FCC Physics
Summary and next steps

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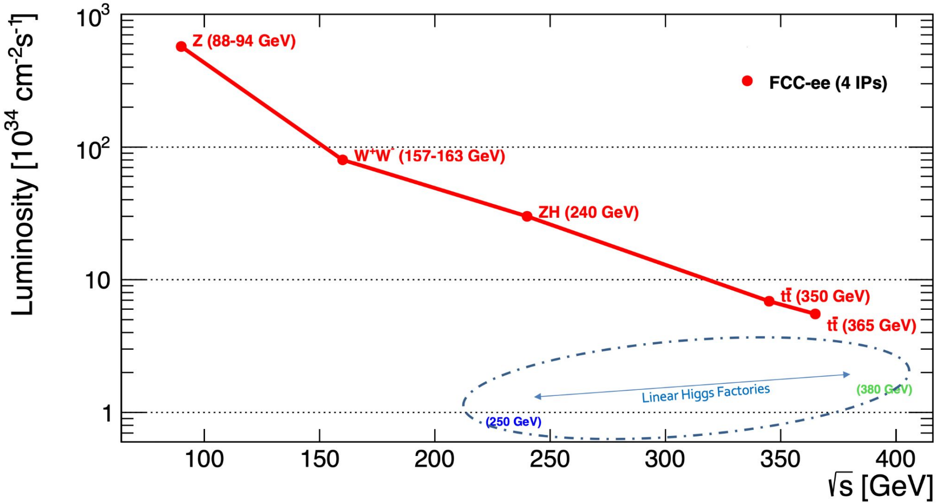
FCC/DRD France Workshop – 26 November 2025

Outline

- The challenges and opportunities
- (Brief) summary of FSR conclusions
- Preparing the pre-TDR phase for the physics group
- Partial and preliminary possible next steps
  - mostly from an experimental perspective

The FCC-ee programme



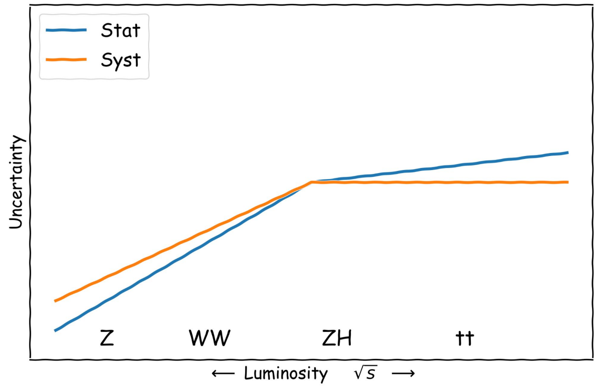
Well beyond LEP, opens novel challenges and opportunities:

- how do we build optimal detectors?
- what precision do we need from TH?
- how do we define an optimal run sequence?

Exquisite luminosity allows for ultimate precision:

- 10^5 larger dataset than LEP at the Z-pole, enables:
  - 300x improvement in statistical precision in EWPO
  - 10x larger statistics vs. planned flavor factories
  - ultra-feebly interactive particle searches up to m_Z
- ~ millions of extremely clean H and Top, allow:
  - [0.1-1%] H, top couplings precision
  - mass and width 10x better precision than LHC

The name of the game



- make optimal use of all available statistics
  - hermeticity, efficiency
  - particle ID
  - energy/momentum/angular resolution

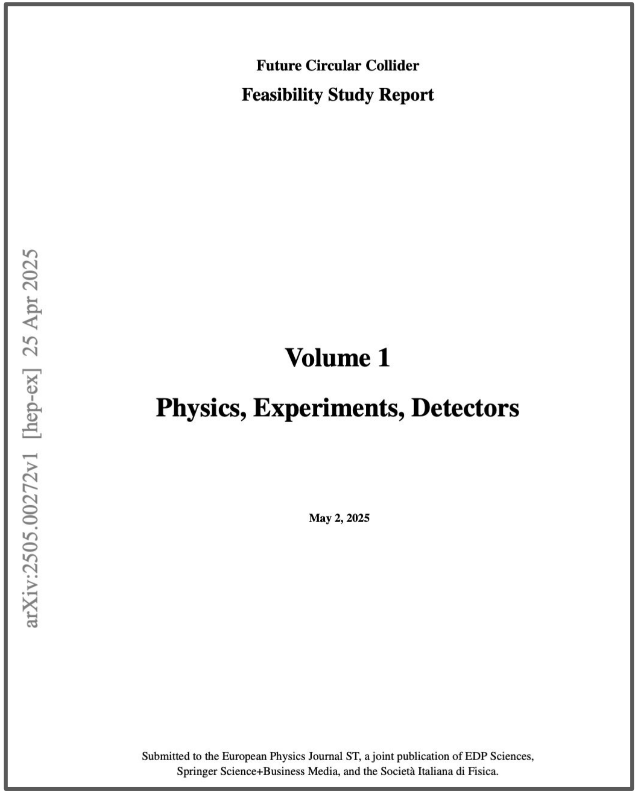
for each observable to measure, need:

→ specific ancillary analyses
→ beyond state-of-the-art analysis tools to be developed

- **match systematic uncertainties to statistical errors**
  - beam energy and spread calibration (absolute, relative)
  - geometrical acceptance
  - absolute luminosity determination
  - momentum scale stability
  - momentum resolution
  - Higher order calculation, and NP modeling

The FCC Feasibility Study

- Conclusion of a long path started in 2020!
- Physics Programme articulated physics case of the integrated programme
- Physics Performance activities exploited "Case Studies" to extract physics motivated detector requirements
  - developed **tools for simulation** and **reconstruction**, **MC production** in coordination with the Software group
  - developed high level tools for **physics analysis**



Future Circular Collider

Feasibility Study Report

arXiv:2505.00272v1 [hep-ex] 25 Apr 2025

Volume 1

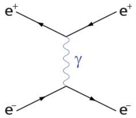
Physics, Experiments, Detectors

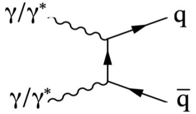
May 2, 2025

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

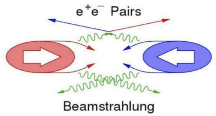
Detector requirements - general considerations

- Requirements for Higgs and above have been studied to some extent by LC:
  - we want a detector that is able to withstand a **large dynamic range**:
    - in energy ($\sqrt{s}$ = 90 - 365 GeV)
    - in luminosity (L = 10^{34} - 10^{36} cm^2/s)

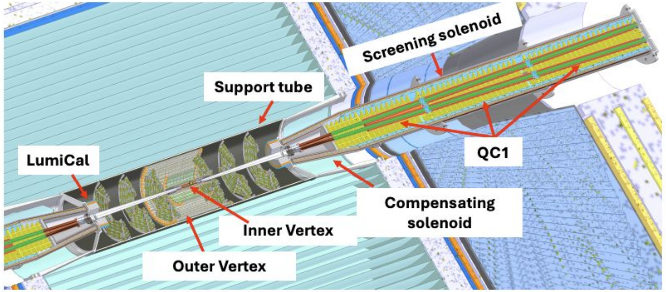




- most of the **machine induced limitations are imposed by the Z pole run**:
  - large collision rates ~ 33 MHz and continuous beams
    - no power pulsing possible
  - large event rates ~ 100 kHz
    - **fast detector response / triggerless** design challenging (but rewarding)
    - **high occupancy** in the inner layers/forward region (Bhabha scattering/incoherent pair production/ γγ hadrons)
  - beamstrahlung



- **complex MDI:** last focusing quadrupole is ~ 2.2m from the IP
  - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical e SR)
    - **limits the achievable track momentum resolution**
  - “anti”-solenoid
    - limits the acceptance to ~ 100 mrad



→ mostly affect Z pole, measurements, in principle 3T field is possible at $\sqrt{s}$ = 240 GeV

Physics landscape at the FCC-ee

FUTURE CIRCULAR COLLIDER

Higgs
factory

m_H, σ, Γ_H
self-coupling
$H\rightarrow$ bb, cc, ss, gg
$H\rightarrow$inv
ee$\rightarrow$H
$H\rightarrow$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..)

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

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

Momentum resolution

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

impact parameter resolution for large displacement

timing

triggerless

Detector Requirements summary

	Aggressive	Conservative	Comments
Beam-pipe	$\frac{X}{X_0} < 0.5\%$	$\frac{X}{X_0} < 1\%$	$\mathrm{B} \to \mathrm{K}^* \tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p \sin^{3/2}\theta)$ µm $\frac{X}{X_0} < 1\%$	–	$\mathrm{B} \to \mathrm{K}^* \tau\tau$ R_c
	$\delta L = 5$ ppm	–	$\delta\tau_\tau < 10$ 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	$\delta\Gamma_Z(\mathrm{BES}) < 10$ 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
	$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 5 \times 5$ mm^2	τ polarization boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100$ µm, $\delta R_{\mathrm{min}} = 10$ µm ($\theta = 20°$)	–	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL	$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	$\mathrm{H} \to s\bar{s}$, $c\bar{c}$, gg, invisible HNLs
	$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 20 \times 20$ mm^2	$\mathrm{H} \to s\bar{s}$, $c\bar{c}$, 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	$\mathrm{H} \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100$ µm, $\delta R_{\mathrm{min}} = 1$ µm acceptance 50-100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$\mathrm{e^+e^-} \to \gamma\gamma$ $\mathrm{e^+e^-} \to \mathrm{e^+e^-}\tau^+\tau^-(c\bar{c})$

- Beyond a Higgs factory
  - Good vertex, excellent PID for flavor tagging
    - In particular for strange
  - jet energy resolution
    - calorimetry/Particle-Flow
- Strong non trivial requirements at the Z pole, e.g
  - Z width (mom. resolution)
  - Tau lifetime (abs. Vertex length scale)
  - Tau pol. (calorimeters)
  - Luminosity: acceptance
  - B physics: beampipe, vertex resolution
  - LLPs: continuous tracking and calorimetry, timing

Non-exhaustive list! .. still much to be understood, in particular at the Z pole!

Precision Physics at the Tera Z

FCC-ee **Z-pole run**: **a gigantic leap towards the unknown**

- The whole LEP dataset is produced every ~ 30 seconds!
- 10^5 x LEP dataset in total
  - > 100 x reduction in stat. uncertainty
  - **10 x increase in physics reach**
    - $\Lambda \sim \delta O^{-½} \sim \mathcal{L}^{-1/4}$ for dim-6

Precise measurements are discovery tools:

- Loop corrections from heavy particles
- LEP/SLC hinted at the existence of the top and Higgs, and estimated their mass
  - $M_t \sim 170 \pm 10$ GeV, $(114 <)\ M_H < 200$ GeV

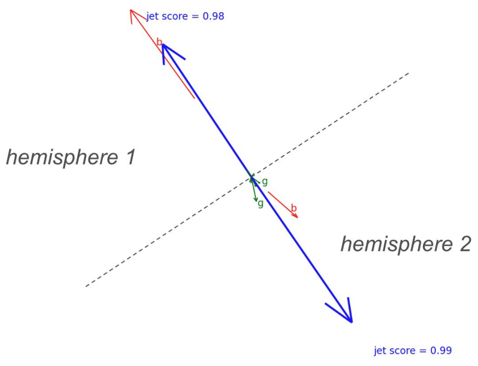
Main Challenge:

- bring systematics down to stat. level
- designing accelerator with required specifications

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ $(\times 10^6)$	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ $(\times 10^3)$	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
$N_\nu (\times 10^3)$	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
$A_{FB}^{b,0}$ $(\times 10^4)$	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
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
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

Heavy Flavor observables

- Defined as $R_q = \Gamma_q / \Gamma_{had}$ with q = b, c, s measure individual chiral couplings to the Z → ($\sim g_L^2 + g_R^2$)
- **A_{FB}^q provides most precise sin θ_W measurement**
- Current (relative) uncertainties **~ 10^{-3}**
- Dramatic improvements compared to LEP are expected, driven by:
  - Reduced beam-spot sizes, light beam-pipe
  - Light and precise vertex detectors (few μm single point resolution)
  - Particle ID allowing strange tagging (K^+ identification up to 30-40 GeV)
    - and NEW measurement of R_s , A_{FB}^s
  - Advanced AI flavor tagging algorithms
    - pure b, c and strange jets → background contamination negligible
- Projections based on fast sim:
  - **2(b) - 10(s) (4-10) x 10^{-6}** for **FCC-ee**



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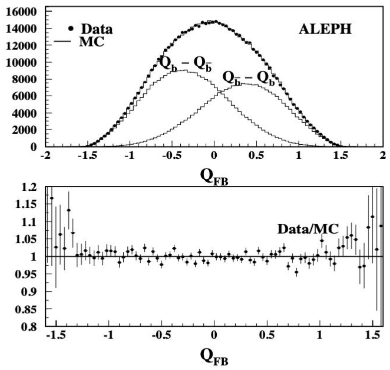


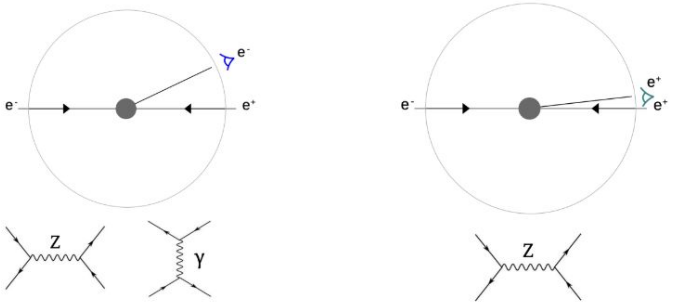
Heavy flavor observables at the Z pole

Aim is to confirm that full-simulation analyses can reproduce the projected 10^{-5}-10^{-6} level precision when including **detector effects,** and **beam-backgrounds**

- Heavy Flavor precision observables (R_b, A_{FB}^b, …)
- Dominant systematics:
  - **Flavour-tagging algorithms and calibration** (b, c jets),
    - hemisphere correlations mainly driven by QCD (gluon emissions, g→bb/cc, etc ..)
      - can be positive (negative) for hard (soft) emissions
    - can be reduced with (acoplanarity) cuts
    - measured directly in data
      - 10^9 (10^6) gluon splitting samples in FCC-ee (LCF)
    - mistag rate/purity
- Detector requirements:
  - **Vertex detector layout and material budget** (for $A_{FB}^{b,c}$)
  - RICH vs dN/dx for R_s, A_{FB}^s
- **ALEPH data** re-analysis ?

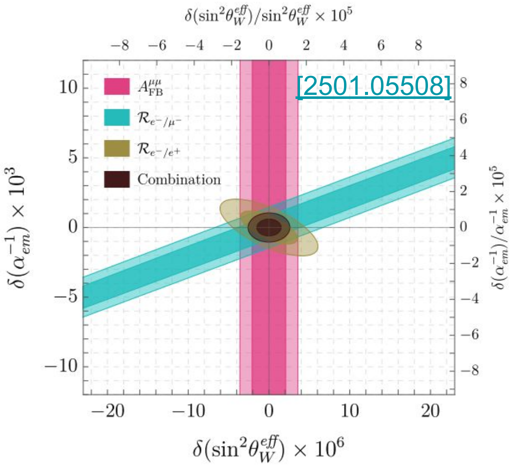
$\alpha_{QED}(m_Z)$

Riembau



$$\mathcal{R}_{e^-/e^+}(\theta) = \frac{\sigma(e^-e^+ \to e^-(\theta) + X)}{\sigma(e^-e^+ \to e^+(\theta) + X)}$$

- Dominant parametric uncertainty in EW precision ($\sin\vartheta_W^{eff}$ and m_W) fit:
  - Current uncertainty $\delta\alpha/\alpha$ = 1.4 x 10^{-4}
- FCC-ee can directly measure it (as opposed to LEP3, LCs)
  - from off-peak FB asymmetry (interference with γ*) in $\mu\mu$ events ($\delta\alpha/\alpha$ = 3x10^{-5})
    - small experimental uncertainty, stat dominated
    - Z-pole energy points chosen to optimize measurement !
  - from $R_{e+/e-}$, $R_{e-/\mu-}$ ($\delta\alpha/\alpha$ = 0.6x10^{-5})
    - e^+/e^- efficiency control (charge mis-id), material budget (impact of bremstrahlung))
    - e^-/μ^- acceptance difference (to be determined from 10^{11} lepton pairs)
    - Sets constraints on tracker, alignment, ECAL, muon detectors
  - Can then provide comparison with Lattice calculation



WW threshold mass (and width)

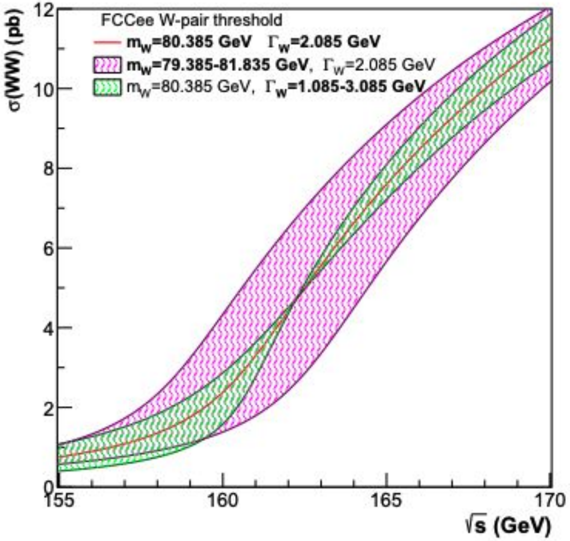
arXiv:2107.04444

- Mass (I) Measure WW production as a function of sqrt(s)

$$\Delta m_W(T) = \left(\frac{d\sigma_{WW}}{dm_W}\right)^{-1} \Delta\sigma_{WW}(T).$$

$$\Delta m_W(E) = \left(\frac{d\sigma_{WW}}{dm_W}\right)^{-1} \left(\frac{d\sigma_{WW}}{dE_{CM}}\right) \Delta E_{CM},$$

THEORY CHALLENGES
(full NNLO EWK calculation)



$\Delta m_W \sim 200$ keV (x50)

- Mass (II)
  - Kinematic fit above threshold (using qqlv events)
    - requires also excellent knowledge of sqrt(s) res.depol
    - lepton momentum scale (calibrated also via radiative return Z events)

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee syst.	Comment and leading uncertainty
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	WW threshold scan Beam energy calibration
$\mathcal{B}(W \to e\nu_e) \times 10^4$	1071	±	16	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \mu\nu_\mu) \times 10^4$	1063	±	15	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \tau\nu_\tau) \times 10^4$	1138	±	21	**0.13**	0.15	From WW scan ZH threshold luminosity
$g_Z^{\nu_e}$	1.06	±	0.18	**0.007**	small	From WW threshold

- Many more opportunities:
  - V_{cb}, V_{cs}, etc …
  - Leptonic BRs > 100x better than today

Precision Frontier at the WW threshold and above

- Validate, with full analyses, the expected precision on **W-mass and Width** measurement using **realistic detector simulation**
- Two measurements (and their combination):
  - threshold scan, full study, including backgrounds and systematics
    - (hadronic) background control to be studied
  - explicit determination at 160 and 240 GeV
    - design constrained kinematic fit (for leptonic and hadronic channels)
    - **absolute beam-energy calibration** (better than 2×10^{-7})
      - at 240 measure $\sqrt{s}$ with radiative return Z events at 240 GeV (including Z hadronic decays, plus other processes? rad. WW/ZZ in-situ)
    - Study systematics due to hadronization, NP effects, ISR, at 240 GeV, but at 160 GeV
    - impact of lepton momentum scale calibration?
  - combination of the two approach, with full treatment of correlations

The Flavored Circular Collider

see Stephane Monteil's talk

- Solid (detector requirements) studies exist for selected physics benchmarks
  - b → s transitions (e.g. B → K* **ττ**, K* νν, …) , CKM (B_s → D_s K), **τ** - physics, …
- 2 -year long workshop has been initiated (1st event, last week in CERN):
  - refine understanding of complementarity between FCC reach vs BELLE2/LHCbII
    - rare decays, final states with π^0, neutrinos
  - refine detector requirements on PID, vertexing, and calorimetry (π^0, taus)
- Future work organised in 5 Working Goups:
  - WG1 Rare decays (i.e. FCNCs)
  - WG2 CPV observables
  - WG3 (mostly) CP conserving observables, e.g. charged current semileptonic b-decays, CKM from WW and ttbar, lattice QCD, V_{cb}
  - WG4 Charm: mixing, CPV and rare decays
  - WG5 Tau and selected EW e.g. tau decays, tau production (including polarisation), and Z→qq with exclusive final states In addition,
  - other topics will be pursued outside WG structure, e.g. spectroscopy, absolute BF measurements, hadronization fractions etc., Kaon physics, and may form new WGs in future if reach critical mass.
- If you are looking for a physics topic to work on, read excellent summaries from Guy Wilkinson (Exp) and Zoltan Ligeti (TH)

Higgs

$\delta(\sigma$ x BR)

$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 (*)
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

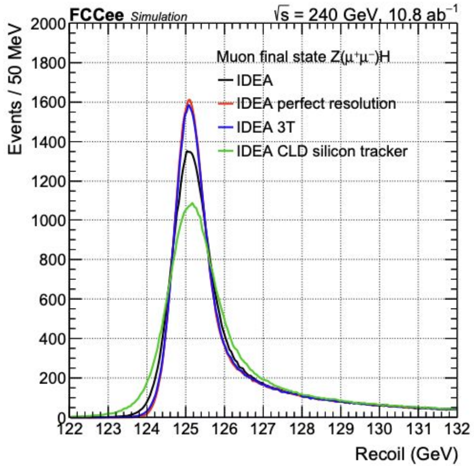
δg

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}

- Permil precision in Higgs gauge couplings (10x vs LHC)
- (sub-)percent precision in fermion couplings (IIIrd gen) (5-50x vs LHC)
  - strange Yukawa in reach (II generation)

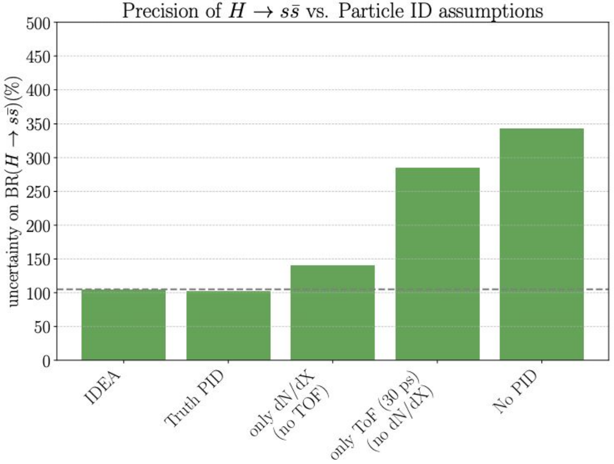
Higgs and Top physics

- Most explored area of the FCC physics program, detector requirements are rather clear
  - excellent track momentum resolution for Higgs mass
  - vertex, PID capabilities for flavor tagging, and excellent hadronic resolution H → bb, cc, ss, gg
- Migrate from fast to full sim (240/365 GeV) and include beam backgrounds
  - systematics less demanding than at Z, WW, but robust systematics & calibrations methods need to be demonstrated
    - √s calibration (Higgs mass, top mass) with rad. return (Z → leptons, hadrons)
      - Only proof of principle, to be assessed with full sim, proper event generators, systematics etc ..
    - flavor tagging calibration
      - How does a calibration at the Z pole extrapolate to ZH threshold (and ttbar threshold)?



	$\sqrt{s}$	E_γ (GeV)	$N_{\mu\mu}$ ($\times 10^6$)	N_{qq} ($\times 10^6$)	$\sigma_{\sqrt{s}}$ ($\mu\mu$)	$\sigma_{\sqrt{s}}$ (qq)	$\sigma_{\sqrt{s}}$ (comb.)	$\sigma_{\sqrt{s}}$ (EPOL)
6 ab^{-1}	m_H	29	107	173	660 keV	280 keV	225 keV	200 keV ?
12 ab^{-1}	$2m_W$	54	47	667	900 keV	340 keV	285 keV	300 keV
5 ab^{-1}	240 GeV	102	5.6	53	4.2 MeV	2.4 MeV	1.7 MeV	–
0.2 ab^{-1}	$2m_{top}$	163	0.1	0.3	51 MeV	60 MeV	26 MeV	–

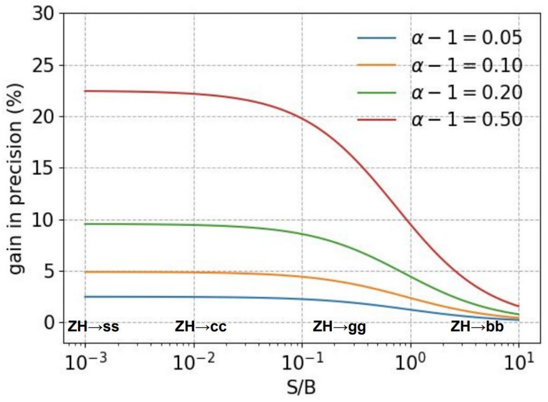
[P. Janot]

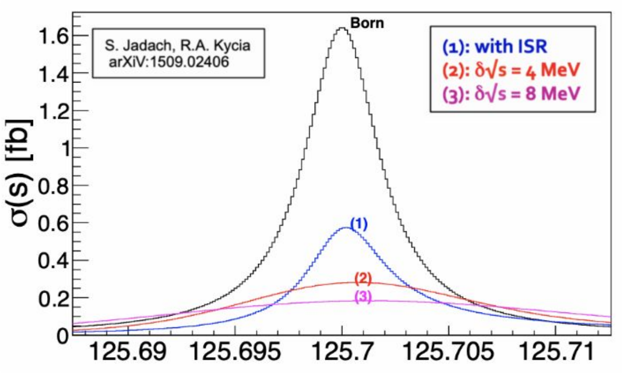


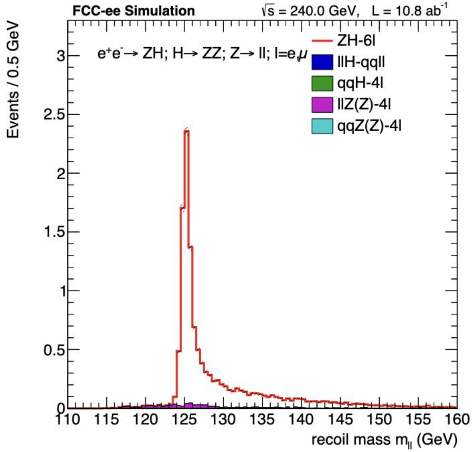
Higgs and Top physics

- Participate in Global Event Reconstruction (PFlow, jet/τ/tagging) to assess potential of various detector concepts to achieve asymptotic performance target
  - Classical PF approach (Pandora) tuning
  - ML-PF approach

- Cover missing channels (HZZ*/HWW* @ 240)
- Electron Yukawa (√s=125 GeV), requires mono-chromatisation implication
  - gluon tagging with NNLL showers
  - missing channels (WW*, ZZ*, ..)
  - study Yukawa precision as a function of the higgs mass (precision)

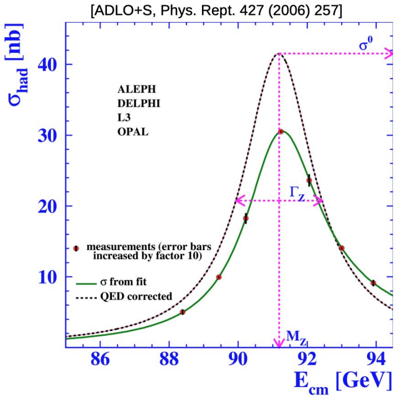






QCD

Z-pole run: Perfect lab to **study QCD** (fragmentation, jet substructure)



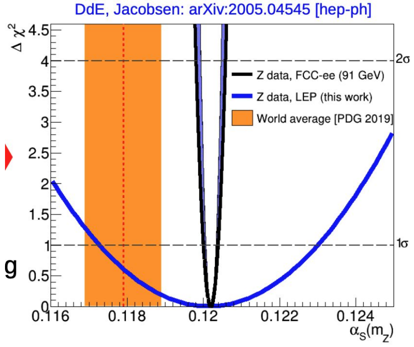
- α_S standard model prediction:

$$R_{W,Z}(Q) = \frac{\Gamma^{had}_{W,Z}(Q)}{\Gamma^{lep}_{W,Z}(Q)} = R^{EW}_{W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{mix} + \delta_{np}\right)$$

  - Known at N3LO QCD, 2-loop EW corrections
  - Experimentally, expected precision on α_S at permil level

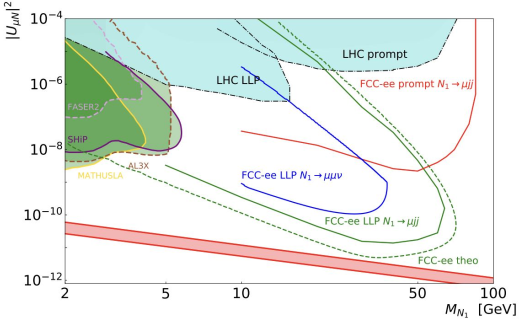
$\alpha_s(m_z) = 0.12030 \pm 0.00028$ (±0.2%)

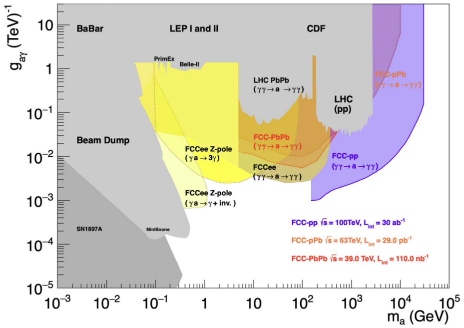
10x improvement



- Non-perturbative modeling: fragmentation/hadronization (in particular strange)
- PID-driven measurements for fragmentation (p/K/π, strange/baryons) → quantify detector PID
- γγ physics and forward e± taggers; $(g-2)_\tau$ via γγ→ττ feasibility
- α_S from event shapes/energy correlators/Lund plane;
- re-evaluation from Z/W/τ widths with latest projections
- PanScales/NNLL shower studies; generator tunes strategy

BSM and FCC-hh

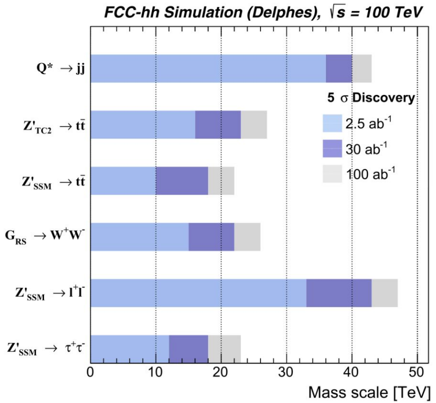




Current benchmarks FCC-ee

- HNLs,
- ALPs,
- dark-sector/shower scenarios

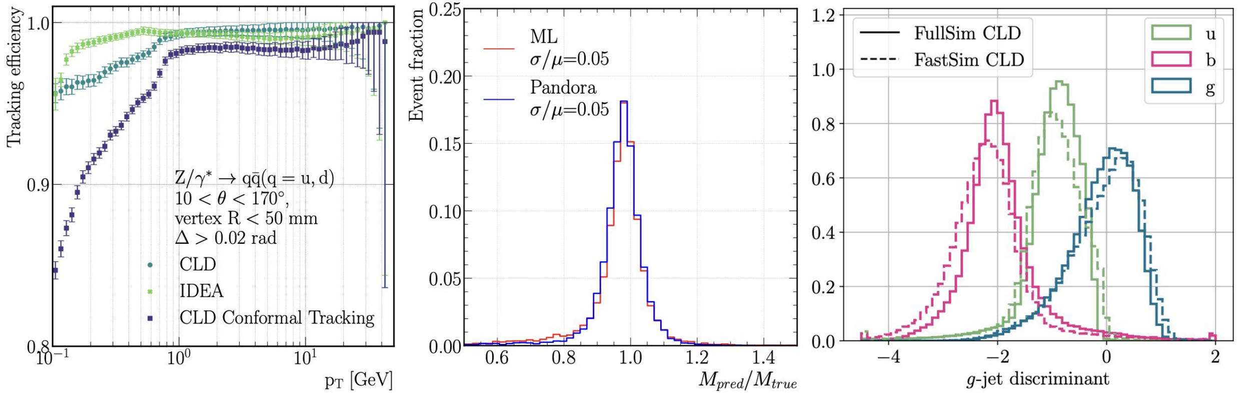
- A lot of the potential has be explored in fast simulation
  - Clear that continuous tracking and high segmentation, timing, helps, but to be quantified systematically for every benchmark
- Backgrounds and detector impact (nuclear interactions, kinks, etcv ..) to be assessed



On the FCC-hh (see also my next talk)

- FCC-ee/hh complementarity in the SMEFT2026 to be fully explored, high-Q² EFT
- Finalise key analyses missing in FSR:
  - HH self-coupling, only bb$\gamma\gamma$, bb$\tau\tau$ studied so far
  - HHH, only bbbb$\tau\tau$ studied so far
  - singlet extensions, more complex models for EWPT
- Pile-up propagation into reconstruction; ultra-boosted tagging performance + calibration

High Level Reconstruction and Montecarlo



- Goal: Deliver analysis-ready chain in full sim: tracking, PFlow, e/μ/γ, jets, flavour/τ for several detector concepts
  - for assessing detector performance (ML-PF/tracking goes in this direction),
    - CLD, IDEA tracking availble
    - CLD ML-PF, Allegro in the working
- Many aspects to be studied:
  - Electron GSF tracking (gas vs silicon) and brem recovery (Crystals vs Imaging)
  - Impact of timing, RICH detector on PFlow performance
  - Detector concept assessment (IDEA, ILD, Grainita?)..

Physics group effort in the pre-TDR phase

PRELIMINARY!

- Unify “Physics Programme” + “Physics Performance” → single “Physics Studies” group
- Mandate:
  - articulate physics case,
  - define requirements,
  - match theory/exp. systematics to statistics
- Physics Physics Update Report (to be produced by summer 2027)
- Physics groups:
  - Electroweak physics
  - Higgs physics
  - Top-quark physics
  - Flavour physics
  - QCD and photon-photon physics
  - BSM physics
  - FCC-hh physics
  - High-level reconstruction (in close collaboration with the Software group)
  - Monte Carlo tools (in close collaboration with the Software group/Precision)
  - Analysis Tools (in close collaboration with the Software group)
  - Precision calculations
  - Global fits and EFT

already exists (Electroweak physics – BSM physics)

informally exists (FCC-hh physics – High-level reconstruction)

new group (Monte Carlo tools – Global fits and EFT)

There will be open calls for the coordination of such groups very soon

Conclusion

- Feasibility Study successfully completed
- Physics projections translated into physics requirements
- Physics groups submitted 5 documents to the ESPPU
  - Higgs, EW, Top/ QCD/ BSM/ Flavor / FCC-hh
- No major show-stopper found

However much work ahead of us, in terms of detector design (R&D) and requirements , both from theory and exp.

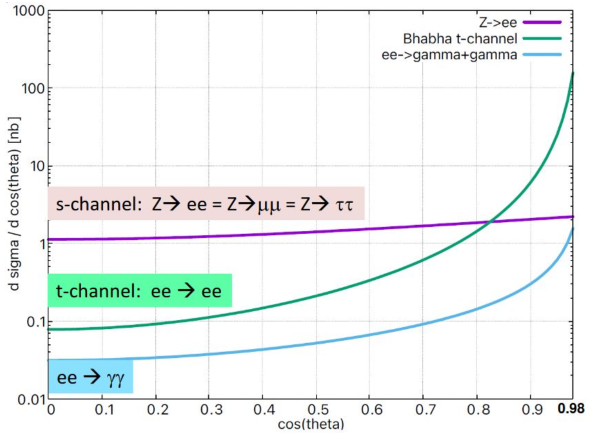
In the pre-TDR phase, physics study groups should focus

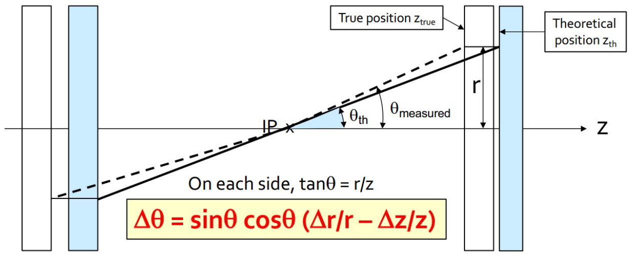
- in consolidating existing studies with more realistic conditions (BIB, full sim)
  - in particular at the Z pole, (EWK precision, FIPs, ..)
- explore and refine physics case
  - flavor (including interplay with EWK)
  - BSM
  - synergy/complementarity with ee/hh

Backup

Luminosity/acceptance

- All **absolute cross-section measurements** rely on precise determination of the **luminosity** uncertainty
  - the ultimate statistical precision
    - 10^{-6} (Z pole) -- 10^{-3} (ZH, top threshold)
- Contrary to pp, can measured in situ via well (very) known processes
  - di-photon : $e^+e^- \rightarrow \gamma\gamma$ ($\delta\sigma_{stat}/\sigma \backsim 10^{-5}$)
    - di-photon: pure QED corrections up to 3-loops
- Theory Challenges:
  - bhabha : $e^+e^- \rightarrow e^+ e^-$ ($\delta\sigma_{TH}/\sigma \backsim 10^{-4}$)
    - large systematics from higher order corrections: low energy vacuum polarisation, EW, QED
- Experimental Challenges:
  - require exquisite **control of acceptance**:
    - detector components positioning to 1-10 μm
    - alignment and monitoring to ensure stability
      - physics μμ, e+e-, γγ events using kinematic from well known **initial state and beam constraints (crossing angle)** will be extremely valuable
      - **full potential to be established!**





Beam energy related challenges for precision

- The statistical precision for precise mass and width determination of Z, W and top is **20-50x better than LHC** (and LEP)
  - e.g **δm_W ~ 200 keV** (reminder: latest CMS δm_W ~ 9.9 MeV)

- Matching such precision requires extraordinary knowledge of beam related parameters

- **Mass** precision determination (m_Z, m_W, m_H, m_t)
  - dominant uncertainty is **absolute knowledge of √s**
    - √s <= $2m_W$ → resonant depolarisation (unique to e+e- colliders)
    - √s > $2m_W$ → monitor using in situ physics events
      - from physics Z(μμ)ɣ events, WW?
        - dominant systematics for m_H,m_t

See Guy Wilkinson

- **Width** precision determination (Γ_Z), dominant systematics can be constrained in situ with μμ pairs
  - **beam energy spread/ relative "point-to-point" √s** uncertainty
    - Impose **tight requirements** on
      - Tracking momentum resolution (single point, B field, material budget)
      - Momentum scale stability (to monitor with B probes or low mass resonances)
      - Optimal analysis techniques still to be developed