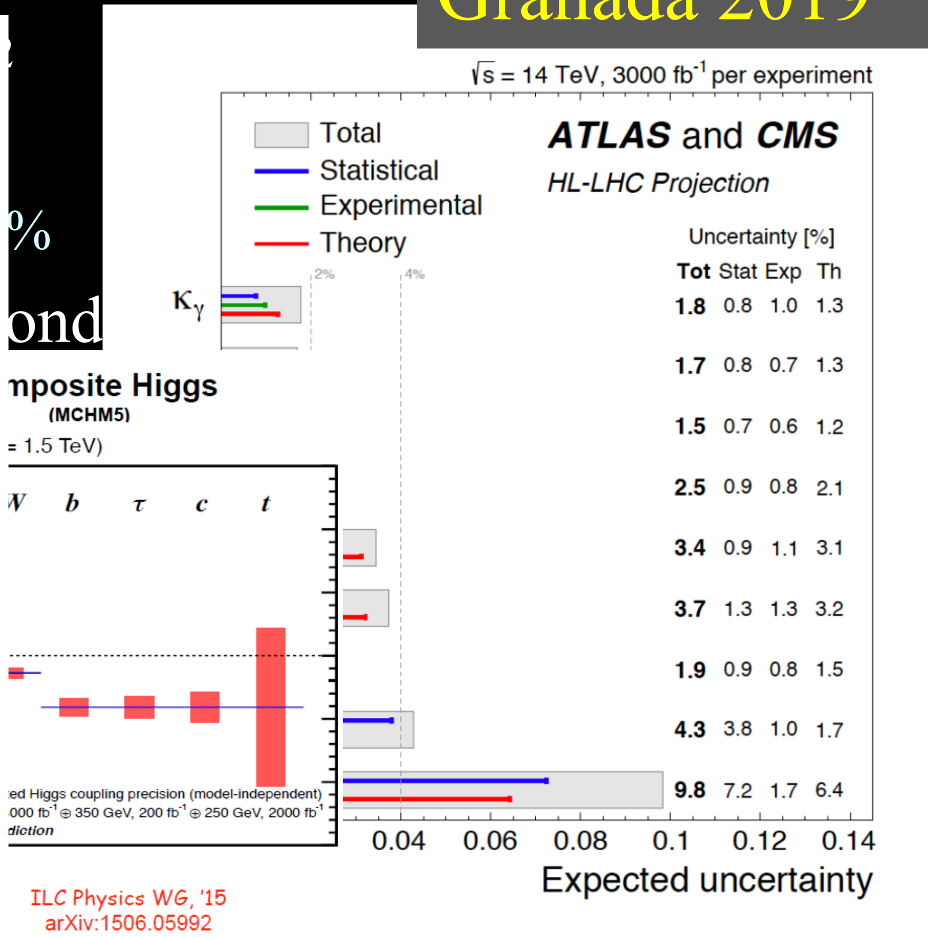
Granada 2019





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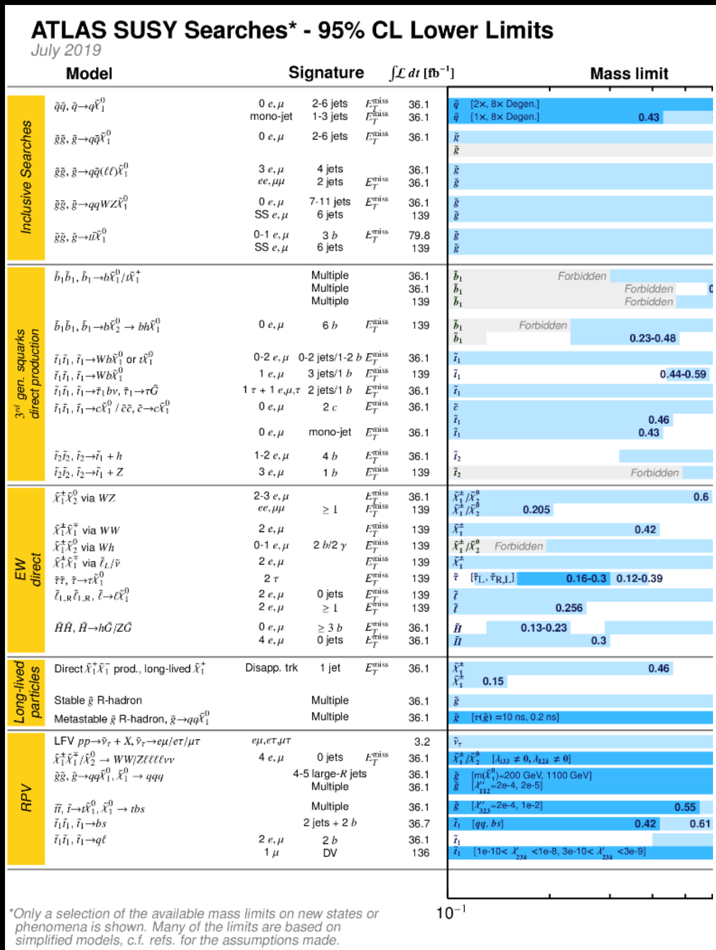
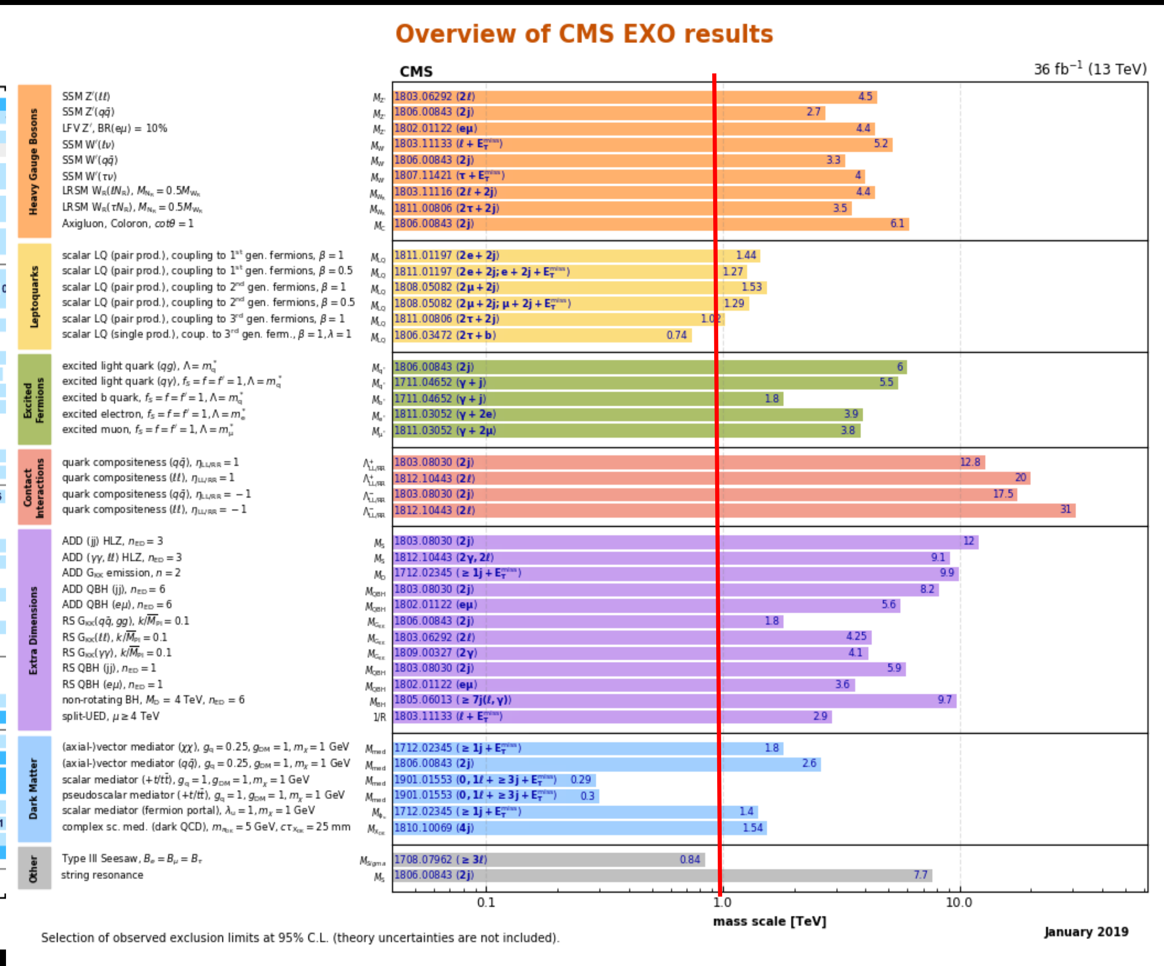
Current physics landscape

- No (additional) signs of BSM physics.
  - After intensive searches at LHC → $M_{NP} > 1$ TeV





Current physics landscape

- Higgs properties SM-like.
  - At current precision level of several %
- No (additional) signs of BSM physics.
  - After intensive searches at LHC
- … but SM is an insufficient description
  - Prevalence of matter over anti-matter.
    - Not explained by current values of CKM elements
  - Neutrinos have masses – not acquired in the SM.
  - Compelling evidence for the existence of dark matter in the Universe with no candidate particle(s) in the SM.
- What new next accelerator to go beyond SM?

Current directions

- ICFA statement - Tokyo, March 2019:
  - "ICFA confirms the international consensus that the highest priority for the next global machine is a "Higgs Factory" capable of precision studies of the Higgs boson.

    ……………………………………………………………………

    ICFA notes with satisfaction the great progress of the various options for Higgs factories proposed across the world. All options will be considered in the European Strategy for Particle Physics Update and by ICFA.
- ICFA report – LP2019, Toronto, August 2019:
  - Worldwide effort for e+e- Higgs Factory ***must not fail!***
    - Linear or Circular
    - Asia or Europe (or elsewhere?)
- Recent comments on ESPPU preparations (B. Vachon – LP2019)
  - Emerging consensus for the importance of a "**Higgs factory**" to fully explore properties of the Higgs, EW sector, etc.
  - Need to prepare a clear path towards **highest energy**.

EU strategy update

- Input documents from all communities by Dec. 2018
- Open symposium to discuss everything in Granada 2019
  - https://indico.cern.ch/event/808335/
- After Granada a “Briefing Book” was produced
  - Supposedly to summarize everything for the group of people who will draft the report for the CERN Council
    - http://cds.cern.ch/record/2691414
  - Some parts of this book are debatable – Will point them out during the talk.

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The planned machines

Higgs factories

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- *e+e-* linear
  - *ILC*
  - *CLIC*
- *e+e-* circular
  - *FCC-ee*
  - *CepC*
- *μ+μ-* circular
  - *μ-HF*

Difficult

Requirement: high luminosity $O(10^{34})$ at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine :

- 27 km long
- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost "1 LHC Unit" *

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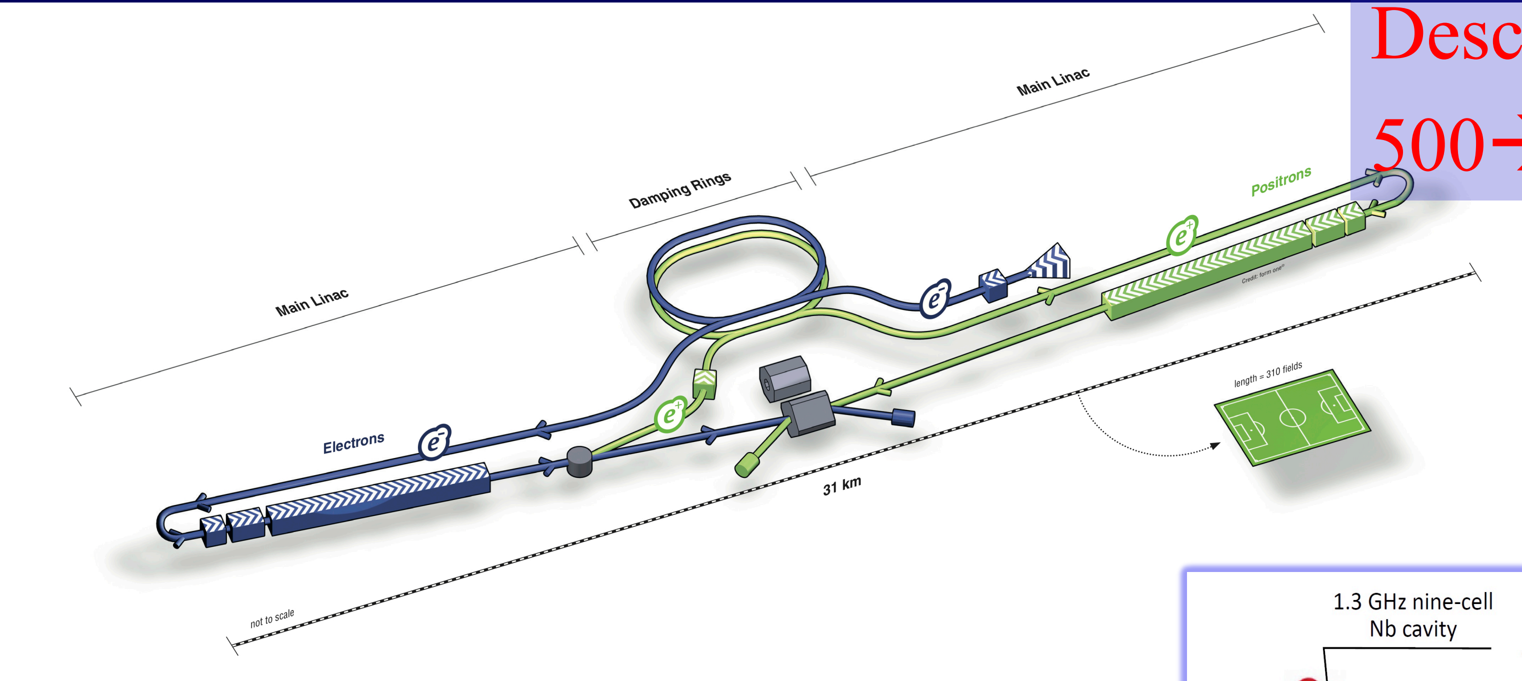
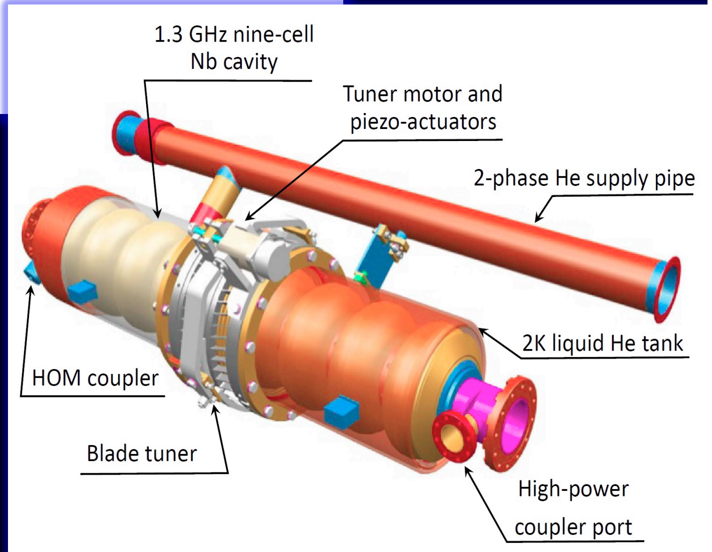
International Linear Collider

Descoped
500→250 GeV





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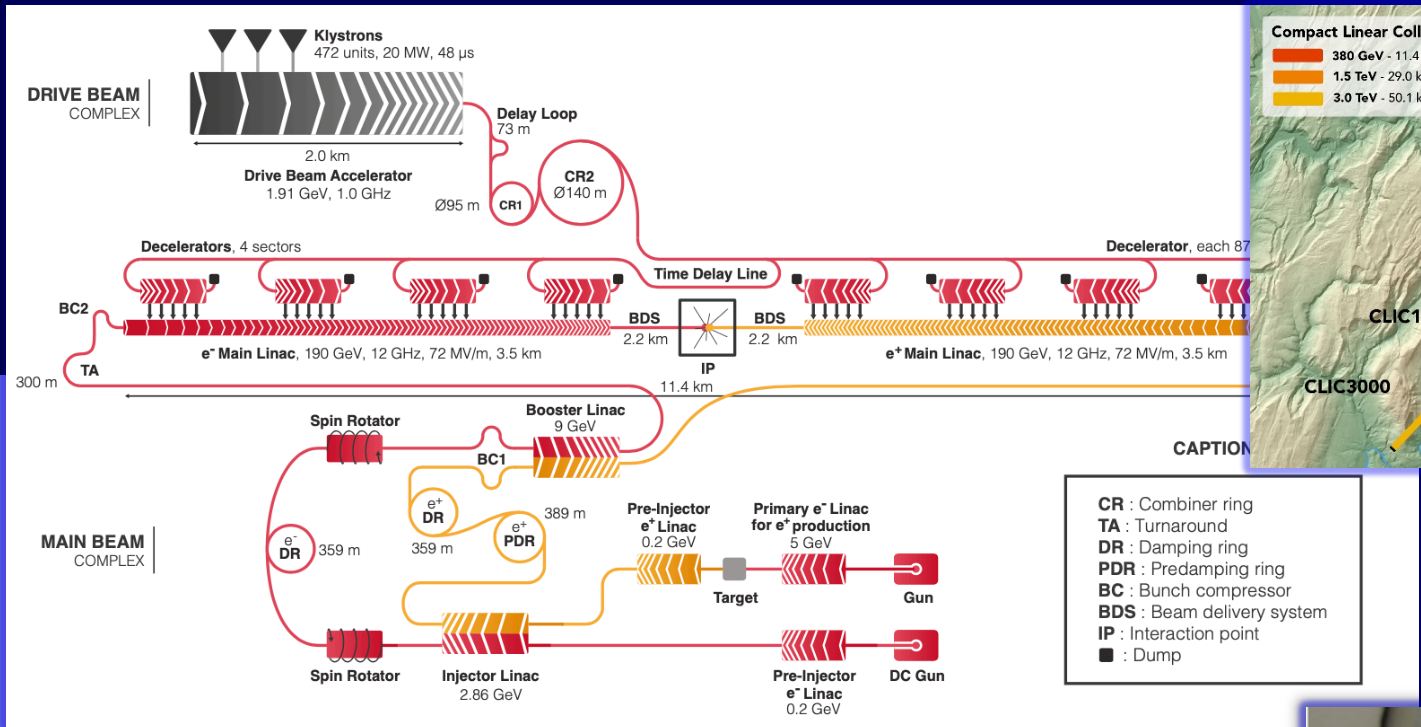
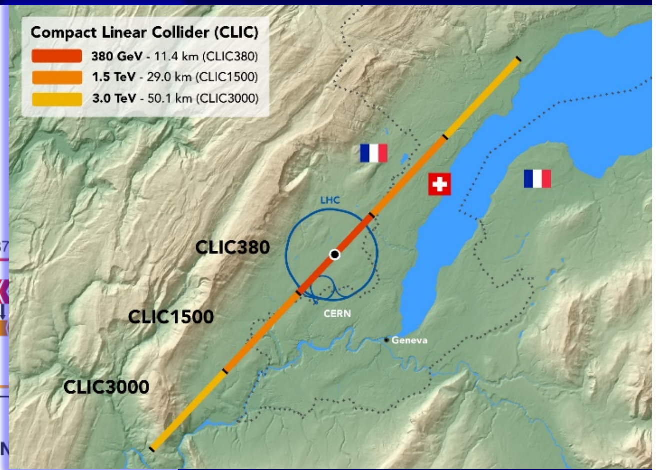
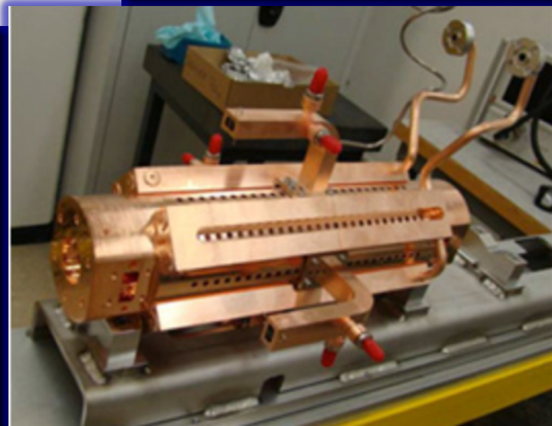
- Key facts:
  - 20 km, including 5 km of Final Focus
  - SRF 1.3 GHz, 31.5 MV/m, 2 K
  - 130 MW site power @ 250 GeV c.m.e.
  - Cost estimate 700 B JPY = 5.8 B€

Compact LInear Collider







❖ Key facts:

- 11 km main linac @ 380 GeV c.m.e.
- NC 12 GHz RF 72 MV/m, two-beam scheme
- 168 MW site power (~9MW beams)
- Cost est. 5.9 BCHF (klystrons + 1.4 BCHF)

Linear Colliders *e+e-* Higgs Factories

- Advantages:
  - Based on mature technology (Normal Conducting RF, SRF)
  - Mature designs: ILC TDR, CLIC CDR and test facilities
  - Polarization (ILC: 80%-30% ; CLIC 80% - 0%)
  - Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
  - Well-organized international collaboration (LCC) → "we're ready"
  - Wall plug power ~130-170 MW (i.e. <= LHC)
- Pay attention to:
  - Cost more than LHC ~(1-1.5) LHC
  - LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:
    - e.g. factor of 4 for ILC: x2 Nbunches and 5 Hz → 10 Hz
  - Limited LC experience (SLC), two-beam scheme (CLIC) is novel,
    - klystron option as backup
  - Wall plug power may grow >LHC for lumi / E upgrades

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Challenges of Linear Colliders
Higgs Factories

Notes from the briefing book:

- The world record for positron production rates is still held by the SLC positron source. LCs require much higher positron production rates than SLC (CLIC about 20 times more, ILC baseline about 40 times, ILC upgrade about 160 times).

Notes from the briefing book:

- ATF2 has achieved the scaled ILC vertical spot size of ~ 40 nm, albeit with a relaxed optics and at roughly 1/10 of the design bunch charge; the charge was reduced to mitigate wakefield effects.

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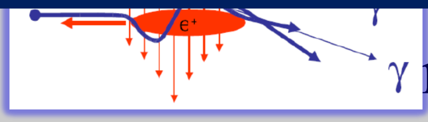

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ILC

- Grows with *E*: 40% of CLIC lumi 1% off $\sqrt{s}$

production (two schemes)

- CLIC high-current drive beam bunched at 12 GHz

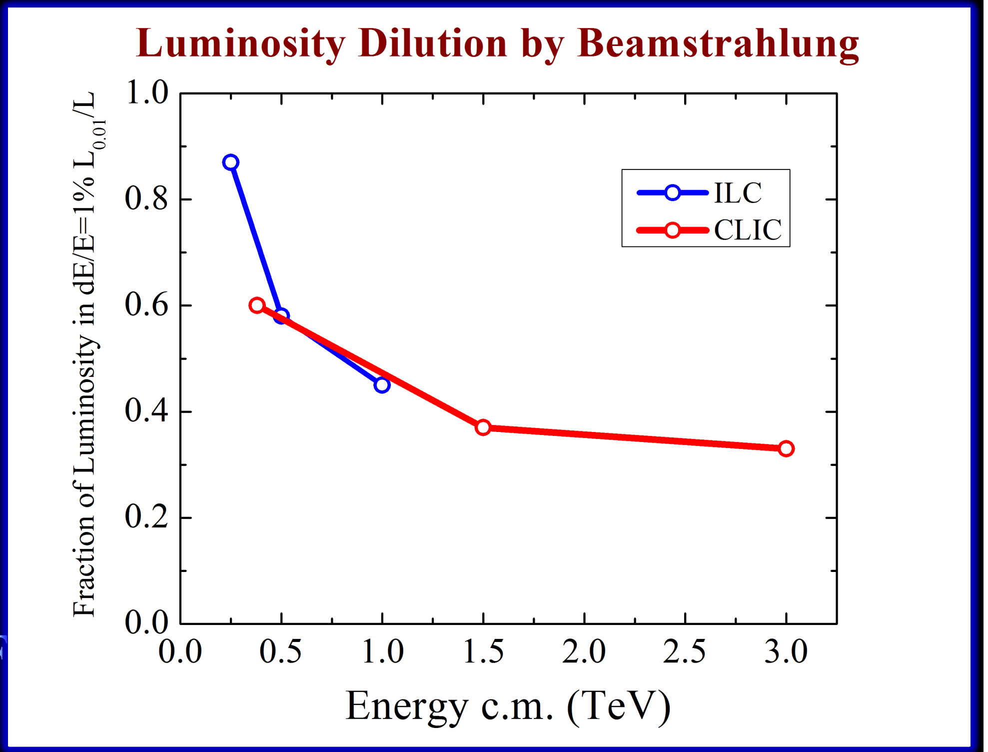
- 0.1 μm BPMs
- IP beam sizes

ILC 8nm/500nm

CLIC 3nm/150nm

Limits of Linear e^+e^- Colliders

- Both ILC and CLIC offer staged approach to ultimate E



- The limits are set by:
  - Cost
    - ILC TDR 1 TeV 17 B$
    - CLIC CDR 3 TeV 18.3BCHF
  - Electric power required
  - Total length
  - (complication of) Beamstrahlung

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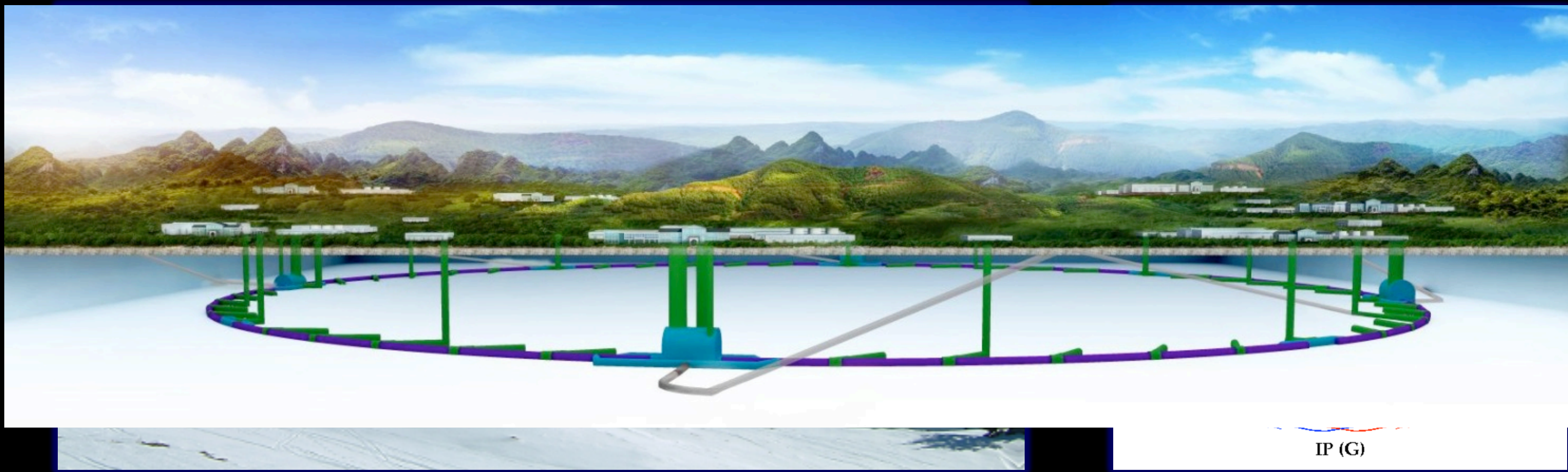
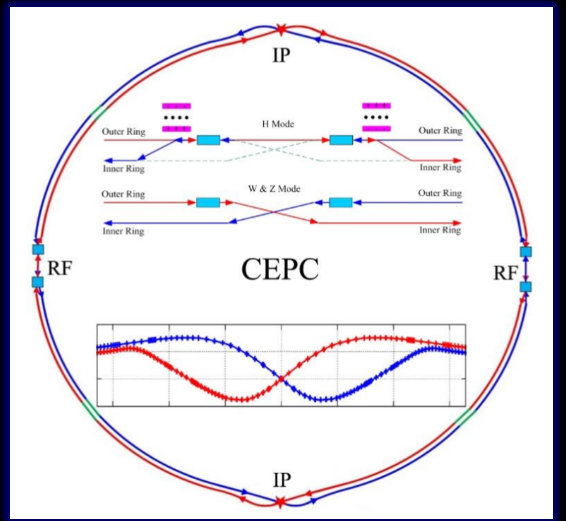
Circular e+e- Higgs Factories



❖ Key facts:
- 100 km tunnel, three rings (e-, e+, booster)
- SRF power to beams 100 MW (60 MW in CepC)
- Total site power <300MW (tbd)
- Cost est. FCCee 10.5 BCHF (+1.1BCHF for tt)
  - (“< 6BCHF” cited in the CepC CDR)



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e^+e^- Ring Higgs Factories

- Advantages:
  - Based on mature technology (SRF) and rich experience
    - → lower risk
  - High(er) luminosity and ratio luminosity/cost;
    - Up to 4 IPs, EW factories
  - 100 km tunnel can be reused for a pp collider in the future
  - Transverse polarization (τ~ 18 min at tt) for E calibration O(100keV)
  - CDRs addressed key design points, may be ready for ca 2039 start
  - Very strong and broad Global FCC Collaboration

Challenges of e^+e^- Ring HF's

- Power limited regime
  - Synchrotron radiation power from both beams limited to 100 MW (P/η=total site power) → current I is set by power

$$I = \frac{e\rho}{2C_\gamma E^4} P_T ,$$

$$\mathscr{L}\gamma^3 \ldots$$

- Lumino…
  - Dete… beam-beam parameter ξ_y, beta function at the IP β_y^* and power
  - Beam life ~18 min requires full energy booster ring

Notes from the briefing book:

- There are no major technical obstacles for their (all Higgs factories) realization, however more effort is required before construction of any of them could start.
  - Not everybody agrees on this flattening

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FCC integrated program
inspired by succesful LEP – LHC programs at CERN

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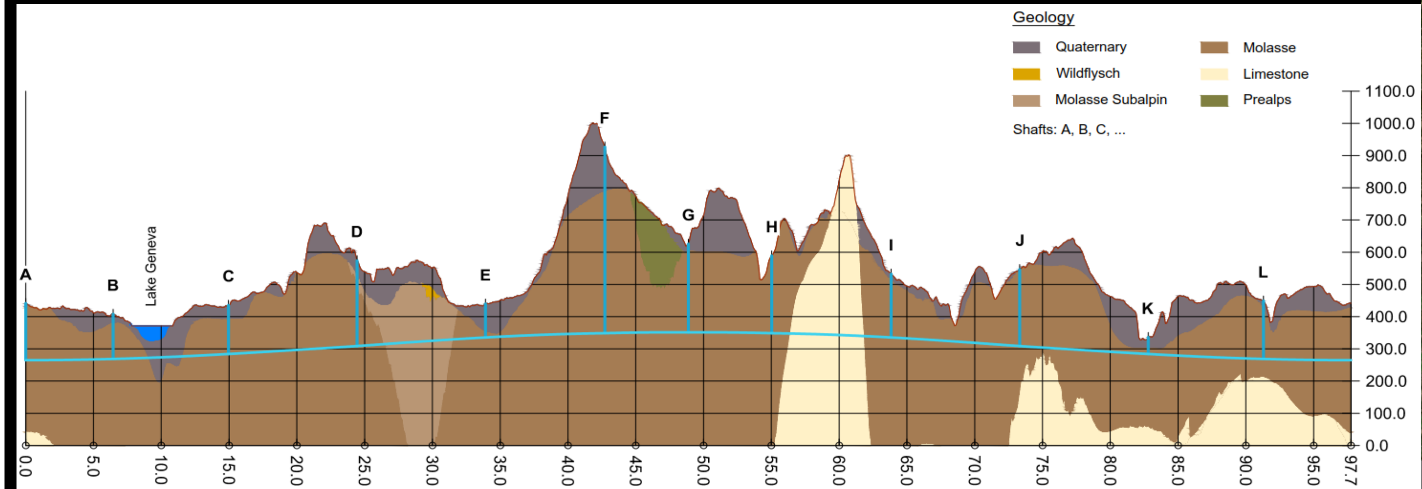
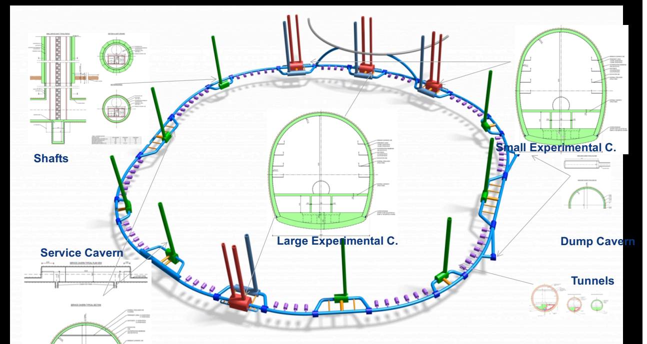
Implementation studies in Geneva basin:



baseline position was established considering:

- minimum risk for construction, fastest and cheapest construction
- efficient connection to CERN accelerator complex



- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

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FCC-ee + FCC-hh

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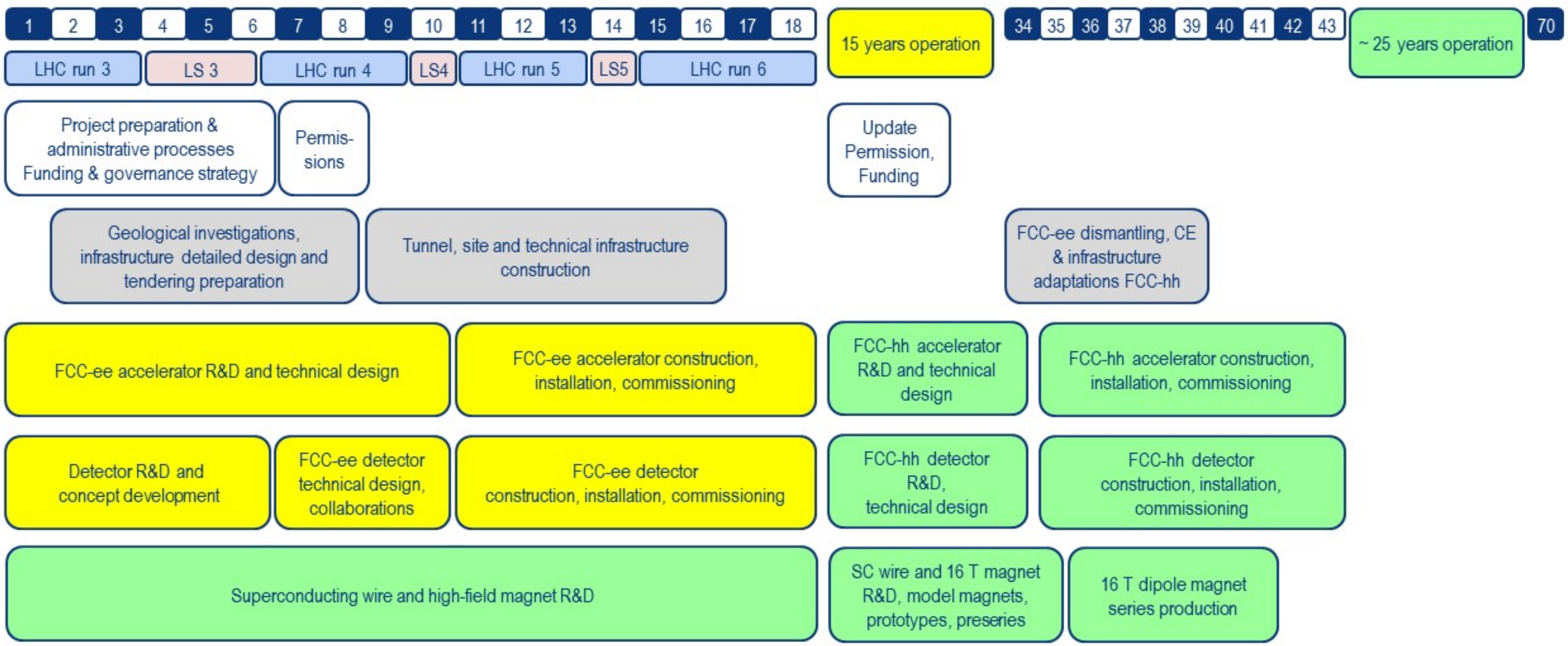
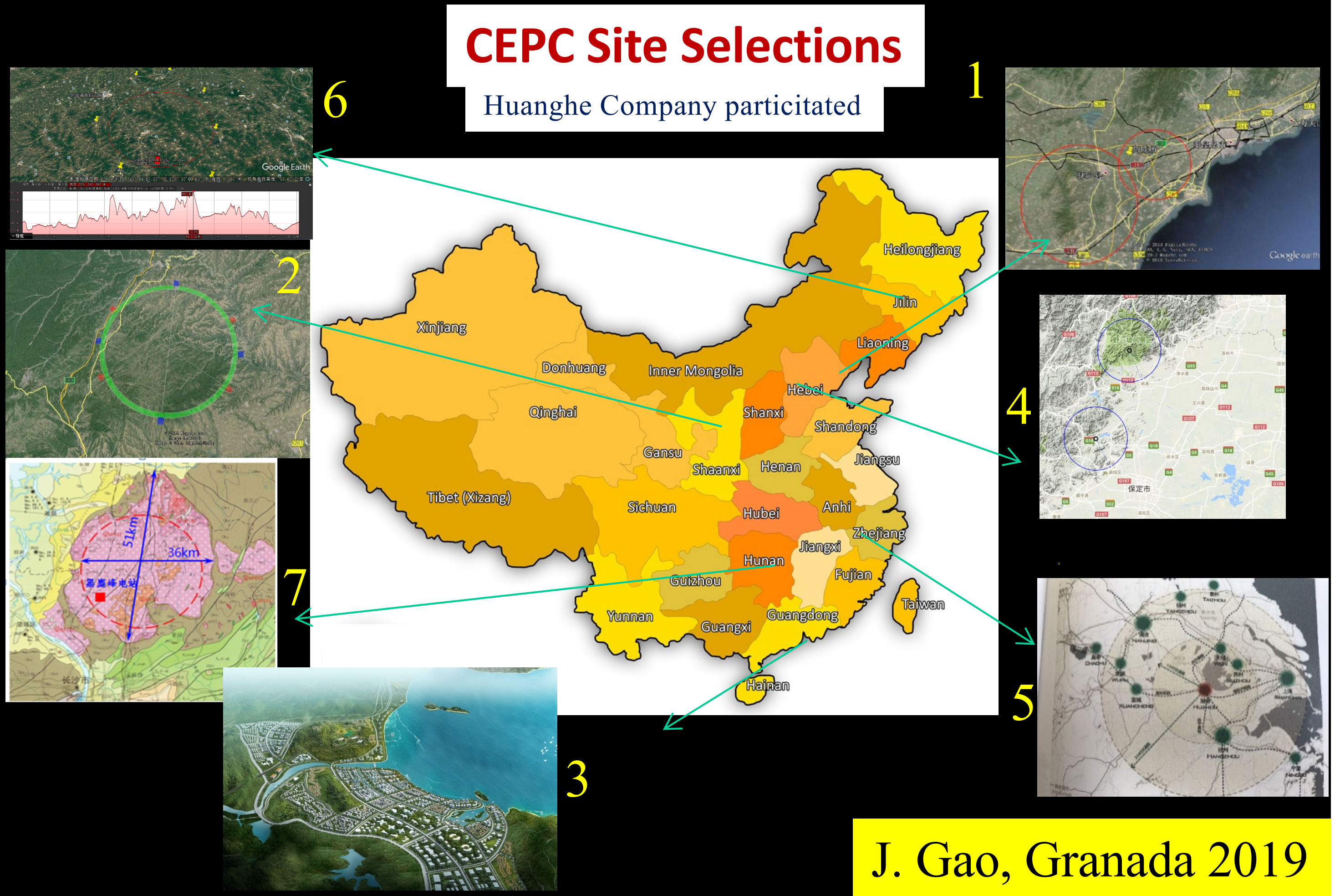


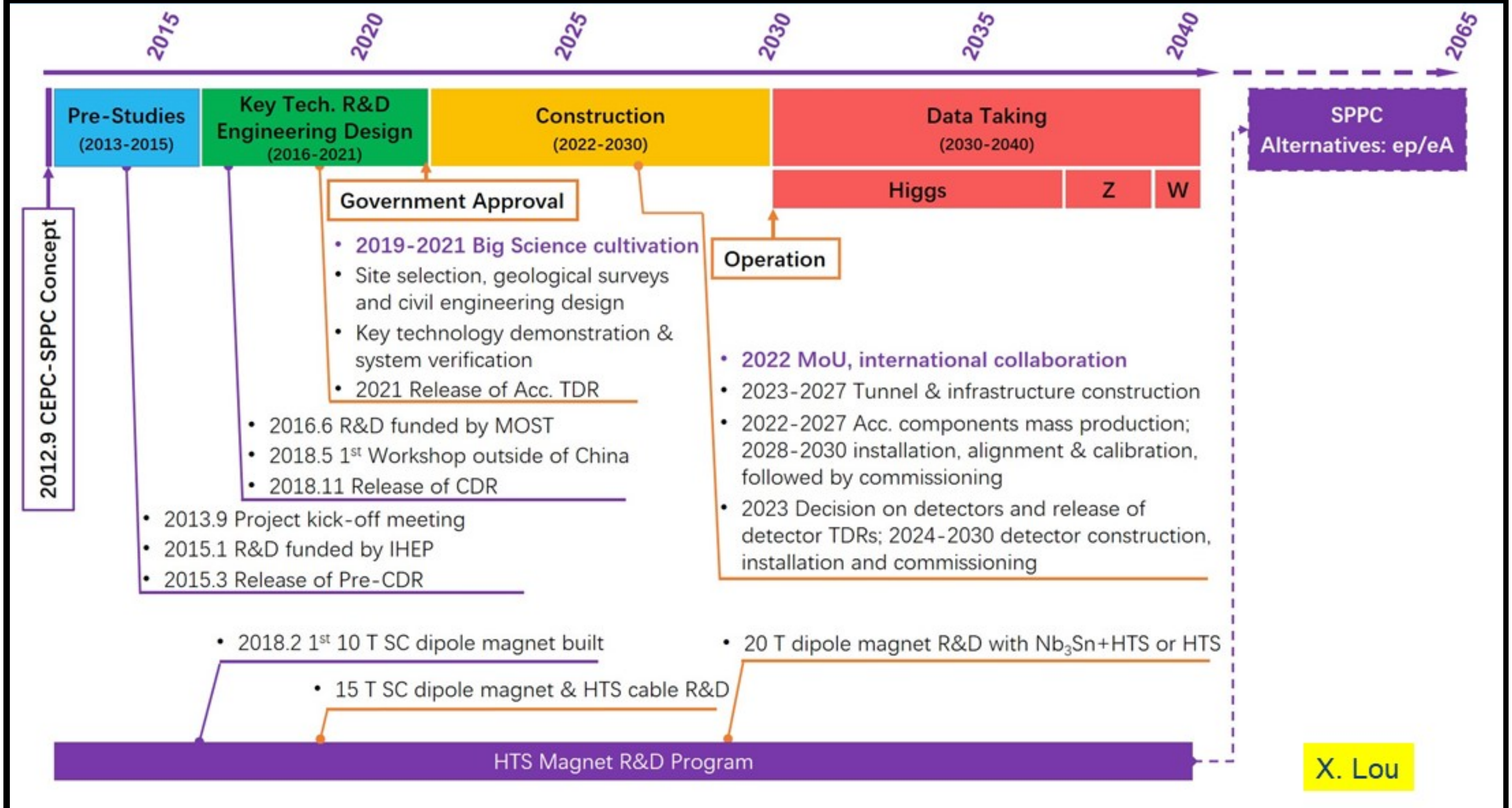
FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

CEPC-SppC: site studies

1) Qinhuangdao, Hebei ProvinceCompleted 2014)
2) Huangling, Shanxi Province （Completed 2017)
3) Shenshan, Guangdong Province(Completed 2016)
4) Baoding (Xiong an), Hebei Province (Started August 2017)
5) Huzhou, Zhejiang Province (Started March 2018)
6) Chuangchun, Jilin Province (Started May 2018)
7) Changsha, Hunan Province (Started Dec. 2018)



CEPC



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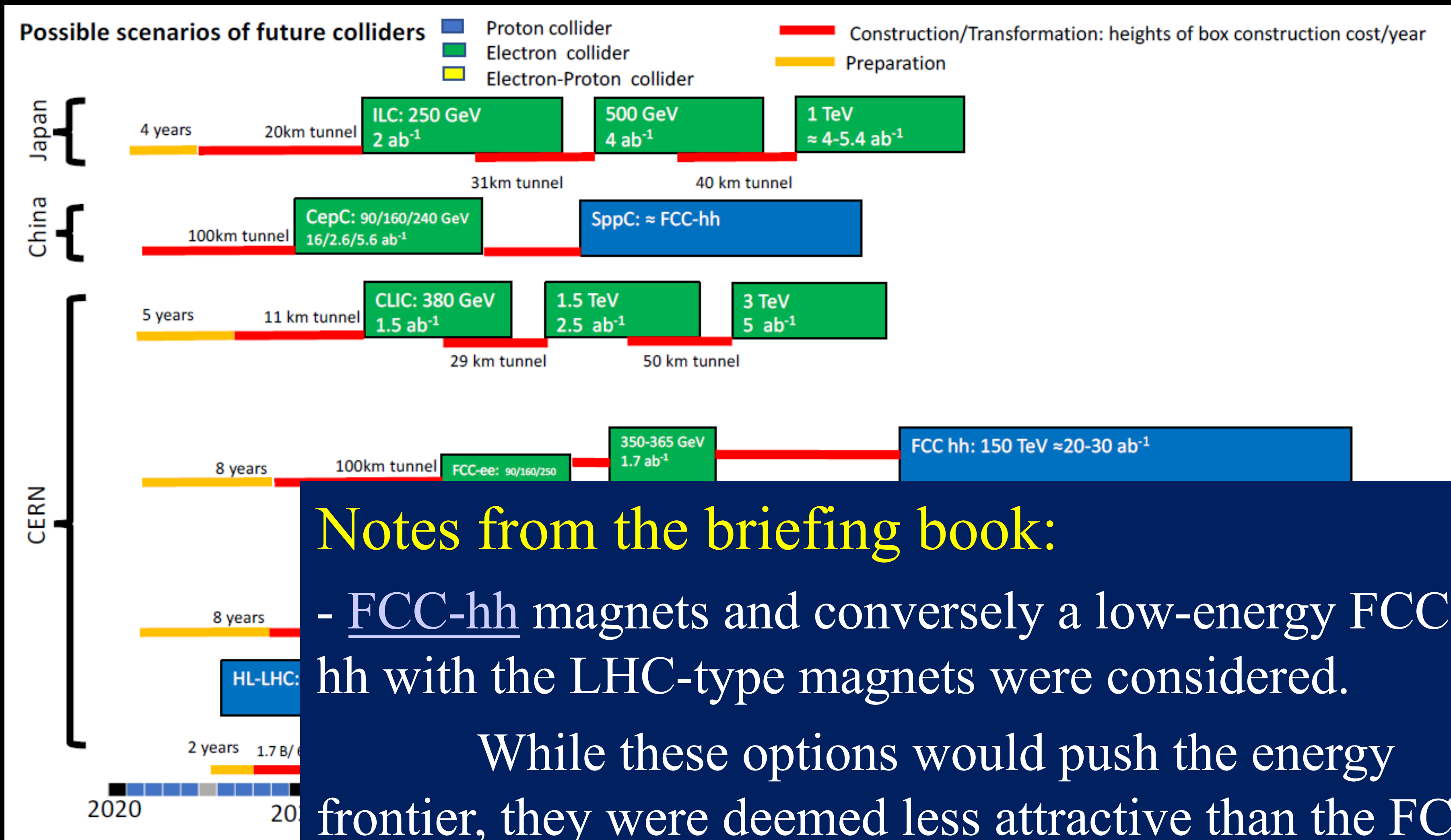
Schedules

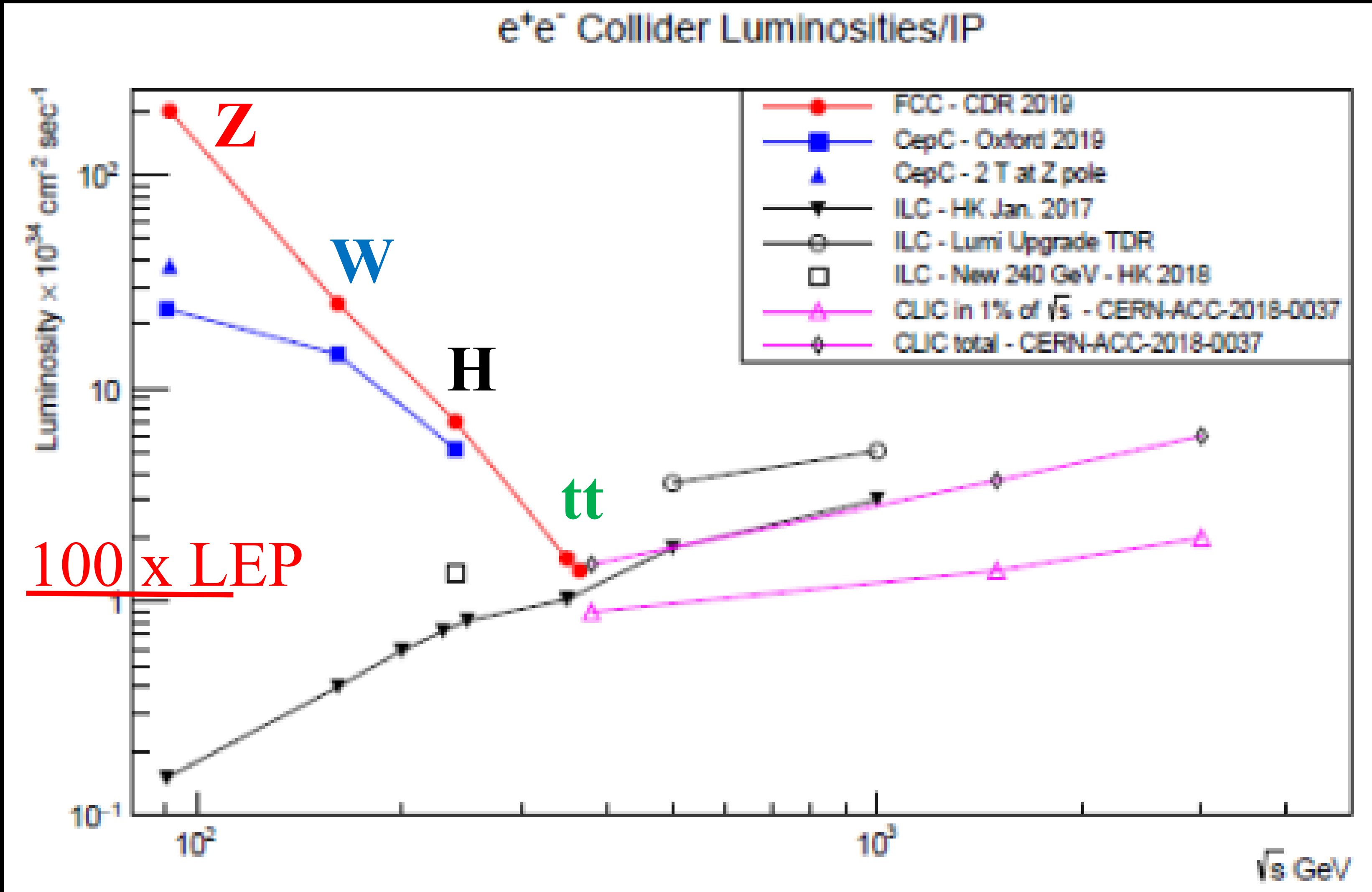


U. Bassler

Notes from the briefing book:

- FCC-hh magnets and conversely a low-energy FCC-hh with the LHC-type magnets were considered. While these options would push the energy frontier, they were deemed less attractive than the FCC integrated programme.

Luminosity comparison



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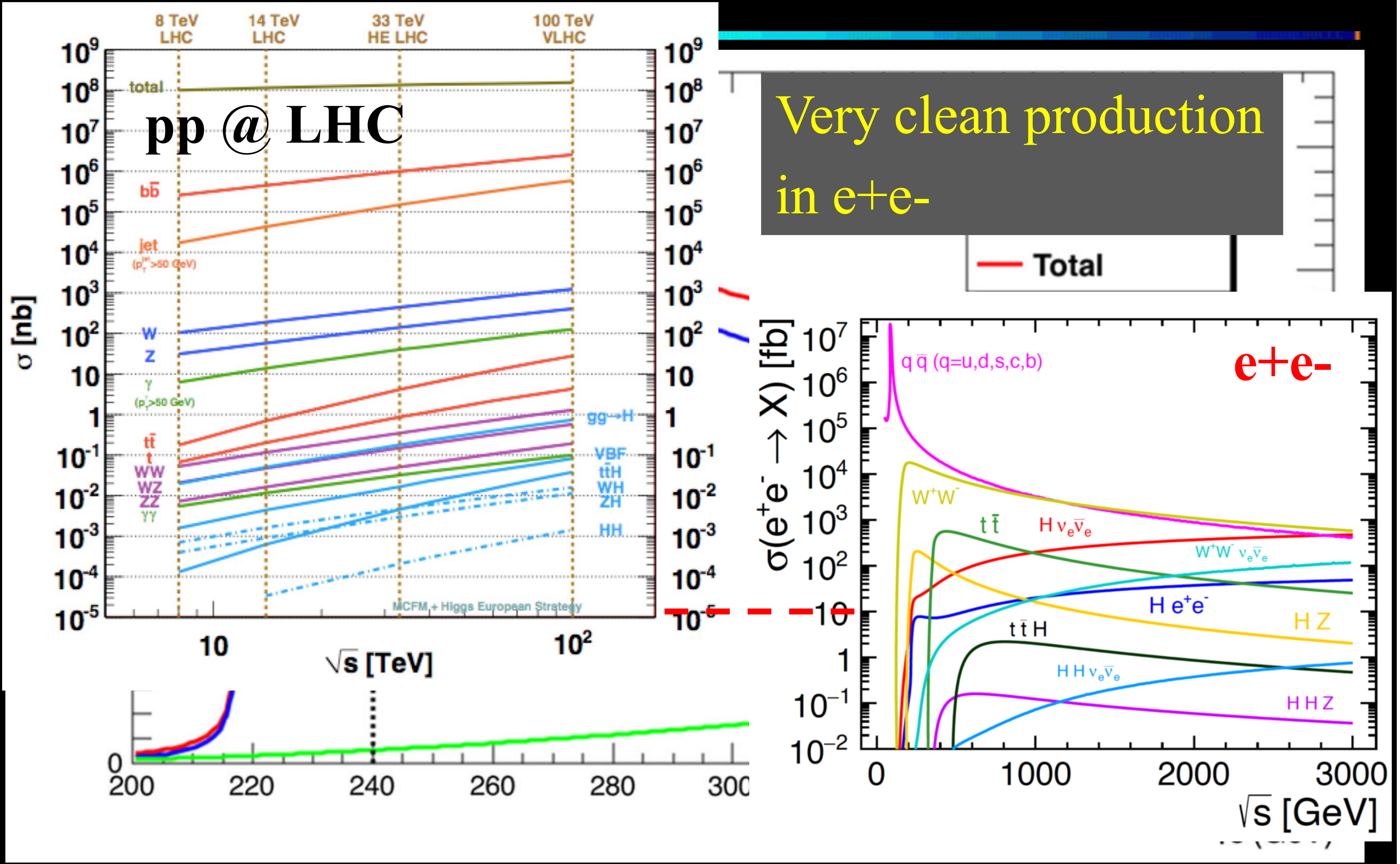
Higgs production



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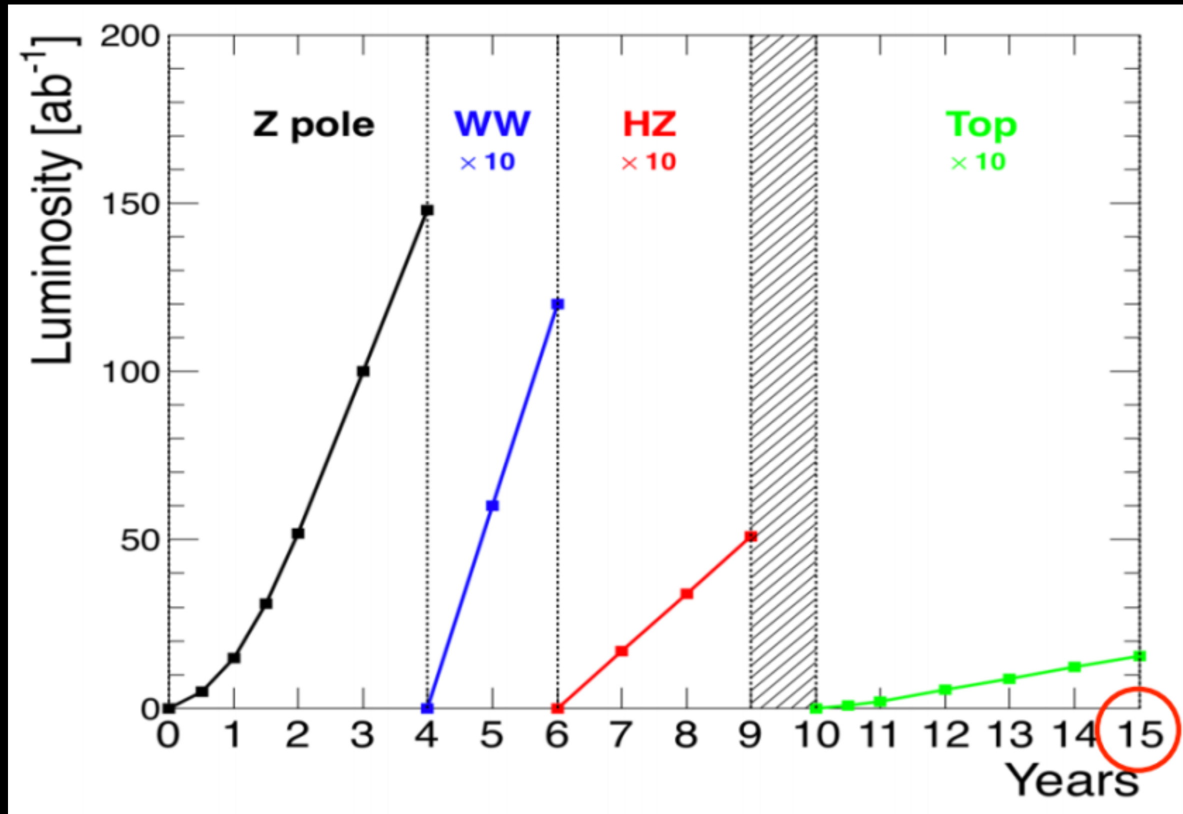
Physics at FCC-ee

- Higgs factory
  - 10^6 e+e- → HZ
- EW & Top factory
  - $3x10^{12}$ e+e- → Z
  - 10^8 e+e- → W+W- ;
  - 10^6 e+e- → tt
- Flavor factory
  - $5x10^{11}$ e+e- → bb, cc
  - 10^{11} e+e- → **τ+τ-**
- Potential discovery of NP
  - ALPs, RH ν's, …

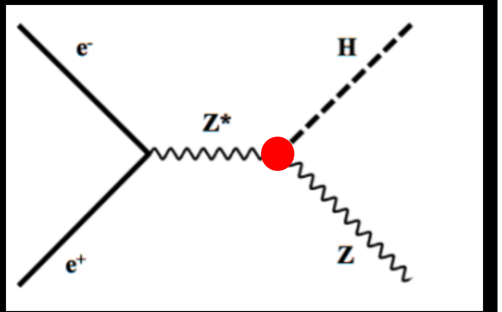


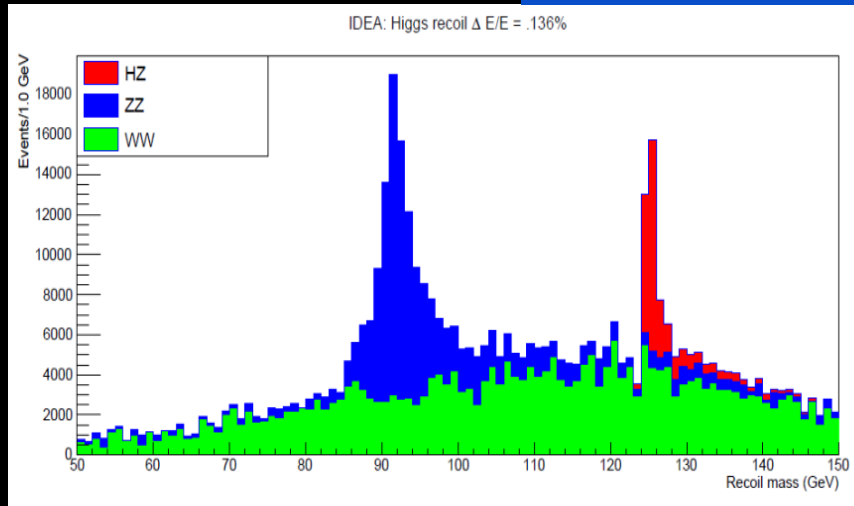
Higgs total width

❖ Higgs recoil provides model independent measurement of coupling to Z

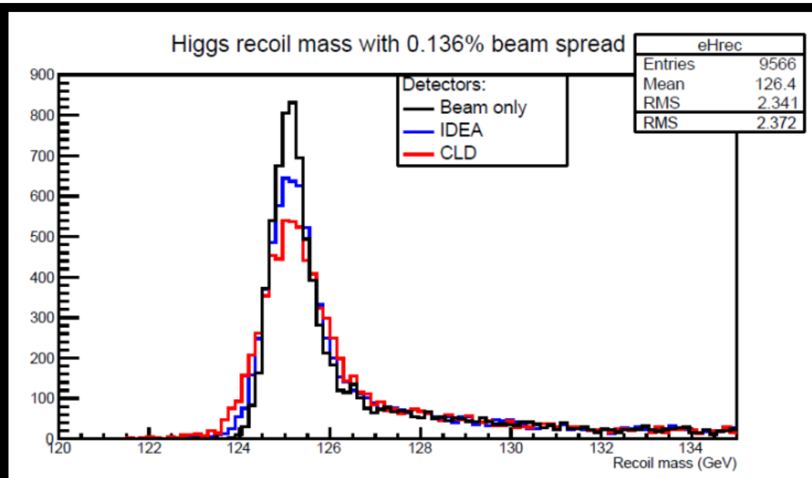
L = 5 ab^{-1}

- $\sigma(HZ) \propto g^2_{HZ}$





- Critical:
  - Beam energy spread: SR+BS
  - Detector resolution



❖ Total width combining with decays in specific channels

$$\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g^4_{HZ}}{\Gamma}$$

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Higgs coupling fits

- Kappa framework

$$(\sigma\cdot\mathrm{BR})(i\to\mathrm{H}\to f)=\frac{\sigma_i\cdot\Gamma_f}{\Gamma_H},$$

$$\kappa_H^2\equiv\sum_j\frac{\kappa_j^2\Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

$$(\sigma\cdot\mathrm{BR})(i\to\mathrm{H}\to f)=\frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2}\quad\to\quad\mu_i^f\equiv\frac{\sigma\cdot\mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot\mathrm{BR}_{\mathrm{SM}}}=\frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

  - Extension $\Gamma_H=\frac{\Gamma_H^{\mathrm{SM}}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$ BRinv measured at FCC-ee
  - BRunt 100% correlated with Γ_H

- EFT framework
  - Leading order NP effects weighted sum of all dim-6 operators
  - $O=O_{\mathrm{SM}}+\delta O_{\mathrm{NP}}\frac{1}{\Lambda^2}$ → 59 B&L conserving operators
  - Includes interference with SM operators
  - Simultaneous fit of Higgs, EWPO, aTGC, topEW
  - Fit results projected into effective Higgs couplings $g_{HX}^{\mathrm{eff}\ 2}\equiv\frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}$

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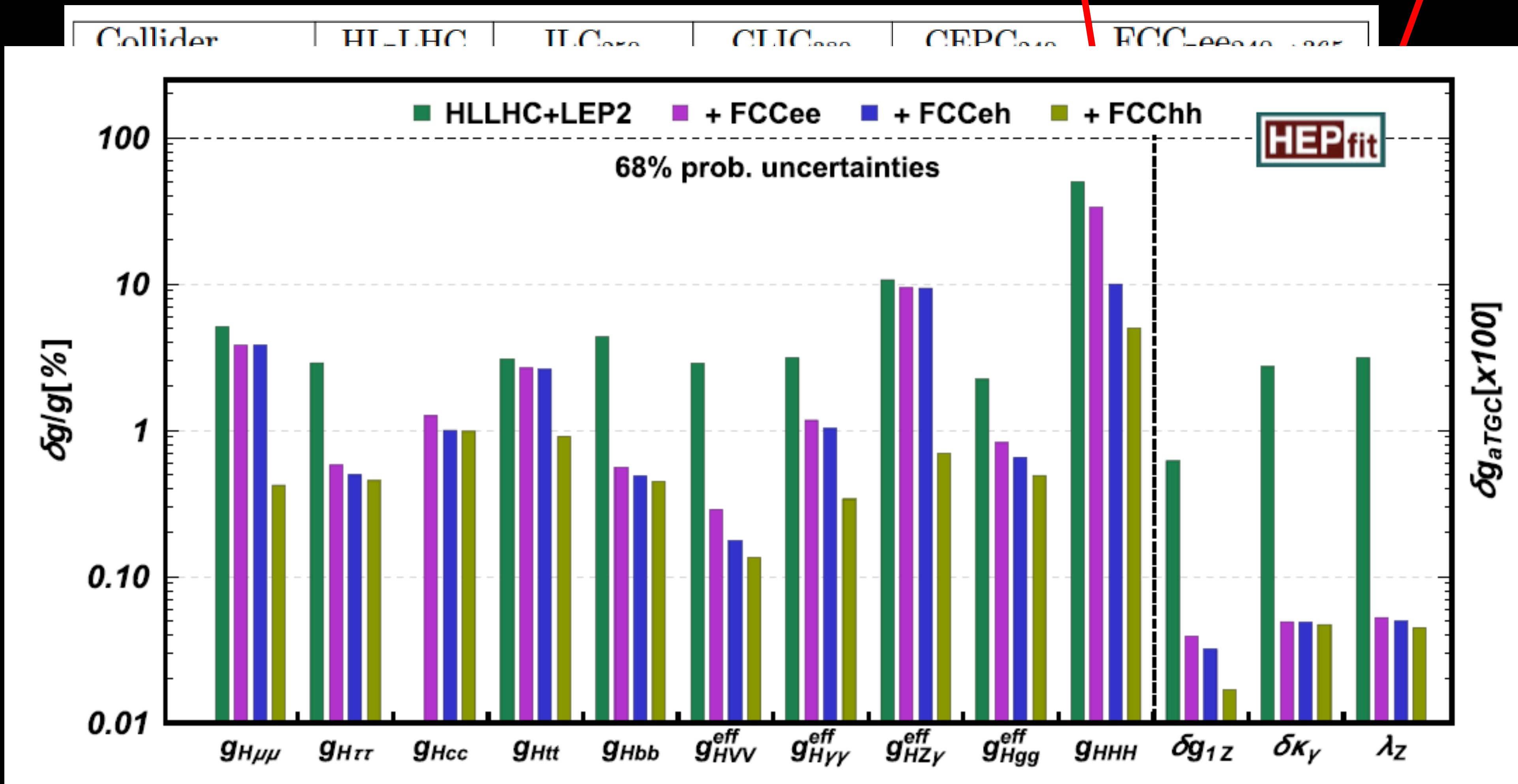
Higgs coupling fits

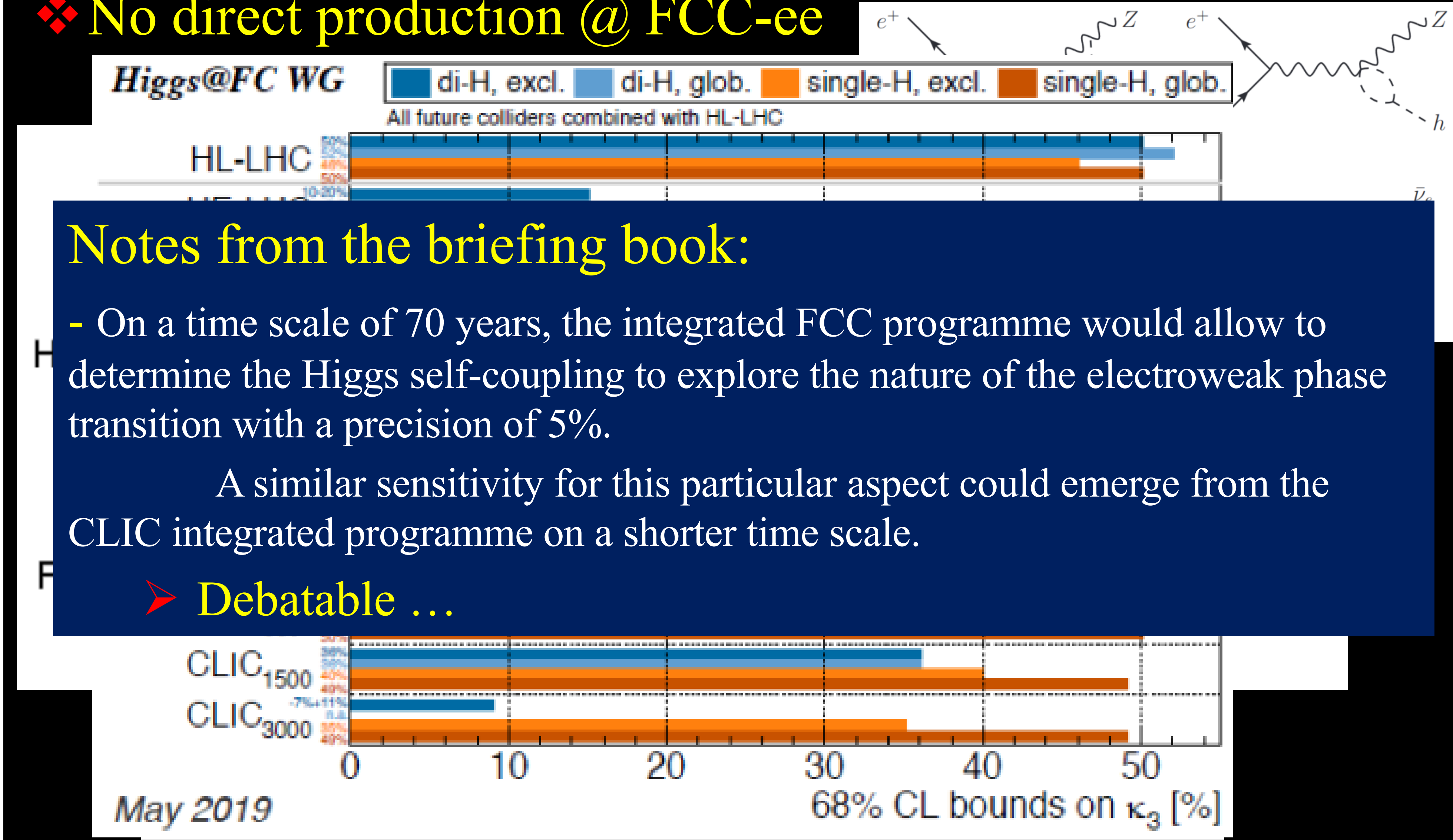
- Results limited only by statistics

κ EFT



Triple Higgs

- No direct production @ FCC-ee



Notes from the briefing book:

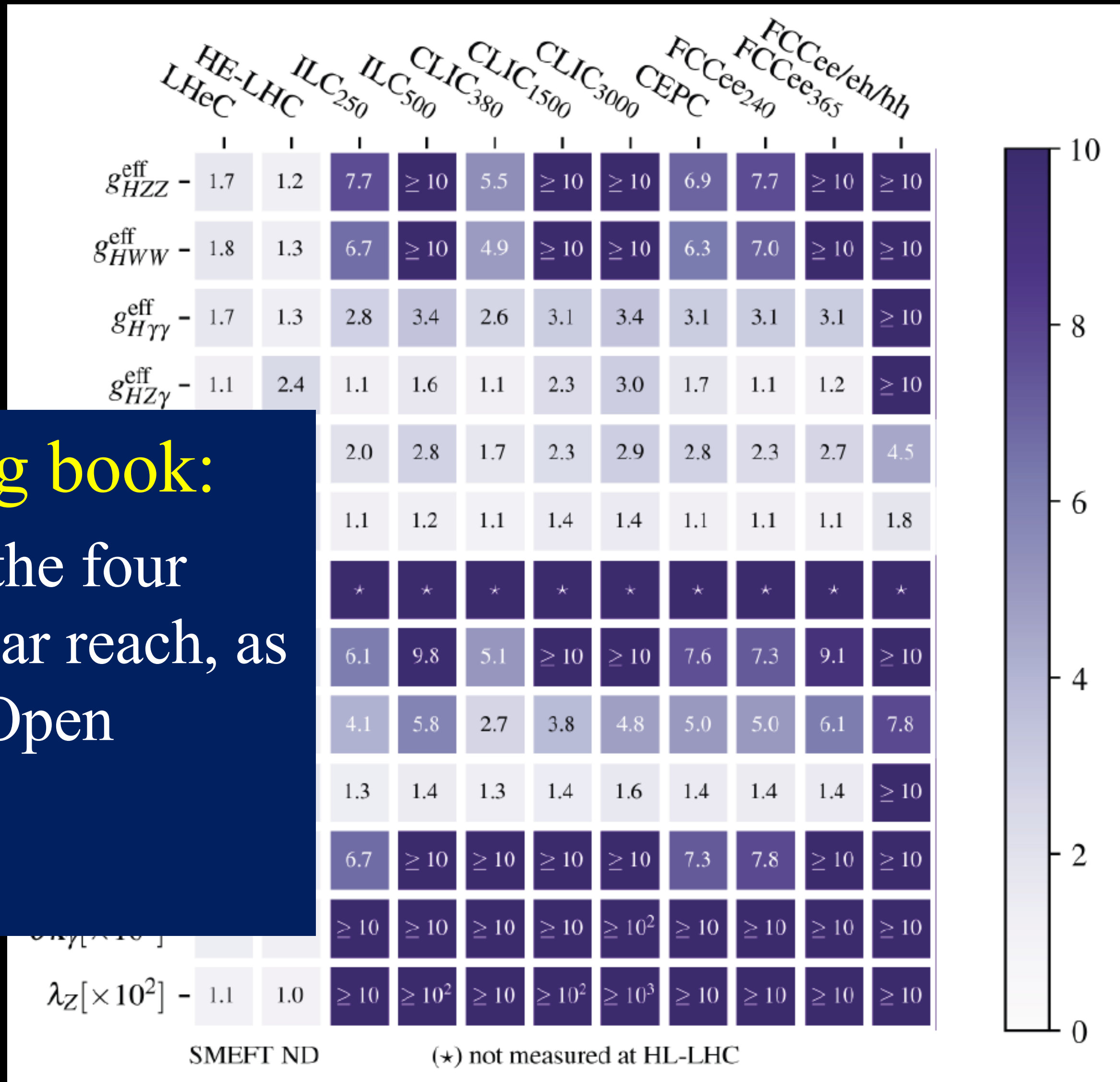
- On a time scale of 70 years, the integrated FCC programme would allow to determine the Higgs self-coupling to explore the nature of the electroweak phase transition with a precision of 5%.

A similar sensitivity for this particular aspect could emerge from the CLIC integrated programme on a shorter time scale.

- Debatable …

Higgs coupling comparison

❖ Improvement factors relative to HL-LHC

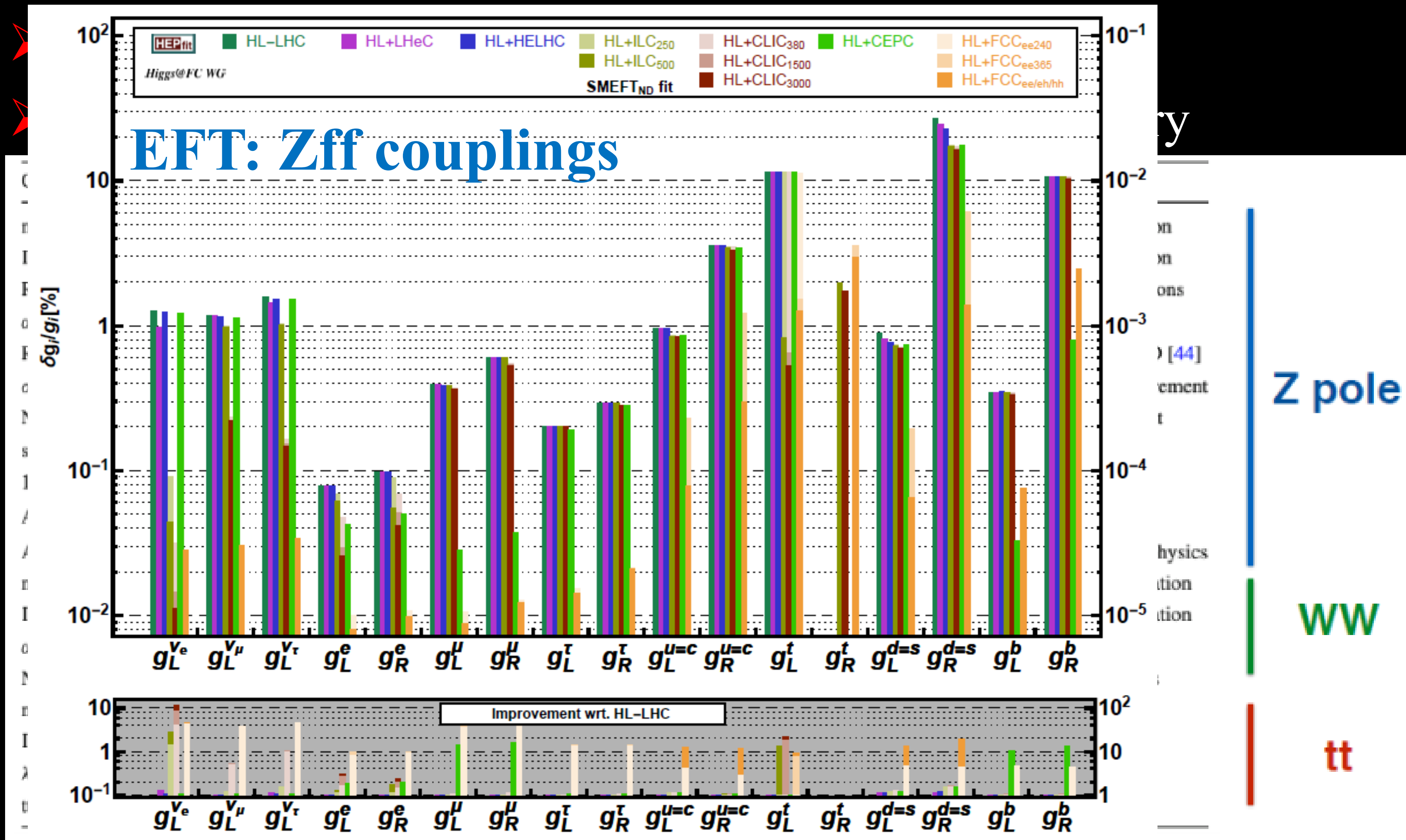


Notes from the briefing book:

- As Higgs factories, all the four contenders have a similar reach, as established during the Open Symposium.
  - ➢ Debatable …

EWK with Circular e+e-

- Outstanding program of precision EWK measurements



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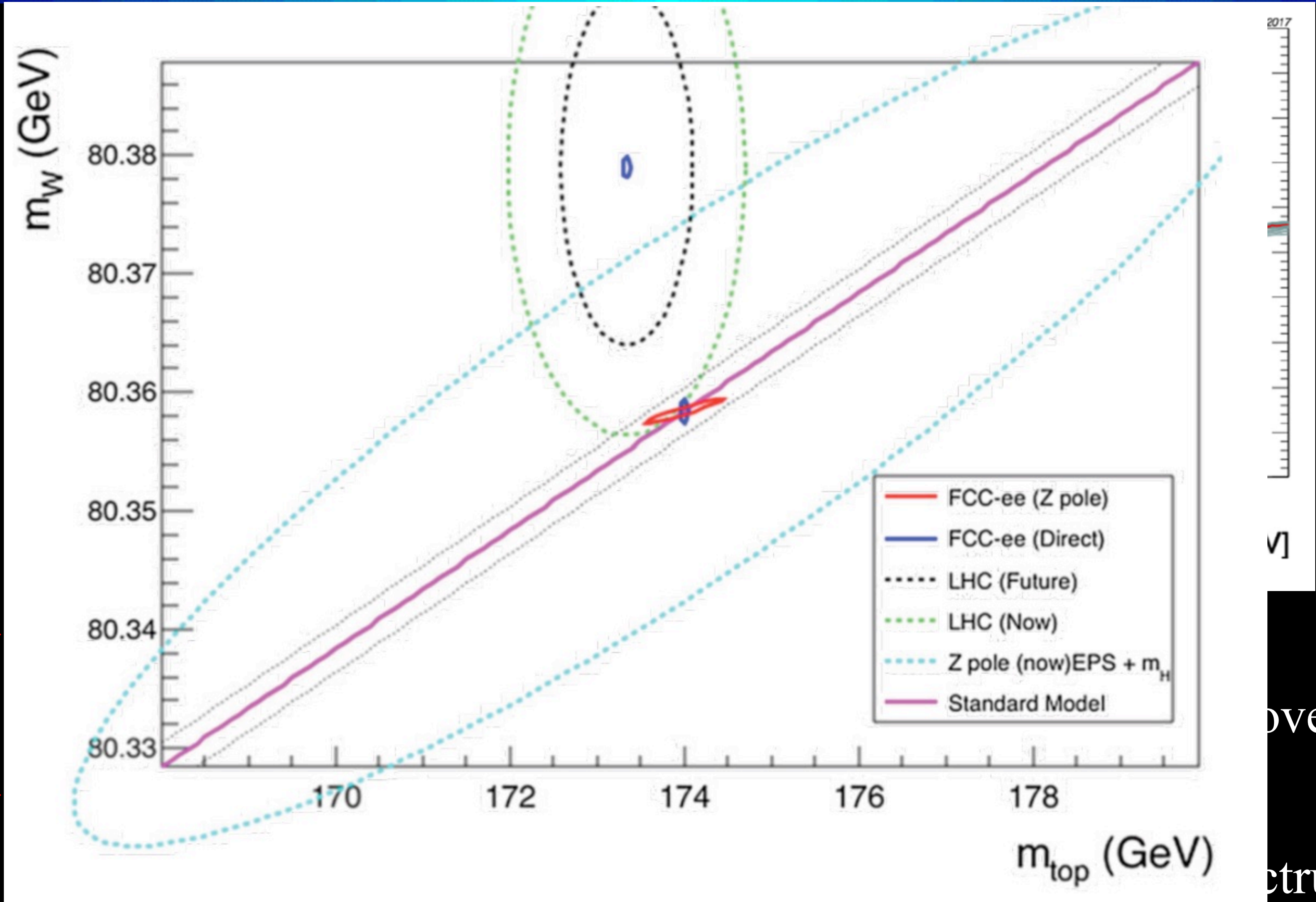
EWK examples



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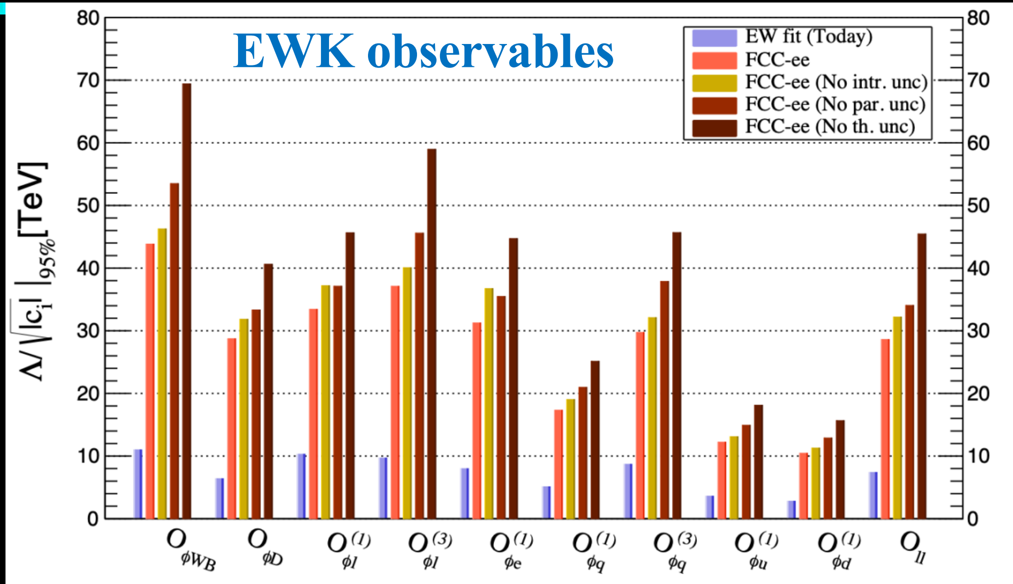
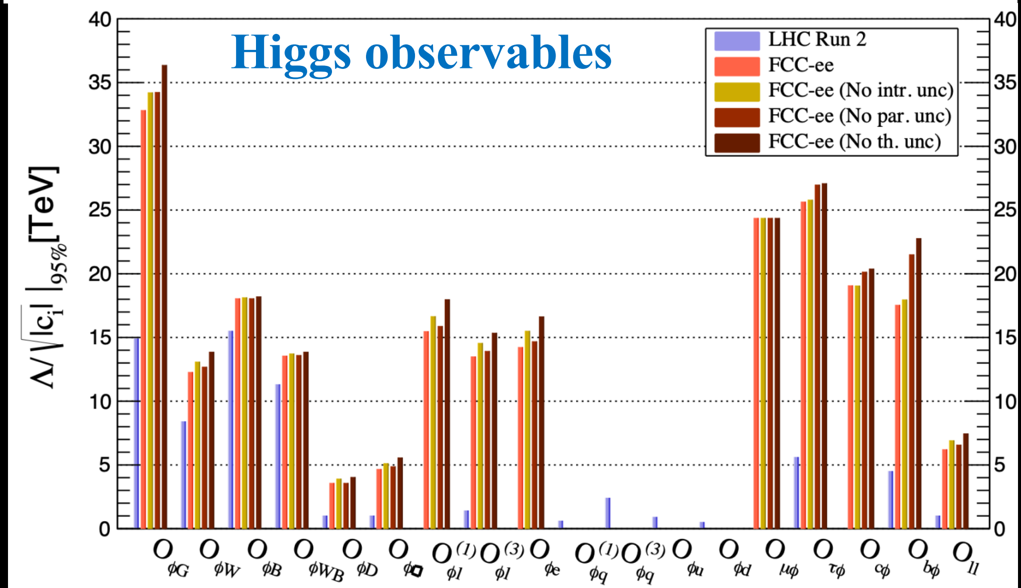
NP sensitivity from EFT fits

- From exclusive fits
  - Reach to several 10's TeV
- Theory uncertainties
  - Parametric~ exp. precision
  - Theory precision need
    - 3 loop Z pole
    - 2 loop WW





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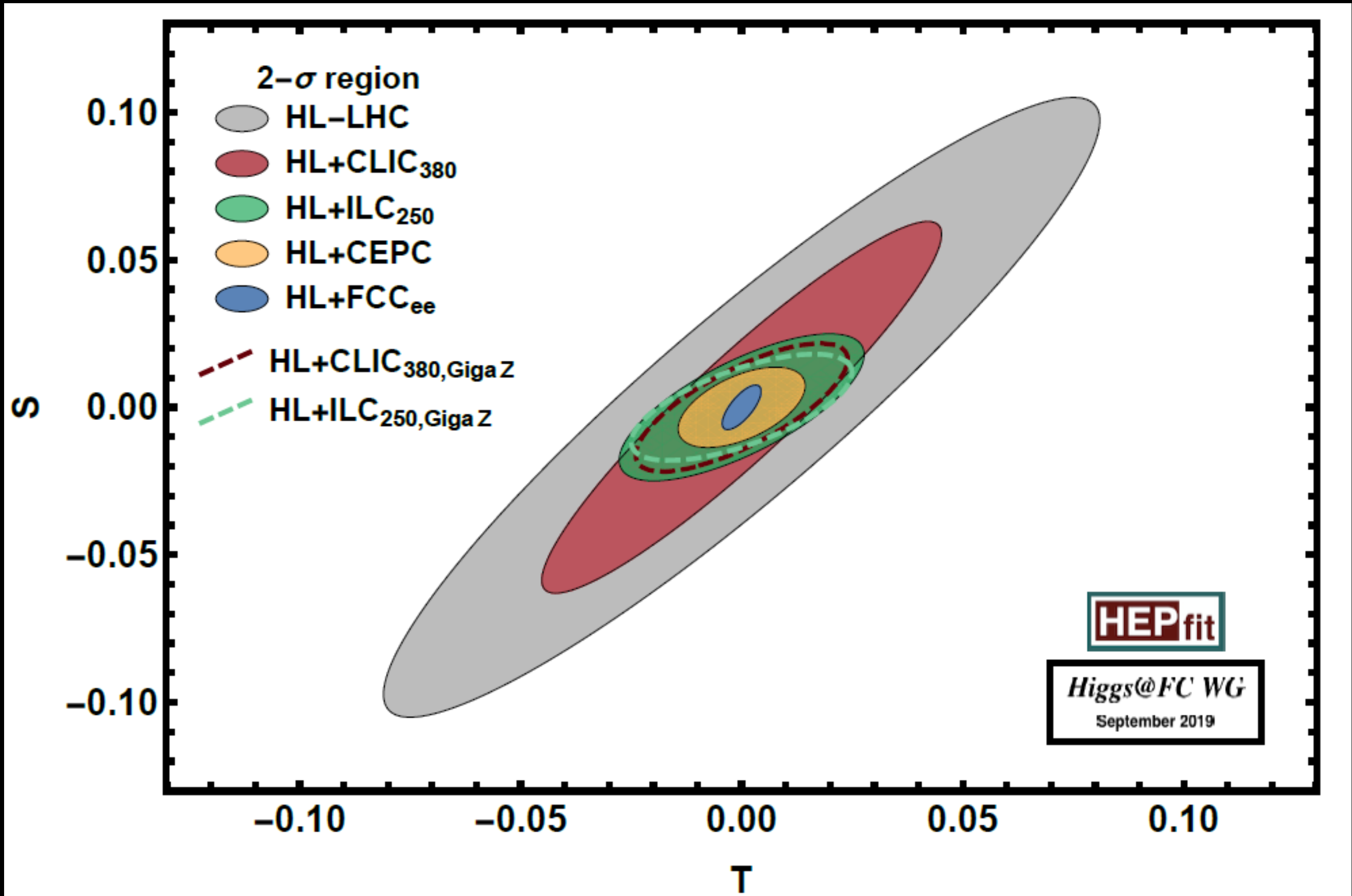
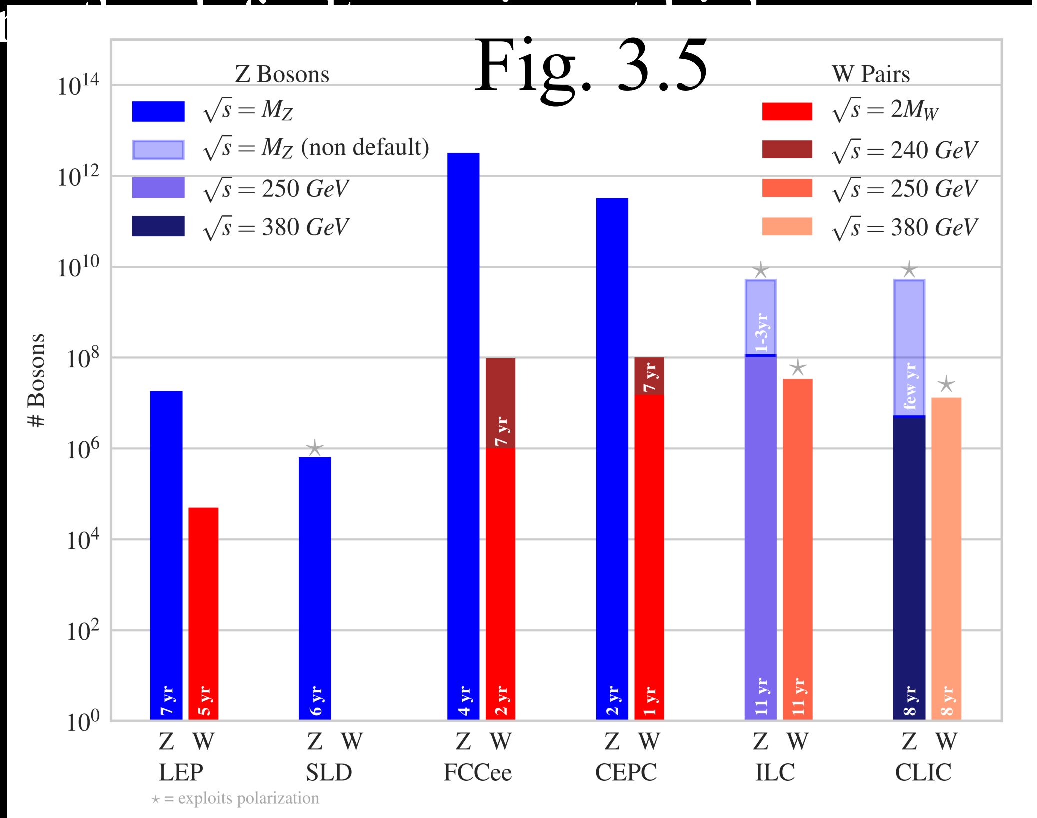
S, T parameters (Peskin–Takeuchi)

❖ Comparison of Higgs factories



Note from briefing book

- …… about $5x10^{12}$ Z bosons will be recorded for FCC-ee within four years. For the linear colliders, ILC and CLIC, within a few years a sample of a few 10^9 Z bosons could be recorded. In addition, a significant improvement for some of the Z boson properties can also be achieved using Z bosons duri
energies; those numbers are also
  - Issues for LC:
    - > x 10 in beam energy spread
    - Much longer collection time
    - HF physics relies on statistics



Heavy flavors

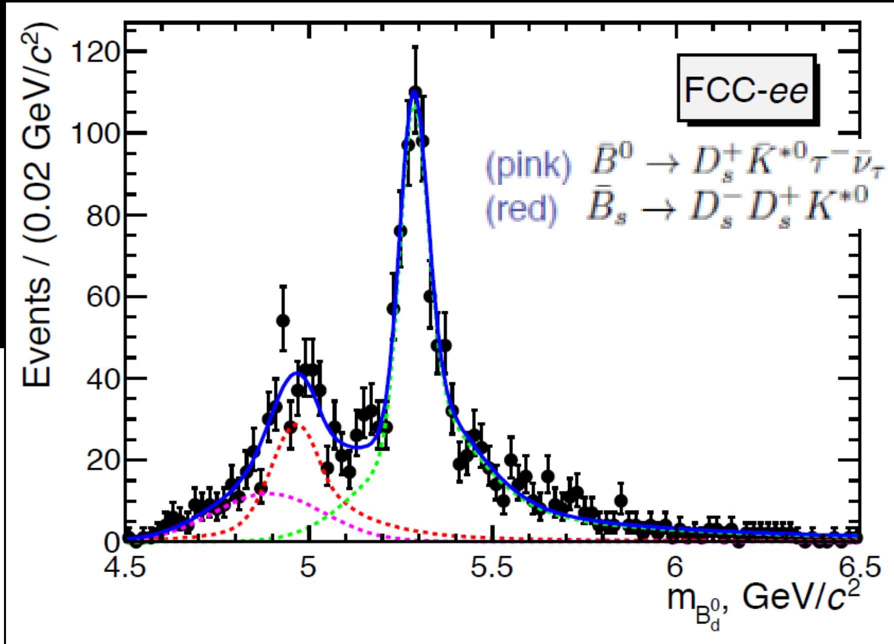
- Large heavy flavor production at Z pole

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

  - Very clean, well separated, pairs
- Example:
  - Lepton universality

in $B^0 \to K^{*0}\ \tau^+\tau^-$

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	~ 2 000	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~1000 (100)



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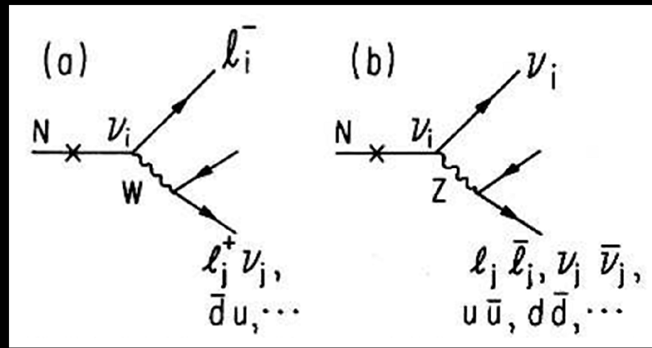
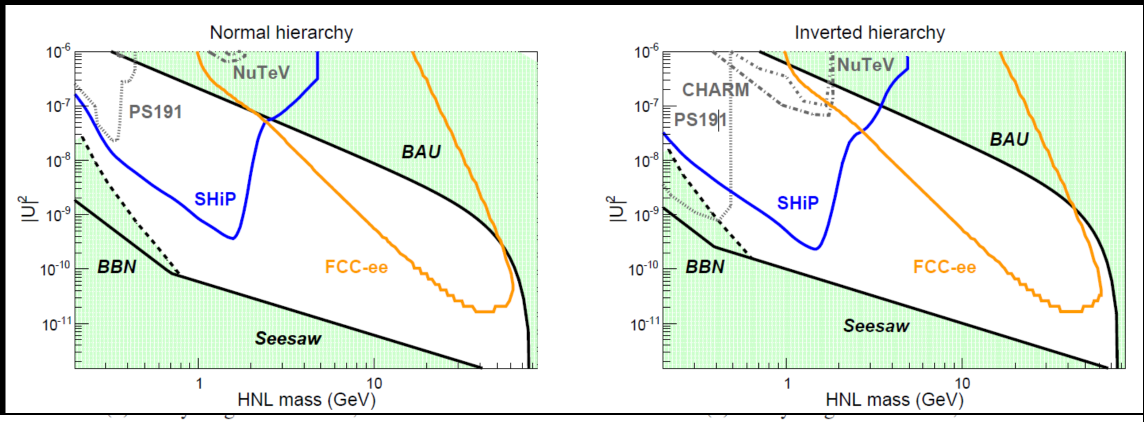
Direct NP search example: HNL

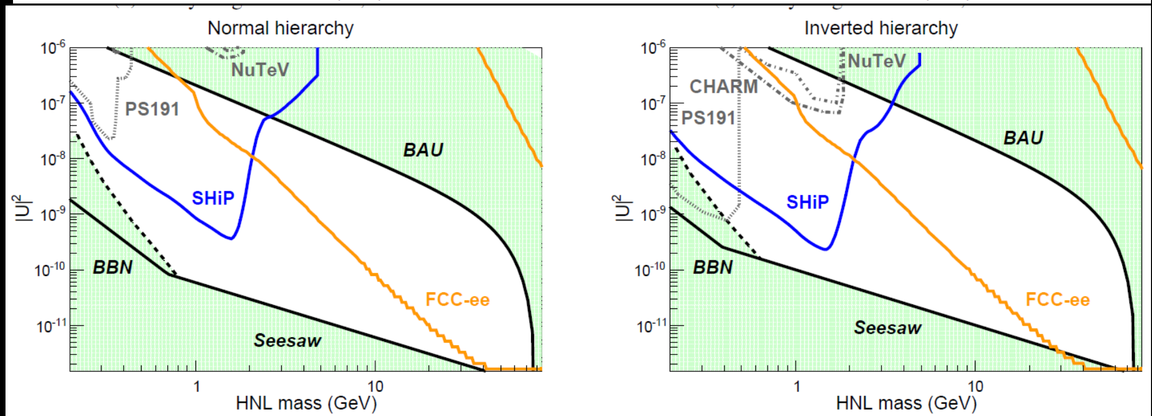
- HNL mix with active neutrino's
  - Fully reconstructable decay with W
  - Small mixing → long lifetime





$10 \text{ cm} < c\tau < 100 \text{ cm}$

10^{12} Z



$0.01 \text{ cm} < c\tau < 500 \text{ cm}$

10^{13} Z

FCCee summary

- Huge potential of physics from FCC-ee (or CepC)
  - Study Higgs x10 better than HL-LHC
  - EWPO x10-100 better than LEP
  - Direct sensitivity to new physics
    - Indirect sensitivity to NP in the 10's TeV range
  - Large potential for HF studies complementary to LHC-b/Belle II
- Can match right time scale immediately after HL-LHC
- Setup infrastructure for highest energy with FCC-hh
  - Gain time for high field magnet development
  - Same infrastructure could be used for a multi TeV muon collider
- Significant activity on detector concepts is in progress

ESG main scenarios

- 5 basic options for the future being explored by ESG

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

- CERN funding:
  - First 3 scenarios: 10-13% CERN budget in 2025-2045
    - Civil engineering assumed outside of CERN budget
  - 4th scenario: ~20% CERN budget in 2025-2045
  - 5th scenario is within the regular CERN budget
- Last 2 scenarios assume that an e+e- collider is built outside of Europe

Comments under discussion

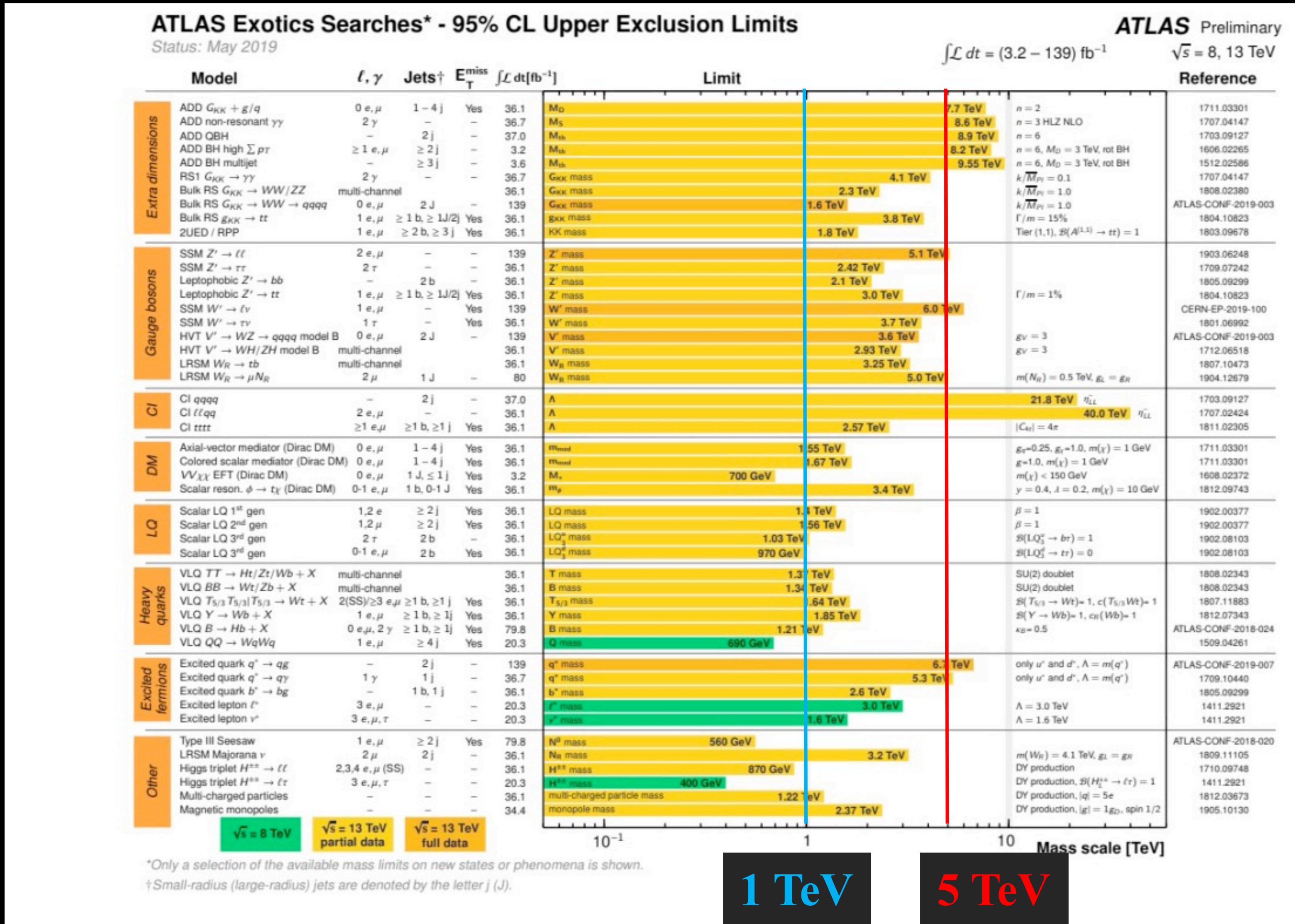
- Agreed by many at INFN:
  - We think that the ESPP update should be based on significant jump in precision and broad exploration potential
  - We believe that, out of the five proposed scenarios, the FCC-all option is the best one in this respect.
  - In the FCC-ee phase electroweak physics will be studied with unprecedented precision not only in the sector related to the newly discovered scalar boson, but also in the Z, W and top quark sectors.
  - The FCC-hh phase would guarantee in the best way direct broad exploration of new territories.

Comments under discussion

- What if Asia builds e+e- first:
  - Option (FCC) robust against any decision taken in other geographical regions.
  - Should ILC (or other e+e- colliders) start construction in the next decade or so, then CERN could directly proceed to FCC-hh, presumably starting with low-field magnets.
  - Otherwise the FCC-ee would be the first step.
  - Moreover FCC is the infrastructure that provides the most flexible tool for our research in the next decades, including the possibility of having at least two detectors operating, which is mandatory in case of discovery or evidence of some anomaly.

ADDITIONAL SLIDES

LHC BSM exclusion



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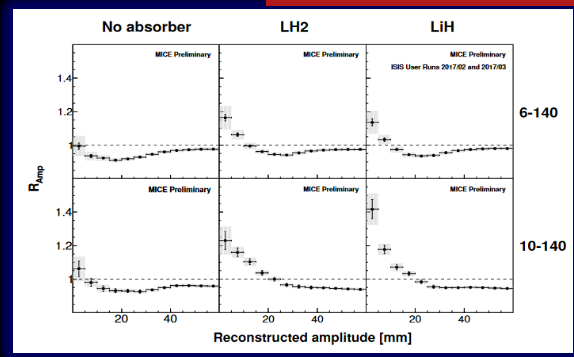
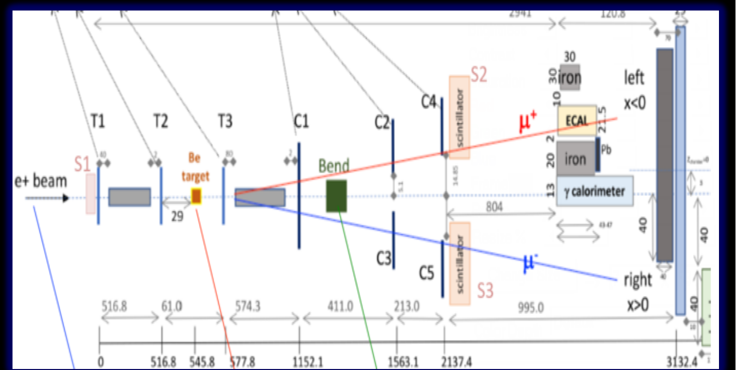
$\mu^+\mu^-$ Collider progress

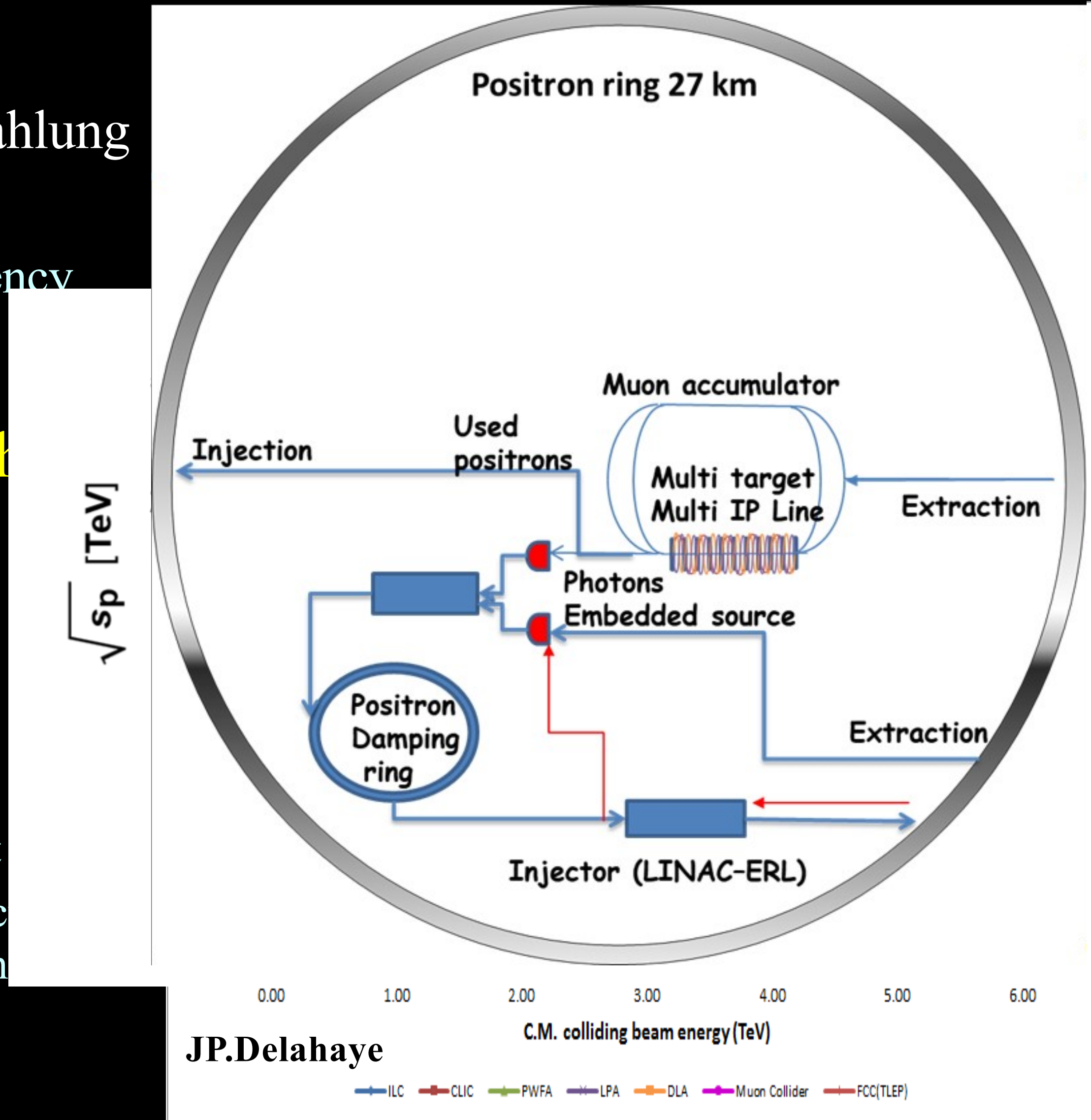
- ❖ Ionization cooling of muons:
  - ➢ Demonstrated in MICE @ RAL
  - ➢ 4D emittance change O(10%)
- ❖ NC RF 50 MV/m in 3 T field
  - ➢ Developed and tested at Fermilab
- ❖ Rapid cycling HTS magnets
  - ➢ Record 12 T/s – built and tested at FNAL
- ❖ First RF acceleration of muons
  - ➢ J-PARC MUSE RFQ 90 KeV
- ❖ US MAP Collaboration → Int'l
- ❖ Low emittance (no cool) concept
  - ➢ 45 GeV $e^+ + e^- \rightarrow \mu^+\mu^-$: CERN fixed target





High Energy $\mu^+\mu^-$ Colliders

- Advantages:
  - μ's do not radiate / no beamstrahlung
    - acceleration in rings
    - low cost & great power efficiency
- ~ x7 energy reach vs pp
- New positron driven approach
- Key to success:
  - Test facility to demonstrate performance implications
    - muon production and 6D cooling,
    - study LEMMA e+-45 GeV + e- at
    - design study of acceleration, detec background and neutrino radiation



Circular *pp* Colliders

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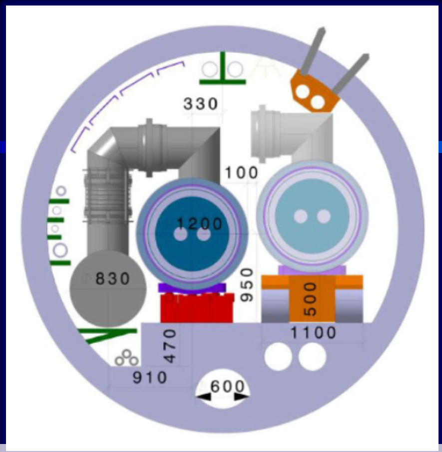
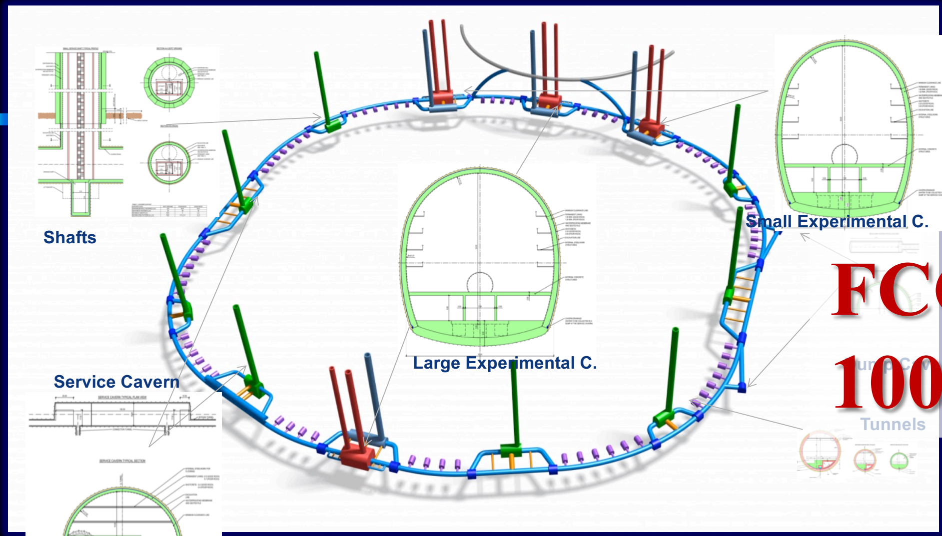
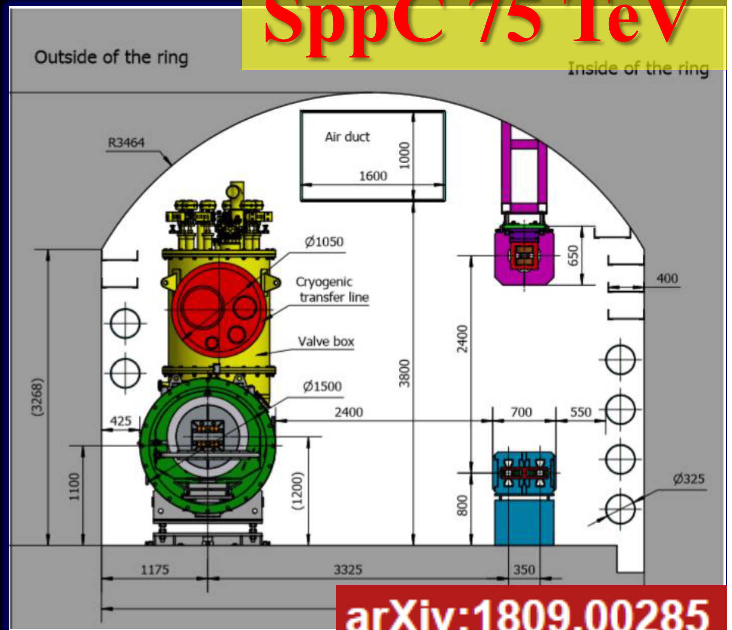


HE-LHC 27 TeV



FCC-hh 100 TeV

SppC 75 TeV



arXiv:1809.00285

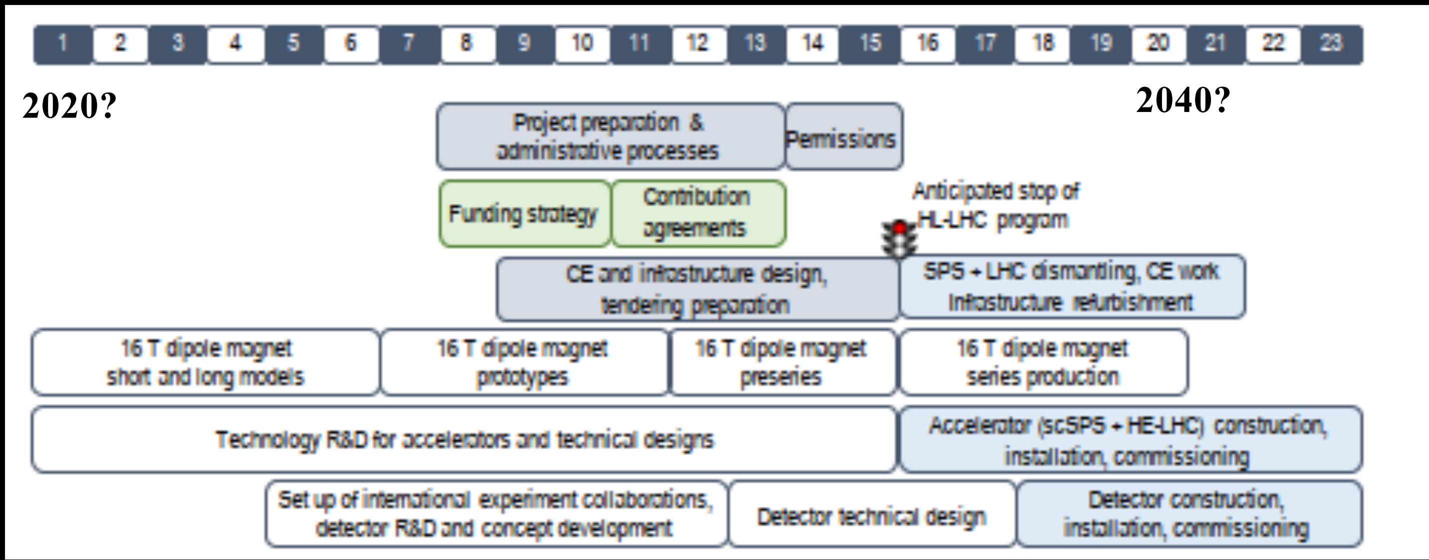
V. SHILTSEV, Granada 2019

- Key facts: HE-LHC / FCC-hh* / SppC*
  - * follow up after e+e- Higgs factories
  - Large tunnel – 27 / 100 / 100 km
  - SC magnets – 16 / 16 / 12 T
  - High Lumi / pileup O(1035) / O(500)
  - Site power (MW) – 200 / 500? / ?
  - Cost (BCHF) – 7.2 / 17.1 / ?
  - Unexplored possibility:
    - FCC with conventional magnets

HE-LHC timeline

Timeline dominated by magnet R&D/Production

L. ROSSI, Granada 2019



Domain	Cost [MCHF]
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil engineering	300
Total cost	7,200

2900 Magnets; 260 for LHC disposal

1 TeV beam from SPS

What if just 12 T magnets

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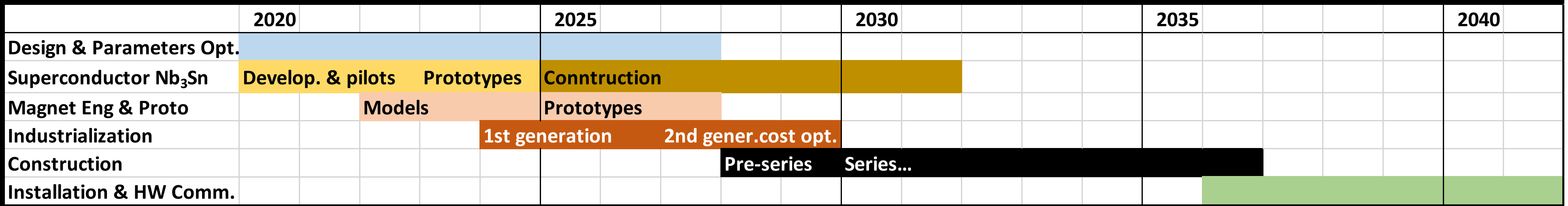
Somewhat faster - Similar cost – 21 TeV



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Cost scaled from 2019 HE-LHC study. If it is of real interest the study could be done

Domain	Cost MCHF	Comments	Wrt HE-LHC
Collider	4500	2400 for Magnets	-500
Injectors	500 ÷ 1100	New optimization TBD	0 ÷ -600
Tech Infr.+C.E.	900 ÷ 1100	Probably is less (< P_{syn})	? (-200?)
TOT	**6100 ÷ 6700**	(LHC2008 was 3400)	Cost should be optimized as upgrade

Other comparisons

- *F1* "Technology Readiness" :

Green	-	TDR
Yellow	-	CDR
Red	-	R&D

- *F2* "Energy Efficiency"

Green	:	100-200 MW
Yellow	:	200-400 MW
Red	:	> 400 MW

- *F3* "Cost" :

Green	:	< LHC
Yellow	:	1-2 x LHC
Red	:	> 2x LHC

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Other comparisons

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Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*

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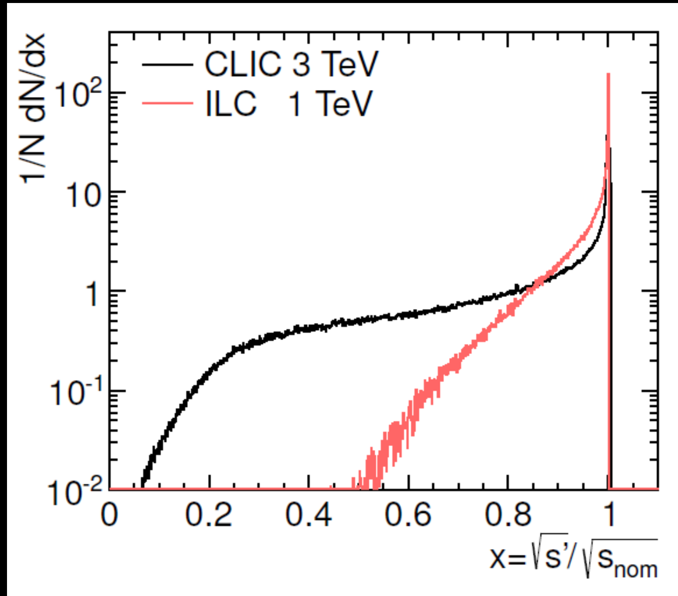
Beamstrahlung

- $\delta_{BS} \propto \left(\frac{E_{CM}}{\sigma_z}\right)\frac{N^2}{\sigma_x{}^2}$

	Unit	ILC		CLIC
$\sqrt{s}$	GeV	500	1000	3000
$\mathscr{L}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5	4.3	5.9
Υ_{av}		0.15	0.20	4.9
δ_B	%	3.7	10	28
n_γ		1.7	2.0	2.1



- ILC 240 ~ 1.6%

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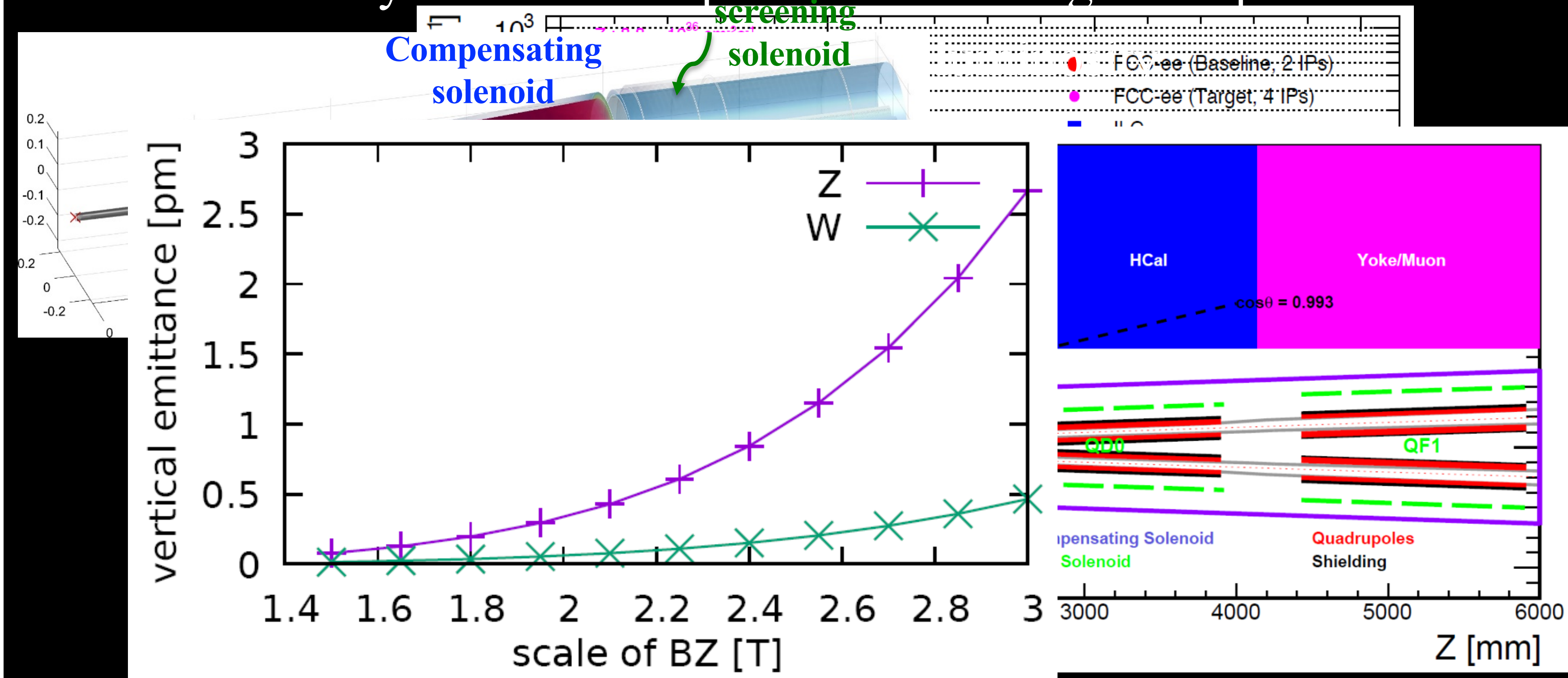
Luminosity issues

❖ Physics reach driven by luminosity

- ➢ Success driven by luminosity!
- ➢ Luminosity relies on complex/sensitive magnetic optics



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