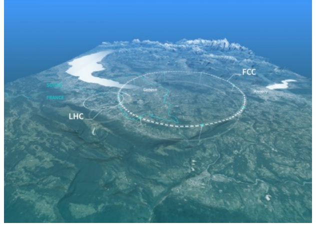

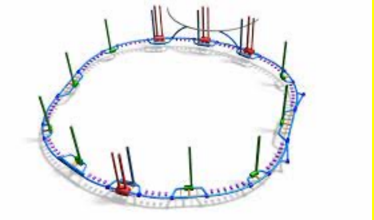

Precision tracking, including measurement of displaced tracks and muons @ FCC-ee

Istituto Nazionale di Fisica Nucleare
Sezione di Bari

Nicola De Filippis
Politecnico and INFN Bari

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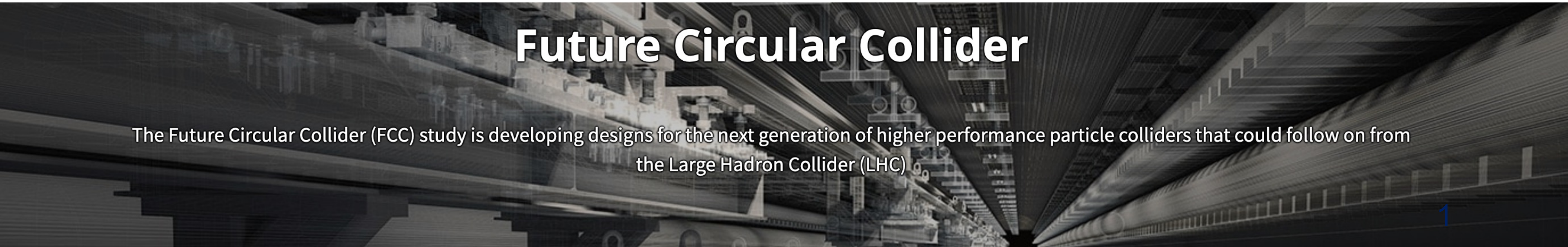
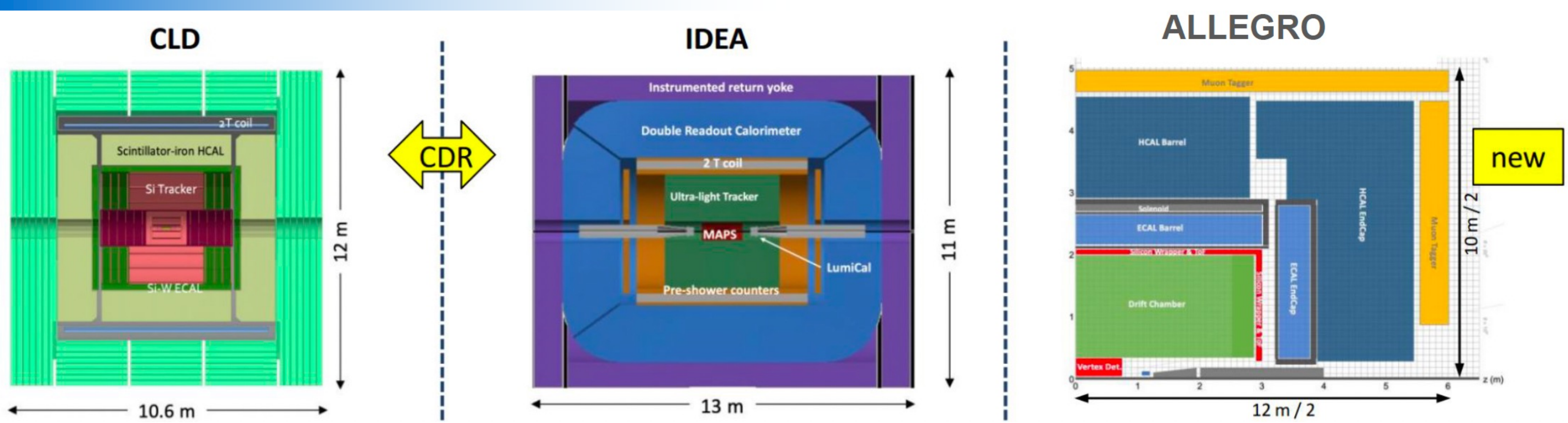
1990
POLITECNICO DI BARI

FCC Week 2024

San Francisco (US), June 10-14, 2024



FCC-ee detector benchmarks



Imported from CLIC

- Full Si tracker
- SiW Ecal HG
- SciFe Hcal HG
- Large coil outside

FCCee specific design

- Si Vtx + wrapper (LGAD)
- Large drift chamber (PID)
- DR calorimeter
- Small coil inside

FCCee specific design

- Tracker as IDEA
- LAr EM calorimeter
- Coil integrated
- Hcal not specified

- High luminosity required for the physics → constraints on the design of the detectors close to the machine components, in particular the LumiCal and VTX detectors

Strategy for detector requirement studies

Some **benchmark analyses** are chosen to study

- the dependence of their sensitivity on some aspects of the detector performance
  - Higgs mass from recoil in $Z \to \mu\mu$
  - LFV $Z \to \tau\mu$
  - $e^+e^- \to \mu\mu(\gamma)$ at the Z and above
  - Exotic Higgs to LLP pairs
  - $K_s \to \pi^+\pi^-$
  - $B \to k^*\tau\tau$
  - Flavor tagging and $H \to cc$
  - τ lifetime
  - Higgs couplings to heavy flavour: bottom and charm

So far:

- rely on **Delphes** with baseline card on the IDEA detector performance
- analysis tools able to provide variations of resolutions to study dependence or precision or sensitivity

Strategy for detector requirement studies

High precision in detection and measurements of charged particles demands:

- the precise measurement of the track momentum and of the track angles
- the reconstruction of far displaced vertices
  - properties mostly related to the large volume, main tracker

- the determination of the track impact parameters
  - mostly related to the vertex detector

N.B. Need of a superb control of the systematic uncertainties → put considerable demands on the acceptance, construction quality and stability of the detectors

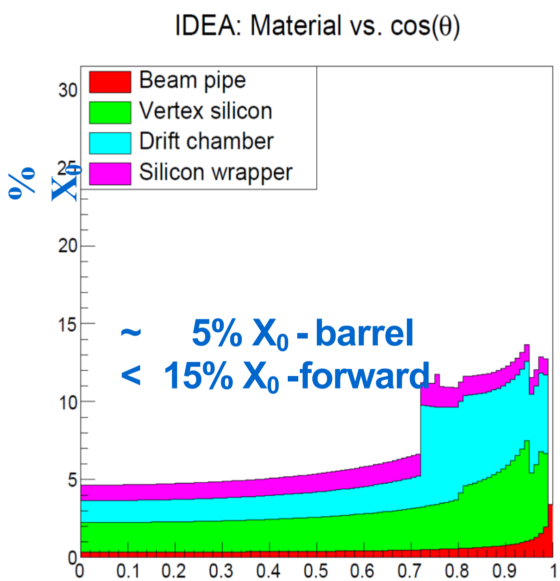
Requirements on track momentum resolution

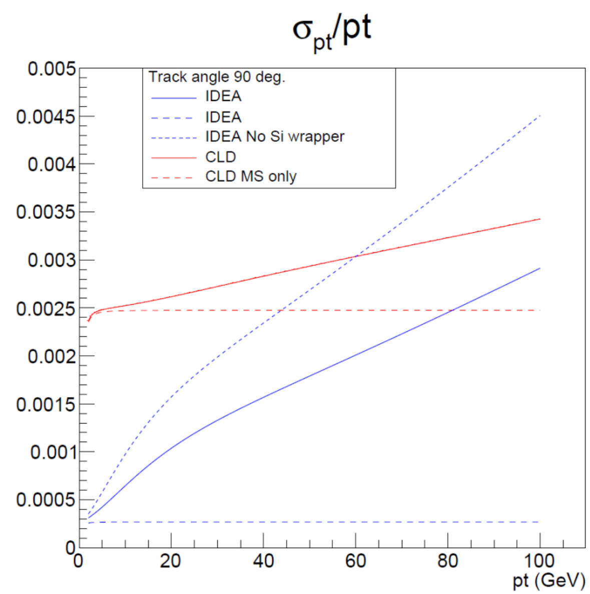
The IDEA Drift Chamber is designed to cope with transparency

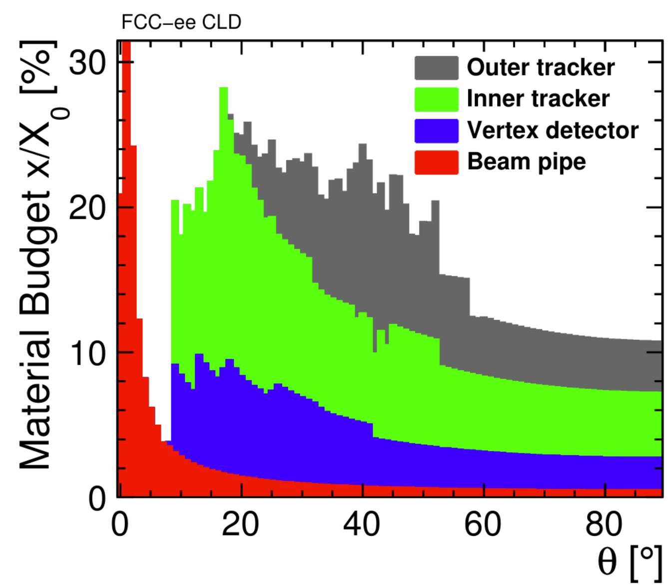
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius 0.35m, outer radius 2m
- length L = 4m

The CLD silicon tracker is made of:

- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules is estimated to be 1.1 − 2.1% of a radiation length per layer







For 10 GeV (50 GeV) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

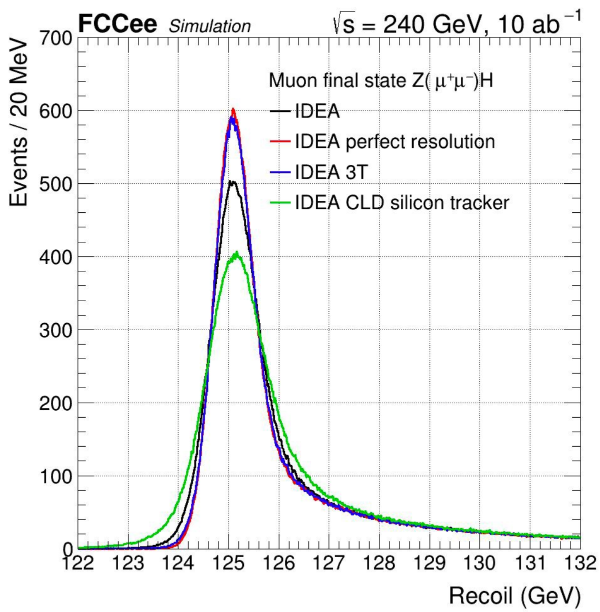
- about 0.05 % (0.15%) with the very light IDEA DCH
- about 0.25% (0.3%) with the CLD full silicon tracker, being dominated by the effect of MS

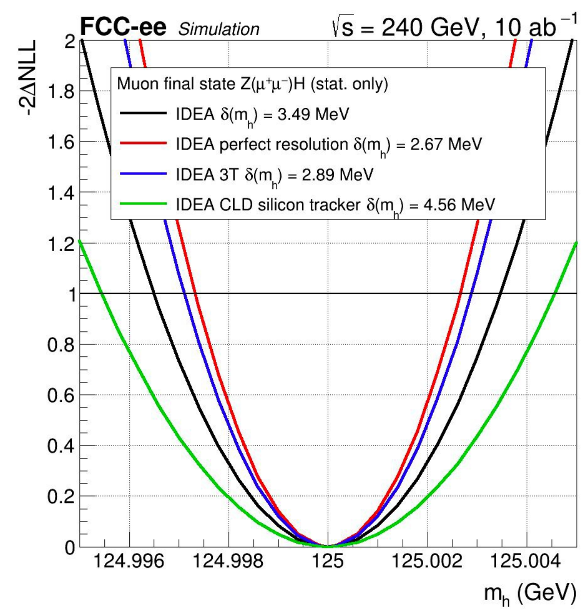
Constraint from Higgs Mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance

Higgs mass reconstructed as the recoil mass against the Z, M_{recoil} , and solely from the Z

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





μ from Z, with momentum of O(50) GeV, to be measured with a p_T resolution smaller than the BES in order for the momentum measurement not to limit the mass resolution

- achieved with the baseline IDEA detector → uncertainty of 4.27 MeV with 10 ab^{-1}
- CLD performs less well because of the larger amount of material → larger effects of MS

If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty

Reconstruction of LLP and very displaced vertices

The reconstruction of:

- long-lived particles (LLP) that decay into charged particles within the tracker volume, but after having crossed the (first) layers of the vertex detector
- decays that involve K_s or Λ's.

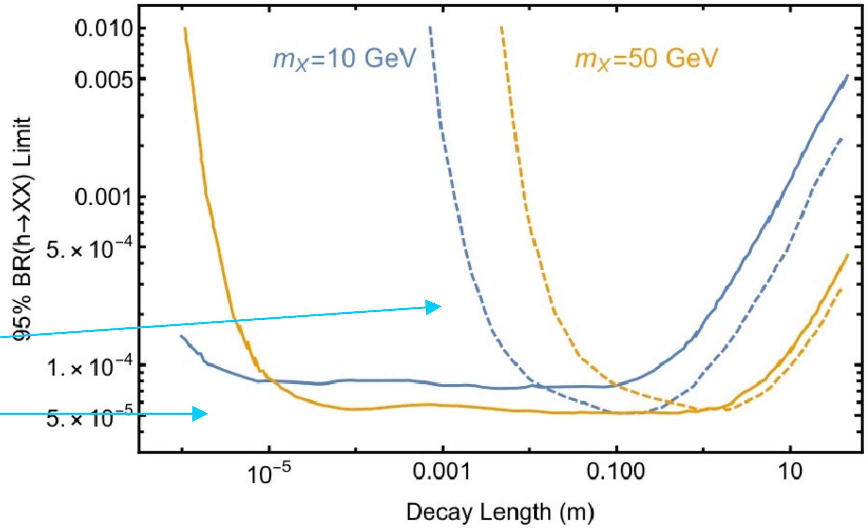
requires **very displaced vertices** to be identified efficiently (primarily) by the **main tracker**

Esample: Higgs boson into pairs of long-lived particles (LLPs) which travel a macroscopic distance before decaying to quark pairs → jets containing candidate secondary/displaced vertices (exotic Higgs decays with decay lengths cτ ranging from microns to meters)

$$e^+e^- \to hZ \to XX + \ell\bar{\ell} \text{ at } \sqrt{s} = 240 \text{ GeV}$$

Tracker-based searches optimal for decay lengths below 1 meter, with sensitivity to shorter LLP decay lengths down to the tracker resolution (impact parameter res. 2-3 μm)

- 'long lifetime': $m_X < 10$ GeV and $c\tau \gtrsim 1$cm
- 'large mass': $m_X \gtrsim 10$ GeV and $c\tau \gtrsim 1\mu$m



Improvement of the vertex resolution → better sensitivity to LLPs with relatively short lifetimes

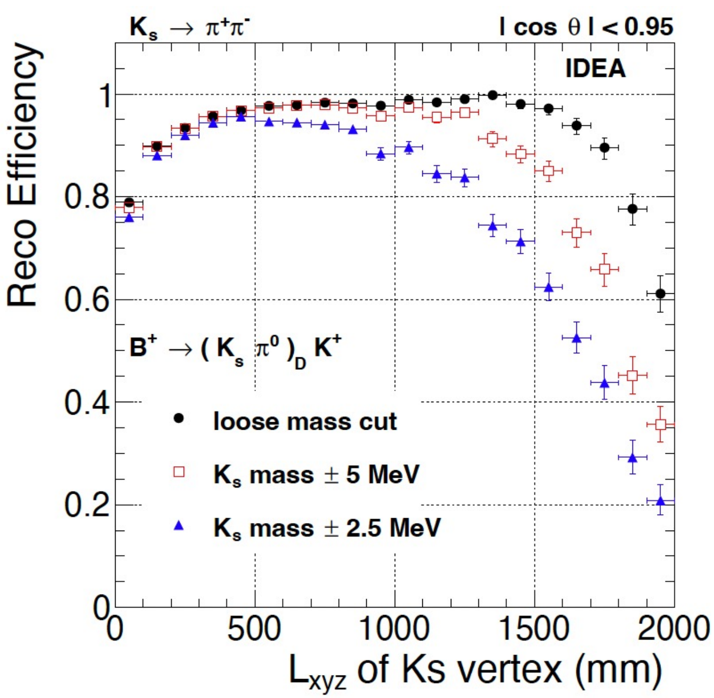
Constraint from $B^+ \to D^0K^+ \to (K_s\pi^0)_D K^+$

The reconstruction of $K_s \to \pi^+\pi^-$ from pairs of opposite charge tracks

- that do not come from the primary vertex,
- that can be fitted to a common vertex
- with a vertex mass that is close to the nominal K_s mass

The efficiency for K_s reconstruction defined:

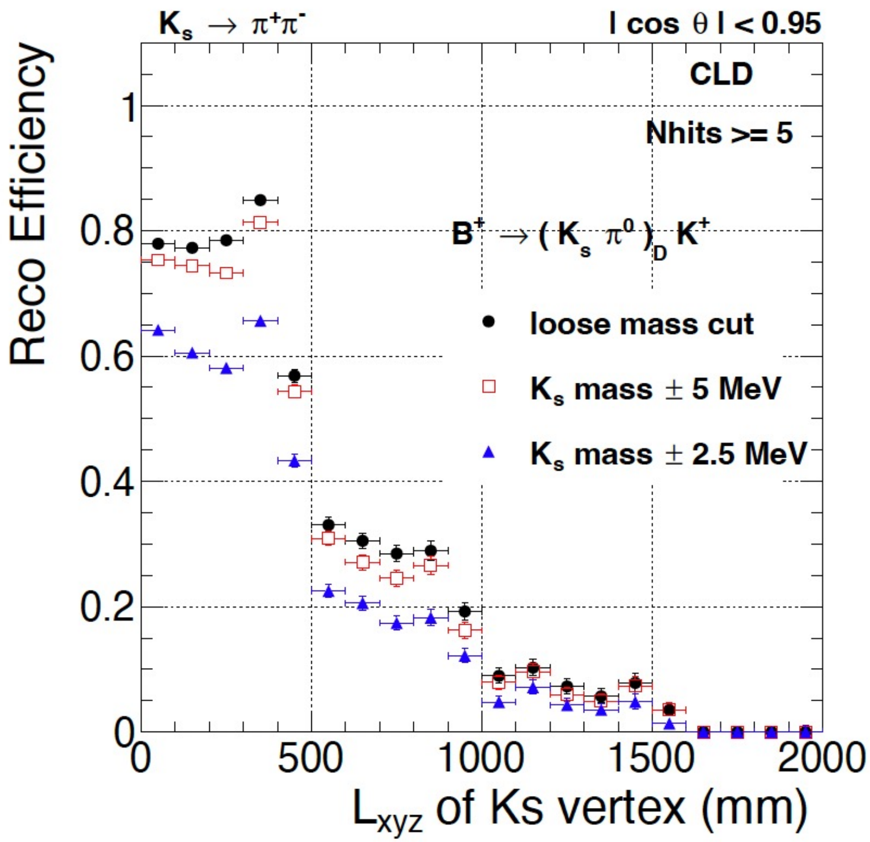
- for the K_s that come from the $B^+ \to (K_s\,\pi^0)_D K^+$ decay, for which the generated daughter pions satisfy the acceptance requirement $|\cos\theta| < 0.95$
- as a function of the distance L_{xyz} between the decay vertex of the K_s and the interaction point



IDEA detector:

- with a mass cut of +/-5 MeV, the efficiency **remains above 80% as long as the K_s decays within 1.5 m** from the interaction point.
- at larger distances, the efficiency drops since the π tracks only go through a small distance in the tracker.

Constraint from $B^+ \rightarrow D^0K^+ \rightarrow (K_s\pi^0)_D K^+$



The performance of **CLD detector** significantly worsens compared to IDEA:

- visible the steps corresponding to the positions of the tracker layers
- the efficiency for selecting 5-hits tracks displaced by more than 40 cm vanishes in the central region
- due to the large amount of material of the full silicon tracker that leads to much larger effects from MS
  - worse resolutions on the K_s vertex and on the K_s mass

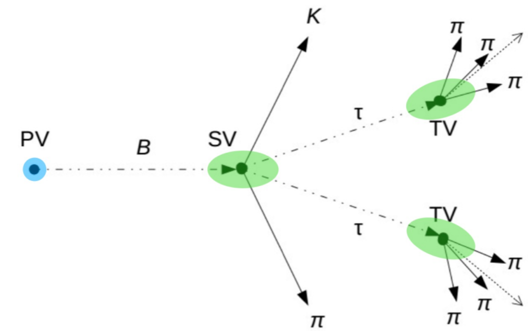
An efficient reconstruction of $K_s \rightarrow \pi^+\pi^-$, and, more generally, of LLP that lead to late appearing tracks, calls for

- a highly transparent tracker
- a large tracking volume
- a considerable number of measurement layers

Constraint from B→ $K^{*}\tau\tau$ reconstruction

The search for the rare $B \to K^{*}\tau\tau$ decay has set some requirements on the track efficiencies

- demanding that both taus decay into three prongs → a final state with 6 soft pion tracks



- a momentum acceptance down to 100−150MeV is necessary to maintain a good signal efficiency
- a minimum number of e.g. 5 hits to reconstruct a track implies that there be at least 5 measurement layers at a radius below 33 cm (50 cm) to reconstruct a track with a transverse momentum of 100MeV (150 MeV)
- this requirement on the position of the layers of the vertex detector and of the innermost layers of the main tracker, is **fulfilled** by both the IDEA and the CLD tracker designs

Impact parameters and vertex detector

Measurement of the impact parameters driven by the **vertex detector** key for:

- for reconstructing vertices
- for efficient identification of heavy quarks and τ
- for a powerful measurement of lifetimes

The radial distance of the first layer of the vertex detector is also crucial

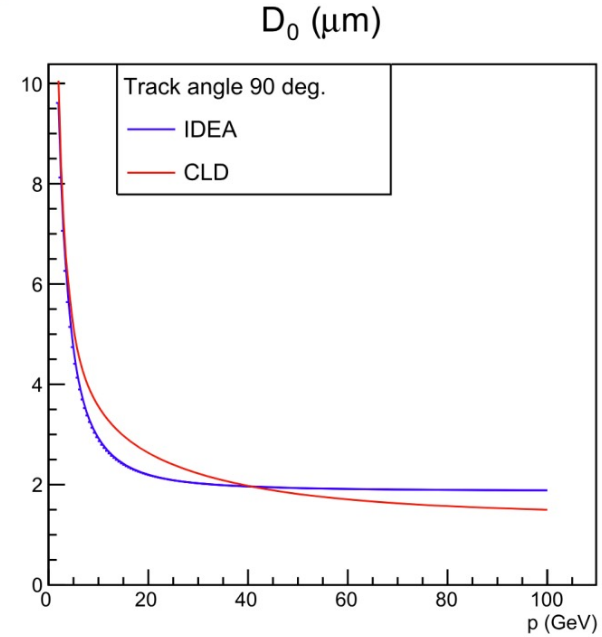
Resolution on impact parameters

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

a ~ 5 μm, b ~ 15 μm·GeV (FCC-ee)
a ~ 25 μm, b ~ 70 μm·GeV (LEP)
a ~ 12 μm, b ~ 70 μm·GeV (LHC)

a, is driven by the single hit resolution

- represents the contribution of multiple scattering
- depends on the material budget of the vertex detector layers and of the beam-pipe



Assumptions used for next studies:

- the radius of the beam pipe is 1 cm
- the radius of the innermost layer of the vertex detector is 1.2 cm
- the material crossed by a particle emitte at a polar angle θ before the first VXD measurement amounts to 0.67%/sin θ of a radiation length

Constraint from Heavy flavour tagging and H→cc

Latest studies based on a graph neural network:

ParticleNet

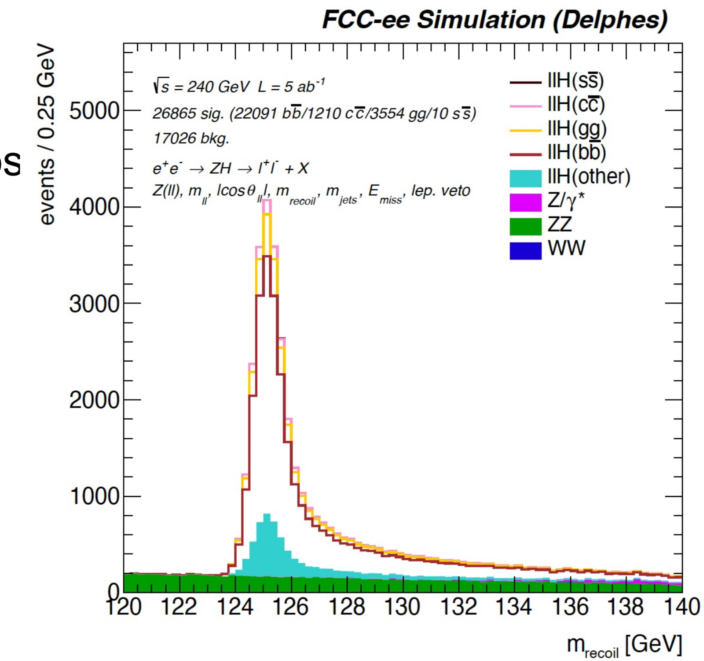
H. Qu, L. Gouskos, ParticleNet: Jet Tagging via Particle Clouds.
Phys. Rev. D 101(5), 056019 (2020)

Features:

- the identification of jets induced by gluons or even strange quarks contemplated
- the tagging efficiency of bottom and charm quarks is much larger than what was achieved with algorithms from the previous generation for the same mistag rate

ParticleNet key for measurement of the **Higgs couplings to bottom, charm and strange quarks, and to gluons**

- HZ events at $\sqrt{s}$ = 240 GeV
- Z decays into an electron or a muon pair, or into neutrinos



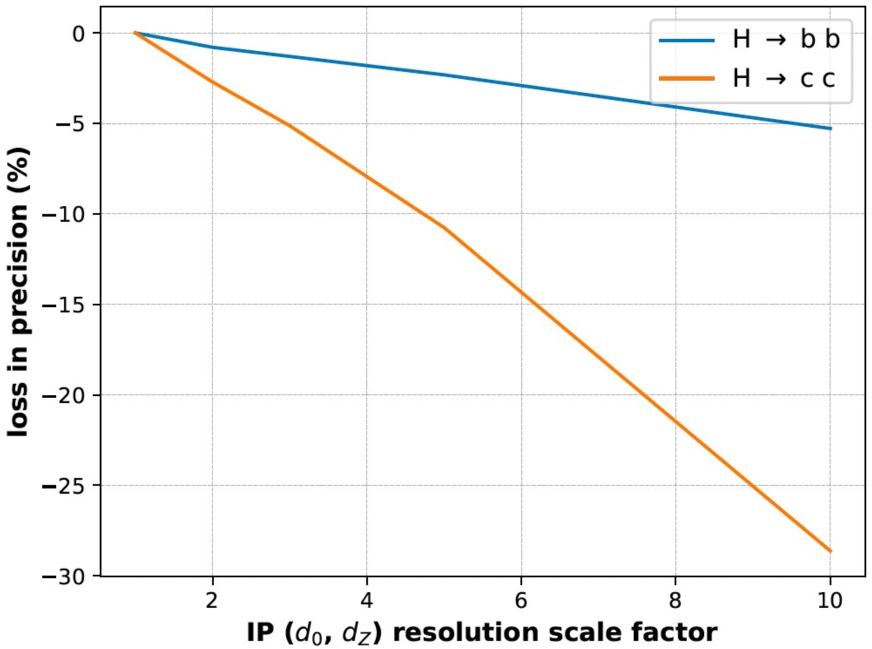
A simultaneous fit to the recoil mass distributions (and, for the Z(vv) channel, to the visible mass distributions) measured in all categories allows the Higgs couplings to bb, cc, ss and gg pairs to be extracted

Heavy flavour tagging and H→cc coupling

For an integrated luminosity of 10 ab^{-1}, the **H → bb** signal strength can be measured with **0.28% uncertainty**, and the one for **H → cc** with **2.1%**

Studied **the dependence of this precision with the track impact parameters resolution**

- by degrading the resolution by a factor ranging between 2 and 10



- the measurement of the Higgs coupling to bottom quarks is only **marginally** degraded when this resolution is worsened

- the uncertainty on the Higgs coupling to charm quarks depends **significantly** on the resolution on the track parameters

due

- to the much worse signal-to-background ratio in this channel
- to the smaller displacement of c quarks compared to b quarks,

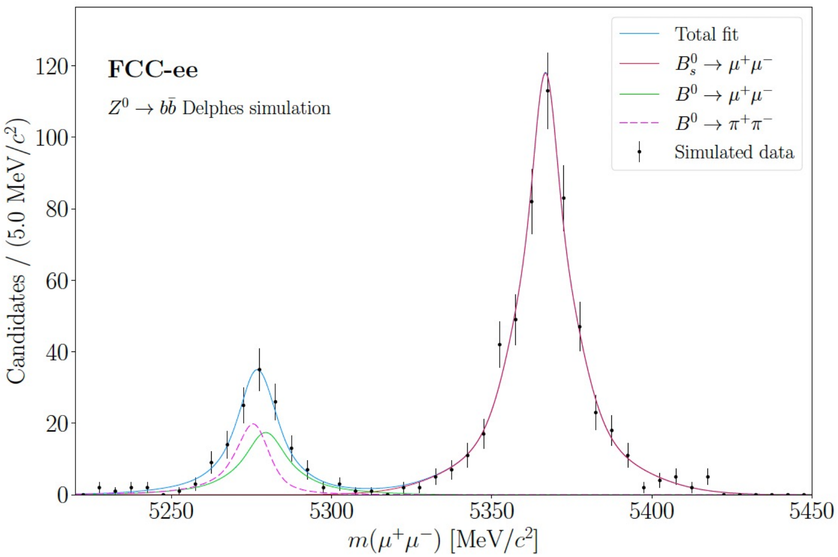
A degradation by a factor of 2 of the impact parameter resolutions → degradation of the H→cc coupling measurement by about 3%.

Requirements on Muon detector

The muon detector has to identify muons with a very high efficiency and to serve as 'tail-catcher' for the hadron showers that may not be fully contained in the calorimeter.

- an important figure of merit is the $\pi \to \mu$ misidentification probability

Example: control of the π contamination via $B^0 \to \mu^+\mu^-$ decay



excellent mass resolution IDEA → a very good separation of the B^0 and B_s peaks

A significant background coming from **$B^0 \to \pi^+\pi^-$** is however present under the B peak.

Assuming a double $\pi \to \mu$ mis-identification probability of 2×10^{-5} → background contribution would be as large as the signal itself

A good standalone resolution will be

- useful to reduce the π contamination and to identify π decays in flight that happen before the muon detector
- important for searches for long-lived particles that decay outside the tracker volume → the requirements on the standalone momentum resolution need to be quantified

Conclusions

- The momentum resolution by IDEA and CLD looks
  - adequate for Higgs measurements
  - as well for most EWK measurements, with the 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 being minimally affected by MS
  - optimisation studies ongoing to improve the momentum resolution of the CLD tracker
  - a silicon+TPCtracker / straw tracker is under consideration for CLD

- very large number of measurement points along the tracks, as offered by a gaseous tracker → crucial for an efficient reconstruction of K_s, Λ's or other longlived particles that decay into charged particles, and a bonus for an experiment with a stronger focus on flavour or BSM

- Examples shown where the physics outcome of FCC-ee would gain from having better vertex detector performances than the one provided by the baseline detectors (IDEA and CLD)
  - ongoing R&D efforts to decrease the material budget of the VTX
  - special care in designing the beam-pipe and its cooling system, in order to minimise the amount of material in front of the vertex detector

Backup

FCC-ee physics programme

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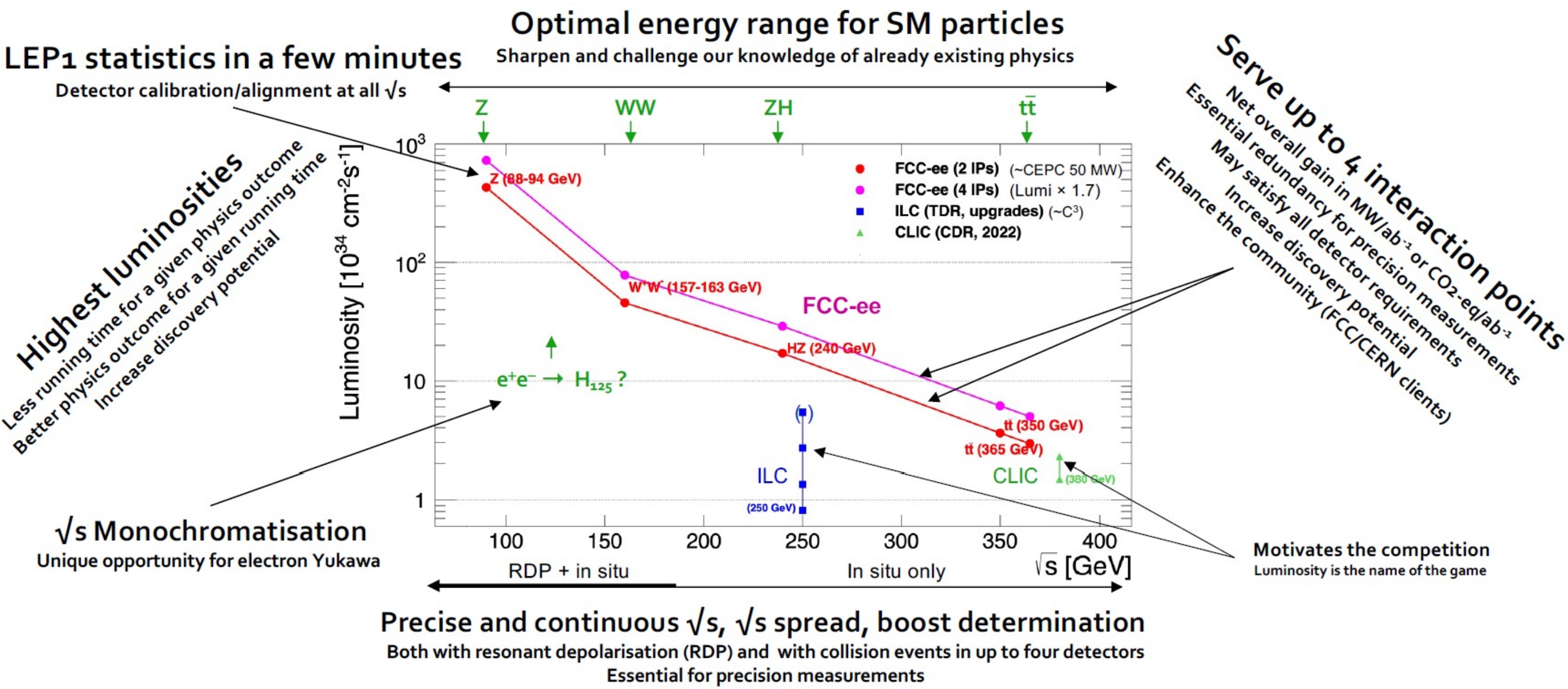
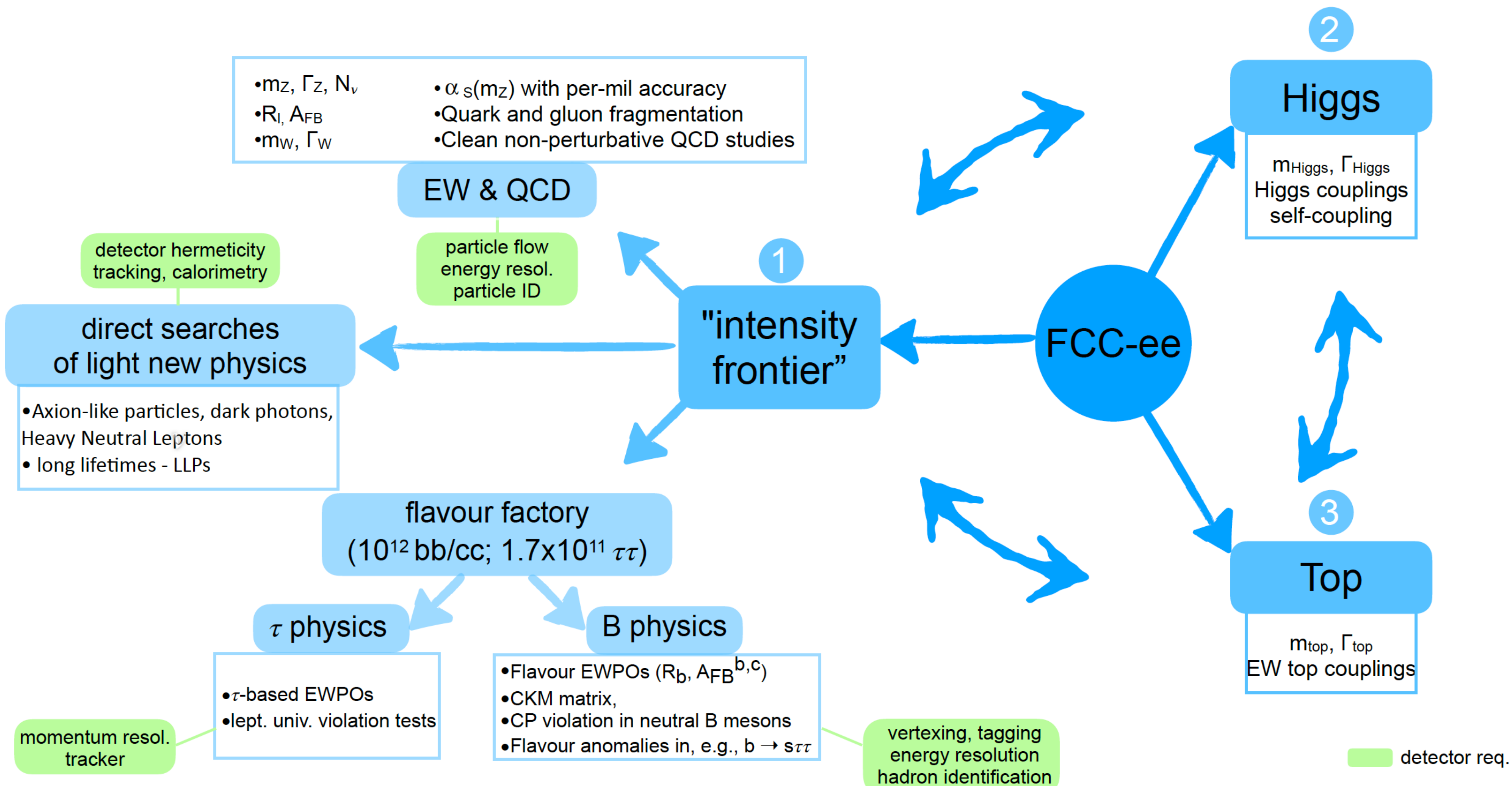


- LLP's, ALPs, RH ν's, …

FCC-ee physics program



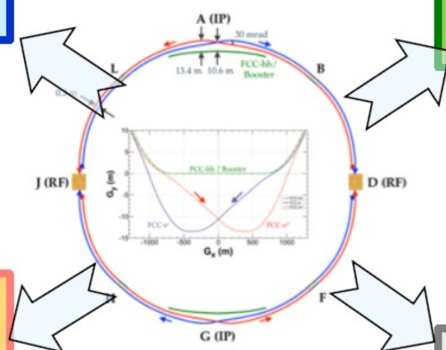
Detector requirements for an experiment at the FCC-ee

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

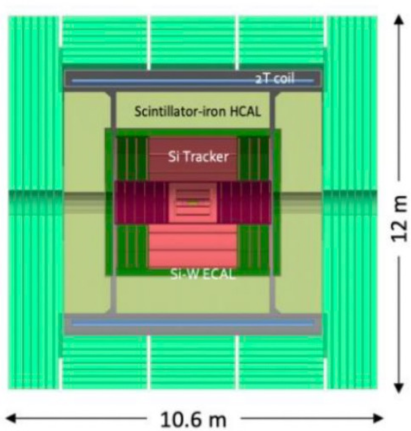
Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

➢ M. Dam, ECFA Det. R&D Roadmap, 2021, https://indico.cern.ch/event/994685/

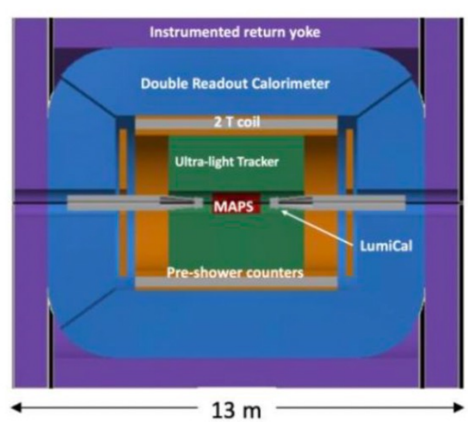
FCC-ee detector concepts

CLD



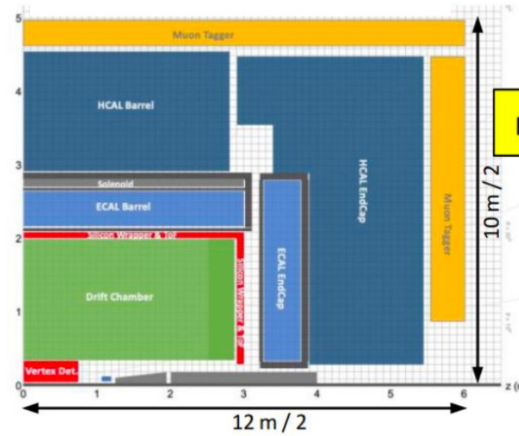
CDR

IDEA



ALLEGRO

new



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- Si Vtx + wrapper (LGAD)
- Large drift chamber (PID)
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FCCee specific design
- Tracker as IDEA
- LAr EM calorimeter
- Coil integrated
- Hcal not specified

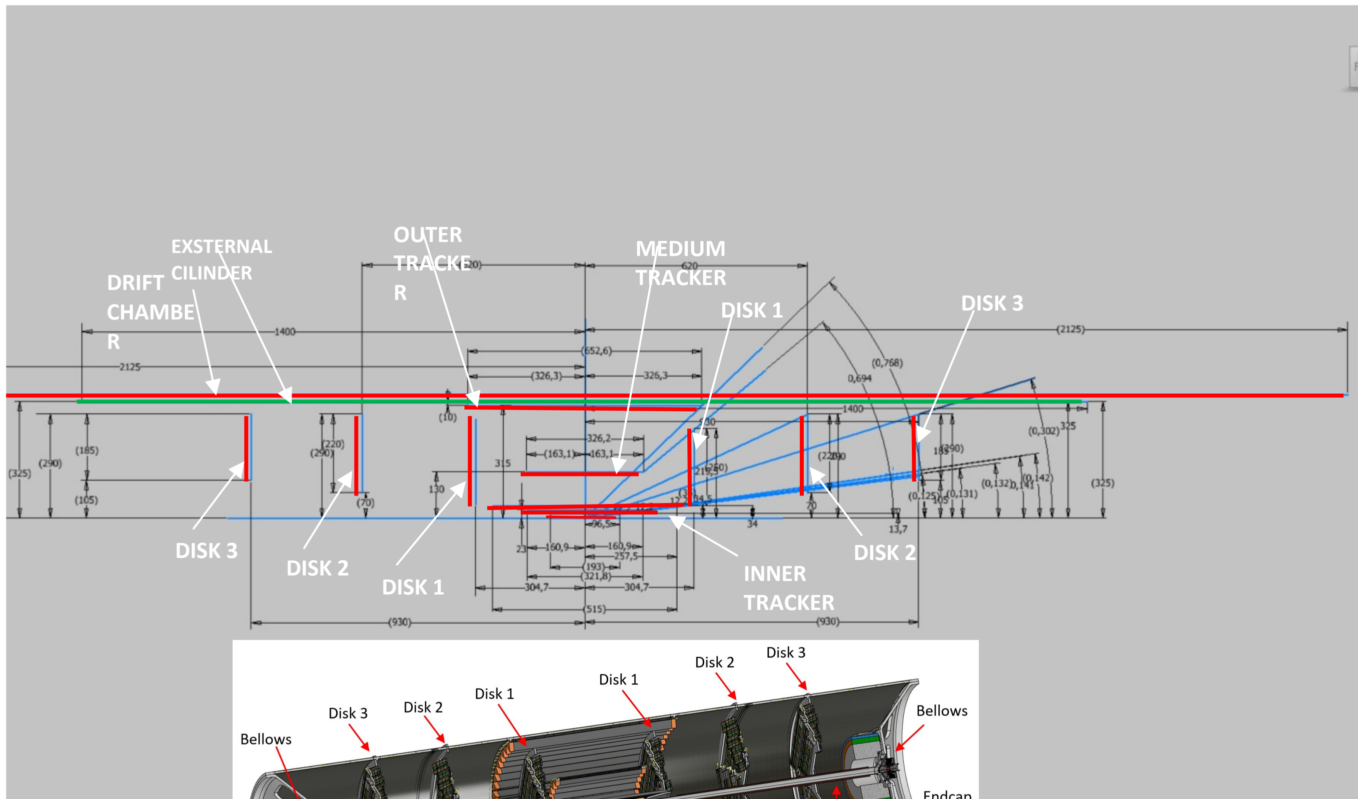
- High luminosity required for the physics → constraints on the design of the detectors close to the machine components, in particular the LumiCal and VTX detectors

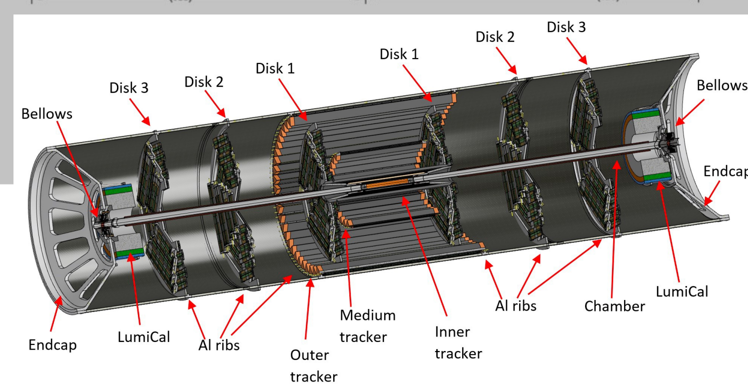
Silicon detectors for precision measurements:

- vertex detector/inner tracker (VTX)
- silicon outer tracker
- silicon wrapper (SET)

+ design of the mechanical structure (light-weight staves)

+ activity with the MDI group for the integration of the vertex detector





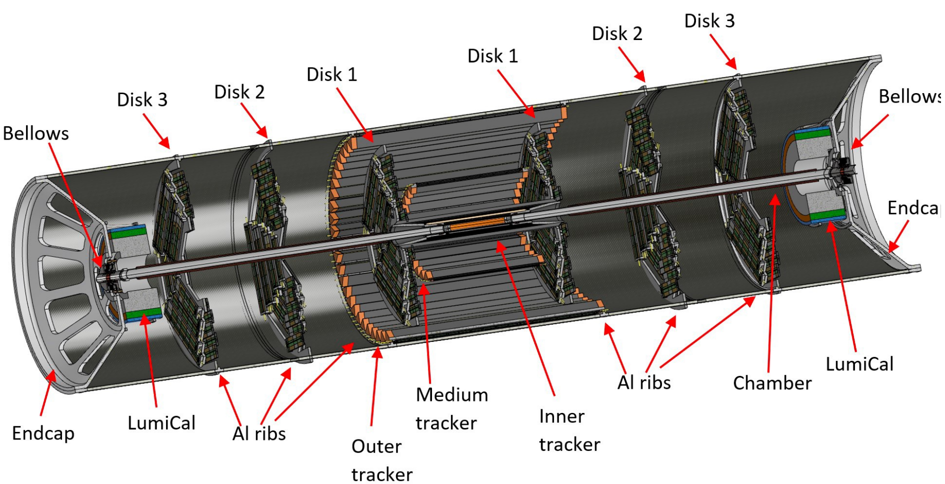
MDI + VTX

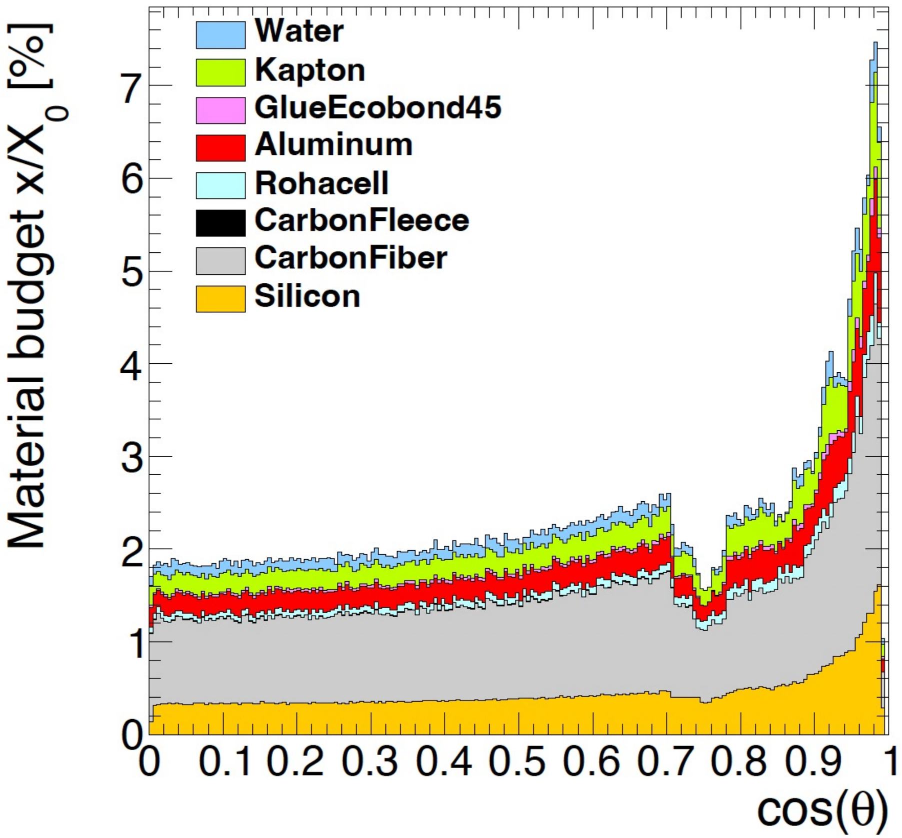
N. De Filippis

Inner tracker

- A three layers inner vertex detector at 13.7, 23.7 and 34mm radii

- An outer vertex detector, located at a larger radius between 11.2 and 31.5 cm, composed of a barrel section and forward disks

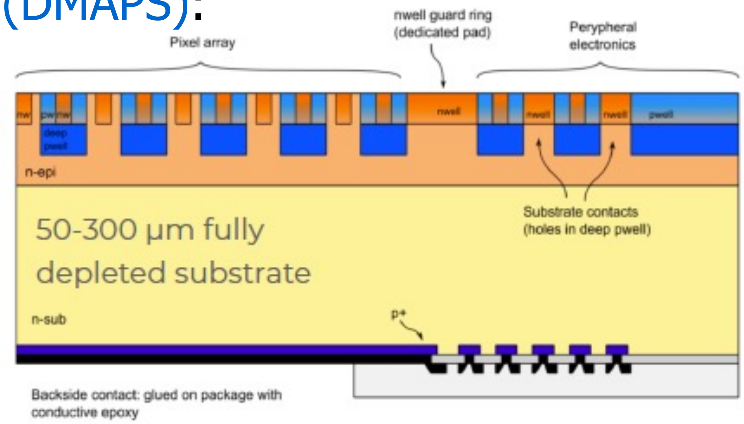




The material budget of the inner vertex detector at cos(θ) = 0 contributes with about 0.3% per layer, and nearly 50% of it comes from the mechanical support structure

Vertex detector Insubria U.+ Milano U.

ARCADIA INFN prototype



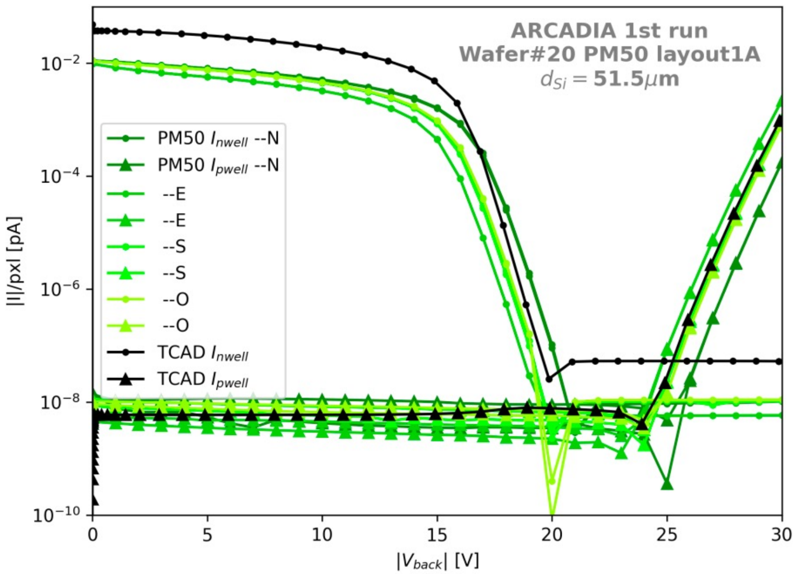
Technology: Depleted Monolithic Active Pixel Sensors (DMAPS):

- 25 x 25μm^2 pixel size for hit resolution ~ 3 μm
- 5 μm shown by ALICE ITS (30 μm pixels)
- prototype with thickness ~ 200 μm down to 50μm
- low power consumption (< 20 mW/cm^2)

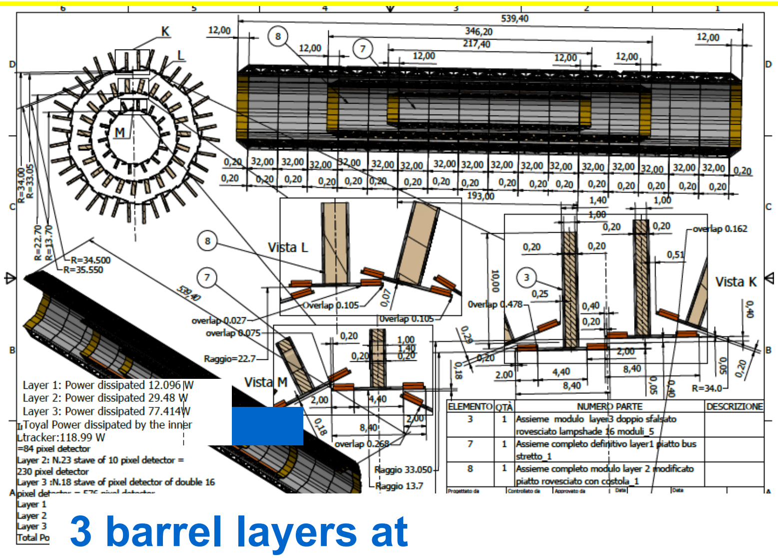
Tests of different design options:

- IV and CV measurements of test-structures from the first and second production run: proven functionality, stable operation at full depletion, and good agreement with TCAD simulations

A 2nd iteration prototype is working and will be tested soon at a test beam area



VTX mechanical strcture



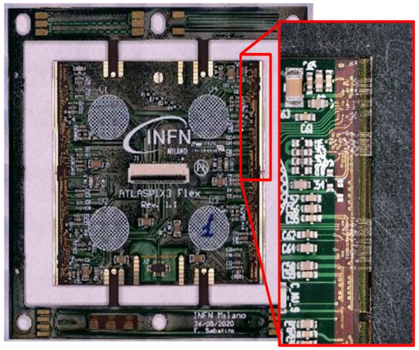
3 barrel layers at
- 13.7, 23.7 and 34-35.4 mm radius

N. De Filippis

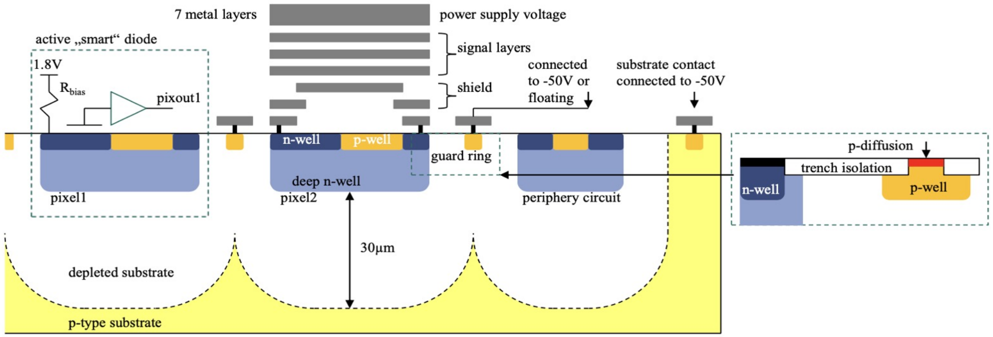
Silicon medium and outer tracker KIT+UK+IHEP+INFN

ATLASPIX3 modules: a full-size system on chip, targeting the outer tracker

- Intermediate barrel at 15 cm radius
- Outer barrel at 31.5 cm radius

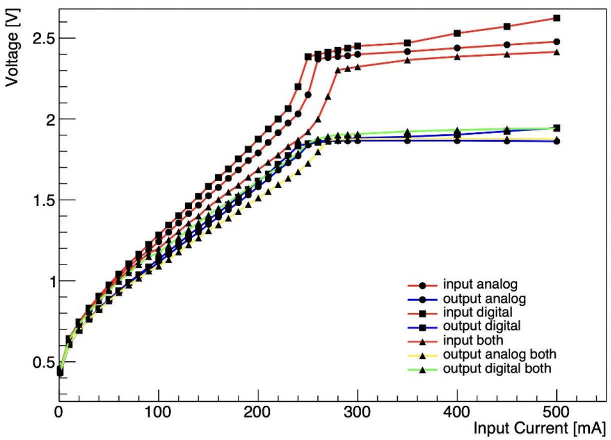


- quad module, inspired by ATLAS ITk pixels
- pixel size 50×150 μm²
- TSI 180 nm process on 200 Ωcm substrate
- 132 columns of 372 pixels



Power consumption:

- ATLASPIX3 power consumption 100-150 mW/cm²



Complete system consists of 900'000 cm² area / 4 cm² chip = 225k chips (56k quad-modules)

Data rate constrained by the inner tracker:

- average rate 10^{-4} - 10^{-3} particles cm^{-2} $event^{-1}$ at Z peak
- assuming 2 hits/particle, 96 bits/hit for ATLASPIX3
- 640 Mbps link/quad-module provides ample operational margin
- 16 modules can be arranged into 10 Gbps fast links: 3.5k links
- can also assume 100 Gbps links will be available: 350 links

The Drift Chamber

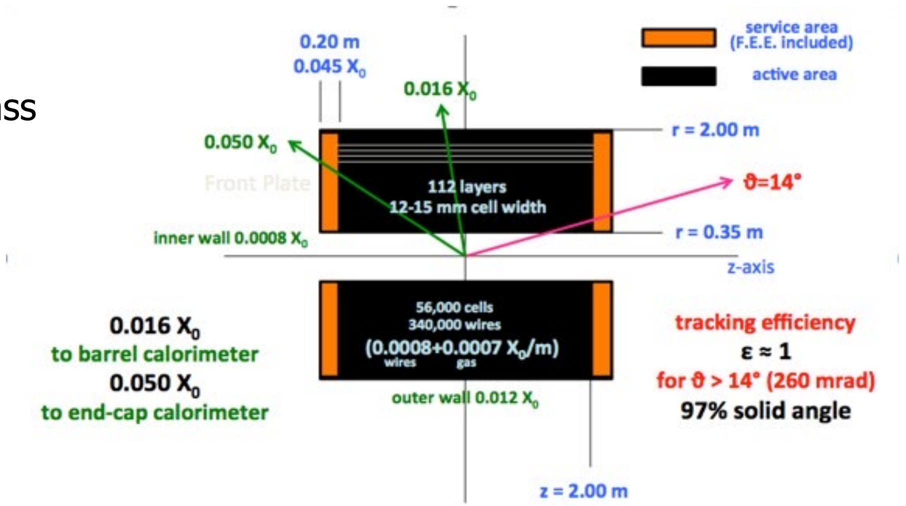
The DCH is:

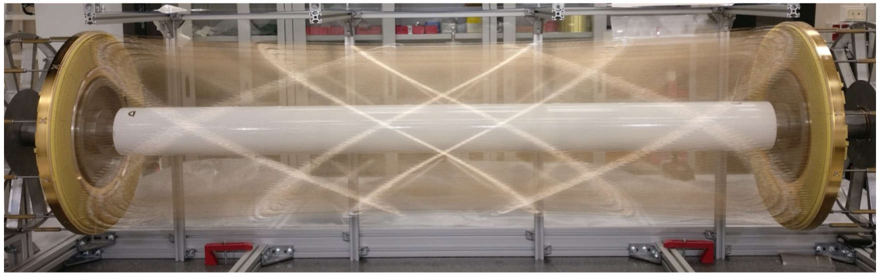
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm
- drift time ~150ns
- σ_{xy} < 100 μm, σ_z < 1 mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors, with frontend electronics
- 343968 wires in total:

  sense vires: 20 μm diameter W(Au) => 56448 wires

  field wires: 40 μm diameter Al(Ag) => 229056 wires

  f. and g. wires: 50 μm diameter Al(Ag) => 58464 wires





- the wire net created by the combination of + and – orientation generates a more uniform equipotential surface → better E-field isotropy and smaller ExB asymmetries)

- a large number of wires requires a non standard wiring procedure and needs a feed-through-less wiring system → a novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

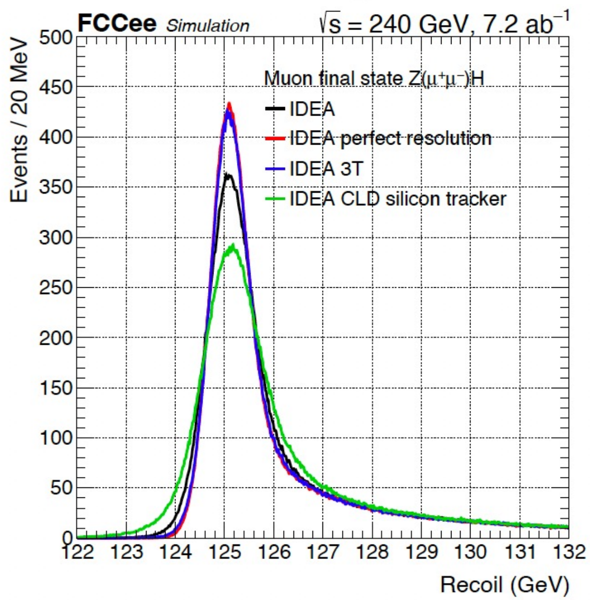
Requirements on
track momentum resolution

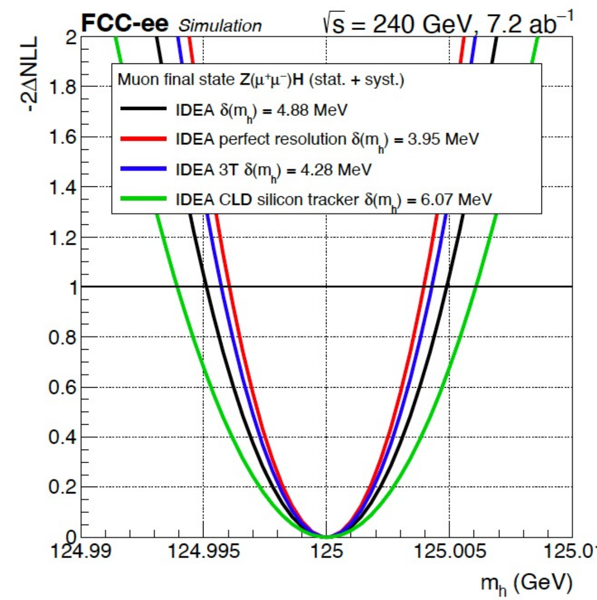
Constraint from Higgs Mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance

Higgs mass reconstructed as the recoil mass against the Z, M_{recoil} , and solely from the Z

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





With a perfect measurement of the muon momentum:

- the width of the M_{recoil} peak determined by BES ~ 0.185% of the beam energy at $\sqrt{s}$ = 240 GeV
- uncertainty on M_H of 4.0 MeV with an int. lumi of 7.2 ab−1 (including the contribution of all systematic unc.)

μ from Z, with momentum of O(50) GeV, to be measured with a p_T resolution smaller than the BES in order for the momentum measurement not to limit the mass resolution

- achieved with the baseline IDEA detector → uncertainty of 4.9 MeV with 7.2 ab^{-1}
- CLD performs less well because of the larger amount of material → larger effects of MS

If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty

Requirements on track angles

Requirements on angular resolution

The polar and azimuthal angles of the momentum of a prompt, charged particle, at production vertex measured as

- the angles of the corresponding track at its distance of closest approach to the detector axis

The corresponding angular resolutions in IDEA and CLD vary between

- about 20 μrad for high momentum particles produced in the central region of the detector
- a few mrad for soft, forward particles

N.B .The contribution of these angular resolutions to the precision of the recoil mass is negligible compared to that of the momentum resolution.

For the reconstruction of the **mass of heavy-flavoured mesons**, the momenta of the daughter particles must be taken at the decay vertex of the meson, and the resolution of the azimuthal angle crucially relies on the reconstruction of this decay vertex.

- N.B: for all examples considered involving B-mesons, the mass resolution remains completely dominated by the momentum resolution

The reconstruction of:

- long-lived particles (LLP) that decay into charged particles within the tracker volume, but after having crossed the (first) layers of the vertex detector
- decays that involve K_s or Λ's.

requires **displaced vertices** to be identified efficiently (primarily) by the main tracker

Constraint from $Z \rightarrow \tau\mu$

A similar requirement, that the momentum resolution for O(50) GeV muons be better than or comparable to the BES, comes from the search for lepton flavour violating Z decays into $\tau\mu$ at $\sqrt{s}$ = 91 GeV. The analysis strategy demands a clear tau decay in one hemisphere, and a beam-energy muon in the other, in order to suppress the $Z \rightarrow \tau\tau$ background

Requirement

The measurement of the luminosity from $e^+e^- \rightarrow \gamma\gamma$ events to a precision of about 10^{-5}, requires the large background from $e^+e^- \rightarrow e^+e^-$ events to be known very precisely

- the targeted precision will set some requirement on the e/γ separation, which, in turn, will constrain the tracker inefficiency and the level at which this inefficiency is known

The ratio of the partial width of the Z boson into hadrons to that into muons, R_μ, will be measured with a statistical precision of about $5\mathrm{x}10^{-6}$ at Tera-Z. Counting the number of $\mu^+\mu^-$ events to a similar level of systematic precision sets a very hard requirement on the knowledge of the tracking (and muon chamber) efficiency

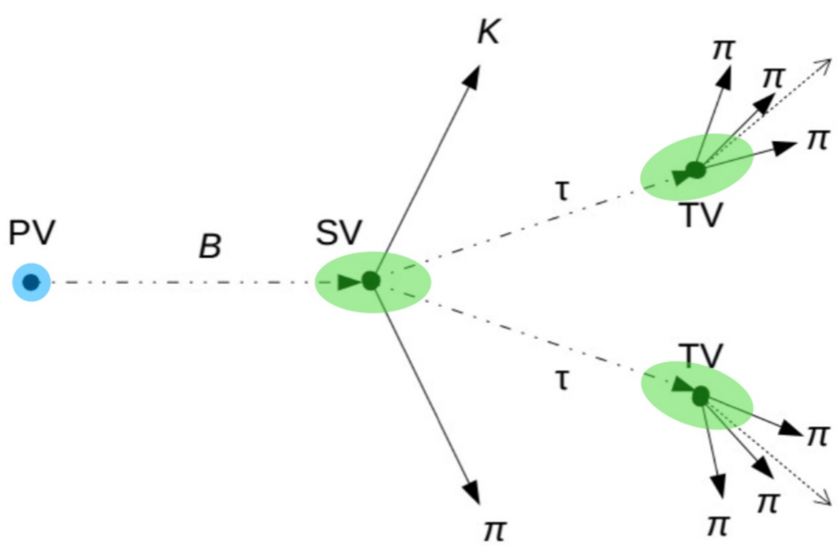
Impact of **beam induced backgrounds;**

- for the CLD tracker, these studies relied on full simulations and concluded that backgrounds should not be an issue
- for the IDEA tracker, the results presented in the CDR will have to be verified with a full simulation
- moreover, these backgrounds should be revisited in view of the updated machine parameters and machine-detector interface.

Requirements on track impact parameters

Constraint from the measurement of BR($B \to K^* \tau\tau$)

The BR($B \to K^* \tau\tau$) ~ O(10^{-7}) in the SM and the current experimental upper limit is larger than this prediction by three orders of magnitude. New physics contribution would enhance the BR.



→ stringent requirements on the performance of the vertex detector come from the measurement of the BR($B \to K^* \tau\tau$)

Both τ leptons decay into three charged pions and a neutrino

The secondary vertex (SV) is given by the kaon and pion tracks that come from the K^* decay

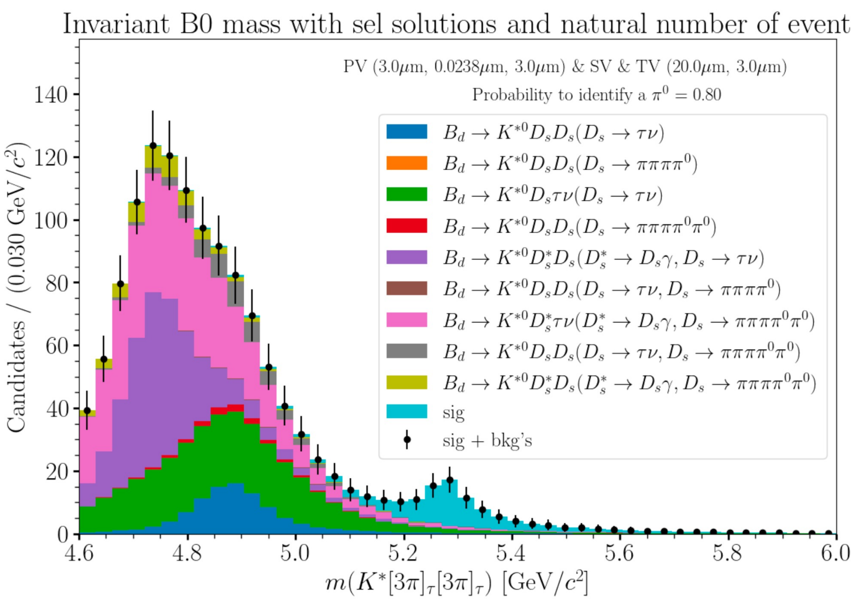
The reconstruction of $B \to K^* \tau\tau$ critically relies on the precise reconstruction of the secondary and tertiary vertices

For displaced vertices, the resolution depends very much:

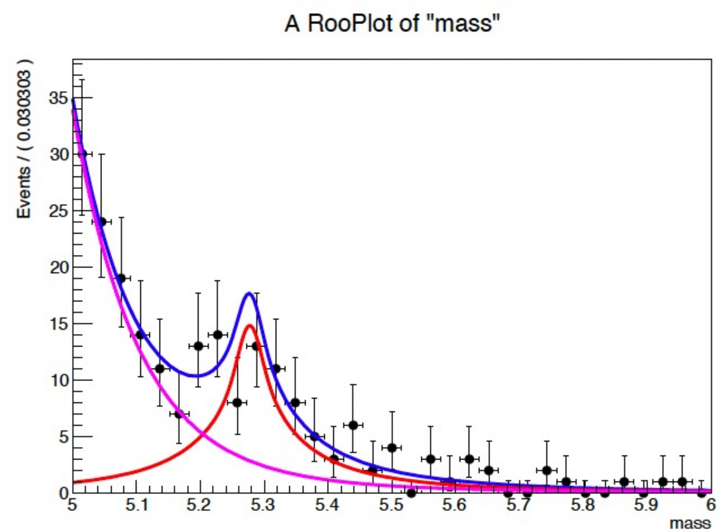
- on the track multiplicity of the vertex
- on the track momenta and angles
- on the angular separation of the tracks

Constraint from the measurement of BR(B→K$^*\tau\tau$)

- a multi-variate analysis allows the background to be reduced to a manageable
- a powerful π^0 identification will be needed to suppress the background



- the remaining background under the B mass peak is dominated by irreducible background processes



Assumptions:

- the resolution of the position of the secondary and tertiary vertices is 20 μm in the longitudinal direction,
- and 3 μm in the transverse direction

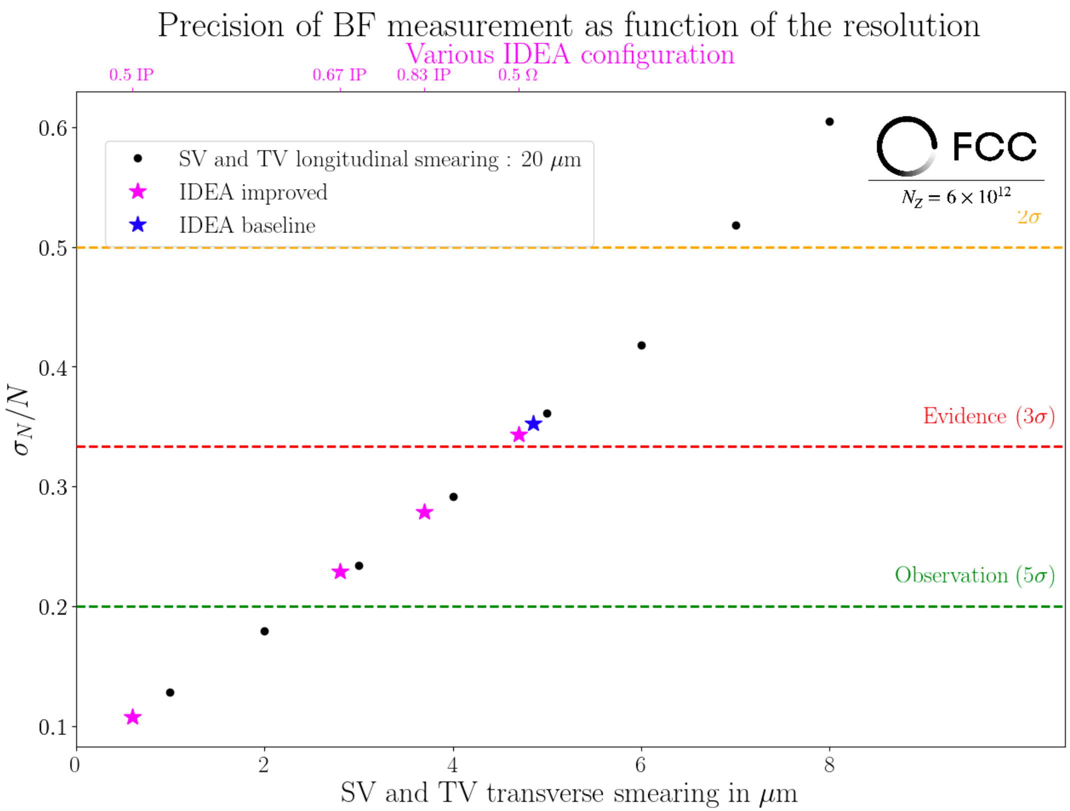
The number N of signal events is extracted from a maximum likelihood fit from which the statistical uncertainty on the measured BR(B→K$^*\tau\tau$) is derived.

That uncertainty determined for several assumptions on the vertex resolutions

N. De Filippis

Constraint from the measurement of BR($B\rightarrow K^{*}\tau\tau$)

The precision of the measurement shows a very strong dependence on the resolution of the position of the secondary and tertiary vertices in the transverse direction



With a statistics of $6\text{x}10^{12}$ Z bosons:

- a resolution better than ~ **4.3 μm** is needed to reach a 3σ evidence of the decay mode
- it should be better than about **2.2 μm** for a 5σ observation of this decay
- For IDEA simulation this resolution is of **5 μm** only

- A better resolution on the track IP by about 10% (about 40%) would allow 3σ (5σ)
- A reduction of the overall VXD material by 35% + with an improvement of the single hit resolution in the VXD layers by 30% (i.e. from 3 μm to 2 μm in the barrel layers) brings the sensitivity beyond 3.7σ

N. De Filippis

Constraint from the measurement of τ lifetime

Precise measurements of the mass, the lifetime and the leptonic branching fraction of the τ offer a crucial test of lepton flavour universality (LFU)

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

currently limited by the precision on

- the τ lifetime (290+/- 0.5 fs)
- BR ($\tau \to e\nu_\tau\nu_e$) (17.82+/- 0.04%)

With about 2×10^{11} τ pair events expected at Tera-Z, FCC-ee has the potential to test LFU at an unprecedented level thanks to a much improved determination of the 3 key ingredients

- statistical uncertainty on the t lifetime is expected to be 10 ppm or better
- the alignment of the vertex detector was the dominant source of systematic uncertainty (Belle and DELPHI) but not the case according to more advanced studies
- expected systematic uncertainty due to misalignment, scaled from the systematics quoted by DELPHI according to the luminosity increase, is below 10 ppm
- one source of uncertainty comes from the knowledge of the overall length scale of the vertex detector. For this uncertainty to be smaller than one half of the statistical uncertainty on the τ lifetime, this scale should be known to better than 5 ppm