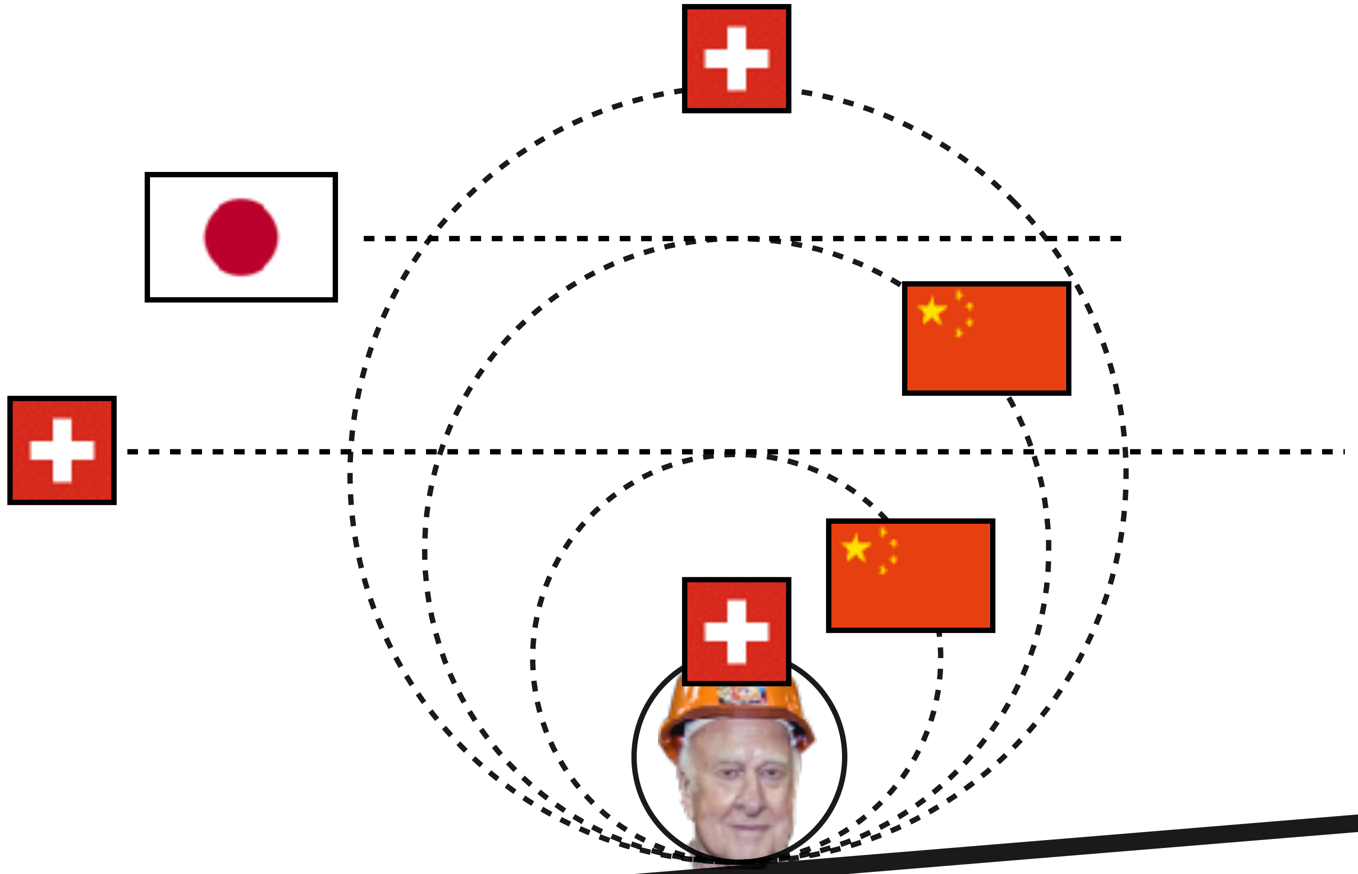
FCC-ee Physics Potentials and Open Questions

Fifth FCC-Physics Workshop
Liverpool/Zoom, Feb. 7, 2022



Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

Why a Higgs Factory?

I want to start by reassuring my UK colleagues:
the “PartyGate” emerged out of a total misunderstanding!

BJ didn’t mean **“Bring your booze”** but rather **“Bring your boozon”**
(when you spend too much time in Brussels, you tend to forget Shakespeare English!)

Let’s remember why we need a Higgs/top/EW factory

Today HEP Status

- SM is now confirmed to high accuracy up to energies of (several) TeV
- Higgs boson discovered
- No direct evidence of new physics at colliders, maybe few indirect hints (B physics, $(g-2)_\mu$…)
- SM is *consistent* but *incomplete* in describing the whole Universe
- SM is only a low-energy approximation energy/effective field theory but we don't know the scale of New Physics
- We need experiments to probe the laws of Nature further and further

One century of tremendous successes brings fundamental questions:

Why something rather than nothing? How did matter dominate over antimatter?
What was the dynamics of the early Universe a nanosecond after the Big-Bang?
Is there exo-matter, i.e. matter that can interact with us?
Are the SM particles really all elementary?

Remarkably, we can build a machine to answers these questions!

Today HEP Status

- SM is now confirmed to high accuracy up to energies of (several) TeV
- Higgs boson discovered
- No direct evidence of new physics at colliders, maybe few indirect hints (B physics, $(g\text{-}2)_\mu$…)
- SM is *consistent* but *incomplete* in describing the whole Universe
- SM is only a low-energy approximation energy/effective field theory but we don't know the scale of New Physics
- We need experiments to probe the laws of Nature further and further

We need a broad, versatile and ambitious programme that
1. sharpen our knowledge of already discovered physics
2. push the frontiers of the unknown

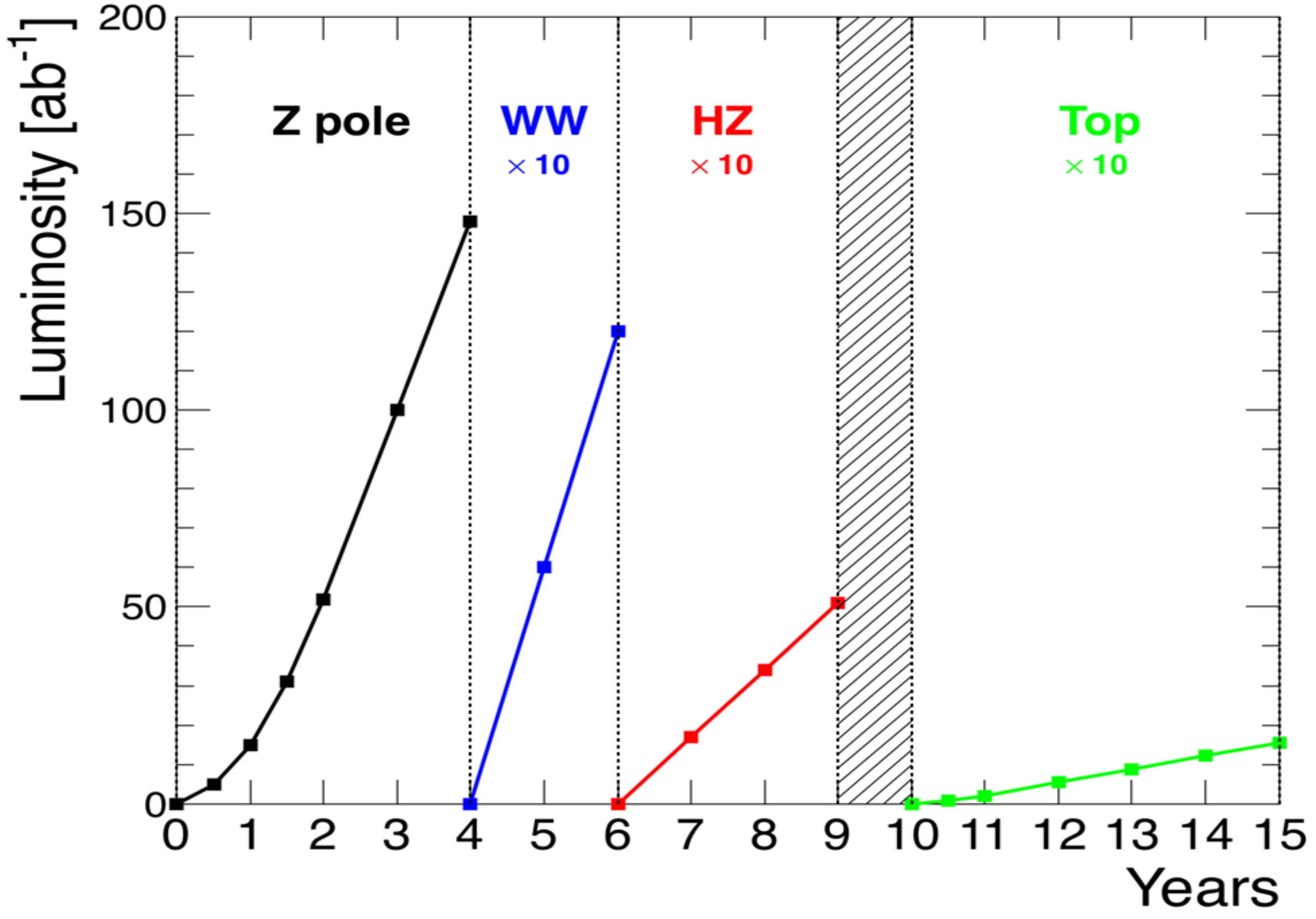
— FCC-ee+eh+hh combine these 2 aspects —

more PRECISION, more ENERGY for more SENSITIVITY to New Physics

FCC-ee Run Plan

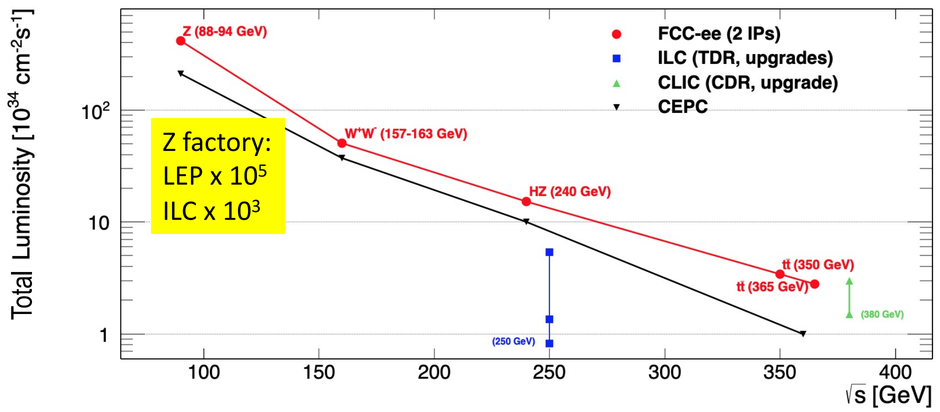
LEP data accumulated in first 3 mn. Then exciting & diverse programme with different priorities every few years.

(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

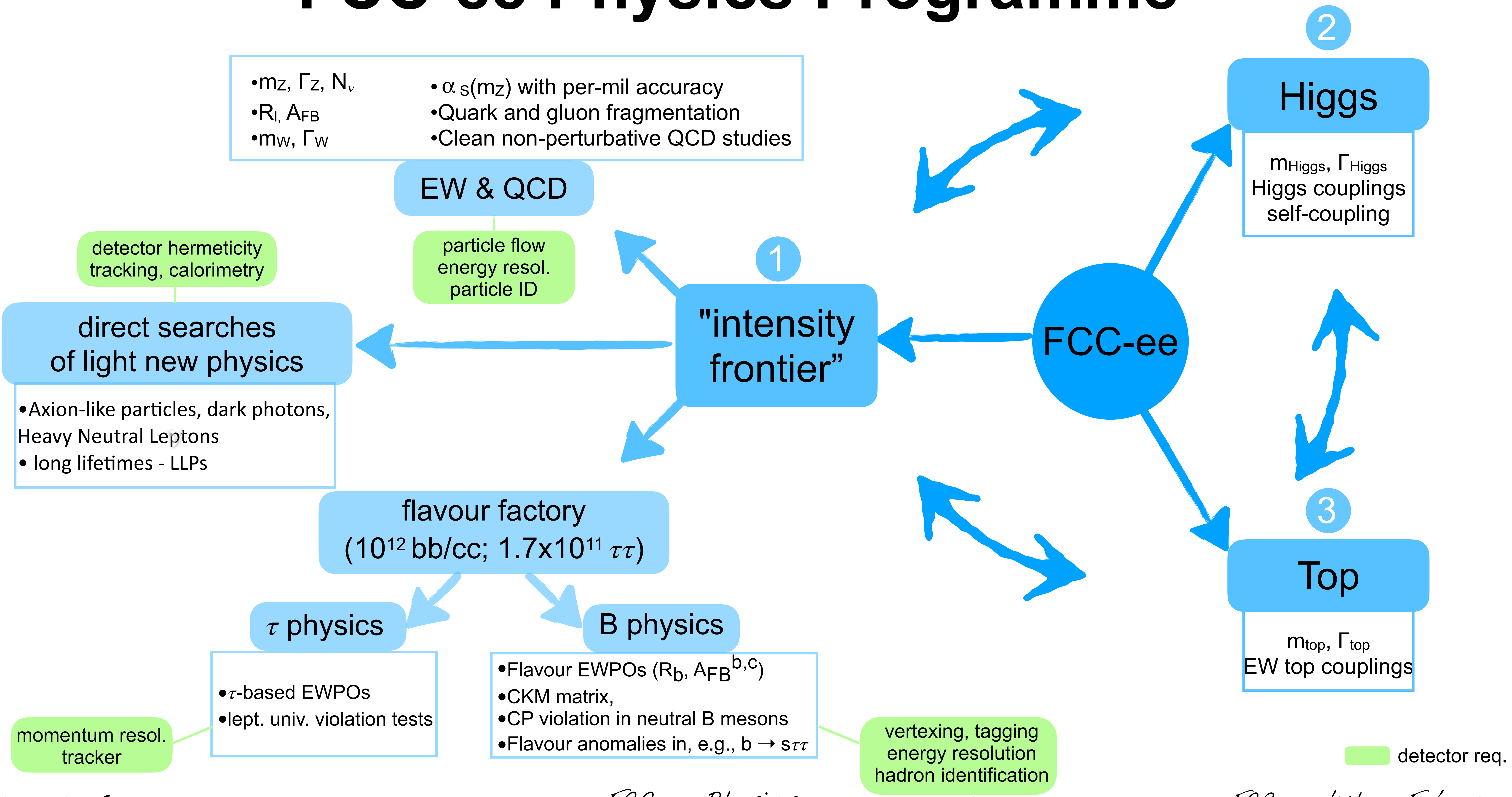
Superb statistics achieved in only 15 years



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 MeV
$t\bar{t}$	E_{cm} : ≥ 350 GeV	5yrs	10^6 e+e- → $t\bar{t}$	Never done	2 MeV

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)
$B_s \to D^\pm_s K^\mp$	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

Probing New Physics w/ τ Decays

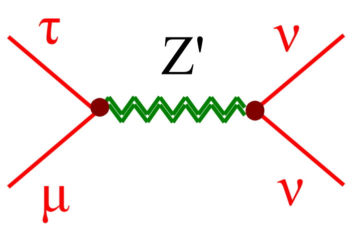
Allwicher, Isidori, Semilovic '21

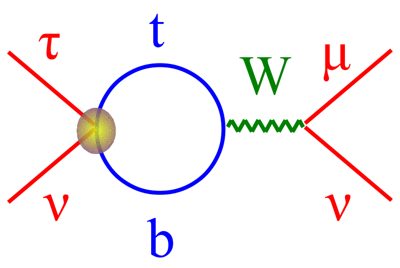
E.g.: (I) LFU tests in tau decays

A. Pich '13

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

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

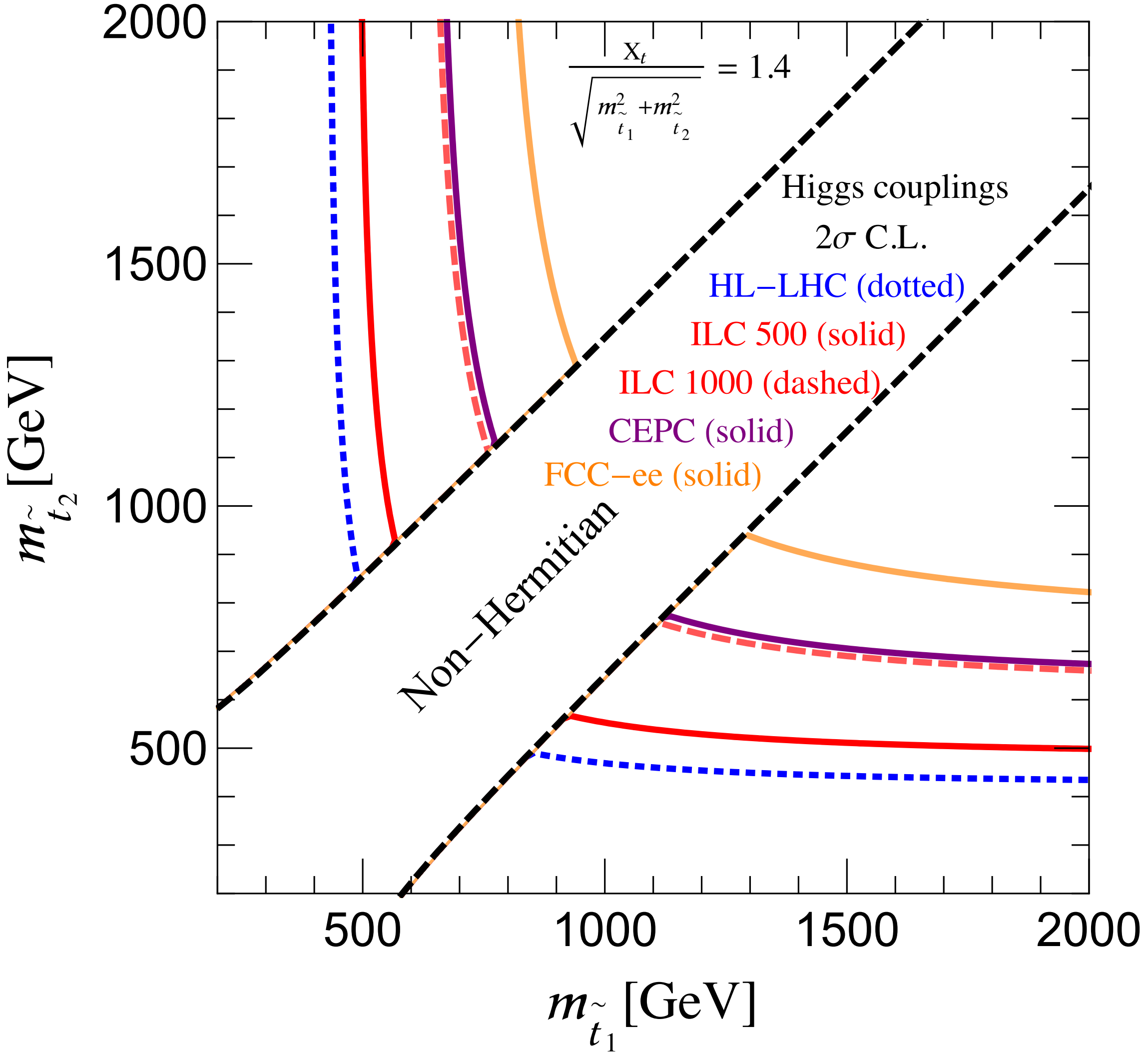
sensitivity good enough to probe BSM models "explaining" current flavour R_K anomalies ($b\to c\tau\nu$)

Discovery Potential Beyond LHC

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

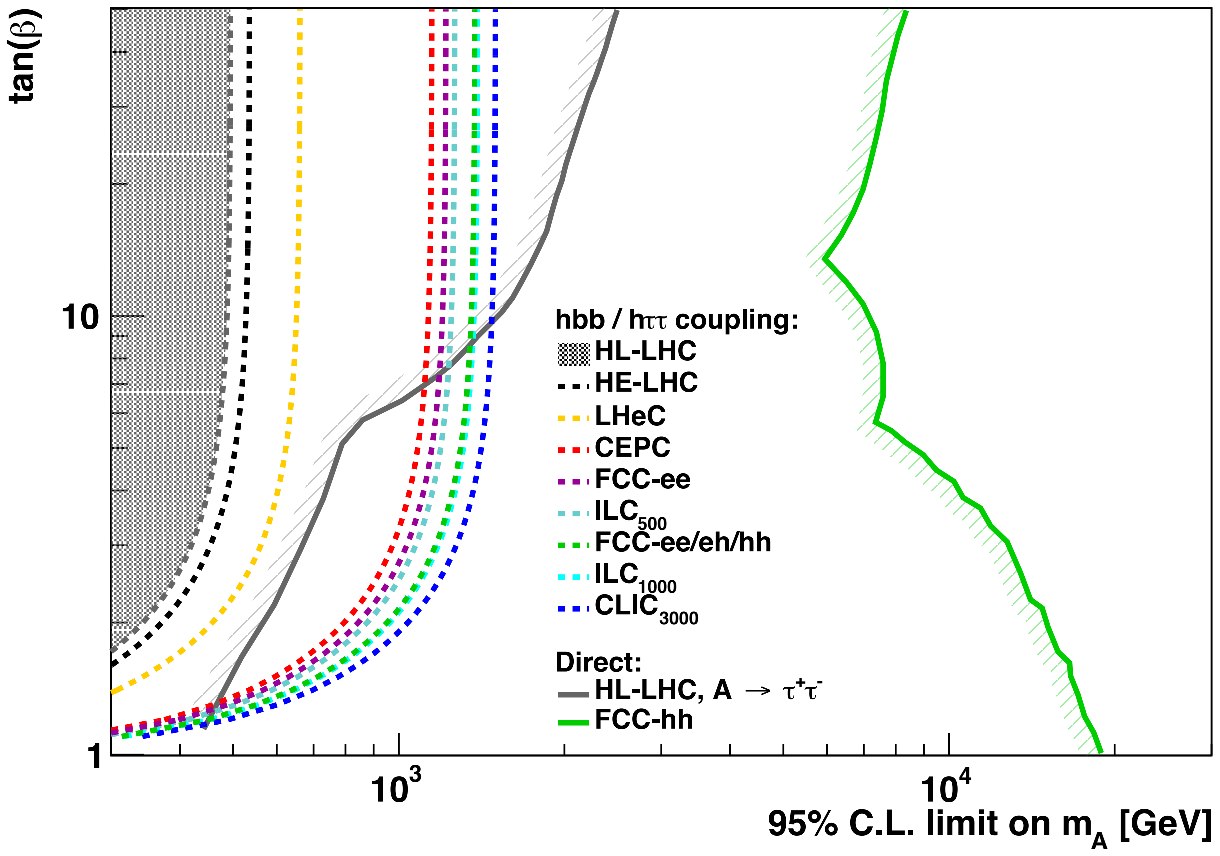
Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY

stops



Fan, Reece, Wang '14

Heavy neutral Higgses

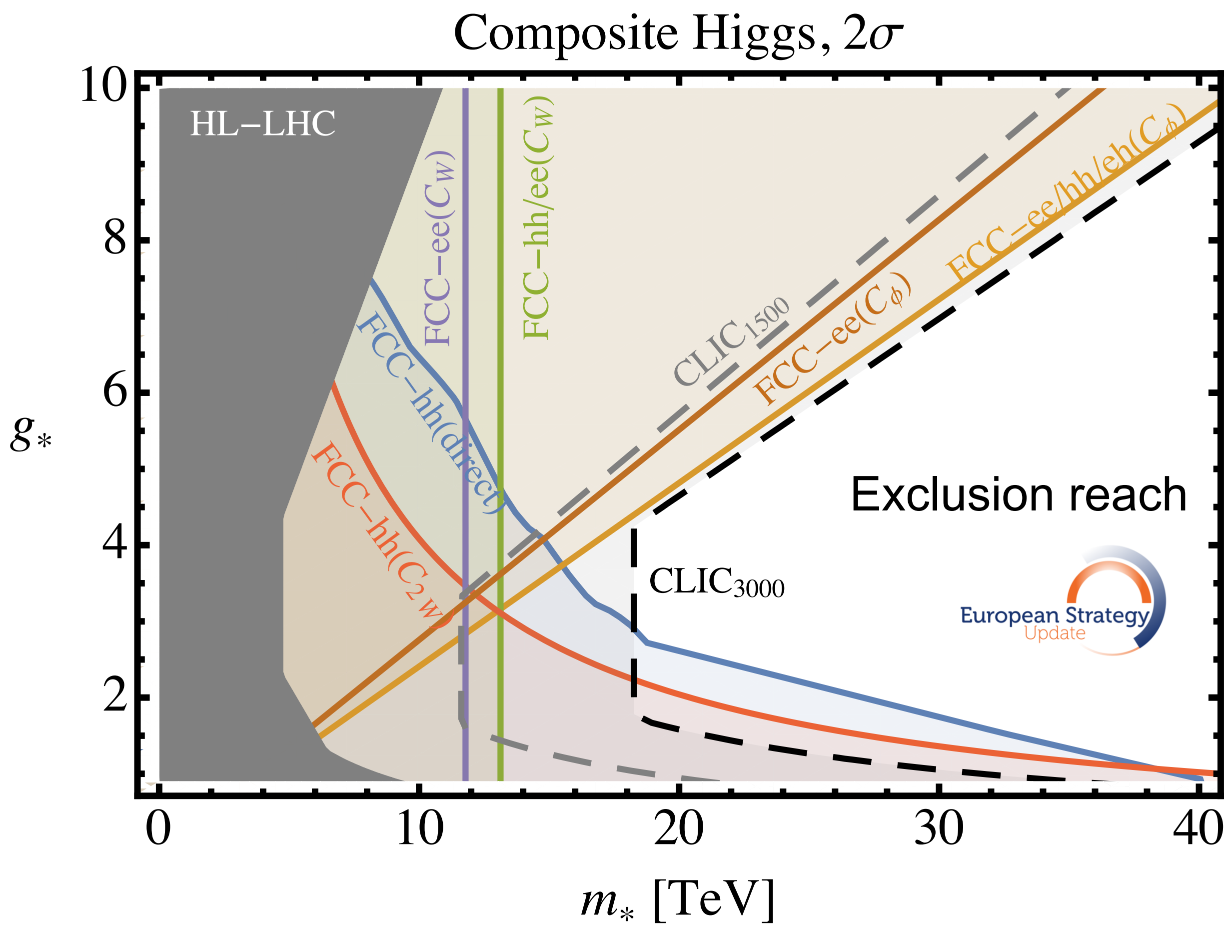


ESU Physics BB '19

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: Composite Higgs



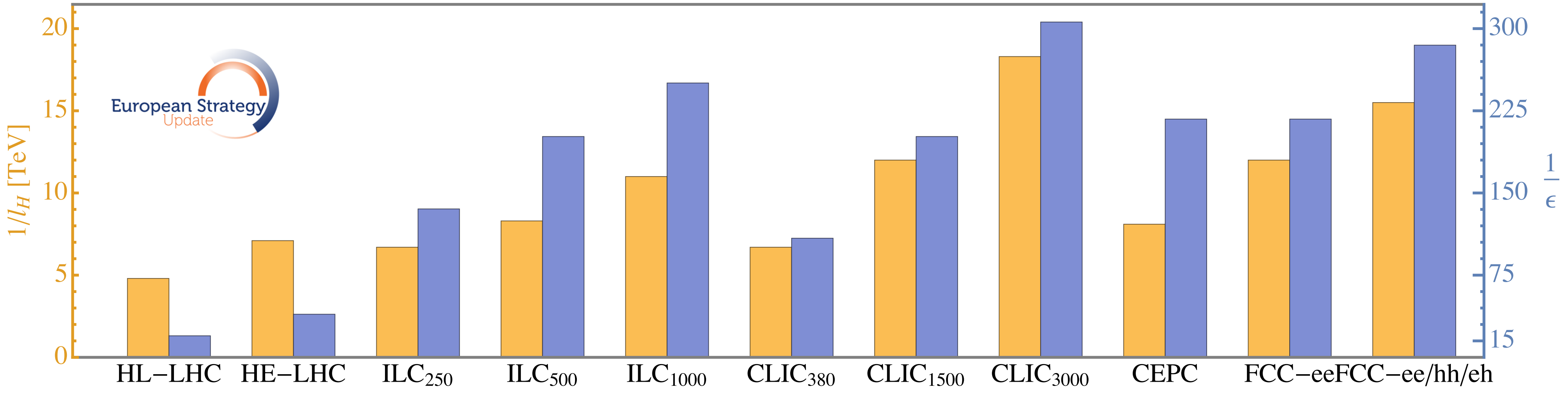


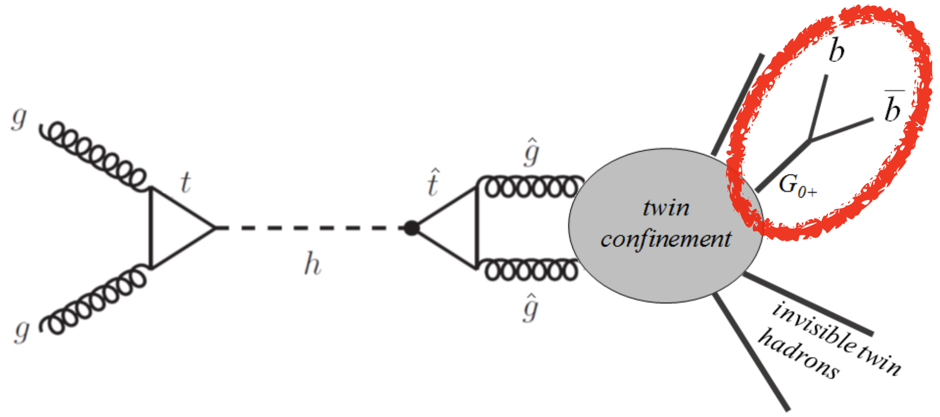
Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\varepsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_*.

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

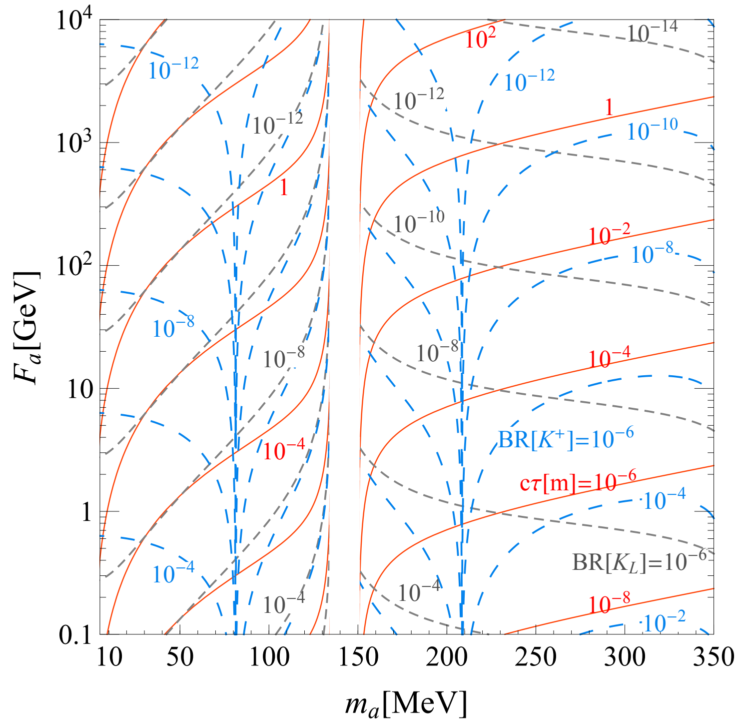
Craig et al, arXiv:1501.05310



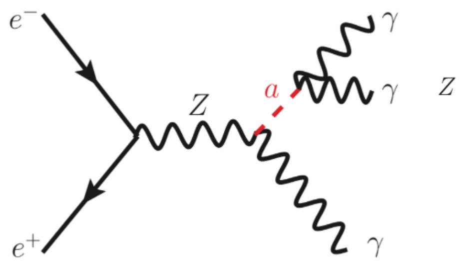
- **Rare decays** Gori et al arXiv:2005.05170
  e.g. ALP mixing w/ SM mesons:

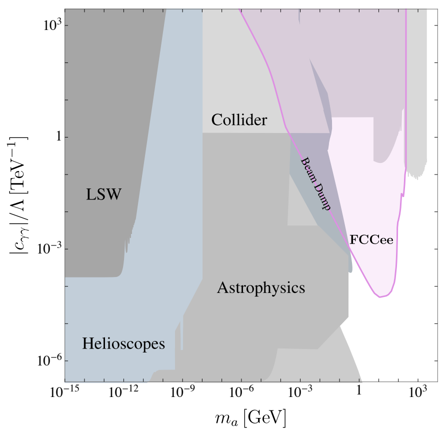
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \text{ (NA62)}$$

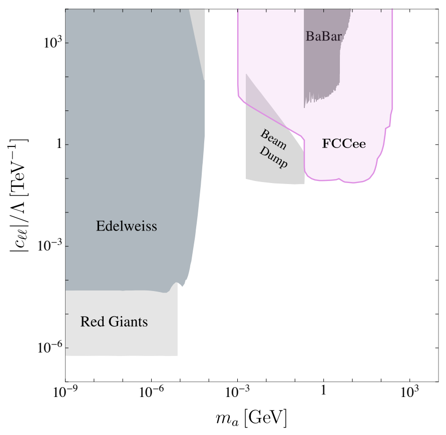
$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu} \tilde{G}^{\mu\nu}$$



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





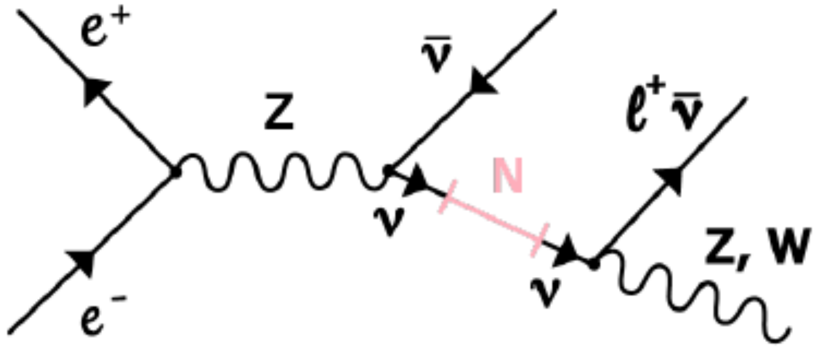


Knapen, Thamm arXiv:2108.08949

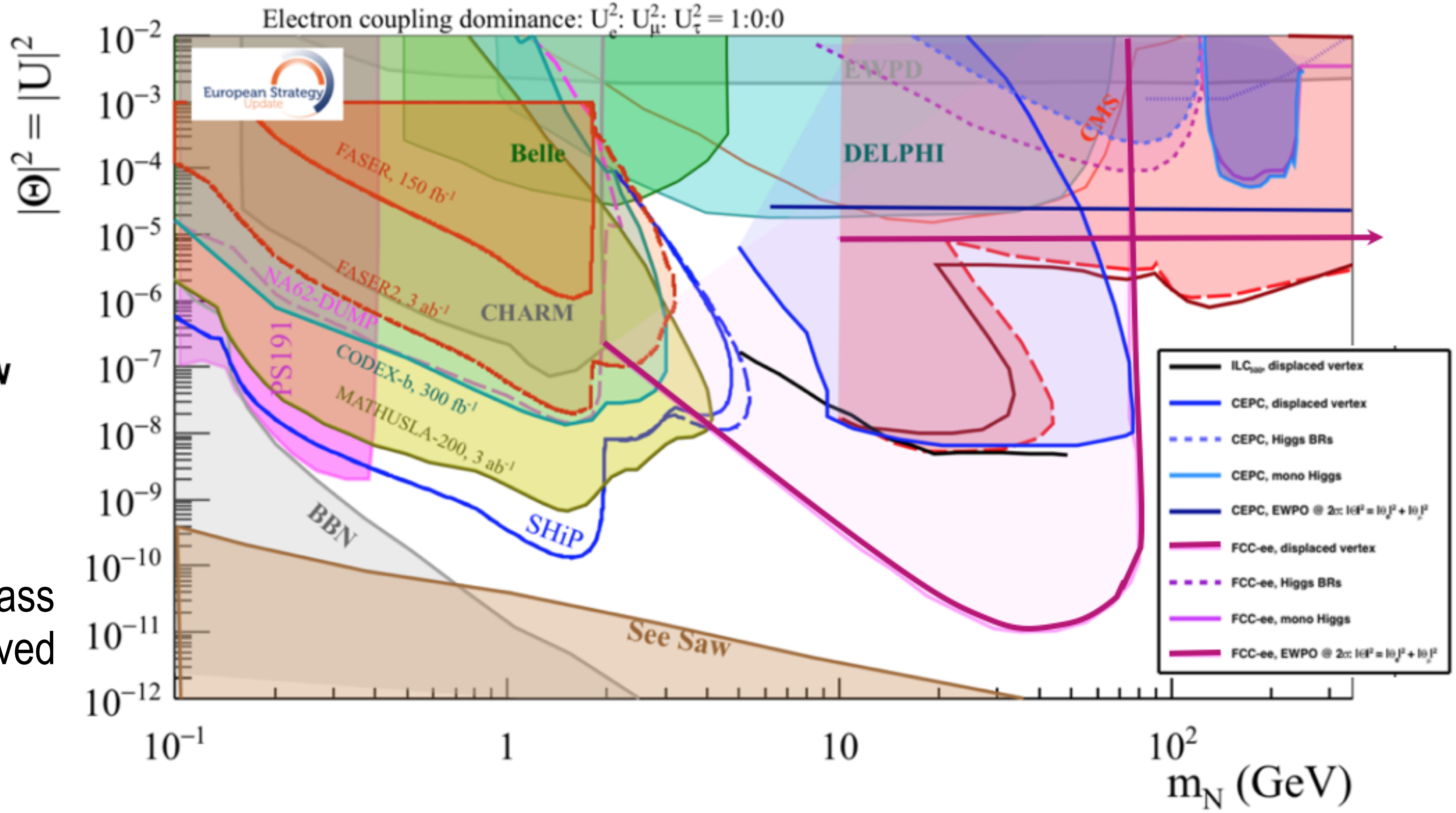
Astro/Cosmo → long-lived ALPs
colliders → short-lives ALPs MeV+

Search for ν_{RH}

Direct observation in Z decays from LH-RH mixing



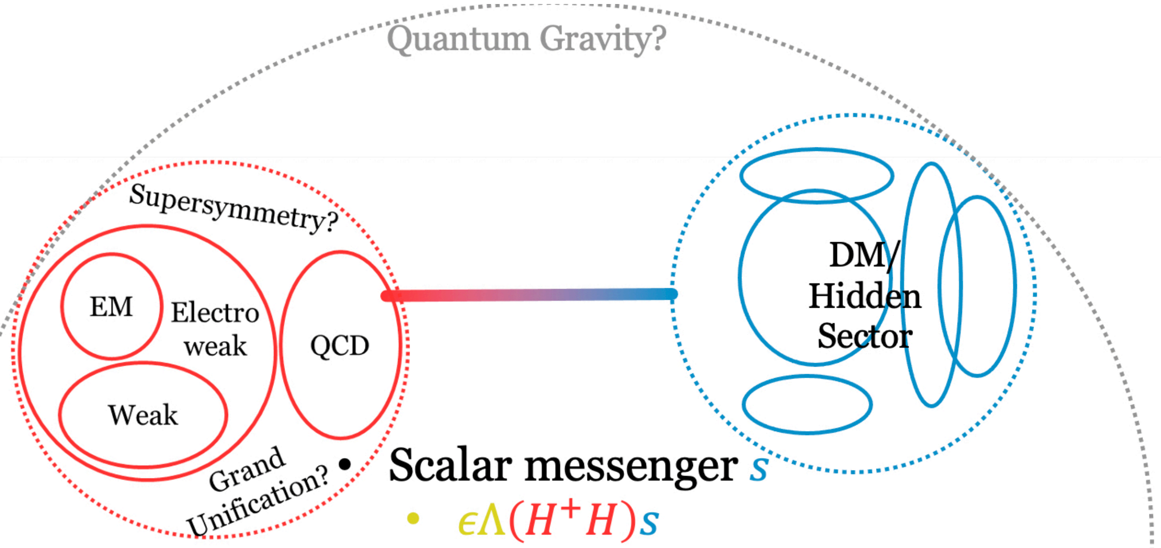
Important to understand
1. how neutrinos acquired mass
2. if lepton number is conserved



ESU Physics BB '19

Exotics/Long Lived Particles

Z. Liu @ CEPC 2020



- Scalar messenger s
  - $\epsilon\Lambda(H^{+}H)s$
  - $\epsilon(H^{+}H)(s^{+}s)$
- Vector messenger A'_{μ}
  - $\epsilon F^{\mu\nu}F'_{\mu\nu}$
  - $\epsilon\, J^{\mu}_{SM}A'_{\mu}$
- Neutrino messenger N
  - $\epsilon(LH)N$
- Axion messenger a
  - $\frac{a}{f_a}(\frac{\alpha_3}{8\pi}G\tilde{G}+\frac{\alpha_2}{8\pi}W\tilde{W})$

The Higgs could be a good portal to Dark Sector
— rich exotic signatures —

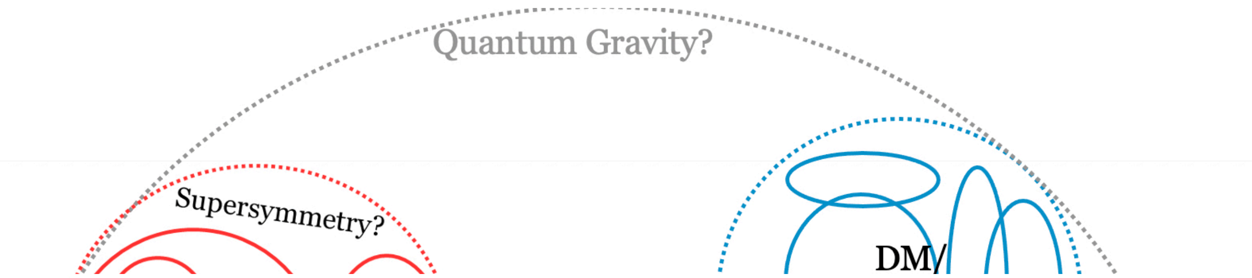
Decay Topologies	Decay mode $\mathcal{F}_i$
$h\to 2$	$h\to \not{E}_T$
$h\to 2\to 3$	$h\to\gamma+\not{E}_T$
	$h\to(b\bar{b})+\not{E}_T$
	$h\to(jj)+\not{E}_T$
	$h\to(\tau^+\tau^-)+\not{E}_T$
	$h\to(\gamma\gamma)+\not{E}_T$
	$h\to(\ell^+\ell^-)+\not{E}_T$
$h\to 2\to 3\to 4$	$h\to(b\bar{b})+\not{E}_T$
	$h\to(jj)+\not{E}_T$
	$h\to(\tau^+\tau^-)+\not{E}_T$
	$h\to(\gamma\gamma)+\not{E}_T$
	$h\to(\ell^+\ell^-)+\not{E}_T$
	$h\to(\mu^+\mu^-)+\not{E}_T$
$h\to 2\to(1+3)$	$h\to b\bar{b}+\not{E}_T$
	$h\to jj+\not{E}_T$
	$h\to\tau^+\tau^-+\not{E}_T$
	$h\to\gamma\gamma+\not{E}_T$
	$h\to\ell^+\ell^-+\not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h\to 2\to 4$	$h\to(bb)(bb)$
	$h\to(b\bar{b})(\tau^+\tau^-)$
	$h\to(b\bar{b})(\mu^+\mu^-)$
	$h\to(\tau^+\tau^-)(\tau^+\tau^-)$
	$h\to(\tau^+\tau^-)(\mu^+\mu^-)$
	$h\to(jj)(jj)$
	$h\to(jj)(\gamma\gamma)$
	$h\to(jj)(\mu^+\mu^-)$
	$h\to(\ell^+\ell^-)(\ell^+\ell^-)$
	$h\to(\ell^+\ell^-)(\mu^+\mu^-)$
	$h\to(\mu^+\mu^-)(\mu^+\mu^-)$
	$h\to(\gamma\gamma)(\gamma\gamma)$
	$h\to\gamma\gamma+\not{E}_T$
$h\to 2\to 4\to 6$	$h\to(\ell^+\ell^-)(\ell^+\ell^-)+\not{E}_T$
	$h\to(\ell^+\ell^-)+\not{E}_T+X$
$h\to 2\to 6$	$h\to\ell^+\ell^-\ell^+\ell^-+\not{E}_T$
	$h\to\ell^+\ell^-+\not{E}_T+X$

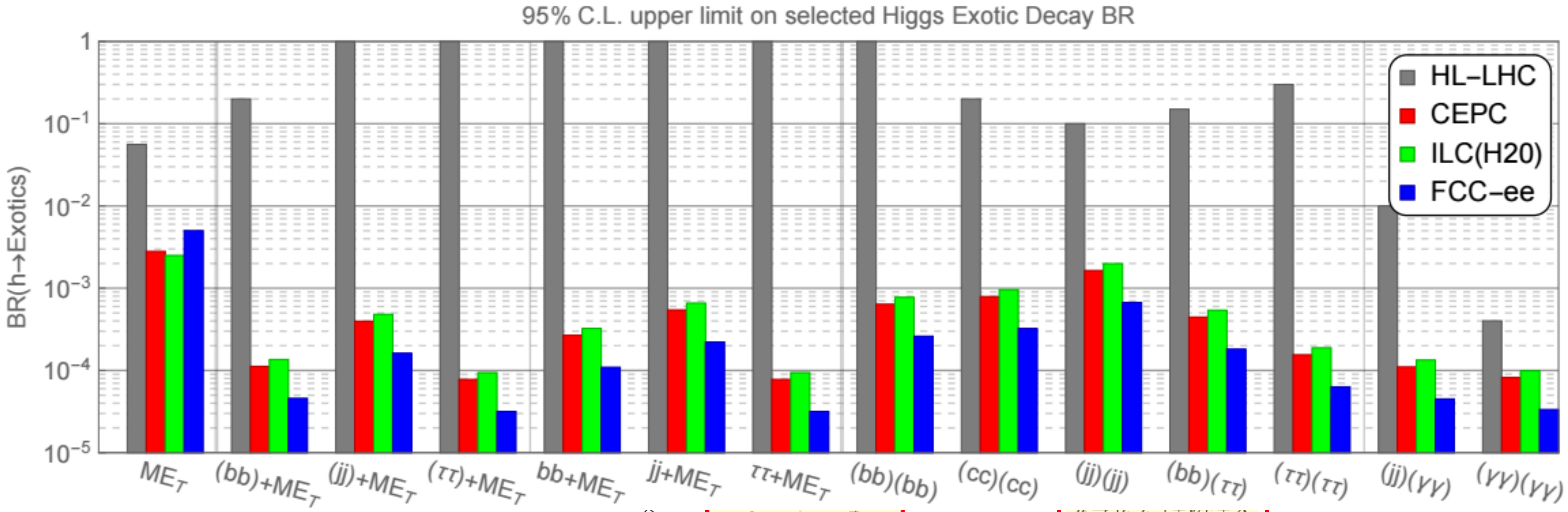
LHC's strength
Hard at LHC due to missing energy
Hard at LHC due to hadronic background
Lepton colliders' strength

Exotics/Long Lived Particles

Z. Liu @ CEPC 2020



The Higgs could be a good portal to Dark Sector
— rich exotic signatures —



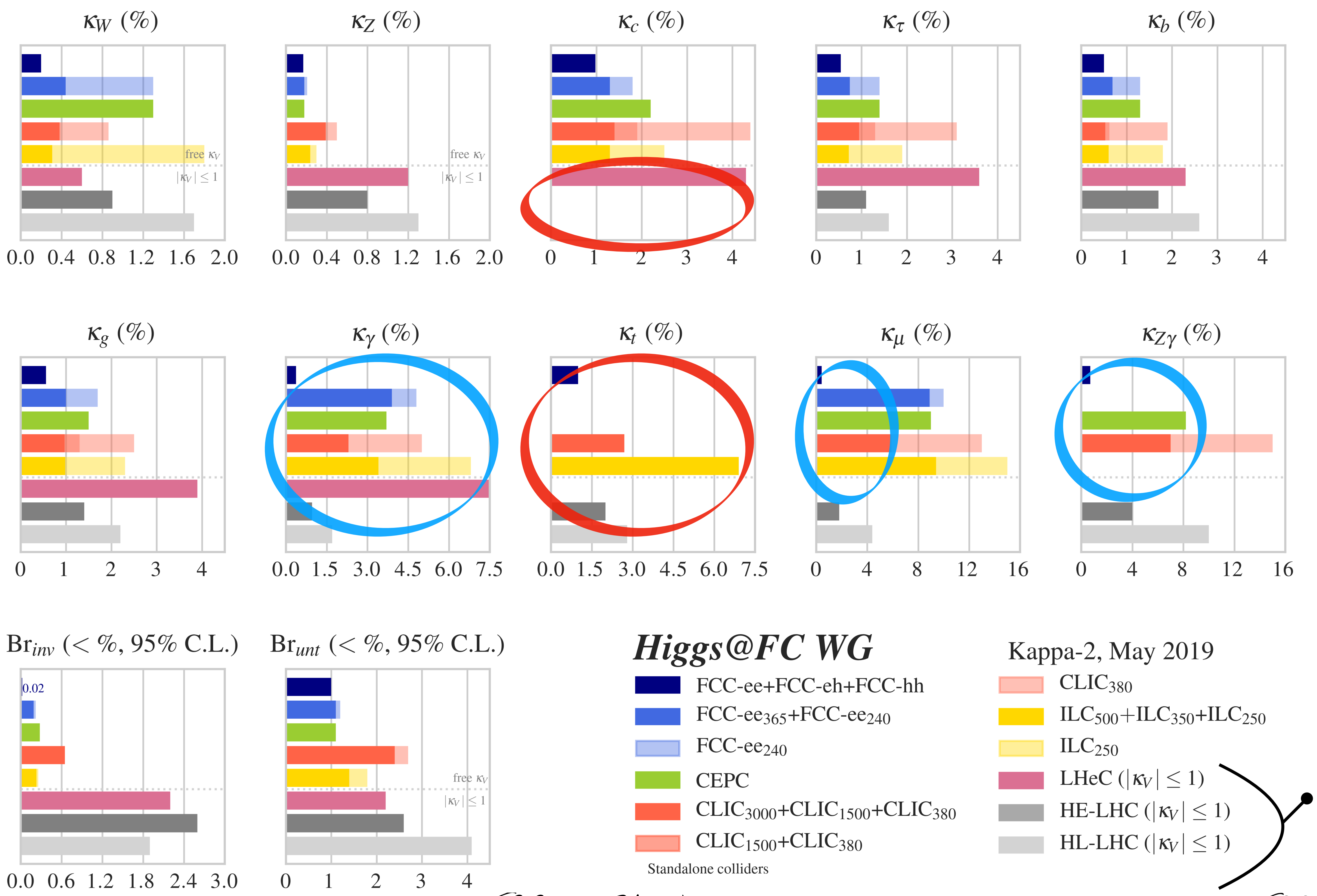
How to improve?
> Dedicated detectors, see e.g. talk by R. Gonzalez Suarez @ FCC week 2021

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

ECFA Higgs study group '19

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-2	measured	measured	no

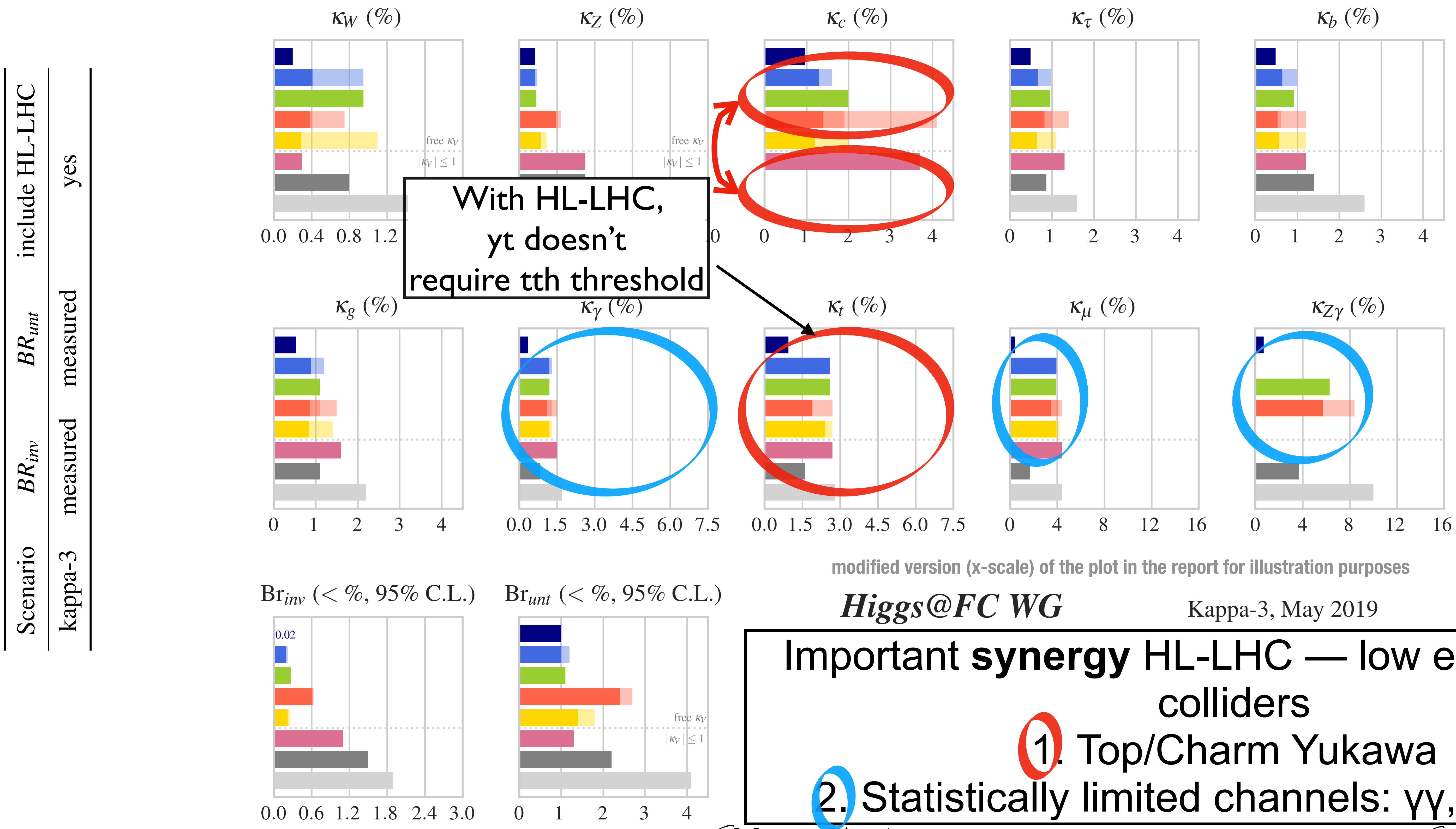
hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V<1$



assumption needed for the fit to close at hadron machines

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

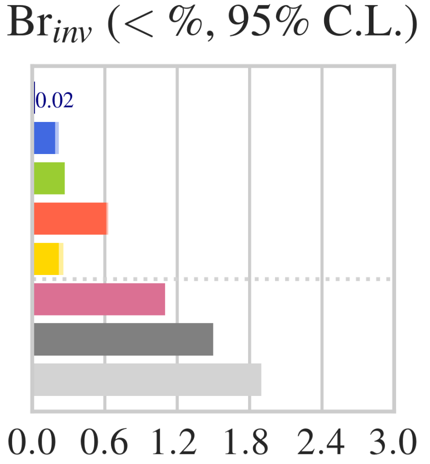
ECFA Higgs study group '19

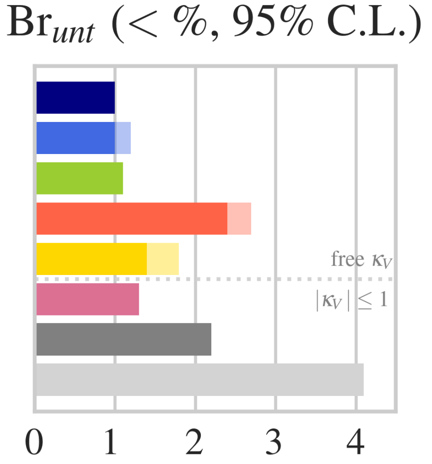


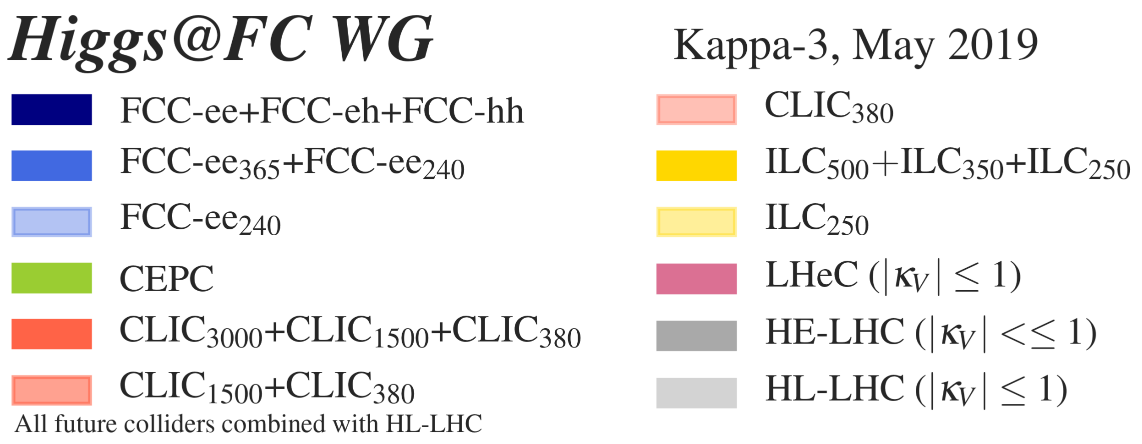
Important **synergy** HL-LHC — low energy lepton colliders

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

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





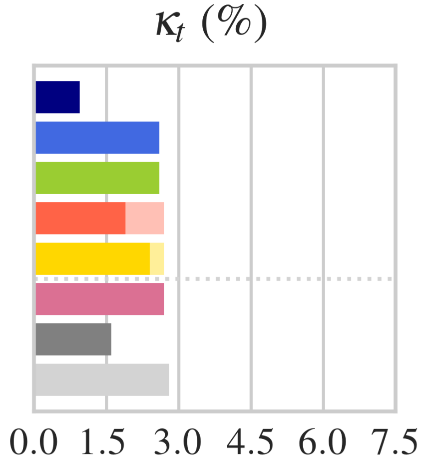


FCC-hh without ee could still bound BR_{inv}

but it could say nothing about BR_{unt}

1

FCC-ee needed for absolute normalisation of Higgs couplings



2

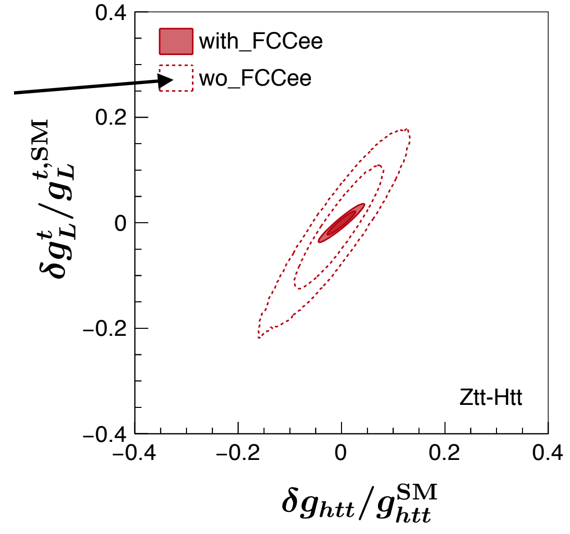
FCC-hh is determining top Yukawa through ratio tth/ttZ

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	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

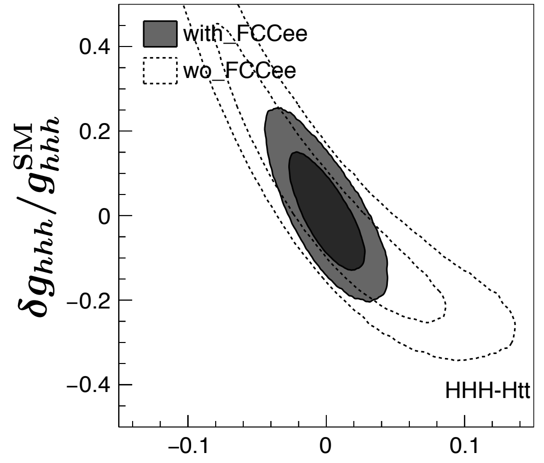
uncertainty drops in ratio

Mangano+ '15



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

Access to s Yukawa

Improved jet flavour tagging opens up new opportunities

Selvaggi @ FCC week 2021

BR(H⟶ ss) = BR (H⟶ cc) $(m_s/m_c)^2$ ~ 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:

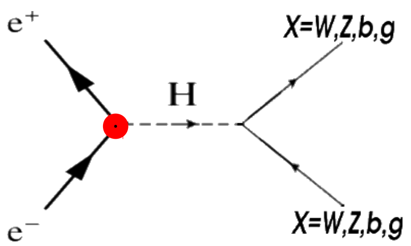
N_{ss} = 30, N_b = 200
(neglecting ee ⟶ vvqq and ee ⟶ qq, can be important given large q ⟶ s fake prob.)

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

Back-of-the envelope estimates

THOROUGH STUDIES NEEDED

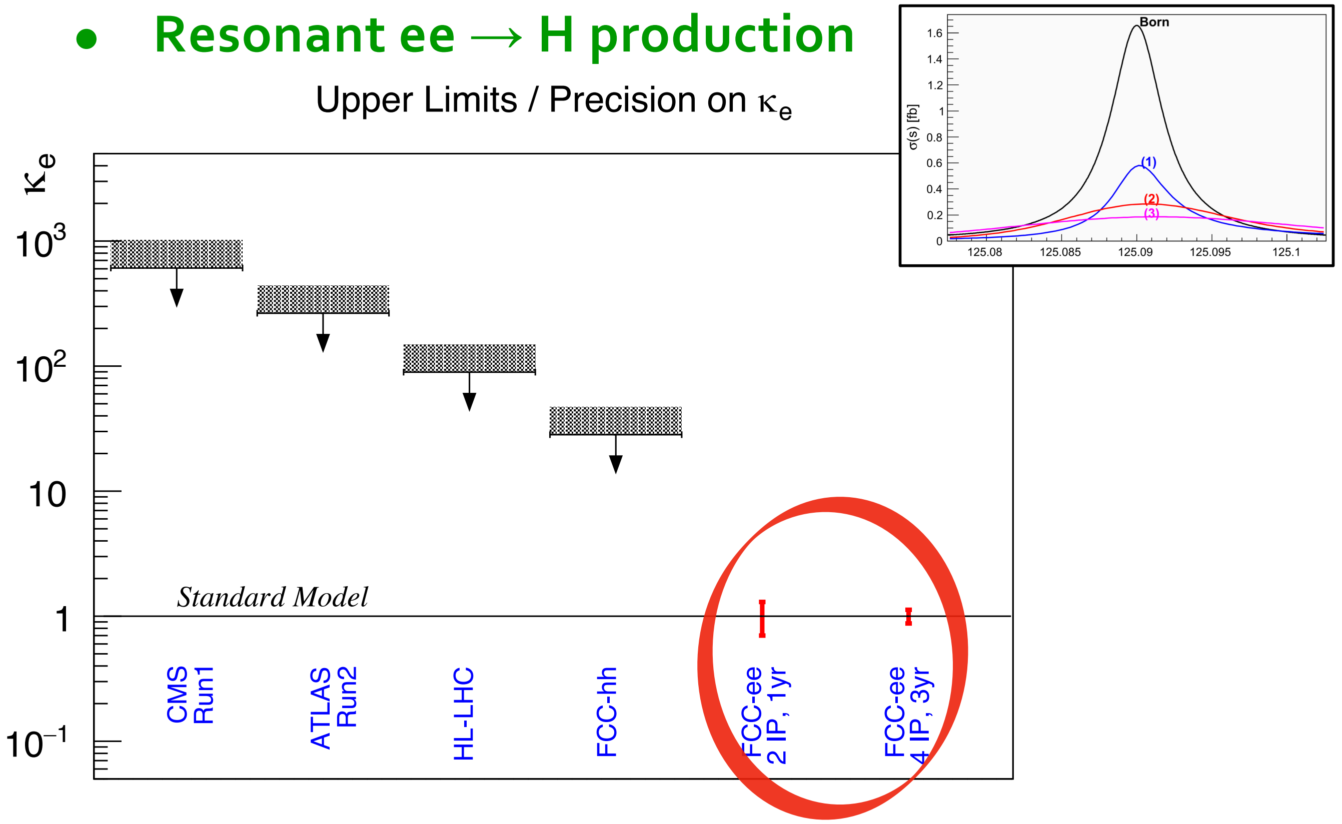
Access to e⁻ Yukawa



$\sigma(e^+e^-\to H)$ = 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 $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**
  - **Resonant ee → H production**



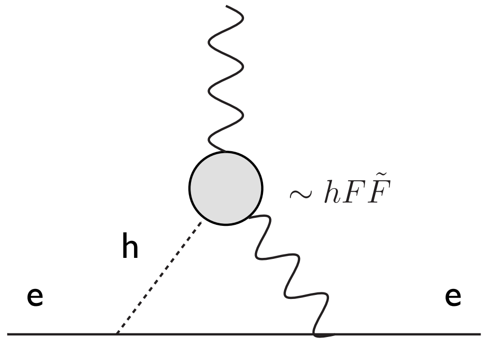
  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Why this measurement is important?

Constraints on CPV from EDM measurements

would vanish if hee is zero!

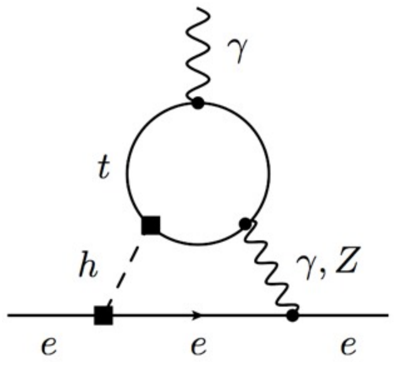
operators with γ — McKeen+ '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

Λ_{CPV} > 25 TeV

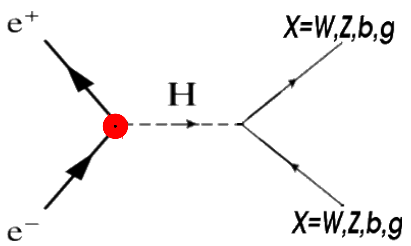
operators with top — Brod+ '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

Λ_{CPV} > 2.5 TeV

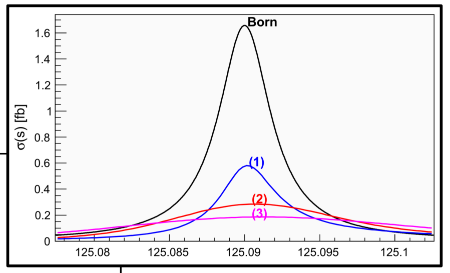
Access to e- Yukawa



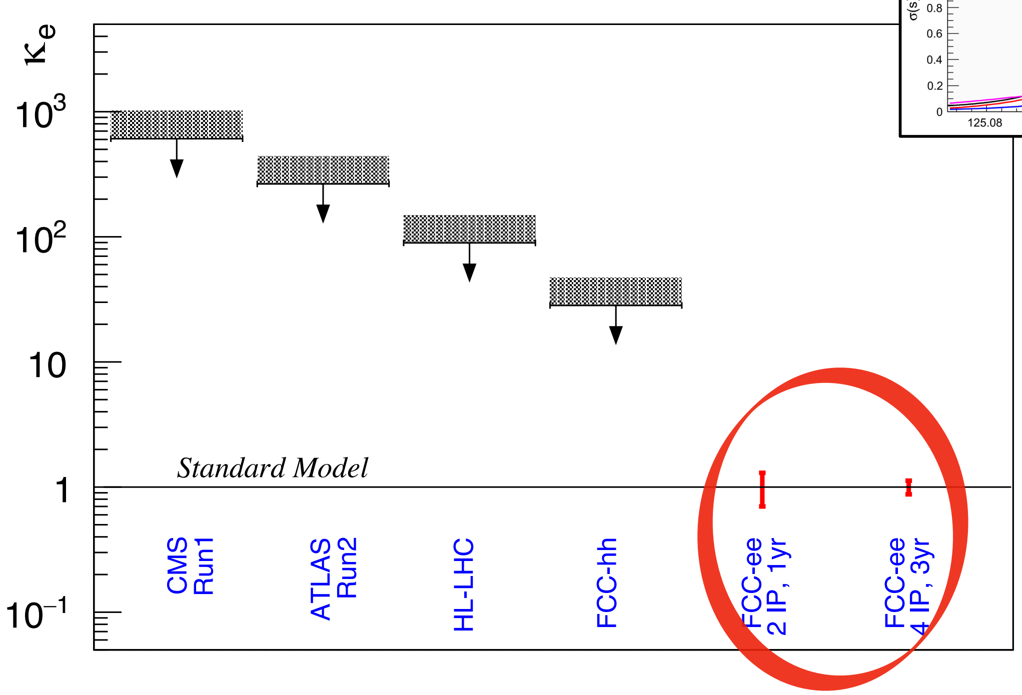
$\sigma(e^+e^-\to H)$ = 1.64 fb

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



Upper Limits / Precision on κ_e



  - **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**

Why this measurement is important?

Constraints on CPV from EDM measurements

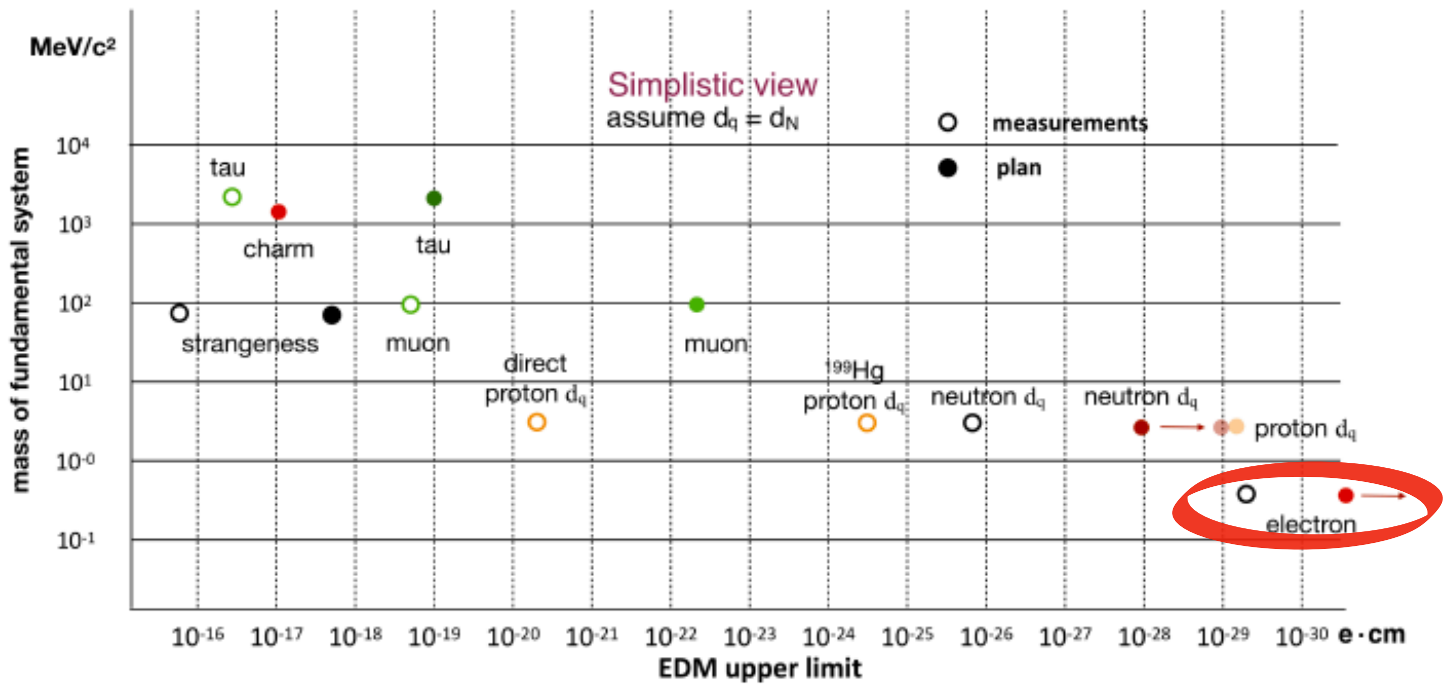
would vanish if hee is zero!

current ACME 90%CL bound on e EDM

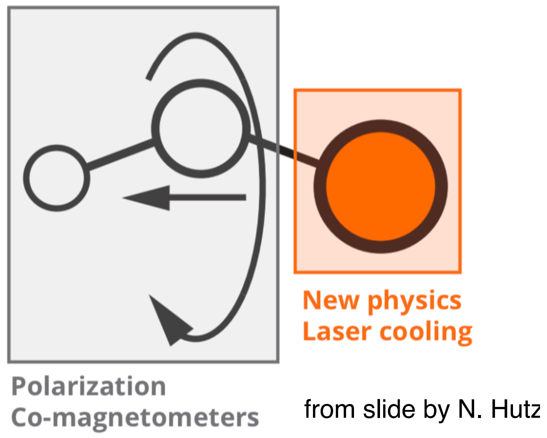
$$|d_e| < 1.1 \times 10^{-29}\, e\,\text{cm}.$$

(SM4 value : 10^{-37}-10^{-44} *e* cm)

ESU, arXiv:1910.11775



Polyatomic EDM



from slide by N. Hutz

Time scale of 5-10 years:

$$|d_e| \lesssim 10^{-32}\, e\,\text{cm}$$

1-loop, PeV scale sensitivity

M. Reece @ Pheno2020
Snowmass LOI

CP Violation in Higgs Sector

Searching for source of CPV that can trigger matter-antimatter imbalance

SM: only 1 CPV invariant (Jarlskog)

BSM: 707 new sources of CPV at leading order

CPV is a Collective effect: CPV is accidentally small in the SM

SM:

$$J_4 = \mathrm{Im}\mathrm{Tr}\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]^3\right) \sim \lambda^{36} \sim 10^{-24}$$

BSM:
(dim.6 Yukawa)

$$L_1^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger\right] \quad L_2^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_u\right] \quad L_3^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_d\right]$$

$$L_4^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_u X_d\right] \quad L_5^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_d X_u\right] \quad L_6^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_u^2 X_d^2\right]$$

$$L_7^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_d^2 X_u^2\right] \quad L_8^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_u X_d^2 X_u^2\right] \quad L_9^{uH} = \mathrm{Im}\,\mathrm{Tr}\left[C_{uH} Y_u^\dagger X_d X_u^2 X_d^2\right]$$

	Generic	MFV
Rank 1	$\mathcal{O}(\lambda^0)$	$\mathcal{O}(\lambda^0)$
Rank 2	$\mathcal{O}(\lambda^4)$	$\mathcal{O}(\lambda 8)$
Rank 3	$\mathcal{O}(\lambda^8)$	$\mathcal{O}(\lambda^{12})$

all suppressed by v^2/(New Physics scale)^2 but no big collective suppression

sizes of CPV sources depend on flavour symmetry of BSM interactions

Bonnefoy et al: arXiv:2112.03889

CP Violation in Higgs Sector

Searching for source of CPV that can trigger matter-antimatter imbalance

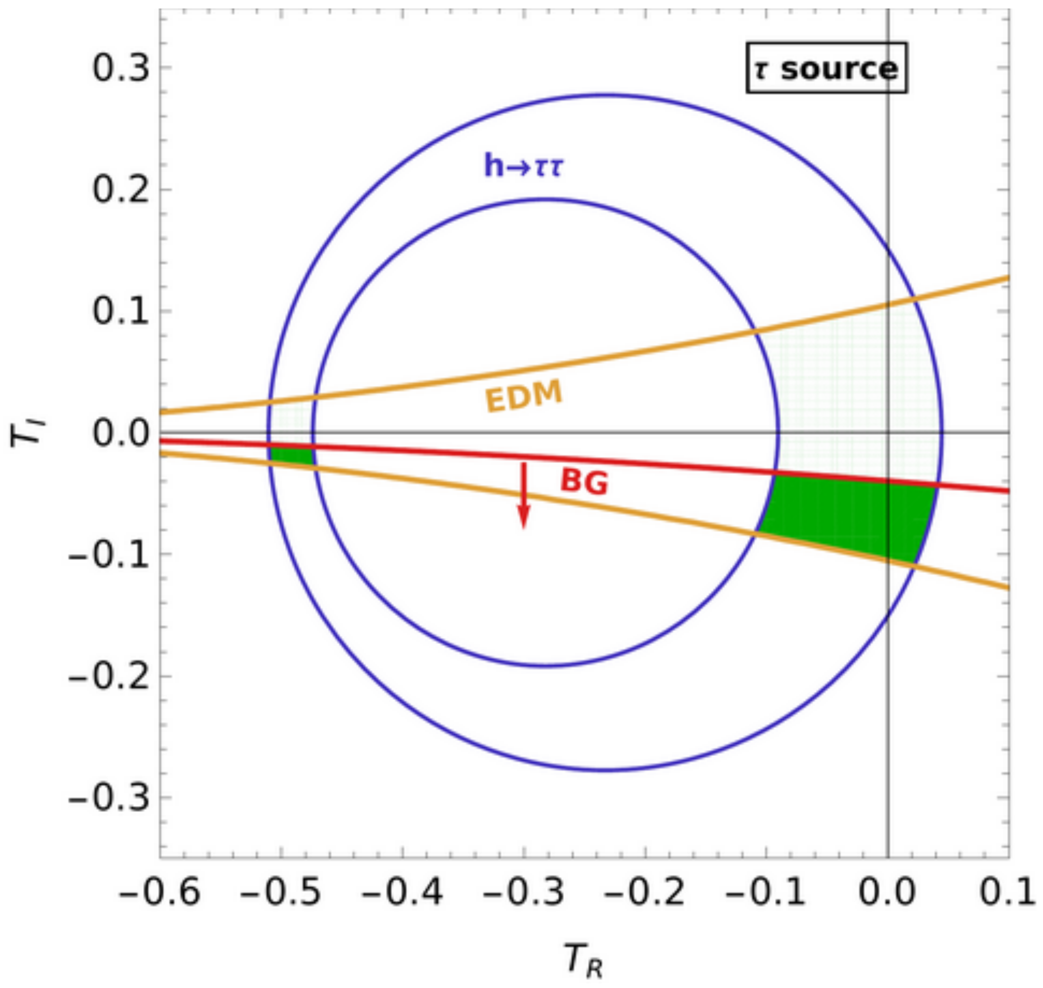
SM: only 1 CPV invariant (Jarlskog)

BSM: 707 new sources of CPV at leading order

CPV Yukawa could still be the source of EW baryogenesis

Fuchs et al. '20

see also
de Vries et al. '17



sufficient baryon asymmetry within LHC & EDM limits?

τ: yes

t, b, μ: no

EDM μ(h→ μμ)<1.7

EFT Cut-off scales $\Lambda/\sqrt{X_{R,I}}$

Minimal scales maximally allowed T (collider, EDM)

τ, b: 1 - 3 TeV; t: 1 TeV (LHC), 9 TeV (EDM)

μ: 10 – 12 TeV

Maximal scales minimally required T_I (EWBG)

$\Lambda/\sqrt{X_I^\tau} \lesssim 18\ \text{TeV}\ (0.01/T_I^\tau)^{1/2}$

— continue the exploration, especially in the tau sector —

Physics Performance On-Going Works

- Common software framework is becoming the "standard" for analyses
- First usage of Full Simulation in analyses will be presented this week
- Several efforts that have started recently will presented for the first time; status reports on other analyses will be given as well.

Join the efforts! Volunteers welcome!

Physics Performance On-Going Works

Flavour

Measurement	Constraining
Bs to Ds K	Many things.. Vertexing, PID, EM resolution
Bc -> tau nu	Flight distance resolution (vertexing)
B -> K* tau tau	Flight distance resolution (vertexing)
Modes with pi0's	EM resolution

Tau

Measurement	Constraining
Tau Lifetime	Construction and alignement of vertex detector
Tau mass	Track momentum scale (in multi-track collimated environment)
Tau leptonic BR	Electron and muon ID
Tau polarisation and exclusive BR	Photon, Pi0, neutrals, K/pi separation
Lepton Flavor Violation in Z and tau decays	Lepton momentum scale

BSM

HNL	- displaced vertices - specific tracking
ALPS: ee $\to$ aγ $\to$ 3γ	- Photon resolution - separation of close-by photons - displaced γ vertices
ALPS: $\gamma\gamma \to \gamma \to \gamma\gamma$	Photon resolution
Dark Photons $ee \to \gamma\bar{\gamma}$	Photon resolution

Physics Performance On-Going Works

Z pole

Measurement	Constraining
Total width of the Z *(see next slide)*	Track momentum (and angular) resolution, scale (magnetic field) stability
Rb, Rc, AFB of heavy quarks	Flavour tagging, acceptance, QCD corrections
alphaS measurement	Z -> jets
Ratio Rl	Geometrical acceptance for lepton pairs
AFB (muons) and $\alpha(QED)$	EW corrections and control of IFI (initial-final state radiation interference)
Luminosity from diphoton events ; NP in diphotons	e/gamma separation, gamma acceptance

WW

Measurement	Constraining
Coupling of Z to nu_e (also, at the Z peak: invisible ALP, dark γ)	Photon energy resolution, acceptance, track efficiency
M_W from WW -> had, semi-lep	Lepton and jet angles, Kinem fits
(d)σ(WW) for M_W, TGCs	Lepton ID, angular resolutions
Vcb via W -> cb	Flavour tagging
W leptonic BRs	Lepton ID, acceptance
Meas of √s via radiative return	lepton and jet angular resolutions, acceptance

Physics Performance On-Going Works

Higgs Physics

Measurement	Constraining
Higgs boson coupling to c quark	Flavour tagging, vertexing
σ(ZH) and mH, Z →leptons (Mrecoil); New scalars in Z + S	Lepton momentum & energy resolution
σ(ZH) and mH, Z → hadrons ; BR(Higgs invisible)	hadronic mass and hadronic recoil-mass resolution ; Maybe b-tagging
Γ(H) in ZH, H → ZZ*	Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits
Higgs boson mass in all exclusive final states (hadronic, taus, etc)	b-tagging eff and purity, jet angular resolution, jet reco, kin fits

Higgs Physics

Measurement	Constraining
Γ(H) with bbnunu events	Visible and missing mass resolutions
HZγ coupling	photon identification, energy and angular scale
ee->H production in s-channel at Higgs pole	- q / g tagging

top

Measurement	Needs good:
EW couplings of the top	Jet reco, b-tagging, kine fits
Top properties from threshold scan	Jet reco, b-tagging, kine fits
FCNC couplings	Idem + photon reco

Summary of Physics Potential

FCC-ee note, 1906.02693

√s → / Physics ↓	m_Z (e⁺e⁻ collisions)	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV (pp collisions)	100 TeV	Leading Physics Questions
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→gg							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	ee → H, $\sqrt{s} = m_H$		1.2×10⁶ HZ and 75k WW→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

Colour coding of the filled cells: green — Transverse polarization (m_Z and $2m_W$), 5×10^{12} Z (QCD, Flavours, RH ν's), ee → H, 3 to 5σ from loop corrections, <1% precision (Higgs rare decays), 10^{11} W. Blue — m_W, α_S, 3×10^{8} W, 10^5 H→gg, 1.2×10⁶ HZ and 75k WW→H, <1% precision (Model-independent Higgs couplings), 10^{-4} BR sensitivity, 5% (HH prod), Up to 40 TeV, W, Z, and the 100 TeV Quark-gluon plasma cell (no text). Pink — Y; hatched pink — the three M_χ cells. In the original table the "ee → H" cell sits across the m_Z and $2m_W$ columns.

Conclusions

A **circular "Higgs factory"** like FCC-ee has a rich potential:
* Direct and indirect sensitivity to New Physics
* Refinements in our understanding of Nature (EW phase transition, naturalness…)

And it is an essential part of an **integrated** programme to probe the energy frontier

Data always brings new understanding.
We need facts and data: Physics is a natural science!
We have profound questions and we need create opportunities to answer them.
FCC-ee will for sure contribute.

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

Let's produce our boozons (and fermions) and have a party (afterwards)

Acknowledgement

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