HIGGS IN THE FUTURE HIGGS FACTORIES

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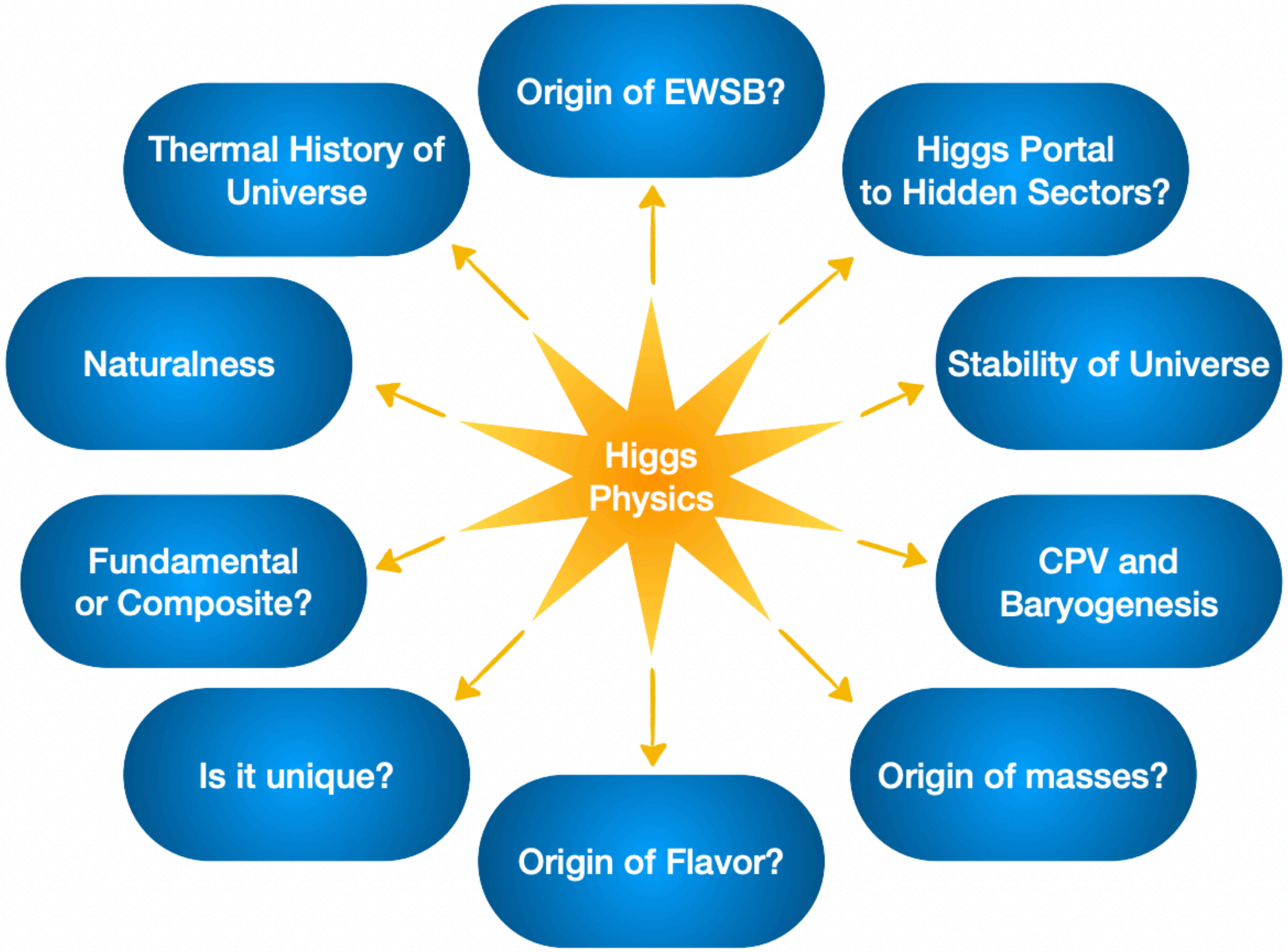
cfp CIEMAT física de partículas

SM@LHC 2024, Rome

AT THE CENTER OF OUR QUESTIONS ABOUT MATTER

- The Higgs boson is the only particle of its kind, a mystery on itself. Understanding its nature is a priority for our field
- The central role of the Higgs Sector in the SM makes it particularly sensitive to new physics
  - Through the precise measurement of the Higgs properties we challenge the limits and the consistency of the SM
  - Studying the Higgs boson can lead us to the next frontier in our understanding of matter and its interactions
- This effort is complementary to both pure BSM searches and to experiments beyond the collider



From the Snowmass Energy Frontier Report

UNDERSTANDING THE HIGGS BOSON AT A COLLIDER

Finding a particle is the beginning of a long way to understand it: what is really the Higgs boson? Does it follow the SM rules?

H^0 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

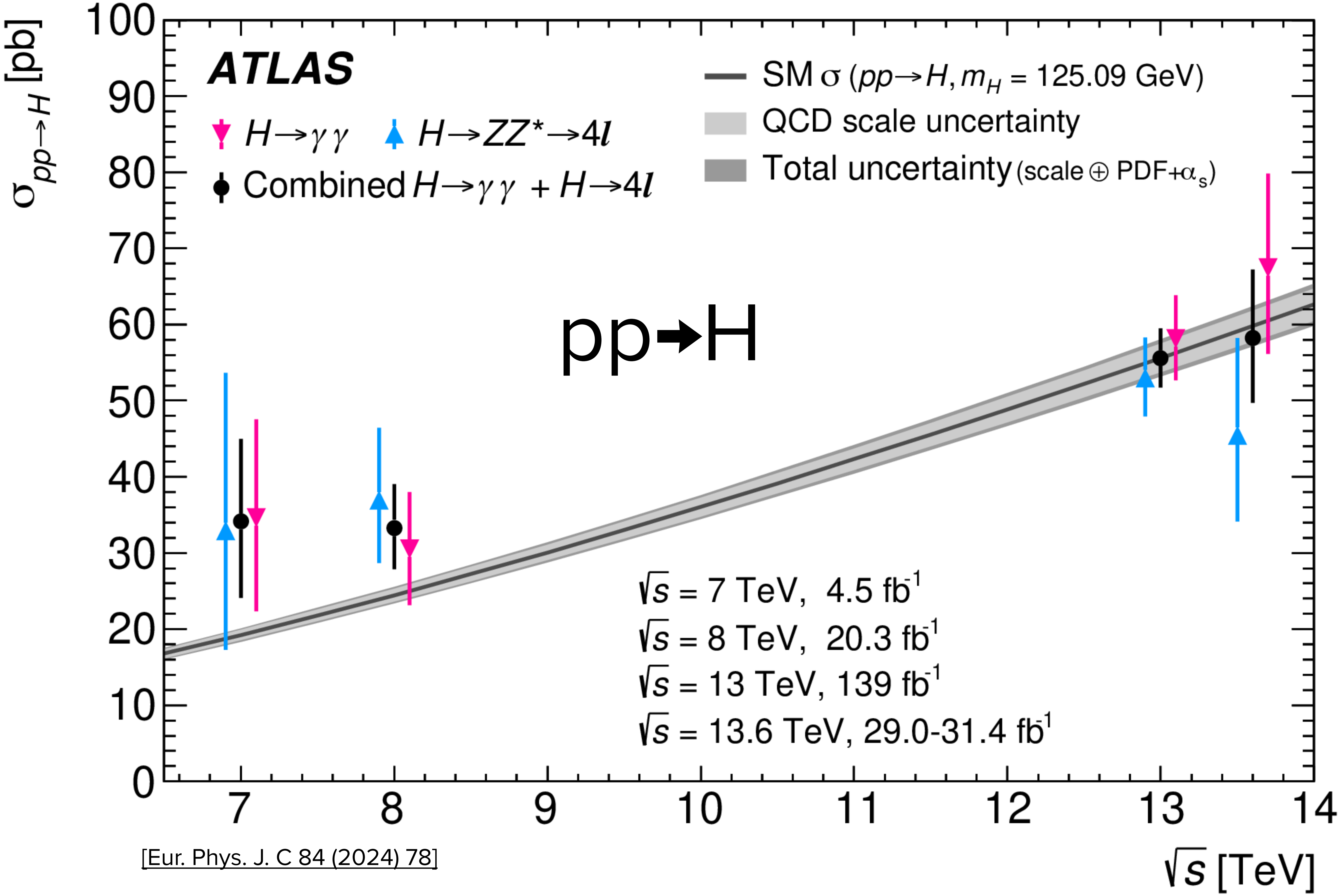
See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

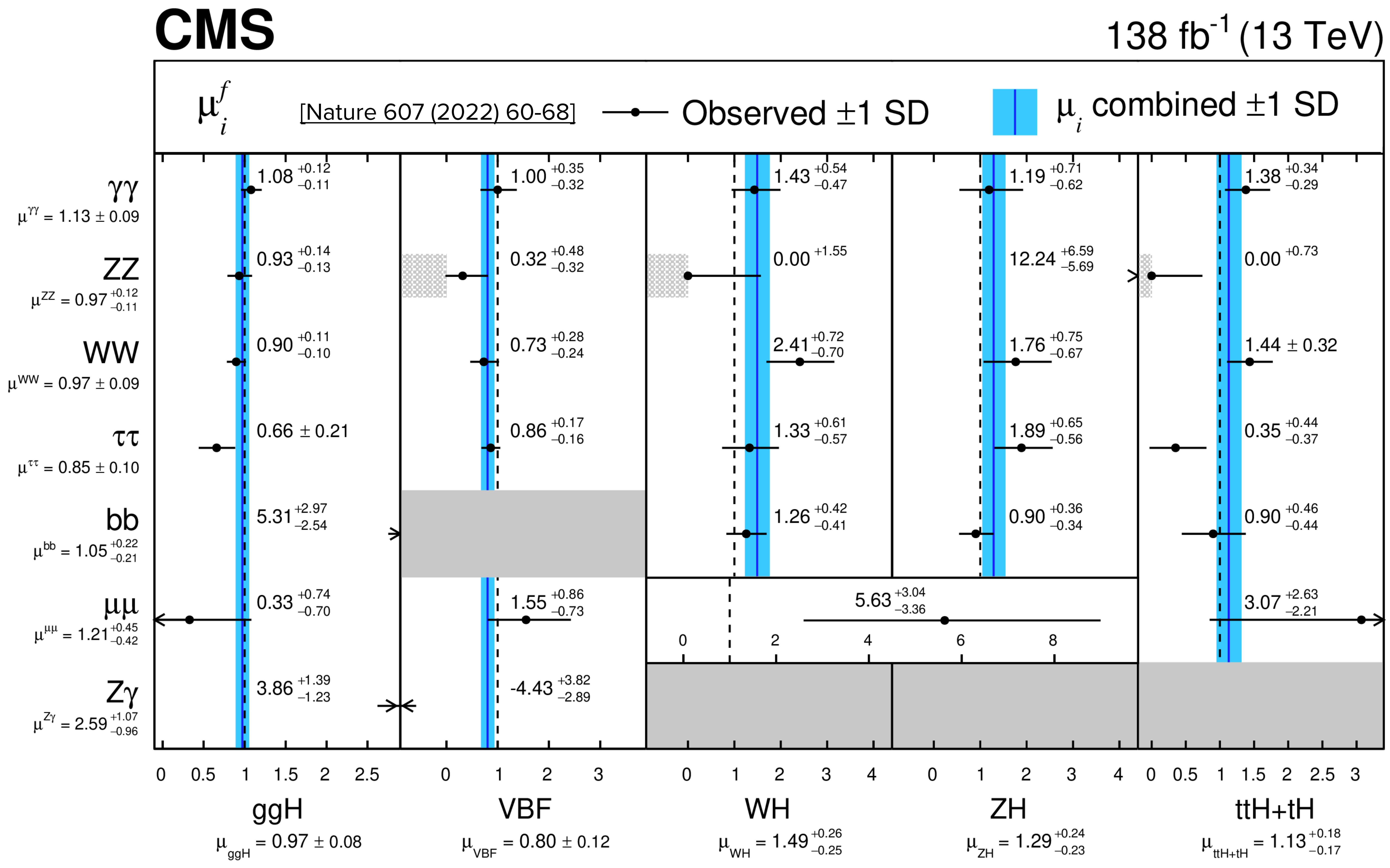
- How is the Higgs boson produced? How does it decay?
- What kind of particle is the Higgs? (Properties: Mass, Width, Spin)
- How does it couple to Standard Model particles?
  - Does it couple to all matter generations?
  - Does it couple to itself?
  - Does it couple unusually? (eg: Dark Matter?)
- Is the Higgs alone?
- Is it really an elementary particle?
- Where does the Higgs mechanism come from?

WHERE ARE WE?
LHC: FROM HUNTING TO MEASURING

HIGGSES AT 7, 8, 13... AND 13.6 TEV!



[Eur. Phys. J. C 84 (2024) 78]



[Nature 607 (2022) 60-68]

PRODUCTION x DECAY

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

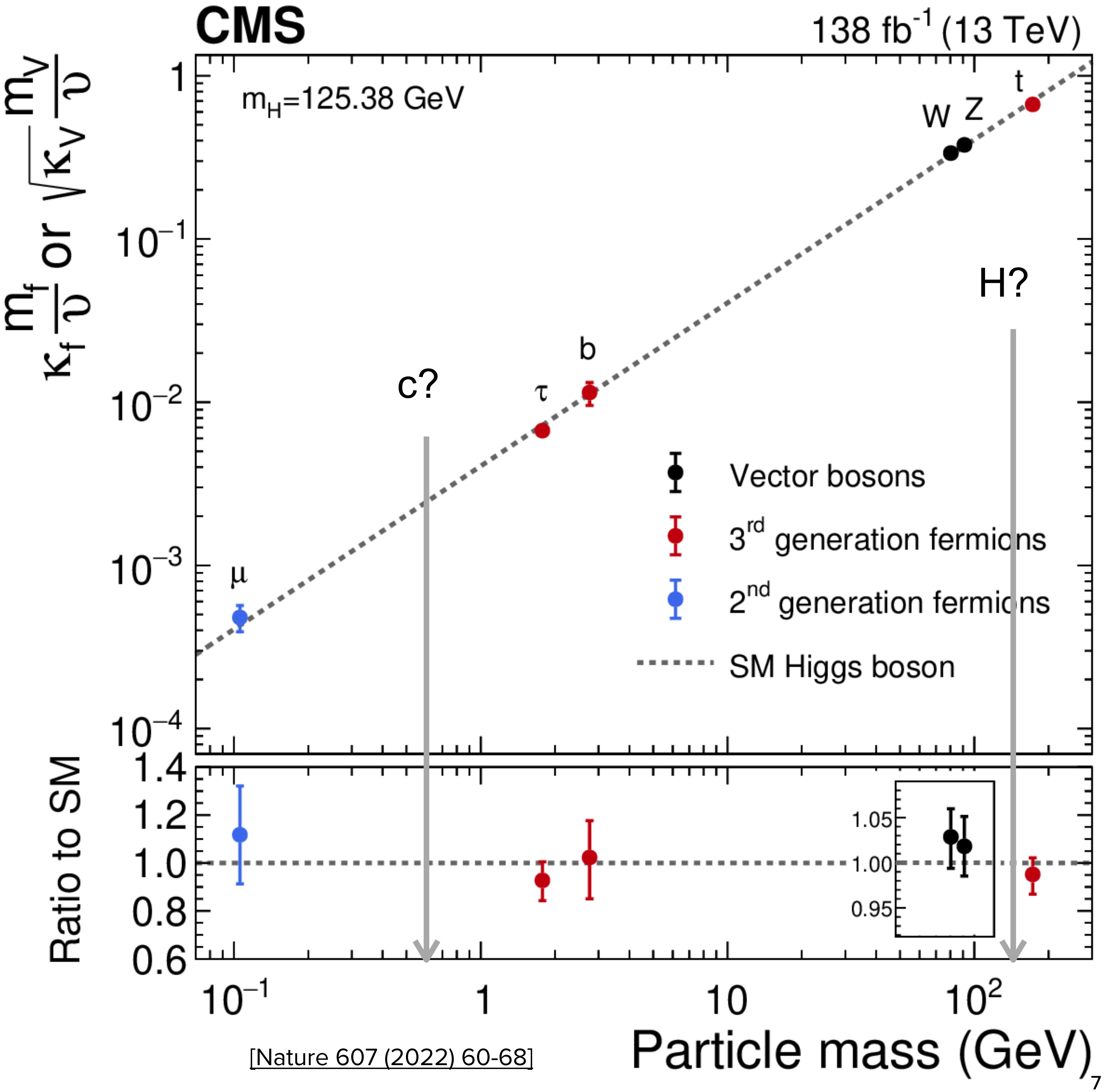
Signal strength

$$\mu_{CMS} = 1.002 \pm 0.057$$

$$\mu_{ATLAS} = 1.05 \pm 0.06$$

6%!

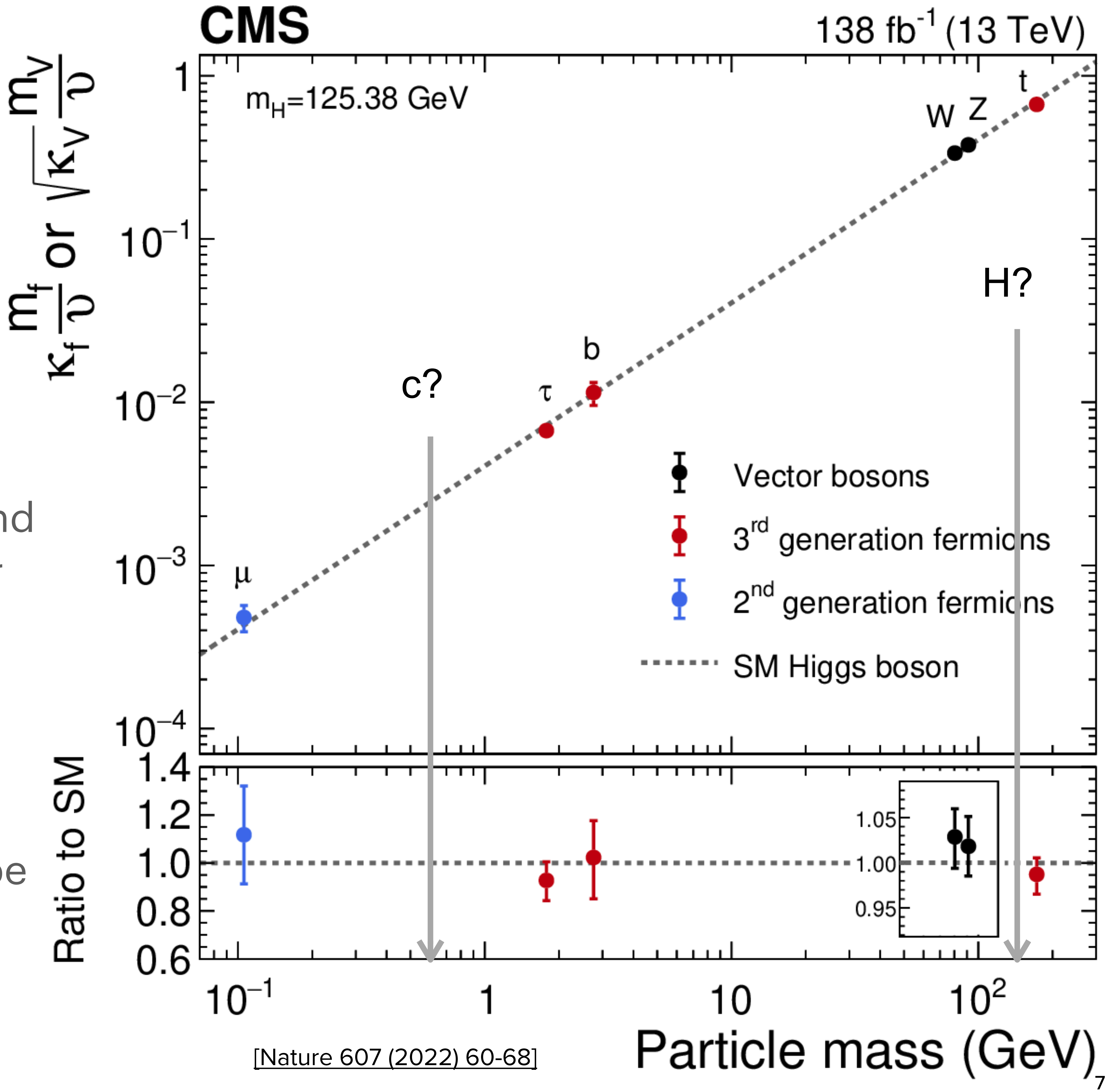
WE HAVE COME A LONG WAY...



[Nature 607 (2022) 60-68]

WE HAVE COME A LONG WAY…

- Mass to 0.1%, first measurements of the width, Spin: 0+ (SM-like)
- And in fact, its couplings behave stubbornly like the SM predict
- However, the picture is not yet complete (second generation, self coupling), and there is room for surprises (eg, what happens with DM?)
- Furthermore, even if the current direct and indirect searches for BSM in Extended Higgs Sectors (high mass, low mass, decay) so far confirm the SM, large phase-spaces remain to be covered



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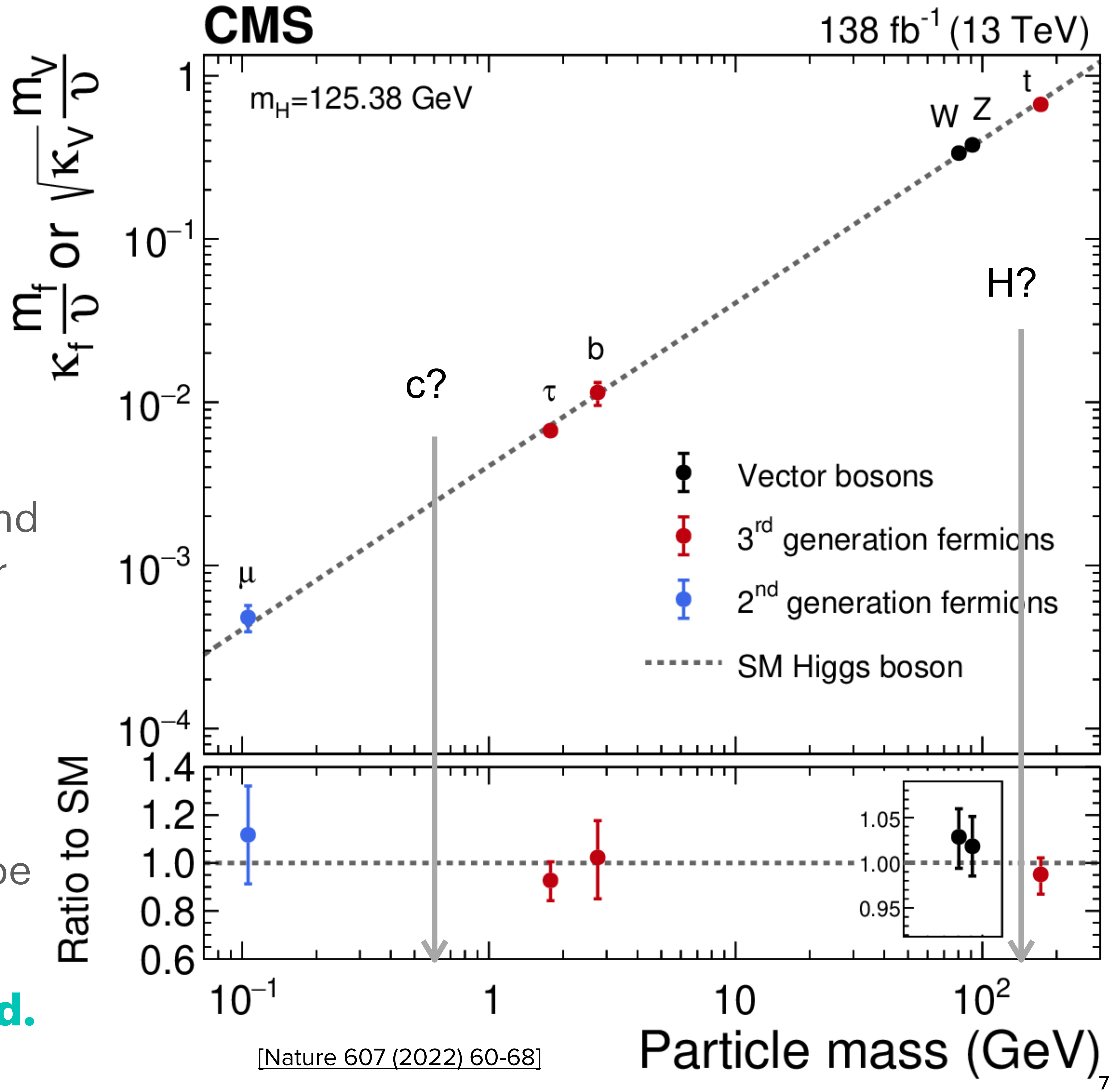
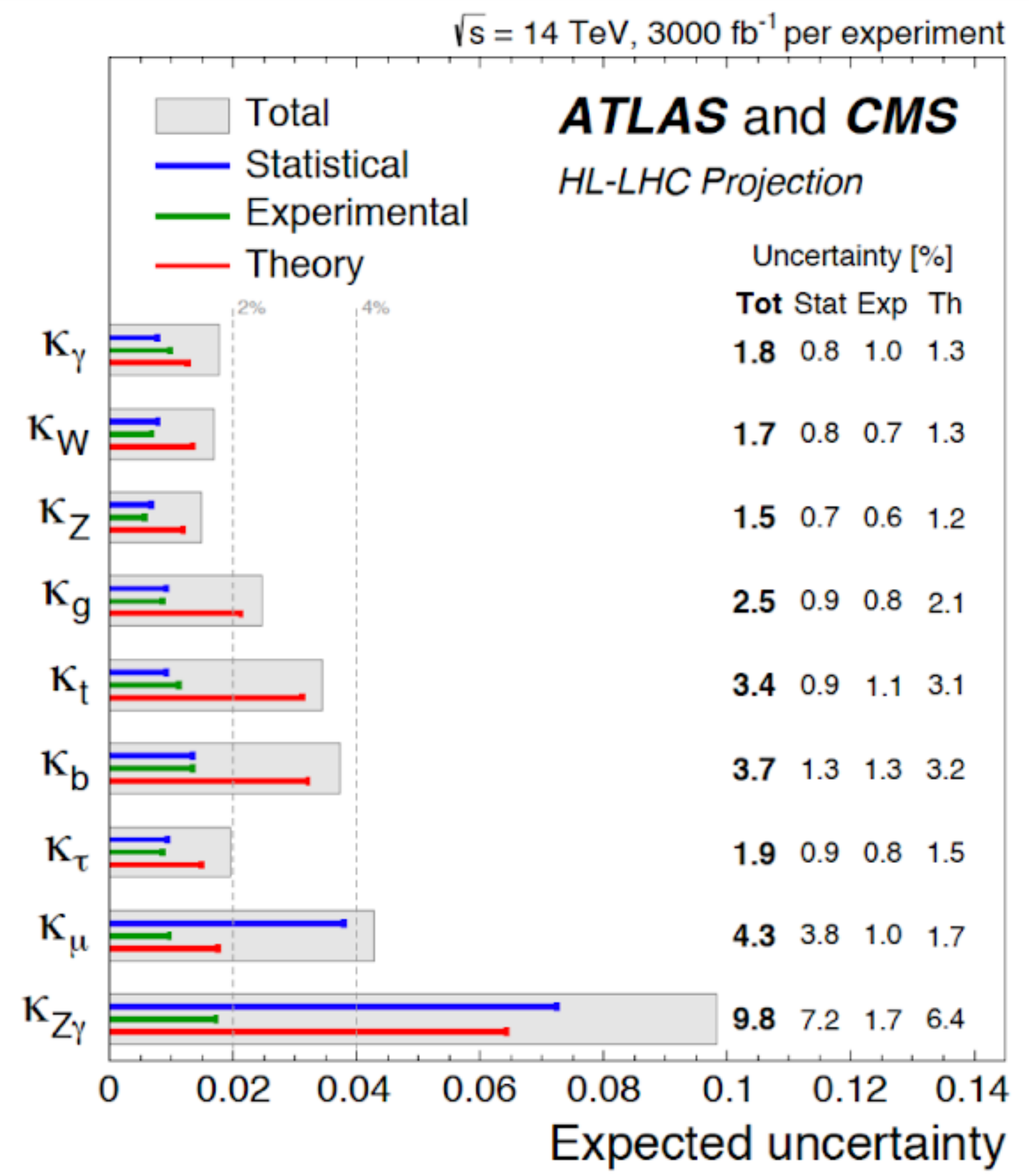
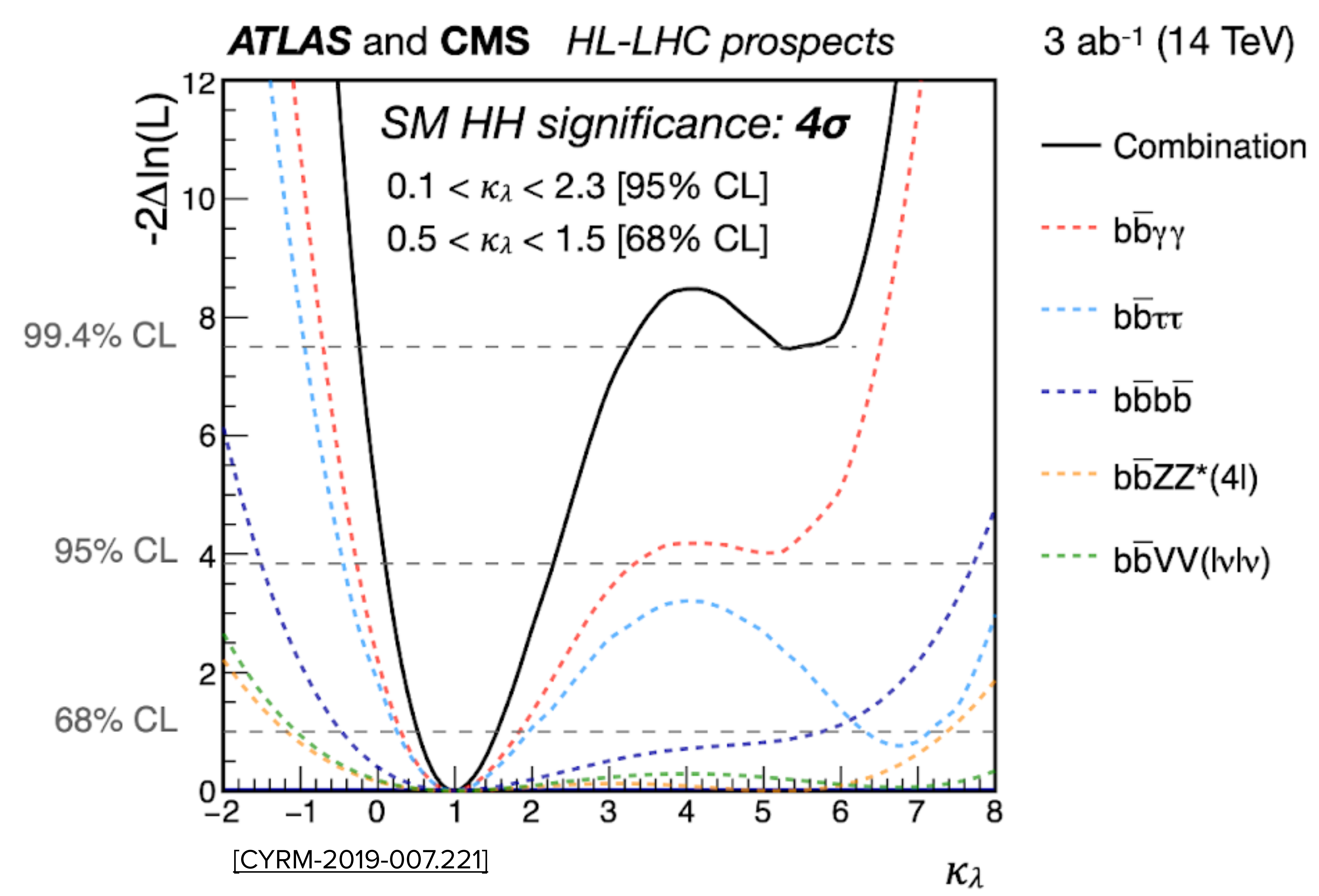
- **More data, and further precision is needed.**



[Nature 607 (2022) 60-68]

HIGGS MEASUREMENTS AT THE END OF THE HL-LHC





[CYRM-2019-007.221]

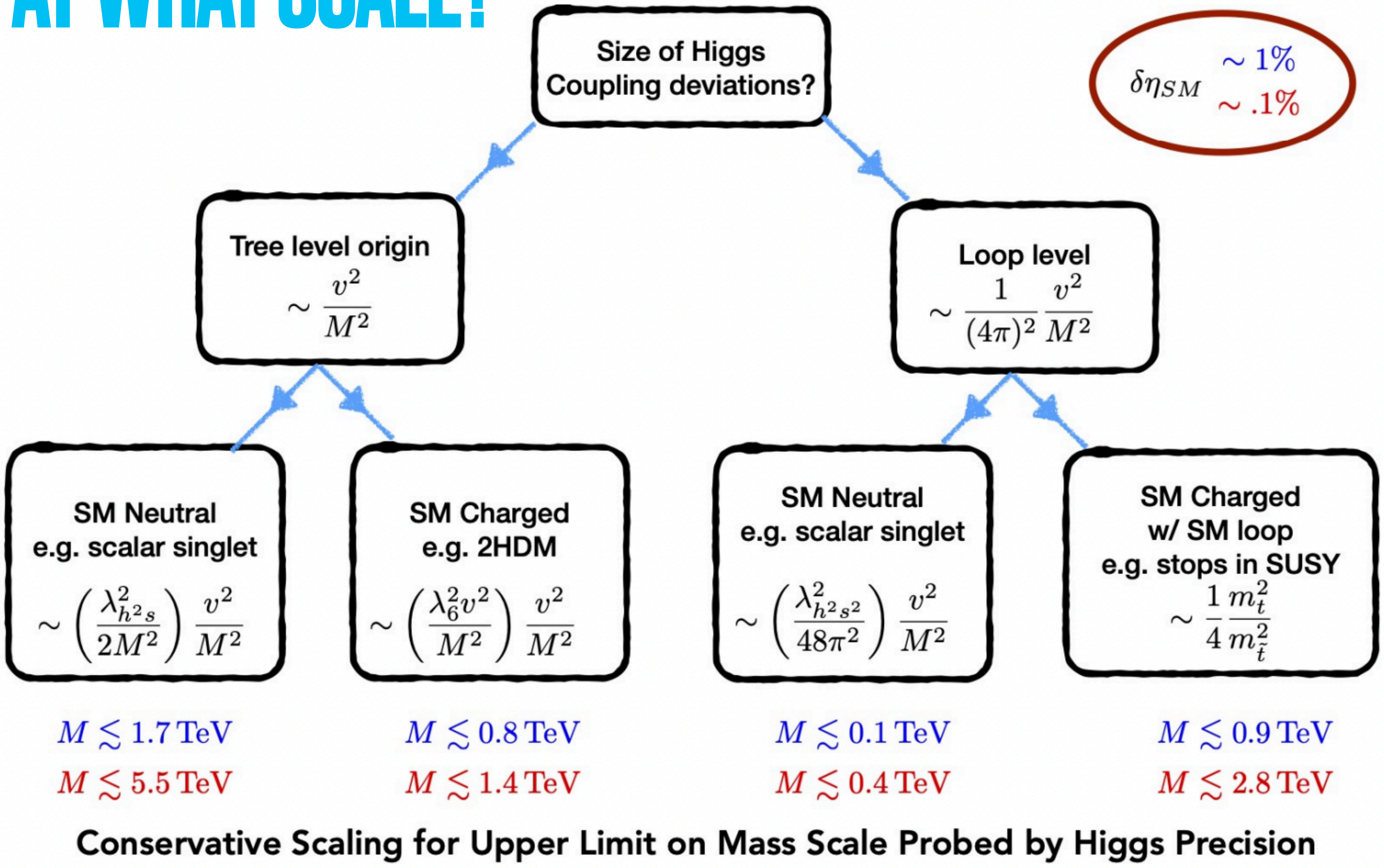
- We will understand how the Higgs couples to many (not all!) SM particles to the few % level
- We will observe HH production and measure for the first time the Higgs self-coupling!
- Precision in properties (Mass to the ~20 MeV level, Width ~20%, increased sensitivity to CP effects)

HIGGS DEVIATIONS: AT WHAT SCALE?

The Higgs sector is extremely sensitive to deviations coming from new physics… but to reach the range in which we could see these effects we need precision

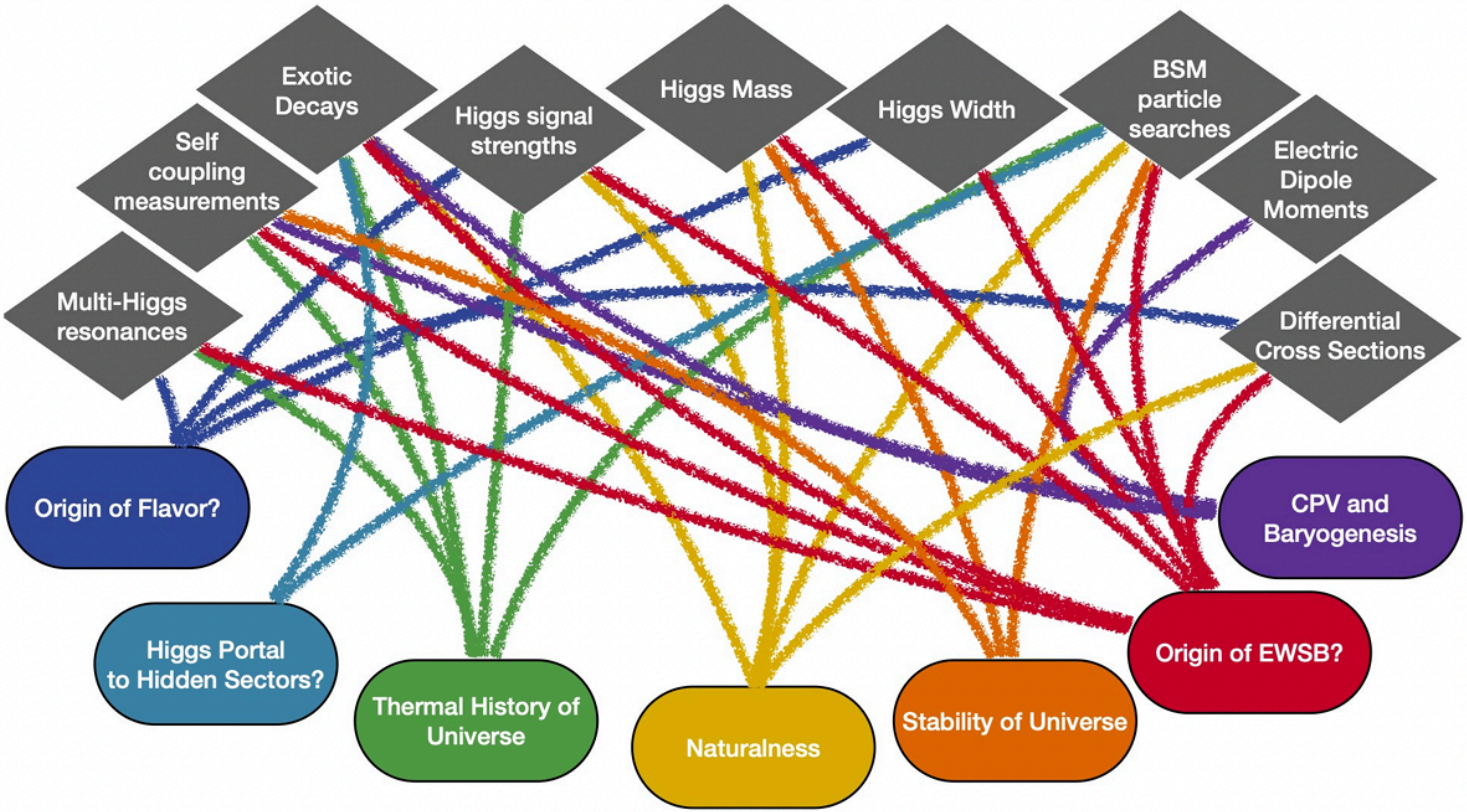
We need to search for deviations of the order of a few per mil in order to go beyond and understand the true Higgs nature

Interplay between precision and direct searches



[Snowmass, hep-ex/2211.11084]

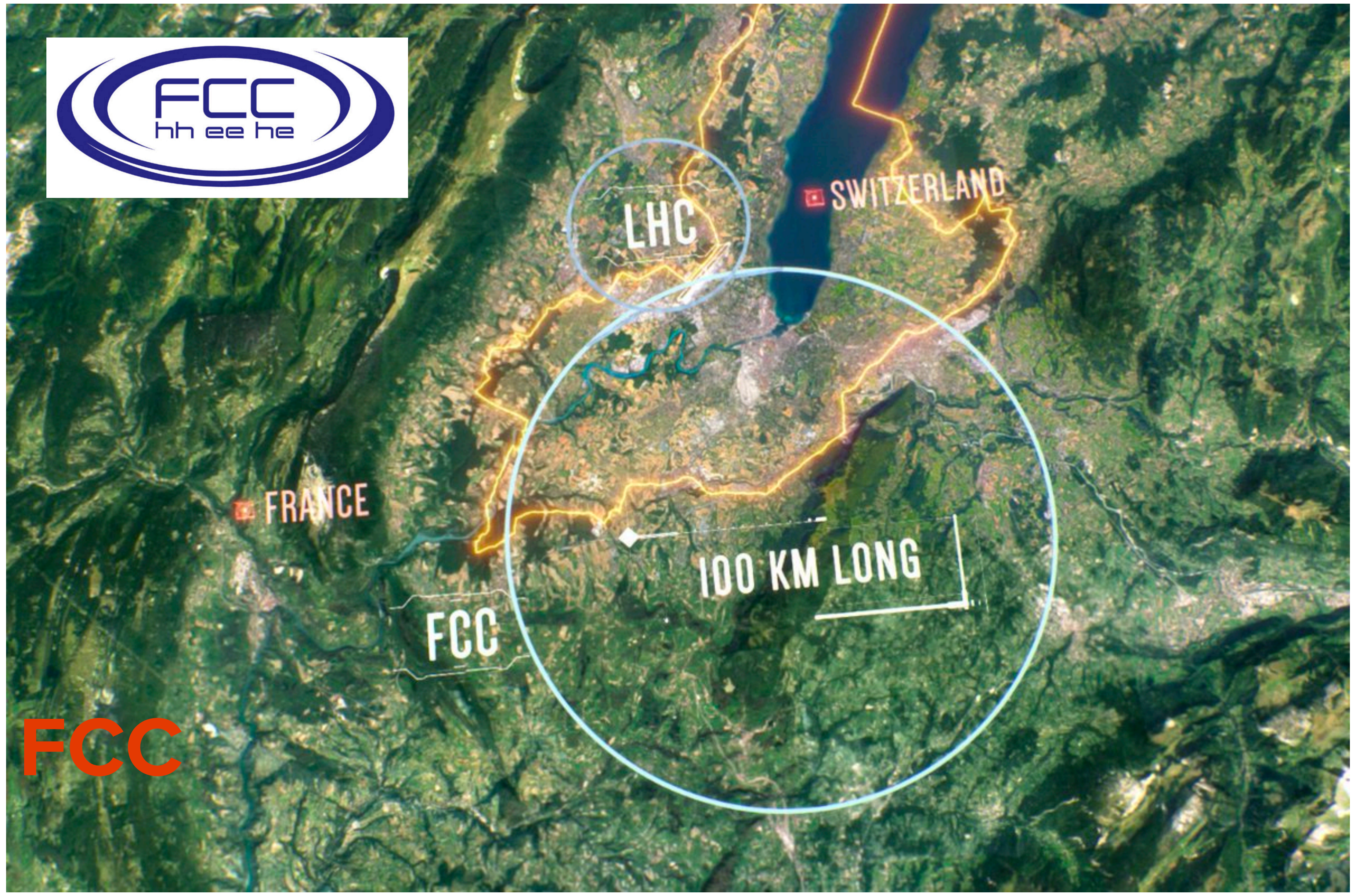
NO HIGGS-CORNER SHOULD BE LEFT UNCHECKED..

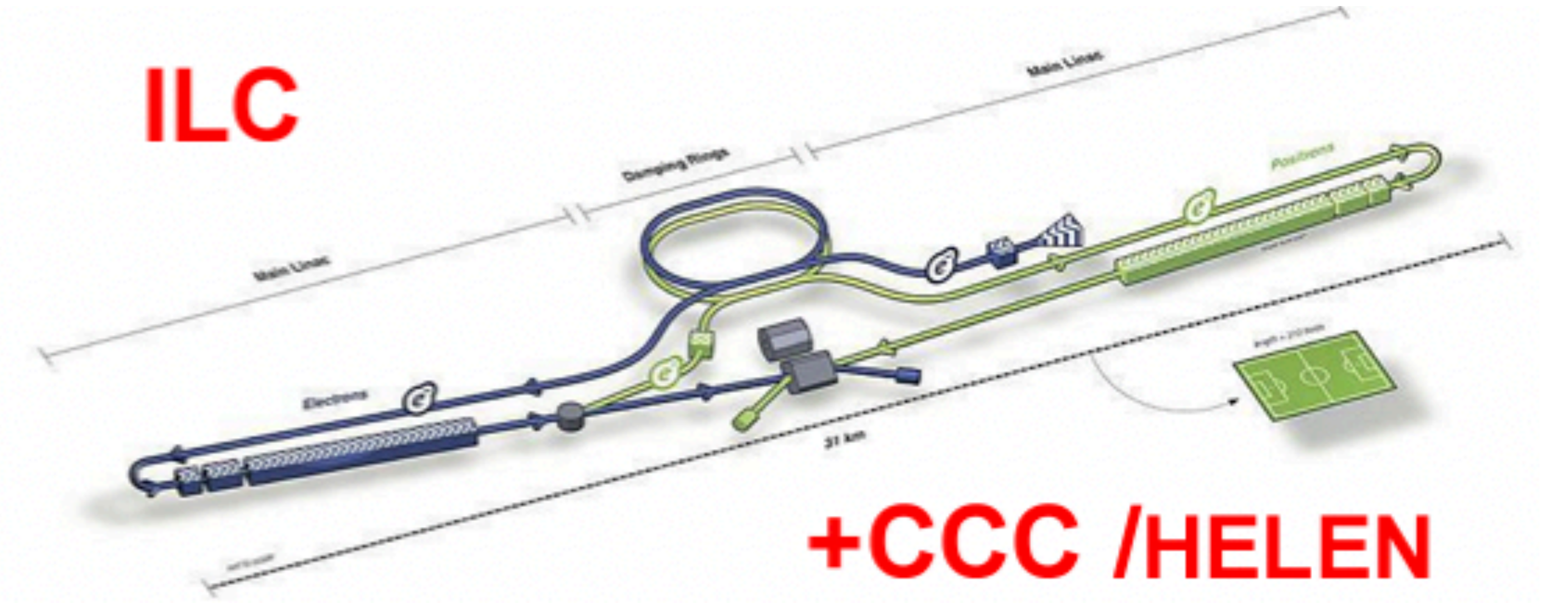


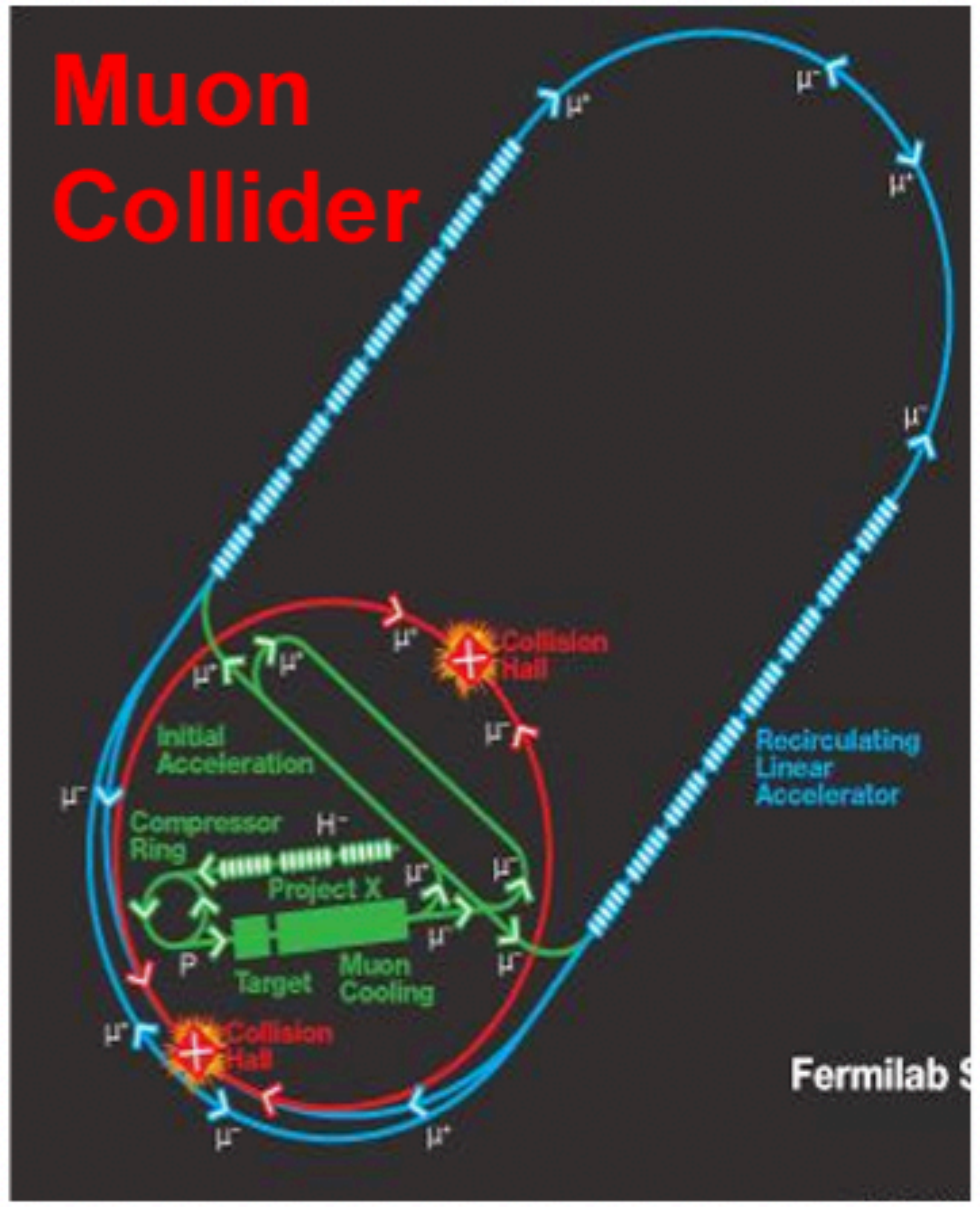
[Snowmass: hep-ex/2211.11084]

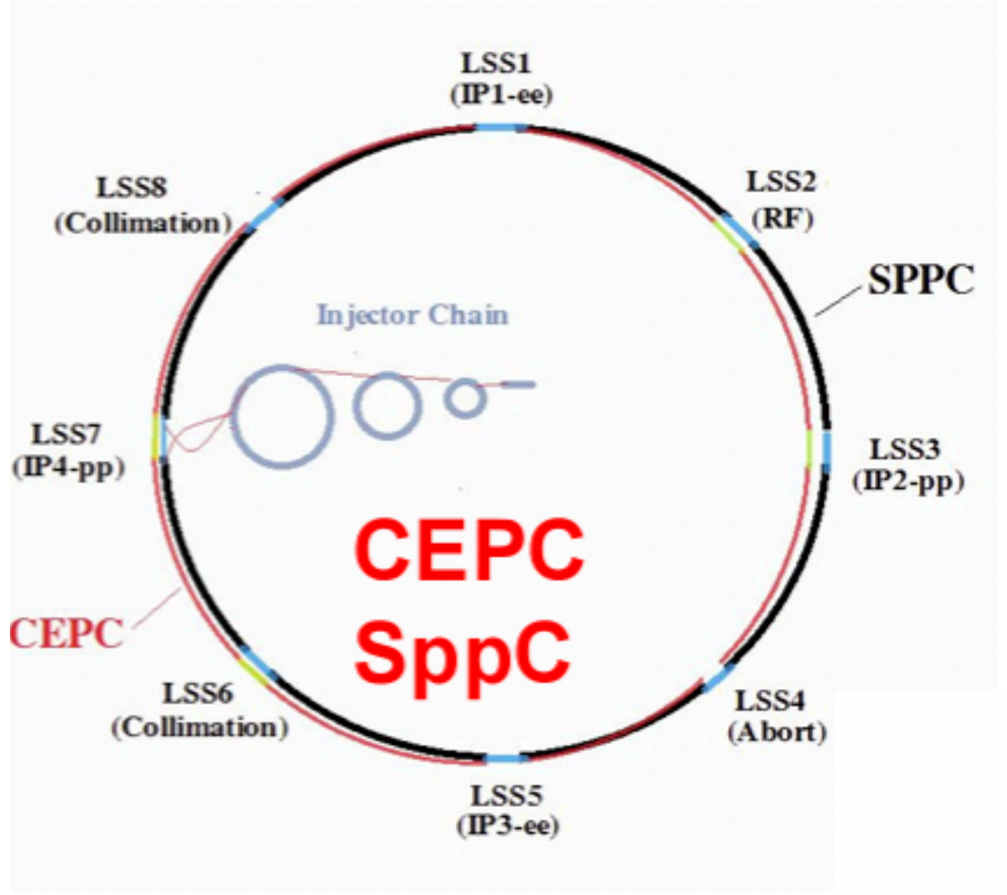
HIGGSTORY (EXPERIMENTALLY) STARTED AT THE LHC…
NEXT CHAPTER: HIGGS FACTORIES

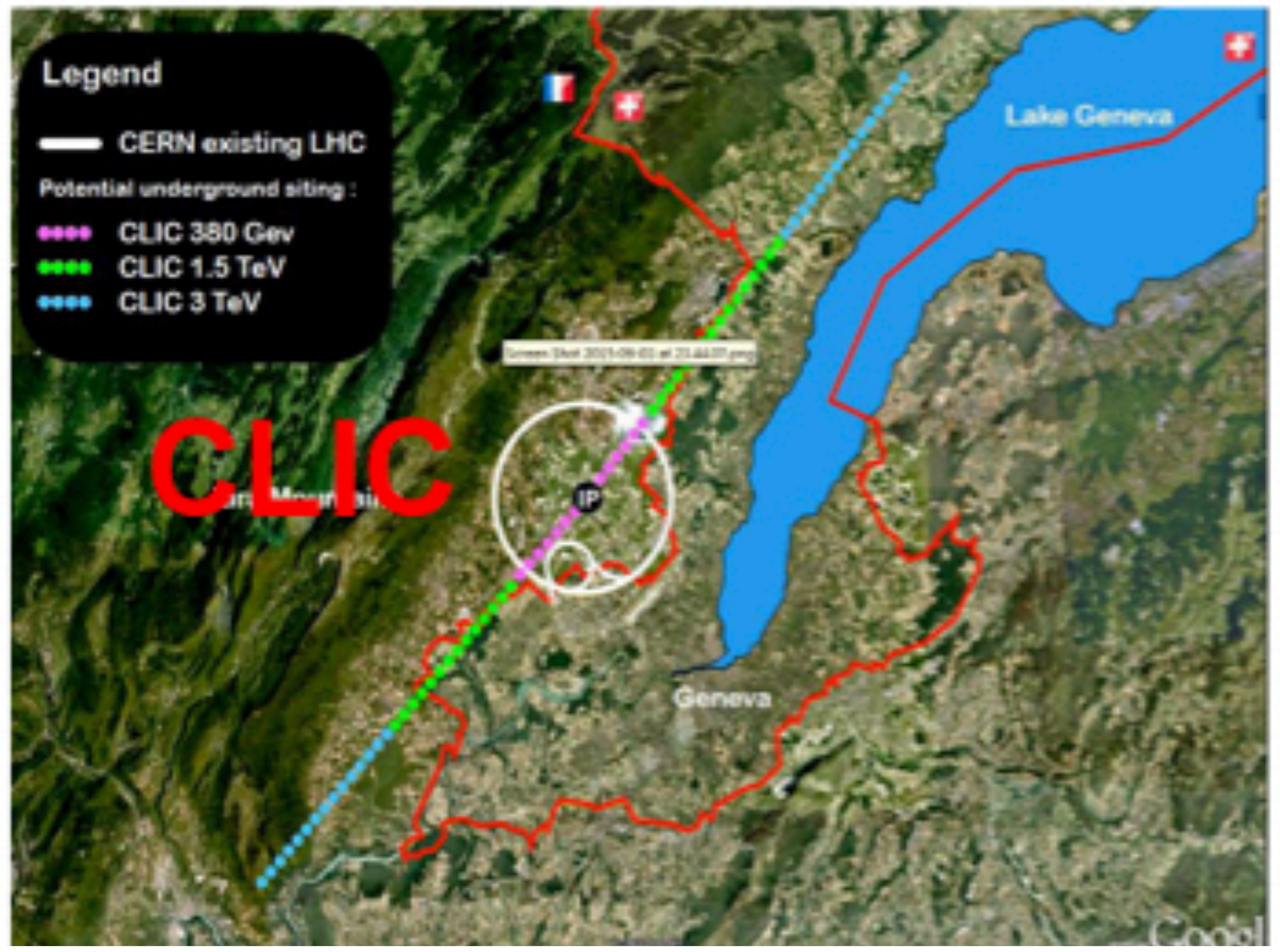
"Higgstory" as a concept stolen from a talk by John Ellis

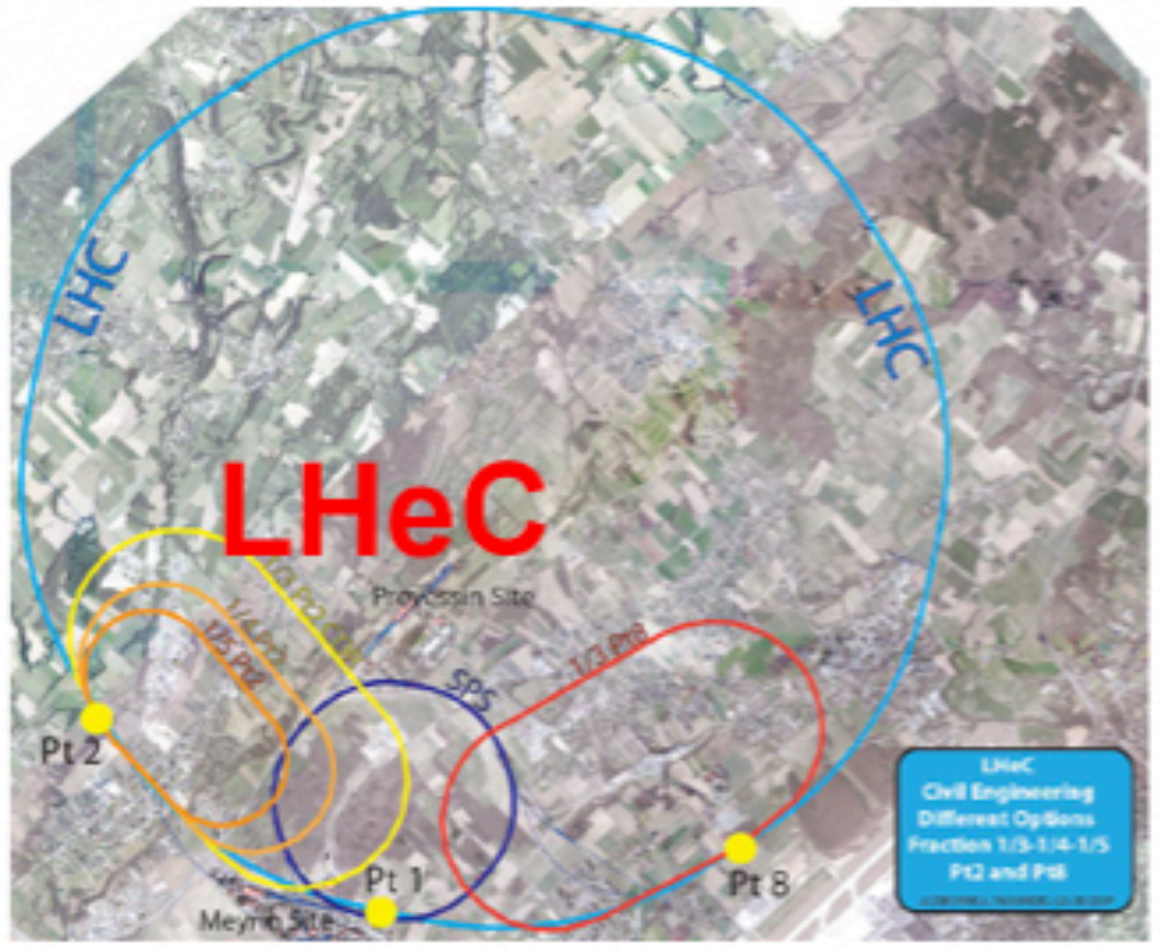

FCC
hh ee he
LHC
SWITZERLAND
FRANCE
100 KM LONG
FCC
FCC

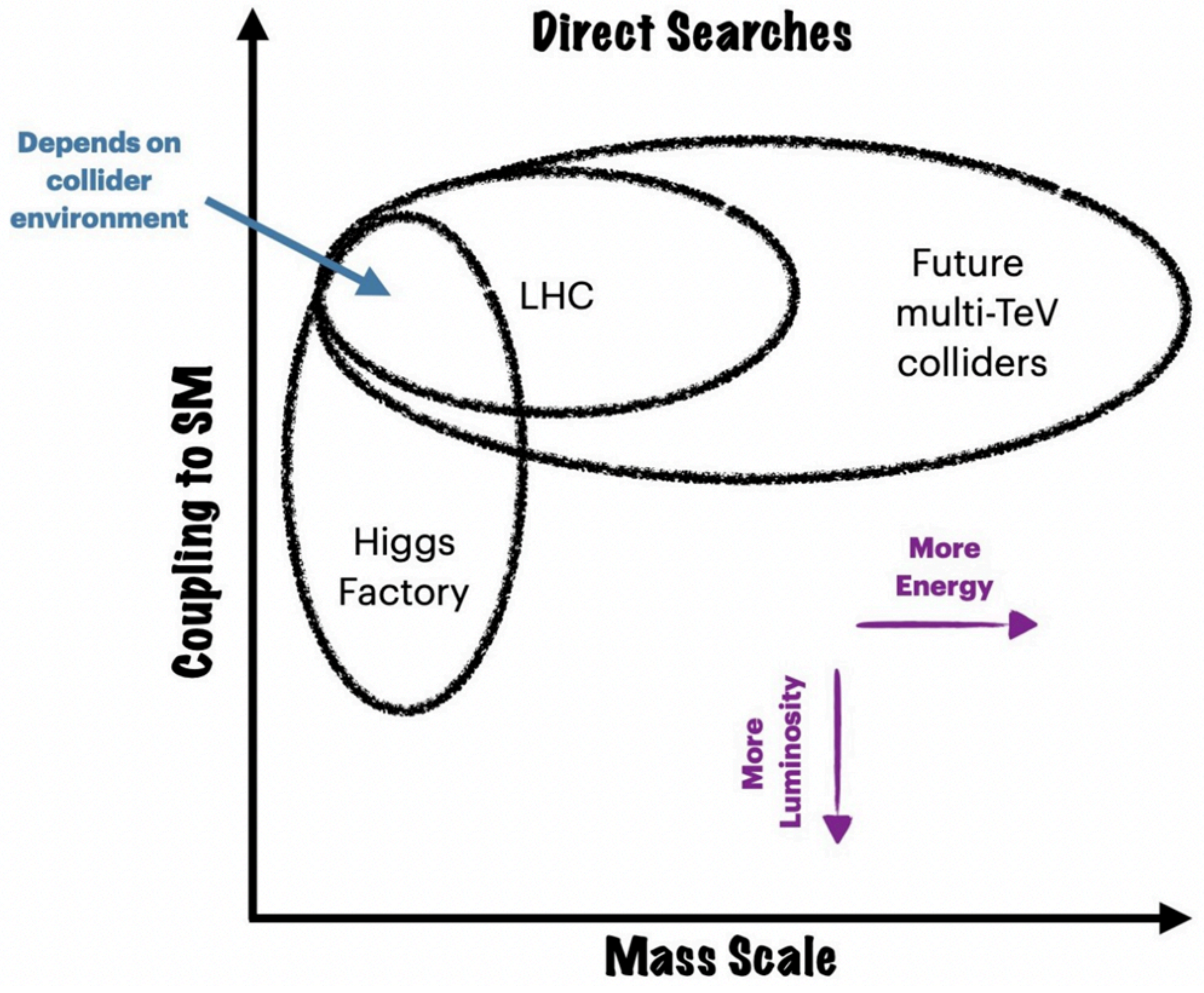

ILC
+CCC /HELEN


Muon
Collider
Collision
Hall
Initial
Acceleration
Compressor
Ring
Project X
Target
Muon
Cooling
Recirculating
Linear
Accelerator
Fermilab


LSS1
(IP1-ee)
LSS2
(RF)
SPPC
LSS8
(Collimation)
Injector Chain
LSS7
(IP4-pp)
LSS3
(IP2-pp)
CEPC
SppC
CEPC
LSS6
(Collimation)
LSS4
(Abort)
LSS5
(IP3-ee)

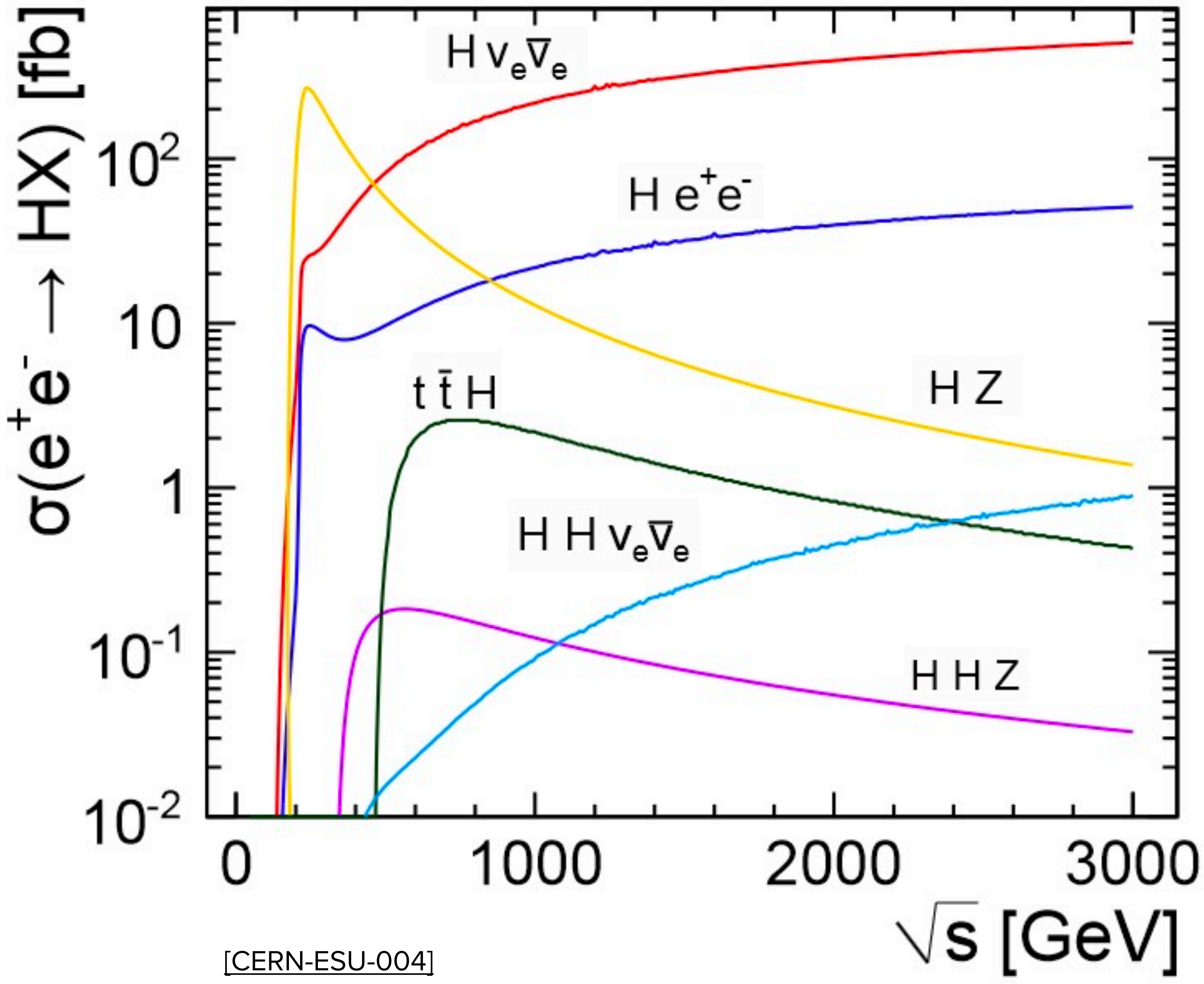

Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
CLIC
Geneva


LHC
LHC
LHeC
SPS
Pt 2
Pt 1
Pt 8


Direct Searches
Depends on
collider
environment
LHC
Future
multi-TeV
colliders
Higgs
Factory
More
Energy
More
Luminosity
Coupling to SM
Mass Scale

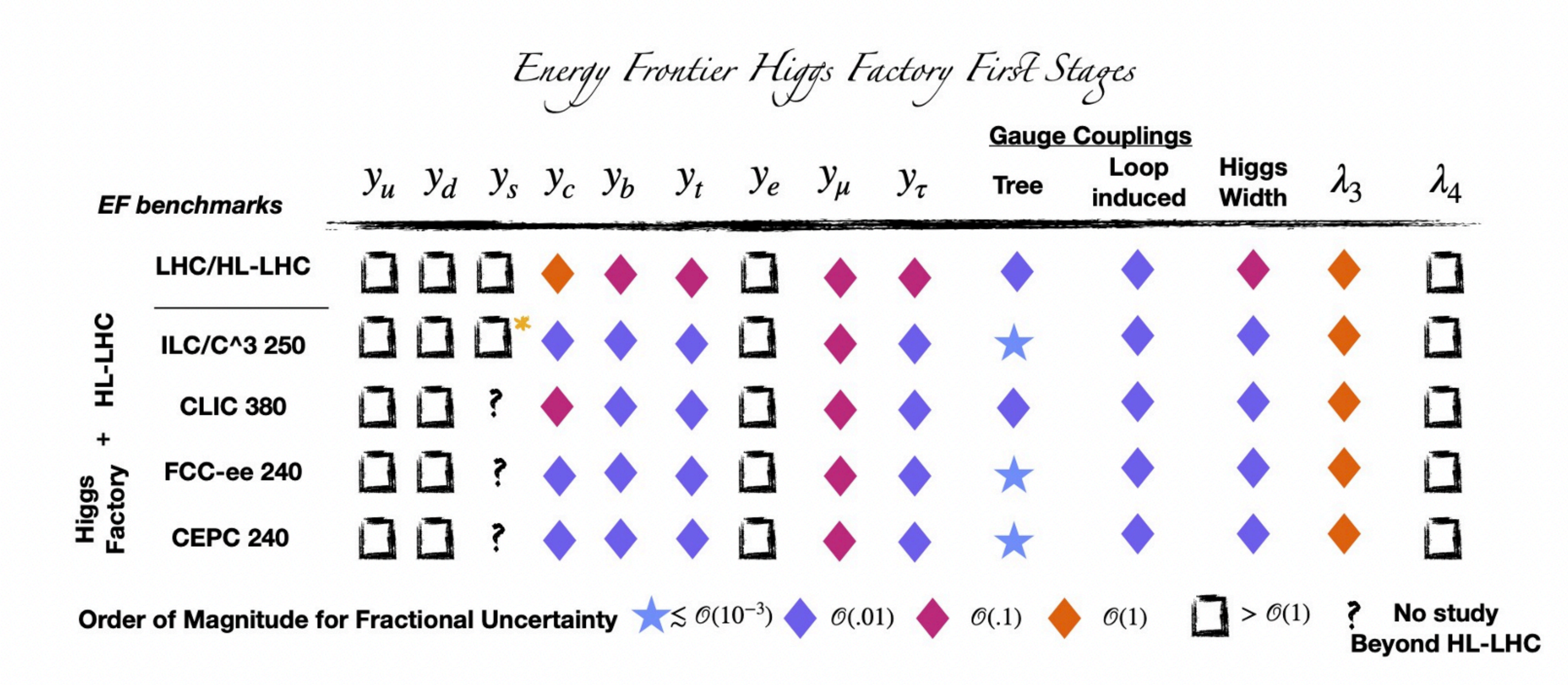
HIGGS FACTORIES

- Completely different experimental scenario to pp physics: precision machines
- Clean Environment
- Perfect to study in depth the Higgs Boson
- Main production mechanism: ZH, VBF



[CERN-ESU-004]

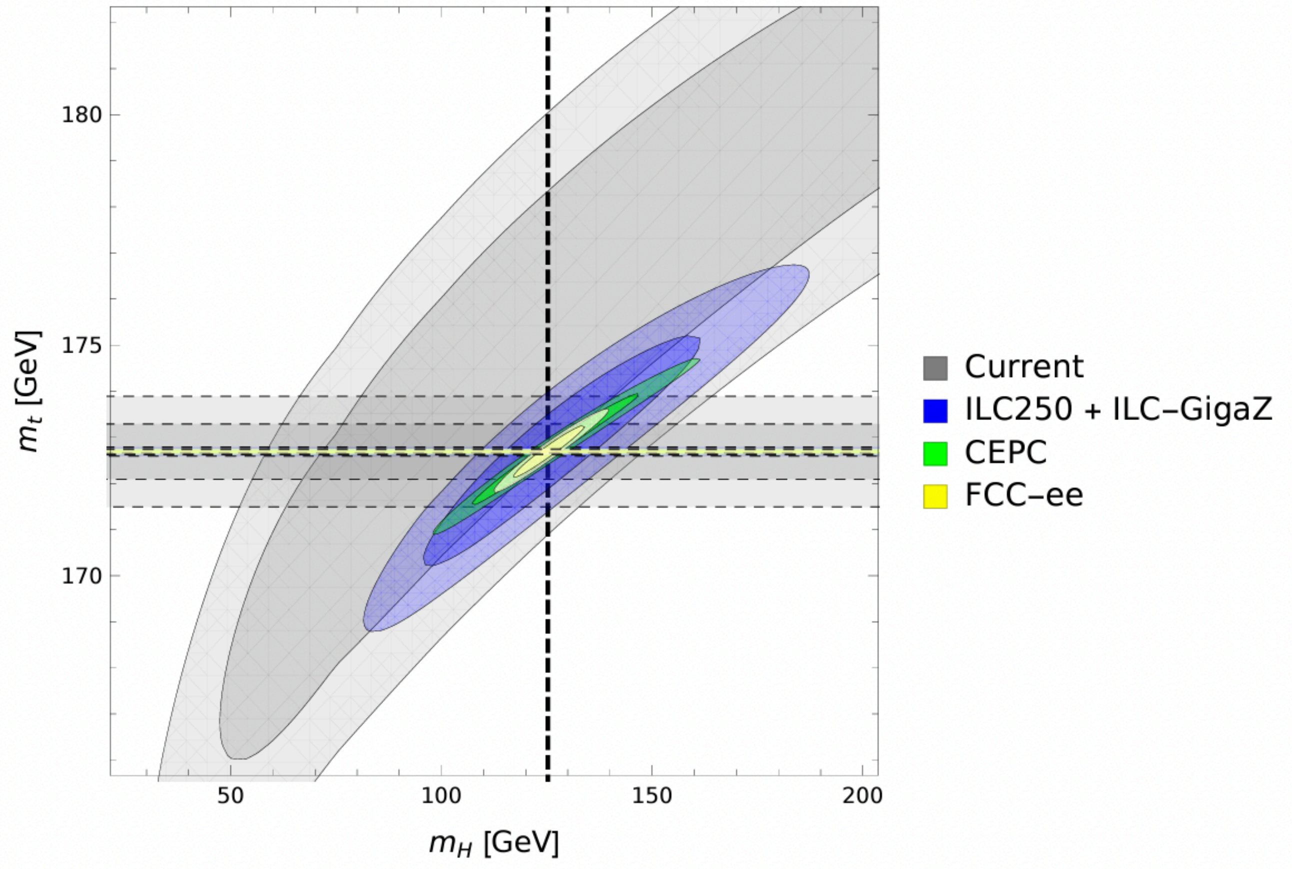
HIGGS COUPLINGS IN THE FUTURE…

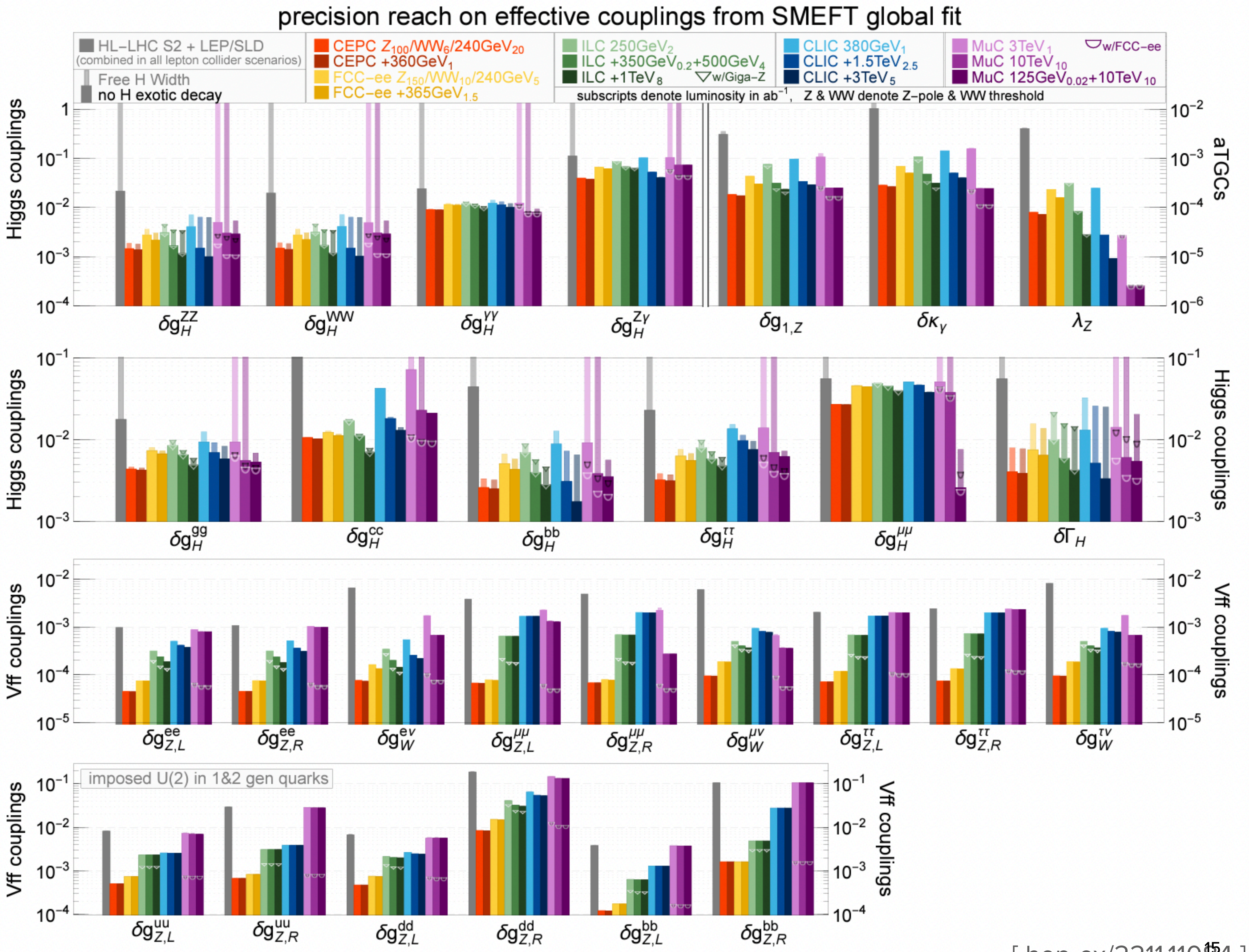


[hep-ex/2211.11084]

THINKING GLOBALLY

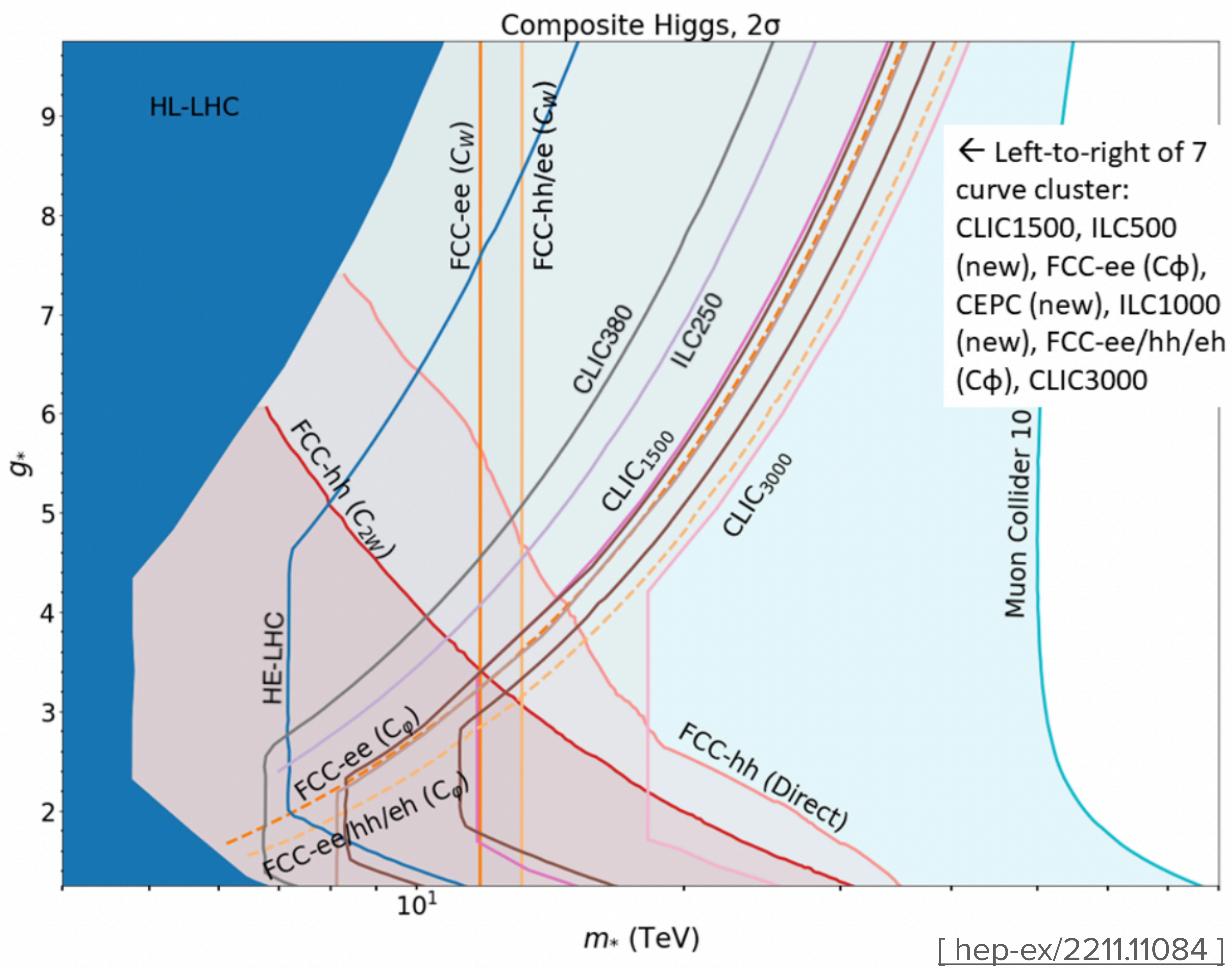
- For the full picture: combine all experimental knowledge
- Global analyses of SM precision observables&Higgs physics





[hep-ex/2211.11084]

TO GO BEYOND.... FOR EXAMPLE, WHAT IS ELEMENTARY?



[hep-ex/2211.11084]

Do we understand the nature of the Higgs? We can go beyond and use precise measurements of its properties to probe fundamental questions of nature.

What is really elementary? Could the Higgs be a composite particle?

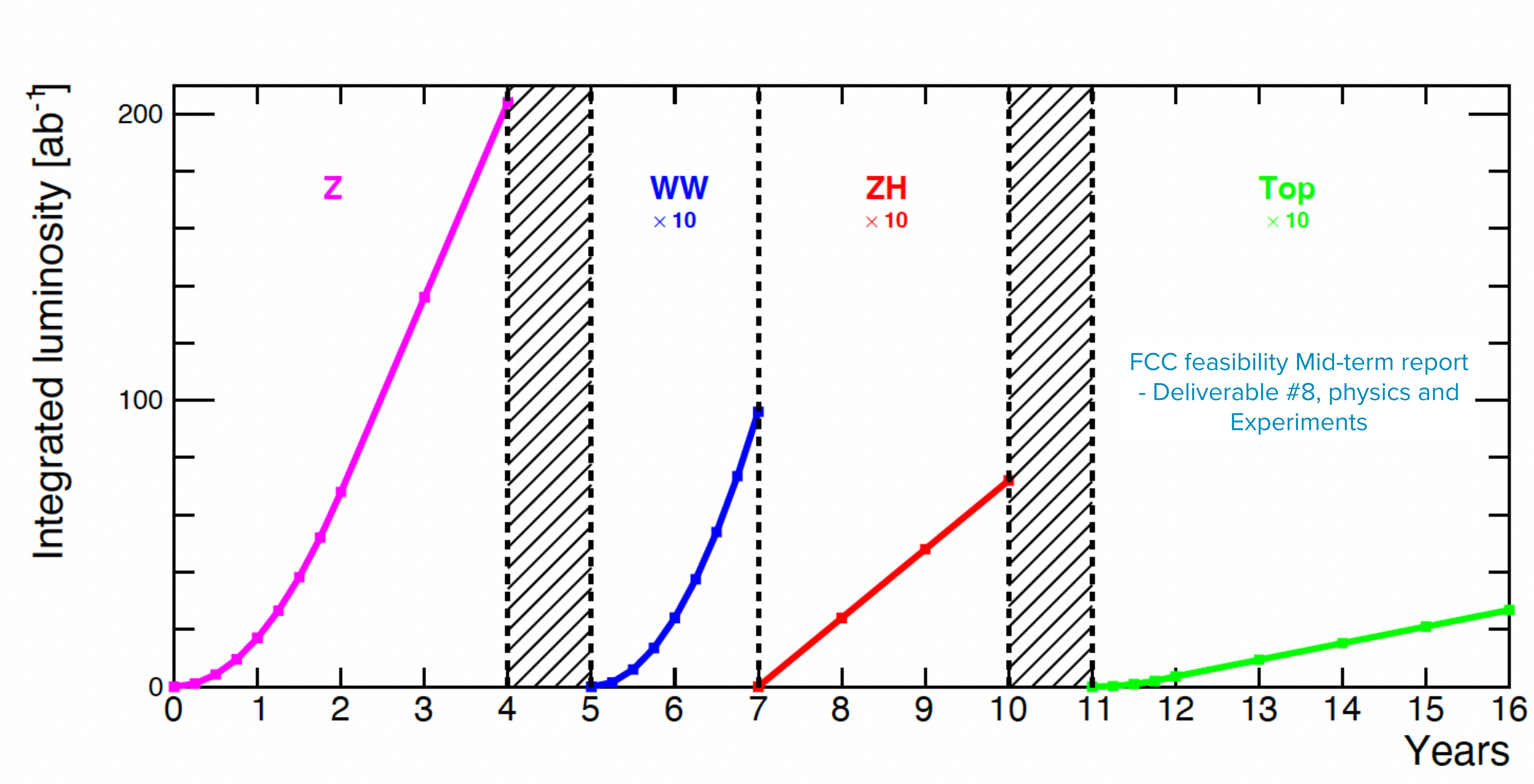
m_* - mass scale of compositeness

g_* - coupling strength of the new composite sector

FCC: JOINT USA-CERN STATEMENT

- "Should the CERN Member States determine the **FCC-e**e is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals."
- https://www.state.gov/joint-statement-of-intent-between-the-united-states-of-america-and-the-european-organization-for-nuclear-research-concerning-future-planning-for-large-research-infrastructure-facilities-advanced-scie/

FCCEE: HUGE STATISTICS & PRECISION



FCC-ee: highest luminosities of all proposed Higgs and EW factories

Range of energies that cover Z, WW, ZH, and tt

Not discussing the detectors here: CLD, IDEA, Allegro

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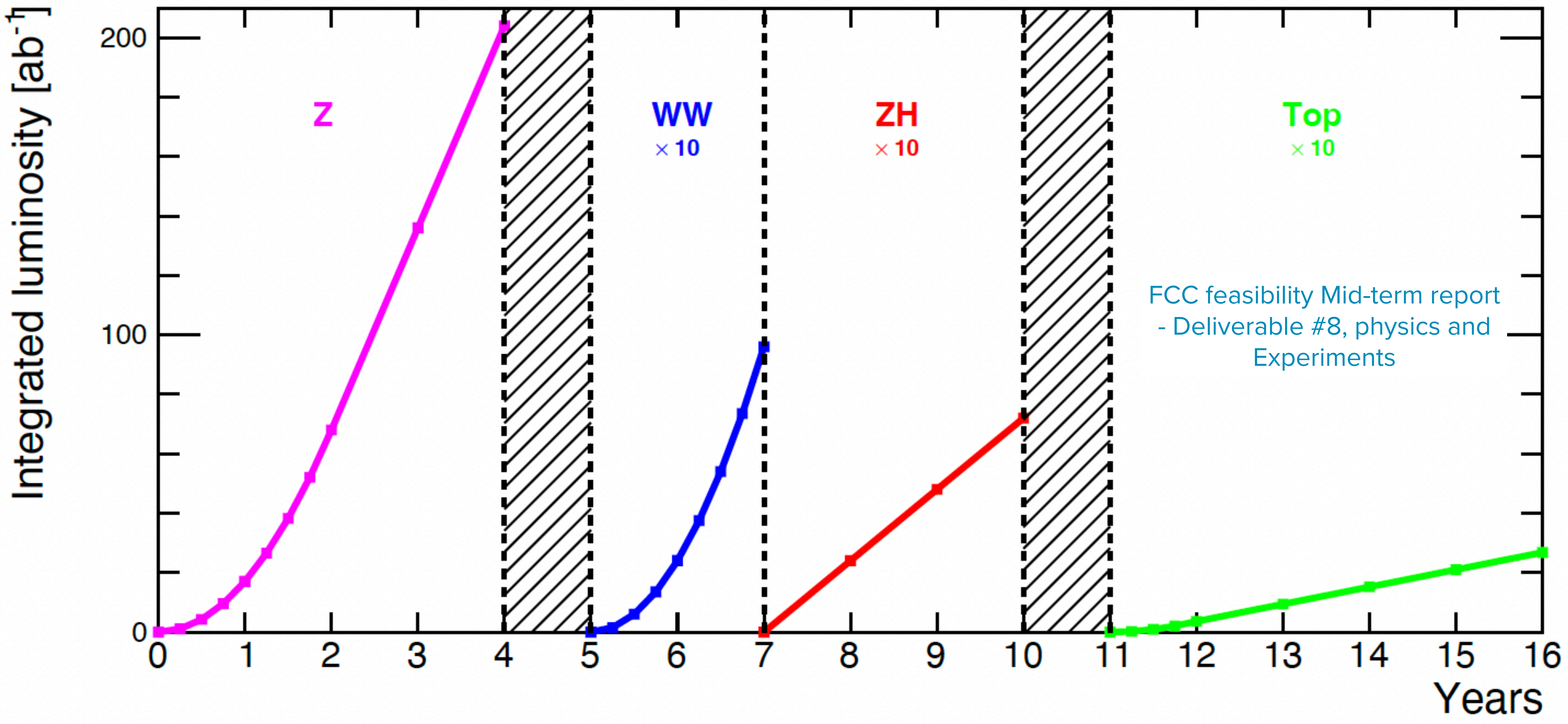


I will be showing some physics updates from the **FCC MidTerm report** (soon to be released). For details see the discussion in the **last FCC week**

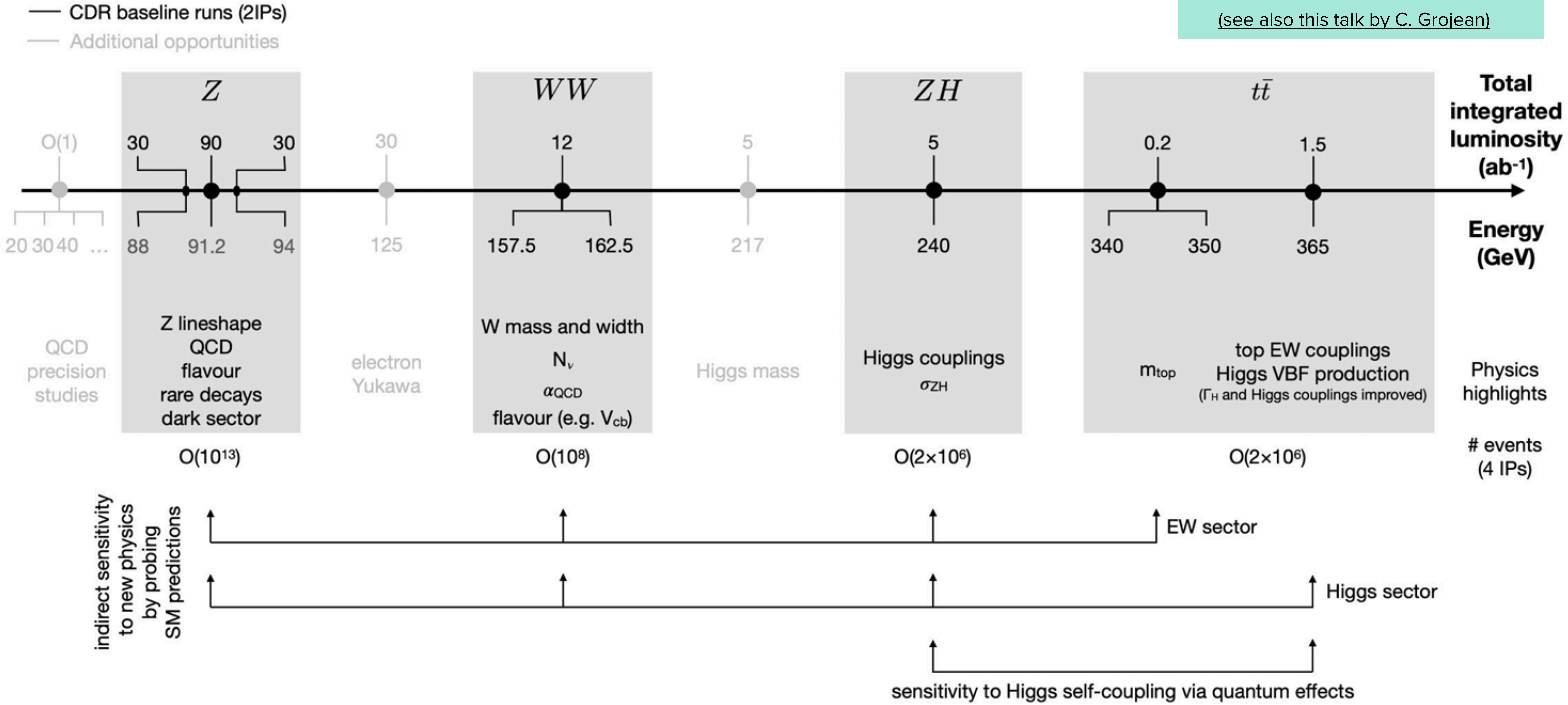
FCC-ee: highest luminosities of all proposed Higgs and EW factories

Range of energies that cover Z, WW, ZH, and tt

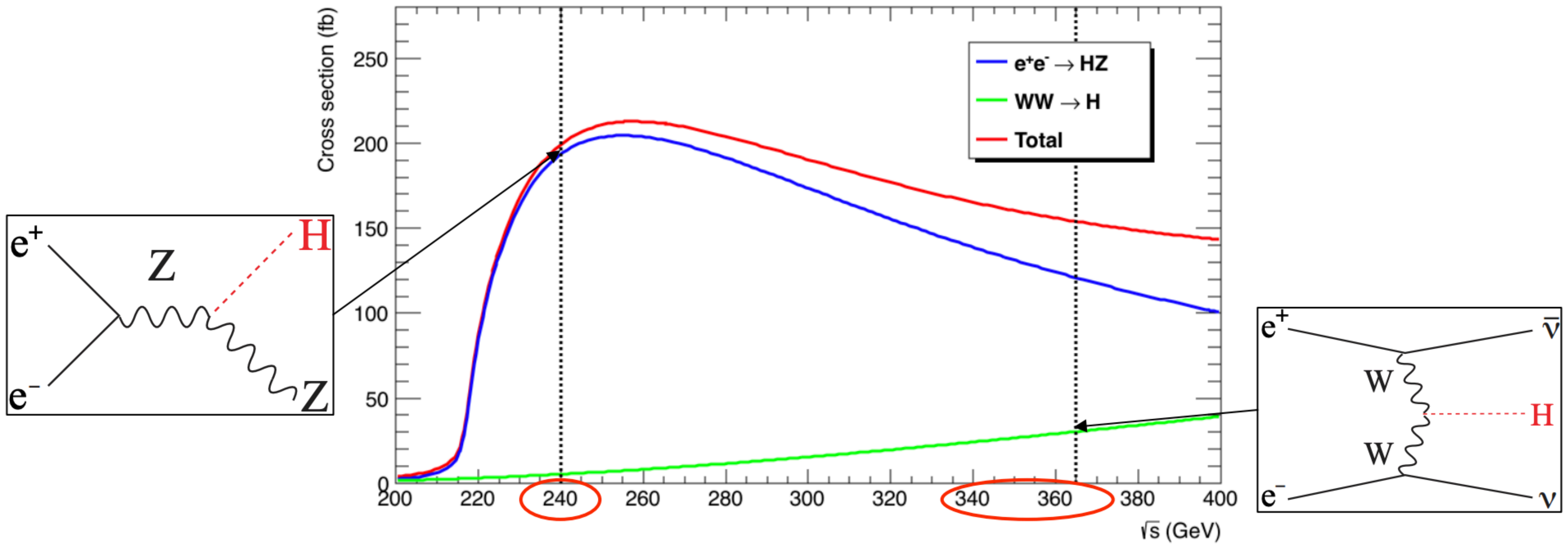
Not discussing the detectors here: CLD, IDEA, Allegro

RUNS ORDERED BY ENERGY

https://doi.org/10.17181/224fq-qtf30
(see also this talk by C. Grojean)

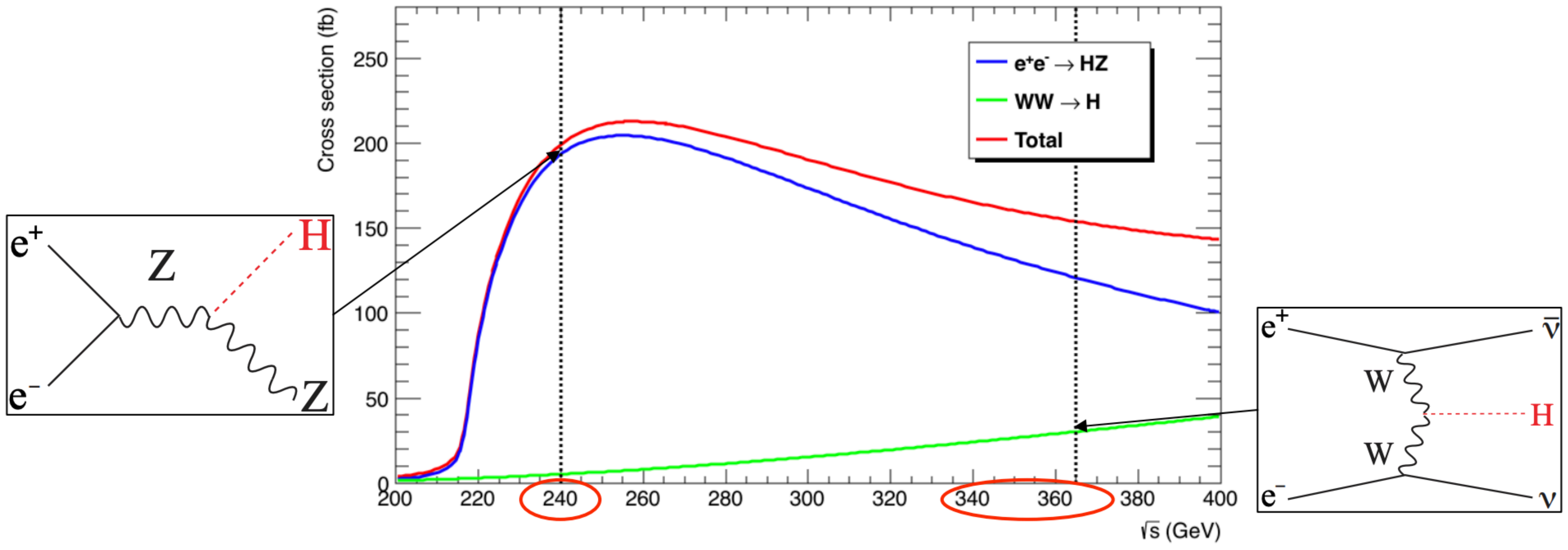


HIGGS @ FCCEE



- **Production of millions of Higgs bosons in a clean environment**
- Baseline (4IP):
  - 240 GeV / 7.2 ab^{-1} : 1.45 M ZH / 45 k VBF
  - 365 GeV / 3 ab^{-1}: 330 k ZH / 80 k VBF
- Systematics:
  - integrated lumi ~ 0.01%
  - tagging efficiency, BES < 1%
  - TH < 1% (no PDFs, QCD corrections are small)

HIGGS @ FCCEE



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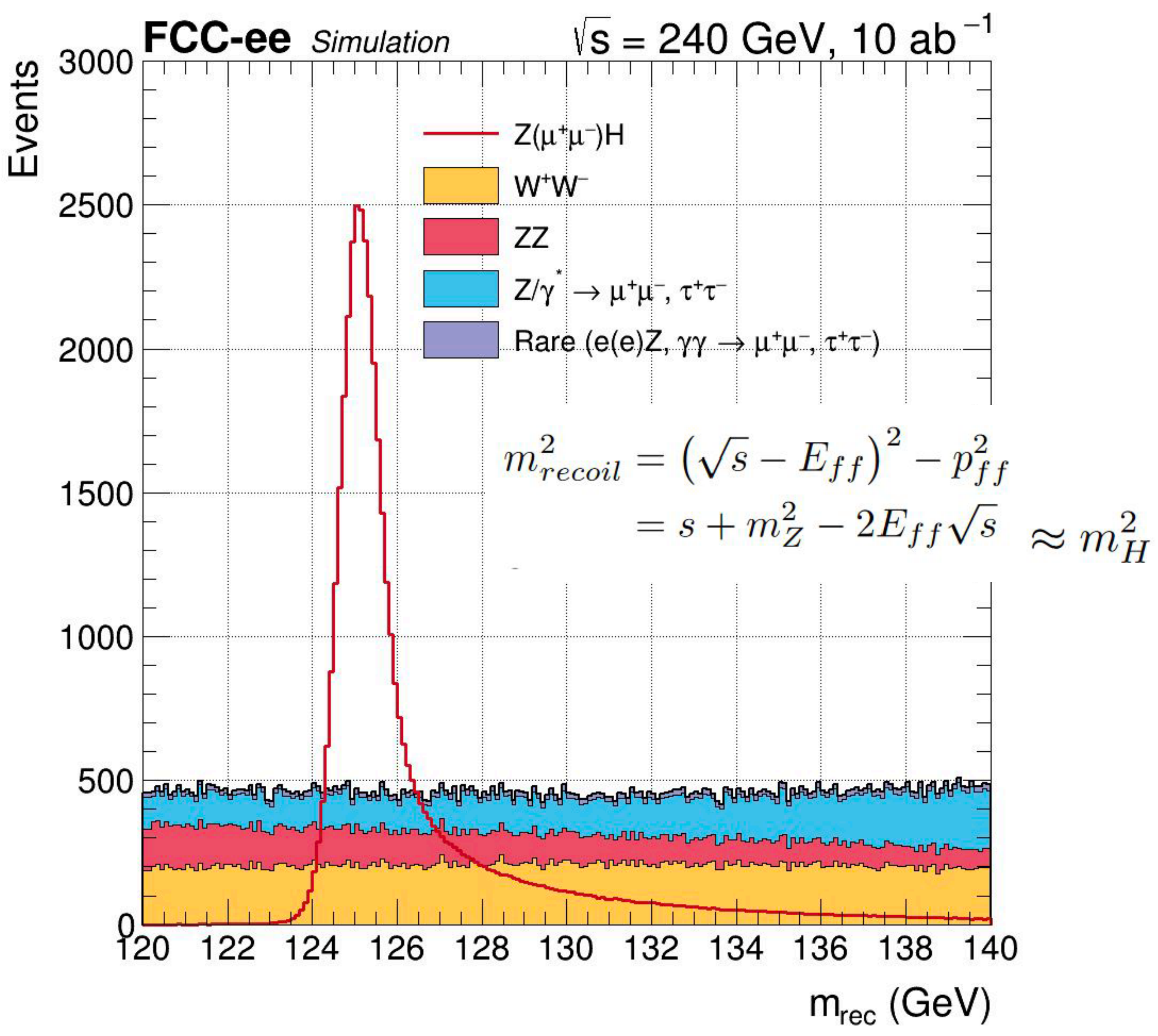
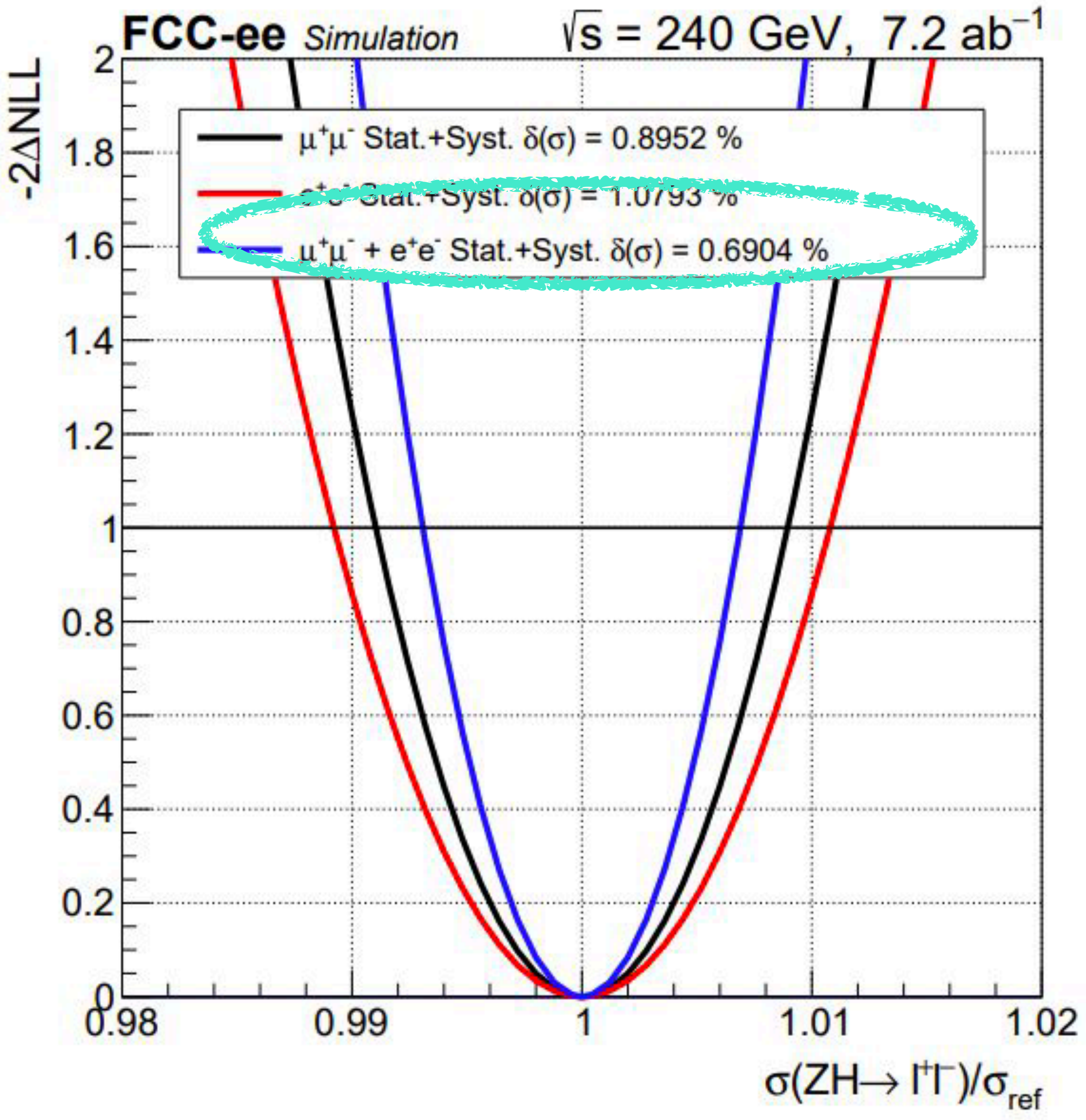
- **Fundamental properties:** model-independent ZH cross section, mass, width, self-coupling, CP
- **Brs/Couplings:** ZZ&WW, Hadrons (bb,cc,ss), Leptons ($\tau\tau$), Rare ($\gamma\gamma$, Zγ,$\mu\mu$), Exotic (BSM/invisible), First Generation (ee, uu/dd?)
- **And more…** Differential measurements, Angular observables, Anomalous Couplings, BSM searches (FCNC, Additional Scalars)

ZH MODEL-INDEPENDENT MEASUREMENTS

- **Recoil method in ZH: unbiased reconstruction of the Higgs (known initial state, tag Z —> Higgs recoil)**
  - Precise inclusive measurement of σ_{ZH}, mass, width,…
  - Not possible in a hadron collider
  - Exploit Z leptonic decays
- **Once σ_{ZH} is known (0.7%) —> g_Z coupling can be determined in a model-independent way ($\delta g_Z/g_Z$ ~ 0.2 %)**
  - Individual decay channel measurements lead to measurement of total width (ZH→ZZZ : rate ~ $\mathbf{g_Z^4 / \Gamma_H}$ → $\delta\Gamma_H/\Gamma_H$ ~ 1 %)





FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HXX}}{\Gamma_H}$$

$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \to ZH, H \to ZZ\right)^2}{\sigma\left(e^+e^- \to ZH\right)}$$

HIGGS COUPLINGS

FCC feasibility Mid-term report -
Deliverable #8, physics and Experiments

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

- HXX coupling measurements:

  ZH → ZXX rate ~ $\mathbf{g_Z^2\, g_X^2/\,\Gamma_H}$

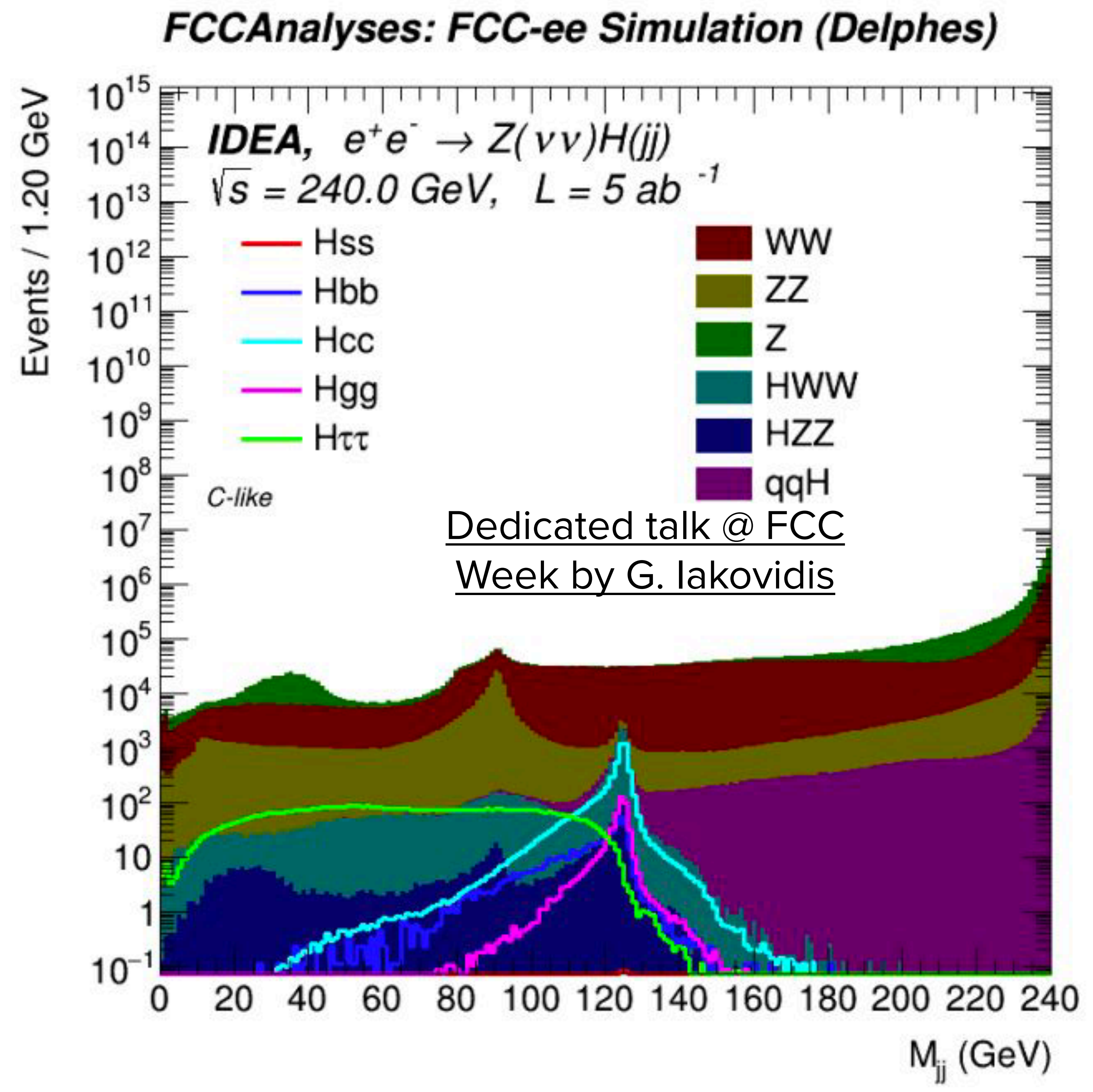
  → $\delta g_X/g_X$ ~ 1 %

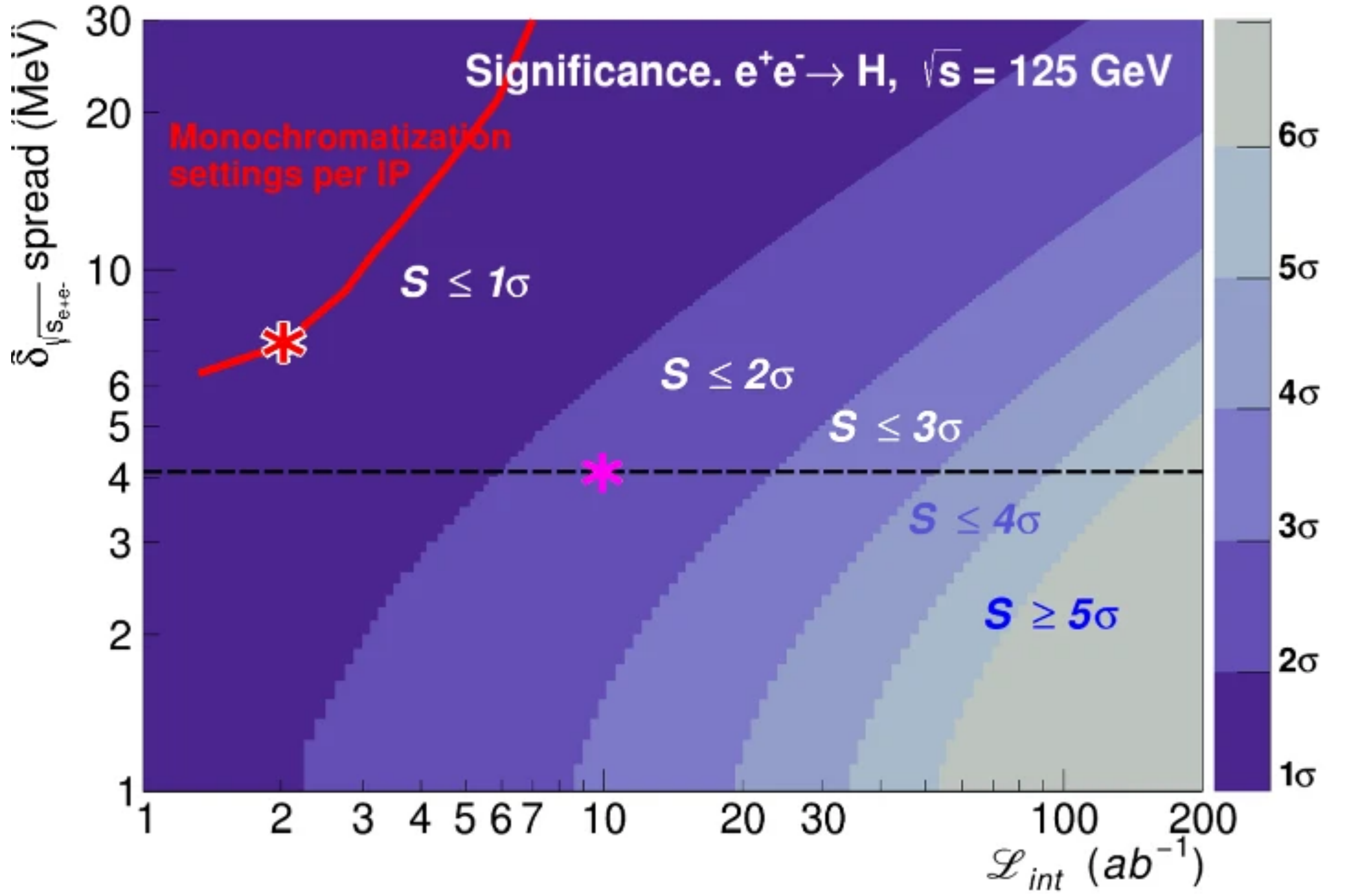
(*) $|\kappa_V| \leq 1$ for HL-LHC

HIGGS COUPLINGS

Going beyond…

- Rare decays (muons, photons) ongoing
- **Several efforts ongoing to measure the Higgs couplings to hadrons (bb, cc, ss) and gluons**
  - Z(ll)H(XX), Z(vv)H(XX), Z(qq)H(qq)
  - Developments in tagging, multidimensional categorization, NN / MVAs
  - Sensitivity for ss?
- Upper limits on light Yukawa (up&down) and FCNCs (bs, bd, cu, sd)
- And of course, the **electron Yukawa**: specific run (Eur.Phys.J.Plus 137 (2022) 2, 201)

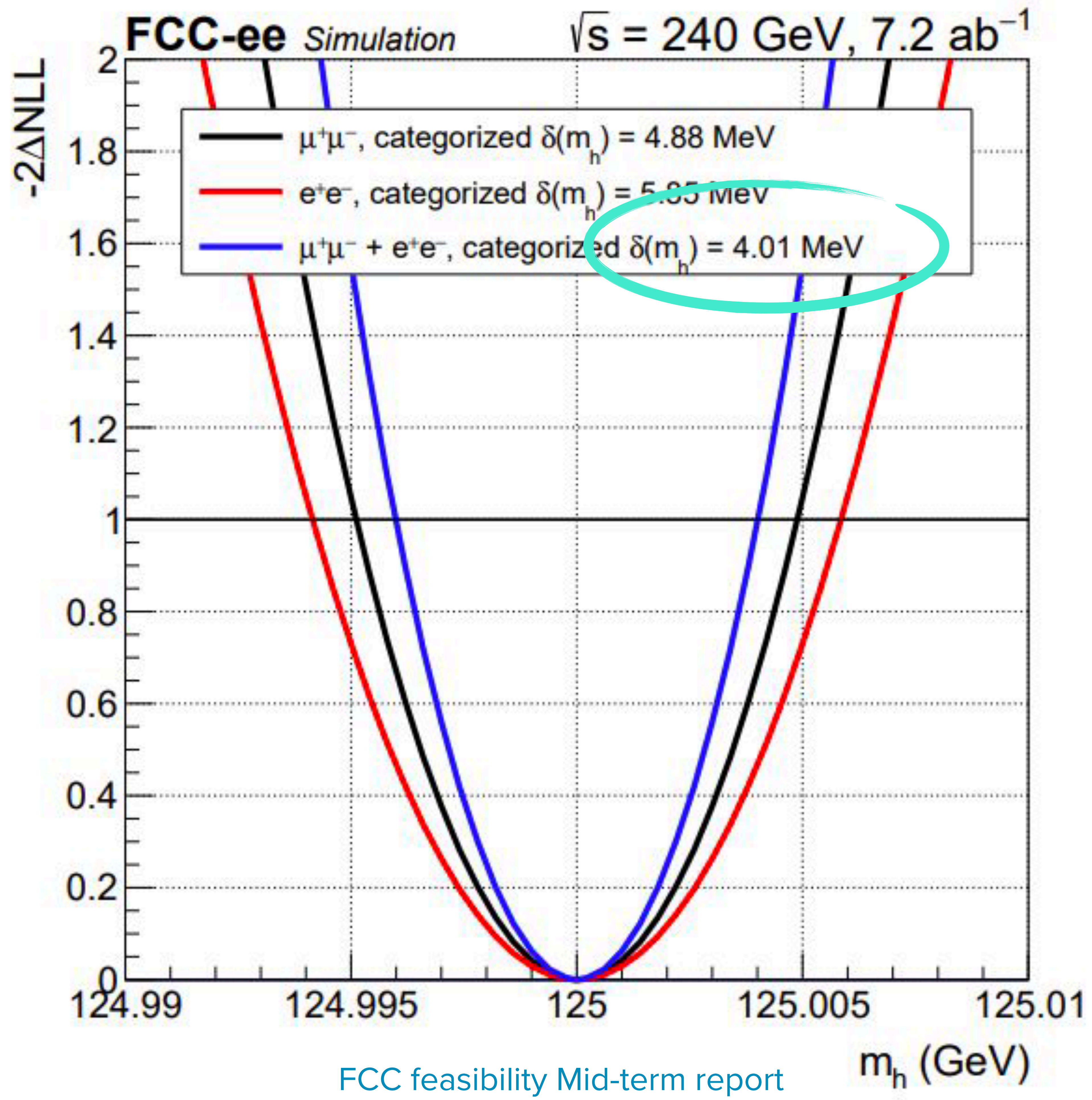




HIGGS MASS

- m_H enters SM EWK parameters via radiative corrections
- Current LHC experimental precision ~0.1%. HL-LHC reach: ~20/30 MeV possible

- **In lepton colliders, m_H needs be improved to around 10 MeV to avoid any limitation on cross sections and branching fraction measurements**
  - Recoil method: **4 MeV @ FCCee**
  - Detailed study of systematics and detector/acelerator effects done for the Midterm report



FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

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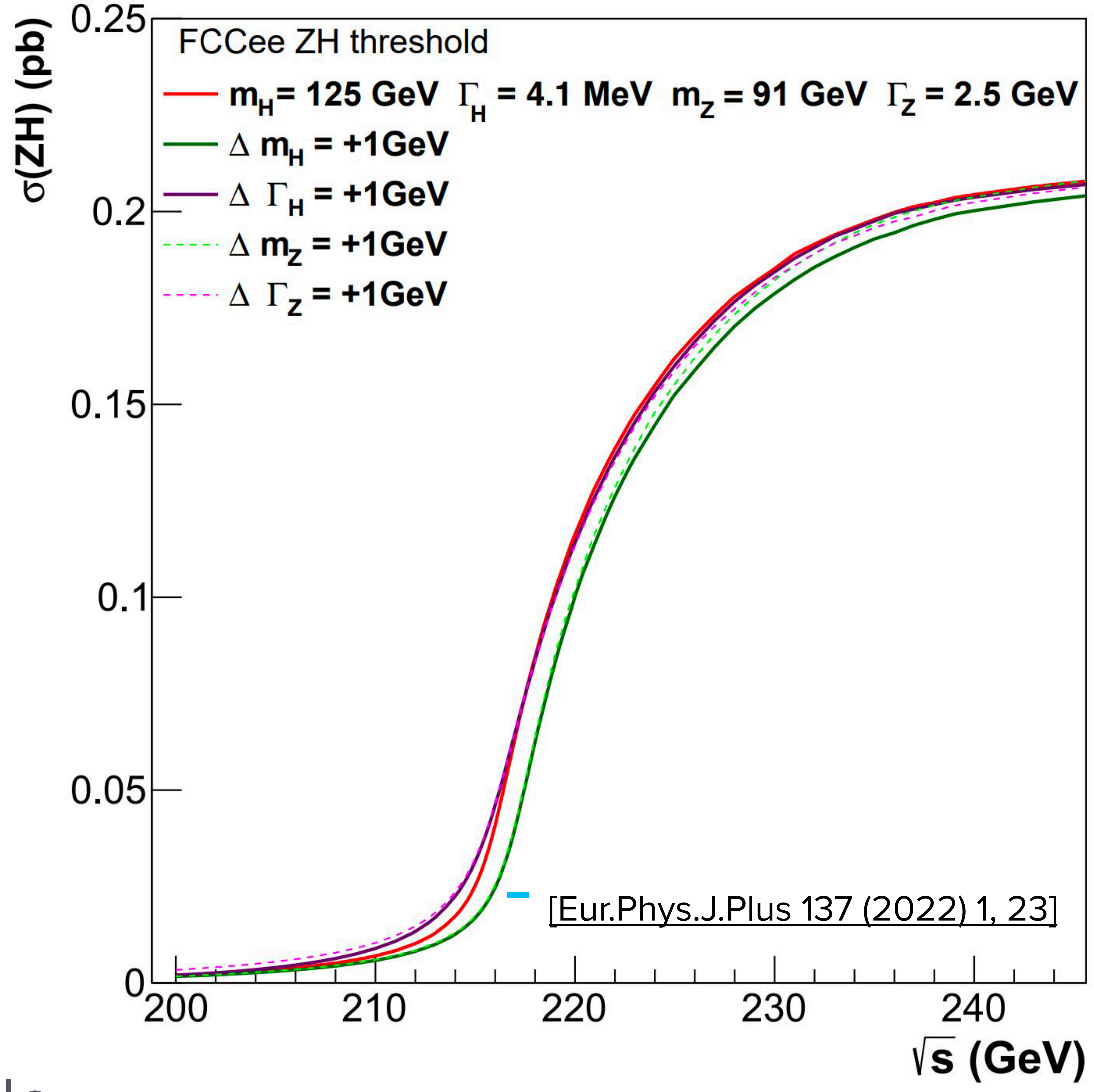
- **In lepton colliders, m_H needs be improved to around 10 MeV to avoid any limitation on cross sections and branching fraction measurements**

- **Alternative proposal to reach <5 MeV with a dedicated √s= 217 GeV run (not in the baseline)!**
  - Higgs mass dependency on the total cross section as a function of √s
  - Rely on accurate measurements of Z mass&width at the Z-pole
  - Ratio between 217 and 240 GeV: experimental and theoretical uncertainties cancel —> reach sensitivity of 5 MeV



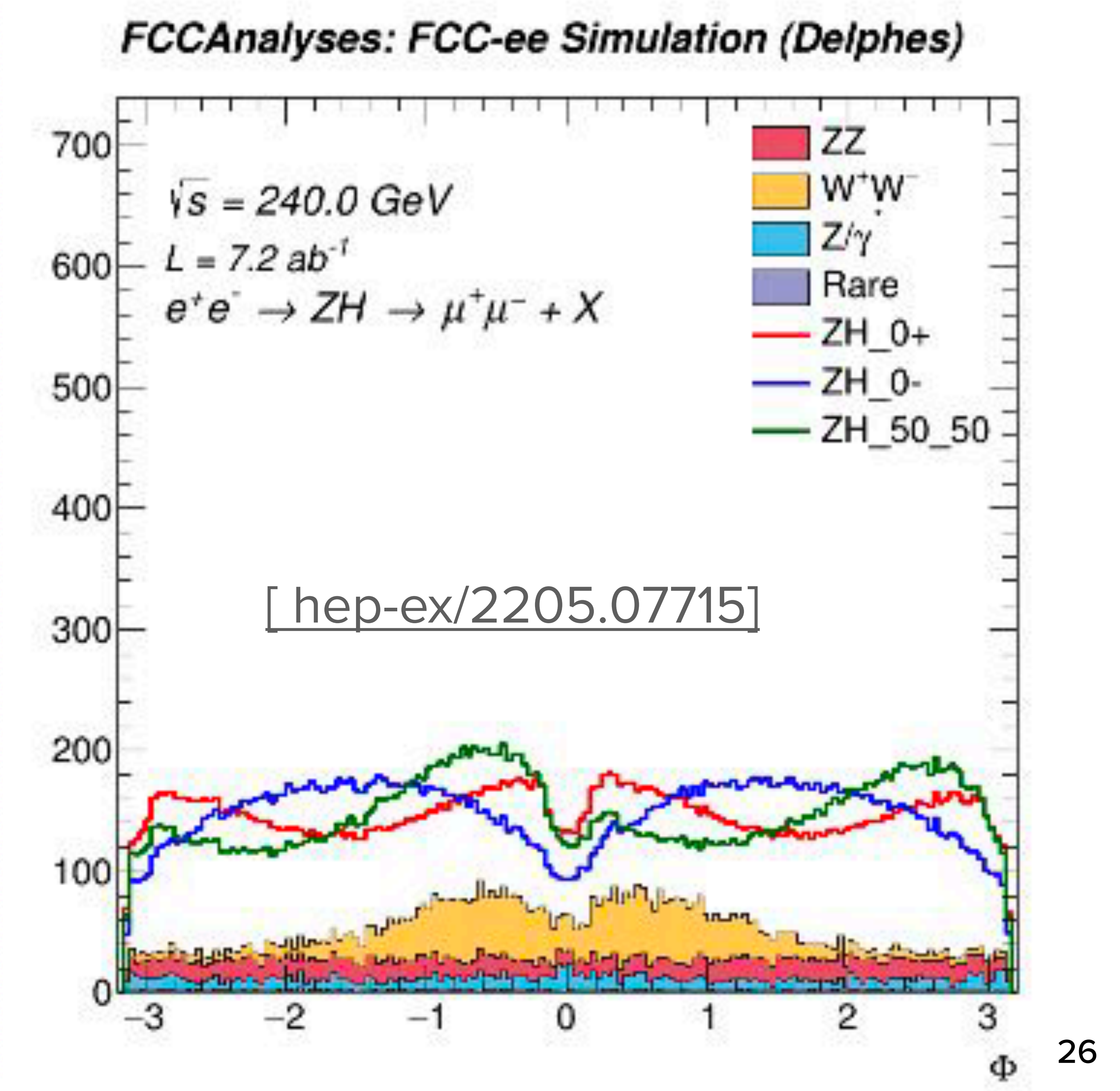
- [Eur.Phys.J.Plus 137 (2022) 1, 23]

HIGGS & CP?

- Exploring the tensor structure of Higgs couplings can bring surprises in years to come. There is still a lot to know!
- Recent work on Higgs CP studies to constrain anomalous couplings using MELA
- CP properties of fermion interactions (taus, tops) only start to be within reach now for LHC: Very important to follow in Run3/HL-LHC… **and beyond**

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000		125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000		250			
hZZ/hWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$h\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$hZ\gamma$	–	~ 1	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	–	✓	$< 10^{-2}$
$h\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$h\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

[hep-ex/2205.07715, Snowmass]

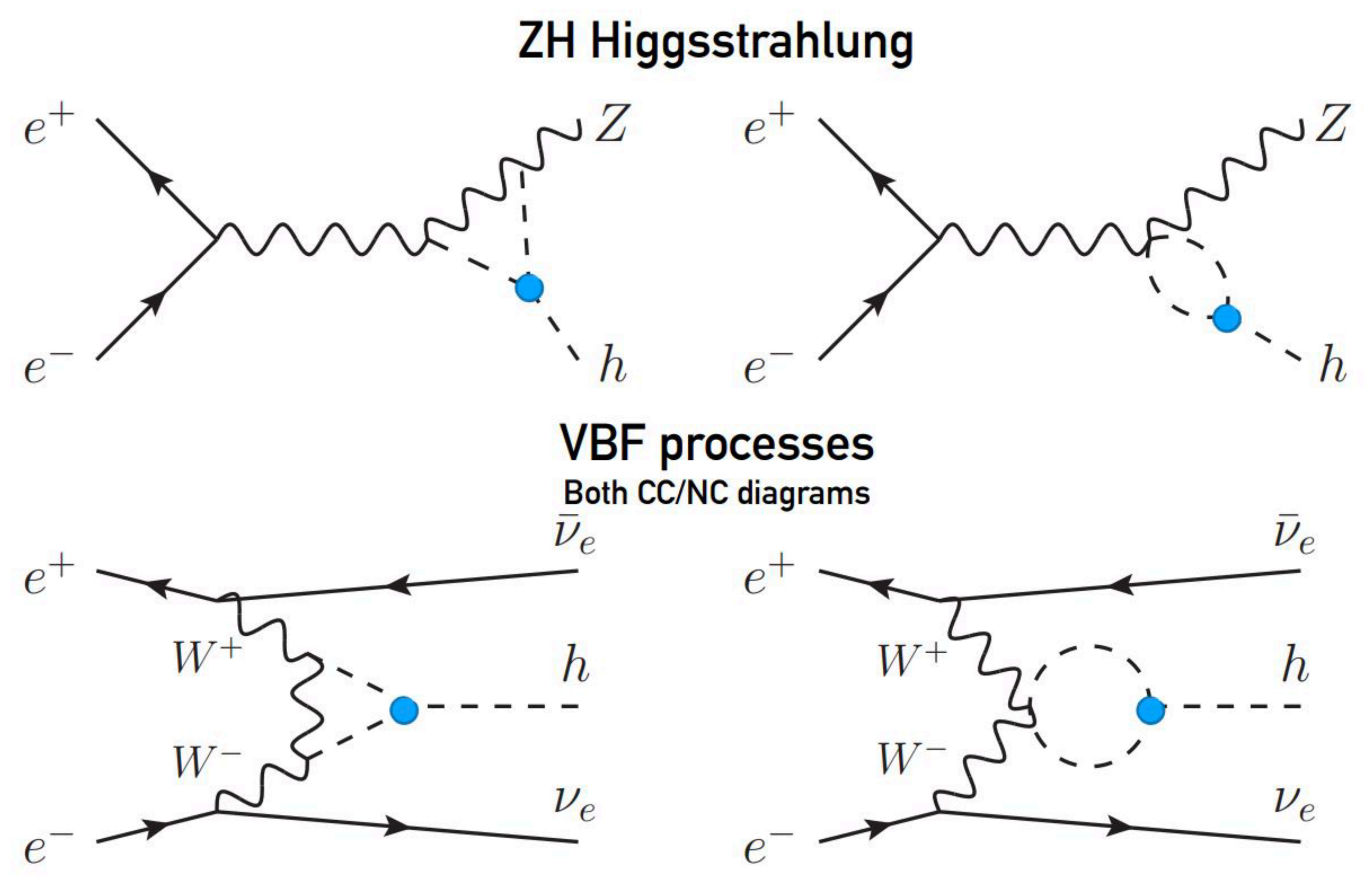


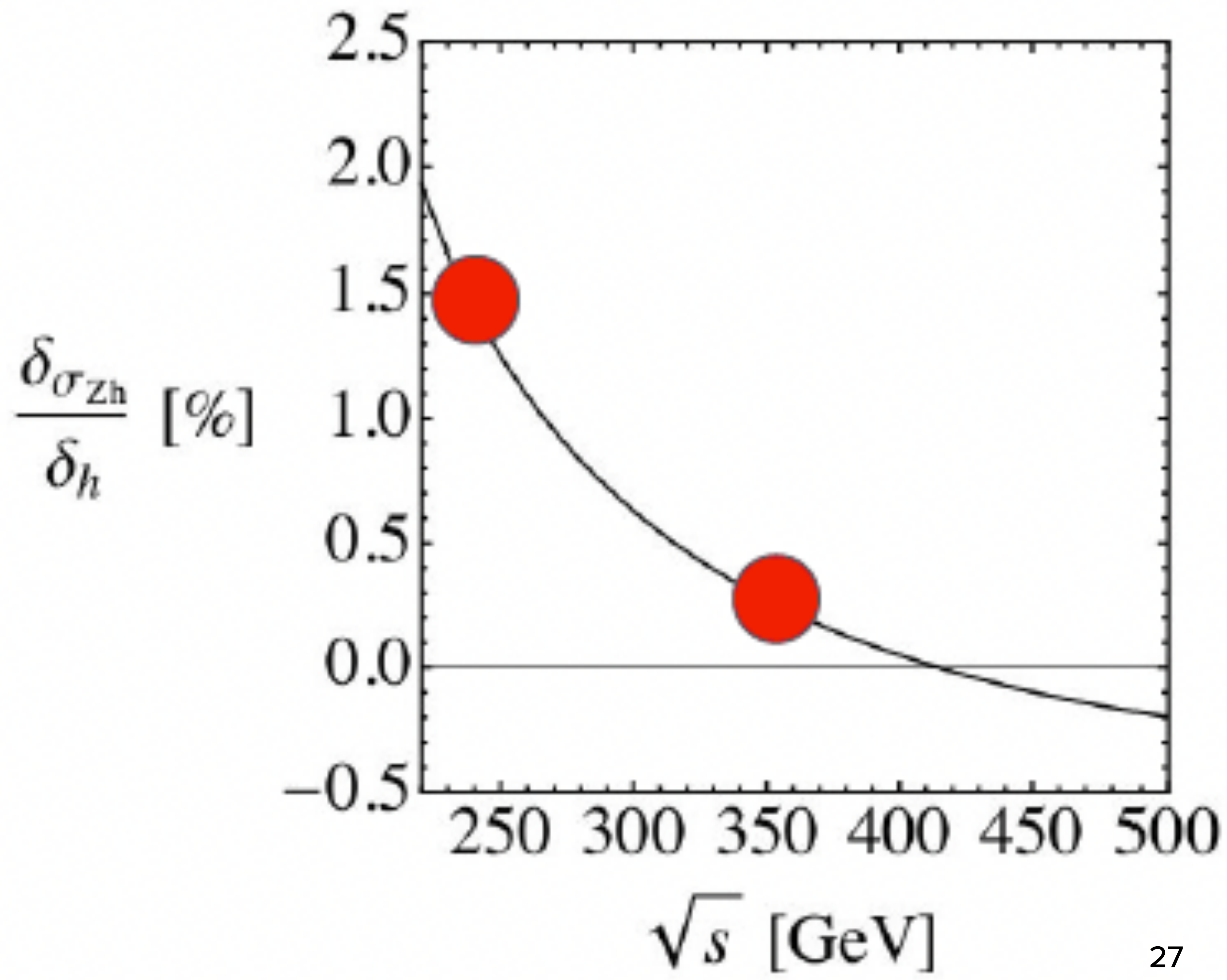
HIGGS SELF-COUPLING

- Observation of HH and 50% uncertainty on κ_λ expected for HL-LHC

- **At FCCee: indirect probe through single Higgs**
  - HHH coupling effects are sqrt(s) dependent
  - HZZ coupling effects maybe constant with sqrt(s)
  - Aim: 30% precision (dedicated analysis ongoing)

- Beyond e+e-: at FCChh 3.5-8% for SM (3% stat. only) and **10-20%** for $\lambda_3 = 1.5^* \lambda_3^{SM}$ (hep-ex/2004.03505)



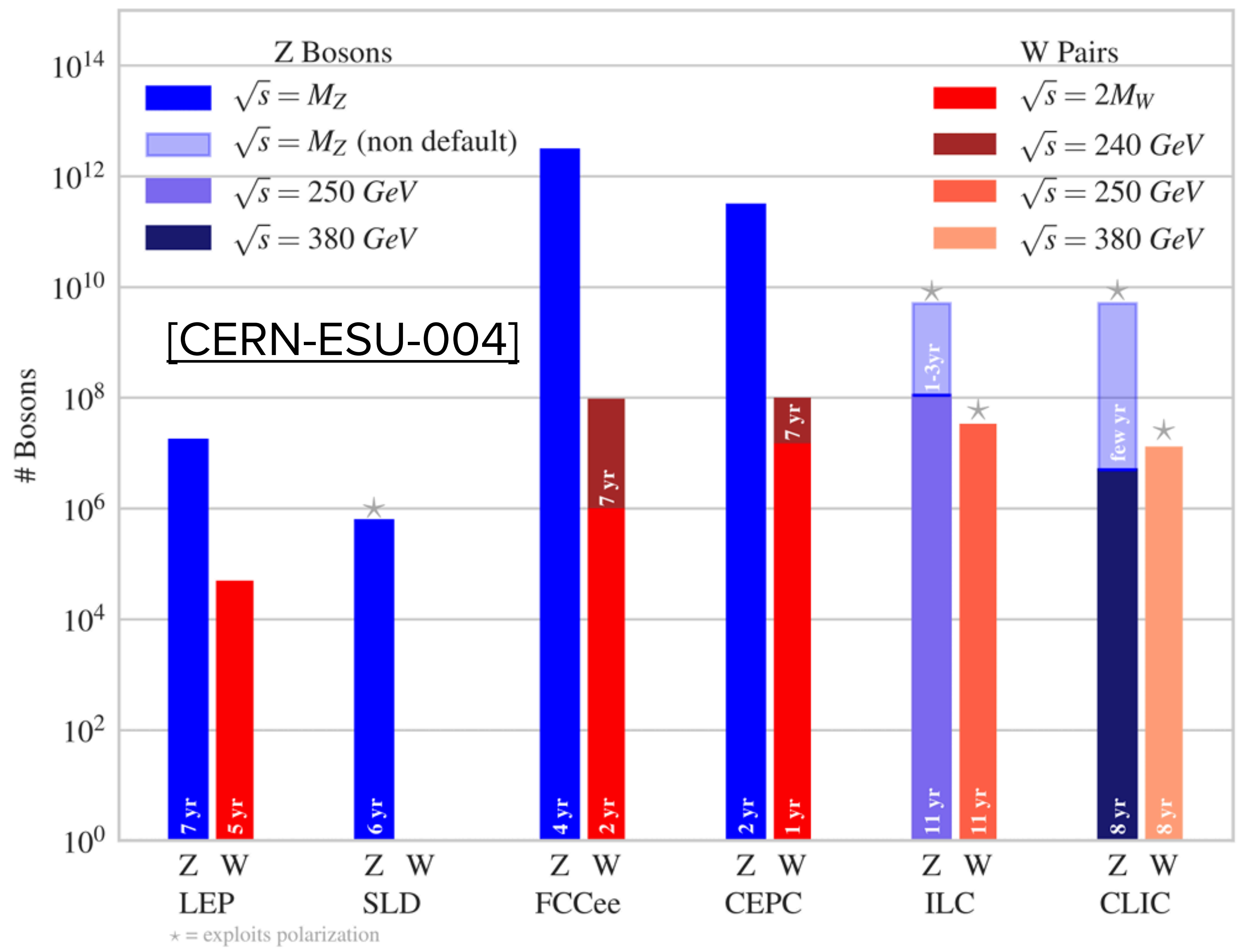


NOT ONLY HIGGS...

FCC feasibility Mid-term report -
Deliverable #8, physics and Experiments

FUTURE CIRCULAR COLLIDER

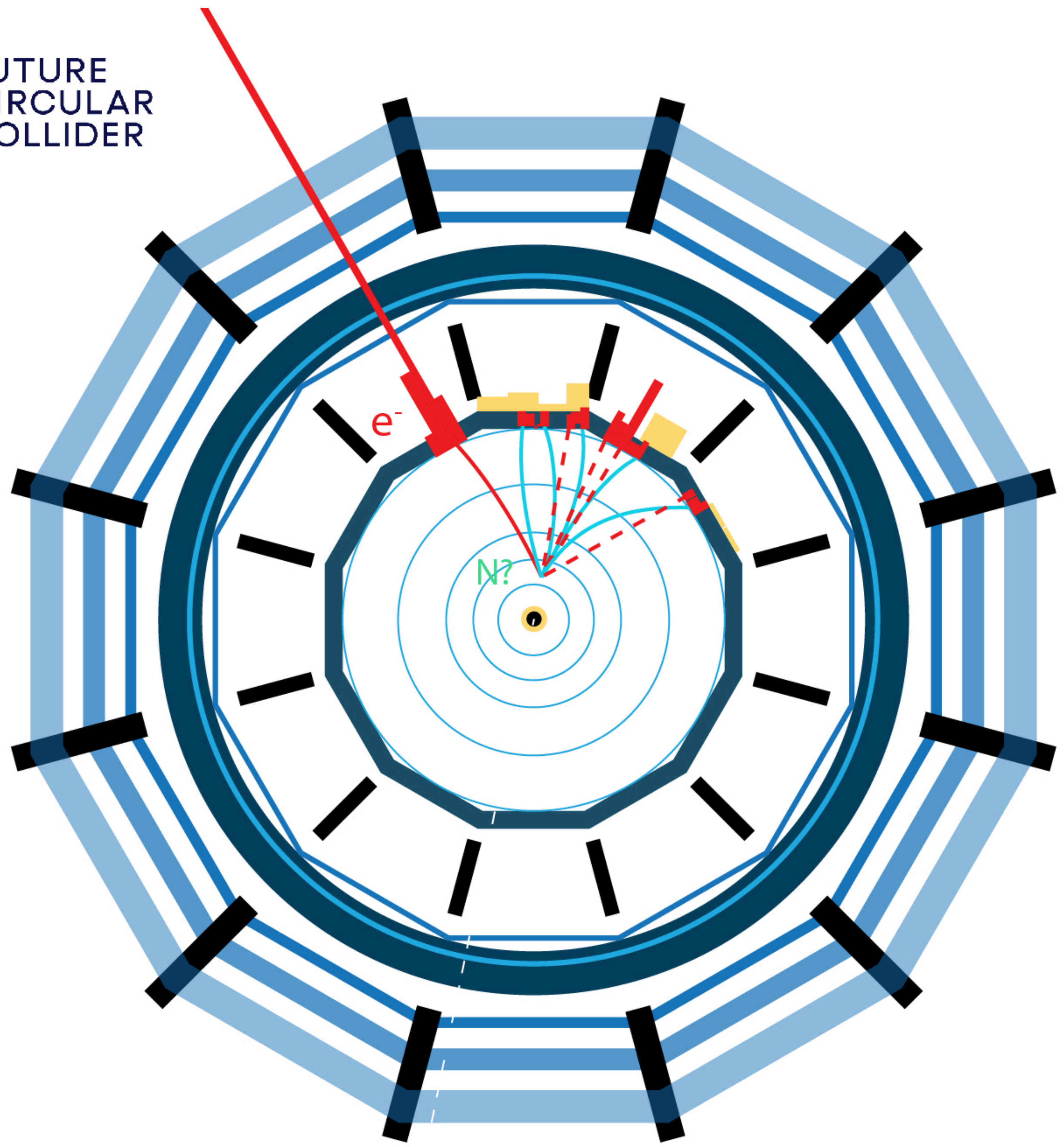
- Dedicated W and Z runs with unprecedented statistics
- Z pole run ➜ LEP Statistical uncertainties divided by ~1000
- Comprehensive measurements of the Z lineshape and many Electroweak Precision Observables
- Direct and uniquely precise determinations of α_{QED}(mZ) (for the first time) and α_S(mZ)



Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma^0_{\rm had}$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	<60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	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

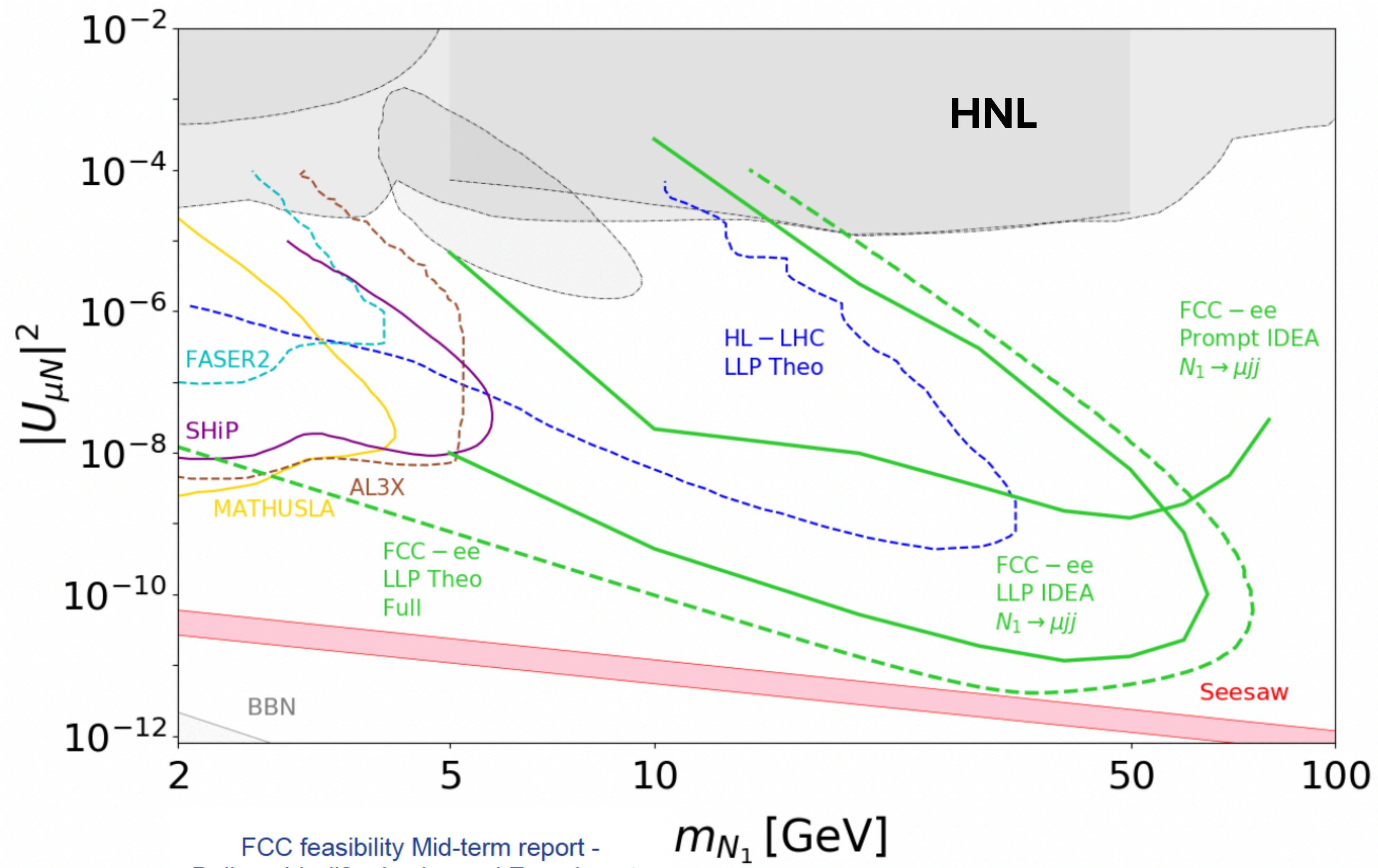
BSM @ FCCee

FUTURE CIRCULAR COLLIDER

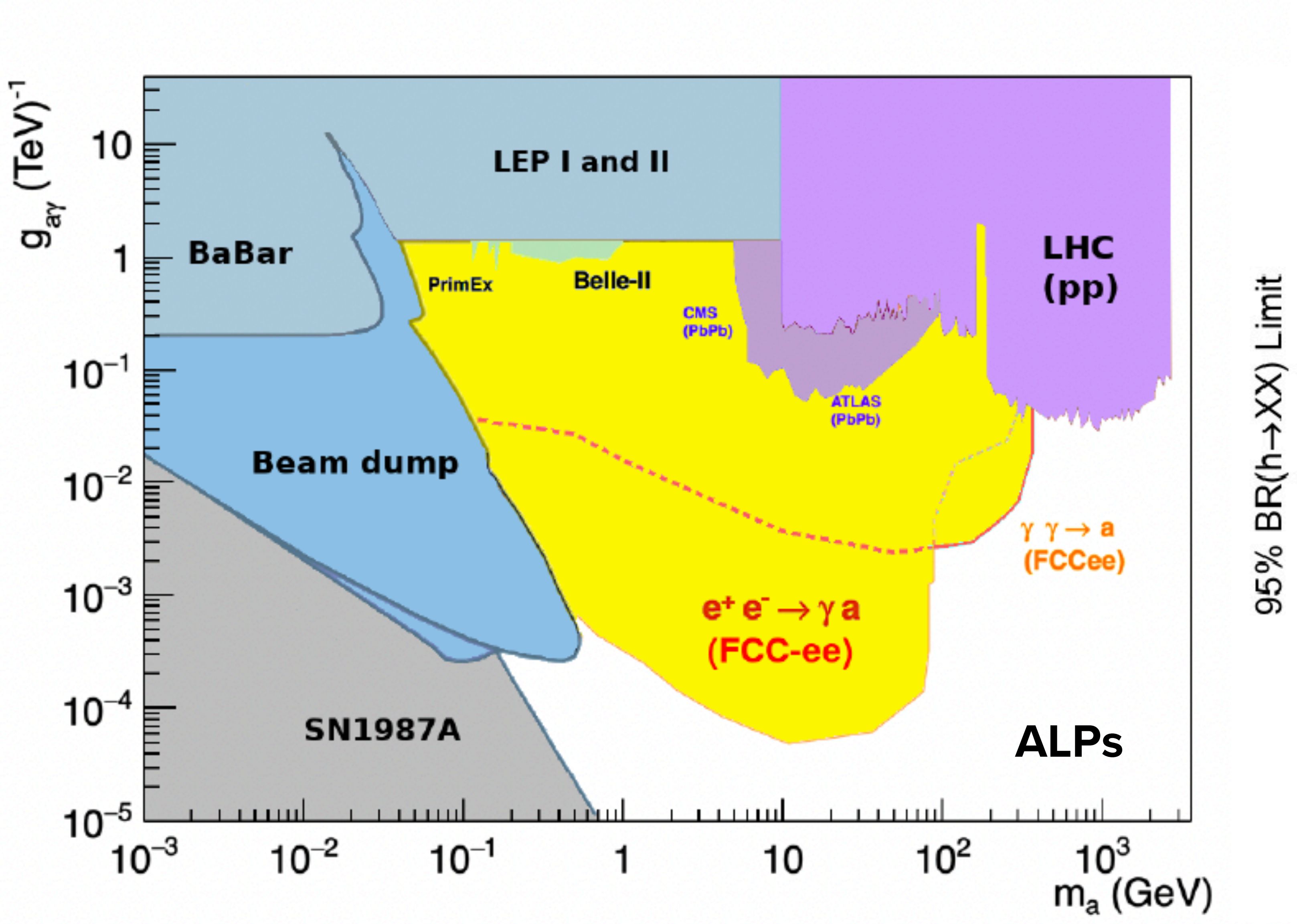


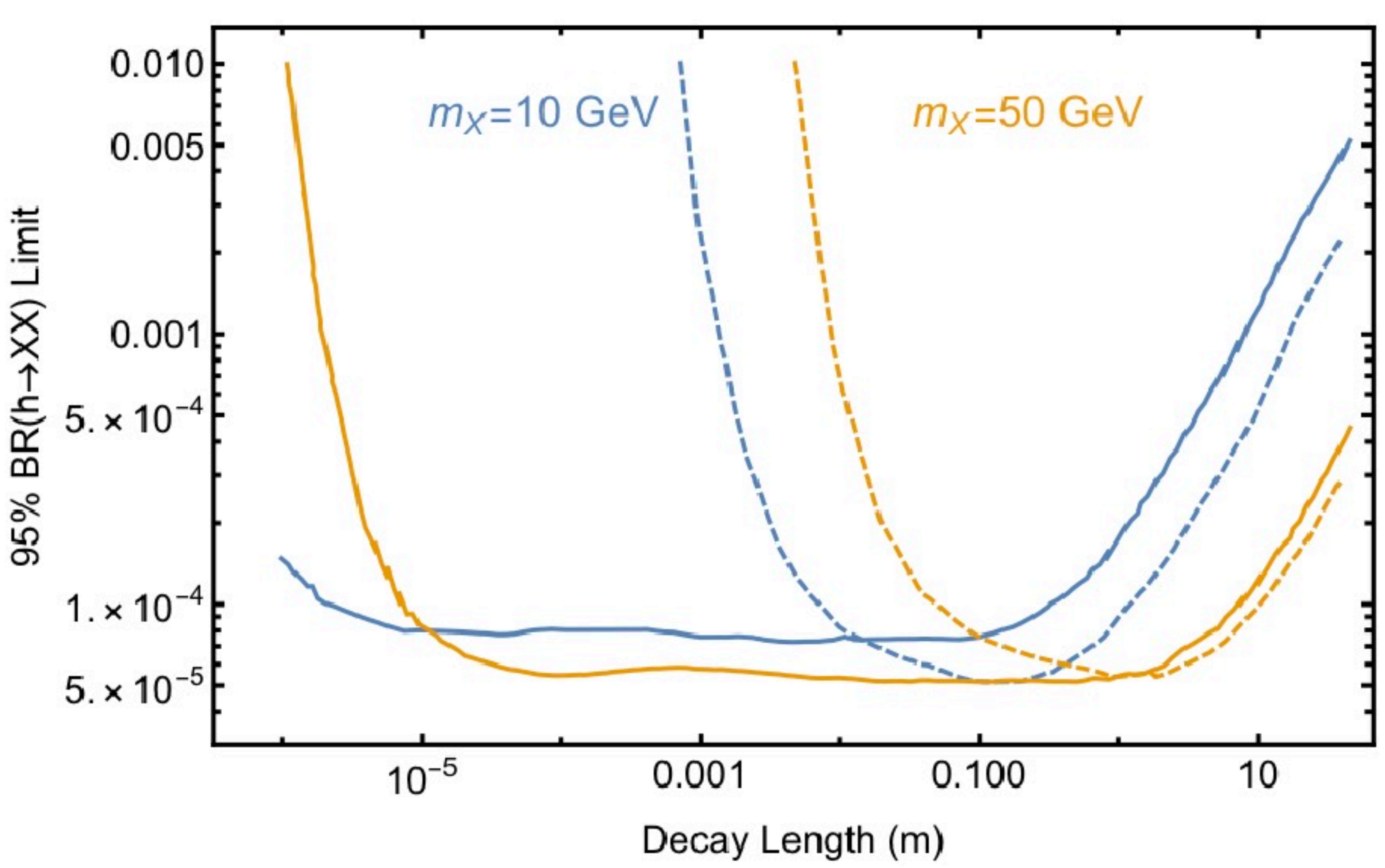
Beyond the potential for indirect BSM exploration through the SMEFT, and other precision/search cases —> Direct searches

- Clean environment, high luminosity, and large acceptance, direct scrutiny of O(1-100) GeV mass range for new particles
- Dark/hidden sectors that connect feebly to the SM via mediators (dark photon)
- Exotic decays of the Z or Higgs boson
- Specially interesting are signature-driven searches for non-mainstream signals

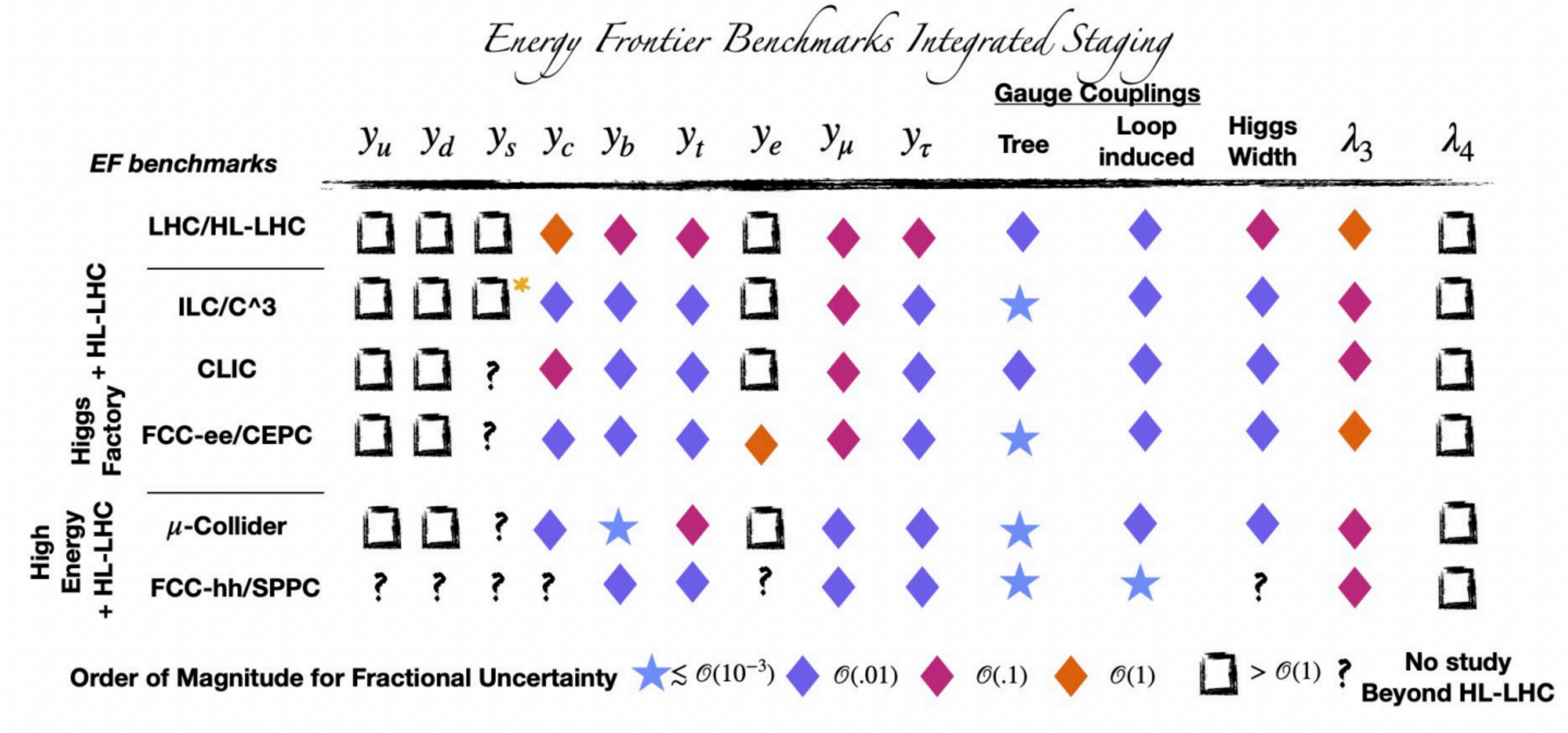


FCC feasibility Mid-term report - Deliverable #8, physics and Experiments





AND LET'S NOT FORGET THE FUTURE BEYOND ee...



[hep-ex/2211.11084]

SUMMARY

- In 2012 we knew we had found a new particle that looked like the Higgs boson, but we did not yet know what it was
- 12 years later, we have measured its properties, observed it couple to bosons and fermions, and studied of its kinematics with increasing precision. It is now one of our best tools to understand the standard model and go beyond.
- Do we really understand what it is, what it implies for the universe? Measuring precisely its properties is one of the keys to the unknown BSM realm, and one of the main goals of experimental particle physics today
- **A deep study of the Higgs sector, together with an exploration of what is beyond the SM, is a priority for the field. And the FCCee is a unique machine for this purpose.**
- **Credit and thanks to J. Alcaraz, D. d'Enterria, J. Eysermans, R. Gonzalez Suarez , M. Selvaggi for their help with material & discussion for preparing the talk!**

THANKS!

MINISTERIO
DE CIENCIA, INNOVACIÓN
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Cofinanciado por
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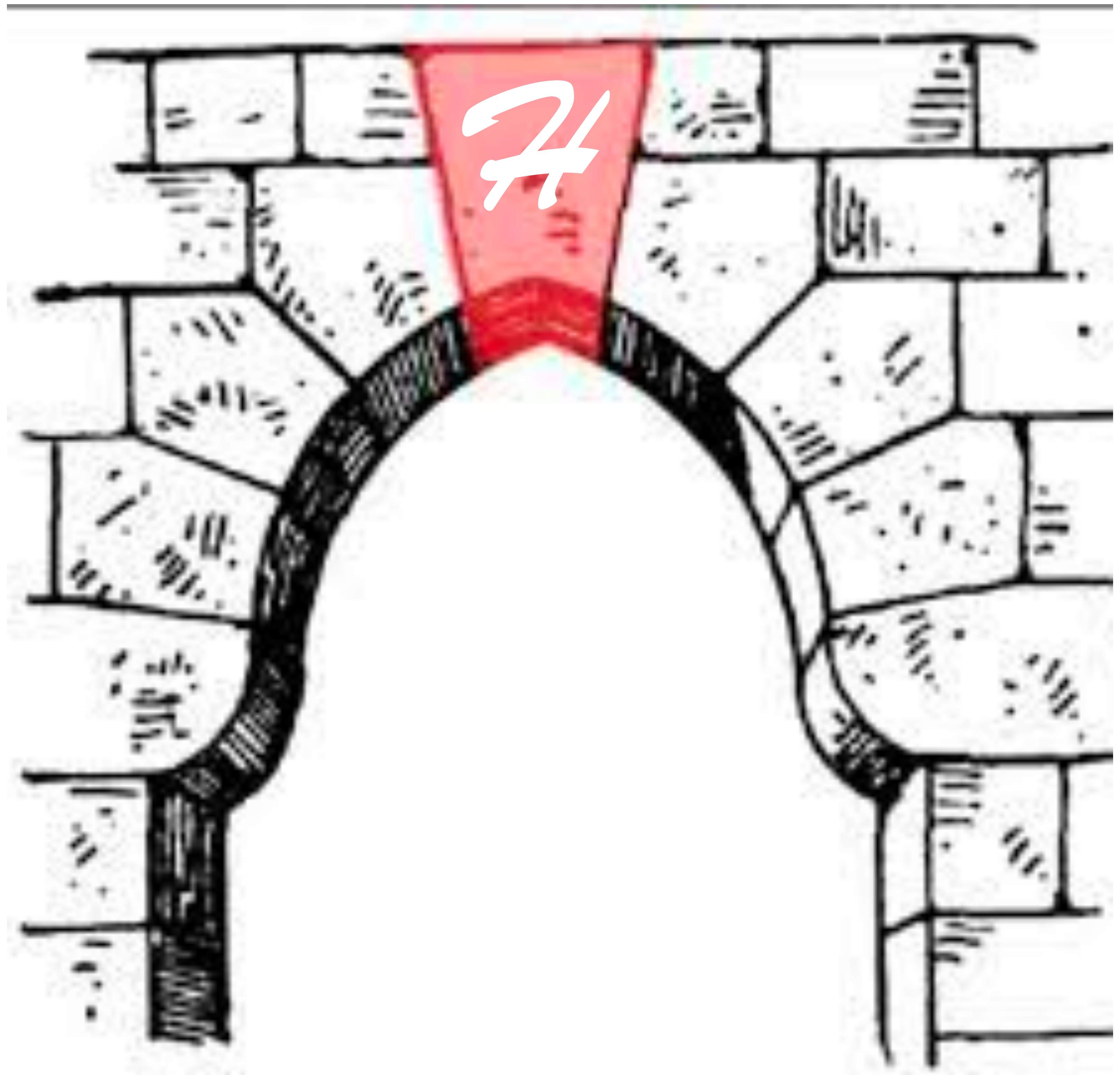
AGENCIA
ESTATAL DE
INVESTIGACIÓN

Grant Generación de Conocimiento 2021: PID2021-122134NB-C21 funded by MICIU/AEI/ 10.13039/501100011033 and ERDF A way of making Europe



Keystone to the Standard Model ?

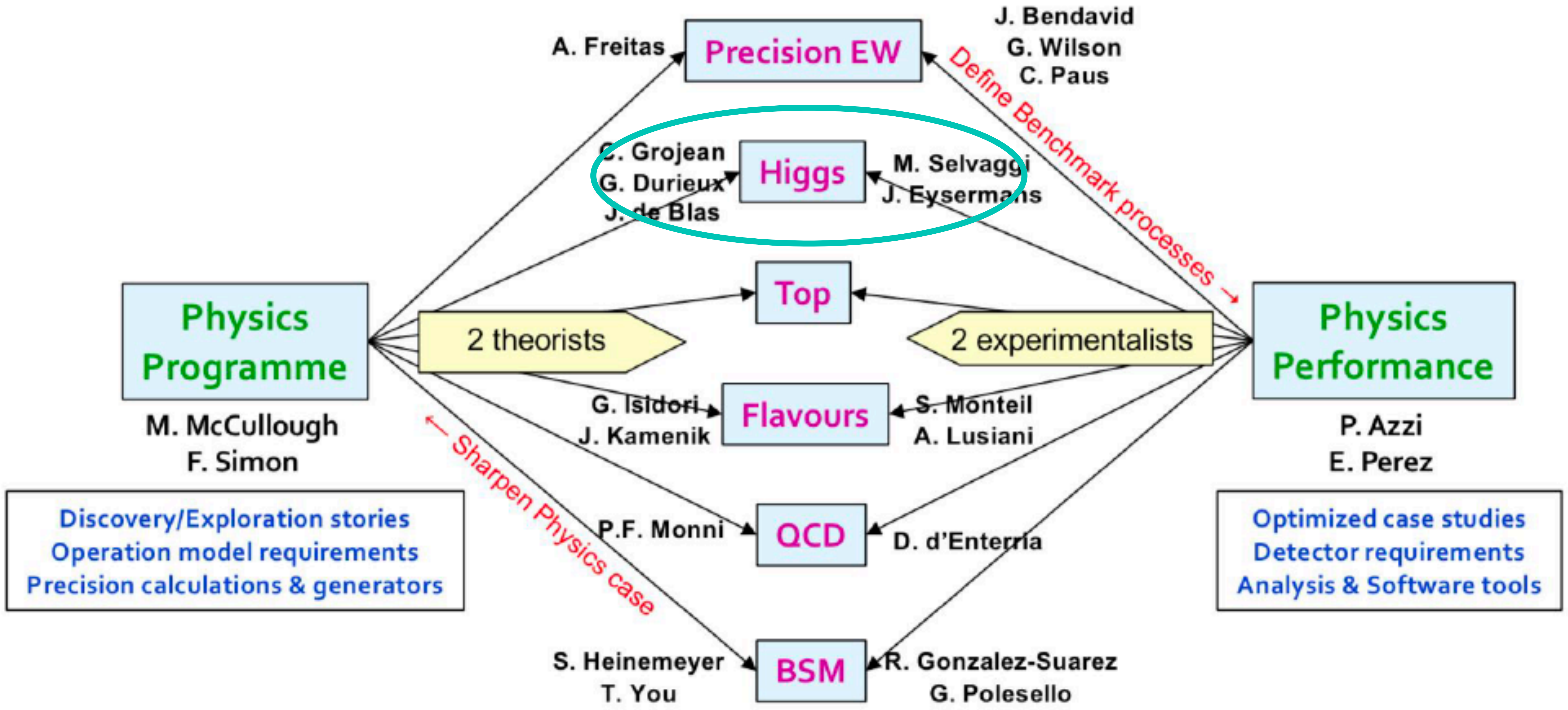
Or key to the portals of BSM?

HIGGS MASS

Collider Scenario	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ (%)
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[83]	1.9
HL-LHC	$m(ZZ)$	10-20	[10]	0.12-0.24
ILC_{250}	ZH recoil	14	[3]	0.17
$CLIC_{380}$	ZH recoil	78	[85]	1.3
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[15]	[85]	0.56
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23	[85]	0.53
FCC-ee	ZH recoil	~~11~~	[86]	0.13
CEPC	ZH recoil	5.9	[2]	0.07

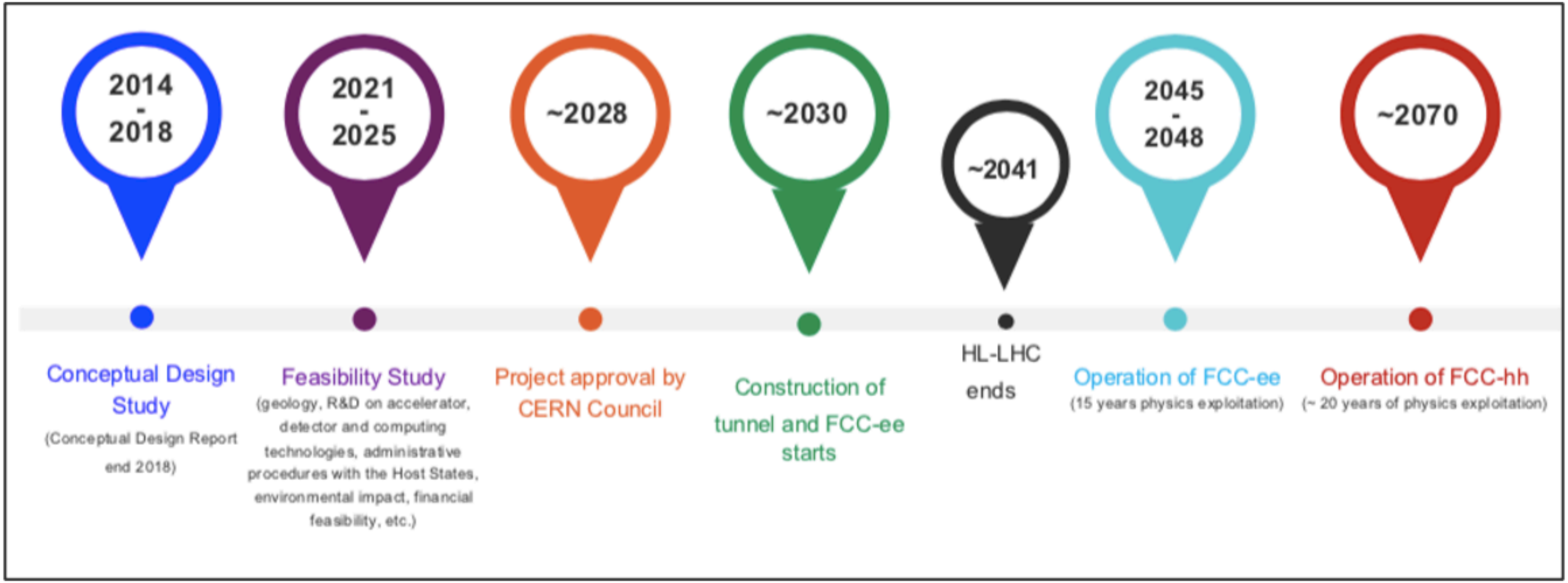
(OLD Summary table
for ECFA 2020)

EXPERIMENTAL PROGRAMME



- Analysis statistically driven, but high precision requires excellent detector performance —> optimizing the detector requirements for Higgs studies for the FCC Feasibility studies (end 2025).
  - Mid-term report (2023, soon to be made public) already includes the base for key Higgs performance.

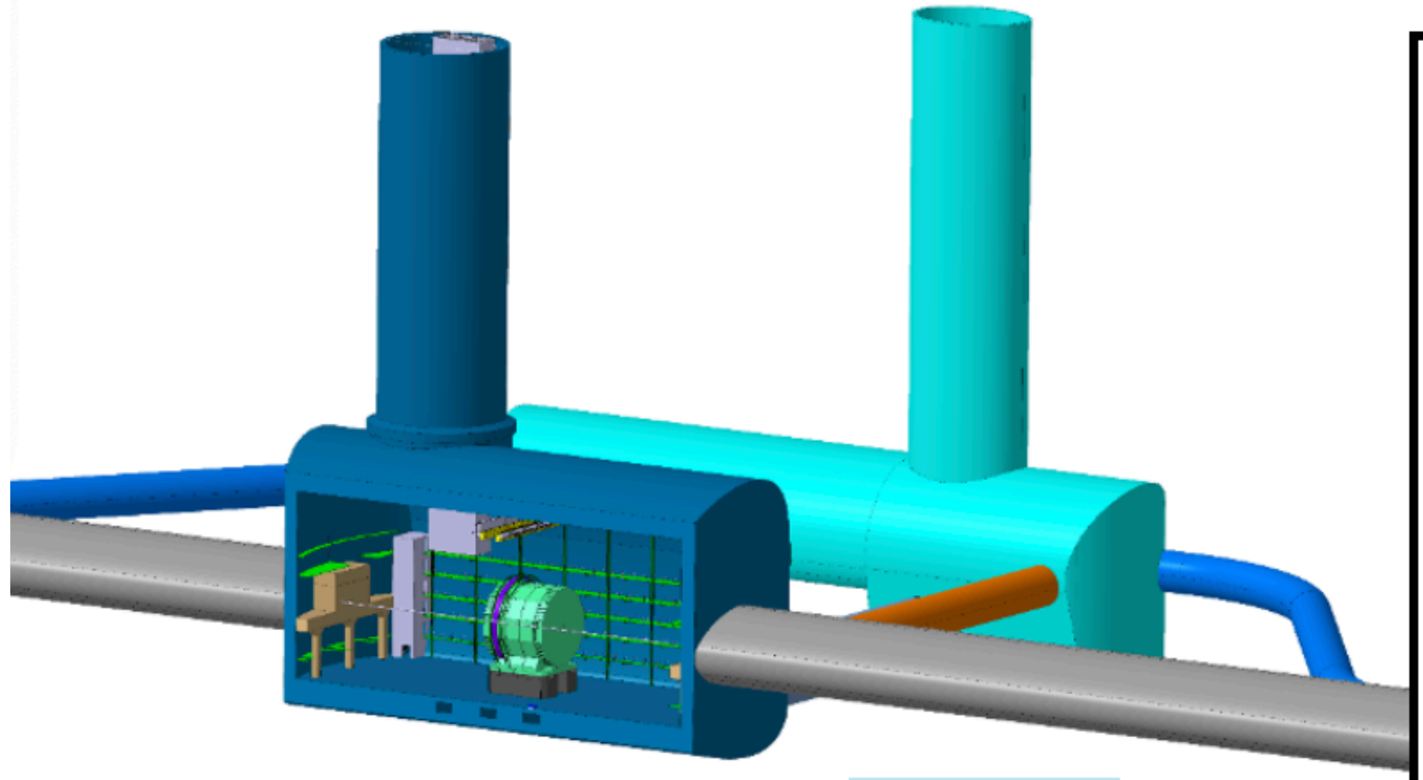
TIMELINE


2014
-
2018
2021
-
2025
~2028
~2030
~2041
2045
-
2048
~2070
Conceptual Design Study
(Conceptual Design Report end 2018)
Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)
Project approval by CERN Council
Construction of tunnel and FCC-ee starts
HL-LHC ends
Operation of FCC-ee
(15 years physics exploitation)
Operation of FCC-hh
(~ 20 years of physics exploitation)

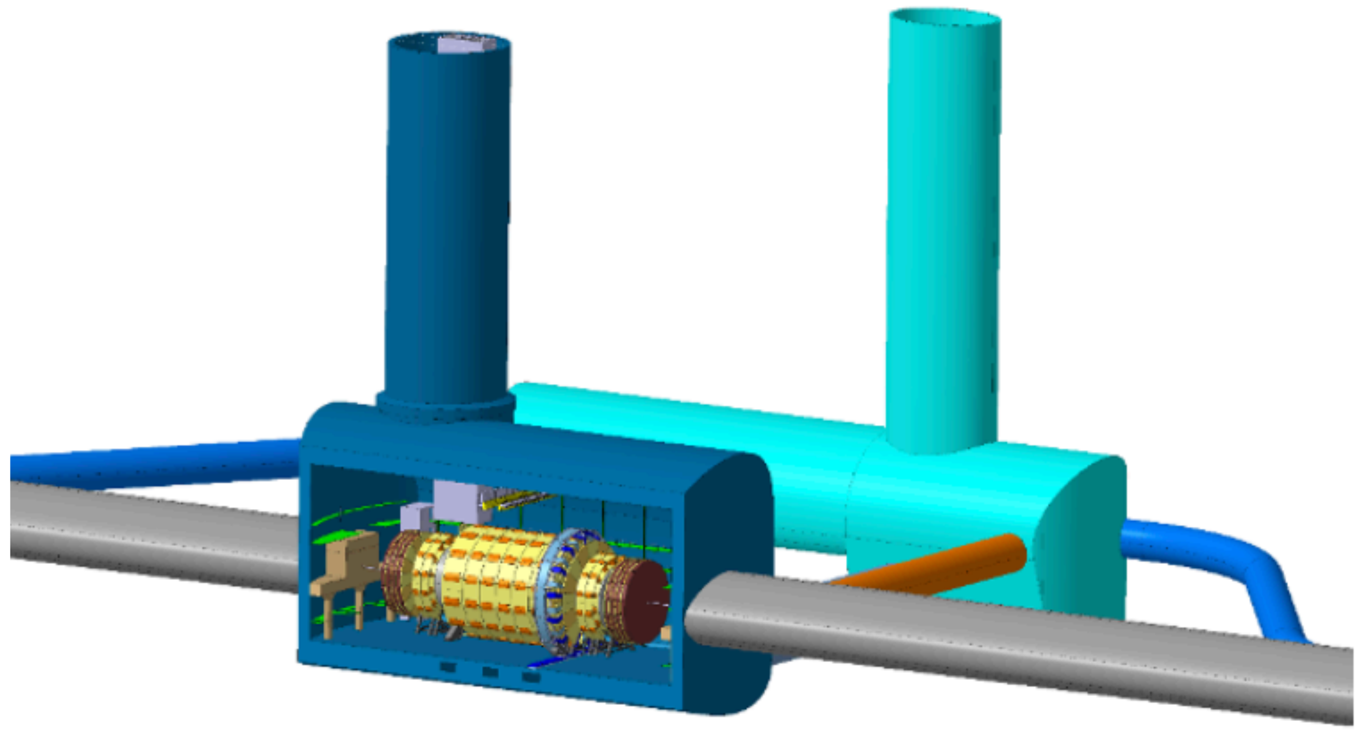
FCCEE: HUGE STATISTICS & PRECISION

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

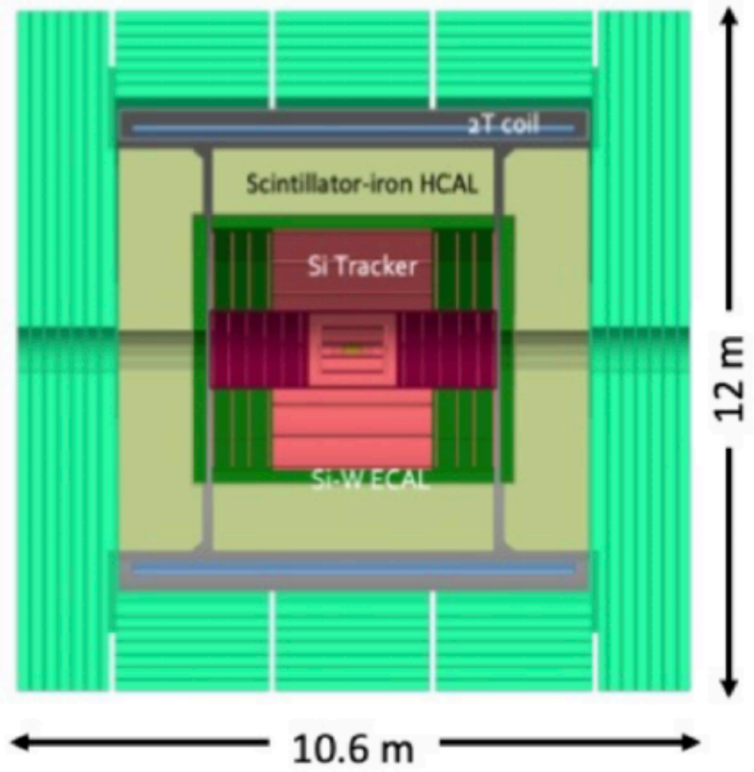
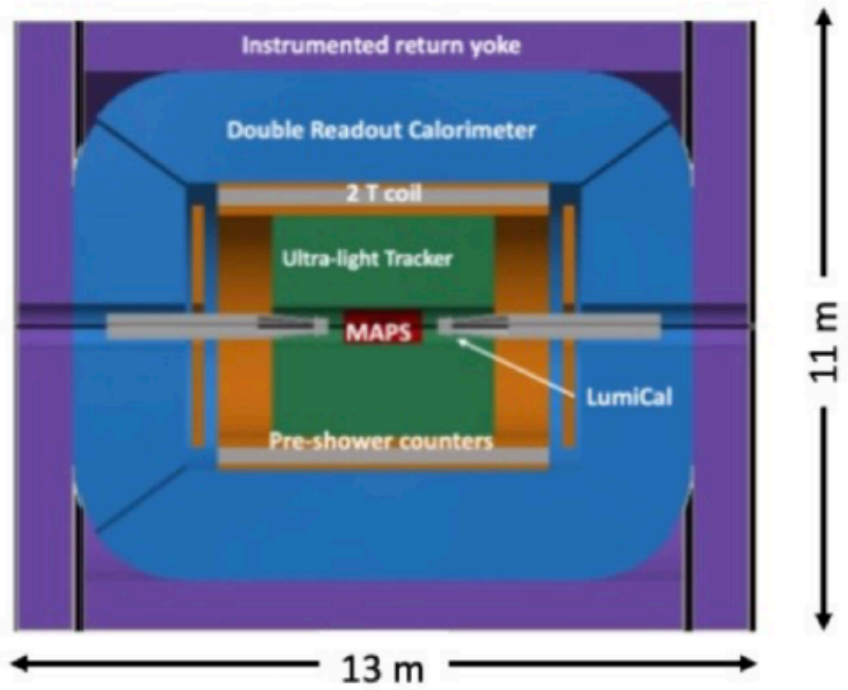
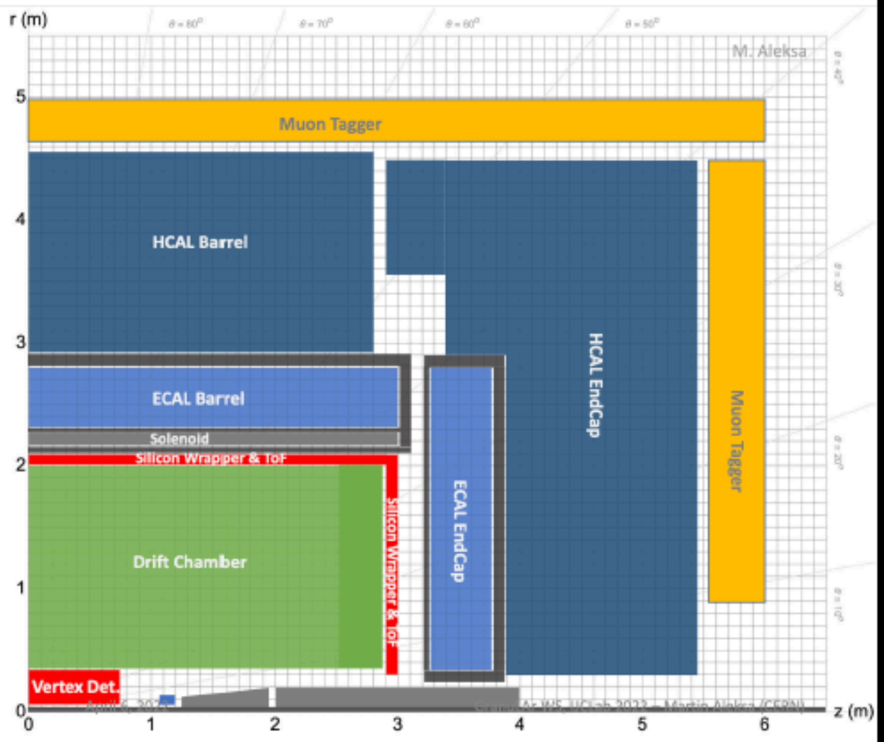
Detector concepts



FCC-ee



FCC-hh

CLD	IDEA	ALLEGRO
		
Based on CLIC detector design, arXiv:1911.12230 Full silicon vertex detector and tracker 3D-imaging highly-granular calorimeter system Coil outside calorimeter system	Innovative, possibly cheaper than CLD https://pos.sissa.it/390/819 Baseline in many ongoing studies Silicon vertex detector Short-drift, ultra-light wire chamber Dual-readout calorimeter Thin and light solenoid coil inside calorimeter system	GranuLAr WS, IJCLab 2022 – Martin Aleksa Highly granular noble-liquid calorimeter Thin 2T solenoid in the calorimeter cryostat.

More complementary options possible (4 IP!) → Can we optimize detector designs for the complete physics program? Yes! opportunities to contribute

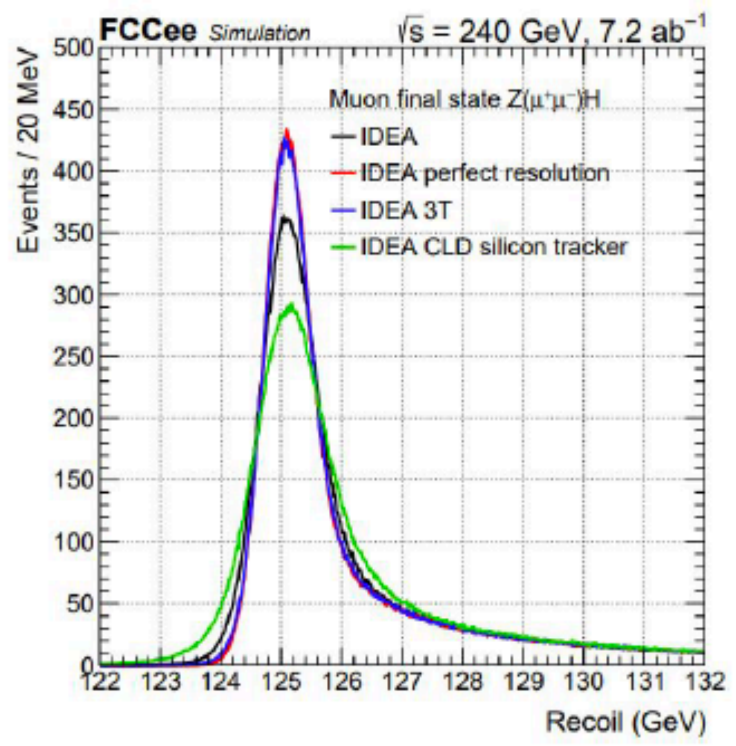
slide by R. Gonzalez Suarez at ZPW 24

Higgs Mass – Detector Requirements

FUTURE CIRCULAR COLLIDER

Extended studies performed regarding detector/accelerator effects on the Higgs mass

→ Looking at impact on m_H uncertainty stat. (stat.+syst.) in MeV



Nominal configuration → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution (*)

Nominal 2 T → field 3 T → Magnetic field 3T

IDEA drift chamber → CLD Si tracker → CLD 2T (silicon tracker)

Impact of Beam Energy Spread uncertainties → BES 6% uncertainty, Disable BES

Perfect (=gen-level) momentum resolution → Ideal resolution

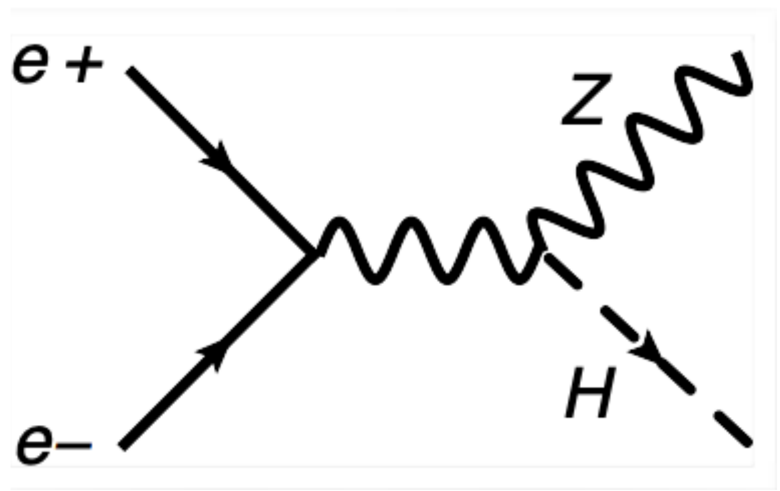
Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	4.10 (4.88)	5.17 (5.85)	3.14 (4.01)
Inclusive	4.84 (5.53)	6.16 (6.73)	3.75 (4.50)
Degradation electron resolution (*)	4.10 (4.88)	5.98 (6.49)	3.32 (4.11)
Magnetic field 3T	3.38 (4.28)	4.30 (5.00)	2.60 (3.54)
CLD 2T (silicon tracker)	5.51 (6.07)	6.20 (6.70)	4.01 (4.66)
BES 6% uncertainty	4.10 (5.01)	5.17 (6.10)	3.14 (4.09)
Disable BES	2.27 (3.42)	3.11 (4.04)	1.80 (2.99)
Ideal resolution	2.89 (3.95)	3.89 (4.56)	2.39 (3.33)
Freeze backgrounds	4.10 (4.88)	5.17 (5.85)	3.14 (4.00)
Remove backgrounds	3.37 (4.34)	3.85 (4.80)	2.49 (3.56)

14

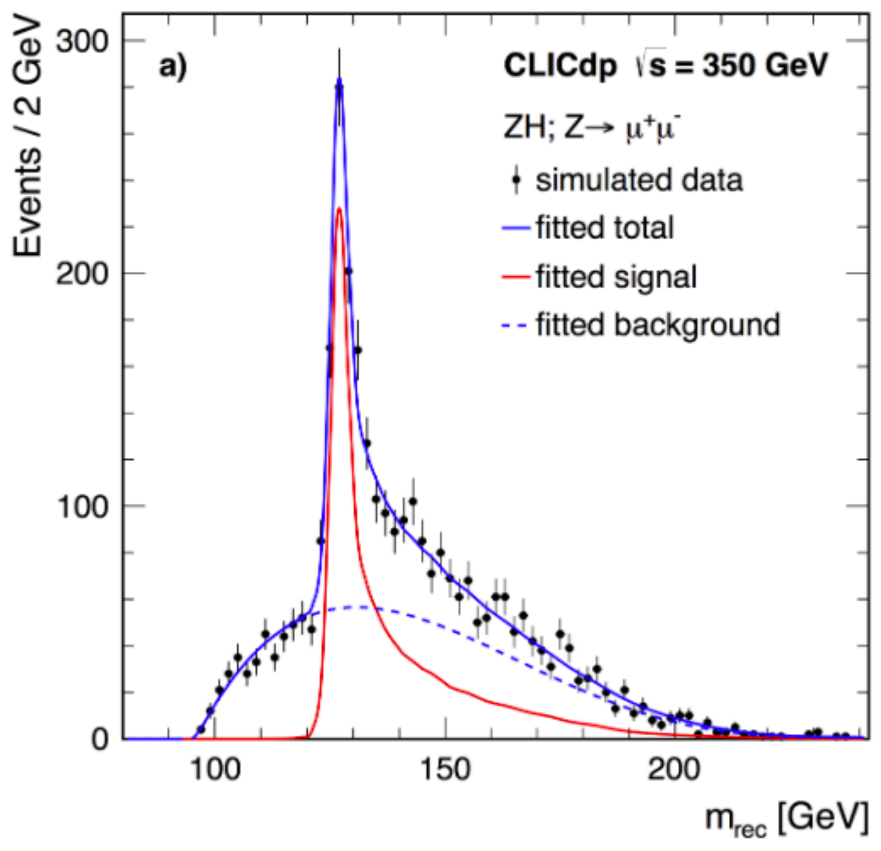
slide from J. Eysermans talk at the last FCC week

WIDTH IN E+E-

- Even with the HL-LHC statistics, with the study of HZZ on-shell and off-shell in pp collisions: 20% precision, and very model dependent
- Future lepton colliders could measure the width to ~1% through the recoil method, with milder model dependence
  - Recoil: measure the inclusive cross-section of the ZH without assumption on the Higgs BR's



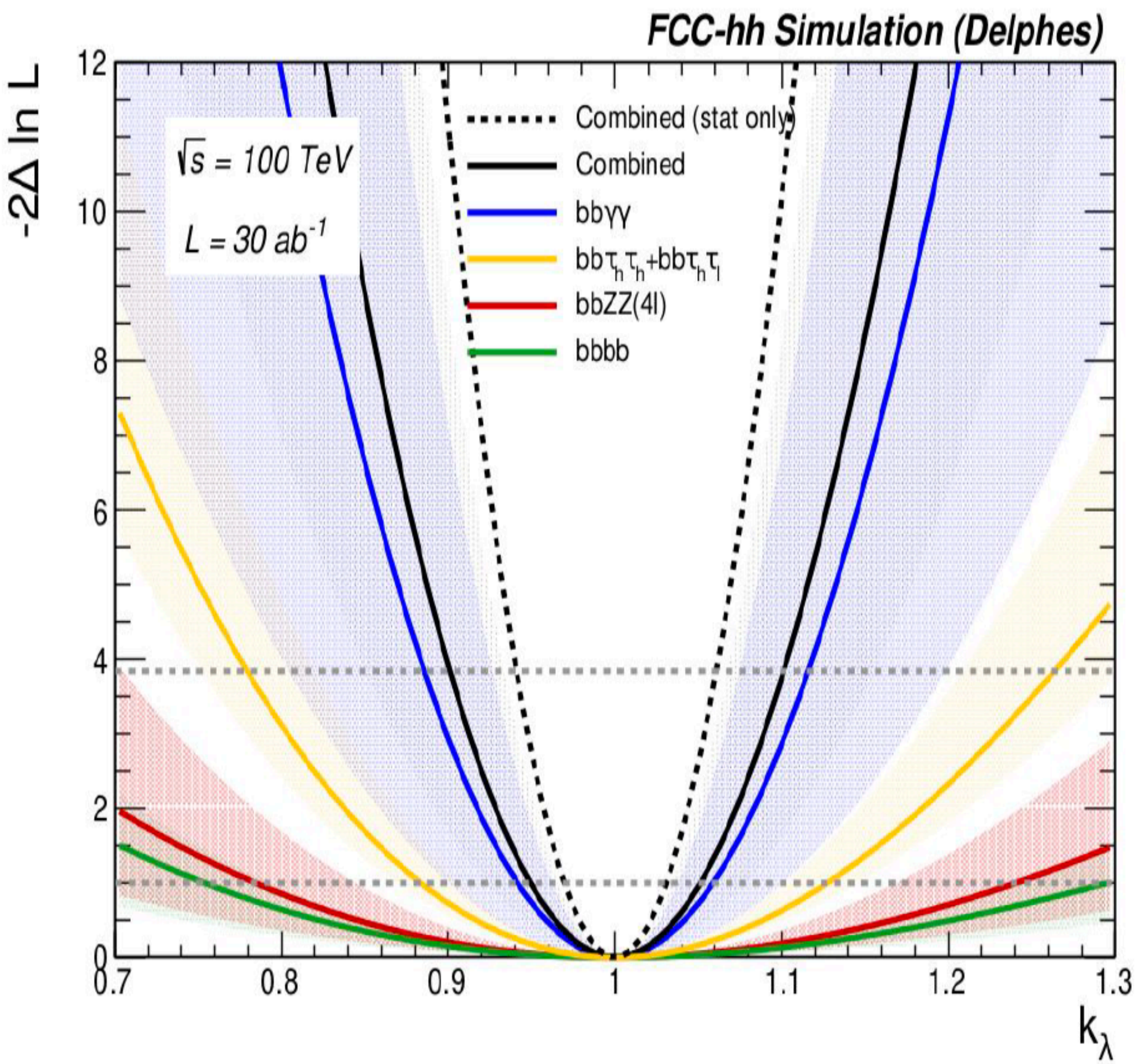
$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

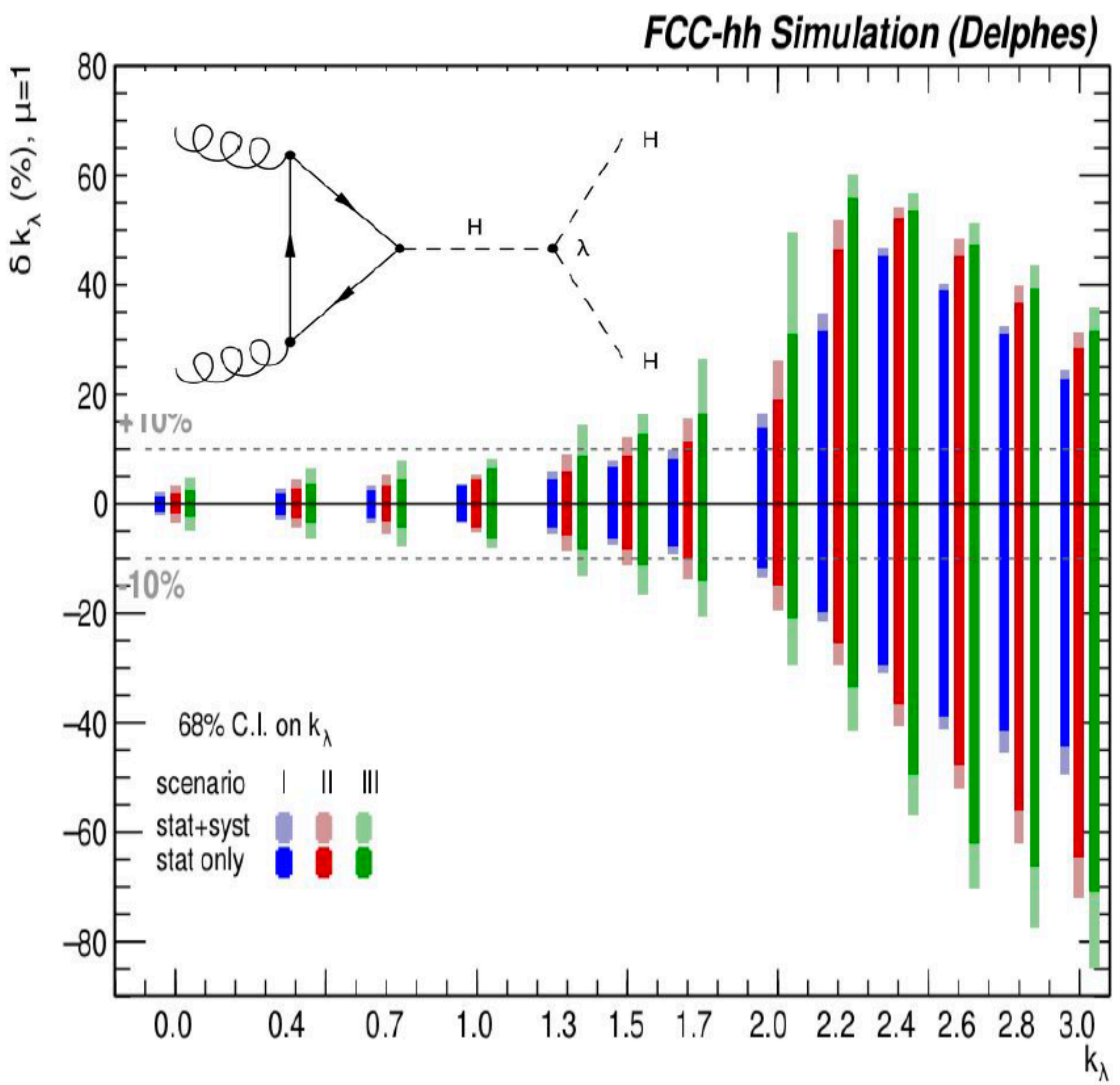


Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [80]	2.6
CLIC_{1500}	2.6	κ-framework [80]	1.7
CLIC_{3000}	2.5	κ-framework [80]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [85]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

JHEP01(2020)139

SELF-COUPLING AT FCCHH: 3-5% PRECISION





(hep-ex/2004.03505)

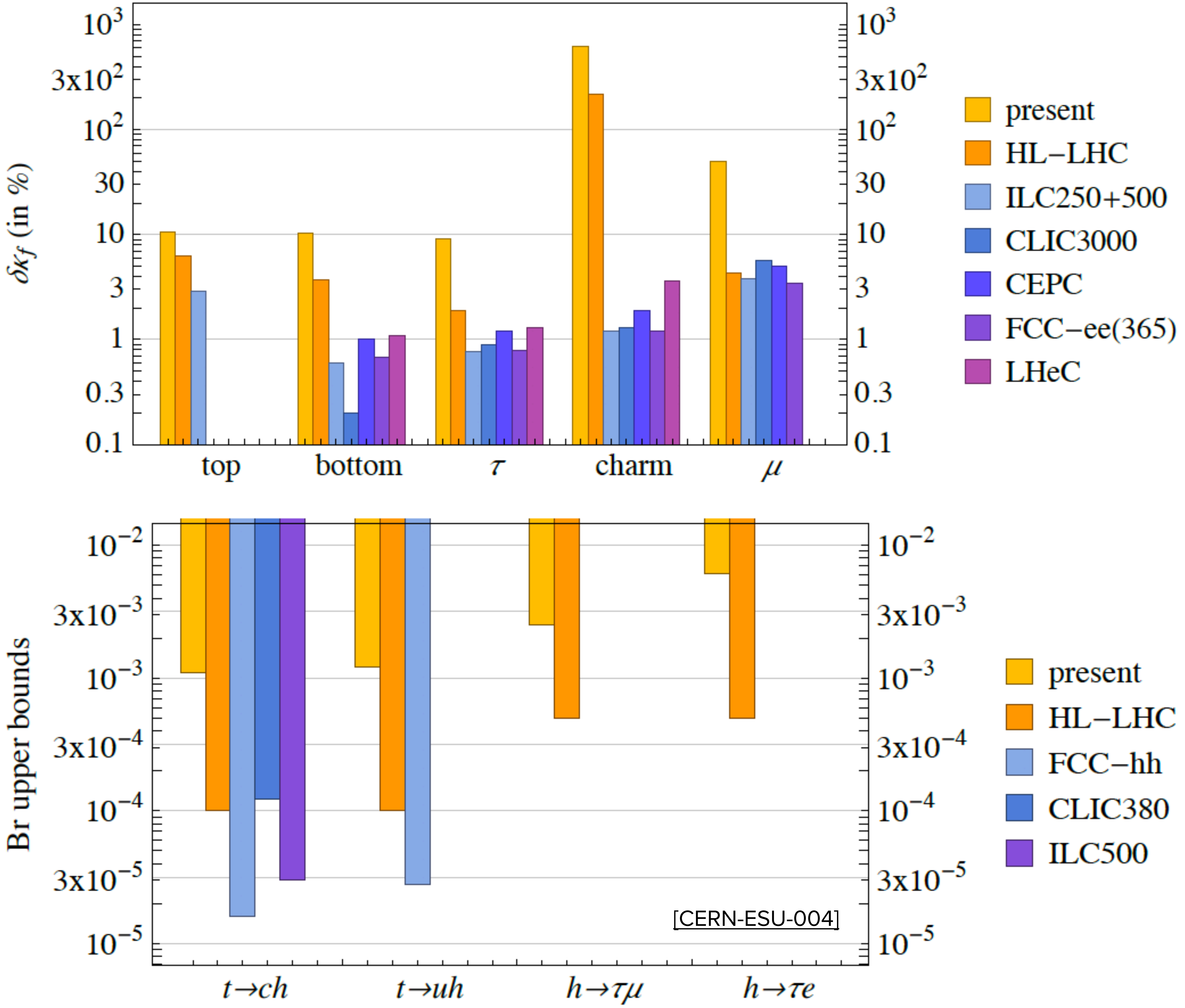
scenario I: Run2 performance (optimal)

scenario III: HL-LHC conditions with performance degradation (pessimistic)

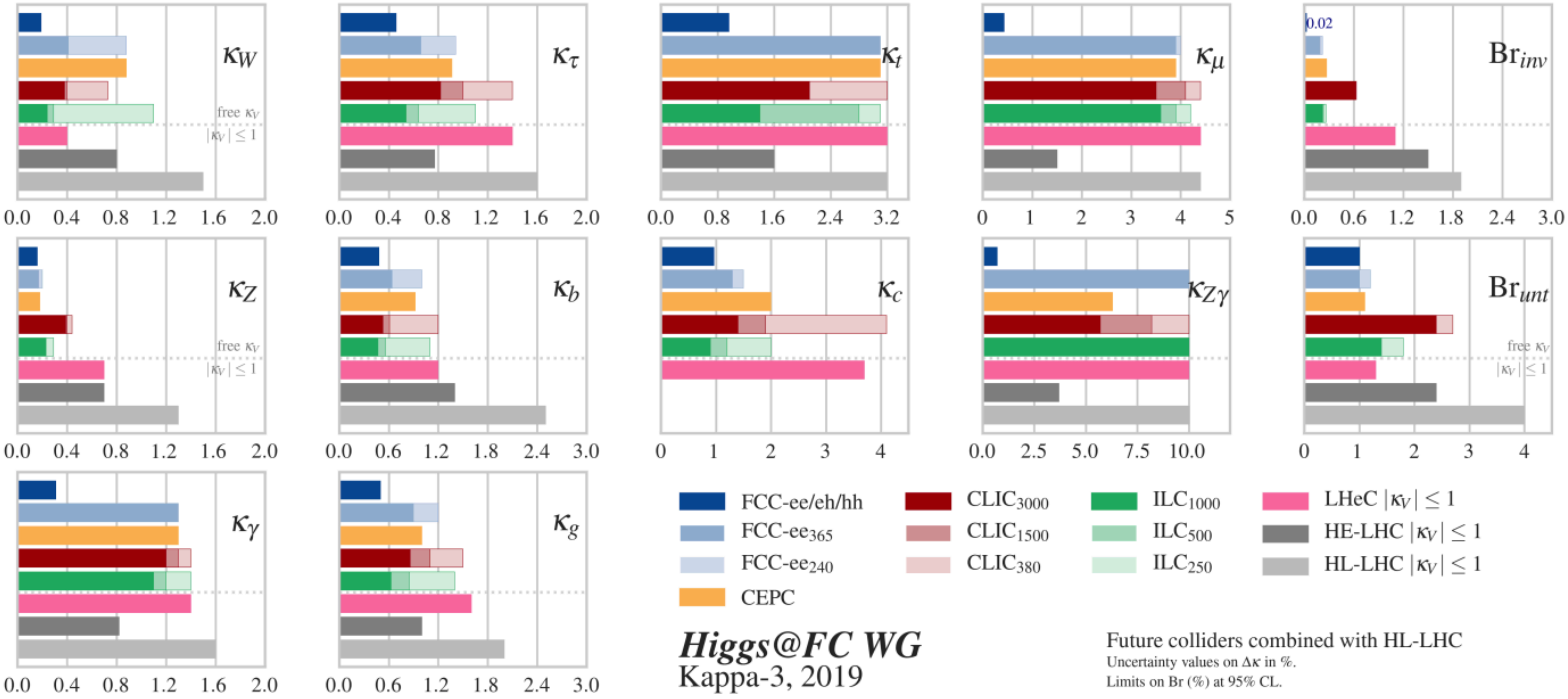
scenario II: intermediate case (assumed for left plot above)

HIGGS&FLAVOUR

- Are there surprises in the flavour sector?



HIGGS COUPLINGS IN THE FUTURE...

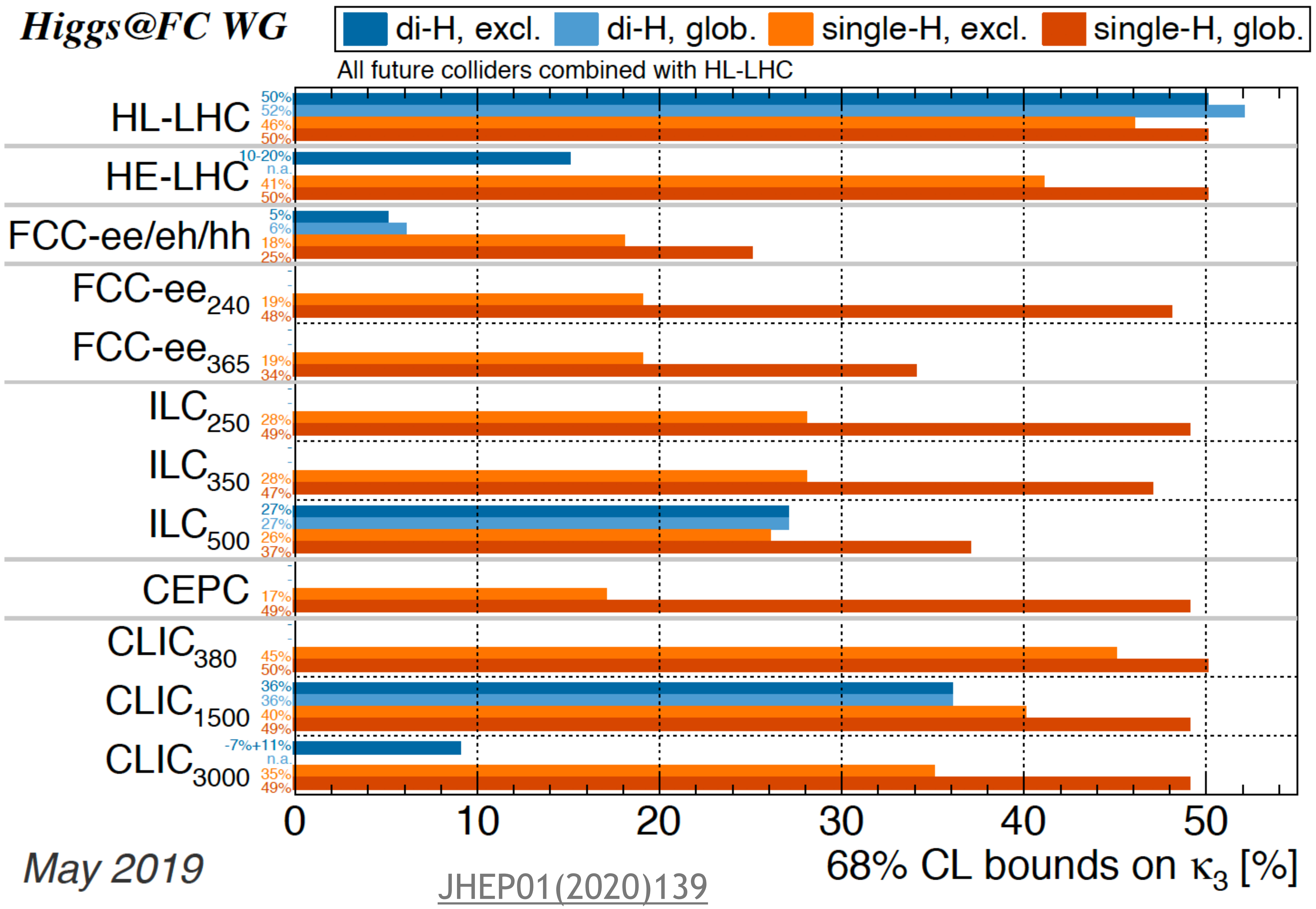


[CERN-ESU-004]

BEYOND HL-LHC

Di-Higgs:
HL-LHC: ~50% or better?
Improved by HE-LHC (~15%), ILC500(~27%), CLIC1500(~36%)
Precisely by CLIC3000(~9%), FCC-hh(~5%)
ILC 1000 (not in the plot) - 10%

Single-Higgs:
Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC (~21% if FCC-ee has 4 detectors)
Exclusive analysis: too sensitive to other new physics to draw conclusion



JHEP01(2020)139

HIGGS & CP?

$$\delta \mathcal{L}_{\rm CPV}^{hVV} = \frac{h}{v}\left[\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \tilde{c}_{aa}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{za}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}\right]$$

$$\mathcal{L}_{\rm CPV}^{hff} = -\bar{\kappa}_f m_f \frac{h}{v}\bar{\psi}_f(\cos\alpha + i\gamma_5\sin\alpha)\psi_f$$

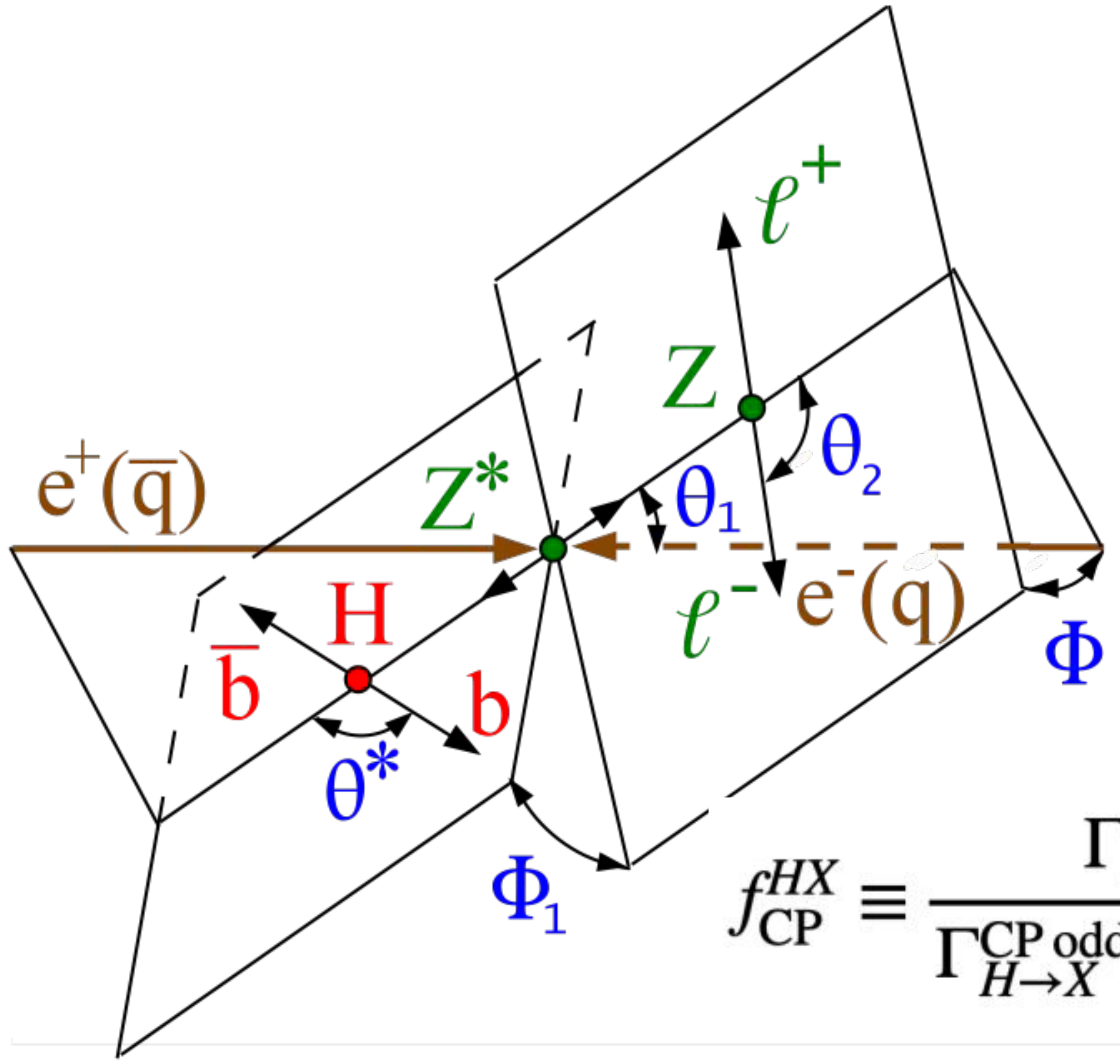
- Sensitivity to the CP-odd hVV weak operators: studies have been performed both at the level of rates/distributions and via CP-sensitive observables
- CP violation in fermionic Higgs decays: ττ decay channel -> measurement of the linear polarisations of both taus and the azimuthal angle between them

Name	α_τ	$\tilde{c}_{zz}$	Ref.
HL-LHC	8°	0.45 (0.13)	[10]
HE-LHC	–	0.18	[10]
CEPC	–	0.11	[2]
FCC-ee$_{240}$	10°	–	[1]
ILC$_{250}$	4°	0.014	[3]

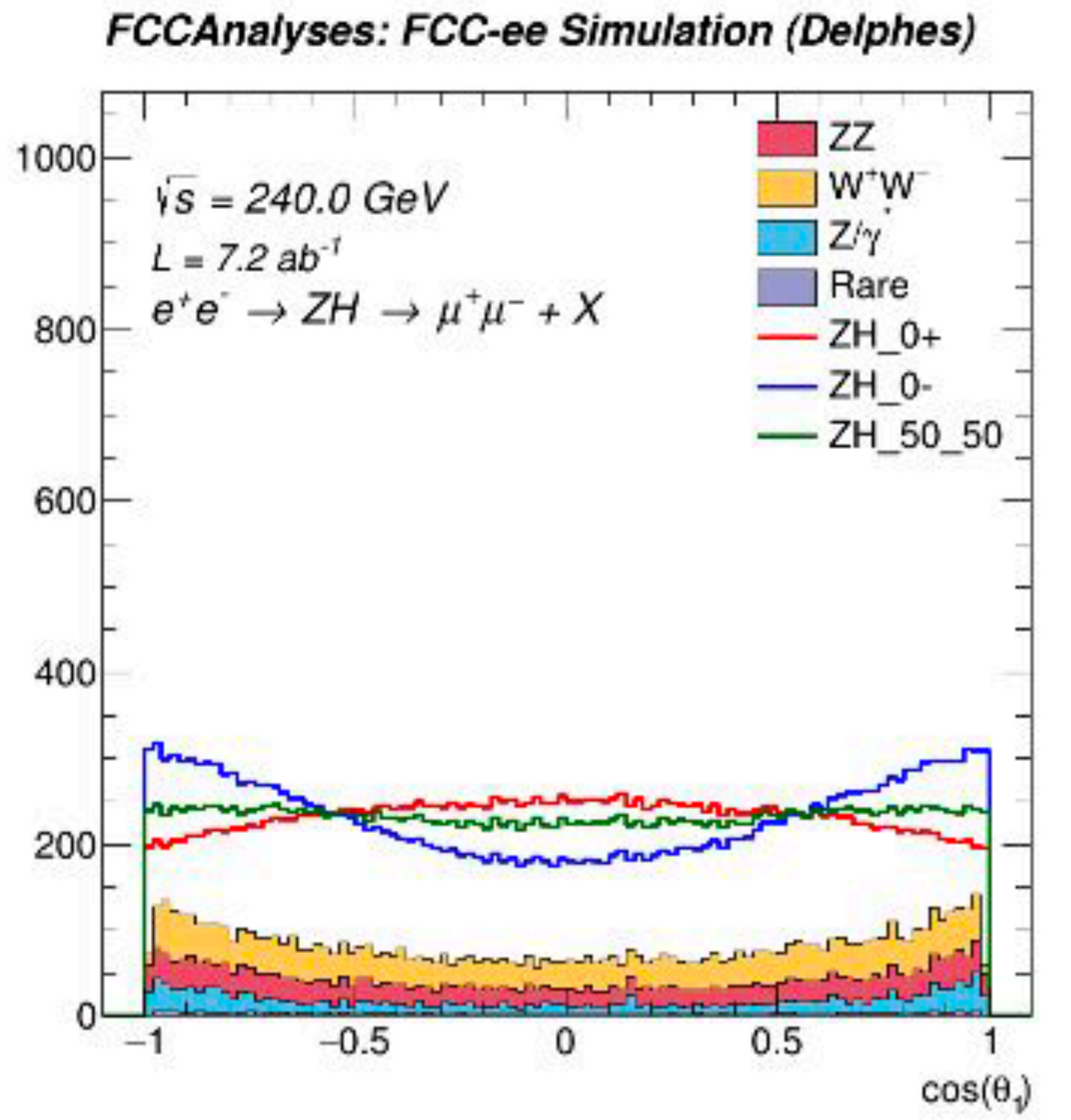
- CP violation in the top quark interactions: ttH and tH (rates and distributions):
  - HL-LHC: CP-odd Higgs excluded with 200fb^{-1}. CLIC 1.5 TeV : α_t (ttH) better than 15°. LHeC: Higgs interacting with the top quarks with CP-odd coupling excluded at 3 sigmas with 3 ab^{-1}. FCC-eh: precision of 1.9% on α_t.
  - Current indirect limits from EDM bounds are stronger than direct (though comparable for tau)

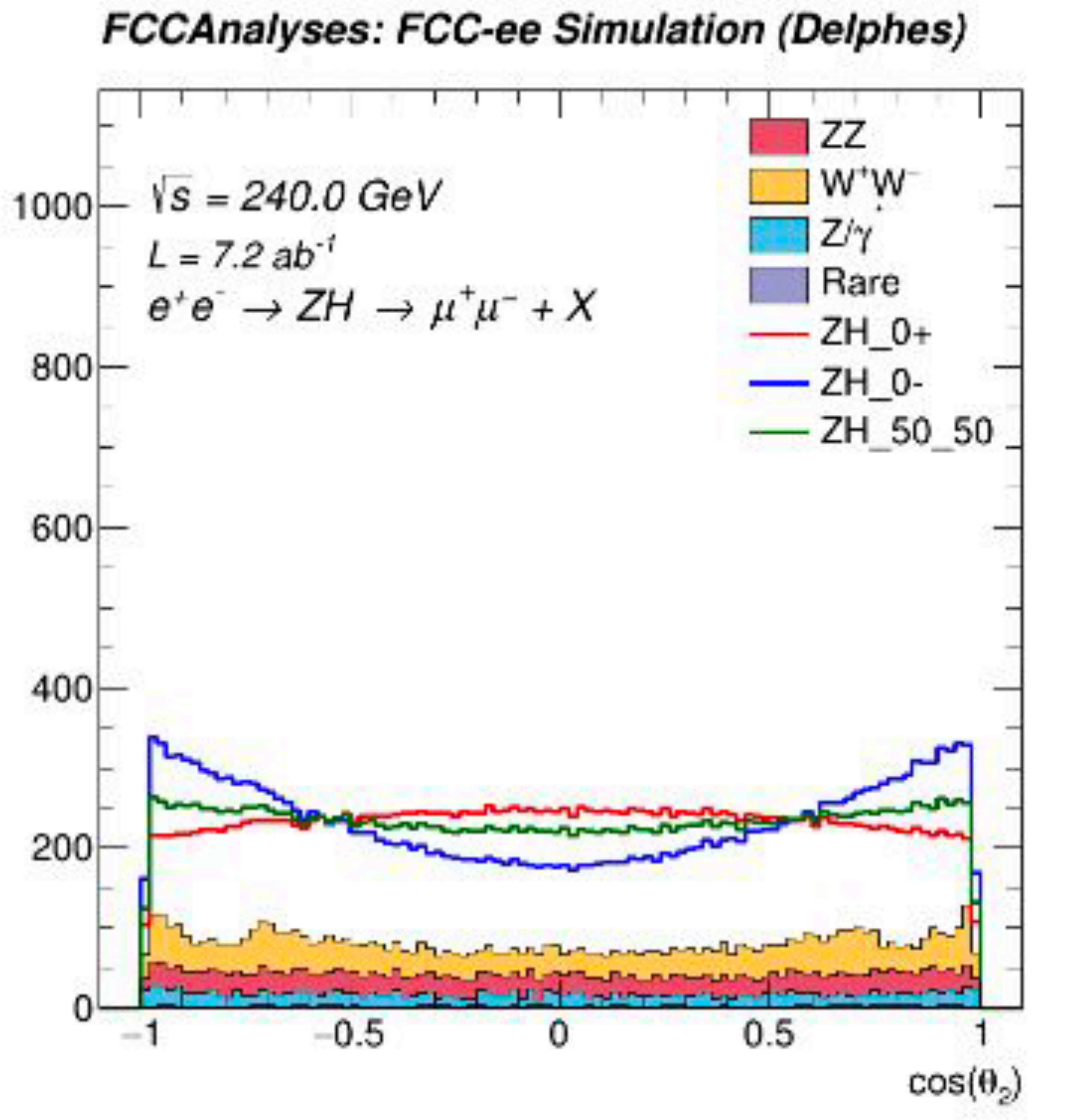
HIGGS & CP?

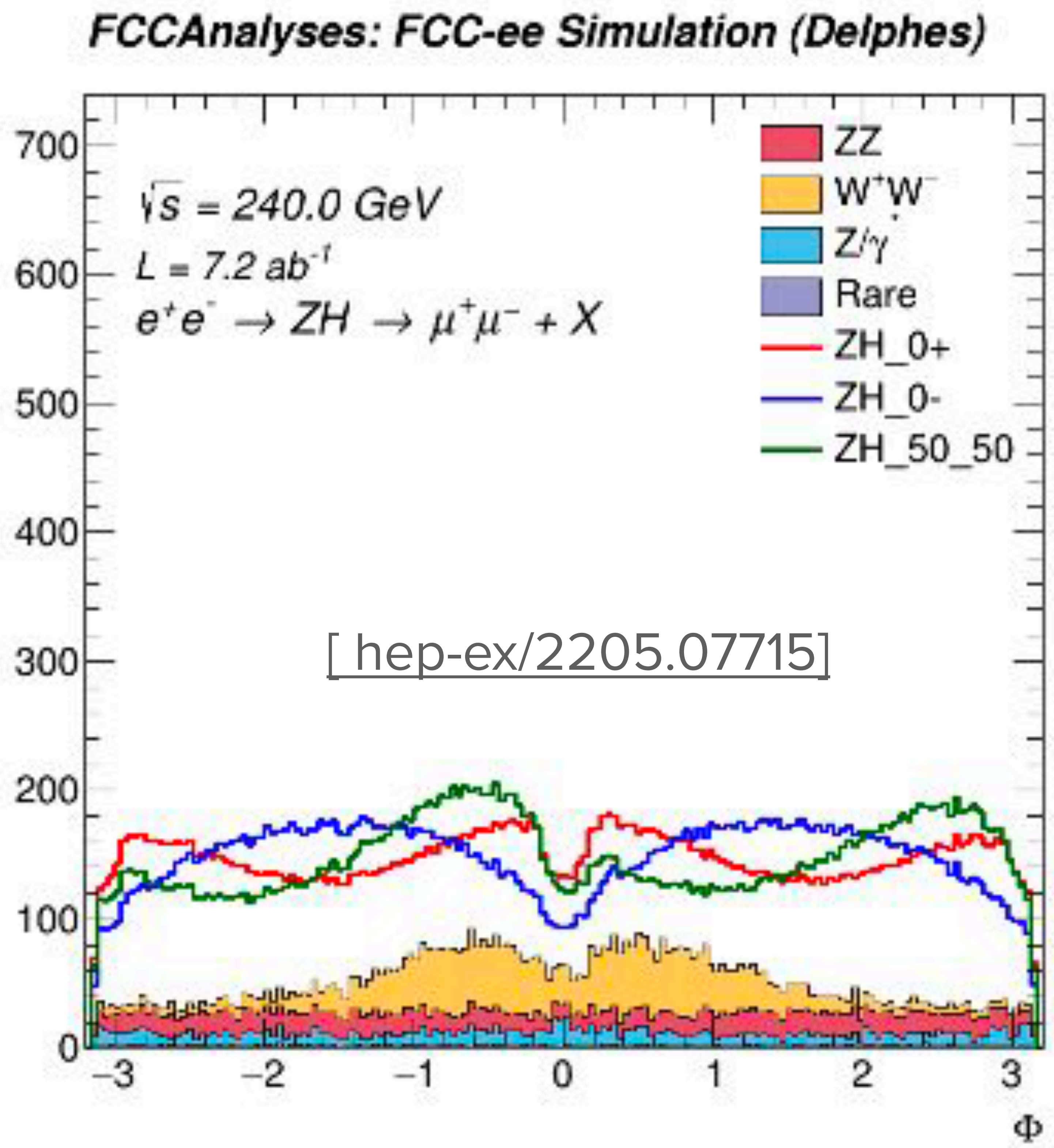
- Recent work on Higgs CP studies to constrain anomalous couplings using MELA
- $\delta f_{CP}^{HZZ} \sim 5.4 \times 10^{-5}$ (68 % CL)



$$f_{CP}^{HX} \equiv \frac{\Gamma^{CP\,odd}_{H\to X}}{\Gamma^{CP\,odd}_{H\to X} + \Gamma^{CP\,even}_{H\to X}}$$







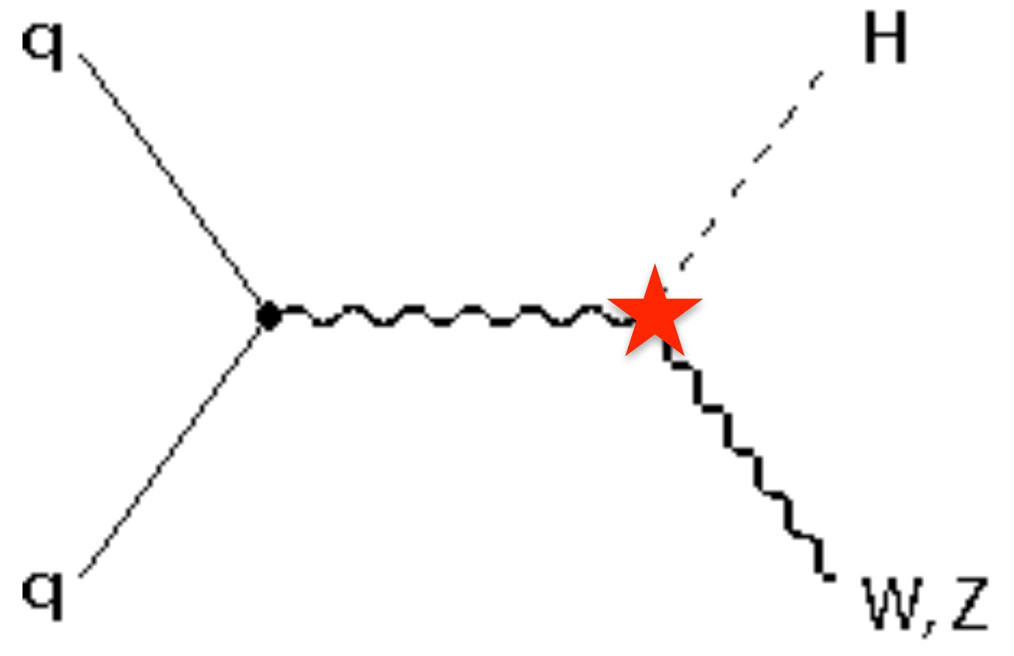
HIGGS COUPLINGS TODAY

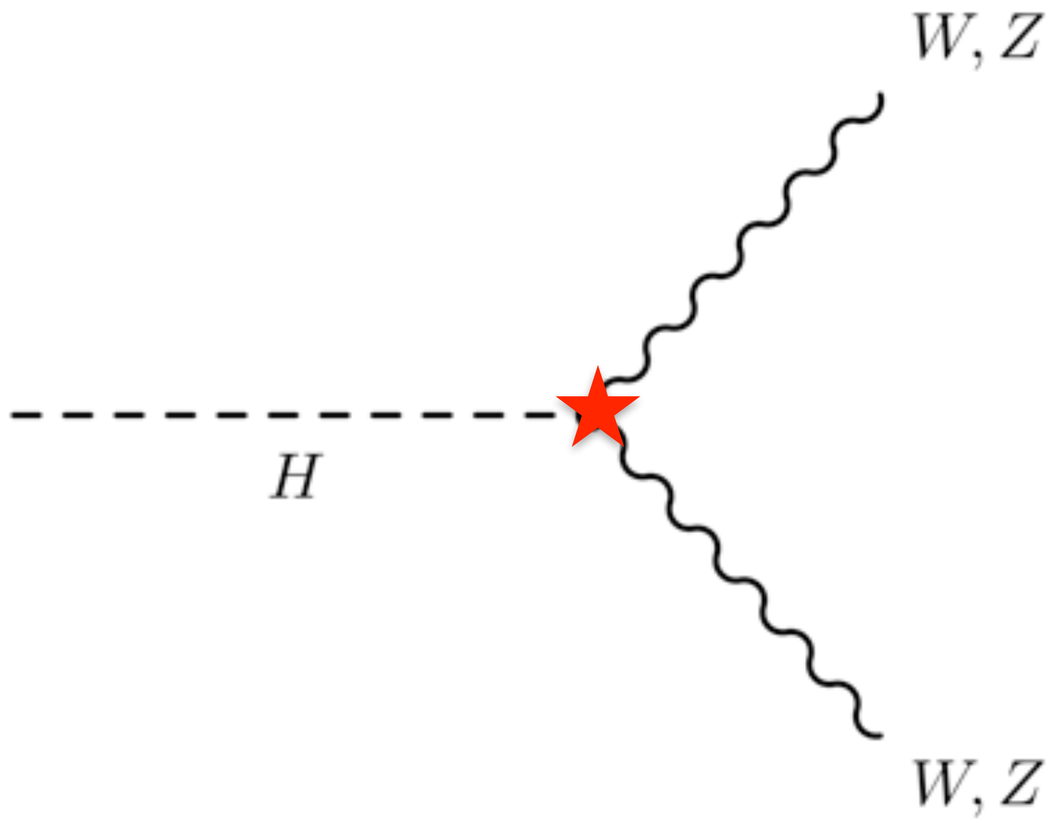
- What is the strength of the interaction of the Higgs to the different SM particles?

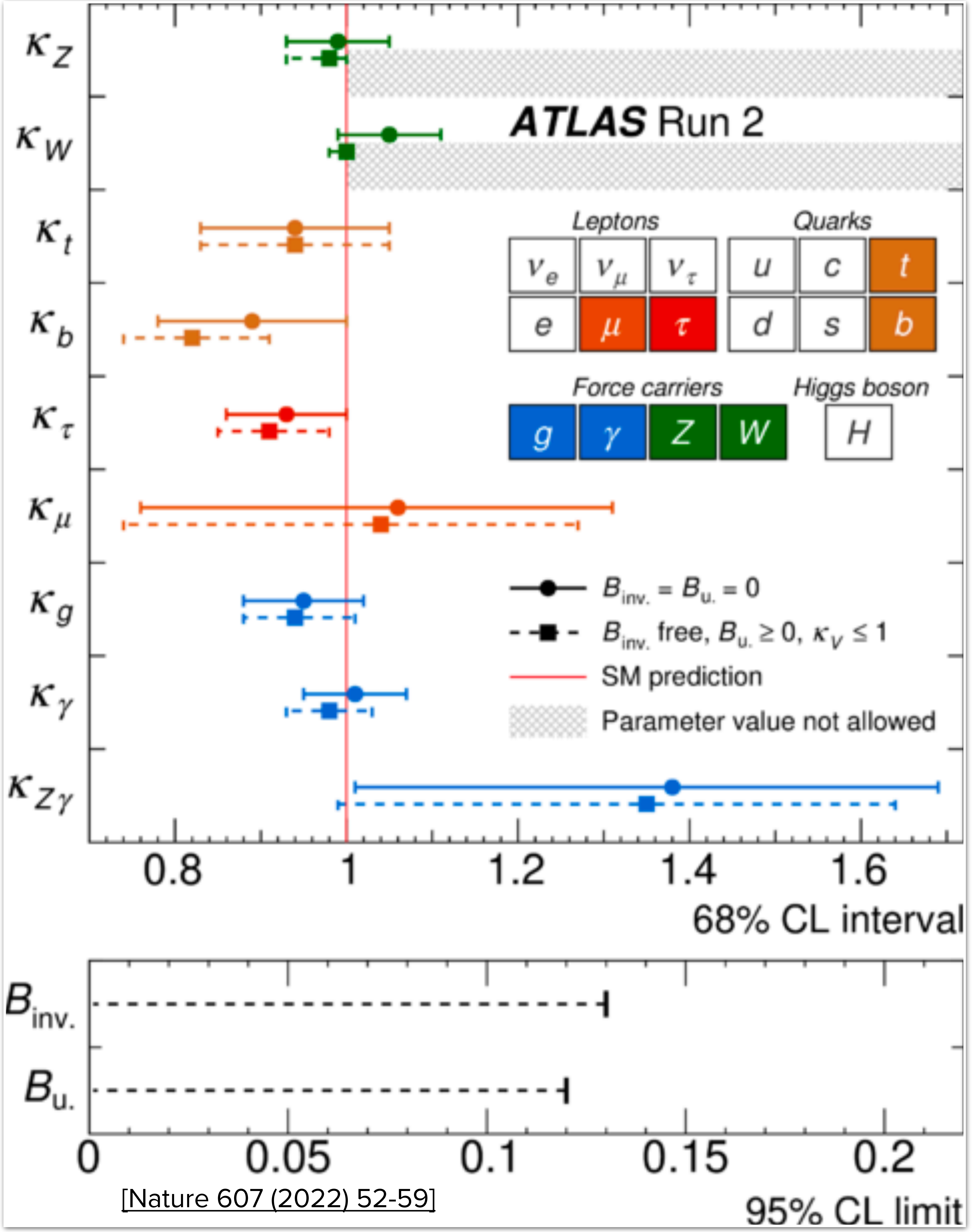
- In the Kappa Framework (simple parametrisation widely used by LHC experiments), known to 6-15%

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

$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$





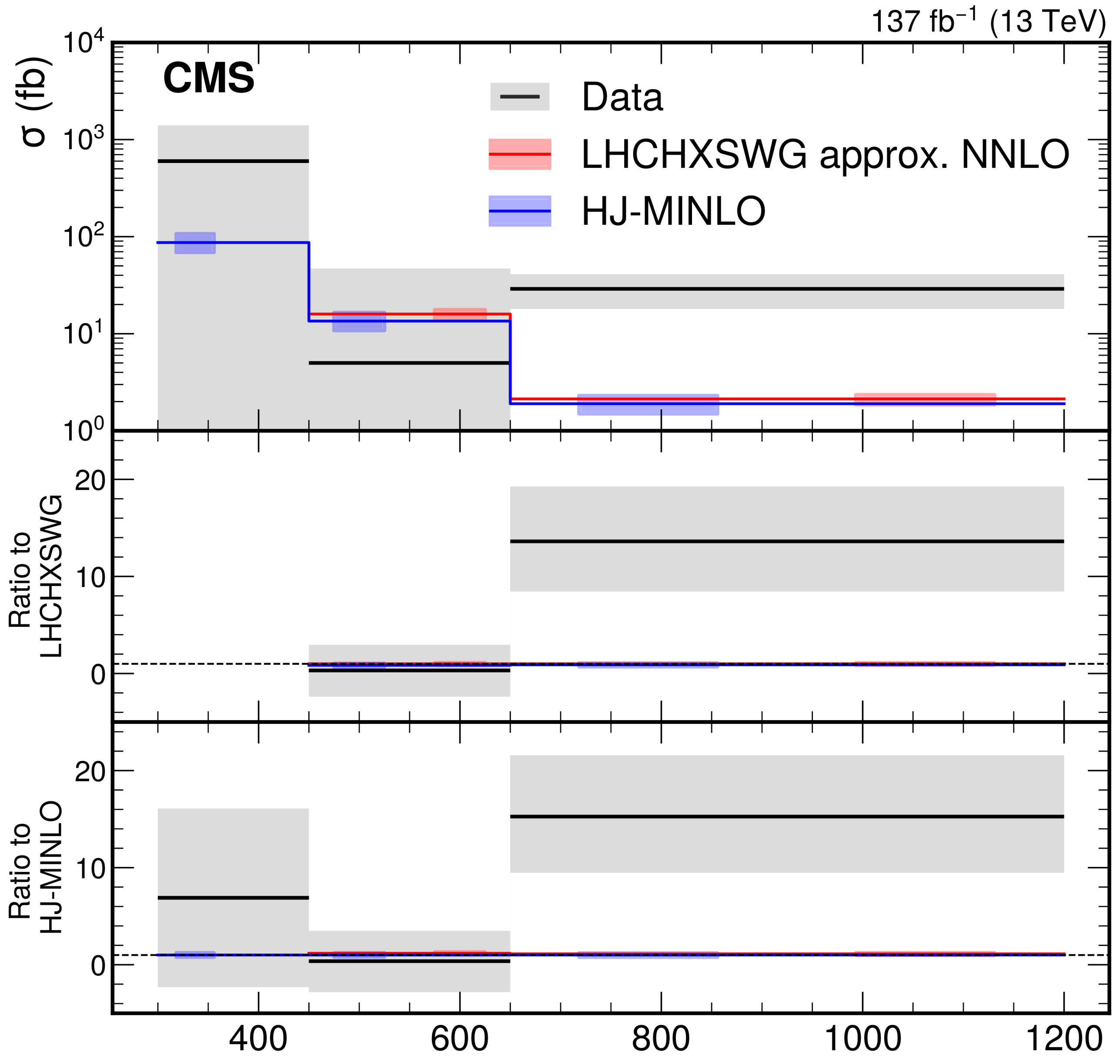


[Nature 607 (2022) 52-59]

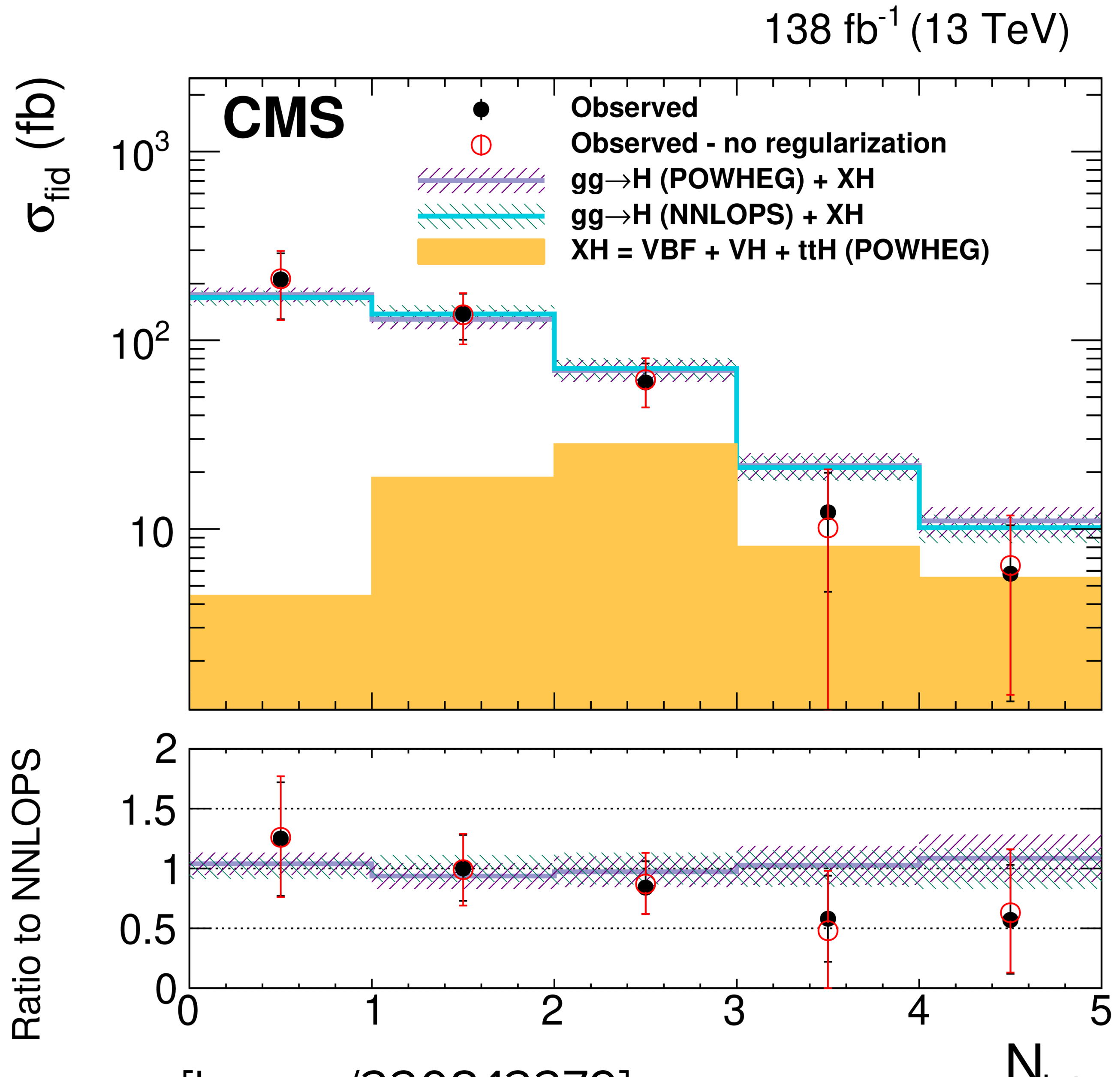
BEYOND COUNTING...

- With more data, new phase spaces open to challenge the SM limits: different techniques can be developed, large control regions to avoid relying on MC

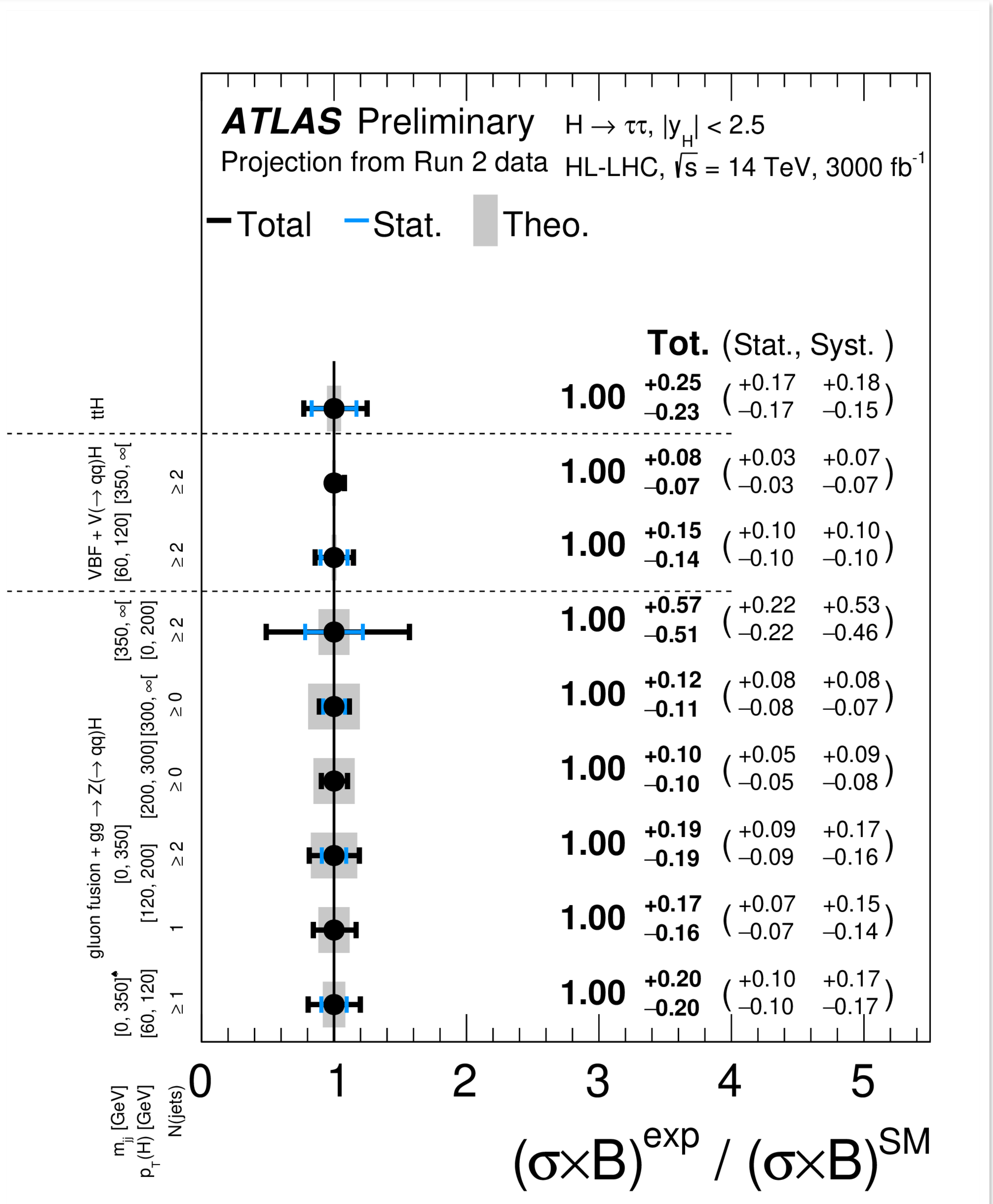
- **The future is not (only) a game of improving precision in discrete measurements, but one of differential distributions**



[JHEP 12 (2020) 085]



[hep-ex/2208.12279]

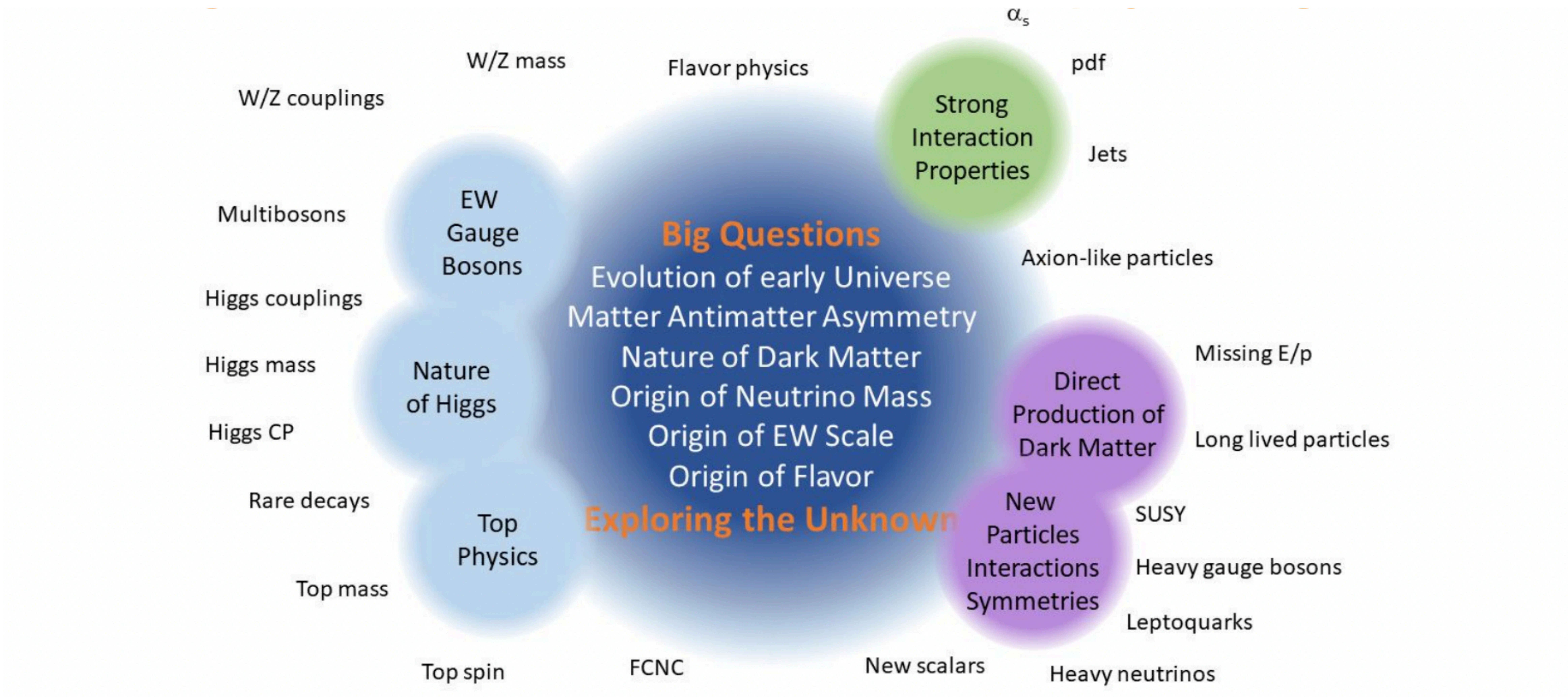


[ATL-PHYS-PUB-2022-018]

PROBING NEW PHYSICS TODAY

- Scales we are sensitive to after Run2 of LHC:
  - Higgs studies: $\Lambda \gtrsim$ 1 TeV
  - SUSY, related with fermions of third generation, diboson resonances, … : $\Lambda \gtrsim$ 2-4 TeV
  - New gauge boson searches (W',Z'): $\Lambda \gtrsim$ 5-6 TeV, smaller for composite Higgs models ($\Lambda \gtrsim$ 3-4 TeV)
- We are still exploring the TeV scale at the LHC
- Need to "fully" explore up to the 10 TeV range (almost any BSM model/theory trying to get around the "hierarchy problem" requires new effects not too far from the TeV scale)

EXPLORING THE TEV SCALE



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