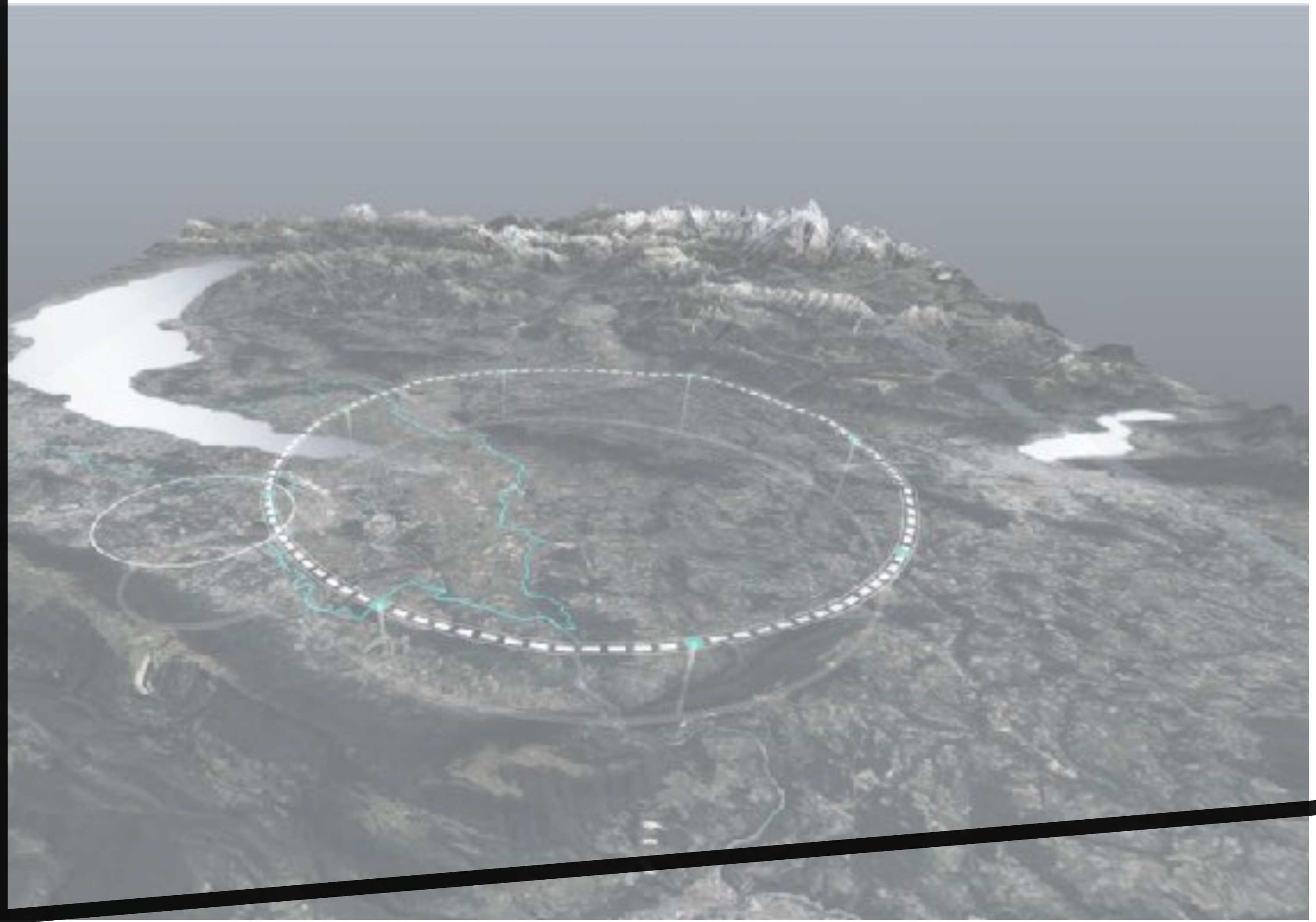
Future e+e- collider(s)

overview of envisioned measurements and precision goals

MITP workshop: Electroweak Corrections at Current and Future Accelerator(s)



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The LHC Legacy (so far)

(LHC = Higgs + Nothing*) ⇒ More energy & More precision

* actually a lot progress in our understanding of the SM:
1) Improved measurements of SM processes; 2) Precise measurements in flavour physics; 3) New frontiers in heavy-ion studies.

Thanks to a firm control of EXP & TH systematic uncertainties, the LHC became a precision machine.

The LHC Legacy (so far)

(LHC = Higgs + Nothing*) ⇒ More energy & More precision

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

The Future Circular Collider integrated programme fits the bill.

1. Higgs Physics @ FCC-ee

The Higgs Requires More Precision

(HL)-LHC will make remarkable progress (O(100M) Higgs=already a Higgs Factory).
But it won't be enough. A new collider is needed!

- Sub-percent precision for most interesting couplings, often with order of magnitude improvement on HL-LHC expectation.
- Asses, for the first time, second generation quarks (H→cč and H→sš)
- Higgs width measured O(1%) → model independent!
- Mass measured to O(4) MeV (vs. 20 MeV at HL-LHC) .
- Tantalising possibility to get close to SM expectation for $H \to e^+e^-$ (unique to FCC-ee)

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

FCC Higgs programme achieved in a compact period of 8 years of operation.
Leaving time for diverse and broad physics programme elsewhere.

1‰ precision on Higgs couplings ↔ indirect sensitivity up to 100 TeV

Higgs @ FCC-hh

FCC-hh completes the job:

- The **large dataset** (> 10^{10}H, > 10^7 HH) allows for precise measurements of the **rare decay** modes (γ, Zγ,μ), and clean samples with small systematics, e.g. from high pT events (>10^6 H w/ pT>1 TeV).
- Top coupling shows a nice **synergy**: FCC-hh mesures ttH/ttZ and denominator comes from FCC-ee
- **Normalisation** provided by FCC-ee measurements allows for full **model independence**, and higher precision.

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	→ 0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	→ 0.67
κ_t (%)	3.2*	3.1	→ 0.75
κ_μ (%)	4.4*	3.3	→ 0.42
$\lvert\kappa_s\rvert$ (%)	–	${}^{+29}_{-67}$	${}^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

EFT Global Fits

See A.N. Rossia, Corfu '26

EFT Calculations

- LO dim.-6: ✓ SMEFTsim [2012.11343] SmeftFR [2302.01353]
- NLO QCD for dim.-6 CP-even: ✓ SMEFTatNLO [2008.11743]
  - For when that means two-loop order: [2204.13045], [2311.15004], [2511.02488]
- NLO QCD for dim.-6 CP-odd: [2405.19083], [2409.00168], [2411.000959], [2412.10309], [2507.21768]
- NNLO QCD: [2204.00663], [2309.16758], [2311.06107], [2502.12846]
- NLO EW: [2406.03557], [2409.11466], [2411.08952], [2412.16076], [2503.07724], [2508.14966], [2601.09599]
- Dim.-8: [2203.11976], [2302.01353], [2303.10493], [2304.03305], [2304.06663], [2306.00053], [2312.09867], [2412.16020], [2511.04338]…

But no tool with the full dim.-8 basis implemented yet!

RGE

- 1-loop Dim.-6: ✓ [1308.2627], [1310.4838], [1312.2014]
- 1-loop Dim.-8: [2106.05291], [2205.03301], [2301.07151], [2409.15408], [2512.21724]
- 2-loop Dim.-6: ✓ [2510.08682], [2601.19974]

EFT Global Fits

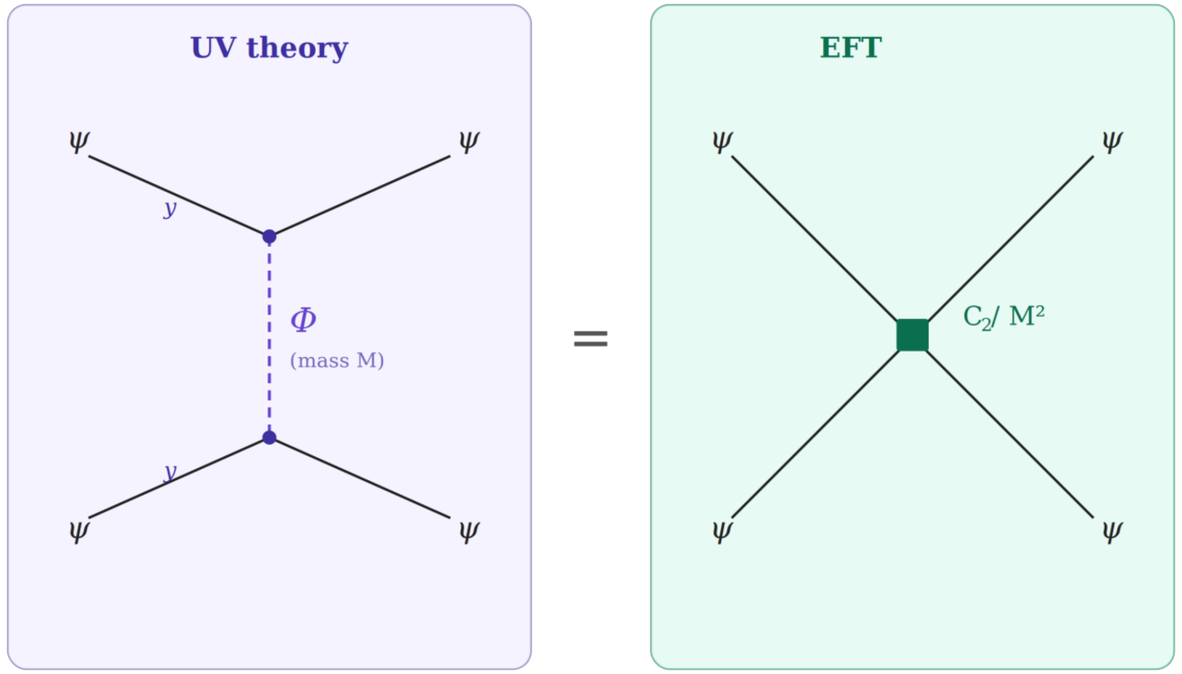
See A.N. Rossia, Corfu '26

UV-EFT MATCHING

- Tree-level matching to dim.-6: ✓ Granada Dictionary [1711.10391]
- 1 loop to dim.-6 for spin 0 and ½: ✓

[2112.10787] [2212.04510] [2303.16965] [2412.14253]

- Up to 1-loop to dim.-8: [2209.00666], [2210.14761], [2402.04306], [2404.01375], [2405.20371], [2408.12508]
- 2-loop matching: [2311.13630] [2412.12270]



EFT Global Fits

See A.N. Rossia, Corfu '26

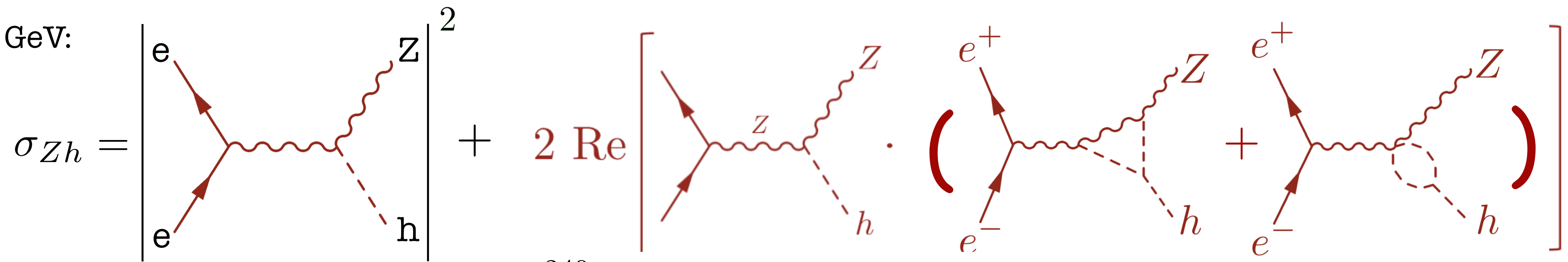
EFT Tools

- Several independent efforts:
  - HEPfit [1910.14012] [2507.06191]
  - SMEFiT [2302.06660] [2604.16596]
  - Fitmaker [2012. 02779]
  - smelli jelli [1810.07698] [2603.15801]
  - [2208.08454] [2311.04963] [2412.09674]
  - ATLAS EXPERIMENT, CMS
- Bayesian (theorists) and Frequentist (experimentalists) methods. ✓
- CP-even Dim.-6 operators. ✓
- 1-loop RGE effects. ✓
- Recycling to fit UV models matched onto SMEFT ✓ match2fit [2309.04523]

Higgs self-coupling

M. McCullough '14

At 240 GeV:

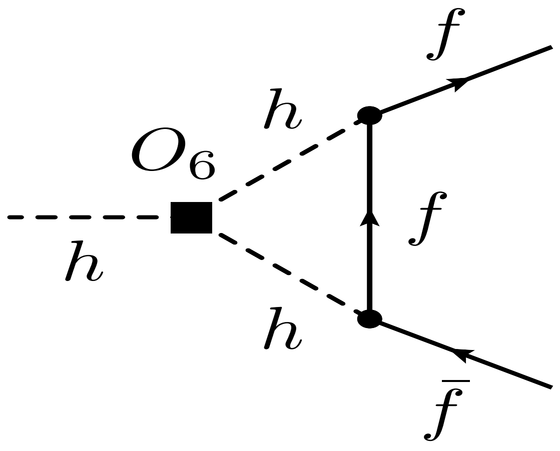


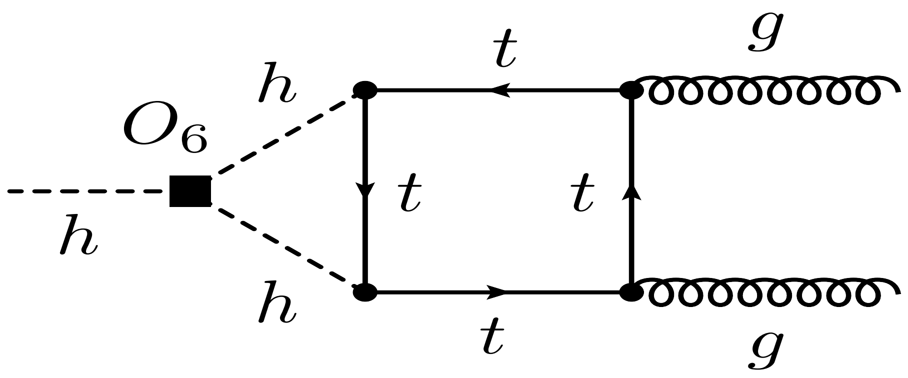
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

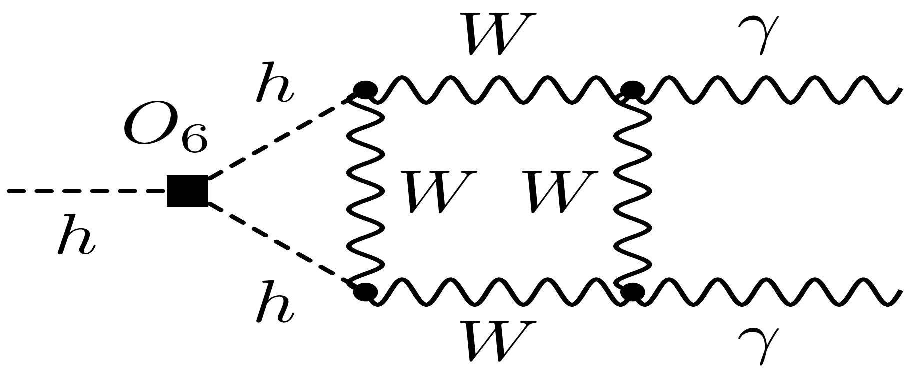
Gorbahn et al '16

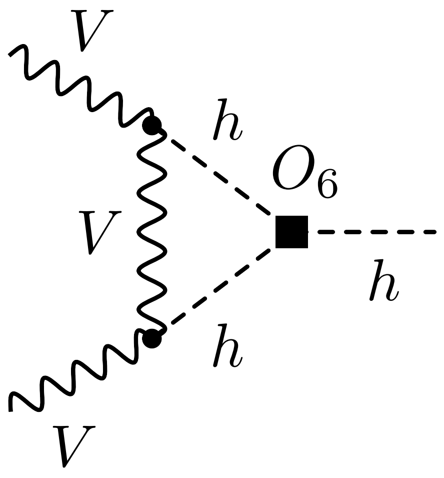
Degrassi et al '16

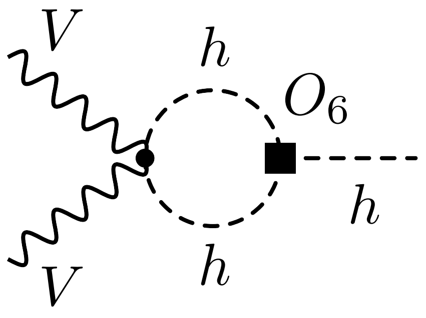
Bizon et al '16

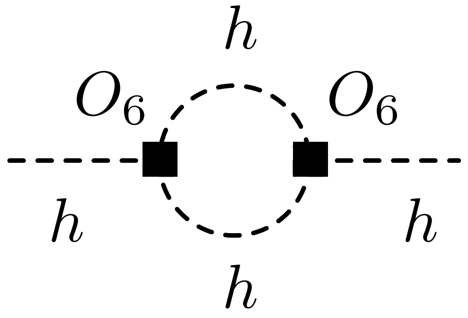






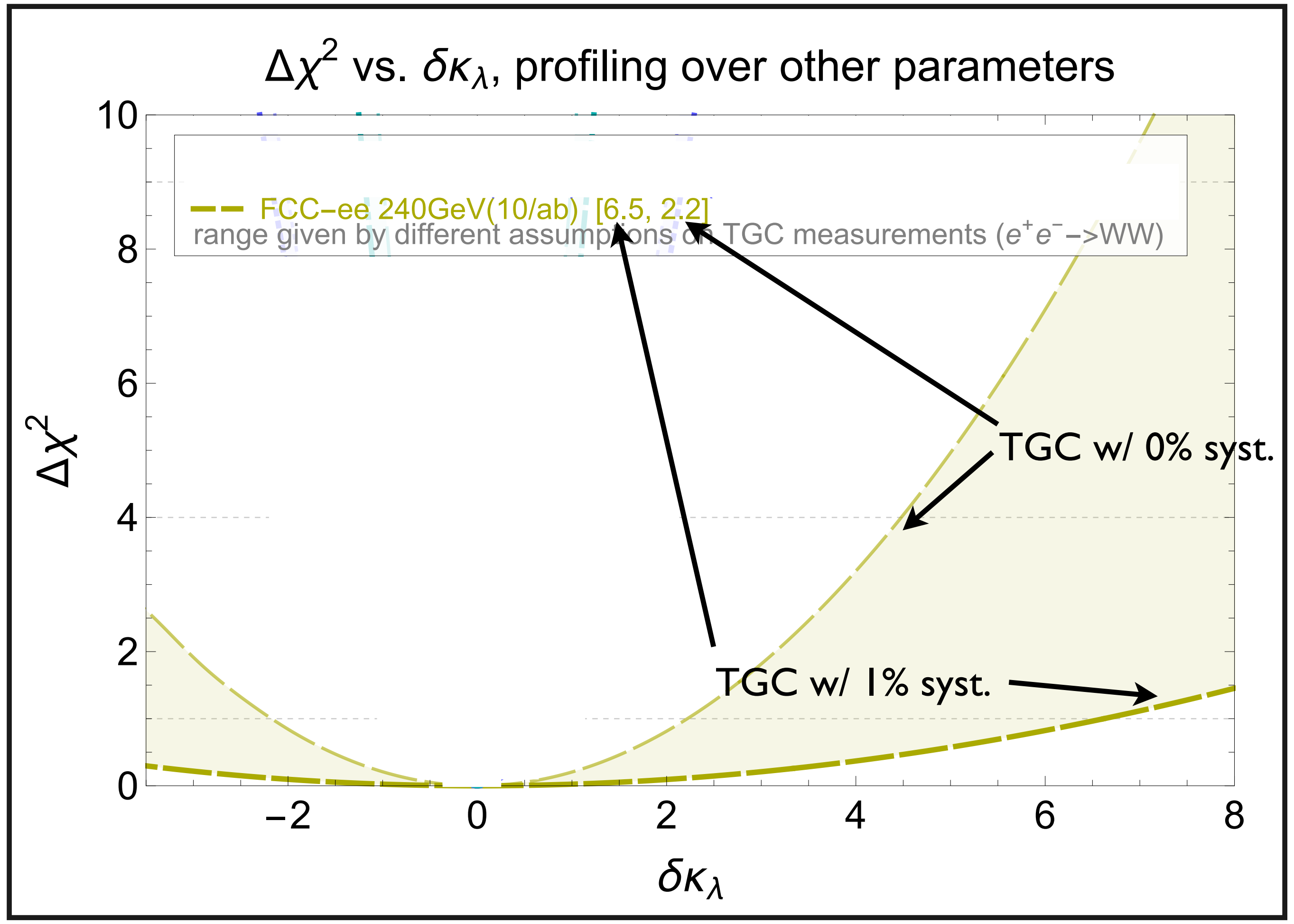






Higgs self-coupling

Higgs self-coupling

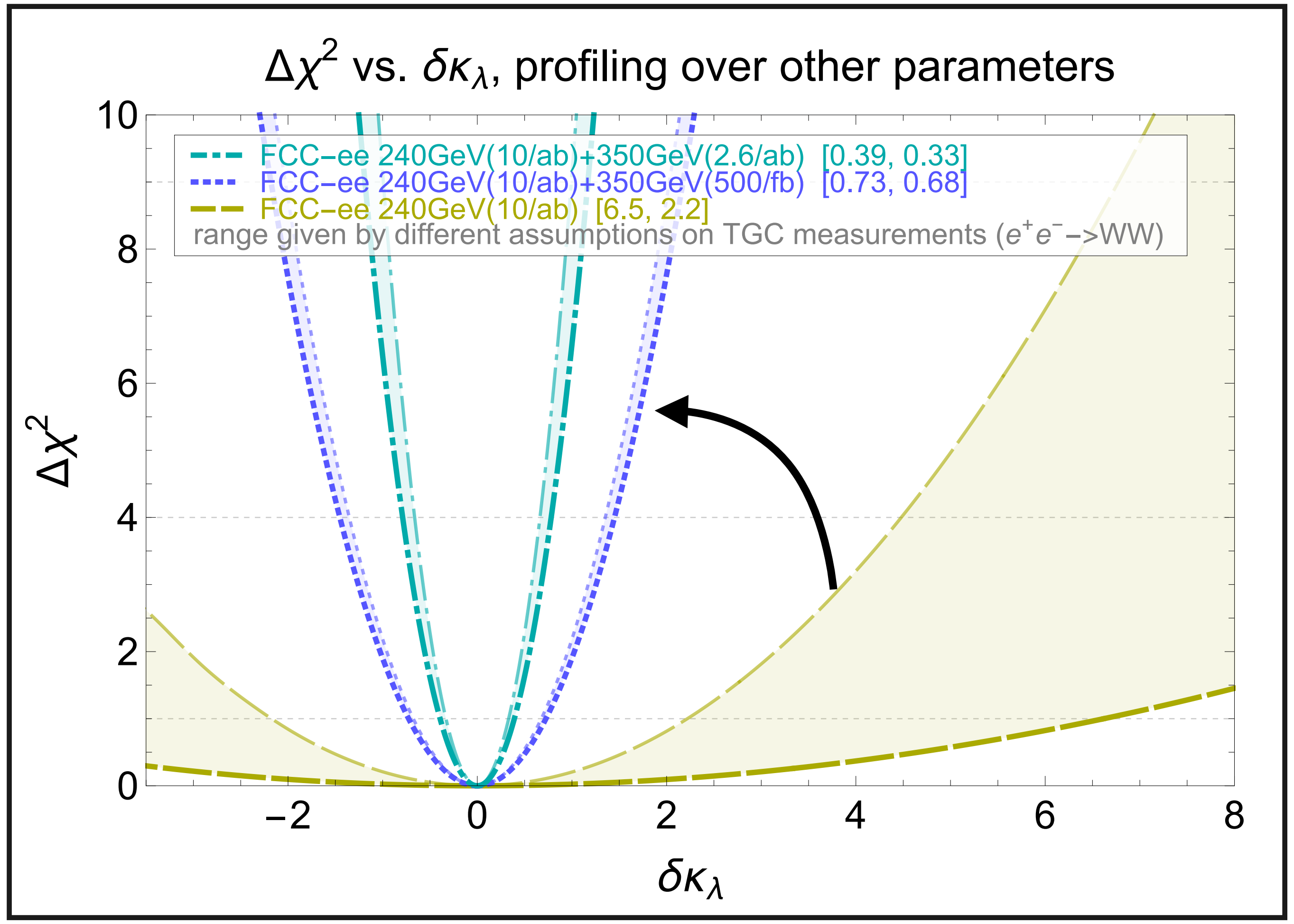


1) with a run at 240 GeV only, bound starts to become meaningful only if perfect control of di-boson

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon '17

See also F. Maltoni, D. Pagani, X. Zhao '18

Higgs self-coupling



1) with a run at 240 GeV only, bound starts to become meaningful only if perfect control of di-boson

2) combining 240+350 improves significantly the bounds on h^3

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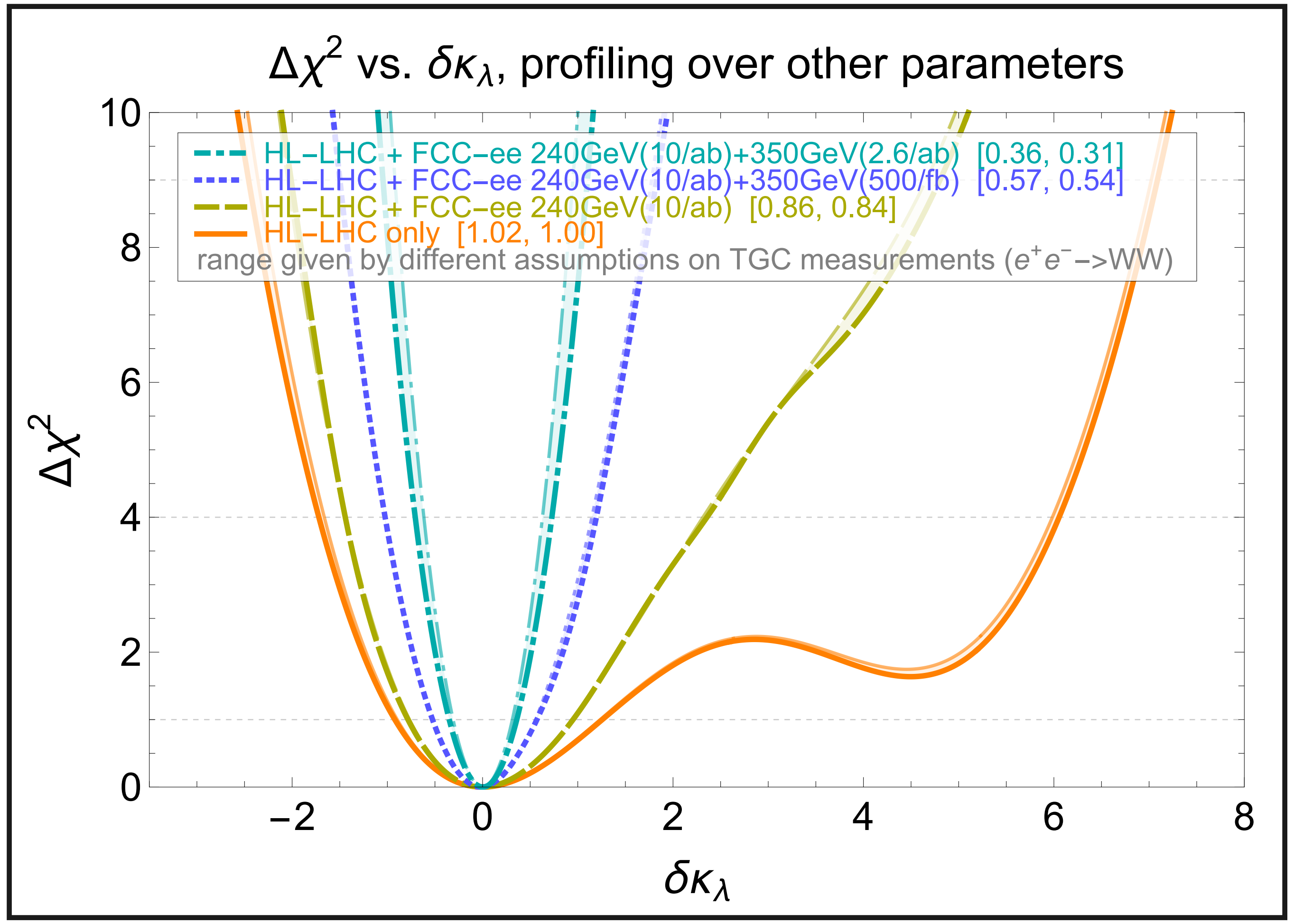
Higgs self-coupling



1) with a run at 240 GeV only, bound starts to become meaningful only if perfect control of di-boson

2) combining 240+350 improves significantly the bounds on h^3

3) combination FCC-ee and HL-LHC is very powerful (especially if cannot afford FCC-ee @ 350GeV)

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon ‘17

See also F. Maltoni, D. Pagani, X. Zhao ‘18

Higgs self-coupling

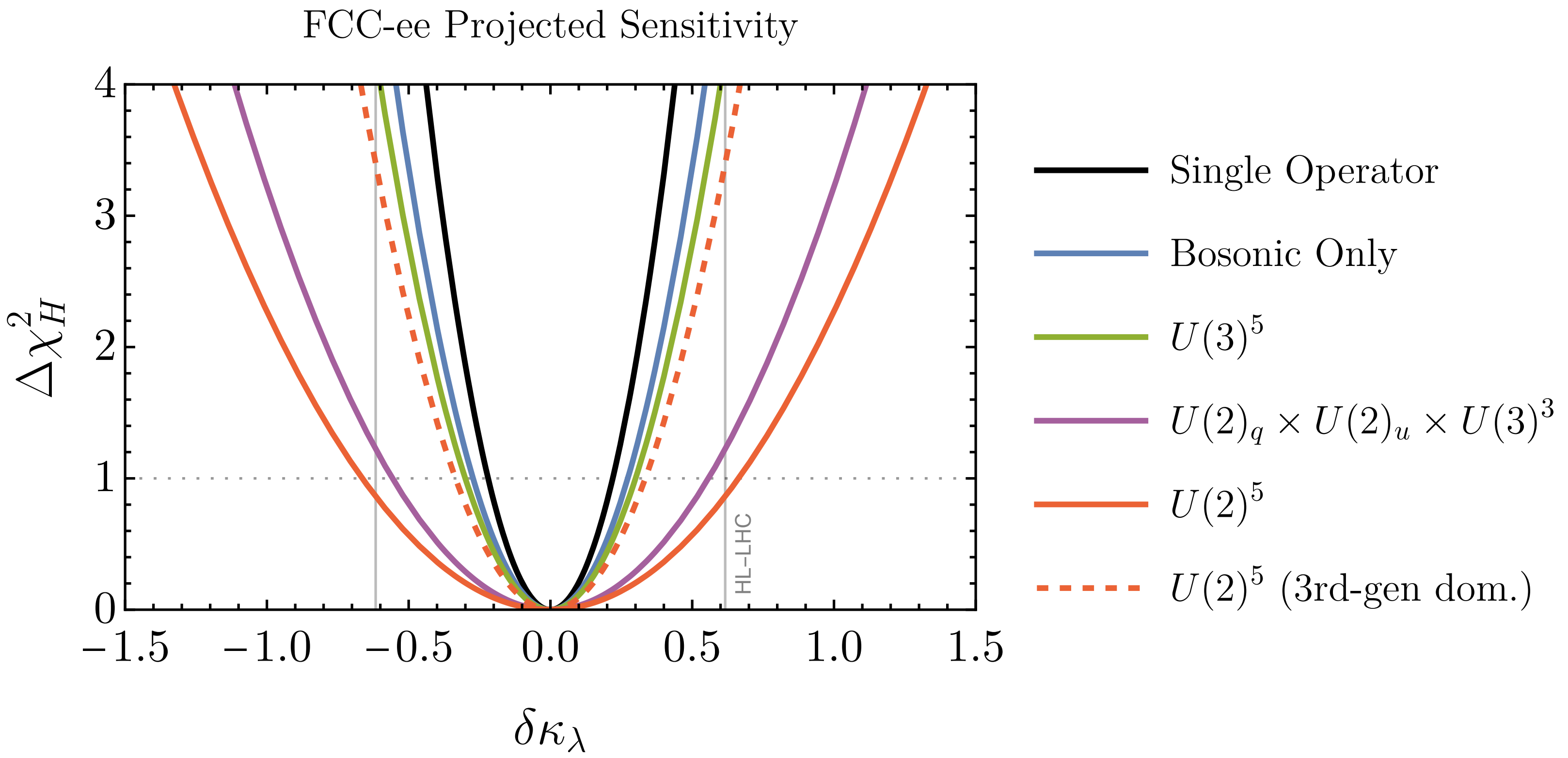
Previous fits were done for Higgs flavour diagonal couplings.
New fits explored impact of different flavour scenarios.

Maura, Stefanek, You arXiv:2503.13719

Flavour symmetry	CP-even parameters
$U(3)^5$	41
$U(2)_q \times U(2)_u \times U(3)^3$	72
$U(2)^5$	124
$U(2)^5$ (third-gen. dominance)	53

(FCC-ee alone)

Scenario	$\sigma_H\,[\mathrm{TeV}^{-2}]$	68% CL $\delta\kappa_\lambda$
C_H Only	0.47	22%
Bosonic Only	0.58	27%
$U(3)^5$	0.64	30%
$U(2)_q \times U(2)_u \times U(3)^3$	1.19	56%
$U(2)^5$	1.41	66%
$U(2)^5$ (3rd-gen. dominance)	0.71	33%

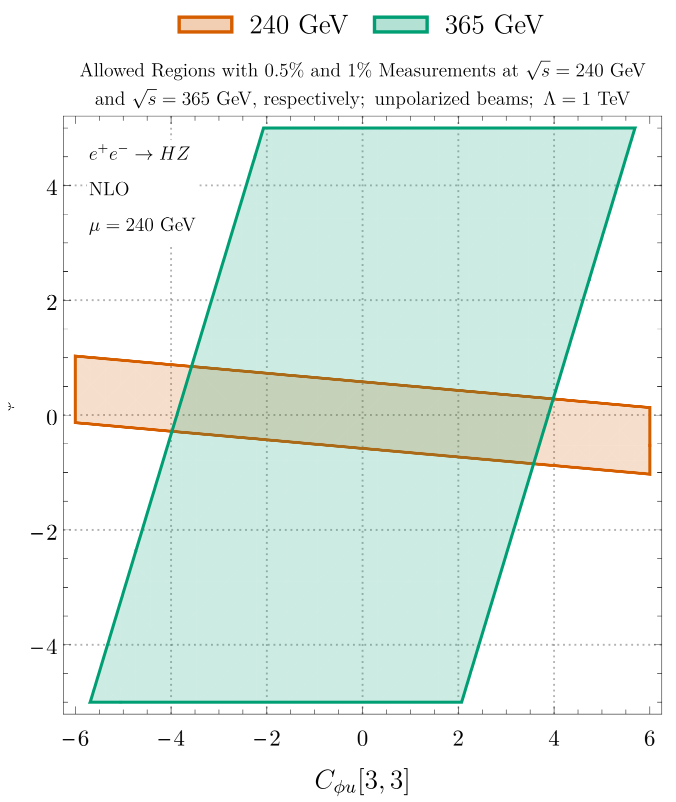


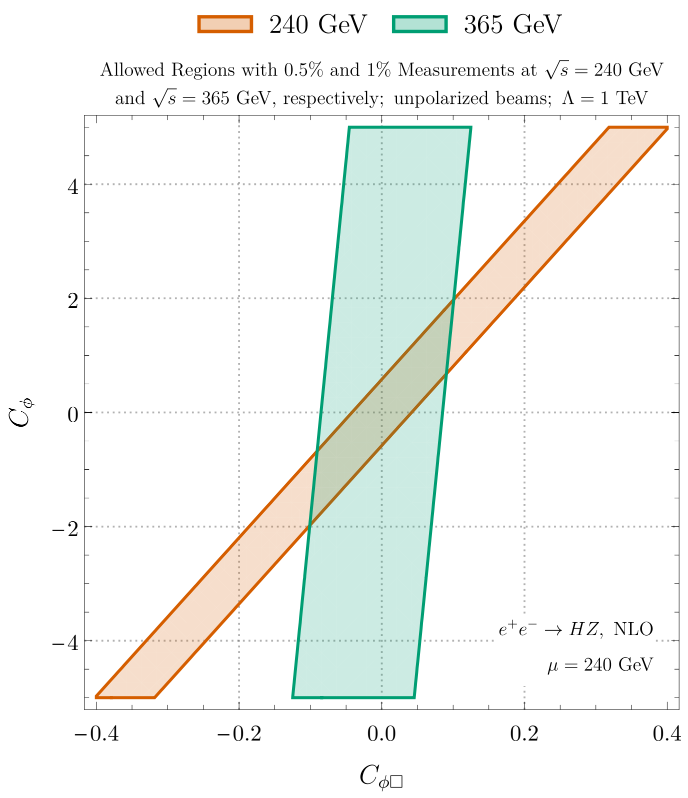
With more parameters, the sensitivity degrades. But the fit still converges!

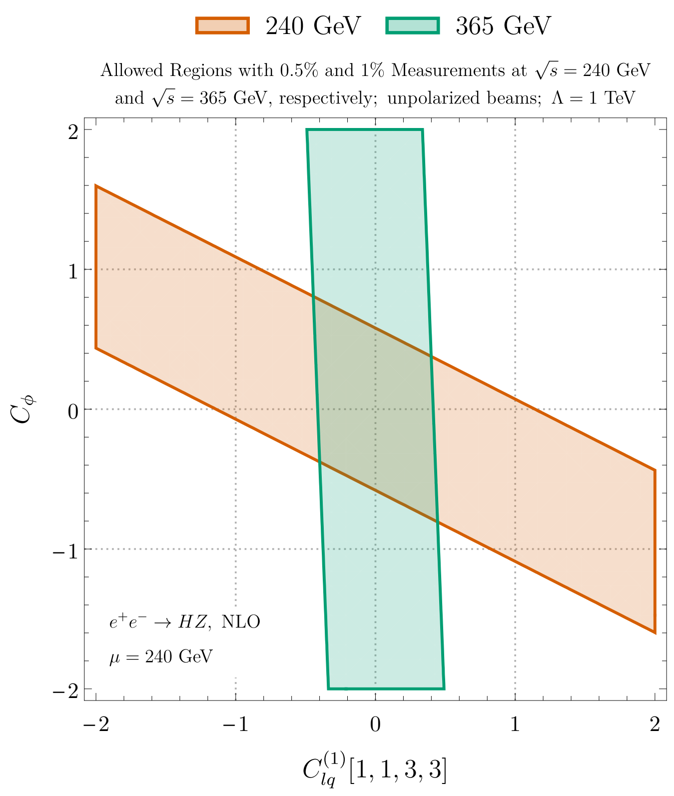
Higgs self-coupling

So far, results presented considered NLO effects of h^3 operator but only LO effects of other operators.
Full NLO effects could also impact the interpretation of ZH xs measurement.

Asteriadis, Dawson, Giardino, Szafron arXiv:2409.11466





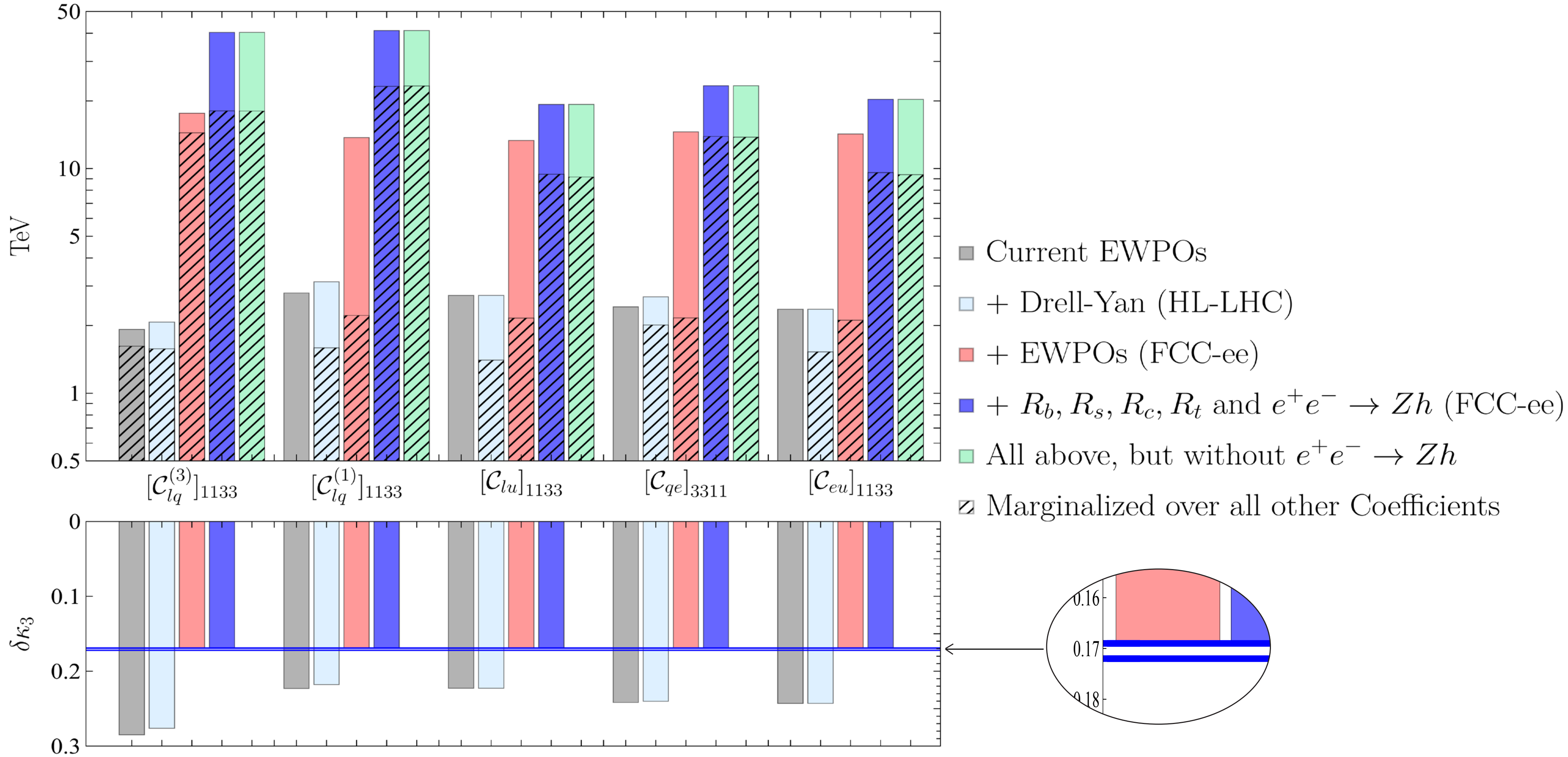


Worry: new (poorly constrained) operators, like eett, could affect ZH xs and hinder h3 extraction.
Again: two runs at different energy are enough to lift the degeneracy and separate the different contributions to ZH xs.

Higgs self-coupling

So far, results presented considered NLO effects of h^3 operator but only LO effects of other operators. Full NLO effects could also impact the interpretation of ZH xs measurement.

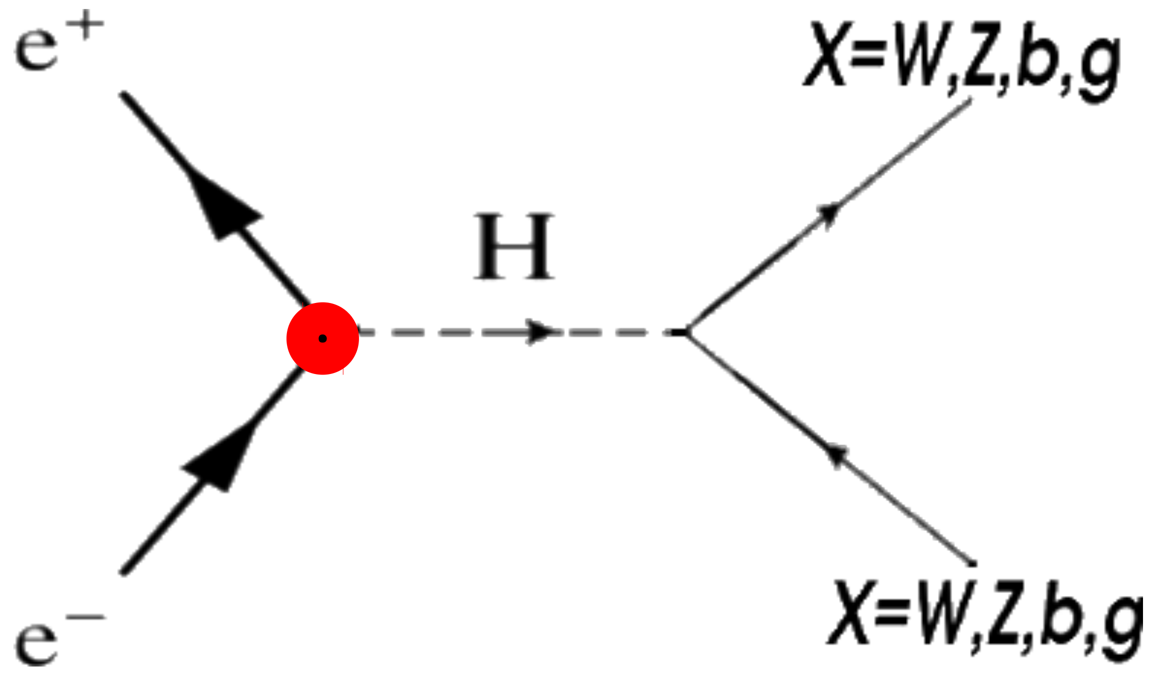
Allwicher, Grojean, Tabatt arXiv:2512.06916



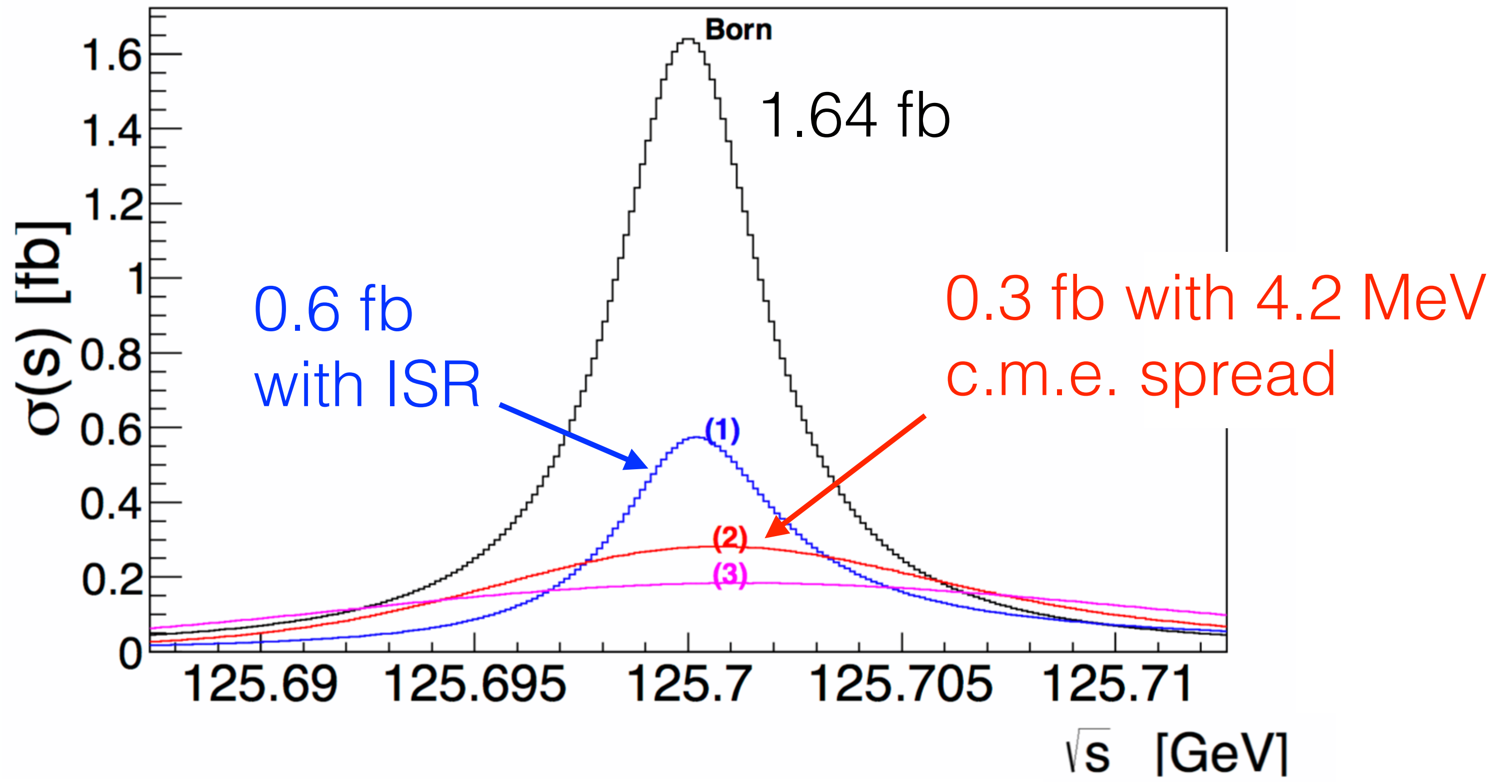
Thanks for different observables, the goal fit determination of the Higgs self-coupling is robust at full NLO.

Electron Yukawa

The high luminosity, the precise control of the beam √s, the clean reconstruction of final states make it possible to observe:



Jadach+, arXiv: 1509.02406



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

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

(note that natural E_{cm} spread is 100 MeV, challenging operation mode)

Electron Yukawa

The high luminosity, the precise control of the beam √s, the clean reconstruction of final states make it possible to observe:

- **20 ab⁻¹ / year at √s = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}}$ ~ 1-2 × Γ_H ~ 6 to 10 MeV**

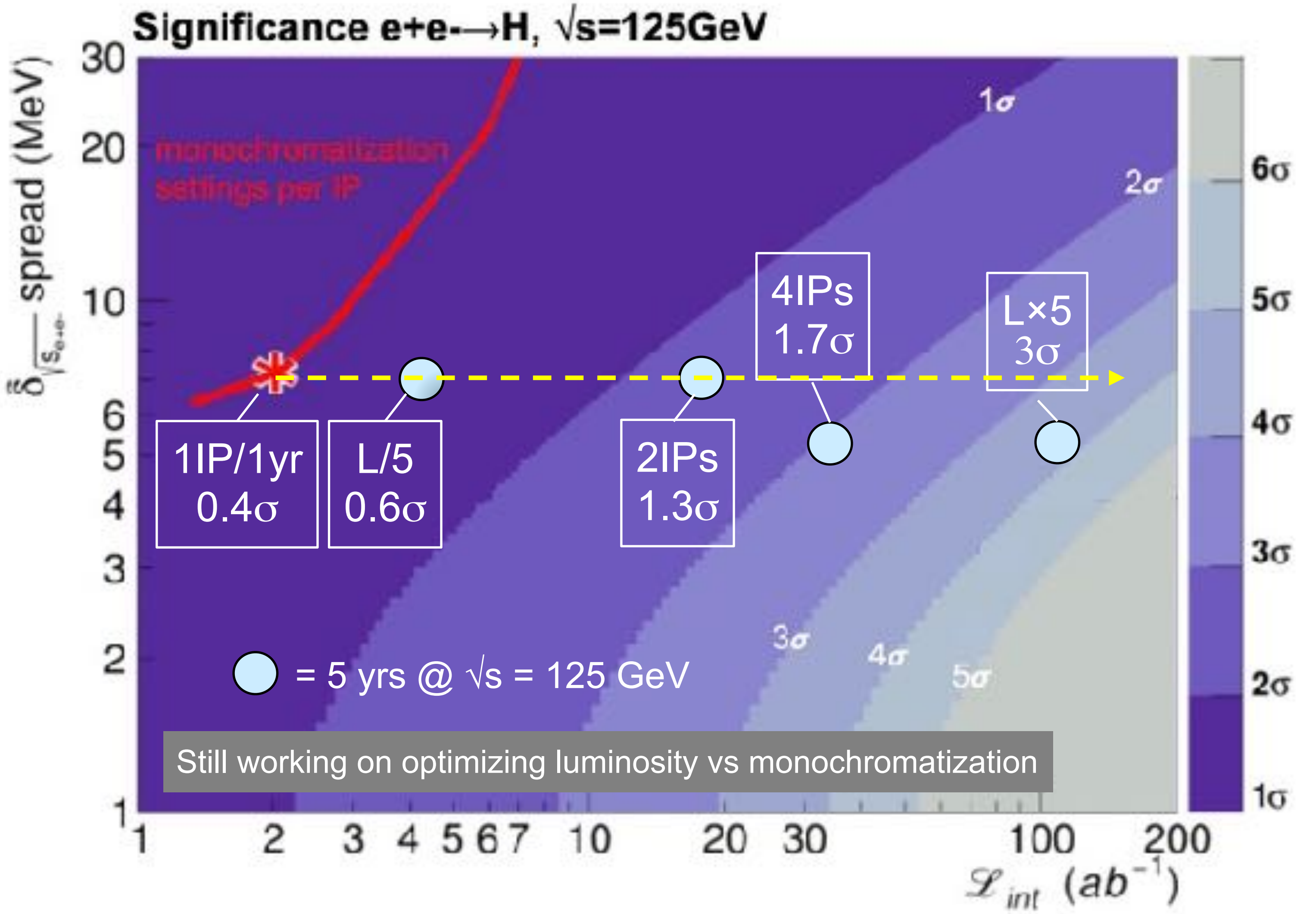
d'Enterria+. arXiv: 2107.02686

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	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

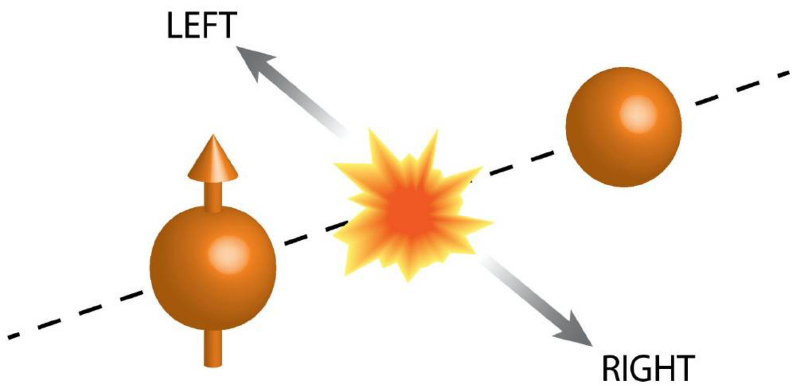
w/ 10/ab: S~55, B~2400 → 1.1σ



4σ expected with 4 IP in 4 years
or
95%CL on 2.5 x SM value in 1 year

Electron Yukawa

A pheno study (Boughezal et al 2407.12975) shows that transverse spin asymmetries can increase the sensitivity to the electron Yukawa



$$A = \frac{N}{D}$$

Electron polarized, positron unpolarized (SP⁰):

$$N = \frac{1}{2}(\sigma^{+0} - \sigma^{-0})$$
$$D = \frac{1}{2}(\sigma^{+0} + \sigma^{-0})$$

Electron transversely polarized, positron longitudinally polarized (DP):

$$N = \frac{1}{4}(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--})$$
$$D = \frac{1}{4}(\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--})$$

Electron transversely polarized, positron longitudinally polarized (SP⁺):

$$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+})$$
$$D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$$

Electron transversely polarized, positron longitudinally polarized (SP⁻):

$$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$$
$$D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$$

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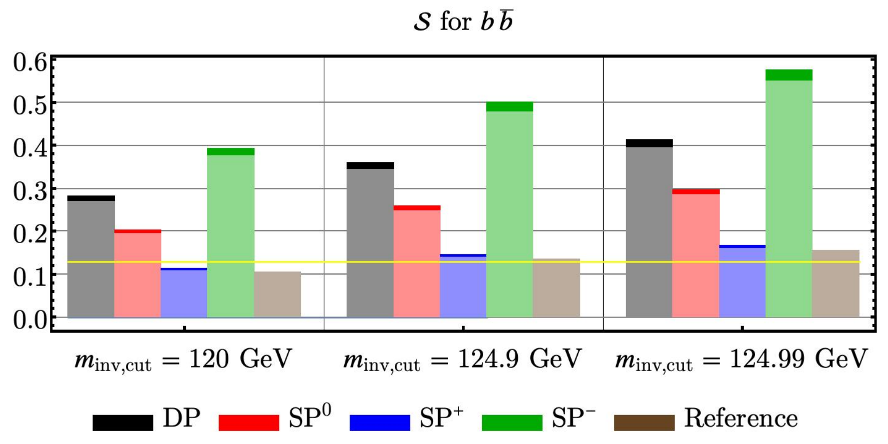
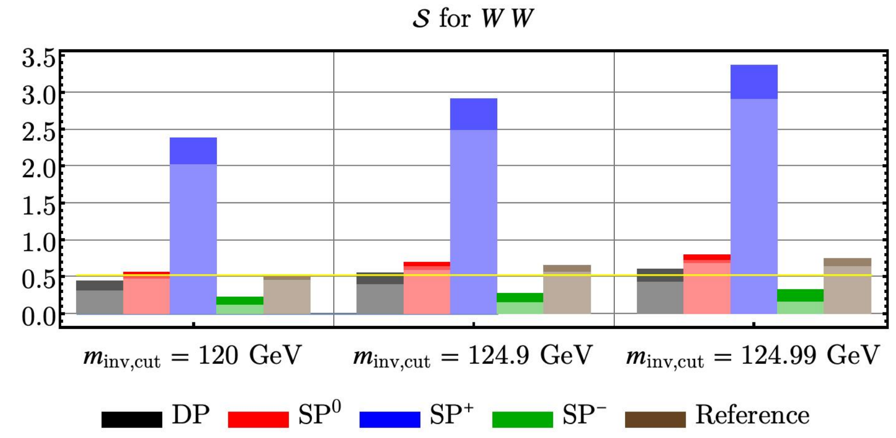




Major improvements of up to factors of 6 possible for bb and WW (doesn't work for gg)

2. EW @ FCC-ee

EW @ FCC-ee

The Tera-Z program (and beyond) yields a data sample size never seen before

- Lineshape scan at the Z pole (~91 GeV) and threshold scan at WW production threshold (~160 GeV)
- 2-3 orders of magnitude improvement w.r.t. current knowledge

Several challenges to keep all systematic uncertainties under control

- Beam calibration (EPOL) ~ 100 keV
- Detectors: acceptance, efficiencies, hermiticity
- Luminosity: using known processes (Bhabha, $\gamma\gamma$)
- Calibration: in situ using available data, monitoring
- Theory: need to cope with orders of magnitude improvement of theoretical calculations and Monte Carlo generators accuracy

Keep in mind that often the systematic uncertainties also scale down with increased statistics (e.g. beam energy determination from ee→Z/γ thus the associated uncertainty decreases with luminosity)

EW Precision Measurements at FCC-ee

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty	improvement factor / now
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration	20
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration	200
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	150
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate	
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons	
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit	
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement	
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement	
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons	2000
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge	
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics	
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass	
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR	
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency	
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration	50
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration	
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit	
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns	
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate	70
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate	
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run	

Experimental (statistical and systematic) precision of a selection of measurements accessible at FCC-ee, compared with the present world-average precision. FCC-ee syst. scaled down from LEP estimates. Room for improvement with dedicated studies.

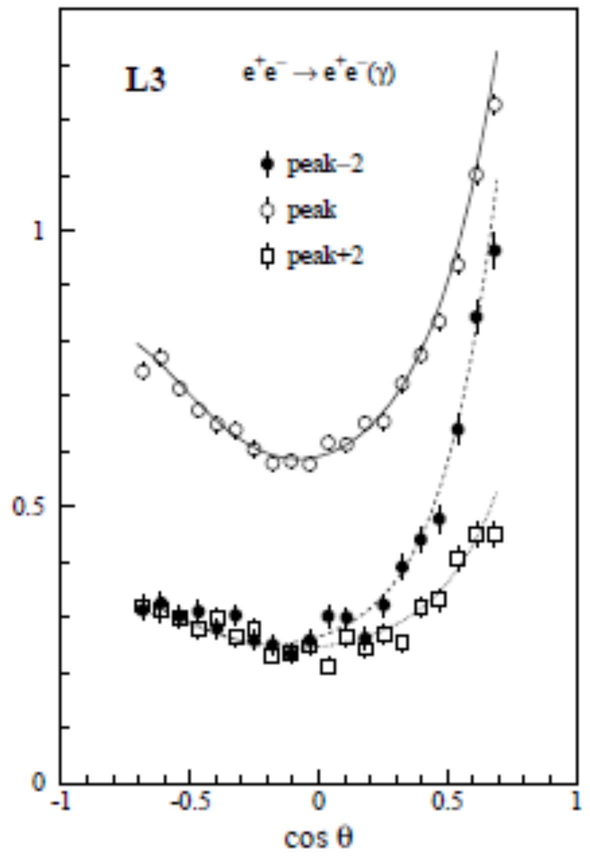
$\alpha_{QED}(m_Z)$

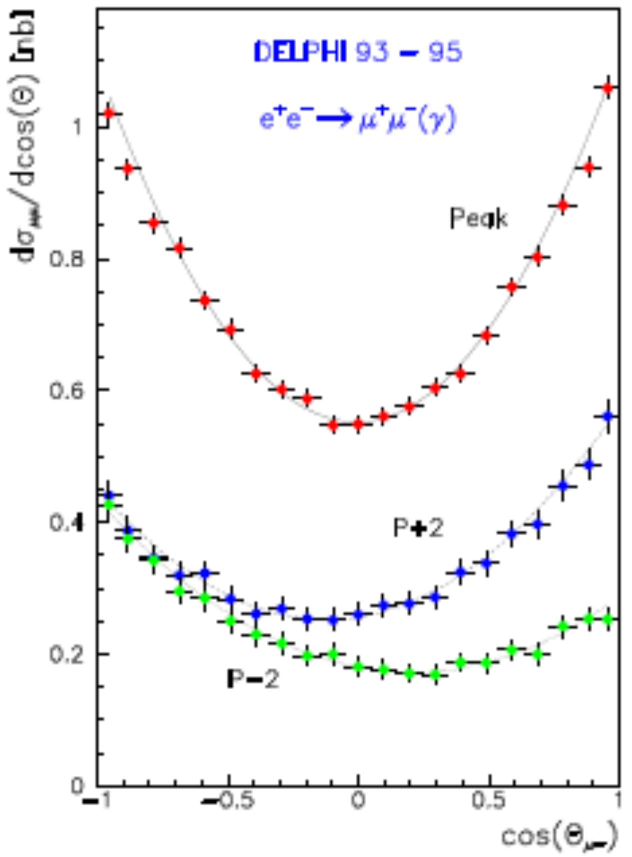
currently **10^{-4}**, a limiting factor to many BSM searches

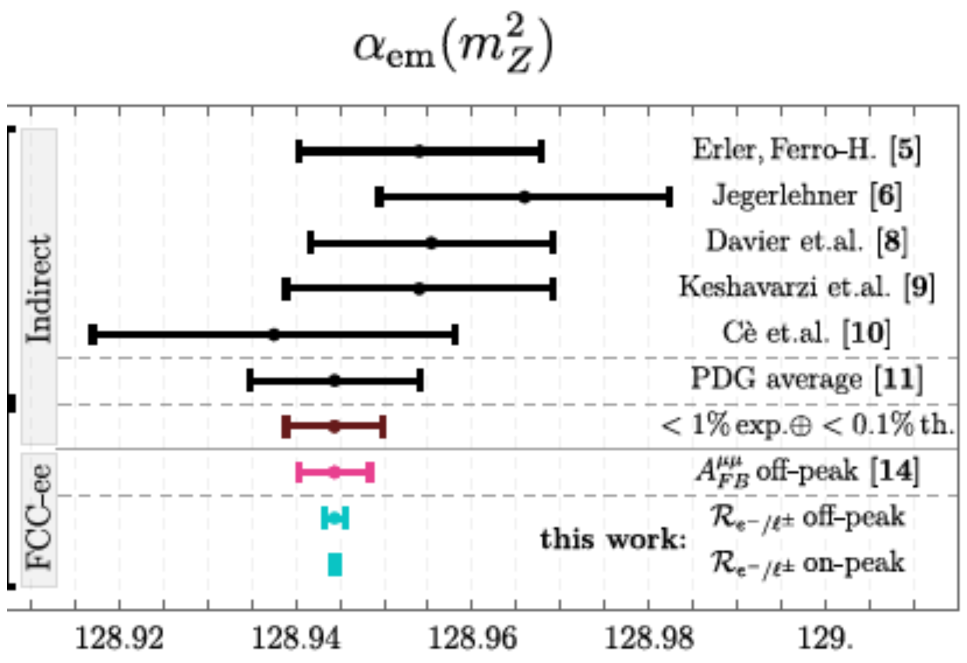
Unique to circular machines (it requires »10^{12} Z and line shape scan)

- **Off-pole** (Janot 2015): so far determined from the slope of $A_{FB}^{\mu\mu}$ vs $\sqrt{s}$ (interference Z and γ channels) → **±3x10^{-5}**
- **On-pole** (Riembau 2025): both s and t- channel $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ at the Z pole (larger data set), sizeable photon contribution for e^- only, not for μ^- → **±0.6x10^{-5}**

What are exp. systematics? Can this be improved by using tau final states, etc...?



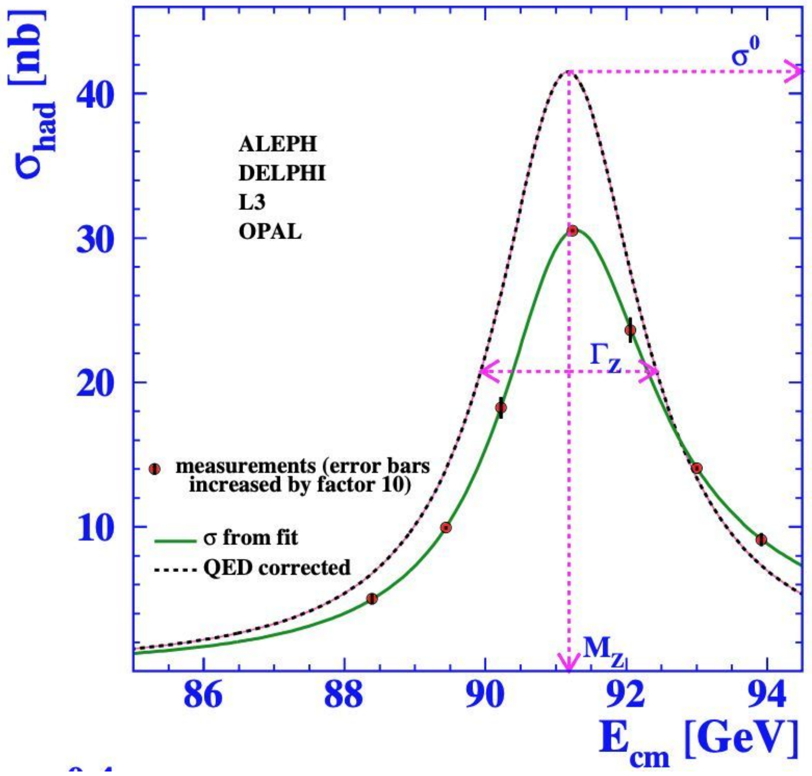




Z lineshape

0509008

- m_Z → input to cross sections, width, branching ratios of the Z boson
  - current uncertainty $\Delta m_Z \sim 2$ MeV (LEP)
  - $\sigma_{stat} \sim \Gamma Z / 2\sqrt{(N_Z^{\text{off-peak}})}$
    - 4 keV at FCC-ee
  - dominant systematic uncertainty: absolute beam energy calibration
    - resonant depolarisation $\Delta\sqrt{s} \sim \Delta m_Z \sim 100$ keV
- Γ_Z → sensitive to fermion couplings and to BSM
  - current uncertainty $\Delta\Gamma_Z \sim 2$ MeV
  - dominant systematic uncertainty: relative absolute beam energy calibration
    - point-to-point $\Delta\sqrt{s}_{p.t.p.}$ → to be measured in-situ with μμ events
    - $\Delta\Gamma_Z \sim 12$ keV at FCC-ee



$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$$

W Mass

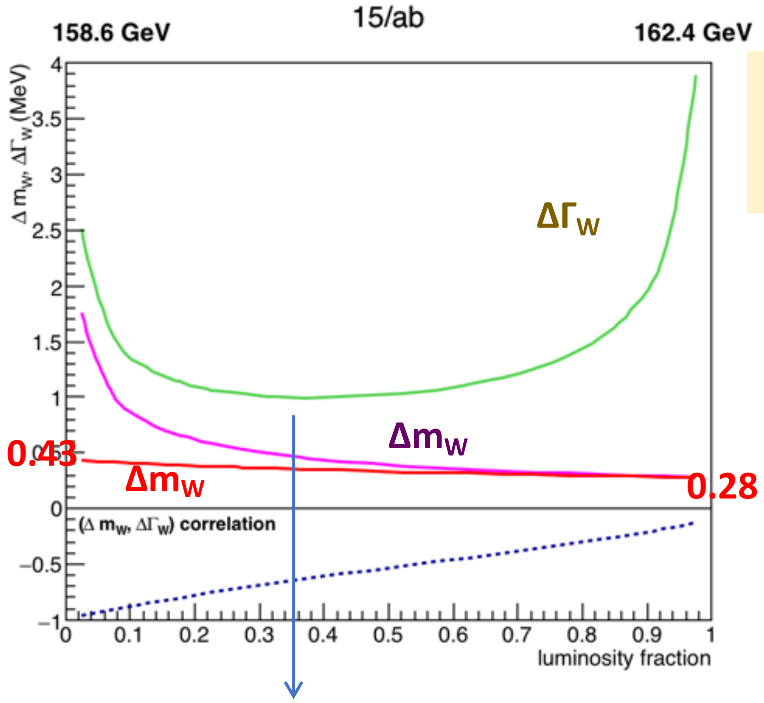
Two independent W mass and width measurements @FCCee :

1. The m_W and Γ_W determinations from the WW threshold cross section lineshape, with 12/ab at $E_{CM} \simeq$ 157.5-162.5 GeV **Δm_W=0.4 MeV $\Delta\Gamma_W$=1 MeV**

2. Other measurements of m_W and Γ_W from the decay products kinematics at $E_{CM} \simeq$ 162.5-240-365 GeV **Δm_W , $\Delta\Gamma_W$= 2-5 MeV ?**

a factor 2 improvement from Feasibility Report

Scans of possible E_1 E_2 data taking energies and luminosity fractions f (at the E_2 point)



Δm_W =0.45 MeV , $\Delta\Gamma_W$=1 MeV (r=-0.6)
Δm_W=0.35 MeV

A -minimum of **$\Delta\Gamma_W$=0.91 MeV** with **Δm_W=0.55 MeV**
taking data at E_1=**156.6** GeV E_2=**162.4** GeV f=**0.25**
yields **Δm_W=0.47 MeV** (as single par)

B- minimum of **Δm_W=0.28 MeV** **$\Delta\Gamma_W$=3.3 MeV** with
E_1=**155.5** GeV E_2=**162.4** GeV f=**0.95**
yields **Δm_W=0.28 MeV** (as single par)

C- minimum of **$\Delta\Gamma_W$=0.96 MeV +Δm_W=0.41 MeV** with
E_1=**157.5** GeV E_2=**162.4** GeV f=**0.45**
yields and **Δm_W=0.37 MeV** (as single par)

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both
Δm_W : error on W mass from fitting only m_W

Comparable in sensitivity with value from EWPO fit.

On-pole/Off-pole observables

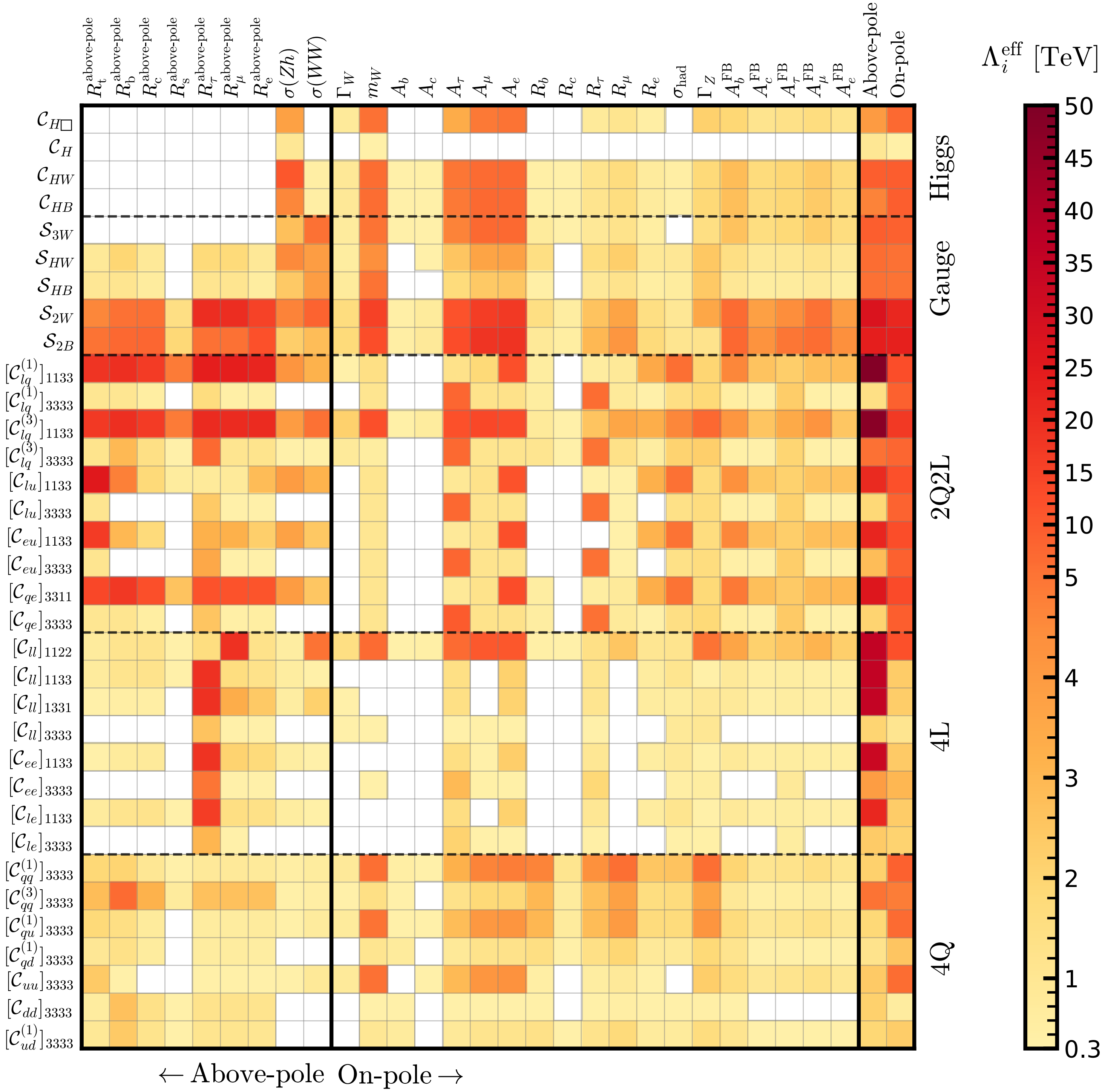
Maura, Stefanek, You arXiv:2412.14241

	Observable	Definition
Z-pole	Γ_Z	$\sum_f \Gamma(Z \to f\bar{f})$
	σ_{had}	$\frac{12\pi}{m_Z}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
	R_f $(f = e, \mu, \tau, c, b)$	$\frac{\Gamma(Z\to f\bar{f})}{\sum_q \Gamma(Z\to q\bar{q})}$
	A_f $(f = e, \mu, \tau, s, c, b)$	$\frac{\Gamma(Z\to f_L\bar{f}_L)-\Gamma(Z\to f_R\bar{f}_R)}{\Gamma(Z\to f\bar{f})}$
	$A_{\text{FB}}^{0,\ell}$ $(\ell = e, \mu, \tau)$	$\frac{3}{4}A_e A_\ell$
	A_q^{FB} $(q = c, b)$	$\frac{3}{4}A_e A_q$
W-pole	m_W	$\sum_{f_1,f_2}\Gamma(W \to f_1 f_2)$
	Γ_W	
	$\text{Br}(W \to \ell\nu)$ $(\ell = e, \mu, \tau)$	

$$R_a = \frac{\sigma(e^+e^- \to a\bar{a})}{\Sigma_{q=u,d,s,c,b}\sigma(e^+e^- \to q\bar{q})}$$

very efficient to constraint
4-fermion operators
thanks to EFT energy-enhancement effects.

On-pole/Off-pole observables



Maura, Stefanek, You arXiv:2412.14241

3. FCC Physics Programme

FCC-ee Run Plan

LEP1 data accumulated in **every 2 mn**.

(for the same power consumption, i.e. machine 100'000 more efficient).

Improved efficiency thanks to

▸ **Double ring collider**

•many bunches, high current, like LHC and B factories, different from LEP.

▸ **Top-up injection**

•standard at modern light sources, like Swiss Light Source.

•used at recent e^+e^- colliders, PEP-II (USA), KEKB (Japan), BEPCII (China).

▸ **Crab-waist collision scheme**

•successfully demonstrated at DAFNE (Italy) and SuperKEKB (Japan).

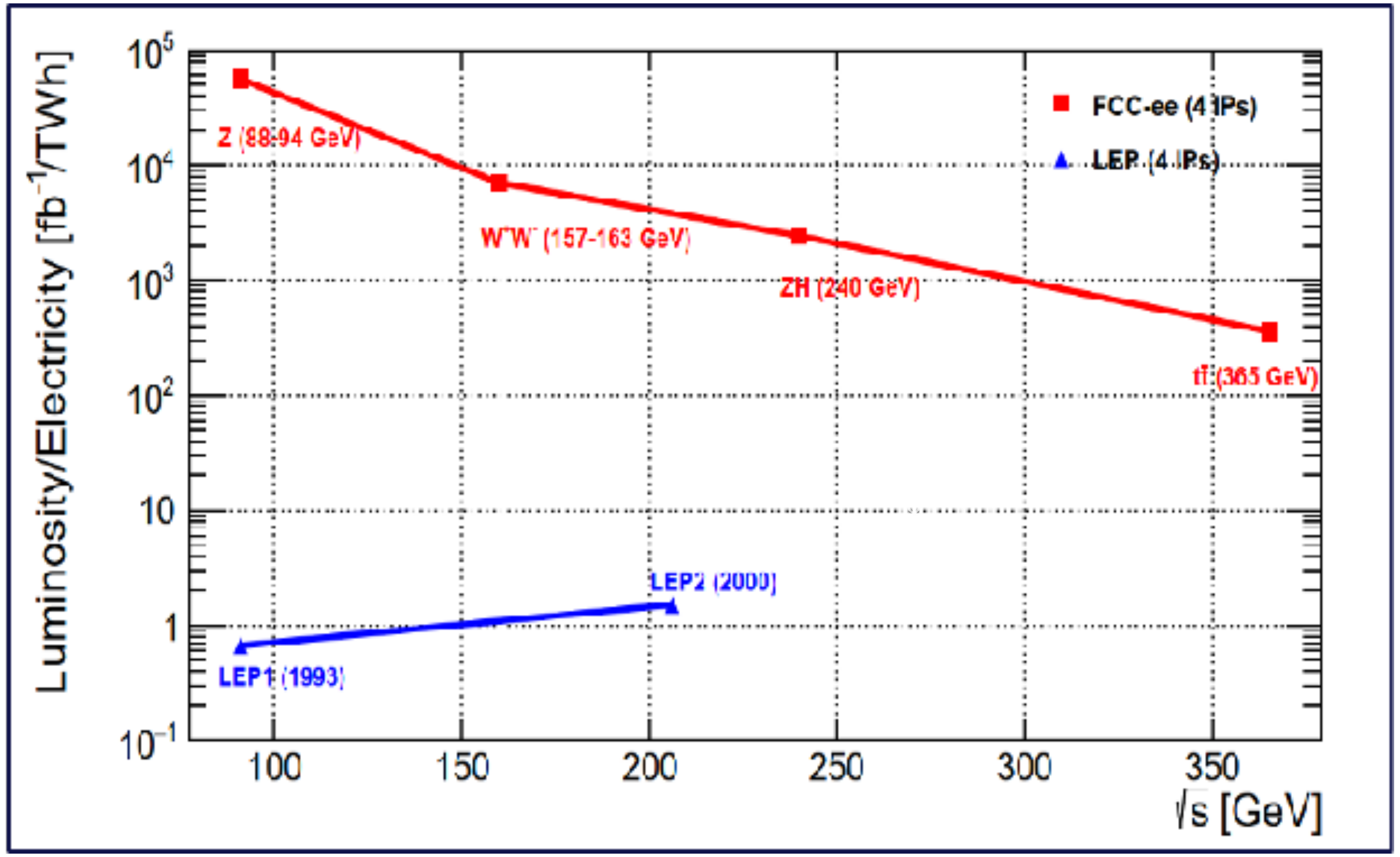
▸ **Superconducting radiofrequency system**

•Nb/Cu 400 MHz SC cavities pioneered at former CERN LEP.

•bulk Nb 800 MHz SC cavities similar to ESS (Sweden), EuXFEL (Germany).

•revolutionary highly efficient RF power sources.

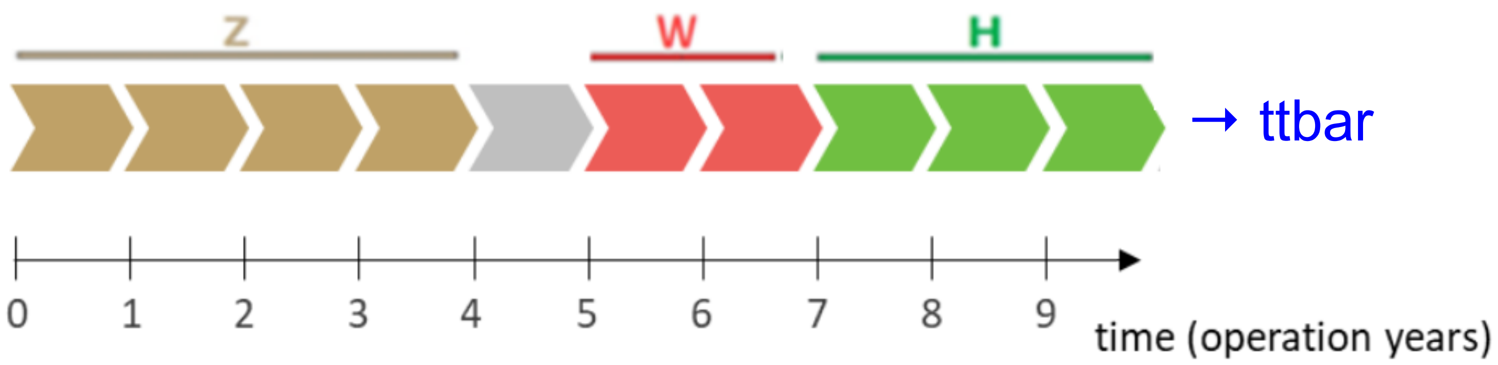
•new operation scheme for flexible energy switching & reduced complexity.



RF operation modes

- Physics at 4 different energy points: Z^0, W^+W^-, Higgs (ZH), t-tbar production
- Same SR power for all 4 modes

P_{SR}= **50 MW** per beam



Lowest energy:
- Low RF voltage
- High beam current

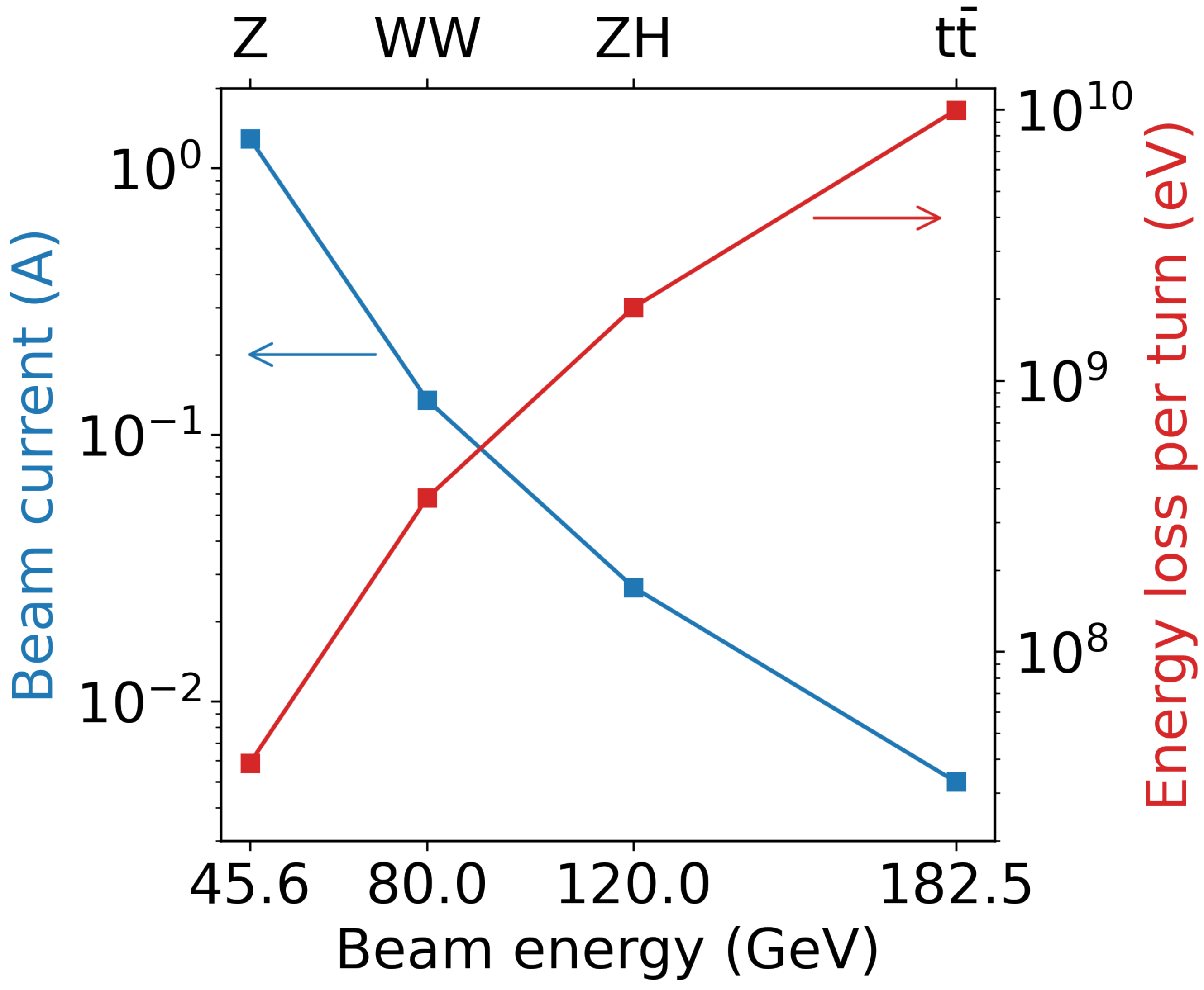
- Few cavities
- Low voltage per cavity
- **High power** per cavity
- Significant HOM power
- Instabilities

- 1- or 2-cell cavities at low RF frequency (400MHz)

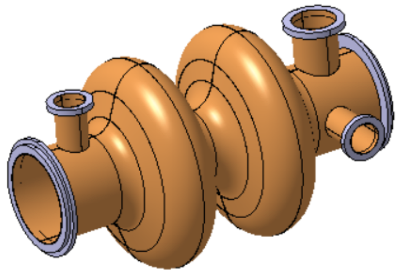
Highest energy:
- High RF voltage
- Low beam current

- Many cavities
- **High voltage** per cavity
- Low power per cavity
- Low HOM power
- High SR damping

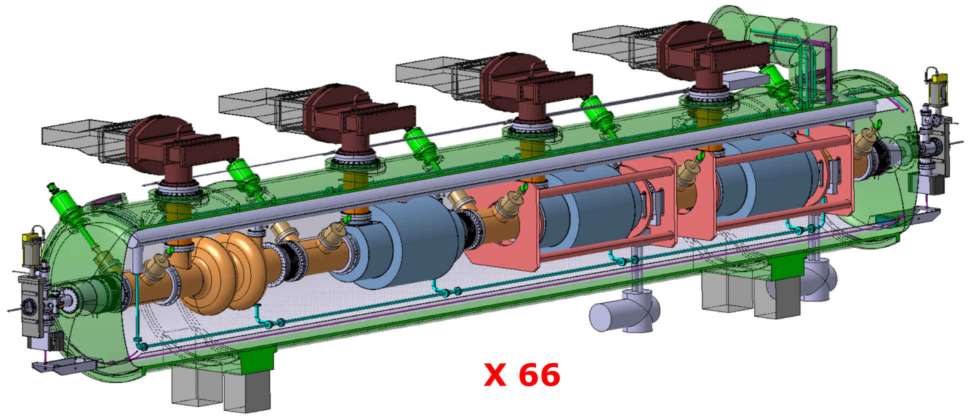
- Multi-cell cavities at higher RF frequency (800MHz)



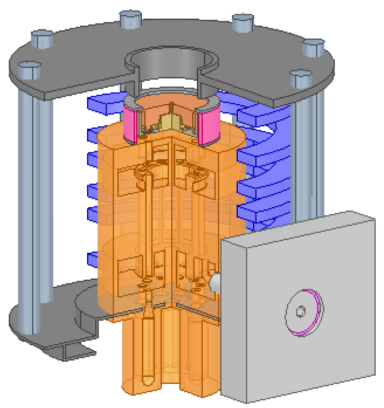
400/800 MHz system



X 264



X 66



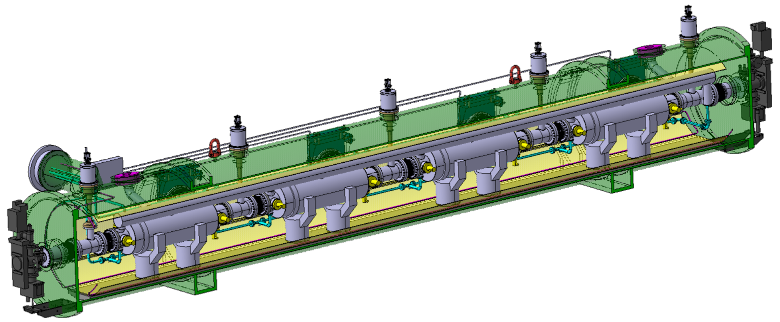
X 264

Superconducting elliptical cavity
- 400 MHz, 2-cell
- 1.5 m. long
- Electropolished and seamless RF surface
- Niobium thin film with HiPIMS

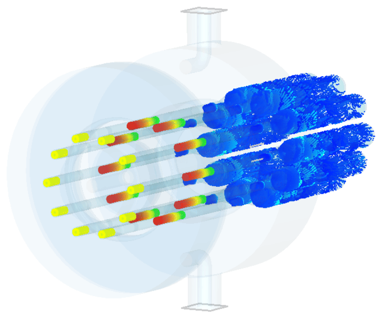
Cryomodule
- Segmented design, 4 cavities
- Vertical FPC, HOM damping and extraction
- Frequency tuning system
- Thermal and magnetic shielding

Multibeam Tristron
- **400 MHz**
- 46 kV
- 500 kW, CW
- ~ 90% efficiency

X (408 + 448)
collider - booster



X (102 + 112)



Multibeam Tristron
- 800 MHz
- 250 kW, CW

X 408

Superconducting elliptical cavity
- 800 MHz, 6-cell
- Nb_3Sn if R&D is successful

Cryomodule
- Segmented design, 4 cavities, 2 K
- Operation at 4.5 K if R&D successful

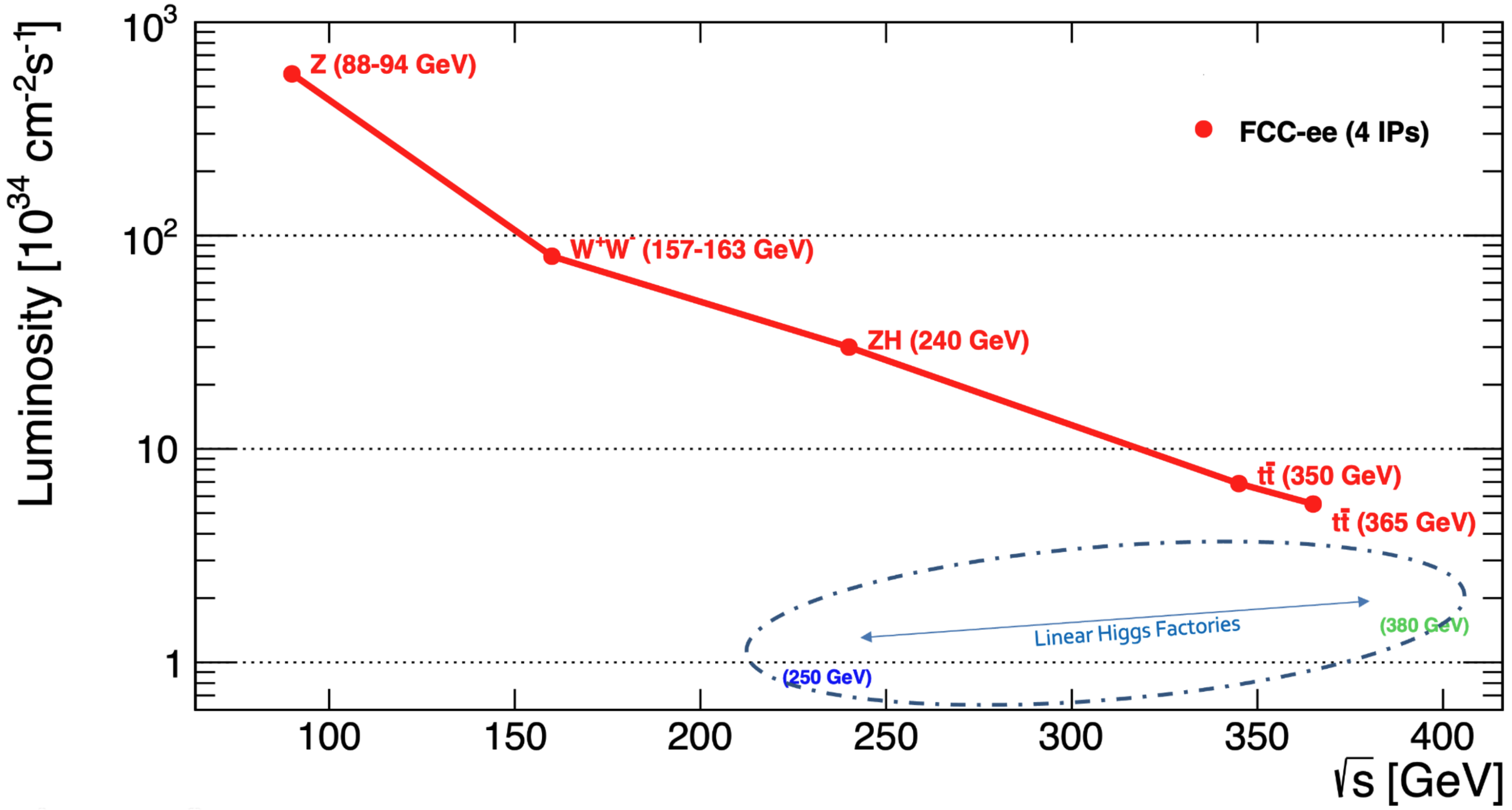
Solid State Amplifier (SSA)
- 800 MHz
- 10-15 kW pulsed

X 448

FCC-ee Run Plan

LEP1 data accumulated in **every 2 mn**.

(for the same power consumption, i.e. machine 100'000 more efficient).



— Superb statistics achieved in only 15 years —

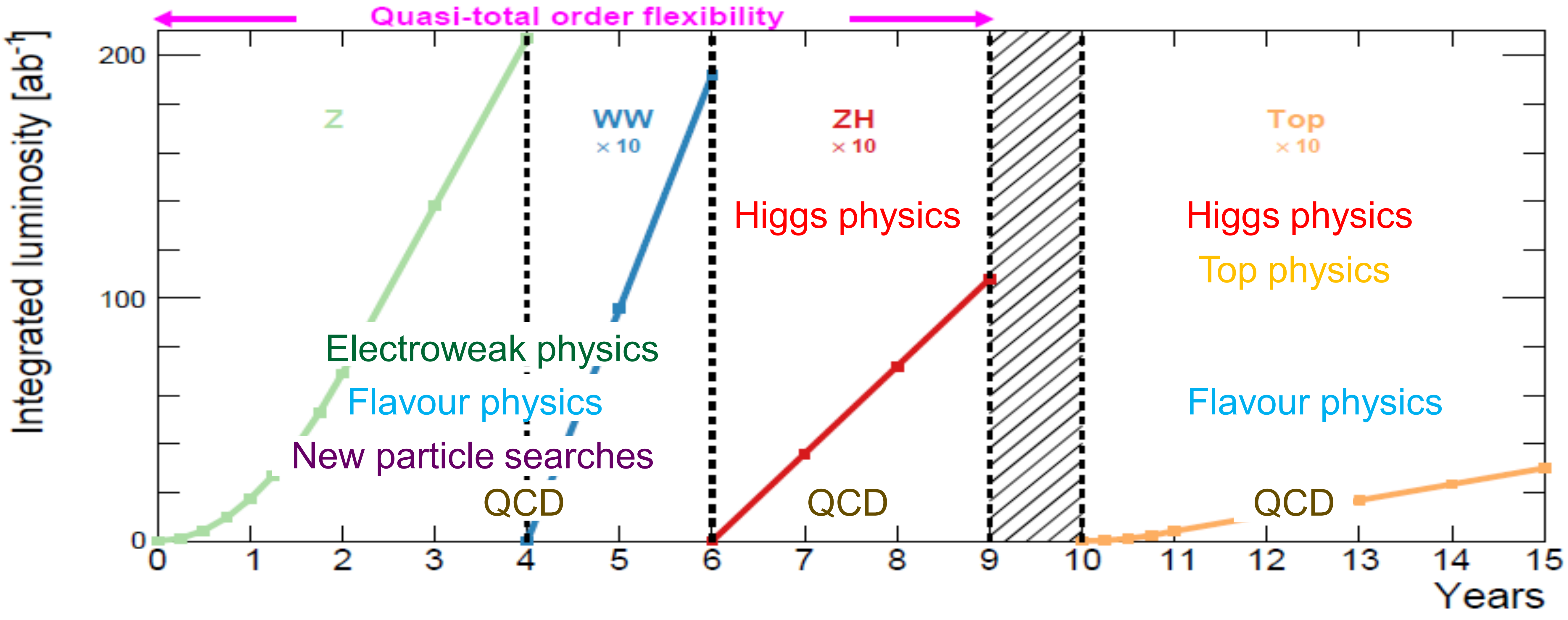
in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

Exciting & diverse programme with different priorities every few years.

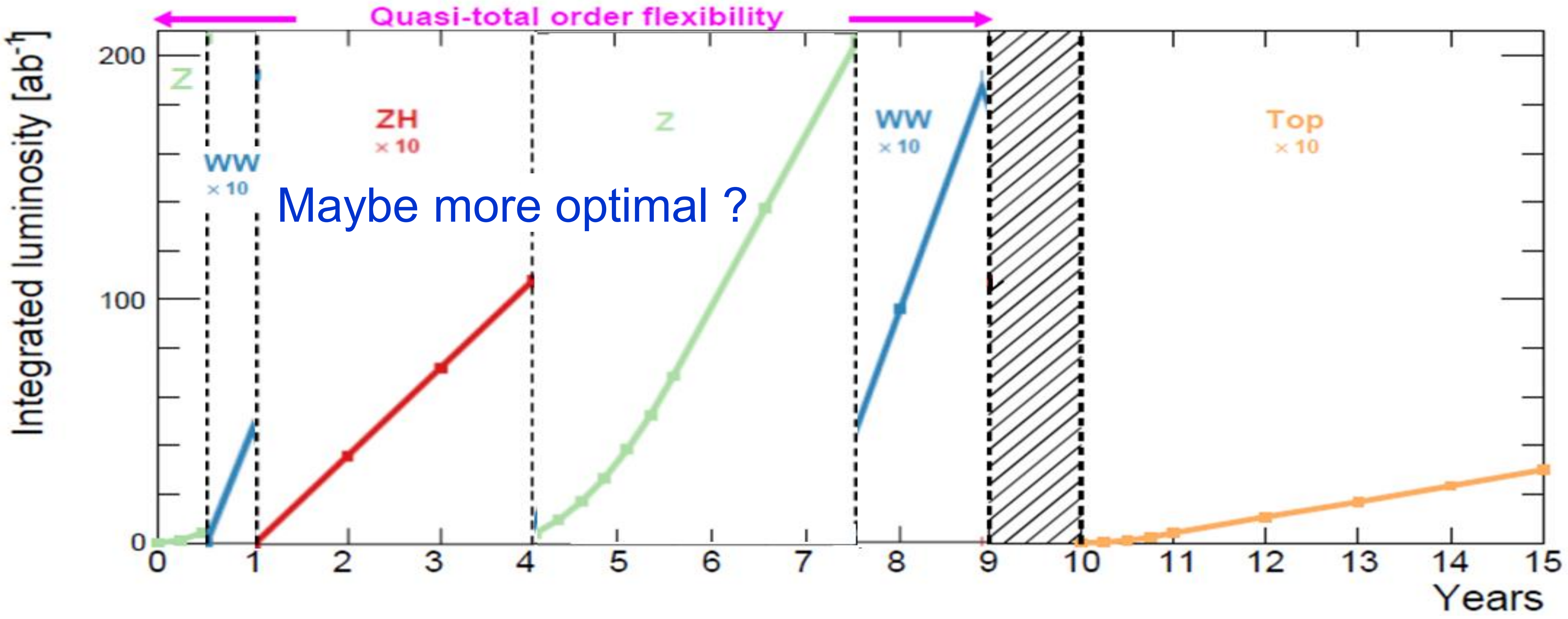
Order of the different stages still subject to discussion/optimisation. Development on **unique RF cavities** to be used from 90 to 240GeV enables great flexibility of operation.

FCC-ee Run Plan



A rich physics programme (yet to be optimised!) achieved in a compact period of fiften years of operation.

FCC-ee Run Plan



A rich physics programme (yet to be optimised!) achieved in a compact period of fiften years of operation.

High lumi - Small uncertainties

— Examples of challenges —

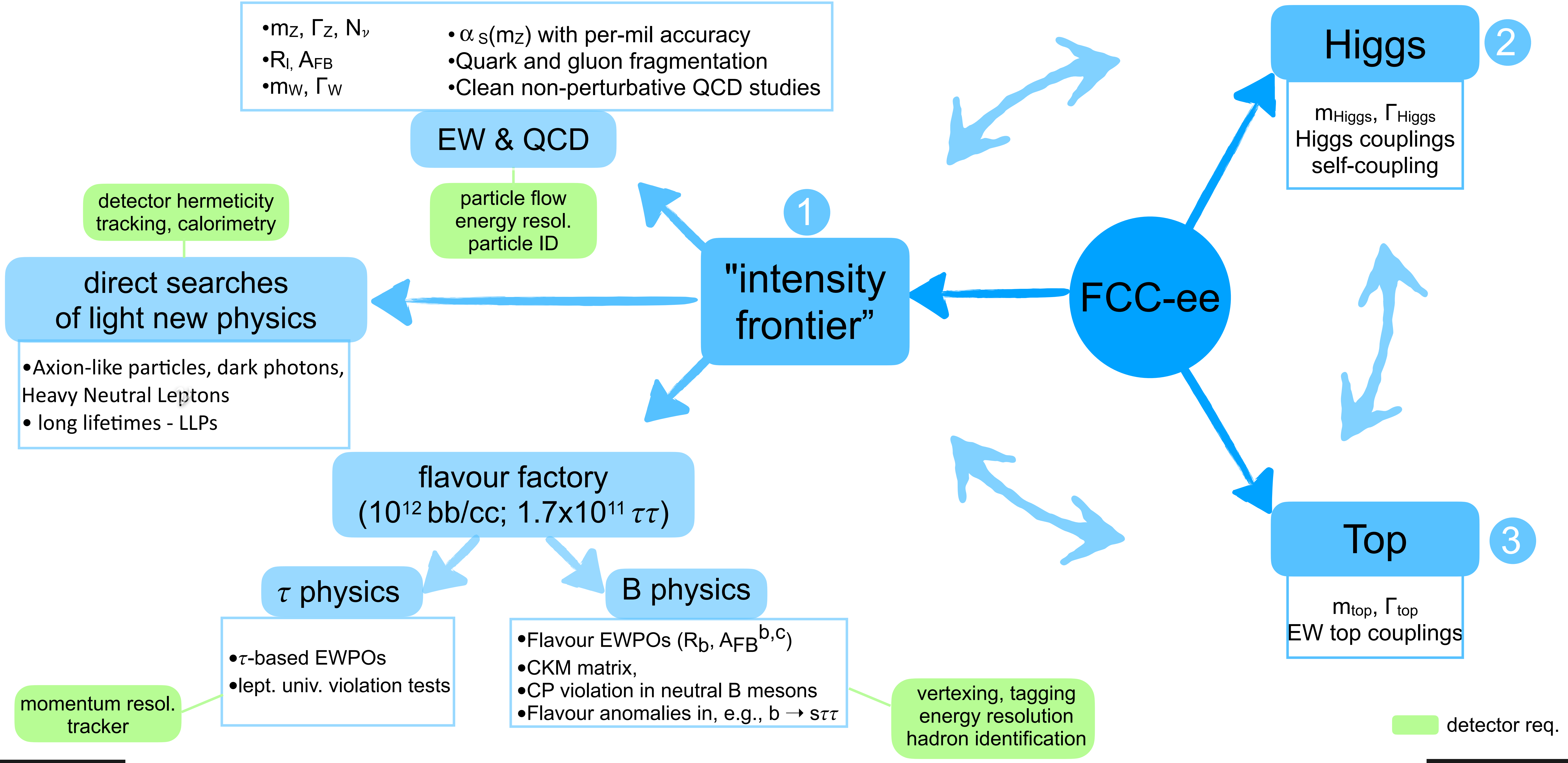
E_{CM}-related uncertainties on selected EWPOs

(E_{CM} determined by resonant spin depolarisation)

Uncertainty	Observable				
	m_Z [keV]	Γ_Z [keV]	$\sin^2\theta_W^{eff}$ [$\times10^{-6}$]	$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)}$ [$\times10^{-5}$]	m_W [keV]
Absolute	100	2.5	/	0.1	150
Point-to-point	14	11	1.2	0.5	50
Sample size	1	1	0.1	/	3
Energy spread	/	5	/	0.1	/
Total $\sqrt{s}$ related	101	12	1.2	0.5	158
FCC-ee statistical	4	4	2	3	180

Need to also control theoretical uncertainties to the same level!

FCC-ee Physics Programme



FCC-ee Physics Programme

Higgs Factory Programme

- At $\sqrt{s}$=240 and $\sqrt{s}$=365 GeV collect 2.6M HZ and 150k WW→ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \to H$ at 125 GeV

→

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^{8} WW events
- × 500 improvement of statistical precision on EWPO: m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 2×10^{8} tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

→

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to ≤ 10^{-5} (e.g. $\Gamma_{had}/\Gamma_{\ell}$)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

→

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/$\sqrt{E}$**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

→

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

FCC-ee Physics Programme

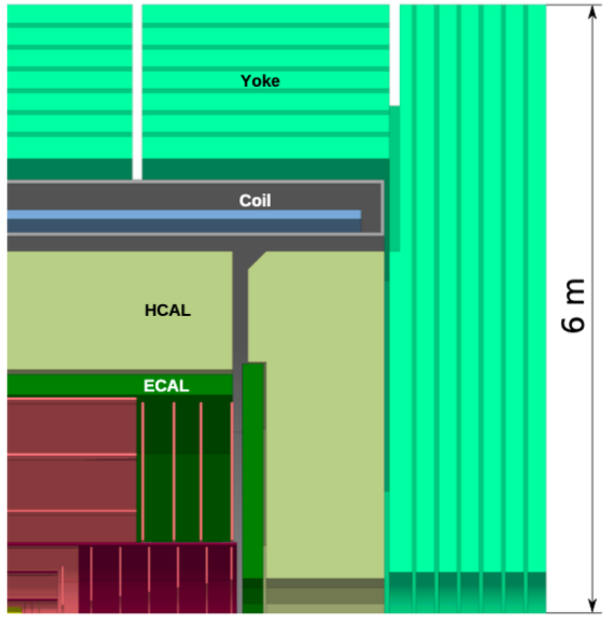
Summary of detector requirements

	Aggressive	Conservative	Comments
Beam-pipe	$\frac{X}{X_0} < 0.5\%$	$\frac{X}{X_0} < 1\%$	$\mathrm{B} \to \mathrm{K}^* \tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p \sin^{3/2}\theta)\ \mu\mathrm{m}$ $\frac{X}{X_0} < 1\%$	–	$\mathrm{B} \to \mathrm{K}^* \tau\tau$ R_c
	$\delta L = 5\,\mathrm{ppm}$	–	$\delta\tau_\tau < 10\,\mathrm{ppm}$
Tracking	$\frac{\sigma_p}{p} < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\frac{\sigma_p}{p} < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4$ MeV $\delta\Gamma_Z = 15$ keV $\mathrm{Z} \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_\mathrm{Z}(\mathrm{BES}) < 10\,\mathrm{keV}$
ECAL	$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$	$\mathrm{Z} \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y = 2 \times 2\ \mathrm{mm}^2$	$\Delta x \times \Delta y = 5 \times 5\ \mathrm{mm}^2$	τ polarization boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\ \mu\mathrm{m}$, $\delta R_{\mathrm{min}} = 10\ \ \mu\mathrm{m}\ (\theta = 20°)$	–	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL	$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	$\mathrm{H} \to \mathrm{s\bar{s}},\ \mathrm{c\bar{c}}$, gg, invisible HNLs
	$\Delta x \times \Delta y = 2 \times 2\ \mathrm{mm}^2$	$\Delta x \times \Delta y = 20 \times 20\ \mathrm{mm}^2$	$\mathrm{H} \to \mathrm{s\bar{s}},\ \mathrm{c\bar{c}}$, gg
Muons	low momentum ($p < 1$ GeV) ID	–	$\mathrm{B_s} \to \nu\bar{\nu}$
Particle ID	3σ K/π $p < 40$ GeV	3σ K/π $p < 30$ GeV	$\mathrm{H} \to \mathrm{s\bar{s}}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\ \mu\mathrm{m}$, $\delta R_{\mathrm{min}} = 1\ \mu\mathrm{m}$ acceptance 50-100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$\mathrm{e^+e^-} \to \gamma\gamma$ $\mathrm{e^+e^-} \to \mathrm{e^+e^-}\tau^+\tau^-(\mathrm{c\bar{c}})$

FCC-ee Physics Programme

M. Dam @ FCC week 2025

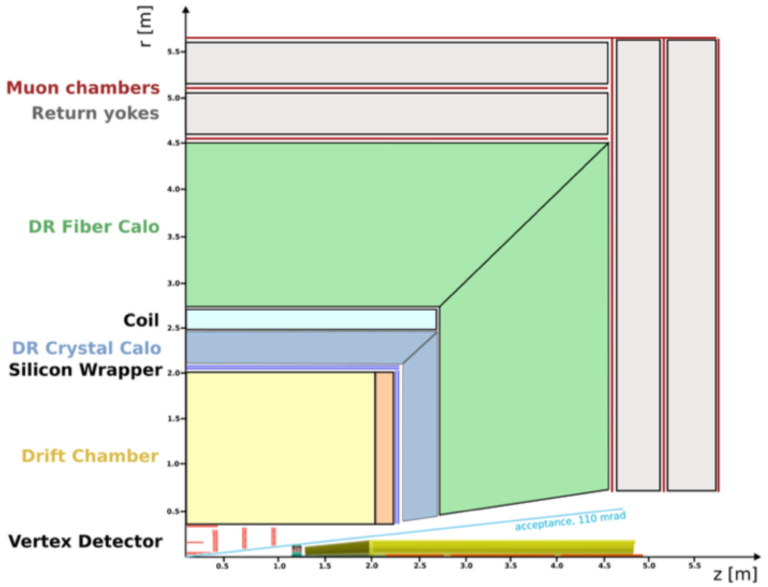
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- **Full Si VTX + tracker**
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

IDEA

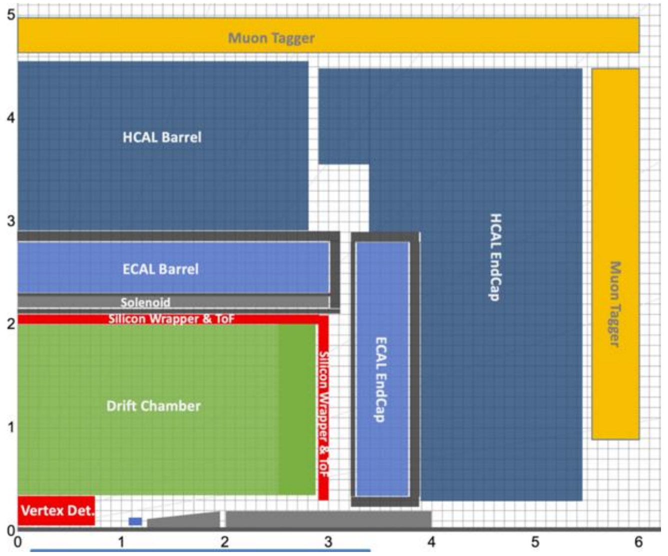


- Design developed specifically for FCC-ee and CEPC
- Si VTX detector; **ultra-light drift chamber** with powerful PID
- **Crystal ECAL w. dual readout**
- Compact, light coil;
- **Dual readout fibre calorimeter**
- Muon system

https://doi.org/10.48550/arXiv.2502.21223

5th concept proposed recently: ALFA (light tracking system and high resolution ECAL)

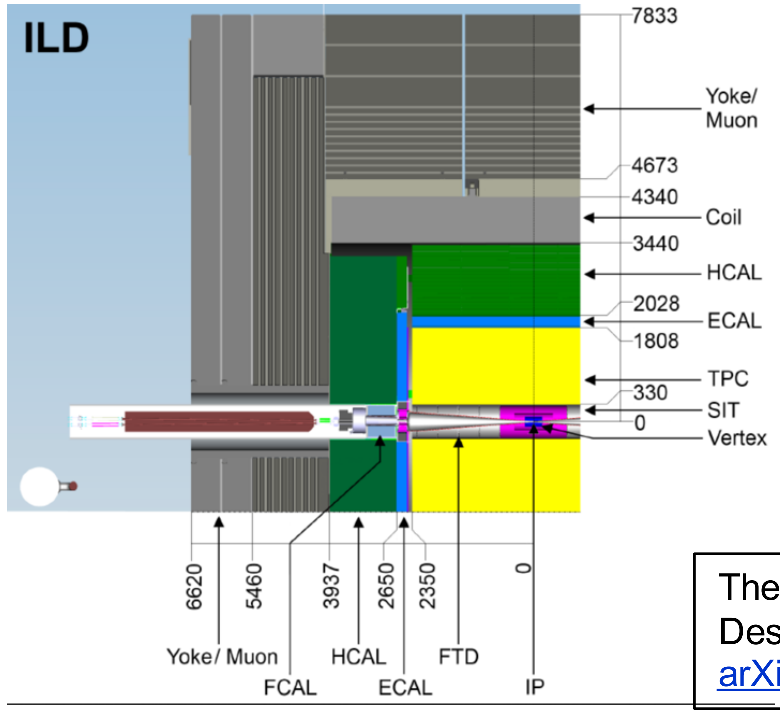
Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VTX detector
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391

ILD



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
- **Large-volume time projection chamber (TPC)**

The International Linear Collider Technical Design Report - Volume 4: Detectors arXiv:1306.6329

Flavour Potential of TeraZ

At present (Z/h/NewPhysics) FCNCs mostly constrained by low energy observables.
The large statistics of FCC will open on-shell opportunities.

See S. Monteil, Flavour@FCC '22

Particle species	B^0	B^-	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

FCC-ee
=
10 x Belle II

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

$\langle E_{X_b}\rangle = 75\% \times E_{\rm beam}; \langle\beta\gamma\rangle \sim 6$

Makes possible
a topological rec.
of the decays
w/ miss. energy

Flavour defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements.

Flavour Potential of TeraZ

At present (Z/h/NewPhysics) FCNCs mostly constrained by low energy observables.

The large statistics of FCC will open on-shell opportunities.

See S. Monteil, Flavour@FCC '22

Particle species	B^0	B^-	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

FCC-ee = 10 x Belle II

Decay mod

EW/H per

$B^0 \to K^*($

$\mathcal{B}(B^0 \to K$

$B_s \to \mu^+\mu$

$B^0 \to \mu^+\mu$

$\mathcal{B}(B_s \to \tau^+$

Leptonic d

$B^+ \to \mu^+\nu$

$B^+ \to \tau^+\nu$

$B_c^+ \to \tau^+\nu$

CP / hadr

$B^0 \to J/\Psi$

$B_s \to D_s^\pm K^\mp$	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

Flavour @ FCC vs Belle/pp

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

boosted b's/τ's at FCC-ee

$\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6$

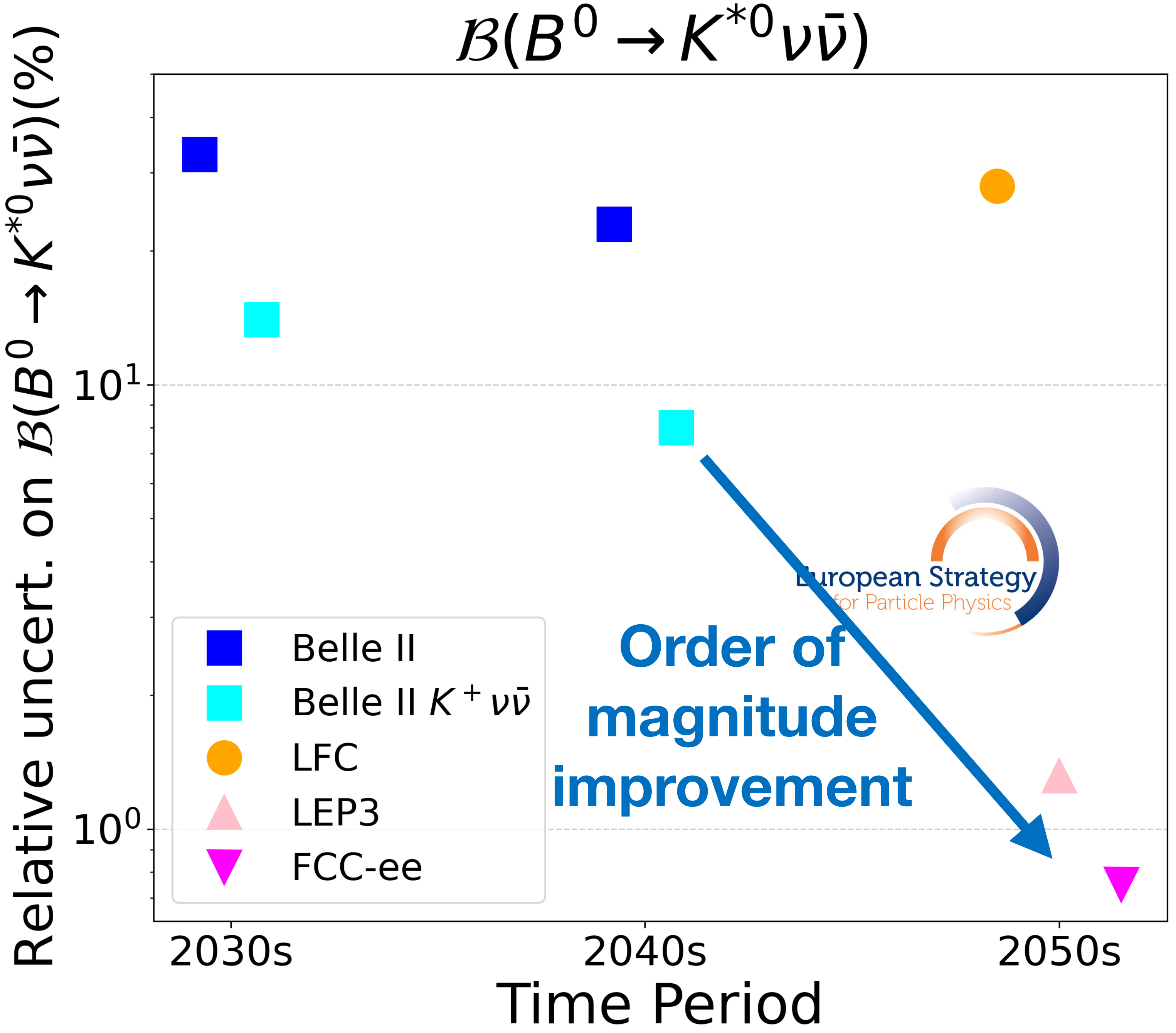
Makes possible a topological rec. of the decays w/ miss. energy

Flavour defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements.

Flavour Potential of TeraZ

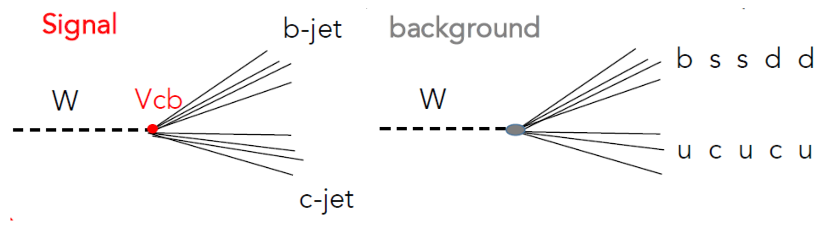
At present (Z/h/NewPhysics) FCNCs mostly constrained by low energy observables.

The large statistics of FCC will open on-shell opportunities.

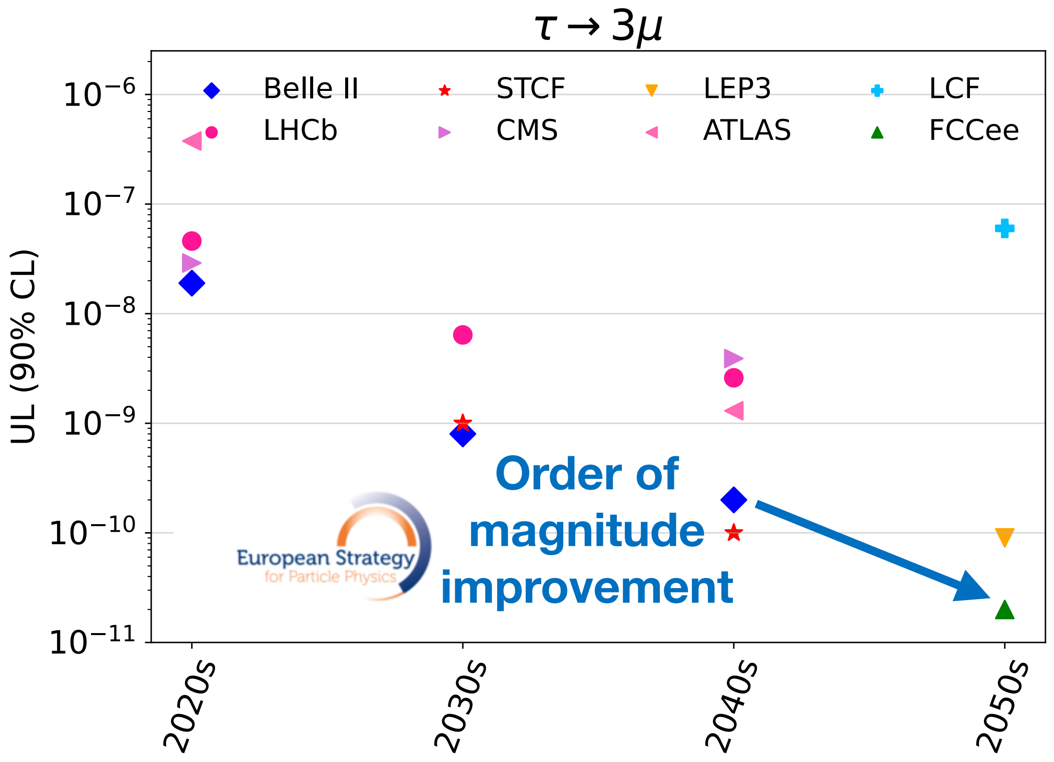


FCC-ee Flavour Opportunities

- **CKM elements:**
  - **CPV angles** (γ, β, ϕ_s) at sub-degree precision
  - **V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays:
    - 3.4% @ now → 0.52-0.14% @ FCC-ee (depending on tracking)
      see Marzocca et al (2024)



- **Tau physics** (>10^{11} pairs of tau's produced in Z decays)
  - test of lepton flavour universality: G_F from tau decays @ 10 ppm @ FCC-ee (0.5 ppm from muon decays)
  - lepton flavour violation:
    - $\tau\to\mu\gamma$: 4×10^{-8} @Belle2021→10^{-9} @ FCC-ee
    - $\tau\to3\mu$: 2×10^{-8} @Belle → 3×10^{-10} @BelleII → 10^{-11} @ FCC-ee
  - tau lifetime uncertainty:
    - 2000 ppm → 10 ppm
  - tau mass uncertainty:
    - 70 ppm → 14 ppm

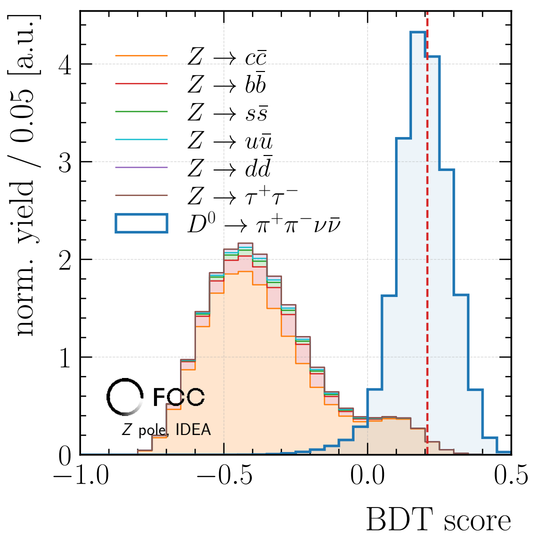


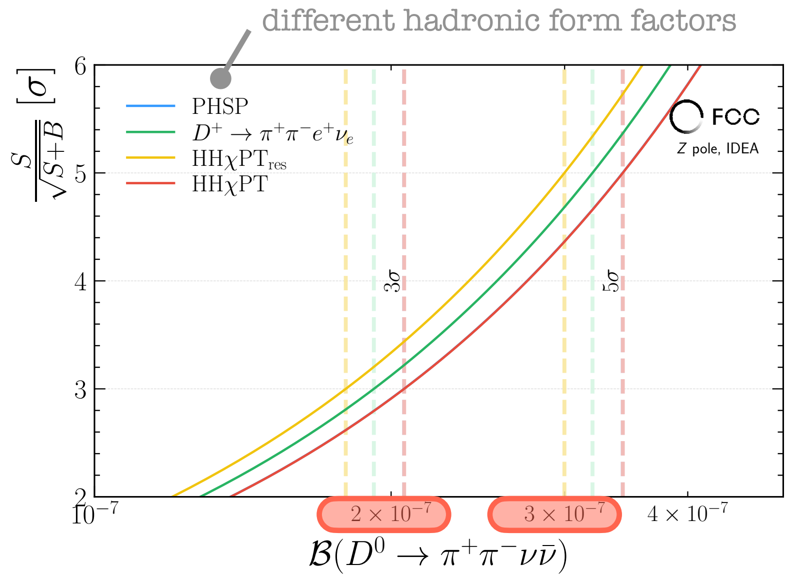
- **Semi-leptonic mixing asymmetries** a^s_{sl} and a^d_{sl}

- …

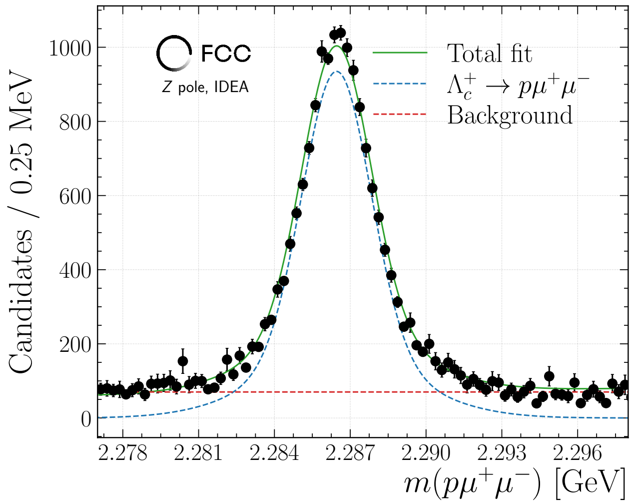
Charm @ FCC-ee

- **Charm** physics plays a unique role in searches for NP in the up-type quark sector
  - charm FCNC induced by quantum loops of down-type quarks, $\Delta m_{down} << m_W \Rightarrow$ high suppression in SM
  - FCC-ee: large rate (like LHCb), clean environment (like BelleII, BESIII)
  - charm meson produced from Z decay and not pp interactions $\Rightarrow$ sizeable polarisation, enabling additional angular observables in $c \to u\ell\ell (\ell = e, \mu)$ transitions
- $D^0 \to \pi^+\pi^-\nu\bar{\nu}$



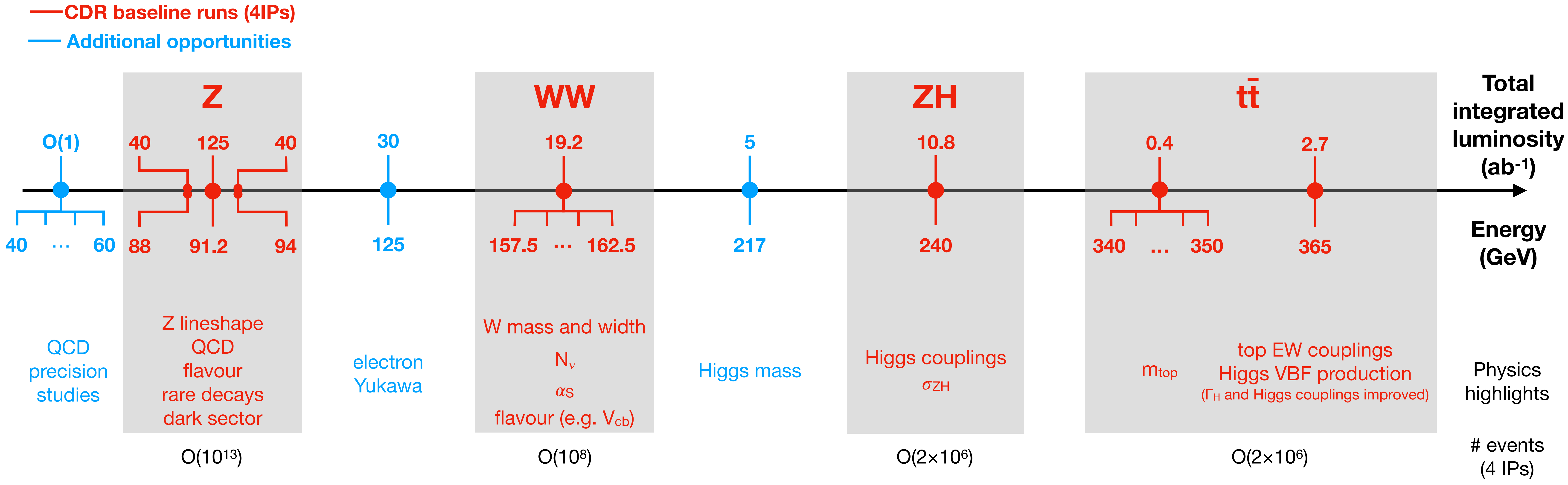


- $\Lambda_c^+ \to p\mu^+\mu^-$



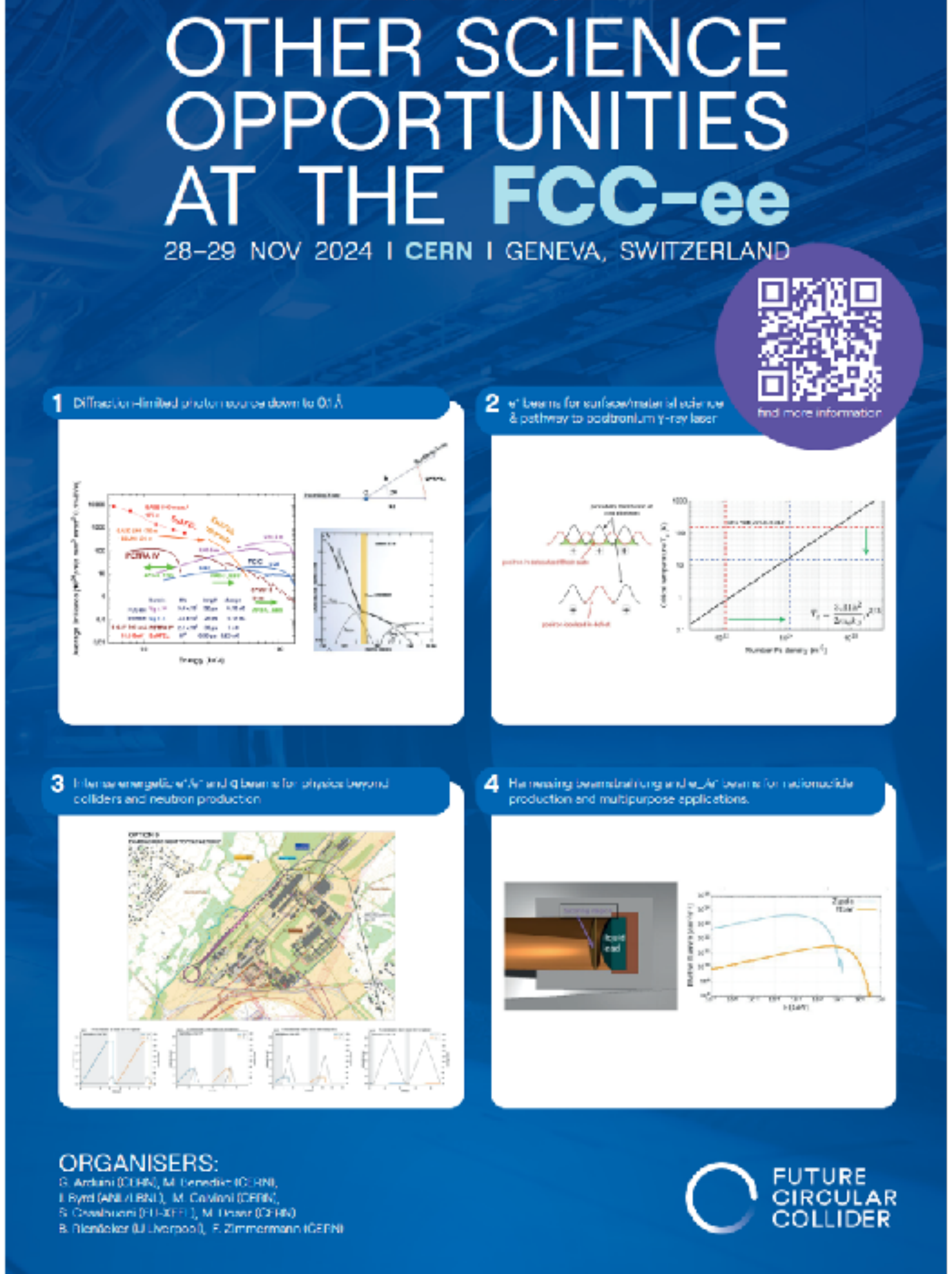
see arXiv:2509.10447

Collider Programme (and beyond)



- **Opportunities** beyond the baseline plan (√s below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

workshop webpage link



photon science
(light source,
Compton Backscattering sources)

HEP applications
(strong QED, dark sector)

e^+ applications
(surface science,
Ps Bose-Einstein Condensate,
511 keV X-ray laser)

multipurpose applications of the e^-/e^+ beams
(radionuclide production,
neutron source)

[workshop webpage link]

photon science

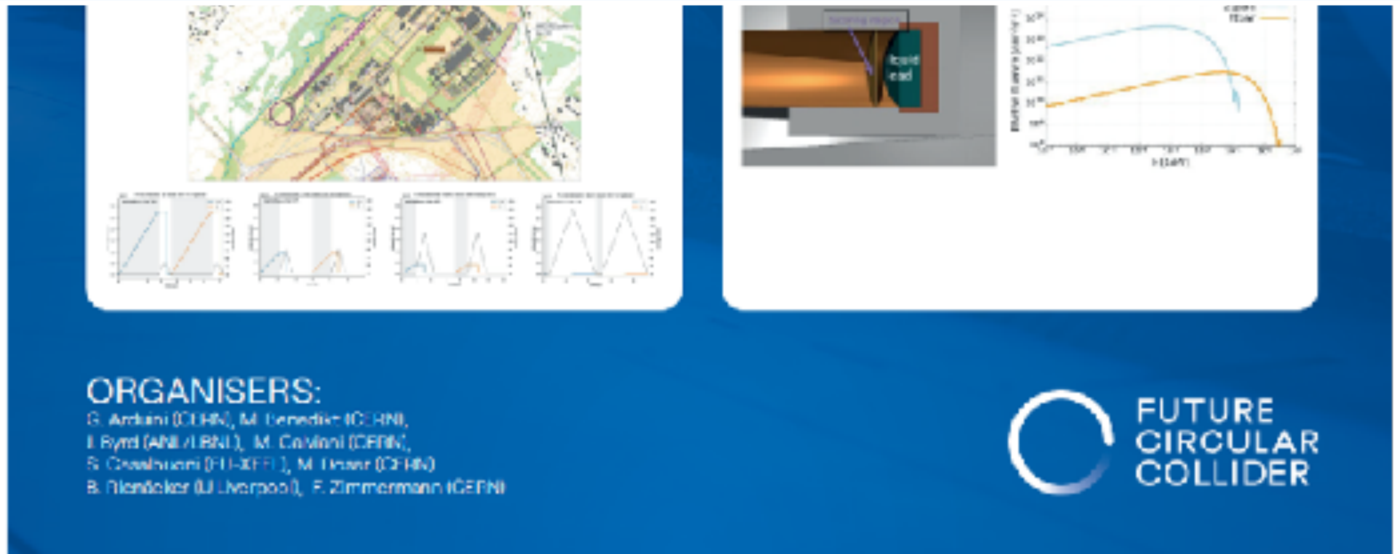
(light source,
Compton Backscattering sources)

e⁺ applications

(surface science,
Ps Bose-Einstein Condensate,
511 keV X-ray laser)

FCC enabling assets:

large circumference, abundant positron production, low-emittance beams, high-power beamstrahlung, injector complex



(radionuclide production,
neutron source)

FCC-LS: Powerful light source for very hard X-rays

The peak and average brilliance can be roughly 1000 times higher than at the proposed future storage ring light source PETRA IV in the very hard X ray regime (>50 keV), opening up new areas of science.

	w/o wiggler	U_0 x3	U_0 x94	XFEL	PETRA IV
beam energy [GeV]	20	20	20	17.5	6
average beam current [mA]	50	50	50	0.03	200
bunch population [10^{10}]	2	2	2		
RF voltage [MV]	60	65	190		
beta at wiggler /undulator [m]	1.6	1.6	1.6		
wiggler field [T]		1	1		
wiggler period [cm]	-	4	4		
wiggler unit length [m]	-	6.4	5		
undulator field [T]		0.71-0.32	0.71-0.32	0.44-1.0	0.3-1.1
undulator period [cm]		2.8	2.8	4	1.8
undulator unit length [m]		5	5	5	10
magnetic gap	10	10	10	10	6
energy loss / turn [MeV]	1.33	4	126	-	4
SR power at 0.15 A [MW]	0.2	0.6	19	-	
total length of wiggler [m]	**-**	**6.4**	**264**	**-**	
horizontal emittance [nm]	**0.046**	**0.015**	**0.0005**	**0.04 (slice)**	**0.02**
vertical emittance [pm]	**<5**	**<1.5**	**<0.05**	**40 (slice)**	**4**
wiggler photon energy 1st harmonic [keV]	10-50	**10-50**	**10-50**	-	
undulator photon energy 1st harmonic [keV]	50-100	50-100	50-100	9.1-30.7	7-16.8
coherence limit [Å]	**5.8** **(2.1 keV)**	**1.9** **(6.5 keV)**	**0.06** **(200 keV)**	**5** **(2.5 keV)**	**1.5** **(8.3 keV)**
peak brilliance [ph/s/0.1%bw/mm²/mrad²]					
@ 12 keV					
@25 keV		4.2×10^{22}	2×10^{25}	5×10^{33}	3×10^{24}
@50 keV		1.1×10^{23}	7.9×10^{25}	4×10^{33}	1.4×10^{24}
@100 keV		**1.0×10^{26}**	**3×10^{26}**	**N/A**	**3.8×10^{23}**
		1.1×10^{26}	**5.2×10^{26}**	**N/A**	**3×10^{22}**
average brilliance [ph/s/0.1%bw/mm²/mrad²] **simulations for the FCC-ee injector with SPECTRA [4]**					
@ 12 keV		4.2×10^{22}	8.2×10^{22}	1.6×10^{25}	8×10^{22}
@25 keV		1.1×10^{23}	3.2×10^{23}	2.5×10^{24}	3.8×10^{22}
@50 keV		**2.2×10^{23}**	**1.2×10^{24}**	**N/A**	**1×10^{22}**
@100 keV		**2.5×10^{23}**	**2.1×10^{24}**	**N/A**	**8×10^{20}**

ultimate photon source up to ~100 keV energies

4.“Indirect” discovery potential

New Physics Reach @ Z-pole

There are 48 different types of particles that can have tree-level linear interactions to SM.

de Blas, Criado, Perez-Victoria, Santiago, arXiv: 1711.10391

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Scalars

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Fermions

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Vectors

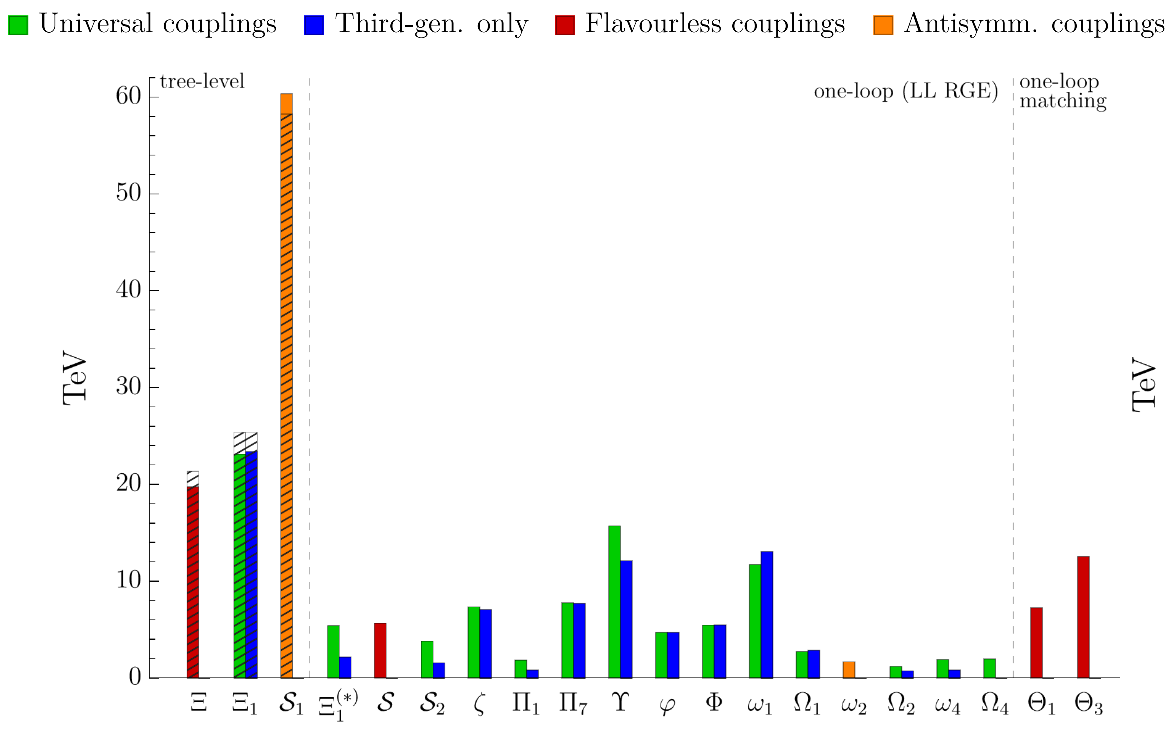
They are not all affecting EW observables at tree-level.

New Physics Reach @ Z-pole

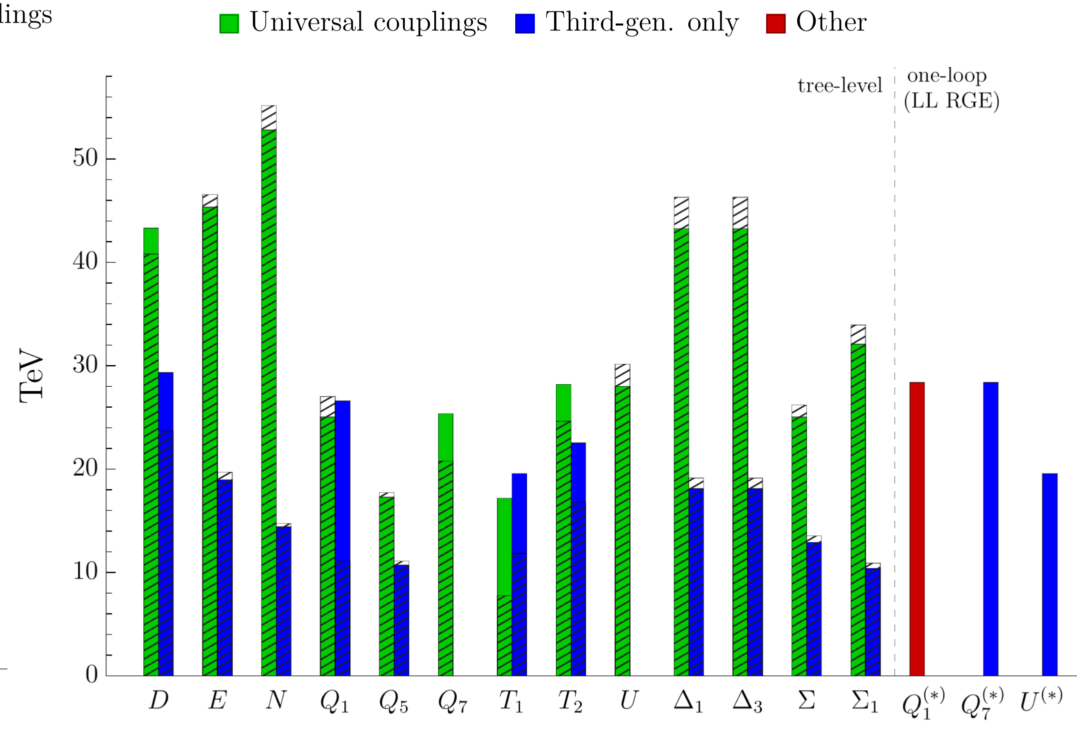
There are 48 different types of particles that can have tree-level linear interactions to SM.

They are not all affecting EW observables at tree-level.
However, all, but a few, have leading log. running into EW observables.

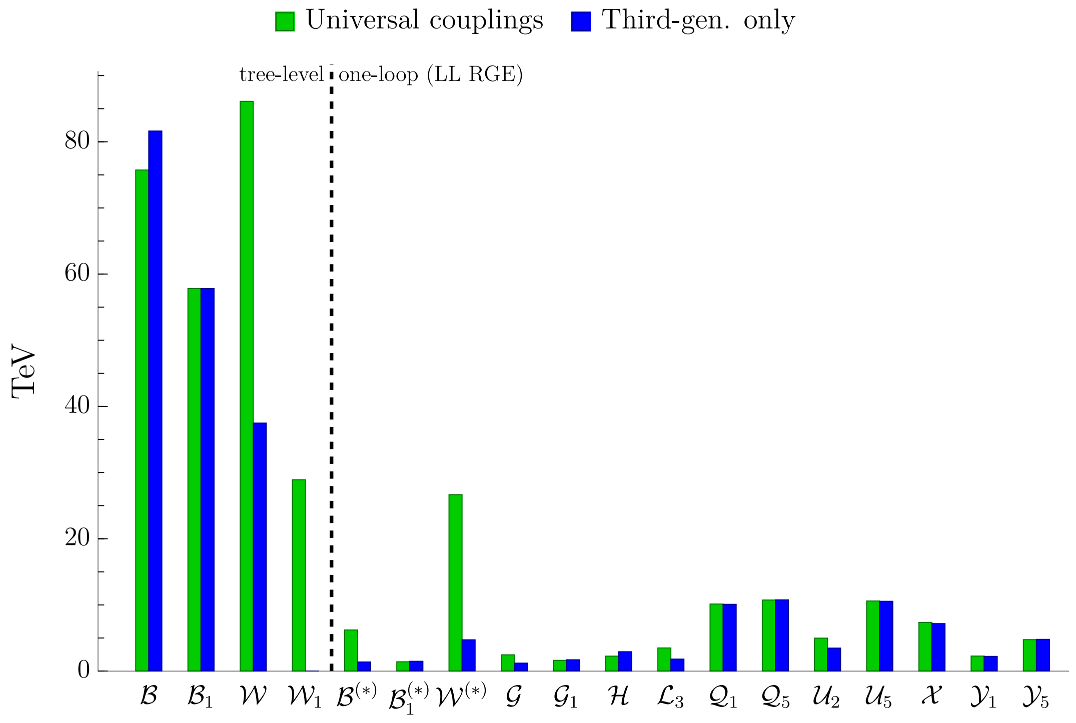
Allwicher, McCullough, Renner, arXiv: 2408.03992



Scalars



Fermions

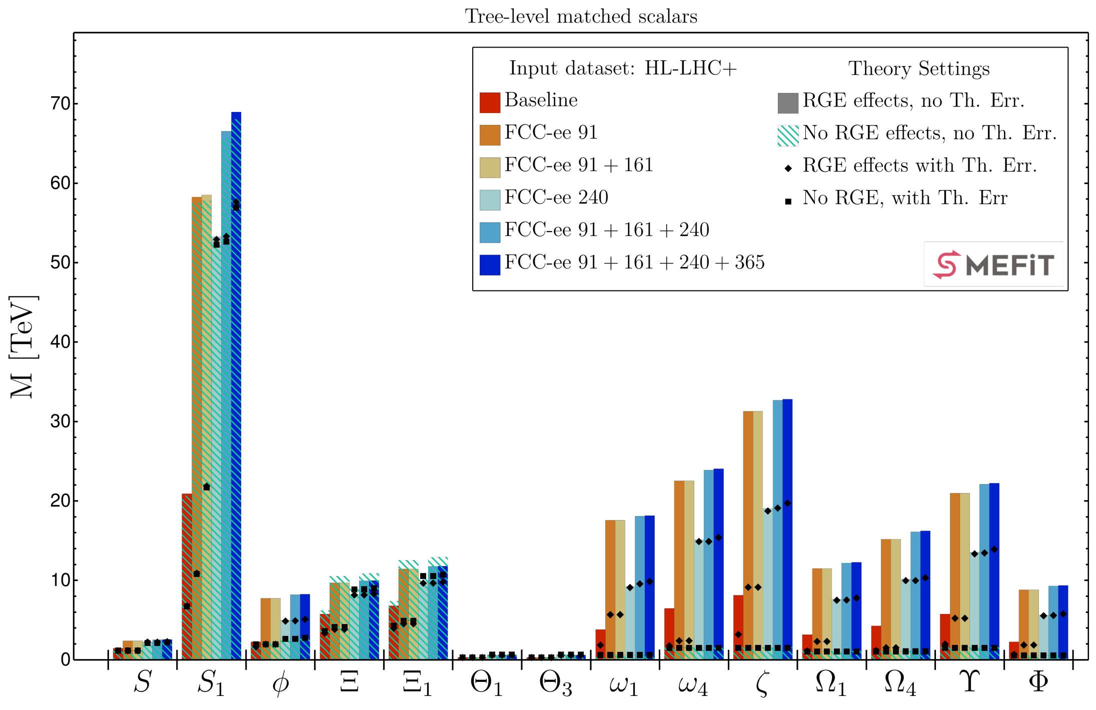


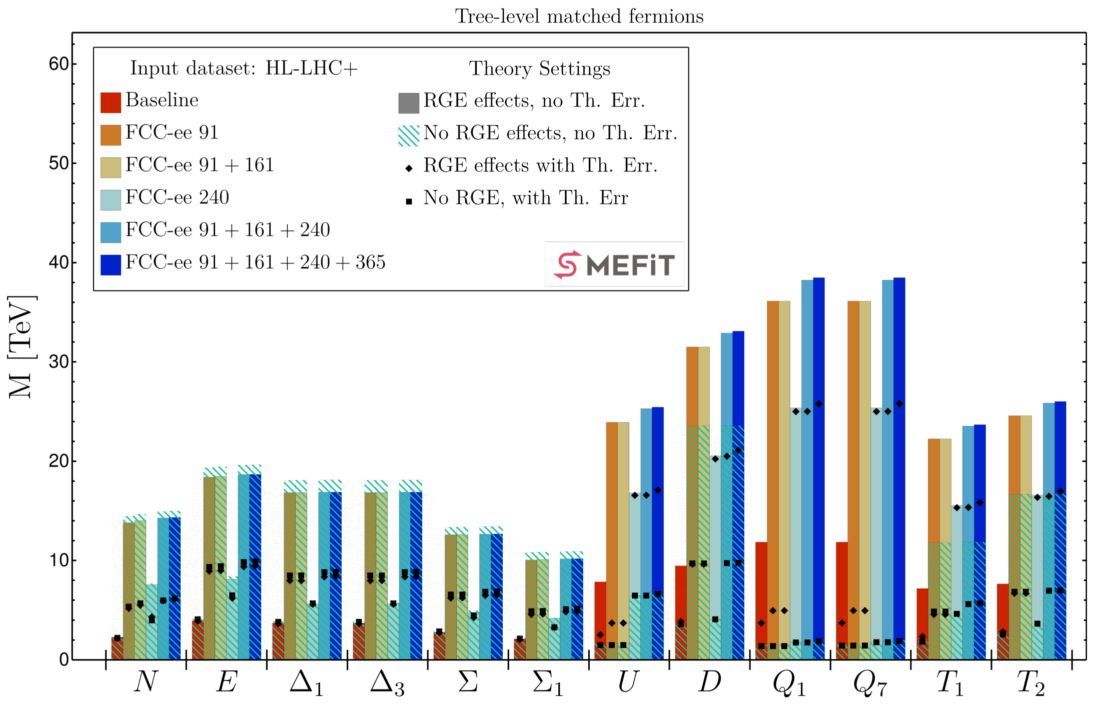
Vectors

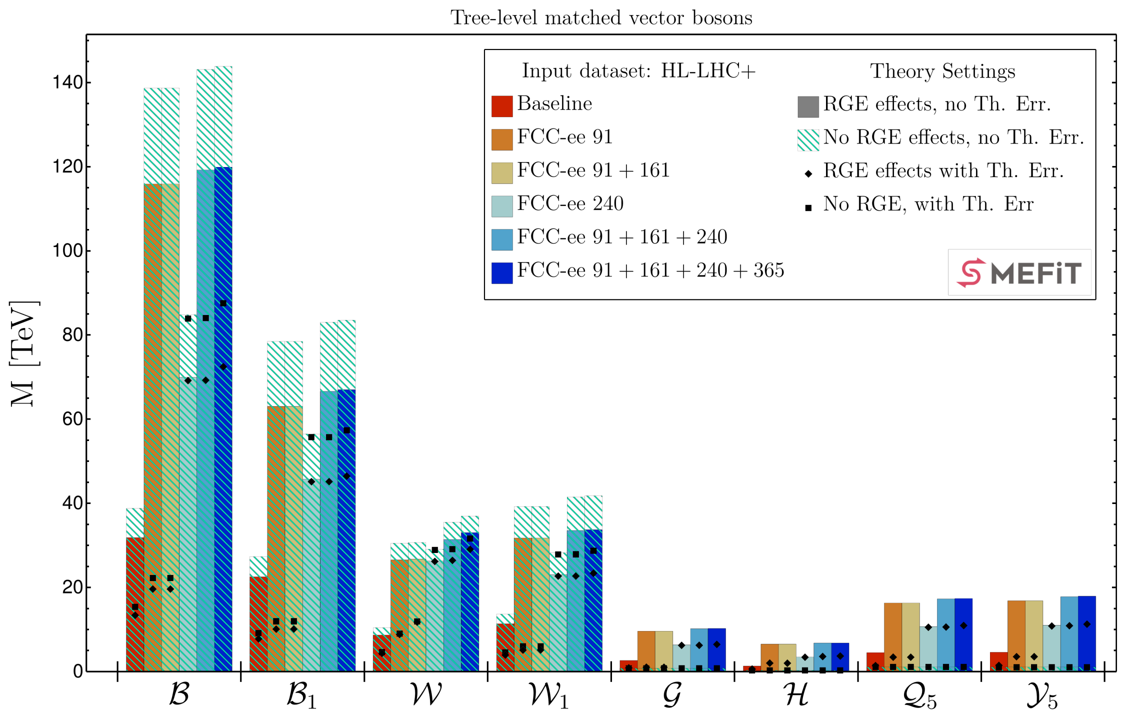
Tree-level matching and running from 1 TeV to Z mass.
W- and Z-pole observables only (no Higgs, no LEP-2 like observables)

New Physics Reach @ Z-pole

There are 48 different types of particles that can have tree-level linear interactions to SM.





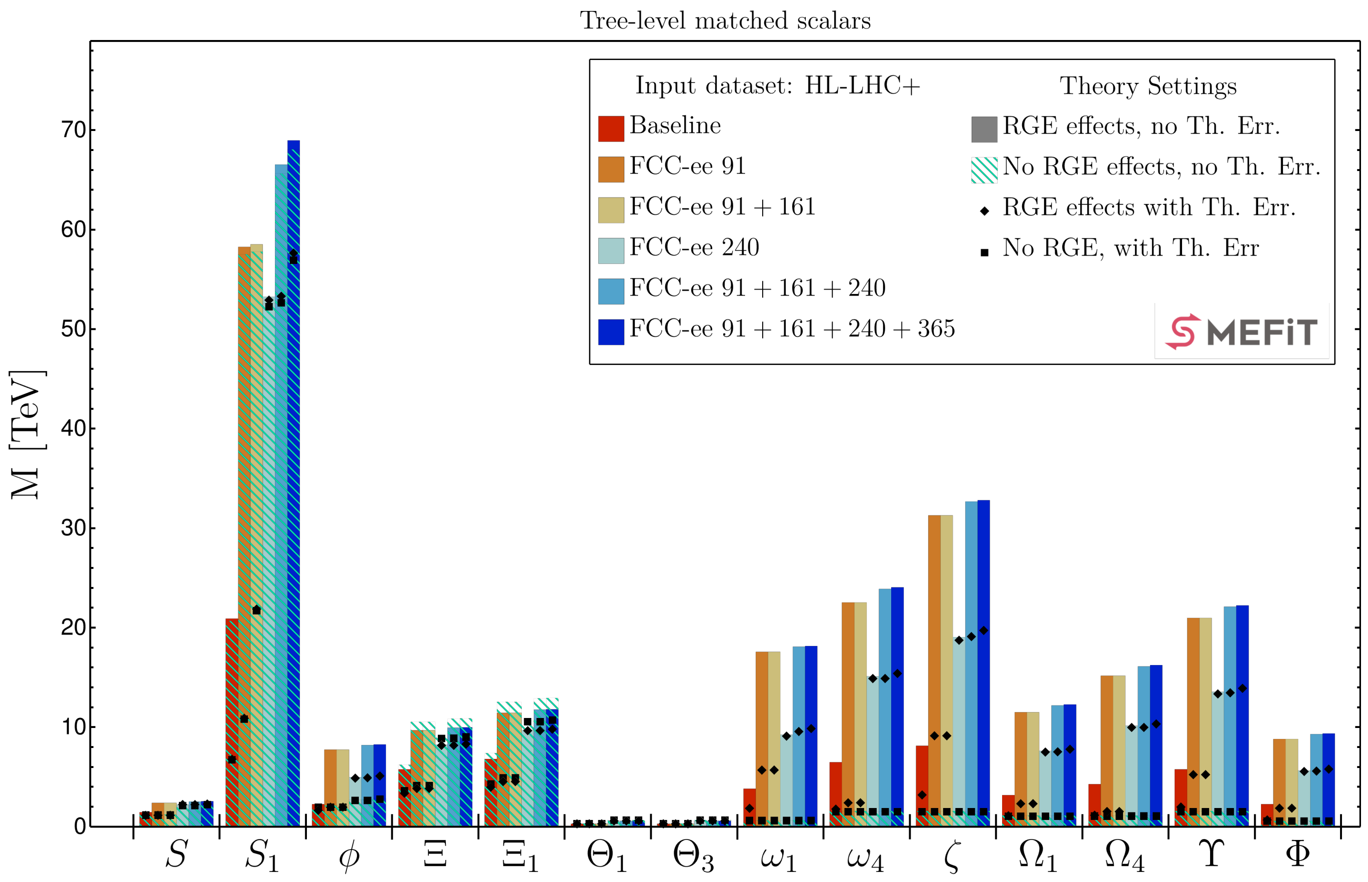


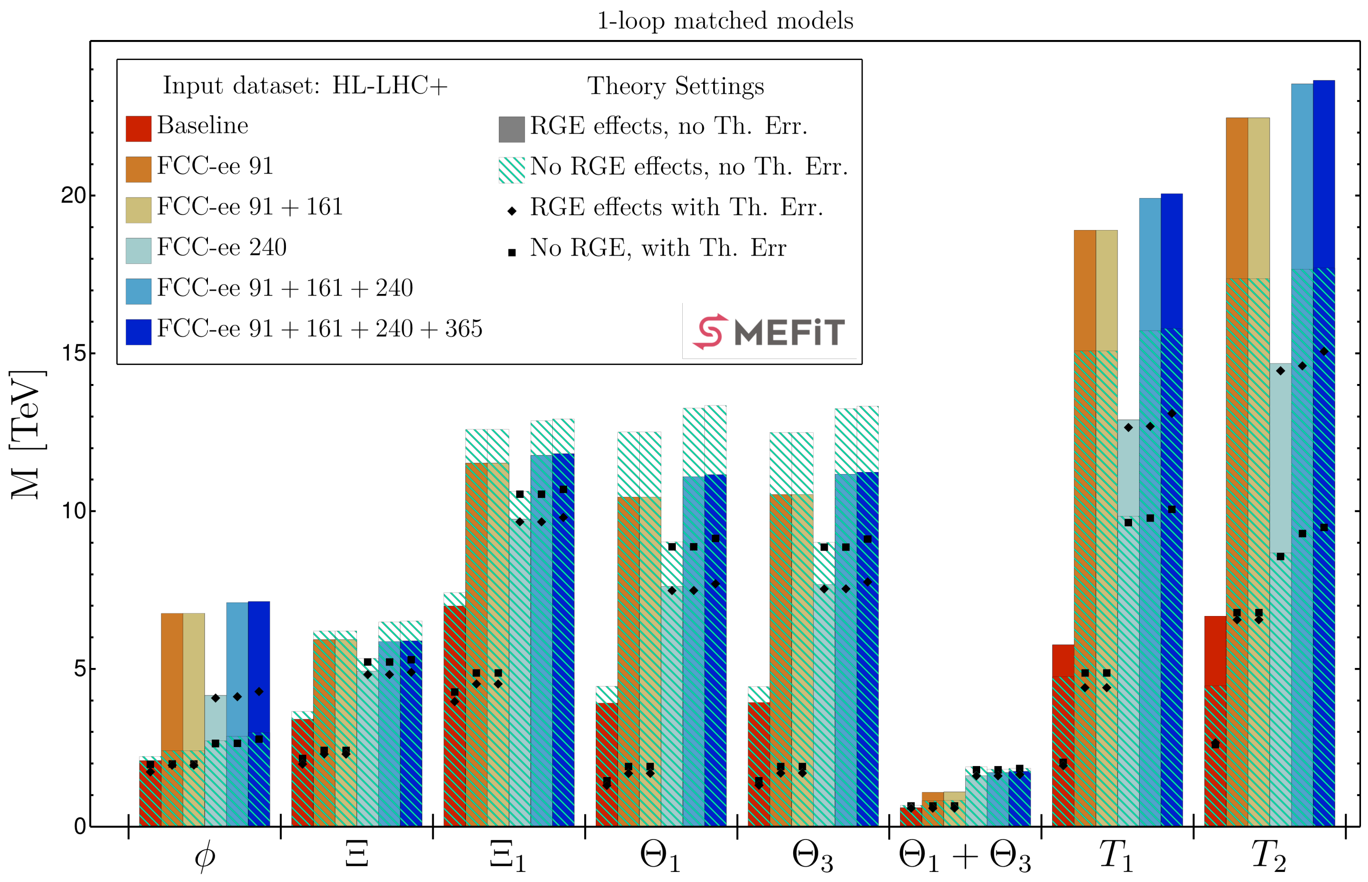
Importance of controlling/reducing the TH syst. errors to exploit Z-pole data.

Role of ZH and tt runs.

New Physics Reach @ Z-pole

There are 48 different types of particles that can have tree-level linear interactions to SM.

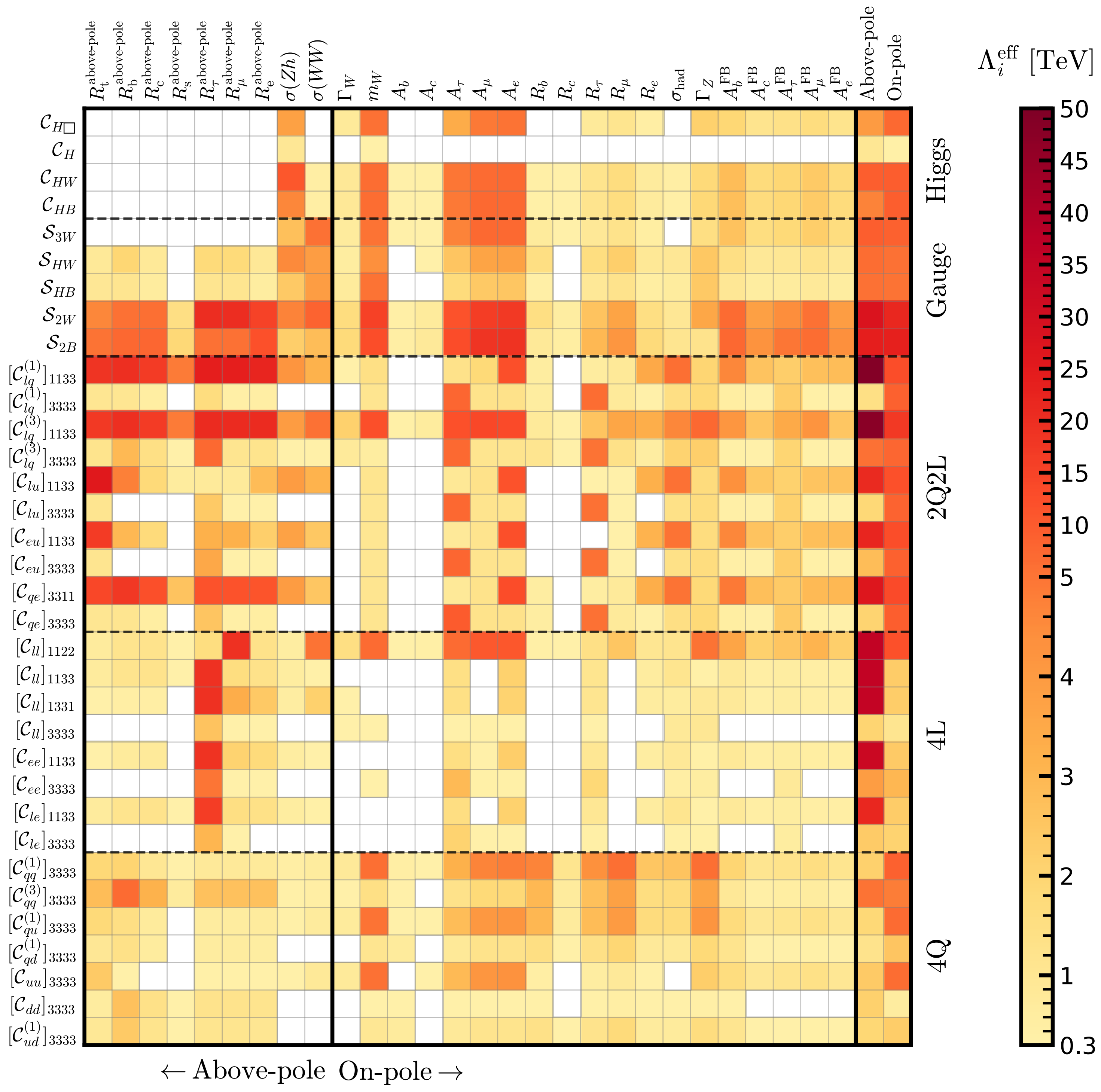




Importance of full 1-loop matching
(finite pieces matter)

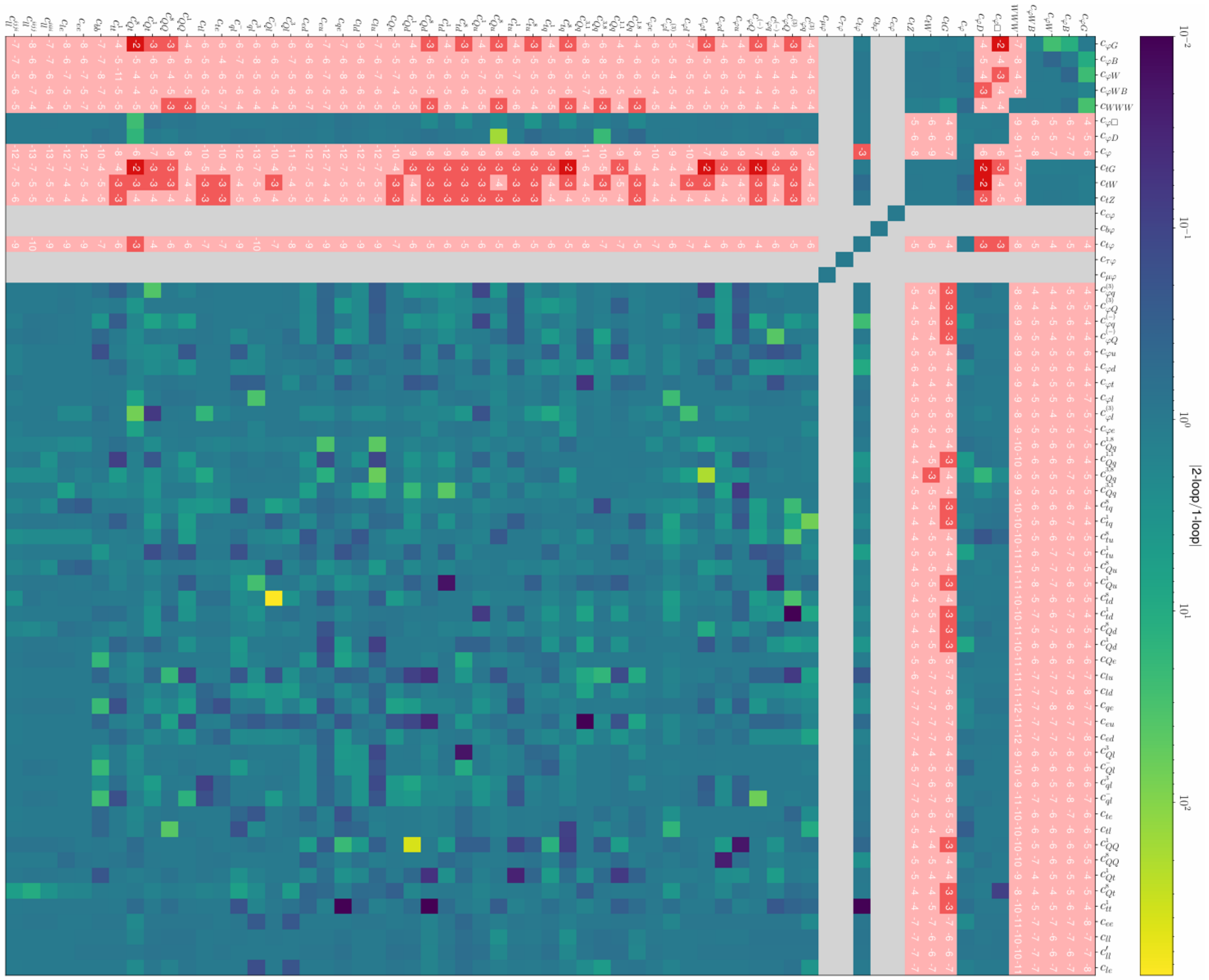
Z-pole vs High Energy

Maura, Stefanek, You arXiv:2412.14241



Z-pole vs High Energy

Mantani, Olgoso, Rossia arXiv:2604.16599



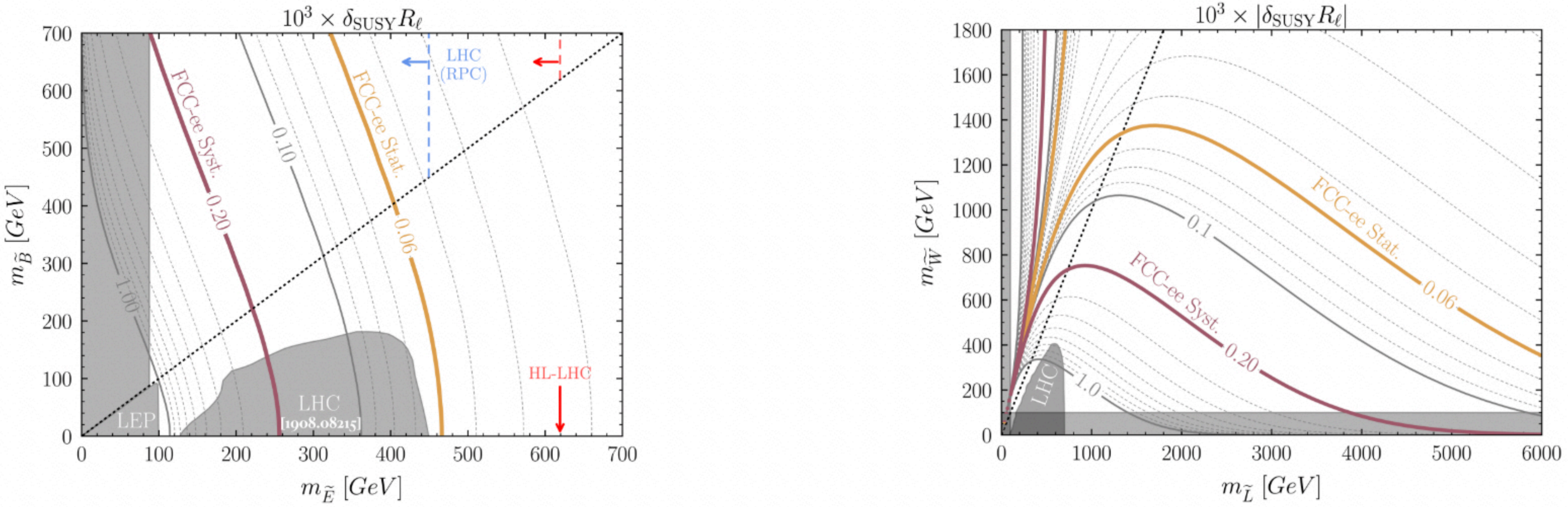
Runs into μ_0

Indirect BSM probe

SUSY discovery via EW precision measurements

$$\frac{\Gamma_{Z\to\ell\ell}-\Gamma^{(SM)}_{Z\to\ell\ell}}{\Gamma^{(SM)}_{Z\to\ell\ell}} \propto \frac{g^2}{16\pi^2}\left(\frac{m_Z}{M_{\rm SUSY}}\right)^2 \longrightarrow \boxed{M^{\rm probed}_{SUSY} \sim 1\ \text{TeV} \times \left(\frac{\delta\Gamma/\Gamma}{10^{-5}}\right)^{-1/2}}$$

25 keV (10^{-5}) syst. uncertainty on Γ_Z probes M_{susy} in the TeV region



Bino + RH slepton model

Wino + LH slepton model

Knapen, Langhoff, Ligeti: 2407.13815

Conclusions

Descoped/Staged/Upscoped FCC

- **Descoped/staged FCC:**
  - No top run: -1.26 BCHF but physics objectives severely impacted
  - 30 MW beam power instead of 50 MW: -0.35 BCHF but luminosity reduced to 60%
  - 2 caverns/IPs instead of 4: -0.80 BCHF but luminosity reduced to 61%

⇒ 12.85 BCHF instead of 15.28 BCHF (construction)

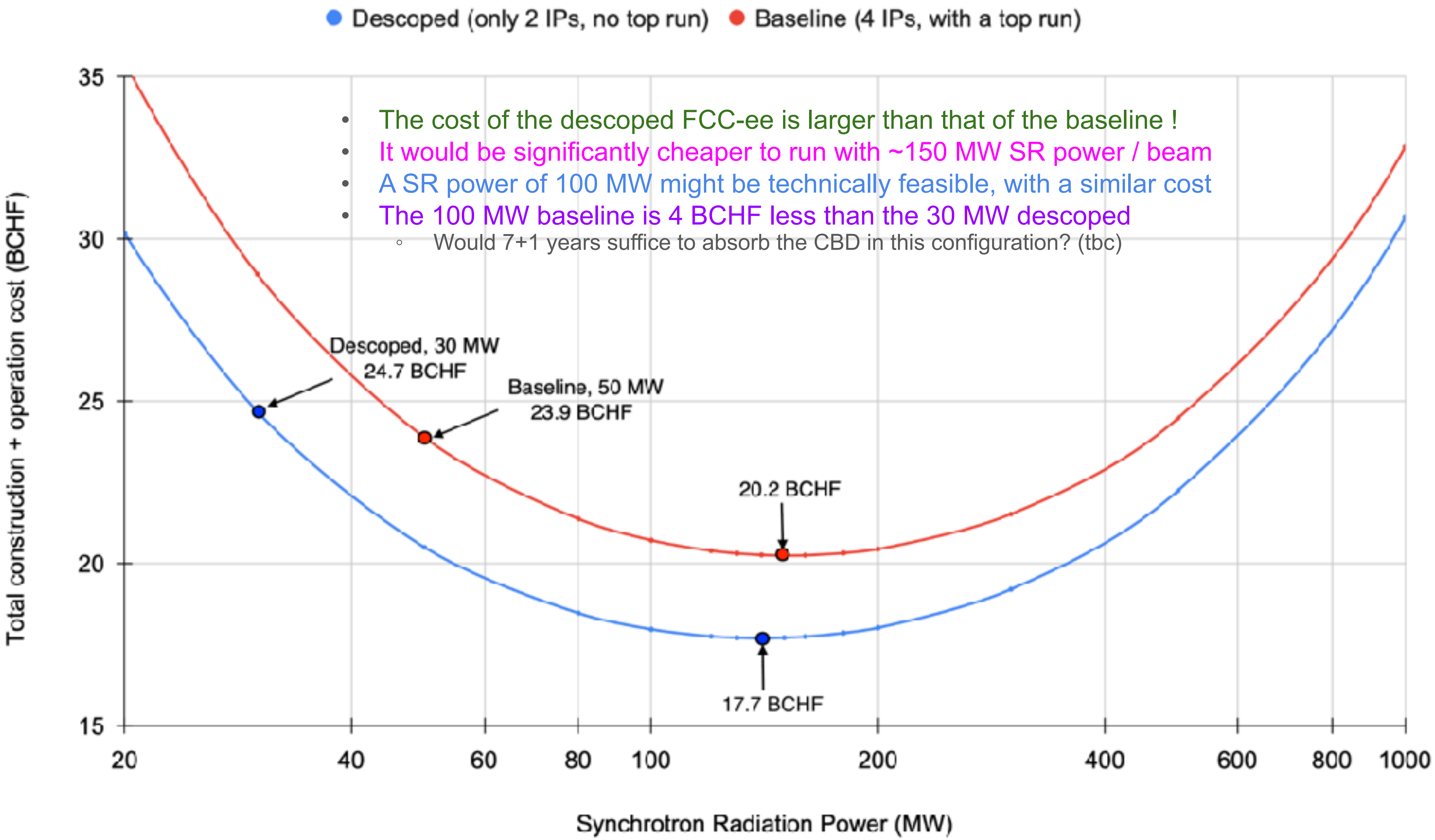
23y instead of 9 years for same physics output at 90, 160 and 240 GeV
(by the way, one needs 21y for CERN CBD →0)

“Time is money!”

Taxpayers will pay the bill for CAPEX+OPEX.

Descoped/Staged/Upscoped FCC

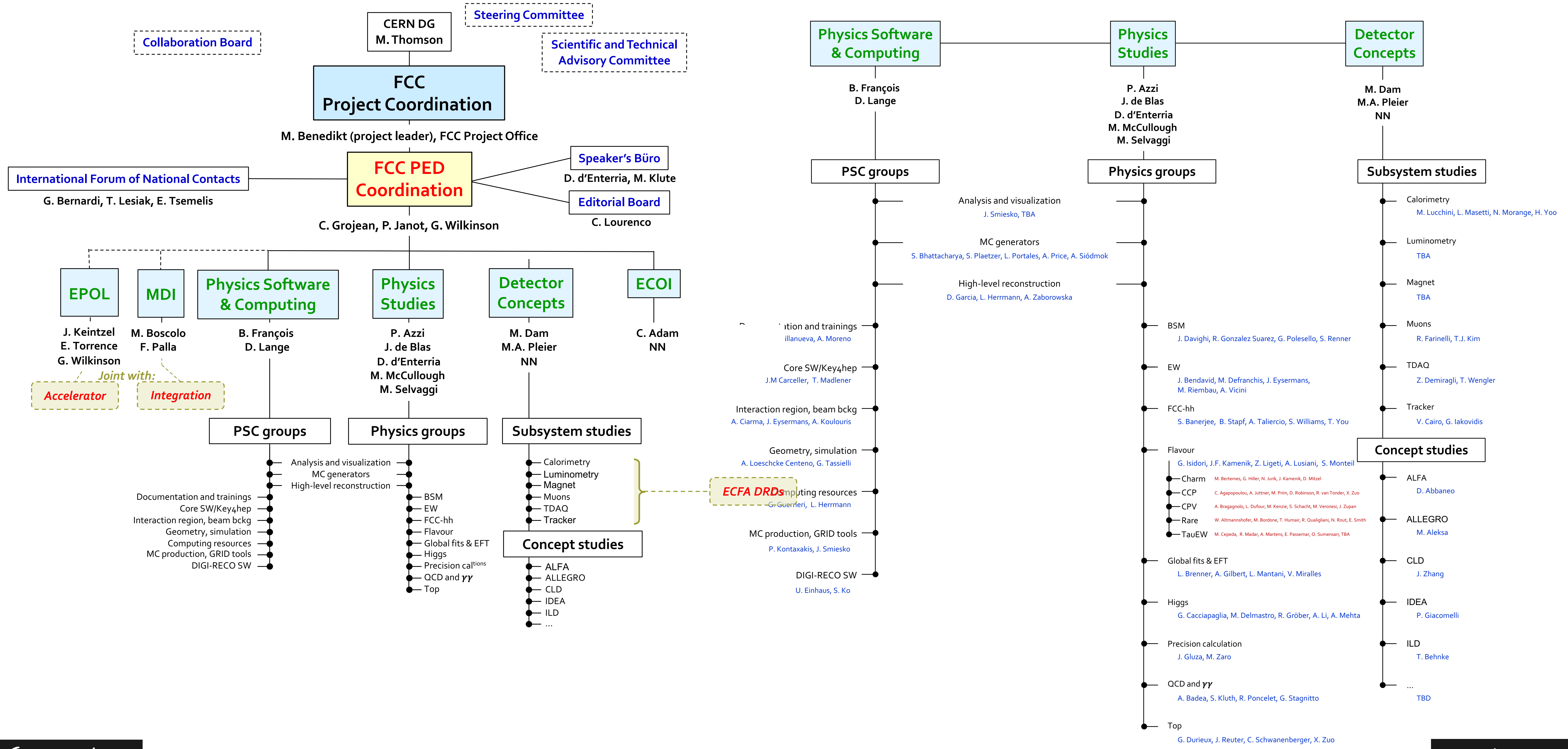
long running time



- The cost of the descoped FCC-ee is larger than that of the baseline !
- It would be significantly cheaper to run with ~150 MW SR power / beam
- A SR power of 100 MW might be technically feasible, with a similar cost
- The 100 MW baseline is 4 BCHF less than the 30 MW descoped
  - Would 7+1 years suffice to absorb the CBD in this configuration? (tbc)

large construction cost

Join FCC-PED



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...
TBD

Twenty Year away from First Collisions

Twenty Year away from First Collisions

Twenty Year away from First Collisions

Many thanks to the FCC Feasibility Study

Any misunderstandings are my own

CERN-FCC-PHYS-2025-0002

Future Circular Collider
Feasibility Study Report

Volume 1

Physics, Experiments, Detectors

April 1, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

arXiv:2505.00272

CERN-FCC-ACC-2025-0004

Future Circular Collider
Feasibility Study Report

Volume 2

Accelerators, Technical Infrastructure and Safety

March 31, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

arXiv:2505.00274

CERN-FCC-ACC-2025-0003

Future Circular Collider
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Volume 3

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arXiv:2505.00273

FCC Further Reading Material

- **Feasibility Study Report** (backup documents) ESPPU#261
  - Volume 1: Physics, Experiments, Detectors (291 pages) CDS arXiv:2505.00272
  - Volume 2: Accelerators, technical infrastructure and safety (615 pages) CDS arXiv:2505.00274
  - Volume 3: Civil Engineering, Implementation and Sustainability (360 pages) CDS arXiv:2505.00273
- **Several 10-page general summaries**
  - FCC Integrated Programme Stage 1: The FCC-ee (ESPPU#233); CDS
  - FCC Integrated Programme Stage 2: The FCC-hh (ESPPU#247); CDS
  - The FCC Integrated Programme: A physics manifesto (ESPPU#241); CDS; arXiv:2504.02634
  - Other Science Opportunities at the FCC-ee CDS
- **Several 10-page more topical summaries**
  - Prospects in Electroweak, Higgs and Top physics at FCC (ESPPU#217); FCC note
  - Prospects in BSM physics at FCC (ESPPU#242); FCC note
  - FCC: QCD physics (ESPPU#209); FCC note
  - Prospects for flavour physics at FCC (ESPPU#196); FCC note
  - Prospects for physics at FCC-hh (ESPPU#227); FCC note
- **Expressions of Interest for the development of Detector Concepts and Sub-detector Systems for FCC**
  - Summary (ESPPU#95); FCC note
  - Backup document ((ESPPU#96)