Future Circular e+e- Colliders

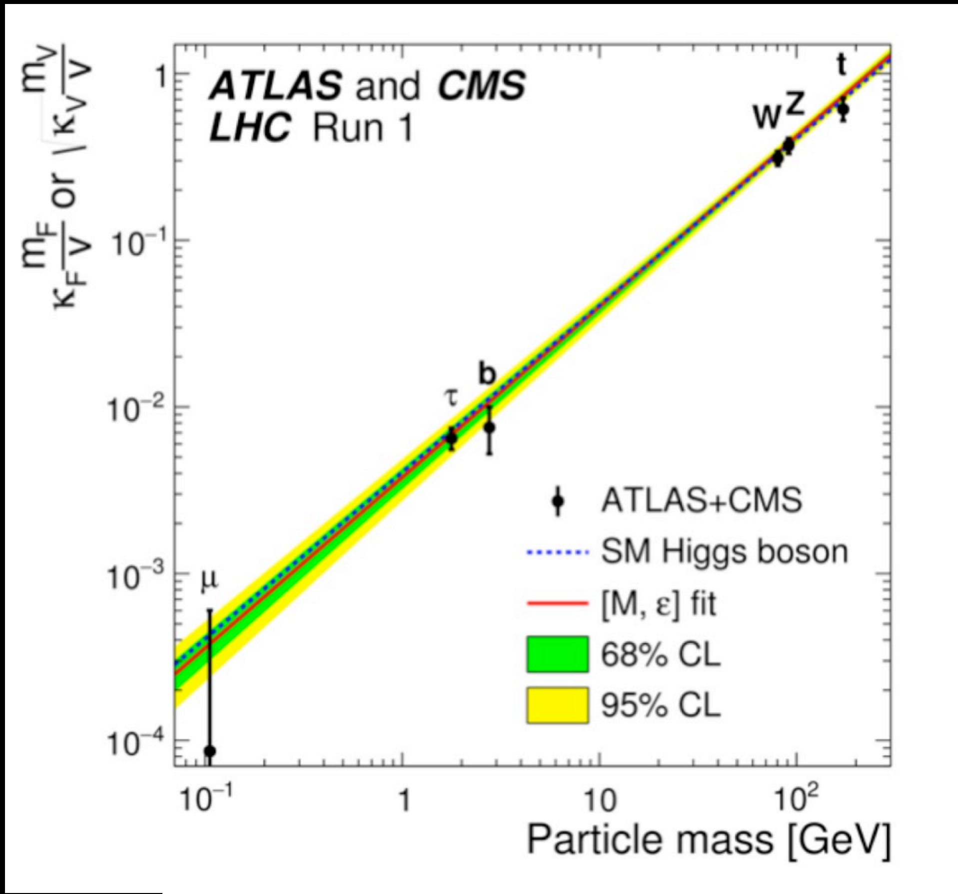
F. Bedeschi
NEWS General Meeting, Pisa
November 2019

Outline

- Current physics landscape
- Current directions
- FCC-ee
  - Key measurements
  - Current status
- Conclusions

Current physics landscape

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



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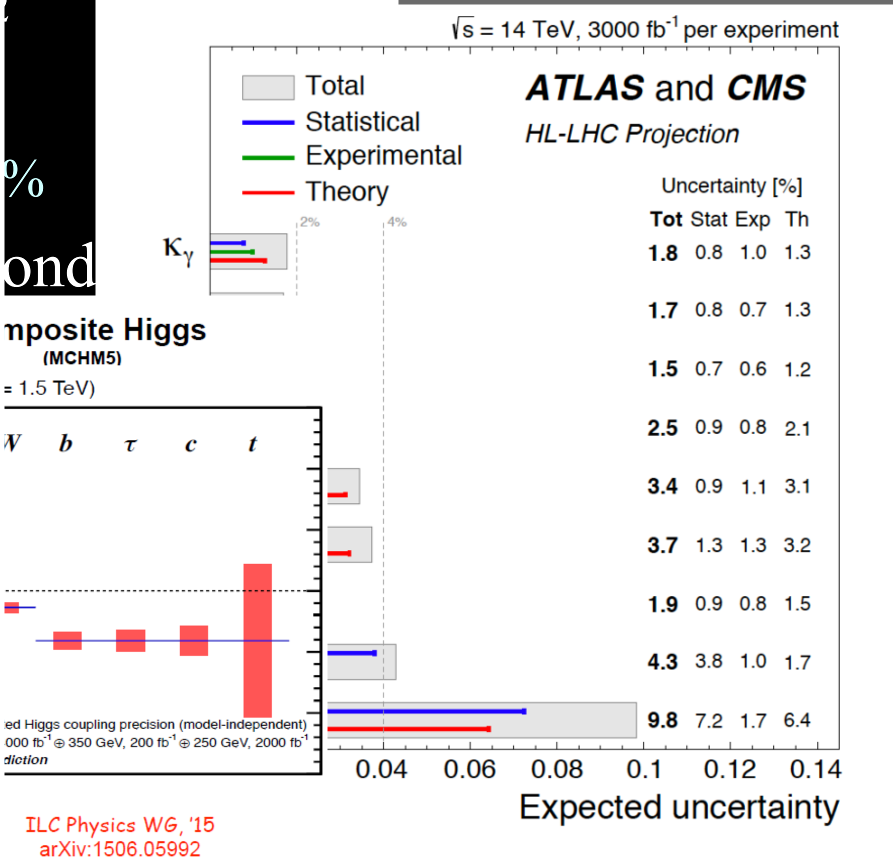

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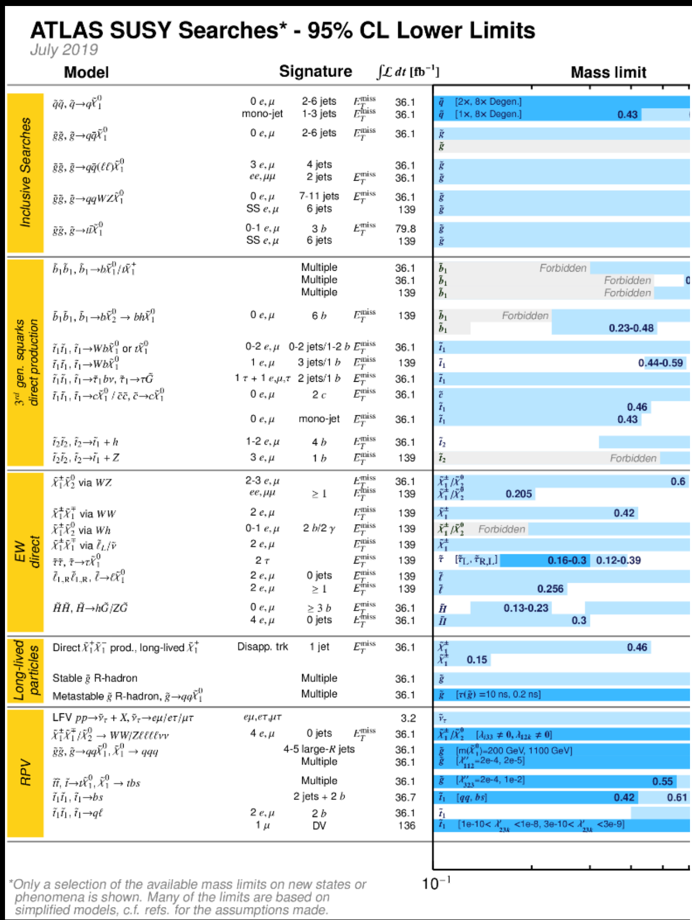
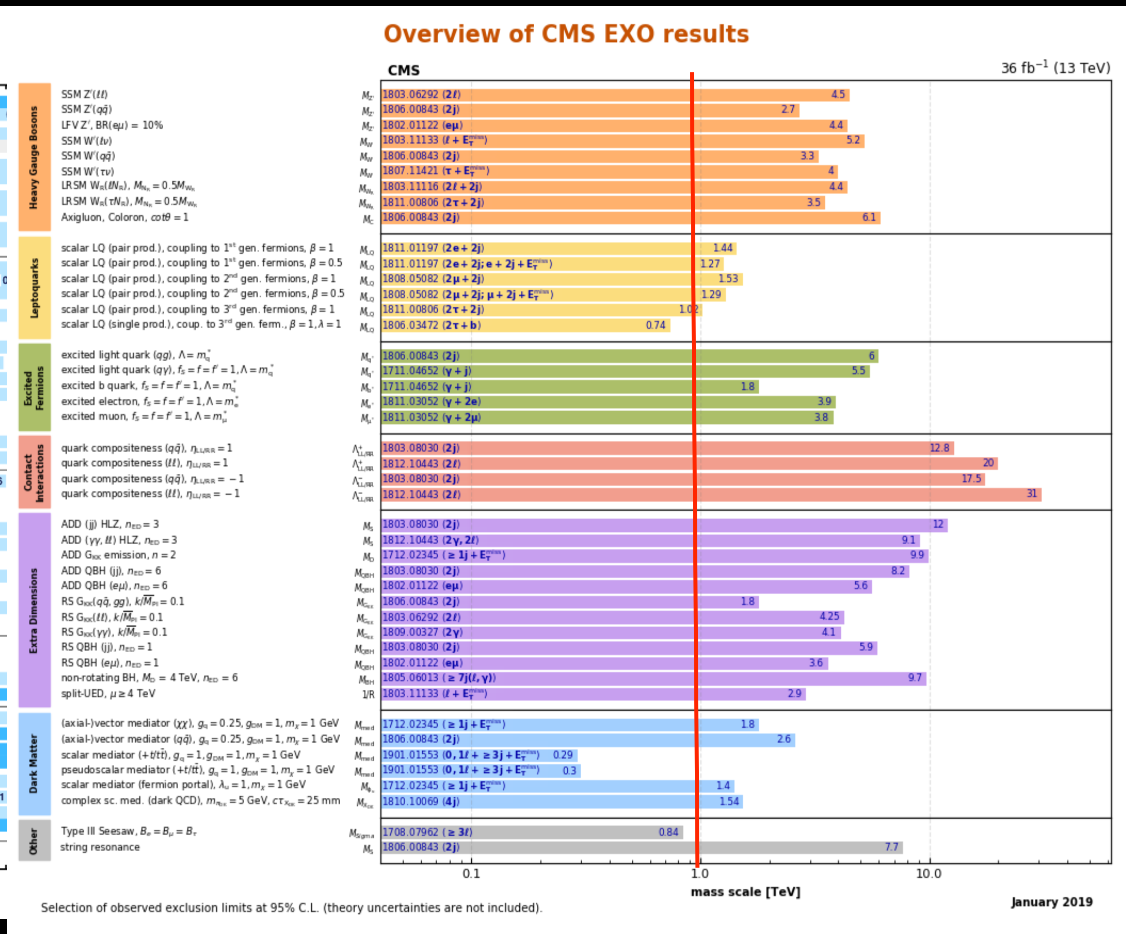
Current physics landscape

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





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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**.

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Higgs factories

- *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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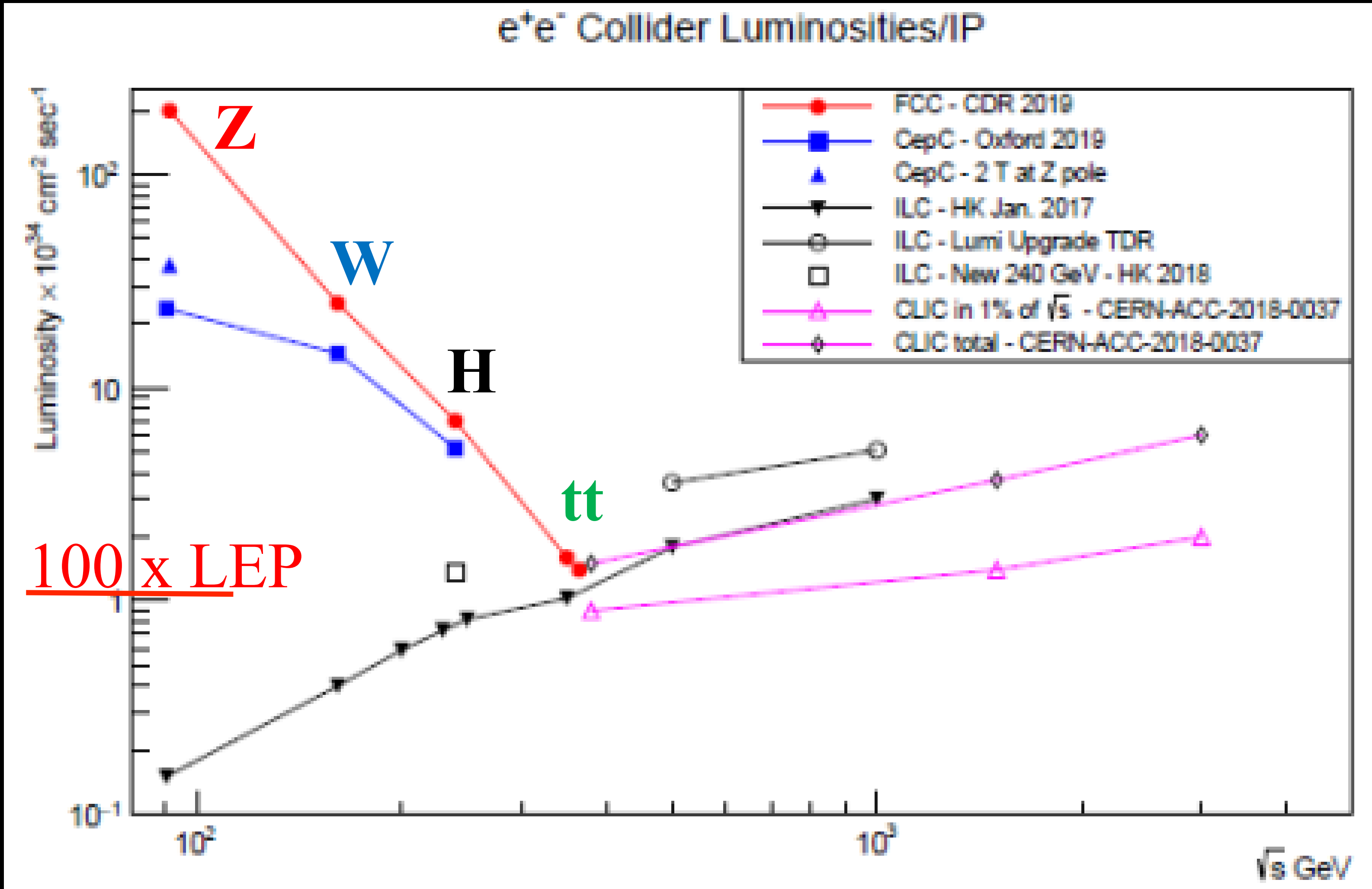
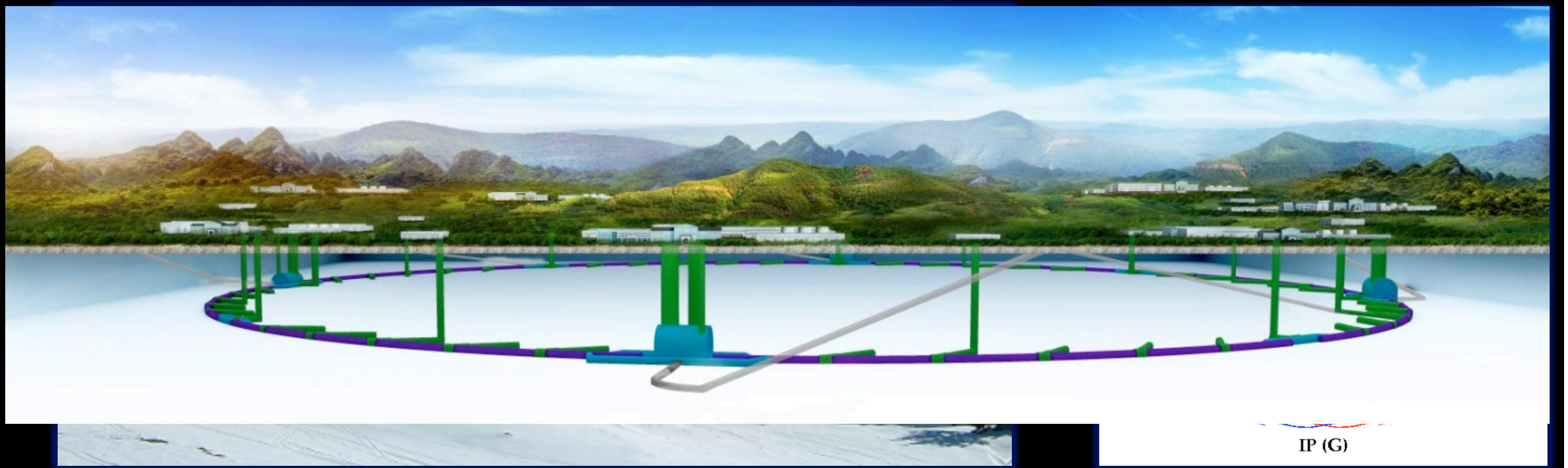
Luminosity comparison

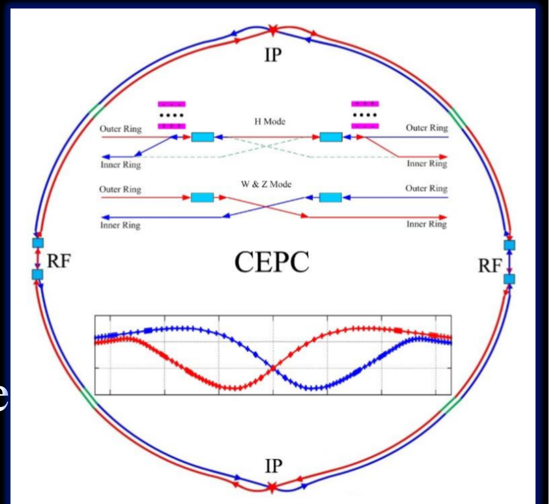


Circular e+e- Higgs Factories



❖ 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 7.4 (tunnel)+ 3.1 BCHF (machine (+1.1BCHF for tt)
  - (“< 6BCHF” cited in the CepC CDR)



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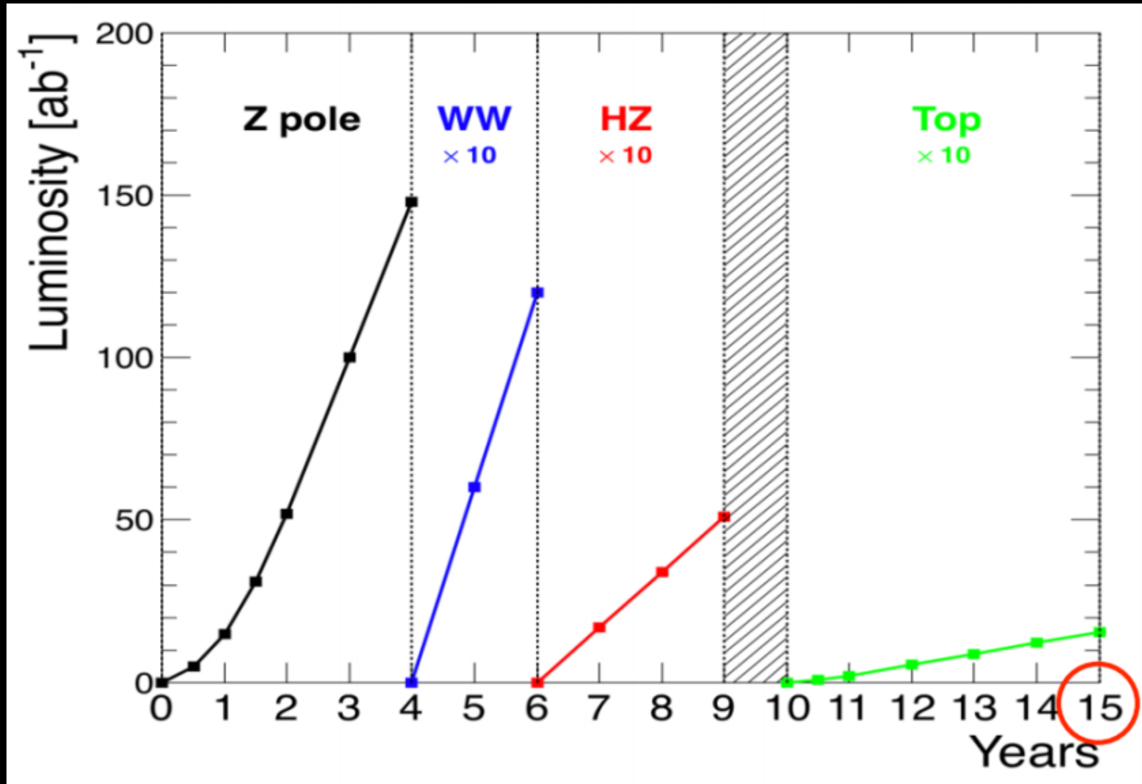
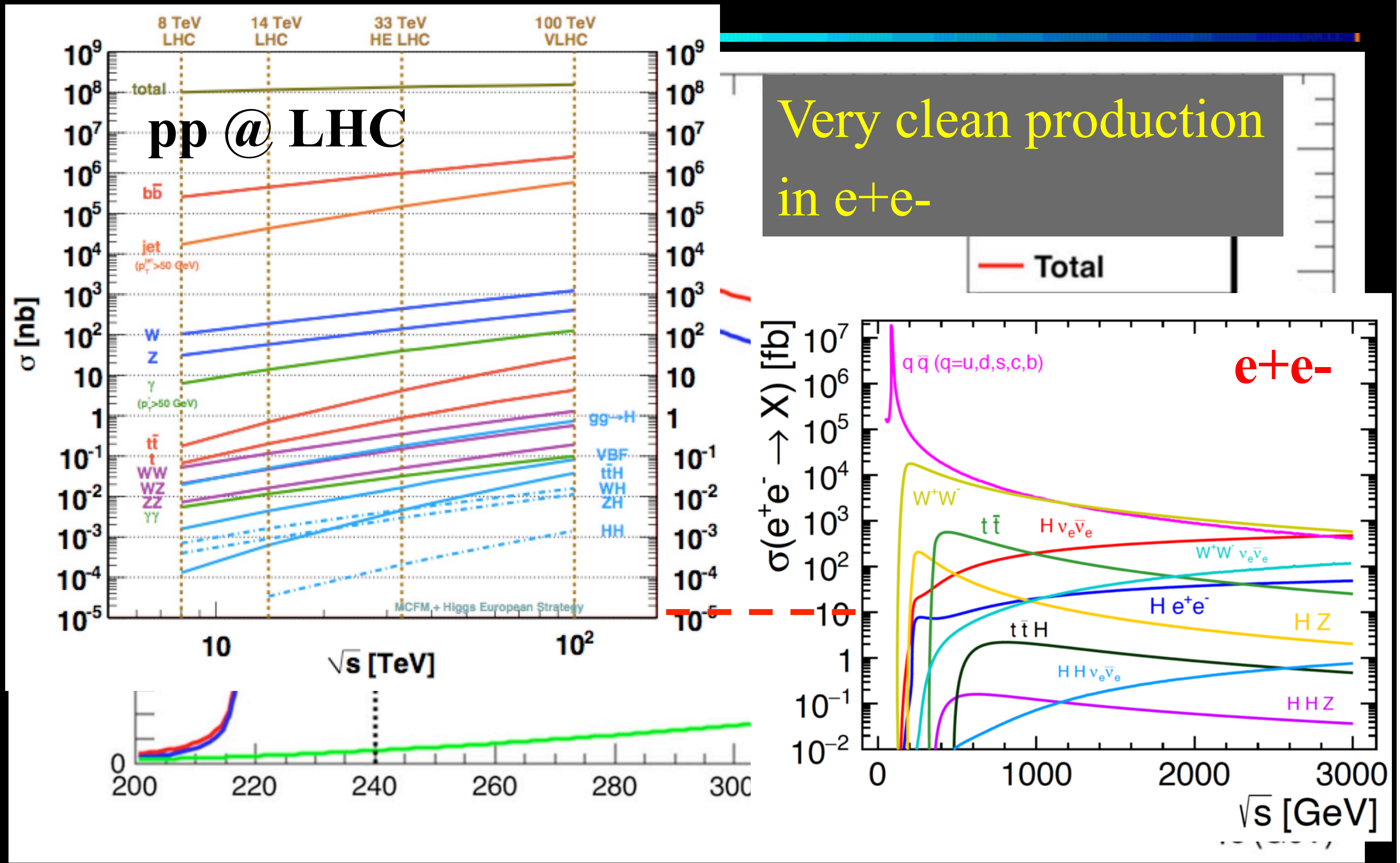
Physics at FCC-ee

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



Higgs production

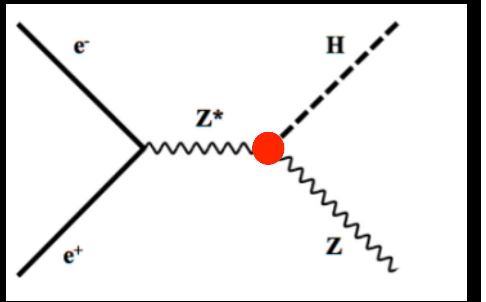


Very clean production in e+e-

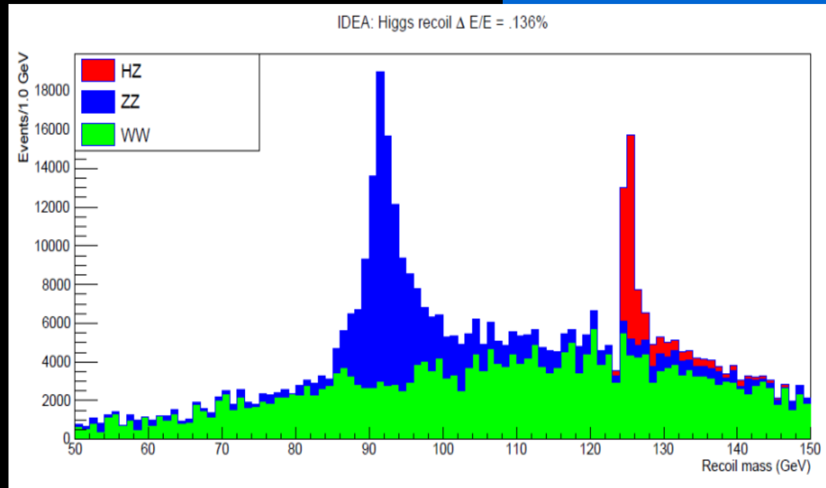
Higgs total width

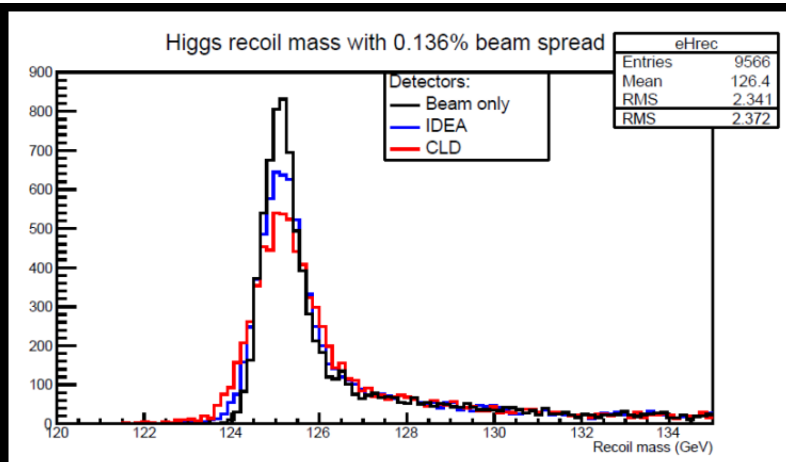
$L = 5\ ab^{-1}$

- Higgs recoil provides model independent measurement of coupling to Z
  - $\sigma(HZ) \propto g^2_{HZ}$



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





- Total width combining with decays in specific channels

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

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 $\Gamma_H = \dfrac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$ 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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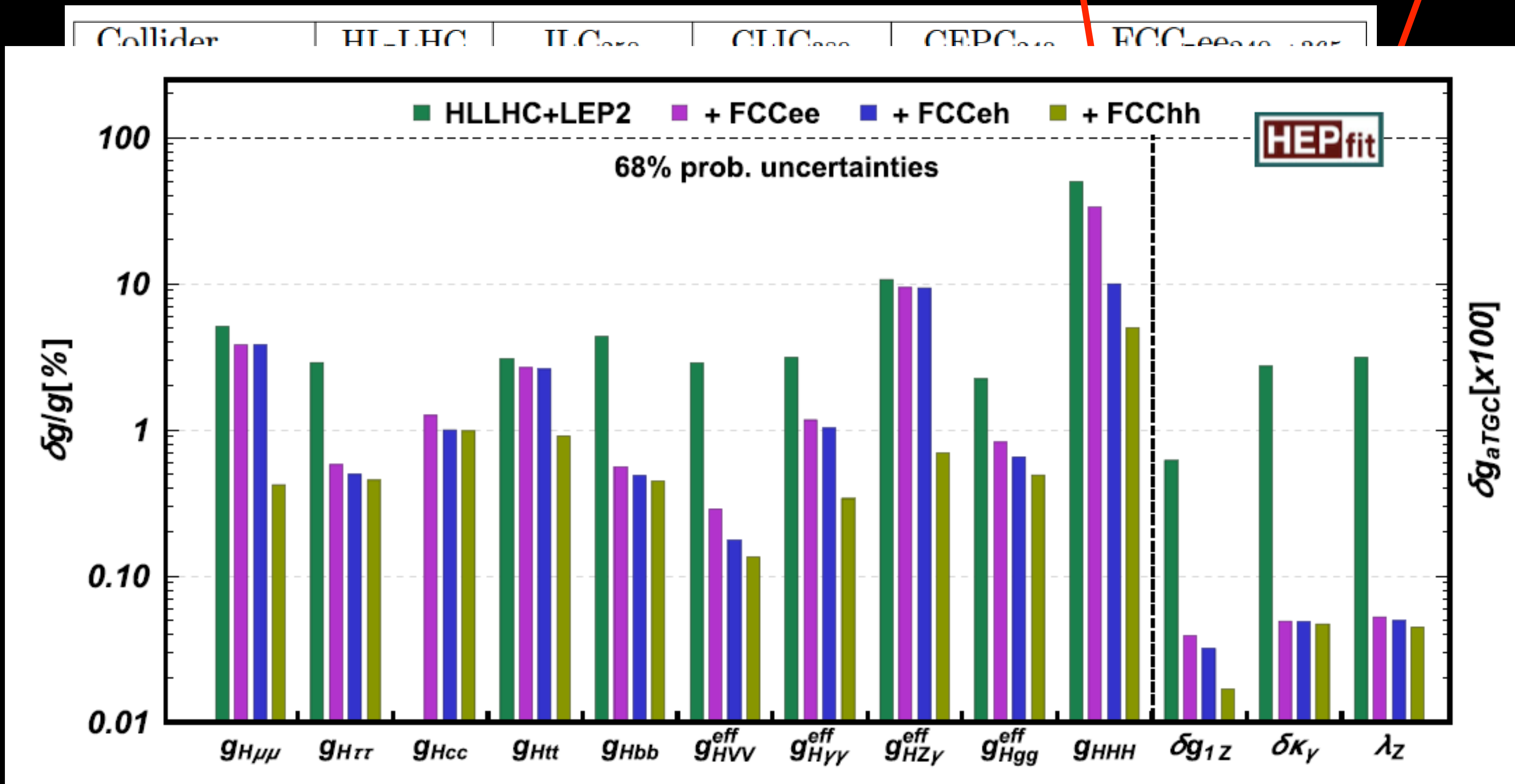
Higgs coupling fits

❖ Results limited only by statistics

κ

EFT



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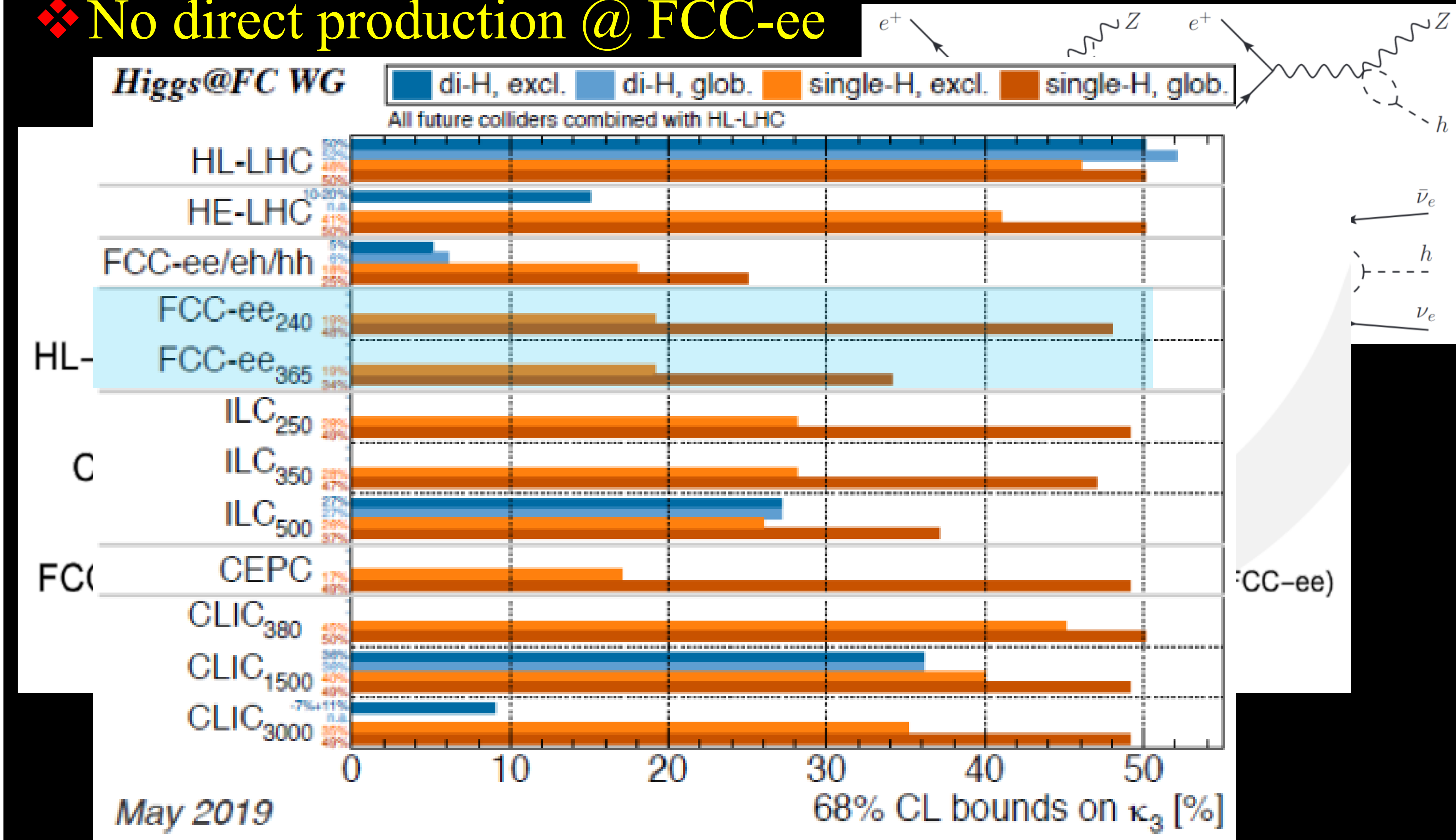
Triple Higgs

❖ No direct production @ FCC-ee



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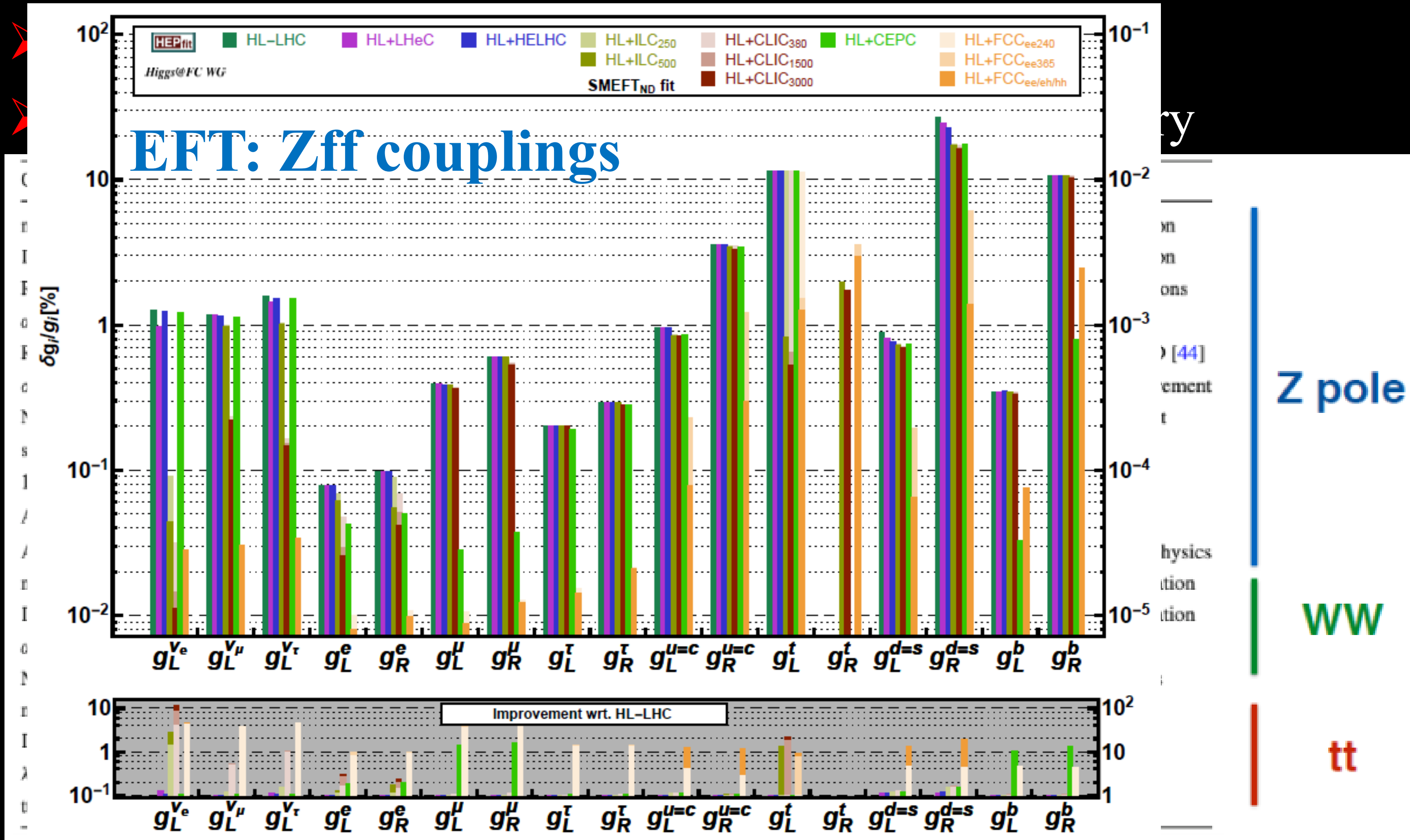
EWK

- Outstanding program of precision EWK measurements



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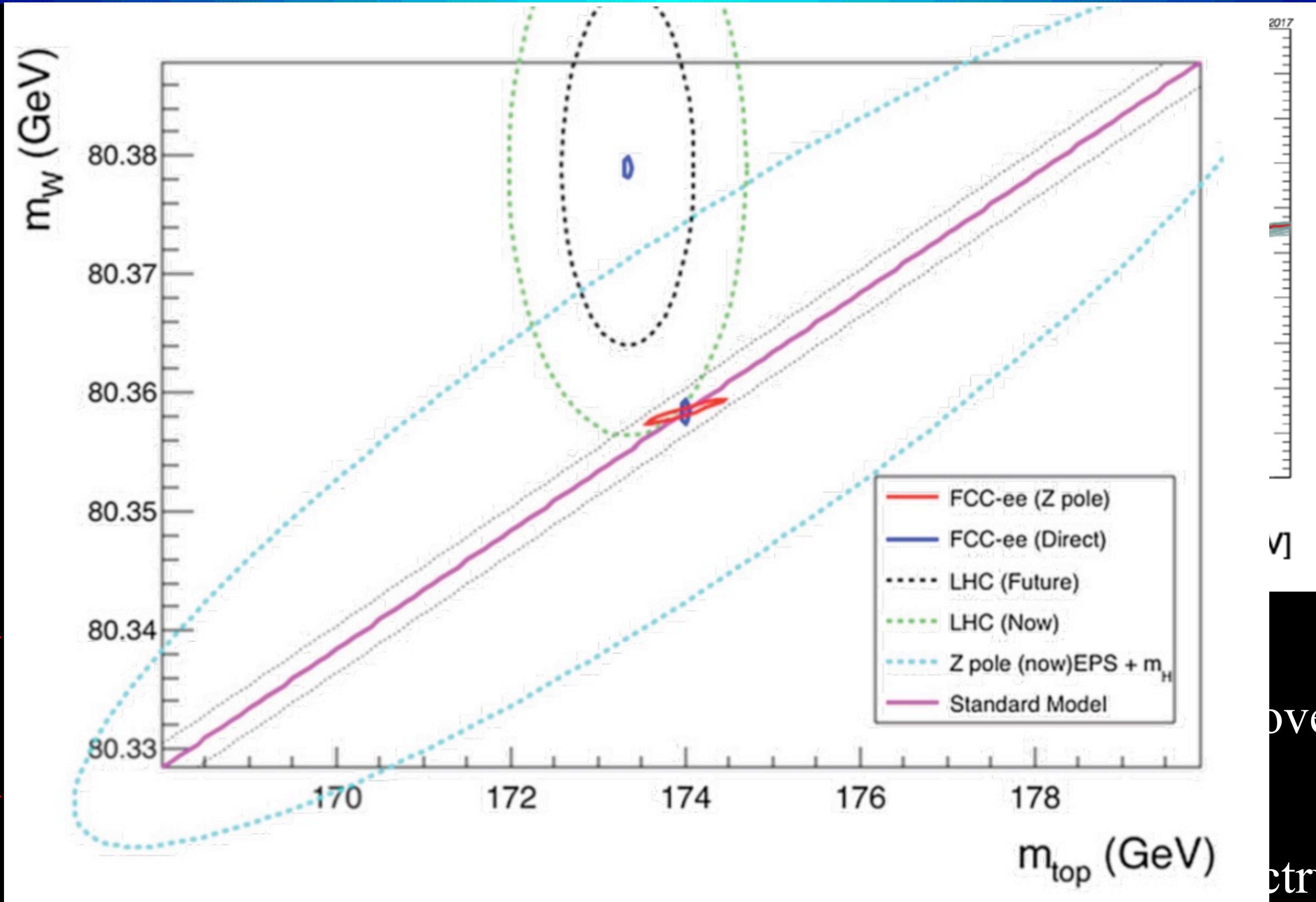
EWK examples



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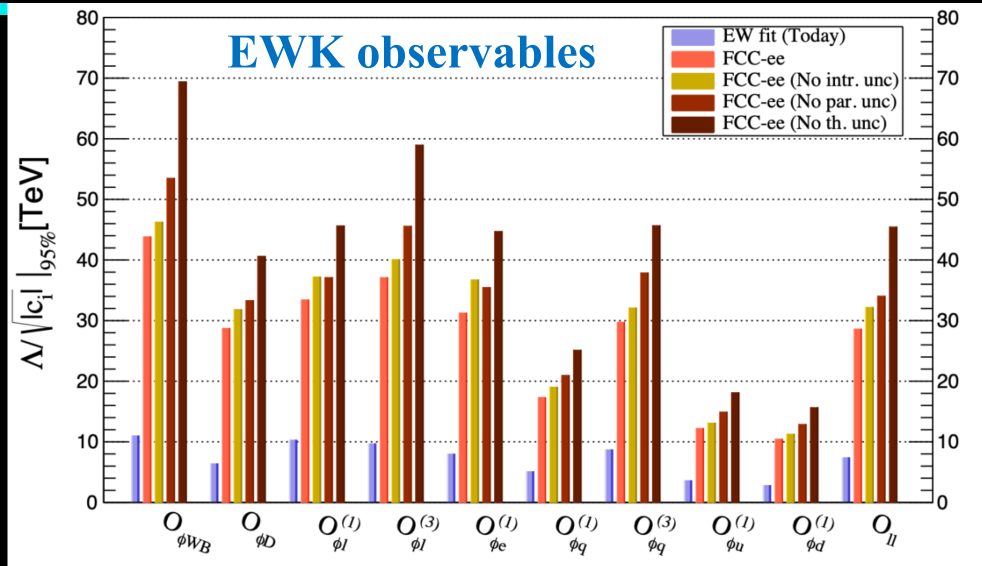
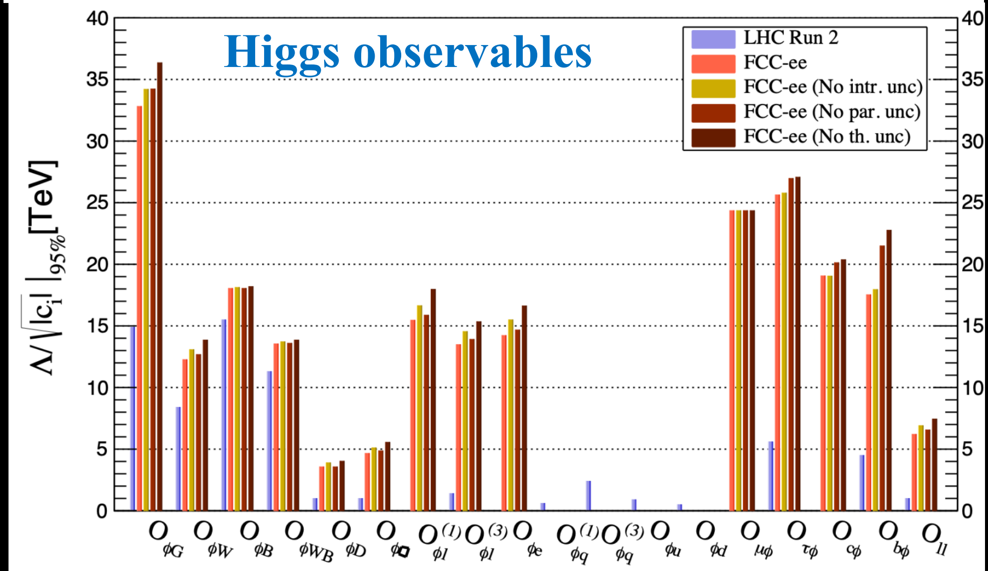
ctrum

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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Heavy flavors

- Large heavy flavor production at Z pole

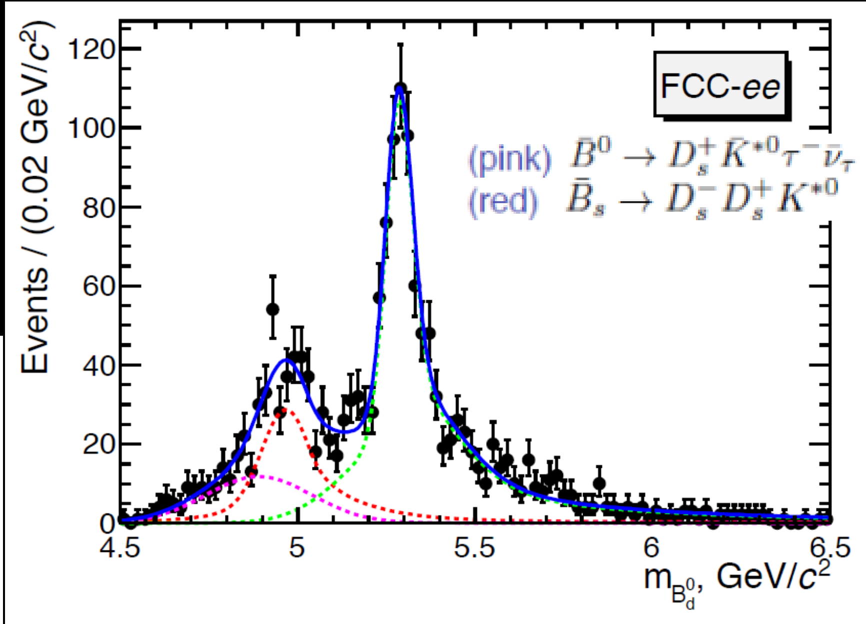
Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

  - Very clean, well separated, pairs

- Example:
  - Lepton universality

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

Decay mode	$B^0 \rightarrow K^*(892)e^+e^-$	$B^0 \rightarrow K^*(892)\tau^+\tau^-$	$B_s(B^0) \rightarrow \mu^+\mu^-$
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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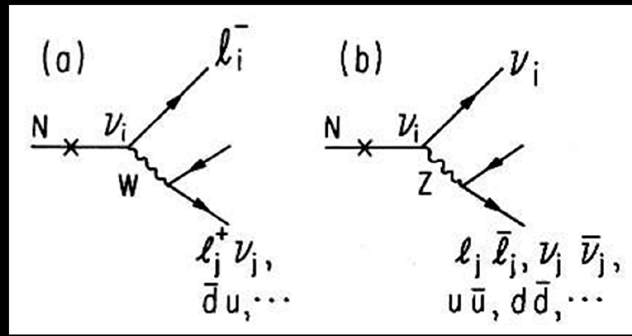
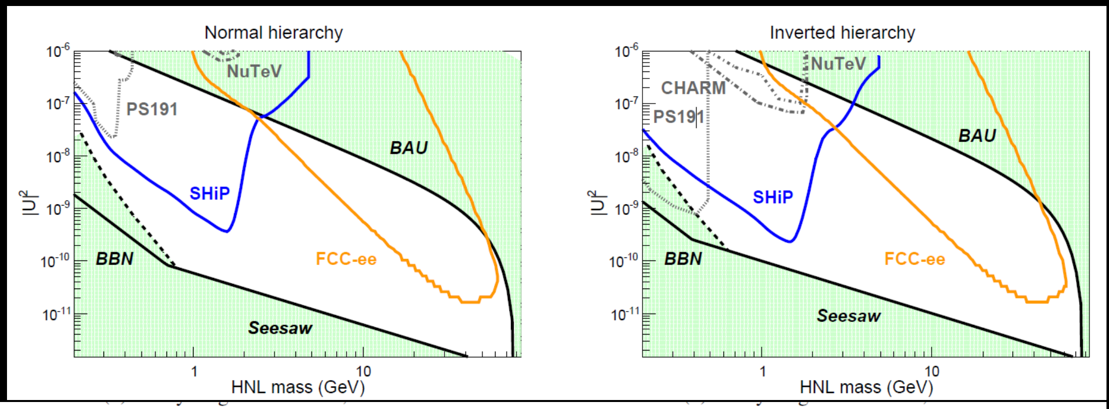
Direct NP search example: HNL

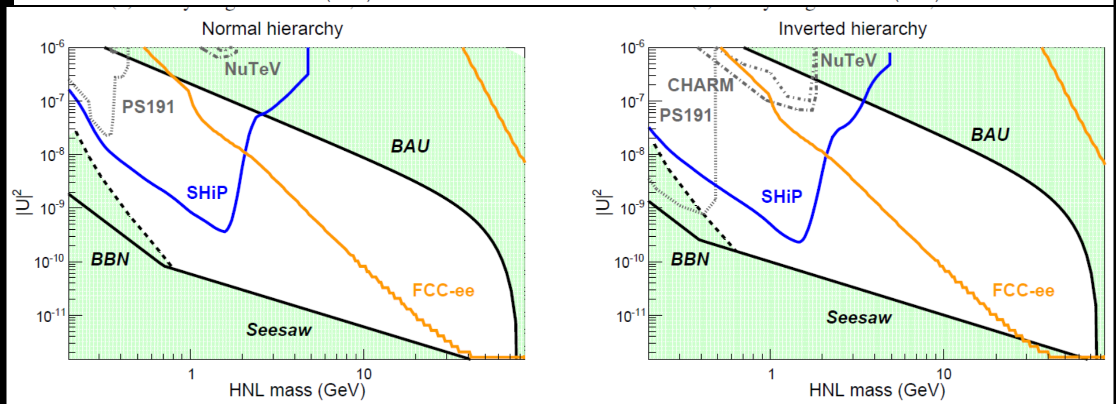
- HNL mix with active neutrino's
  - Fully reconstructable decay with W
  - Small mixing → long lifetime





10 cm < cτ < 100 cm

10^{12} Z



0.01 cm < cτ < 500 cm

10^{13} Z

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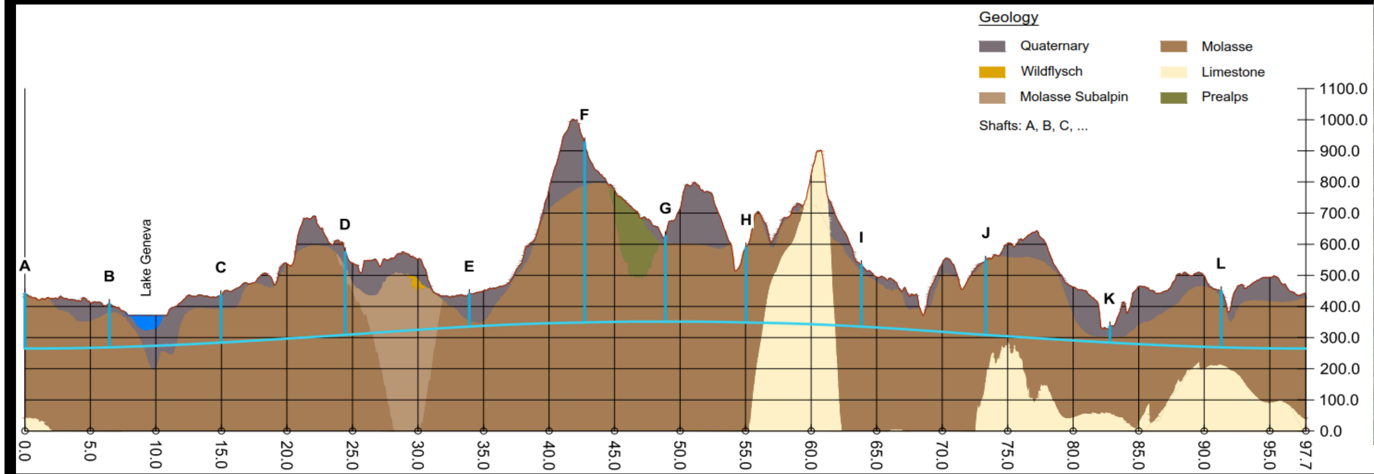
The planned machines

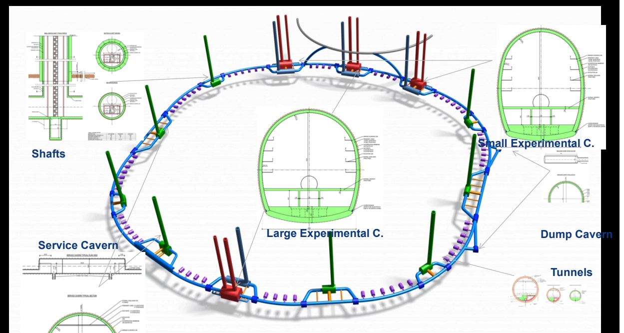
FCC integrated program
inspired by succesful LEP – LHC programs at CERN

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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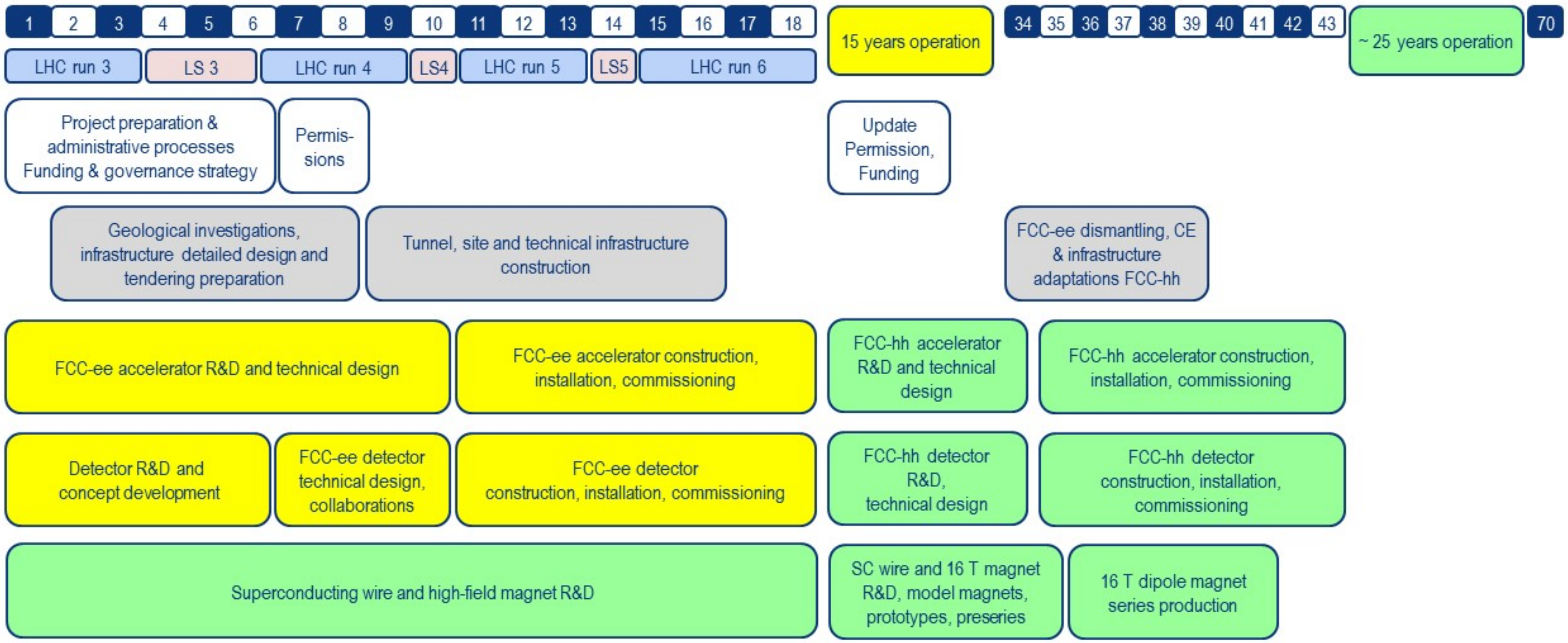
FCC-ee + FCC-hh



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

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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 Site Selections

Huanghe Company particitated

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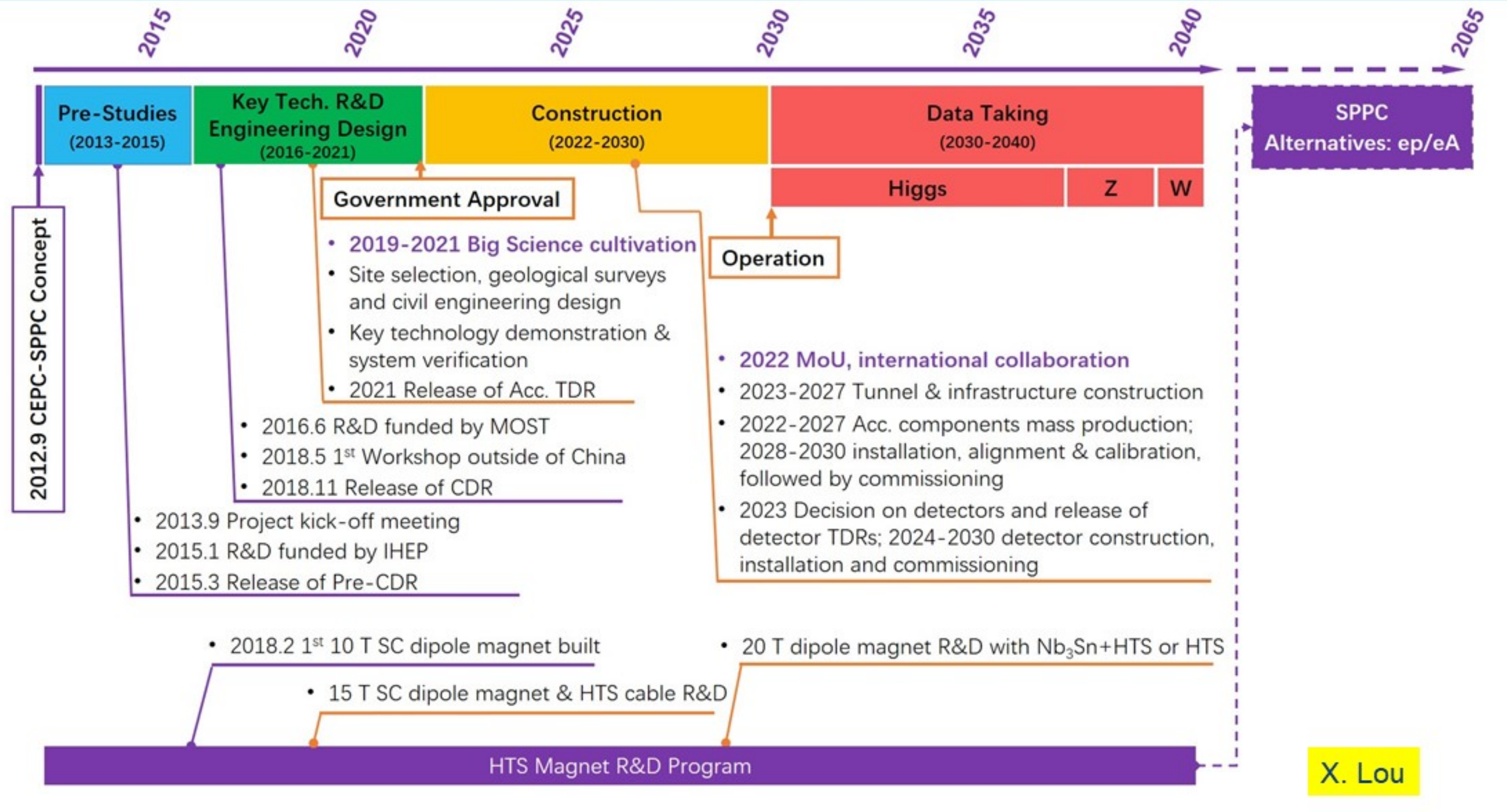
CEPC



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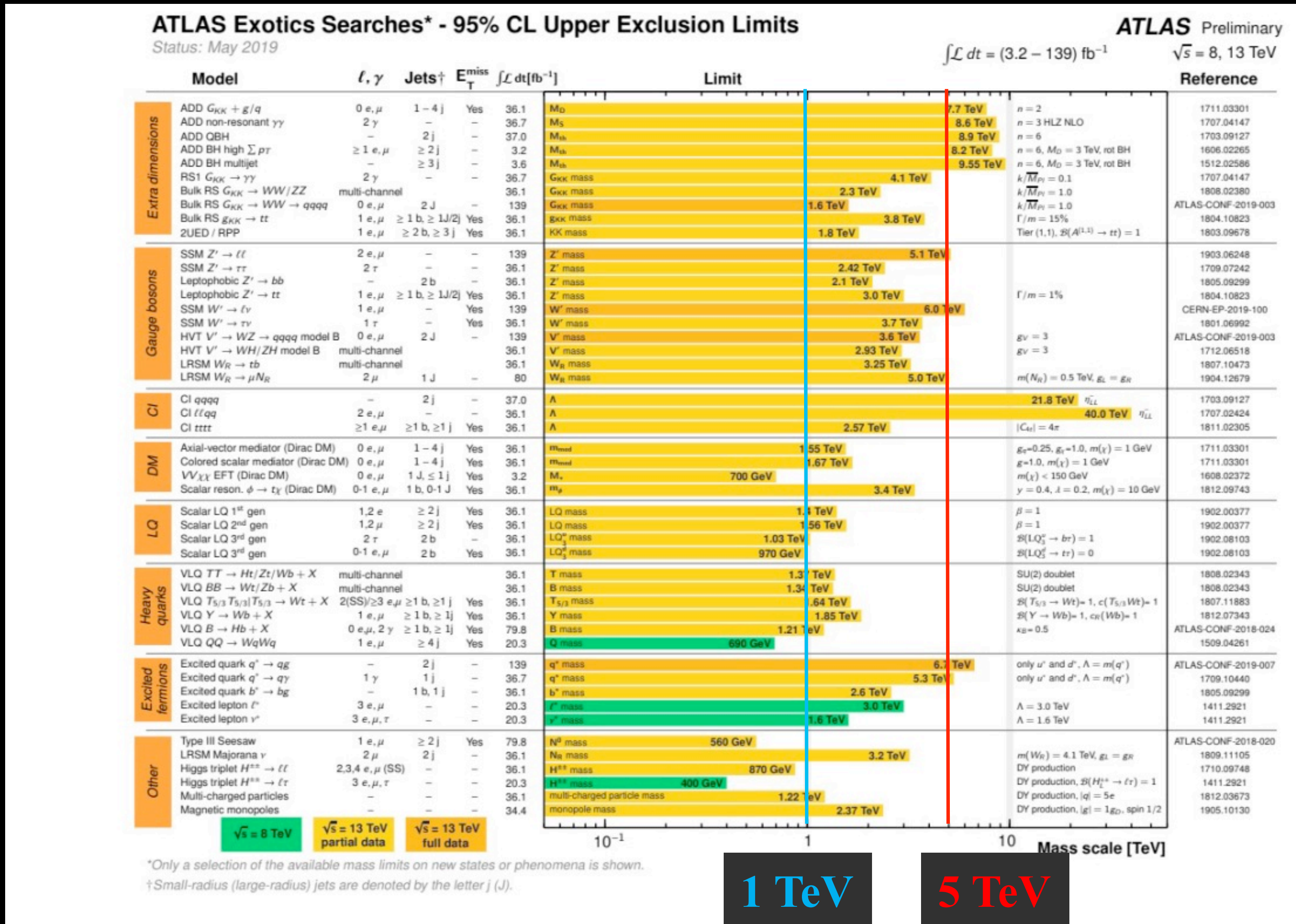
Conclusions

- **Let's do it!**

ADDITIONAL SLIDES

LHC BSM exclusion



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Higgs coupling comparison

- Improvement factors relative to HL-LHC

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
$g^{\rm eff}_{HZZ}$	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
$g^{\rm eff}_{HWW}$	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{\rm eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{\rm eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
$g^{\rm eff}_{Hgg}$	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
$g^{\rm eff}_{Htt}$	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
$g^{\rm eff}_{Hcc}$	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
$g^{\rm eff}_{Hbb}$	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{\rm eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{\rm eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_{\gamma}[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

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e^+e^- Ring Higgs Factories

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- 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, mb 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

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

$$\mathscr{L}\gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)} \left[\rho \frac{\xi_y P_T}{\beta_y^*} H(\beta_y^*, \sigma_z) \right]$$

- Luminosity
  - Determined by bend radius ρ, beam-beam parameter ξ_y, beta function at the IP β_y^* and power
  - Beam life ~18 min requires full energy booster ring

Linear Colliders *e+e-* Higgs Factories

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- 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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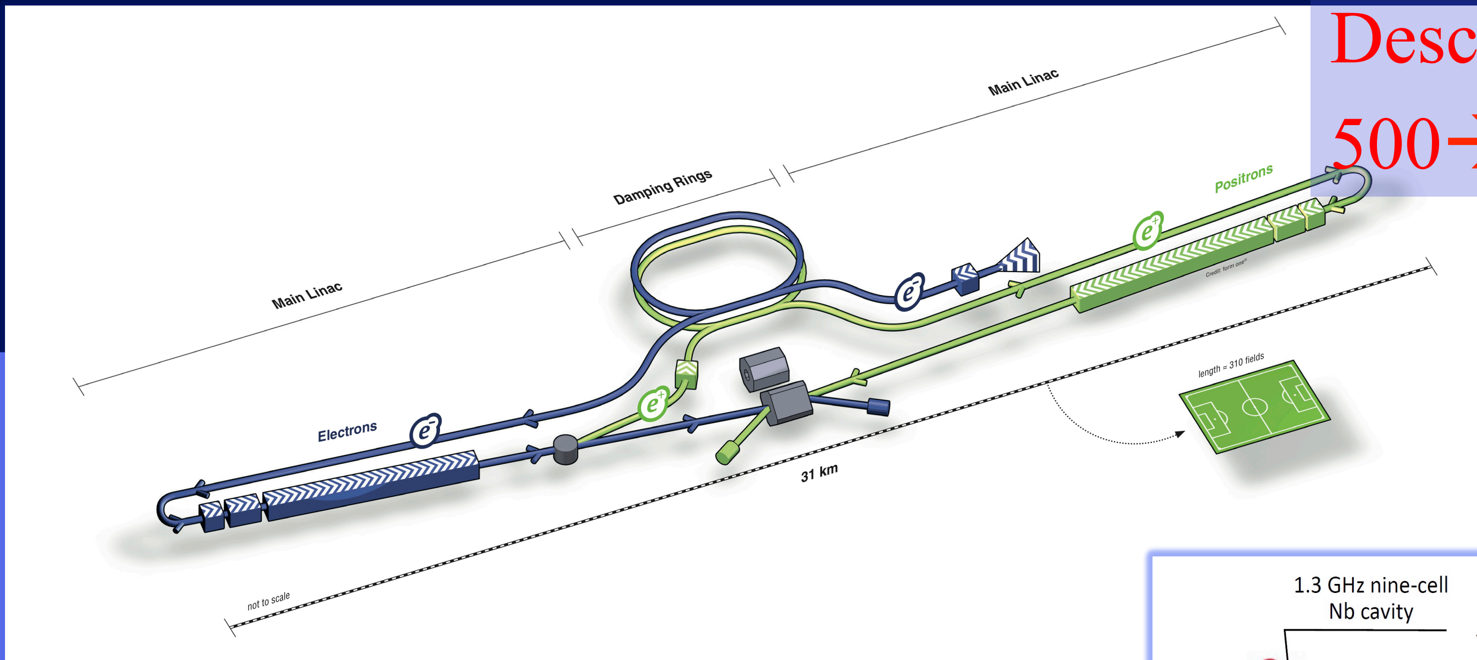
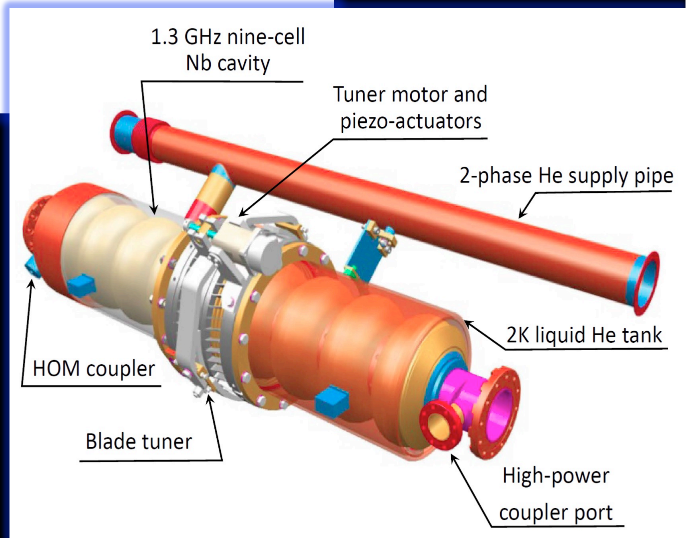
International Linear Collider



Descoped
500→250 GeV

- 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€



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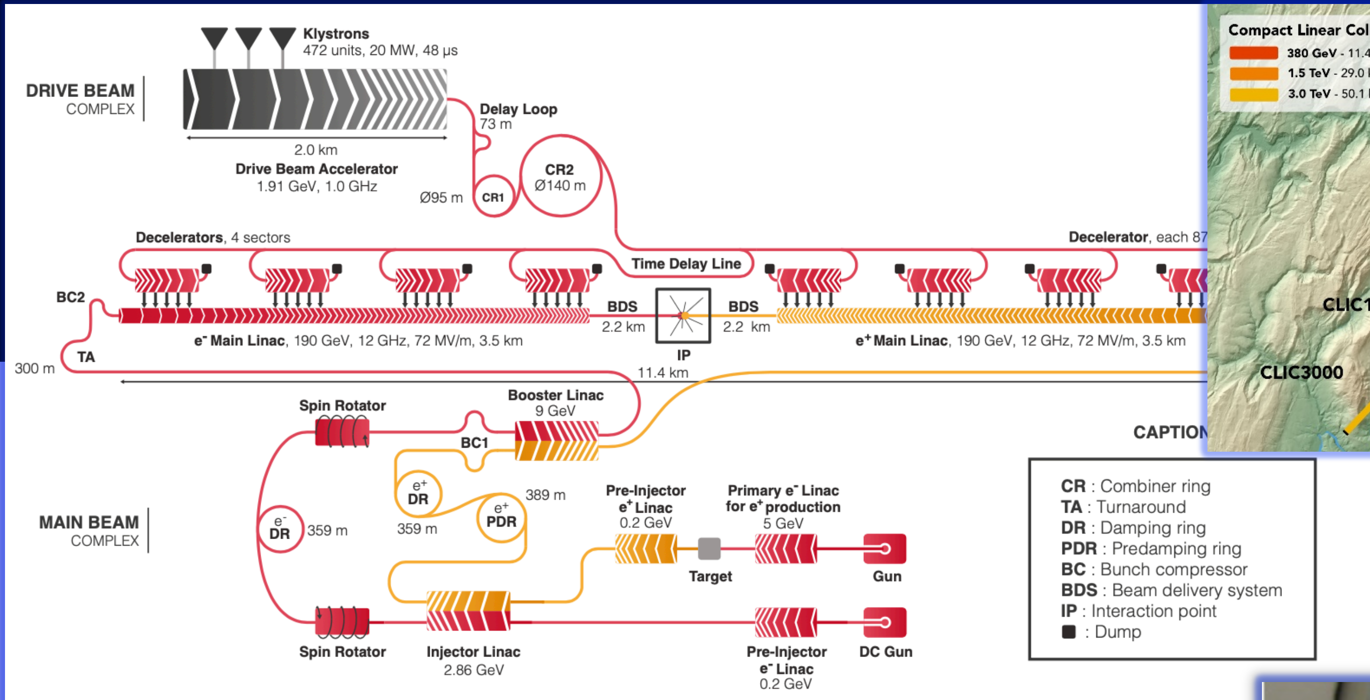
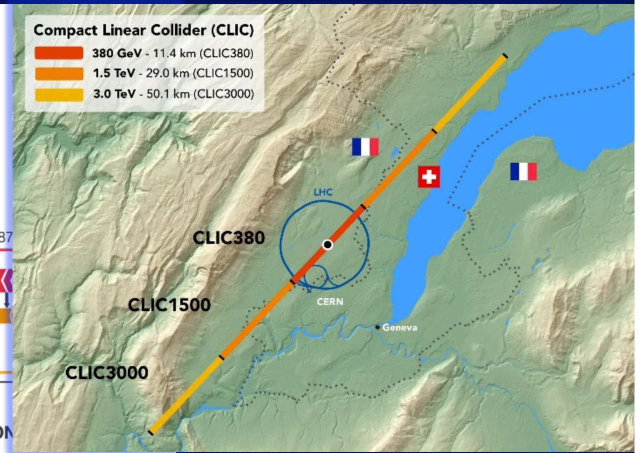
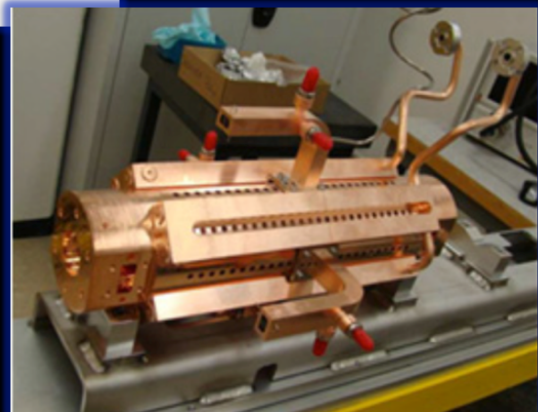
Compact LInear Collider





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



Challenges of Linear Colliders Higgs Factories

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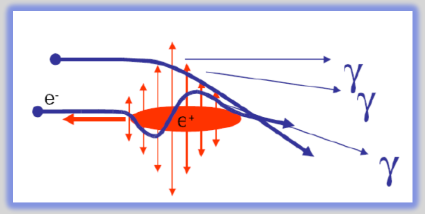
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

❖ Luminosity spectrum (Physics)



- $\delta E/E \sim 1.5\%$ in ILC
- Grows with E: 40% of CLIC lumi 1% off $\sqrt{s}$

❖ Beam Current (RF power limited, beam stability)

- Challenging $e+$ production (two schemes)
- CLIC high-current drive beam bunched at 12 GHz

❖ Beam Quality (Many systems)

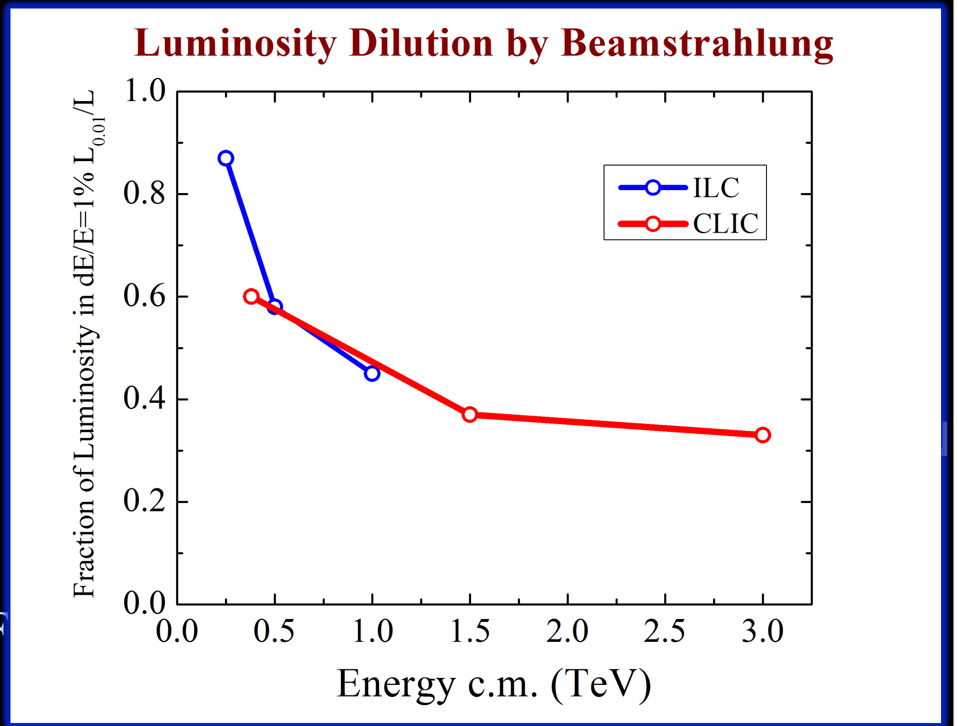
- Record small DR emittances
- 0.1 μm BPMs
- IP beam sizes

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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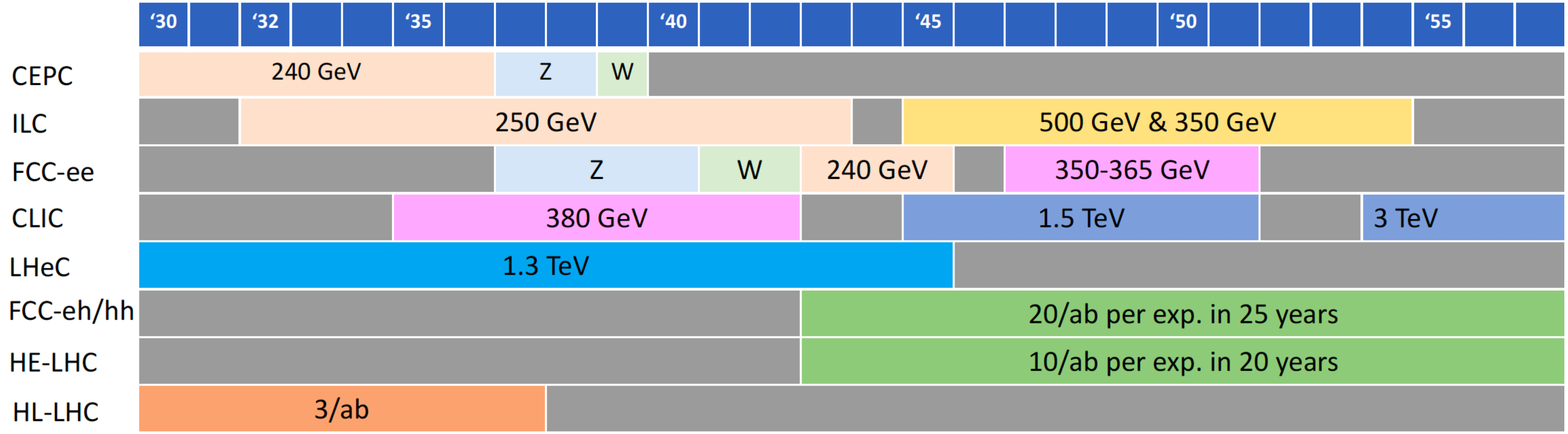
Schedules



Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)

- Very optimistic!!!

D. SCHULTE, Granada 2019

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

V. SHILTSEV, Granada 2019

Other comparisons

INFN Istituto Nazionale di Fisica Nucleare

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

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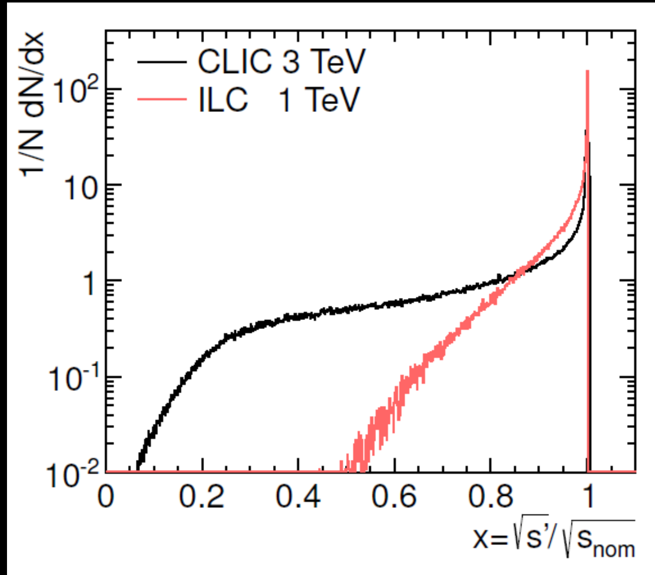
Comparison table

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Beamstrahlung

- δBS ? $(ECM/\sigma z)N2/\sigma x2$

	Unit	ILC		CLIC
$\sqrt{s}$	GeV	500	1000	3000
$\mathscr{L}$	10^{34} cm^{-2}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%