30th IFT Xmas Workshop
December 11, 2024

Physics at future
e^+e^- EW/Higgs/Top factories

Jorge de Blas

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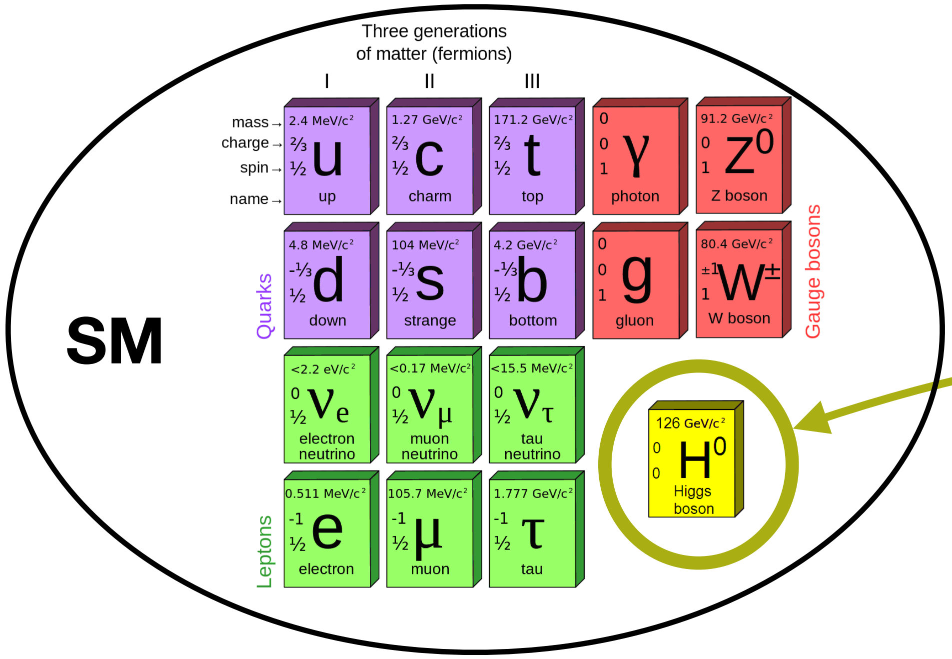
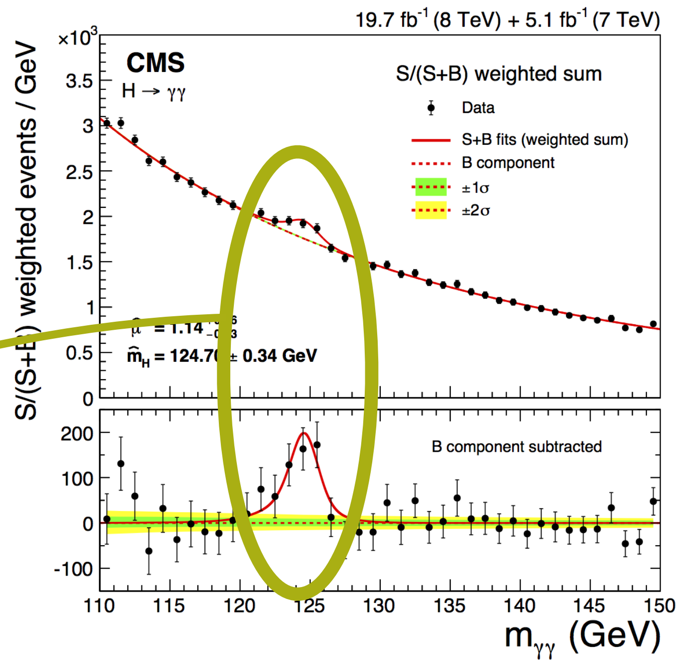
Based on the work of A LOT of people

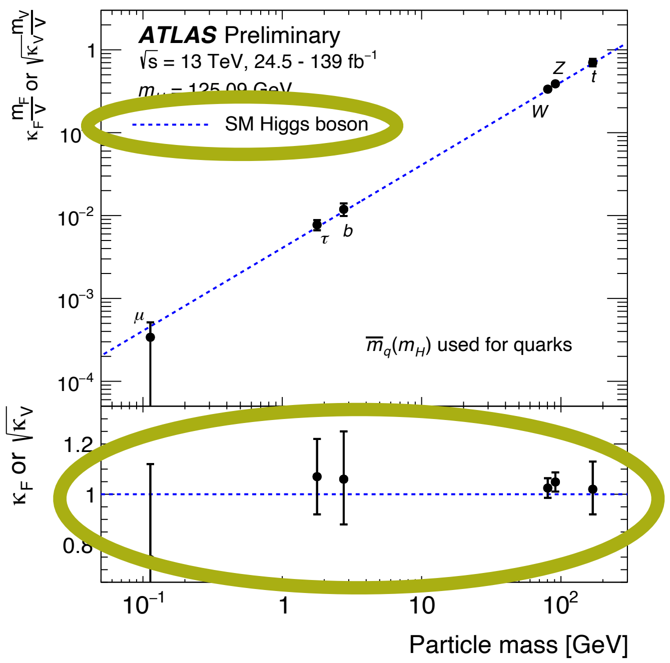
Universidad de Granada

Introduction

- **10+ yrs after its discovery, the 125 GeV Higgs boson remains as the biggest achievement of the LHC**
  - ✓ It finally proves the existence of the last ingredient required to fully test the validity of the SM at low energies…







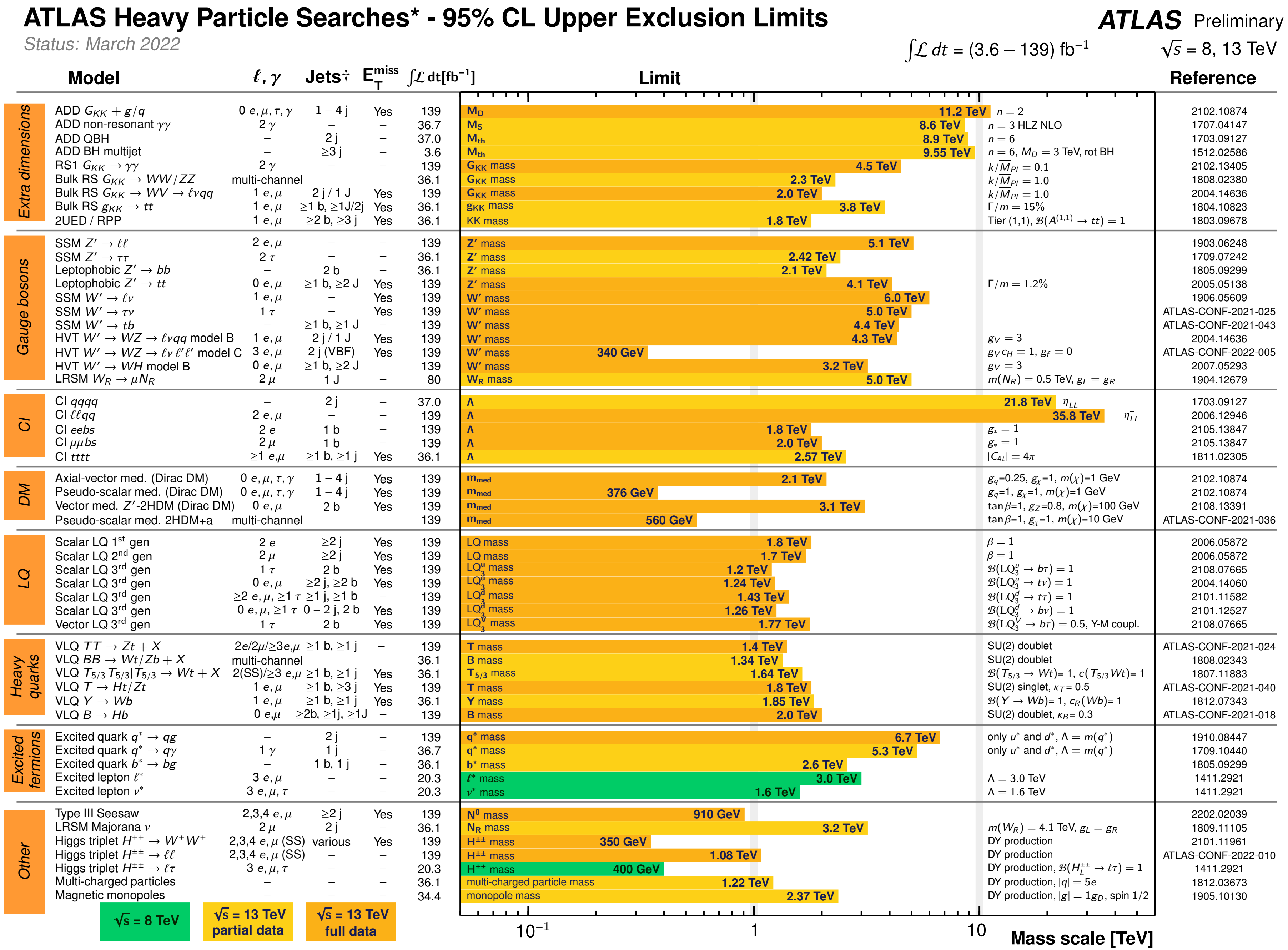
- With the LHC in the Run 3 and with much more luminosity expected to be collected during the HL-LHC phase, we find ourselves in the situation of deciding what should be the next big experiment in high-energy particle physics…

How to decide?

It would be much easier if we had any hint of what we are looking for…

Introduction

Unfortunately, nature is not being kind to us in that regard, and the Higgs is the only "new" physics we found thus far…



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2022

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK}+g/q$	0 e,μ,τ,γ	1 – 4 j	Yes	139	M_D	11.2 TeV	$n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n=6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl}=0.1$	2102.13405
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
	Bulk RS $G_{KK}\to WV\to\ell\nu qq$	1 e,μ	2 j / 1 J	Yes	139	G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl}=1.0$	2004.14636
	Bulk RS $g_{KK}\to tt$	1 e,μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	1 e,μ	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	0 e,μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m=1.2\%$	2005.05138
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W'\to\tau\nu$	1 τ	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W'\to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W'\to WZ\to\ell\nu qq$ model B	1 e,μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V=3$	2004.14636
	HVT $W'\to WZ\to\ell\nu\,\ell'\ell'$ model C	3 e,μ	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H=1$, $g_f=0$	ATLAS-CONF-2022-005
	HVT $W'\to WH$ model B	0 e,μ	≥1 b, ≥2 J		139	W' mass	3.2 TeV	$g_V=3$	2007.05293
	LRSM $W_R\to\mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ	1.8 TeV	$g_*=1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ	2.0 TeV	$g_*=1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e,μ,τ,γ	1 – 4 j	Yes	139	m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e,μ,τ,γ	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e,μ	2 b	Yes	139	m_{med}	3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med}	560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta=1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta=1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass	1.2 TeV	$\mathcal{B}(\mathrm{LQ}_3^u\to b\tau)=1$	2108.07665
	Scalar LQ 3rd gen	0 e,μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u\to t\nu)=1$	2004.14060
	Scalar LQ 3rd gen	≥2 e,μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d\to t\tau)=1$	2101.11582
	Scalar LQ 3rd gen	0 e,μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d\to b\nu)=1$	2101.12527
	Vector LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^V mass	1.77 TeV	$\mathcal{B}(\mathrm{LQ}_3^V\to b\tau)=0.5$, Y-M coupl.	2108.07665
Heavy quarks	VLQ $TT\to Zt+X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T\to Ht/Zt$	1 e,μ	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y\to Wb$	1 e,μ	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B\to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1910.08447
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	Type III Seesaw	2,3,4 e,μ	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
	Higgs triplet $H^{\pm\pm}\to W^\pm W^\pm$	2,3,4 e,μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert=5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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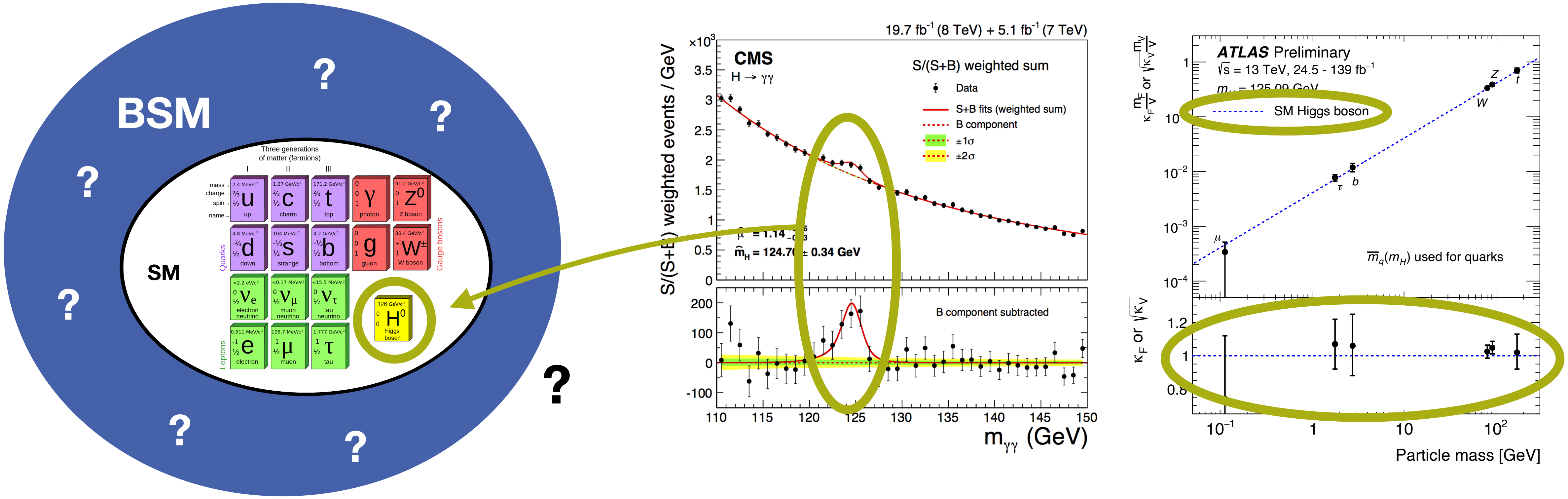
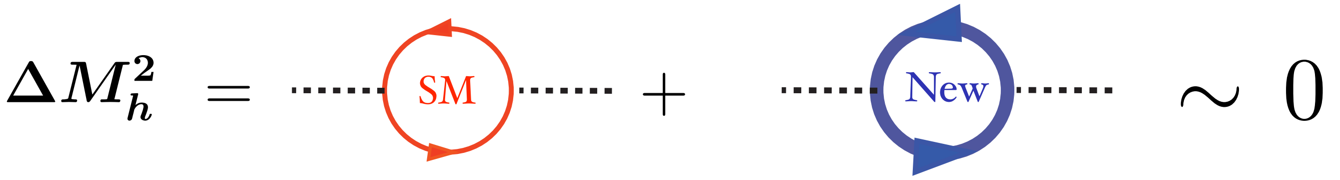
  - ✓ It finally proves the existence of the last ingredient required to fully test the validity of the SM at low energies…



- ✓ However, the Higgs itself reminds us of the limitations of the SM…
  - How do we understand the mechanism of EWSB?
  - Hierarchy problem: Why $M_h \ll M_P$?

⇒ **BSM:**



$$\Delta M_h^2 = \text{SM} + \text{New} \sim 0$$

Introduction

- This is just one of many “open” questions related to HEP and that motivate our belief in New Physics

Origin of EWSB?

Thermal History of Universe

Higgs Portal to Hidden Sectors?

Naturalness

Stability of Universe

Fundamental or Composite?

CPV and Baryogenesis

Is it unique?

Origin of masses?

Origin of Flavor?

arXiv: 2209.07510 [hep-ph]

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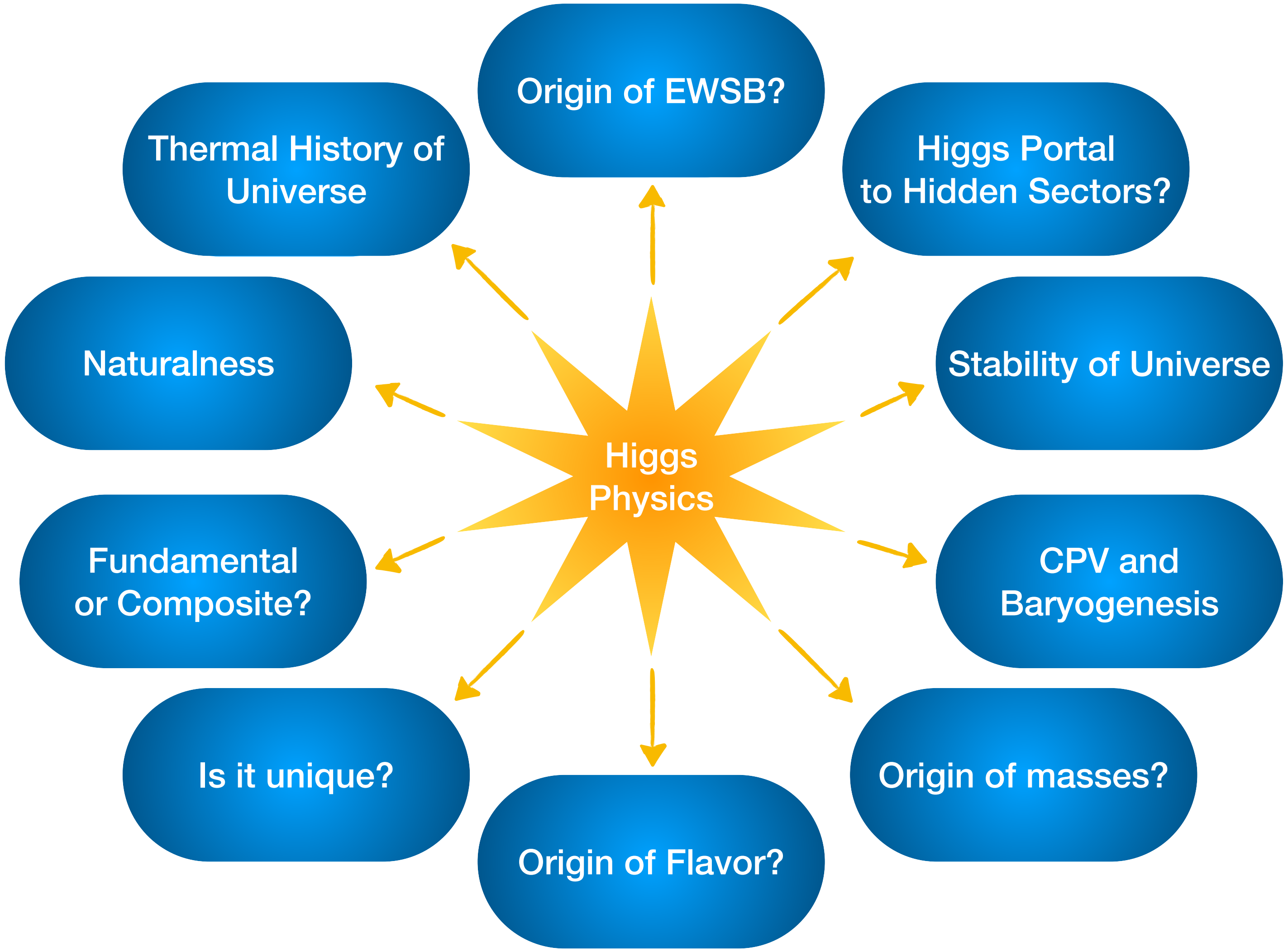


arXiv: 2209.07510 [hep-ph]

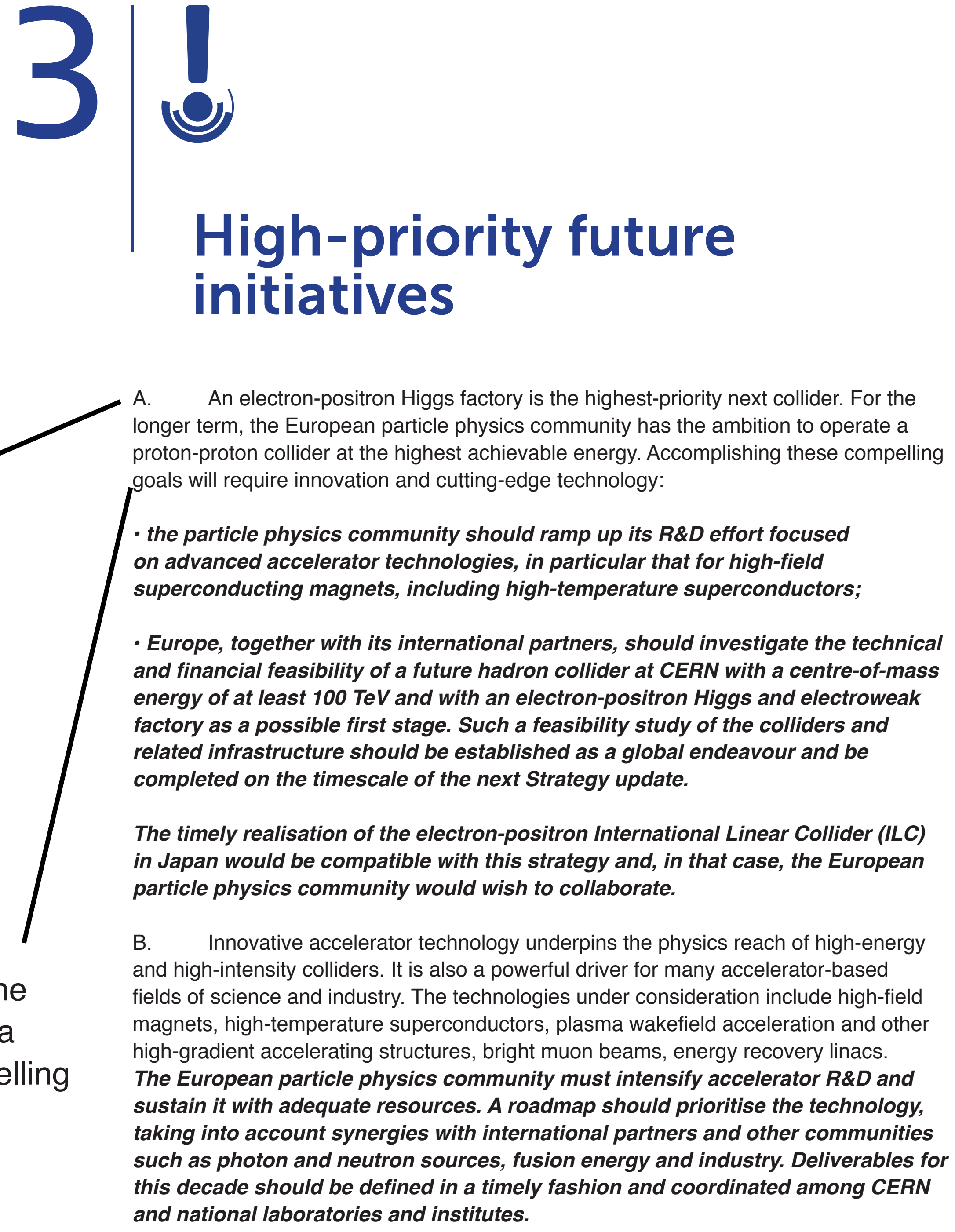
- Solutions to most of these questions involve BSM physics "talking" to any of the sectors of the SM, in particular the Higgs → <u>Modifications of its properties</u>
- Pushing the precision of SM measurements of the Higgs sector is a way of learning about new physics (indirectly)!

2020 European Strategy Update

2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:



3

High-priority future initiatives

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• the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

• Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

2020 European Strategy Update

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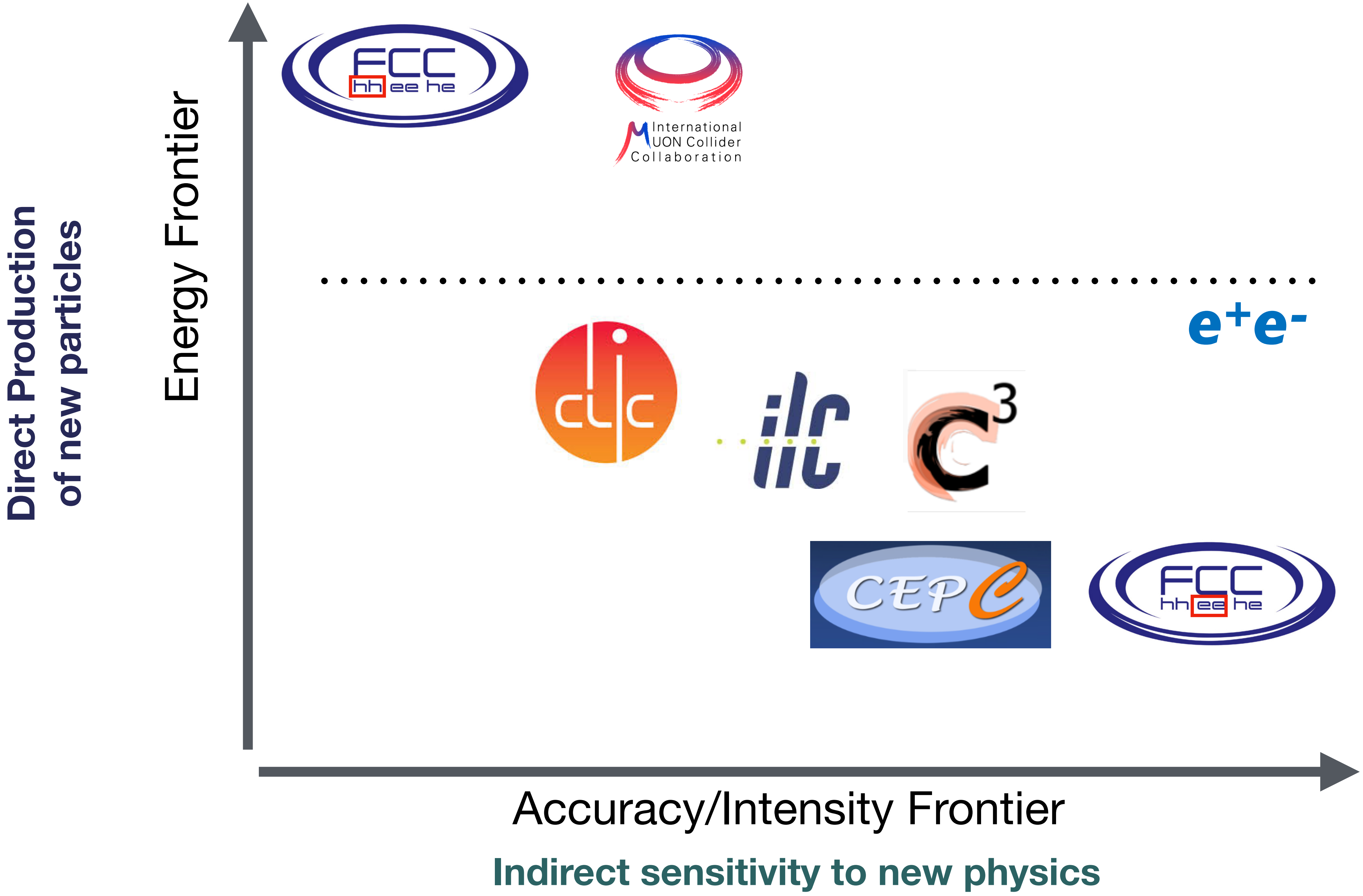
Now we just have to decide which one…

Future collider projects (e^+e^- and more)

Now we just have to decide which one…

- The "players"



Direct Production of new particles

Energy Frontier

Accuracy/Intensity Frontier

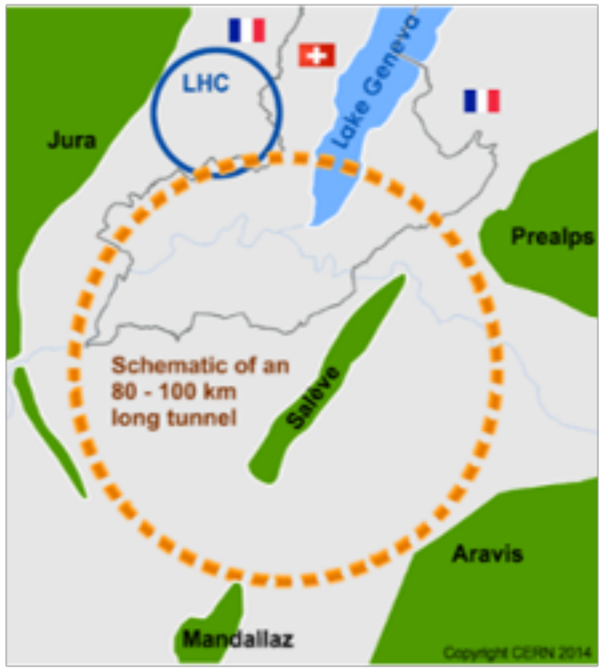
Indirect sensitivity to new physics

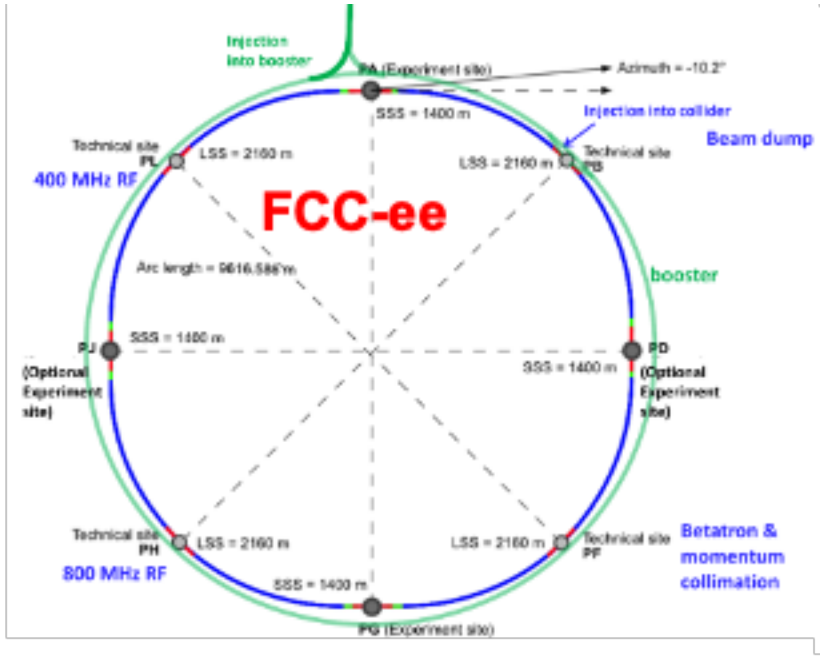
The FCC integrated program

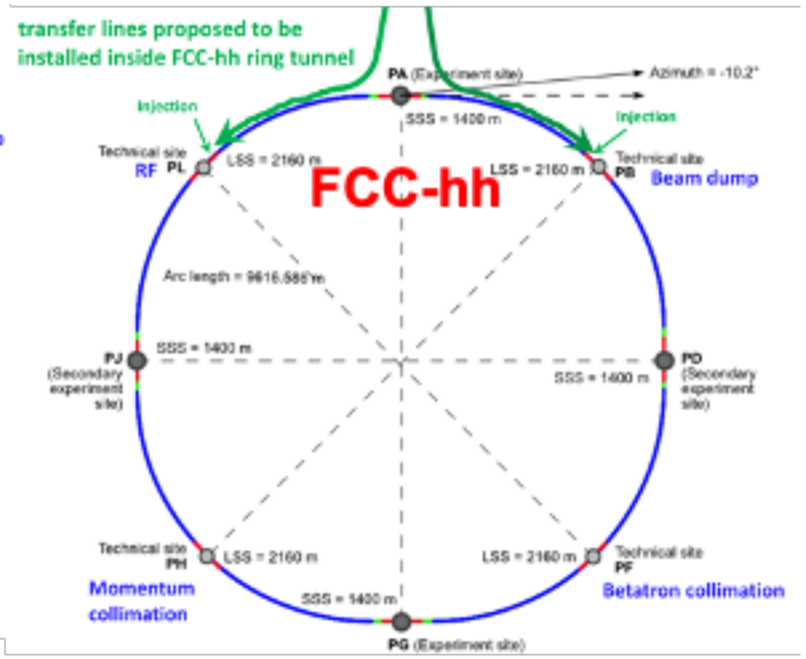
https://fcc-ped.web.cern.ch/

FUTURE CIRCULAR COLLIDER

- The **Future Circular Collider** (FCC) is CERN's current flagship project
  - 90.7 Km ring, 8 surface points, 4 interaction points (IPs)
- **Stage 1: FCC-ee** (Z-pole, WW [161 GeV], ZH [240 GeV], tt [345/65 GeV]) as e^+e^- Higgs/EW/Top factory for precision measurements
- **Stage 2: FCC-hh** (pp @ 100 TeV) as natural continuation of the exploration of the energy frontier
- Currently finishing the *FCC feasibility study* (available in March 2025)







2020 - 2045 | 2045 - 2065 | 2070 -

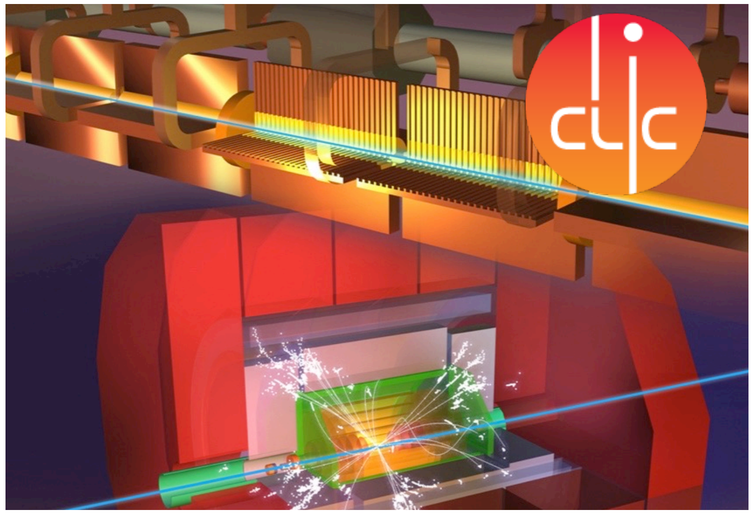
Linear Colliders

- **Linear Colliders (LC):** several proposed Higgs factories:
  - The **International Linear Collider (ILC)**, proposed to operate in Japan

Stage 1: 250 GeV CM energy. Polarized beams (±80%,∓30%)

Stages 2 and 3: extensions to 500 GeV and 1 TeV CM energies

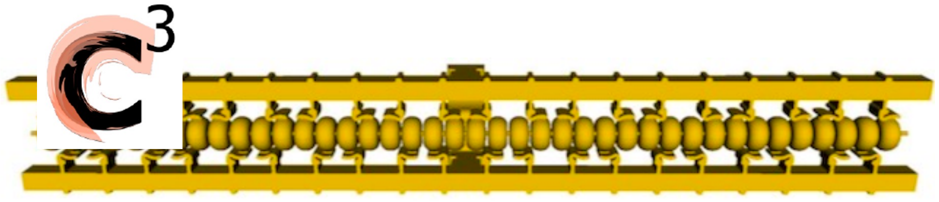
  - The **Compact Linear Collider (CLIC)**, proposed at CERN



Stage 1: 380 GeV CM energy. Polarized beams (±80%, 0%)

Stages 2 and 3: extensions to 1.5 and 3 TeV CM energies

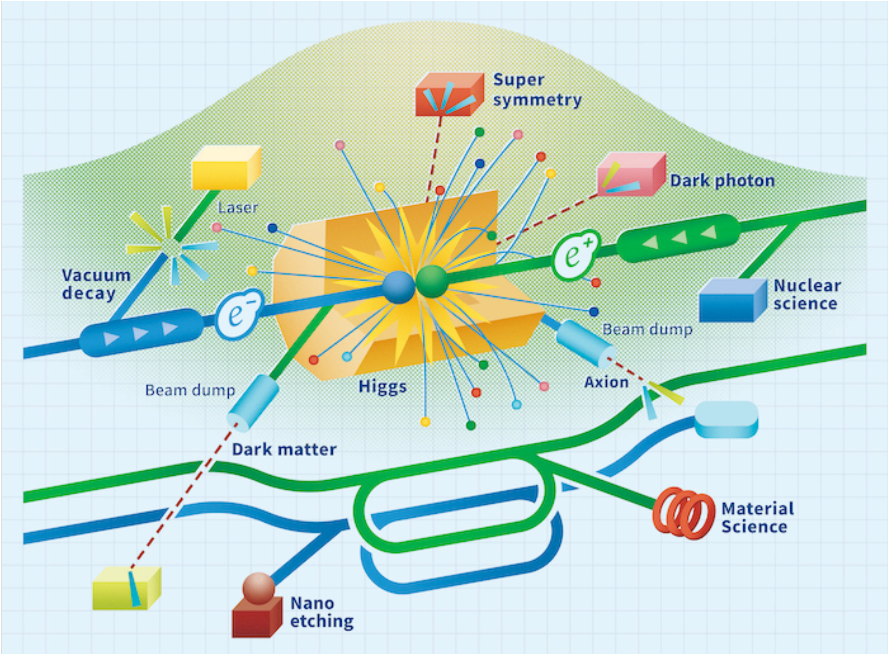
  - The **Cool Copper Collider (C^3)** proposed at SLAC, to run at 250 GeV and 550 GeV ⇒ similar physics potential than ILC (different technology)



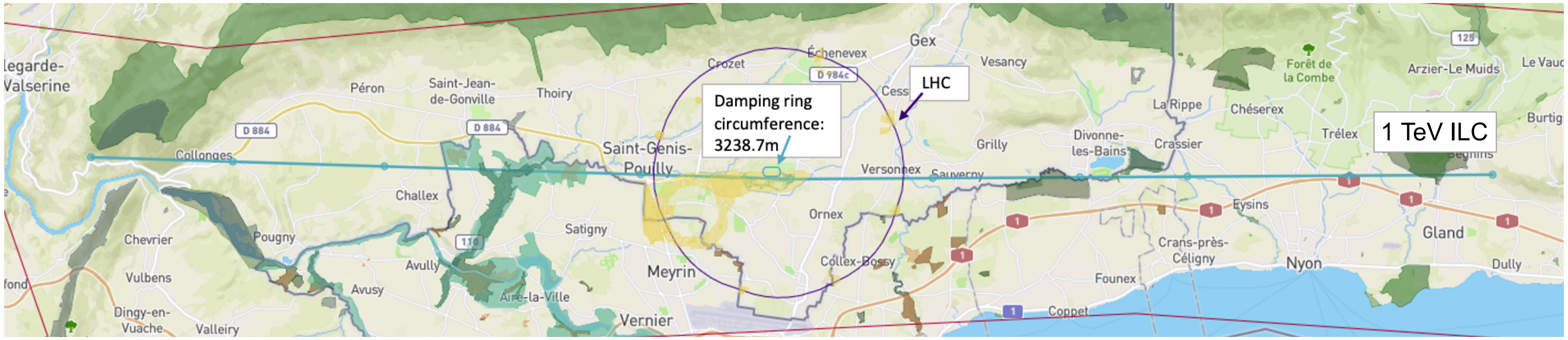
LC Vision

https://indico.cern.ch/event/1471891/

- The **Linear Collider Vision** (LC Vision) brings together proponents and supporters of all kind of LC projects, to propose such a facility for CERN



- Initial e^+e^- CM energy to be decided based on budget and science:
  - Minimum: 250 GeV / Higher: e.g. 550 GeV (more science but more expensive)
  - Upgrade to higher CM energy via advanced technology or tunnel extension
- 2nd Beam Delivery System ⇒ 2 IPs
  - 2 detectors for redundancy, cross checks, complementarity, …
  - But not double the luminosity


Damping ring circumference: 3238.7m

LHC

1 TeV ILC

The Circular Electron Positron Collider (CEPC)

http://cepc.ihep.ac.cn/intro.html

- CEPC is an e^+e^- Higgs factory, proposed in 2012 after the Higgs discovery, to be built in China
  - ✓ Similar run modes as FCCee, though with different luminosities
  - ✓ Tunnel can be re-used for pp collisions up to 100 TeV
    ⇒ Super proton-proton Collider (SPPC)
- If approved, could start construction in ~2027/28
- Not proposed to be built at CERN but could play an important role in the discussions for the strategy

Mode	√s (GeV)	Events
ZH	240	>1 million
WW	160	
Z	90	Tera-Z

Also projected a “tt run” at 360 GeV

2024-26 European Strategy Update

https://europeanstrategyupdate.web.cern.ch/

Remit of the European Strategy Group

”The aim of the Strategy update should be to develop a ***visionary and concrete plan*** *that greatly advances human knowledge in fundamental physics through the* ***realisation of the next flagship project at CERN****. This plan should attract and value* ***international collaboration*** *and should* ***allow Europe to continue to play a leading role in the field.”***

Timeline

End September 2024
Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024
Council decision on the venue for the **ESG Strategy Drafting Session**

31 March 2025
Deadline for the submission of main input from the community

26 May 2025
Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025
Open Symposium (in Venice)

End September 2025
Submission of the “Briefing Book” to the **ESG**

14 November 2025
Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025
ESG Strategy Drafting Session

End January 2026
Submission of the draft strategy document to the Council

March and June 2026
Discussion of the draft strategy document by the Council and **updating of the Strategy**

2024-26 European Strategy Update

ECFA guidelines for national inputs to the ESPP

Central element of the next ESPP: the choice of next collider at CERN.

ESG remit: "The Strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive".

→ It is imperative that the European HEP community should provide explicit feedback on both the preferred and alternative options for this "next collider at CERN", which will be the Laboratory's next flagship project, and an explanation of any specific prioritisation.

a) Which is the preferred next major/flagship collider project for CERN?

b) What are the most important elements in the response to (a)?

  i) Physics potential
  ii) Long-term perspective
  iii) Financial and human resources: requirements and effect on other projects

…

c) Should CERN/Europe proceed with the preferred option set out in (a) or should alternative options be considered:

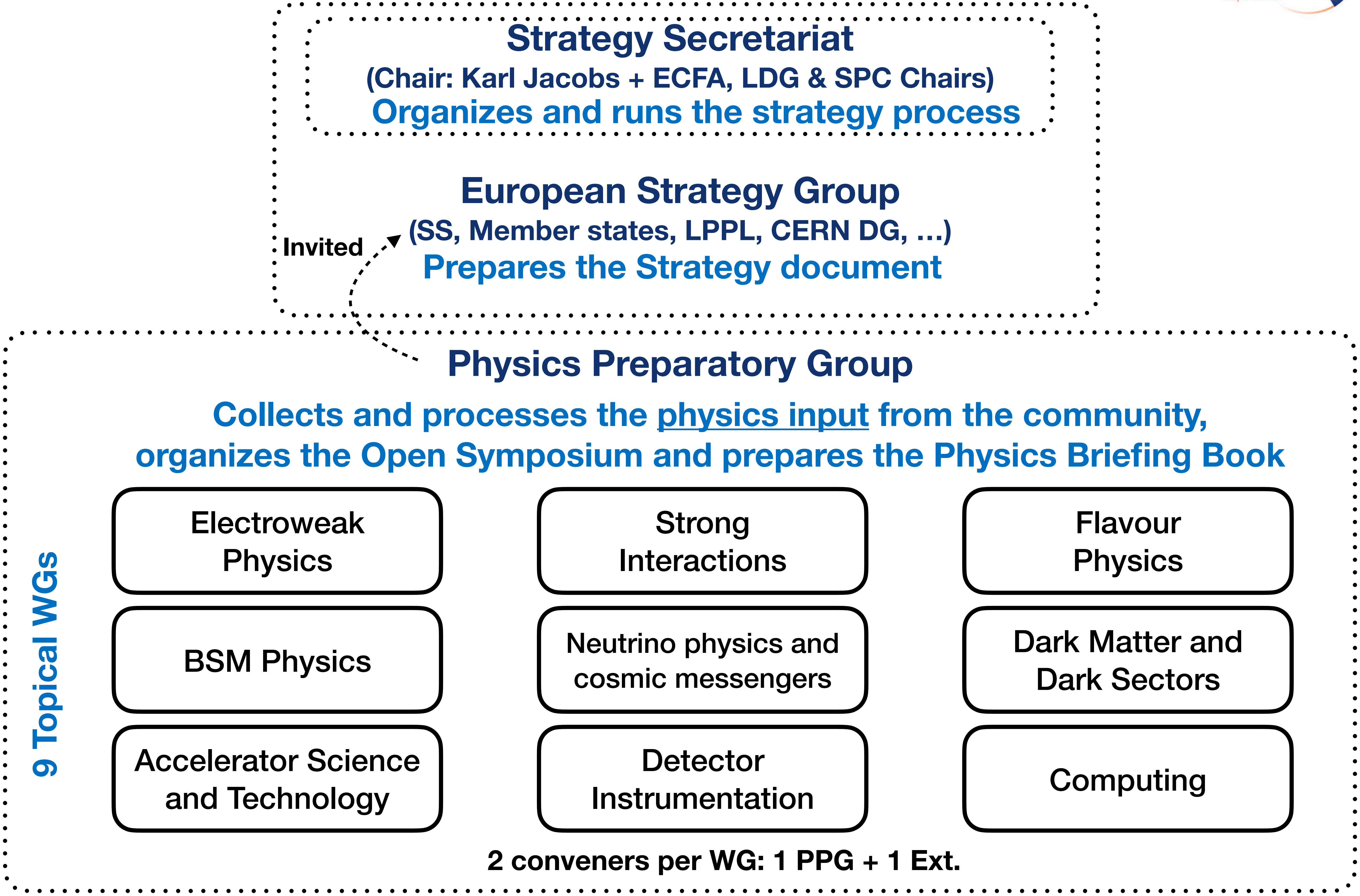
  i) if Japan proceeds with the ILC in a timely way?
  ii) if China proceeds with the CEPC on the announced timescale?
  iii) if the US proceeds with a muon collider?
  iv) if there are major new (unexpected) results from the HL-LHC or other HEP experiments?

⋮

e) What is the prioritised list of alternative options if the preferred option is not feasible (due to cost, timing, international developments, or for other reasons)?

From P. Sphicas' talk at 3rd ECFA workshop in Paris

2024-26 European Strategy Update



Strategy Secretariat

(Chair: Karl Jacobs + ECFA, LDG & SPC Chairs)

Organizes and runs the strategy process

European Strategy Group

(SS, Member states, LPPL, CERN DG, …)

Prepares the Strategy document

Physics Preparatory Group

Collects and processes the physics input from the community, organizes the Open Symposium and prepares the Physics Briefing Book

9 Topical WGs

- Electroweak Physics
- Strong Interactions
- Flavour Physics
- BSM Physics
- Neutrino physics and cosmic messengers
- Dark Matter and Dark Sectors
- Accelerator Science and Technology
- Detector Instrumentation
- Computing

2 conveners per WG: 1 PPG + 1 Ext.

ECFA study

on e^+e^- EW/Higgs/Top factories

ECFA Study on Higgs/EW/Top factories

- Based on the recommendations of the European Strategy for Particle Physics Update, the *European Committee for Future Accelerators* (ECFA) launched a series of workshops on physics studies, experiment design, and detector technologies towards a future e^+e^- Higgs/EW/Top factory.

- The aim was to <u>bring together the efforts of various e^+e^- projects, to share challenges and expertise, to explore synergies</u>, and to respond coherently to the 2020 ESU high-priority strategy item.

- Structure based on three working groups:
  - WG 1: Physics Potential - Further divided in 5 subgroups

    Conveners: J.B (Univ. Granada), P. Koppenburg (Nikhef), J. List (DESY), F. Maltoni (UC Louvain/Bologna)

  - WG 2: Physics Analysis Methods

    Conveners: P. Azzi (INFN-Padova /CERN), F. Piccini (INFN Pavia), D. Zerwas (IJCLab/DMLab)

  - WG 3: Detector R&D

    Conveners: M.C. Fouz (CIEMAT Madrid), G. Marchiori (APC Paris), F. Sefkow (DESY)

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Contents of this talk based on the results related to Physics potential

- Structure based on three working groups:
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ECFA Study: WG 1 structure

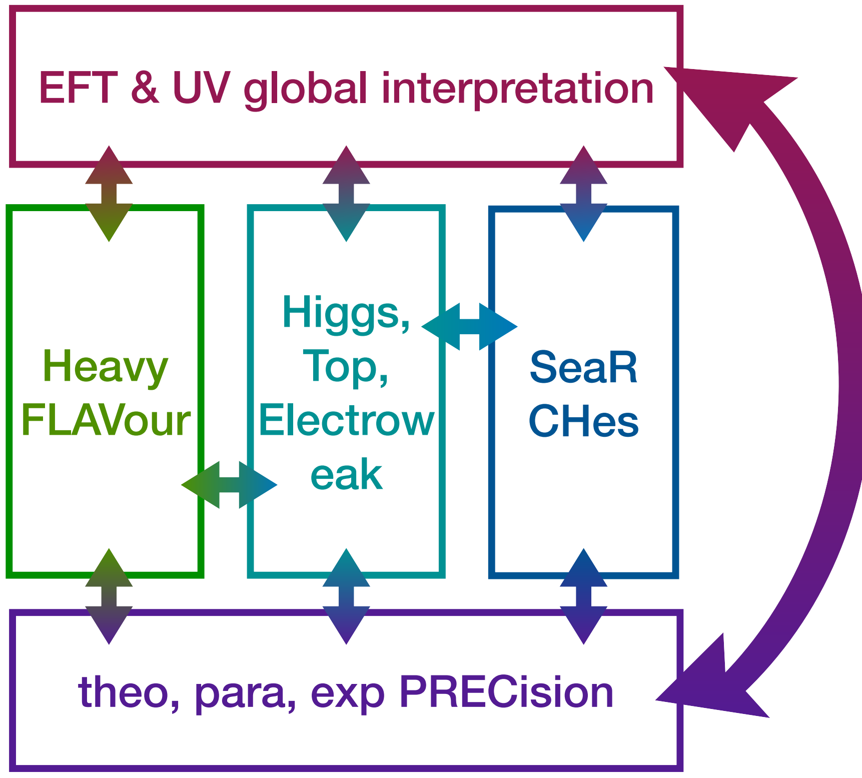
- **WG1-GLOB:** Global Interpretation in (SM)EFT and UV complete models
  - **TH:** J. B., S. Heinemeyer
  - **EXP:** A. Grohsjean, M. Vos, J. Tian

- **WG1-PREC:** Precision Calculations and Theo., param. and exp. sys. uncertainties
  - **TH:** A. Freitas
  - **EXP:** A. Meyer, P. Azzurri, A. Irles

- **WG1-HTE:** Higgs/Top/EW physics
  - **TH:** F. Maltoni
  - **EXP:** K. Köneke, C. Hays

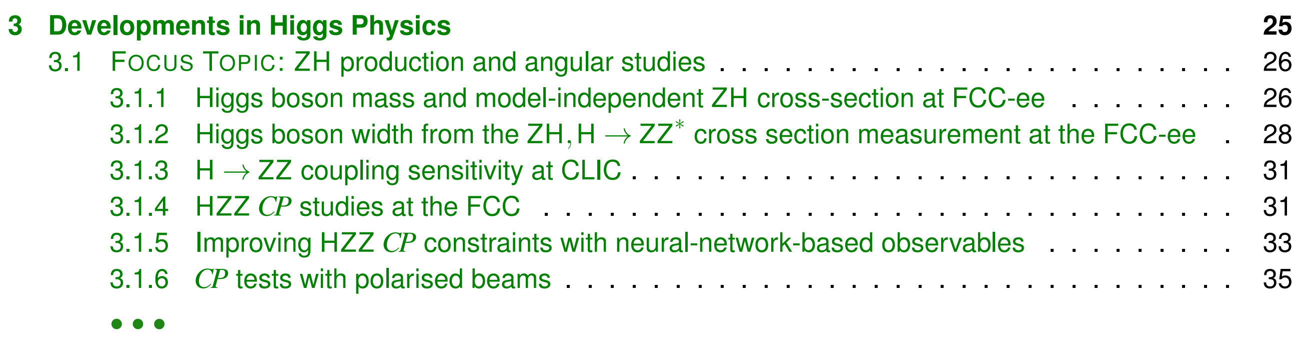
- **WG1-FLAV:** Flavour physics
  - **TH:** D. Marzocca
  - **EXP:** S. Monteil, P. Goldenzweig

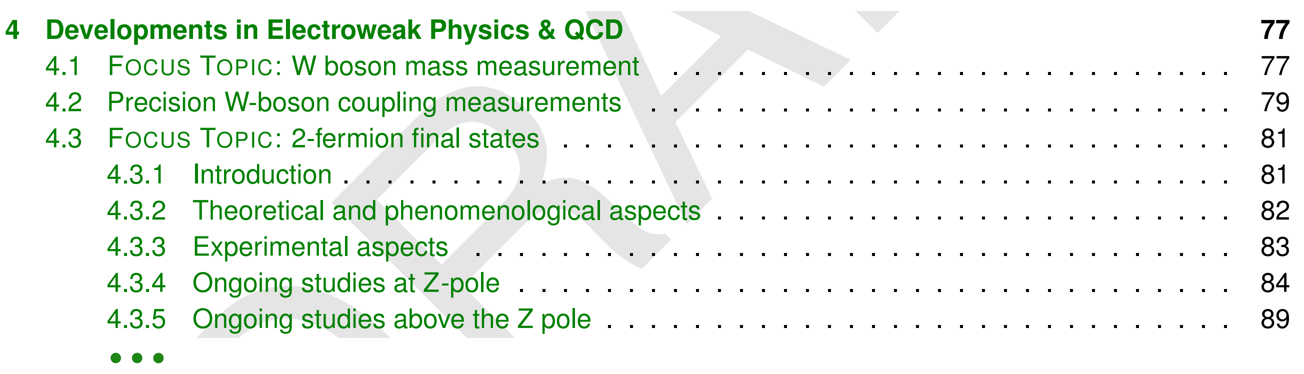
- **WG1-SRCH:** Direct discovery potential
  - **TH:** R. Franceschini
  - **EXP:** R. Gonzalez, F. Zarnecki

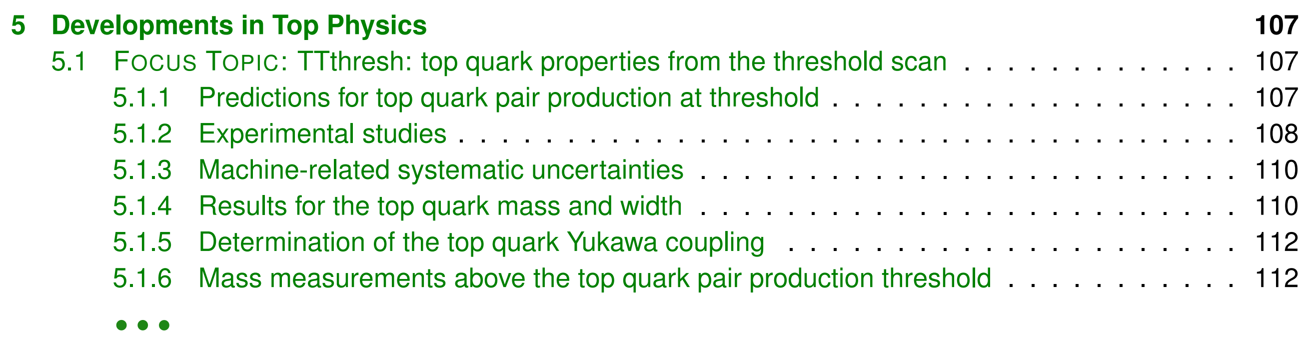


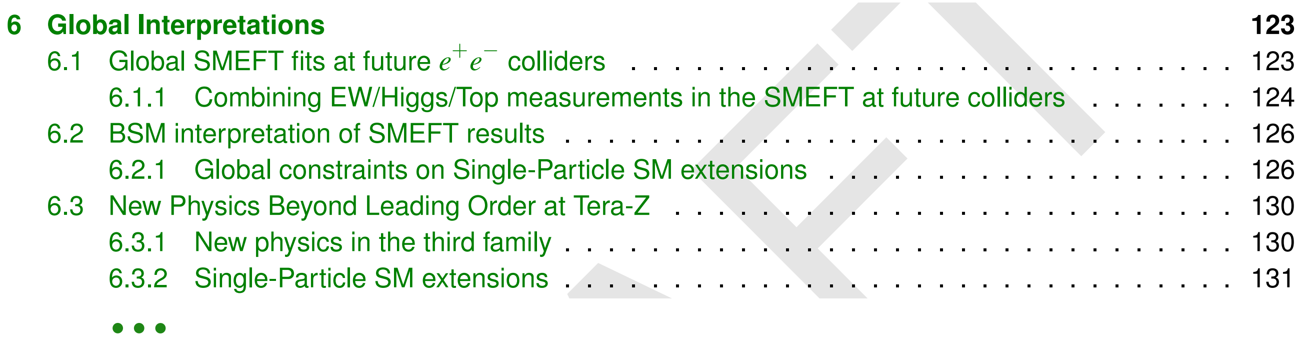
ECFA Study on Higgs/EW/Top factories

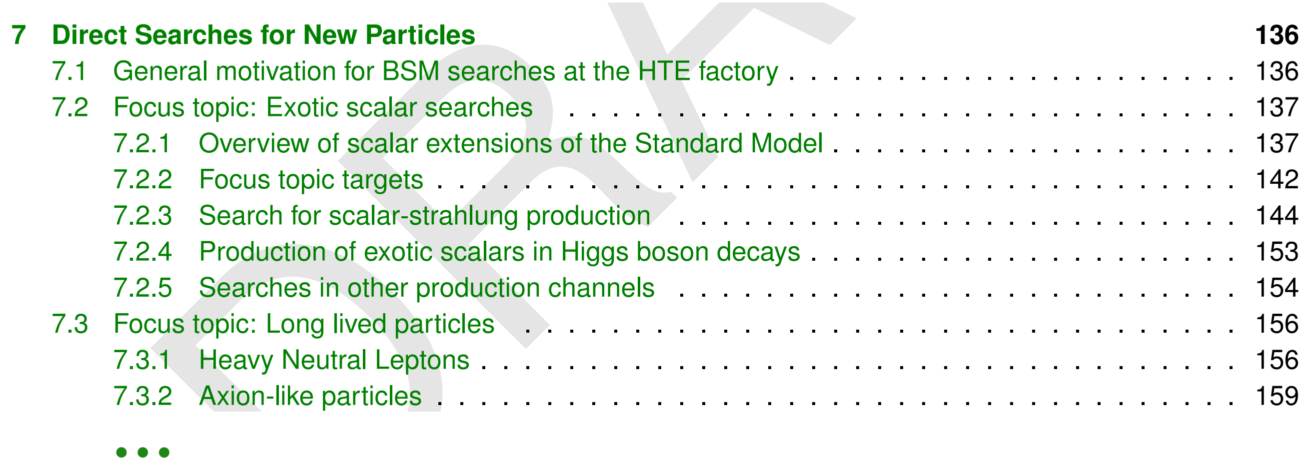
- **ECFA study report:** Currently editing more than 300 pages…

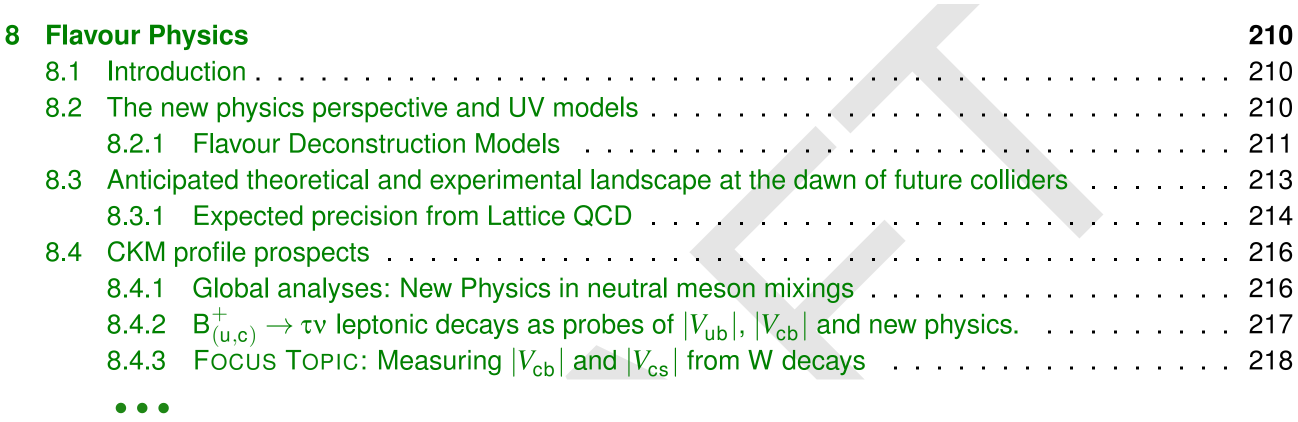












ECFA study report

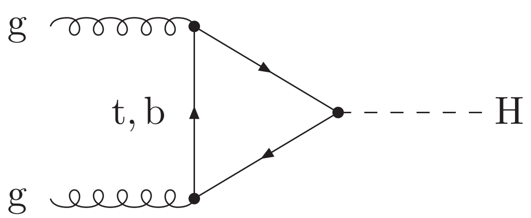
Higgs/EW/Top studies

Higgs/EW/Top Studies
Higgs Physics

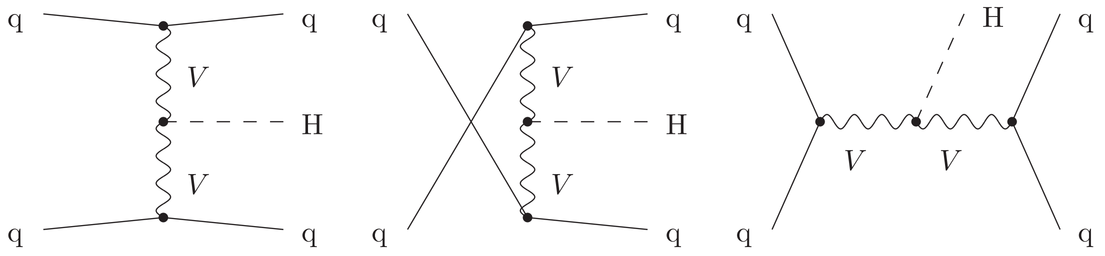
Higgs physics at e^+e^- Higgs factories

- Higgs physics at the LHC

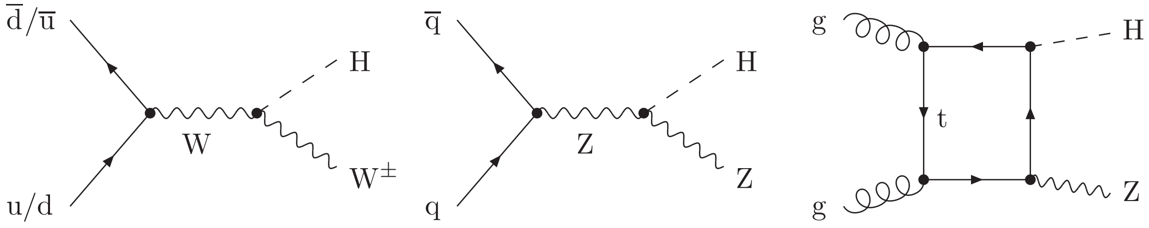
ggH:



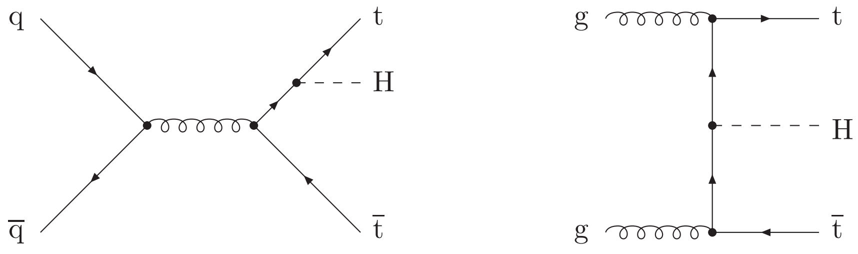
VBF:



VH:



ttH:



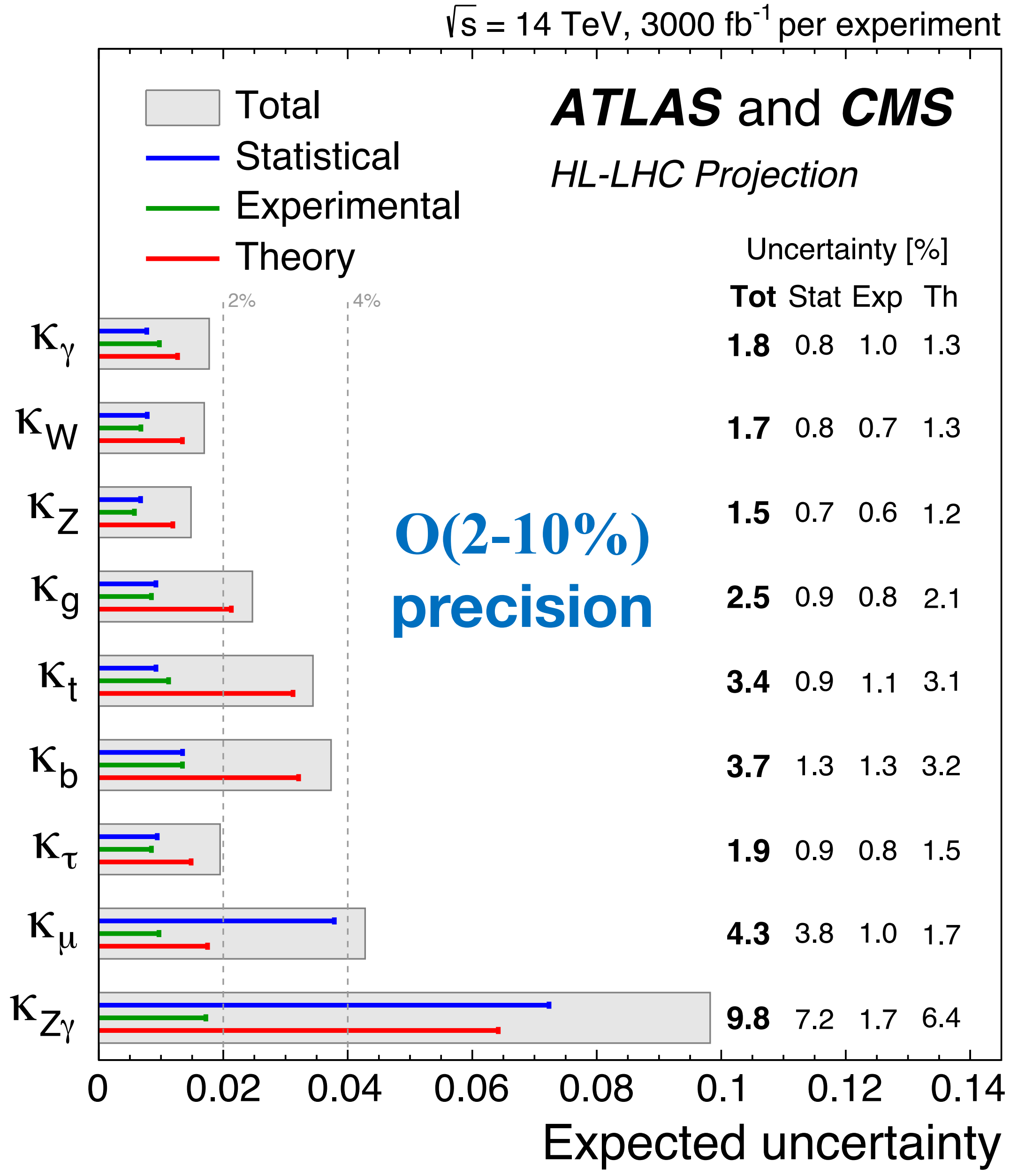
Run 2: ~8×10⁶ Higgses collected

HL-LHC: 15×10⁶ Higgses/year

Higgs coupling (ratios) in "κ framework":

From Higgs σxBR measurements

$$\mu_i^f \equiv \frac{\sigma . BR}{\sigma_{SM} . BR_{SM}} = \frac{\kappa_i^2 . \kappa_f^2}{\kappa_H^2} \qquad (\sigma . BR)(i \to H \to f) = \frac{\sigma_i . \Gamma_f}{\Gamma_H}$$



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

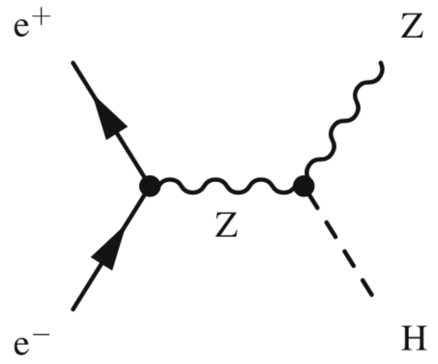
O(2-10%) precision

Higgs mass: expected ΔM_H~10-20 MeV

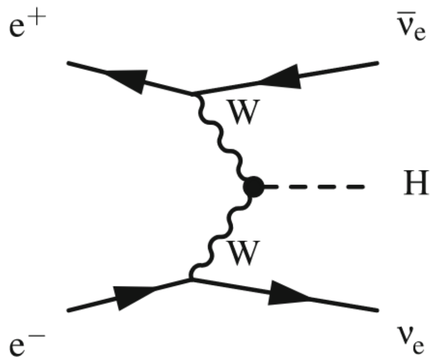
Higgs physics at e^+e^- Higgs factories

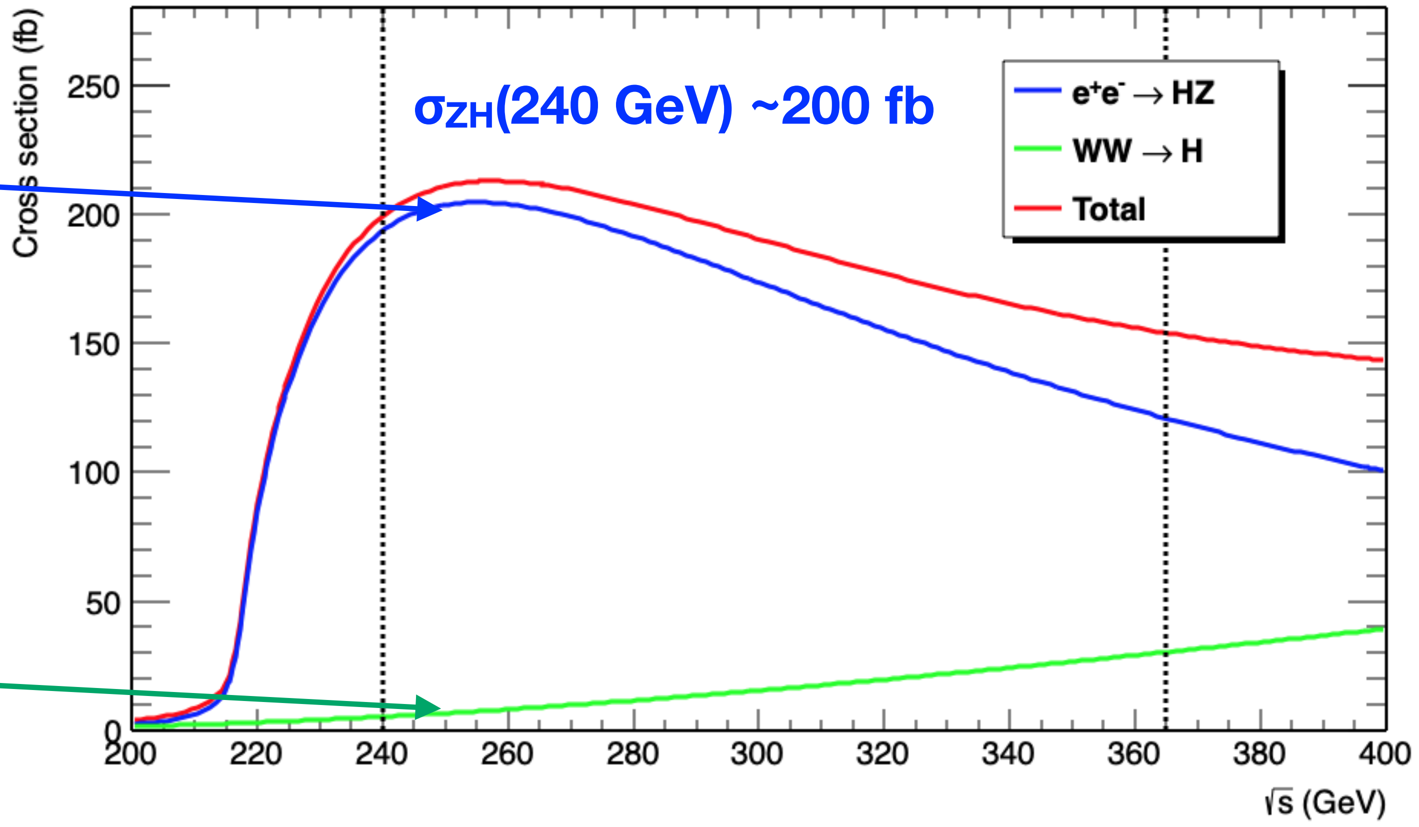
- Higgs physics at the e^+e^- colliders

ZH:



WWH:





σ_{ZH}(240 GeV) ~200 fb

Some example numbers (FCCee):

Statistics (2IPs):

10^6 (ZH) Higgses

~10^5 (WWH) Higgses

But in a clean environment:

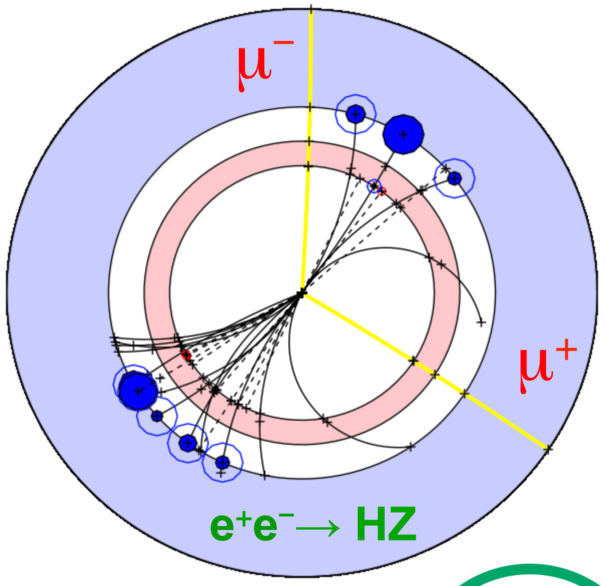
-No pileup
-Beam background under control
-E, p constraints

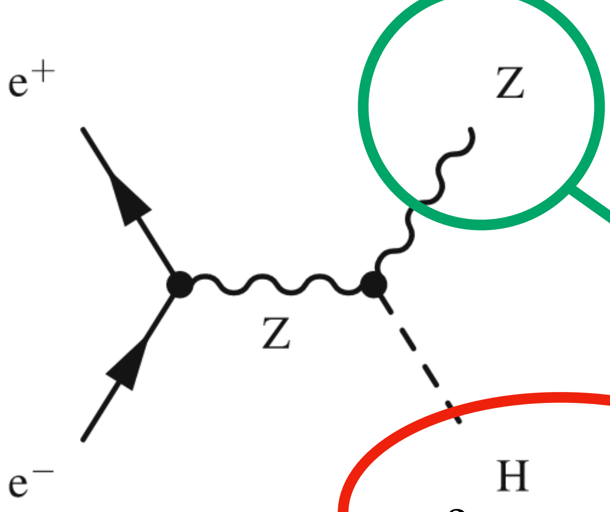
4 IPs: 1.7x Stats using same running time

Higgs physics at e^+e^- Higgs factories

- Higgs physics at the e^+e^- colliders: Recoil mass measurement

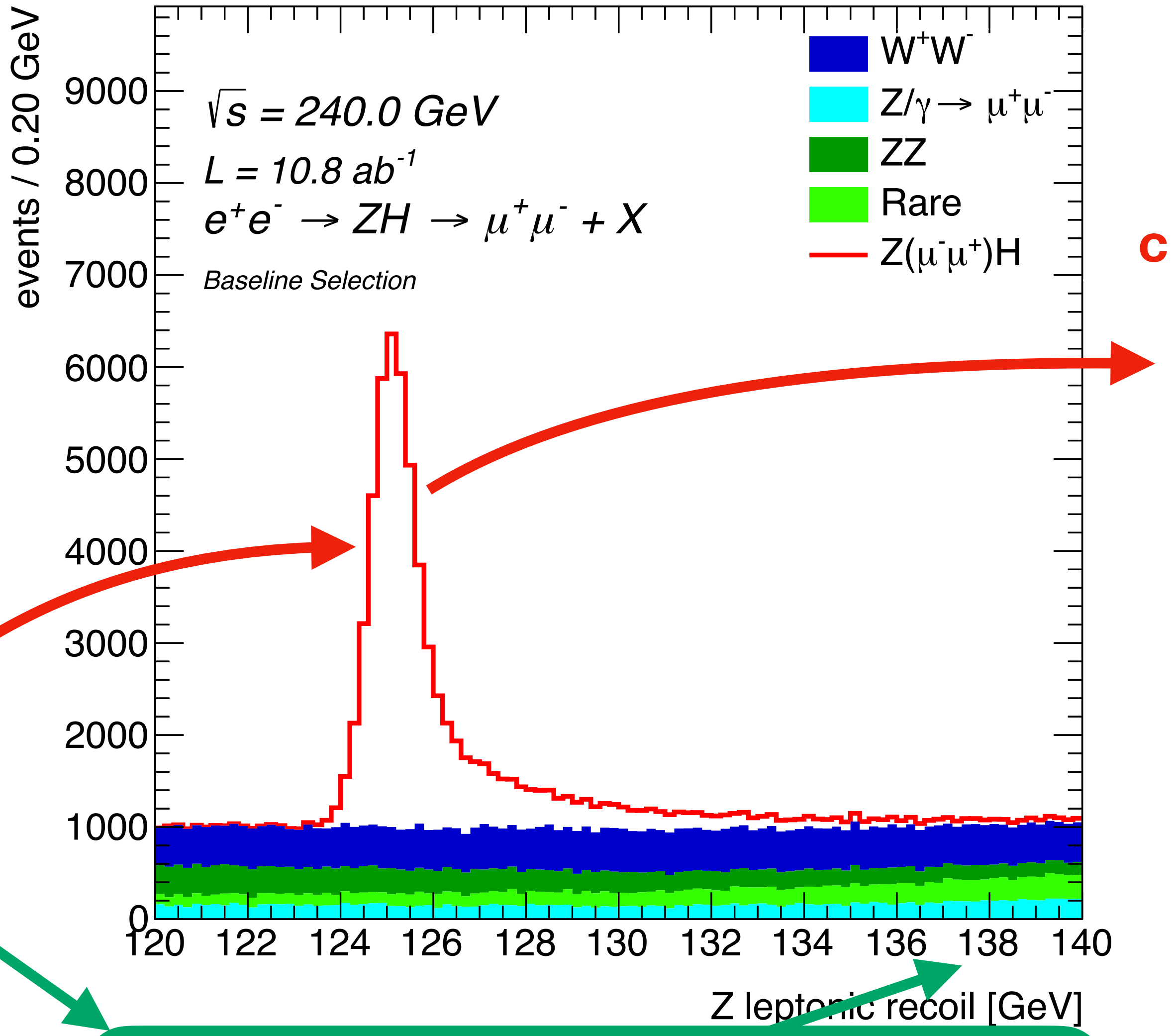
Tag the Higgs from *ZH* looking at the *Z* in, e.g., $Z\to\mu^+\mu^-$





$$M^2_{\text{Recoil}} = M^2_H$$

FCCAnalyses: FCC-ee Simulation (Delphes)



$$M^2_{\text{Recoil}} = s + M^2_Z - 2E_Z\sqrt{2}$$

Inclusive
$e^+e^-\to ZH$
cross section

σ_{ZH}

Measurement of σ_{ZH} ⇒ Absolute measurement of *HZZ* interactions (not ratios)

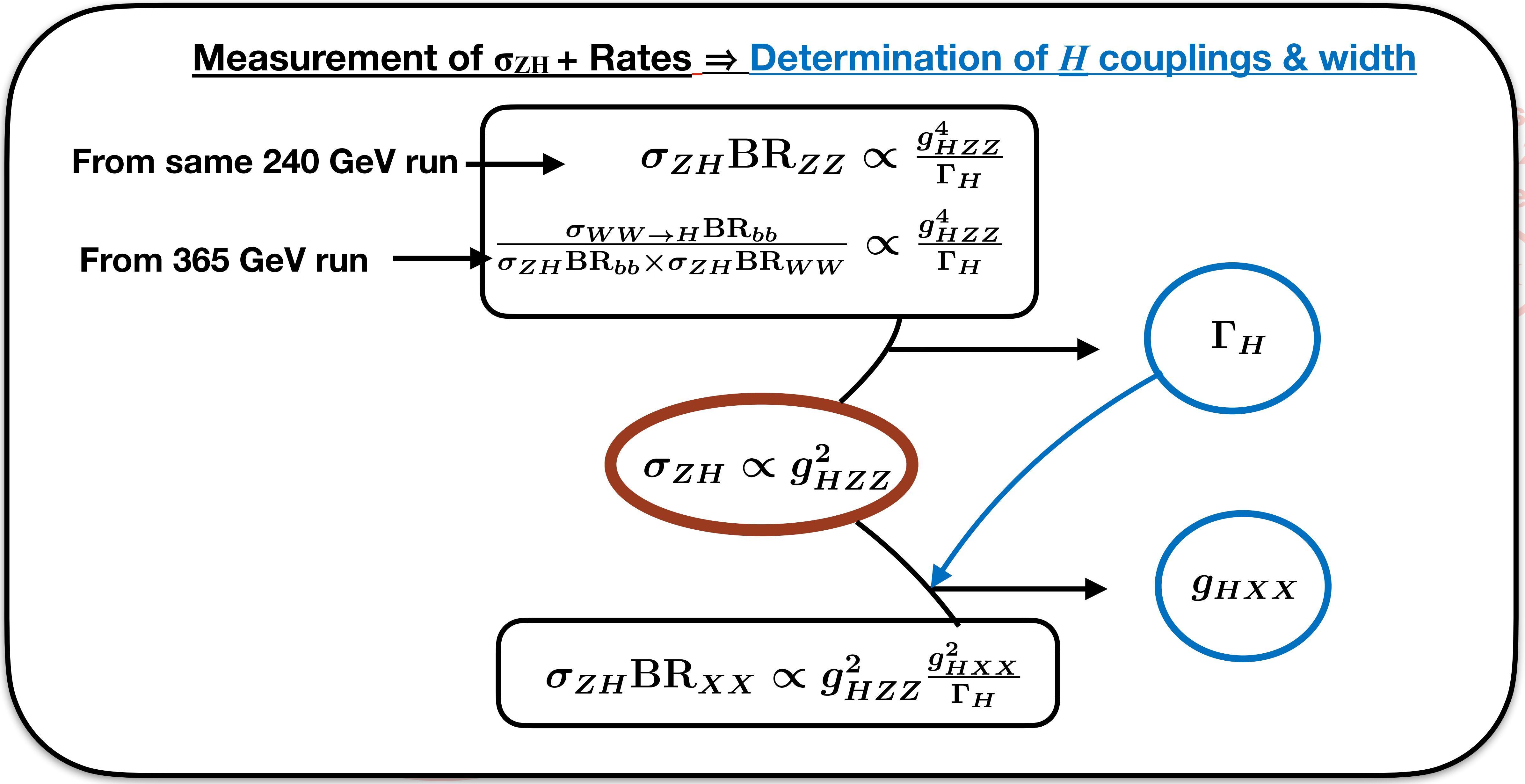
Precise Higgs mass determination: $\Delta M_H \sim O(3\ \text{MeV})$

Higgs physics at e⁺e⁻ Higgs factories

- Higgs physics at the e⁺e⁻ colliders: Recoil mass measurement

Tag the Higgs from *ZH* looking at the Z in, e.g., $Z\to\mu^+\mu^-$

sive
ZH
ection



Measurement of σ_{ZH} + Rates ⇒ Determination of *H* couplings & width

From same 240 GeV run → $\sigma_{ZH}\mathrm{BR}_{ZZ} \propto \frac{g^4_{HZZ}}{\Gamma_H}$

From 365 GeV run → $\frac{\sigma_{WW\to H}\mathrm{BR}_{bb}}{\sigma_{ZH}\mathrm{BR}_{bb}\times\sigma_{ZH}\mathrm{BR}_{WW}} \propto \frac{g^4_{HZZ}}{\Gamma_H}$

Γ_H

$\sigma_{ZH} \propto g^2_{HZZ}$

g_{HXX}

$\sigma_{ZH}\mathrm{BR}_{XX} \propto g^2_{HZZ}\frac{g^2_{HXX}}{\Gamma_H}$

Measurement of σ_{ZH} ⇒ Absolute measurement of *HZZ* interactions (not ratios)

Precise Higgs mass determination: $\Delta M_H \sim O(3\ \mathrm{MeV})$

Higgs physics at e^+e^- Higgs factories

- Higgs physics at the e^+e^- colliders: What do ~10^6 Higgses bring to the table?

E.g. FCCee Higgs precision (2IPs)

$\sqrt{s}$	240 GeV		365 GeV	
Integrated luminosity	$5\,\mathrm{ab}^{-1}$ **(3 yrs)**		$1.5\,\mathrm{ab}^{-1}$ **(4 yrs)**	
Channel	ZH	$\nu_e\bar{\nu}_e$ H	ZH	$\nu_e\bar{\nu}_e$ H
$H \to$ any	± 0.5		± 0.9	
$H \to b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \to c\bar{c}$	± 2.2		± 6.5	± 10
$H \to gg$	± 1.9		± 3.5	± 4.5
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau^+\tau^-$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invisible	< 0.3		< 0.6	

($H \to Z\gamma$ $\pm 17^*$ ← **Ongoing study.**)

Extrapolated from CEPC precision

Statistical uncertainties:

Experimental systematics not expected to be a limiting factor for Higgs measurements

0.5% precision in σ_{ZH}

SM: 1-loop EW corrections ~3%

Tests of quantum corrections in the Higgs sector

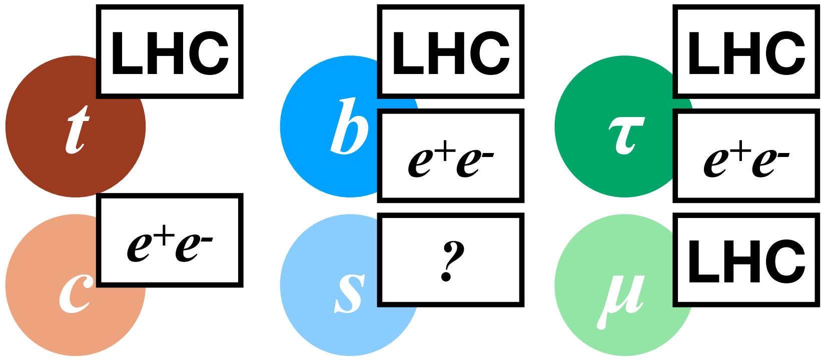
Higgs width measured to 1%

Access to light quark couplings:
Charm (~1%)
Strange (?)

Higgs physics at e^+e^- Higgs factories

Focus Topic: **H →ss**

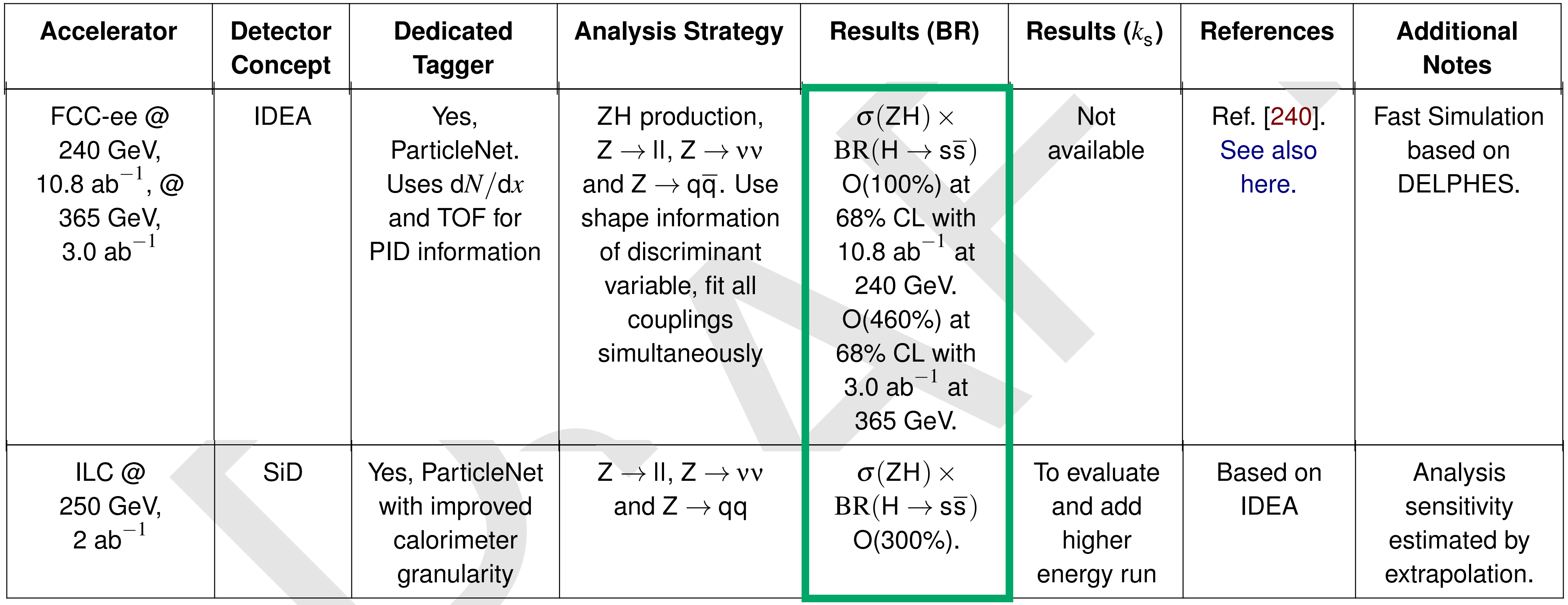
- Sensitivity to H→ss would allow for a *complete exploration of the 2nd generation Yukawa couplings*



- At the LHC this is inaccessible because:
  - Tiny expected rates vs. large QCD backgrounds
  - Current detector capabilities
    - Strange tagging: one of the most powerful handles to ID strange-quarks jets is the possibility to distinguish between Kaons and Pions up to tens of GeV in momentum ⇒ Requires dedicated detector subsystems not present in LHC multi-purpose detectors
- Proof of concepts studied in past years focused in strange-tag algorithms and potential detector designs

Higgs physics at e^+e^- Higgs factories

Focus Topic: H →ss



Accelerator	Detector Concept	Dedicated Tagger	Analysis Strategy	Results (BR)	Results (k_s)	References	Additional Notes
FCC-ee @ 240 GeV, 10.8 ab^{-1}, @ 365 GeV, 3.0 ab^{-1}	IDEA	Yes, ParticleNet. Uses $\mathrm{d}N/\mathrm{d}x$ and TOF for PID information	ZH production, $\mathrm{Z}\to\mathrm{ll}$, $\mathrm{Z}\to\nu\nu$ and $\mathrm{Z}\to\mathrm{q\bar{q}}$. Use shape information of discriminant variable, fit all couplings simultaneously	$\sigma(\mathrm{ZH})\times\mathrm{BR}(\mathrm{H}\to\mathrm{s\bar{s}})$ O(100%) at 68% CL with 10.8 ab^{-1} at 240 GeV. O(460%) at 68% CL with 3.0 ab^{-1} at 365 GeV.	Not available	Ref. [240]. See also here.	Fast Simulation based on DELPHES.
ILC @ 250 GeV, 2 ab^{-1}	SiD	Yes, ParticleNet with improved calorimeter granularity	$\mathrm{Z}\to\mathrm{ll}$, $\mathrm{Z}\to\nu\nu$ and $\mathrm{Z}\to\mathrm{qq}$	$\sigma(\mathrm{ZH})\times\mathrm{BR}(\mathrm{H}\to\mathrm{s\bar{s}})$ O(300%).	To evaluate and add higher energy run	Based on IDEA	Analysis sensitivity estimated by extrapolation.

⇒ Sensitivity to O(1) deviations to strange Yukawa

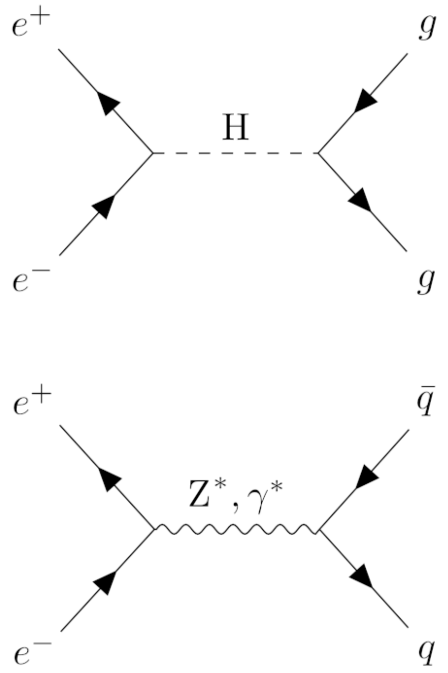
present in LHC multi-purpose detectors

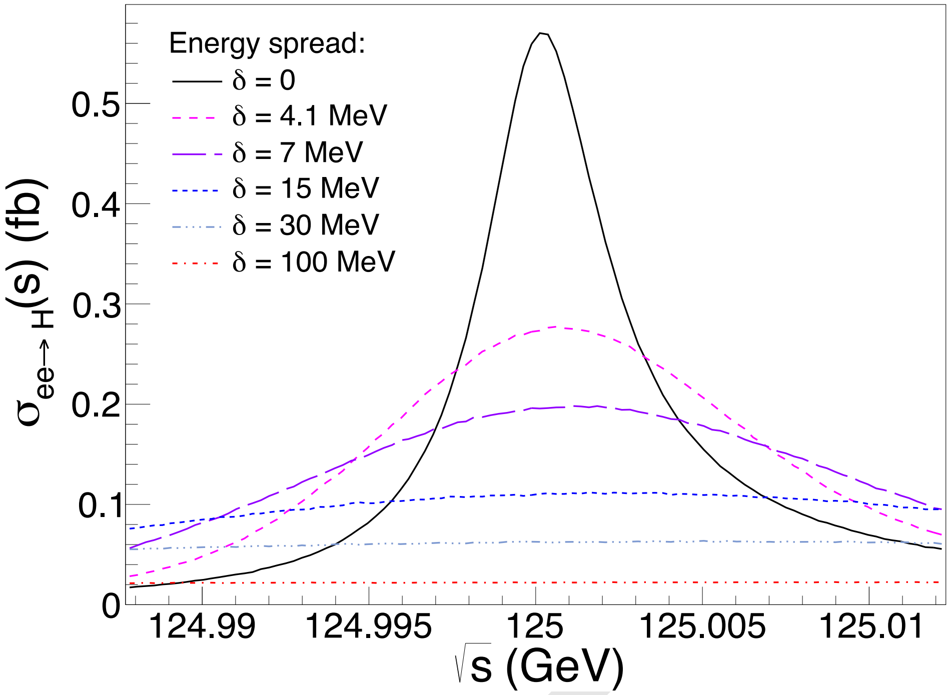
- Proof of concepts studied in past years focused in strange-tag algorithms and potential detector designs

Higgs physics at e^+e^- Higgs factories

Electron Yukawa coupling

- Hopeless at the LHC, given the tiny value of the electron mass (→ tiny width)
- With an integrated luminosity of 10 ab^{-1}/year expected at $\sqrt{s}\sim 125$ GeV, FCCee could attempt an observation of $e^+e^- \to H \Rightarrow$ Electron Yukawa





Benchmark

(δ, L)= (4.1 MeV, 10 ab^{-1})

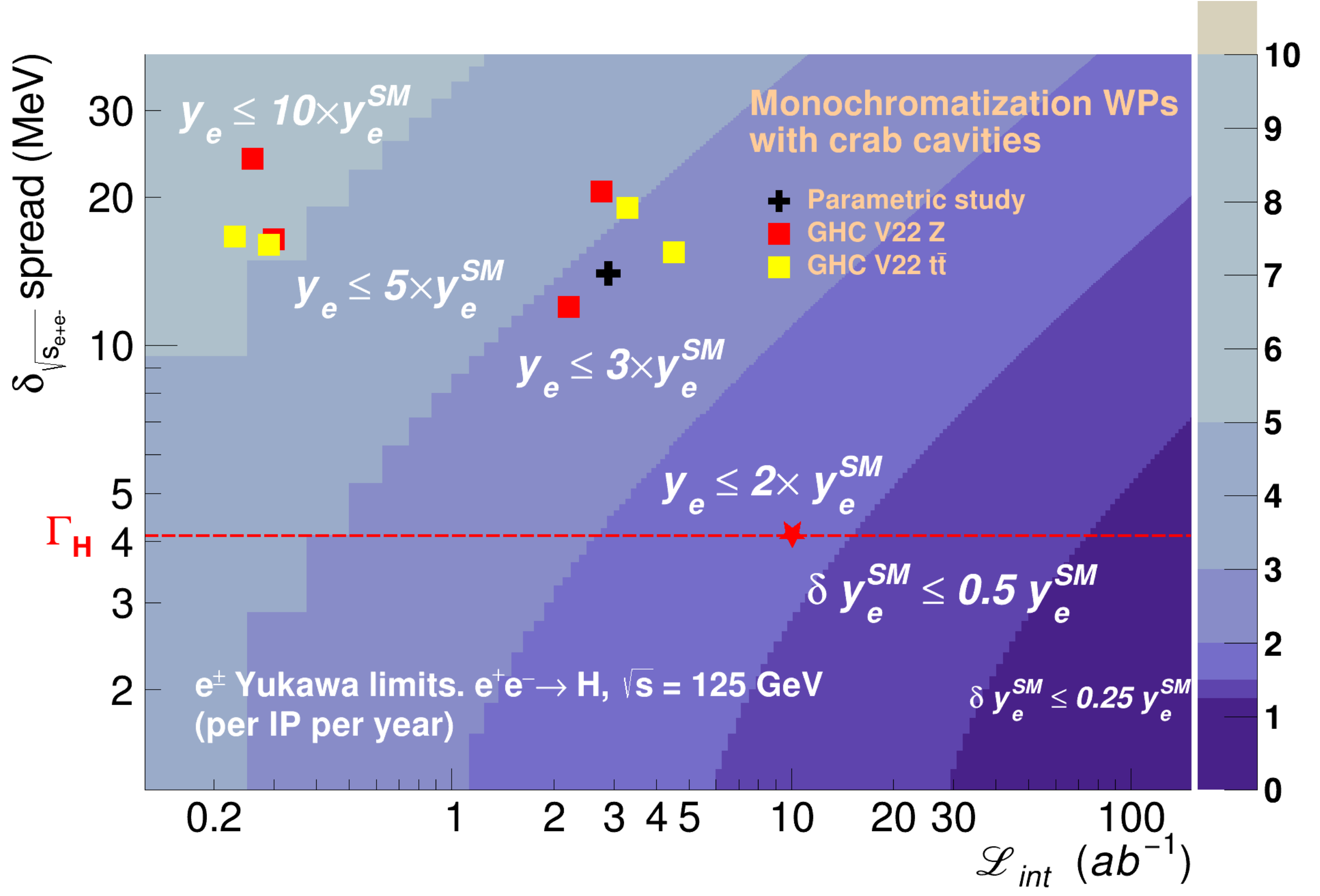
→~2800 Higgses

- Challenges:
  - Need to know first m_H with MeV precision
  - Small resonant σ → Need high beam monochromatization (δ~MeV)
  - Multiple backgrounds orders of magnitude larger than signal

Higgs physics at e^+e^- Higgs factories

Electron Yukawa coupling

Most sensitive channel H→gg (no irreducible Z→gg background but requires to reduce light-quark for mistag below 1% while keeping high gluon efficiency (~70%))



Benchmark

(δ, L)= (4.1 MeV, 10 ab^{-1})

→~2800 Higgses

1.3 σ significance

$|y_e|<1.6\,|y_e^{SM}|$ @ 95% C.L.

per IP per year

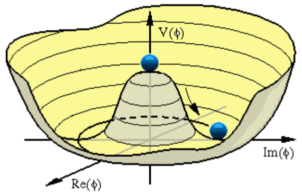
Currently not in FCC-ee default running plan

- Multiple backgrounds orders of magnitude larger than signal

Higgs physics at e^+e^- Higgs factories

Focus Topic: Higgs self-coupling

- The **Higgs self coupling** characterizes the structure of the Higgs potential. Relevant for BSM questions, e.g. baryogengesis

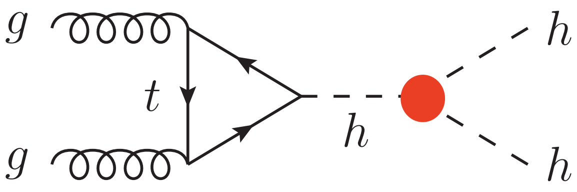
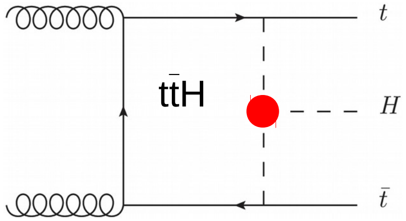
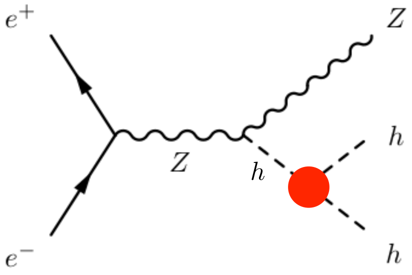
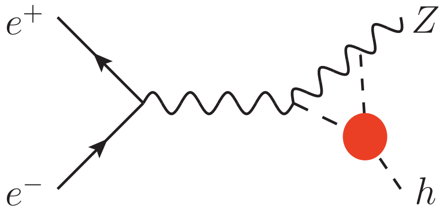


$$V(\phi) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 \longrightarrow V(h) = \frac{1}{2}m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

$$\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \lambda_\phi = \frac{G_\mu m_h^2}{\sqrt{2}} \approx 0.129$$

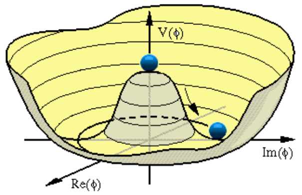
- Two complementary approaches:

	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		
Lepton Colliders		

Higgs physics at e^+e^- Higgs

Focus Topic: Hig

- The **Higgs self coupling** characteriz
potential. Relevant for BSM questions, e



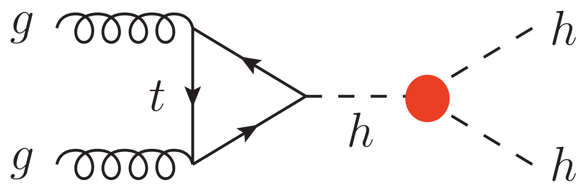
$$V(\phi) = -\mu_\phi^2\,|\phi|^2 + \lambda_\phi\,|\phi|^4 \longrightarrow V$$

$$\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \lambda_\phi$$

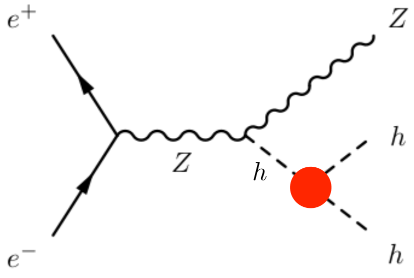
- Two complementary approaches:

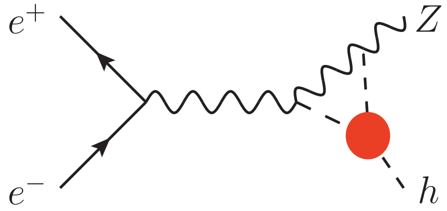
Higgs-pair production

Hadron Colliders

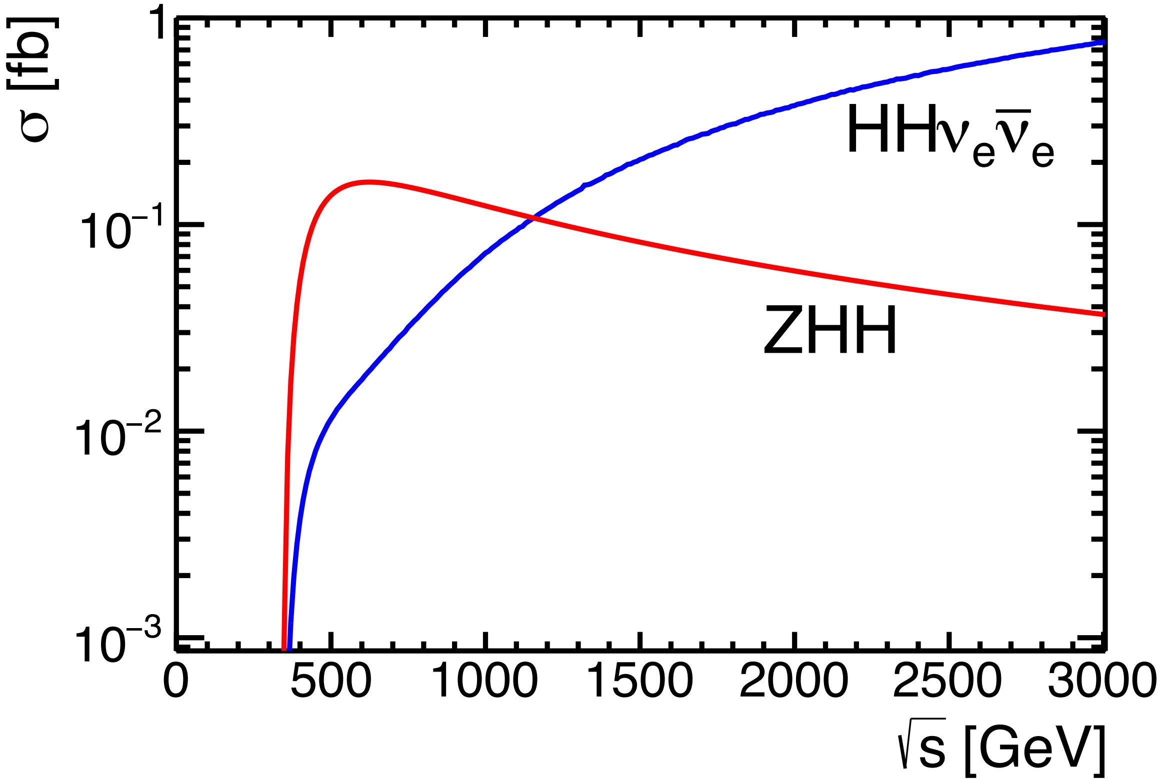


Lepton Colliders





e+e-: Requires √s significantly higher than nominal threshold

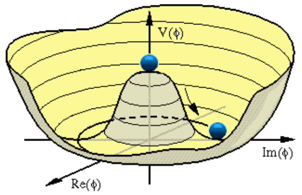


Accessible at high-energy linear colliders √s≳500 GeV

Higgs physics at e+e- Higgs factories

Focus Topic: Higgs self-coupling

- The **Higgs self coupling** characterizes the structure of the Higgs potential. Relevant for BSM questions, e.g. baryogengesis



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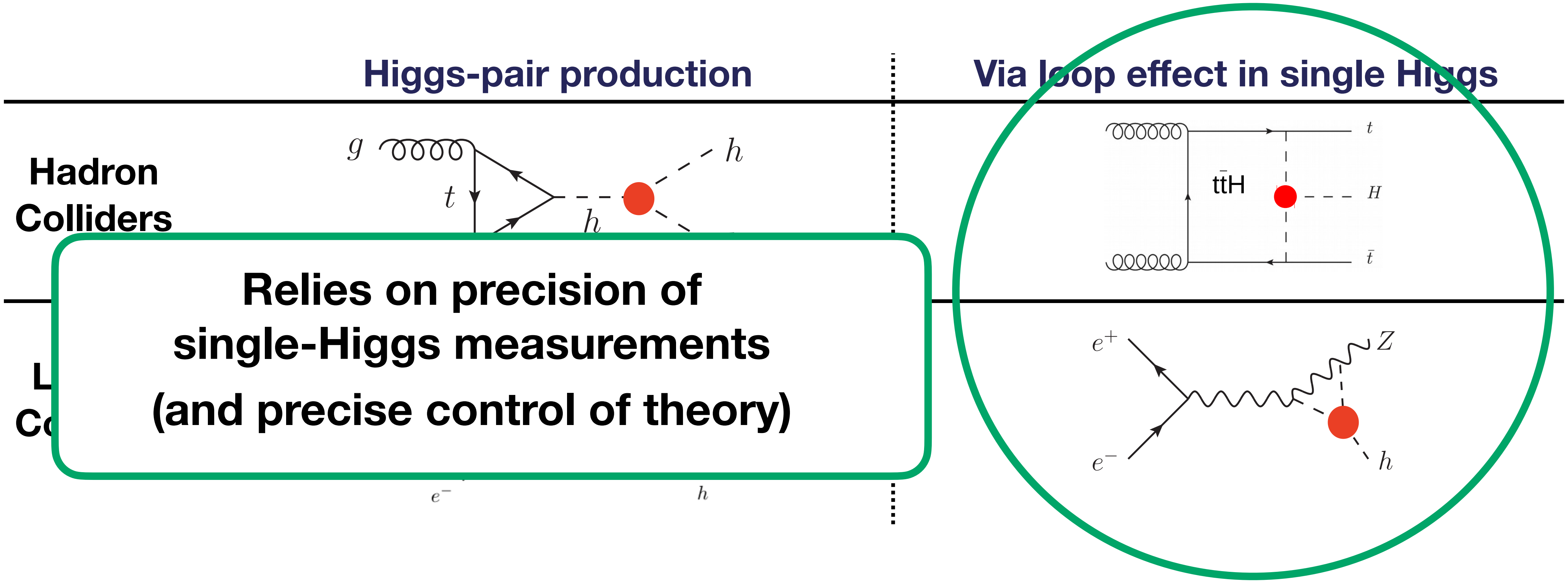
- Two complementary approaches:



Higgs-pair production

Via loop effect in single Higgs

Hadron Colliders

Relies on precision of single-Higgs measurements (and precise control of theory)

Higgs physics at e^+e^- Higgs factories

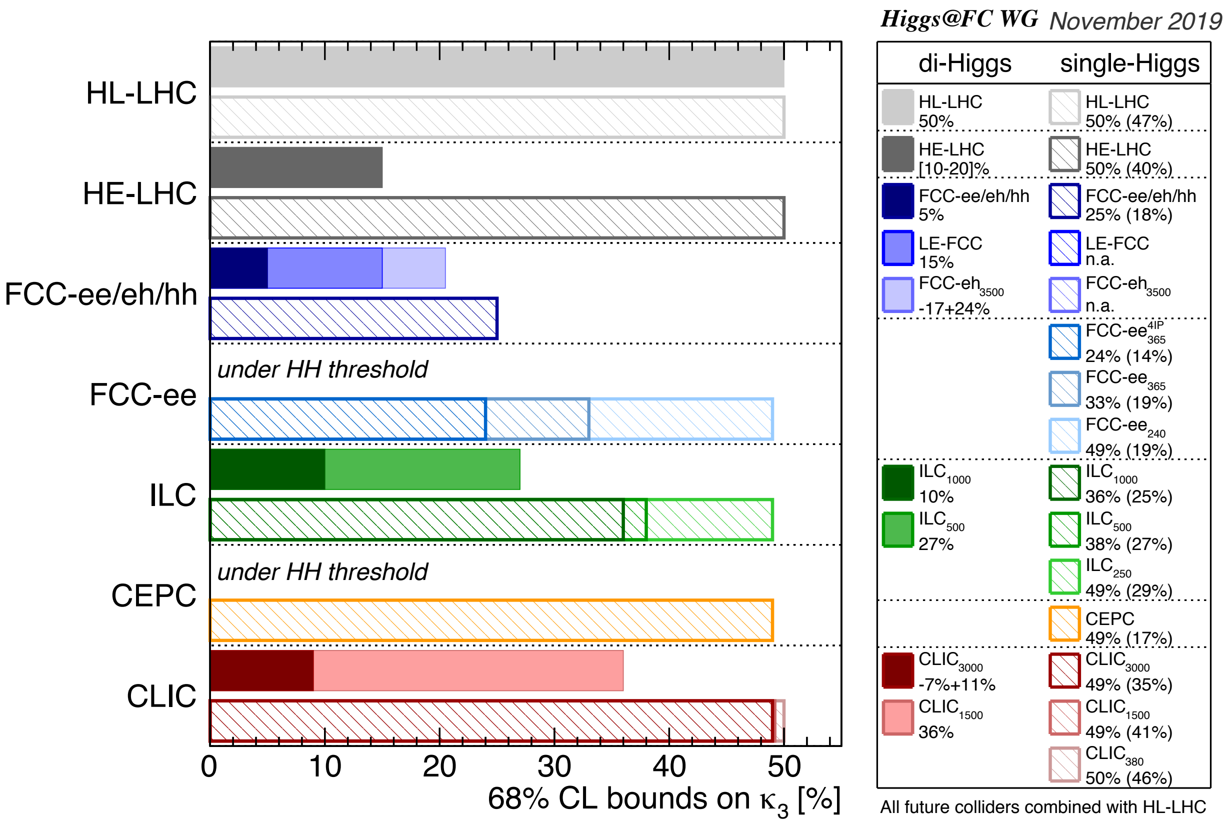
Focus Topic: Higgs self-coupling

From previous ESU and Snowmass

To be updated in March 2025

collider	single $-h$	hh	combined
HL-LHC	100-200%	50%	50%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250	49%	–	49%
$\mathrm{ILC}_{500}/\mathrm{C}^3$-550	38%	20%	20%
CLIC_{380}	50%	–	50%
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
FCC-hh	-	3.4-7.8%	3.4-7.8%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

Combined with HLLHC 50%

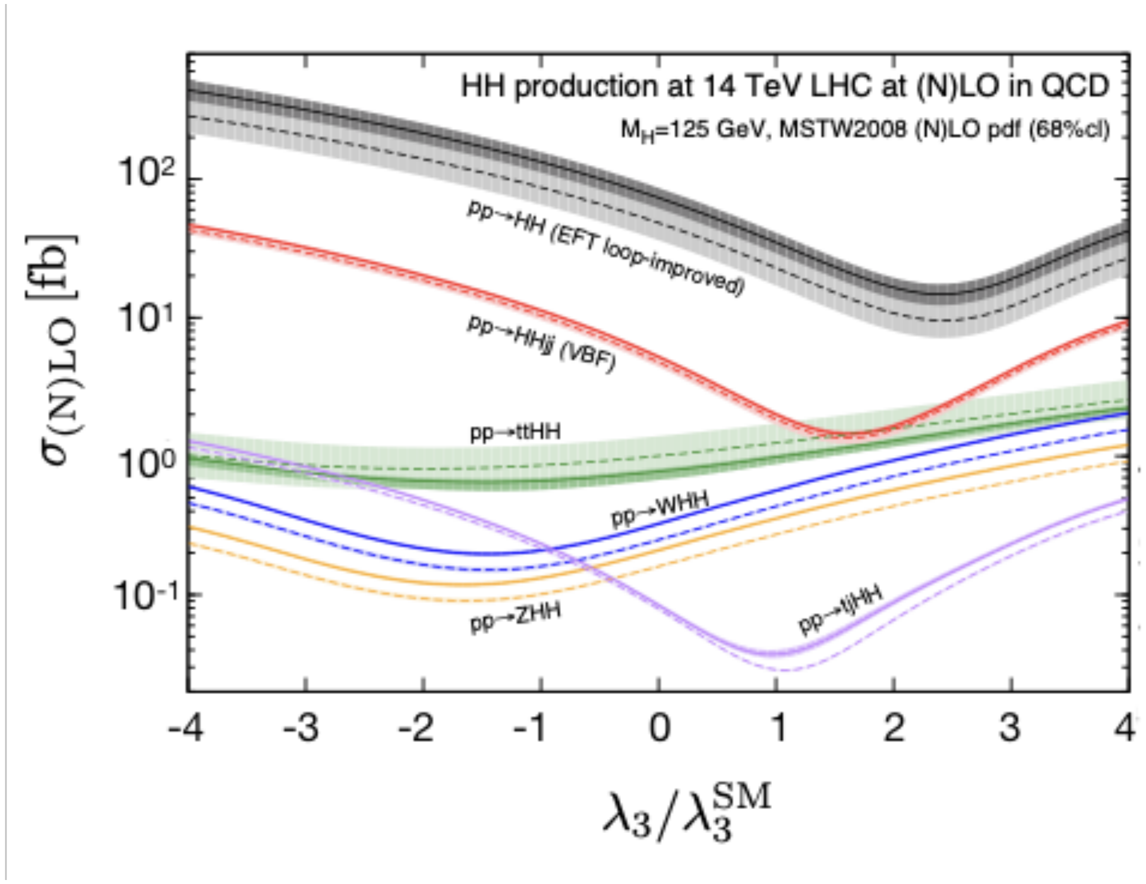


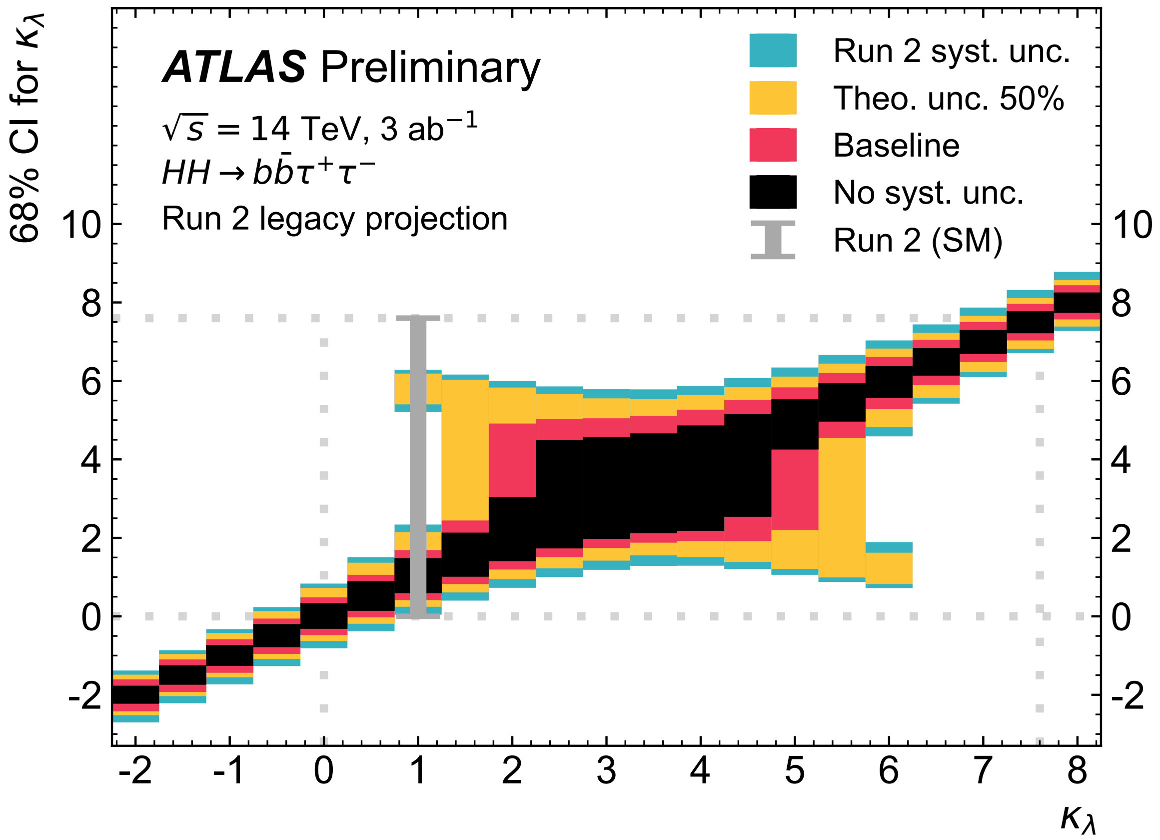
Outdated in several relevant aspects (theory and/or exp. analyses) or do not cover all possibilities

Higgs physics at e^+e^- Higgs factories

Focus Topic: Higgs self-coupling

- Previous studies always focused around the SM value. That makes a big difference for HH probes of the self-coupling:





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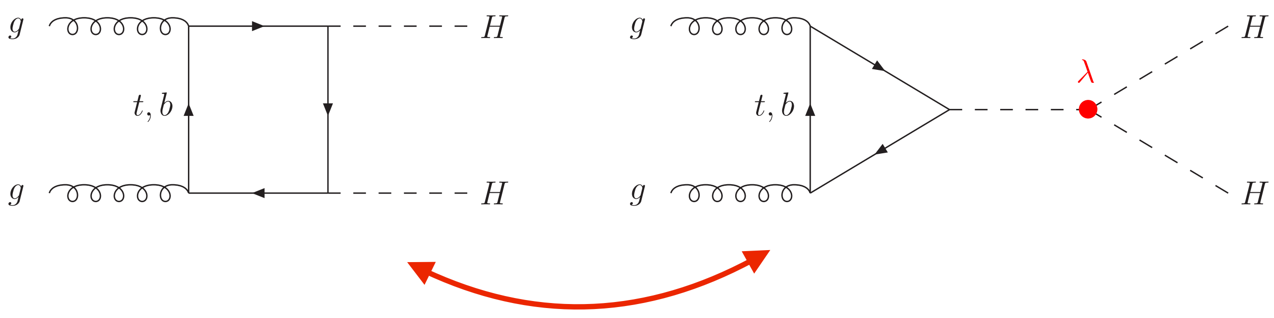

Negative interference in ggHH: suppression for $\Delta\lambda_3 \sim 0$

Higgs physics at e^+e^- Higgs factories

Focus Topic: **Higgs self-coupling**

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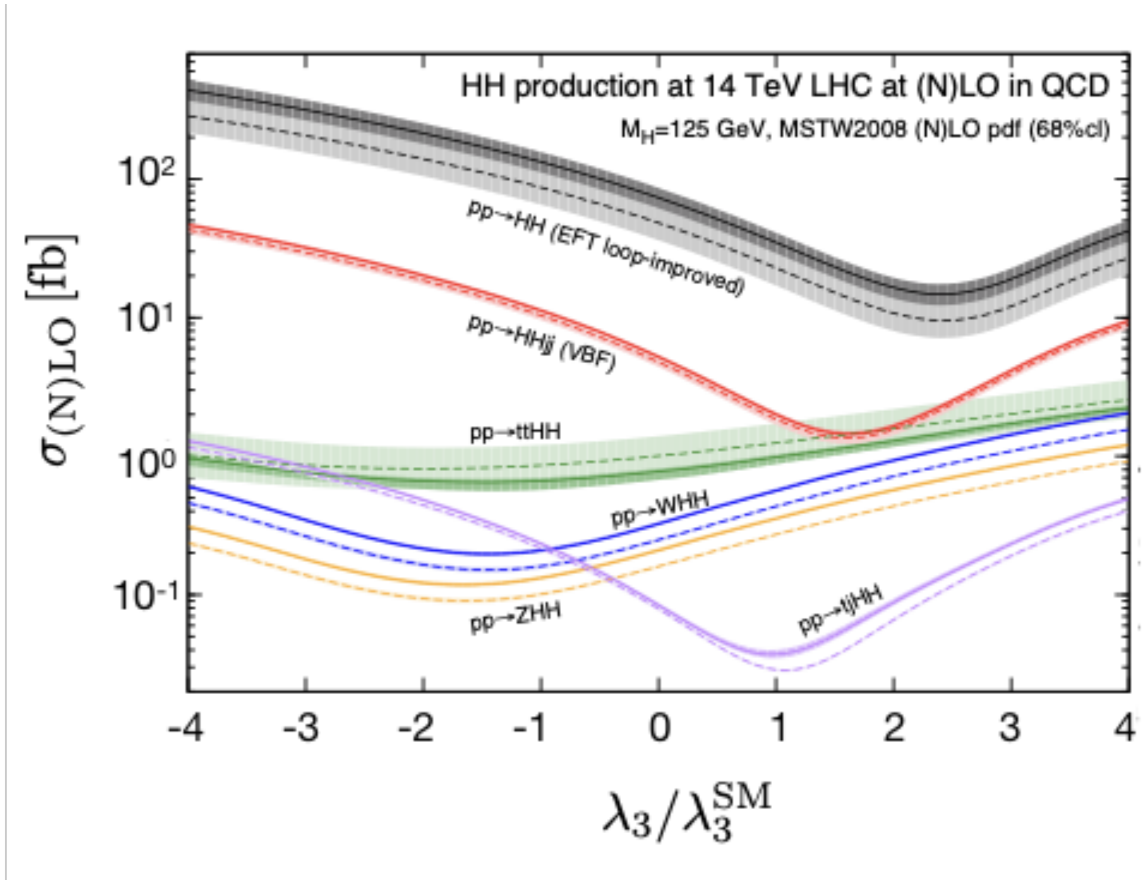
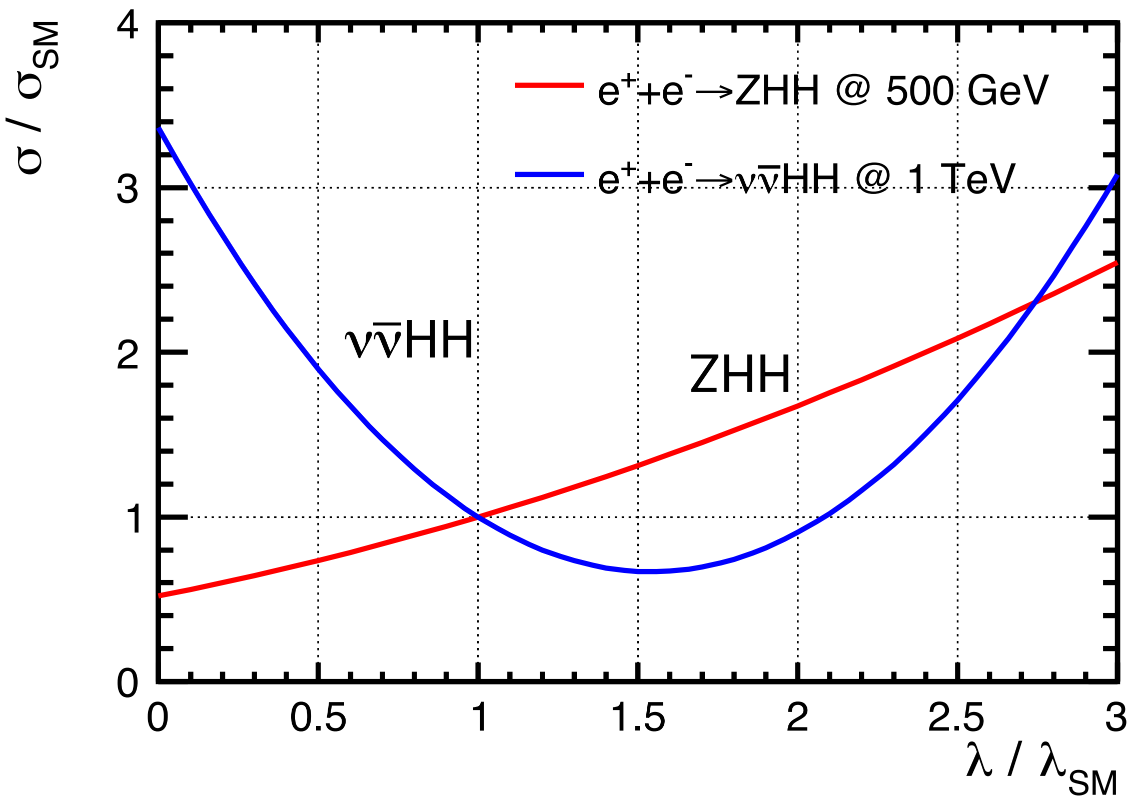
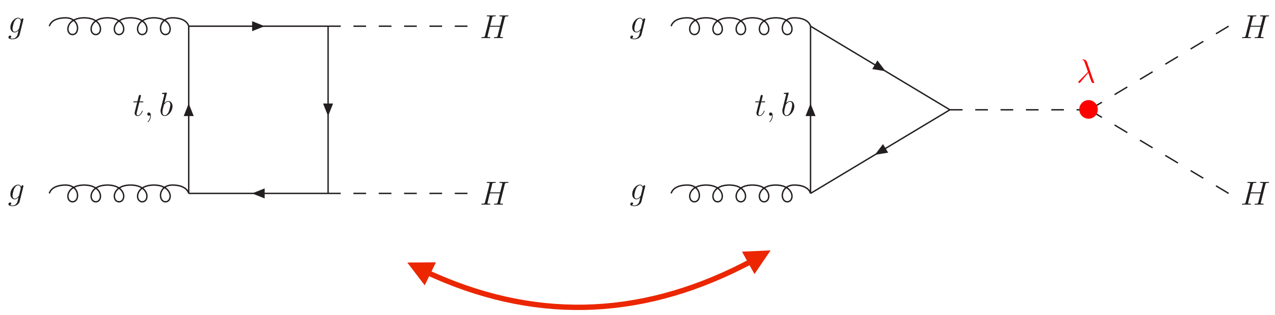
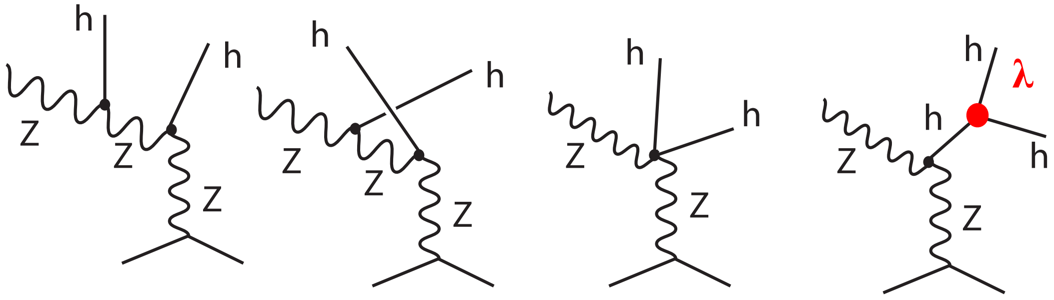








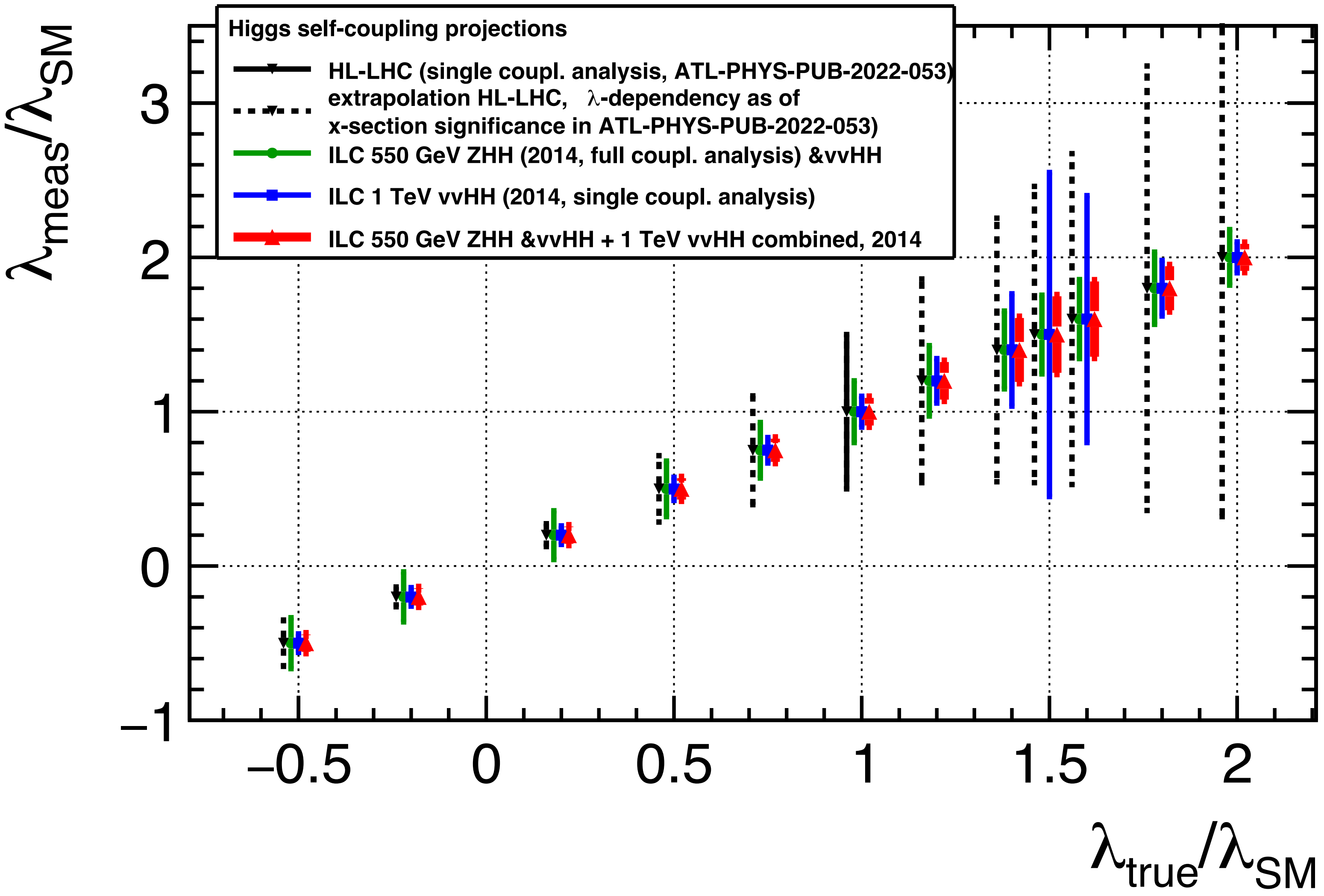
Negative interference in ggHH: suppression for $\Delta\lambda_3$~0

Positive interference in ZHH

Higgs physics at e^+e^- Higgs factories

Focus Topic: Higgs self-coupling

Higgs pair-production at 550 GeV e+e-: κ_λ sensitivity



- $\kappa_\lambda=1$
  - HLLHC: ~50%
  - ILC 550 GeV: ~20%
- $\kappa_\lambda=2$
  - HLLHC: ~84% (estimated)
  - ILC 550 GeV: ~9%

Improvements in both projections will be available soon (Jan/March)

Negative interference in ggHH: suppression for $\Delta\lambda_3$~0

Positive interference in ZHH

Higgs physics at e^+e^- Higgs factories

Focus Topic: Higgs self-coupling

Why care about large κ_λ?

- O(1) corrections expected in scenarios with strong 1st order phase transition: In 2HDM this suggest $\kappa_\lambda=2$
- But… "traditional wisdom" suggests that any NP inducing large corrections to κ_λ would be seen first via its effects on single Higgs couplings (more precise)?
- Several counter-examples to the last point:
  - Tree-level EFT arguments: EW scalar quadruplets only correct κ_λ at LO
  - Loop-level in concrete BSM scenarios: large NLO corrections to self-coupling possible, with small modifications of single-Higgs couplings

Negative interference in ggHH: suppression for $\Delta\lambda_3$~0

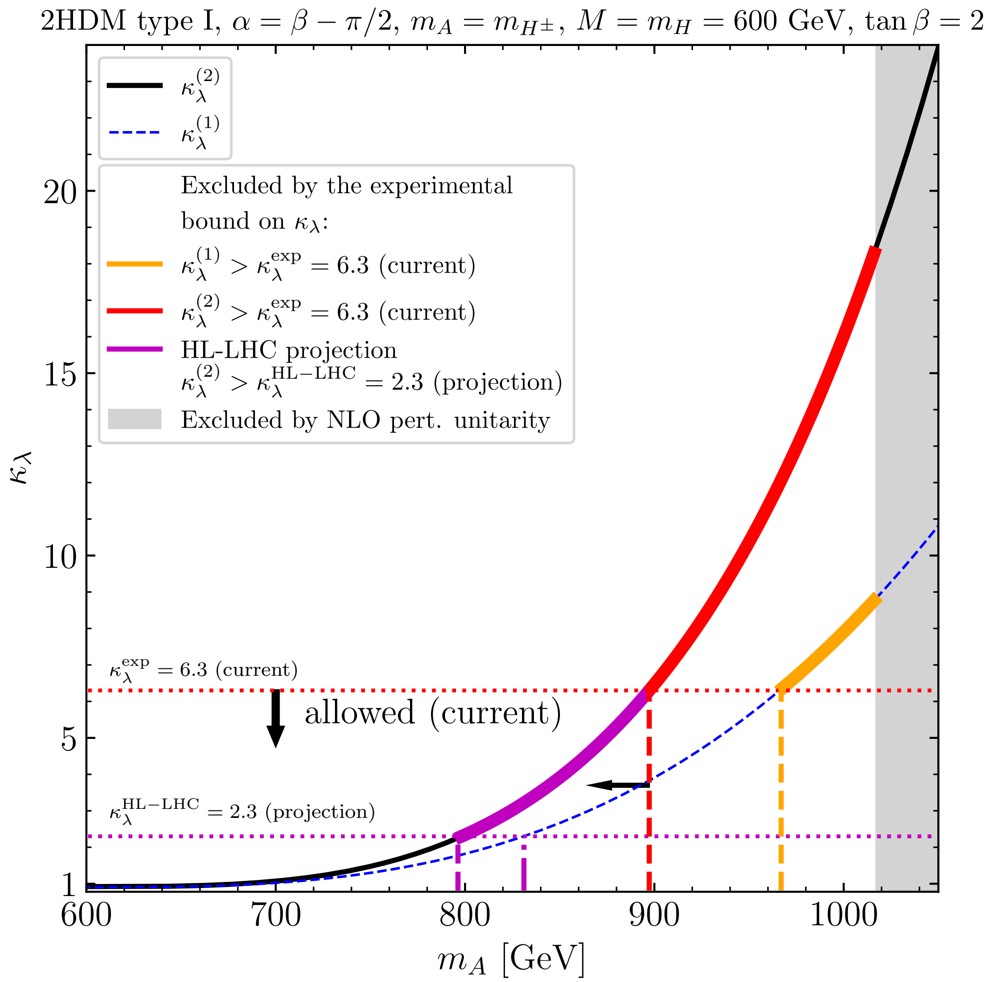
Positive interference in ZHH

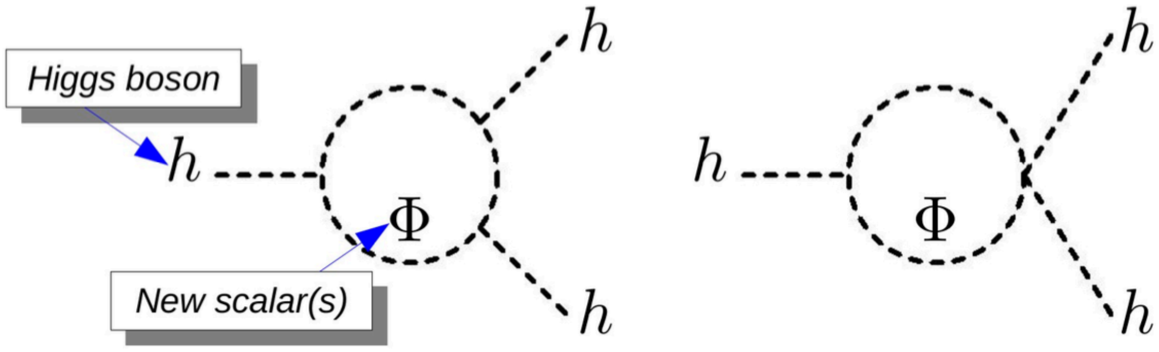
Higgs physics at e$^+$e$^-$ Higgs factories

Focus Topic: Higgs self-coupling

Why care about large κλ?

- Large κλ in BSM models: Extensions with BSM scalars (Φ)





Higgs boson

New scalar(s)

$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

Controls decoupling of BSM states

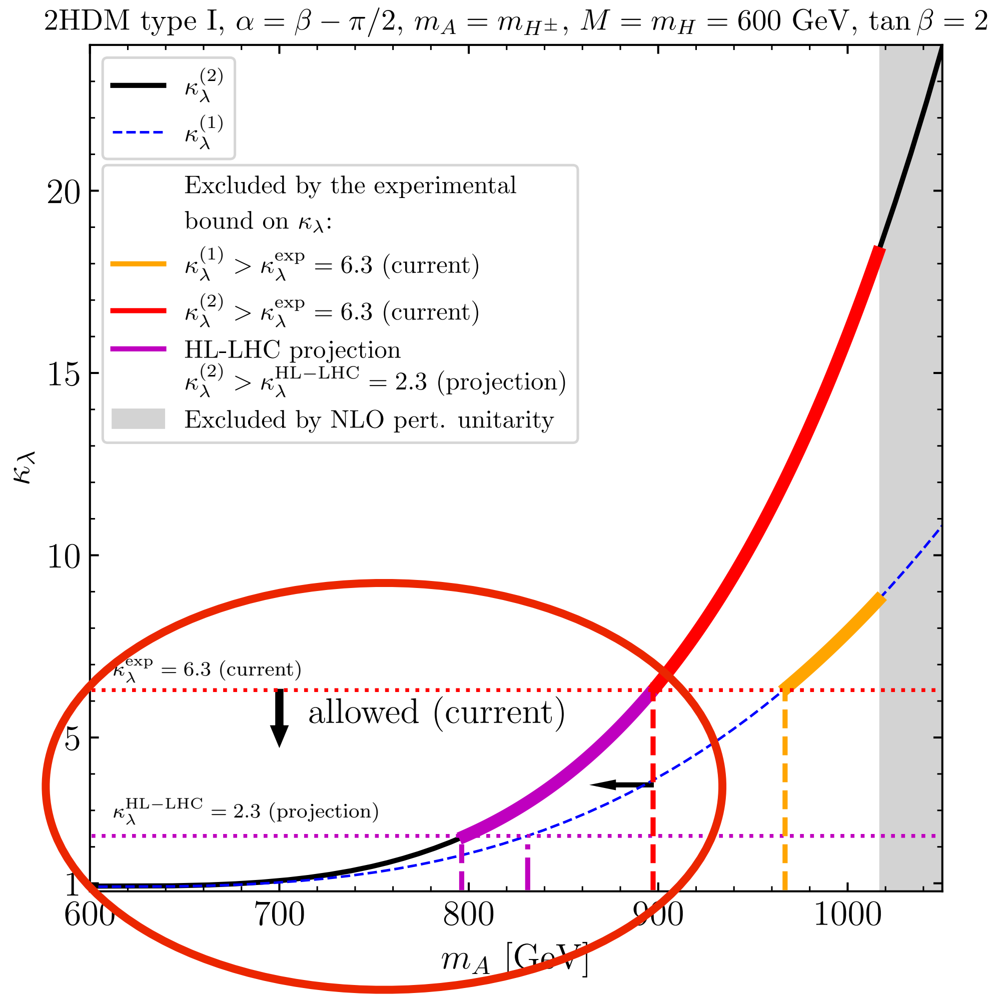
Power-counting: $\Delta\kappa_\lambda \sim O(g_{hh\Phi\Phi}^2)$

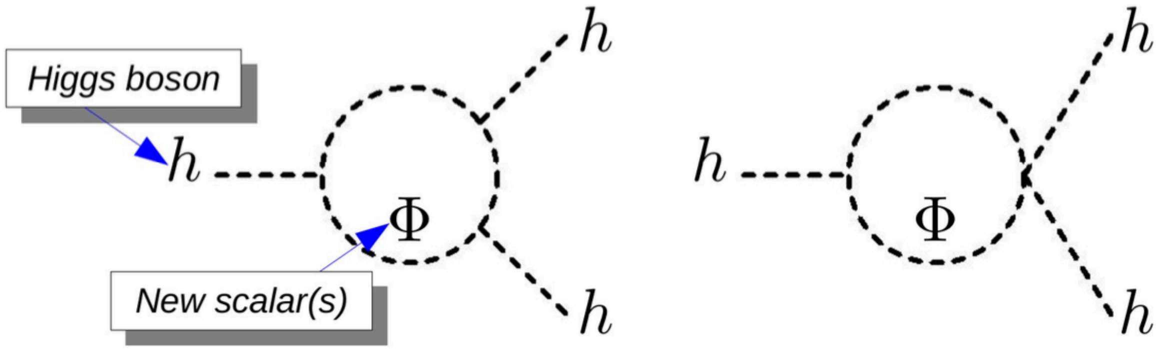
Higgs physics at e^+e^- Higgs factories

Focus Topic: Higgs self-coupling

Why care about large κλ?

- Large κλ in BSM models: Extensions with BSM scalars (Φ)





Higgs boson

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Controls decoupling of BSM states

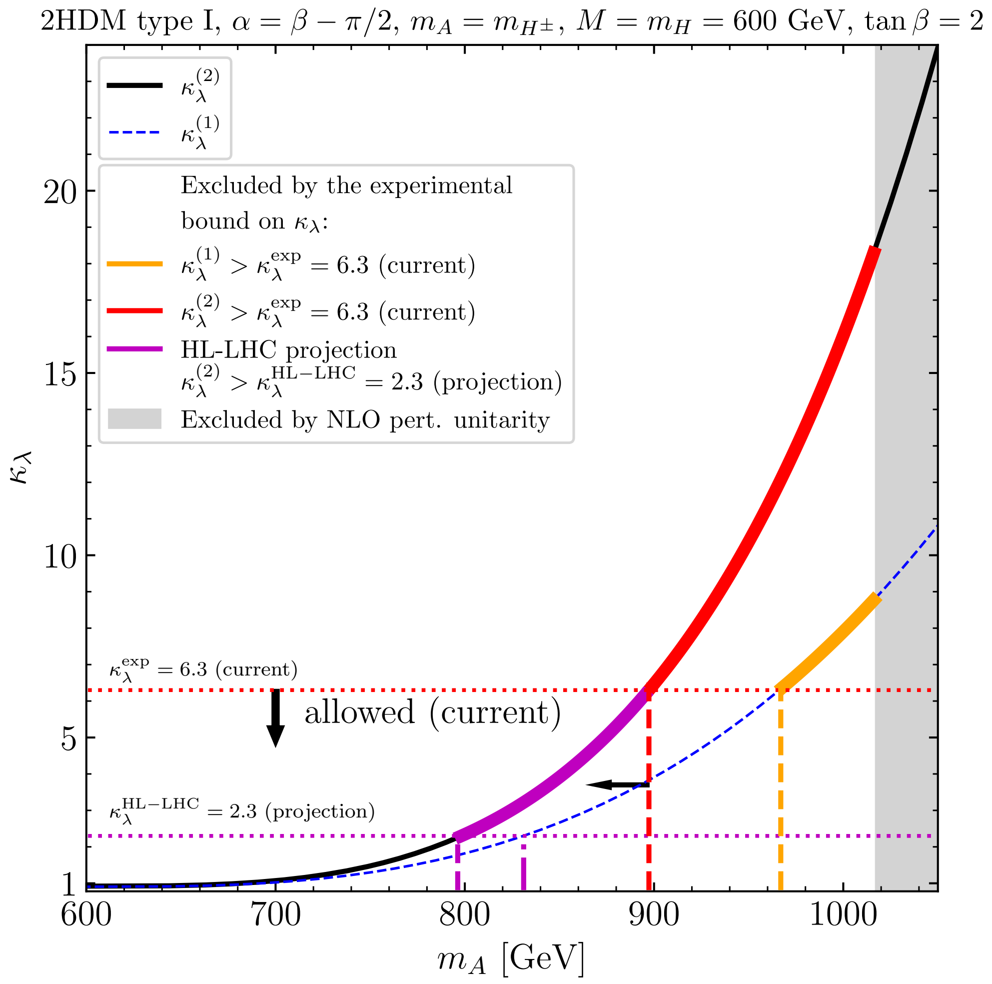
Power-counting: $\Delta\kappa_\lambda \sim O(g_{hh\Phi\Phi}^2)$ ⇒ Mass splitting can produce large corrections

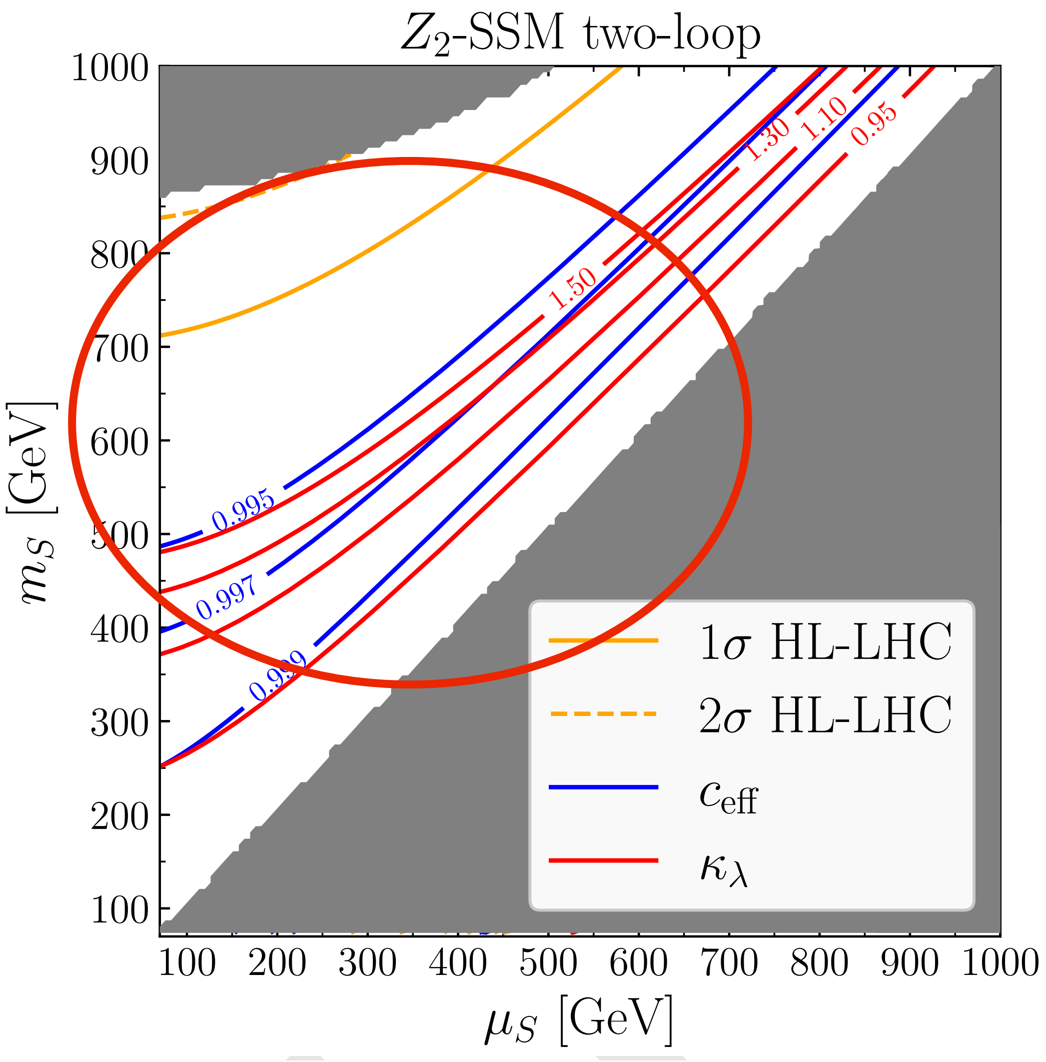
Higgs physics at e^+e^- Higgs factories

<u>Focus Topic:</u> **Higgs self-coupling**

Why care about large κλ?

- Large κλ in BSM models: Extensions with BSM scalars (Φ)





Power-counting: $\Delta\kappa_\lambda \sim O(g^2_{hh\Phi\Phi})$ **vs.** $\Delta g_h \lesssim O(g_{hh\Phi\Phi})$

($g_{hh\Phi\Phi} \propto (m_\Phi^2 - \mathcal{M}^2)/v^2$)

But corrections to g_h can remain small

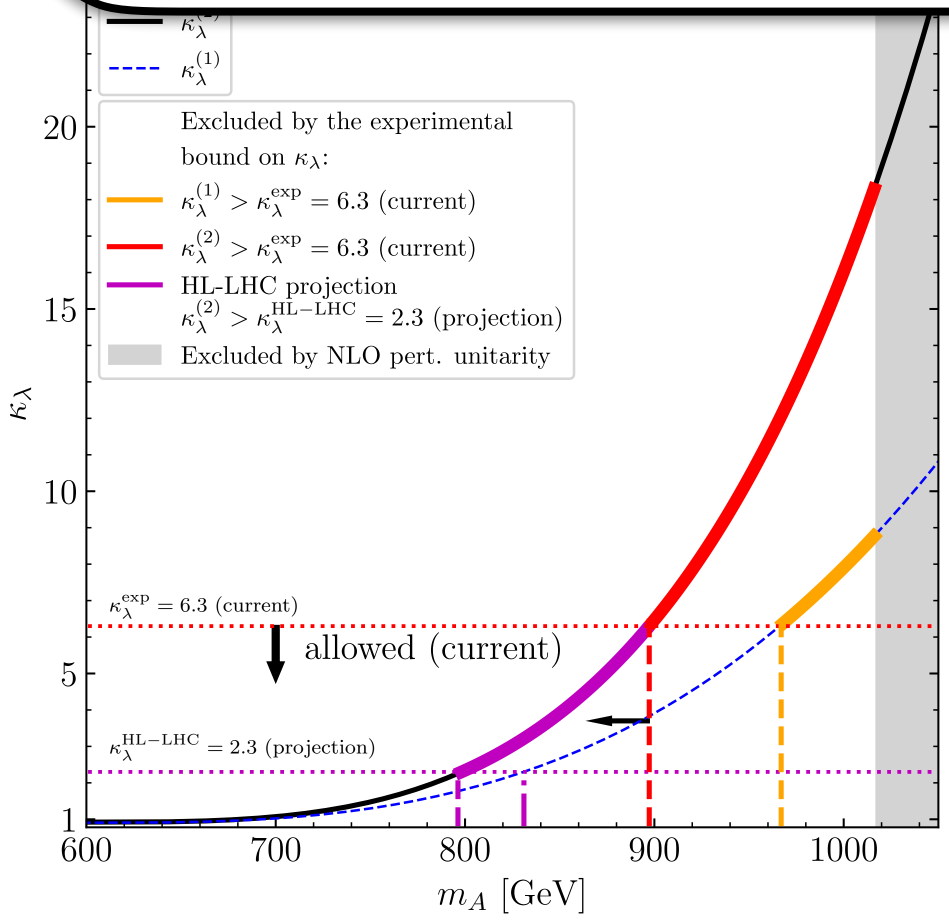
Higgs physics at e^+e^- Higgs factories

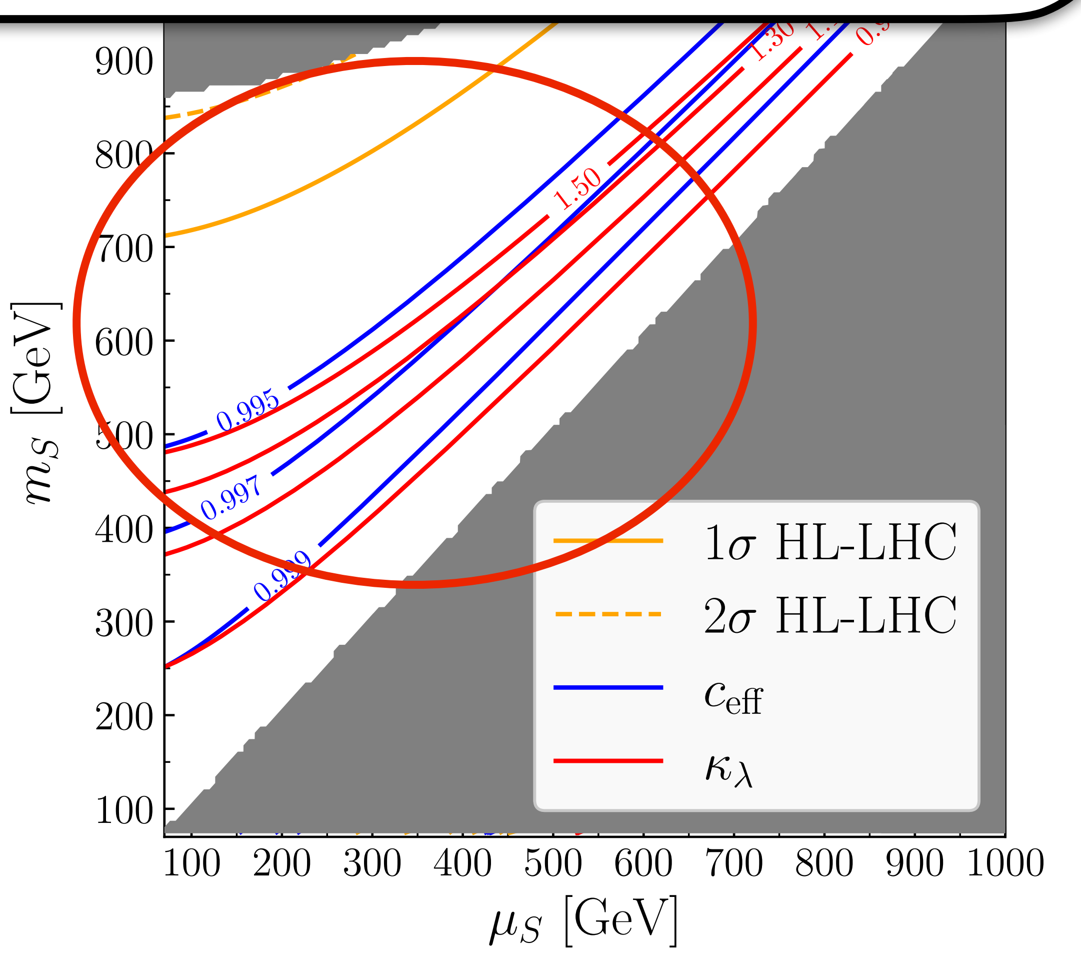
Focus Topic: Higgs self-coupling

Why care about large κ_λ?

- Lar

⇒ Even comparatively weak bounds on κ_λ, e.g. current bound from LHC, $\kappa_\lambda<7$, can be informative for these type of BSM scenarios





Power-counting: $\Delta\kappa_\lambda \sim O(g^2_{hh\Phi\Phi})$ vs. $\Delta g_h \lesssim O(g_{hh\Phi\Phi})$

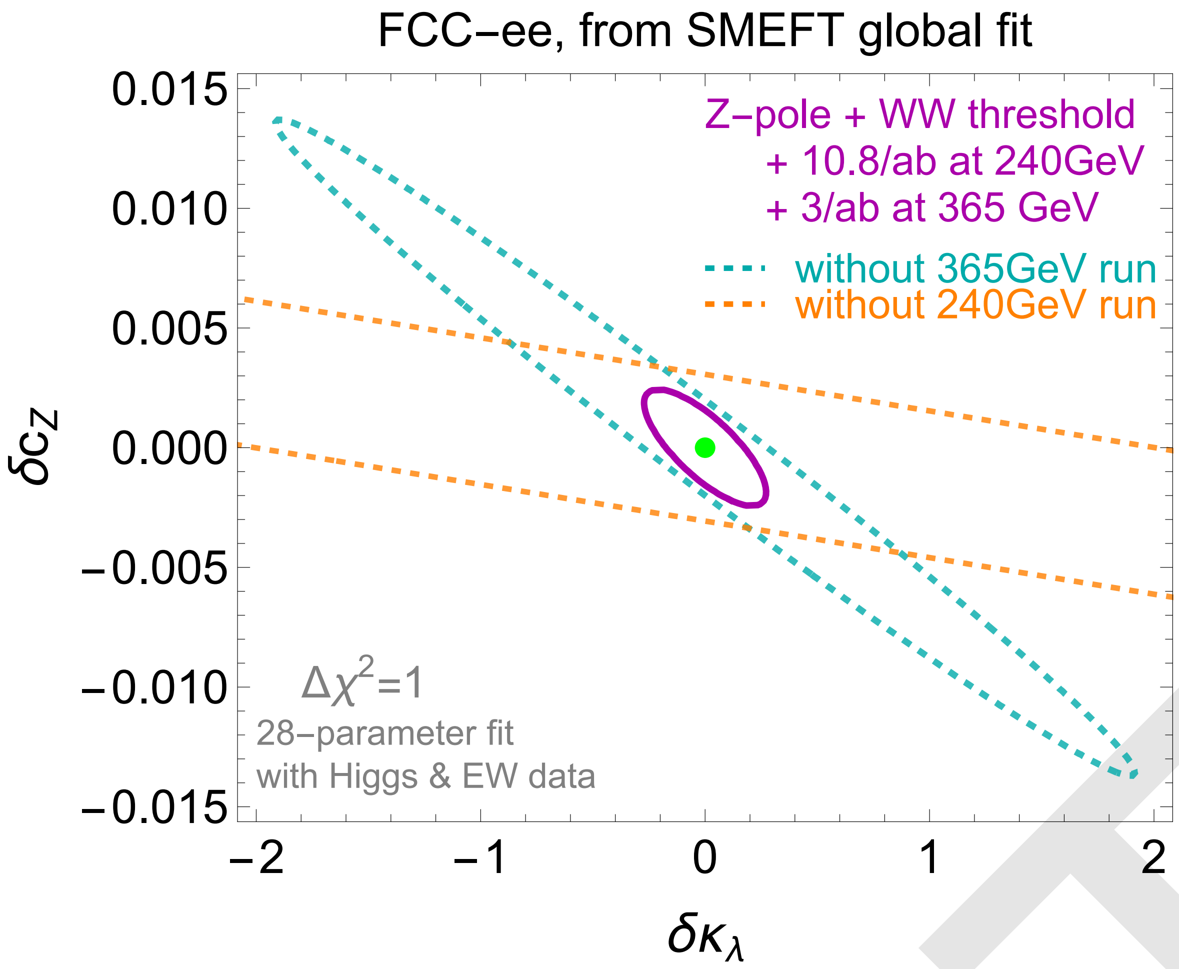
($g_{hh\Phi\Phi} \propto (m^2_\Phi - \mathcal{M}^2)/v^2$)

But corrections to g_h can remain small

Higgs physics at e^+e^- Higgs factories

Focus Topic: Higgs self-coupling

- The absolute precision of the determination from *single-Higgs measurements*, coming from NLO effects, is much less dependent on central value of κ_λ:



- ▸ Sizable modification of κ_λ, small effect in statistical precision
- ▸ Changes in dependence around different values of κ_λ small compared to effect of uncertainties from LO interactions

- This interpretation is typically performed in a global fit to all Higgs observables within the EFT framework and it is not without (several) complications… Let's come back at this after we have at least introduced the EFT global analyses…

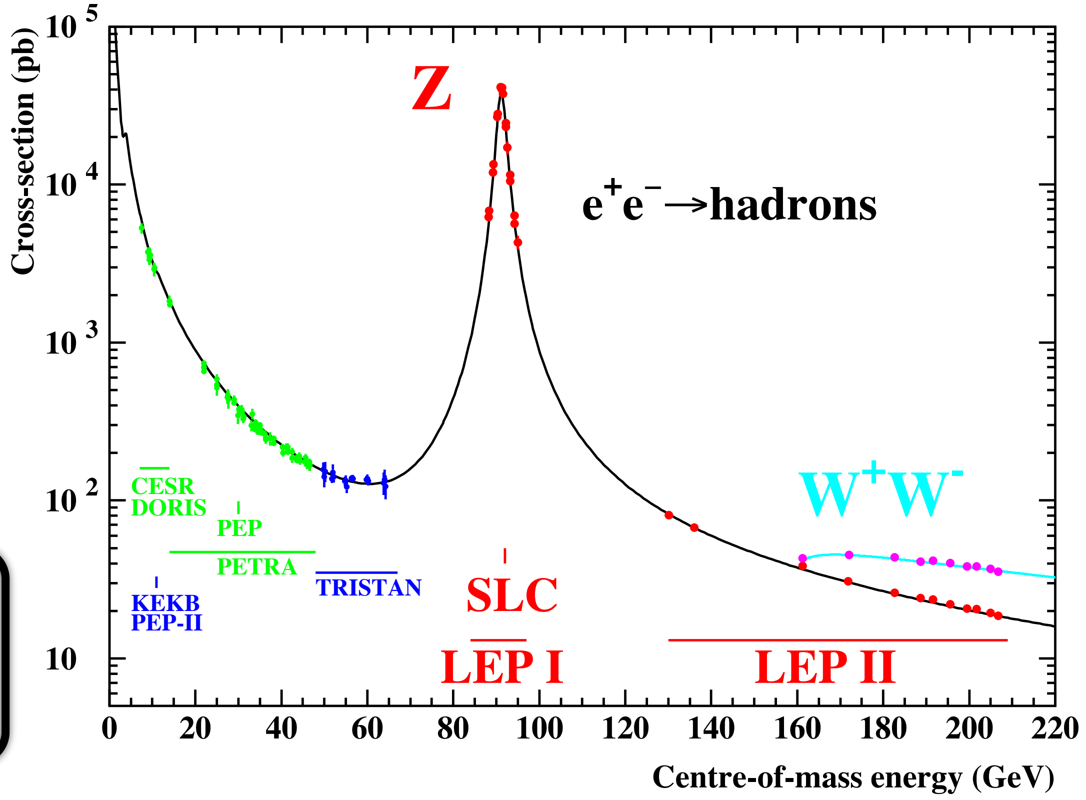
Higgs/EW/Top Studies
Electroweak Physics

EW physics at e^+e^- Higgs factories

- Future e^+e^- factories will also help us improve our knowledge of the EW interactions:
  - Improved Z pole run:
    - LEP/SLC: ~10^7 Z → O(0.1-1%)
    - FCCee/CEPC: 10^{12} Z
    - ILC (GigaZ): 10^9 Z

Z-pole EWPO:

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$



  - Significantly lower stats at linear colliders but can benefit from use of polarization ⇒ Extra observables wrt unpolarized case. E.g. asymmetries

$$A_f=\frac{g_{Lf}^2-g_{Rf}^2}{g_{Lf}^2+g_{Rf}^2}\ \rightarrow$$

Polarized beams

Unpolarized beams

$$A^f_{FB}=\frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B}=\frac{3}{4}A_eA_f$$

$$A_{LR}=\frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R}\frac{1}{\langle|P_e|\rangle}=A_e$$

$$A^f_{LR,FB}=\frac{3}{4}A_f$$

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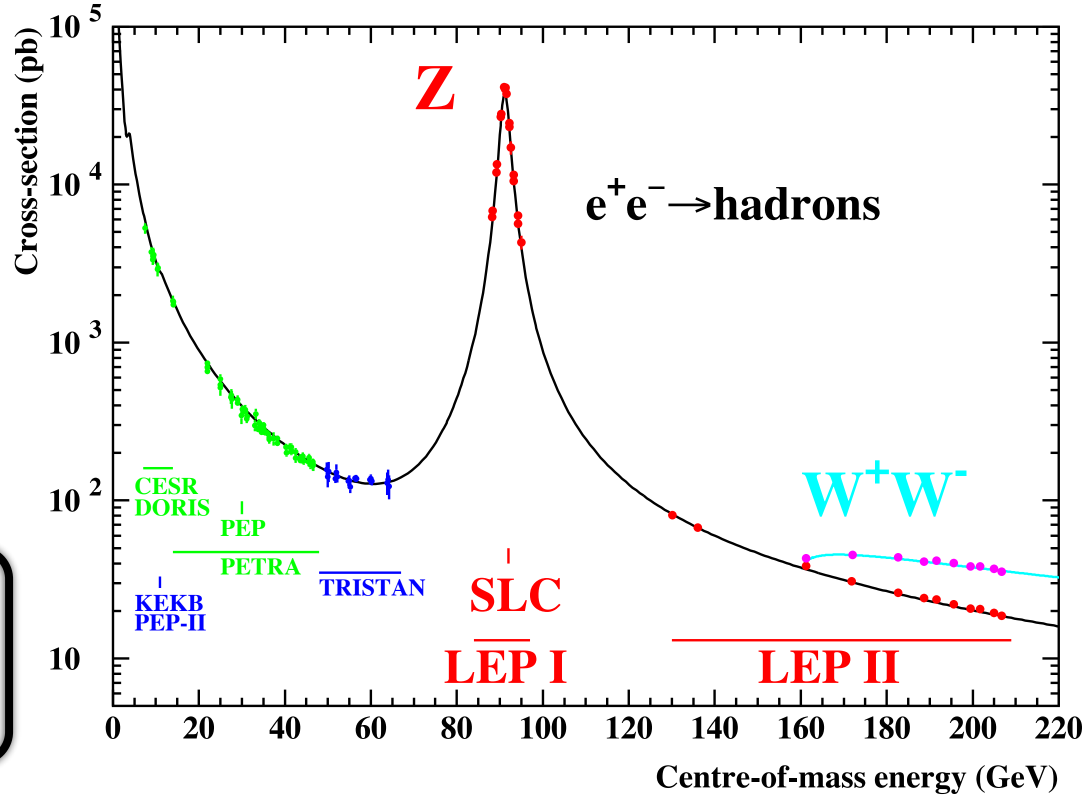


- Z-pole measurements are also possible during the Higgs factory phase (√s ~250 GeV) via radiative return to the Z resonance

$$e^+e^- \to \gamma Z$$

ILC 250 with 2 ab^{-1}: 77 (12) million hadronic (leptonic) Zs
5 (100) times more statistics than LEP (SLC)!

K. Fuji et al. , arXiv: 1908.11299 [hep-ex]
T. Mizuno, K. Fuji, J. Tian, arXiv: 2203.07944 [hep-ph]

EW physics at e⁺e⁻ Higgs factories

- Projections for future EWPO have been extensively studied in the past, e.g. improvement in Z pole observables can reach up to 2 orders of magnitude at Tera Z for leptonic and heavy flavor observables

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	18^*	18^*		3.8 (1.2)	18^*	
Δm_Z (MeV)	2.1^*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1^*
$\Delta\Gamma_Z$ (MeV)	2.3^*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3^*
ΔA_e $(\times 10^5)$	190^*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ $(\times 10^5)$	1500^*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ $(\times 10^5)$	400^*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b $(\times 10^5)$	2000^*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c $(\times 10^5)$	2700^*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_\mathrm{had}$ (pb)	37^*			0.035 (4)	0.05 (2)	37^*
δR_e $(\times 10^3)$	2.4^*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ $(\times 10^3)$	1.6^*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ $(\times 10^3)$	2.2^*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b $(\times 10^3)$	3.1^*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
$\delta R_c (\times 10^3)$	17^*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

stat (sys)

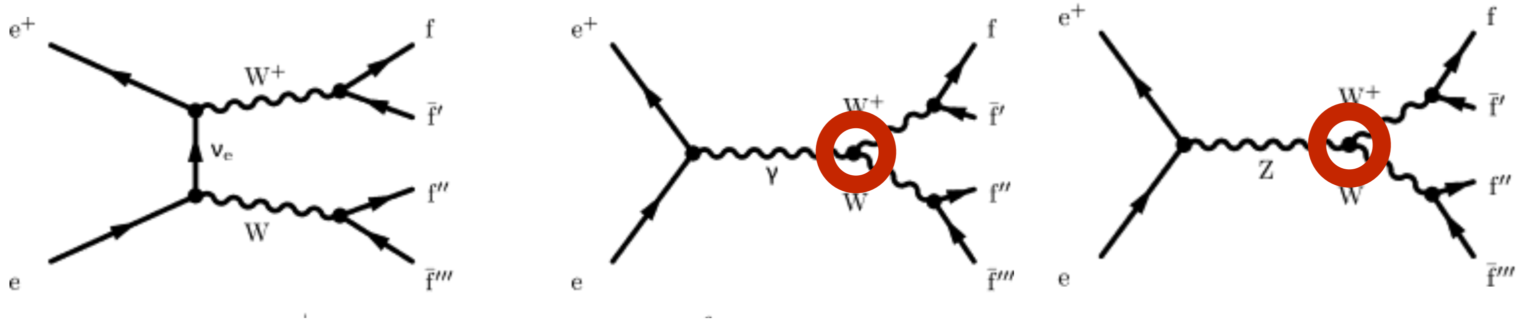
- Could also measure properties of light family quarks (up & down) using QED FSR (see backup slides)

EW physics at e^+e^- Higgs factories

- Future e^+e^- factories will also help us improve our knowledge of the EW charged current interactions:

✓ WW production at 161 GeV and above: O(10^8) WW pairs to improve measurements W mass and width, BRs, aTGCs, …

$e^+e^- \to W^+W^-$



$$\boxed{\textbf{W mass:} \quad \Delta M_W: \quad 10\ \text{MeV} \longrightarrow \lesssim 1\ \text{MeV}}$$

✓ W couplings:

Decay mode relative precision	$B(W \to e\nu)$	$B(W \to \mu\nu)$	$B(W \to \tau\nu)$	$B(W \to q\bar{q})$
LEP2	1.5%	1.4%	1.8%	0.4%
LHC	1.0%	0.8%	2.1%	0.3%
future e^+e^-	$3{\cdot}10^{-4}$	$3{\cdot}10^{-4}$	$4{\cdot}10^{-4}$	$1{\cdot}10^{-4}$

Improvement of order 50

✓ aTGC: Measured across a wider ranger of energies than LEP2 (avoiding the approximate degeneracy between some of the aTGC present there)

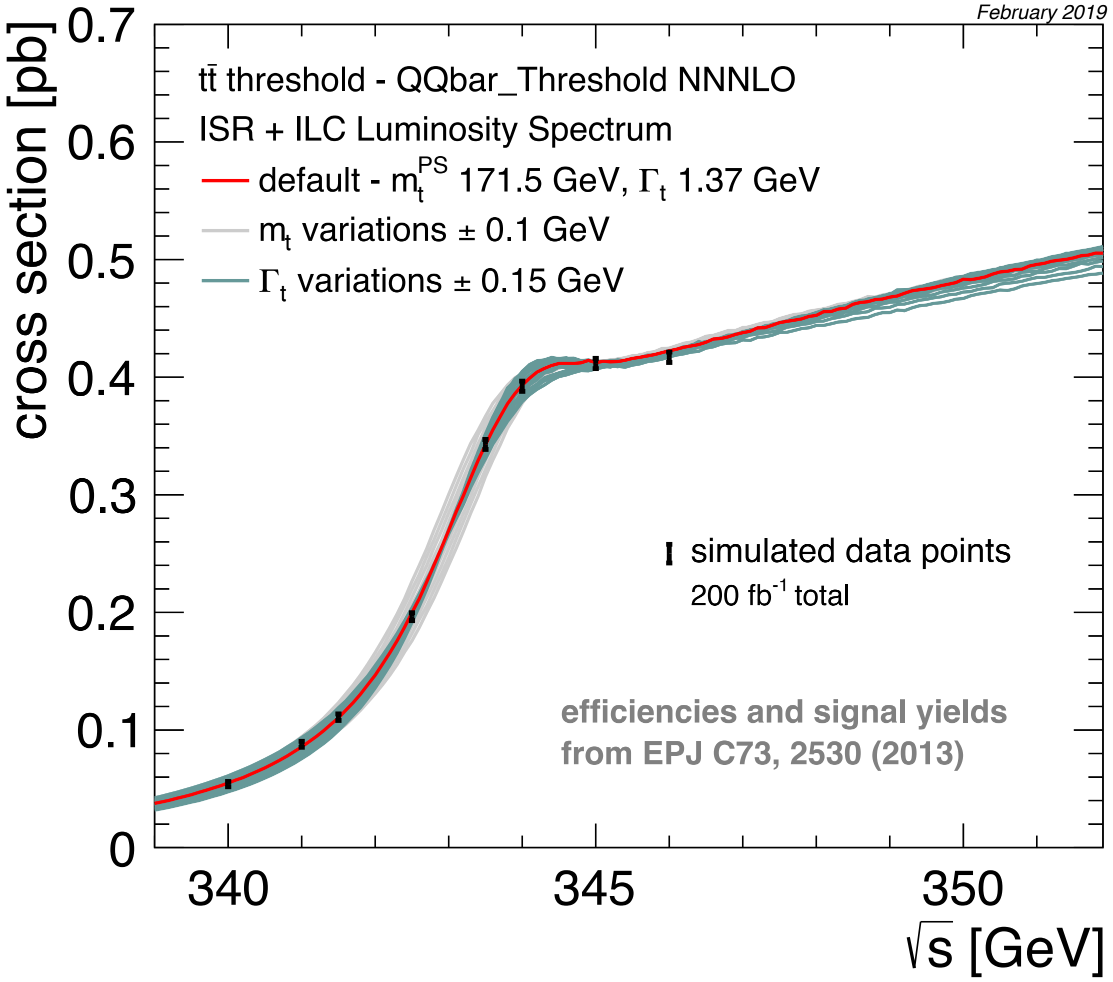
Higgs/EW/Top Studies

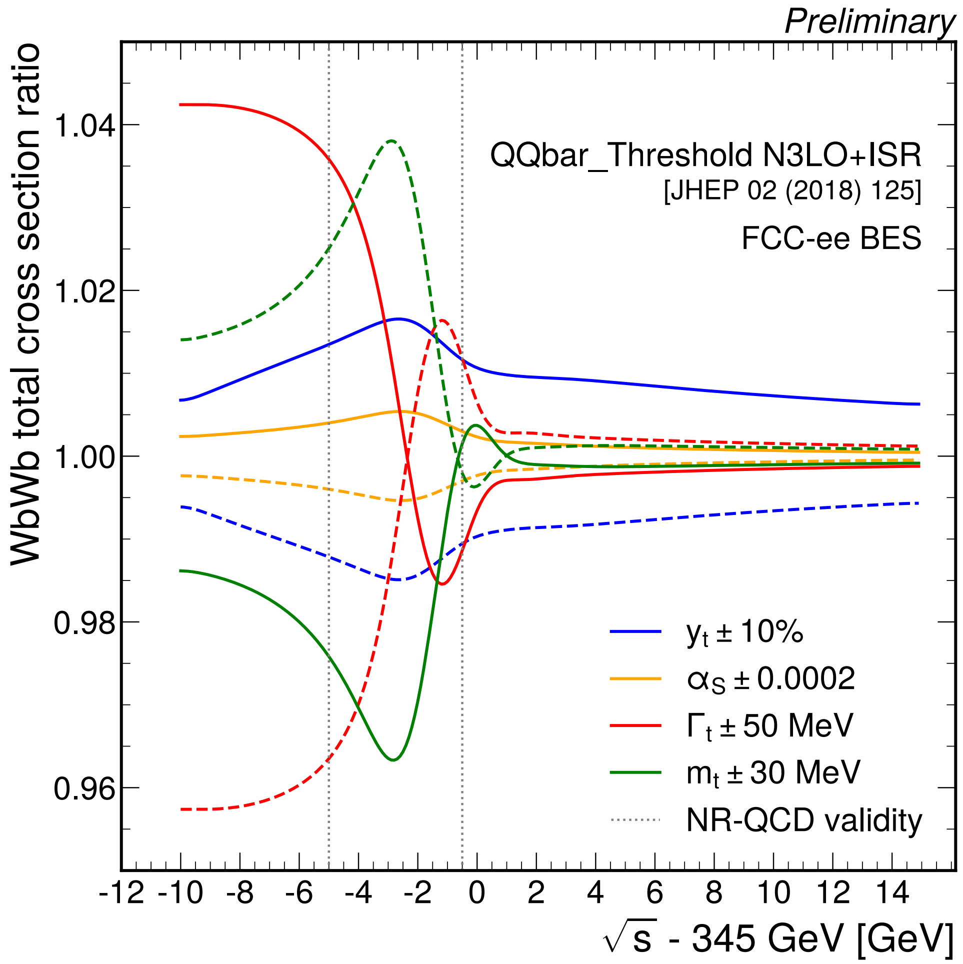
Top Physics

Top physics

Focus Topic: Top quark properties from threshold

- Top mass is one a key input of the SM, of particular relevance for the EW fit
  - ✓ Rapid cross section increase around √s~2m_t → Multi-point scan around threshold and fit to determine position of top mass and width (shape)





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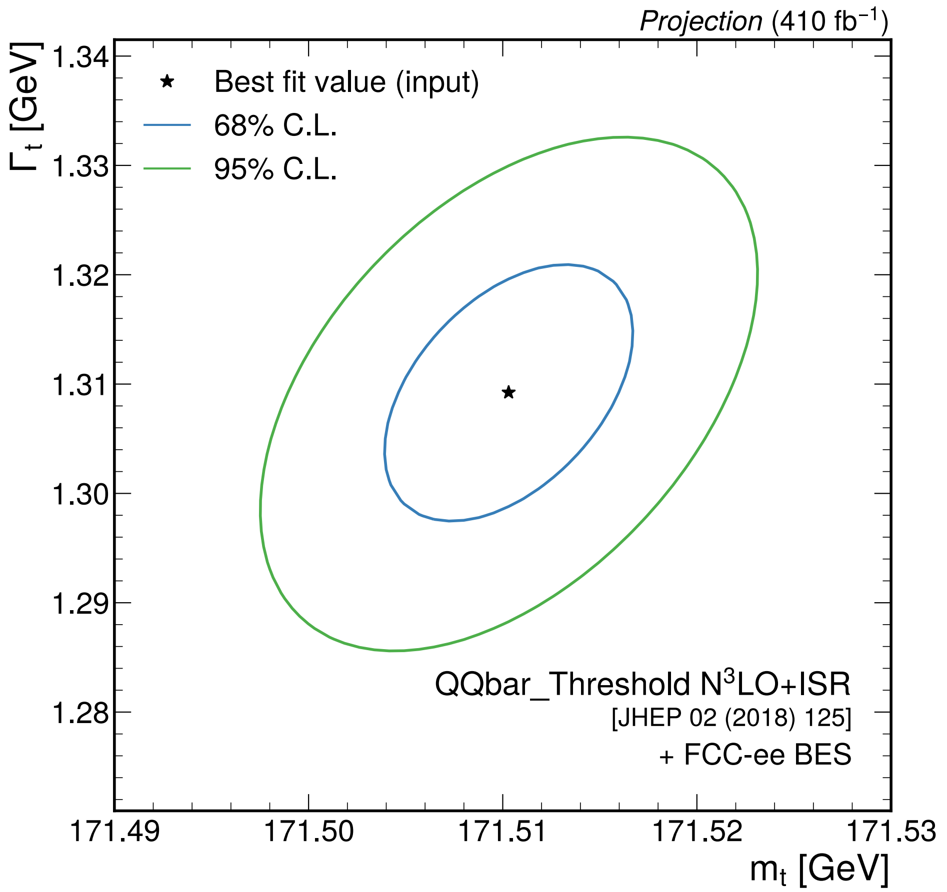

uncertainty	m_t^{PS} [MeV]	Γ_t [MeV]	comment
statistical	3.7	9.6	FCC-ee, 410 fb^{-1}
b-tagging, background	-	-	controlled in-situ
luminosity calibration (uncorr.)	0.6	1.1	$\delta L/L = 1 \times 10^{-3}$
luminosity calibration (corr.)	0.3	0.5	$\delta L/L = 0.5 \times 10^{-3}$
beam energy calibration (uncorr.)	1.2	2.0	$\delta\sqrt{s} = 5$ MeV [794, 795]
beam energy calibration (corr.)	1.2	0.1	$\delta\sqrt{s} = 2.5$ MeV
beam energy spread (uncorr.)	0.6	1.1	$\delta\Delta E = 1\%$ [795]
beam energy spread (corr.)	< 0.1	1.5	$\delta\Delta E = 0.5\%$
parametric (α_s)	2.0	1.9	$\delta\alpha_s = 1 \times 10^{-4}$
parametric (y_t)	3.8	4.5	$\delta y_t = 3\%$
total profiled	6.2	11.3	
theory, unprofiled (scale)	35	25	N^{3}LO NRQCD [787]

LHC: Δm_t~O(300 MeV);
$\Delta\Gamma_t$~O(150 MeV)

e^+e^-: Δm_t~O(40 MeV);
$\Delta\Gamma_t$~O(30 MeV)

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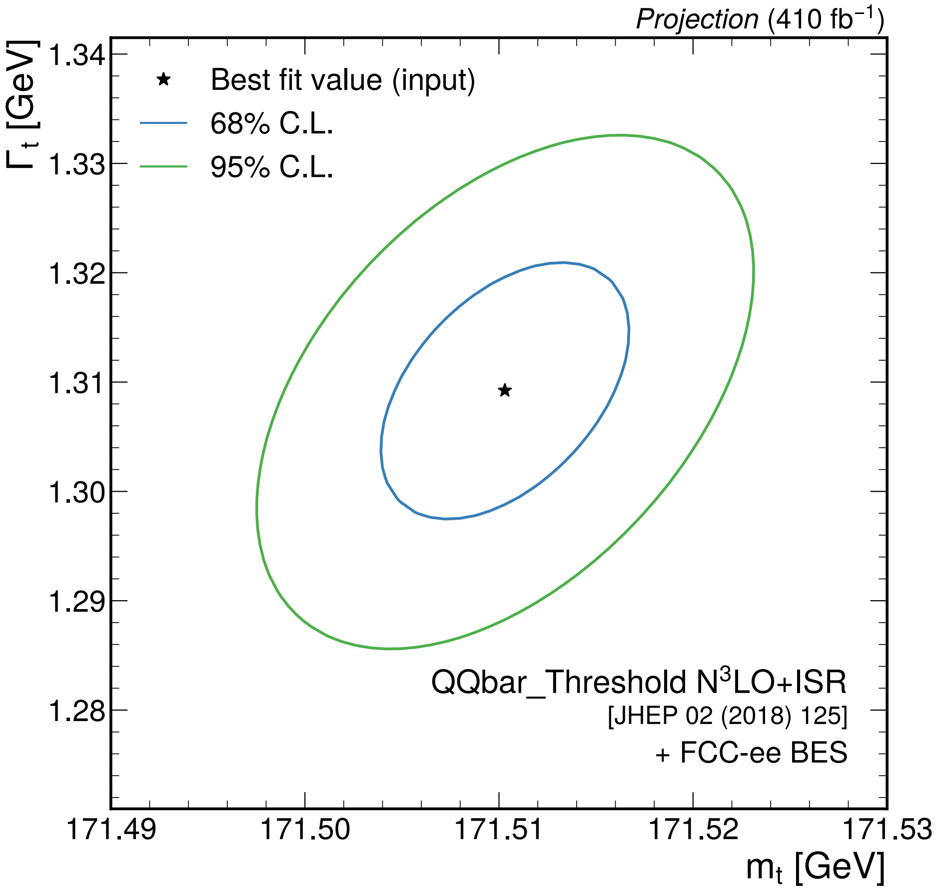
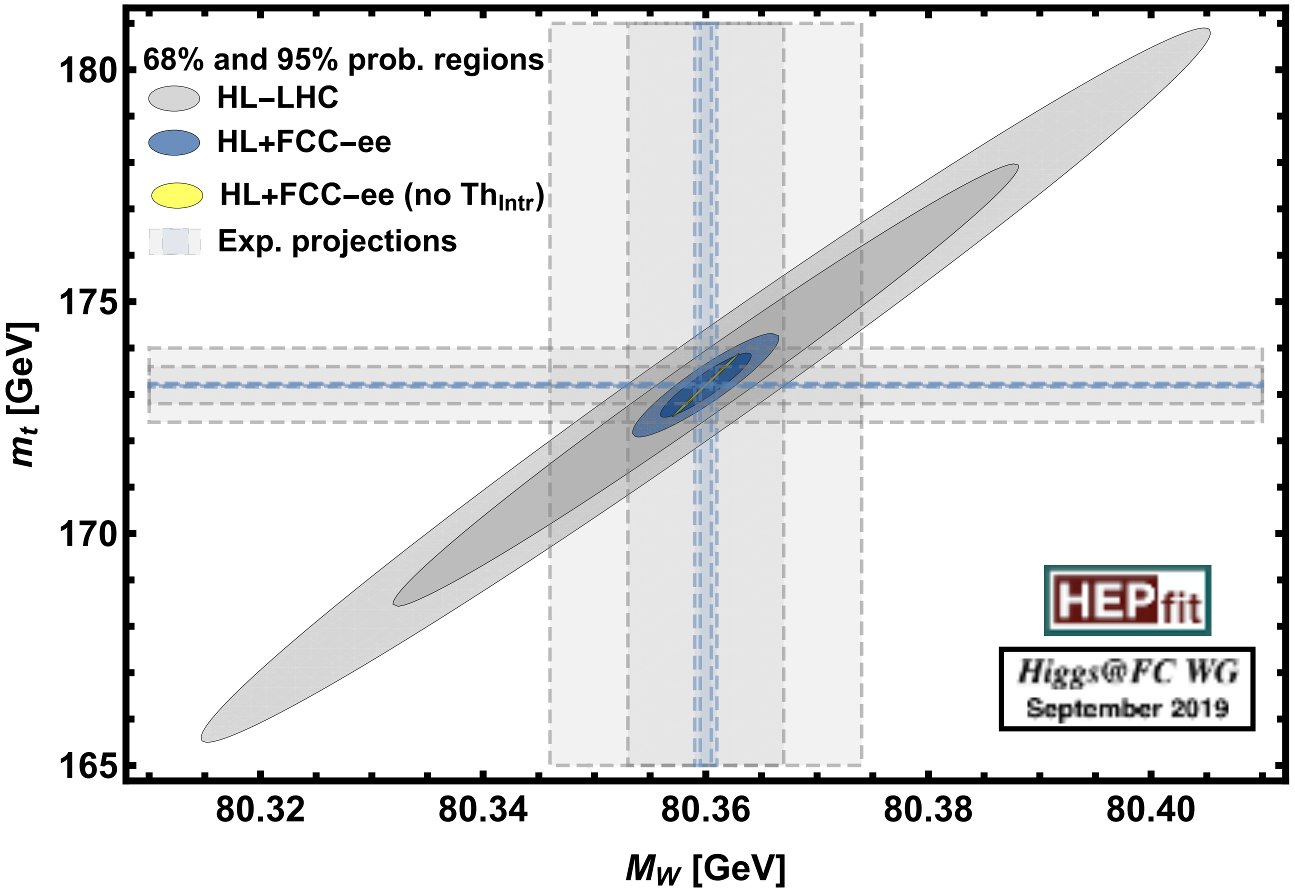
Focus Topic: Top quark properties from threshold

- Top mass is one a key input of the SM, of particular relevance for the EW fit
  - ✓ Rapid cross section increase around $\sqrt{s}\sim 2m_t$ → Multi-point scan around threshold and fit to determine position of top mass and width (shape)



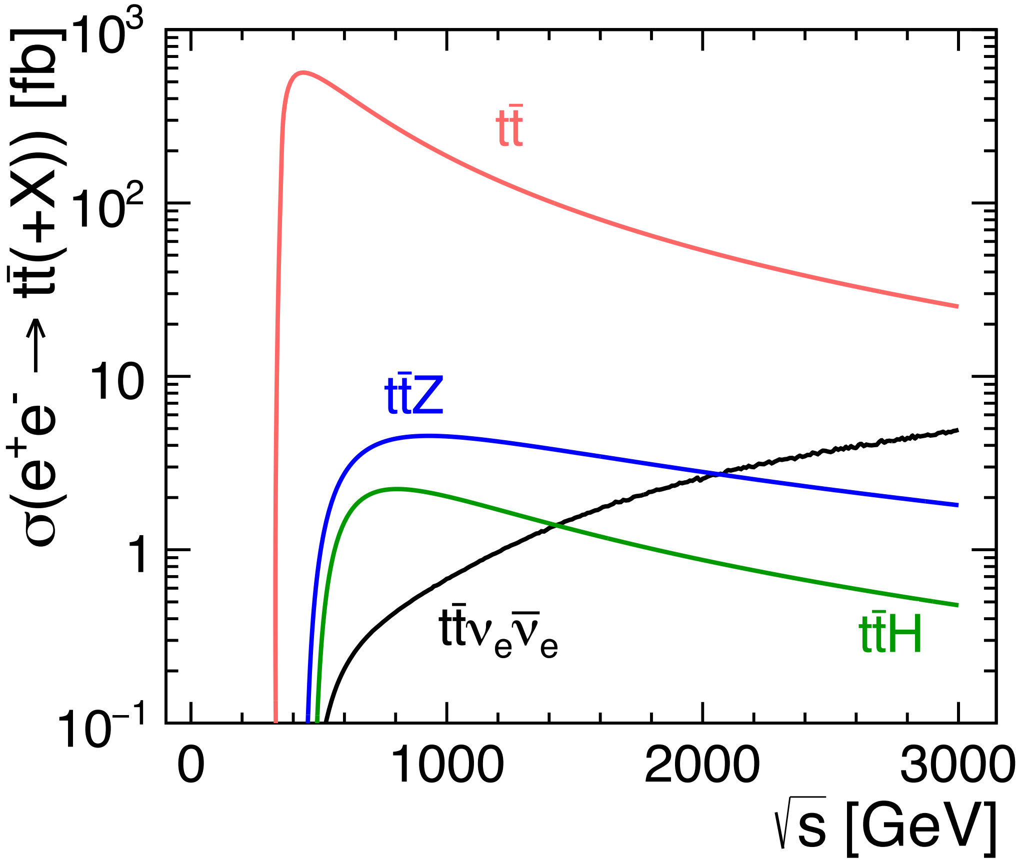


Together with the rest of EWPO (Z-pole, W mass, etc) this would bring extremely strong consistency test of validity of the SM description of EW interactions

Top physics

Focus Topic: Top quark couplings

- $e+e^-$ above the tt threshold enable measurements of the Top-quark couplings to the Z and γ, in a way that is complementary to hadron colliders:
  - LHC: accessible via $pp \to ttZ$, $tt\gamma$
    Not very precisely measured
  - $e+e^- \to tt$: mediated by Z/γ interactions. Clean environment. Better cross section slightly above threshold ~365 GeV



- Top Yukawa coupling: tth is the golden channel ($pp \to tth$ and $e+e^- \to tth$)
  - $e+e^-$: only available to high-E (e.g. 550 GeV)
- The determination of the Top couplings depends on the theory framework and it is typically done within the SMEFT
  - Via a global fit to different types of top processes available at pp and $e+e^-$
  - Complete characterization of the top properties requires the combination of the HLLHC and $e+e^-$ colliders

ECFA study report

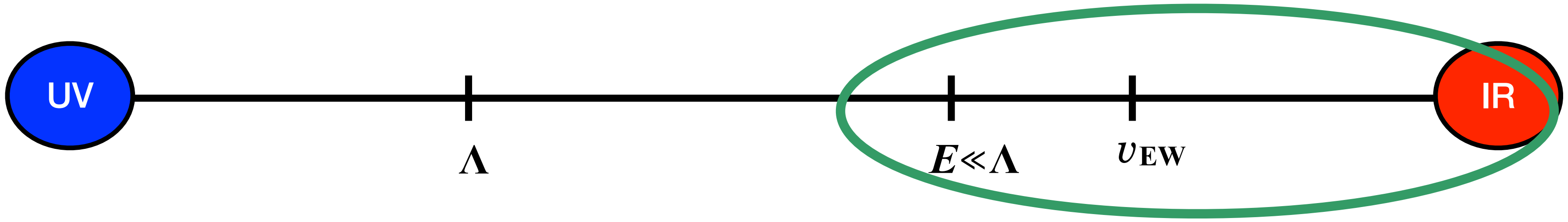
Global combinations in the SMEFT

Global fits at future e^+e^- colliders

- **SMEFT:** general, theoretically consistent, QFT description of BSM effects for E≪Λ (EFT cutoff) with minimal assumptions:
  - Mass gap with new physics: $\Lambda \gg v$ (justified by absence of new particles in direct searches?)

    ⇒ Low-energy particles & symmetries: SM (Higgs in $2 \sim SU(2)_L$)
  - Power counting: Decoupling NP. New effects → 0 as $\Lambda \to \infty$

    ⇒ Expansion of BSM effects in $1/\Lambda$



to describe the physics here

$$\mathcal{L}_{\rm UV}(?) \xrightarrow[E \ll \Lambda]{} \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \xrightarrow{\text{Observable Effects}} \left(\frac{q}{\Lambda}\right)^{d-4} \quad q = v, E < \Lambda$$

Leading Order (LO) Beyond the SM effects (assuming B & L)
⇒ Dim-6 SMEFT: 2499 Operators/Wilson coefficients

Global fits at future e⁺e⁻ colliders

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Ignoring flavour)

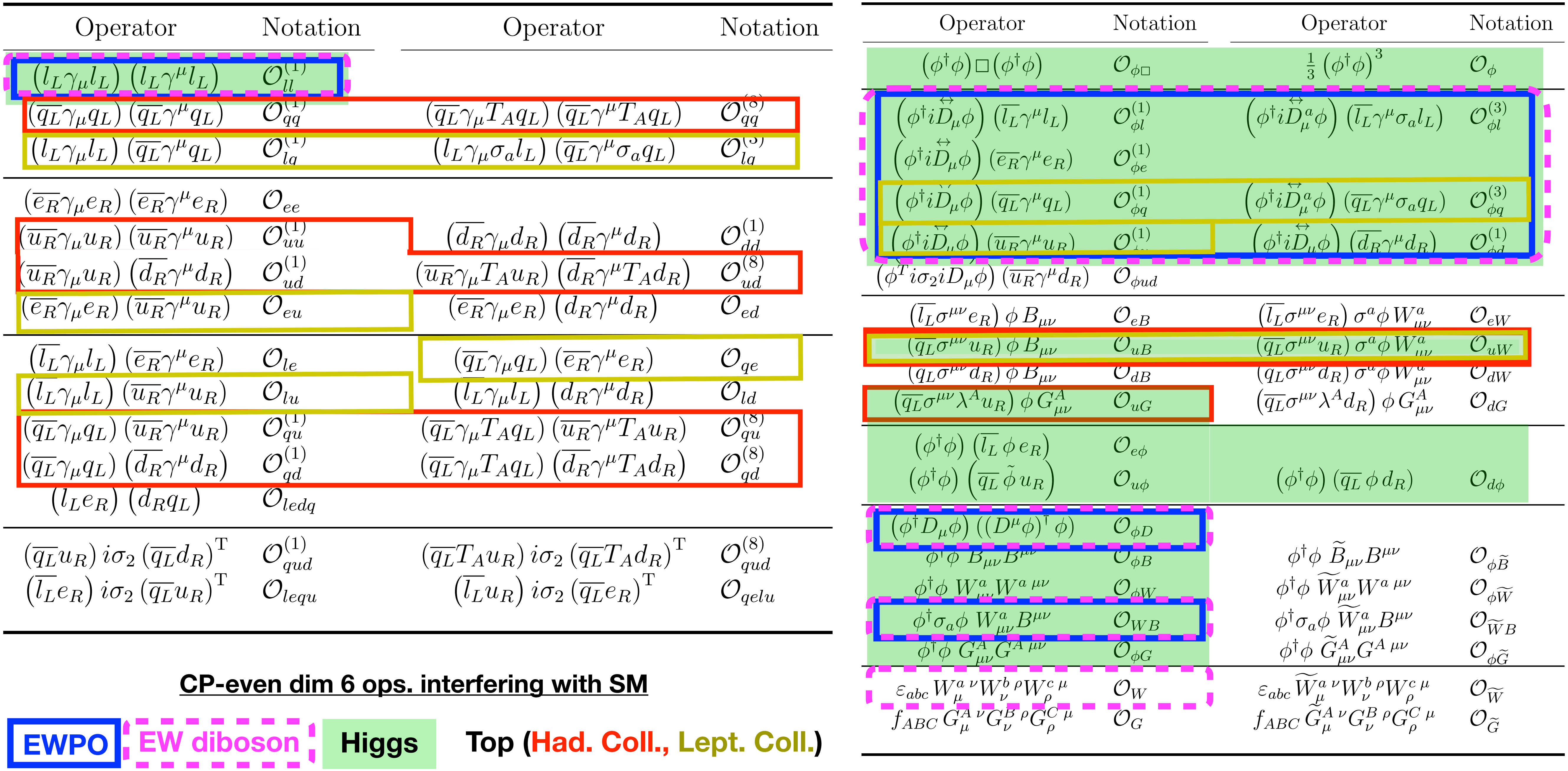
Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\, i\sigma_2\, (\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\, i\sigma_2\, (\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\, i\sigma_2\, (\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\, i\sigma_2\, (\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\tilde{\phi}\, B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\tilde{\phi}\, W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\tilde{\phi}\, G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\overline{l_L}\,\phi\, e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)(\overline{q_L}\,\tilde{\phi}\, u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\overline{q_L}\,\phi\, d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\; B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\; \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\; W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\; \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\; W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\; \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\; G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\; \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\, W^{a\,\nu}_{\mu} W^{b\,\rho}_{\nu} W^{c\,\mu}_{\rho}$	$\mathcal{O}_{W}$	$\varepsilon_{abc}\, \widetilde{W}^{a\,\nu}_{\mu} W^{b\,\rho}_{\nu} W^{c\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_{\mu} G^{B\,\rho}_{\nu} G^{C\,\mu}_{\rho}$	$\mathcal{O}_{G}$	$f_{ABC}\, \widetilde{G}^{A\,\nu}_{\mu} G^{B\,\rho}_{\nu} G^{C\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{G}}$

Global fits at future e^+e^- colliders

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Ignoring flavour)



Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\, i\sigma_2\, (\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\, i\sigma_2\, (\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\, i\sigma_2\, (\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\, i\sigma_2\, (\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\right)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\right)(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\phi\,G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi\,G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\overline{l_L}\,\phi\,e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)\left(\overline{q_L}\,\tilde{\phi}\,u_R\right)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\overline{q_L}\,\phi\,d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\; B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\;\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\; W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\;\widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\; W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\;\widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\; G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\;\widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\,W^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_W$	$\varepsilon_{abc}\,\widetilde{W}^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\,G^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_G$	$f_{ABC}\,\widetilde{G}^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{G}}$

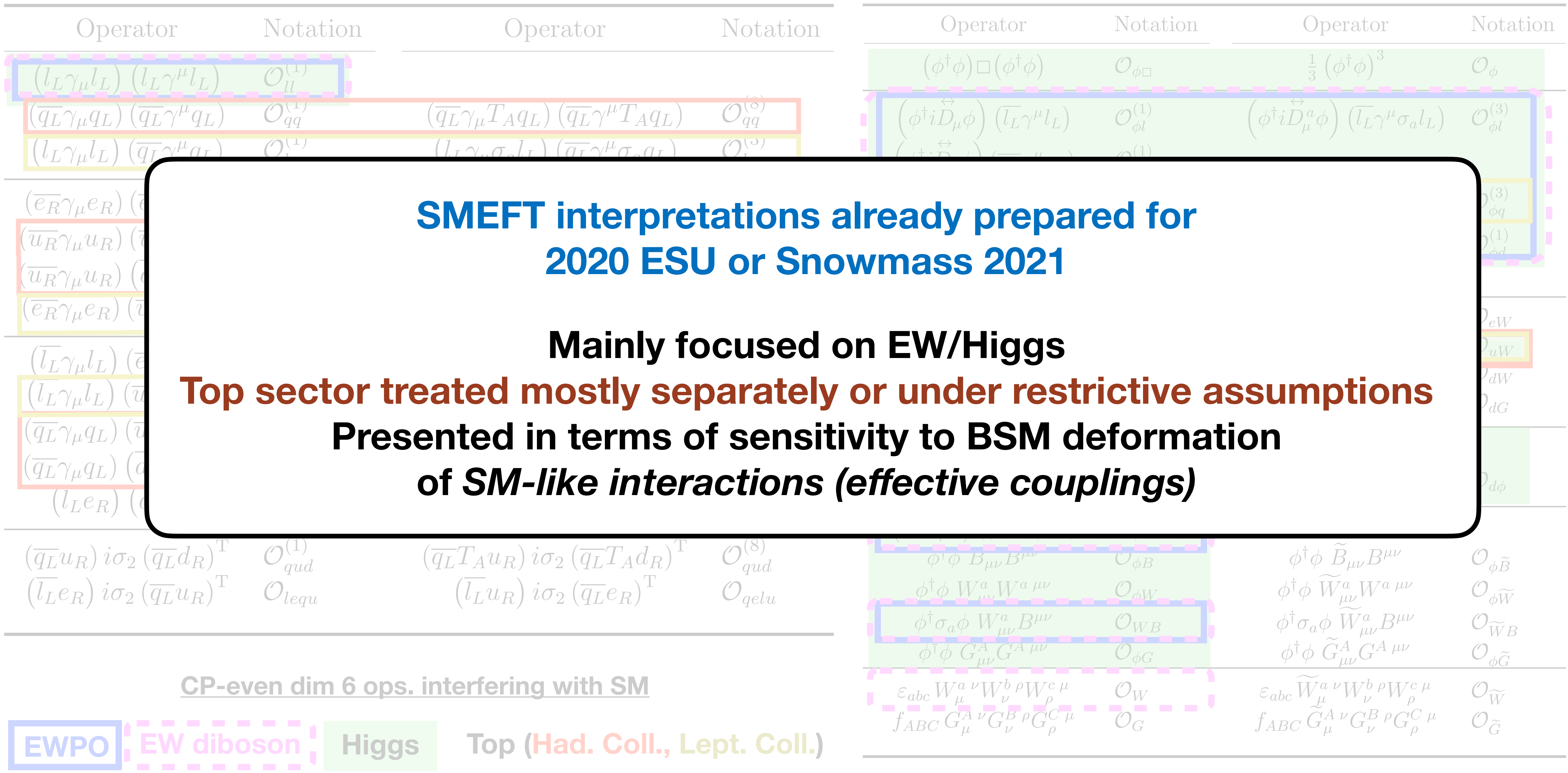
CP-even dim 6 ops. interfering with SM

EWPO **EW diboson** **Higgs** **Top (Had. Coll., Lept. Coll.)**

Global fits at future e⁺e⁻ colliders

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Ignoring flavour)



Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{q_L}u_R)\, i\sigma_2\, (\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\, i\sigma_2\, (\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\, i\sigma_2\, (\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\, i\sigma_2\, (\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_\phi$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$\phi^\dagger\phi\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\, W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\, \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\, W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\, \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\, G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\, \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_W$	$\varepsilon_{abc}\widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_G$	$f_{ABC}\widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

CP-even dim 6 ops. interfering with SM

EWPO | EW diboson | Higgs | Top (Had. Coll., Lept. Coll.)

SMEFT interpretations already prepared for 2020 ESU or Snowmass 2021

Mainly focused on EW/Higgs

Top sector treated mostly separately or under restrictive assumptions

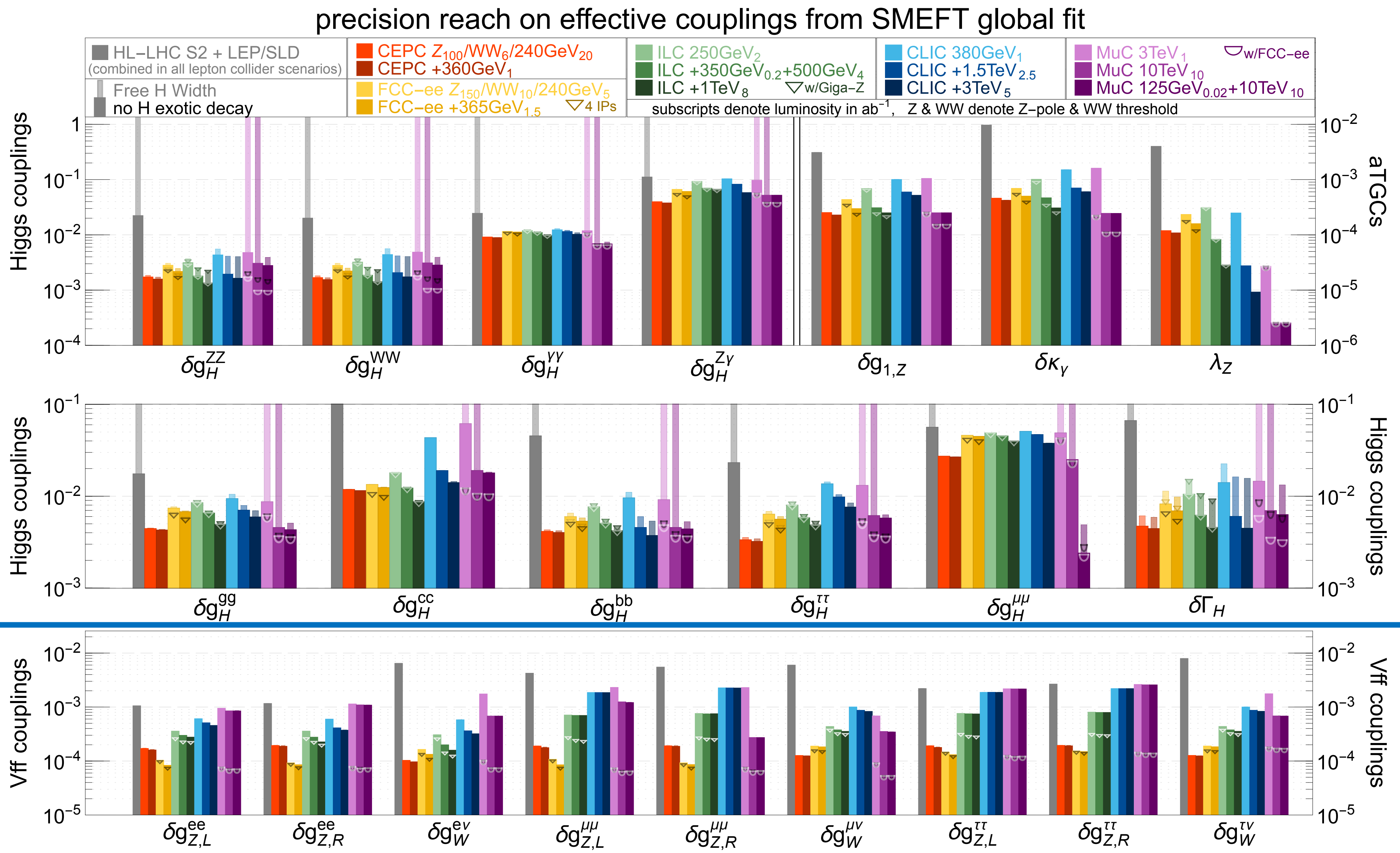
Presented in terms of sensitivity to BSM deformation of *SM-like interactions (effective couplings)*

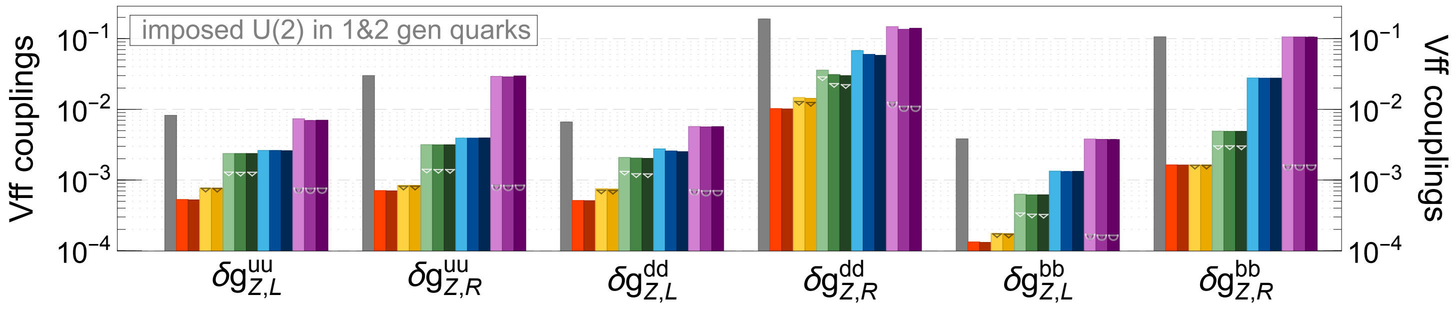
Global fits at future e^+e^- colliders

Higgs interactions

aTGC

EW Vff interactions





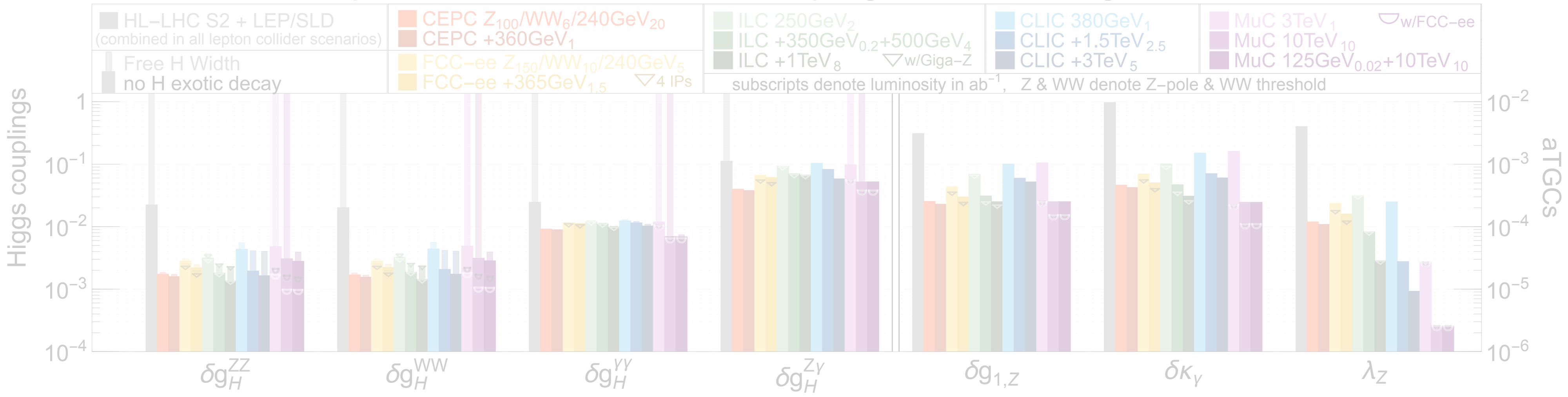
Flavor assumptions: SMEFT$_{\text{ND}}$

Effective couplings

$$g_{HX}^{\text{eff }2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}. \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(|g_{Zee,L}^{\text{eff}}|^2 + |g_{Zee,R}^{\text{eff}}|^2\right), \qquad A_e = \frac{|g_{Zee,L}^{\text{eff}}|^2 - |g_{Zee,R}^{\text{eff}}|^2}{|g_{Zee,L}^{\text{eff}}|^2 + |g_{Zee,R}^{\text{eff}}|^2}.$$

Global fits at future e^+e^- colliders

precision reach on effective couplings from SMEFT global fit

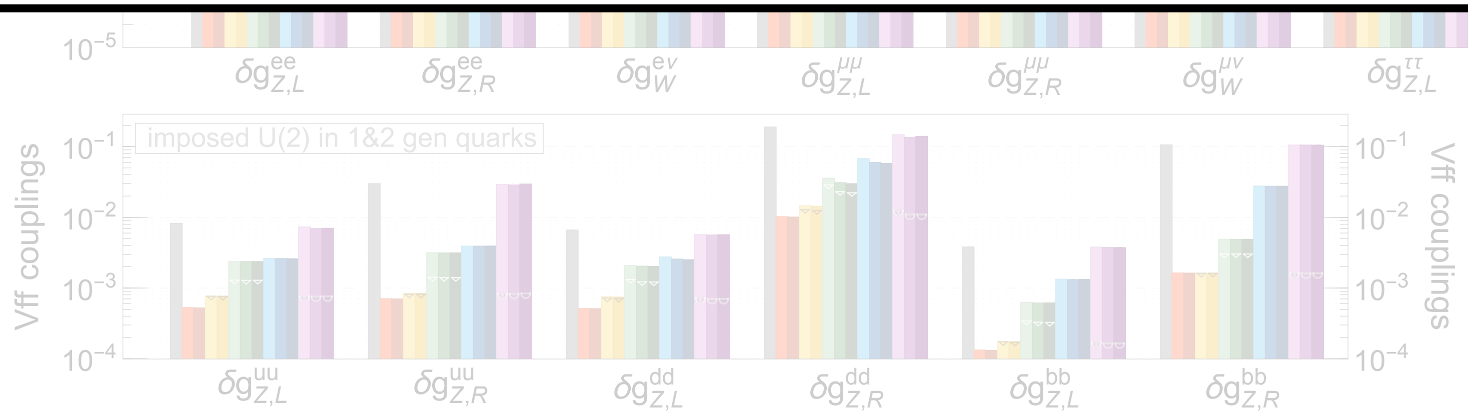


aTGC

EW Vff interactions

Future Collider Legend

Circular e^+e^- Colliders	Linear e^+e^- Colliders		Circular $\mu^+\mu^-$ Colliders
🟥 CEPC Z_{100}/WW_6/240GeV$_{20}$	🟩 ILC 250GeV$_2$	🟦 CLIC 380GeV$_1$	🟪 MuC 3TeV$_1$ ◡w/FCC–ee
🟫 CEPC +360GeV$_1$	🟩 ILC +350GeV$_{0.2}$+500GeV$_4$	🟦 CLIC +1.5TeV$_{2.5}$	🟪 MuC 10TeV$_{10}$
🟨 FCC–ee Z_{150}/WW_{10}/240GeV$_5$	🟩 ILC +1TeV$_8$ ▽w/Giga–Z	🟦 CLIC +3TeV$_5$	🟪 MuC 125GeV$_{0.02}$+10TeV$_{10}$
🟧 FCC–ee +365GeV$_{1.5}$	subscripts denote luminosity in ab^{-1}, Z & WW denote Z–pole & WW threshold		

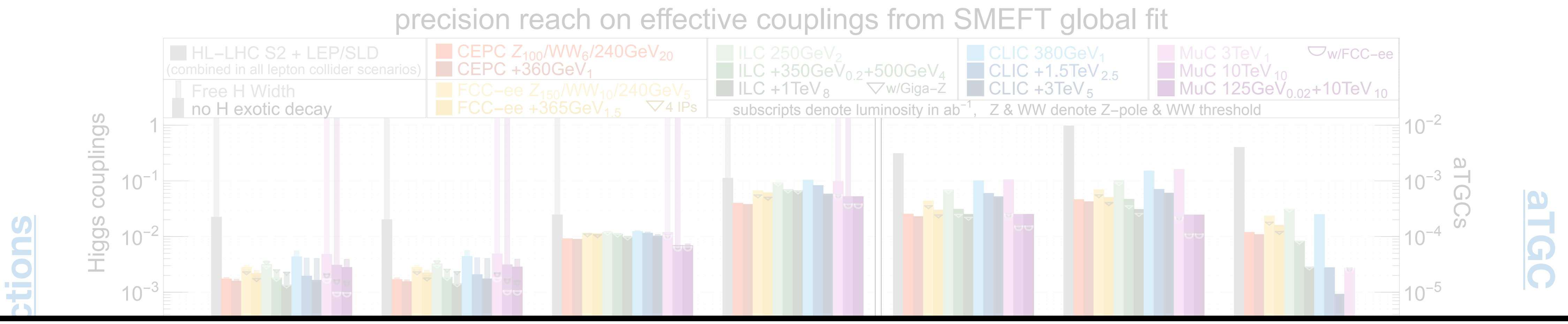


Flavor assumptions: SMEFT$_{ND}$

Effective couplings

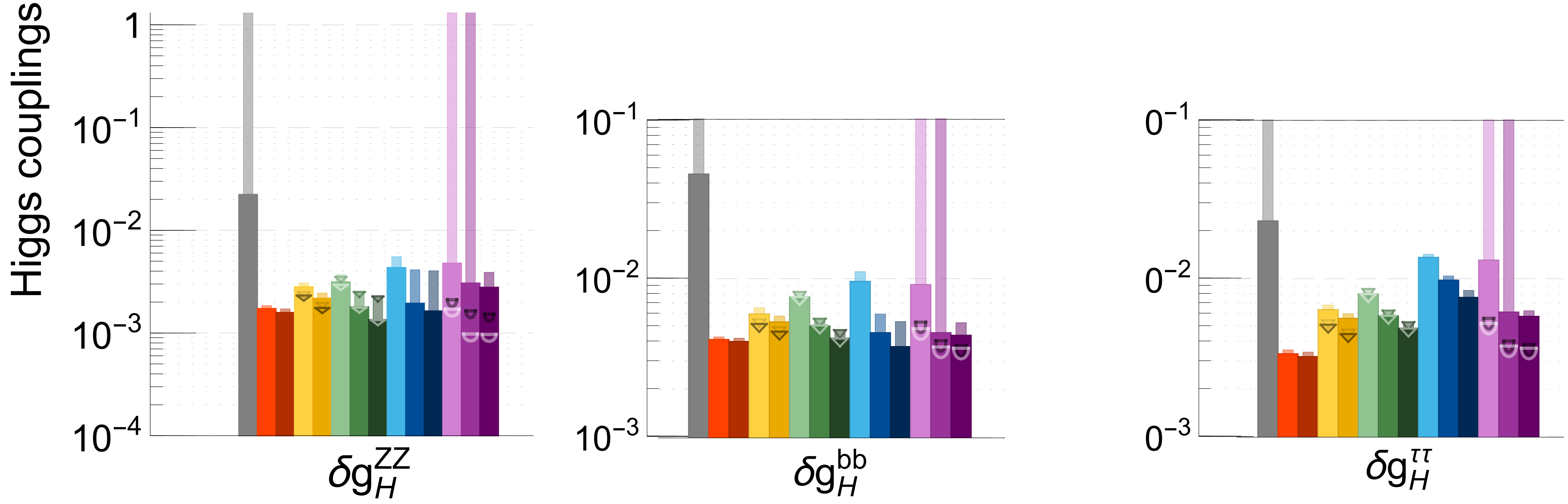
$$g^{\text{eff}\,2}_{HX} = \frac{\Gamma_{H\to X}}{\Gamma^{SM}_{H\to X}}, \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}\left(|g^{\text{eff}}_{Zee,L}|^2+|g^{\text{eff}}_{Zee,R}|^2\right), \qquad A_e = \frac{|g^{\text{eff}}_{Zee,L}|^2-|g^{\text{eff}}_{Zee,R}|^2}{|g^{\text{eff}}_{Zee,L}|^2+|g^{\text{eff}}_{Zee,R}|^2}.$$

Global fits at future e^+e^- colliders



e^+e^- improves HL-LHC precision typically by a factor ~10

Reaching in some cases few per mile accuracy

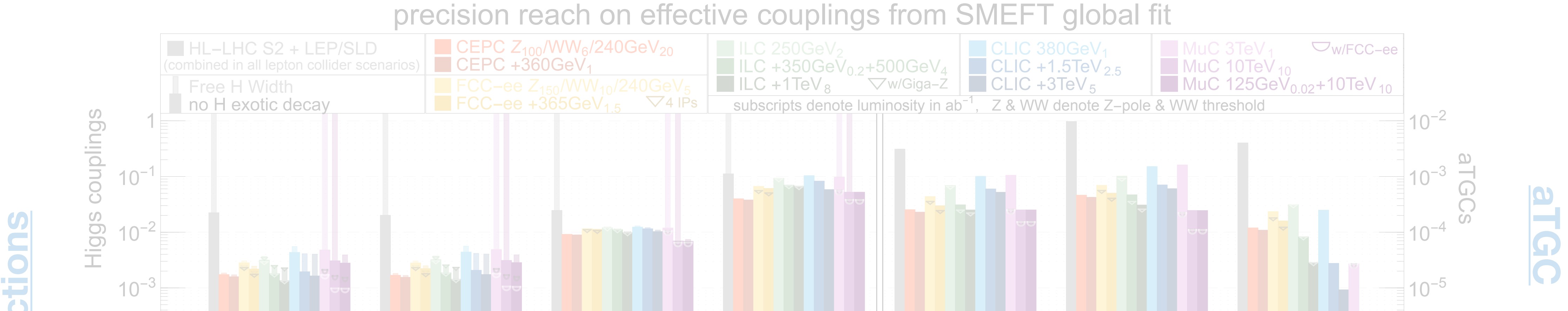


$$\Lambda_{\rm NP} \gtrsim 4500 \frac{g_{\rm NP}}{g_{\rm SM}}\ \text{GeV}$$

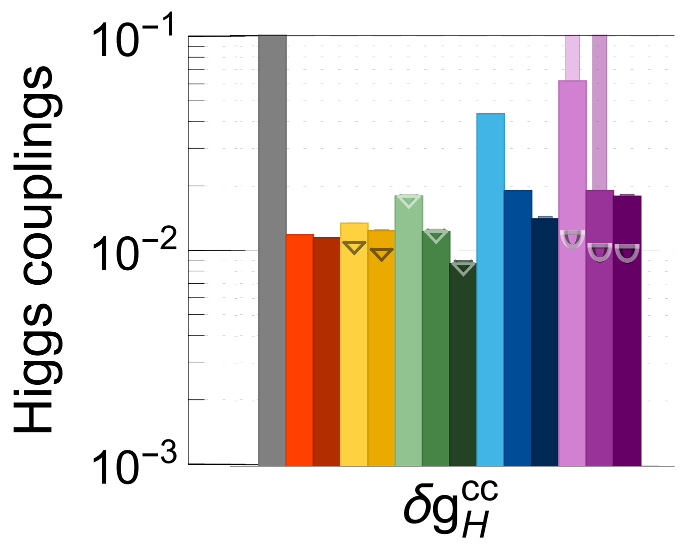
Effective couplings

$$g_{HX}^{\text{eff}\,2} = \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\rm SM}}, \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(|g_{Zee,L}^{\text{eff}}|^2 + |g_{Zee,R}^{\text{eff}}|^2\right), \qquad A_e = \frac{|g_{Zee,L}^{\text{eff}}|^2 - |g_{Zee,R}^{\text{eff}}|^2}{|g_{Zee,L}^{\text{eff}}|^2 + |g_{Zee,R}^{\text{eff}}|^2}.$$

Global fits at future e$^+$e$^-$ colliders

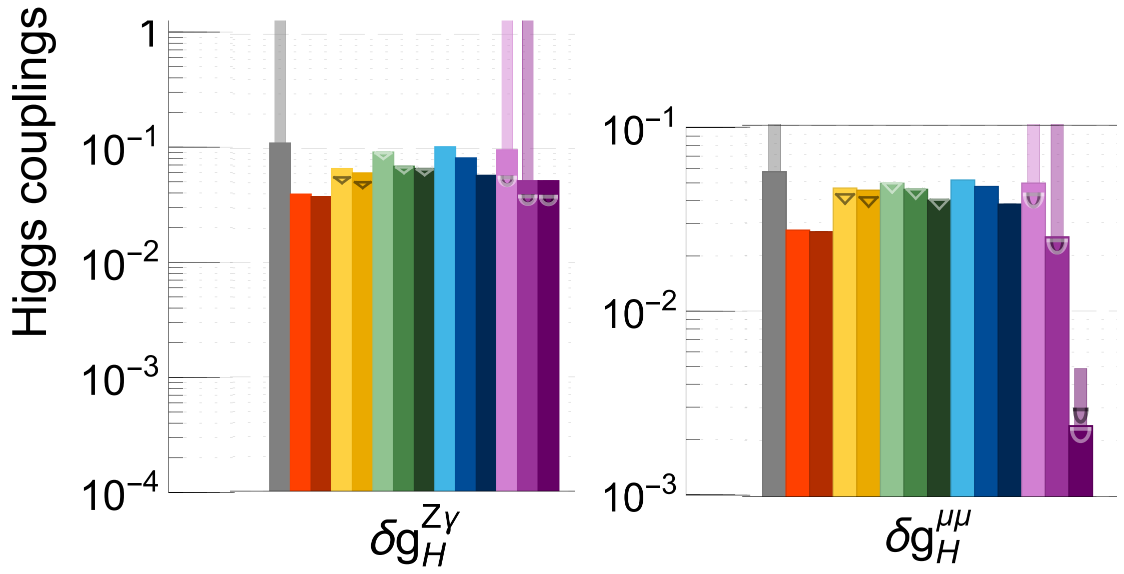


e^+e^- gives access to the second family of quarks. Very difficult at the HL-LHC…



O(1%) precision for charm coupling

…but HL-LHC still provides the leading constraints on couplings modifying rare decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)

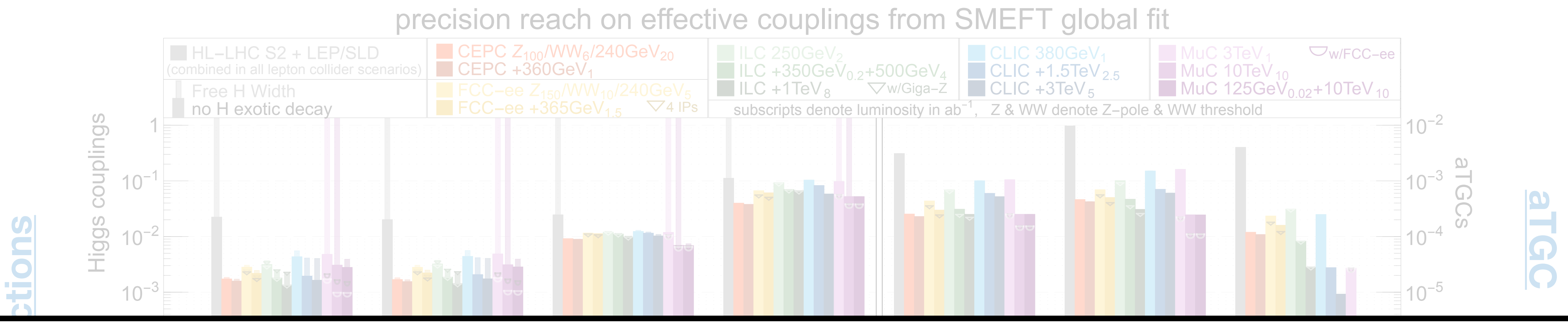


O(5-10%) precision

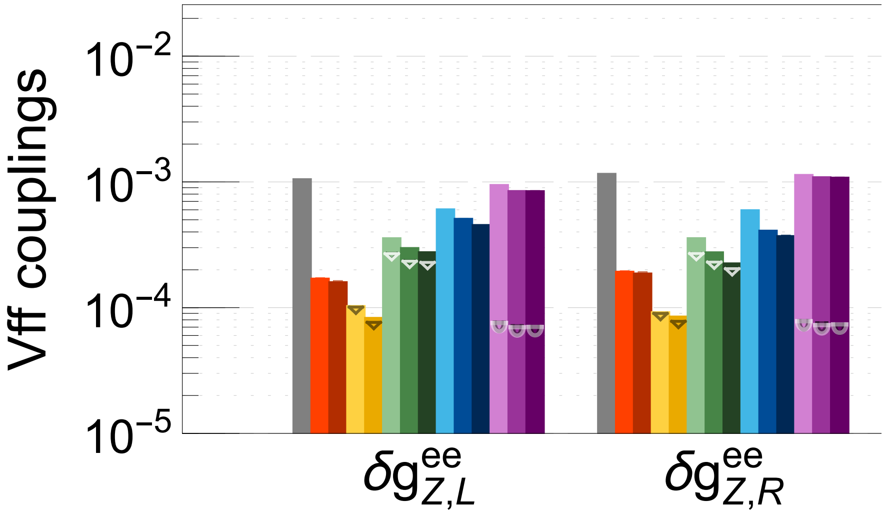
Effective couplings

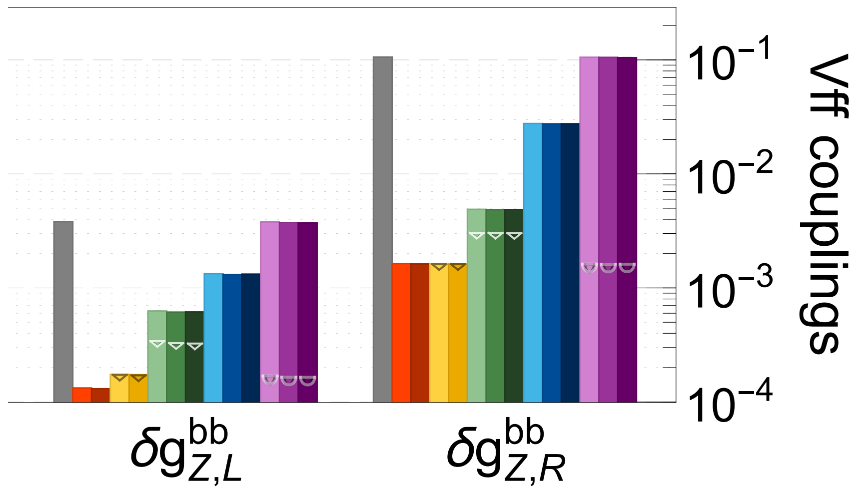
$$g^{\text{eff}\,2}_{HX} = \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}, \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}\left(|g^{\text{eff}}_{Zee,L}|^2 + |g^{\text{eff}}_{Zee,R}|^2\right), \qquad A_e = \frac{|g^{\text{eff}}_{Zee,L}|^2 - |g^{\text{eff}}_{Zee,R}|^2}{|g^{\text{eff}}_{Zee,L}|^2 + |g^{\text{eff}}_{Zee,R}|^2}.$$

Global fits at future e^+e^- colliders



e^+e^- improves sensitivity to BSM in EW interactions by more than 1 order of magnitude





Radiative return measurements still bring a significant improvement in our knowledge of EW interactions

Still, a clear advantage for the Tera Z option (and Giga Z for most couplings) in terms of precision reach

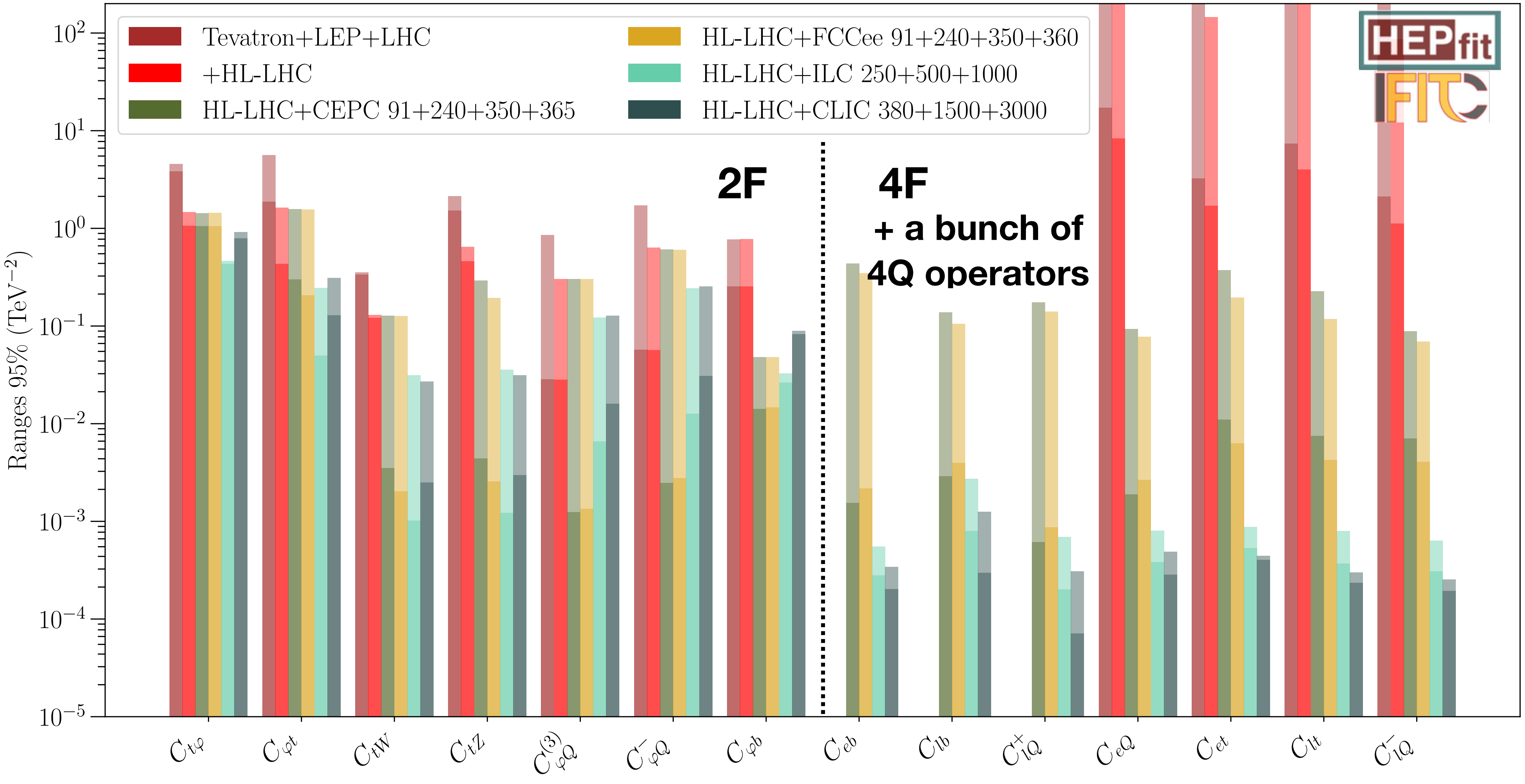
(In any case, enough precision to clarify current tensions in the EW fit: A_{FB}^b)

couplings

Top physics

Focus Topic: Top quark couplings

- At a "standalone" *e+e-* collider two distinct √s points are required to separate vertex corrections from, e.g. four-fermion operators (different E-scaling).
- *e+e- & pp* complementarity in Top production: sensitive to completely different four fermion interactions but combination with HLLHC helps *e+e-* if only one energy point is used, by controlling common 2-fermion operators



Top physics

Focus Topic: Top quark couplings

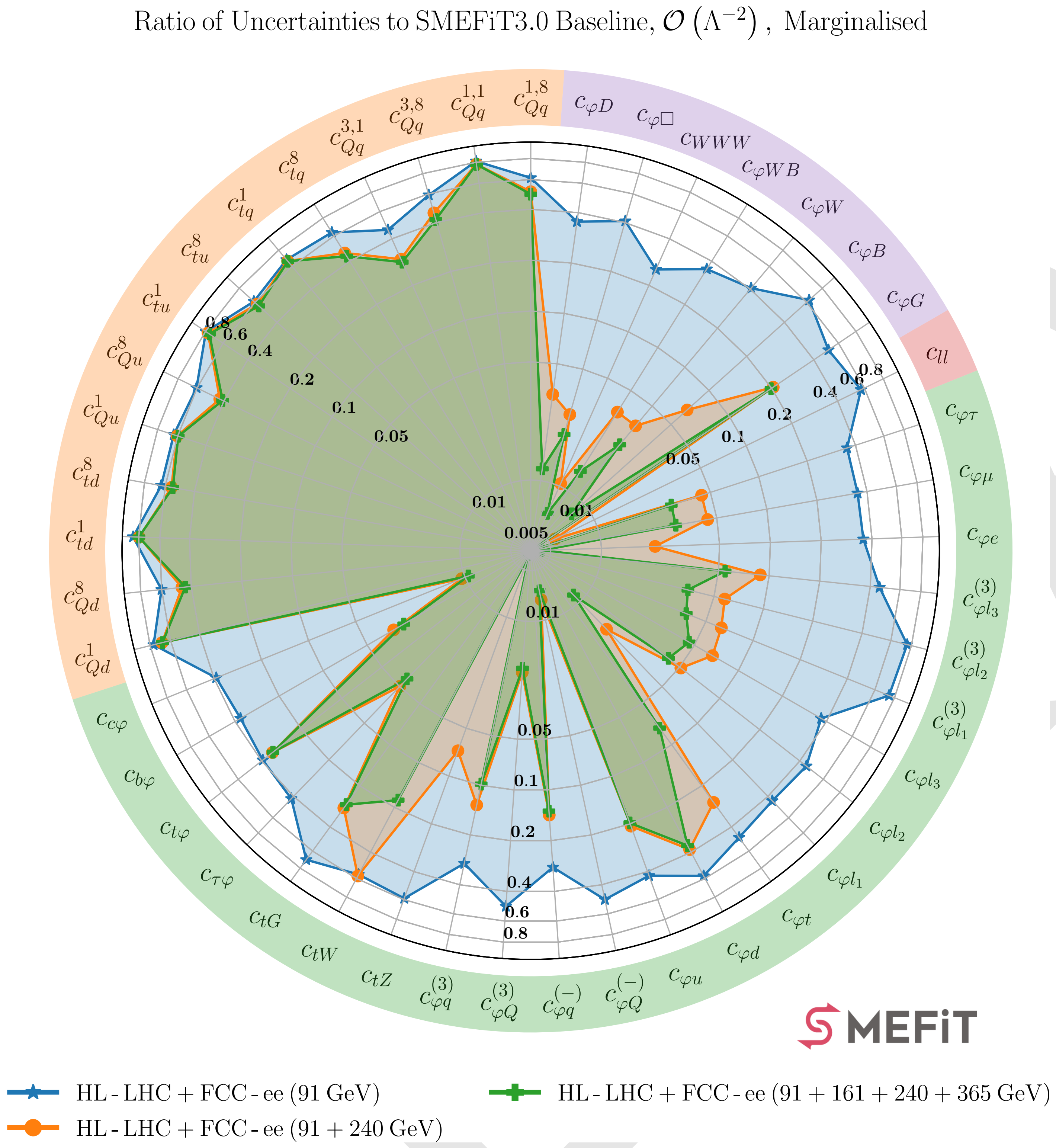
- At a "standalone" e^+e^- collider two distinct √s points are required to separate vertex corrections from, e.g. four-fermion operators (different E-scaling).
- e^+e^- & pp complementarity in Top production: sensitive to completely different four fermion interactions but combination with HLLHC helps e^+e^- if only one energy point is used, by controlling common 2-fermion operators
- Global precision on Top Yukawa

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC	FCChh	μ-coll
δy_t	Global fit	12%	5.1%	3.1%	2.6%	1.5%	3.0%	-	-
	Indiv. fit	10%	3.7%	2.8%	2.3%	1.4%	2.5%	1%	1.5%

Relatively small improvement wrt HLLHC until very high-E lepton collider or FCC-hh

Global fits at future e^+e^- colliders

Combining EW, Higgs and Top sectors

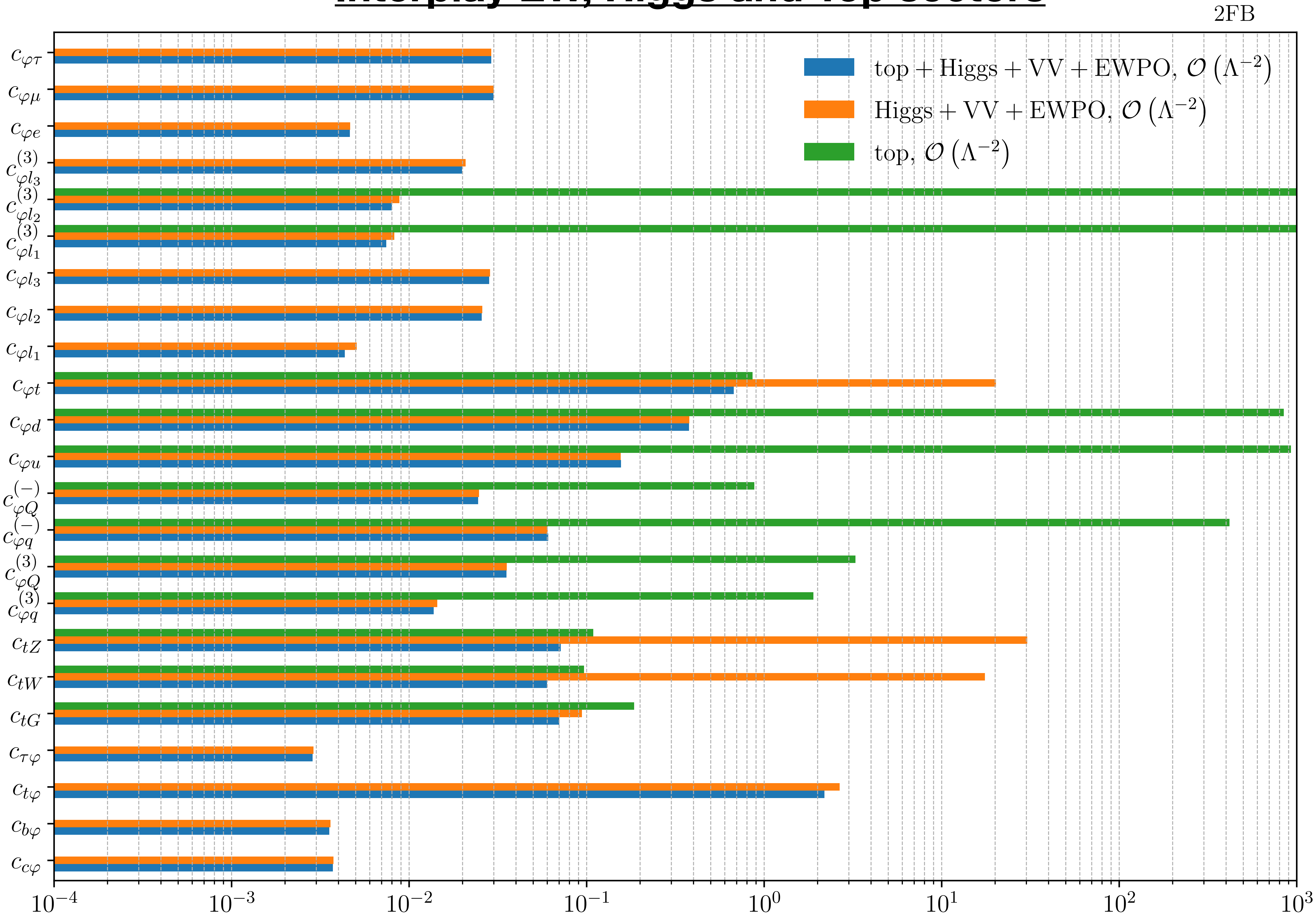


- Global fit of HLLHC+ Future e^+e^- CC including simultaneously EW, Higgs at Top measurements
- Also including:
  - NLO QCD effects in LHC obs.
  - Impact of quadratic terms (small for operators entering in e^+e^- measurements)
- Confirms that, to a large extent, EW/Higgs and Top sector are approximately orthogonal at e^+e^-

Global fits at future e^+e^- colliders

Interplay EW, Higgs and Top sectors

2 Fermion operators

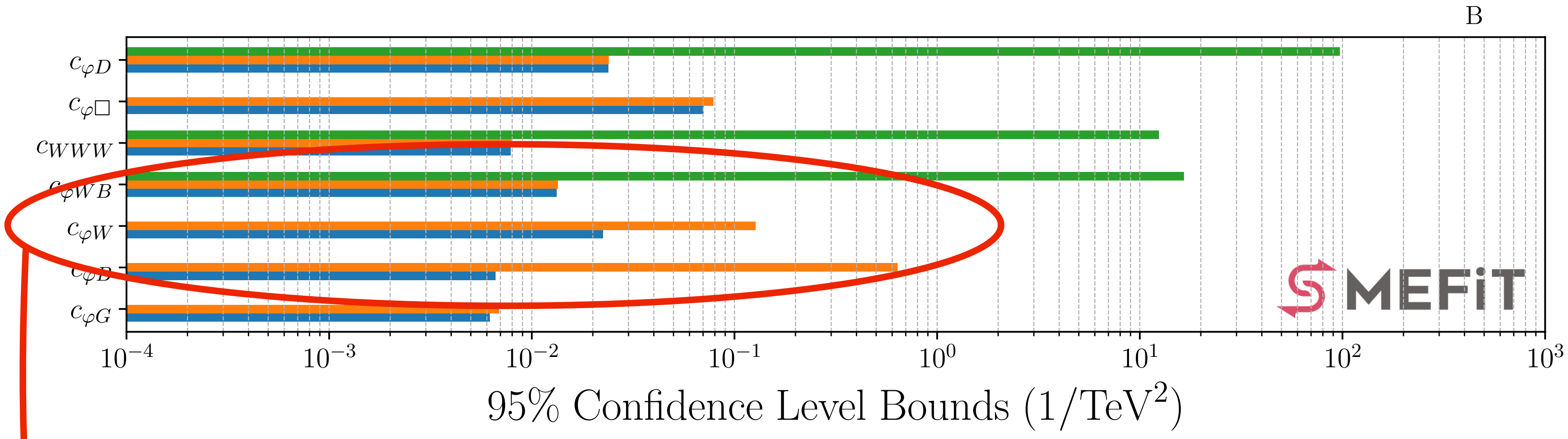


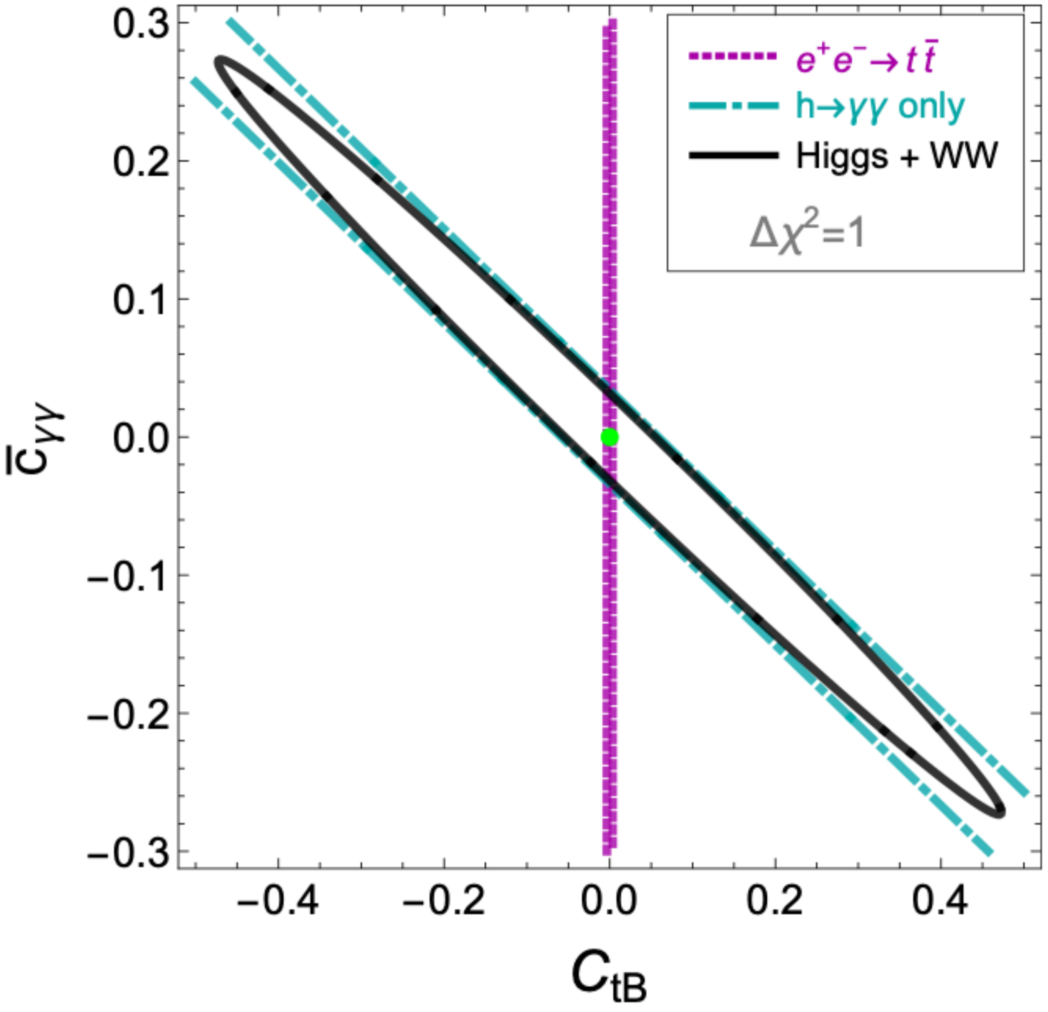
Bounds dominated by either EW+Higgs+VV or by Top data

Global fits at future e^+e^- colliders

Interplay EW, Higgs and Top sectors

Bosonic operators





Approx. flat direction in H→γγ between Bosonic operators and weak dipoles

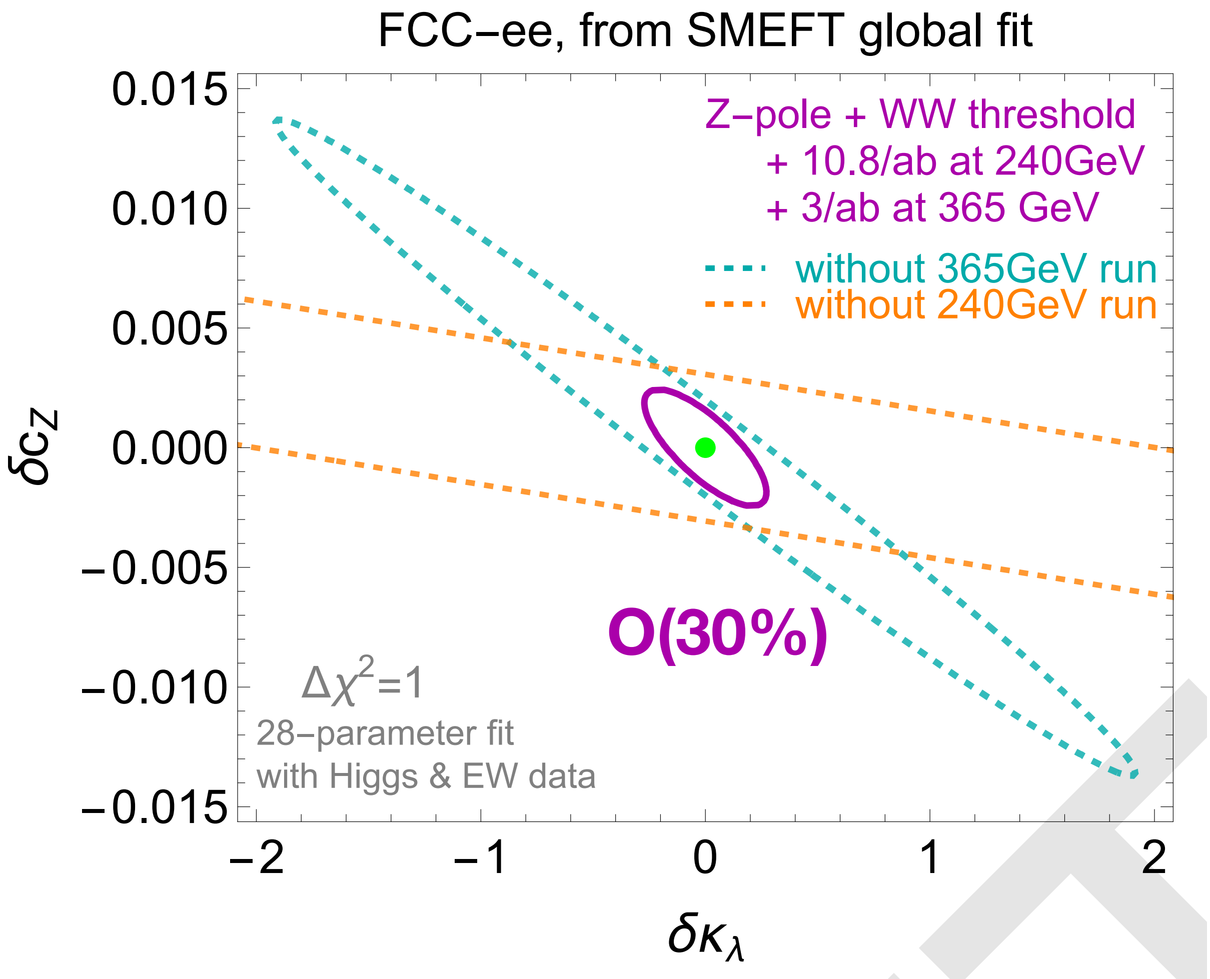
Lifted by $e^+e^- \to tt$

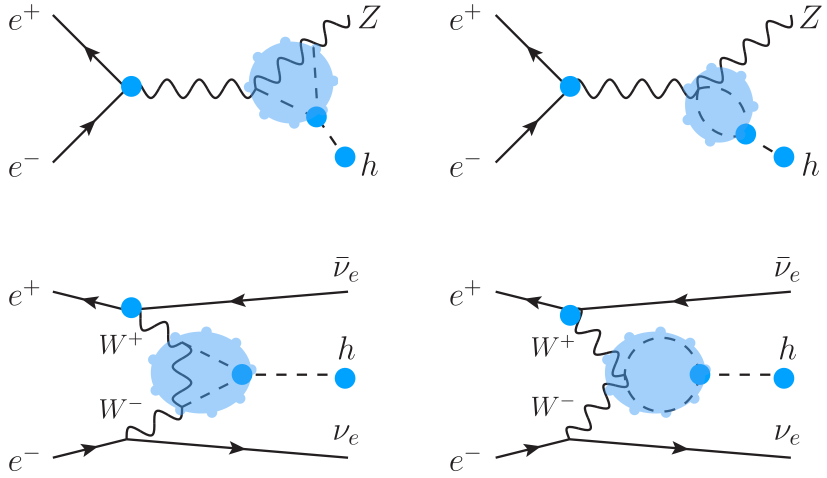
arXiv: 1809.03520 [hep-ph]

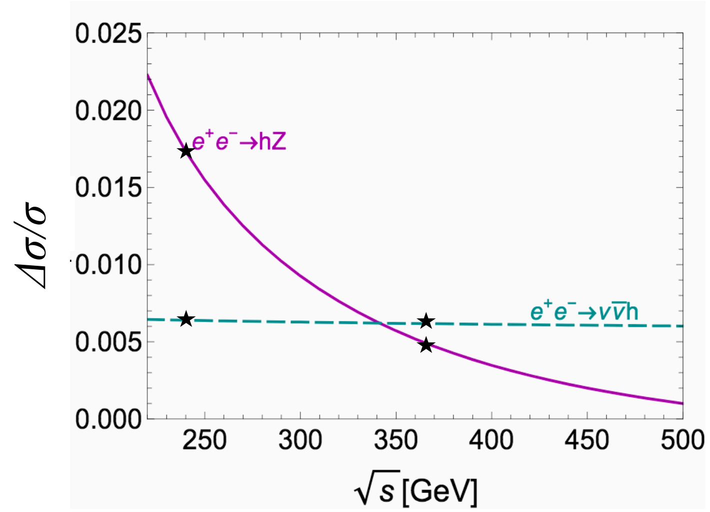
Global fits at future e^+e^- colliders

Coming back to the **Higgs self-coupling**

- Current determination from single-Higgs are based in EFT analysis including ALL LO contributions BUT ONLY the one-loop effects from κ_λ :







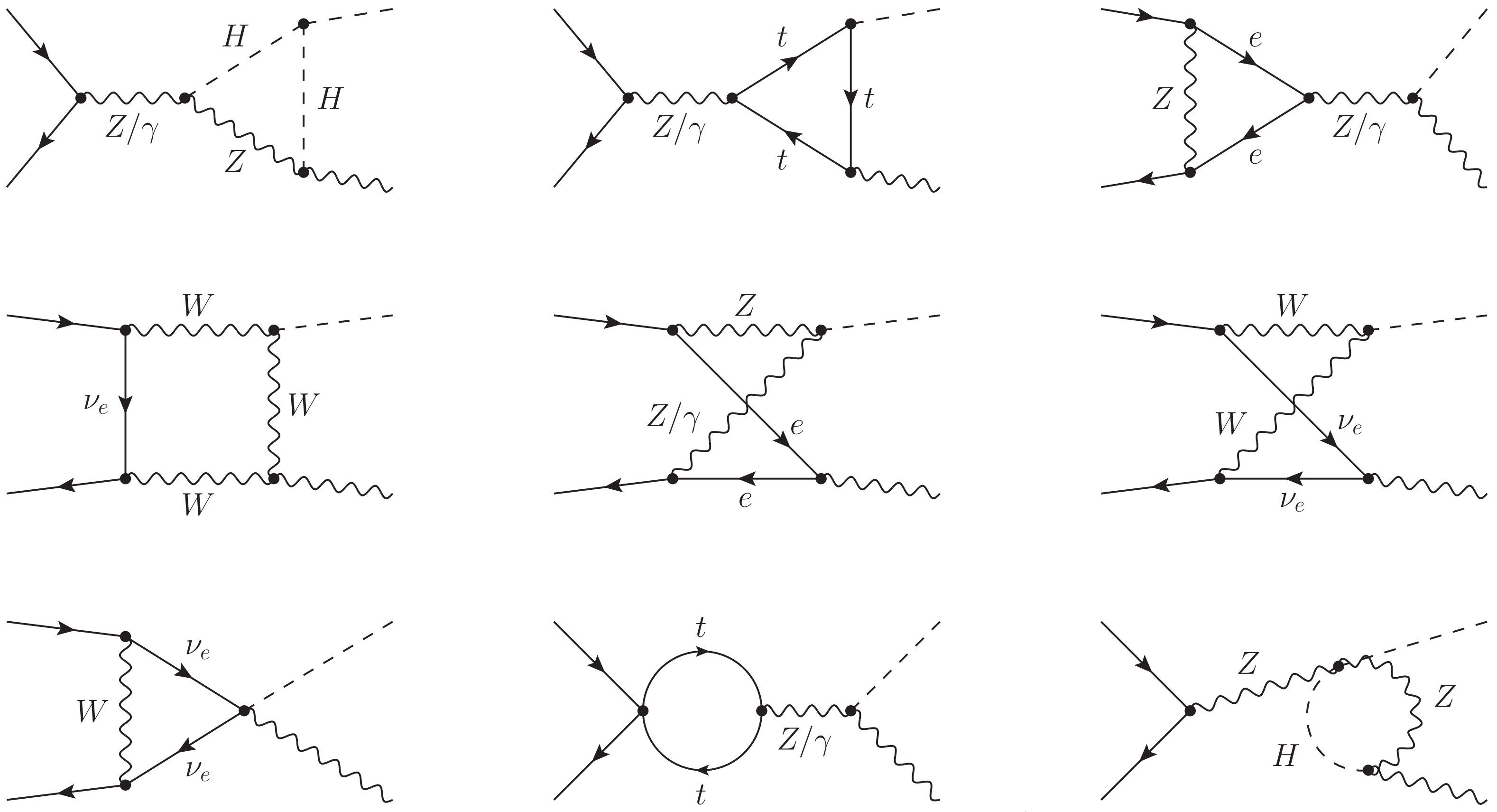
- You can still learn from this (e.g. need at least two energy points to separate κ_λ from LO), but a *"model-independent" interpretation of κ_λ within the SMEFT assumptions requires introducing all operators that contribute at NLO*!

Global fits at future e^+e^- colliders

Coming back to the Higgs self-coupling

- Full SMEFT calculation of ZH at NLO:

arXiv: 2409.11466 [hep-ph]



- Aside from the LO interactions, a total of 6 boson operator (4 CP violating), 9 two-fermion operators and 14 four-fermion operators contribute to dimension six at NLO…

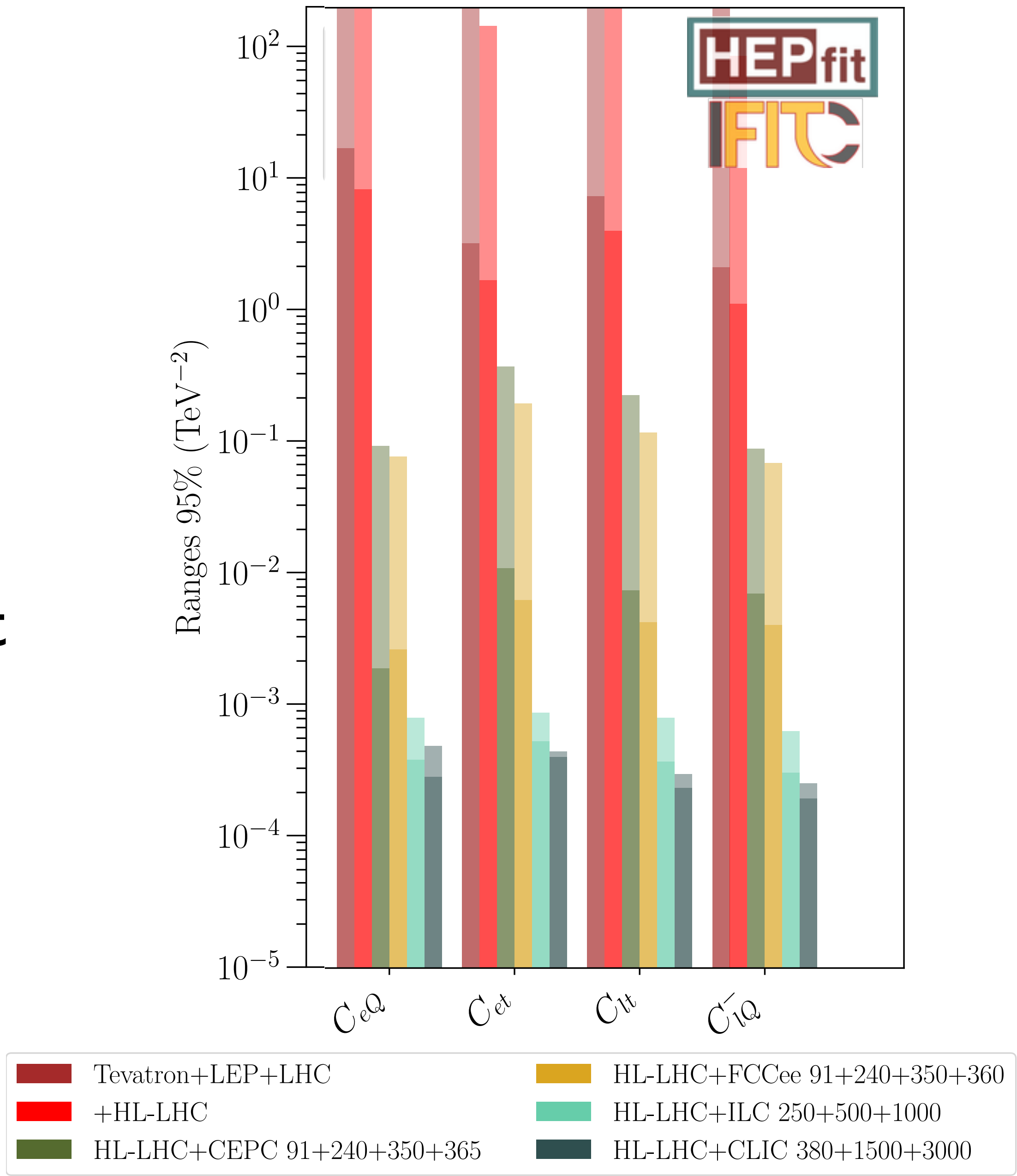
- Some of them which will remain relatively weakly constrained at the LHC!

$\Rightarrow$ e^+e^- tt operators

Global fits at future e^+e^- colliders

Coming back to the **Higgs self-coupling**

- Very weak bounds from HL-LHC
- But also enter in e+e- →tt
  - Even for Circular Colliders a combined analysis with HLLHC would reduce the bounds to O(10^{-1}) TeV^{-2}
- Preliminary results suggest this would result in a mild degradation, of order 35%, of the bound from the simplified analysis
- VERY PRELIMINARY: Including NLO effects of these and other operators in other observables of the fit



- Some of them which will remain relatively weakly constrained at the LHC!

⇒ e^+e^- tt operators

Global fits at future e^+e^- colliders

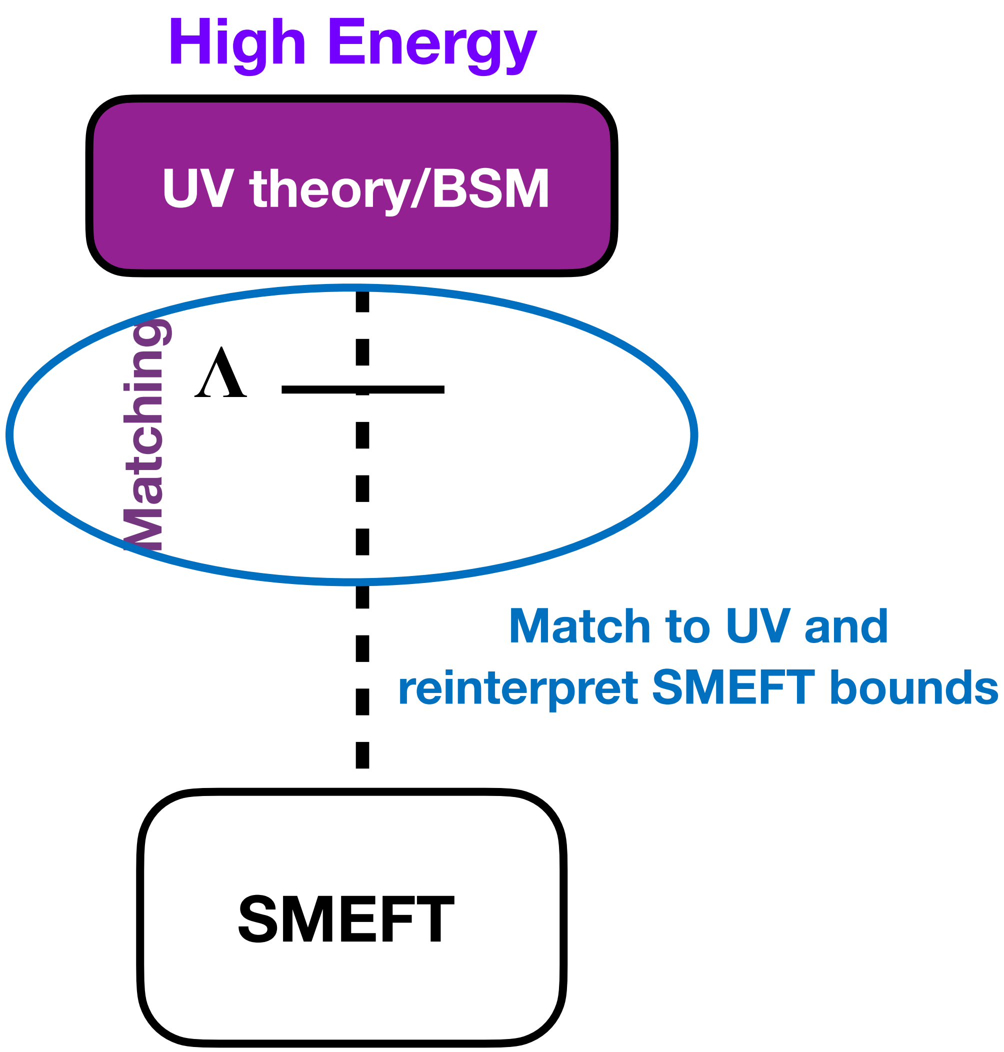
What do we learn from these EFT analyses?

Sensitivity to BSM deviations in future projections within the framework of dimension-6 SMEFT can be translated into any specific scenarios (consistent with the SMEFT assumptions)

⇒ Match c_i to specific models to learn about UV

Global fits at future e^+e^- colliders

- What can we learn with all this precision about UV physics?



High Energy

UV theory/BSM

Matching

Λ

Match to UV and reinterpret SMEFT bounds

SMEFT

Low Energy

48 multiplets contributing to $\mathcal{L}_{\mathrm{SMEFT}}^{d\leq 6}$

@ Tree level

19 spin 0

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$

Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$

Name	Ω_1	Ω_2	Ω_4	Υ	Φ
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

13 spin 1/2

Name	N	E	Δ_1	Δ_3	Σ	Σ_1
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$

Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

17 spin 1

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$

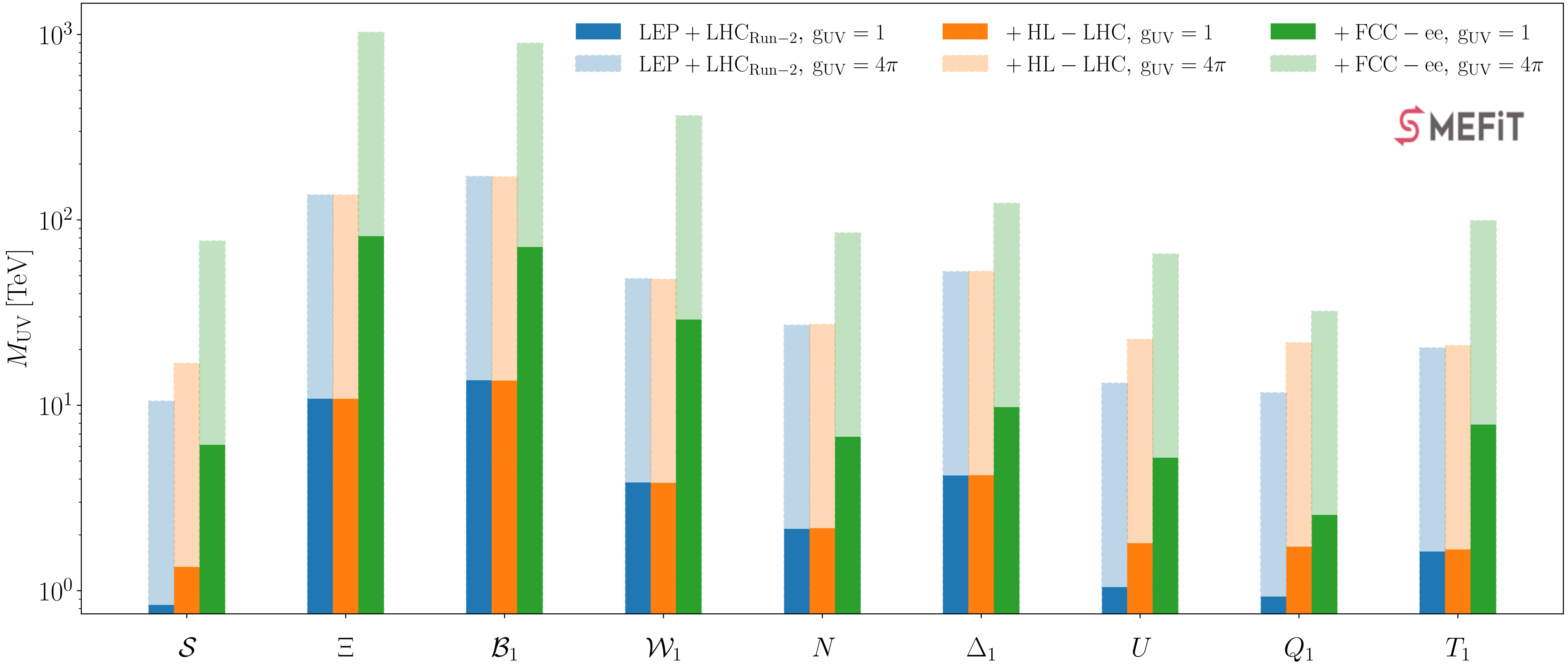
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

JB, J.C. Criado, M. Pérez-Victoria, J. Santiago, JHEP 03 (2018) 109

Global fits at future e^+e^- colliders: BSM scenarios

- Global SMEFT fit translated in terms of New Particle extensions of the SM

A few examples of new scalars/vectors/fermions



Spin 0 **Spin 1** **Spin 1/2 (leptons)** **Spin 1/2 (quarks)**

Multi-TeV sensitivity, depending on couplings

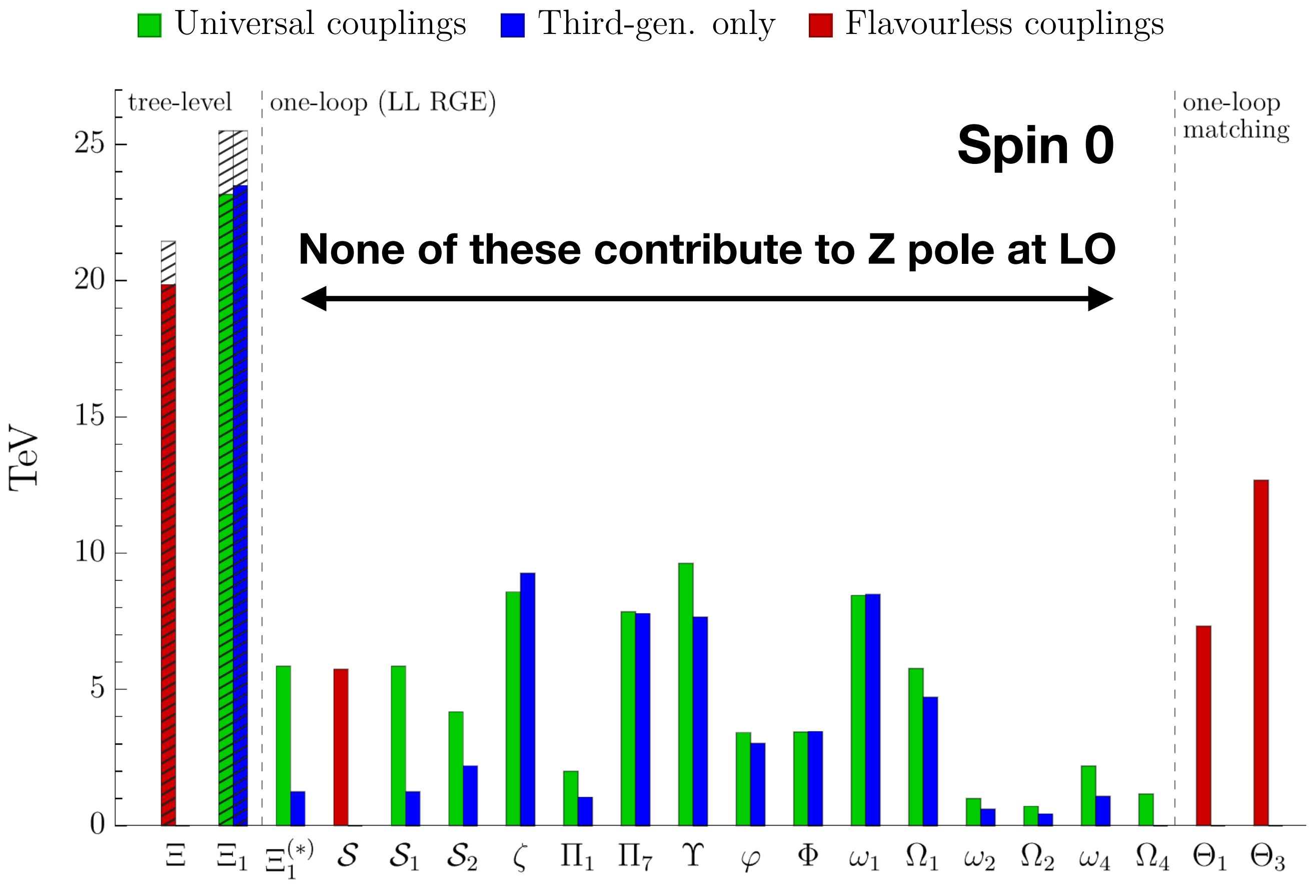
- Including only LO effects. Going beyond further illustrates the importance of precision measurements at the Tera Z (and theory calculations)

Global fits at future e^+e^- colliders: BSM scenarios

- Global SMEFT fit translated in terms of New Particle extensions of the SM

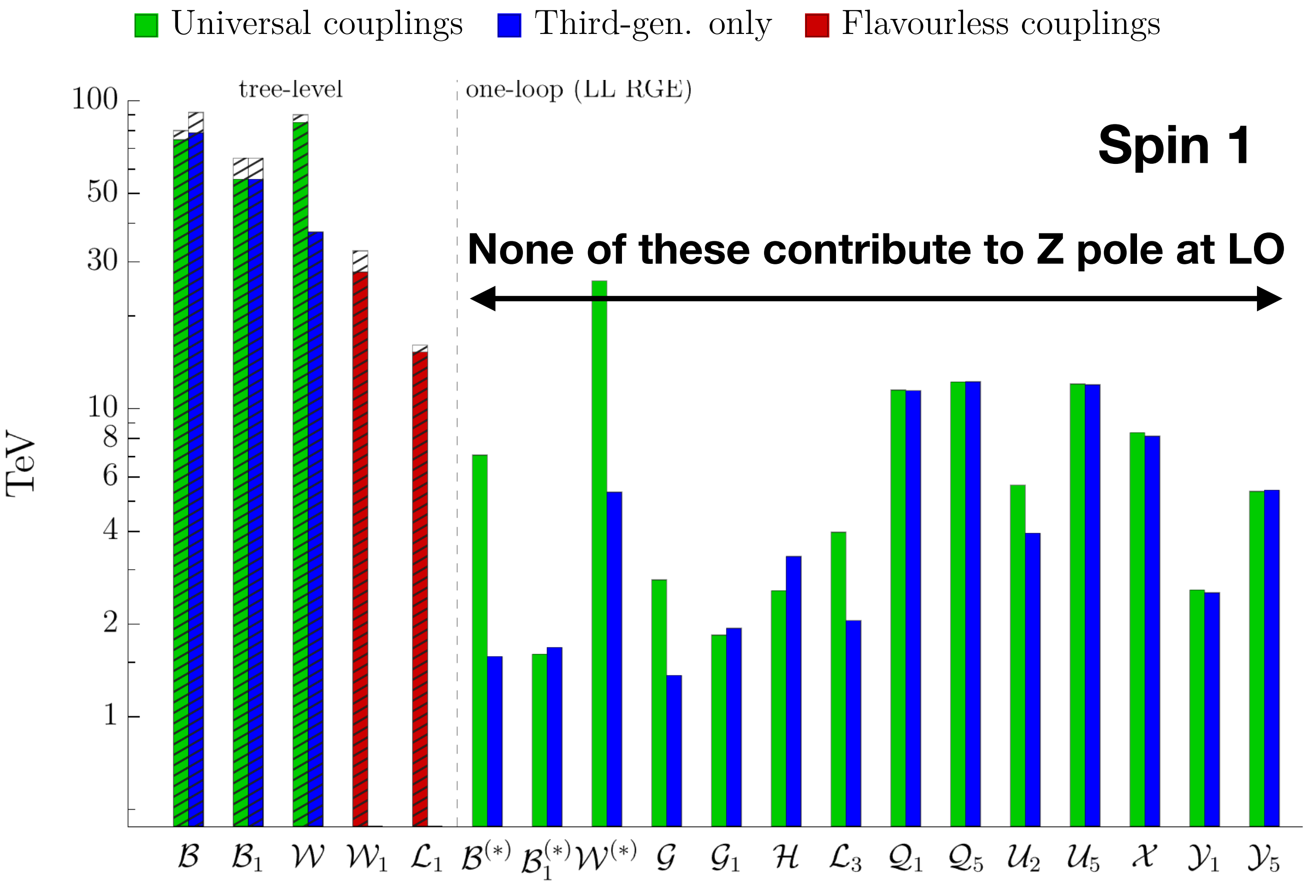
NLO sensitivity to New Physics at the Tera-Z

- Even if no tree-level effects at Tera Z, the very high precision of these measurements could set strong constrained via loop effects (here RGE only)



Spin 0

None of these contribute to Z pole at LO



Spin 1

None of these contribute to Z pole at LO

Considering loop effects, any particle contributing to the dimension 6 effective Lagrangian at tree level would be strongly constrained by future EWPO

Summary

Summary

- There are MANY aspects of the study that I didn't cover. Just a small selection of the huge amount of work collected in the nearly 300 pages of the *ECFA study report*
- Still, I tried to emphasize the case for precision physics at a future e^+e^- machine
  - Higgs: Permille precision of single-Higgs + access to couplings beyond the reach of HLLHC. Complementary ways to access self-coupling, depending on collider energy
  - EW: huge luminosity at Z-pole enables extremely precise measurements of EWPO, in some cases two orders of magnitude better than today
  - Flavor: Tera-Z luminosity also enables Flavor physics beyond the reach of B and Tau factories (see backup slides)
  - Top: Precise measurements of top properties. Complementarity with LHC.
- All combined, these measurements can cover many different directions where BSM effects could enter, with precision that enables multi-TeV indirect sensitivity to new physics

Backup slides

BSM and Higgs

- Higgs couplings modifications can tell us about BSM, but the O(10%) precision at the LHC gives limited information:

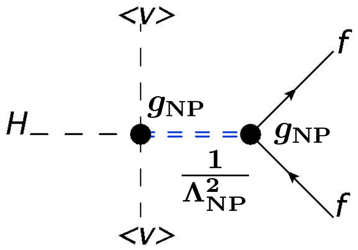
$$\left.\frac{\delta g_h}{g_h}\right|_{\text{LHC}}^{\text{Run II}} \sim O(10\text{ - }20)\%$$

Typical BSM deformation: $$\frac{\delta g_h}{g_h} \sim \frac{g_{\mathrm{NP}}^2 v^2}{\Lambda_{\mathrm{NP}}^2} \Longrightarrow \Lambda_{\mathrm{NP}} \gtrsim 600\,\frac{g_{\mathrm{NP}}}{g_{\mathrm{SM}}}\ \mathrm{GeV}$$

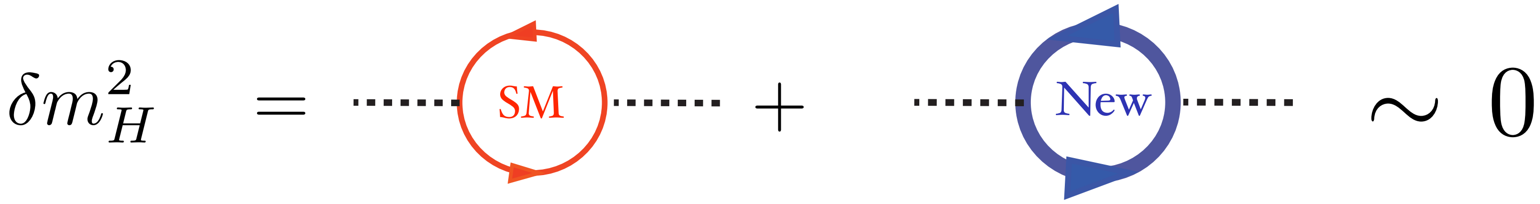
Not better than direct searches

(unless NP is strongly coupled)

E.g.



- Higgs couplings also provide information about Naturalness

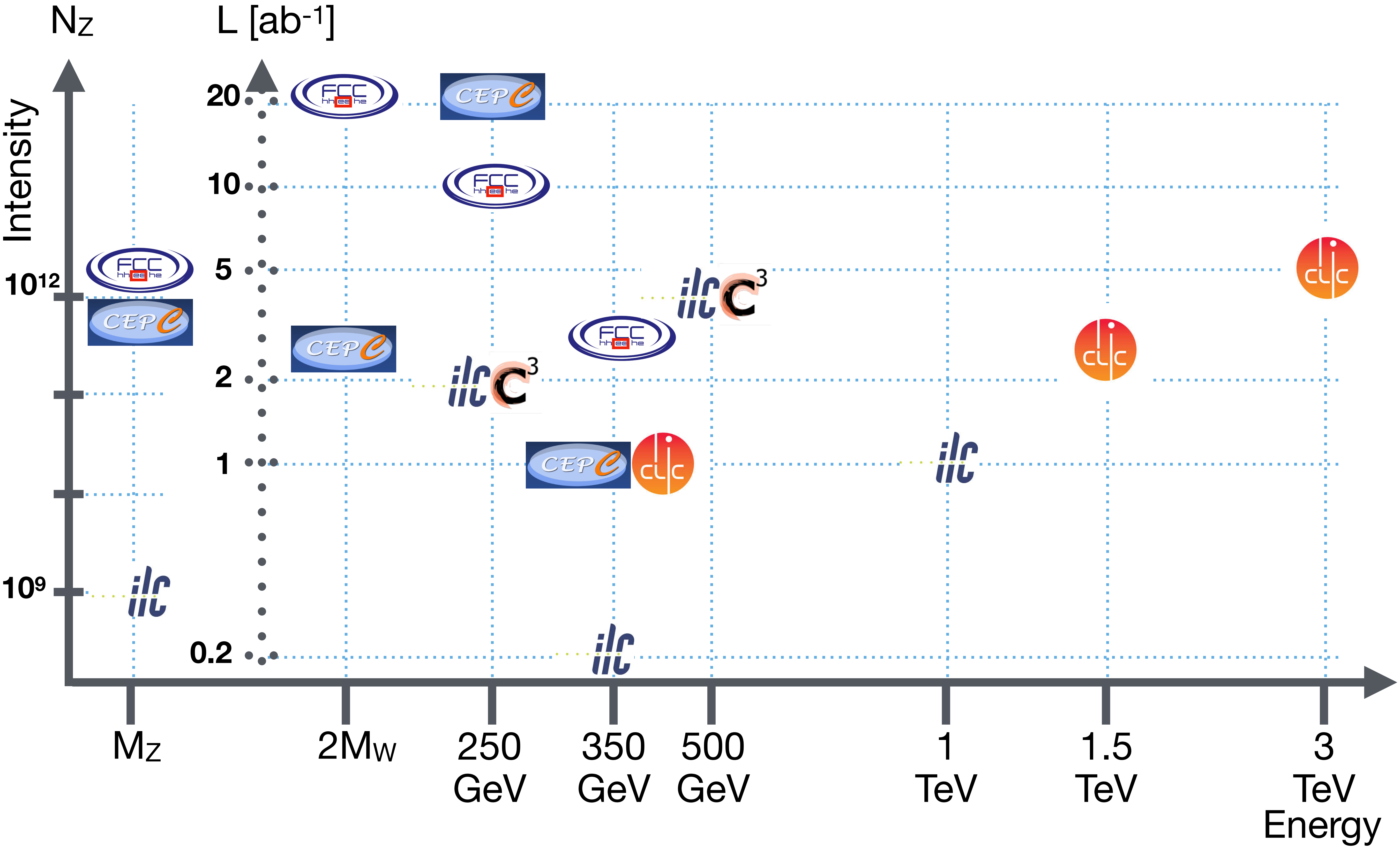


$$\delta m_H^2 = \cdots\text{SM}\cdots + \cdots\text{New}\cdots \sim 0$$

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon_T \equiv \text{fine tuning}$$

⇒ Higgs precision physics is a key tool to learn from BSM
⇒ Need of an e^+e^- Higgs factory

2024-26 European Strategy Update



ECFA Study on Higgs/EW/Top factories

- Study focused on stages common to all future e^+e^- colliders ($\sqrt{s} \lesssim 365$ GeV)
  - Exceptions made for some studies where higher energies are relevant

- Kick-off meeting on June 21, 2021: https://indico.cern.ch/event/1033941/
- Preliminary status presented in 3 workshops:
  - 2022 in DESY: https://indico.desy.de/event/33640/
  - 2023 in Paestum (Salerno): https://agenda.infn.it/event/34841/
  - 2024 in Paris: https://indico.in2p3.fr/event/32629/

- Plus many dedicated small meetings organized by the different subgroups, seminars, etc:
  - See https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories

- Currently finishing first version of a report with the conclusions of the study, in preparation as (extended) input for 2026 ESU

Higgs/EW/Top Studies
Electroweak Physics

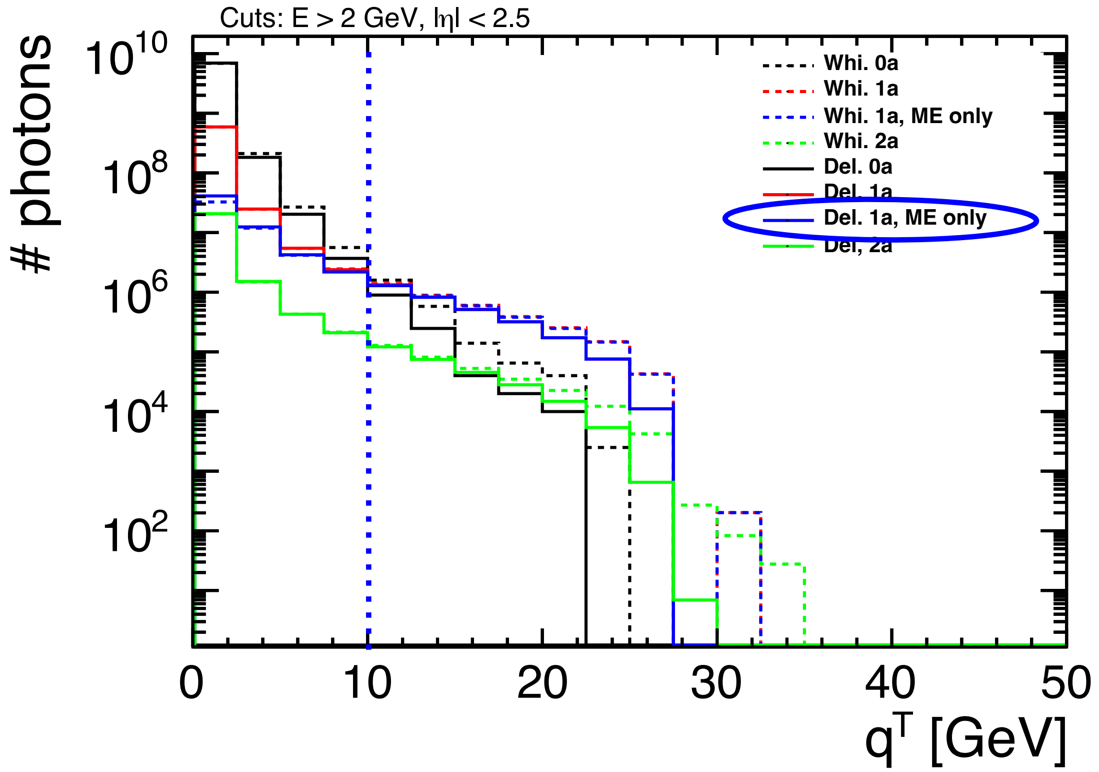
EW physics at e⁺e⁻ Higgs factories

Determining quark couplings to light quarks via FSR

- Up and down-type quarks radiate differently ⇒ Use QED FSR to separate

$$\Gamma_{had+\gamma} \sim \frac{\alpha}{2\pi} f(y_{cut})(3Q_d^2 c_d + 2Q_u^2 c_u)$$

- Challenges: Need to separate from ISR or decays from hadronization products
- Cut study using fast detector sim. with Delphes (ILCgen cards)

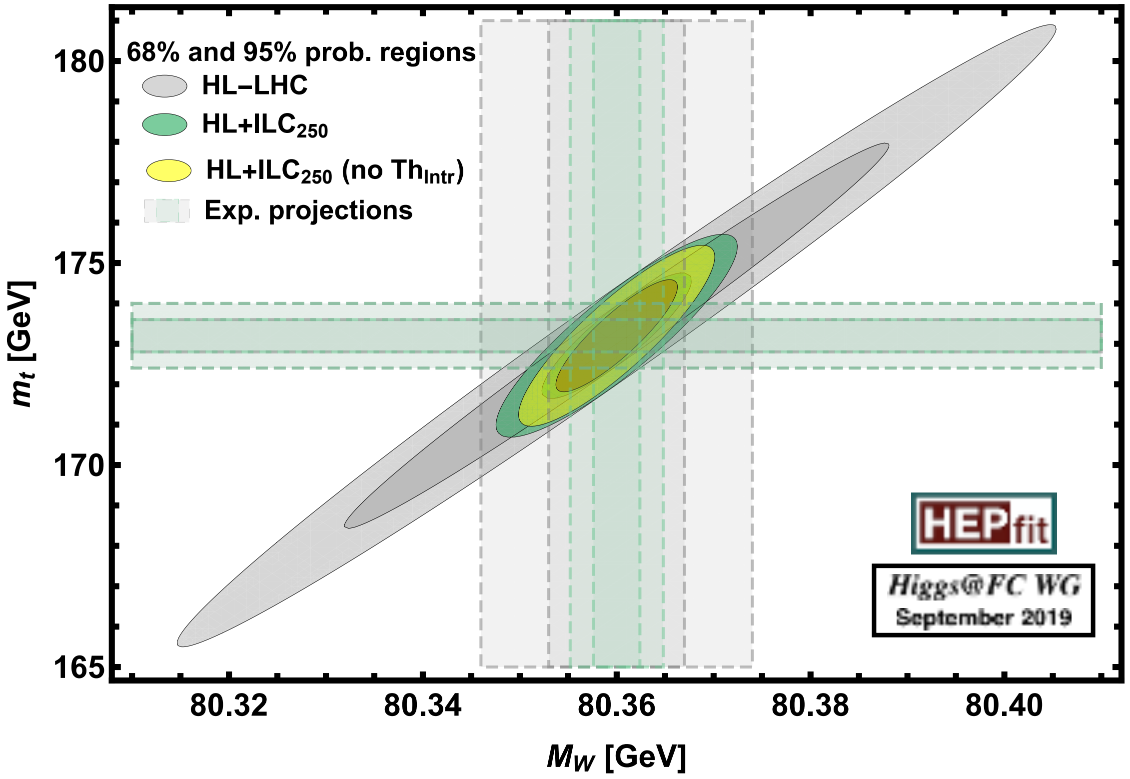


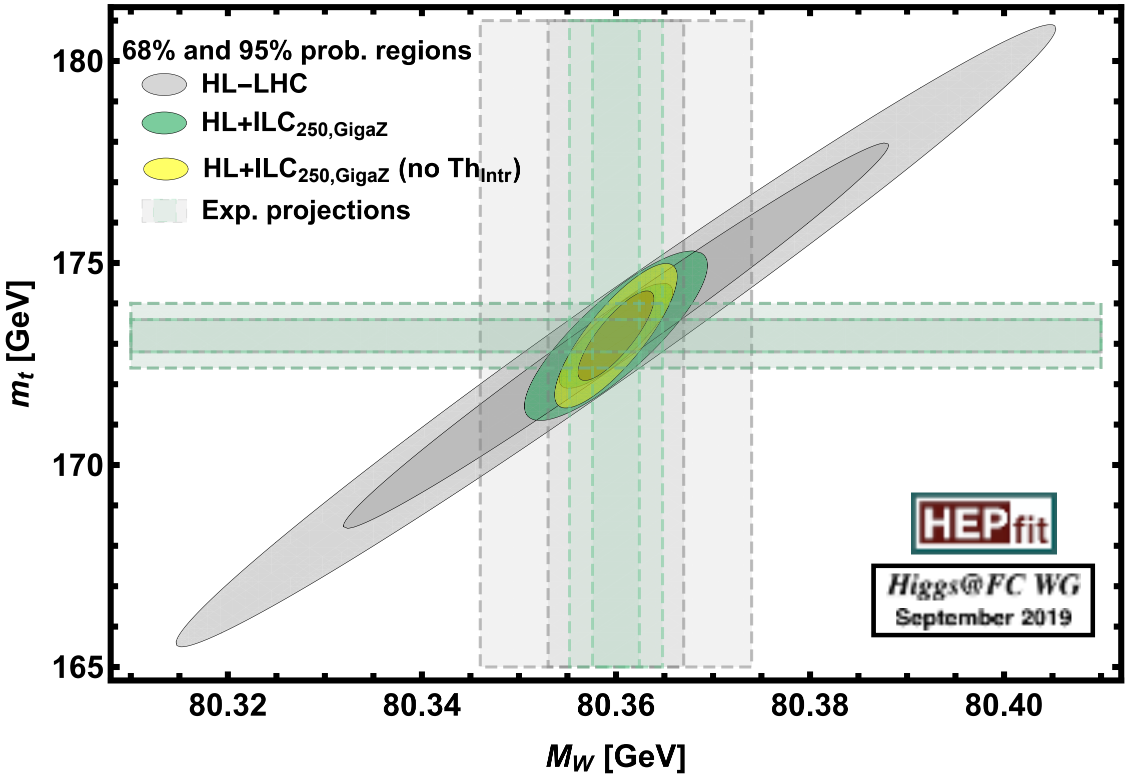
- Above 10 GeV the sample with FSR γ becomes dominant
- Several sources of uncertainty considered: Lumi; acceptance; b, c, s, light jet tagging

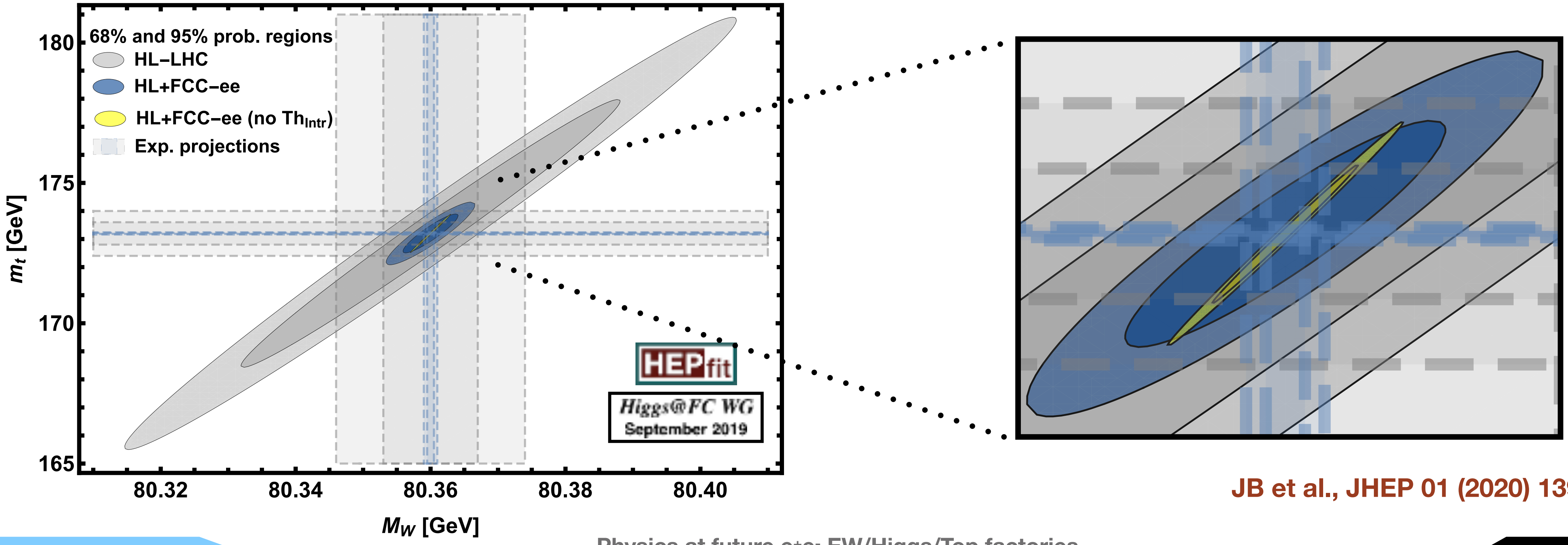
- Prelim. results suggest sub-percent precision could be achievable for light quarks

EW physics at e^+e^- Higgs factories

- Consistency tests of the EW sector: HL-LHC vs. Giga Z vs. Tera Z





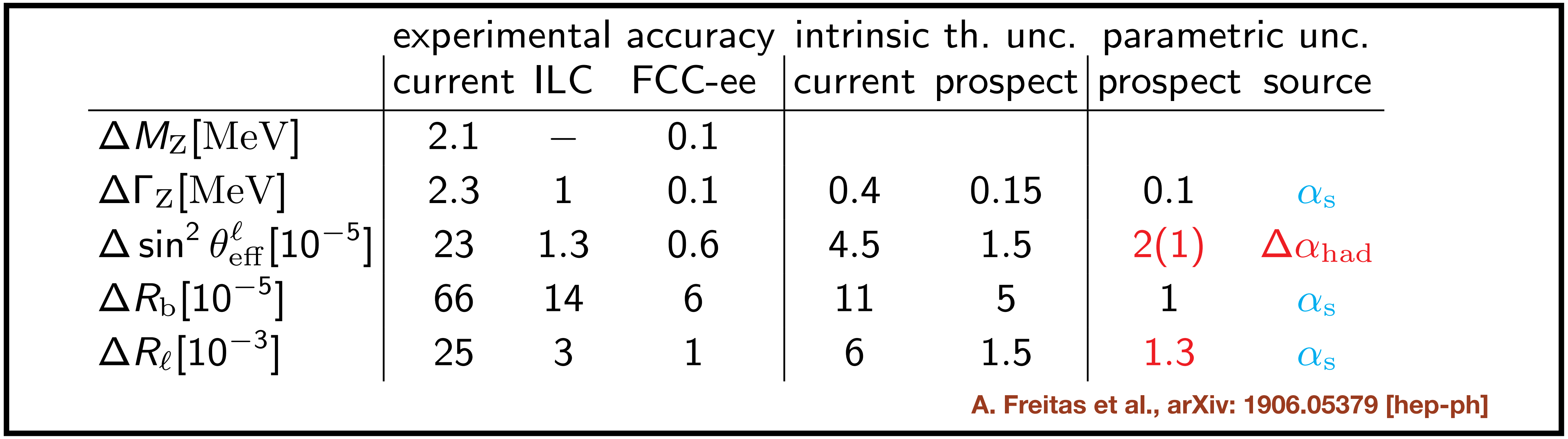


JB et al., JHEP 01 (2020) 139

Theory Challenges at the precision frontier

- Proper interpretation of precision measurements require precision theory
    - The goal of improved precision measurements is to learn about new physics ⇒ We need to distinguish between new physics (signal) and SM (background)

- We need to have very good control of the background so its uncertainties do not affect the new physics interpretation



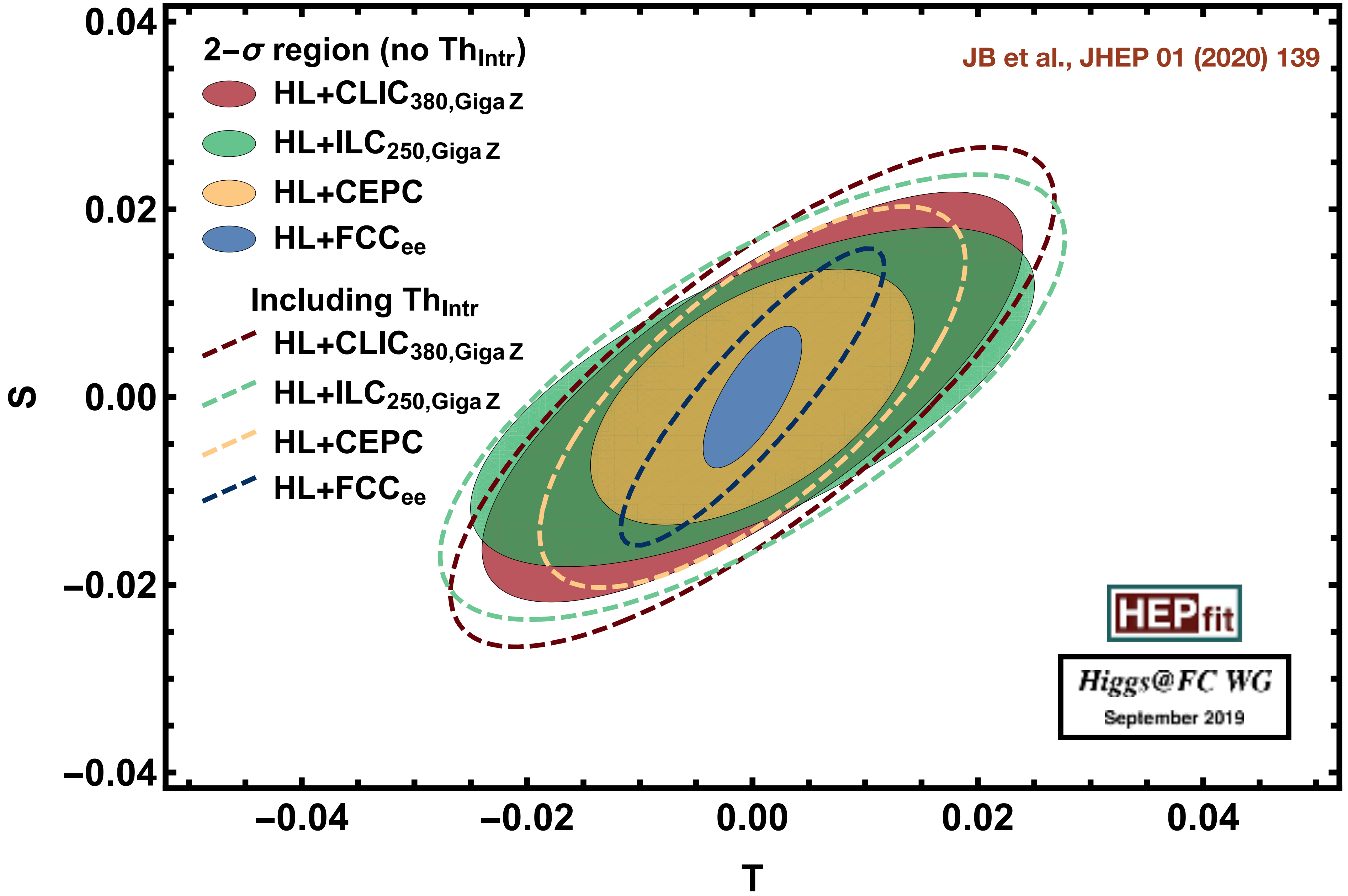
	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
$\Delta M_Z[\mathrm{MeV}]$	2.1	–	0.1				
$\Delta \Gamma_Z[\mathrm{MeV}]$	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta \sin^2\theta^\ell_{\mathrm{eff}}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_{\mathrm{had}}$
$\Delta R_b[10^{-5}]$	66	14	6	11	5	1	α_s
$\Delta R_\ell[10^{-3}]$	25	3	1	6	1.5	1.3	α_s

A. Freitas et al., arXiv: 1906.05379 [hep-ph]

- Theory challenges: Future projections assume full EW & QCD-EW 3-loop + leading 4 loop (Y_t enhanced) are computed by the time of future e+e-
    - ✓ Enough only to lower theory uncertainty to the experimental level

Theory Challenges at the precision frontier

- Precision Experiment vs. Theory: Impact of SM theory uncertainties



- Even accounting for future progress, SM theory uncertainties will have an impact on BSM interpretation of EWPO

- Parametric uncertainties expected to have similar effect ($\alpha_{\text{em}} \to A_l \to S$ par.)

ECFA study report

Flavor

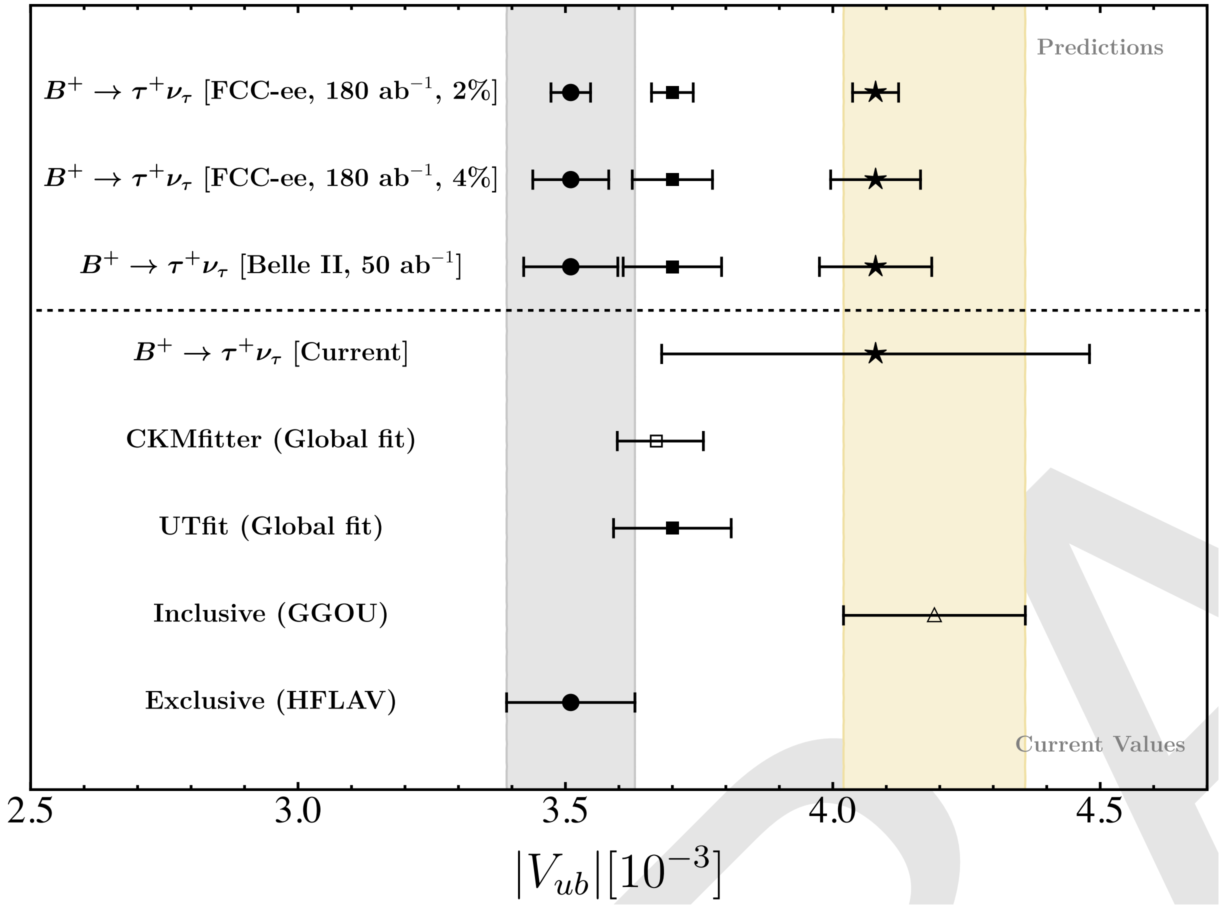
Flavor Physics at e^+e^- Higgs factories

- Current flagship experiments:
  - LHCb at the LHC
    - ATLAS & CMS also contribute, e.g. $B^0 \to \mu\mu$, $B^0_s \to \mu\mu$
  - Belle II at the SuperKEKB collider: $e^+e^- \to \Upsilon(4S) \to bb$
- Future e^+e^- colliders running at the Z pole (Tera-Z): $e^+e^- \to Z \to bb$
  - Combines advantages of both Belle II (high signal-to-noise, fully efficient trigger) and LHCb (full spectrum of hadrons, high boost)
  - Momenta of b and c hadrons not known a priori but distribution well understood
  - Also $e^+e^- \to Z \to \tau^+\tau^-$: momentum of produced τ exactly known
- Flavor measurements also possible in $e^+e^- \to WW$: CKM elements

Flavor Physics at e^+e^- Higgs factories

B physics at Tera-Z

- Determination of CKM elements: $|V_{ub}|$ and $|V_{cb}|$
  - Tensions between inclusive vs exclusive determinations
  - Prospective studies at Tera-Z from B→τν, assuming precision between to 2% to 4% in BR

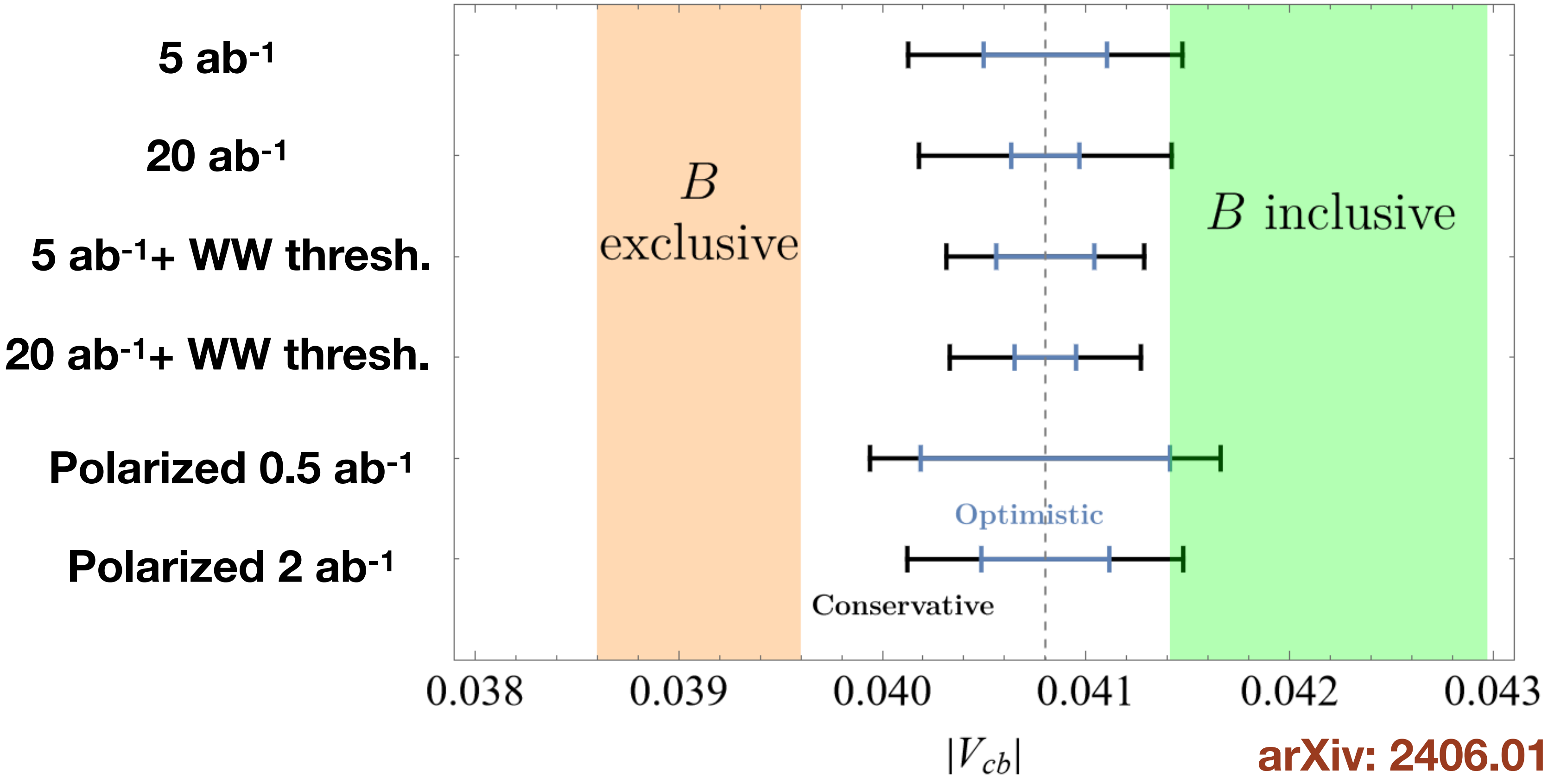


  - $|V_{cb}|$ estimate not available (depends on production fraction of B_c. No measurement currently available)

Flavor Physics at e^+e^- Higgs factories

CKM from W decays

- FCCee, CEPC and ILC will produce order of 10^8 W boson pairs
- Combined with state-of-the-art jet-flavor tagging techniques this offers a unique opportunity to enhance the precision of CKM matrix elements, particularly $|V_{cb}|$ and $|V_{cs}|$
- Studies available or ongoing at all types of e^+e^- colliders, in some cases with full detector simulation. From the CEPC study at 250 GeV:



arXiv: 2406.01675 [hep-ph]

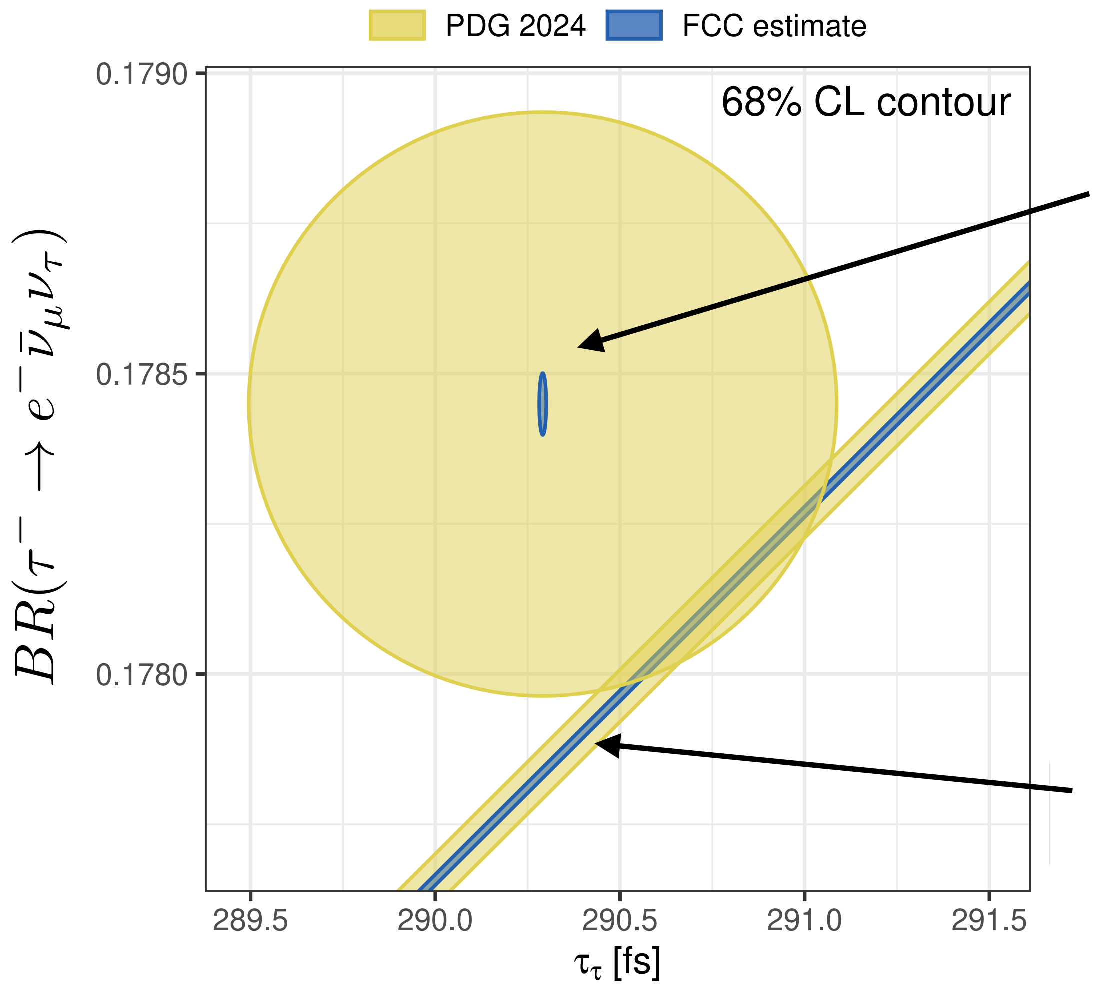
Flavor Physics at e⁺e⁻ Higgs factories

Tau physics at Tera-Z

- Similar to the case case of B physics, with 6 x10¹² Z decays at a Tera-Z factory, we'll have a large sample of 2 x10¹¹ τ pairs to deepen studies of τ physics.
  - Tau mass and lifetime: Extrapolated from DELPHI and OPAL analyses with Tera-Z statistics (+ estimates in systematics)

$\delta m_\tau \sim 5\times10^{-5}$ (current) → 10^{-5} **$\delta\tau_\tau \sim 1.7\times10^{-3}$ (current) → 2.2×10^{-5}**

  - Lepton universality in τ decays



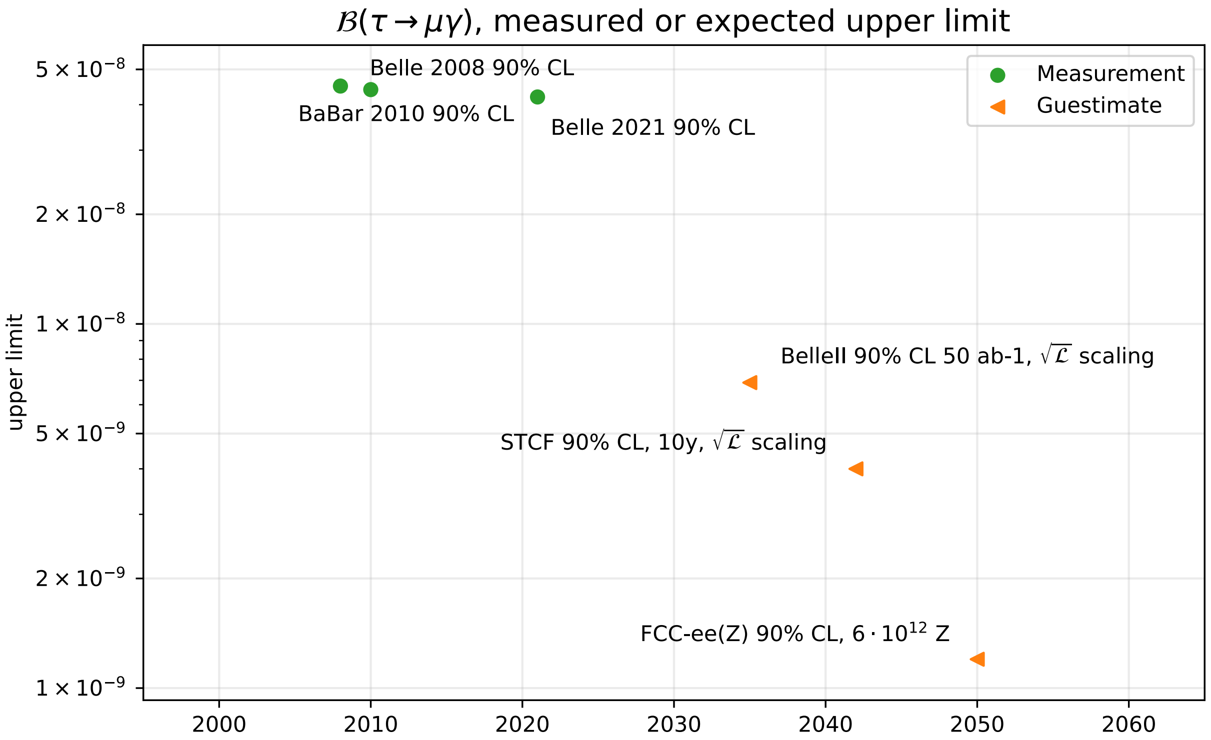
Average between Direct measurement and SM prediction from $\tau \to \mu\nu_\mu\nu_\tau$

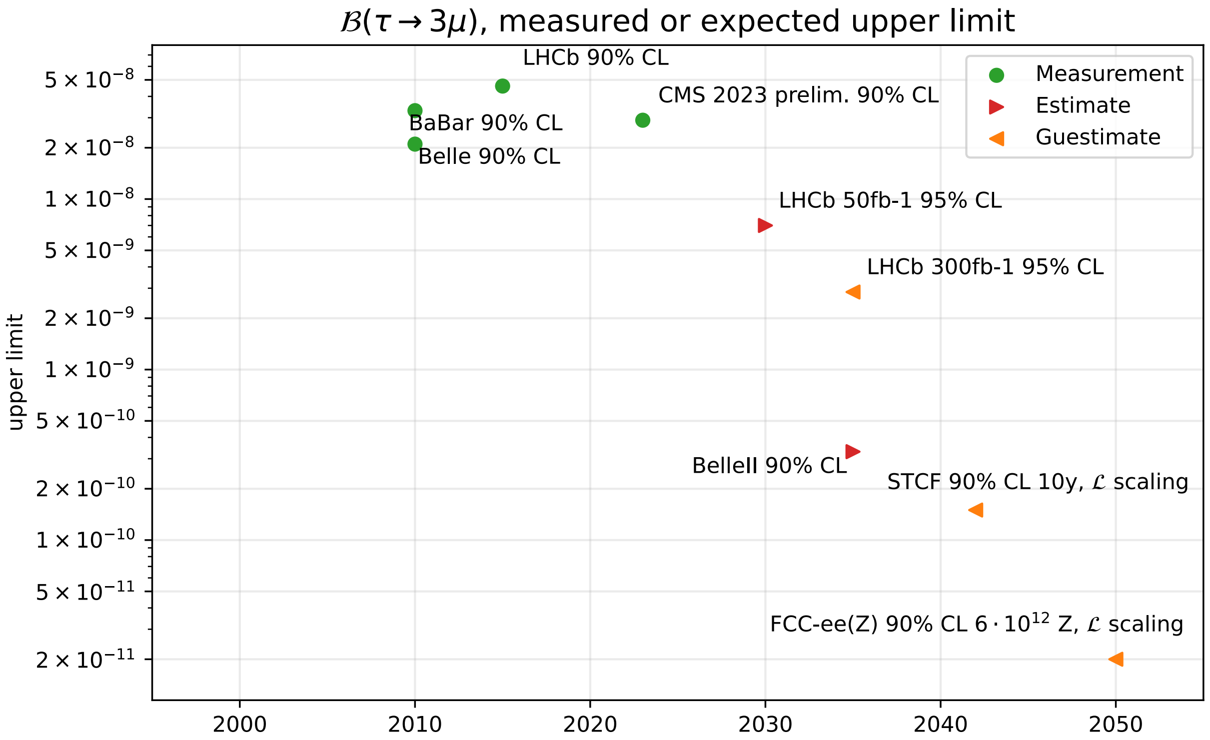
SM prediction

Flavor Physics at e^+e^- Higgs factories

Tau Physics

- Similar to the case case of B physics, with 6 $\times10^{12}$ Z decays at a Tera-Z factory, we'll have a large sample of 2 $\times10^{11}$ τ pairs to deepen studies of τ physics.
    - Lepton Flavor Violating decay modes: τ→μγ and τ→μμμ


$\mathcal{B}(\tau \to \mu\gamma)$, measured or expected upper limit


$\mathcal{B}(\tau \to 3\mu)$, measured or expected upper limit

ECFA study report
Direct Searches

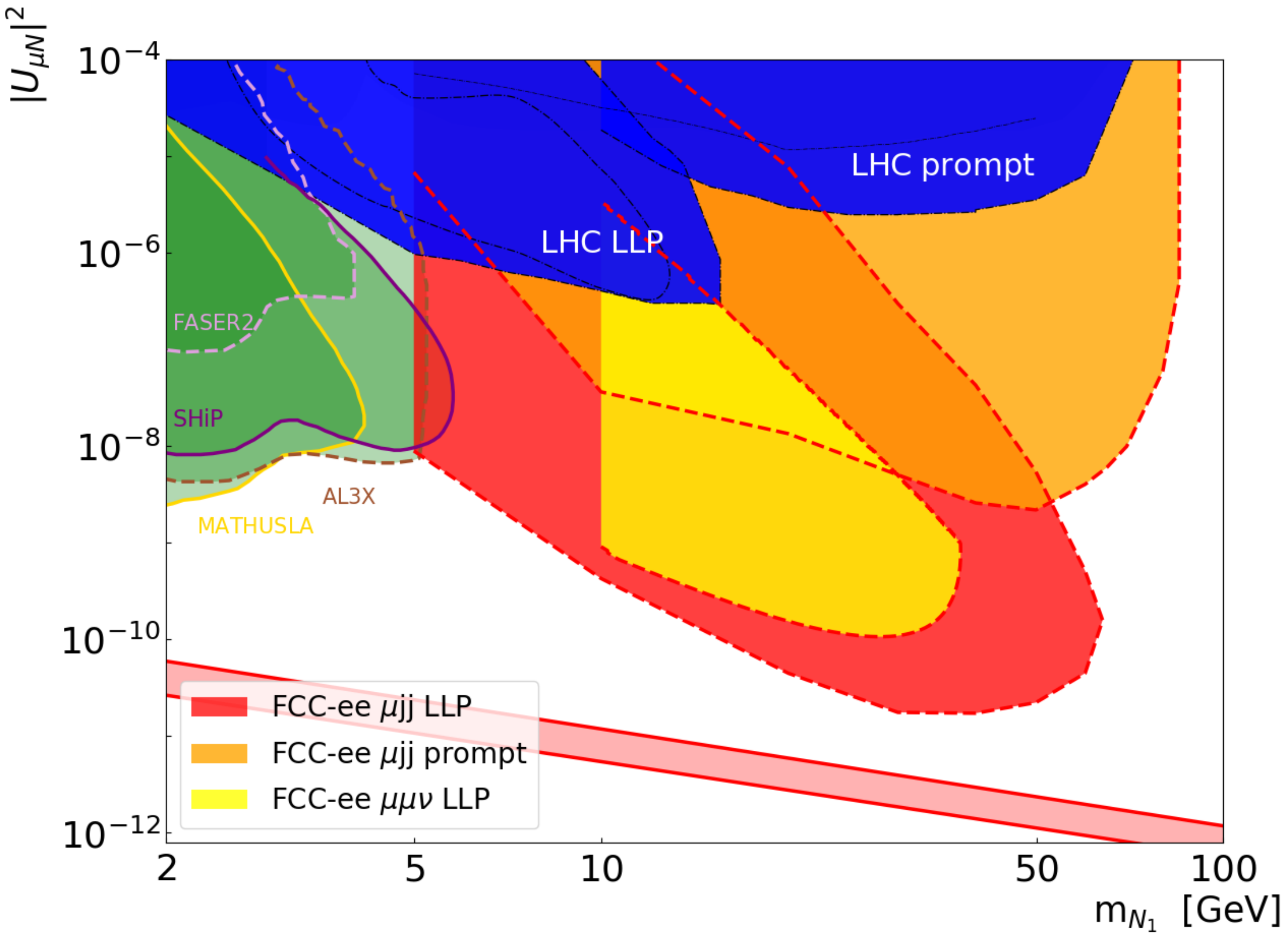
Direct searches at e^+e^- Higgs factories

- Energy reach at future e^+e^- factories won't be much larger than, e.g. LEP2. Still they have the potential to discover NP not accessible to current high intensity machines because
  - Too heavy for the 10 GeV machine like superKEK-B
  - Too elusive to be seen with the (relatively) low luminosity of LEP2
- They would also cover scenarios whose signals are too faint at the LHC:
  - Small couplings (or no couplings) to QCD and can only be produced via EW ⇒ Relatively small cross section compared to background
  - e^+e^- HTE complementary: cross sections comparable to backgrounds
- or where produced new states live too long to be detected at the LHC detectors ⇒ Long lived particles
  - Triggering less of an issue in e^+e^-
  - Learn from challenges at LHC and optimize searches

Direct searches at e^+e^- Higgs factories

Focus Topic: Long-Lived Particles

- Centered around several scenarios where small couplings give rise to LLPs, e.g.
    - Heavy Neutral Leptons (HNLs)



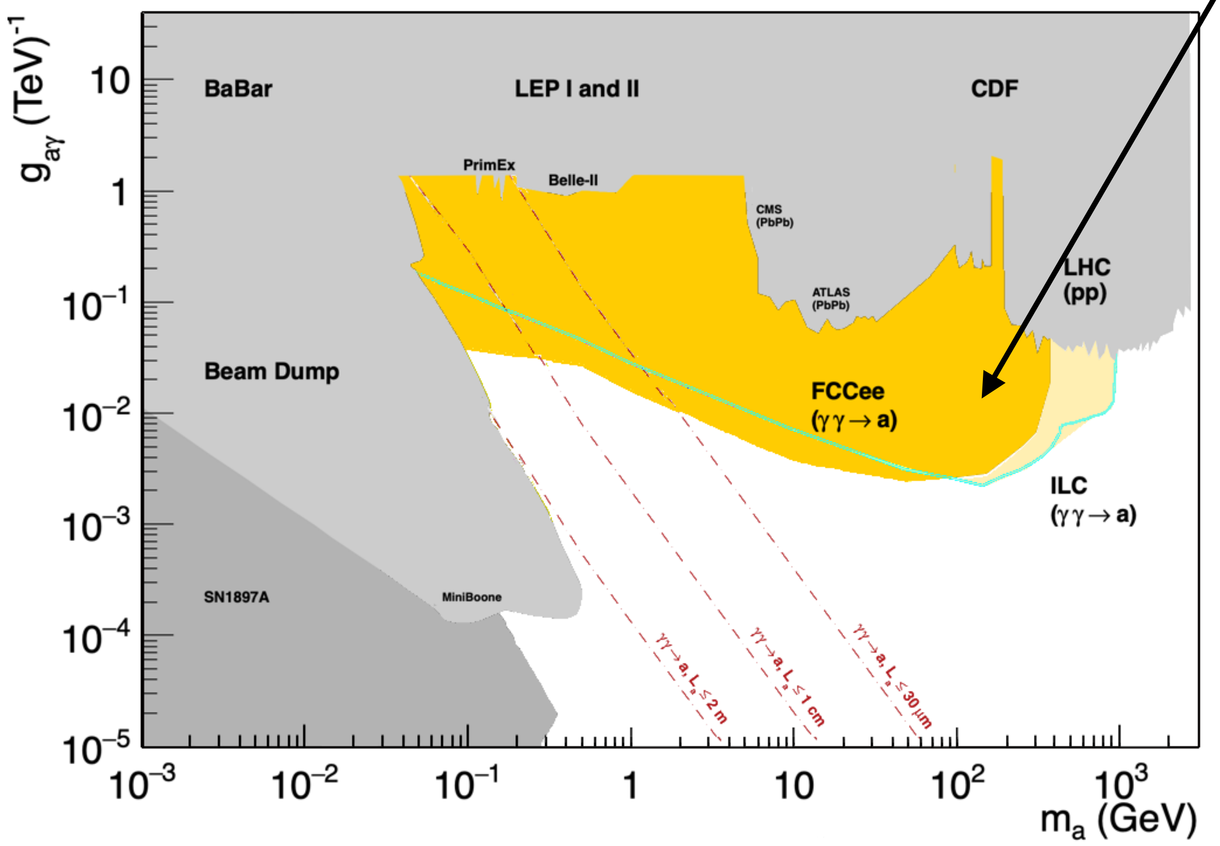
- ▸ Search at Z-pole run (Tera Z)
- ▸ Pythia8 + Fast Sim using Delphes card of simulation of IDEA detector
- ▸ Studies at ZH run (240-250 GeV) from ILC also available

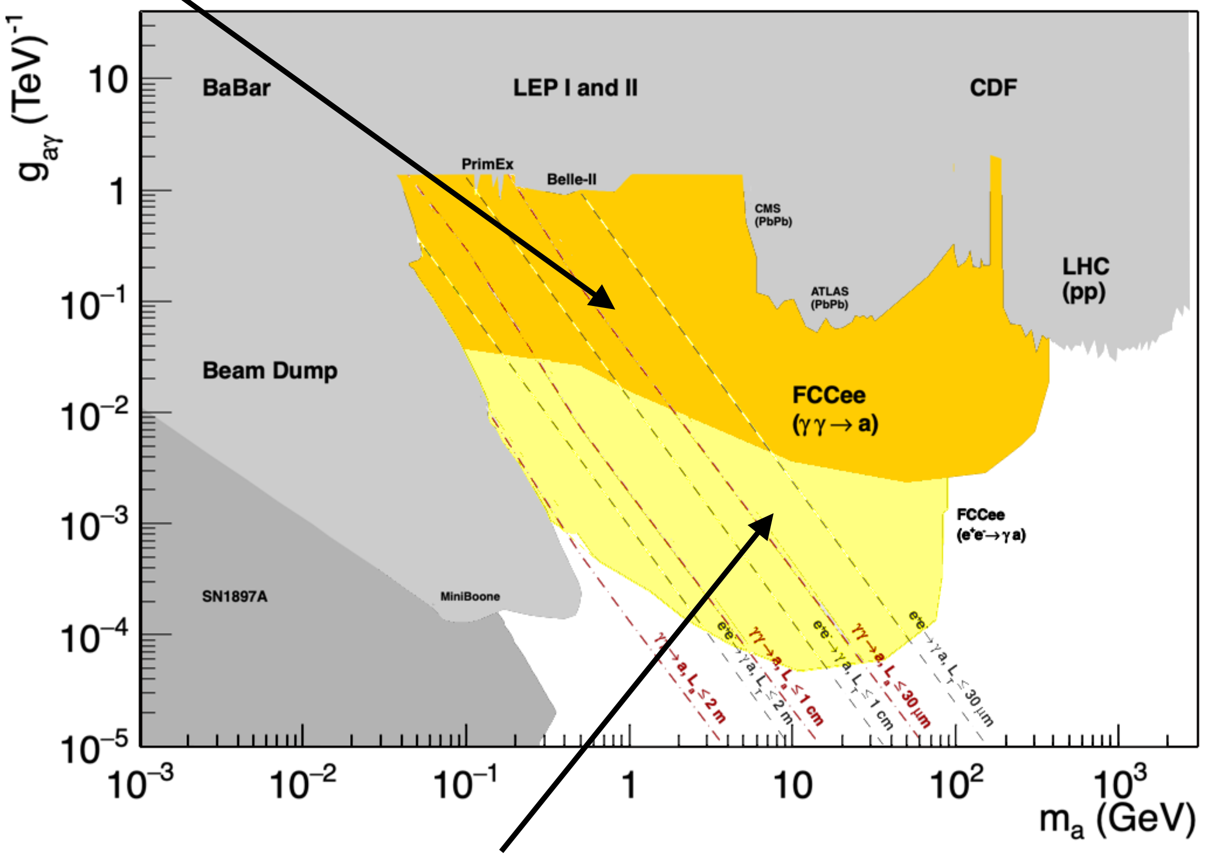
Direct searches at e⁺e⁻ Higgs factories

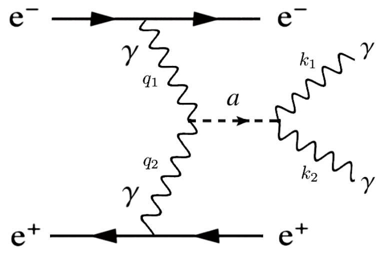
Focus Topic: Long-Lived Particles

- Centered around several scenarios where small couplings give rise to LLPs, e.g.
    - Axion-Like Particles (ALPs)

ILC and FCCee reach $\gamma\gamma \to a \to \gamma\gamma$ **Vs. Tera Z reach**







$$e^+e^- \to Z \to \gamma a$$

Up to 2 orders of magnitude better if $m_a < M_Z$

(Virtually no background)