FCC-ee Physics performance and detector requirements

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Detector requirements from the exp. environment and from physics

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

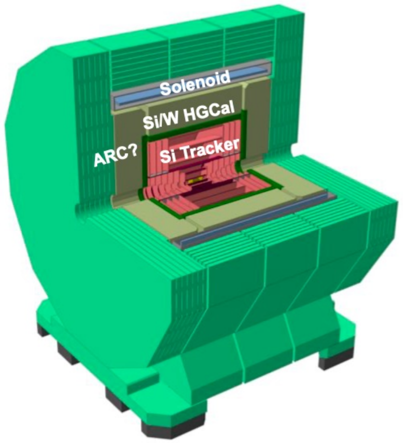
- Exp. environment at FCC-ee ≠ LC
  - E.g. no power pulsing of electronics, more cooling for VXD or less power
  - Specific conditions at the Z peak: large physics event rates (100kHz), small bunch spacing (approx. 20 ns)

- 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)

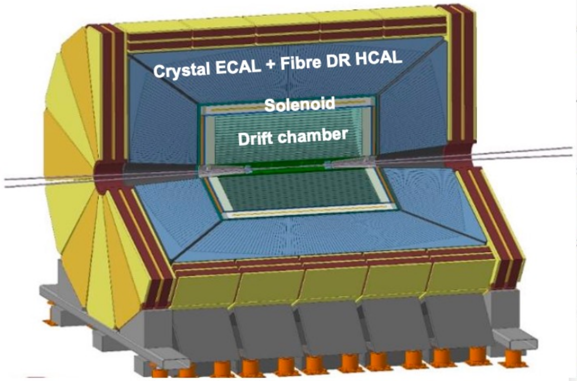
- Up to 4 detectors are considered for FCC-ee. Could be some complementarity w.r.t. the physics reach.

Detector benchmarks : existing / oldish (adapted) proposals

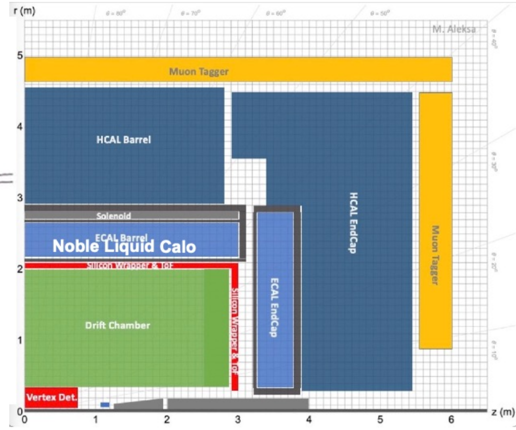
CLD



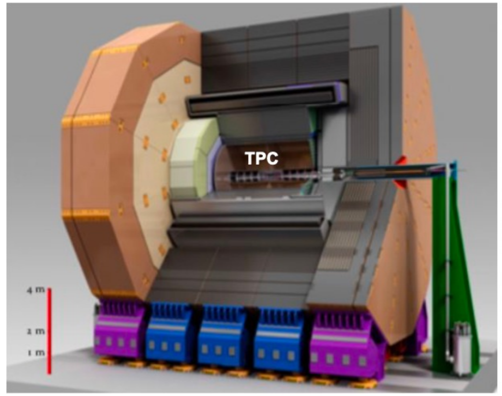
IDEA



ALLEGRO



ILD



(CLD and IDEA considered in the CDR)

More details [in the next talk !

Silicon Vertex Detector

Main tracker : Silicon (CLD), or gaseous detector - drift chamber (IDEA) , TPC ?)

Calorimeter: High-granularity Si/W, or dual readout, or noble liquid

Muon system

Context of post-CDR exp. studies

Current understanding of detector performance and det requirements summarized in the PED chapter of the Feasibility Study mid-term review report. Being updated for the final report, to be sent as input to the ESU process

- Most analyses documented in FCC notes, to become public soon

Most physics analyses use a fast simulation of the response of the detector

- baseline chosen: IDEA detector

Variations around this baseline, study the sensitivity of several benchmark analyses or measurements

- e.g.compare different tracker designs (gaseous vs silicon)
- or change parameters in the simulation model, e.g. material budget, single hit resolution of vertex detector, etc

Performance studies in FullSim have also started

A few examples shown here.

- Some emphasis on what is new / not a mere repetition of LEP / LHC
- Some areas where further work is needed are highlighted in red

Vertex detector

Drives: impact parameters; reconstruction of secondary vertices; flavour tagging; measurement of lifetimes

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

[IDEA baseline: a ≃ 3 μm]

- Distance to beam line
- single hit resolution
- Material budget (MS)
- Beam-pipe transparency

- Jet flavour tagging
  - Benchmark: Uncertainty on Hcc and Hbb couplings. Not much affected by reasonable degradation w.r.t.baseline performance (e.g. material budget).

- Precise reconstruction of displaced vertices
  - Two examples for which better performance than IDEA baseline is desirable :

Meas. of $B \to K^* \tau\tau$
- Complex analysis !
- Only had tau decays so far

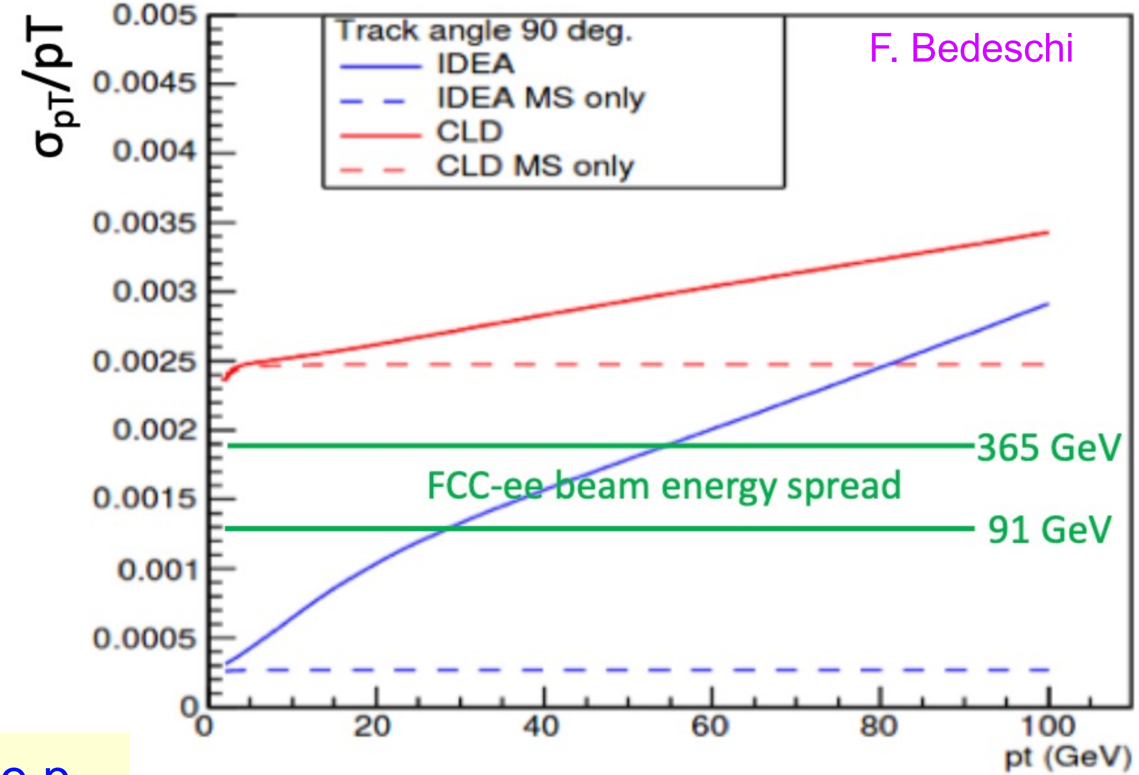
Meas. of Rc using exclusive decays
- Rc = Γ(Z -> cc) / Γ(Z -> had)
- Exclusive tagger, double-tagged events: high purity, low systematics
- New ! Not possible at LEP because of statistics

Main tracker: track momentum resolution

$$\sigma(p_T)/p_T^2 = a \oplus \frac{b}{p \sin\theta}$$

mult.scat

resolution



Full Si tracker (CLD) : in the energy range of interest, resolution is dominated by the multiple scattering

Importance of transparency in the p range of FCC-ee !

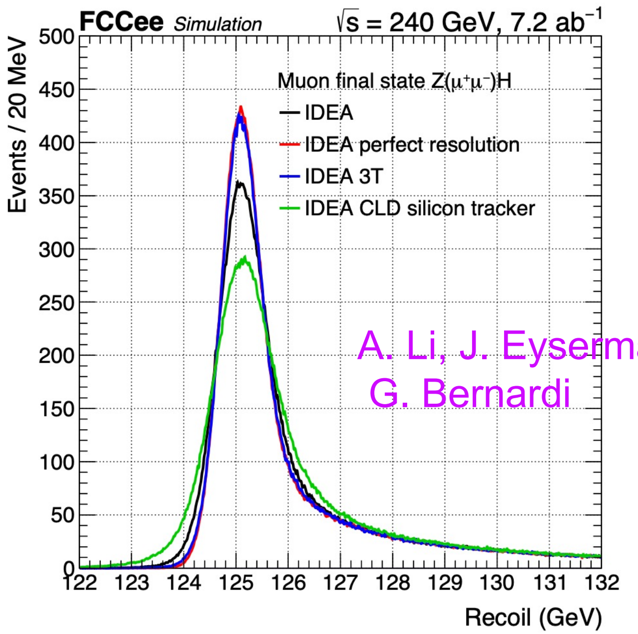
Ideally: $\sigma(p) / p \approx$ rel. BES

Light drift chamber of IDEA close to this limit.

At 90 degrees:

	IDEA	CLD
10 GeV	0.6 ‰	2.5 ‰
50 GeV	1.5 ‰	3 ‰

Track momentum resolution: examples



A. Li, J. Eysermans, G. Bernardi

Unique to lepton colliders: ZH events tagged by the Z

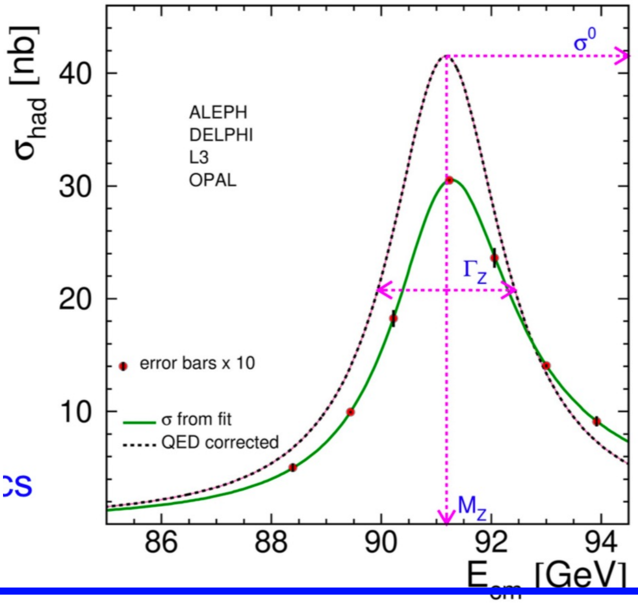
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}}$$

A fit to the recoil mass distribution allows a meas of:

- σ(ZH), independent of the Higgs decay mode
- **the Higgs mass**

Goal: $\Delta(m_H) \sim \Gamma_H \sim 4$ MeV !

~ reached with IDEA's drift chamber or with CLD Si tracker after combining with ee channel.
For this use case, both tracker designs meet the reqs.



Dominant systematic uncertainty on the **Z width**: point-to-point uncertainty on √s
With $\delta(\sqrt{s})_{ptp} \sim 10$ keV, syst. uncertainty on Γ_Z would be 5 keV, at the level of the stat. !

Can be controlled in –situ from μμ events (peak position of M μμ at various √s).

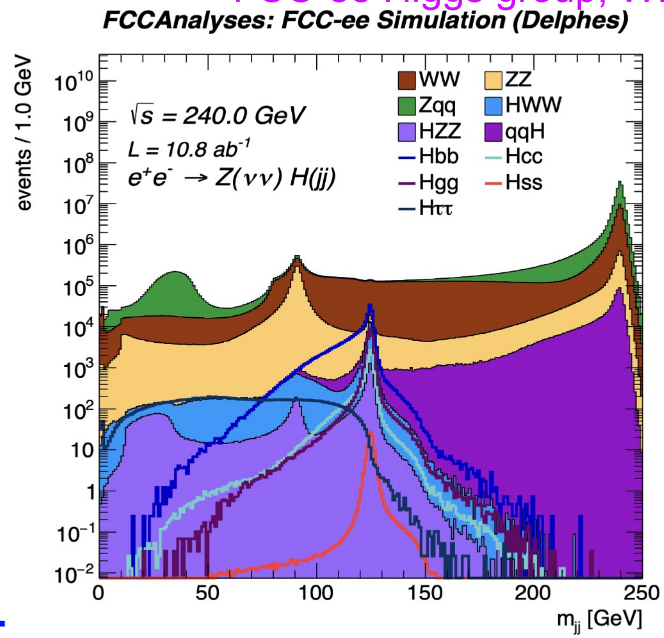
- Imposes tight constraints on p resolution and momentum scale stability
- Optimal analysis techniques still to be developed

Charged hadron PID – needed in a broad p range

Gaseous tracker: powerful separation via ionisation measurements, dE/dx or dN/dx
TOF measurements at 2m from the IP: fill the gap around 1 GeV
- but TOF alone: pi/K separation at low p only, e.g. 3σ up to 3 (5) GeV with 30 (10) ps resol

Compact RICH: design exists, could provide separation in whole p range

FCC-ee Higgs group, WIP



Benchmark processes considered:
- Several flavour physics processes
- Higgs to strange coupling
  - Tantalising possibility for a 50% measurement of s Yukawa with 10 ab-1
  - Needs excellent K/π separation up to 40 GeV for rejecting H→gg contamination and Z→qq
  - Also excellent resolution on visible mass

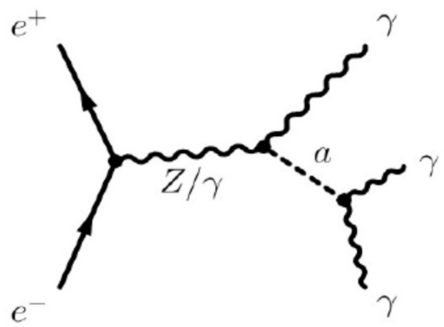
Requirements have been set and studied in fast simulation,
- but can we meet them with a real detector?
- we need a fully working Particle-Flow algorithm with integrated PID
- an ML-PF approach would allow to quickly iterate between different detector full simulation implementation

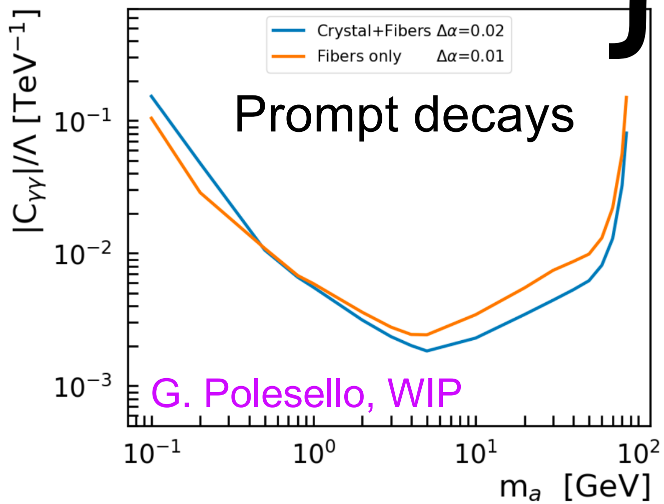
Calorimetry: examples

- Benchmark processes studied for the resolution of hadronic masses: Higgs physics (Hss, Higgs to invisible), one HNL signal

- Photons and electrons:
  - Flavour physics - e.g. Bs versus Bd in final states with pi0's or photons
  - Recovery of brem photons
  - pi0's from tau decays in Z $\rightarrow \tau\tau$, for τ polarisation
  - Axion-like particles

} Still WIP, FullSim studies





Blue: better E resolution
Orange: better granularity

Long-lived ALPs: Pointing photons ?

- Precise photon angle determination: should allow an in-situ determination of the acceptance for ee $\rightarrow \gamma\gamma$ events (lumi to 10^{-5})
  - New method, exploiting kinematic constraints and crossing angle, full potential yet to be established !

Muon detector

- Main objective: identify muons with high efficiency + tail-catcher for had showers

- Standalone measurement of track's momentum
  - Useful to identify pions that decay in flight and reduce the pion contamination
  - Also relevant for LLPs that decay outside of the tracker volume
  - Requirements on standalone resolution need to be quantified.

Timing measurements

- TOF measurements
  - For PID: see earlier, e.g. at 2m from the IP, in dedicated layer or in SiW Ecal
  - Determination of mass and lifetime of new massive particles. Example: HNL: need resolution < 50 ps

- Time measurements very close to the IP
  - Allows a determination of the ”event t0”
    - Robust reference for the TOF measurements
    - Width of t0 distribution -> independent determination of the BES
    - Exploit correlation between t0 and longitudinal position (within the bunch) of the interacting electrons
  - Achieving precise timing measurements in the innermost layer of the VXD, without compromising heavily the material budget, will probably be a challenge.

- Time measurements in the calorimeters
  - Handles to exploit the shower development in space and time
    - Possible benefit remains to be studied in detail
  - DR calo: precision timing -> longitudinal segmentation

Conclusions

Several analyses have been developed in the past years, from which some requirements on the detectors can be inferred

- comparison of gaseous vs silicon detector
- importance of low mass, high granularity vertex detector
- charged hadron PID is not only needed for flavour physics !

More robust statements on the requirements on calorimetry require full simulation studies with a realistic particle-flow reconstruction.

Several other areas where further work is needed, e.g.

- precision with which basic EW observables can be measured
- required precision on alignments and other fiducial markers
- muon detector, needs for precise timing
- …

Additional material

Some references and useful reading (oldish but still relevant)

- **FCC Conceptual Design Reports**
  - Vol. 1 – Physics; Vol. 2 – FCC-ee; Vol. 3 – FCC-hh : 1338 authors
    - Preprints (Jan. 2019) on http://fcc-cdr.web.cern.ch
    - Published in EPJ C (Vol. 1) and EPJ ST (Vol. 2 & 3)

- **Symposia and workshops, with many further details**
  - Public presentation of the CDR, 4-5 March 2019: https://indico.cern.ch/event/789349/
  - Physics workshops (Jan. 20, Nov. 20), FCC Week 2019: https://indico.cern.ch/category/5225/

- **Other useful documentation, to extend and deepen knowledge**
  - FCC-ee: Your questions answered – https://arxiv.org/abs/1906.02693
  - Circular vs Linear colliders: Another story of complementarity – https://arxiv.org/abs/1912.11871
  - Theory calculations for FCC-ee – https://arxiv.org/abs/1809.01830 & https://arxiv.org/abs/1905.05078
  - Polarization and centre-of-mass energy calibration at FCC-ee - https://arxiv.org/abs/1909.12245

Some useful reading beyond the CDR

- **EPJ+ special issue "A future Higgs and EW Factory: Challenges towards discovery"**

All 34 references in this Overleaf document: https://www.overleaf.com/read/xcssxqyhtrgt

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MDI, √s

Challenges to match statistical precision

Detector requirements & possible solutions

Theory challenges

Software and computing challenges

P. Janot — ECFA Plenary Meeting 19 Nov 2021 — 8