The FCC Option

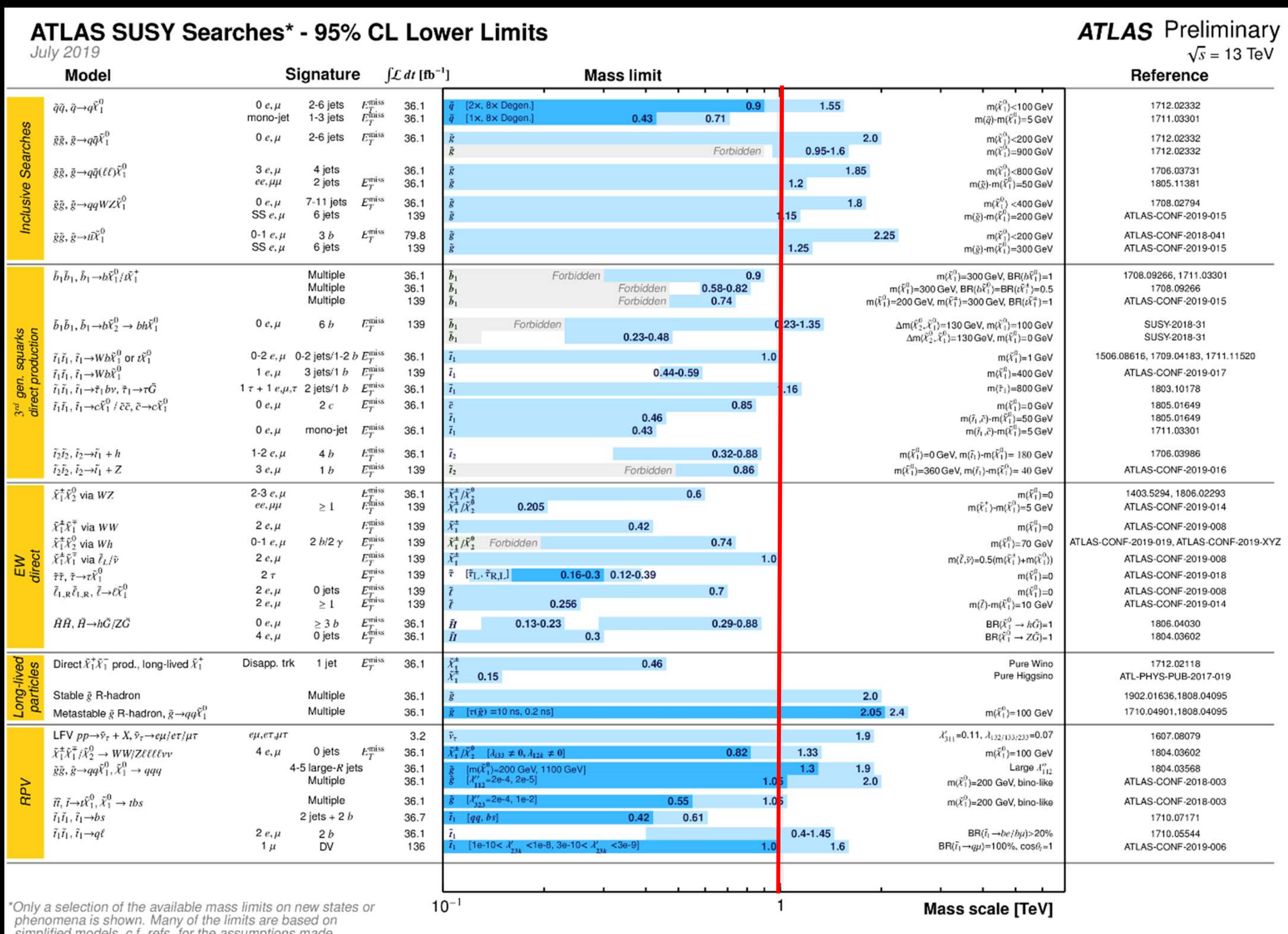
F. Bedeschi, INFN
Roma3, January 29, 2020

Outline

- Very brief motivations
- FCCee
  - Machine and physics
- FCChh
  - Machine and physics
- Schedule and costs
- Final comments

Physics motivations

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



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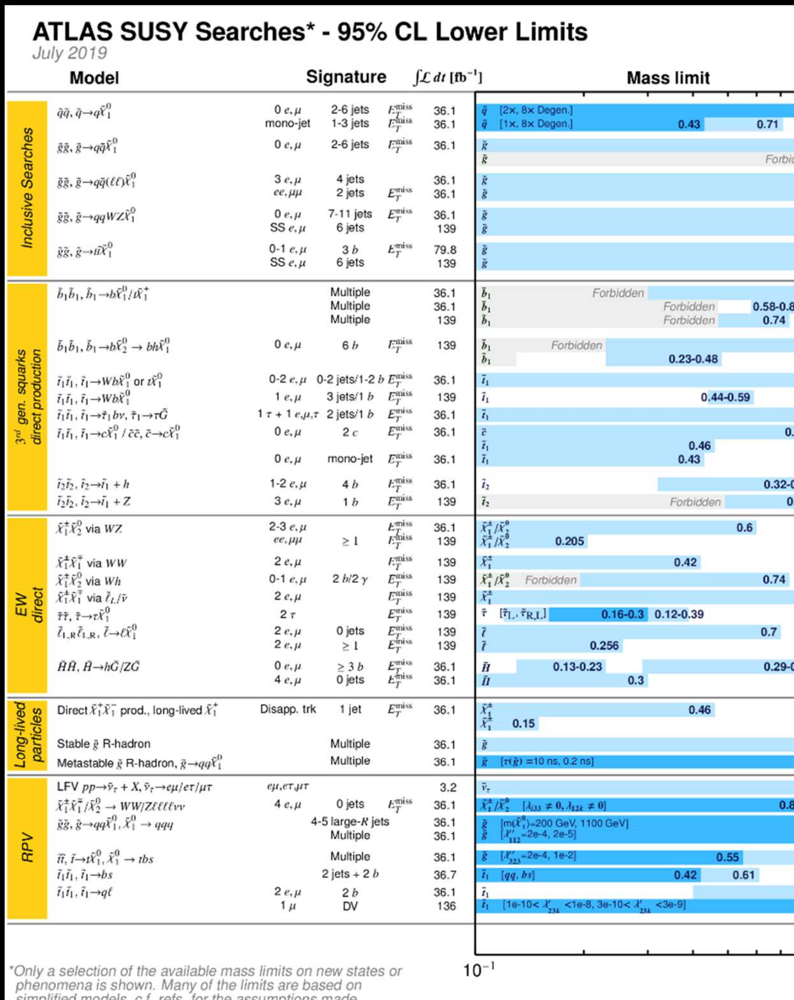

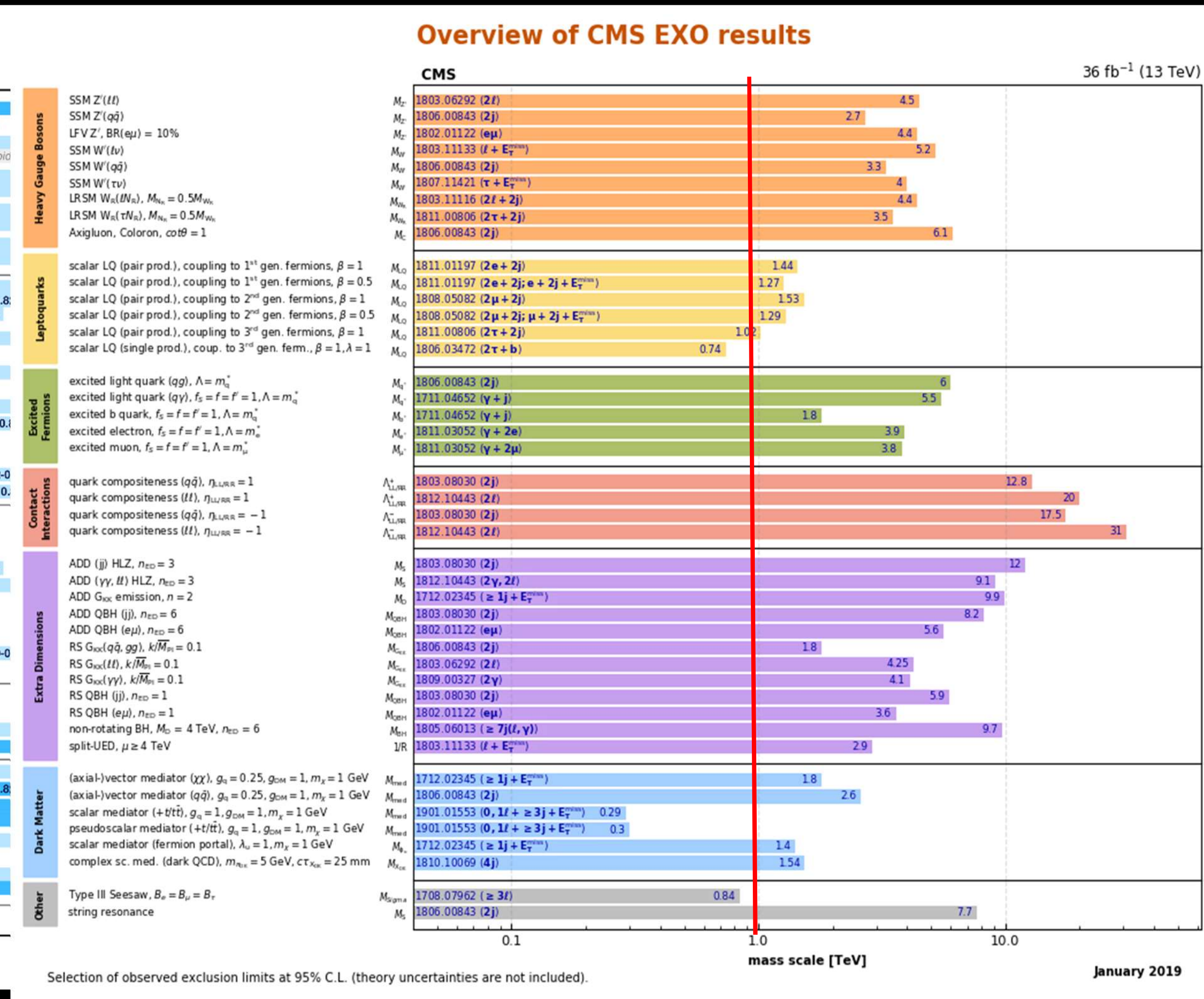

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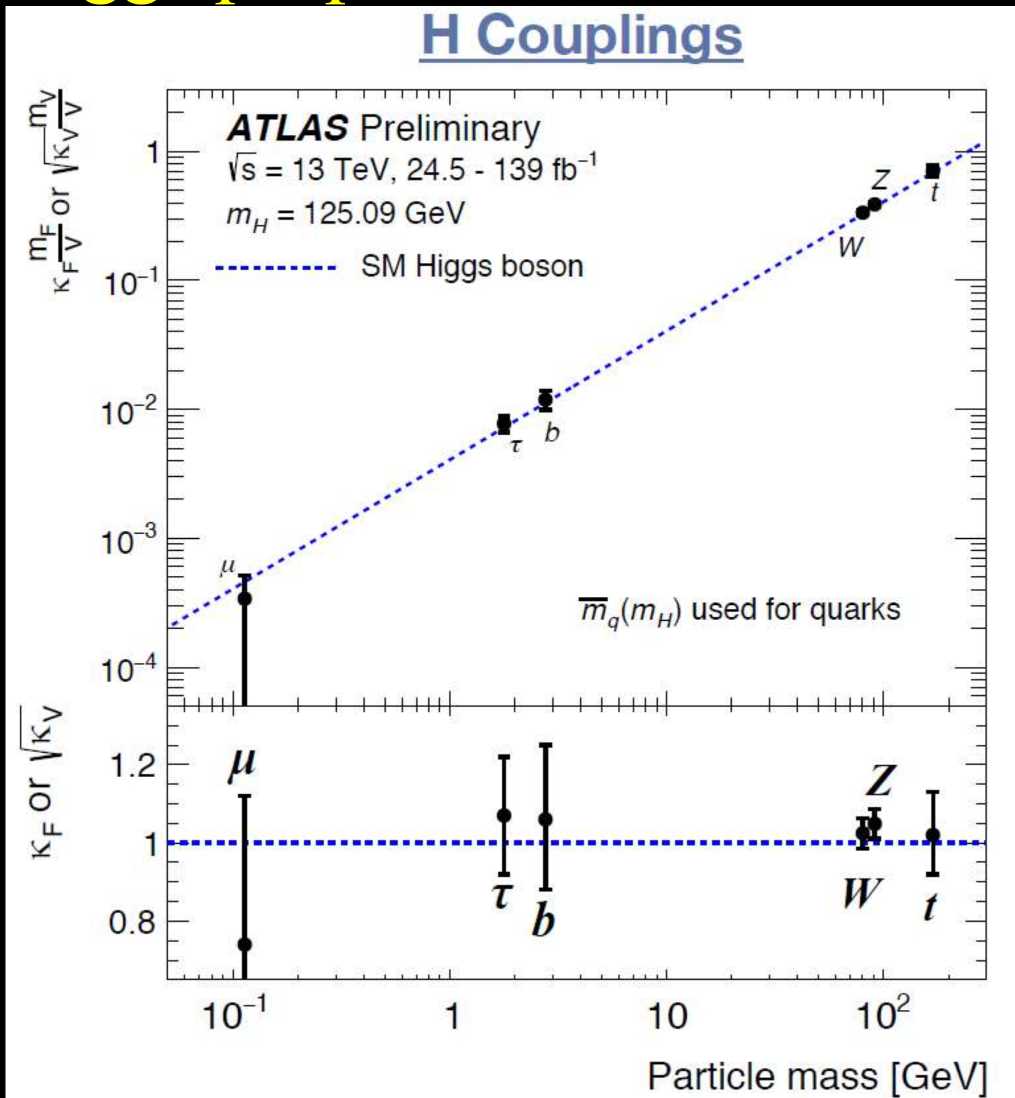

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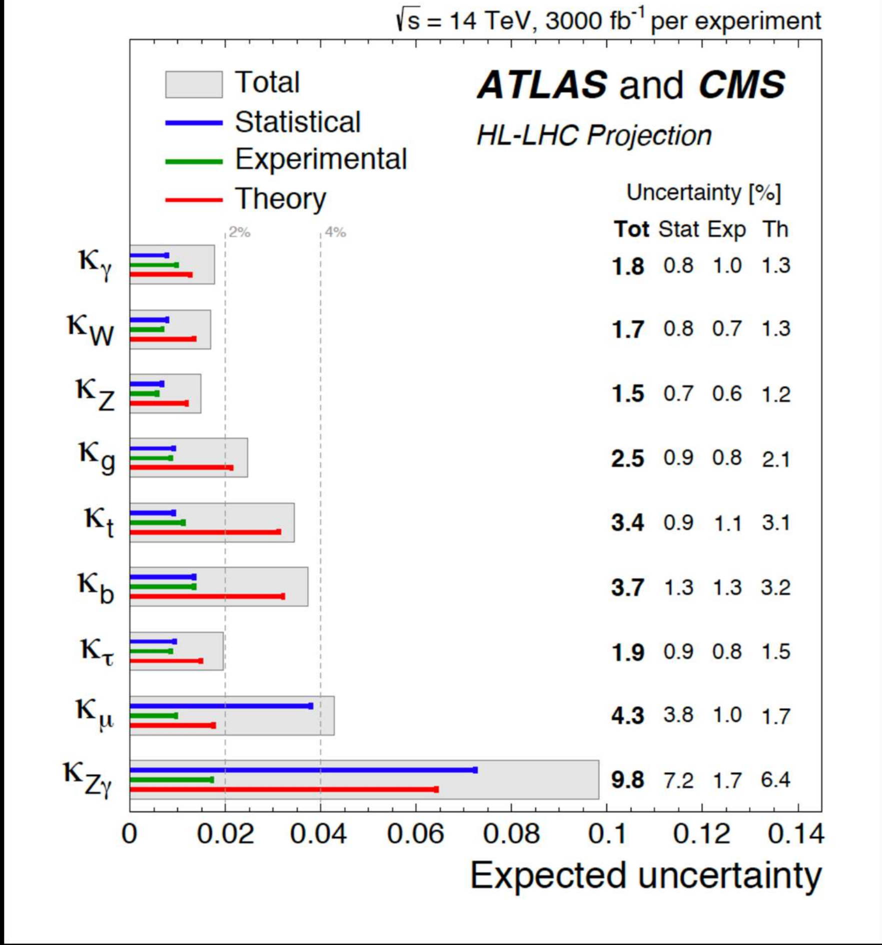
  - After HL-LHC precision level of several %

Granada 2019



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  - Deviation from SM: $\delta \sim v^2/M^2$ $v = 246$ GeV
    - M scale of new physics
    - $M \sim 1 - 10$ TeV → $\delta \sim 6 - 0.06\%$

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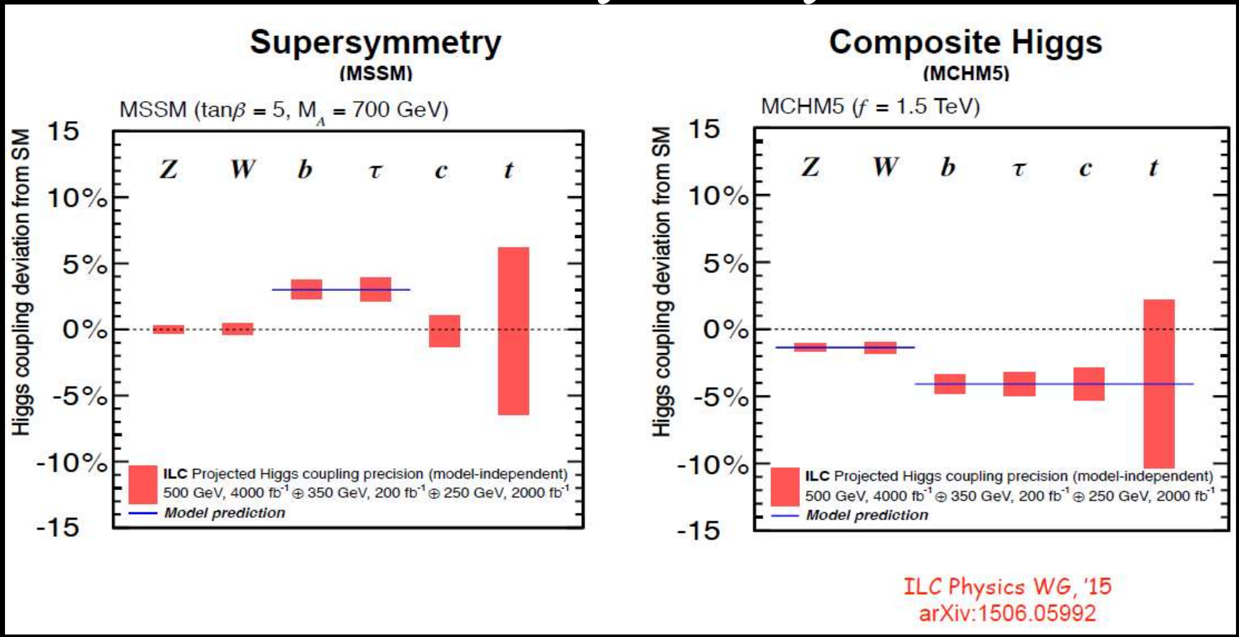
    - M scale of new physics
    - M ~ 1 – 10 TeV → $\delta \sim 6 - 0.06\%$
  - Need < ~ % sensitivity → beyond HL-LHC



Current physics landscape

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- Higgs properties SM-like.
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- … 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 machine in this scenario?

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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  - Stage 1: FCC-ee (Z, W, H, tt)
    - Higgs factory, EW and top factory at highest luminosities.

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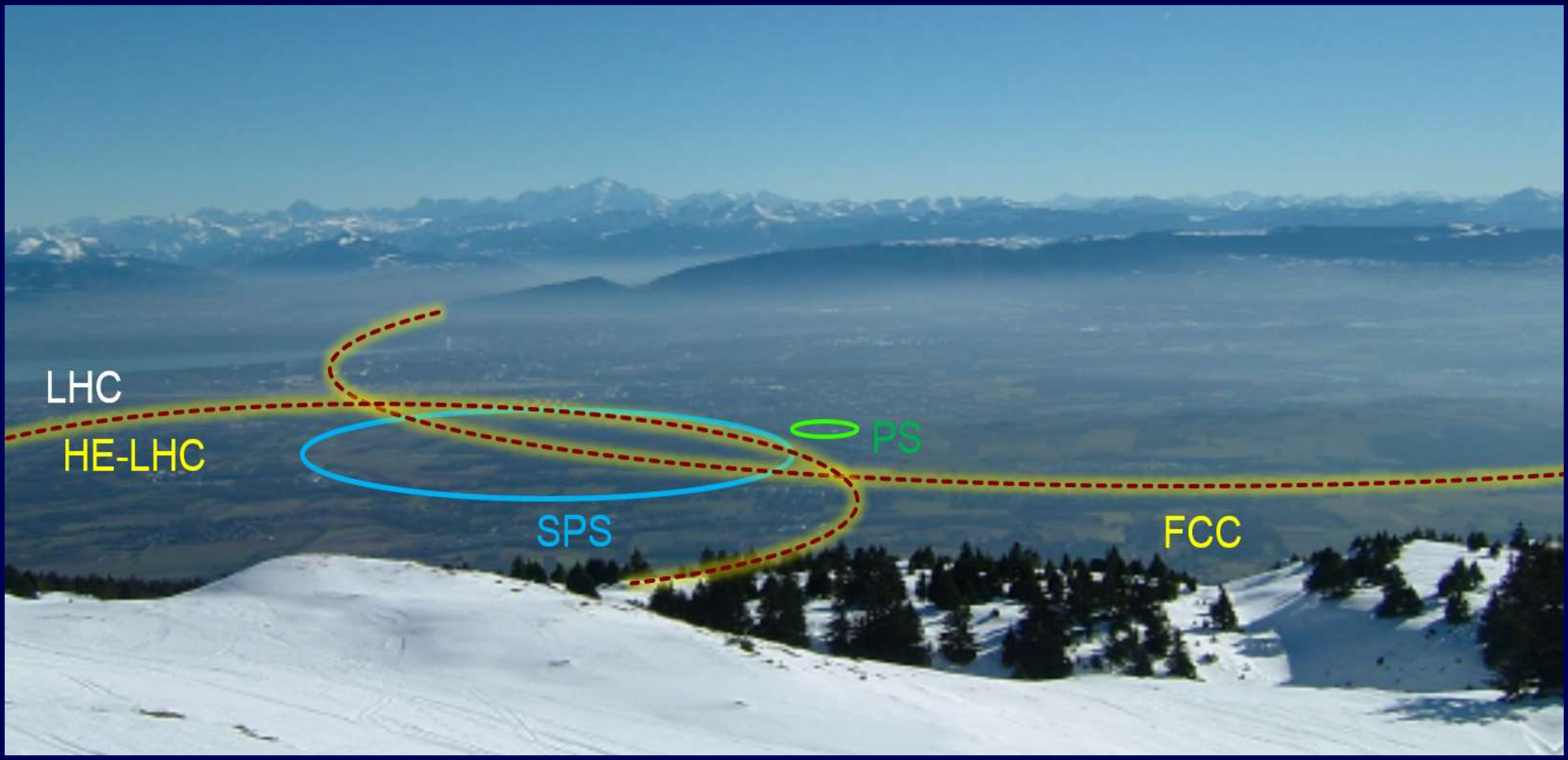
- Comprehensive program to optimize physics opportunities
  - Stage 1: FCC-ee (Z, W, H, tt)
    - Higgs factory, EW and top factory at highest luminosities.
  - Stage 2: FCC-hh (~100 TeV)
    - Natural continuation at energy frontier, with ion and eh options.
    - Complementary physics
    - Common civil engineering and technical infrastructures
    - Integrating an ambitious high-field magnet R&D program

The e+e- machine

FCC-ee

- Double ring e+e- collider ~ 100 km
  - RF power limited to 50 MW/beam
  - 2 IP currently - 4 IP possible



FCC-ee

- Double ring e+e- collider ~ 100 km
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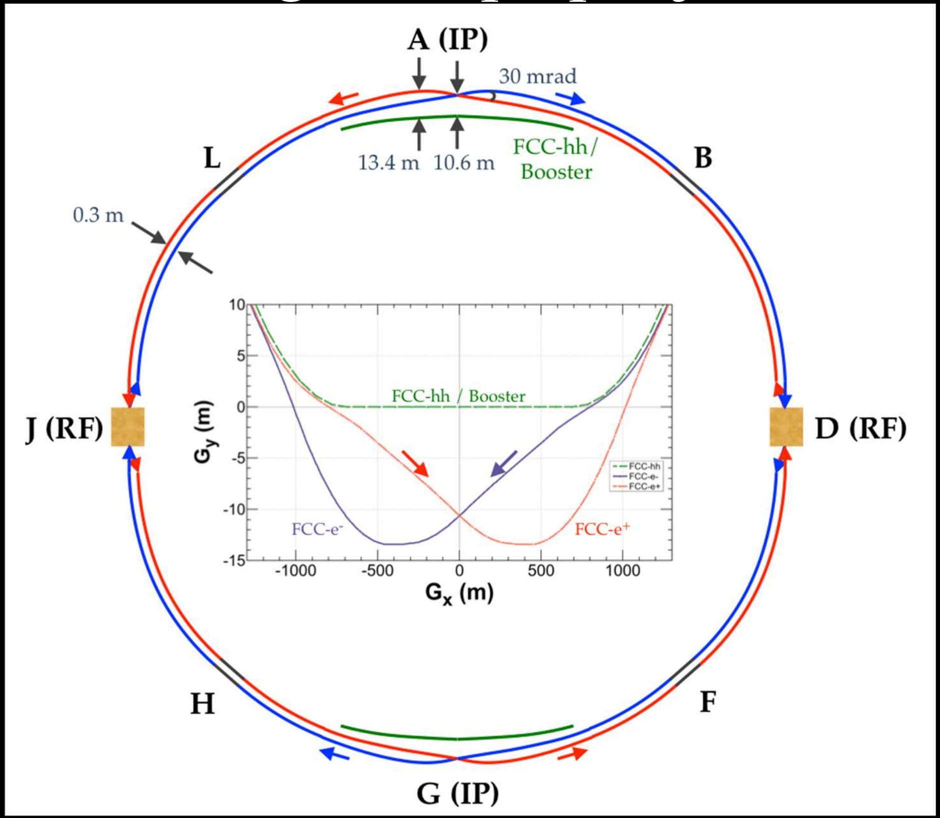
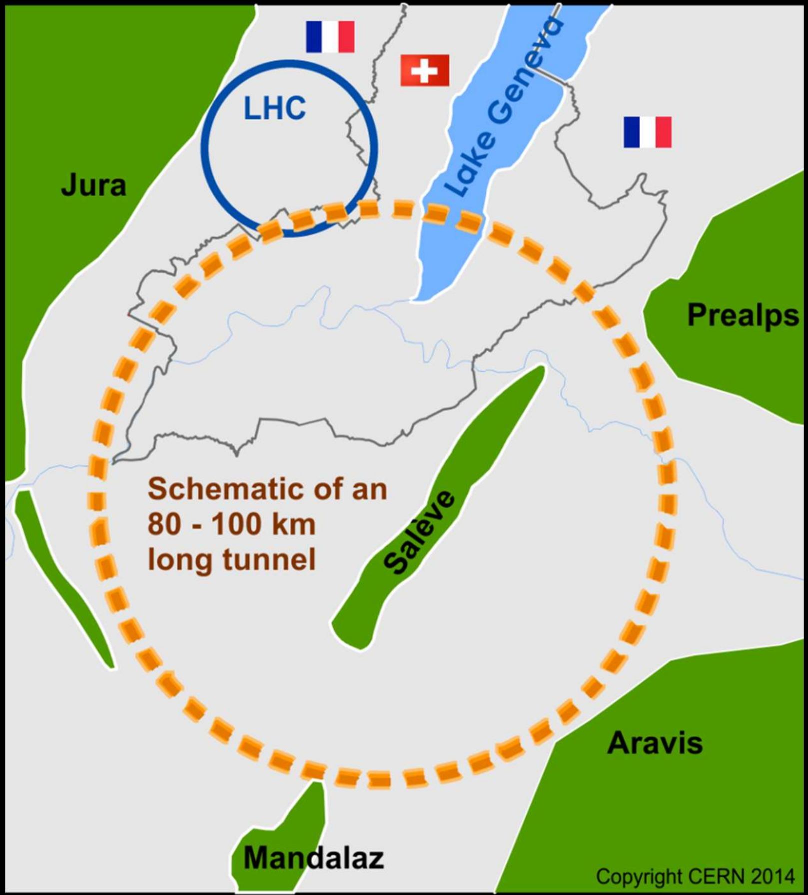
  - 2 IP currently - 4 IP possible
  - Booster ring for top up injection



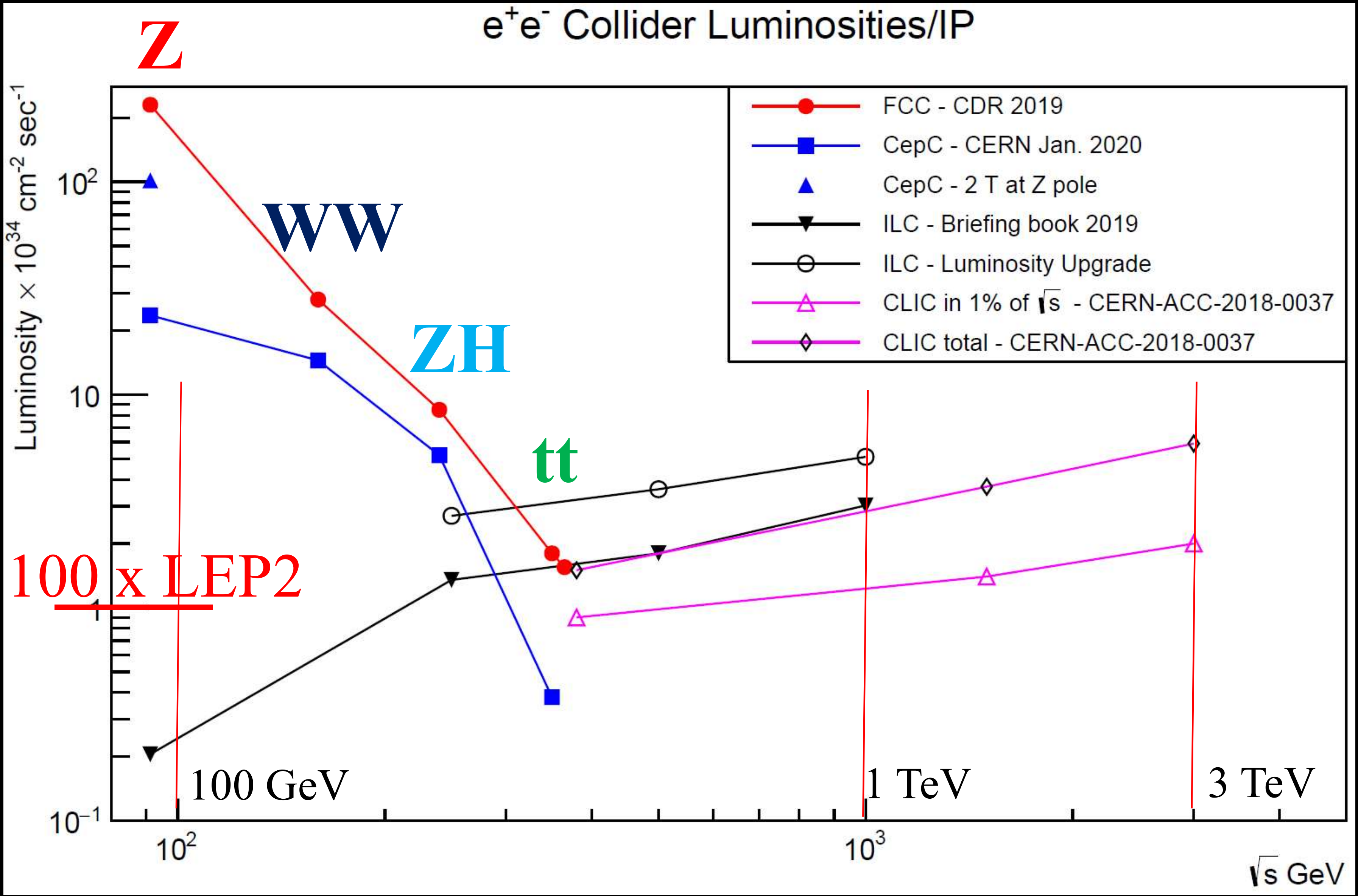


FCCee parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

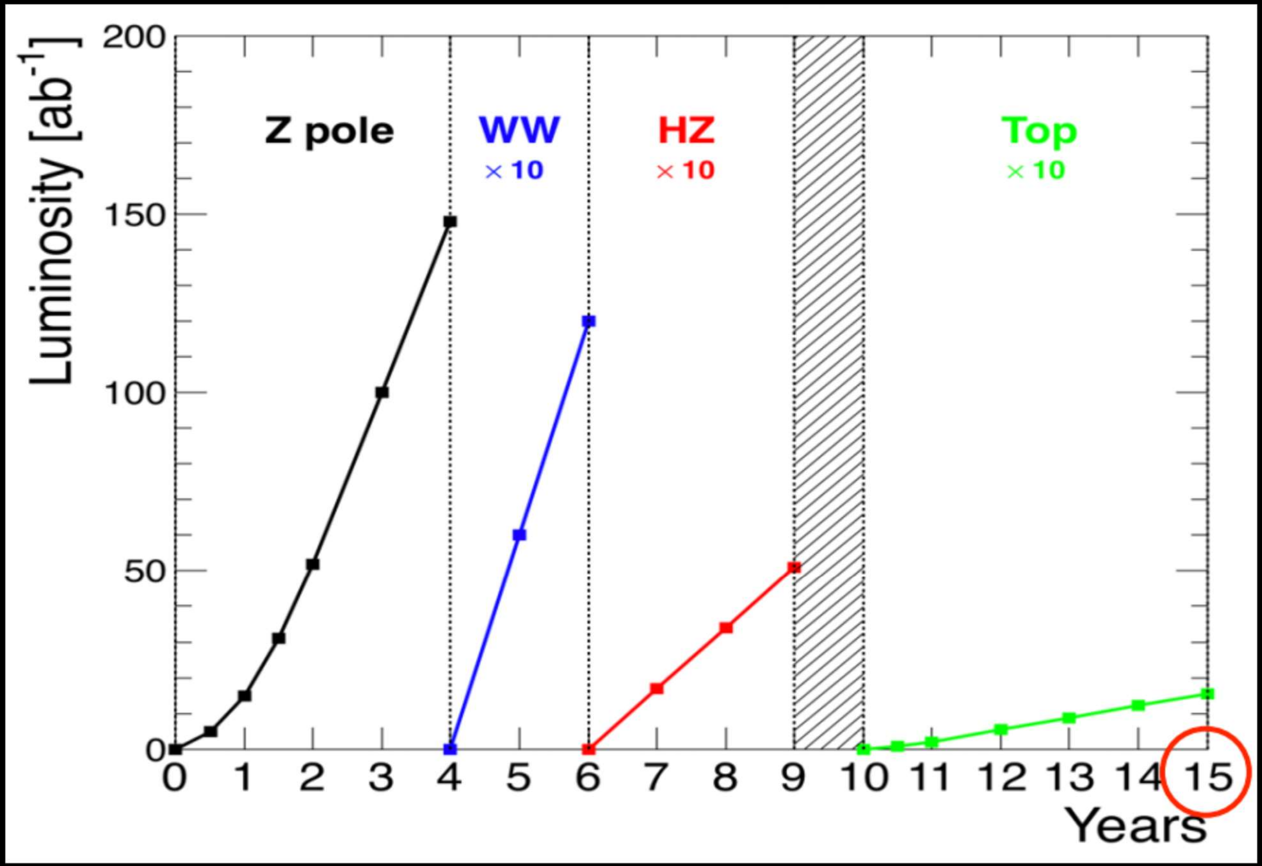
- SR power 50 MW/beam
- Total site power <300 MW

Luminosity comparisons



Physics at FCC-ee

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



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- Higgs factory
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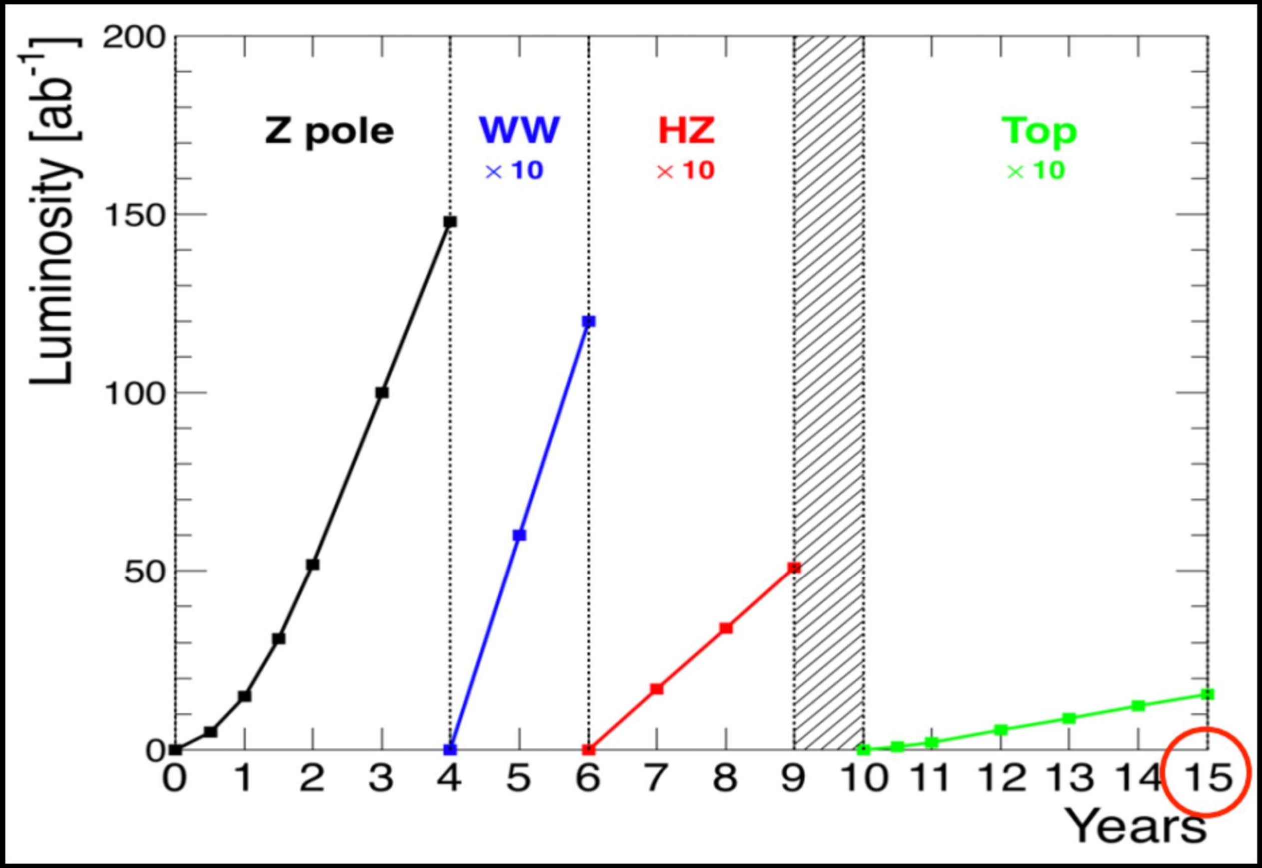
- EW & Top factory
  - $5x10^{12}$ e+e- → Z
  - 10^8 e+e- → W+W- ;
  - 10^6 e+e- → tt



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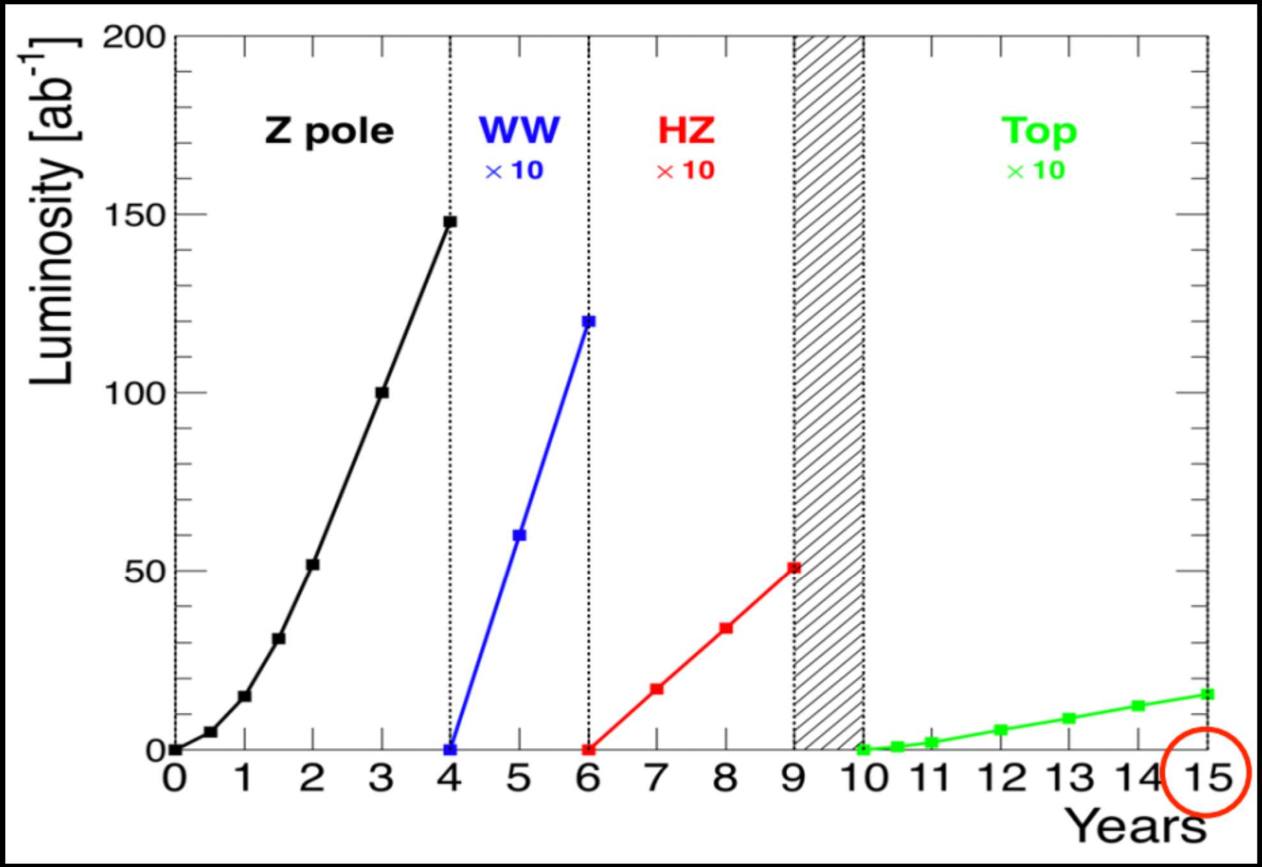
  - 10^{12} e+e- → bb, cc
  - 10^{11} e+e- → τ+τ-



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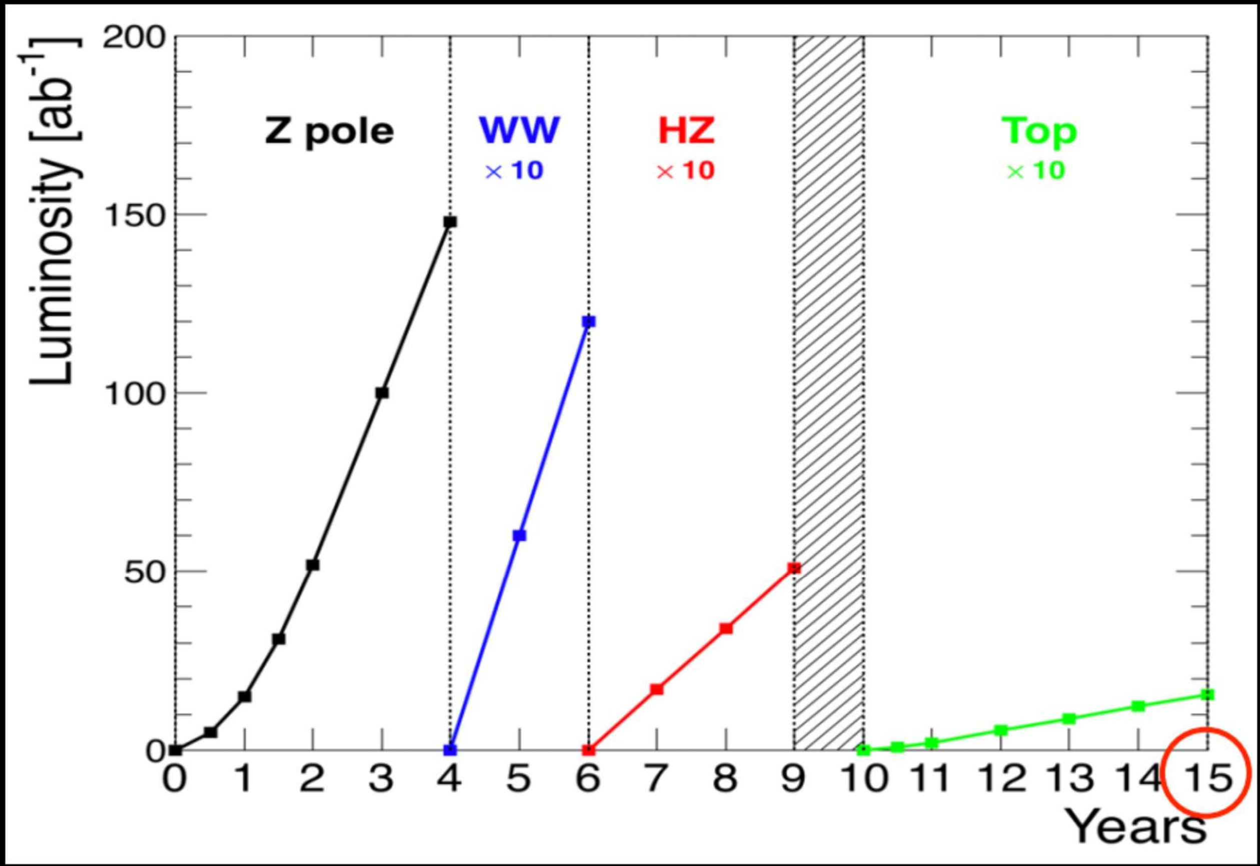
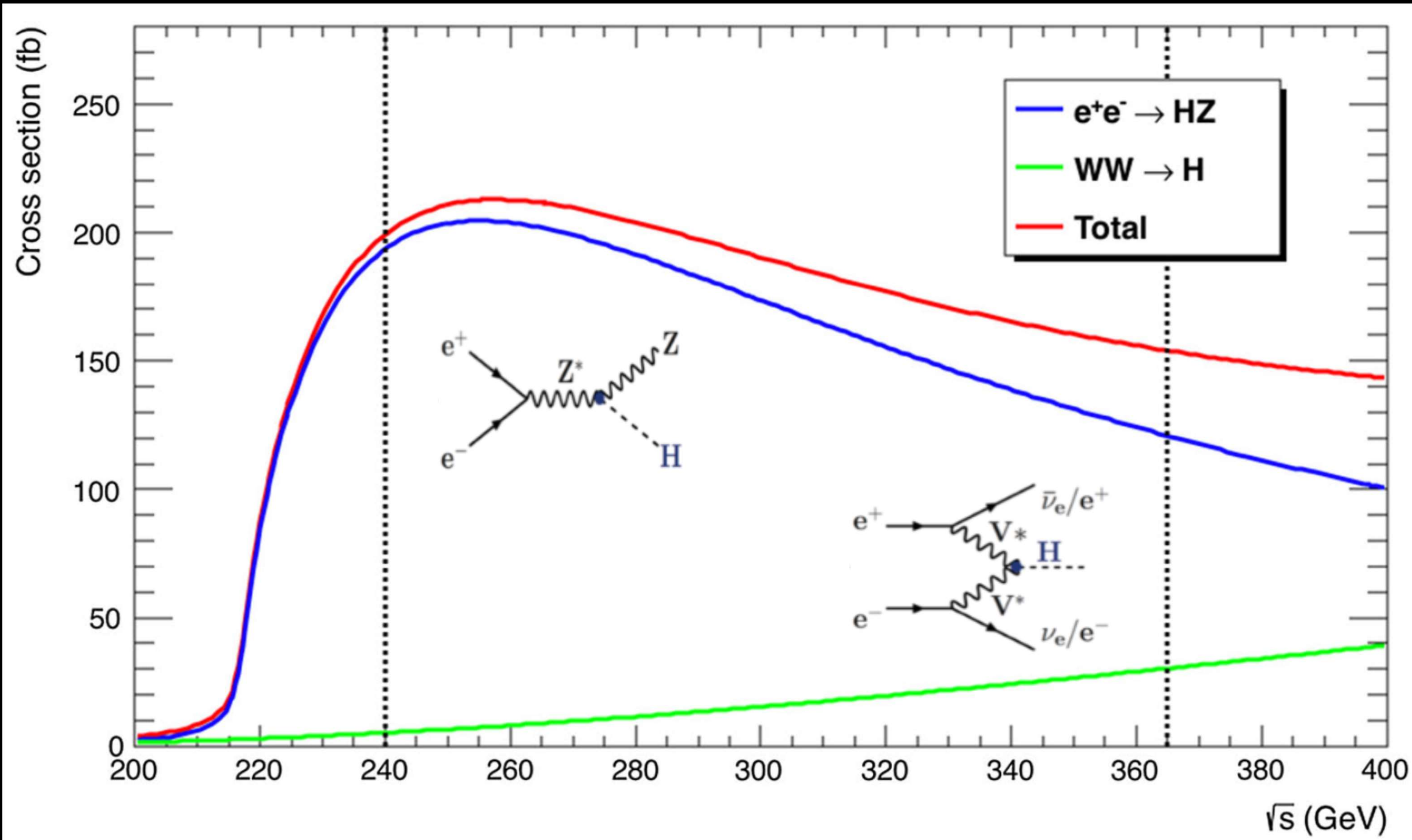
- Potential discovery of NP
  - ALPs, RH ν's, …

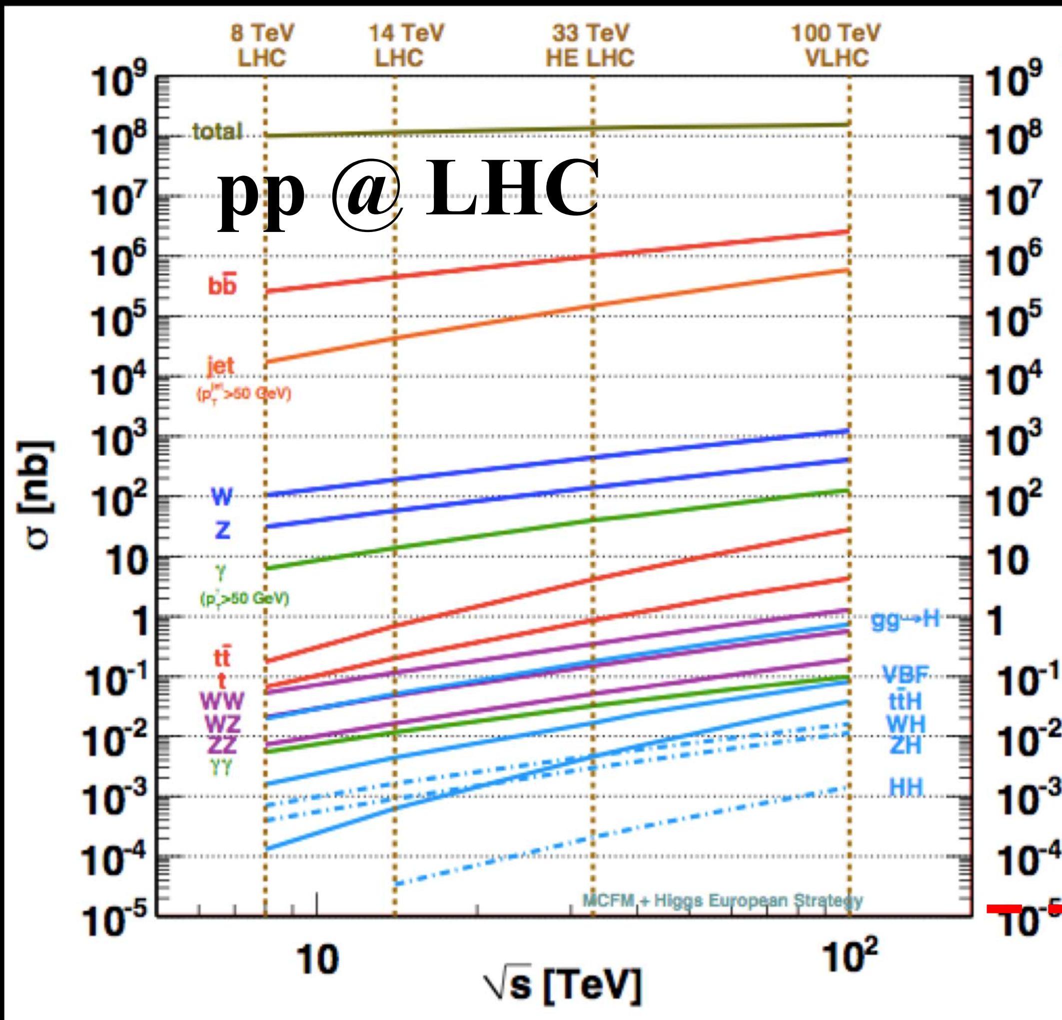


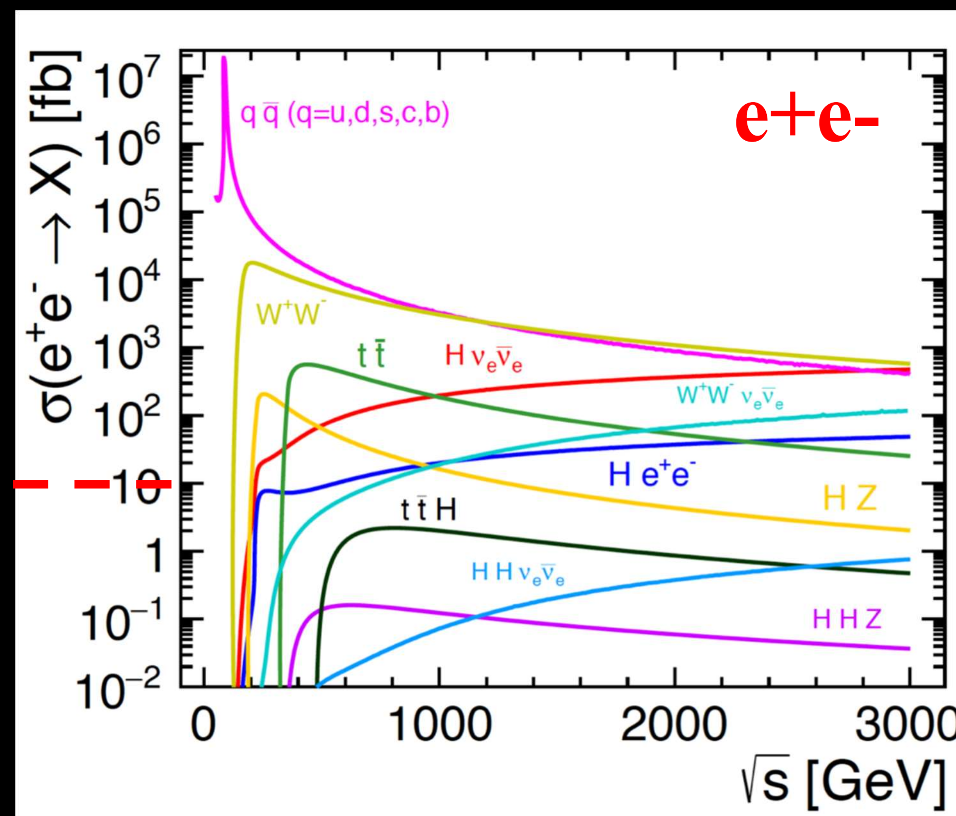
Higgs production



Higgs production

Very clean production in e+e-

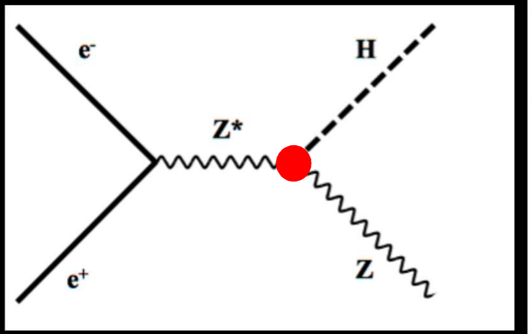


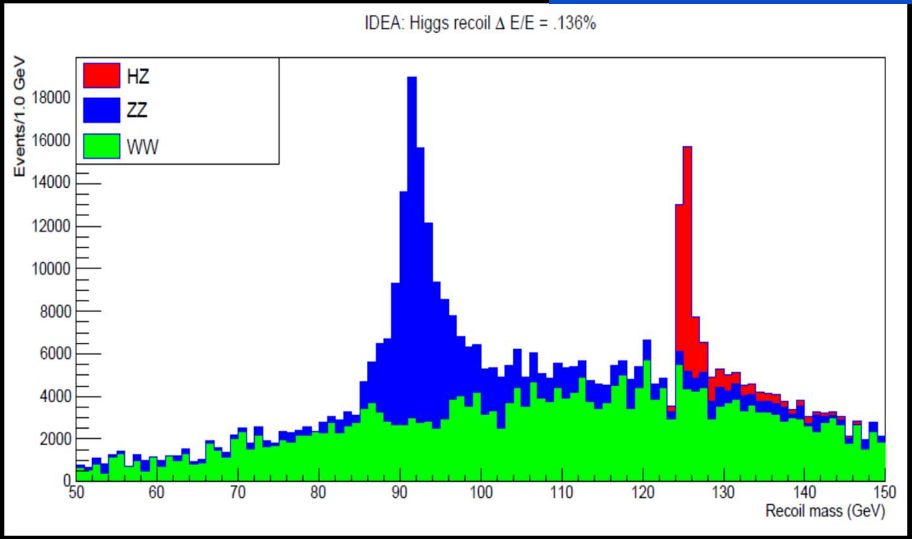


Higgs total width

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

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





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- Higgs recoil provides model independent measurement of coupling to Z
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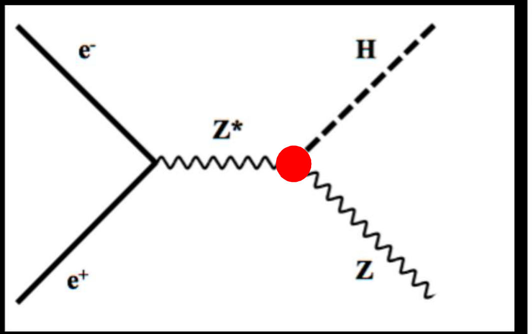
  - Critical:
    - Beam energy spread: SR+BS



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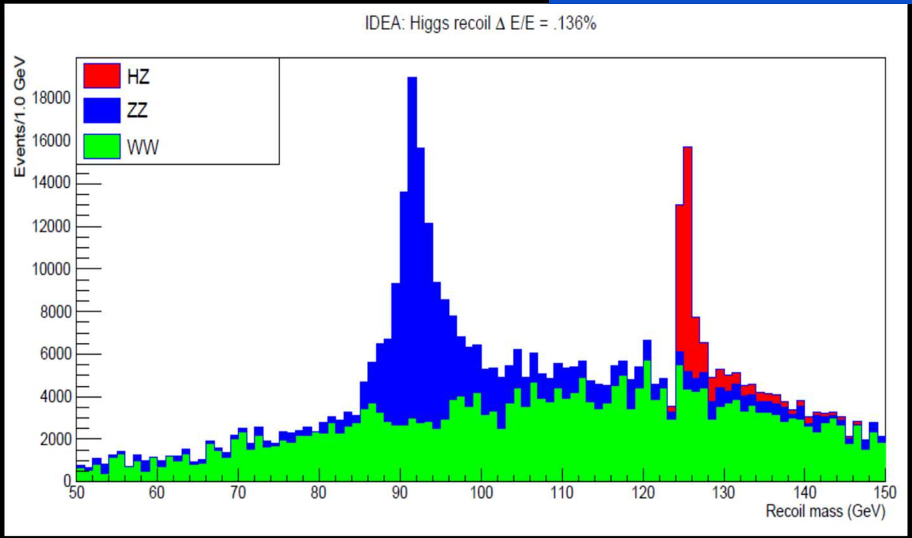

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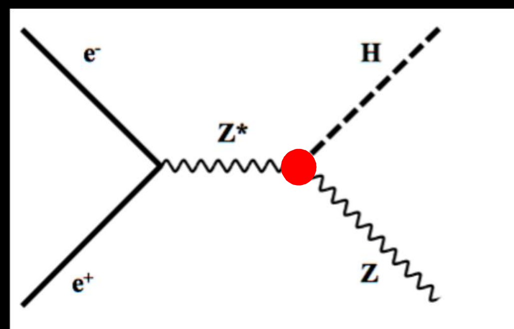

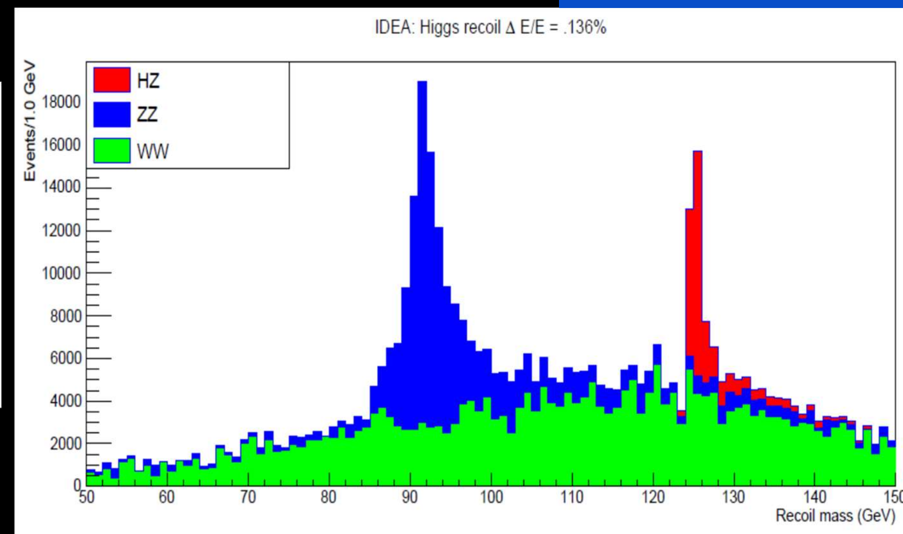

  - Critical:
    - Beam energy spread: SR+BS

- 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

❖ Results limited only by statistics

κ EFT

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\rightarrow 365}$
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**

Higgs coupling fits

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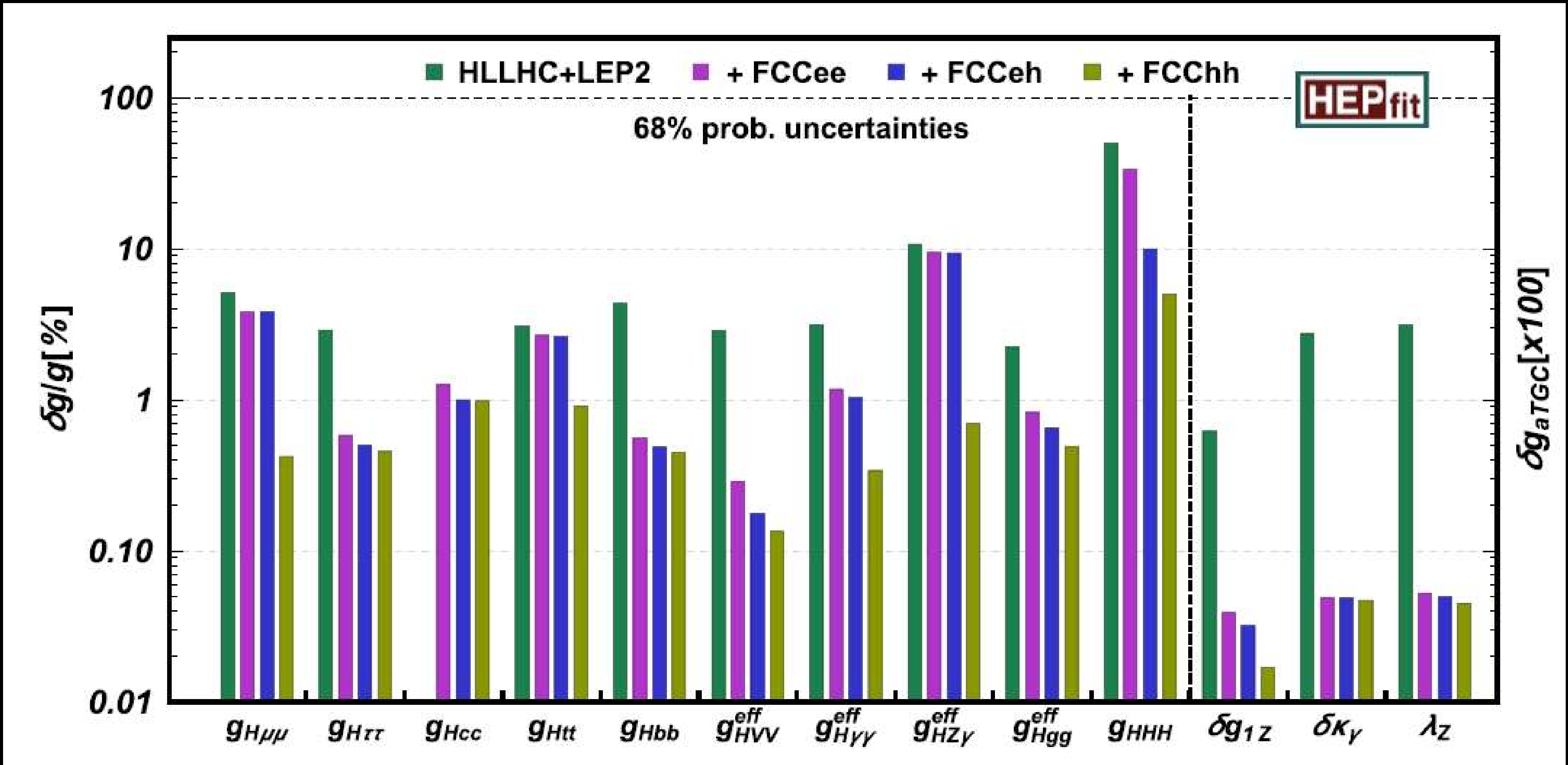
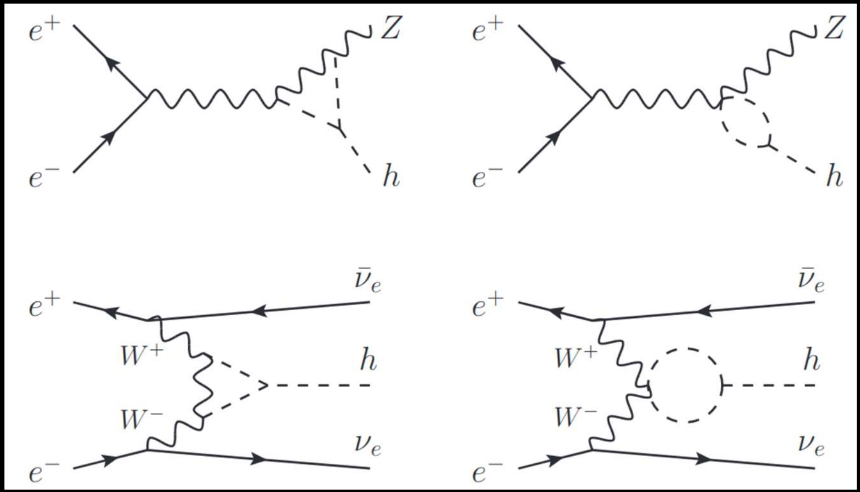


Triple Higgs

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



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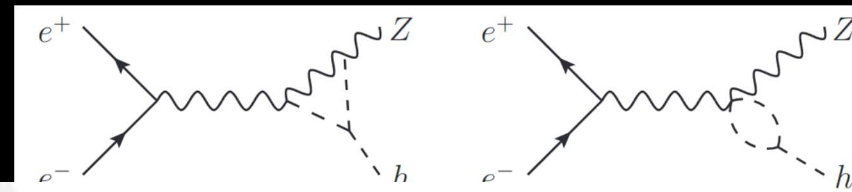

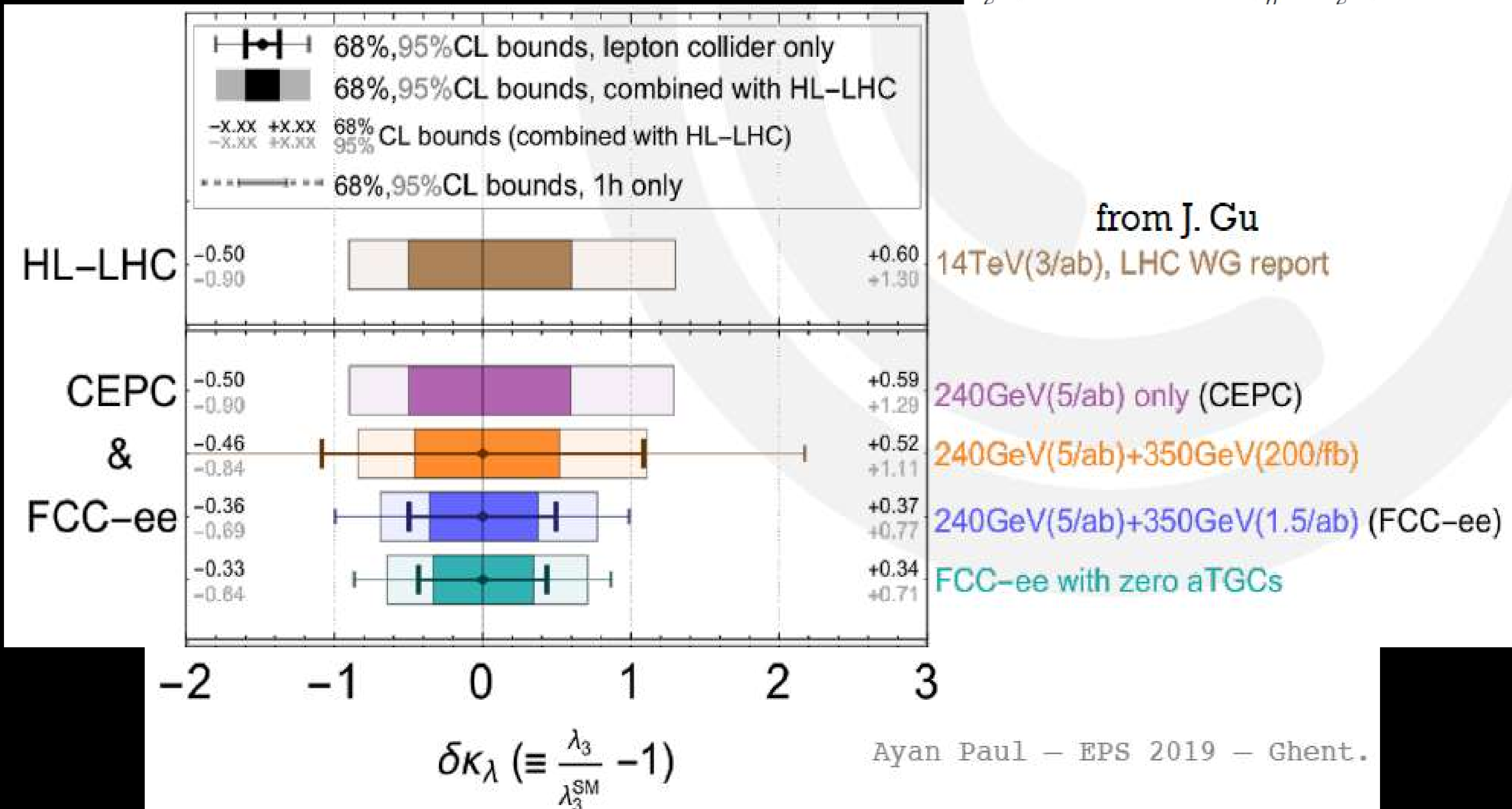

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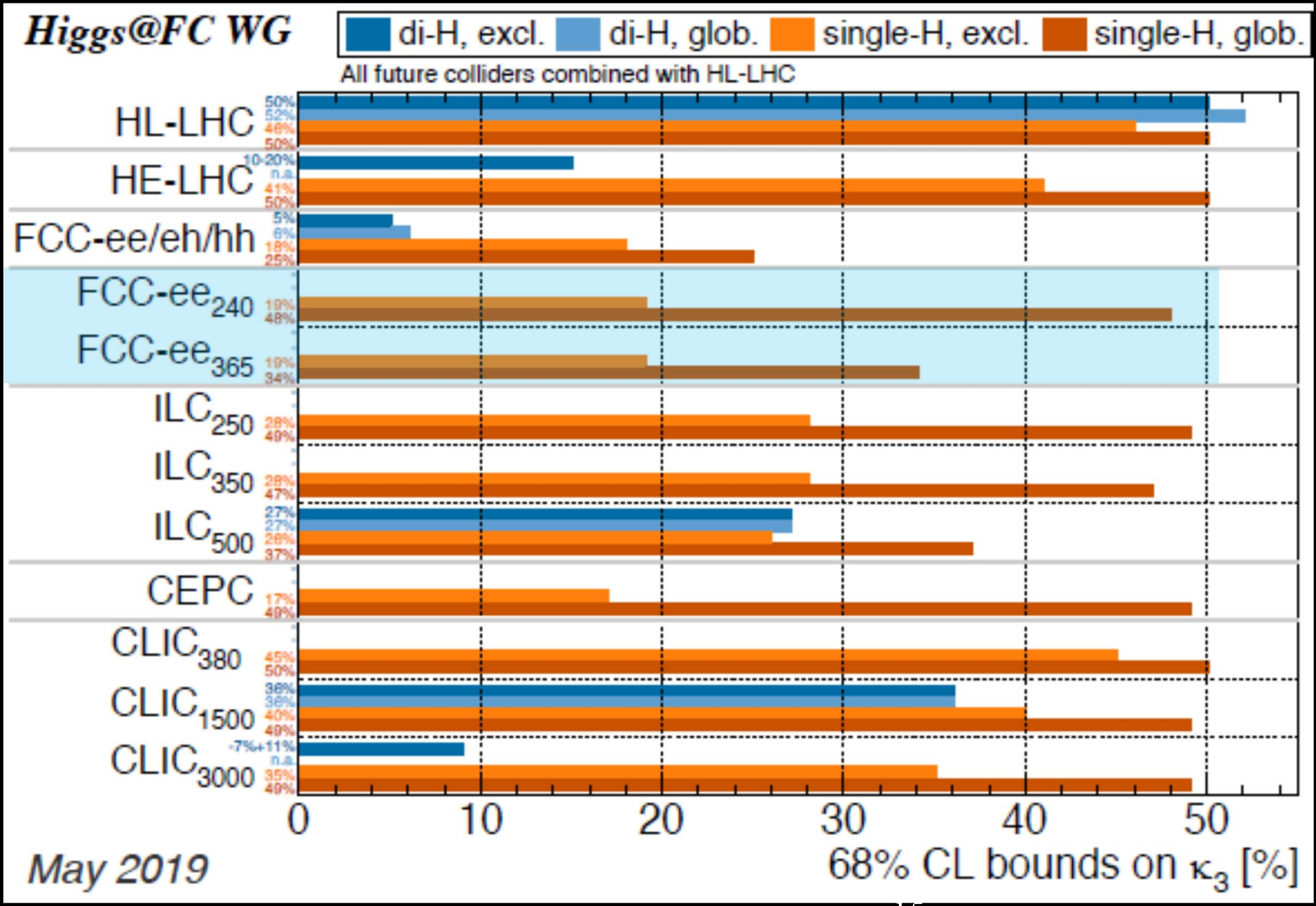

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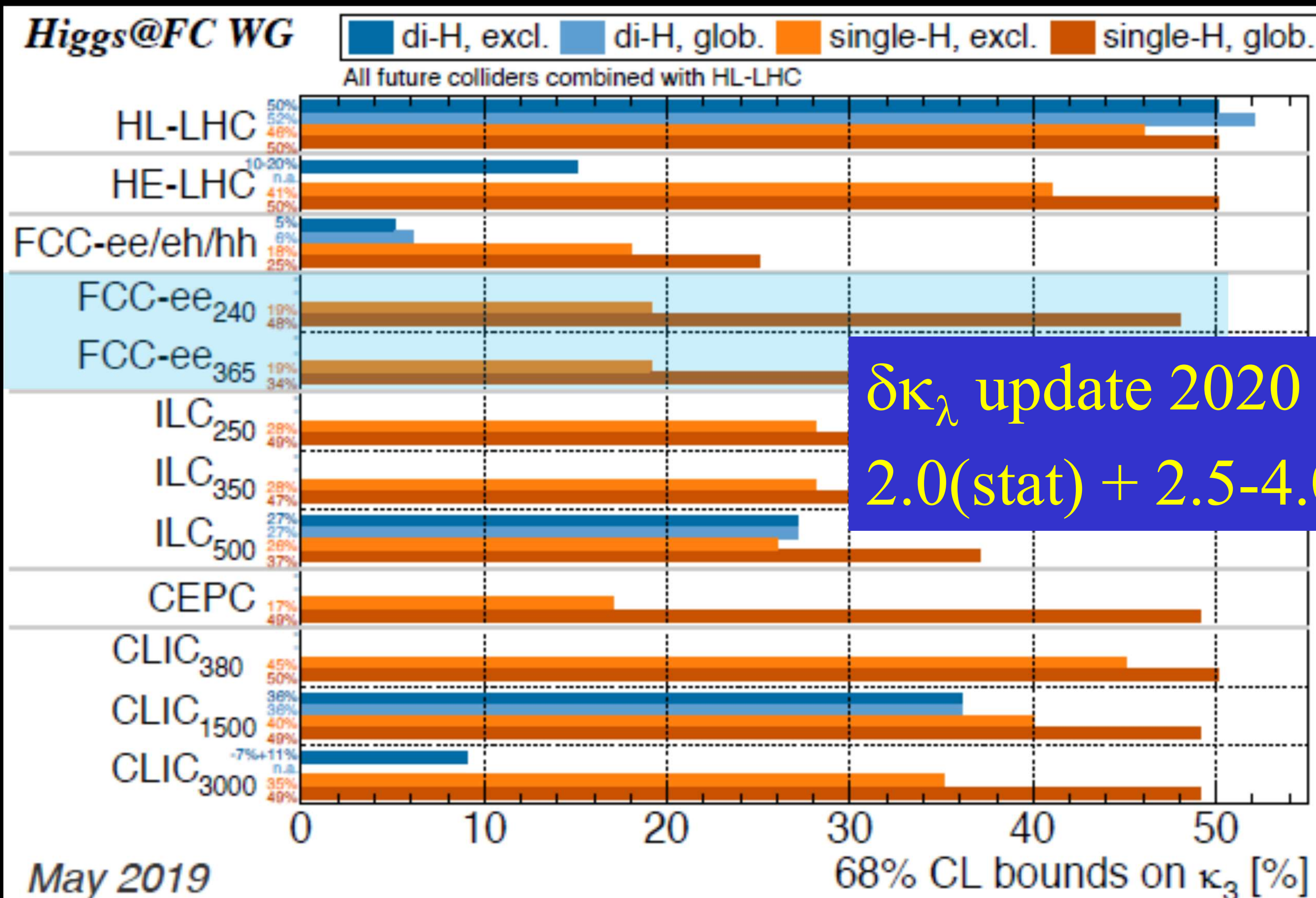


$\delta\kappa_\lambda$ update 2020 FCChh
2.0(stat) + 2.5-4.0(syst) %

EWK

INFN Istituto Nazionale di Fisica Nucleare

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

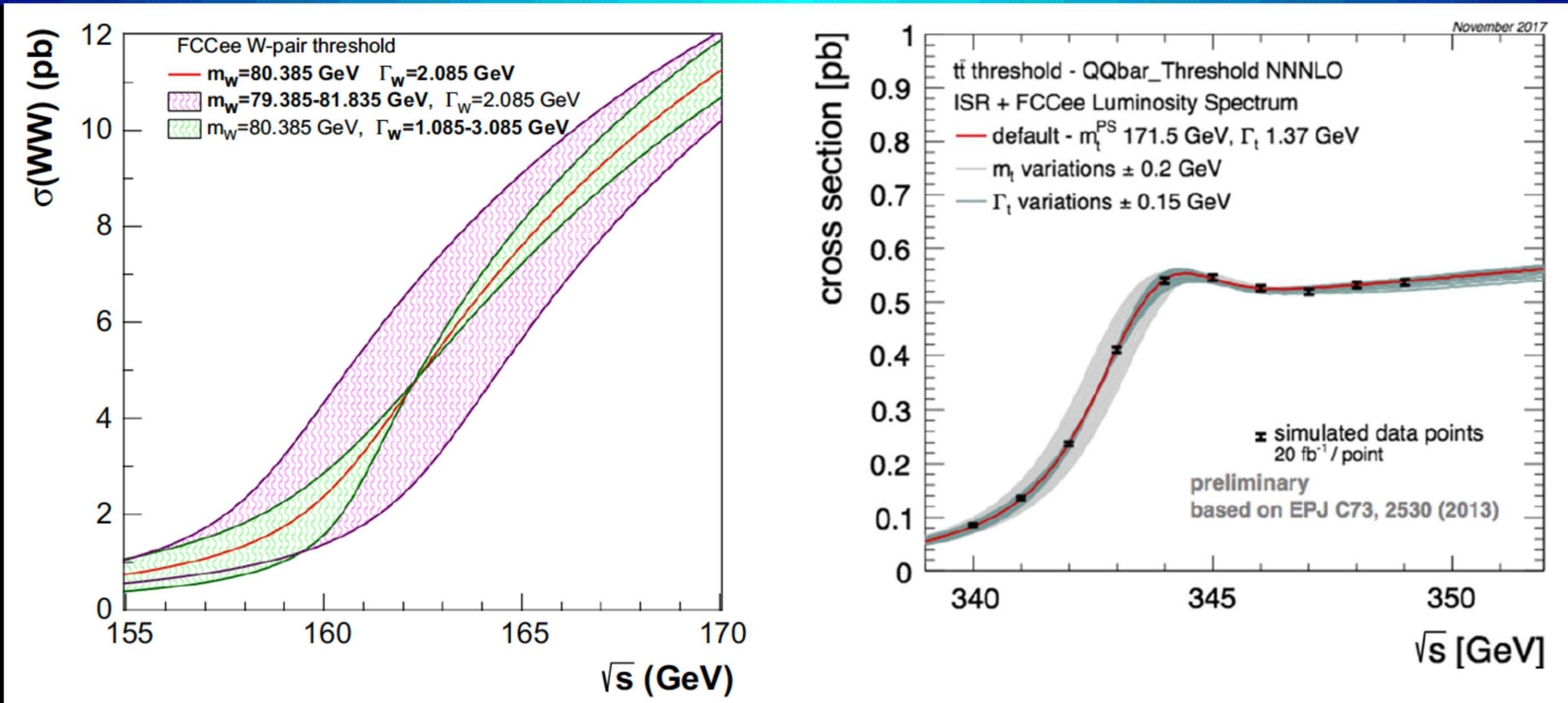
Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	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
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
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
$\lambda_{top}/\lambda_{top}^{SM}$	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

Z pole

WW

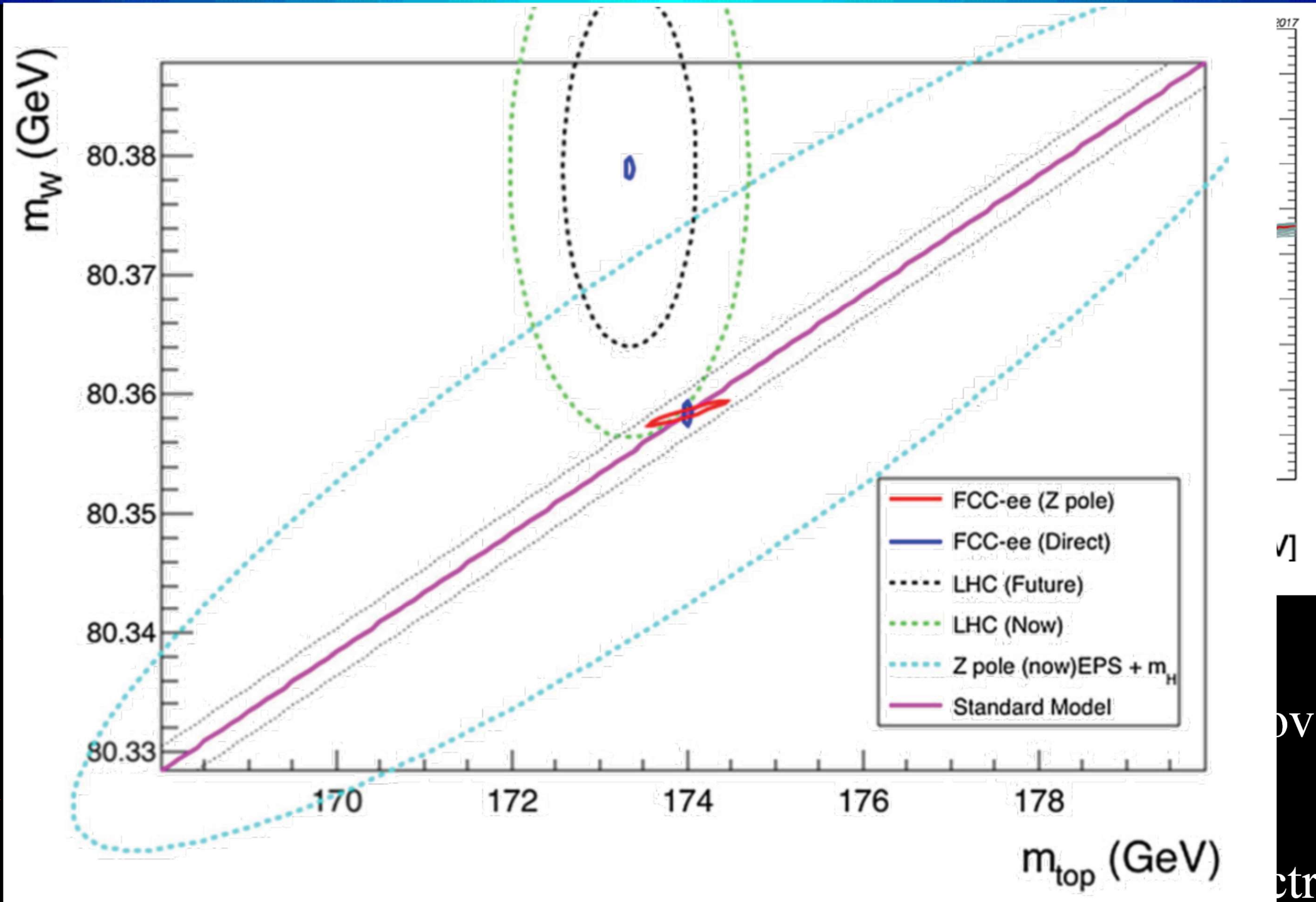
tt

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

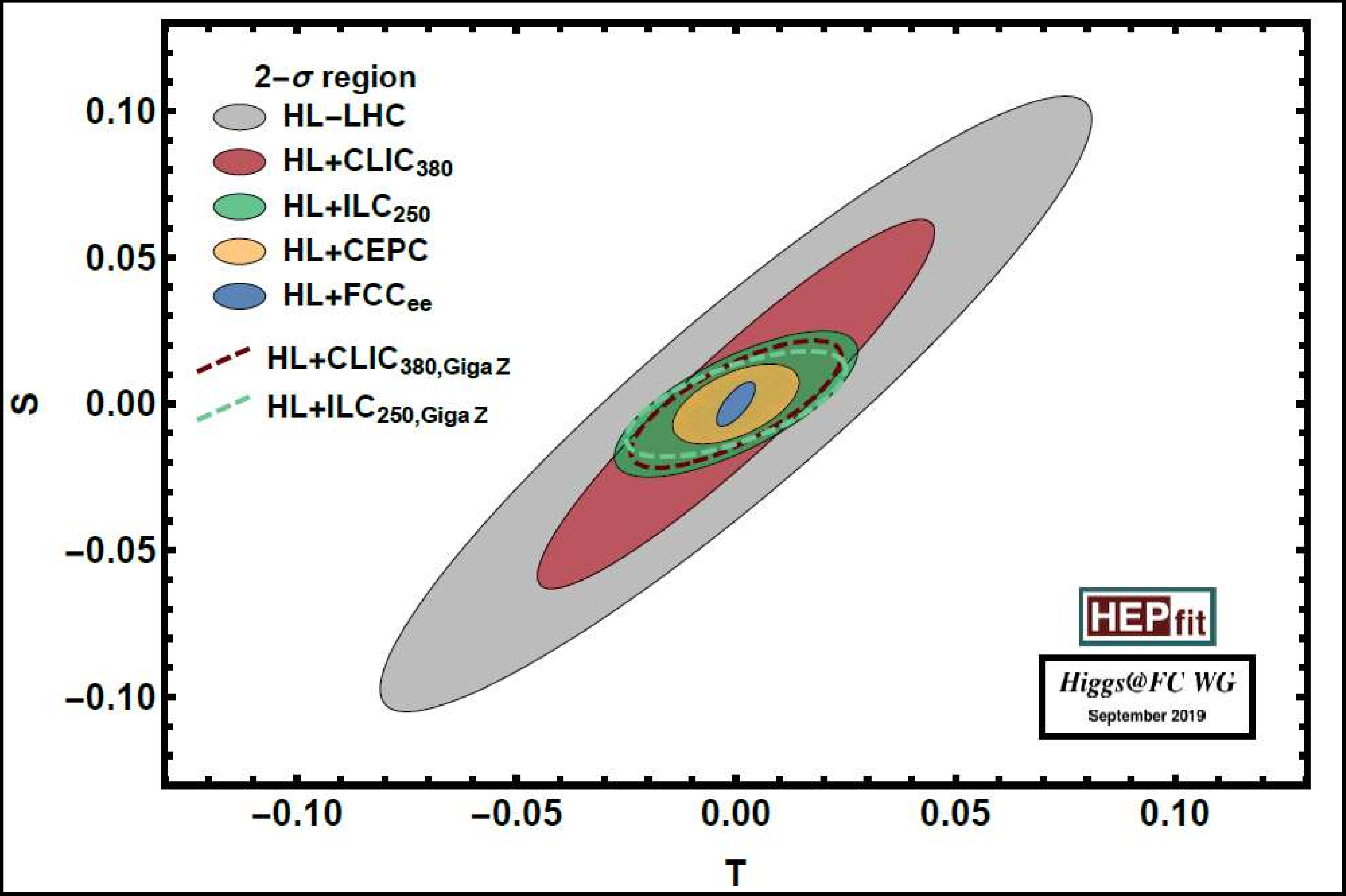


ove

ctrum

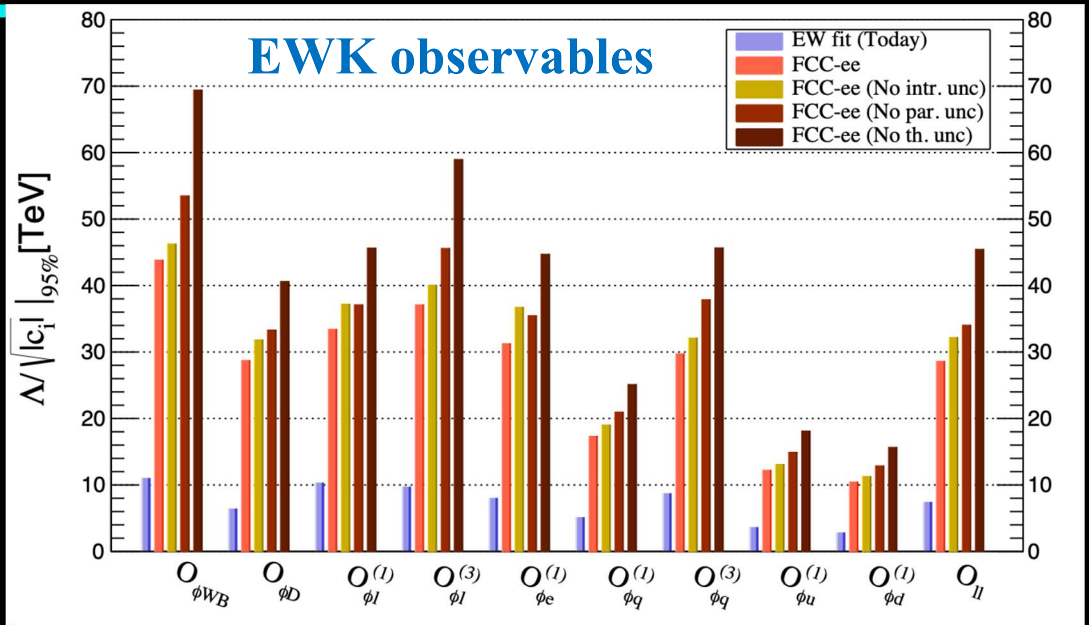
S, T parameters (Peskin–Takeuchi)

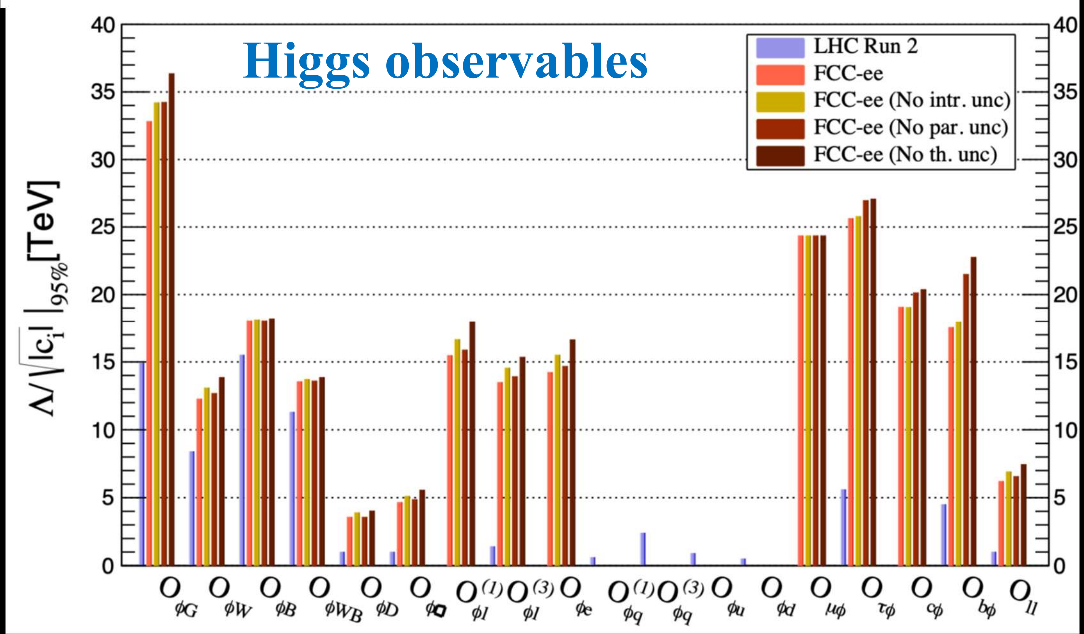
❖ Comparison of Higgs factories



NP sensitivity from EFT fits

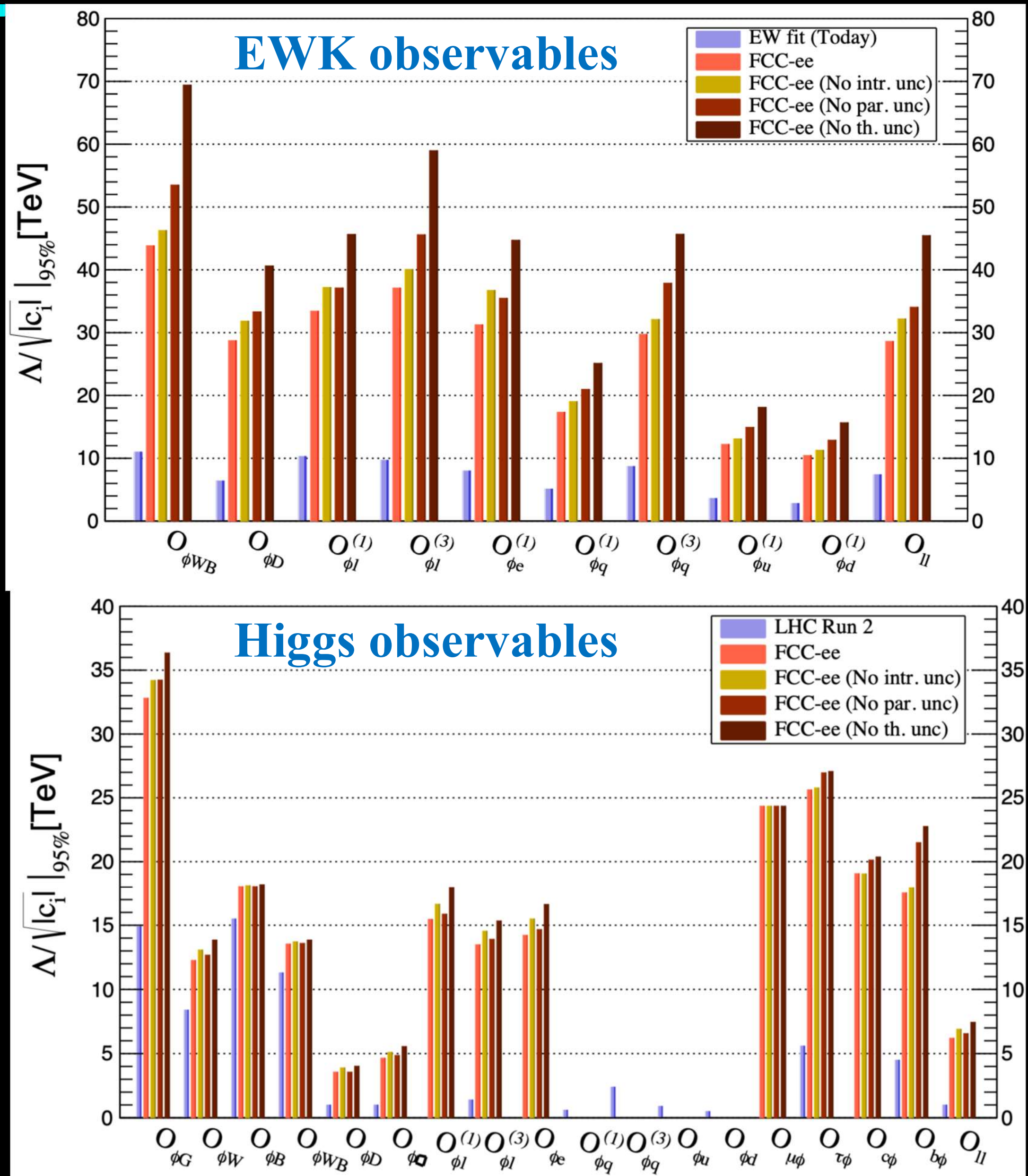
- From exclusive fits
  - Reach to several 10's TeV





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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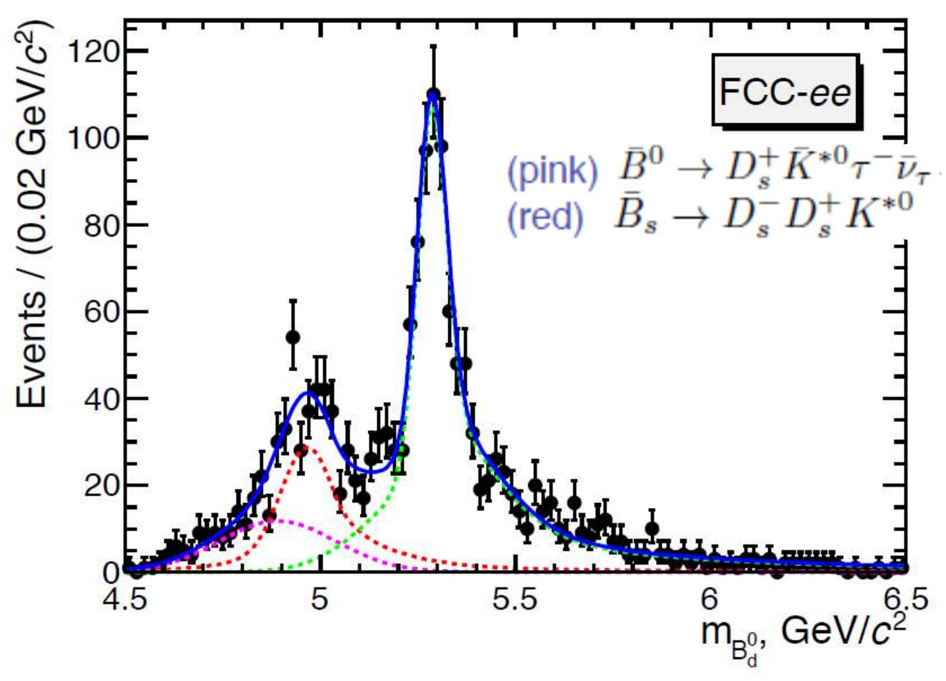
❖ Example:

➢ Lepton universality

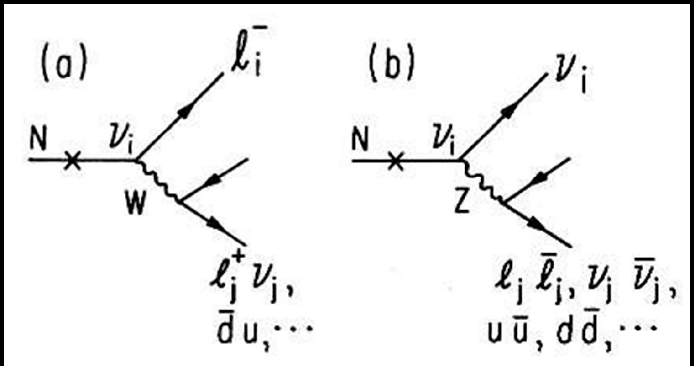
in $B^0 \rightarrow K^{*0}\ \tau+\tau-$



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	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$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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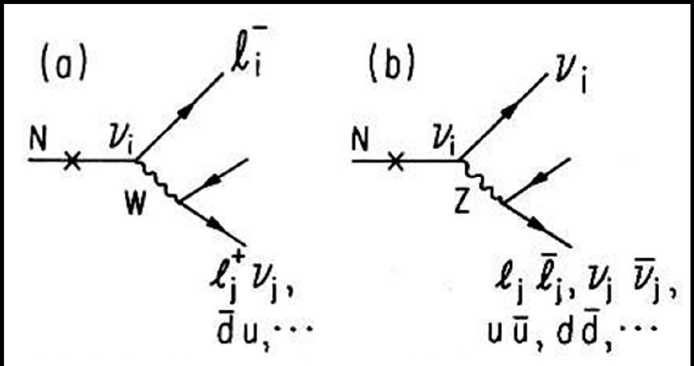

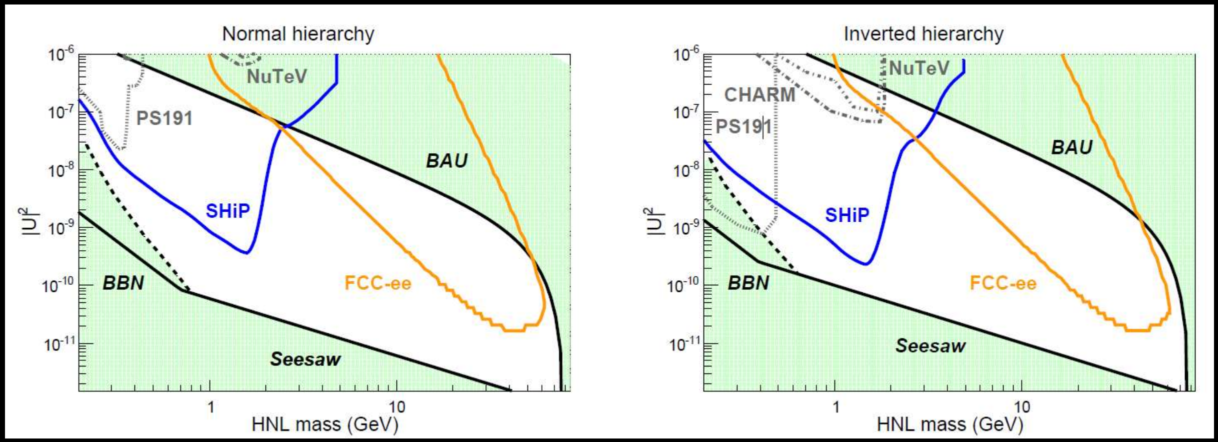

10 cm < cτ < 100 cm

10^{12} Z

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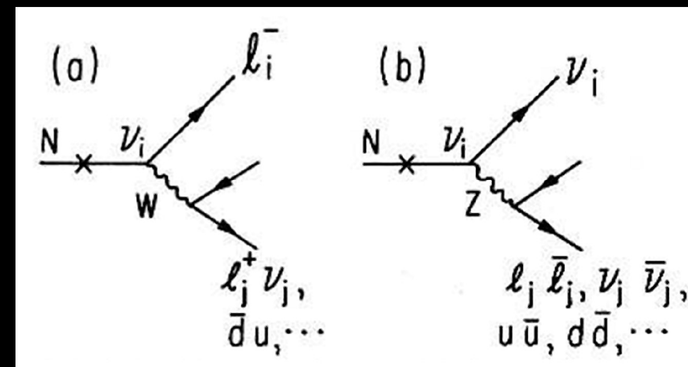

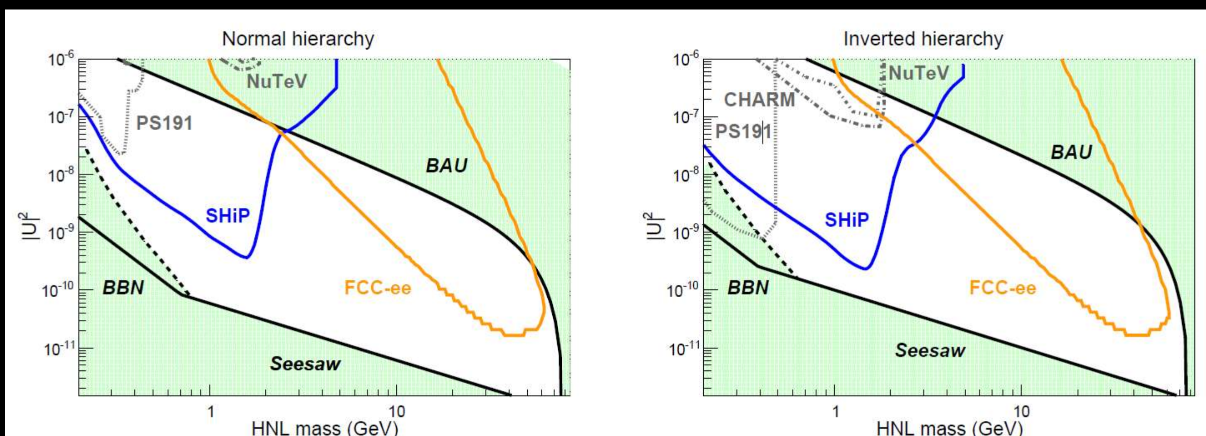

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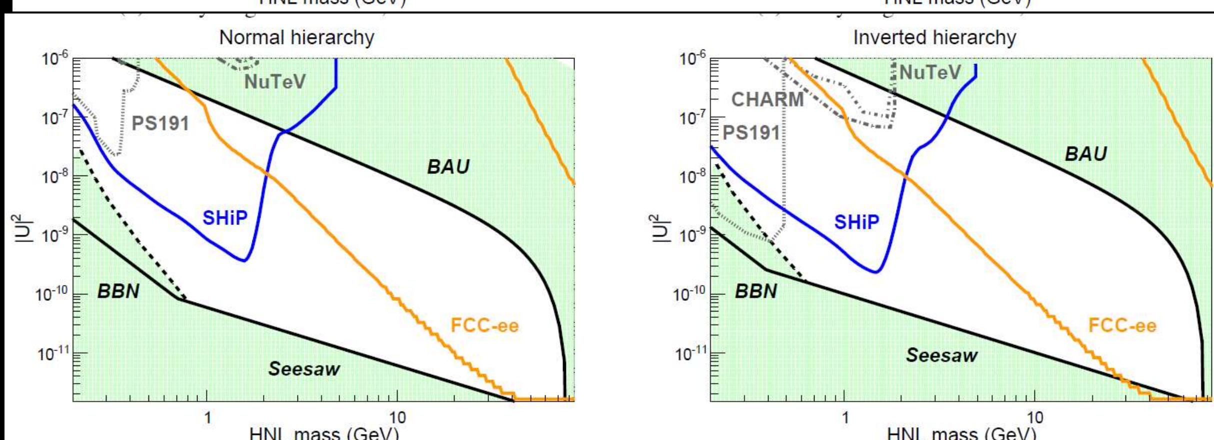


0.01 cm < cτ < 500 cm

10^{13} Z

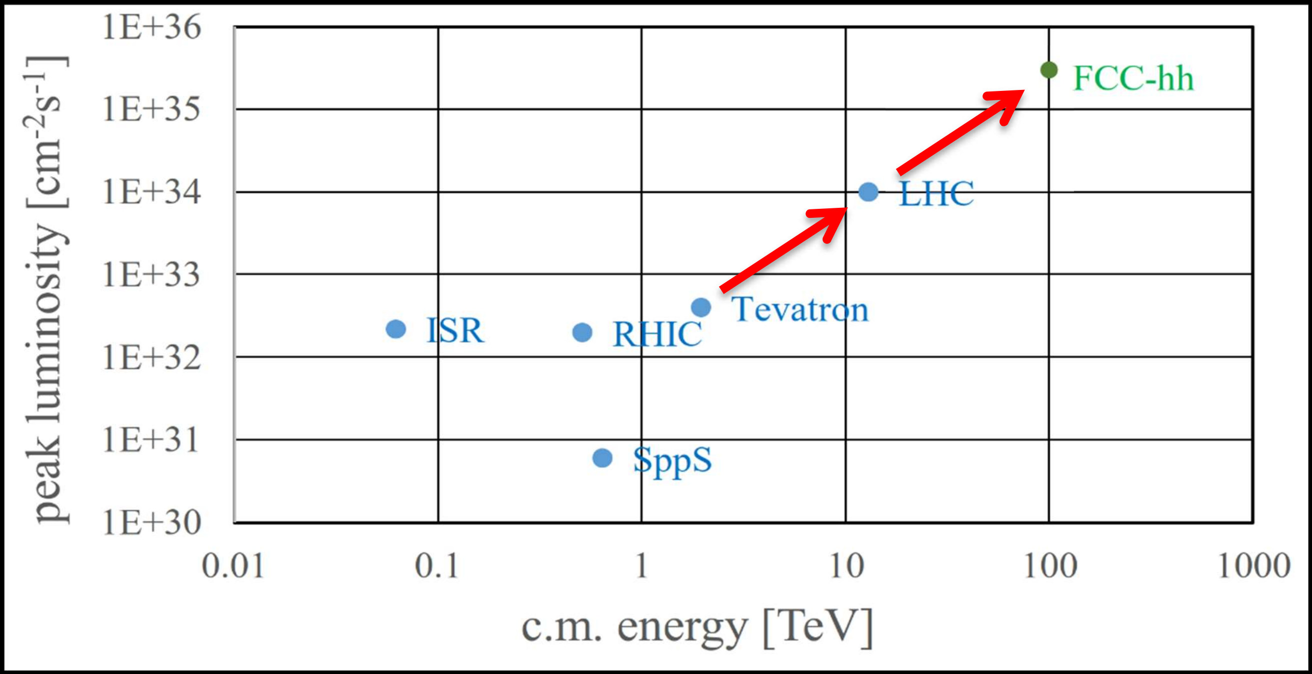
The pp machine

FCChh parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.27	1.1	0.58
bunch intensity [10^{11}]	1	1	2.5	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.1	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.45	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	16	5 (lev.)	1
events/bunch crossing	170	1000	460	132	27
stored energy/beam [GJ]	8.4		1.4	0.7	0.36

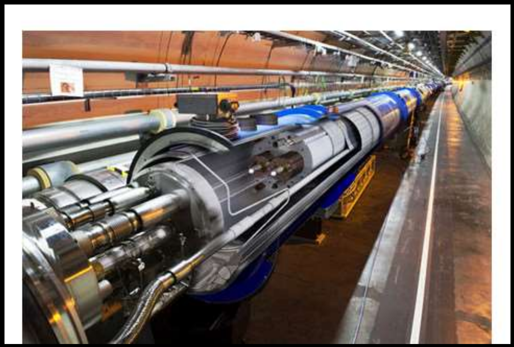
- Total site power <600 MW

FCChh key facts



- O(x10) E and L
  - 100 TeV
  - 20 ab^{-1}/exp.
    - In 25 years
- Key tech. issue:
  - High field magnets
  - 20 T with HTS

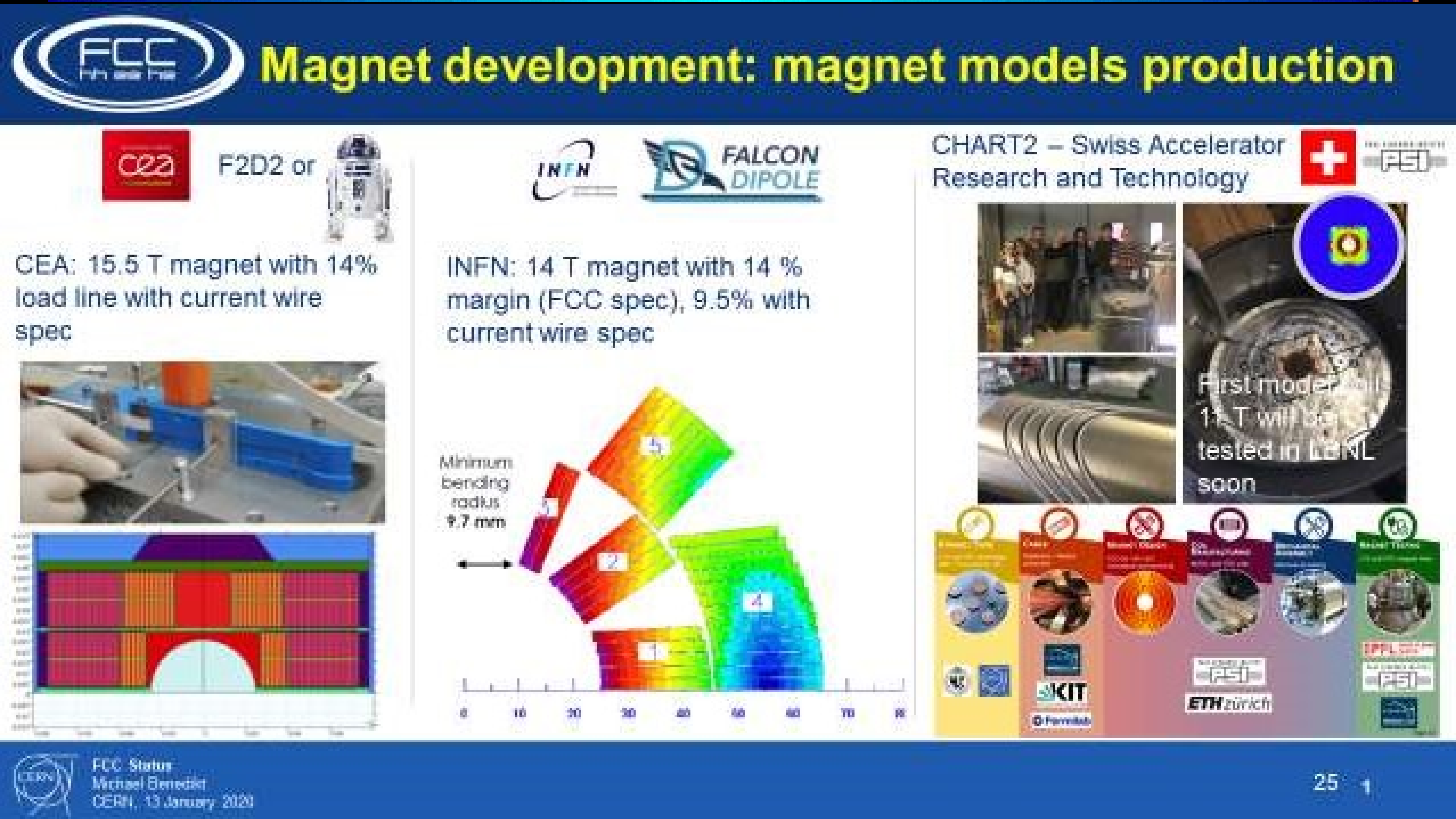
LHC technology
8.3 T NbTi



HL-LHC technology
11 T Nb_3Sn

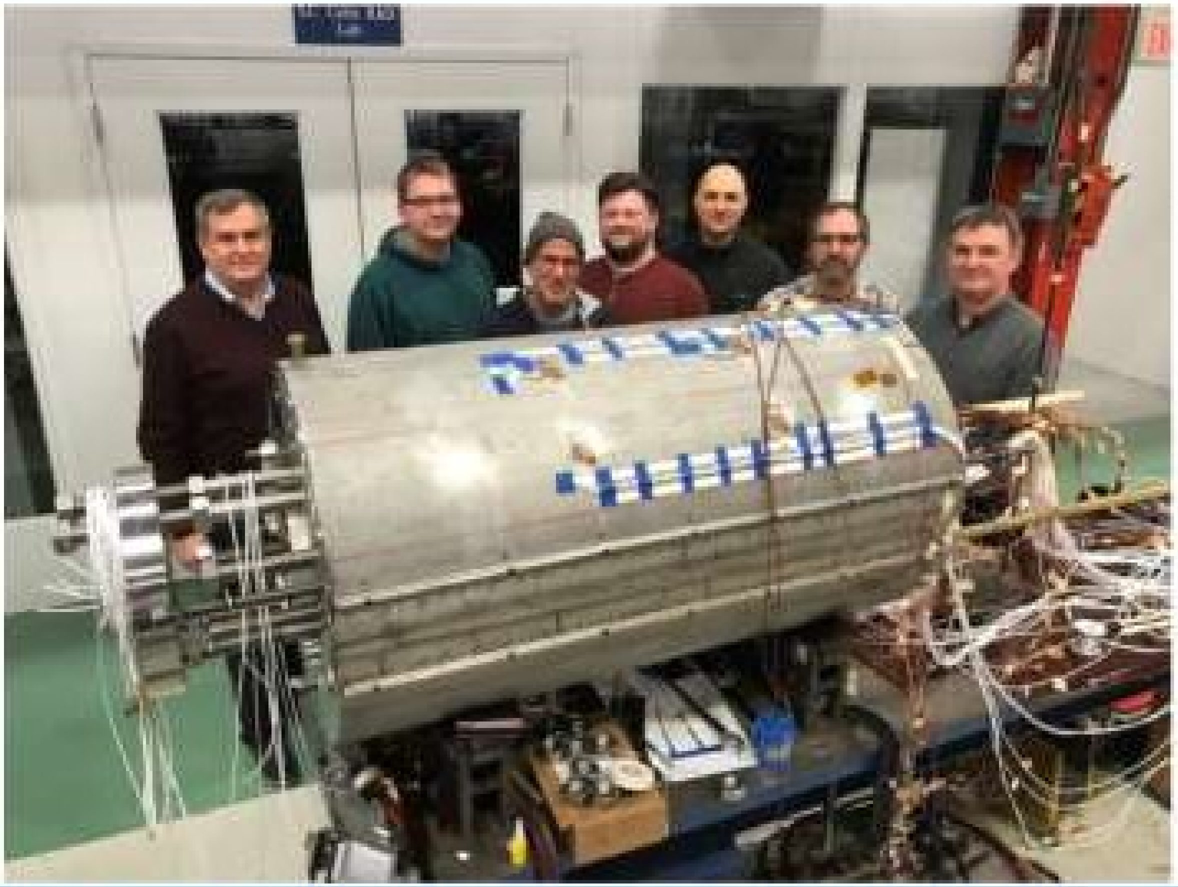
→ **16 T Nb_3Sn**

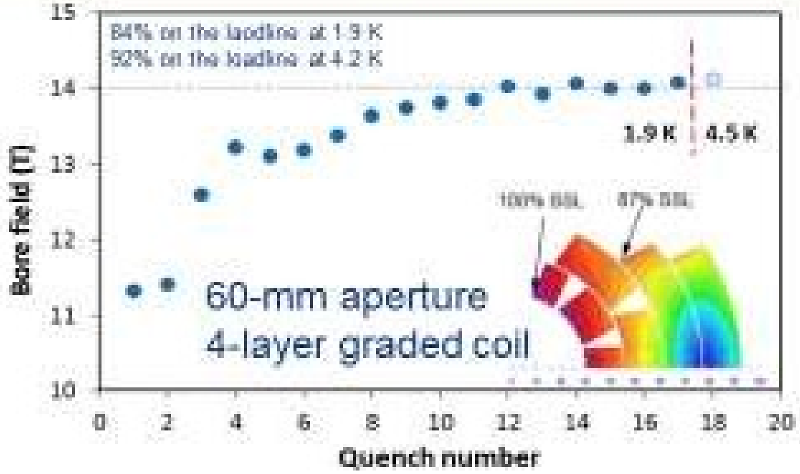
FCChh magnets



FCChh magnets

US – MDP: 14 T magnet tested at FNAL





- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test foreseen in fall 2019 with additional pre-stress for 15 T

FCC Status
Michael Benedikt
CERN, 13 January 2020

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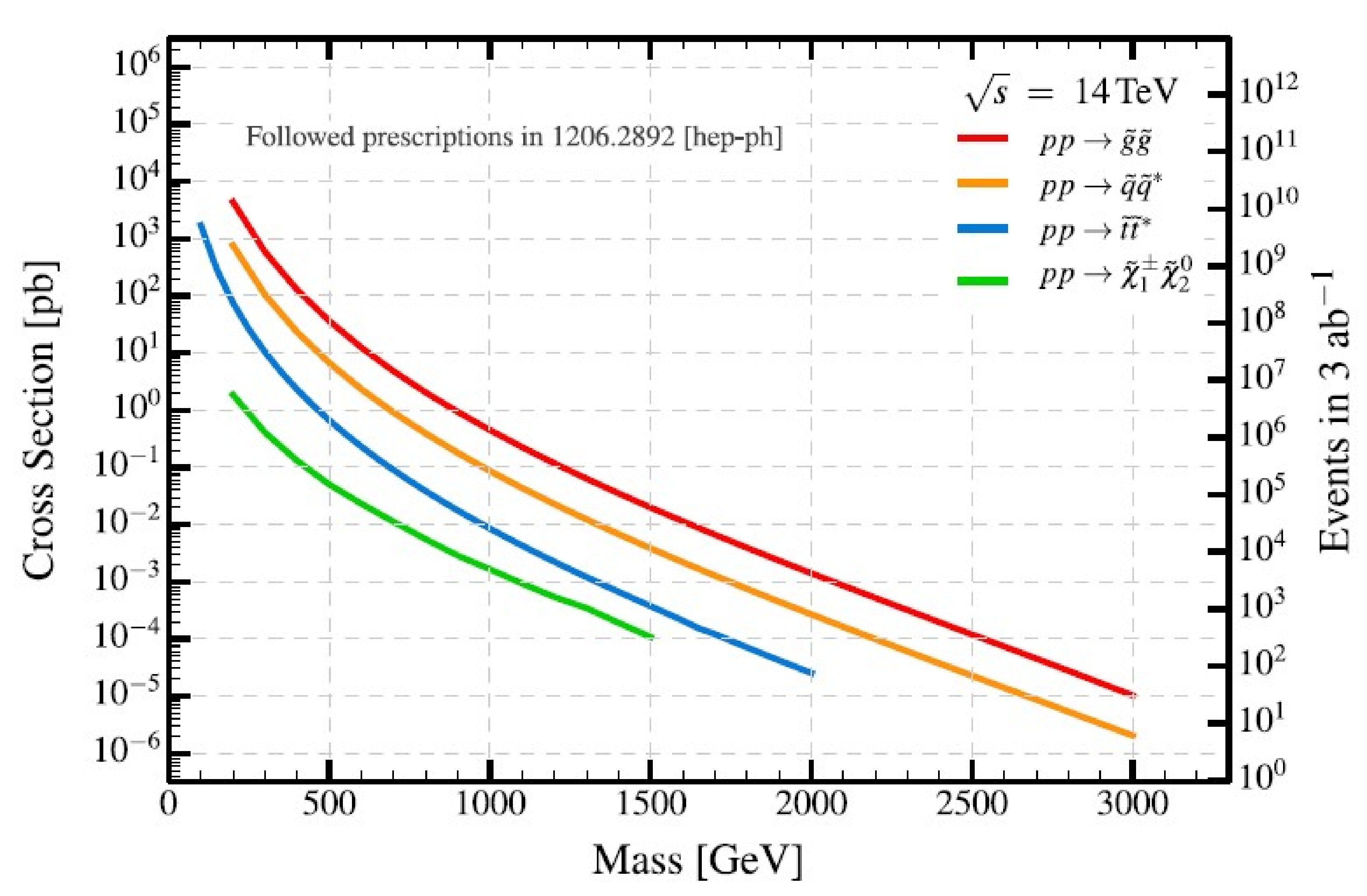
Exploration potential

- Search reach scaled from HL-LHC (2-3 TeV for SUSY)



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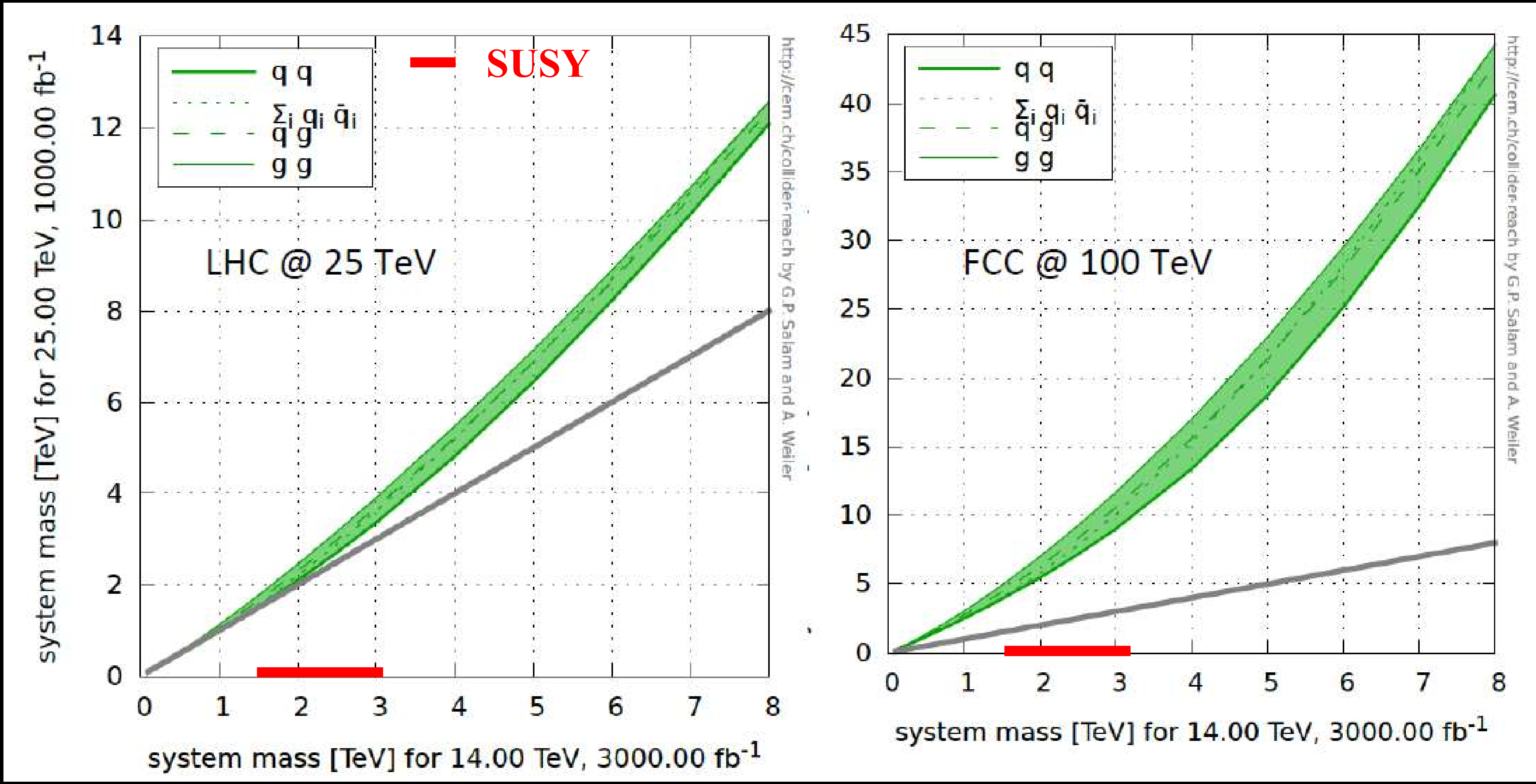

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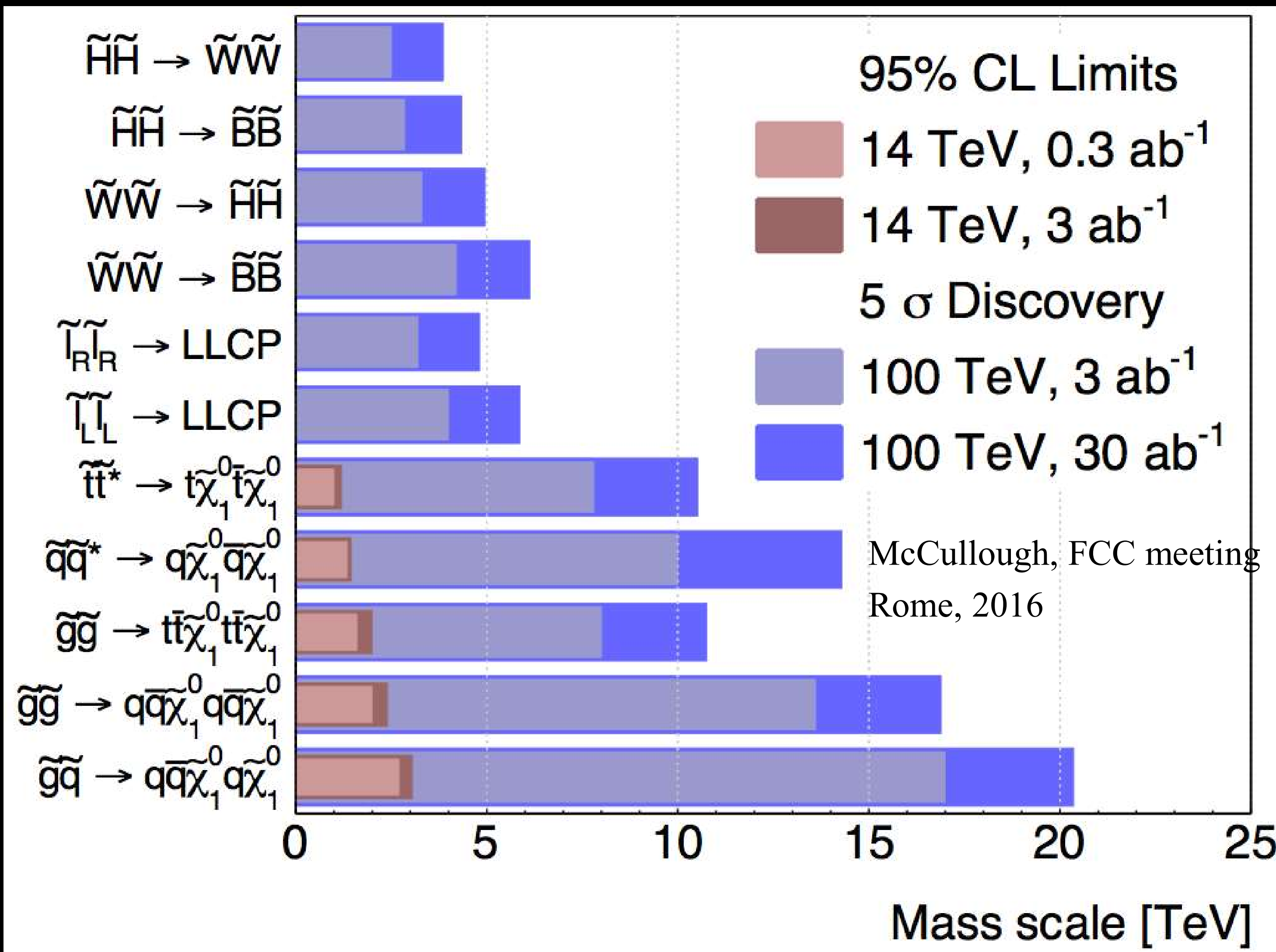

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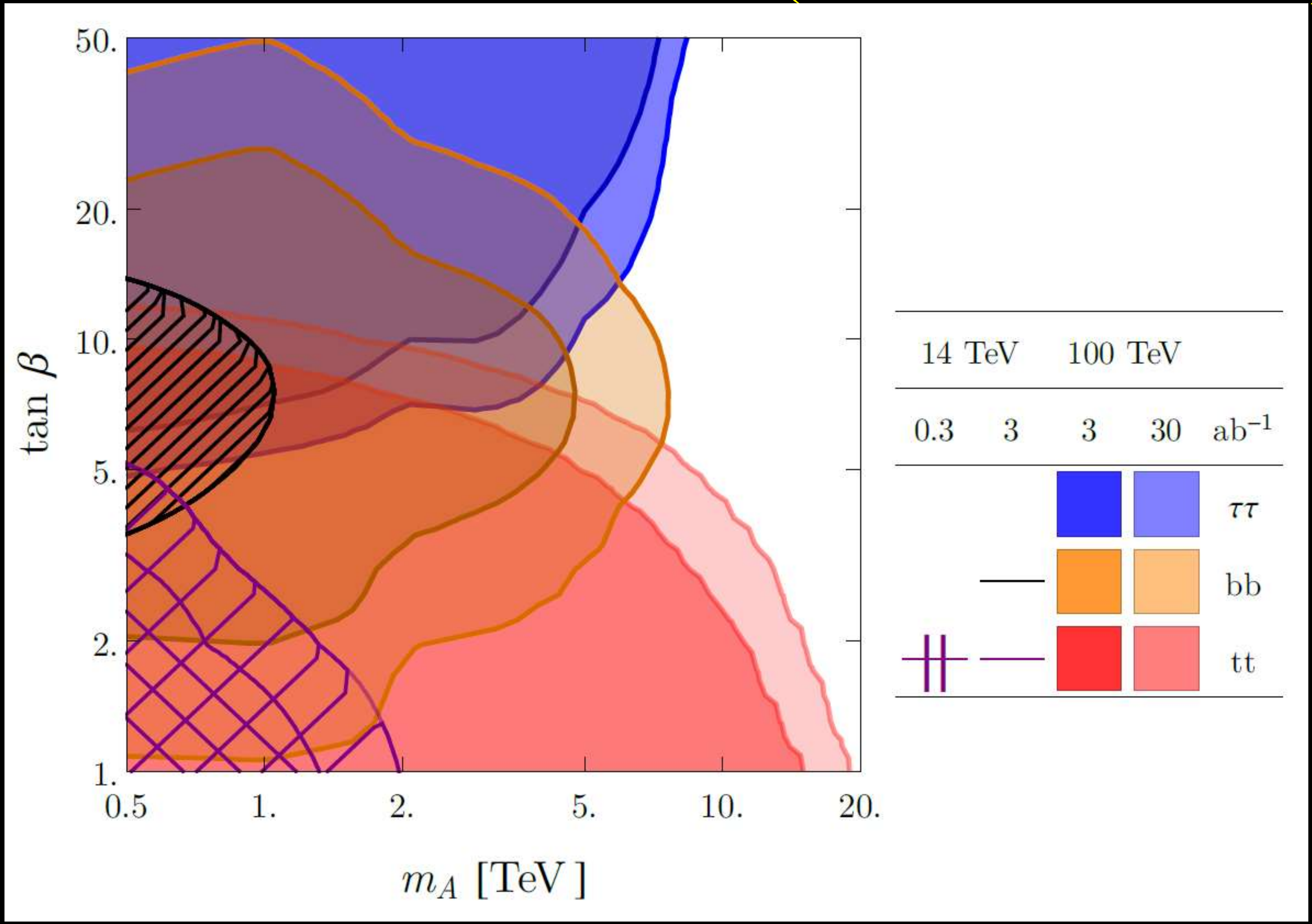
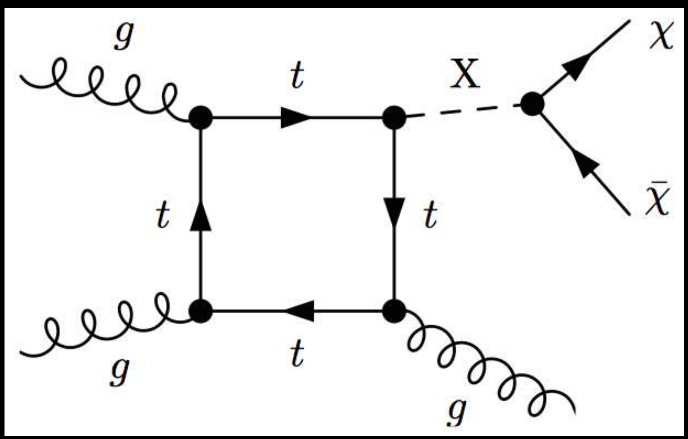
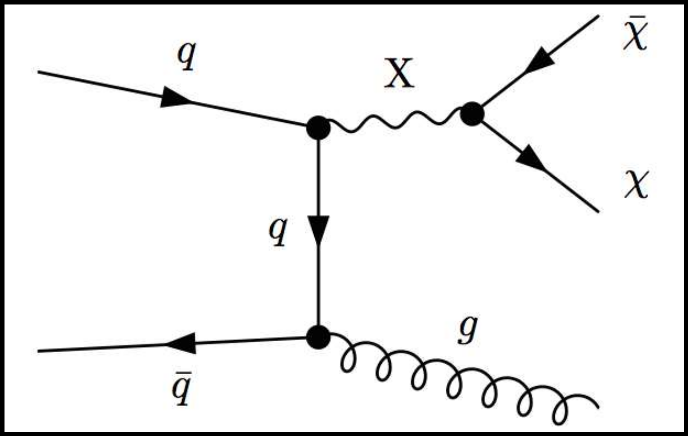
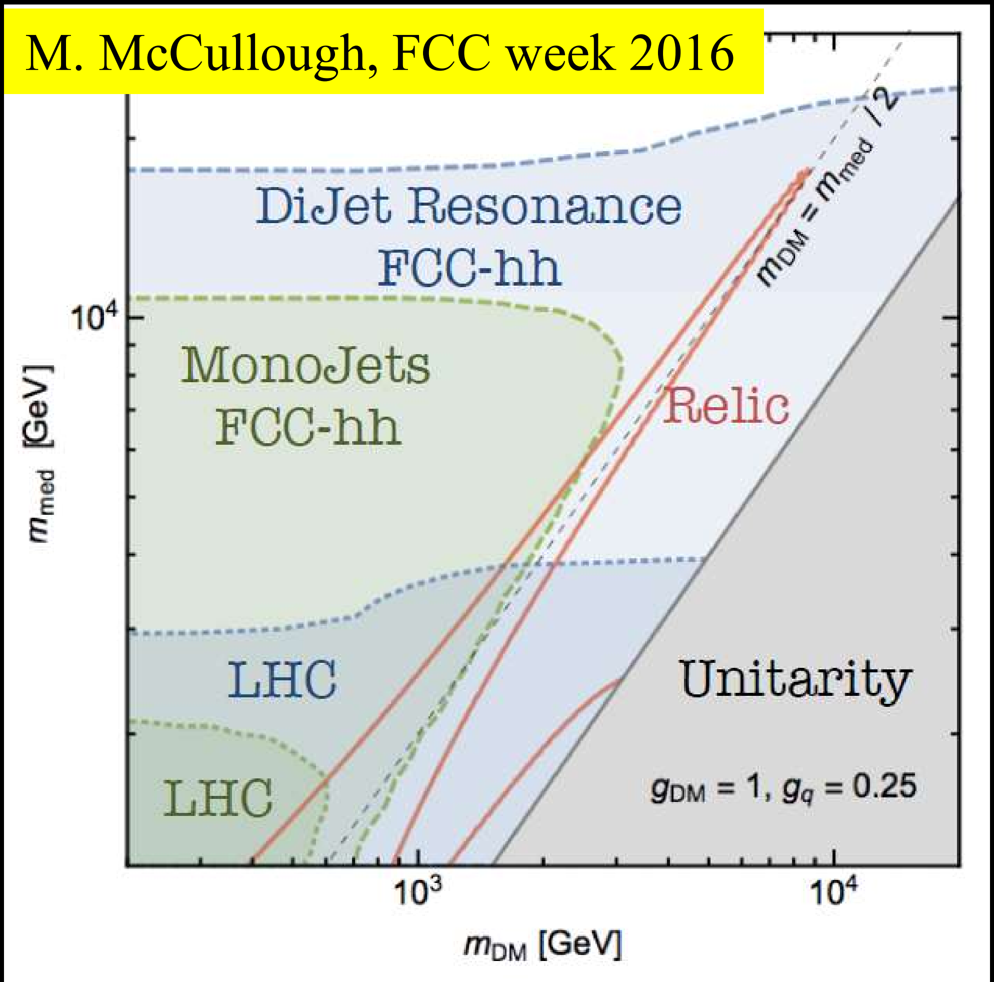


Dark matter

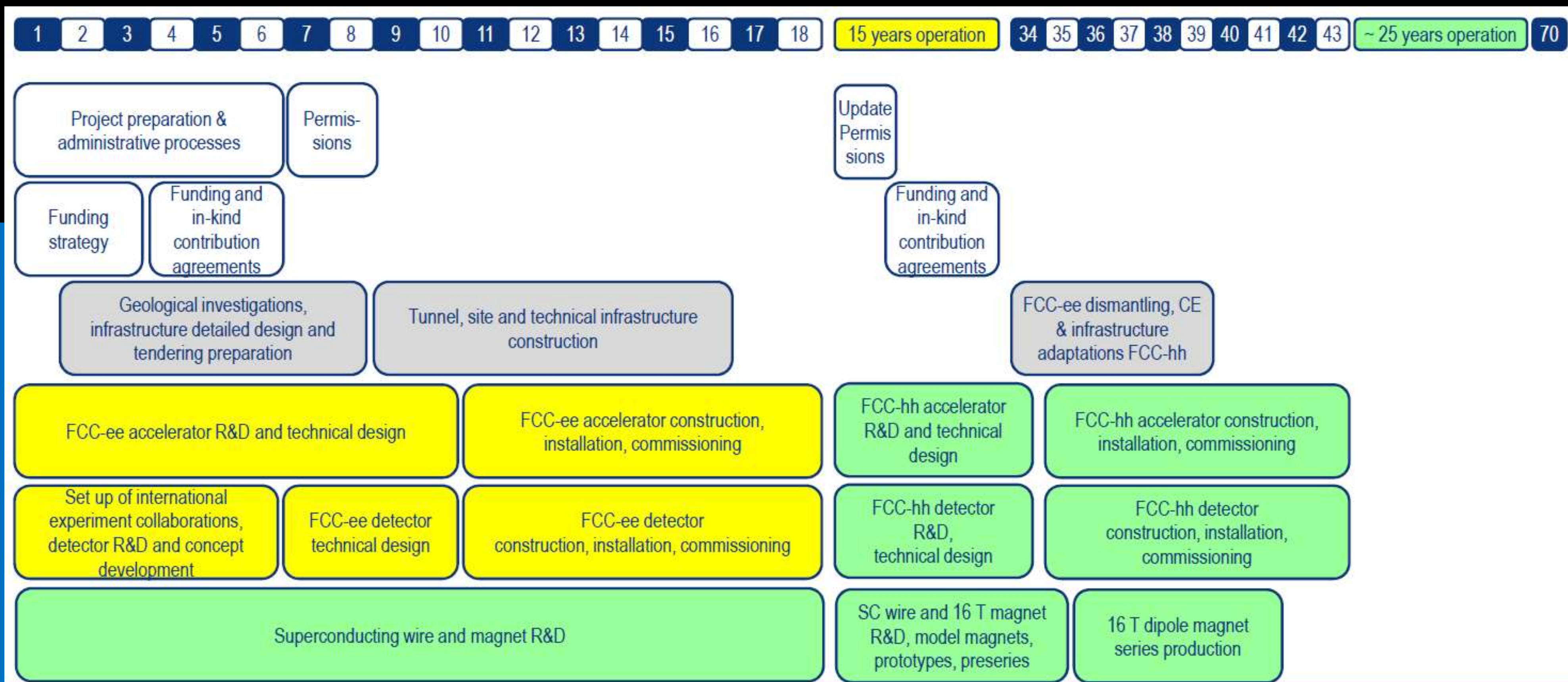
- Dark matter (simplified models)
  - 100 TeV pp could cover all parameter space allowed by cosmological bounds







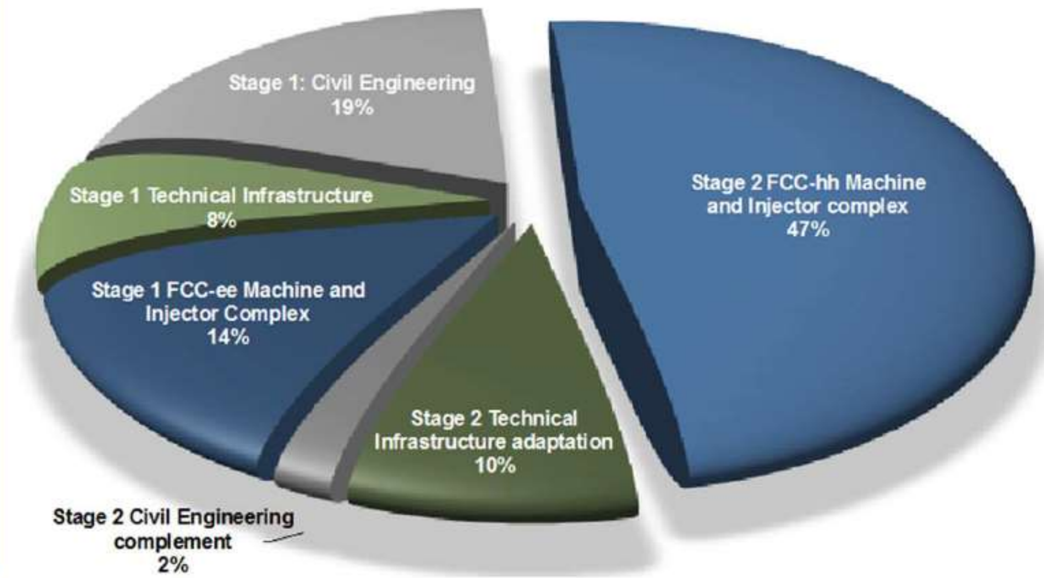
FCC-ee + FCC-hh schedule



M. BENEDIKT, CERN 2020

FCC costs

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



- Total cost FCCee: 10,600 MCHF
  - Addition for tt 1,100 MCHF
- Total additional cost for FCChh: 17,000 MCHF
  - Stand alone ~25 BCHF

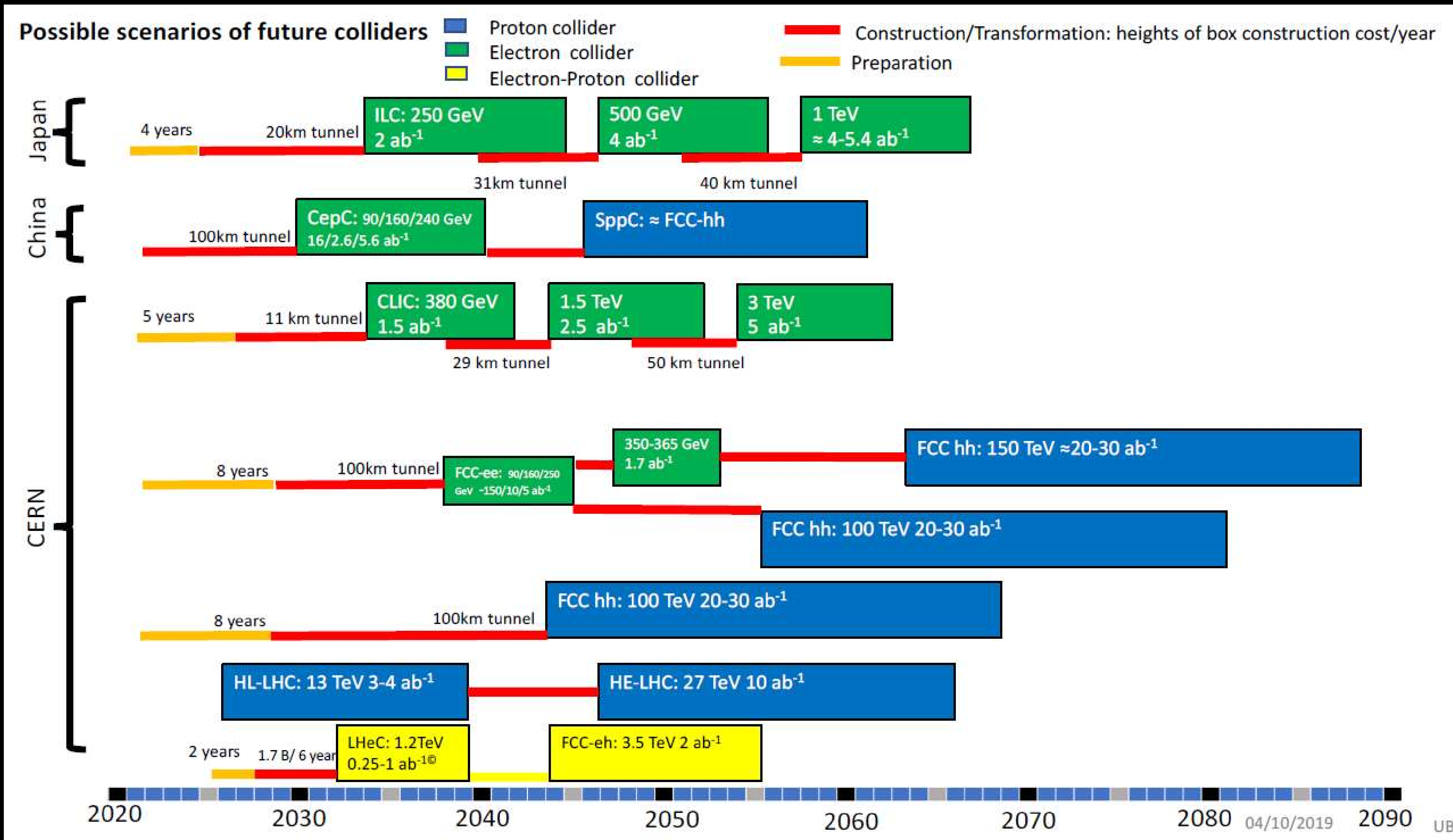
ESG main scenarios

- 5 basic options for the future being explored by ESG

	2020-2040	2040-2060 1st gen technology	2060-2080 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

Schedule comparisons



U. Bassler

Final comments

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  - EWPO x10-100 better than LEP
  - HF studies complementary to LHC-b/Belle II

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  - HHH to 5% precision
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- Great vision and plan for the next 70 years of HEP