FCC-ee Physics performance and detector requirements

E. Perez (CERN)

November 22, 2023

4th FCC-France workshop, November 2022, Strasbourg

Context of post-CDR exp. studies

1st documentation of detector requirements was one of the mid-term review PED (Physics, Detectors & Experiments) deliverables

Current understanding of detector performance and det requirements summarized in the PED chapter of the FS mid-term review report.

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

Most physics analyses use a fast simulation of the response of the detector concepts presented in the CDR

- Radius of the central beam-pipe reduced from 1.5 cm to 1 cm, allowing the 1st layer of the vertex detector to be closer to the beam line
- variations around these baselines, study the sensitivity of several benchmark analyses or measurements

Performance studies in FullSim are also starting

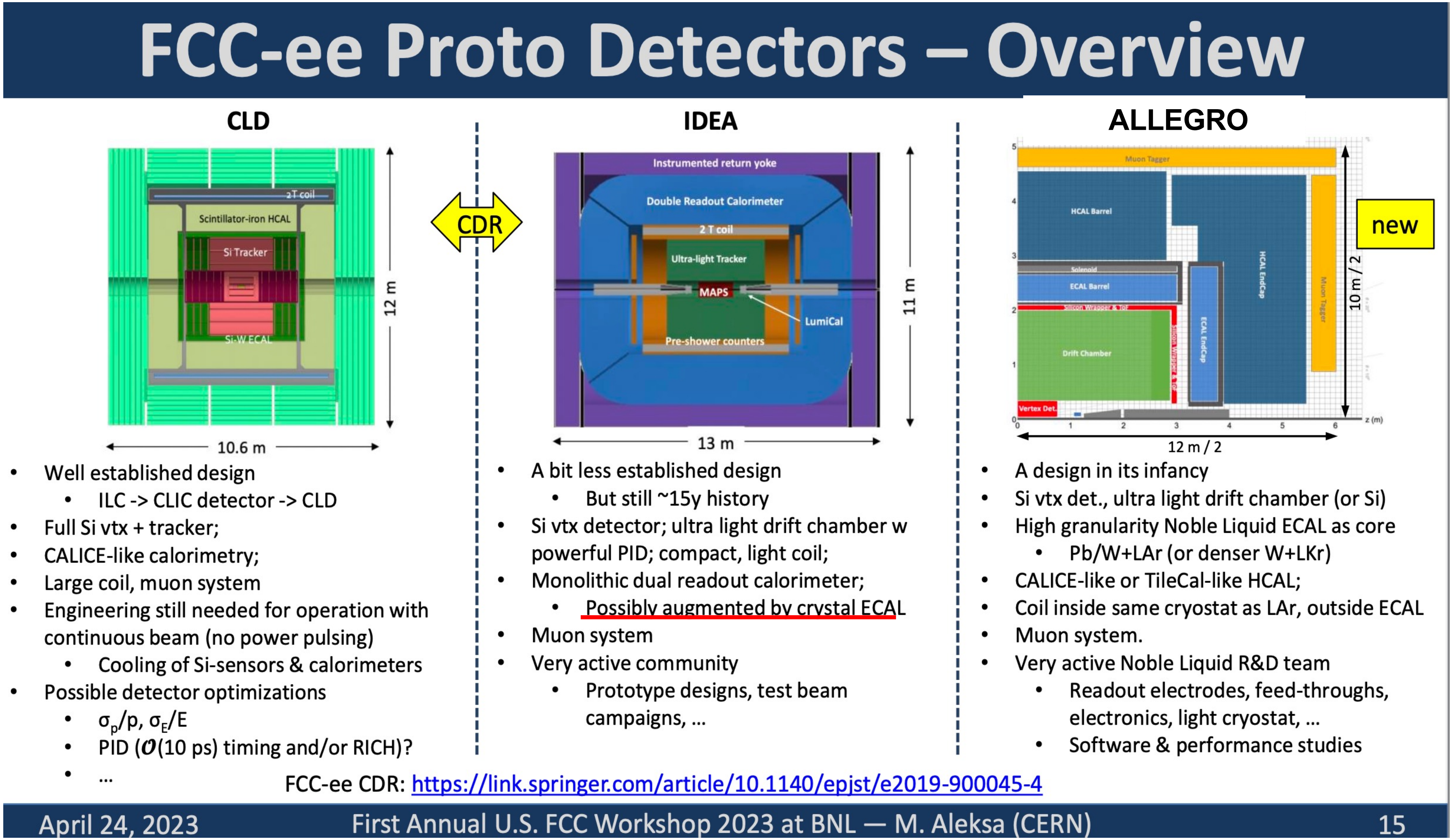
Detector requirements from the exp. environment and from physics

- 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.



FCC-ee Proto Detectors – Overview

CLD

- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

IDEA

- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO

- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

April 24, 2023 First Annual U.S. FCC Workshop 2023 at BNL — M. Aleksa (CERN) 15

Crystal ECAL in front of DR used for Delphes simulations shown here

Vertex detector

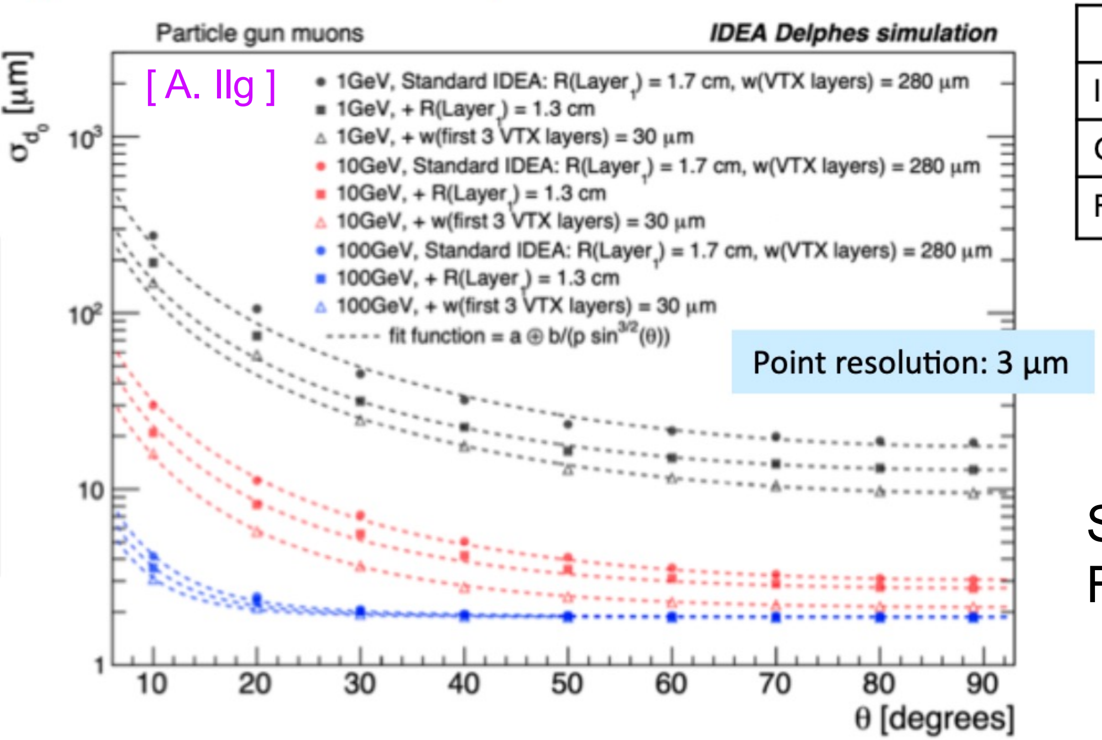
Drives: impact parameters; reconstruction of secondary vertices; flavour tagging; measurement of lifetimes

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

[ILC / CLIC : a ≃ 5 µm and b ≃ 15 µm/GeV]

- Distance to beam line
- single hit resolution
- Material budget (mult. scattering)
- Beam-pipe transparency

- Closer (■), lighter (△): Substantial improvement on impact parameter resolution in particular at low momenta



Point resolution: 3 µm

A. Ilg, L. Freitag, 6th FCC Physics Workshop

	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee / CEPC	10 mm	12 mm

Central beam-pipe:
0.67% / sin θ of X0

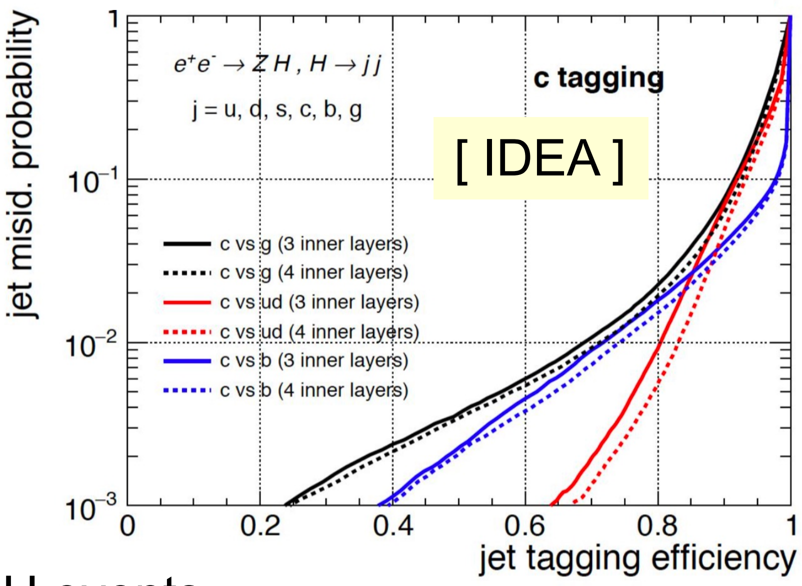
Similar performance studies in FullSim with CLD @ IPHC
[J. Andrea, G. Sadowski, Z. el Bitar]

Vertex detector: flavour tagging

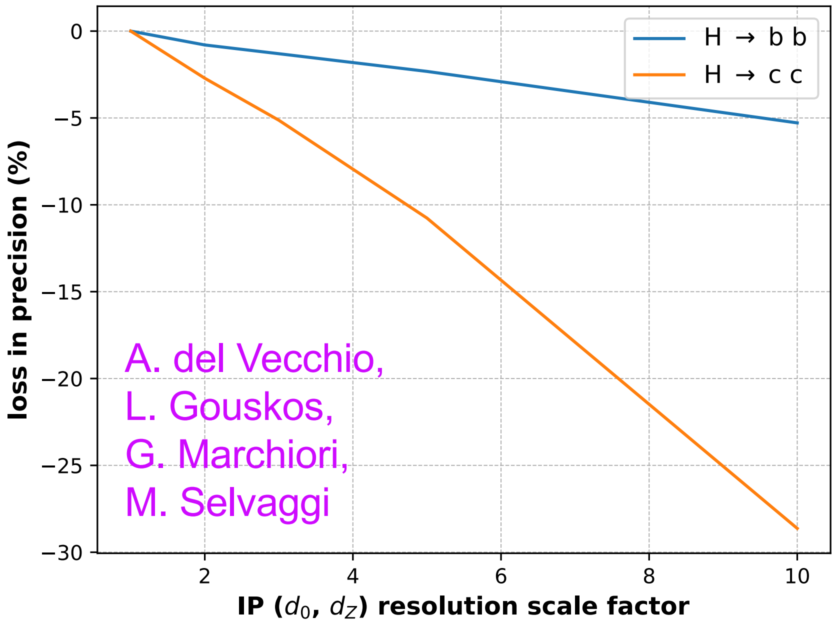
- Key to meas. of Hgg and Hqq couplings
  - These measurements = main motivation developing state-of-the-art tagging algorithms
  - Algorithms based on advanced Neural Networks: see e.g. arXiv:2202.03285

Position of innermost layer of VXD: smaller BP reduces by x2 the mistag rate for c-tagging.

L. Gouskos, M. Selvaggi, F. Bedeschi



- Higgs coupling prospects in Z(ll)H and Z(nunu)H events



A. del Vecchio,
L. Gouskos,
G. Marchiori,
M. Selvaggi

Evts in orthogonal categories, simultaneous fit of M_{recoil} and M_{vis}

Baseline IDEA, 10 ab^{-1} :

H → bb	H → cc	H → gg	H → ss
0.28%	2.1%	0.85%	100%

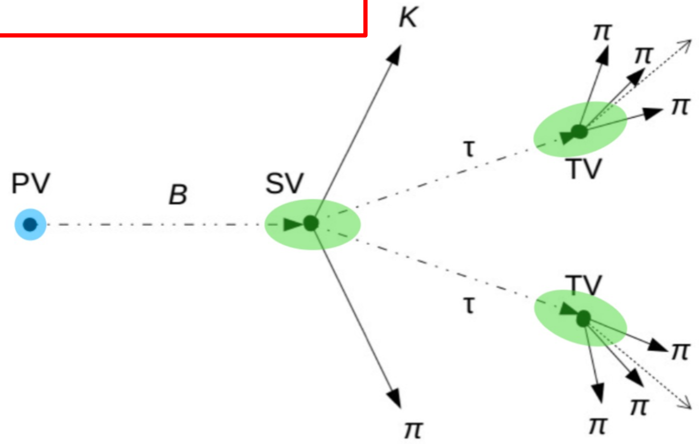
Hbb not much affected by worsening of IP resolution, but Hcc is (lower S/B)

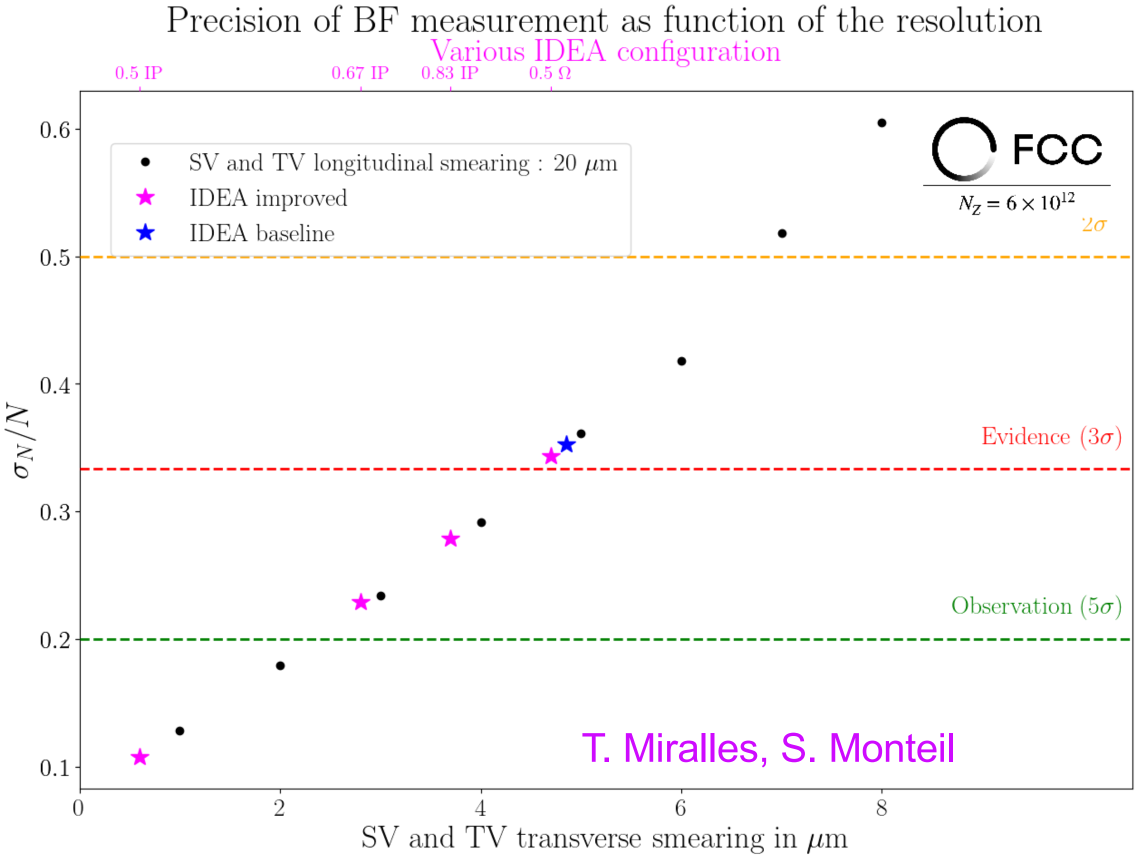
Vertex detector: precise reconstruction of displaced vertices

Current IDEA:
- primary vertex reco'ed to 2-3 µm in x,z and a few 10's of nm in y with BSC
- secondary vertices in B decays: typically 10 µm – 80 µm

Tighter constraint from B → K* $\tau\tau$

With both τ → 3π, vertexing allows the decay to be fully reco'ed - complex analysis !





T. Miralles, S. Monteil

W.r.t. IDEA baseline, resolution on IPs must be improved by 10% (40%) to reach the 3σ (5σ) threshold

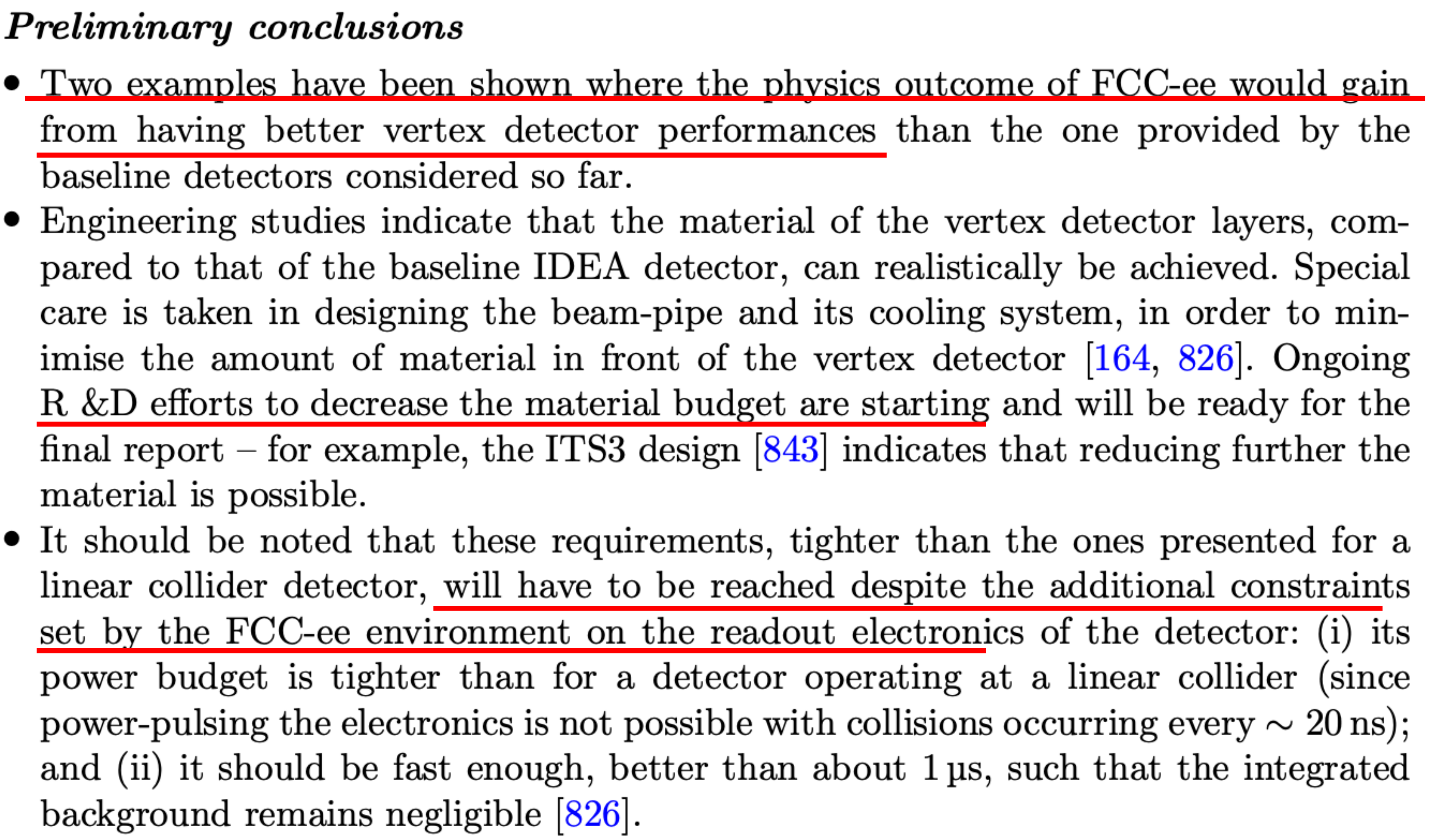
e.g. reduction VXD material by 35% and improving single hit resolution by 30% : 3.7 σ

E.Perez

Vertex detector: work ahead & preliminary conclusions

Work in progress: requirements from heavy-quark EW measurements

L. Rohrig,
S. Monteil



Preliminary conclusions

- Two examples have been shown where the physics outcome of FCC-ee would gain from having better vertex detector performances than the one provided by the baseline detectors considered so far.
- Engineering studies indicate that the material of the vertex detector layers, compared to that of the baseline IDEA detector, can realistically be achieved. Special care is taken in designing the beam-pipe and its cooling system, in order to minimise the amount of material in front of the vertex detector [164, 826]. Ongoing R &D efforts to decrease the material budget are starting and will be ready for the final report – for example, the ITS3 design [843] indicates that reducing further the material is possible.
- It should be noted that these requirements, tighter than the ones presented for a linear collider detector, will have to be reached despite the additional constraints set by the FCC-ee environment on the readout electronics of the detector: (i) its power budget is tighter than for a detector operating at a linear collider (since power-pulsing the electronics is not possible with collisions occurring every $\sim 20\,\mathrm{ns}$); and (ii) it should be fast enough, better than about $1\,\mu\mathrm{s}$, such that the integrated background remains negligible [826].

Main tracker: track momentum resolution

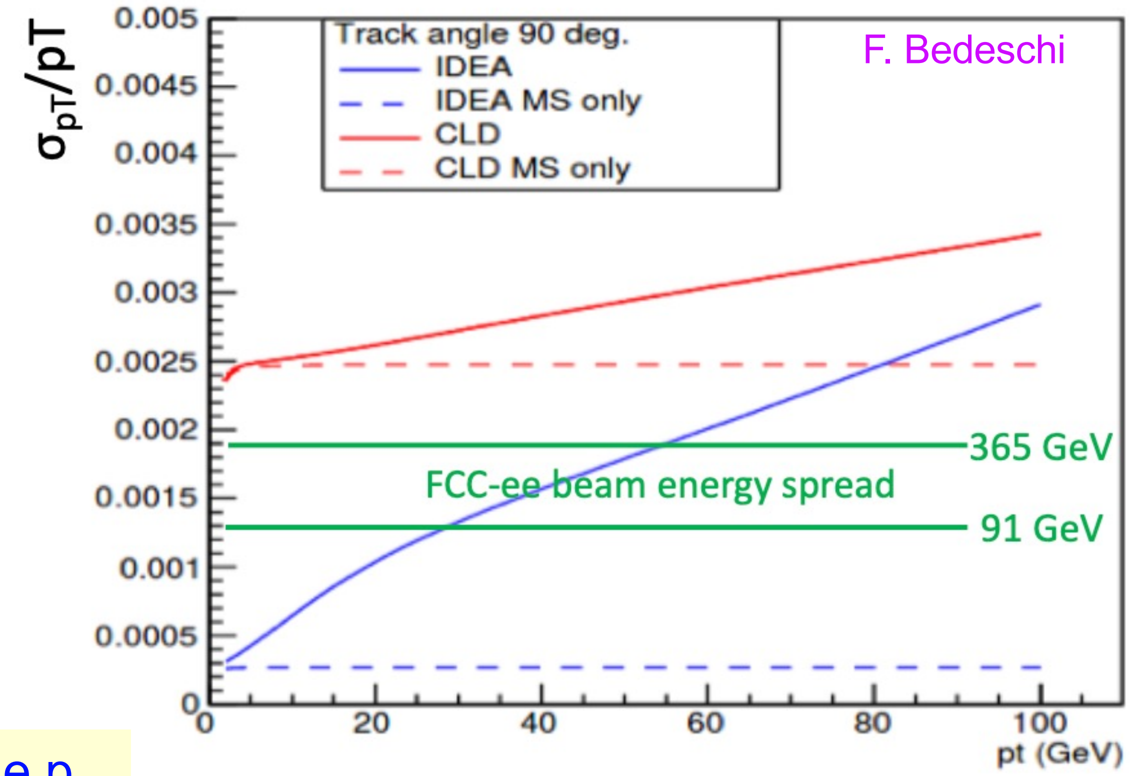
$$\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}^2 = \underbrace{a}_{\text{resolution}} \oplus \underbrace{\frac{b}{p\sin\theta}}_{\text{mult.scat}}$$

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: σ(p) / p ≈ rel. BES

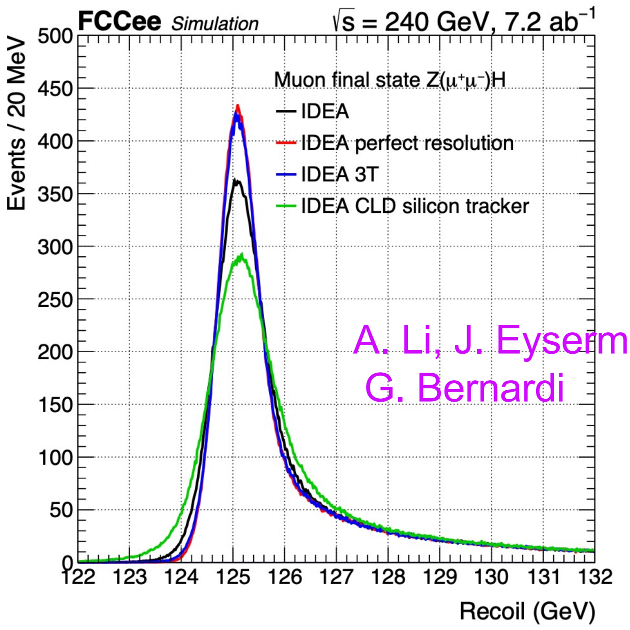
Light drift chamber of IDEA close to this limit.



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

$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2$$

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

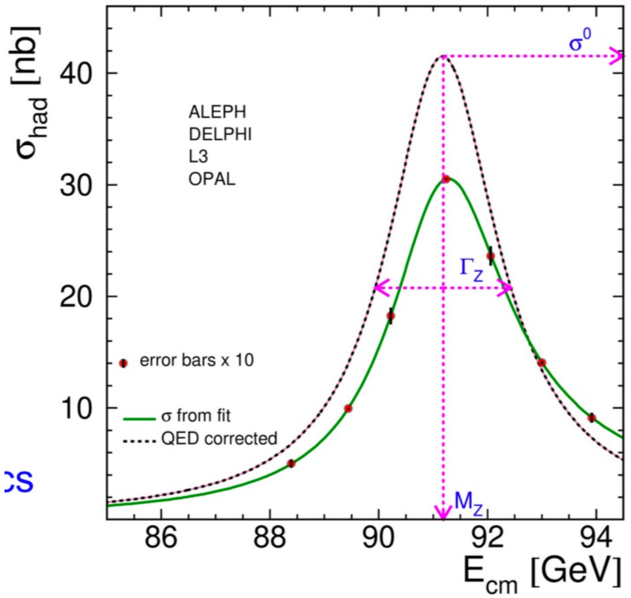
- σ(ZH), independent of the Higgs decay mode
- **the Higgs mass**

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

~ reached even w CLD after combining with ee channel

μμ channel only, 7.2 ab-1

Ideal resol	3.95 MeV
IDEA (2T)	5.5 MeV
CLD (2T)	6.1 MeV
IDEA (3T)	4.3 MeV



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

With exquisite p resolution:

- δ(√s)$_{\text{ptp}}$ from μμ events (peak position of M μμ at various √s).
- Control of p scale (B stability) to a few 10^{-7} using low mass resonances ?

Volunteer ?

Measurement of track angles

Angular resolution in IDEA / CLD varies between 20 µrad (high p, central) and a few mrad (soft, forward)

- Mass resolutions in processes considered remains completely dominated by the track momentum resolution.

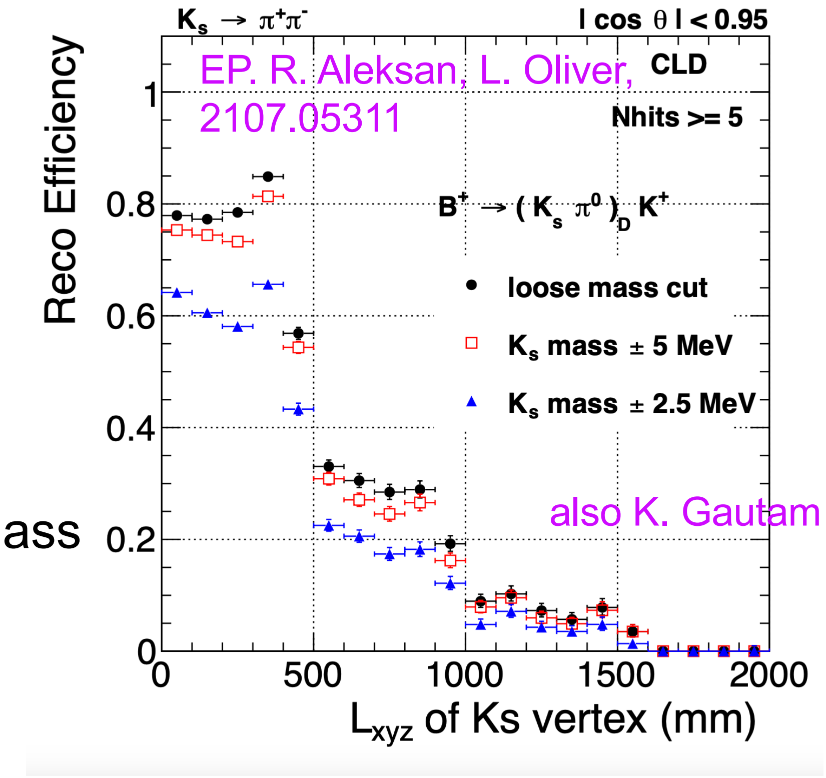
- Many measurements inferred from angles only in ee → µµ(γ) thanks to over-constrained kinematics:
  - Determination of the beam-energy spread, crossing angle
  - of the beam energies asymmetry
  - of √s at ZH and above from angles only

[P. Janot, 1909.12245]

For the BES and crossing angle: a resolution of 100 µrad is enough. Systematic uncertainty of the determination of the energy asymmetry requires further work, may call for better angular resolutions.

- Methods under development to determine acceptances in situ may set tighter requirements on the angles, and/or on external alignment systems.

Main tracker: other considerations



EP. R. Aleksan, L. Oliver, 2107.05311

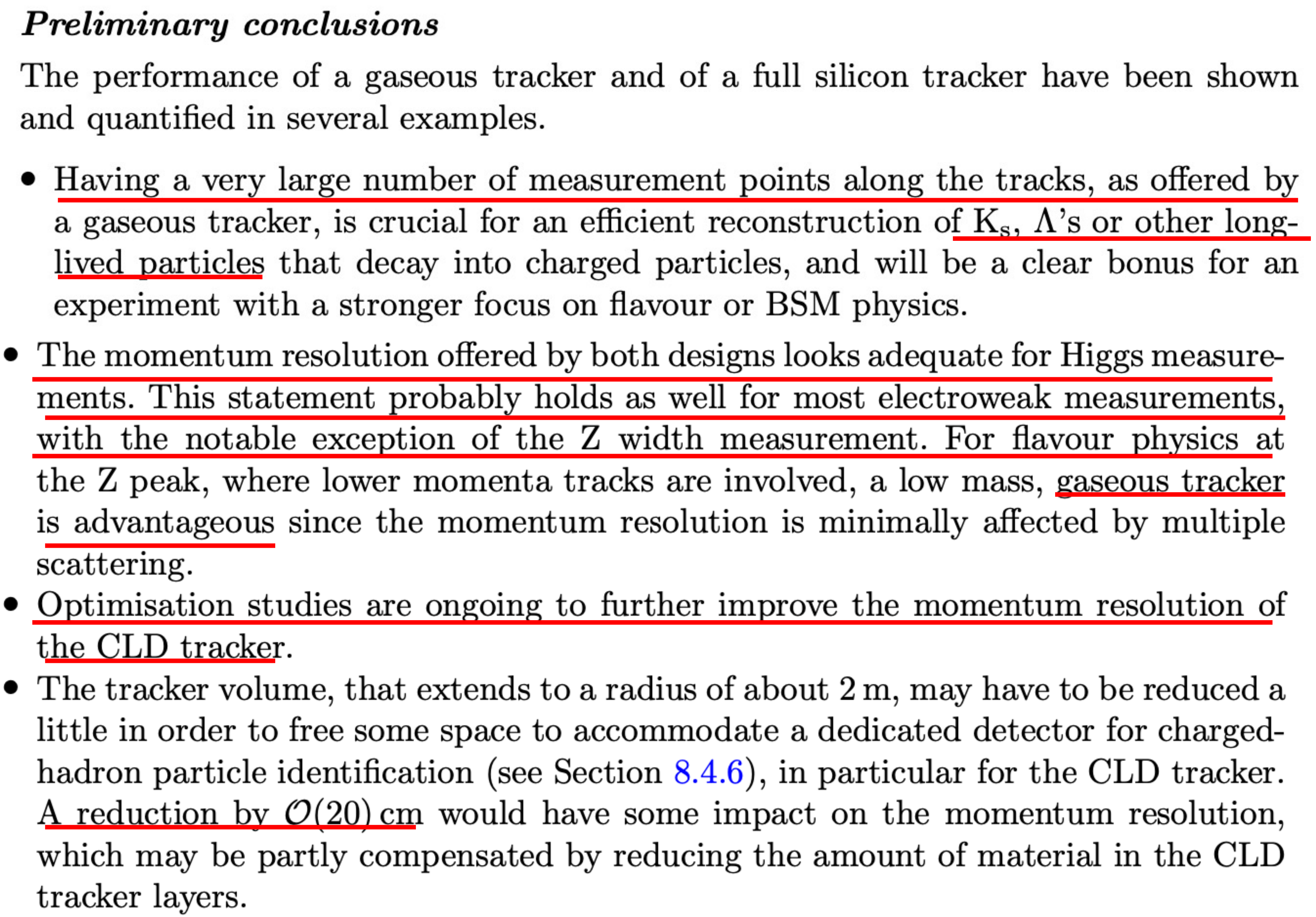
also K. Gautam

- Many layers and large volume for Ks or LLPs

- Ability to separate close-by tracks
  - E.g. Bs to Phi Phi to 4 K
  - $\tau \rightarrow$ 5p ? Could be interesting for a tau mass measurement

- Track acceptance and efficiency :
  - High efficiency crucial for particle-flow
    - NB: Minimal tracker material also helps PF - limits the number of photon conversions and hadronic interactions
  - And for precision EW measurements, e.g. $R_\mu = \Gamma(Z \rightarrow \mu\mu) / \Gamma_Z$: stat precision about 5×10^{-6} at TeraZ
  - And down to very low p e.g. for some flavour measurements
    - E.g. B → K* $\tau\ \tau$ with $\tau \rightarrow$ 3p, need acceptance down to ~ 150 MeV, achieved in current designs

Main tracker: preliminary conclusions



Preliminary conclusions

The performance of a gaseous tracker and of a full silicon tracker have been shown and quantified in several examples.

- Having a very large number of measurement points along the tracks, as offered by a gaseous tracker, is crucial for an efficient reconstruction of K_s, Λ's or other long-lived particles that decay into charged particles, and will be a clear bonus for an experiment with a stronger focus on flavour or BSM physics.
- The momentum resolution offered by both designs looks adequate for Higgs measurements. This statement probably holds as well for most electroweak measurements, with the notable exception of the Z width measurement. For flavour physics at the Z peak, where lower momenta tracks are involved, a low mass, gaseous tracker is advantageous since the momentum resolution is minimally affected by multiple scattering.
- Optimisation studies are ongoing to further improve the momentum resolution of the CLD tracker.
- The tracker volume, that extends to a radius of about 2 m, may have to be reduced a little in order to free some space to accommodate a dedicated detector for charged-hadron particle identification (see Section 8.4.6), in particular for the CLD tracker. A reduction by $\mathcal{O}(20)$ cm would have some impact on the momentum resolution, which may be partly compensated by reducing the amount of material in the CLD tracker layers.

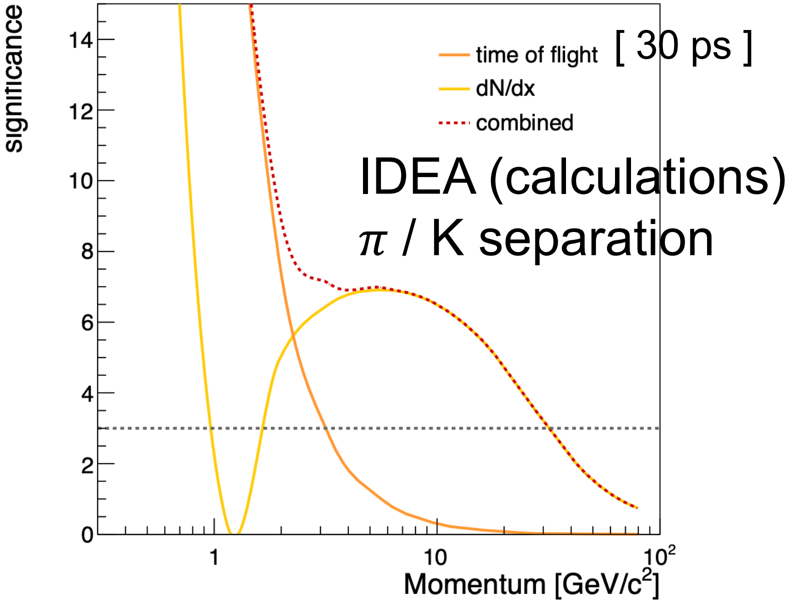
Charged hadron PID

- Essential for flavour physics / spectroscopy - from very low p to ~ 40 GeV
- Key input for strange tagging

Gaseous tracker: powerful separation via ionisation measurements, dE/dx or dN/dx
- IDEA DC: resolution of dN/dx typically 2% (calculations)

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

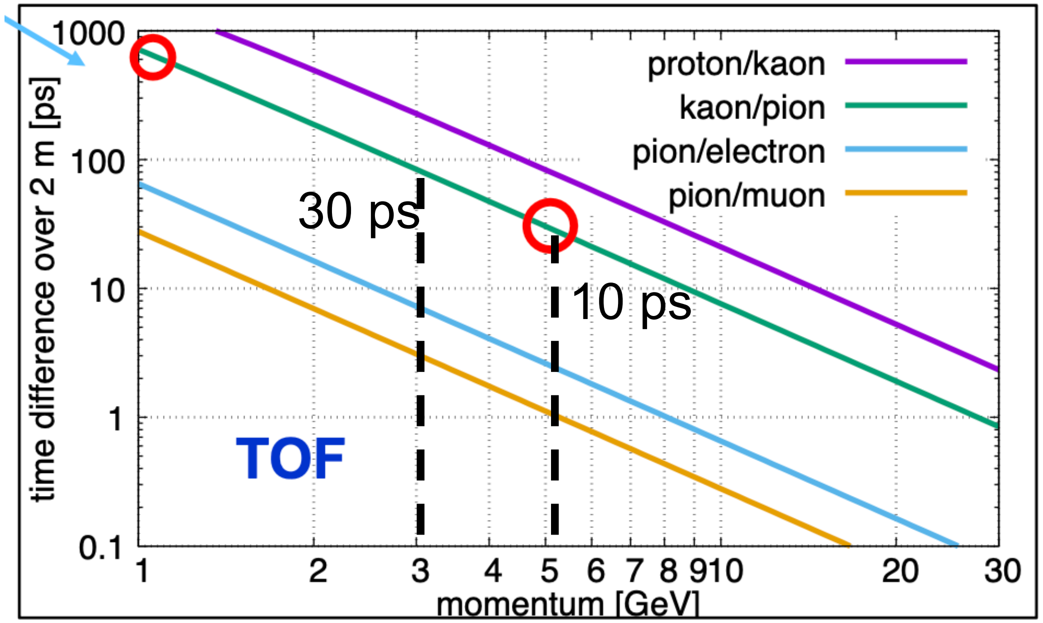
Compact RICH: design exists, could provide separation in whole p range



[30 ps]

IDEA (calculations)
π / K separation

M. Dam



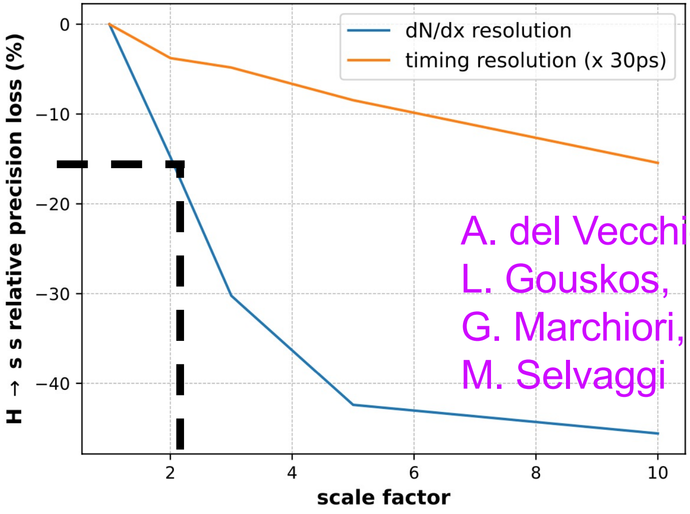
30 ps

10 ps

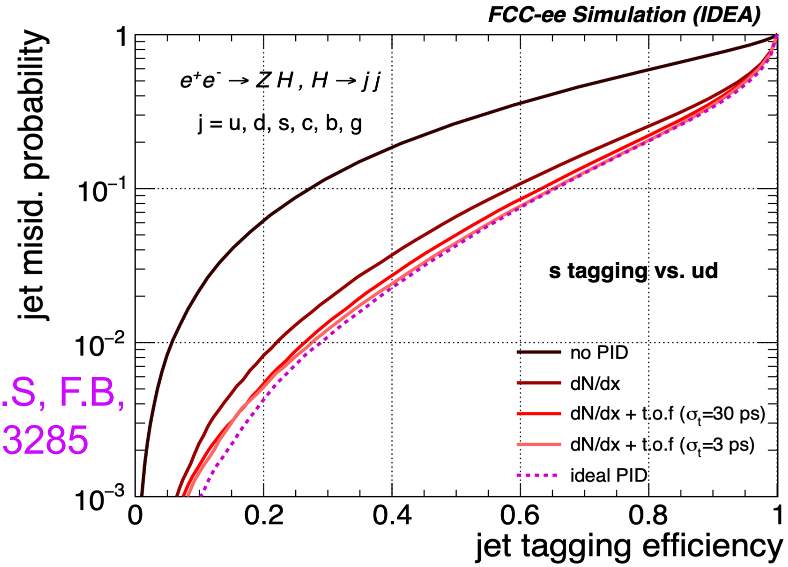
TOF

PID performance: examples

With 10 ab-1: Higgs to ss coupling could be measured to ~ 50%



A. del Vecchio,
L. Gouskos,
G. Marchiori,
M. Selvaggi

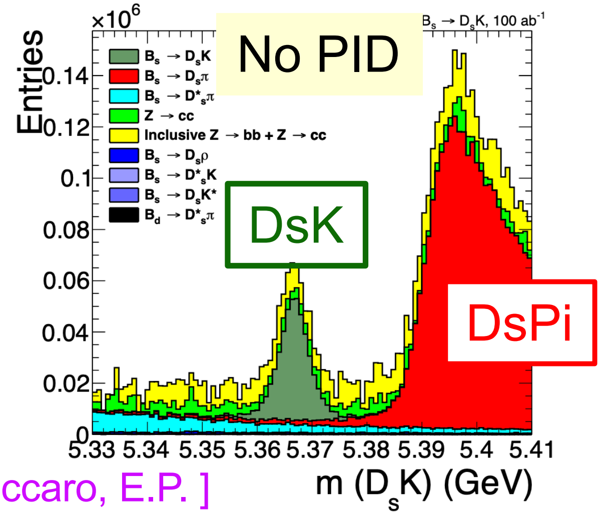


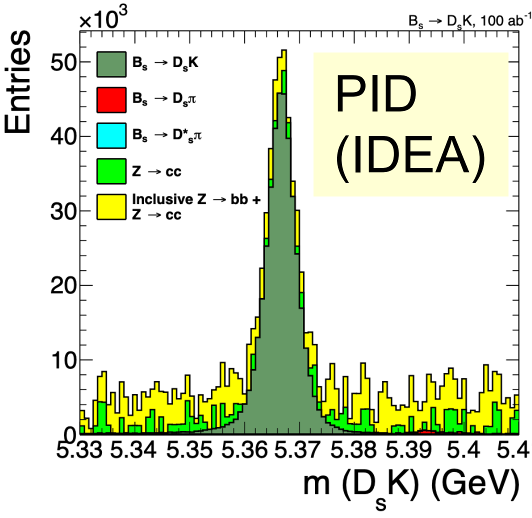
L.G, M.S, F.B,
2202.03285

Significant degradation of this expected precision if the dNdx resolution degrades: e.g. relative 15% worse with a resolution x2 worse.

Bs → Ds K (meas. of γ CKM)

PID needed even in modes with no neutrals !
Reduces by O(2.5) the bckgd contamination under the signal peak (green).

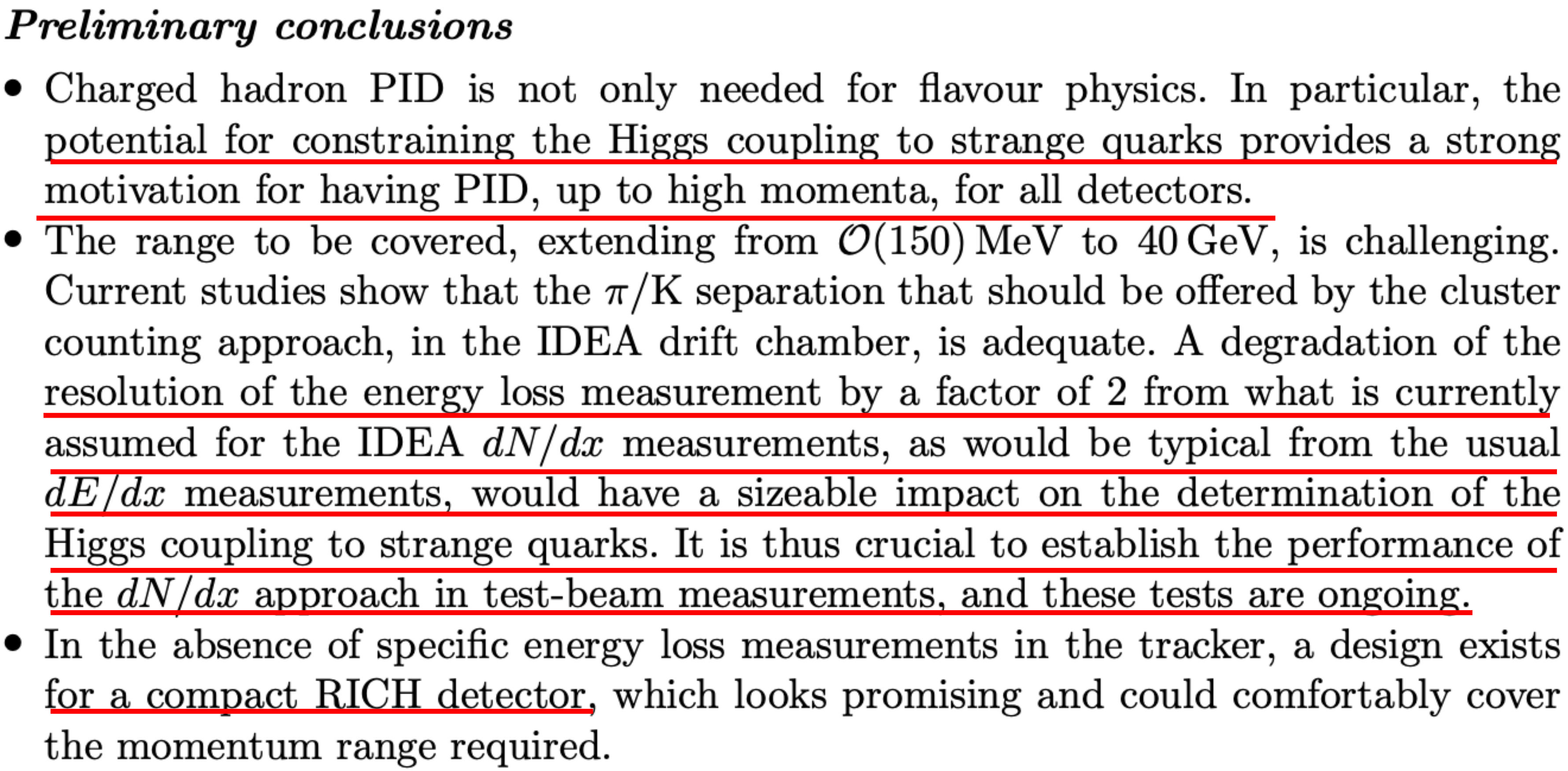




[R. Aleksan, F. Parodi, A. Coccaro, E.P.]

PID: preliminary conclusions and work ahead

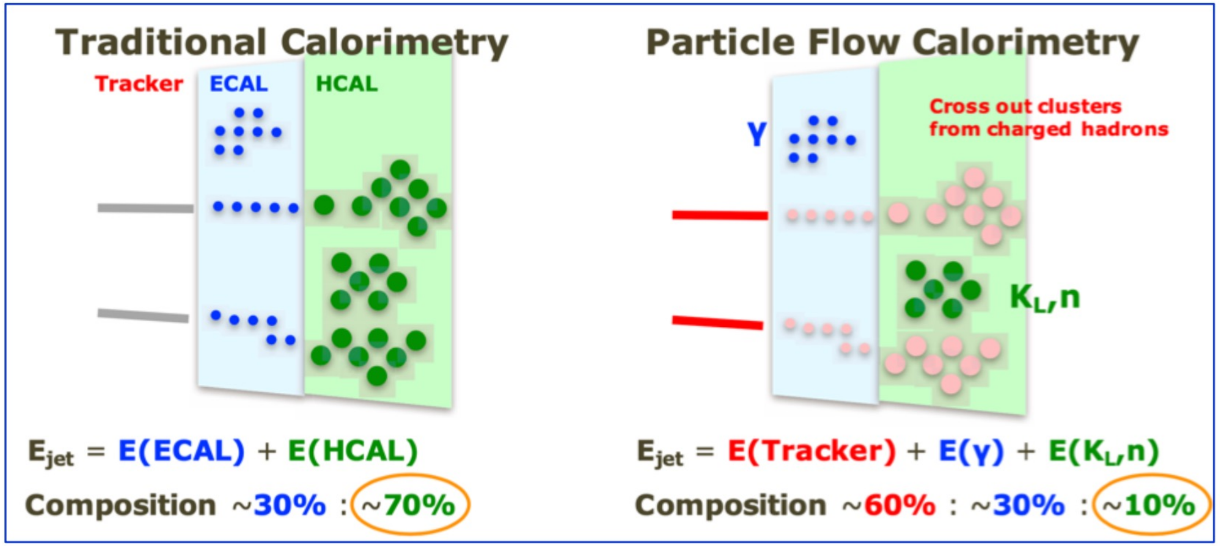
Work ahead: flavour tagging (Bs or Bsbar) using kaons (soft); Vcs from WW events; use of dNdx in e / pi separation (possible benchmark = BR(tau → e))



Preliminary conclusions

- Charged hadron PID is not only needed for flavour physics. In particular, the potential for constraining the Higgs coupling to strange quarks provides a strong motivation for having PID, up to high momenta, for all detectors.
- The range to be covered, extending from $\mathcal{O}(150)$ MeV to 40 GeV, is challenging. Current studies show that the π/K separation that should be offered by the cluster counting approach, in the IDEA drift chamber, is adequate. A degradation of the resolution of the energy loss measurement by a factor of 2 from what is currently assumed for the IDEA dN/dx measurements, as would be typical from the usual dE/dx measurements, would have a sizeable impact on the determination of the Higgs coupling to strange quarks. It is thus crucial to establish the performance of the dN/dx approach in test-beam measurements, and these tests are ongoing.
- In the absence of specific energy loss measurements in the tracker, a design exists for a compact RICH detector, which looks promising and could comfortably cover the momentum range required.

Calorimetry



CLD: sandwich calorimeter [ECAL: Si/W, HCAL: steel/scint] optimised for ParticleFlow (very fine resolution)

EM: $\sigma / E \sim 16\% / \sqrt{E}$
Jet energy resolution at 50 GeV: ~ 4%, i.e. separates $Z \to jj$ from $W \to jj$

ALLEGRO: noble liquid ECAL instead, EM resol $\simeq 7\% / \sqrt{E}$ or better

IDEA Dual Readout calorimeter: very good intrinsic calo resolution
$30\% / \sqrt{E}$ for single had, $13\% / \sqrt{E}$ for EM
transverse granularity down to 2 mm if each fiber is read out.
Option: crystal-based ECAL in front of the DR: EM resolution fo $3\% / \sqrt{E}$ (+ some longitudinal segmentation)

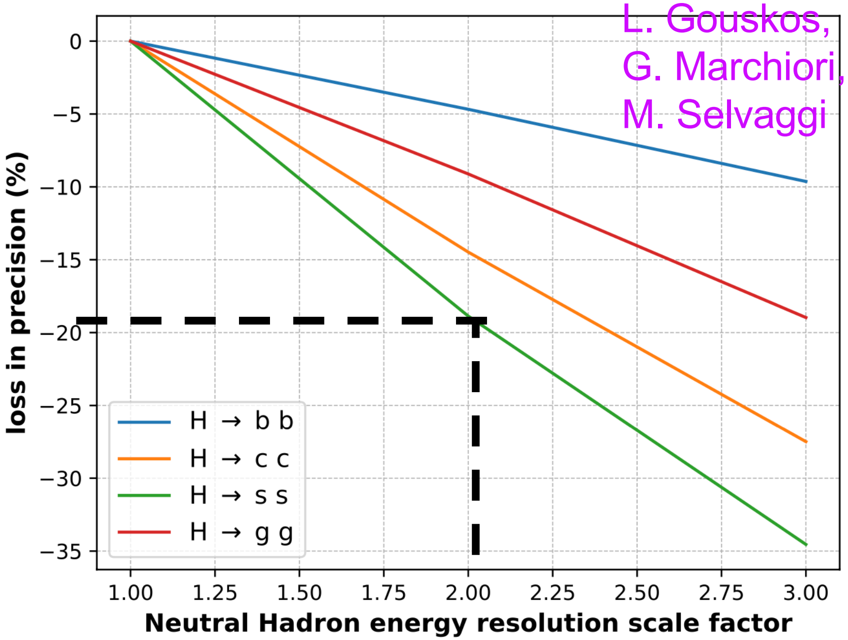
Calorimetry: impact of resolution on hadronic energies (examples)

[Delphes based, hence approximate]

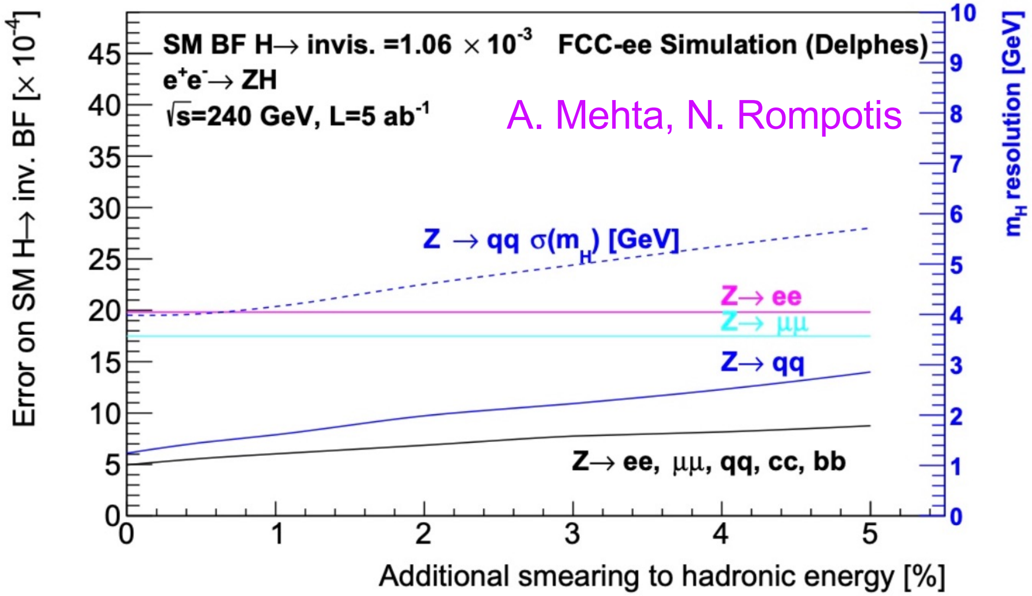
Resolution on hadronic masses matters for Higgs physics :

Higgs couplings from ZH evts w/ Z → ll or $\nu\,\nu$:

Hss coupling to 50% with 10 ab^{-1}. Precision degrades quickly with worse resolution, e.g. 20% worse with a x2 worse HCAL energy resolution.



A. del Vecchio, L. Gouskos, G. Marchiori, M. Selvaggi



A. Mehta, N. Rompotis

[also Higgs width: N. Morange, I. Combes]

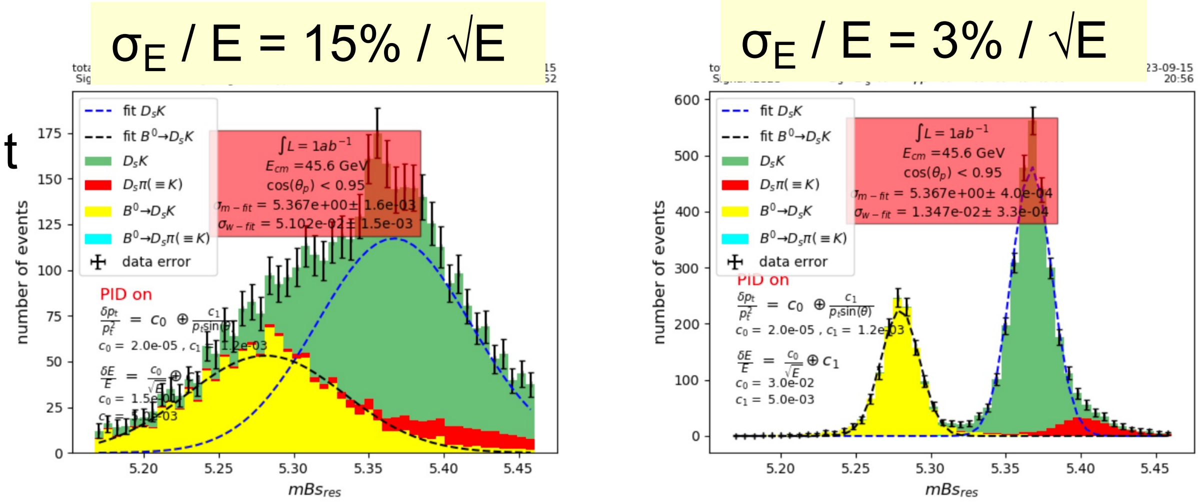
Higgs → inv: with a 50% worse Z → qq mass resolution, precision on invisible BR worsens by 80%.

Calorimetry: photons and electrons

Energy resolution: 10-15% / √E good enough for Higgs studies but flavour physics calls for better.

Example: Bs → Ds K, modes with neutrals

R. Aleksan



σ_E / E = 15% / √E

σ_E / E = 3% / √E

B0 background in yellow, Bs sisgnal in green

Identification of pi0's and pi0 / γ separation : importance of resolution and transverse granularity

e.g. pi0's from tau decays in Z → $\tau\tau$, for τ polarisation. Cf LEP experience.

at ECAL entrance, photons from pi0 decay separated by 2 cm or less

Full simulation is needed for this study.

Brem recovery: also demands granularity and resolution.

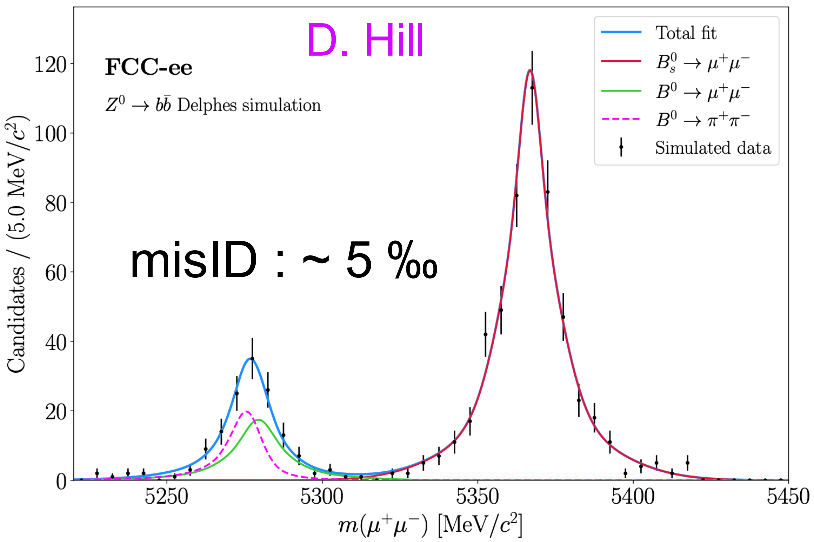
Precise photon angle determination: should allow an in-situ determination of the acceptance for ee → $\gamma\gamma$ events (lumi to 10^{-5}), WIP

Muon detector

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

Figure of merit: ID efficiency vs $\pi \rightarrow$ μ misID probability

Example benchmark: control of pion contamination in measurement of B -> mumu



misID : ~ 5 ‰

- 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

- 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 O(2 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.

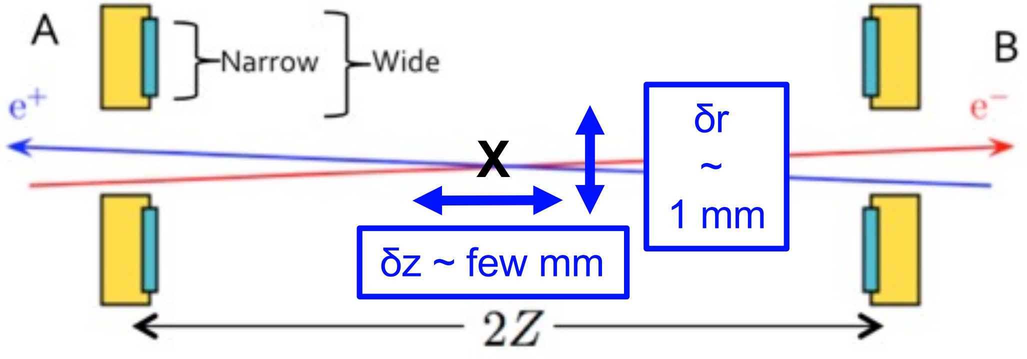
Several other areas where further work is needed by the end of the FS identified, e.g.

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

Backup, old slides

Key: Definition of and precision on the acceptance [LumiCal]

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 !
  - 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} .

challenging !

[P. Janot, FCC week London, 2023]

Luminosity measurement with $e^+e^- \to \gamma\gamma$ events

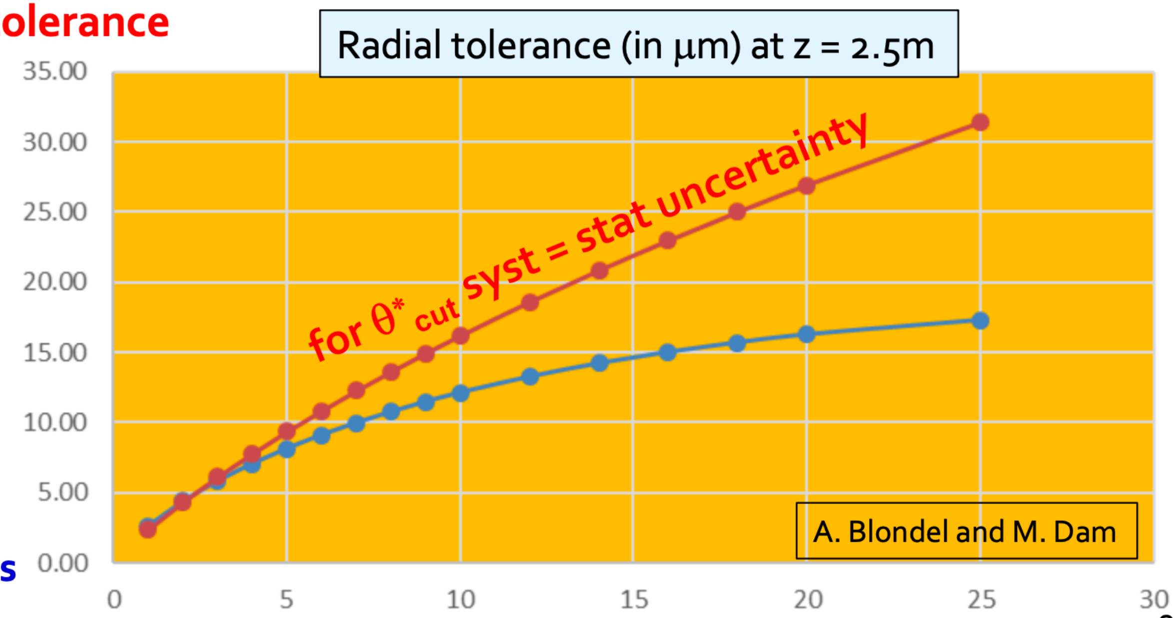
- **At the Z pole, σ_{tot} = 60 (40) pb for θ^*_{cut} = 10° (20°) – Total luminosity = 45 ab^{-1} / expt**
  - Total of 3 (2) 10^9 $e^+e^- \to \gamma\gamma$ events / expt $\Delta L/L \sim 2.10^{-5}$ stat
    - Cross section is strongly peaked forward/backward →
      - ➔ Major systematic uncertainty : θ^*_{cut} accuracy

$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} = \frac{\alpha^2_{em}}{s}\frac{1+\cos^2\theta^*}{\sin^2\theta^*}$$

- **Challenging detector design tolerance**
  - For θ^*_{cut} = 20°
    - $\Delta r \ll 27\ \mu m$ & $\Delta z \ll 75\ \mu m$
  - For θ^*_{cut} = 10°
    - $\Delta r \ll 16\ \mu m$ & $\Delta z \ll 90\ \mu m$
  - Even smaller for dileptons!
    - Δr (Δz) $\ll$ 8 (22) μm at 20°

Also relative between the two endcaps

- **Angular cut accuracy (10/20°)**
  - $\Delta\theta^* \ll$ 6.5 (10) μrad for $\gamma\gamma$
  - $\Delta\theta^* \ll$ 5 (3) μrad for dileptons



Is H → μμ a relevant benchmark ? Not really…

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

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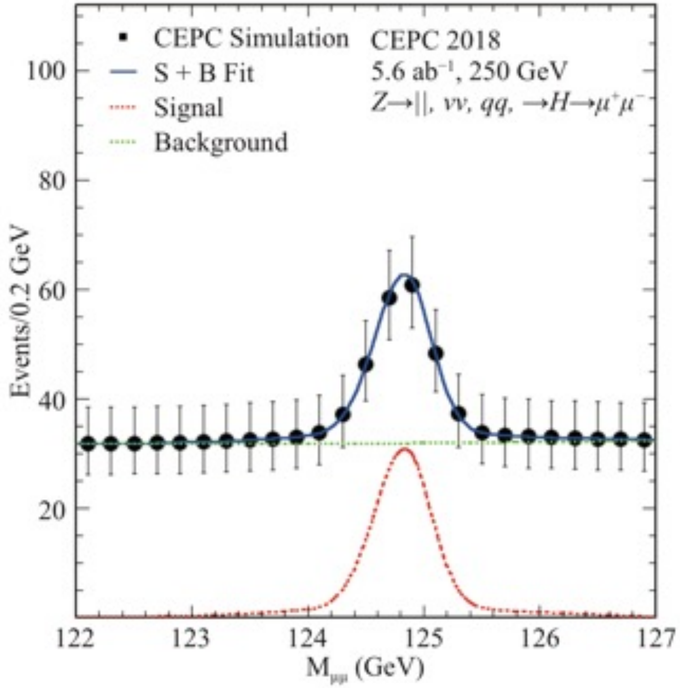


CEPC 2018 study:

- With ILD like tracker and B = 3.5 T

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

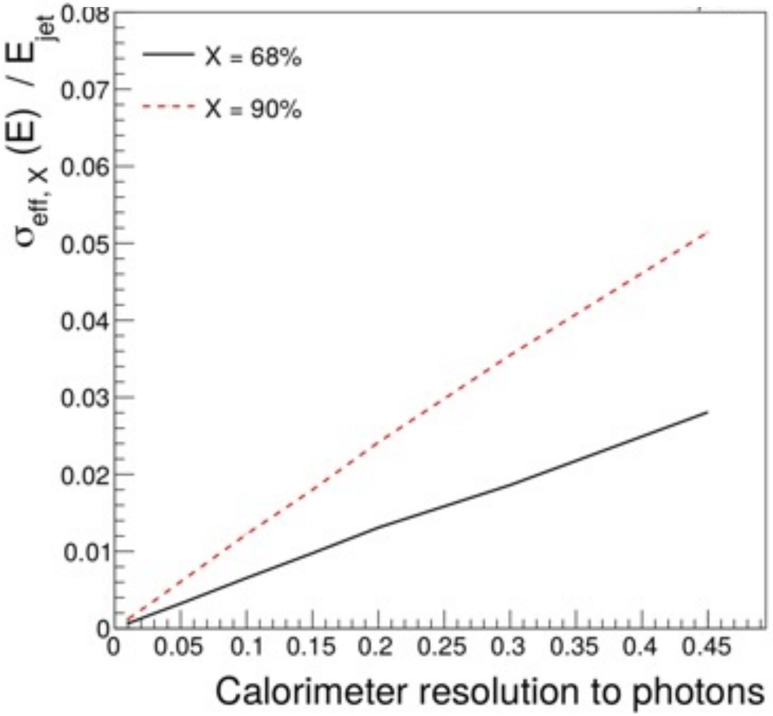
with 5.6 ab^{-1}: expected precision on σ(ZH) x BR(H → μμ) of 16 %.
2x worse than the expected precision from HL-LHC.

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

Electromagnetic calorimeter

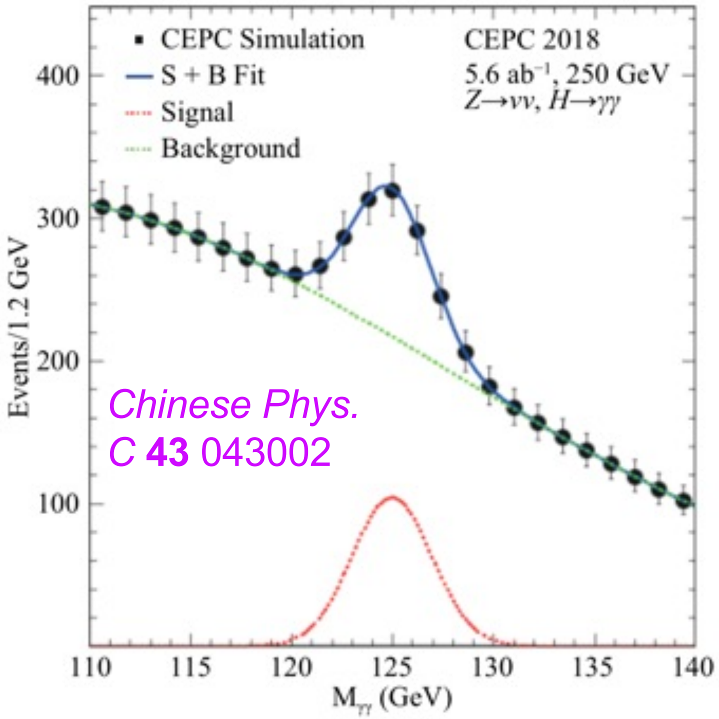
M.T Lucchini et al, arXiv:2008.00338



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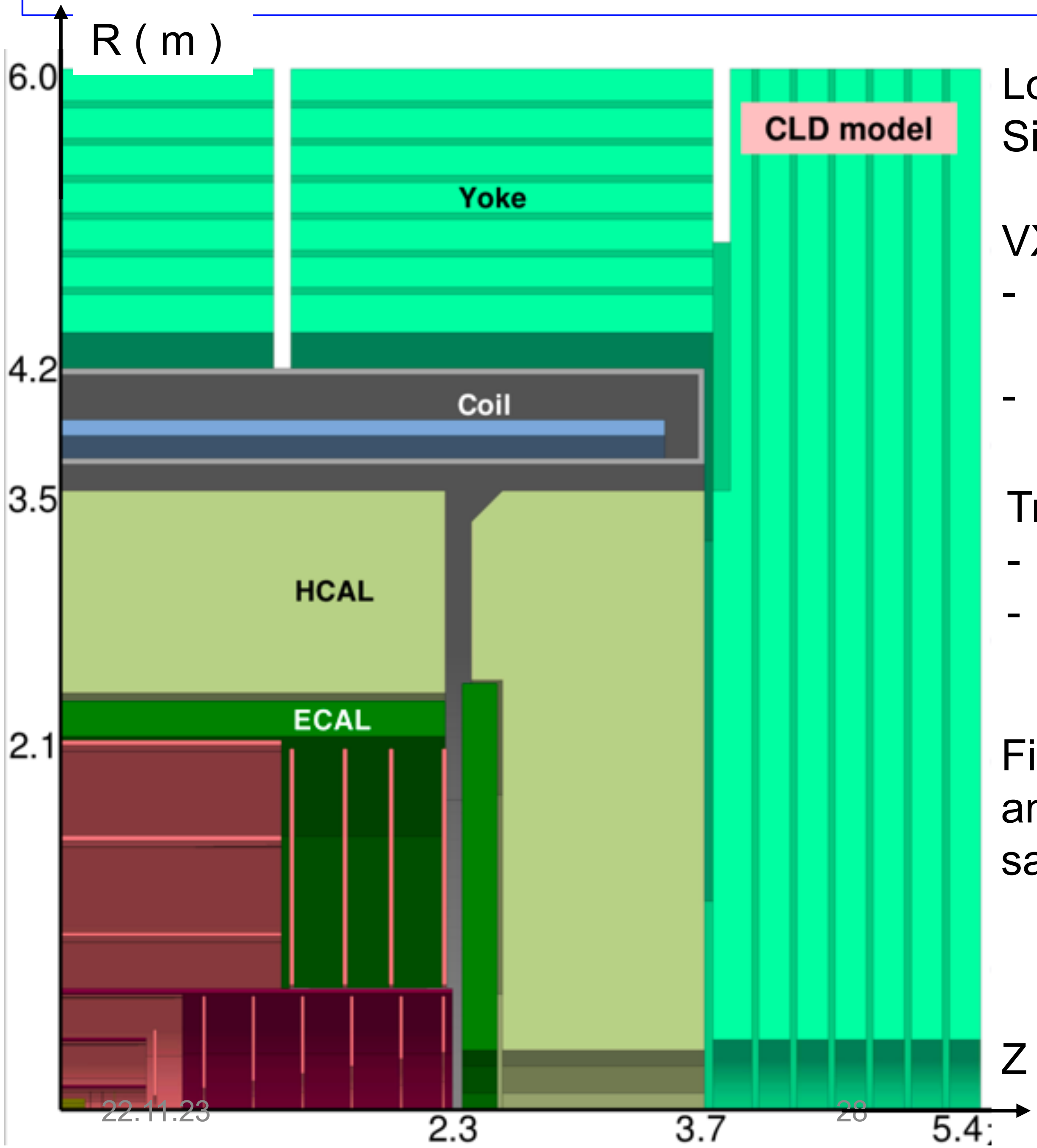
With σ(E) / E = 16% / √E +1% and mass resolution of 3% : expected precision on the σ(ZH) x BR(H→$\gamma\gamma$) is O(6%).

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.

Detector concept #1 : CLD detector – based on the CLIC detector



Low mass vertex and tracker, both Si detectors

VXD: double-layers of pixels

- 3 barrel (Rin = 17.5 mm), 3 disks in endcap)
- 0.6% X0 per double-layer

Tracker: pixels and micro-strips

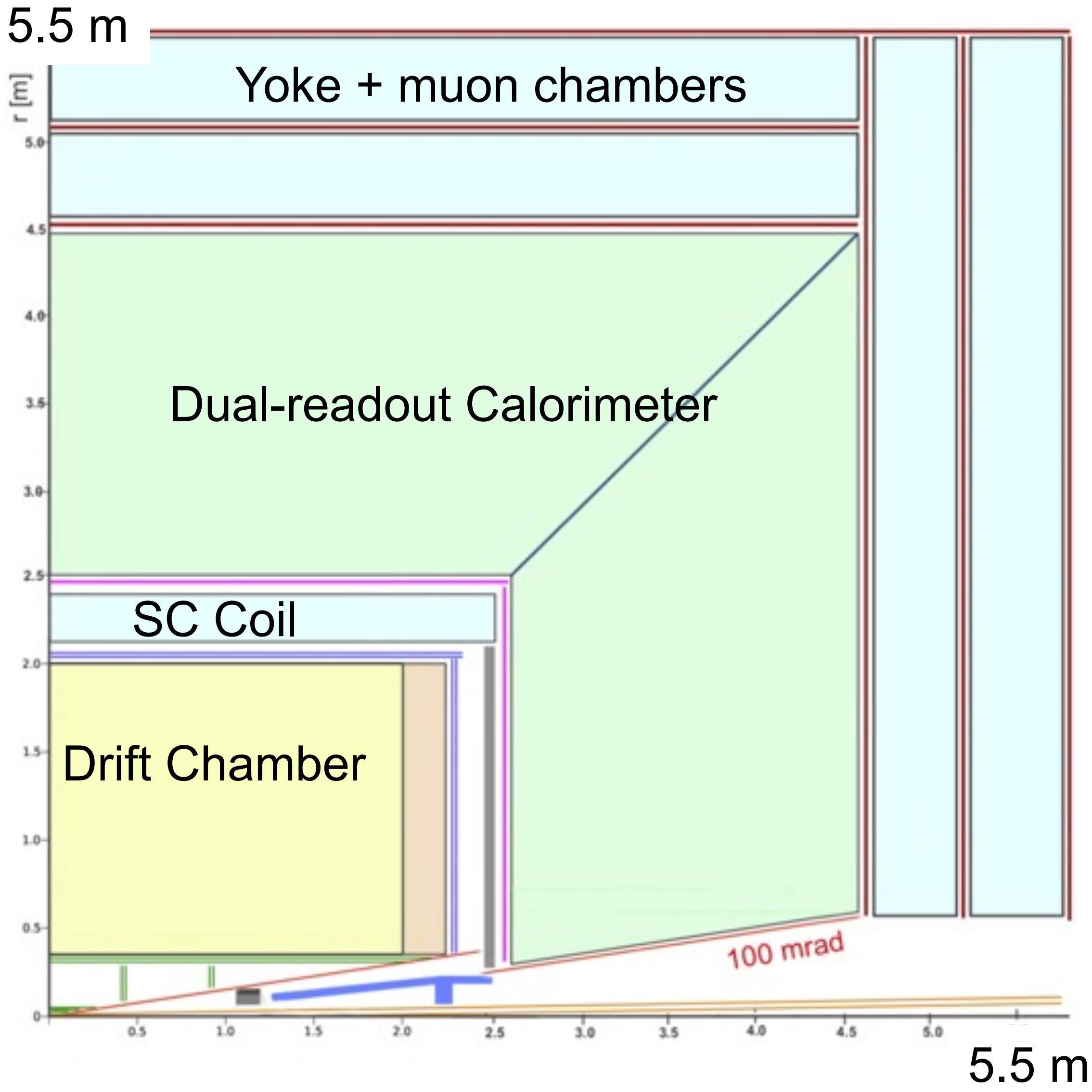
- 6 barrel layers, 11 endcap disks
- 1.1 – 1.6% X0 per layer

Fine granularity ECAL (tungsten-Si) and HCAL (scintillator-Steel) sampling calorimeters

- optimised for particle flow reco

Detector concept #2 : the IDEA detector

“ International Detector for
Electron-positron Accelerators “



- VXD : MAPS sensors
- Ultra-light drift chamber with PID
  - 1.6% X0
- Dual readout calorimeter
- Si disks between DCH and DR

Drift chamber :

L = 400 cm, R = 35-200
Gas: 90% He - 10% iC_4H_{10}
Drift length: 1 cm → drift time: 350 ns

Spatial res: $\sigma_{xy} < 100\ \mu m$, $\sigma_z < 1000\ \mu m$
56448 squared drift cells of 12 - 13.5 mm
112 layers (stereo)

Control of energy spread with $\mu^+\mu^-$

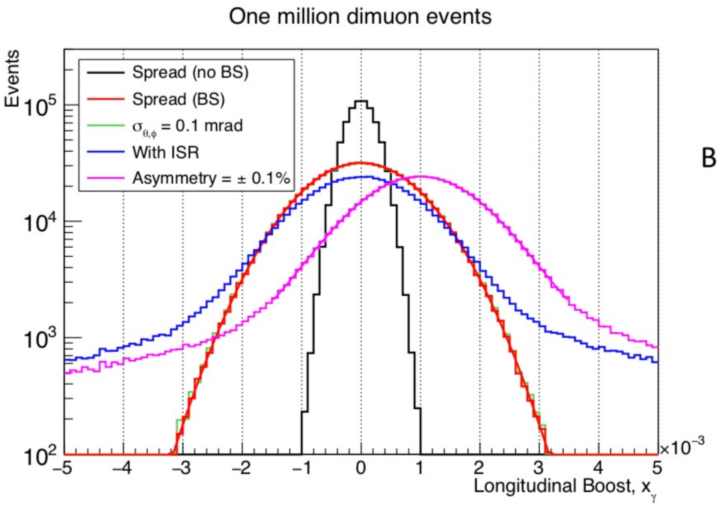
Patrick Janot

- FCC-ee: Asymmetric optics with beam crossing angle α of 30 mrad
- α is measured in e+e-→$\mu^+\mu^-(\gamma)$

$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$

together with γ (ISR) energy, both distributions sensitive to energy spread.

- Energy spread measured at 0.1% with 10^6 muons (4 min at FCC-ee)
- Current calculations of ISR emission spectrum sufficient
- Detector requirement on muon angular resolution 0.1 mrad



BS=beamstrahlung

$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|}$$

Can keep related systematic uncertainty on Γ_Z at less than 30 keV