Physics opportunities at a Tera-Z e^+e^- collider and requirements on the detectors

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Two future projects that could lead to a very large number of $e^+e^- \rightarrow Z$ events:
- CEPC and FCC-ee (largest lumi. prospects so far)

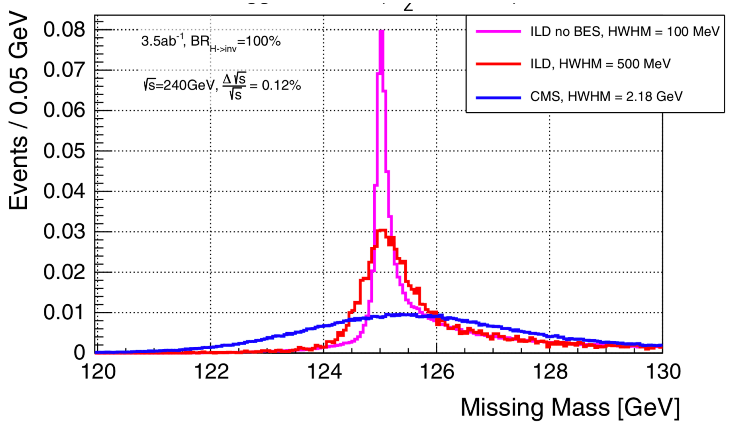
Focus on FCC-ee in this talk.

Introduction : Detectors for FCC-ee

Two detector concepts are described in the FCC-ee CDR :
- CLD, derived from the CLIC detector
- IDEA, see talk earlier in this session

They both comply with :
- the constraints imposed by the machine-detector interface, e.g. :
  - B(sol.) ≤ 2T, θ > 150 mrad, L* = 2.2 m
- Requirements imposed by basic Higgs analyses
  - E.g. Z(μμ)H : the recoil mass: resolution driven by beam energy spread, not by the muon momentum resolution.

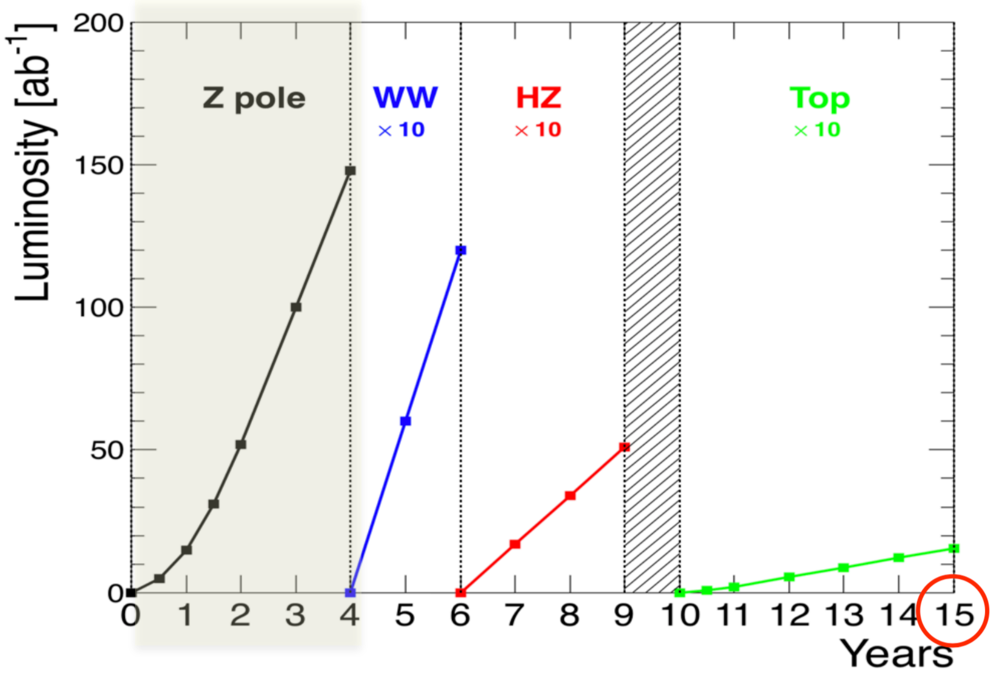
[O. Cerri et al., EPJ C(2017) 77:116]



But the huge statistics to be delivered at $\sqrt{s} \approx M_Z$ sets specific requirements :
- Very small statistical errors call for very small systematic uncertainties too
- σ(syst.) commensurate with σ(stat.) (or with other systematic "wall" of non-detector origin) ? What are the limiting factors ?
- Not studied earlier - Linear Colliders are not a Tera-Z factory

FCC-ee : the Tera-Z facility

FCC-ee operational mode considered in the CDR :



150 ab^{-1} (2 IPs) at and around the Z peak, = LEP stat x 2.5 10^5 !

stat. errors of Z-pole measurements can be reduced by a factor of O(500)

5 x 10^{12} $e^+e^- \rightarrow Z$ evts: “Tera-Z”

Hence 7.5 10^{11} $b\bar{b}$, 1.7 10^{11} $\tau\tau$

Also a b, c and τ factory !

- Indirect discovery of new physics via high precision measurements
  - Especially when combining the Z data with the higher energy data
    - Sensitivity to scales of new physics (EFT) up to 50-70 TeV. Sets the scale of new particles that would be studied later at FCC-hh.
- Discoveries in very rare SM processes, e.g. Lepton Flavour Violation
- Direct discoveries, e.g.
  - Very weakly-coupled particles, $Z \rightarrow$ dark γ's or RH ν's etc.

Electroweak Precision Observables (Z pole) at FCC-ee

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	4	25	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν ($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z^2)$ ($\times 10^3$)	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
A_{FB}^b, 0 ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{\mathrm{pol},\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics

First "estimates" of the systematics. In most cases we are working on (reducing) them.

Key for the exquisite precision of several observables at FCC-ee: √s will be known to 100 keV (continuous calibration via resonant depolarisation measurements).

[see arXiv:1909.12245]

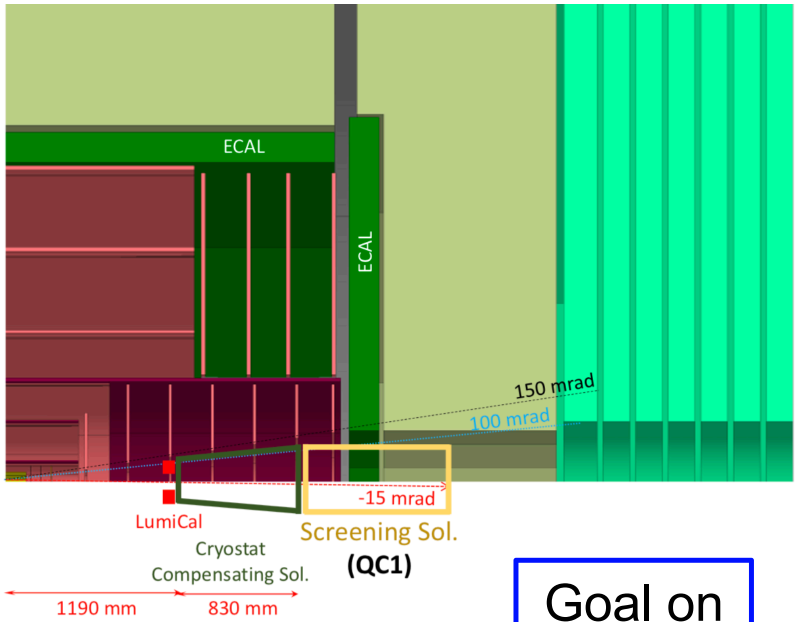
- The Z mass to 100 keV, the Z width to ~ 25 keV
- $\sin^2\theta_W^{\mathrm{eff}}$ to a few 10^{-6} thanks to $A_{FB}(\mu\mu)$ at the Z peak
- $\alpha_{\mathrm{QED}}(m_Z)$: gain x4 thanks to $A_{FB}(\mu\mu)$ (off-peak). Unique !

Detector requirements for m_Z, $\sin^2\theta_W^{\mathrm{eff}}$, $\alpha_{\mathrm{QED}}(m_Z)$: not expected to be challenging.

Luminosity : for the number of light neutrino species

- N_ν from LEP : still sets today one of the most stringent constraints on BSM ν mass models
- Determined from the total cross-section of σ^0_{had} , hence luminosity is the key

Determine the luminosity from the rate of Bhabha events, measured in two forward calorimeters centered around the outgoing beam-pipes.



W+Si sandwich, (cf ILC-FCAL)
Very close to the IP (~ 1 m !)

Sensitive region: 55 < R < 115 mm
Fiducial volume for the measurement:
64 – 86 mrad

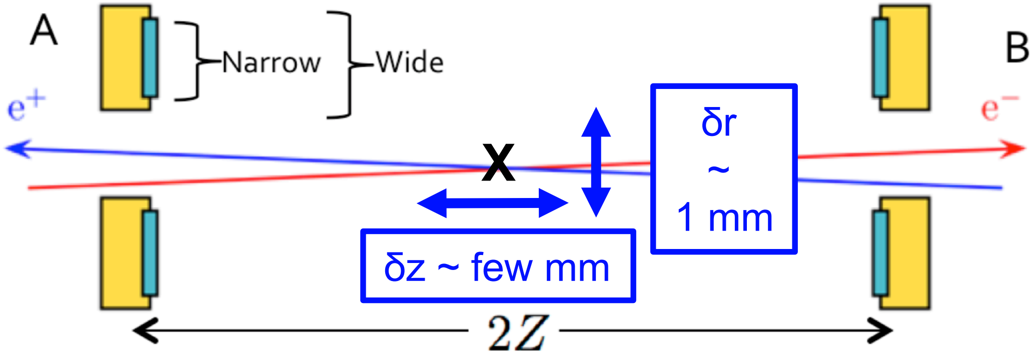
Goal on $\sigma(L)/L$:

10^{-4} (absolute)

- match the anticipated theo. precision
- OPAL reached (exp.) 3.4 x 10^{-4}
- Leads to a reduction of the uncertainty on N_ν by a factor of O(8)

Key: Definition of and precision on the acceptance

Method of “asymmetric acceptance” :



Events are selected if :
e- in Narrow and e+ in Wide
or
e+ in narrow and e- in Wide

Largely reduces the dependence of A on:

- radial or longitudinal displacements of the IP wrt lumi system.
- Any displacement of the vertex (e.g. ISR)

With θ(Wide) = θ (Narrow) +/- 2 mrad :

$$\frac{\Delta A}{A} \approx -\left(\frac{\delta z}{6\,\mathrm{mm}}\right)^2 \times 10^{-4}$$

$$\frac{\Delta A}{A} \approx +\left(\frac{\delta r}{0.6\,\mathrm{mm}}\right)^2 \times 10^{-4}$$

- Distance 2Z between the two arms (2m) : must be known to ~ 100 μm

- Inner radius of the luminometer: must be known to 1.6 μm ! challenging !
  - OPAL achieved $\Delta R_{in} \approx 5$ μm
  - Compact detector: each Si sensor from one wafer only. Vertical assembly of the two halves will then drive ΔR_{in} .

Lepton acceptance: Partial width ratios

$$R_l = \Gamma_l / \Gamma_{had} = \sigma_l / \sigma_{had}$$

- Robust measurement
- Necessary input for a precise measurement of the lepton couplings
  - Precise tests of lepton universality
- Enters in the determination of N_ν
- Very sensitive to α_S !

FCC-ee: stat. uncertainty on R_l : 6×10^{-5}, i.e. $\sigma(R) / R = 3\ 10^{-6}$!

Geometric acceptance for lepton pairs: dominant syst at LEP, typically $5\ 10^{-4}$ (relative) in μμ. Would need to reduce the LEP syst. by O(100) to reach σ(stat).

- "asymmetric" selection as done for the luminosity measurement
- R_e with $\theta > 30^o$: bias in θ should be less than O(3 μrad). The radial position of the endcap calorimeter must be known to 6 μm. Mechanical constraints, easier with an hermetic calorimeter (no cracks).

Muon momentum resolution: Γ_Z , LFV Z decays

- Determination of Γ_Z : Relative uncertainty of $\sqrt{s}$ between the different energy points

  Relative stability of the calibration of the $\sqrt{s}$ measurement can be controlled via the direct measurement of M(μμ) in dimuon events.

  Full Si tracker: for p = 45 GeV, < θ > = 50^o : $\sigma(p_T) / p_T$ = O (0.5 %) [material]

σ(M, res) ≈ 300 MeV > σ($\sqrt{s}$) ≈ 85 MeV : width of M(μμ) dominated by the resolution.

  Still allows the stability to be controlled to O(40 keV). Such a pt-to-pt uncertainty corresponds to σ(Γ_Z) ~ 25 keV (remember: stat. error = 4 keV)

- LFV decays $Z \rightarrow \tau\,\mu$: strategy = a clear τ decay in one hemisphere + a "beam-energy" muon in the other hemisphere, to suppress $Z \rightarrow \tau\,\tau(\mu)$ bckgd.

  Ideally: σ(p) / p ≈ e.g. half of beam energy spread for 45 GeV muons, i.e. 5 10^{-4}
  With a full Si tracker: off by factor of 10 !

  With a resolution of 0.5% : sensitivity on $Z \rightarrow \tau\,\mu$ down to BR = 2 10^{-9}.
  - Already big improvement w.r.t. current limit : BR < 12 10^{-6} (LEP)
  - but sensitivity improves linearly with the momentum resolution !

  [M. Dam, arXiv:1811.09408]

Z running: benefits from a light tracker, with minimal mult. scatt. for 45 GeV muons !

Vertexing & Impact parameter: Heavy quarks

- Anticipate large improvements in the HQ EW observables: R_b, R_c, A_{FB}^Q
  - Huge progress in technology of vertex detectors since LEP / SLD
  - LHC detectors: 3x better b-tag efficiency then LEP for the same rejection
  - Hence, stat. gain w.r.t. LEP > 500.
  - Moreover, smaller beam-pipe radius (1.5 cm), VXD closer to beam-line

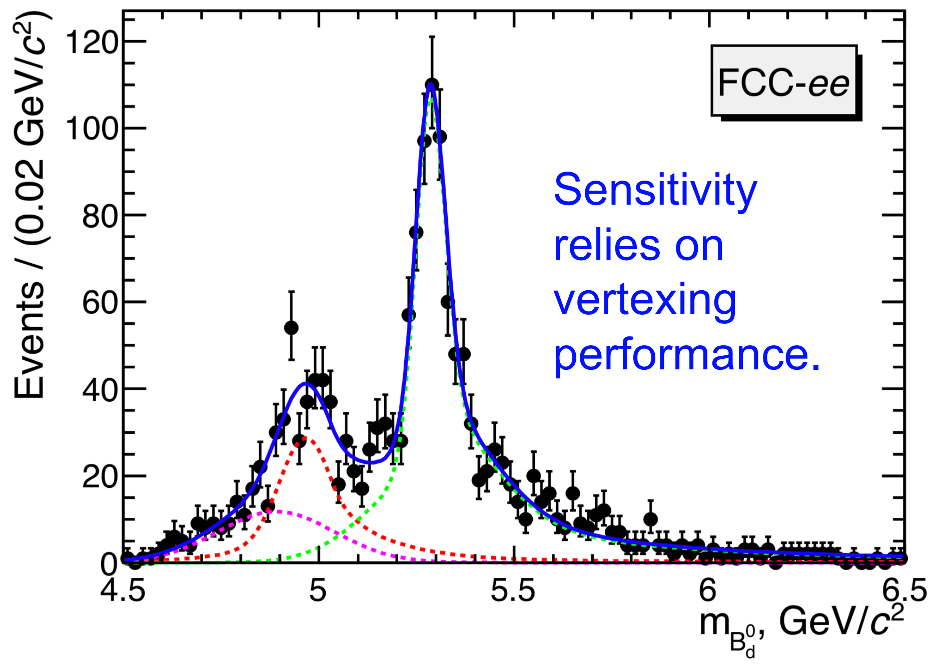
- VXD has to be precise, thin, low power (no pulsing) and cope with BX rate (50 MHz)

- Example of usage in exclusive decays : $B \rightarrow K^* \tau\, \tau$

Lepton Flavour Universality is challenged in $b \rightarrow s$ transitions at LHCb:
- R(K) and R(K*) ; angular distributions in $B0 \rightarrow K^*\, \mu\mu$
- also departures in R(D*) and R(D)

Models that explain these deviations usually predict large enhancements in $b \rightarrow s\, \tau\, \tau$. And $B \rightarrow K^*\, \tau\, \tau$ is a "model killer".

σ(PV) = 3 μm, σ(SV – TV) = 5 -7 μm :
> 1000 evts of reco'ed signal.
Likely unique to FCC.



Sensitivity relies on vertexing performance.

Vertexing & Impact parameter : Taus

- Tau lifetime : current average: 290.3 ± 0.5 fs
- Best single measurement from BELLE : 290.17 ± 0.53 (stat) ± 0.22 (syst) fs
  - From reconstructing the decay length in 3-prong decays
  - Dominant systematics (alignment of the vertex detector) in the shadow of the stat. uncertainty

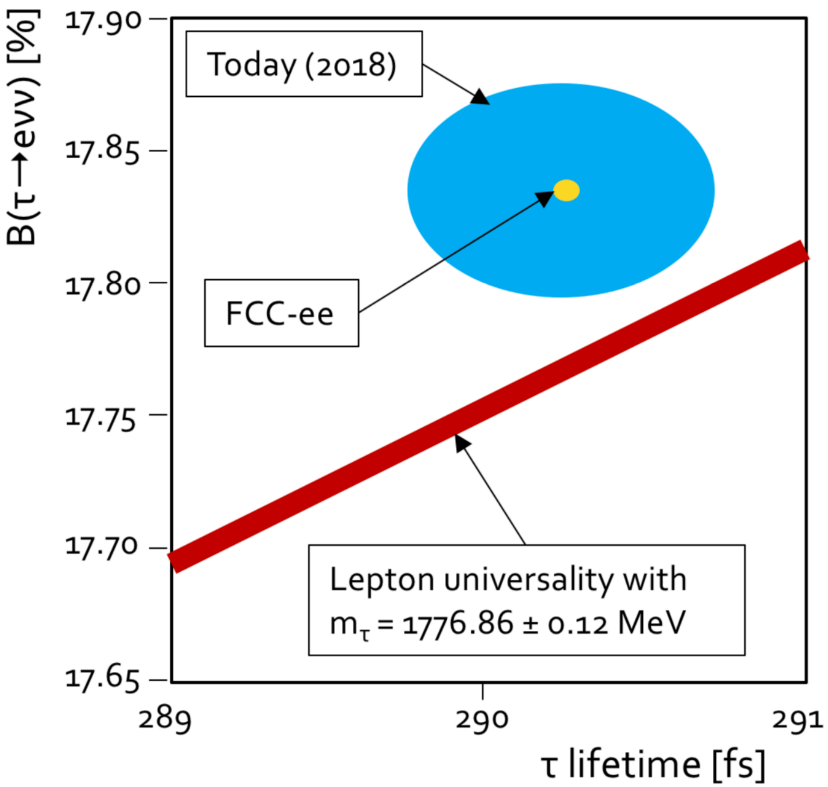
FCC-ee: stat uncertainty = 0.001 fs
Alignment uncertainties decrease with increasing statistics - and partially cancel.

Systematics due to the overall radial scale of the vertex detector : should be possible to control it at the level of 10^{-4}
→ a potential uncertainty of 0.03 fs

Allows a precise test of lepton τ - μ universality.

$$\left(\frac{g_\tau}{g_\mu}\right)^2 \simeq \frac{\tau_\mu}{\tau_\tau} BF(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \left(\frac{m_\mu}{m_\tau}\right)^5$$

(while comparing $\tau \to$ e and $\tau \to$ μ tests
e- μ universality)



Much more displaced vertices…

Tera-Z: unique opportunity to discover new particles that are very weakly coupled

Example: right-handed neutrinos
Very strong theoretical motivations : could explain all the observational evidence for physics beyond the Standard Model :

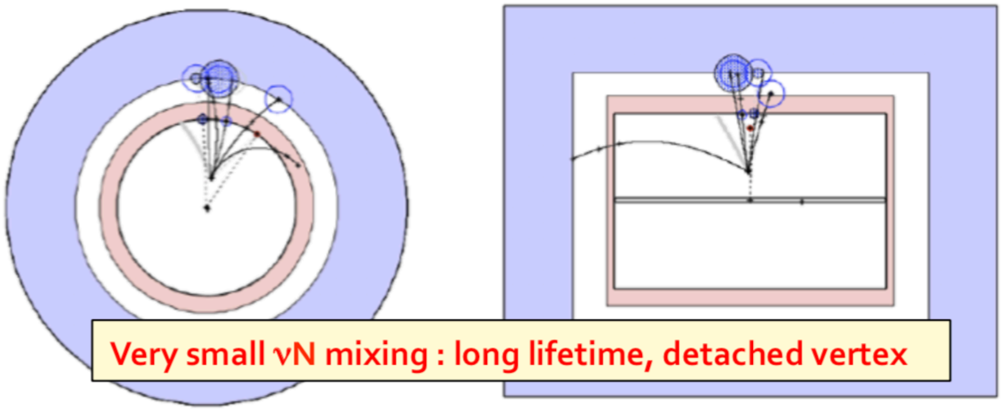
- neutrino masses (see-saw)
- can provide a Dark Matter candidate (the lightest ν_R, N1)
- baryon asymmetry

The N's only interact via their mixing with the light neutrinos.

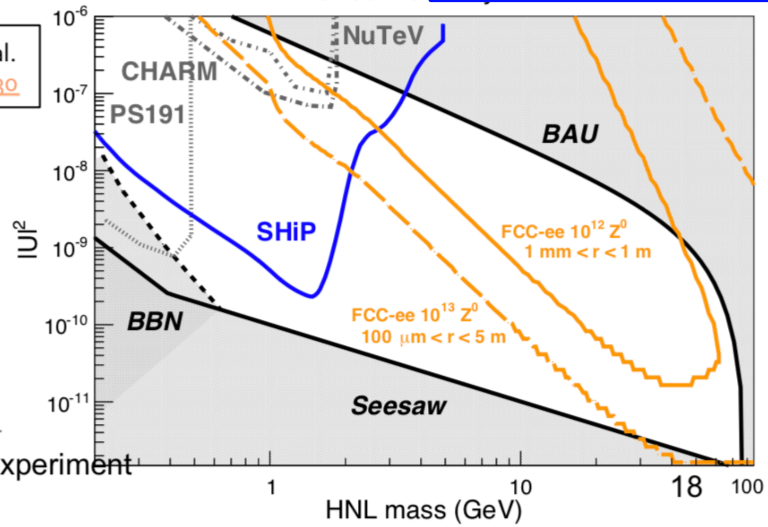
Reconstruct far-detached (~ m) vertices

- Searched for in very rare $Z \to \nu N_{2,3}$ decays
  - Followed by $N_{2,3} \to W^* \ell$ or $Z^* \nu$

A. Blondel et al. arXiv:1411.5230



Very small νN mixing : long lifetime, detached vertex



Particle Identification at FCC-ee

- π / K separation : most useful in the range 1 – 10 GeV
  - From spectrum of kaons in b → c → s decay chain
  - Example: Bs → Ds K
    - Fully charged mode, Ds → Φ π : signal can be separated from Ds π background with excellent pT resolution
    - With neutral (Ds → Φ ρ^-) : an excellent ECAL energy resolution is not enough, PID is mandatory.
- Ideally at higher momentum too, up to 30-40 GeV

Candidate technologies :

[Guy Wilkinson, FCC workshop, Jan 2020]

- IDEA drift chamber : cluster counting looks promising.
- Classical RICH : robust and performant. Could cover the full p range of interest, but it requires space.
  → significant consequences for overall experiment design.
- TOF detectors : limited to low momentum
- DIRC (Babar) / TOP (Belle) / TORCH (LHCb) : require little space, but but will struggle to cover much of the momentum range of interest.

Not easy to cover the whole range of interest within the space and hermiticity constraints !

Conclusions

Huge physics potential of FCC-ee at the Z pole :

- a gain of 1 – 2 orders of magnitude in precision for EW observables
- Unique sensitivity to new physics

Lots of work ahead on the front of systematics in order to

- design detectors and analyses
- improve theoretical calculations

so that systematic uncertainties are commensurate with statistical uncertainties.

A first set of "case studies" has been identified in order to better quantify the requirements on the detectors that are set by the huge physics potential:
https://snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF0-016.pdf