Future Circular e+e- Colliders

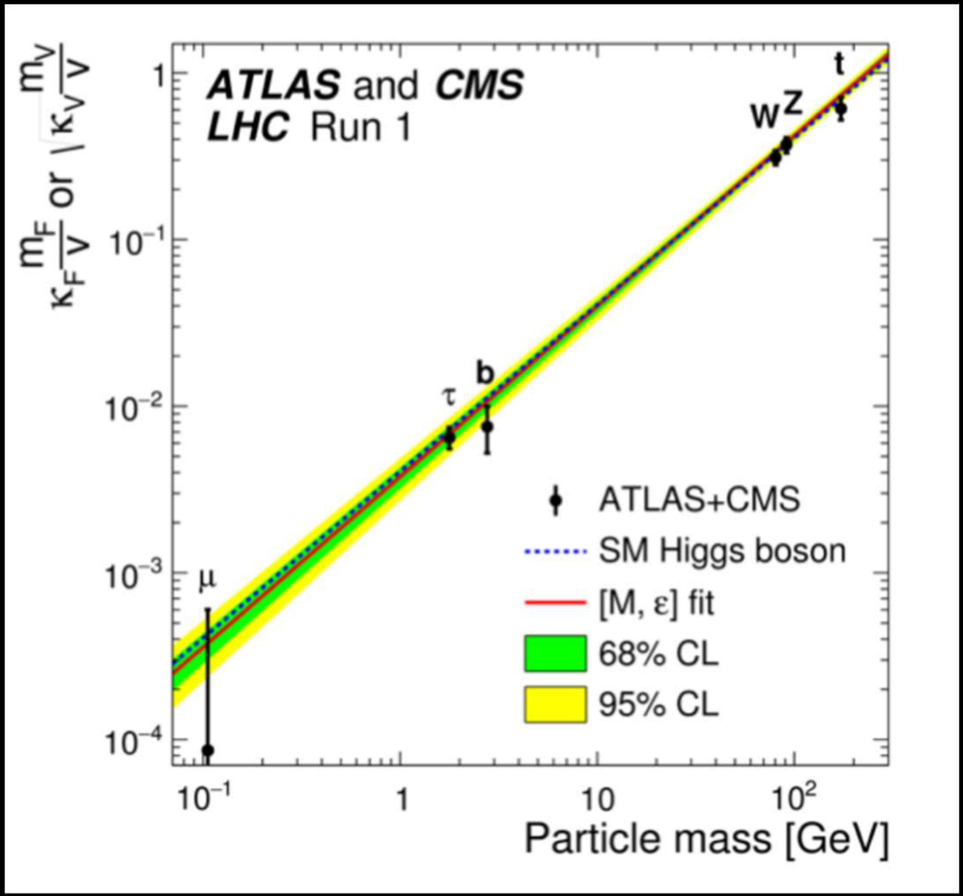
F. Bedeschi
LFC19, Trento
Settembre 2019

Outline

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

Current physics landscape

- Higgs properties SM-like.



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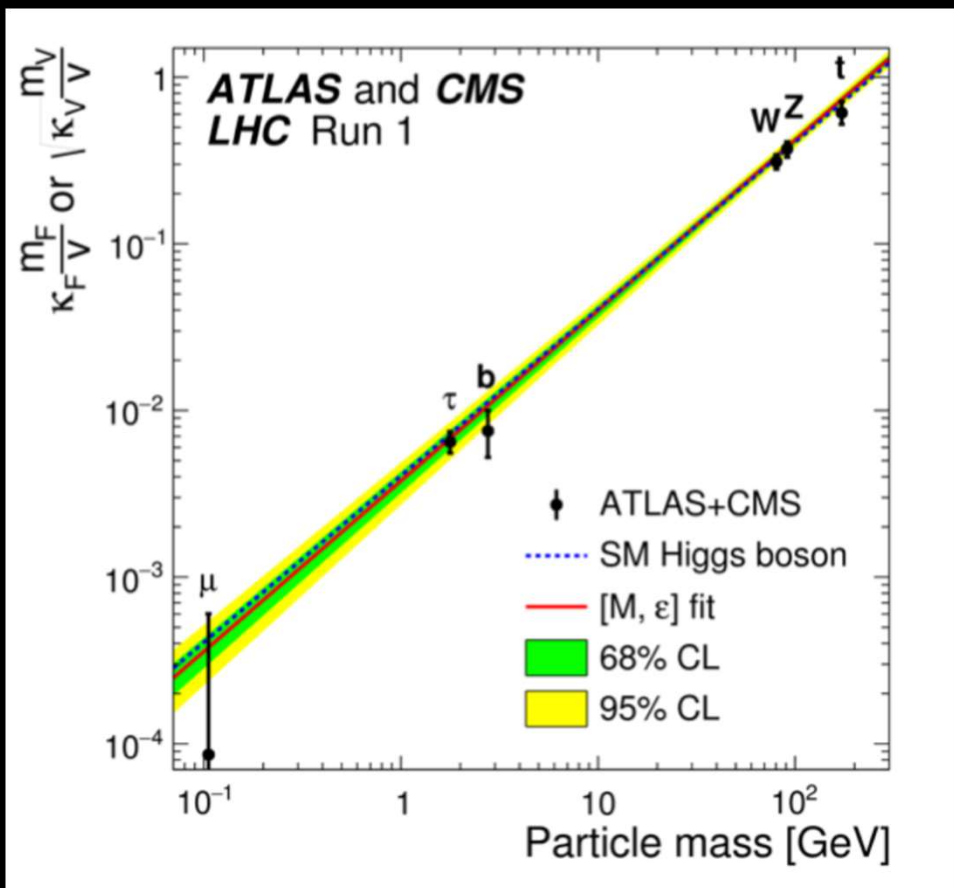
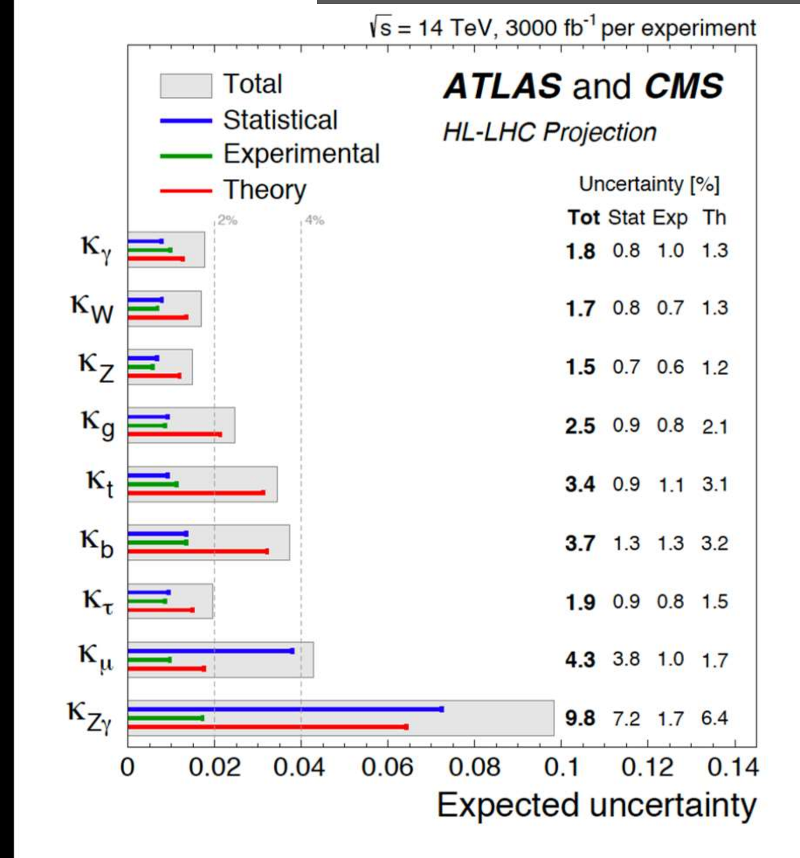


Granada 2019



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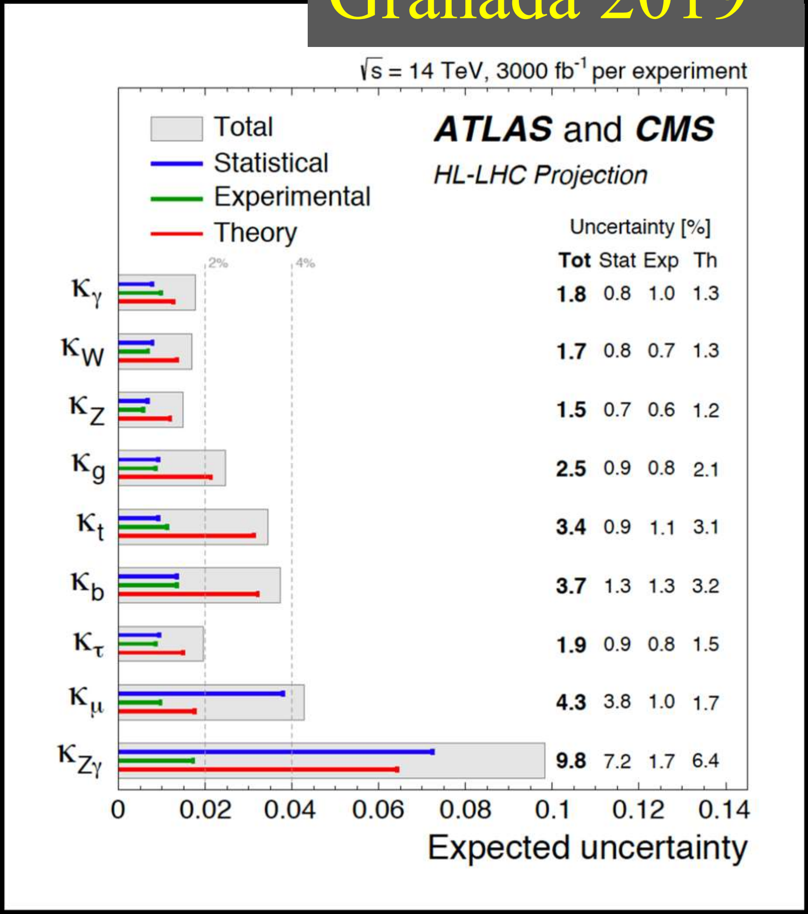

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  - After HL-LHC precision level of several %
  - Deviation from SM: $\delta \sim v^2/M^2$ $v = 246$ GeV
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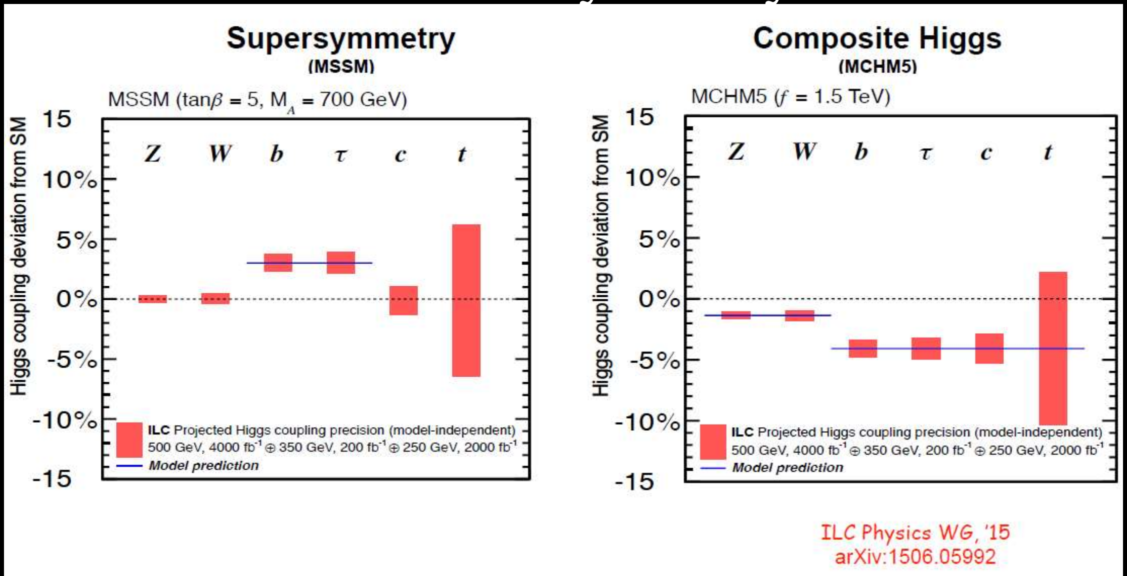
    - M ~ 1 – 10 TeV → $\delta \sim 6 - 0.06\%$
  - Need < ~ % sensitivity → beyond HL-LHC



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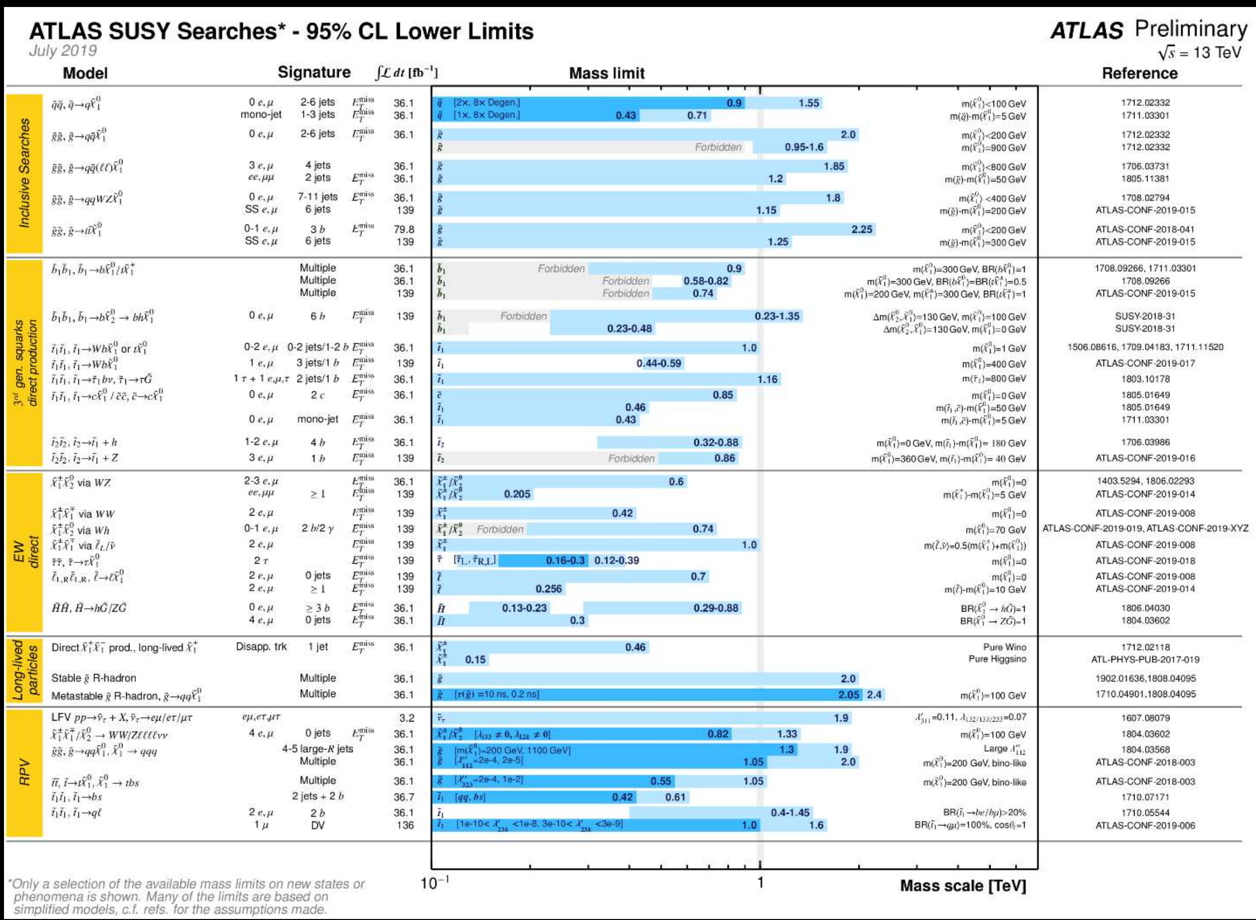

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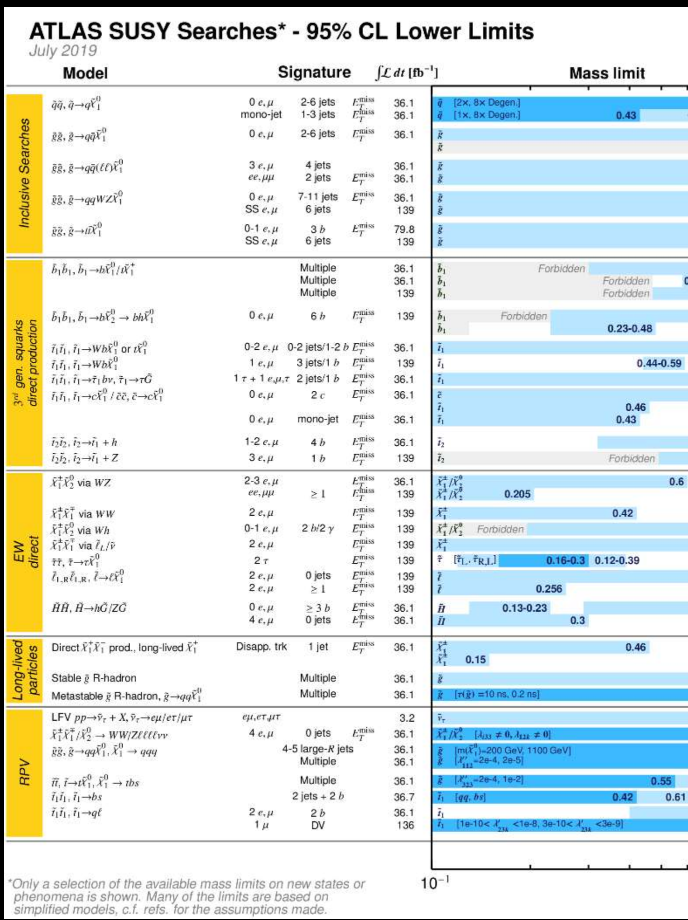

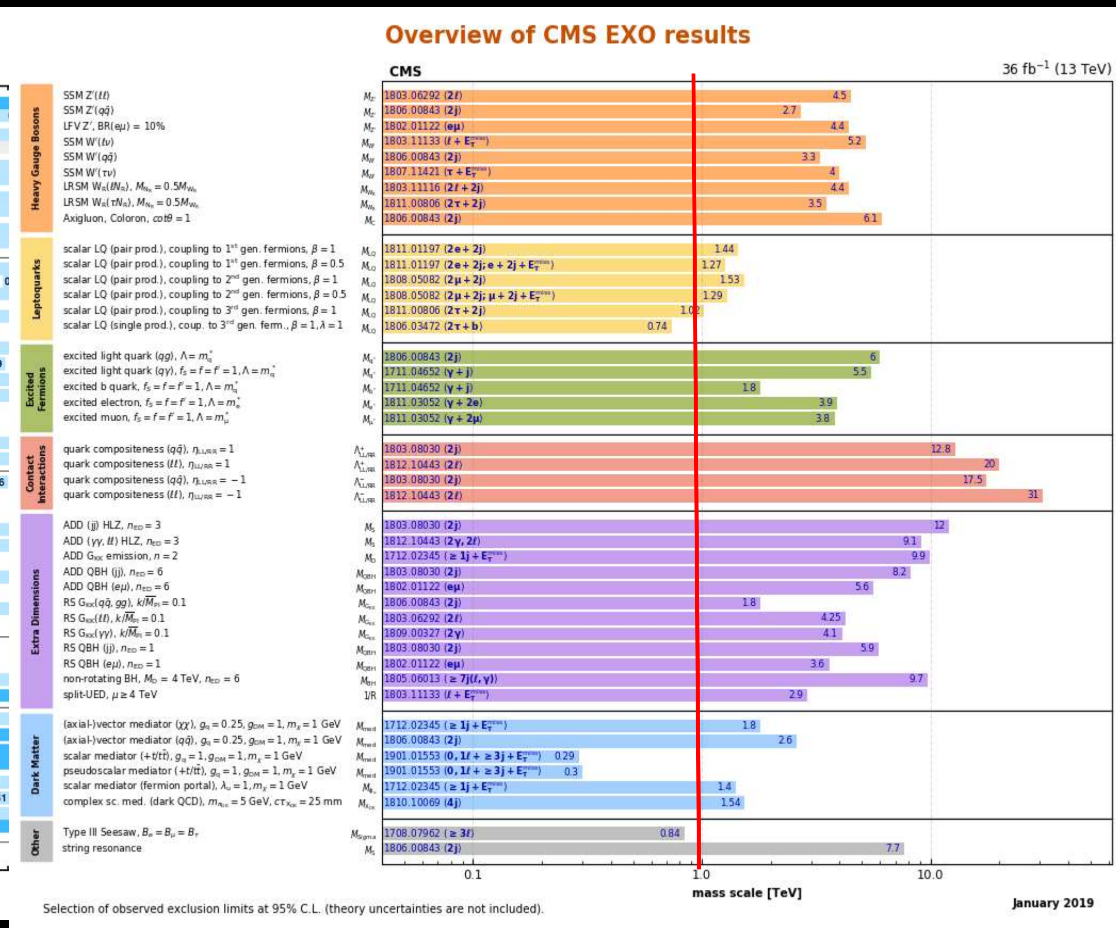

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- What new next accelerator to go beyond SM?

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**.

Higgs factories

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

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
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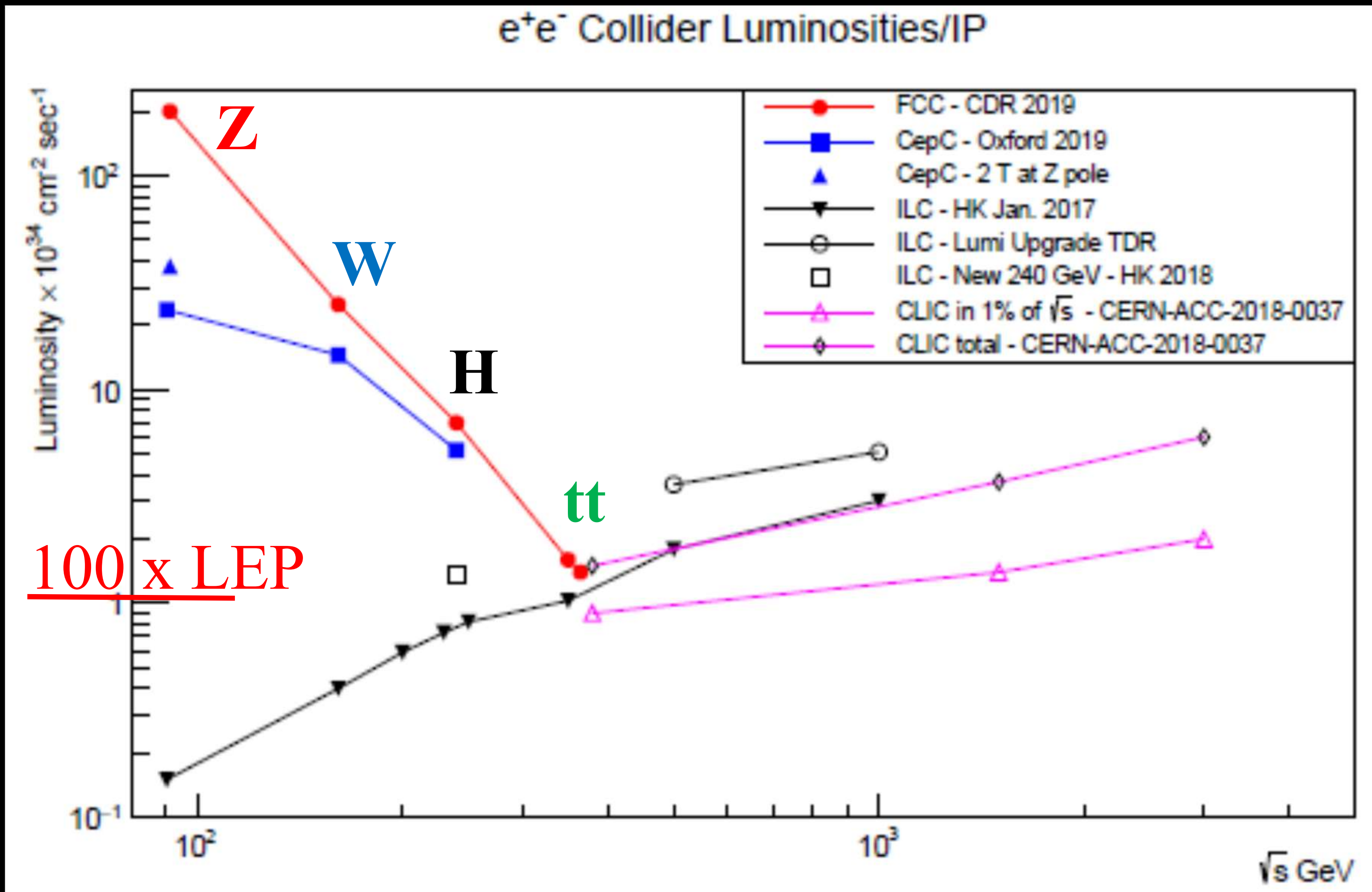
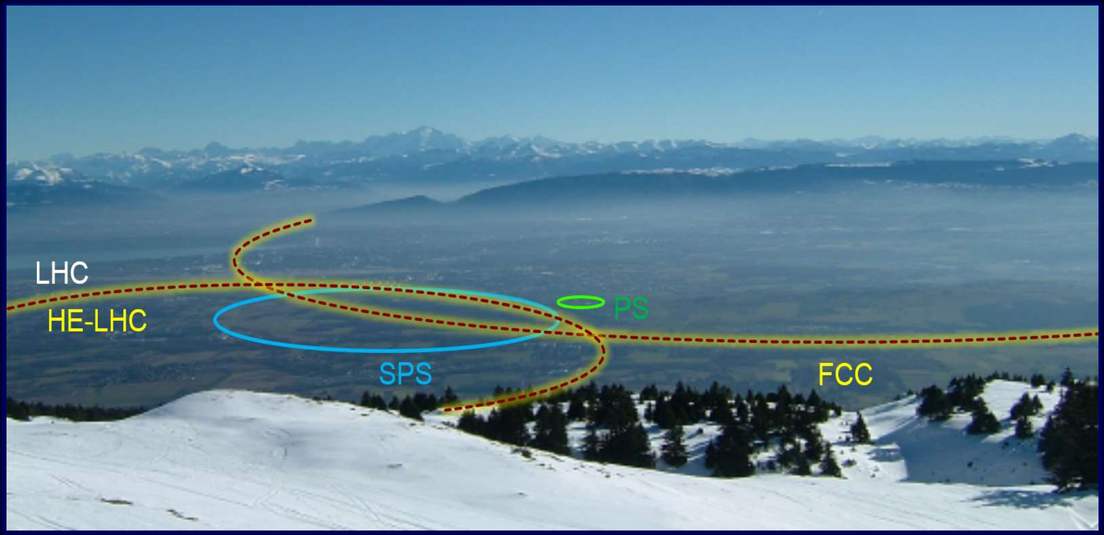
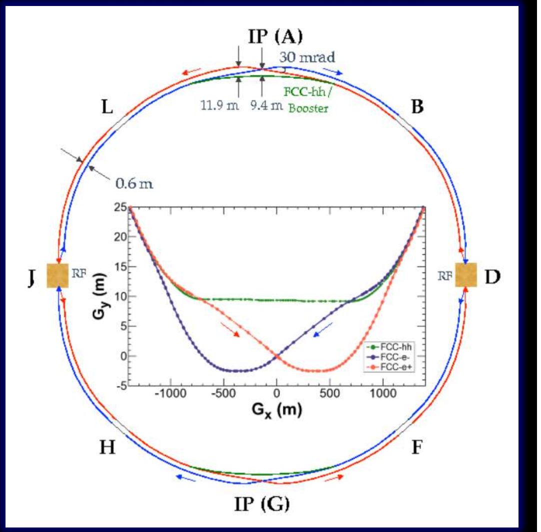
Luminosity comparison



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)

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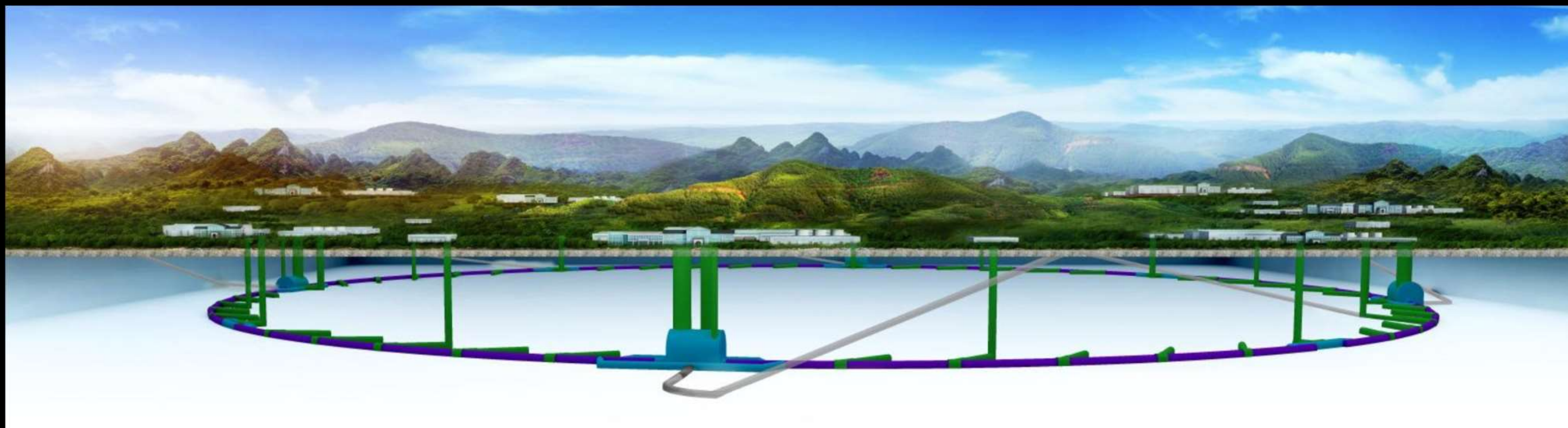

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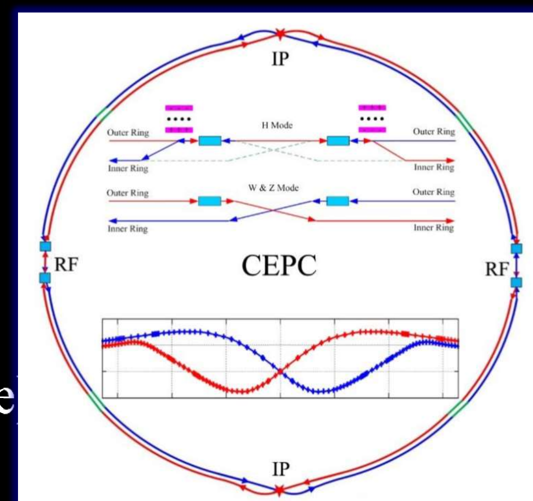
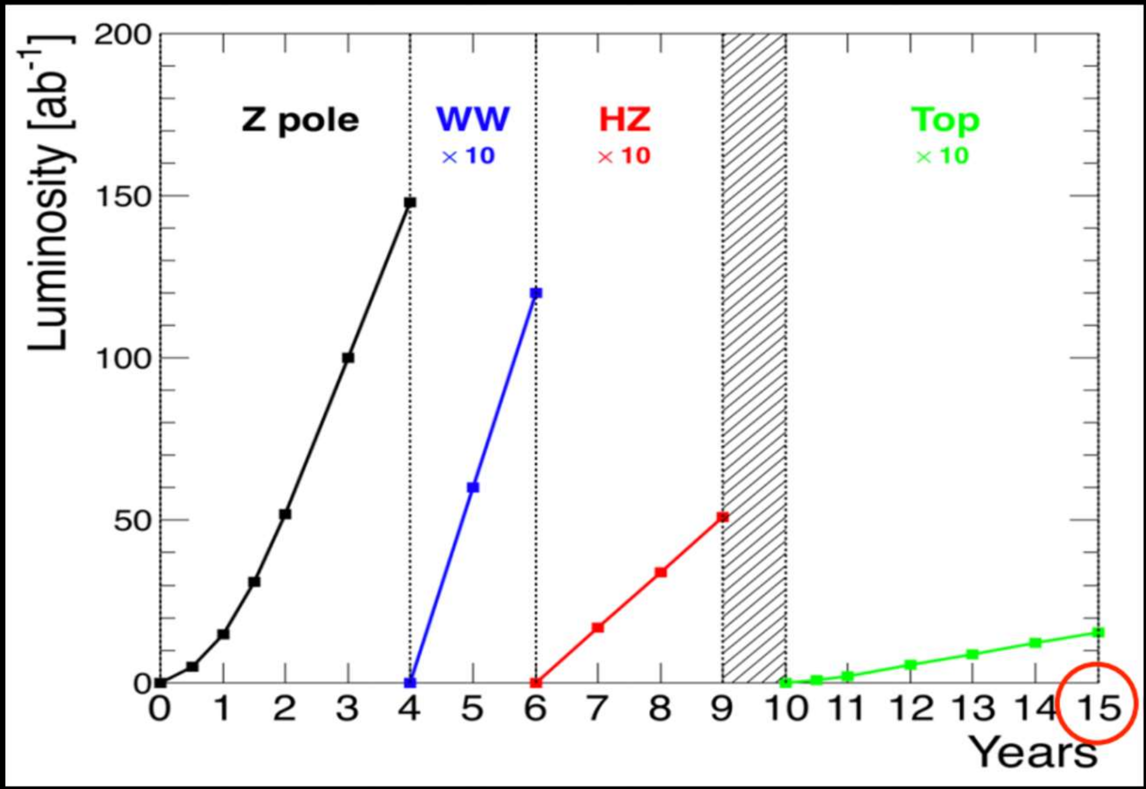
    - ("< 6BCHF" cited in the CepC CDR)



Physics at FCC-ee

- Higgs factory
  - 10^6 e+e- $\rightarrow$ HZ



Physics at FCC-ee

- Higgs factory
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- EW & Top factory
  - $3x10^{12}$ e+e- → Z
  - 10^8 e+e- → W+W- ;
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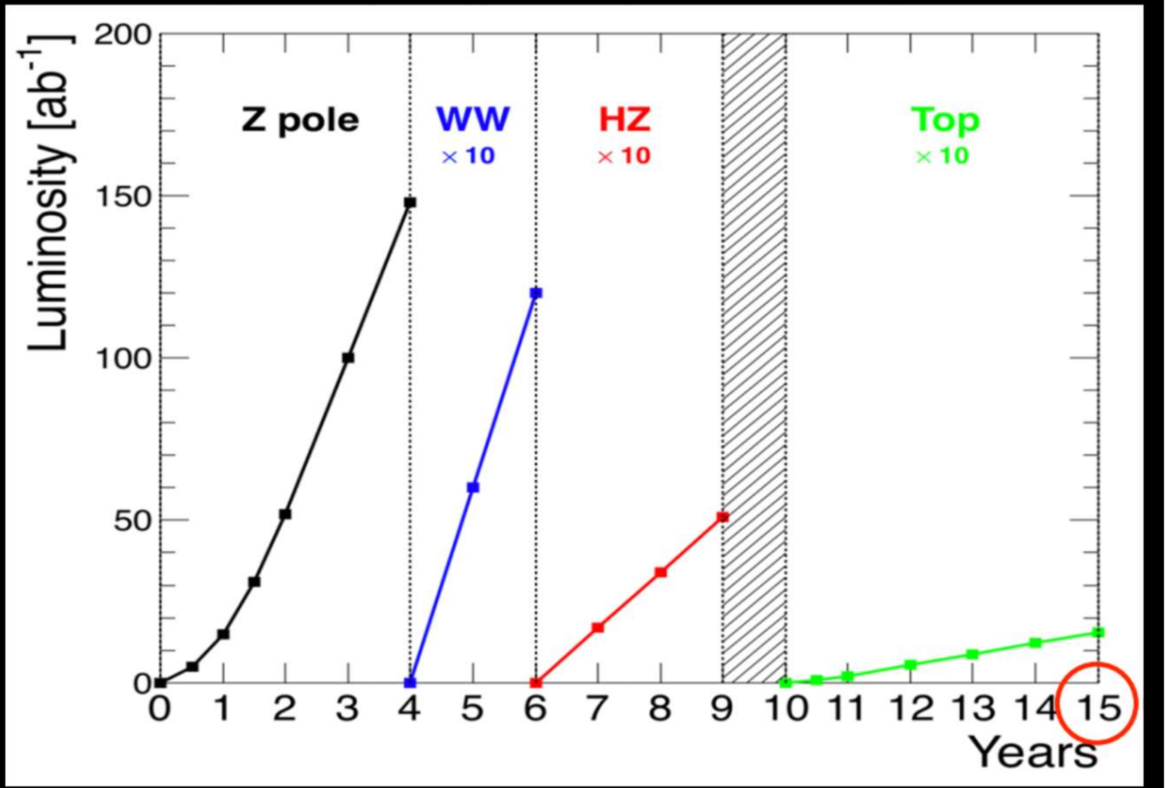

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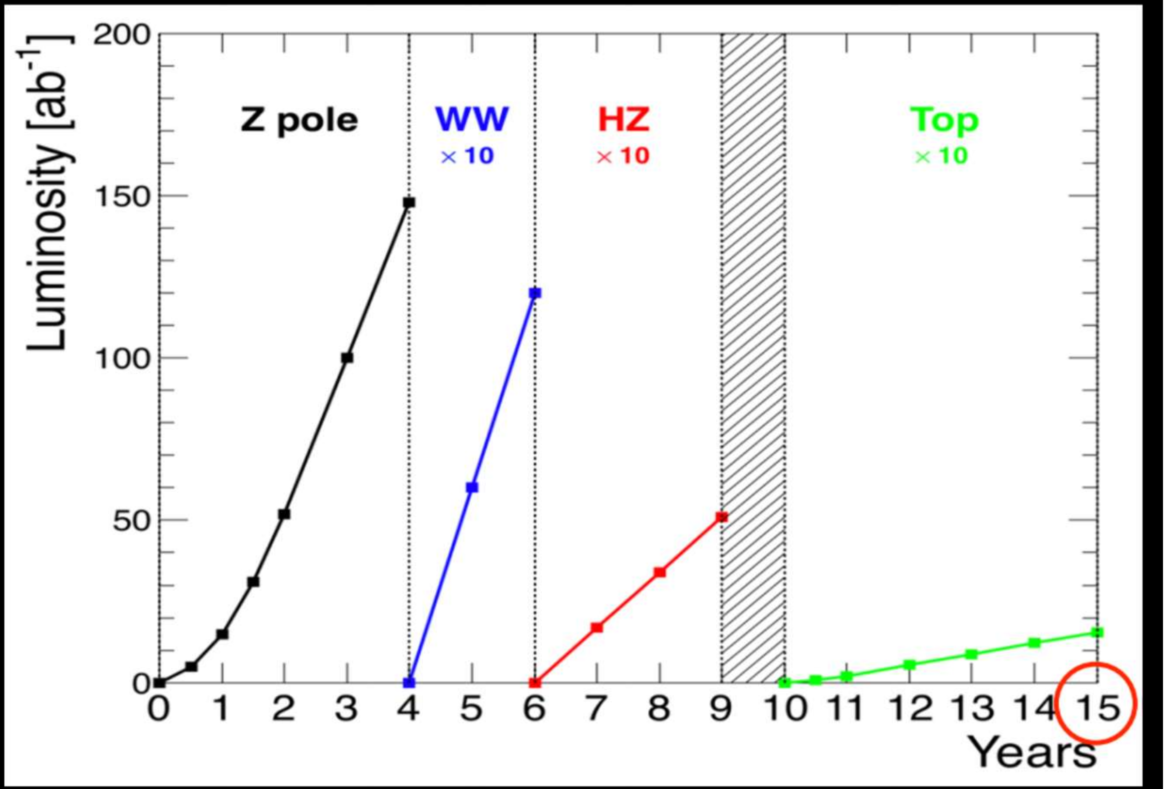
  - $5x10^{12}$ e+e- → bb, cc
  - 10^{11} e+e- → **τ+τ-**



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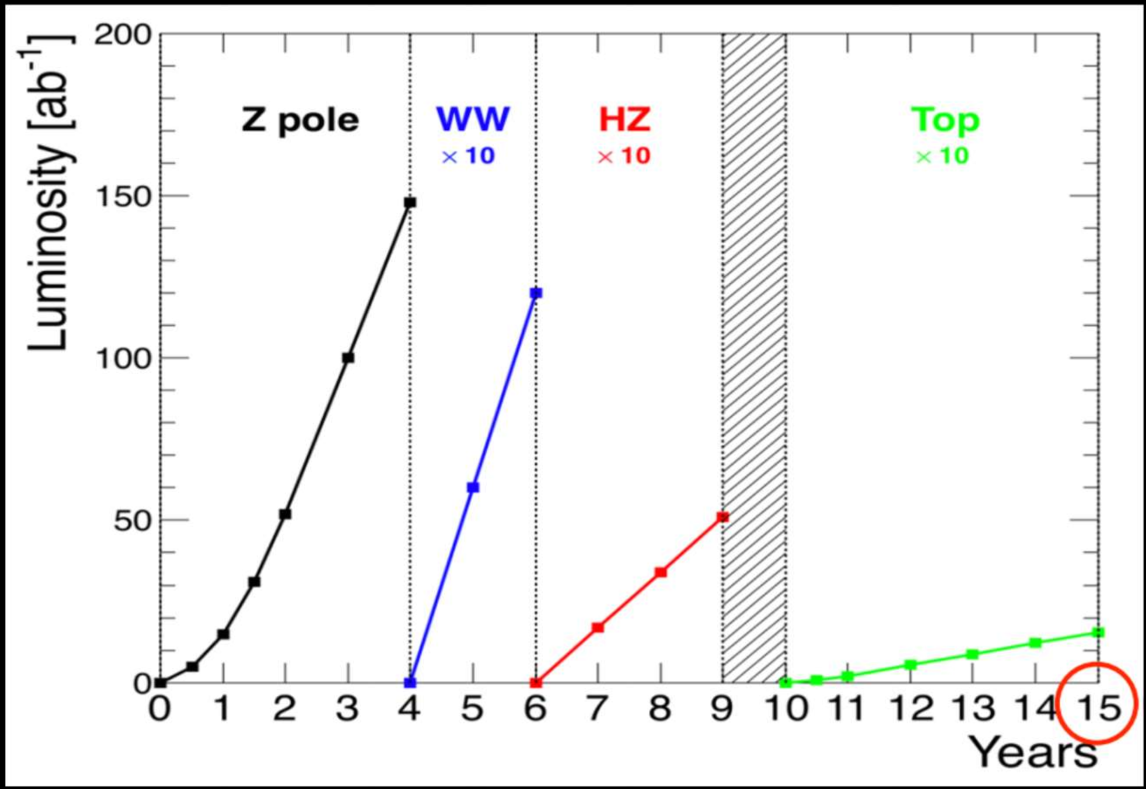
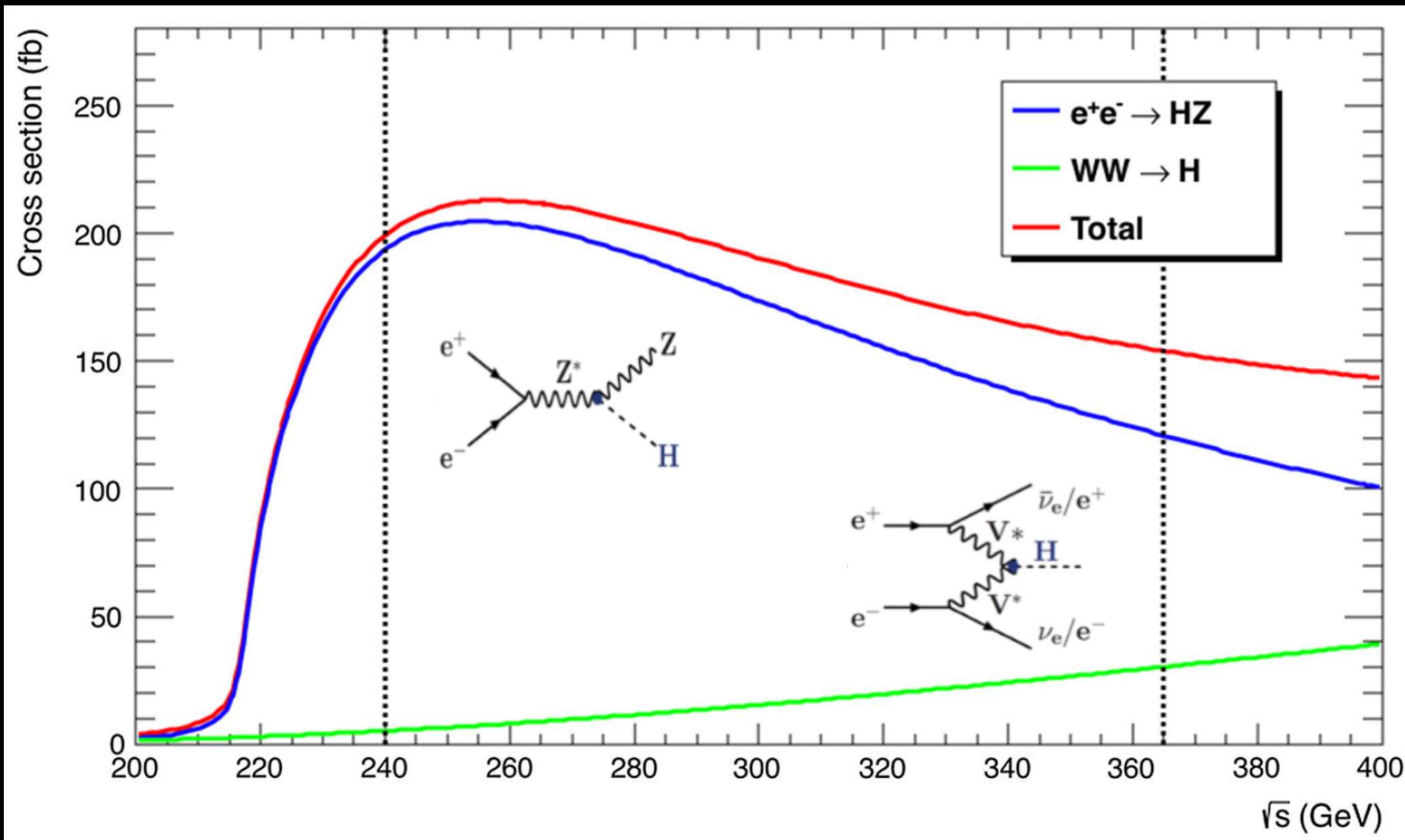
- Potential discovery of NP
  - ALPs, RH ν's, …



Higgs production



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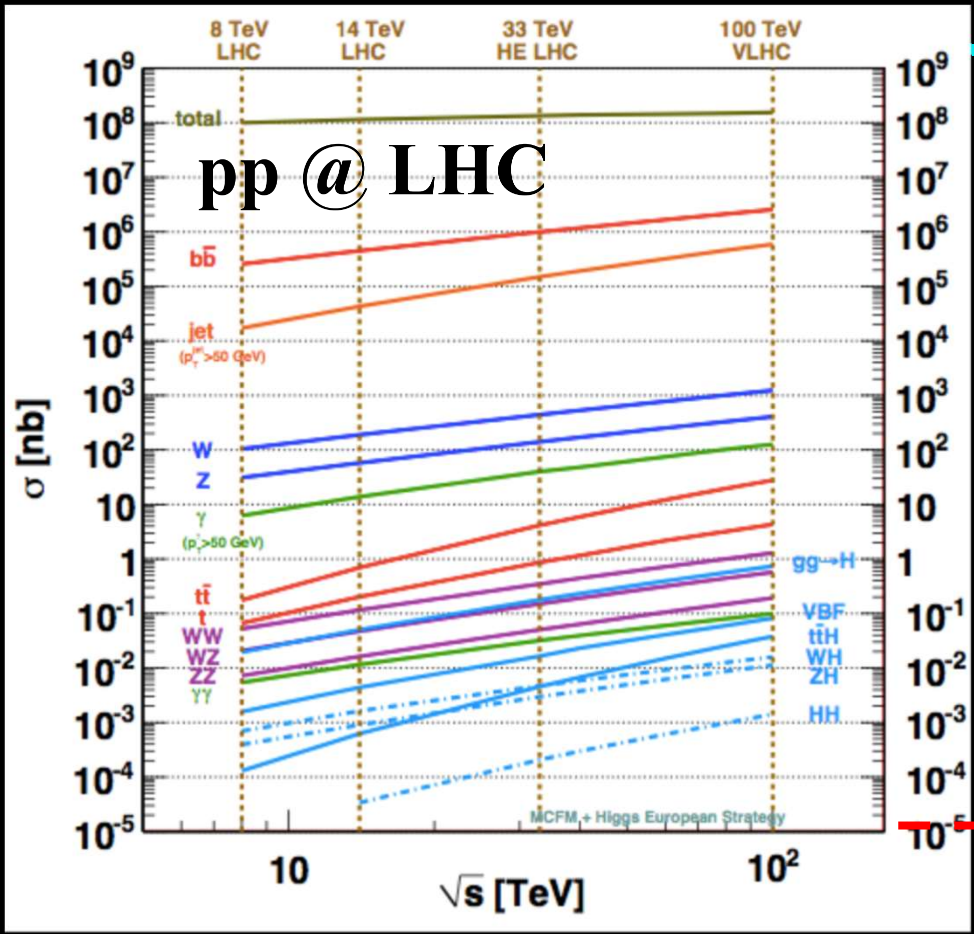
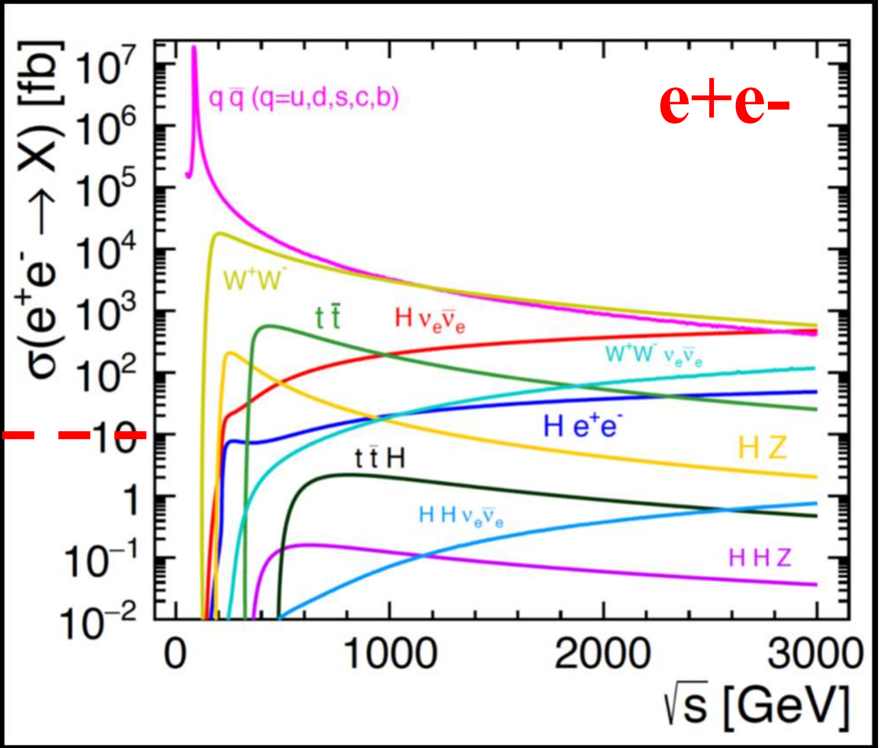


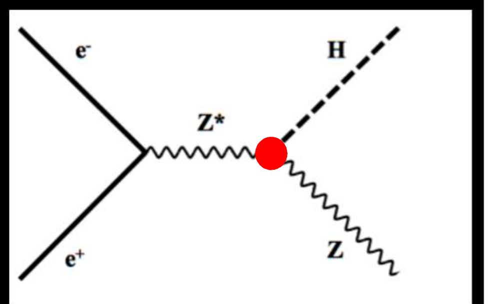
Very clean production in e+e-

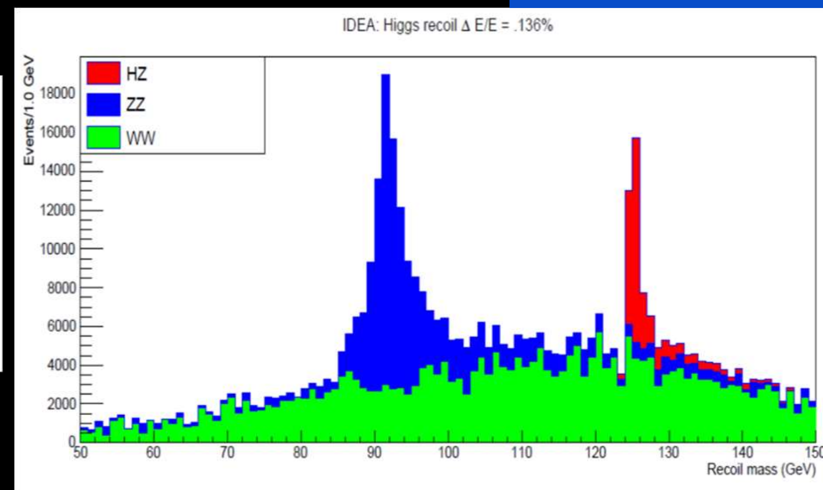


Higgs total width

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

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





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    - Beam energy spread: SR+BS
    - Tracking resolution

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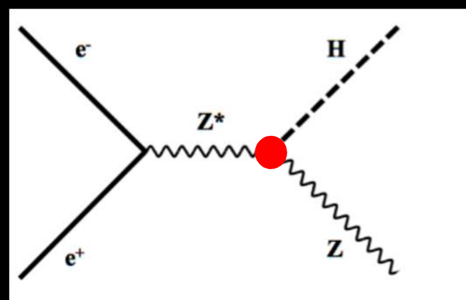

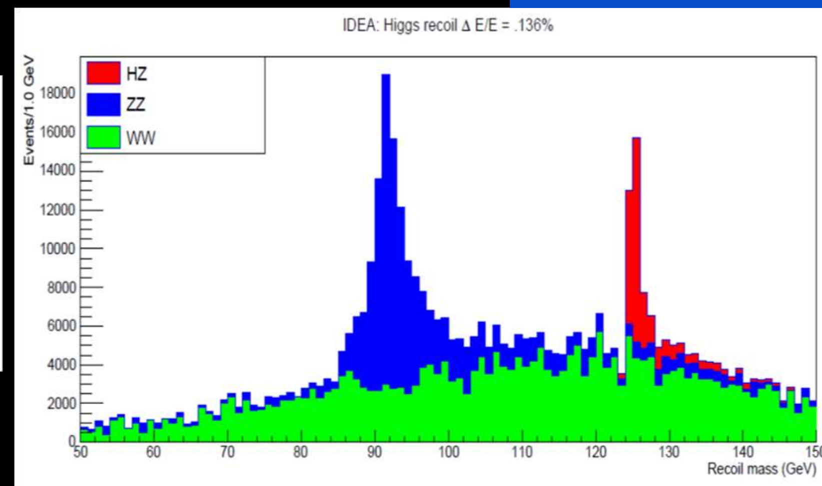

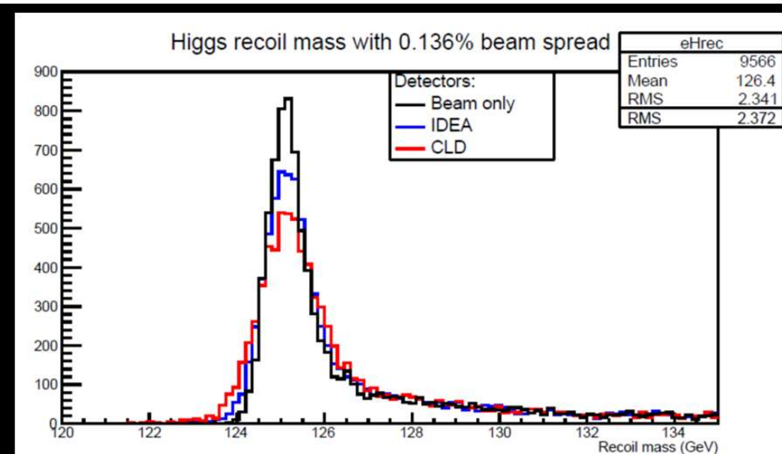

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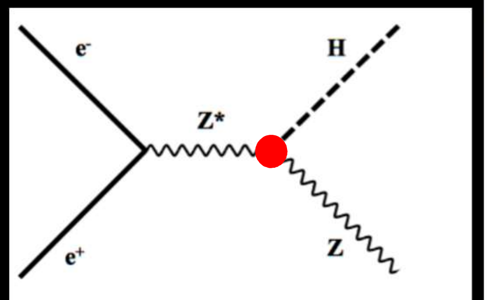

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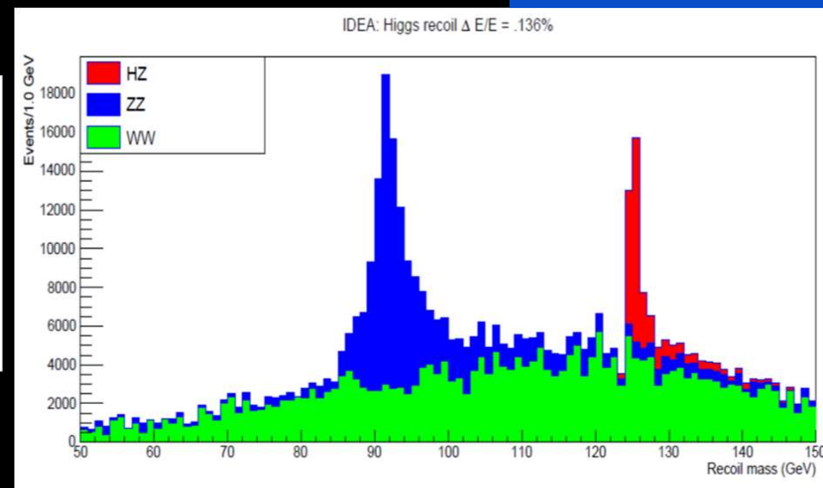

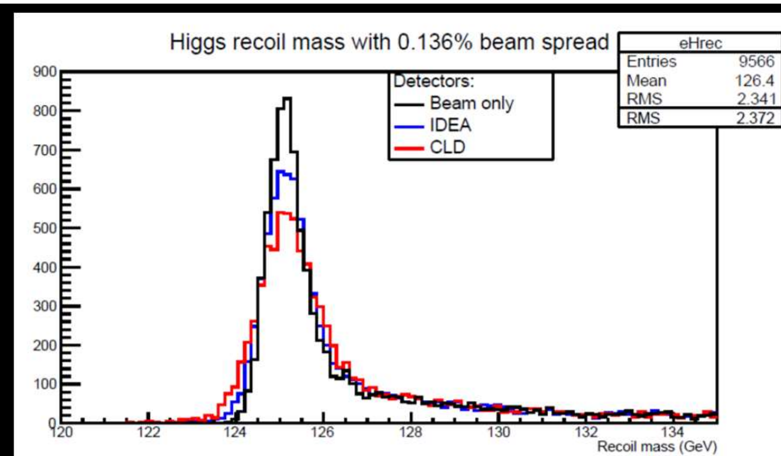

- Total width combining with decays in specific channels

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

Higgs coupling fits

- Kappa framework

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

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  - Extension

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BRinv measured at FCC-ee

BRunt 100% correlated with Γ_H

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  - Leading order NP effects weighted sum of all dim-6 operators

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□ 59 B&L conserving operators

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59 B&L conserving operators

  - Includes interference with SM operators
  - Simultaneous fit of Higgs, EWPO, aTGC, topEW
  - Fit results projected into effective Higgs couplings

$$g_{HX}^{\mathrm{eff}\ 2} \equiv \frac{\Gamma_{H \to X}}{\Gamma_{H \to X}^{\mathrm{SM}}}$$

Higgs coupling fits

- Results limited only by statistics

κ   EFT

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_H (%)	SM	2.4	2.6	1.9	**1.2**
BR_{inv} (%)	1.9	0.26	0.63	0.27	**0.19**
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

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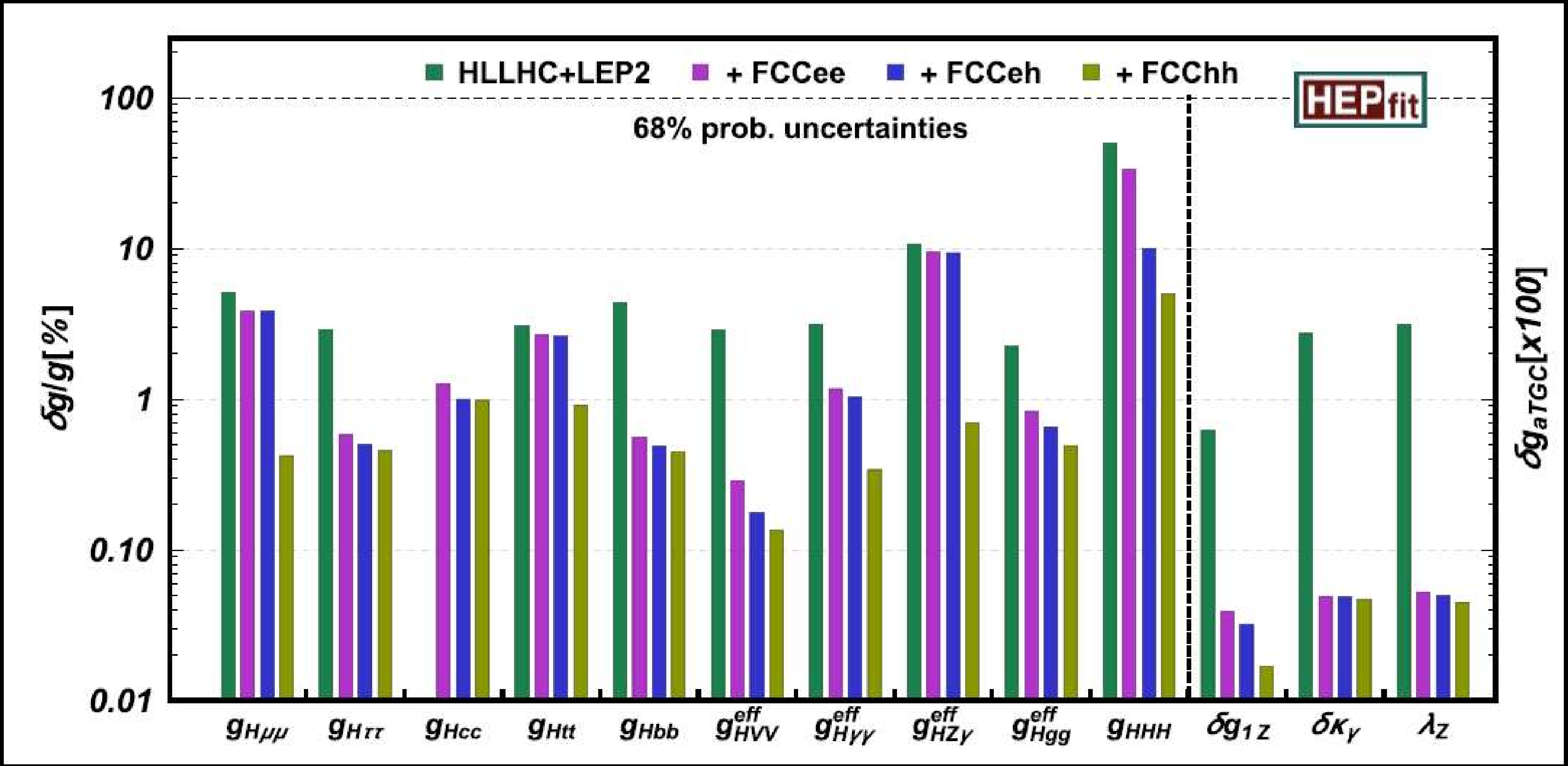
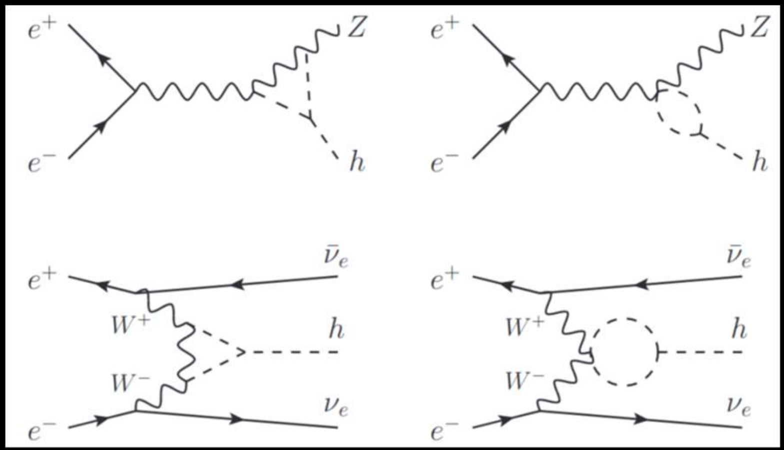


Triple Higgs

- No direct production @ FCC-ee
  - Sensitivity through loop effects



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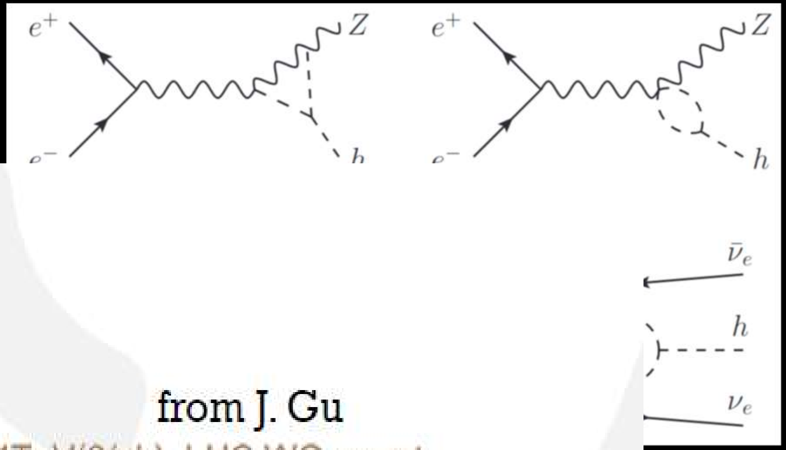

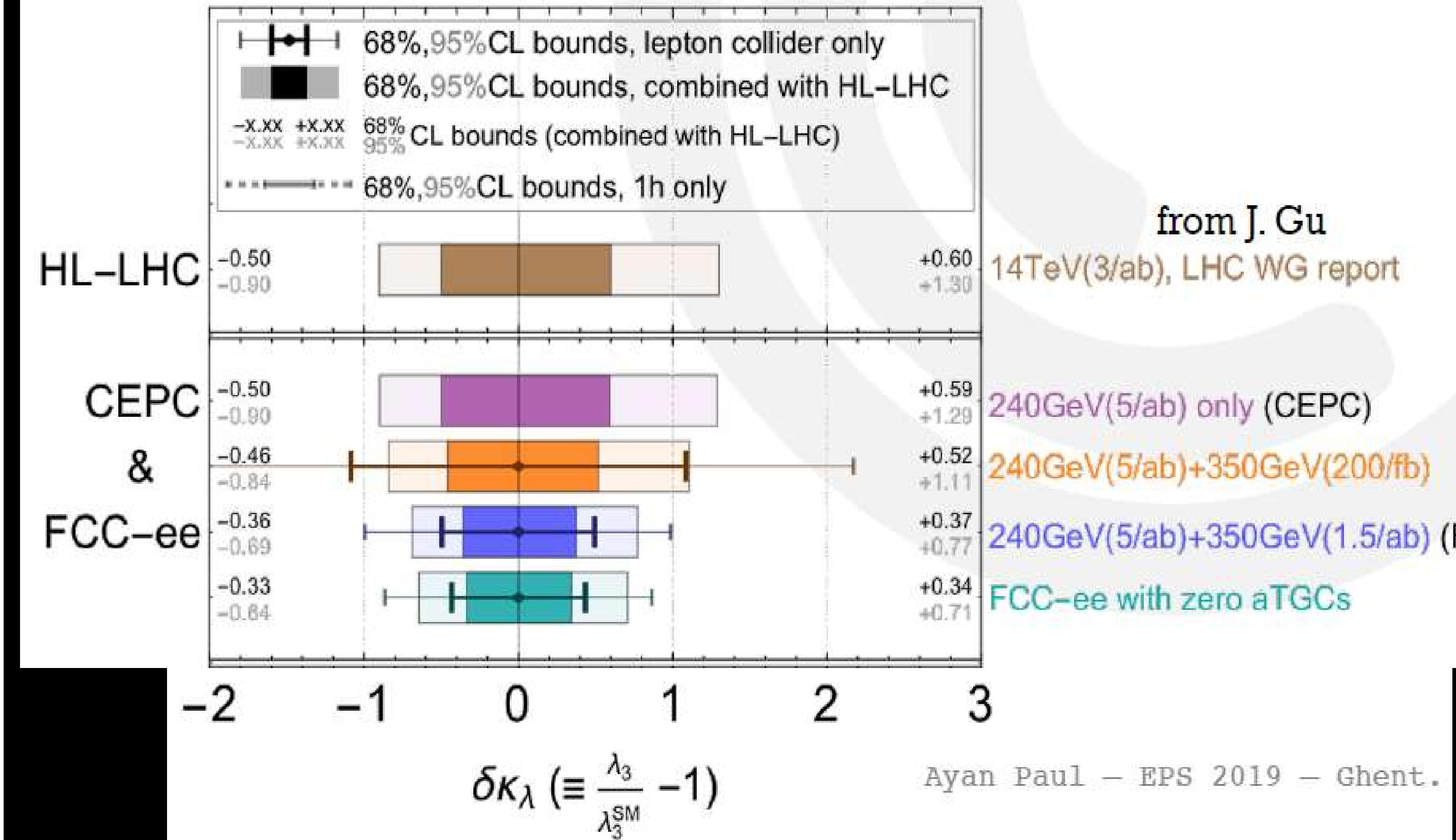

from J. Gu

Ayan Paul – EPS 2019 – Ghent.

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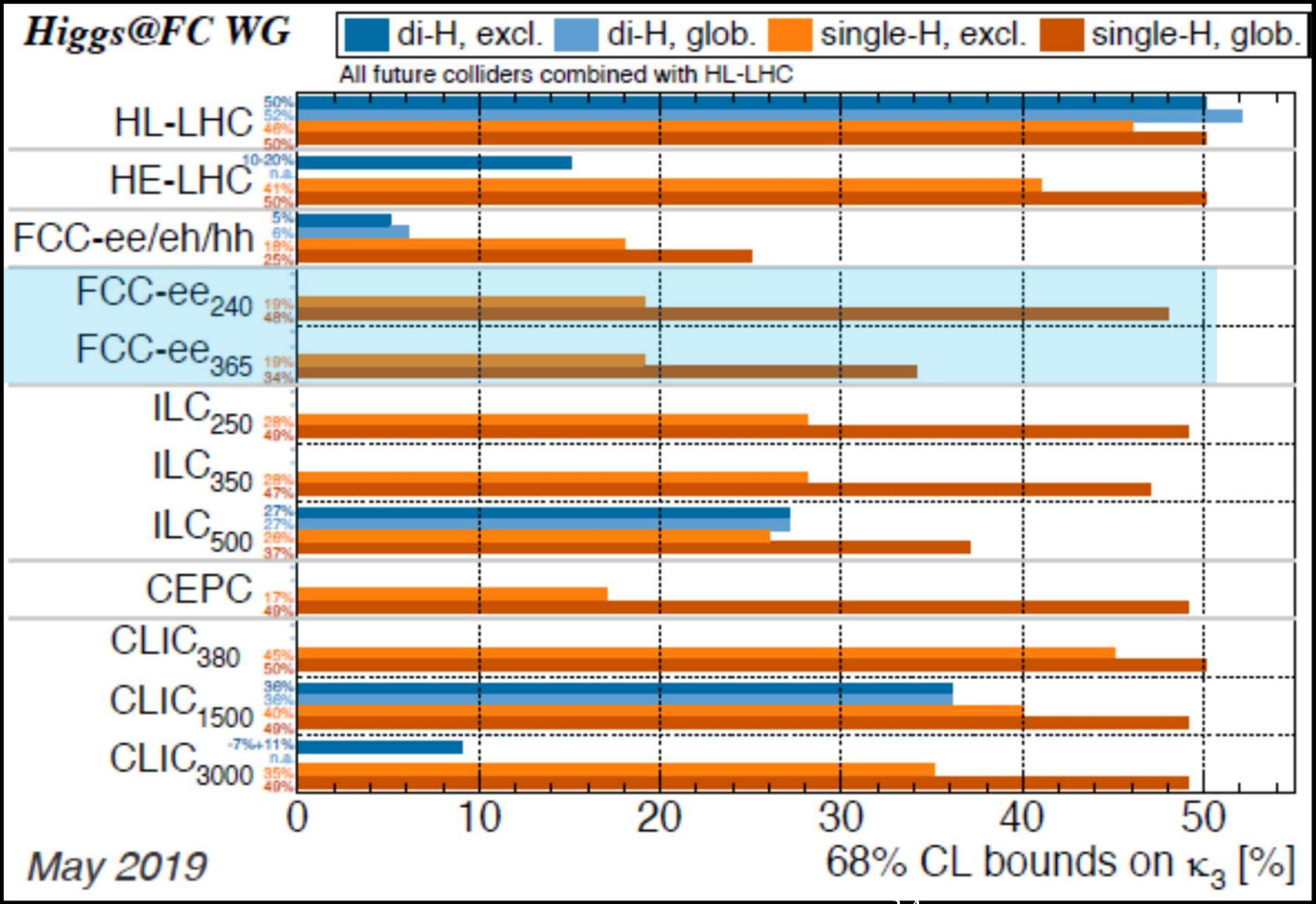


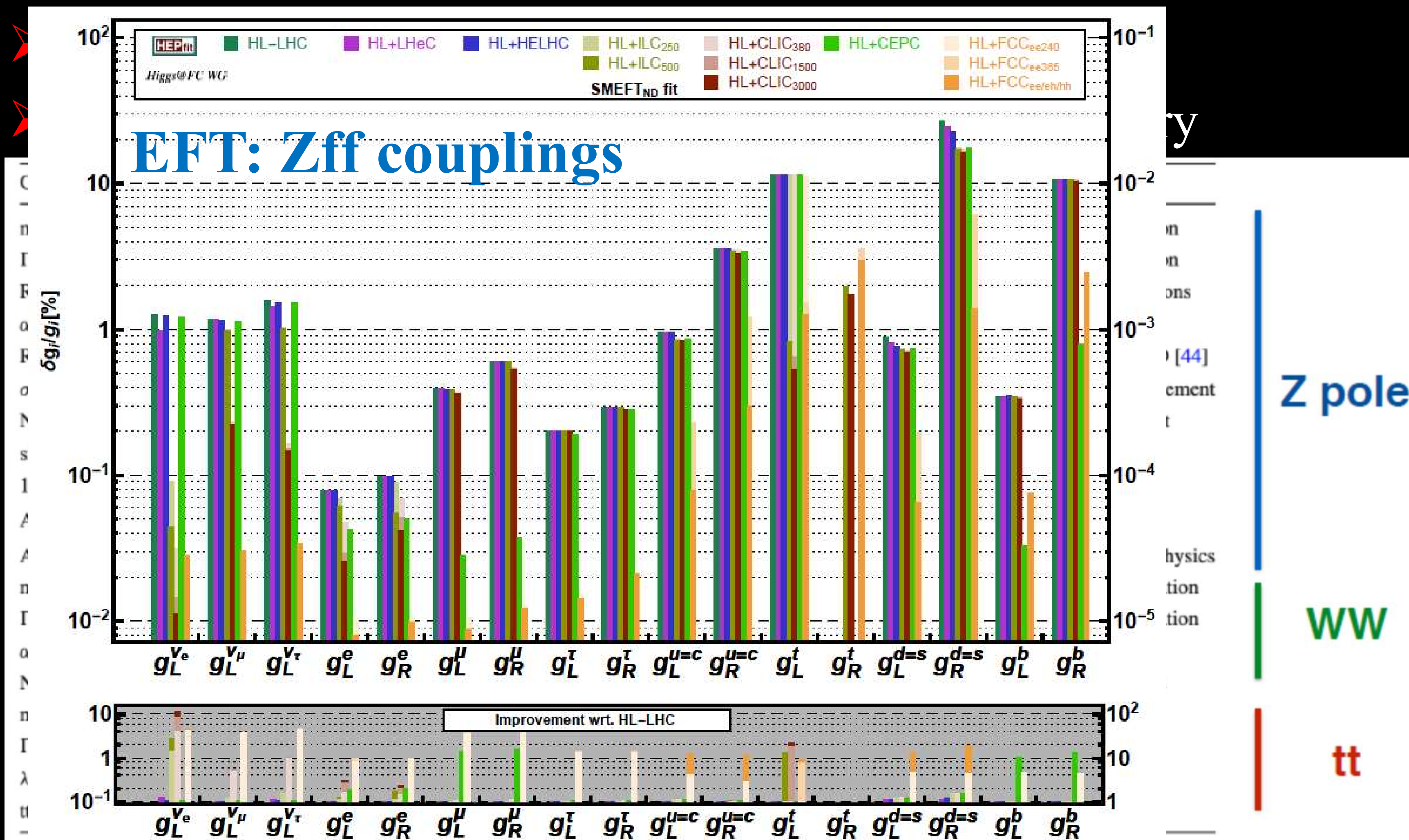
EWK

- Outstanding program of precision EWK measurements
  - O(10-100) better than LEP precision
  - Substantially reduce parametric uncertainties in theory

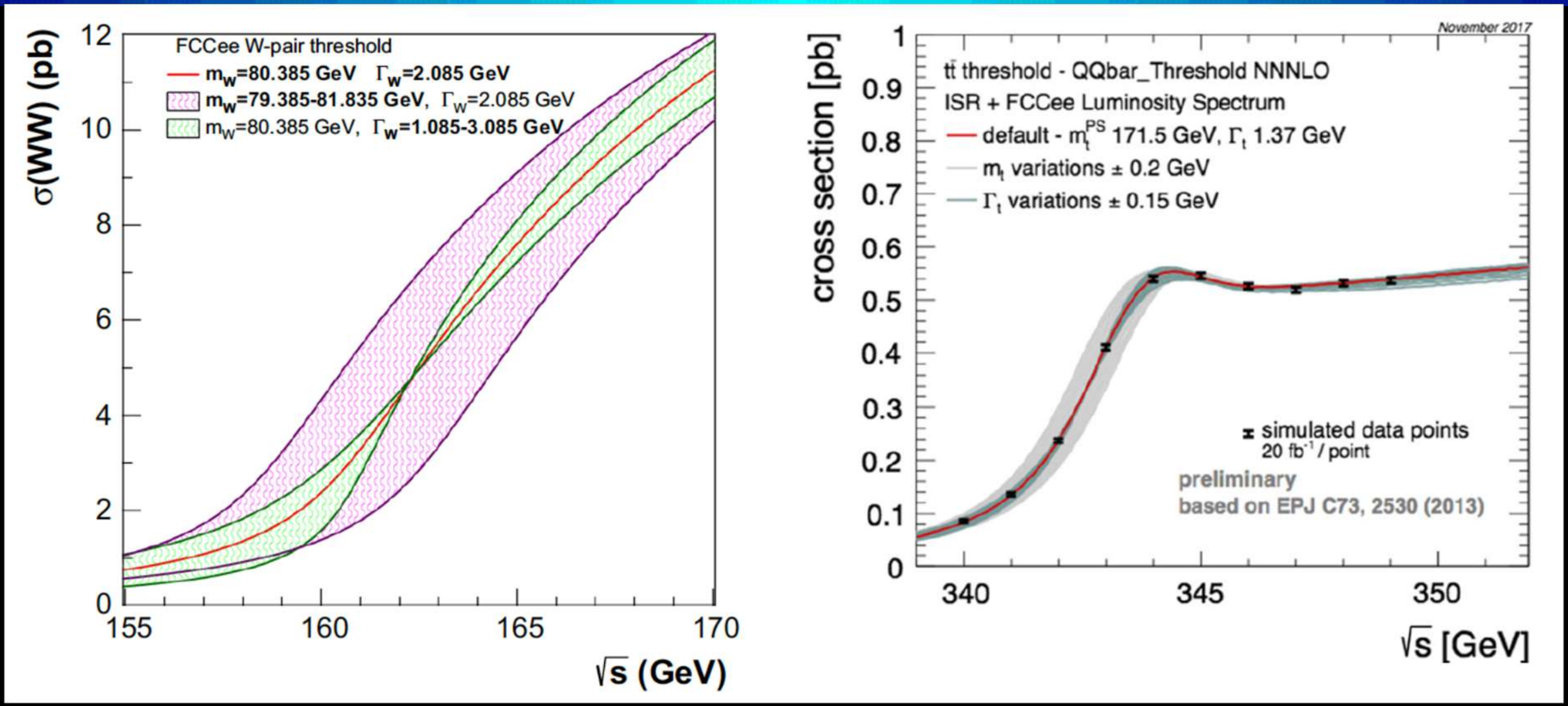
Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error	
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration	
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration	
R_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons	
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]	
R_b ($\times 10^6$)	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]	
σ^0_{had} ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement	Z pole
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement	
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]	
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge	
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics	
m_W (MeV)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration	
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration	WW
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W [45]	
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns	
m_{top} (MeV)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate	tt
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run	

EWK

- Outstanding program of precision EWK measurements

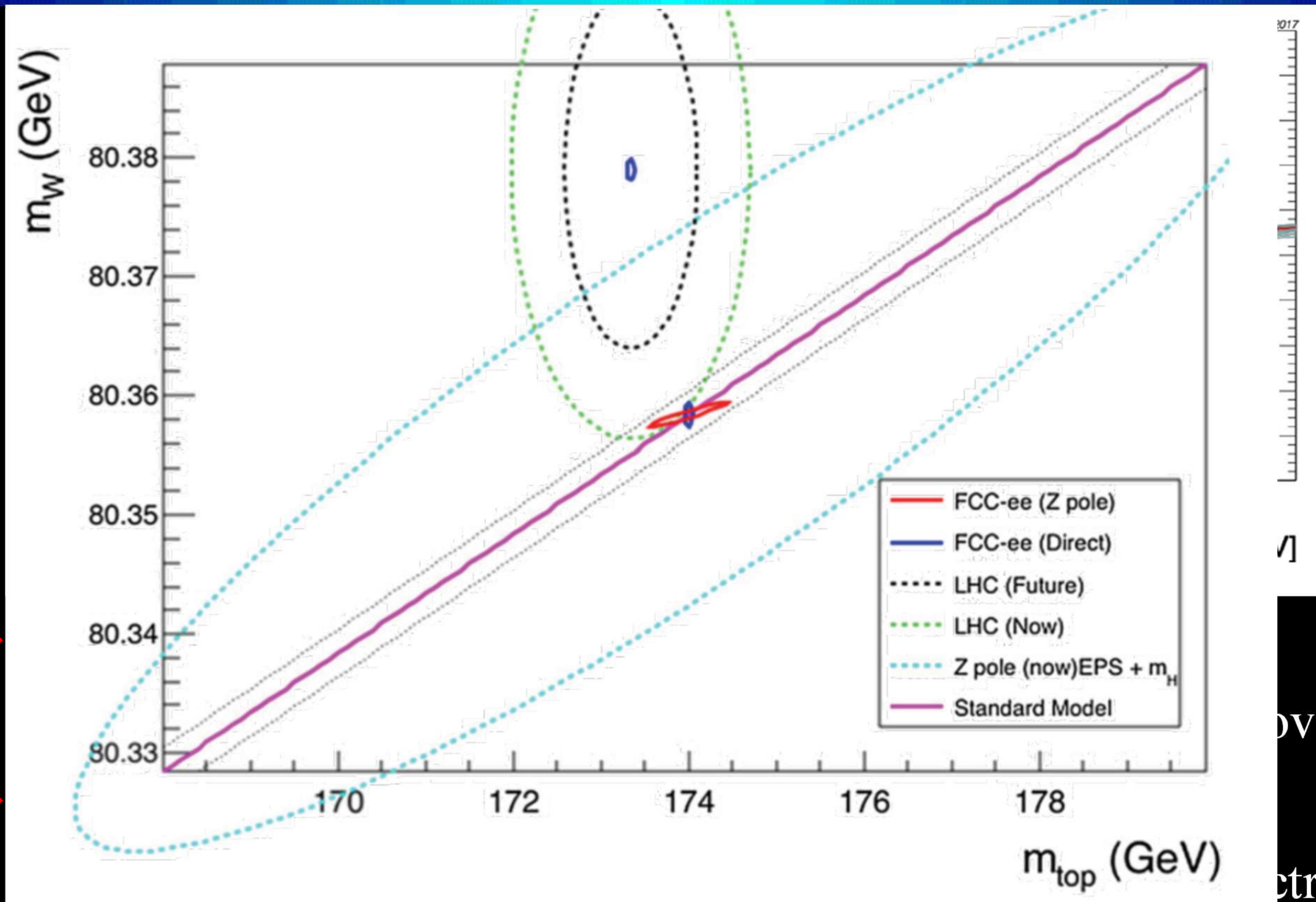


EWK examples



- W mass/width → 0.5/1.2 MeV resolution
  - WW threshold scan/ direct measurements check and improve
- Top quark mass/width → 17/45 MeV resolution
  - tt threshold scan – N^3LO, ISR and FCCee luminosity spectrum

EWK examples



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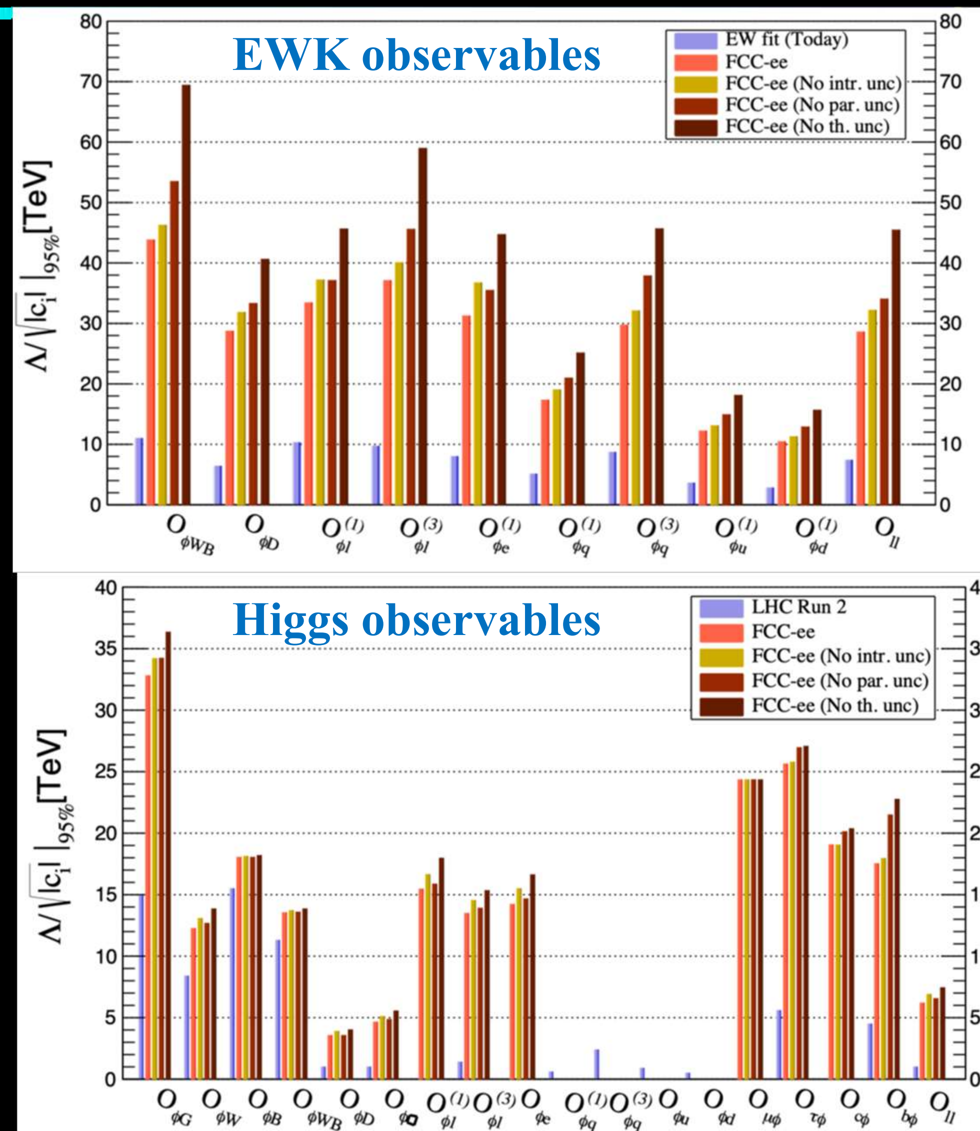
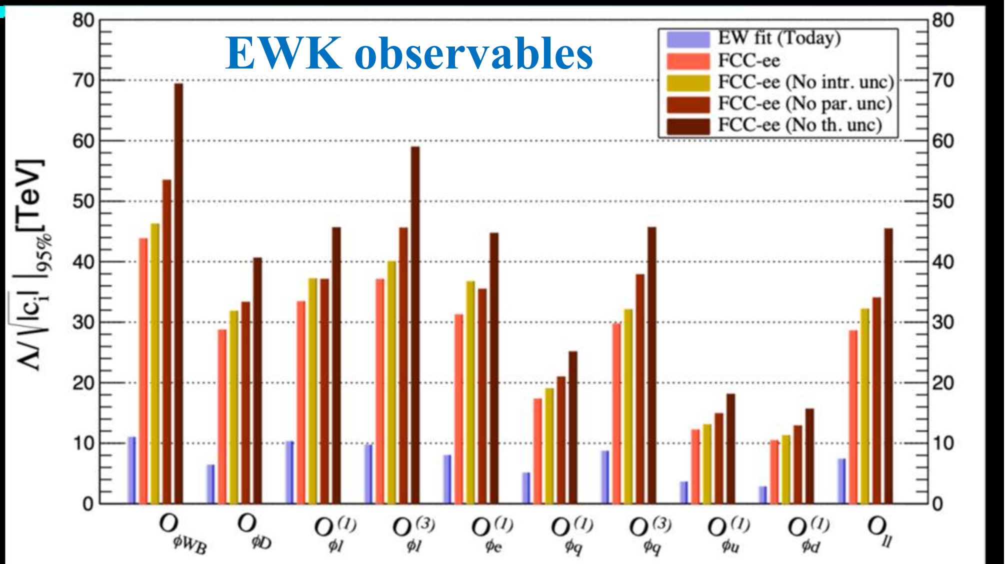
NP sensitivity from EFT fits

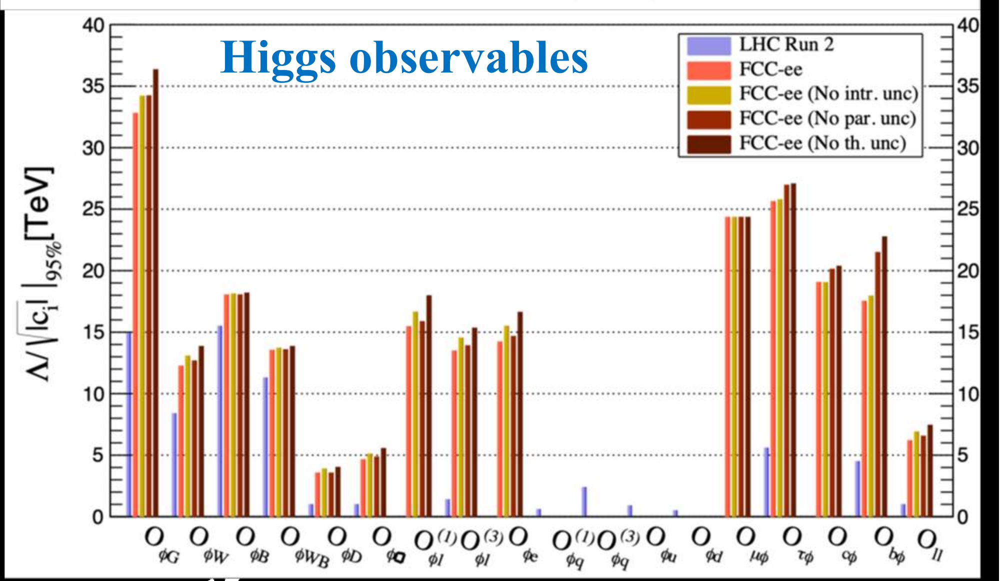
- From exclusive fits
  - Reach to several 10's TeV



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





Heavy flavors

- Large heavy flavor production at Z pole

Particle production (10^9)	B^0	B^-	B_s^0	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

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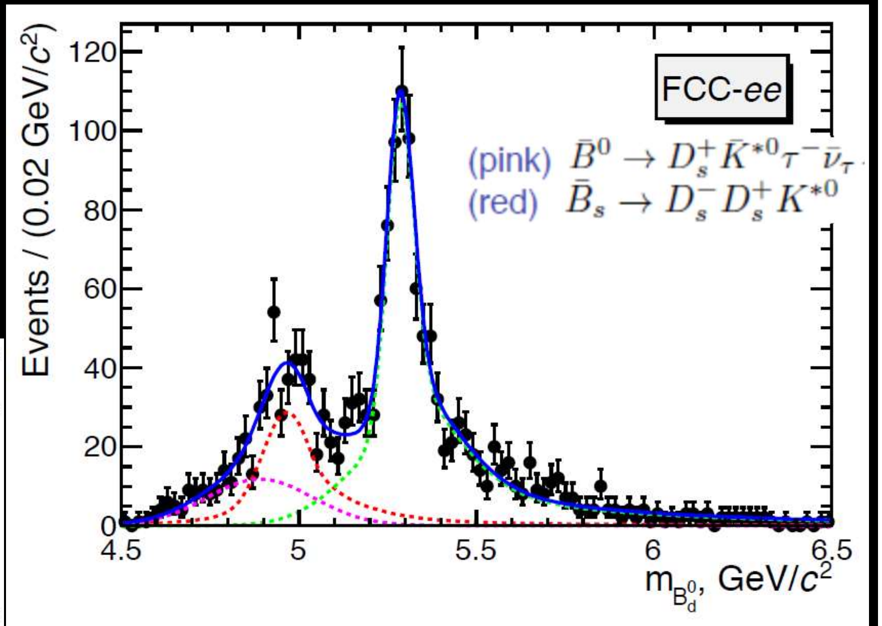
  - Very clean, well separated, pairs
- Example:
  - Lepton universality

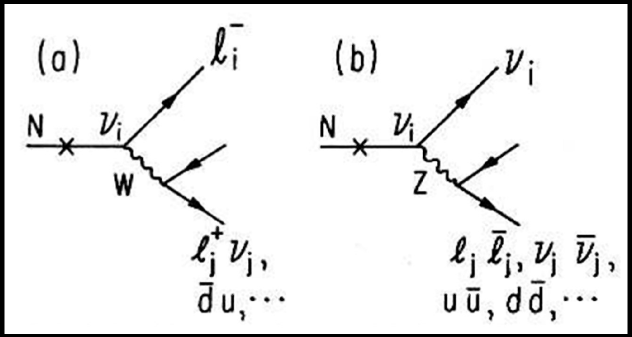
in $B^0 \rightarrow K^{*0}\ \tau+\tau-$

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)



Direct NP search example: HNL

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



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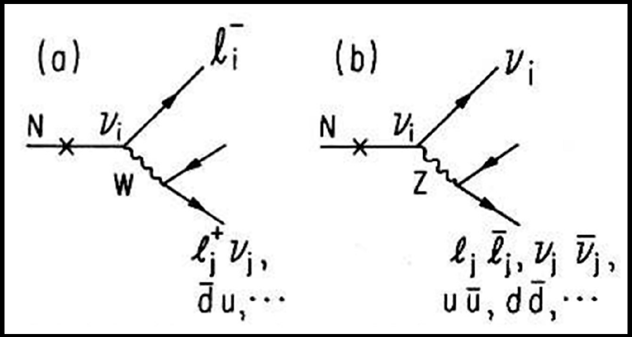

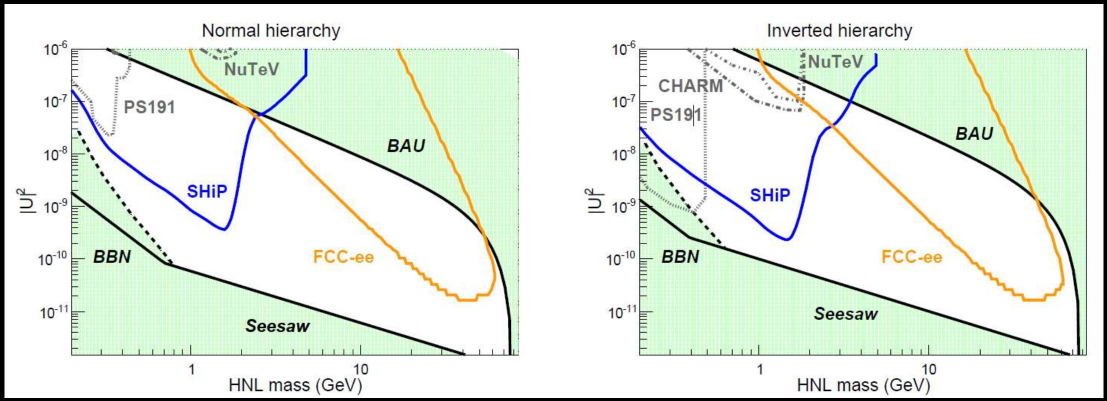

10 cm < cτ < 100 cm

10^{12} Z

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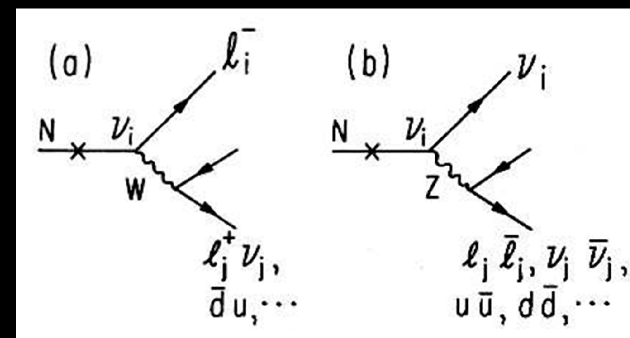

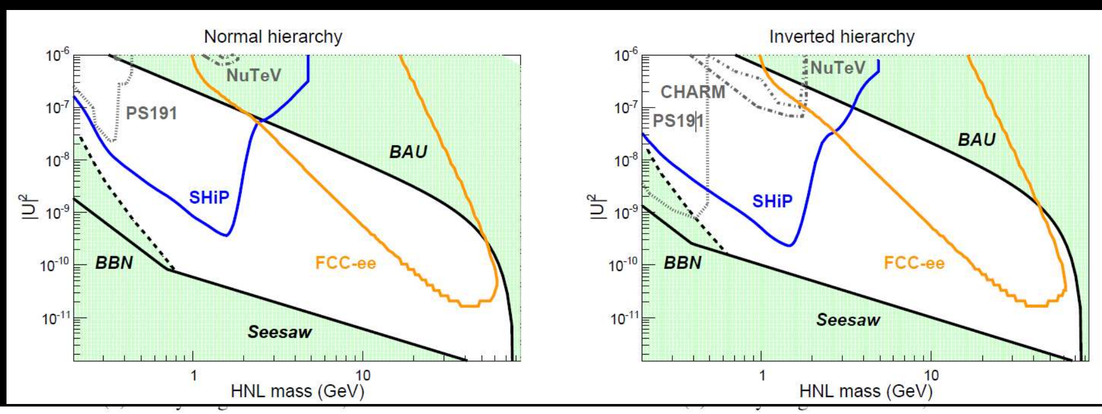

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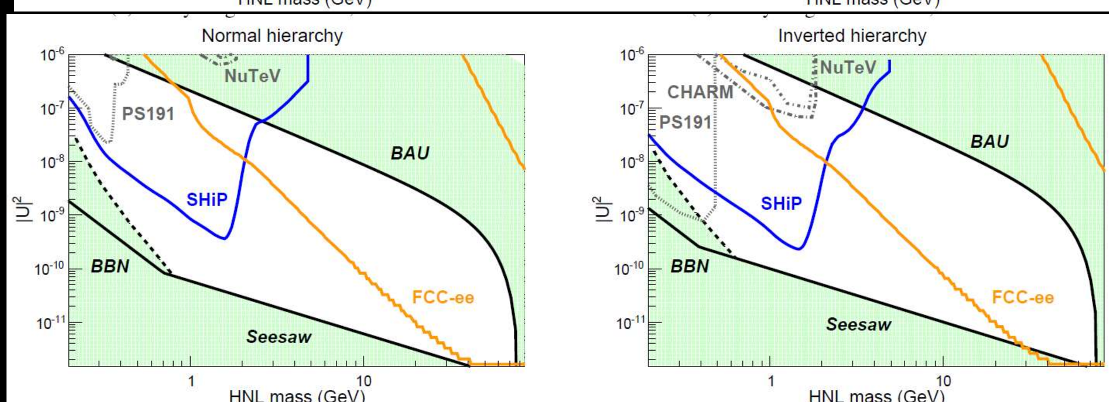


0.01 cm < cτ < 500 cm

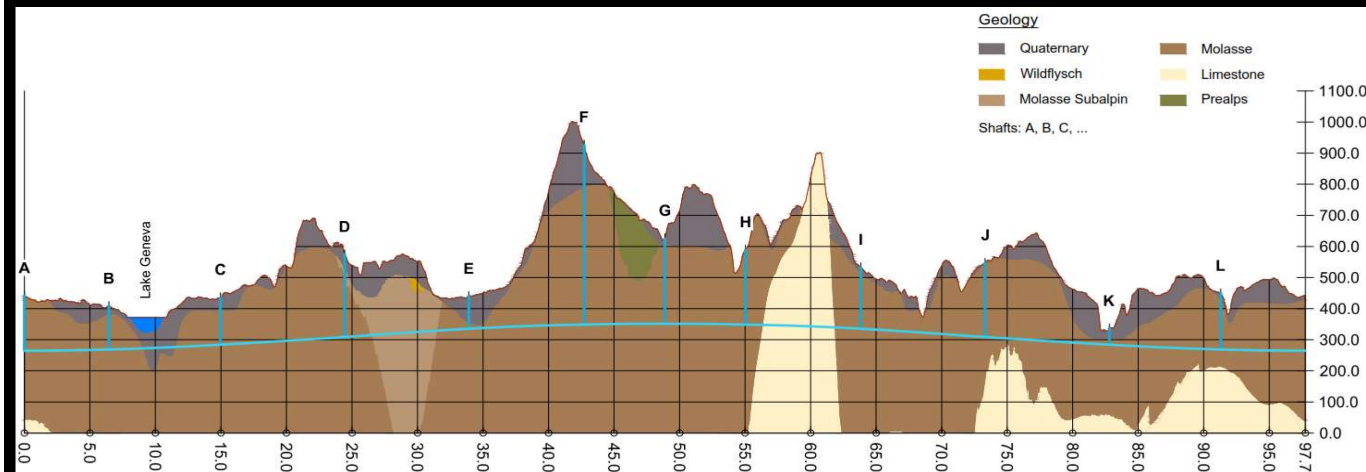
10^{13} Z

The planned machines

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

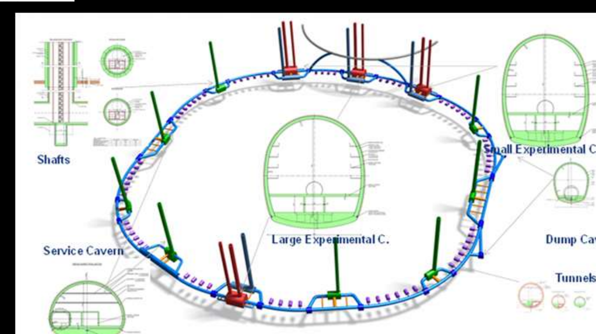
INFN Istituto Nazionale di Fisica Nucleare

Implementation studies in Geneva basin:



baseline position was established considering:

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

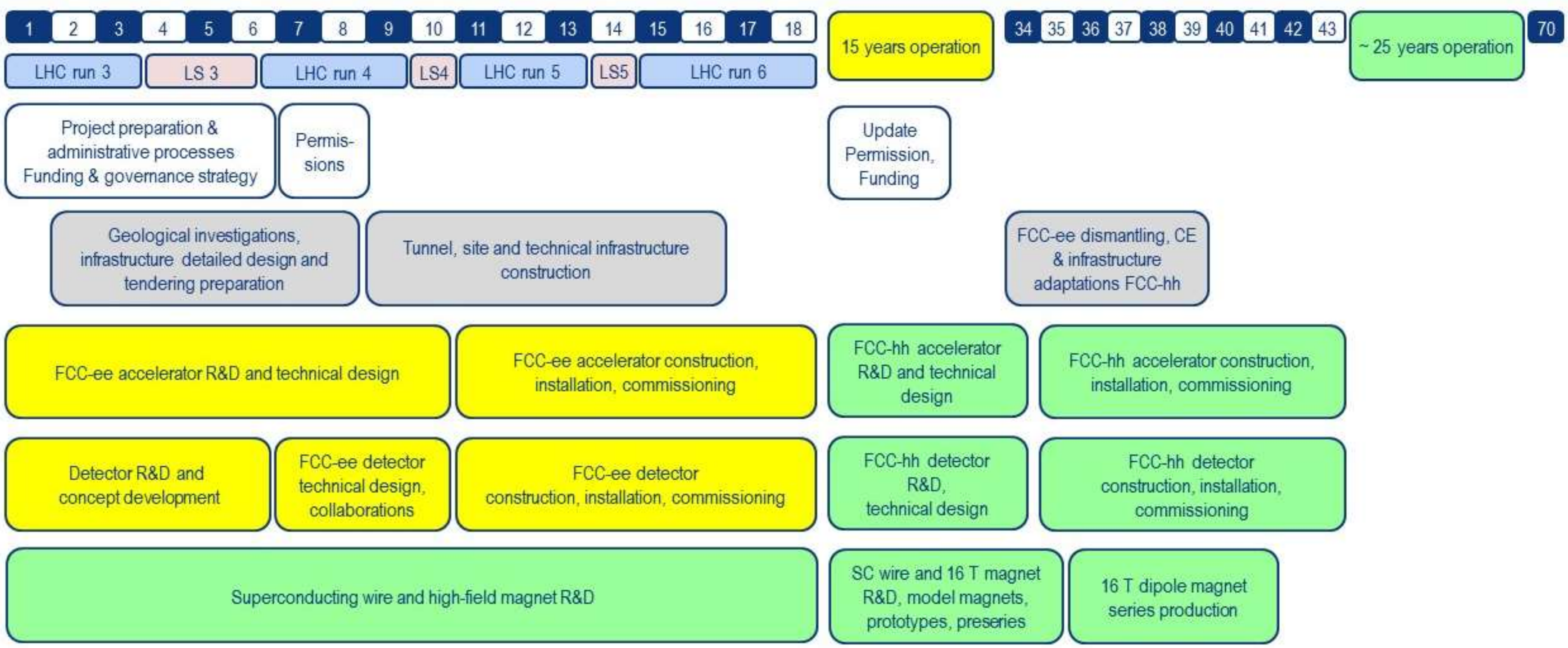


- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

M. BENEDIKT, Granada 2019

FCC-ee + FCC-hh

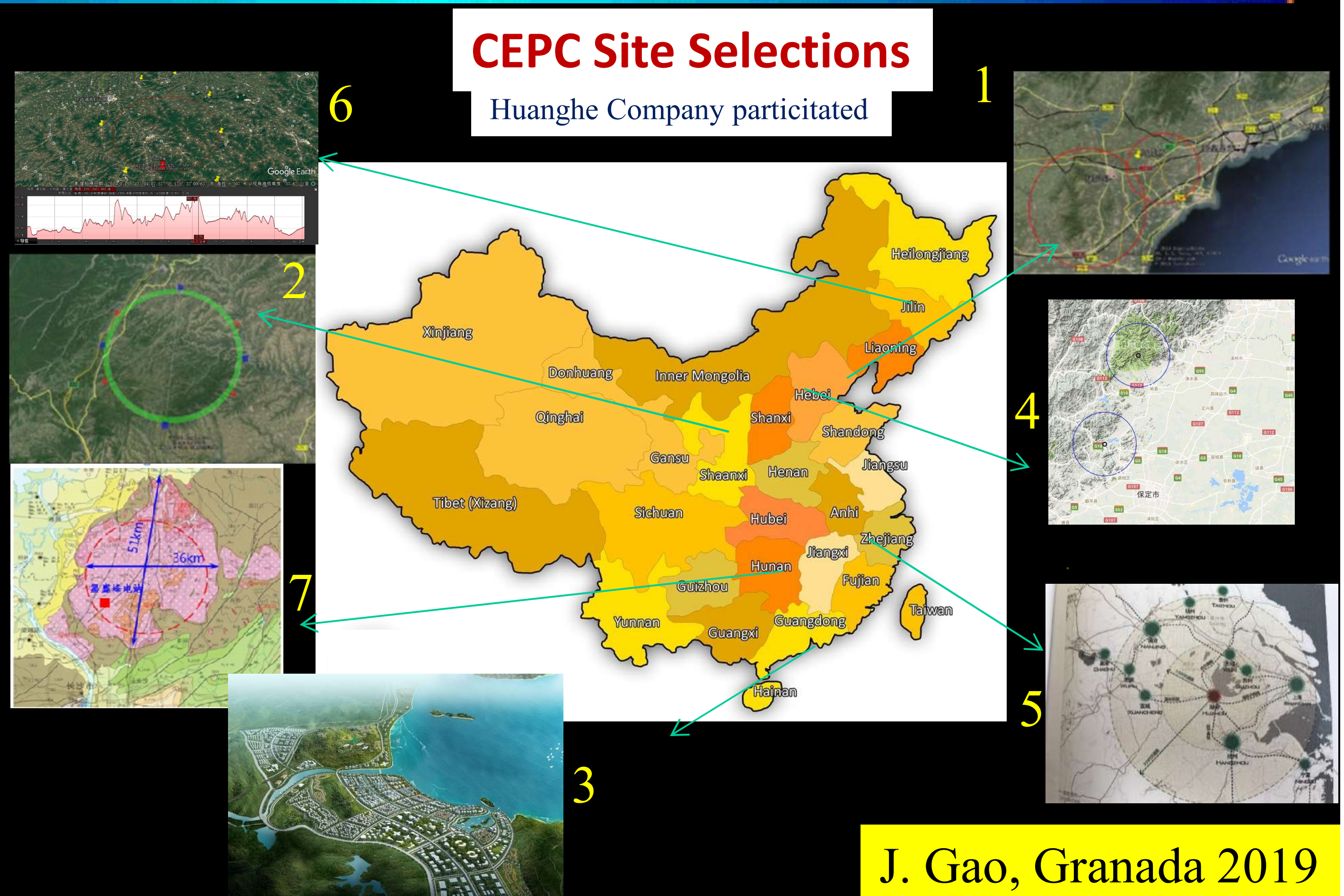
M. BENEDIKT, Granada 2019



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

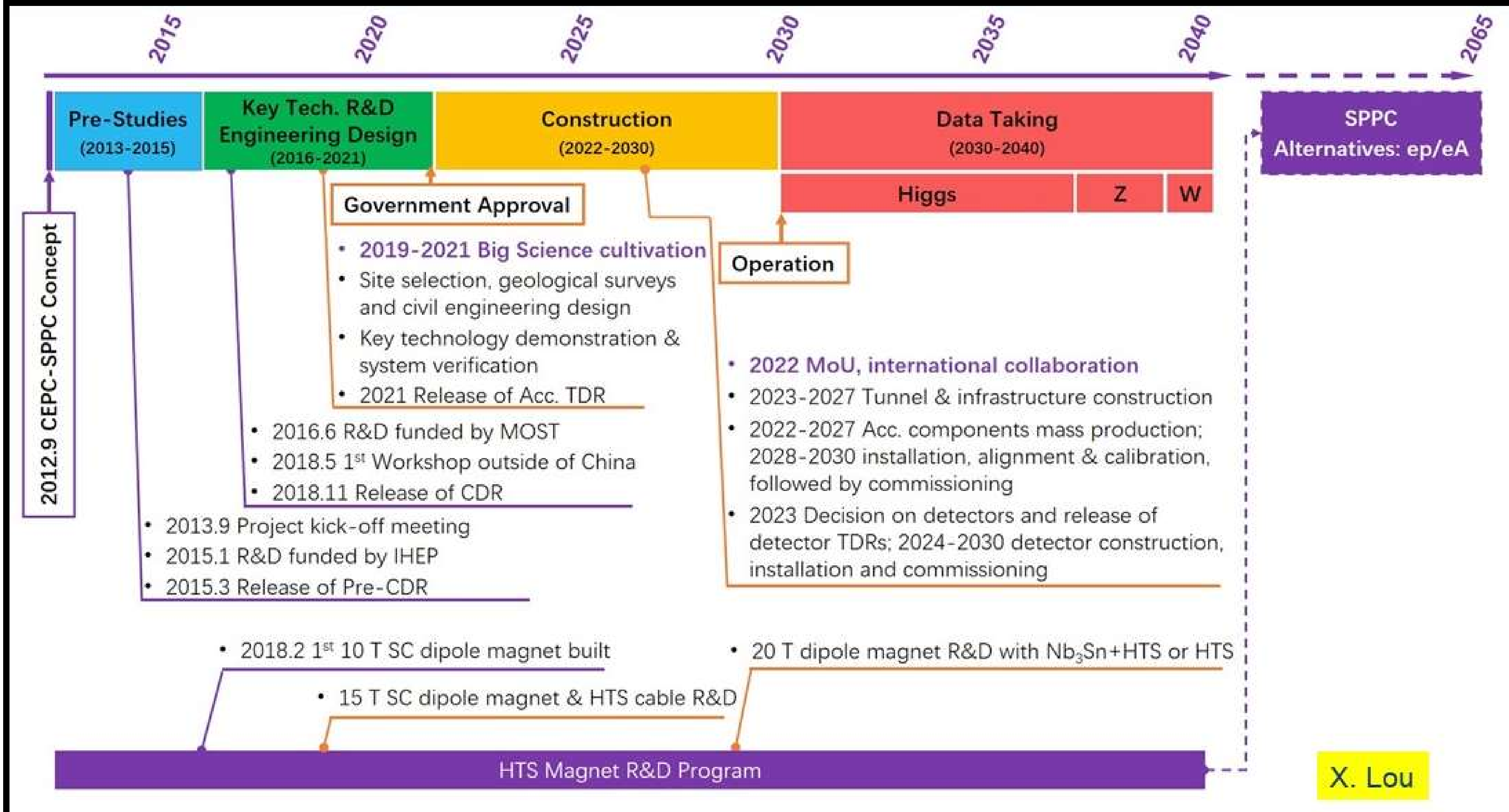
CEPC-SppC: site studies

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)



J. Gao, Granada 2019

CEPC


2015
2020
2025
2030
2035
2040
2065
Pre-Studies (2013-2015)
Key Tech. R&D Engineering Design (2016-2021)
Construction (2022-2030)
Data Taking (2030-2040)
Higgs
Z
W
SPPC Alternatives: ep/eA
2012.9 CEPC-SPPC Concept
Government Approval
• 2019-2021 Big Science cultivation
• Site selection, geological surveys and civil engineering design
• Key technology demonstration & system verification
• 2021 Release of Acc. TDR
Operation
• 2016.6 R&D funded by MOST
• 2018.5 1st Workshop outside of China
• 2018.11 Release of CDR
• 2013.9 Project kick-off meeting
• 2015.1 R&D funded by IHEP
• 2015.3 Release of Pre-CDR
• 2022 MoU, international collaboration
• 2023-2027 Tunnel & infrastructure construction
• 2022-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
• 2023 Decision on detectors and release of detector TDRs; 2024-2030 detector construction, installation and commissioning
• 2018.2 1st 10 T SC dipole magnet built
• 15 T SC dipole magnet & HTS cable R&D
• 20 T dipole magnet R&D with Nb_3Sn+HTS or HTS
HTS Magnet R&D Program
X. Lou

Conclusions

- Huge potential of physics from FCC-ee (or CepC)
  - Study Higgs x10 better than HL-LHC
  - EWPO x10-100 better than LEP
  - → sensitivity to NP in the 10’s TeV range
  - Large potential for HF studies complementary to LHC-b/Belle II
  - Direct sensitivity to new physics

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  - Direct sensitivity to new physics
- 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

Conclusions

❖ **Let's do it!**