



# FCC Physics Studies

Status of the activities and how to contribute

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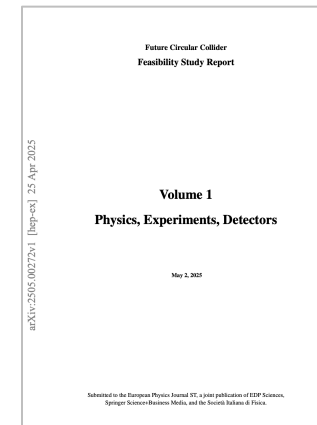
ILD Meeting, 15/09/2026

# Outline

- Status of the FCC project and the Reference Design Phase
  - 2026–2028: the physics case has to be supported by **full-simulation results**
- What is in common with the ILC/ILD studies, and what is different
  - the Higgs factory programme at 240–365 GeV is well known to this community
  - the **Z pole** has been less of a focus: electroweak, QCD and flavour measurements
- Organisation of the Physics Studies work package and activities of the groups
  - 13 physics groups, including a new group on flavour tagging
- How to follow the activities and how to contribute
  - meetings, e-groups, list of possible contributions
- This talk focuses more on the experimental aspects than on the theory ones

# Feasibility Study → Reference Design Phase

- **Feasibility Study completed (started in 2020)**
  - [FCC Feasibility Study Report Vol. 1, \*Physics, Experiments, Detectors\* \(290 pages, April 2025\)](#)
  - Physics Programme: physics case of the integrated programme
  - Physics Performance: case studies → detector requirements, simulation and reconstruction tools, MC production, analysis tools
  - seven documents submitted to the 2026 European Strategy update (links on the right)
- **ESPPU recommendation**
  - A. FCC-ee is the preferred option for the next flagship collider at CERN
  - B. a descoped FCC-ee is the preferred alternative
- **Reference Design Phase, 2026–2028**
  - goal: **answer the possible questions of the CERN Council** before the approval (around 2028)
- **Many aspects go beyond the two years of the RDP**
  - detector optimisation, algorithm design, exploration of the broader physics case, theory calculations, control of the systematics: **this takes more than 2 years**
  - these are complex topics, the goal is to **do things properly** and not in a rush

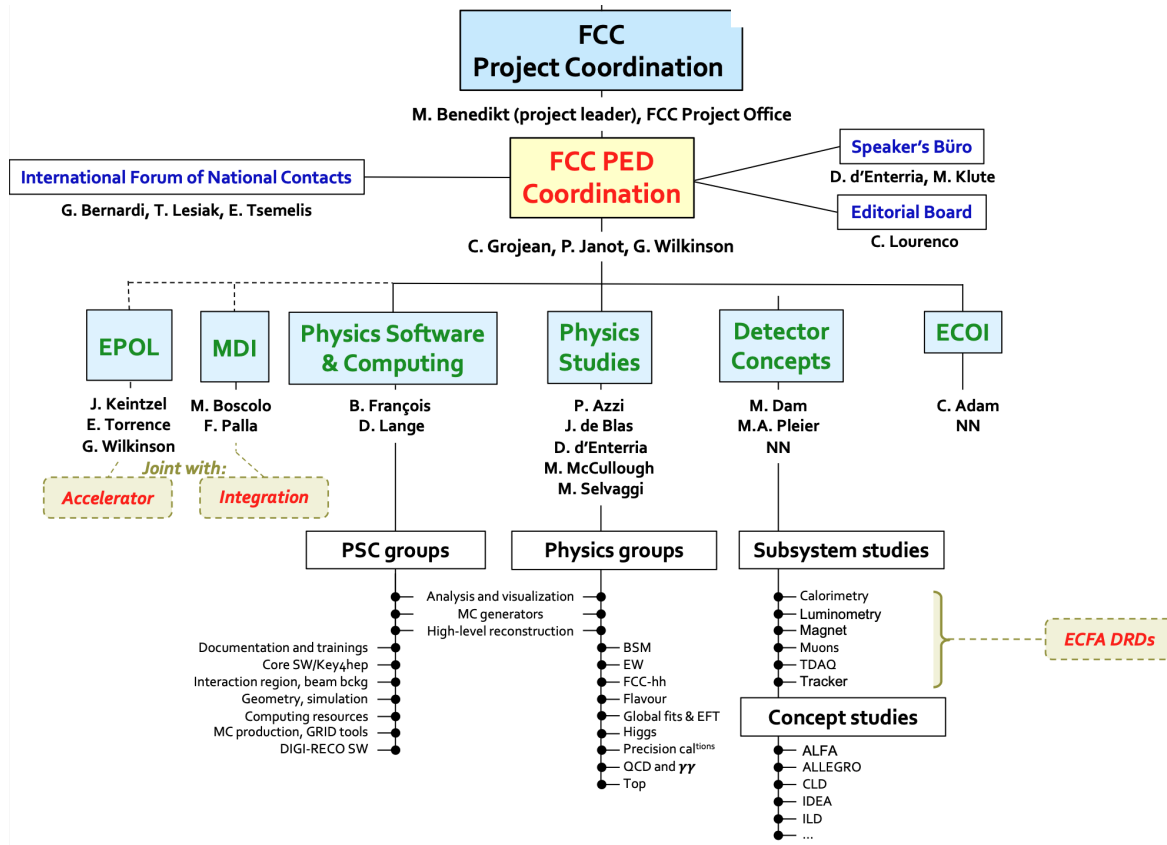


[arXiv:2505.00272, EPJ C 85 \(2025\) 1468](#)

ESPPU submissions (10 pages each):

[FCC Manifesto](#)  
[EW, Higgs, top](#)  
[BSM](#)  
[QCD](#)  
[Flavour](#)  
[FCC-hh](#)  
[Detector Folds](#)

# Organisation of the PED pillar



- **Physics, Experiments and Detectors**

- 6 work packages, coordination:
- C. Grojean, P. Janot, G. Wilkinson

- **Physics Studies**

- P. Azzi, D. d'Enterria, M. Selvaggi (exp.)
- J. de Blas, M. McCullough (th.)
- 13 groups (3 in common with Software & Computing), including the new flavour tagging group

- **Detector Concepts**

- M. Dam, M.A. Pleier
- ALFA, ALLEGRO, CLD, IDEA, ILD, AGORA
- the physics groups provide the requirements to the detector concepts, and the requirements for the theory calculations

# Mandate of the Physics Studies work package

- **Physics Programme and Physics Performance merged in one work package**
  - theorists and experimentalists in the same groups, with common deliverables
- **Main tasks**
  - articulate the physics case, feasibility and schedule implications of the different stages, not only the ones currently proposed
  - involve the theory community on the theoretical challenges, and on the tools needed to interpret the measurements
  - **match the experimental and theoretical uncertainties** to the projected statistical precision
- **Provides the physics requirements to the other work packages**
  - Detector Concepts, Software & Computing, MDI, EPOL
- **Deliverables in this phase**
  - list of key physics topics per group, each with a contact person
  - typically one workshop per group per year, with dedicated schools

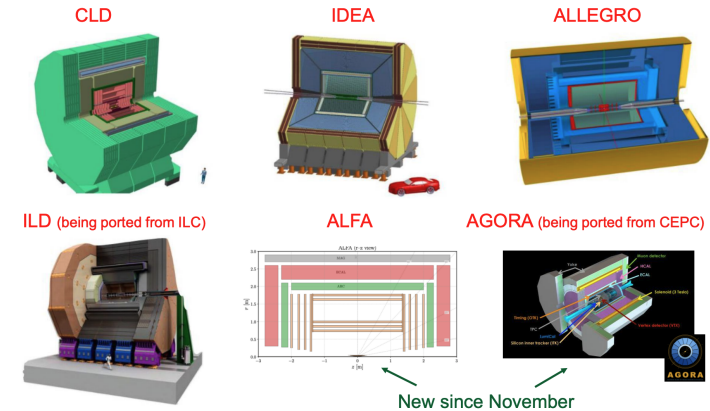
# FCC-ee run plan

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

- 4 interaction points, about 15 years of running,  $\sqrt{s}$  from 88 to 365 GeV
  - $6 \times 10^{12} \text{ Z}$ ,  $2.4 \times 10^8 \text{ WW}$ ,  $2.2 \times 10^6 \text{ ZH}$ ,  $2 \times 10^6 t\bar{t}$
  - the Z-pole run corresponds to  **$3.5 \times 10^5$  times the LEP statistics**

# What is in common with the ILC/ILD studies

- The Higgs factory programme has been studied in detail by the LC community
  - recoil method: model-independent  $\sigma(\text{ZH})$ ,  $m_{\text{H}}$ , Higgs width
  - particle flow (Pandora), jet energy resolution
  - vertexing and flavour tagging,  $\tau$  reconstruction, kinematic fits
  - full simulation, and the software is already common (iLCSoft  $\rightarrow$  Key4hep/EDM4hep)
- ILD is one of the six FCC-ee detector concepts, with some differences
  - **beam backgrounds, detector electronics** (no power pulsing), **3.5 T vs 2 T**
  - the physics is in principle unaffected to first order, but this has to be studied further
- The requirements at 240–365 GeV are the **best understood** part of the programme
  - **repeat the key studies in full simulation**, with beam backgrounds
  - the running conditions at the Z pole are different (continuous beams, no power pulsing, 2 T, smaller  $L^*$ )



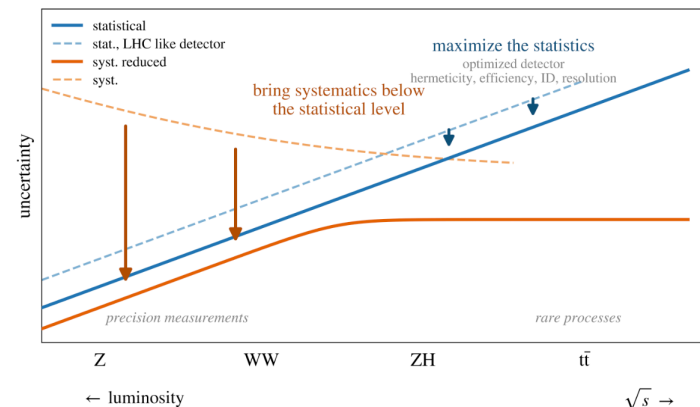
# Systematic uncertainties at the Z pole

- The statistical uncertainties are small, the precision is **limited by the systematics**

- **beam energy:** absolute and point-to-point  $\sqrt{s}$  (resonant depolarisation,  $10^{-6}$ )
- acceptance and absolute luminosity:  $10^{-4}$  with small-angle Bhabha (LumiCal position known to  $\delta R_{\min} = 1 \mu\text{m}$  and  $\delta z = 100 \mu\text{m}$ ),  $10^{-5}$  with  $e^+e^- \rightarrow \gamma\gamma$  (ECAL acceptance and alignment at a similar level)
- momentum scale and resolution ( $\Gamma_Z$ ), alignment
- flavour tagging efficiency and mistag rate, calibrated on data
- hadronisation and higher-order calculations

- Each of these needs a **dedicated ancillary analysis**

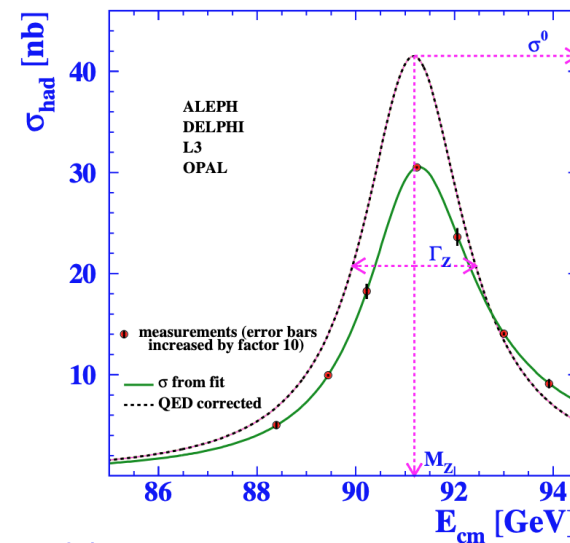
- a measurement whose purpose is to control the systematics of another measurement
- most of them do not exist yet: they have to be developed and demonstrated in full simulation



at the Z and WW the systematics have to be reduced below the statistical level, at ZH and  $t\bar{t}$  the statistics has to be maximised

# Electroweak measurements at the Z pole

- The SM predicts all electroweak observables from three inputs ( $\alpha$ ,  $G_F$ ,  $m_Z$ ), the fit is over-constrained
  - $m_Z$ ,  $\Gamma_Z$ ,  $\sin^2\theta_{\text{eff}}$ ,  $R_t$ ,  $m_W$ ,  $m_{\text{top}}$ ,  $m_H$  measured independently
- Expected precision at FCC-ee, from the line shape and the asymmetries
  - $m_Z$ ,  $\Gamma_Z$ : 4 keV statistical (today  $\pm 2$  and  $\pm 2.3$  MeV)
  - $\sin^2\theta_W^{\text{eff}}$ :  $1.2 \times 10^{-6}$ ,  $R_t^Z$ :  $5 \times 10^{-5}$ ,  $N_\nu$ :  $9 \times 10^{-5}$
  - $\alpha_{\text{QED}}(m_Z)$  measured directly: from  $A_{\text{FB}}^{\mu\mu}$  off peak, from the  $e^+/e^-$  ratio in the forward region, or from the  $e^-/\mu^-$  ratio, today  $\delta\alpha/\alpha = 1.1 \times 10^{-4}$  is the dominant parametric uncertainty
- Already turned into detector requirements
  - $m_Z$ ,  $\Gamma_Z$ : momentum resolution and scale, angular resolution for the beam energy spread
  - $R_t$ : lepton acceptance and identification efficiency
- Still to be done properly
  - $\alpha_{\text{QED}}$ : charge sign flip and material control for the  $e^+/e^-$  mis-identification, mock-up fit of the line shape, ...
- The mitigation of the systematics can be translated into **detector or machine requirements**



Z line shape at LEP:  $m_Z$ ,  $\Gamma_Z$ ,  $\sigma_{\text{had}}^0$

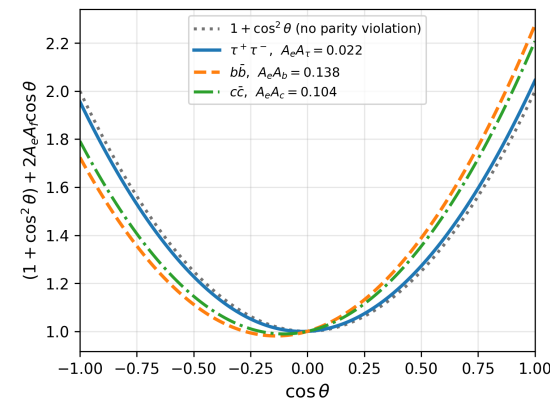
# From the expected precision to the detector requirements

- Part of the expected precision has **already been translated into requirements** (FSR, Table 14)
  - a few examples below, the same exercise is still to be done for many other measurements

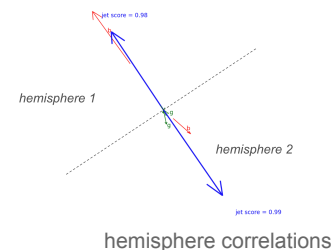
| Measurement                                   | Precision                                                                                                                 | Requirement                                                                                                                                                                                                                                                        |
|-----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Luminosity, small-angle Bhabha                | $10^{-4}$                                                                                                                 | LumiCal acceptance 50–100 mrad, position known to $\delta R_{\min} = 1 \mu\text{m}$ and $\delta z = 100 \mu\text{m}$                                                                                                                                               |
| Luminosity, $e^+e^- \rightarrow \gamma\gamma$ | $10^{-5}$                                                                                                                 | ECAL acceptance down to 100 mrad without gaps, ECAL alignment $\delta z = 100 \mu\text{m}$ , $\delta R_{\min} = 10 \mu\text{m}$ at $\theta = 20^\circ$                                                                                                             |
| $R_\ell = \Gamma_{\text{had}}/\Gamma_\ell$    | $\delta R_\ell = 5 \times 10^{-5}$<br>(today $2.5 \times 10^{-2}$ )                                                       | lepton acceptance and identification efficiency controlled at the same level, from $10^{11}$ lepton pairs                                                                                                                                                          |
| $\Gamma_Z$                                    | 4 keV stat.                                                                                                               | $\sigma_p/p < 0.1\%$ for 50 GeV tracks (0.2% conservative) $\rightarrow \delta\Gamma_Z = 15 \text{ keV}$ , beam energy spread from the acollinearity of $\mu\mu$ pairs: $\sigma_\theta < 0.1 \text{ mrad} \rightarrow \delta\Gamma_Z(\text{BES}) < 10 \text{ keV}$ |
| $\tau$ polarisation                           | $0.07 \times 10^{-4}$ on $A_{\text{FB}}^{\text{pol},\tau}$                                                                | ECAL granularity $2 \times 2 \text{ mm}^2$ ( $5 \times 5$ conservative) for $\pi^0$ from boosted $\tau$ , $\tau$ decay classification                                                                                                                              |
| $A_{\text{FB}}^b$                             | $0.04 \times 10^{-4}$                                                                                                     | jet charge, tagging calibration, vertex resolution, knowledge of the material budget                                                                                                                                                                               |
| $a_{\text{QED}}(m_Z)$                         | $\delta\alpha/\alpha = 3 \times 10^{-5}$ ( $A_{\text{FB}}^{\mu\mu}$ )<br>$0.6 \times 10^{-5}$ ( $e^+/e^-$ , $e^-/\mu^-$ ) | $e^\pm$ efficiency and charge identification, material budget (bremsstrahlung), $e/\mu$ relative acceptance                                                                                                                                                        |
| $m_W$ , threshold scan                        | 0.18 MeV stat.                                                                                                            | $\sqrt{s}$ at the $10^{-6}$ level (resonant depolarisation), control of the hadronic background                                                                                                                                                                    |

# Heavy flavour electroweak observables

- $R_q = \Gamma_q / \Gamma_{\text{had}}$  measures the chiral couplings of the Z to the quarks
  - $A_{\text{FB}}^b$  gives the most precise determination of  $\sin^2\theta_W$
  - today  $\sim 10^{-3}$  relative, FCC-ee projections **2 (b) – 10 (s)  $\times 10^{-6}$**
- Improvements with respect to LEP
  - smaller beam spot, lighter beam pipe, vertex resolution of a few  $\mu\text{m}$
  - particle identification for strange tagging:  $K^\pm$  identified up to 30–40 GeV
  - modern taggers, with high purity for b, c and s jets,  **$R_s$  and  $A_{\text{FB}}^s$**  become measurable
- Dominant systematics
  - flavour tagging efficiency and mistag calibration for b and c
  - hemisphere correlations from QCD (gluon emission,  $g \rightarrow b\bar{b}/c\bar{c}$ ), measurable in data with  $10^9$  gluon splitting events
- $R_q$  and  $A_{\text{FB}}^q$  for  $q = b, c, s$ : specific work needed
  - design of the **jet charge tagging**, demonstration of the **self-calibration in data**, systematics possibly related to the knowledge of the material budget (can be tracked and measured with conversion? )
  - **going towards  $10^{-6}$ , do we meet new systematics?** in that case, design mitigation strategies: constrain them in situ, or translate them into detector requirements

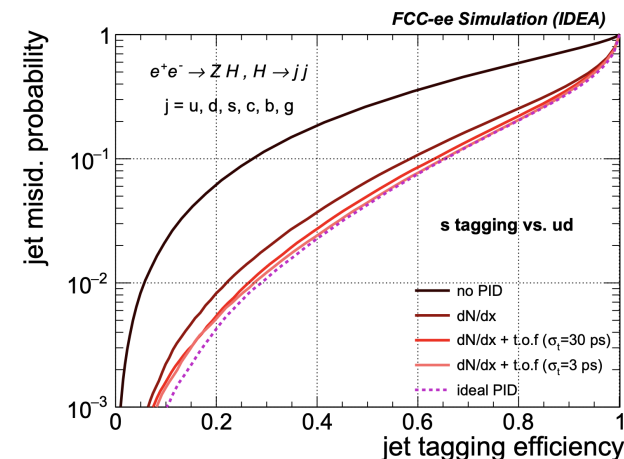


angular distribution  $(1 + \cos^2\theta) + 2 A_e A_f \cos \theta$   
for  $\tau$ , c and b: the asymmetries are small, 2–14%



# QCD at the Z pole

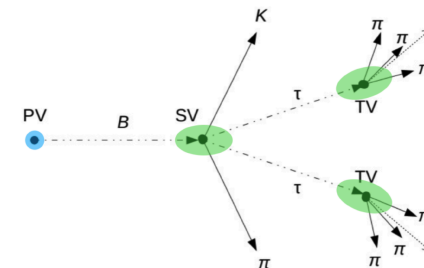
- $\alpha_s$  at the per-mille level, about ten times better than today
  - from the combined fit of  $R_{\ell}^Z$ ,  $\Gamma_Z$ ,  $\sigma_{\text{had}}^0$ : N<sup>3</sup>LO QCD + 2-loop EW
  - other extractions: event shapes, energy correlators, Lund plane, W and  $\tau$  hadronic widths
- Non-perturbative modelling becomes a limiting systematic
  - fragmentation and hadronisation, in particular for strange quarks
  - p/K/ $\pi$  spectra and baryon production **define the PID requirement**
  - colour reconnection, parton shower accuracy (PanScales/NNLL), tuning strategy
- Other topics
  - jet substructure, quark/gluon separation, dead cone,  $\gamma\gamma$  physics
- Hadronisation uncertainties enter in many measurements:  $R_b$ ,  $m_W$ ,  $m_{\text{top}}$ , Higgs couplings



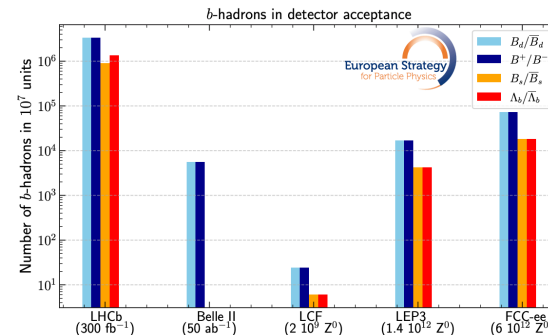
strange tagging vs ud jets: no PID, dN/dx, dN/dx + ToF, ideal PID.  
The mistag rate changes by an order of magnitude with the PID option.

# Flavour physics at the Z pole

- $6 \times 10^{12} Z \rightarrow 15\% b\bar{b}, 12\% c\bar{c}, 3.4\% \tau^+\tau^-$ 
  - $\sim 10^{12}$  b hadrons,  $\sim 10^{12}$  charm hadrons,  $2 \times 10^{11}$   $\tau$  pairs, produced with a large boost
- Specific features of the Z pole
  - all b hadron species:  $B^0, B^+, B_s, B_c, \Lambda_b$ , the b baryons are polarised
  - **large boost** ( $\langle \beta \gamma \rangle \sim 25$  for  $\tau$ ): **topological reconstruction of decays with missing energy**, e.g.  $B^0 \rightarrow K^* \tau^+ \tau^-$ ,  $b \rightarrow s \nu \bar{\nu}$ ,  $B_c \rightarrow \tau \nu$ ,  $B \rightarrow$  invisible
  - low multiplicity and back-to-back production, hermetic detector, efficient for soft tracks: multi-body final states with  $\pi^0$  and  $\gamma$
  - initial-state flavour tagging
- $5 \times 10^8 W$  and  $2 \times 10^6 t\bar{t}$ : CKM elements from on-shell decays
  - $|V_{cb}|$  at  $\sim 0.1\%$  statistical from  $W \rightarrow c\bar{b}$ , 20 times better than today
- Fewer b hadrons than LHCb Upgrade II, but a complementary environment



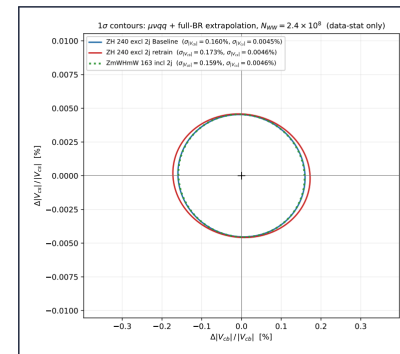
$B \rightarrow K^* \tau^+ \tau^-$ : primary, secondary and tertiary vertices



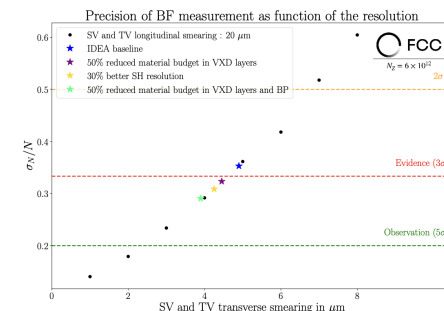
b hadrons in the detector acceptance, by species  
[G. Wilkinson, FCC Week, June 2026]

# Flavours@FCC and open detector questions

- **Two-year workshop series, started in November 2025**
  - five working groups: rare decays, CP violation, charged currents and QCD (CKM from semileptonic b decays and from WW), charm,  $\tau$  and selected electroweak
  - [workshop page, November 2025](#)
  - [workshop page, June 2026](#)
- $|V_{cb}|, |V_{cs}|$  from W decays
  - studies exist in fast simulation (plot), the work to be done is on the **calibration of the tagging**, e.g. with radiative-return Z events, in common with Higgs, EW and top
- **Detector requirements for flavour: partially defined**
  - **ECAL energy and angular resolution**: crucial for the  $\pi^0/\gamma$  discrimination and for the  $\pi^0$  energy resolution ( $\tau$  decays, flavour decays with  $\pi^0$ )
  - **$\pi/K$  separation** (cluster counting or RICH, with time of flight), **best possible vertex resolution** (plot)
- **Open questions**
  - is low-momentum PID needed, and can time of flight provide it?
  - is the identification of pions against all other particles needed, or only the  $\pi/K$  separation?
  - muon identification at low momentum ( $p < 1$  GeV, e.g.  $B_s \rightarrow \nu\bar{\nu}$ ,  $K_S \rightarrow \mu\mu$ ): a CALICE-type calorimeter as in ILD can certainly do it, to be quantified as a function of momentum



$|V_{cb}|, |V_{cs}|$  from W decays:  $1\sigma$  contours, statistics only



$B \rightarrow K^*\tau\tau$ : precision vs vertex resolution

# Feebly interacting and long-lived particles

- Heavy neutral leptons

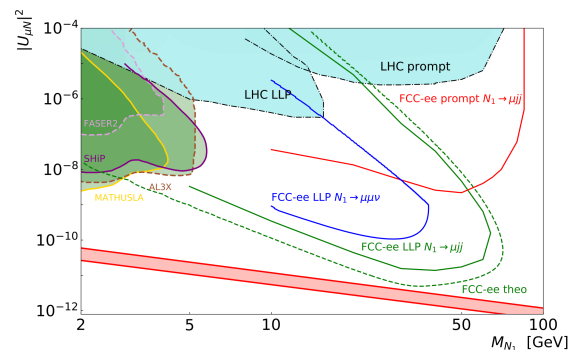
- sensitivity in  $|U|^2$  down to  $10^{-11}$  for masses between 10 and 80 GeV, with prompt and displaced vertices ( $N \rightarrow \mu jj, \mu \mu \nu$ )

- Axion-like particles

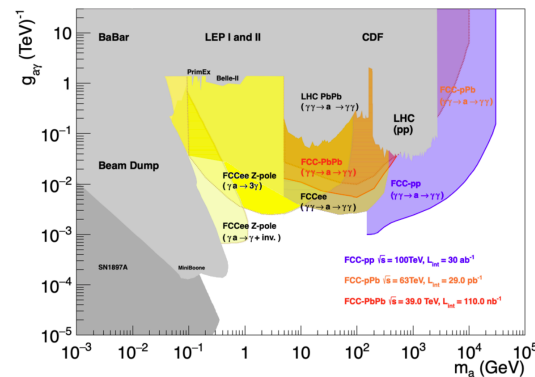
- $Z \rightarrow \gamma a$ , with  $a \rightarrow \gamma \gamma$  or  $a \rightarrow$  invisible: region not covered by LEP and beam dumps, the sensitivity depends on the separation of close photons in the ECAL

- Detector aspects

- continuous tracking** for displaced vertices, timing, low material, hadronic energy resolution, the studies have to be done **with beam backgrounds, cosmics** and the other sources of fake displaced vertices, most of them are still in fast simulation
  - DAQ**: triggerless readout at 100–200 kHz, the efficiency for exotic signatures (displaced, delayed, out of time) has to be verified



HNL:  $|U_{\mu N}|^2$  vs mass



ALP:  $g_{a\gamma}$  vs mass

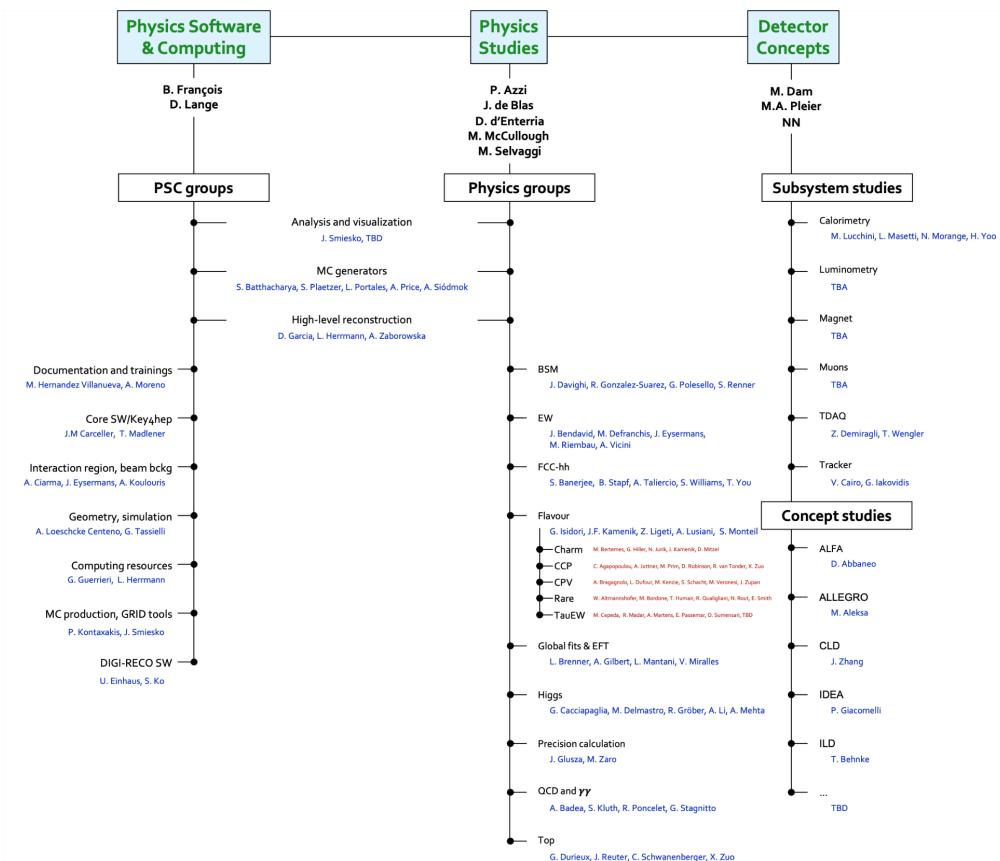
# Higgs and top: the role of full simulation

- The Higgs and top programme is well established, mostly with fast simulation
  - the next step is to **repeat the key measurements in full simulation**, with beam backgrounds
- ILD detector simulation: the tools are in place, ILD is in a good position for this
  - impact of the **beam backgrounds on the jet energy resolution**
  - impact of **2 T vs 3 (3.5) T on the hadronic performance**: the jets are less opened up, but fewer low-energy particles are lost in the beam pipe and in the interactions with the MDI
  - **acceptance and missing momentum** (100–150 mrad cone, MDI)
  - consequences on the **total ZH cross section**, the **Higgs hadronic couplings** ( $H \rightarrow b\bar{b}$ ,  $c\bar{c}$ ,  $s\bar{s}$ ,  $gg$ ),  **$H \rightarrow$  invisible**, and on the top mass
  - this is where the ILD expertise is very valuable: these full-simulation studies can be started right away with the existing ILD reconstruction

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

relative precision (%) on  $\sigma \times \text{BR}$ , from the ESPPU submission

# Physics groups



## Physics groups

- Electroweak, Higgs, Top, Flavour
- QCD and  $\gamma\gamma$ , BSM, FCC-hh
- Global fits and EFT, Precision calculations

## In common with Software & Computing

- High-level reconstruction
- Monte Carlo generators
- Analysis and visualisation tools

## New: Flavour Tagging

- algorithms and calibration techniques

## Conveners

- at least one experimentalist and one theorist per group
- Flavour has in addition 5 sub-groups

# Activities of the groups (1)

## Electroweak

- confirm the current estimates with full analyses in full simulation, and with LEP data
- $\alpha_{\text{QED}}(m_Z)$  from  $A_{\text{FB}}^{\mu\mu}$  and from  $R_e/R_\mu$ , Z line-shape scan
- $m_W$ : threshold scan and direct reconstruction at 160/240 GeV
- **in-situ alignment, luminosity and object calibration**

## Top

- full simulation for the threshold scan and for  $m_{\text{top}}$  from decays at 365 GeV
- **effect of beam backgrounds** on tracking, jets, flavour tagging, missing energy
- $|V_{ts}|$  from  $t \rightarrow Ws$ , FCNC, top SMEFT,  $t\bar{t}$  spin entanglement, toponium

## Higgs

- **repeat the key studies in full simulation**, with beam-induced backgrounds
- **impact of the jet energy resolution on the Higgs couplings**
- missing channels at 365 GeV,  $H \rightarrow WW^*/ZZ^*$  at 240 GeV, rare production ( $e^+e^- \rightarrow H$  at 125 GeV,  $\gamma H$ )
- contribute to the global event reconstruction together with High-Level Reco

## QCD and $\gamma\gamma$

- non-perturbative modelling: fragmentation and hadronisation, re-analysis of LEP data
- quantify the PID performance needed for strange-quark fragmentation
- $\alpha_s$  from event shapes, energy correlators, Lund plane,  $\gamma$  structure function
- $\gamma\gamma$  collisions and forward  $e^\pm$  taggers

# Activities of the groups (2)

## Flavour (5 sub-groups)

- define what FCC-ee adds with respect to Belle II and HL-LHC/LHCb
- rare decays, final states with  $\pi^0$  and  $\nu$ , CKM angles, charm,  $\tau$  properties and LFV
- **detector requirements for flavour**: PID, vertexing and calorimetry

## Global fits and EFT, Precision calculations

- common SM/EFT interpretation across all groups, with common assumptions and correlations
- dim-6 fits with NLO RGEs, unitarity bounds, FCC-hh processes at NLO QCD
- theory wish-list:  $m_W$  at N<sup>3</sup>LO,  $ee \rightarrow ZH$  at NNLO, EWPO at 3 loops, electron PDF at N<sup>3</sup>LO,  $\Delta\alpha_{\text{QED}}$  from the lattice

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## BSM

- HNL, ALPs, dark photons, dark showers, LLPs, mostly still in fast simulation
- **design of dedicated reconstruction for exotic objects in full simulation**: displaced vertices, non-pointing photons, vertex timing, standalone muons
- far-forward and far-away detectors for long-lived particles

## Monte Carlo, Analysis tools, FCC-hh

- **integration and validation of the generators** in Key4hep/FCCSW, MC accuracy at the FCC-ee precision
- FCCAnalyses: analysis file format, ML integration, vertex and kinematic fitting, statistics and visualisation tools
- FCC-hh: pile-up, boosted tagging, HH and HHH, ee/hh complementarity

# Electroweak precision: work list

- **Z line shape and asymmetries**

- $m_Z, \Gamma_Z$ : beam energy calibration, beam energy spread from the  $\mu\mu$  acollinearity, momentum scale stability
- $A_{FB}^{\mu\mu}$ : acceptance and charge measurement,  $\alpha_{QED}(m_Z)$  off peak,  $R_e/R_\mu$
- $R_\ell$ : lepton acceptance and identification,  $N_\nu$  from radiative return

- **Heavy flavour and  $\tau$**

- $R_b, R_c, A_{FB}^{b,c}$ : jet charge, tagging calibration, hemisphere correlations, material budget
- $\tau$  polarisation:  $\pi^0$  and  $\gamma$  reconstruction in the ECAL, classification of the  $\tau$  decays

- **WW threshold and luminosity**

- $m_W, \Gamma_W$ : threshold scan, direct reconstruction,  $\sqrt{s}$  at 240 GeV from radiative-return Z events
- luminosity: Bhabha and  $\gamma\gamma$ , LumiCal alignment, 100 mrad acceptance

- **Simulation**

- $10^{12}$  events cannot be produced in full simulation
- **the calibration methods can be demonstrated on a pilot sample with limited statistics, 10–100 times LEP ( $10^9$ – $10^{10}$  Z), and the systematics extrapolated**

[Full list of the proposed contributions, for all groups: PED in-kind contributions document](#)

# High-Level Reconstruction group

- **Mandate: reconstruction chain in full simulation, ready for analysis**

- tracking, particle flow,  $e/\mu/\gamma$ , jets,  $\tau$ , for all the detector concepts, integrated in Key4hep/FCCSW, with alignment, calibration and beam backgrounds

- **Status**

- tracking: CLD and IDEA available, ALLEGRO in progress, ACTS being integrated
- particle flow: ML-PF for CLD available, Pandora to be integrated for the other concepts, end-to-end ML particle flow and hit-level particle flow (HitPF) in development

- **High-level objects**

- the ILD community has already worked on high-level objects, full-simulation analyses have progressed over the years
- however, some things do not translate directly: beam spot constraints, V0 reconstruction, secondary vertex algorithms, at least those available in the standard CLD configuration are largely unoptimised
- a lot of effort is needed, and it should be done **with the physics case and the other physics groups in mind**

- **Open topics**

- electron tracking (GSF) and bremsstrahlung recovery
- effect of timing, and of a RICH, on the particle flow
- V0 and kink finders, displaced tracks,  $\tau$  reconstruction
- ML tracking with beam backgrounds
- magnetic field above 2 T and corresponding tracker choice
- how critical is the 100 mrad acceptance: how much physics is lost going to 150 mrad?

# Flavour Tagging group (new)

## • Motivation

- jet flavour tagging (b, c, s, g,  $\tau$ ) is used in a large part of the programme: Higgs ( $H \rightarrow b\bar{b}/c\bar{c}/s\bar{s}/gg$ ), EW ( $R_b$ ,  $R_c$ ,  $R_s$ ,  $A_{FB}$ ), flavour ( $|V_{cb}|$ ,  $|V_{cs}|$  from W), top ( $|V_{ts}|$ ), BSM
- until now developed inside each analysis

## • Modern developments

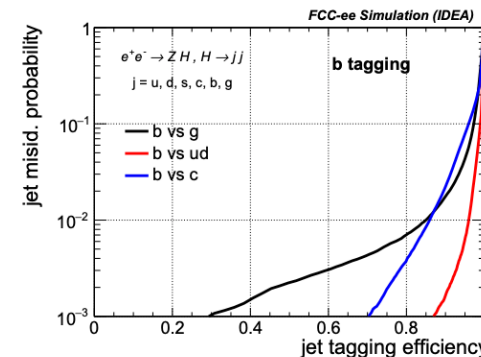
- ML taggers (ParticleNet, transformers) using the full information of the jet constituents, with PID and secondary vertices, go much beyond what was done at LEP: mistag rates at the  $10^{-3}$ – $10^{-4}$  level, strange tagging

## • Two activities

- algorithms: taggers in full simulation, from particle-flow objects and from hits, strange tagging with PID, dependence on jet energy and on beam backgrounds
- calibration: methods to measure efficiency and mistag rate in data, the calibration with Z events and the extrapolation to higher energies should be studied in detail

## • Objectives

- demonstrate that a calibration done with Z events can be extrapolated to 240 and 365 GeV**
- integration and validation of the taggers in full simulation with the physics analyses** (Higgs, EW, top)



b tagging in full simulation (IDEA,  $ZH \rightarrow jj$ ):  
mistag rate at the  $10^{-3}$  level

the group is being set up: to join, or to propose yourself as convener, write to [FCC-PED-Physics-admin@cern.ch](mailto:FCC-PED-Physics-admin@cern.ch)

# LEP data in EDM4hep

- **ALEPH data converted to EDM4hep / Key4hep**

- 1994 run: 9.3 M events,  $\sim 58 \text{ pb}^{-1}$ ,  $\sim 1 \text{ M}$  selected  $Z \rightarrow q\bar{q}$ , same event data model as the FCC-ee full simulation, other years and DELPHI/OPAL are foreseen

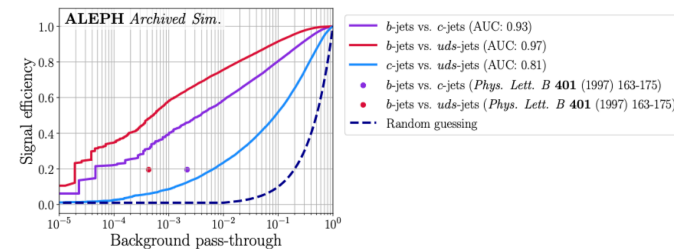
- **Motivation**

- opportunity to study the **calibration and the data/MC differences in real conditions**, these are the skills needed for the Tera-Z
  - example: the stored primary vertex was not usable, it had to be refitted, with a beam spot fitted per run

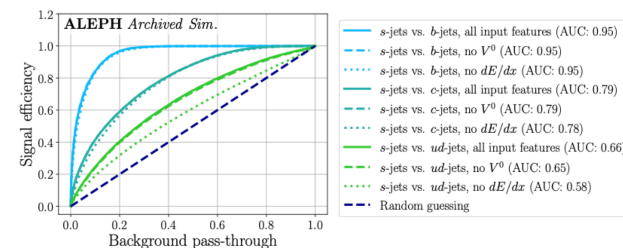
- **Results and ongoing work**

- transformer-based jet flavour tagging on ALEPH data: mistag rate up to 10 times better than the original ALEPH algorithms, first ML strange-jet tagger trained and calibrated on LEP data
- tagger scores calibrated on data with a tag-and-probe method (hemisphere correlations not yet included)
- $dE/dx$  calibration with ALEPH data: in progress, the  $dE/dx$  mismodelling is the main cause of the data/MC difference in the strange score

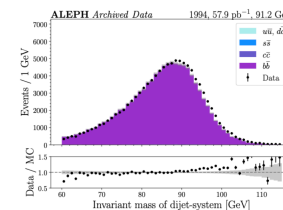
- **Good entry point for students: develop the method on ALEPH data, apply it to FCC-ee simulation**



b and c tagging vs the original ALEPH taggers (points)



strange tagging, with and without  $V^0$  and  $dE/dx$



$m_{jj}$  in  $b\bar{b}$ -enriched events, data vs MC

# Meetings

- **Indico categories**

- each group organises its own meetings, in its Indico category
- [FCC PED Physics Group meetings](#)
- [High-Level Reconstruction, MC and Analysis tools: under Software & Computing](#)

- **Upcoming workshops**

- [22 September: FCC-hh workshop](#)
- [23–25 September: BSM workshop](#)
- [26–29 October: Reconstruction workshop](#)
- no separate Physics Workshop in January 2027: merged with the FCC Week in Madrid
- Flavours@FCC, schools, typically one workshop per group per year

FCC PED Physics Group meetings

|                                |           |   |
|--------------------------------|-----------|---|
| Electroweak physics            | 19 events | ⇒ |
| Higgs physics                  | 65 events | ⇒ |
| Top-quark physics              | 1 event   | ⇒ |
| Flavour physics at FCC         | 24 events | ⇒ |
| QCD and $\gamma\gamma$ physics | 13 events | ⇒ |
| BSM physics                    | 71 events | ⇒ |
| FCC-hh                         | 42 events | ⇒ |
| Global Fits                    | empty     | ⇒ |
| Monte Carlo Event Generators   | empty     | ⇒ |
| Precision Calculations         | empty     | ⇒ |

FCC PED Physics Group meetings (Indico)

# E-groups

- > **FCC-PED-Physics**   
  - FCC-PED-PhysicsCoordinationGroup   
  - FCC-PED-PhysicsGroup-BSM   
  - FCC-PED-PhysicsGroup-EWPrecision   
  - FCC-PED-PhysicsGroup-Flavours   
    - FCC-PED-PhysicsGroup-Flavours-Coordination   
    - FCC-PED-PhysicsGroup-Flavours-CPC   
    - FCC-PED-PhysicsGroup-Flavours-Charm   
    - FCC-PED-PhysicsGroup-Flavours-CPV   
    - FCC-PED-PhysicsGroup-Flavours-Rare   
    - FCC-PED-PhysicsGroup-Flavours-TauEW   
  - FCC-PED-PhysicsGroup-GlobalFits   
  - FCC-PED-PhysicsGroup-hh   
  - FCC-PED-PhysicsGroup-Higgs   
  - FCC-PED-PhysicsGroup-HighLevelReco   
  - FCC-PED-PhysicsGroup-MCgenerators   
  - FCC-PED-PhysicsGroup-PrecisionCalculations   
  - FCC-PED-PhysicsGroup-QCD   
  - FCC-PED-PhysicsGroup-Top   
- > **FCC-PED-SoftwareAndComputing**   

## • Subscription

- [gms.web.cern.ch/group/<NAME>](https://gms.web.cern.ch/group/<NAME>)
- (the older [e-groups.cern.ch](https://e-groups.cern.ch) subscription link also works)
- use your institutional address, the conveners approve the requests

## • General lists

- FCC-PED-Physics
- FCC-PED-PhysicsCoordinationGroup

## • Per group: FCC-PED-PhysicsGroup-...

- EWPrecision, Higgs, Top, QCD, BSM, hh
- HighLevelReco, MCgenerators
- PrecisionCalculations, GlobalFits
- Flavours (+ Rare, CPV, CPC, Charm, TauEW)

## • Contacts

- [FCC-PED-Physics-admin@cern.ch](mailto:FCC-PED-Physics-admin@cern.ch): coordination
- [FCC-PED-Physics@cern.ch](mailto:FCC-PED-Physics@cern.ch): all conveners

# Summary

- **Higgs and top programme**

- physics and requirements are to first approximation **similar to the ILC ones**, and have been **extensively demonstrated**
- this physics is useful to benchmark the detector and reconstruction performance, and should be used to improve both

- **Z pole and WW threshold**

- integral part of the FCC-ee physics programme, with unprecedented statistics for electroweak physics, flavour, QCD and searches for feebly interacting particles, **there is a lot to contribute there to make sure that the detectors can deliver**
- the Z pole operation is the most challenging: ILD is a mature detector concept, it needs to be adapted to the Z pole conditions

- **Reconstruction**

- the ILD reconstruction (e.g. PFA) is **the most mature among the concepts**: it can be used **right away** to develop the complex analyses that require detailed simulation
- synergy between the physics groups, High-Level Reconstruction and the detector design is essential, in order to iterate

- **This community is welcome to contribute with its expertise and experience**

- contact: FCC-PED-Physics-admin@cern.ch, or the conveners of the groups  
[List of the proposed contributions, for all groups: PED in-kind contributions document](#)

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# Backup

# Running conditions: ILC and FCC-ee

|                    | ILC (ILD design)                                                        | FCC-ee                                                                               |
|--------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| $\sqrt{s}$ stages  | 250 – 500 (1000) GeV                                                    | 88–95, 157–163, 240, 340–365 GeV                                                     |
| Interaction points | 1, two detectors in push-pull                                           | 4, permanently installed                                                             |
| Beam structure     | 1312 bunches, 554 ns apart,<br>0.73 ms train at 5 Hz                    | continuous: 11 200 bunches,<br>27 ns apart at the Z                                  |
| Duty cycle         | 0.5%, with a 199 ms gap between trains                                  | 100%, no gap                                                                         |
| Power pulsing      | yes, passive cooling of the calorimeters                                | not possible, electronics permanently powered                                        |
| Readout            | data buffered during the train,<br>read out during the gap              | 100–200 kHz recorded continuously                                                    |
| Solenoid field     | 3.5 T (free choice)                                                     | 2 T at the Z pole (vertical emittance)                                               |
| Beam polarisation  | $e^-$ 80% / $e^+$ 30%, fast helicity flip                               | none for physics, resonant depolarisation<br>gives $\sqrt{s}$ at the $10^{-6}$ level |
| MDI                | $L^* = 4.1$ m, 14 mrad, machine elements<br>outside the tracking region | $L^* = 2.2$ m, 30 mrad, machine elements<br>inside a 100 mrad cone                   |
| Z bosons           | $5 \times 10^9$ (GigaZ, 100 fb $^{-1}$ )                                | $6 \times 10^{12}$                                                                   |

# Consequences for the ILD design

- No power pulsing

- the calorimeter cooling has to be redesigned, with the cooling integrated in the absorber, some longitudinal granularity is lost

- Magnetic field from 3.5 T to 2 T

- momentum resolution ( $\sigma(1/p_T) \propto 1/(B L^2)$ ) and particle-flow separation degrade, ILD\_FCCee\_v01 keeps the same TPC and calorimeters, so this is not compensated for the moment
- beamstrahlung pairs reach larger radii, with consequences for the vertex detector

- Machine elements inside the detector

- $L^*$  from 4.1 to 2.2 m, crossing angle from 14 to 30 mrad, the main source of beamstrahlung scattering moves from the BeamCal ( $z = 4$  m) to the beam-pipe crotch at  $z = 1.3$  m, which is less shielded from the tracker

- TPC

- ions drift at  $\sim 5$  m/s over 2.2 m, i.e.  $\sim 0.5$  s: a few thousand bunch crossings at ILC,  $O(10^7)$  at the FCC-ee Z pole, gating between trains is not possible

- No beam polarisation

- the Z-pole programme uses  $A_{FB}$  and  $\tau$  polarisation instead of  $A_{LR}$ : the requirements move from polarimetry to momentum scale, acceptance and alignment stability

Reference: D. Jeans, *Adapting ILC detector concepts to other facilities*, arXiv:2604.04512

# Documents submitted to the 2026 European Strategy update

- [FCC Feasibility Study Report, Vol. 1: Physics, Experiments, Detectors \(290 pages\)](#)
- [FCC Manifesto \(10 pages\)](#)
- [Electroweak, Higgs and top physics \(10 pages\)](#)
- [BSM physics \(10 pages\)](#)
- [QCD physics \(10 pages\)](#)
- [Flavour physics \(10 pages\)](#)
- [FCC-hh physics \(10 pages\)](#)
- [Detector expressions of interest \(10 pages\)](#)
- [Physics Briefing Book, arXiv:2511.03883](#)
- [ESPPU recommendation, CDS record 2950671](#)

# FCC-ee detector concepts

|                | CLD                  | IDEA                     | ALLEGRO                  | ILD                   | ALFA<br>emerging          | AGORA<br>from CEPC, new for FCC-ee |
|----------------|----------------------|--------------------------|--------------------------|-----------------------|---------------------------|------------------------------------|
| <b>Vertex</b>  | Si                   | MAPS (ITS-3 like)        | MAPS (ITS-3 like)        | Si                    | MAPS (ITS-3 like)         | MAPS                               |
| <b>Tracker</b> | Full Si              | Drift Chamber + Si strip | DCH / Straw / SciFi + Si | TPC + Si strips       | All MAPS                  | TPC + Si strips                    |
| <b>ECAL</b>    | Si-W highly granular | Crystals w. DR           | Noble Liquid (LAR)       | Si-W highly granular  | GRAiNITA (crystal grains) | Crystals                           |
| <b>HCAL</b>    | Scint. sampling      | Fibre DR                 | TileCal (steel/scint.)   | Scint. or RPC         | Tile DR + steel yoke      | Glass scint. + steel               |
| <b>Muon</b>    | RPC in iron yoke     | $\mu$ RWELL              | TBD                      | Scint. in iron yoke   | TBD                       | Scint. in yoke                     |
| <b>PID</b>     | RICH (option)        | tracker dN/dx (+ TOF)    | tracker dN/dx (+ TOF)    | tracker dN/dx (+ TOF) | Čerenkov ARC              | tracker dN/dx (+ TOF)              |
| <b>Coil</b>    | Outside HCAL         | Inside HCAL              | Inside HCAL              | Outside HCAL          | Inside HCAL               | Outside HCAL                       |
| <b>B-field</b> | 2T                   | 2T (3T HTS R&D)          | 2T                       | 3.5 T -> 2-3 T        | 3T                        | 3T                                 |

vertex, tracker, ECAL, HCAL, muon system, PID, coil position and B field (2 T – 3.5 T)

# Detector requirements from the Feasibility Study

Table 14: Summary of detector requirements

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

aggressive and conservative targets, each with the physics channel that drives it, not exhaustive, the numbers will be revised during the RDP

# Electroweak observables: statistics and systematics

| Observable                                   | present<br>value | ± | uncertainty | FCC-ee<br>Stat.          | FCC-ee<br>Syst. | Comment and<br>leading uncertainty                                                                         |
|----------------------------------------------|------------------|---|-------------|--------------------------|-----------------|------------------------------------------------------------------------------------------------------------|
| $m_Z$ (keV)                                  | 91 187 600       | ± | 2000        | <b>4</b>                 | 100             | From Z line shape scan<br>Beam energy calibration                                                          |
| $\Gamma_Z$ (keV)                             | 2 495 500        | ± | 2300        | <b>4</b>                 | 12              | From Z line shape scan<br>Beam energy calibration                                                          |
| $\sin^2 \theta_W^{\text{eff}} (\times 10^6)$ | 231,480          | ± | 160         | <b>1.2</b>               | 1.2             | From $A_{\text{FB}}^{\mu\mu}$ at Z peak<br>Beam energy calibration                                         |
| $1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$ | 128 952          | ± | 14          | <b>3.9</b><br><b>0.8</b> | small<br>tbc    | From $A_{\text{FB}}^{\mu\mu}$ off peak<br>From $A_{\text{FB}}^{\mu\mu}$ on peak<br>QED&EW uncert. dominate |
| $R_\ell^Z (\times 10^3)$                     | 20 767           | ± | 25          | <b>0.05</b>              | 0.05            | Ratio of hadrons to leptons<br>Acceptance for leptons                                                      |
| $\alpha_S(m_Z^2) (\times 10^4)$              | 1 196            | ± | 30          | <b>0.1</b>               | 1               | Combined $R_\ell^Z$ , $\Gamma_{\text{tot}}^Z$ , $\sigma_{\text{had}}^0$ fit                                |
| $\sigma_{\text{had}}^0 (\times 10^3)$ (nb)   | 41 480.2         | ± | 32.5        | <b>0.03</b>              | 0.8             | Peak hadronic cross section<br>Luminosity measurement                                                      |
| $N_V (\times 10^3)$                          | 2 996.3          | ± | 7.4         | <b>0.09</b>              | 0.12            | Z peak cross sections<br>Luminosity measurement                                                            |
| $R_b (\times 10^6)$                          | 216 290          | ± | 660         | <b>0.25</b>              | 0.3             | Ratio of $b\bar{b}$ to hadrons                                                                             |
| $A_{\text{FB}}^{b,0} (\times 10^4)$          | 992              | ± | 16          | <b>0.04</b>              | 0.04            | b-quark asymmetry at Z pole<br>From jet charge                                                             |

| Observable                                              | present<br>value | ± | uncertainty | FCC-ee<br>Stat.  | FCC-ee<br>Syst. | Comment and<br>leading uncertainty                     |
|---------------------------------------------------------|------------------|---|-------------|------------------|-----------------|--------------------------------------------------------|
| $A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$         | 1 498            | ± | 49          | <b>0.07</b>      | 0.2             | $\tau$ polarisation asymmetry<br>$\tau$ decay physics  |
| $\tau$ lifetime (fs)                                    | 290.3            | ± | 0.5         | <b>0.001</b>     | 0.005           | ISR, $\tau$ mass                                       |
| $\tau$ mass (MeV)                                       | 1 776.93         | ± | 0.09        | <b>0.002</b>     | 0.02            | estimator bias, ISR, FSR                               |
| $\tau$ leptonic ( $\mu\nu_\mu\nu_\tau$ ) BR (%)         | 17.38            | ± | 0.04        | <b>0.00007</b>   | 0.003           | PID, $\pi^0$ efficiency                                |
| $m_W$ (MeV)                                             | 80 360.2         | ± | 9.9         | <b>0.18</b>      | 0.16            | From WW threshold scan<br>Beam energy calibration      |
| $\Gamma_W$ (MeV)                                        | 2 085            | ± | 42          | <b>0.27</b>      | 0.2             | From WW threshold scan<br>Beam energy calibration      |
| $\alpha_S(m_W^2) (\times 10^4)$                         | 1 010            | ± | 270         | <b>2</b>         | 2               | Combined $R_\ell^W$ , $\Gamma_{\text{tot}}^W$ fit      |
| $N_V (\times 10^3)$                                     | 2 920            | ± | 50          | <b>0.5</b>       | small           | Ratio of invis. to leptonic<br>in radiative Z returns  |
| $m_{\text{top}}$ (MeV)                                  | 172 570          | ± | 290         | <b>4.2</b>       | 4.9             | From $t\bar{t}$ threshold scan<br>QCD uncert. dominate |
| $\Gamma_{\text{top}}$ (MeV)                             | 1 420            | ± | 190         | <b>10</b>        | 6               | From $t\bar{t}$ threshold scan<br>QCD uncert. dominate |
| $\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$ | 1.2              | ± | 0.3         | <b>0.015</b>     | 0.015           | From $t\bar{t}$ threshold scan<br>QCD uncert. dominate |
| ttZ couplings                                           |                  | ± | 30%         | <b>0.5–1.5 %</b> | small           | From $\sqrt{s} = 365$ GeV run                          |

# Z-pole precision on the fermion-specific observables

| fermion (f) | $R_f \equiv \Gamma_{\text{had}}/\Gamma_f$ relative ( $10^{-6}$ ) | $\mathcal{A}_f$ ( $10^{-6}$ ) | $A_{\text{FB}}^{0,f}$ ( $10^{-6}$ ) | comment                                 |
|-------------|------------------------------------------------------------------|-------------------------------|-------------------------------------|-----------------------------------------|
| e           | $\pm 3.4 \pm 2.3 (300)$                                          | $\pm 14 \pm 11$               | $\pm 3.3 \pm 2.4$                   | from $e^+e^- \rightarrow e^+e^-$        |
| e           | -                                                                | $\pm 7 \pm 20$                | -                                   | from $A_{\text{FB}}^{\text{pol}(\tau)}$ |
| e           | -                                                                | $\pm 13.5 (20)$               | -                                   | combined                                |
| $\mu$       | $\pm 2.4 \pm 2.3 (50)$                                           | $\pm 32 (32)$                 | $\pm 2.3 \pm 2.4$                   | from $e^+e^- \rightarrow \mu^+\mu^-$    |
| $\tau$      | $\pm 2.7 \pm 2.3 (100)$                                          | $\pm 34$                      | $\pm 2.8 \pm 2.4$                   | from $e^+e^- \rightarrow \tau^+\tau^-$  |
| $\tau$      | -                                                                | $\pm 5 \pm 200$               | -                                   | from $\tau$ polarisation                |
| $\tau$      | -                                                                | $\pm 34 (200)$                | -                                   | combined                                |
| b           | $\pm 1.2 \pm 1.6 (300)$                                          | $\pm 98 (210)$                | $\pm 4 \pm 4$                       |                                         |
| c           | $\pm 1.4 \pm 2.2 (150)$                                          | $\pm 60 (150)$                | $\pm 5 \pm 5$                       |                                         |
| s           | $\pm 2.5 \pm 11$                                                 | $\pm 124$                     | $\pm 7.4 \pm 7.4$                   |                                         |

$R_f$ ,  $A_f$  and  $A_{\text{FB}}^{0,f}$  for  $f = e, \mu, \tau, b, c, s$ ,  $R_s$  and  $A_{\text{FB}}^s$  were not measurable at LEP

# Luminosity and acceptance

- All absolute cross sections depend on the luminosity measurement
  - statistical precision:  $10^{-6}$  at the Z pole,  $10^{-3}$  at ZH and  $t\bar{t}$
- Differently from pp, it can be measured in situ with well known processes
  - $e^+e^- \rightarrow \gamma\gamma$ :  $\delta\sigma_{\text{stat}}/\sigma \sim 10^{-5}$ , pure QED, known up to 3 loops
  - small-angle Bhabha  $e^+e^- \rightarrow e^+e^-$ :  $\delta\sigma_{\text{TH}}/\sigma \sim 10^{-4}$ , limited by higher-order corrections, low-energy vacuum polarisation, EW and QED corrections
- Experimental challenge: precise control of the acceptance
  - LumiCal tolerances  $\delta R_{\text{min}} = 1 \mu\text{m}$ ,  $\delta z = 100 \mu\text{m}$ , acceptance 50–100 mrad
  - no gap between the LumiCal and the tracker + calorimeter: this gives the 100 mrad acceptance requirement
  - alignment and monitoring, to guarantee the stability during the run
  - $\mu\mu$ ,  $ee$  and  $\gamma\gamma$  events, with a known initial state and the beam crossing constraint, will be very useful, the full potential still has to be established

# Beam energy and precision measurements

- The precision on  $m$  and  $\Gamma$  of  $Z$ ,  $W$  and  $t$  improves by 20–50 times with respect to LEP and LHC
  - $\delta m_W \sim 200$  keV, compared to  $\sim 10$  MeV from CMS today
- The absolute  $\sqrt{s}$  dominates the mass measurements
  - $\sqrt{s} \leq 2m_W$ : resonant depolarisation, possible only at circular  $e^+e^-$  colliders, intrinsic precision  $10^{-6}$ , measured several times per hour on non-colliding pilot bunches
  - $\sqrt{s} > 2m_W$ : monitored in situ with physics events (radiative return  $Z(\mu\mu)\gamma$ ,  $WW$ )
  - this is the dominant systematic for  $m_H$  and  $m_{top}$
- Widths and energy spread
  - $\Gamma_Z$  systematics constrained in situ with  $\mu\mu$  pairs
  - relative beam energy spread from 0.12% ( $Z$ ) to 0.18% ( $t\bar{t}$ ), dominated by beamstrahlung
- Detector requirements
  - tracking momentum resolution (single-point resolution, B field, material budget)
  - momentum scale stability, monitored with B probes or low-mass resonances
  - the optimal analysis techniques still have to be developed

# W mass and width

- Two independent methods, to be combined with the full correlations
  - threshold scan:  $\sigma(WW)$  as a function of  $\sqrt{s}$ , needs background control and beam energy calibration at the  $10^{-6}$  level (resonant depolarisation)
  - direct reconstruction at 160 and 240 GeV: constrained kinematic fit in the leptonic and hadronic channels
- To be demonstrated in full simulation
  - control of the hadronic background in the threshold scan
  - $\sqrt{s}$  at 240 GeV from radiative-return Z events, including hadronic Z decays
  - lepton momentum scale calibration, also with radiative-return Z
  - hadronisation, colour reconnection and ISR systematics, at 240 and at 160 GeV
- Target:  $\delta m_W \approx 0.18$  MeV statistical, 0.16 MeV systematic (50 times better than today)
  - on the theory side, the full NNLO electroweak calculation is needed
  - other measurements with the same sample:  $|V_{cb}|$ ,  $|V_{cs}|$ , leptonic branching ratios

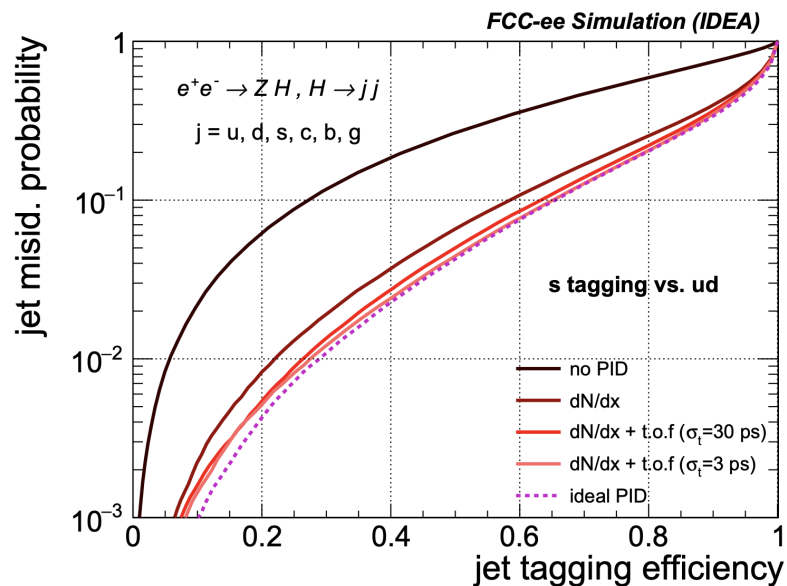
# $\alpha_{\text{QED}}(m_Z)$

- Today  $\delta\alpha/\alpha \approx 1.1 \times 10^{-4}$ : the main parametric uncertainty on  $\sin^2\theta_{\text{eff}}$  and  $m_W$
- FCC-ee can measure it directly, in situ
  - from the off-peak forward-backward asymmetry in  $\mu\mu$  (interference with  $\gamma^*$ ):  $\delta\alpha/\alpha = 3 \times 10^{-5}$ , dominated by statistics
  - the Z-pole energy points are chosen to optimise this measurement
  - from  $R_{e^+e^-}$  and  $R_{e^-\mu^-}$ :  $\delta\alpha/\alpha = 0.6 \times 10^{-5}$
- Detector requirements
  - $e^\pm$  efficiency and charge mis-identification
  - material budget (bremsstrahlung)
  - $e/\mu$  acceptance differences, to be determined from  $10^{11}$  lepton pairs
  - tracker and alignment, ECAL, muon detectors
- The result can then be compared with the lattice calculation
  - it requires  $\sim 10^{12}$  Z off peak and the beam energy from resonant depolarisation: a combination available only at a circular machine

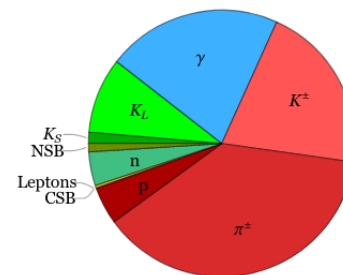
# Higgs couplings: HL-LHC, FCC-ee, FCC-ee+hh

| Coupling                                        | HL-LHC                 | FCC-ee               | FCC-ee + FCC-hh      |
|-------------------------------------------------|------------------------|----------------------|----------------------|
| $\kappa_Z$ (%)                                  | 1.3*                   | 0.10                 | 0.10                 |
| $\kappa_W$ (%)                                  | 1.5*                   | 0.29                 | 0.25                 |
| $\kappa_b$ (%)                                  | 2.5*                   | 0.38 / 0.49          | 0.33 / 0.45          |
| $\kappa_g$ (%)                                  | 2*                     | 0.49 / 0.54          | 0.41 / 0.44          |
| $\kappa_\tau$ (%)                               | 1.6*                   | 0.46                 | 0.40                 |
| $\kappa_c$ (%)                                  | —                      | 0.70 / 0.87          | 0.68 / 0.85          |
| $\kappa_\gamma$ (%)                             | 1.6*                   | 1.1                  | 0.30                 |
| $\kappa_{Z\gamma}$ (%)                          | 10*                    | 4.3                  | 0.67                 |
| $\kappa_t$ (%)                                  | 3.2*                   | 3.1                  | 0.75                 |
| $\kappa_\mu$ (%)                                | 4.4*                   | 3.3                  | 0.42                 |
| $ \kappa_s $ (%)                                | —                      | +29<br>−67           | +29<br>−67           |
| $\Gamma_H$ (%)                                  | —                      | 0.78                 | 0.69                 |
| $\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$ | $1.9 \times 10^{-2} *$ | $5 \times 10^{-4}$   | $2.3 \times 10^{-4}$ |
| $\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$ | $4 \times 10^{-2} *$   | $6.8 \times 10^{-3}$ | $6.7 \times 10^{-3}$ |

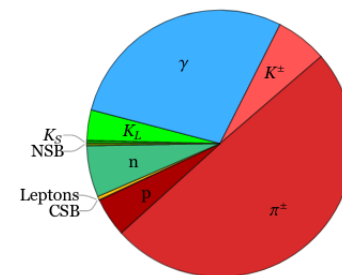
# Strange tagging and particle identification



ROC vs ud jets: no PID, dN/dx, dN/dx + ToF, ideal PID



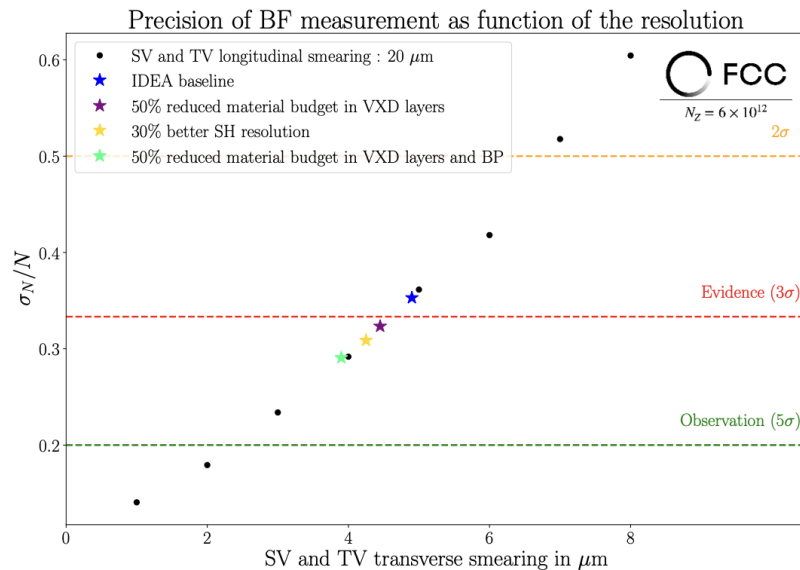
Strange  $p_T = 45$  GeV



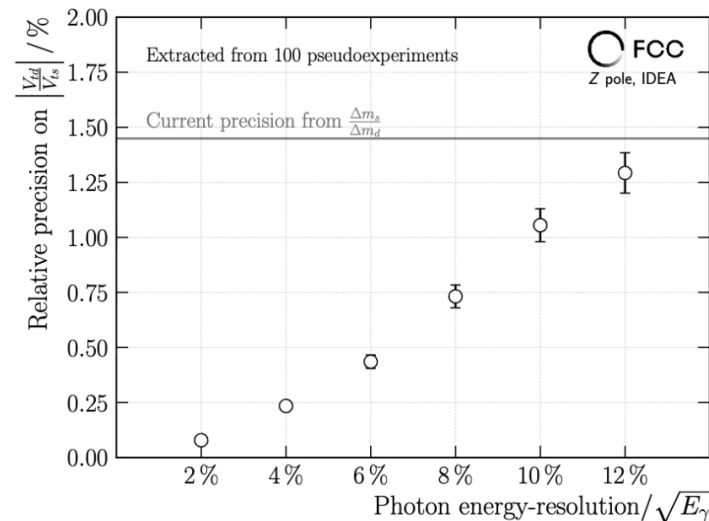
Down  $p_T = 45$  GeV

particle composition of s and d jets at  $p_T = 45$  GeV

# Detector requirements from flavour physics: examples

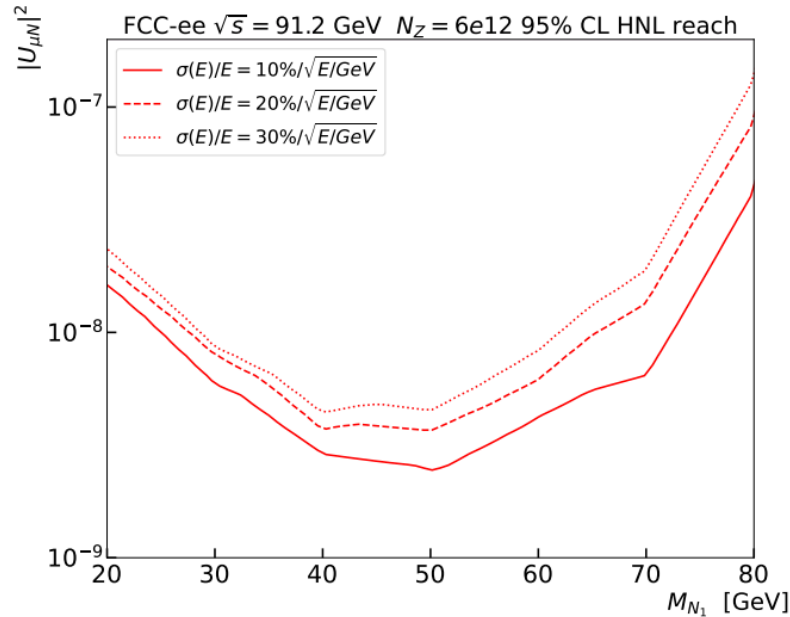


$B \rightarrow K^*\tau\tau$ : precision on the branching fraction as a function of the vertex smearing



$|V_{td}/V_{ts}|$  from  $B \rightarrow K^*\gamma$  as a function of the ECAL energy resolution

# HNL reach and hadronic energy resolution



95% CL reach at the Z pole ( $6 \times 10^{12}$  Z) for  $\sigma(E)/E = 10\%$ ,  $20\%$  and  $30\%/\sqrt{E}$ : a factor  $\sim 2$  between  $10\%$  and  $30\%$

# Theory wish-list

Table 4.2: Wish-list for calculations of missing higher-order perturbative QCD  $\mathcal{O}(\alpha_s^n)$  and/or EW  $\mathcal{O}(\alpha^n)$  to match the expected experimental uncertainty at future  $e^+e^-$  and  $e p$  colliders.

| Observable                                                           | Missing higher-order & power-suppressed corrections                                                                                                                                                                                                               |
|----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hadronic $Z$ width                                                   | $\mathcal{O}(\alpha_s^5), \mathcal{O}(\alpha_s^6), \mathcal{O}(\alpha^3), \mathcal{O}(\alpha_s \alpha^3), \mathcal{O}(\alpha_s^2 \alpha^2)$                                                                                                                       |
| Hadronic $W$ width                                                   | $\mathcal{O}(\alpha_s^5), \mathcal{O}(\alpha^2), \mathcal{O}(\alpha_s^2 \alpha)$                                                                                                                                                                                  |
| Hadronic $\tau$ width                                                | $\mathcal{O}(\alpha_s^5)$                                                                                                                                                                                                                                         |
| Hadronic event shapes ( $Z, W, H$ decays)                            | $N^3$ LO differential, $N^{3,4}$ LL resummation, power corrections                                                                                                                                                                                                |
| Inclusive jet rates                                                  | 3-jet cross-sections at $N^3$ LO, 4-jets at $N^2$ LO, 5-jets at NLO                                                                                                                                                                                               |
| Lattice QCD results<br>( $\alpha_s$ extr.; quark masses $m_c, m_b$ ) | $\mathcal{O}(\alpha_s^6)$ $\beta$ -function; $\mathcal{O}(\alpha_s^5)$ heavy quark decoupling; $\mathcal{O}(\alpha_s^4)$ static potential<br>$\mathcal{O}(\alpha_s^3)$ lattice perturbation theory matching (lattice coupling to $\alpha_s^{\overline{MS}}$ etc.) |
| $\sigma(e^+e^- \rightarrow W^+W^-)$ vs. $\sqrt{s}$                   | EW $N^2$ LO: $\mathcal{O}(\alpha^2)$ , Mixed EW-QCD: $\mathcal{O}(\alpha_s \alpha^2), \mathcal{O}(\alpha_s^2 \alpha)$                                                                                                                                             |
| $\sigma(e^+e^- \rightarrow t\bar{t})$ vs. $\sqrt{s}$                 | NRQCD: $\mathcal{O}(\alpha_s^5)$ , Non-resonant: $\mathcal{O}(\alpha_s^5), \mathcal{O}(\alpha_s^3)$ differential; QED: $\mathcal{O}(\alpha^3)$ at NNLL                                                                                                            |
| $H \rightarrow b\bar{b}$ width                                       | $N^4$ LO ( $m_b \neq 0$ ); $N^4$ LO differential ( $m_b = 0$ )                                                                                                                                                                                                    |
| $H \rightarrow gg$ width                                             | $N^5$ LO (heavy-top limit), $N^4$ LO ( $m_t \neq 0$ ); $N^4$ LO differential, $N^3$ LO differential ( $m_t \neq 0$ )                                                                                                                                              |
| MC simulations for $e^+e^- \rightarrow X$ processes                  | $N^{2,3}$ LO matched to $N^{2,3}$ LL PS. Per mille control of non-pQCD effects (hadronization, CR, ...)                                                                                                                                                           |

missing higher-order QCD and electroweak corrections needed to match the expected experimental precision [EPPSU Physics Briefing Book]

# Useful links

- Documentation and web pages

- [hep-fcc.github.io/FCCeePhysicsStudies](https://hep-fcc.github.io/FCCeePhysicsStudies/): Physics Studies documentation
- [fcc-ped.web.cern.ch](https://fcc-ped.web.cern.ch/): PED web page, work packages, contacts, events
- [fcc-ped.web.cern.ch/work-packages/physics-studies/](https://fcc-ped.web.cern.ch/work-packages/physics-studies/)
- [hep-fcc.github.io/FCChhPhysicsPerformance](https://hep-fcc.github.io/FCChhPhysicsPerformance/): the hadron phase

- Indico

- [indico.cern.ch/category/5251/](https://indico.cern.ch/category/5251/): FCC Physics, Experiments and Detectors
- → Physics programme and performance → meeting categories of the groups

- E-groups

- [gms.web.cern.ch/group/FCC-PED-Physics](https://gms.web.cern.ch/group/FCC-PED-Physics/) (and one per physics group)
- [groups-portal.web.cern.ch/group/memberships/my/](https://groups-portal.web.cern.ch/group/memberships/my/): your current subscriptions

- Contacts and contributions

- [FCC-PED-Physics-admin@cern.ch](mailto:FCC-PED-Physics-admin@cern.ch): Physics Studies coordination
- [FCC-PED-SpeakersBuro@cern.ch](mailto:FCC-PED-SpeakersBuro@cern.ch): conference talks, [fcc-ee-conference.web.cern.ch](https://fcc-ee-conference.web.cern.ch/): list of talks
- PED in-kind contributions document (link)