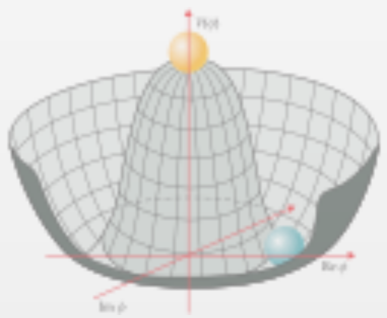
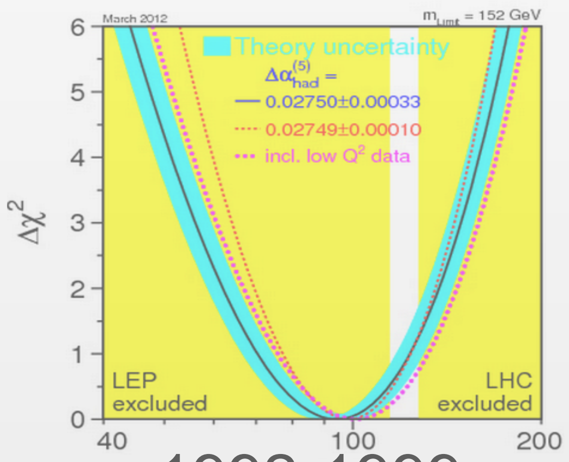
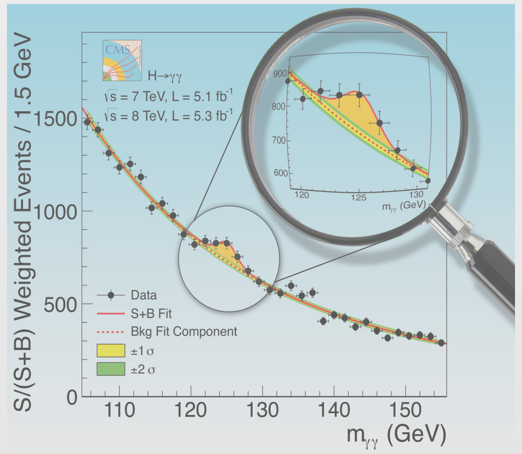


1964



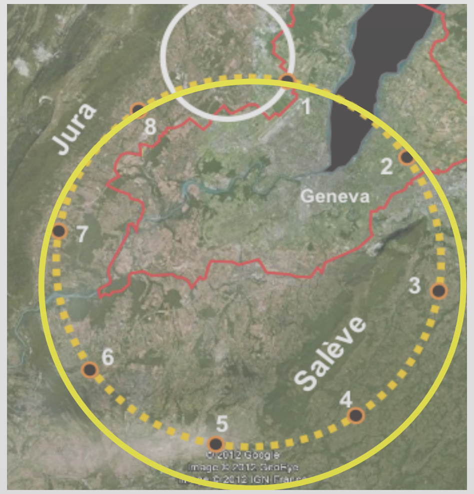
1992-1999

2010



2012

2020



2040

FCC Physics Case:
the once, the now, the future

FCC week

Paris, May 30, 2022

Christophe Grojean

DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

The HEP landscape after LHC$_{I\text{-}II}$

Nicely summarised by MLM@Aspen'14:

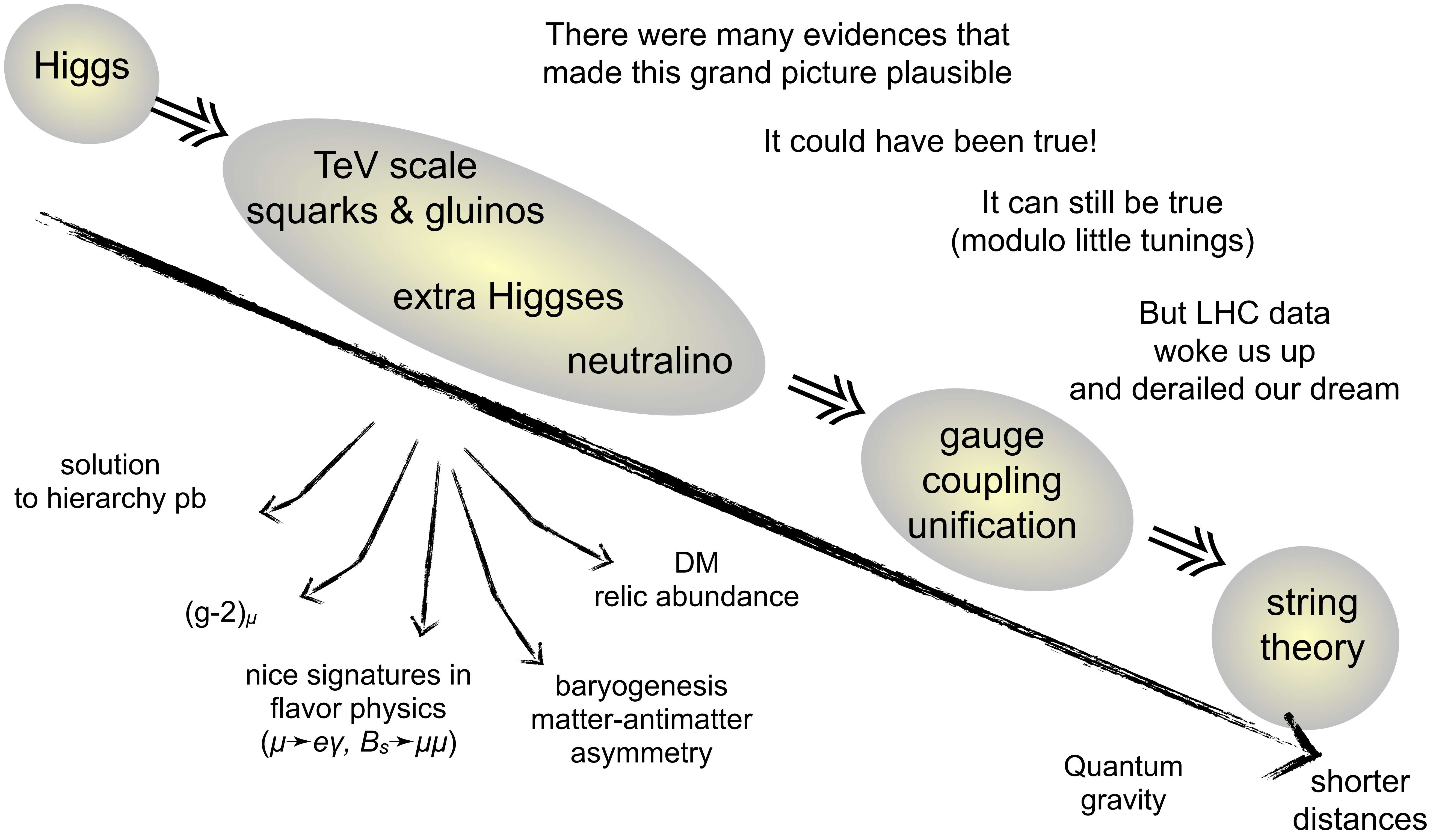
My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

The Higgs discovery sets a large part of the agenda for
the theoretical and experimental HEP programs
over the next couple of decades…
unless a new major discovery happens soon (supersymmetry, DM...)

B$_{(LH)}$C: We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model



LHC: driving cultural change forward

Theorists had a clear agenda for physics beyond the Standard Model

the once

the guaranteed future

the now

shorter distances

The LHC has revolutionised our views on the particle world.
It didn't find (yet) any BSM physics.
But its results have forced us to think differently about BSM physics.

G. Giudice@DESY'22

LHC: driving cultural change forward

Absence (so far) of new physics where it was expected (TeV)
&
progresses in string theory/quantum gravity (swampland, no global symmetries)

⬇ ⬇

question our description of Nature in terms of effective quantum field theories
(non-locality, IR/UV correlation)

IR parameters are functions of some fields whose value vary during the cosmological history or throughout a complex vacuum structure

Axion: $\mathcal{L}_{\text{dim}=4} = \frac{g_s^2}{32\pi^2}\,\bar{\theta} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$ $\bar{\theta} \longrightarrow a$

Higgs mass: relaxion, etc. $\mu|H|^2 \to g\Lambda\phi|H|^2$

LHC: driving cultural change forward

Absence (so far) of new physics where it was expected (TeV)
&
progresses in string theory/quantum gravity (swampland, no global symmetries)

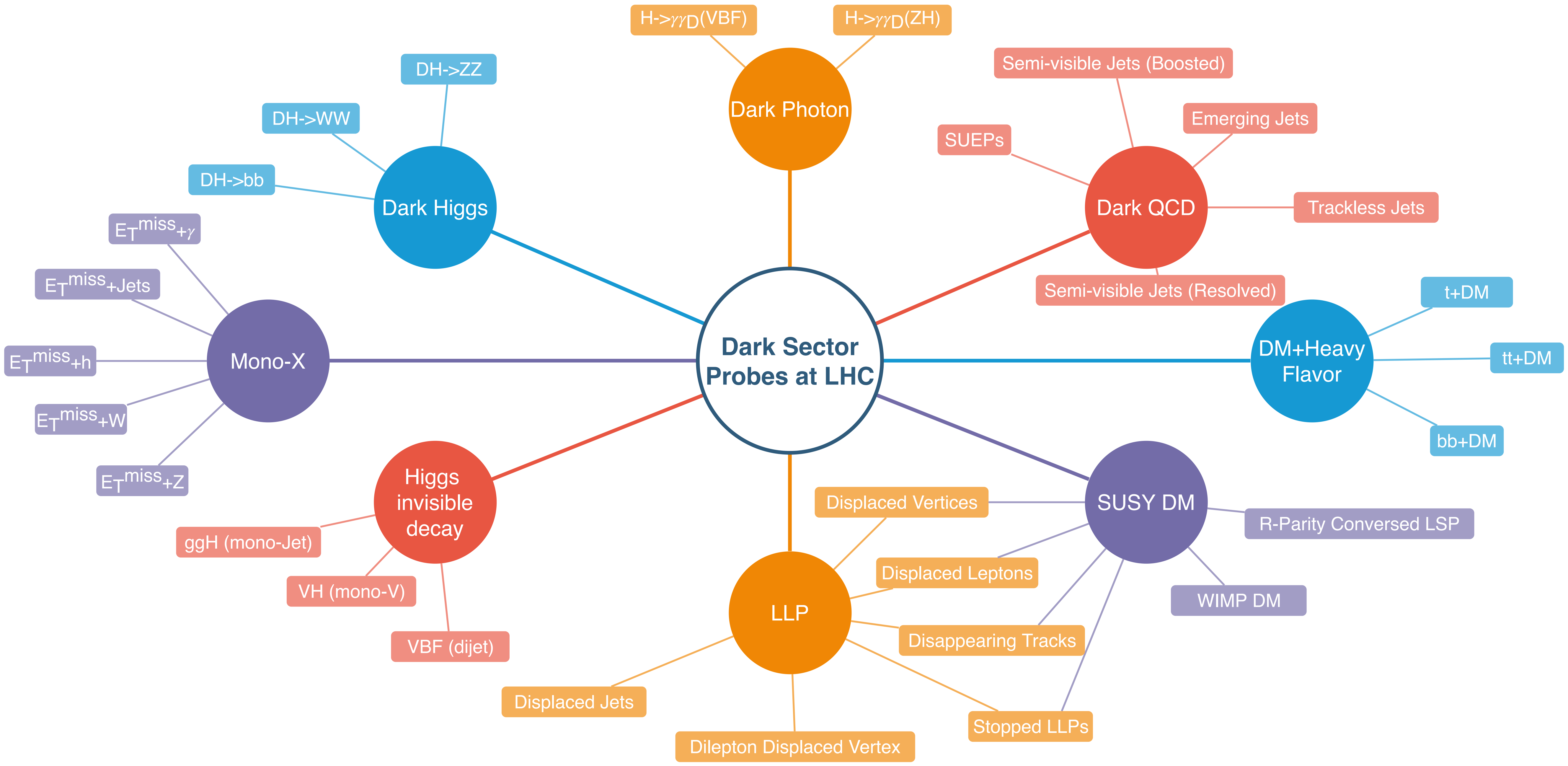
We need a broad, versatile and ambitious programme that
1. sharpens our knowledge of already discovered physics
2. pushes the frontiers of the unknown in the intensity and energy frontiers
— FCC-ee+eh+hh combine these different aspects —
more PRECISION, more ENERGY for more SENSITIVITY to New Physics

"Intensity frontier" is not only about precise measurements but
it could reveal light and weakly coupled structures as solution to the main open HEP questions.

This makes FCC-ee valuable on its own, though the synergy with FCC-hh remains invaluable.

LHC: driving cultural change forward

Beyond WIMP: signature-driven DM portals



L. Wang@Blois'22

Snowmass 2021 Higgs Factory Considerations

J. Bagger+ arXiv:2203.06164

— Physics Considerations —

P1	P2	P3	P4	P5	P6	P7
Precision Higgs measurements to SM particles	Measurements of Higgs self-coupling(s)	Sensitivity to rare and exotic Higgs decays	New Physics discovery potential	Direct measure of EW/Yukawa top coupling	Indirect sensitivity to New Physics	Improved measurements of α_s

— Technological Considerations —

T1	T2	T3	T4	T5	T6	T7
Range of operating E/ease of changing E	Annual integrated luminosity	Upgradability to higher energy/ luminosity	Extent and cost of remaining R&D	Ability to operate at the tt threshold	Ability to run at the Z pole	Ability to run at the WW threshold

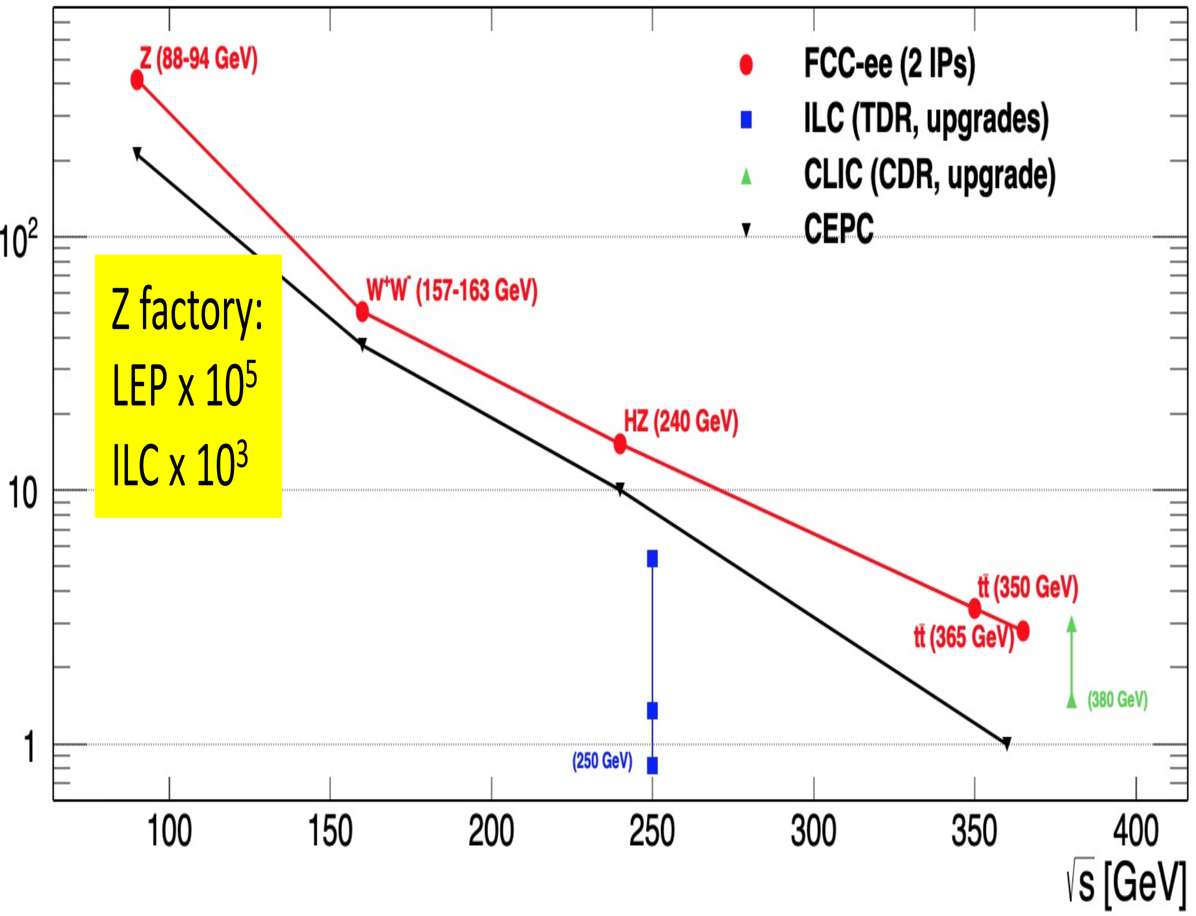
T8	T9	T10	T11	T12-T13	T14-T15	T16
Stability and calibration of collision energy	Beam stability and luminosity calibration	Ability to control beam-related backgrounds	Ability to provide independent confirmation of new discoveries	Ability to provide polarised electrons/ positrons	Possibility to reconfigure as $\gamma\gamma$, $e^-\gamma$, e^-e^-, ep, pp collider	Opportunities for beam dumps experiments

T17
Need for, and scientific utility of, technology demonstrators

FCC-ee Run Plan

LEP data accumulated in first 3 mn. Then exciting & diverse programme with different priorities every few years.

(order of the different stages still subject to discussion/optimisation)



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

— Superb statistics achieved in only 15 years —

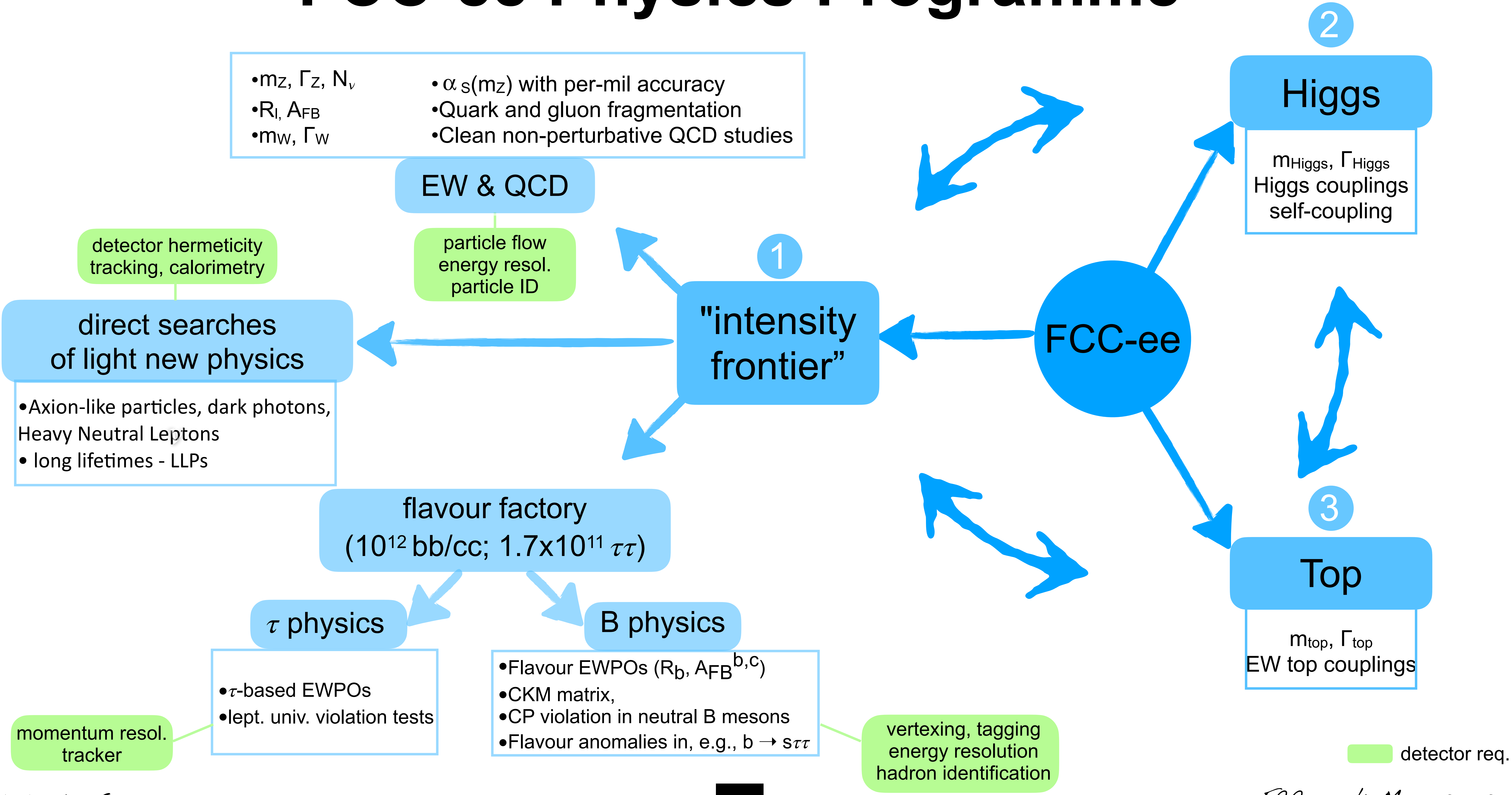
in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

Event statistics (2IP)

						E_{CM} errors:
Z peak	E_{cm} : 91 GeV	4yrs	5 10^{12}	e+e- → Z	LEP x 10^5	<100 keV
WW threshold	$E_{cm} \geq$ 161 GeV	2yrs	>10^8	e+e- → WW	LEP x 2.10^3	<300 keV
ZH maximum	E_{cm} : 240 GeV	3yrs	> 10^6	e+e- → ZH	Never done	1 MeV
s-channel H	*E_{cm} : m_H*	*(3yrs?)*	*O(5000)*	*e+e- → H*	*Never done*	<< 1 Me
$t\bar{t}$	E_{cm} : ≥ 350 GeV	5yrs	10^6	e+e- → $t\bar{t}$	Never done	2 MeV

6

FCC-ee Physics Programme



FCC-ee Physics Programme

2

Higgs

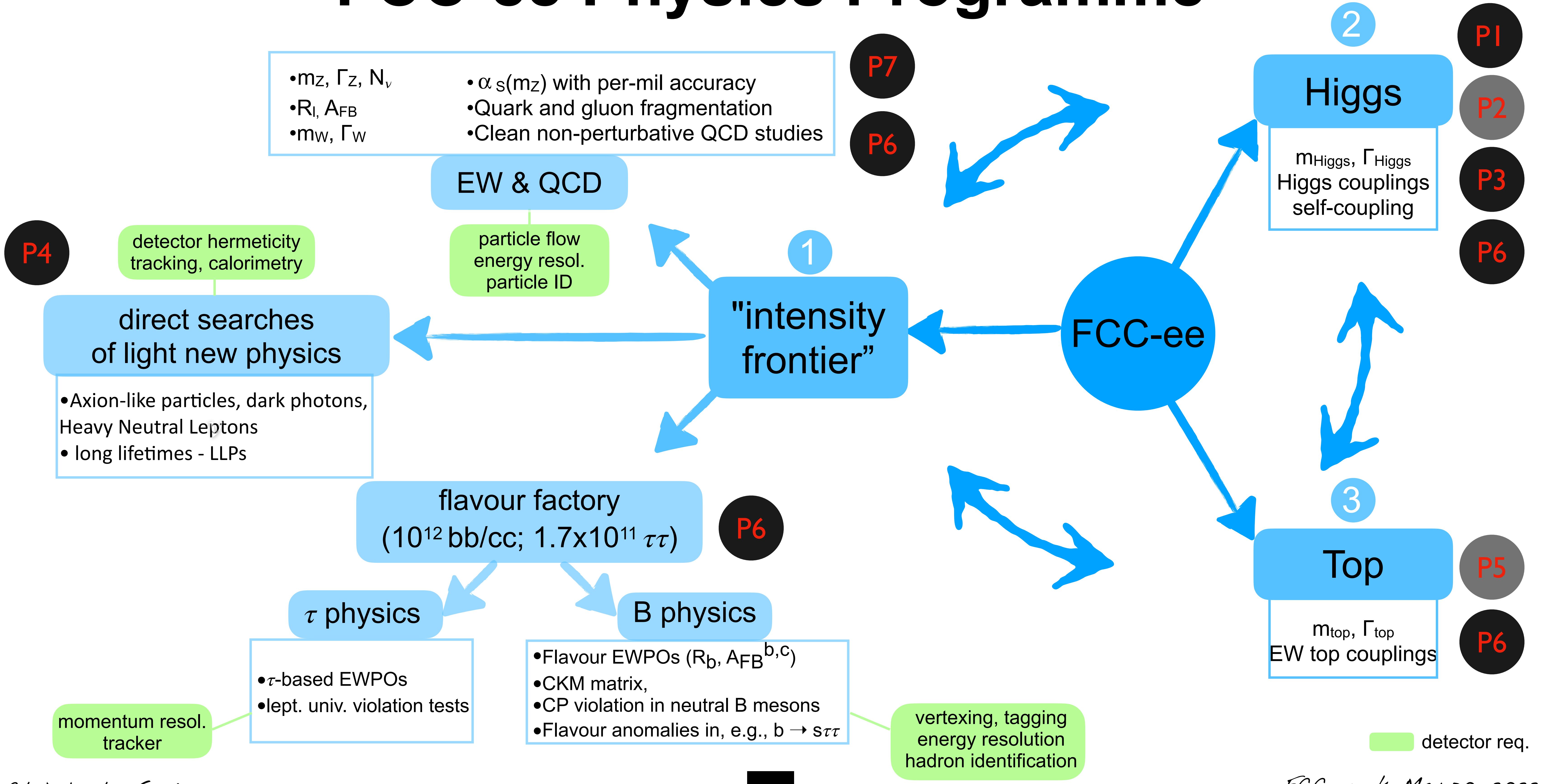
m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

Higgs sector definition imposes initial requirements on **hadronic resolution, tracking and vertexing**

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$BR(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$BR(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu m$
$H \to q\bar{q},\ VV$	$BR(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{jet}/E \sim 3-4\%$
$H \to \gamma\gamma$	$BR(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

detector req.

FCC-ee Physics Programme



Z-Factories are great Flavour Factories

See S. Monteil, FCC CDR overview '19

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	1000	500

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

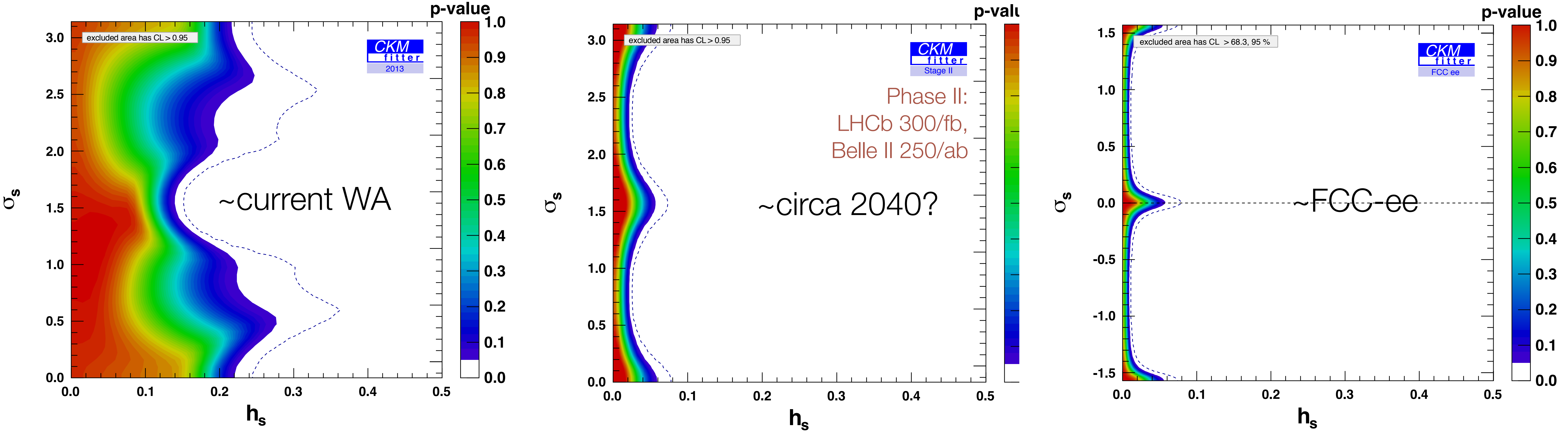
out of reach at LHCb/Belle

boosted b's/τ's at FCC-ee

Z-Factories are great Flavour Factories

Kamenik @ FCC Physics WS '22

$$\langle B_q|\mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2}|\bar{B}_q\rangle = \langle B_q|\mathcal{H}^{\mathrm{SM}}_{\Delta B=2}|\bar{B}_q\rangle \left(1+h_q e^{i\sigma_q}\right)$$

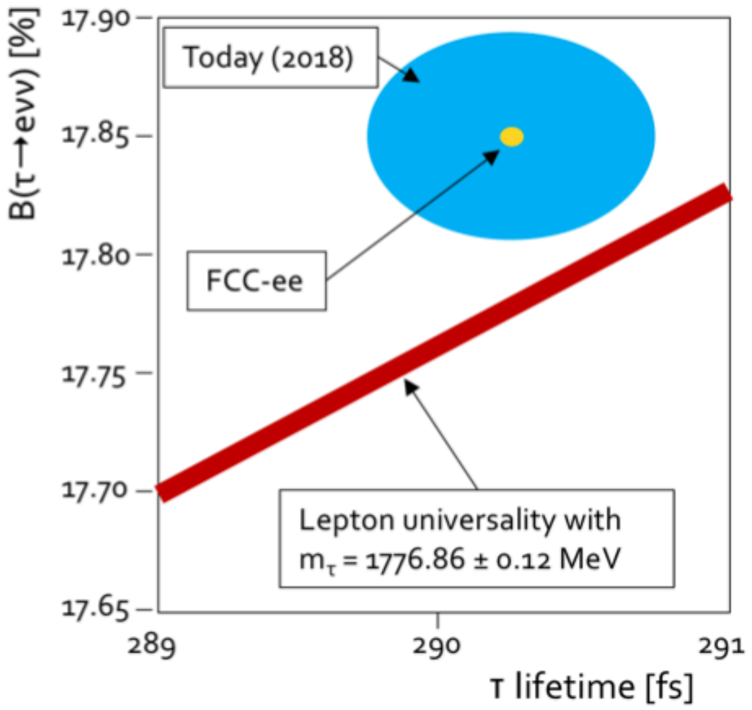


FCC-ee: sensitivity of scale of new physics (with MVF structure) > 20 TeV

Probing New Physics w/ τ Decays

Allwicher, Isidori, Semilovic '21

$$\left|g_e^{(\tau)}/g_e^{(\mu)}\right|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar\nu)}{\Gamma(\mu\to e\nu\bar\nu)}\left[\frac{\Gamma_{\rm SM}(\tau\to e\nu\bar\nu)}{\Gamma_{\rm SM}(\mu\to e\nu\bar\nu)}\right]^{-1}$$

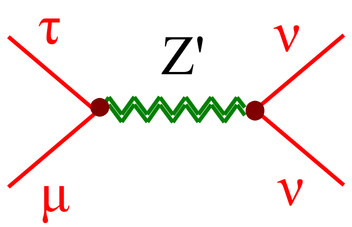


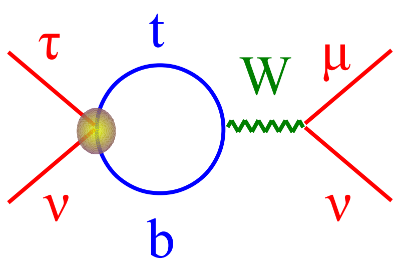
sensitivity good enough to probe BSM models "explaining" current flavour R_K anomalies ($b\to c\tau\nu$)

E.g.: (I) LFU tests in tau decays

A. Pich '13

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\|g_\mu/g_e\|$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\|g_\tau/g_\mu\|$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\|g_\tau/g_e\|$	1.0030 (15)	1.031 (13)			





"Model-independent" effect linked to present anomalies

- NP expectation from current anomalies in the range $(0.2 - 4.0) \times 10^{-3}$
- SM theory precision ~ 10^{-5}
- Belle-II can (at most) reach an error ~ 0.3×10^{-3}
- FCC-ee could go below 10^{-4} !

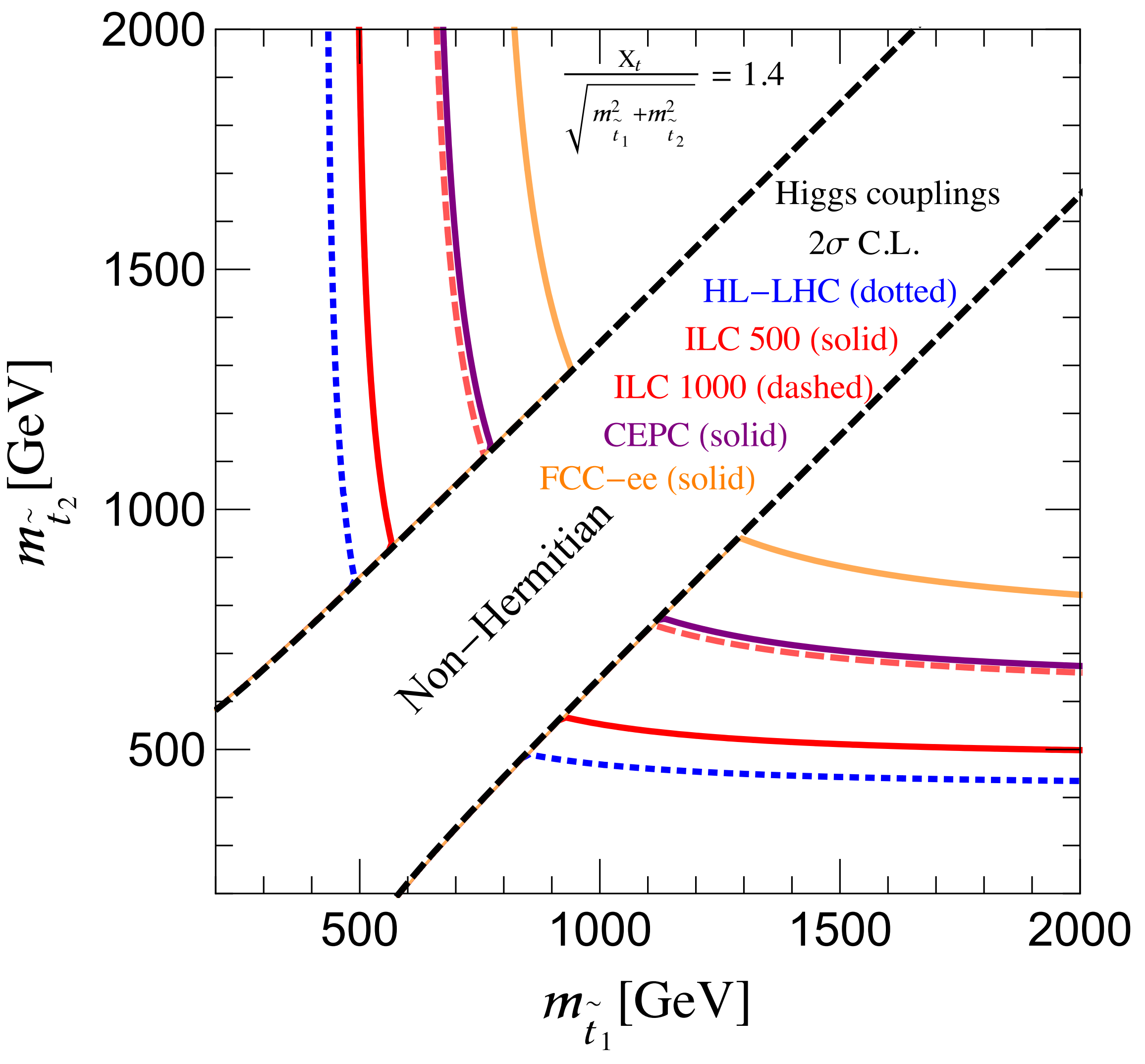
Unique opportunity !

Discovery Potential Beyond LHC

Precisely measured EW and Higgs observables are sensitive to heavy New Physics

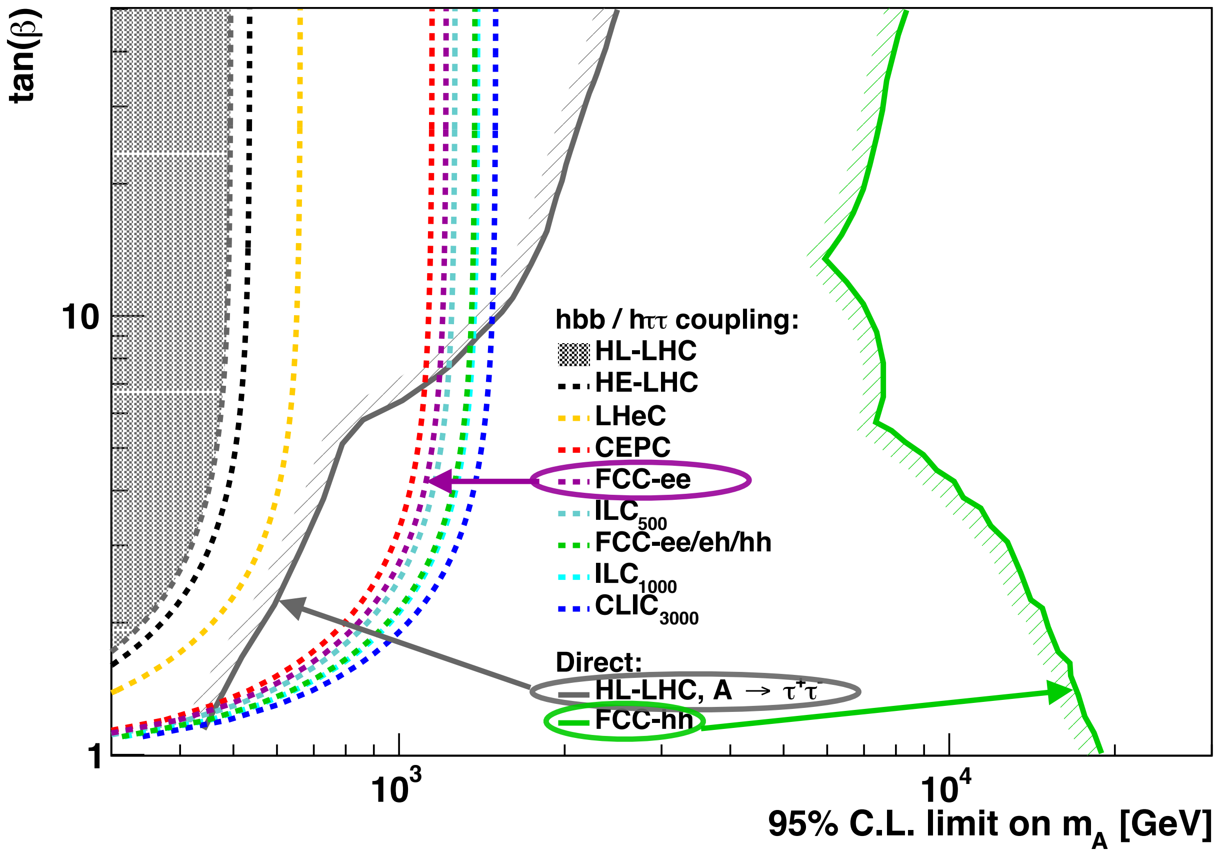
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

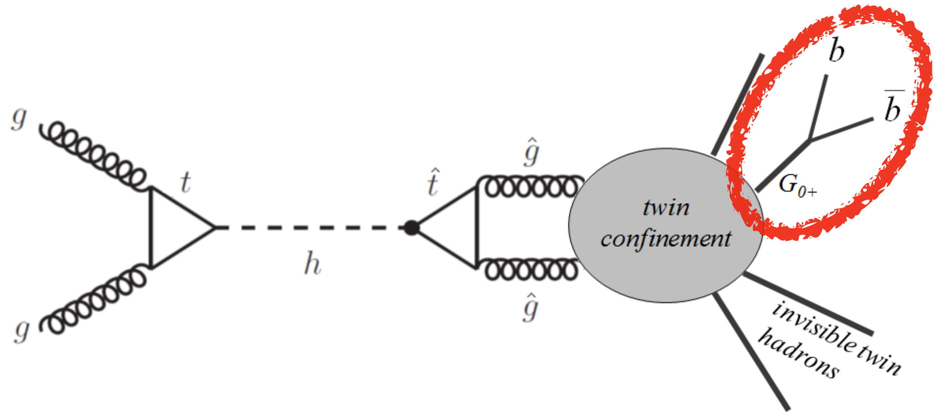


ESU Physics BB '19

Direct Searches for Light New Physics

- **LLP searches with displaced vertices**
  e.g. in twin Higgs models glueballs that mix with the Higgs and decay back to b-quarks

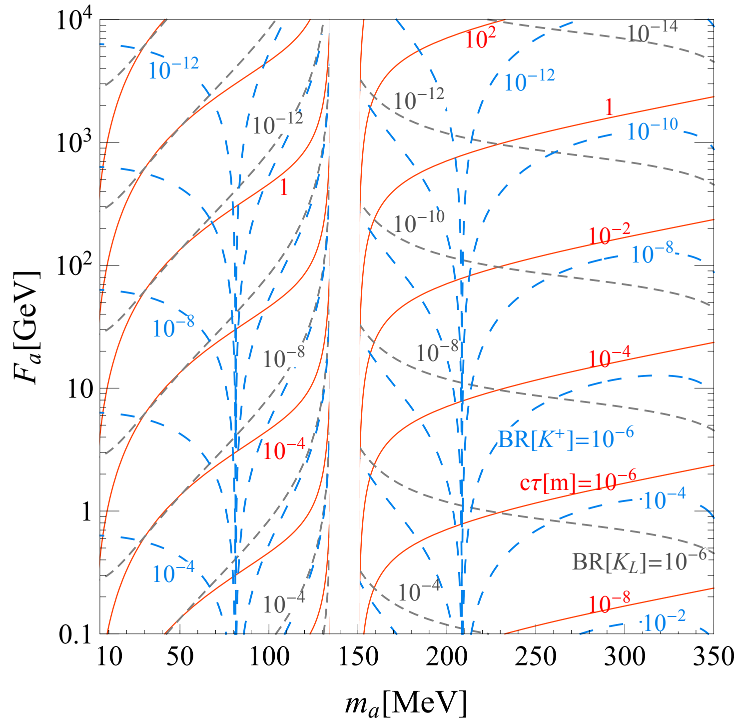
Craig et al, arXiv:1501.05310



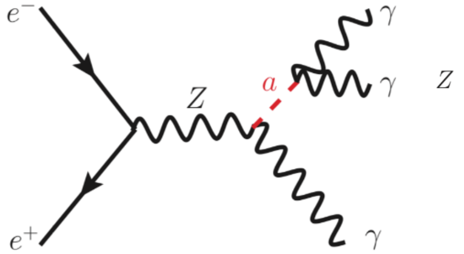
- **Rare decays** Gori et al arXiv:2005.05170
  e.g. ALP mixing w/ SM mesons:

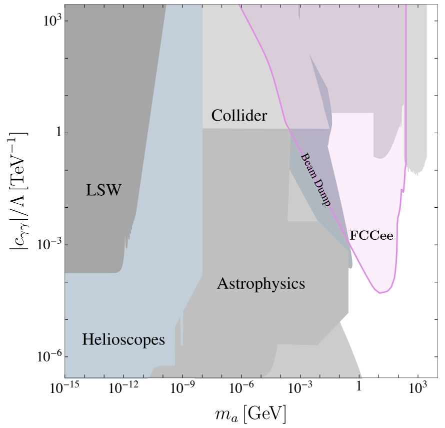
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \ \text{(KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \ \text{(NA62)}$$

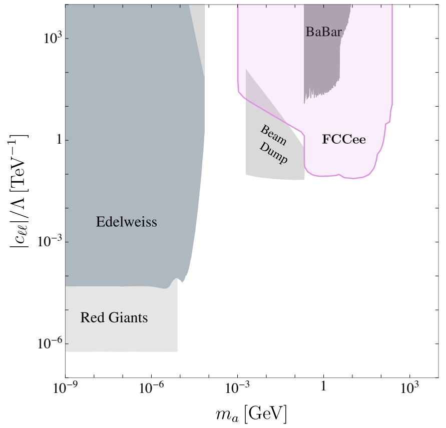
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu}\tilde{G}^{\mu\nu}$$



- **ALPs@ colliders**
  e.g. $e^+e^- \to \gamma a$
  $e^+e^- \to ha$





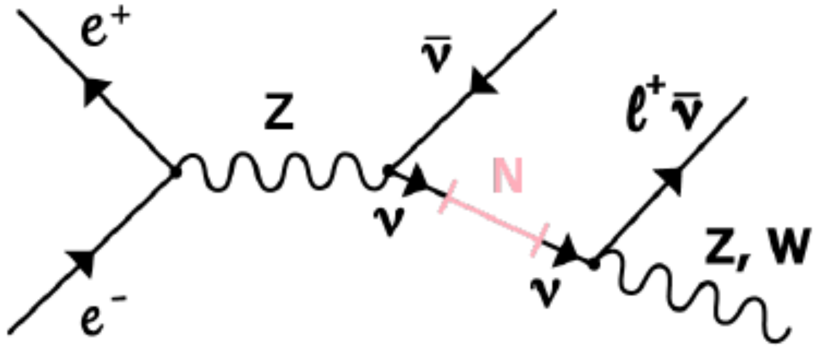


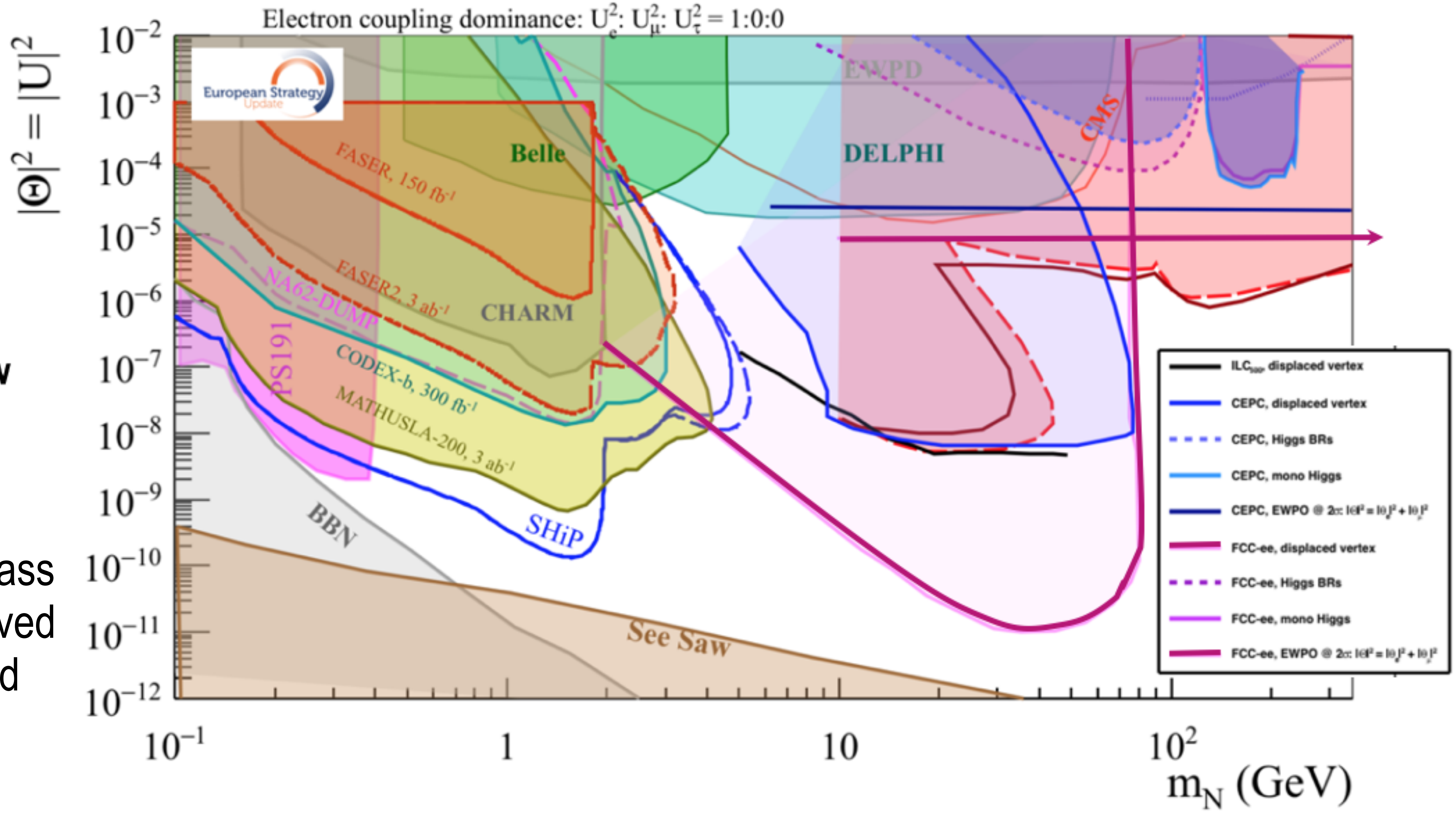
Astro/Cosmo → long-lived ALPs
colliders → short-lived ALPs MeV+

Knapen, Thamm arXiv:2108.08949

Search for ν_{RH}

Direct observation in Z decays from LH-RH mixing





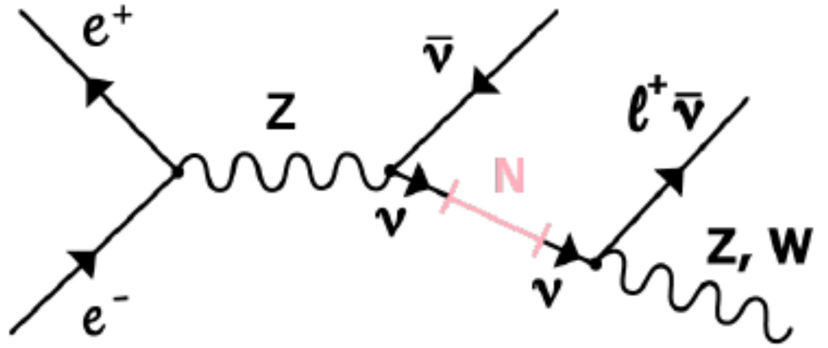
ESU Physics BB '19

Important to understand
1. how neutrinos acquired mass
2. if lepton number is conserved
3. if leptogenesis is realised

Search for ν_{RH}

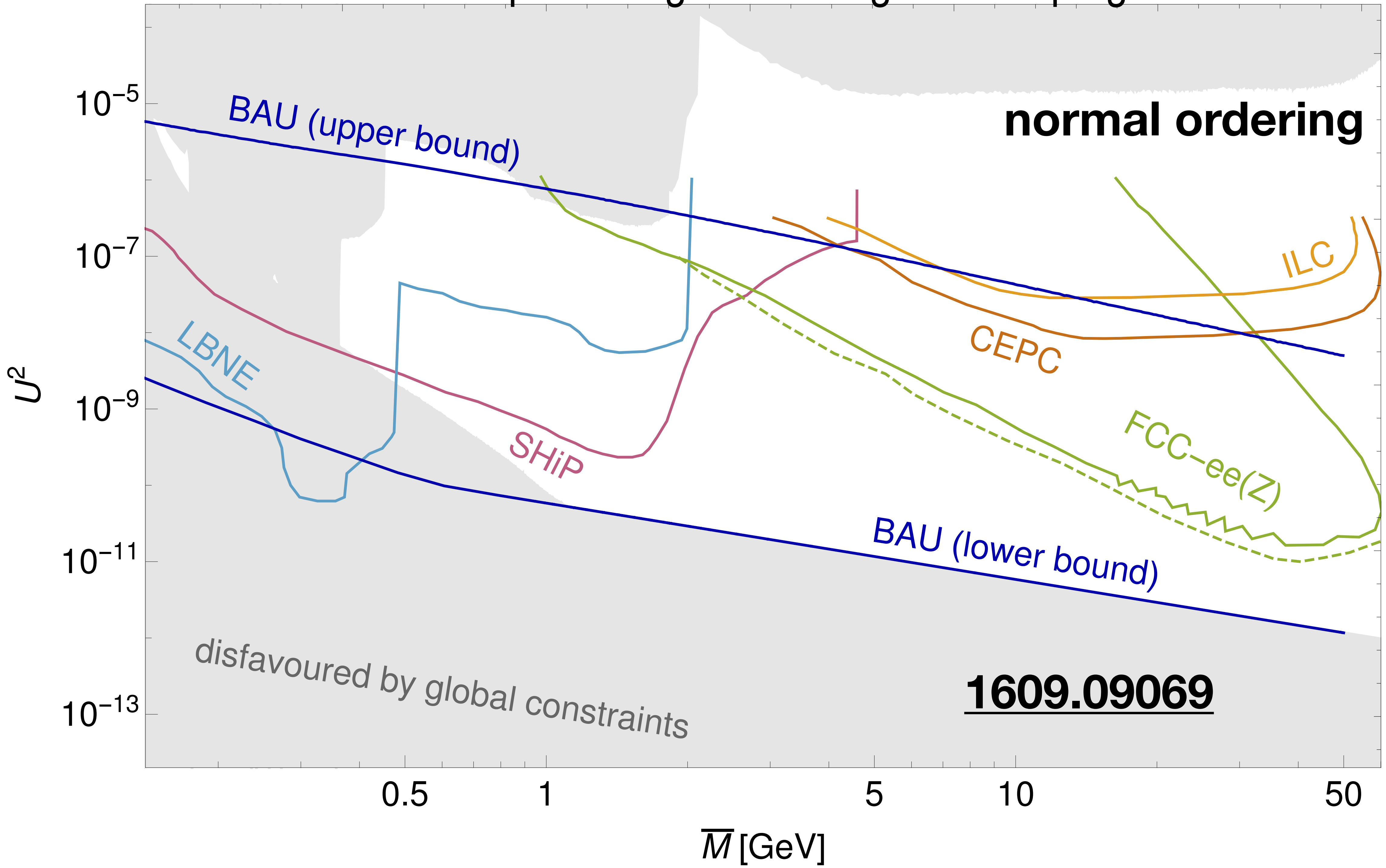
Direct observation
in Z decays
from LH-RH mixing

$|\Theta|^2 = |U|^2$



Important to understand
1. how neutrinos acquired mass
2. if lepton number is conserved
3. if leptogenesis is realised

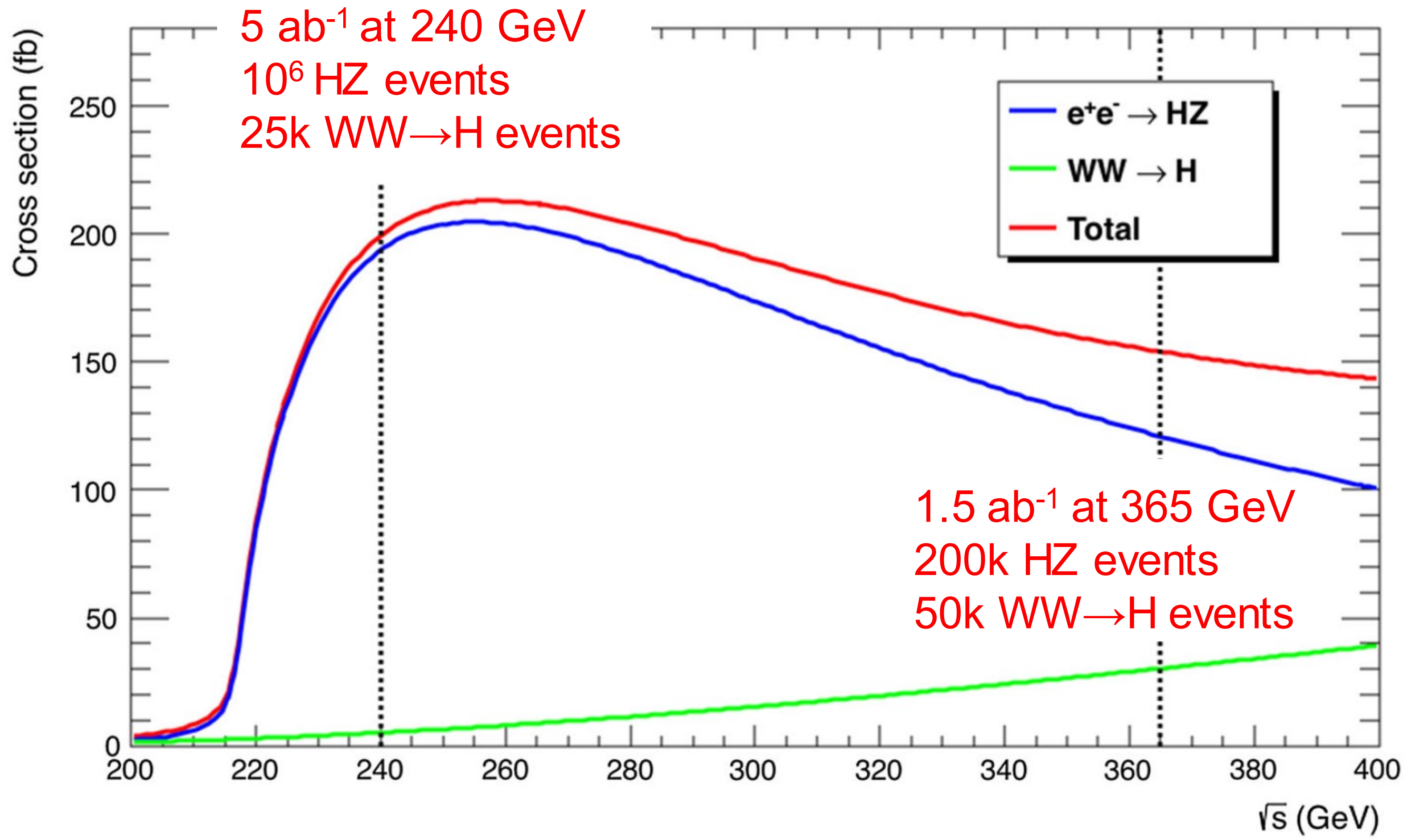
FCC-ee can probe large viable regions of leptogenesis

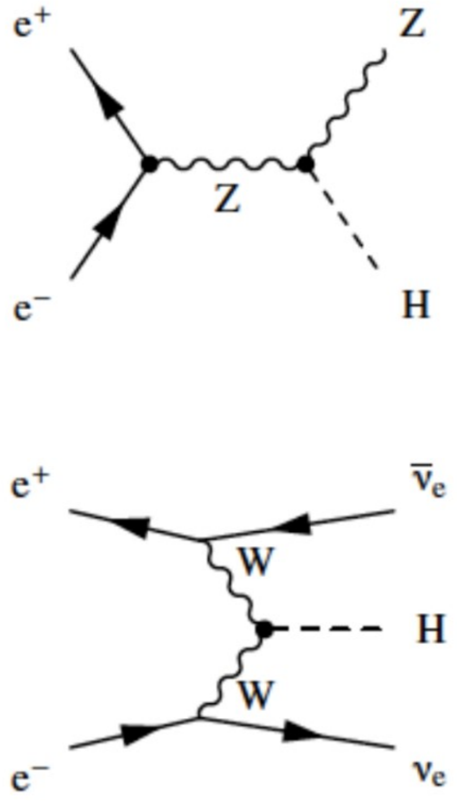


Higgs @ FCC-ee

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)% precision. Achieved through operation at two energy points.

G. Wilkinson, FCC Physics WS '22





see talks by G. Durieux and J. Eysermans

Sensitivity to both processes very helpful in improving precision on couplings.

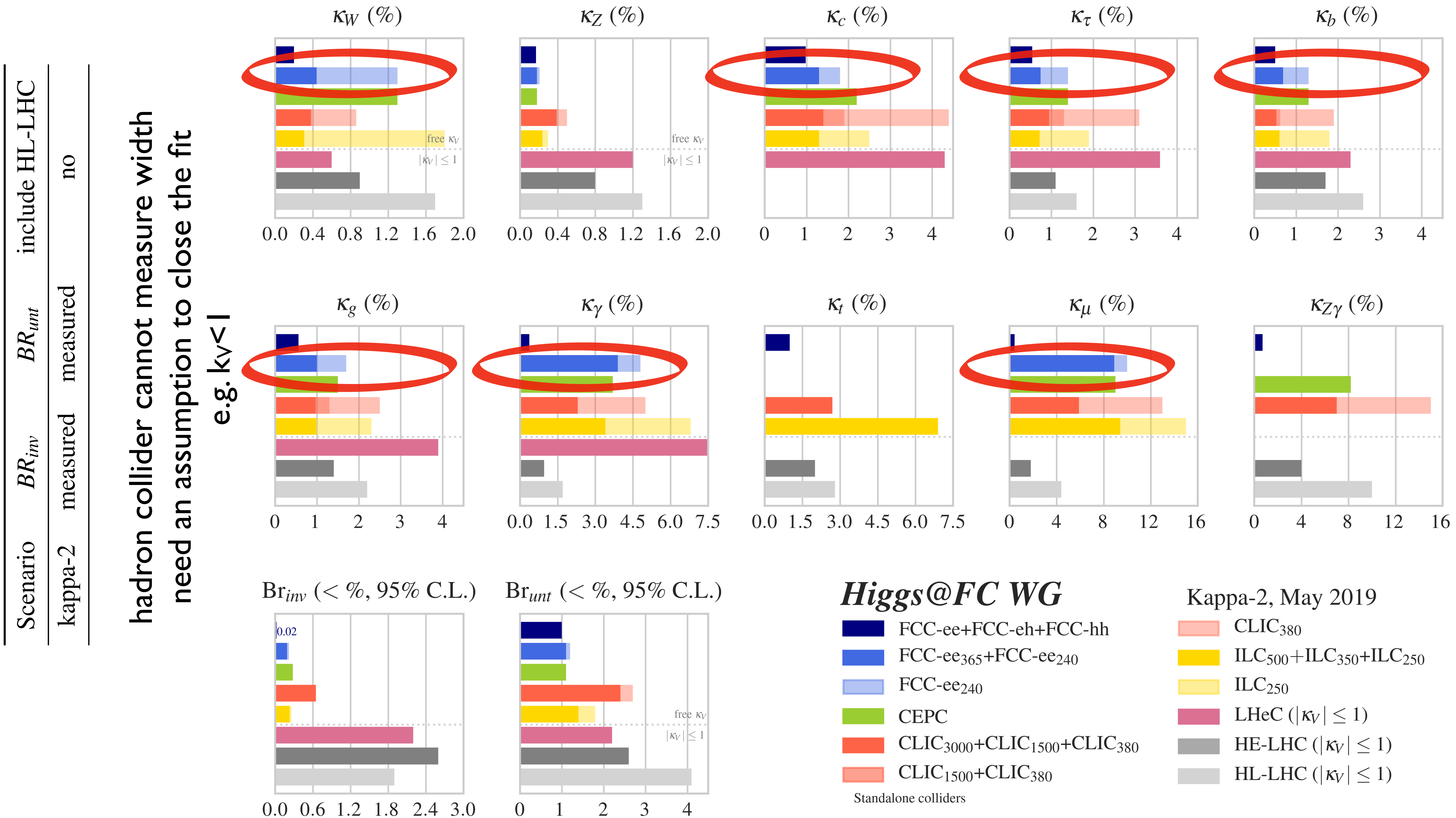
Table 8: Operation costs of low-energy Higgs factories, expressed in Euros per Higgs boson.

Collider	ILC_{250}	$CLIC_{380}$	FCC-ee_{240}
Cost (Euros/Higgs)	7,000 to 12,000	2,000	255

FCC-ee, 1906.02693

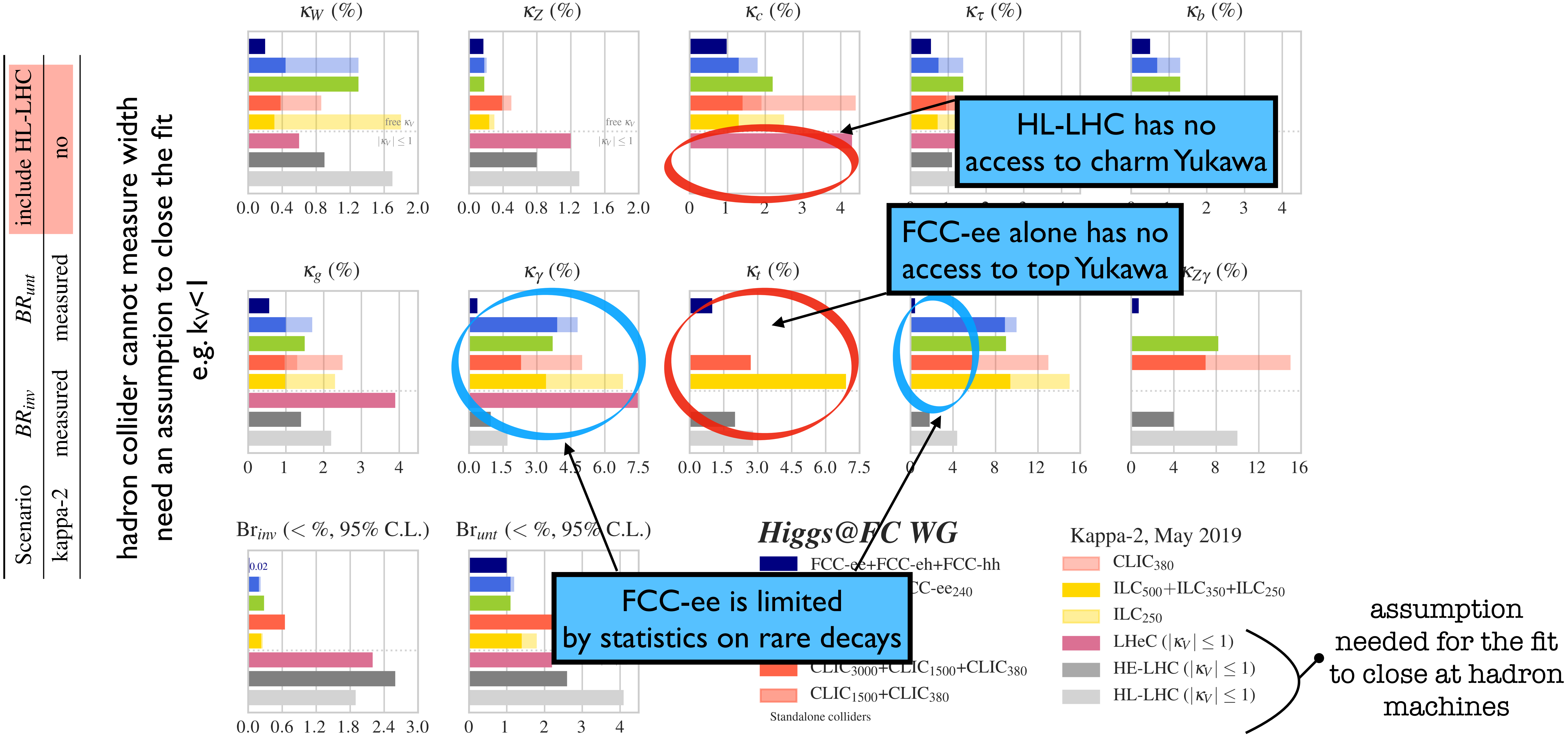
Higgs @ FCC-ee: Complementarity of 240/365 GeV

ECFA Higgs study group '19



Higgs @ FCC-ee: Complementarity with HL-LHC

ECFA Higgs study group '19



Higgs @ FCC-ee: Complementarity with HL-LHC

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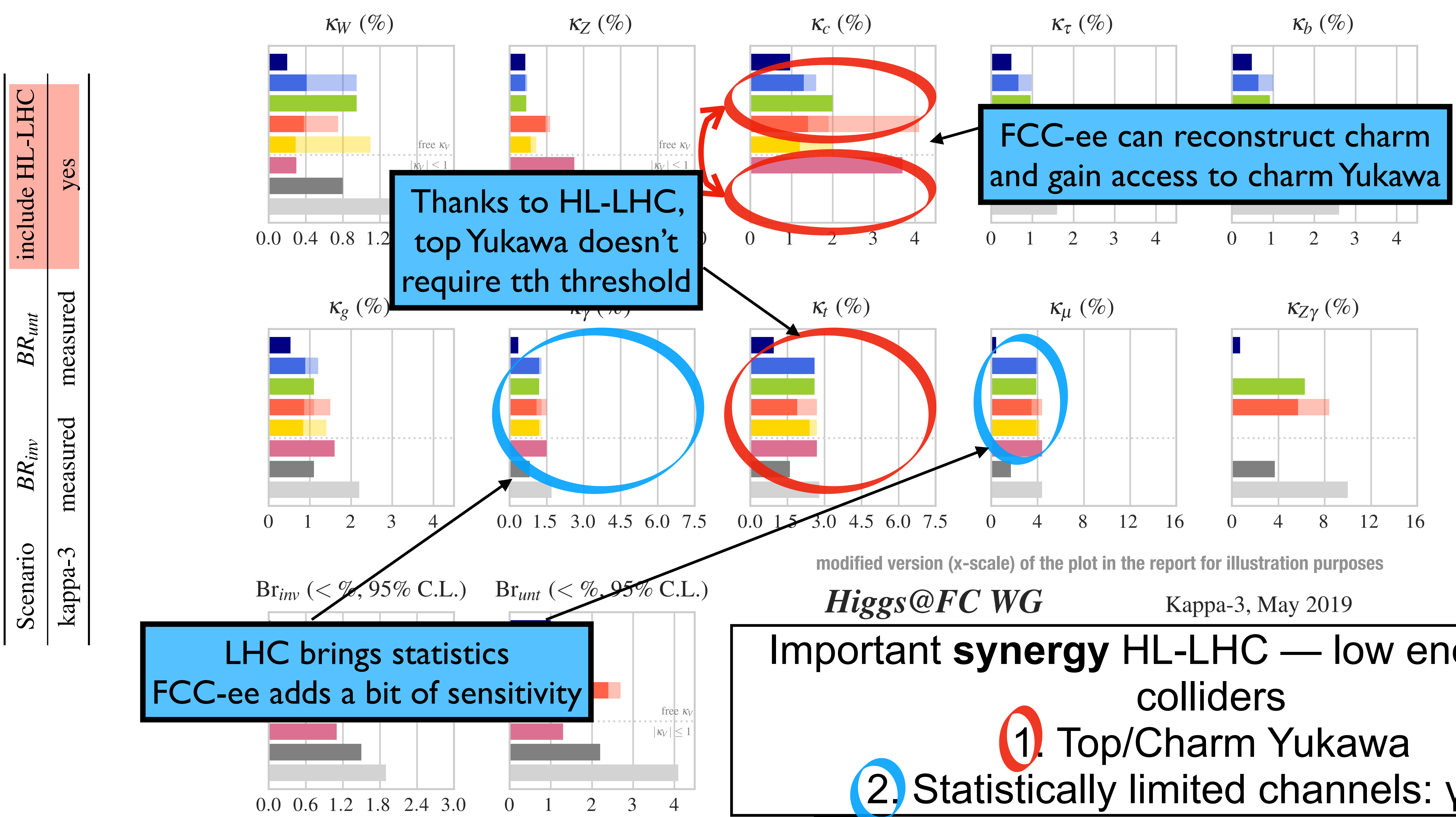
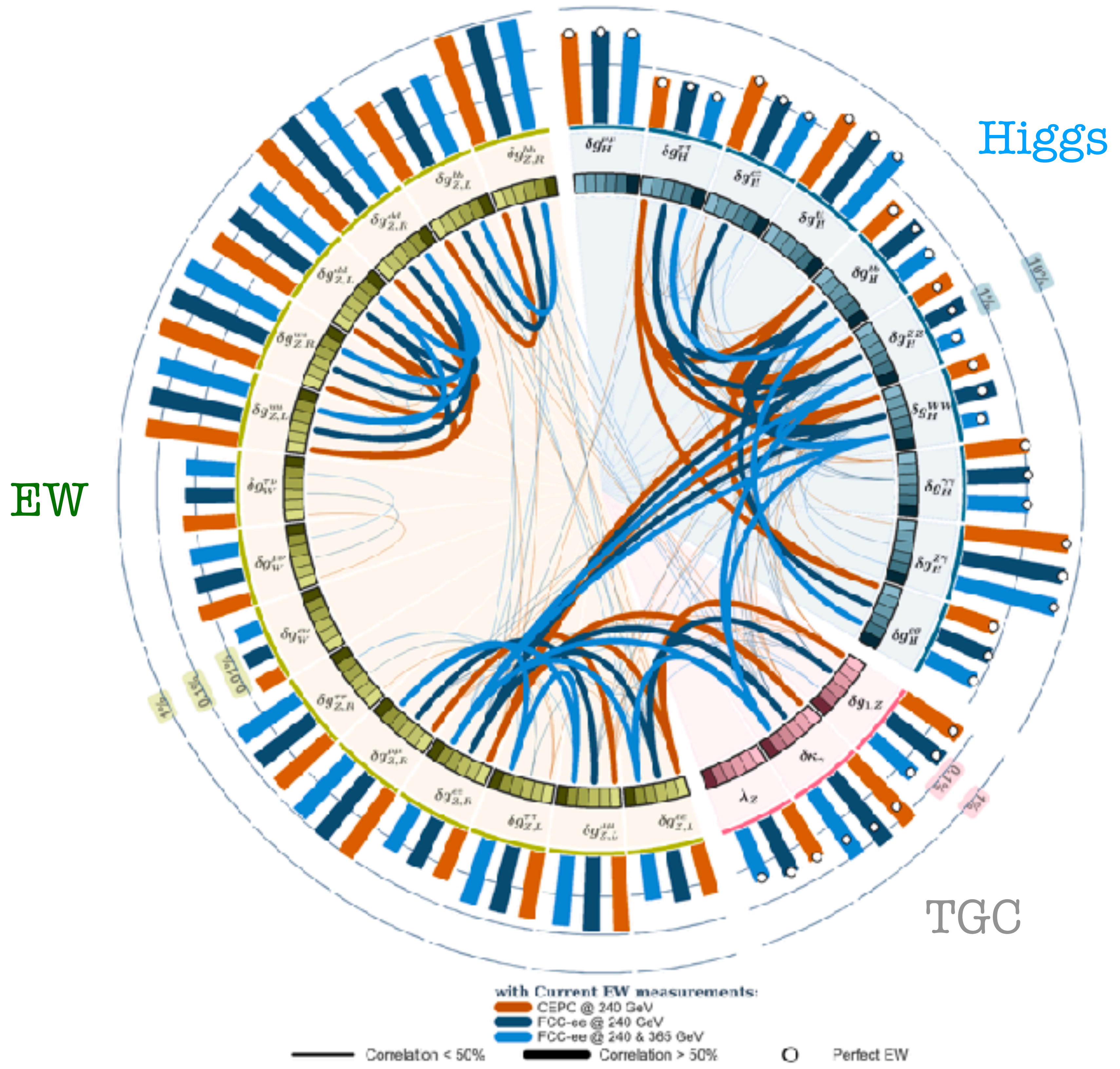


Important **synergy** HL-LHC — low energy lepton colliders

1. Top/Charm Yukawa
2. Statistically limited channels: γγ, μμ

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311

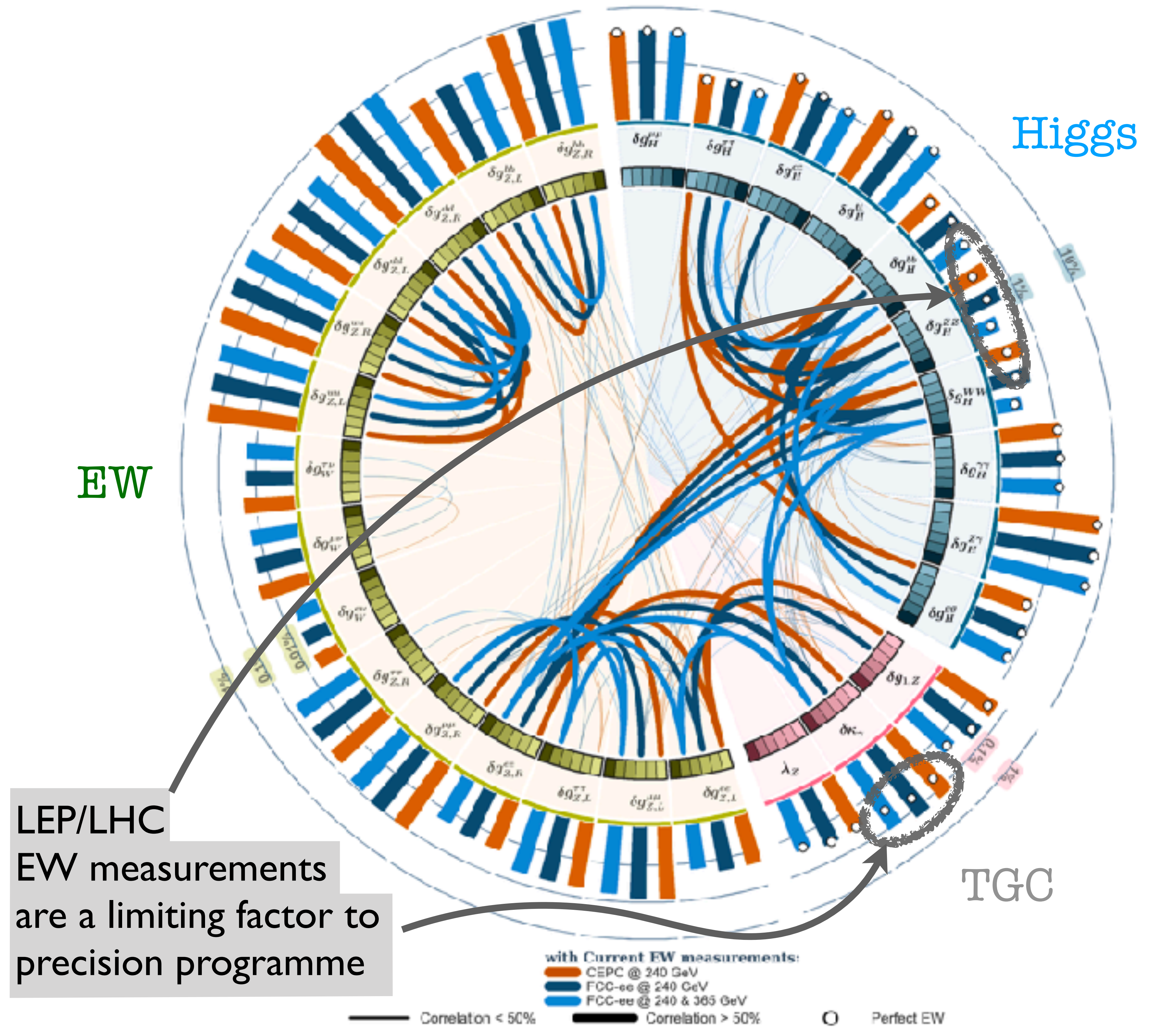


Contamination EW/TGC/Higgs can be understood by looking at correlations

Without Z-pole runs, there are large correlations between EW and Higgs

Impact of Z-pole Measurements

J. De Blas et al. 1907.04311



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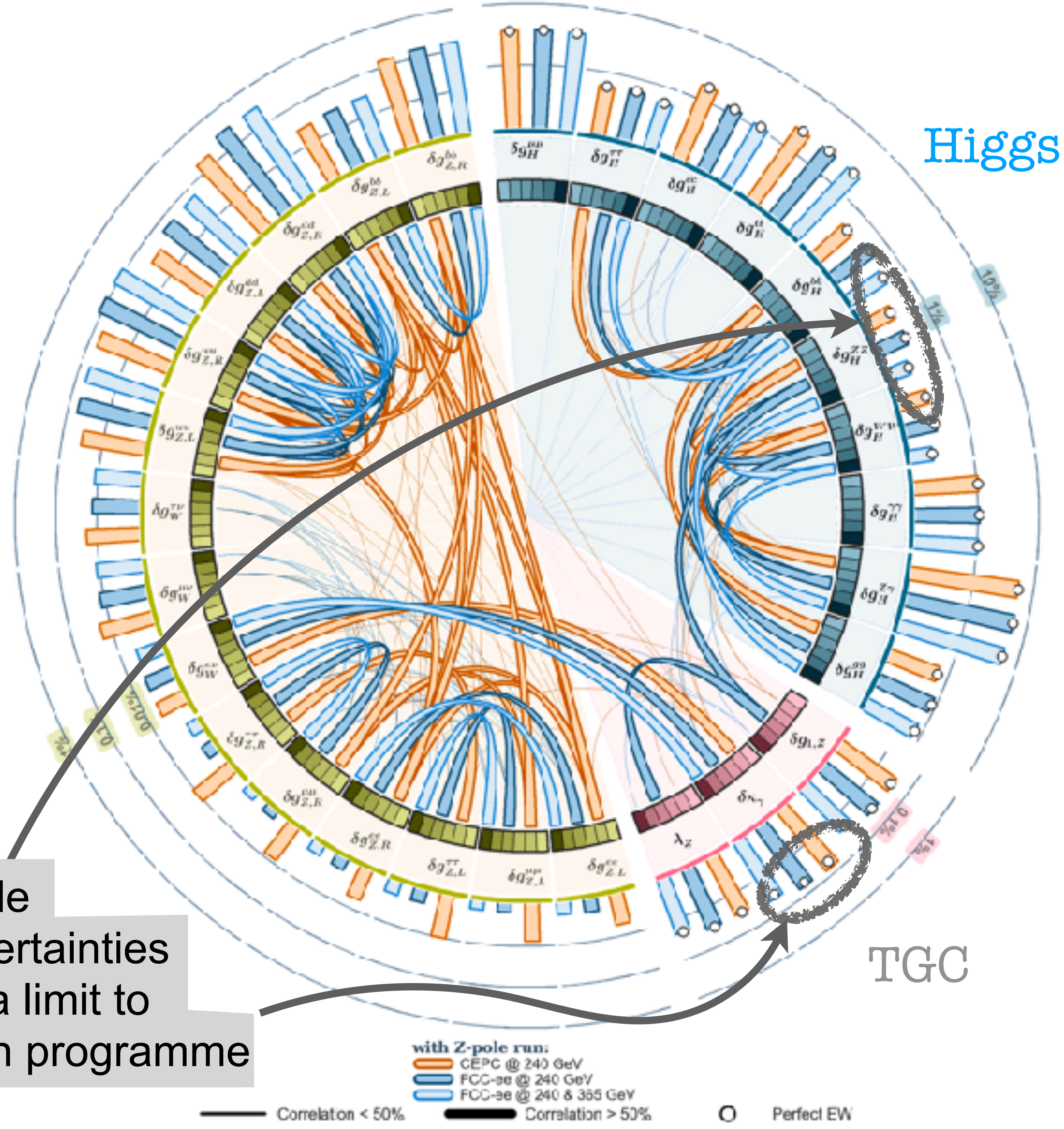
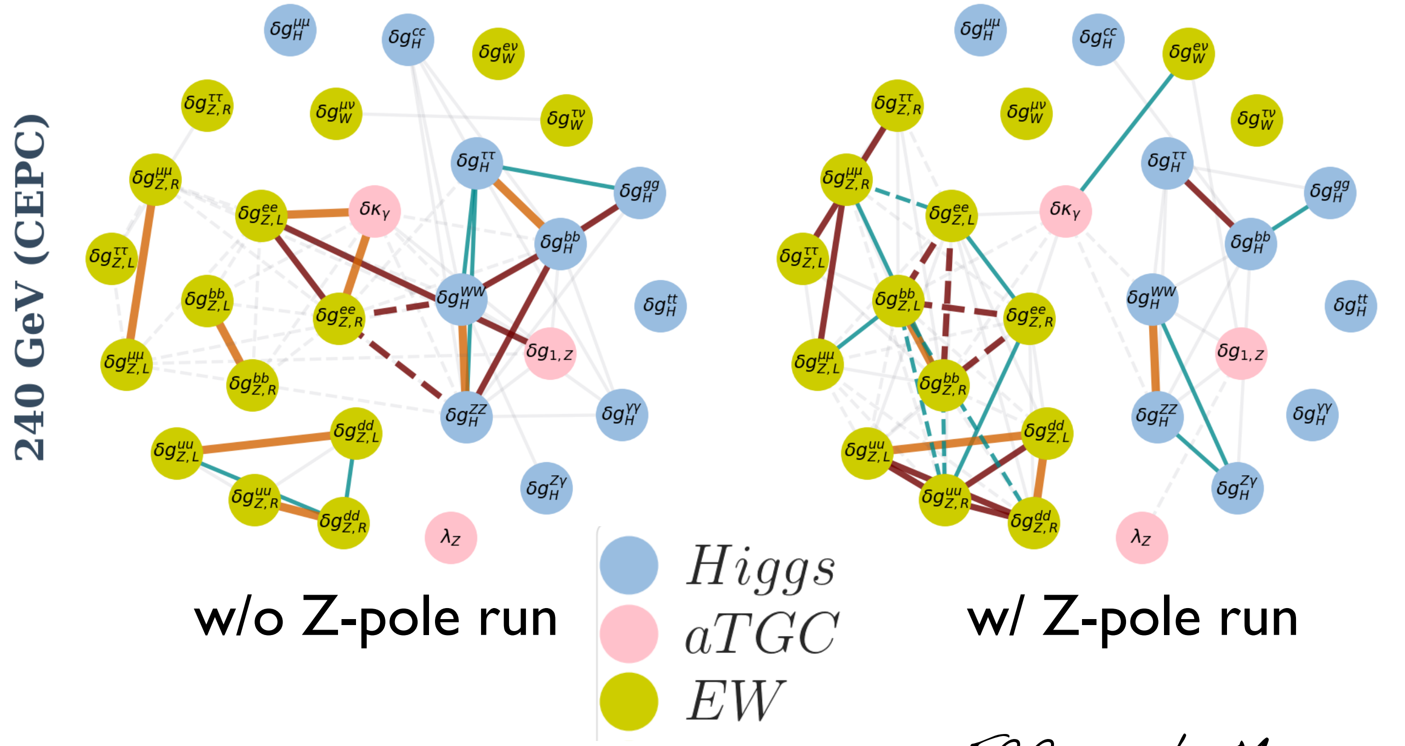
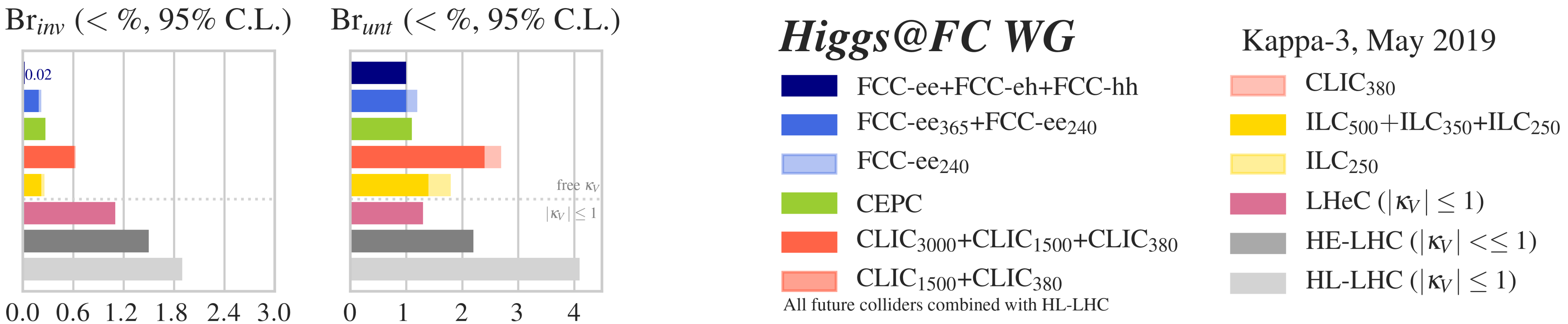


Z-pole runs at circular colliders isolate EW and Higgs sectors from each others



Higgs @ FCC-ee: Pivot between LHC and FCC-hh

1

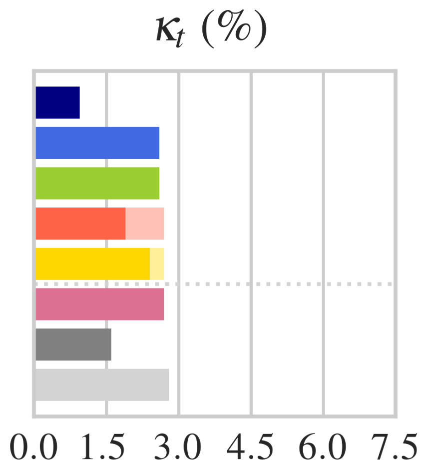


FCC-hh without ee could still bound BR_{inv}

but it could say nothing about BR_{unt}

FCC-ee needed for absolute normalisation of Higgs couplings

2

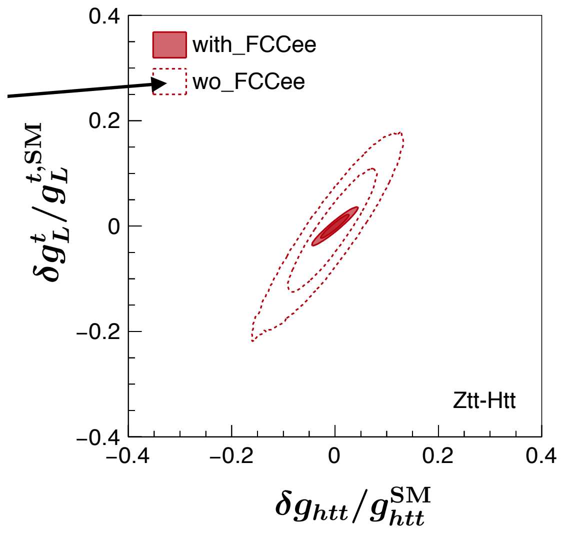


FCC-hh is determining top Yukawa through ratio tth/ttZ
So the extraction of top Yukawa heavily relies on the knowledge of ttZ from FCC-ee

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

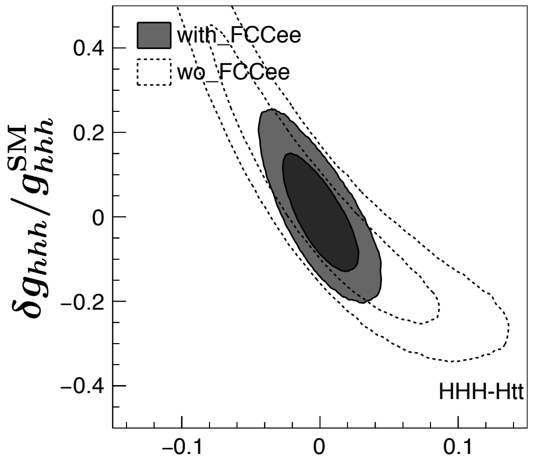
Mangano+ '15

uncertainty drops in ratio



3

Subsequently, the 1% sensitivity on tth is essential to determine h^3 at O(5%) at FCC-hh



Plots by J. de Blas, '19

Heavy Flavour Tagging

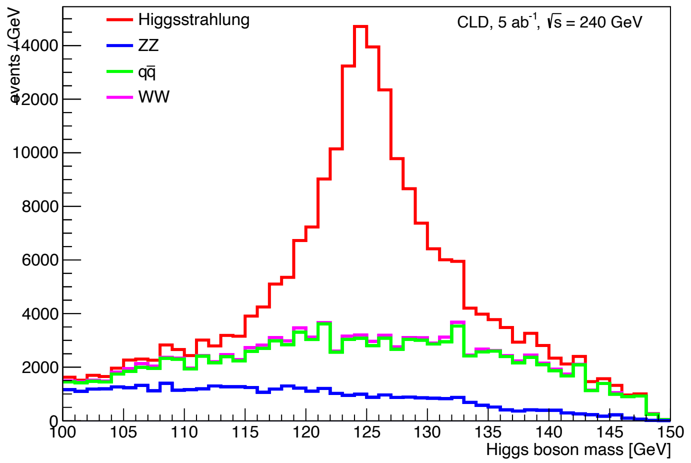
K. Peeters @ DESY '22

- Jet energy determination from jet direction

  Example: Z(qq)H(bb) four jet channel

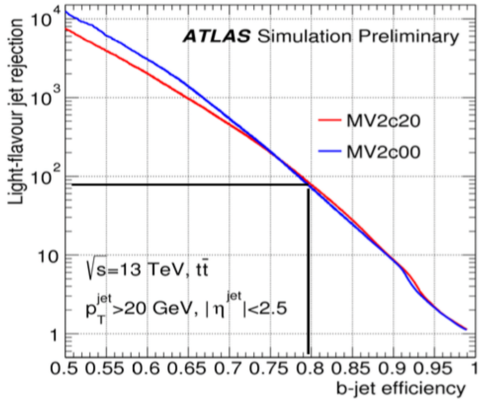
  Huge gain from directional jet energy determination

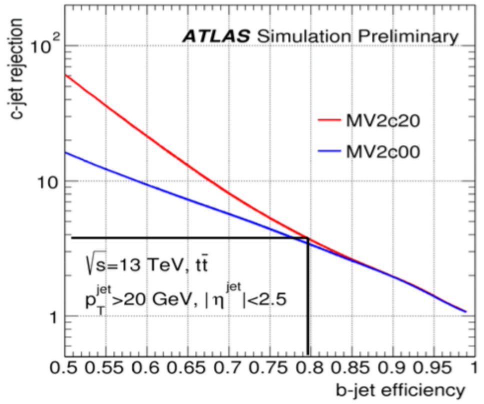
Directional measurement



- Precise knowledge of tagging rates are important to correct for cross contaminations in H→bb,cc,gg measurements

Branching Ratio @ 125 GeV	
$H \to bb$	57.7%
$H \to gg$	8.57%
$H \to c\bar{c}$	2.91%





b and c separation is particularly important due to the large H→bb and small H→cc BRs

- ATLAS example, for a b-jet tagging efficiency of 80%, the rejection factors are about 100 for light-jets and only a factor of 4 for c-jets
- Such low c-jet rejection will lead to a huge contamination of H → bb in H → cc candidate sample

Access to s Yukawa

Improved jet flavour tagging opens up new opportunities

Selvaggi @ FCC week 2021

$BR(H \to ss) = BR(H \to cc)\,(m_s/m_c)^2 \sim 2.3\ 10^{-4}$

FCCee: σ_{ZH}~200fb, L ~ 5 ab^{-1} (2 IP): **~1M ZH**
[600k H→bb, 100k H→gg, 30k H→cc, **200 H→ ss**]

Use Loose WP:
[**s-tag: 90%**, **g-mist: 10%**, c-mist: 1%, b-mist: 0.4%

- **Scenario 1:** Z(→all)H:

N_{ss} = 150, N_b = 1000
(neglecting ee→ VV backgrounds)

δ(σxBR)/σxBR (%) ~ 21 % (~ 5σ) [no systematics, only higgs backgrounds, no combinatorics]

- **Scenario 2:** Z(→vv)H:

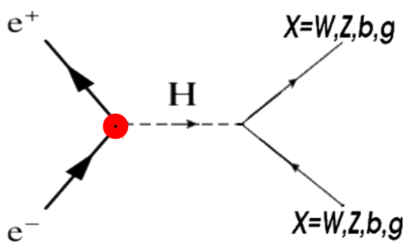
N_{ss} = 30, N_b = 200
(neglecting ee → vvqq and ee → qq, can be important given large q → s fake prob.)

δ(σxBR)/σxBR (%) ~ 49% (~ 2σ) [no systematics]

Back-of-the envelope estimates

THOROUGH STUDIES NEEDED

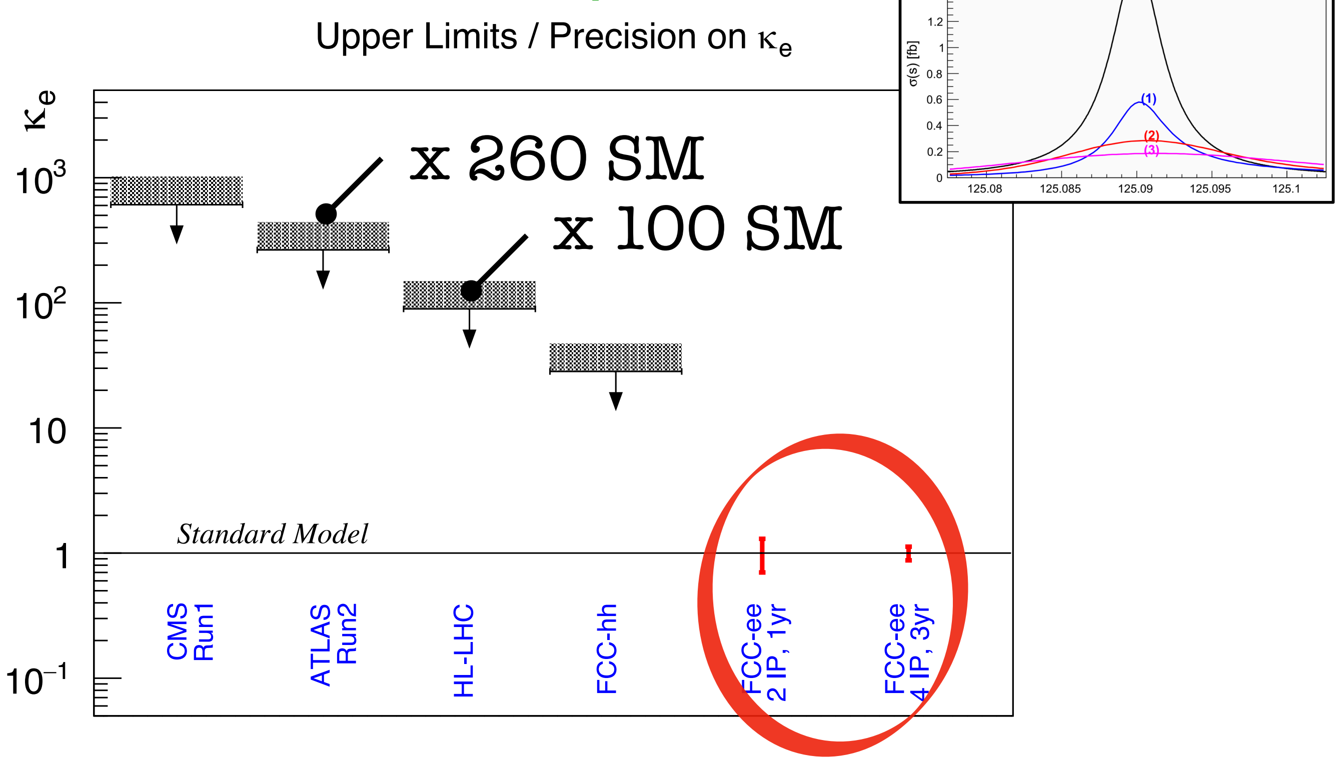
Access to e- Yukawa



$\sigma(e^+e^-\to H)$ = 1.64 fb

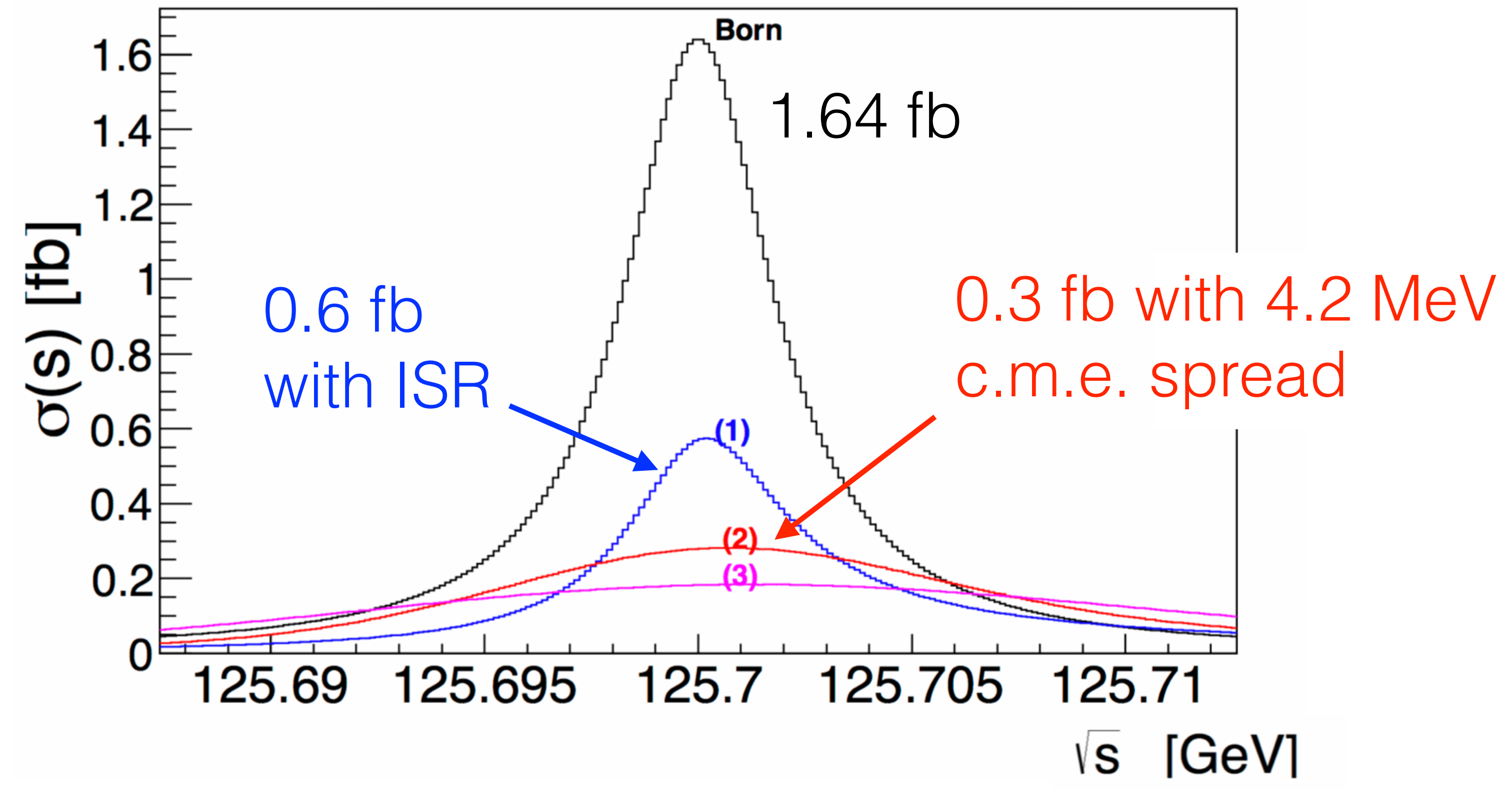
$\sigma_{spread+ISR}(e^+e^-\to H)=0.17\times\sigma(e^+e^-\to H)$=290 ab

- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim$ 1-2 × $\Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**



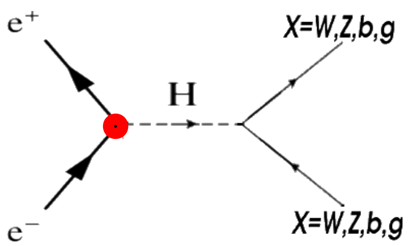
  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Jadach+, arXiv: 1509.02406



Producing these Higgses is not enough.
One needs to "see" them too.
To distinguish them from offshell Z's,
better to look at decays to particles that don't couple to Z's

Access to e⁻ Yukawa



$\sigma(e^+e^- \to H)$ = 1.64 fb

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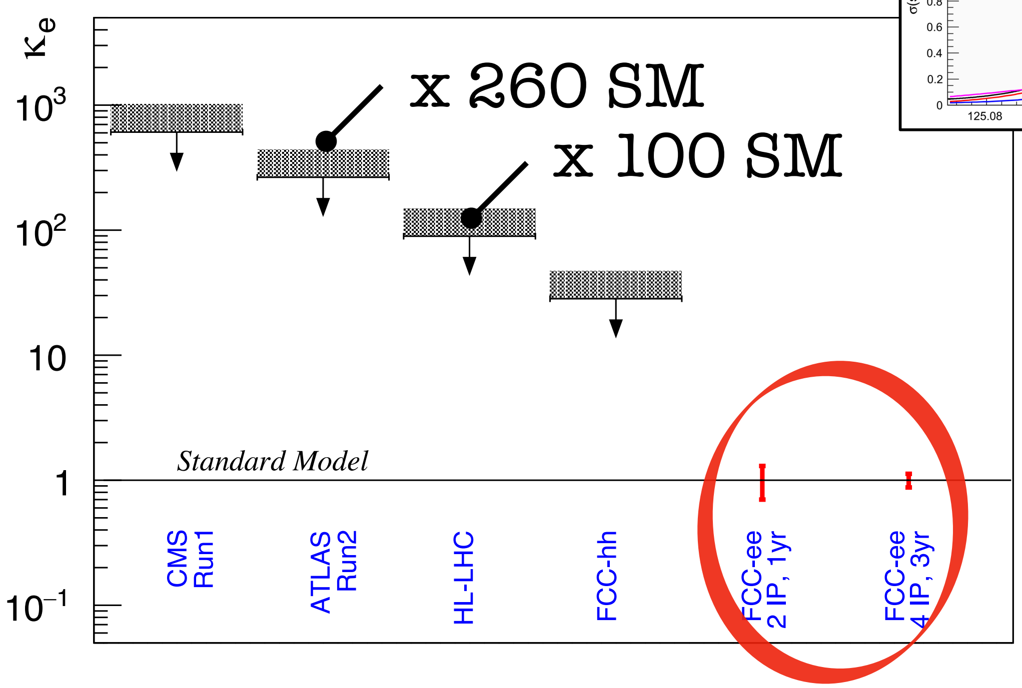
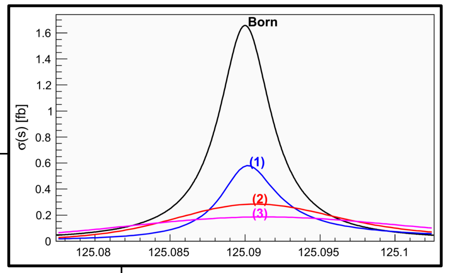
- **20 ab⁻¹ / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim 1\text{-}2 \times \Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**

Upper Limits / Precision on κ_e





  - **2σ excess in one year with 2 IP**
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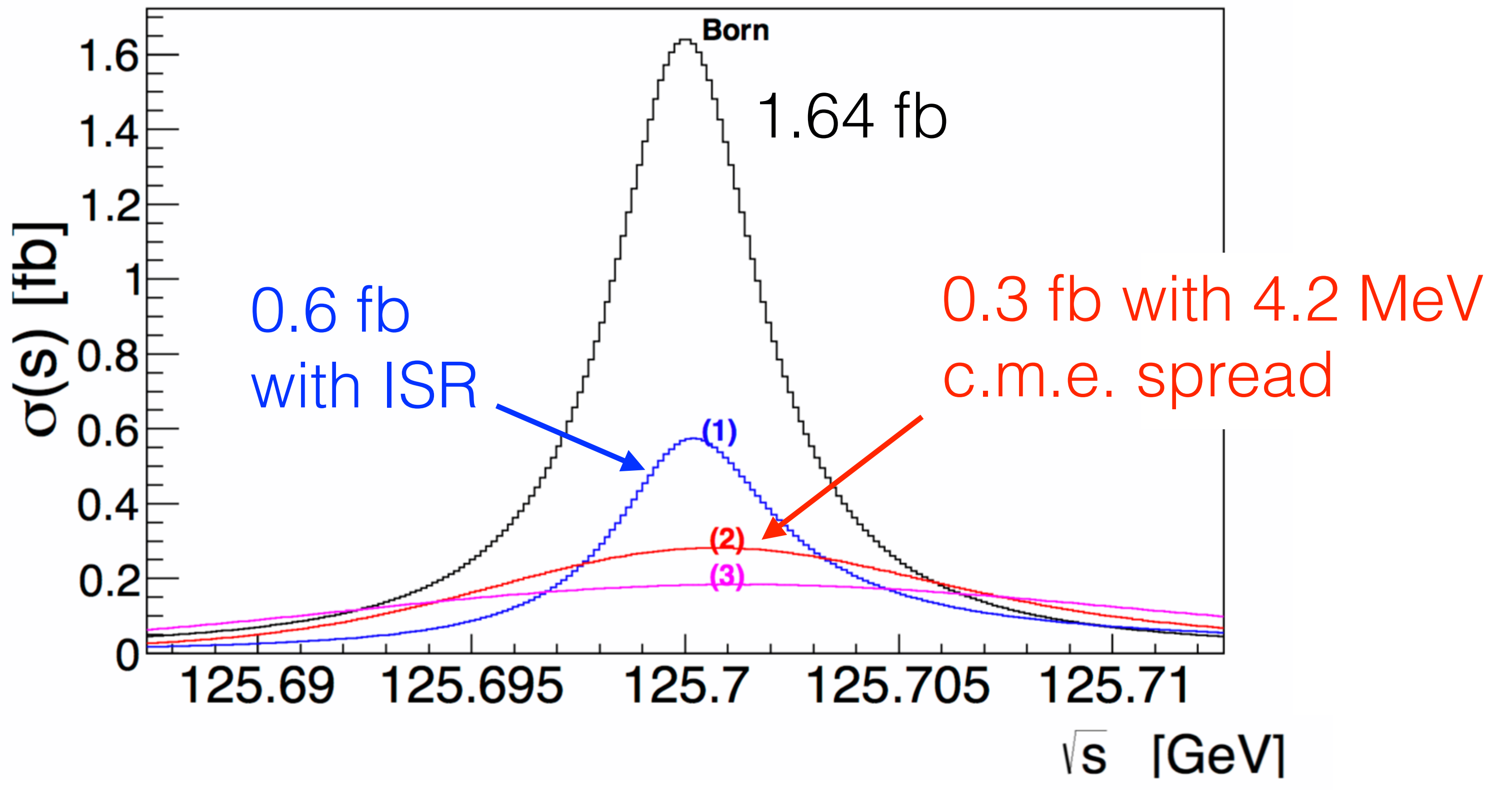


d'Enterria+, arXiv: 2107.02686

Higgs decay channel	$\mathcal{B}$	$\sigma \times \mathcal{B}$	Irreducible background	σ	S/B
$e^+e^- \to H \to b\bar{b}$	58.2%	164 ab	$e^+e^- \to b\bar{b}$	19 pb	$\mathcal{O}(10^{-5})$
$e^+e^- \to H \to gg$	8.2%	23 ab	$e^+e^- \to q\bar{q}$	61 pb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to \tau\tau$	6.3%	18 ab	$e^+e^- \to \tau\tau$	10 pb	$\mathcal{O}(10^{-6})$
$e^+e^- \to H \to c\bar{c}$	2.9%	8.2 ab	$e^+e^- \to c\bar{c}$	22 pb	$\mathcal{O}(10^{-7})$
$e^+e^- \to H \to WW^* \to \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26.5 ab	$e^+e^- \to WW^* \to \ell\nu\, 2j$	23 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.4 ab	$e^+e^- \to WW^* \to 2\ell\, 2\nu$	5.6 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to WW^* \to 4j$	21.4%×67.6%×67.6%	27.6 ab	$e^+e^- \to WW^* \to 4j$	24 fb	$\mathcal{O}(10^{-3})$
$e^+e^- \to H \to ZZ^* \to 2j\, 2\nu$	2.6%×70%×20%×2	2 ab	$e^+e^- \to ZZ^* \to 2j\, 2\nu$	273 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2j$	2.6%×70%×10%×2	1 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2j$	136 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to ZZ^* \to 2\ell\, 2\nu$	2.6%×20%×10%×2	0.3 ab	$e^+e^- \to ZZ^* \to 2\ell\, 2\nu$	39 ab	$\mathcal{O}(10^{-2})$
$e^+e^- \to H \to \gamma\gamma$	0.23%	0.65 ab	$e^+e^- \to \gamma\gamma$	79 pb	$\mathcal{O}(10^{-8})$

w. 10/ab

$H \to gg$	$H \to WW^* \to \ell\nu\, 2j;\, 2\ell\, 2\nu;\, 4j$	$H \to ZZ^* \to 2j\, 2\nu;\, 2\ell\, 2j;\, 2\ell\, 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};\, c\bar{c};\, \gamma\gamma$	Combined
1.1σ	(0.53 ⊗ 0.34 ⊗ 0.13)σ	(0.32 ⊗ 0.18 ⊗ 0.05)σ	0.13σ	< 0.02σ	1.3σ

w/ 10/ab: S~55, B~2400 → 1.1σ

The future: other directions not explored yet

- **Non-diagonal flavour structures:**
  1. in SM, no Higgs FCNC
  2. in BSM, Higgs FCNC are the rule rather than the exception
  3. combination with flavour data (irrelevant in diag. flavour structure)

on-going work

- **CP violation couplings:**
  1. in SM, a single CPV phase captured by Jarlskog invariant: $J_4 = \mathrm{Im Tr}\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]^3\right)$
  2. how many at dim-6 level?

large parameter space, largely unconstrained

—

potentially large new physics effects since they do not suffer from same collective suppression factor of the SM

	Type of op.	# of ops	# real	# im.	inv. under $U(1)_{L_i} - U(1)_{L_j}$ # real	# im.
bilinears	Yukawa	3	27	27	21	21
	Dipoles	8	72	72	60	60
	current-current	8	51	30	42	21
	all bilinears	19	150	129	123	102
4-Fermi	LLLL	5	171	126	99	54
	RRRR	7	255	195	186	126
	LLRR	8	360	288	246	174
	LRRL	1	81	81	27	27
	LRLR	4	324	324	216	216
	all 4-Fermi	25	1191	1014	774	597
	all		1341	1143	897	699

699 new Jarlskog BSM invariants

Bonnefoy+ 2112.03889

- **Beyond SMEFT** analyses, e.g. HEFT

On-Going Studies

Higgs Performance meeting
Monday 28 Mar 2022, 14:30 → 17:05 Europe/Zurich

Videoconferen | Higgs performance meeting | Join

14:30 → 14:40 **Introduction** 10m
Speakers: Jan Eysermans (Massachusetts Inst. of Technology (US)), Michele Selvaggi (CERN)
Higgs_perf...

14:40 → 14:50 **ZH, Z->ee/mumu: Higgs mass, cross-section and H --> hadrons** 10m
Speakers: Ang Li (APC, CNRS/IN2P3 and Université de Paris), Giovanni Marchiori (APC, CNRS/IN2P3 and Université de Paris), Gregorio Bernardi (APC Paris CNRS/IN2P3), Jan Eysermans (Massachusetts Inst. of Technology (US))
2022_03_2...

14:50 → 15:00 **ZH, Z->vv, Higgs ->hadron** 10m
Speakers: Laurent Forthomme (CERN), Loukas Gouskos (CERN), Michele Selvaggi (CERN)
lg_fccee_z...

15:00 → 15:10 **H->ss and strange tagging** 10m
Speakers: Christopher Damerell (Science and Technology Facilities Council STFC (GB)), Jerry Vavra (SLAC), Matthew Basso (University of Toronto (CA)), Valentina Cairo (CERN)
StrangeCo...

15:10 → 15:20 **Higgs -> invisible** 10m
Speakers: Andrew Mehta (University of Liverpool (GB)), Nikolaos Rompotis (University of Liverpool (UK))
mehta.pdf

15:20 → 15:30 **Higgs self coupling** 10m
Speakers: Roberto Salerno (Centre National de la Recherche Scientifique (FR)), Roy Crawford Lemmon (STFC Daresbury Laboratory (GB)), Roy Lemmon (STFC Daresbury Laboratory (GB))
RoyLemm...

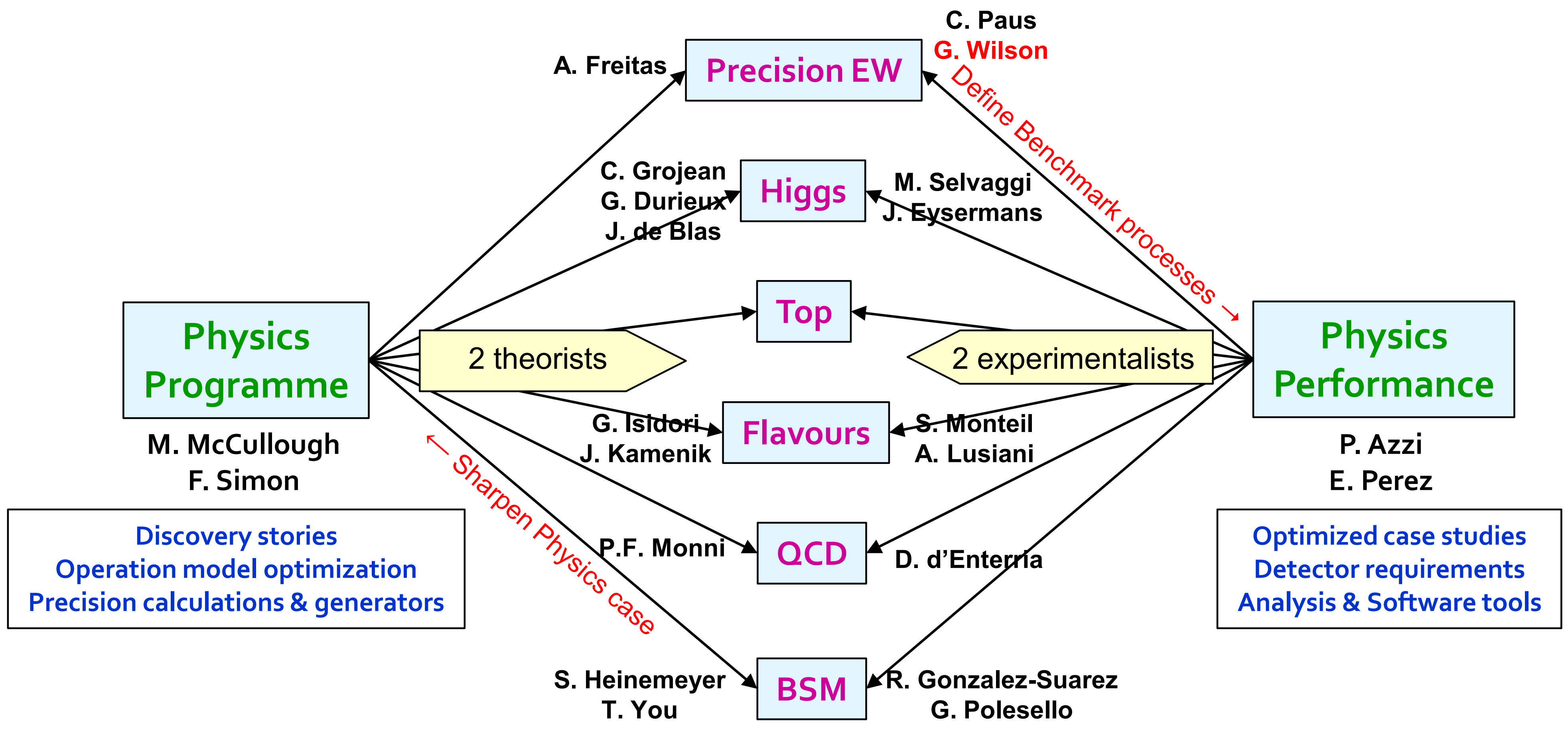
15:30 → 15:40 **ee->H** 10m
Speaker: David d'Enterria (CERN)
dde_Higgs...

15:40 → 15:50 **H->tau tau and new scalars** 10m
Speakers: Clement Helsens (CERN), Markus Klute (Karlsruhe Inst. of Technology (GER)), Xunwu Zuo (Rice University (US))
FCCee-Hig...

15:50 → 16:00 **Anomalous couplings** 10m
Speakers: Juan Alcaraz Maestre (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Madrid)), Maria Cepeda (CIEMAT)
CIEMAT_F...

Join the team!

https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Higgs



Short-term Goals

1. Documentation of the specificities of the FCC-ee and FCC-hh **physics cases** and their complementarity for the characterisation of the Standard Model Higgs boson and beyond;
   - identify key topics and observables
   - propose new benchmark measurements
2. Strategic plans for improved **theoretical calculations** needed to reduce the theoretical uncertainties towards matching the FCC-ee expected statistical precision for the most important measurements: QCD and EW sectors

see talks by D. d'Enterria, J. Gluza, C. Paus

3. A first list of coherent sets of **detector requirements** to fully exploit the FCC-ee physics opportunities, in particular to reduce the experimental systematic uncertainties towards matching the FCC-ee expected statistical precision for the most important measurements.

Exemples of On-Going Studies

Flavour Physics at FCC

G. Isidori & J. Kamenik (conveners)

see talks by J. Kamenik and S. Monteil

Contents

Summary of Physics Potential

FCC-ee note, 1906.02693

$\sqrt{s}$ → / Physics ↓	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	Leading Physics Questions
	e^+e^- collisions							**pp collisions**		
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_W, α_S						Existence of more SM-Interacting particles
QCD (α_S) QED (α_{QED})	5×10^{12} Z	3×10^{8} W	10^5 $H\to gg$							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	ee → H $\sqrt{s} = m_H$		1.2×10^6 HZ and 75k $WW\to H$ at two energies						<1% precision (*)	Test Higgs nature
Higgs rare decays									<1% precision (*)	Portal to new physics
Higgs invisible decays									10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling			3 to 5σ from loop corrections to Higgs cross sections						5% (HH prod) (*)	Key to EWSB
Flavours (b, τ)	5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting particles	5×10^{12} Z								10^{11} W	Direct NP discovery At low couplings
Direct search at high scales					M_χ<250GeV Small ΔM	M_χ<750GeV Small ΔM	M_χ<1.5TeV Small ΔM		Up to 40 TeV	Direct NP discovery At high mass
Precision EW at high energy							*Y*		*W, Z*	Indirect Sensitivity to Nearby new physics
Quark-gluon plasma Physics w/ injectors										QCD at origins

Green = Unique to FCC; **Blue = Best with FCC**; **(*) = if FCC-hh is combined with FCC-ee**; **Pink = Best with other colliders**

Conclusions

A **circular "Higgs factory"** like FCC-ee has a rich potential:

* Direct and indirect sensitivity to New Physics
* Establish new organising principles of Nature (LEP⟶ gauge symmetries, FCC⟶??)
* Probe the **HEP-Cosmo connections** thanks to the high statistics of the Z-pole run (omitting this exploration would be ignoring the outcome of LHC).

And FCC-ee is an essential part of an **integrated** programme to probe the energy frontier.

We have profound questions and we need create opportunities to answer them.
FCC-ee will for sure contribute.

We can learn a lot from nice pictures/**observations** (e.g. EHT Sgr A*)
but **experiments** remain the driver of physics.

High-Energy Physics provides tools to others fields
(medicine/climate/energy)
It remains a good investment for the future of mankind

Acknowledgement

This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.