

**The Future Circular Collider:
Physics, Technology, and Korean Contributions**

Physics Landscape and Opportunities at High Energy Colliders

**Zhen Liu
Oct. 22, 2026**



Now: Explore the **Uncharted**

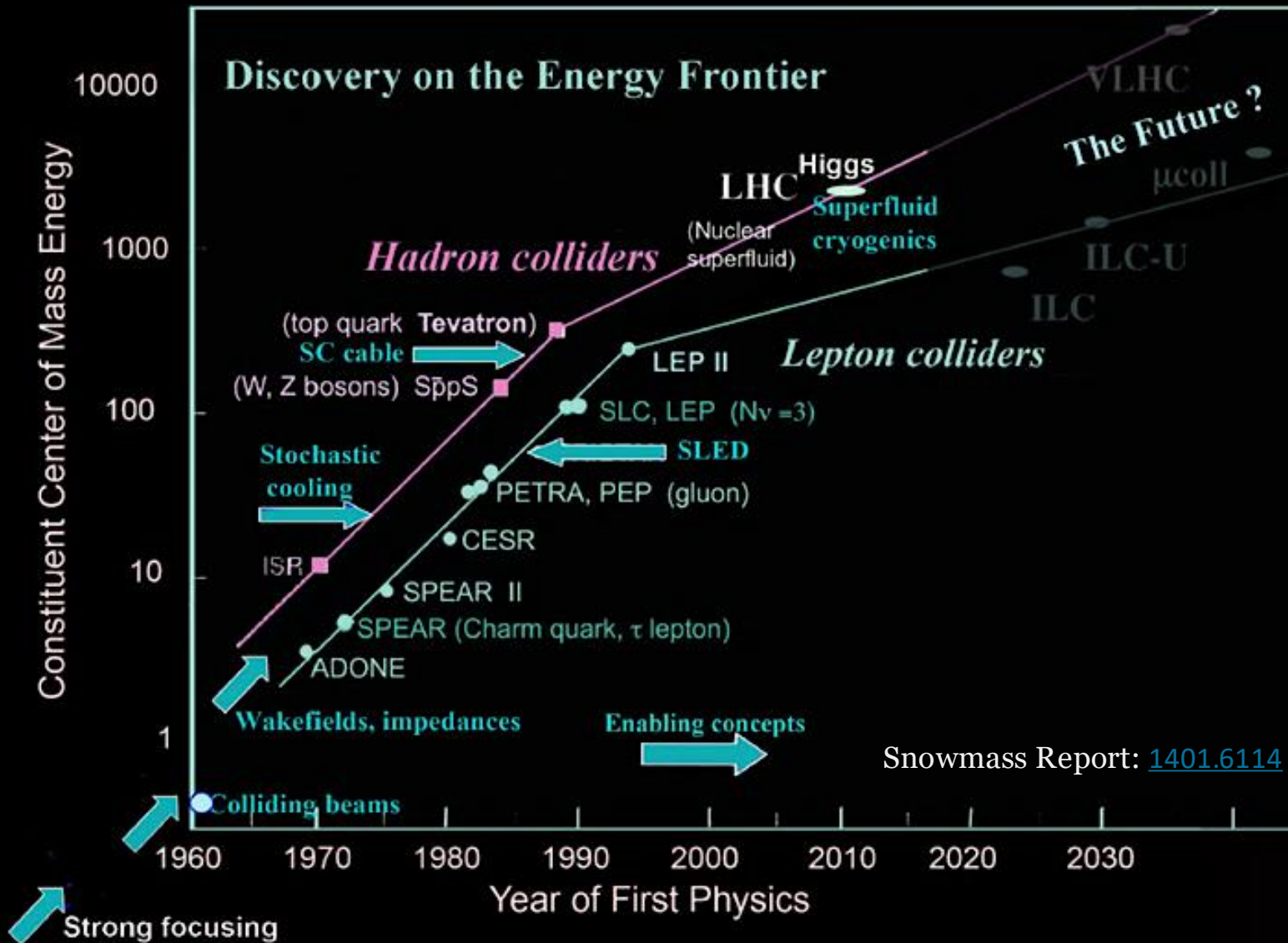


$$\text{Resolution} = 1/E_{cm}$$

Large # of independent observables

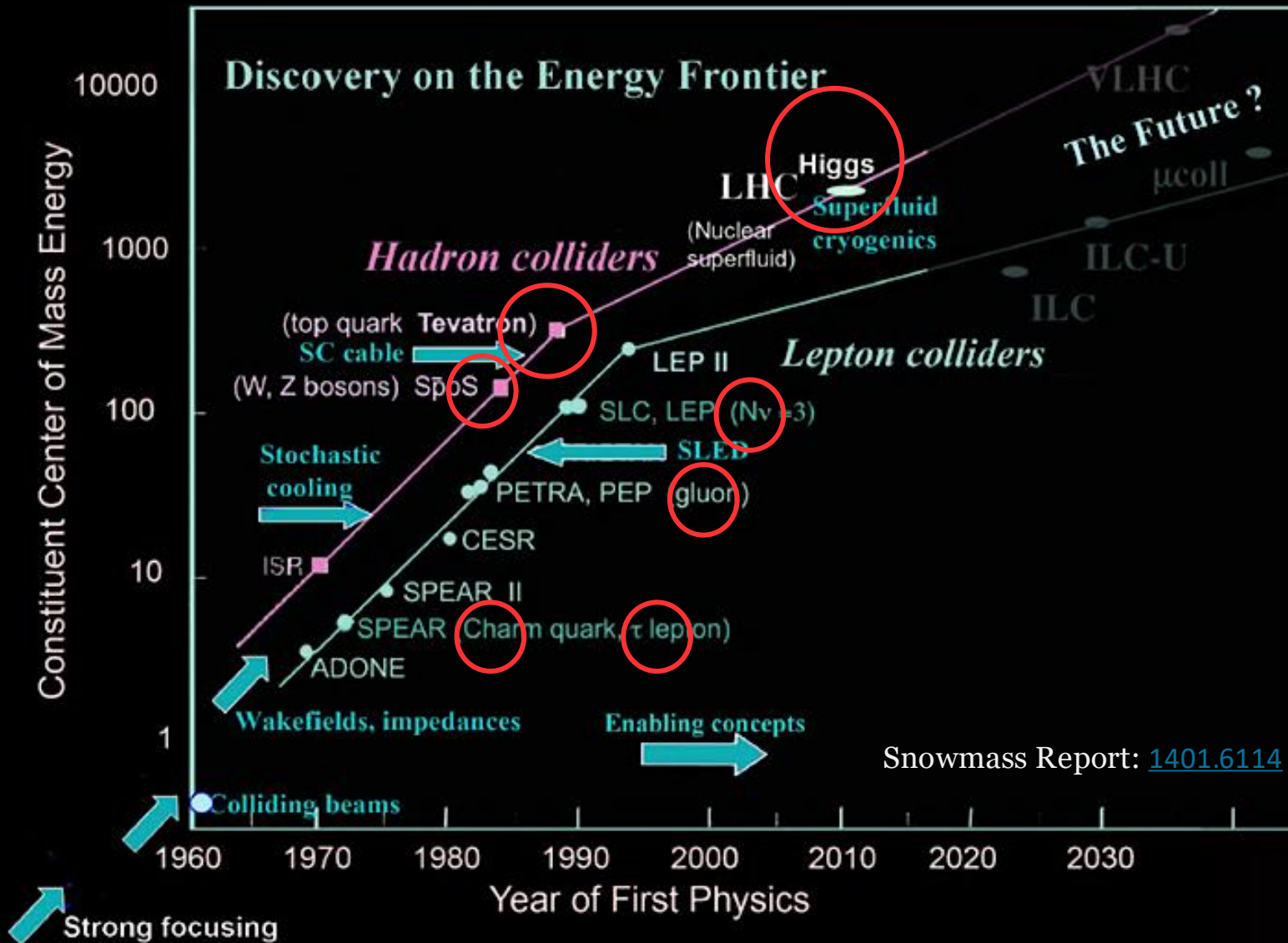
Precise control + Background Rejection

High Energy Drives



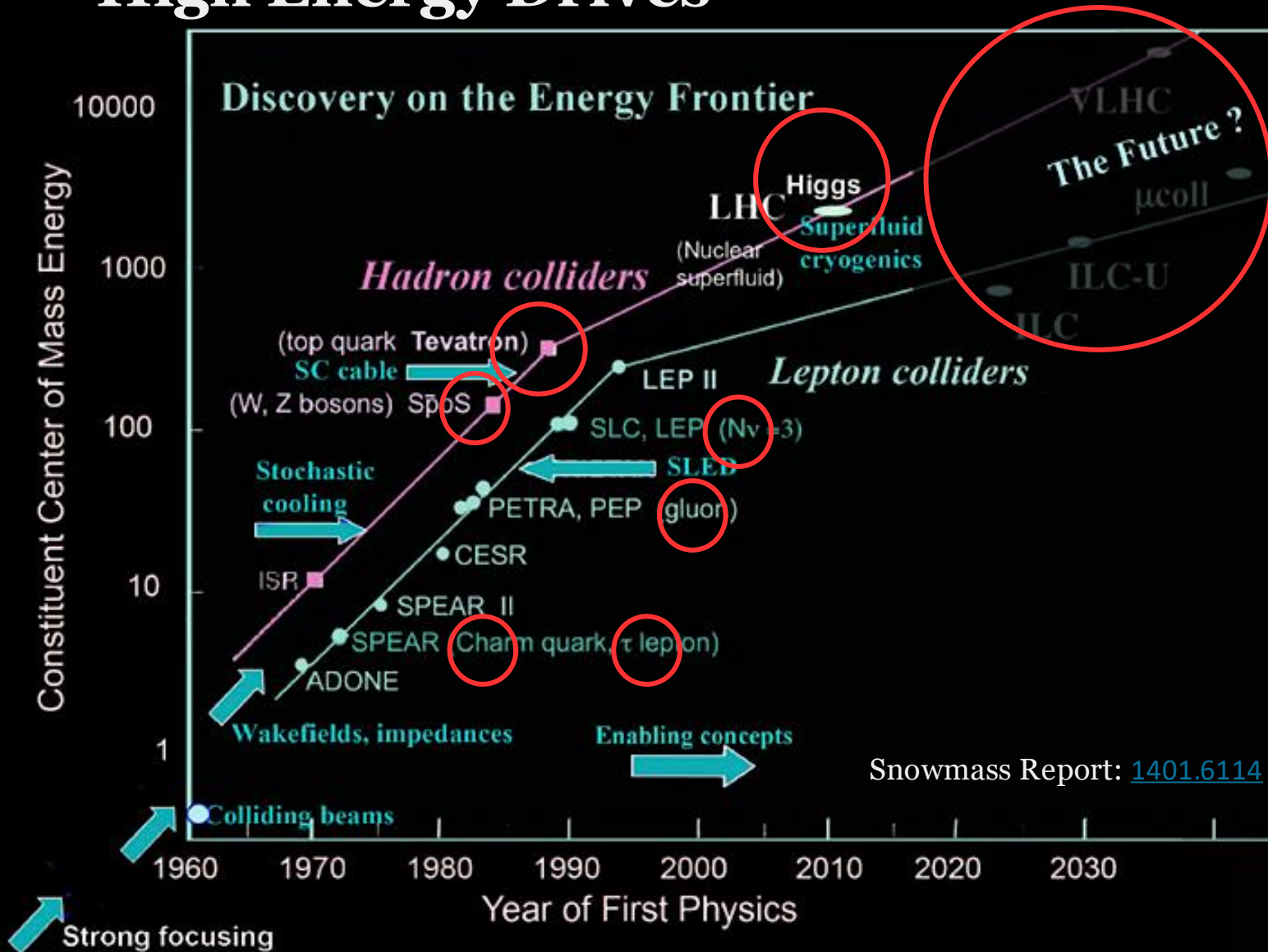
The forefront of tech & ambitions leads to discoveries.

High Energy Drives



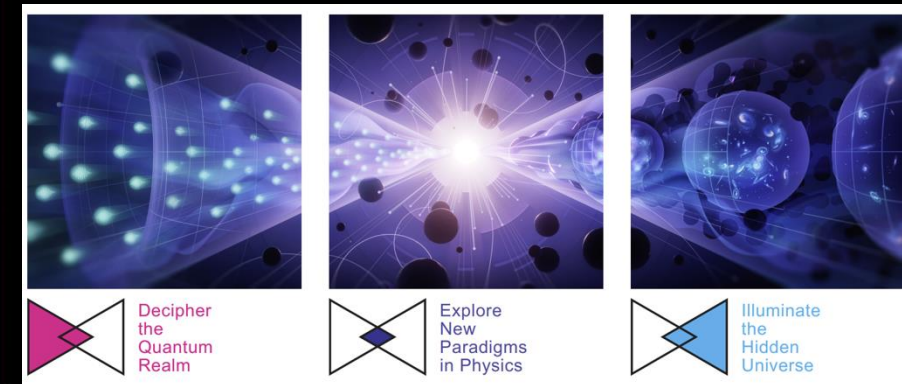
The forefront of tech & ambitions leads to discoveries.

High Energy Drives

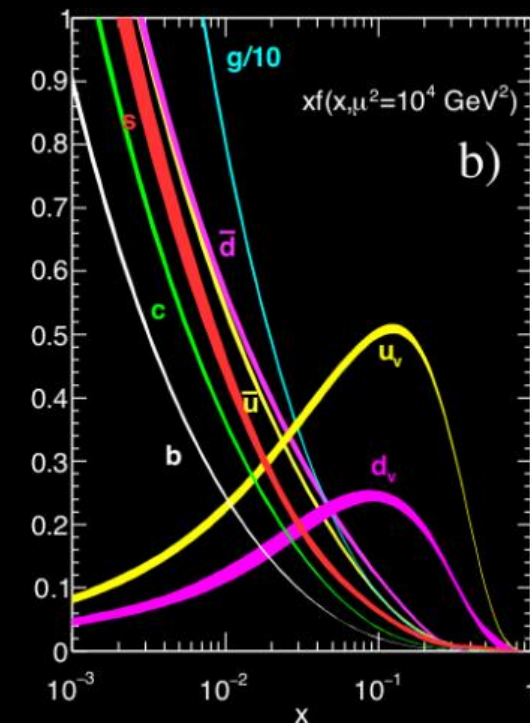
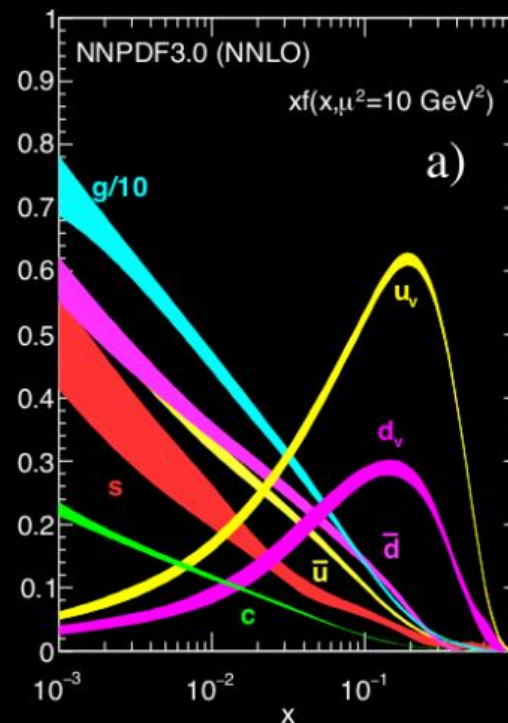
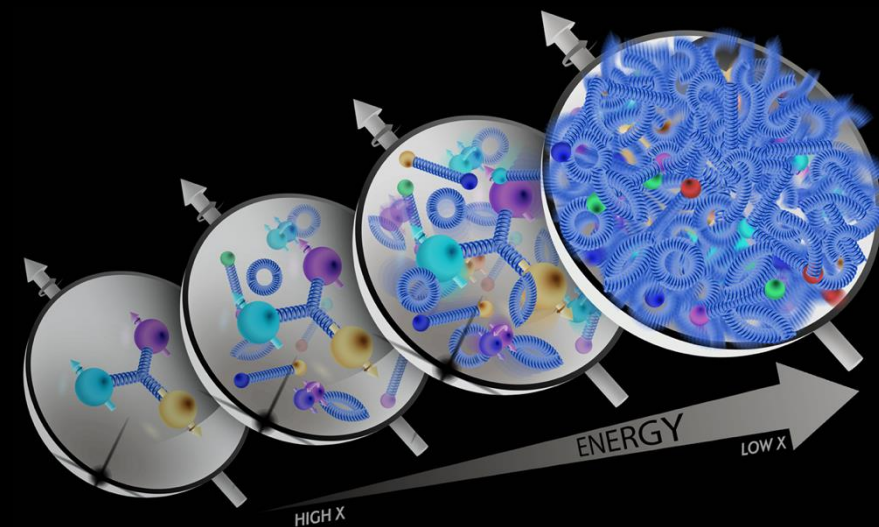
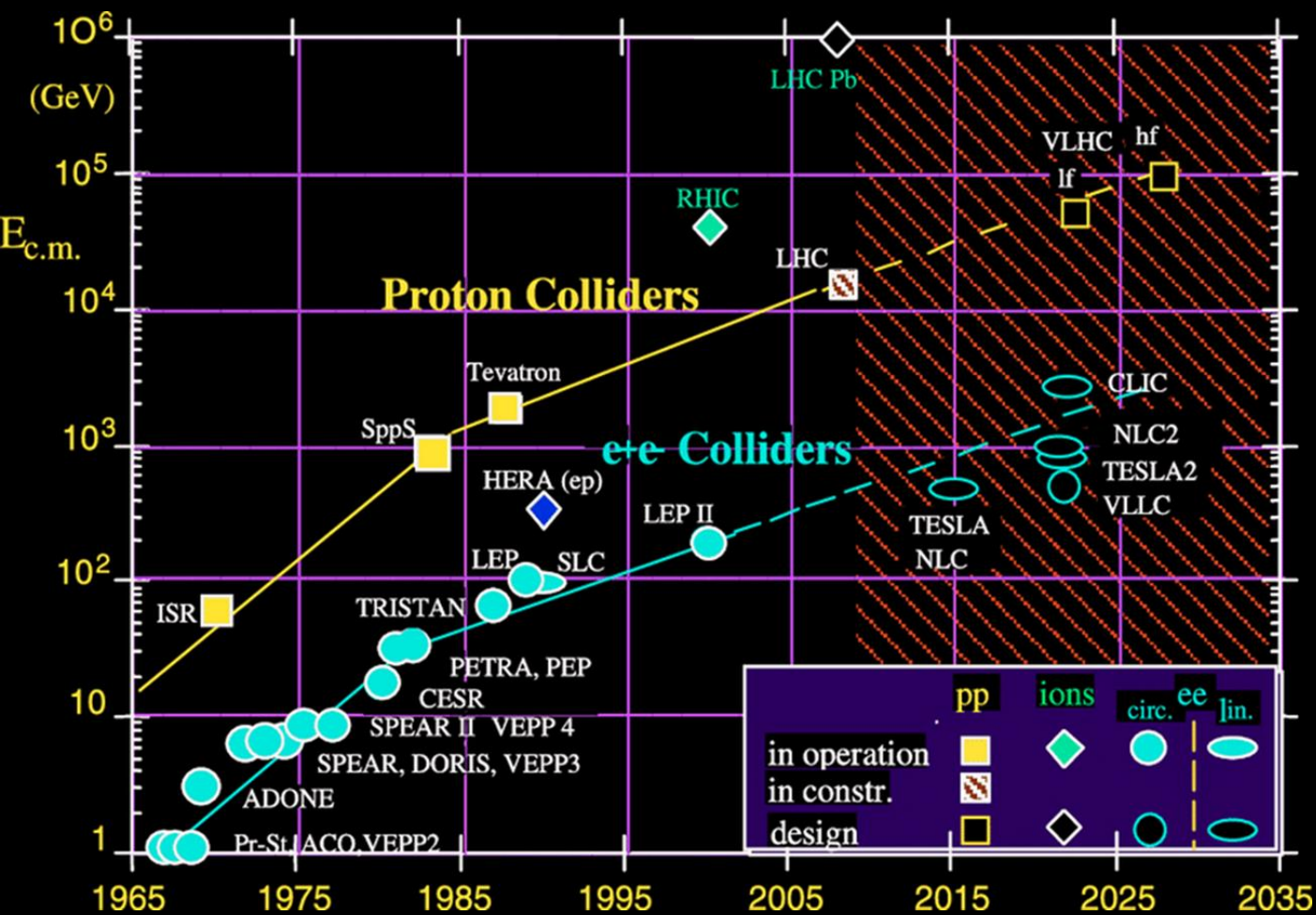


The forefront of tech & ambitions leads to discoveries.

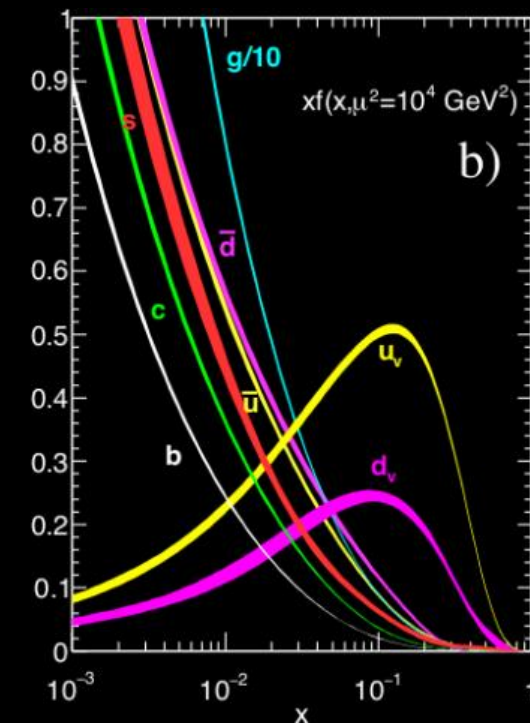
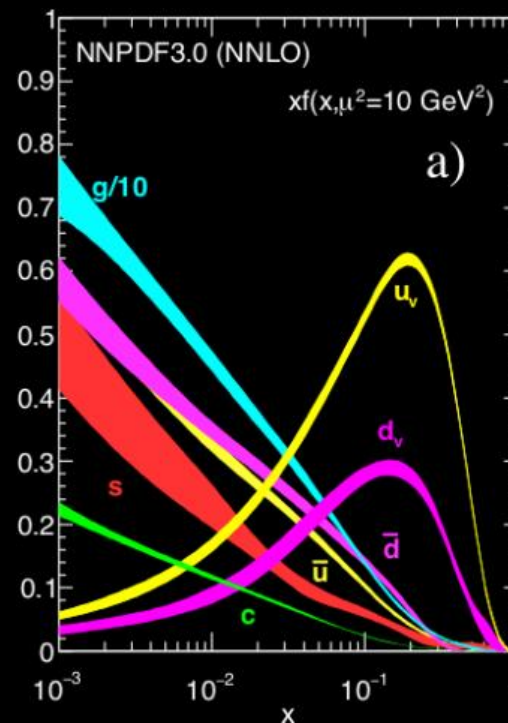
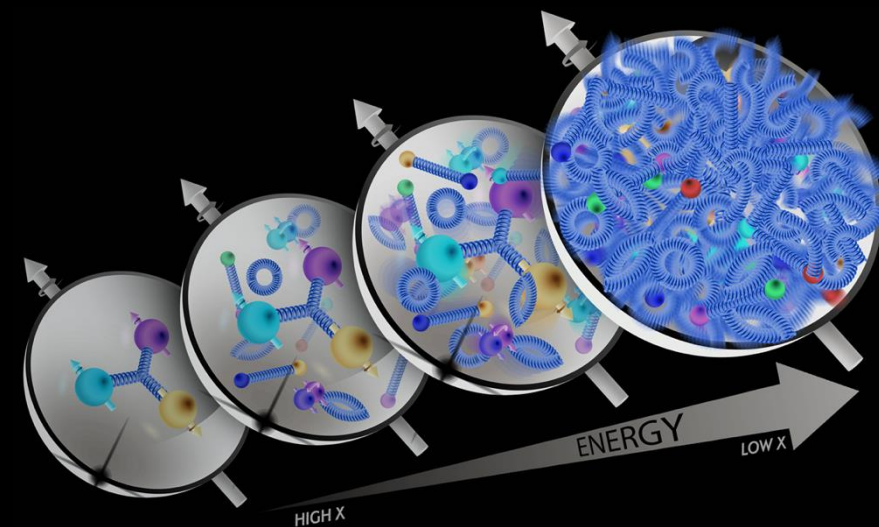
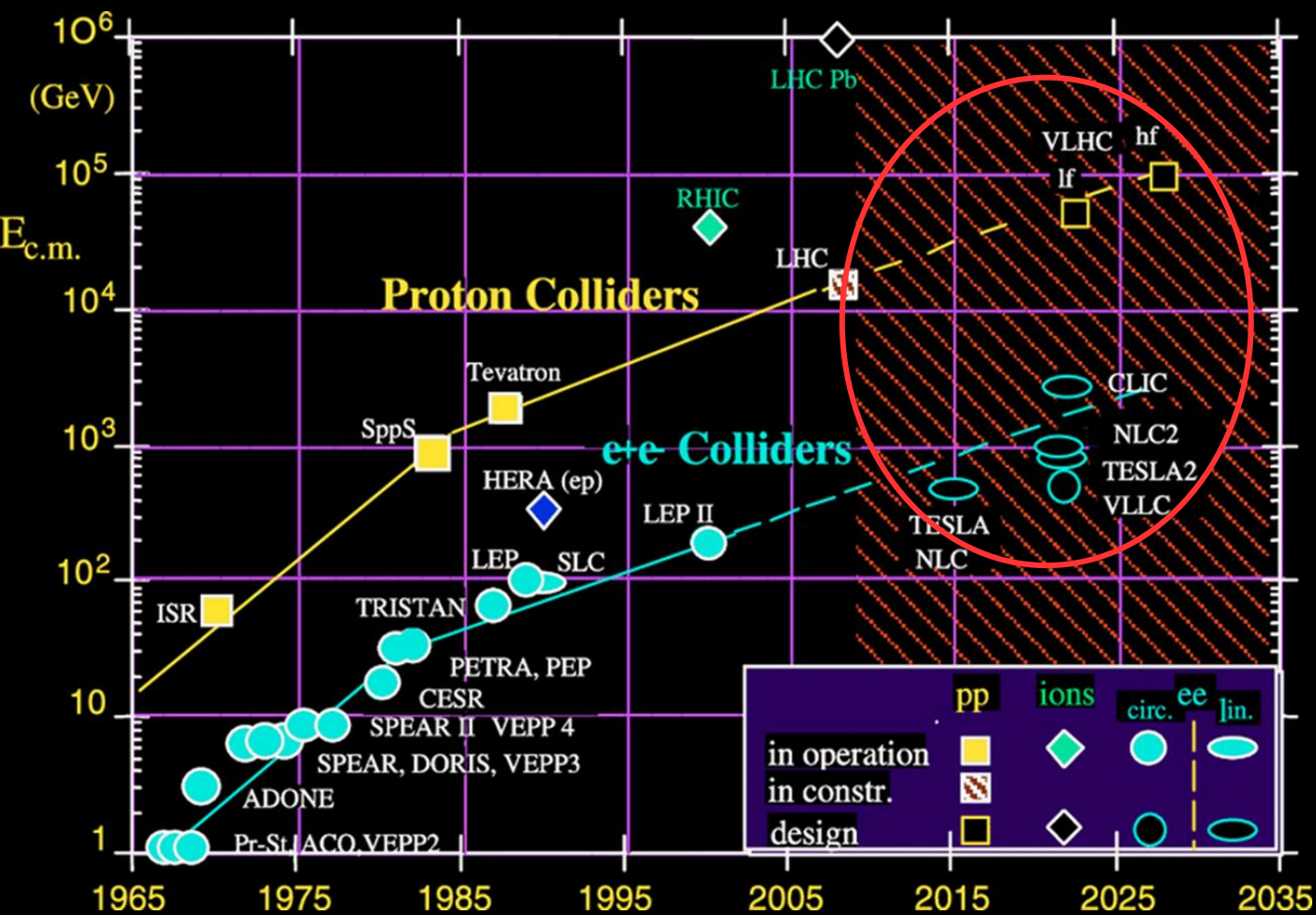
A clear and persistent desire for high energy machines.



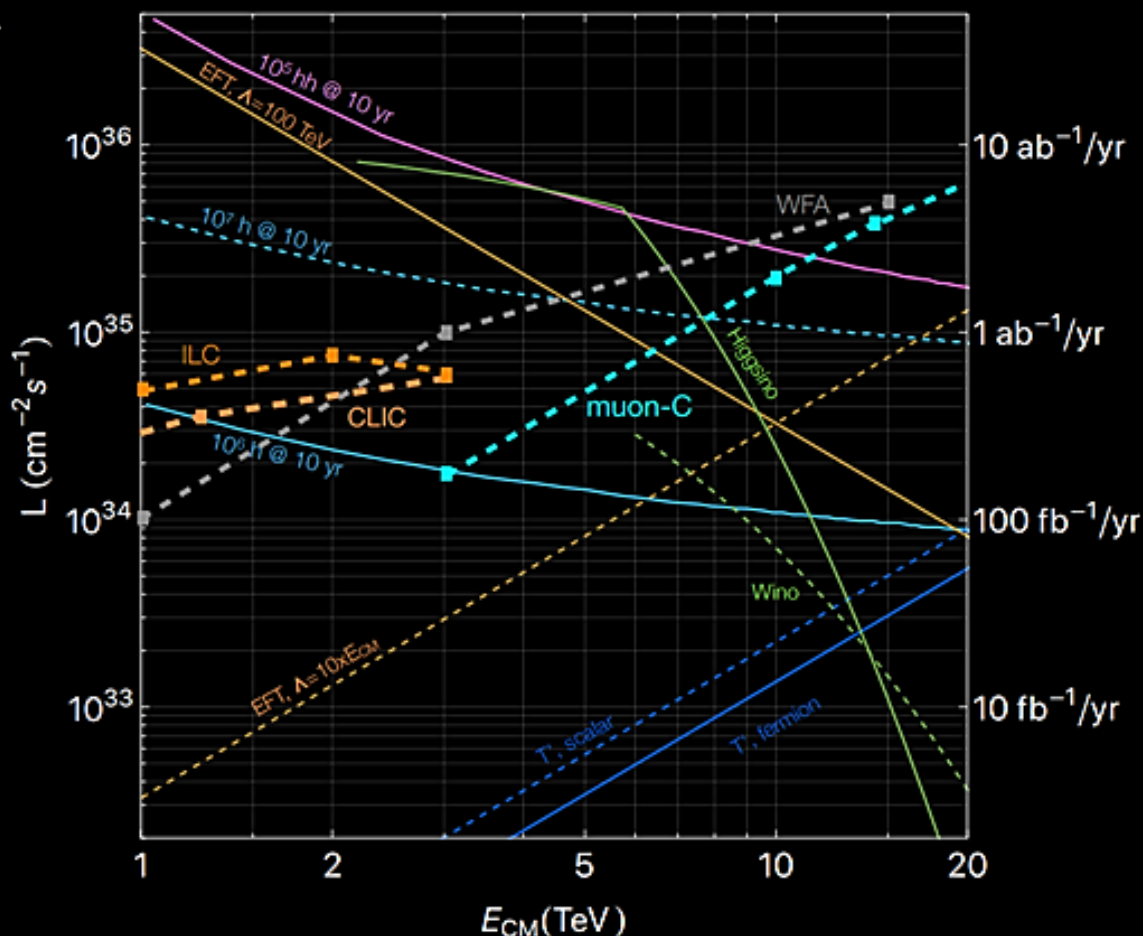
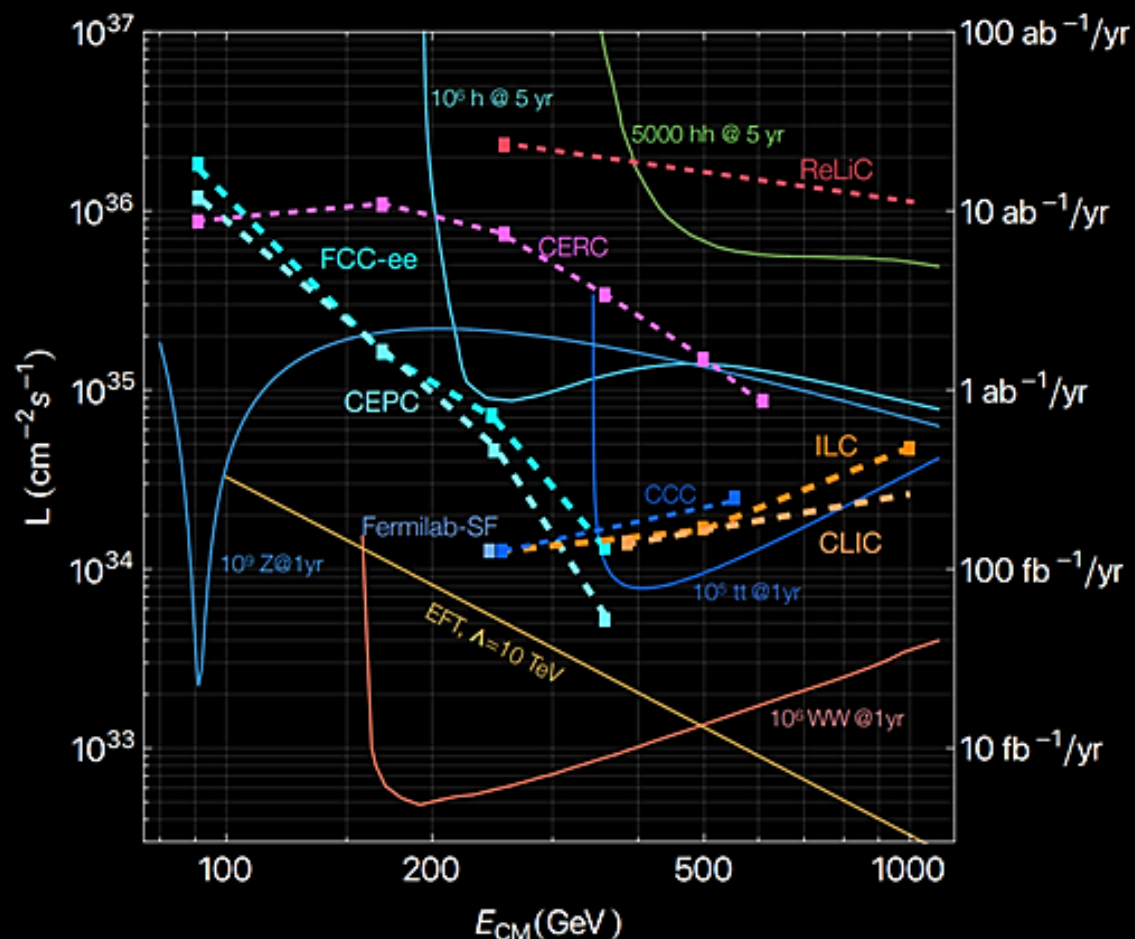
A Strong Desire for High Energy



A Strong Desire for High Energy



Many more future collider concepts



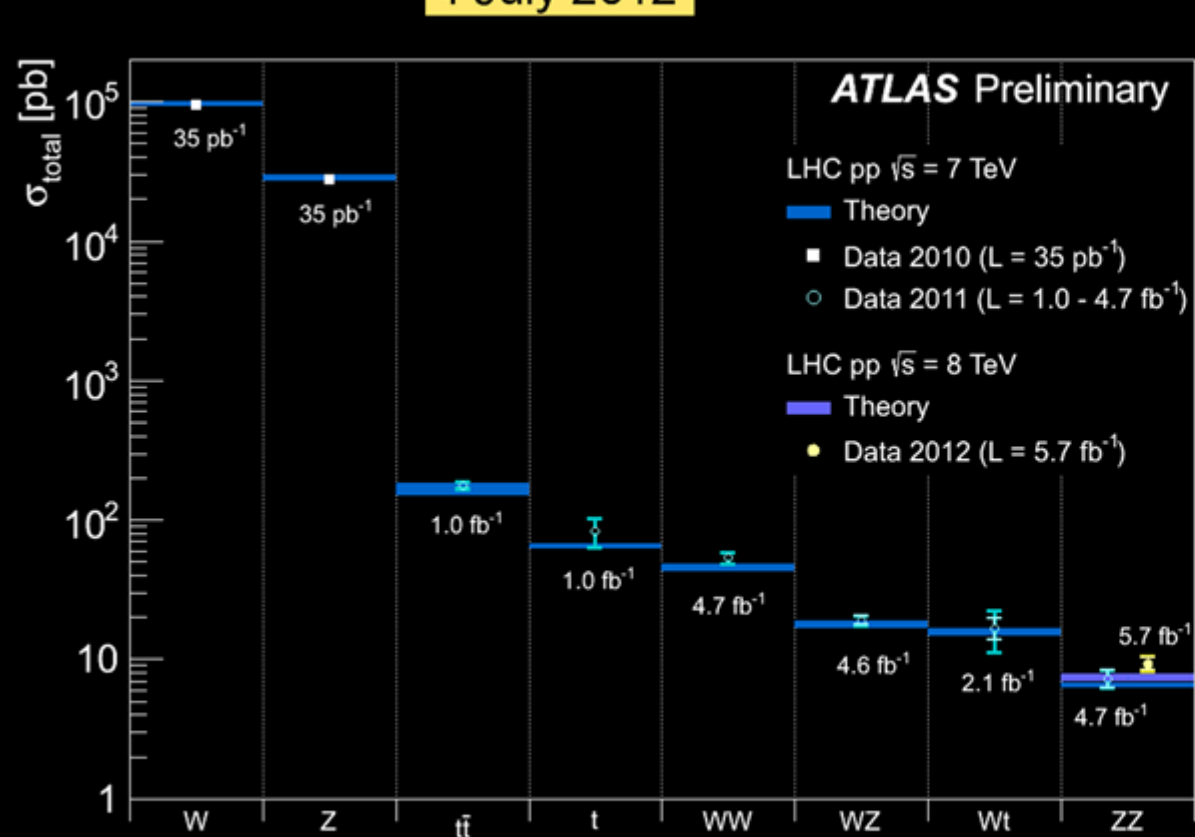
Many future collider options and excitement!

ZL, Wang, [2205.00031](#), also
in ITF report, [2208.06030](#)

LHC

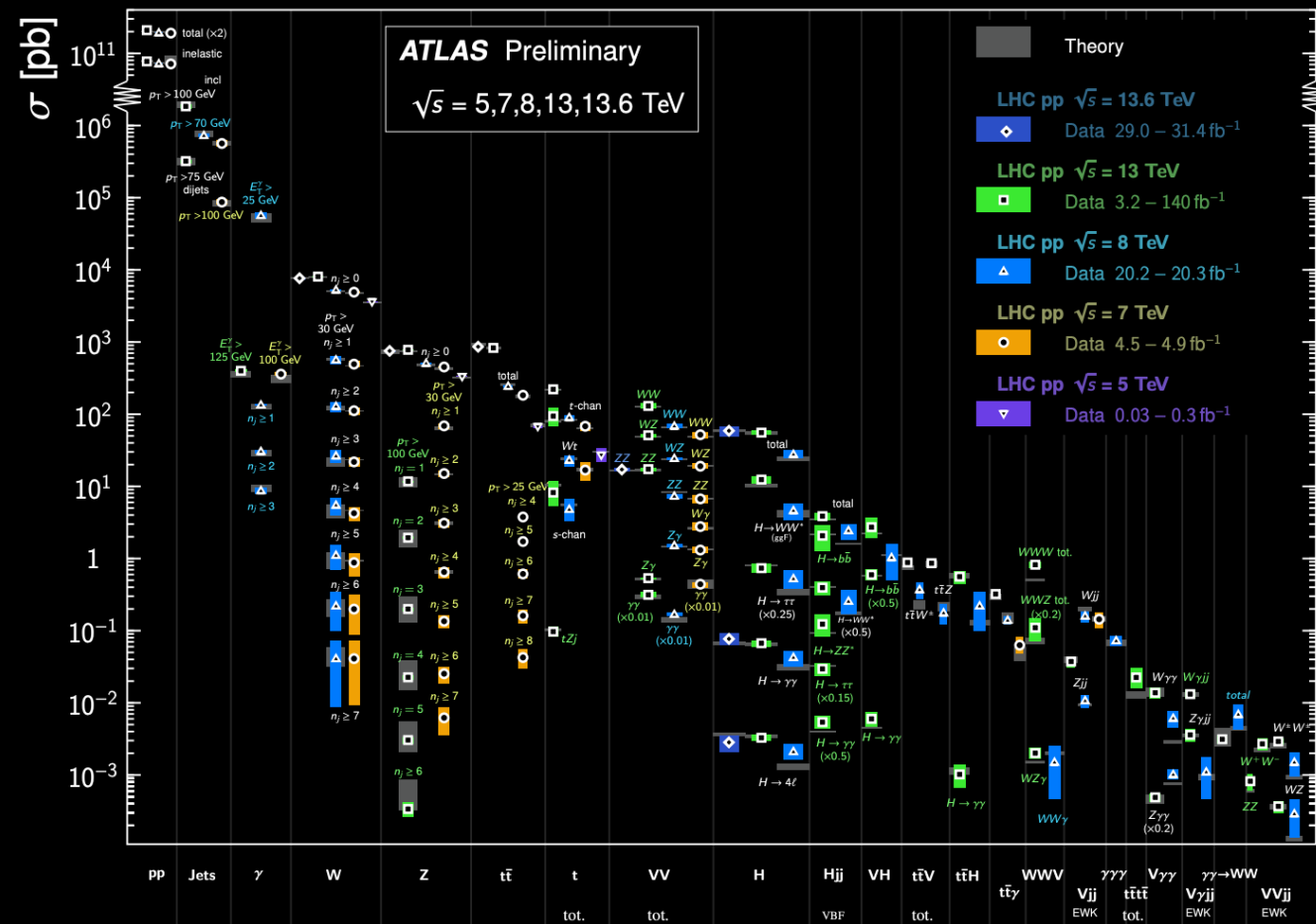
LHC's successes

4 July 2012



Standard Model Production Cross Section Measurements

Status: June 2024



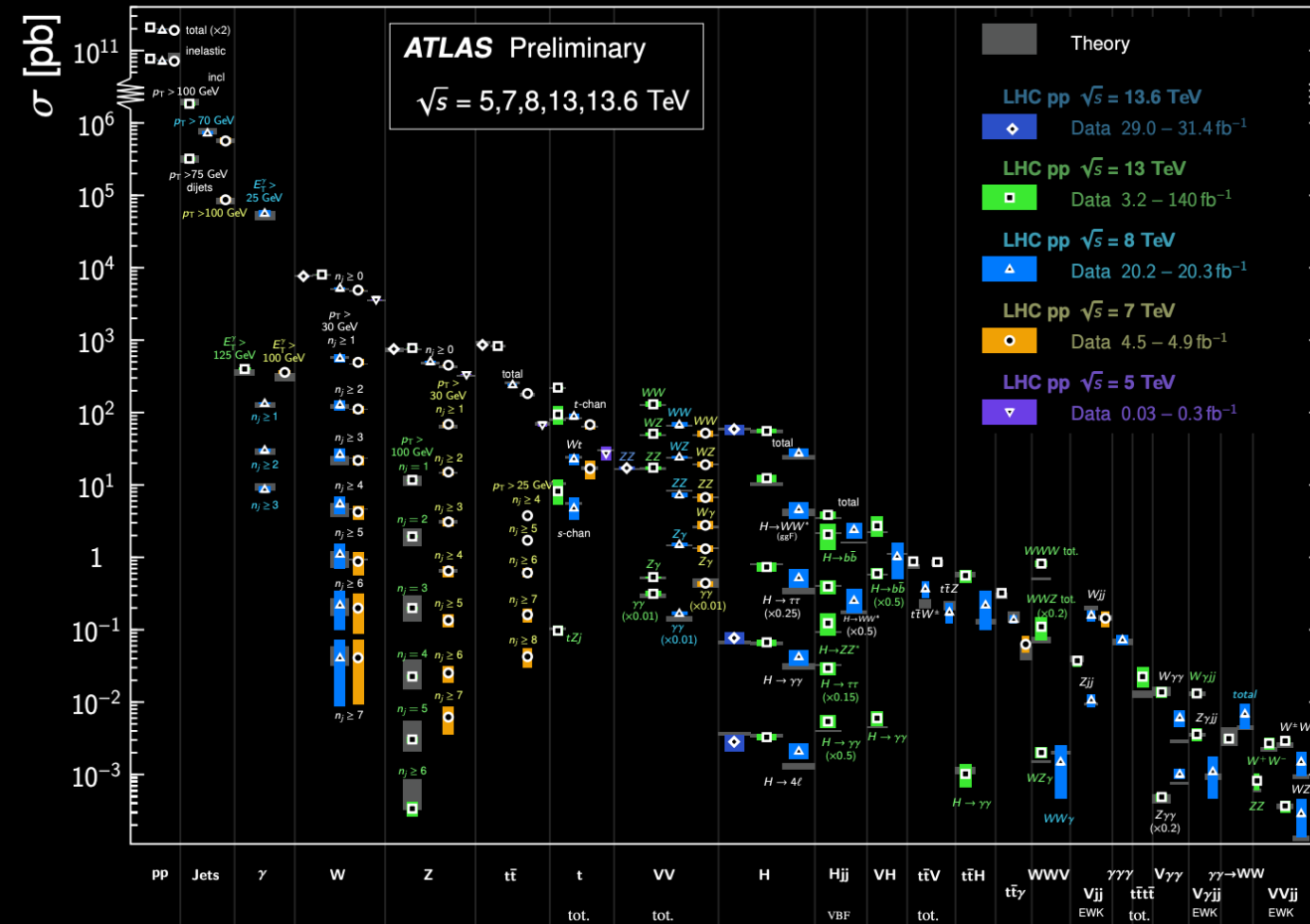
LHC's successes

- Higgs Discovery
- Precision measurements
- Direct searches on
 - Simplified models
 - SUSY
 - Extra Dim/Compositeness
 - ...

+new upgrades in Energy,
Detector, Trigger, Analysis
methods

Standard Model Production Cross Section Measurements

Status: June 2024



LHC's successes

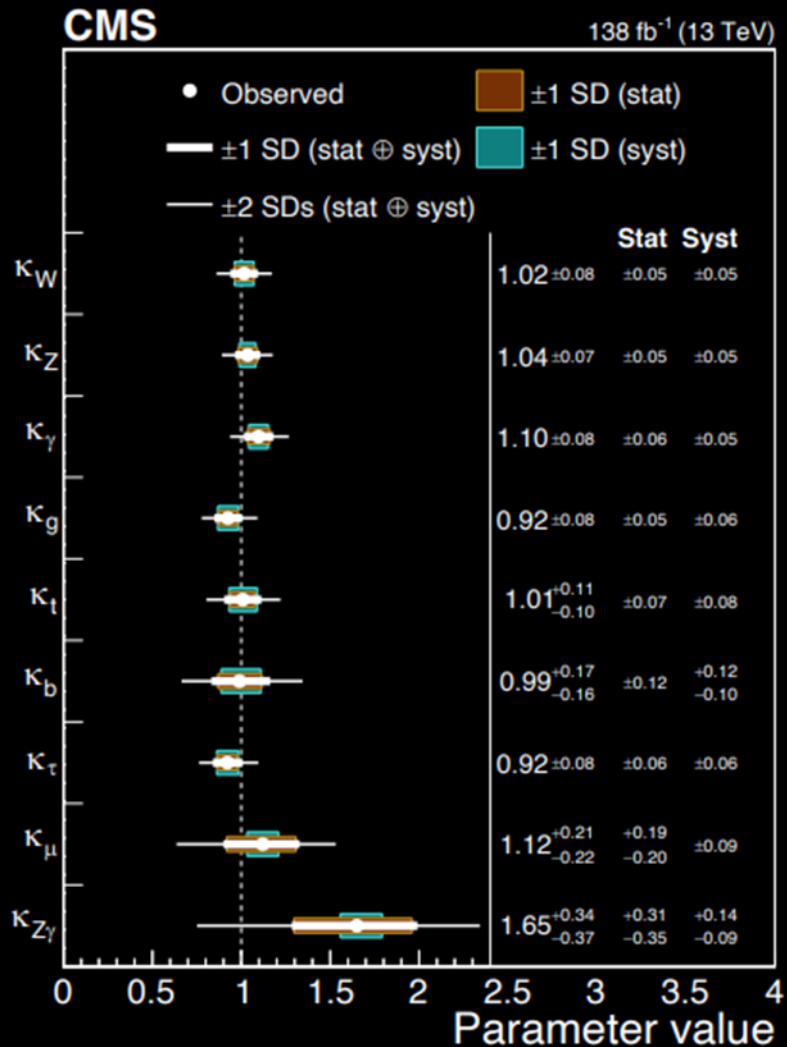
- Higgs Discovery
- Precision measurements
- Direct searches on
 - Simplified models
 - SUSY
 - Extra Dim/Compositeness
 - ...

+new upgrades in Energy,
Detector, Trigger, Analysis
methods

drove a paradigm shift

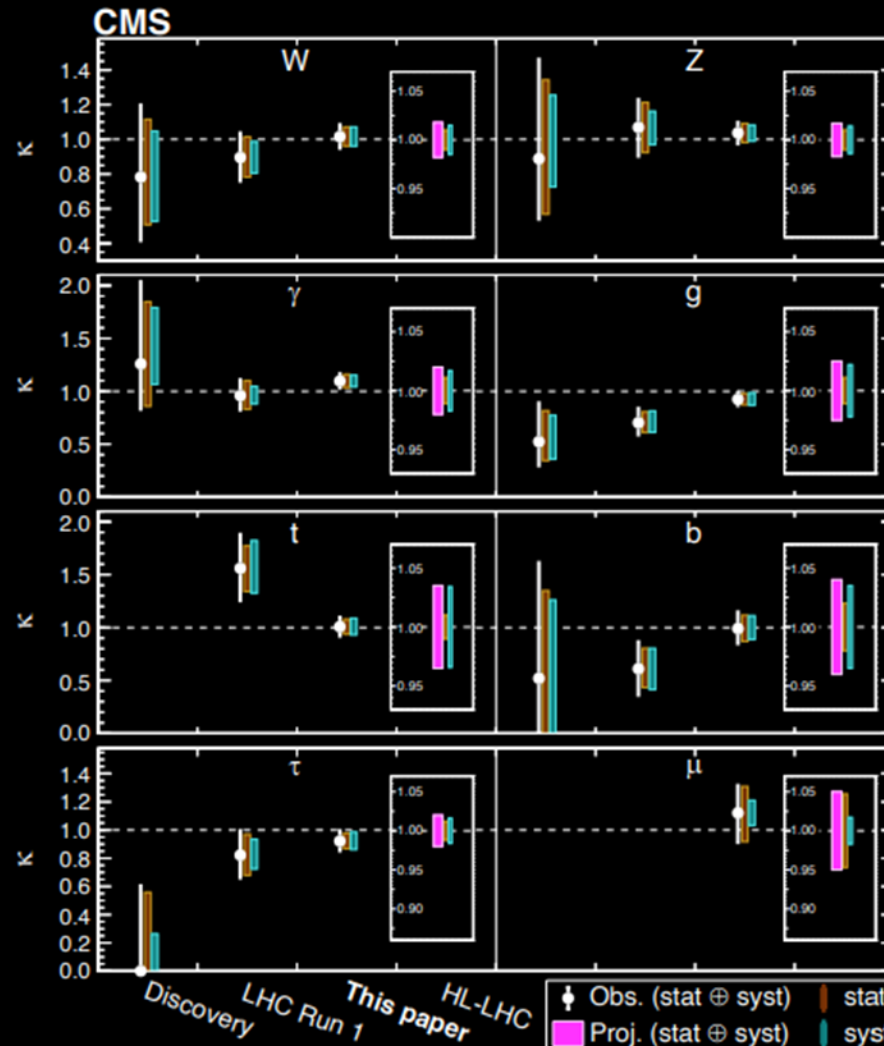
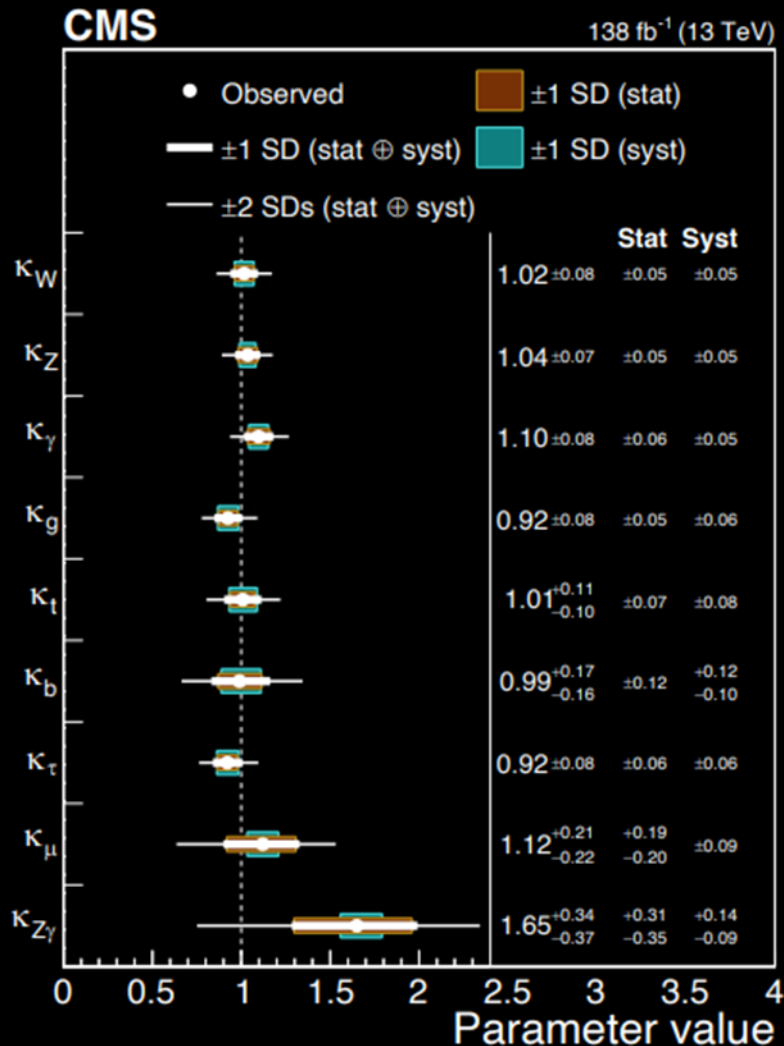
- (we become) humble (about how and where new physics would show up)
- more adventurous

LHC Higgs



The Higgs looks like the SM Higgs boson at 10% level now.

LHC Higgs



The Higgs looks like the SM Higgs boson at 10% level now.

We are to measure it to 3% level.

Anything Beyond the Higgs?

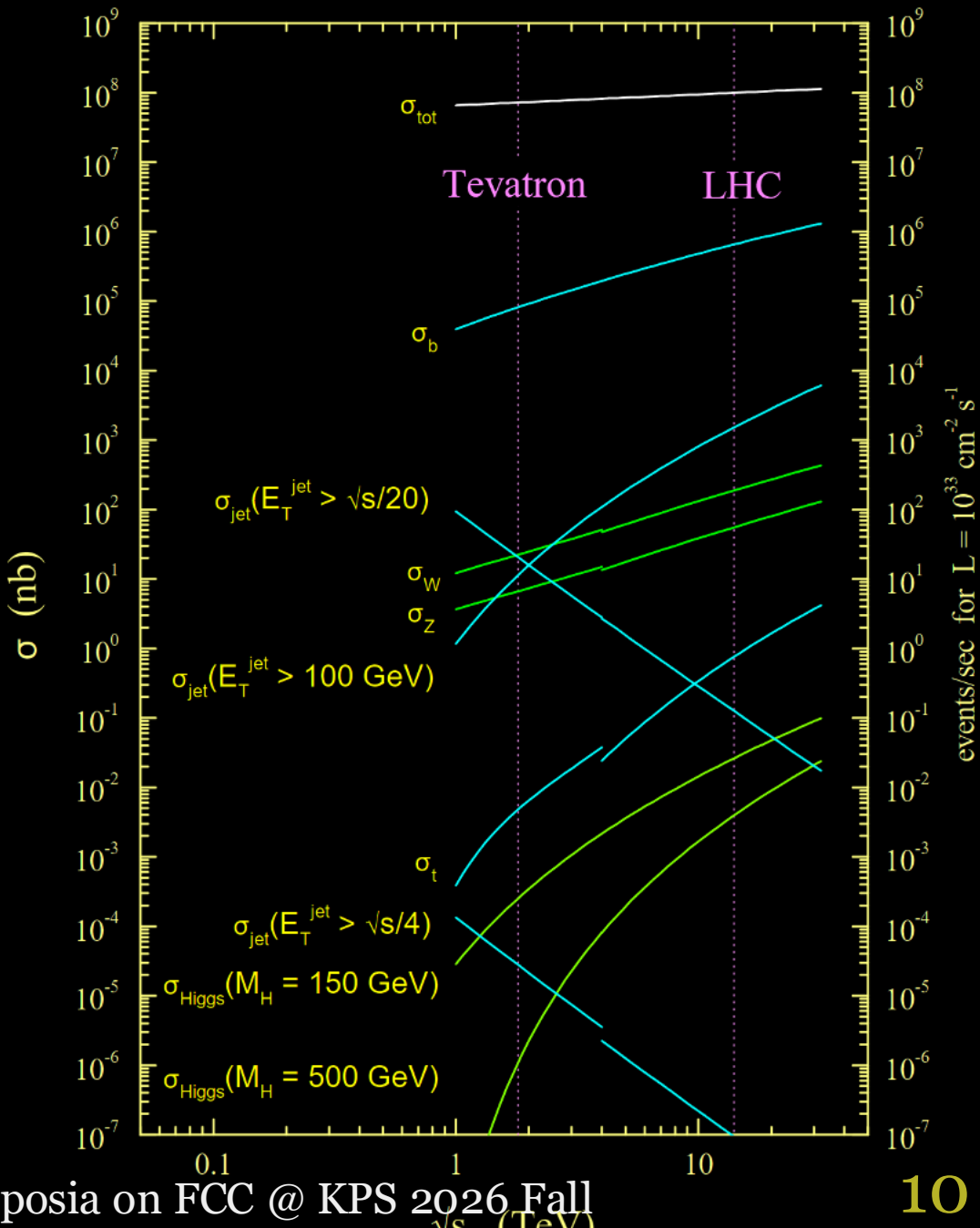
Anything Beyond the Higgs?

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
$\Gamma_1 \quad \ell^+ \nu$	^[2] $(10.86 \pm 0.09) \%$		▼
$\Gamma_2 \quad e^+ \nu$	$(10.71 \pm 0.16) \%$		40185 ▼
$\Gamma_3 \quad \mu^+ \nu$	$(10.63 \pm 0.15) \%$		40185 ▼
$\Gamma_4 \quad \tau^+ \nu$	$(11.38 \pm 0.21) \%$		40165 ▼
$\Gamma_5 \quad \text{hadrons}$	$(67.41 \pm 0.27) \%$		▼
$\Gamma_6 \quad \pi^+ \gamma$	$< 1.9 \times 10^{-6}$	CL=95%	40184 ▼
$\Gamma_7 \quad \rho^+ \gamma$	$< 5.2 \times 10^{-6}$	CL=95%	40181 ▼
$\Gamma_8 \quad K^+ \gamma$	$< 1.7 \times 10^{-6}$	CL=95%	40183 ▼
$\Gamma_9 \quad D_s^+ \gamma$	$< 6 \times 10^{-4}$	CL=95%	40160 ▼
$\Gamma_{10} \quad c X$	$(33.3 \pm 2.6) \%$		▼
$\Gamma_{11} \quad c \bar{s}$	$(31^{+13}_{-11}) \%$		▼
$\Gamma_{12} \quad \text{invisible}$	^[3] $(1.4 \pm 2.8) \%$		▼
$\Gamma_{13} \quad \pi^+ \pi^+ \pi^-$	$< 1.01 \times 10^{-6}$	CL=95%	40184 ▼

proton - (anti)proton cross sections



We have a full and nice program for the Higgs boson

We've been calling the LHC

- Higgs factory
- Top factory
- QCD factory

A huge program around them

But LHC is also

- BSM explorer
- (and) EW factory!

We have a full and nice program for the Higgs boson

We've been calling the LHC

- Higgs factory
- Top factory
- QCD factory

Maybe we should look into W and Z more.
For instance:

$$W \rightarrow 3\ell + \nu$$

$$Z \rightarrow 2\ell + \gamma$$

A huge program around them

Y.F. Fei, P.R. Li, K.F. Lyu, ZL, M. Pospelov, [2407.15930](#).

Y.F. Fei, P.R. Li, ZL, M. Pospelov, [2604.13156](#)

But LHC is also

- BSM explorer
- (**and**) EW factory!

We have a full and nice program for the Higgs boson

We've been calling the LHC

- Higgs factory
- Top factory
- QCD factory

Maybe we should look into W and Z more.
For instance:

$$W \rightarrow 3\ell + \nu$$

$$Z \rightarrow 2\ell + \gamma$$

A huge program around them

Y.F. Fei, P.R. Li, K.F. Lyu, ZL, M. Pospelov, [2407.15930](#).

Y.F. Fei, P.R. Li, ZL, M. Pospelov, [2604.13156](#)

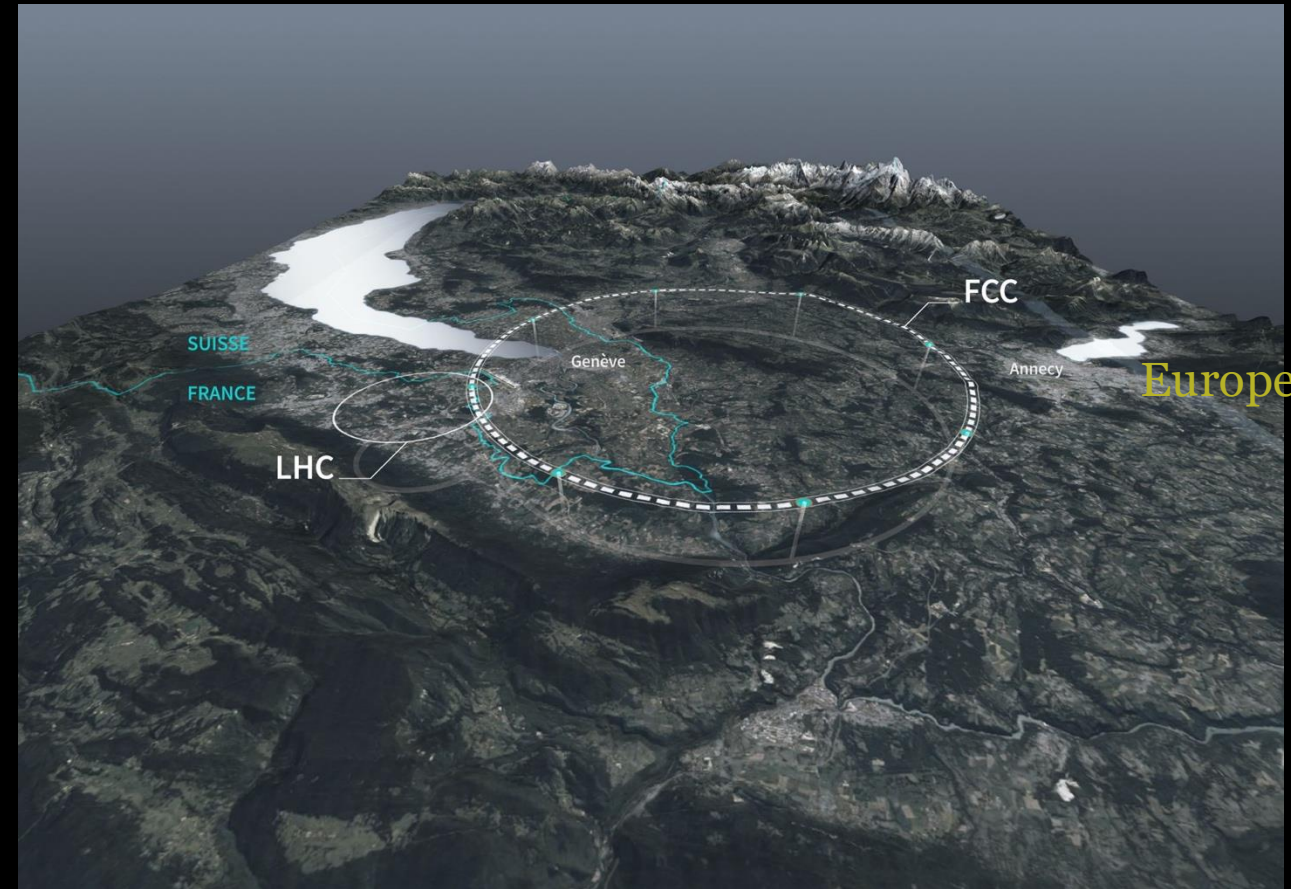
But LHC is also

- BSM explorer
- (**and**) EW factory!

Many differential and precision measurements, some are **QCD** (such as recent studies on Energy-Energy correlators), some are **EW** (Higgs STXS). We are learning SM, QFT (e.g., positivity tests, J. Gu, C. Shu [2311.07663](#) K.F. Lyu, ZL, T. Wu, [2512.04336](#)), and stress testing the SM from all angles! Busy Higgs (Li, Wang, ZL, [2604.14284](#)), Electroweak Symmetry Restoration (Lewis, ZL et al [2012.00774](#), [2605.08433](#)), ...

Future Colliders

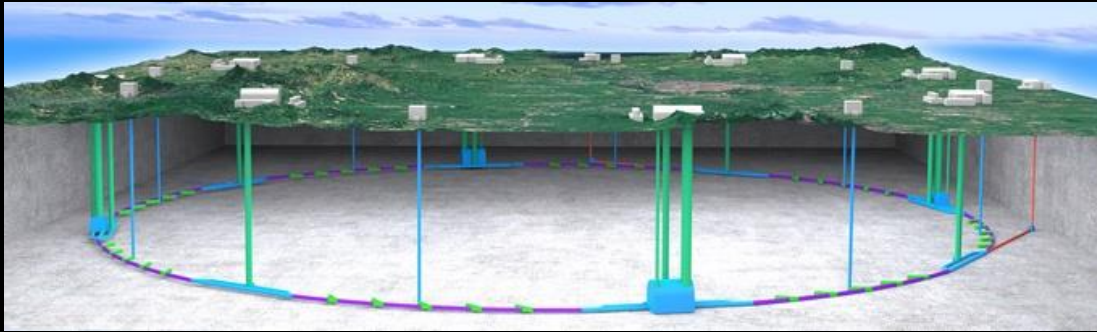
Future Colliders



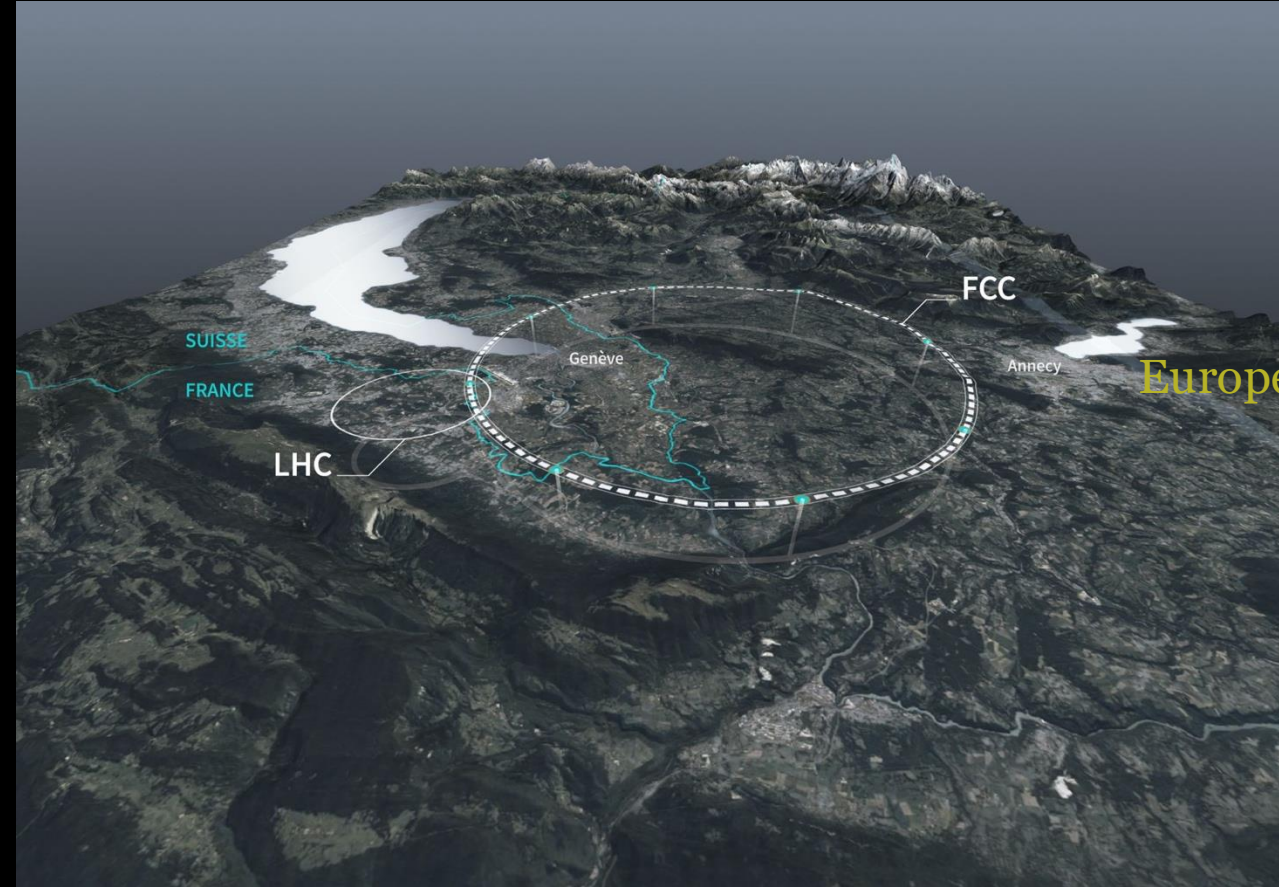
~100 km FCC
 e^+e^- (Z factory, 240 GeV Higgs + 365 GeV Top)
ep, pp (~100 TeV)

Future Colliders

China



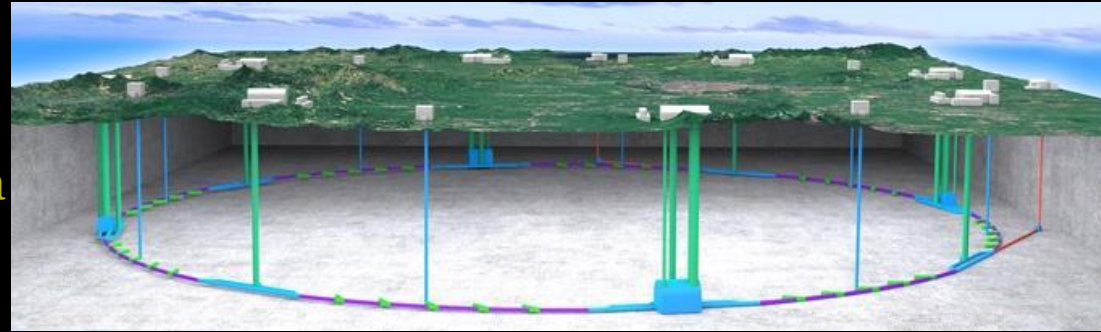
~CEPC (e^+e^-) 240 GeV Higgs + pp (~100 TeV)



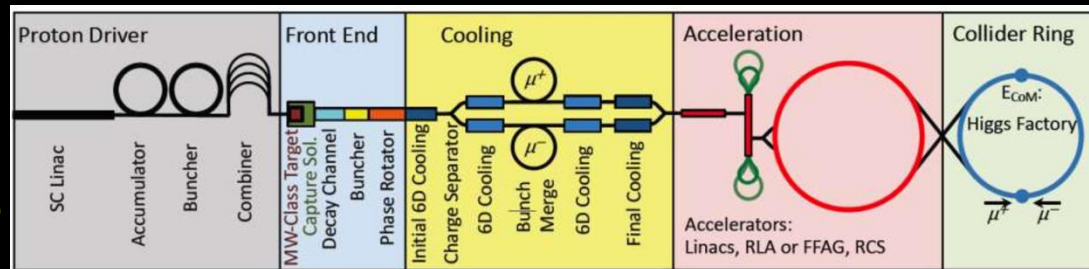
Europe

~100 km FCC
 e^+e^- (Z factory, 240 GeV Higgs + 365 GeV Top)
ep, pp (~100 TeV)

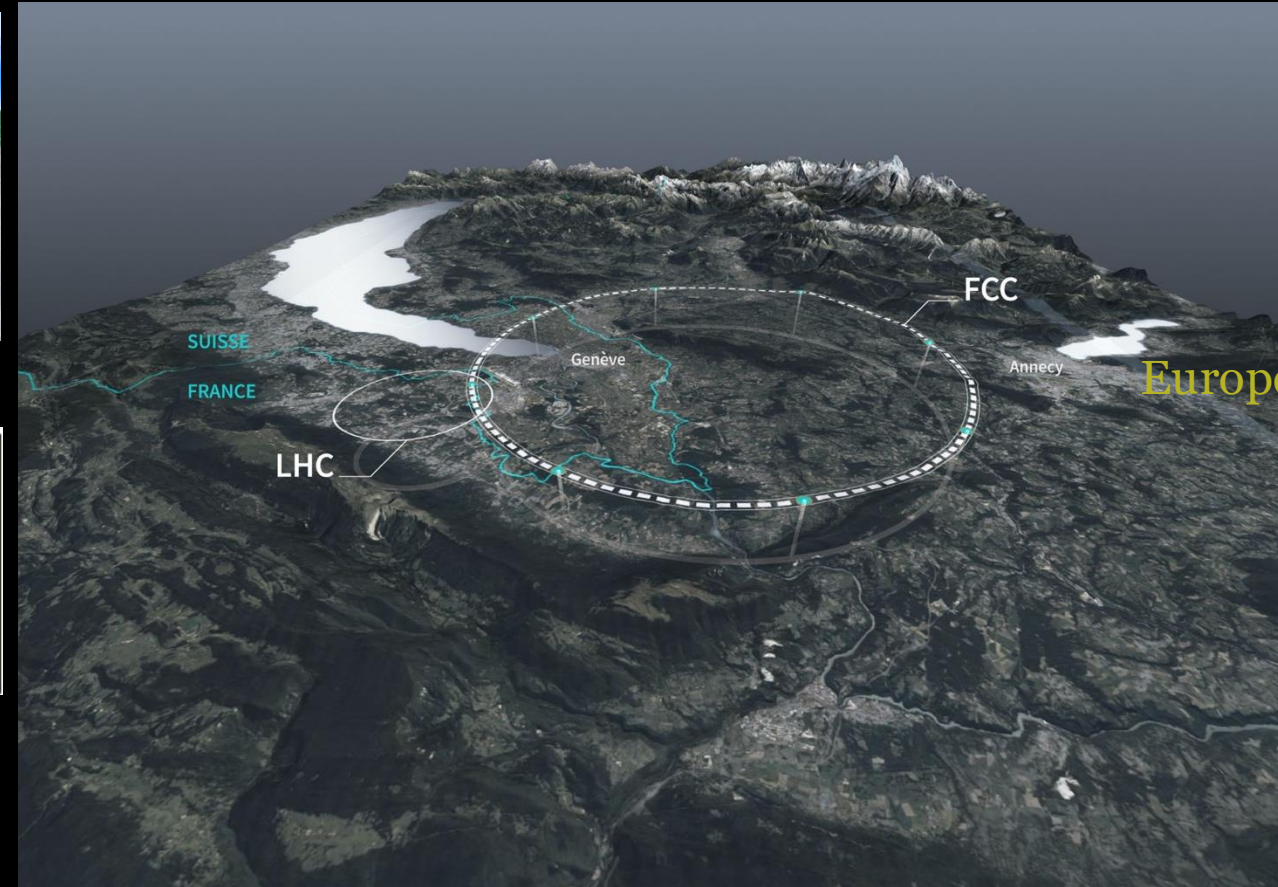
Future Colliders



~CEPC (e^+e^-) 240 GeV Higgs + pp (~100 TeV)



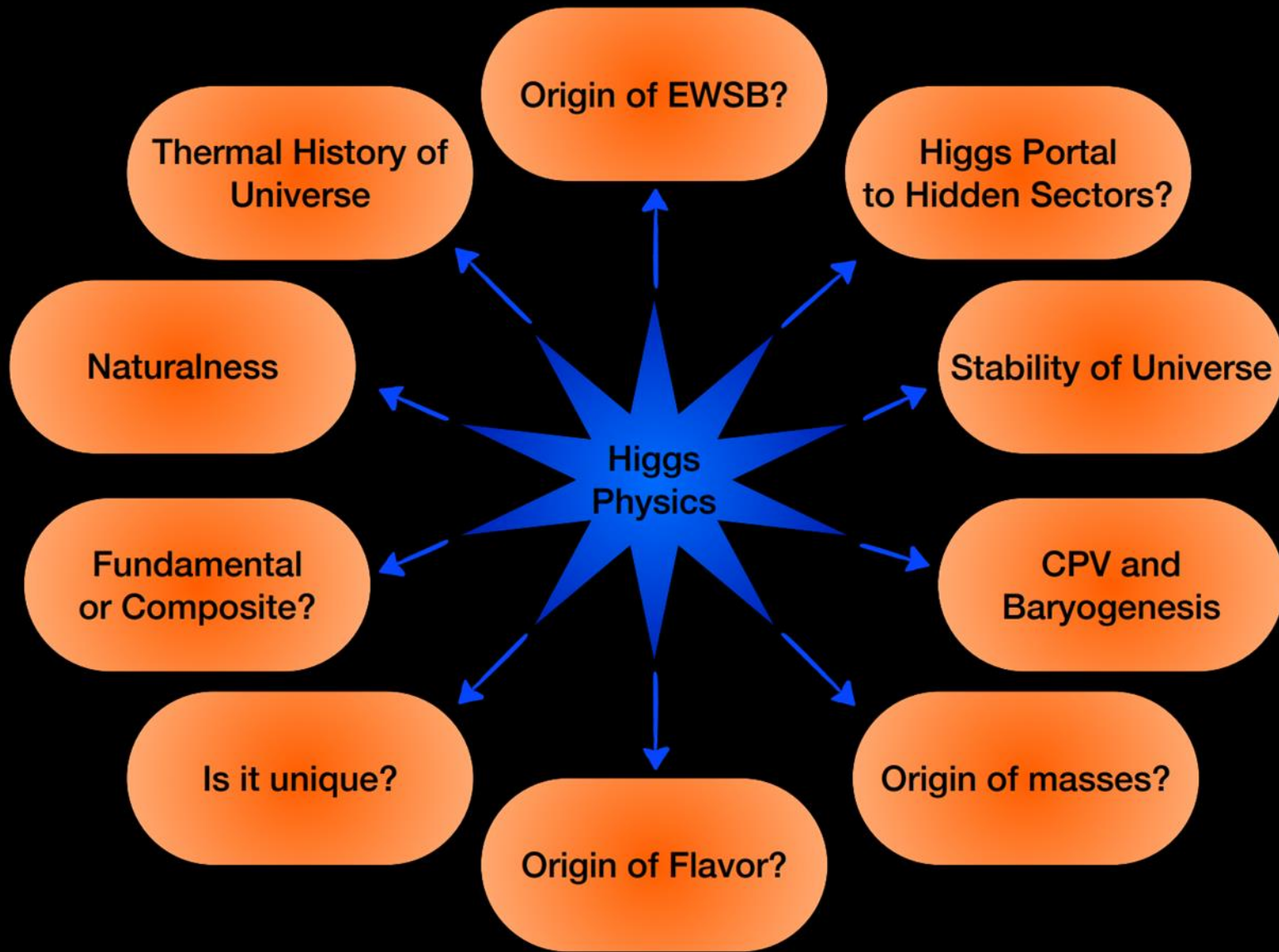
Muon collider, Higgs, 3~10 TeV

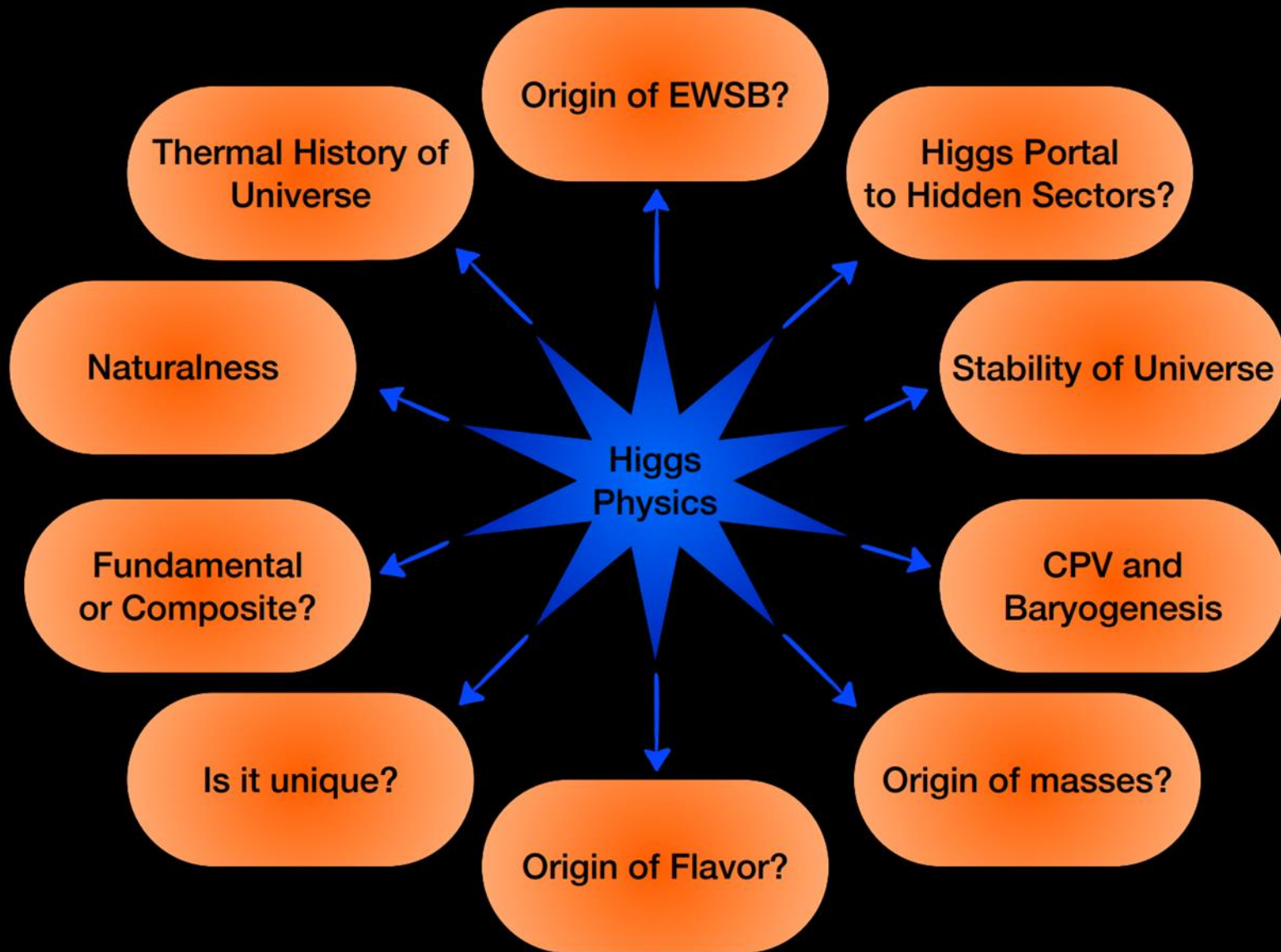


~100 km FCC
 e^+e^- (Z factory, 240 GeV Higgs + 365 GeV Top)
 ep, pp (~100 TeV)

FCC





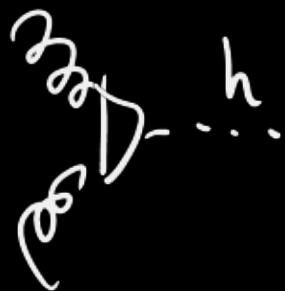


Information encoded in Higgs properties:

- HVV
- Yukawa
- Self-coupling
- Exotic decays
- New Higgs Channels
- ...

Basics:

pp

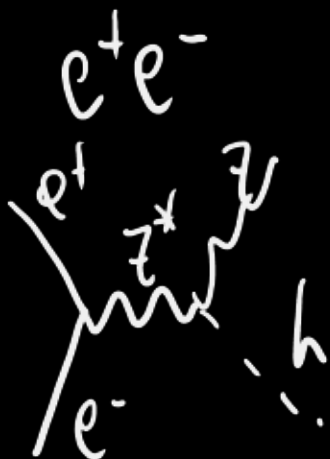


LHC 14 TeV

50 pb

3 ab⁻¹

0.15 billion Higgs

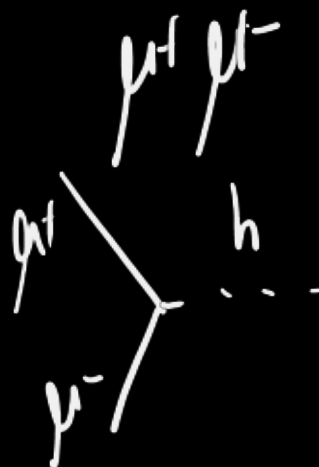


e⁺e⁻ 240 ~ 250 GeV

200 fb

5 ab⁻¹

1 million Higgs

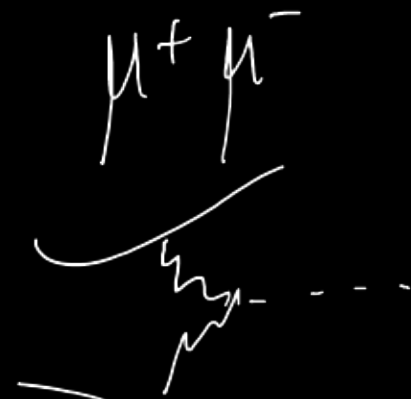


mu⁺mu⁻ 125 GeV

22 pb X 65%

5 ~ 20 fb⁻¹

0.07 million Higgs
~ 0.28



mu⁺mu⁻ 10 TeV

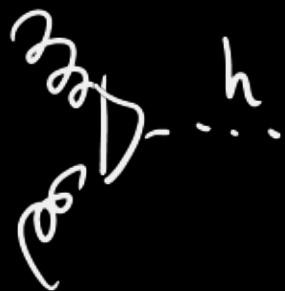
~ 1 pb

10 ab⁻¹

~ 10 million Higgs

Basics:

pp

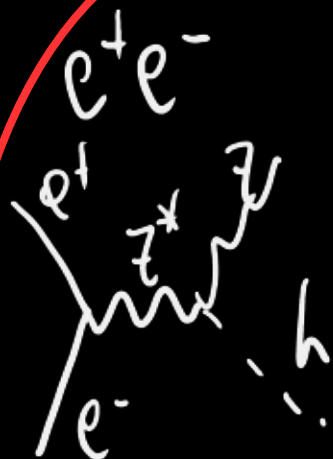


LHC 14 TeV

50 pb

3 ab⁻¹

0.15 billion Higgs

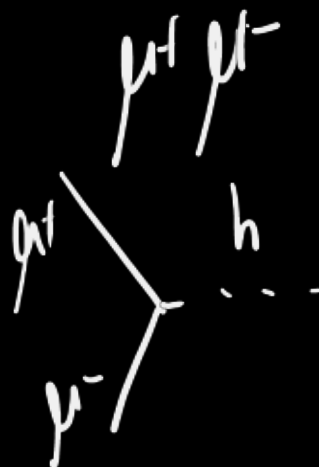


e⁺e⁻ 240~250 GeV

200 fb

5 ab⁻¹

1 million Higgs

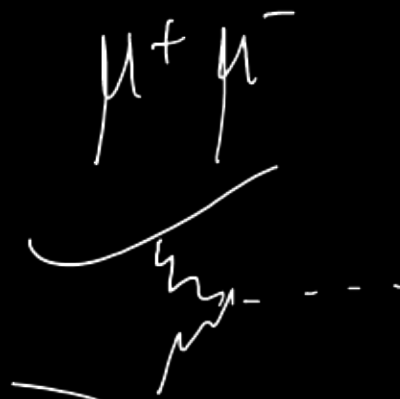


μ⁺μ⁻ 125 GeV

22 pb × 65%

5~20 fb⁻¹

0.07 million Higgs
~0.28



μ⁺μ⁻ 10 TeV

~1 pb

10 ab⁻¹

~10 million Higgs

Higgs Physics Performance

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_C (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_S $ (%)	—	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

Future Circular Collider Feasibility Study Report

[CERN-FCC-PHYS-2025-0002](#)

See more from Jae Sik Lee's talk next.

Higgs Physics Performance

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_C (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_S $ (%)	—	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

Future Circular Collider Feasibility Study Report

[CERN-FCC-PHYS-2025-0002](#)

See more from Jae Sik Lee's talk next.

Higgs Physics Performance

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_C (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_S $ (%)	—	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

Future Circular Collider Feasibility Study Report

[CERN-FCC-PHYS-2025-0002](#)

See more from Jae Sik Lee's talk next.

Higgs Physics Performance

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_S $ (%)	—	+29 −67	+29 −67
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

Future Circular Collider Feasibility Study Report

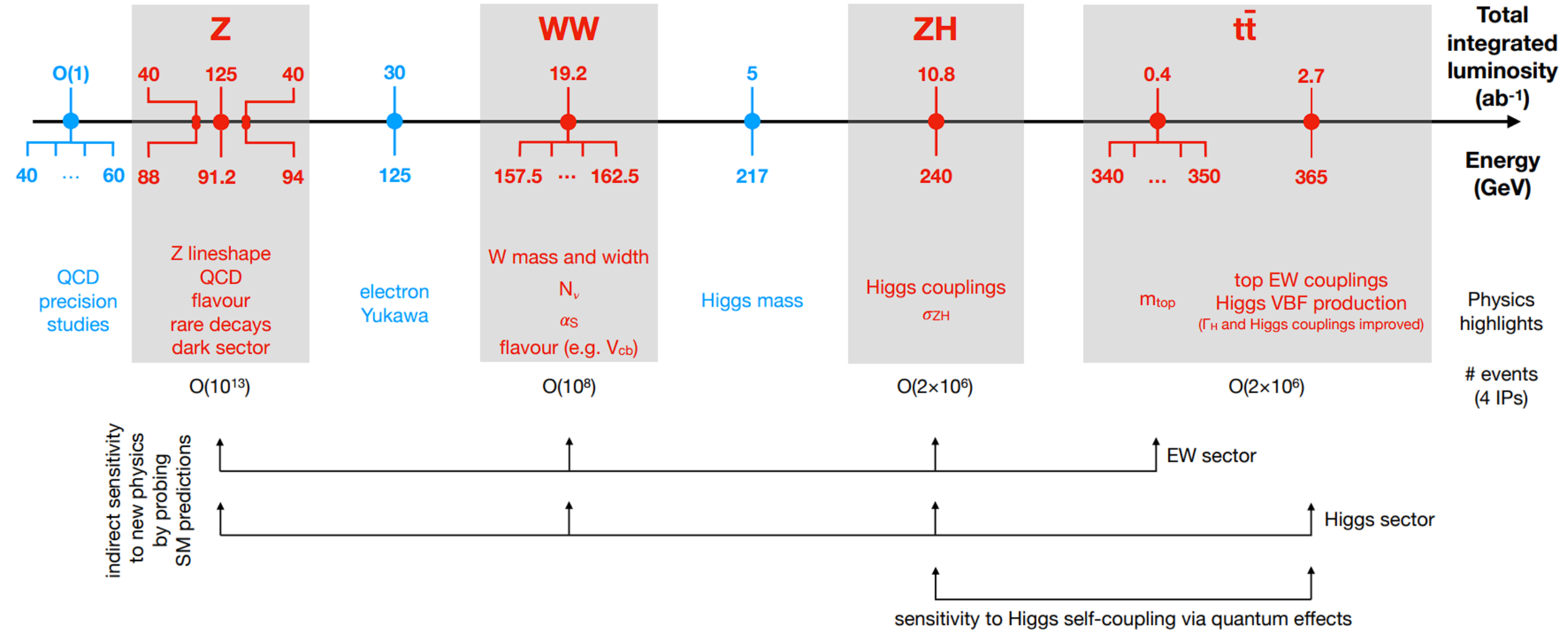
[CERN-FCC-PHYS-2025-0002](#)

See more from Jae Sik Lee's talk next.

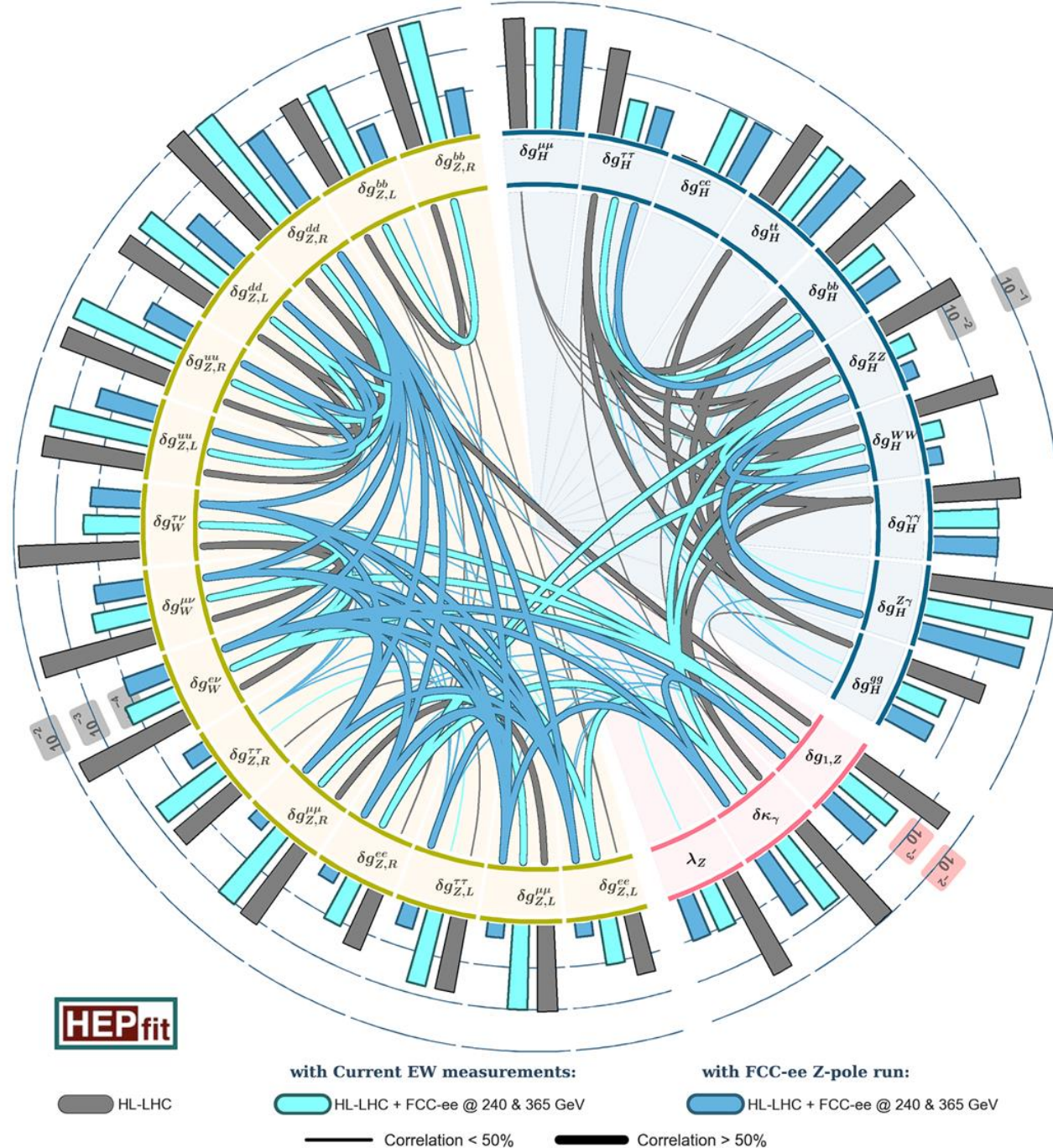
FCC-ee is an integrated comprehensive program

— CDR baseline runs (4IPs)

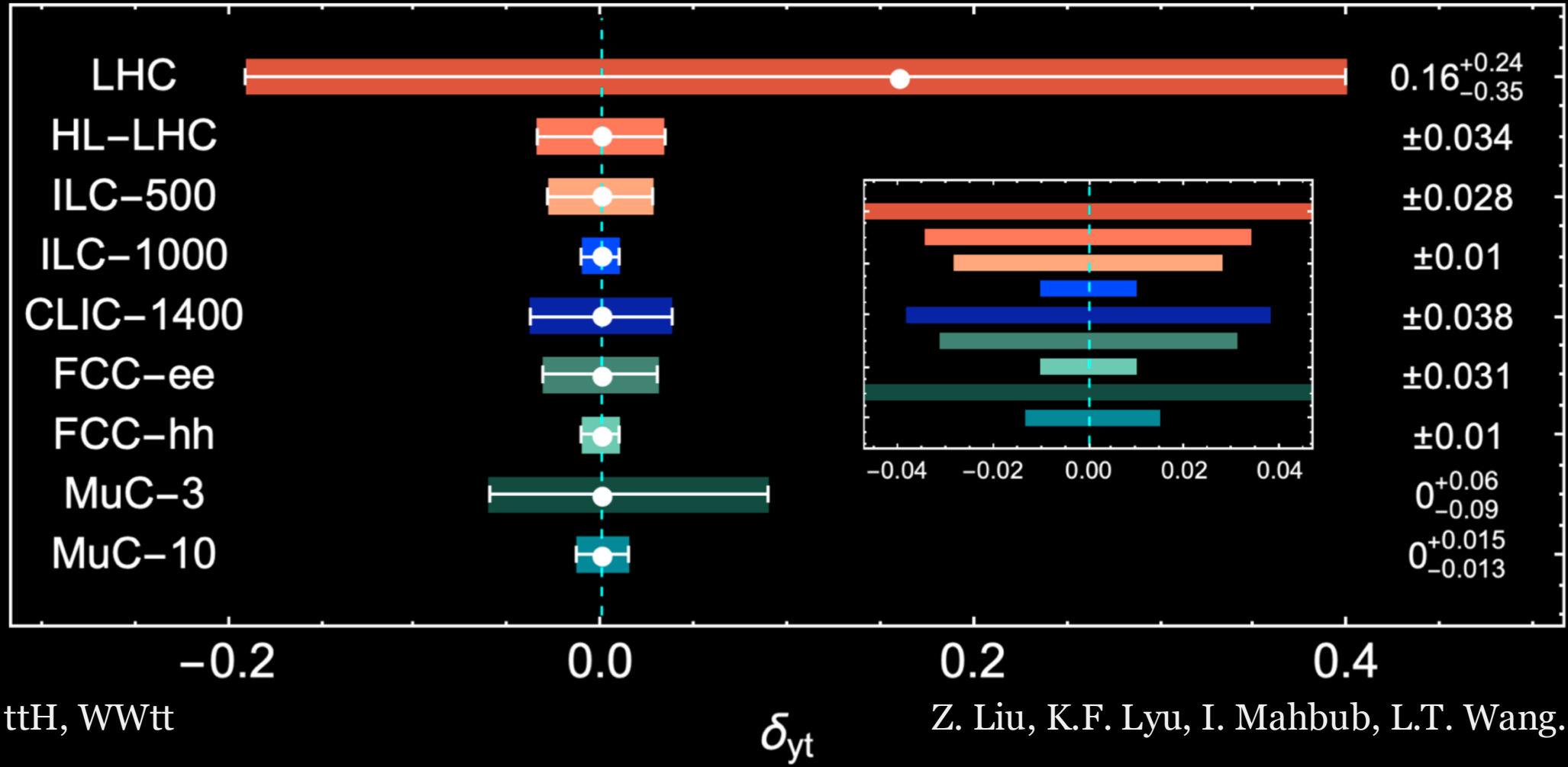
— Additional opportunities



Integrated program with different runs



Projected Top Yukawa precision



**Not “just” Precision
LOTS of Direct BSM sensitivities**

Higgs Exotic Decay

- There is a whole zoo of light BSM particle to be explored at colliders.
(checking all the possibility; theoretical interests.)
(Higgs Portal: $(H^+ H)$, HNL, ALPs, Dark Matter ...)
- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **
(complementarity)

Higgs Exotic Decay

- Higgs has **tiny width** ~ 4 MeV

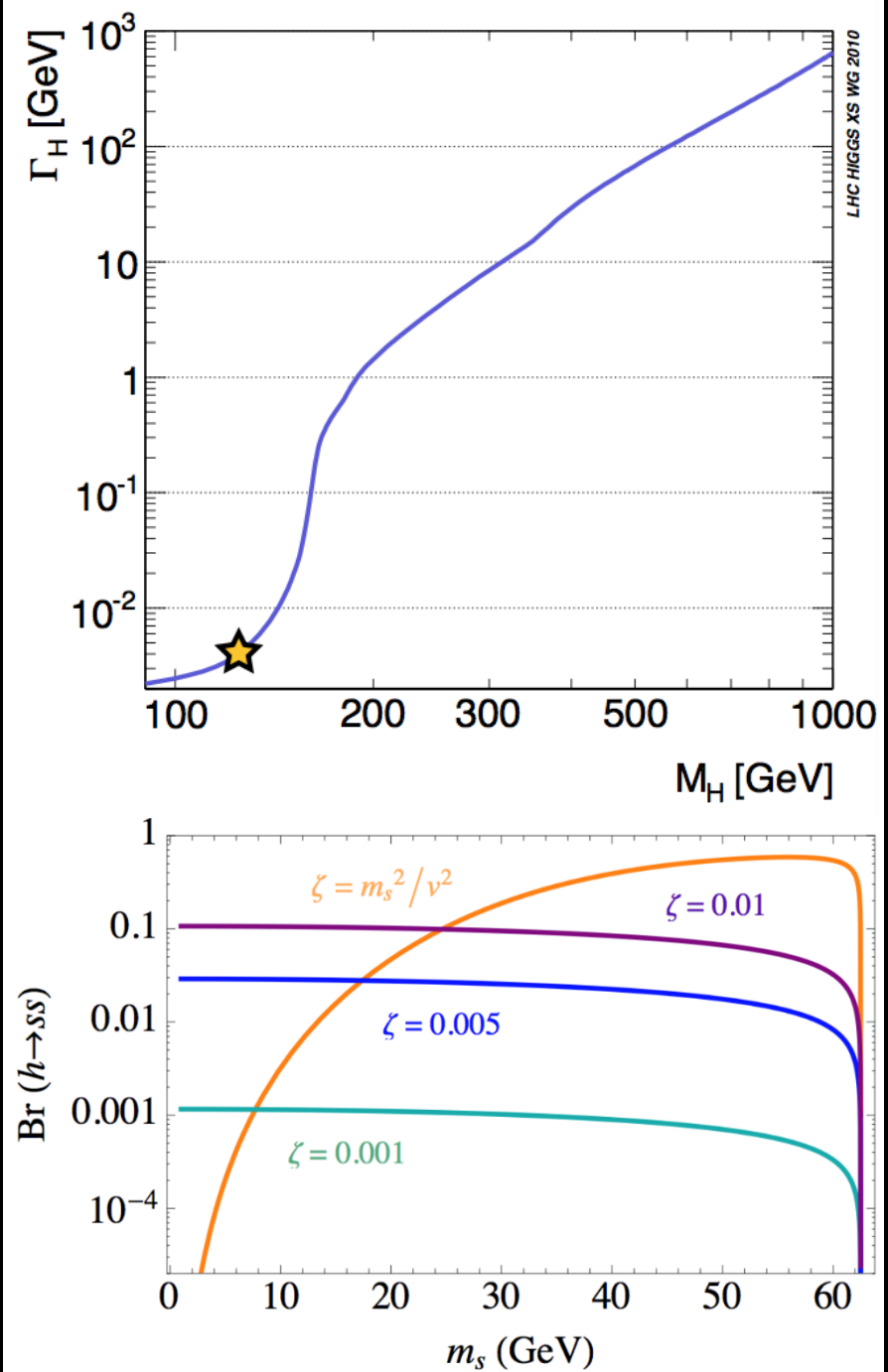
$$\frac{\Gamma}{M} = O(10^{-5})$$

all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc. Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$

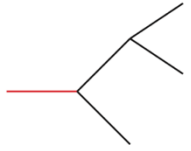
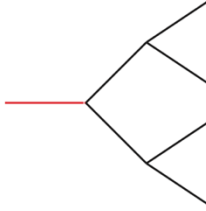
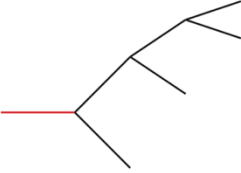
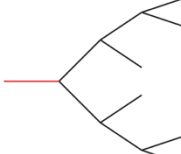
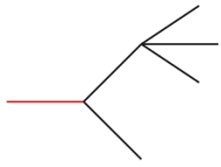
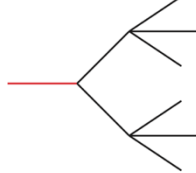
- small couplings** to BSM could have **sizeable** branching, e.g.,

$$\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

(common building block in extended Higgs sectors) can give $\text{BR}(h \rightarrow ss) \sim O(10\%)$ for ζ as small as 0.01 !

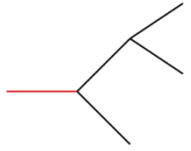
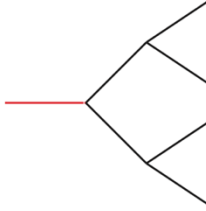
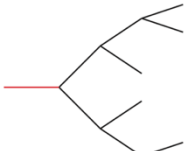
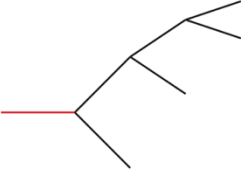
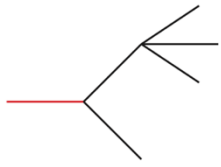
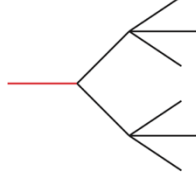


A global view

Decay Topologies	Decay mode $\mathcal{F}_i$	Decay Topologies	Decay mode $\mathcal{F}_i$
$h \rightarrow 2$	$h \rightarrow \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$
$h \rightarrow 2 \rightarrow 3$	$h \rightarrow \gamma + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\tau^+\tau^-)$
	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (jj)(\gamma\gamma)$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (jj)(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
$h \rightarrow 2 \rightarrow (1+3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+\tau^- + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 6$	$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$		

Curtin, Essig, Gori, Jaiswal, Katz, Liu, ZL, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong [1312.4992](#), H. Zhang, ZL, LT Wang, [1612.09284](#) and corresponding updates for various future colliders

A global view

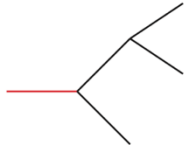
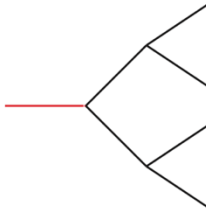
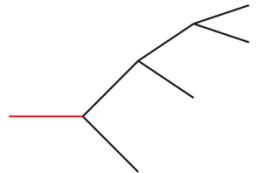
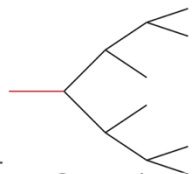
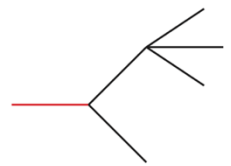
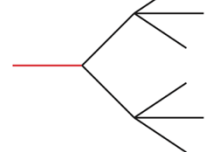
Decay Topologies	Decay mode $\mathcal{F}_i$	Decay Topologies	Decay mode $\mathcal{F}_i$
$h \rightarrow 2$	$h \rightarrow \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$
$h \rightarrow 2 \rightarrow 3$	$h \rightarrow \gamma + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\tau^+\tau^-)$
	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (jj)(\gamma\gamma)$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (jj)(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
$h \rightarrow 2 \rightarrow (1+3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+\tau^- + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 6$	$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$		

LHC's strength

HL-LHC has large number of Higgs produced (0.2 Billion), having great sensitivity to exotic decays into leptons and photons

Curtin, Essig, Gori, Jaiswal, Katz, Liu, ZL, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong [1312.4992](#), H. Zhang, ZL, LT Wang, [1612.09284](#) and corresponding updates for various future colliders

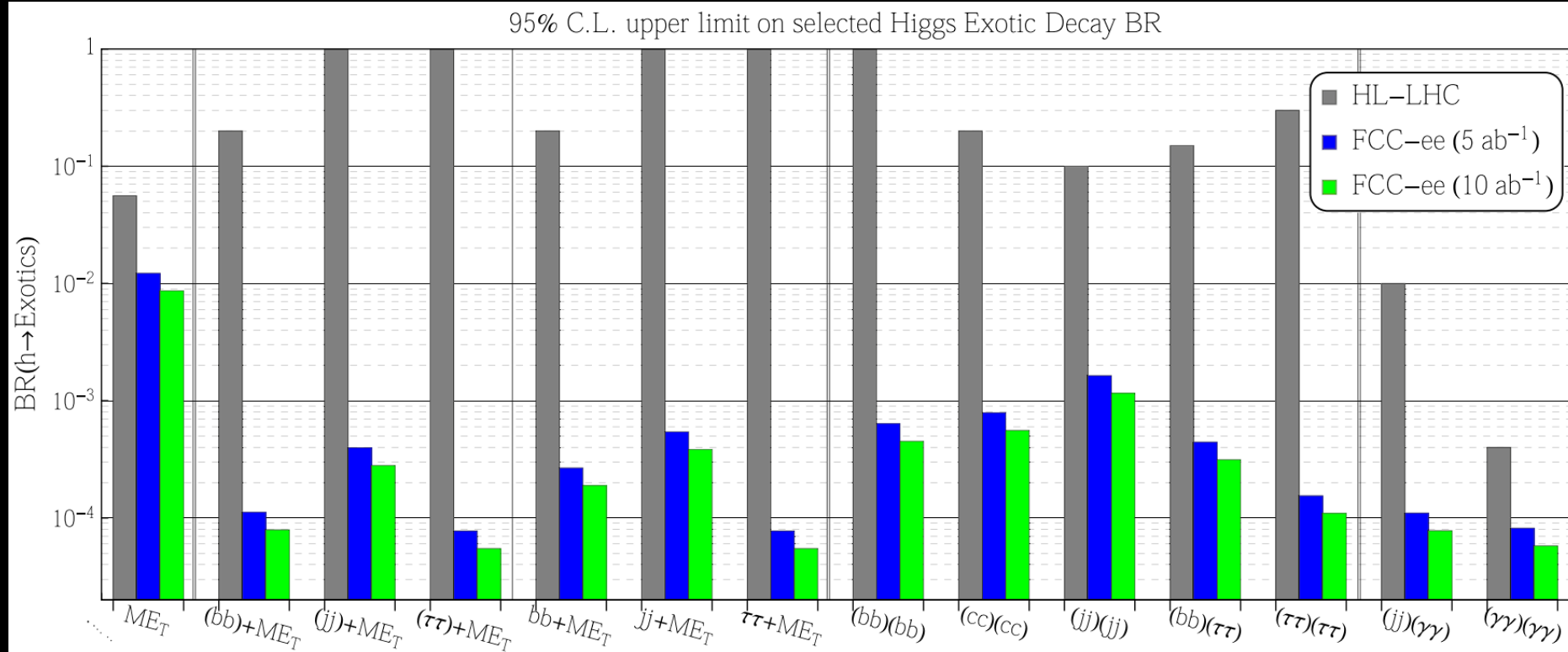
A global view

Decay Topologies	Decay mode $\mathcal{F}_i$	Decay Topologies	Decay mode $\mathcal{F}_i$
$h \rightarrow 2$	$h \rightarrow \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$
$h \rightarrow 2 \rightarrow 3$	$h \rightarrow \gamma + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\tau^+\tau^-)$
	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (jj)(\gamma\gamma)$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (jj)(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
$h \rightarrow 2 \rightarrow (1+3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+\tau^- + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 6$	$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$		

LHC's strength
 Hard at LHC due to missing energy
 Hard at LHC due to hadronic background
 (HL-)LHC will provide valuable first-hand information on these challenging channels
 Future colliders cover deeper

Decay Mode	95% C.L. limit on BR	
	LHC	HL-LHC
$\cancel{E}_T$	0.23	0.056
$(b\bar{b}) + \cancel{E}_T$	[0.2]	—
$(jj) + \cancel{E}_T$	—	—
$(\tau^+\tau^-) + \cancel{E}_T$	[1]	—
$b\bar{b} + \cancel{E}_T$	[0.2]	—
$jj + \cancel{E}_T$	—	—
$\tau^+\tau^- + \cancel{E}_T$	—	—
$(b\bar{b})(b\bar{b})$	1.7 (0.2)	—
$(c\bar{c})(c\bar{c})$	(0.2)	—
$(jj)(jj)$	[0.1]	—
$(b\bar{b})(\tau^+\tau^-)$	0.1 [0.15]	—
$(\tau^+\tau^-)(\tau^+\tau^-)$	1.2 [0.2~0.4]	—
$(jj)(\gamma\gamma)$	[0.01]	—
$(\gamma\gamma)(\gamma\gamma)$	7×10^{-3}	4×10^{-4}

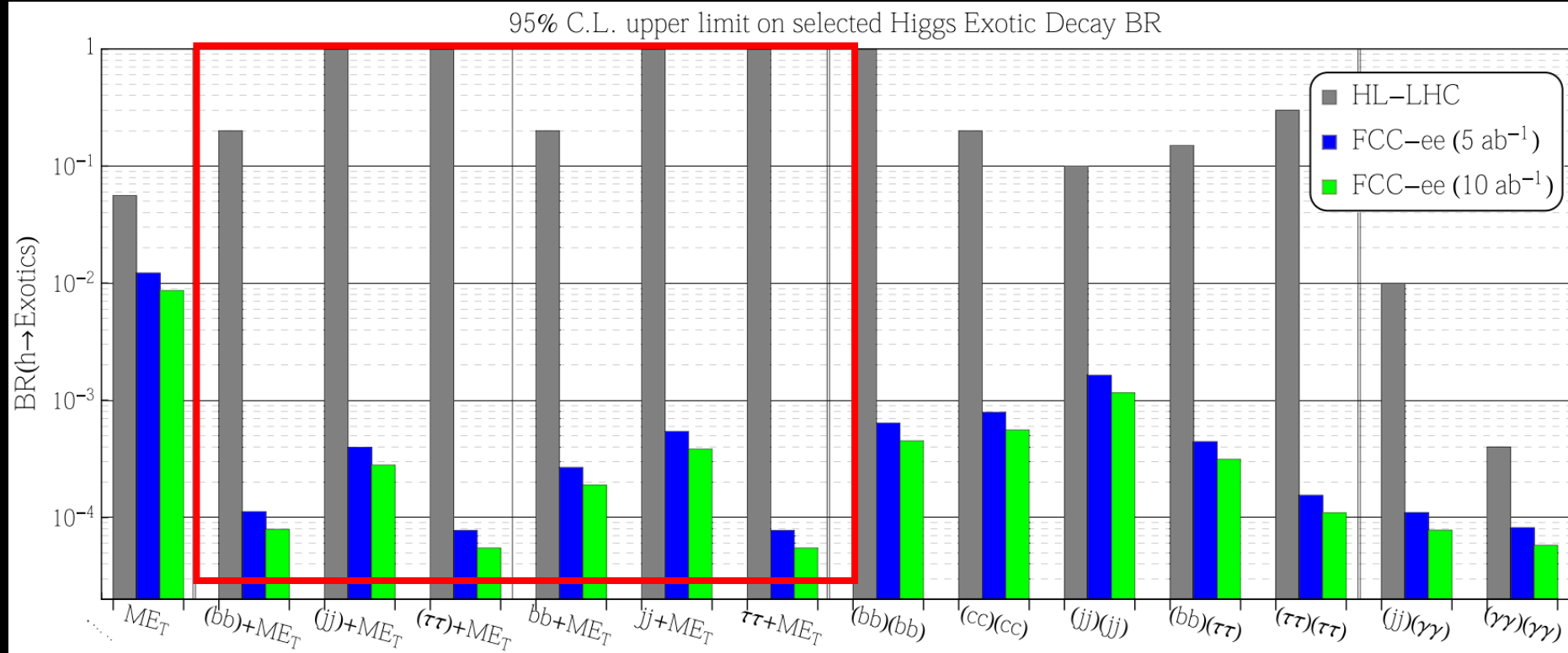
FCC-ee coverage



The HL-LHC are from various studies and projections available in the literature, but there are many more channels to include to fully represent the power of HL-LHC.

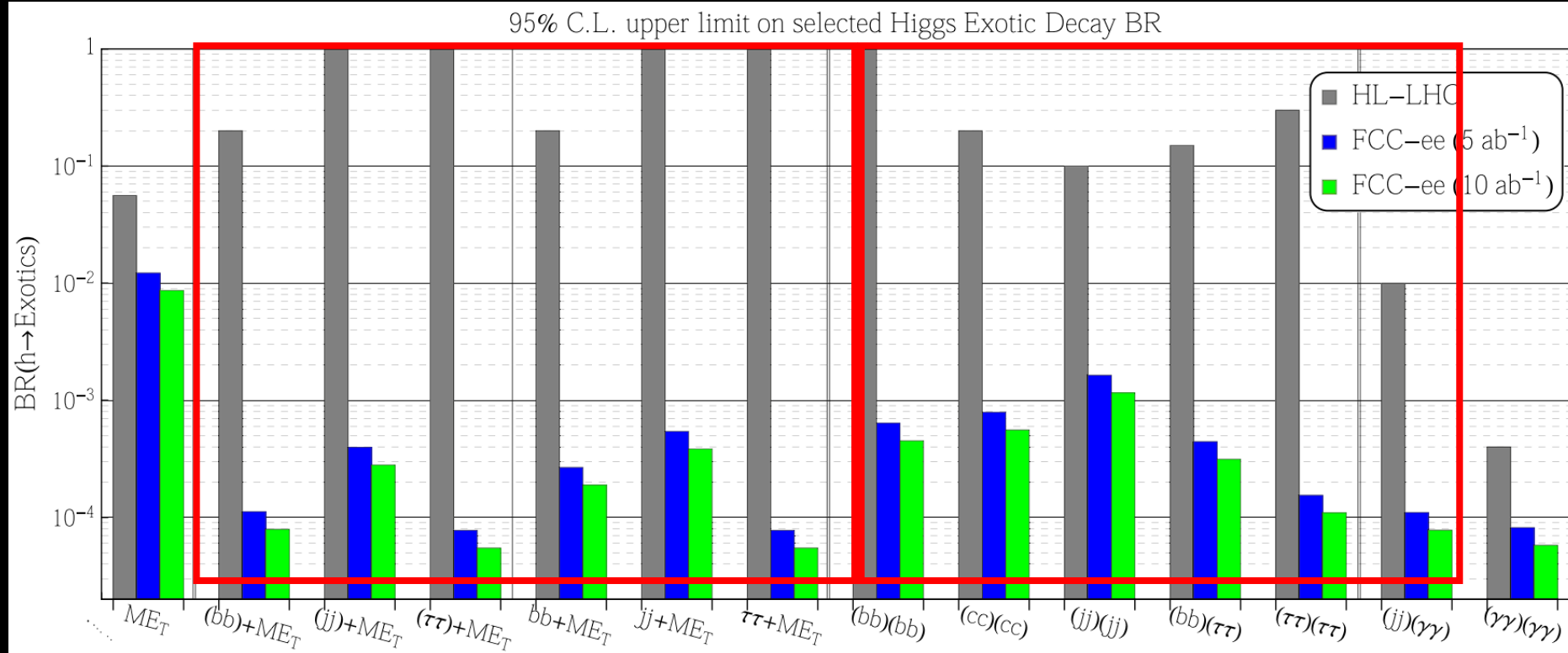
The lepton collider sensitivities (except for the first channel, $h \rightarrow \text{inv}$) are from our study with different $ee \rightarrow ZH$ integrated luminosities.

FCC-ee coverage



with missing Energy (SUSY motivated, DM motivated channels, e.g., recent review by Barman, Belanger, Godbole, [2010.11674](#)), 3-4 orders of magnitude improvement for the constraints on such exotic branching fractions

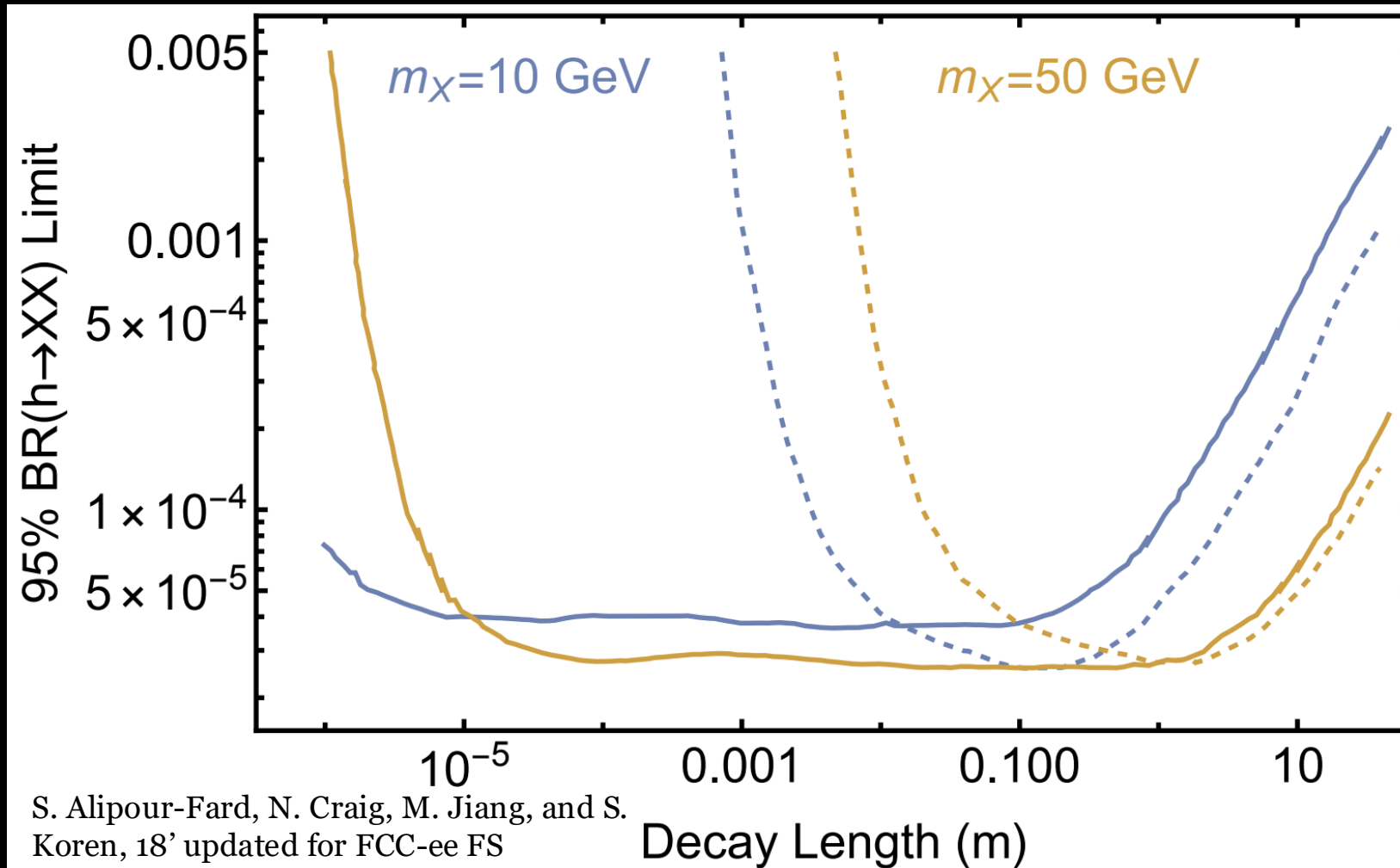
FCC-ee coverage



with missing Energy (SUSY motivated, DM motivated channels, e.g., recent review by Barman, Belanger, Godbole, [2010.11674](#)), 3-4 orders of magnitude improvement for the constraints on such exotic branching fractions

$h \rightarrow 4f$ generic Higgs sector extensions, also Higgs portals, 2-3 orders of magnitude improvement for the constraints on such exotic branching fractions

FCC-ee coverage: Long-lived particles

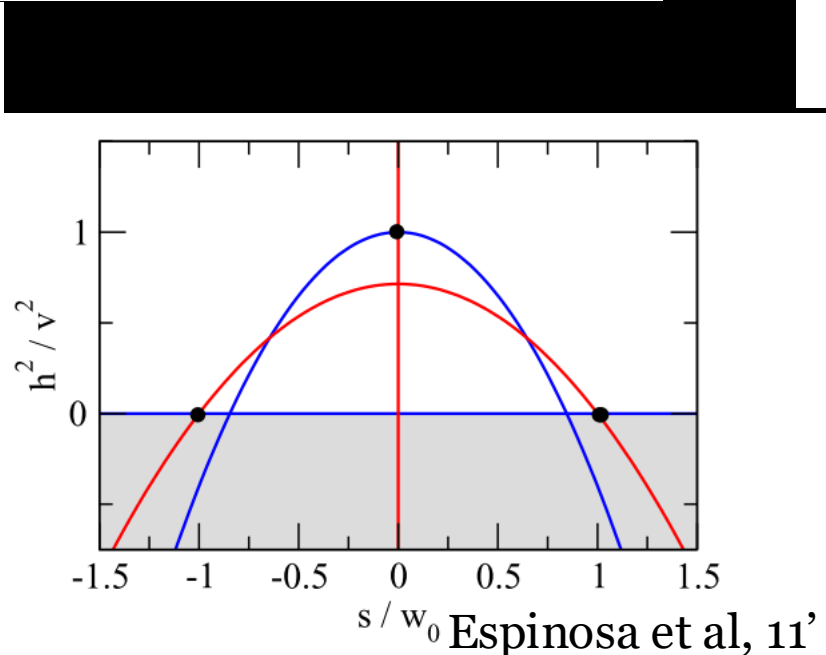
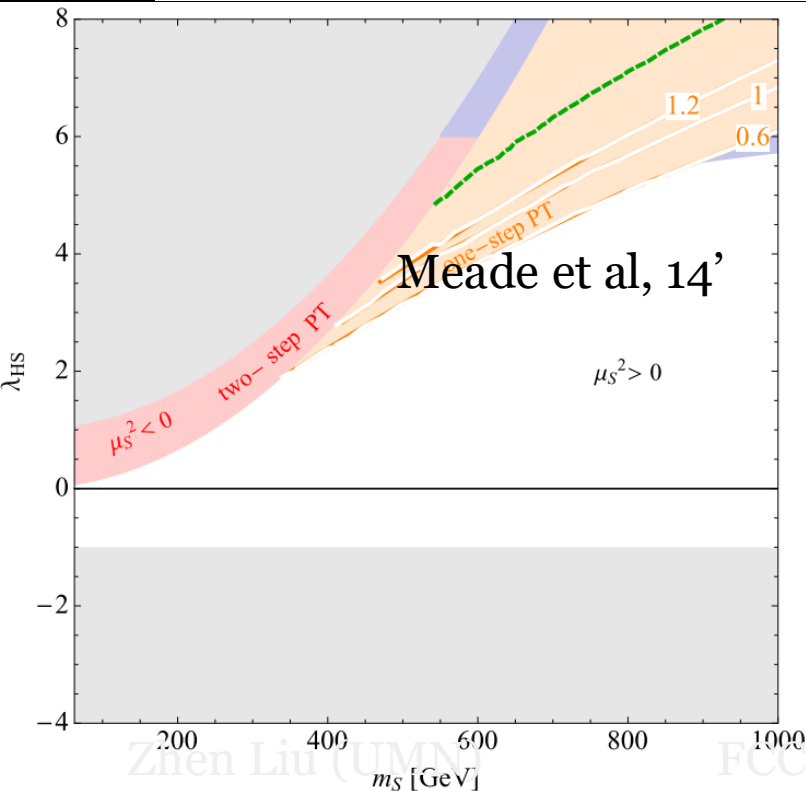


Enhancing EWPT through Singlet Extensions

One of the most generic extensions to Enhance EWPT; Many predicts new light scalar.

$$V_0(h, s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

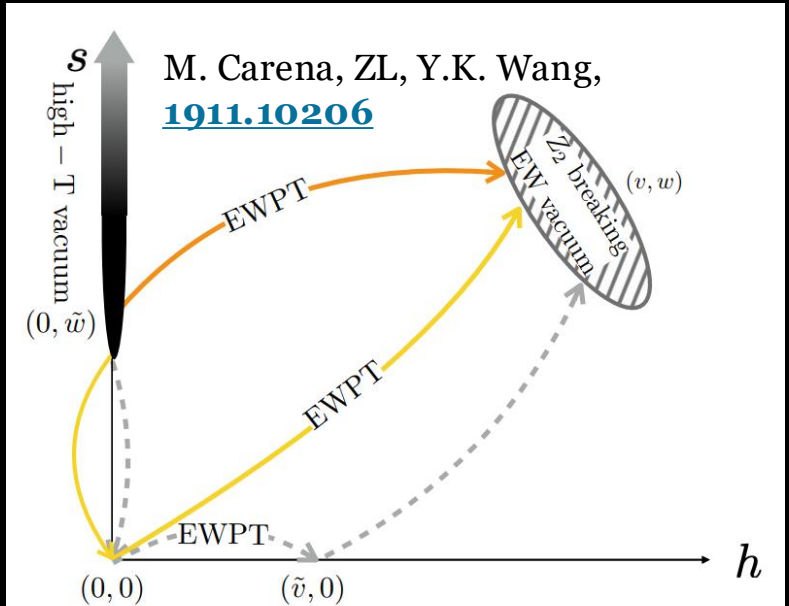
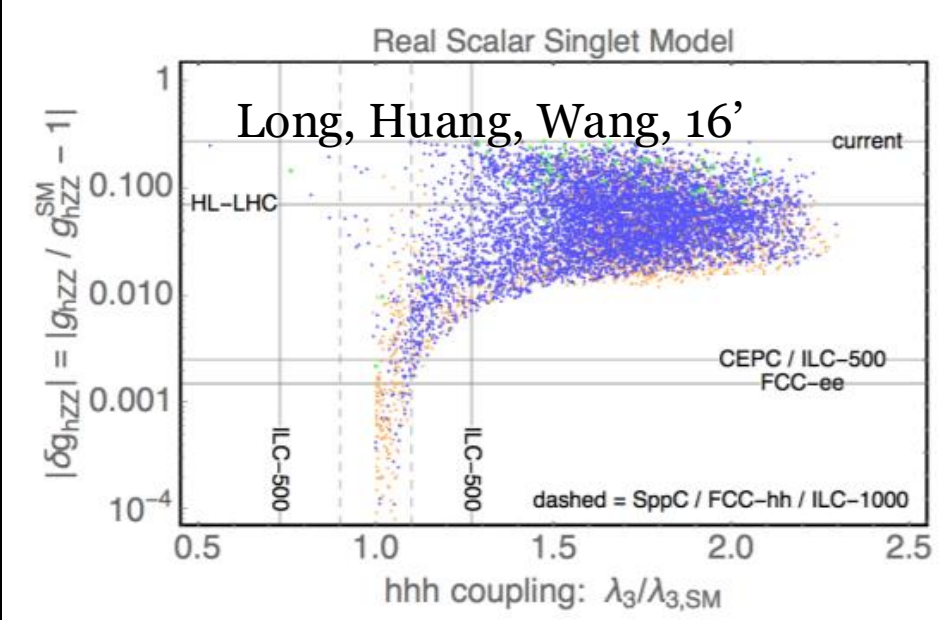
+ (explicit Z2 – breaking terms)



also Ramsey-Musolf et al 07'

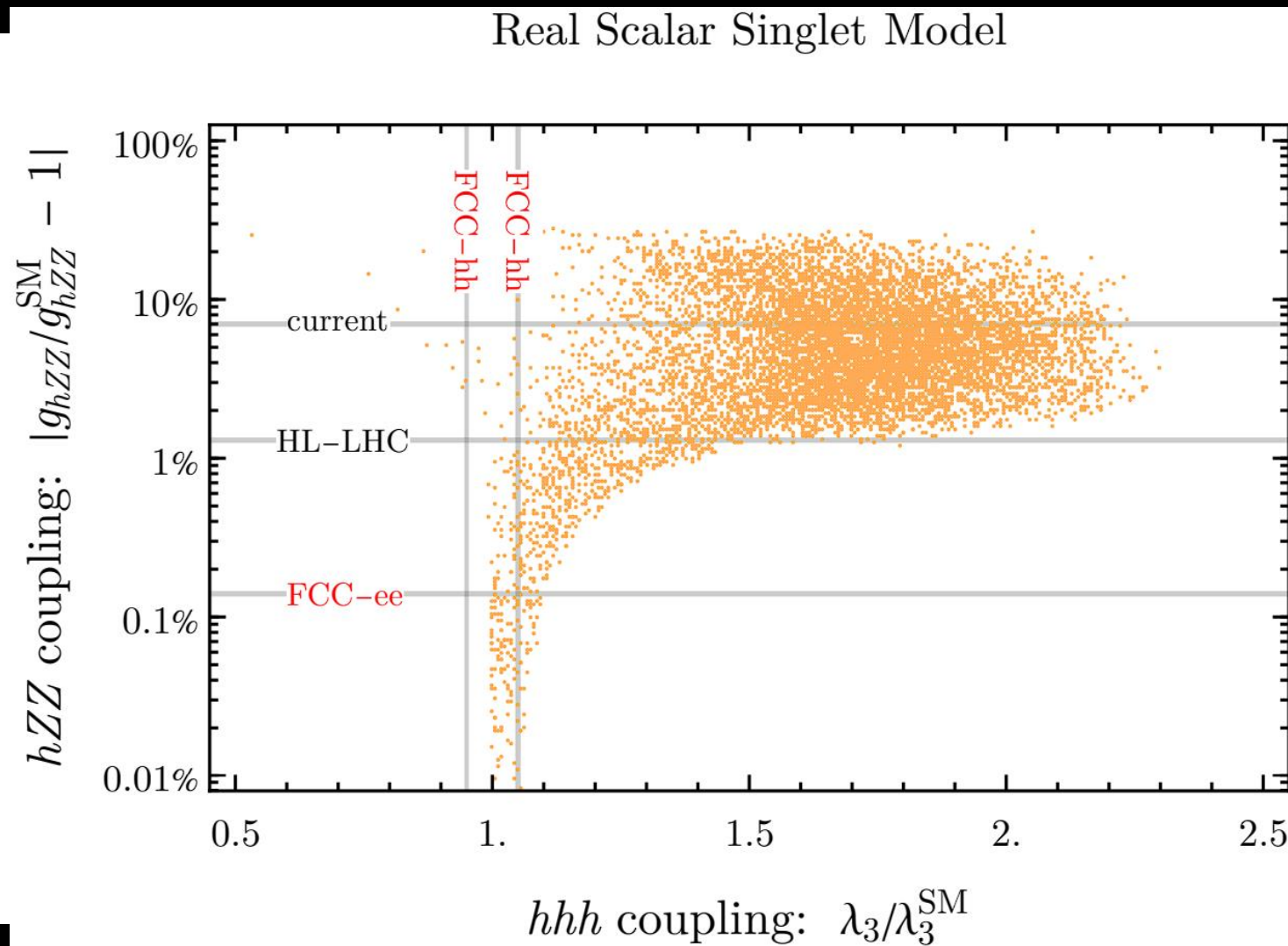
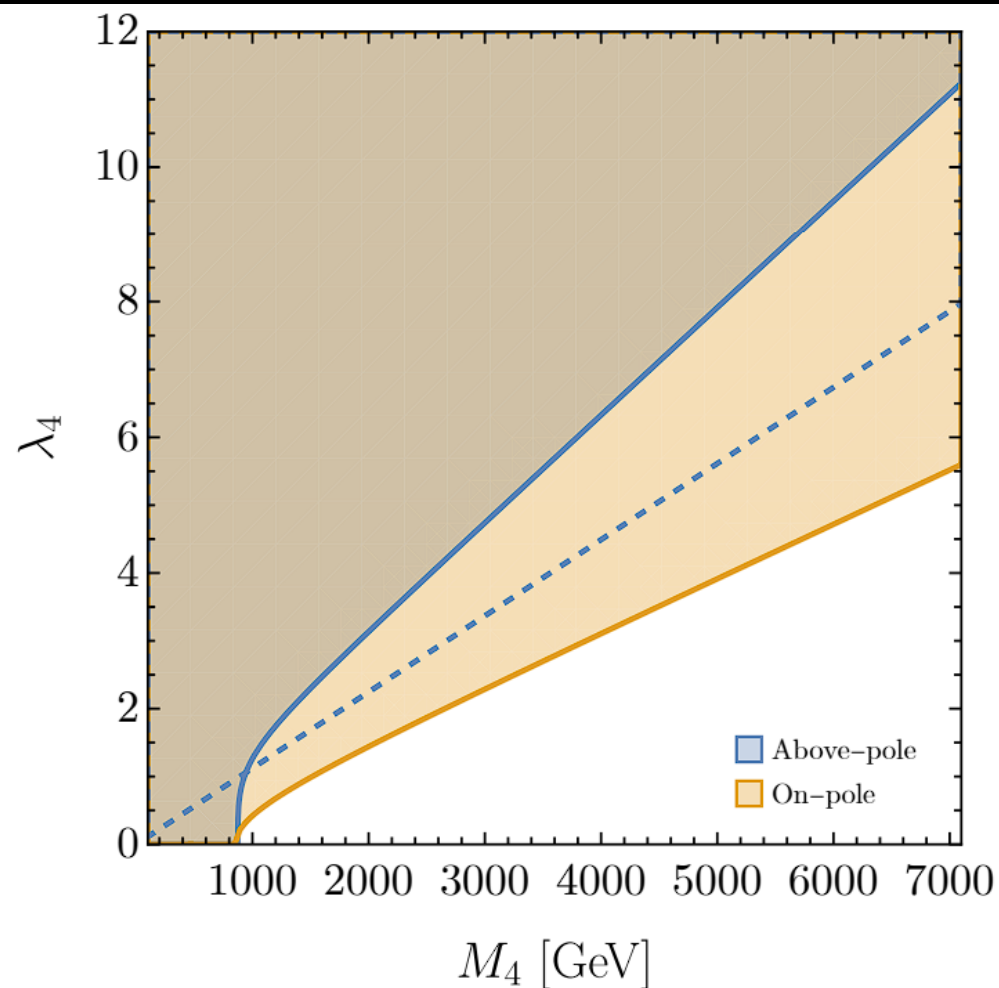
Physics

Pioneer Symposia on FCC

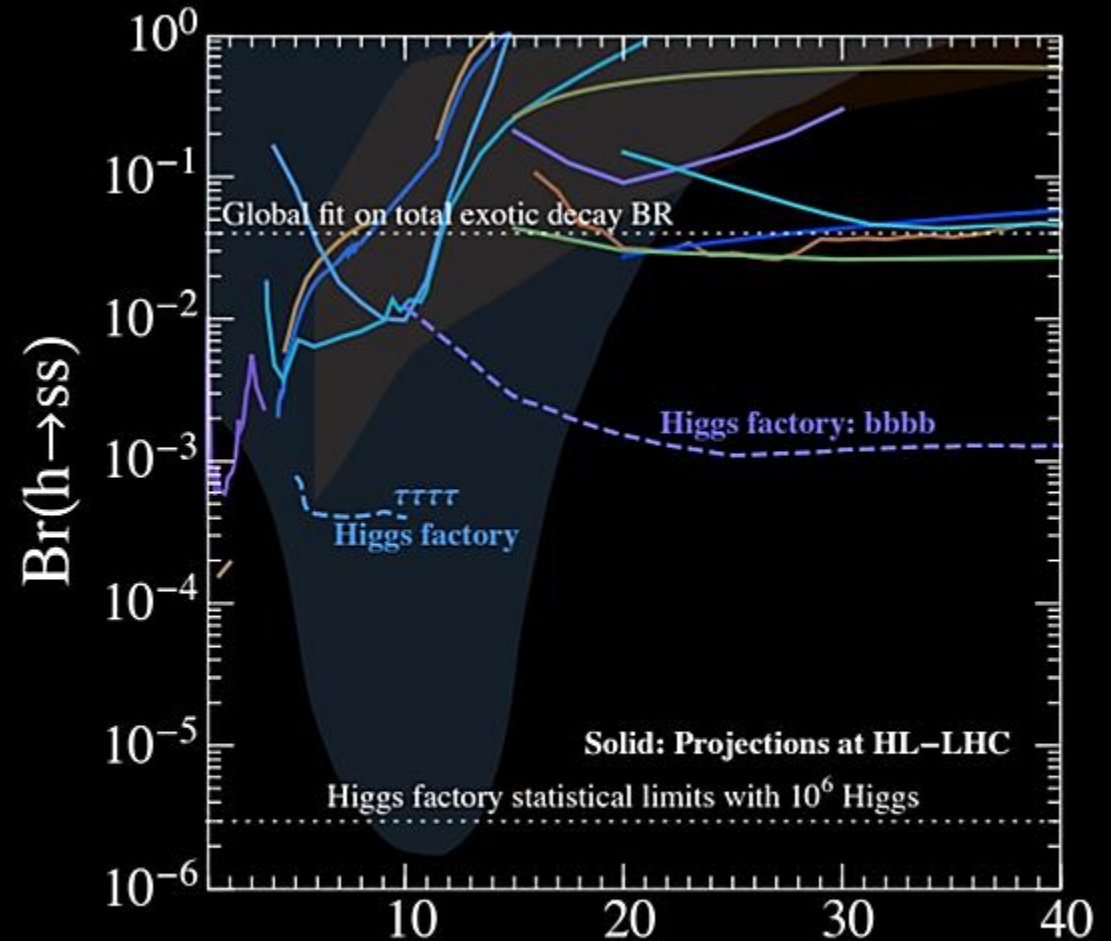
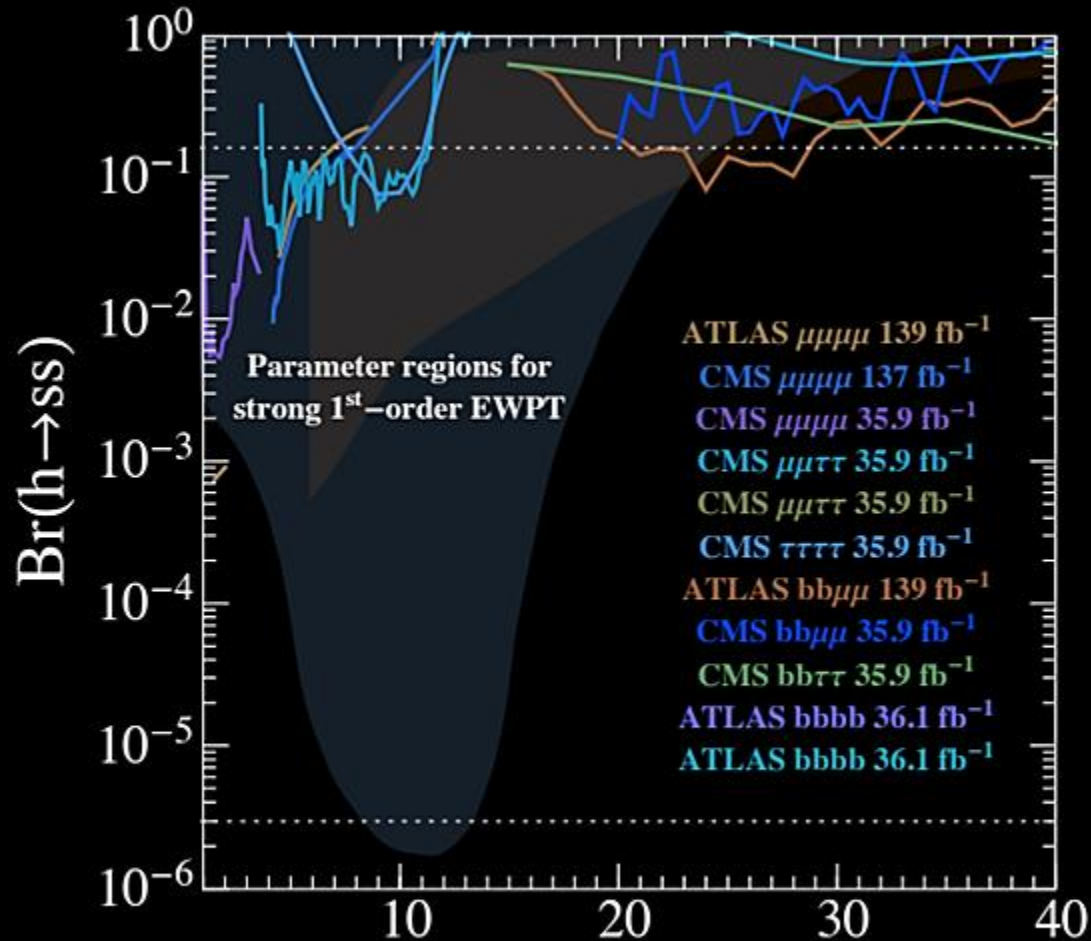


@ KPS 2026 Fall

Recent updates

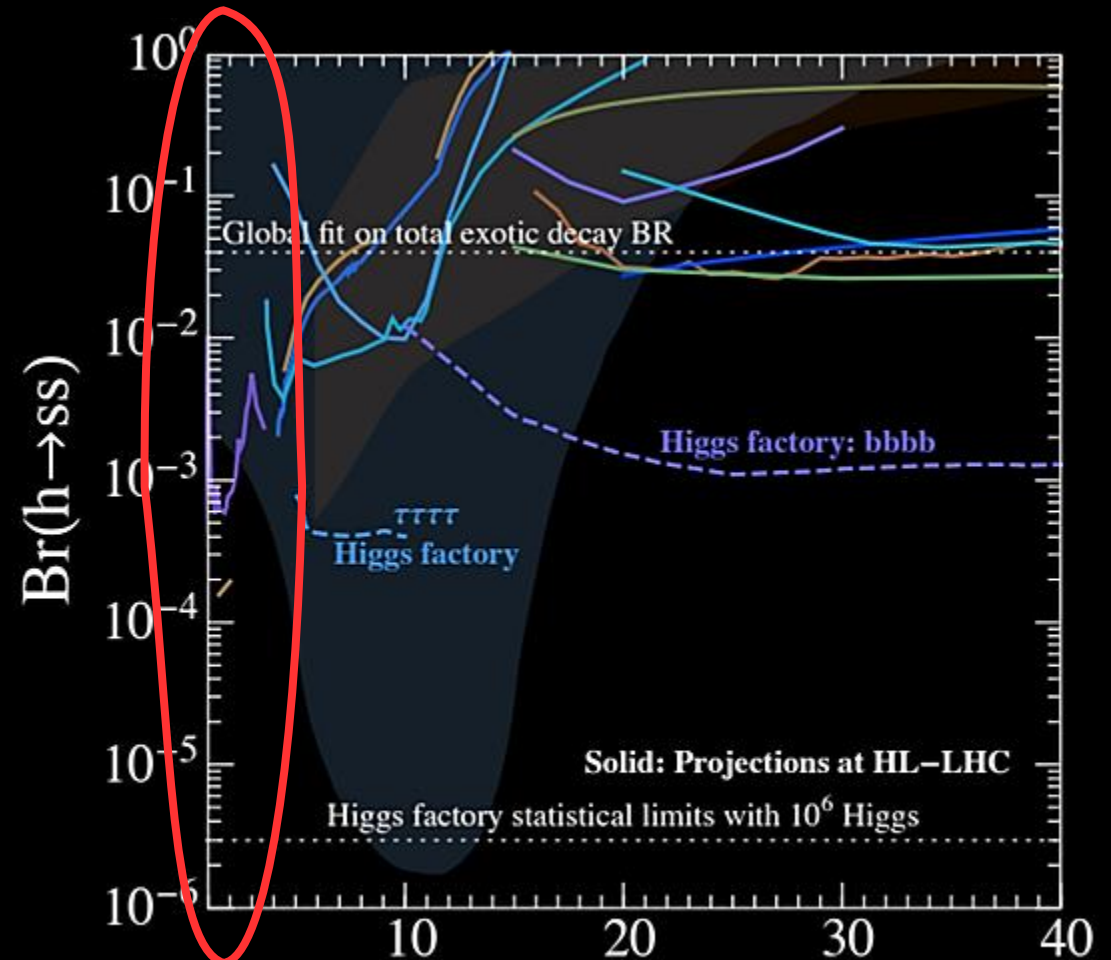
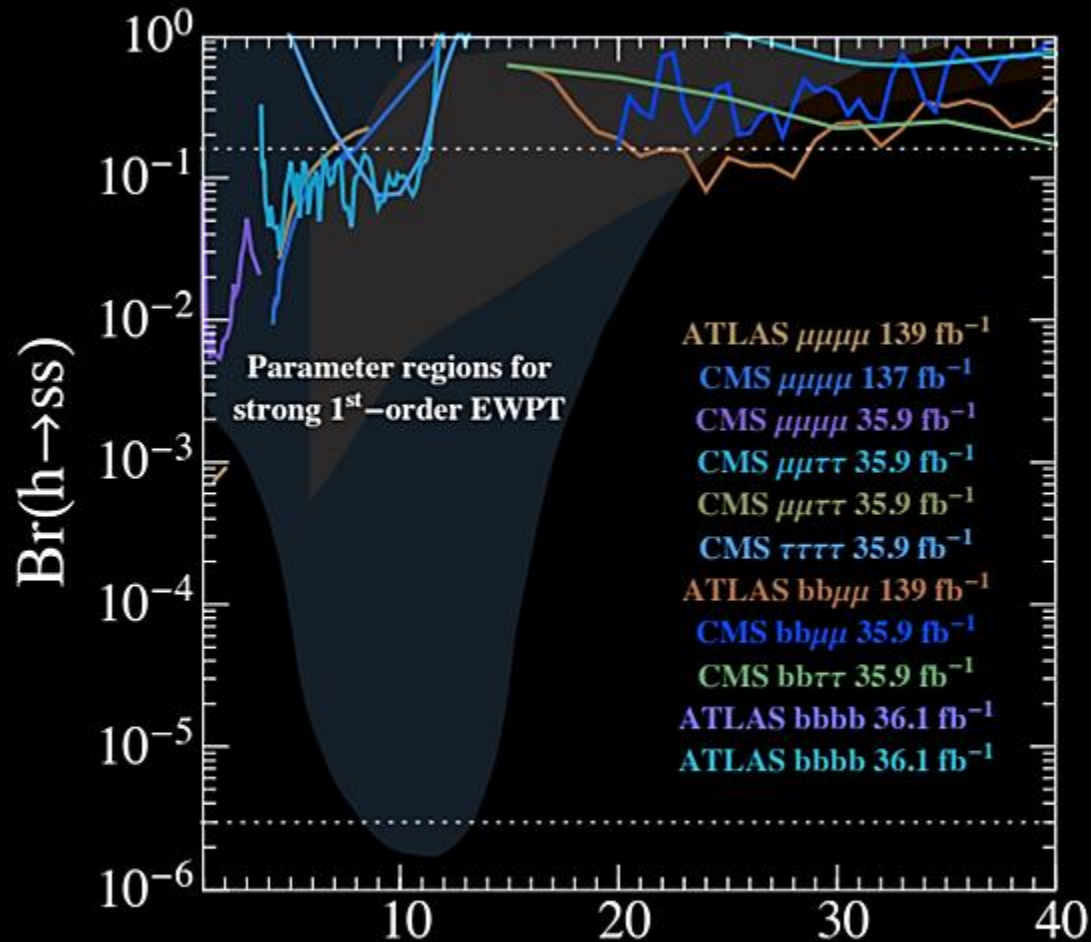


Translated Into Exotic BR to SS



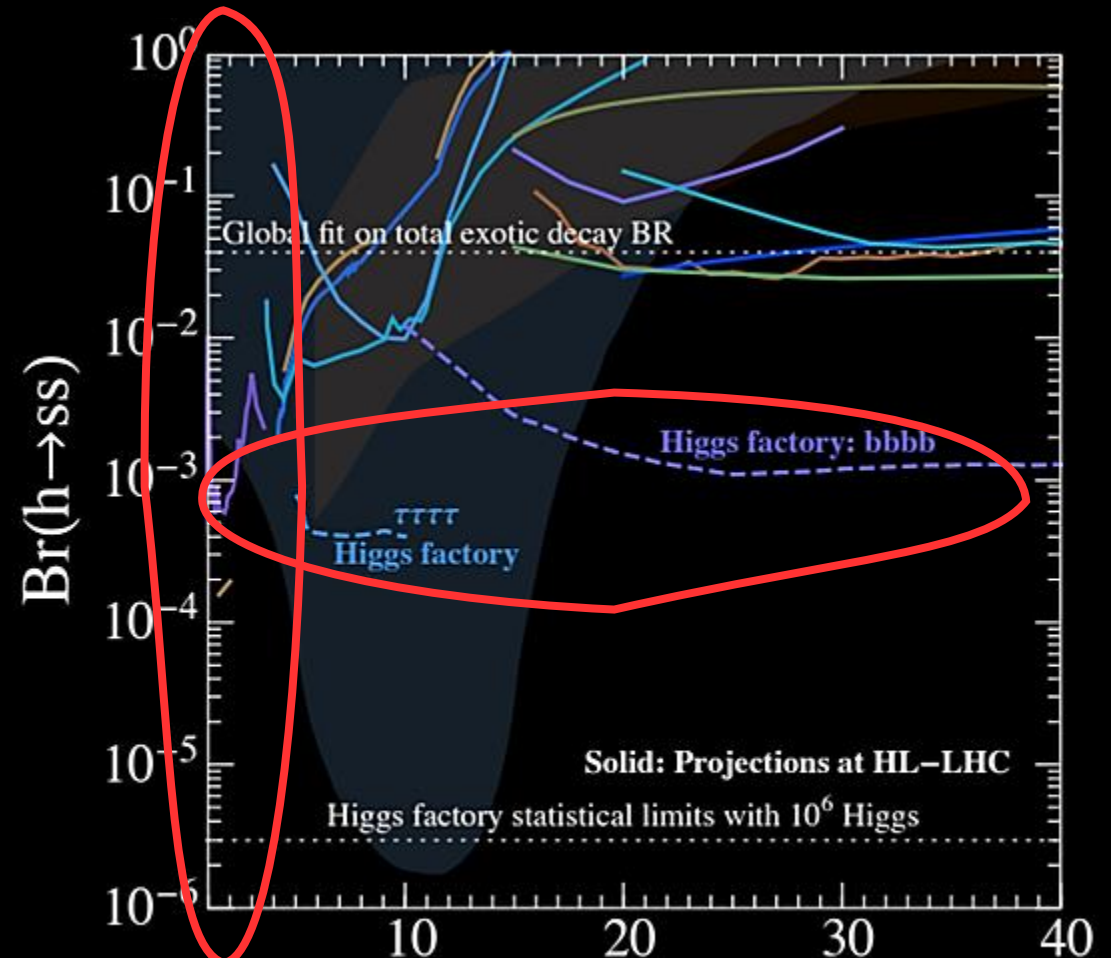
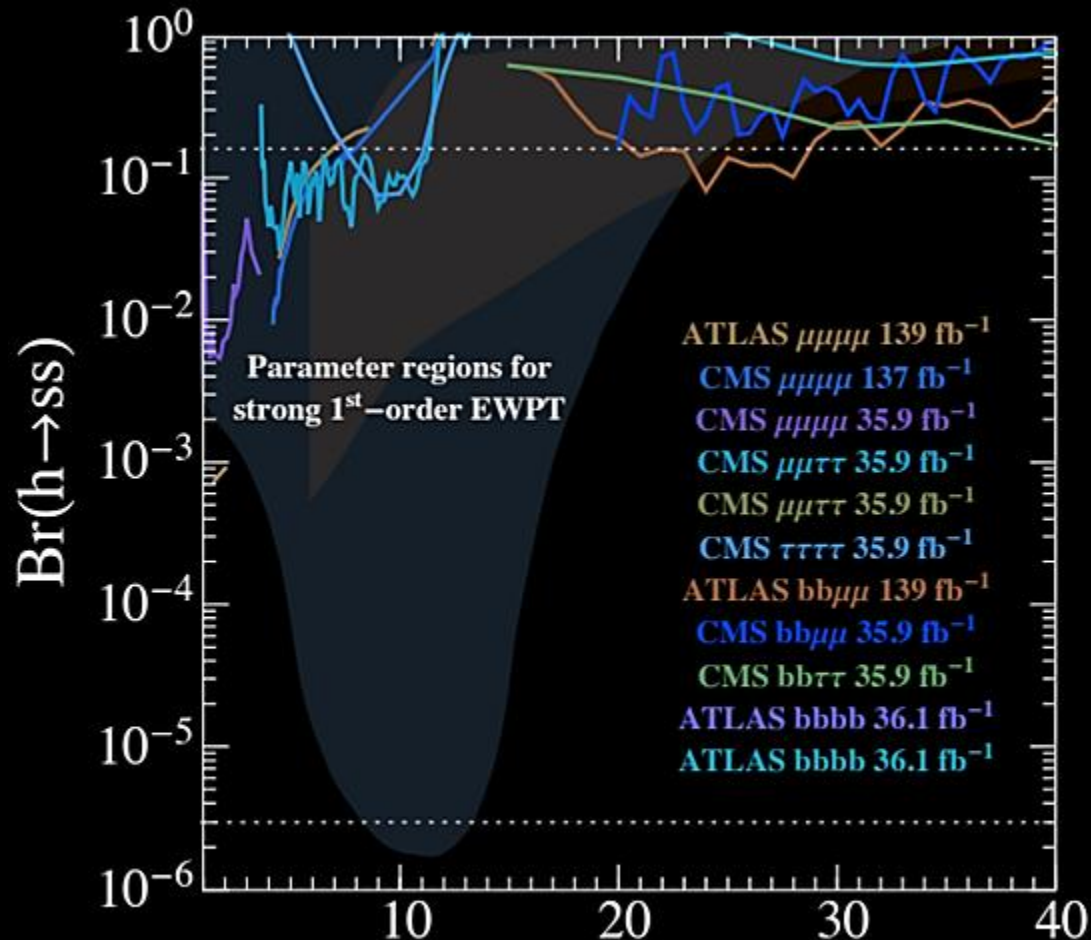
Carena, Kozaczuk, ZL, Gu, Ramsey-Musolf, Shelton, Wang, Xie, [2203.08206](#)

Translated Into Exotic BR to SS



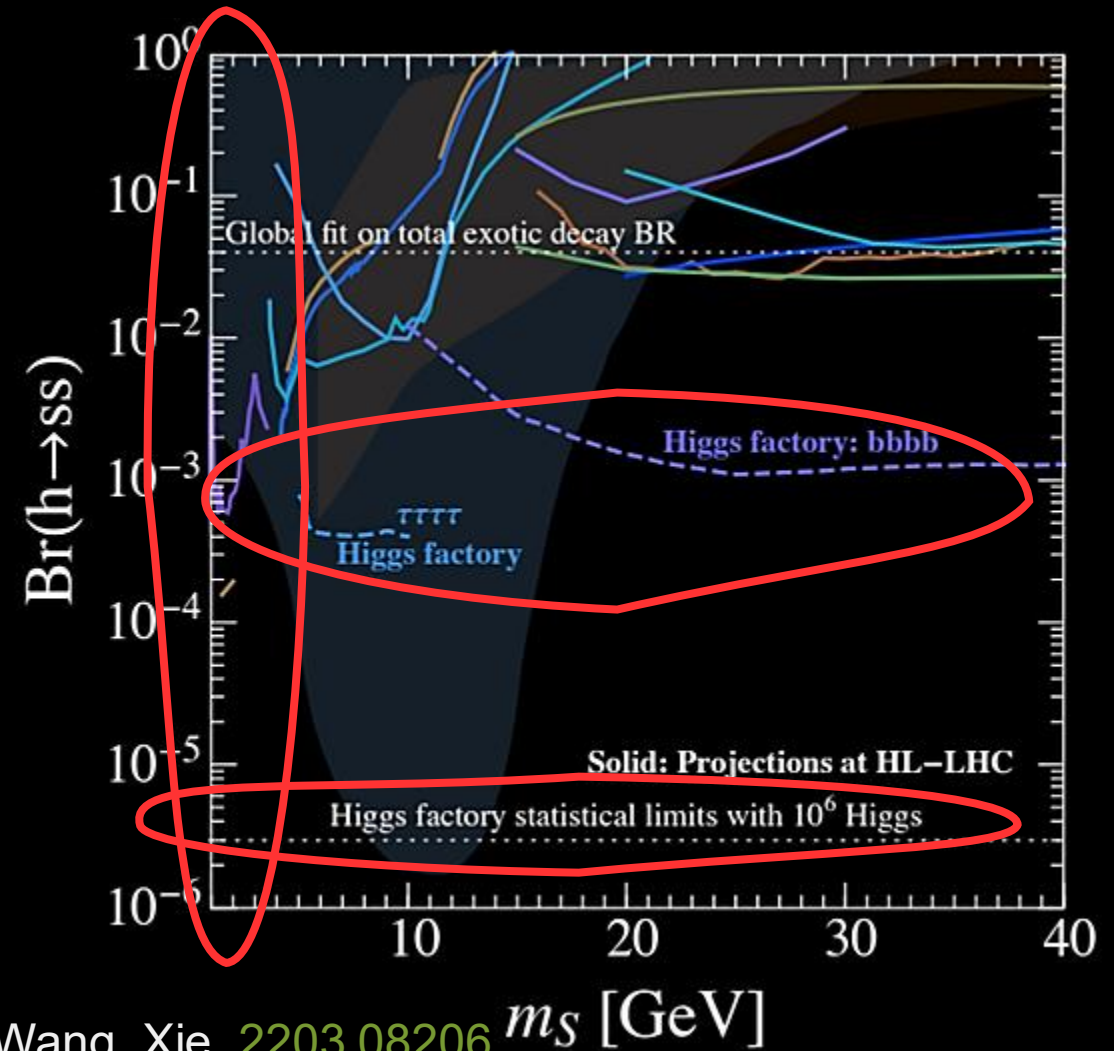
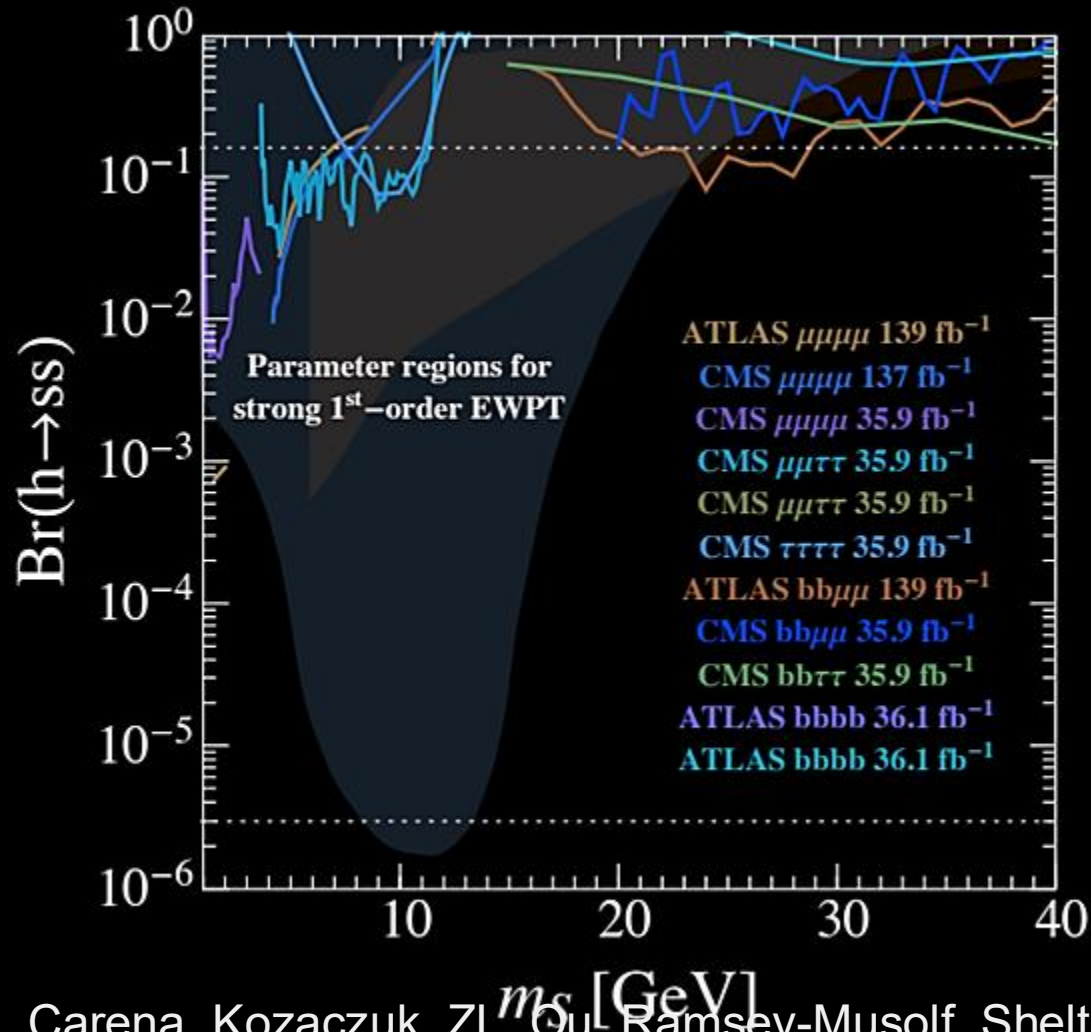
Carena, Kozaczuk, ZL, Gu, Ramsey-Musolf, Shelton, Wang, Xie, [2203.08206](#)

Translated Into Exotic BR to SS



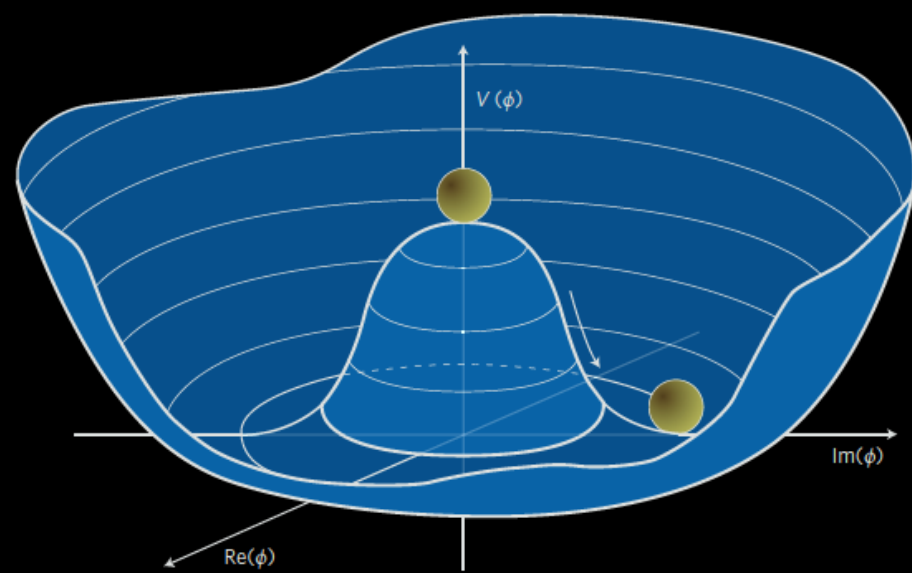
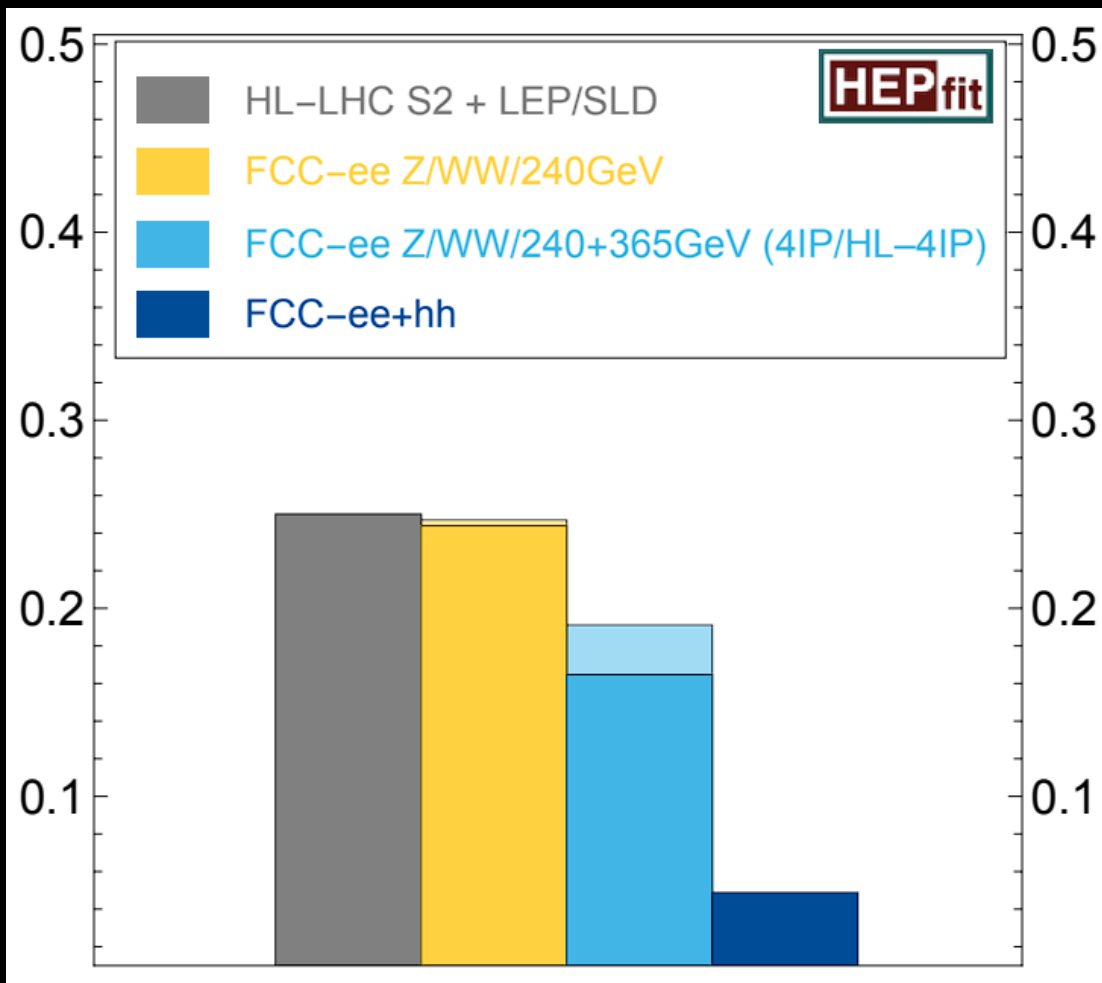
Carena, Kozaczuk, ZL, Gu, Ramsey-Musolf, Shelton, Wang, Xie, [2203.08206](#)

Translated Into Exotic BR to SS

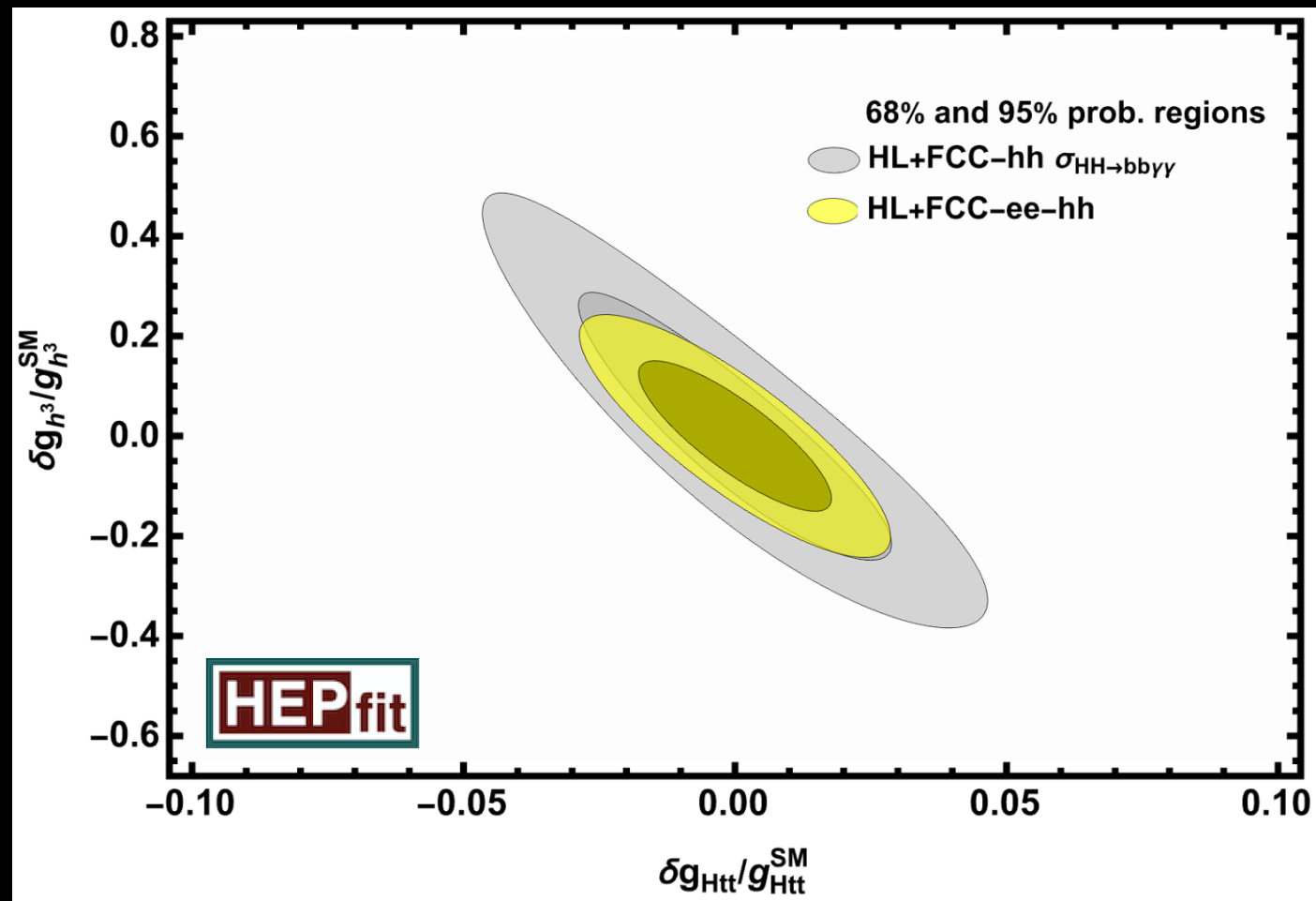
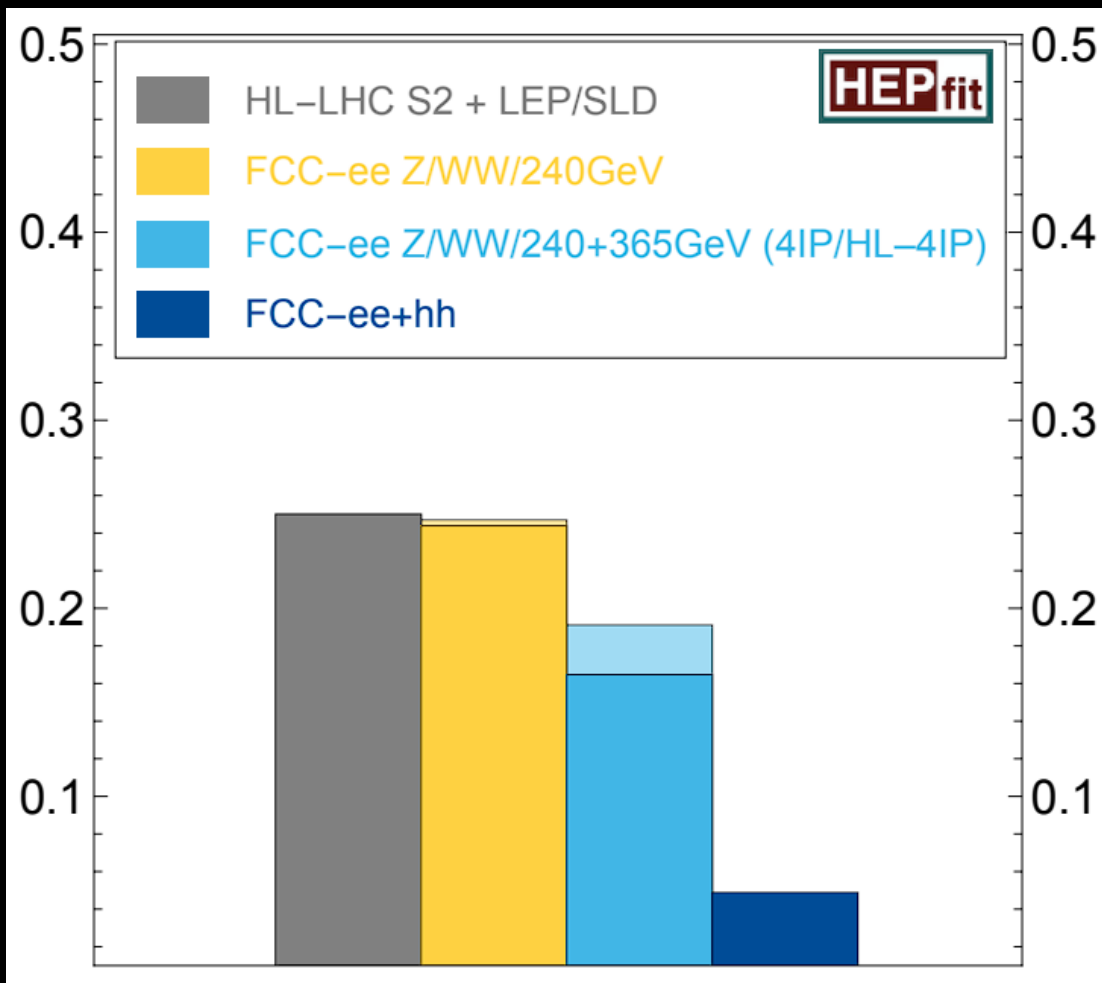


Carena, Kozaczuk, ZL, Gu, Ramsey-Musolf, Shelton, Wang, Xie, [2203.08206](#)

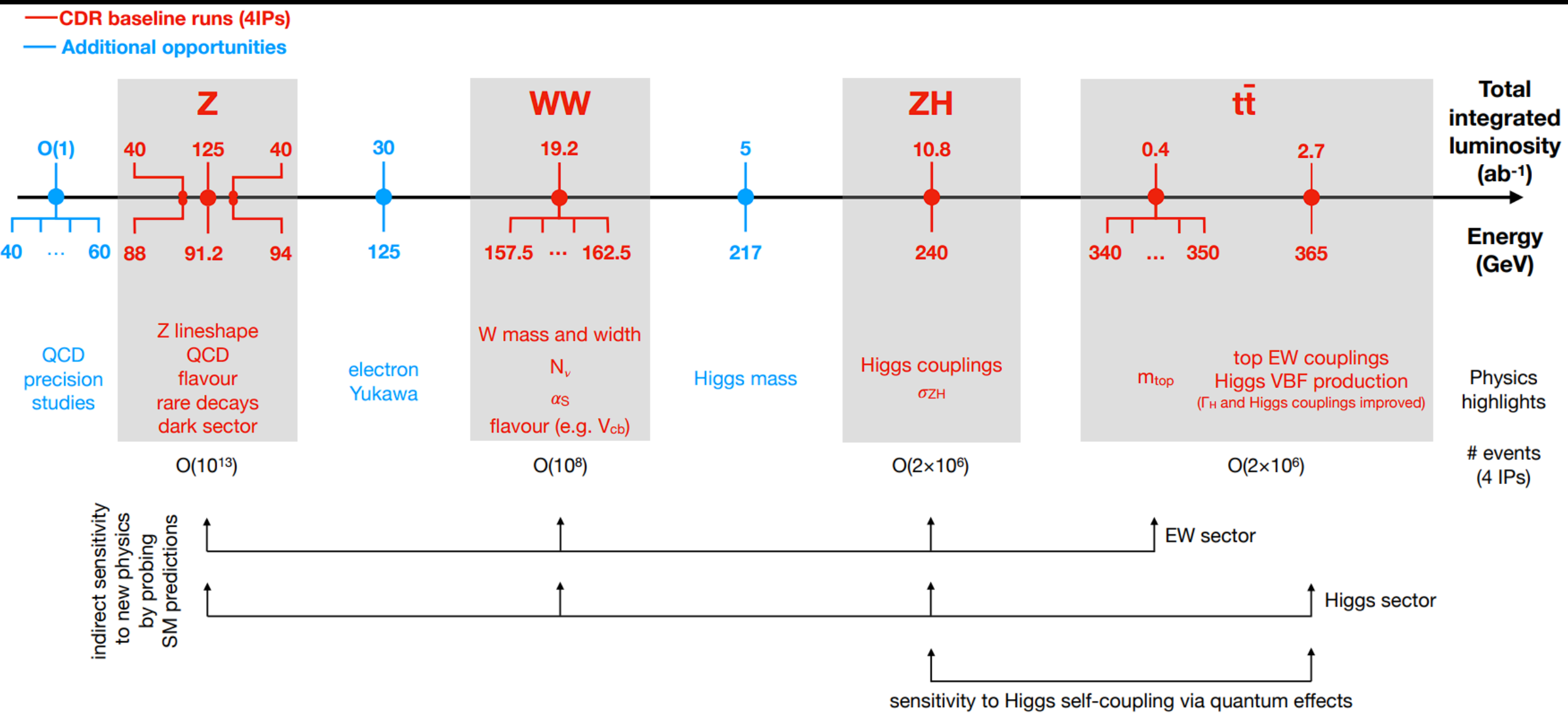
Trilinear Higgs



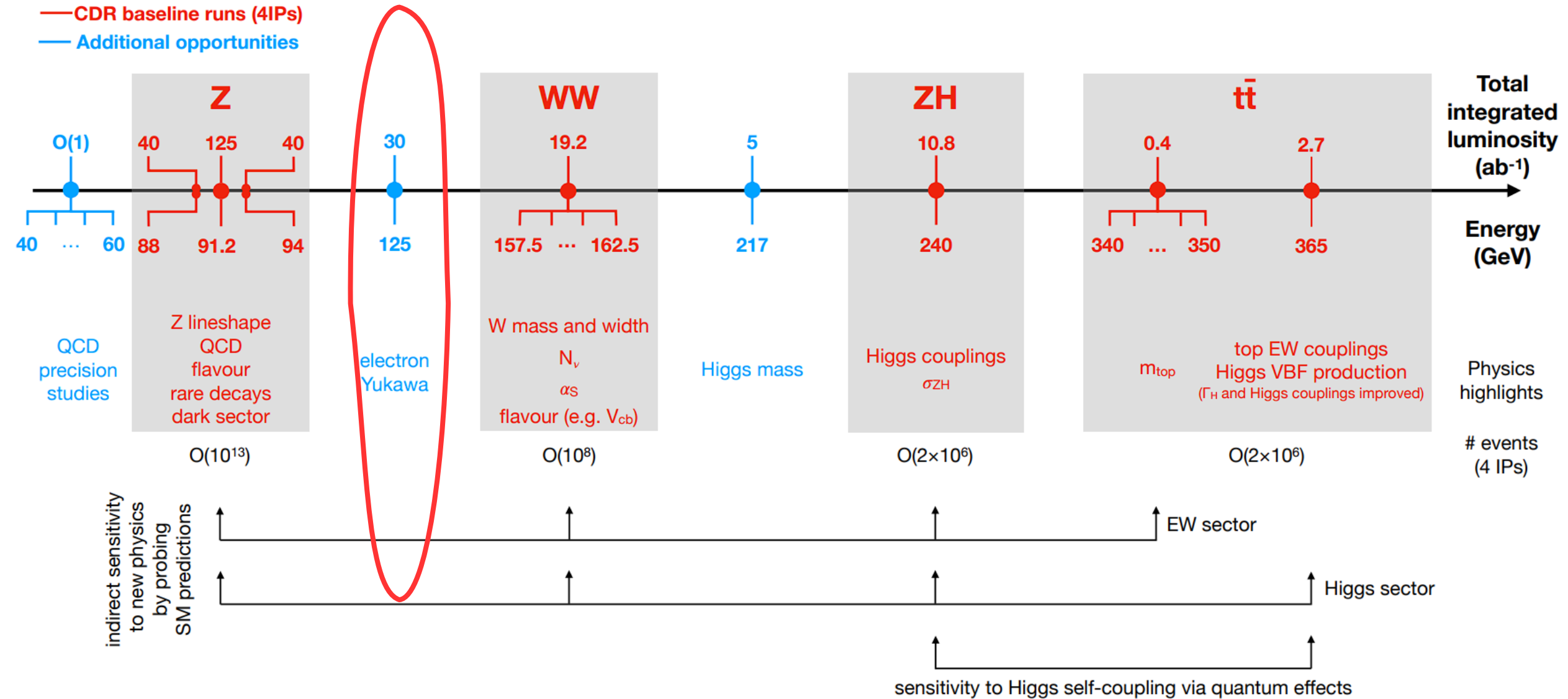
Trilinear Higgs



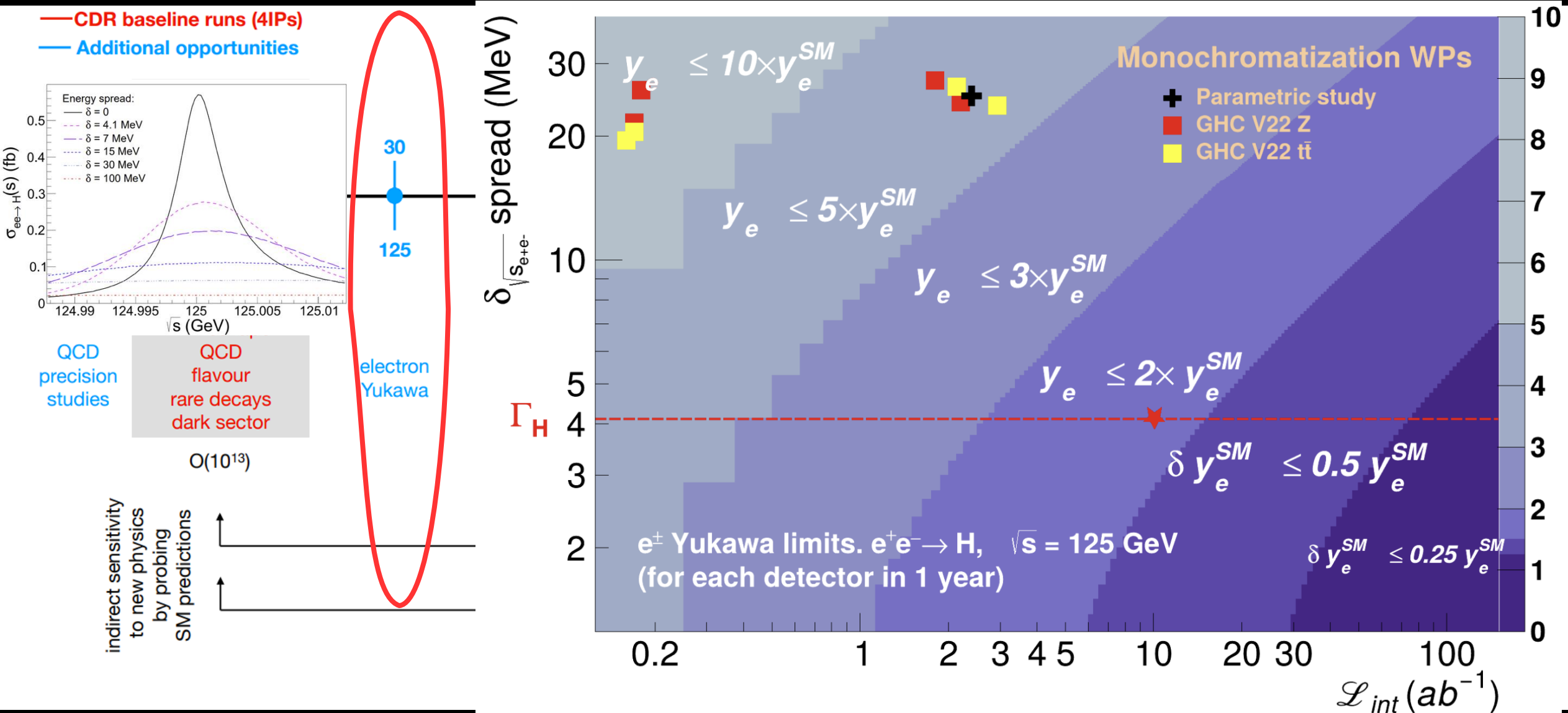
Opportunity Run: Electron Yukawa



Opportunity Run: Electron Yukawa

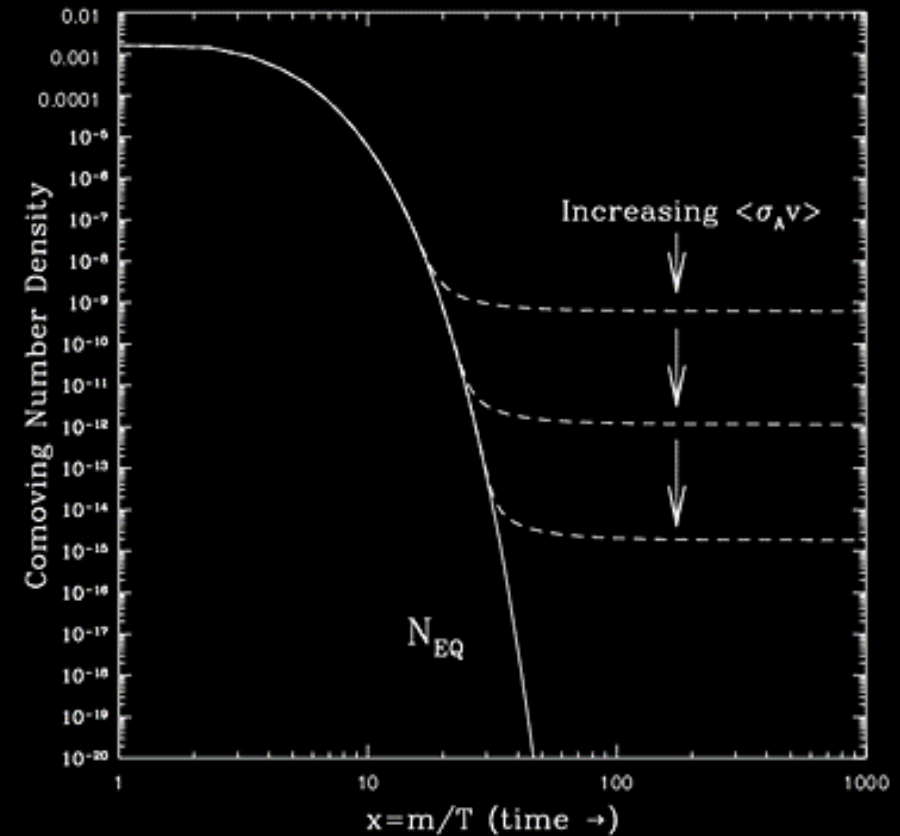
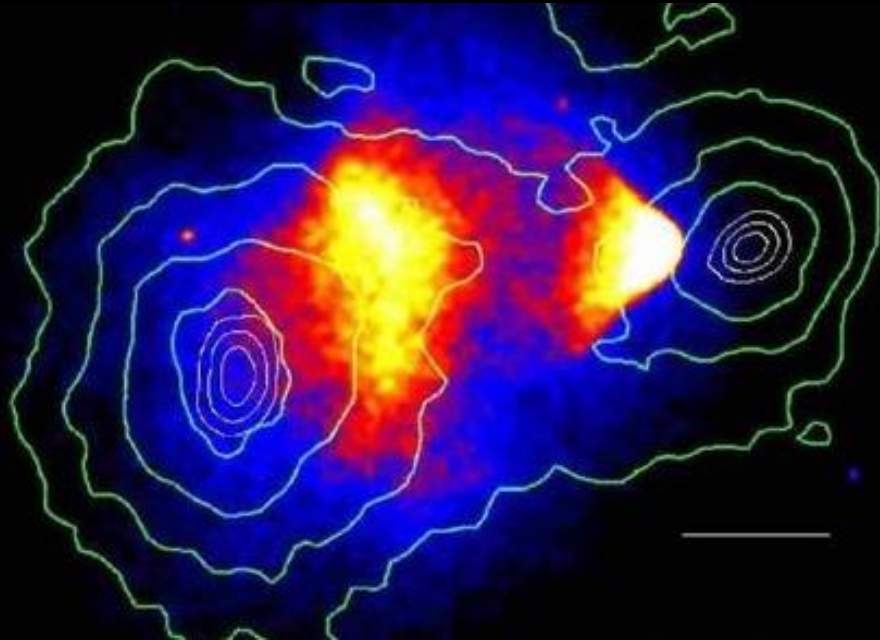


Opportunity Run: Electron Yukawa



WIMP Dark Matter

Compelling, simple, predictive explanation for thermal, cold dark matter

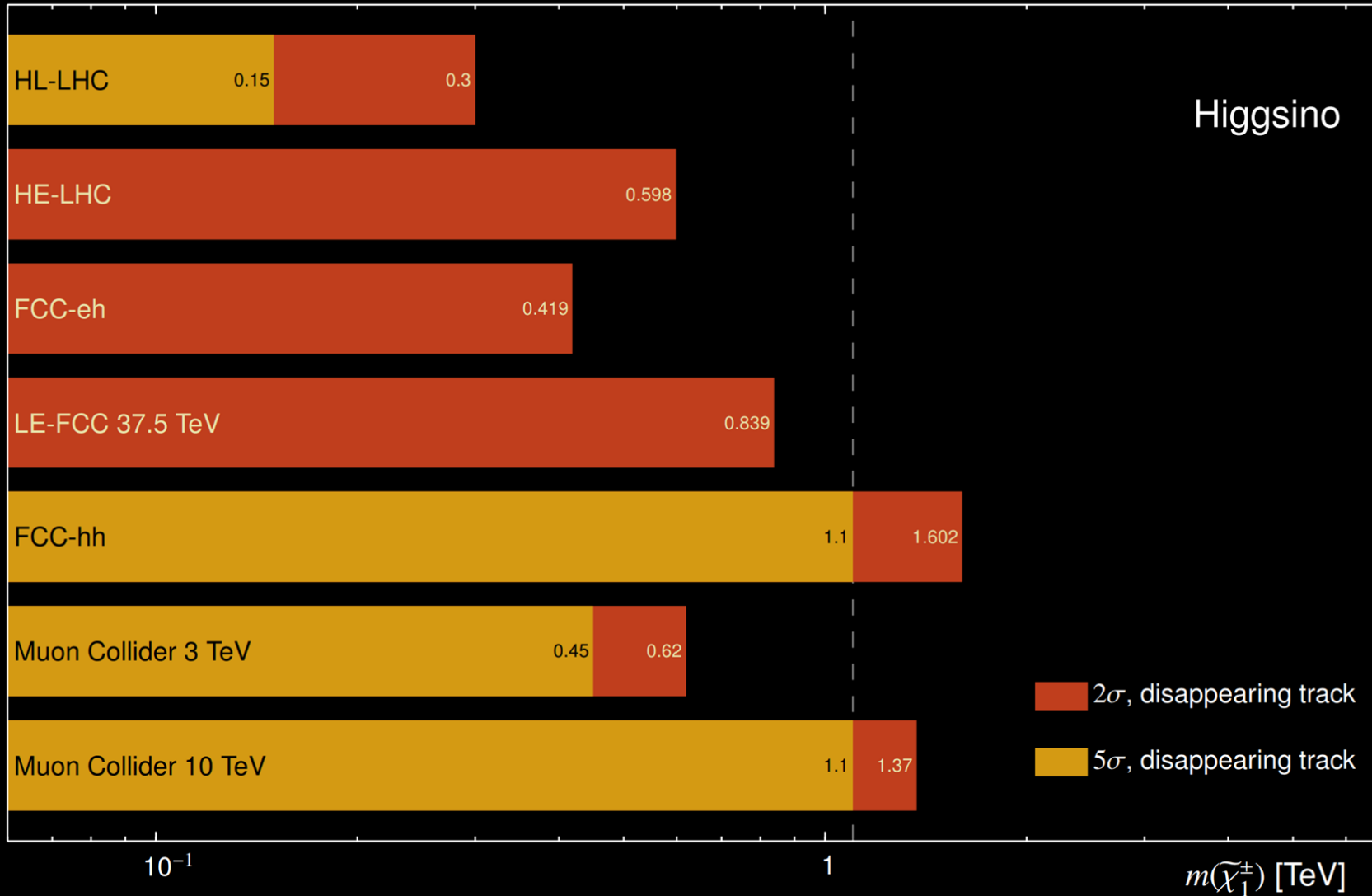


$$\Omega h^2 \simeq 0.1 \times \left(\frac{2 \times 10^{-26} \text{ cm}^3/\text{sec}}{\langle \sigma_{\text{eff}} v \rangle_{\text{freeze-out}}} \right)$$

$$\langle \sigma_{\text{eff}} v \rangle_{\chi \bar{\chi} \rightarrow VV} \simeq \frac{\pi \alpha_{\chi}^2}{m_{\chi}^2}$$

There is a scale...

A Challenging Target: pure Higgsino



1.1 TeV Higgsino a challenging signal:

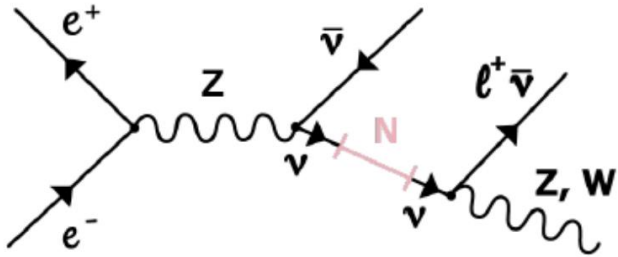
- Low production rate;
- Nearly degenerate states;
- Short lifetime for the charged partners;
- Not probed by the DMDD

Future colliders:

- Disappearing track searches at 10 TeV MuC or 100 TeV FCC-hh could probe it.
- Hard to reach the target for others.

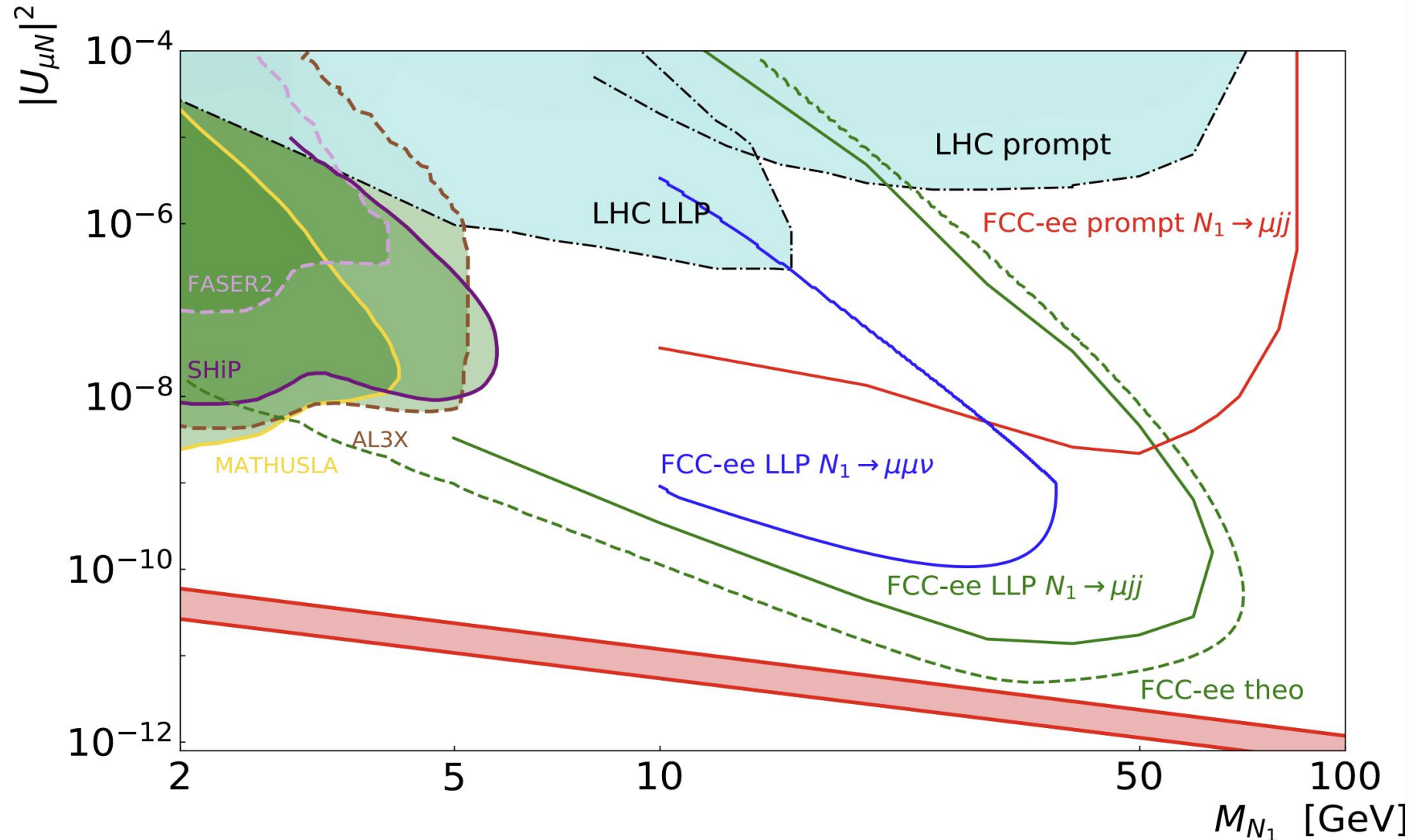
Heavy Neutral Leptons

Direct observation
in Z decays
from LH-RH mixing

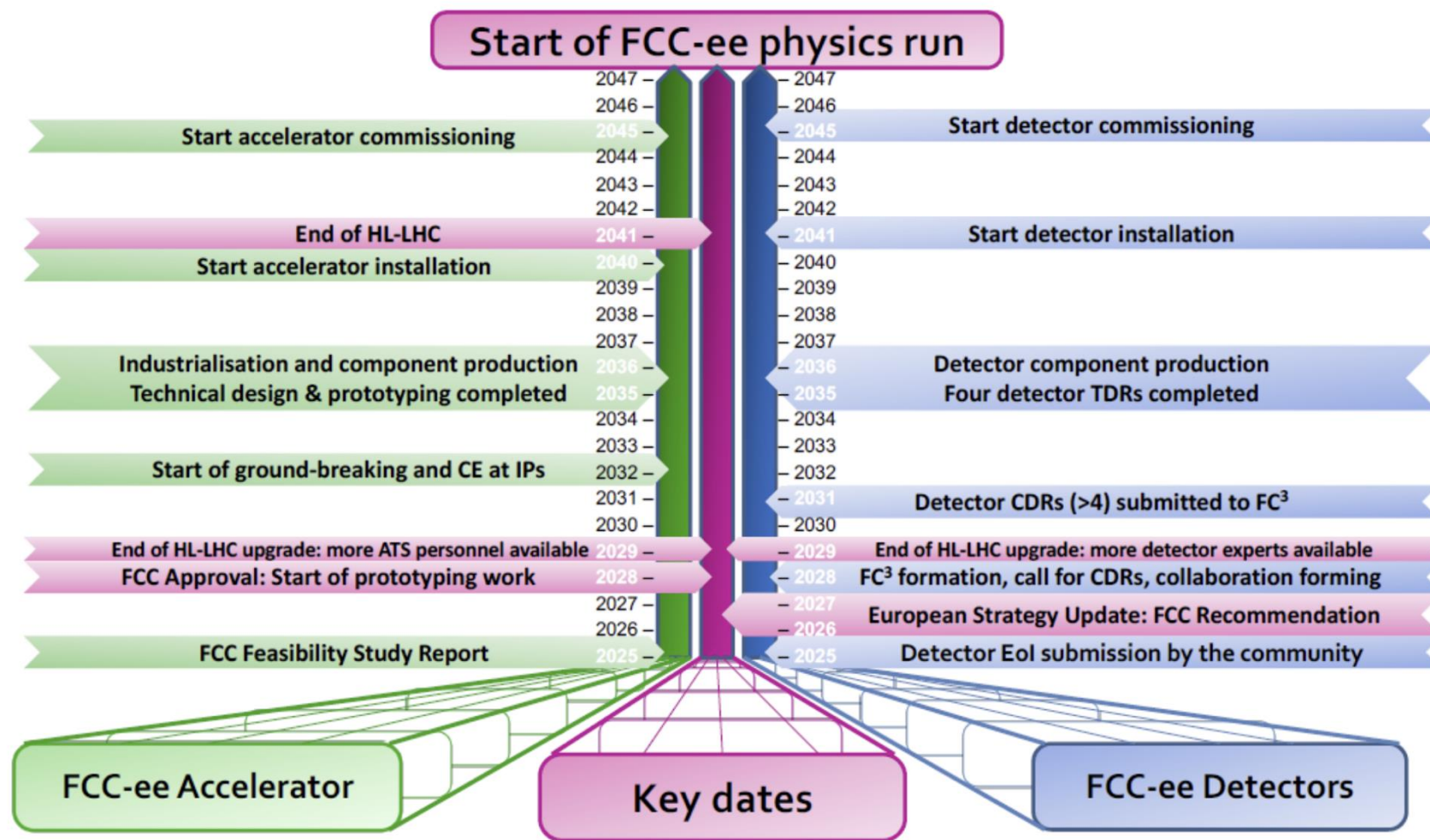


Important to understand

1. how neutrinos acquired mass
2. if lepton number is conserved
3. if leptogenesis is realised



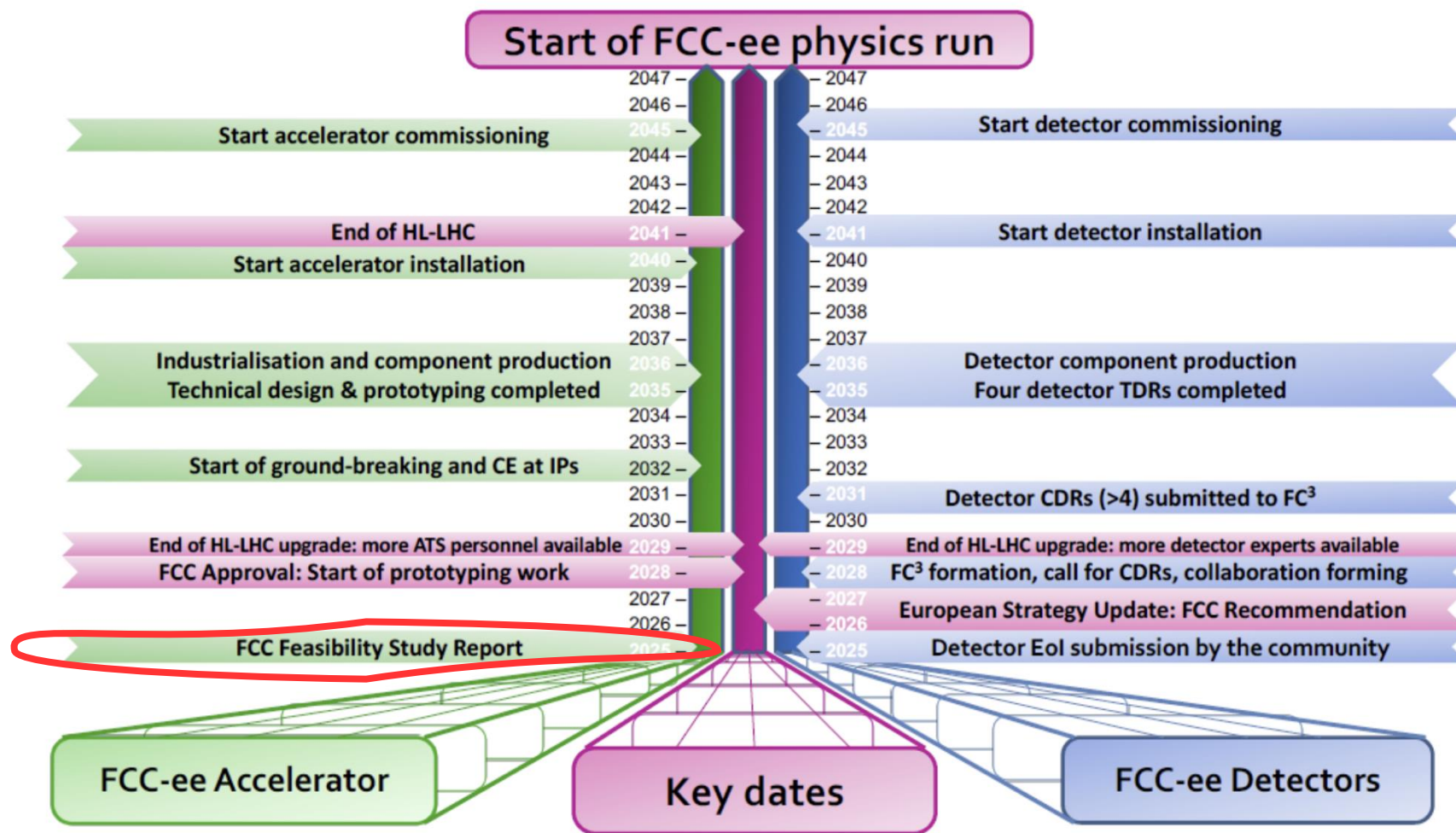
From now until first physics



FCC-ee PED: status and challenges

Guy Wilkinson

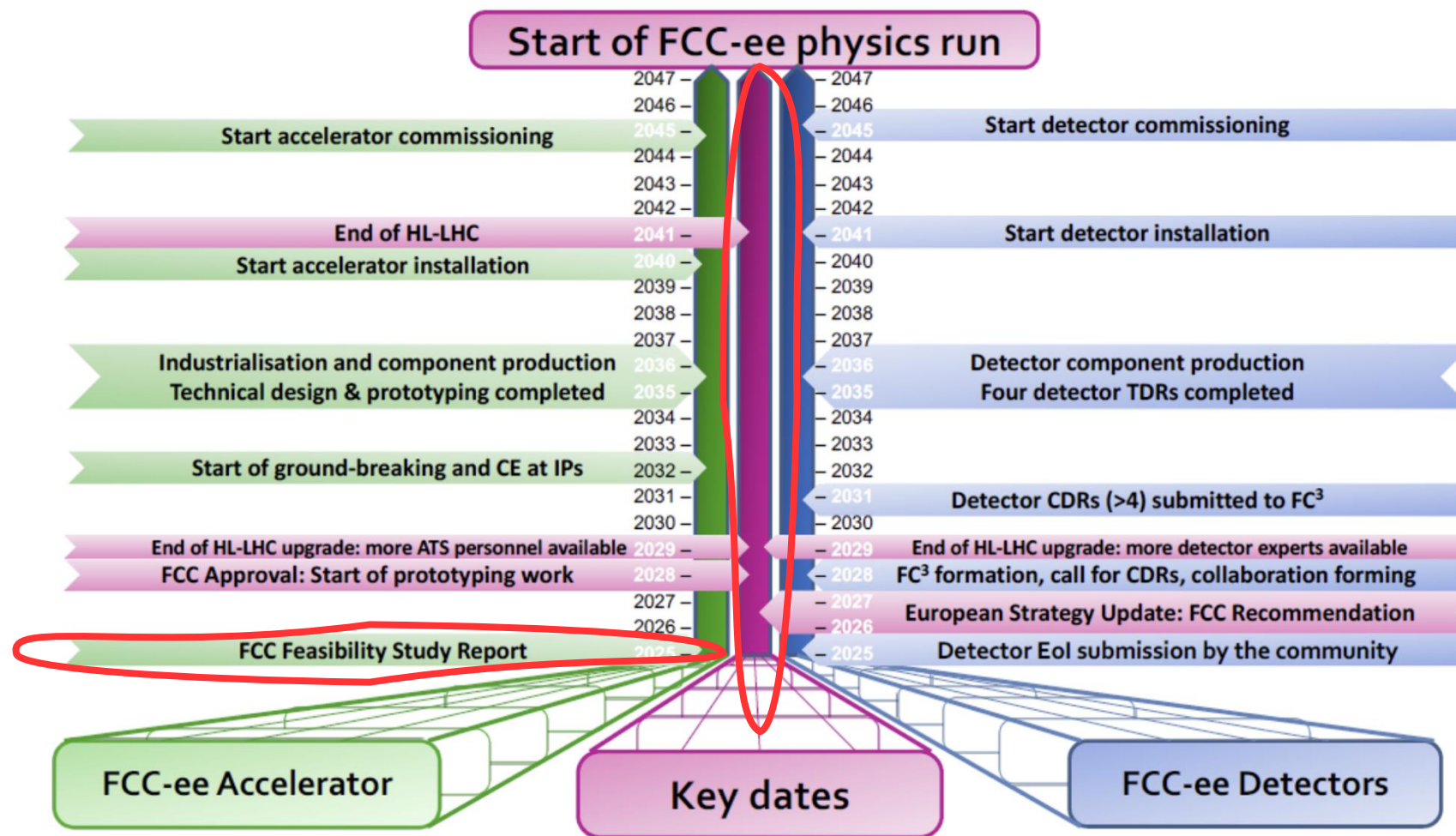
From now until first physics



FCC-ee PED: status and challenges

Guy Wilkinson

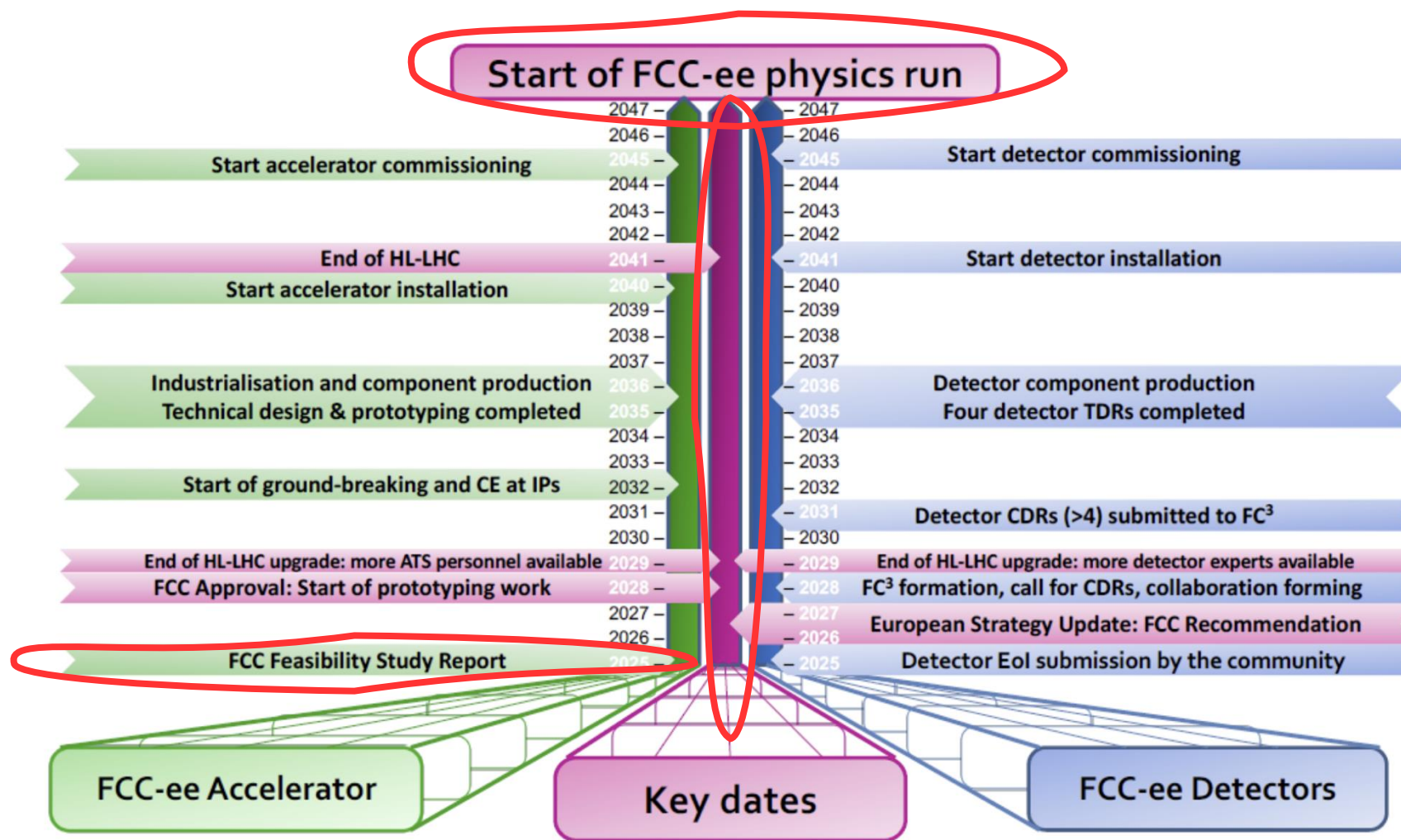
From now until first physics



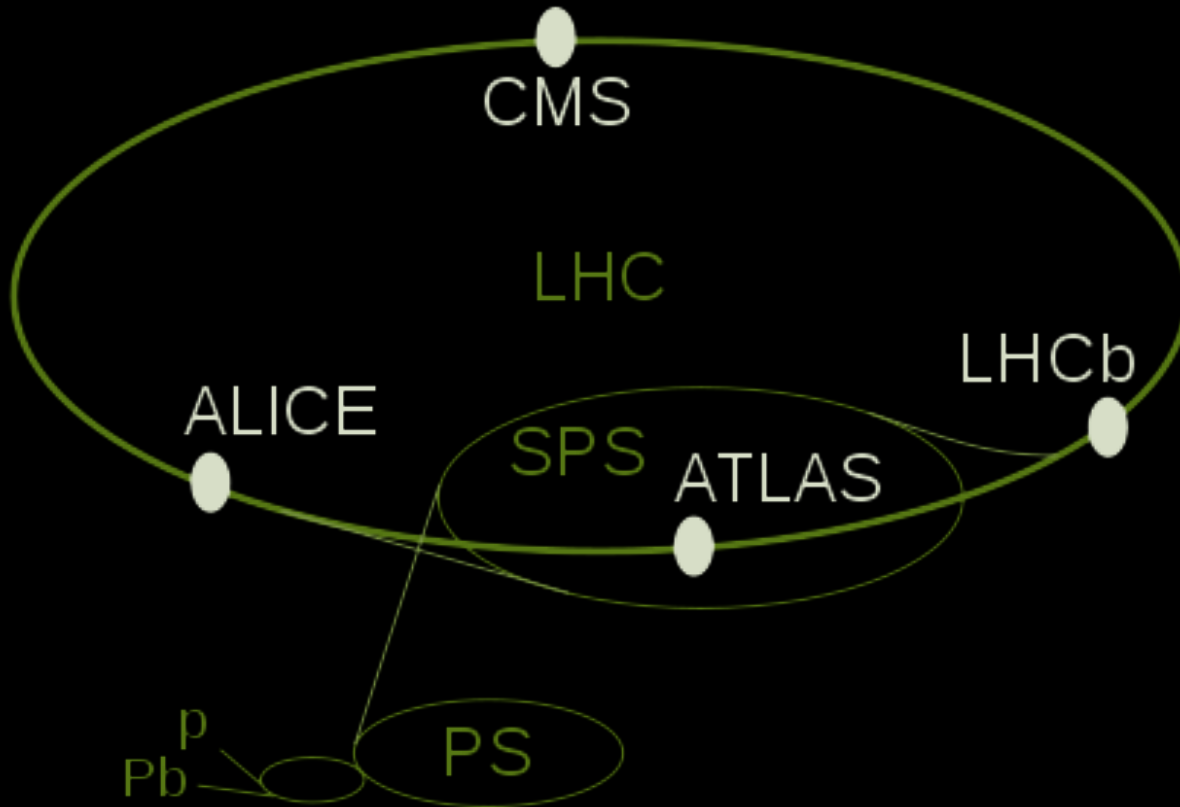
FCC-ee PED: status and challenges

Guy Wilkinson

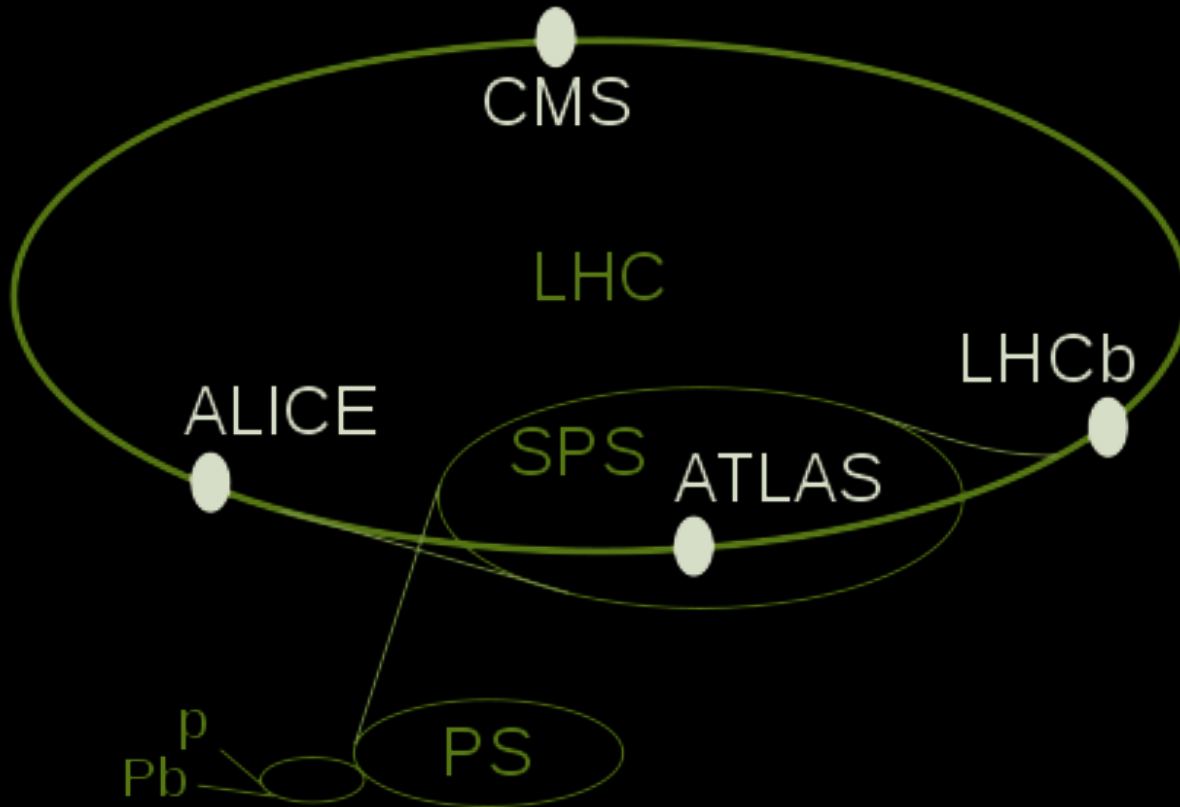
From now until first physics



Higgs was then Discovered in 2012 at the LHC

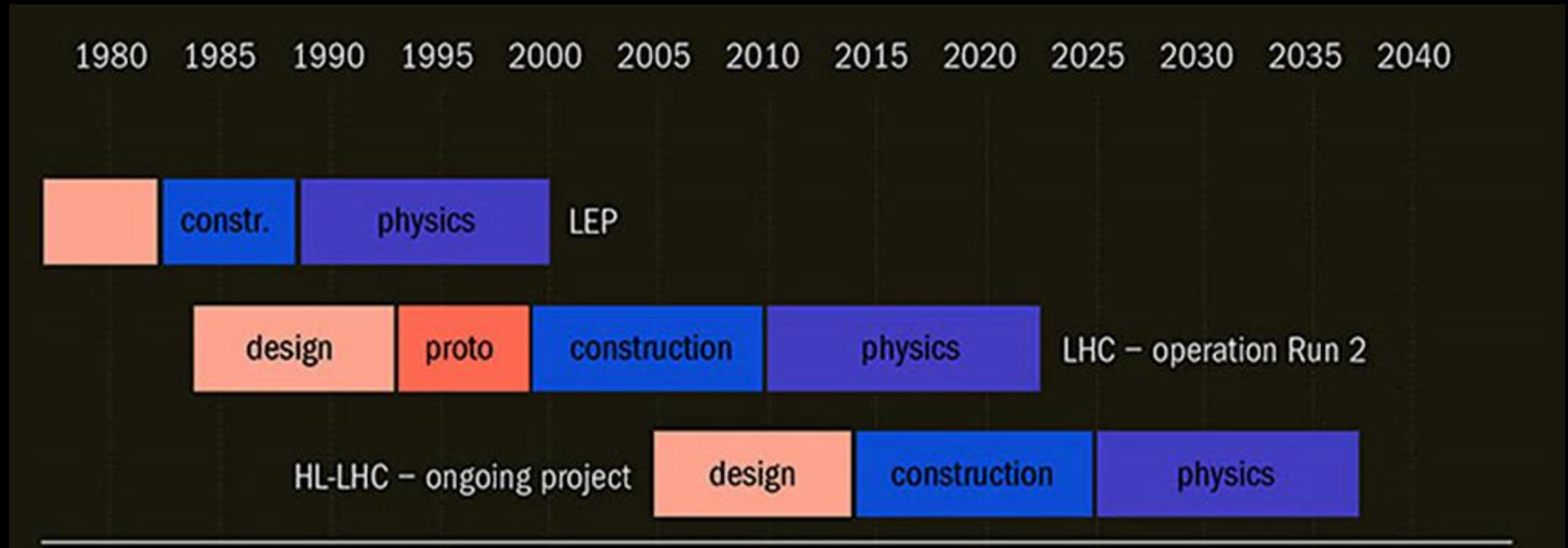


Higgs was then Discovered in 2012 at the LHC

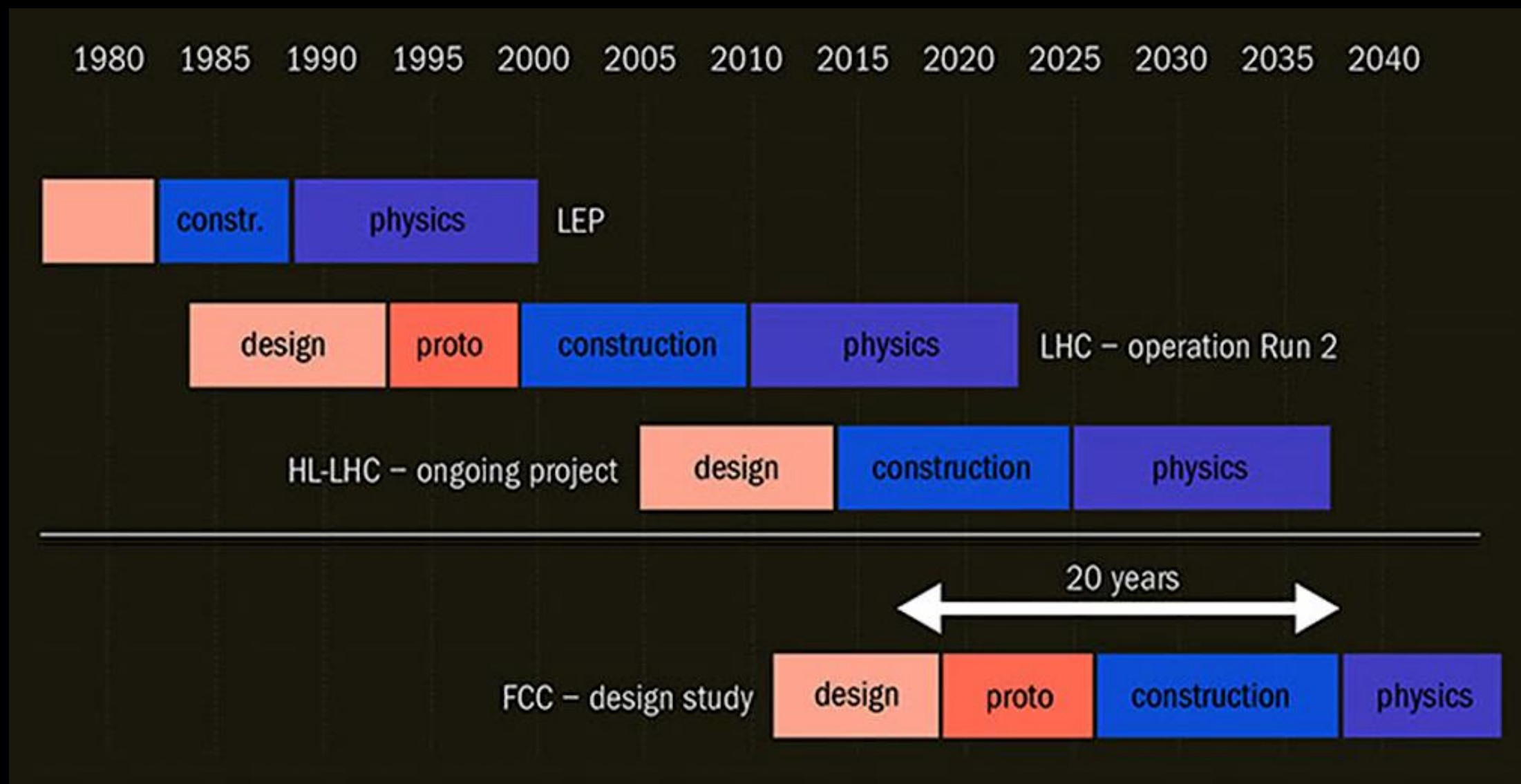


Does this ring look familiar?

The Lifespans of HEP programs are long...



The Lifespans of HEP programs are long...



Predictable future

Predictable future

- (HL-)LHC will continue to drive/dominant until ~2041;

Predictable future

- (HL-)LHC will continue to drive/dominant until ~2041;
- FCC-ee has a feasible plan to deliver physics in ~2048 for 15 years;

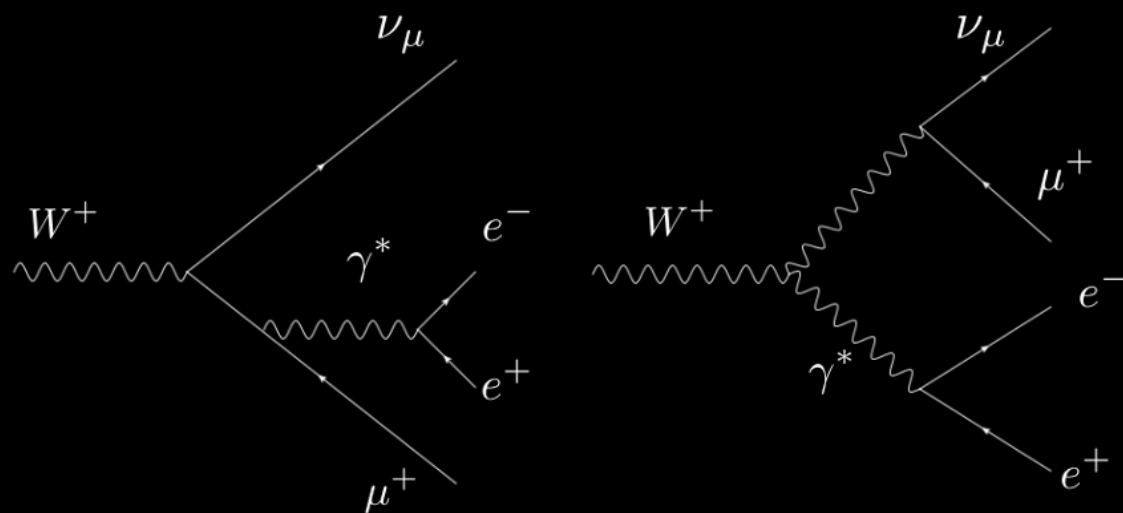
Predictable future

- (HL-)LHC will continue to drive/dominant until ~2041;
- FCC-ee has a feasible plan to deliver physics in ~2048 for 15 years;
- FCC-hh, after the FCC-ee program, bring us to the longing $P_{cm}=10$ TeV realm;

Predictable future

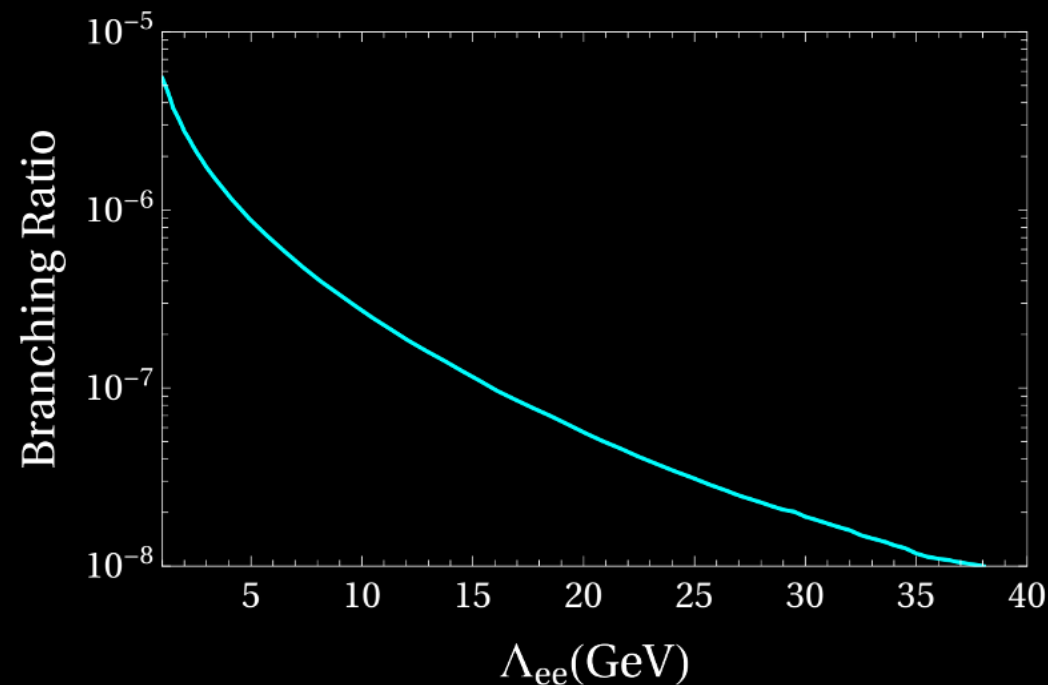
- (HL-)LHC will continue to drive/dominant until ~ 2041 ;
- FCC-ee has a feasible plan to deliver physics in ~ 2048 for 15 years;
- FCC-hh, after the FCC-ee program, bring us to the longing $P_{cm}=10$ TeV realm;
- Muon Collider, a direct pathway to $P_{cm}\sim 10$ TeV. R&D.
- Other accelerator possibilities (C3, PWFA...) R&D.
- Other intense beam opportunities, DUNE/PIP-II, SHiP, LDMX, etc.

SM physics of $W \rightarrow 3\ell + \nu$



Signal process	cross section [pb]
$pp \rightarrow \ell^+ \ell^- \ell^+ \nu_\ell + (j), M_{\ell\ell\ell\nu} \in \text{OR}$	0.36
$pp \rightarrow \ell^+ \ell^- \ell^- \bar{\nu}_\ell + (j), M_{\ell\ell\ell\nu} \in \text{OR}$	0.25

On-shell Region (OR) defined as: $m_W \pm 2\Gamma_W$



Subtily: one cannot strictly separate on-shell W decay and off-shell W-decay. We define on-shell regime and compare the rate and kinematic distribution of a zero-width approximation W-decay.

Projected sensitivity

The SM Br on such a channel is at 10^{-6} level

Current LHC data (with current trigger and selection, 150 fb^{-1})

$$\delta Br(W \rightarrow 3\ell + \nu) = 6\%$$

HL-LHC data (with improved trigger on multileptons)

$$\delta Br(W \rightarrow 3\ell + \nu) = 0.6\%$$

A clean, high-statistics laboratory: $Z \rightarrow \mu\mu\gamma$ at the LHC

Γ_{58}	$e^+e^-\gamma$	[6]	$< 5.2 \times 10^{-4}$	CL=95%	45594	✓
Γ_{59}	$\mu^+\mu^-\gamma$	[6]	$< 5.6 \times 10^{-4}$	CL=95%	45594	✓
Γ_{60}	$\tau^+\tau^-\gamma$	[6]	$< 7.3 \times 10^{-4}$	CL=95%	45559	✓

- The LHC produces billions of Z bosons; $Z \rightarrow \mu^+\mu^-\gamma$ is rare ($\sim 10^{-4}$) but exceptionally clean
- Final state: two opposite-sign muons + a hard photon — minimal hadronic background
- Fiducial branching ratio isolates a theoretically safe fixed-order regime
- Statistical precision: $\Delta\text{Br}/\text{Br} \sim 0.26\%$ (Run-2) and 0.04% (HL-LHC) — sub-percent SM test

Our re-interpretation of a Run-1 study
 $\text{Br}^{\text{fid}}(Z \rightarrow \mu\mu\gamma) = (3.34 \pm 0.016) \times 10^{-4}$

A clean, high-statistics laboratory: $Z \rightarrow \mu\mu\gamma$ at the LHC

Γ_{58}	$e^+e^-\gamma$	[6]	$< 5.2 \times 10^{-4}$	CL=95%	45594	✓
Γ_{59}	$\mu^+\mu^-\gamma$	[6]	$< 5.6 \times 10^{-4}$	CL=95%	45594	✓
Γ_{60}	$\tau^+\tau^-\gamma$	[6]	$< 7.3 \times 10^{-4}$	CL=95%	45559	✓

- The LHC produces billions of Z bosons; $Z \rightarrow \mu^+\mu^-\gamma$ is rare ($\sim 10^{-4}$) but exceptionally clean
- Final state: two opposite-sign muons + a hard photon — minimal hadronic background
- Fiducial branching ratio isolates a theoretically safe fixed-order regime
- Statistical precision: $\Delta\text{Br}/\text{Br} \sim 0.26\%$ (Run-2) and 0.04% (HL-LHC) — sub-percent SM test

Our re-interpretation of a Run-1 study
 $\text{Br}^{\text{fid}}(Z \rightarrow \mu\mu\gamma) = (3.34 \pm 0.016) \times 10^{-4}$

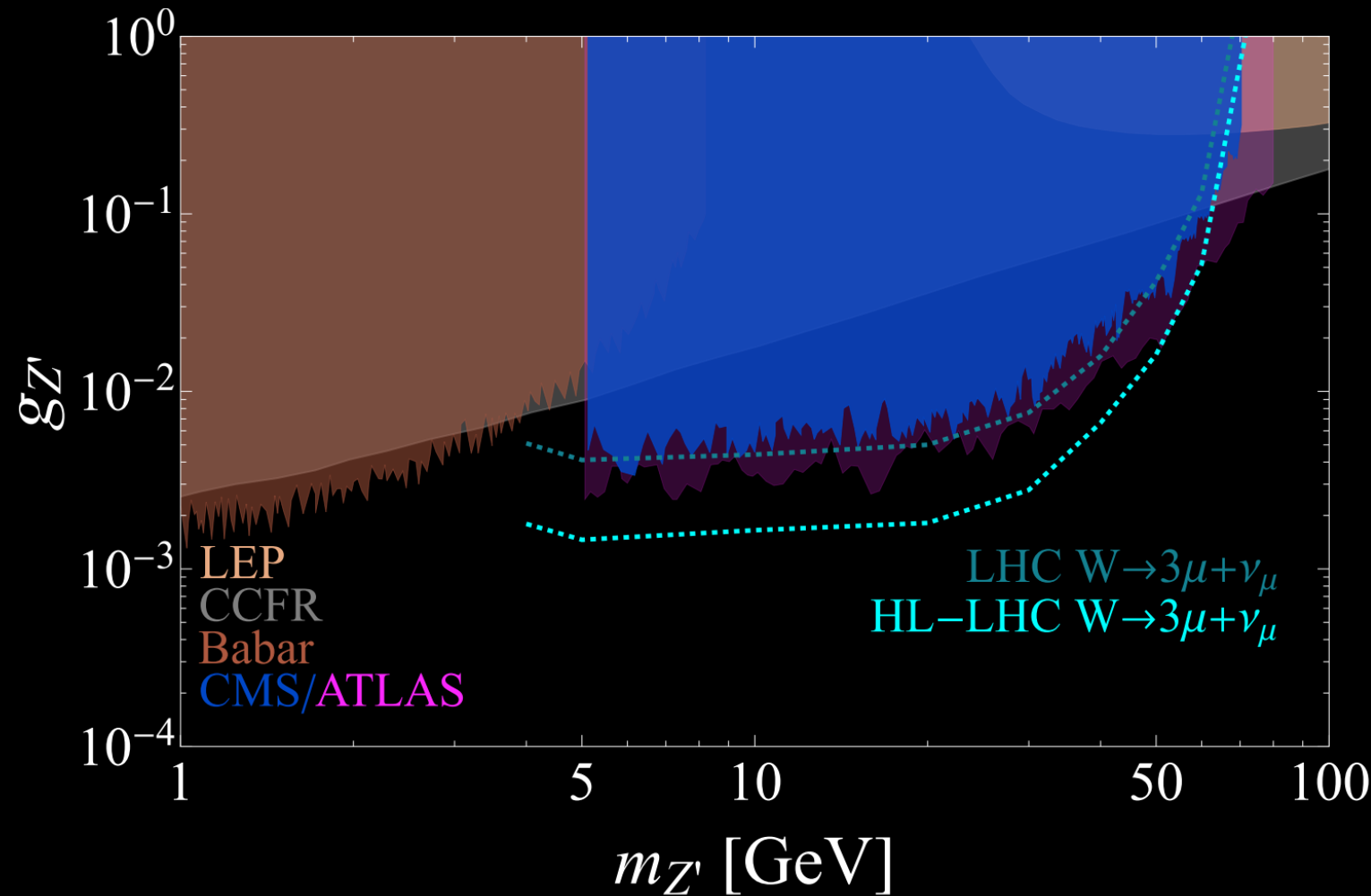
So, we can add a few more entries to PDG, then what?

One can also look for dark photon/ Z' , ALPs, SMEFT precision, subtle SM effects, in these channels.

E.g., an $L_\mu - L_\tau$ Z'

- Standard search channel $Z \rightarrow 4\ell$.
- W rate is a factor of **4~5 larger** than Z
- W leptonic branching fraction is a factor of **3 larger** than Z

W exotic should be a **competitive** channel.



ATLAS Search: [2402.15212](#)

Light Higgs Branching Ratios: A rich search program

