

# The FCC Option

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## 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  $\rightarrow M_{NP} > 1$  TeV

ATLAS SUSY Searches* - 95% CL Lower Limits				ATLAS Preliminary			
July 2019				$\sqrt{s} = 13$ TeV			
Model	Signature	$[L dt] [\text{fb}^{-1}]$	Mass limit	Reference			
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{q}_1^0$	0 $e, \mu$	2-6 jets $E_T^{\text{miss}}$ 36.1	$\tilde{q}$ [2x, 8x Degrad.] 1.55	$m(\tilde{q}_1^0) < 100$ GeV		
		mono-jet	$E_T^{\text{miss}}$ 36.1	$\tilde{q}$ [1x, 8x Degrad.] 0.43, 0.71, 0.9	$m(\tilde{q}) - m(\tilde{q}_1^0) = 5$ GeV		
	$\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{q}_1^0$	0 $e, \mu$	2-6 jets $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ Forbiddn	$m(\tilde{g}_1^0) < 200$ GeV		
					$m(\tilde{g}_1^0) = 900$ GeV		
	$\tilde{g}, \tilde{g} \rightarrow q\bar{q}(t\bar{t})\tilde{q}_1^0$	3 $e, \mu$	4 jets $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 0.95-1.6, 2.0	$m(\tilde{g}_1^0) < 800$ GeV		
		$ee, \mu\mu$	2 jets $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 1.2, 1.85	$m(\tilde{g}) - m(\tilde{q}_1^0) = 50$ GeV		
	$\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{q}_1^0$	0 $e, \mu$	7-11 jets $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 1.5, 1.8	$m(\tilde{g}_1^0) < 400$ GeV		
3 <sup>rd</sup> gen. squarks direct production	$\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}_1^0$	SS $e, \mu$	6 jets $E_T^{\text{miss}}$ 139	$\tilde{g}$ 1.5	$m(\tilde{g}) - m(\tilde{q}_1^0) = 200$ GeV		
		SS $e, \mu$	6 jets $E_T^{\text{miss}}$ 139	$\tilde{g}$ 1.25, 2.25	$m(\tilde{g}_1^0) < 200$ GeV		
					$m(\tilde{g}) - m(\tilde{q}_1^0) = 300$ GeV		
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{q}_1^0$	Multiple	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{b}_1$ Forbiddn	$m(\tilde{q}_1^0) = 300$ GeV, $BR(\tilde{b}_1 \rightarrow b\tilde{q}_1^0) = 1$		
		Multiple	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{b}_1$ Forbiddn	$m(\tilde{q}_1^0) = 300$ GeV, $BR(\tilde{b}_1 \rightarrow t\tilde{q}_1^0) = 0.5$		
		Multiple	Multiple $E_T^{\text{miss}}$ 139	$\tilde{b}_1$ Forbiddn	$m(\tilde{q}_1^0) = 200$ GeV, $m(\tilde{t}_1) = 300$ GeV, $BR(\tilde{b}_1 \rightarrow t\tilde{q}_1^0) = 1$		
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{q}_1^0$	0 $e, \mu$	6 $b$ $E_T^{\text{miss}}$ 139	$\tilde{b}_1$ Forbiddn	$\Delta m(\tilde{q}_1^0, \tilde{q}_1^0) = 130$ GeV, $m(\tilde{q}_1^0) = 100$ GeV		
					$\Delta m(\tilde{q}_1^0, \tilde{q}_1^0) = 130$ GeV, $m(\tilde{q}_1^0) = 0$ GeV		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{q}_1^0$ or $t\tilde{q}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 $b$ $E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 1.0	$m(\tilde{q}_1^0) = 1$ GeV		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{q}_1^0$	1 $e, \mu$	3 jets/1 $b$ $E_T^{\text{miss}}$ 139	$\tilde{t}_1$ 0.44-0.59	$m(\tilde{q}_1^0) = 400$ GeV		
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 b, \tilde{t}_1 \rightarrow t\tilde{q}_1^0$	1 $\tau + 1 e, \mu, \tau$	2 jets/1 $b$ $E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 0.16	$m(\tilde{t}_1) = 800$ GeV			
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}\tilde{q}_1^0 / \tilde{t}\tilde{q}_1^0, \tilde{t} \rightarrow c\tilde{q}_1^0$	0 $e, \mu$	2 $c$ $E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 0.46, 0.85	$m(\tilde{t}_1) = 0$ GeV			
	0 $e, \mu$	mono-jet $E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1, \tilde{t}_1) - m(\tilde{q}_1^0) = 50$ GeV			
				$m(\tilde{t}_1, \tilde{t}_1) - m(\tilde{q}_1^0) = 5$ GeV			
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 $b$ $E_T^{\text{miss}}$ 36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{q}_1^0) = 0$ GeV, $m(\tilde{t}_1) - m(\tilde{q}_1^0) = 180$ GeV			
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$	1 $b$ $E_T^{\text{miss}}$ 139	$\tilde{t}_2$ Forbiddn	$m(\tilde{q}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{q}_1^0) = 40$ GeV			
EW direct	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WZ	2-3 $e, \mu$	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 0.205, 0.6	$m(\tilde{q}_1^0) = 0$		
		$ee, \mu\mu$	Multiple $E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 0.42, 0.74	$m(\tilde{q}_1^0) = 5$ GeV		
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 $e, \mu$	Multiple $E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ Forbiddn	$m(\tilde{q}_1^0) = 0$		
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	0-1 $e, \mu$	2 $h/2 \gamma$ $E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ 0.16, 0.39	$m(\tilde{q}_1^0) = 70$ GeV		
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ via $t\bar{t}\tilde{\chi}_1^{\pm}$	2 $e, \mu$	Multiple $E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^{\pm}$ 0.16-0.3, 0.12-0.39	$m(\tilde{q}_1^0) = 0.5m(\tilde{q}_1^0) + m(\tilde{q}_1^0)$		
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ via $t\bar{t}\tilde{\chi}_1^{\pm}$	2 $\tau$	Multiple $E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^{\pm}$ 0.256, 0.7	$m(\tilde{q}_1^0) = 0$		
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{q}_1^0$	2 $e, \mu$	0 jets $E_T^{\text{miss}}$ 139	$\tilde{t}_1$ 0.13-0.23, 0.3, 0.29-0.88	$m(\tilde{q}_1^0) = 0$		
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{q}_1^0$	2 $e, \mu$	$\geq 1$ $E_T^{\text{miss}}$ 139		$m(\tilde{t}_1) - m(\tilde{q}_1^0) = 10$ GeV		
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{q}_1^0$	2 $e, \mu$	0 jets $E_T^{\text{miss}}$ 36.1		$BR(\tilde{t}_1^+ \rightarrow h\tilde{q}_1^0) = 1$		
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{q}_1^0$	4 $e, \mu$	0 jets $E_T^{\text{miss}}$ 36.1		$BR(\tilde{t}_1^+ \rightarrow Z\tilde{q}_1^0) = 1$		
Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet $E_T^{\text{miss}}$ 36.1	$\tilde{\chi}_1^{\pm}$ 0.15, 0.46	Pure Wino		
					Pure Higgsino		
	Stable $\tilde{g}$ R-hadron	Multiple	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 2.0, 2.05, 2.4	$m(\tilde{q}_1^0) = 100$ GeV		
Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{q}_1^0$	Multiple	Multiple $E_T^{\text{miss}}$ 36.1					
RPV	LFV $pp \rightarrow \tilde{q}_1^0 + X, \tilde{q}_1^0 \rightarrow q\bar{q}t/\mu\tau$	$q\bar{q}, e\bar{t}/\mu\tau$	3.2	$\tilde{q}_1^0$ 1.9, 1.9	$\tilde{q}_{11} = 0.11, \tilde{q}_{12/13/21/22} = 0.07$		
	$\tilde{\chi}_1^0\tilde{\chi}_1^0 / \tilde{\chi}_2^0 \rightarrow WWZZ\ell\ell\nu\nu$	4 $e, \mu$	0 jets $E_T^{\text{miss}}$ 36.1	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 0.82, 1.33, 1.9	$m(\tilde{q}_1^0) = 100$ GeV		
	$\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}_1^0, \tilde{q}_1^0 \rightarrow qq\tilde{q}_1^0$	4-5 large- $R$ jets	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 1.0, 1.3, 1.9, 2.0	Large $\tilde{q}_{12}$		
		Multiple	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 0.55, 1.05	$m(\tilde{q}_1^0) = 200$ GeV, bino-like		
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{q}_1^0, \tilde{q}_1^0 \rightarrow t\tilde{h}$	Multiple	Multiple $E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 0.42, 0.51	$m(\tilde{q}_1^0) = 200$ GeV, bino-like		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 jets + 2 $b$	Multiple $E_T^{\text{miss}}$ 36.7	$\tilde{t}_1$ 0.4, 1.45, 1.6	$BR(\tilde{t}_1 \rightarrow b\tilde{q}_1^0) > 20\%$		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	2 $e, \mu$	2 $b$ $E_T^{\text{miss}}$ 36.1		$BR(\tilde{t}_1 \rightarrow q\tilde{\ell}) = 100\%$ , $\cos\theta_0 = 1$		
	1 $\mu$	DV $E_T^{\text{miss}}$ 136					

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

# Physics motivations

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## ATLAS SUSY Searches\* - 95% CL Lower Limits

July 2019

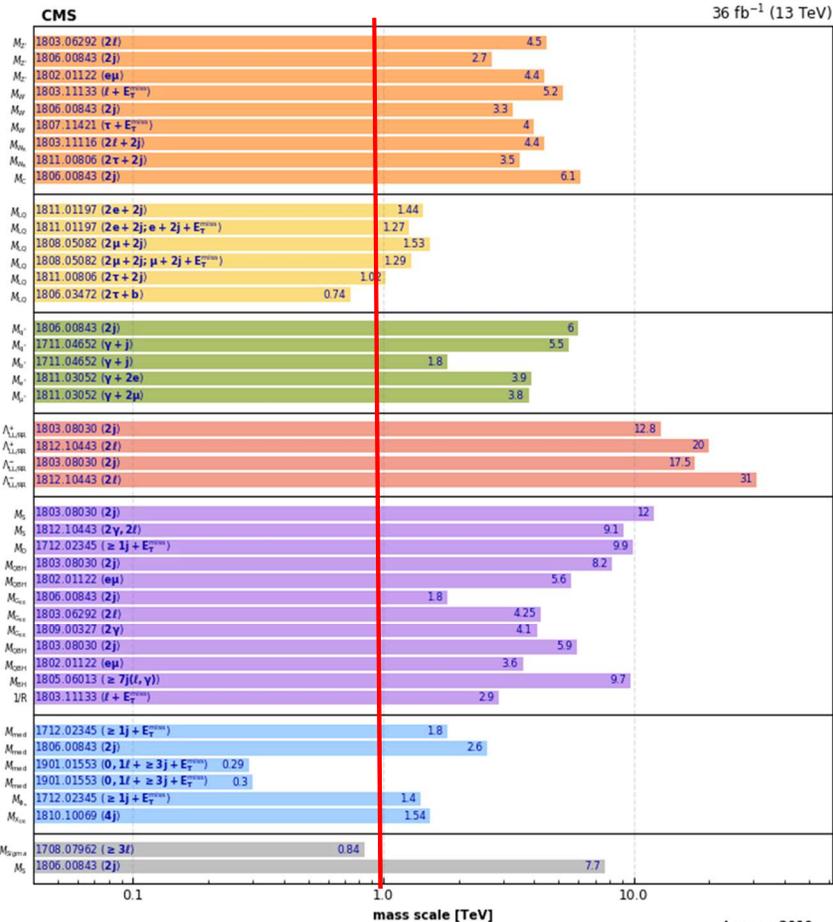
Model	Signature	[ $\mathcal{L} dt$ (fb $^{-1}$ )]	Mass limit		
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{q}^0$	0 $e, \mu$	2-6 jets $E_T^{miss}$ 36.1		
	mono-jet	1-3 jets $E_T^{miss}$ 36.1	0.43, 0.71		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 $e, \mu$	2-6 jets $E_T^{miss}$ 36.1	Forbidden	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(t\bar{t})\tilde{\chi}_1^0$	3 $e, \mu$	4 jets $E_T^{miss}$ 36.1		
	$ee, \mu\mu$	2 jets $E_T^{miss}$ 36.1			
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	Multiple	36.1		
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	Multiple	36.1	Forbidden 0.58-0.8	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	Multiple	139	Forbidden 0.74	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0 $e, \mu$	6 b $E_T^{miss}$ 139	Forbidden 0.23-0.48	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 b $E_T^{miss}$ 36.1		
EW direct	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via WZ	2-3 $e, \mu$	$E_T^{miss}$ 36.1	0.6	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via WW	2 $e, \mu$	$E_T^{miss}$ 139	0.42	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via Wh	0-1 $e, \mu$	2 h/2 $\gamma$ $E_T^{miss}$ 139	0.74	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via $t\bar{t}/b\bar{b}$	2 $e, \mu$	0 jets $E_T^{miss}$ 139	0.7	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$	$\geq 1$ $E_T^{miss}$ 139	0.256	
Long-lived particles	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet $E_T^{miss}$ 36.1	0.15, 0.46	
	Stable $\tilde{g}$ R-hadron	Multiple	36.1		
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple	36.1		
RPV	LFV $pp \rightarrow \nu\tau + X, \nu\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	3.2		
	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 $e, \mu$	0 jets $E_T^{miss}$ 36.1	0.8	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	4-5 large-R jets	Multiple	36.1	
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	Multiple	36.1	0.55	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 jets + 2 b	36.7	0.42, 0.51	

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10<sup>-1</sup>

## Overview of CMS EXO results

36 fb $^{-1}$  (13 TeV)

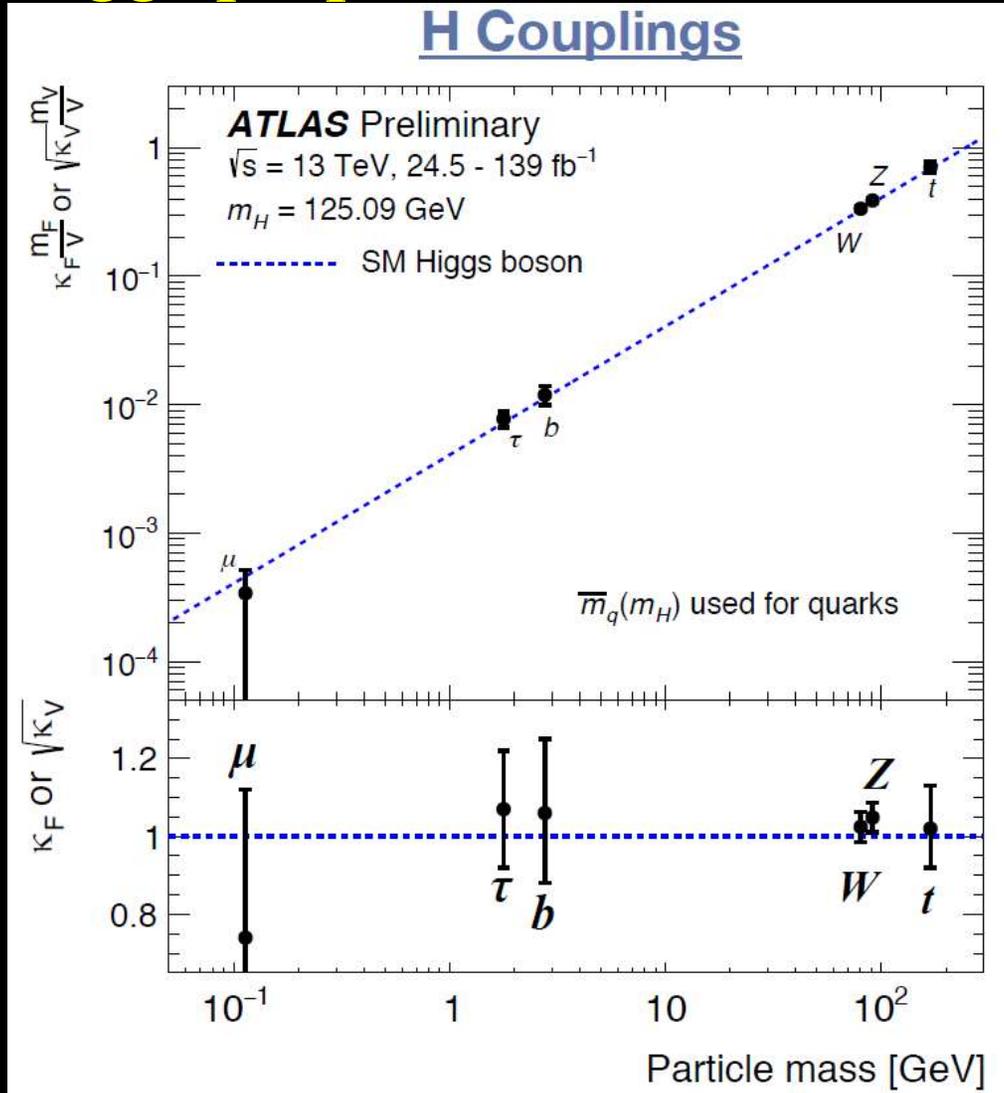


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019

# Physics motivations

## ❖ Higgs properties SM-like.

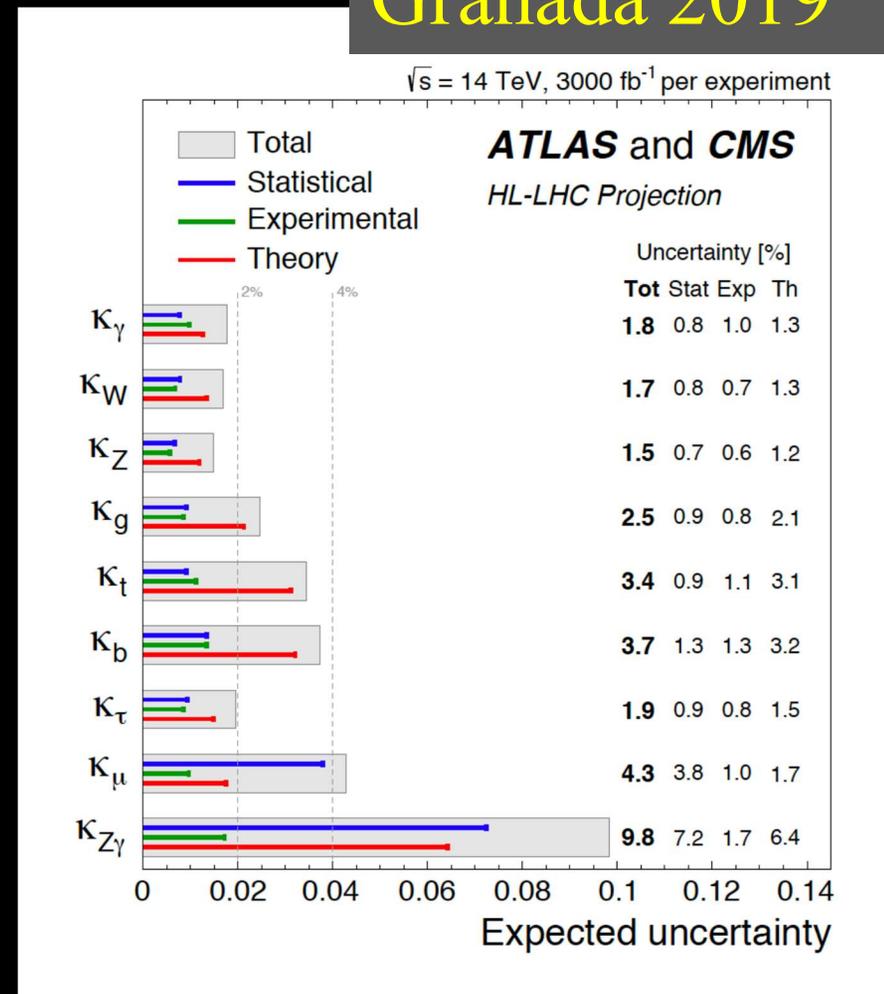


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➤ After HL-LHC precision level of several %

Granada 2019



# Physics motivations

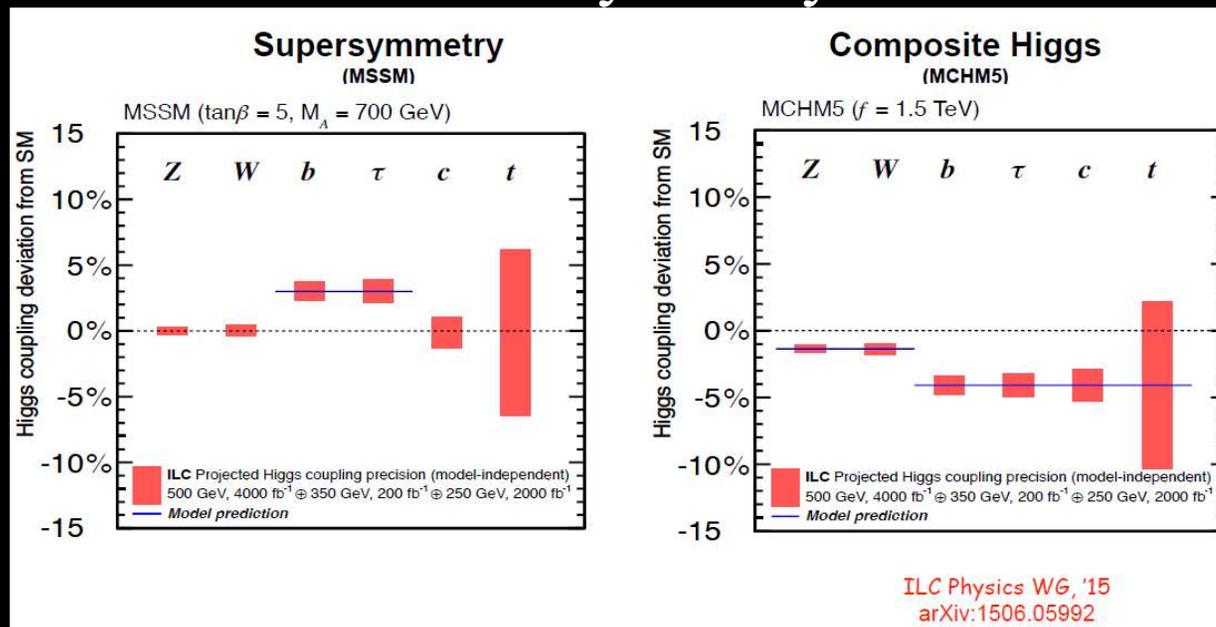
## ❖ Higgs properties SM-like.

- After HL-LHC precision level of several %
- Deviation from SM:  $\delta \sim v^2/M^2$       $v = 246 \text{ GeV}$ 
  - M scale of new physics
  - $M \sim 1 - 10 \text{ TeV} \rightarrow \delta \sim 6 - 0.06\%$

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## ❖ Higgs properties SM-like.

- After HL-LHC precision level of several %
- Deviation from SM:  $\delta \sim v^2/M^2$      $v = 246 \text{ GeV}$ 
  - M scale of new physics
  - $M \sim 1 - 10 \text{ TeV} \rightarrow \delta \sim 6 - 0.06\%$
- Need  $< \sim \%$  sensitivity  $\rightarrow$  beyond HL-LHC



# Current physics landscape

- ❖ No (additional) signs of BSM physics.
  - After intensive searches at LHC
- ❖ Higgs properties SM-like.
  - At current precision level of several %
- ❖ ... but SM is an insufficient description

# Current physics landscape

- ❖ No (additional) signs of BSM physics.
  - After intensive searches at LHC
- ❖ Higgs properties SM-like.
  - At current precision level of several %
- ❖ ... **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<sup>+</sup>e<sup>-</sup> 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.

# The FCC integrated program

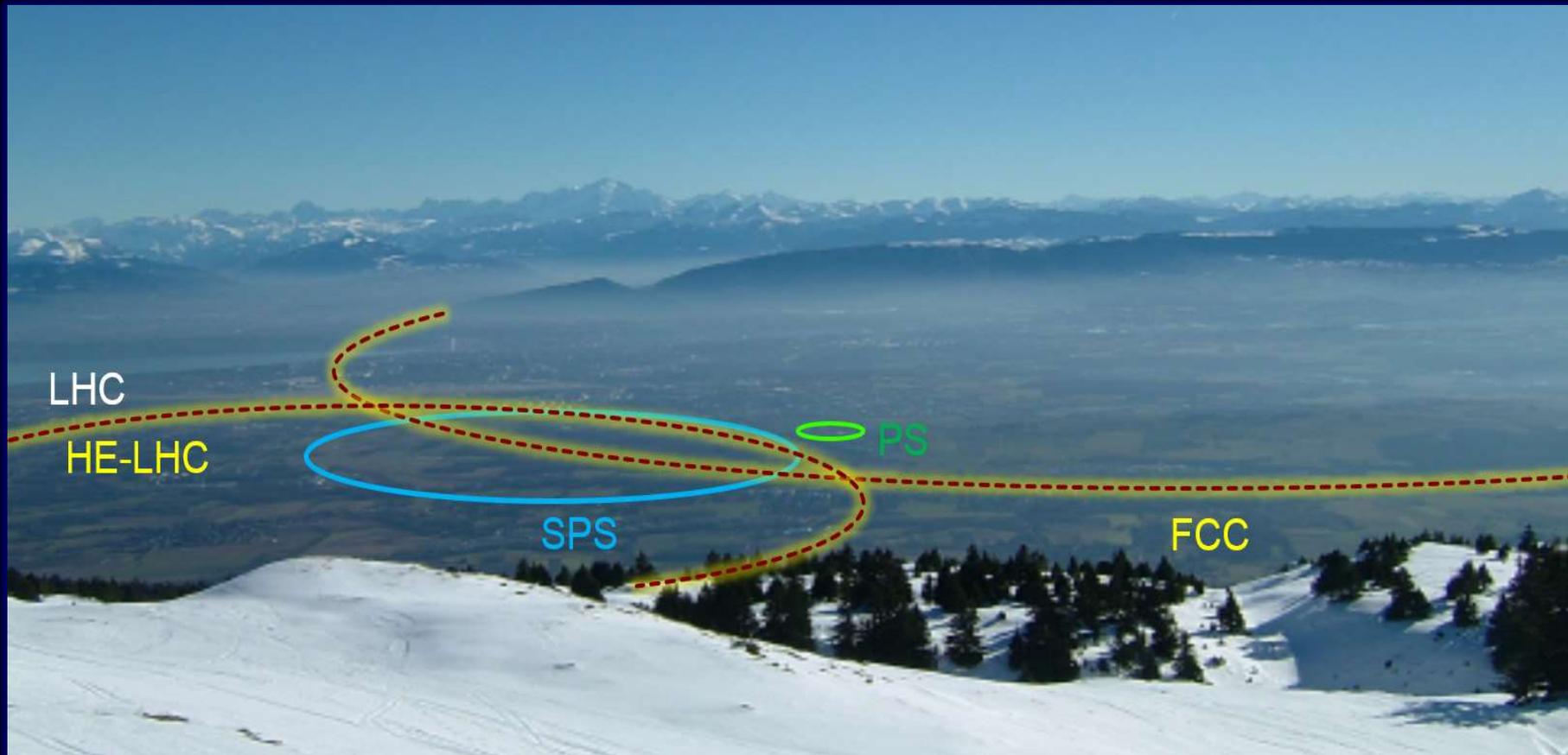
- ❖ FCC integrated program can respond to these requests in an optimal way
- ❖ Comprehensive program to optimize physics opportunities
  - Stage 1: FCC-ee (Z, W, H, tt)
    - Higgs factory, EW and top factory at highest luminosities.
  - Stage 2: FCC-hh (~100 TeV)
    - Natural continuation at energy 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 $\sim 100$ km

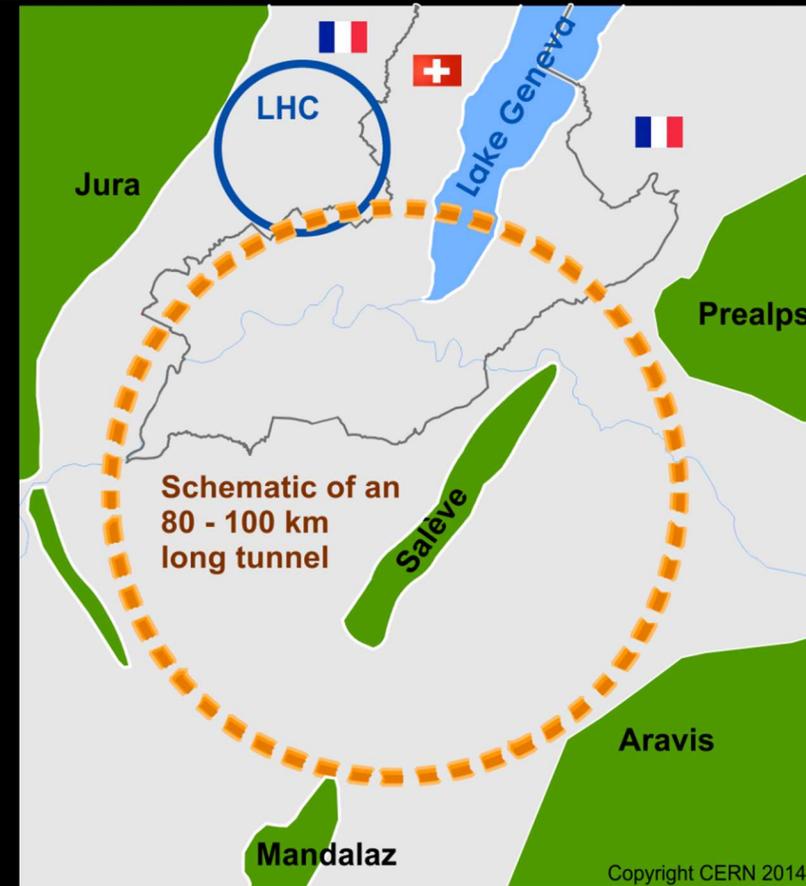
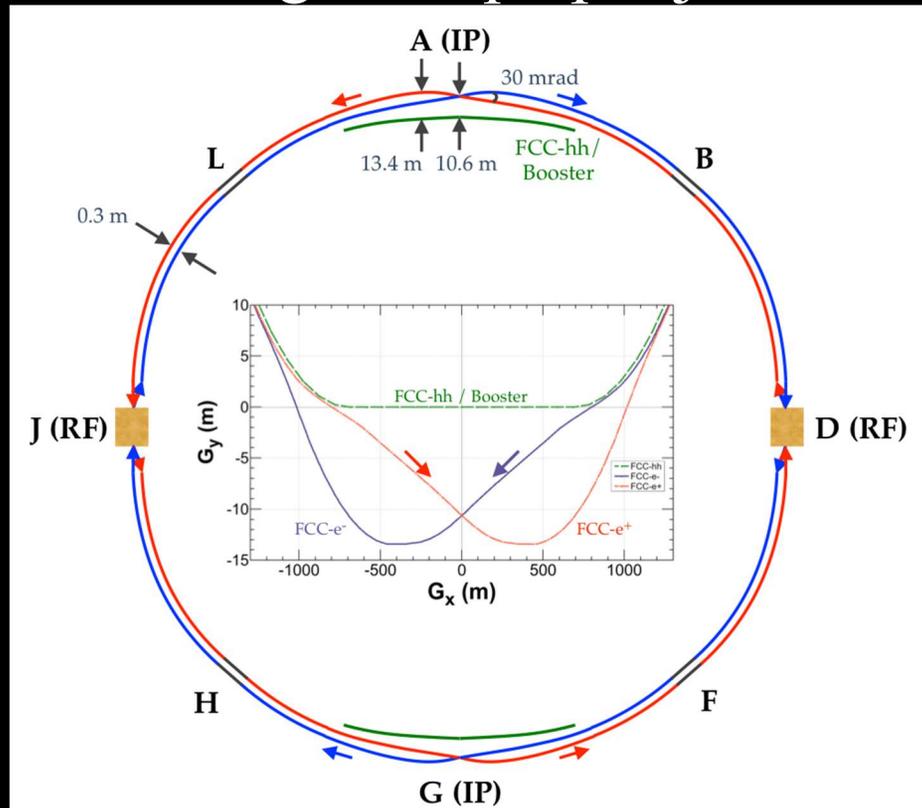
- RF power limited to 50 MW/beam
- 2 IP currently - 4 IP possible



# FCC-ee

## ❖ Double ring $e^+e^-$ collider $\sim 100$ km

- RF power limited to 50 MW/beam
- 2 IP currently - 4 IP possible
- Booster ring for top up injection



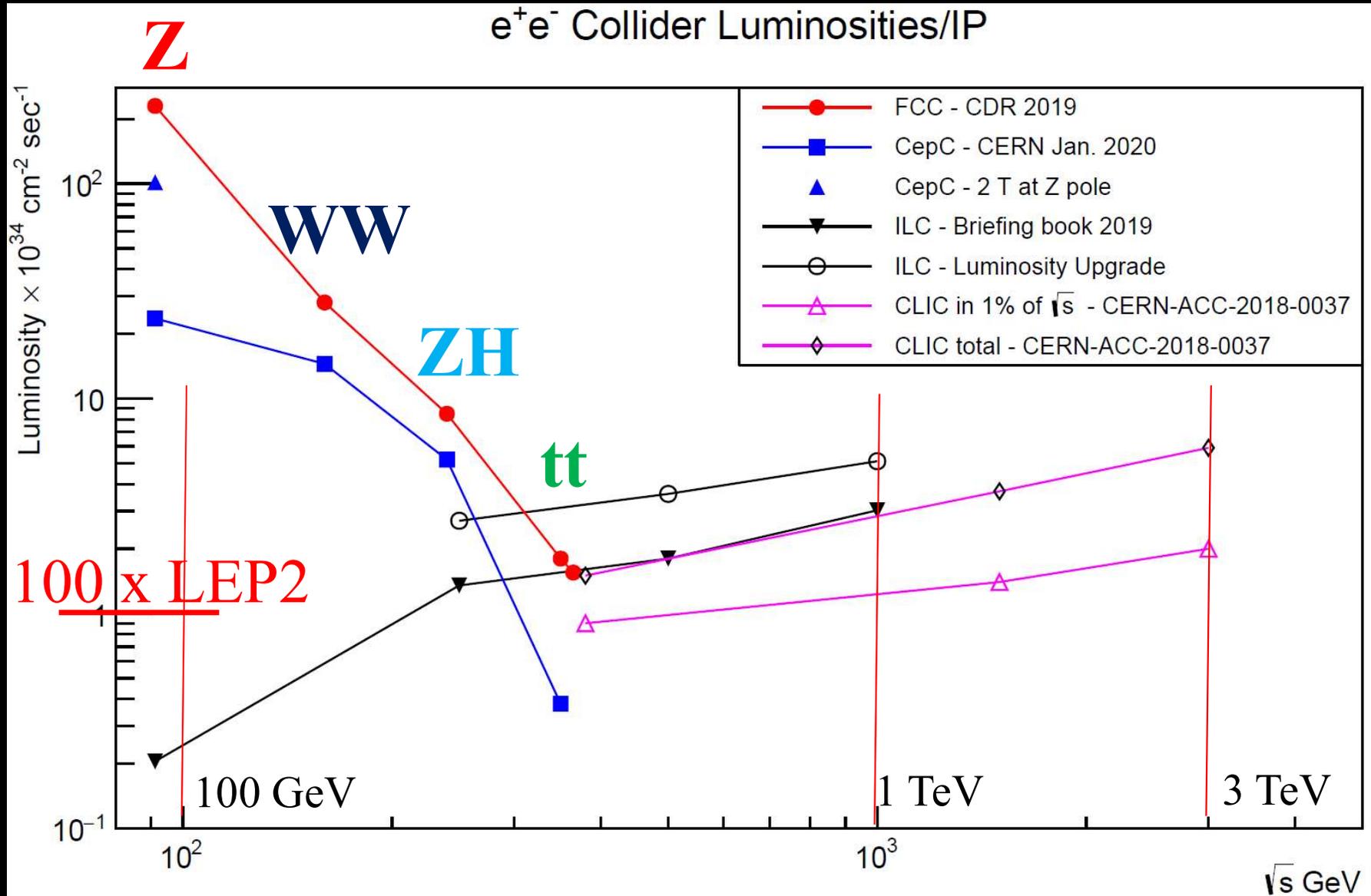
# FCCee parameters

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 [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	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

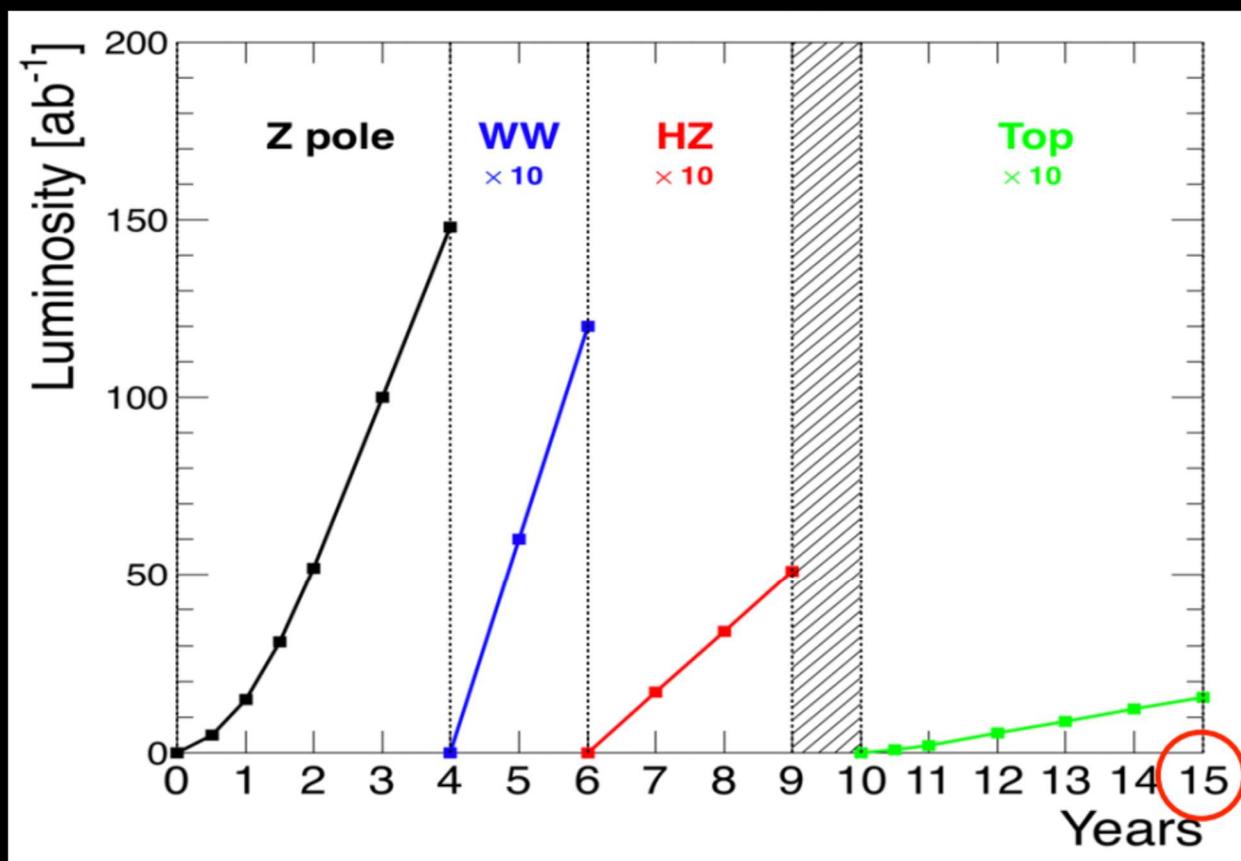
# Luminosity comparisons



# Physics at FCC-ee

## ❖ Higgs factory

➤  $10^6 e^+e^- \rightarrow HZ$



# Physics at FCC-ee

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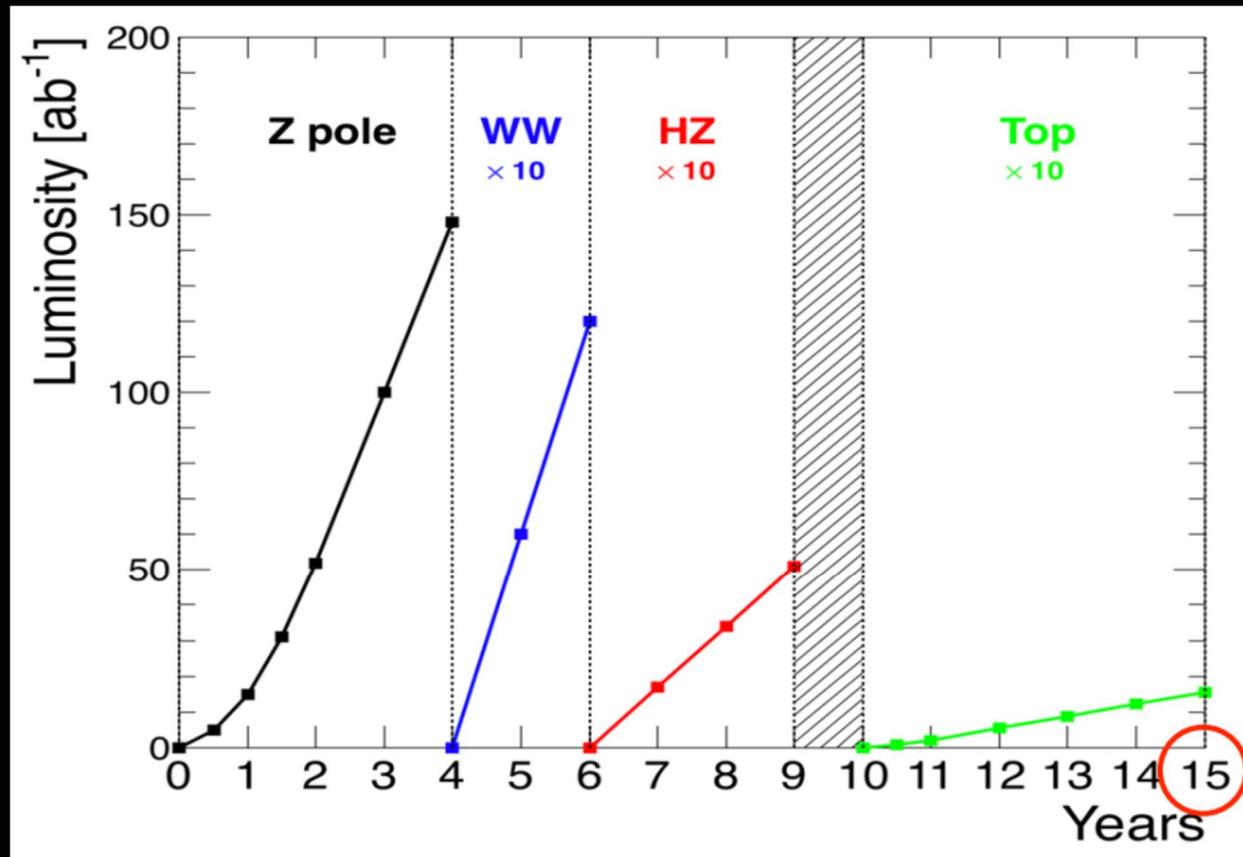
➤  $10^6 e^+e^- \rightarrow HZ$

## ❖ EW & Top factory

➤  $5 \times 10^{12} e^+e^- \rightarrow Z$

➤  $10^8 e^+e^- \rightarrow W+W^-$  ;

➤  $10^6 e^+e^- \rightarrow t\bar{t}$



# Physics at FCC-ee

## ❖ Higgs factory

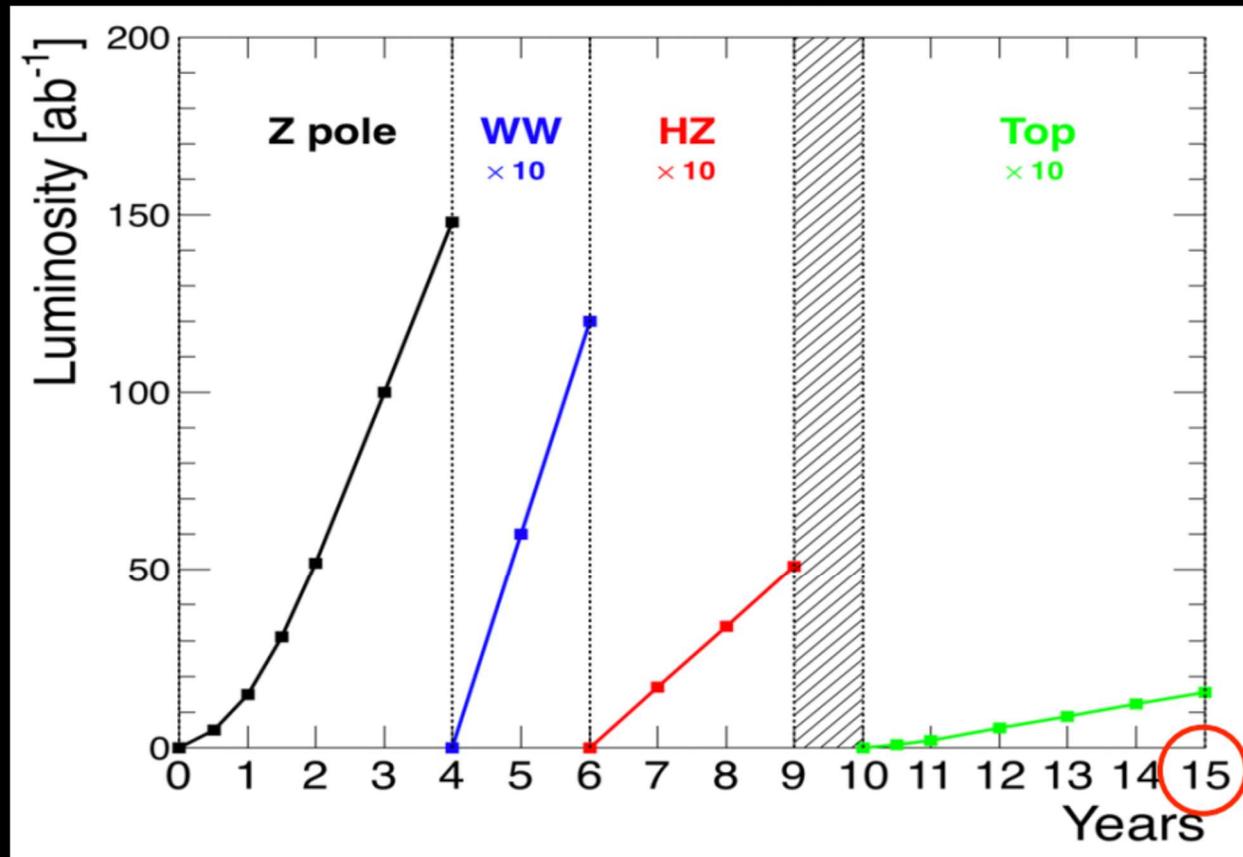
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## ❖ EW & Top factory

- $5 \times 10^{12} e^+e^- \rightarrow Z$
- $10^8 e^+e^- \rightarrow W+W^-$  ;
- $10^6 e^+e^- \rightarrow t\bar{t}$

## ❖ Flavor factory

- $10^{12} e^+e^- \rightarrow b\bar{b}, c\bar{c}$
- $10^{11} e^+e^- \rightarrow \tau^+\tau^-$



# Physics at FCC-ee

## ❖ Higgs factory

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

## ❖ EW & Top factory

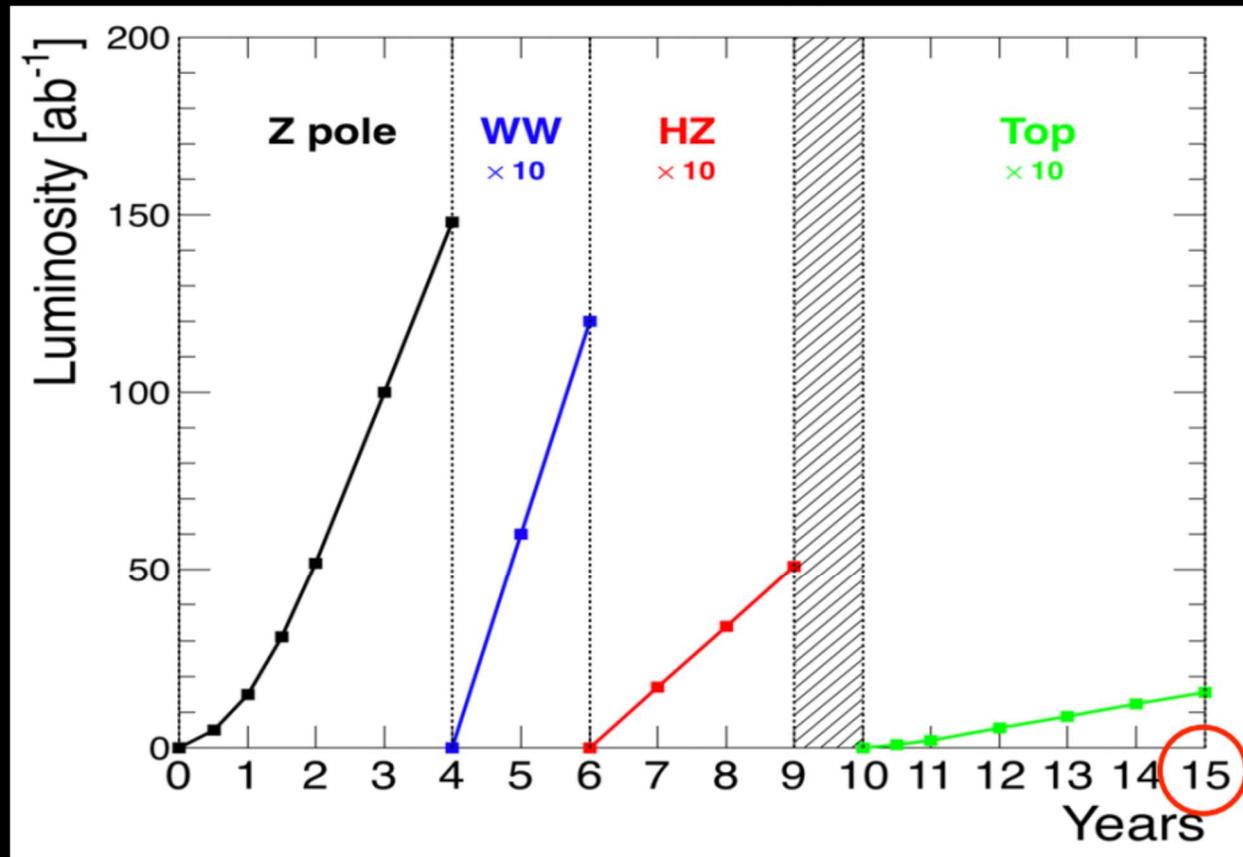
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- $10^6 e^+e^- \rightarrow t\bar{t}$

## ❖ Flavor factory

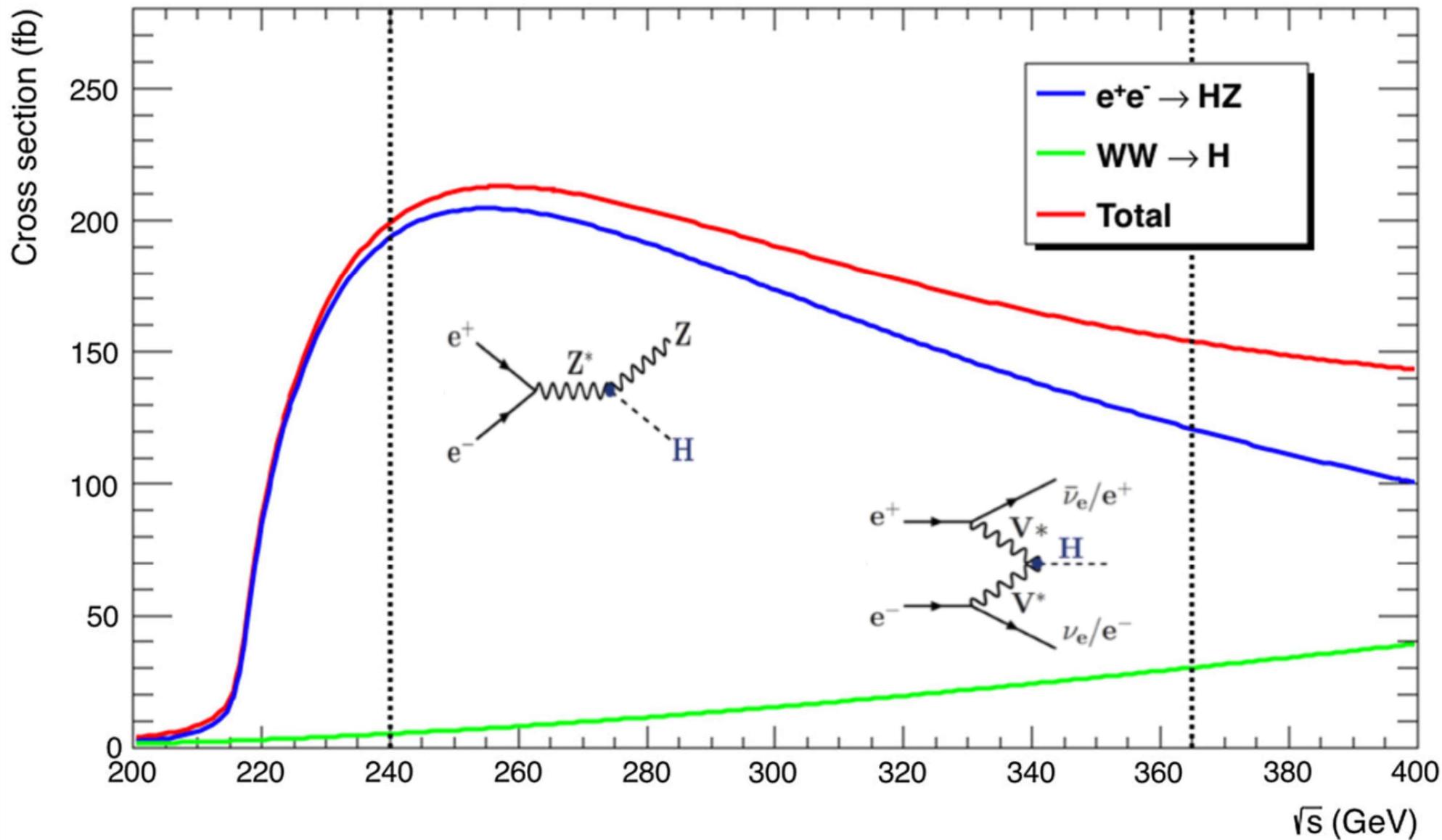
- $10^{12} e^+e^- \rightarrow b\bar{b}, c\bar{c}$
- $10^{11} e^+e^- \rightarrow \tau^+\tau^-$

## ❖ Potential discovery of NP

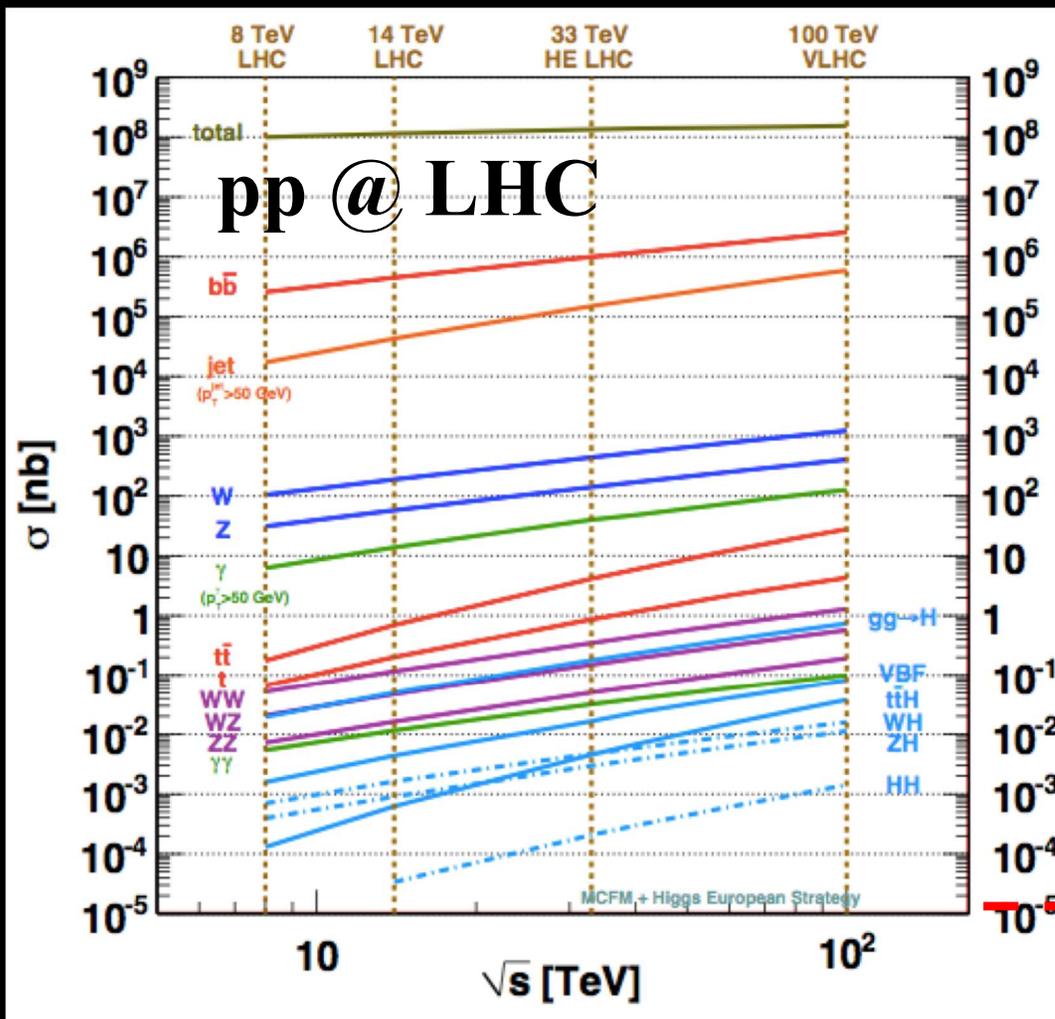
- ALPs, RH  $\nu$ 's, ...



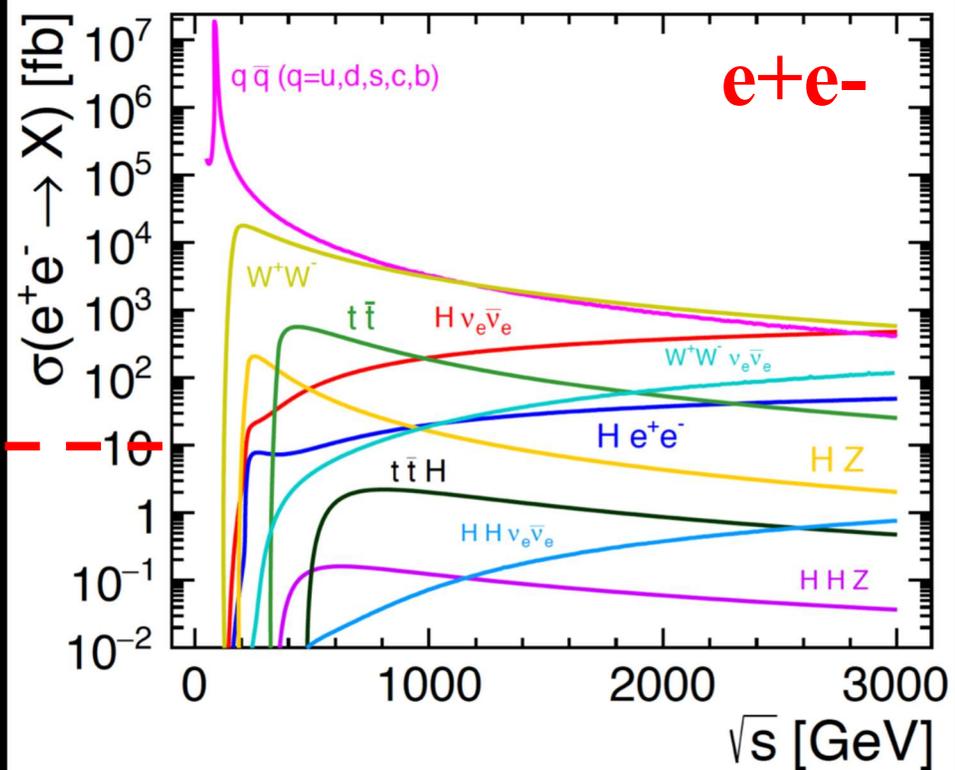
# Higgs production



# Higgs production



Very clean production  
in  $e^+e^-$

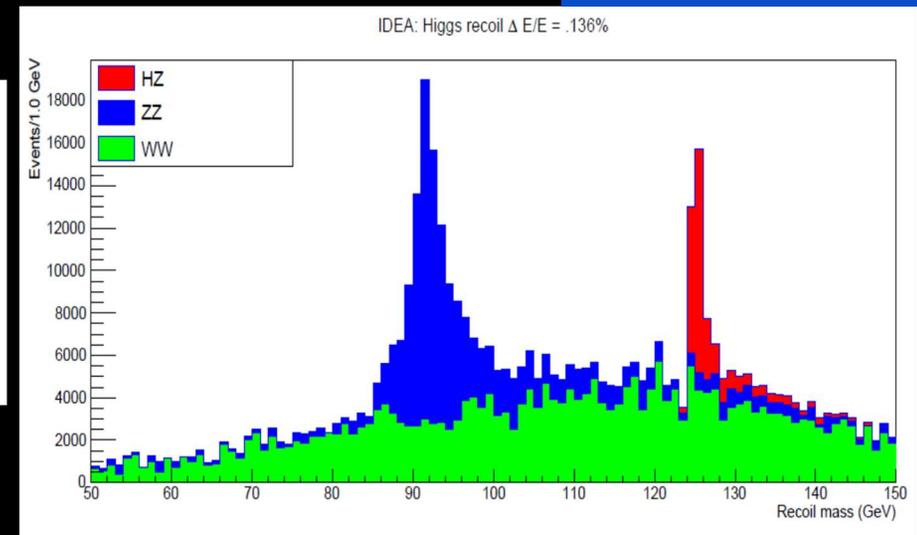
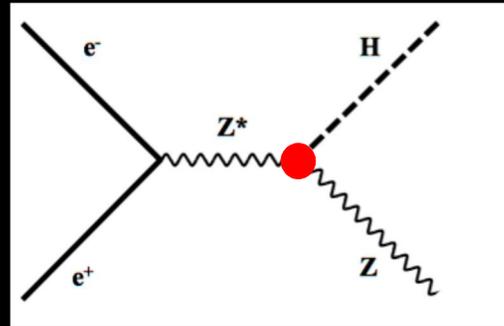


# Higgs total width

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

❖ Higgs recoil provides model independent measurement of coupling to Z

➤  $\sigma(\text{HZ}) \propto g_{\text{HZ}}^2$

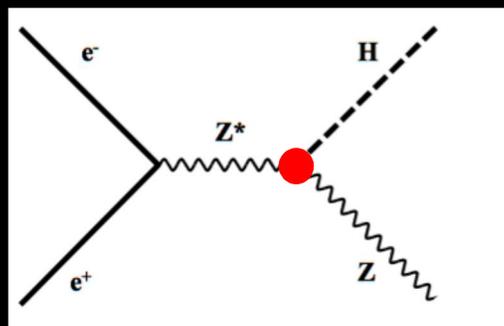


# Higgs total width

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

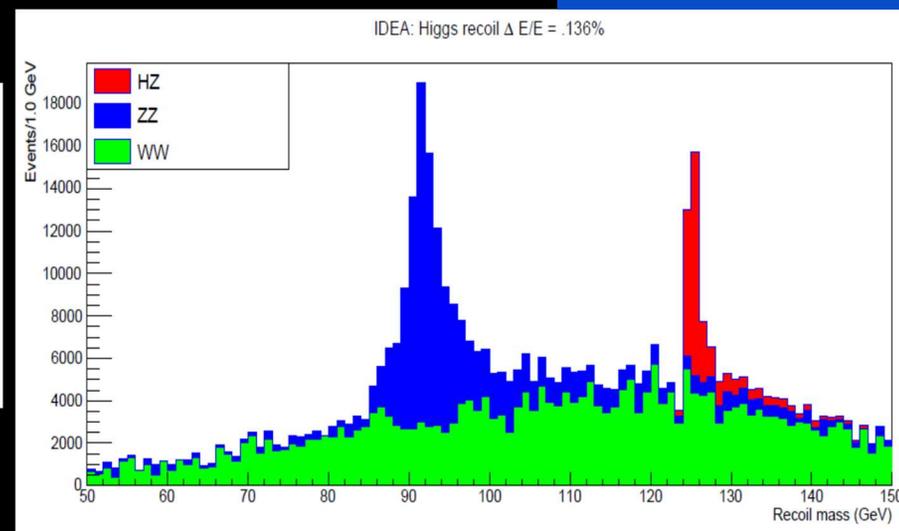
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➤ Critical:

■ Beam energy spread: SR+BS

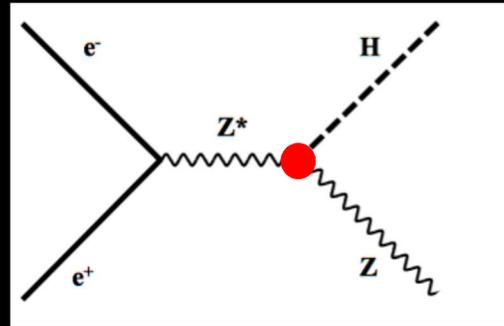


# Higgs total width

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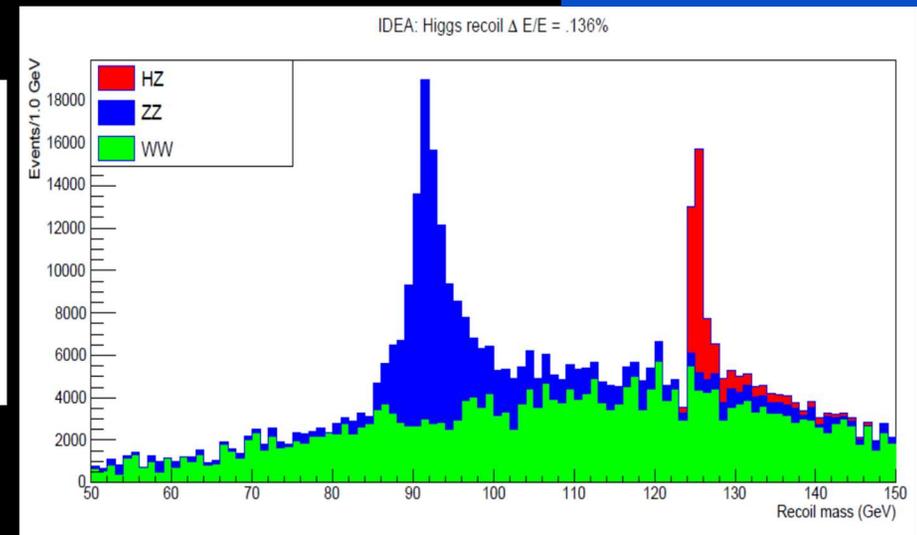
❖ Higgs recoil provides model independent measurement of coupling to Z

➤  $\sigma(\text{HZ}) \propto g_{\text{HZ}}^2$



➤ Critical:

■ Beam energy spread: SR+BS



❖ Total width combining with decays in specific channels

$$\sigma(ee \rightarrow ZH) \cdot \text{BR}(H \rightarrow ZZ) \propto \frac{g_{\text{HZ}}^4}{\Gamma}$$

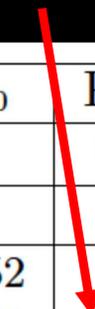
# Higgs coupling fits

## ❖ Results limited only by statistics

Collider	HL-LHC	ILC <sub>250</sub>	CLIC <sub>380</sub>	CEPC <sub>240</sub>	FCC-ee <sub>240→365</sub>
Lumi (ab <sup>-1</sup> )	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 <sup>5</sup>	8	7	3 + 1 + 4
$g_{HZZ}$ (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	<b>0.17 / 0.26</b>
$g_{HWW}$ (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	<b>0.41 / 0.27</b>
$g_{Hbb}$ (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	<b>0.64 / 0.56</b>
$g_{Hcc}$ (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	<b>1.3 / 1.3</b>
$g_{Hgg}$ (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	<b>0.89 / 0.82</b>
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	<b>0.66 / 0.57</b>
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	<b>3.9 / 3.8</b>
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	<b>1.2 / 1.2</b>
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	<b>10. / 9.4</b>
$g_{Htt}$ (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	<b>2.6 / 2.6</b>
$g_{HHH}$ (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	<b>19. / 34.</b>
$\Gamma_H$ (%)	SM	2.4	2.6	1.9	<b>1.2</b>
BR <sub>inv</sub> (%)	1.9	0.26	0.63	0.27	<b>0.19</b>
BR <sub>EXO</sub> (%)	SM (0.0)	1.8	2.7	1.1	<b>1.0</b>

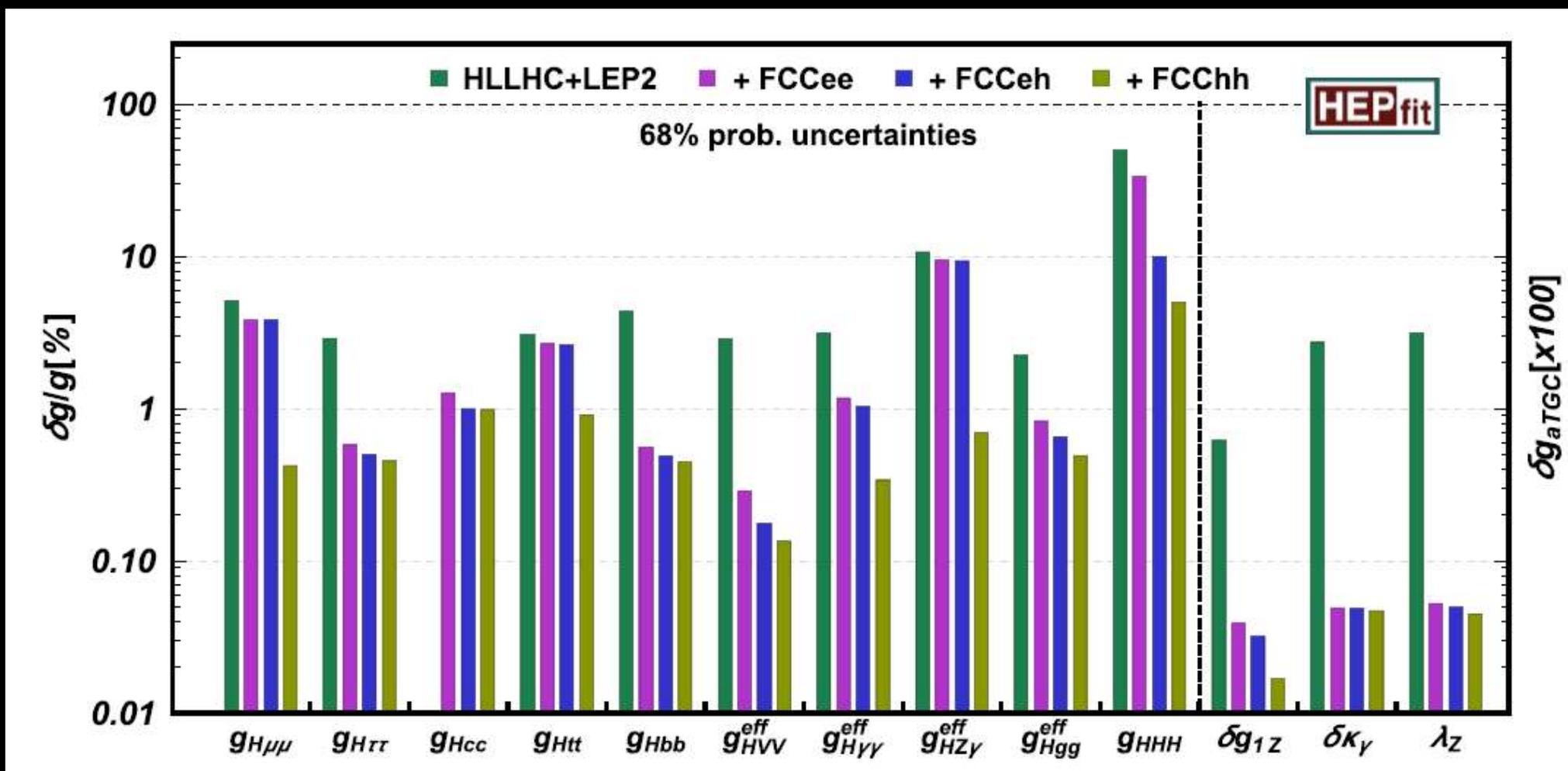
**K**

**EFT**



# Higgs coupling fits

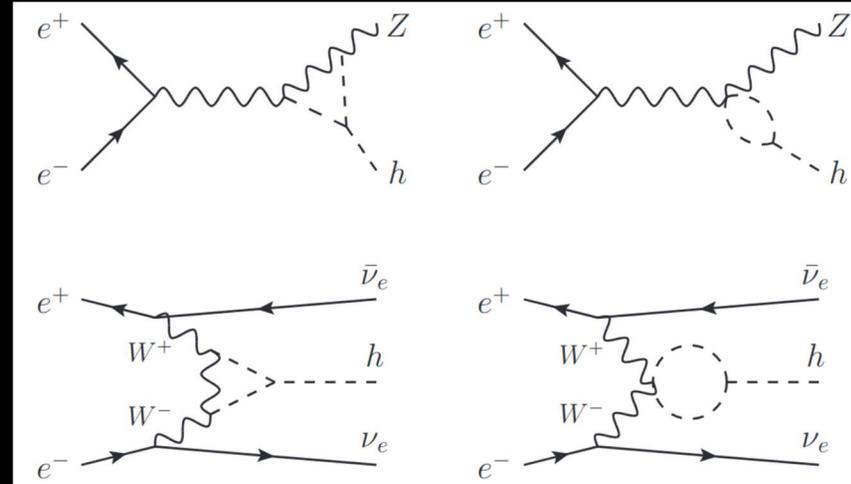
❖ Results limited only by statistics



# Triple Higgs

❖ No direct production @ FCC-ee

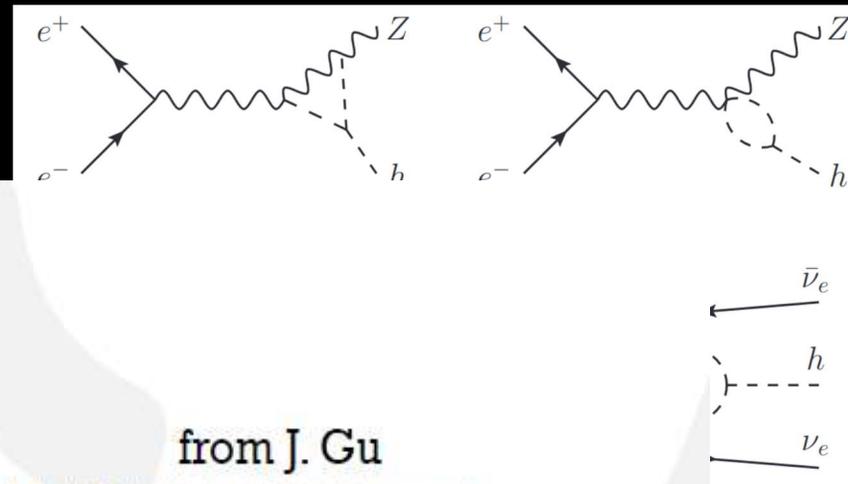
➤ Sensitivity through loop effects



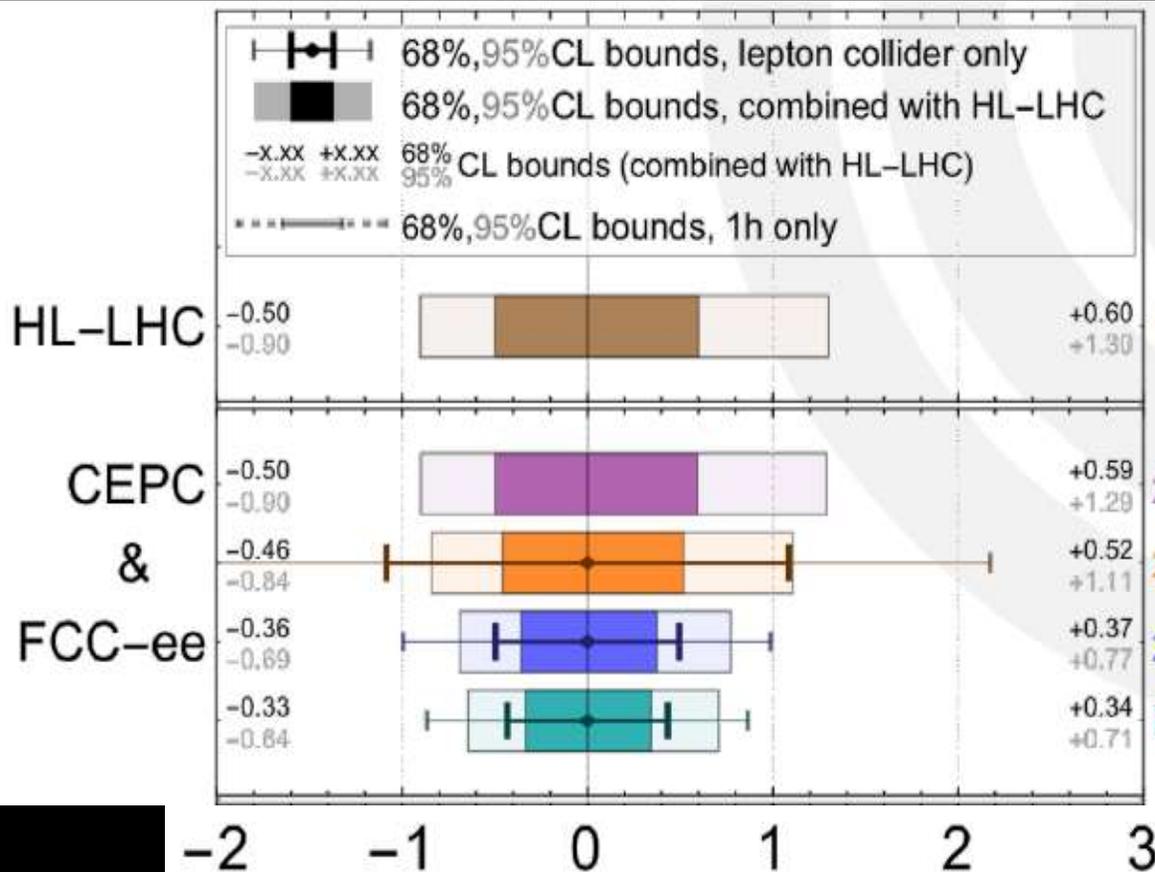
# Triple Higgs

❖ No direct production @ FCC-ee

➤ Sensitivity through loop effects



from J. Gu



14TeV(3/ab), LHC WG report

240GeV(5/ab) only (CEPC)

240GeV(5/ab)+350GeV(200/fb)

240GeV(5/ab)+350GeV(1.5/ab) (FCC-ee)

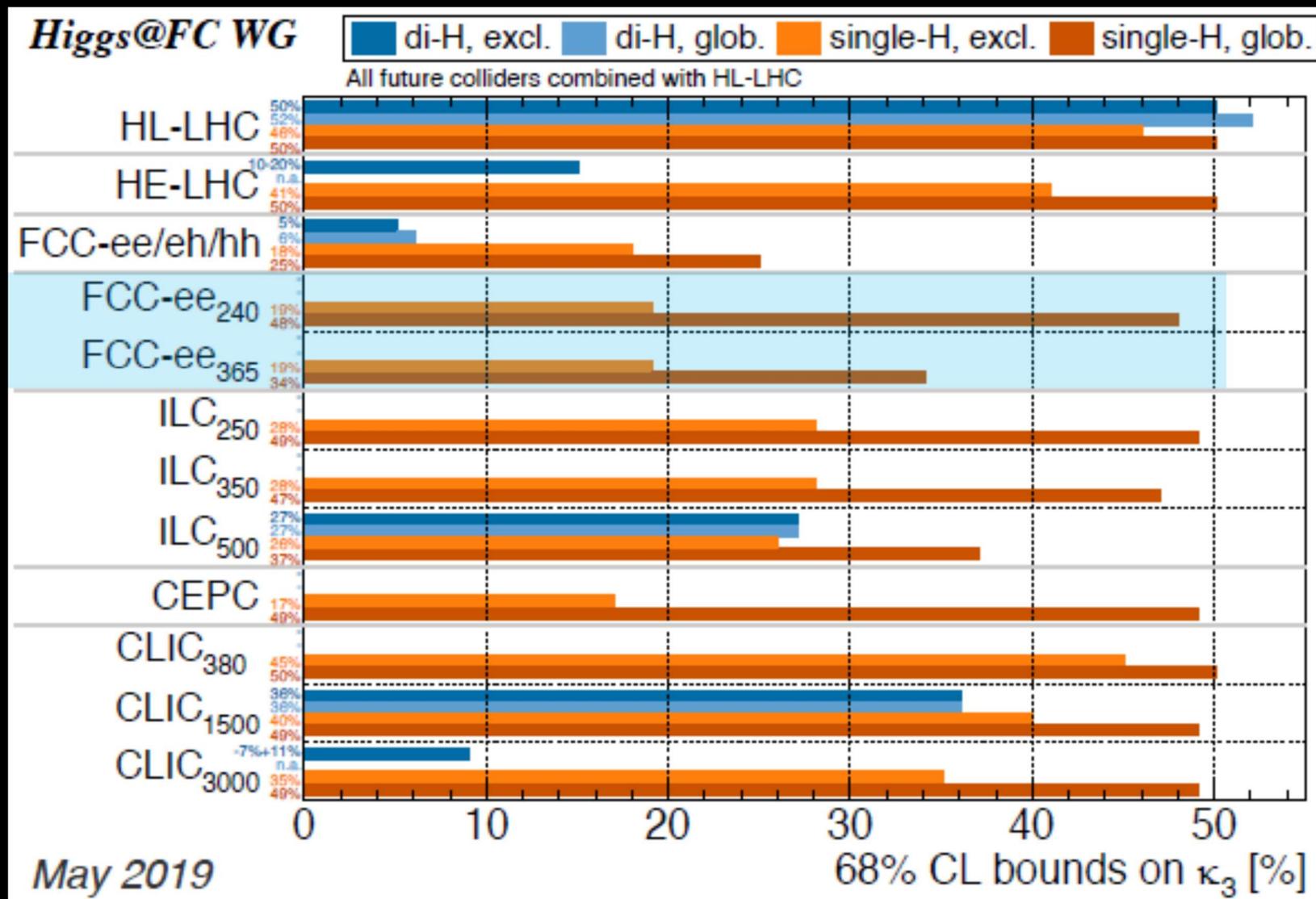
FCC-ee with zero aTGCs

$$\delta K_\lambda \left( \equiv \frac{\lambda_3}{\lambda_3^{\text{SM}}} - 1 \right)$$

Ayan Paul – EPS 2019 – Ghent.

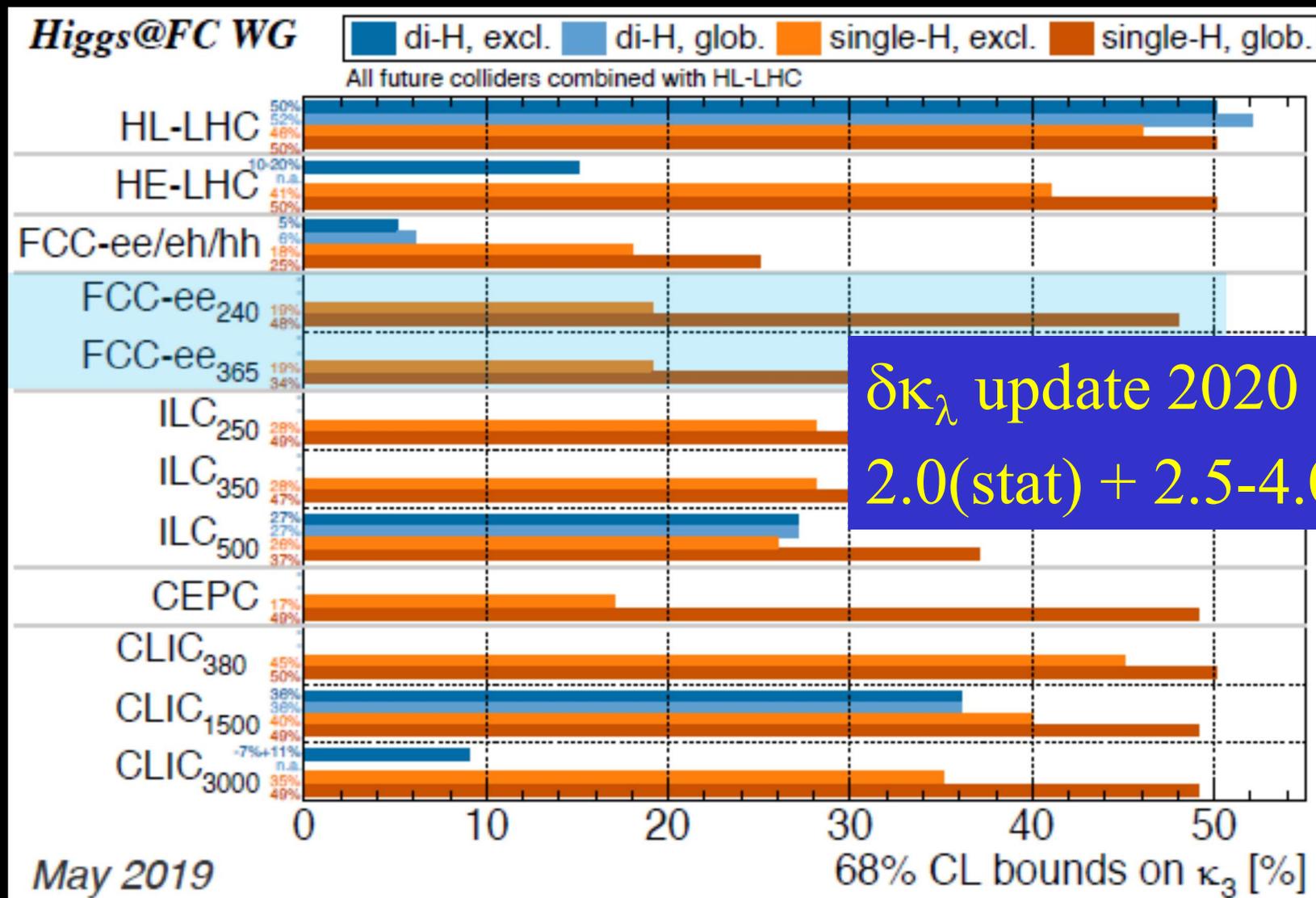
# Triple Higgs

## ❖ No direct production @ FCC-ee



# Triple Higgs

## ❖ No direct production @ FCC-ee



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

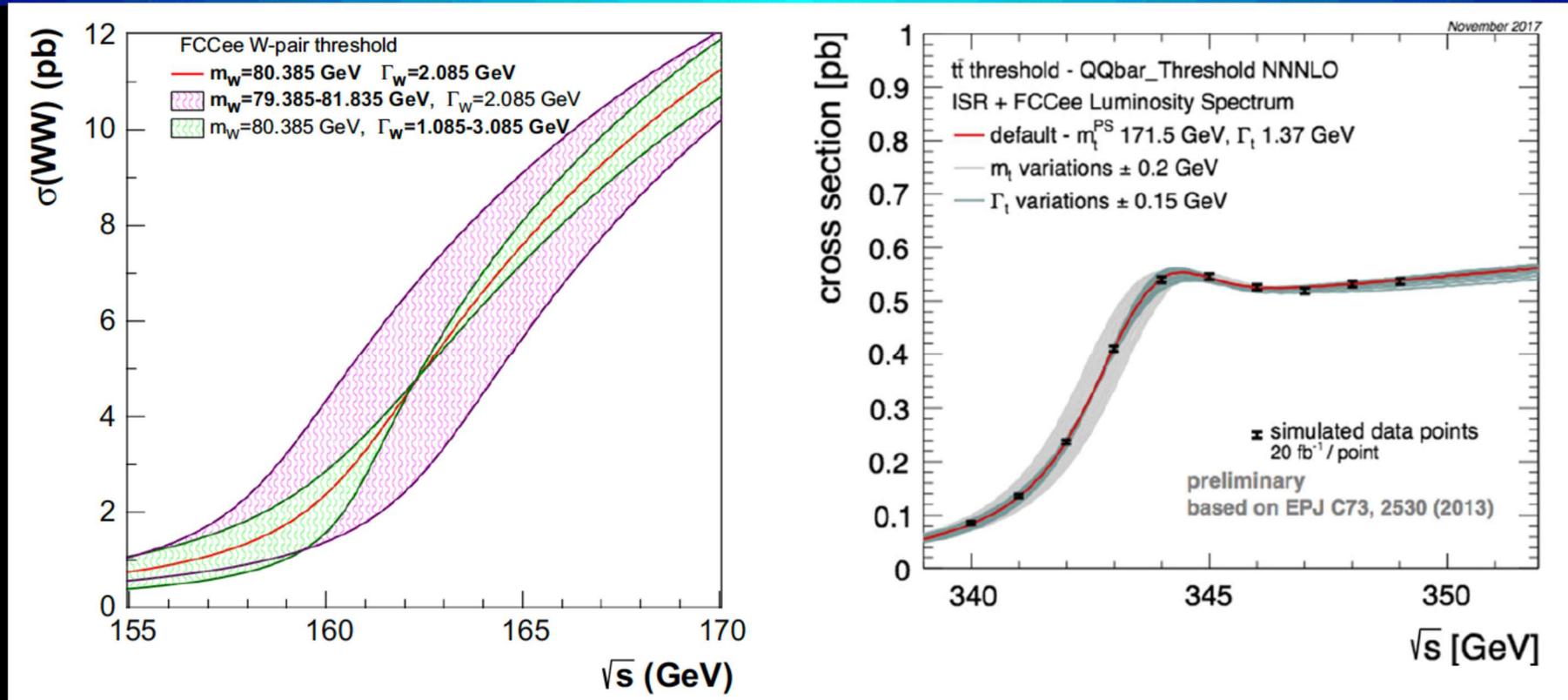
# EWK

## ❖ Outstanding program of precision EWK measurements

- O(10-100) better than LEP precision
- Substantially reduce parametric uncertainties in theory

Observable	Present value $\pm$ 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	Z pole
$\Gamma_Z$ (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration	
$R_\ell^Z (\times 10^3)$	$20,767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons	
$\alpha_s (m_Z) (\times 10^4)$	$1196 \pm 30$	0.1	0.4–1.6	From $R_\ell^Z$ 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]	
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement	
$N_\nu (\times 10^3)$	$2991 \pm 7$	0.005	1	Z peak cross sections Luminosity measurement	
$\sin^2\theta_W^{\text{eff}} (\times 10^6)$	$231,480 \pm 160$	3	2–5	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration	
$1/\alpha_{\text{QED}} (m_Z) (\times 10^3)$	$128,952 \pm 14$	4	Small	From $A_{\text{FB}}^{\mu\mu}$ off peak [34]	
$A_{\text{FB}}^{b,0} (\times 10^4)$	$992 \pm 16$	0.02	1–3	b-quark asymmetry at Z pole from jet charge	
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	$1498 \pm 49$	0.15	< 2	$\tau$ Polarisation and charge asymmetry $\tau$ decay physics	WW
$m_W$ (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration	
$\Gamma_W$ (MeV)	$2085 \pm 42$	1.2	0.3	From WW threshold scan Beam energy calibration	tt
$\alpha_s (m_W) (\times 10^4)$	$1170 \pm 420$	3	Small	From $R_\ell^W$ [45]	
$N_\nu (\times 10^3)$	$2920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns	
$m_{\text{top}}$ (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
$\Gamma_{\text{top}}$ (MeV)	$1410 \pm 190$	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	$1.2 \pm 0.3$	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate	
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{\text{CM}} = 365$ GeV run	

# EWK examples



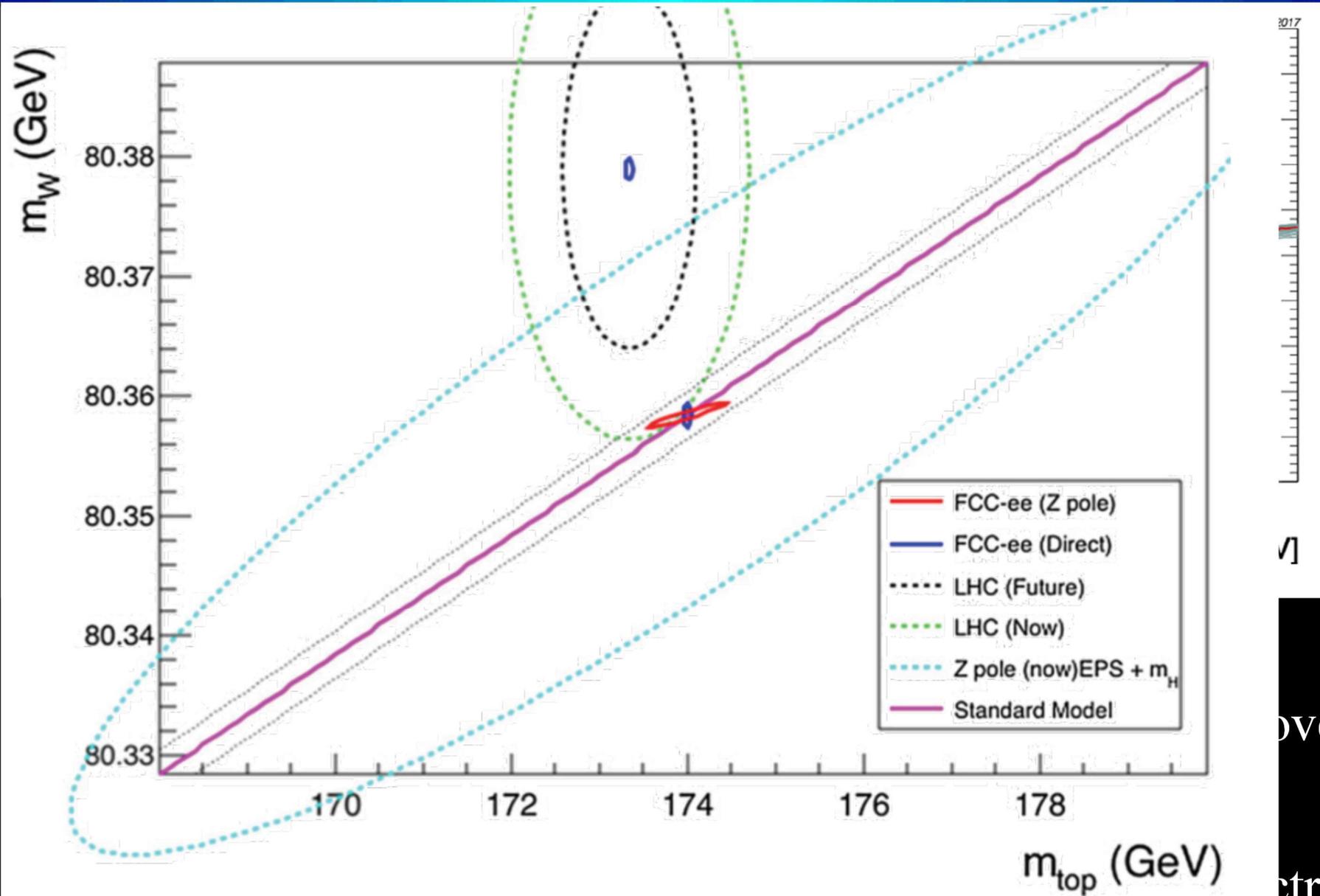
❖ **W mass/width  $\rightarrow$  0.5/1.2 MeV resolution**

➤ WW threshold scan/ direct measurements check and improve

❖ **Top quark mass/width  $\rightarrow$  17/45 MeV resolution**

➤ tt threshold scan – N<sup>3</sup>LO, ISR and FCCee luminosity spectrum

# EWK examples

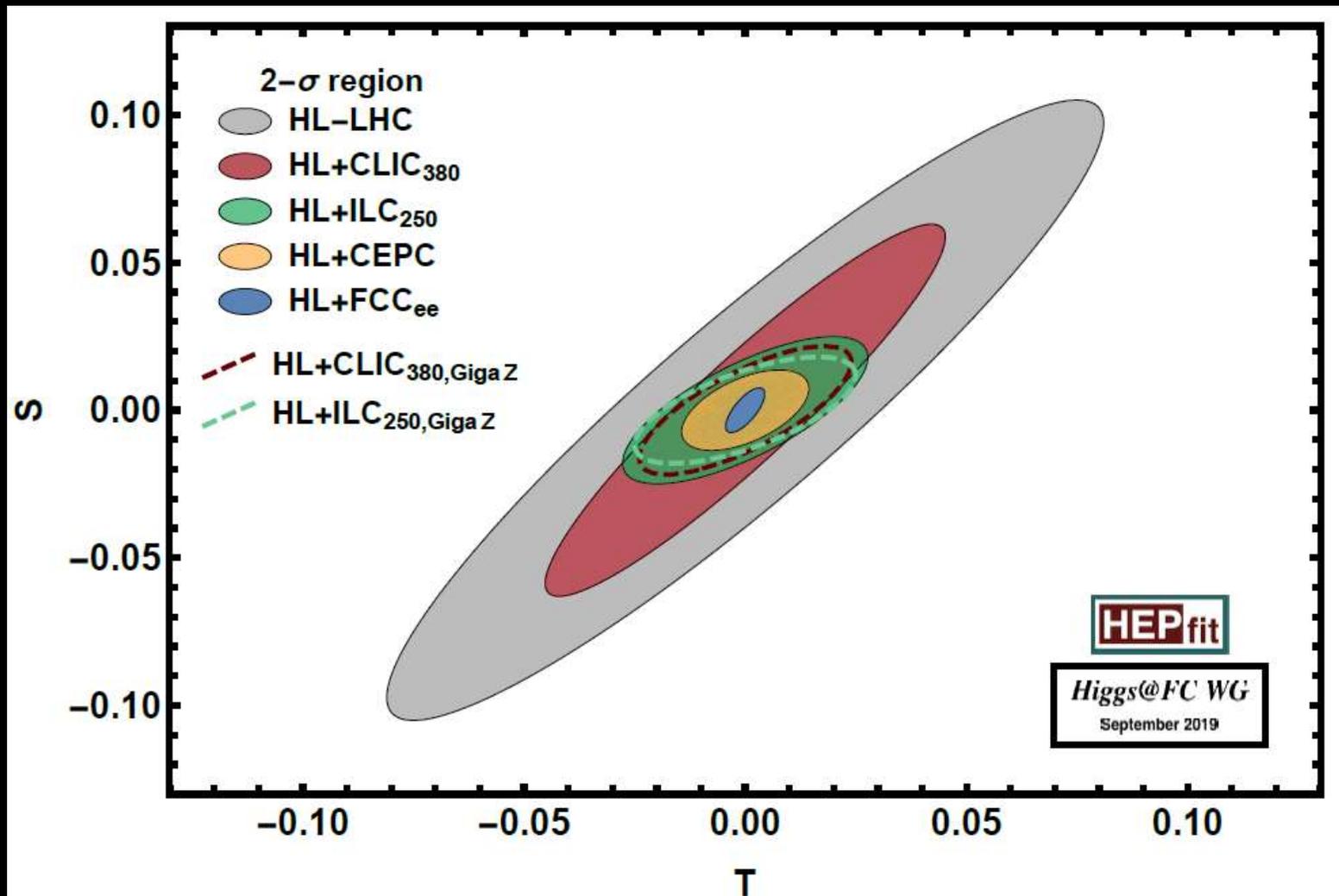


ove

ctrum

# S, T parameters (Peskin–Takeuchi)

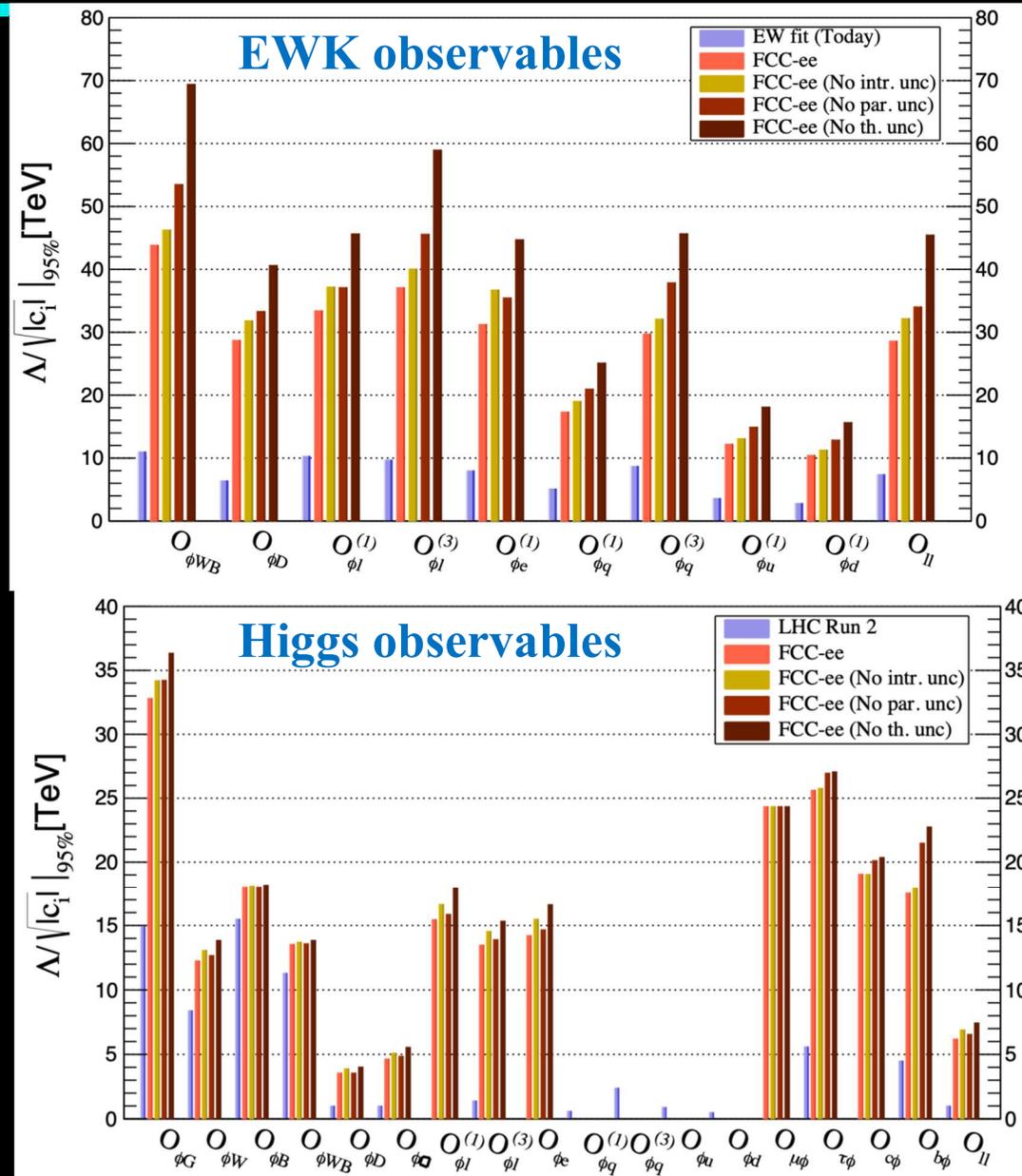
## ❖ Comparison of Higgs factories



# NP sensitivity from EFT fits

## ❖ From exclusive fits

➤ Reach to several 10's TeV



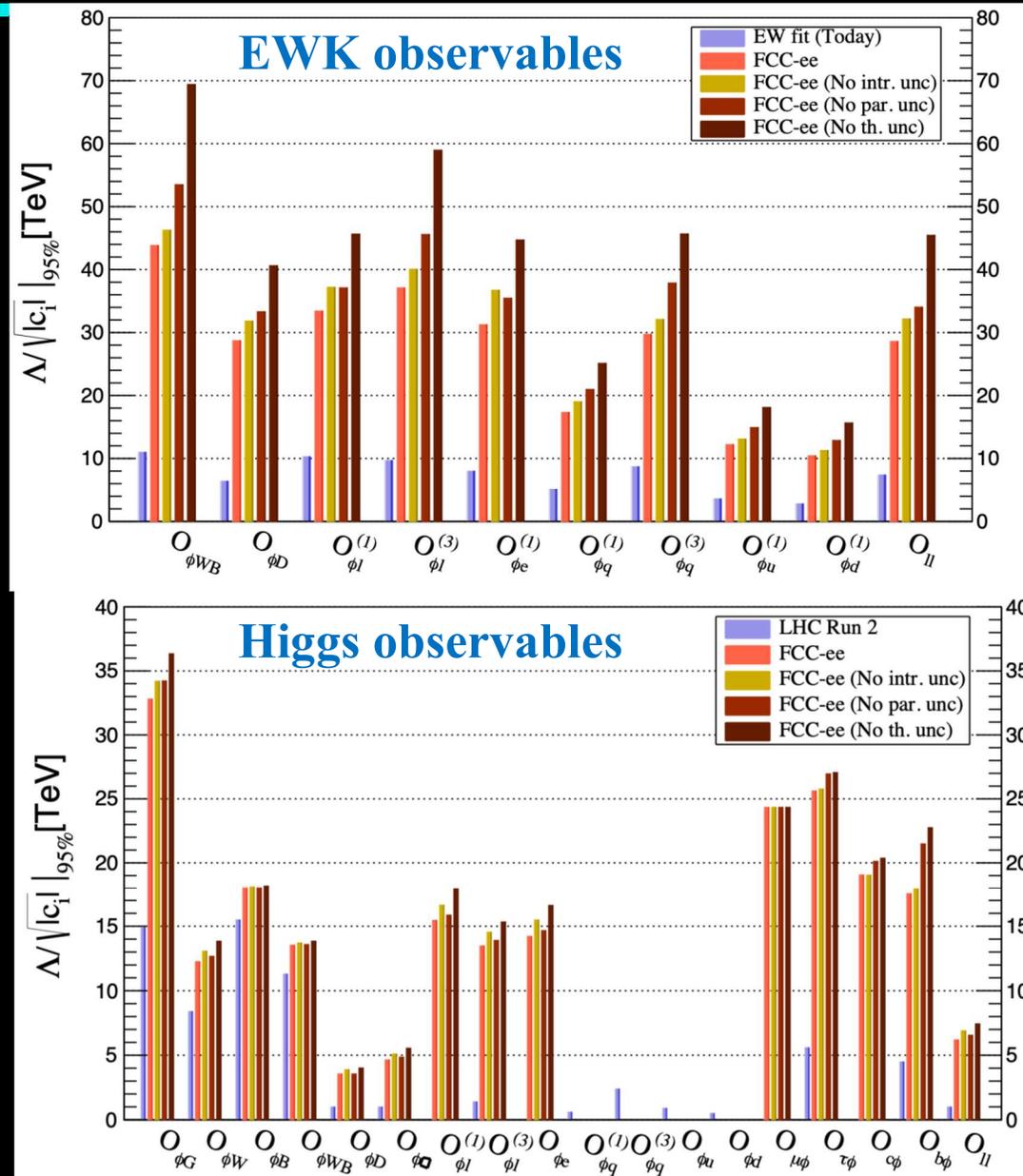
# NP sensitivity from EFT fits

## ❖ 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 ( $10^9$ )	$B^0$	$B^-$	$B_s^0$	$\Lambda_b$	$c\bar{c}$	$\tau^-\tau^+$
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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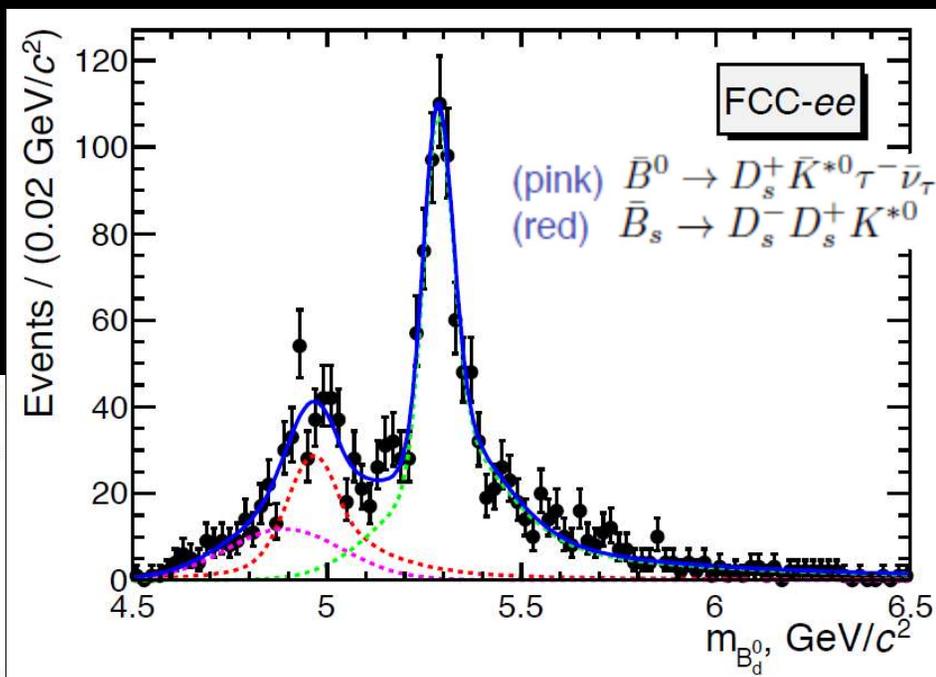
➤ Very clean, well separated, pairs

## ❖ Example:

➤ Lepton universality

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

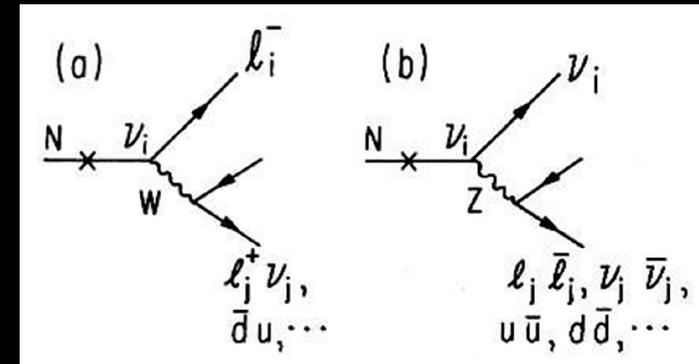
Decay mode	$B^0 \rightarrow K^*(892)e^+e^-$	$B^0 \rightarrow K^*(892)\tau^+\tau^-$	$B_s(B^0) \rightarrow \mu^+\mu^-$
Belle II	$\sim 2000$	$\sim 10$	n/a (5)
LHCb Run I	150	-	$\sim 15$ (-)
LHCb Upgrade	$\sim 5000$	-	$\sim 500$ (50)
FCC- $ee$	$\sim 200000$	$\sim 1000$	$\sim 1000$ (100)



# Direct NP search example: HNL

## ❖ HNL mix with active neutrino's

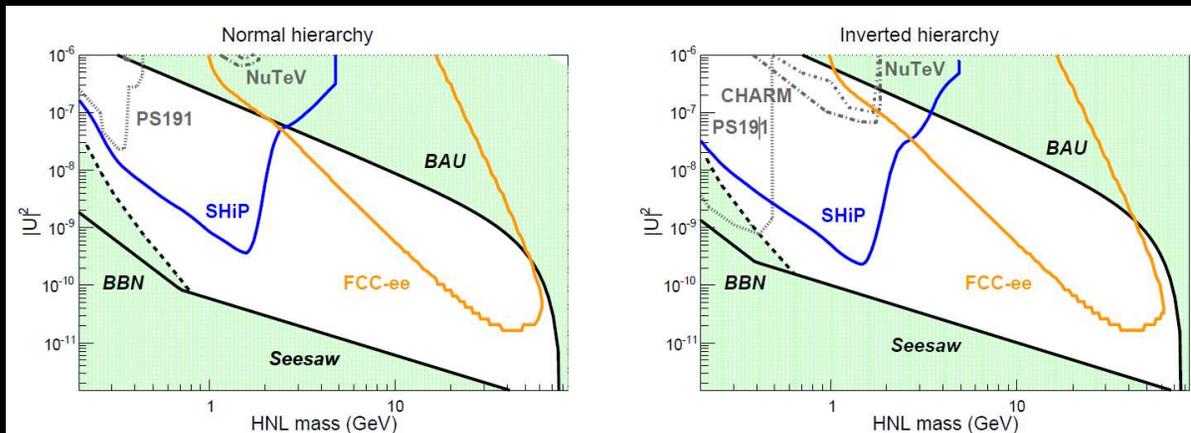
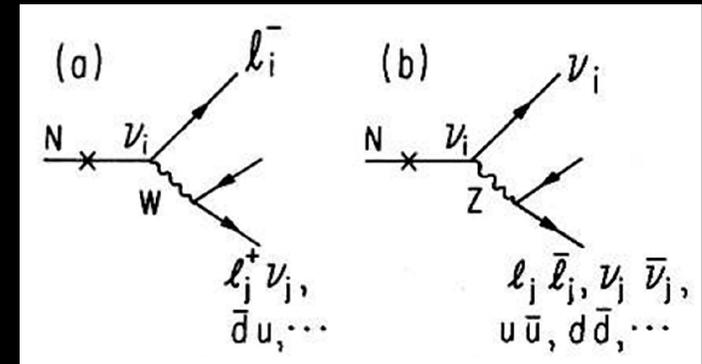
- Fully reconstructable decay with W
- Small mixing  $\rightarrow$  long lifetime



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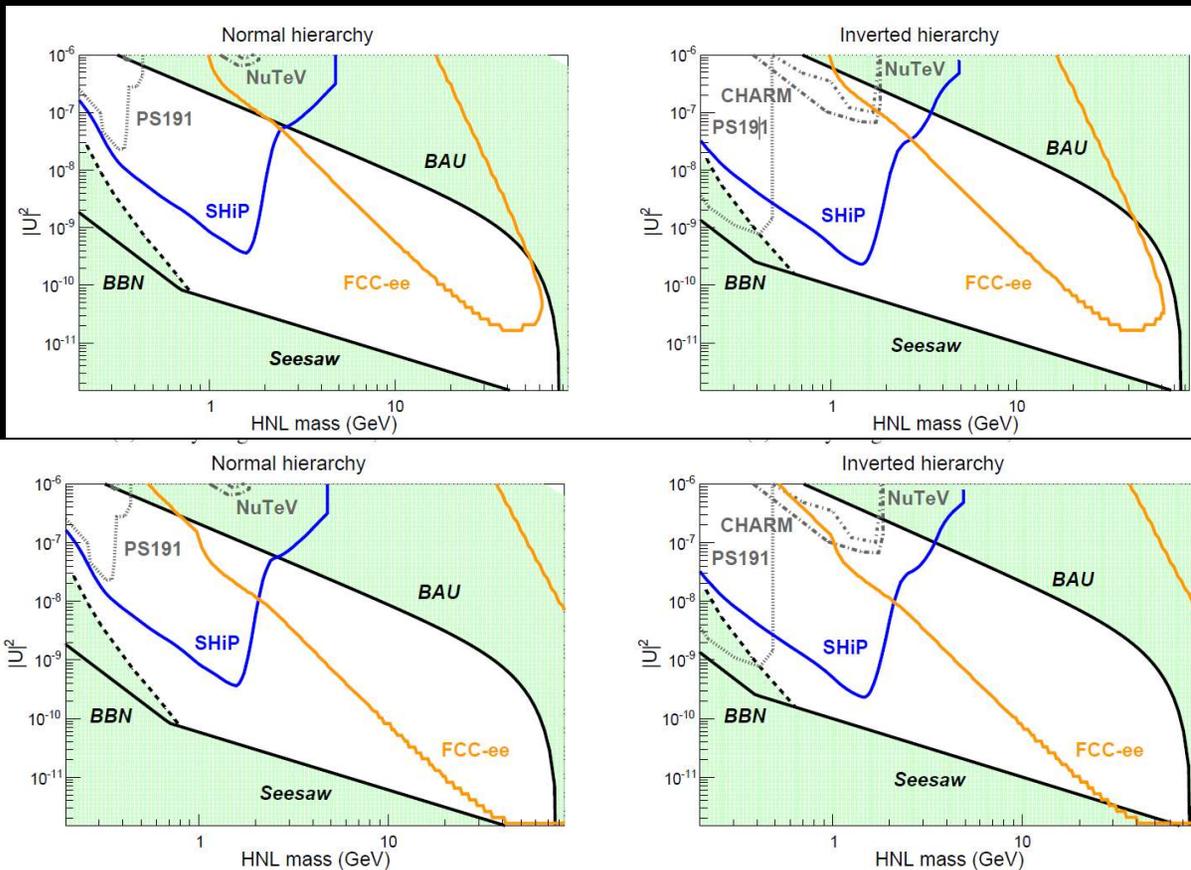
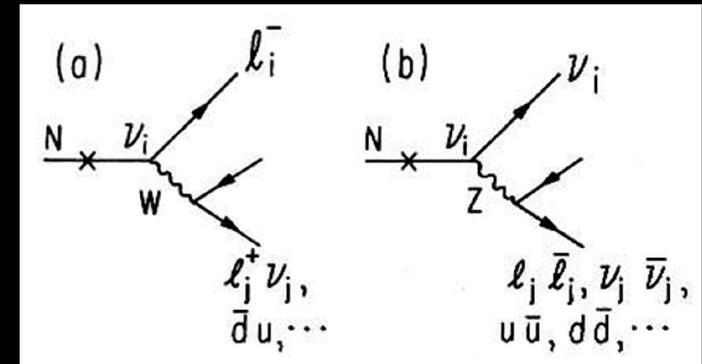


$10 \text{ cm} < c\tau < 100 \text{ cm}$   
 $10^{12} \text{ Z}$

# Direct NP search example: HNL

## ❖ HNL mix with active neutrino's

- Fully reconstructable decay with W
- Small mixing  $\rightarrow$  long lifetime



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

$$10^{12} Z$$

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

$$10^{13} Z$$

FCChh

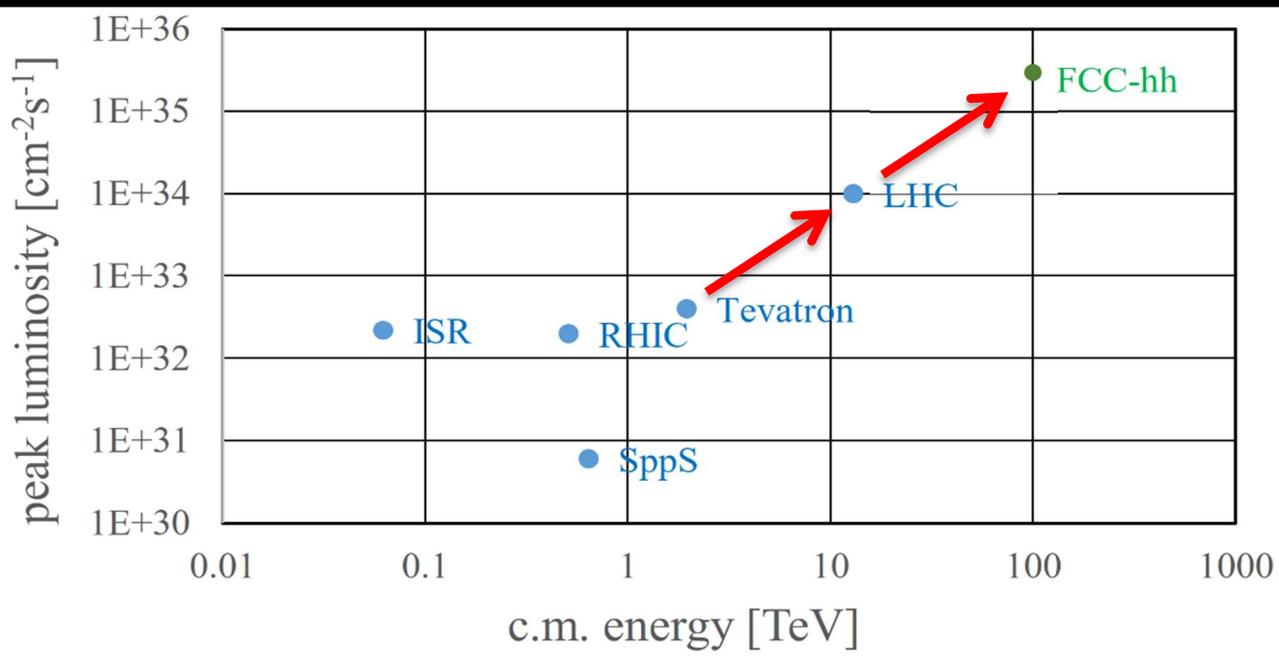
# The pp machine

# 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 [ $\mu\text{m}$ ]	2.2		2.5	2.5	3.75
peak luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	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  $\text{ab}^{-1}/\text{exp.}$

■ In 25 years

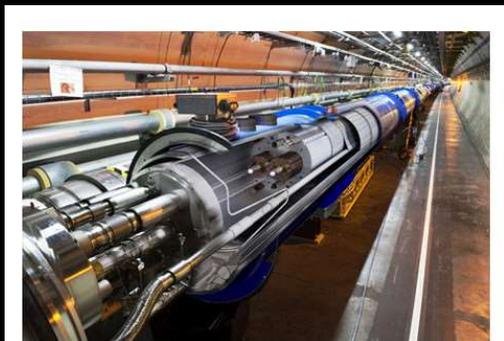
❖ **Key tech. issue:**

➤ High field magnets

➤ 20 T with HTS

**LHC technology**

**8.3 T NbTi**



**HL-LHC technology**

**11 T Nb<sub>3</sub>Sn**



**16 T Nb<sub>3</sub>Sn**

# FCCh magnets



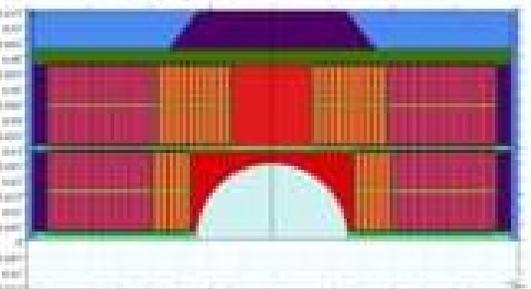
## Magnet development: magnet models production



F2D2 or



CEA: 15.5 T magnet with 14% load line with current wire spec



INFN: 14 T magnet with 14 % margin (FCC spec), 9.5% with current wire spec

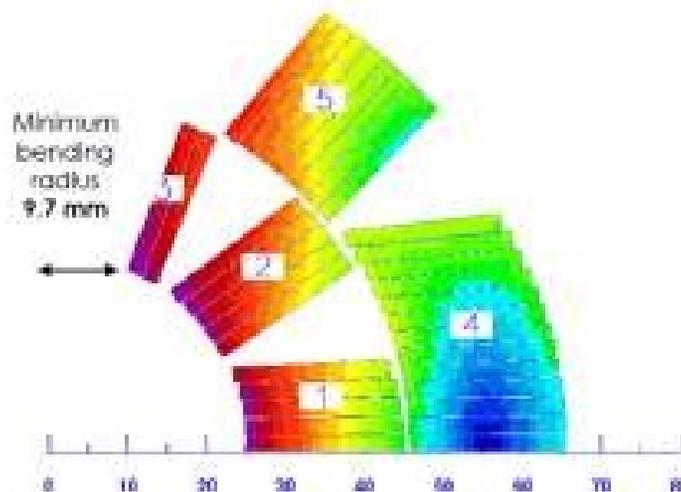


CHART2 – Swiss Accelerator Research and Technology

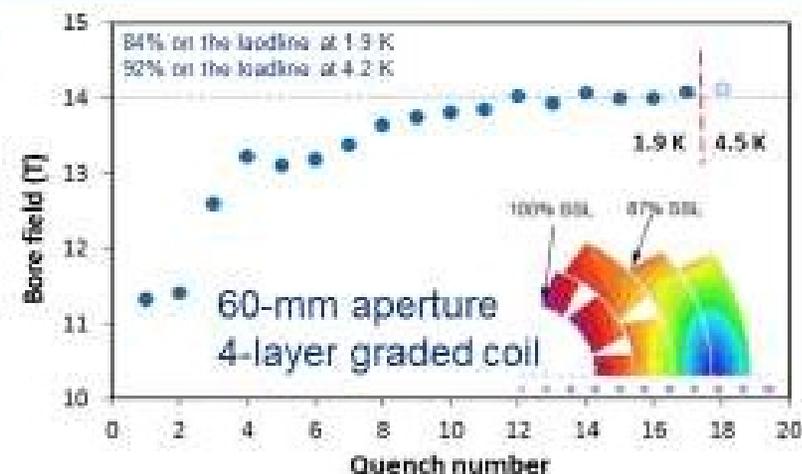


First model with 11 T will be tested in LBNL soon

# FCCh magnets



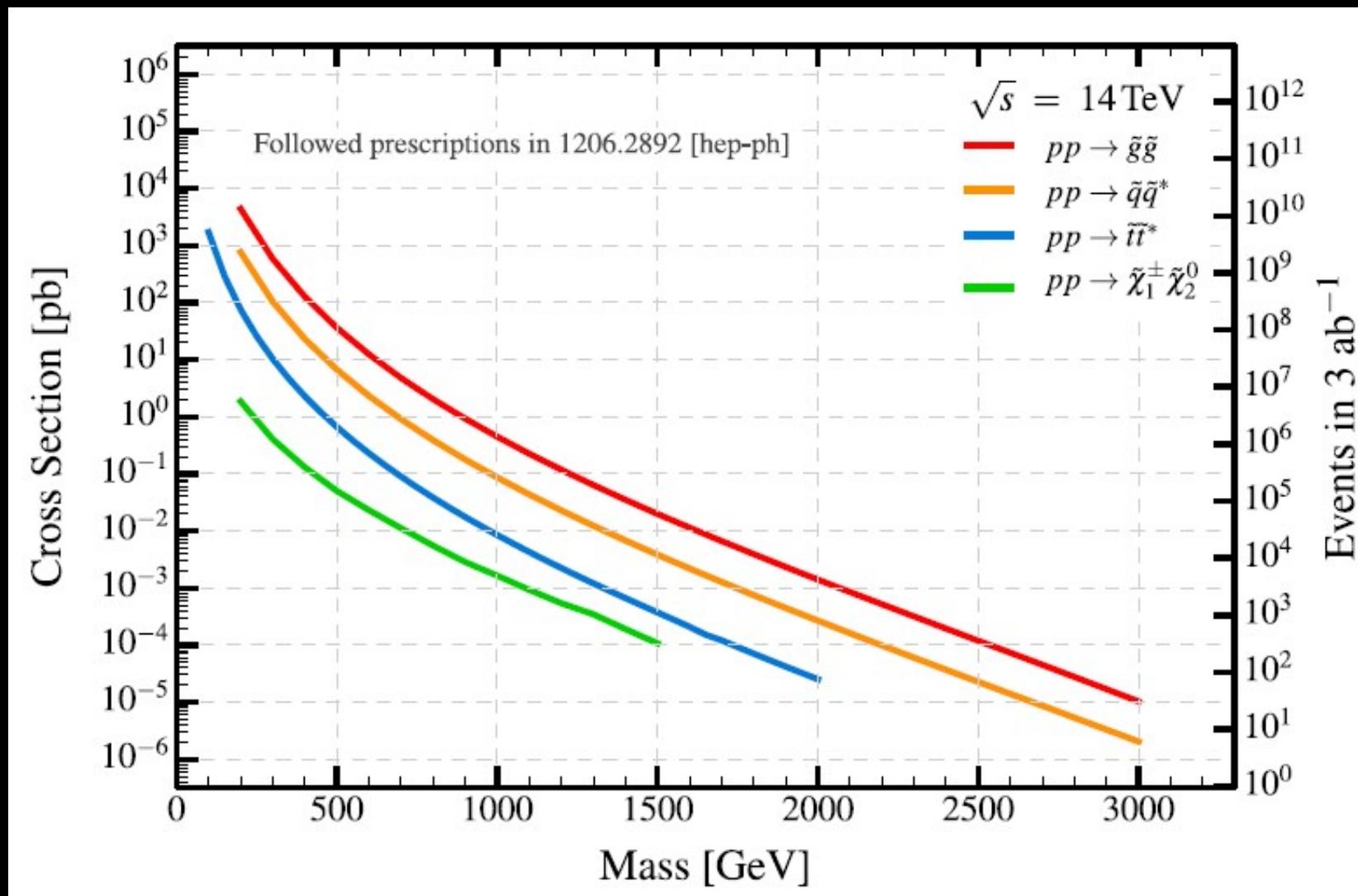
## US – MDP: 14 T magnet tested at FNAL



- 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

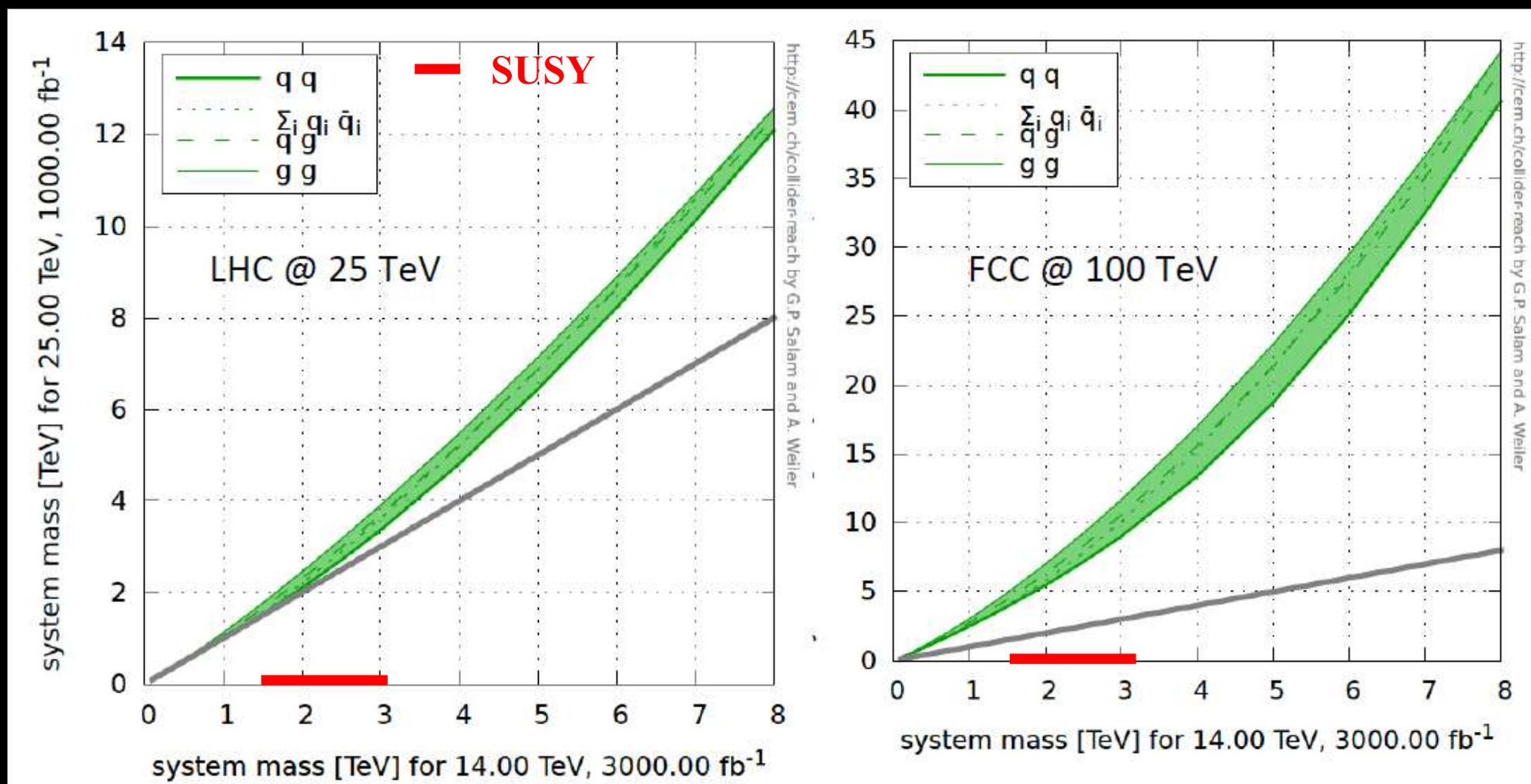
# Exploration potential

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



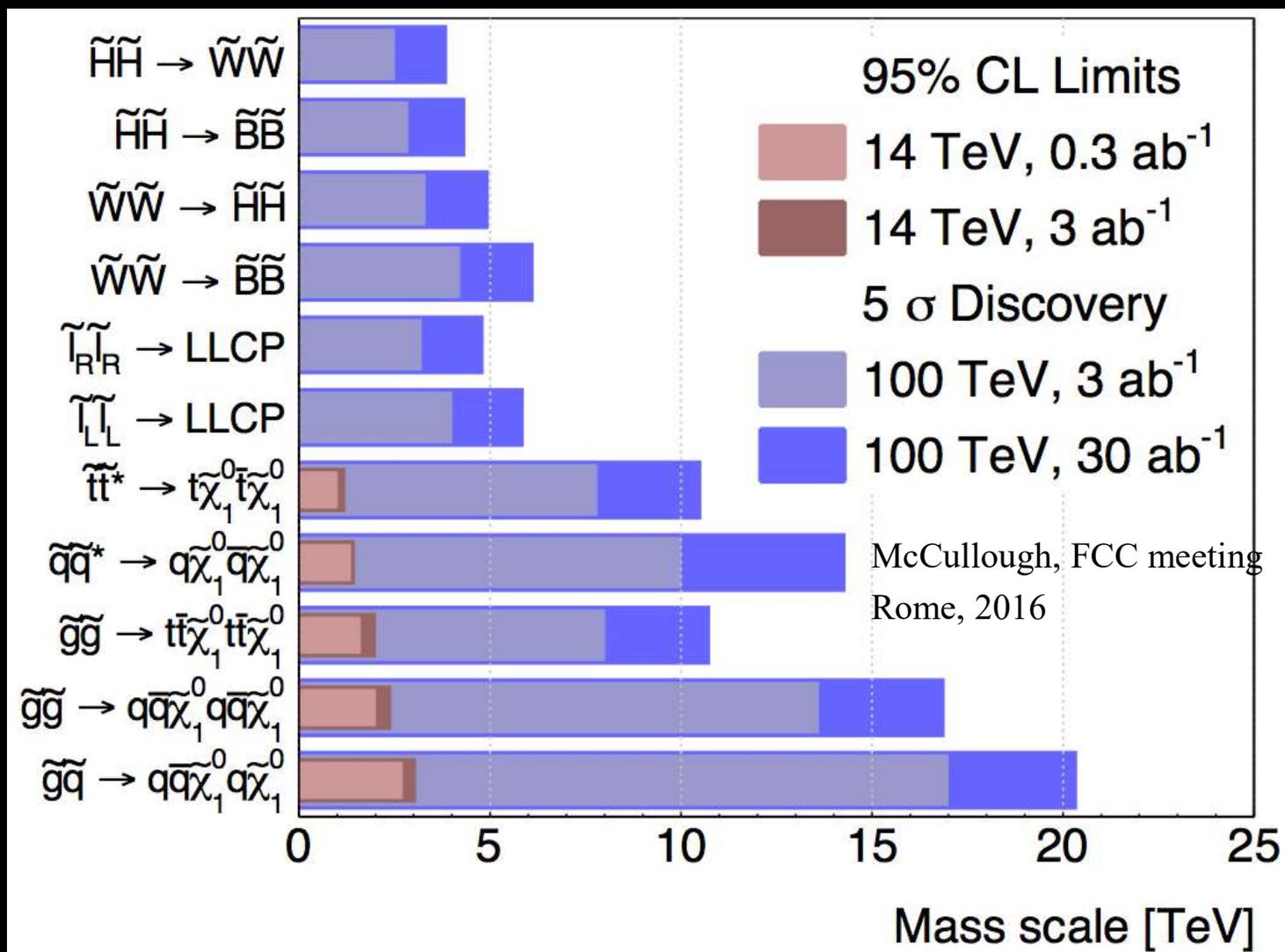
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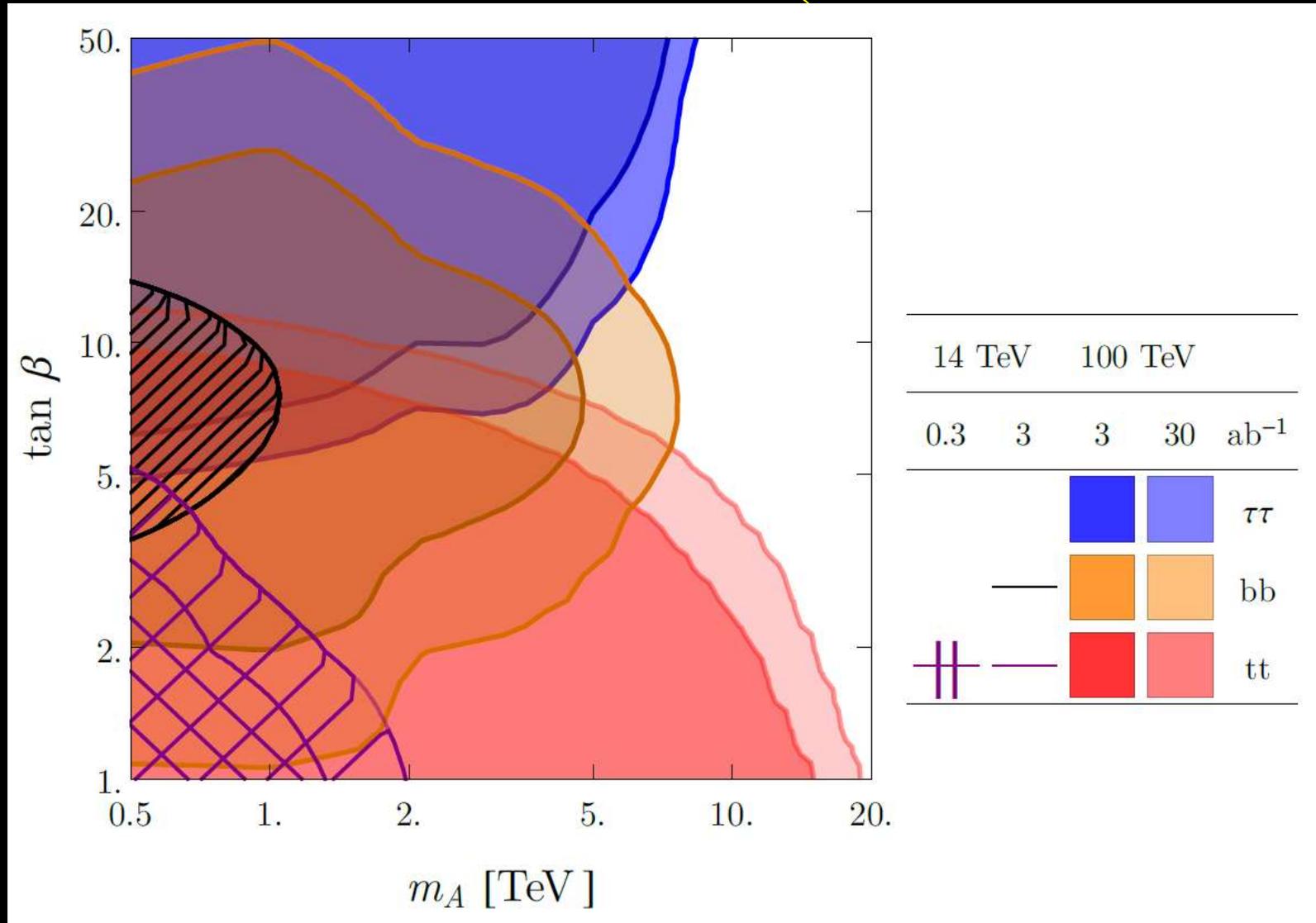
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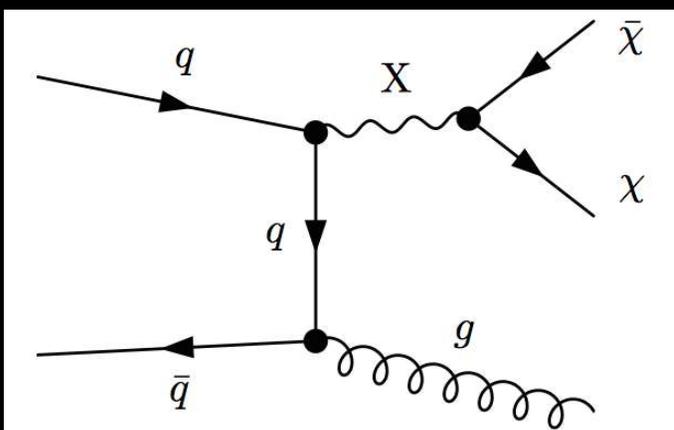
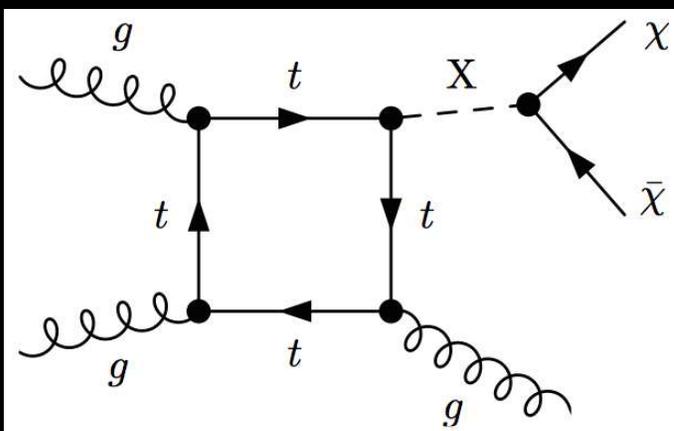
❖ Search reach scaled from HL-LHC (2-3 TeV for SUSY)



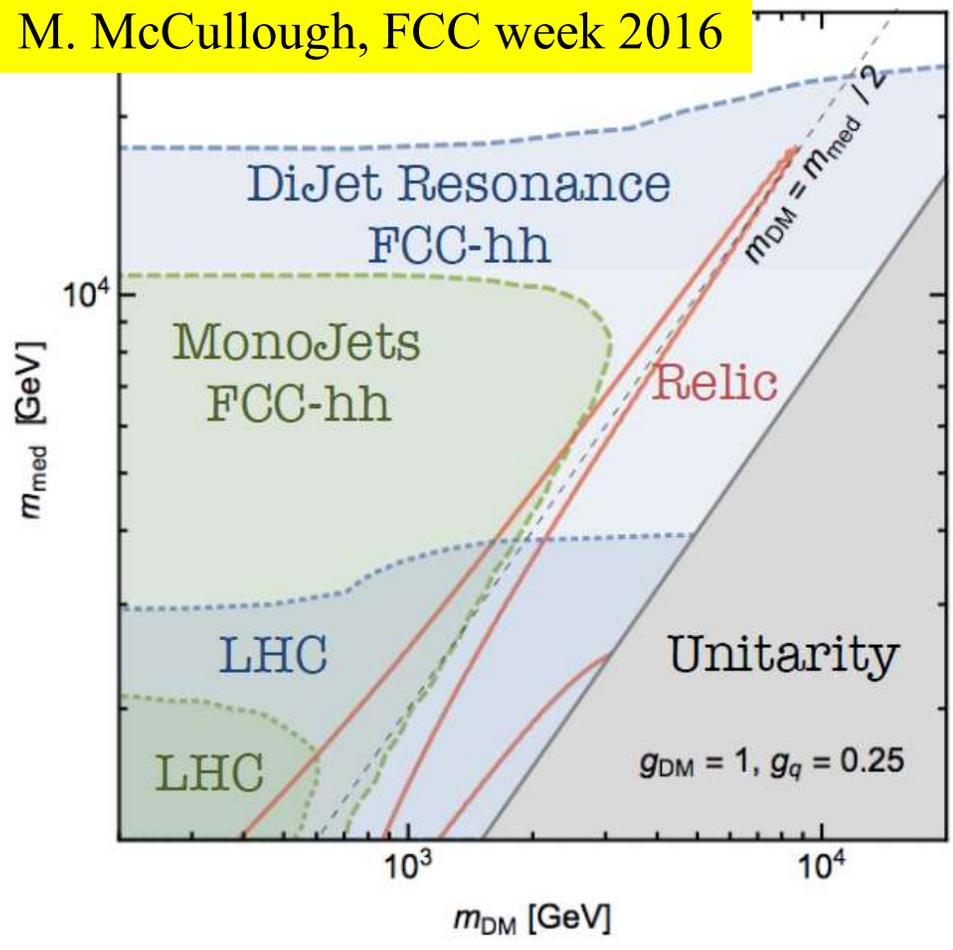
# Dark matter

## ❖ Dark matter (simplified models)

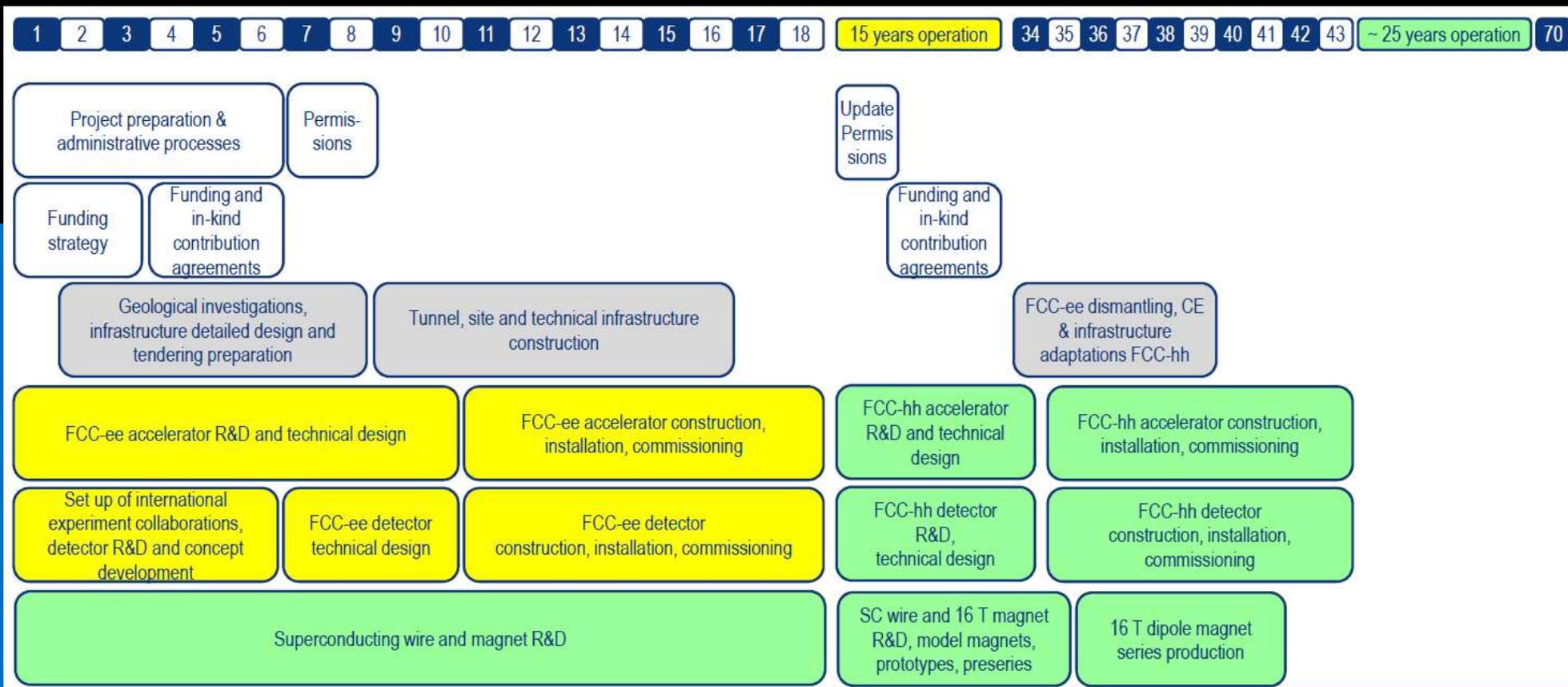
- 100 TeV pp could cover all parameter space allowed by cosmological bounds



M. McCullough, FCC week 2016

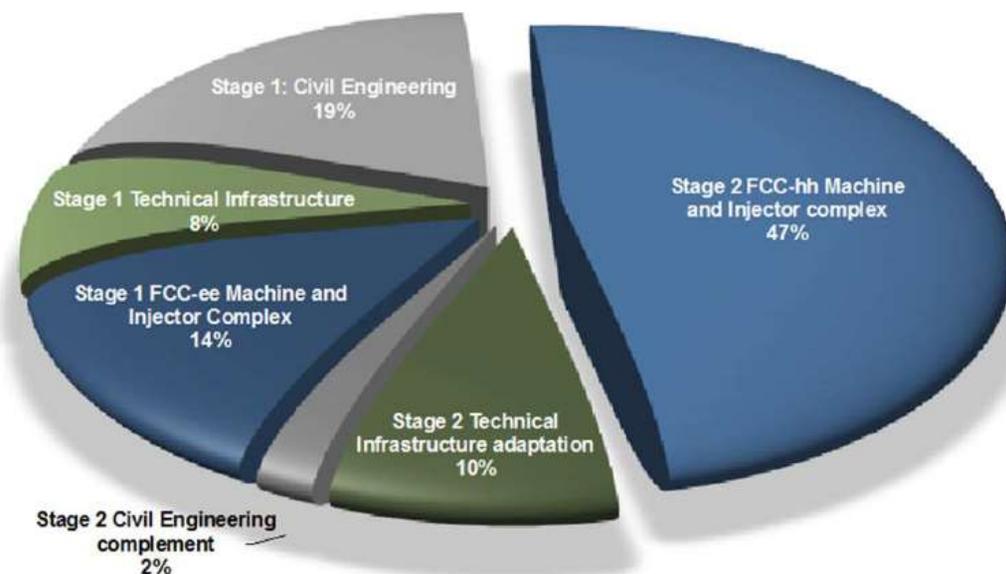


# FCC-ee + FCC-hh schedule



# 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
<b>TOTAL construction cost for integral FCC project</b>	<b>28,600</b>



❖ **Total cost FCCee: 10,600 MCHF**

➤ Addition for tt 1,100 MCHF

❖ **Total additional cost for FCCChh: 17,000 MCHF**

➤ Stand alone ~25 BCHF

# ESG main scenarios

## ❖ 5 basic options for the future being explored by ESG

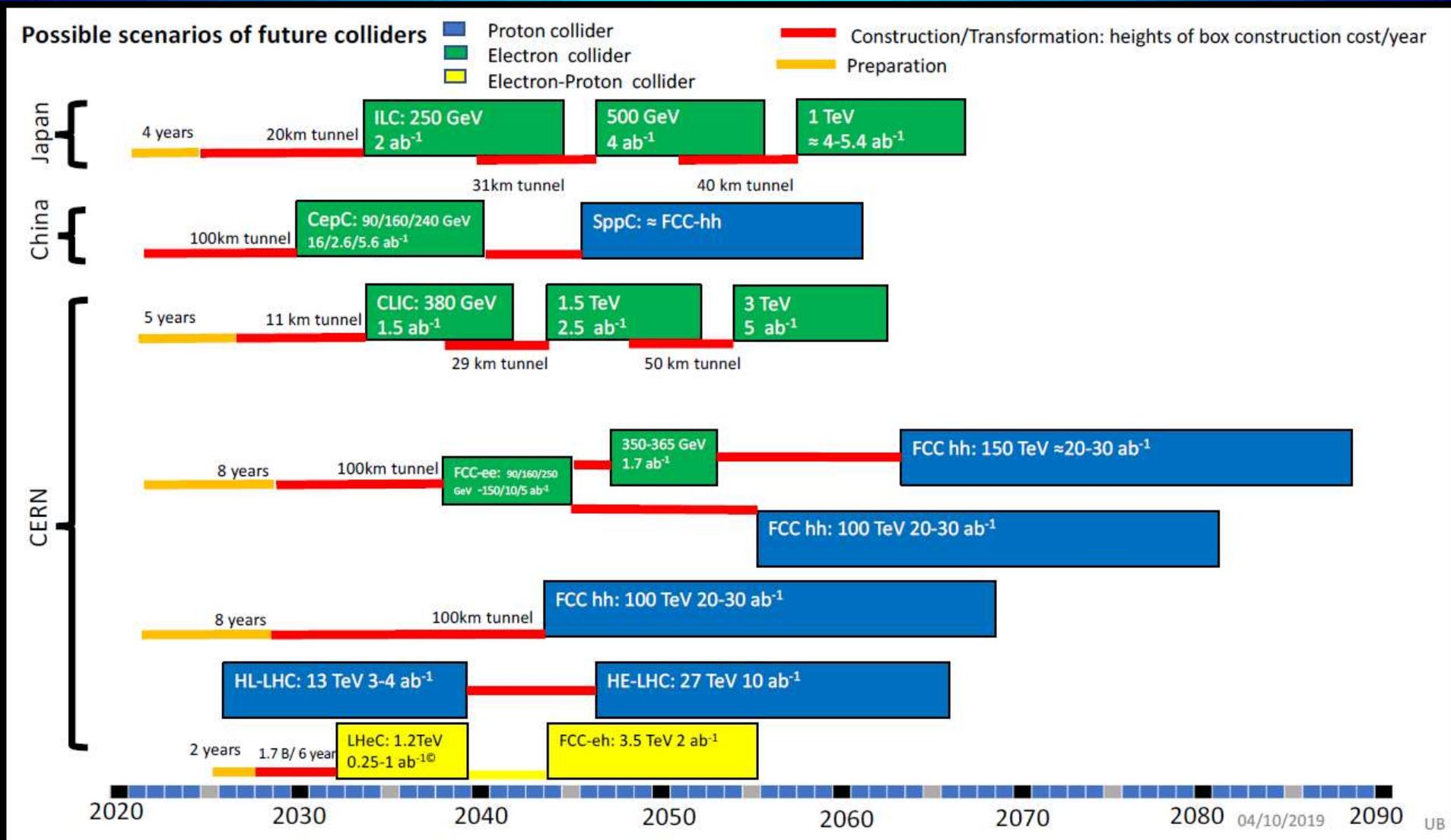
	2020-2040	2040-2060	2060-2080
		1st gen technology	2nd gen technology
CLIC-all	HL-LHC	CLIC380-1500	CLIC3000 / other tech
CLIC-FCC	HL-LHC	CLIC380	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC	FCC-ee (90-365)	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC	LE-FCC-h/e/A (low-field 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
- 4<sup>th</sup> scenario: ~20% CERN budget in 2025-2045
- 5<sup>th</sup> scenario is within the regular CERN budget

## ❖ Last 2 scenarios assume that an e<sup>+</sup>e<sup>-</sup> 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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## ❖ Great vision and plan for the next 70 years of HEP