

Highlights of the Physics Studies towards the 2026 ESPP Update

Jorge de Blas
University of Granada

Physics Preparatory Group Studies

Electroweak Physics

Conveners: M. Dunford, JB

Strong Interactions

Conveners: C. Diaconu , A. Dainese

Flavour Physics

Conveners: G. Isidori, M-H. Schune

BSM Physics

Conveners: F. Maltoni, R. Gonzalez-Suarez

Neutrino Physics and Cosmic Messengers

Conveners: P. Hernandez, S. Bolognesi

Dark Matter and Dark Sectors

Conveners: J. Monroe, M. McCullough

Accelerator Science and Technology

Conveners: G. Arduini, P. Burrows

Detector instrumentation

Conveners: T. Bergauer, U. Husemann

Computing

Conveners: T. Boccali, B. Kersevan

320 pages

CERN-ESU-2025-001
4 November 2025

Physics Briefing Book

Input for the 2026 update of the European Strategy for Particle Physics

Electroweak Physics: Jorge de Blas¹, Monica Dunford² (Conveners), Emanuele Bagnaschi³ (Scientific Secretary), Ayres Freitas⁴, Pier Paolo Giardino⁵, Christian Grefe⁶, Michele Selvaggi⁷, Angela Taliercio⁸, Falk Bartels² (Contributors)

Strong Interaction Physics: Andrea Dainese⁹, Cristinel Diaconu¹⁰ (Conveners), Chiara Signorile-Signorile¹¹ (Scientific Secretary), Néstor Armesto¹², Roberta Arnaldi¹³, Andy Buckley¹⁴, David d’Enterria⁷, Antoine Gérardin¹⁵, Valentina Mantovani Sarti¹⁶, Sven-Olaf Moch¹⁷, Marco Pappagallo¹⁸, Raimond Snellings^{19,83}, Urs Achim Wiedemann⁷ (Contributors)

Flavour Physics: Gino Isidori²⁰, Marie-Hélène Schune²¹ (Conveners), Maria Laura Piscopo⁸³ (Scientific Secretary), Marta Calvi⁸⁴, Yuval Grossman²³, Thibaud Humair²⁴, Andreas Jüttner^{7,25}, Jernej F. Kamenik^{26,65}, Matthew Kenzie²⁷, Patrick Koppenburg⁸³, Radoslav Marchevski²⁸, Angela Papa²⁹, Guillaume Pignol³⁰, Justine Serrano¹⁰ (Contributors)

Neutrino Physics & Cosmic Messengers: Pilar Hernandez³⁹, Sara Bolognesi⁴⁰ (Conveners), Ivan Esteban⁴¹ (Scientific Secretary), Stephen Dolan⁷, Valerie Domcke⁷, Joseph Formaggio⁴², M. C. Gonzalez-Garcia^{80,81,82}, Aart Heijboer¹⁹, Aldo Ianni⁴⁴, Joachim Kopp^{7,79}, Elisa Resconi⁴⁵, Mark Scott³³, Viola Sordini⁸⁷ (Contributors)

Beyond the Standard Model Physics: Fabio Maltoni^{8,31}, Rebeca Gonzalez Suarez³² (Conveners), Benedikt Maier³³ (Scientific Secretary), Timothy Cohen^{7,28,78,*}, Annapaola de Cosa^{34,*}, Nathaniel Craig³⁵, Roberto Franceschini³⁶, Loukas Gouskos³⁷, Aurelio Juste³⁸, Sophie Renner¹⁴, Lesya Shchutska²⁸ (Contributors)

Dark Matter and Dark Sector: Jocelyn Monroe^{54,46}, Matthew McCullough⁷ (Conveners), Yohei Ema^{7,†} (Scientific Secretary), Paolo Agnes⁴⁷, Francesca Calore⁴⁸, Emanuele Castorina²², Aaron Chou⁴⁹, Monica D’Onofrio⁵⁰, Maksym Ovchynnikov^{7,†}, Tina Pollmann¹⁹, Josef Pradler^{59,86}, Yotam Soreq⁵², Julia Katharina Vogel⁵³ (Contributors)

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Theoretical Overview: Eric Laenen^{19,83,85}

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Editors: Roger Forty⁷, Karl Jakobs⁷⁴, Hugh Montgomery⁷⁵, Mike Seidel^{28,76}, Paris Sphicas^{7,77}

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Physics studies

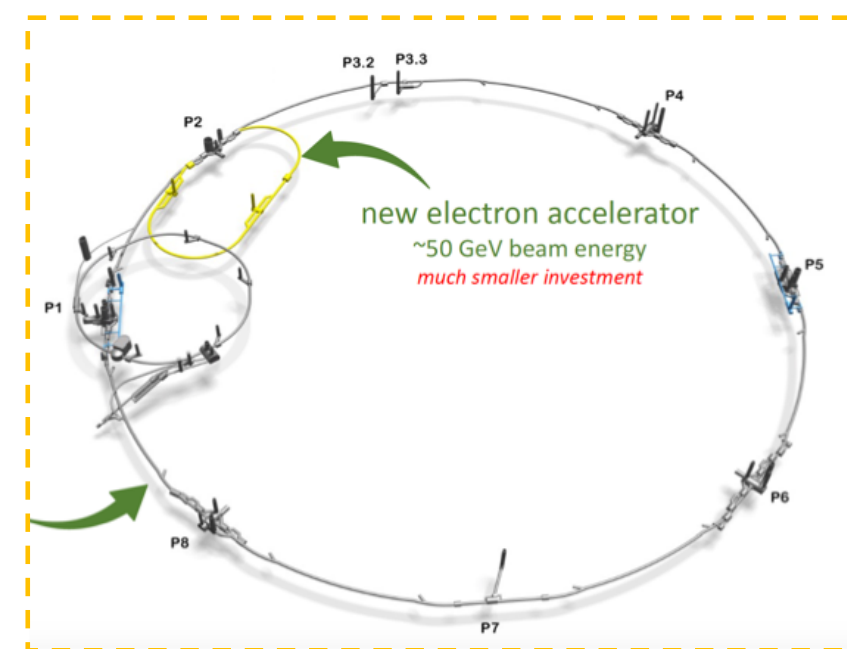
Evaluate and compare the physics potential of the different future collider projects

In this talk: Focus on the large scale projects proposed for the next particle collider at CERN, after the LHC

Physics Preparatory Group Studies

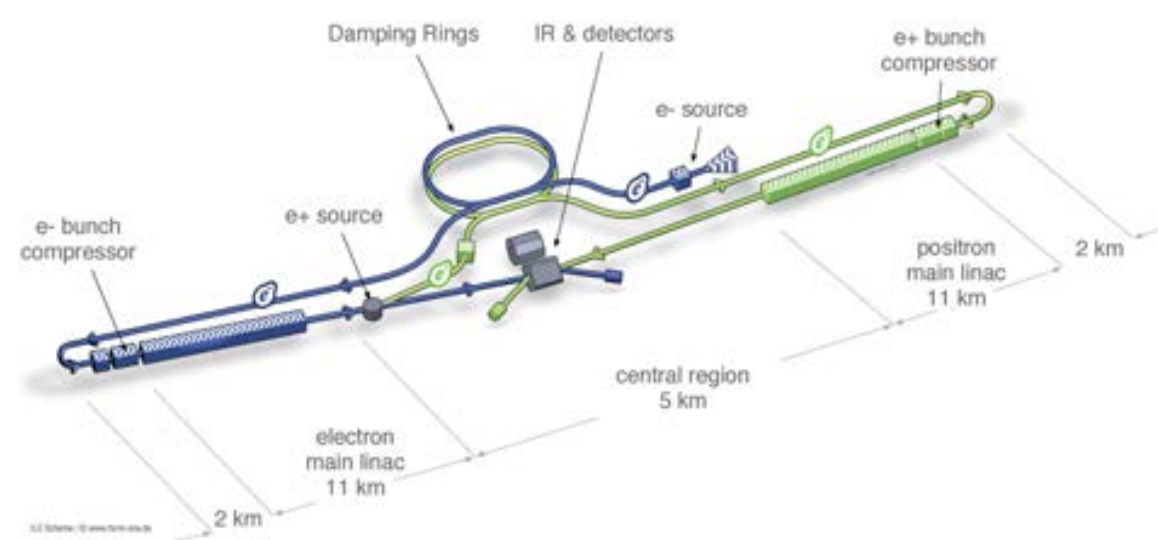
Very different design to address the search for new physics

From K. Jacobs' talk at
Open Symposium in Venice

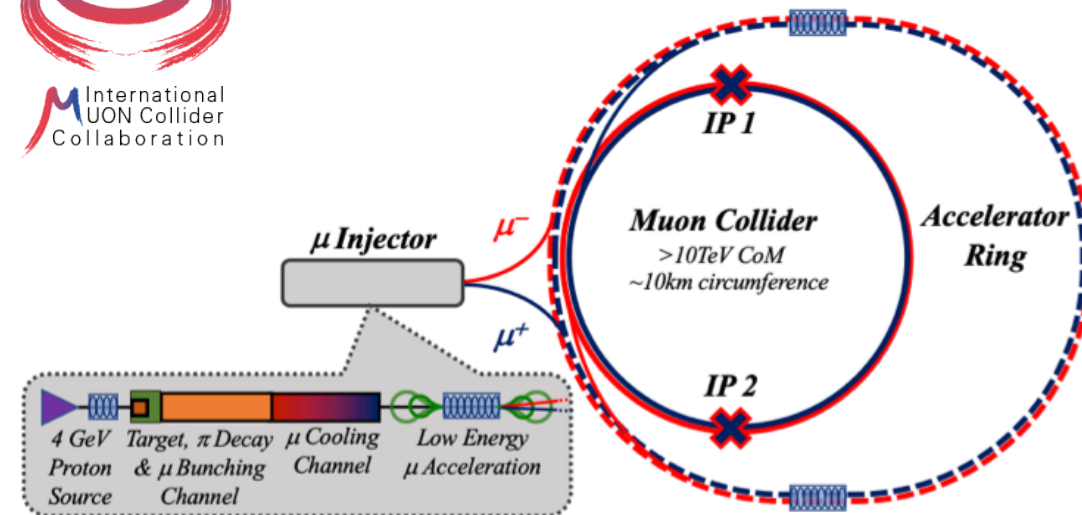


PERLE

Linear Collider Vision



FCC-hh,
baseline 85 TeV ($\rightarrow$ 120 TeV)
+ possibility for Hl collisions



Muon Collider (3, 10 TeV)

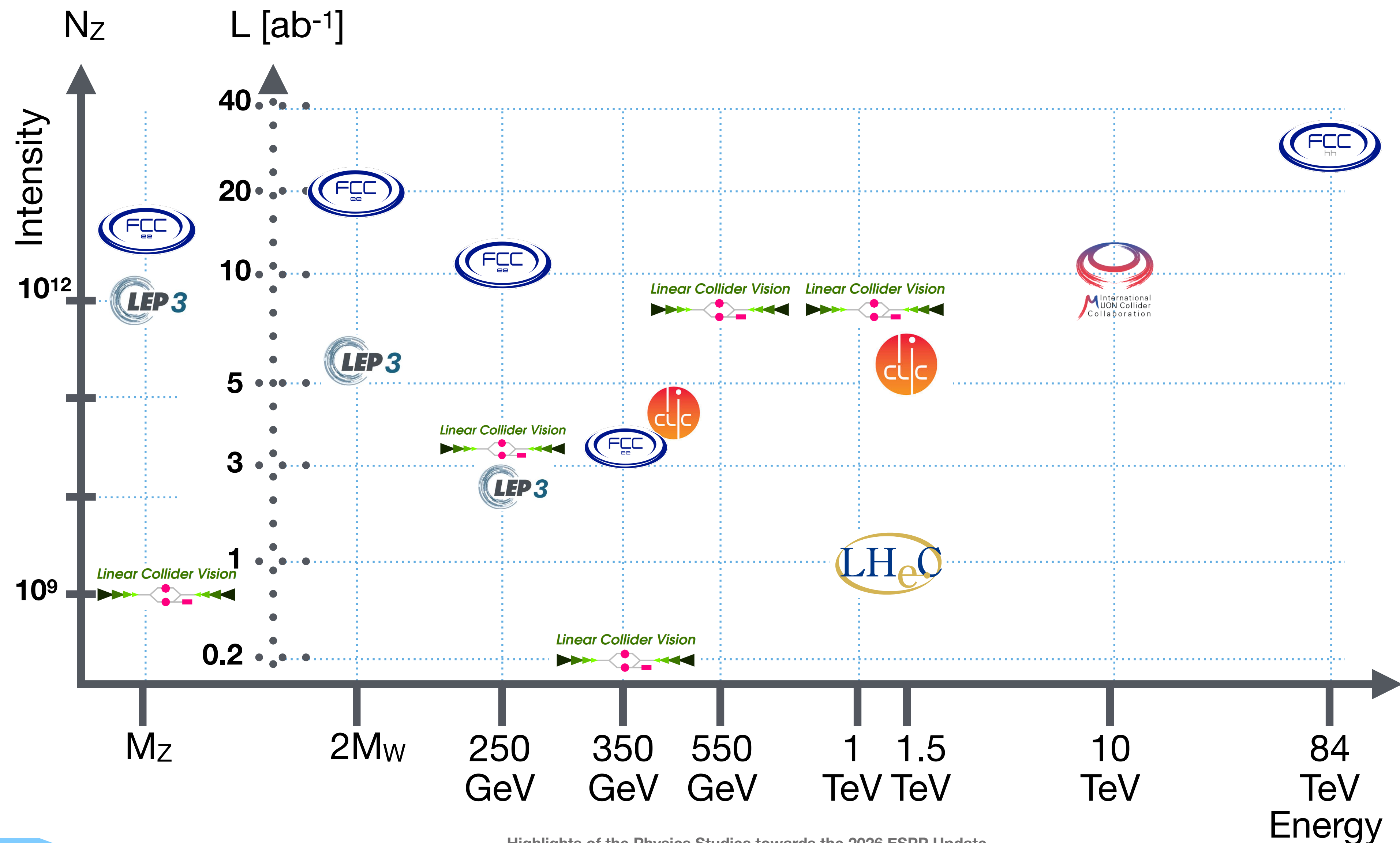
R&D



e^+e^- with improved acceleration technologies
LCF, C³ ($\rightarrow$ 1 TeV), CLIC (1.5 TeV), HALHF, ...
 $\rightarrow$ plasma acceleration for higher energies

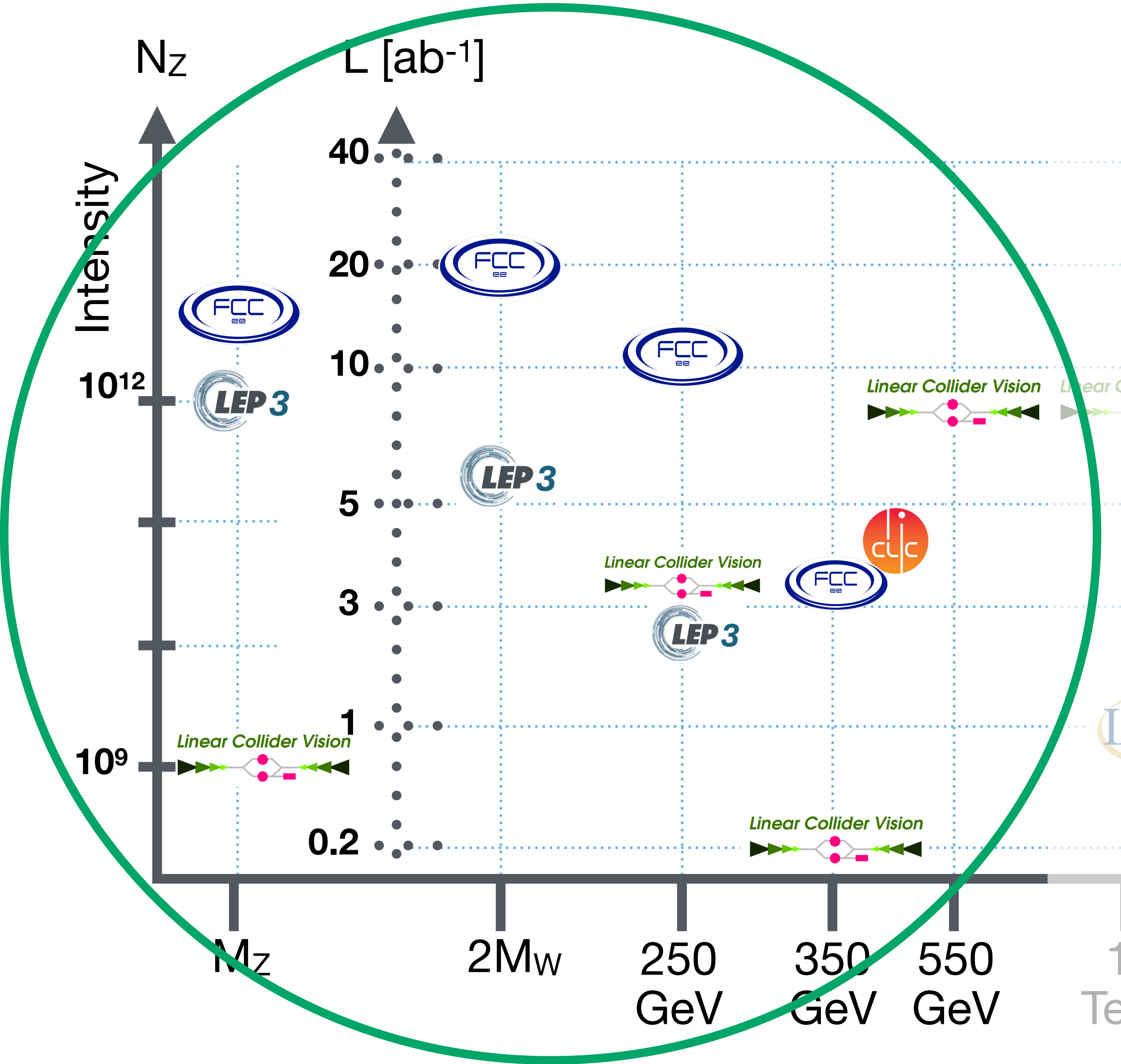
Physics Preparatory Group Studies

Very different design to address the search for new physics



Physics Preparatory Group Studies

Very different design to address the search for new physics

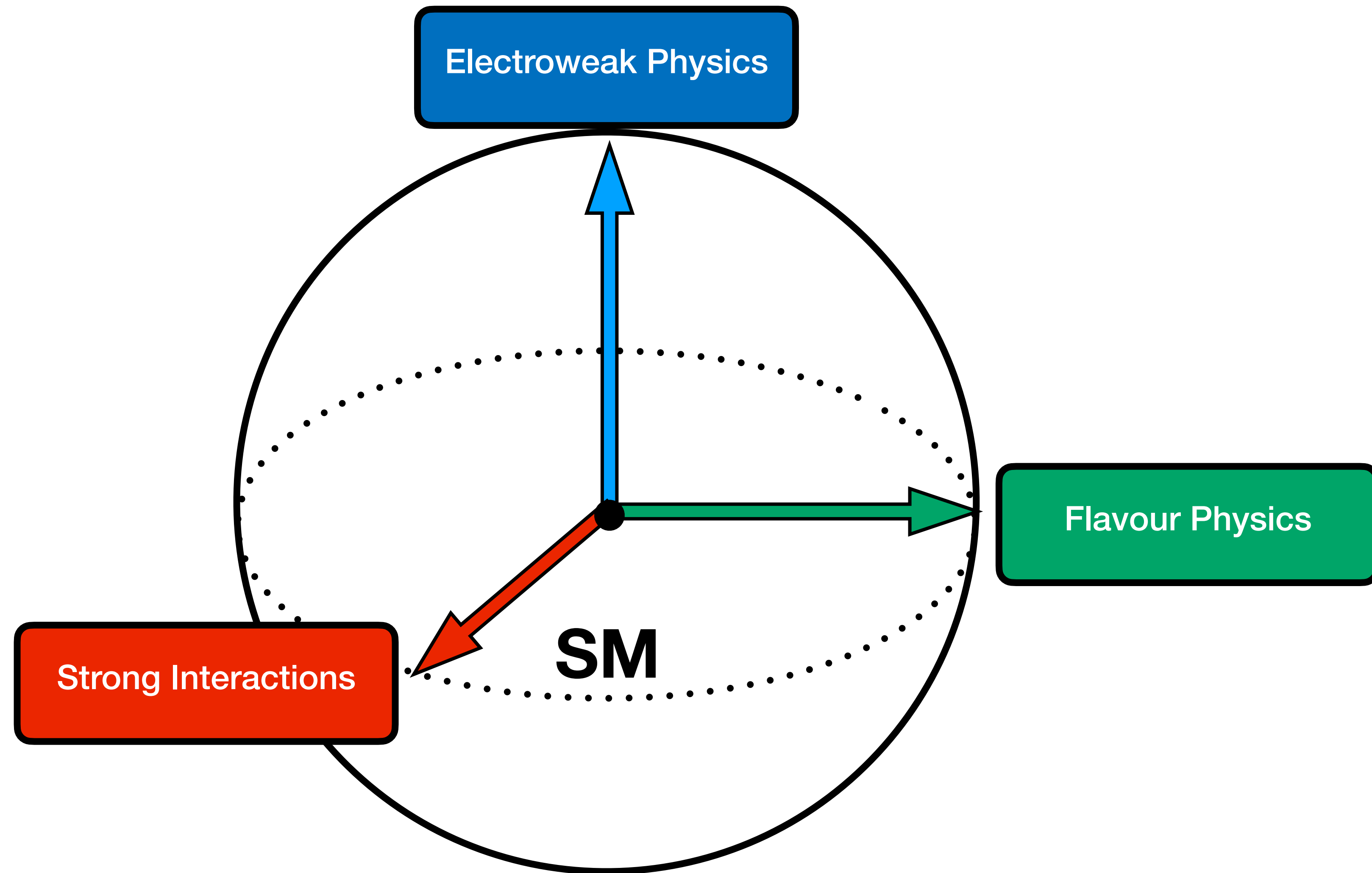


A significant part of the physics programme at any of the proposed future colliders will focus on precision physics

Improving our current knowledge of the SM and testing those aspects that remain unexplored

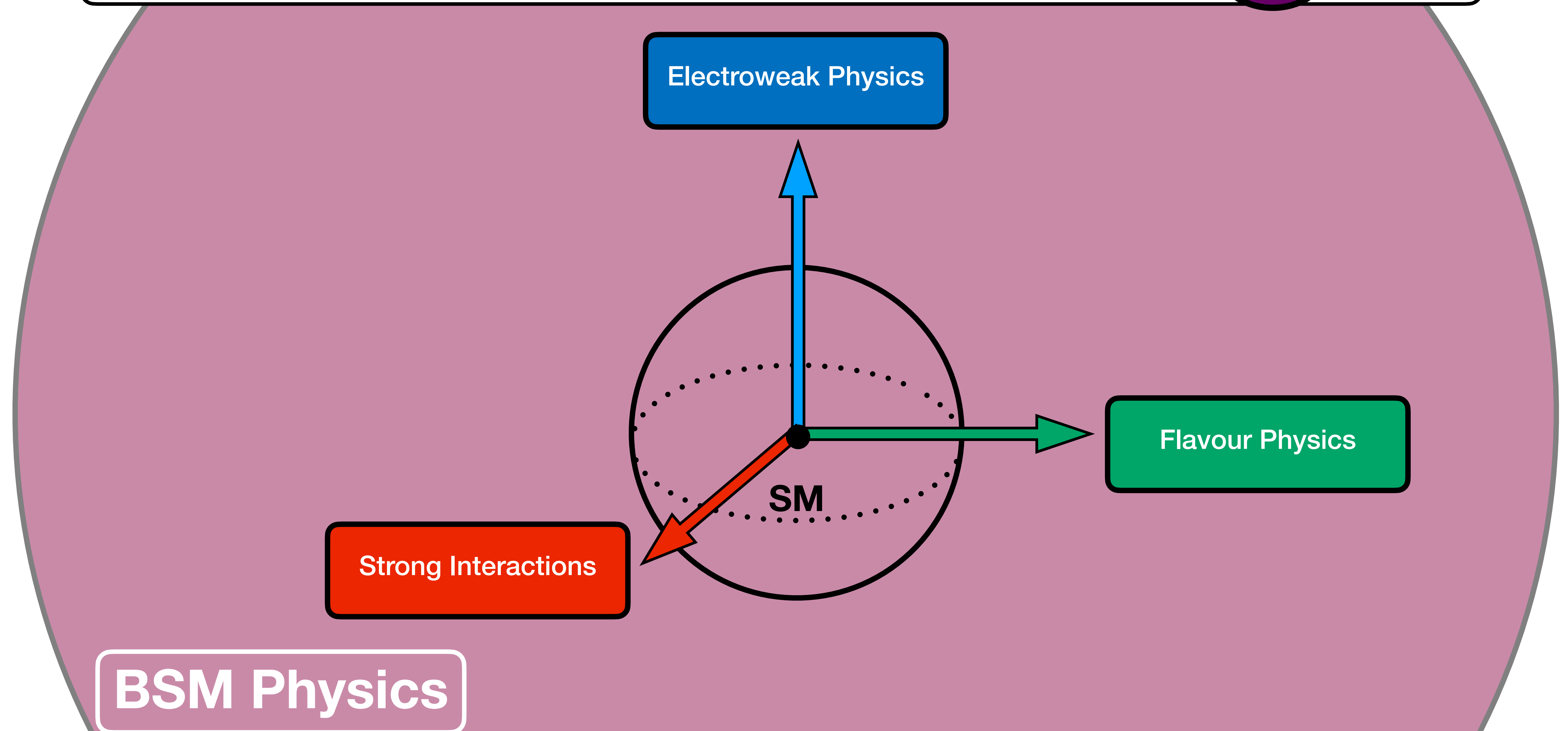
Studying different aspects of SM physics...

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right)$$



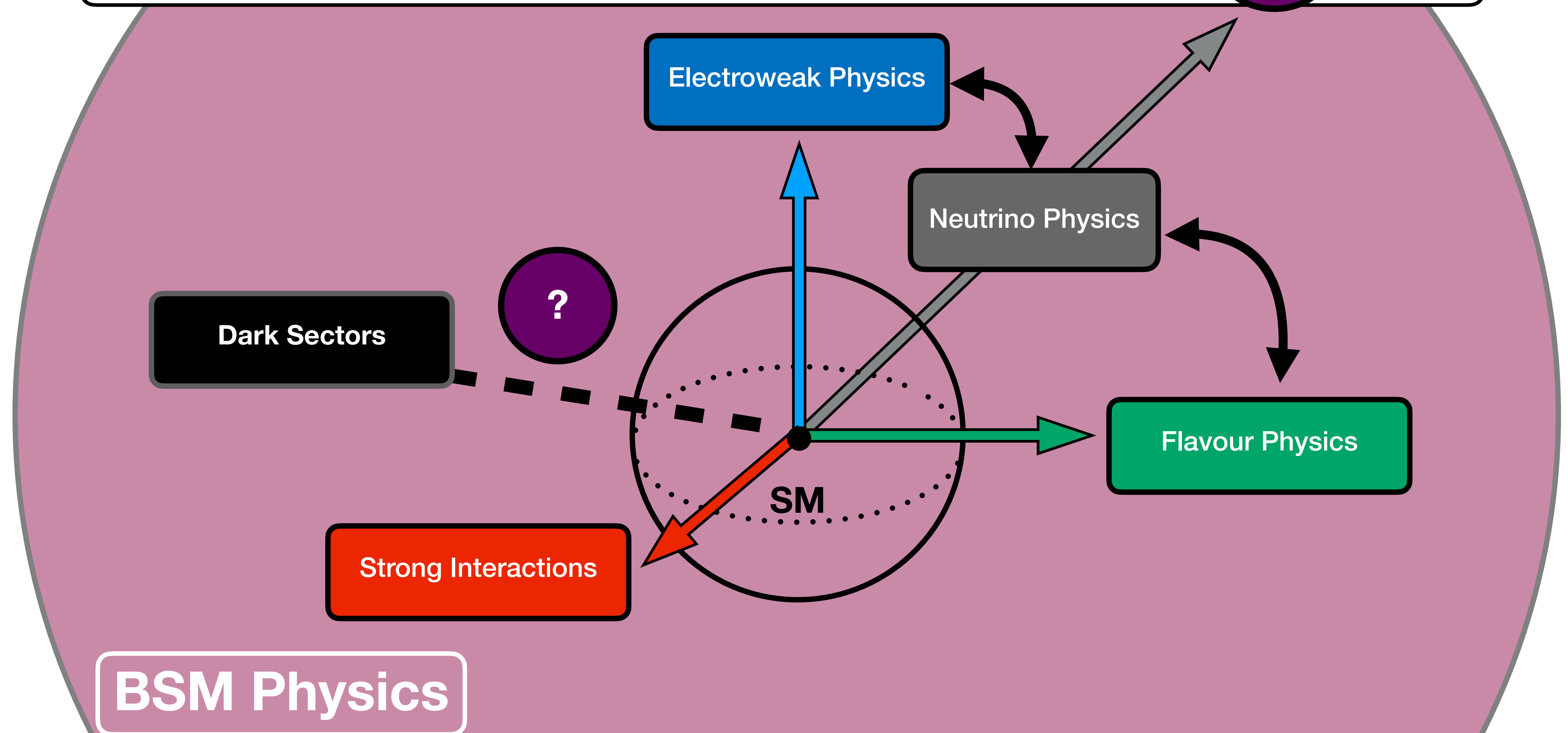
To find what is Beyond...

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$



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To find what is Beyond...

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Understanding EWSB

What triggers EWSB?

Naturalness? Is the Higgs elementary/composite?

Nature of the EWPT $\leftrightarrow$ Matter/Anti-Matter Asymmetry?

Is the EW vacuum stable?

Electroweak Physics

What is the origin of neutrino masses?

Neutrino Physics

The SM Flavour puzzle

Why 3 copies of fermions?
What explains the hierarchical structure of their masses?

Dark Sectors

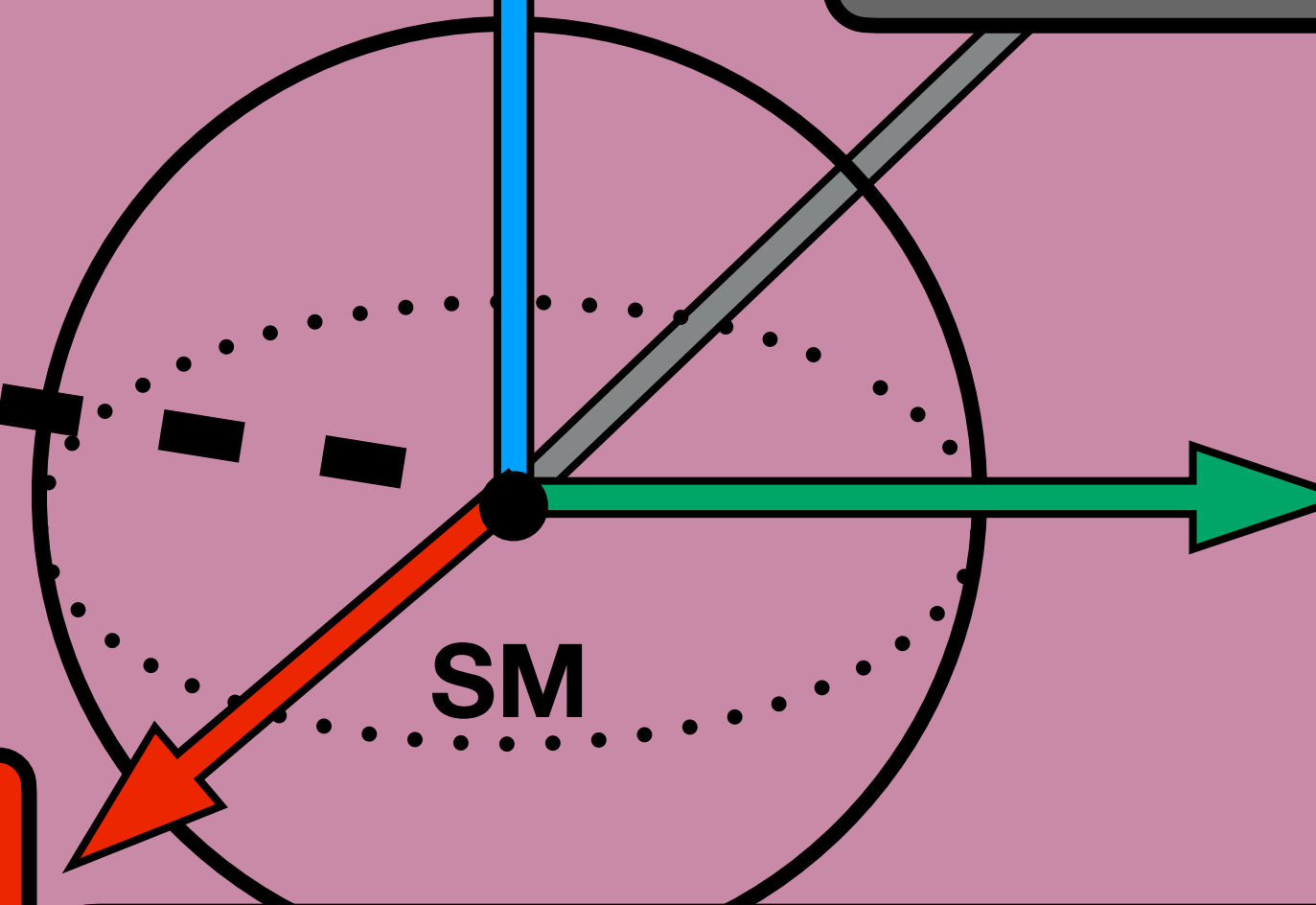
What is the nature of Dark Matter?

Strong Interactions

How well do we know the strong force?

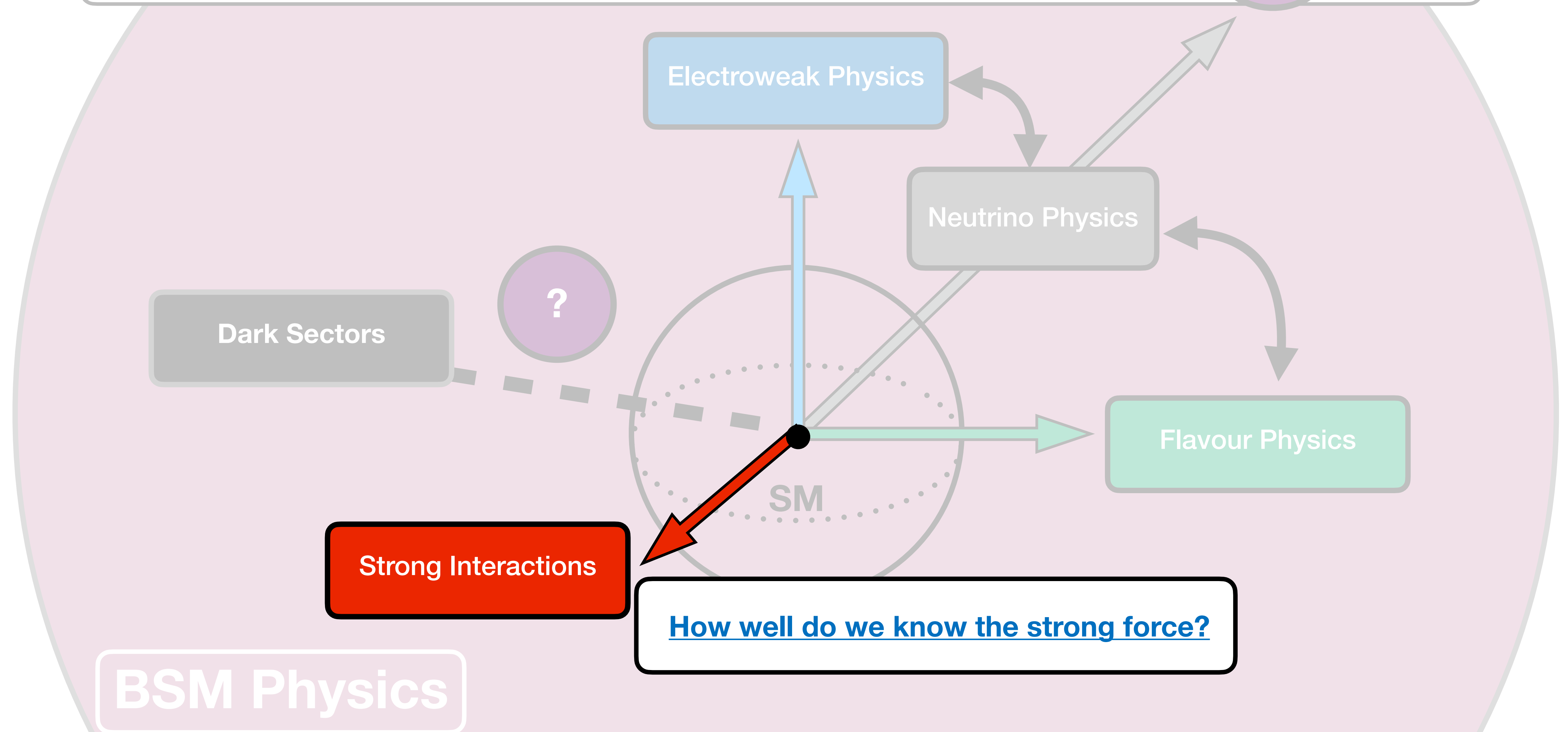
Flavour Physics

BSM Physics



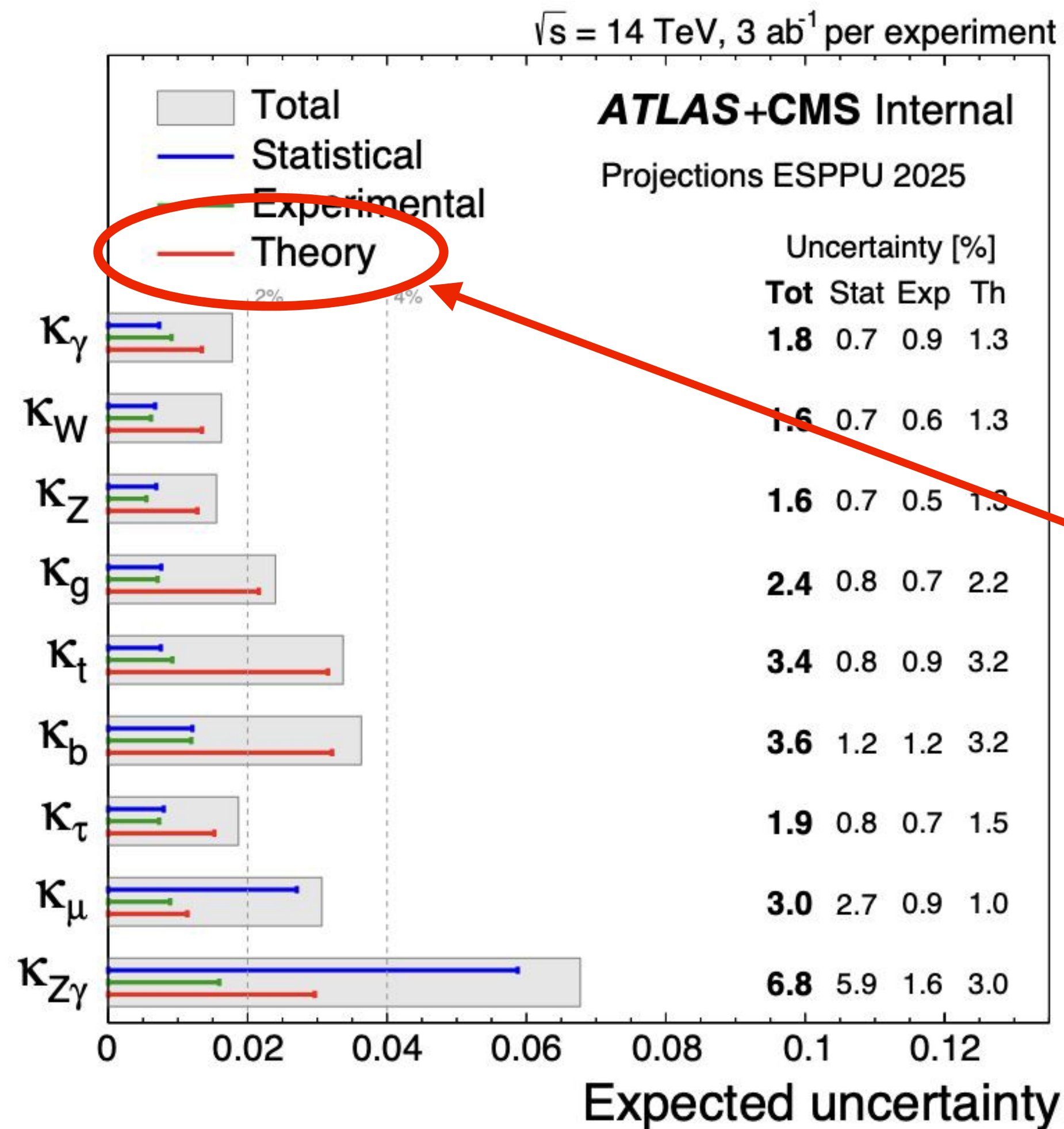
The importance of knowing the strong force

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$



The importance of knowing the strong force

Example: Higgs physics at the HL-LHC



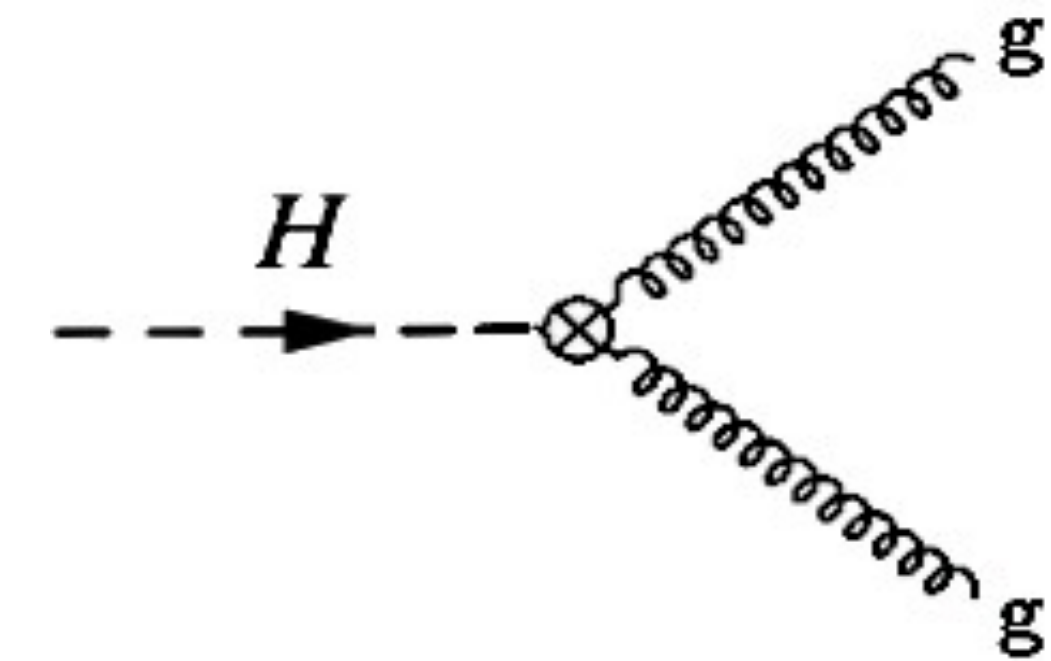
- HL-LHC precision on Higgs coupling modifier at the level of:
 - ▶ 2-4% for dominant decays
 - ▶ 3%-7% for rare decays
- Assumes progress on theory calculations
 - ▶ S2 scenario: TH systematics halved (where feasible)
- Even in this case results limited by TH uncertainties!
 - ▶ **Precision QCD needed** for our understanding of the Higgs
 - ▶ **PDF uncertainties** also significantly impact Higgs observables (also in EW and BSM searches!)

The importance of knowing the strong force

- **Precision QCD** (pQCD & non-pQCD) needed to fully exploit the precision Higgs measurements
 - ▶ Not only at the HL-LHC but *at any future Higgs factory*

- **Example:** Higgs interactions with gluons

- ▶ Identifying gluon jets requires significantly **improved gluon fragmentation in Parton showers** (NNLL) MCs
- ▶ Interpretation of $H \rightarrow gg$ with a precision of 0.7% (EXP):
 - ▶ Requires QCD TH uncertainties in $\Gamma_{H \rightarrow gg}$ to be reduced below 1% (currently, N⁴LO ~3%)



TH	$H \rightarrow b\bar{b}$ width	N ⁴ LO ($m_b \neq 0$); N ⁴ LO differential ($m_b = 0$)
Requirements	$H \rightarrow gg$ width	N ⁵ LO (heavy-top limit), N ⁴ LO ($m_t \neq 0$); N ⁴ LO differential, N ³ LO differential ($m_t \neq 0$)

- ▶ Also requires knowledge of $\alpha_s(M_Z)$ with a precision of 0.1% (relevant also for other hadronic channels)

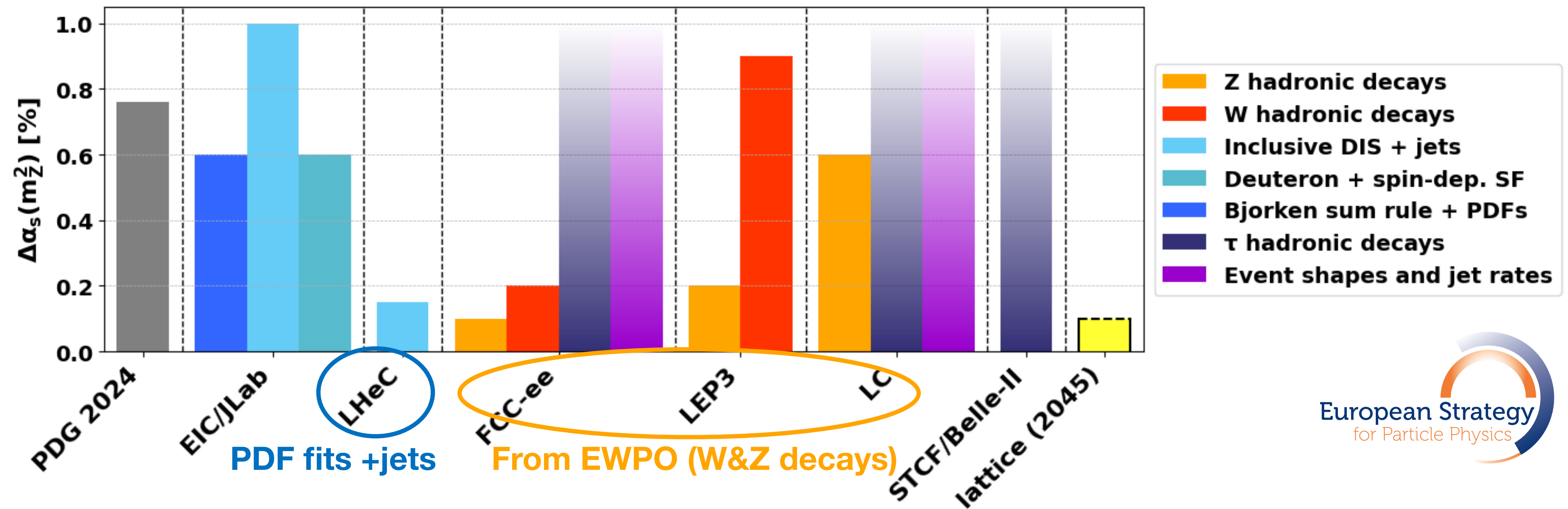
$\alpha_s(M_Z)$ currently known with a precision of ~0.8% !

The importance of knowing the strong force

- **Precision QCD** (pQCD & non-pQCD) needed to fully exploit the precision Higgs measurements

► Not only at the HL-LHC but *at any future Higgs factory*

Strong Coupling Constant precision summary



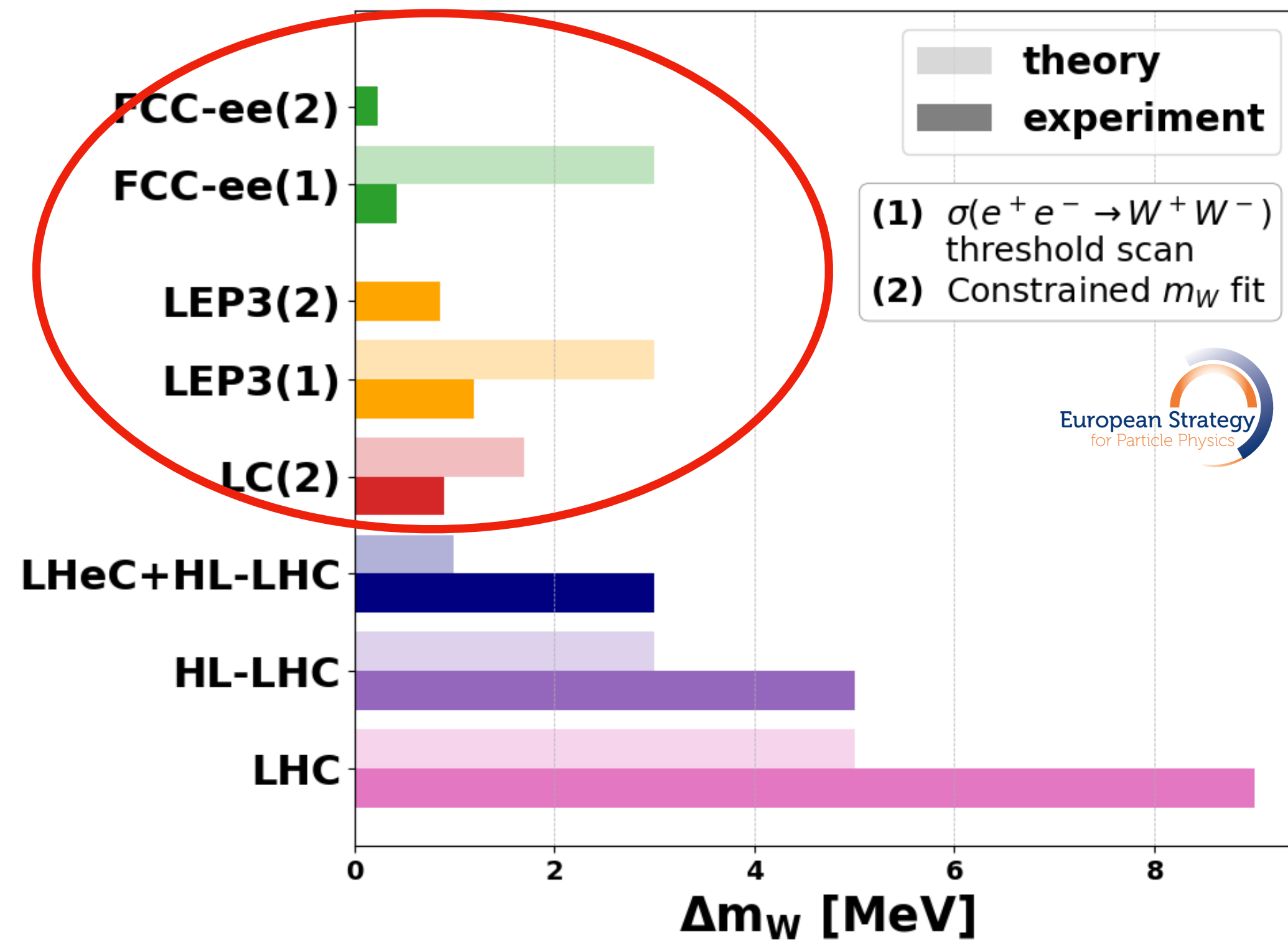
LHeC & FCC-ee comparable to future Lattice QCD projections $\sim 0.1\%$



The importance of knowing the strong force

- **Precision QCD** also needed future EW and Top measurements

M_W (key observable in the EW fit)

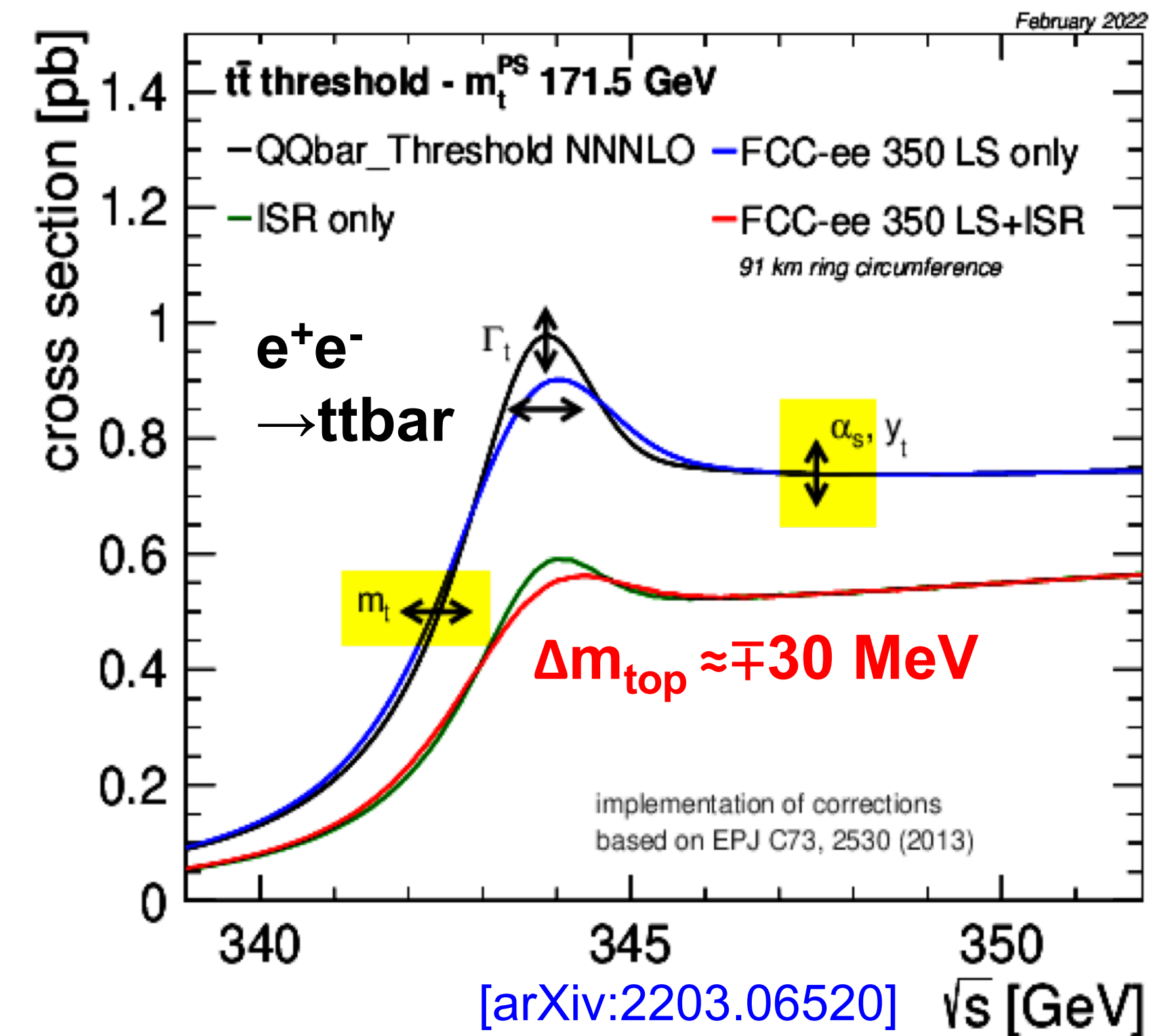


EXP precision expected below 1 MeV

TH requirements:

EW N²LO: $\mathcal{O}(\alpha^2)$, Mixed EW-QCD: $\mathcal{O}(\alpha_s \alpha^2)$, $\mathcal{O}(\alpha_s^2 \alpha)$

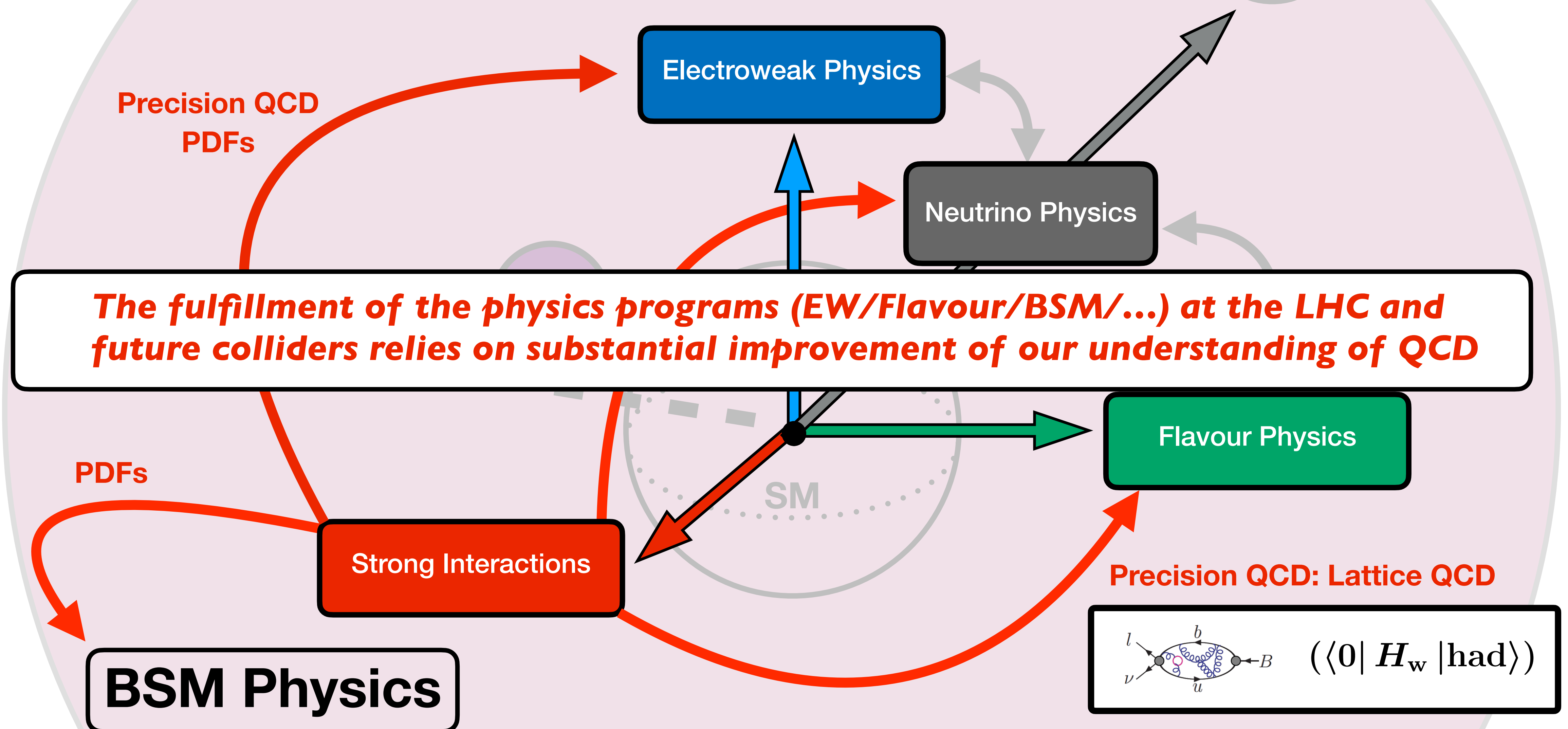
Top mass (key observable in the EW fit): accessible at e^+e^- from the $t\bar{t}$ threshold scan



N3LO QCD theory uncertainty: 35 MeV vs. O(10) MeV stat.

The importance of knowing the strong force

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Understanding the Electroweak Scale and the Higgs boson

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_\mu\phi D^\mu\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$

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Is the EW vacuum stable?

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Flavour Physics

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BSM Physics

SM

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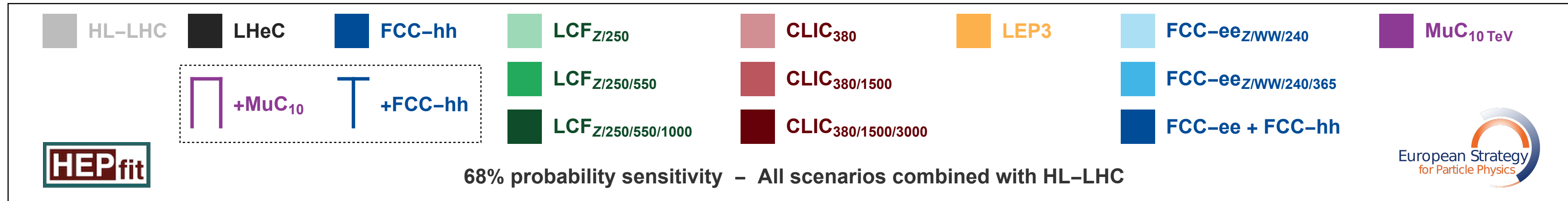
SM

Higgs

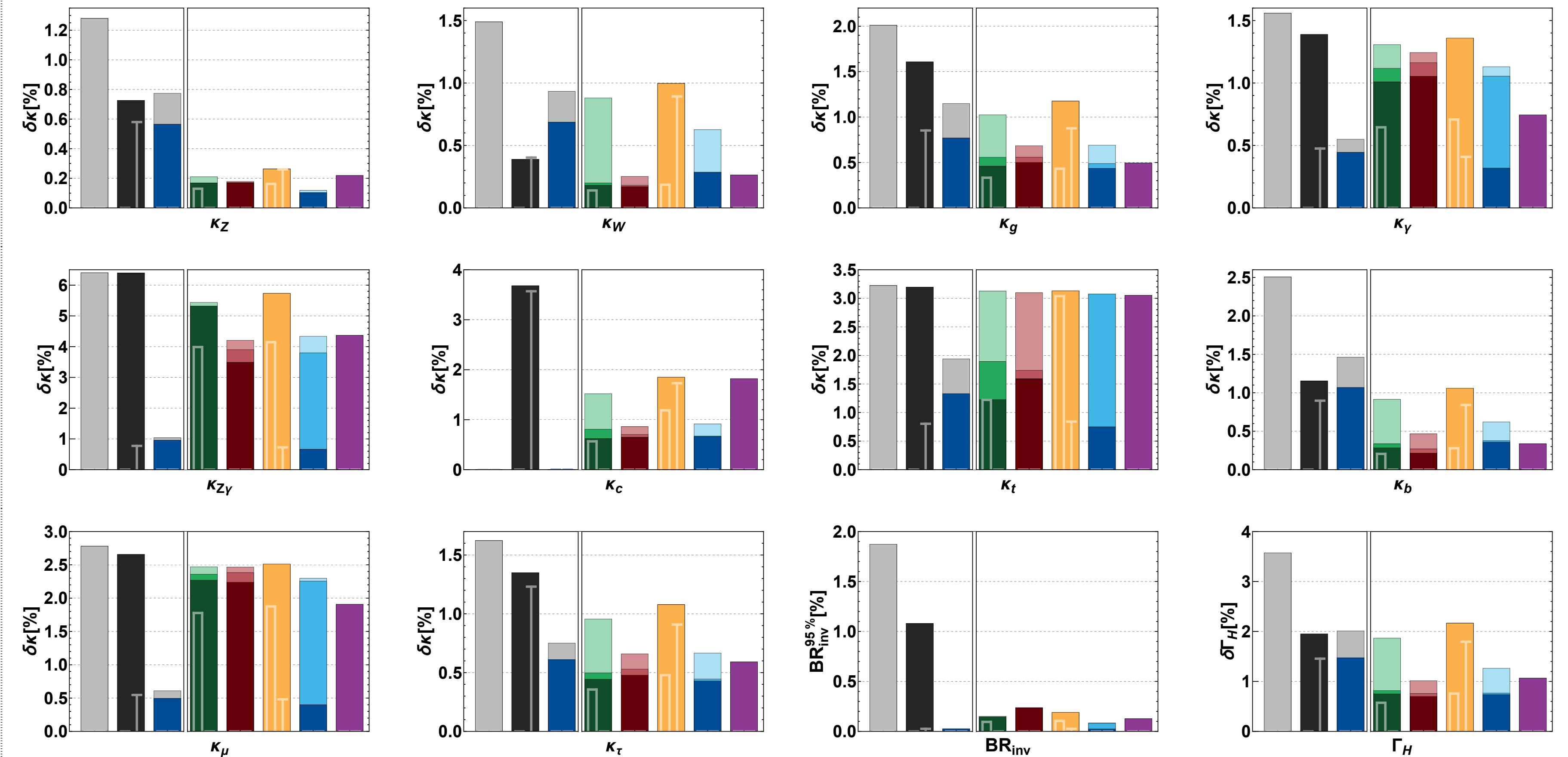
Most of these questions revolve around the nature of the Higgs and require BSM
 $\Rightarrow$ Modification of the properties of the Higgs boson

$$\Delta M_h^2 = \text{.....} \text{SM} \text{.....} + \text{.....} \text{New} \text{.....} \sim 0 \quad \frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon_T \equiv \text{fine tuning}$$

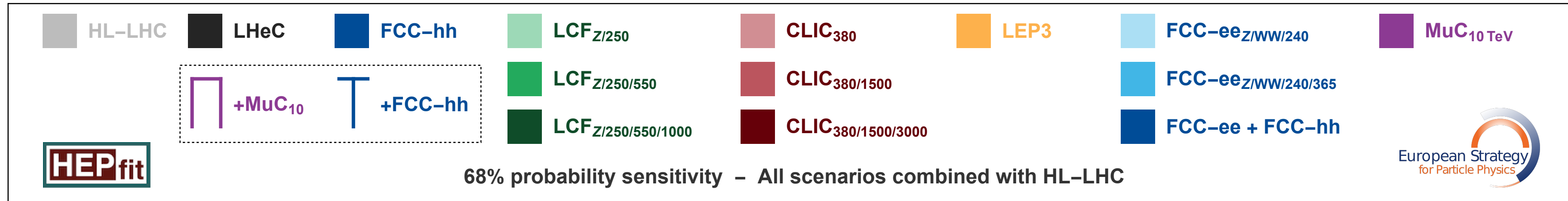
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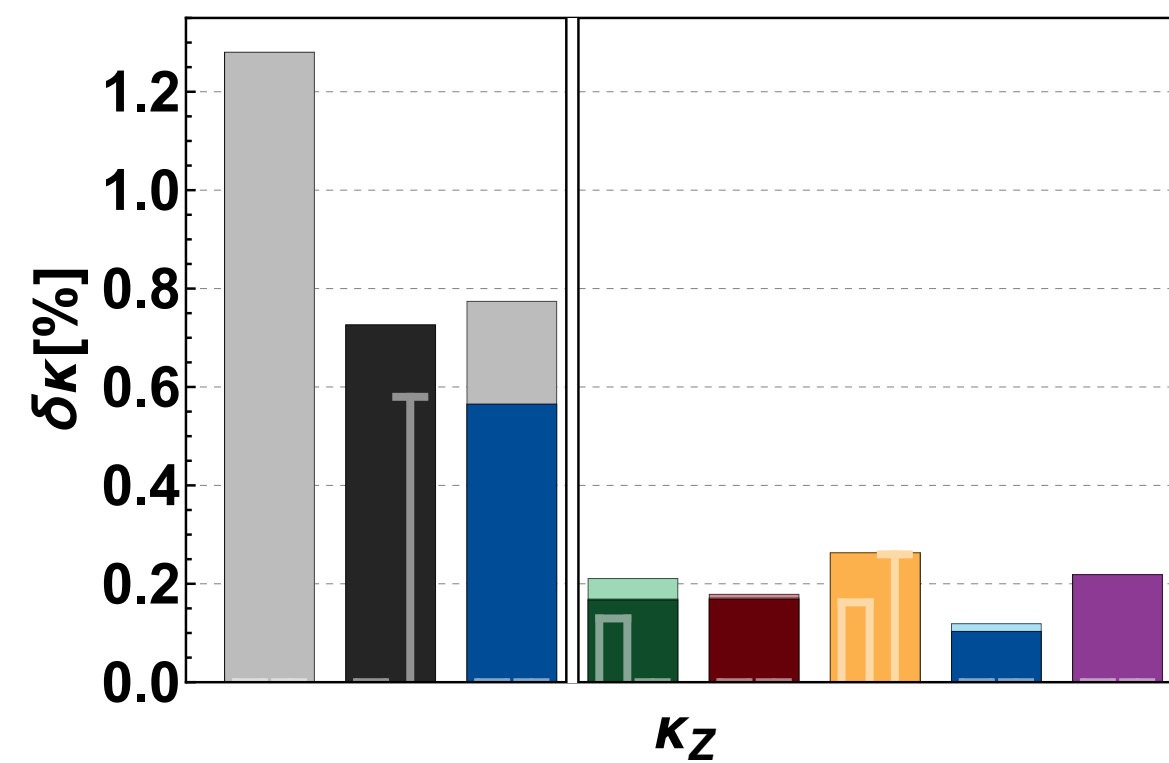
Precision Reach Higgs couplings



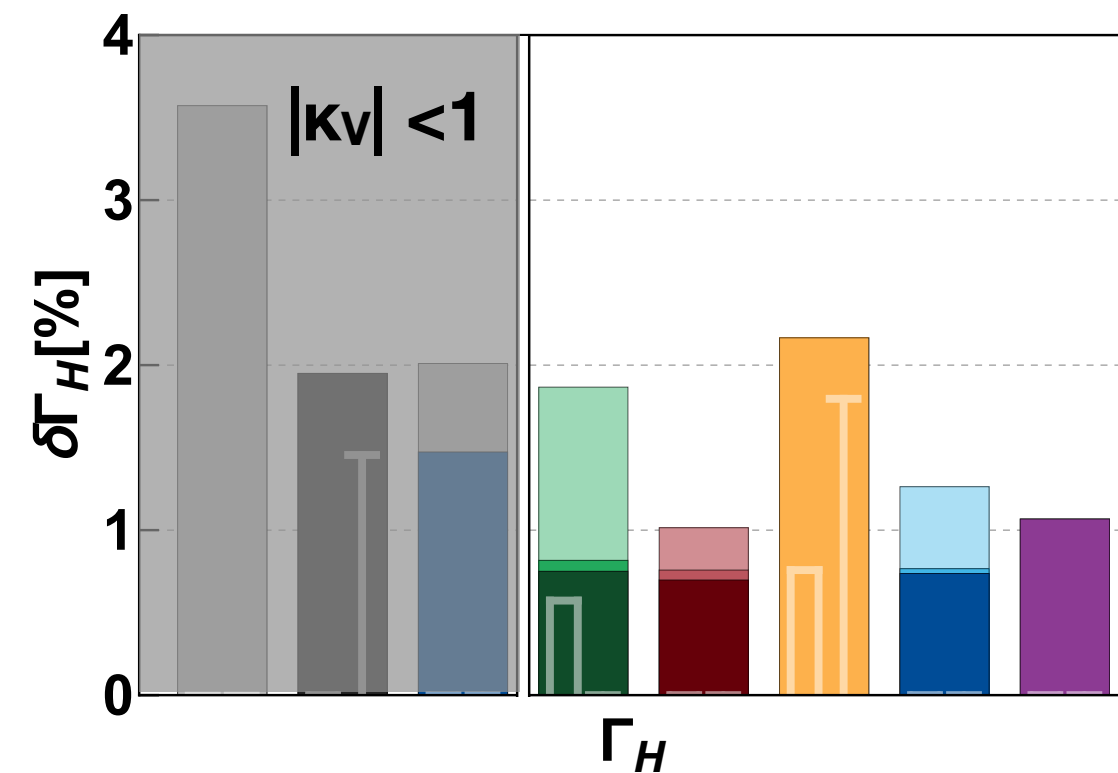
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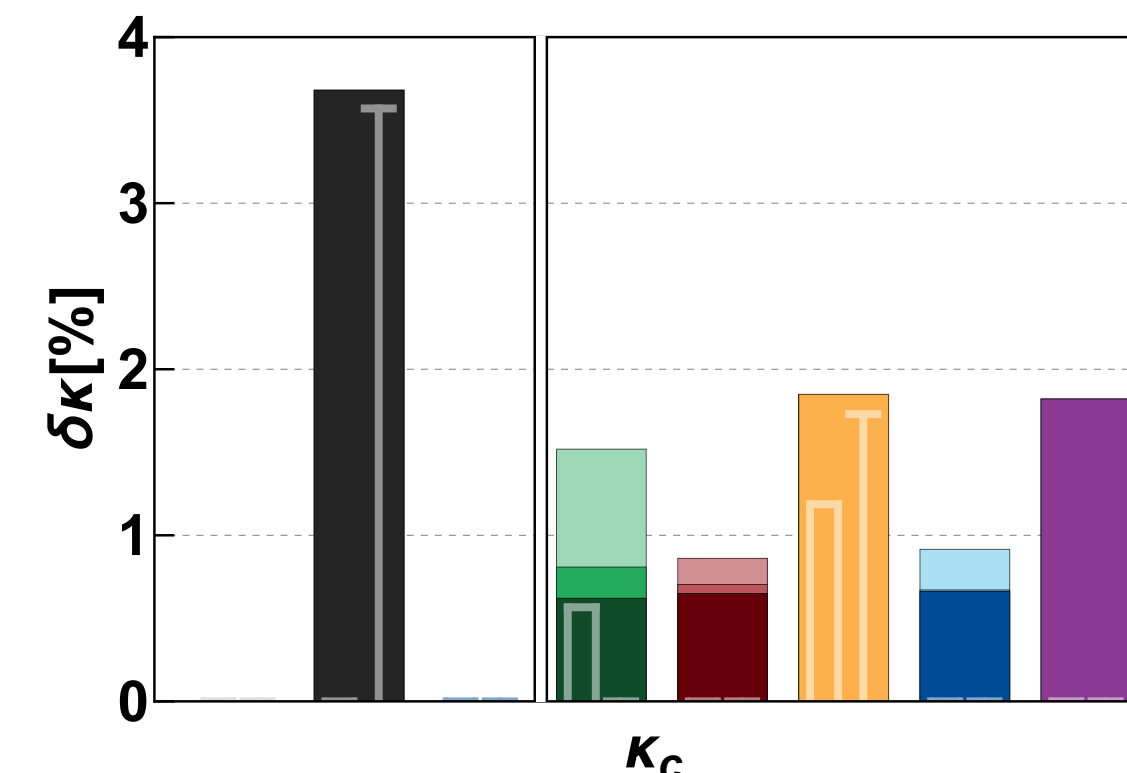
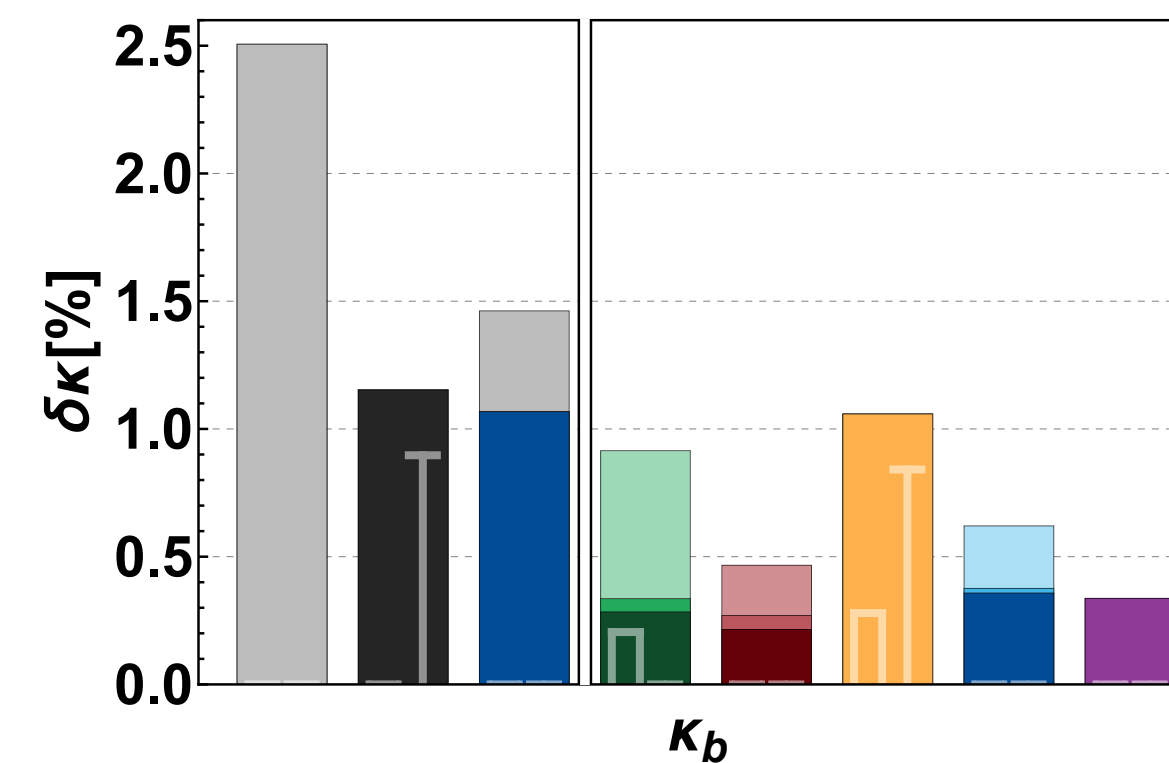
HZZ
factor ~10 improvement
wrt LHC
O(0.1%)



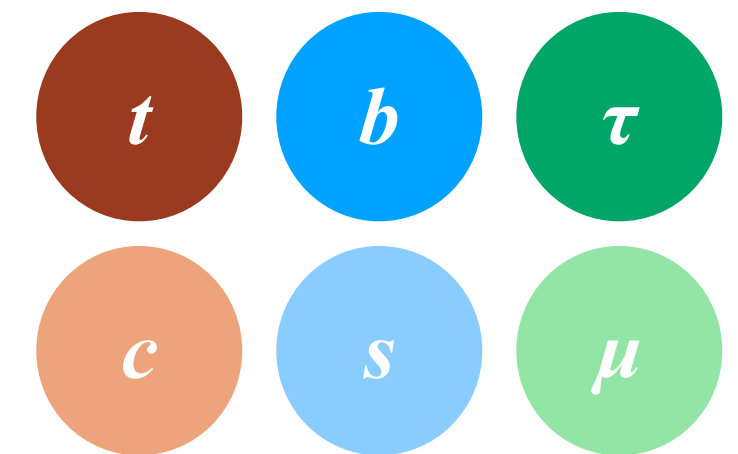
H width
Model-independent
at e^+e^- O(1%)



H → BSM
 $\text{BR}(H \rightarrow \text{inv}) < 0.08\%$
 $\text{BR}(H \rightarrow \text{exo}) < 0.7\%$



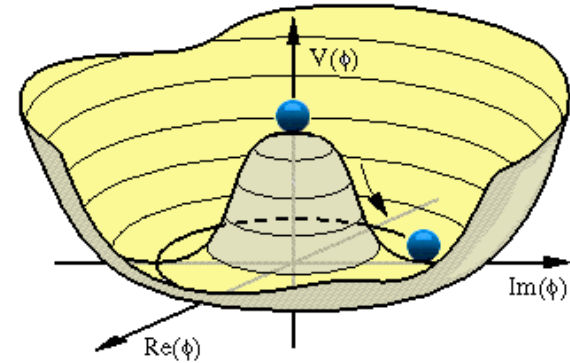
3rd family:
factor ~10 improvement
wrt LHC



2nd quark family (charm):
Beyond the LHC reach
(O(1) sensitivity to strange)

Understanding the Electroweak Scale and the Higgs boson

Testing the Higgs potential: Higgs self-coupling precision



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

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

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

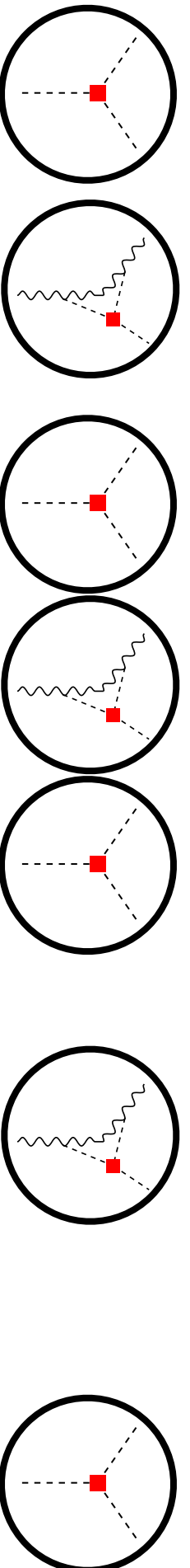
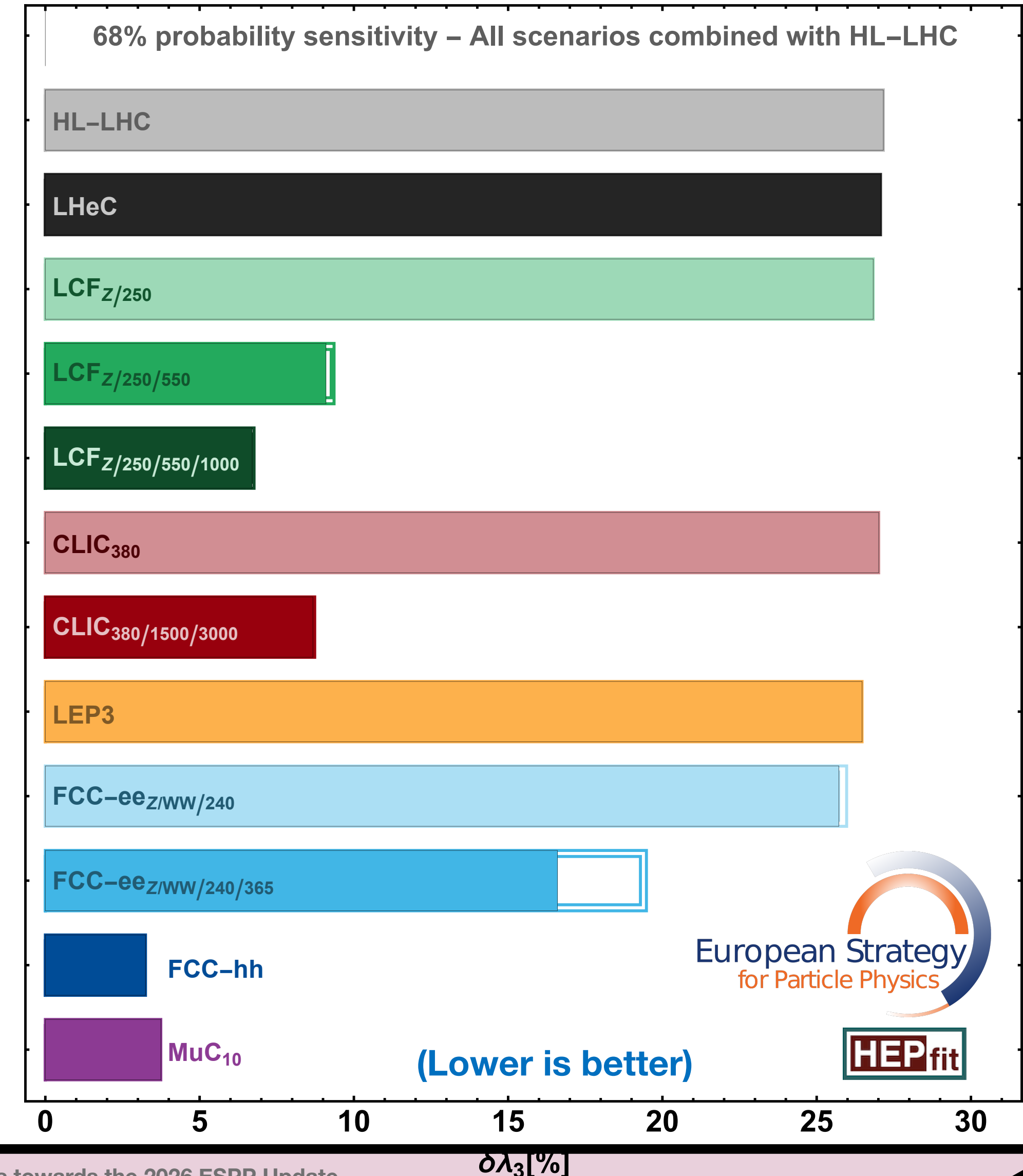
$$\delta\lambda_3 \sim 17-20\%$$

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)

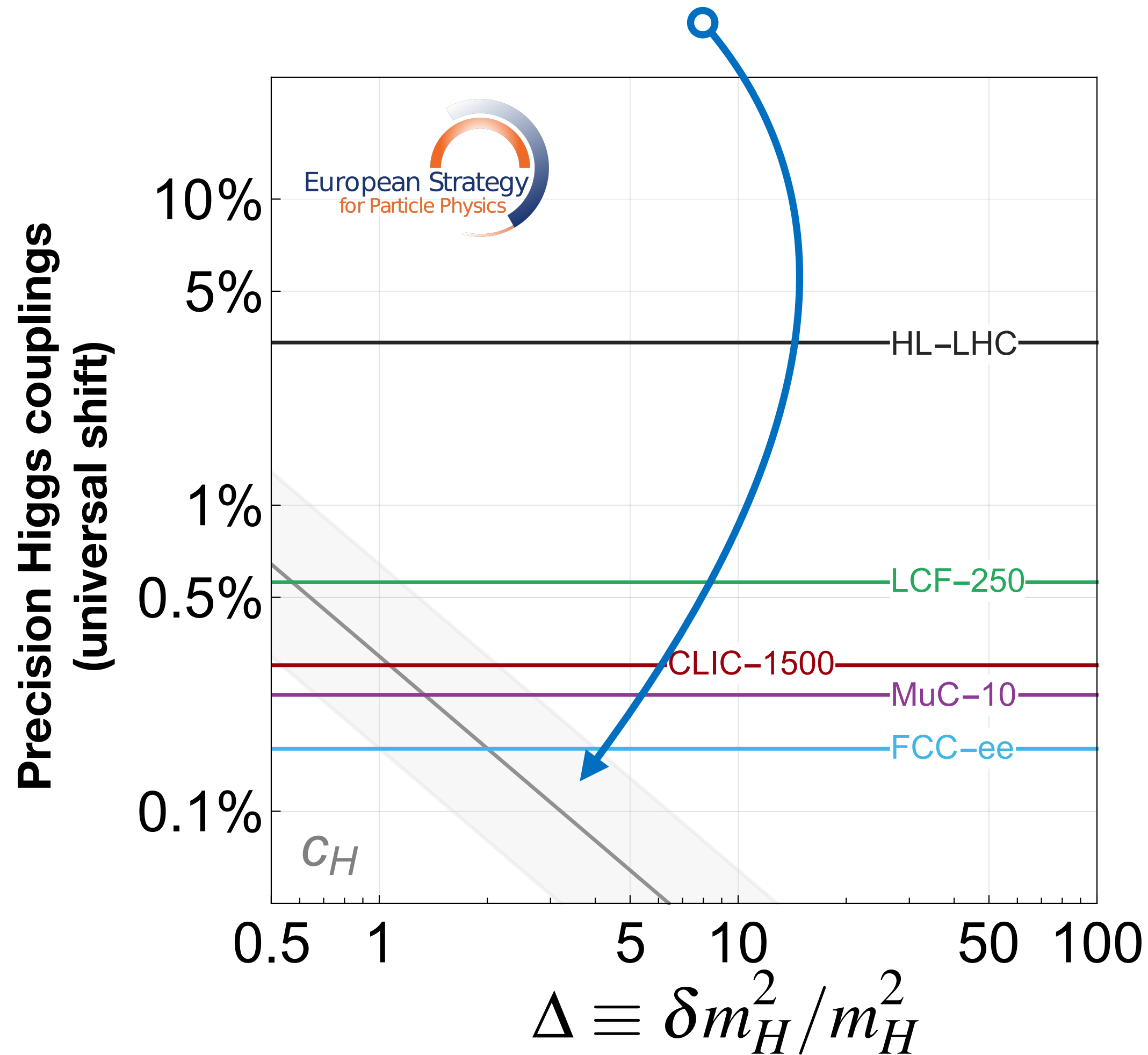
$$\delta\lambda_3 \lesssim 5\%$$



Understanding the Electroweak Scale and the Higgs boson

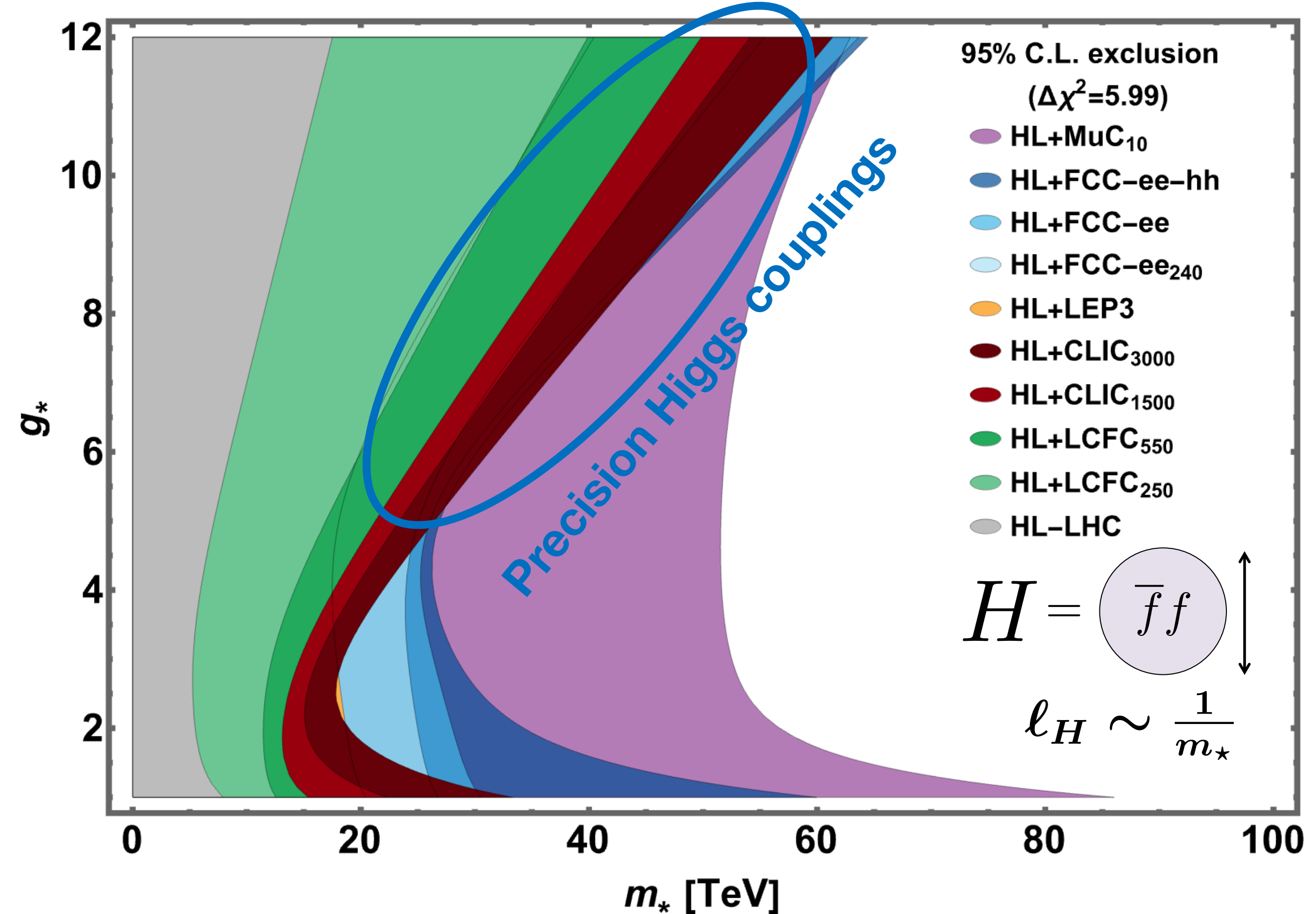
Precision Higgs Physics $\Rightarrow$ BSM: Naturalness

Fine tuning in Neutral Naturalness



Composite Higgs scenarios

Higgs pNGB of strongly interacting sector with (mass, coup)
 (m_*, g_*)

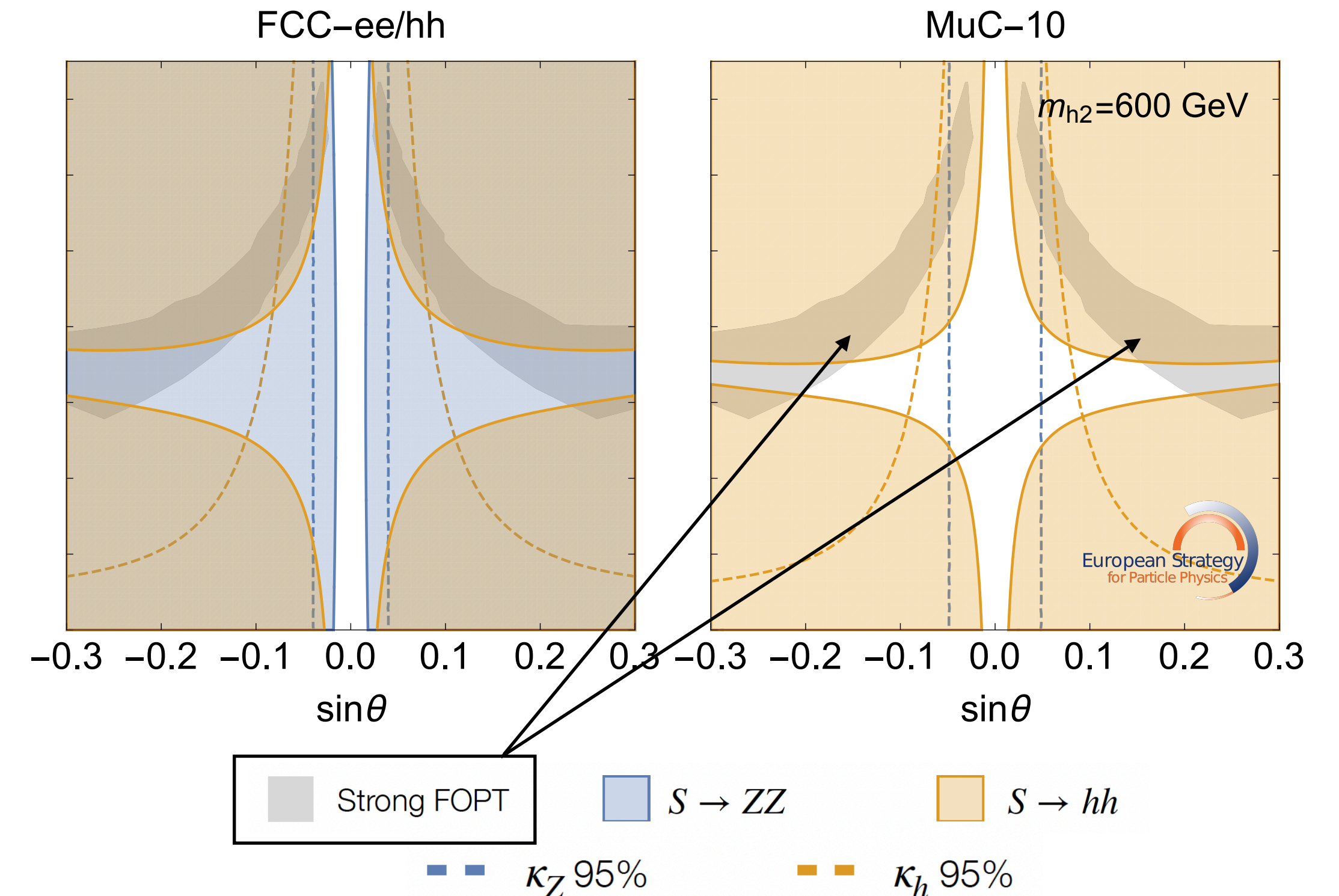
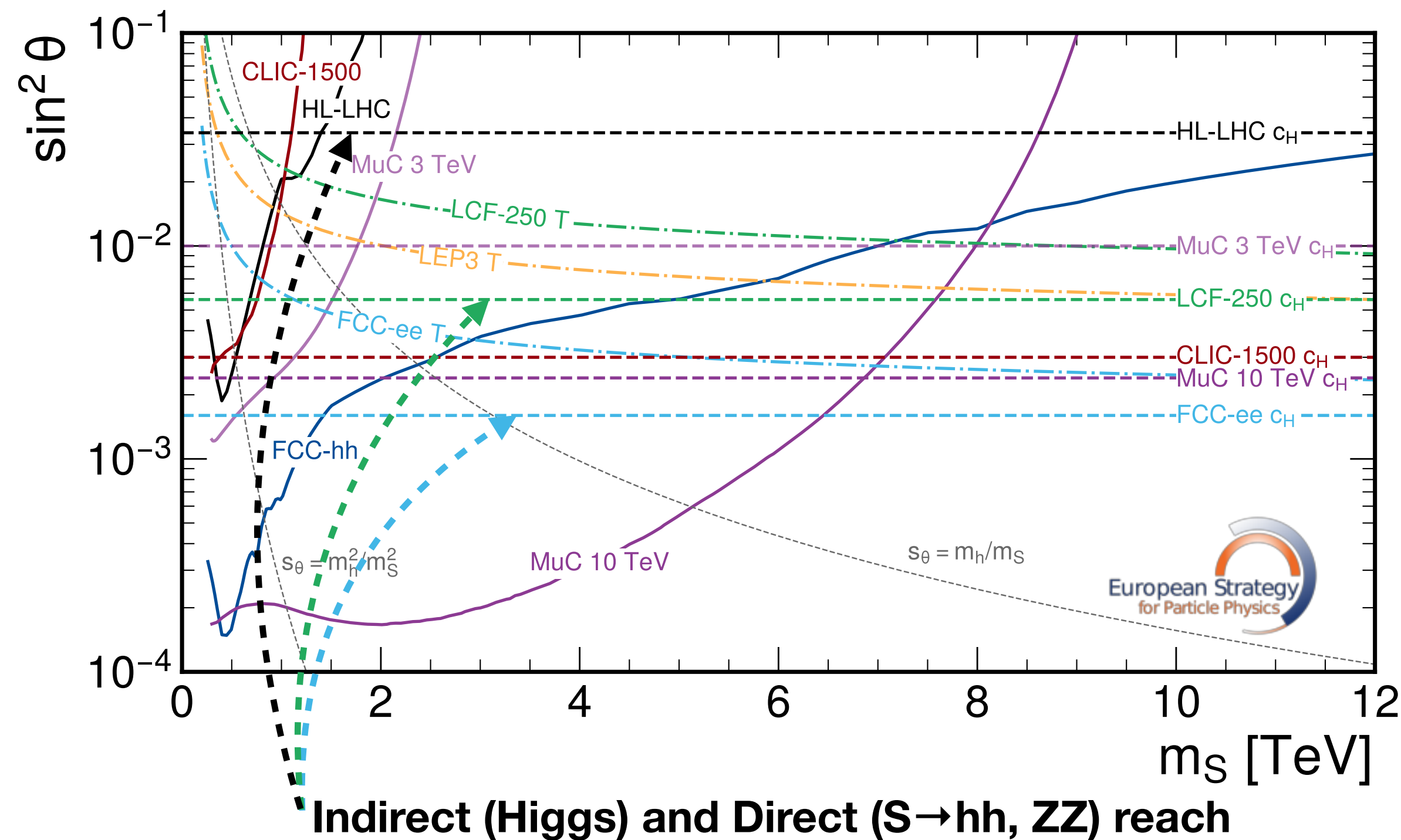


Understanding the Electroweak Scale and the Higgs boson

Precision Higgs Physics $\Rightarrow$ BSM: EWPT

The simplest scenario: Singlet extensions

$$V(\phi, S) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 + b_1 S - \mu_S^2 S^2 + \frac{b_4}{4} S^4 + \frac{a_2}{2} |\phi|^2 S^2 + \frac{b_3}{3} S^3 + \frac{a_1}{2} |\phi|^2 S$$



**Many other possible interesting extensions of the scalar sector:
Complex Singlets, Two Higgs Doublet Models, Georgi-Machacek...**

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Most of these questions revolve around the nature of the Higgs and require BSM
 $\Rightarrow$ Modification of the properties of the Higgs boson

$$\Delta M_h^2 = \text{.....} \text{SM} \text{.....} + \text{.....} \text{New} \text{.....} \sim 0 \quad \frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon_T \equiv \text{fine tuning}$$

Understanding the Electroweak Scale and the Higgs boson

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$

Understanding EWSB

What triggers EWSB?

Naturalness? Is the Higgs elementary/composite?

Nature of the EWPT $\leftrightarrow$ Matter/Anti-Matter Asymmetry?

Is the EW vacuum stable?

Electroweak Physics

Dark Sectors

?

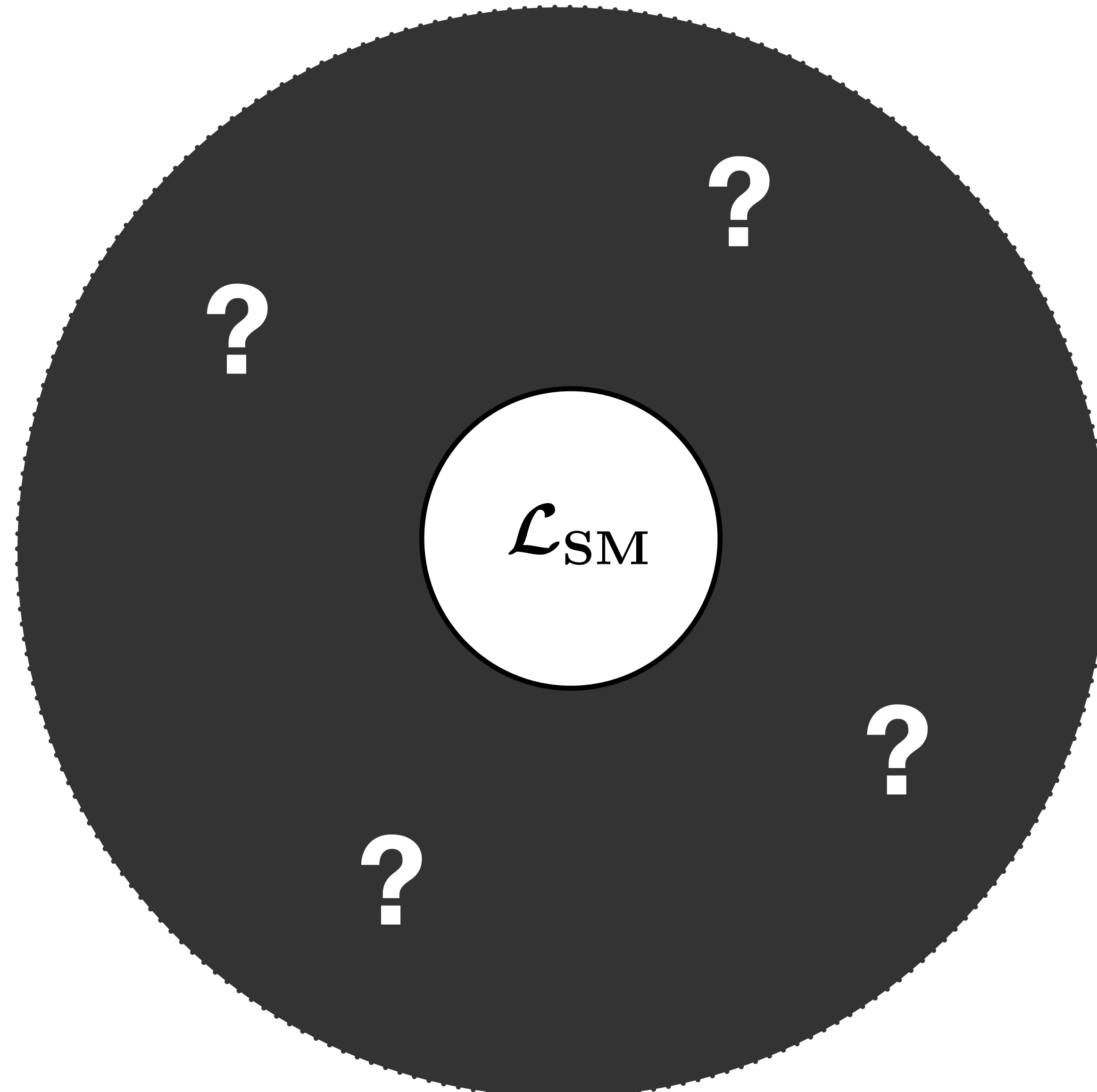
SM

Higgs

***Most of these questions revolve around the nature of the Higgs and require BSM
 $\Rightarrow$ Modification of the properties of the Higgs boson***

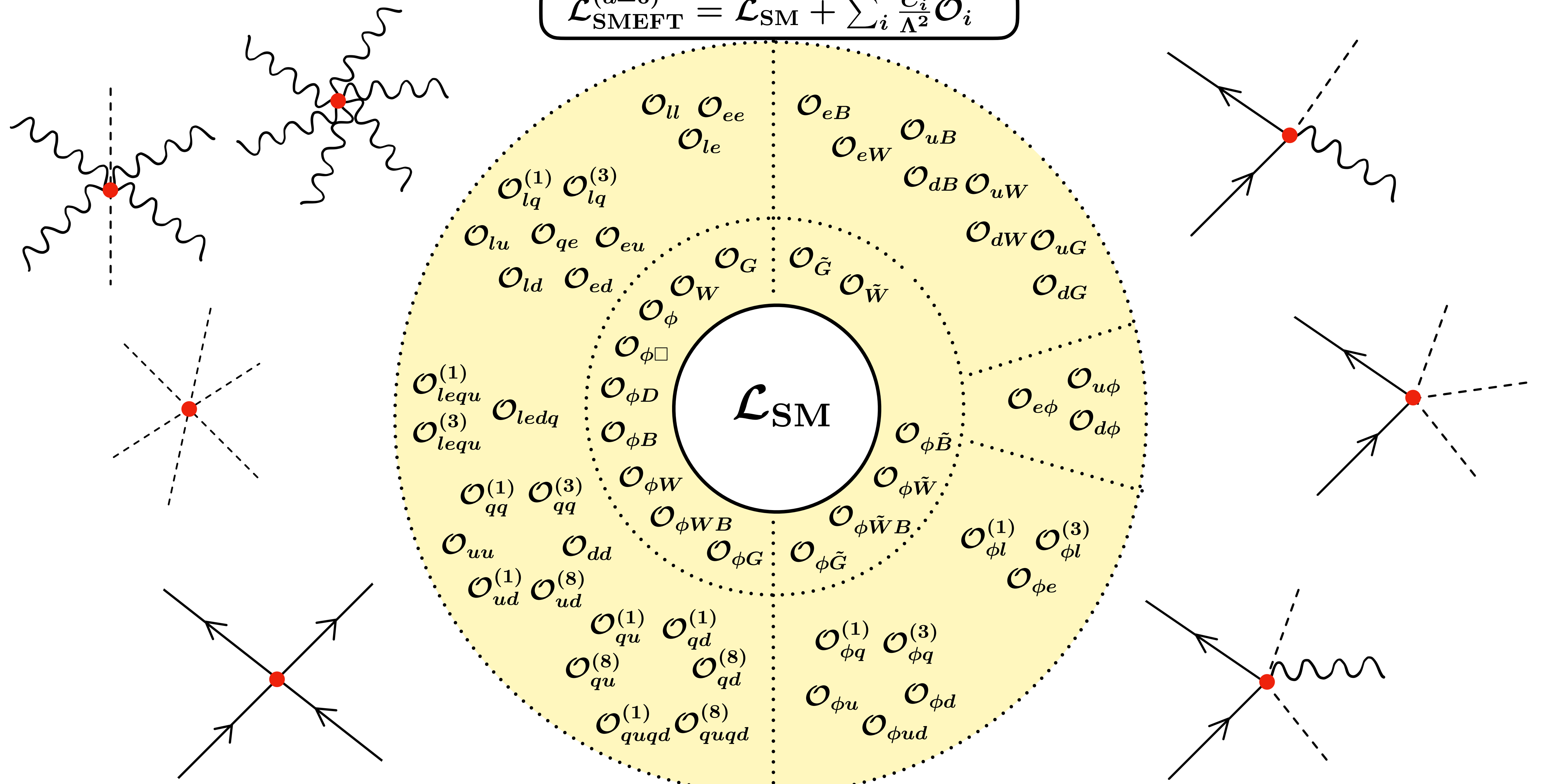
But new physics may be hiding in many other places!

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



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

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

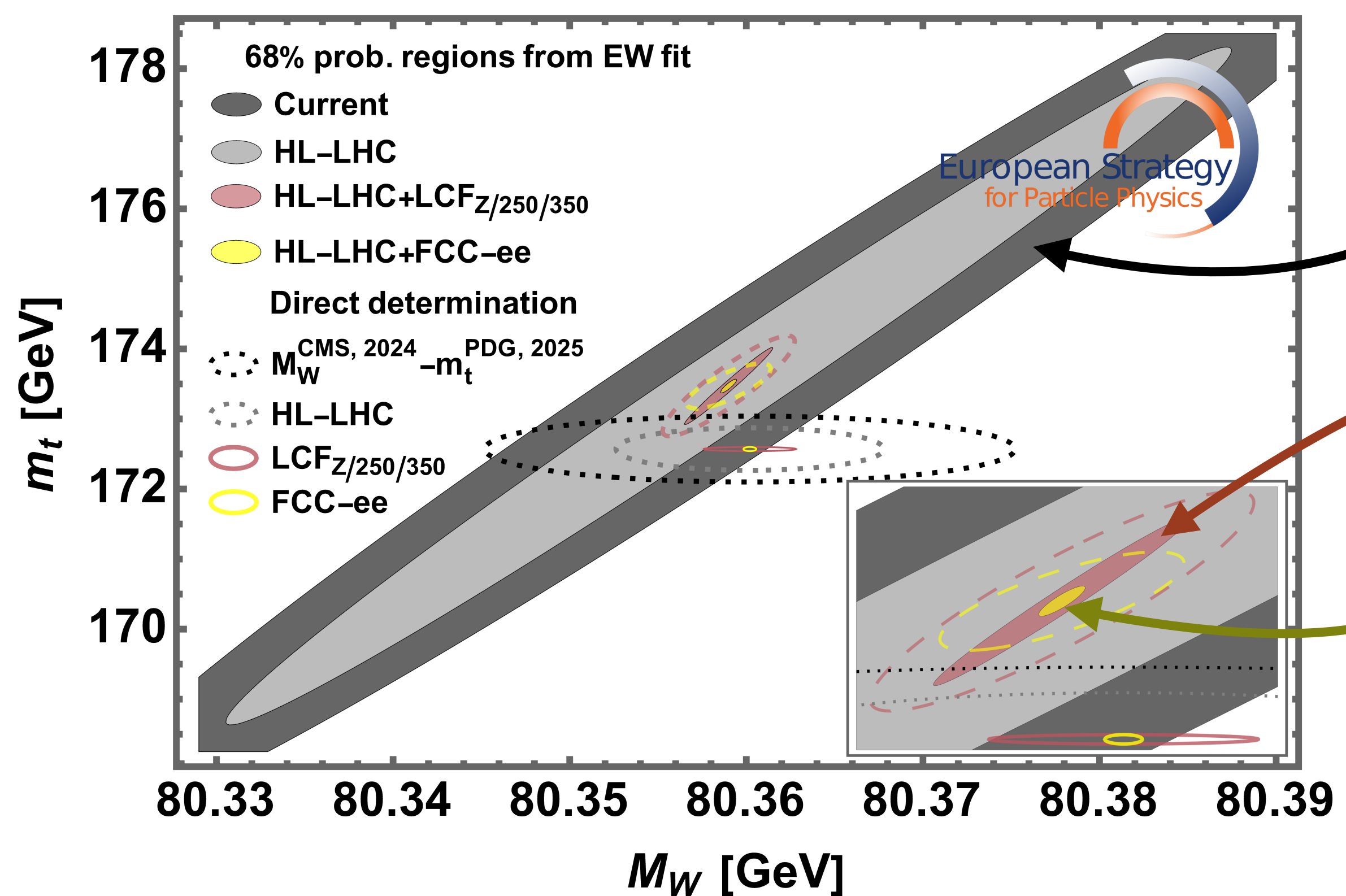
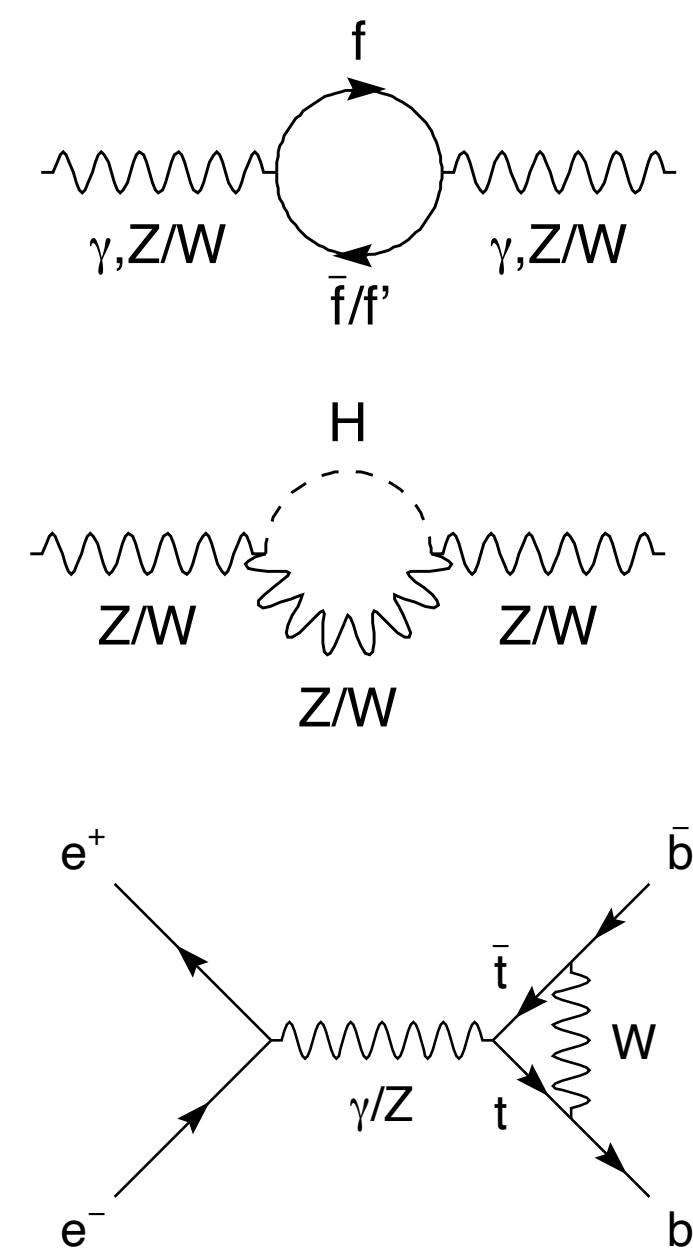


BSM can “change” the SM in many different ways...

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

And this is just the

- **Electroweak Precision Observables (Z pole, M_W , ...)** provide one of the strongest tests of consistency of the SM at the quantum level → Future improvements would increase sensitivity to even smaller NP effects entering via radiative corrections



Today (LEP/SLC: 10^7 Z)

LCF (Giga-Z: 10^9 Z)

FCC-ee (Tera-Z: 10^{12} Z)



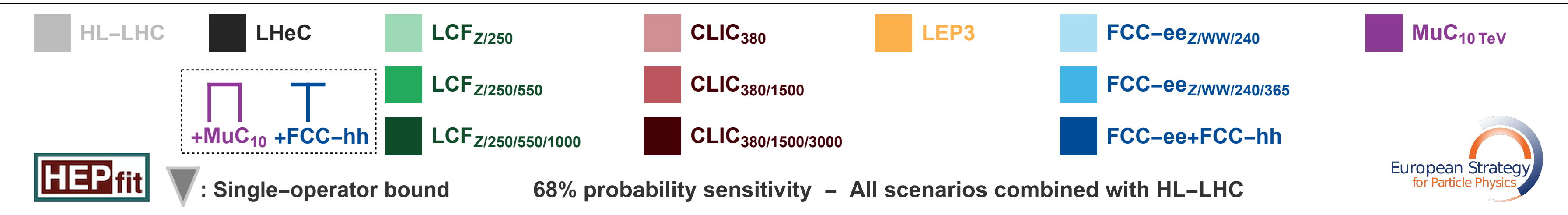
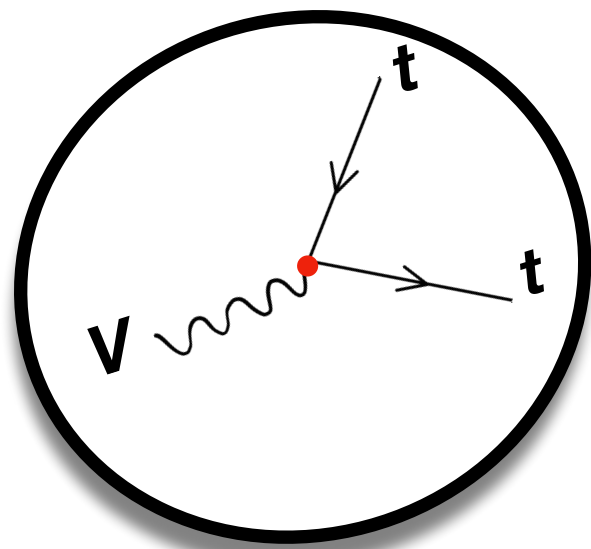
**Strong dependence on precision of theory calculations
(challenging to match future experimental precision)**

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

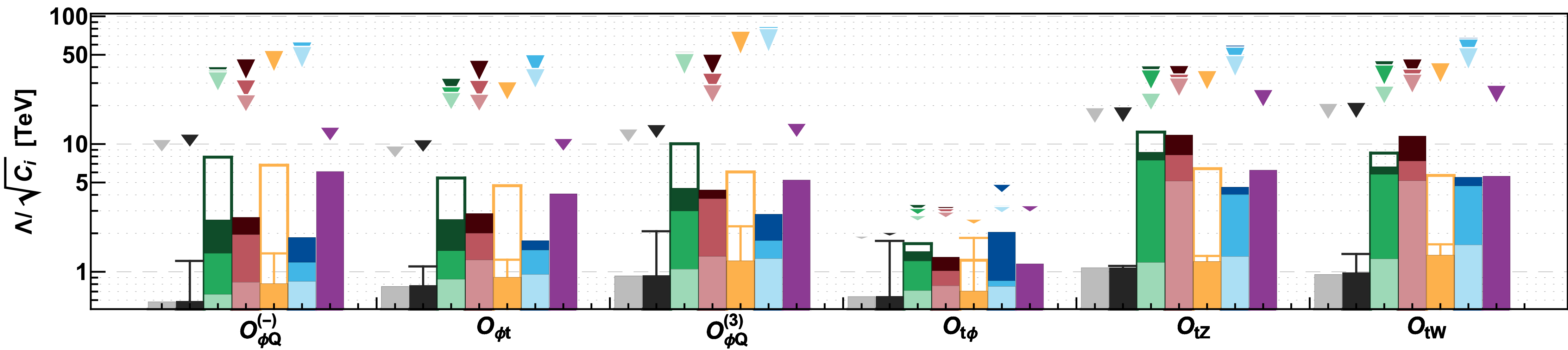
$$\mathcal{L}^{(d=6)} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

And this is just the

- The **top quark**: Connected to BSM in many models. It's properties are currently measured to comparatively lower precision than other SM particles



Dimension-6 operators modifying EW/Higgs Top interactions

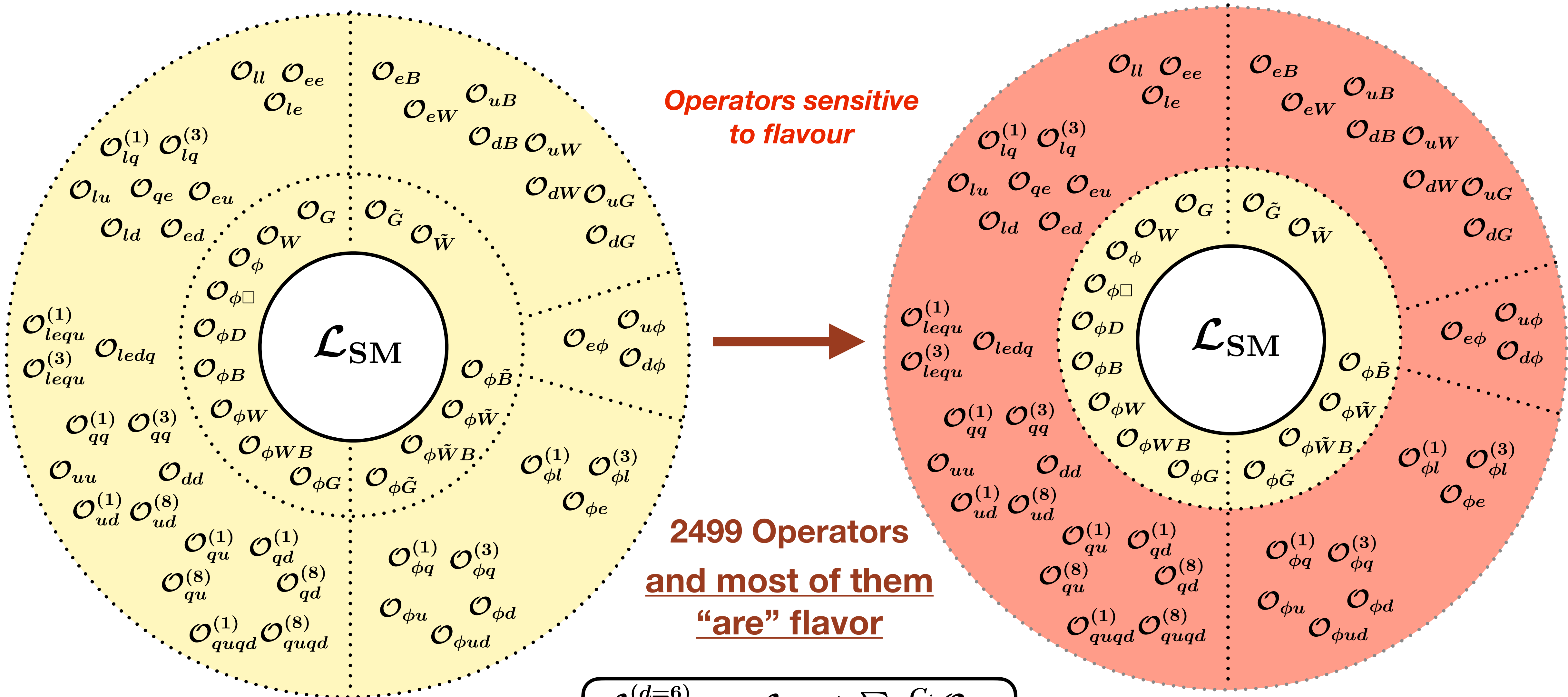


V_{tt}: Advantage for LC/MuC thanks to high-E reach
Sensitivity at CC via EWPO

Y_t: Best at FCC-hh

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

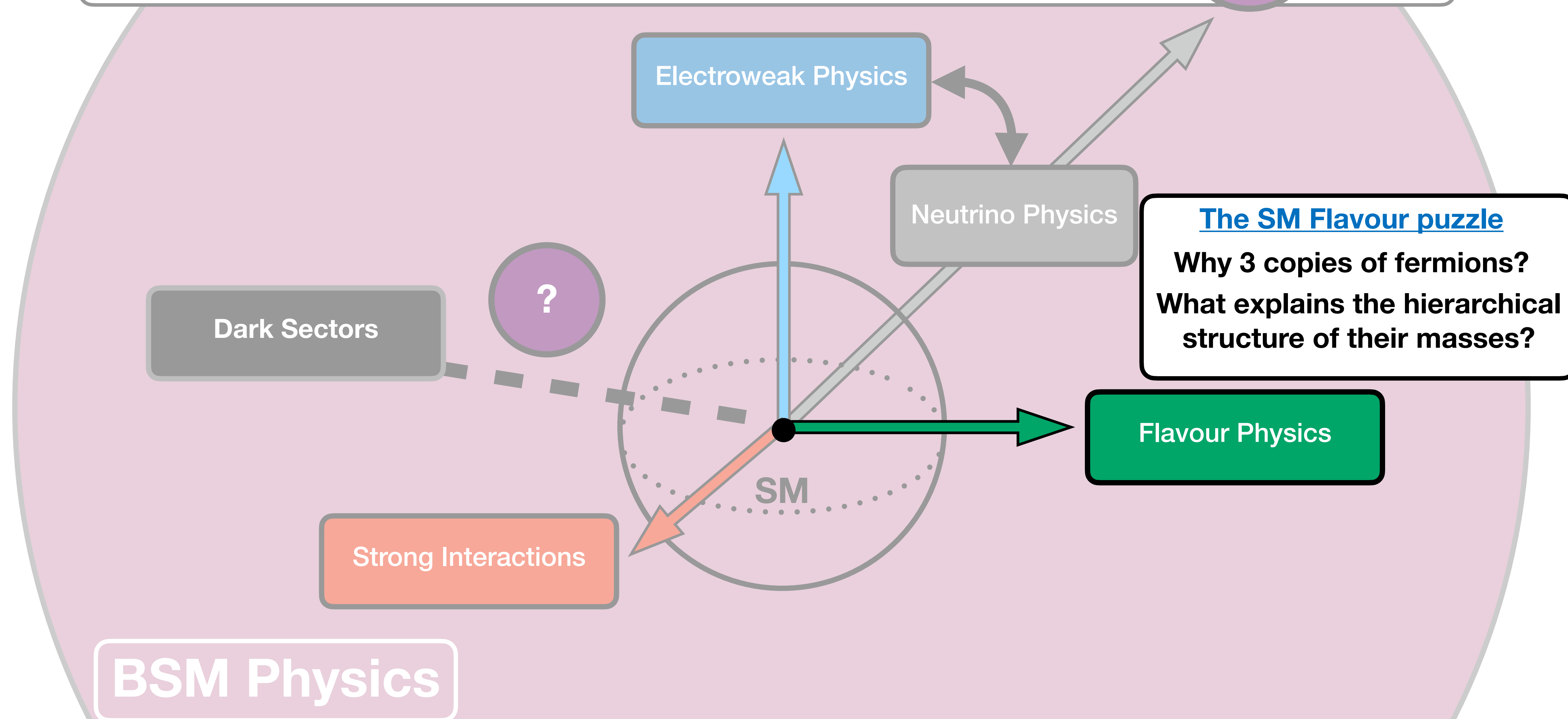
The importance of flavour in new physics searches



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

The Flavour of New Physics

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$



The Flavour of New Physics

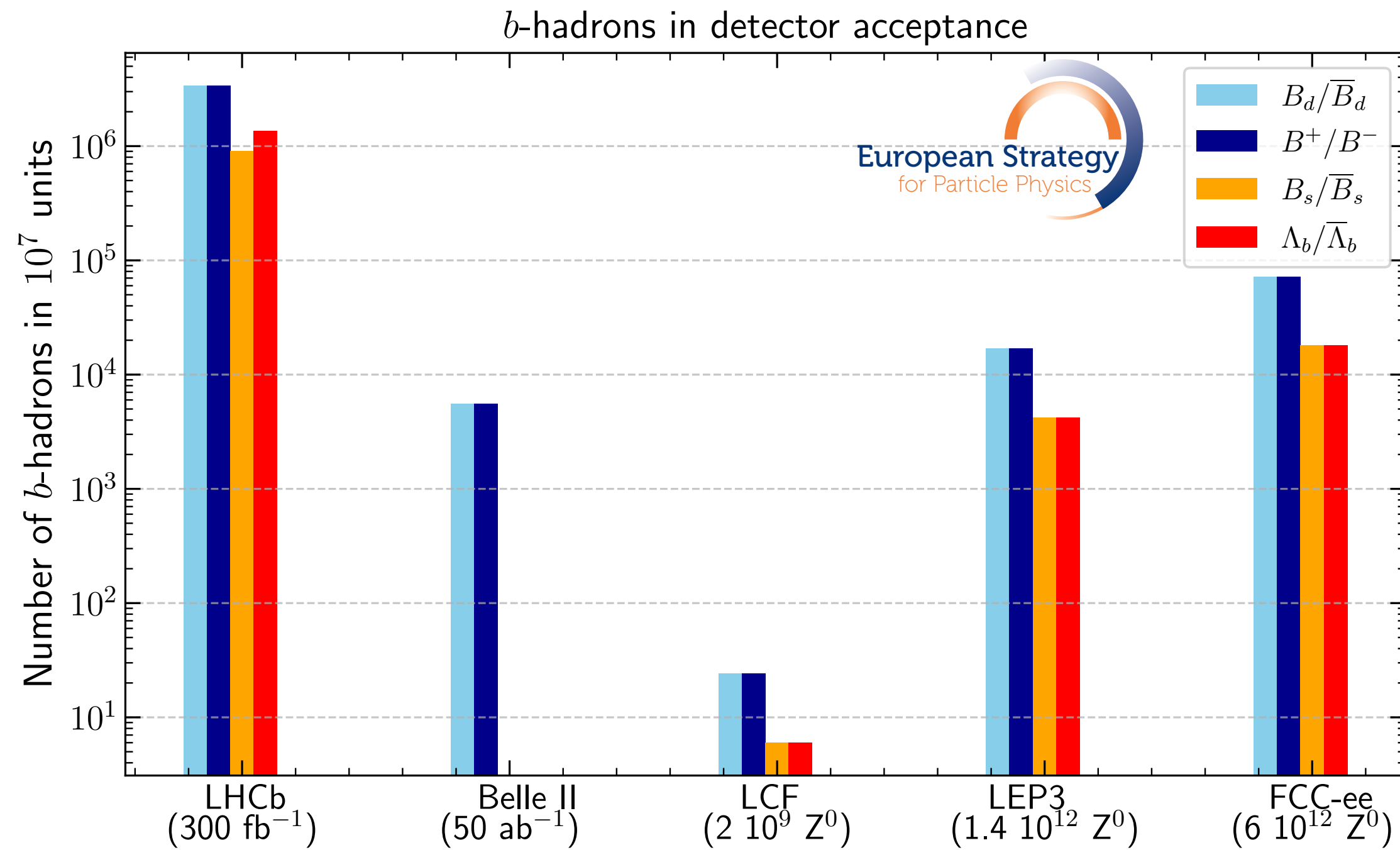
Flavour Physics Opportunities at future colliders

Major progress in many processes at HL-LHC & Belle II and future Z factories

Flavour Transition	Transition type					
	γ	quarks	μ	e	τ	ν
$3_q \rightarrow 2_q$	$b \rightarrow s \gamma$ [*]	$B_s \leftrightarrow \bar{B}_s$ [*]	$b \rightarrow s \bar{\mu} \mu$ [*] $b \rightarrow c \mu \bar{\nu}$	$R_{bs}(e/\mu)$ [*] $R_{bc}(e/\mu)$ [•]	$b \rightarrow s \bar{\tau} \tau$ [•] $b \rightarrow c \tau \bar{\nu}$ [•]	$b \rightarrow s \nu \bar{\nu}$ [•]
$3_q \rightarrow 1_q$	$b \rightarrow d \gamma$ [*]	$B_d \leftrightarrow \bar{B}_d$ [*]	$b \rightarrow d \bar{\mu} \mu$ [*] $b \rightarrow u \mu \bar{\nu}$	$R_{bd}(e/\mu)$ [*] $R_{bu}(e/\mu)$ [•]	$b \rightarrow d \bar{\tau} \tau$ [•] $b \rightarrow u \tau \bar{\nu}$ [•]	$b \rightarrow d \nu \bar{\nu}$ [•]
$2_q \rightarrow 2_q$ 1_q	$c \rightarrow u \gamma$	$D \leftrightarrow \bar{D}$ [*]	$c \rightarrow u \bar{\mu} \mu$ $c \rightarrow s \bar{\mu} \nu$ $c \rightarrow d \bar{\mu} \nu$	$R_{cu}(e/\mu)$ [*] $R_{cs}(e/\mu)$ [•] $R_{cd}(e/\mu)$ [•]		$c \rightarrow u \nu \bar{\nu}$ [•]
$3_\ell \rightarrow 2_\ell$ 1_ℓ	$\tau \rightarrow \mu \gamma$ [•] $\tau \rightarrow e \gamma$ [•]	$\tau \rightarrow \mu \bar{q} q$ [•] $\tau \rightarrow e \bar{q} q$ [•]	$\tau \rightarrow \mu \bar{\mu} \mu$ [•] $\tau \rightarrow e \bar{\mu} \mu$ [•]	$\tau \rightarrow \mu \bar{e} e$ [•] $\tau \rightarrow e \bar{e} e$ [•]		$\tau \rightarrow \mu \nu \bar{\nu}$ [•] $\tau \rightarrow e \nu \bar{\nu}$ [•]
[*] = major progress @ HL-LHC, limited impact of e^+e^- colliders [•] = major progress @ HL-LHC & Belle II + significant further progress @ FCC-ee [•] = FCC-ee allows one order of magnitude precision improvement, or more, after HL-LHC & Belle II						
$2_q \rightarrow 1_q$ 1_q	$s \rightarrow d \gamma$	$K^0 \leftrightarrow \bar{K}^0$	$s \rightarrow d \bar{\mu} \mu$ $s \rightarrow u \mu \bar{\nu}$ $d \rightarrow u \mu \bar{\nu}$	$R_{sd}(e/\mu)$ $R_{su}(e/\mu)$ $R_{du}(e/\mu)$		$s \rightarrow d \nu \bar{\nu}$
$2_\ell \rightarrow 1_\ell$	$\mu \rightarrow e \gamma$	$\mu N \rightarrow e N$		$\mu \rightarrow e \bar{e} e$		$\mu \rightarrow e \nu \bar{\nu}$

The Flavour of New Physics

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



2030s

Belle II 10 ab⁻¹
LHCb 50 fb⁻¹

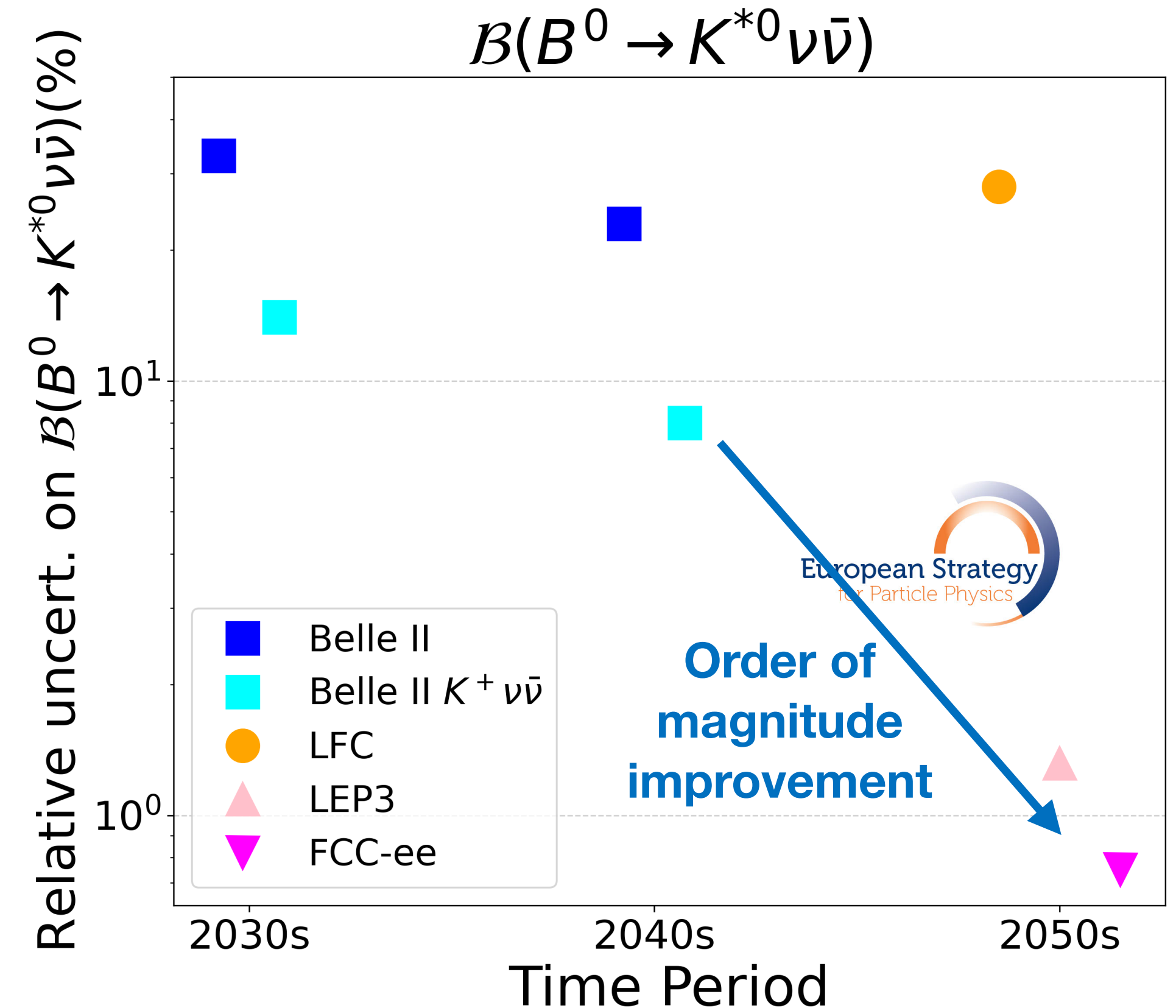
2040s

Belle II 50 ab⁻¹
LHCb 300 fb⁻¹

2050s

LCF 2 10⁹ Z⁰
LEP3 1.4 10¹² Z⁰
FCC-ee 6 10¹² Z⁰

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



Additional opportunities from W decays (FCC-ee: 10^8 W pairs) $\Rightarrow$ CKM

The Flavour of New Physics

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

τ Lepton Flavour Violation

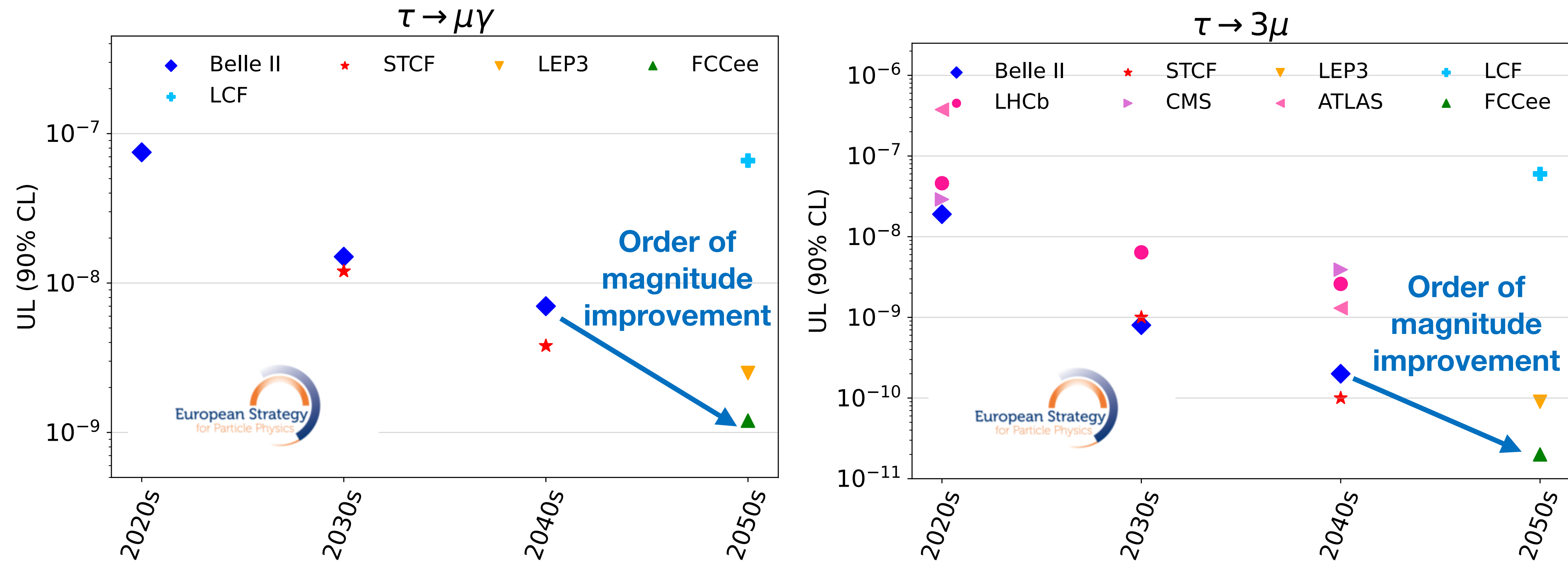


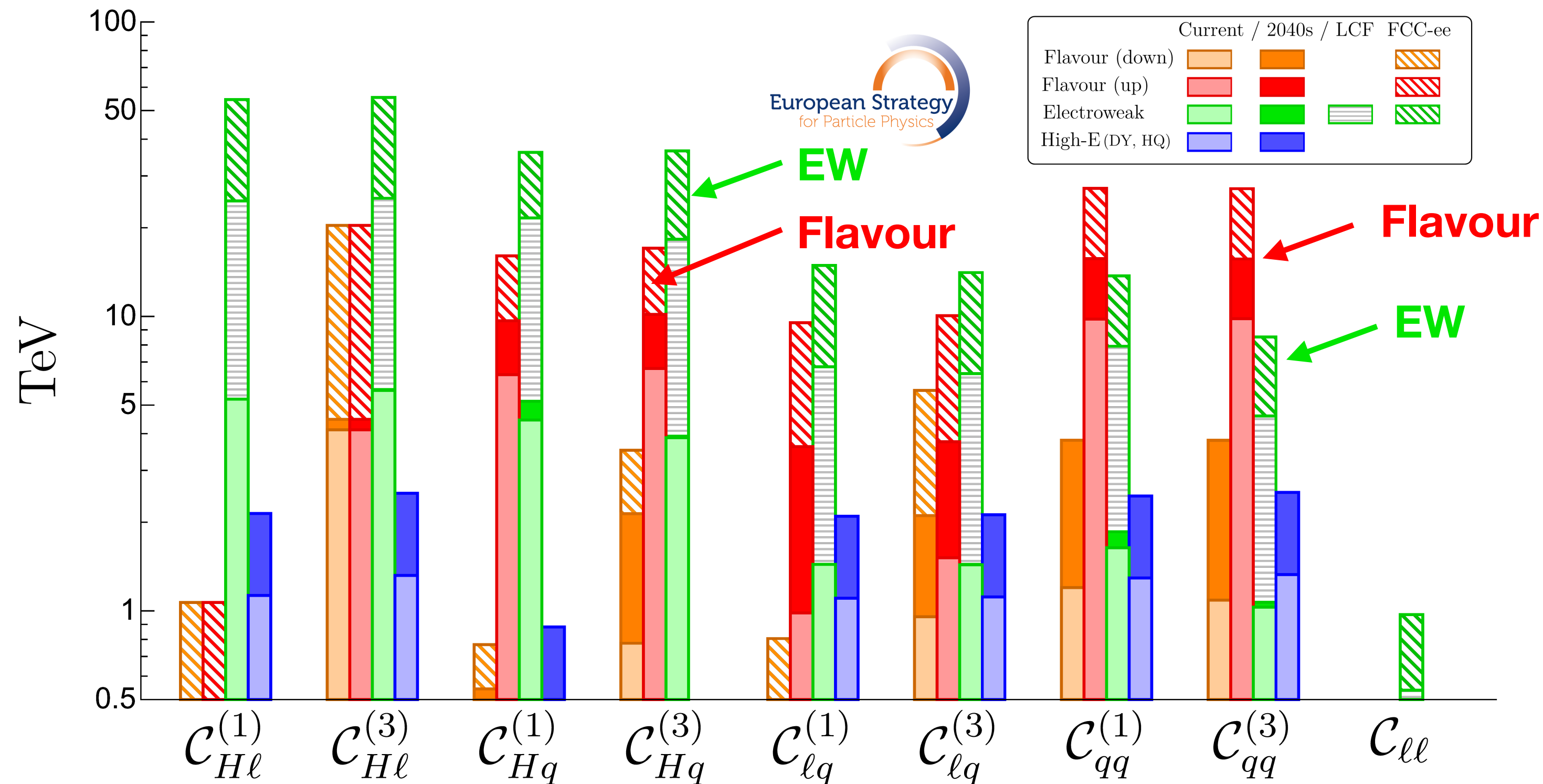
Fig. 5.7: Expected upper limits at 90% on $\mathcal{B}(\tau \rightarrow \mu\gamma)$ and $\mathcal{B}(\tau \rightarrow \mu\mu\mu)$.

The Flavour of New Physics

- Complementarity Electroweak/Flavour:

EFT bounds: EW vs. Flavour

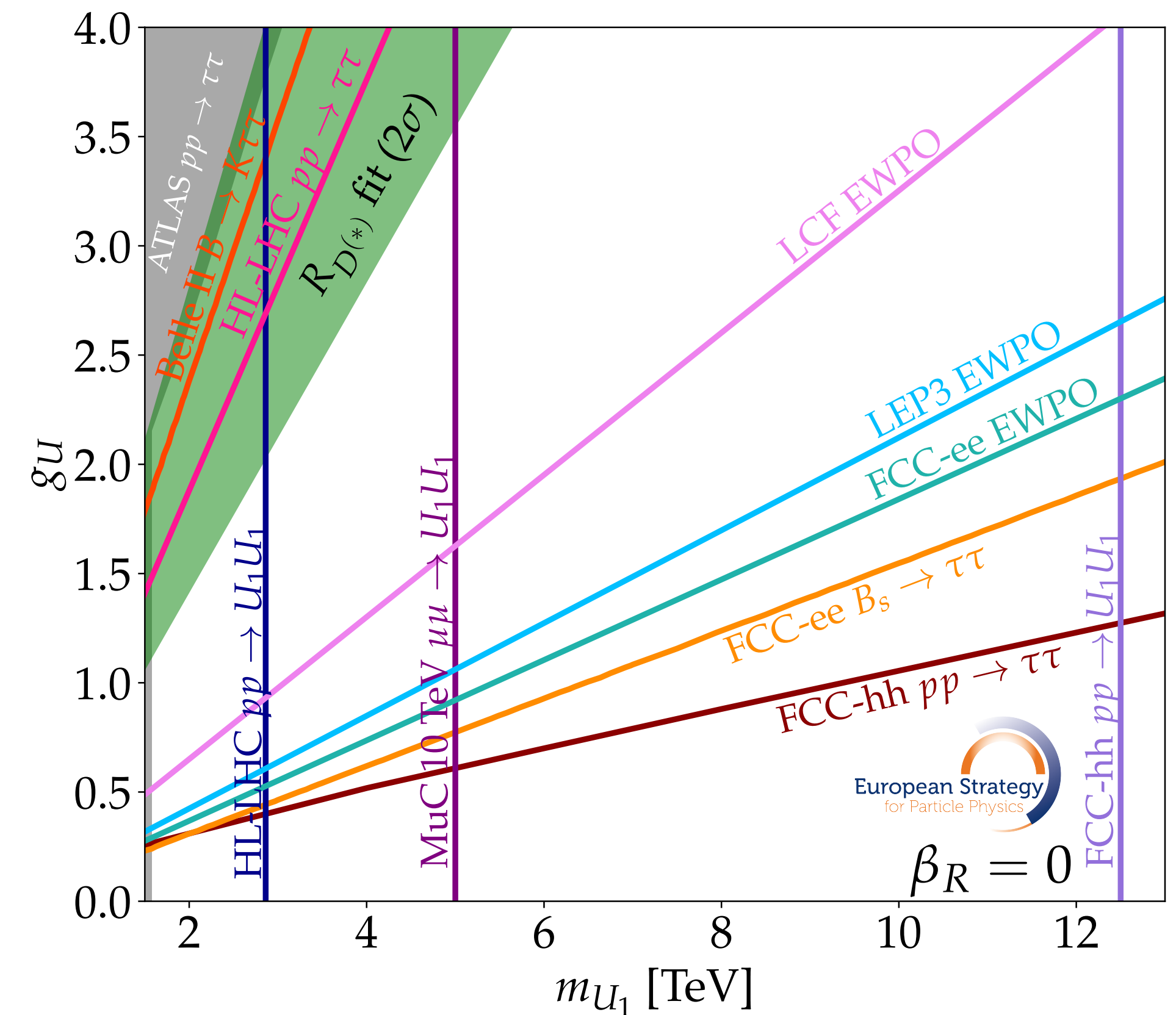
New physics in 3rd family (U(2)⁵ flavour “protection”)



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

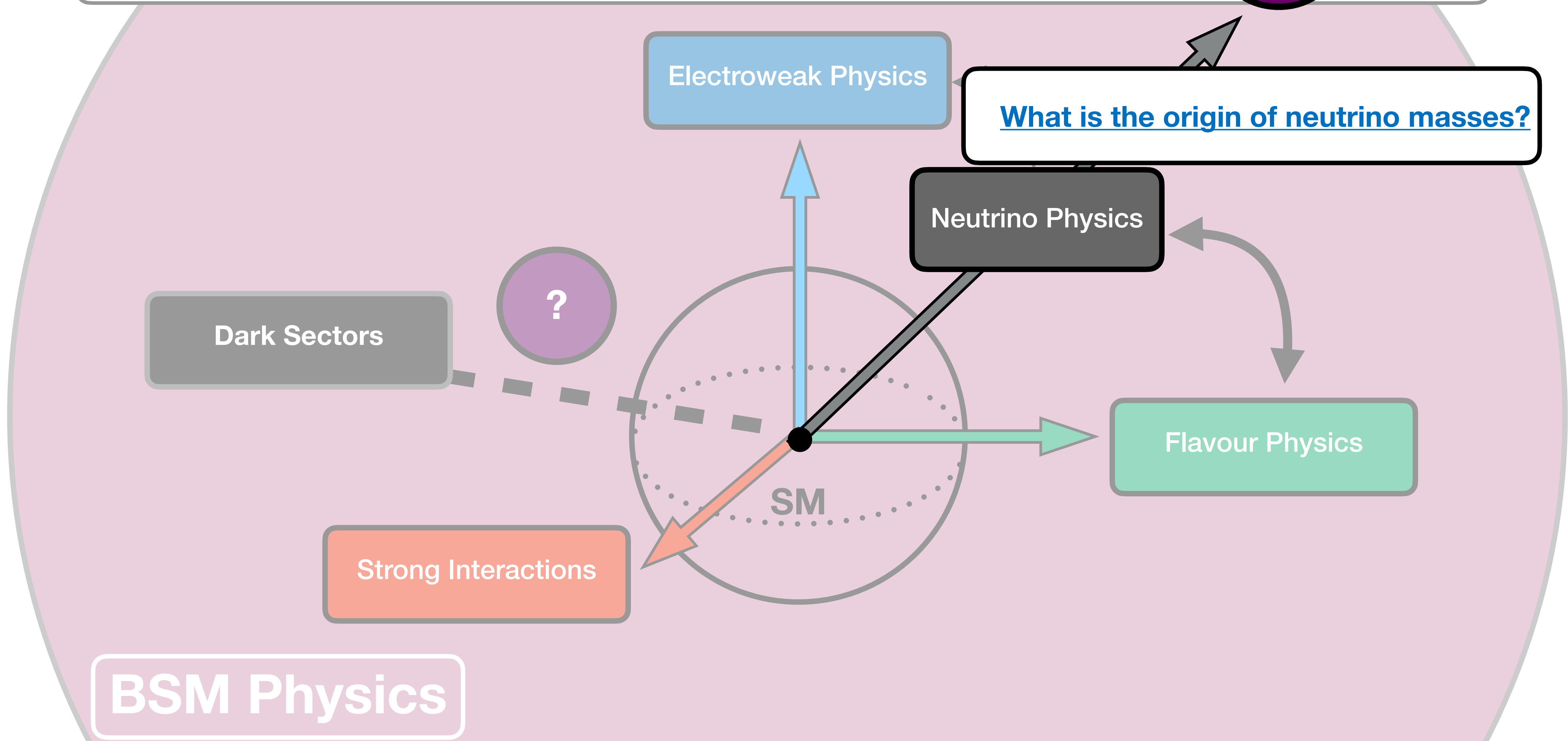
BSM: Vector lepto-quark (3rd gen.)

$$\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} \beta_{ij} \bar{Q}_L^i \gamma_\alpha L_L^j U_1^\alpha + h.c.$$



Neutrino Physics = New Physics

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$



Neutrino Physics = New Physics

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$

Electroweak Physics

What is the origin of neutrino masses?

Neutrino Physics

- We know that neutrino have masses $\Rightarrow$ Neutrino Physics is BSM physics

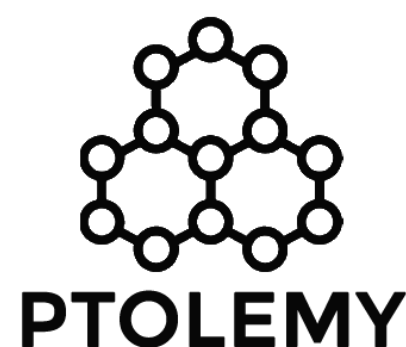
Neutrino oscillation experiments

- What we do not know:

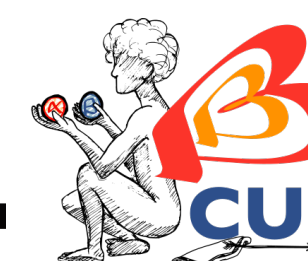
- ▶ Their ordering and absolute scale
- ▶ CP violation
- ▶ Their nature
- ▶ What generates them?



β -decay/e-capture experiments

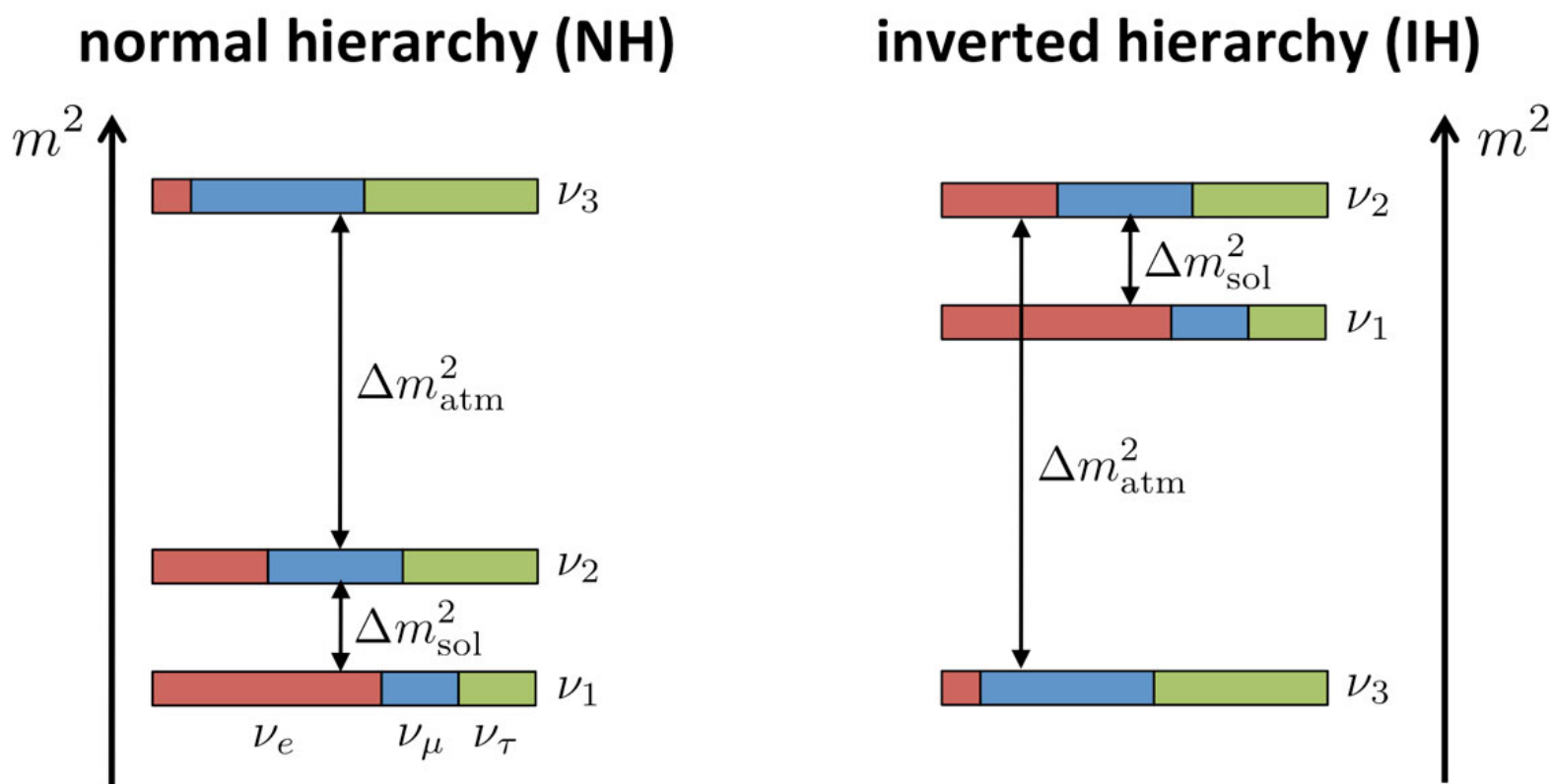


$0\nu\beta\beta$ -decay experiments



Neutrino Physics = New Physics

Neutrino mass ordering



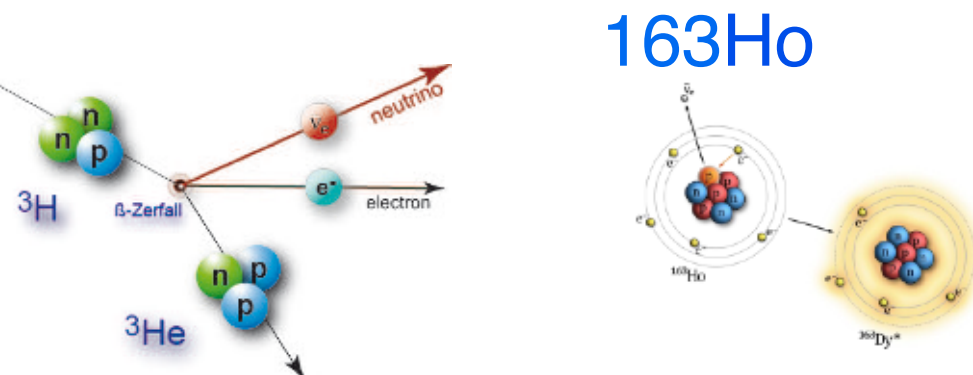
Leptonic CP violation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \dots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

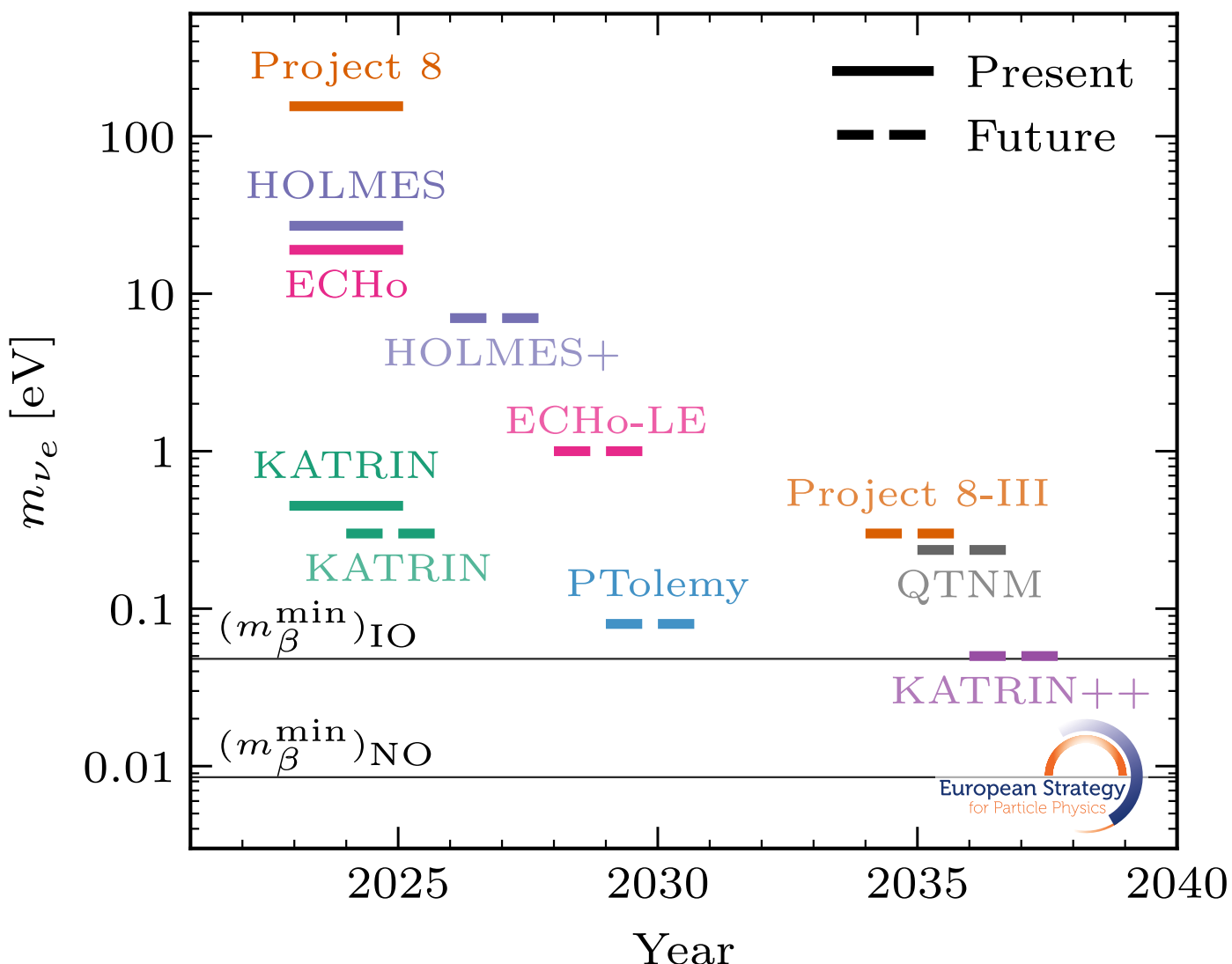
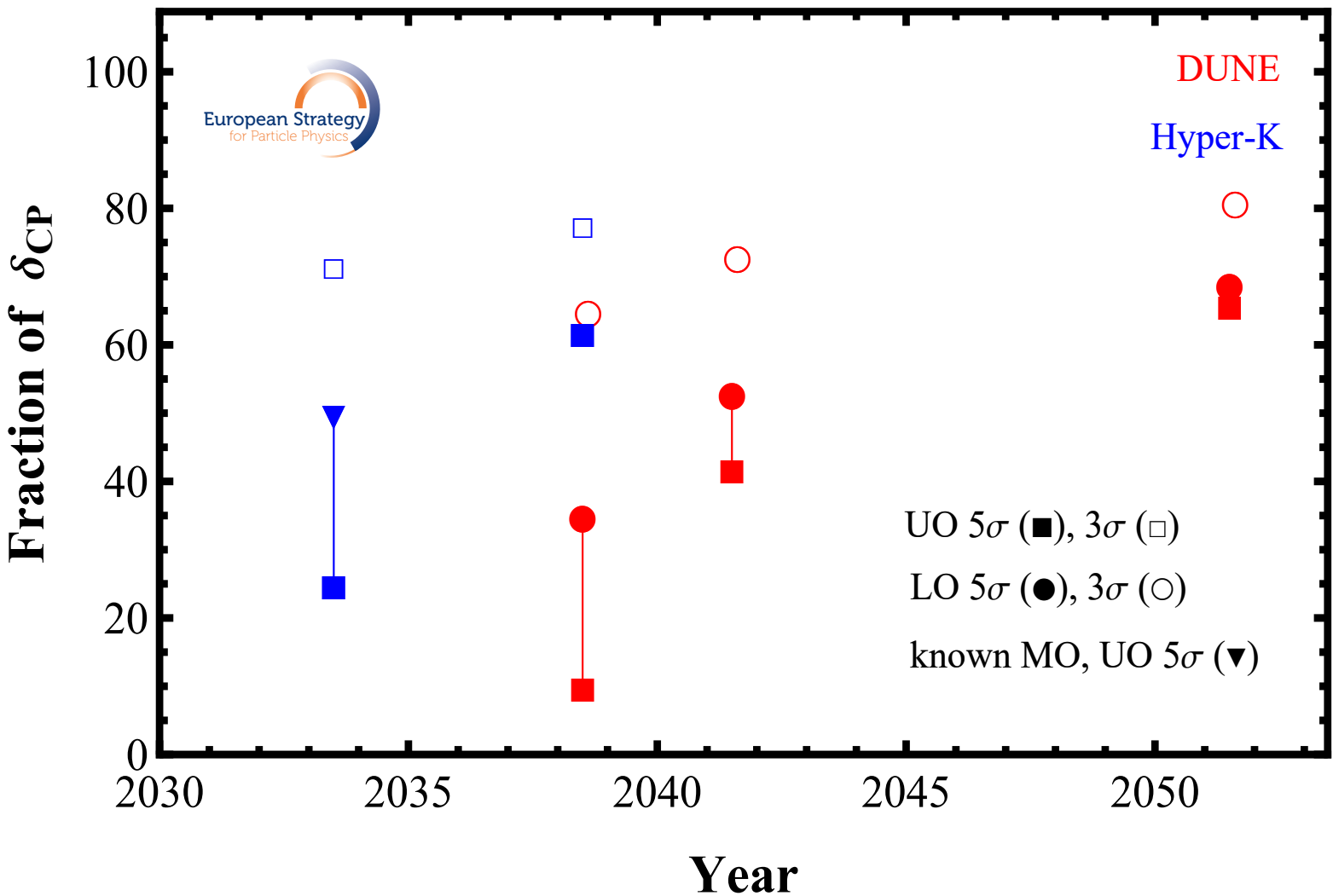
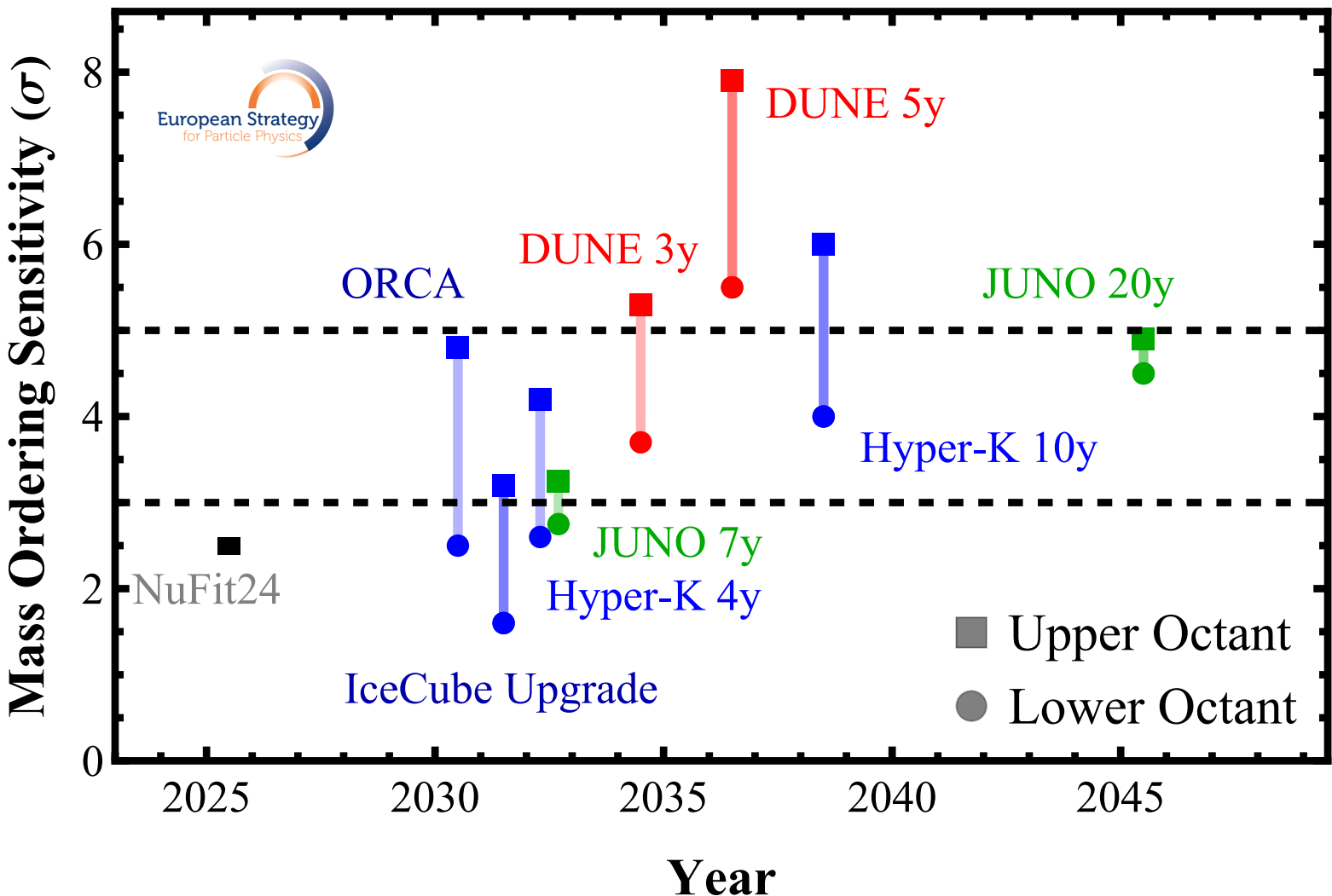
Neutrino mass scale

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

β -decay/e-capture $\Rightarrow \lesssim 0.1$ eV



Next-gen oscillation experiments $\Rightarrow$ Establish MO & CP (for large fraction of δ_{CP})



Neutrino Physics = New Physics

- The nature of neutrinos: Majorana? (Testable via $0\nu\beta\beta$ decay exp.) $\Rightarrow$ new physics scale is connected to neutrino masses:

$$\Delta\mathcal{L}_{\text{SMEFT}}^{(5)} = \frac{(C_5)_{ij}}{\Lambda} (\bar{l}_L^c i \tilde{\phi}^* \tilde{\phi}^\dagger l_L^j) + \text{h.c.}$$

- BSM models for physics at Λ ?

$$\mathcal{L}_{\text{Neutrino Portal}} = \mathcal{L}_{\text{Type-I}} = -i\bar{L}Y\sigma_2 H^* N - \bar{N}M N^c$$

Neutrino Portal = Low scale Type I seesaw

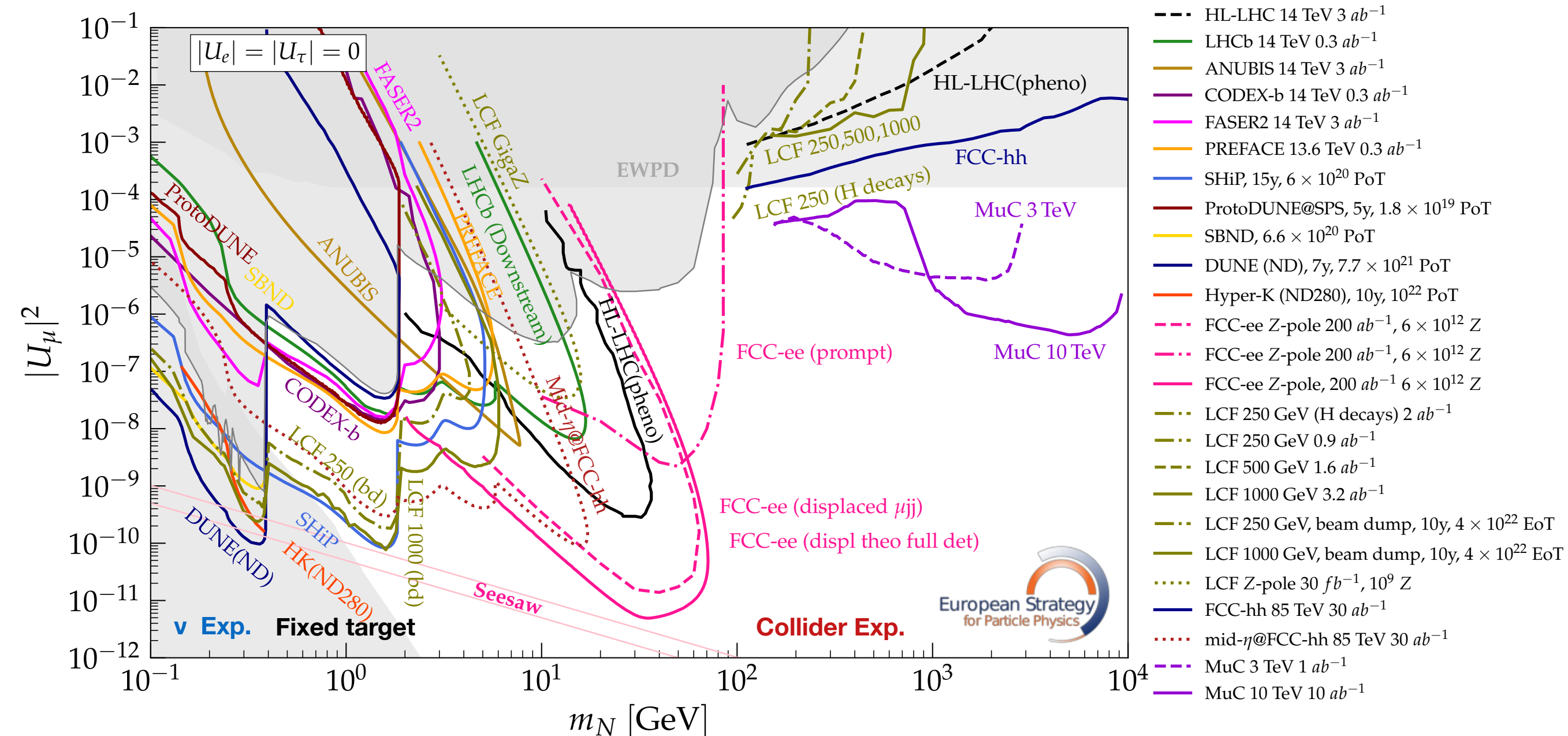
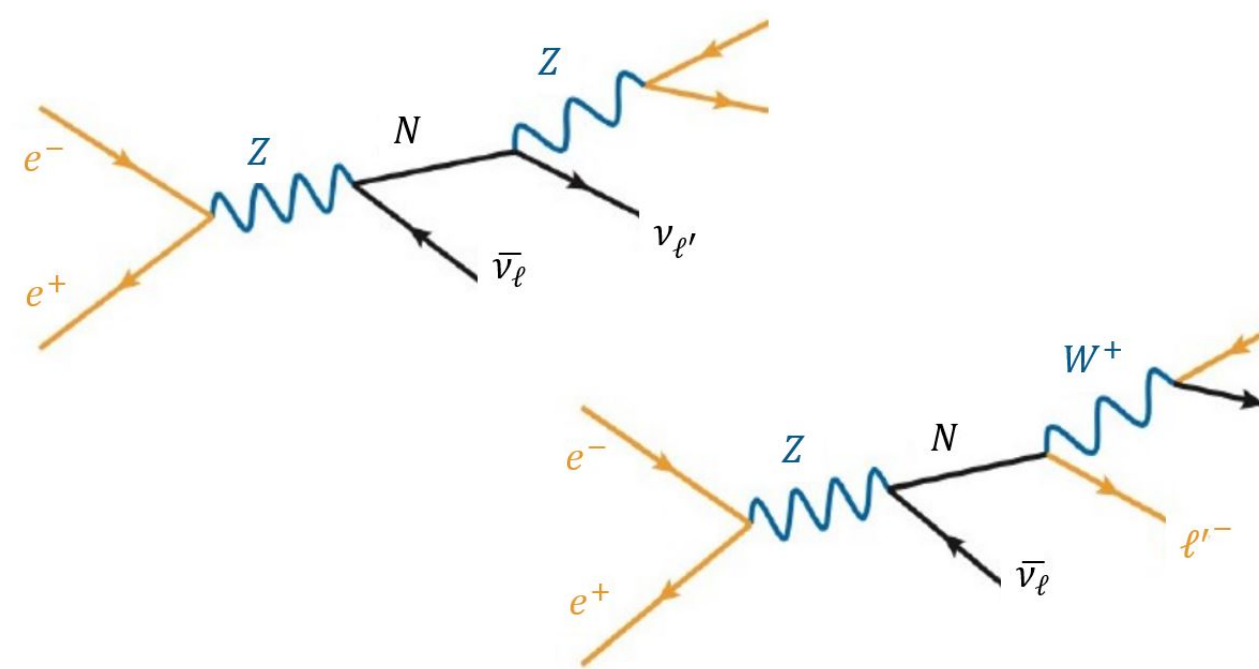


modified oscillations

long-lived ν_s ("HNLs") – decay signatures in near detectors & collider searches

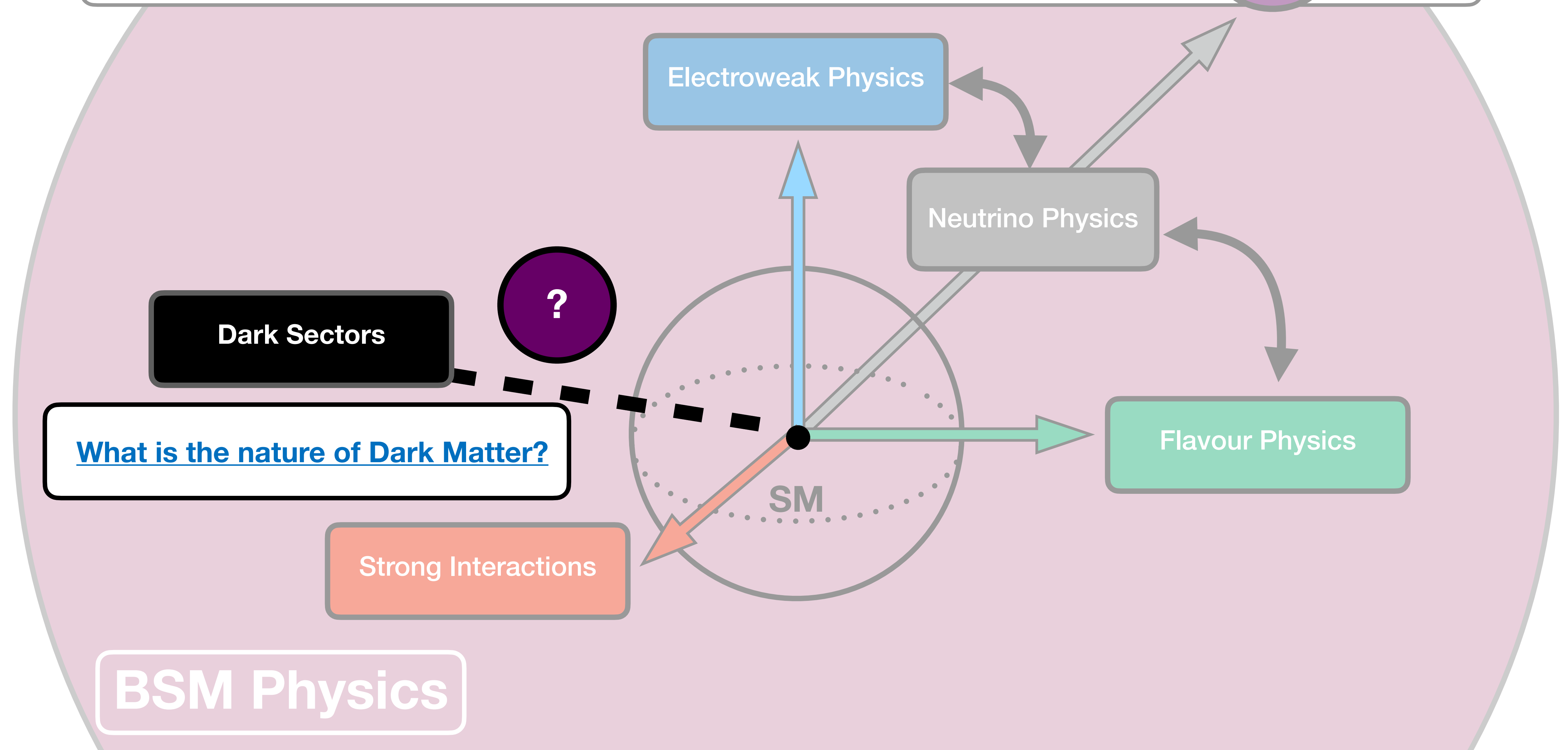
seesaw mechanism, leptogenesis

BSM benchmark:
Heavy neutral leptons (HNL)



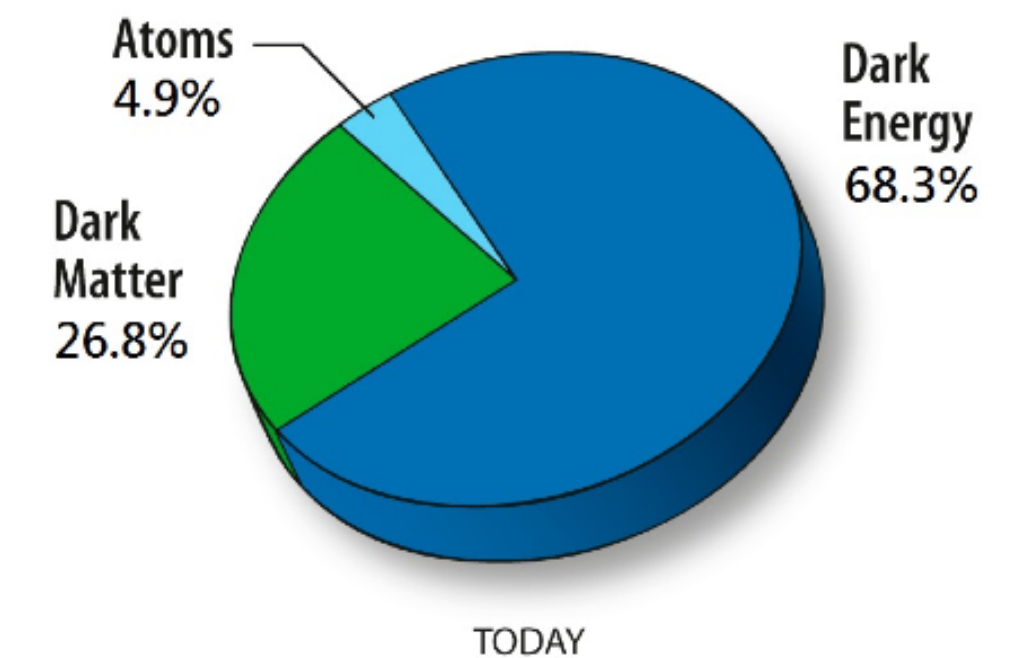
What lies in the Dark?

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$

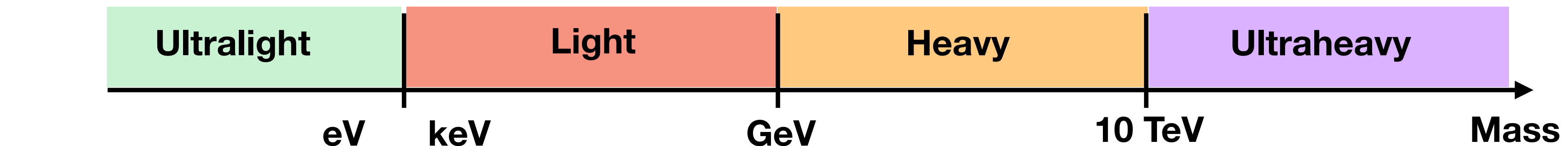


What lies in the Dark?

- The evidence for the existence of some form of Dark Matter seems incontrovertible
⇒ A key task in particle physics is to identify its nature

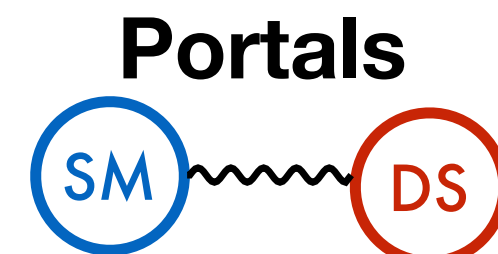


- Dark Matter/Dark Sectors:** many models for DM candidates



Eg:

ALPs

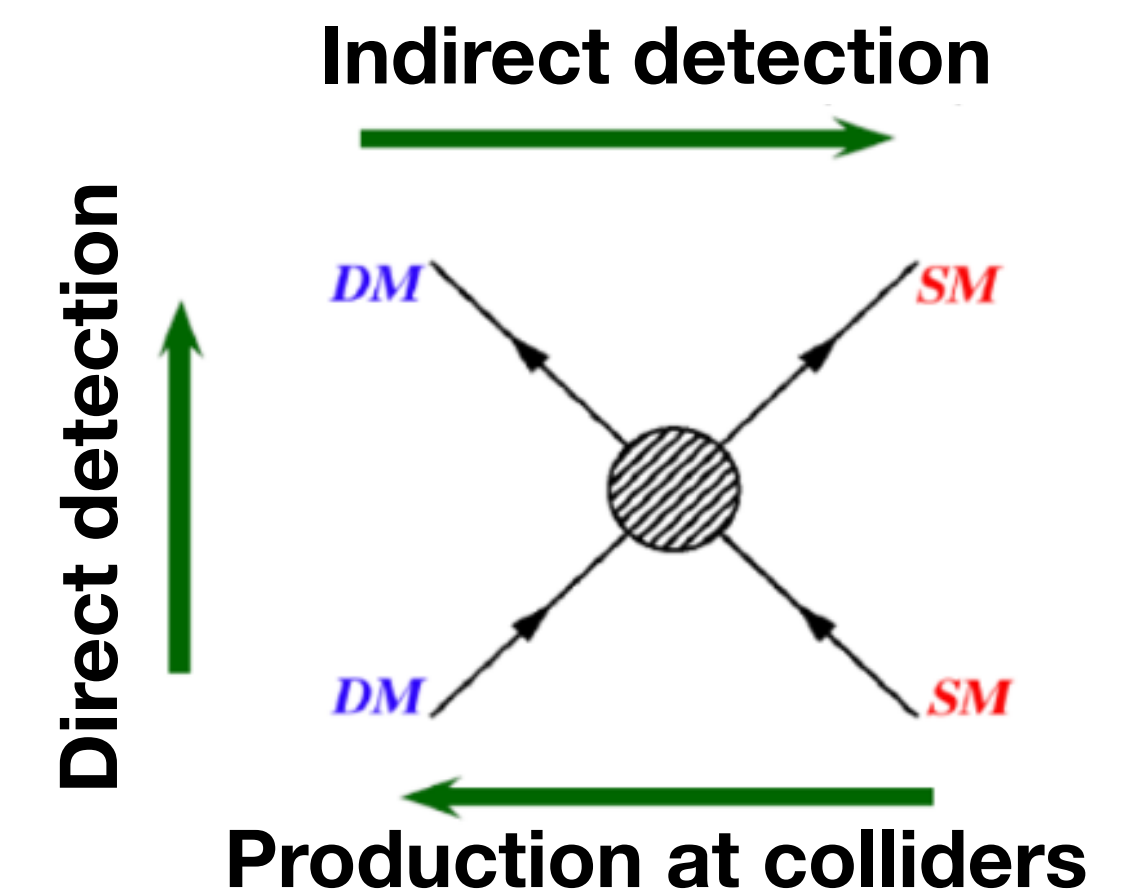


Dark photon
Higgs portal
Neutrino (HNL) portal
...

WIMP Benchmark

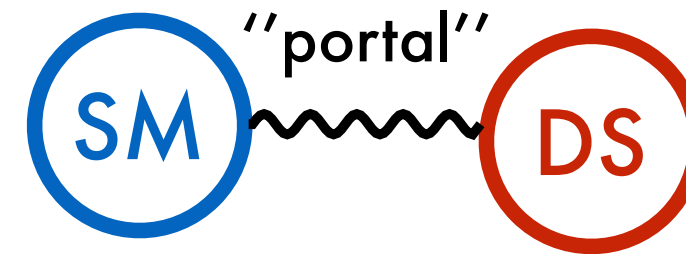
PBH

Valuable information at future collider experiments
Complementary to Direct and Indirect detection

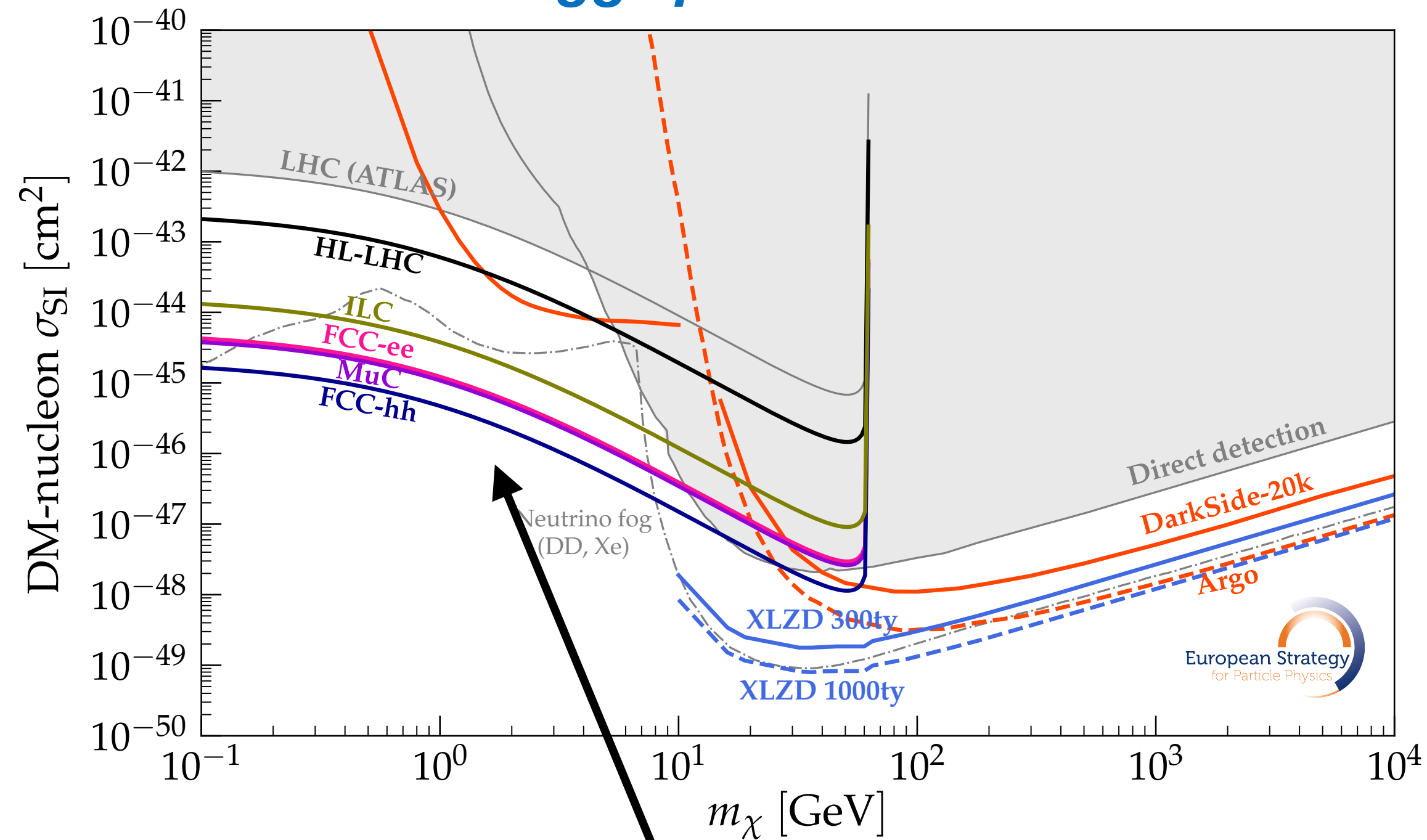


What lies in the Dark?

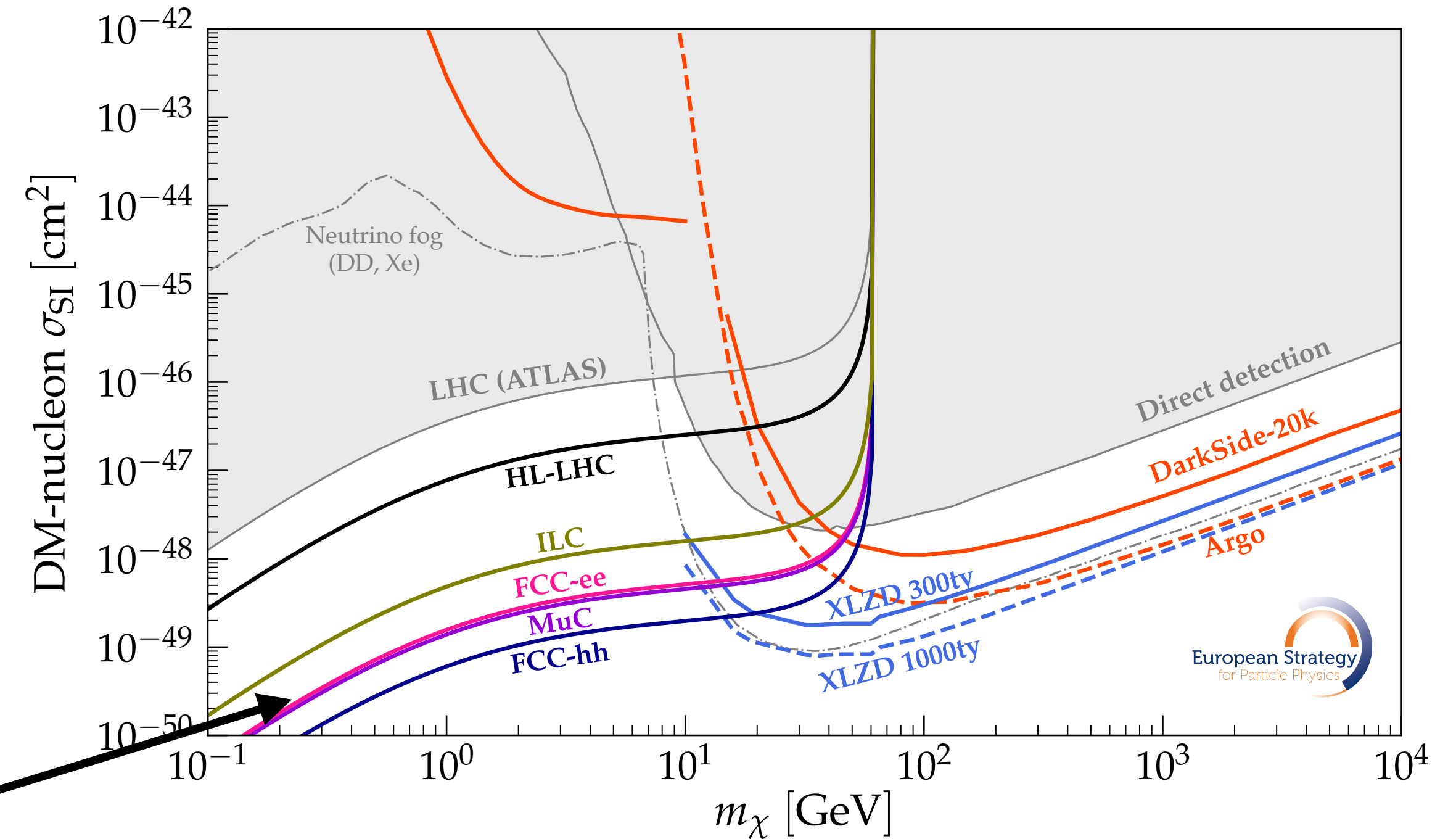
Direct Detection - Collider complementarity (Precision Higgs)



Higgs portal scalar DM



Higgs portal Majorana DM

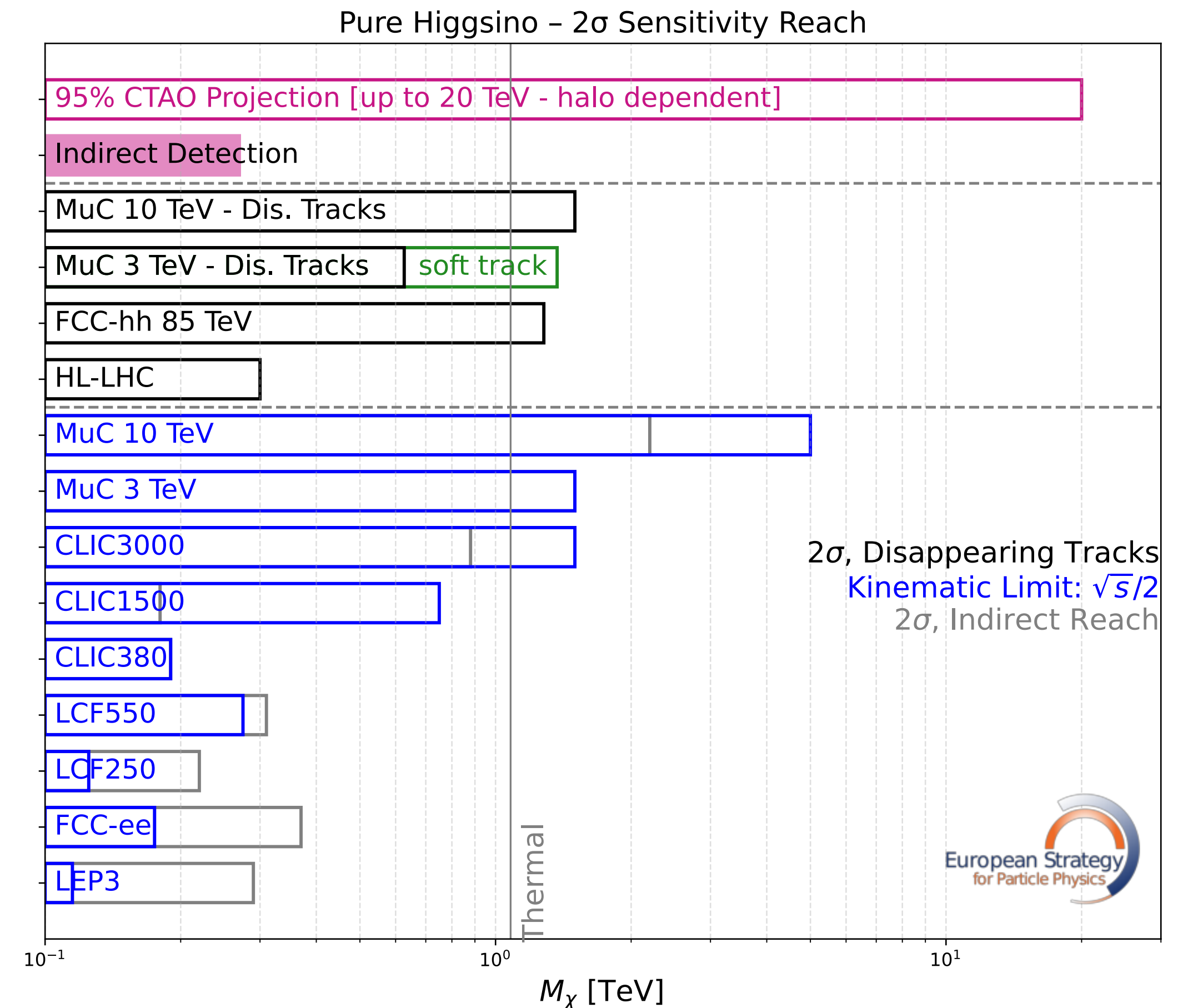
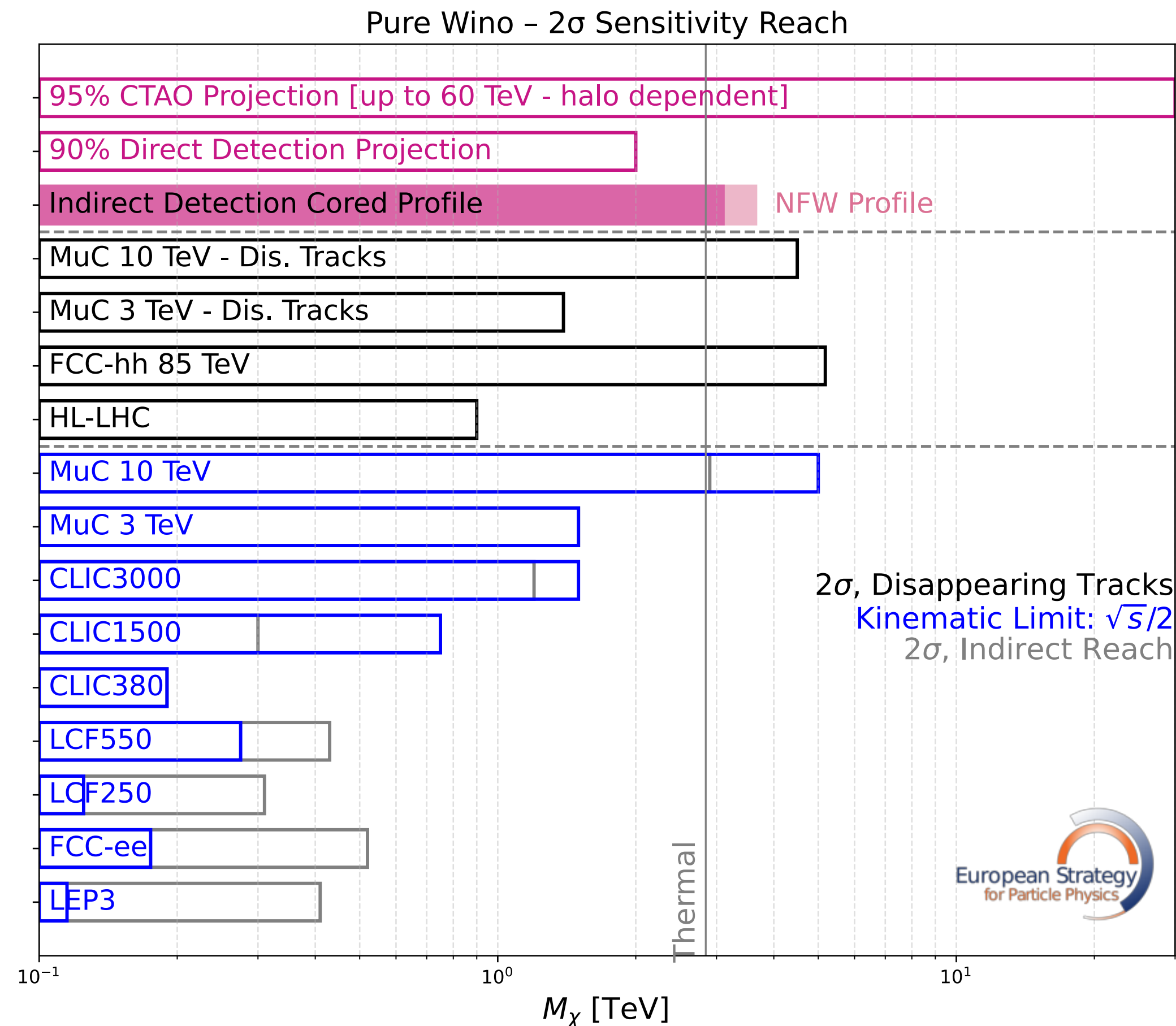


From reach of $H \rightarrow \text{invisible}$

Covers region unexplored by direct detection experiments due to Neutrino “fog”

What lies in the Dark?

Direct Detection - Collider complementarity (Direct searches & EWPO)



Example: Wino and Higgsino scenarios

- Direct detection: Limited sensitivity for Higgsino

- Direct searches: WIMP mass range within the FCC-hh & MuC reach
- Indirect searches: Model-dependent bounds from EWPO

Concluding...

Concluding...

- **Disclaimer:** Only a subset of the physics studies prepared for the Briefing Book was summarized here, focused on the physics potential of large scale projects for a future collider at CERN. **Not covered:**
 - ▶ **QCD:** Aspects related to Hot and dense QCD, connections with Astroparticle physics, ...
 - ▶ Prospects for **flavour** measurements at low scale experiments
 - ▶ **Cosmic messengers**
 - ▶ Many of the zillion benchmarks prepared by the **BSM WG**
 - ▶ And more... $\Rightarrow$ Read the book!
- Most of the proposed future colliders were planned for (and can bring significant progress in terms of) precision Higgs physics. Progress in other areas is “*collider dependent*”:
 - ▶ Circular e^+e^- colliders: EWPO, Flavour $\Rightarrow$ Access to high energies when followed by a future pp or MuC options
 - ▶ Linear e^+e^- colliders: high-energies (Top, HH, ...)
 - ▶ ep colliders (LHeC): QCD physics, heavy ions, PDFs (relevant for future pp colliders), ...
- To fully exploit the experimental capabilities of any future collider, significant **progress on the theory side** will be needed...

Concluding...

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_\mu\phi D^\mu\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$

Understanding EWSB

What triggers EWSB?

Naturalness? Is the Higgs elementary/composite?

Nature of the EWPT $\leftrightarrow$ Matter/Anti-Matter Asymmetry?

Is the EW vacuum stable?

Electroweak Physics

What is the origin of neutrino masses?

Neutrino Physics

The SM Flavour puzzle

Why 3 copies of fermions?
What explains the hierarchical structure of their masses?

Flavour Physics

Dark Sectors

?

What is the nature of Dark Matter?

Strong Interactions

How well do we know the strong force?

BSM Physics

SM

Concluding...

$$\mathcal{L}_{\text{BSM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + D_{\mu}\phi D^{\mu}\phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right) + \text{???}$$

Conclusions

Progress in only one of these areas is not enough

Interplay between different areas is deep and necessary to maximize our chances of learning about BSM:

Via exploration of BSM space in complementary ways: Direct/Indirect (EW/Higgs/Flavour/Neutrino/...)

Enabling the precision of measurements/reducing uncertainties in the interpretation: Theory precision (e.g. QCD)

In absence of a clear hint of what we are looking for, *what matters most in any future experiment* is to have access to the **largest possible collection of measurements** (at the highest precision possible) plus a **theory program that can match the EXP precision**

How well do we know the strong force?

BSM Physics