Physics Performance Highlights

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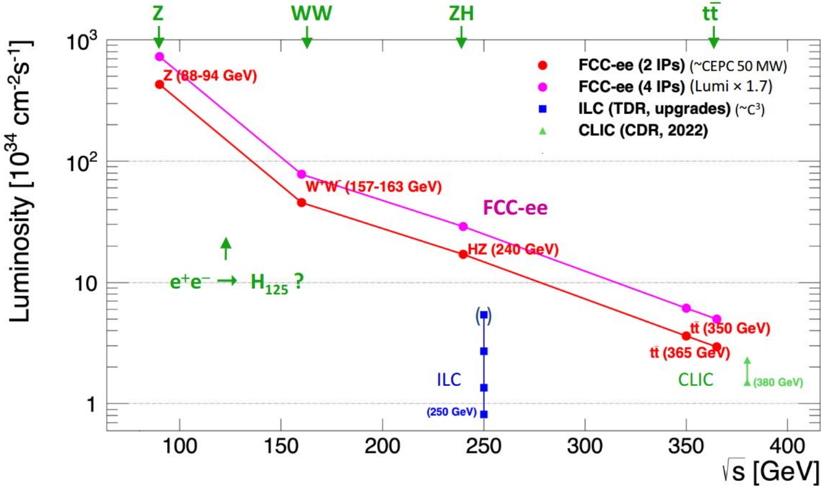
FCC Physics Week - Annecy

February 2nd, 2023

A few general considerations



15 (20?) years of operations

	Z pole	? H pole ?	WW	ZH	ttbar
√s [GeV]	88 - 91 - 94	125	157 - 161	240	350 - 365
Lumi / IP [10^{34} cm^2 s^{-1}]	182	80	19.4	7.3	1.33
Int. lumi / 4IP [ab^{-1} / yr]	87	38	9.3	3.5	0.65
N_{years}	**4**	**5**	**2**	**3**	**5**
N_{events}	8 Tera	8 K	300 M	2 M	2 M

Exquisite luminosity allows for ultimate precision:

- 100K Z bosons / second
  - LEP dataset in 1 minutes
- 10k W boson / hour
- 2k Higgs bosons / day
- 3k tops / day

Physics landscape at the FCC-ee

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Detector requirements at the FCC-ee

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
“boosted” B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

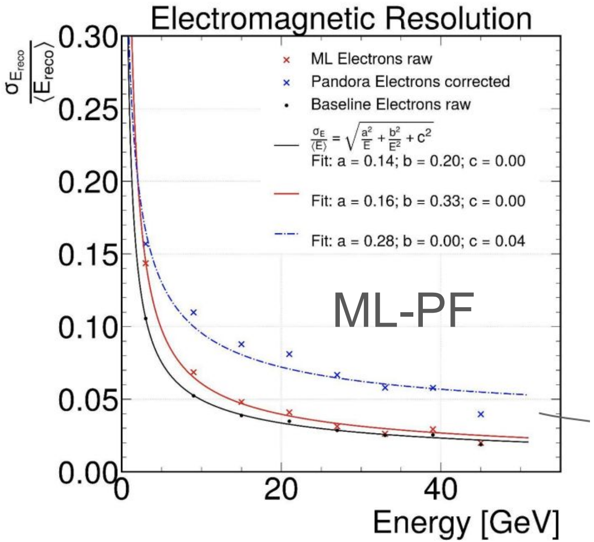
impact parameter resolution for large displacement

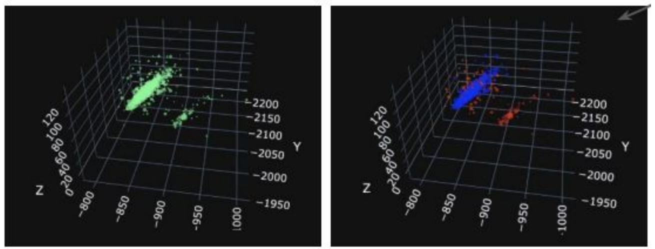
timing

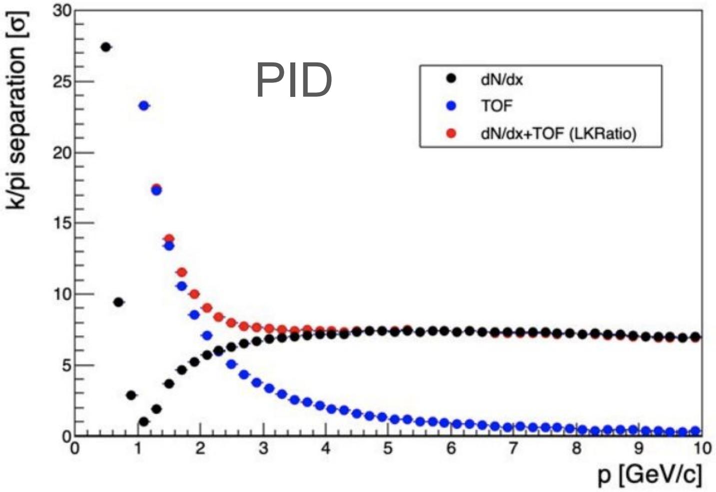
triggerless

Reconstruction and ID

Coccaro, Garcia







Likelihood K/π discriminant

Highlights from recent activities

Luminosity/acceptance

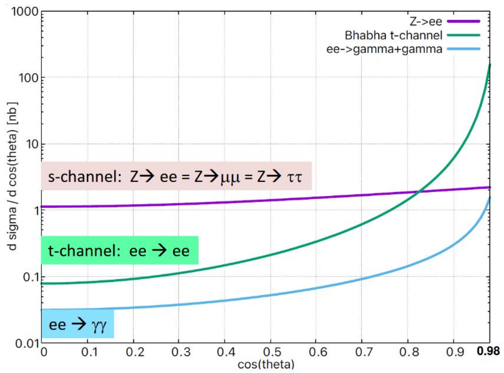
Blondel, Dam, Piccinini, Wilson

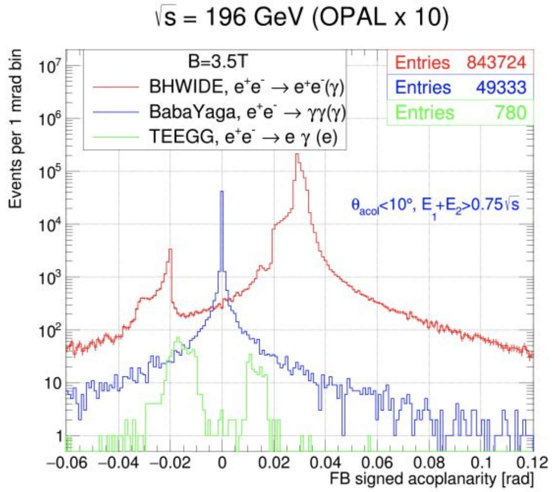
- Precise knowledge of the **geometrical acceptance** required by
  - R^Z_ℓ measurement (as limiting systematics)
  - absolute luminosity measurement at Z pole, required by
    - peak Z cross section (σ_0)

- At LEP, via Bhabha scattering at low angle, here we require 10^{-5} precision (for point-to-point), 10^{-4} being absolute target
  - un-matched by theoretical calculations
  - use **ee → γγ** process as an alternative, rarer but cleaner

- To match stat. precision (2×10^{-5})
  - must know **$\Delta\theta_{min}$ ~ 10 μrad ~Δr ~ 30 μm**, **Δz ~ 80 μm** at θ = 20° and z = 2.6m
    - challenging design requirement !!

ee → γγ **require excellent bhabha rejection: acoplanarity**



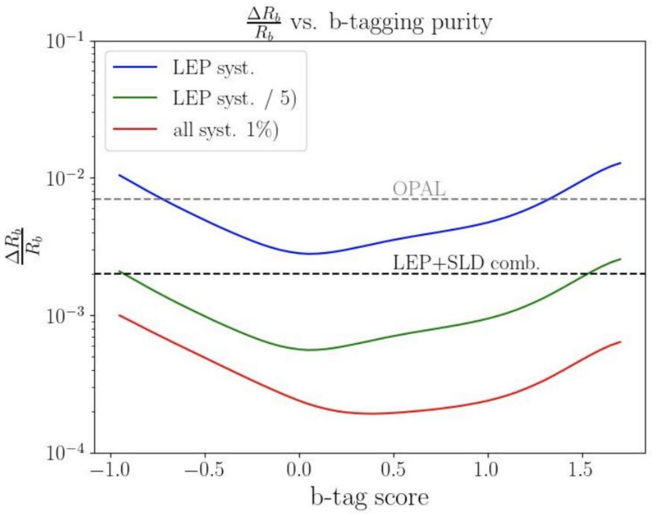


Precision at the Z - Rb

Rohrig, MS

Double-tag method

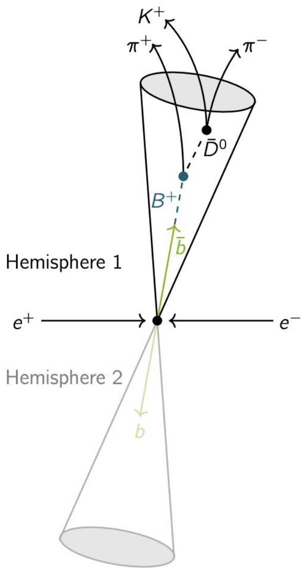
inclusive



- syst. budget ~ correlation
- same hemisphere events dominate

exclusive

- syst. budget ~ correlation
- PV estimate dominates

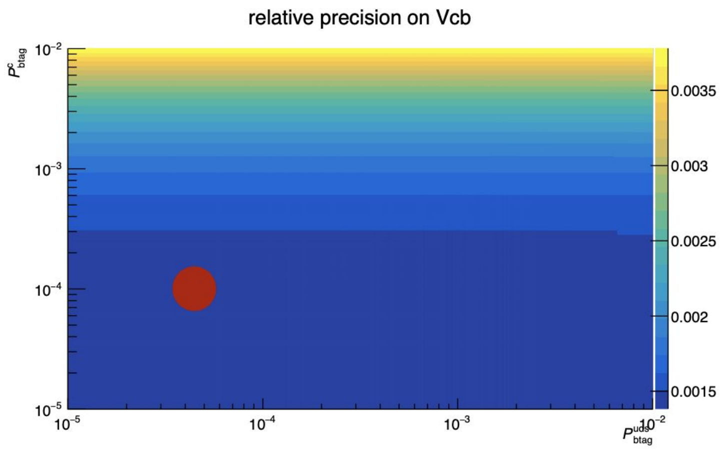


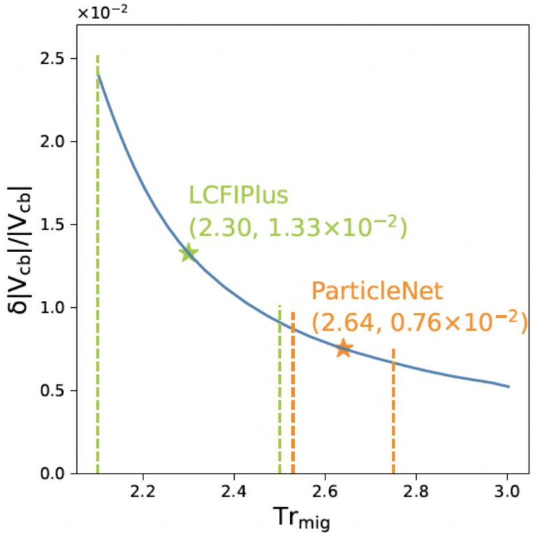
	Luminous region
Current syst. precision	$\sigma^{tot.}(R_b) = 6.4 \cdot 10^{-4}$
1 % syst. precision	$\sigma^{tot.}(R_b) = 2.9 \cdot 10^{-5}$

< 10^{-4} seems to be within reach, but 1% control on correlation must be proven

V_{cb}

Monteil, Ruan





- V_{cb} could be measured with a precision 0.15%
- **10x improvement** w.r.t to current

assessing impact of tagging systematics

		conservative	baseline	optimal
$\nu\nu Hc\bar{c}$	LCFIPlus	0.071	0.057	0.047
	ParticleNet	0.045	0.042	0.038
	$\frac{\text{LCFIPlus}}{\text{ParticleNet}}$	1.58	1.38	1.26
$\lvert V_{cb}\rvert$	LCFIPlus	0.0241	0.0133	0.0091
	ParticleNet	0.0086	0.0076	0.0067
	$\frac{\text{LCFIPlus}}{\text{ParticleNet}}$	2.80	1.75	1.36

Flavor

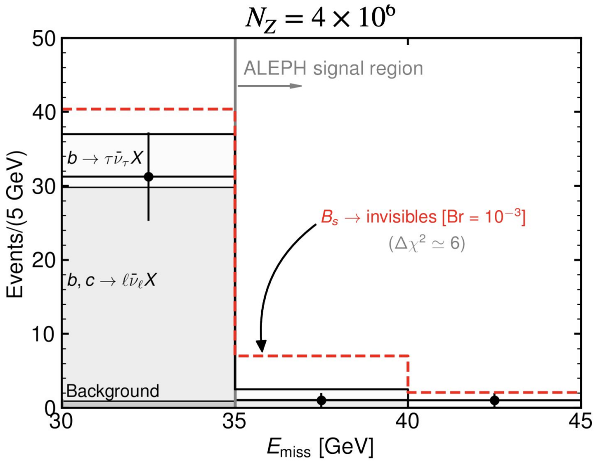
Abenza, Aleksan, Kenzie, Perez

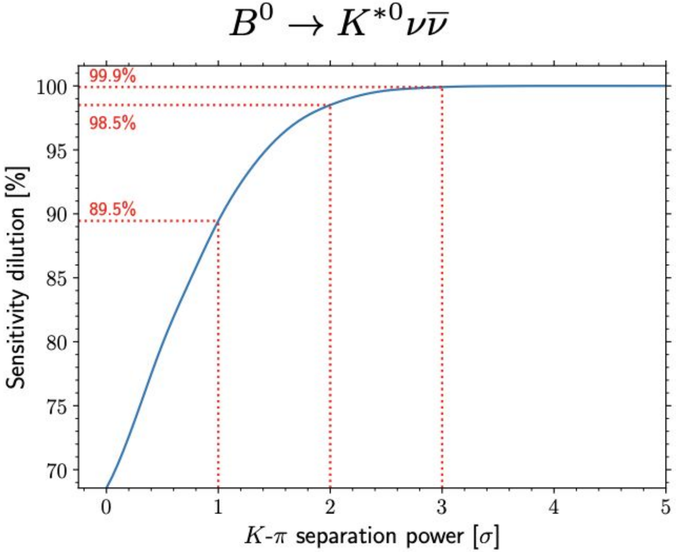
recast of LEP analysis

$$\mathrm{BR}(B_s \to \bar{\nu}\nu) < 6 \times 10^{-4}$$

Mode	N_S	N_B	ϵ^s	$\epsilon^{b\bar{b}}$	$\epsilon^{c\bar{c}}$	$\epsilon^{q\bar{q}}$	S/B	$\sqrt{S+B}/S$
$B^0 \to K^{*0}\nu\bar{\nu}$	231 K	1.27 M	3.7%	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-9})$	0.17	0.53%
$B_s^0 \to \phi\nu\bar{\nu}$	61 K	0.48 M	7.4%	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-9})$	0.13	1.20%

Electron and Muon ID at low momenta
PID in general





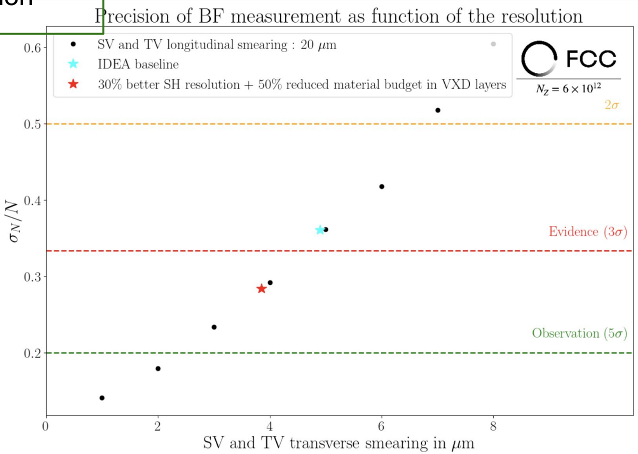
PID, PID, PID …

More flavour ..

Coccaro, Miralles, Perez

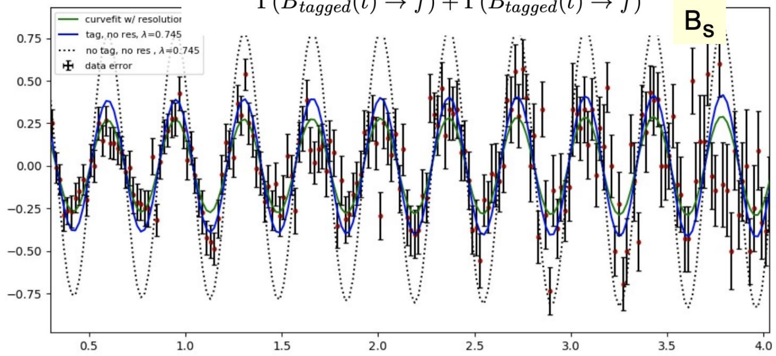
5σ observation with **2 μm** vertex resolution

$B^0 \to K^{*0}\tau\tau$



$B_s \to \phi K_s \to K K \pi \pi$

$$\mathcal{A}s = \frac{\Gamma(\overline{B}_{tagged}(t) \to f) - \Gamma(B_{tagged}(t) \to f)}{\Gamma(\overline{B}_{tagged}(t) \to f) + \Gamma(B_{tagged}(t) \to f)}$$



$\Phi_{CKM}(B_s) = \pi + 2\,\alpha_{ds}$

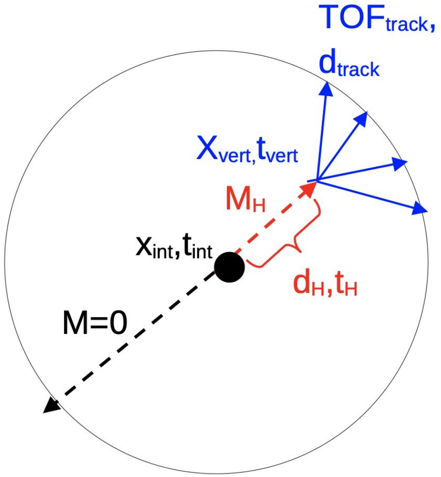
- minimisation of material budget
- beam pipe eventually becomes the asymptotic limitation

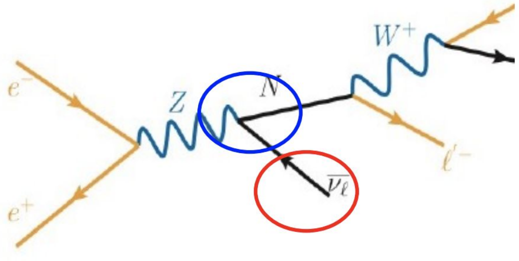
A good reconstruction of Ks decays up to large flight distance

- hence a large tracking volume
- excellent mass and vertex resolutions
- light tracker and highly performant vertex detector
- PID crucial for the Bs

Mass with time-of-flight

Polesello, Valle

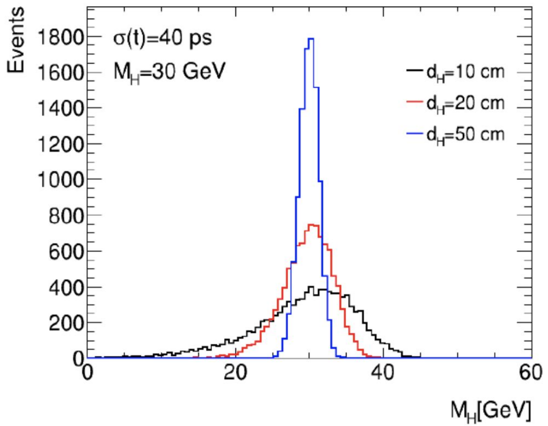




$$p_H = \frac{\sqrt{(E_{CM}^2 - (M_H + M)^2)(E_{CM}^2 - (M_H - M)^2)}}{2E_{CM}}$$

$$p_H = M_H \gamma \beta$$

$$\beta \;=\; d_H/t_H/c,$$



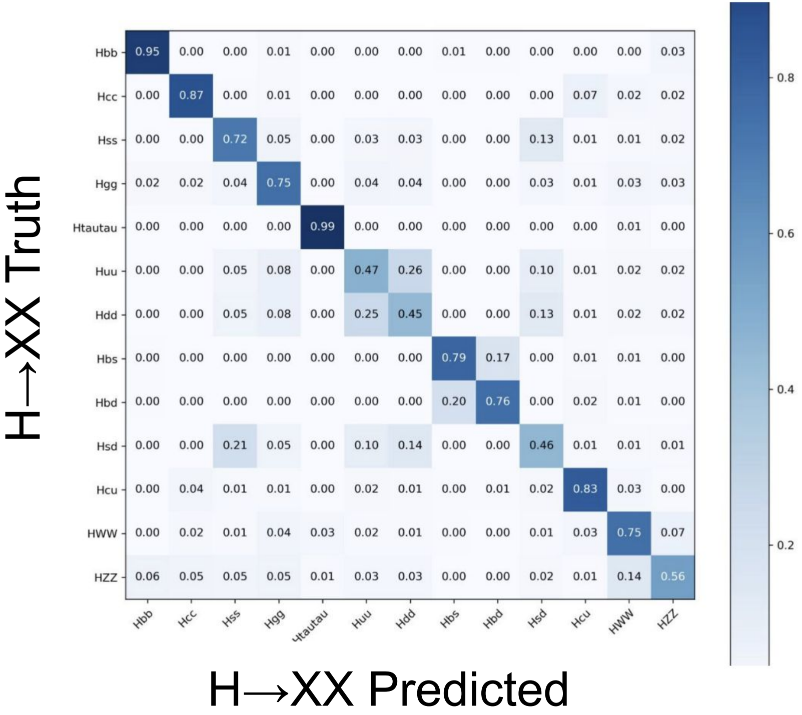
- For a timing layer with σ(t) a few tens of ps, mass resolution at percent level for long enough path and high enough mass
- Timing resolution dominated by unknown time of primary vertex

Higgs Hadronic Couplings (light +FCNCs)

Eysermans, Iakovidis

Can use up, down, strange, charm and bottom flavour categories to extract upper limits on:

- Light Yukawa: up and down
- FCNCs: bs, bd, cu, sd



Final state	**upper limit BR(H→xx) 95% CL**
H → dd	1.7e-03
H → uu	1.8e-03
H → bd	3.3e-04
H → bs	4.5e-04
H → cu	3.0e-04
H → sd	9.5e-04

Reducing the Systematic Uncertainties

Eysermans

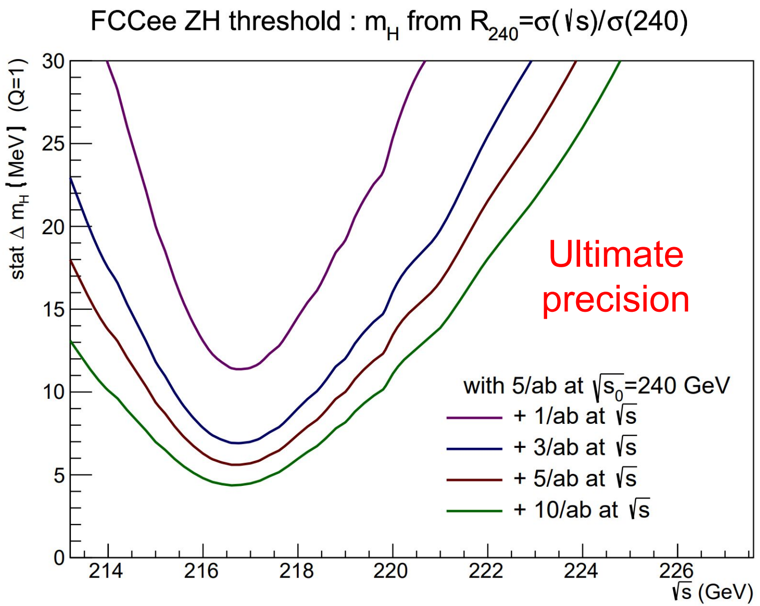
Construct the cross-section ratio using √s = 217 and 240 GeV

$$R = \frac{\sigma_{ZH} \times \mathcal{B}(Z \to f\bar{f}) \times \mathcal{B}(H \to X\bar{X})|_{\sqrt{s}=217\,\text{GeV}}}{\sigma_{ZH} \times \mathcal{B}(Z \to f\bar{f}) \times \mathcal{B}(H \to X\bar{X})|_{\sqrt{s}=240\,\text{GeV}}} = \frac{\sigma_{ZH}(\sqrt{s} = 217\,\text{GeV})}{\sigma_{ZH}(\sqrt{s} = 240\,\text{GeV})}$$

→ **Experimental and theory uncertainties cancel mostly**

→ Sensitivity reached ~ 5 MeV

Run config	Uncertainty (MeV)
5 ab^{-1} @ 217, 5 ab^{-1} @ 240	5 MeV
10 ab^{-1} @ 240 GeV	3 MeV



Can provide independent measurement of Higgs mass w.r.t. recoil mass method

But need to perform the "real" analysis for realistic numbers

Where are we today?

Eysermans, Iakovidis, Morange

Made a lot of progress over the past years, mainly focused at the 240 GeV threshold

Missing elements for the Feasibility Study for next 1.5 years

- Higgs @ 240 GeV: WW, ZZ (expansion of H width efforts)
- Higgs @ 365 GeV: the total cross-section, couplings, width
- Tau physics
  - Higgs → tau tau can put unique detector requirements for tau ID and reconstruction
  - Synergies with Tau polarization at Z pole
- Others: angular analysis, differential measurements

Top activities

- Threshold mass, width
- EW couplings ttZ, Vts, FCNCs

Parameter	FCC-ee CDR	FCCee today
$H \to WW$	1 %	2.0 %
$H \to ZZ$	3.6 %	4.6 %
$H \to gg$	1.6 %	0.78 %
$H \to \gamma\gamma$	7.5 %	3.5 %
$H \to cc$	1.8 %	1.6 %
$H \to bb$	0.25 %	0.18 %
$H \to \mu\mu$	15.8 %	19.5 %
$H \to \tau\tau$	0.75 %	0.9%
$H \to Z\gamma$		
$H \to ss$	–	103 %
Invisible	< 0.25 %	< 0.18 %
m_H	5 MeV	4 MeV
Γ_H	1 %	4%
κ_λ	42 %	30%

FCC-hh

MLM, Taliercio, Stapf

precision

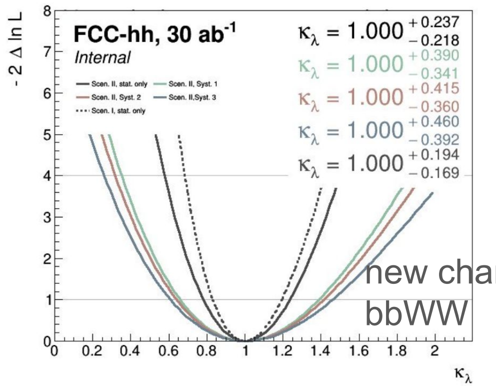
Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0	0.8

CollliderReach ECM extrapolation of 5σ 30ab^{-1} discovery reach

	100 TeV	80 TeV	120 TeV
Q*	40	33	46
$Z'_{TC2} \to tt$	23	20	26
$Z'_{SSM} \to tt$	18	15	20
$G_{RS} \to WW$	22	19	25
$Z'_{SSM} \to ll$	43	36	50
$Z'_{SSM} \to \tau\tau$	18	15	20

+/- 15% variation (as expected)

Higgs self-coupling



new channel bbWW

	Stat only	Syst 1
No assumption on $m_{\bar{b}b}$ resolution	3.2%	3.6%
10 GeV $m_{\bar{b}b}$ res	2.5%	2.7%
5 GeV $m_{\bar{b}b}$ res	2.0%	2.3%
3 GeV $m_{\bar{b}b}$ res	**1.8%**	**2.0%**

improved bbγγ

Thank you

FCC-ee conditions

FCC-ee parameters		Z	WW	ZH	ttbar
$\sqrt{s}$	GeV	88 - 94	157.2 - 162.5	240	350-365
Inst. Lumi / IP	10^{34} cm^{2} s^{-1}	182	19.4	7.3	1.33
Integrated lumi / 4IP	ab^{-1} / yr	87	9.3	3.5	0.65
N bunches/beam	-	10 000	880	248	36
bunch spacing	ns	30	340	1 200	8 400
L*	m	2.2	2.2	2.2	2.2
crossing angle	mrad	30	30	30	30
vertex size (x)	µm	5.96	14.7	9.87	27.3
vertex size (y)	nm	23.8	46.5	25.4	48.8
vertex size (z)	mm	0.4	0.97	0.65	1.33
vertex size (t)	ps	36.3	18.9	14.1	6.5
Beam energy spread	%	0.132	0.154	0.185	0.221