LCWS2024 International Workshop on Future Linear Colliders

July 8, 2024

Physics case for e^+e^- Higgs/Electroweak factories: Precision physics

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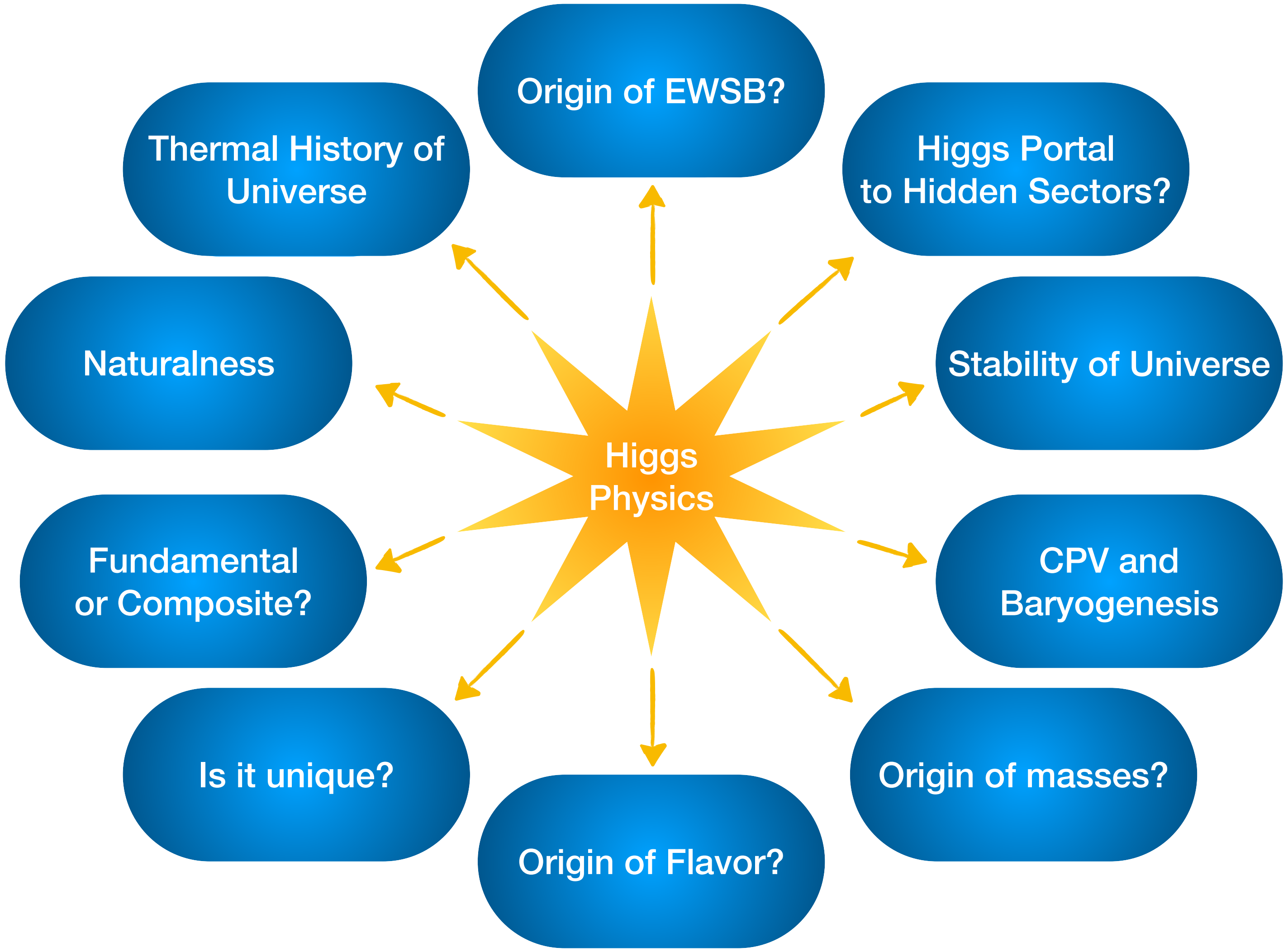
Why do we need more precision?

The case for precision physics

- **The bigs questions:**

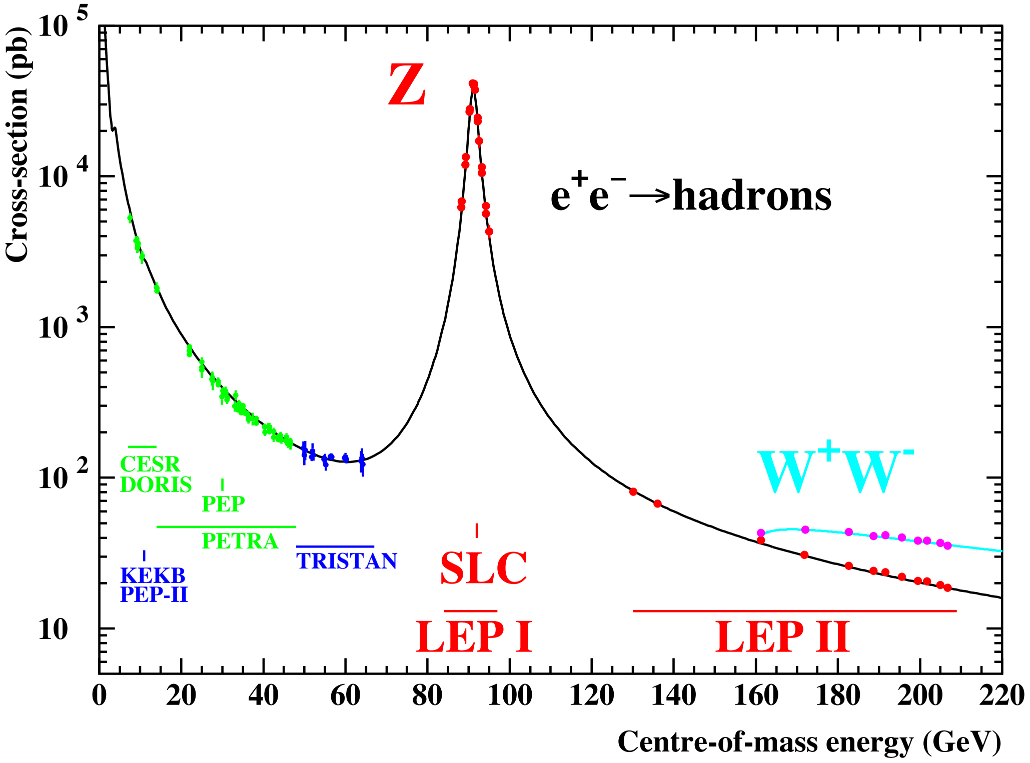


- Solutions to most of these questions involve BSM physics "talking" to any of the sectors of the SM, in particular the Higgs ⇒ Virtual effects in SM observables
- Pushing the precision of SM measurements is a way of learning about new physics (indirectly)!

The case for precision physics

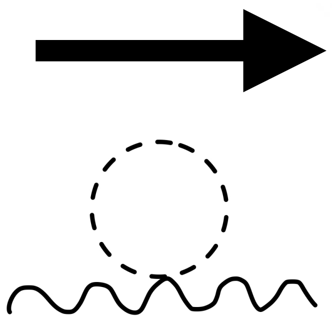
- **Looking back at the LEP/SLC legacy: Electroweak precision era**
  - ✓ By measuring precisely the properties of the W/Z bosons we learned about the Higgs (and Top) before they were discovered…

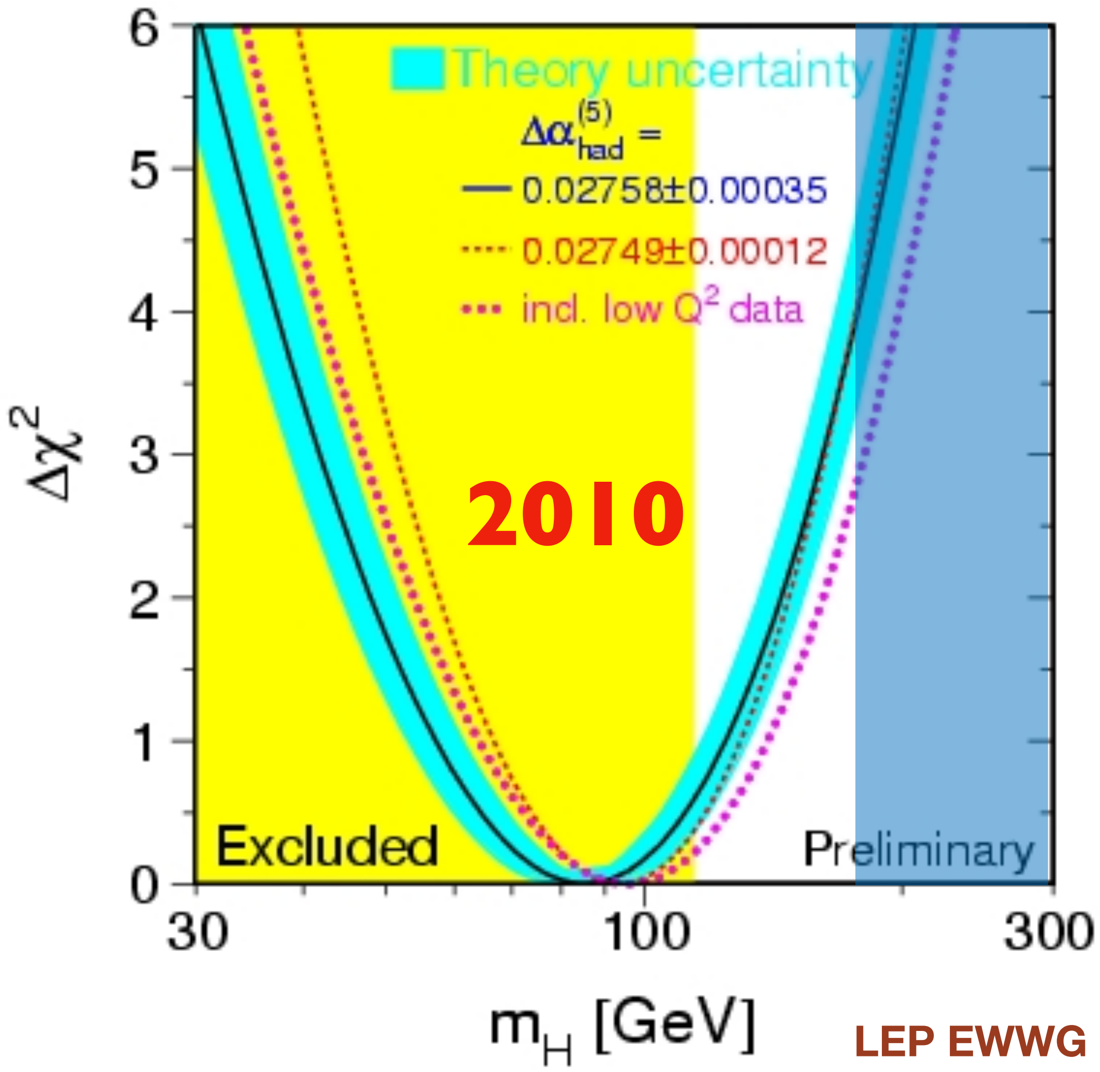
Z-pole EWPO



O(0.1%) precision

SM EW fit





LEP EWWG

$$\text{EWPO (2010)}: \quad m_H < 152~\text{GeV} \quad 95\%~\text{C.L.}$$

$$\text{EWPO} + \text{LEP2}: \quad m_H < 171~\text{GeV} \quad 95\%~\text{C.L.}$$

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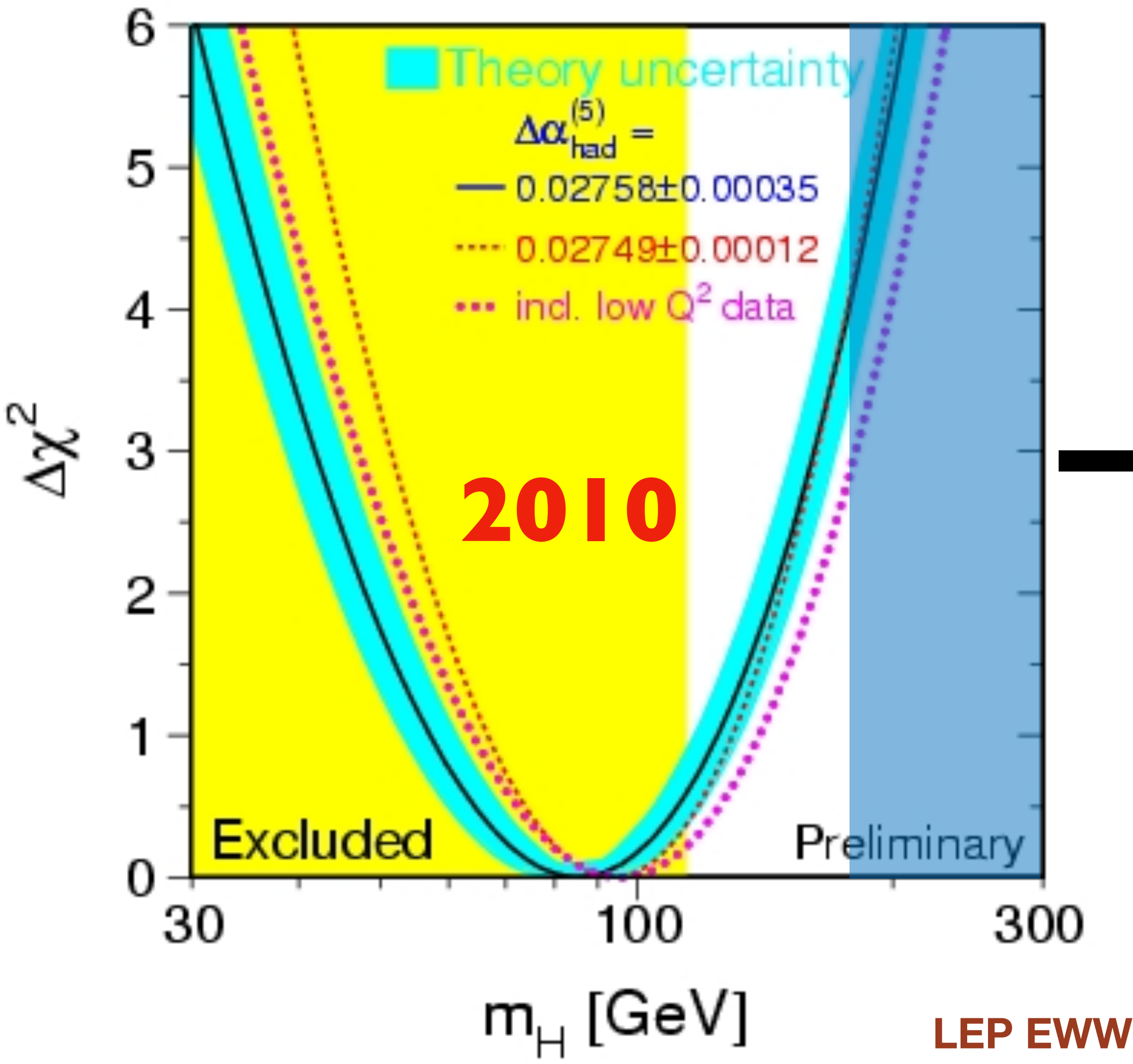
  - ✓ …and thus how to optimize the direct search of the Higgs boson



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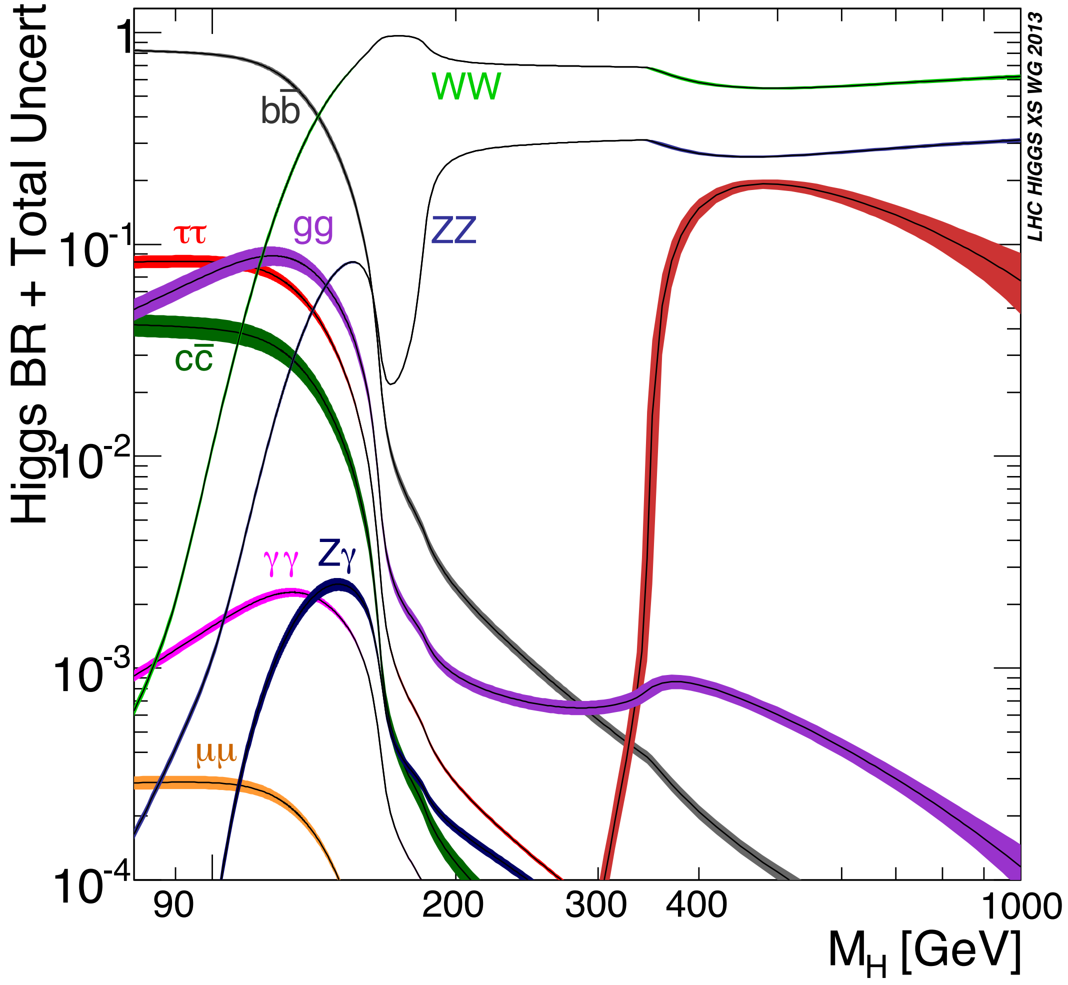

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LHC Higgs WG Yellow report 3: arXiv: 1307.1347 [hep-ph]

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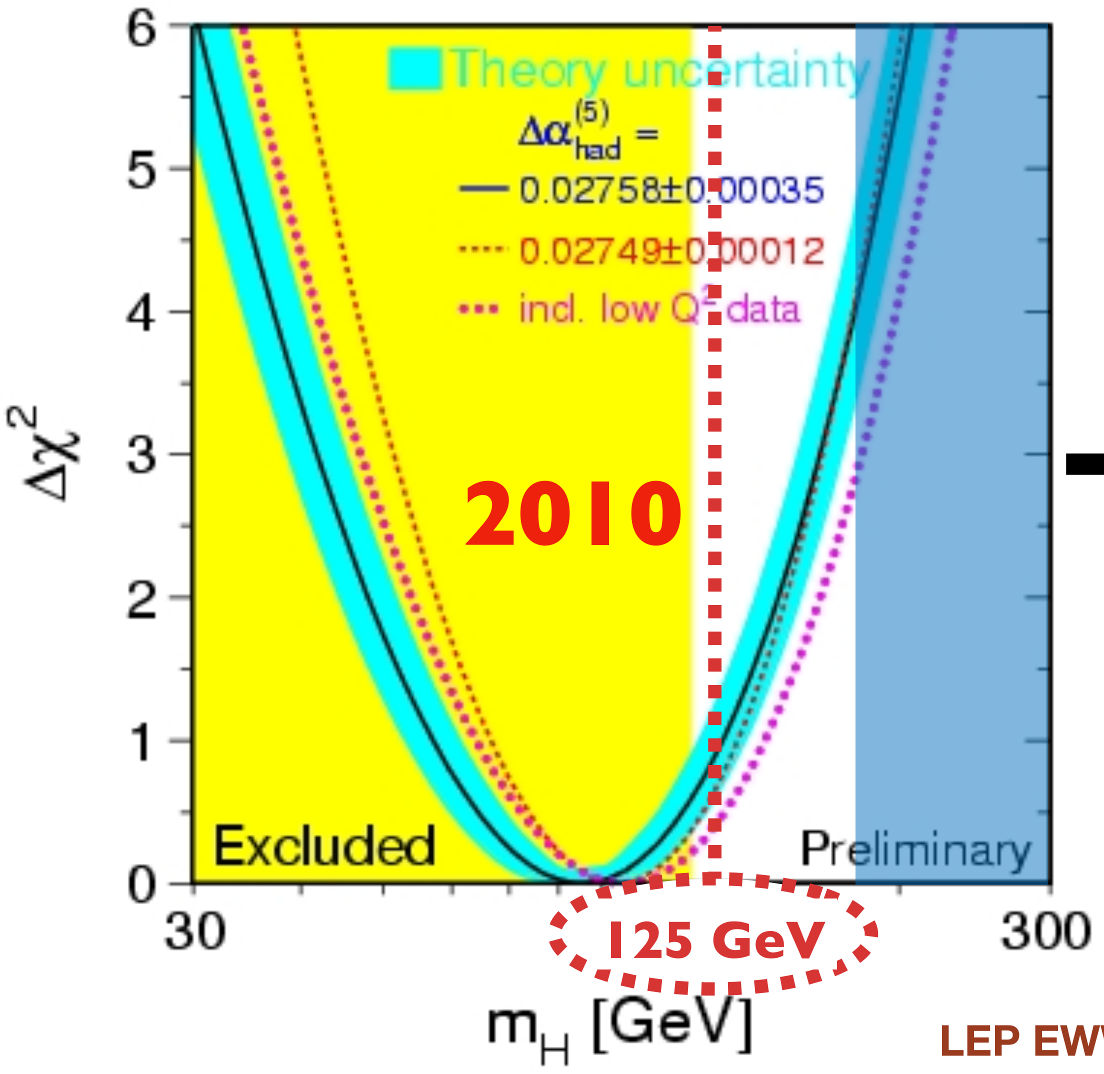

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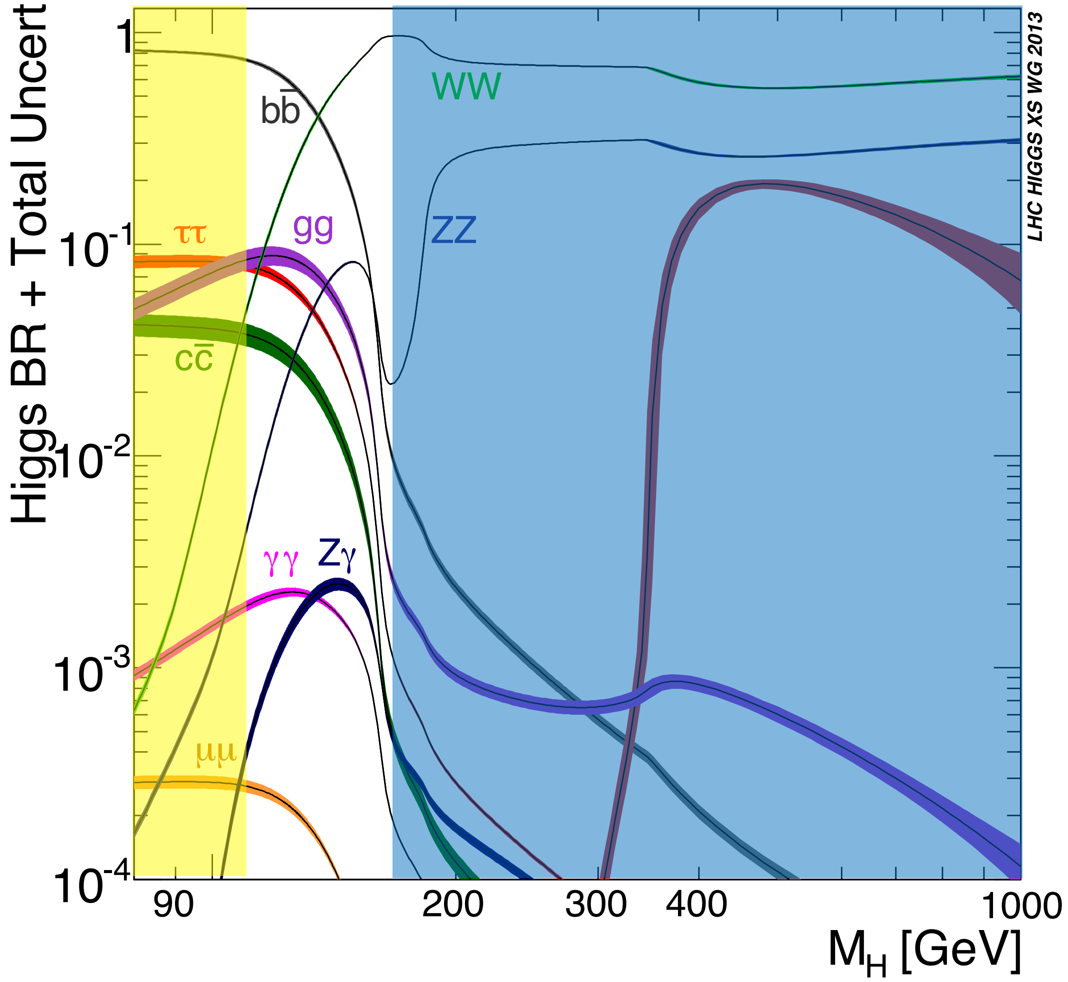

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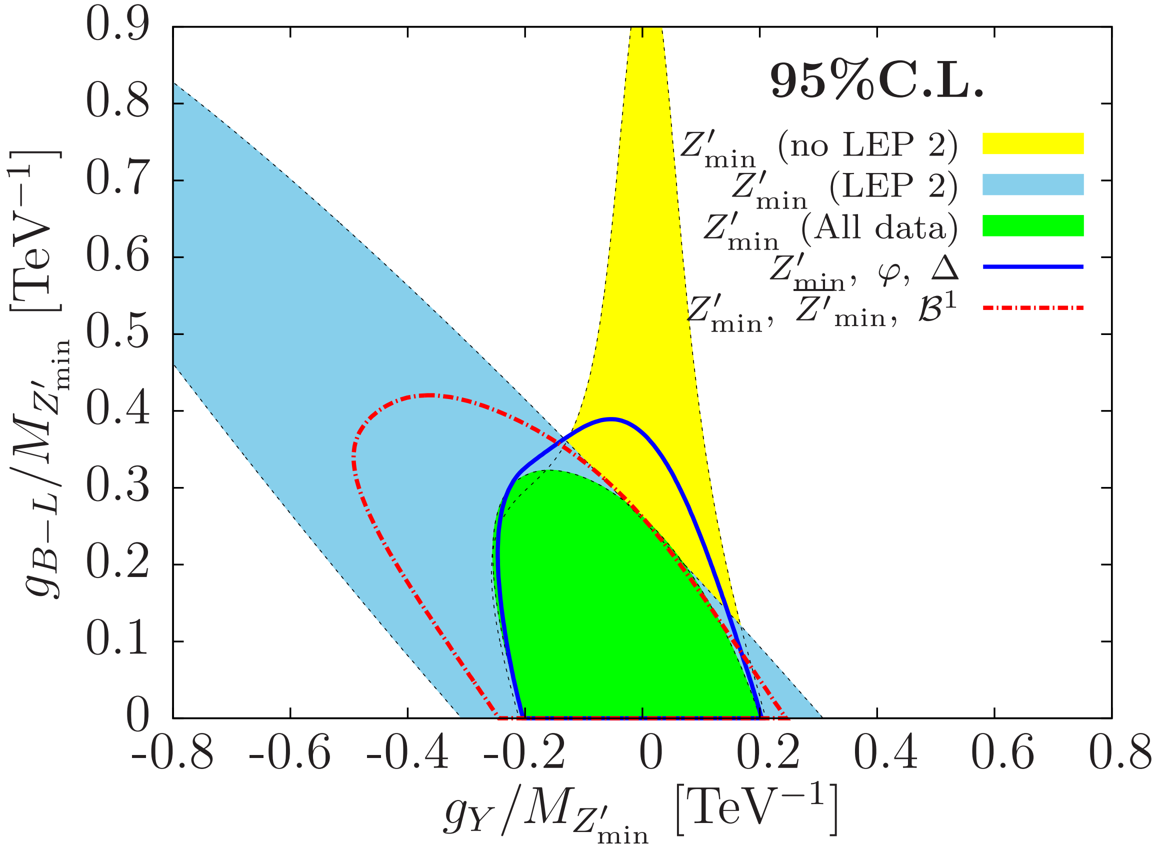
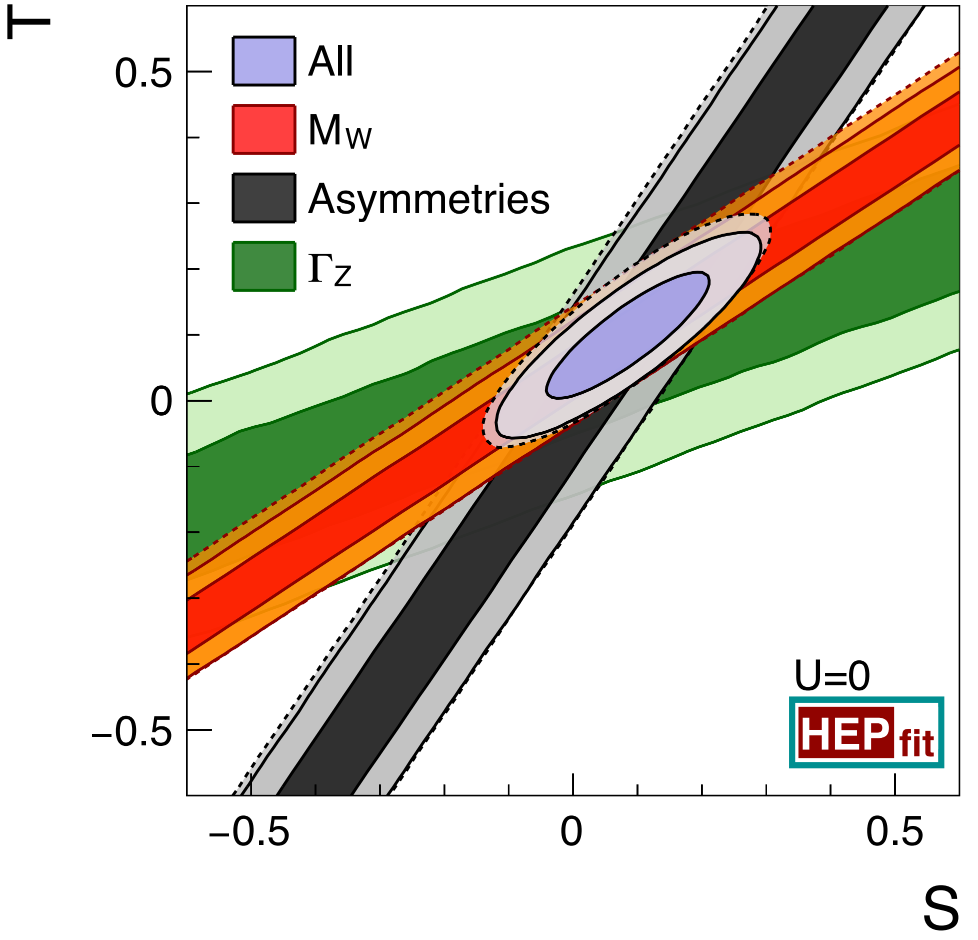
The case for precision physics

- **The LEP/SLC legacy: After the Higgs discovery**
  - ✓ The same precision turned into valuable source of information about new physics (strong constraints on what it could be)
  - ✓ Important for BSM phenomenology and to guide direct LHC searches
  - ✓ Especially when we do not know what we are looking for!

Constraints on specific models: Minimal Z'



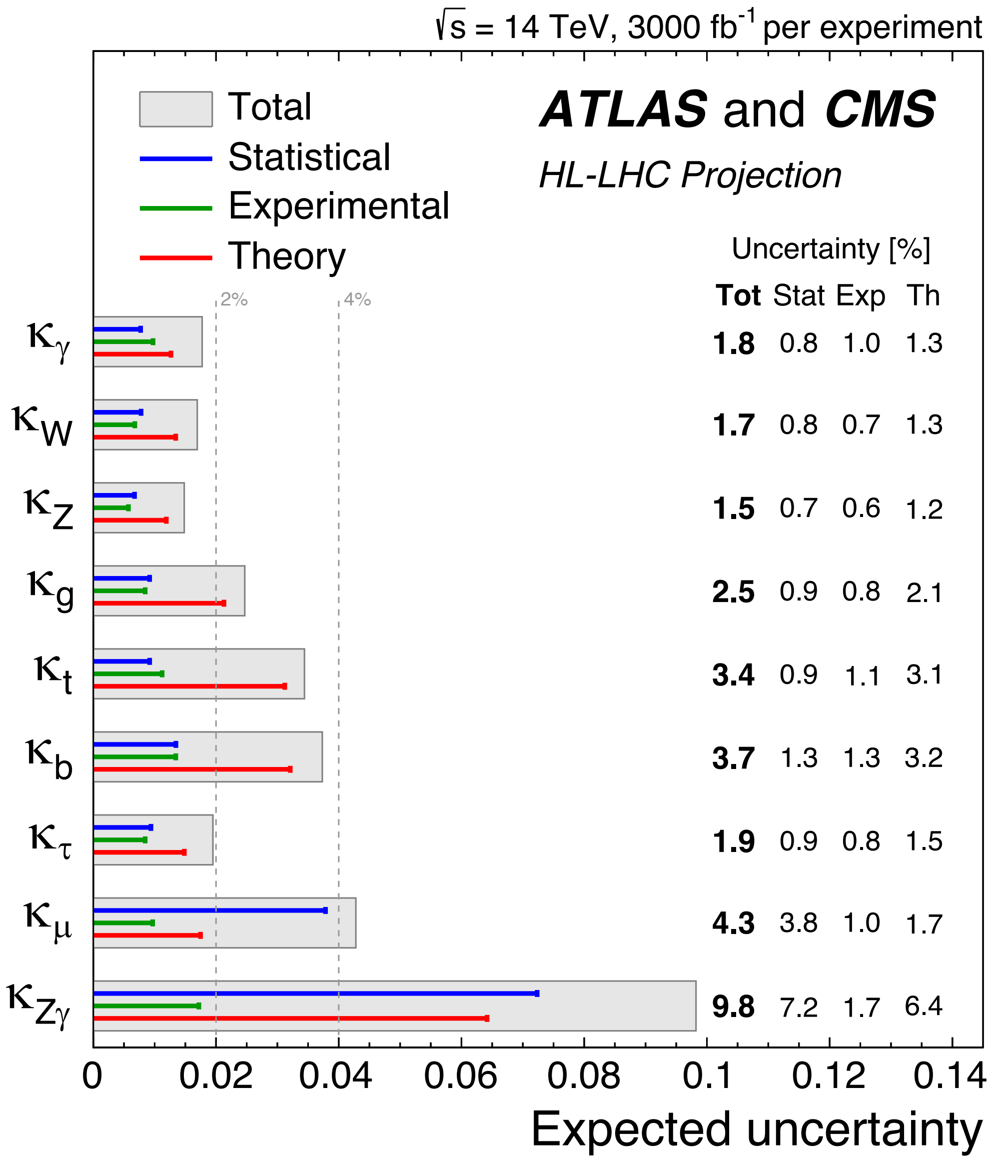
Model-independent: Oblique parameters



- All this with ~ permille precision on W/Z physics

The case for precision physics

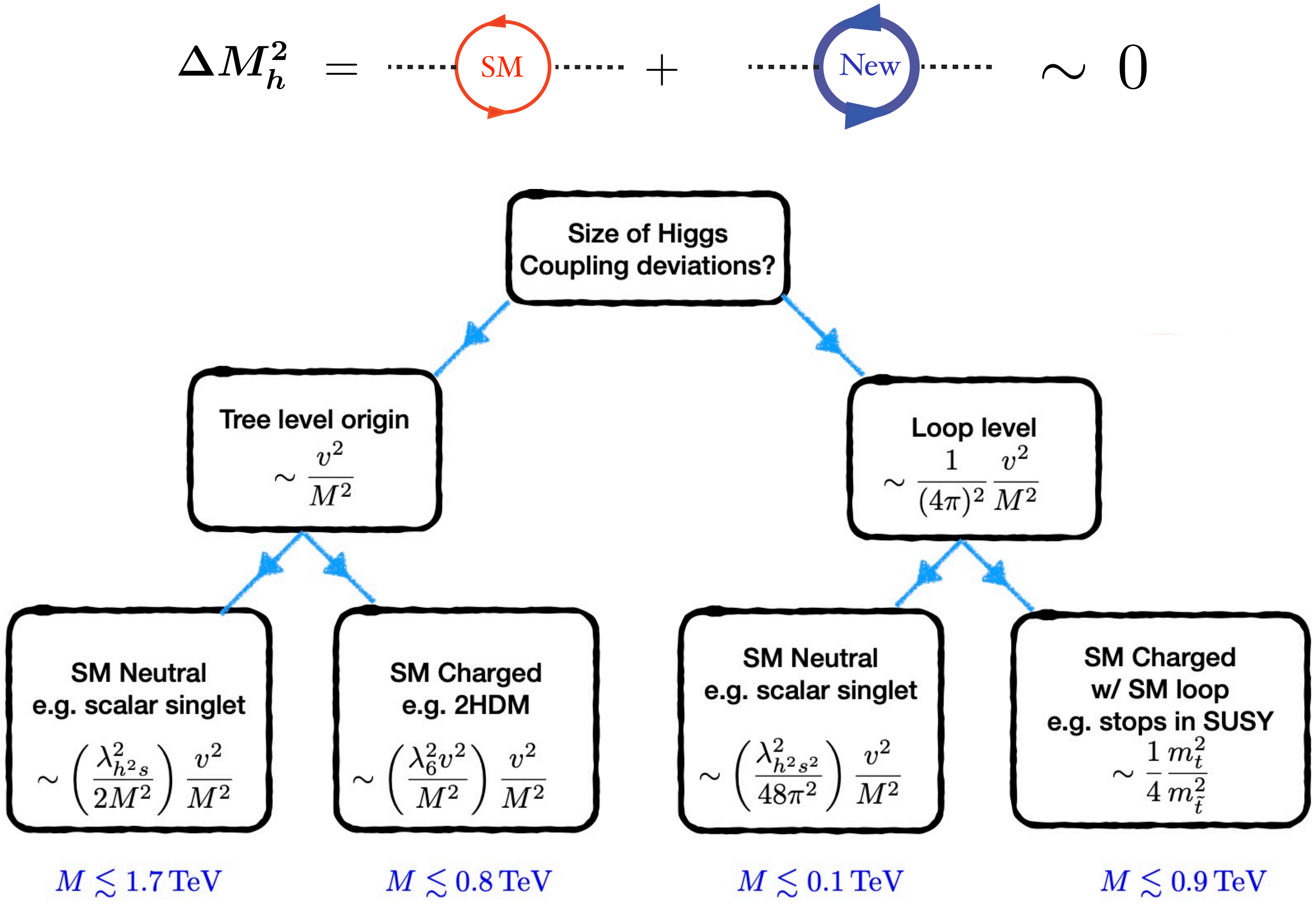
- The HLLHC will open the door to percent precision Higgs physics…



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

New Physics solving naturalness problem interacts with Higgs



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

Size of Higgs Coupling deviations?

Tree level origin $\sim \frac{v^2}{M^2}$

Loop level $\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda_{h^2 s}^2}{2M^2}\right)\frac{v^2}{M^2}$

SM Charged e.g. 2HDM $\sim \left(\frac{\lambda_6^2 v^2}{M^2}\right)\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda_{h^2 s^2}^2}{48\pi^2}\right)\frac{v^2}{M^2}$

SM Charged w/ SM loop e.g. stops in SUSY $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$

$M \lesssim 1.7\,\text{TeV}$ $M \lesssim 0.8\,\text{TeV}$ $M \lesssim 0.1\,\text{TeV}$ $M \lesssim 0.9\,\text{TeV}$

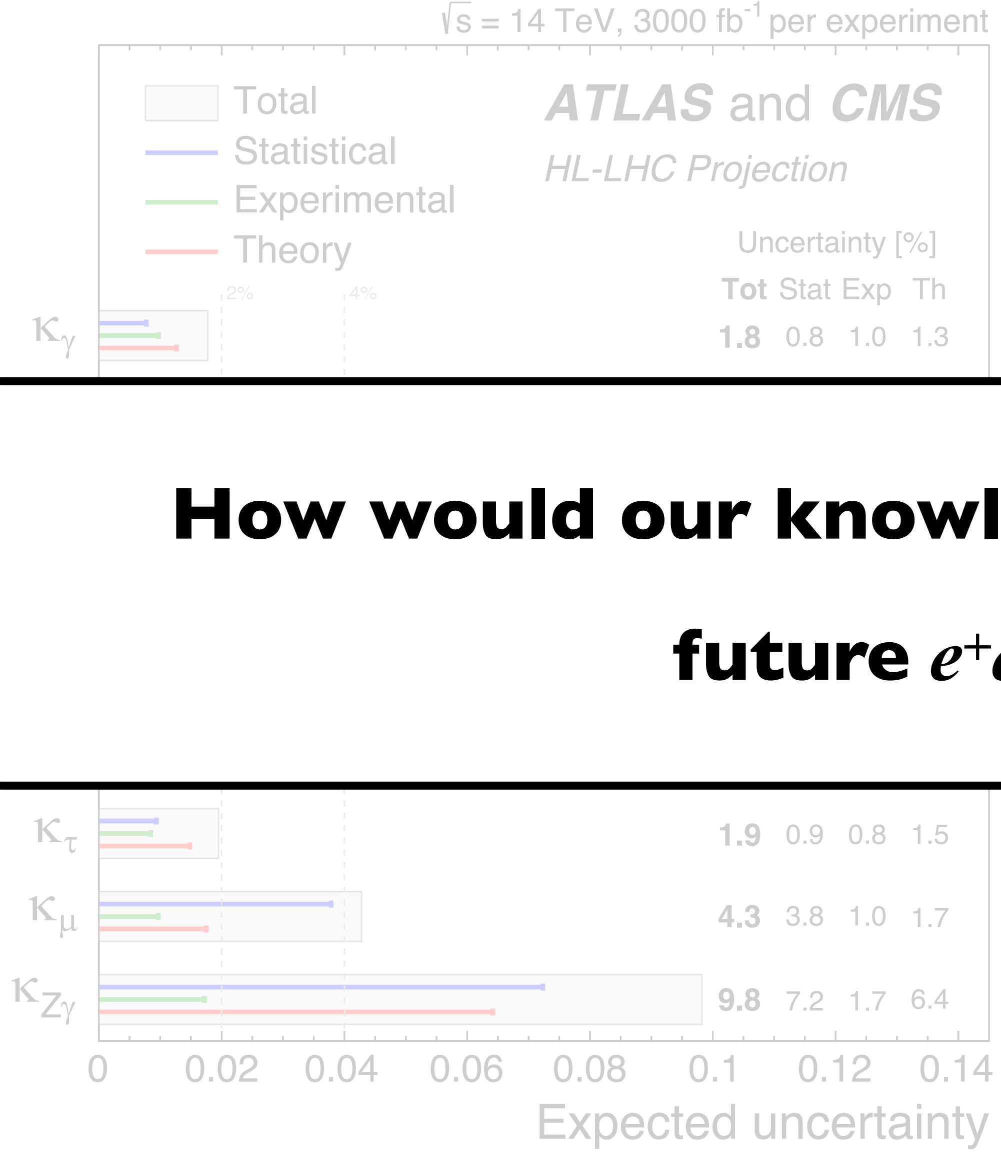
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

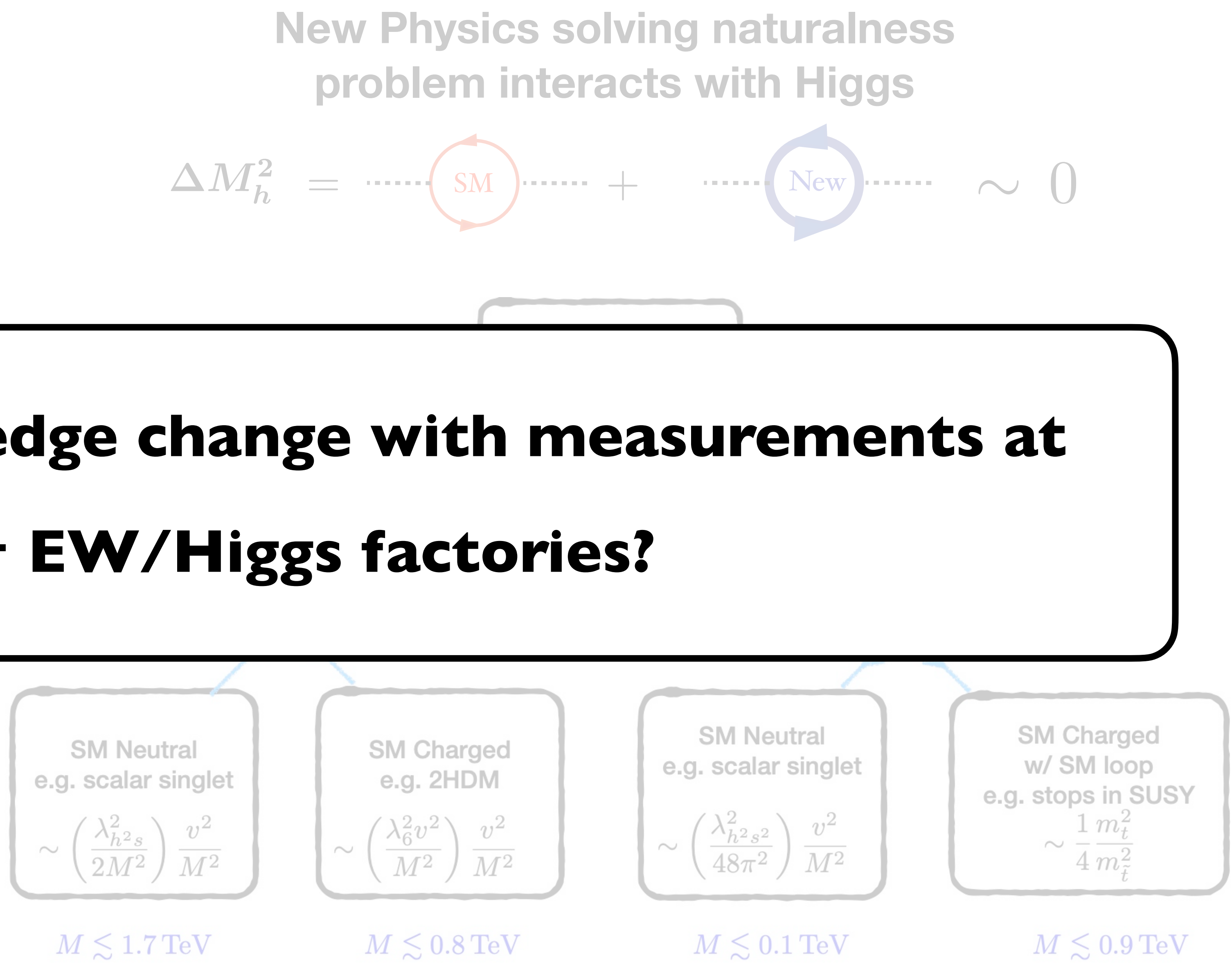
$$\delta\kappa \sim 1\%$$

- … but percent precision gives only limited access to TeV scale new physics

The case for precision physics

- The HLLHC will open the door to percent precision Higgs physics…





Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

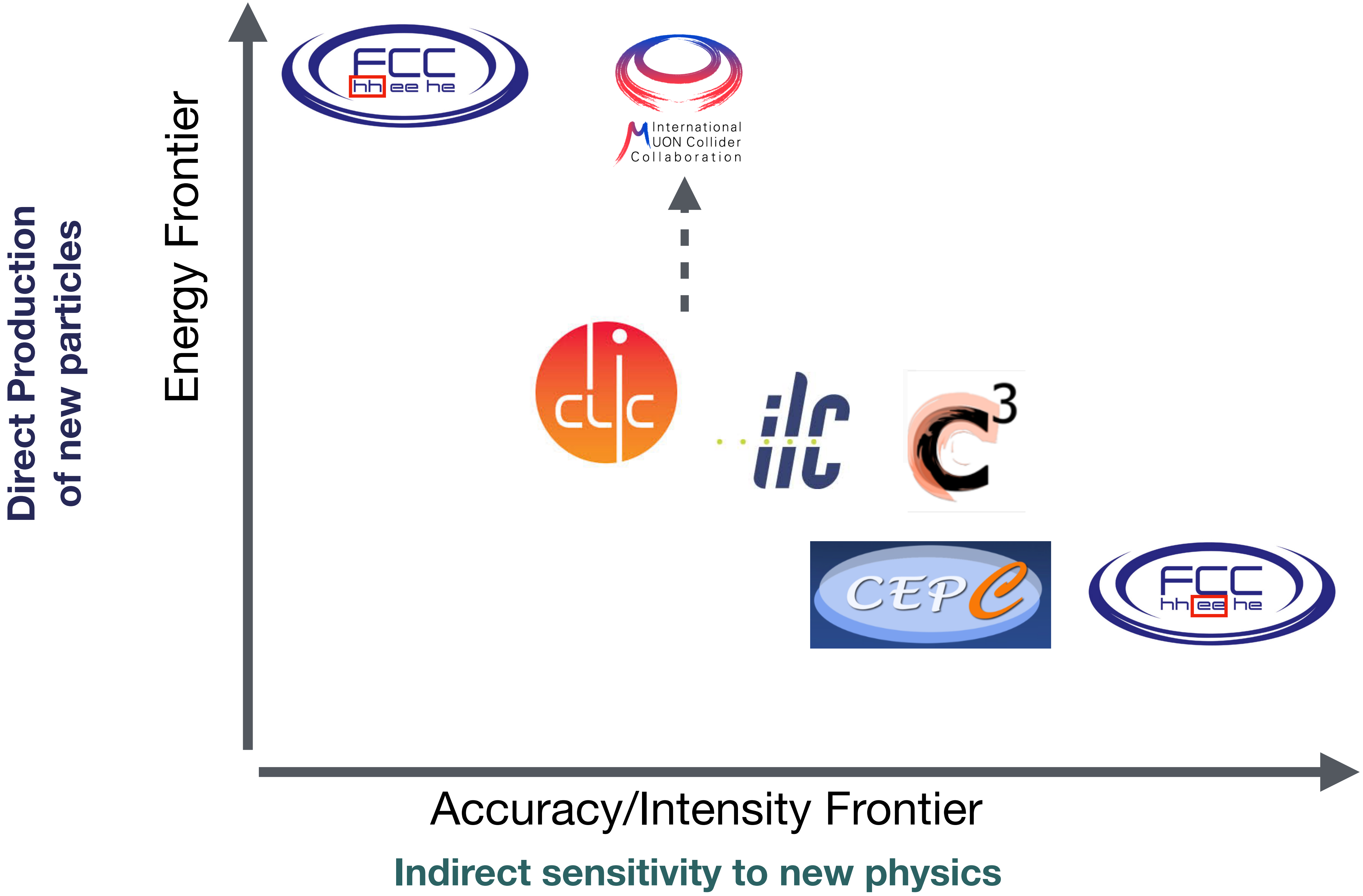
$\delta\kappa \sim 1\%$

How would our knowledge change with measurements at future e^+e^- EW/Higgs factories?

- … but percent precision gives only limited access to TeV scale new physics

The case for precision physics

- Future collider projects: The Intensity/Energy frontier



Direct Production of new particles

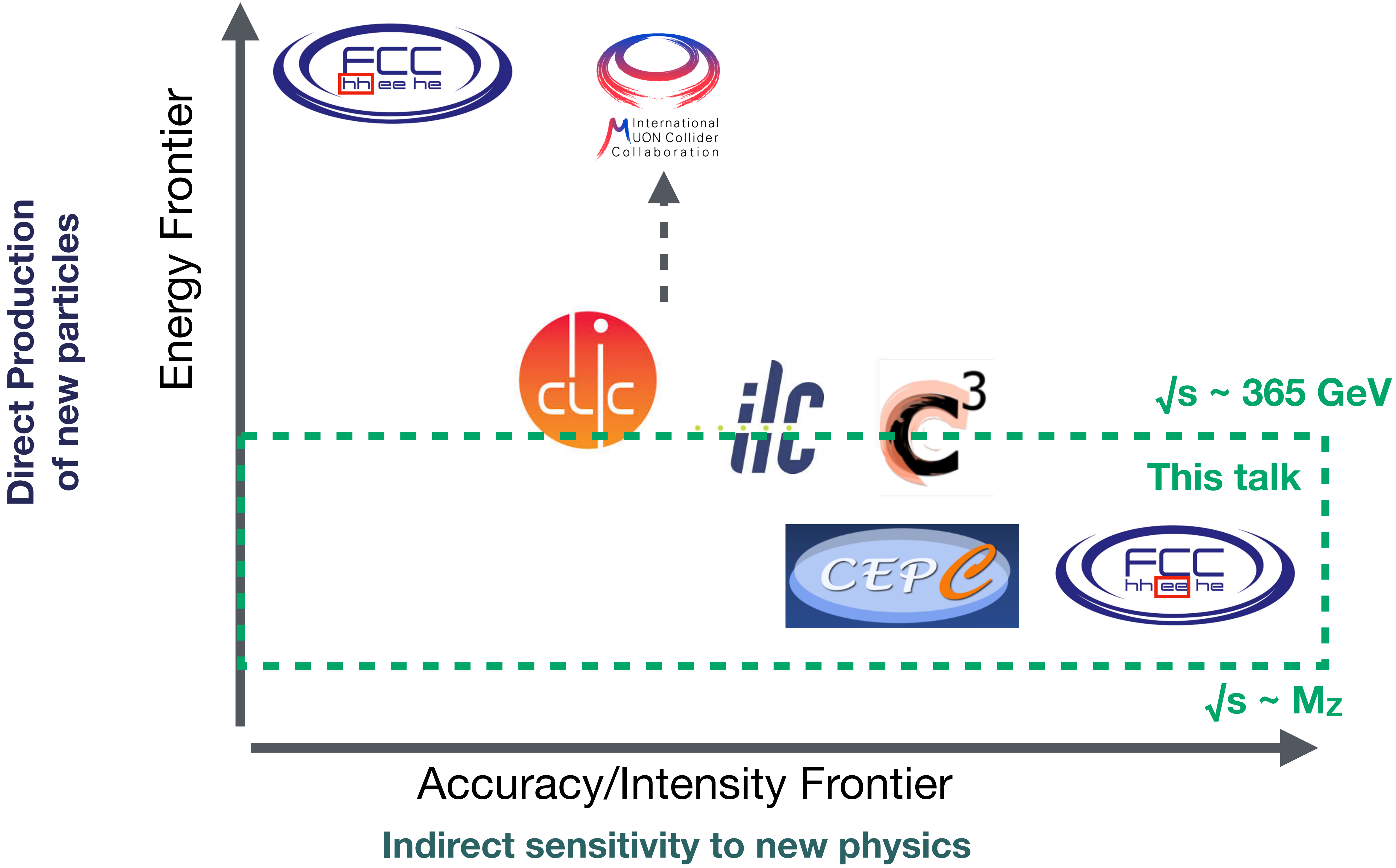
Energy Frontier

Accuracy/Intensity Frontier

Indirect sensitivity to new physics

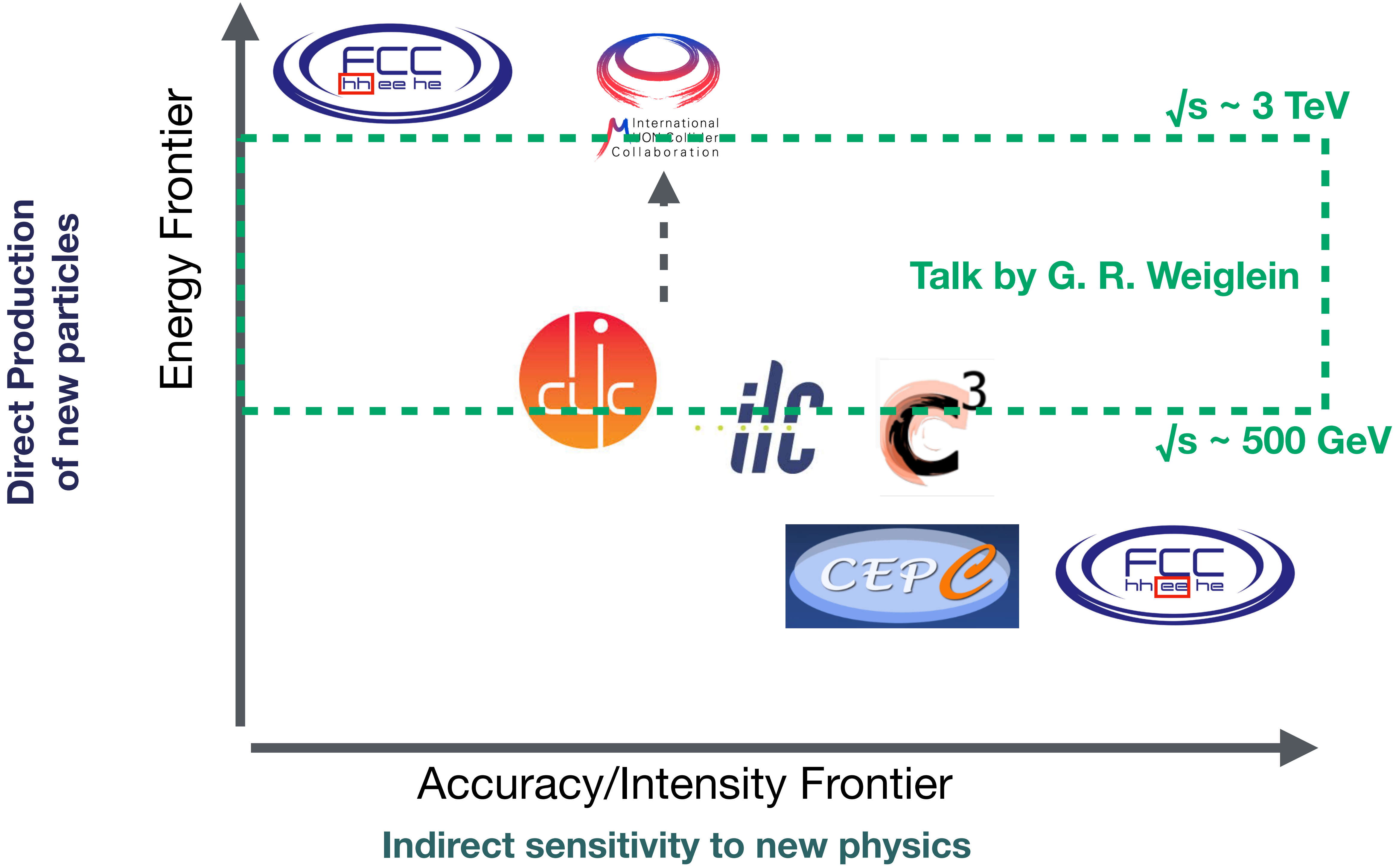
The case for precision physics

- Future collider projects: The Intensity/Energy frontier



The case for precision physics

- Future collider projects: The Intensity/Energy frontier



Direct Production of new particles

Energy Frontier

√s ~ 3 TeV

Talk by G. R. Weiglein

√s ~ 500 GeV

Accuracy/Intensity Frontier

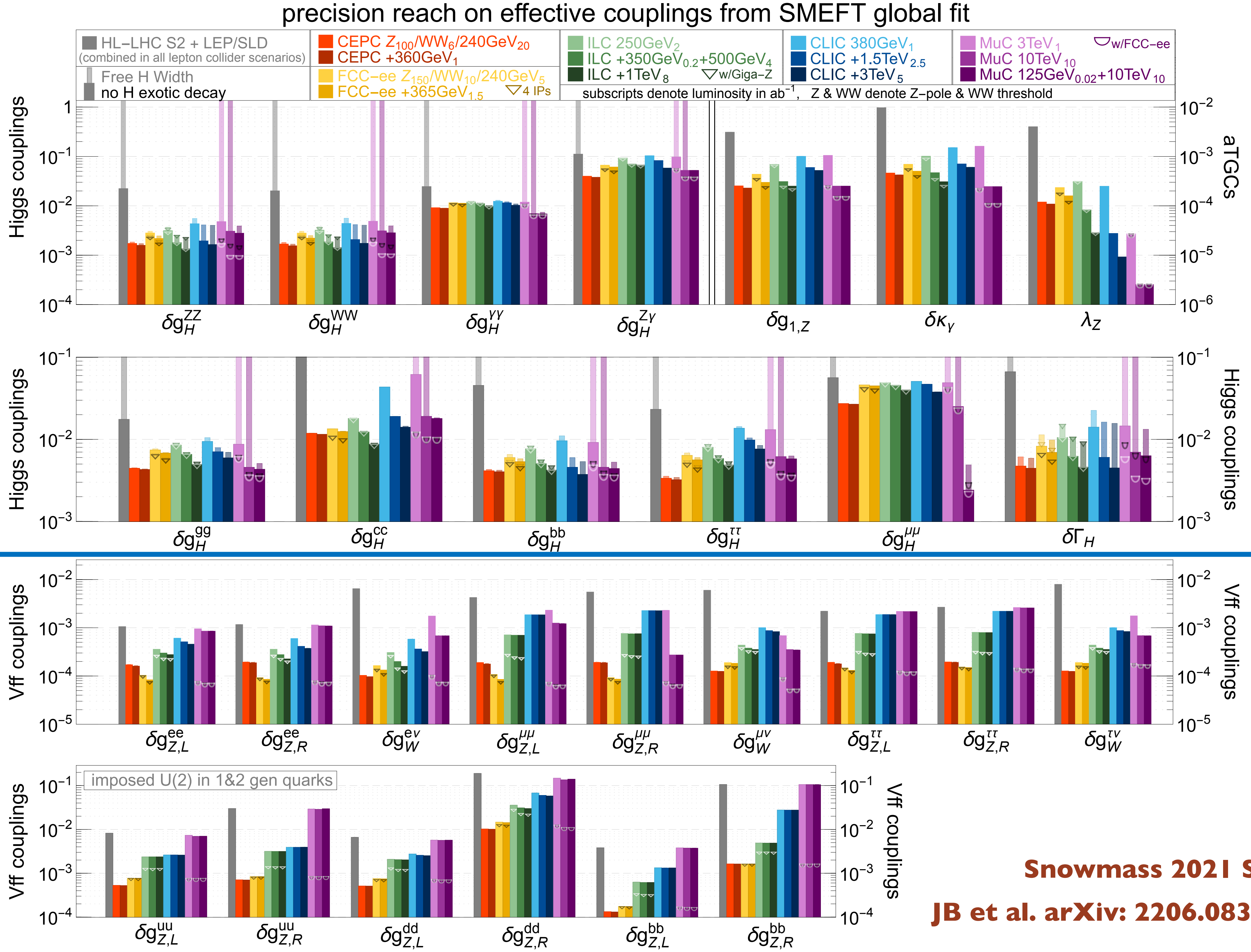
Indirect sensitivity to new physics

The case for precision physics

Higgs interactions

EW Vff interactions

aTGC



Snowmass 2021 Study

JB et al. arXiv: 2206.08326 [hep-ph]

Effective couplings

$$g_{HX}^{\mathrm{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\mathrm{SM}}_{H\to X}}.$$

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}\left(|g^{\mathrm{eff}}_{Zee,L}|^2+|g^{\mathrm{eff}}_{Zee,R}|^2\right),$$

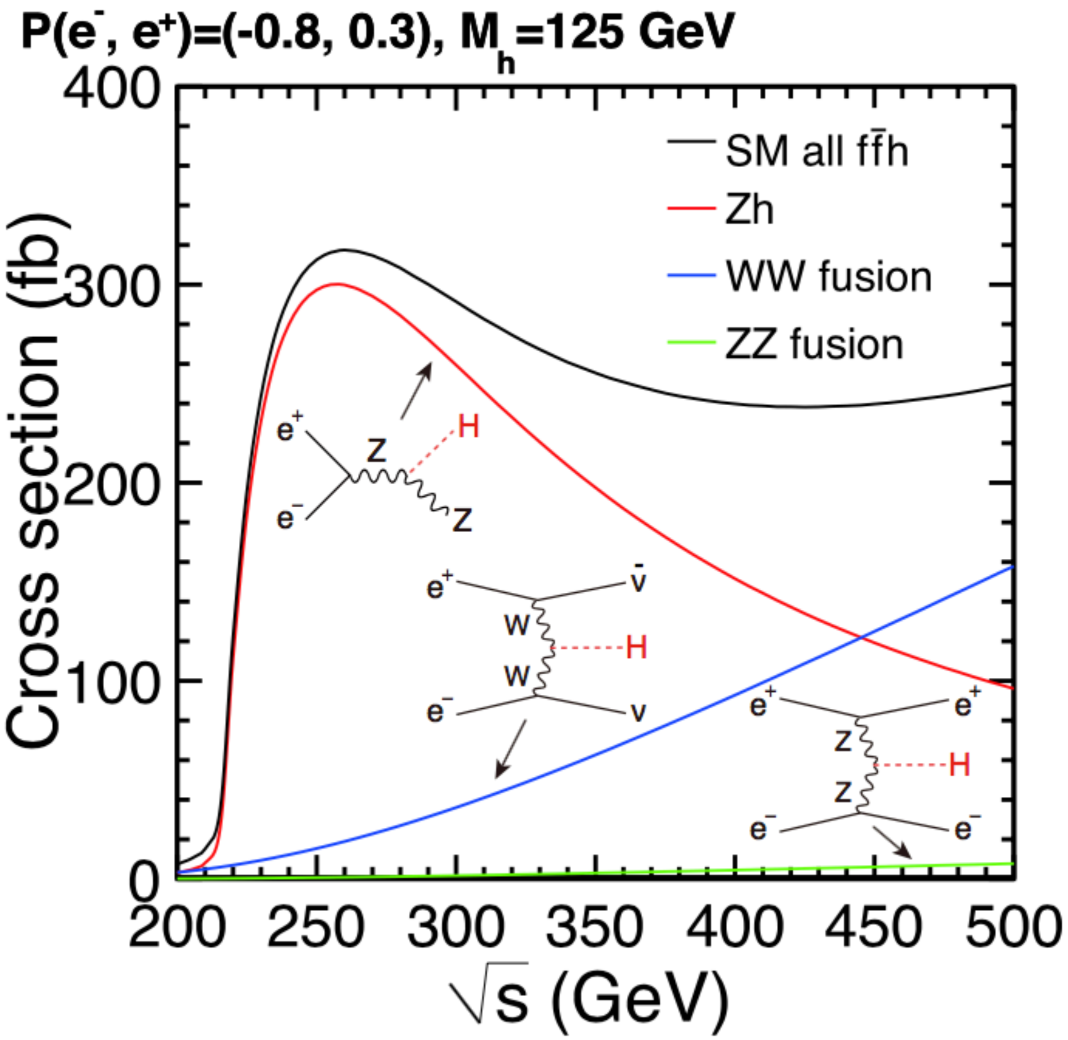
$$A_e = \frac{|g^{\mathrm{eff}}_{Zee,L}|^2-|g^{\mathrm{eff}}_{Zee,R}|^2}{|g^{\mathrm{eff}}_{Zee,L}|^2+|g^{\mathrm{eff}}_{Zee,R}|^2}.$$

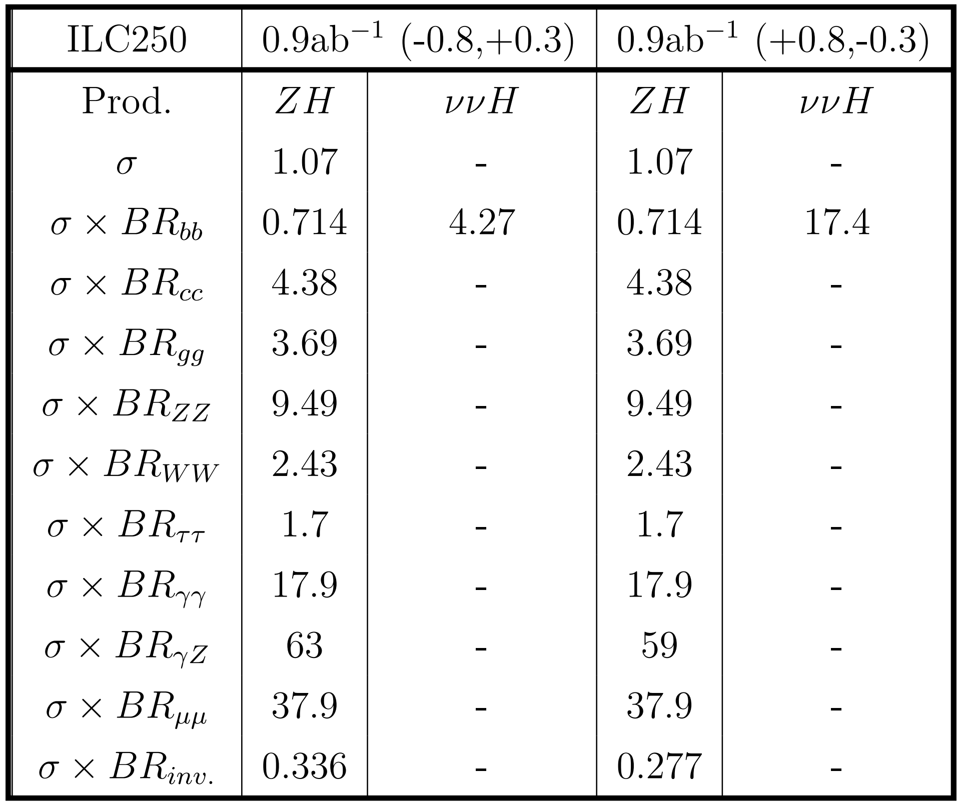
The case for Precision Higgs physics
at future e^+e^- colliders

Precision physics at e^+e^- Higgs factories

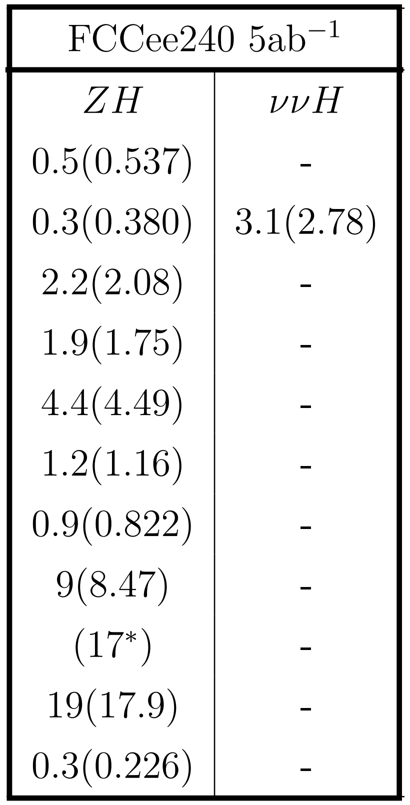
- Precision Higgs physics at future e^+e^- colliders:

What do O(10^6) Higgses at e^+e^- bring to the table?





ILC250	0.9ab^{-1} (-0.8,+0.3)		0.9ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.07	-	1.07	-
$\sigma \times BR_{bb}$	0.714	4.27	0.714	17.4
$\sigma \times BR_{cc}$	4.38	-	4.38	-
$\sigma \times BR_{gg}$	3.69	-	3.69	-
$\sigma \times BR_{ZZ}$	9.49	-	9.49	-
$\sigma \times BR_{WW}$	2.43	-	2.43	-
$\sigma \times BR_{\tau\tau}$	1.7	-	1.7	-
$\sigma \times BR_{\gamma\gamma}$	17.9	-	17.9	-
$\sigma \times BR_{\gamma Z}$	63	-	59	-
$\sigma \times BR_{\mu\mu}$	37.9	-	37.9	-
$\sigma \times BR_{inv.}$	0.336	-	0.277	-



FCCee240 5ab^{-1}	
ZH	$\nu\nu H$
0.5(0.537)	-
0.3(0.380)	3.1(2.78)
2.2(2.08)	-
1.9(1.75)	-
4.4(4.49)	-
1.2(1.16)	-
0.9(0.822)	-
9(8.47)	-
(17*)	-
19(17.9)	-
0.3(0.226)	-

Statistics: **O(10^6) (ZH) Higgses**
O(10^5)(WWH) Higgses

Statistical uncertainties below 1%:
Experimental systematics not expected to be a limiting factor for Higgs measurements

Clean environment:
No pileup
Beam background under control
E, p constraints

Precision physics at e^+e^- Higgs factories

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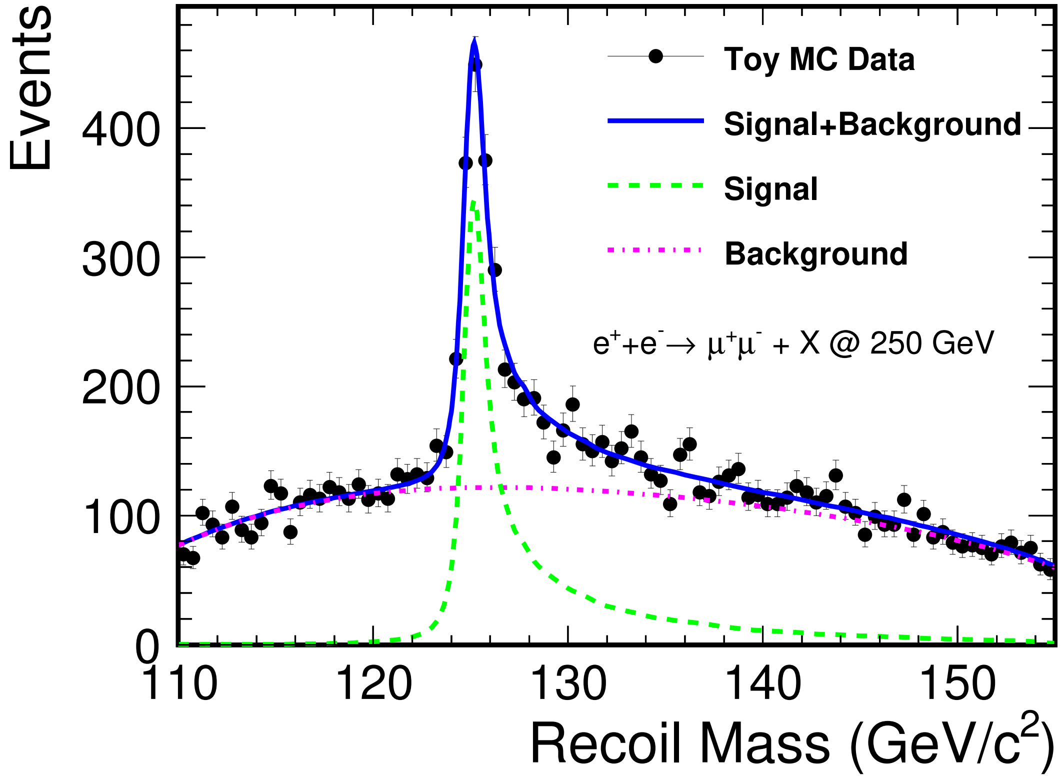
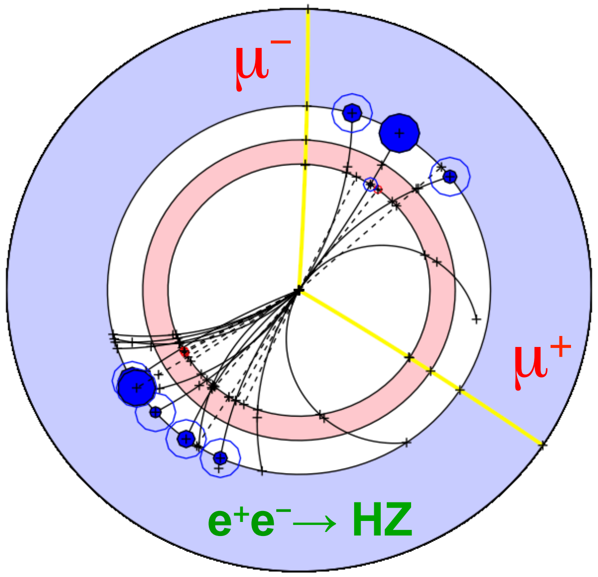


Inclusive $e^+e^- \to ZH$ cross section

$\boxed{\sigma_{ZH} \sim g_{HZZ}^2 < 1\%}$

Absolute measurements of Higgs couplings
→Normalizes all couplings
(In HLLHC only access to ratios)

Together with Rate measurements
allow determination of Higgs width
$\delta\Gamma_H \sim 1\%$



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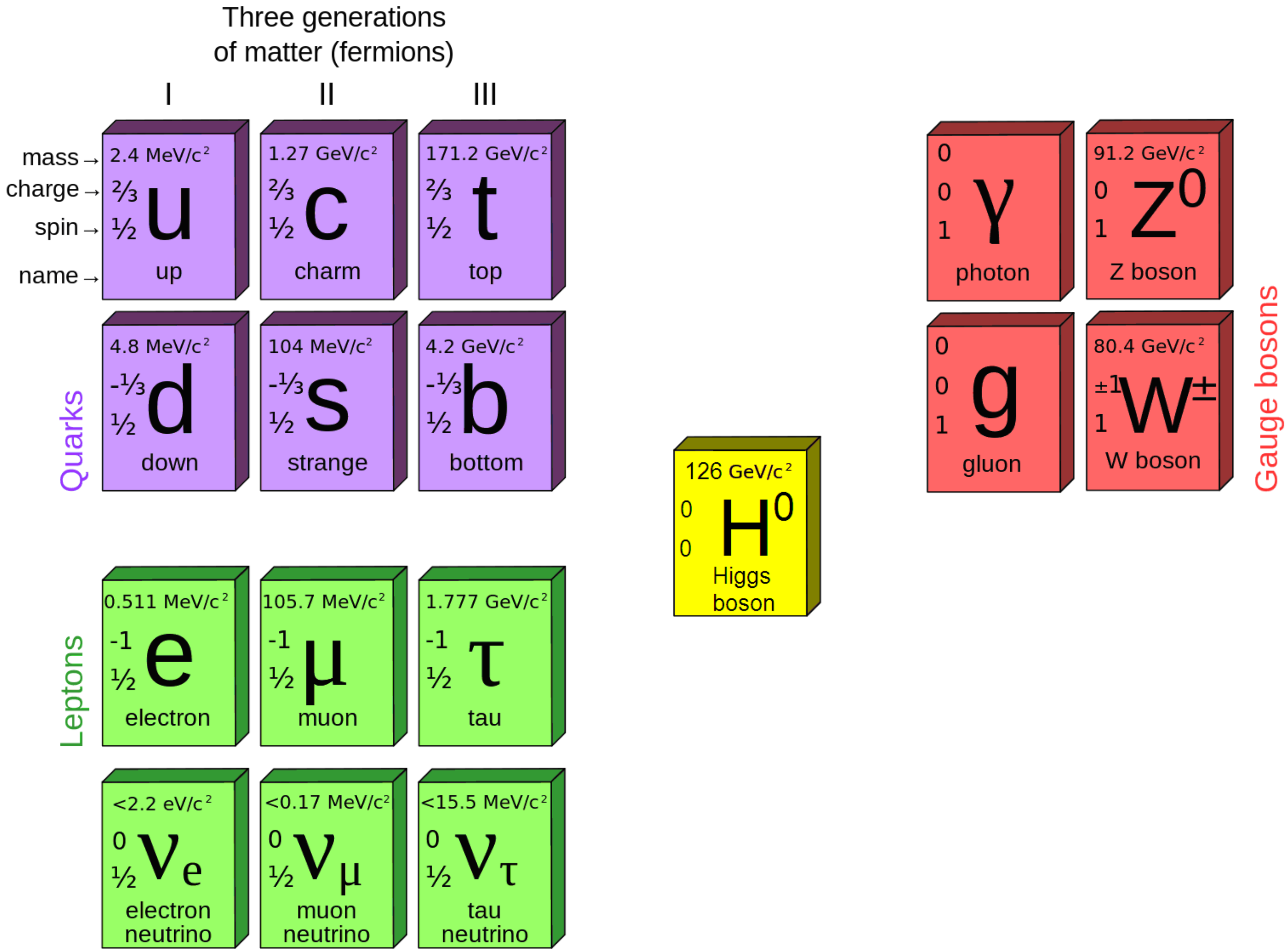

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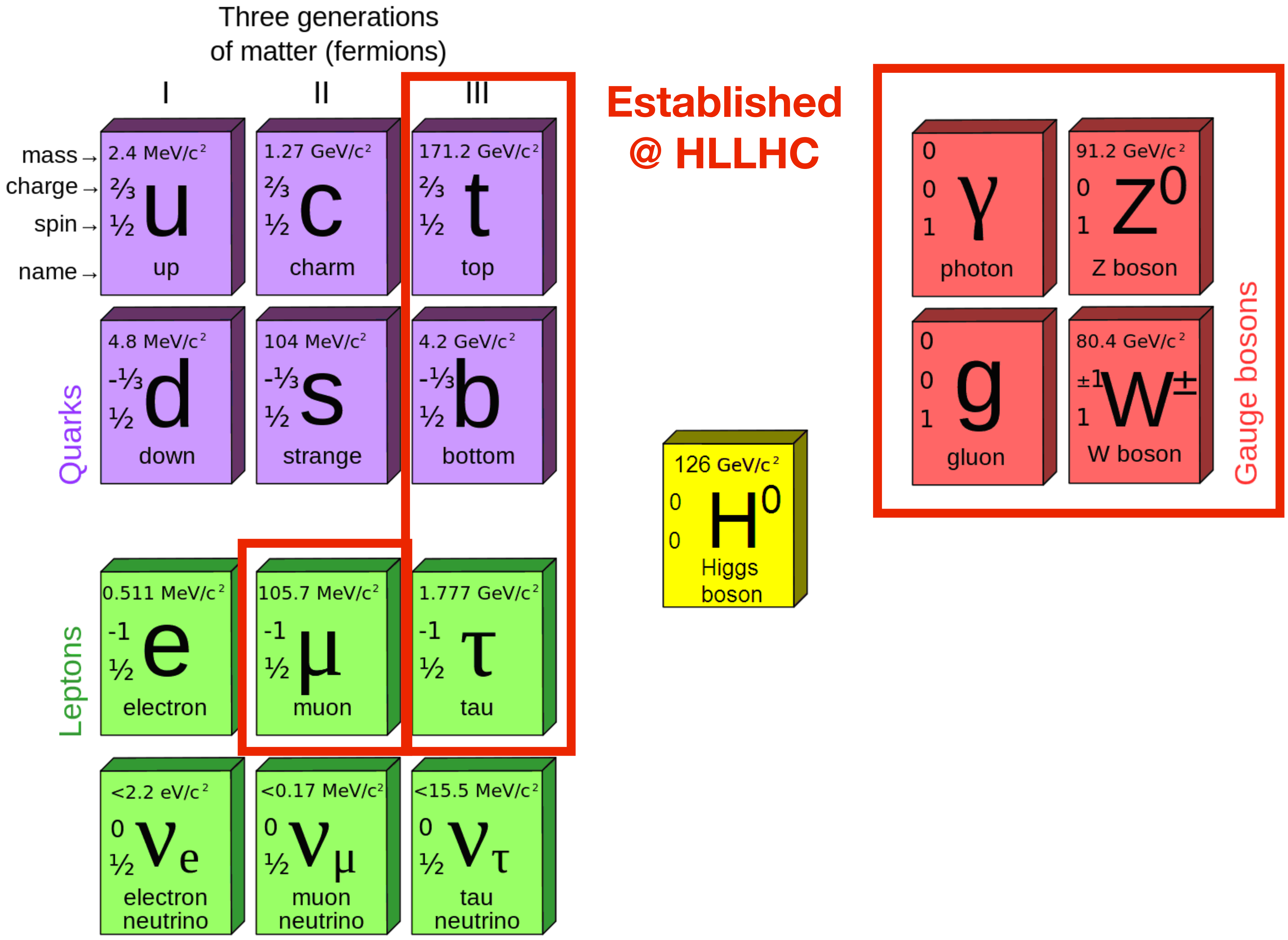

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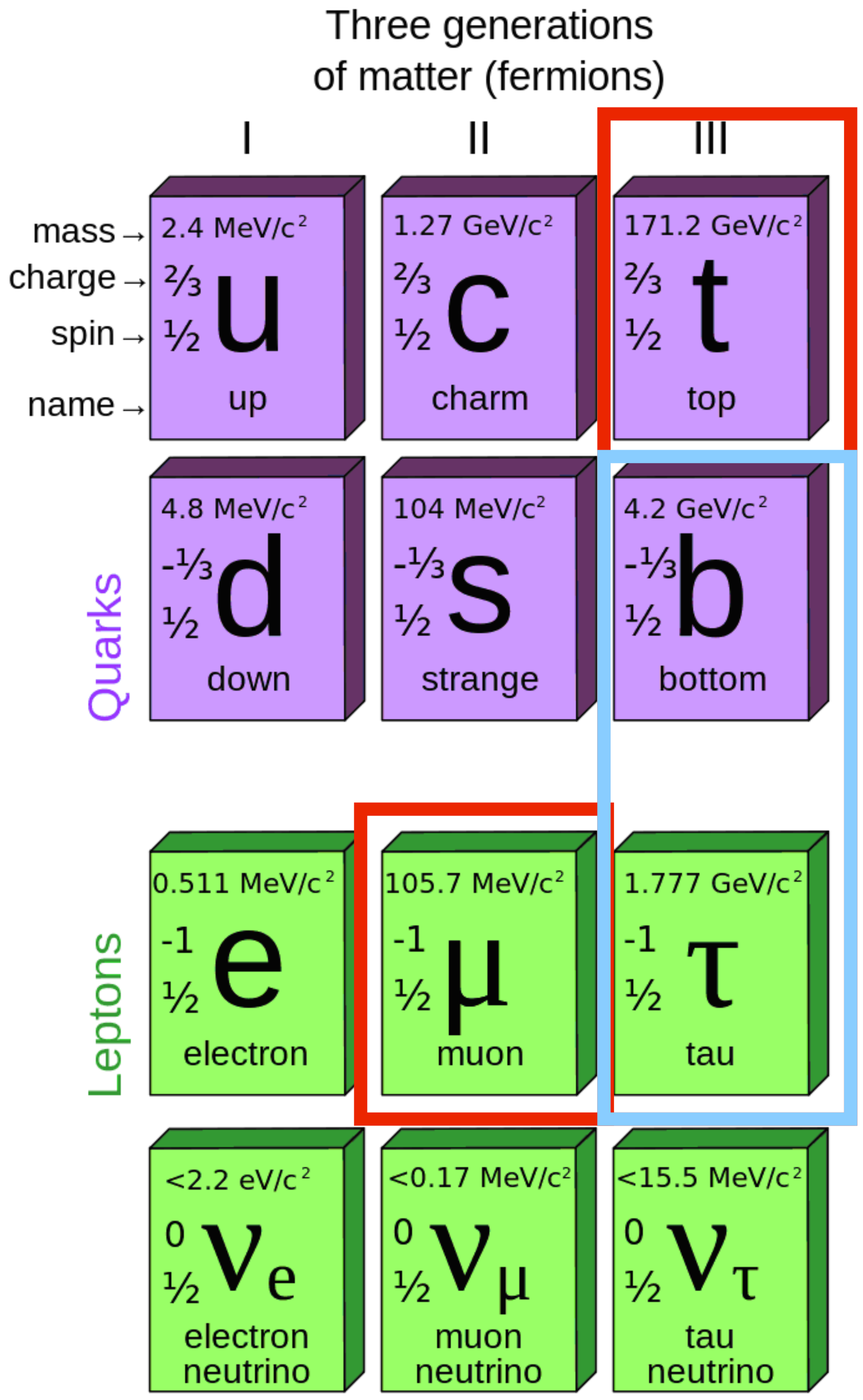

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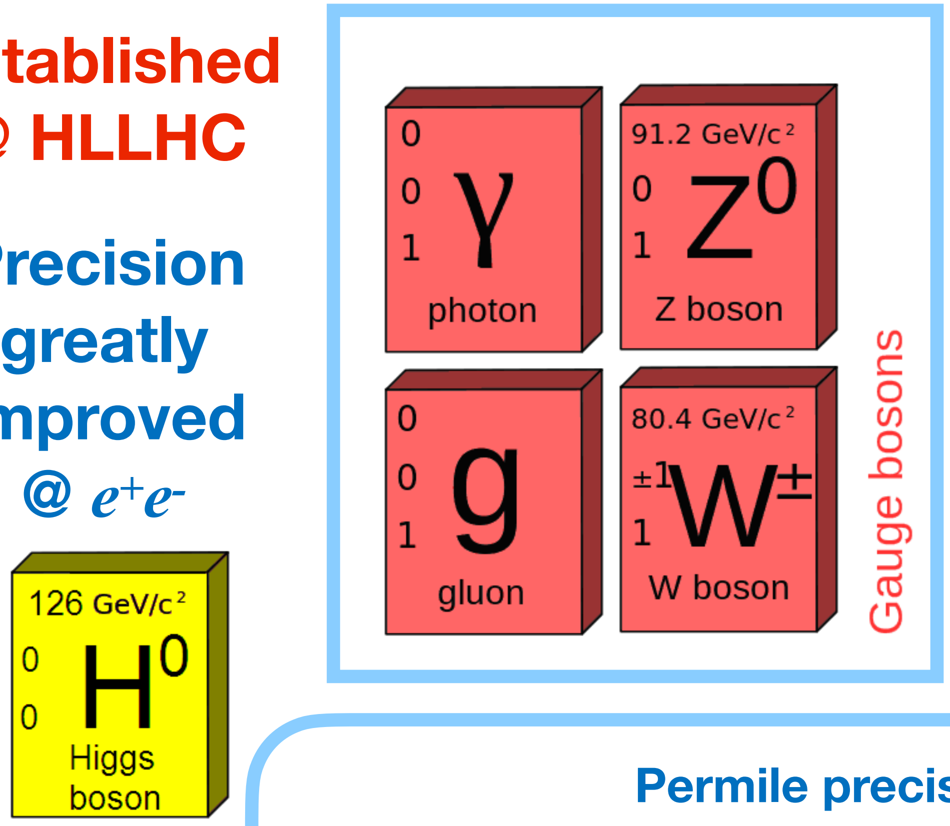
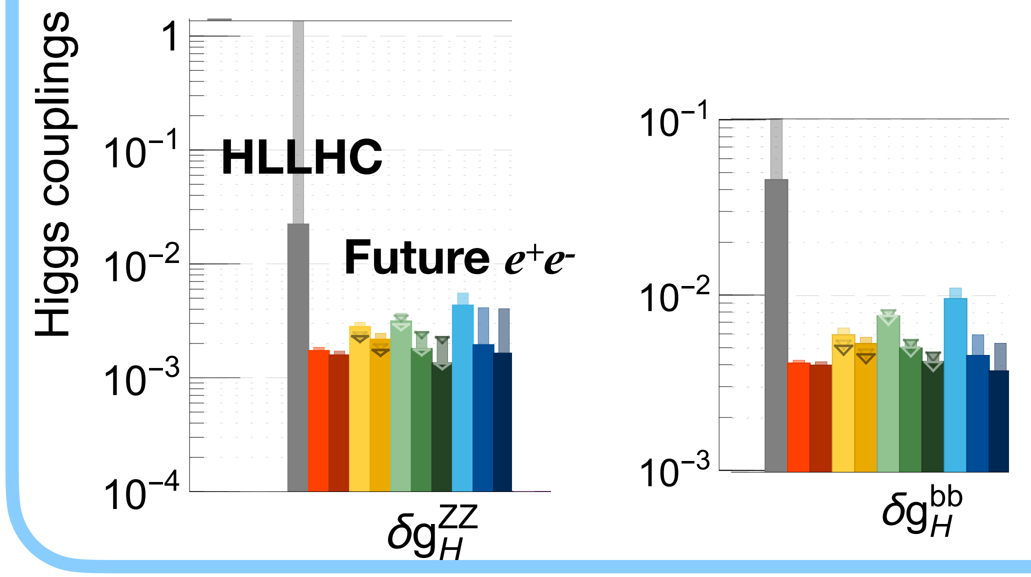
Precision greatly improved @ e^+e^-



Permile precision on Higgs



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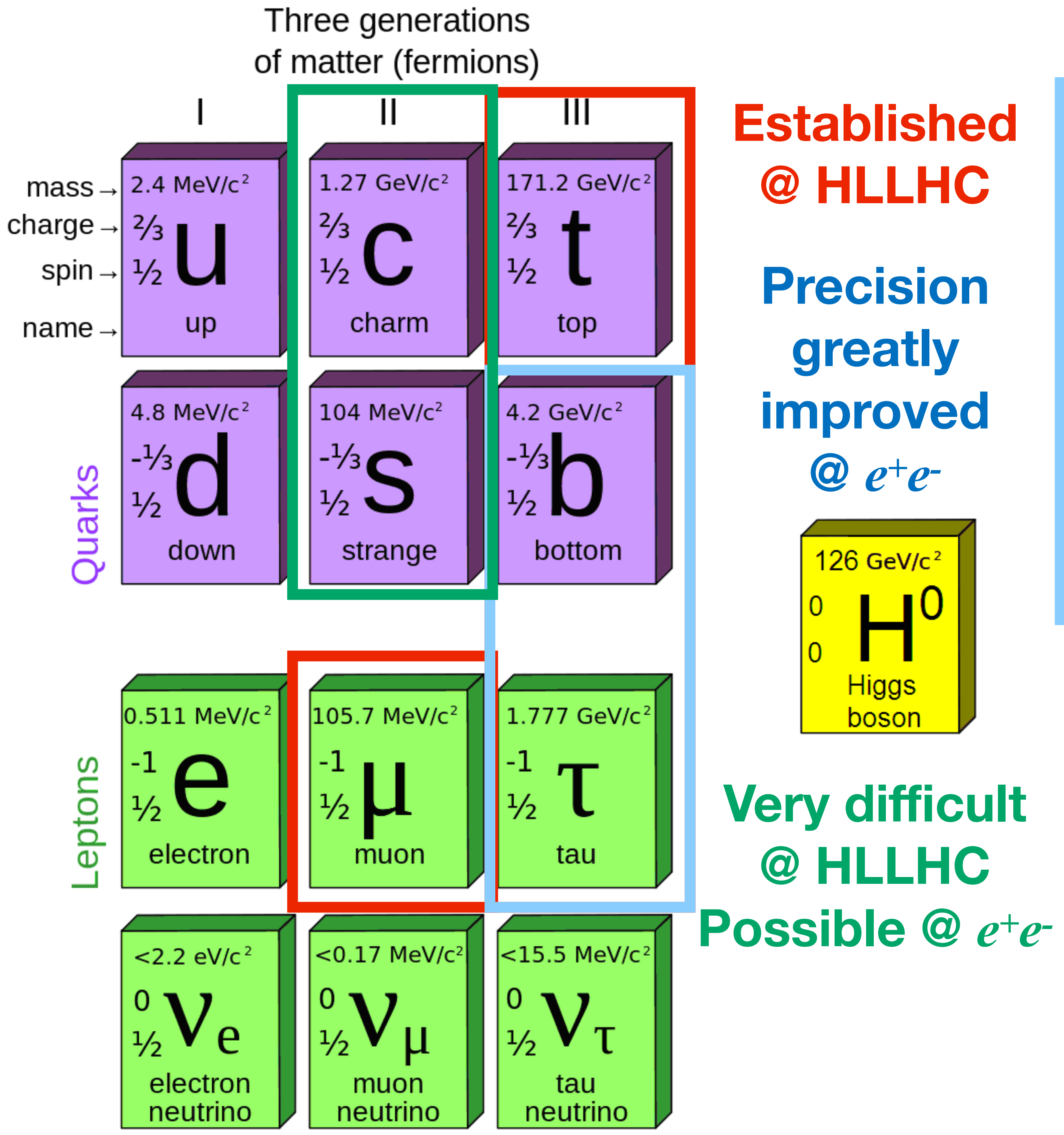

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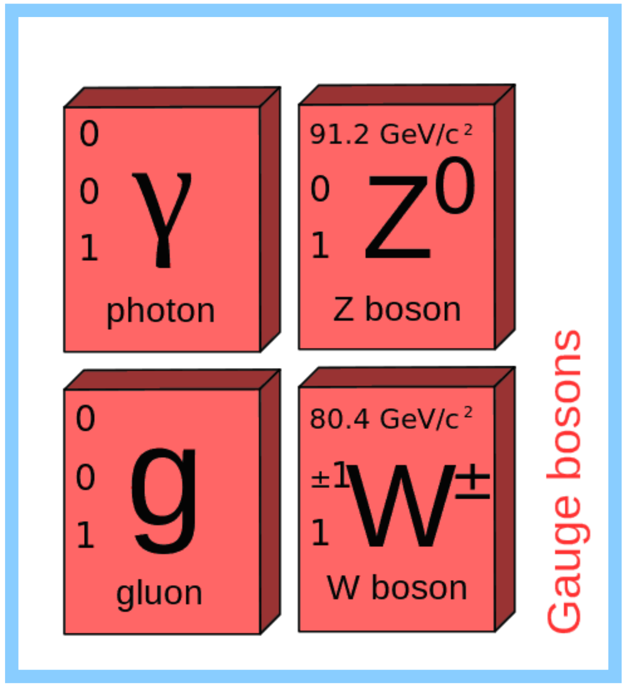
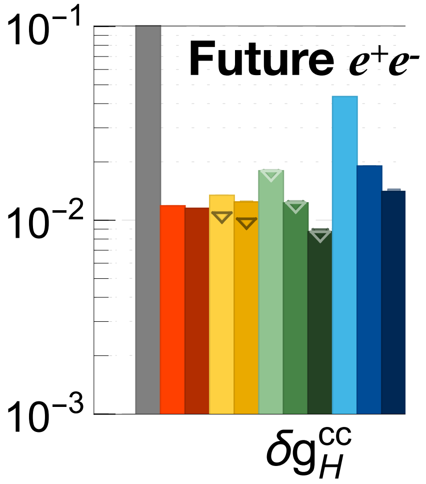
Very difficult @ HLLHC
Possible @ e^+e^-



Access to 2nd fam. Quarks
Precision 1%



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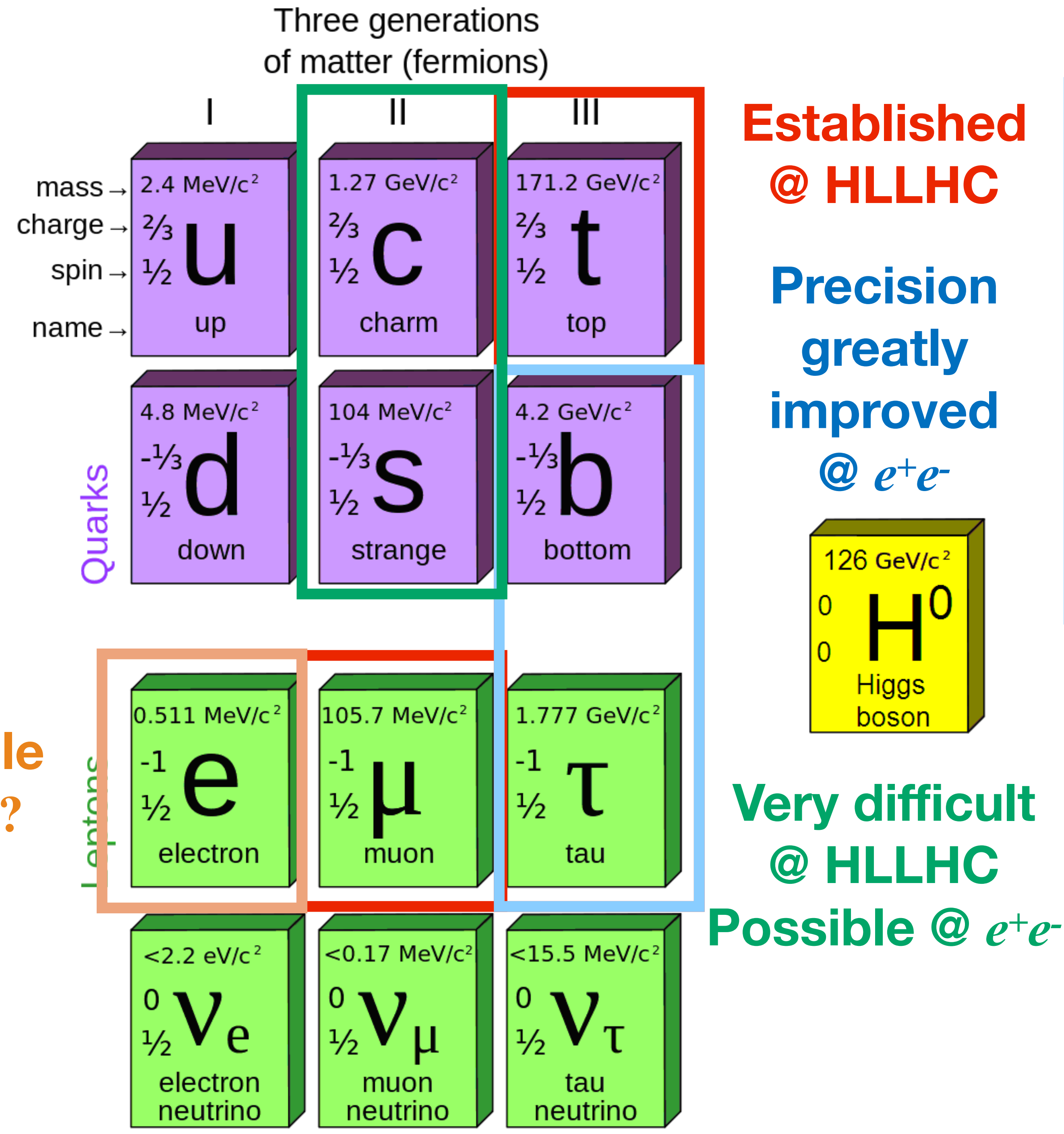

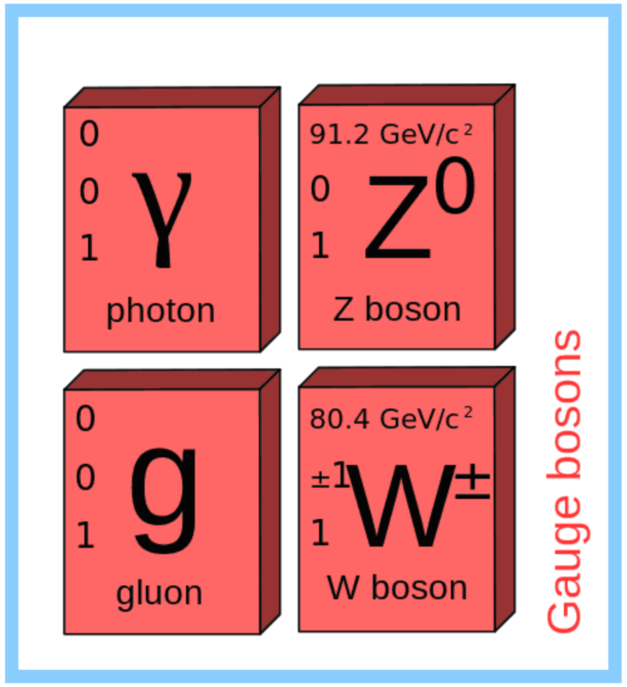

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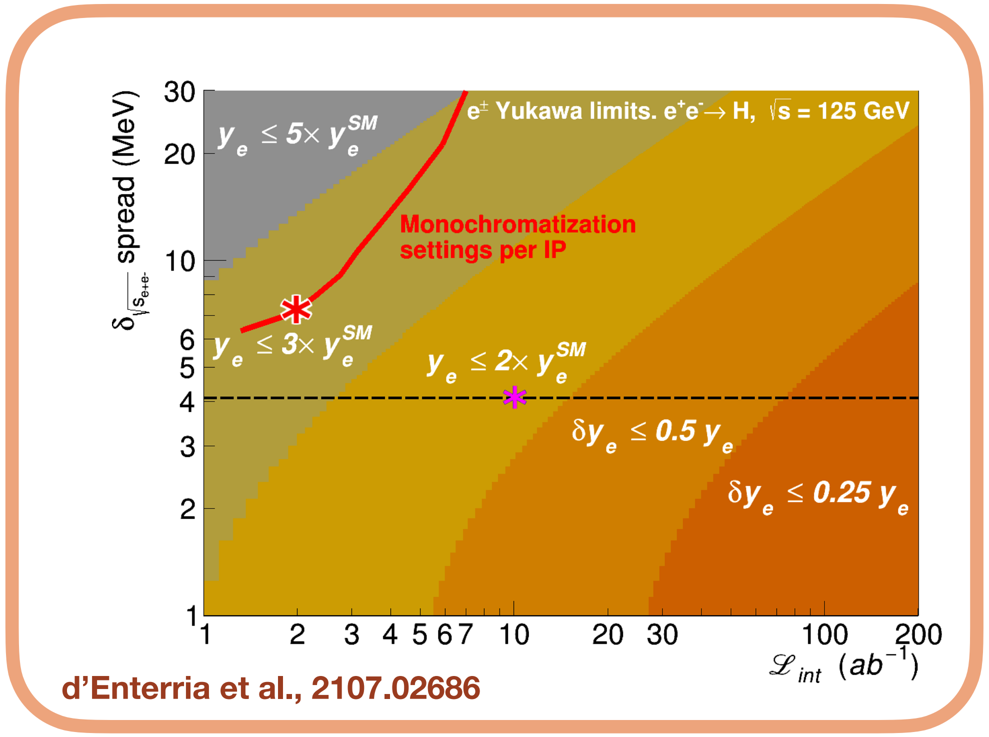
Very difficult @ HLLHC Possible @ e^+e^-

Possible @ e^+e^- ?



d'Enterria et al., 2107.02686

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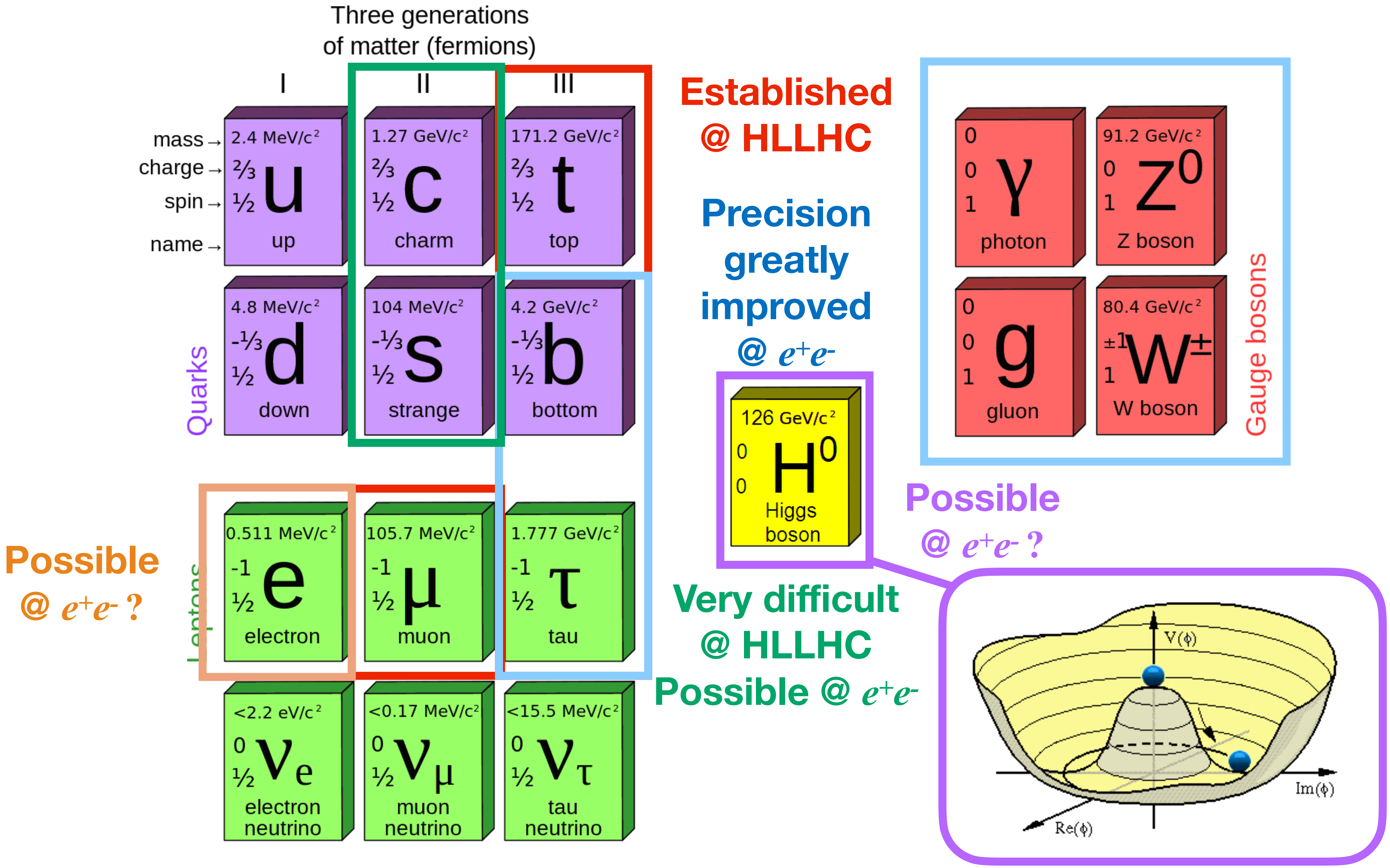

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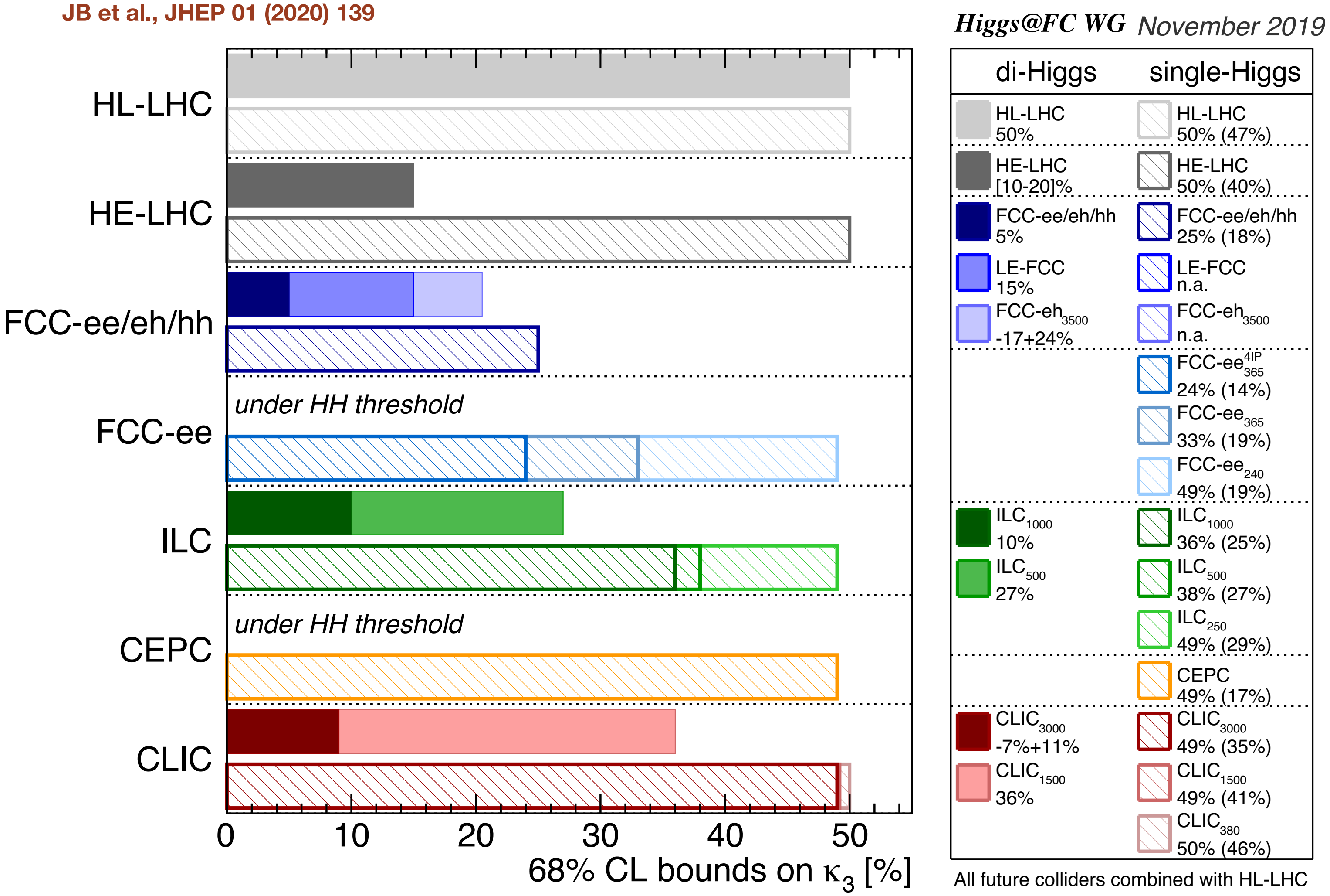
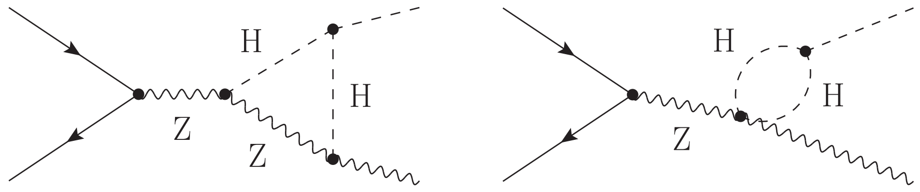
Precision physics at e^+e^- Higgs factories

Higgs self-coupling from single-Higgs processes

JB et al., JHEP 01 (2020) 139



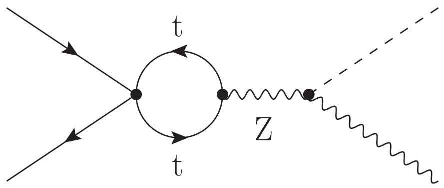
h^3 enters in single Higgs @ NLO



M. McCullough, PRD90 (2014) no.1, 015001

50% HLLHC → ~30% @ e^+e^-?

Careful, other effects enter at NLO!



Asteriadis, Dawson, Giardino, arXiv: 2406.03557 [hep-ph]

Contributions from (poorly constrained) *eett* operators affect interpretation!

⇒ Interplay Higgs/Top

O(1) TeV^{-2} bounds needed:

Difficult to constrain only with 365 GeV data in $e^+e^- \to t\,t$ (Flat directions)

Bounds from HLLHC ($pp \to t\,t\,e^+e^-$) could ameliorate the issue

Still useful for particular models but model-independence needs to be clarified

Precision physics at e^+e^- Higgs factories

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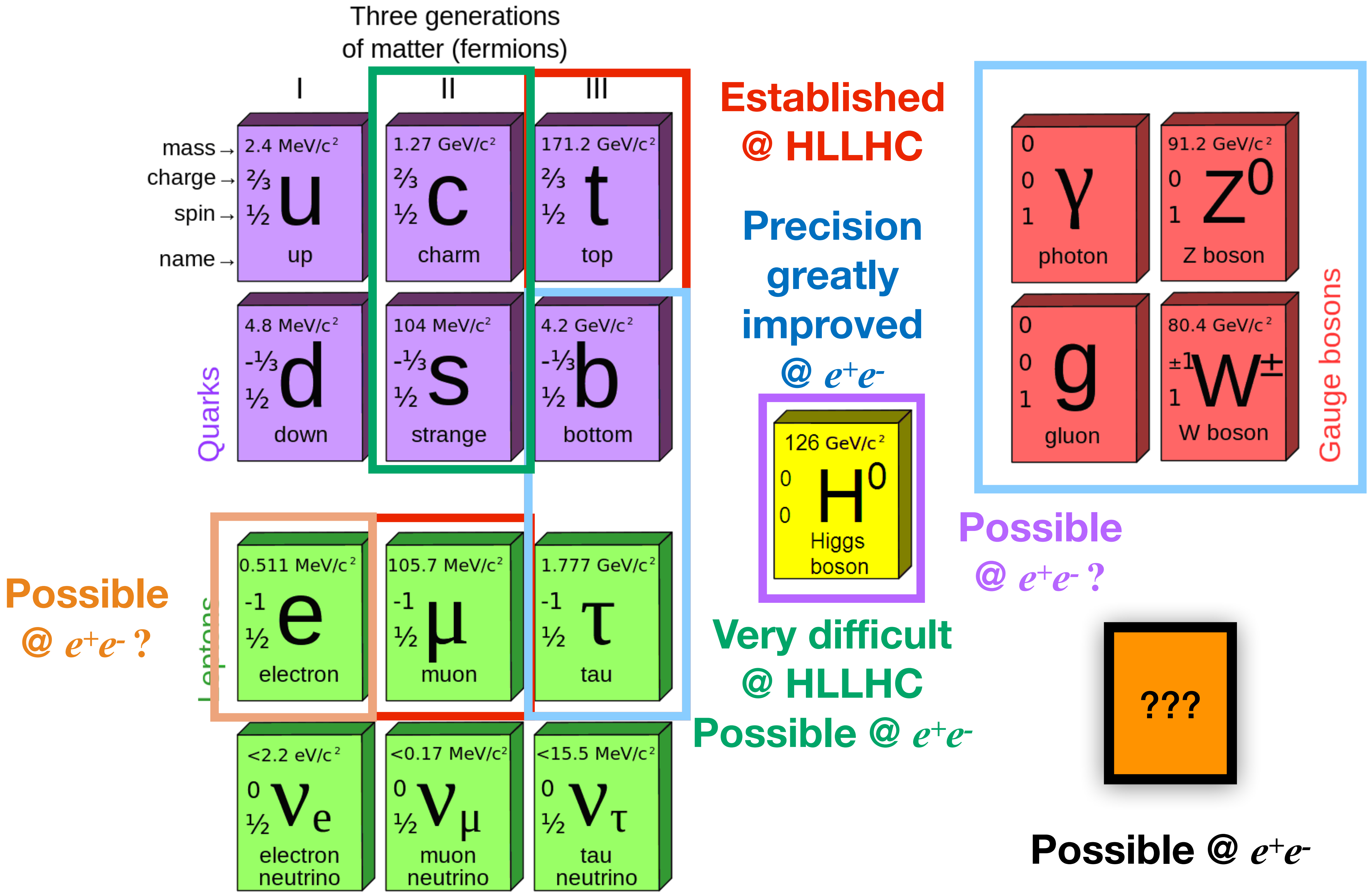

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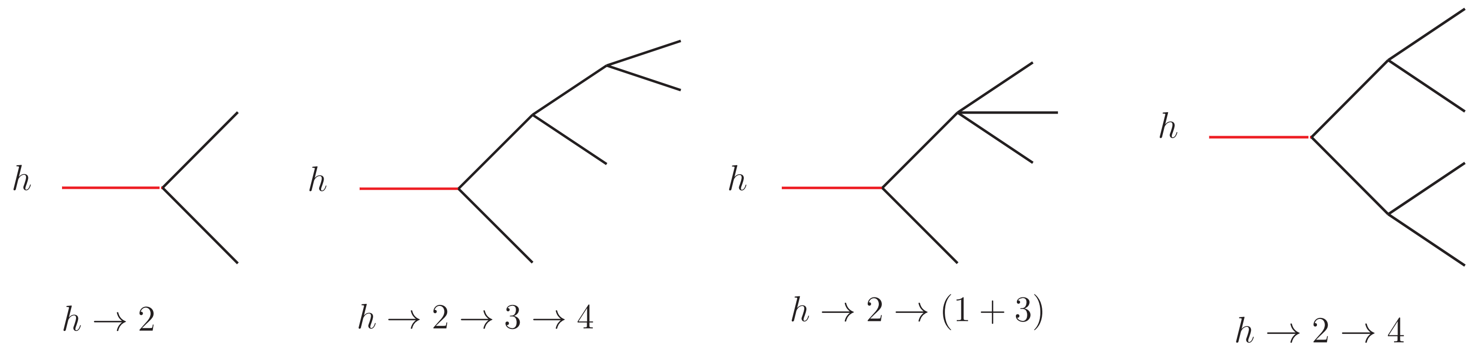
Very difficult @ HLLHC Possible @ e^+e^-

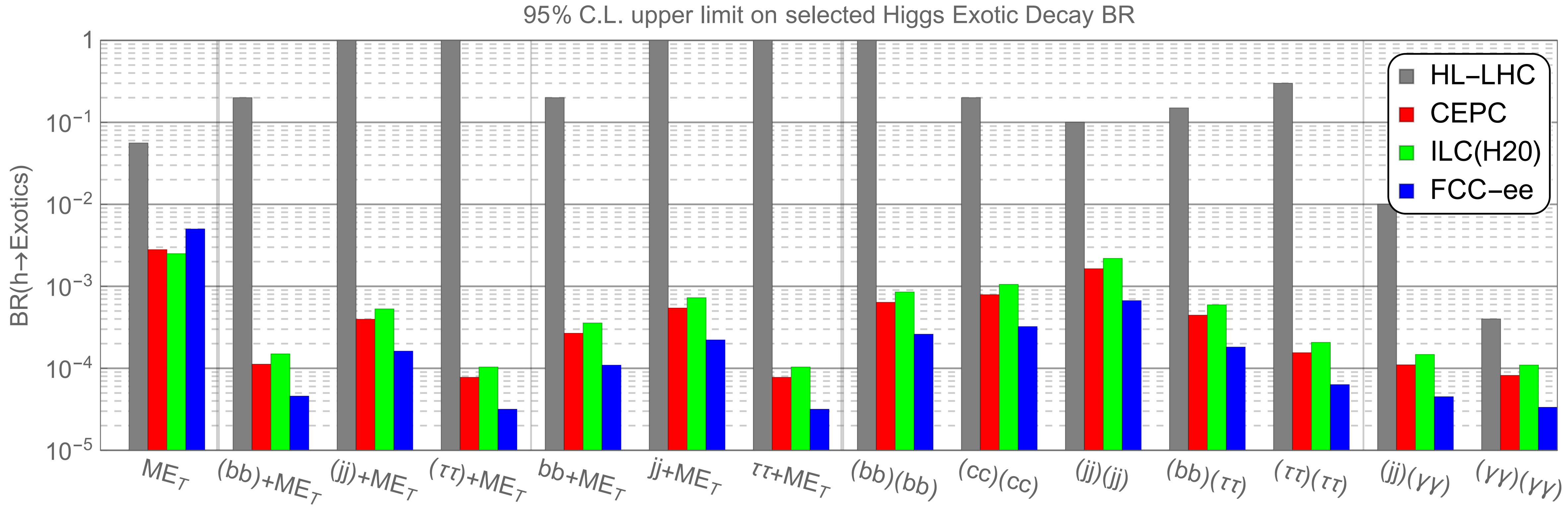
Possible @ e^+e^-

Precision physics at e^+e^- Higgs factories

- Higgs portals to SM-neutral new physics sectors: $\Delta\mathcal{L} \sim |\phi|^2\, \mathcal{O}_{\rm NP} \to h\mathcal{O}_{\rm NP}$
  - ✓ Clean environment allows to detect any Higgs decay (many exotic decays could "escape" untagged at the LHC)



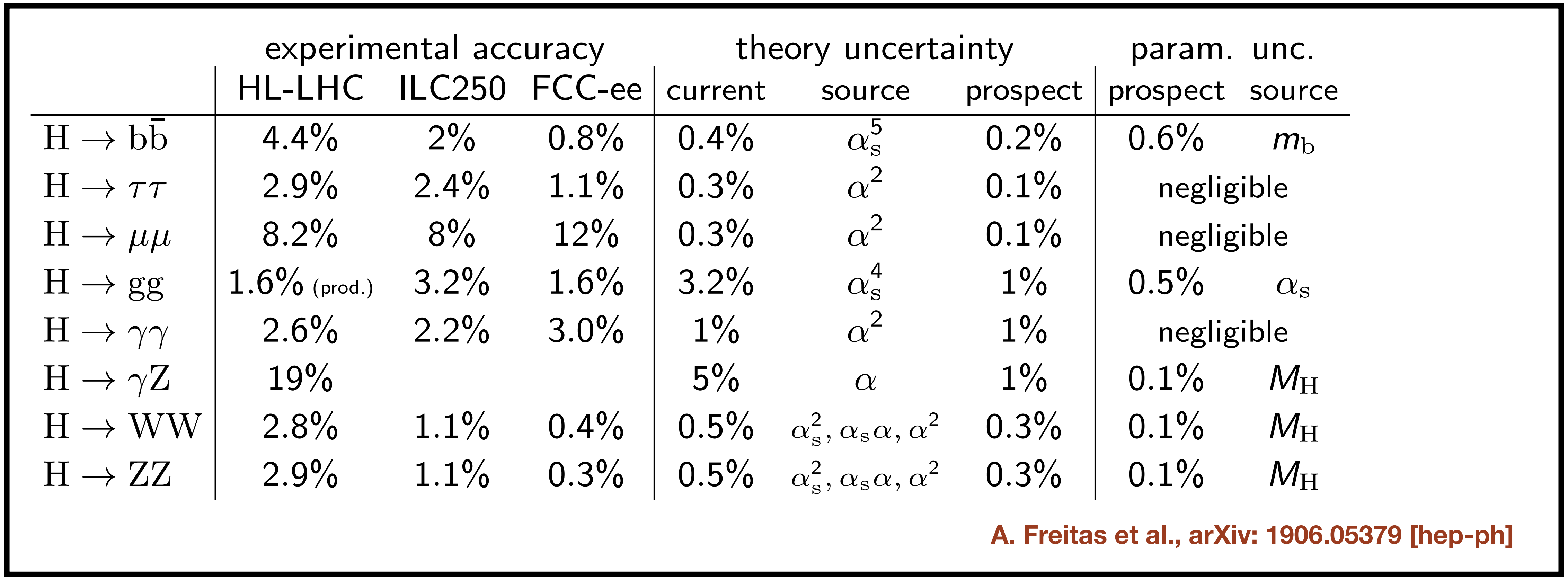
From Higgs coupling fit $\mathrm{BR}_{\rm unt} < 1$ - 2% @ 95% prob.



Z. Liu, L-T. Wang, H. Zhang, Chin. Phys. C 41, 6 (2017) 063102

Precision physics at e⁺e⁻ Higgs factories

- Precision Experiment vs. Theory



	experimental accuracy			theory uncertainty			param. unc.	
	HL-LHC	ILC250	FCC-ee	current	source	prospect	prospect	source
$\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$	4.4%	2%	0.8%	0.4%	α_s^5	0.2%	0.6%	m_b
$\mathrm{H} \to \tau\tau$	2.9%	2.4%	1.1%	0.3%	α^2	0.1%	negligible	
$\mathrm{H} \to \mu\mu$	8.2%	8%	12%	0.3%	α^2	0.1%	negligible	
$\mathrm{H} \to \mathrm{gg}$	1.6% (prod.)	3.2%	1.6%	3.2%	α_s^4	1%	0.5%	α_s
$\mathrm{H} \to \gamma\gamma$	2.6%	2.2%	3.0%	1%	α^2	1%	negligible	
$\mathrm{H} \to \gamma\mathrm{Z}$	19%			5%	α	1%	0.1%	M_H
$\mathrm{H} \to \mathrm{WW}$	2.8%	1.1%	0.4%	0.5%	$\alpha_s^2, \alpha_s\alpha, \alpha^2$	0.3%	0.1%	M_H
$\mathrm{H} \to \mathrm{ZZ}$	2.9%	1.1%	0.3%	0.5%	$\alpha_s^2, \alpha_s\alpha, \alpha^2$	0.3%	0.1%	M_H

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

- Theory challenges:
  - ✓ Full 2-loop calculation for e⁺e⁻ → ZH
  - ✓ Partial 2-loop effects for WBF
  - ✓ 4-/5-loop QC calculation in H→bb, cc

Recent progress:

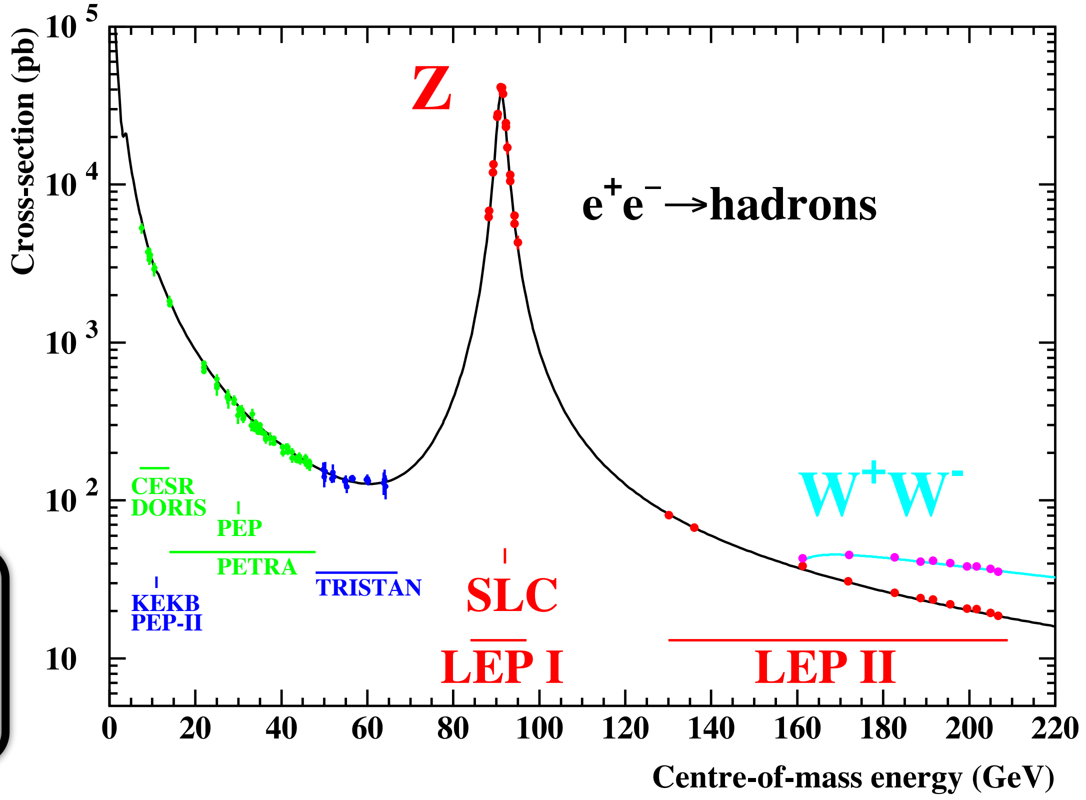
A. Freitas, Q. Song, PRL 130 (2023) 3, 031801
A. Freitas, Q. Song, K. Xie, PRD 1080 (2023) 5, 053006

- Theory expected to be ready and SM TH uncertainties (intrinsic & parametric) to have small impact in BSM interpretation

The case for Precision EW physics
at future e^+e^- colliders

Precision physics at e⁺e⁻ Electroweak 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

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

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

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

Precision physics at e^+e^- Electroweak factories

- Future e^+e^- factories will also help us improve our knowledge of the EW interactions:
    - Also very precise measurements of other crucial inputs of the EW fit:

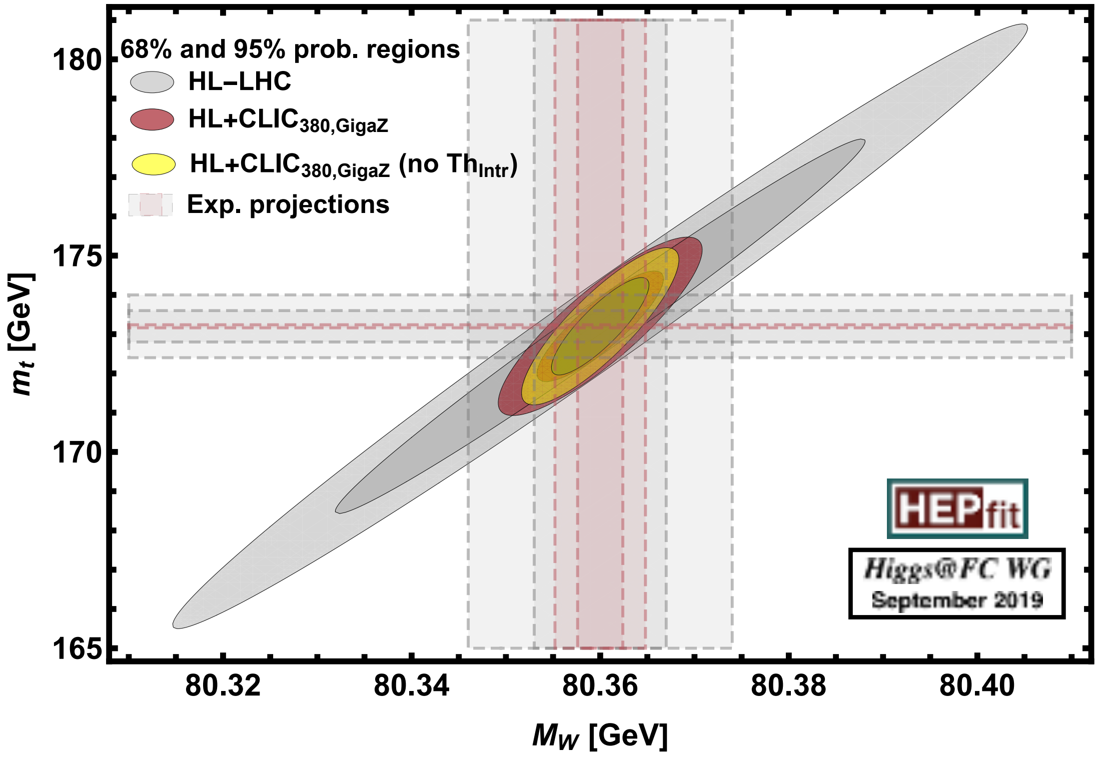
W mass:

$$\Delta M_W: \quad 12\ \mathrm{MeV} \longrightarrow \lesssim 1\ \mathrm{MeV}$$

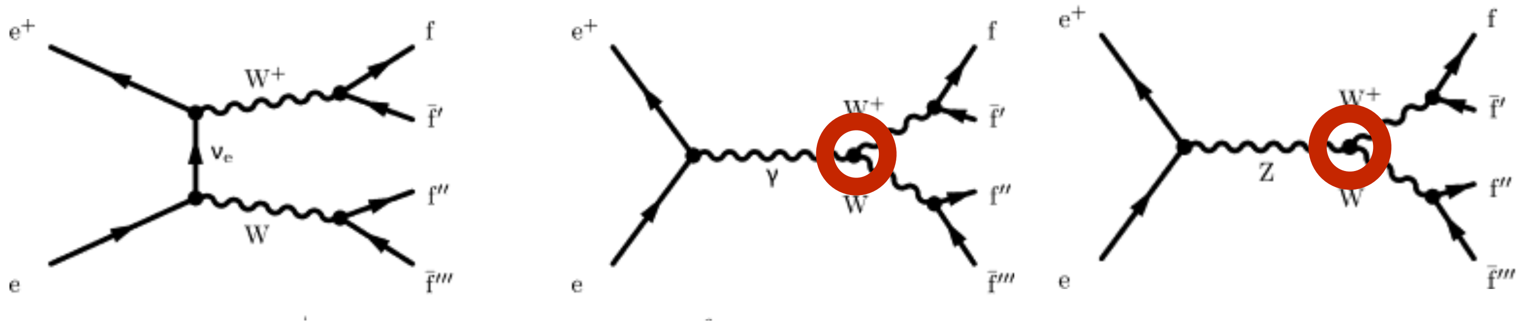
Top mass

$$\Delta m_t: \quad \sim 400\ \mathrm{MeV} \longrightarrow \sim 20\ \mathrm{MeV}$$

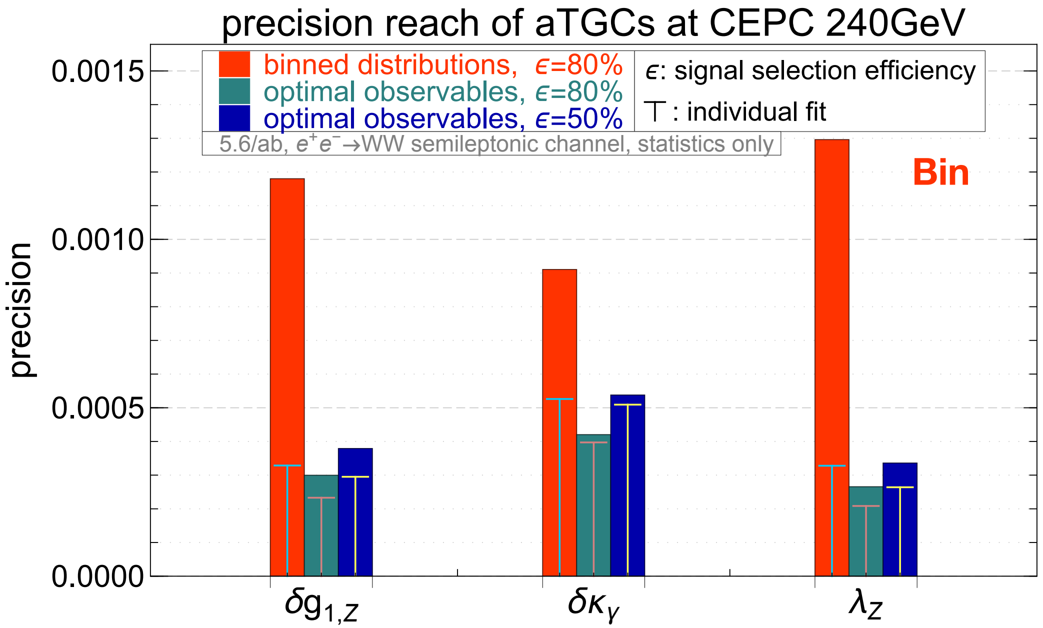
Consistency tests of the SM EW sector →



- Anomalous Triple Gauge Couplings:



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

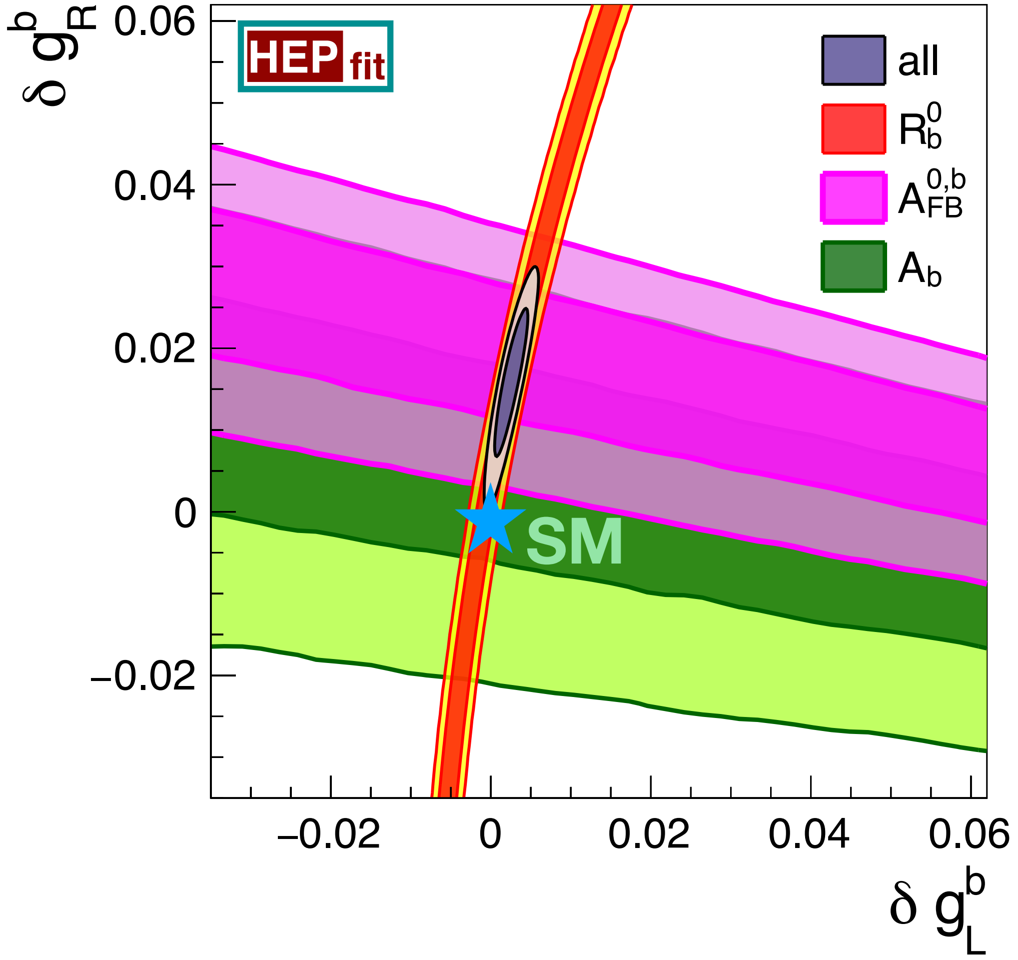


Precision physics at e^+e^- Electroweak factories

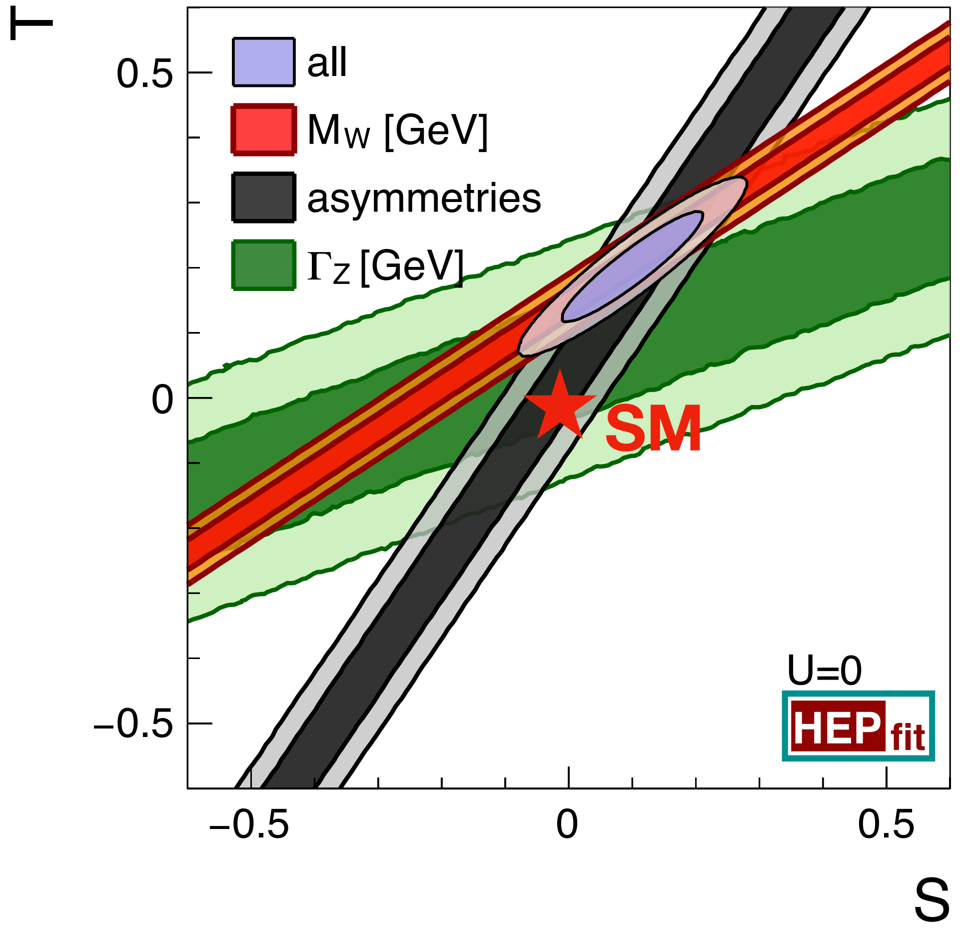
What can we do with future EW measurements?

- Solve old and new “puzzles” in current EWPO

Forward-Backward Asymmetry
Bottom quark



W mass after CDF measurement



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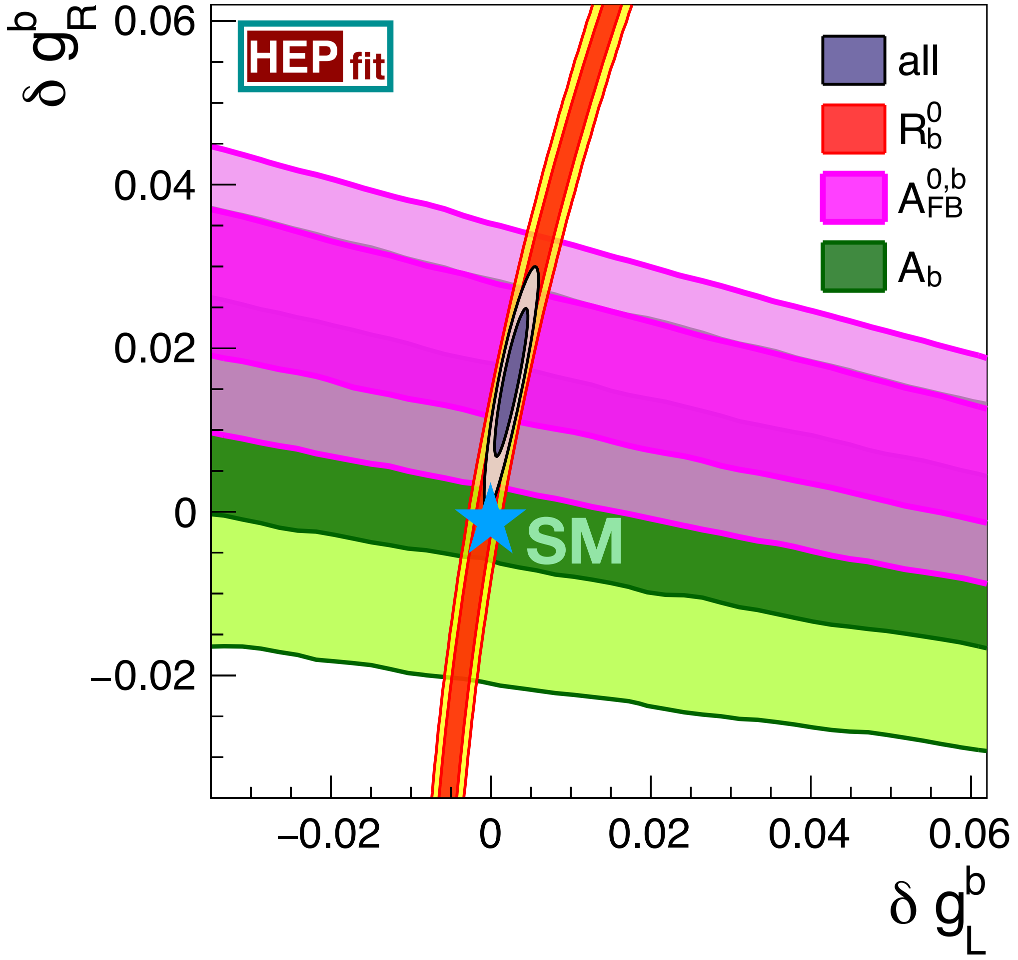
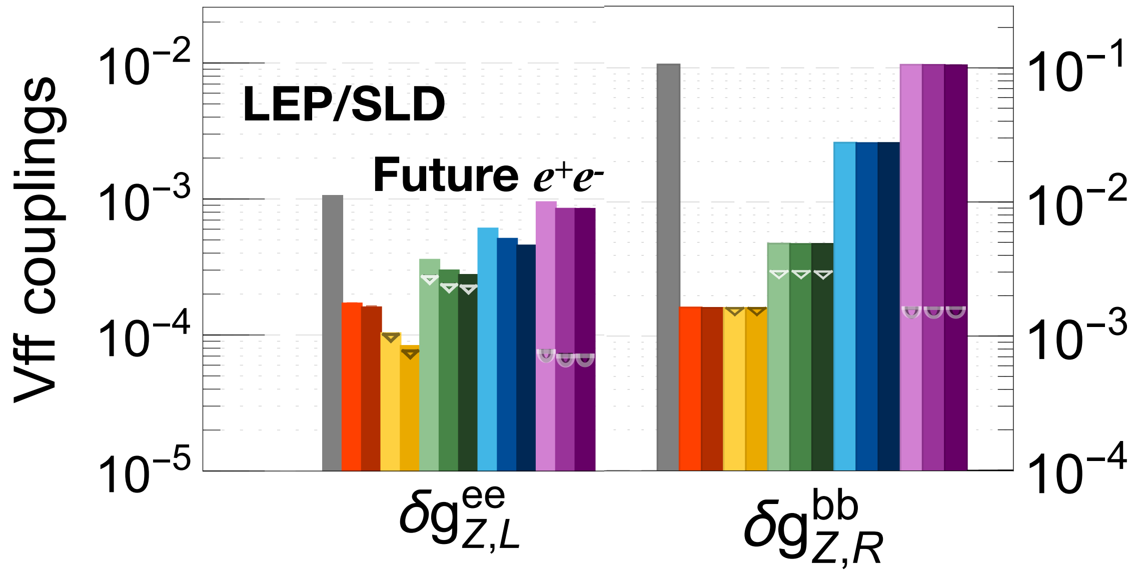


Future e^+e^- improves LEP/SLD EW precision typically by a factor ~10

Tera Z: O(0.01%) in some couplings

Tera Z/Giga Z/Rad. return: Enough to clarify current tensions in EW fit: A_{FB}^b



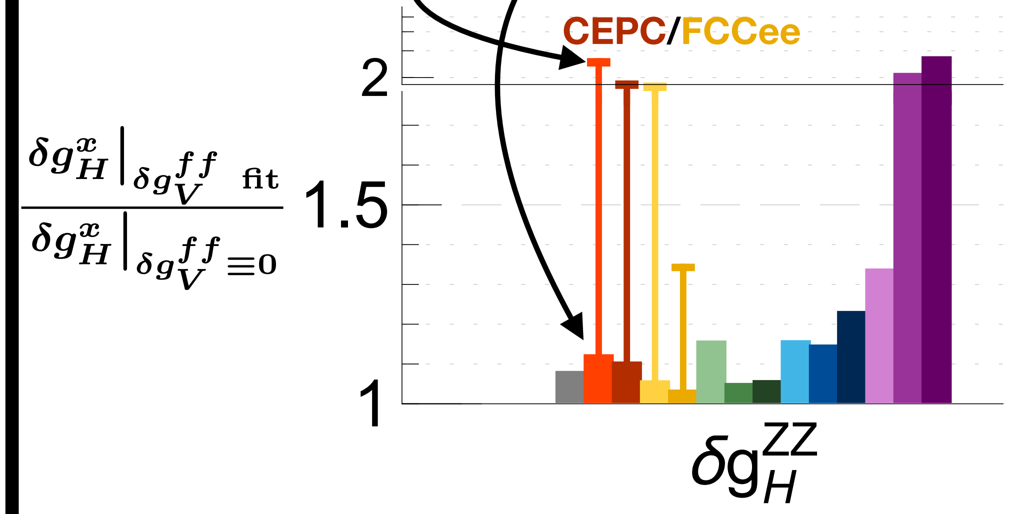
Precision physics at e^+e^- Electroweak factories

What can we do with future EW measurements?

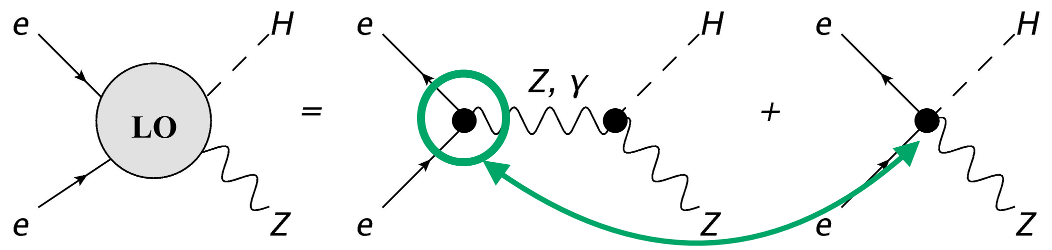
- Make sure we do not hinder Higgs precision:

Needed at circular colliders to not hinder Higgs precision

- **fit assuming LEP/SLD Z-pole**
- **fit including Future Z-pole**



EW-Higgs SMEFT correlations



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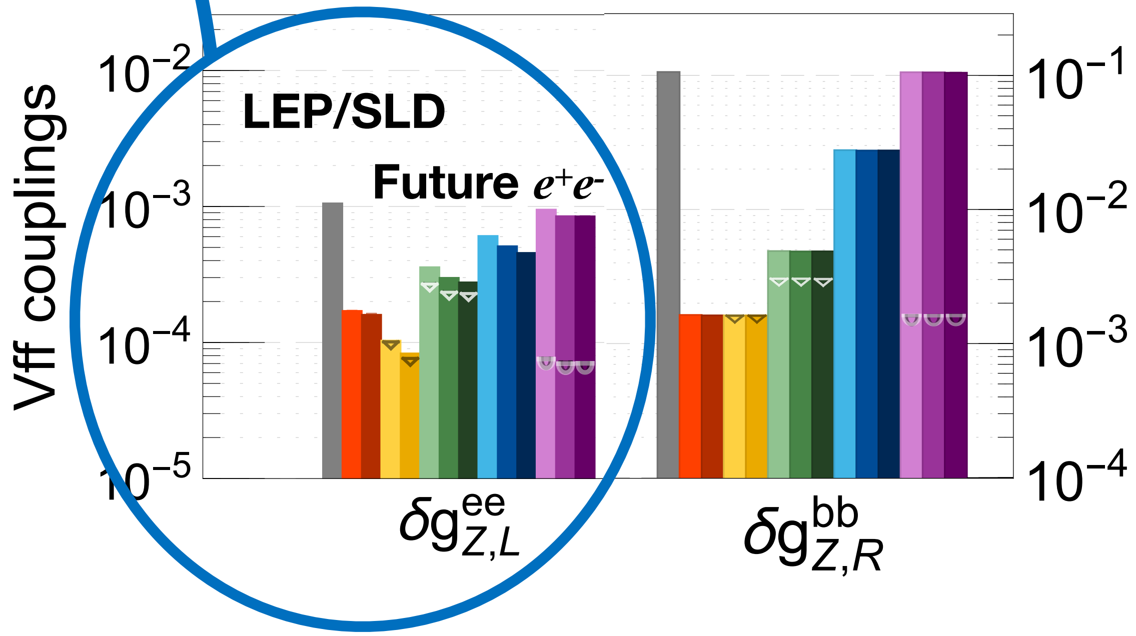


Precision physics at e^+e^- Electroweak factories

What can we do with future EW measurements?

- Precision Flavor Physics:

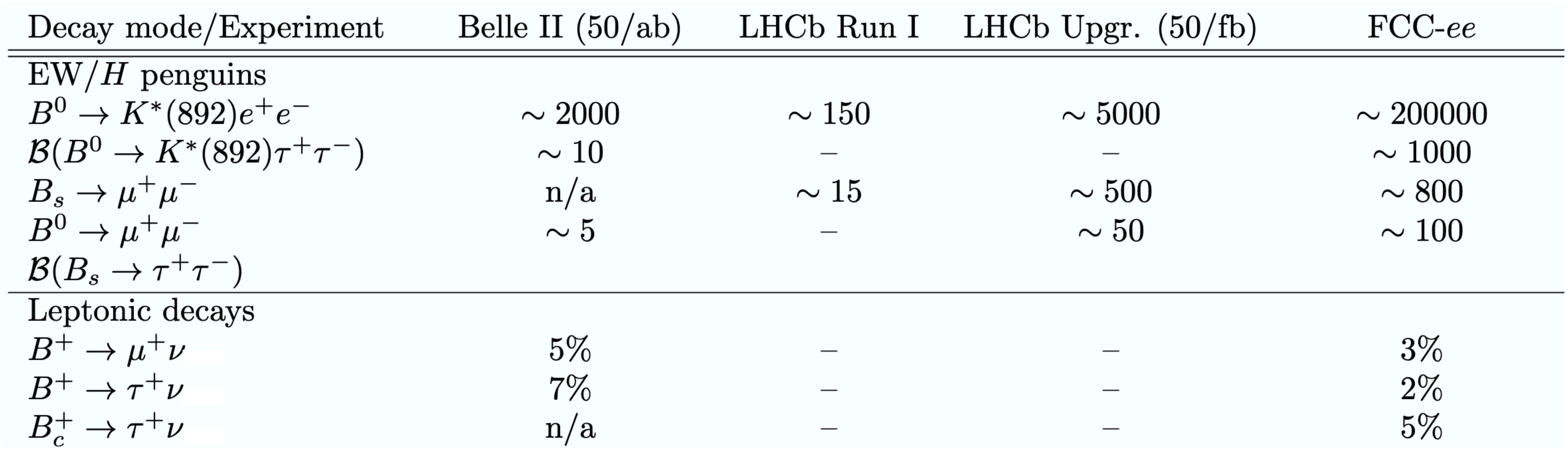
5×10^{12} Z

~15% $Z\rightarrow bb$

~3.4% $Z\rightarrow \tau\tau$

Huge sample for Flavor measurements

- E.g. B physics:



Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu$	5%	–	–	3%
$B^+ \to \tau^+\nu$	7%	–	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	–	5%

Table from S. Monteil

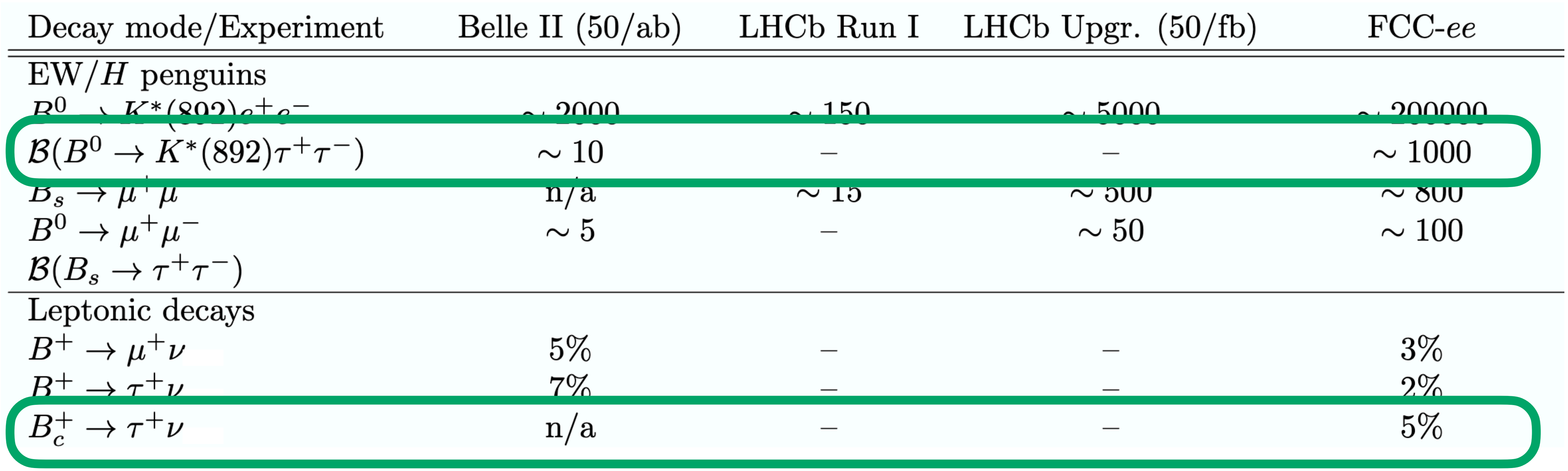
Precision physics at e^+e^- Electroweak factories

What can we do with future EW measurements?

- Precision Flavor Physics:

$5\times10^{12}\ Z$	~15% $Z\rightarrow bb$ ~3.4% $Z\rightarrow\tau\tau$	Huge sample for Flavor measurements

- E.g. B physics:



Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
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Leptonic decays				
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$B^+ \to \tau^+\nu$	7%	–	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	–	5%

Outside the reach of LHCb/Belle II

Table from S. Monteil

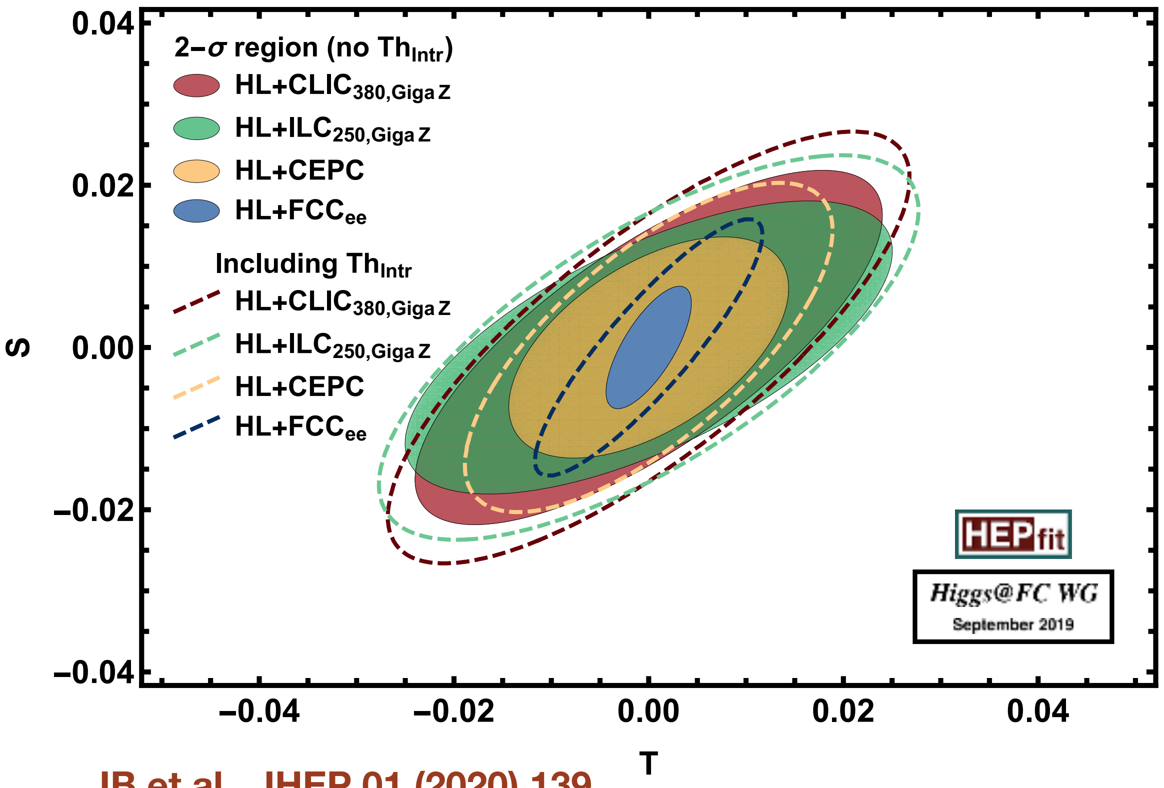
Precision physics at e^+e^- Electroweak factories

- Precision Experiment vs. Theory

	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
ΔM_Z[MeV]	2.1	–	0.1				
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_{\rm had}$
$\Delta R_b[10^{-5}]$	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
    - ✓ EW & QCD-EW 3-loop + leading 4 loop (Y_t enhanced)
- Even accounting for future progress, SM theory uncertainties will have an impact on BSM interpretation of EWPO
- Parametric uncertainties ($\alpha_{\rm em}$) expected to have similar effect



JB et al., JHEP 01 (2020) 139

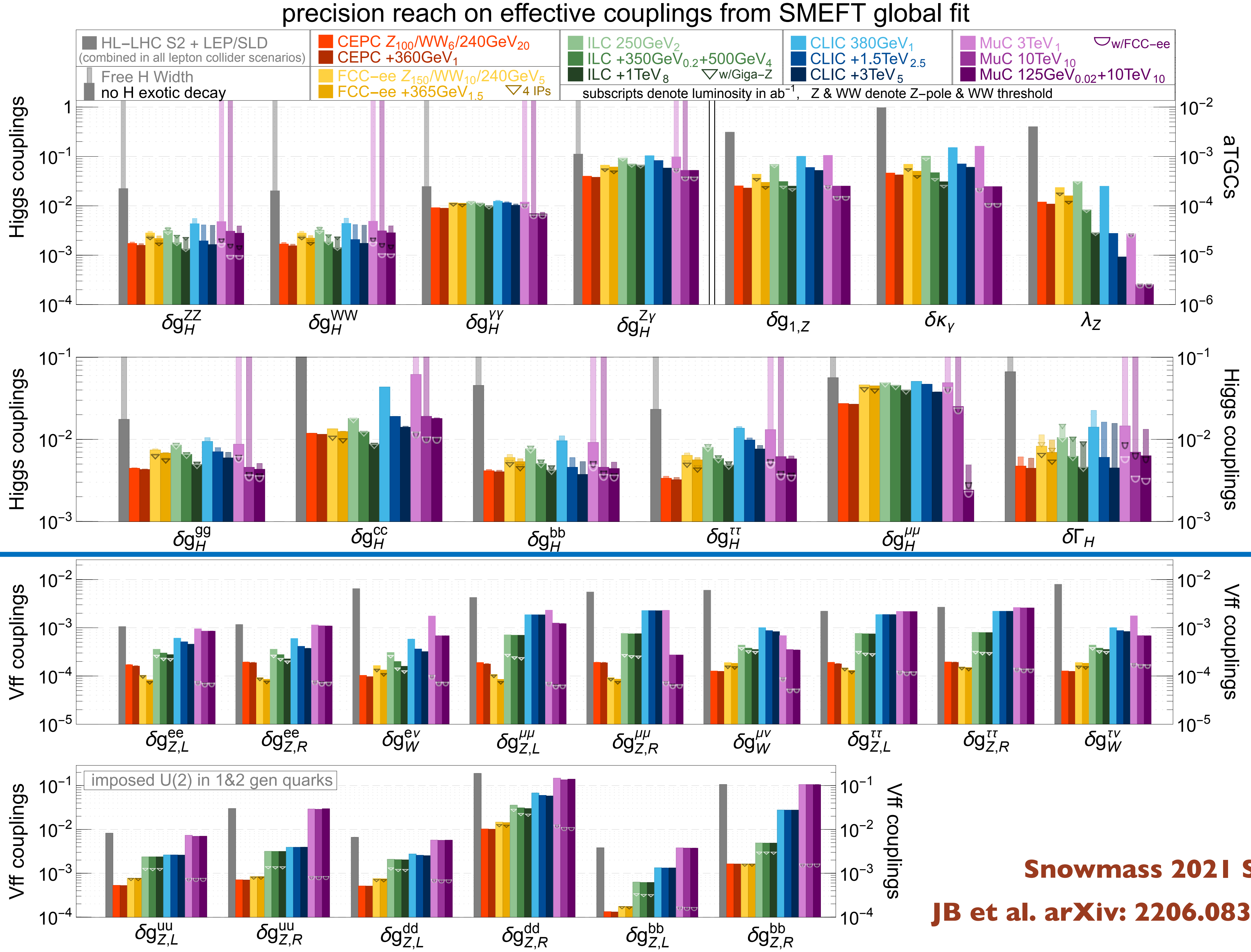
BSM precision
at future e$^+$e$^-$ EW/Higgs factories

Global precision at e⁺e⁻ EW/Higgs factories

Higgs interactions

aTGC

EW *Vff* interactions



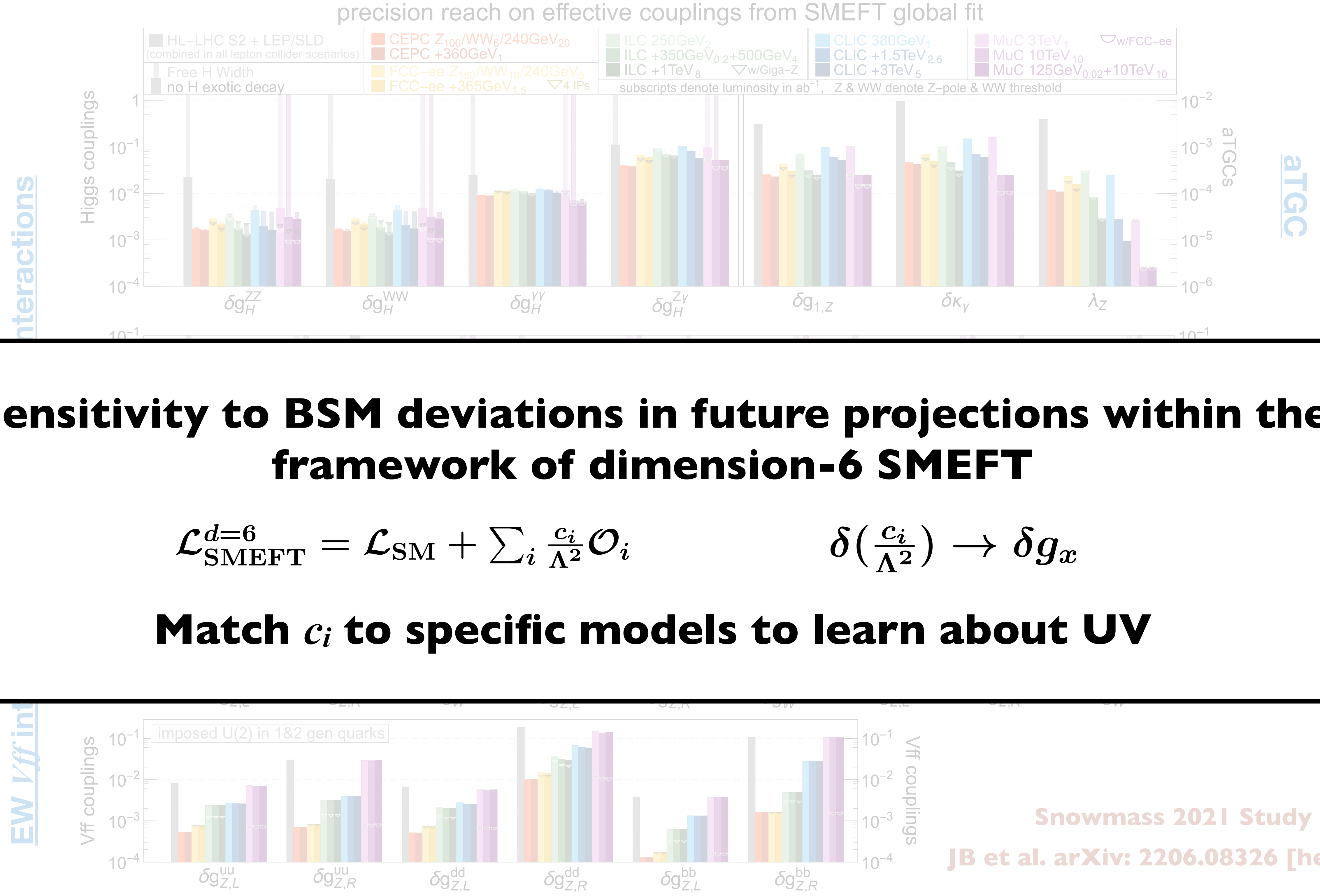
Snowmass 2021 Study

JB et al. arXiv: 2206.08326 [hep-ph]

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 precision at e+e- EW/Higgs factories



Sensitivity to BSM deviations in future projections within the framework of dimension-6 SMEFT

$$\mathcal{L}^{d=6}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i \qquad\qquad \delta\left(\frac{c_i}{\Lambda^2}\right) \rightarrow \delta g_x$$

Match c_i to specific models to learn about UV

Snowmass 2021 Study

JB et al. arXiv: 2206.08326 [hep-ph]

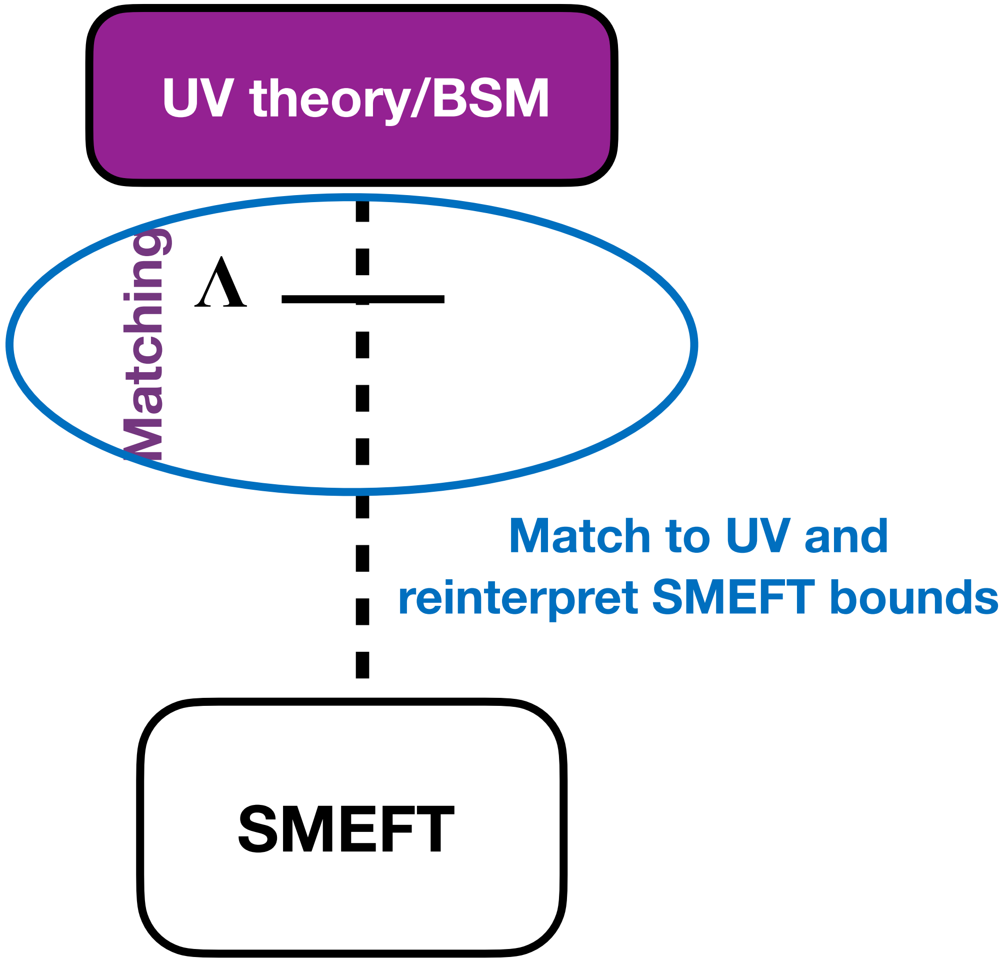
Effective couplings

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

Global precision at e⁺e⁻ EW/Higgs factories

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

High Energy



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

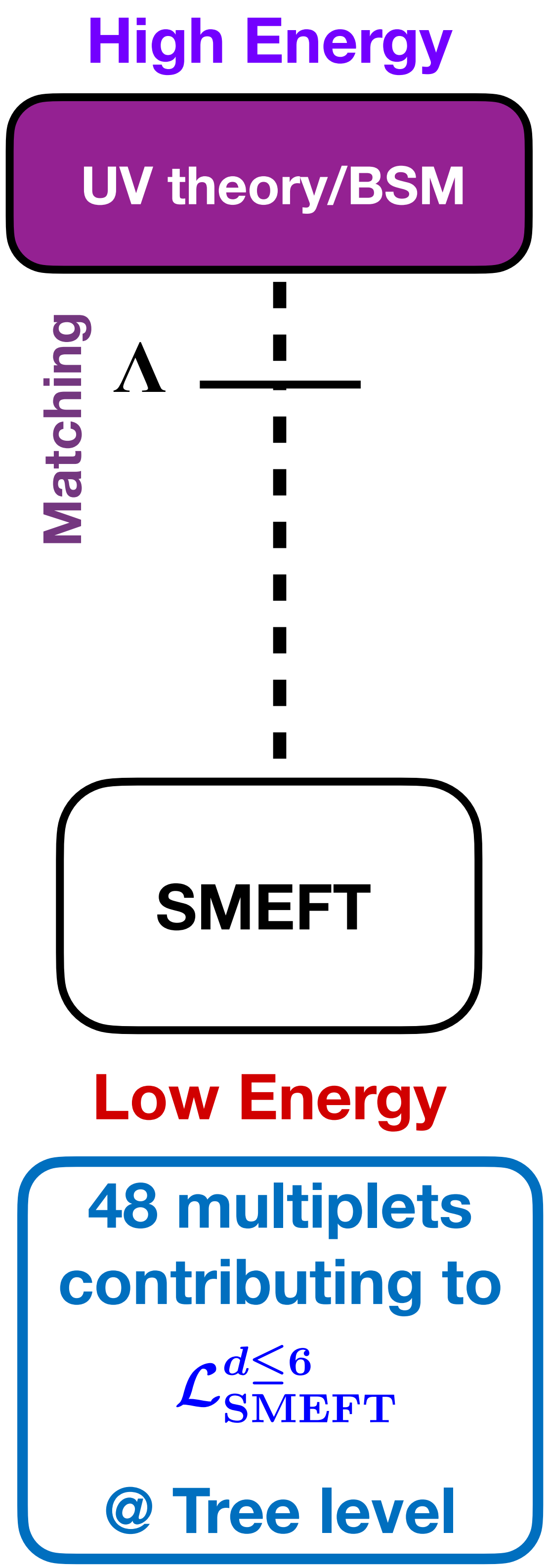
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$

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 precision at e⁺e⁻ EW/Higgs factories

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



High Energy

UV theory/BSM

Matching

Λ

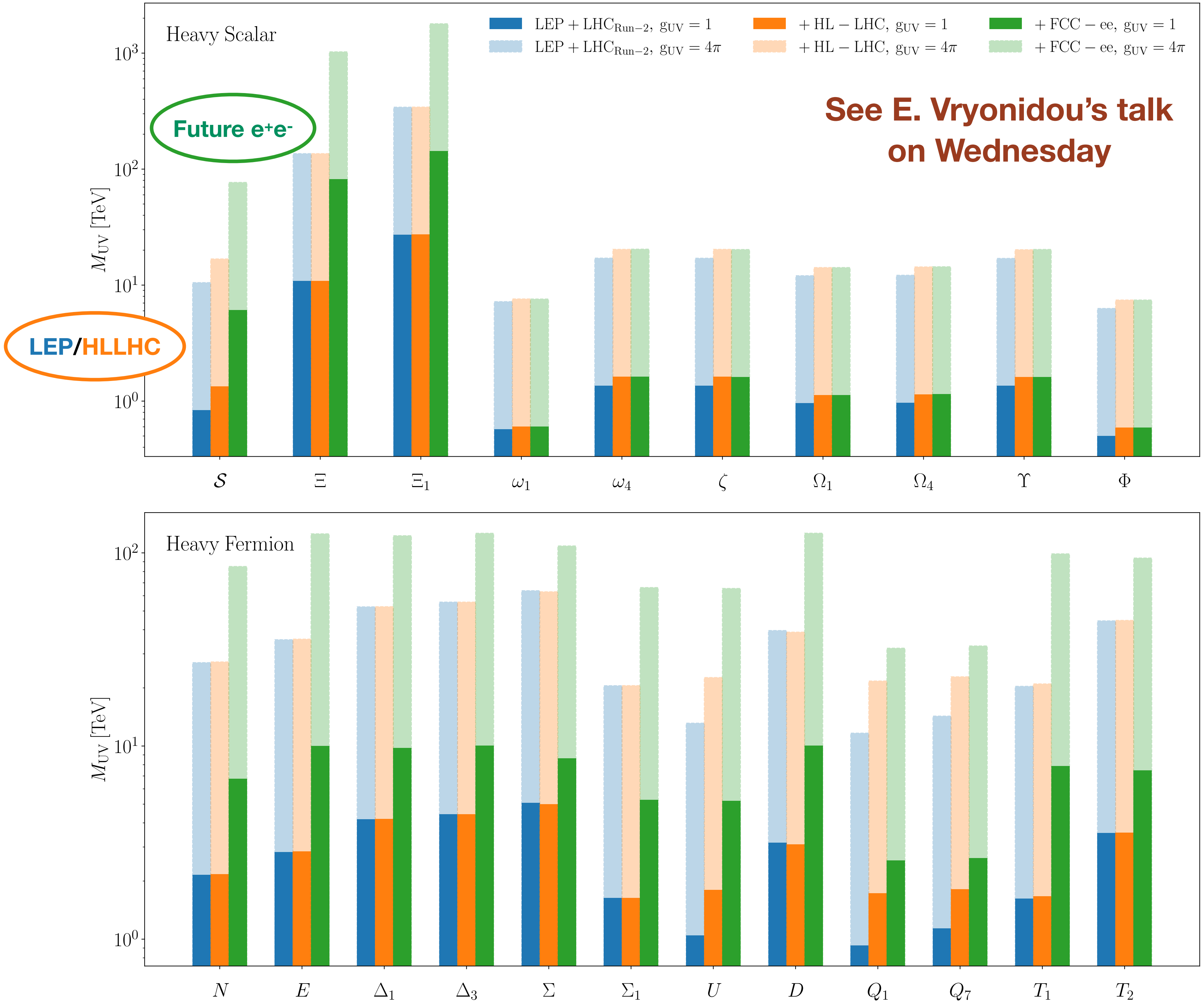
SMEFT

Low Energy

48 multiplets contributing to

$\mathcal{L}_{\mathrm{SMEFT}}^{d\leq 6}$

@ Tree level



See E. Vryonidou's talk on Wednesday

E. Celada et al., arXiv: 2404.12809 [hep-ph]

Global precision at e⁺e⁻ EW/Higgs factories

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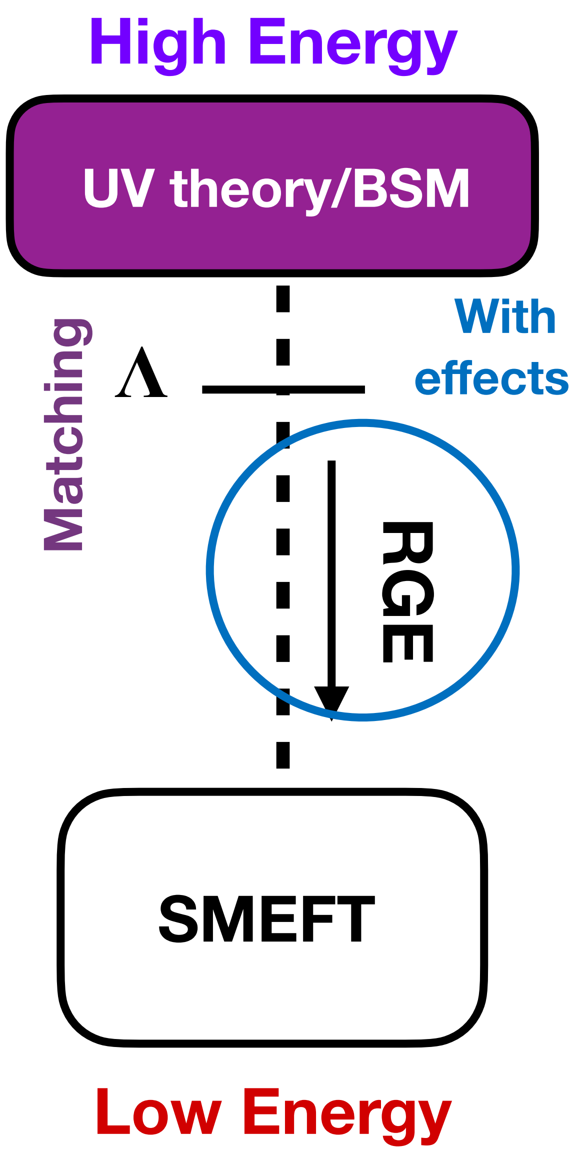


High Energy

UV theory/BSM

Matching

Λ

RGE

SMEFT

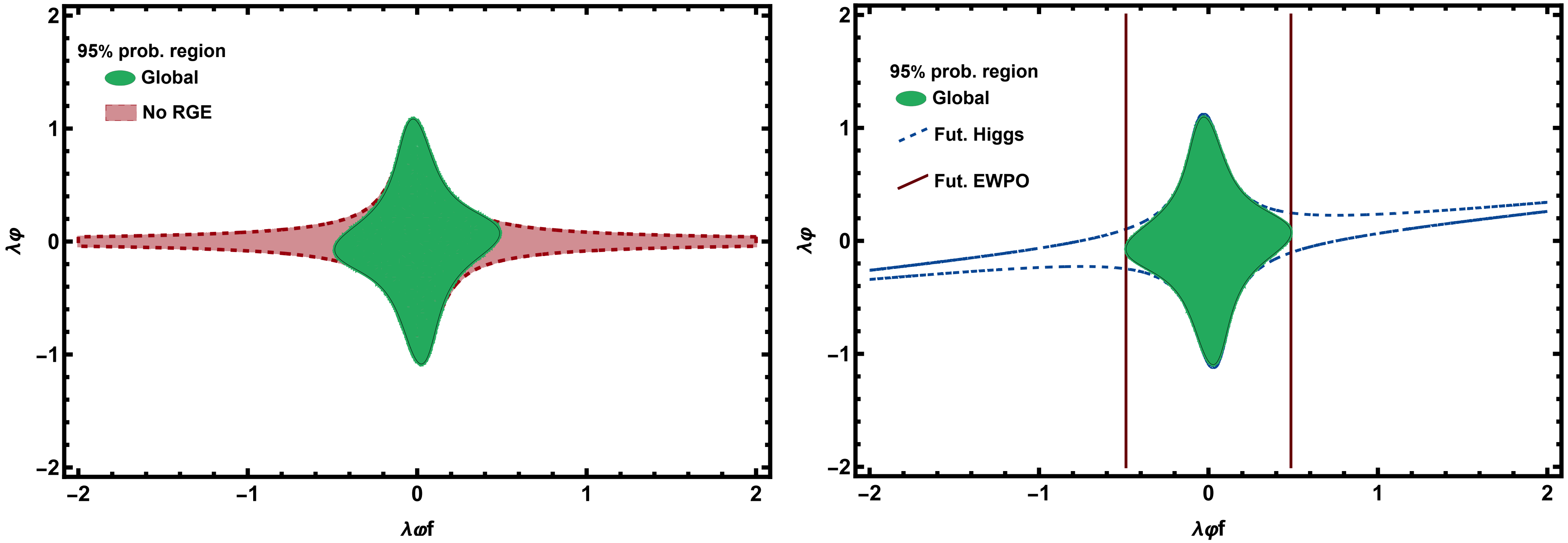
Low Energy

With precision RG effects are important!

$$\varphi \sim (1,2)_{\frac{1}{2}}$$

$$\Delta\mathcal{L}_{\varphi-\mathrm{SM}} = -\lambda_\varphi(\varphi^\dagger\phi)(\phi^\dagger\phi)$$

$$-\lambda_{\varphi f}(y_e\varphi^\dagger\bar{e}_R l_L + y_d\varphi^\dagger\bar{d}_R q_L + y_u\varphi^\dagger i\sigma_2\bar{q}_L^T u_R) + \mathrm{h.c.}$$



PRELIMINARY

48 multiplets contributing to

$$\mathcal{L}_{\mathrm{SMEFT}}^{d\leq 6}$$

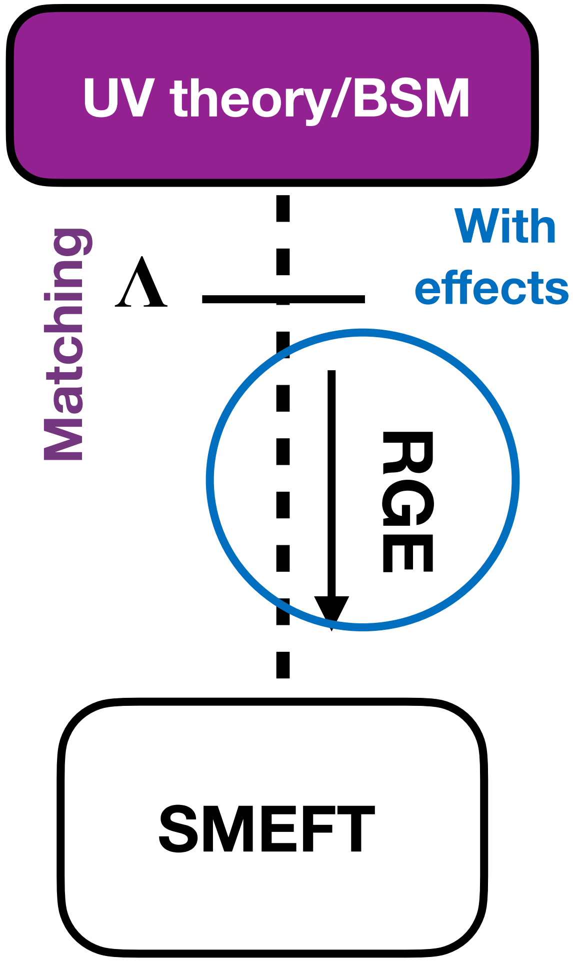
@ Tree level

Good complementarity between EWPO-Higgs even for models where Higgs is the source of LO constraints

Global precision at e^+e^- EW/Higgs factories

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

High Energy



UV theory/BSM

Matching

Λ

RGE

With precision RG effects are important!

SMEFT

Low Energy

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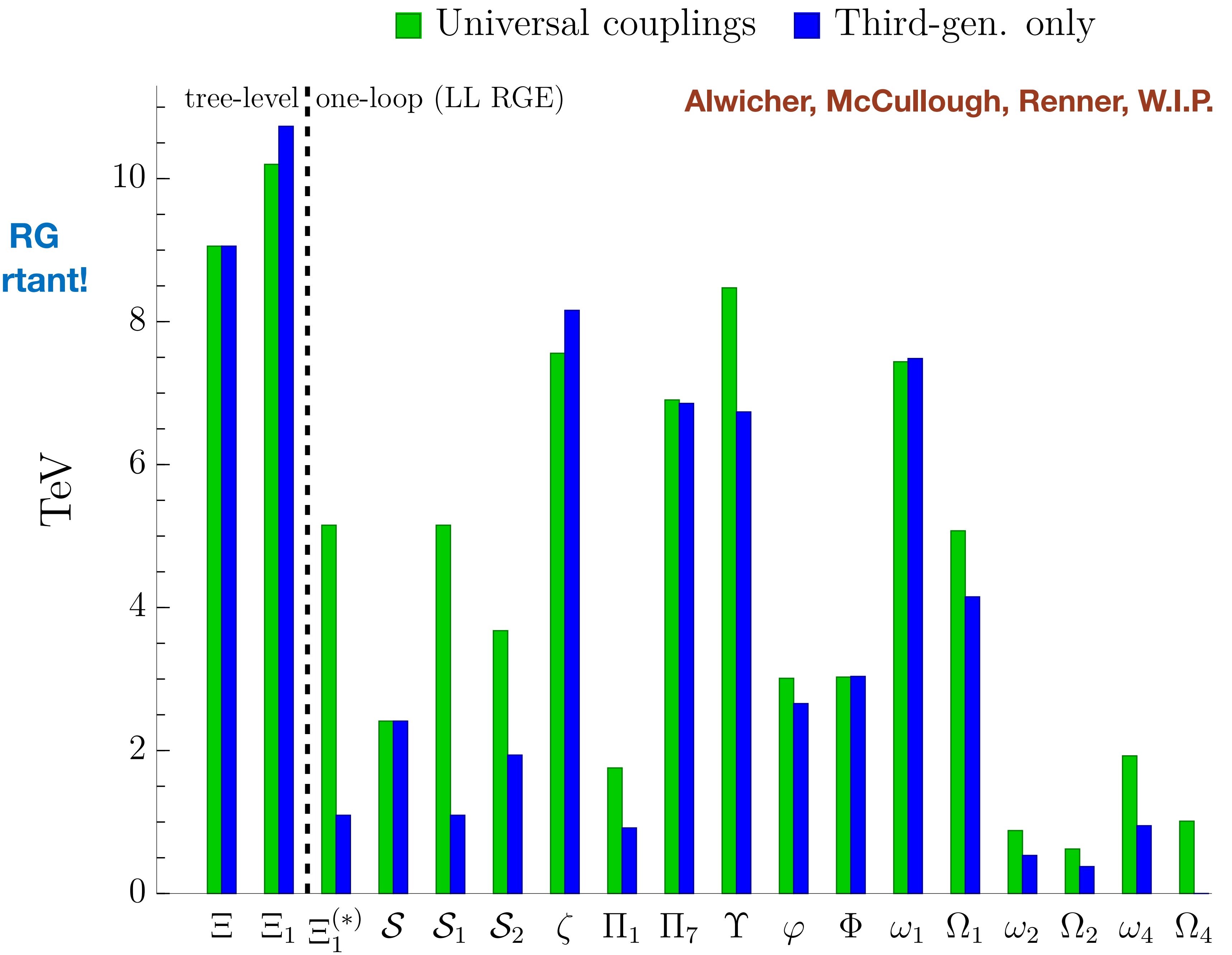

Alwicher, McCullough, Renner, W.I.P.

None of these contribute at tree level to EWPO

Z-pole precision enables sensitivity to effects via mixing

Summary

Summary

- EW/Higgs physics at future e^+e^- colliders will bring a giant step forward with respect to LEP/SLD/HL-LHC:
  - ✓ Increase precision x10 → per-mile level in Higgs couplings (not ratios)
  - ✓ Access to interactions not easy or impossible to access at HL-LHC:
    - ▸ E.g. charm Yukawa, strange Yukawa? electron Yukawa?
  - ✓ Higgs width with 1% precision
  - ✓ Great power to testing BSM scenarios indirectly
- Higgs and EW precision are highly complementary: important for interpretation of measurements
- Precision experiments needs precision theory!
- There is a clear physics case for a future program of precision measurements at future e^+e^- colliders. They could give a hint of where NP may be hiding…
- Even if no significant deviation is seen, precision measurements at low-energy EW/Higgs factories will help to optimize/guide measurements/direct searches:
  - ✓ Future hadron colliders
  - ✓ High-energy phase of e^+e^- colliders ⇒ **Talk by G. R. Weiglein**