

Interplay with the 2026 European Strategy Update: Theory challenges at the FCC-ee

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University of Granada

Conclusions from the 2026 update of the European Strategy for Particle Physics

The European Strategy for Particle Physics: 2026 Update

European Strategy Group Recommendations

The next CERN flagship collider project

A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

B. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN.

The European Strategy for Particle Physics: 2026 Update

European Strategy Group Recommendations

The next CERN flagship collider project

A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

- Multiple considerations go into this strategic decision, with the *physics potential* being one of the main pillars:
 - ▶ *Broadest high-precision physics programme, covering the EW, Higgs, Top, Flavour (and even QCD) sectors*
 - ▶ *Paving the way towards the exploration of the high-Energy frontier by the FCC-hh (access to ≈ 10 TeV Parton scale)*

Machine	Precision Physics	BSM physics	Physics vs CEPC	Technical readiness	Constr. cost (BCHF)	Time scale	Path to ≥ 10 TeV
FCC-ee	22	23			15.3	2046-2060	
Descoped FCC-ee	15	17			12.9	2046-2055	
LCF550	15	17			14.8	2045-2065	
CLIC1500	14	18			14.6	2045-2066	
LCF250	10	16			9.4	2045-2053	
CLIC380	10	16			7.5	2045-2054	
LEP3	15	17			4.1	2047-2062	
LHeC	8	7			2.1	2044-2051	

The European Strategy for Particle Physics: 2026 Update

Competitiveness wrt CEPC running in parallel					Project estimates + exp. (CERN part)		
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Viability
(tech., econ., soc.)
for transition
to high-E frontier
FCC-ee/LEP3 → FCC-hh
LCF/CLIC → Plasma?
Muon Collider?

WG2b report
(From Briefing Book)

WG2a report

The European Strategy for Particle Physics: 2026 Update

Competitiveness wrt
CEPC running in parallel

Precision Physics	BSM physics	Physics vs CEPC
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WG2b report
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WG2a report

Project estimates
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Project	Scope	TRL	R&D	Test facilities	Performance Uncertainty	Site Preparation	Schedule Uncertainty	Cost Uncertainty	Risk
CLIC: 380-1500 GeV		4 - 6 / 5.2							
FCC-ee: 91-365 GeV		4 - 7 / 6.0							
FCC-hh: 85 TeV		4 - 7 (Nb ₃ Sn) / 4.3							
		2 - 7 (HTS) / 3.2							
FCC-hh (SA): 85 TeV		4 - 7 (Nb ₃ Sn) / 5					Nb ₃ Sn		
LCF: 250-550 GeV		5 - 7 / 5.5							
LEP 3: 91-230 GeV		3 - 6 / 4.0							
LHeC		3 - 6 / 4.5							
Muon Collider 3-8 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							

WG2b r
(From Briefi

The European Strategy for Particle Physics: 2026 Update

Long-term vision of the field: Strong constraints in terms of defining avenues towards exploring the high-energy frontier in the future, with the FCC-hh currently being the most clear option

Project estimates
+ exp. (CERN part)

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2046-2060	
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WG2b report
(From Briefing Book)

WG2a report

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WG2b report
(From Briefing Book)

Technical readiness

WG2a report

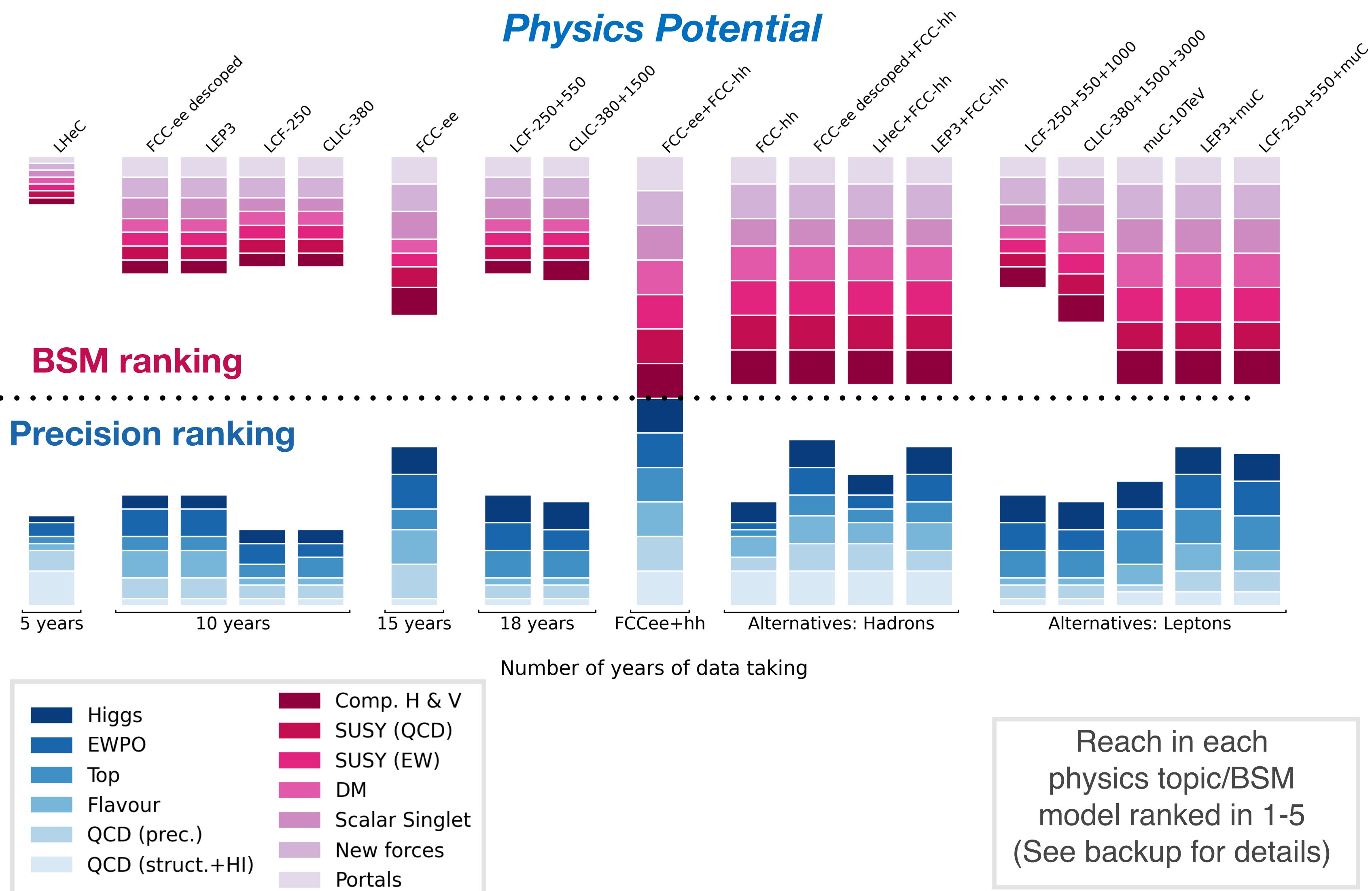
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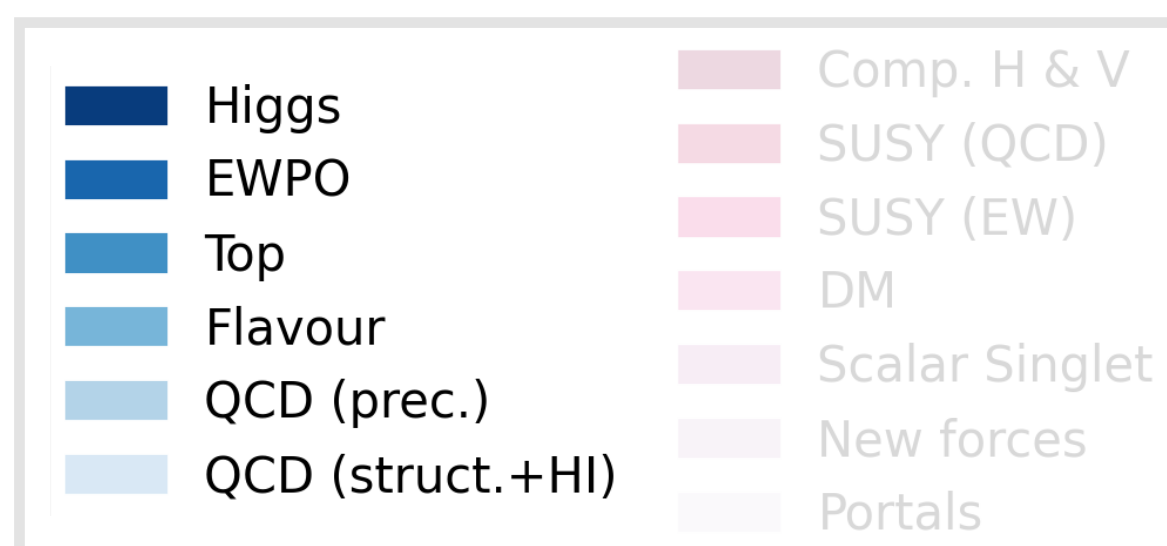
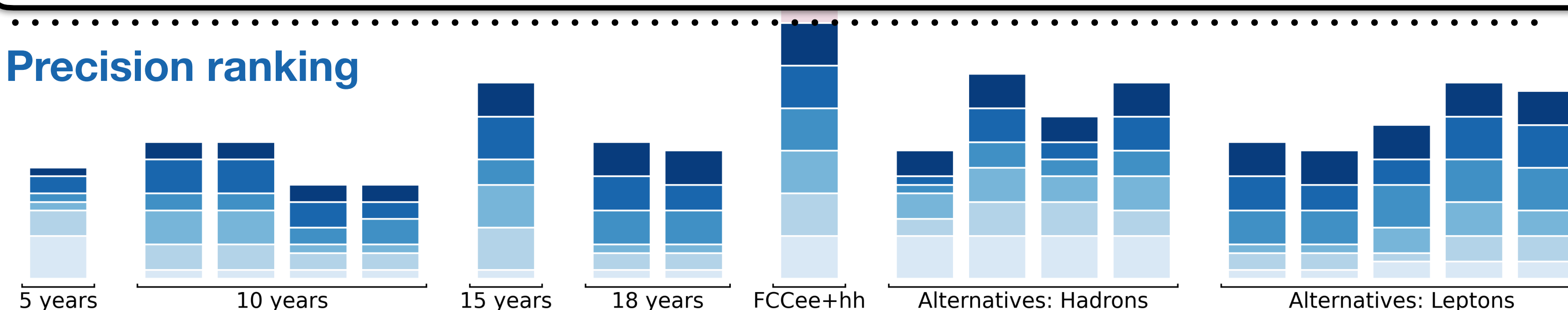
WG2b report
(From Briefing Book)

Physics Potential

The main driver of the **FCC-ee** physics case is precision across different domains:

Electroweak Higgs Top Flavour QCD

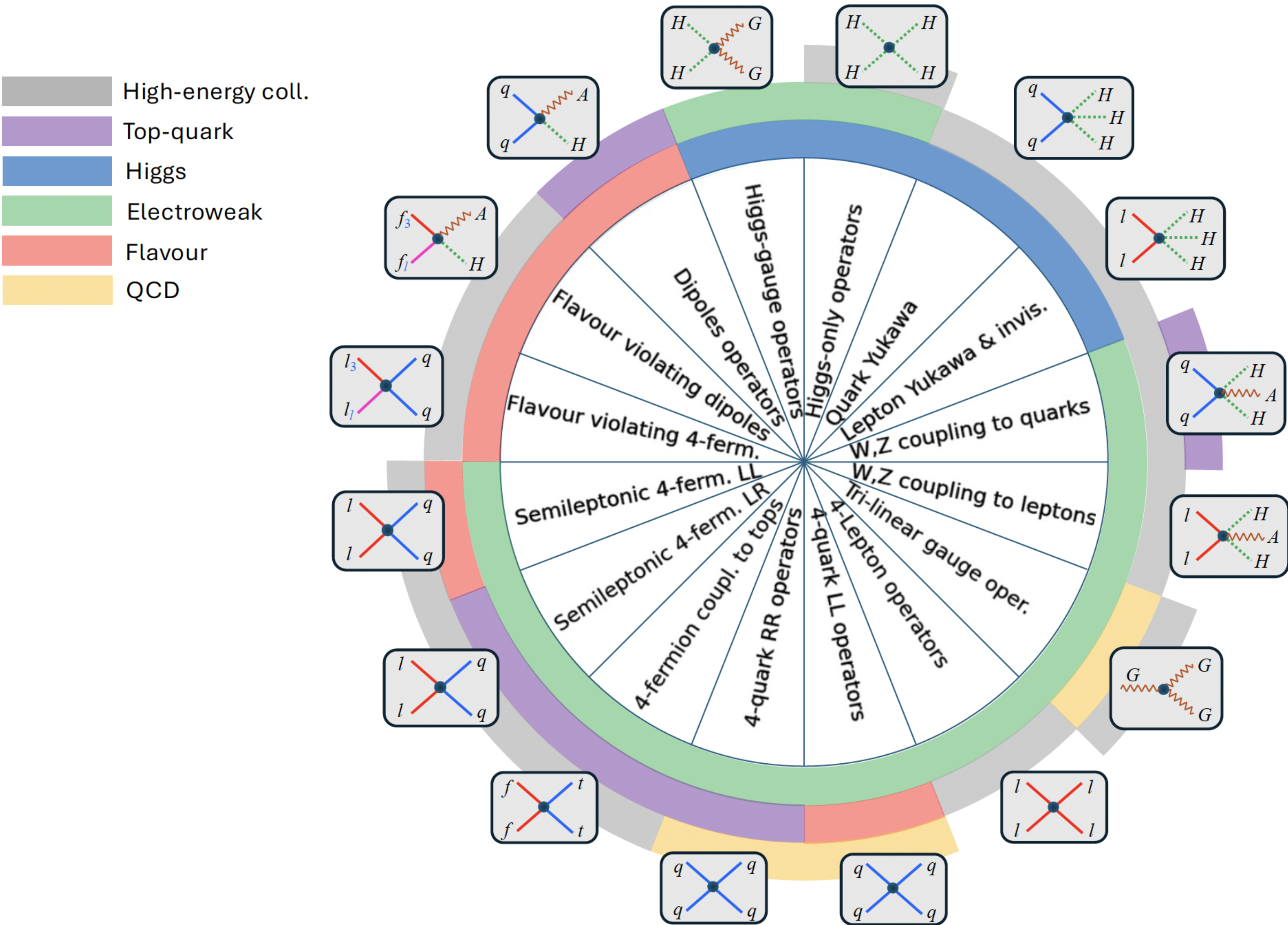
Precision ranking



Reach in each physics topic/BSM model ranked in 1-5 (See backup for details)

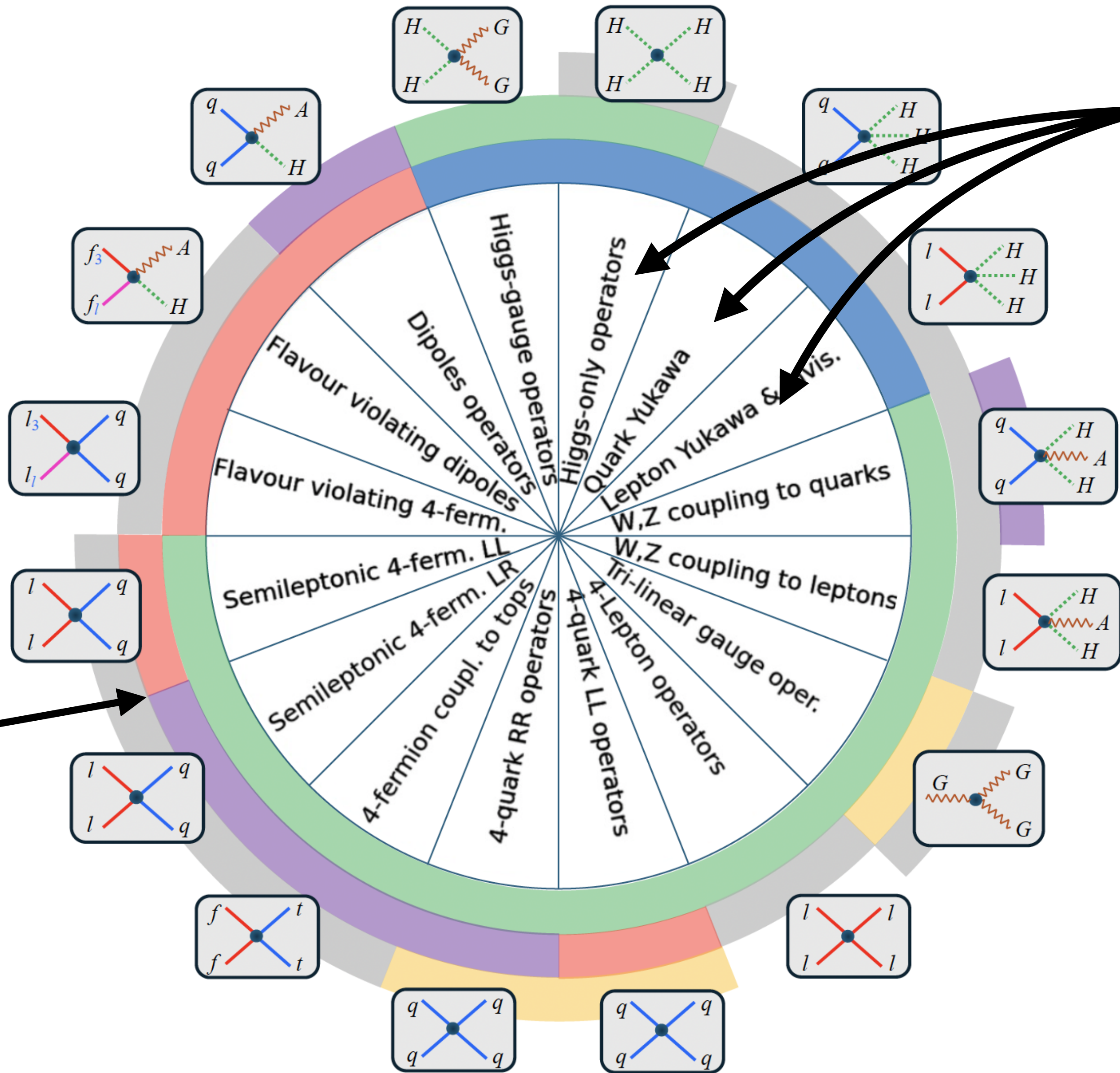
WG2a report

Future Collider Comparison: Precision Physics



Future Collider Comparison: Precision Physics

- High-energy coll.
- Top-quark
- Higgs
- Electroweak
- Flavour
- QCD



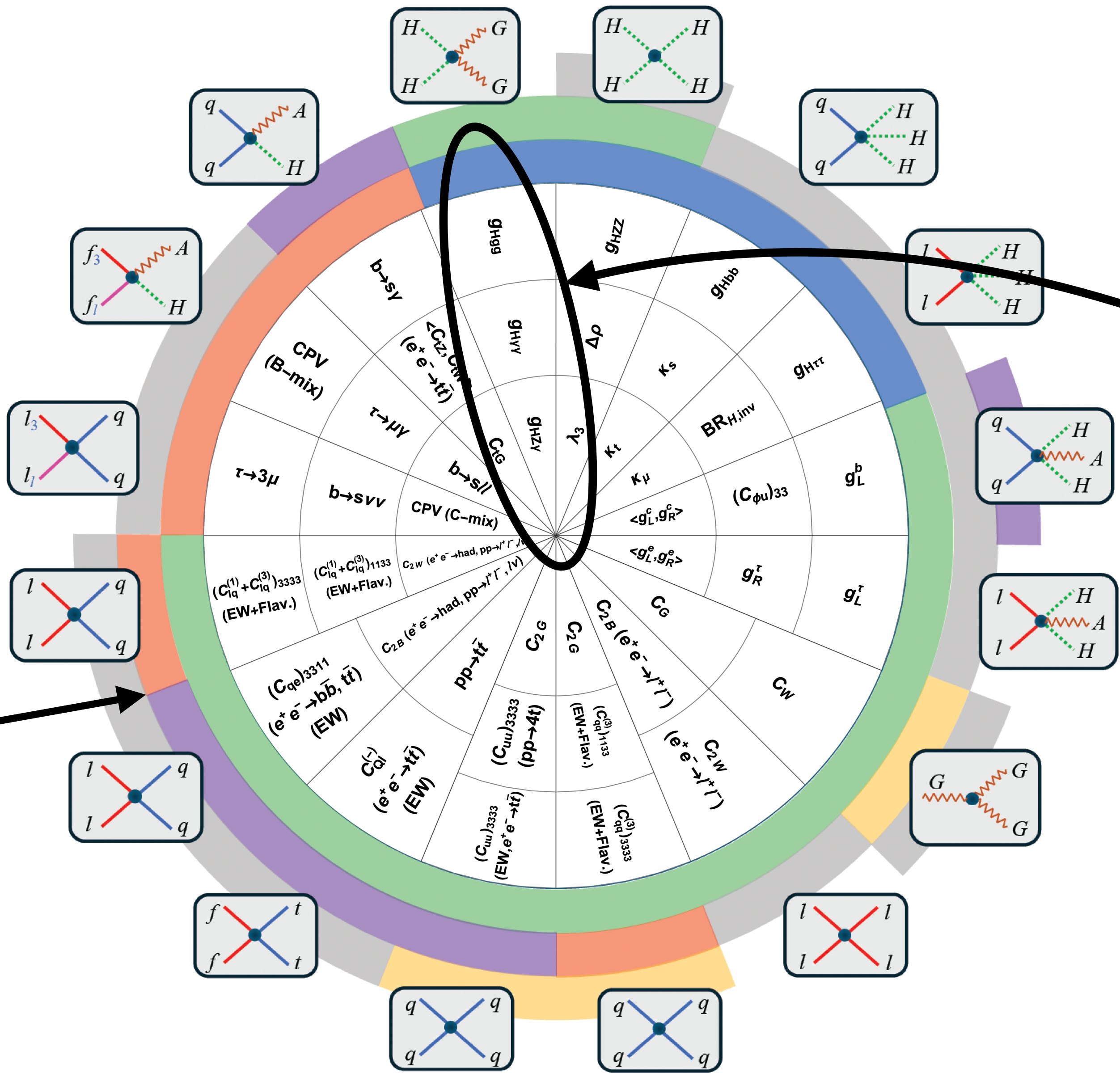
Characterization of BSM physics landscape (SMEFT inspired):
16 different sectors representing possible BSM deformations

Ring color:
Measurement(s) providing leading constraints

Future Collider Comparison: Precision Physics

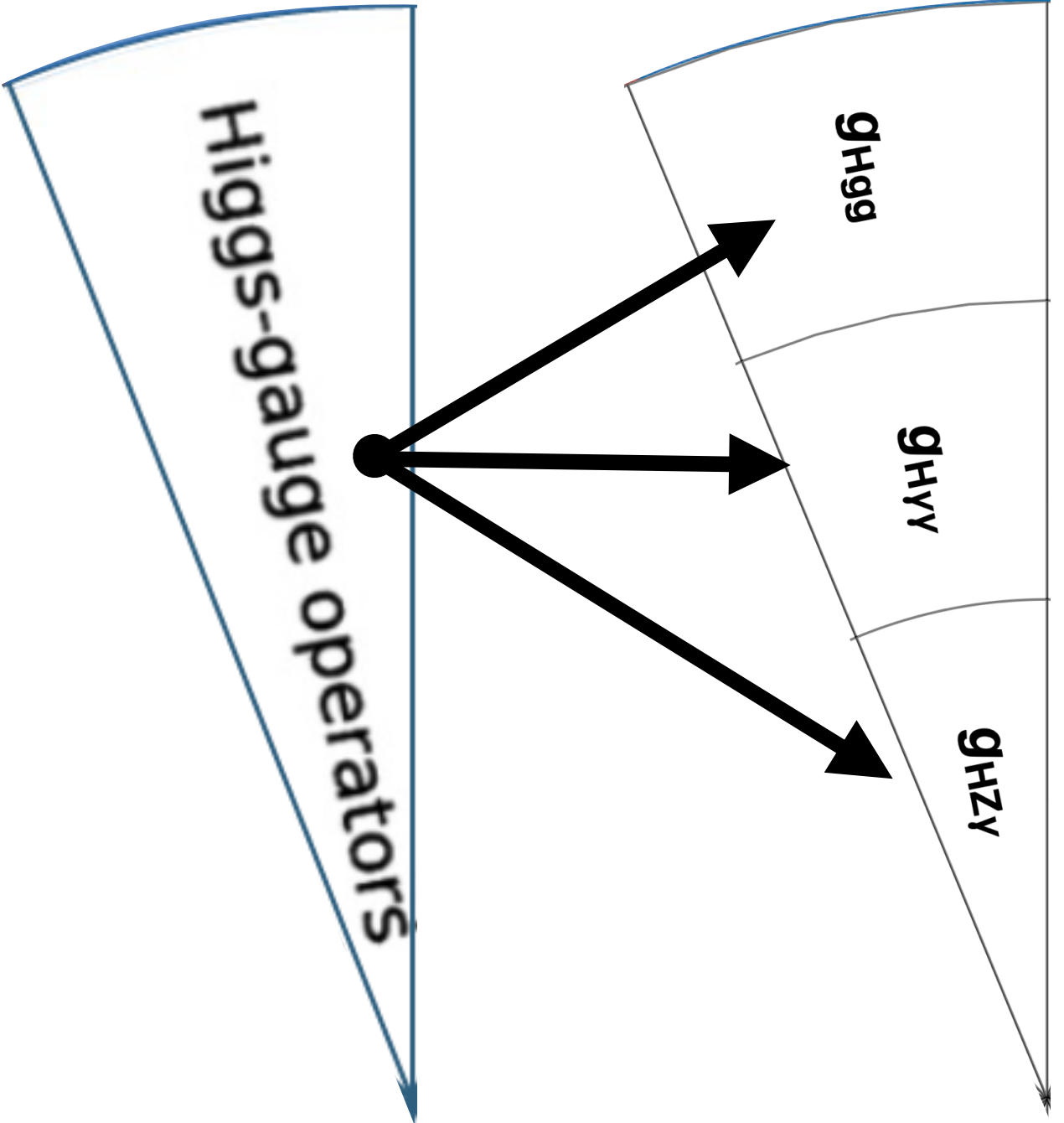
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**Characterization of BSM physics
landscape (SMEFT inspired):
16 different sectors representing
possible BSM deformations**

**Each sector further divided in 2-3
subsections for a more detailed
characterization (43 in total)**

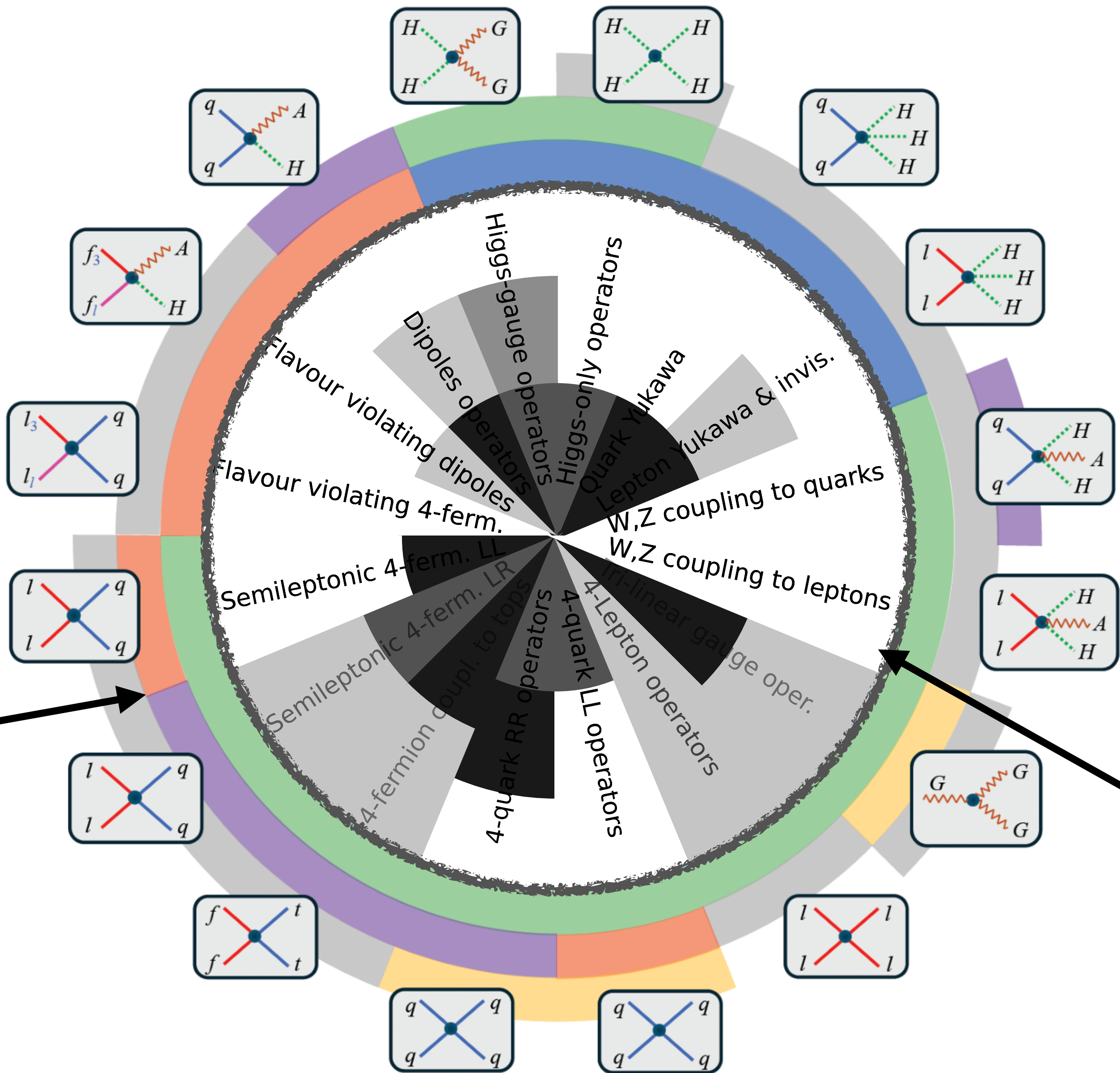


Future Collider Comparison: Precision Physics

FCCee

- High-energy coll.
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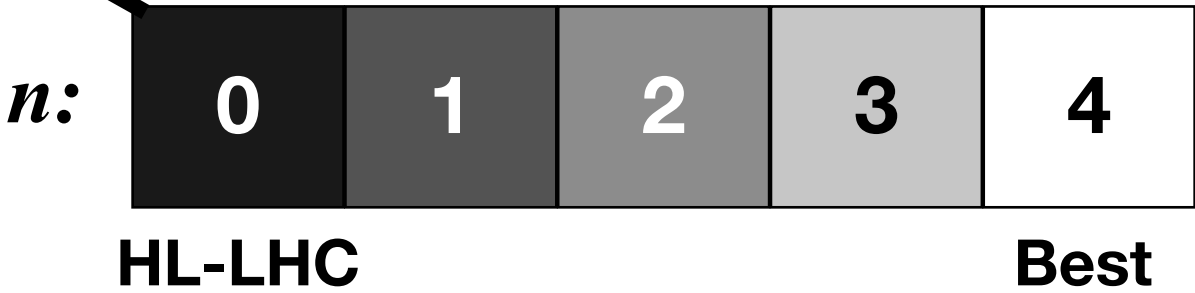


Characterization of BSM physics landscape (SMEFT inspired):
16 different sectors representing possible BSM deformations

Each sector further divided in 2-3 subsections for a more detailed characterization (44 in total)

Collider comparison
For each sector, compute improvement, x , wrt HL-LHC
Map into $n \in [0,4]$ using a log scale
 $x = p^n$

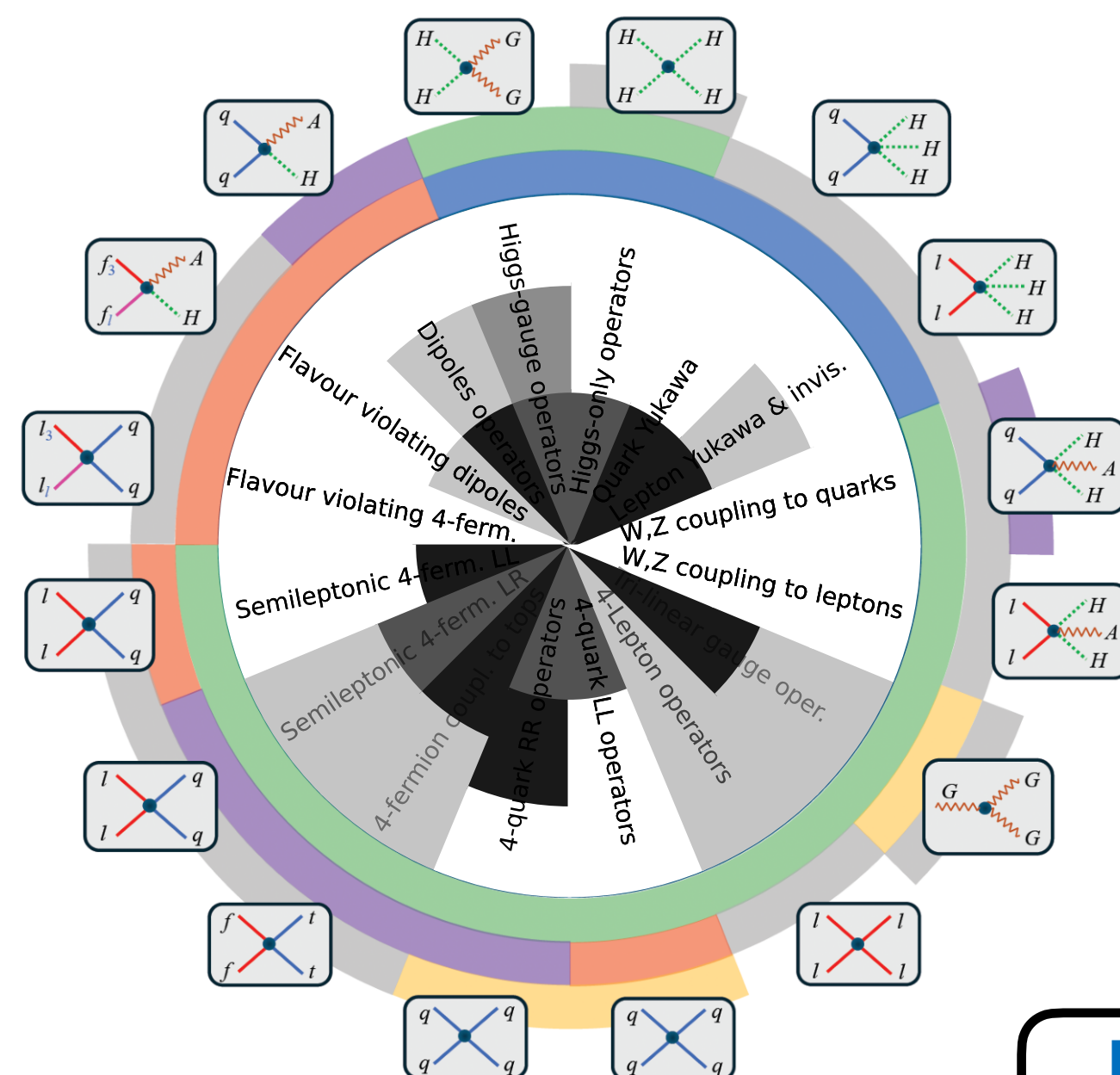
Ranking mapped to a 5-level gray scale:



Future Collider Comparison: Precision Physics

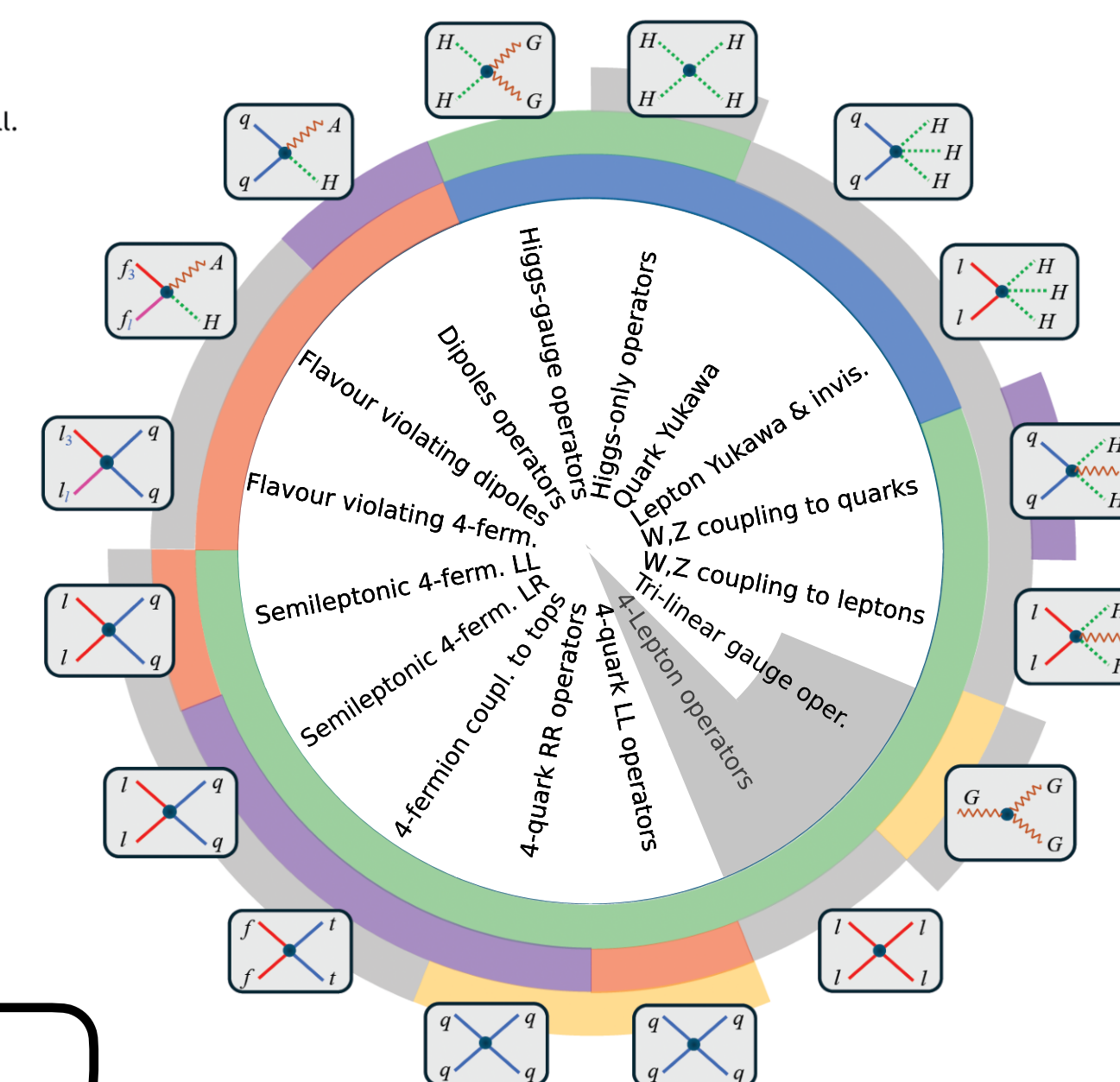
FCCee

- High-energy coll.
- Top-quark
- Higgs
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- QCD



FCCeehh

- High-energy coll.
- Top-quark
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FCC vs. high-Energy e^+e^-

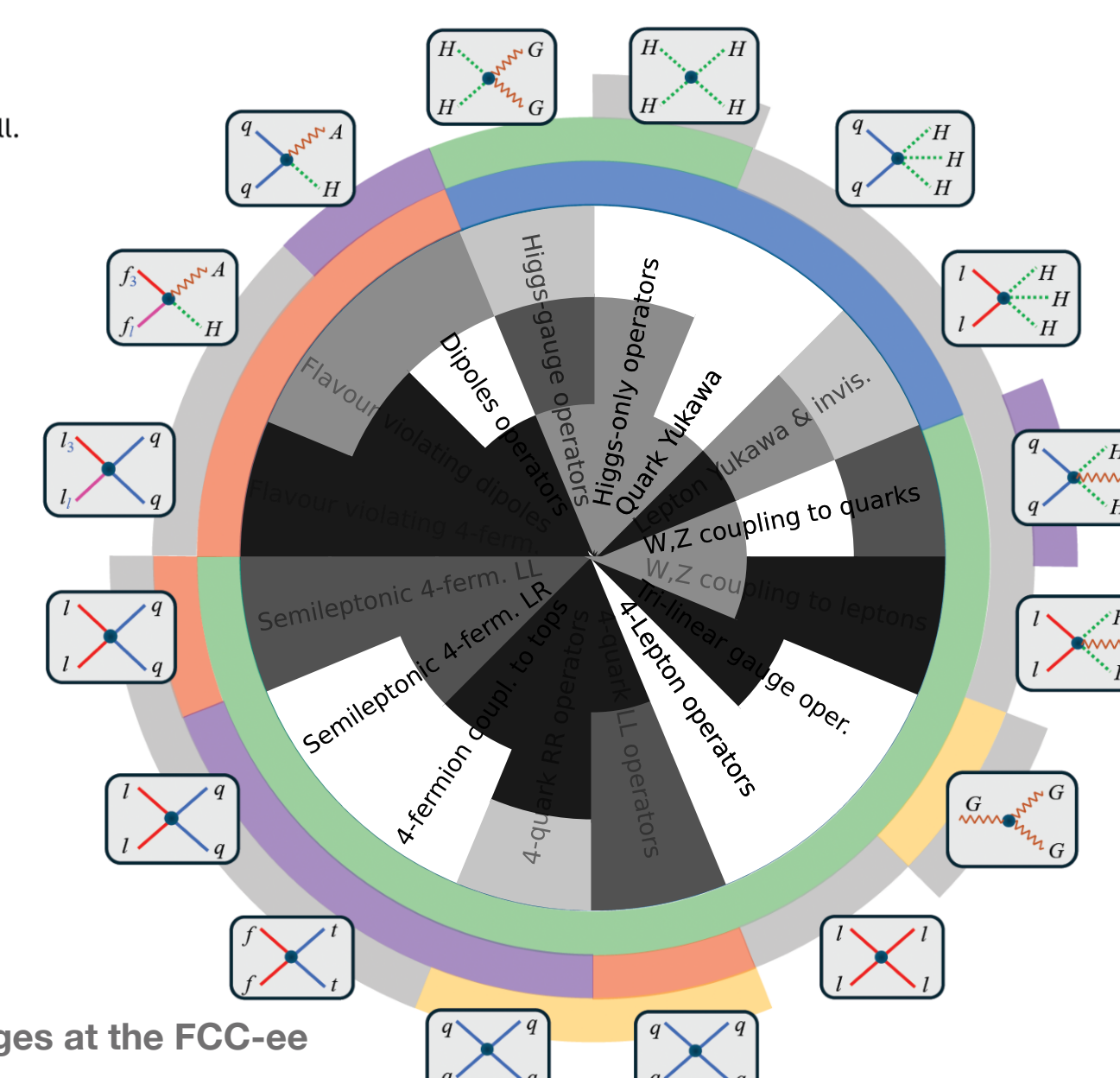
LCF550

- High-energy coll.
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- Higgs
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- Flavour
- QCD



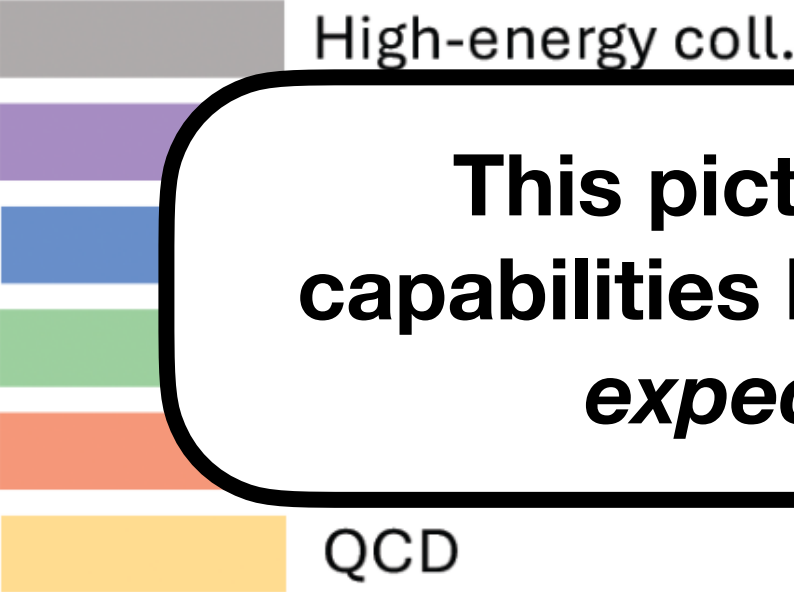
CLIC1500

- High-energy coll.
- Top-quark
- Higgs
- Electroweak
- Flavour
- QCD

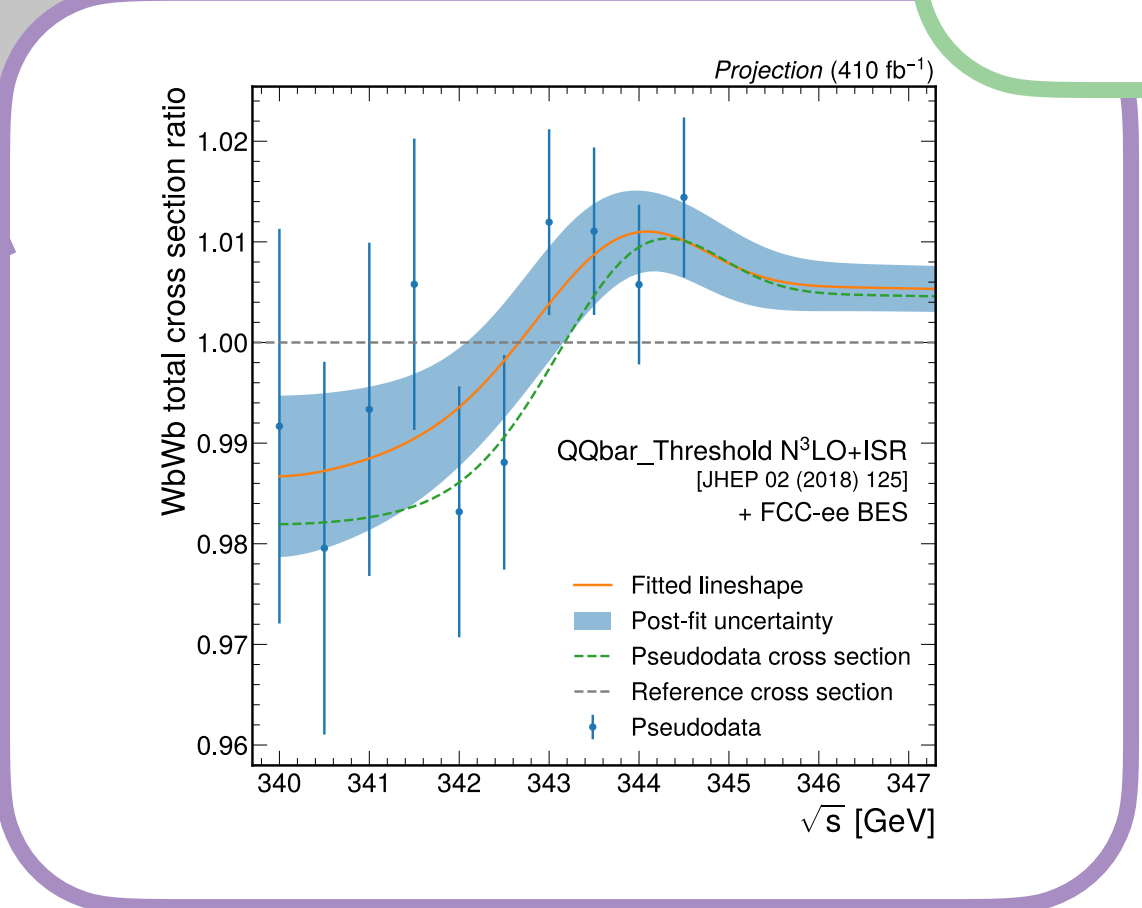
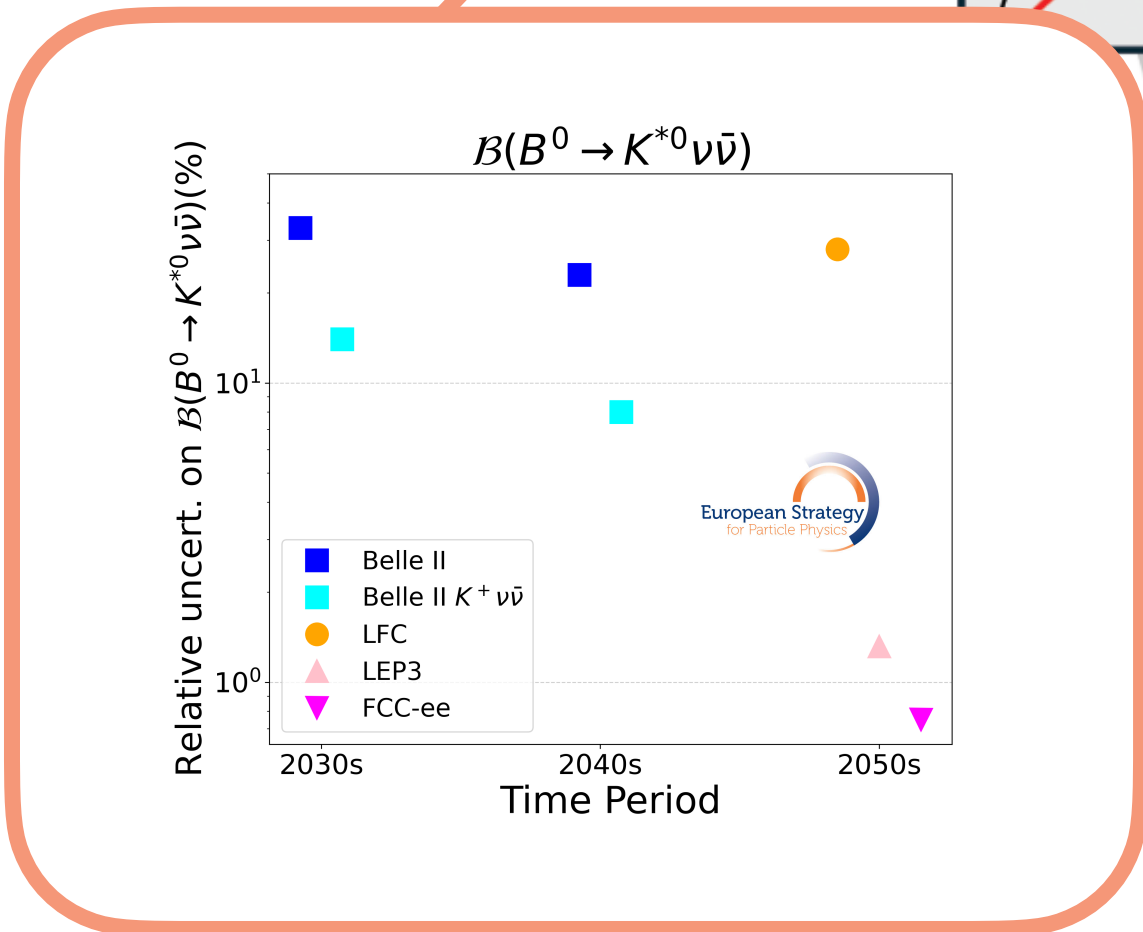
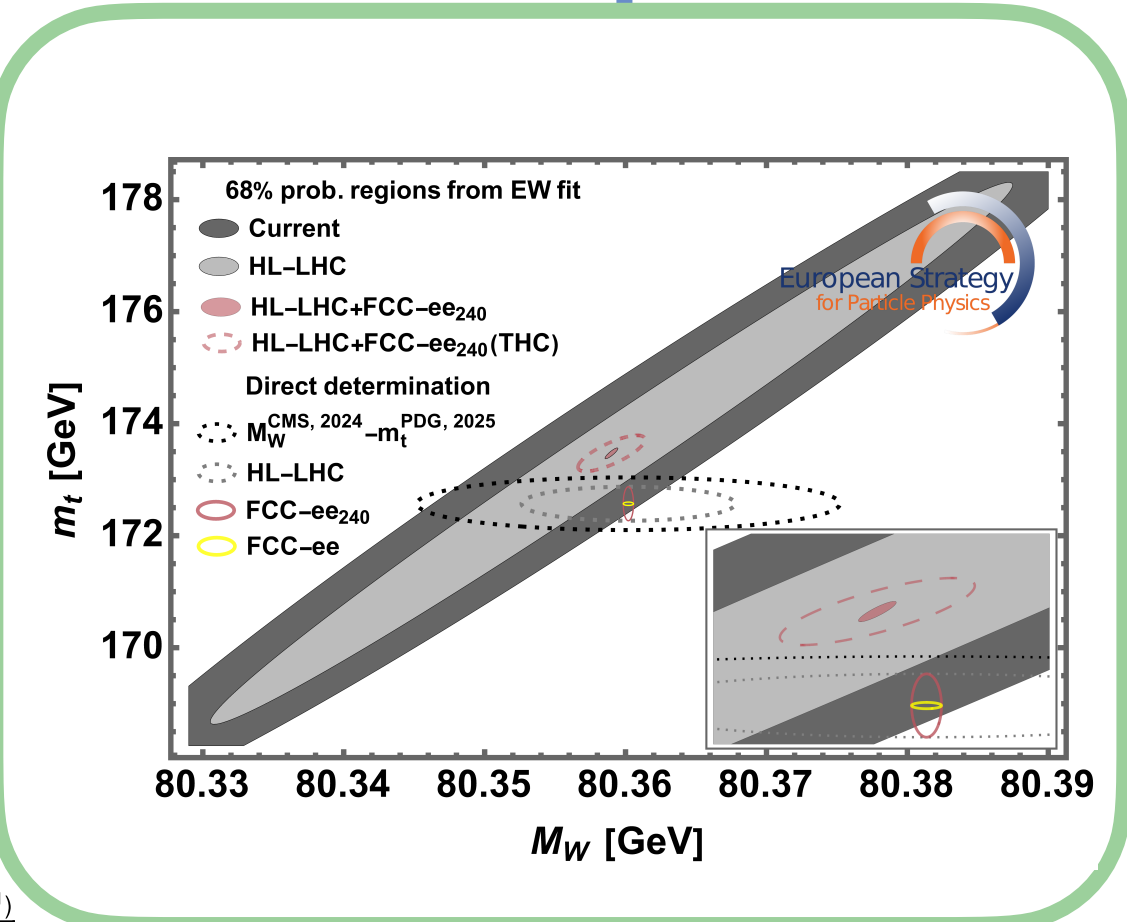
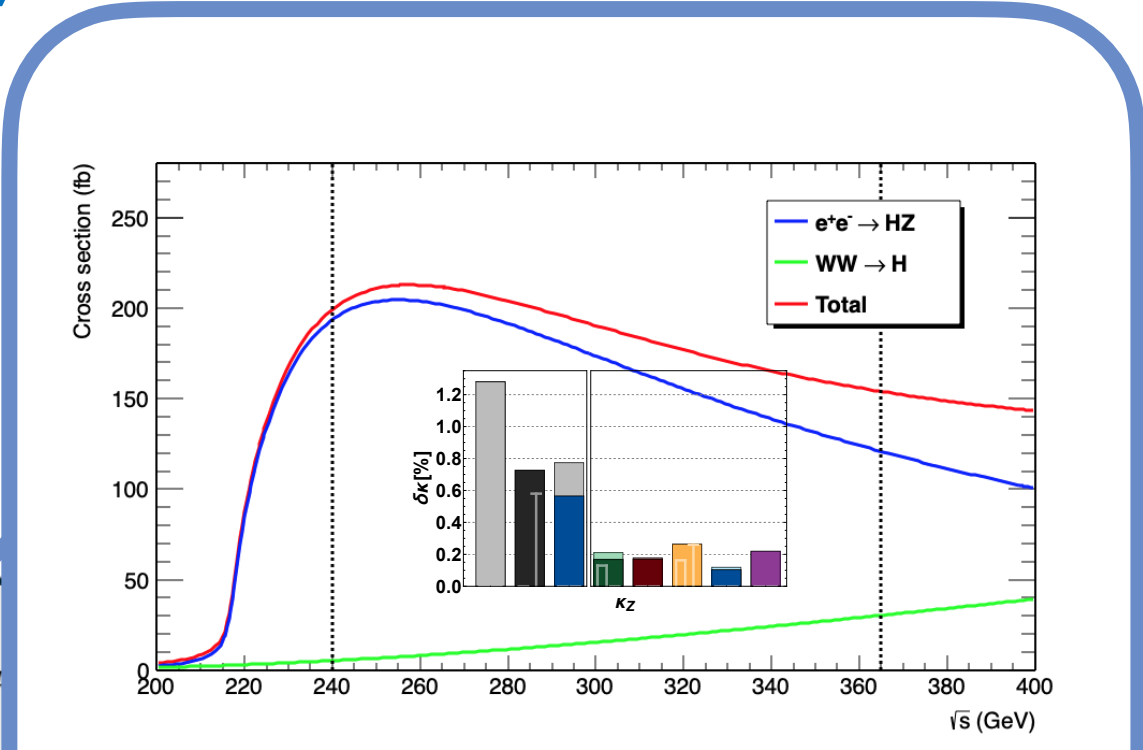
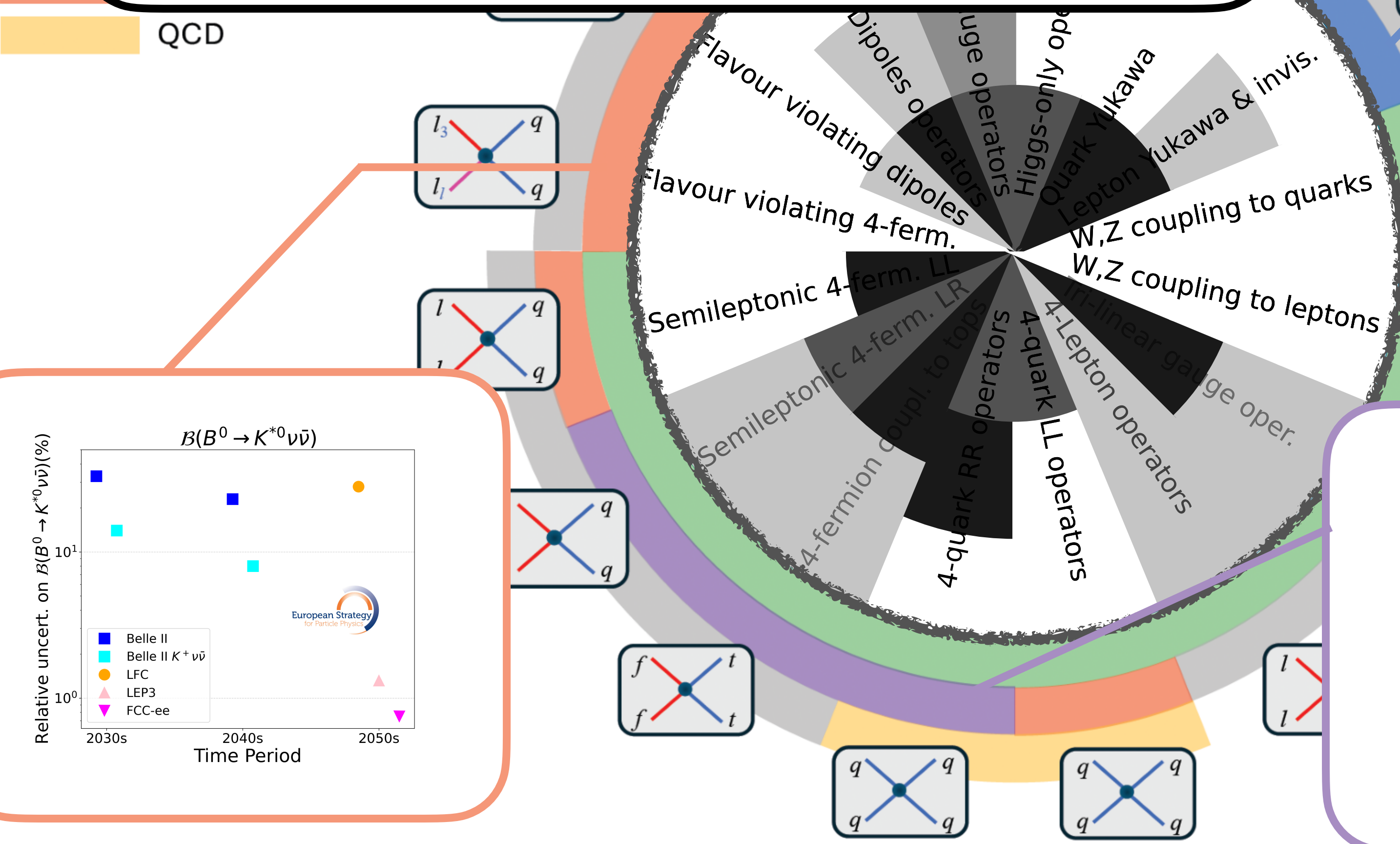


Future Collider Comparison: Precision Physics

FCCee



This picture relies not only on the experimental capabilities but also on *theory being able to match the expected level of experimental precision*



The European Strategy for Particle Physics: 2026 Update

European Strategy Group Recommendations

Theory Recommendations

A. Europe should maintain a strong and diverse particle theory landscape, from formal to phenomenological aspects, while further strengthening and leveraging connections to neighbouring fields.

B. Collaborative efforts to improve the precision of theoretical predictions should be recognised and supported. Europe is world-leading in these areas and should strive to remain so by attracting, fostering and retaining early-career global talent. CERN should continue to be an integral part of all these efforts.

See Matthew's talk

Crucial for exploitation of physics program at future colliders (not only FCC-ee, but also HL-LHC)

Theory challenges at the FCC-ee: The Electroweak/Higgs/Top factory

Theory challenges: Electroweak Physics

Treatment of SM uncertainties

- Studies in the Physics Briefing Book were based on two scenarios for the projected precision of **future** TH calculations:

Conservative: assuming theory improvements that are likely to be achieved by building on existing computational methods

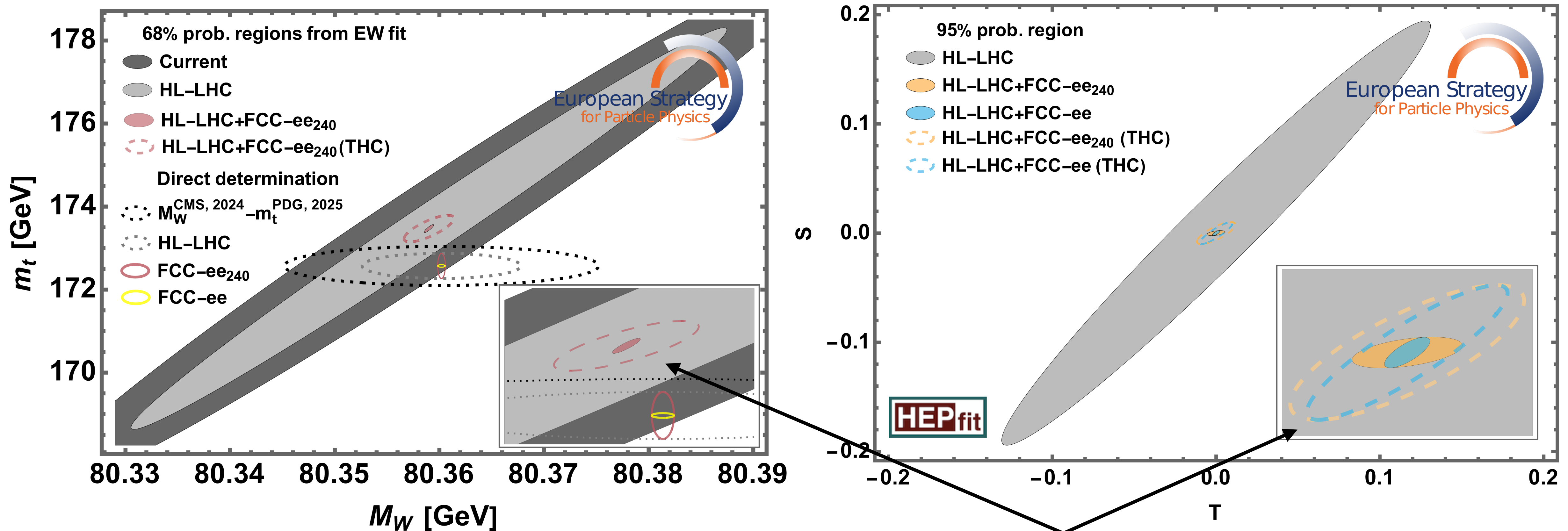
Aggressive: would require more fundamental advances in techniques and tools

The goal was to estimate the level of TH improvement required to match the future EXP precision, NOT to assess which scenario is most likely to be realized

- Sensitivity studies in different frameworks were prepared to illustrate the impact of theory uncertainties, comparing these two scenarios (also with the ideal case of *negligible TH uncertainties*)

Theory challenges: Electroweak Physics

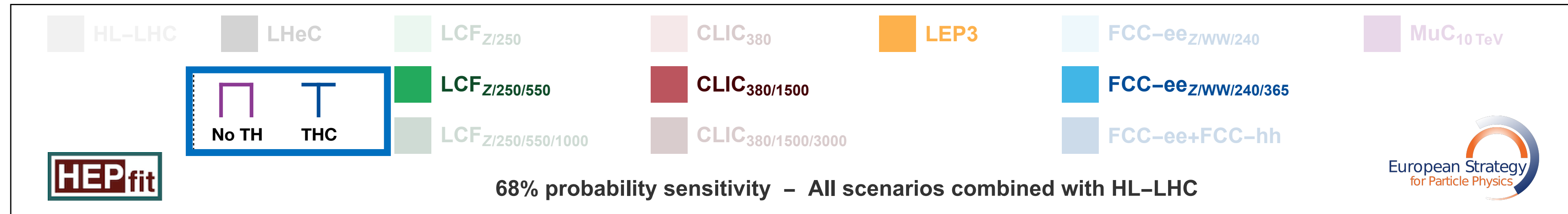
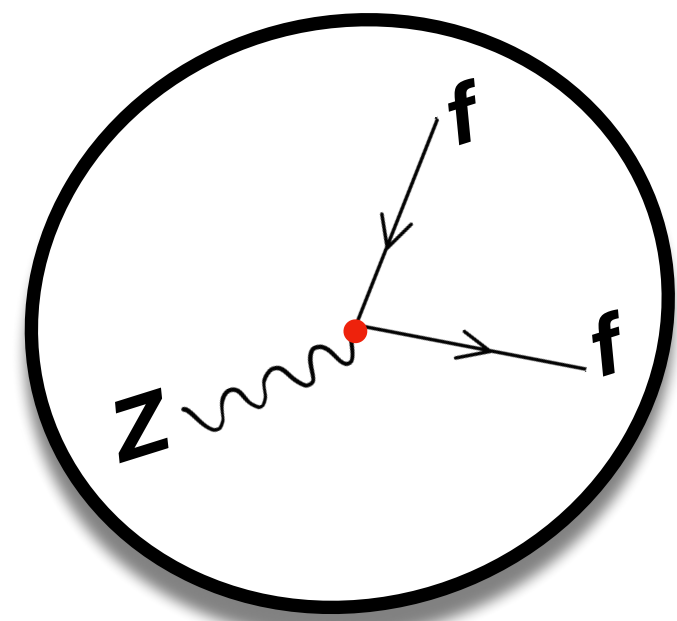
- Matching the projected experimental precision will require significant effort from the theory side



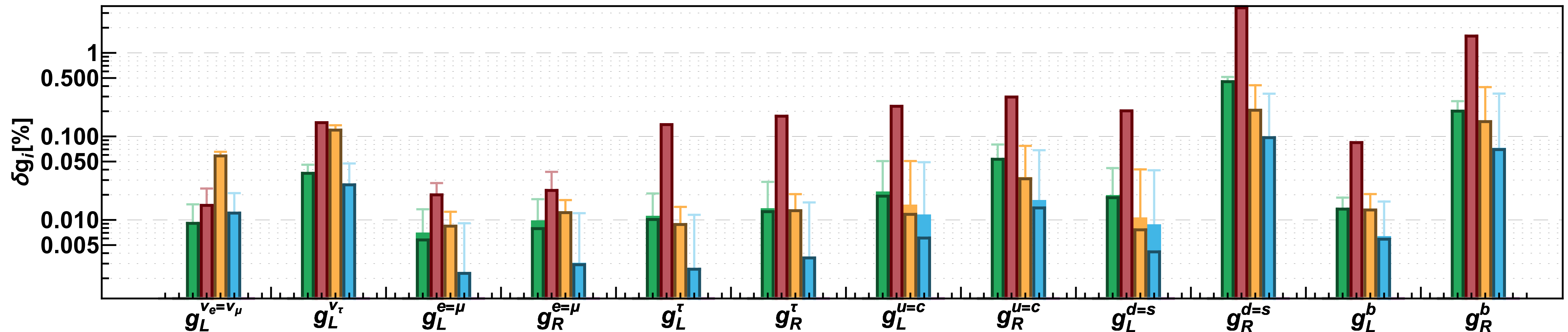
Impact of different assumptions for projected TH uncertainties in EWPO (Conservative - - - /Aggressive —)
(Conservative still assumes significant improvement wrt today!)

Theory challenges: Electroweak Physics

- Electroweak physics potential of the different colliders evaluated in the dimension-6 SMEFT framework:

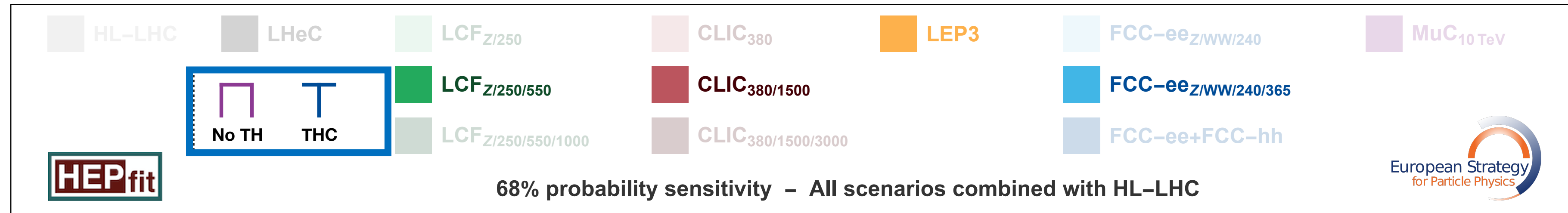
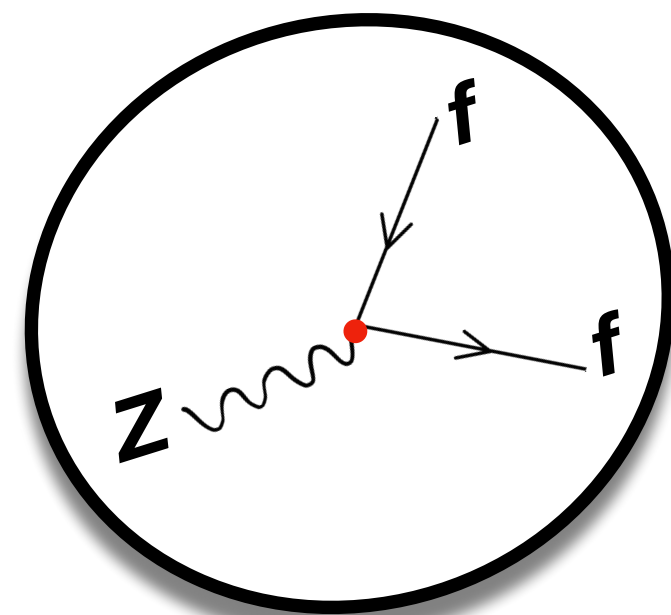


Impact of assumptions on TH uncertainties (EW)

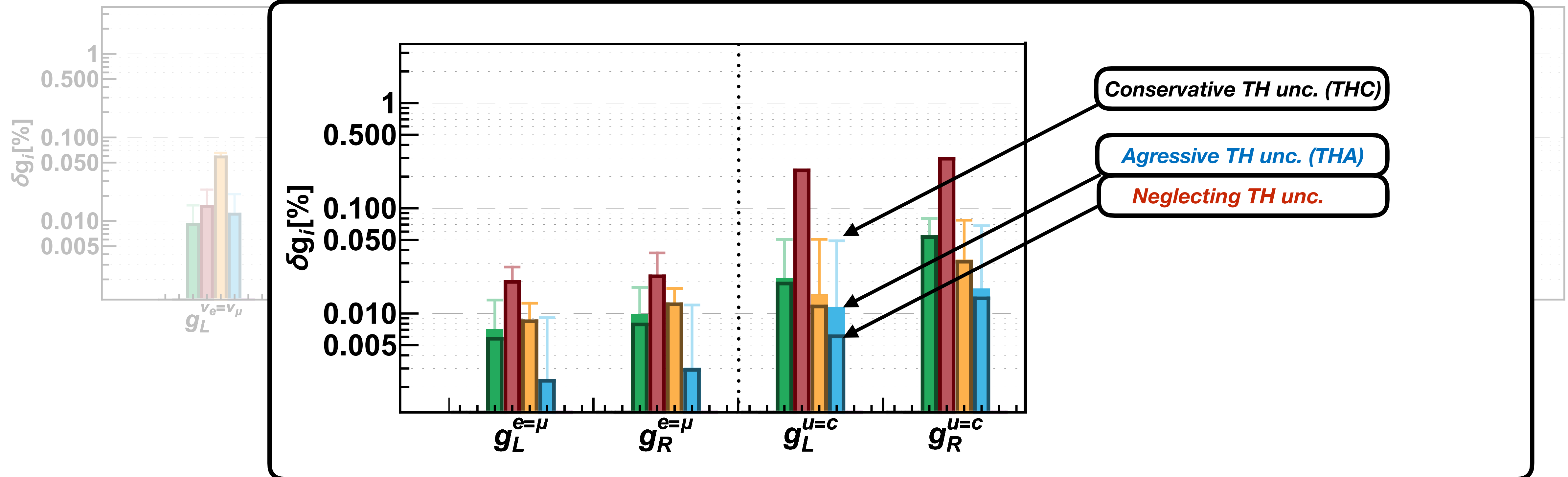


Theory challenges: Electroweak Physics

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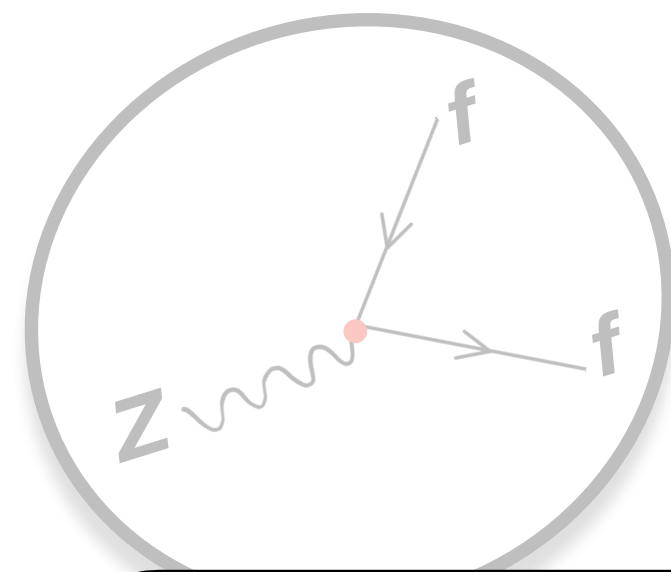


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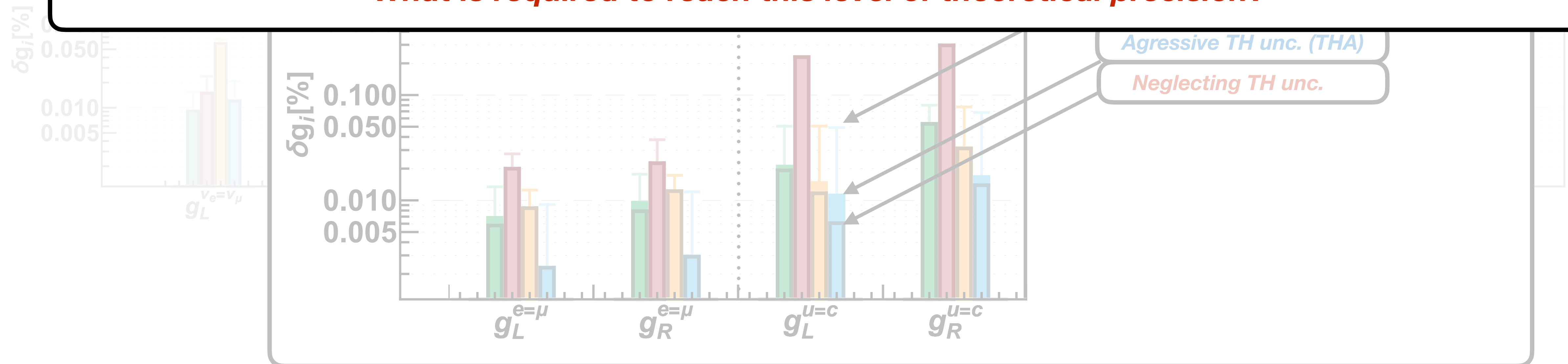
Theory challenges: Electroweak Physics

- Electroweak physics potential of the different colliders evaluated in the dimension-6 SMEFT framework:



In general, the Aggressive TH scenario seems to be a reasonable goal from the point of view of FCC-ee electroweak precision measurements

What is required to reach this level of theoretical precision?



Theory challenges: Electroweak Physics

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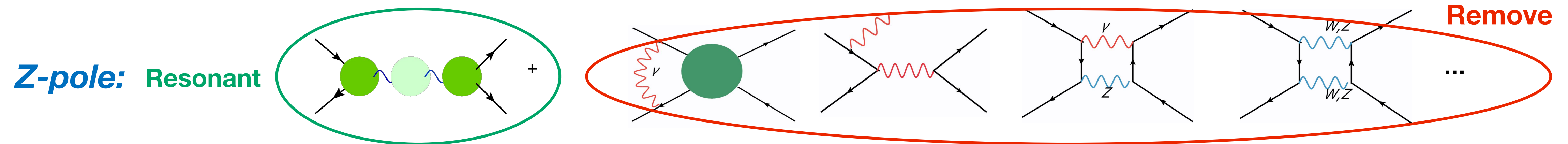
Aggressive: would require more fundamental advances in techniques and tools

The goal was to estimate the level of TH improvement required to match the future EXP precision, NOT to assess which scenario is most likely to be realized

- Different sources of theory uncertainties in predictions and systematic errors:
 - ▶ **Missing higher-order uncertainties (MHOUs):** from the truncation of perturbative expansions
 - ▶ **Non-perturbative effects**, e.g., hadronization and low-scale dynamics
 - ▶ **Parametric uncertainties:** from the propagation of uncertainties of model input parameters into predictions

Theory challenges: Electroweak Physics

- **EWPO are pseudo-observables (PO):** extracted from real observables “isolating” the EW information by correcting for the presence of other effects, *thus introducing theory systematics*



Z-pole background subtraction: non-resonant γ exchange, boxes, ...

Observable	Current	Conservative	Aggressive
Γ_Z [MeV]	0.11	0.016	—
R_ℓ [10^{-3}]	2.1	0.27	—
R_b [10^{-4}]	0.015	0.0023	—
R_c [10^{-4}]	0.023	0.0034	—
σ_{had} [pb]	5	0.8	—
A_{FB}^ℓ [10^{-4}]	3.4	0.42	—
A_{FB}^b [10^{-4}]	1.1	0.22	—
A_{FB}^c [10^{-4}]	0.8	0.16	—
A_{LR} [10^{-4}]	1.4	0.29	—
P_τ [10^{-4}]	3.0	0.4	—

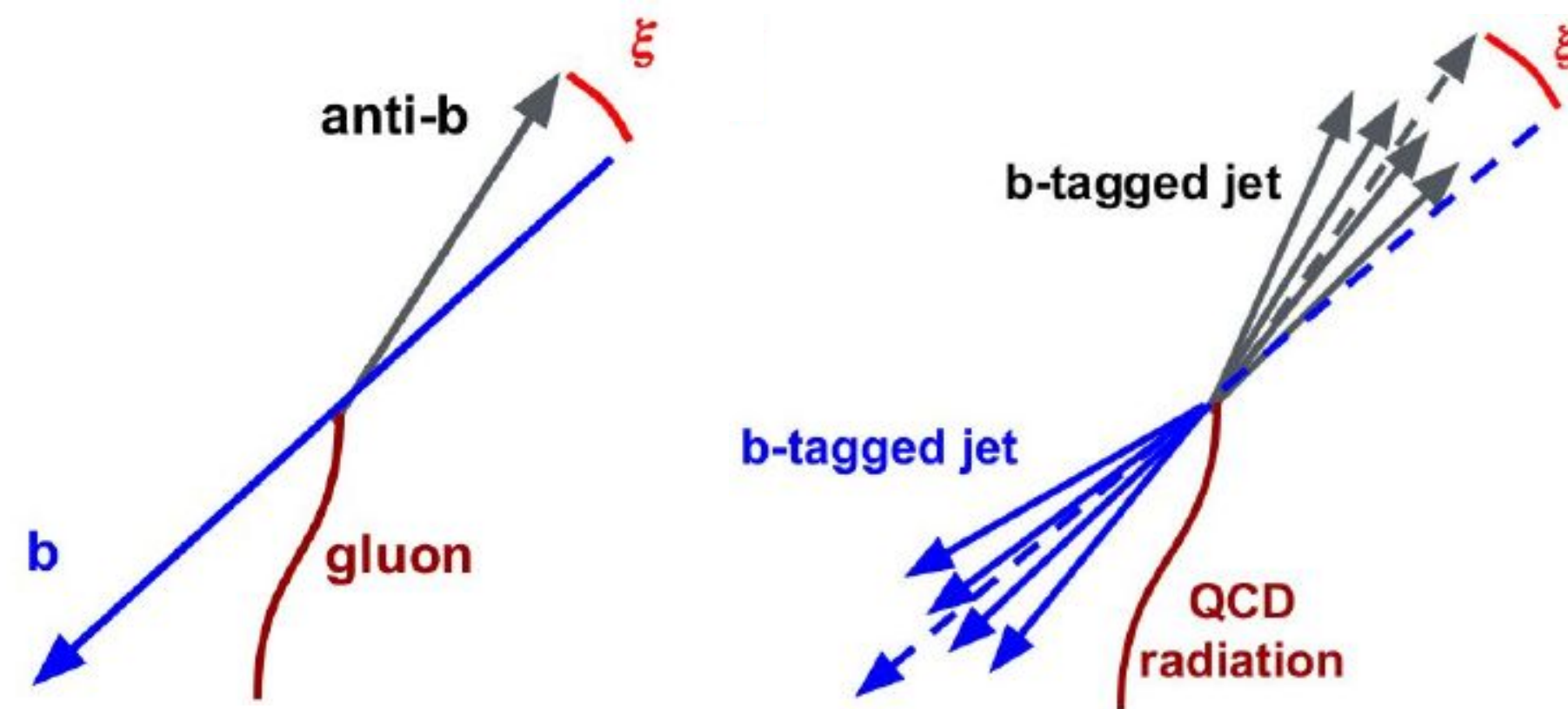
- **Current:** NLO corrections
- **Conservative:** Assumes NNLO will be available

Theory challenges: Electroweak Physics

- **EWPO are pseudo-observables (PO):** extracted from real observables “isolating” the EW information by correcting for the presence of other effects, *thus introducing theory systematics*

QCD MonteCarlo modeling

Observable	Current	Conservative	Aggressive
$R_b [10^{-4}]$	4.4	0.44	0.09
$R_c [10^{-4}]$	17	1.7	0.34
$A_{\text{FB}}^b [10^{-4}]$	1.0	0.22	0.028
$A_{\text{FB}}^c [10^{-4}]$	0.75	0.16	0.021



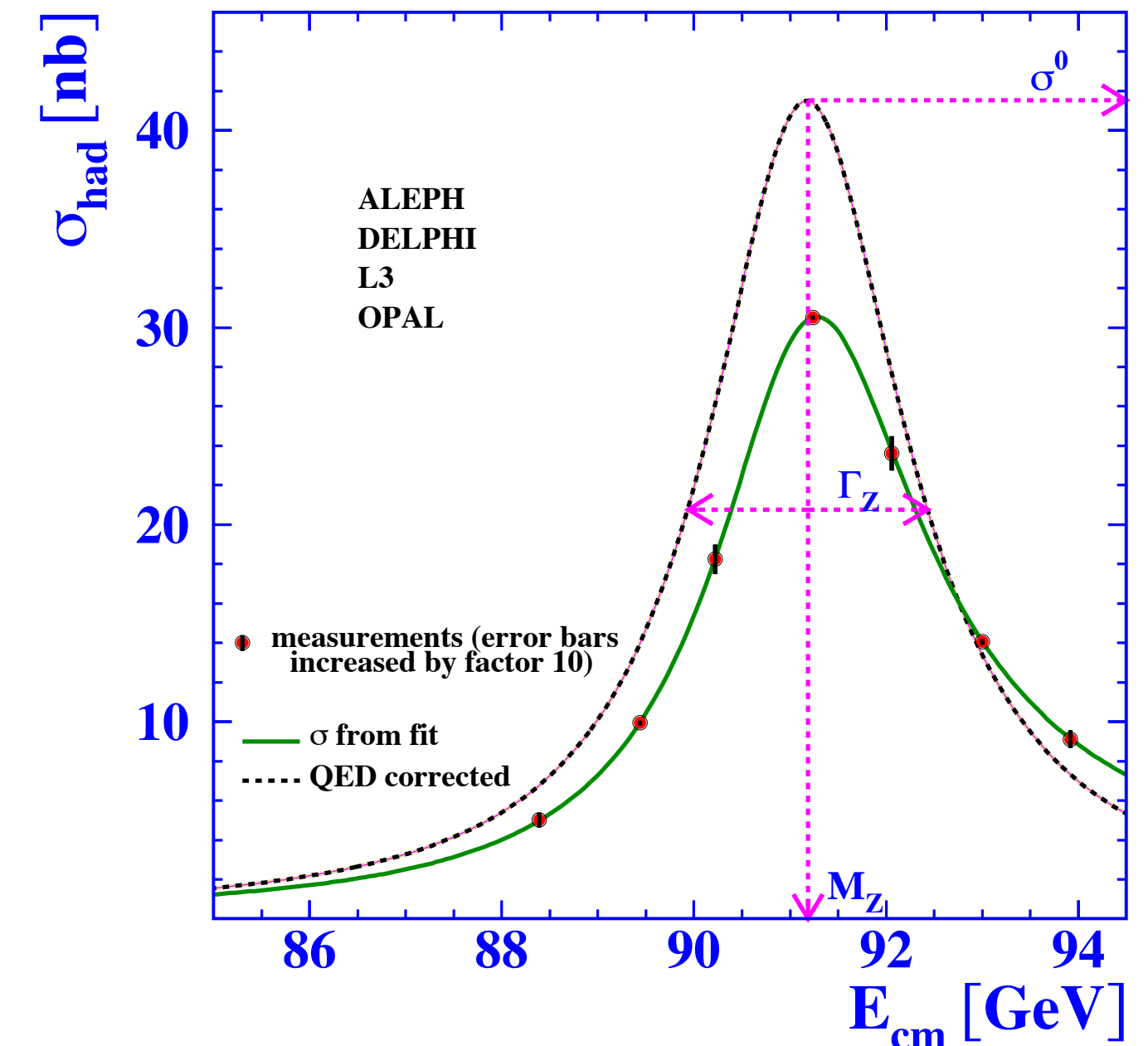
- **Different sources:**
- *Perturbatively* improvable, e.g. gluon splitting functions
 - ▶ **Conservative:** $\text{NNLO QCD} \rightarrow 10^{-4}$
 - ▶ **Aggressive:** $\text{N}^3\text{LO QCD} \rightarrow 10^{-4} \times C_A \alpha_s/\pi$
- *Non-perturbative*, e.g. hadronization from
 - ▶ Limited precision of data for generator tuning
 - ▶ Intrinsic modeling assumptions in MC generators
 - ▶ **Conservative:** Improvement by factor 5-10
 - ▶ **Aggressive:** Improvement by a factor 50
 - ▶ Not possible with current models in MC generators

Theory challenges: Electroweak Physics

- **EWPO are pseudo-observables (PO):** extracted from real observables “isolating” the EW information by correcting for the presence of other effects, *thus introducing theory systematics*

QED MonteCarlo modeling

Observable	Current	Conservative	Assumed improvements for “Conservative”
m_Z [MeV]	0.3	0.03	Fermion pairs
Γ_Z [MeV]	0.2	0.03	Fermion pairs
R_ℓ [10^{-3}]	12	0.3	Fermion pairs; FSR+IFI beyond $\mathcal{O}(\alpha)$
σ_{had} [pb]	25	1.5	Fermion pairs; IFI beyond $\mathcal{O}(\alpha)$
A_{FB}^ℓ [10^{-4}]	5	0.09	Full $\mathcal{O}(\alpha^2)$ QED plus log-enhanced $\mathcal{O}(\alpha^3)$
M_W [MeV]	3	0.3	For M_W from threshold scan: $\mathcal{O}(\alpha^2)$ QED corrections for W production and decay; soft photon exponentiation for photons emitted from W bosons; improved ISR



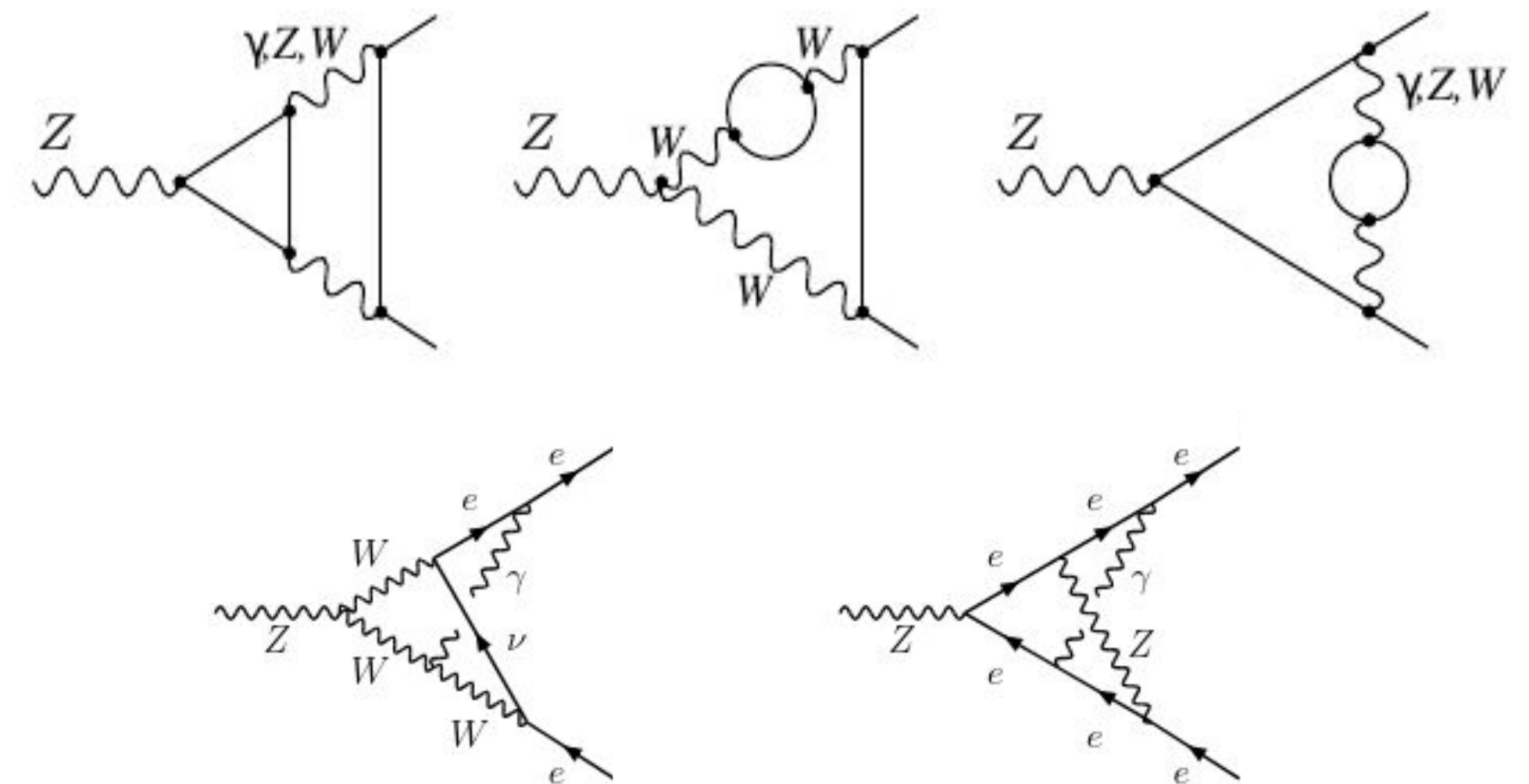
- **Open issues:** No available TH unc. estimate for MC generator effects for W/H/t production and decay

Theory challenges: Electroweak Physics

- **Precision of the SM predictions for EWPO:** crucial to establish any potential deviation as a sign of new physics

SM EWPO uncertainties

Observable	Current	Conservative	Aggressive
Γ_Z [MeV]	0.4	0.08	0.016
R_ℓ [10^{-3}]	6	1.2	0.2
R_b [10^{-4}]	1	0.2	0.035
R_c [10^{-4}]	0.5	0.1	0.02
σ_{had} [pb]	6	1.6	0.3
$\sin^2 \theta_{\text{eff}}$ [10^{-5}]	4.5	0.7	0.06
M_W [MeV]	4.0	1.0	0.1



- **Current (*2025):** $O(\alpha^2)$, $O(\alpha \alpha_s)$ + HO Y_t -enhanced $O(\alpha_t \alpha_s^2)$, $O(\alpha_t^2 \alpha_s)$, $O(\alpha_t^3)$ and $O(\alpha_t \alpha_s^3)$. Final state QCD corrections to $O(\alpha_s^4)$.
- **Conservative:** includes $O(\alpha \alpha_s^2)$, $O(\alpha^2 \alpha_s)$ and $O(\alpha_f^2 \alpha)$ + HO Y_t -enhanced $O(\alpha_t^2 \alpha_s^2)$, $O(\alpha_t^3 \alpha_s)$ and $O(\alpha_s^2 \alpha_t^4)$. Final state QCD corrections to $O(\alpha_s^5)$.
- **Aggressive:** + Full corrections $O(\alpha^3)$, $O(\alpha^2 \alpha_s^2)$, $O(\alpha_f^2 \alpha \alpha_s)$ & $O(\alpha_f^2 \alpha_s^2)$ + HO Y_t -enhanced $O(\alpha_t \alpha_s^4)$, $O(\alpha_t^2 \alpha_s^3)$. Final state QCD corrections to $O(\alpha_s^6)$.

Theory challenges: Electroweak Physics

- **Precision of the SM predictions for other EW processes:** crucial to establish any potential deviation as a sign of new physics

SM uncertainties

Fermion-pair production

W-boson properties/WW production

Quantity	Current	Conservative	Aggressive
Γ_W^{lep} (%)	0.1	0.013	—
Γ_W^{had} (%)	0.1	0.015	—
$\Gamma_W^{\text{had}}/\Gamma_W^{\text{lep}}$ (%)	0.015	< 0.01	—
$\sigma[e^+e^- \rightarrow W^+W^-]$ (%)	0.4	0.07	—

• **Current → Future (Conservative)**

- ▶ WW: NLO, incl. off-shell → + full NNLO on-shell (double-pole)
- ▶ $W \rightarrow l\nu$: NLO → + full NNLO
- ▶ $W \rightarrow qq$: $O(\alpha, \alpha \alpha_s, \alpha_s^4) \rightarrow + \text{full NNLO} + O(\alpha \alpha_s^2)$

Quantity	$\sqrt{s} = 250 \text{ GeV}$		$\sqrt{s} = 365 \text{ GeV}$	
	Current	Conservative	Current	Conservative
$\sigma[e^+e^- \rightarrow \ell^+\ell^-]$ (%)	1.2	0.15	1.2	0.15
$\sigma[e^+e^- \rightarrow c\bar{c}]$ (%)	0.8	0.1	0.7	0.09
$\sigma[e^+e^- \rightarrow b\bar{b}]$ (%)	0.43	0.06	0.45	0.06
$\sigma[e^+e^- \rightarrow \text{had.}]$ (%)	0.6	0.08	0.6	0.08
$\sigma[e^+e^- \rightarrow t\bar{t}]$ (%)	—	—	1.2	0.4
A_{FB}^ℓ (%)	0.4	0.05	0.35	0.045
A_{FB}^c (%)	0.47	0.06	0.64	0.08
A_{FB}^b (%)	0.25	0.03	0.3	0.04

- **Current:** NLO EW + 4th-order QCD for light-quarks
- **Conservative:** Full NNLO + $O(\alpha \alpha_s^2)$, $O(\alpha^2 \alpha_s)$

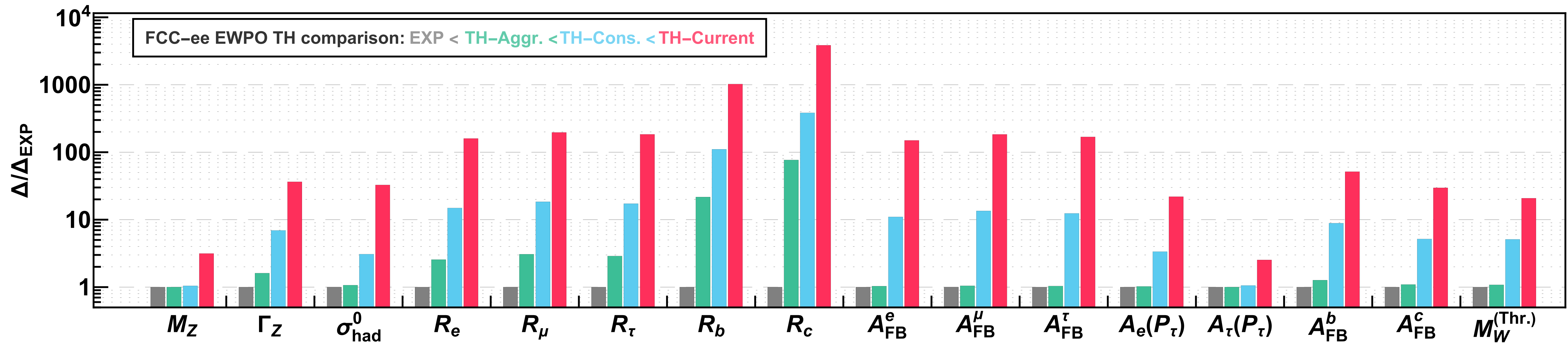
Theory challenges: Electroweak Physics

Treatment of SM uncertainties

- Studies in the Physics Briefing Book were based on two scenarios for the projected precision of **future** TH calculations:

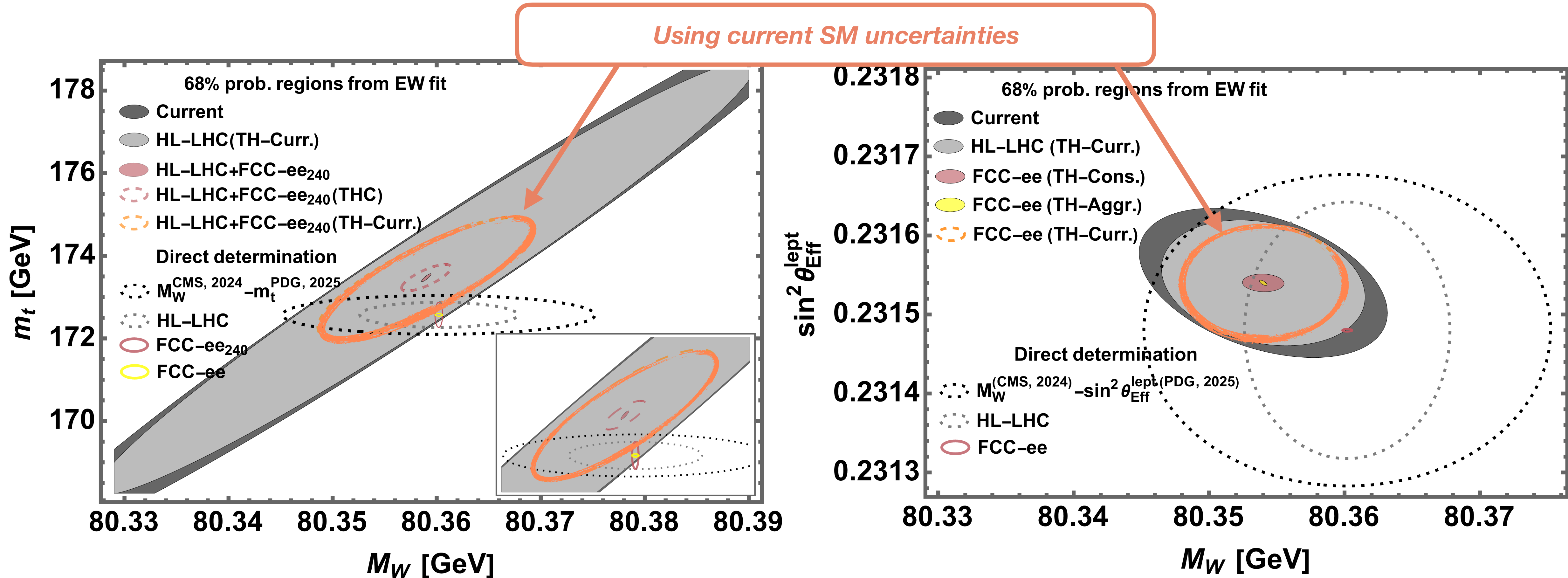
Conservative: assuming theory improvements that are likely to be achieved by building on existing computational methods

Aggressive: would require more fundamental advances in techniques and tools



Theory challenges: Electroweak Physics

- Matching the projected experimental precision should be goal...

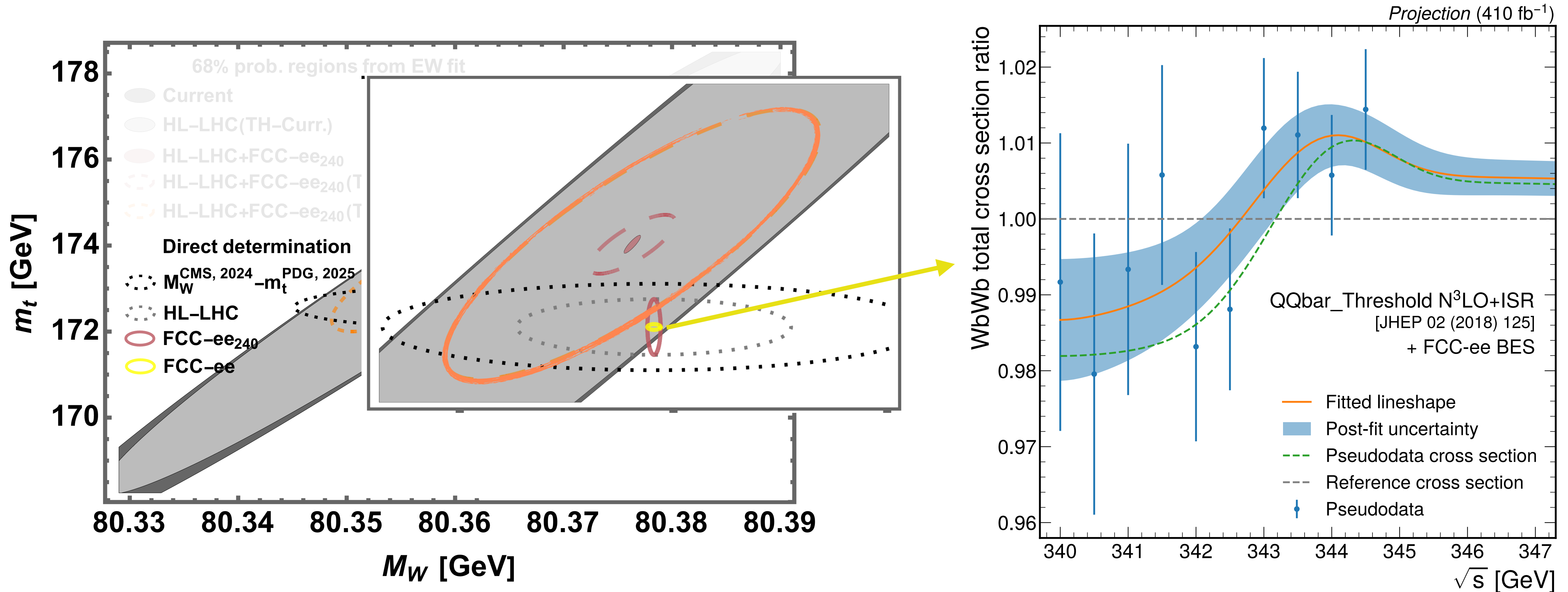


But more important than that is to motivate the work to greatly improve our current knowledge of SM calculations

Precision of current theory calculations would dramatically hinder the FCC-ee EW physics program

Theory challenges: Electroweak Physics

- Matching the projected experimental precision should be goal...



m_t @ tt threshold: matching ~ 7 MeV EXP precision would require large improvement in NR QCD effects at threshold: Currently N³LO $\rightarrow \Delta m_t \sim 35$ MeV (going down to ~ 20 MeV going be enough for EW)

Theory challenges: Higgs Physics

- Compared to EW, Higgs precision will be at the level 10^{-3} , imposing less demanding requirements on theory

	Process	Error est. (%)	Current	Conservative Error est. (%)	Add'l. orders	Aggressive Error est. (%)	Add'l. orders
			Available orders				
Decay	$H \rightarrow bb/cc$	< 0.4	$\alpha_s^4 + \alpha + \alpha_t^2 + \alpha_t \alpha_s$	0.2	$\alpha^2 + \alpha \alpha_s$	0.1	α_s^5
	$H \rightarrow \tau\tau/\mu\mu$	< 0.3	$\alpha + \alpha_t^2 + \alpha_t \alpha_s$	< 0.1	$\alpha^2 + \alpha \alpha_s$		
	$H \rightarrow WW^*/ZZ^*$	0.5	$\alpha_s + \alpha + \alpha_t^2 + \alpha_t \alpha_s$	0.3	α_s^2		
	$H \rightarrow gg$	3.2	$\alpha_s^3 + \alpha$	1.0	α_s^4	0.5	$\alpha_s^5 + \alpha \alpha_s$
	$H \rightarrow \gamma\gamma$	< 1.0	$\alpha_s^2 + \alpha$	< 1.0		0.4	$\alpha \alpha_s$
	$H \rightarrow Z\gamma$	1.5	$\alpha_s + \alpha$	1.5			
Prod.	$e^+e^- \rightarrow ZH$	0.3	$\alpha + \alpha \alpha_s + \alpha \alpha_f$	< 0.1	α^2		
	$e^+e^- \rightarrow \nu\bar{\nu}H$	~ 1	α	~ 0.1	$\alpha \alpha_s + \alpha^2$		

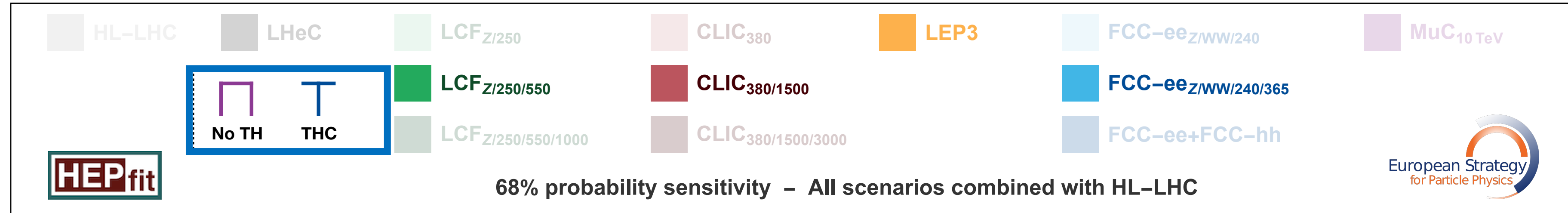
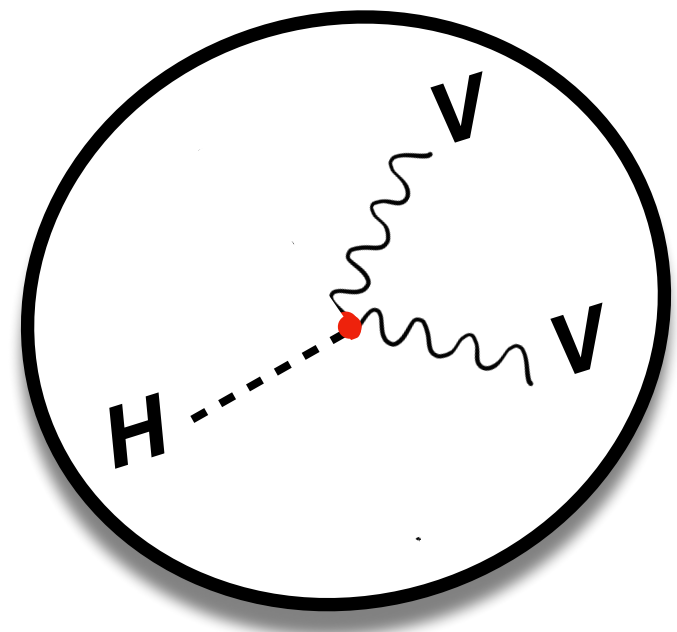
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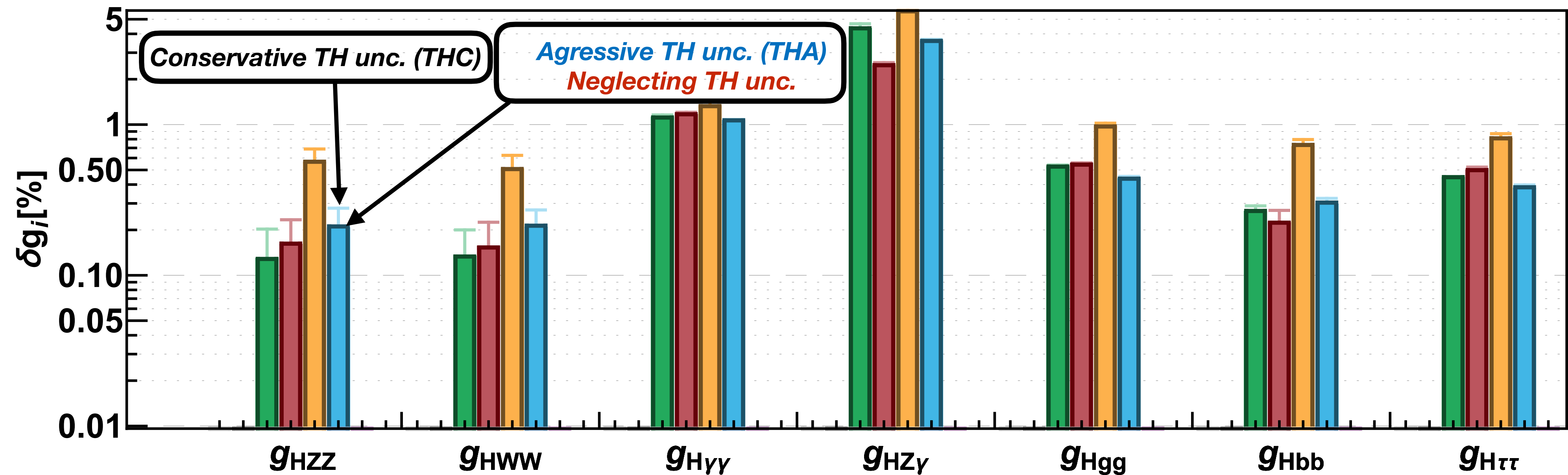
	Process	Error est. (%)	Current	Error est. (%)	Conservative	Error est. (%)	Aggressive
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	$H \rightarrow gg$	3.2	$\alpha_s^3 + \alpha$	1.0	α_s^4	0.5	$\alpha_s^5 + \alpha \alpha_s$
	$H \rightarrow \gamma\gamma$	< 1.0	$\alpha_s^2 + \alpha$	< 1.0		0.4	$\alpha \alpha_s$
	$H \rightarrow Z\gamma$	1.5	$\alpha_s + \alpha$	1.5			
Prod.	$e^+e^- \rightarrow ZH$	0.3	$\alpha + \alpha \alpha_s + \alpha \alpha_f$	< 0.1	α^4	Getting there...	
	$e^+e^- \rightarrow \nu\bar{\nu}H$	~ 1	α	~ 0.1	$\alpha \alpha_s + \alpha^2$	More challenging (2→3) Doable?	

Theory challenges: Higgs Physics

- Higgs physics potential of the different colliders evaluated in the dimension-6 SMEFT framework:

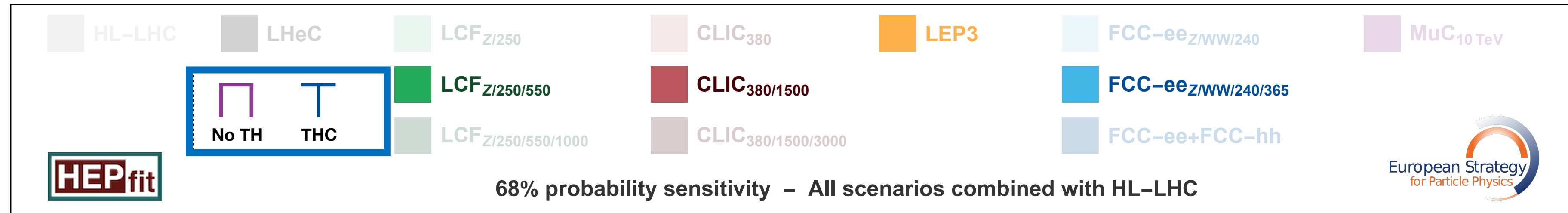
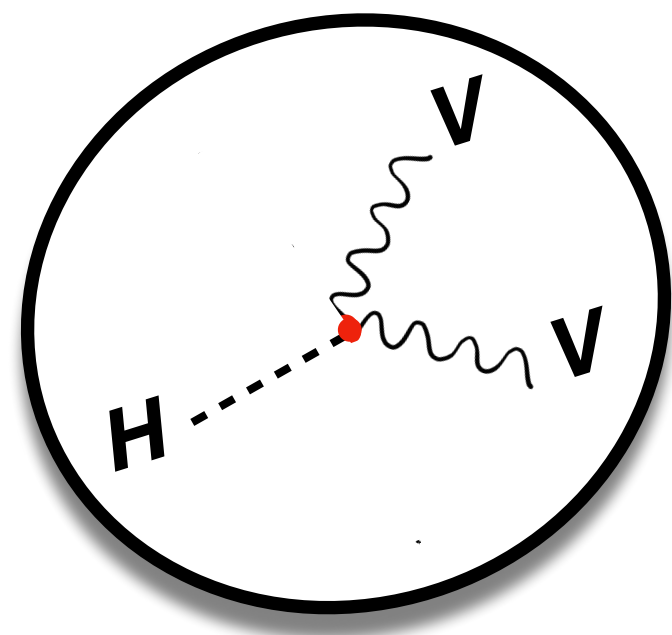


Impact of assumptions on TH uncertainties (Higgs)

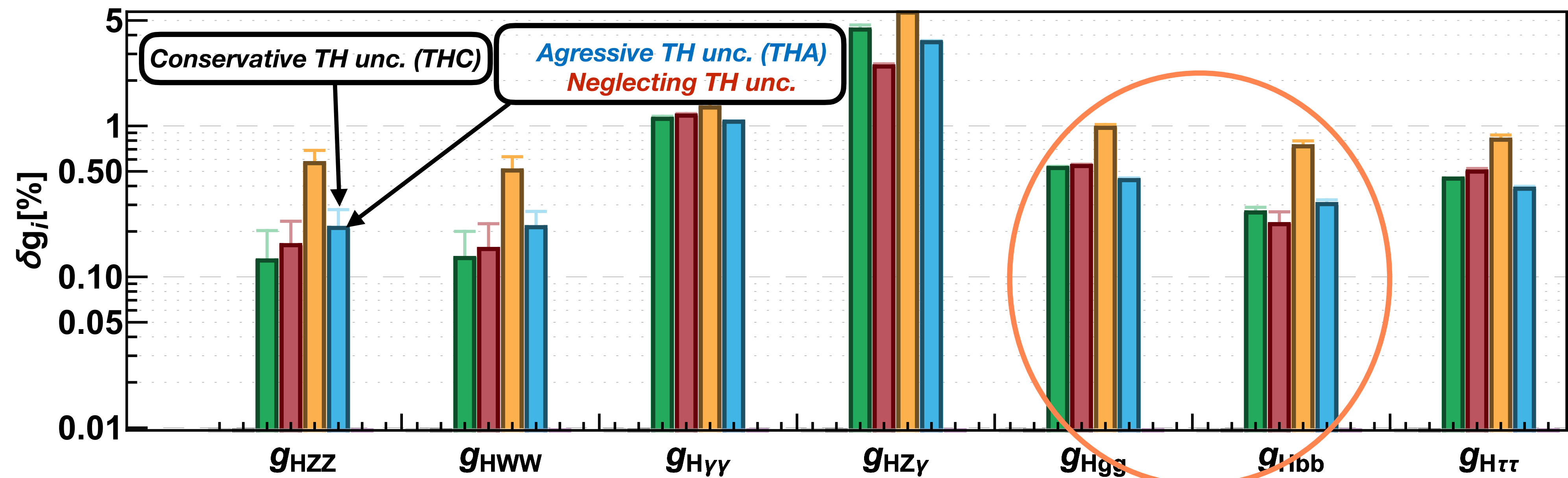


Theory challenges: Higgs Physics

- Higgs physics potential of the different colliders evaluated in the dimension-6 SMEFT framework:



Impact of assumptions on TH uncertainties (Higgs)



Some of these results also rely on precise inputs from Lattice QCD (α_s , m_b , ...)
Lattice QCD also impacts other aspects of the FCC-ee physics program

***Theory challenges at the FCC-ee:
More than a Electroweak/Higgs/Top factory***

The European Strategy for Particle Physics: 2026 Update

European Strategy Group Recommendations

The next CERN flagship collider project

A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

- Multiple considerations go into this strategic decision, with the *physics potential* being one of the main pillars:
 - ▶ *Broadest high-precision physics programme, covering the EW, Higgs, Top, Flavour (and even QCD) sectors*
 - ▶ *Paving the way towards the exploration of the high-Energy frontier by the FCC-hh (access to ≈ 10 TeV Parton scale)*

Machine	Precision Physics	BSM physics	Physics vs CEPC	Technical readiness	Constr. cost (BCHF)	Time scale	Path to ≥ 10 TeV
FCC-ee	22	23			15.3	2046-2060	
Descoped FCC-ee	15	17			12.9	2046-2055	
LCF550	15	17			14.8	2045-2065	
CLIC1500	14	18			14.6	2045-2066	
LCF250	10	16			9.4	2045-2053	
CLIC380	10	16			7.5	2045-2054	
LEP3	15	17			4.1	2047-2062	
LHeC	8	7			2.1	2044-2051	

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Breadth of physics program is key, going beyond an EW/Higgs factory

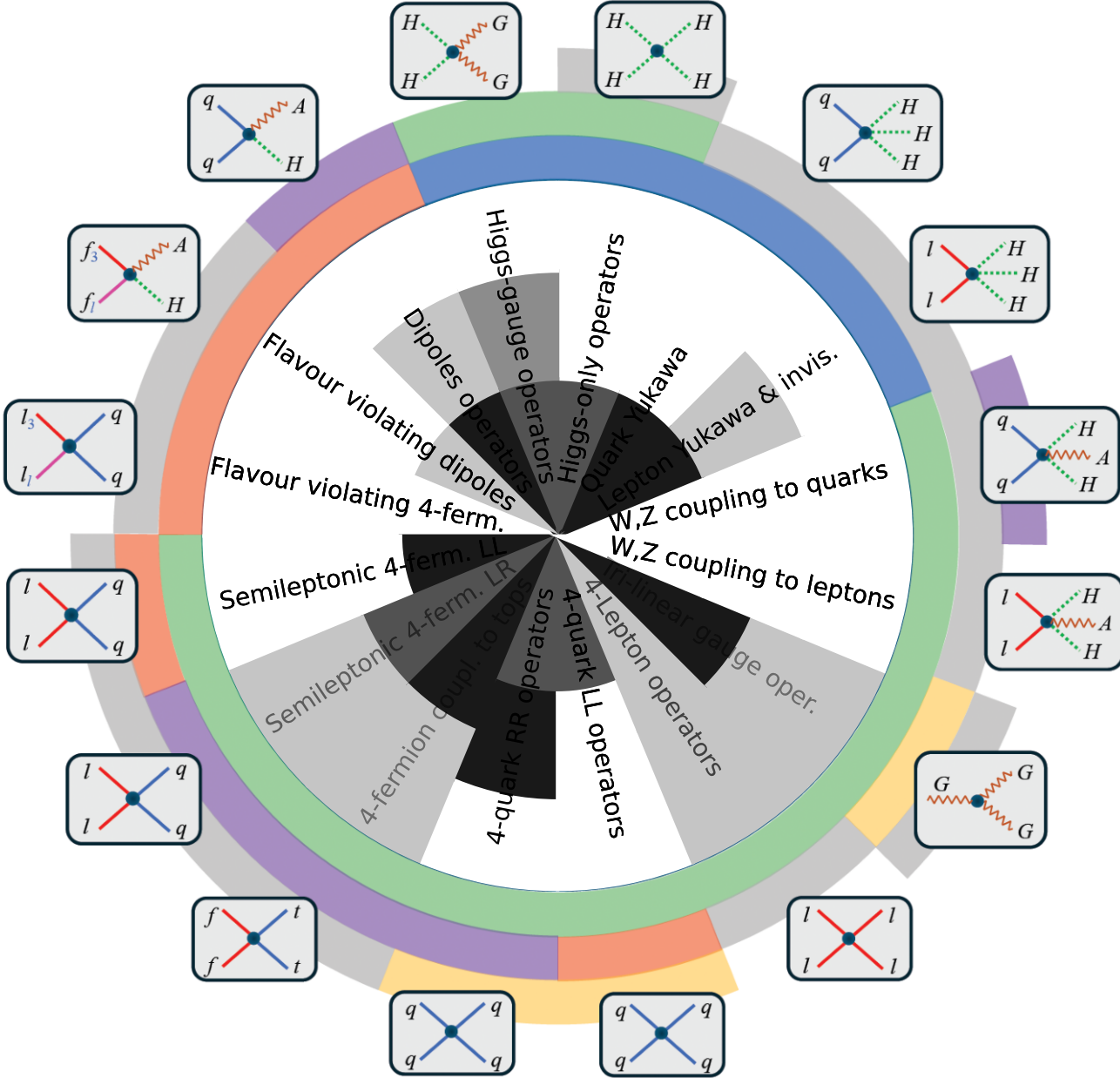
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Future Collider Comparison: Precision Physics

Flavour in the global picture:

FCCee

- High-energy coll.
- Top-quark
- Higgs
- Electroweak
- Flavour
- QCD



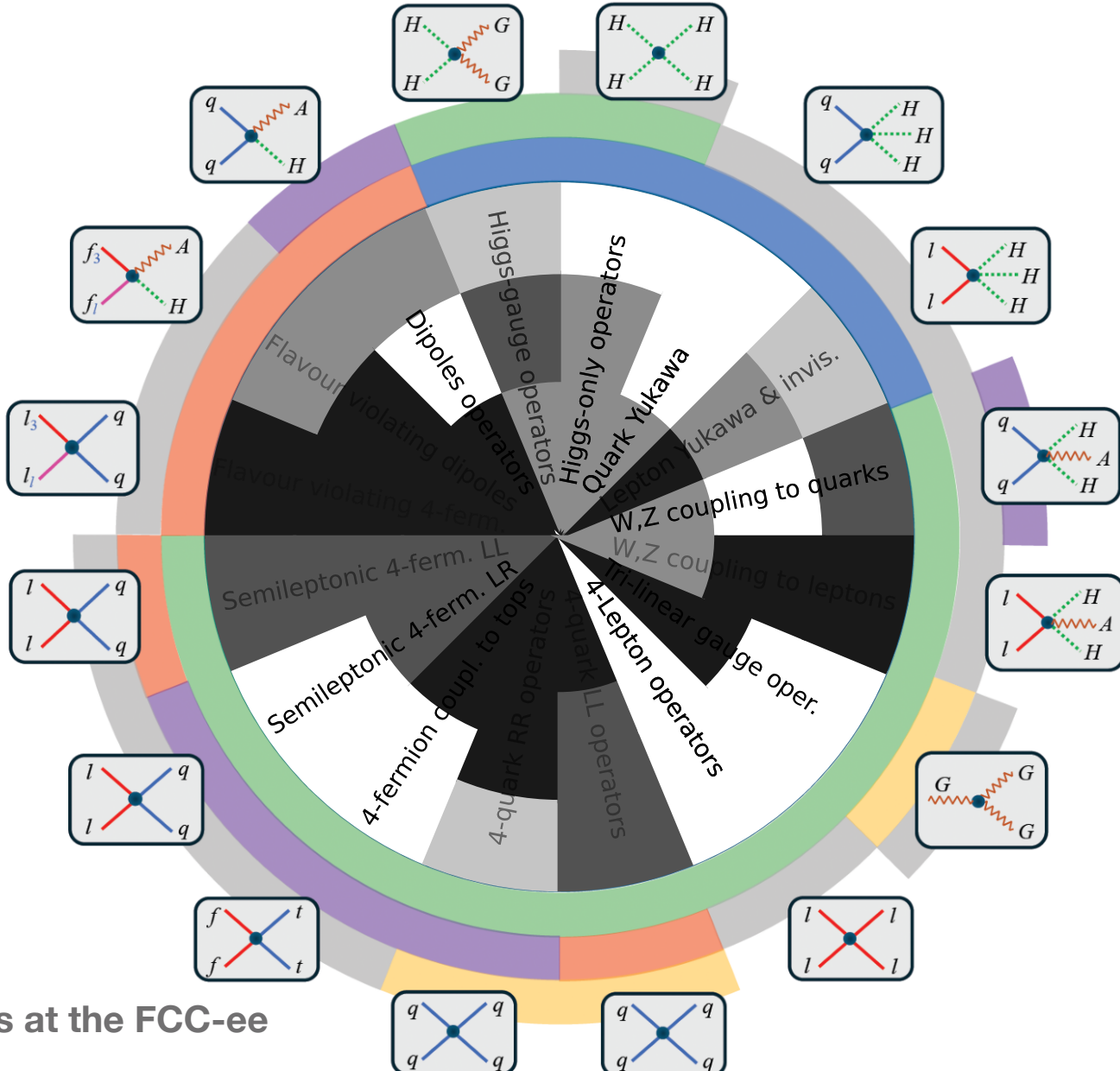
LCF550

- High-energy coll.
- Top-quark
- Higgs
- Electroweak
- Flavour
- QCD



CLIC1500

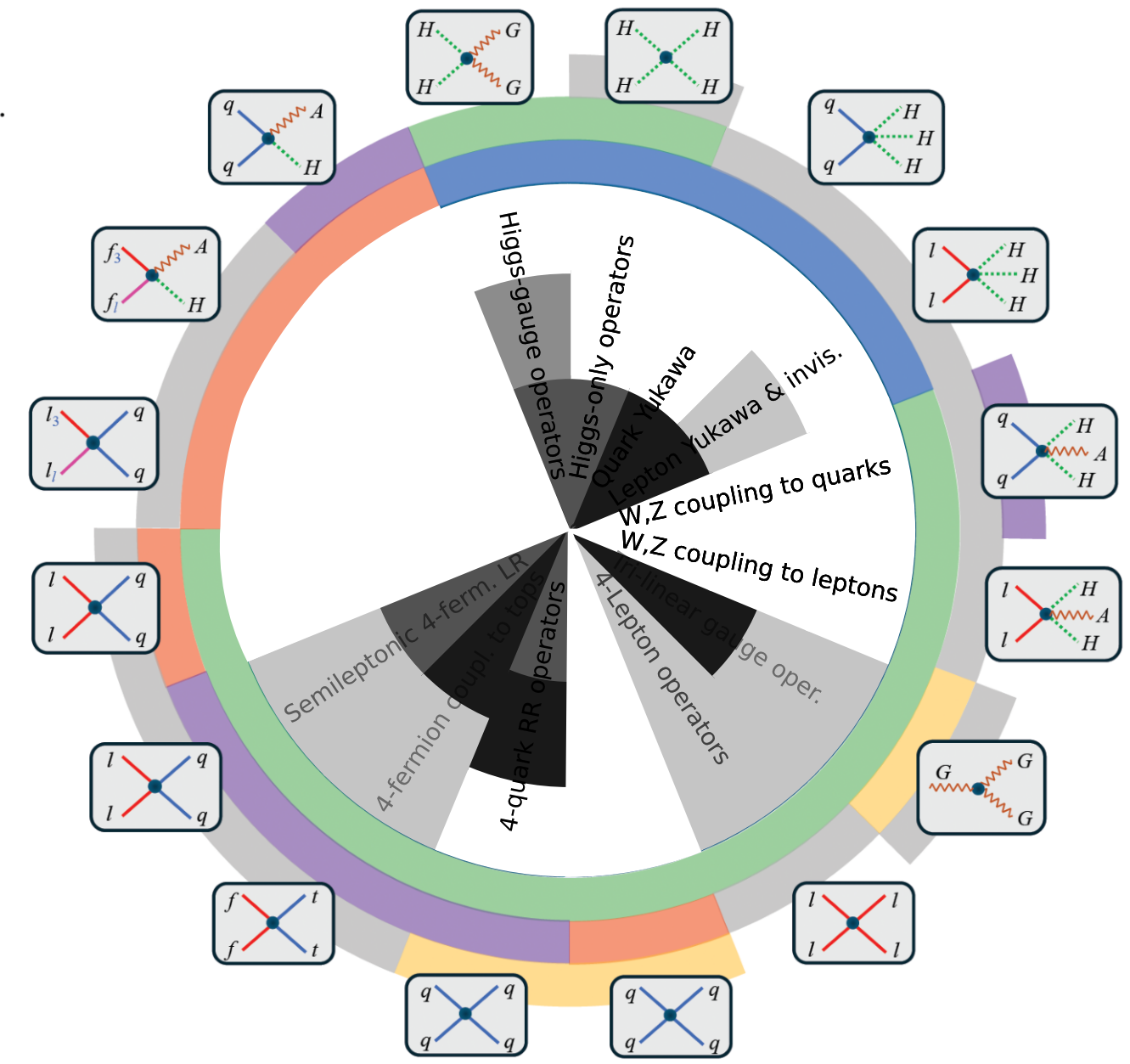
- High-energy coll.
- Top-quark
- Higgs
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- Flavour
- QCD



Future Collider Comparison: Precision Physics

FCCee

- High-energy coll.
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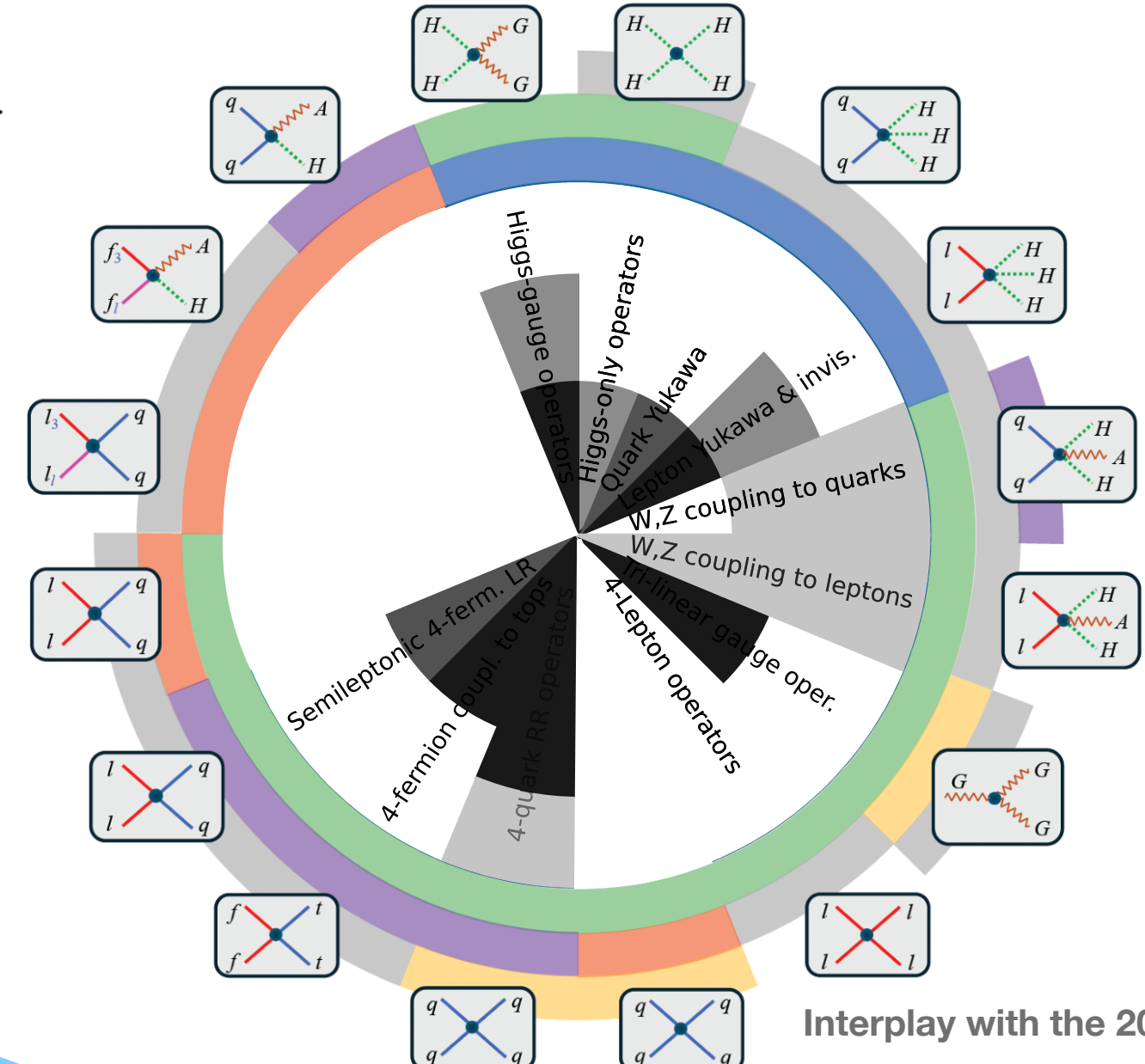


Flavour in the global picture:

Capabilities for flavour measurement play a key role in separating FCC-ee from other e^+e^- options

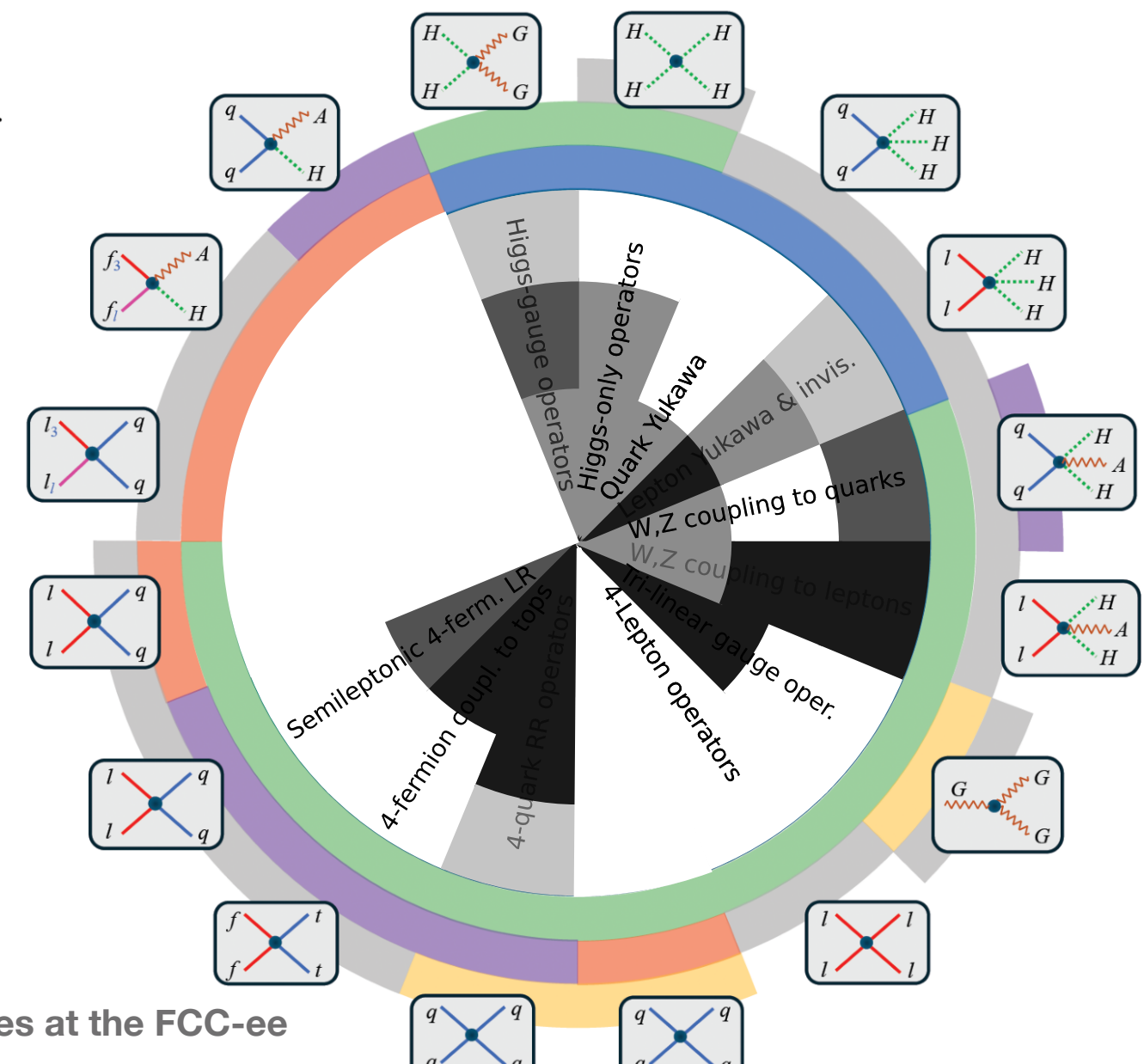
LCF550

- High-energy coll.
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- QCD



CLIC1500

- High-energy coll.
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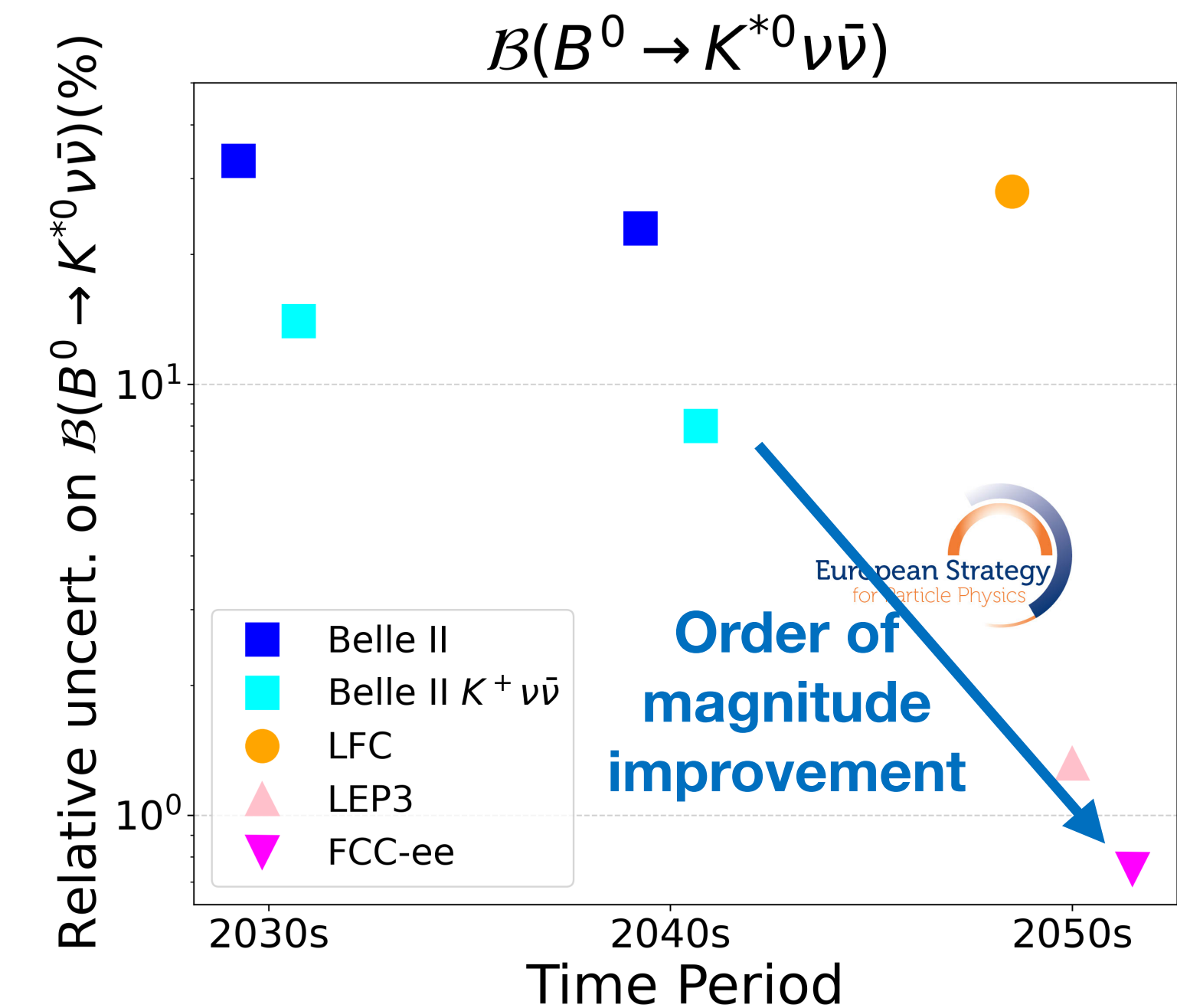


Theory challenges: Flavour Physics

- The very high luminosity at the Z-pole (and WW threshold) would allow substantial improvements in Flavour measurements *with respect to LHCb and BELLE* experiments
 - Tera Z:** 10^{12} Z bosons $\Rightarrow$ Plenty of b, c & τ for clean flavour physics $\Rightarrow$ O(10) improvement
 - WW threshold:** Decays of 10^8 WW pairs $\Rightarrow$ To further improve CKM

Flavour Transition	Transition type					
	γ	quarks	μ	e	τ	ν
$3_q \rightarrow 2_q$	$b \rightarrow s \gamma$ [*]	$B_s \leftrightarrow \bar{B}_s$ [*]	$b \rightarrow s \bar{\mu} \mu$ [*] $b \rightarrow c \mu \bar{\nu}$	$R_{bs}(e/\mu)$ [*] $R_{bc}(e/\mu)$ [•]	$b \rightarrow s \bar{\tau} \tau$ [•] $b \rightarrow c \tau \bar{\nu}$ [•]	$b \rightarrow s \nu \bar{\nu}$ [•]
$3_q \rightarrow 1_q$	$b \rightarrow d \gamma$ [*]	$B_d \leftrightarrow \bar{B}_d$ [*]	$b \rightarrow d \bar{\mu} \mu$ [*] $b \rightarrow u \mu \bar{\nu}$	$R_{bd}(e/\mu)$ [*] $R_{bu}(e/\mu)$ [•]	$b \rightarrow d \bar{\tau} \tau$ [•] $b \rightarrow u \tau \bar{\nu}$ [•]	$b \rightarrow d \nu \bar{\nu}$ [•]
$2_q \rightarrow \begin{smallmatrix} 2_q \\ 1_q \end{smallmatrix}$	$c \rightarrow u \gamma$	$D \leftrightarrow \bar{D}$ [*]	$c \rightarrow u \bar{\mu} \mu$ $c \rightarrow s \bar{\mu} \nu$ $c \rightarrow d \bar{\mu} \nu$	$R_{cu}(e/\mu)$ [*] $R_{cs}(e/\mu)$ [•] $R_{cd}(e/\mu)$ [•]		$c \rightarrow u \nu \bar{\nu}$ [•]
$3_\ell \rightarrow \begin{smallmatrix} 2_\ell \\ 1_\ell \end{smallmatrix}$	$\tau \rightarrow \mu \gamma$ [•] $\tau \rightarrow e \gamma$ [•]	$\tau \rightarrow \mu \bar{q} q$ [•] $\tau \rightarrow e \bar{q} q$ [•]	$\tau \rightarrow \mu \bar{\mu} \mu$ [•] $\tau \rightarrow e \bar{\mu} \mu$ [•]	$\tau \rightarrow \mu \bar{e} e$ [•] $\tau \rightarrow e \bar{e} e$ [•]		$\tau \rightarrow \mu \nu \bar{\nu}$ [•] $\tau \rightarrow e \nu \bar{\nu}$ [•]

[*] = 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

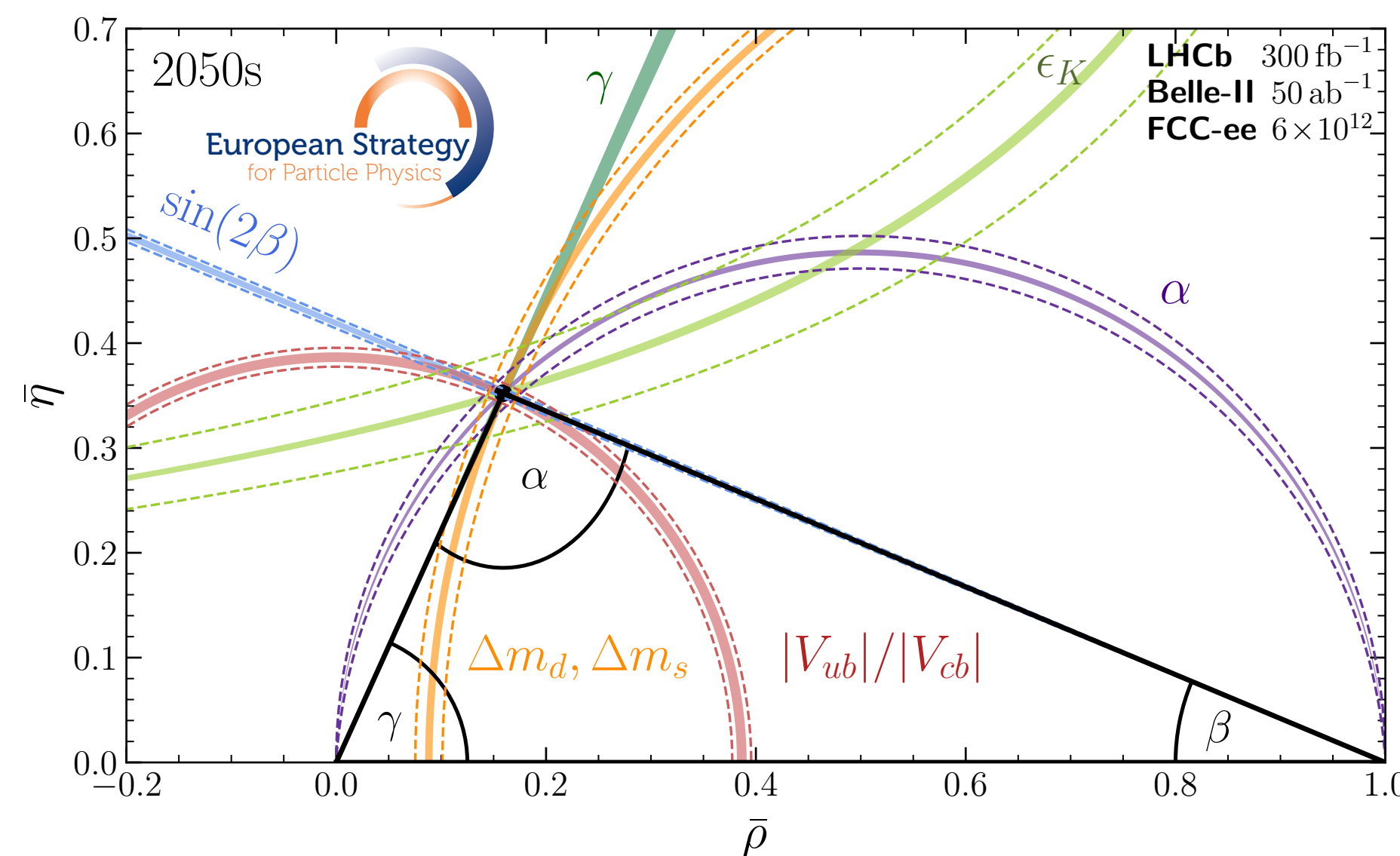


FCC-ee:
Exp. precision $\sim 0.5\%$
(systematics at the same level)

Theory challenges: Flavour Physics

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 - **Tera Z:** 10^{12} Z bosons $\Rightarrow$ Plenty of b, c & τ for clean flavour physics $\Rightarrow$ O(10) improvement

Unitarity Triangle at FCC-ee



- FCC-ee:** Experimental precision

$$\frac{\text{EXP}}{\Gamma(A_i \rightarrow B_j)} \propto \frac{|V_{ij}|^2 |\langle B_j | \mathcal{H}_W | A_i \rangle|^2}{\text{QCD (+QED)}} f_K, f_D, f_B, \dots$$

- Theory:** Need (**non-perturbative**) knowledge of Hadronic matrix elements $\Rightarrow$ **Lattice QCD**

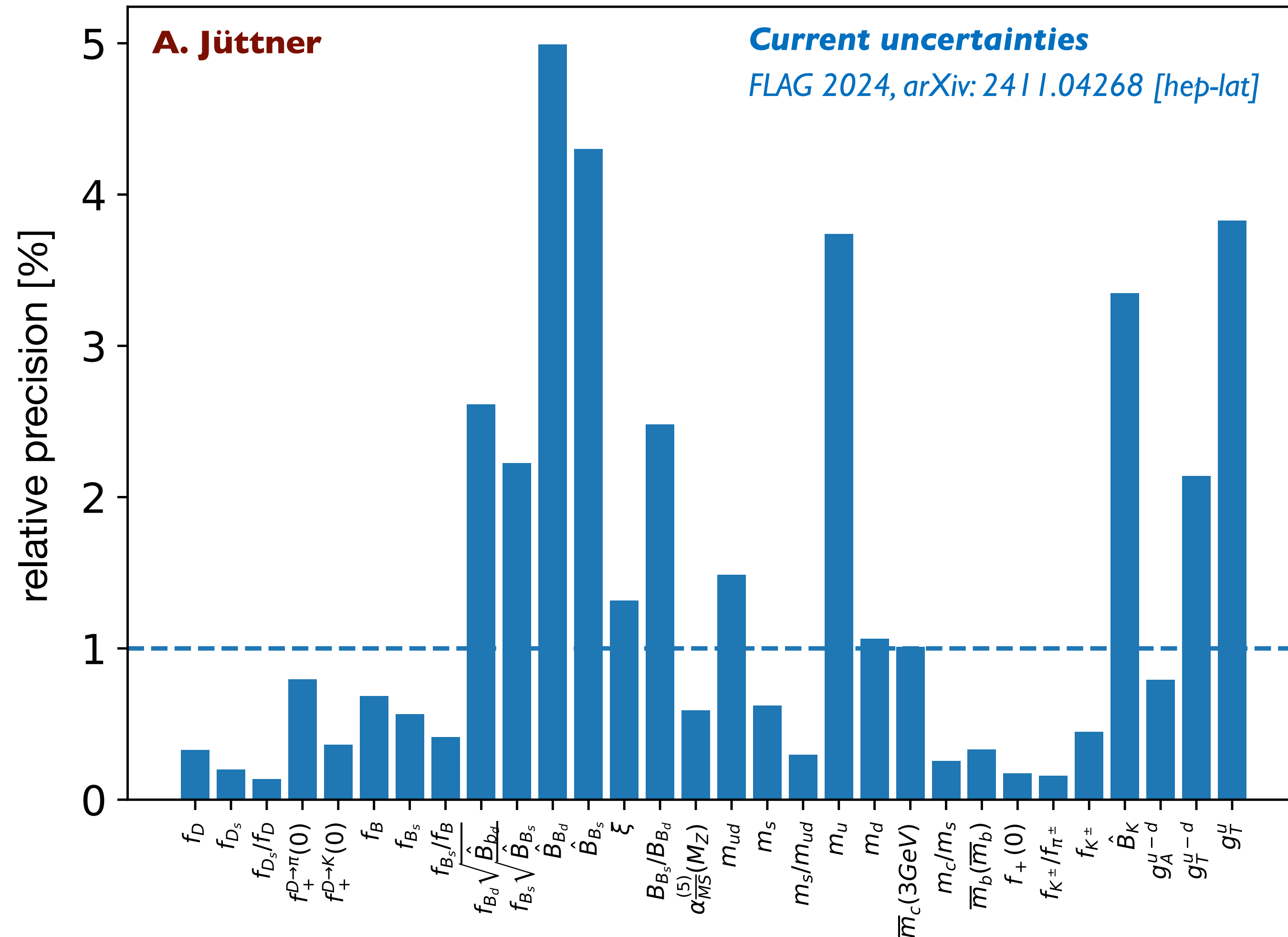
Target precision:

- Uncertainties in form factors:
 - Below percent for $B \rightarrow K$
 - O(1%) for other transitions

Theory challenges: Flavour Physics

Precision Physics in the Lattice

- Lattice QCD (LQCD) provides de theoretical accuracy for SM predictions required to interpret flavour observables:



Target precision:

- Uncertainties in form factors:
 - Below percent for $B \rightarrow K$
 - $O(1\%)$ for other transitions
- Strong requirements on lattice calculations in terms of
 - High-performance (parallel-)computing resources/Algorithmic innovation
 - Precision AND accuracy
 - Some tensions exist between lattice results
 - Set of calculated observables

Theory challenges: Flavour Physics

Sub-Percent Precision Physics in the Lattice

- **Computing:** To tackle larger volumes, smaller lattice spacings and high statistics
- Improved computing **algorithms**, novel ideas in **QFT**, AI/ML To tackle larger volumes, smaller lattice spacings and high statistics
- **Precision and Accuracy:** Going below 1% one cannot neglect several effects in lattice calculations:

Strong-Isospin breaking (SIB)

$$\frac{m_u - m_d}{\Lambda_{\text{QCD}}} \sim O(1\%)$$

QED

$$\alpha(0) \approx \frac{1}{137.036} \sim O(1\%)$$

- ▶ State-of-the-art includes combined treatment of QCD+QED+SIB for hadron spectra, $(g-2)_\mu$ and some leptonic decays
- ▶ Progress needed to extend it to semi-leptonic decays and other more complicated quantities but no fundamental show-stopper has been identified

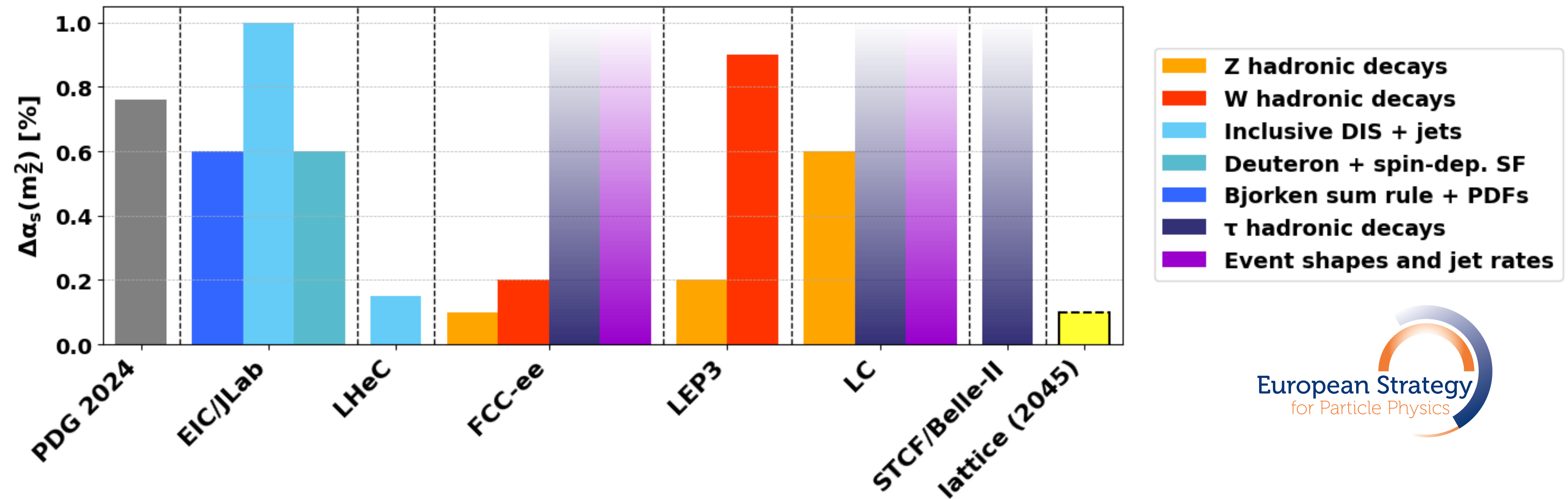
Theory challenges: Flavour Physics

Precision Physics in the Lattice

- Lattice QCD (LQCD) also provides important inputs for the study of EW and Higgs

Precision tests of QCD (α_s)

(Less precisely known SM input)



EWPO sensitivity to α_s (R_l , Γ_Z , $W \rightarrow \text{had}$, ...): $\sim 0.1\%$ precision BUT new physics affecting these observables would affect this determination

Lattice-QCD provides a complementary determination of this important parameter

Conclusions

Conclusions

- The 2026 ESSP recommendation of FCC-ee is largely supported by the superb capabilities of the project for precision experiments
 - ▶ Covering not only the exploration of Higgs properties (one of the main motivations) but also ultra-precise measurements of electroweak, top, flavour and QCD observables
- Significant advancements on the theory side are however required to make sure we get the most of those experiments
 - ▶ Critical progress is required for EW physics, both in perturbative and non-perturbative aspects
 - ▶ Less stringent requirements in other areas, but still sustained effort is needed to improve current precision to the level required at FCC-ee
- Theory is a crucial ingredient for the success of FCC-ee:
 - ▶ Towards the approval of the project in 2028 it is important to show that the community is taking initiatives targeting the challenges of the future large particle collider at CERN
 - ▶ Exploring synergies with the calculations needed for HL-LHC physics is also important, to motivate these FCC-ee studies in parallel to the needs for the completion of the LHC program

Conclusions

- Very clear and strong message from the 2026 European Strategy Group, regarding the next large-scale project at CERN:

The realization of the FCC as the next flagship project at CERN is the best plan for Europe to continue playing a leading role in the field

➔ All efforts (Council, CERN management) should be made to make FCC a reality

- The physics potential is clear but not without challenges

- FCC PED studies during the *Reference Design Phase* are focused in identifying and addressing such challenges:

Link to [FCC Physics Groups Activities](#)

Mailing list: **FCC-PED-PhysicsGroup-XXX**

XXX: BSM, EWPrecision, Flavours, GlobalFits, hh, Higgs, HighLevelReco, MCgenerators, PrecisionCalculations, QCD, Top

