FUTURE CIRCULAR COLLIDER

4th FCC Physics and Experiments Workshop

Detector requirements for FCC-ee

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Still lots of work ahead of us in order to determine these requirements
- Goal of the Physics Performance group for the coming year, see previous talk

Contents: “What we know today of detector requirements”, as charged, but also mention question marks and where work is ongoing.

Requirements from the exp. environment and from physics

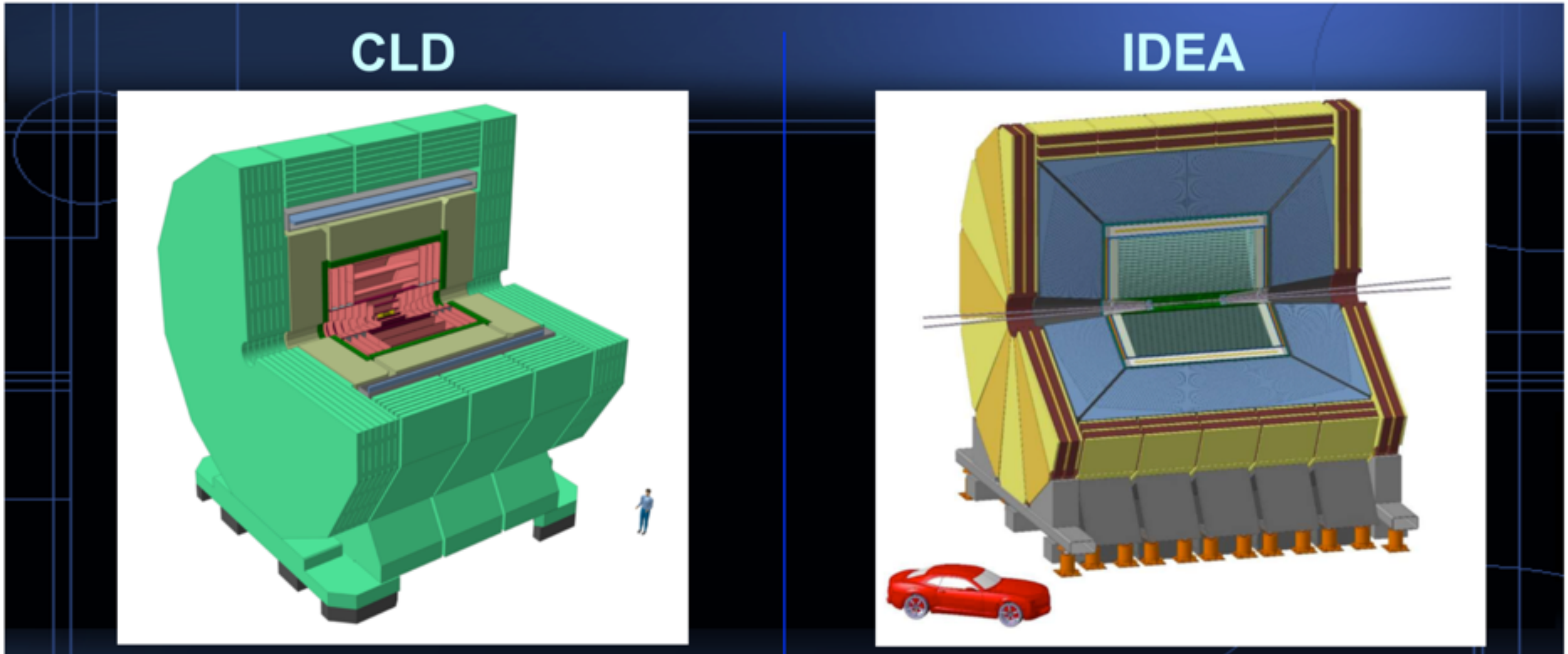
- Constraints imposed by the machine-detector interface, e.g. :
  - B(sol.) ≤ 2T, L* = 2.2 m, θ > 100 mrad

- Exp. environment at FCC-ee ≠ LC
  - E.g. no power pulsing of electronics, more cooling for VXD or less power
  - Specific conditions at the Z peak: large physics event rates (100kHz), small bunch spacing (approx. 20 ns)

- Physics requirements:
  - For √s > about 240 GeV: considered already in ILC / CLIC studies, to be revisited for FCC
  - Z pole running: extremely large statistics !
    - Very small stat errors call for very small systematic uncertainties
    - Specific detector requirements, not studied earlier (LCs are not a Tera-Z factory)

- Up to 4 detectors can be considered for FCC-ee. Could be some complementarity w.r.t. the physics reach.

Starting point: concepts in the CDR, CLD and IDEA



CLD

Full silicon tracker
3D High granularity calorimeter
Solenoid outside calorimeter

derived from the CLIC detector

IDEA

Ultra-light drift chamber
Dual-readout calorimeter
Solenoid inside calorimeter

new, possibly more cost effective design

Variants also under study – e.g. LAr calorimeter, crystal-based ECAL, …

Tera-Z : excellent control of acceptances needed

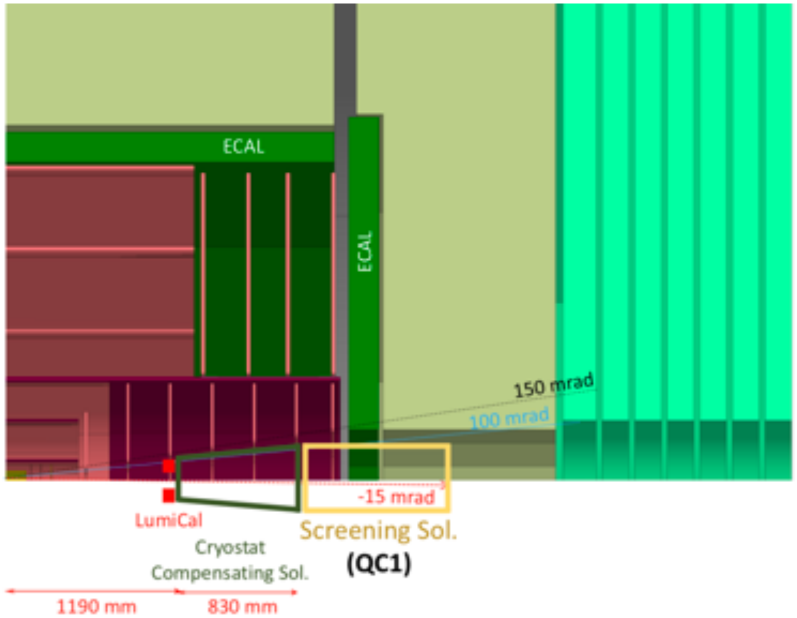
At the level of sub-10^{-5} - 10^{-4} - stronger than requirements for Higgs measurements. Examples:

- Luminosity measurement: goal on σ(L) / L is 10^{-4} (absolute) from low-angle Bhabha events
  - Would match the anticipated theo. precision
  - With LumiCal at z ~ 1 m, Bhabha measurement above 65 mrad: Inner radius of the luminometer: must be known to 1.6 μm

- Lepton acceptance: partial width ratios Rlep = σ(had) / σ(lep)
  - FCC-ee: stat. uncertainty on R_l : σ(R) / R = 3 10^{-6} !
  - To reach σ(stat), acceptance for lepton pairs must be known to that level
  - For a measurement at θ > 15^o : bias in θ should be less than O(8 μrad).
    - Radial position of the endcap calorimeter: to O (15 μm)

Set constraints on the design and mechanical assembly of the LumiCal and endcap calorimeter.

Tracker: angular coverage



MDI constraint: θ < 100 mrad is reserved for the machine magnets & instrumentation (exception = LumiCal)

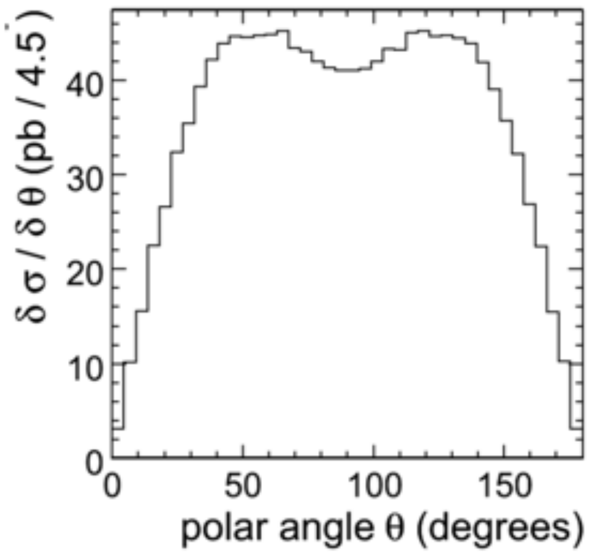
LumiCal extends up to 150 mrad (along the direction of the outcoming beam)

i.e. forward tracks down to about 10 degrees only.

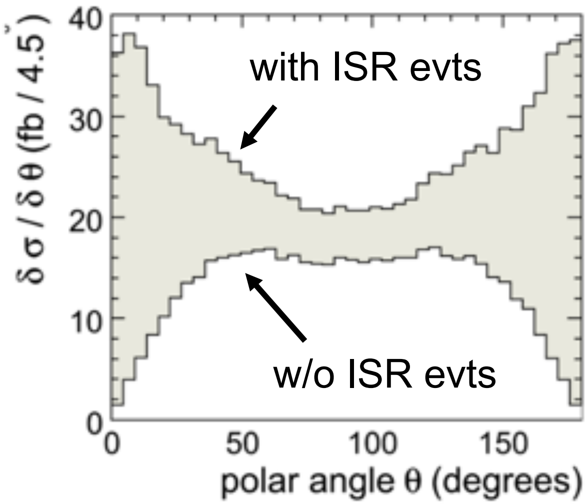
J. Fuster et al, arXiv:0905.2038

But the very forward region (< 10 deg) much less relevant at the FCC-ee energies than at ILC or CLIC.

Plots: ee → ff events



(a) $\sqrt{s} = 91$ GeV



(b) $\sqrt{s} = 500$ GeV

Tracker: angular resolution

Angular resolutions : 0.1 mrad needed for the control of the beam energy spread

Energy spread (60 MeV at the Z peak): affects the line shape, large impact on ΓZ (4 MeV !) -> must be controlled experimentally.

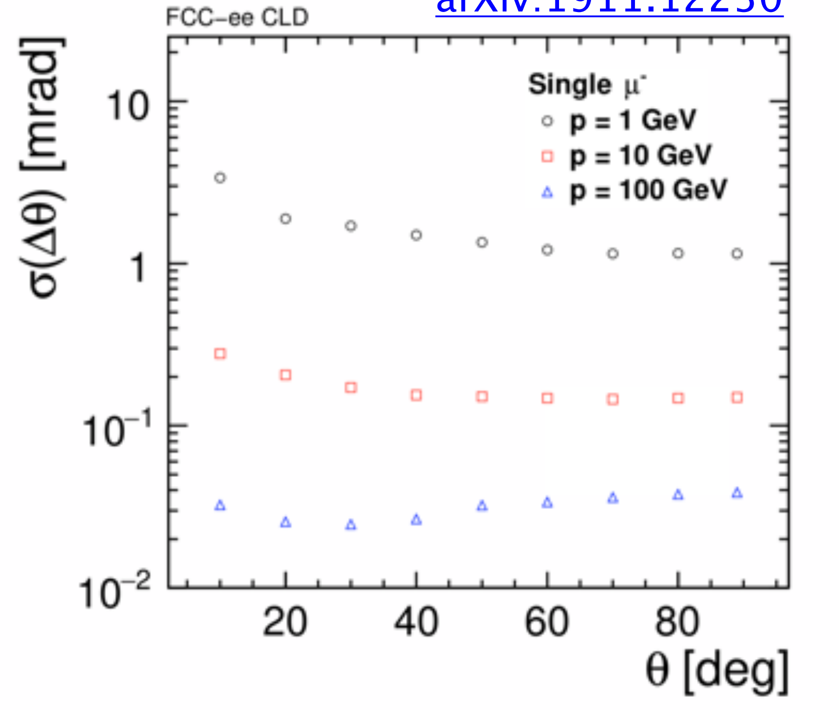
Can not be derived from the width of the z_{vertex} distribution as at LEP because of the crossing angle.

But can be measured at a few per-mille level from the scattering angles of dimuon events.
Constrained kinematics: the longitudinal imbalance can be reco'ed. The width of its distribution gives the energy spread.

Requirement on angular resolution:
0.1 mrad for muon tracks from Z decays.

arXiv:1909.12245

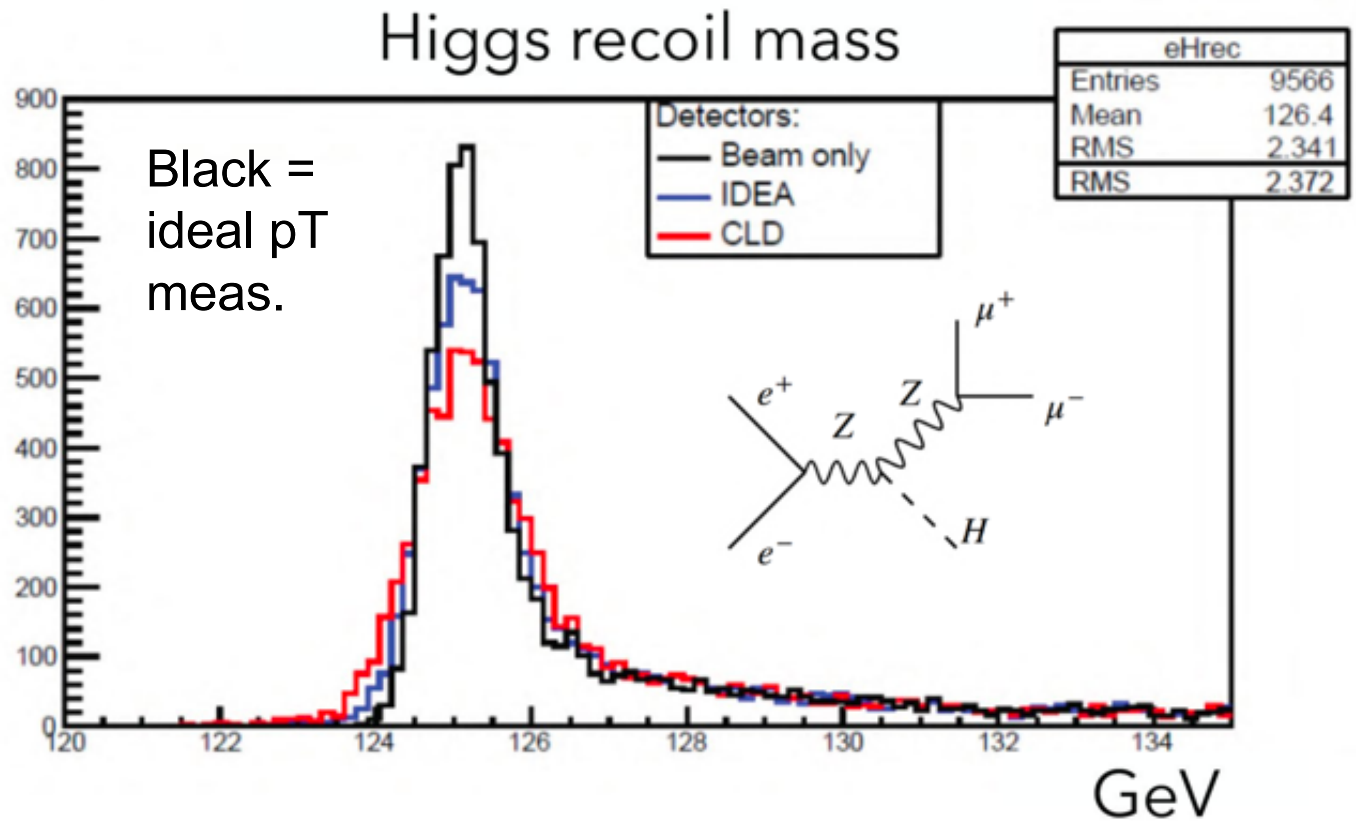
arXiv:1911.12230



Tracker momentum: resolution

Higgs Recoil mass distribution in ZH evts, Z -> mumu

Requirement on the muon momentum resolution is bounded by the beam energy spread (0.16% on E_b at $\sqrt{s}$ = 240 GeV)



- IDEA tracker is close to this limit.
- Full Si tracker (CLD) a bit worse: in the energy range of interest, resolution is dominated by the multiple scattering

Higgs mass measurement: mH within O(Γ_H = 4 MeV) desirable (e+ e- $\rightarrow$ H).
Determination of m_H via the fit to M_{recoil} : would benefit from being as close as possible to the BES limit.

Tracker: momentum resolution

- At the Z peak : BES = 0.13%

  - Ideally: for muons from $Z \to \mu\mu$, resolution ≈ BES.
  - $\sigma(p) / p = O$ (0.5 %) for 45 GeV muons at < θ > = 50 – 60 deg in CLD

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

  With a resolution of 0.5% : sensitivity on $Z \to \tau\,\mu$ 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]

- Determination of the τ mass: constrain the measurement of tracks in a collimated environment ($\tau \to$ 3-prong decays)

- Flavour physics: mass reconstruction important for exclusive final states, to suppress the irreducible backgrounds.

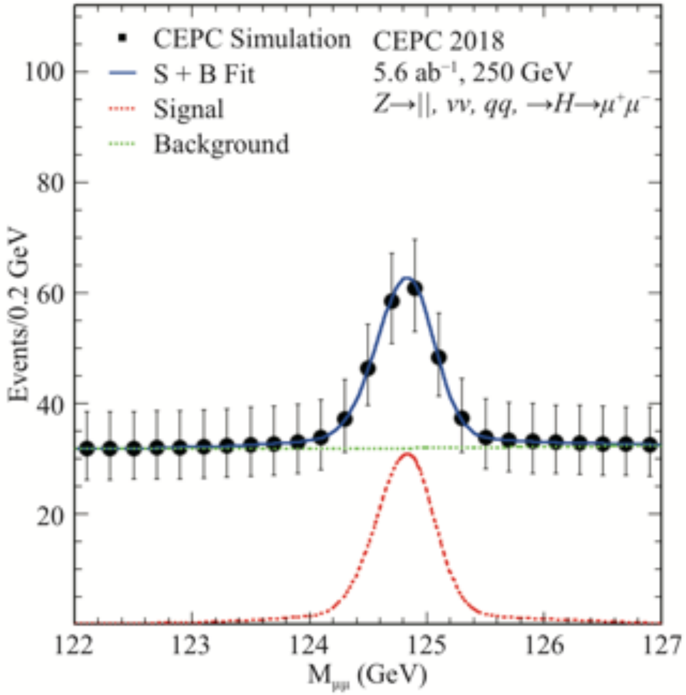
Z running: benefits from a light tracker, with minimal mult. scatt. for 45 GeV muons and for softer tracks. This would also limit the γ conversions and hadronic interactions (beneficial esp. for particle-flow reconstruction).

Tracker: momentum resolution

Requirement from the measurement of the Hμμ coupling ?

Very low statistics : with 5 ab-1 at 240 GeV, expect 1 M Higgs bosons.
BR(μμ) = 2.2 10^{-4} hence O(200) events only

Chinese Phys. C **43** 043002



CEPC 2018 study:

- With ILD like tracker and B = 3.5 T

  Obtain a mass resolution on H → μμ of 200 MeV, i.e. 0.16%

with 5.6 ab^{-1}: expected precision on σ(ZH) x BR(H → μμ) of 16 %.
2x worse than the expected precision from HL-LHC.

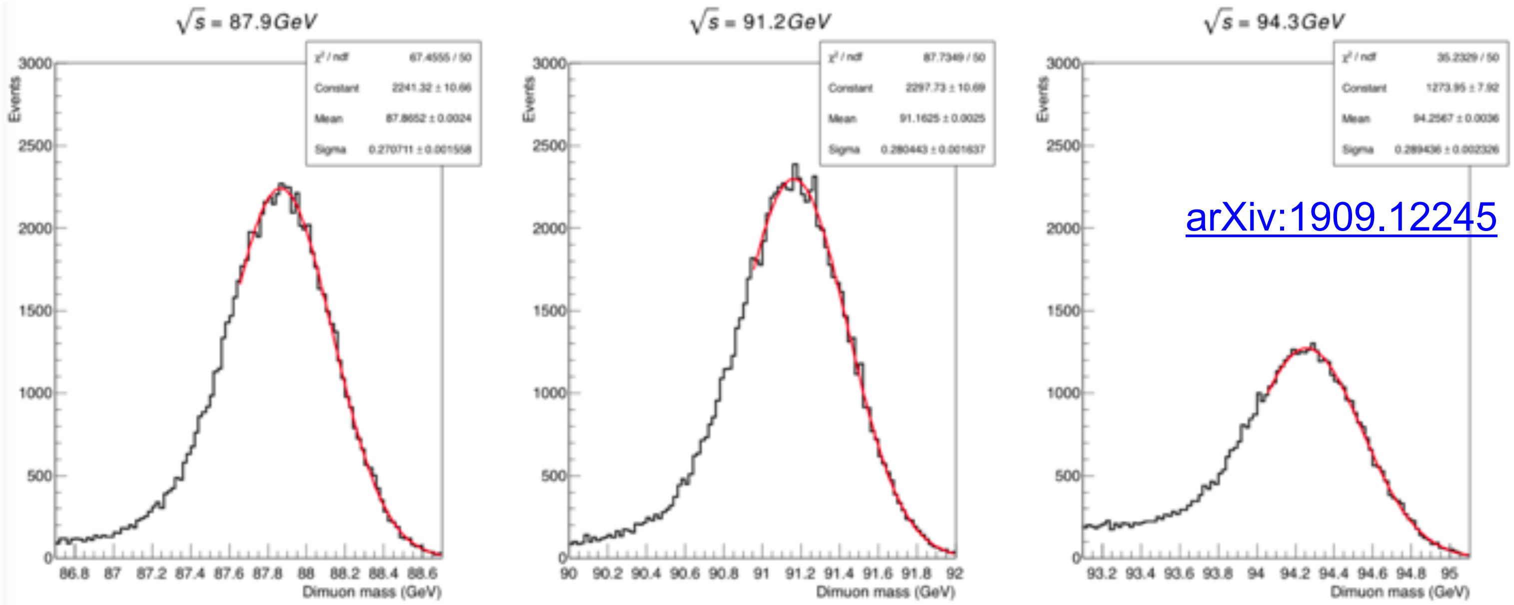
To be comparable with HL-LHC, would need a resolution ~ 4x better than what was assumed here (very light tracker and large field)

i.e. even with excellent tracker, unlikely to be improve wr.t. the HL-LHC measurement

Stability of the magnetic field (of the tracker scale)

Determination of Γ_Z : key = Relative uncertainty of $\sqrt{s}$ between the different energy pts.

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



[arXiv:1909.12245](https://arxiv.org/abs/1909.12245)

With σ(M, res) ≈ 300 MeV (Si tracker): relative δ($\sqrt{s}$) could be controlled to O(40 keV)

provided the stability of the scale, esp. of B, to that level, i.e. 40 keV / 90 GeV < 10^{-6}

- see talk on Wednesday, Matthias Mentink
- may also be monitored using the J/ψ (0.15 $J/\psi \rightarrow$ μμ per 1000 had. events) with an excellent (few MeV) σ(M) of $J/\psi \rightarrow$ μμ

NB: A point-to-point uncertainty of O(40 keV) corresponds to σ(Γ_Z) ~ 25 keV (still quite large compared to the stat. error = 4 keV)

Vertex detector

- VXD has to be precise, thin, low power (no pulsing), readout electronics should integrate over less than O(1 μs) (backgrounds)

- Current requirements on impact parameter resolution inherited from former Higgs studies at ILC / CLIC :

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\text{m}; \quad b \simeq 15\,\mu\text{m}\,\text{GeV}$$

- Will be revisited in the FCC-ee context: precise Hcc, Hbb, Hgg determination

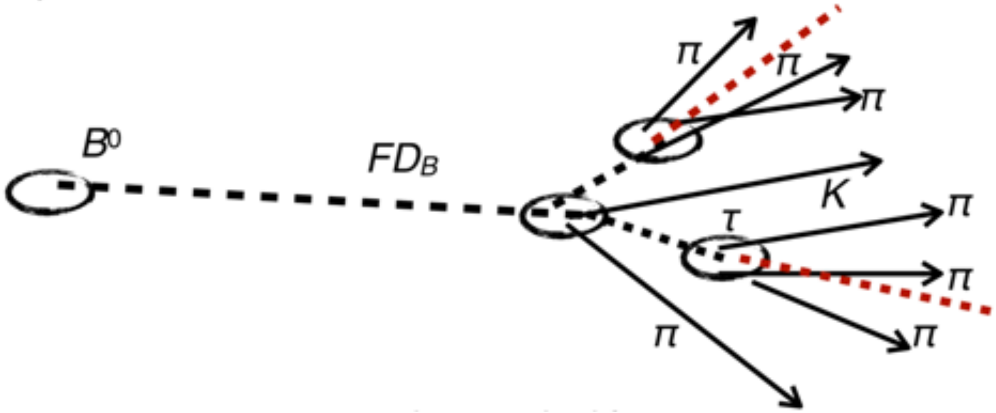
- Requirements from EW Heavy Flavor observables R_b, R_c, $A_{FB}^{b,c}$

  Anticipate large improvements in the HQ EW observables
  - 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

Vertex detector: Flavour physics

Example of usage in exclusive decays : B → K* τ τ

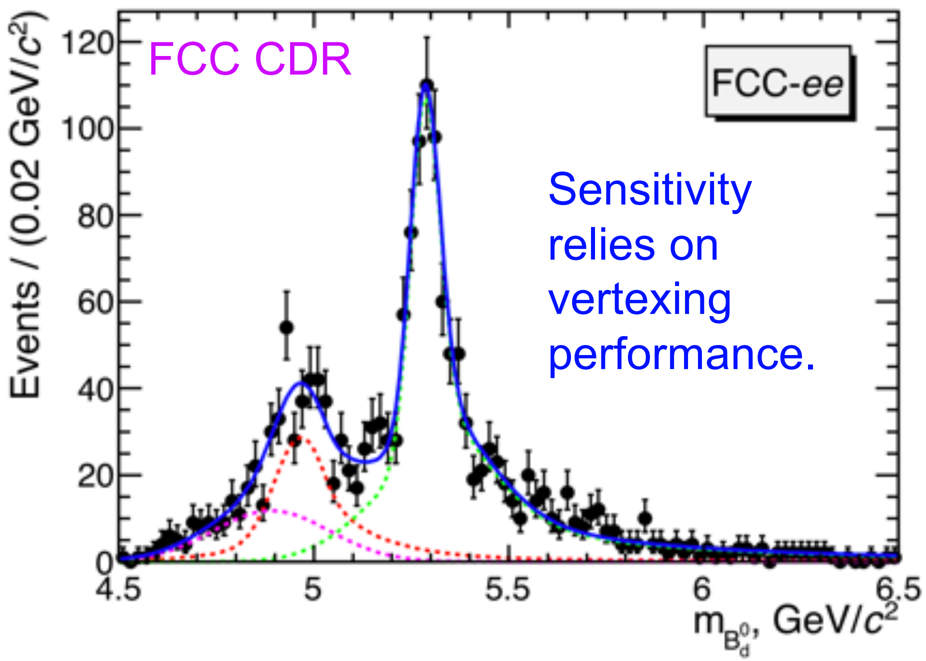
Lepton Flavour Universality is challenged in b → s transitions at LHCb. Models that explain these deviations usually predict large enhancements in b → s τ τ. And B → K* τ τ is a "model killer".



With both τ → 3 pi: with a precise determination of the 2ary vtx (Kpi) and of the two 3ary vertices, the kinematics is overconstrained (SV and TVs give the directions of both taus)

With σ(PV) = 3 µm, σ(SV) = 7 µm , σ(TV) = 5 µm :
> 1000 evts of reco'ed signal.

Measurements of angular properties of the decay possible. Likely unique to FCC.



Vertex detector : Taus

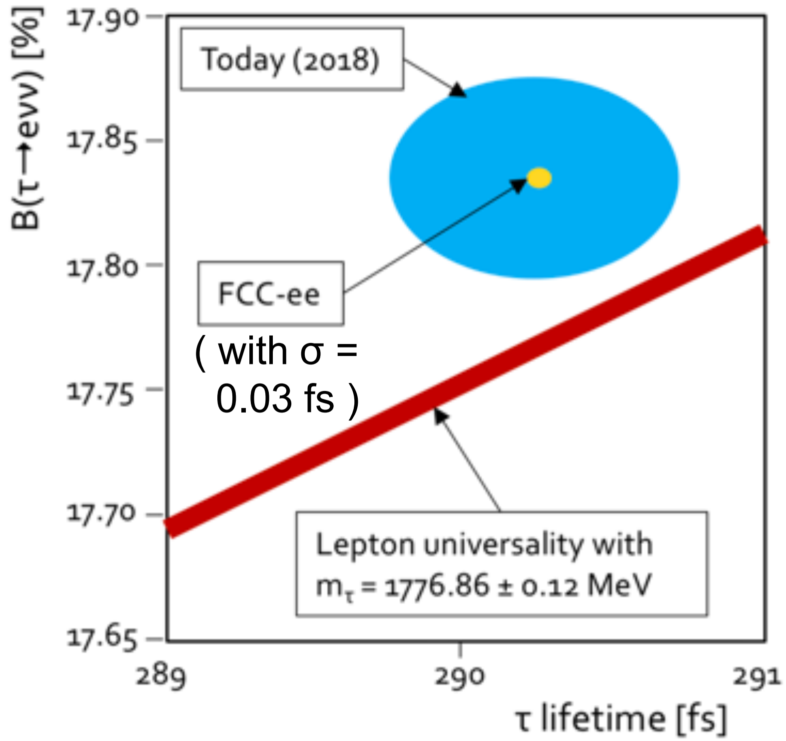
- Tau lifetime : current average: 290.3 ± 0.5 fs
- Best single measurement from BELLE : 290.17 ± 0.53 (stat) ± 0.22 (syst) fs
  - From reconstructing the decay length in 3-prong decays
  - Dominant systematics (alignment of the vertex detector) in the shadow of the stat. uncertainty

[arXiv:1811.09408]

FCC-ee: stat uncertainty = 0.001 fs

Allows a precise test of lepton τ - μ universality.

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



$\Delta\tau$ = 0.001 fs would correspond to a few tens of nanometers on the flight-distance.

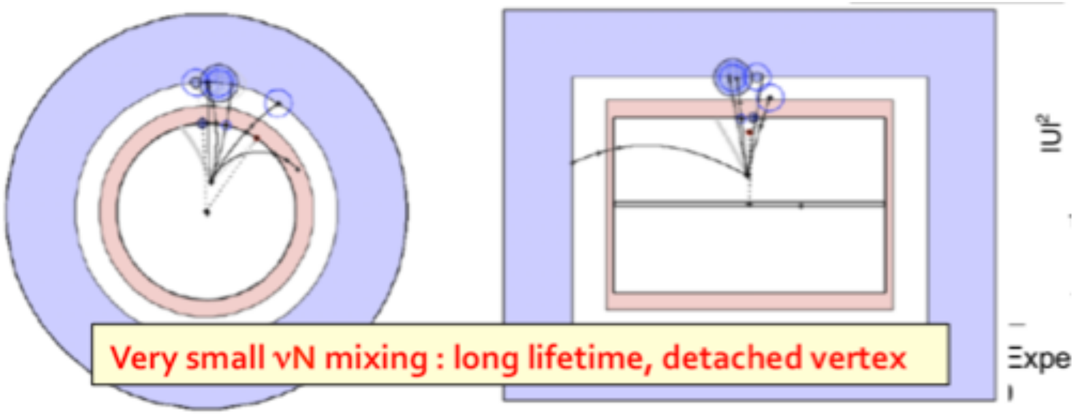
Likely to set requirements on the offline alignment and on the overall radial scale of the vertex detector, to be determined.

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.

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

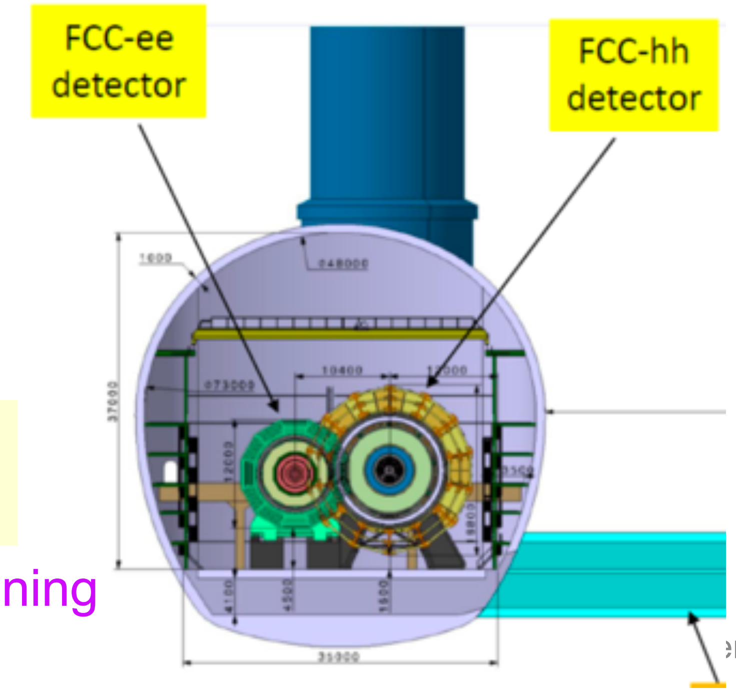


Searched for in rare $Z \to \nu$ N decays
Followed by $N \to$ Wl or Z ν

Reconstruct far-detached (~ m) vertices

Two detectors will sit in the very large caverns foreseen for the subsequent FCC-hh detectors

- Deep underground (180 m / 300 m)
- 66m x 35m x 35m (L x W x H)



Complementarity: one IP could accommodate a very large detector.

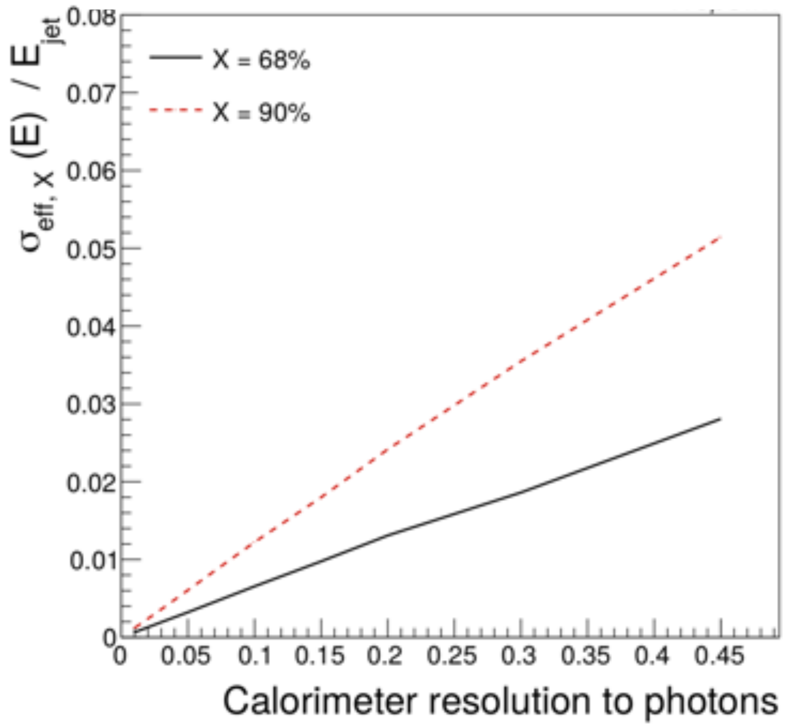
See M. Mannelli and J .Hajer, Thursday evening

Electromagnetic calorimeter

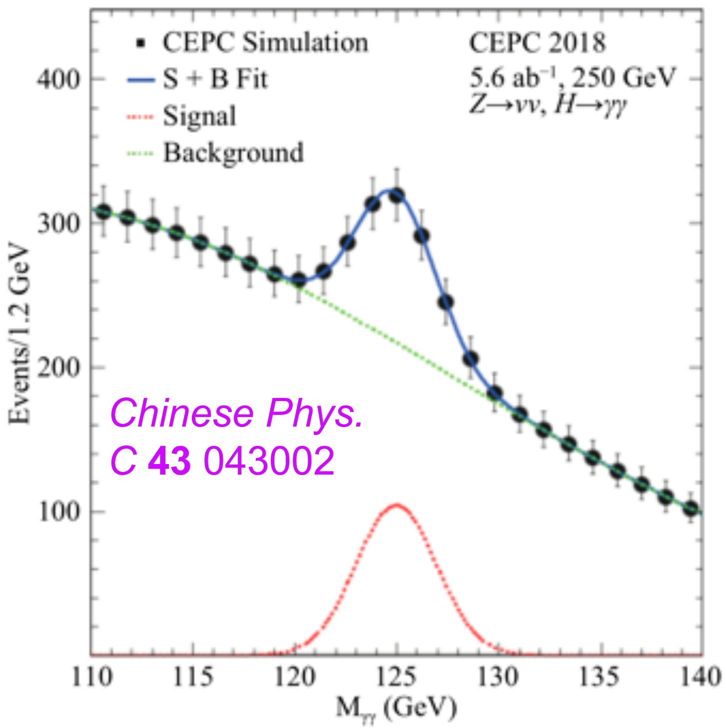
M.T Lucchini et al, arXiv:2008.00338

- Photons: typically 25% of the jet energy

15% / √E on γ's sufficient to ensure a jet energy resolution < 3% for O(50 GeV) jets, using a particle-flow algorithm to reconstruct the jets.



- H → $\gamma\gamma$?



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With σ(E) / E = 16% / √E +1% and mass resolution of 3% : expected precision on the σ(ZH) x BR(H→$\gamma\gamma$) is O(6%).

O(x2) worse than the HL-LHC predictions.

Would need a very small stochastic term and a constant term << 1% to compete with HL-LHC.

Electromagnetic calorimeter

See Roy Aleksan, Wednesday morning

EM resolution much better than 15% / √E needed for :

- B physics: e.g. $Bs \rightarrow Ds\ K$ in modes with Pi0's may require 5% / √E
- Separation of $Z \rightarrow \nu_e \nu_e$ from the other neutrinos (single photon events, radiative return) also requires 5% / √E
- Maximal sensitivity to rare / forbidden processes, $Z \rightarrow \tau$ e or μ e, $\tau \rightarrow \mu\ \gamma$

and would be useful for :

M.T Lucchini et al, arXiv:2008.00338

- performant FSR recovery on electrons : with 3% / √E, resolution of Mrecoil in Z(ee)H events would be only 20% larger than in Z(μμ)H evts
- Clustering photons from Pi0s, prior to jet reconstruction – improves the jet resolution

EM Granularity :

- Very good transverse granularity required e.g. for tau physics
- Requirements on the resolution of photon position and angles to be studied

Jets and resolution of hadronic systems

Role of calorimeter(s) = complement the tracking system, with the goal of a pure and efficient identification of individual particles in the final state, and of their reconstruction (i.e particle-flow reconstruction).

- At ILC / CLIC : $\sigma(E_{jet}) / E_{jet} \sim 30\% / \sqrt{E_{jet}}$ to separate $Z \rightarrow jj$ from $W \rightarrow jj$
- For FCC: requirements on the resolution on the energy, momentum and mass of hadronic systems (Z, W or H –> had.) to be determined
    - In many final states, fully constrained kinematics + mass constraints: jet energies can be inferred from angular measurements.
    - In other cases: jet energies from PF algorithm: tracking + good calorimeter granularity + basic particle identification (+ calorimeter resolution)
        - Example case: separation of $ee \rightarrow H\nu\nu$ (via g_{WWH}) from HZ with $Z \rightarrow \nu\nu$
            - Important for Γ_H determination
            - Key = resolution on the missing mass

Particle Identification

- Need excellent lepton and photon ID
  - Separation e / γ, γ / π0, e / π, μ / π,
  - and excellent photon / neutral hadron separation (neutral had = KL, n, etc ..): very important for particle-flow reconstruction
  - Constraints from many analyses
- Also in collimated topologies, e.g. for tau polarisation measurement

- π / K separation : essential in the range 1 – 10 GeV
  - From spectrum of kaons in b $\rightarrow$ c $\rightarrow$ s decay chain
  - Example: Bs $\rightarrow$ Ds K
    - Fully charged mode, Ds $\rightarrow$ Φ π : signal can be separated from Ds π background with excellent pT resolution
    - With neutral (Ds $\rightarrow$ Φ ρ^-) : an excellent ECAL energy resolution is not enough, PID is mandatory.
- Ideally at higher momentum too, up to 30-40 GeV (τ physics)
- Not easy to cover the whole range of interest within the space and hermiticity constraints

Conclusions

- Work in progress to determine the requirements on the detector performance or design that must be satisfied to ensure that the systematic uncertainties of the measurements are commensurate with their statistical precision.

- The usage of the data themselves, in order to reach the challenging goals on the stability and on the alignment of the detector, in particular for the programme at and around the Z peak, will also be studied.

- The potential for discovering very weakly coupled new particles, in decays of Z or Higgs bosons, could motivate dedicated detector designs that would increase the efficiency for reconstructing the unusual signatures of such processes.