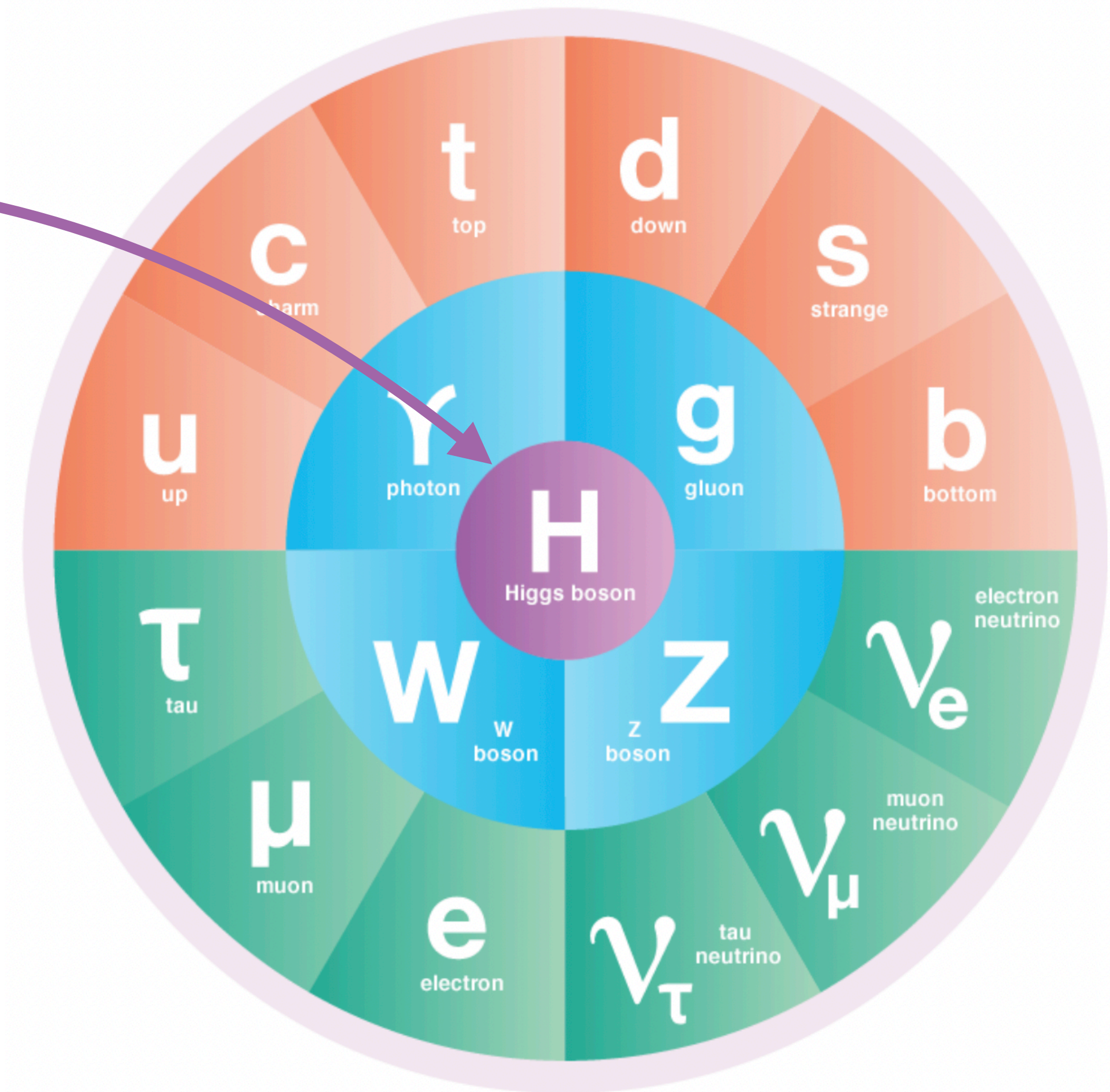
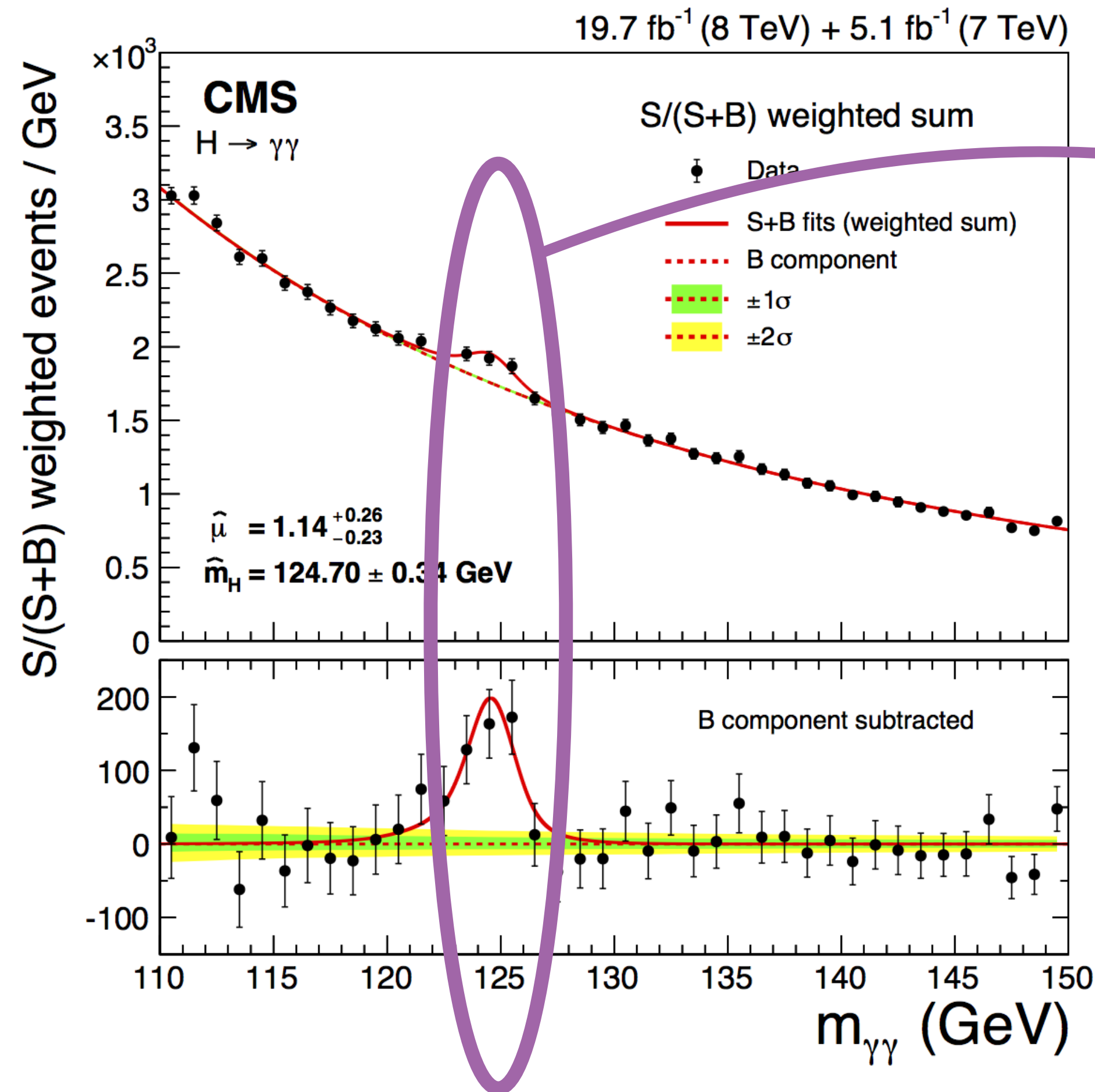


Physics Opportunities at Future e^+e^- Colliders

Jorge de Blas
University of Granada

Looking at the future from today's perspective

- After the discovery of the Higgs at the LHC we have confirmation of all particles predicted by the Standard Model $\Rightarrow$ The model is “structurally” complete

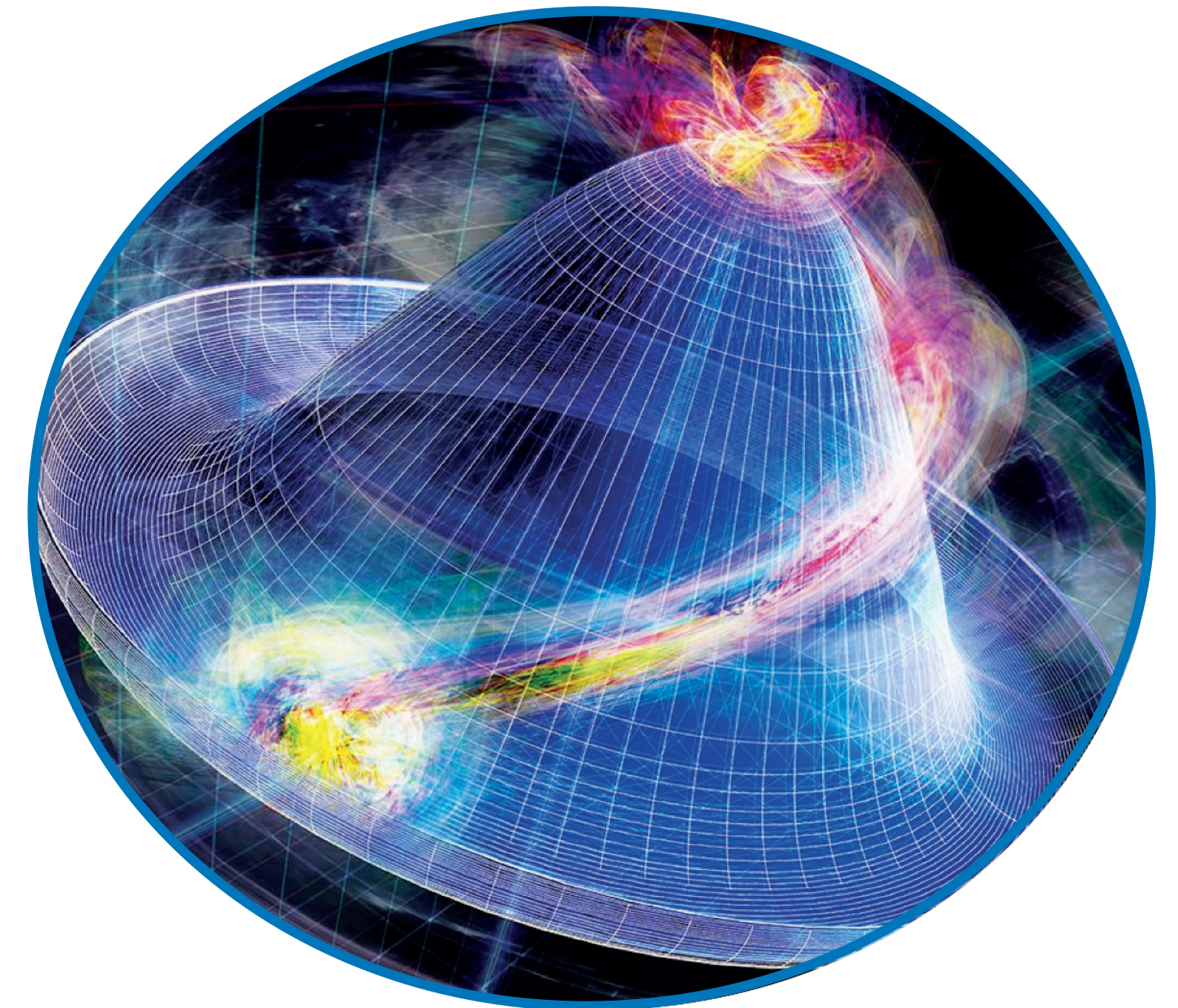


Looking at the future from today's perspective

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- Now it is time to start addressing the big questions about such structure...

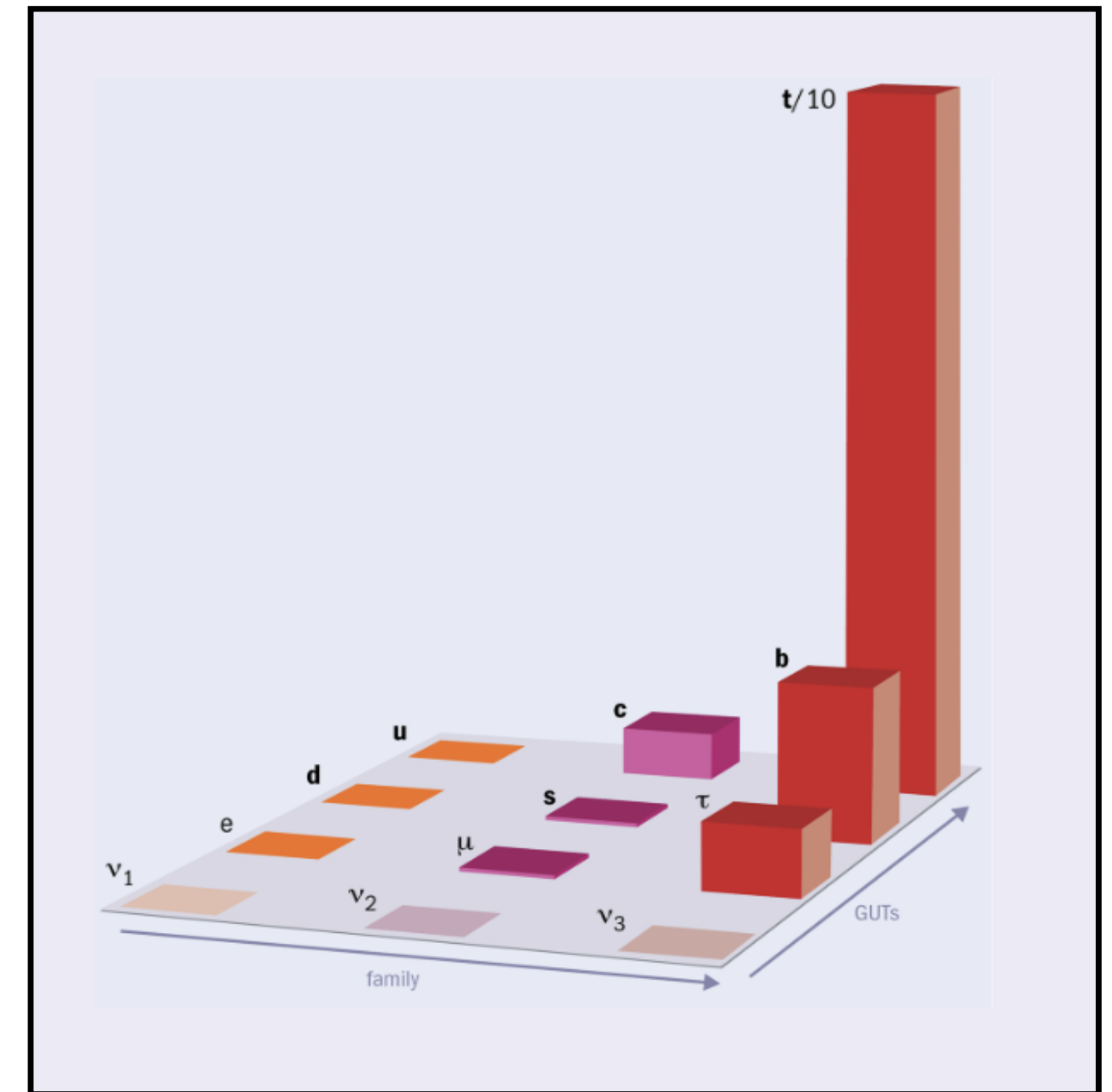
Looking at the future from today's perspective

- After the discovery of the Higgs at the LHC we have confirmation of all particles predicted by the Standard Model $\Rightarrow$ The model is “structurally” complete
- Now it is time to start addressing the big questions about such structure... Most of these require to go beyond the Standard Model...
 - ▶ What is the origin of the Higgs potential and EWSB?
Is the Higgs mass natural?
 - ▶ Is there only one Higgs? Is it elementary or composite?
 - ▶ Nature of the EWPT $\leftrightarrow$ Matter/Anti-Matter Asymmetry?
 - ▶ Is the EW vacuum stable?



Looking at the future from today's perspective

- After the discovery of the Higgs at the LHC we have confirmation of all particles predicted by the Standard Model $\Rightarrow$ The model is “structurally” complete
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Most of these require to go beyond the Standard Model...
 - ▶ What is the origin of flavor and its hierarchies?
(The SM flavour puzzle)
 - ▶ What gives mass to neutrinos?
 - ▶ What is the nature of Dark Matter?
Does it interact with the SM?



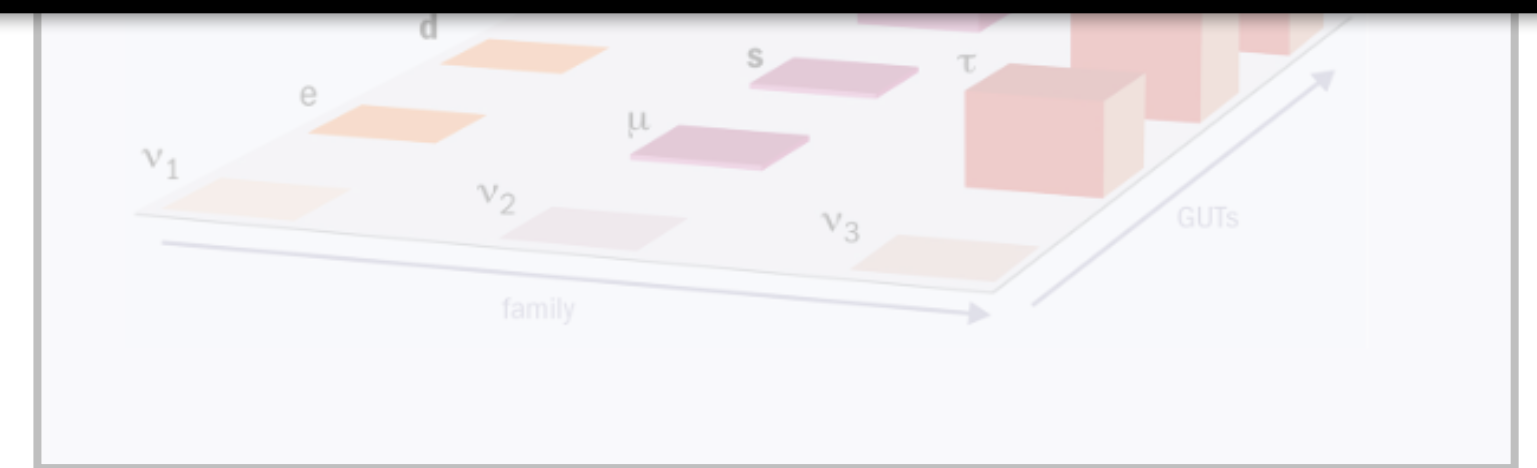
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If new physics is to explain any of these open questions... What is its nature?

(The SM flavour puzzle)

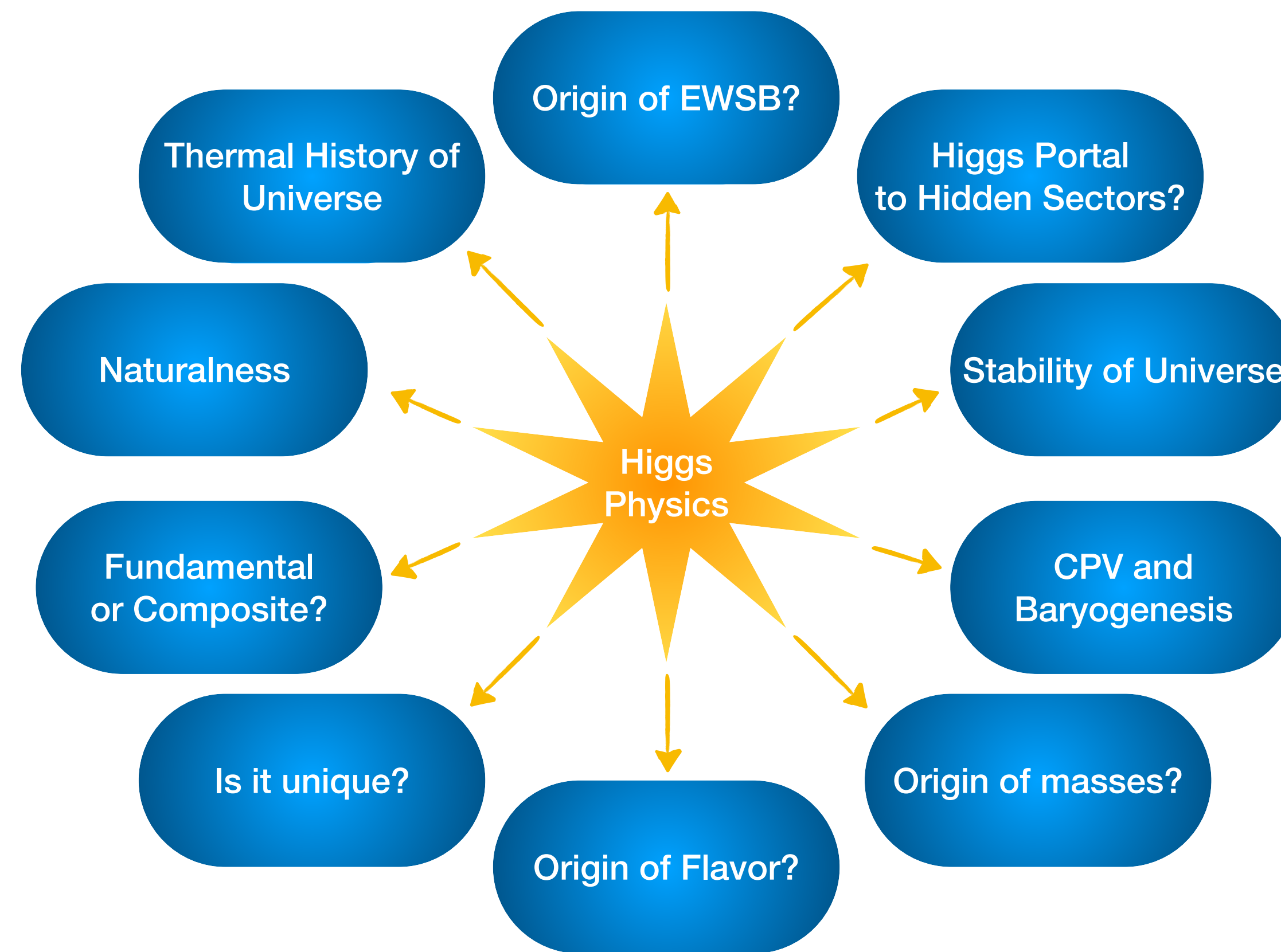
What do need from the next generation of high-energy particle physics experiments to maximize our chances of learning about this new physics?



If new physics is to explain any of these open questions...

What is its nature?

- **No clear hint of new physics at the LHC...** But the nature of the questions point to a connection to the Higgs boson



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BSM will typically modify the properties of the Higgs boson

⇒ We need a Higgs factory with capabilities for precision Higgs physics

In particular, there are several parts of the SM which we have not tested yet...

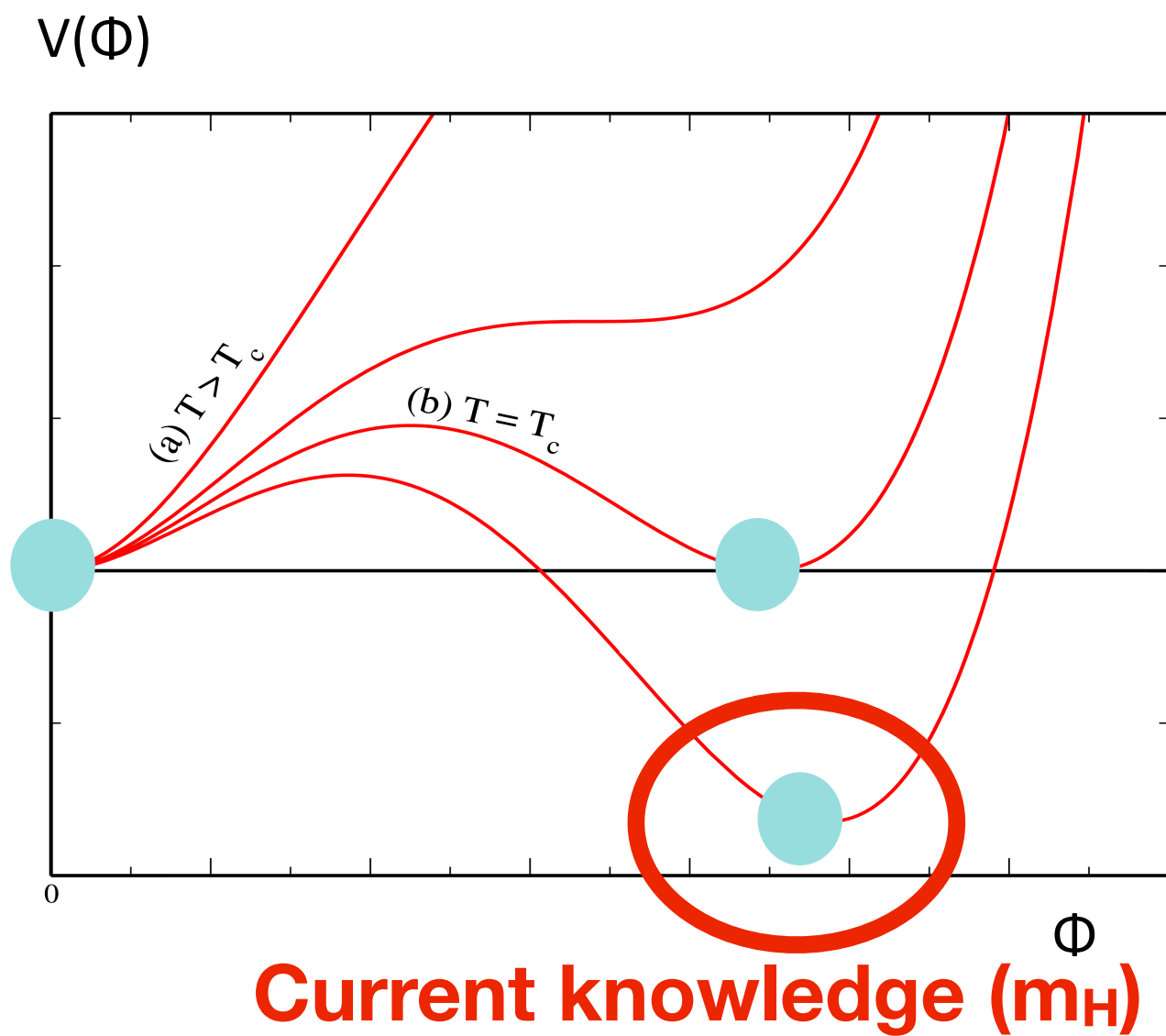
$$\mathcal{L}_{\text{SM}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + \overline{\psi}^i i \not{D} \psi^i + (D_\mu \phi)^\dagger D^\mu \phi \\ - V(\phi) - (y_{ij}^f \overline{\psi}_L^i \phi f_R^j + \text{h.c.})$$

Several of these interactions still remain unknown!

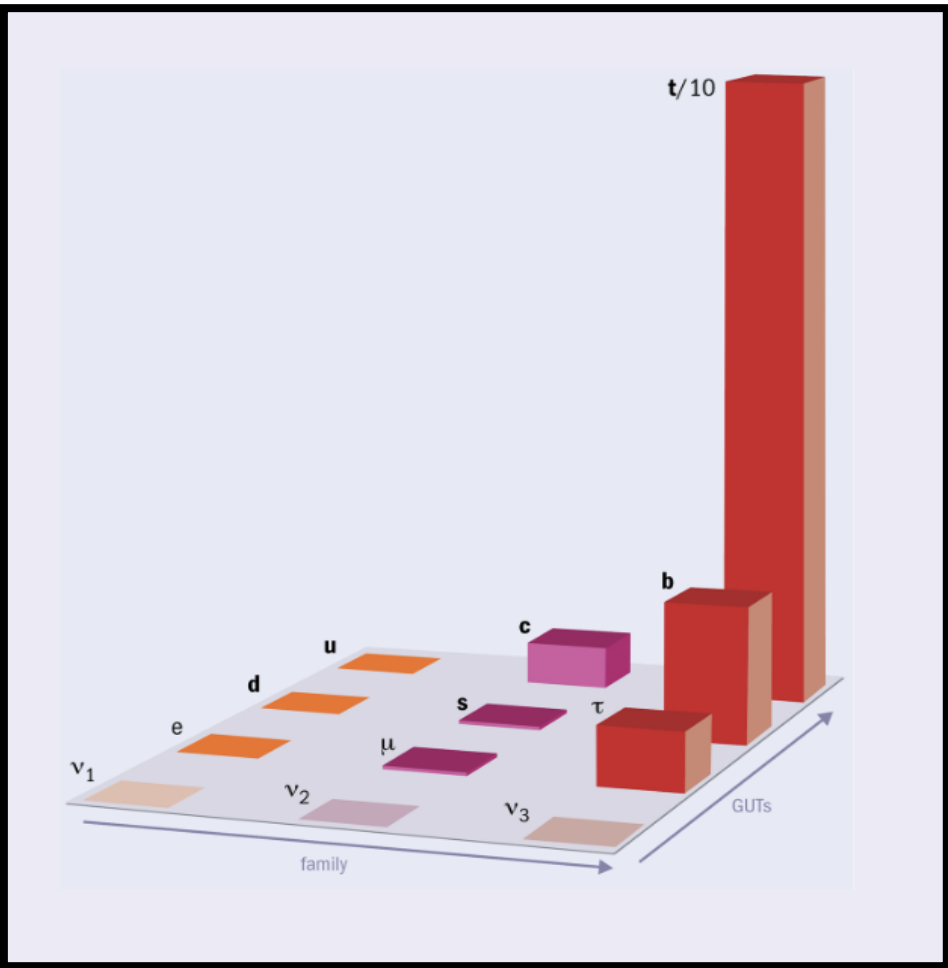
If new physics is to explain any of these open questions...

What is its nature?

Nature of the EWPT



Structure of fermion masses and mixings



$-V(\phi) - (y_{ij}^f \overline{\psi}_L^i \phi f_R^j + \text{h.c.})$

Several of these interactions still remain unknown!

If new physics is to explain any of these open questions...

What is its nature?

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BSM will typically modify the properties of the Higgs boson

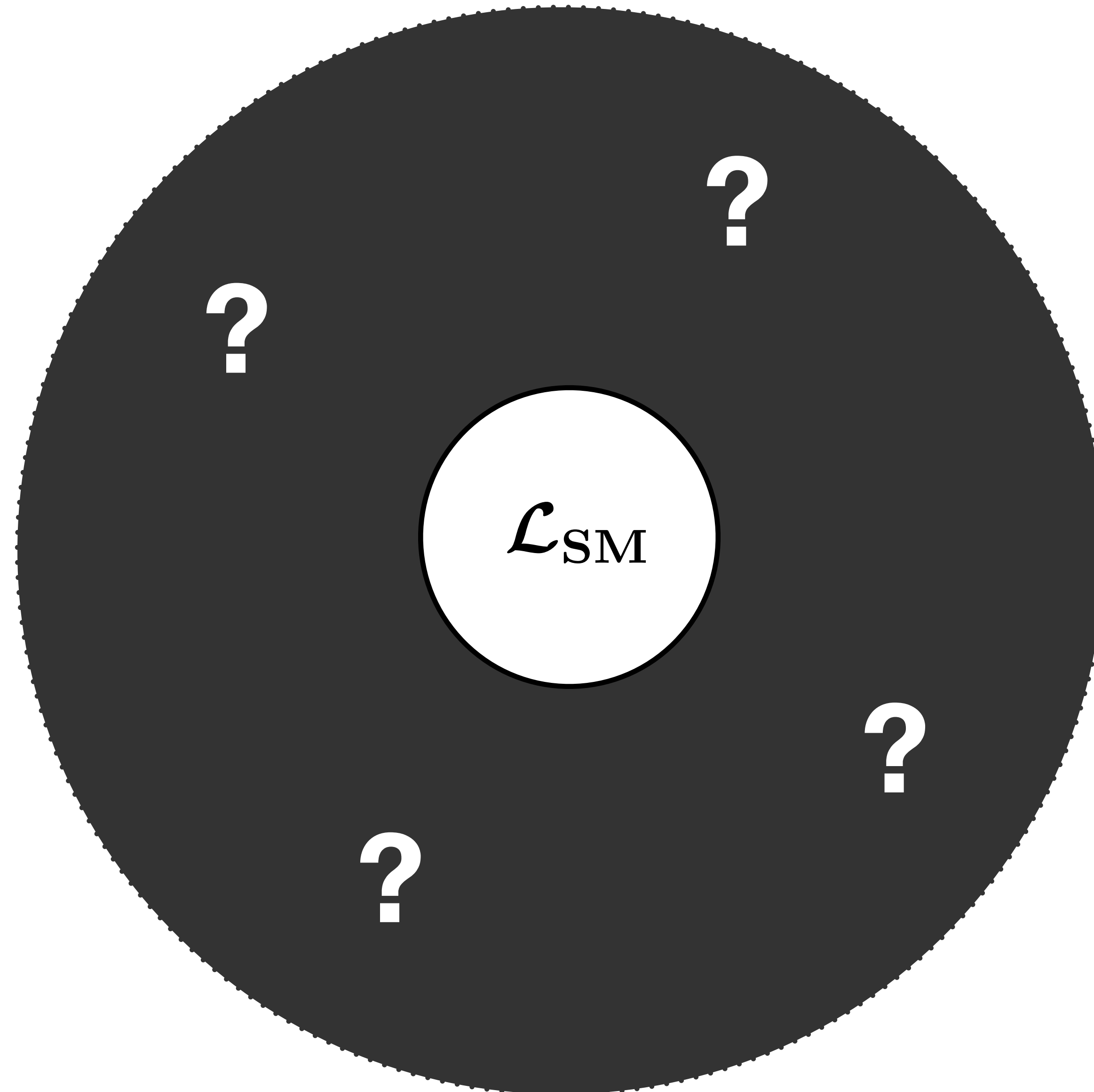
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$$\begin{aligned}\mathcal{L}_{\text{SM}} = & -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + \overline{\psi}^i i \not{D} \psi^i + (D_\mu \phi)^\dagger D^\mu \phi \\ & -V(\phi) - (y_{ij}^f \overline{\psi}_L^i \phi f_R^j + \text{h.c.})\end{aligned}$$

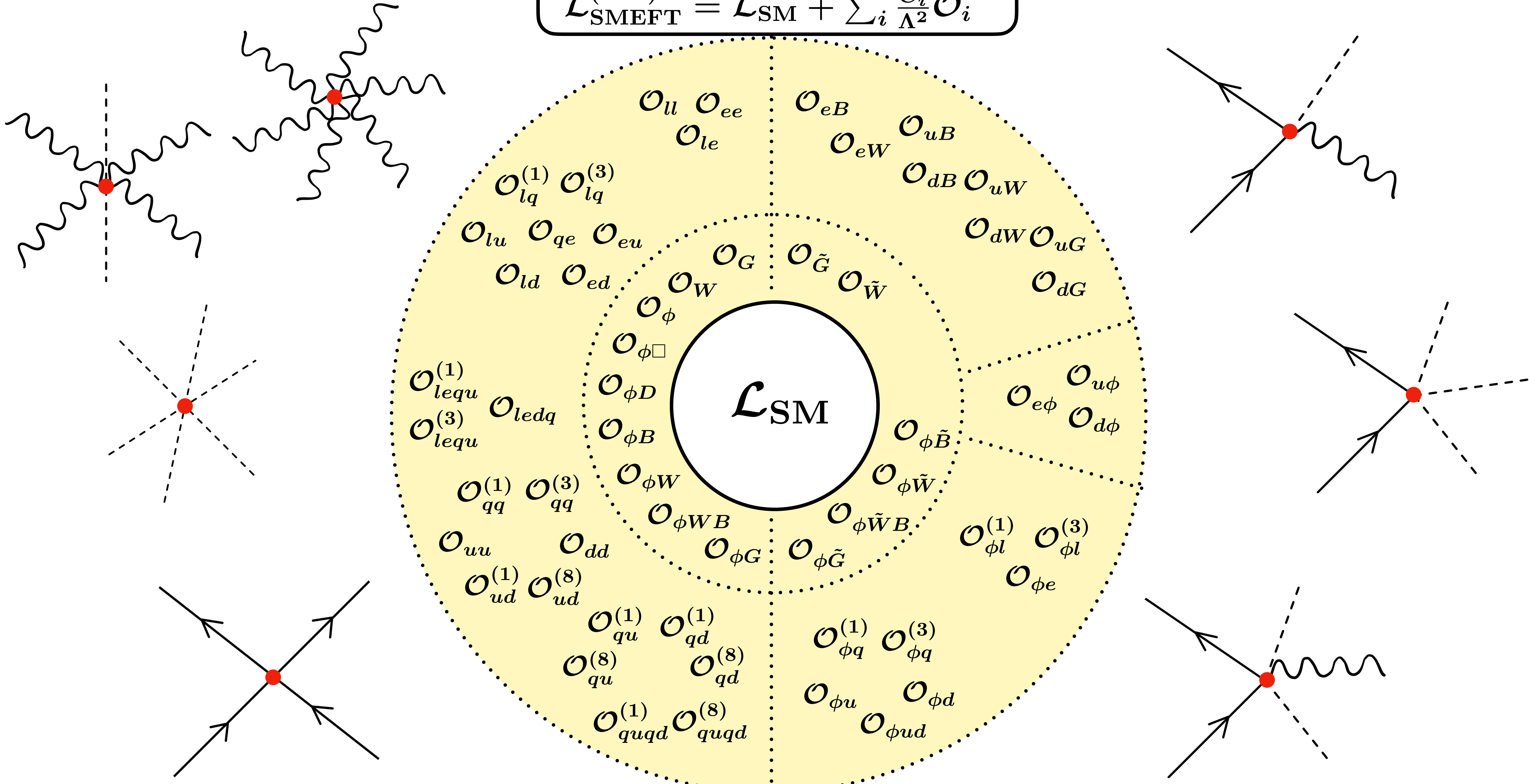
But new physics may be hiding in many other places!

BSM can “change” the SM in many different ways...



BSM can “change” the SM in many different ways...

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$



BSM can “change” the SM in many different ways...

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

And this is just the simple picture at LO

2 to 2 fermion processes

Top/Higgs/EW physics @ e+e-

Top couplings

Top/Higgs/EW physics

Higgs self-coupling

Higgs “couplings”

EWPO: Z-pole, W obs.

EW precision/Higgs precision

Also in Higgs physics (VBF, VH)

Top/Higgs/EW physics @ pp

BSM can “change” the SM in many different ways...

$$\mathcal{L}_{\text{SM EFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

And this is just the

What do need from the next generation of high-energy particle physics experiments to maximize our chances of learning about this new physics?

In the search of the unknown, the best tool is that which can explore as many directions as possible in the BSM parameter space

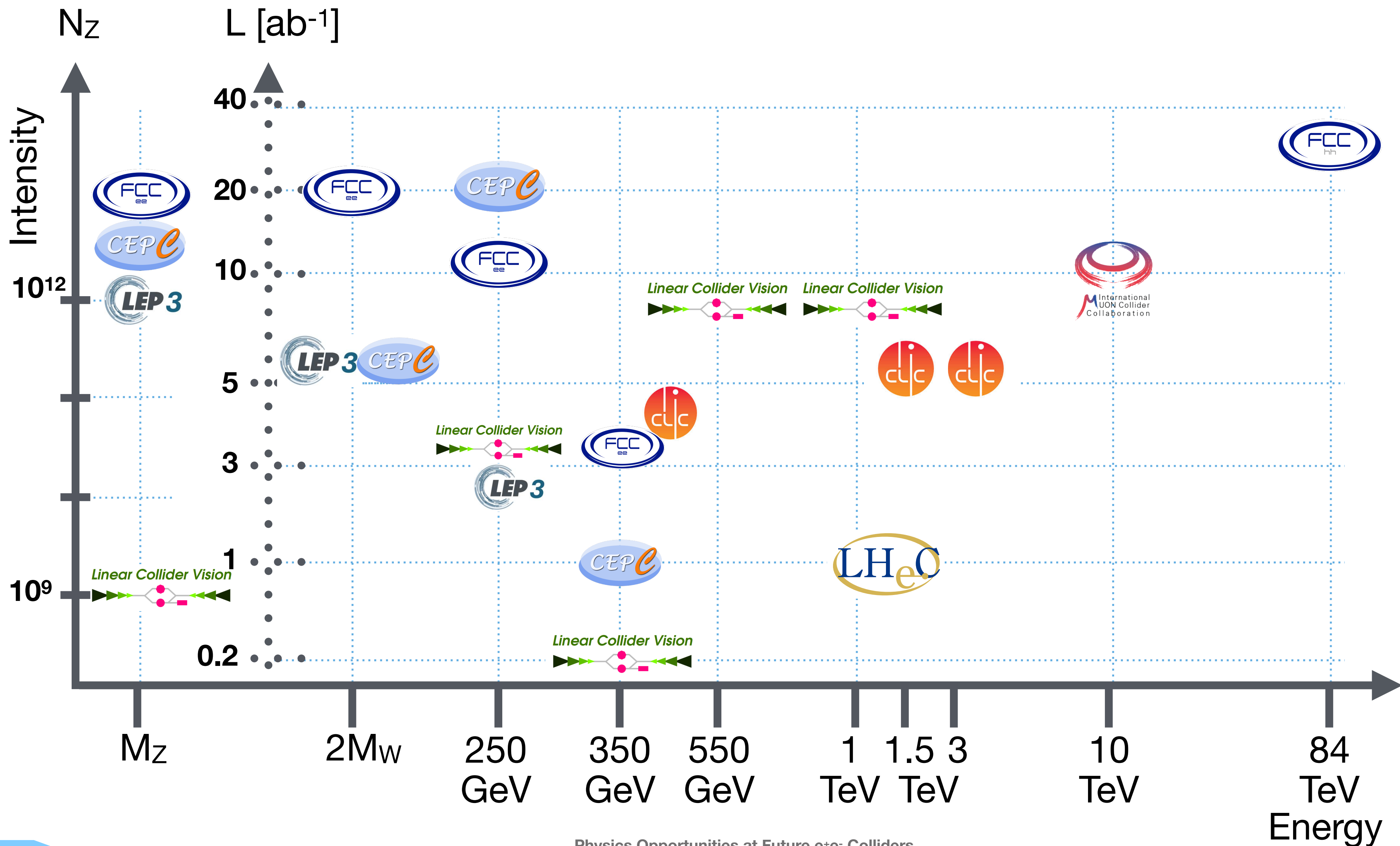
More than Higgs factories

e⁺e⁻ colliders can offer a broad physics programme for precision measurements that will allow to chart deviations of the SM in many directions

⇒ Indirect test of NP at e⁺e⁻ ⇒ Guide direct searches at future pp

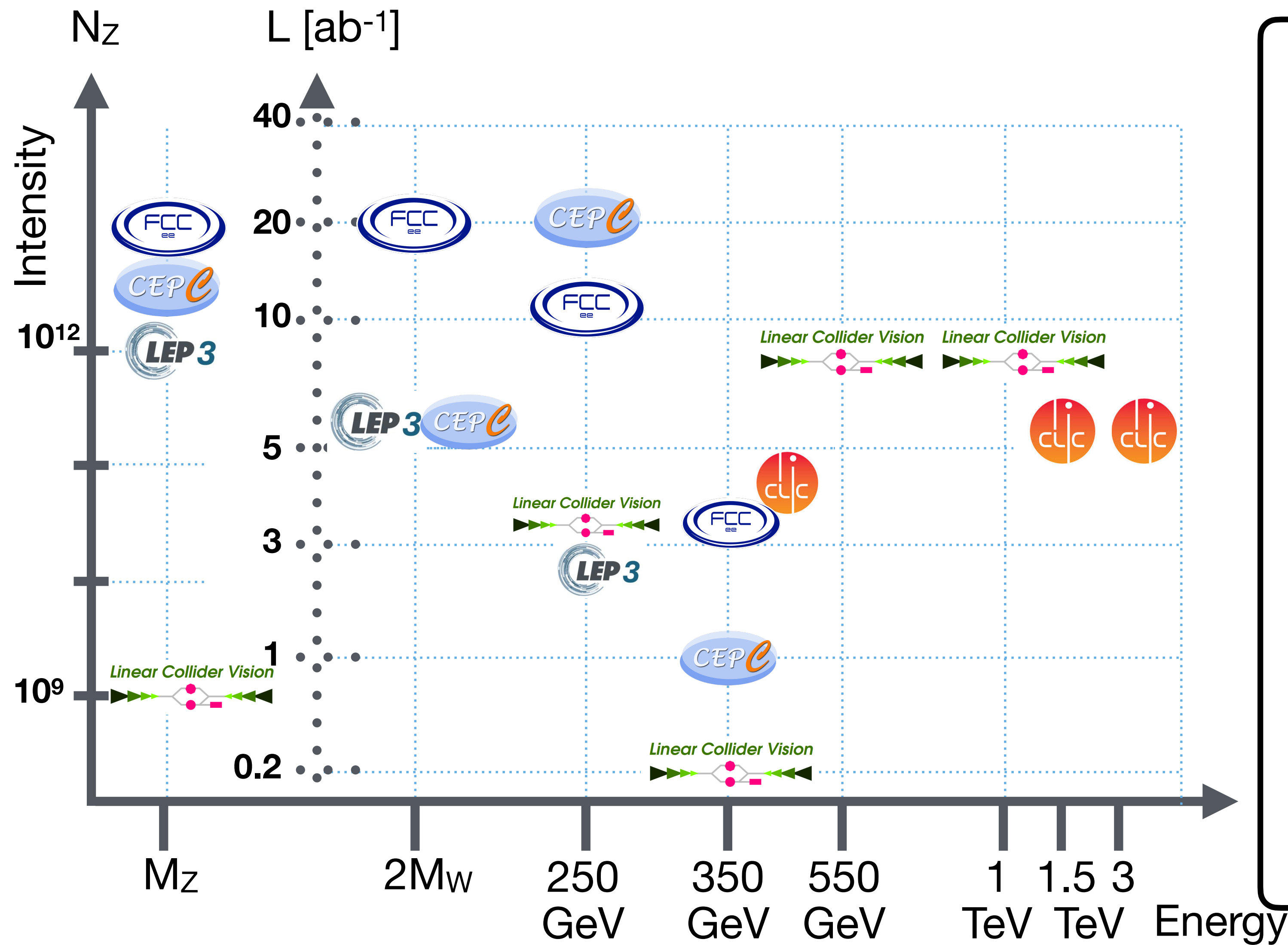
Future collider proposals for all tastes

Very different design to address the search for new physics

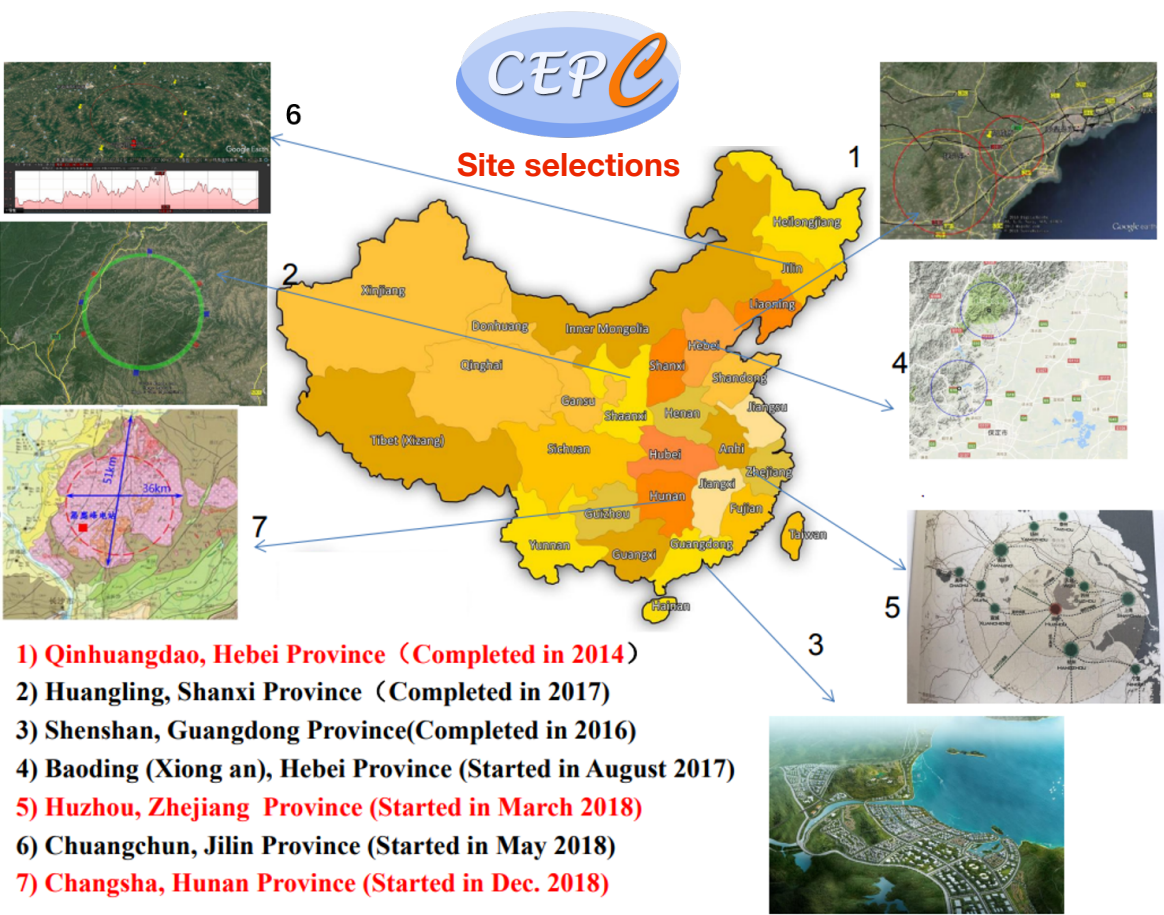
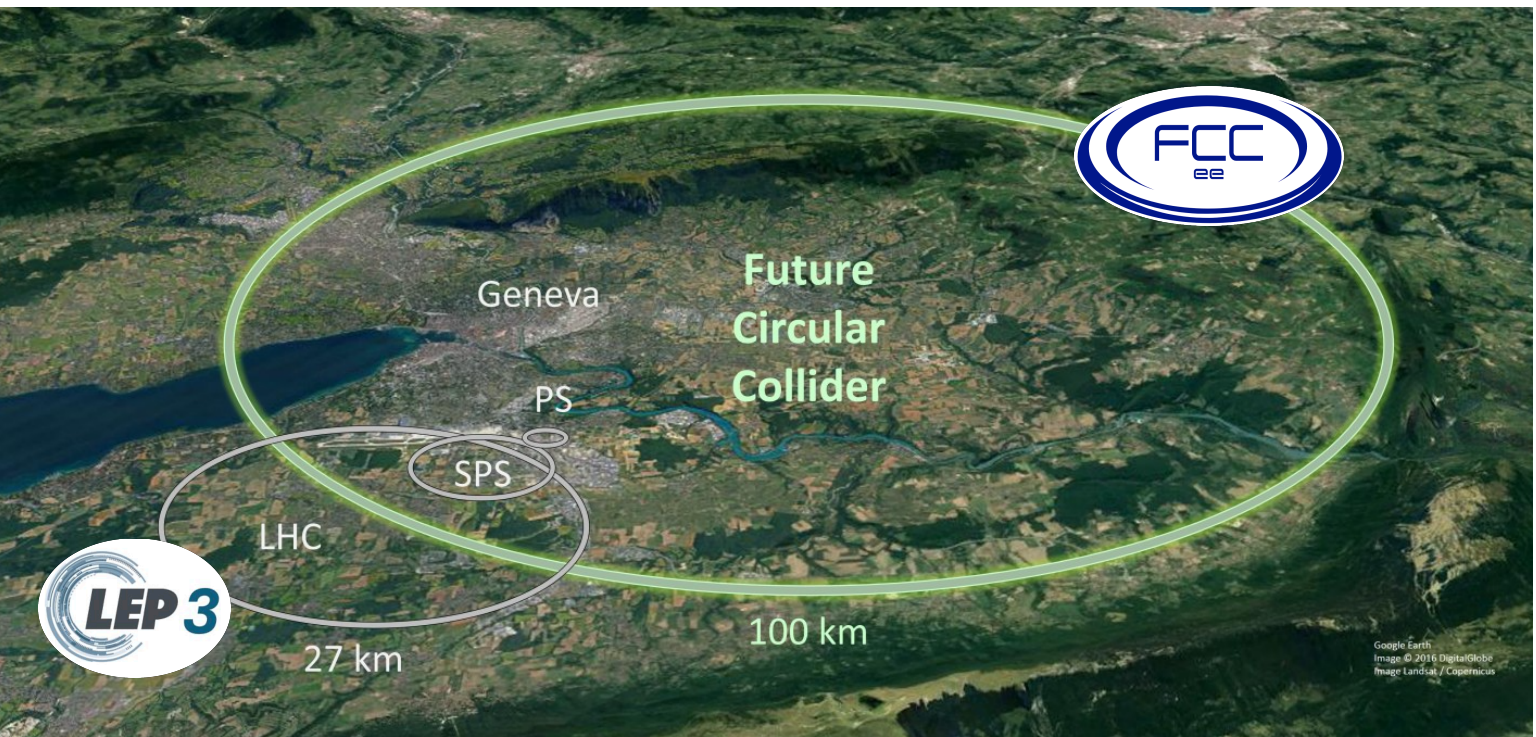


Future collider proposals for all tastes

Future e⁺e⁻ collider projects

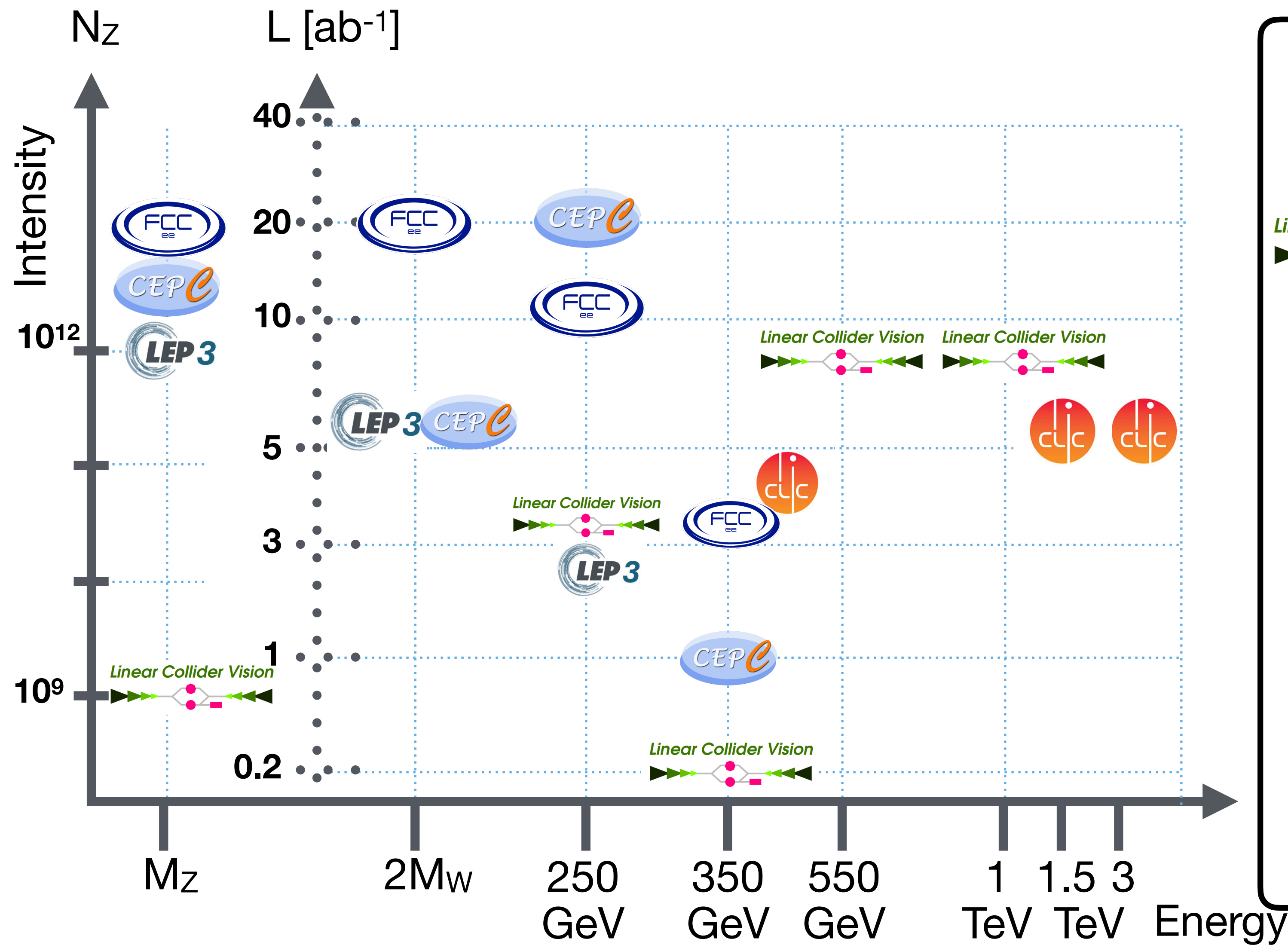


e⁺e⁻ Linear Colliders: FCC-ee, CEPC and LEP3



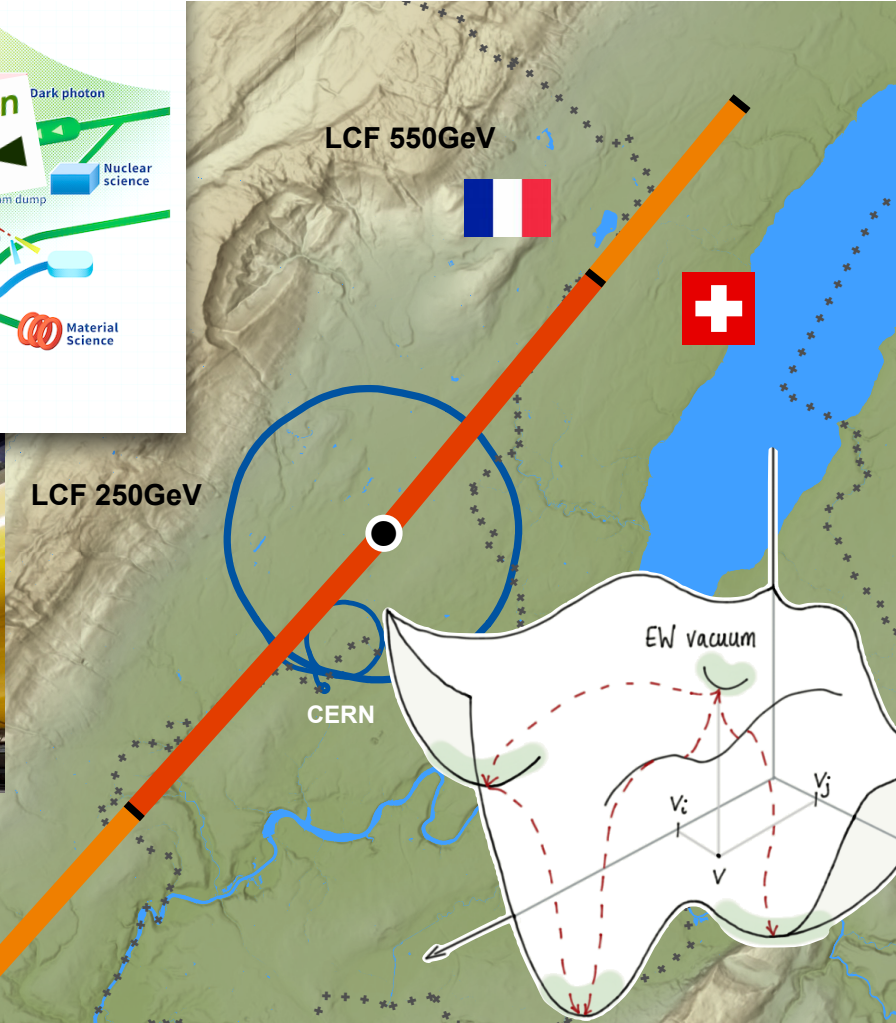
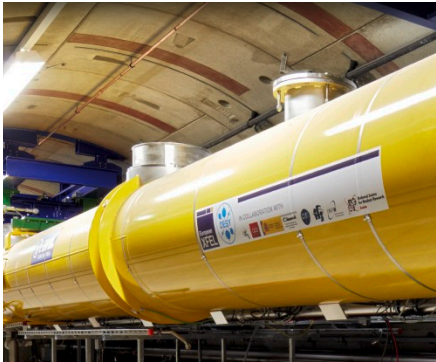
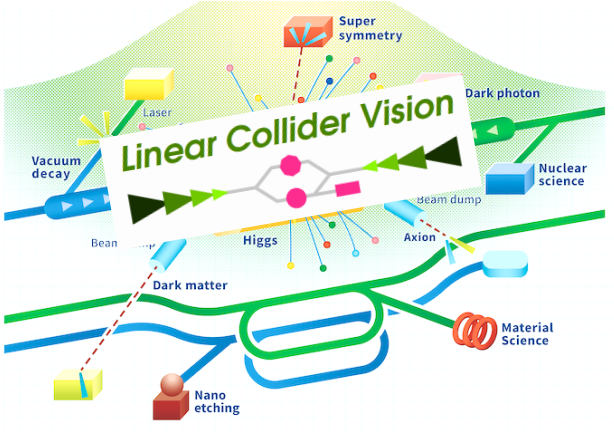
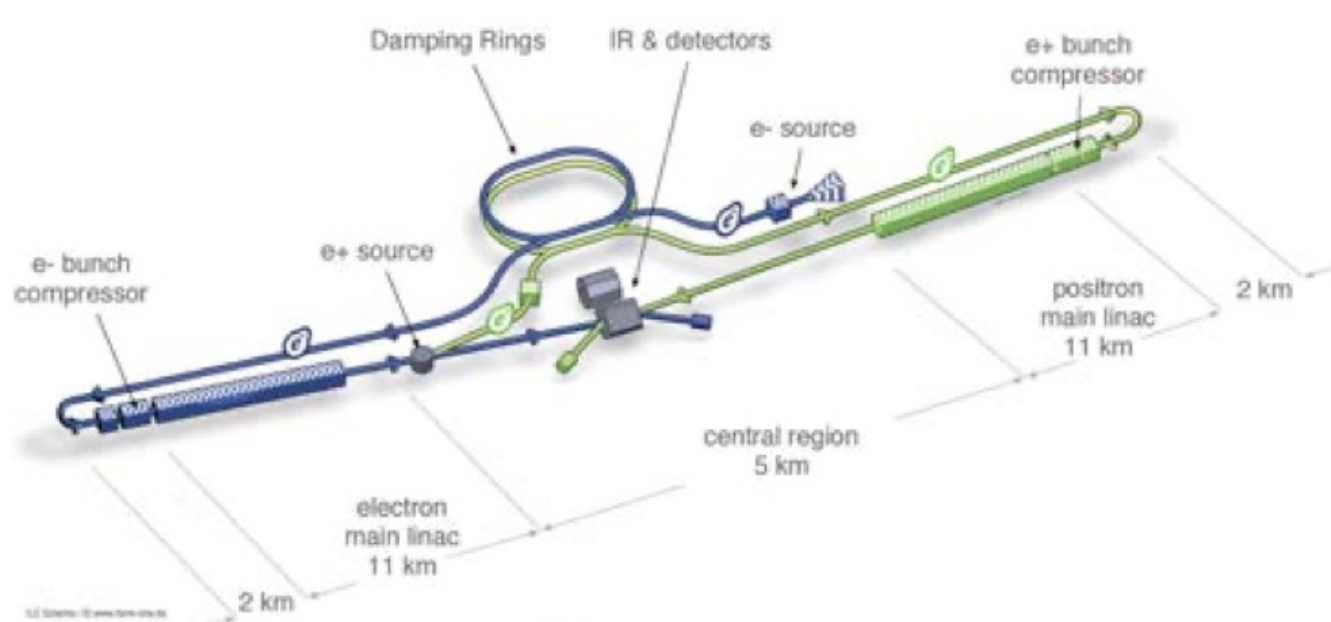
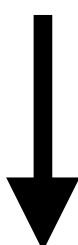
Future collider proposals for all tastes

Future e^+e^- collider projects



e^+e^- Linear Colliders: LCF and CLIC

Linear Collider Vision



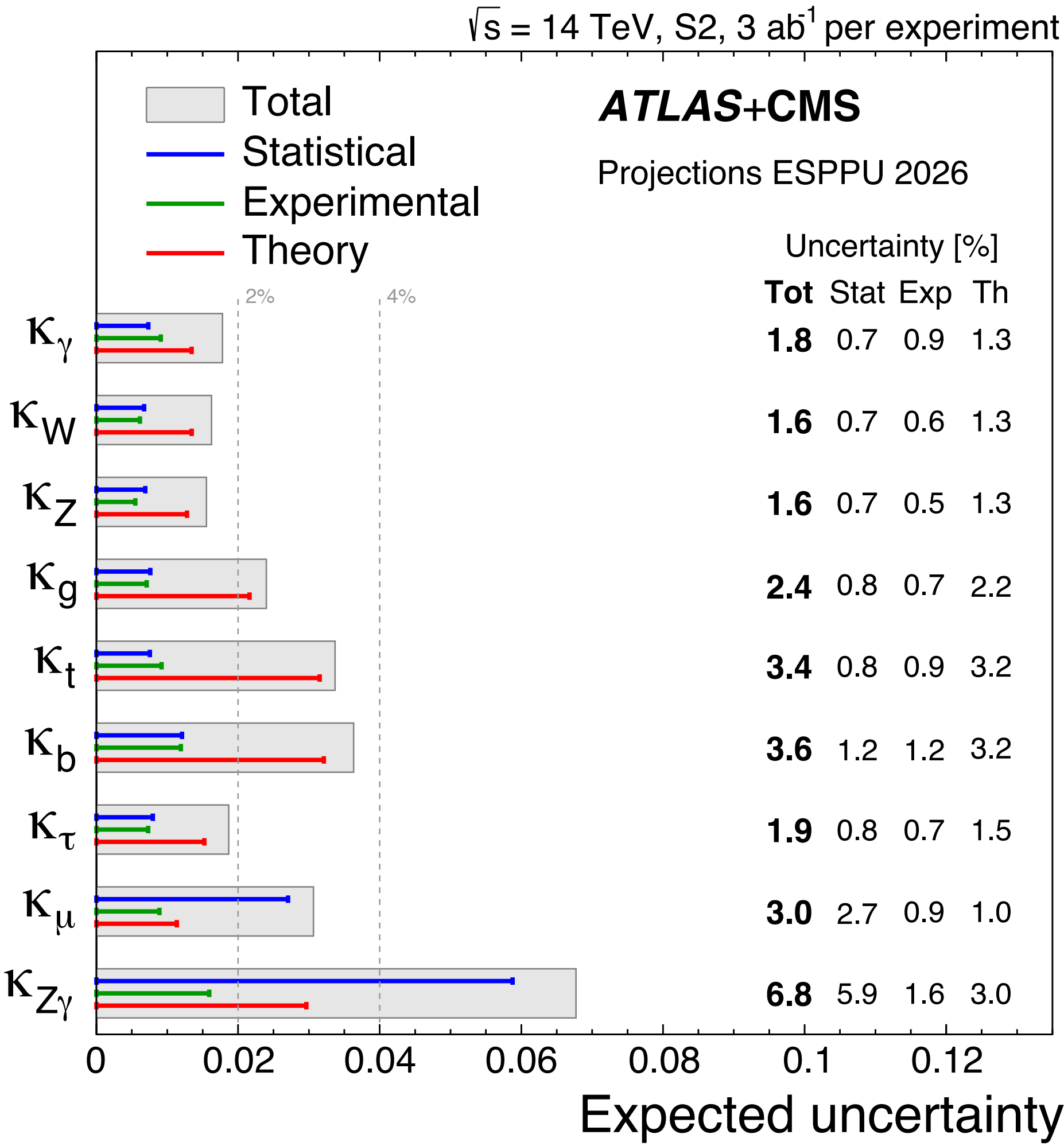
The need for a

e^+e^- Higgs factory

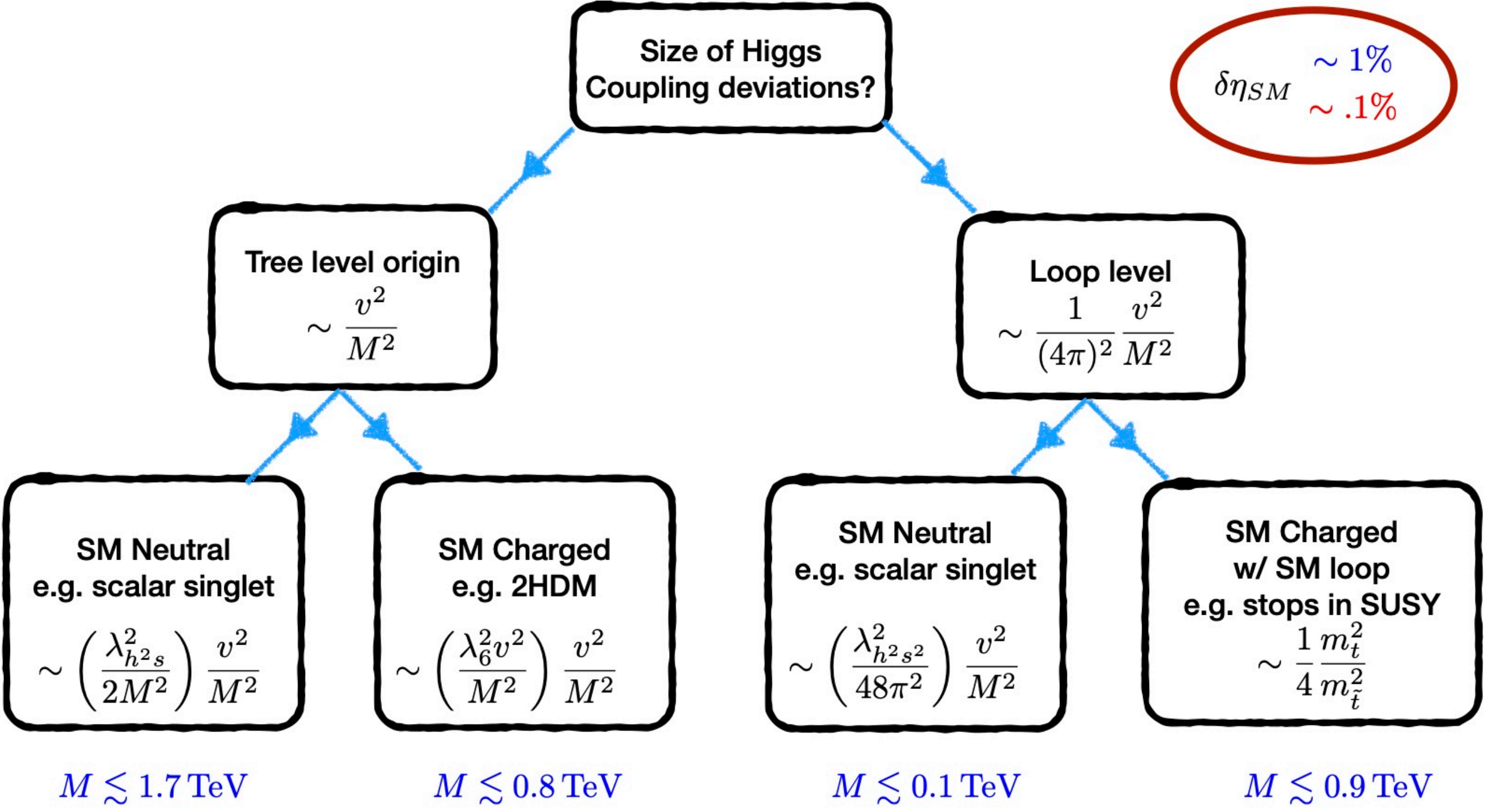
Physics Opportunities at e⁺e⁻ Higgs factories

- The HL-LHC will open the door to percent-level precision Higgs physics...

This first exploration of Higgs properties provides limited information about NP!



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



Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision
 $\delta\kappa \sim 1\%$

Physics Opportunities at e⁺e⁻ Higgs factories

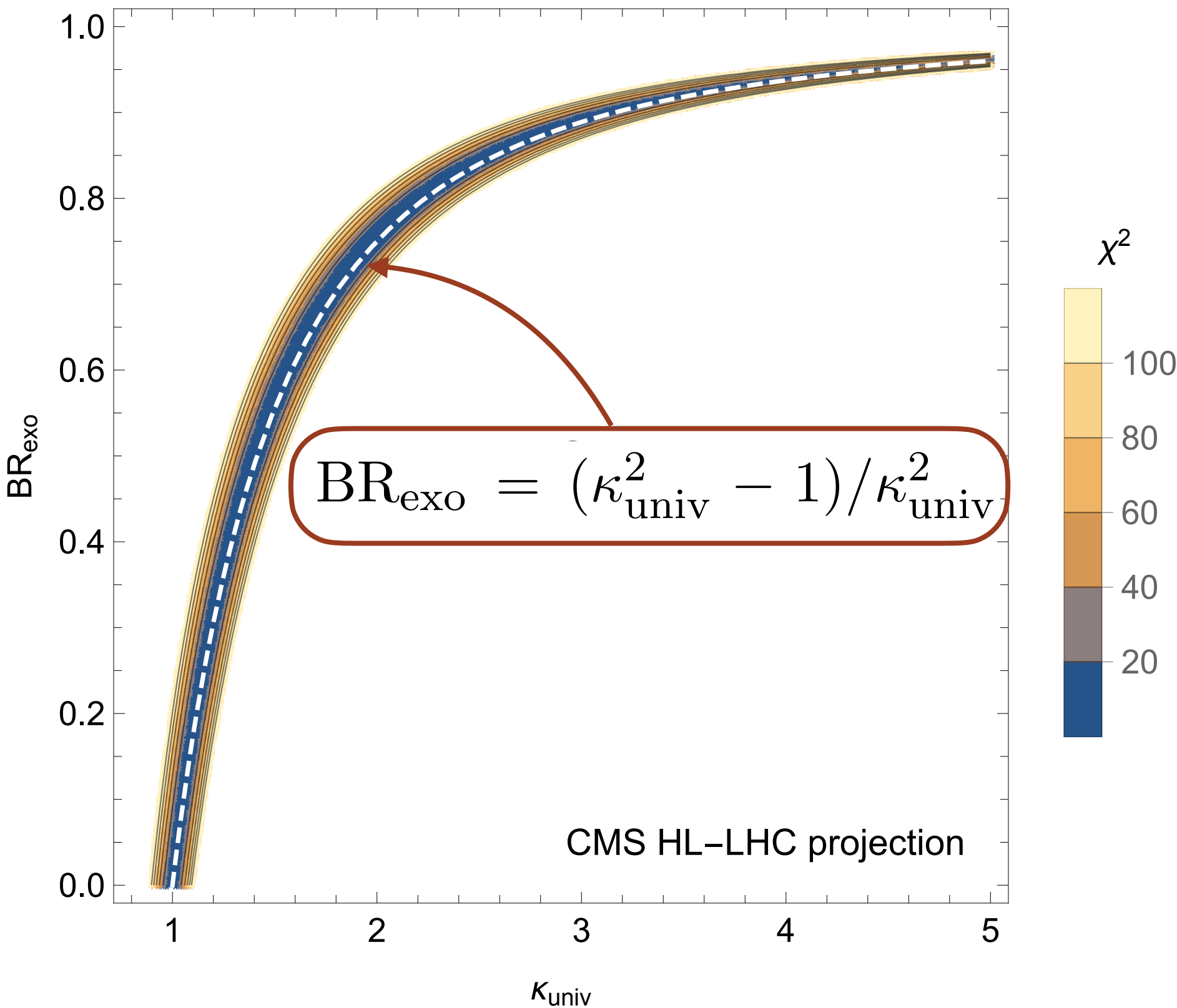
- The HL-LHC will open the door to percent-level precision Higgs physics...

This first exploration of Higgs properties provides

Plus this is only information about coupling “ratios”

LHC measurements $\Rightarrow$ on-shell rates

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

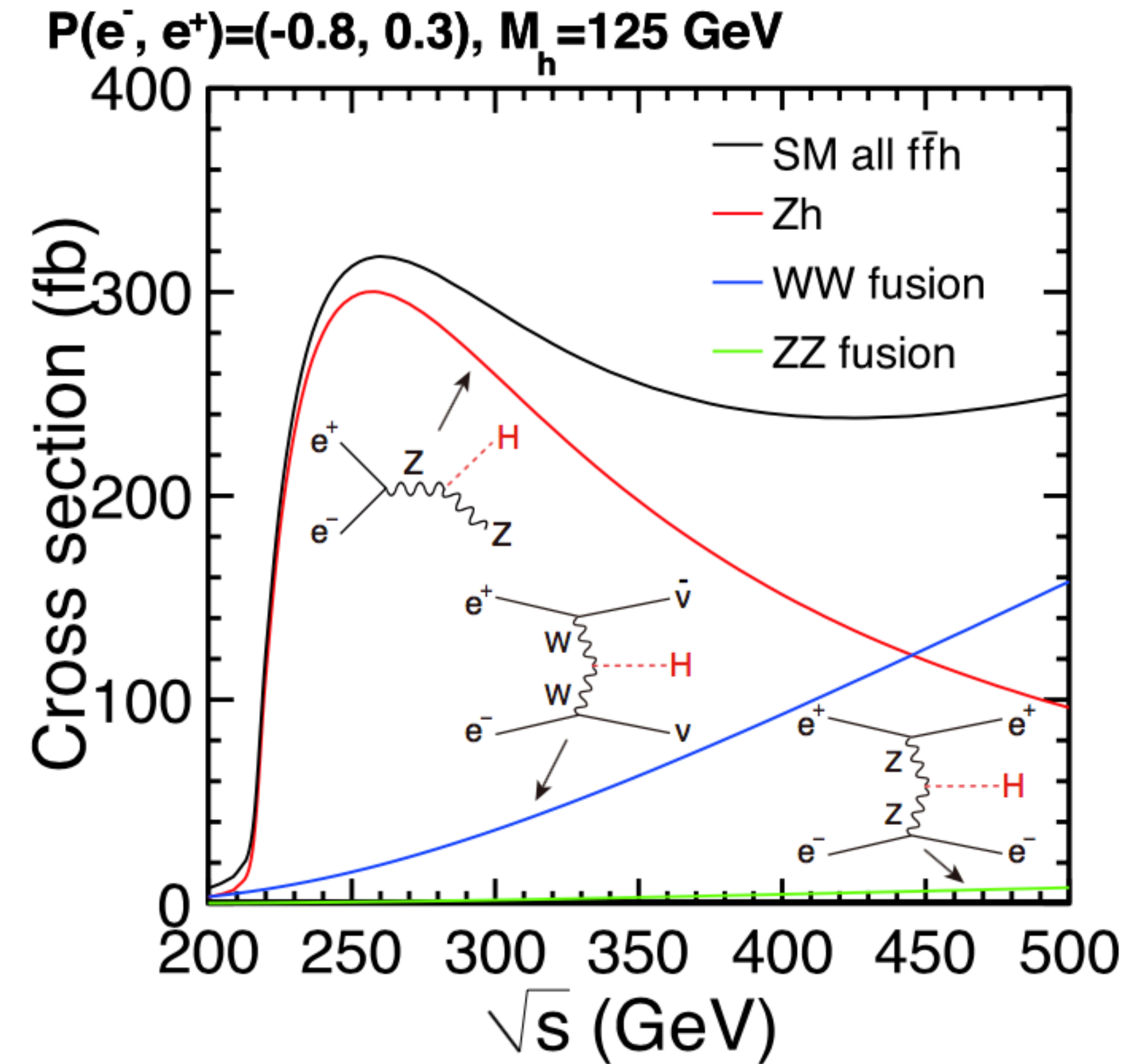
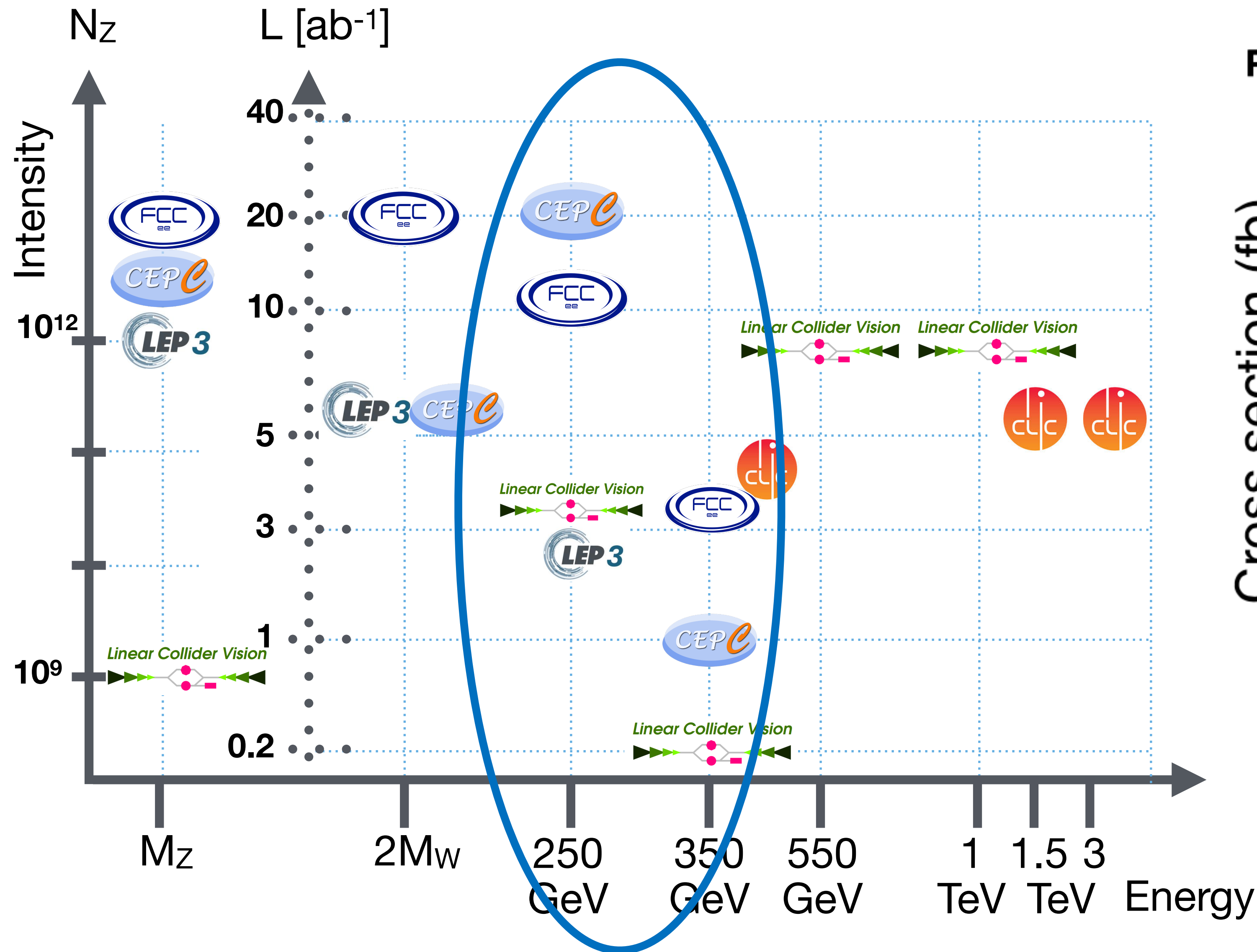


No absolute cross section $\Rightarrow$ No absolute measurement of Higgs couplings

$\delta\kappa \sim 1\%$

Physics Opportunities at e^+e^- Higgs factories

Higgs factory runs



Physics Opportunities at e^+e^- Higgs factories

Higgs factory runs

N_Z L [ab^{-1}]

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

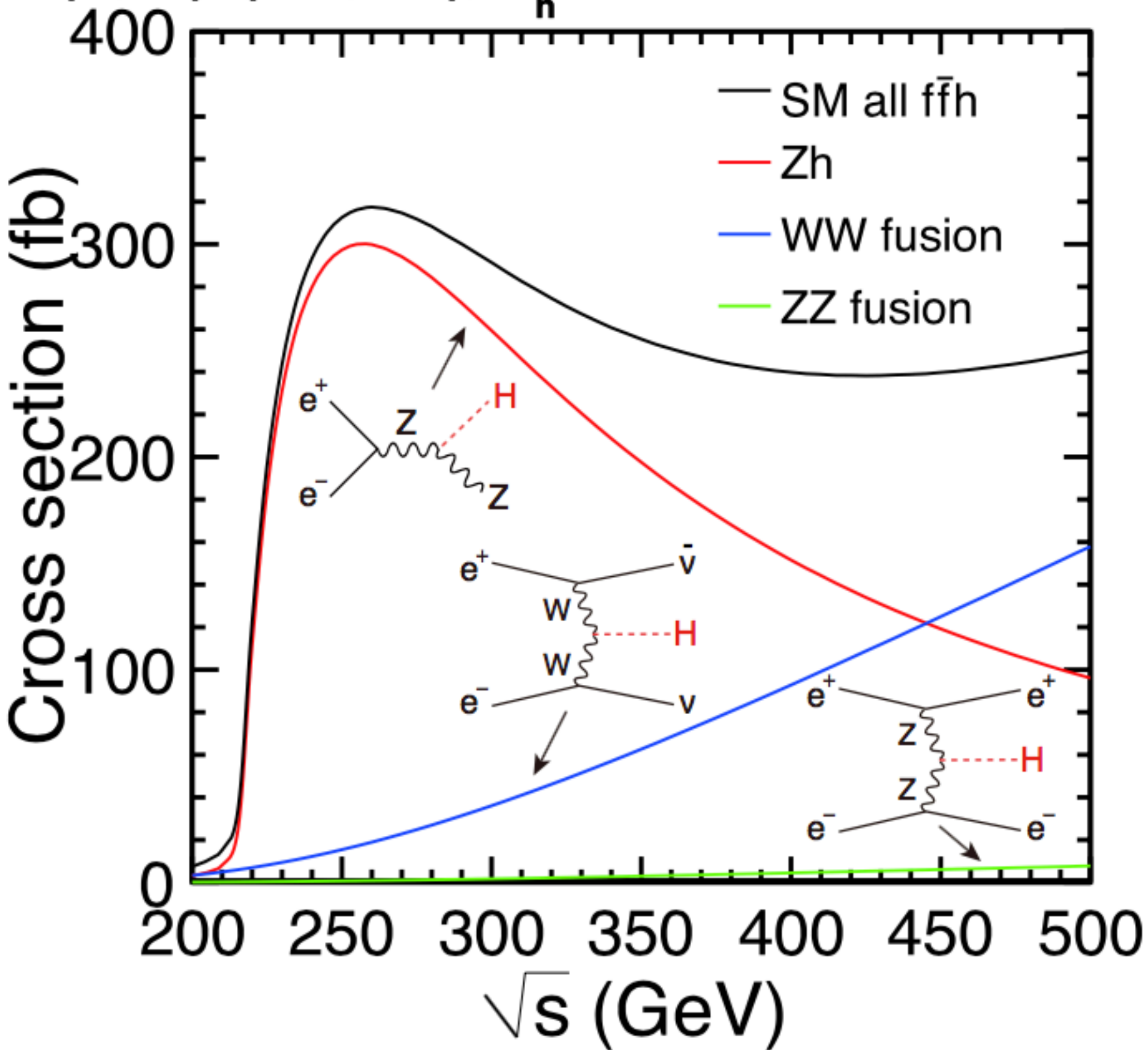
Less number of Higgses than at HL-LHC but...

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

Enables measurements not possible at LHC



$P(e^-, e^+) = (-0.8, 0.3)$, $M_h = 125 \text{ GeV}$

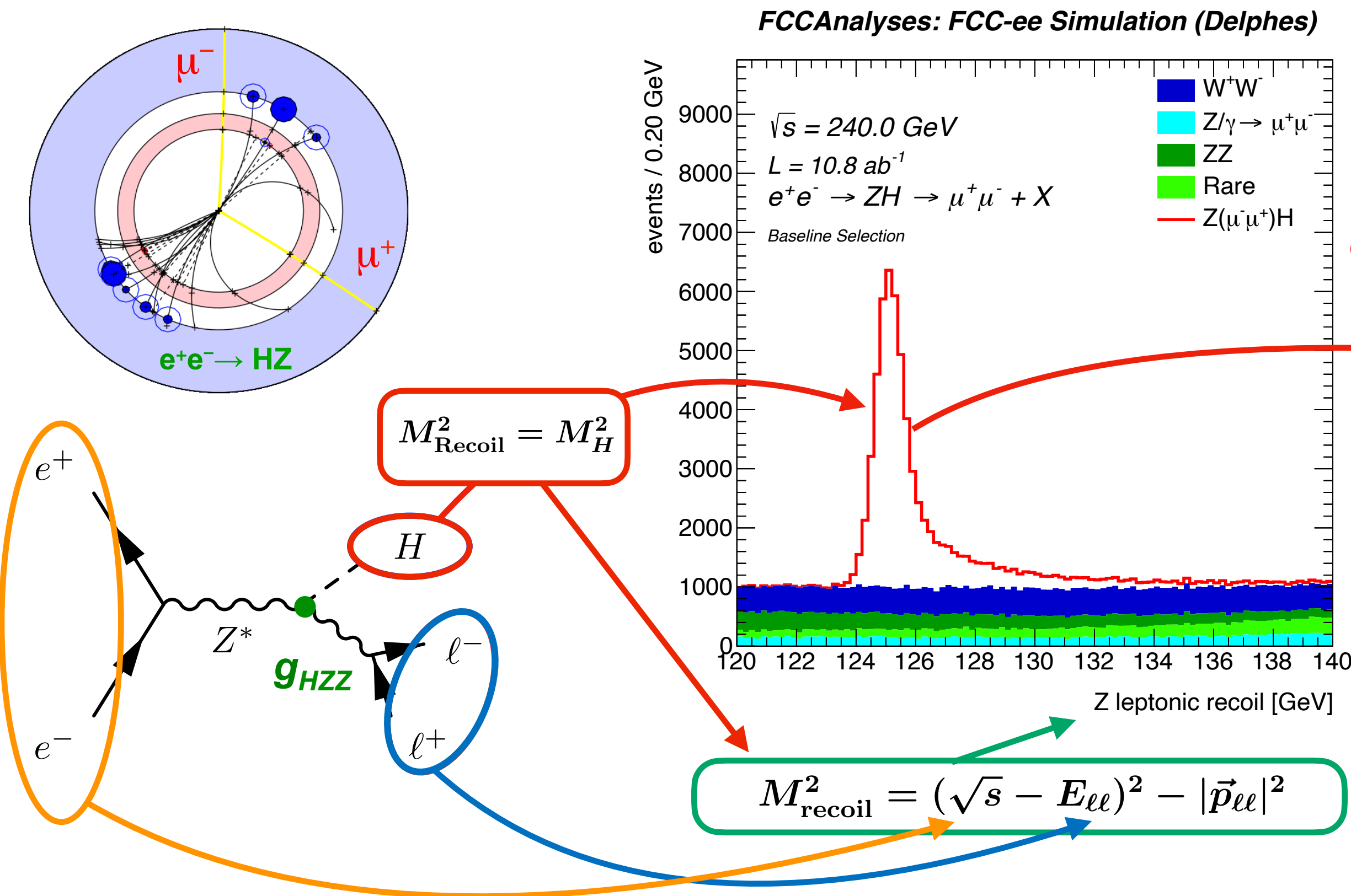


Physics Opportunities at e⁺e⁻ Higgs factories

Higgs factory runs

Recoil mass method

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



$$\sigma_{ZH} \text{BR}_{ZZ} \propto \frac{g_{HZZ}^4}{\Gamma_H}$$
$$\frac{\sigma_{WW \rightarrow H} \text{BR}_{bb}}{\sigma_{ZH} \text{BR}_{bb} \times \sigma_{ZH} \text{BR}_{WW}} \propto \frac{g_{HZZ}^4}{\Gamma_H}$$

$$\sigma_{ZH} \propto g_{HZZ}^2$$

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

$$\Gamma_H$$

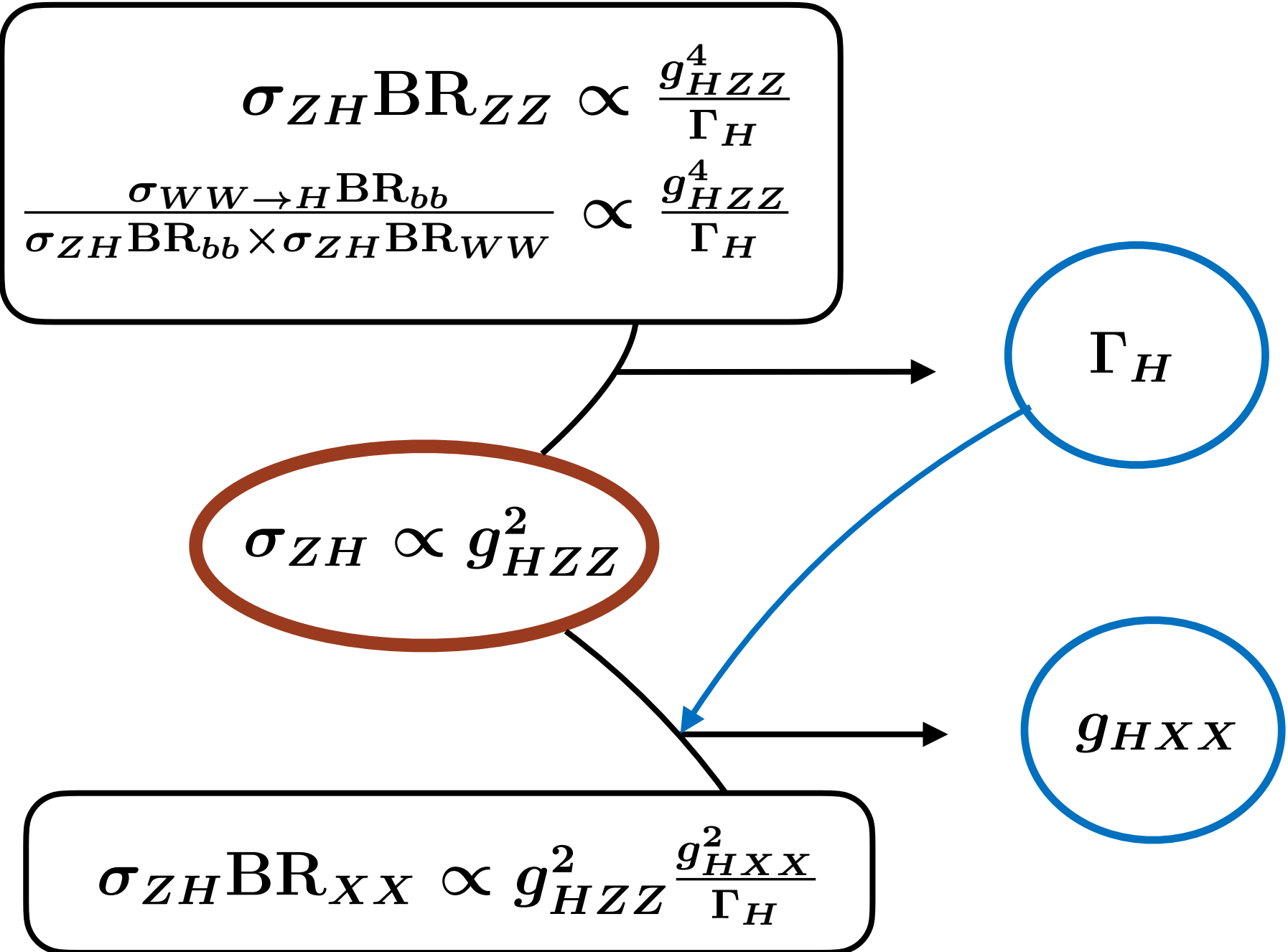
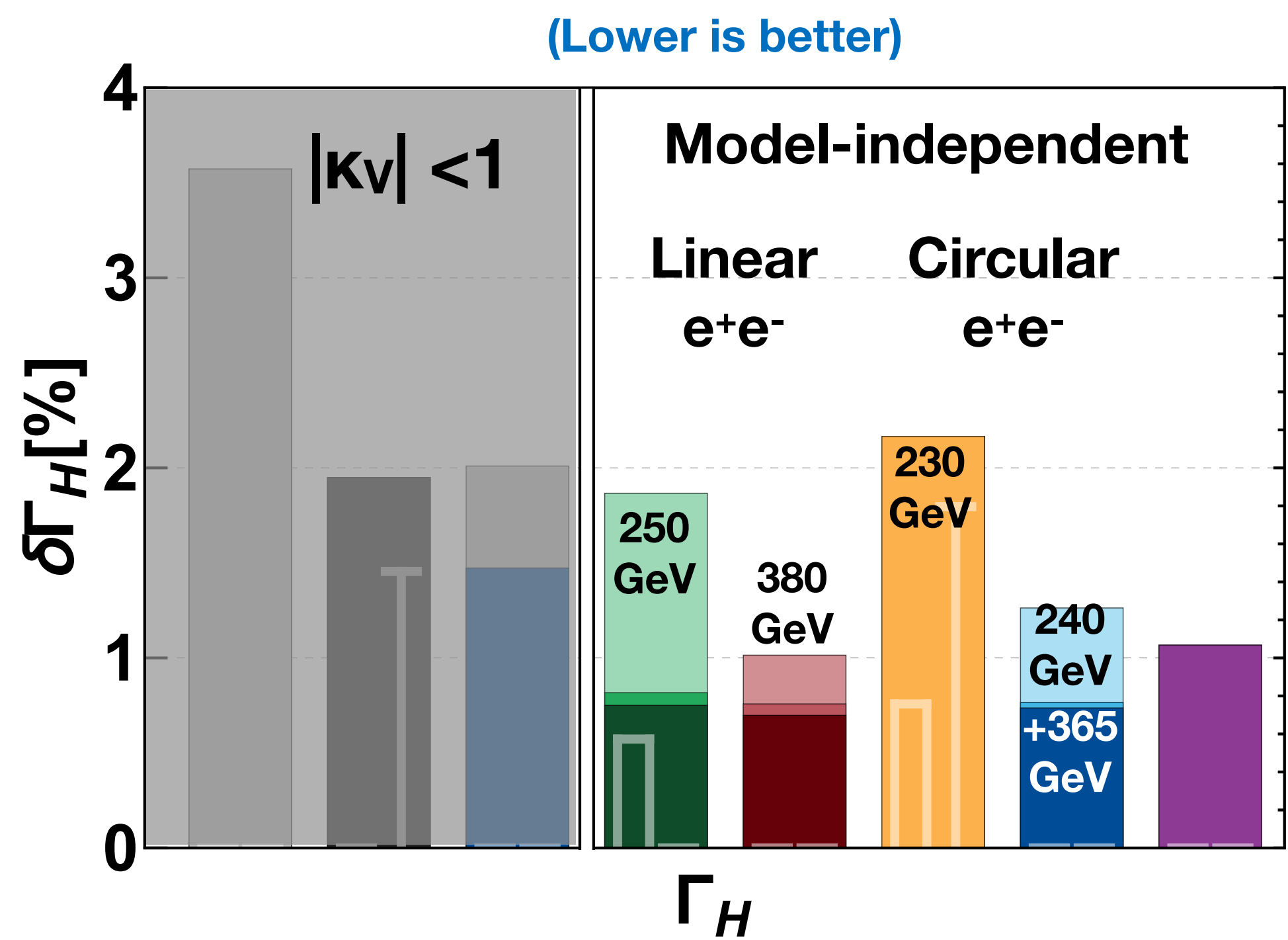
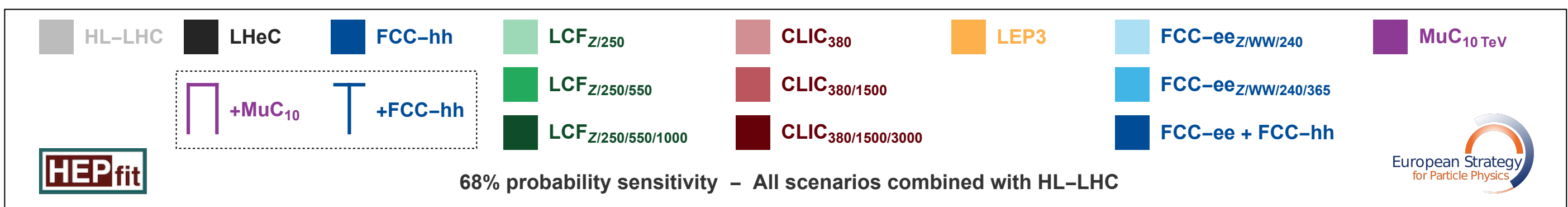
$$g_{HXX}$$

Absolute determination of H couplings & width

GeV GeV GeV TeV TeV Energy

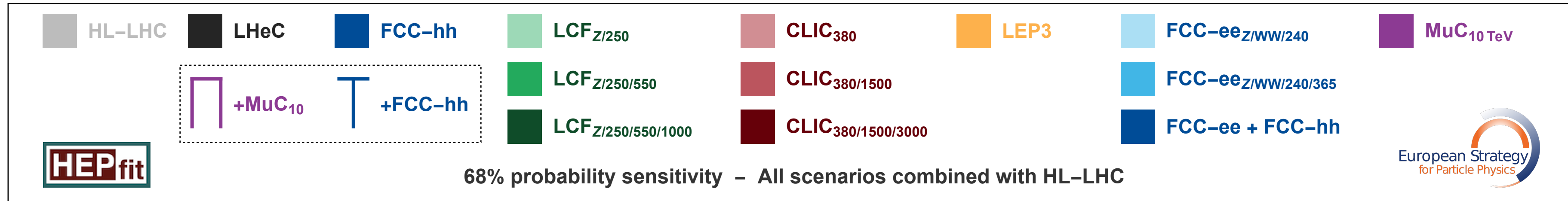
Physics Opportunities at e⁺e⁻ Higgs factories

Higgs factory runs

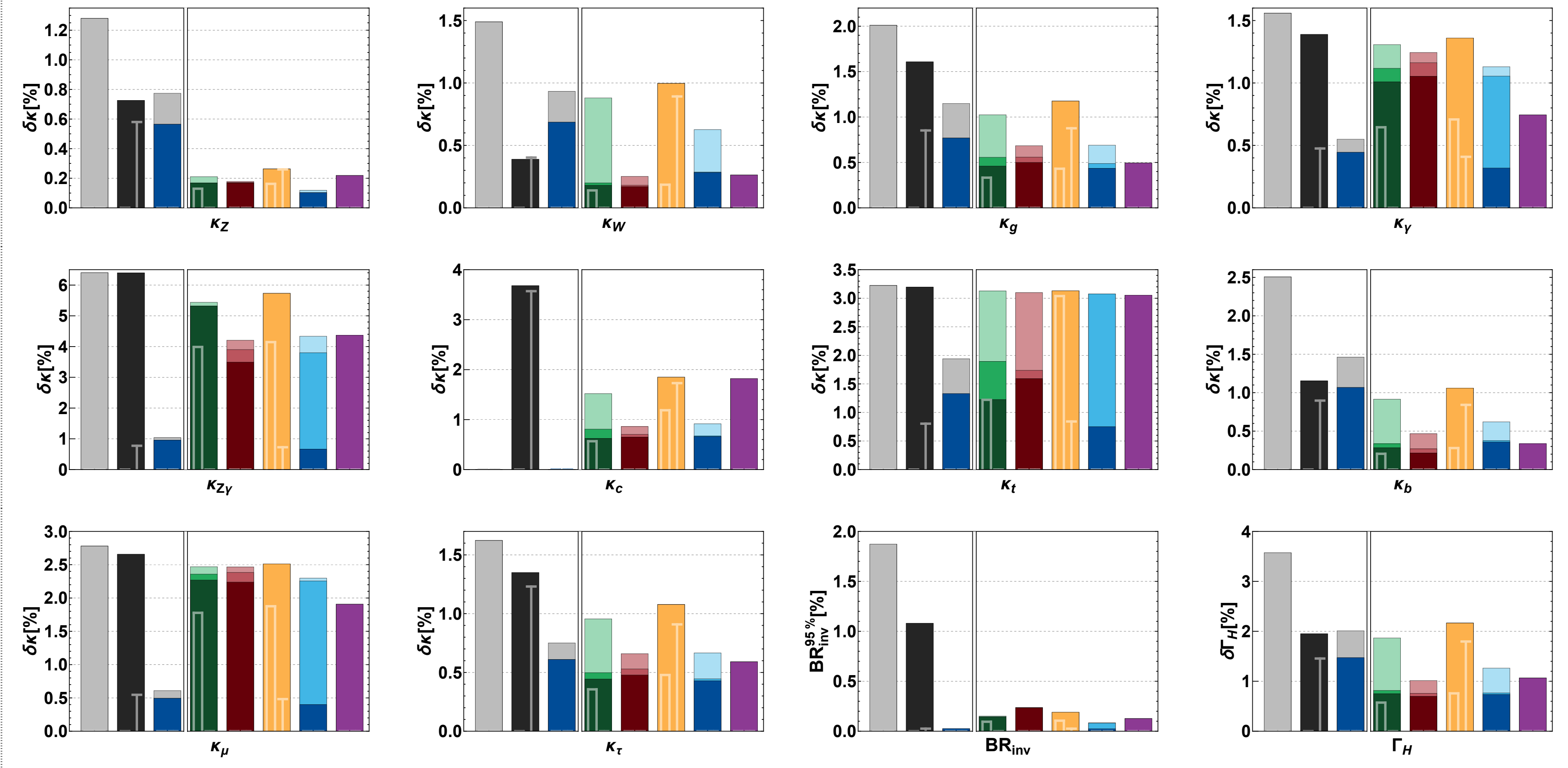


Absolute determination of H couplings & width

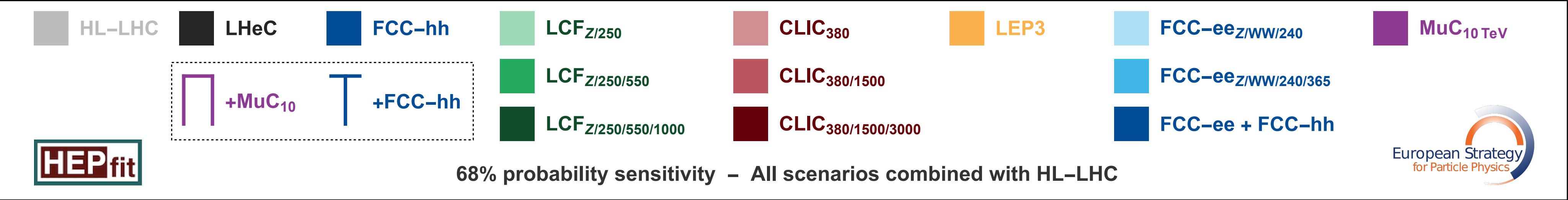
Physics Opportunities at e^+e^- Higgs factories



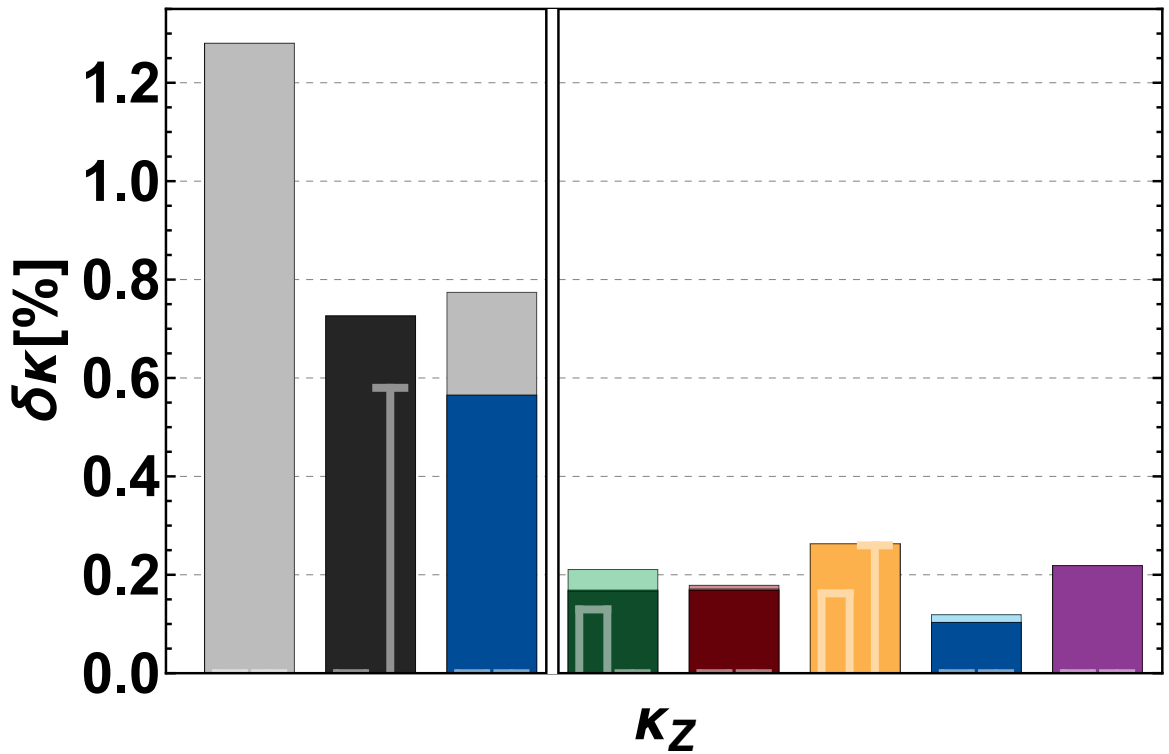
Precision Reach Higgs couplings



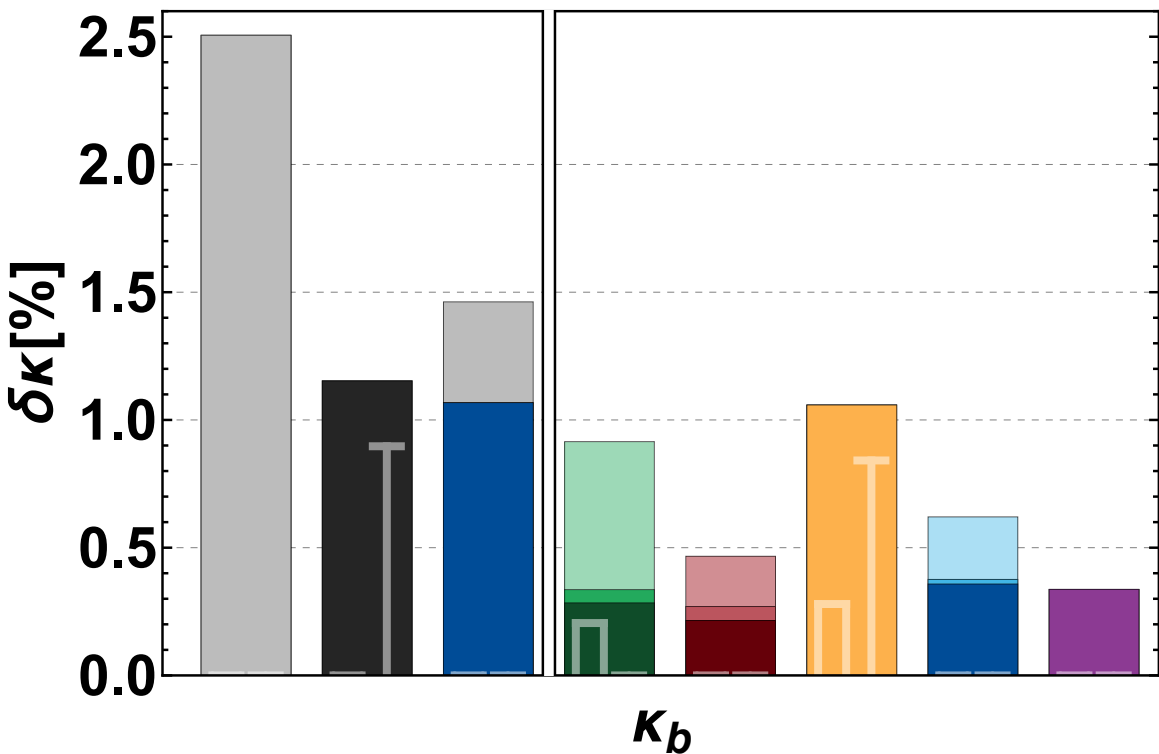
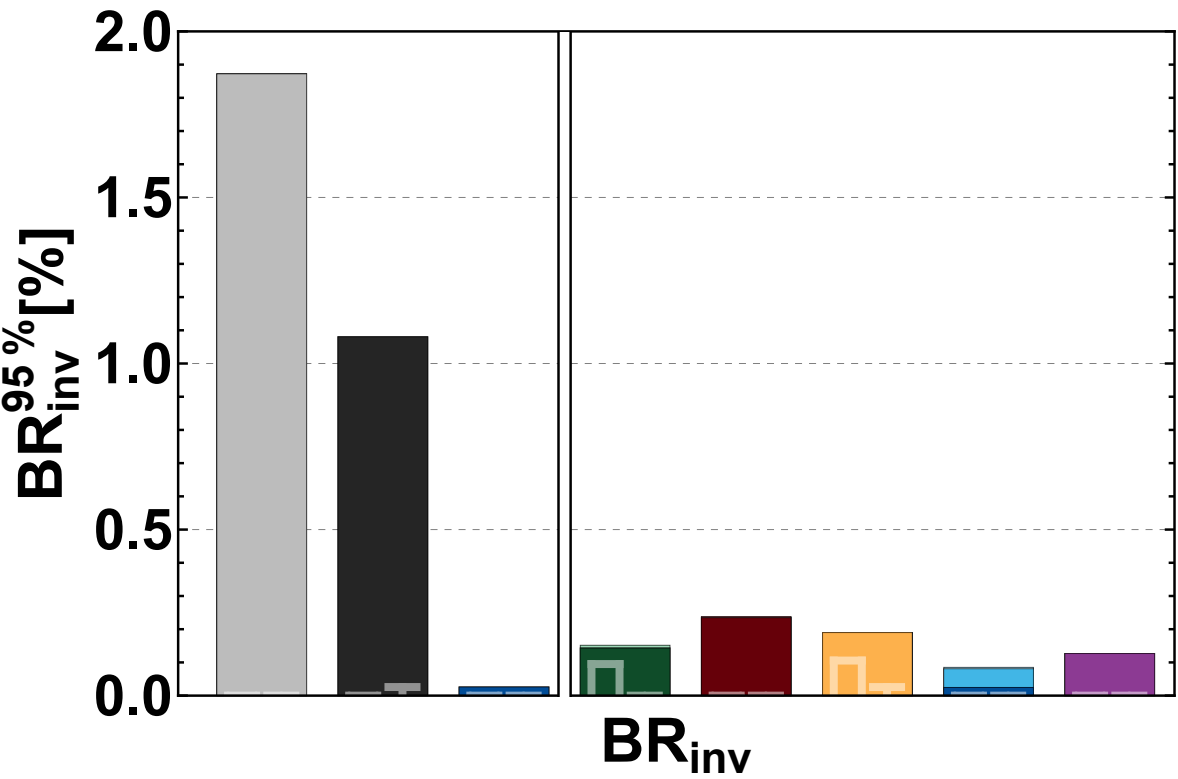
Physics Opportunities at e^+e^- Higgs factories



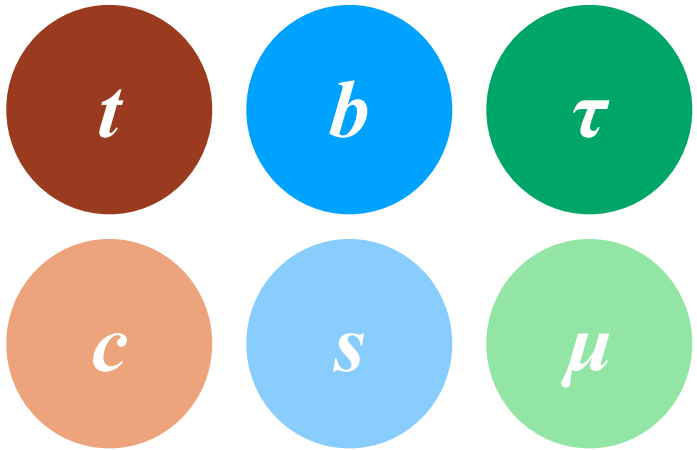
HZZ
factor ~10 improvement
wrt LHC
O(0.1%)



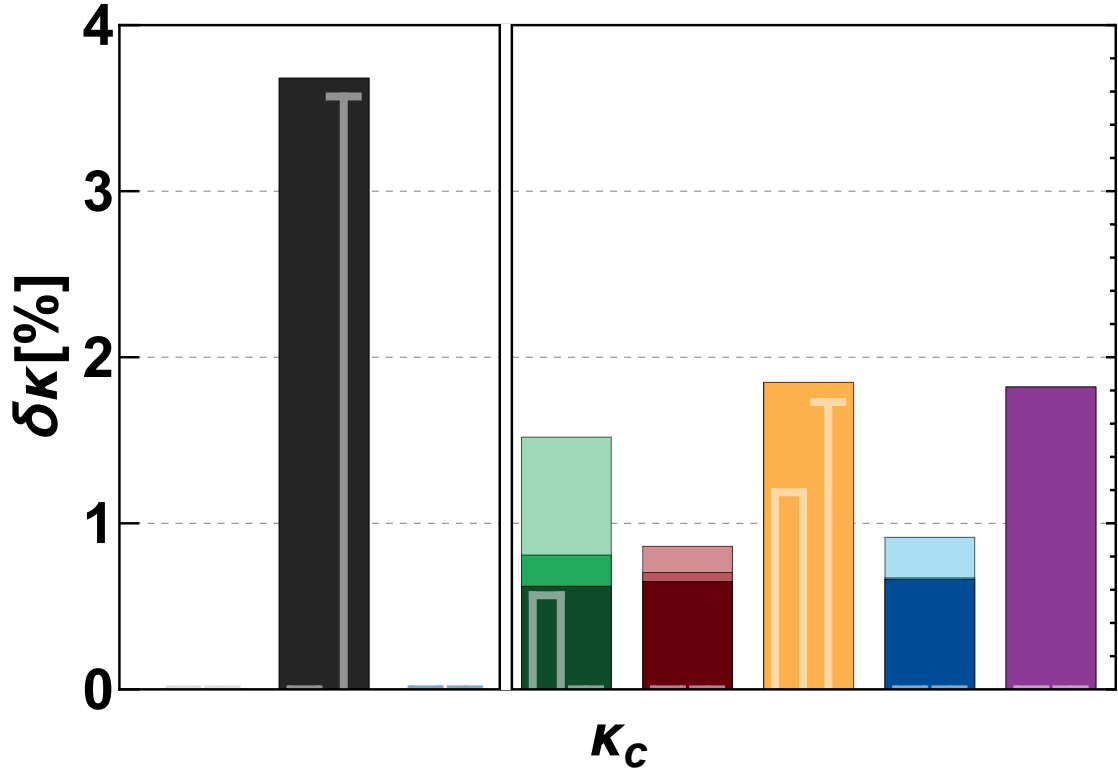
$H \rightarrow BSM$
 $BR(H \rightarrow inv) < 0.08\%$
 $BR(H \rightarrow exo) < 0.7\%$



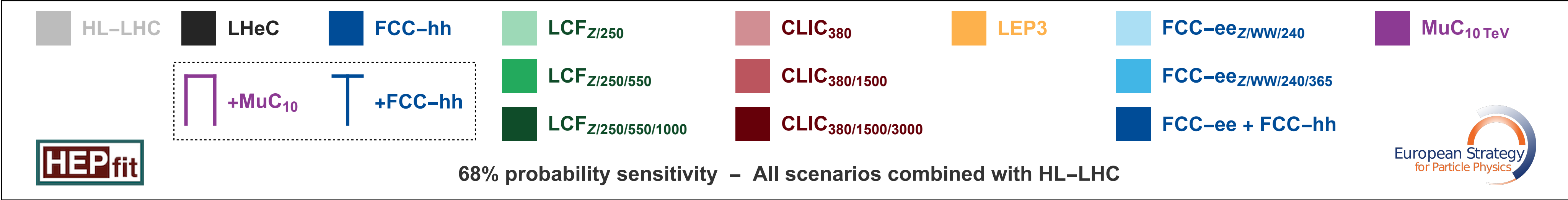
3rd family:
factor ~10 improvement
wrt LHC



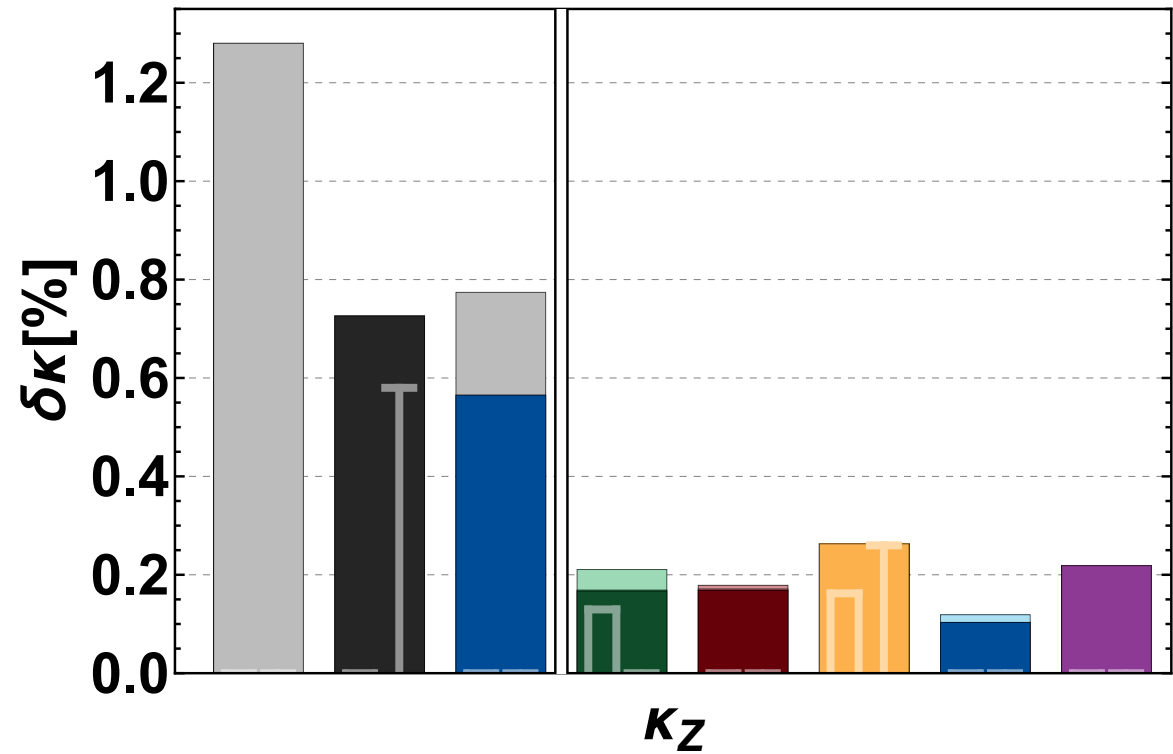
2nd quark families
Beyond the LHC reach
(O(1) sensitivity to strange)



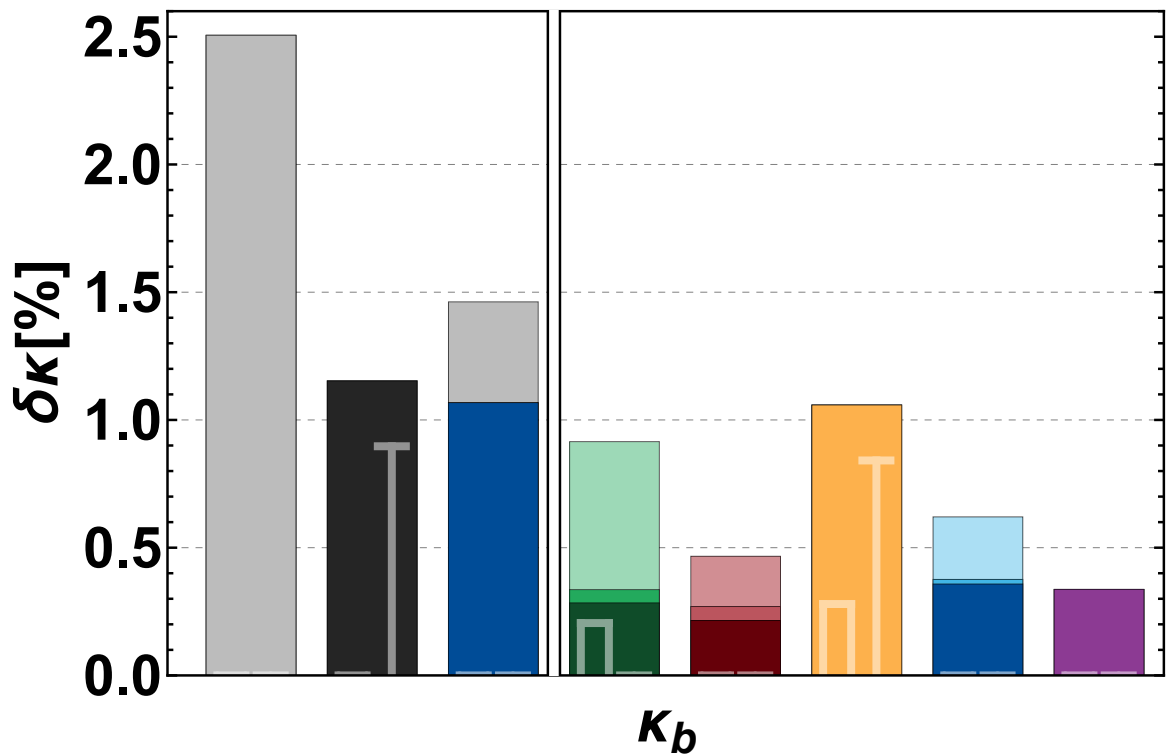
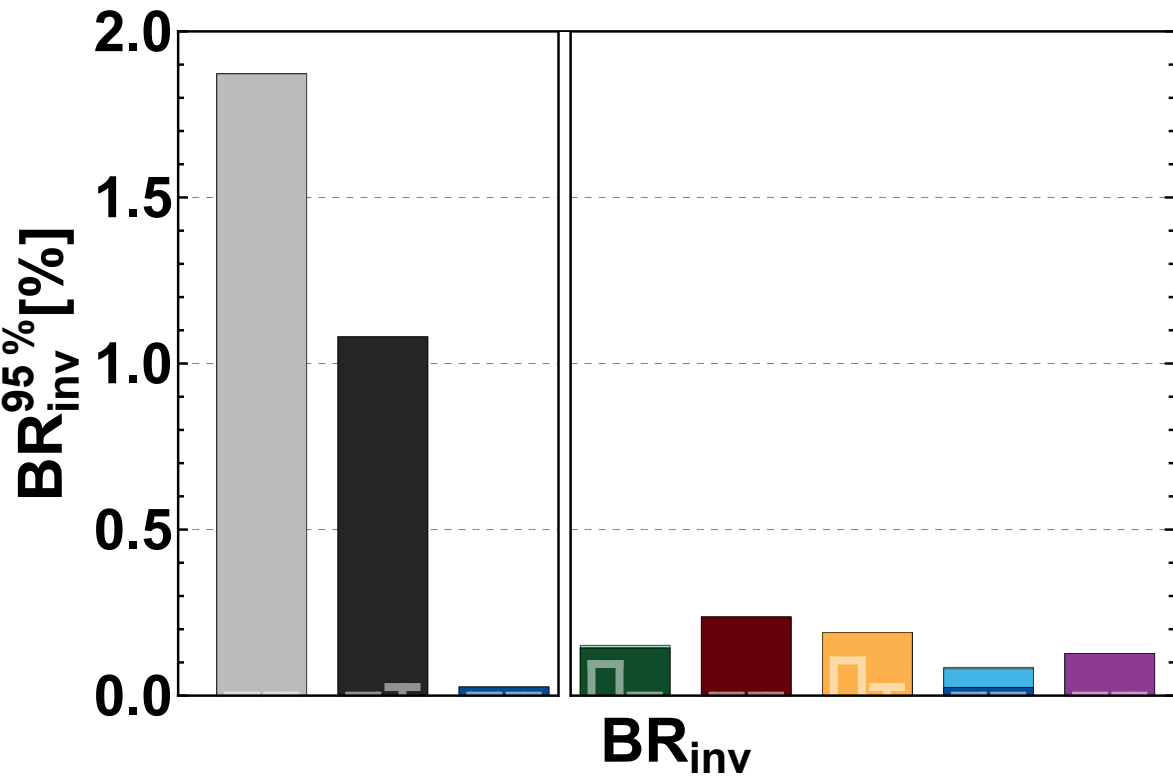
Physics Opportunities at e^+e^- Higgs factories



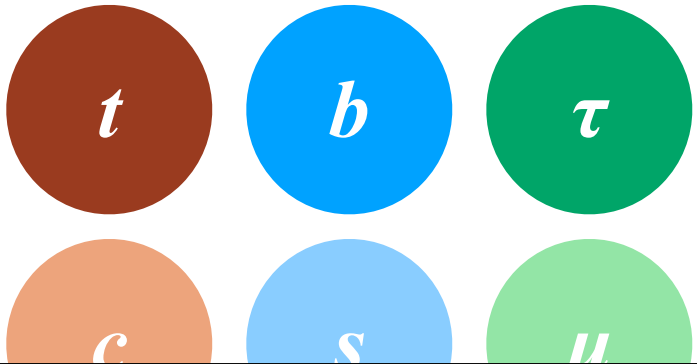
HZZ
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wrt LHC
O(0.1%)



H → BSM
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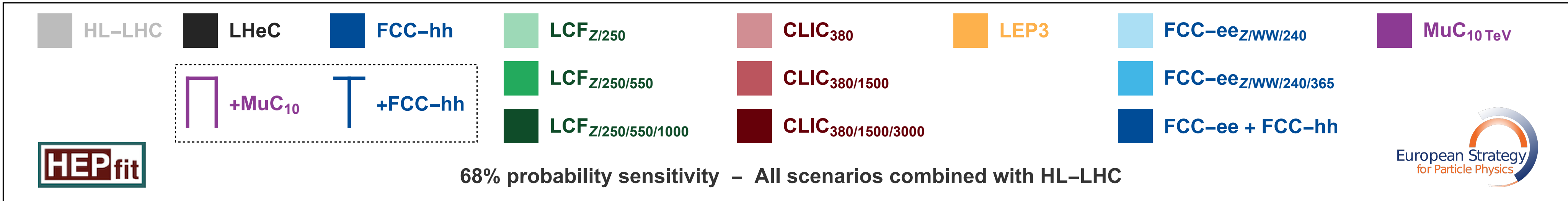
3rd family:
factor ~10 improvement
wrt LHC



1st family

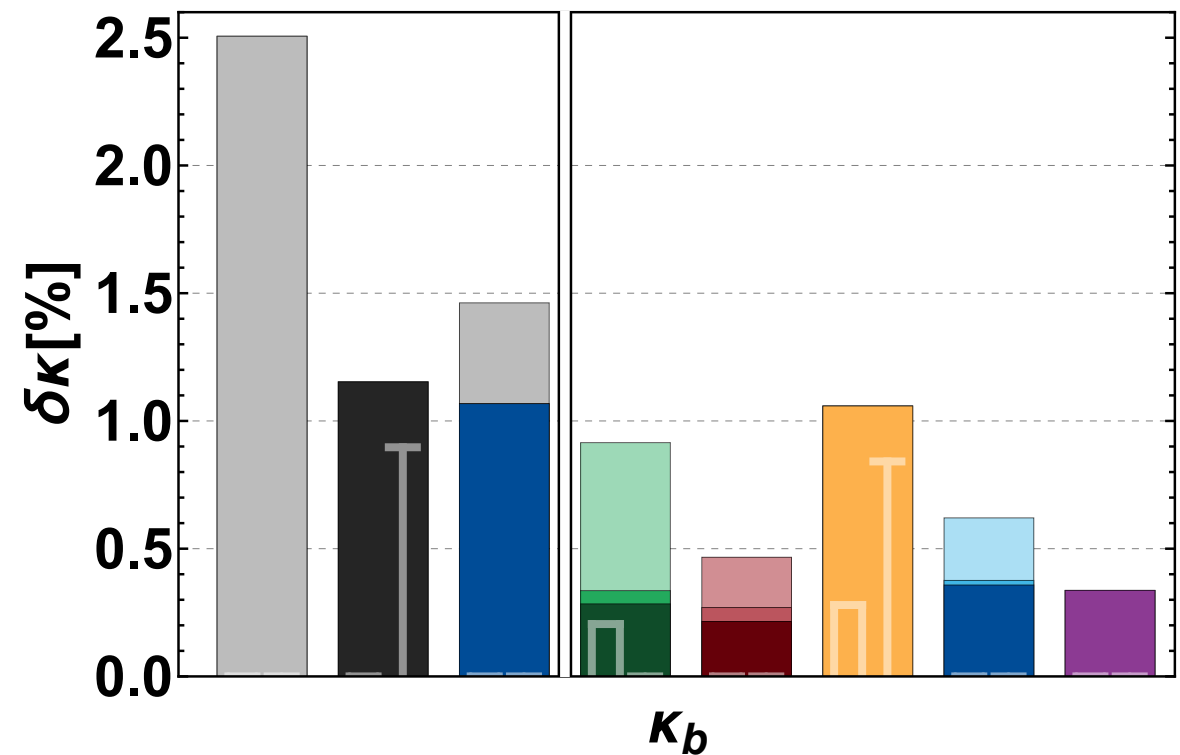
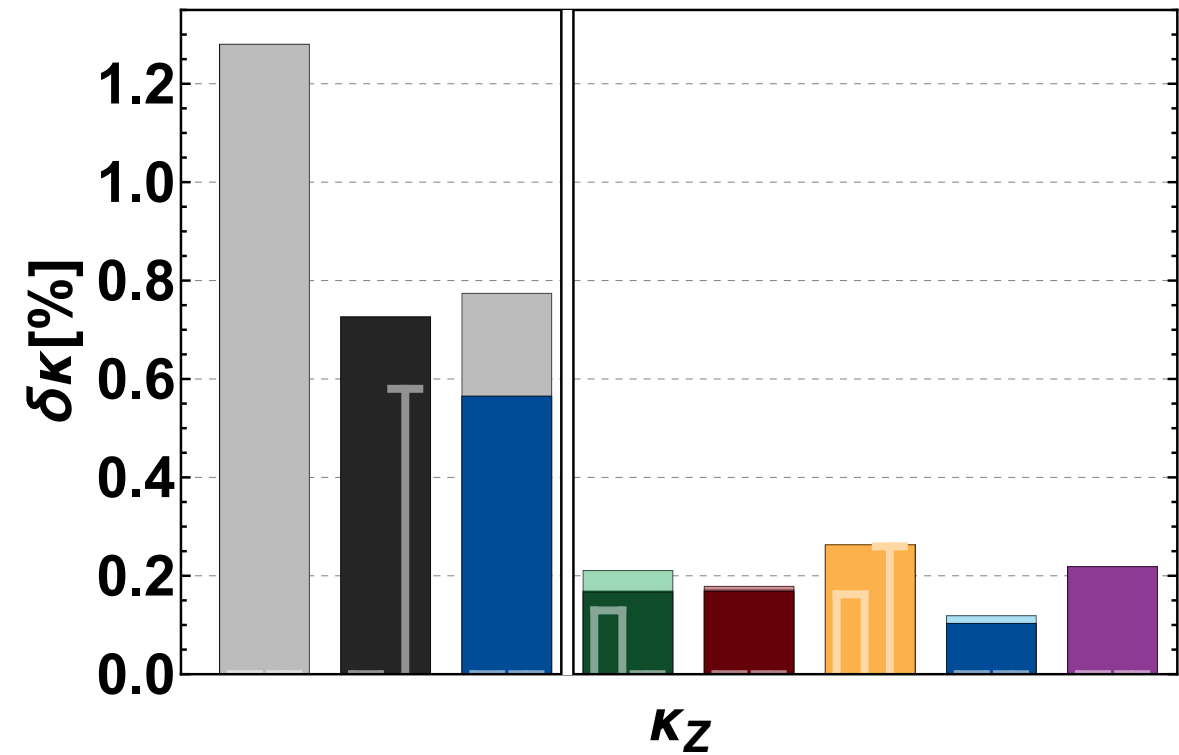
Sensitivity to SM value of electron Yukawa
at FCC-ee if running at 125 GeV
(Not in baseline)
Challenging experimentally

Physics Opportunities at e^+e^- Higgs factories

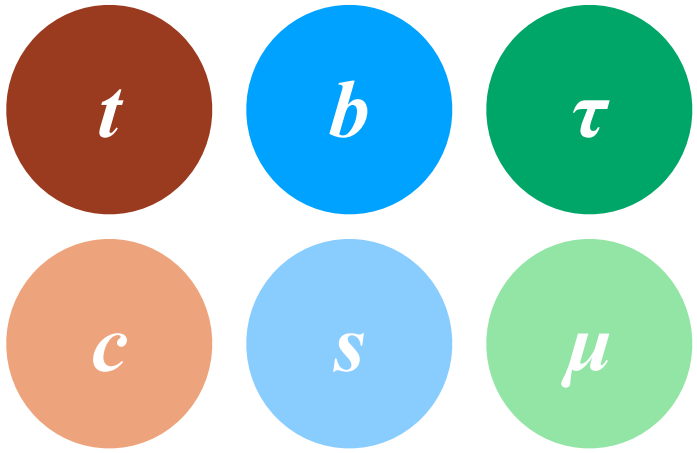


HZZ

factor ~10 improvement
wrt LHC
 $O(0.1\%)$



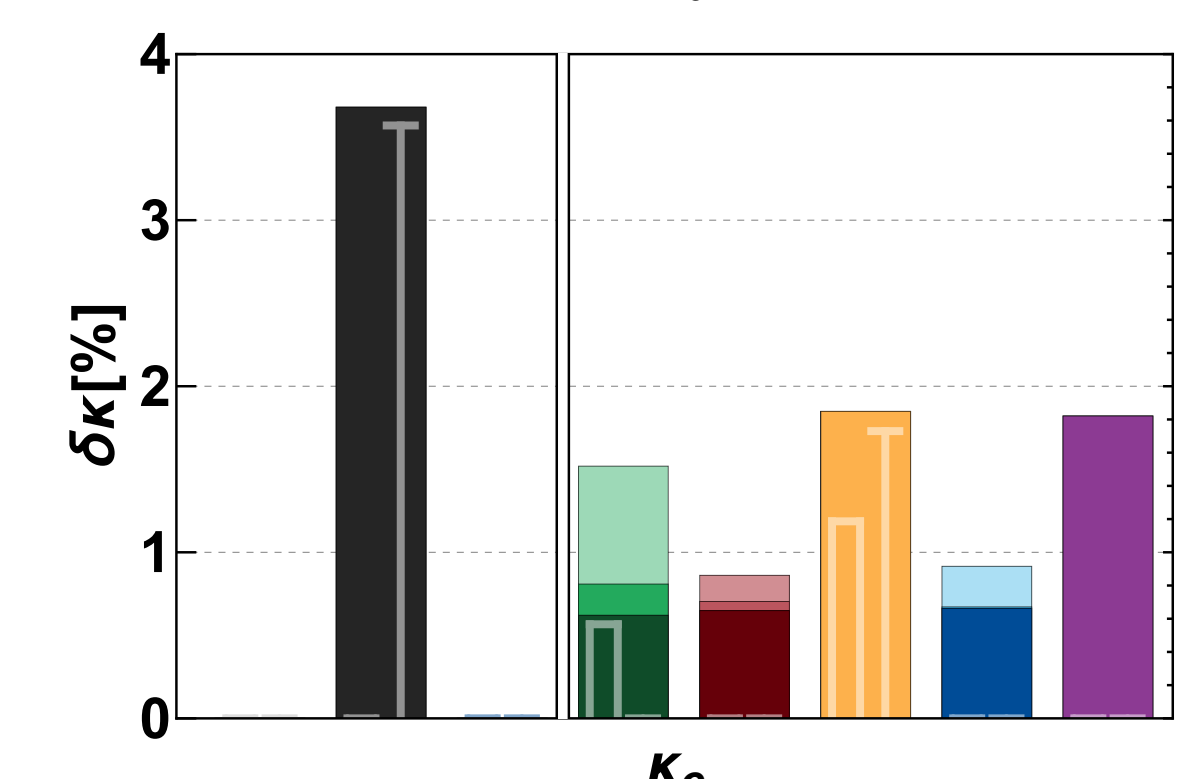
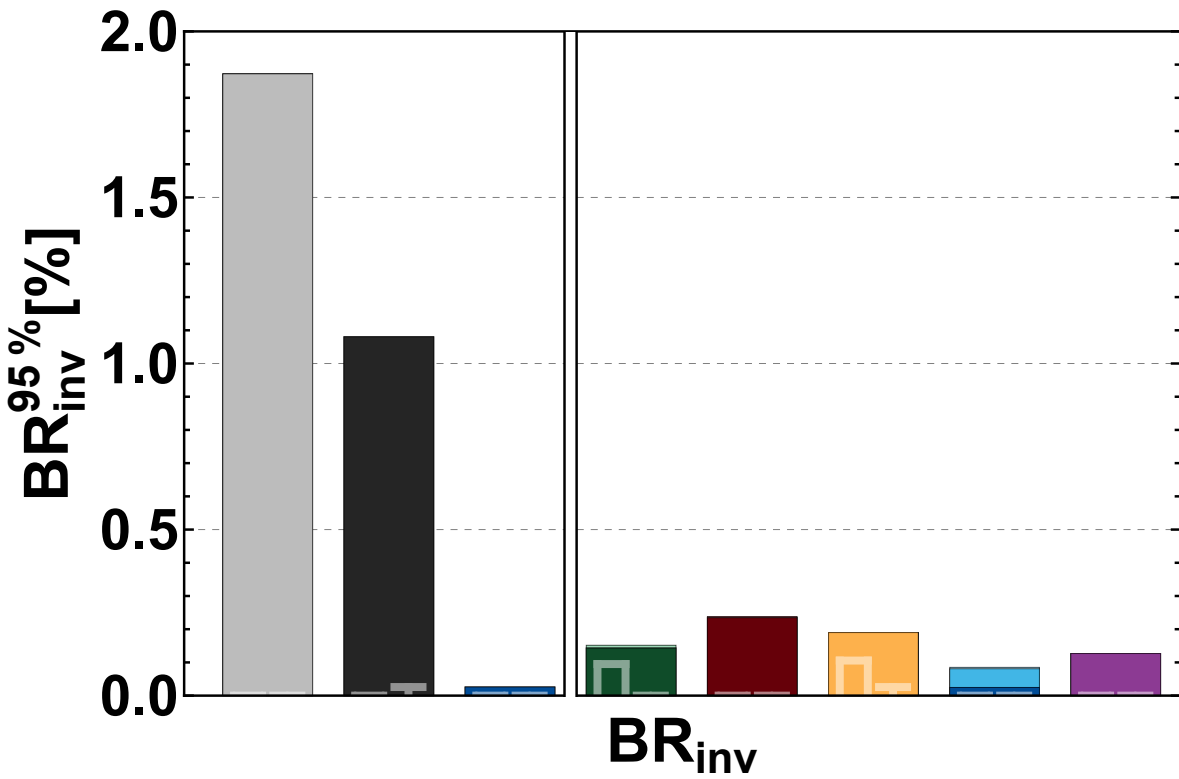
3rd family:
factor ~10 improvement
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2nd quark families
Beyond the LHC reach
($O(1)$ sensitivity to strange)

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$BR(H \rightarrow inv) < 0.08\%$
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Physics Opportunities at e^+e^- Higgs factories

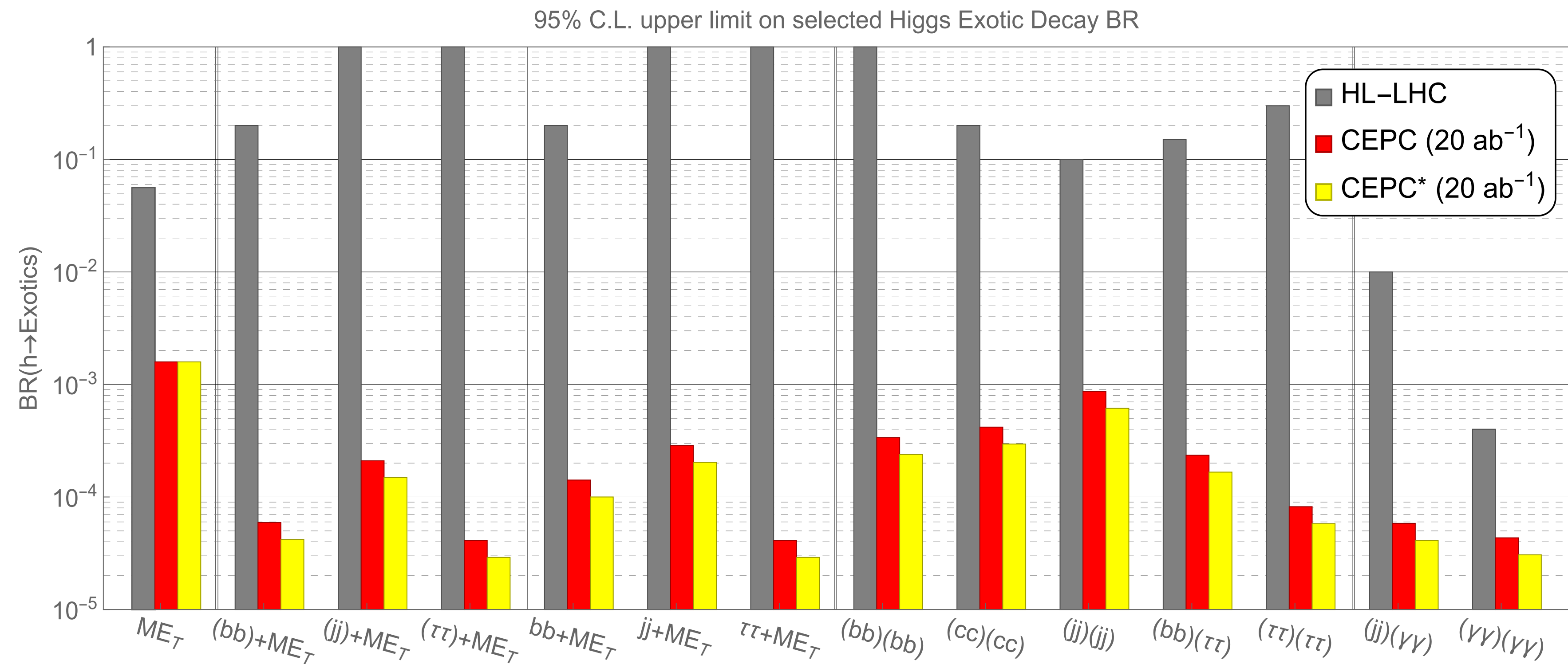
HL-LHC
HEPfit

BR($H \rightarrow \text{exo}$): Selected Exotic decay channels

Higgs as a “window” to NP: $H \rightarrow ? \rightarrow \text{SM}$

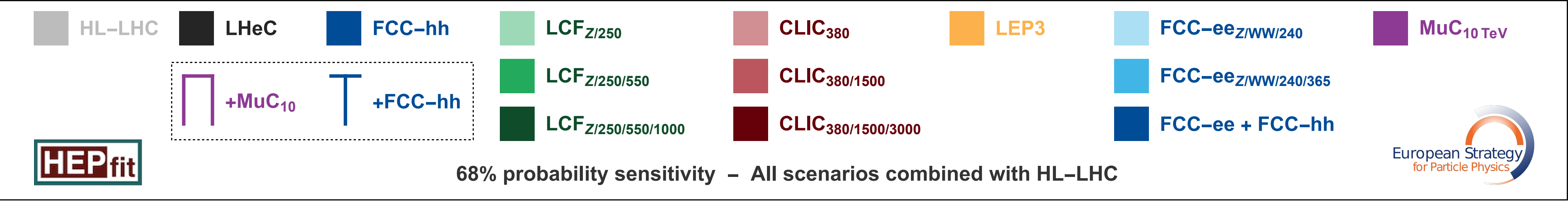
HZZ
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$H \rightarrow \text{BSM}$
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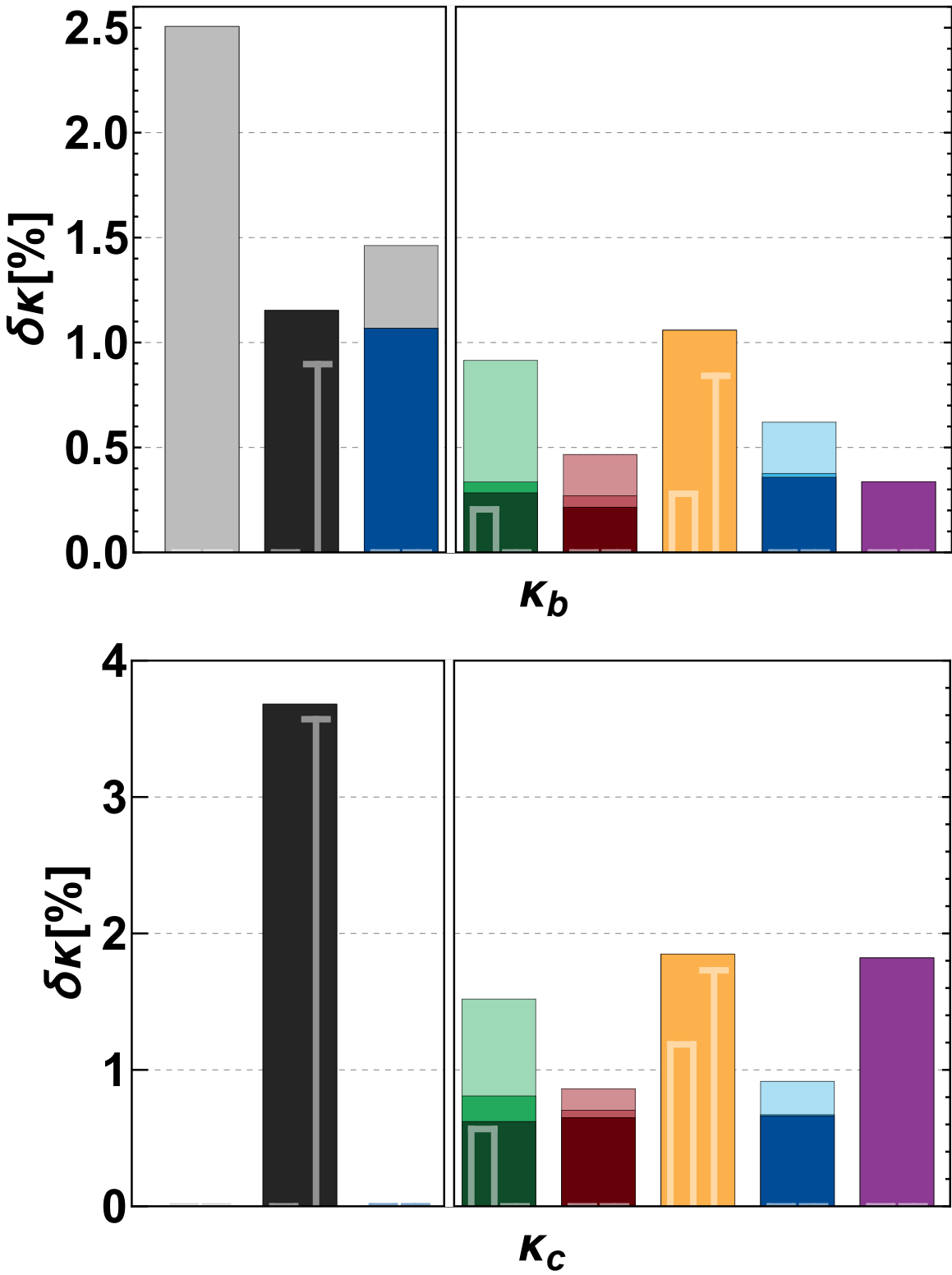
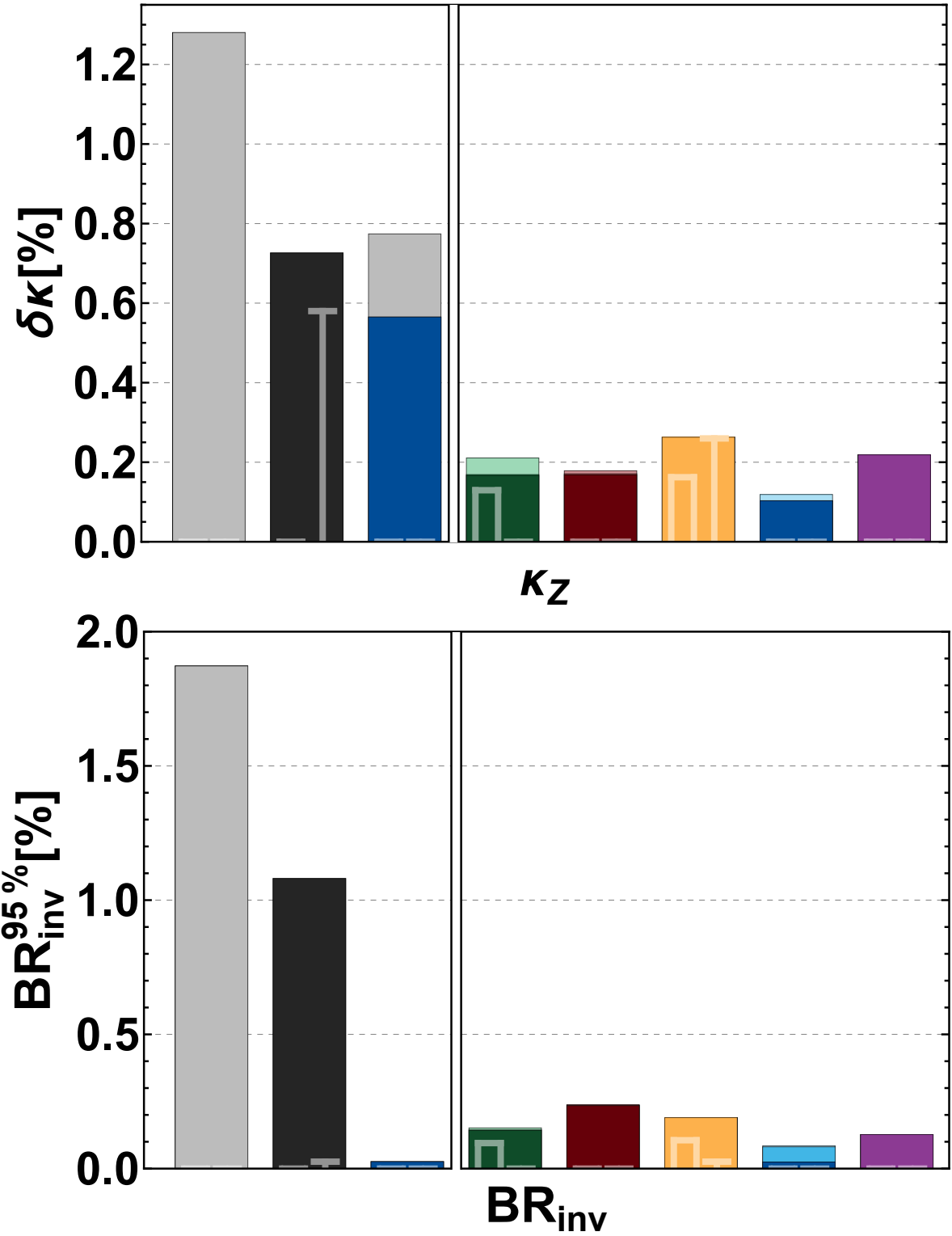
CEPC BSM White paper, arXiv: 2505.2481 [hep-ex]

Physics Opportunities at e^+e^- Higgs factories



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3rd family:
factor ~10 improvement
wrt LHC

t b τ
 c s μ

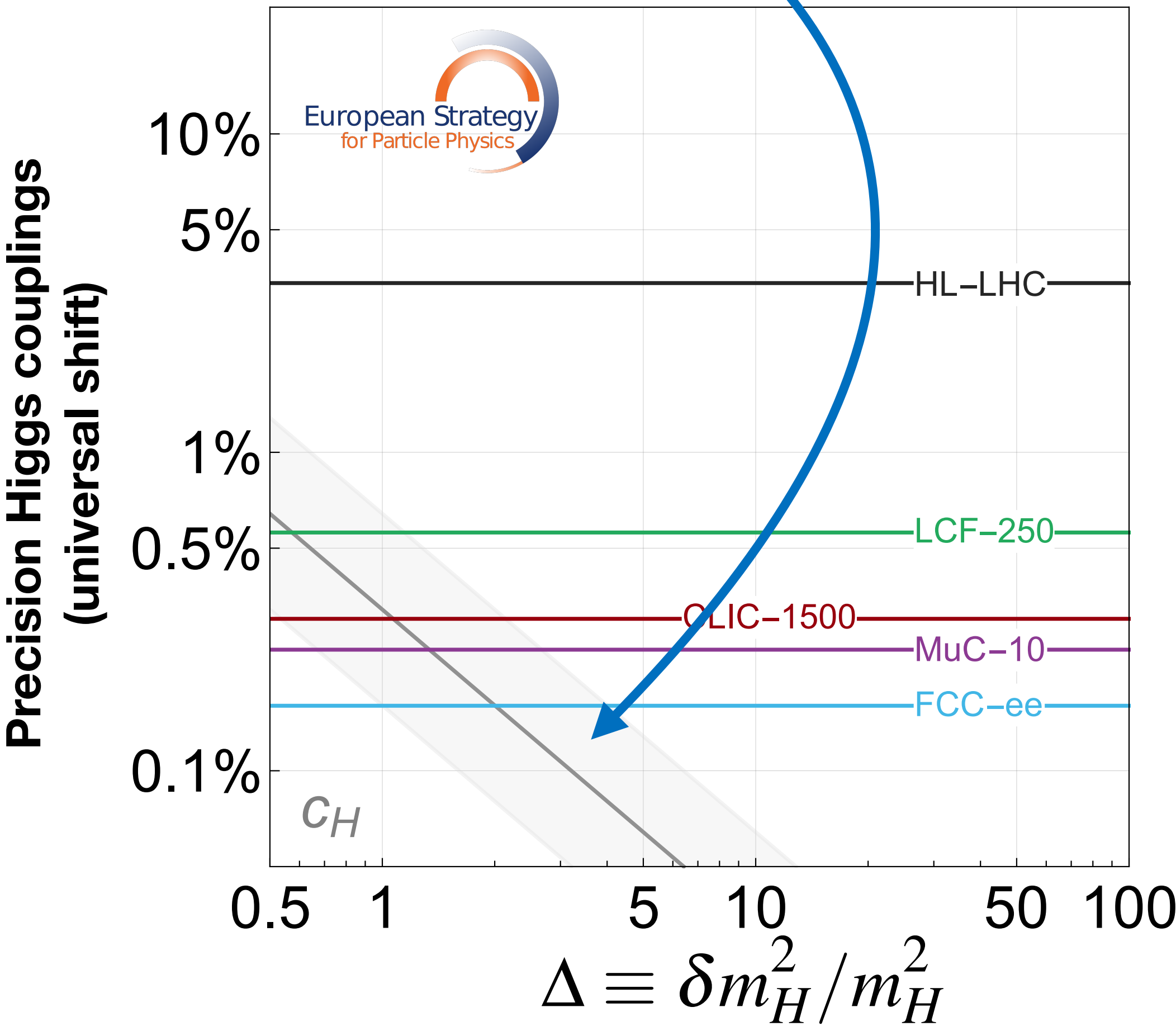
2nd quark families
Beyond the LHC reach
(O(1) sensitivity to strange)

What does this precision bring to the table?

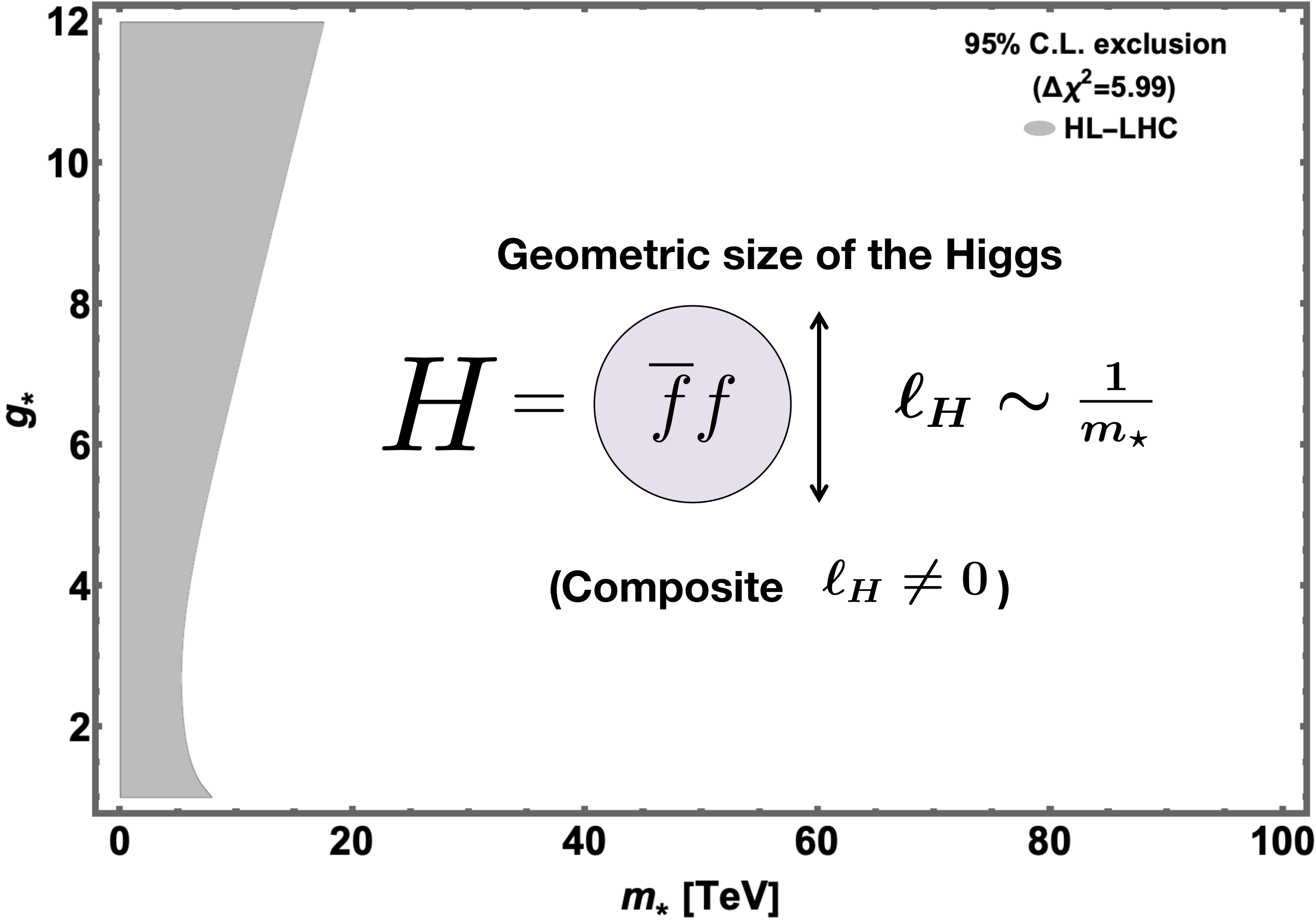
Physics Opportunities at e^+e^- Higgs factories

Precision Higgs Physics $\Rightarrow$ BSM

Fine tuning in Neutral Naturalness



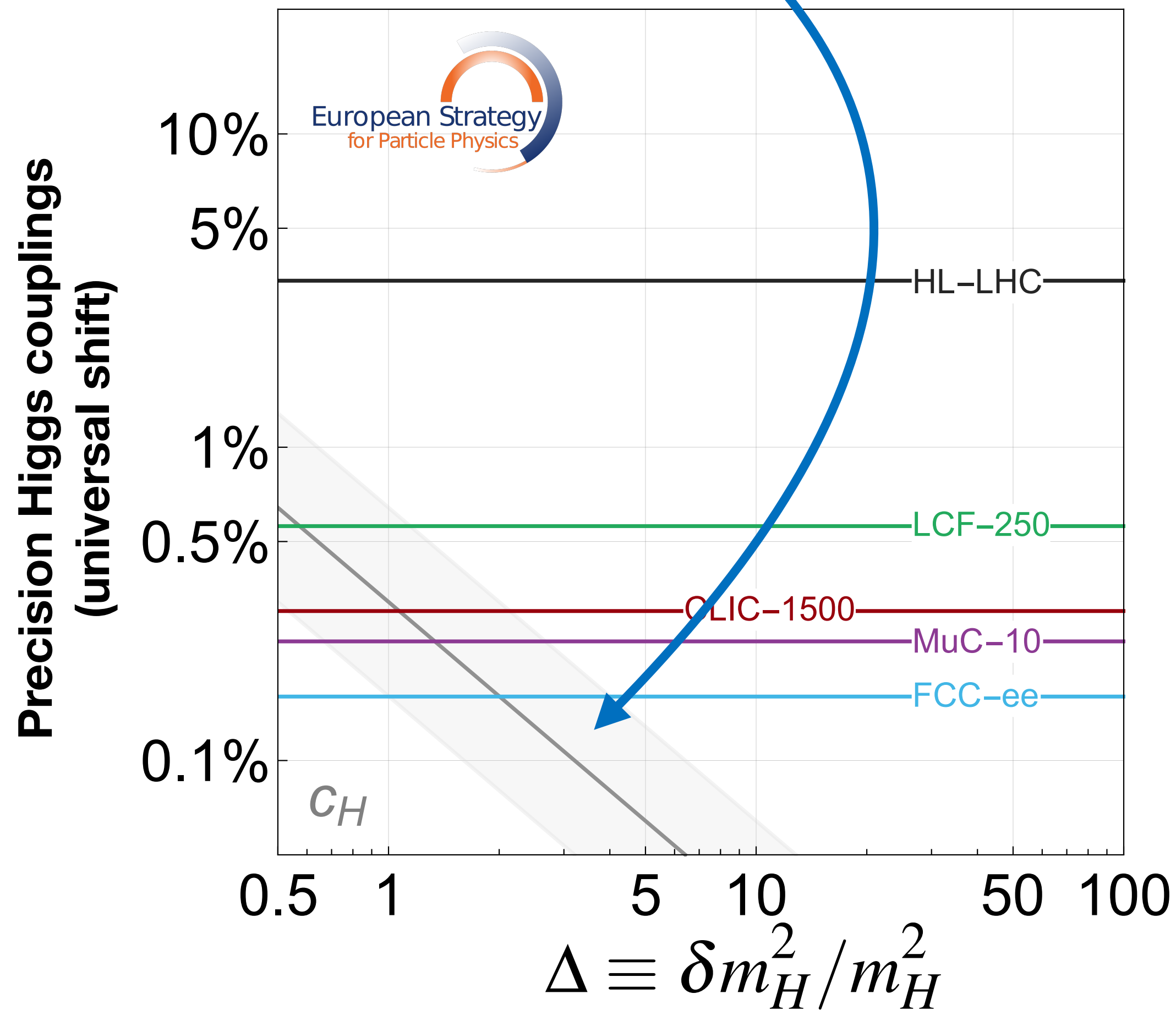
Composite Higgs scenarios



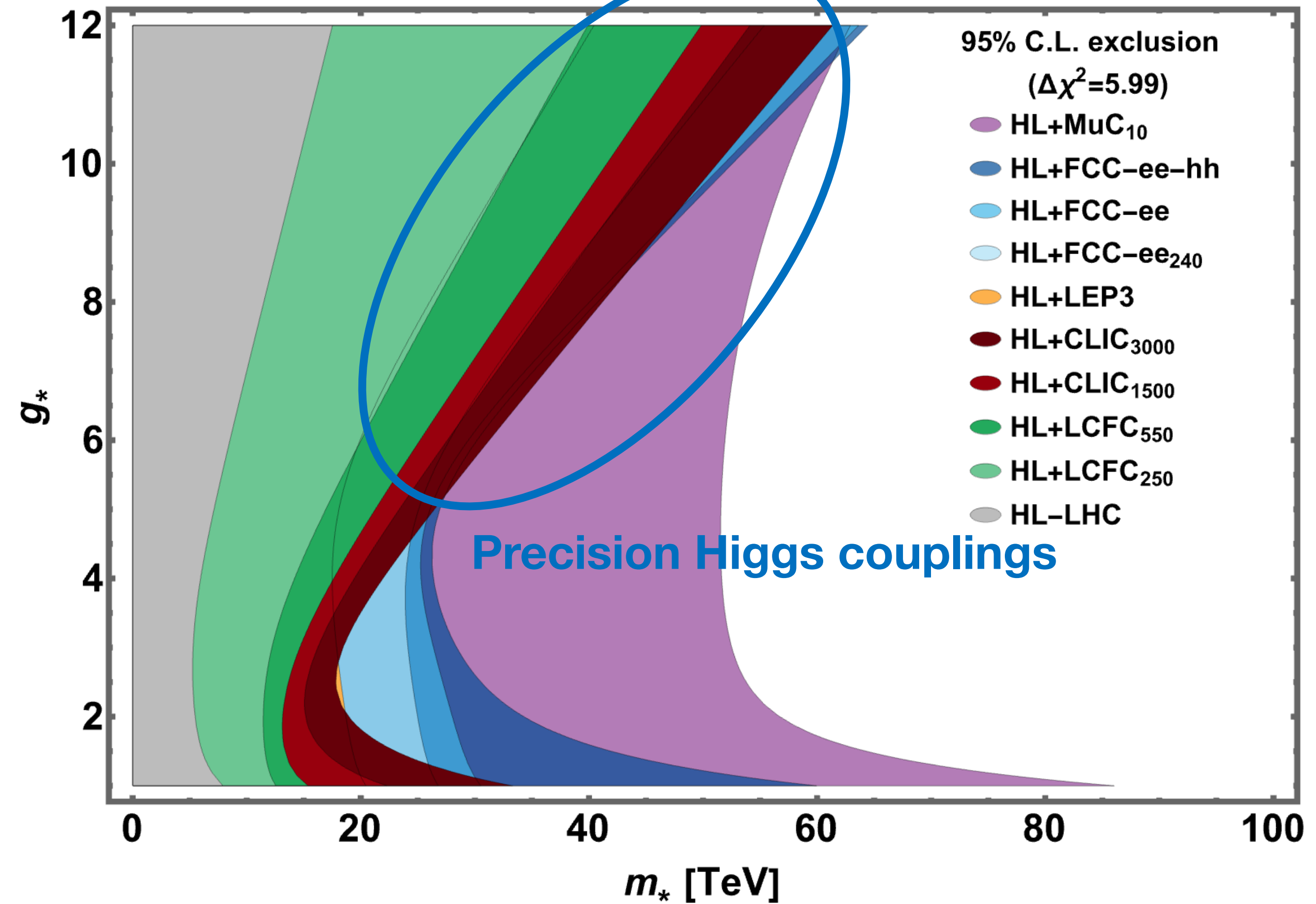
Physics Opportunities at e^+e^- Higgs factories

Precision Higgs Physics $\Rightarrow$ BSM

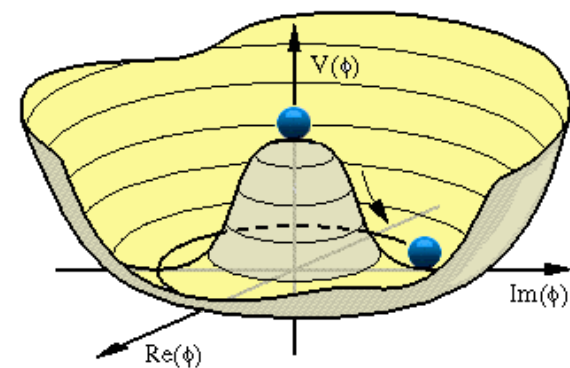
Fine tuning in Neutral Naturalness



Composite Higgs scenarios



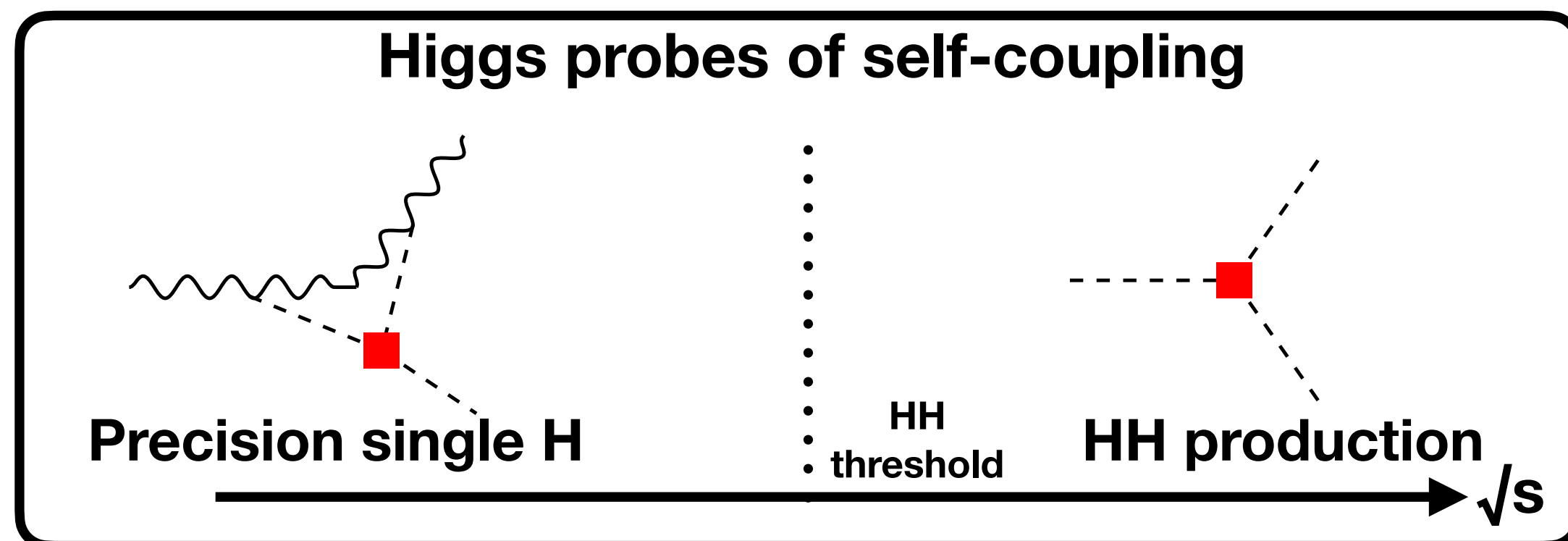
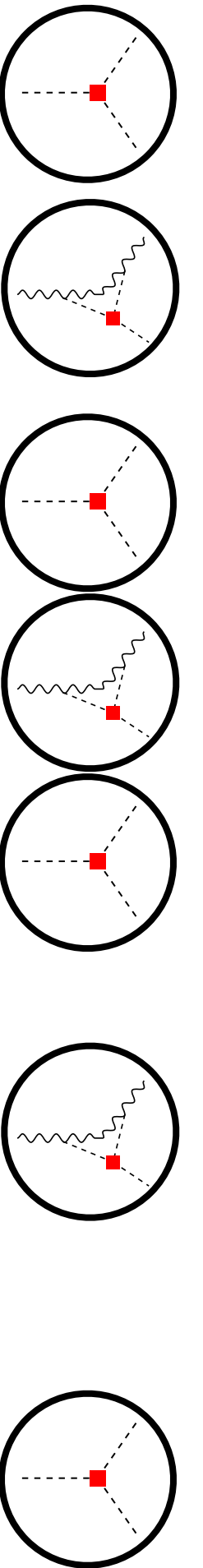
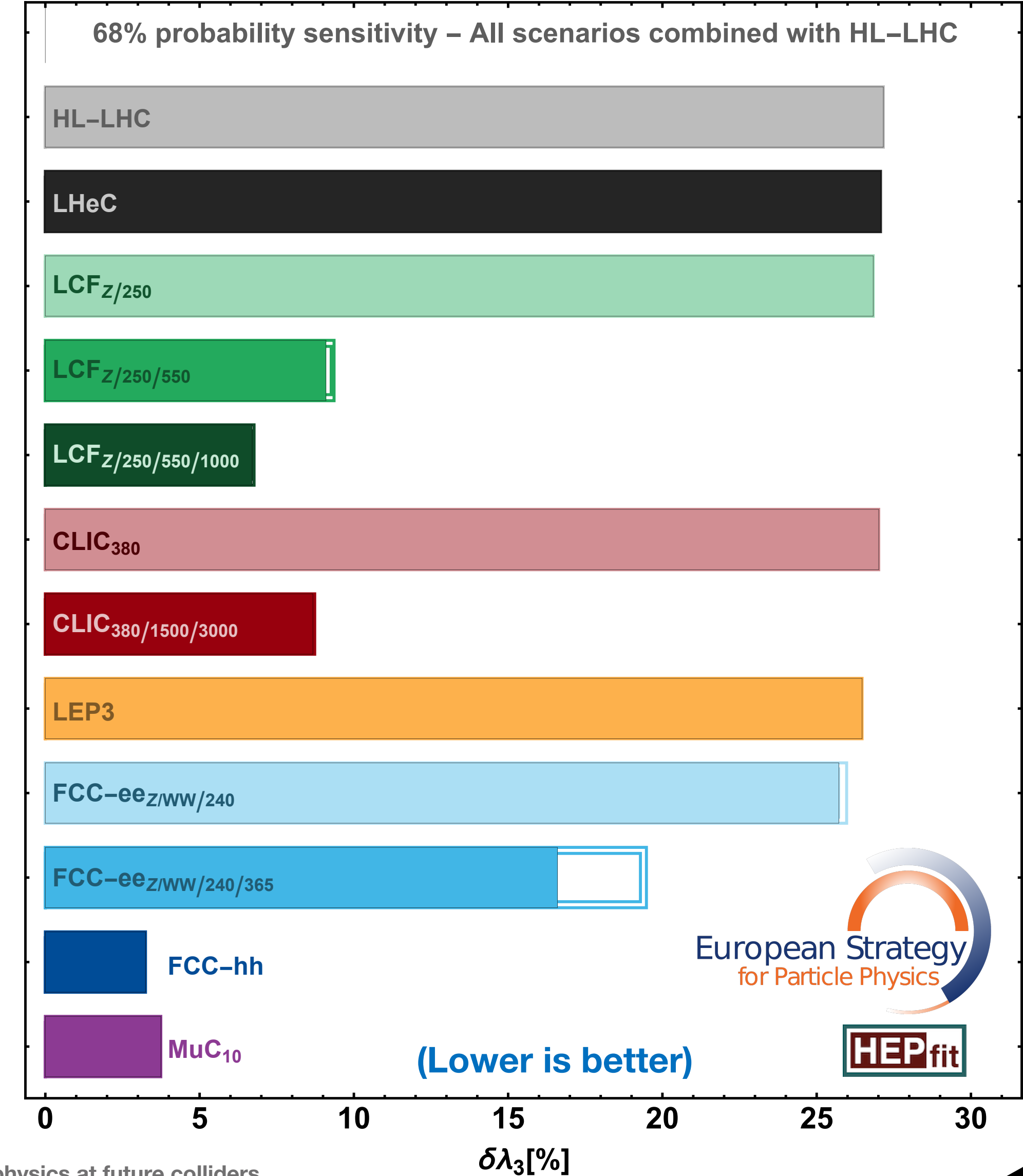
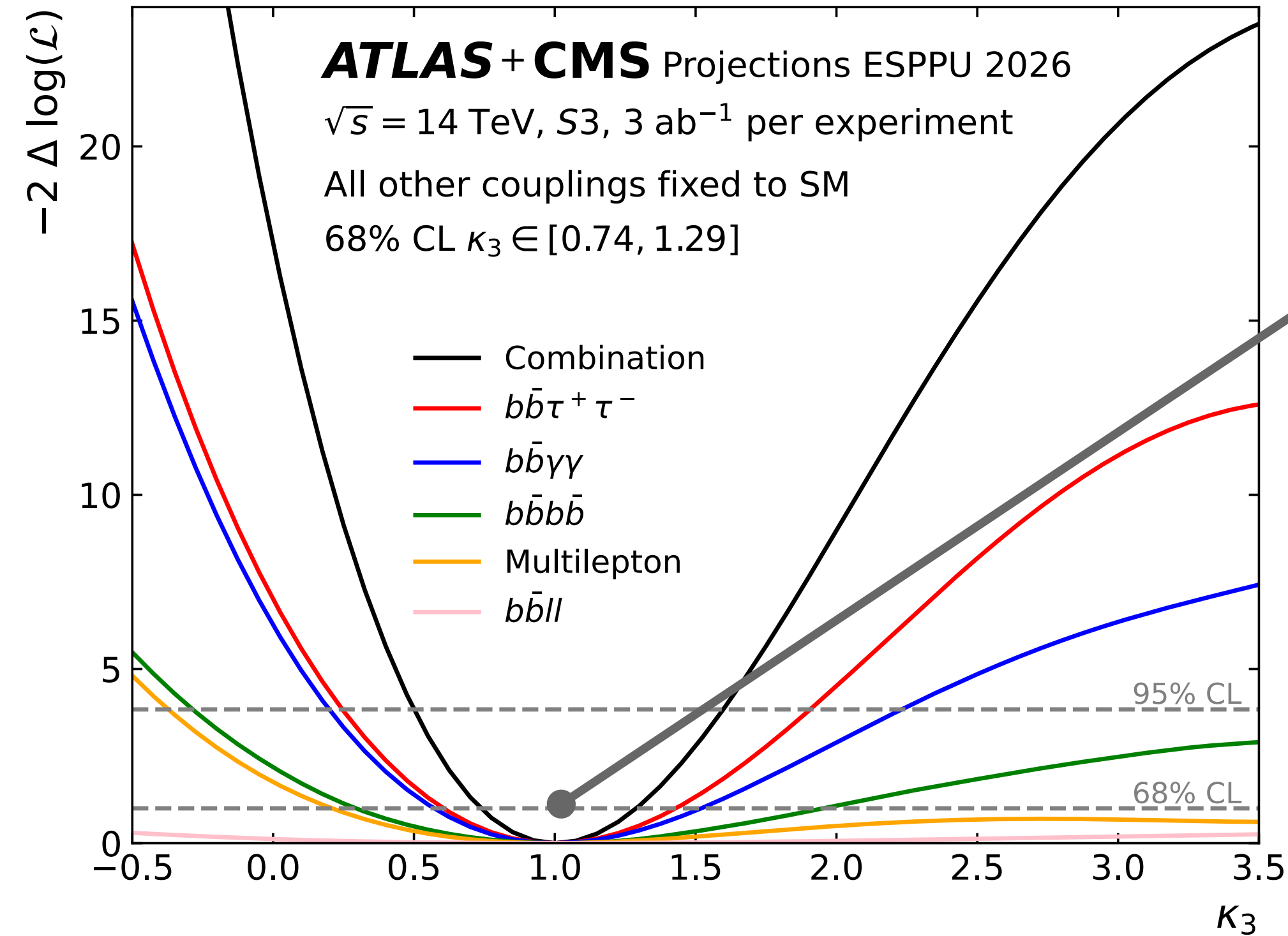
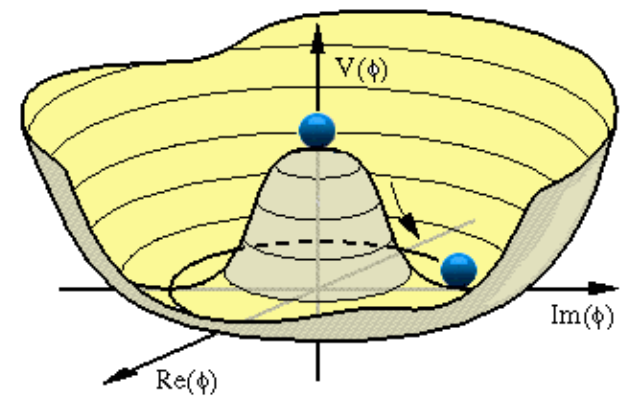
Testing the Higgs potential at Future Colliders: The Higgs self-coupling



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

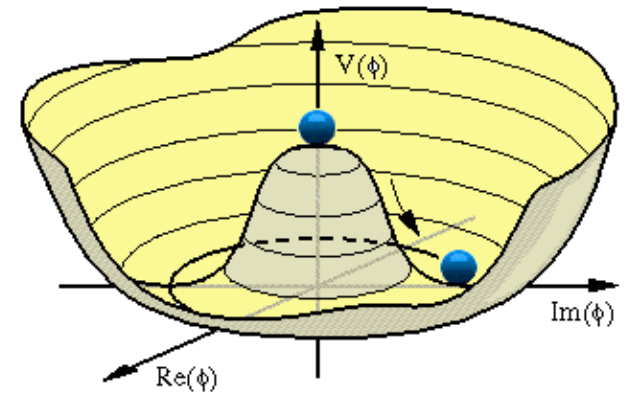
Testing the Higgs potential at future colliders

Higgs self-coupling precision

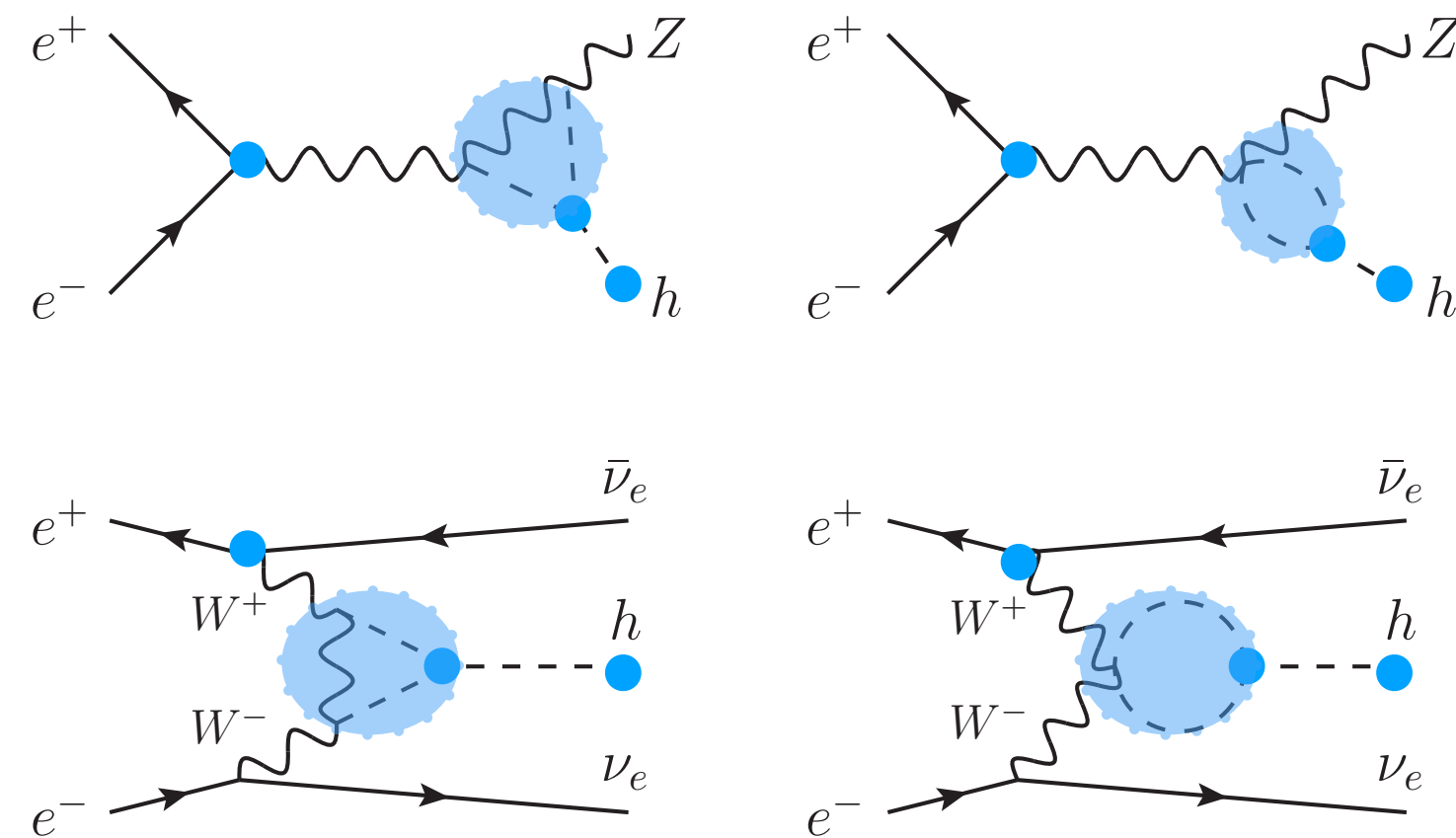


Testing the Higgs potential at future colliders

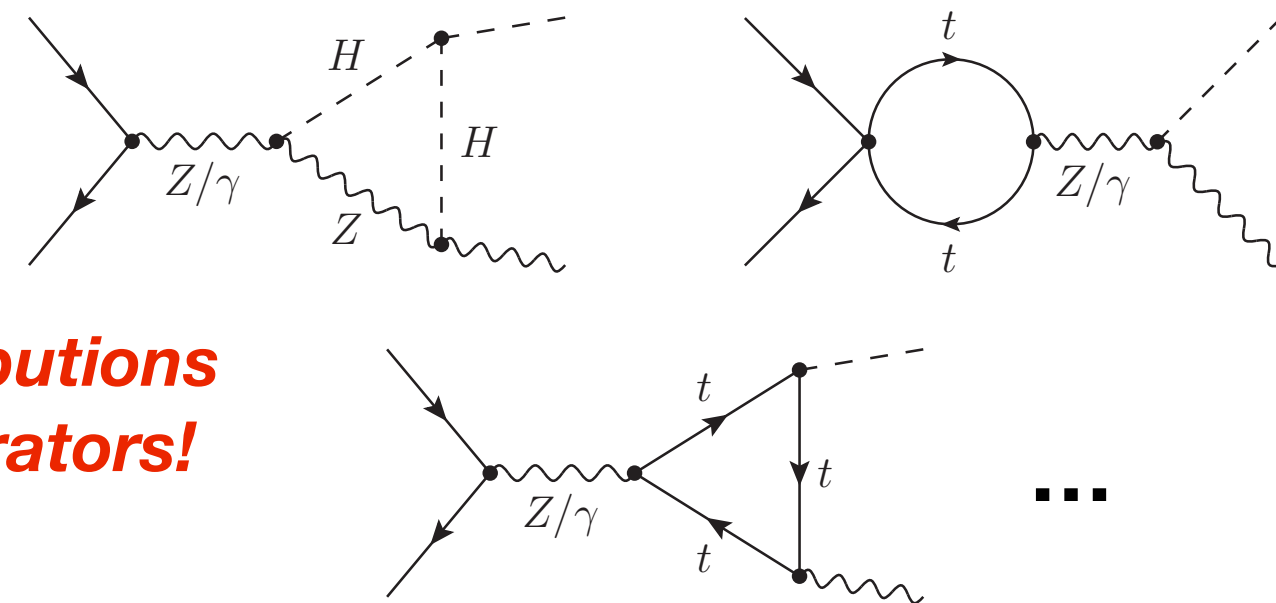
Higgs self-coupling precision



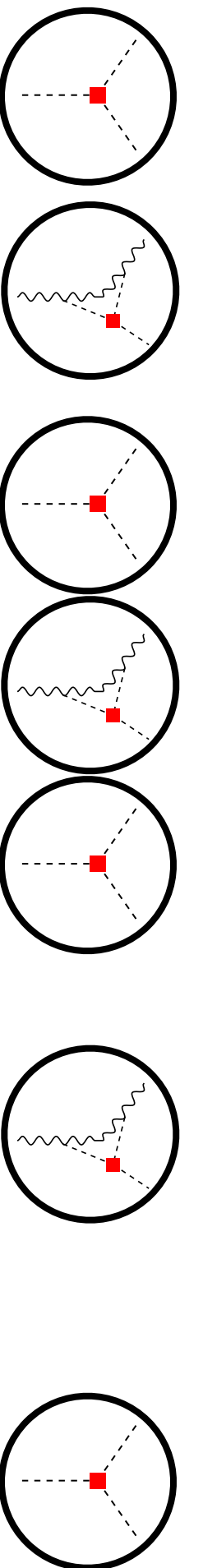
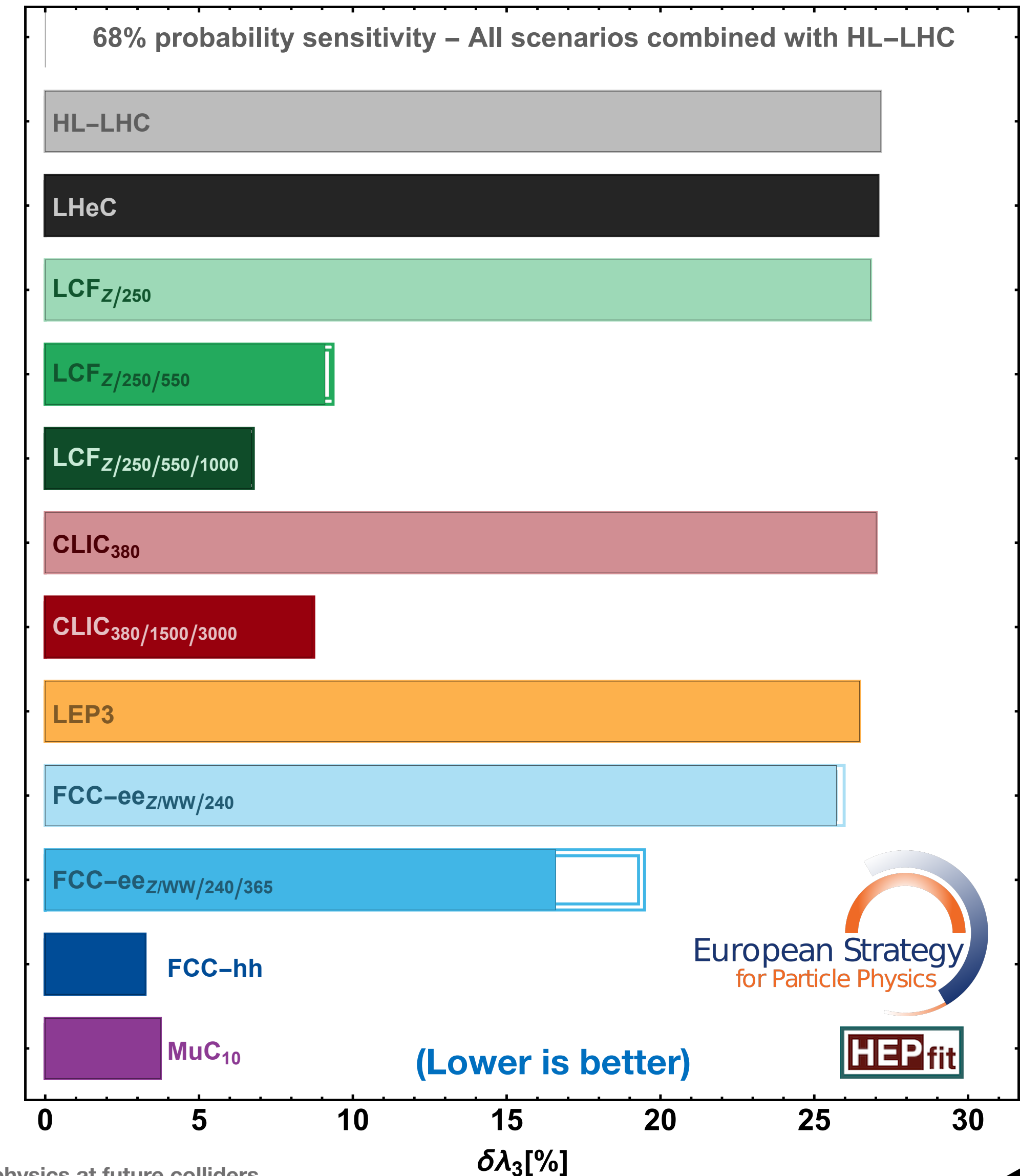
Higgs self-coupling via H production @ e^+e^-
 $\Rightarrow <1\%$ precision in single- H + $2\sqrt{s}$



+ control over other loop contributions

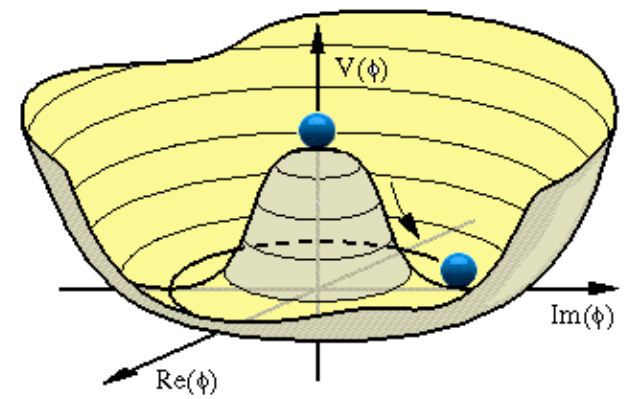


Sizable contributions from Top operators!



Testing the Higgs potential at future colliders

Higgs self-coupling precision



Higgs self-coupling via H production @ e^+e^-
 $\Rightarrow <1\%$ precision in single- $H + 2 \sqrt{s}$

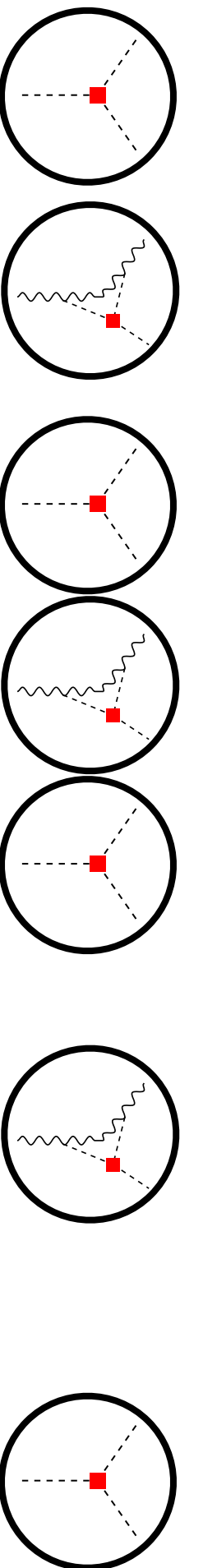
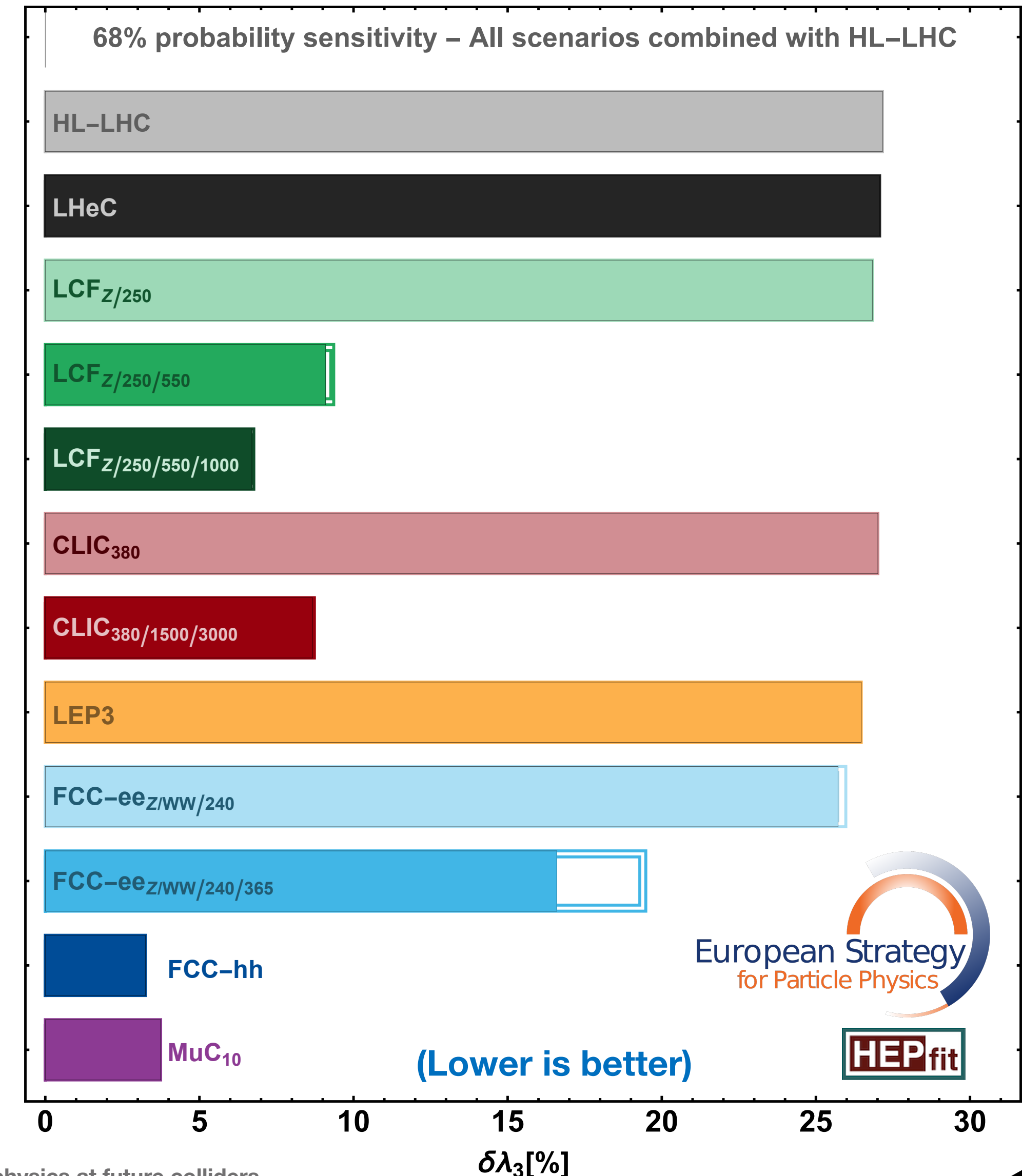
$$\delta\lambda_3 \sim 17\text{-}20 \%$$

Higgs self-coupling via HH production @ e^+e^-
 $\Rightarrow$ Run energy above ~ 500 GeV ($\Rightarrow$ LC)

$$\delta\lambda_3 \sim 10 \%$$

Higgs self-coupling via HH production @ FCC-hh and Muon Colliders (10 TeV)

$$\delta\lambda_3 \lesssim 5 \%$$



More than Higgs factories

Physics opportunities at the Tera-Z

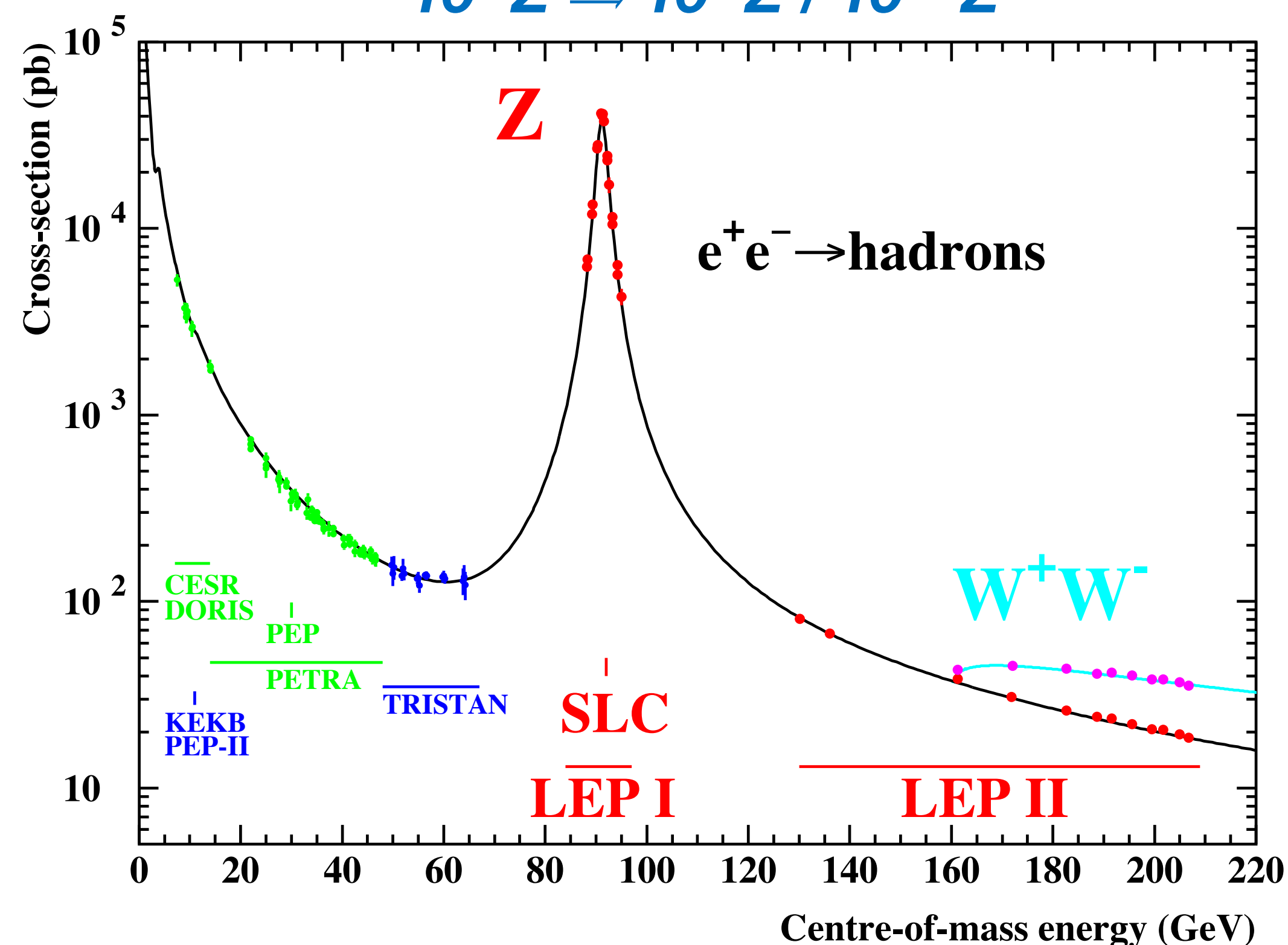
Testing the quantum structure of the SM (& NP)

Electroweak Precision Measurements

Physics Opportunities at the Tera-Z: EWPO

LEP/SLC $\Rightarrow$ Giga Z / Tera Z

10^7 Z $\Rightarrow$ 10^9 Z / 10^{12} Z

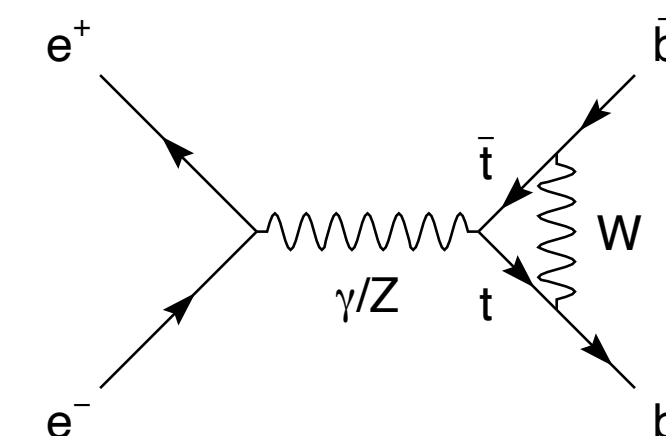
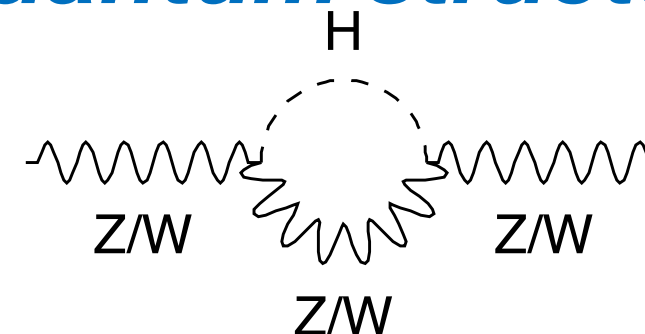
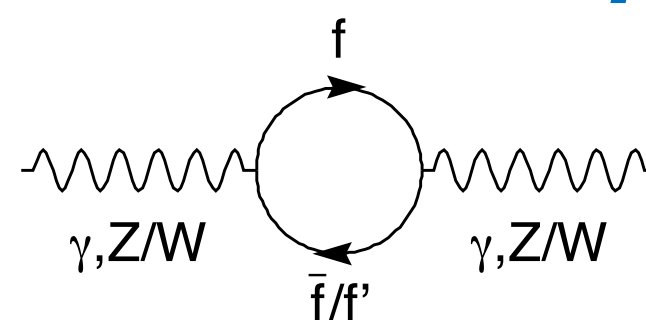


Electroweak Precision Observables (EWPO)
strongest test of consistency of the SM we have today

Observable	Current	FCC-ee	LCF	LEP3
Δm_Z (keV)	2000	4 (100)	200	7.5 (100)
$\Delta \Gamma_Z$ (keV)	2300	4 (12)	125	7.5 (23)
$\delta R_\mu (\times 10^{-6})$ $R_\mu \equiv \frac{\Gamma_{\text{had}}}{\Gamma_\mu}$	1600	2.4 (2.3)	90 (90)	4.5 (2.3)
$\delta R_b (\times 10^{-6})$ $R_b \equiv \frac{\Gamma_b}{\Gamma_{\text{had}}}$	3300	1.2 (1.6)	70 (60)	2.2 (3.0)
$\Delta \sin^2 \theta_W (\times 10^6)$	130	0.4 (0.5)	2.7 (2.3)	0.75 (0.95)
$\Delta \alpha(m_Z)^{-1} (\times 10^3)$	14	0.8, 3.8	–	1.4, 7.3
Δm_W (keV)	9900	180 (160)	500 (1600)	430 (700)
$\Delta \Gamma_W$ (keV)	42000	270 (200)	2000	650 (500)

**More than an order of magnitude
improvement in precision at future e^+e^-**

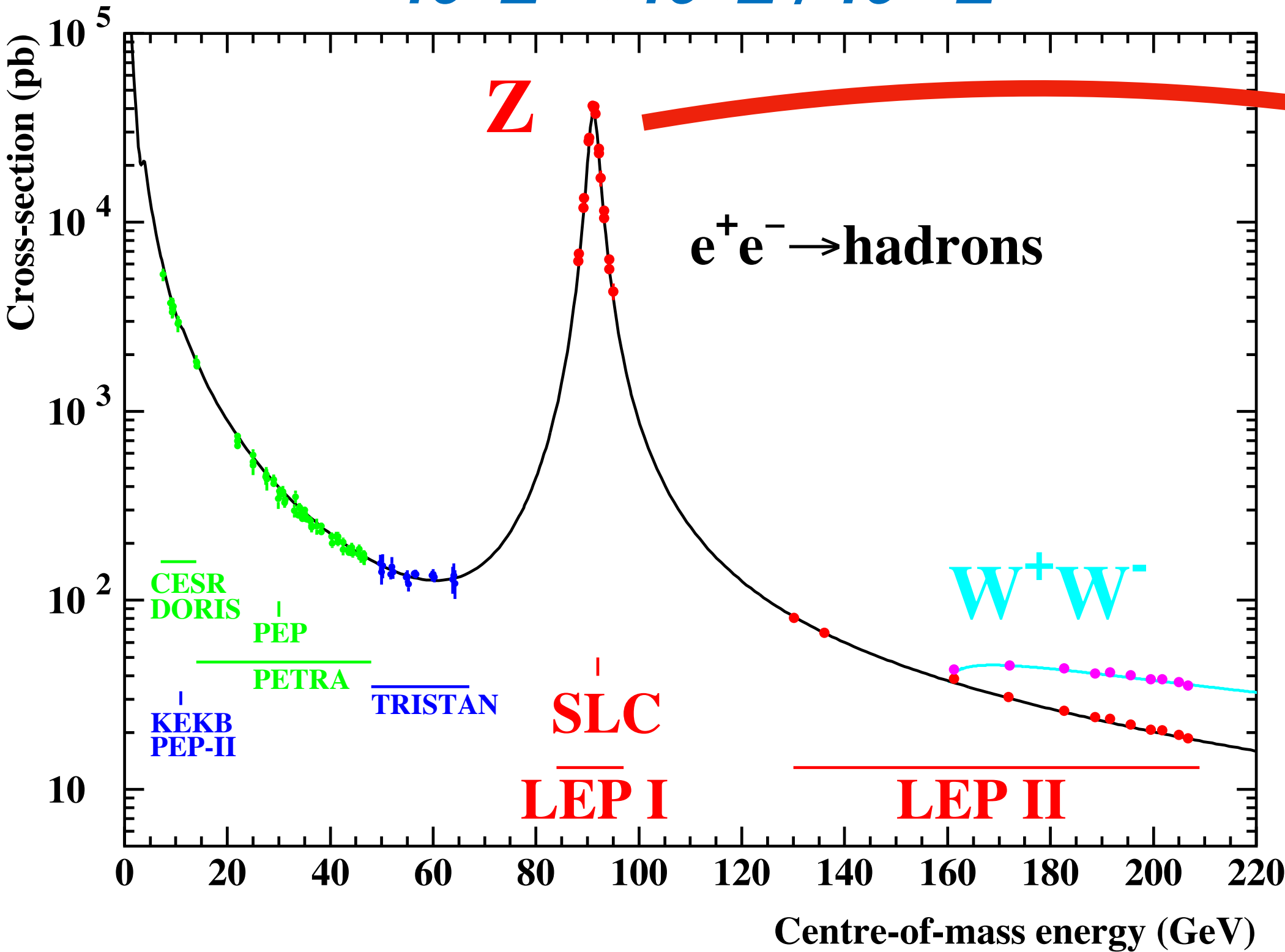
Tests of the quantum structure of the SM



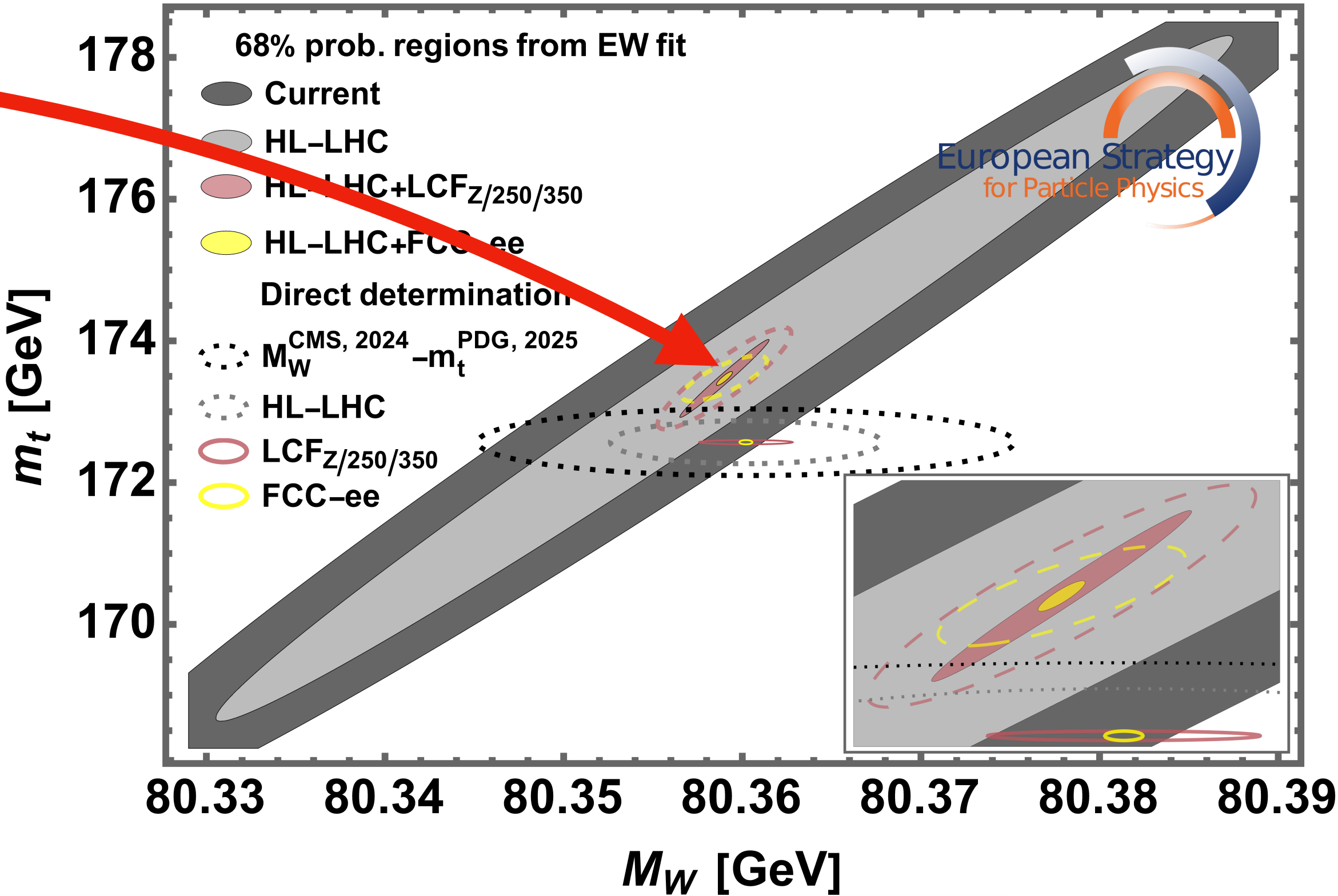
**EW physic in detail
in talk by
Alessandro Vicini**

Physics Opportunities at the Tera-Z: EWPO

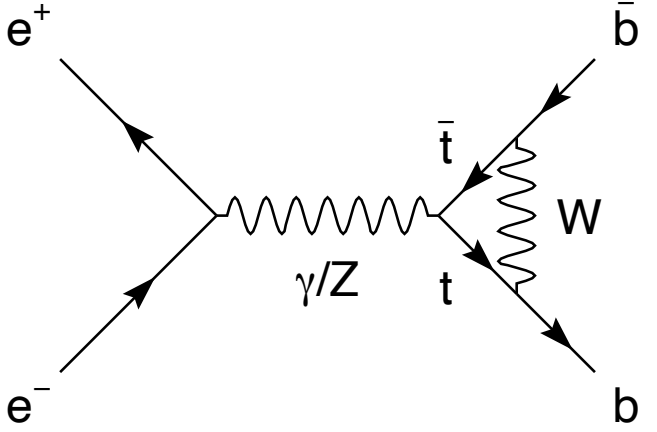
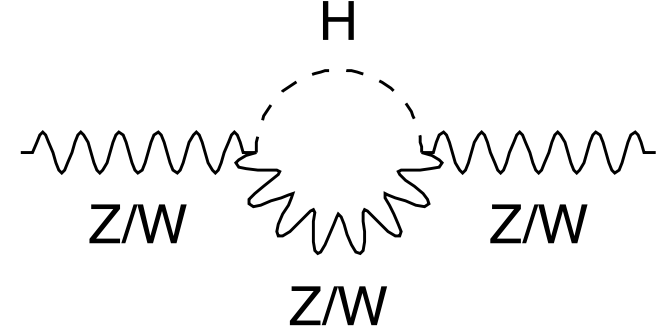
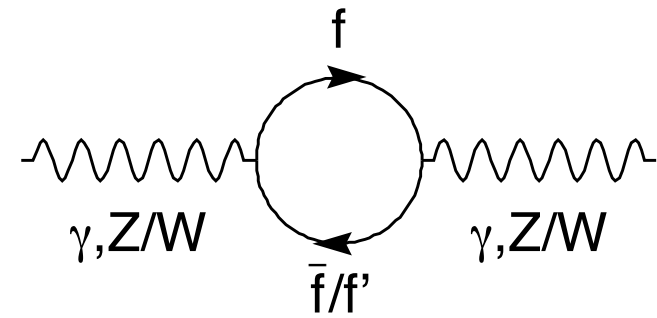
LEP/SLC $\Rightarrow$ *Giga Z / Tera Z*
 $10^7 Z \Rightarrow 10^9 Z / 10^{12} Z$



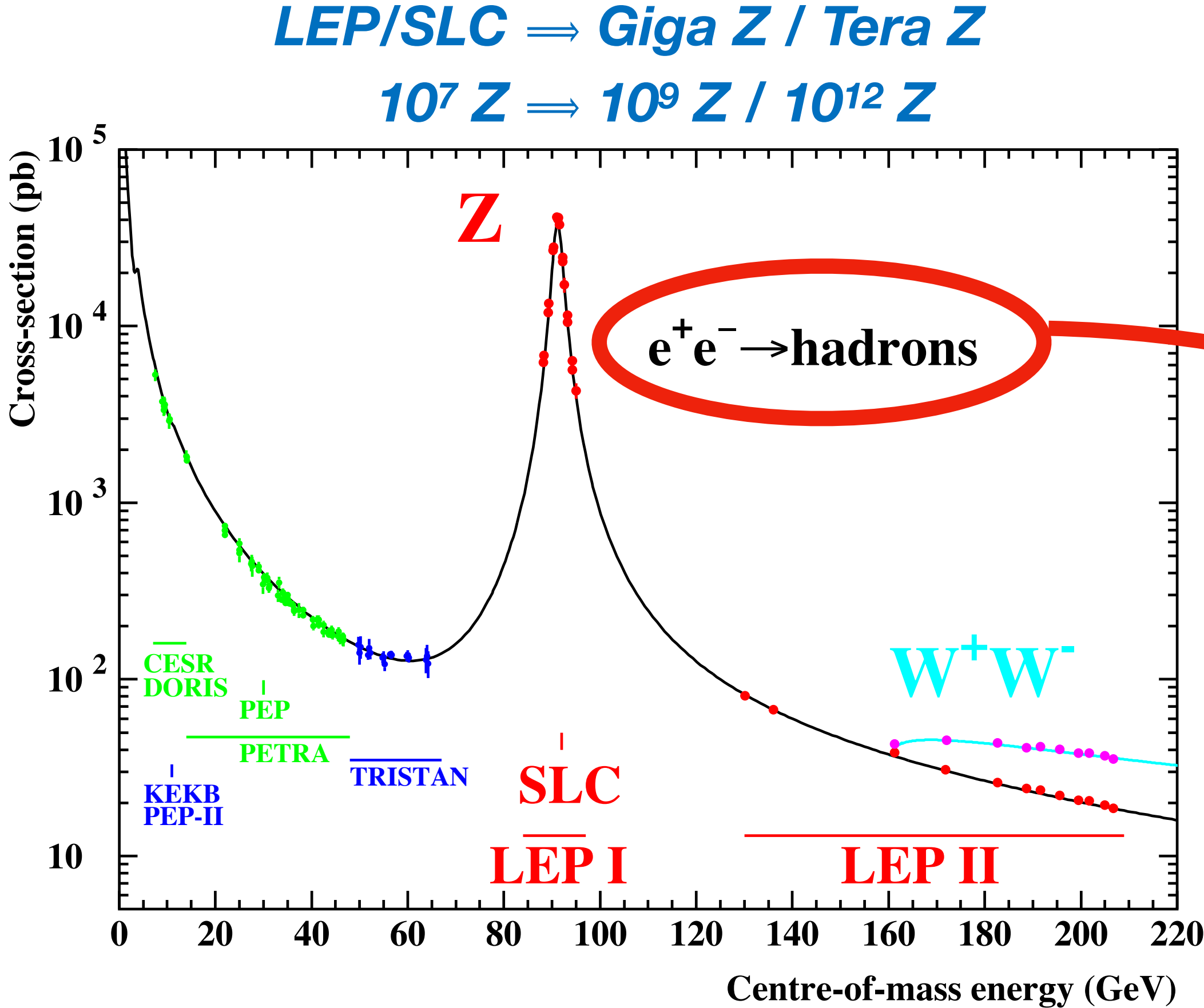
Capabilities for “closure tests” of SM



Tests of the quantum structure of the SM



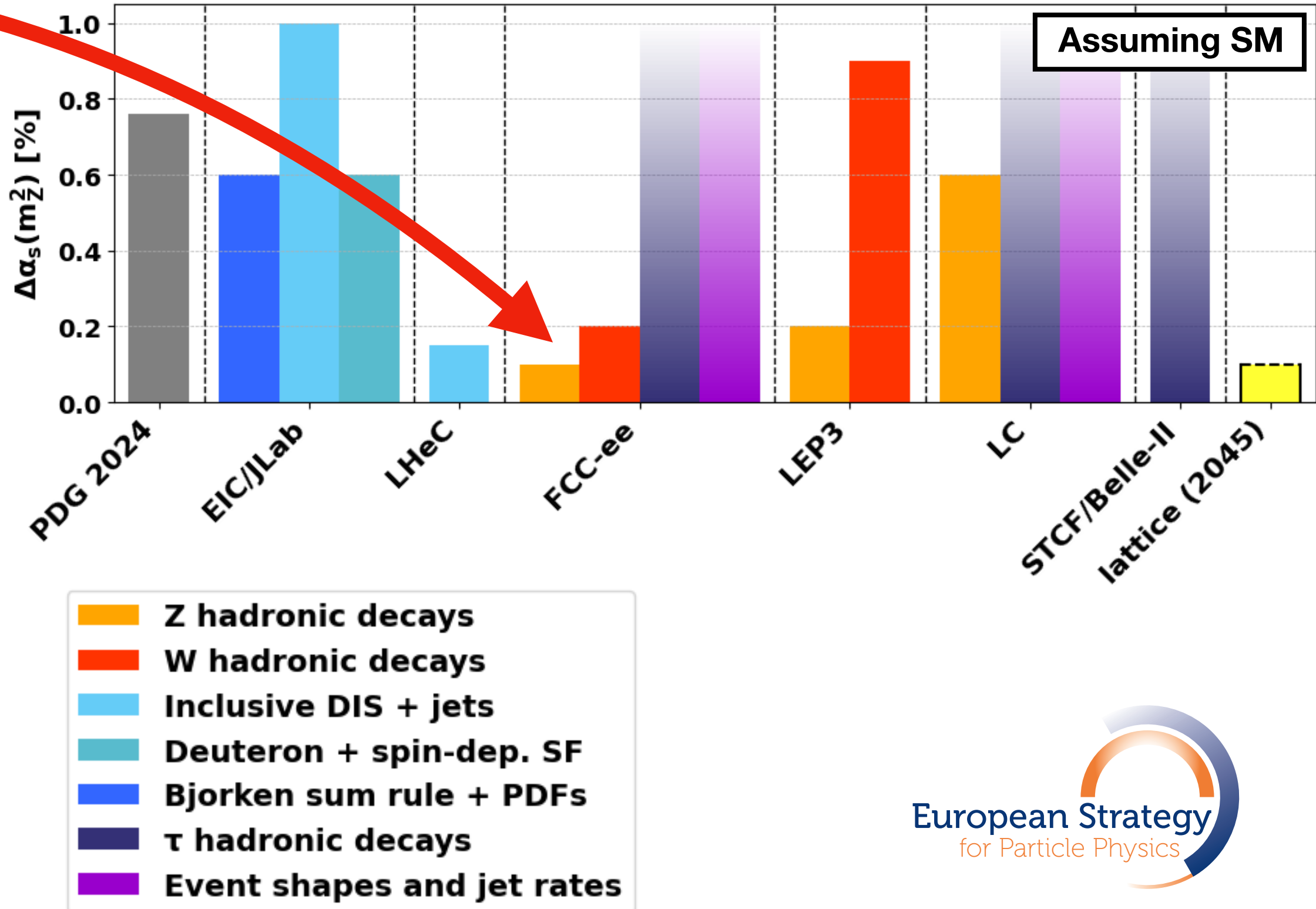
Physics Opportunities at the Tera-Z: EWPO



Opportunities for QCD

**Some of these EWPO
are very sensitive to α_s**

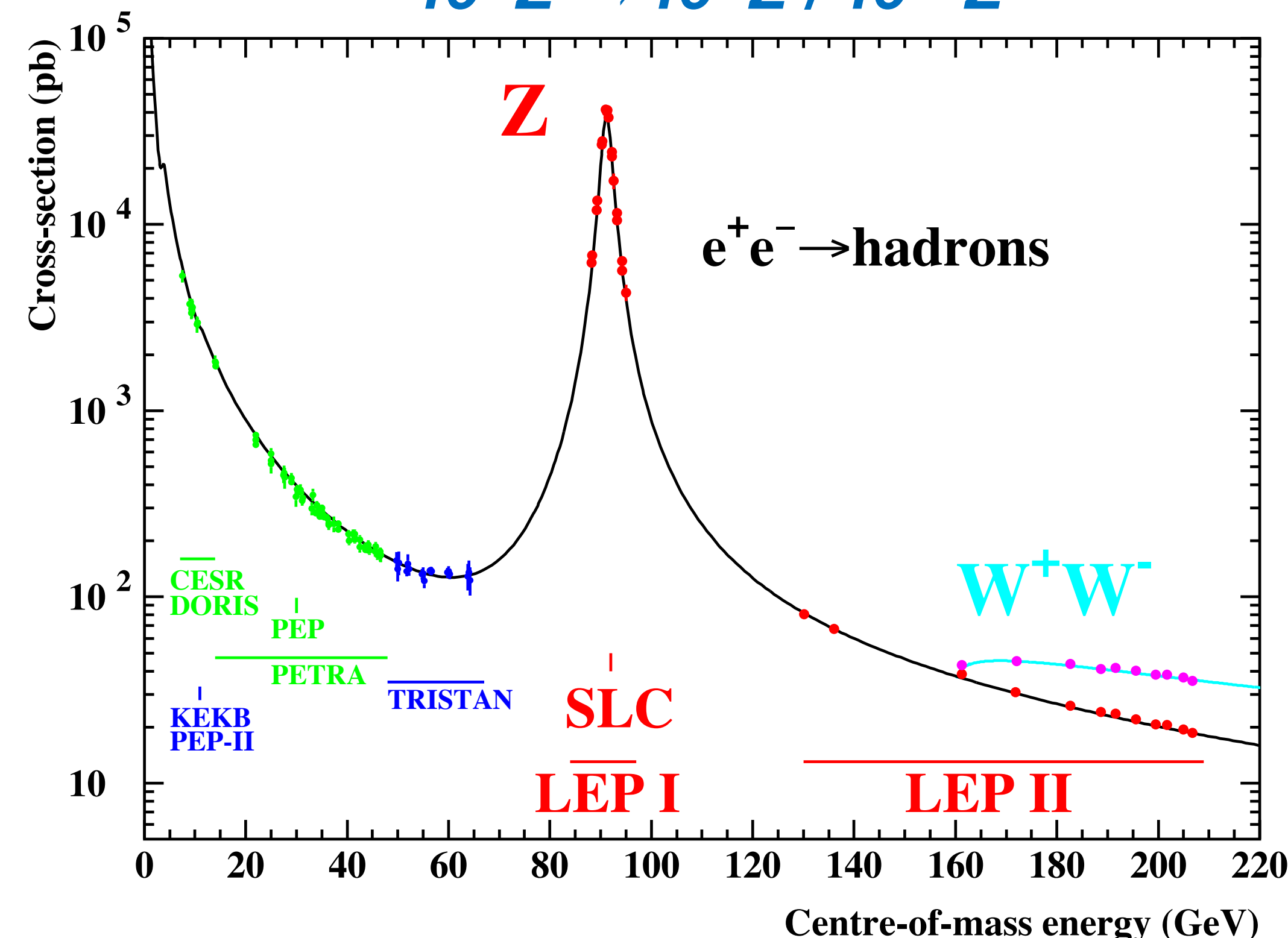
(Less precisely know SM input)



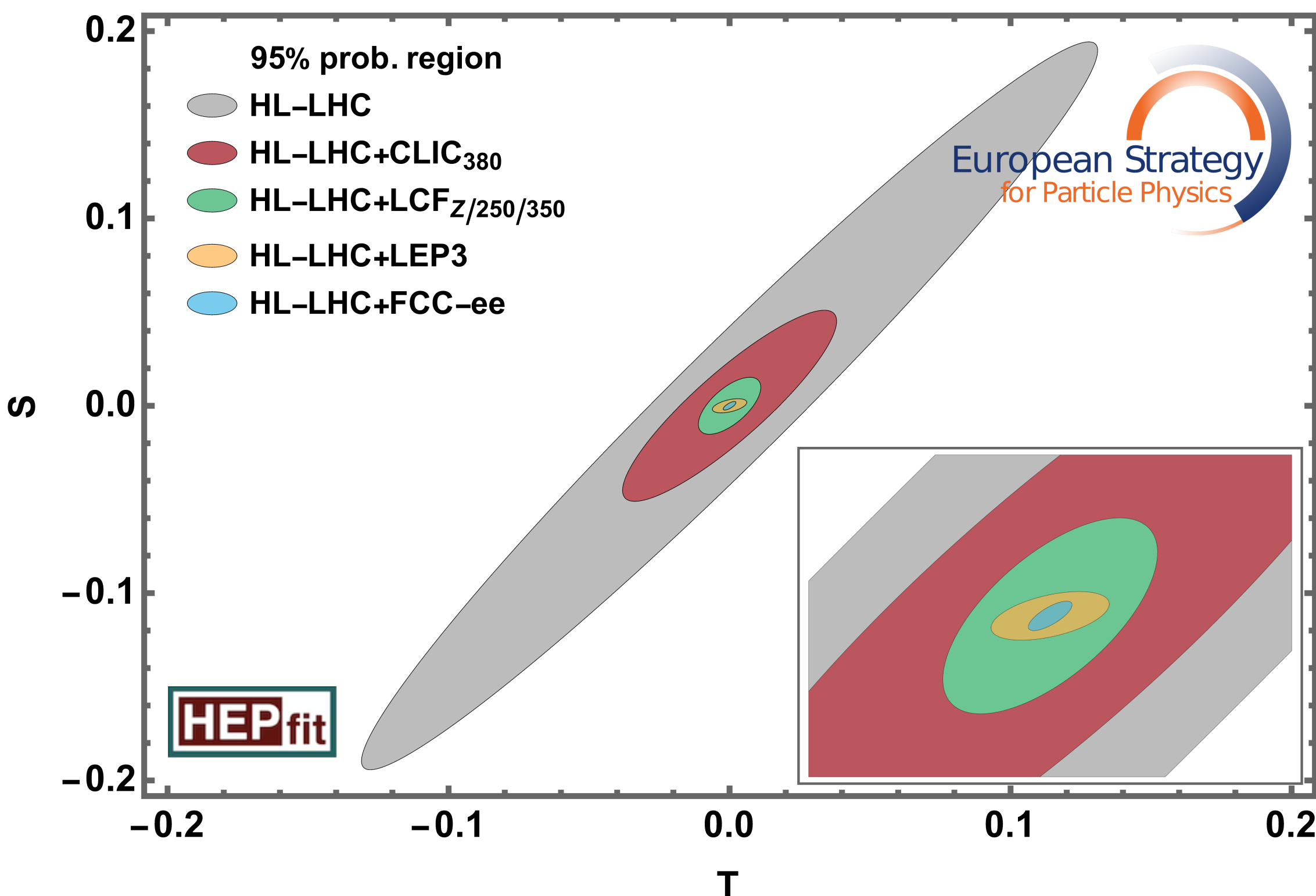
European Strategy
for Particle Physics

Physics Opportunities at the Tera-Z: EWPO

LEP/SLC $\Rightarrow$ Giga Z / Tera Z
 10^7 Z $\Rightarrow$ 10^9 Z / 10^{12} Z



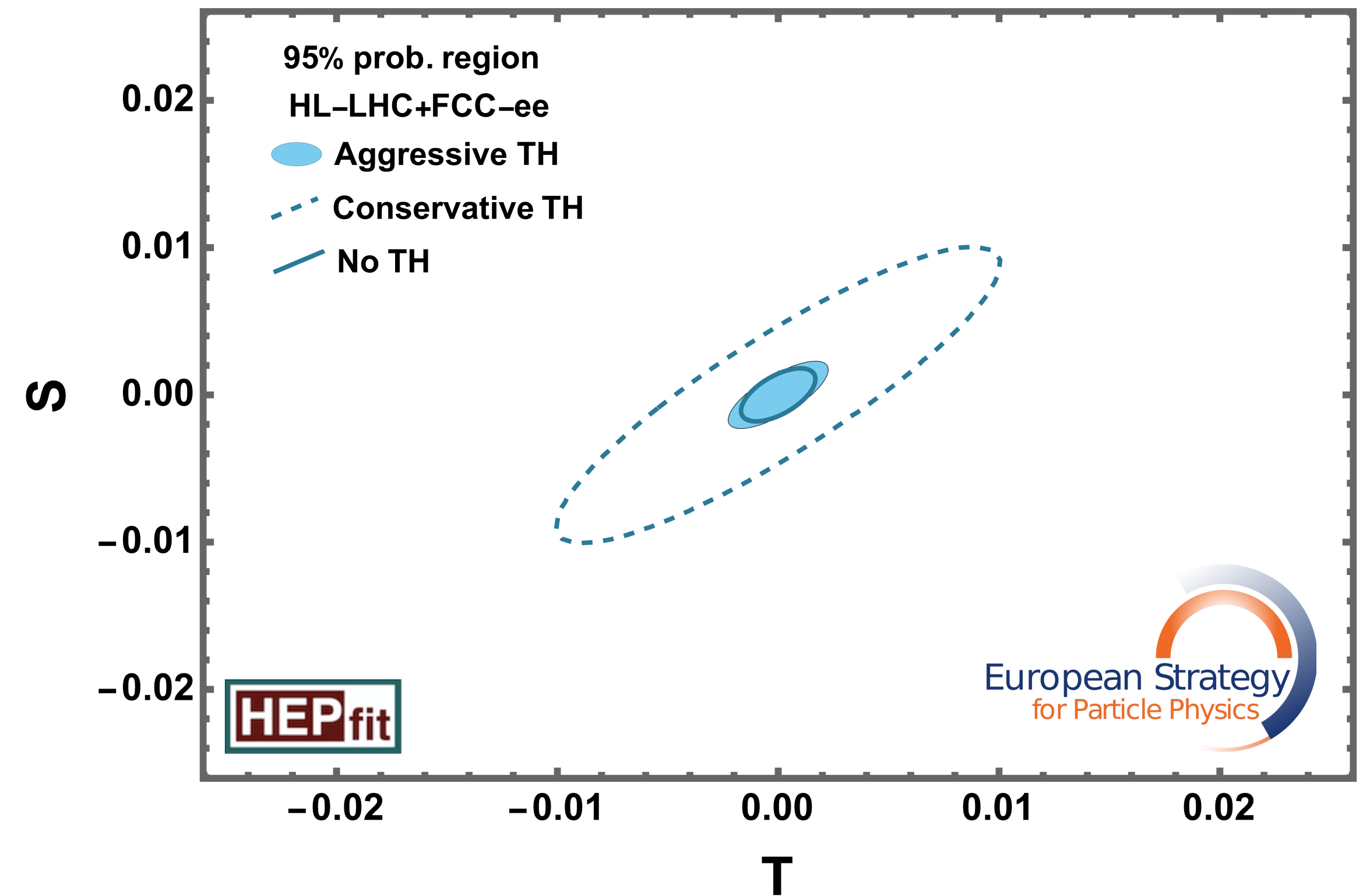
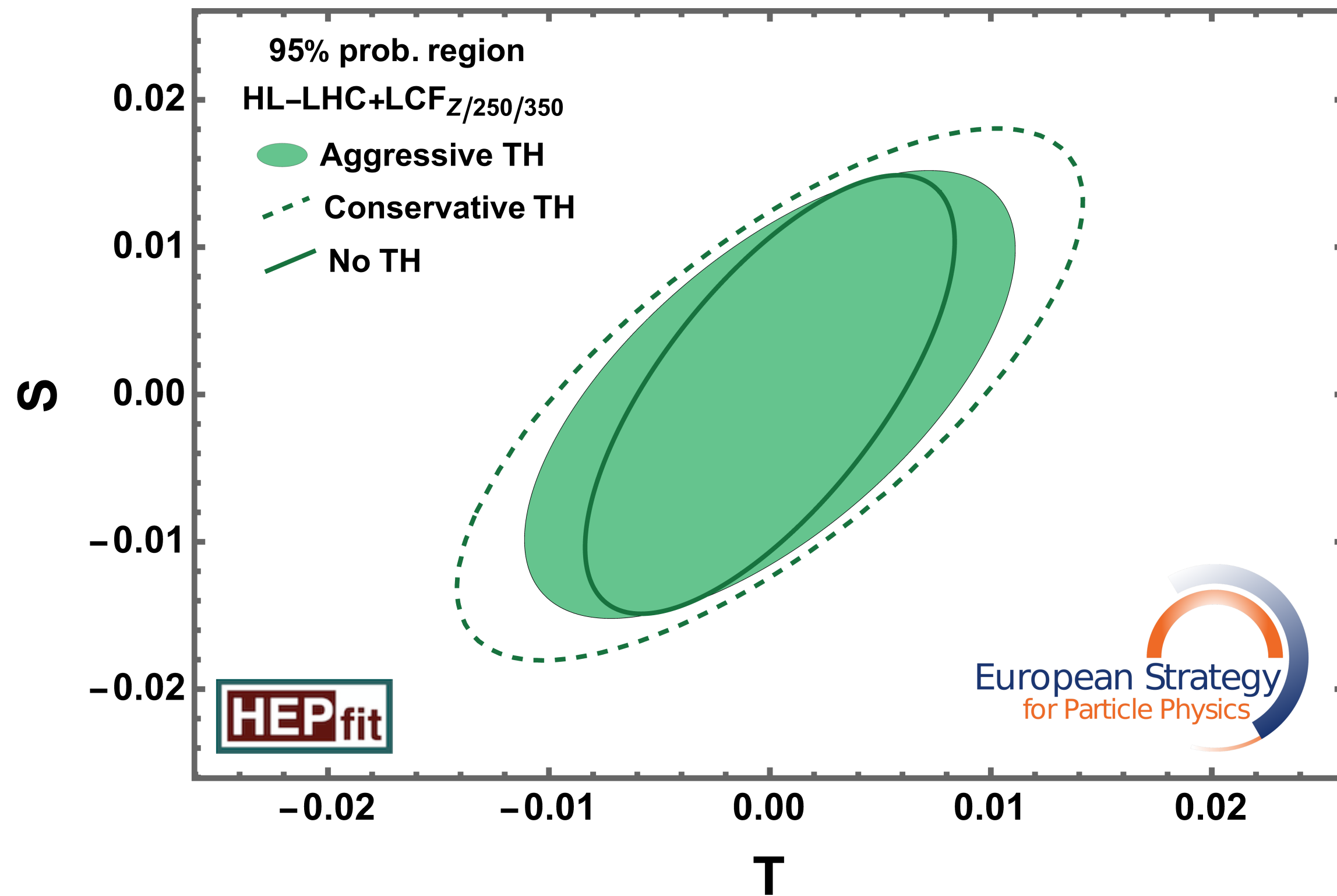
Capabilities for precision tests of (universal) NP



Results depend strongly on the assumptions made about the improvement of theory calculations

Physics Opportunities at the Tera-Z: EWPO

Impact of theory precision on experimental bounds from EWPO



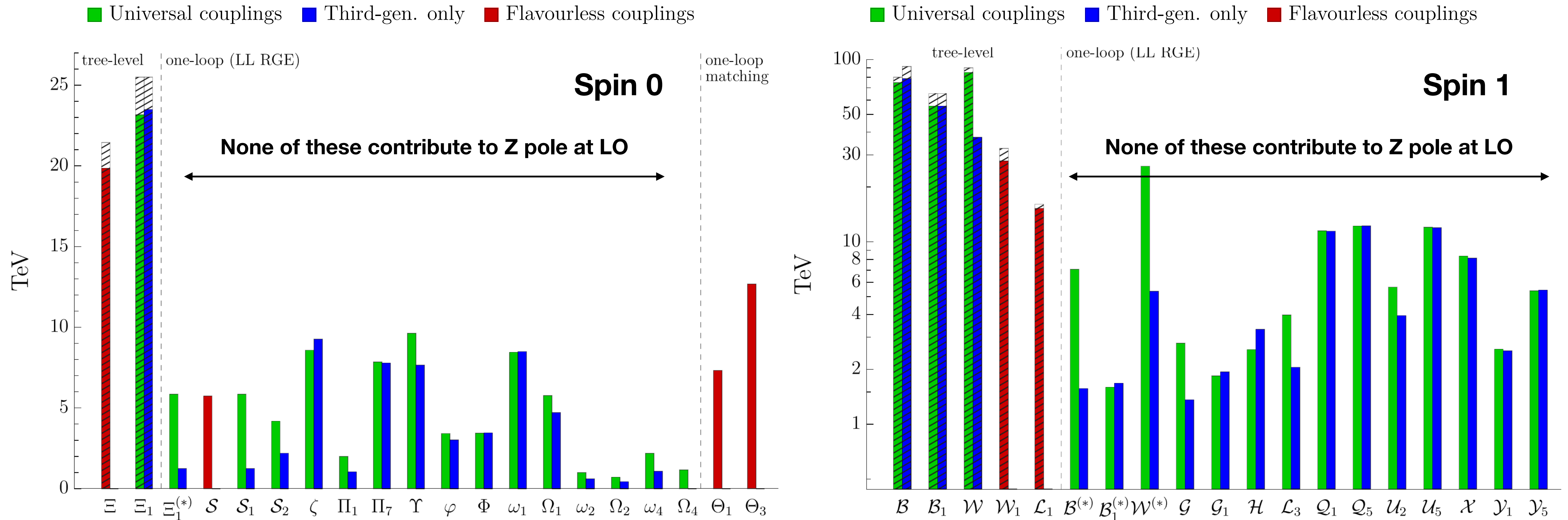
Results depend strongly on the assumptions made about the improvement of theory calculations
Current calculations and even our conservative estimates of future precision seem to be not enough
Future parametric uncertainties also still limit the final precision

Physics Opportunities at the Tera-Z: Reach for simplified models

- Tera-Z precision enables sensitive to scales up to $O(100 \text{ TeV})$ if new particles modify EWPO at tree level

► Even if only loop corrections, $O(10 \text{ TeV})$ sensitivity

Allwicher et al., JHEP 02 (2025) 164

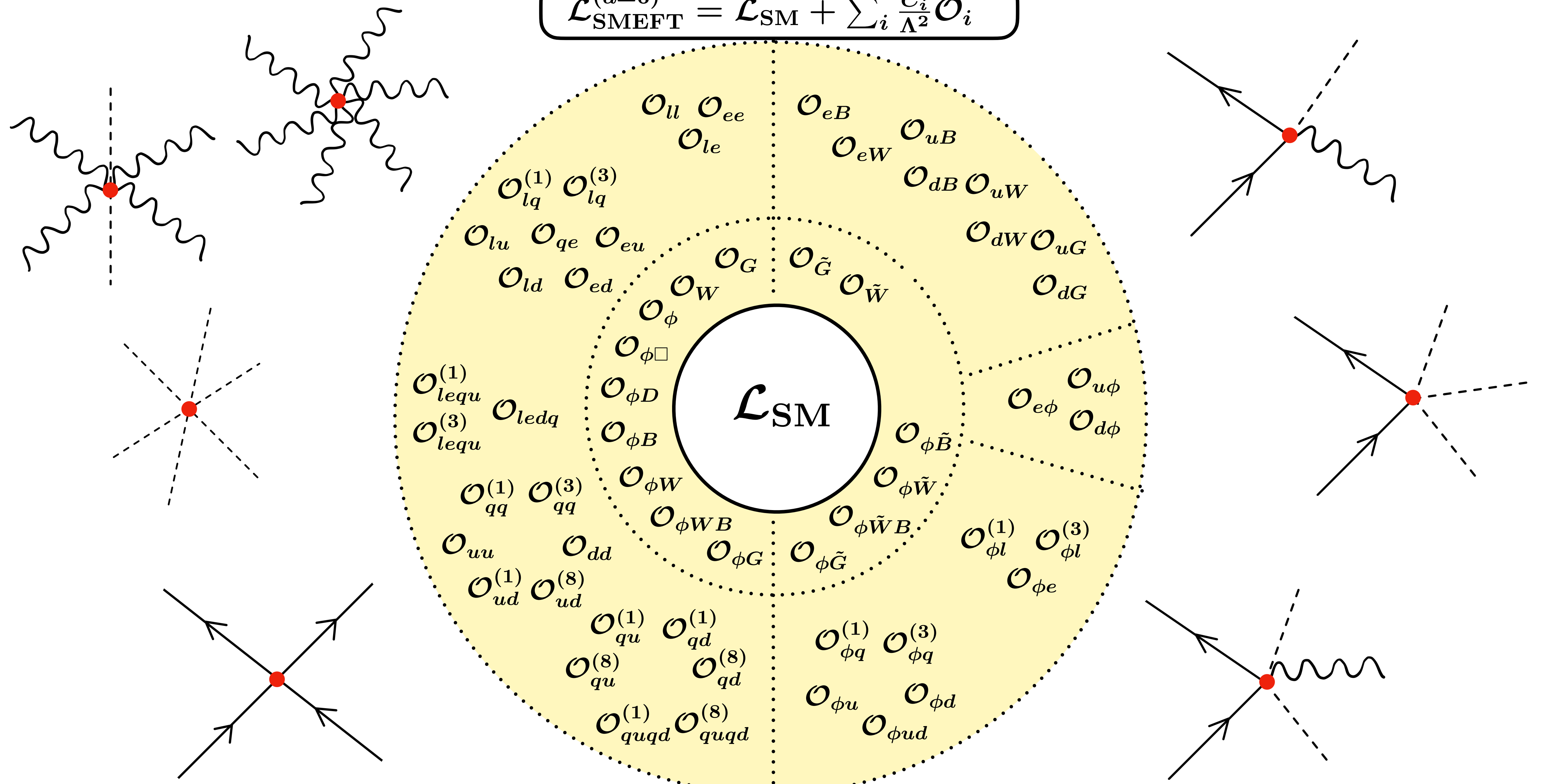


Any particle generating dimension 6 effects at low energies at tree level
can be strongly constrained by future EWPO

Opportunities for Flavour Physics at e^+e^- Electroweak factories

BSM can “change” the SM in many different ways...

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$



BSM can “change” the SM in many different ways...

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

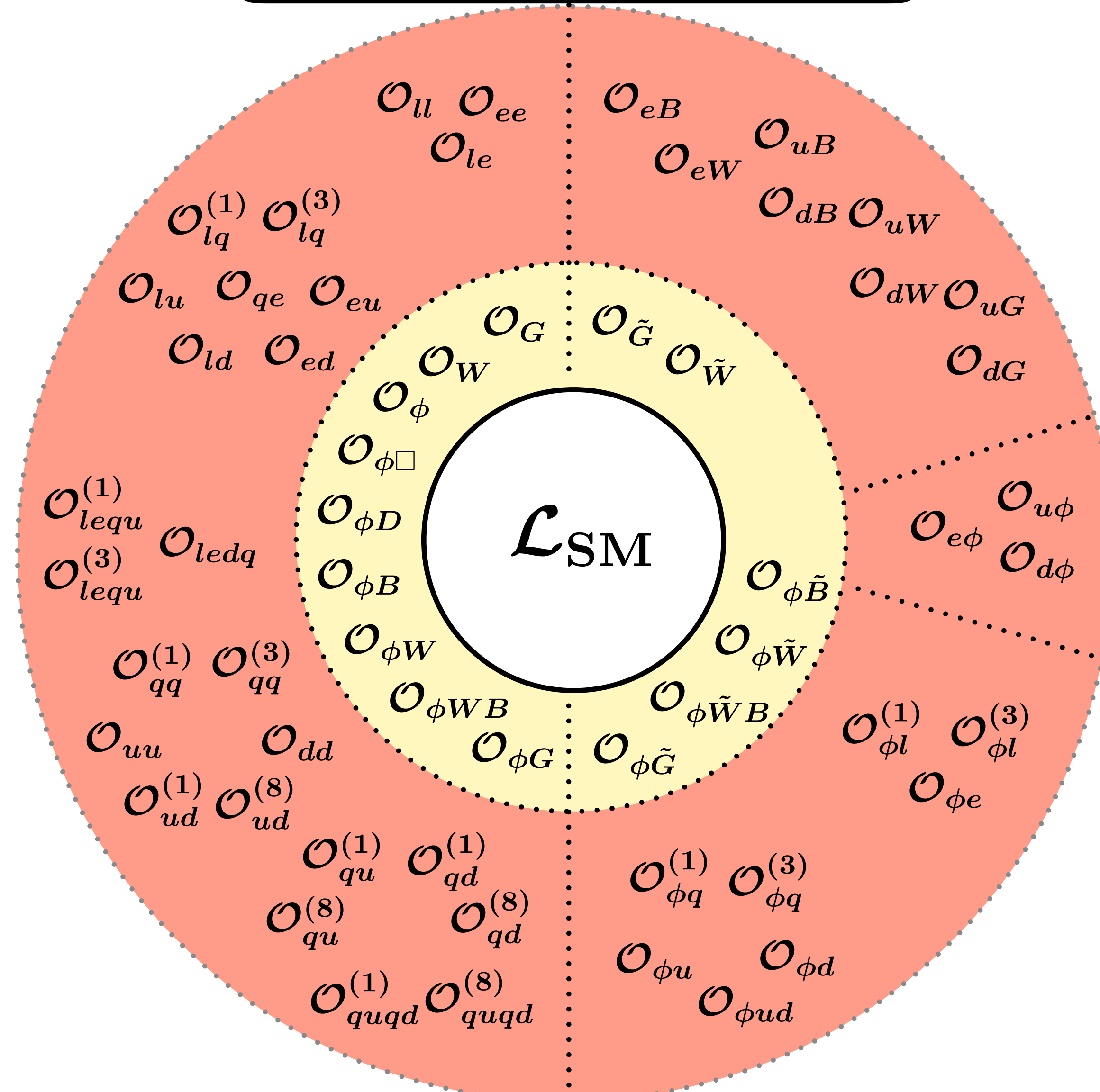
SMEFT @ d=6

59 Operator structures



2499 Operators

Most of the SMEFT is Flavor

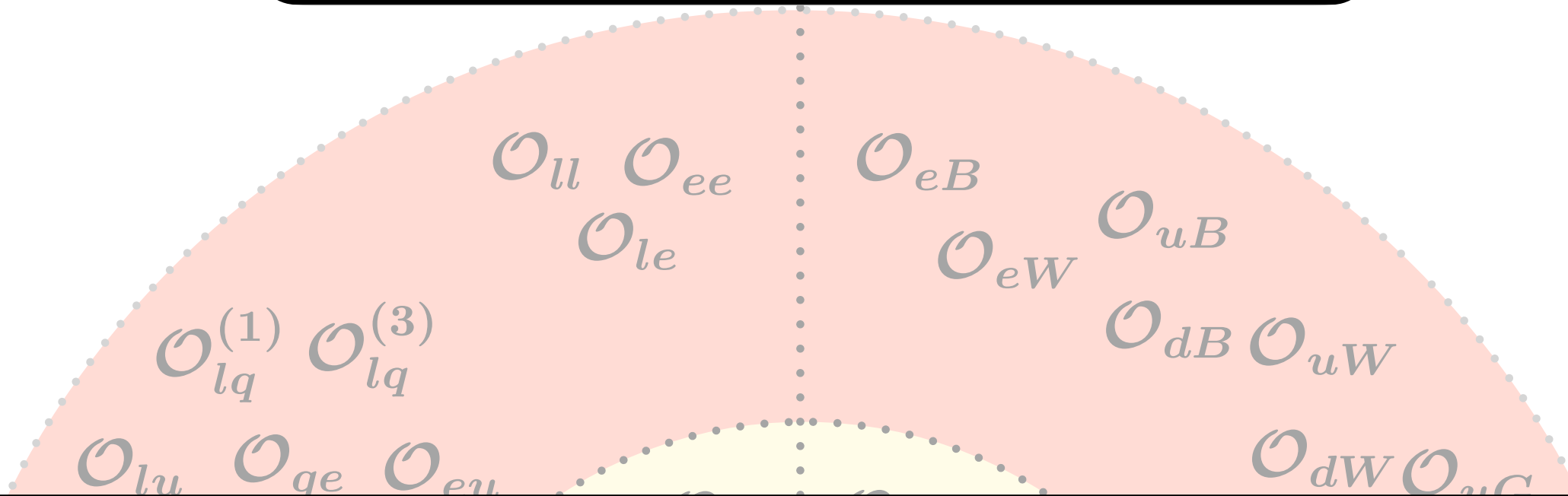


BSM can “change” the SM in many different ways...

$$\mathcal{L}_{\text{SMEFT}}^{(d=6)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

SMEFT @ d=6

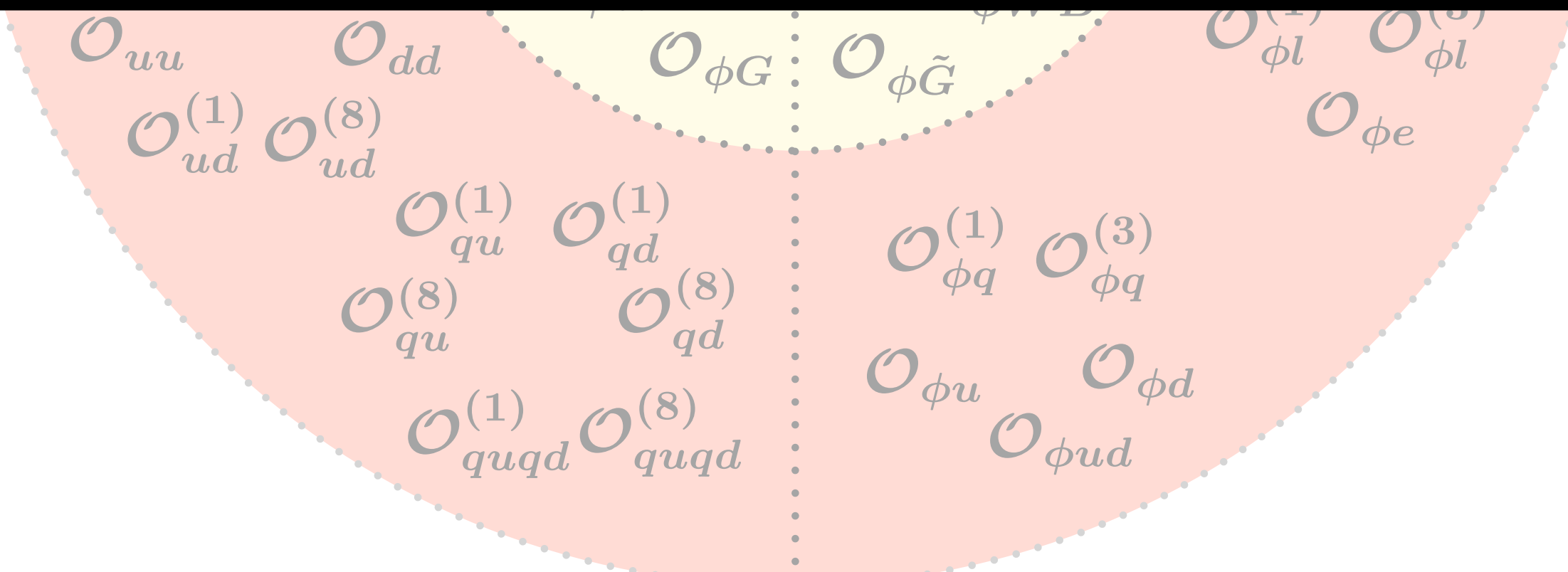
59 Operator structures



**Even when BSM has some flavour “protection” (e.g. U(2)⁵)
Flavour measurements provide strong (and complementary) constraints on BSM**

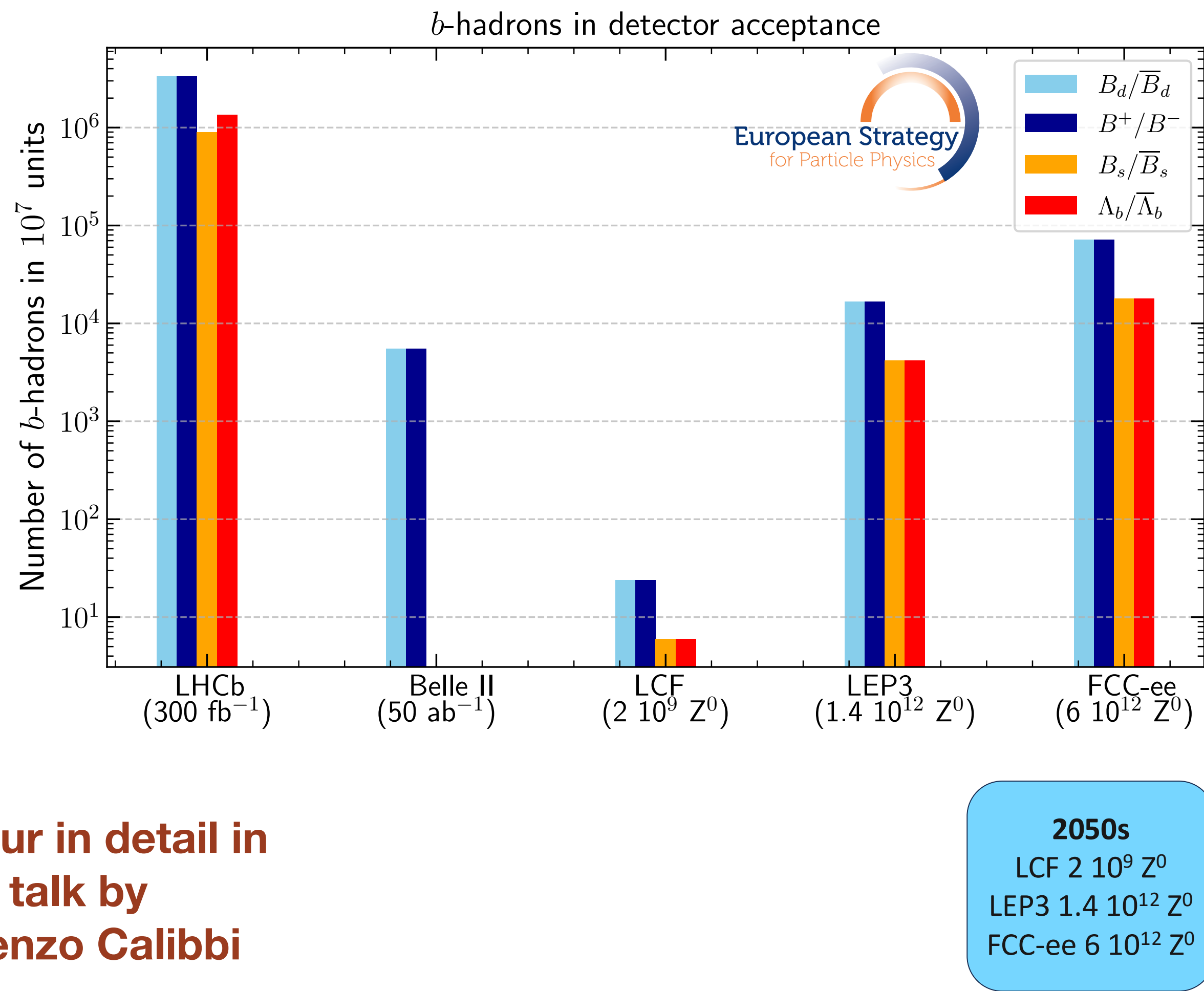
⇒ Flavour physics opportunities at future e⁺e⁻?

Most of the
SMEFT is Flavor

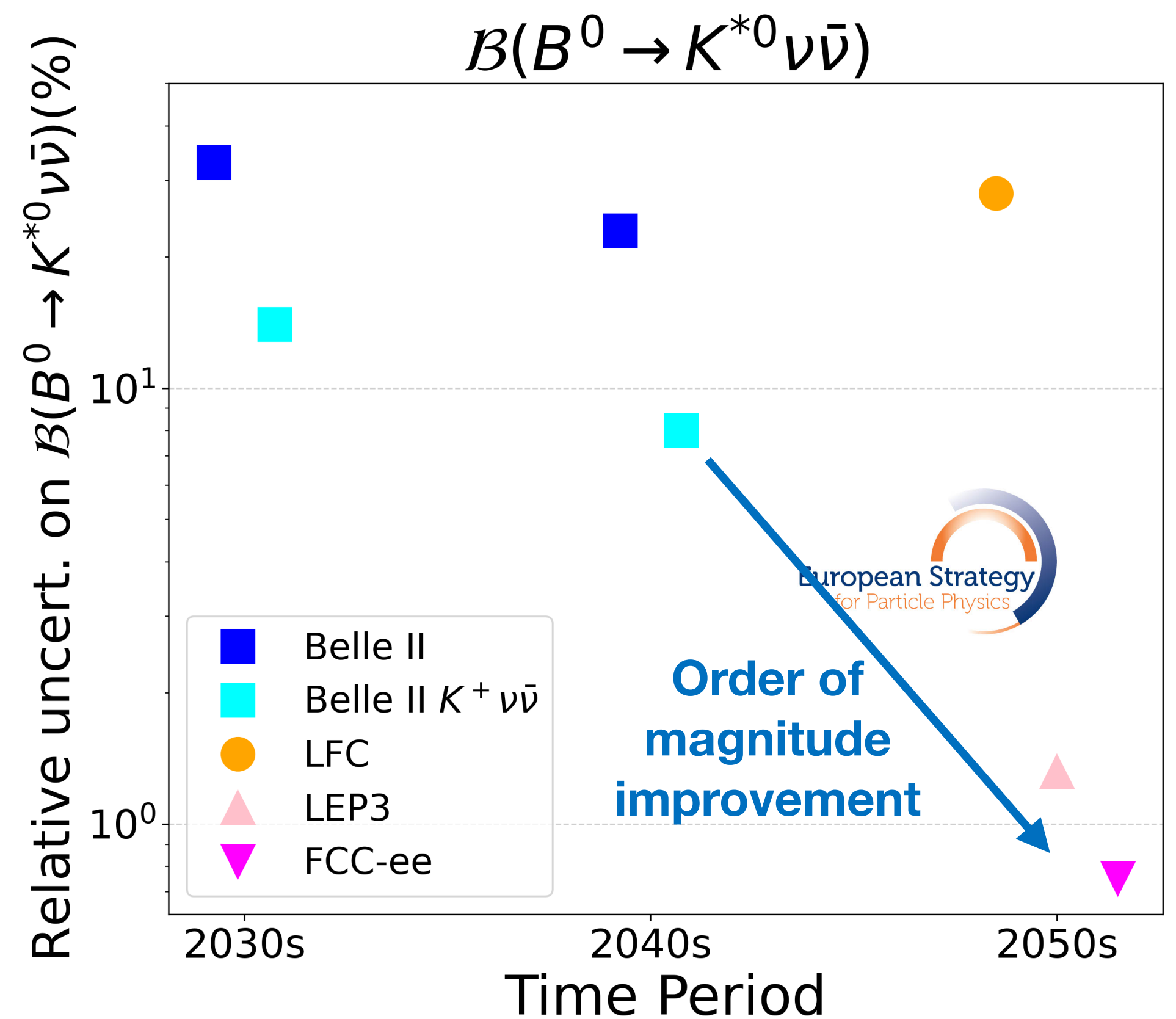


Flavour physics at the Z-pole

- Tera Z: 10^{12} Z bosons $\Rightarrow$ Plenty of bottom, charm and τ fermions for clean flavour physics



Opportunities for probing NP in FCNC $b \rightarrow s \nu \bar{\nu}$



Flavour in detail in
talk by
Lorenzo Calibbi

Additional opportunities from W decays (10^8 W pairs) $\Rightarrow$ CKM

Flavour physics at the Z-pole

- Tera Z: 10^{12} Z bosons $\Rightarrow$ Plenty of bottom, charm and τ fermions for clean flavour physics

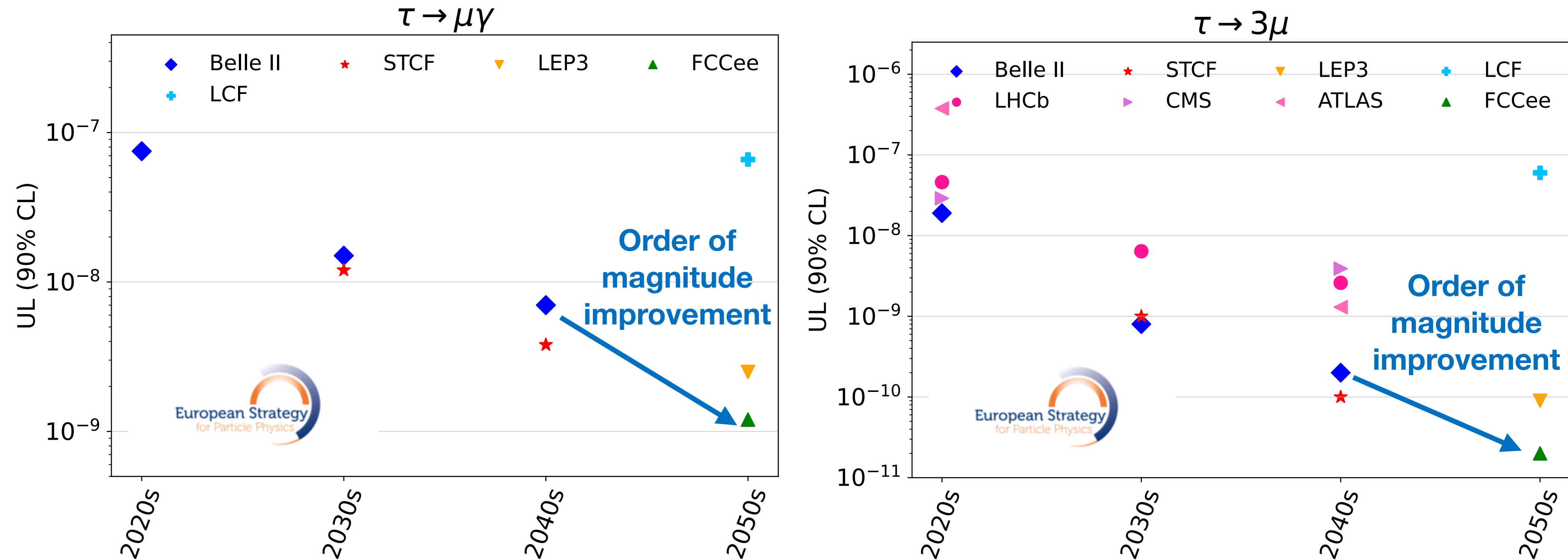
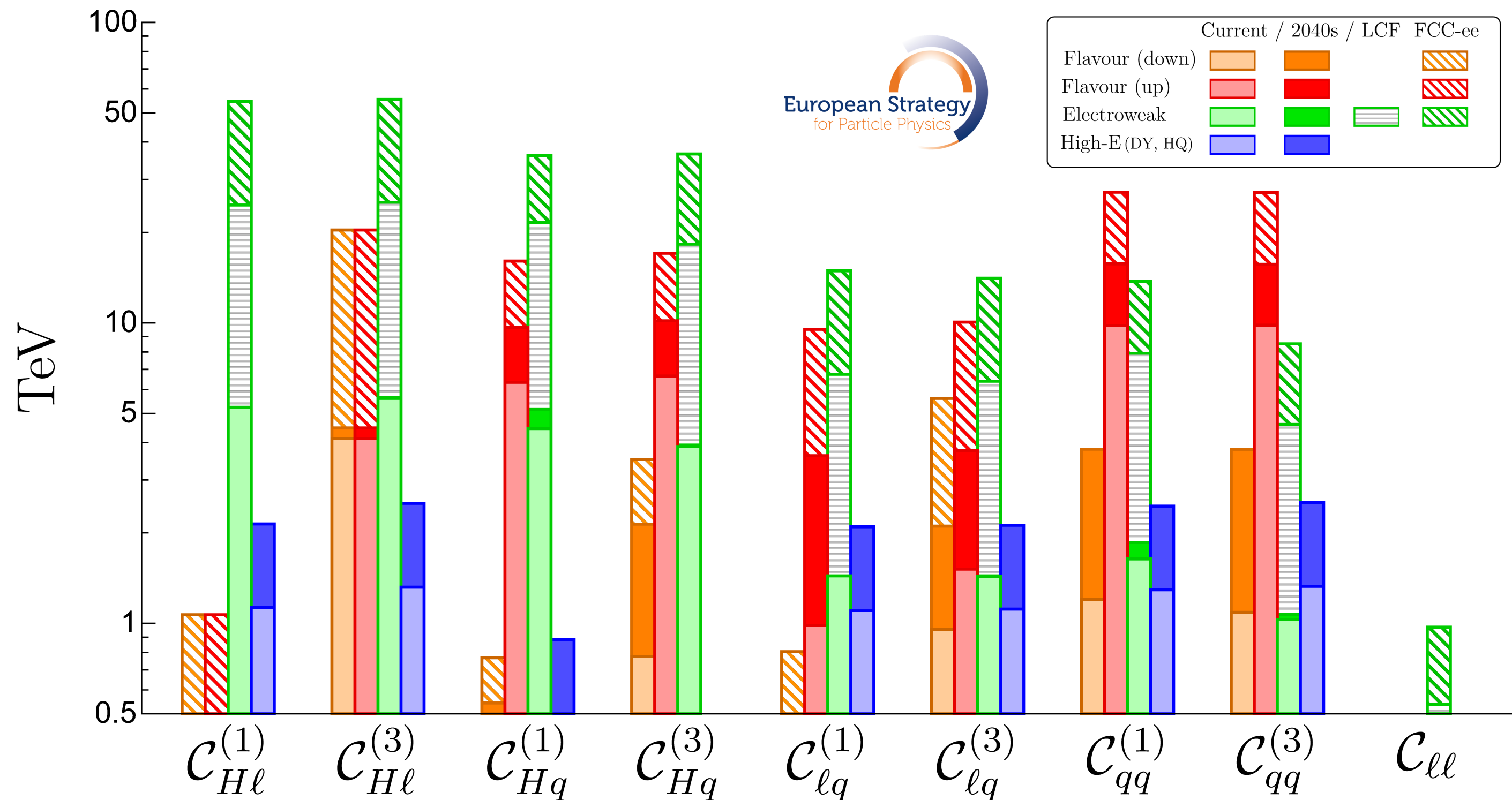


Fig. 5.7: Expected upper limits at 90% on $\mathcal{B}(\tau \rightarrow \mu\gamma)$ and $\mathcal{B}(\tau \rightarrow \mu\mu\mu)$.

Electroweak vs. Flavour

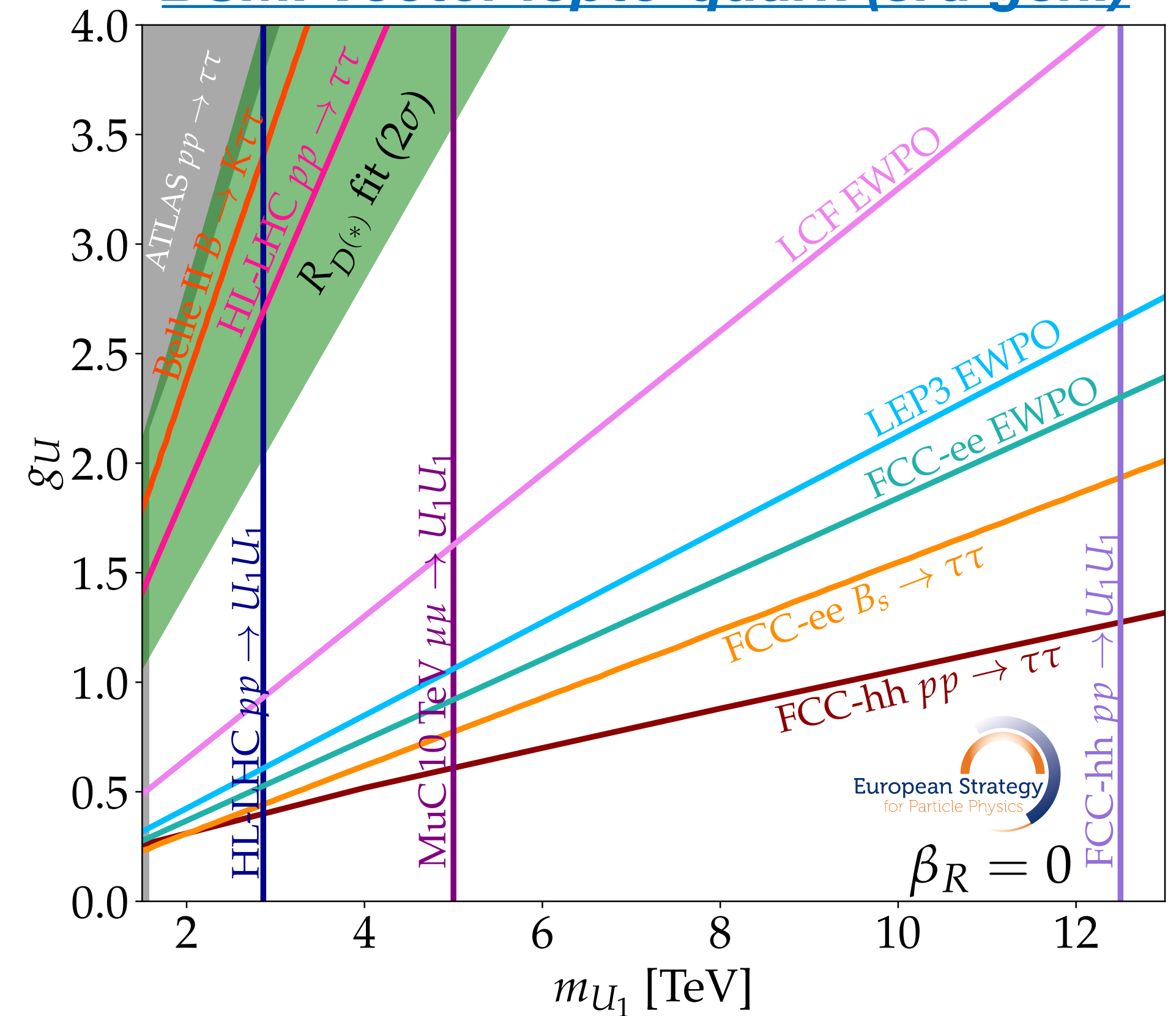
- Complementarity Electroweak/Flavour:

EFT bounds: EW vs. Flavour



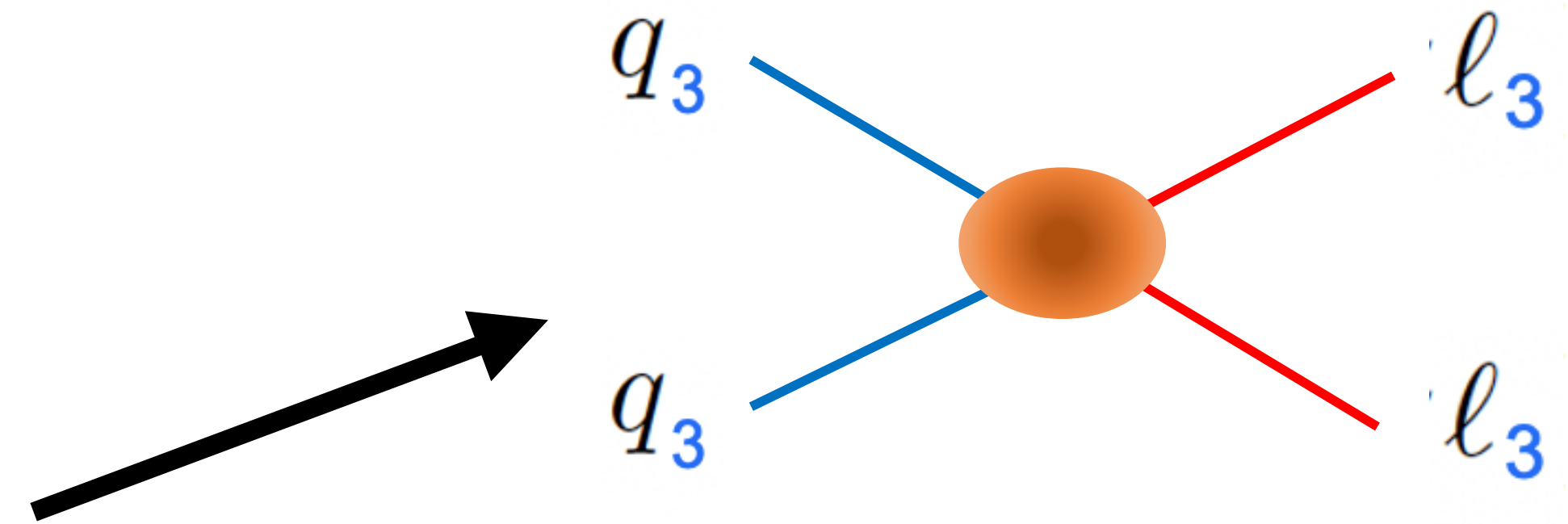
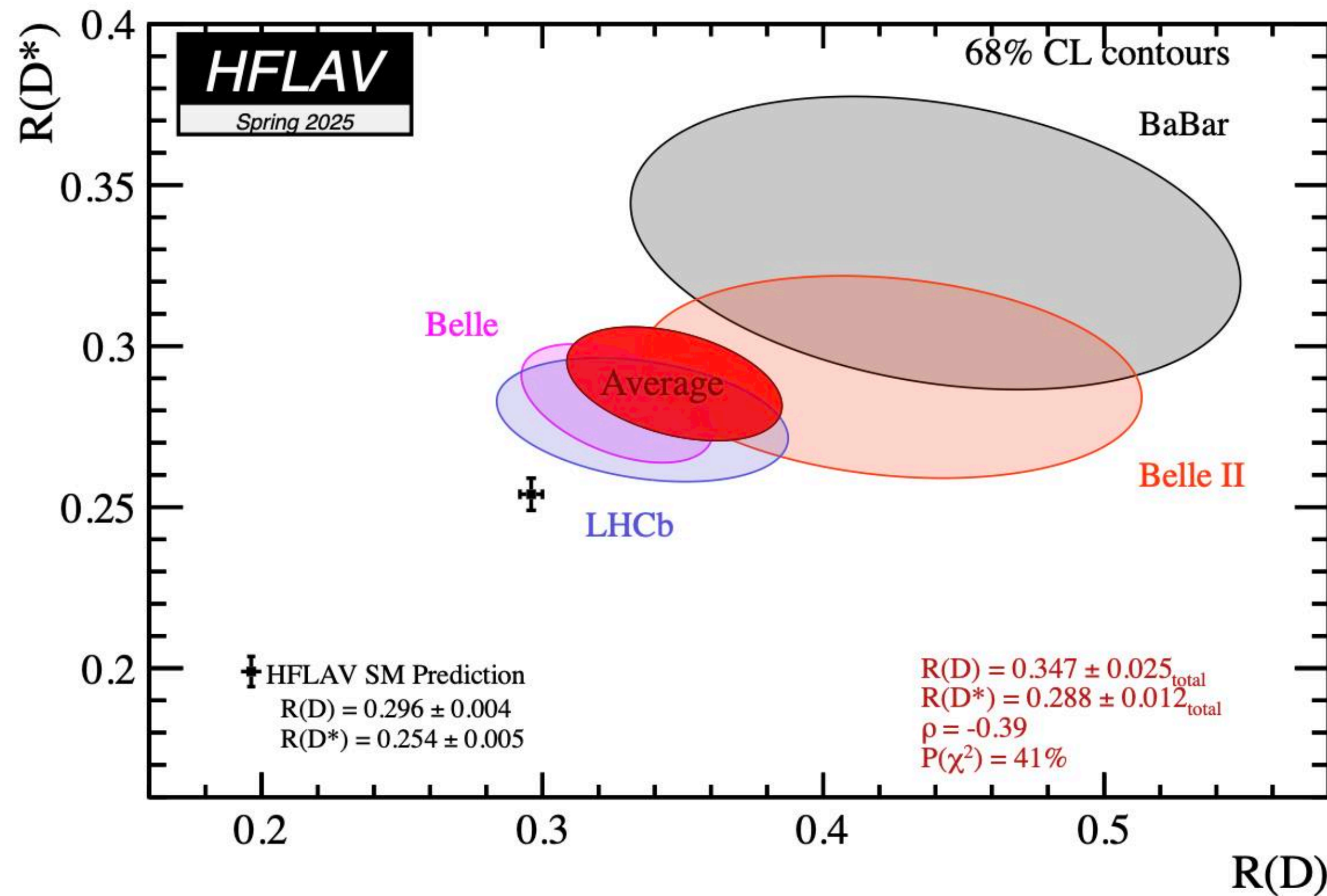
**Complementarity: Best bound depend on operator
(and flavour assumptions of BSM)**

BSM: Vector lepto-quark (3rd gen.)



Electroweak and Flavour interplay

- A simple example* to identify the origin of a potential new physics signal



- Explanation requires only 3 parameters:
2 Wilson Coefficients + one flavour mixing

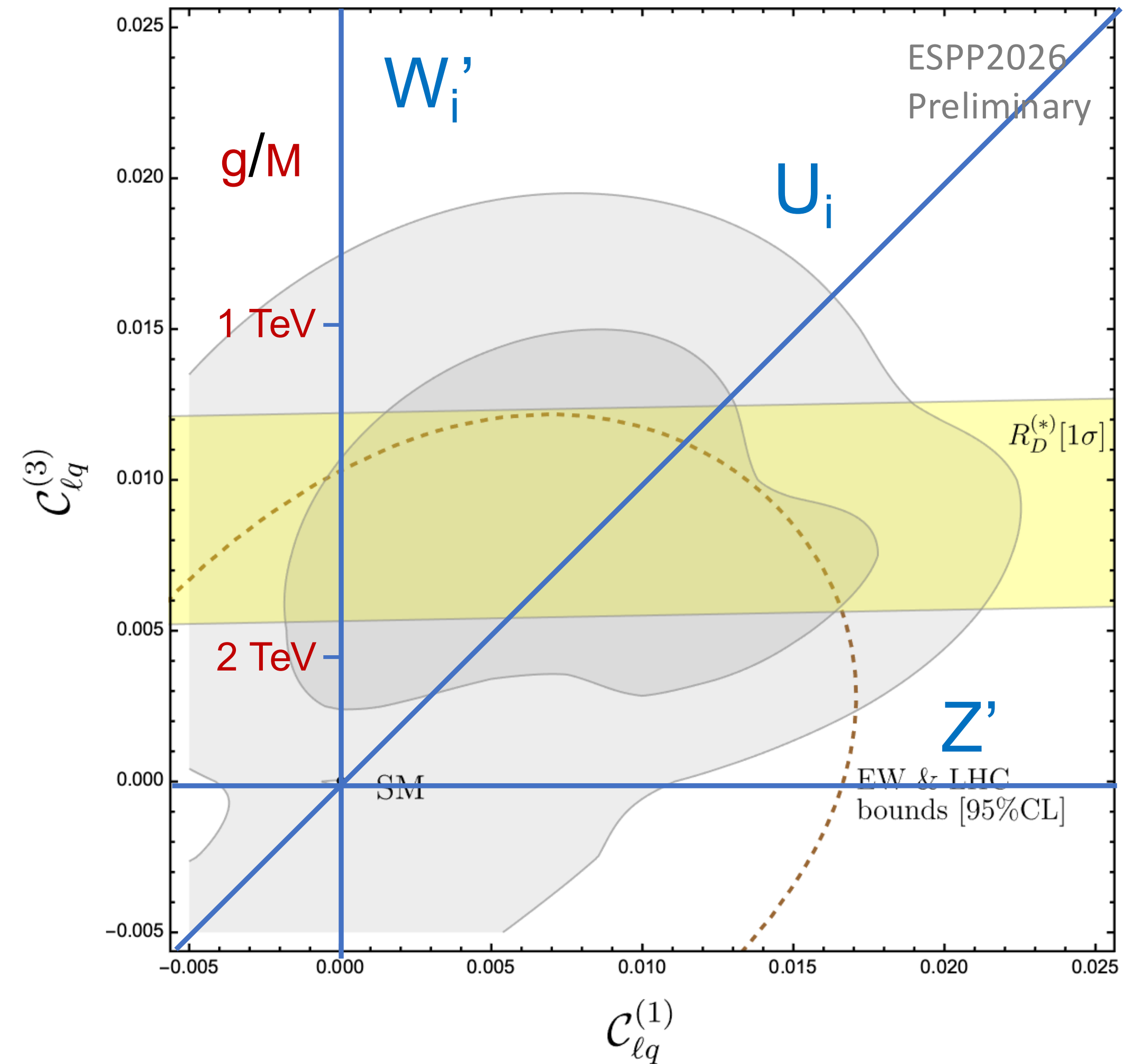
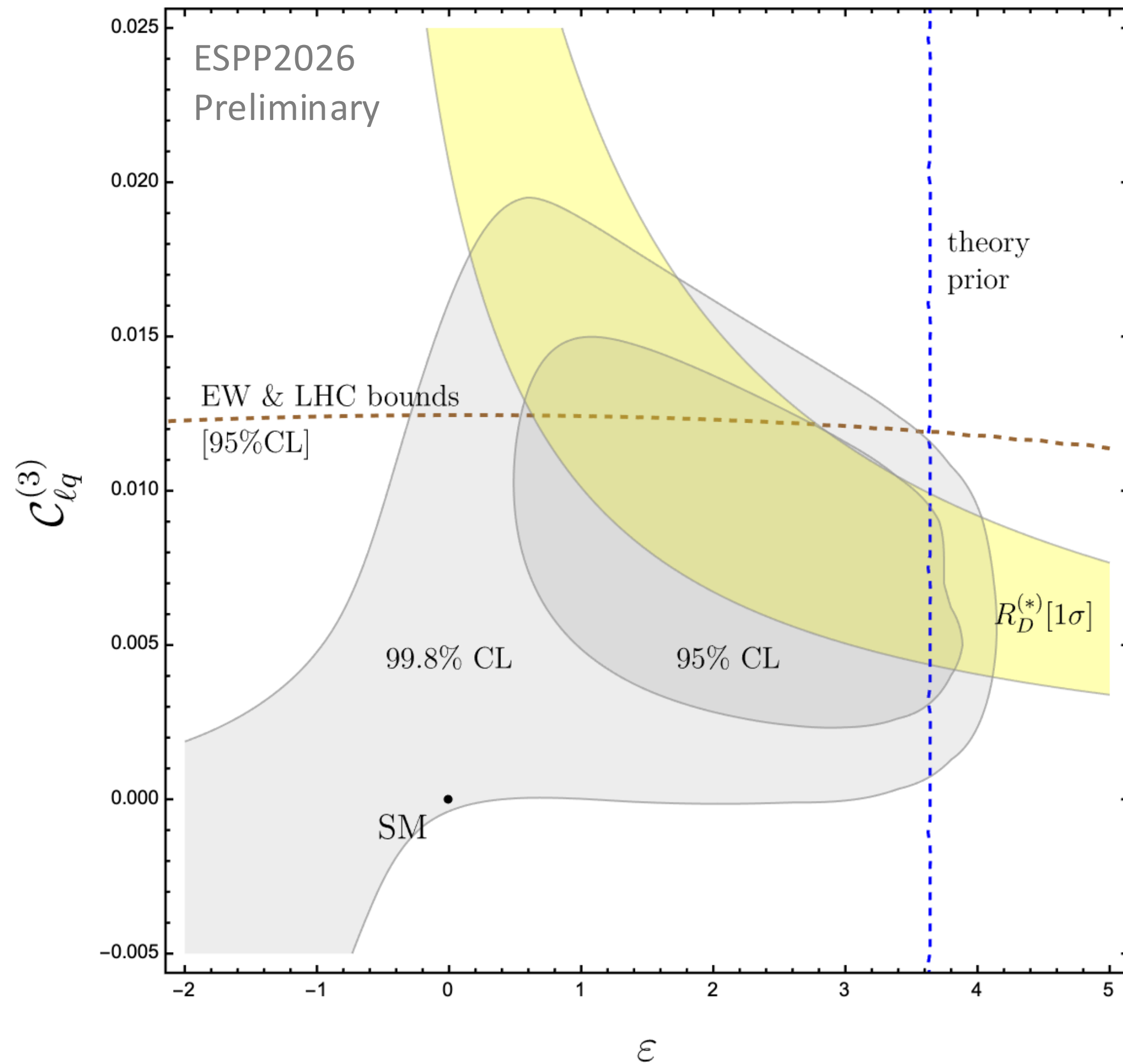
$$\mathcal{C}_{\ell q}^{(1)} \quad \mathcal{C}_{\ell q}^{(3)}$$

$$\varepsilon = \mathcal{O}(1): \quad q_3 = b_L + \varepsilon |V_{ts}| s_L$$

*Example from G. Isidori's plenary talk at Venice Open Symposium

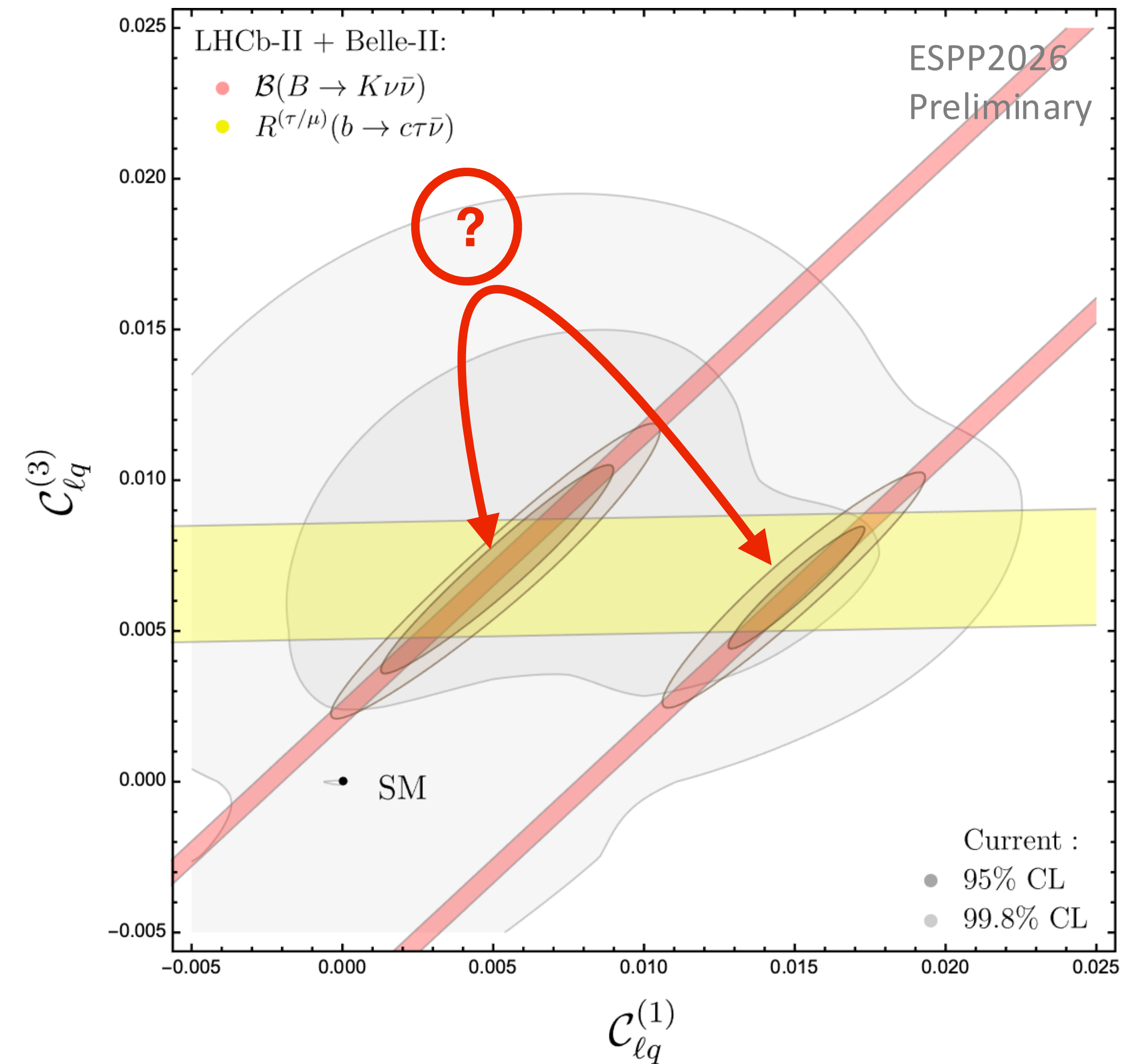
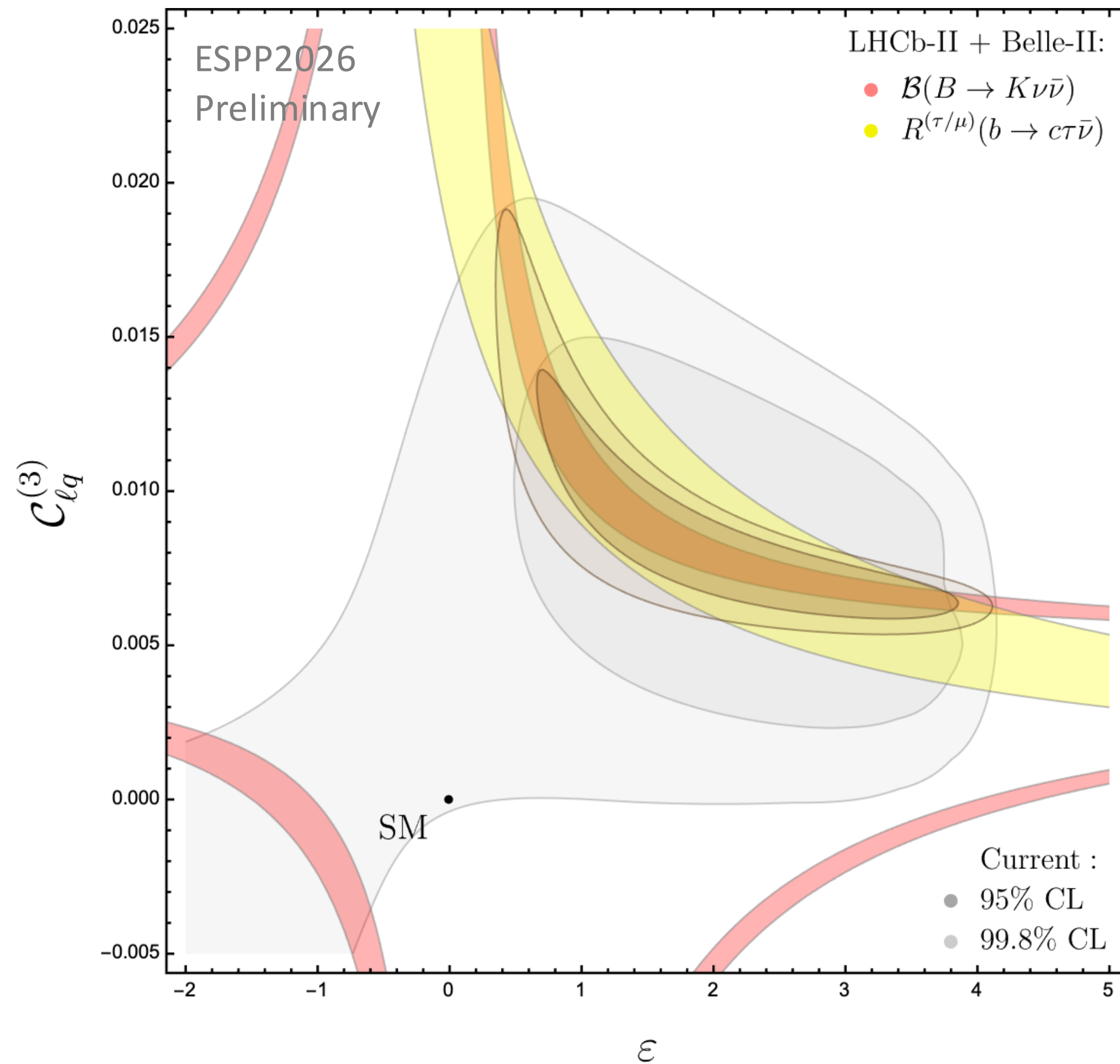
Electroweak and Flavour interplay

- A simple example* to identify the origin of a potential new physics signal



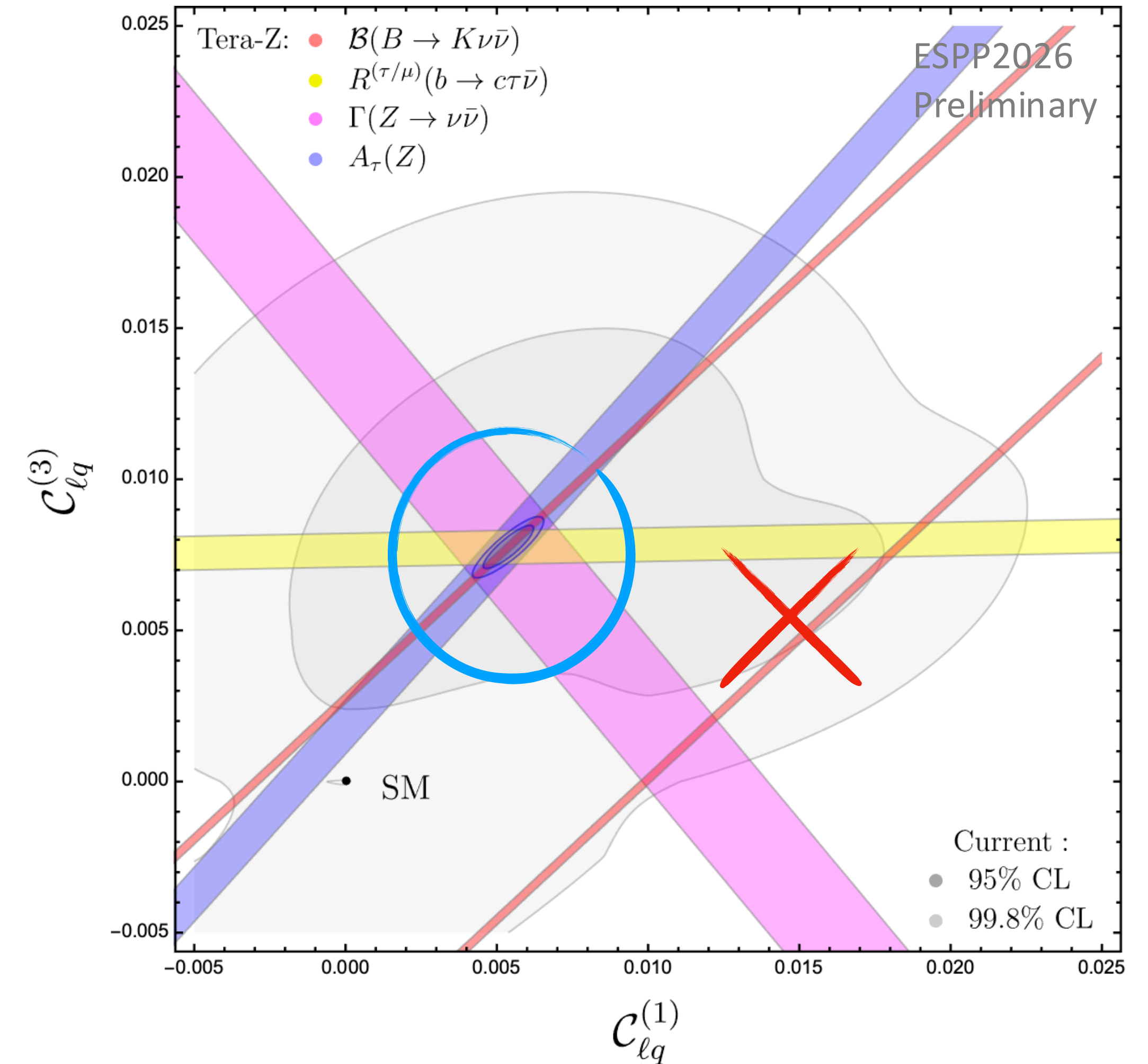
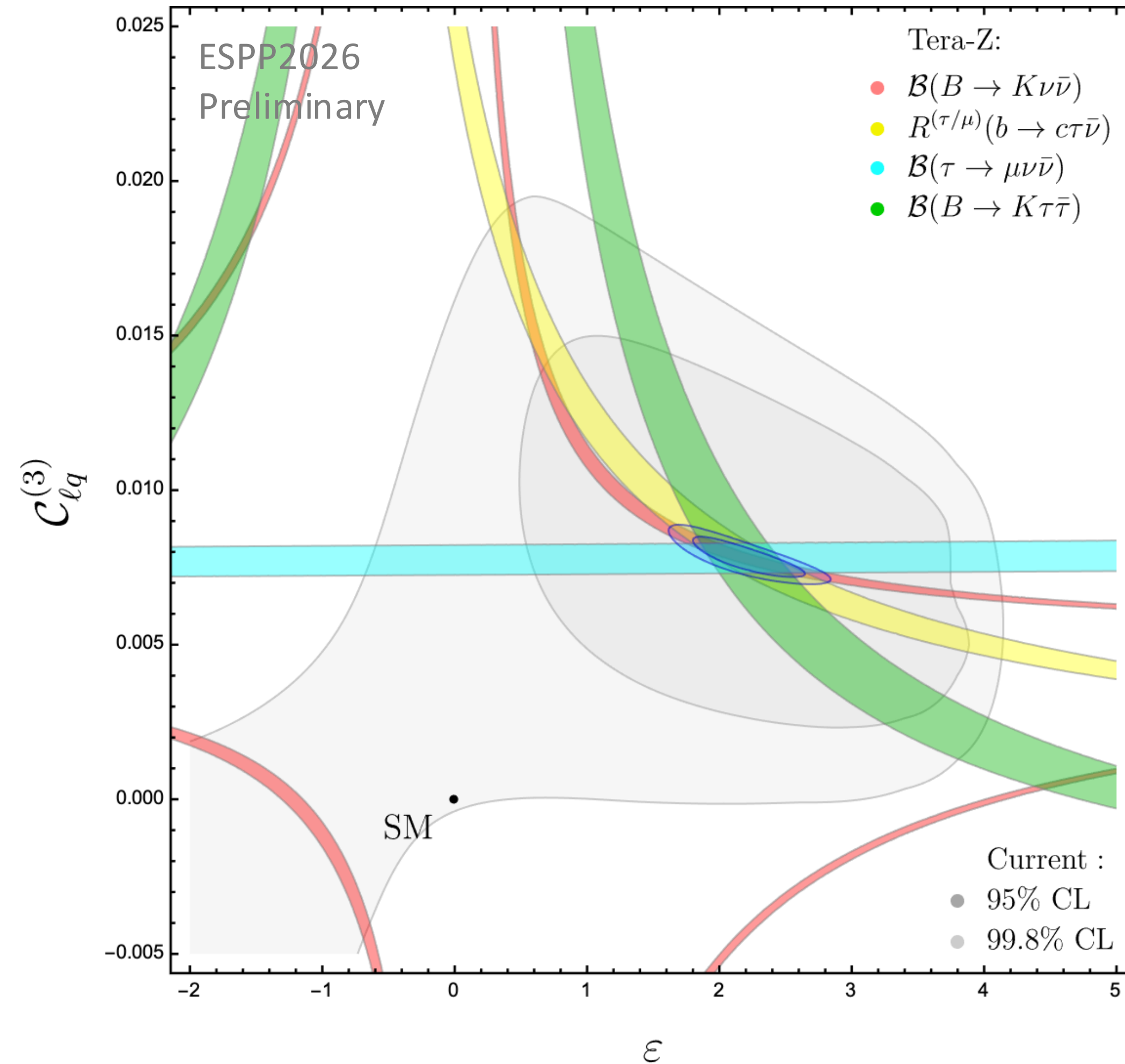
Electroweak and Flavour interplay

- Adding the information from future B-flavour measurements from LHCb & Belle-II



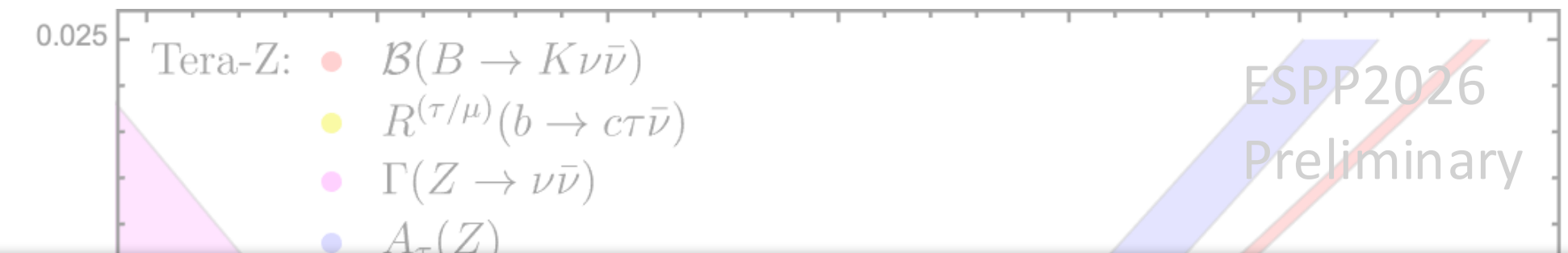
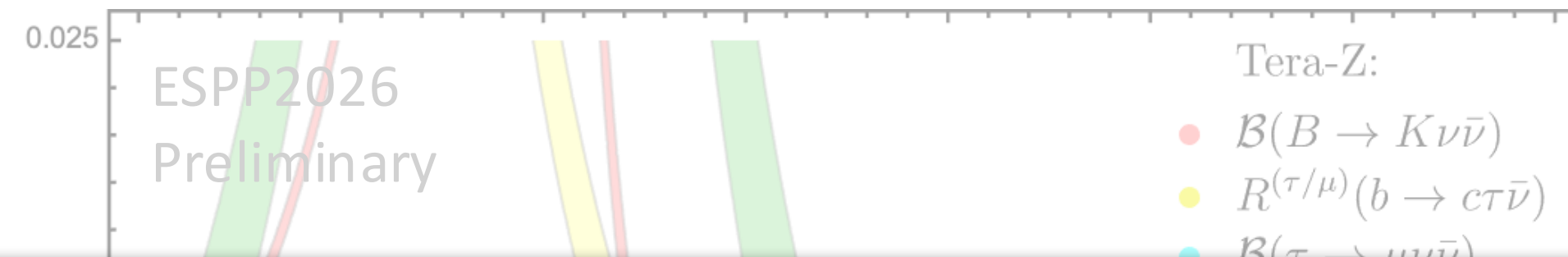
Electroweak and Flavour interplay

- Adding improvements from Tera-Z on B-measurements + τ observables + Tera-Z EWPO:



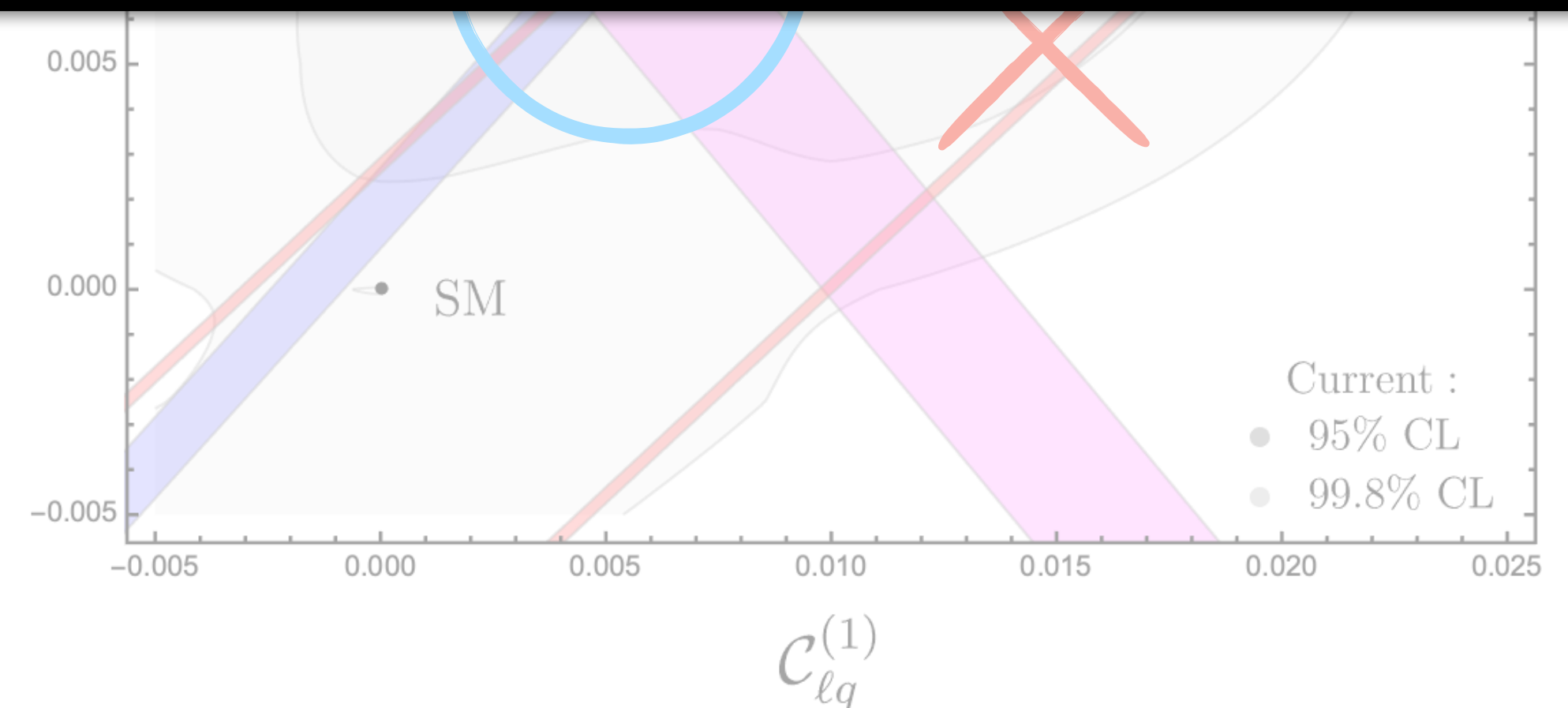
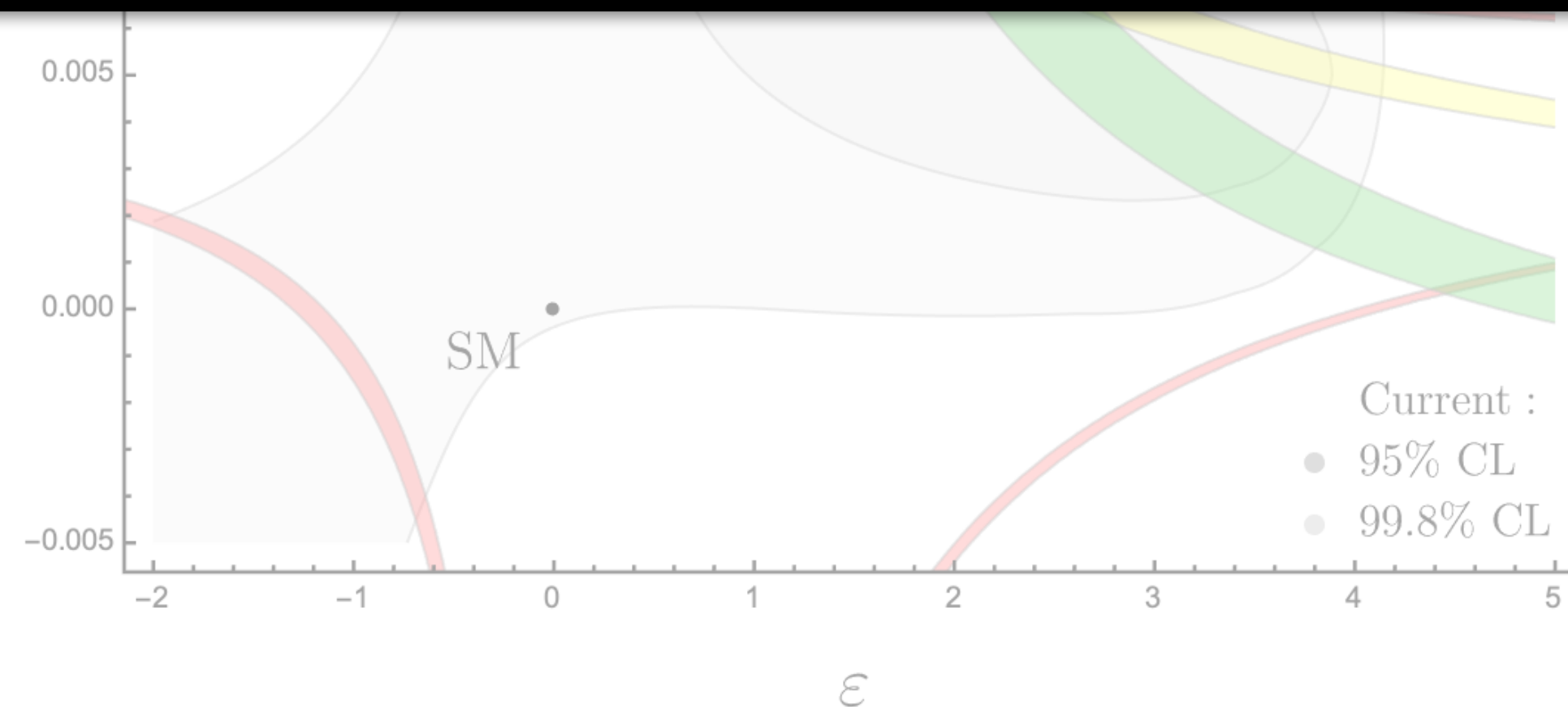
Electroweak and Flavour interplay

- Adding improvements from Tera-Z on B-measurements + τ observables + Tera-Z EWPO:



Interplay between different measurements is crucial to characterize the origin of any possible indirect signal of new physics at current or any future experiments

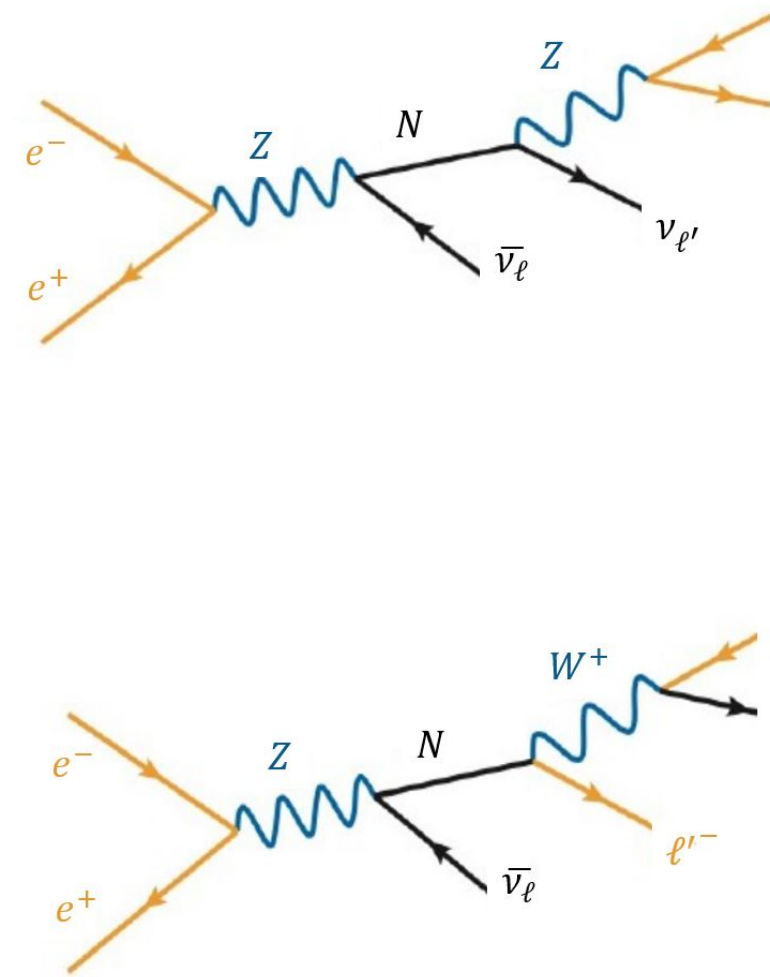
Indirect tests via EW & Flavour measurements explore of BSM in complementary ways



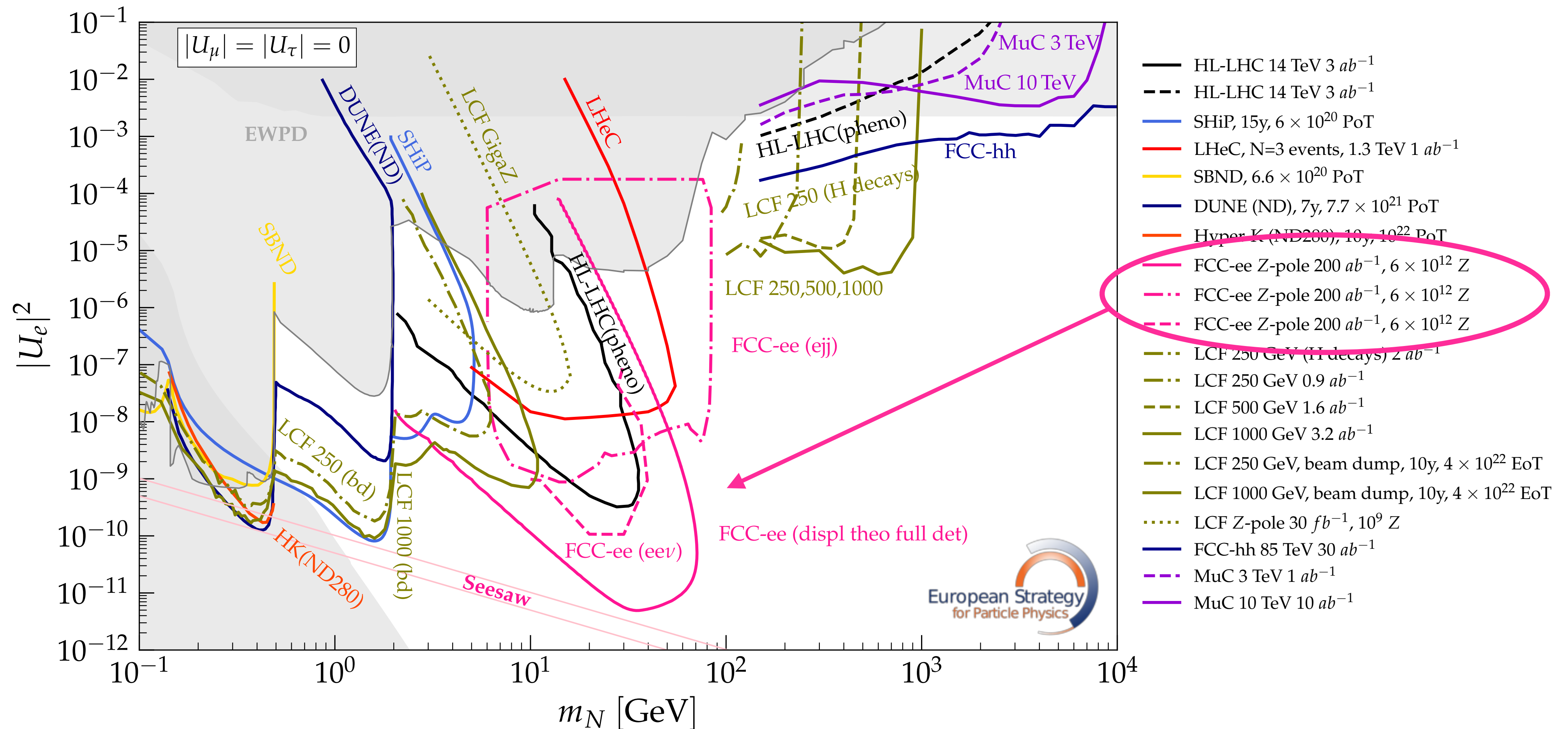
Additional opportunities
Direct searches of “light” particles

Direct searches (one example)

- The focus of e^+e^- colliders may be on indirect tests of NP, via precision measurements, but they can also bring improvements on direct searches of light particles
 - Example: “Heavy” Neutral Leptons (Predicted in models explaining neutrino masses via see-saw)



BSM in detail in
talk by
Juraj Klarić

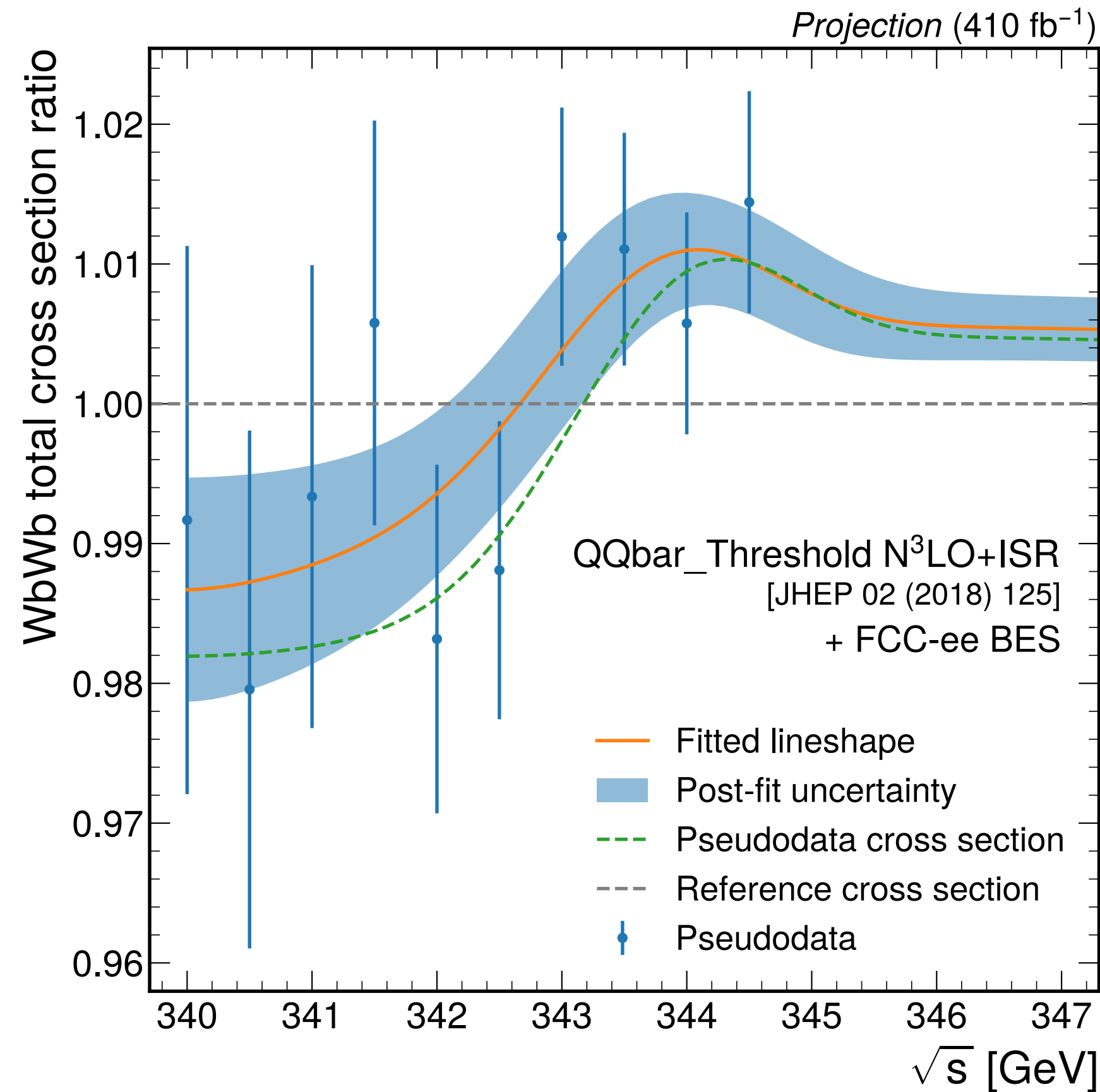


More than Higgs factories

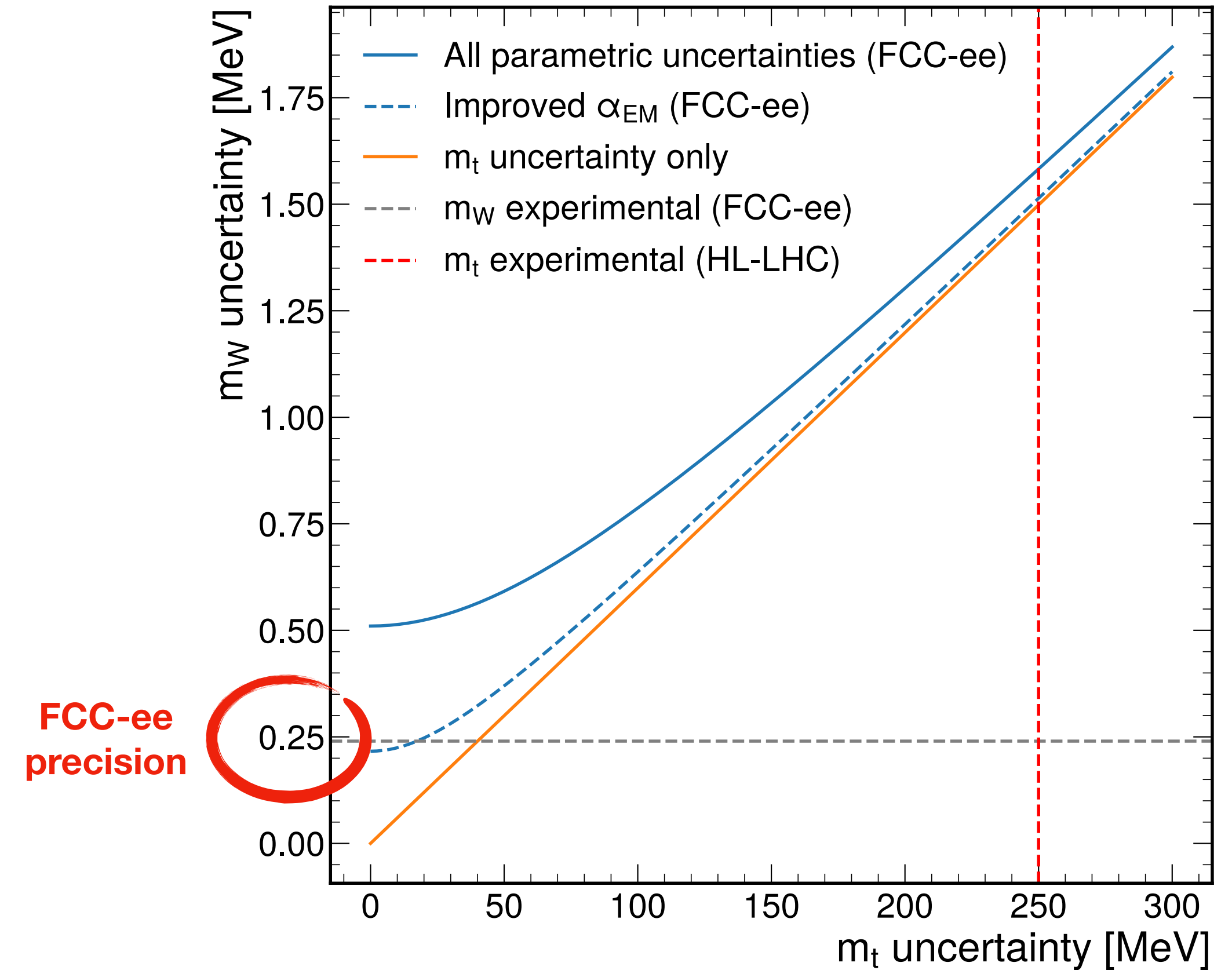
Looking from the Top (and beyond)

Physics opportunities at the Top threshold and above

Top mass at e^+e^- $t\bar{t}$ threshold scan



Parametric uncertainty on W mass



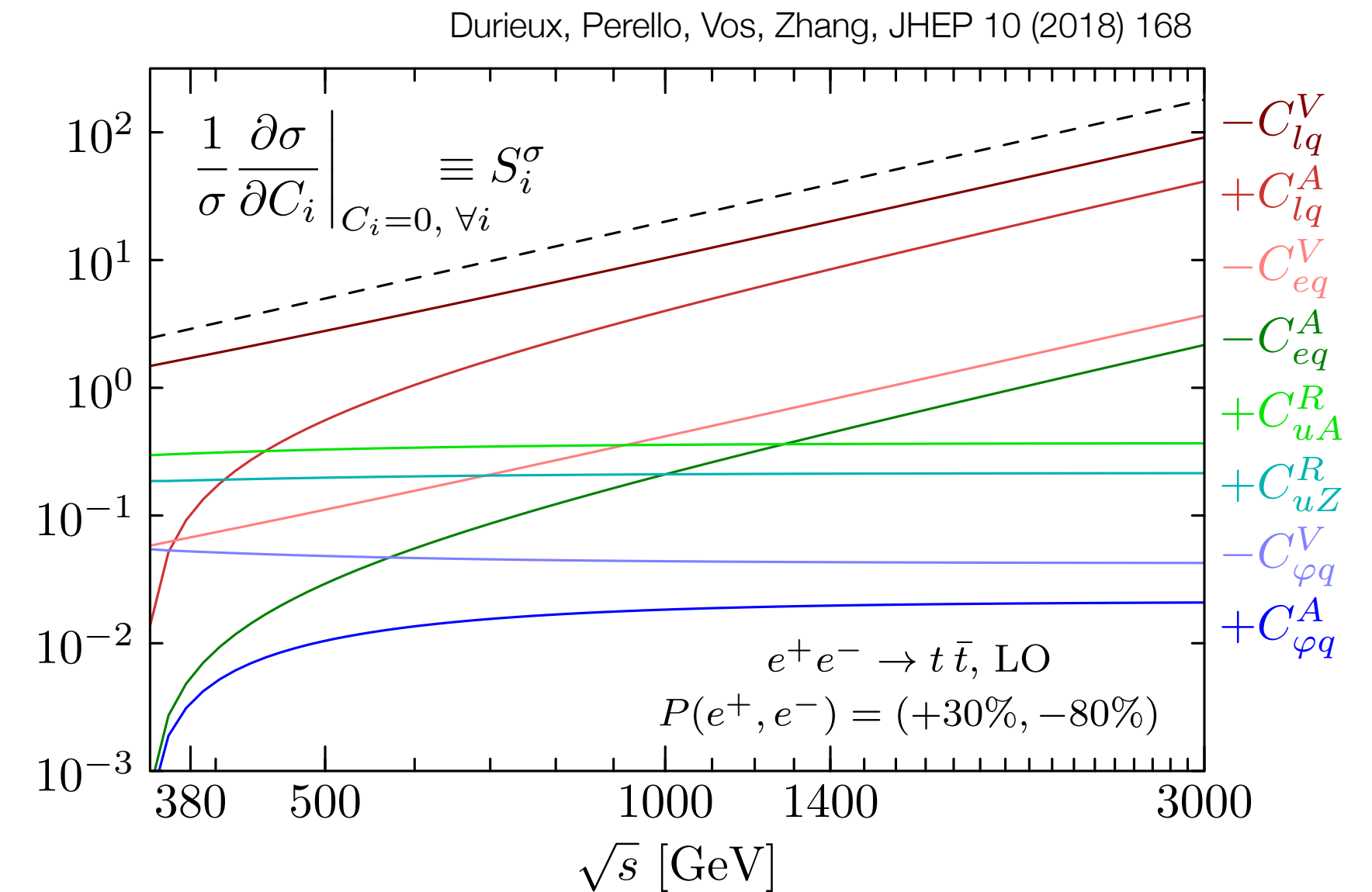
HL-LHC: $\Delta m_t \sim 200 \text{ MeV}$ vs. e^+e^- : $\Delta m_t \sim 4\text{-}20 \text{ MeV}$ (stat.)
(Pole mass limited by Λ_{QCD}) (Theory (current) $\Delta m_t \sim 35 \text{ MeV}$)

$\Delta m_t \lesssim 50 \text{ MeV}$ needed for future EWPO
Beyond the HL-LHC reach!

Physics opportunities at the Top threshold and above

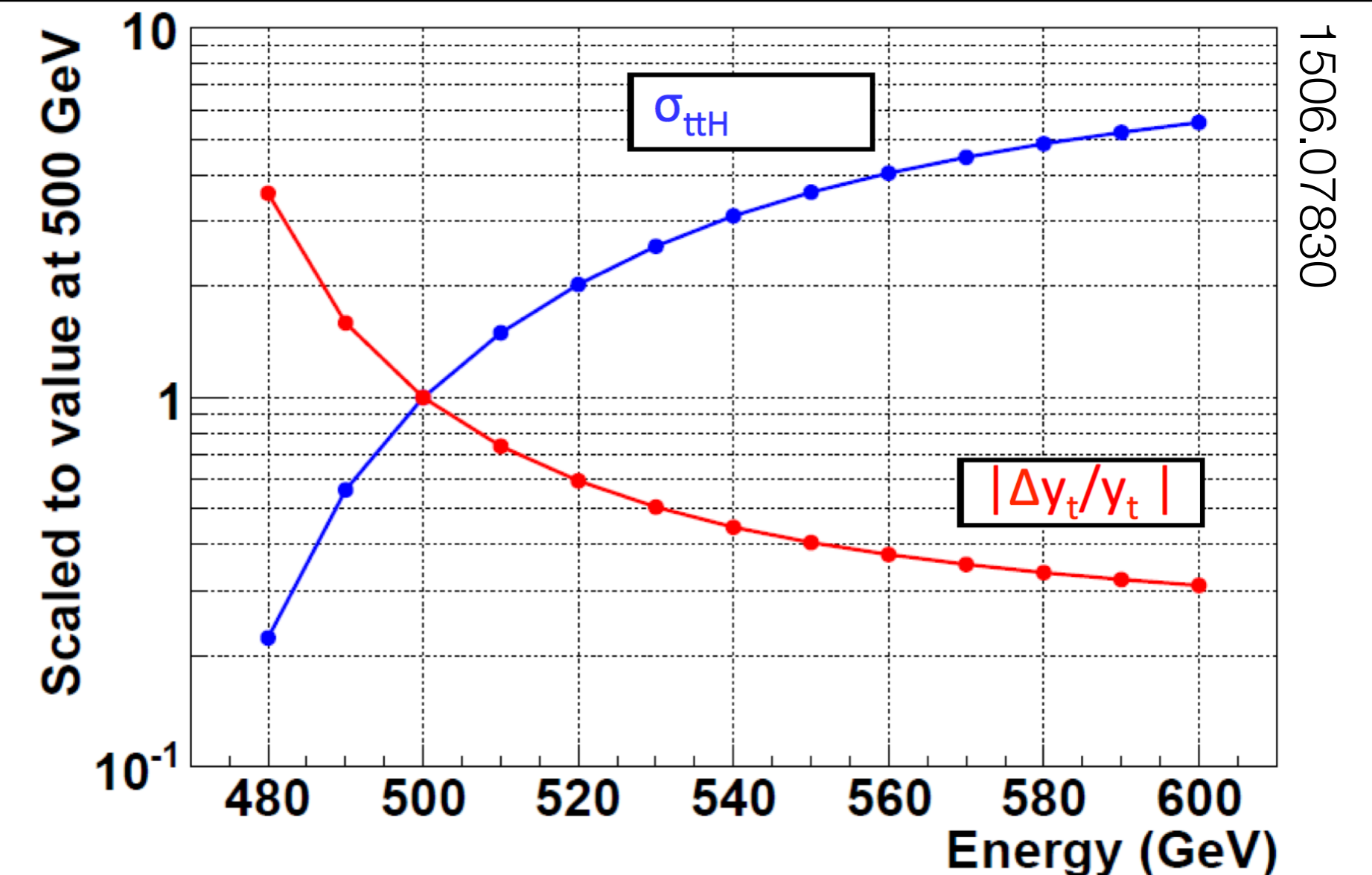
Top EW couplings

- $t\bar{t}$ threshold opens the possibility of measuring the LO contributions of Top EW couplings
 - ▶ Disentangling these from other effects (e.g. 4-fermion ops.) benefits from running at more than one energy
- Advantage for linear colliders**
- ▶ Circular colliders: additional handles provided by larger precision of EW measurements

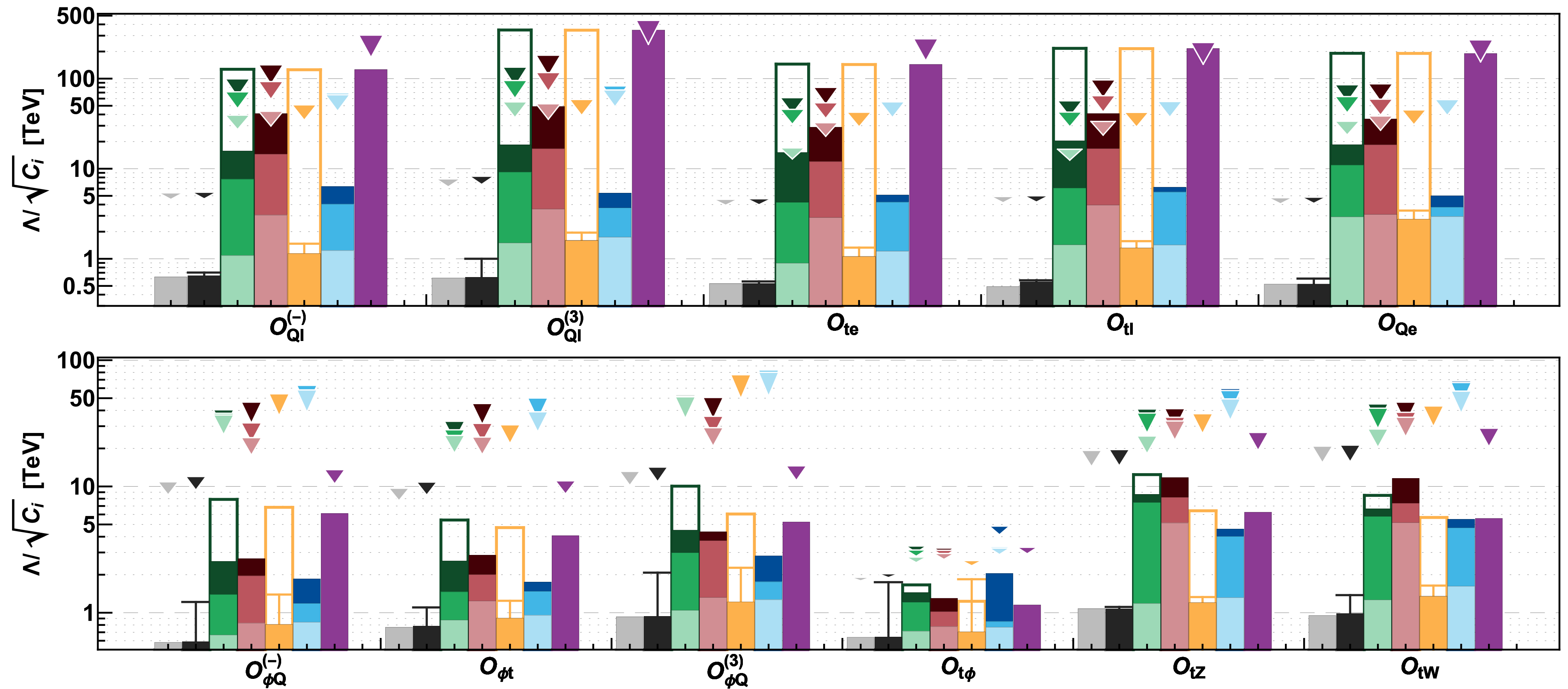
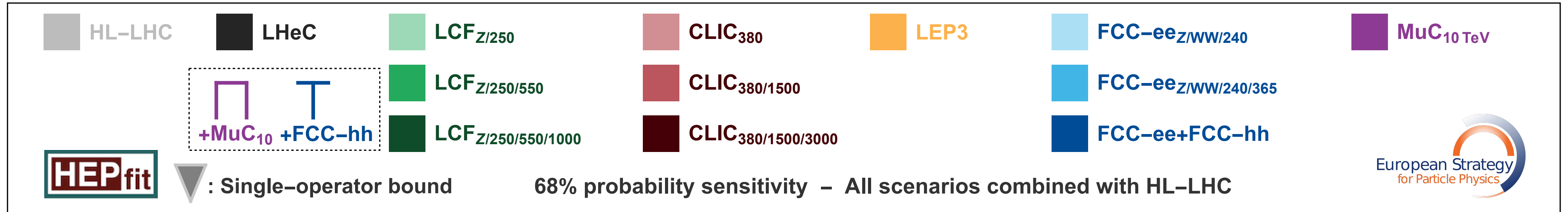


Top Yukawa coupling

- Tree-level determination via $t\bar{t}H$ requires energies above 480 GeV
 - Only possible at linear colliders (or muon colliders)
- ▶ Circular colliders: sensitivity via loop effects (in precision Higgs and at threshold)

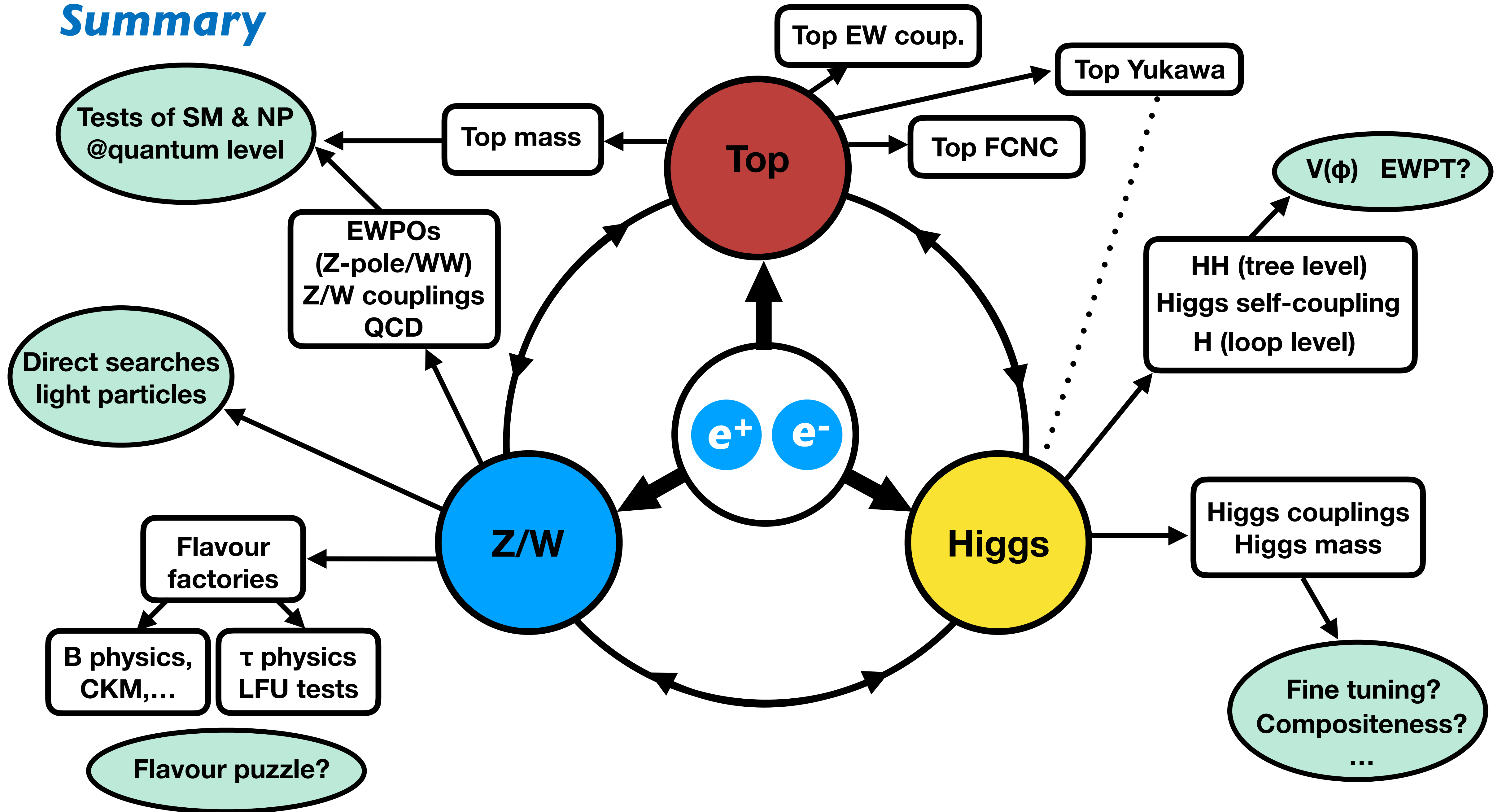


Physics opportunities at the Top threshold and above



Concluding...

Summary



Summary

Top EW coup.

Top Yukawa

Summary: Plenty of reasons to build an e^+e^- collider

Order of magnitude improvement (in some cases more) with respect to HL-LHC in many areas

Access to properties beyond the reach of the HL-LHC

(e.g. charm or strange Yukawa couplings, absolute Higgs couplings, ...)

Interplay between direct and indirect searches: even if no deviation is seen in indirect tests of BSM, results are crucial to guide future direct searches!

Conclusions? We'll draw them when we build one...

factories

B physics,
CKM,...

τ physics
LFU tests

Flavour puzzle?

Fine tuning?
Compositeness?
...