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UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare

The Future Circular Collider

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Università and INFN, Bologna

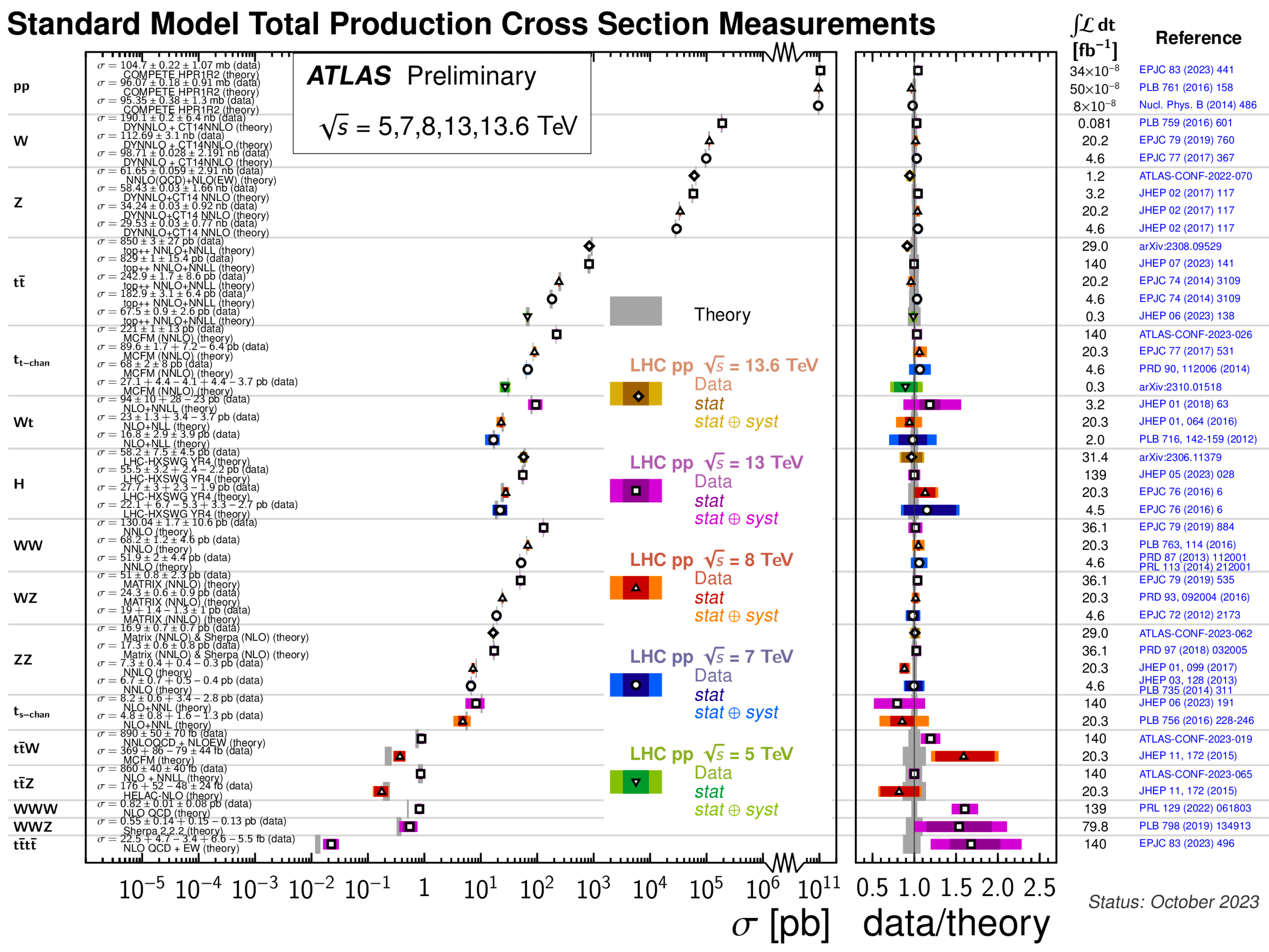
22-24 January 2025 - Workshop on FCC-ee and Lepton Colliders

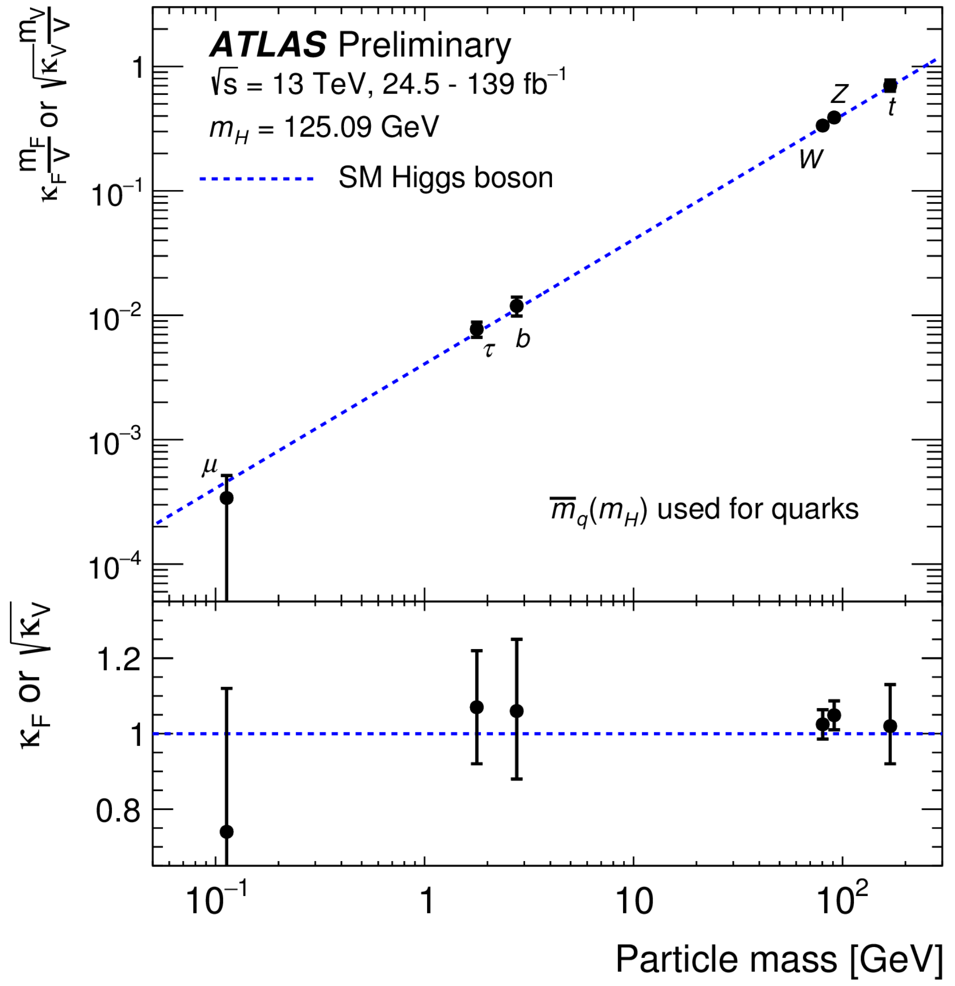
These projects have received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreements No. 101004761 (AIDAinnova), 101057511 (EURO-LABS).

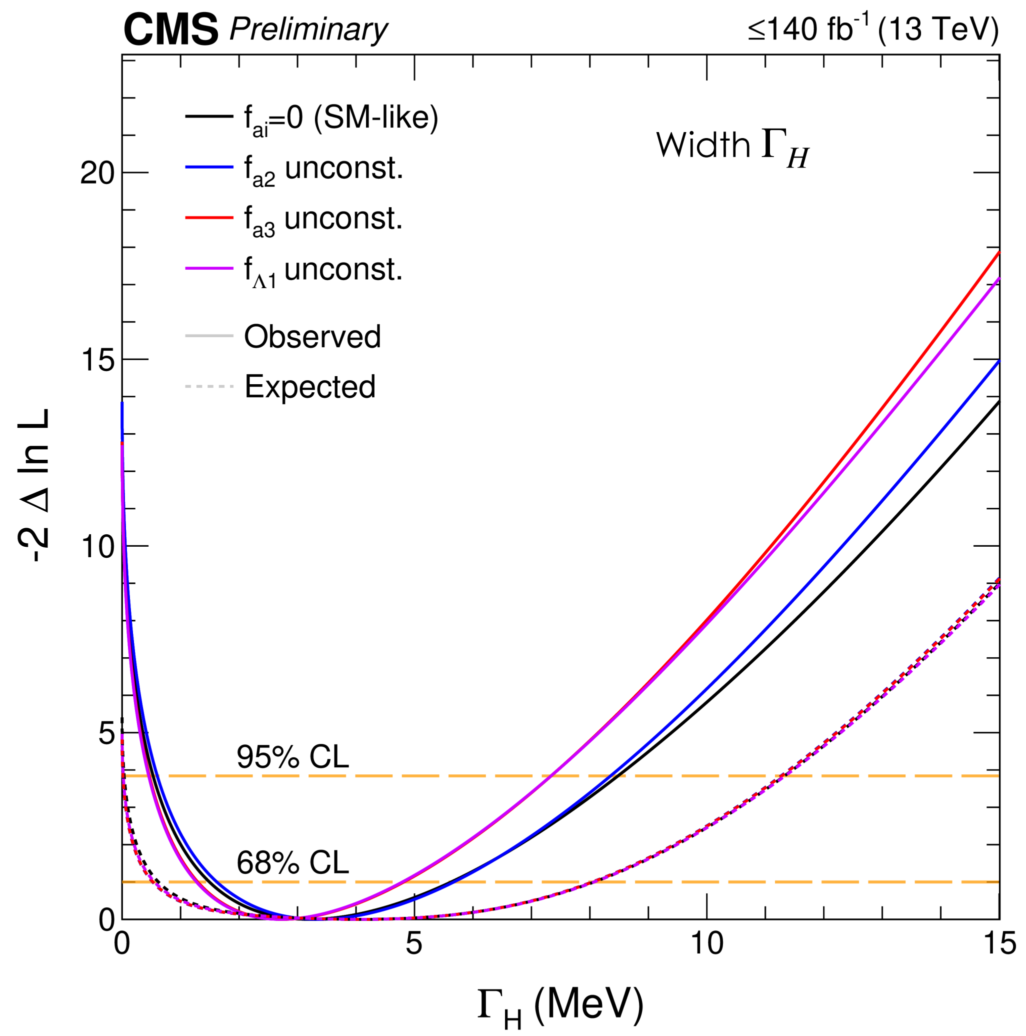
The physics we have

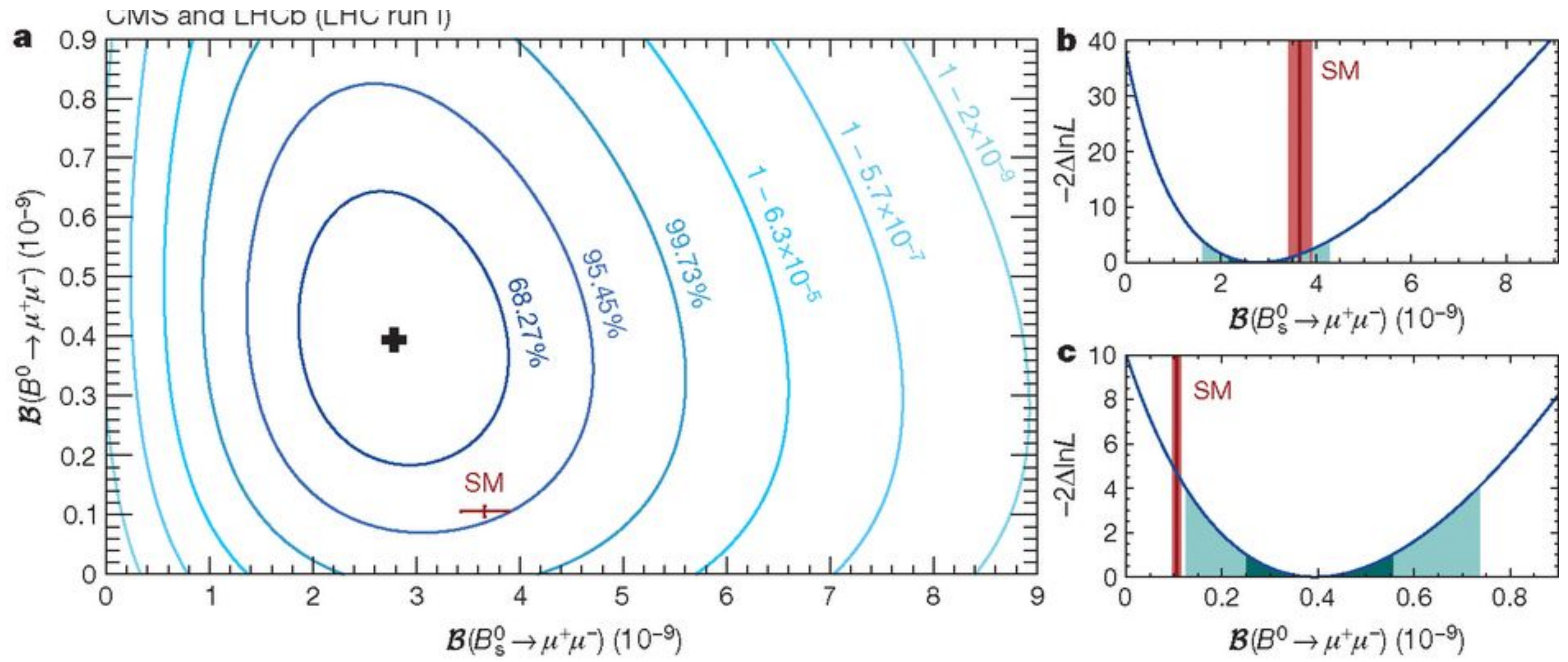
- The take-home message from the LHC so far: **this universe is very SM-like.**

No significant deviation from SM with 140 fb^{-1} of pp collisions (not promising for BSM at HL-LHC)









The physics we do not have

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EW scale stability under quantum corrections

CP and baryon/lepton number violation

Dark Energy

Dark Matter

EW-phase transition

Neutrino masses

Priorities:
- Take the most from LHC.
- Put the standard model under a microscope
- Pave the way for the next discovery machine

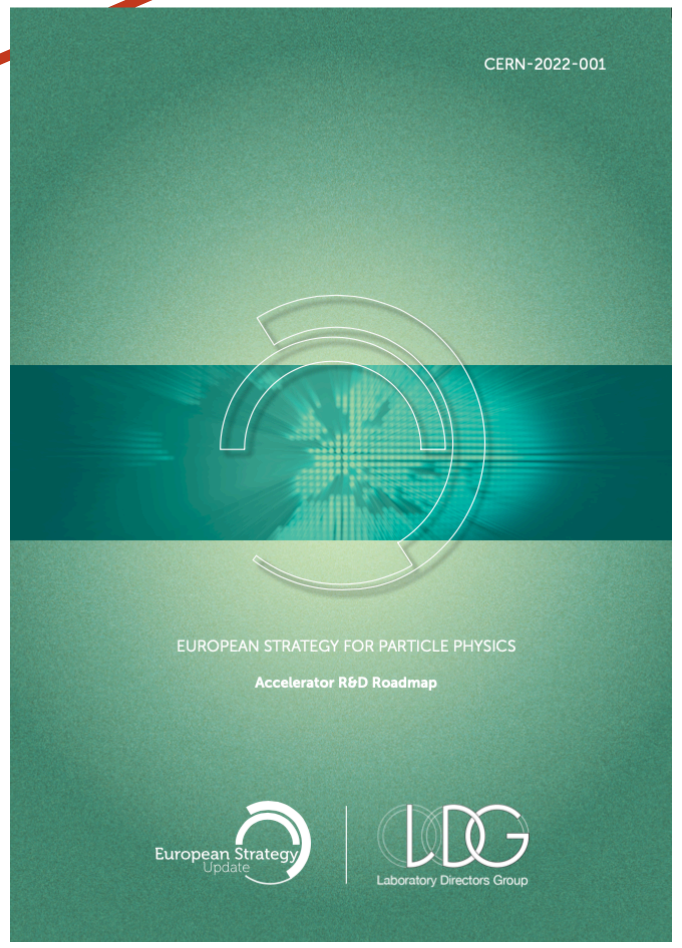
European Strategy for Particle Physics Update (2020)

- These questions **are not new** (neither is the LHC outcome).
- Some of the key (for this talk) outcomes of the **2020 ESPPU**:
  - Europe, together with its international partners, should **investigate the technical and financial feasibility of a future hadron collider at CERN** with a centre-of-mass energy of at least 100 TeV **and with an electron-positron Higgs and electroweak factory as a possible first stage**. Such a **feasibility study of the colliders and related infrastructure** should be established as a global endeavour and be completed **on the timescale of the next Strategy update**.
- It has been a long five-years:

ECFA **roadmapping exercise on detectors** lead to the **creation of the DRDs**.

Parallel **exercise on accelerators** highlighted a number of **strengths/weaknesses**, and gave a **snapshot on status of various technologies**.

Launch of the FCC feasibility study.



European Strategy for Particle Physics - Accelerator R&D Roadmap

The 2021 ECFA Detector Research and Development Roadmap (+ Synopsis)

European Strategy for Particle Physics Update (2026)

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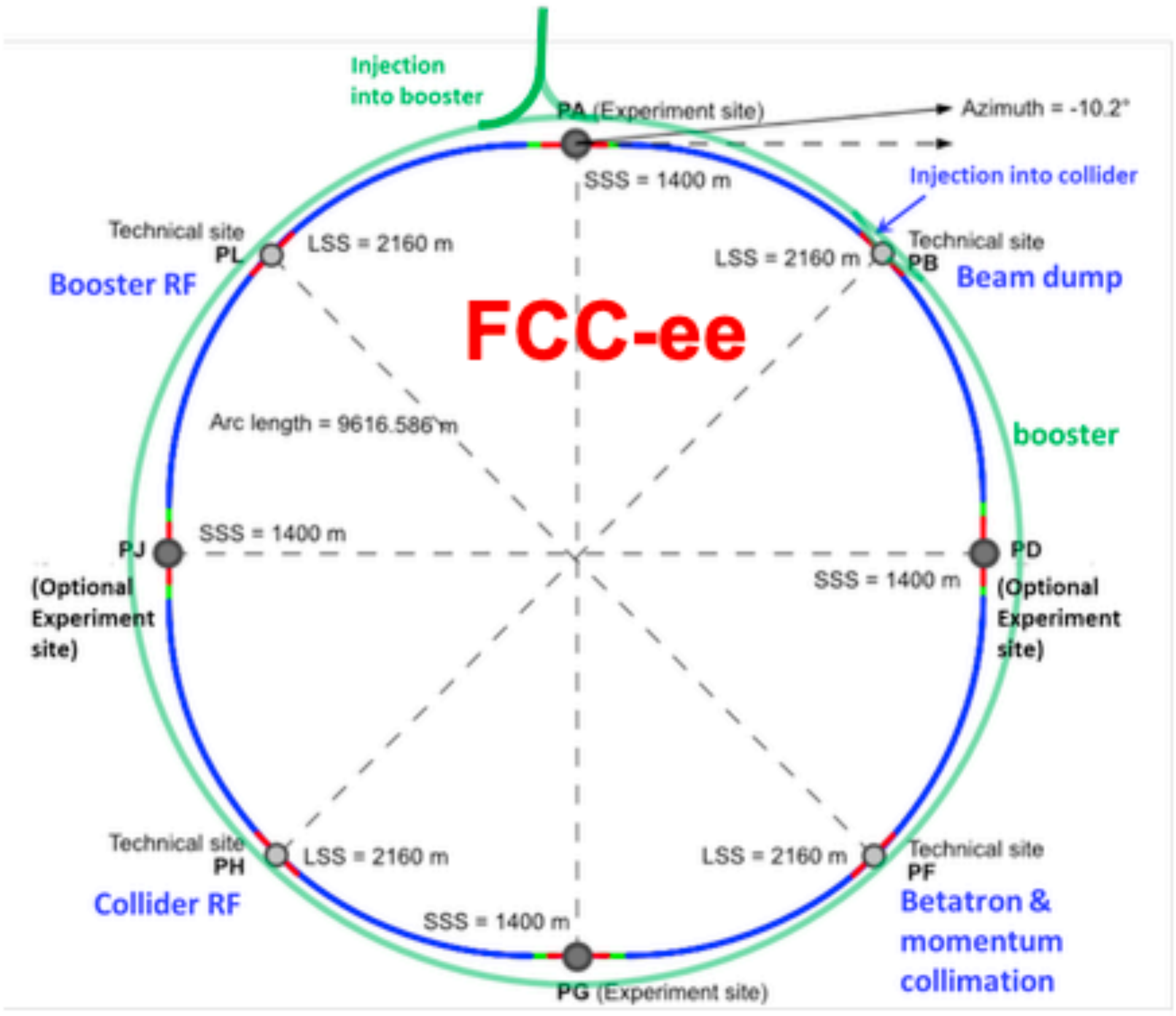
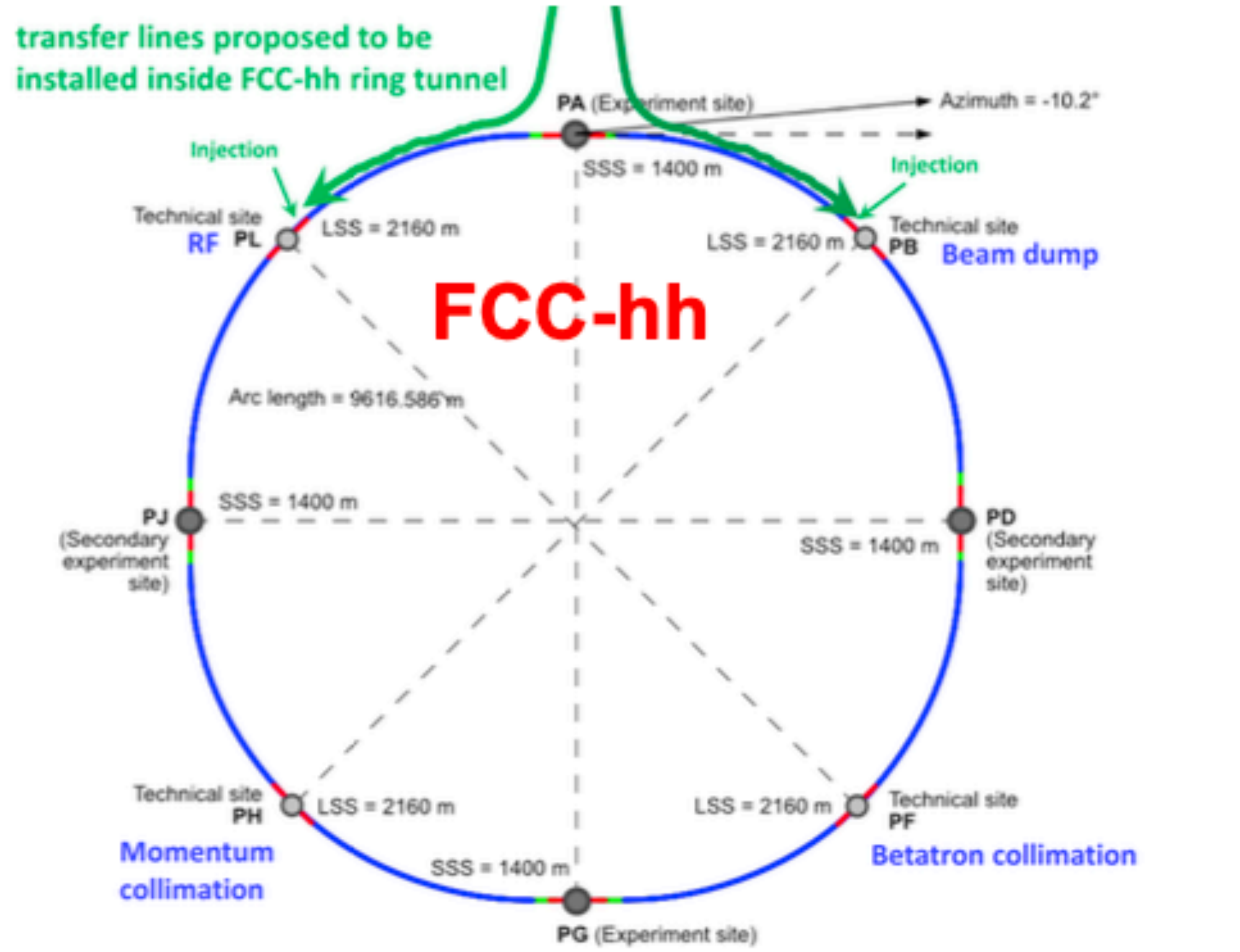
- The **new update of the ESPPU** is on us.
- **National processes** already in full swing. ECFA has published guidelines to provide national input.
  - … and let me remind you of the INFN workshop at Bicocca.
- The **integrated FCC programme** is the **baseline** option.

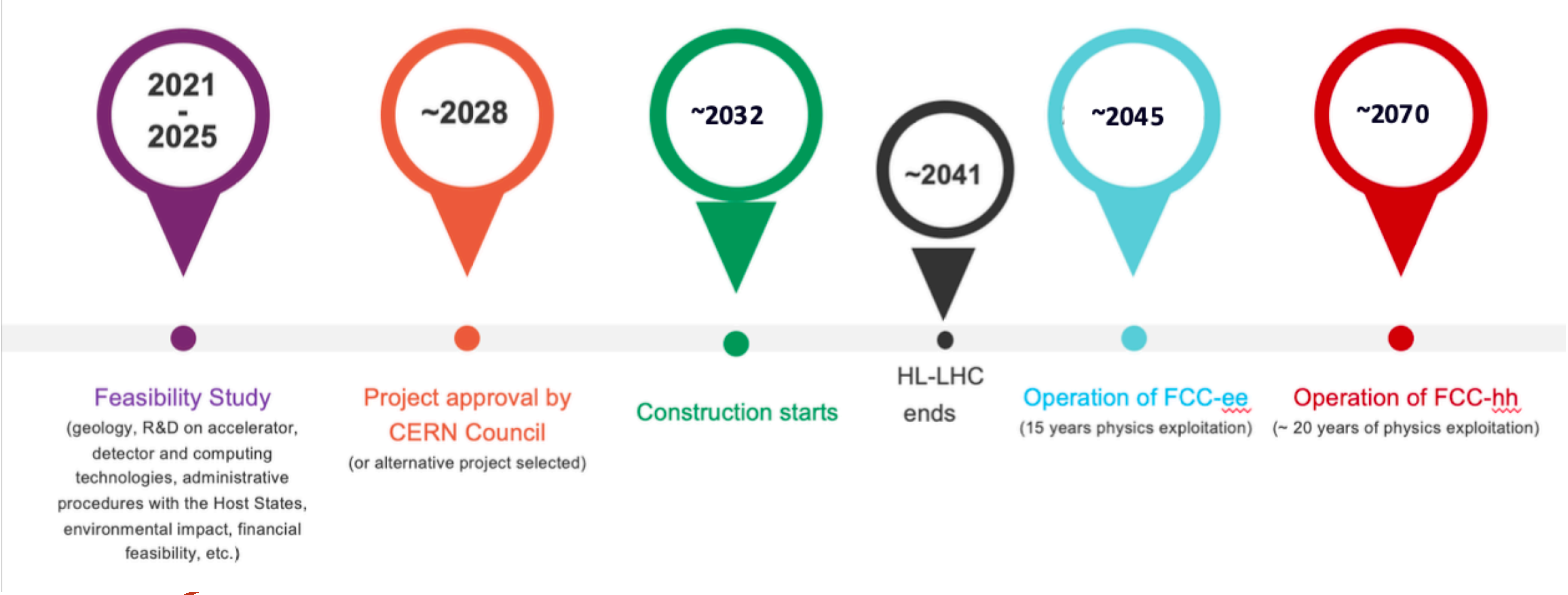




2045 - 2065 | **2070 -**

- **Stage 1:** FCC-ee (Z, H, WW, $t\bar{t}$) - high-precision exploration of the EW sector of the Standard Model, flavour physics, feebly coupled BSM physics.
- **Stage 2:** FCC-hh (pp @ 100 TeV) - exploration of the energy frontier.
- **Synergic programme** starting **a few years** after the completion of the **high-priority HL-LHC physics.**

FCC timeline



FCC-ee in pills

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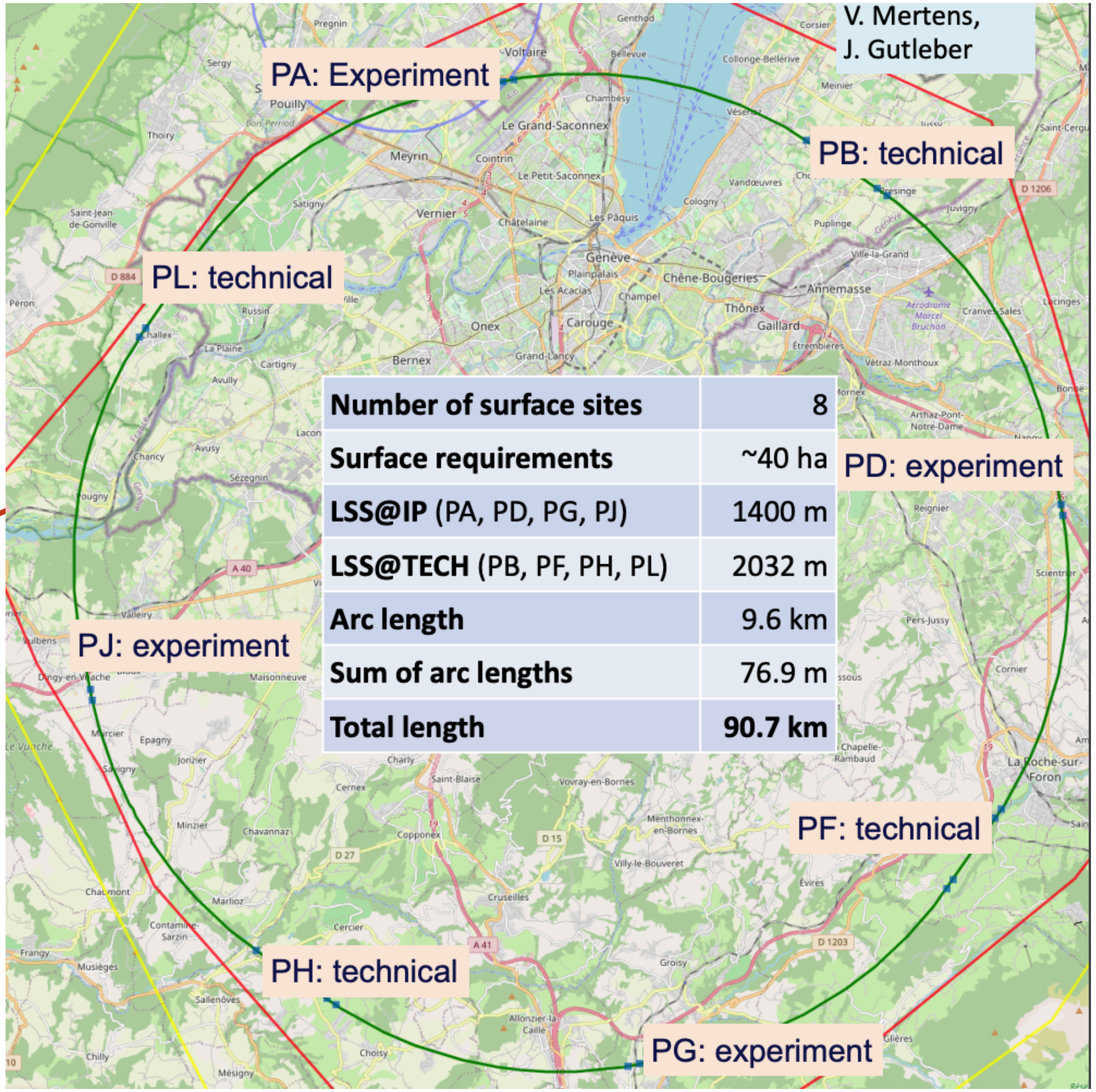
	Z pole	WW pole	ZH pole	Top pair pole
Beam energy (GeV)	45.6	80	120	182.5
Beam current (mA)	1270	137	26.7	4.9
Number of bunches	11200	1780	440	60
Luminosity (per IP - 10^{34} cm^{-2} s^{-1})	140	20	5	1.25
Integrated luminosity (per IP - ab^{-1}/year)	17	2.4	0.6	0.15
Planned running time (years)	4	2	3	5

Which translates in

- 5×10^{12} Z (LEP $\times 10^5$)
- $\sim 10^8$ WW (LEP $\times 10^4$)
- 2×10^6 H unprecedented at e^+e^-
- 2×10^6 $t\bar{t}$ unprecedented at e^+e^-



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

The FCC feasibility study

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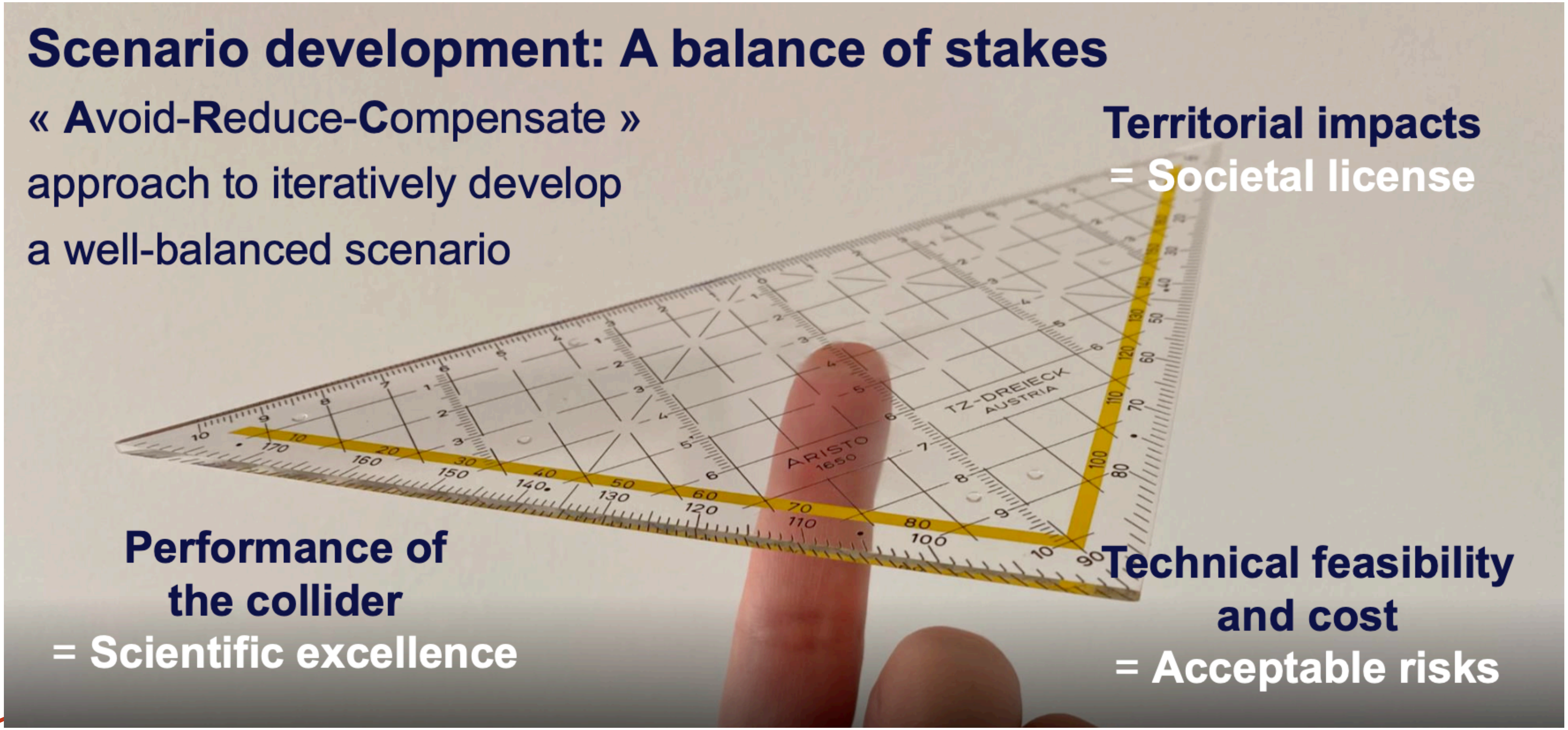
- An effort to document the feasibility of the project in terms of:
  - Civil engineering, implementation and sustainability.
  - Accelerator, technical infrastructure, safety concepts.
  - Physics, experiments and Detectors.
- A set of high-level objectives are listed here.
- Feasibility study to be **delivered by March 2025**.
  - A mid-term review was **successfully passed in 2024**.

Civil engineering, implementation and sustainability



Civil engineering, implementation and sustainability

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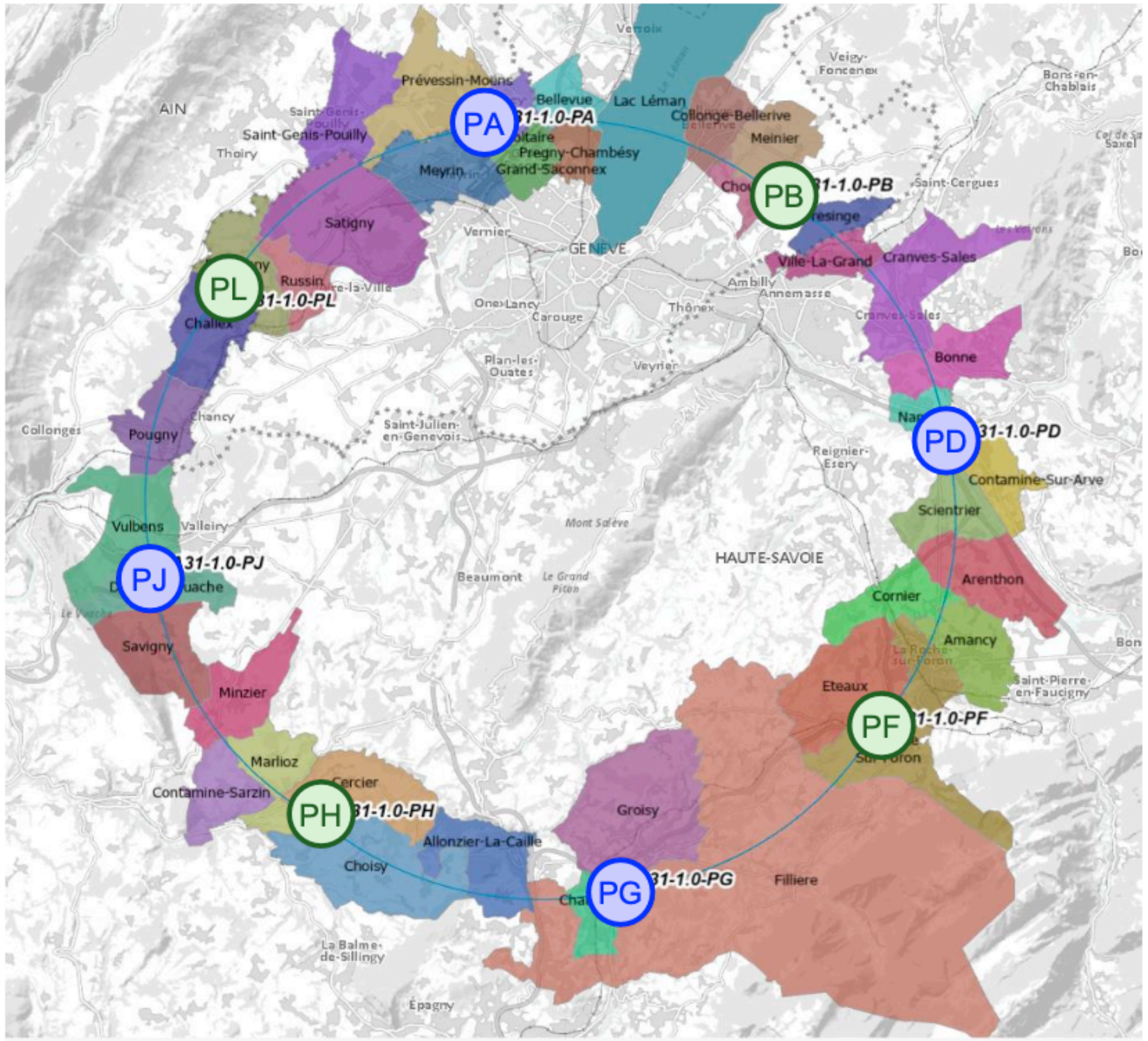
1. **PA – Ferney Voltaire** (FR, 01) – experiment
2. **PB – Choulex** (CH) – technical
3. **PD – Nangy** (FR, 74) – experiment
4. **PF – Etaux** (FR, 74) – technical
5. **PG – Charvonnex/Groisy** (FR, 74) - experiment
6. **PH – Cercier/Marlioz** (FR, 74) – technical
7. **PJ – Vulbens/Dingy en Vuache** (FR, 74) – experiment
8. **PL – Challex** (FR, 01) – technical

LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**



Civil engineering, implementation and sustainability

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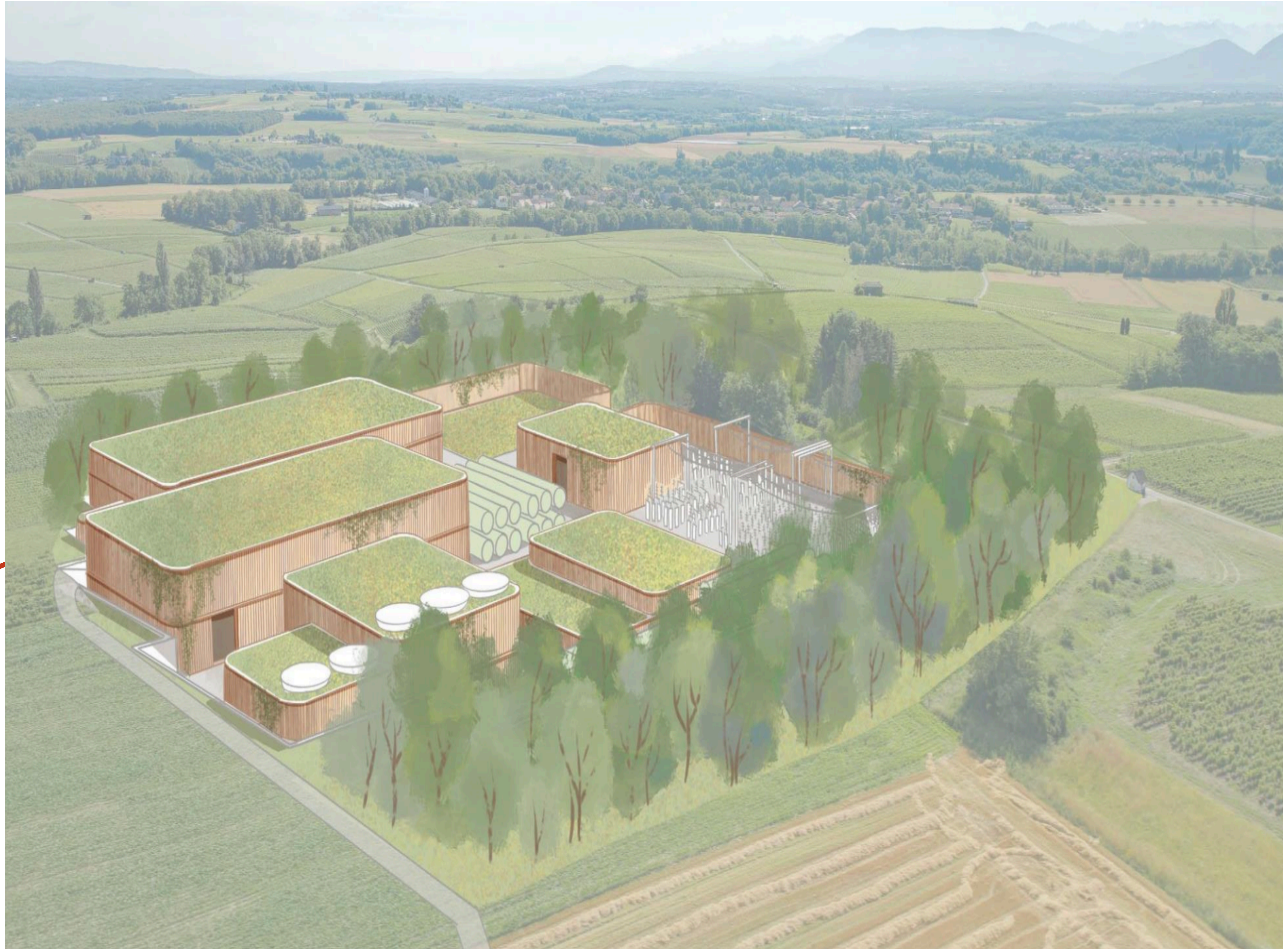
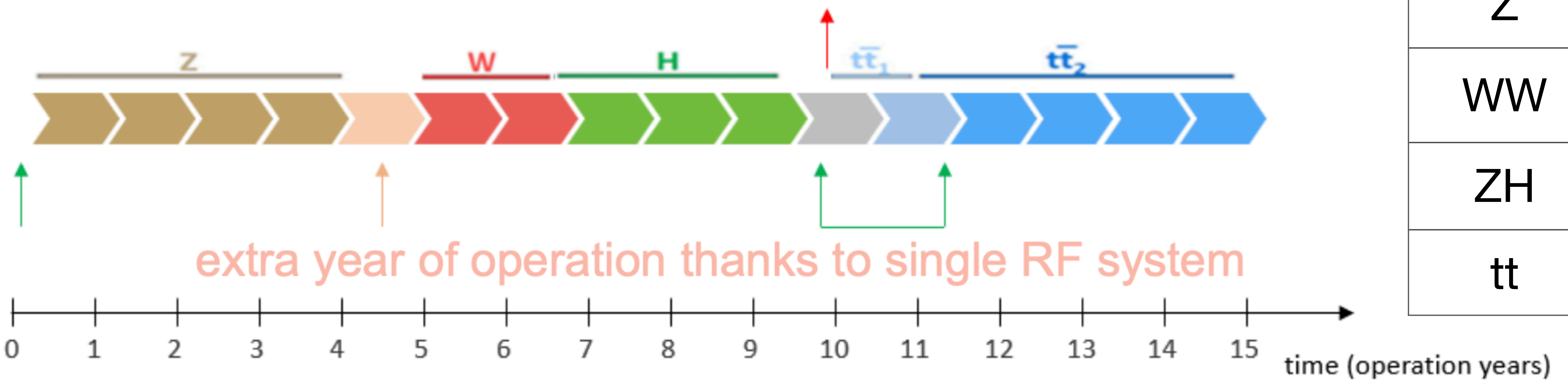
- See talk from J. Gutleber at the 8th FCC Physics Workshop (13-17 January 2025) for **a recent, detailed update**, including:
  - Update on **surface investigations**.
  - Design of **surface sites**.
  - Design of **injector**.
  - Sustainability needs on **electricity consumption, waste management** (including excavation materials), **construction carbon footprint**, etc.



Accelerator (ee) - Superconducting RF



	Energy (GeV)	Current (mA)	RF Voltage (GV)
Z	45.6	1270	0.08
WW	80	135	1
ZH	120	26.7	2.08
tt	182.5	5	11.67

See Talk from Cristian Pira

- Maximum beam power **limited to 50 MW** (determines the maximum current at each cos, hence the luminosity).
- Different technology for **Z, WW and ZH** (400 MHz, Nb coating on Cu) and $t\bar{t}$**/booster** (800 MHz, Nb bulk).
- International R&D ongoing for high-Q cavities, thin-film coating, cryomodules, efficient power sources (with INFN involvement, for example in Nb_3Sn).

Machine-Detector Interface

See Talk from Manuela Boscolo

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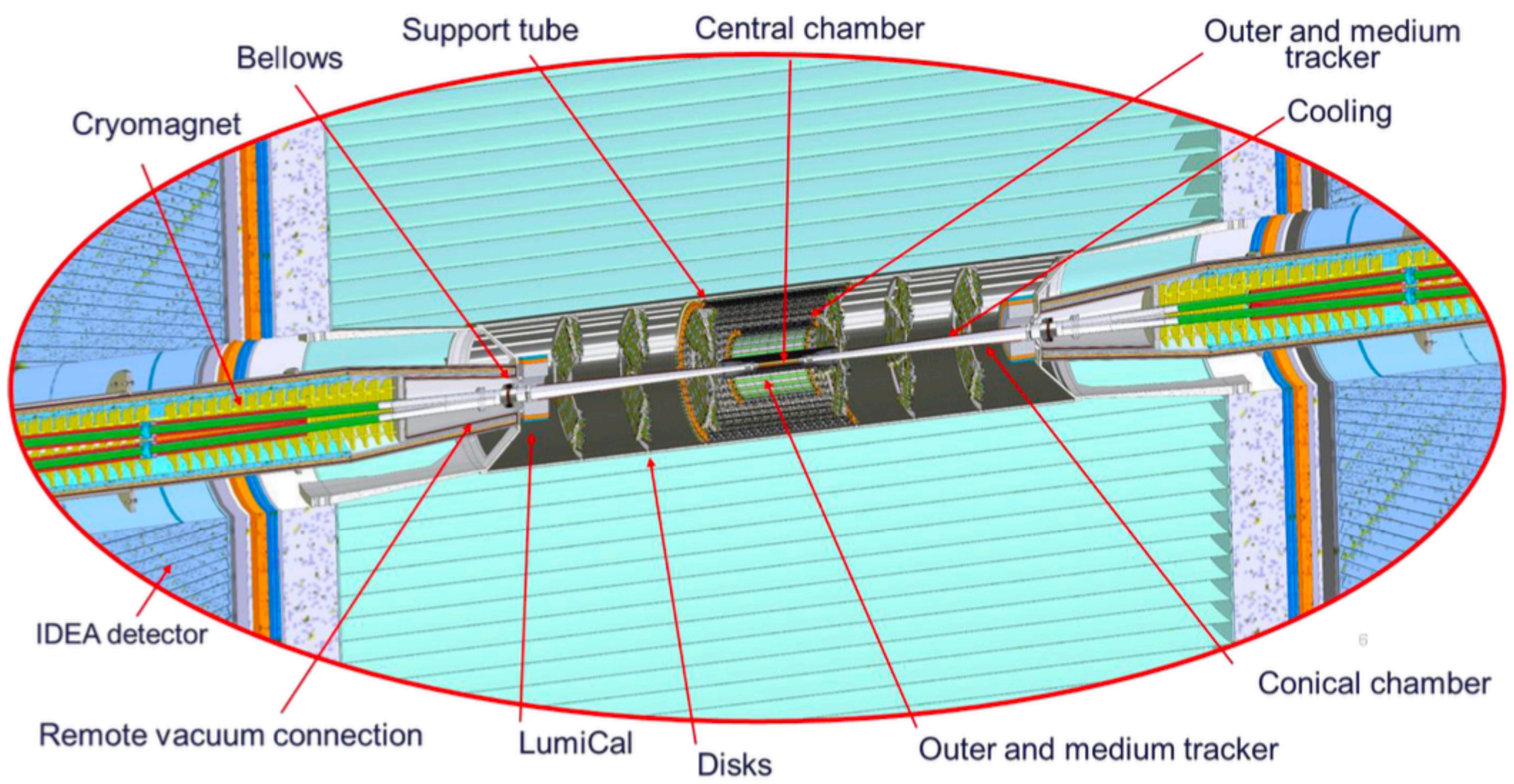
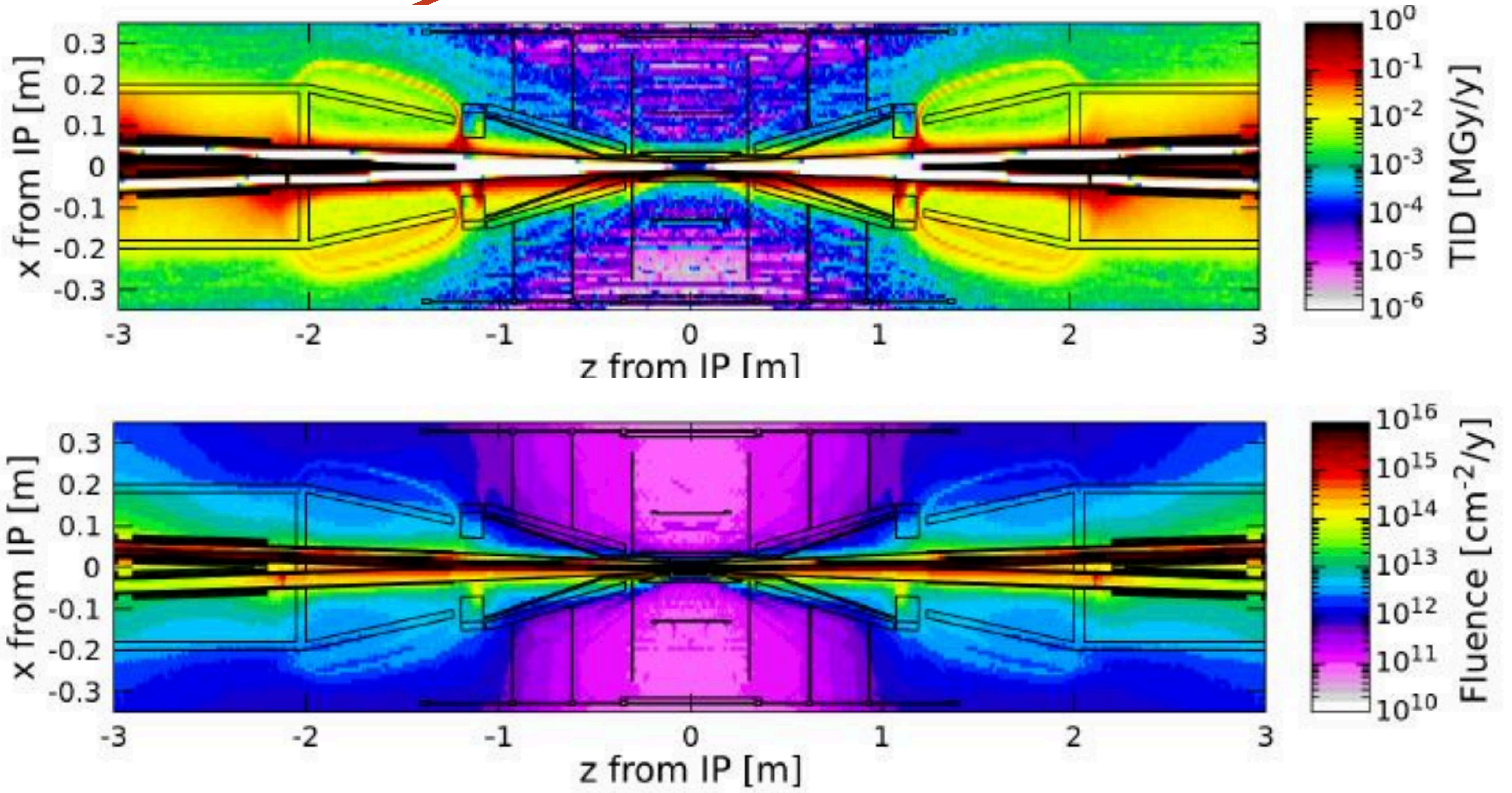
- MDI design nearly finalised.
- **Cooled beam pipe** with vertex detector anchored to it.
  - **Low-material** (0.68% X_0 for the central beam pipe).
- Mock of the interaction region **being built in Frascati**.

Radiation studies (mainly synchrotron radiation and incoherent pair production) **fully performed** with FLUKA, **worst conditions** at the Z pole (total ionisation dose of tens of kGy/y, fluence of 10^{13} 1 MeV n_{eq}/cm^2).





The physics of FCC-ee

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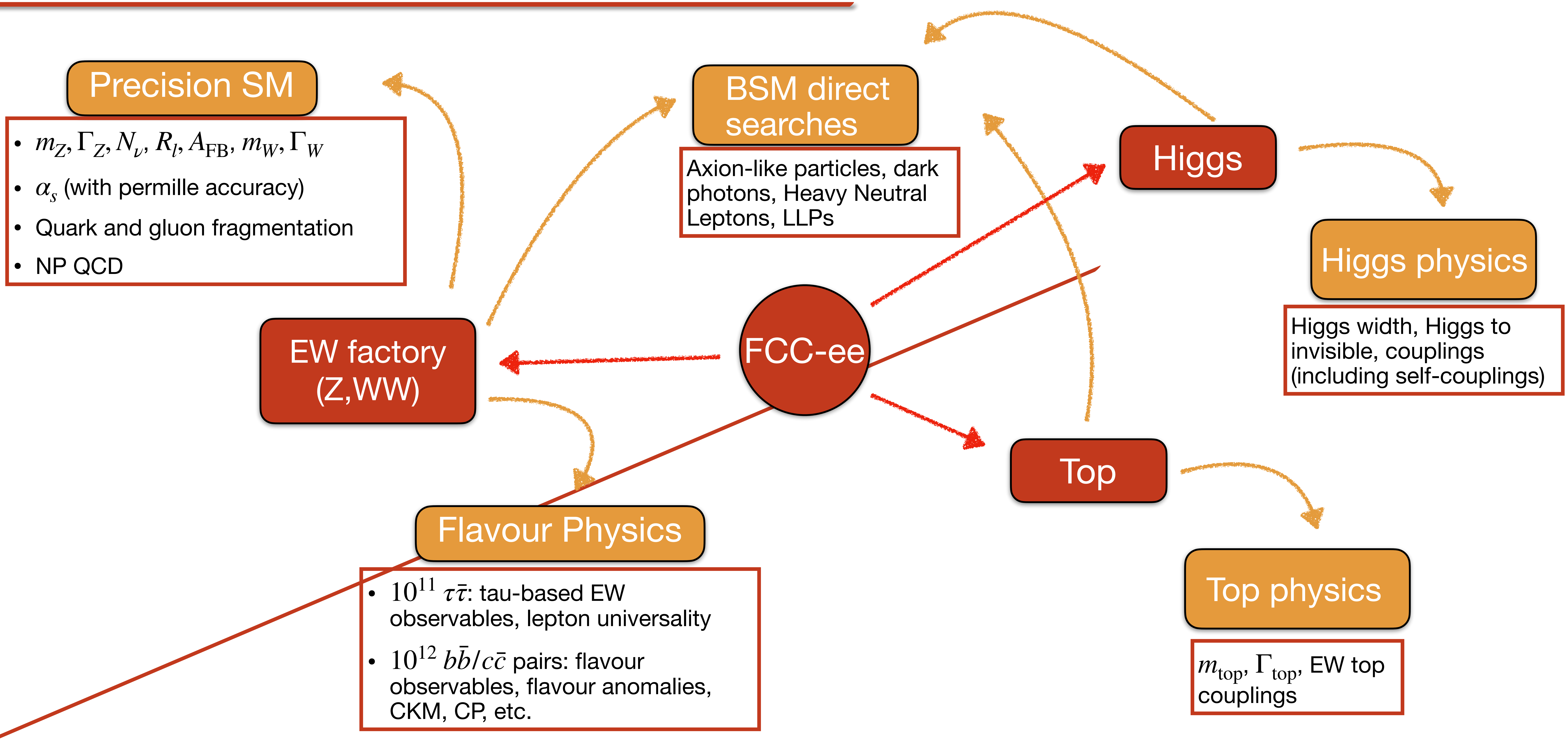
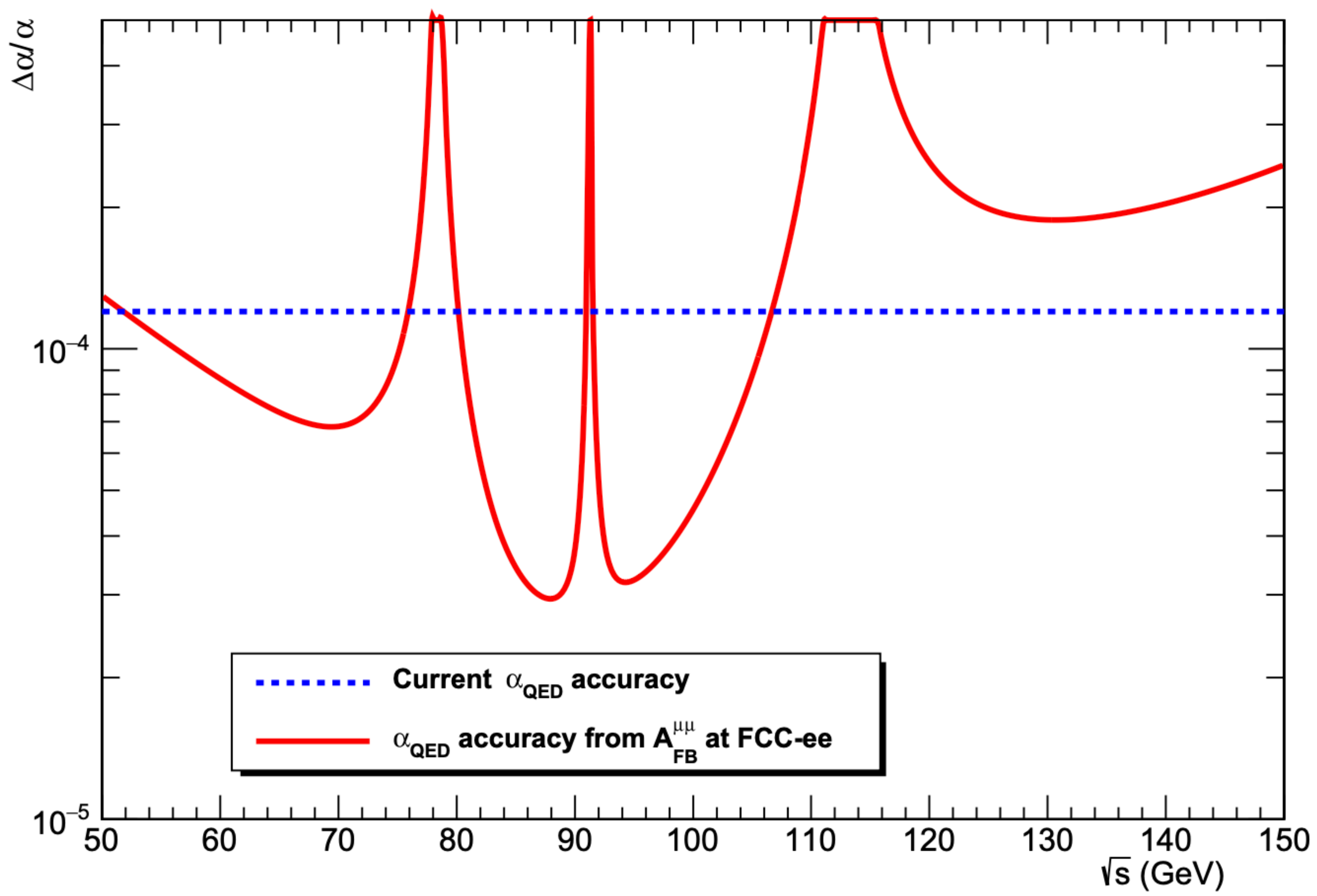
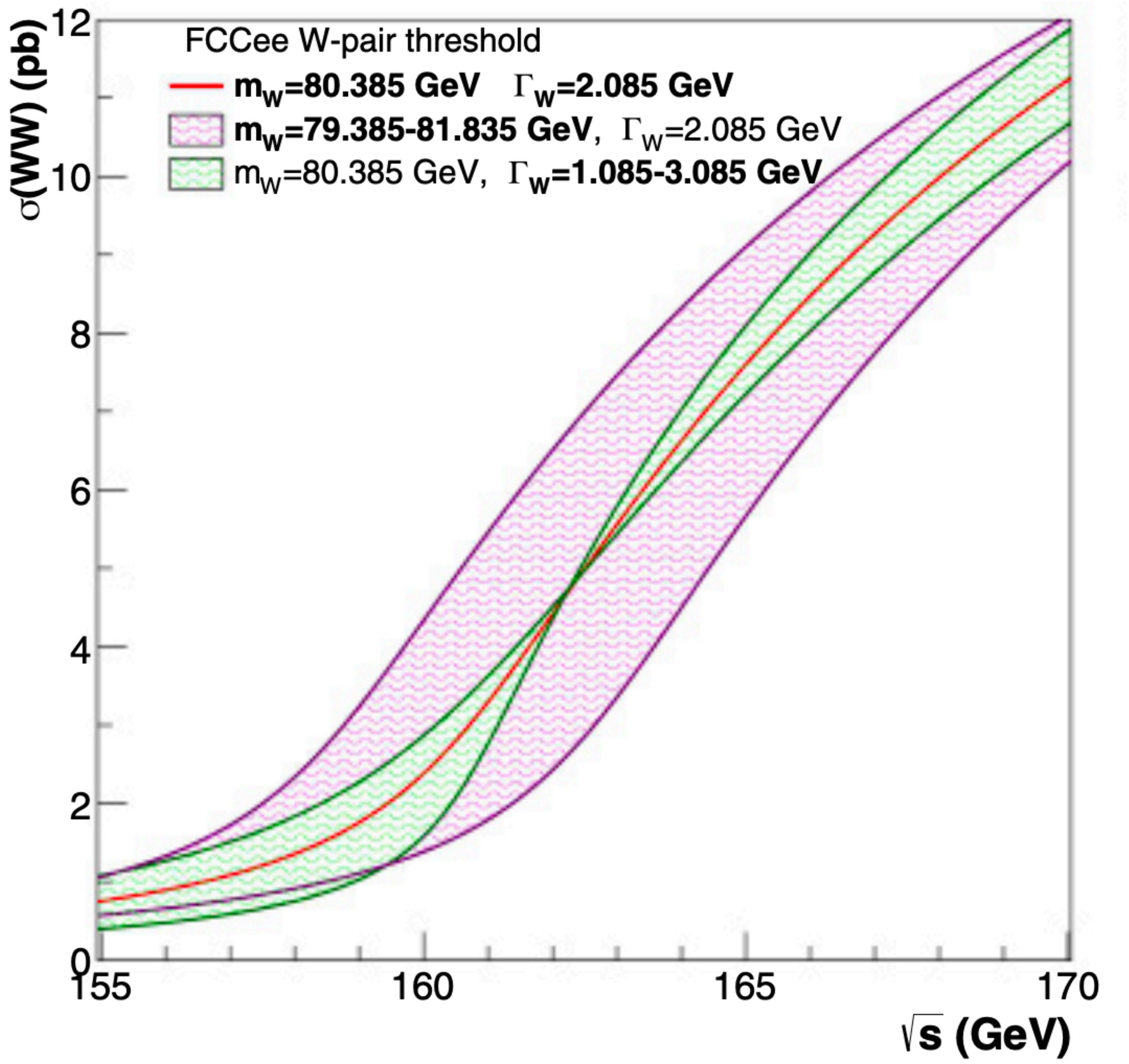


Original idea/slide from C. Grojean

FCC-ee - EW physics

- An **unprecedented Standard Model precision test.**
- At the Z pole
  - Exquisite (better than 1/10^5) precision on $\sin^2\theta_W^{\rm eff}$, mainly from $A_{\rm FB}^{\mu\mu}$.
  - Measurements of $\alpha(m_Z^2)$ from the slope of $A_{\rm FB}^{\mu\mu}$ close to the Z pole.
  - $\alpha_S(m_Z^2)$ from **ratio of Z partial widths** in leptons and hadrons.
- At the WW pole:
  - $m(W)$ with sub-MeV precision from dependency of WW production cross-section on $\sqrt{s}$.
- All this assumes **ability to control cms beam energy at the $0.1-0.5$ MeV level** (see talk from G. Wilkinson), **detector acceptance at the 0.01% level**.





FCC-ee - top physics

See recent talk from Matteo Defranchis

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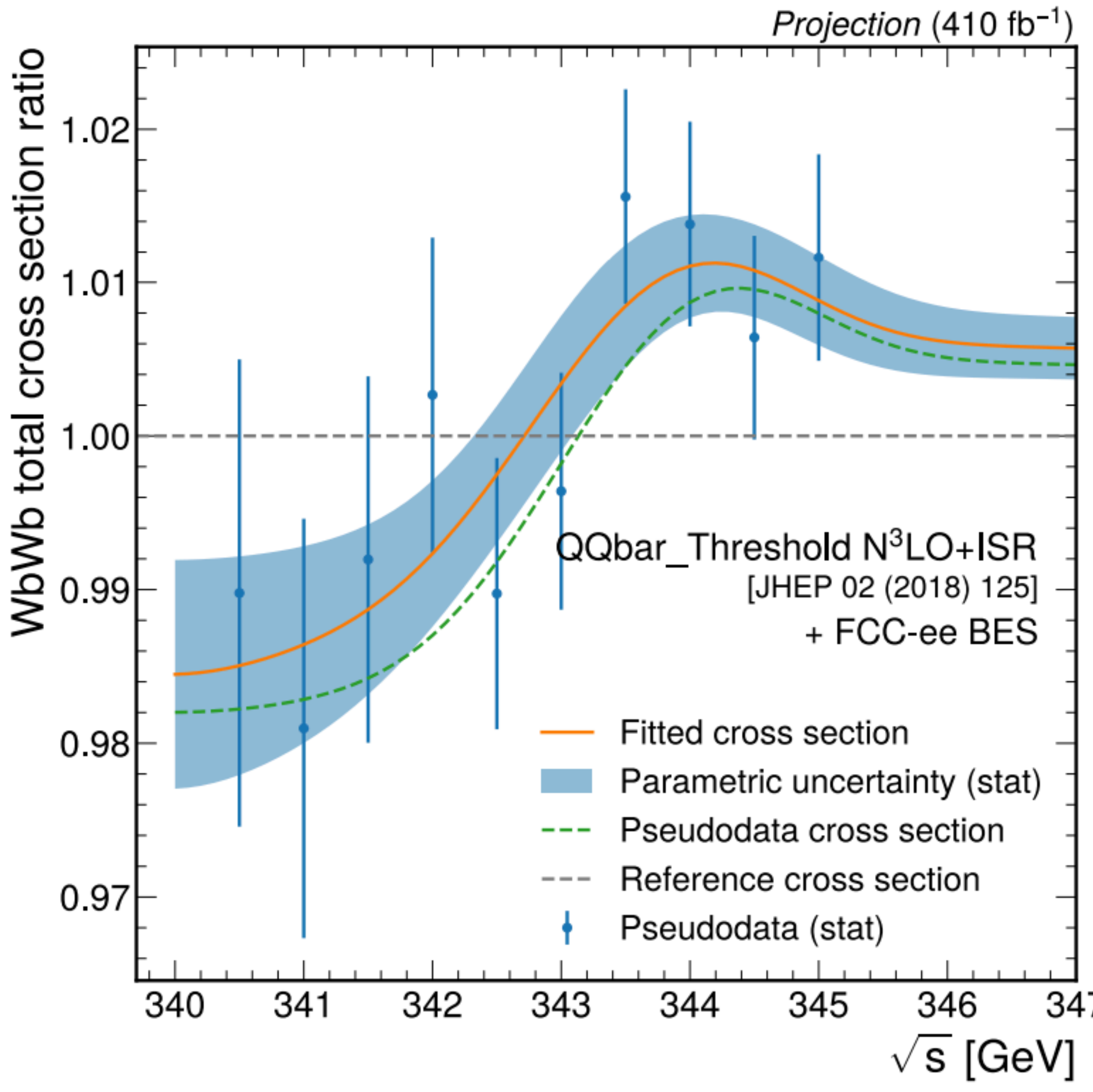
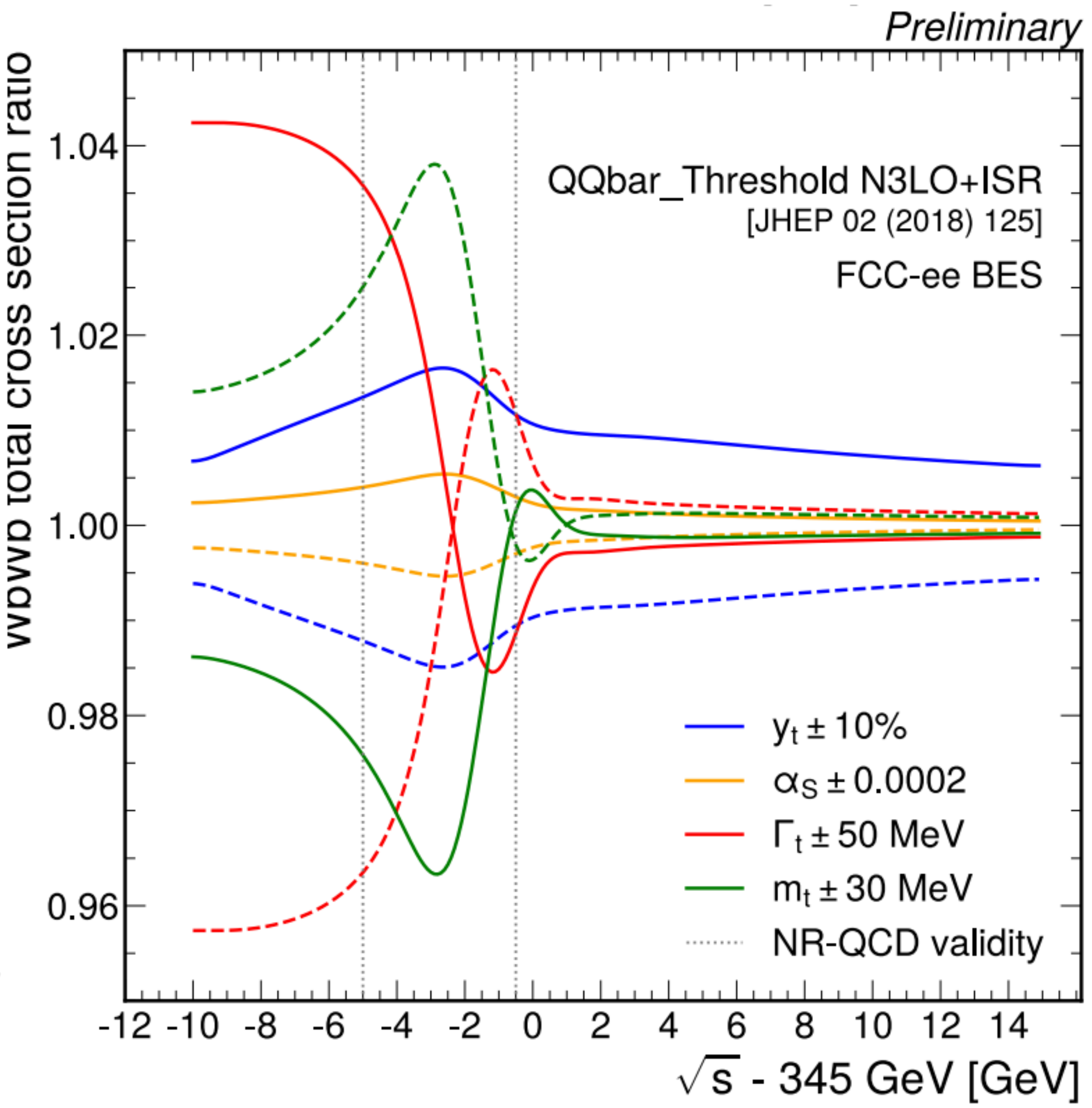
- Simultaneous determination of m_t and Γ_t from the **production cross section determination** as a function of $\sqrt{s}$.

- Expected uncertainty (**35 MeV for** m_t, 25 for the Γ_t) dominated by theory uncertainties on N³LO calculation.
  - Compare with the **300 MeV model-dependent** LHC uncertainty.

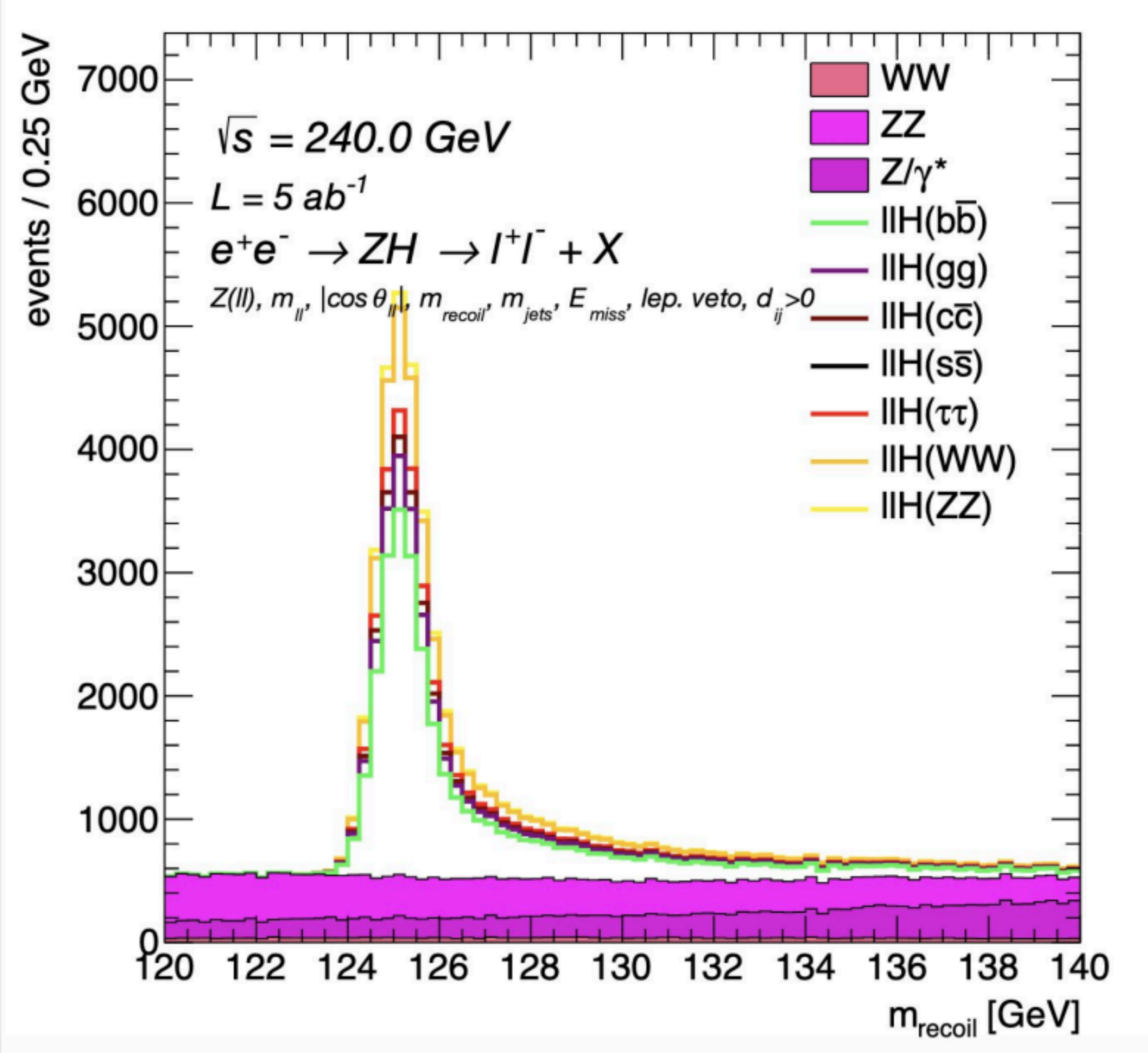




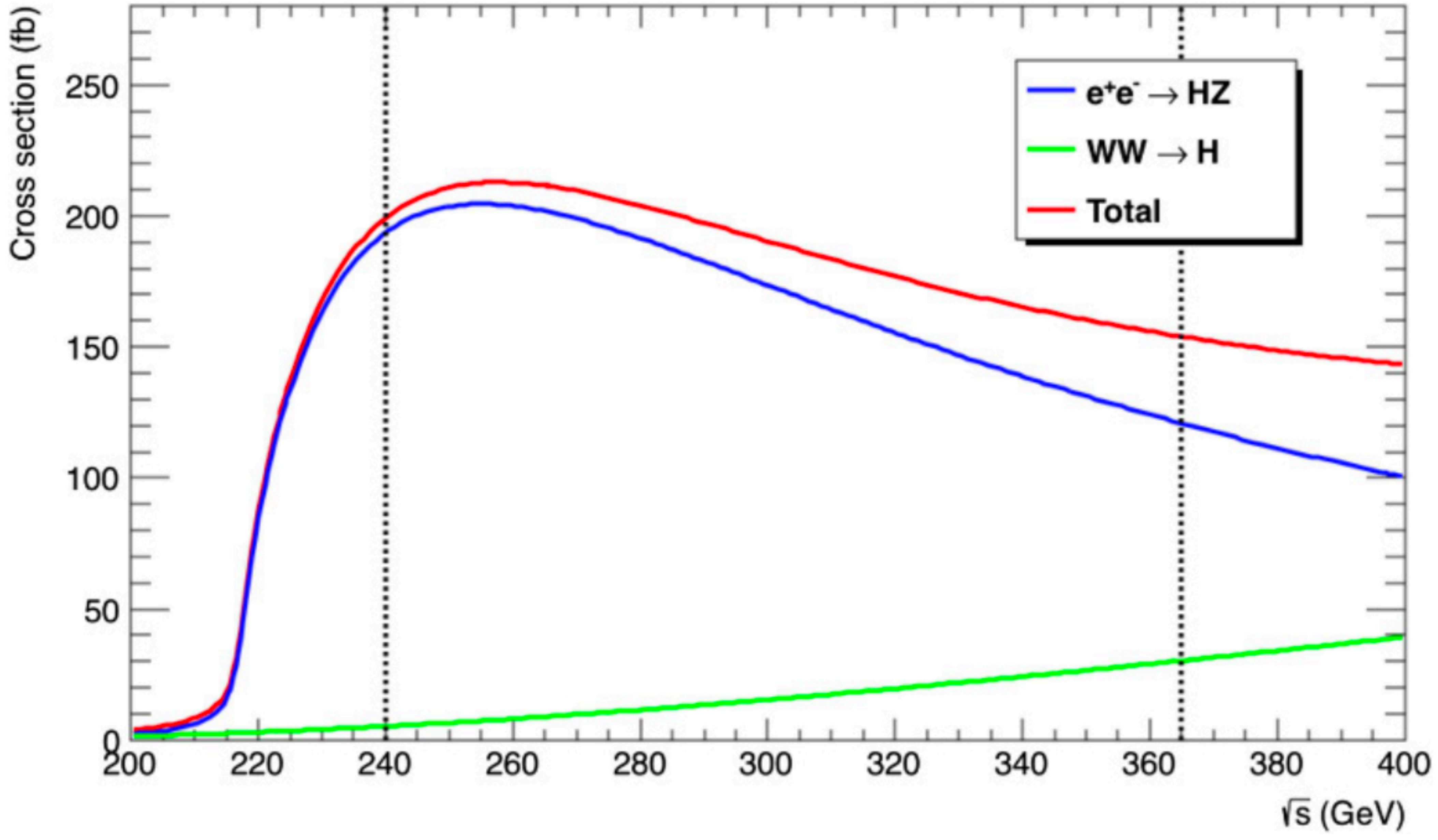
Higgs physics

- If built, FCC may be the **first leptonic Higgs factory** ever built.

- A **few million Higgs production events** at $\sqrt{s} = 240$ GeV and $\sqrt{s} = 365$ GeV.



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



- Higgs recoil gives **unique access to Higgs boson decays** without looking at the Higgs.

- Direct Γ_H (and $H \to \text{invisibles}$).

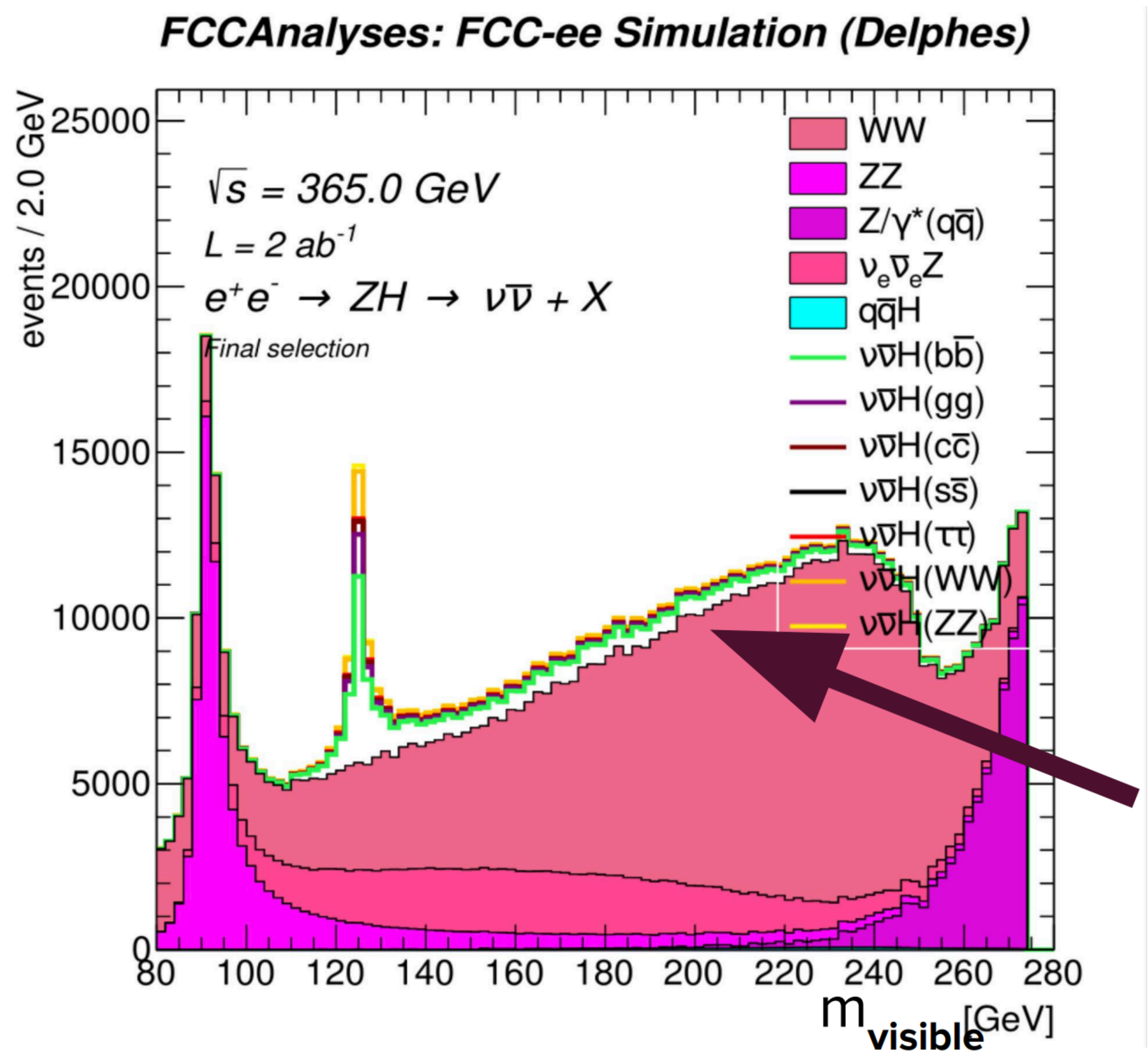
- Access to H decay into hadrons ($H \to c\bar{c}$, $H \to s\bar{s}$, but also improved $H \to b\bar{b}, H \to gg, H \to \tau\tau$, etc.)

Higgs couplings

- Important contribution from FCC-ee to Higgs coupling determination
  - Clean access to hadronic decay mode (see slides about combination of hadronic state measurements).

From FCC-ee CDR

Collider	HL-LHC	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\mathrm{FCC\text{-}ee}_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	<1.7	<2.1	<1.6	<1.2	<1.2	**<1.0**	**<1.0**



Final states separated via a neural network

$$m_{visible} = m_{jj}$$

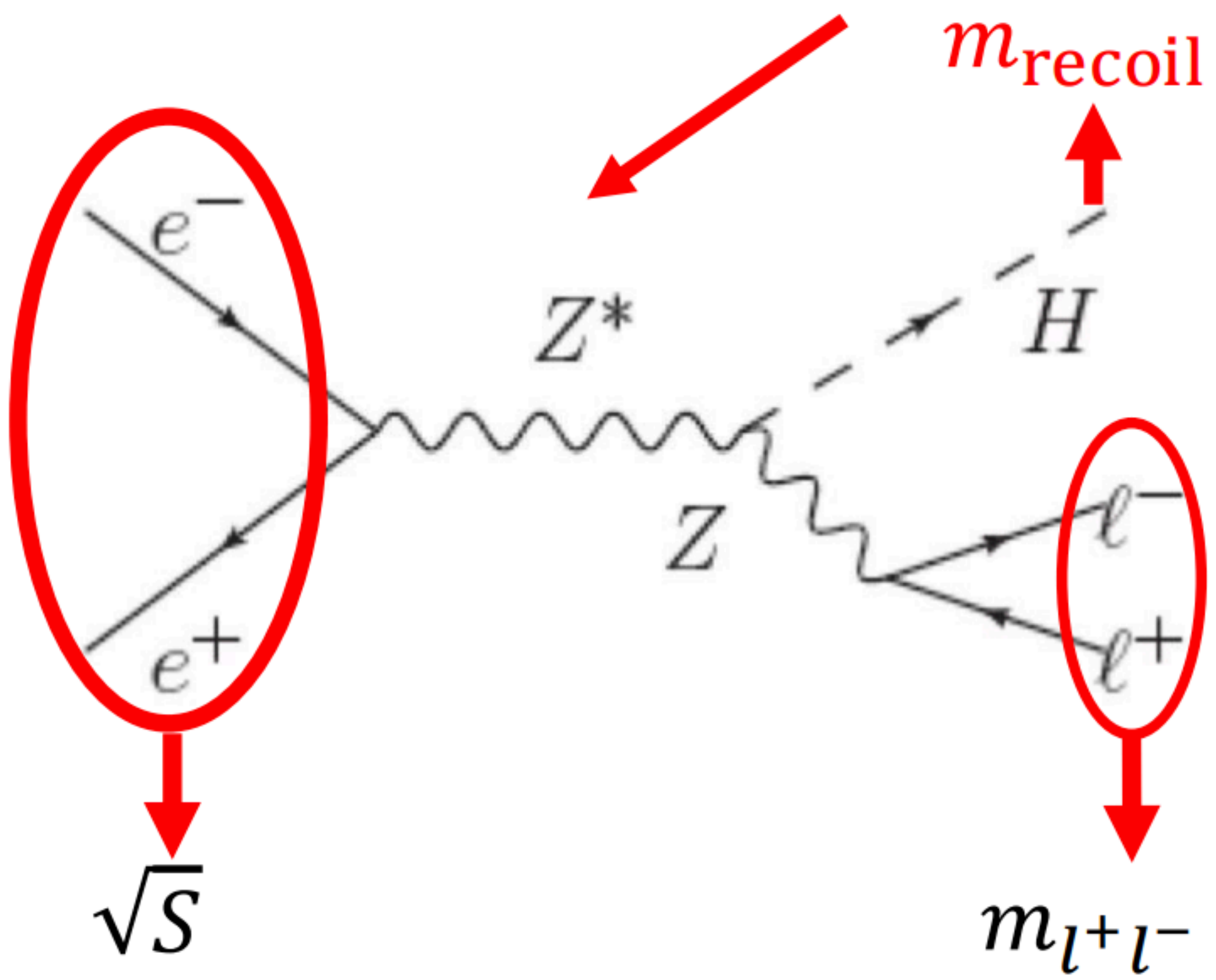
Expected sensitivity (%) of σ.BR(H⟶jj) at 68% CL **L = 10.8ab-1**

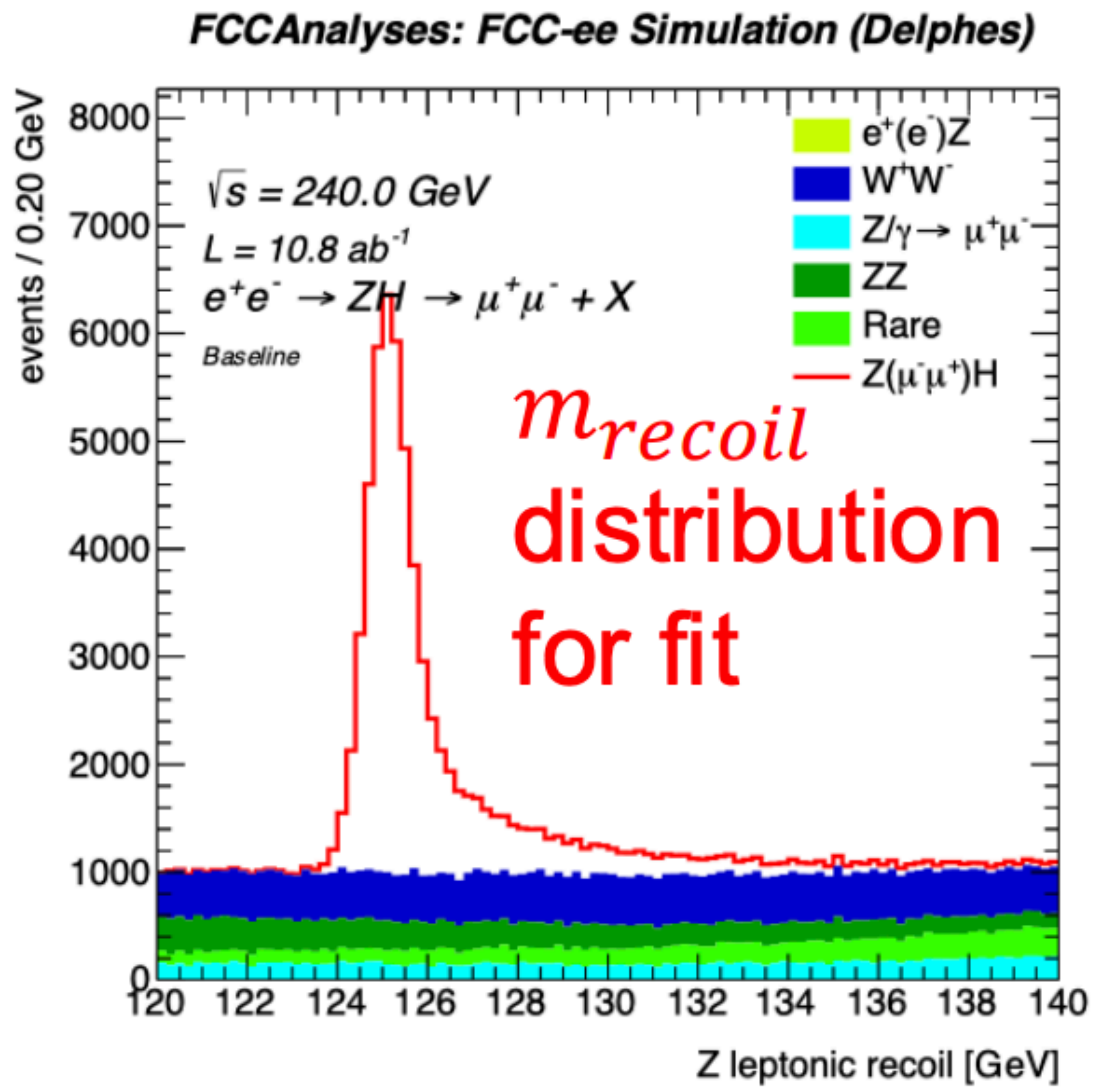
240 GeV		**H⟶bb**	**H⟶cc**	**H⟶gg**	**H⟶ss**	**H⟶ZZ**	**H⟶WW**	**H⟶ττ**
Combined (BNL)		0.21	1.66	0.8	104.99	10.07	1.16	3.97
Combined (APC)		0.22	1.65	0.93	121	9.56	1.11	3.79
365 GeV		**H⟶bb**	**H⟶cc**	**H⟶gg**	**H⟶ss**	**H⟶ZZ**	**H⟶WW**	**H⟶ττ**
Combined	**ZH**	0.41	3.13	2.21	356.12	26.01	3.18	10.97
	VBF	0.67	3.49	2.66	290	37.12	5.36	24.2

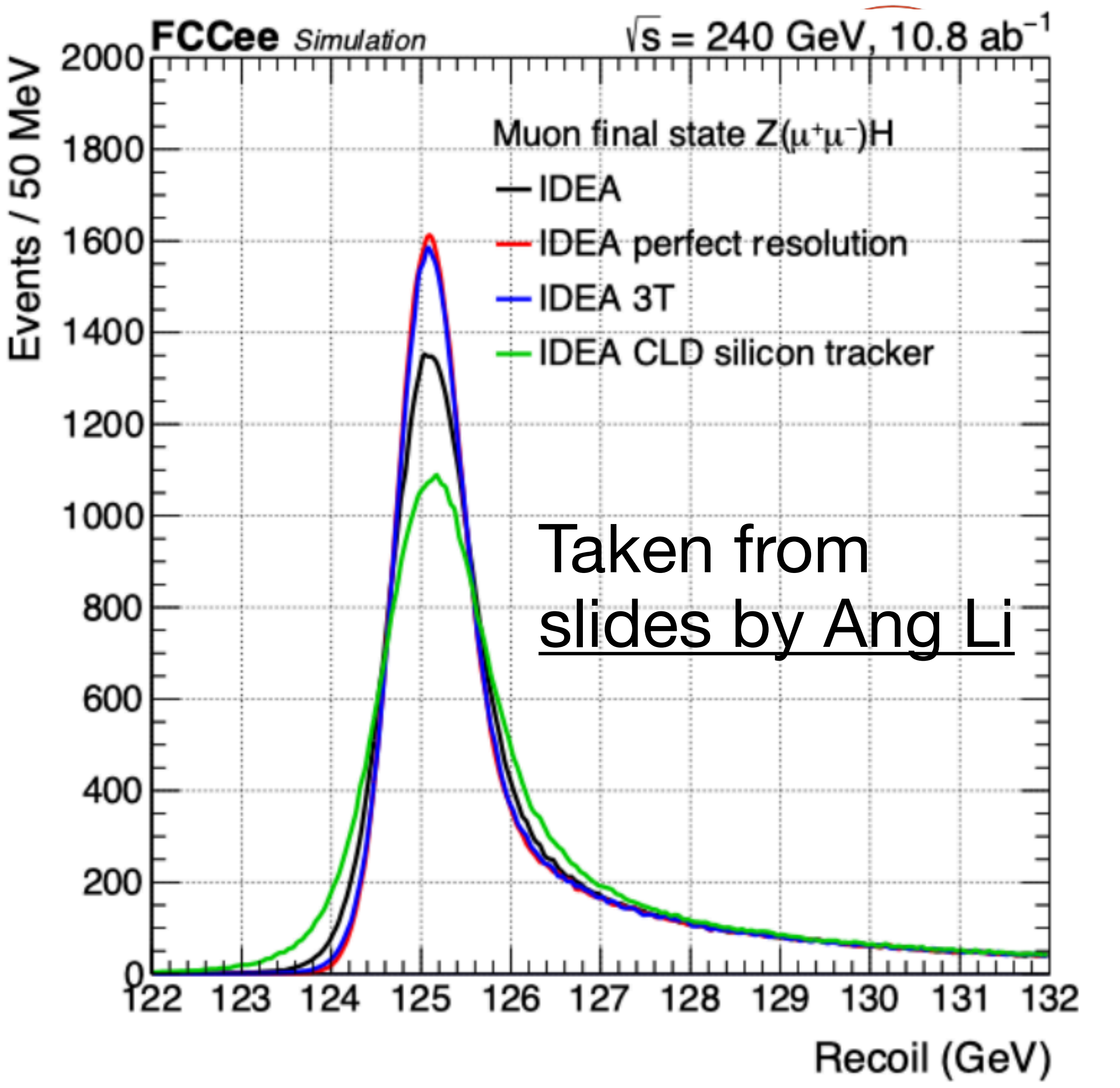
Higgs mass and width

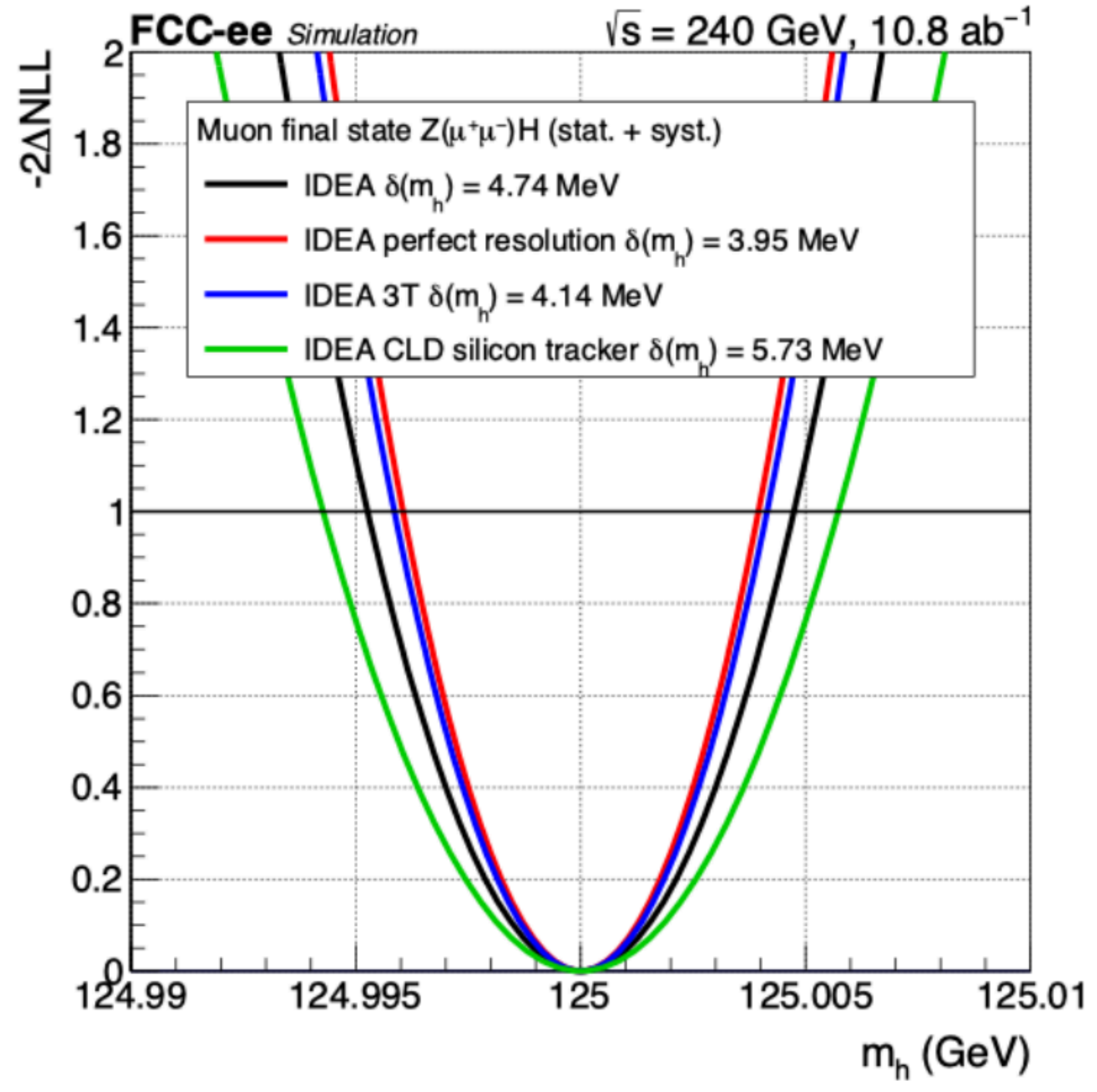
- Higgs mass precision **today** $o(100\ \mathrm{MeV})$. Recoil mass distribution will **bring it to only a few MeV**.
- Higgs width ($\Gamma_H = 4.1\ \mathrm{MeV}$ in the SM) **measured only indirectly at the LHC**. Will be measured directly, with percent level precision.

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



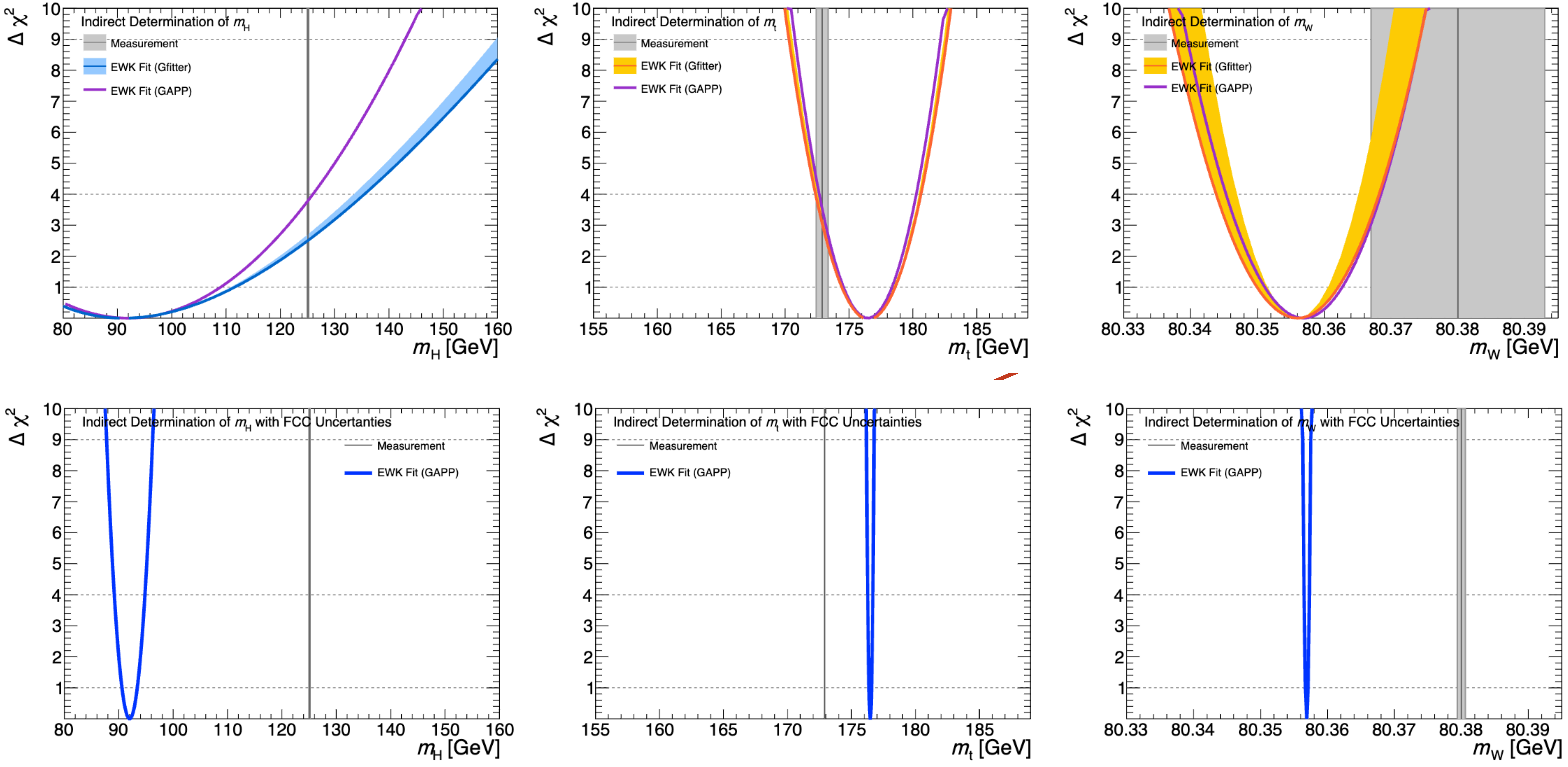






The EW fit

Taken from J. Erler, M. Schott



Current systematic uncertainties

Expected FCC-ee uncertainties on current central values

Flavour physics

See slides from J. Davighi

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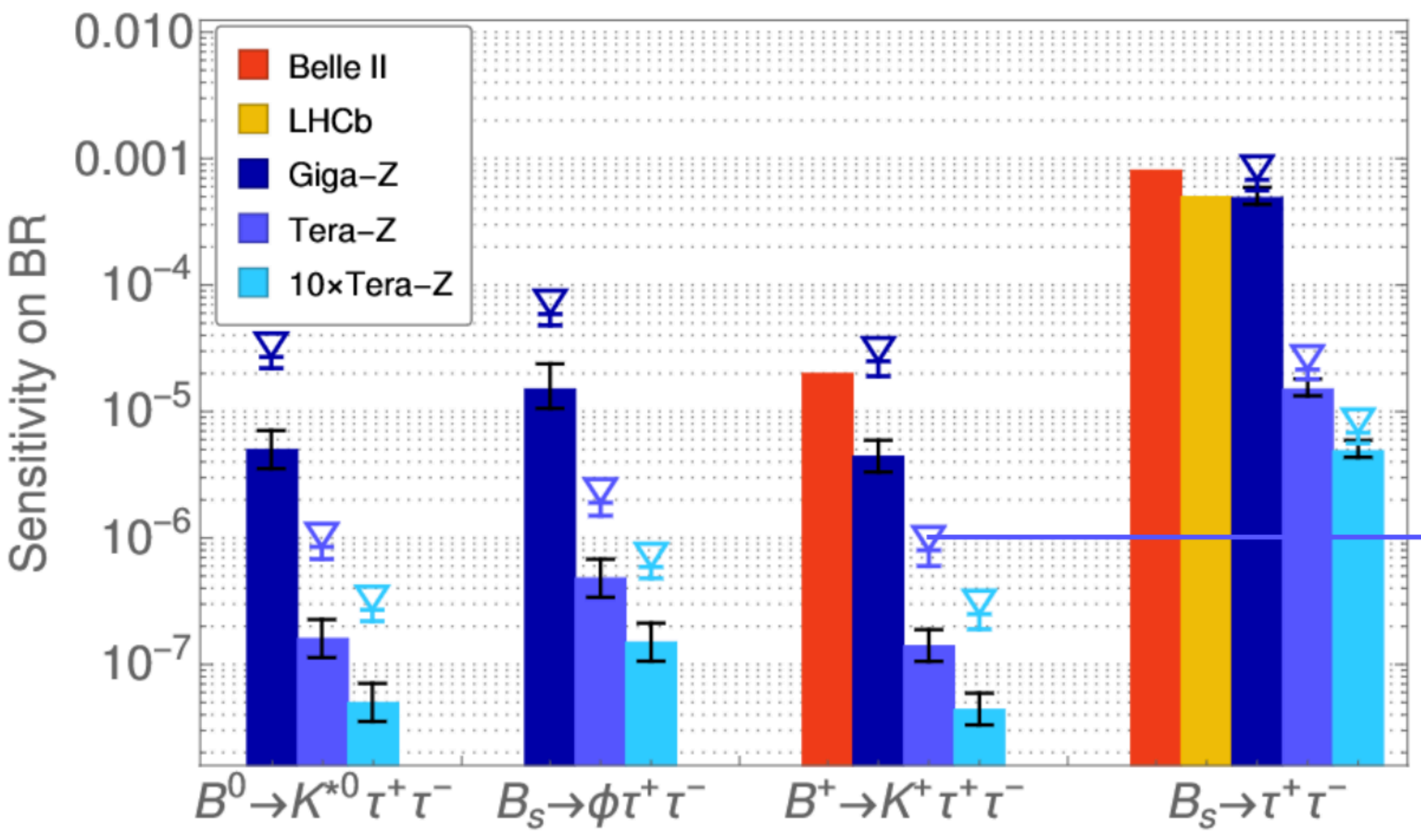
- FCC-ee at the Z pole: 10^{12} Z ($BR(b\bar{b}) = 15\,\%\,, BR(c\bar{c}) = 12\,\%\,, BR(\tau\bar{\tau}) = 3\,\%$).
- **LHC-like statistics**, full range of hadrons, **but e^+e^- precision a-la-Belle II**.



One example: $b \to s\tau^+\tau^-$. (Suppressed in SM, important for R(D(*)) anomalies)

Rate too low to be measured at Belle II. But LHC experiments cannot effectively deal with the two neutrinos.

FCC-ee overcomes both problems (closed kinematics and high production rate).

More conservative projection includes **finite tracker resolution**

The physics of FCC-ee

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FCC-ee

EW factory (Z,WW)

Higgs

Top

Precision SM

- $m_Z, \Gamma_Z, N_\nu, R_l, A_{\rm FB}, m_W, \Gamma_W$
- α_s (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

BSM direct searches

Axion-like particles, dark photons, Heavy Neutral Leptons, LLPs

Higgs physics

Higgs width, Higgs to invisible, couplings (including self-couplings)

Flavour Physics

- 10^{11} $\tau\bar{\tau}$: tau-based EW observables, lepton universality
- 10^{12} $b\bar{b}/c\bar{c}$ pairs: flavour observables, flavour anomalies, CKM, CP, etc.

Top physics

$m_{\rm top}$, $\Gamma_{\rm top}$, EW top couplings

Original idea/slide from C. Grojean

The physics of FCC-ee

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FCC-ee

EW factory (Z,WW)

Precision SM

- $m_Z, \Gamma_Z, N_\nu, R_l, A_{FB}, m_W, \Gamma_W$
- α_s (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

Particle ID, detector resolution, systematics, stability

Flavour Physics

- 10^{11} $\tau\bar{\tau}$: tau-based EW observables, lepton universality
- 10^{12} $b\bar{b}/c\bar{c}$ pairs: flavour observables, flavour anomalies, CKM, CP, etc.

Vertexing, Particle ID (tracking,calo)

BSM direct searches

Axion-like particles, dark photons, Heavy Neutral Leptons, LLPs

Detector hermeticity, flexibility

Higgs

Higgs physics

Higgs width, Higgs to invisible, couplings (including self-couplings)

Tracking resolution (tagging), vertexing (flavour), jet resolution

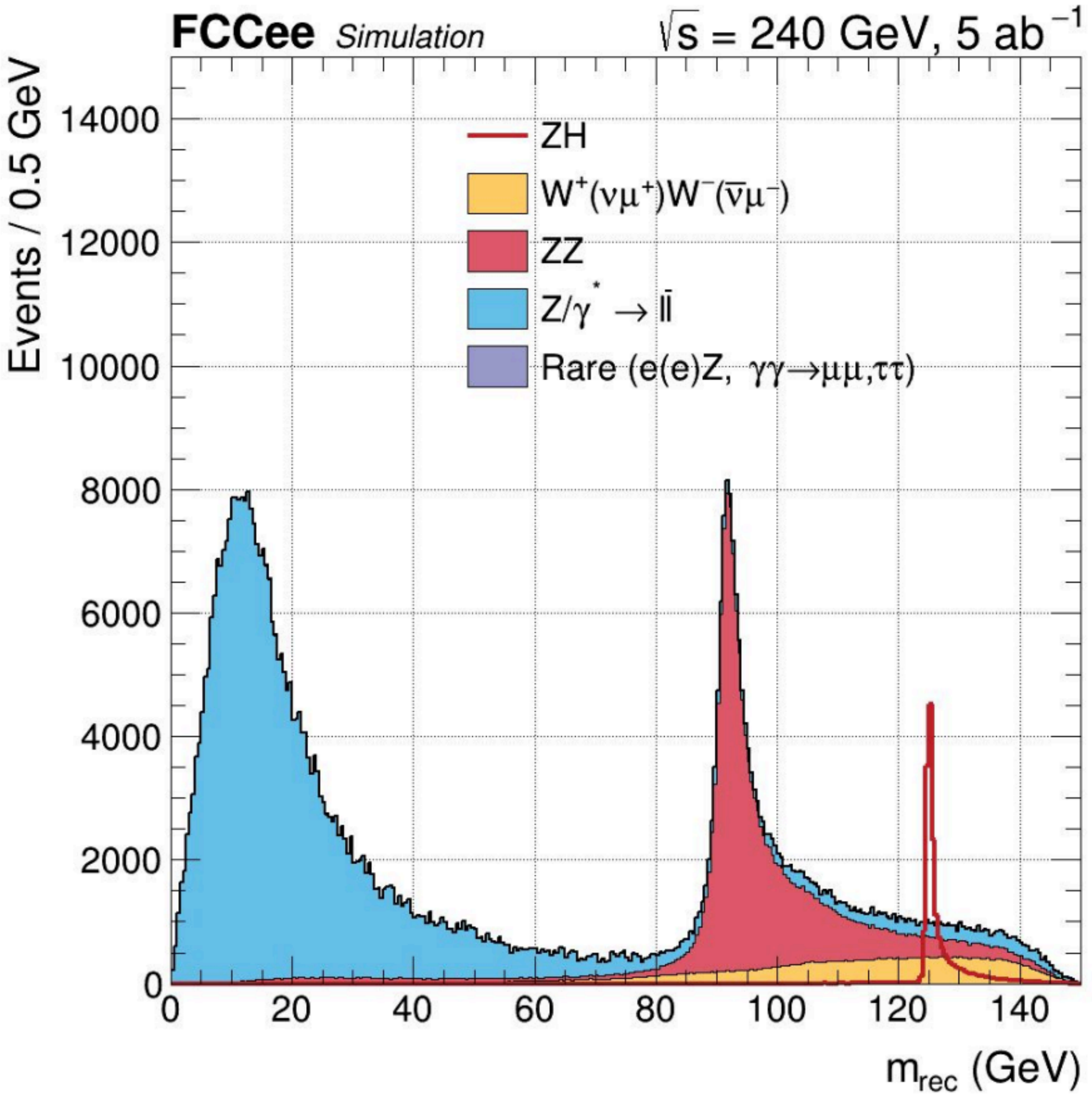
Top

Top physics

m_{top}, Γ_{top}, EW top couplings

The physics case drivers

- **Higgs boson tagging** and **BR into invisibles** sets requirements on:
  - Tracking performance:
    - Material in the tracking volume.
    - Magnetic field (and thickness of solenoid).
- Higgs boson BR sets requirements on e, γ **and jet energy and angular resolutions.**
- Tagging $H \to b\bar{b}, c\bar{c}(s\bar{s}?)$ sets requirements **on tracking and vertexing.**
- …and in general requirements grow as more and more physics is explored.



$$M_{\rm rec} = \left(\sqrt{s} - E_{\mu\mu}\right)^2 - p^2_{\mu\mu}$$

	Critical detector	Requirement	Comments
$ZH \to \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2 \cdot 10^{-5}$	But also precision EW, flavour, BSM
$H \to b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}[\mu\mathrm{m}]$	Additional case study: B→K*ττ
$H \to gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{\rm jet})}{E_{\rm jet}} \sim 4\,\%$ (at $E_{\rm jet} \sim 50$ GeV)	Also BSM and missing energy reconstruction
$H \to \gamma\gamma$	ECAL	$\frac{\sigma(E_\gamma)}{E_\gamma} \sim \frac{10-15\,\%}{\sqrt{E_\gamma}}$	But flavour physics may need better EM energy resolution

Benchmark physics channels for Higgs/Top/EW factories discussed in 2401.07564 will improve detector requirements by spring 2025

FCC detectors

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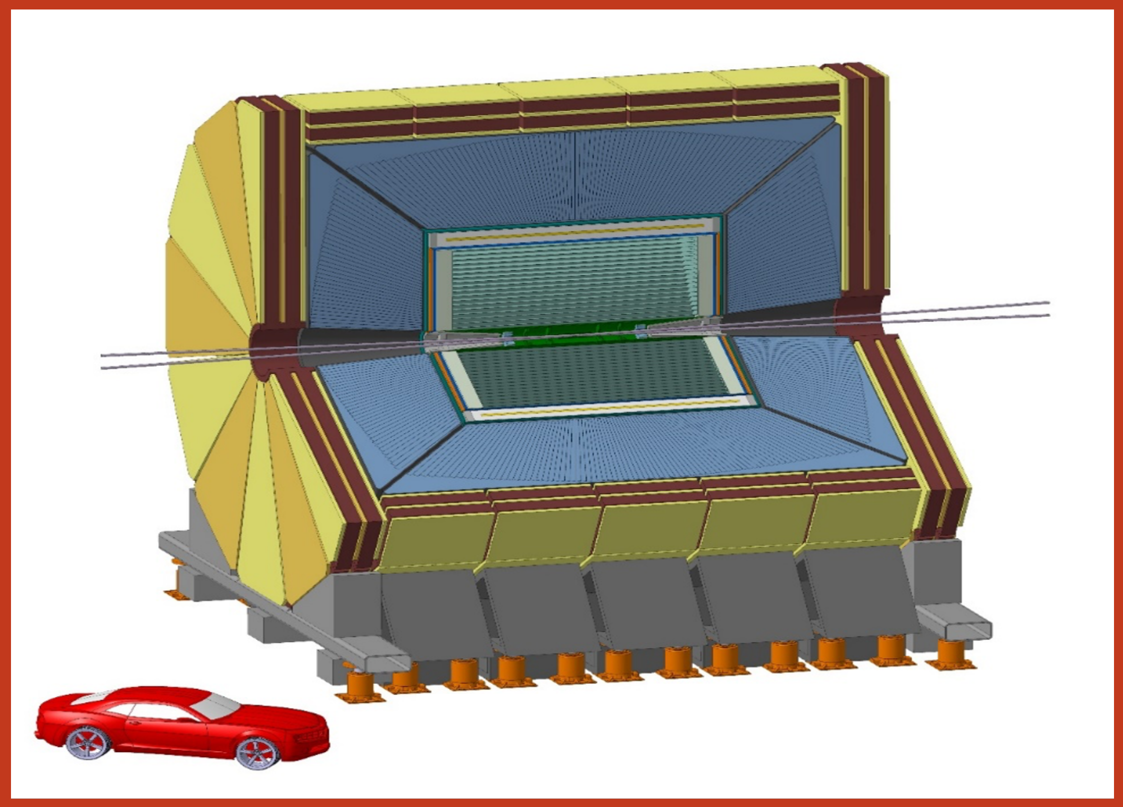
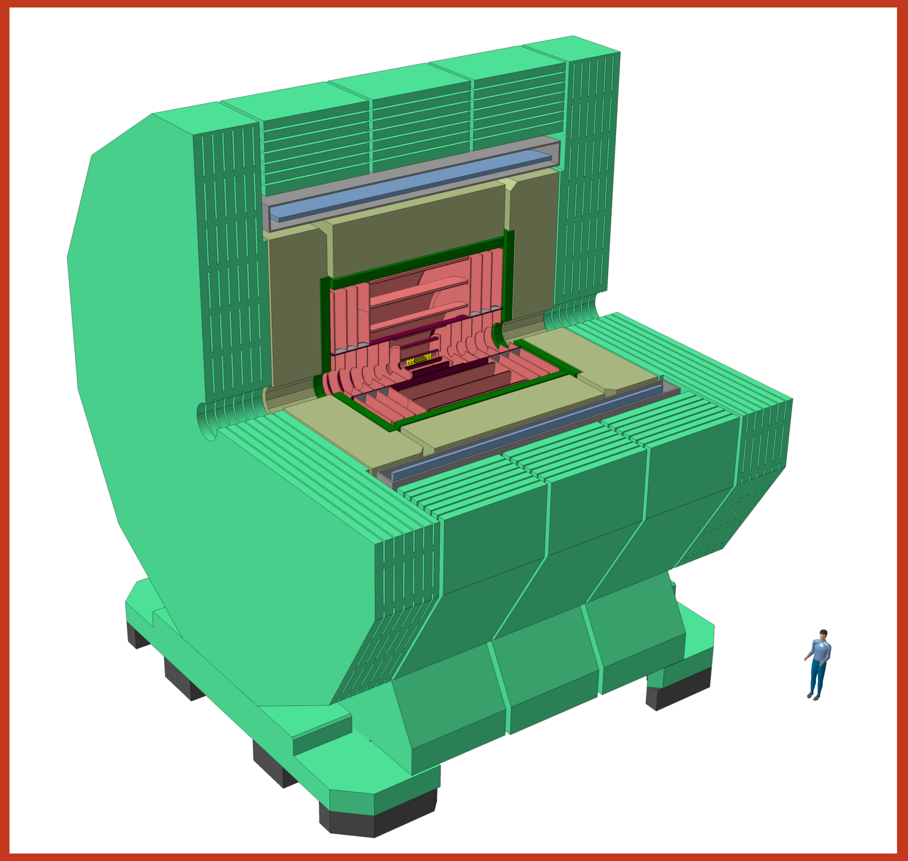
IDEA (Innovative Detector for e^+e^- Accelerators)



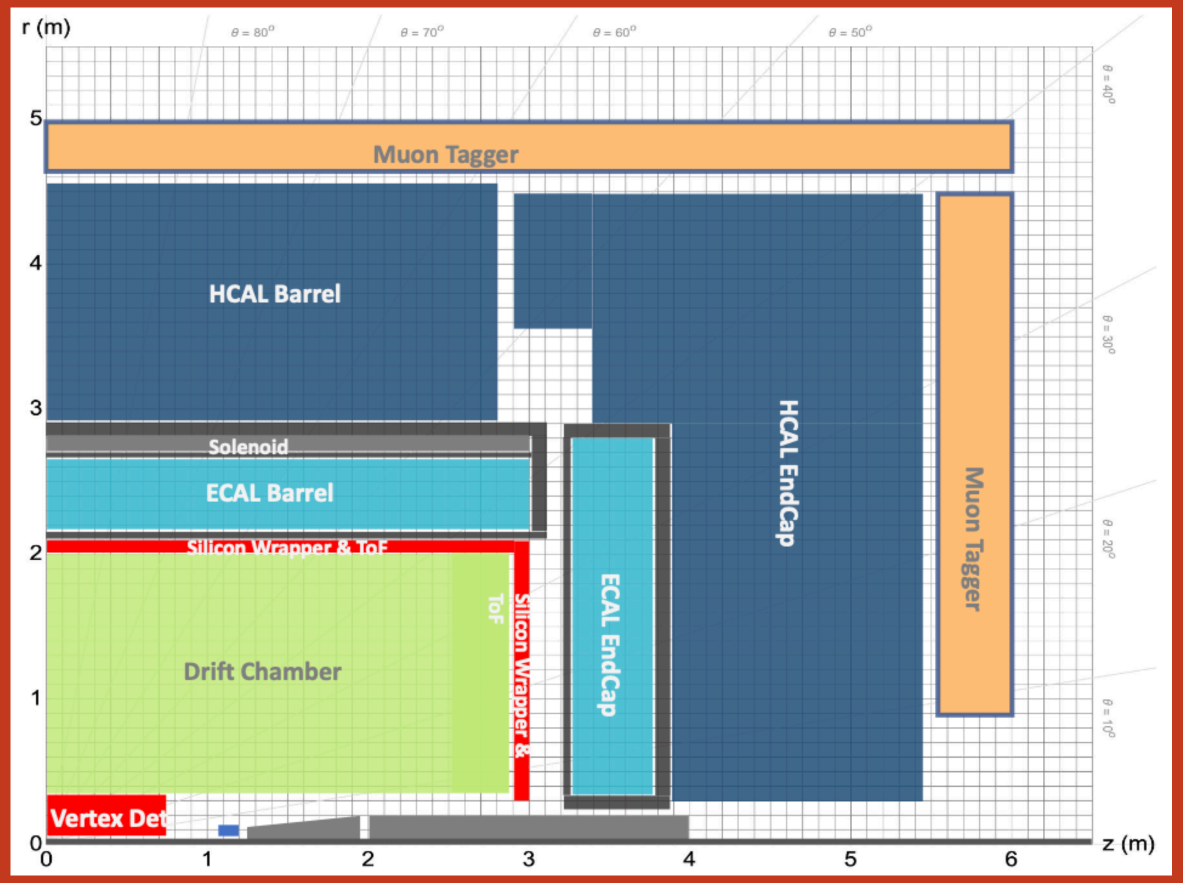
2 T thin solenoid within calo
Si vertex detector
Tracking with ultra light drift chamber
Dual Readout Calorimeter + pre-shower
MPGD (μRwell) based Muon detector

CLD (CLIC-like Detector)



2 T solenoid **outside calo**
Full silicon tracker
SiW high-granularity EM Calo
Sci-steel high-granularity HAD Calo
RPC-based Muon detector

ALLEGRO - A Noble-Liquid Ecal based

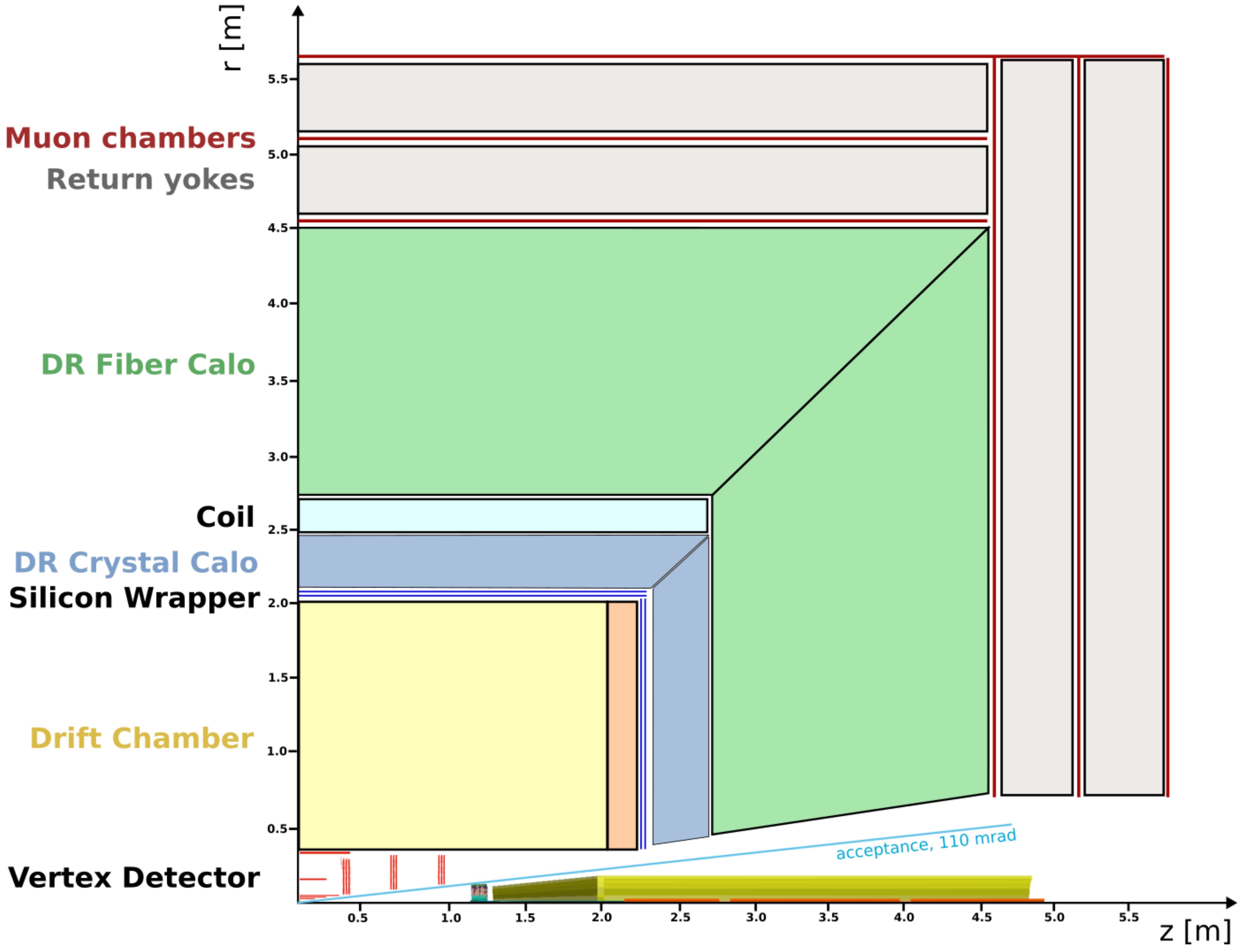


2 T solenoid **outside calo**
Tracking with ultra light drift chamber +
Si Wrapper (improved tracking + timing)
LAr EM Calo + Sci-steel HAD Calo

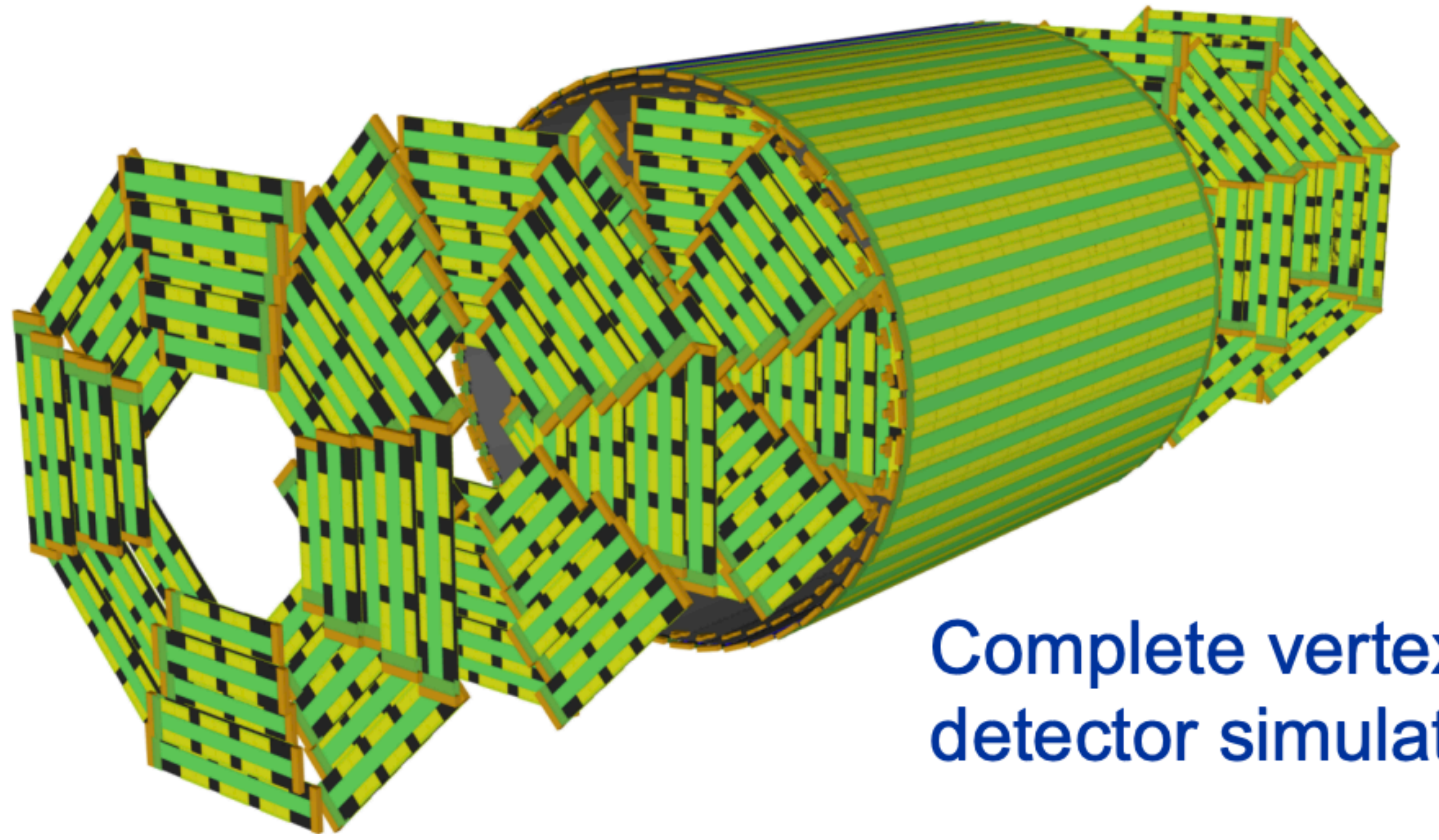
- Beam crossing angle + need to keep vertical beam emittance low ⟹ **B field limited to 2 T**
- They should be taken as **frameworks/benchmarks** - a lot of room for (even radical) changes.
  - These concepts show already different approaches to tracking/calorimetry.

IDEA

- Innovative detector for e^+e^- accelerators:
  - **Large INFN contribution** to many parts of the detector.
- An **international study group** was created recently.
  - **Large room for contribution** from young (and less young) researchers.
- Tracking with **ultra-light drift chamber**.
- Calorimetry uses a **homogeneous crystal EM section + a fibre-based HAD section** (both dual-readout).
- **Ultra-thin solenoid** (2 T with the opportunity of 3 T) in-between EM and HAD calo sections.



Vertex detectors



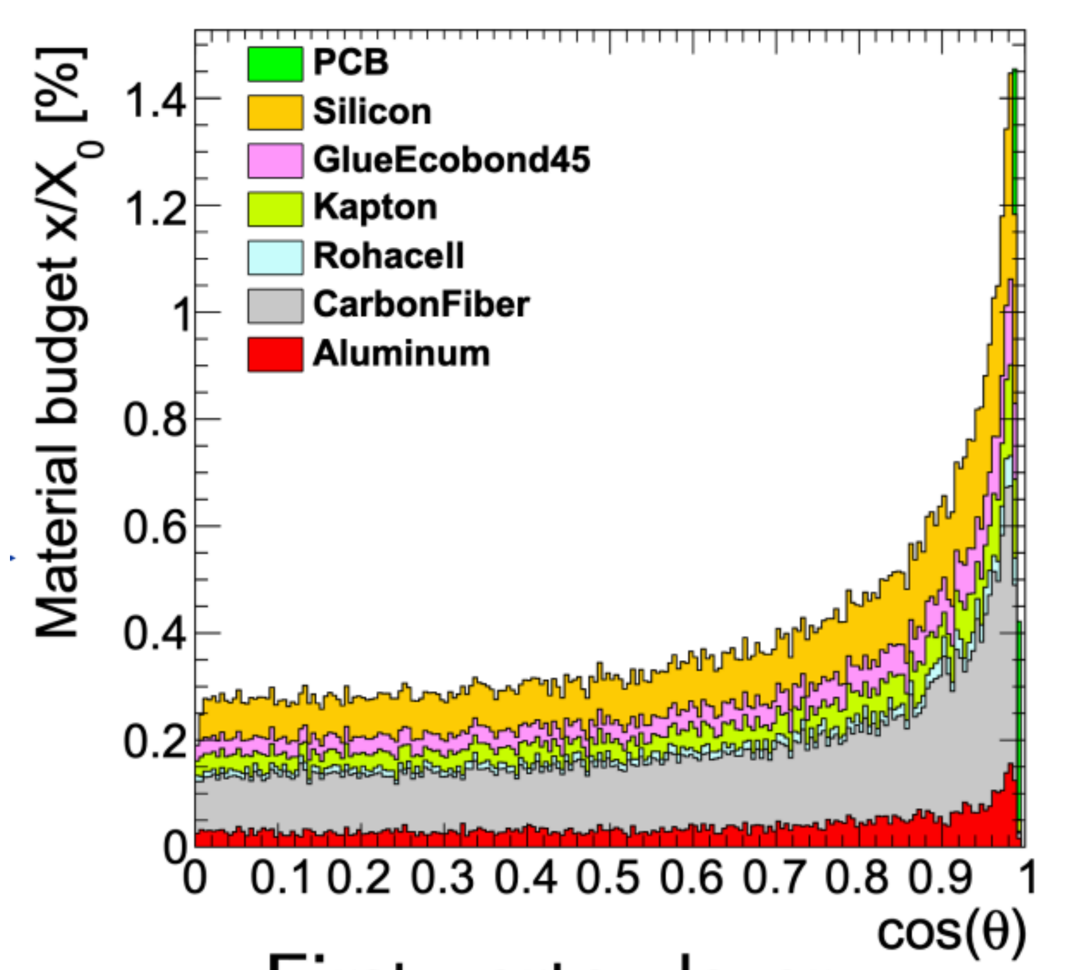
Complete vertex detector simulation

General requirements

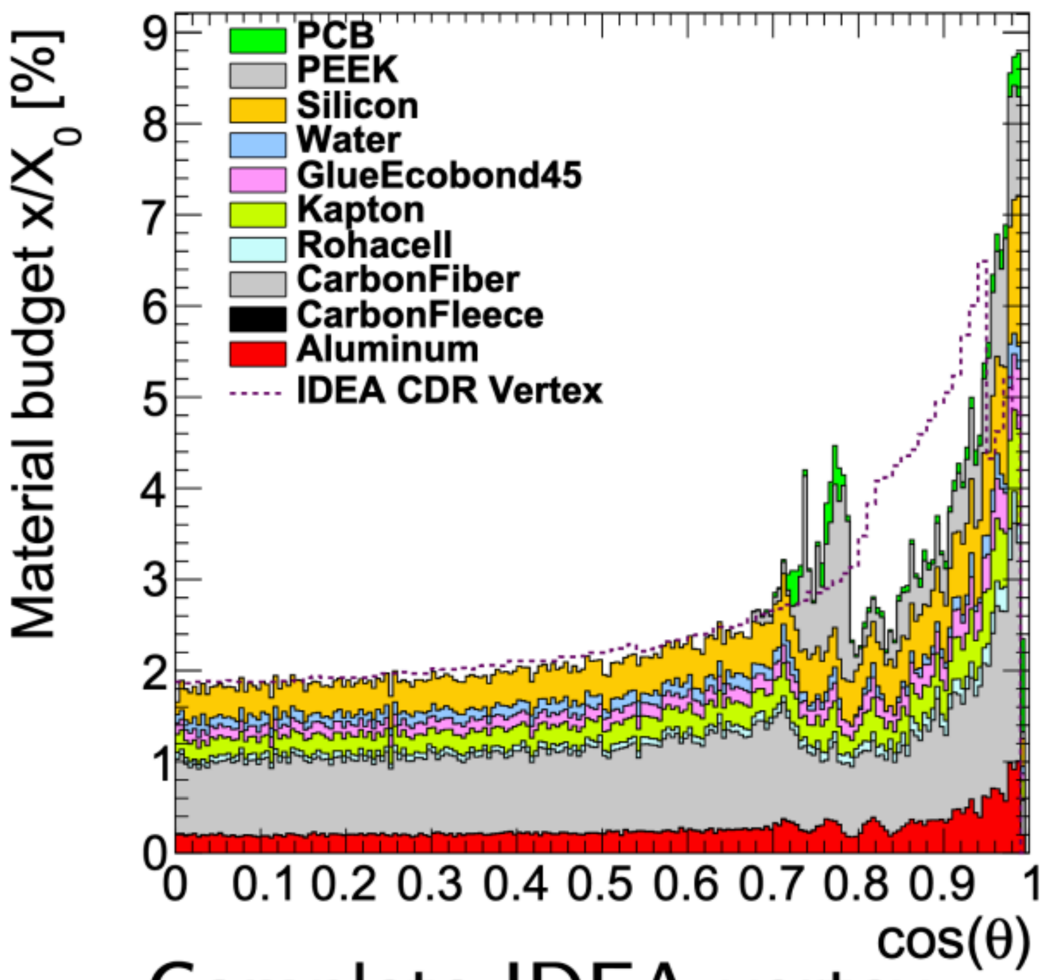
Flavour physics and tagging requires 3-5 μm → pixel size ~15 μm.
Small material budget (0.1% of X_0/layer) → Thickness ~ 50 μm.
Low power consumption (especially inner layers) → 10-30 mW/cm^2.

Solution: CMOS MAPS

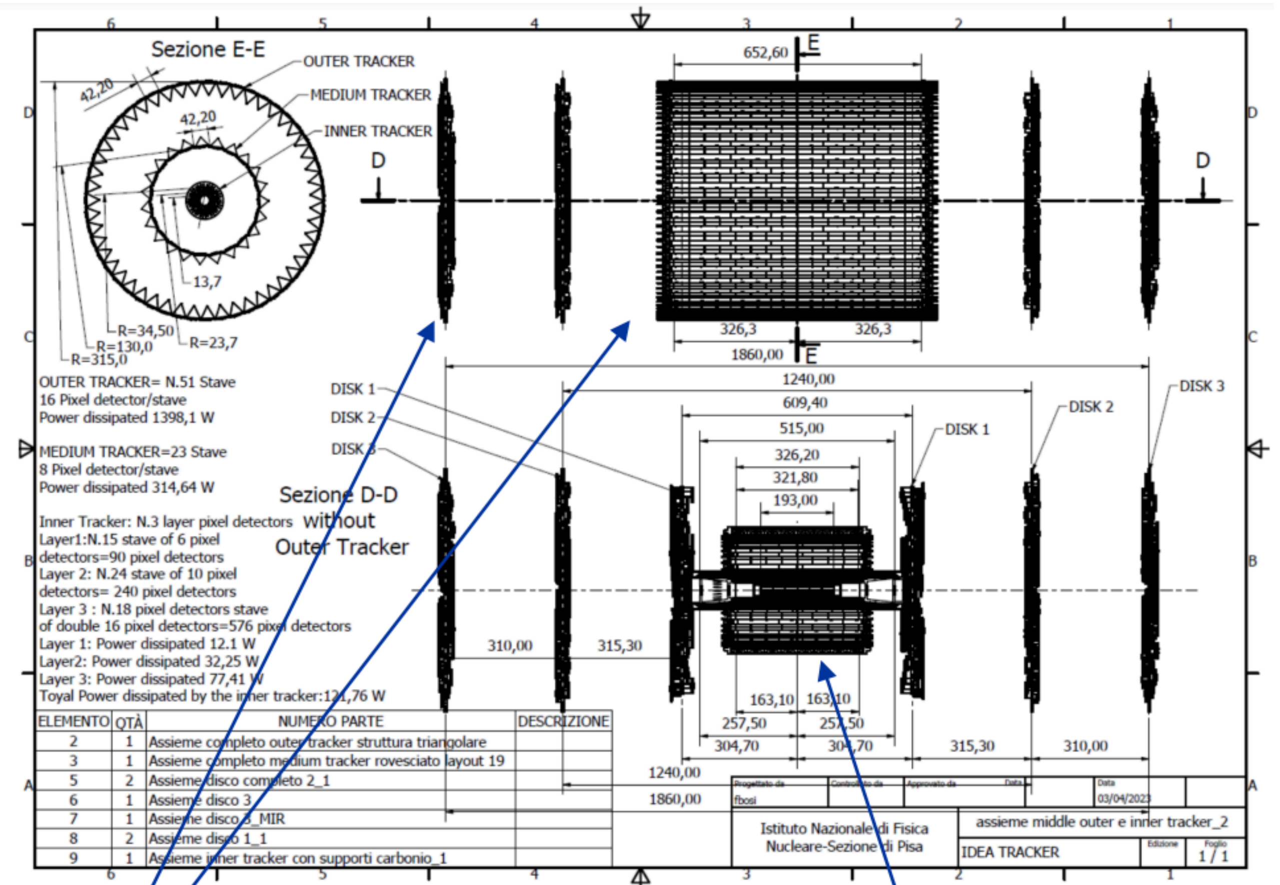
high spacial resolution and **small material** (integrated circuitery)
- Used in a number of LHC experiment upgrades (ALICE ITS, ATLAS ITK, etc.).



First vertex layer



Complete IDEA vertex



Outer vertex tracker
- intermediate layer at 13 cm radius
- outer layer at 31.5 cm radius
- 3 disks on each side

based on the ATLASPix3 sensors with modules of 50 x 150 μm^2 pixel size

Inner vertex tracker
- three layer at 13.7, 23.7 and 35.8 mm radius

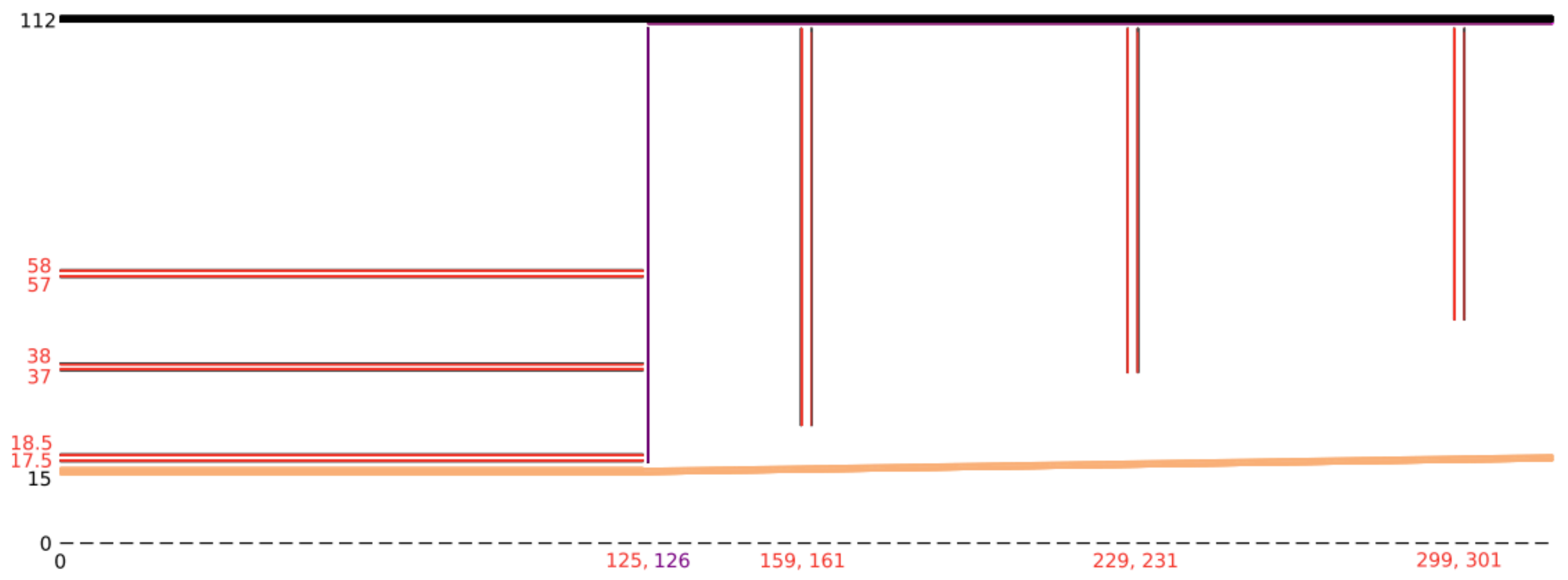
based on the ARCADIA sensors with modules of 25 x 25 μm^2 pixel size

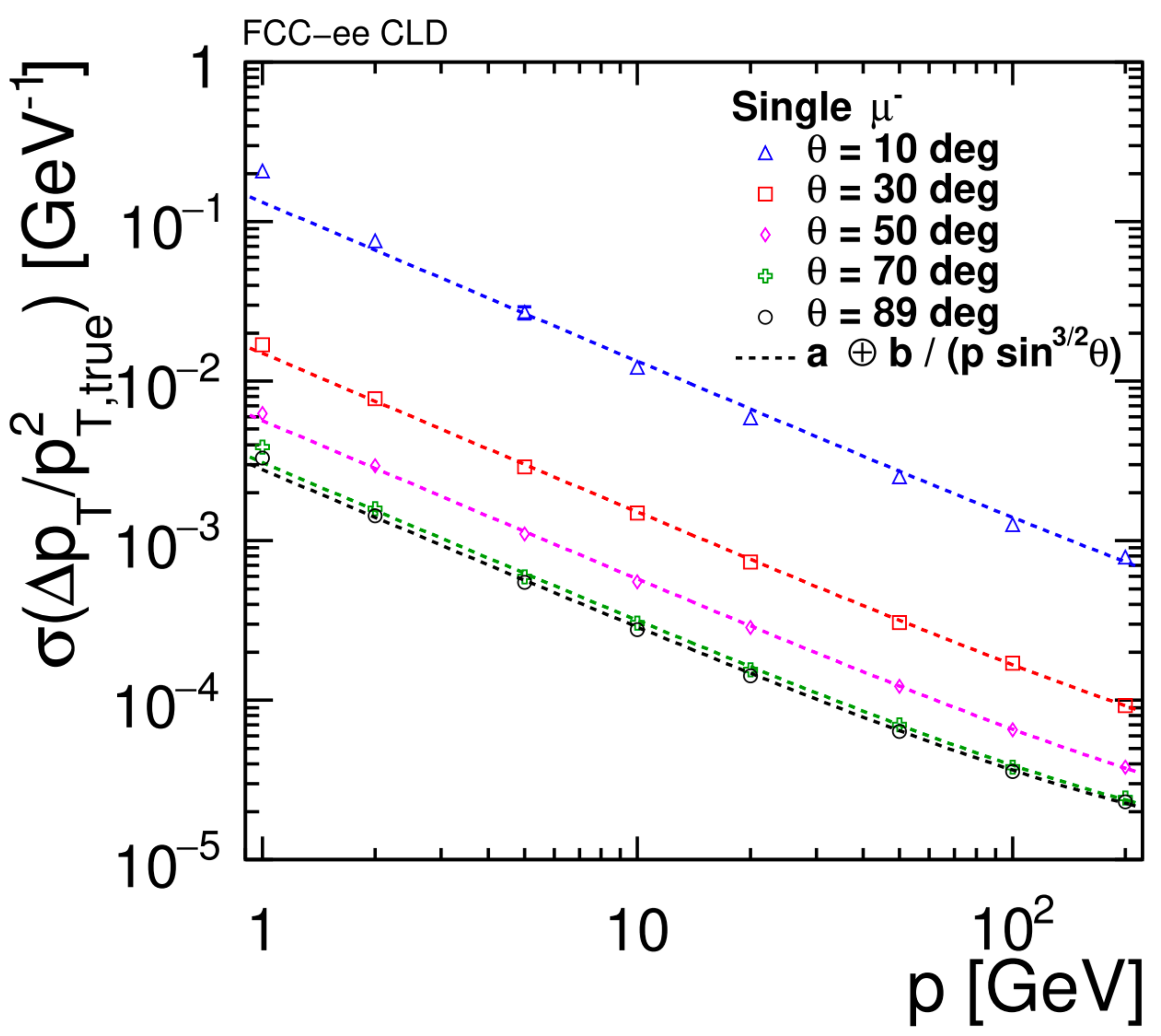
Ultra-light option using bent sensors, see A. Ilg, F. Palla

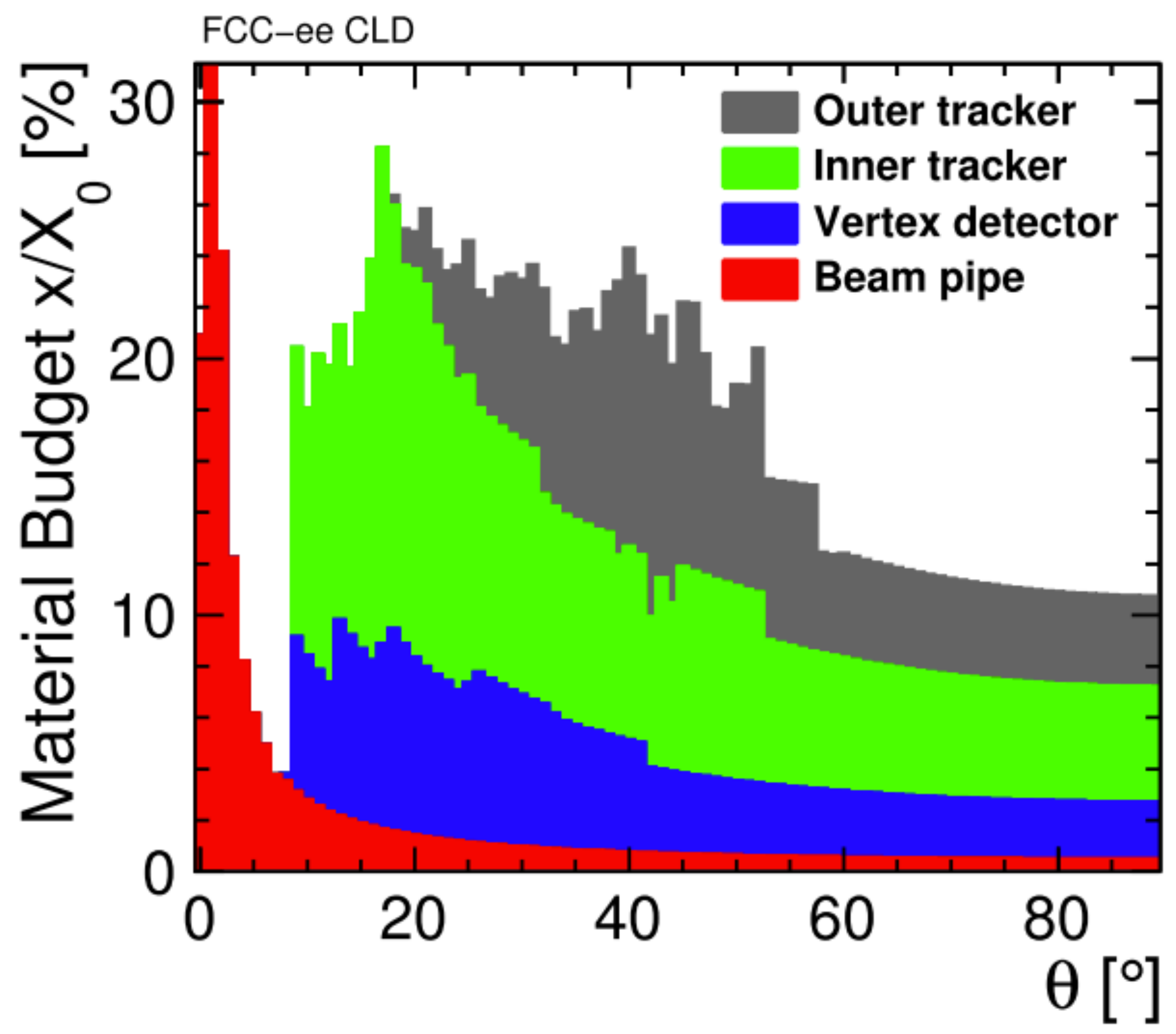
All-silicon tracking - the CLD approach

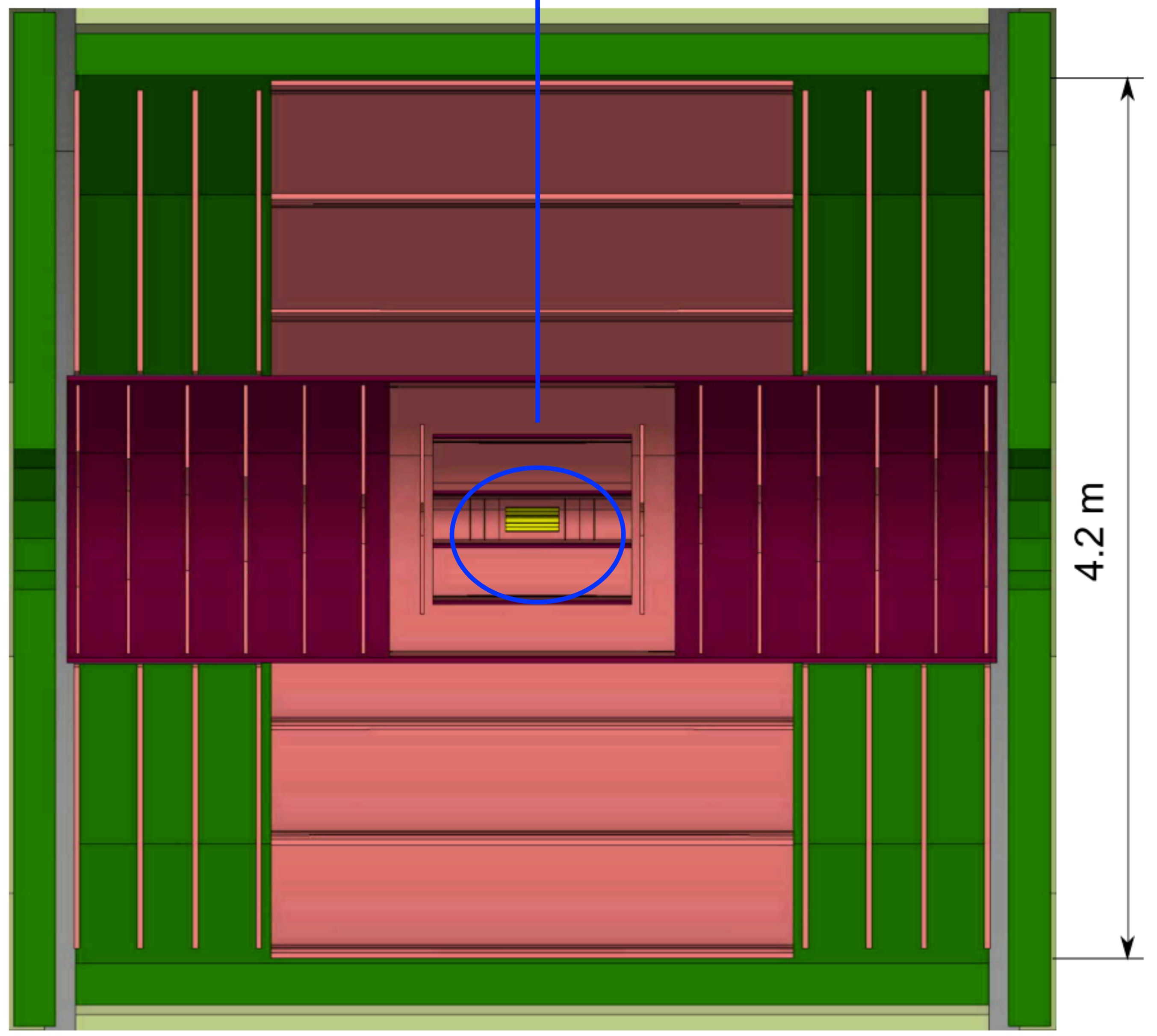
Silicon vertexing, and silicon also for the ID:

- Single point resolution 7x90 μm² - 5x5 μm² in 1st layer.
- Inner tracker: Barrel 3 layers, end-cap 7 discs.
- Outer tracker: Barrel 3 layers, end-cap 4 discs.



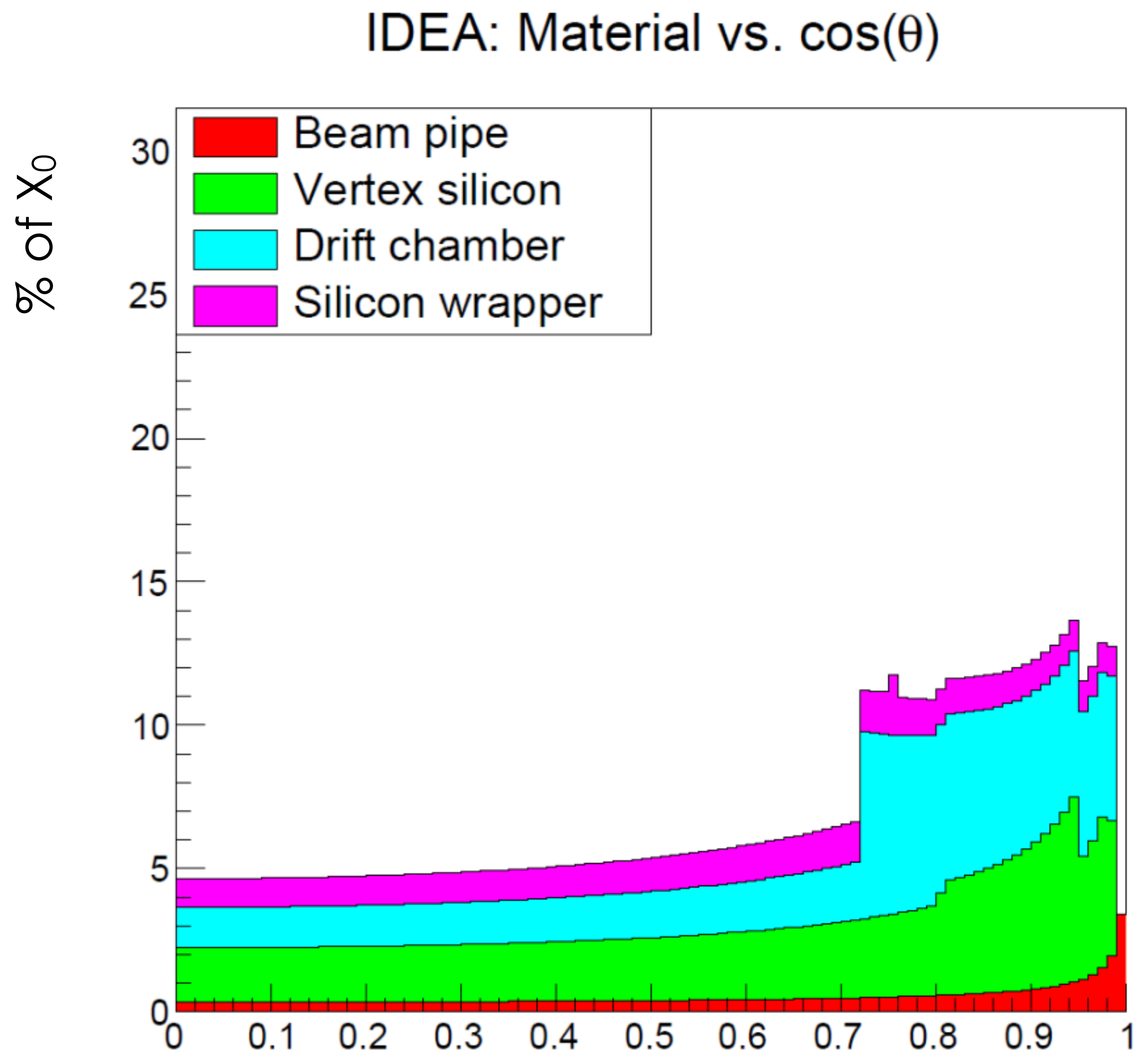


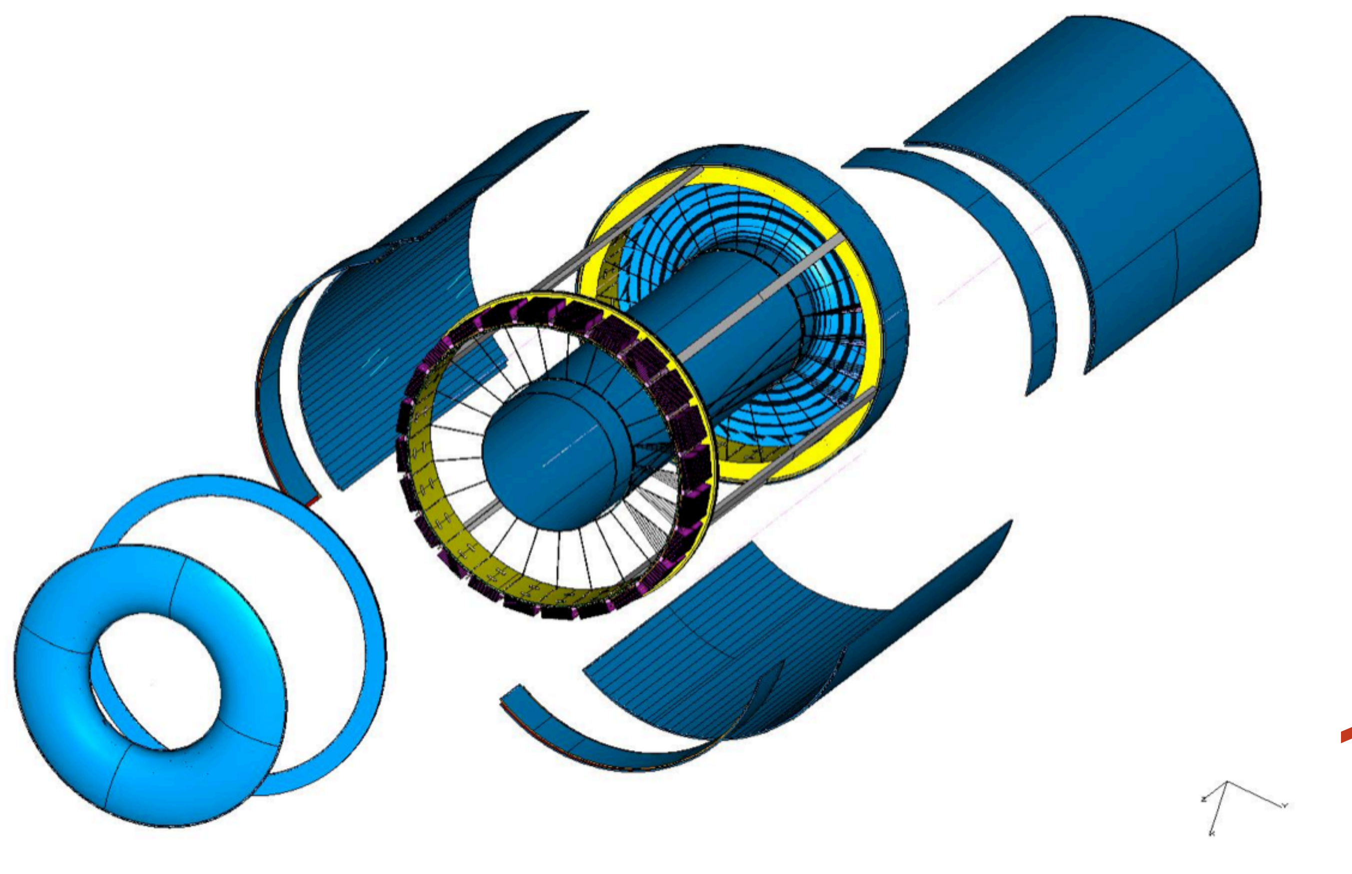


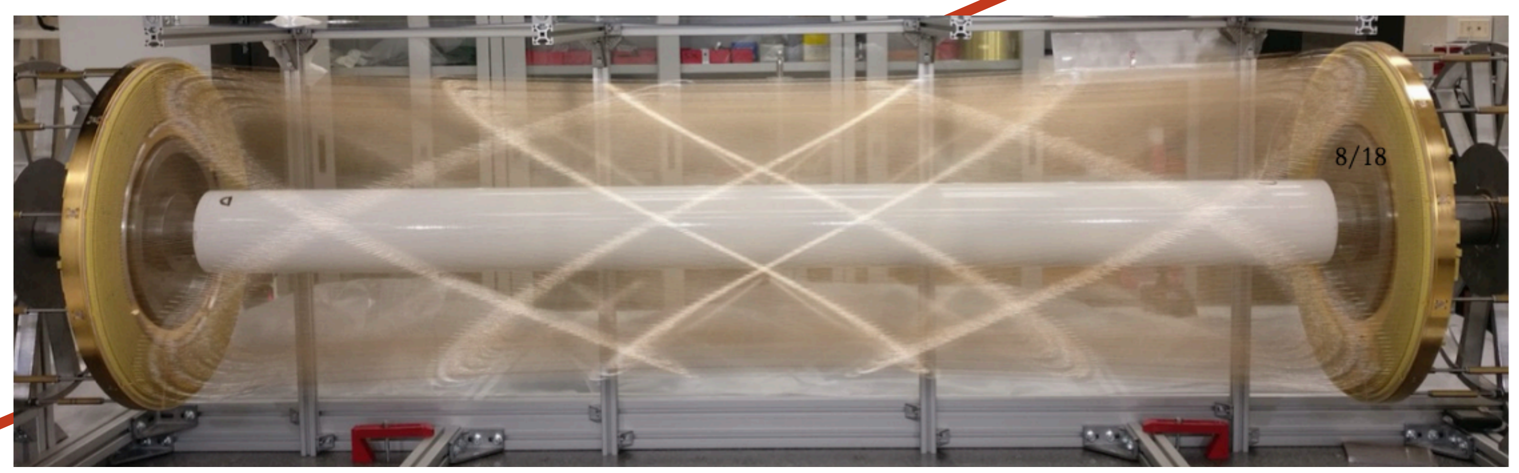


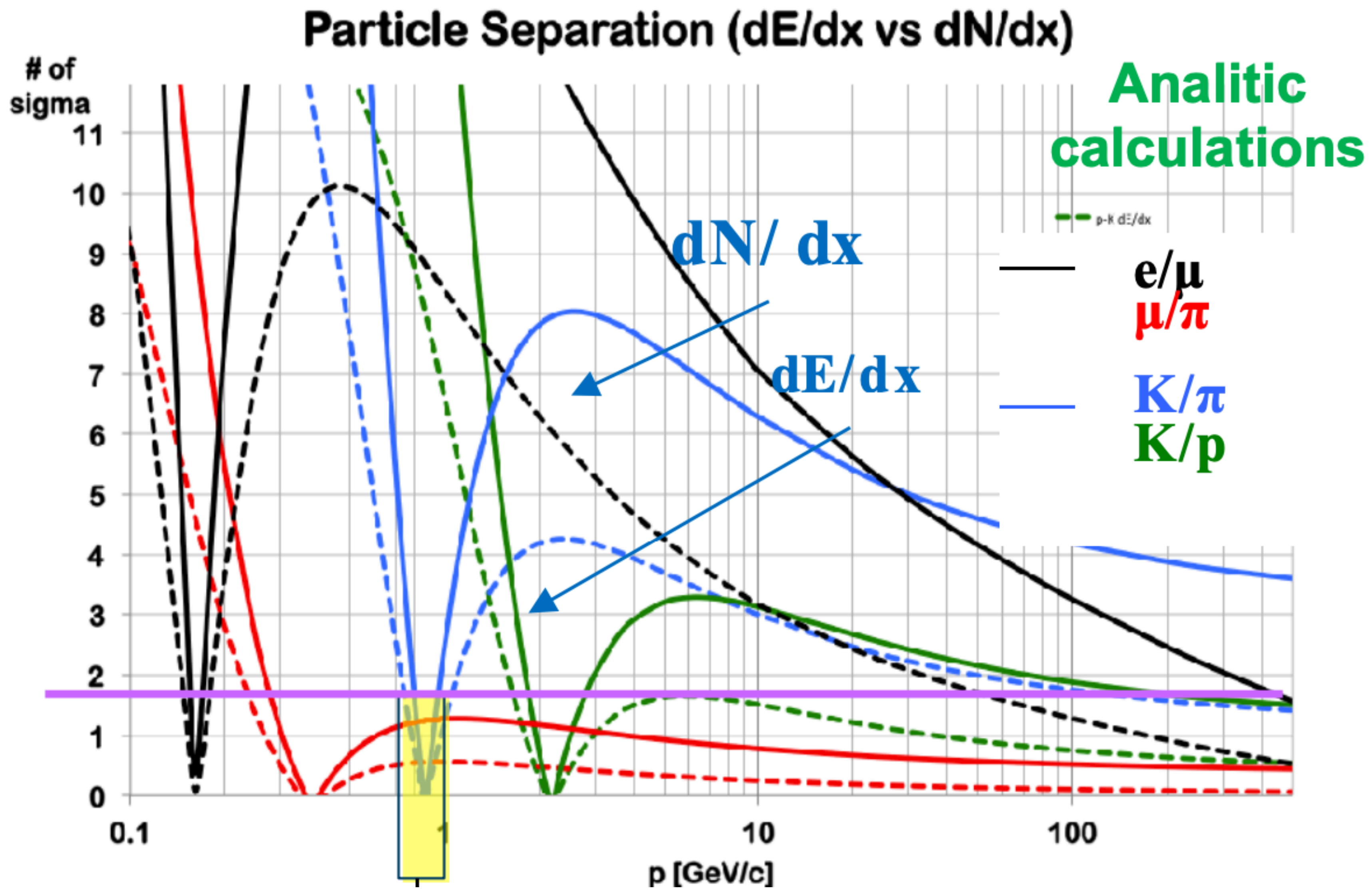
Light-weight tracking

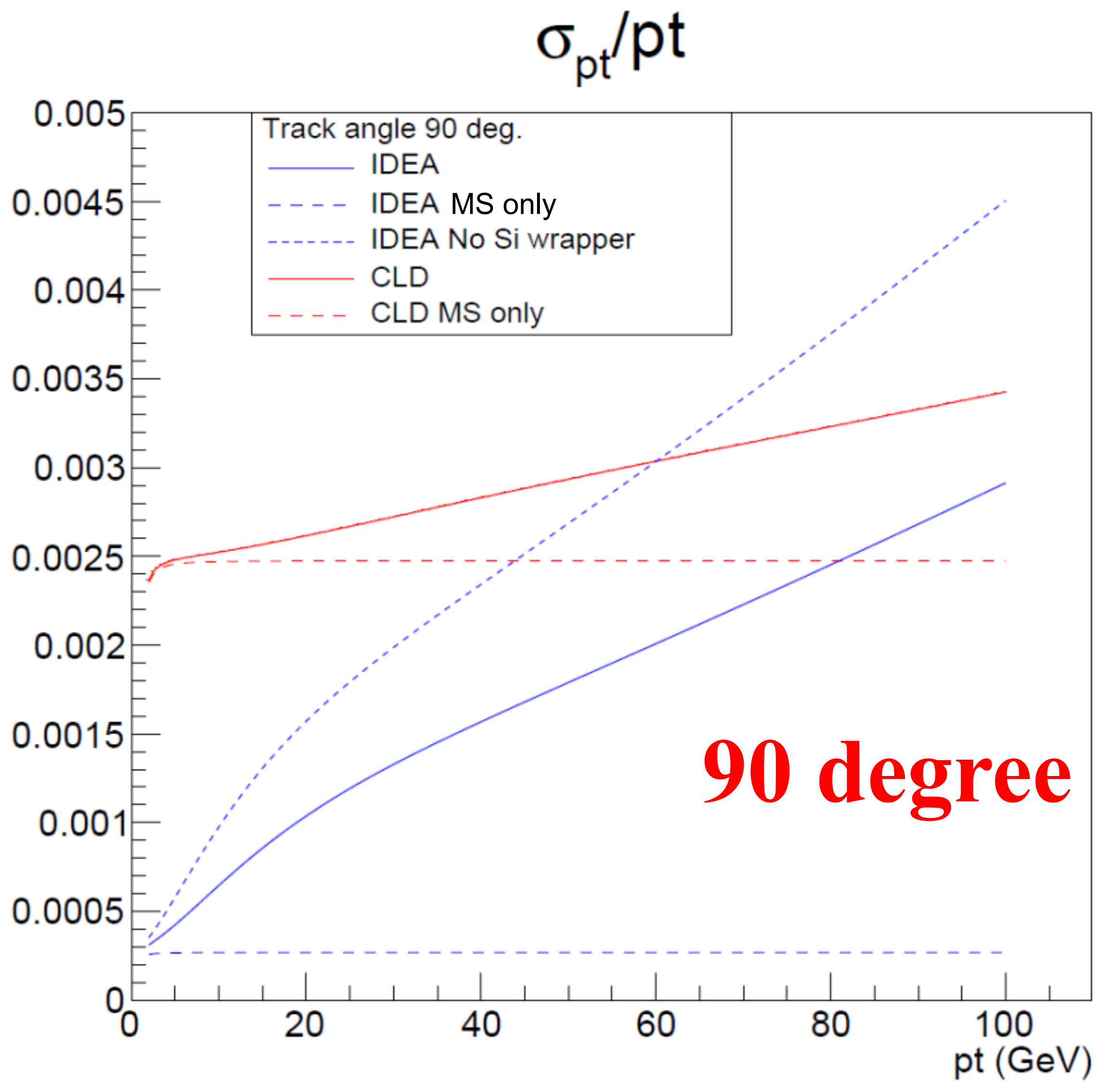
ALLEGRO and IDEA:
Tracking with **drift chamber** (similar in concept to MEG II chamber).
- **Minimising multiple scattering**, adding **only 2%** X_0 to material in front of calorimeter.
- Single point precision better than ~ 100 µm. **Many points on each track**.
- **Particle ID via cluster counting technique** yields interesting performance.











Particle-flow oriented calorimeters

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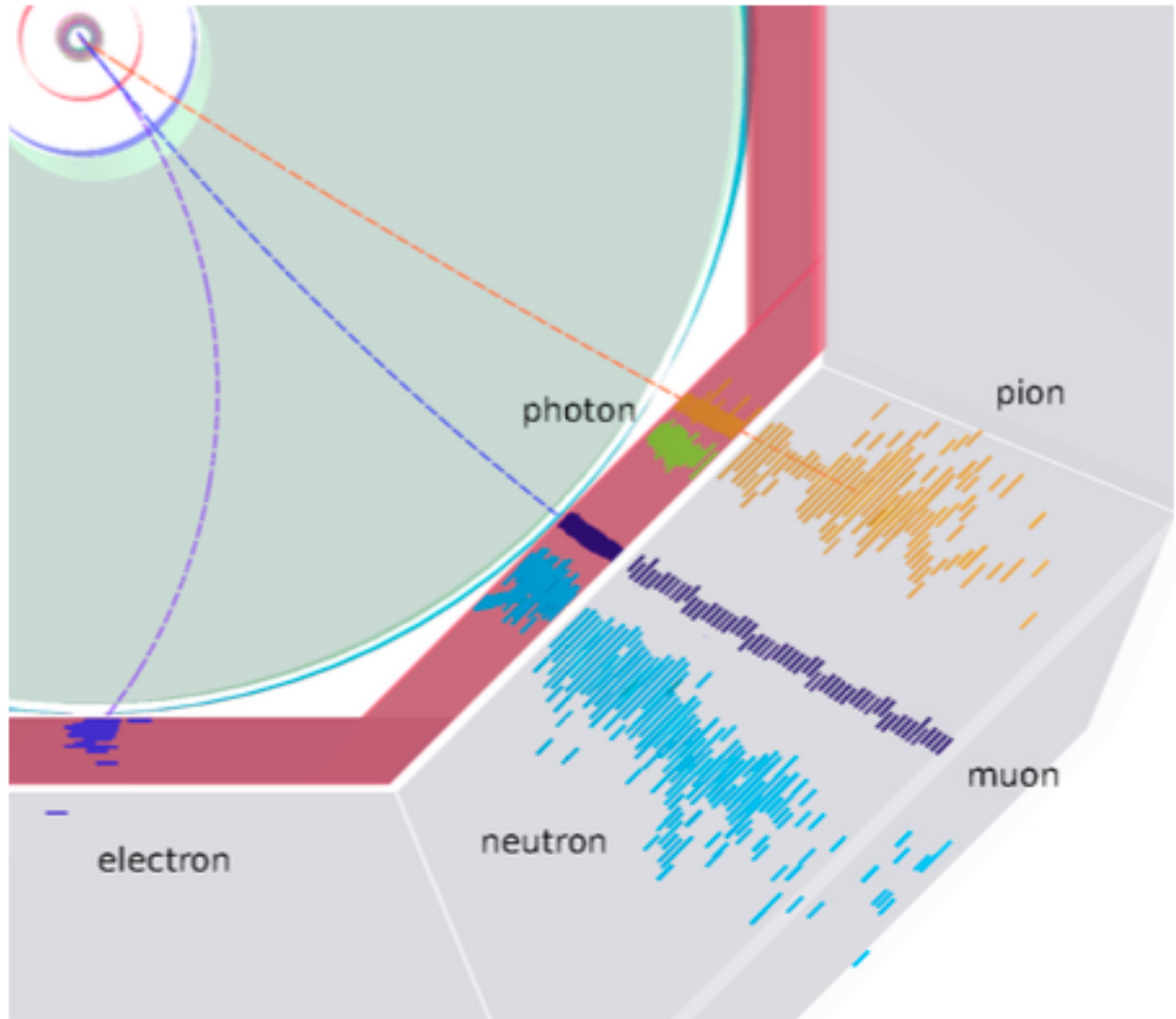
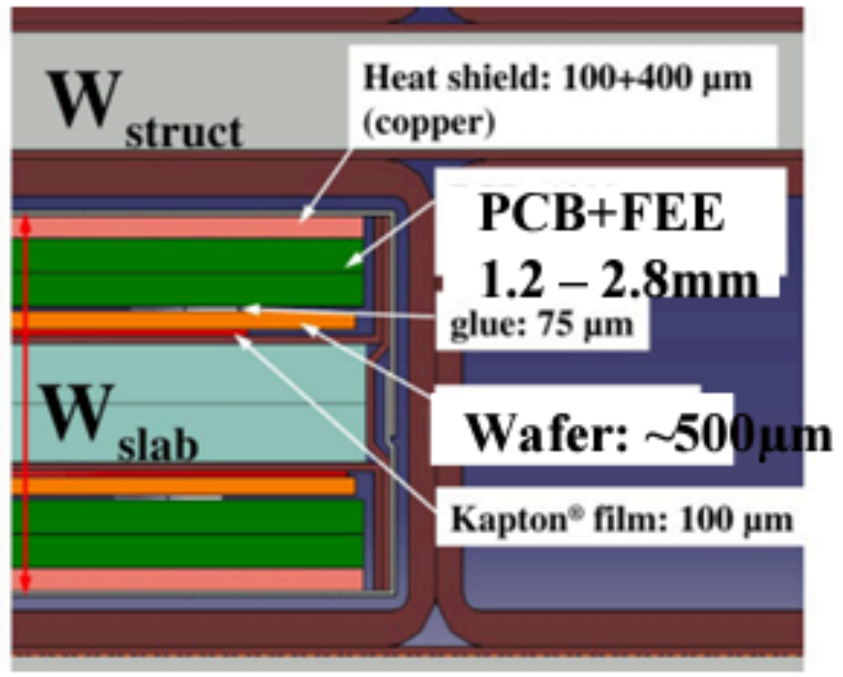
- Basic idea: for charged particles, measure their contribution to jets by **using tracker rather than calorimeter**.
- Requirements: High granularity - compactness (small Moliere radius).
- Studied in detail for linear colliders.

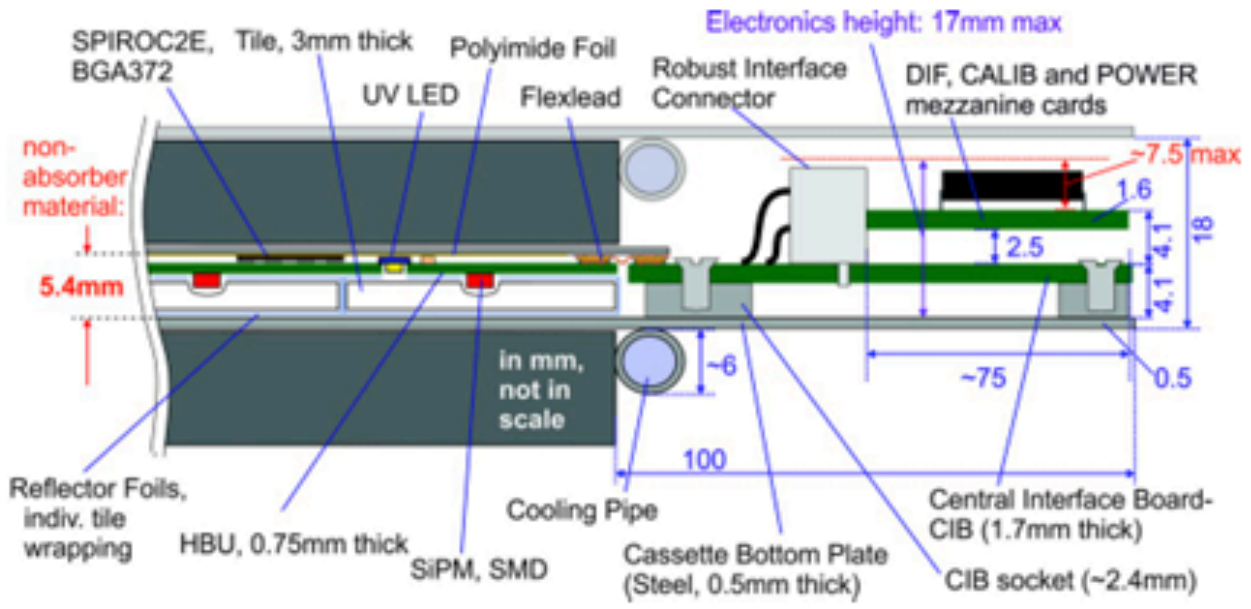


SiW ECAL



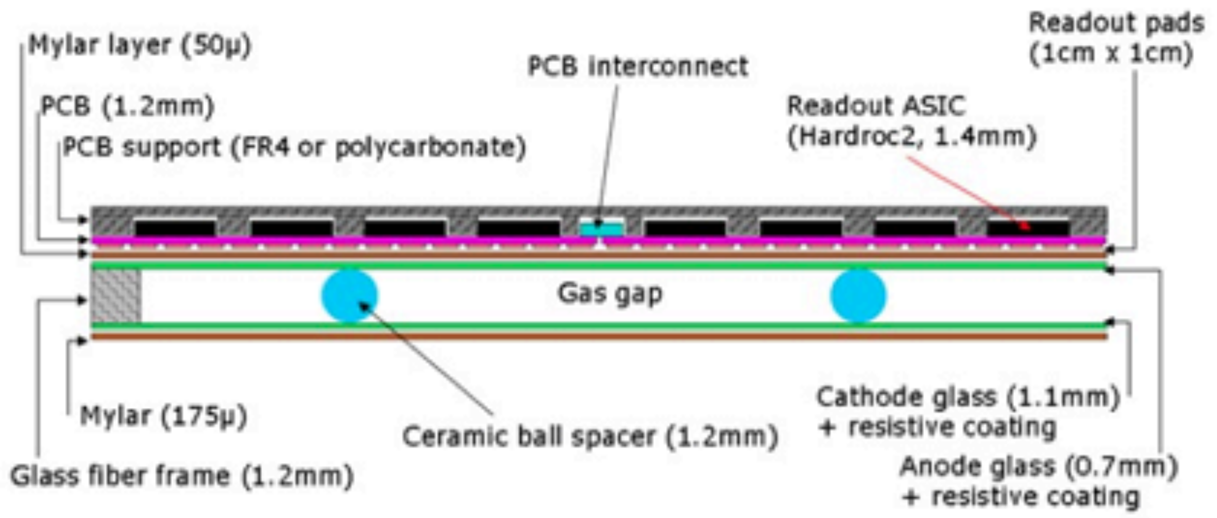
Active area: silicon PiN Diodes
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Scintillator tiles/strips + SiPM
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gas RPCs
Typical segmentation: 1x1cm^2

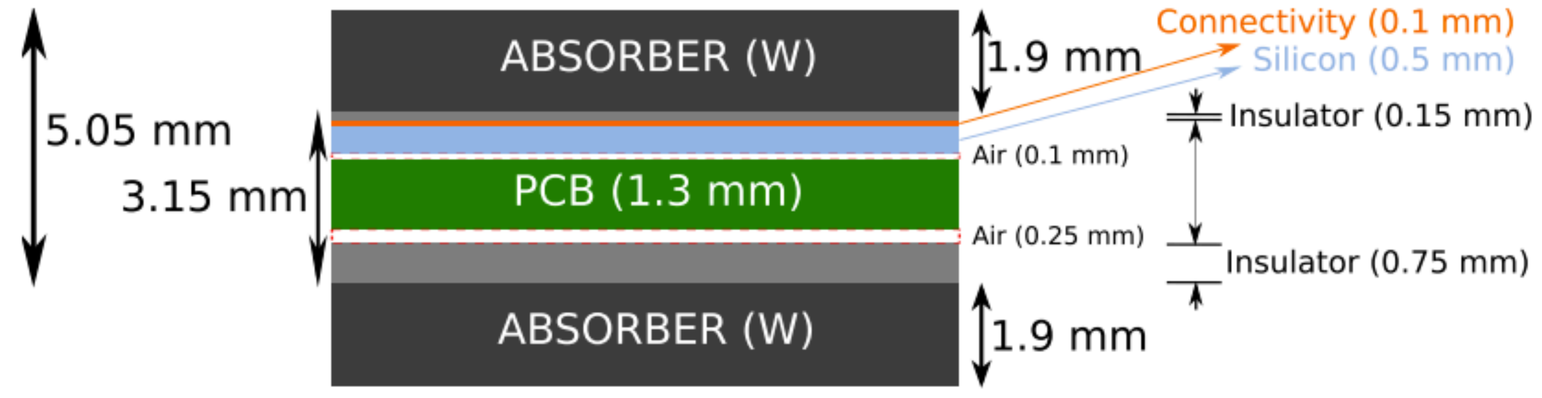
Challenges:

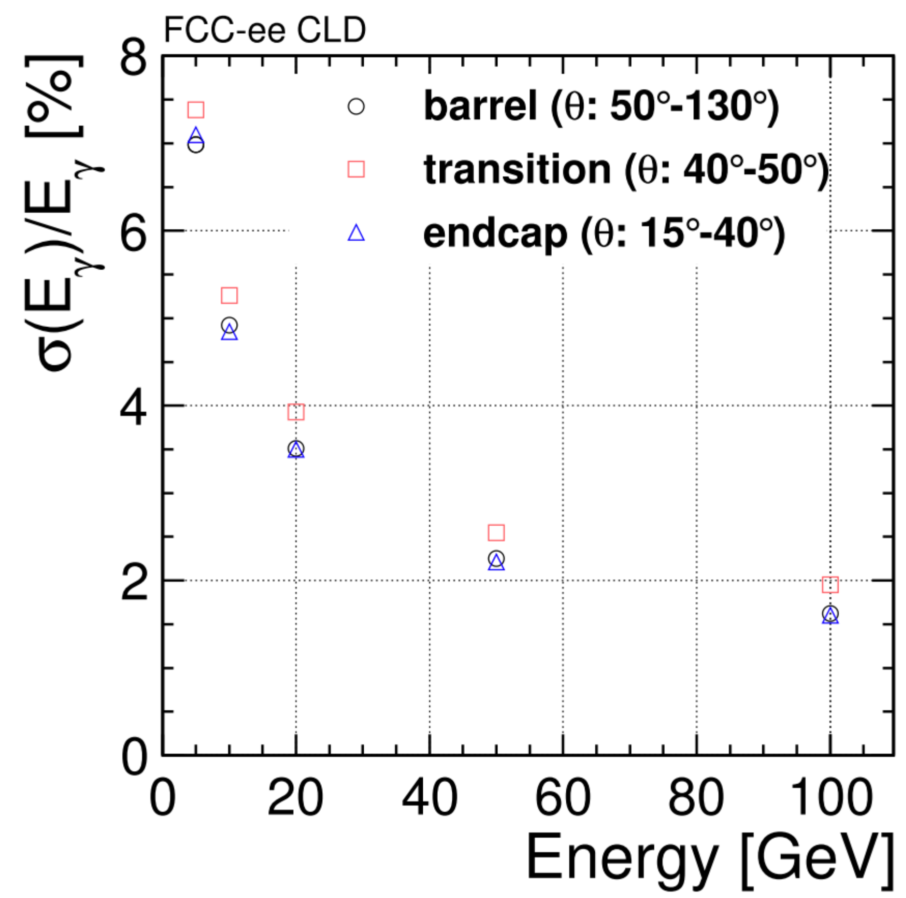
- Cooling despite challenging environment (no power pulsing possible).
- Large area of silicon.
- Timing for particle flow?

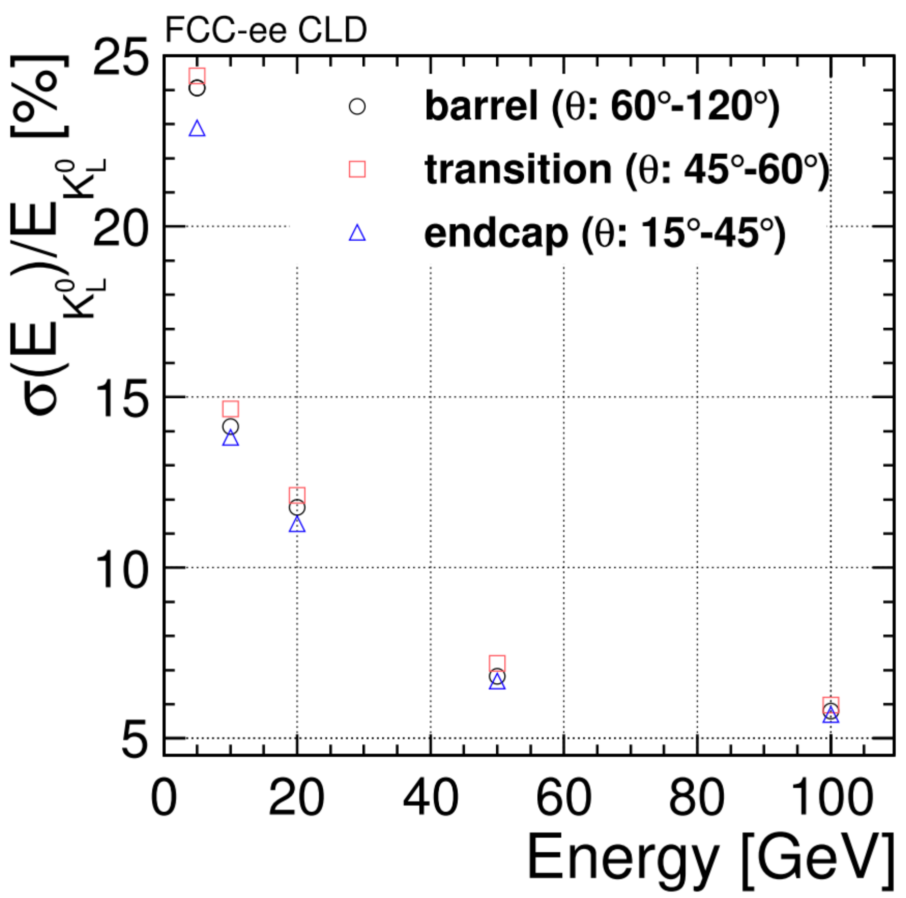
Calorimeters (CLD)

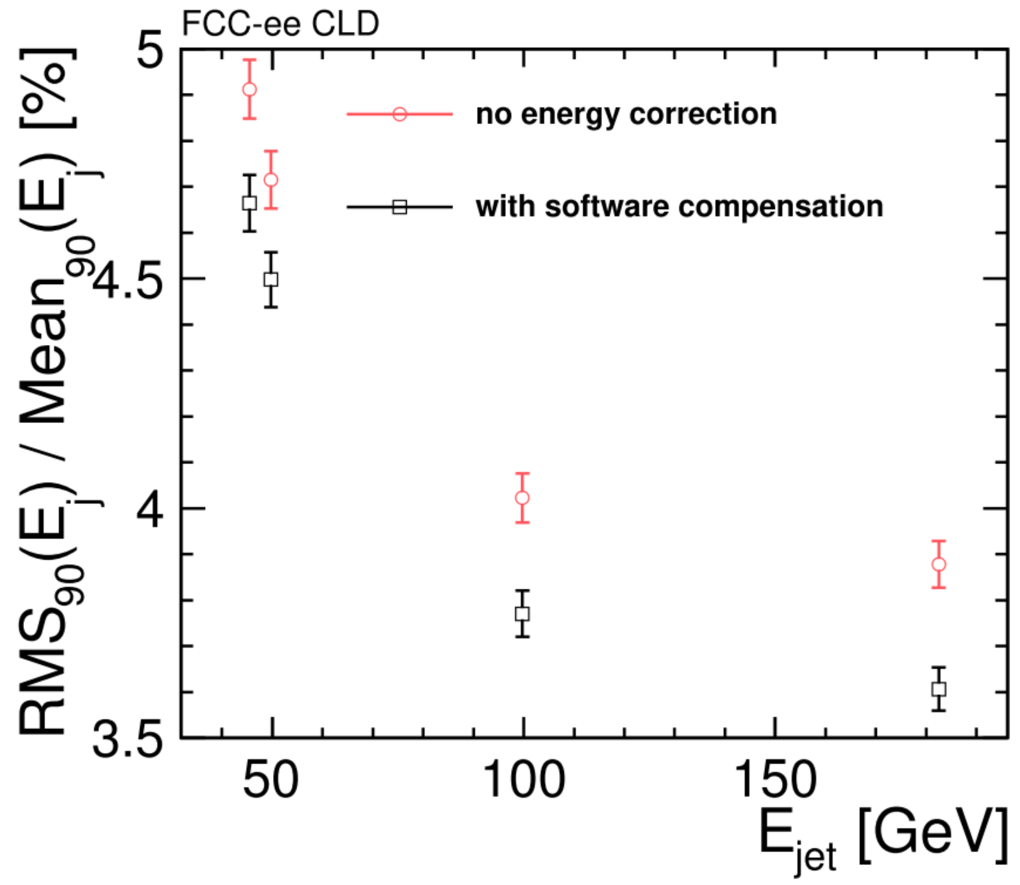
- CLD paradigm: calorimeter **optimised for particle flow** (emphasis on **granularity** rather than **quality of the energy measurement**)

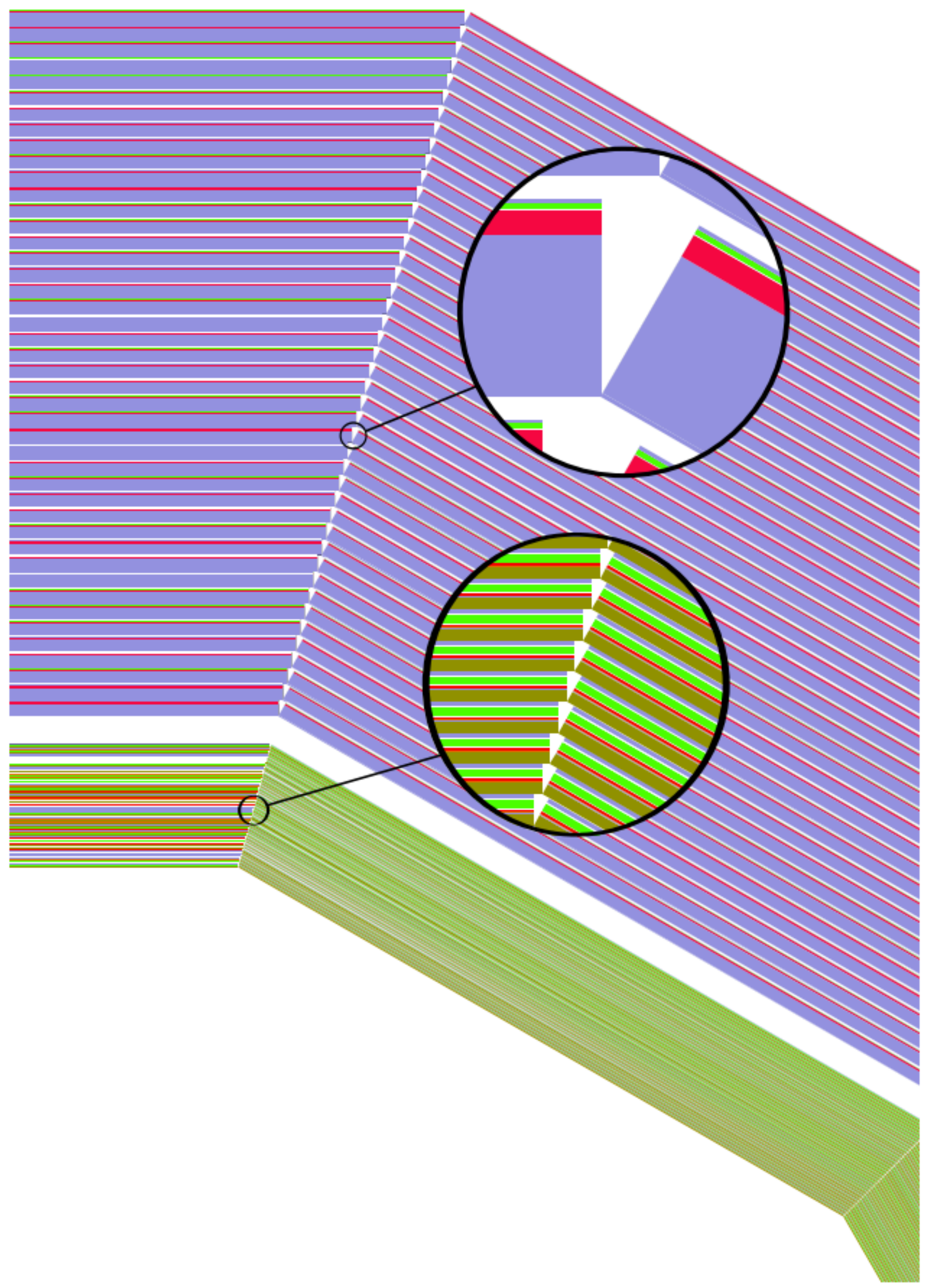
ECAL (CDR numbers - See <u>here</u> for optimisation studies):
  Cell size 5x5 mm^2 with Si-W.
  40 layers - 5.05 mm thickness each.
  Total 20 cm, 22 X_0, ~ 1 λ_I.
  No power pulsing - cooling is an issue - part of the optimisation process.
HCAL:
  Cell size 30x30 mm^2 scintillator-steel.
  44 layers - 26.5 thickness each.
  Total 117 cm, 5.5 λ_I.









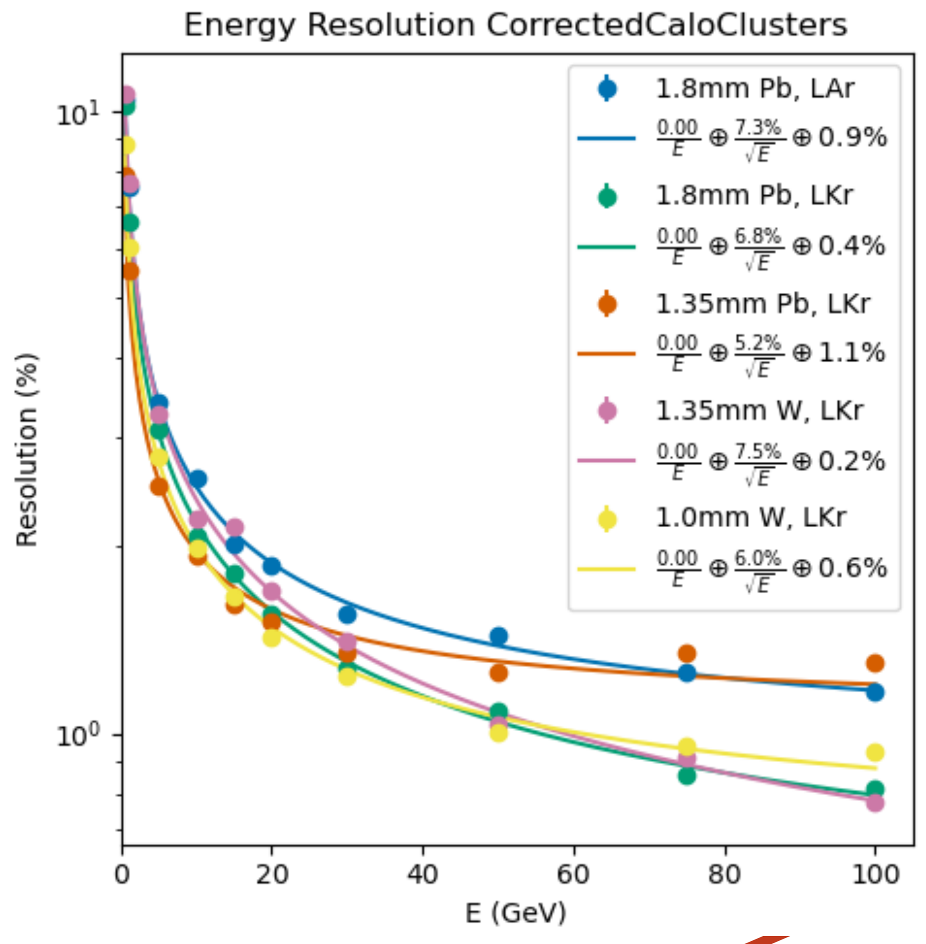


Calorimeters (ALLEGRO)

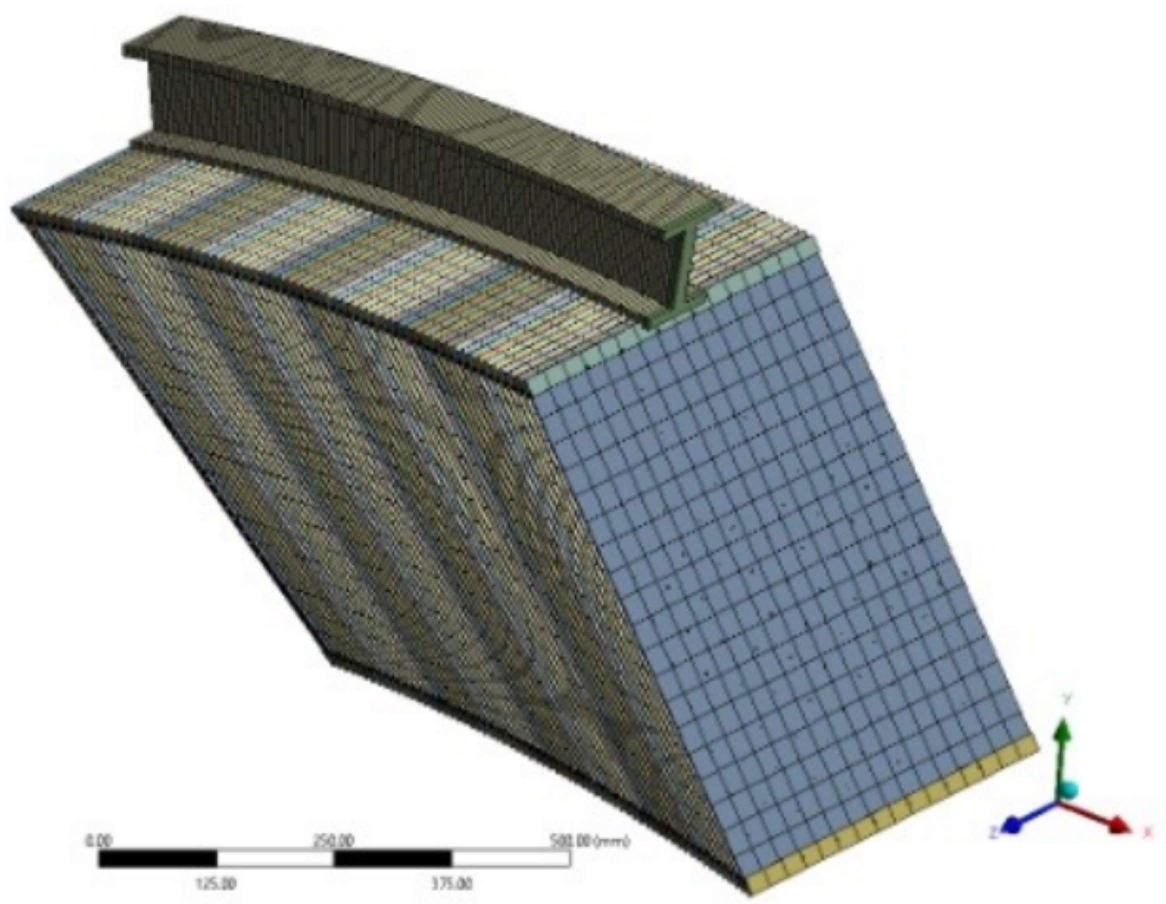
EM Calorimeter:

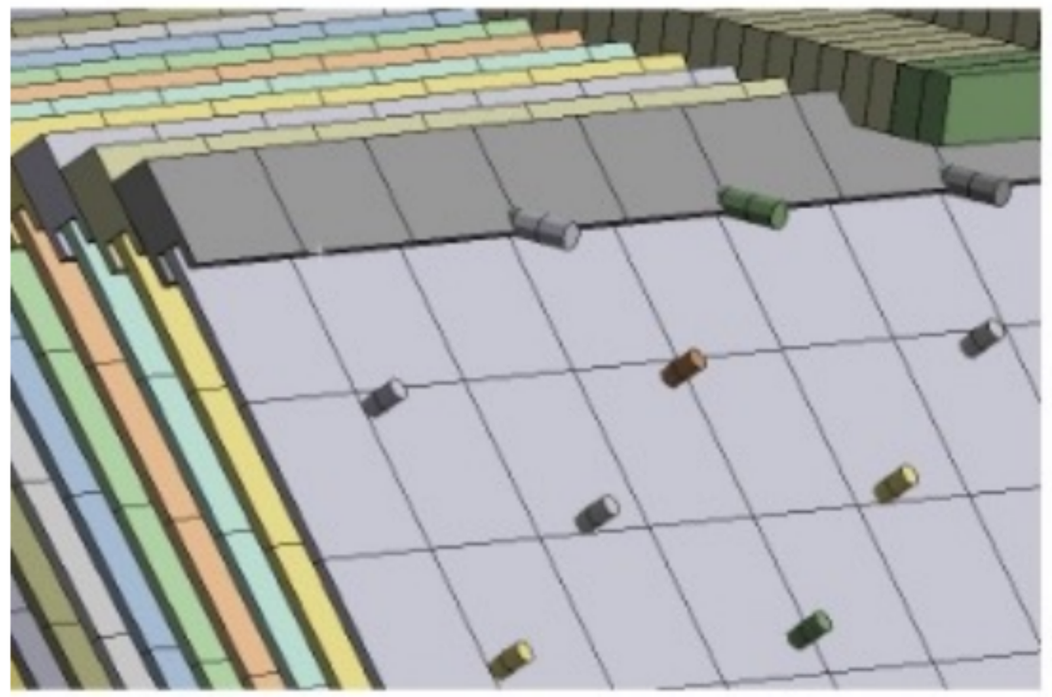
- Noble liquid calorimeters: good energy resolution, long-term stability, easy to calibrate.
    - Ideas to **achieve high granularity** targeting particle flow.
- Solution heavily inspired to ATLAS: LAr + copper - but different geometry.

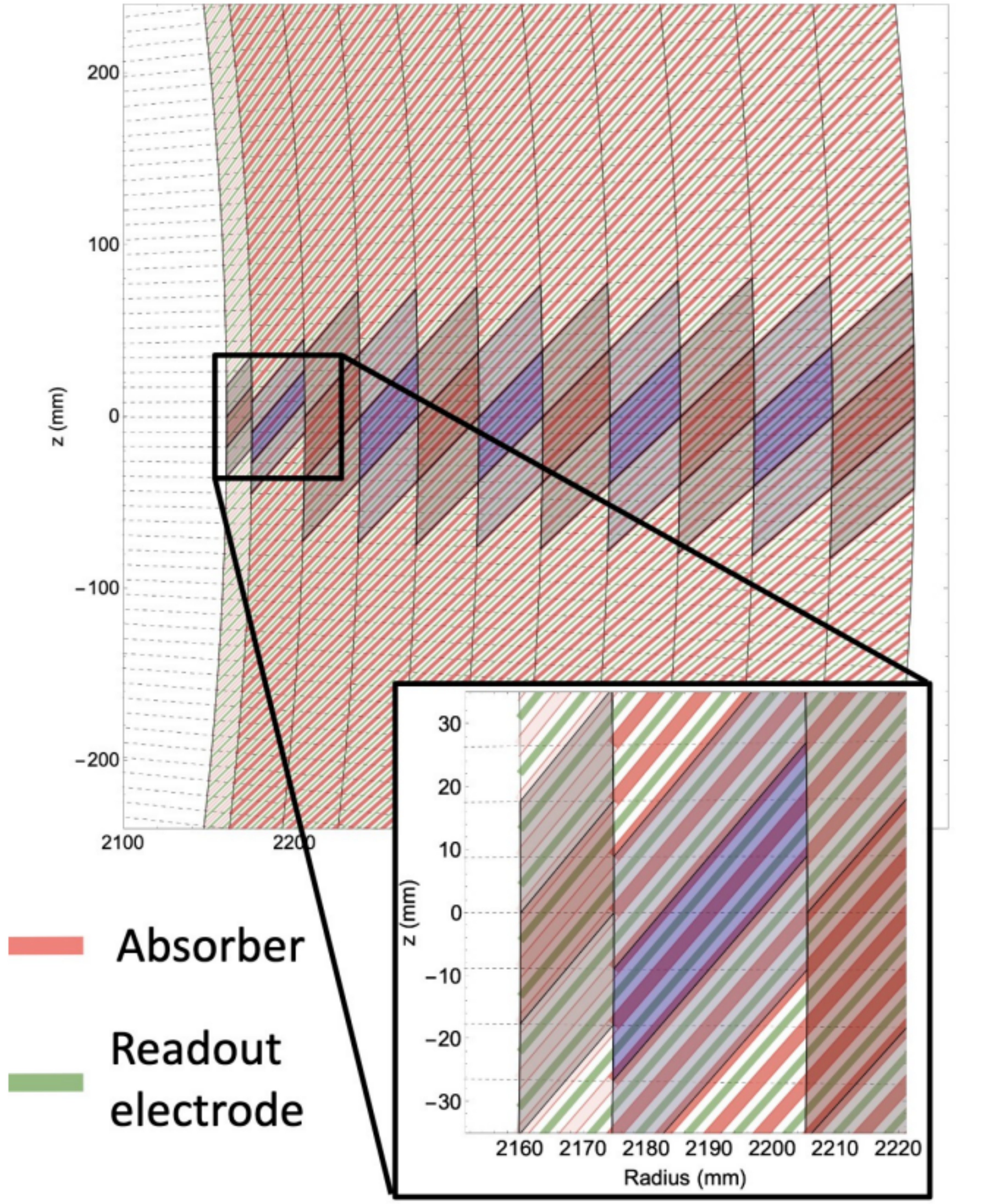
Hadronic section with an increased granularity scintillator tile + steel (a la TileCal).



Example optimisation of material





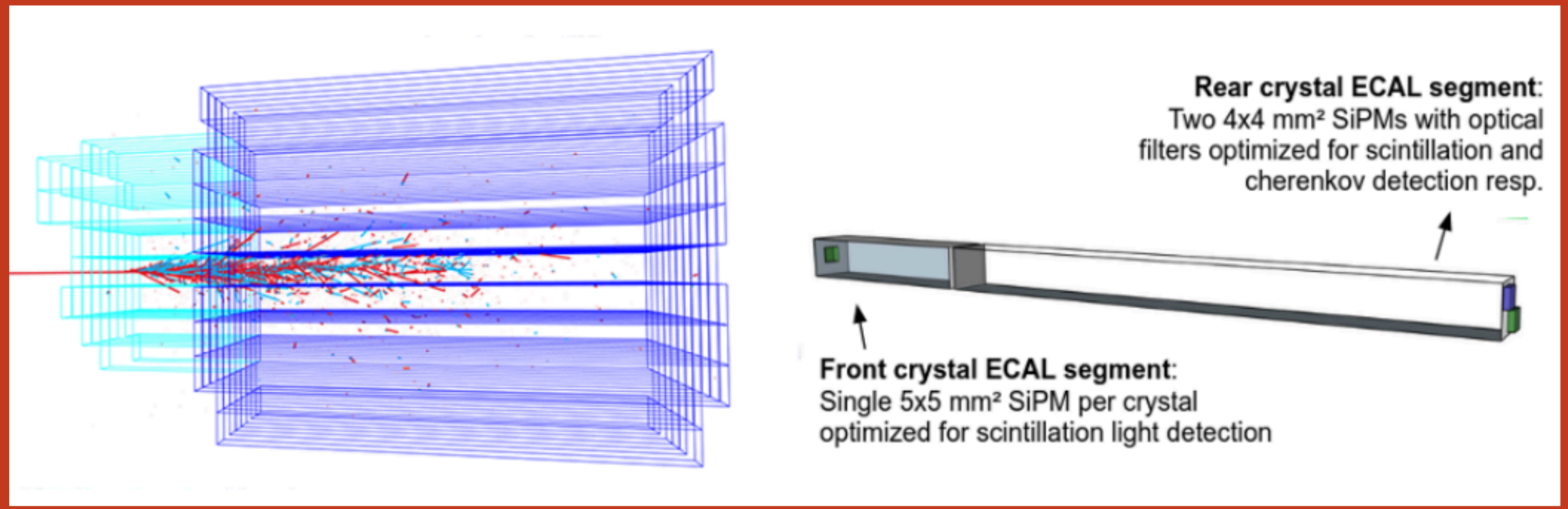


Calorimeters (IDEA)

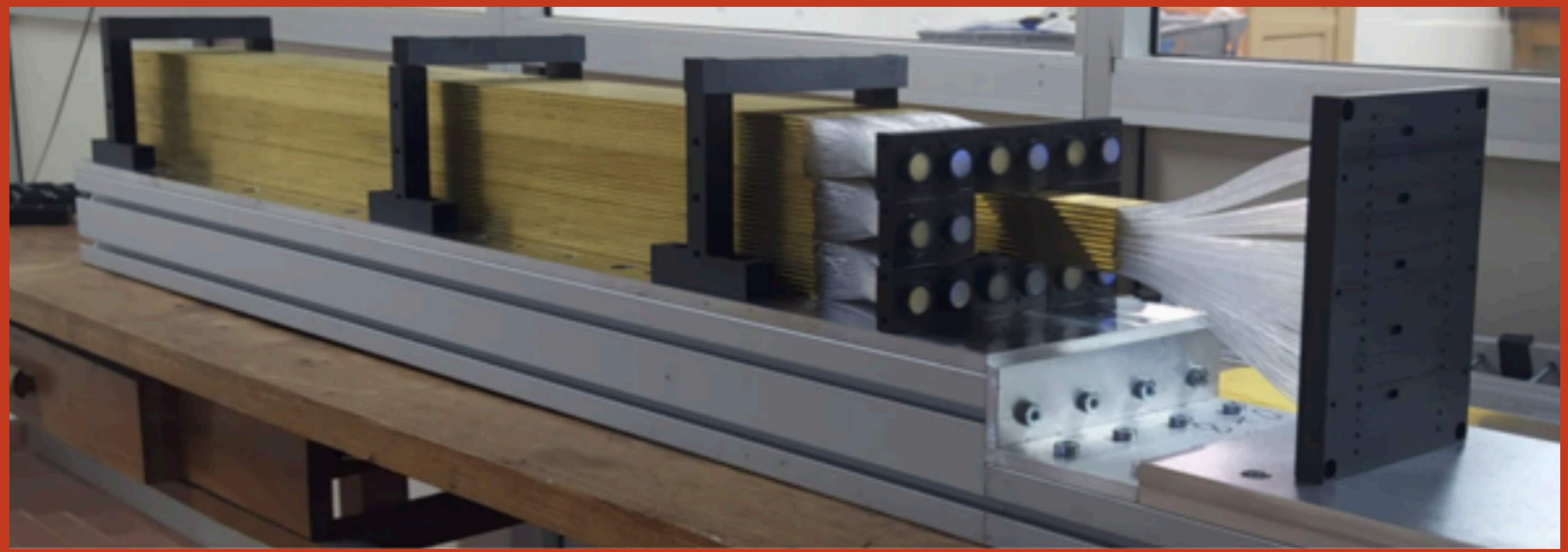
- Dual-readout calorimeters:
  - Extract **Cherenkov signal** (produced by electrons in hadronic shower).
  - Also extract **scintillation signal** (produced by all particles in the shower).
  - The **combination** enables an **event-by-event** correction for fluctuations in the **electromagnetic fraction.**

Challenges:
- Potentially large number of channels.
- Challenging mechanics (for fibre option.)
- Limited longitudinal segmentation.

Homogeneous crystal EM dual-readout calorimeter:
- Superior EM energy resolution
- Dual-readout achieved by separating signals in wavelength



Fibre-based dual-readout hadronic calorimeter:
- Nice lateral granularity.
- Dual-readout achieved by using different fibres for Cherenkov and Scintillation signals.



Performance

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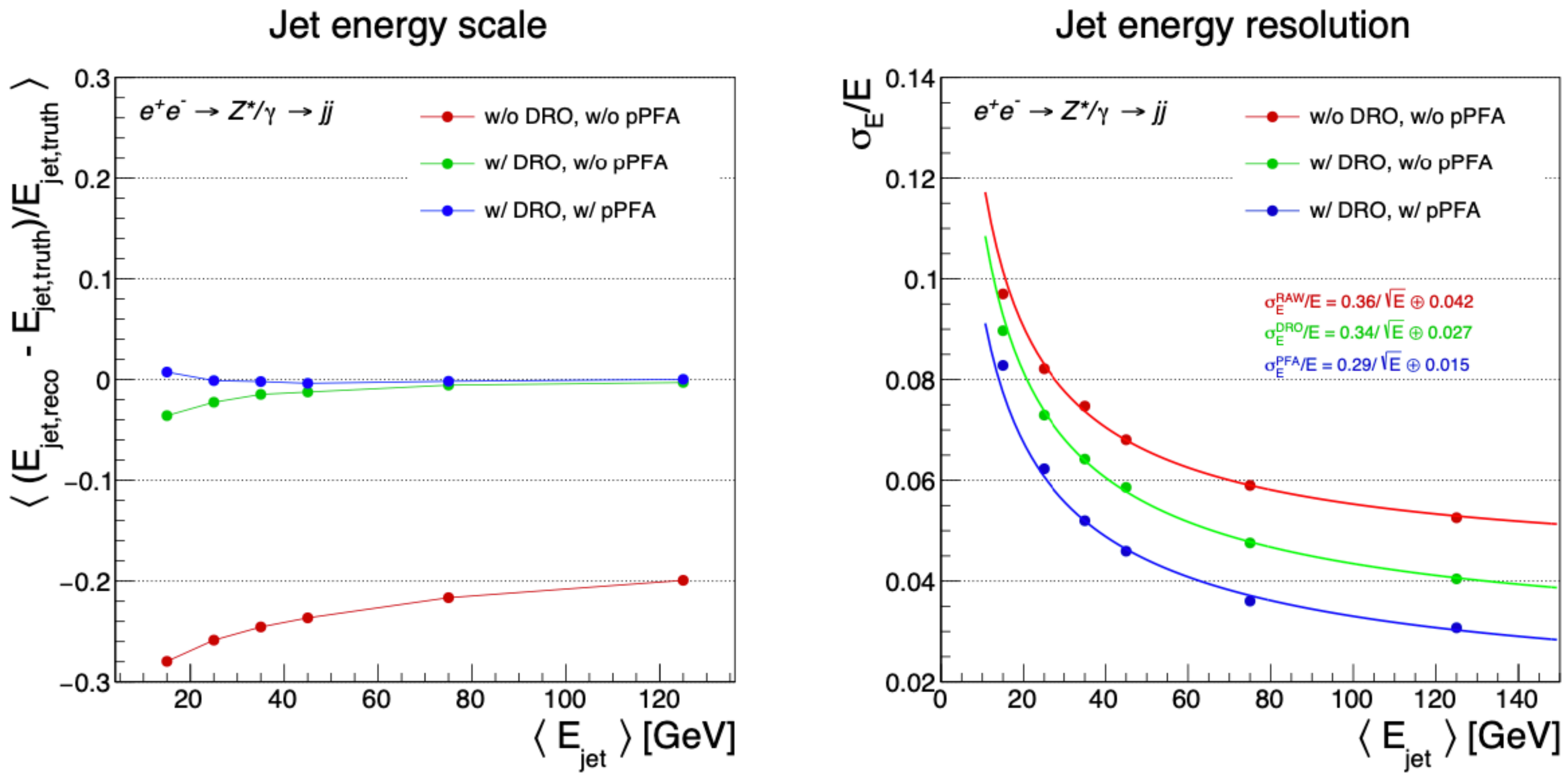
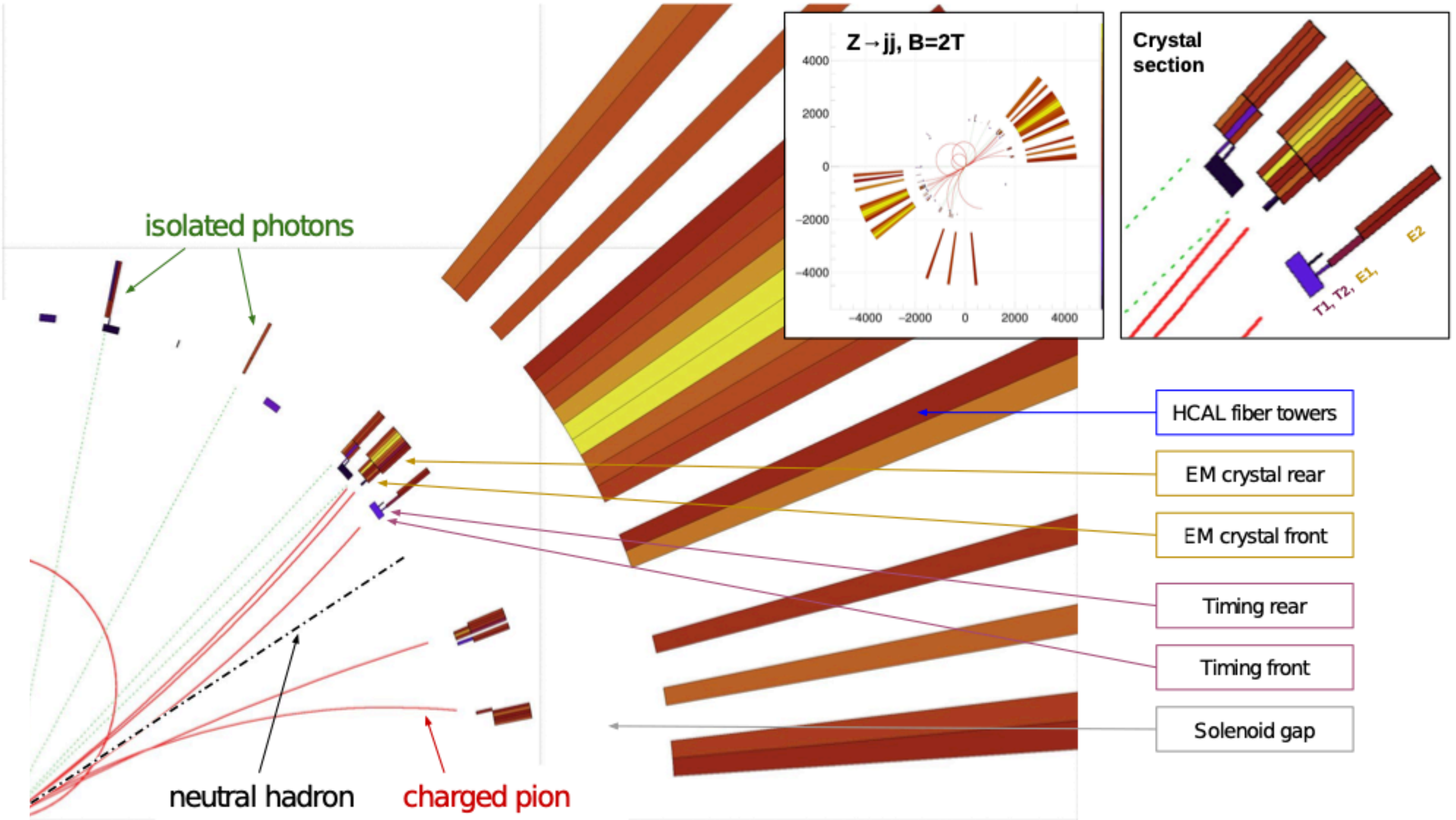
Taken from https://doi.org/10.1088/1748-0221/17/06/P06008

The combination of a (very simple) particle flow-like technique and dual readout achieves very interesting results





Software tools

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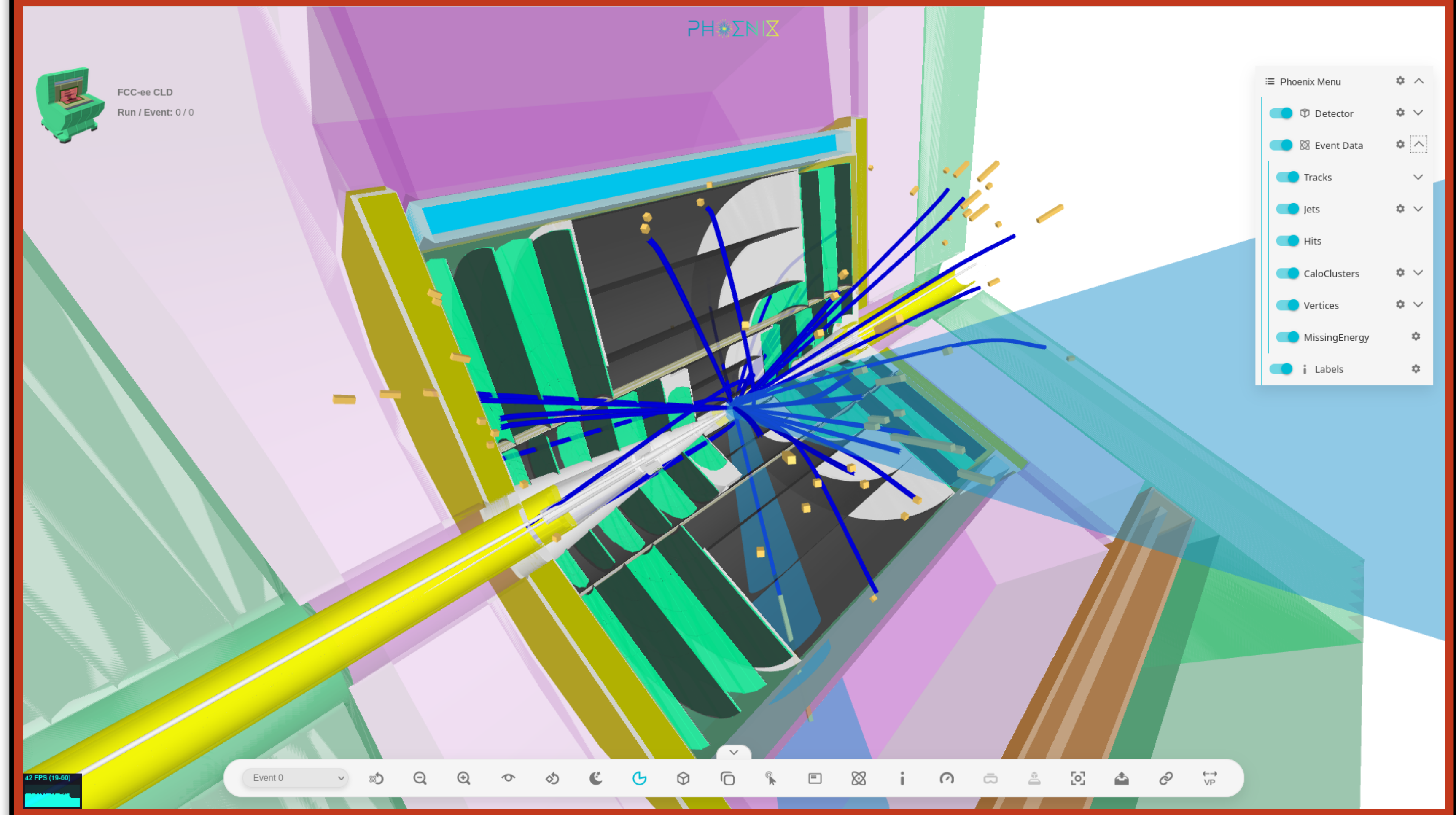
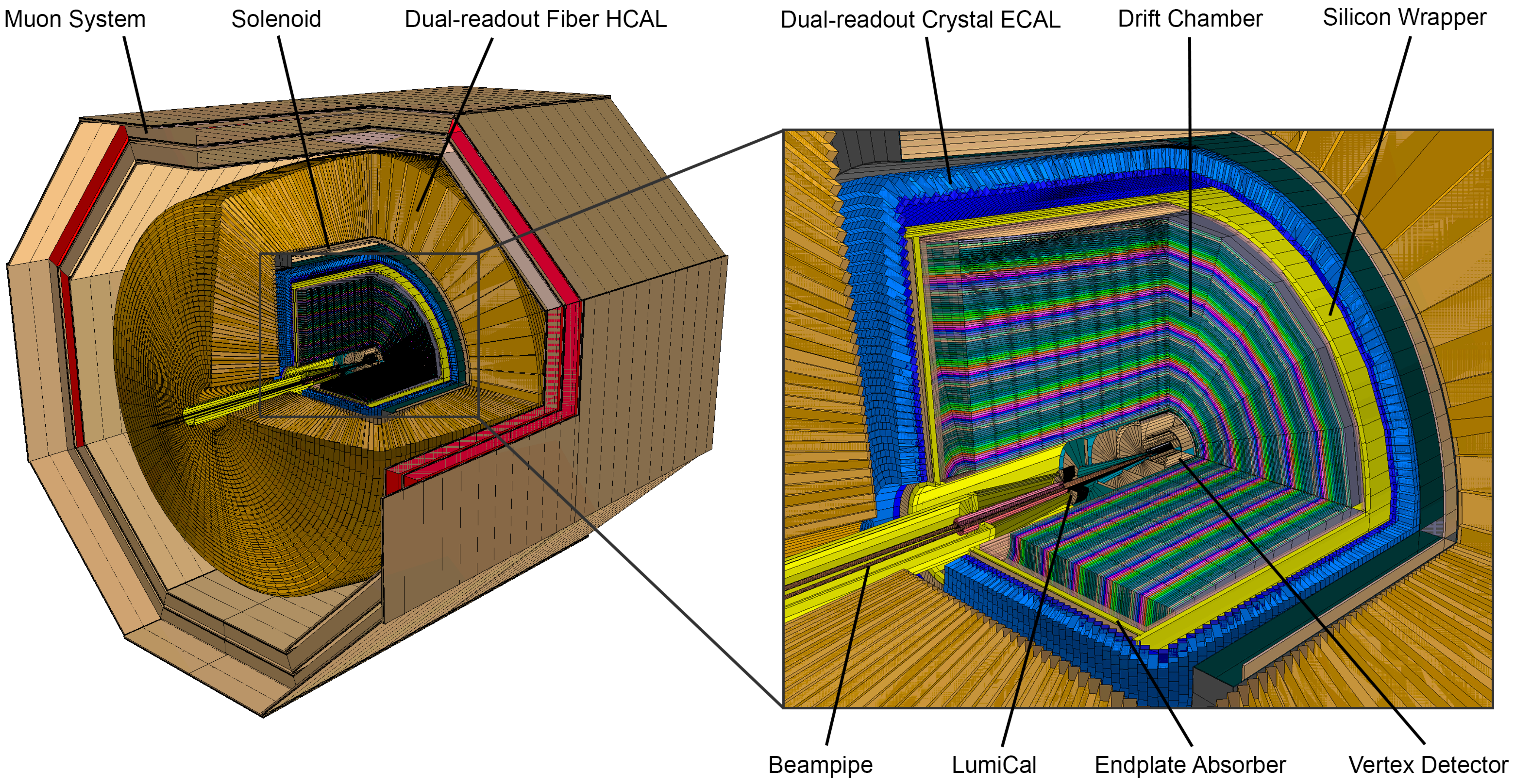
- Common software framework available for **detector simulation** (and reconstruction) and for **physics use**.
  - **Geometry/simulation available for all detector concepts.** Digitisation and reconstruction at different level of maturities.

Key4HEP
A **common software framework** used for FCC, but also for many of the other future collider projects. Includes a common **event data model**, tools for easy and portable **detector geometry handling**, a consistent set of tags of **the most used HEP softwares**.





See also a recent talk from L. Pezzotti

Where can I contribute?

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- Detector concepts are **nice frameworks** - fresh ideas and redesign are **more than welcome.**
  - … and we have 3 detector concepts and 4 IPs….
  - **New technologies** (timing? Radically new options for calorimeters and/or tracking?).
  - **Software is in development** (simulations are there, but digitisation and reconstruction need work).
- “communities” fairly compact (o(20) people) - a lot of room for new collaborators).
  - Opportunities for **younger colleagues**:
    - Doing **“core” HEP detector/software work** after highly optimised LHC detectors.
    - Talks and proceedings - $\frac{N_{contributors}}{N_{talks}} \sim 1$ (maybe while spending the majority of their time on a major LHC experiment).

Summary

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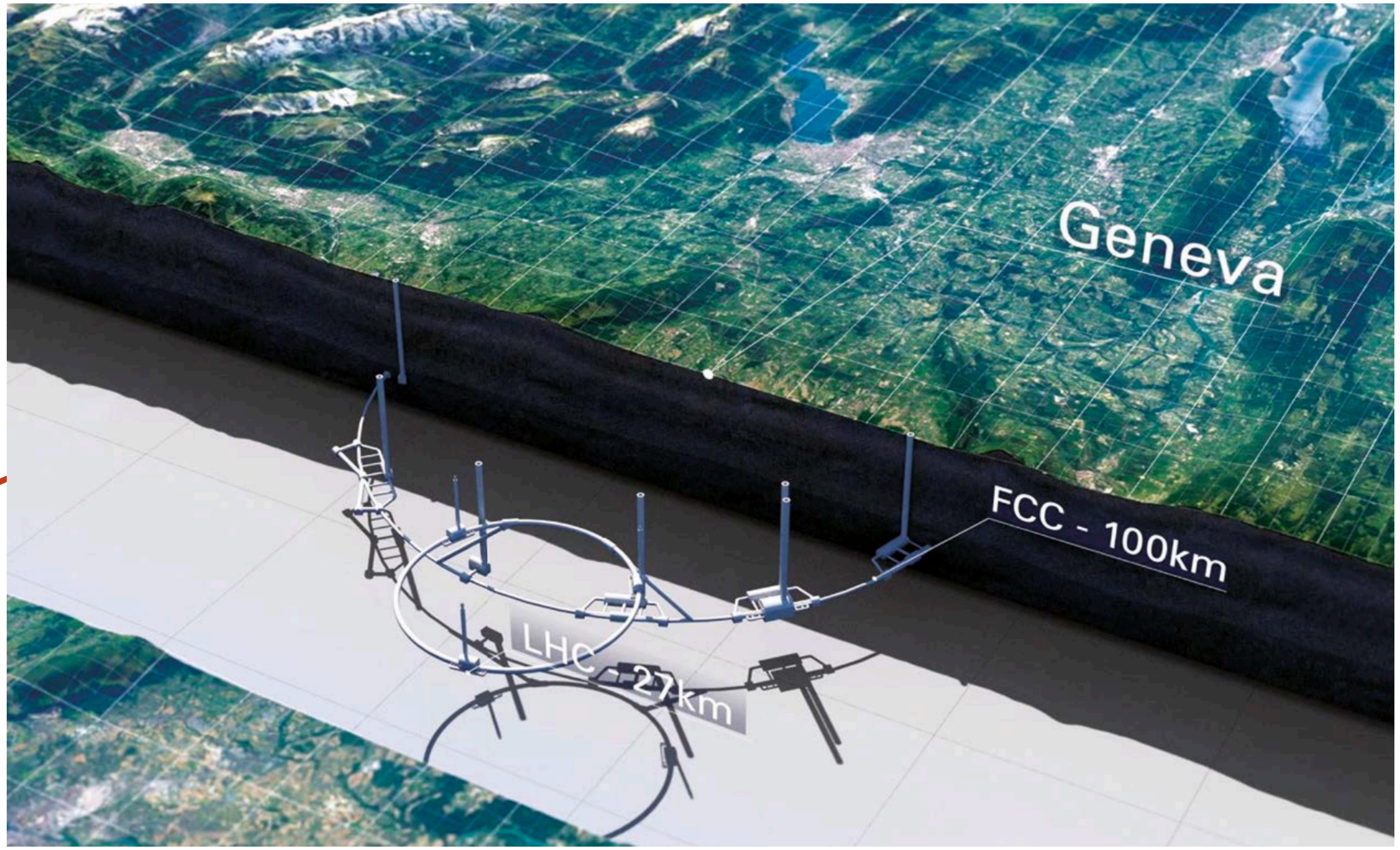
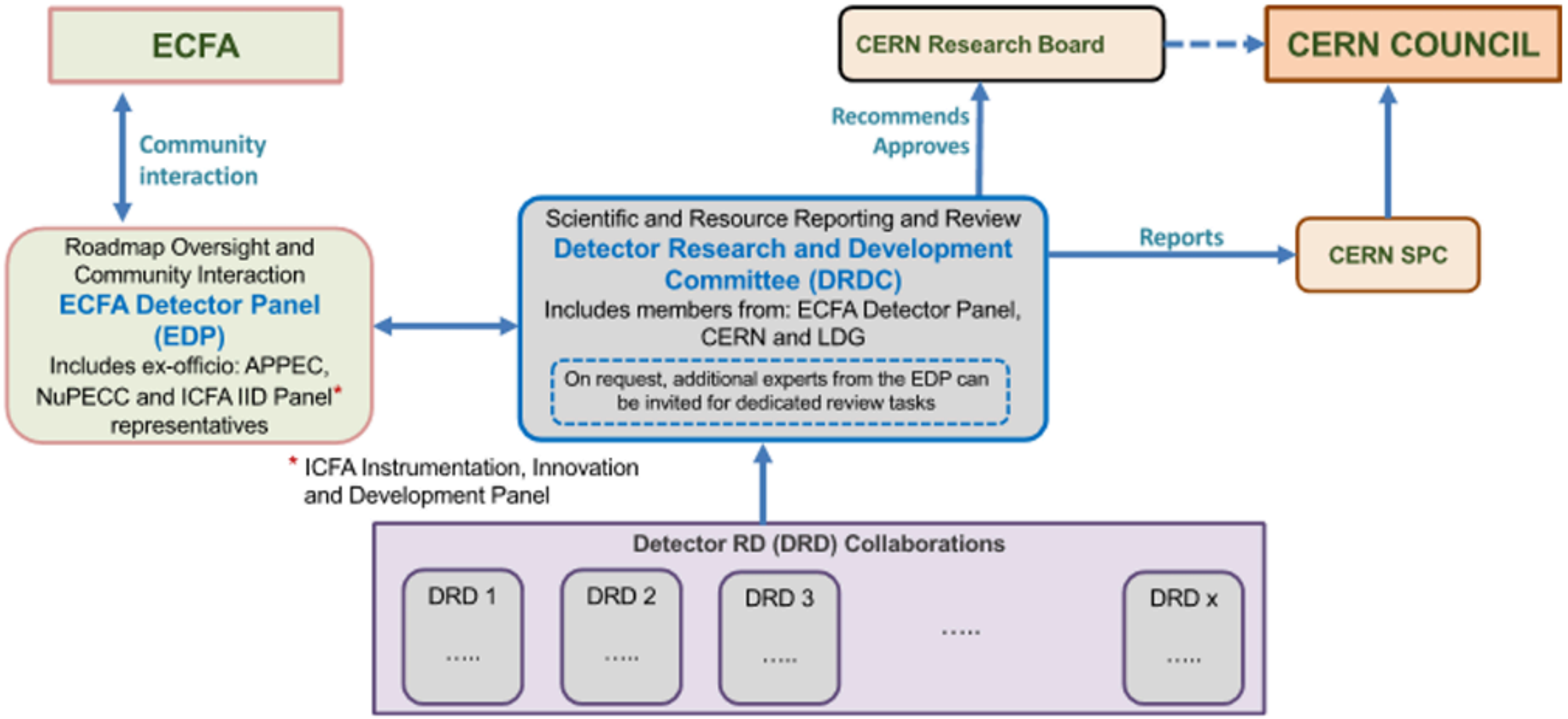
- The development of the case for FCC (and in particular FCC-ee) is **in full swing** in view of the European strategy of particle physics update in 2026.
    - The physics case is compelling - The project is very ambitious!
- INFN is seen **as an example** from abroad: nicely structured for future projects and **strategically placed** in many of the key R&Ds (both in software and hardware).
- It is a long time to FCC-ee…
    - **But a lot is happening right now!** Feasibility study + European Strategy update key ingredients for project approval.



Backup

Synergies: Consortia and ECFA DRD

- A lot of leverage done in the past within **consortia and proto-collaborations.**
- Challenges connected with detector R&D find **a common framework** (aimed at increasing coherence and optimising resources) with ECFA DRD.
- **INFN positioning for many of these items is strategic.**



EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

CRYSTAL CLEAR

RD51 Collaboration

AIDA innova

High-level feasibility study objectives

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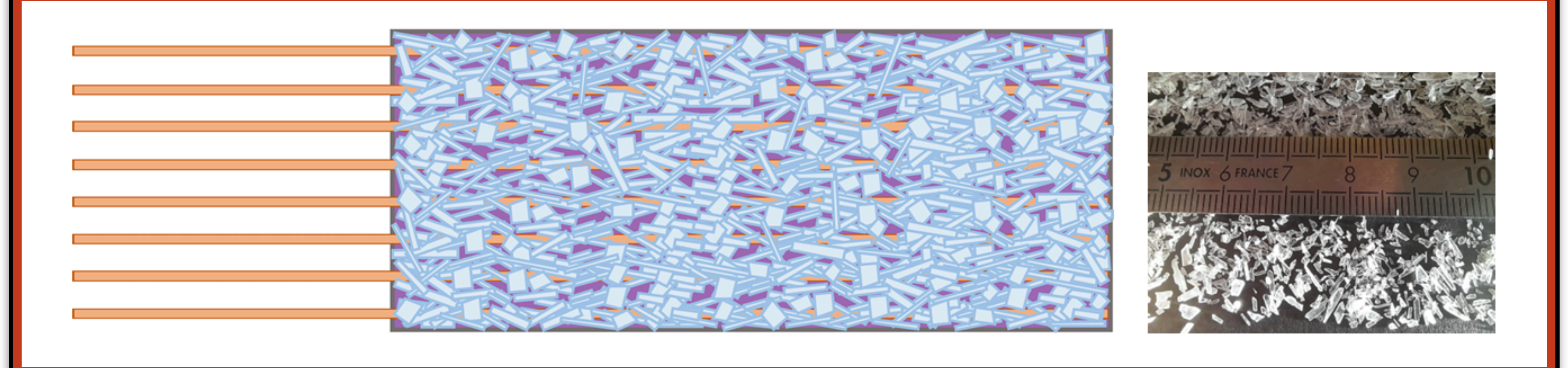
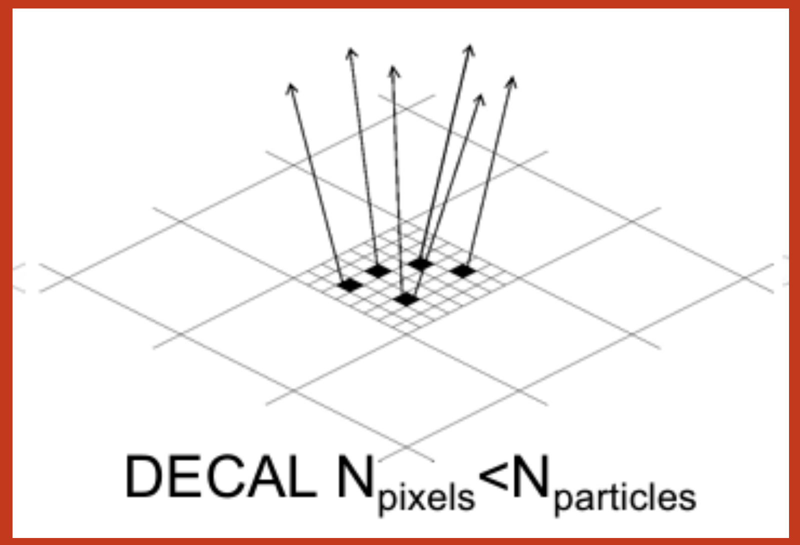
- High-level objectives:
  - demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
  - pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
  - optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
  - elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
  - development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
  - identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
  - consolidation of the physics case and detector concepts for both colliders.

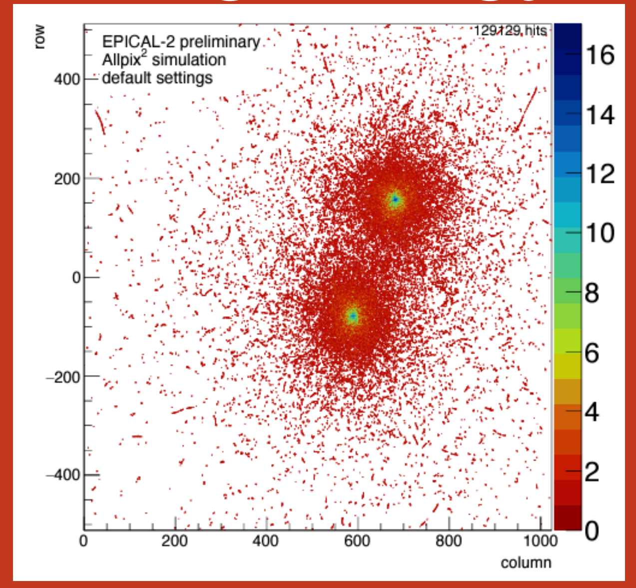
Calorimeters (other ongoing R&Ds)

GRAiNITA
scintillator grains and absorber suspended in a liquid. Trapped light extracted with WLS fibres - high density EM calorimeter.

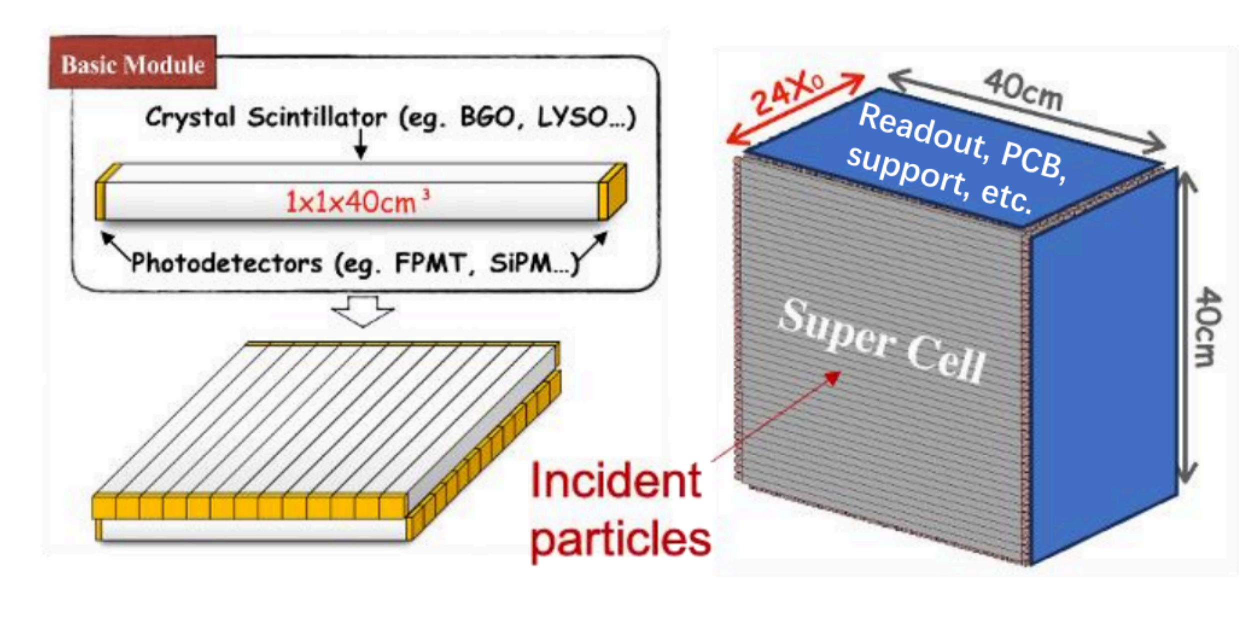


DECAL - Ultra-high granularity CMOS Ecal
High-density digital CMOS readout - count hits rather than measuring energy



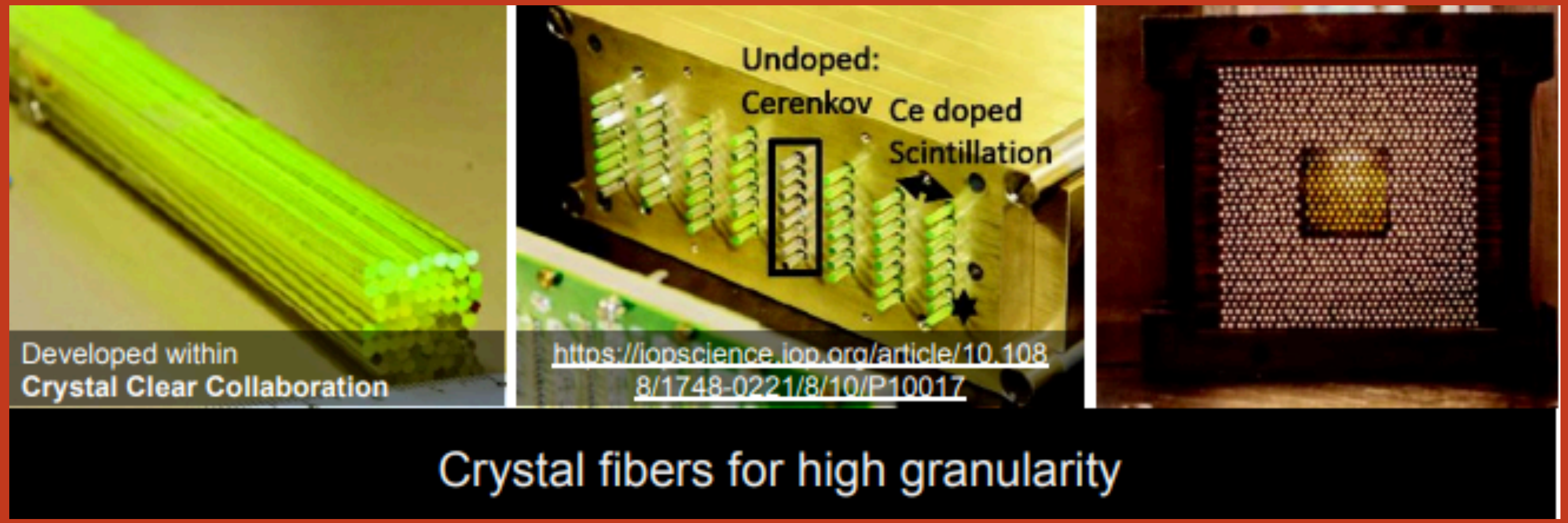


A crystal calorimeter for FCC-ee?



Traditionally achieve superb EM resolution but limited granularity.

Recent R&D shows potential for particle flow.

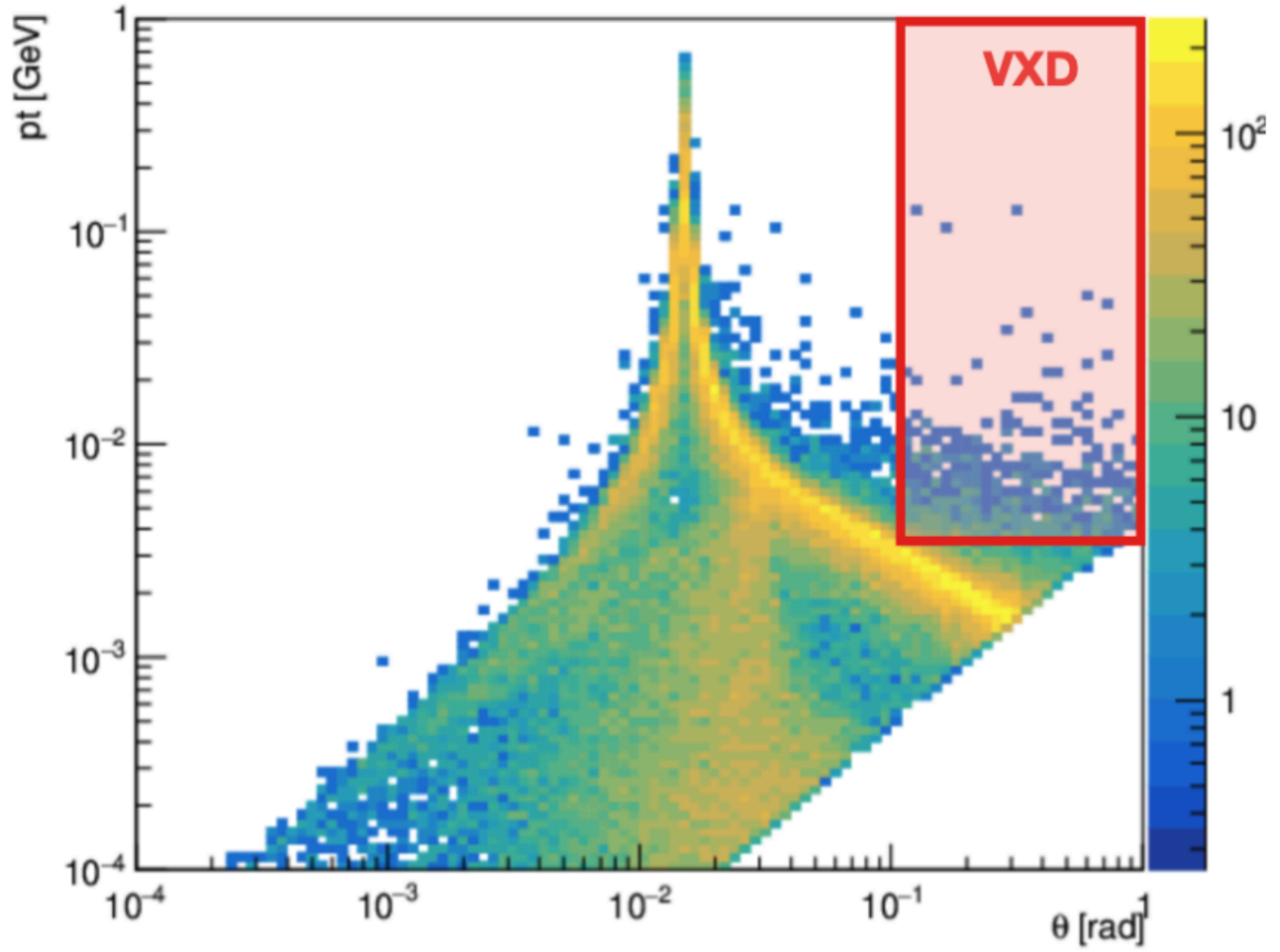


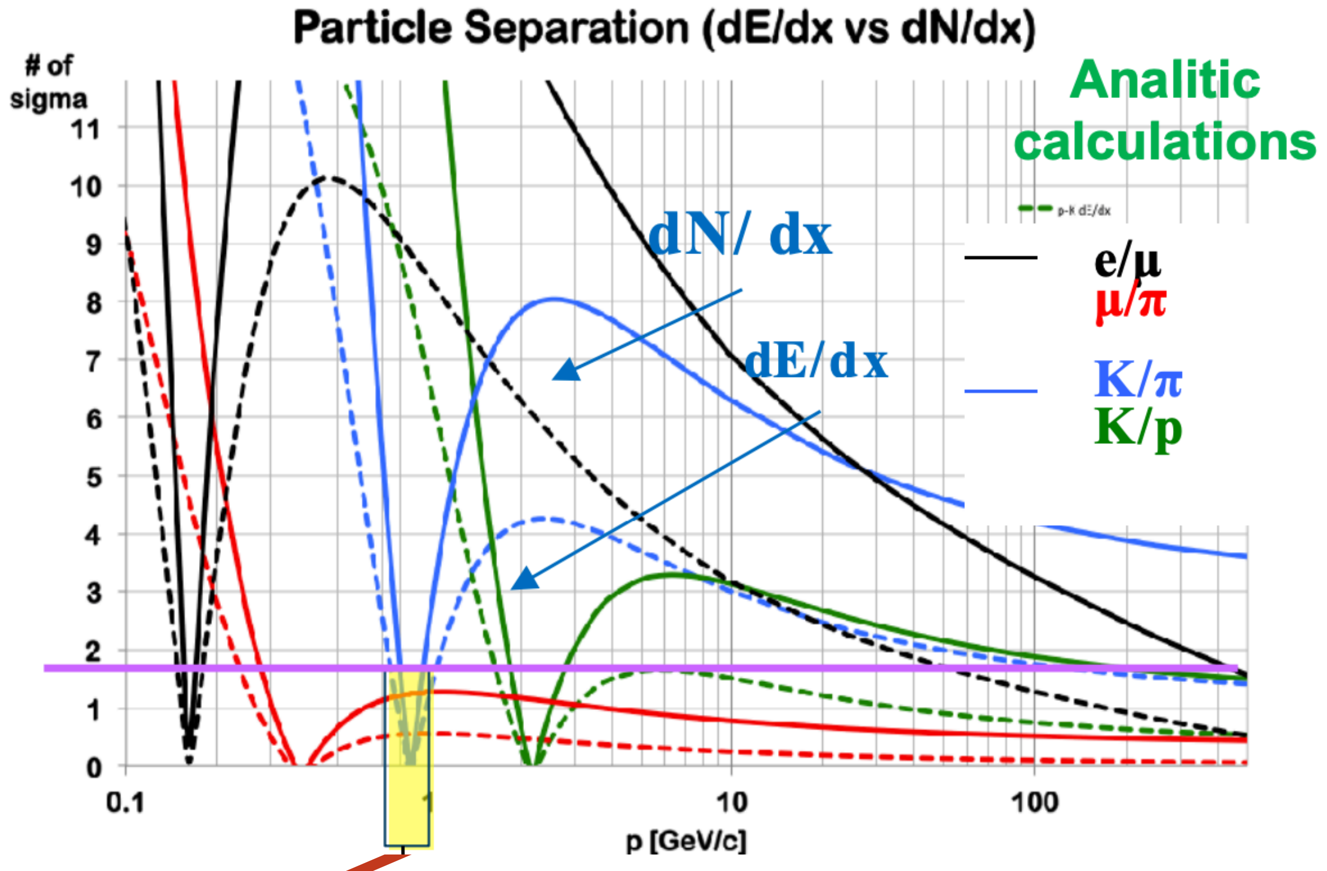
Crystal fibers for high granularity

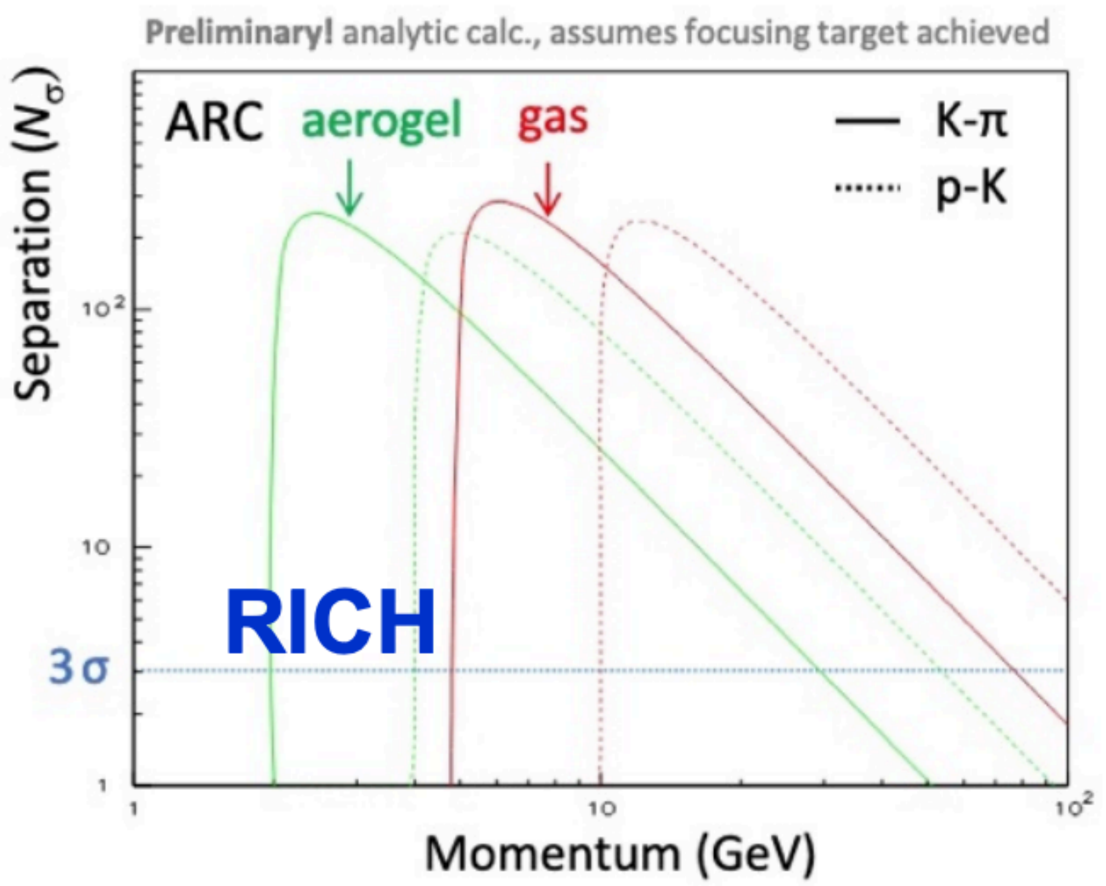
Challenges

- Full silicon tracking:
  - **Keep material down**, despite cooling and services
  - Particle identification **may need alternative detectors** (RICH?)
- Drift chamber:
  - Mechanical stability, cluster-counting compatible electronics

Taken from here







Detector occupancy driven by incoherent pair creation and synchrotron radiation photons.

Estimated < 1% for full silicon detectors.
It is almost a no-go for a TPC (see here)
OK (but need to keep an eye on) for DWC.

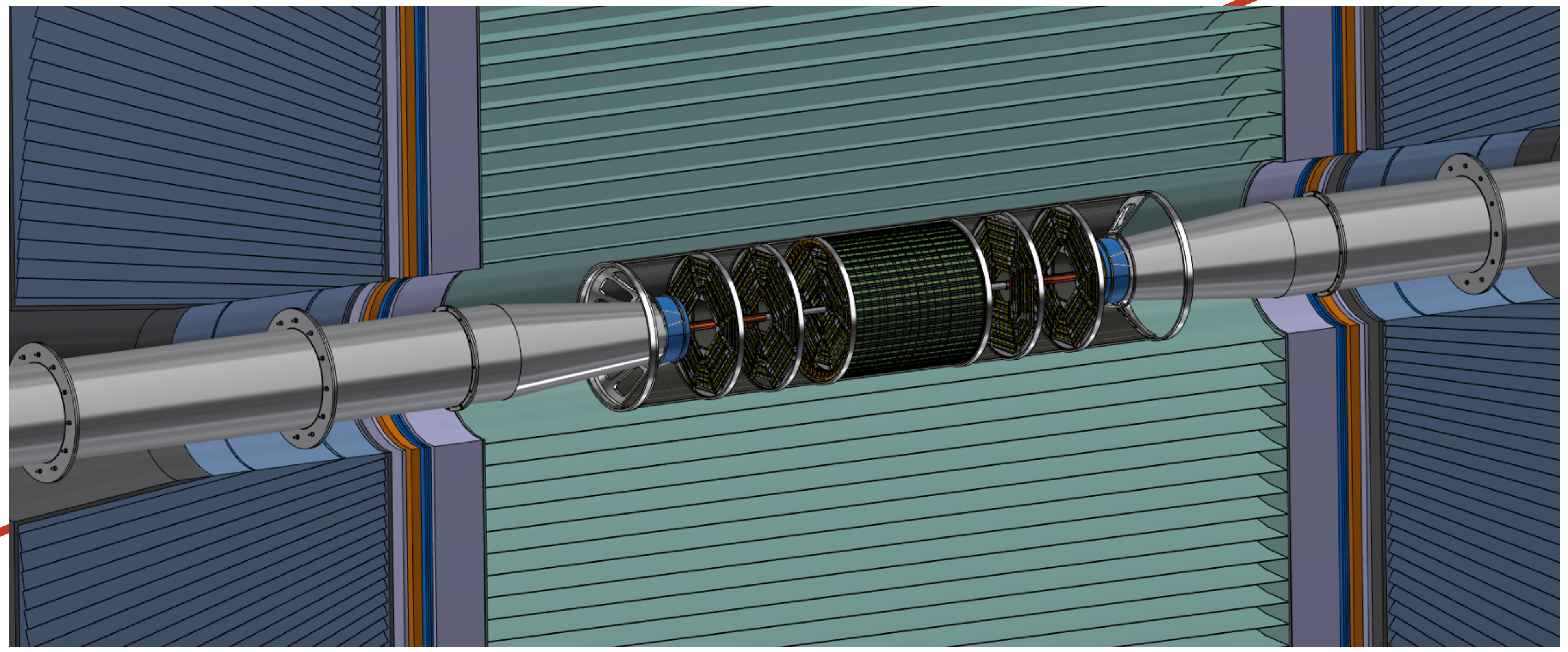
Vertex detectors

General requirements

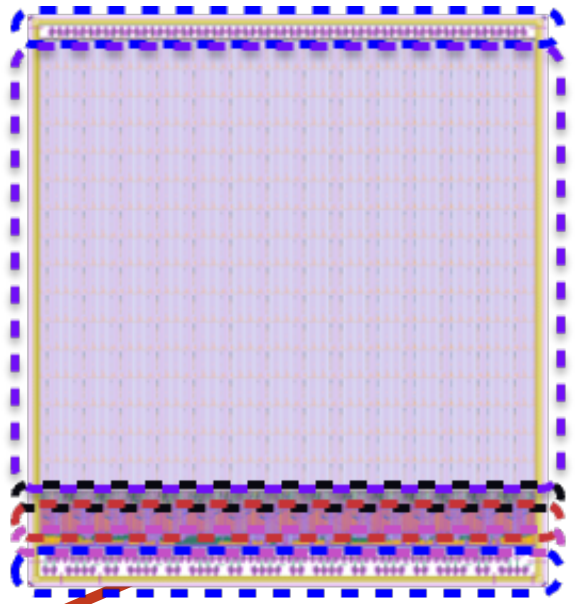
Flavour physics and tagging requires 3-5 μm → pixel size ~15 μm.
Small material budget (0.1% of X_0/layer) → Thickness ~ 50 μm.
Low power consumption (especially inner layers) → 10-30 mW/cm^2.

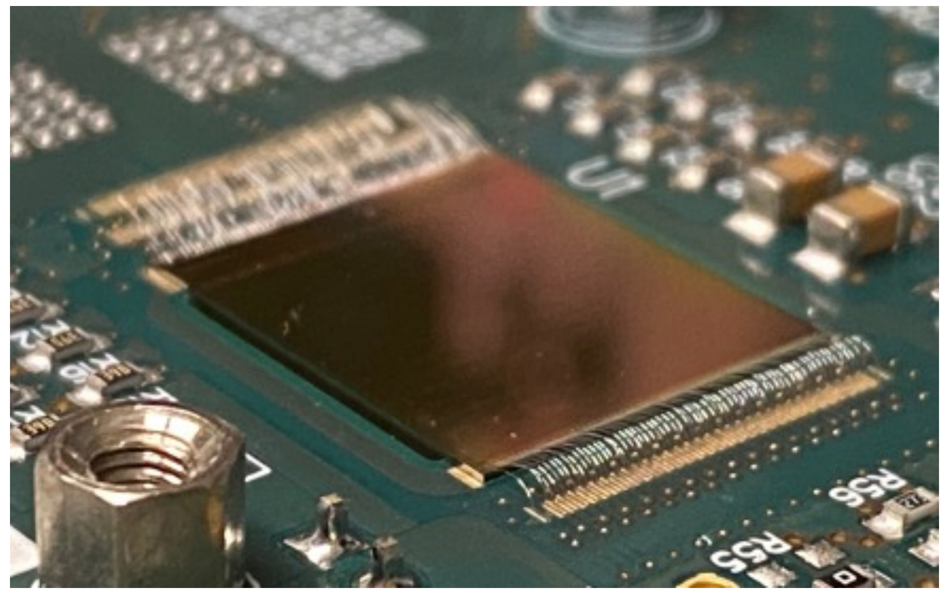
Solution: CMOS MAPS

high spacial resolution and **small material** (integrated circuitery)
- Used in a number of LHC experiment upgrades (ALICE ITS, ATLAS ITK, etc.)
- No need for bump-bonding: allow smaller pixel size
- Affordable overall

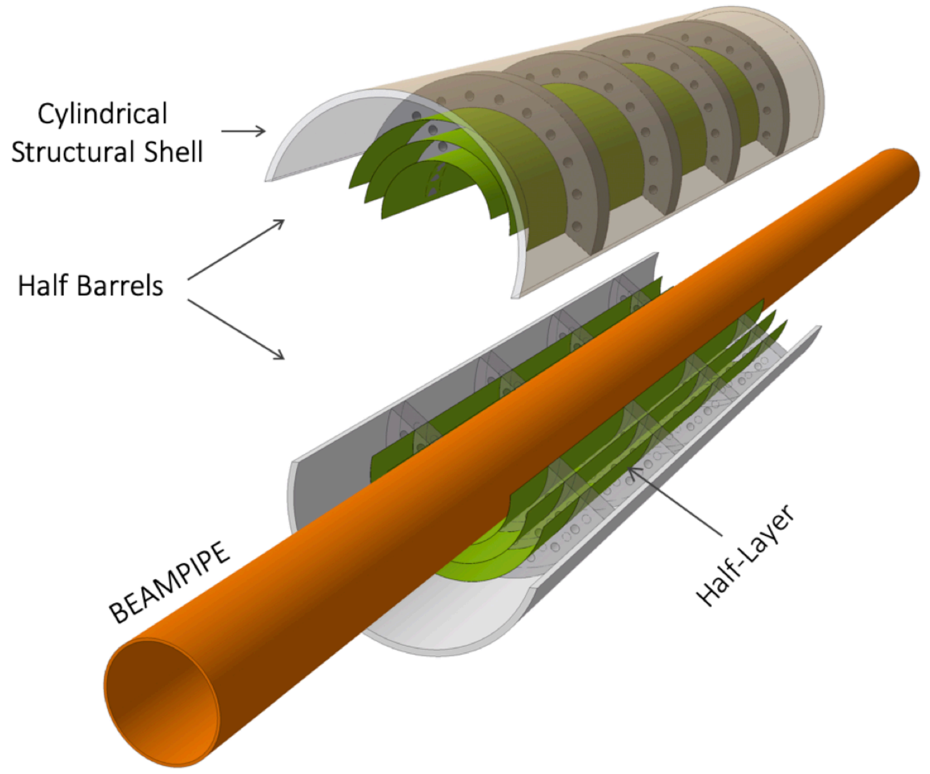


ARCADIA

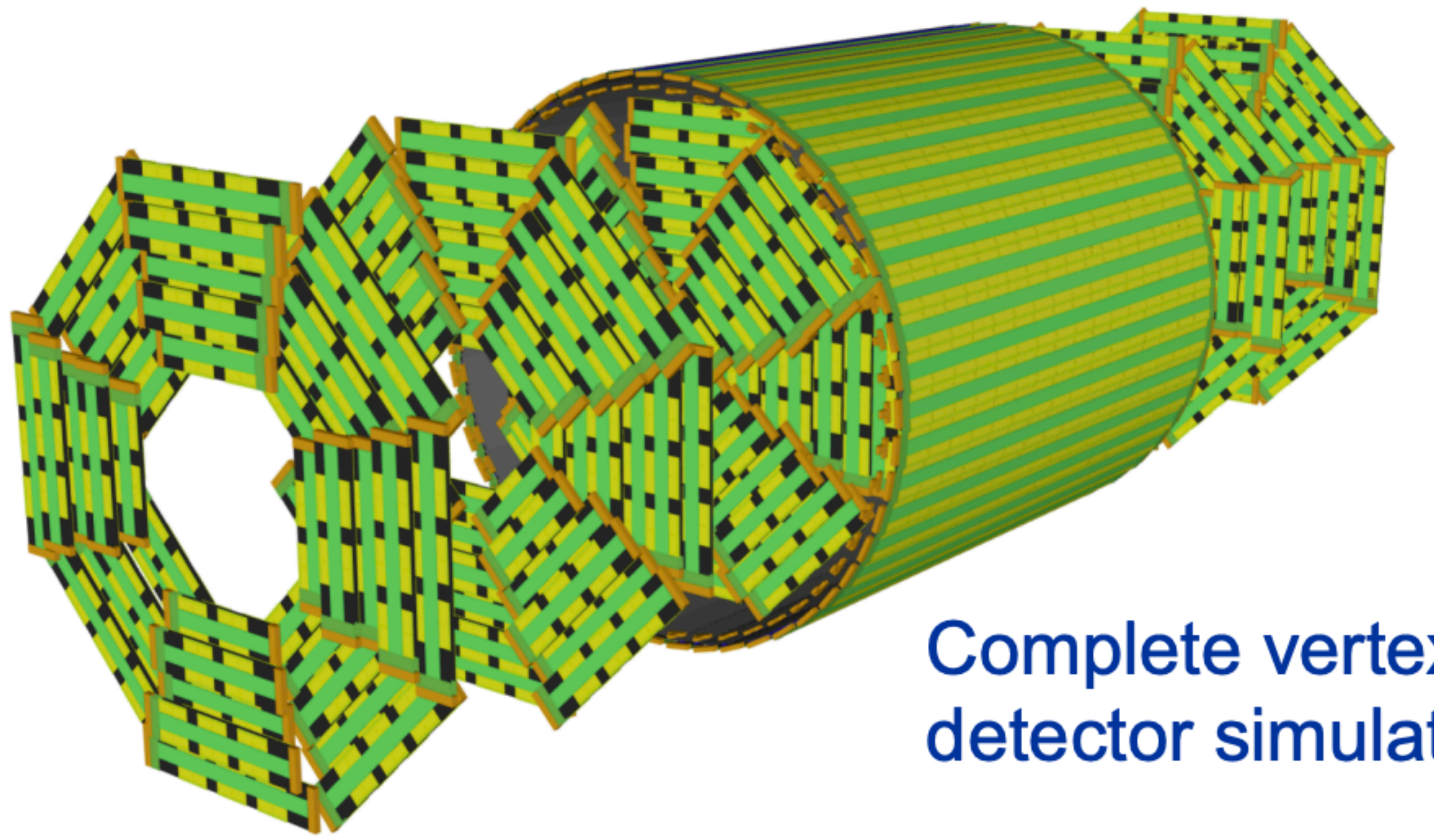




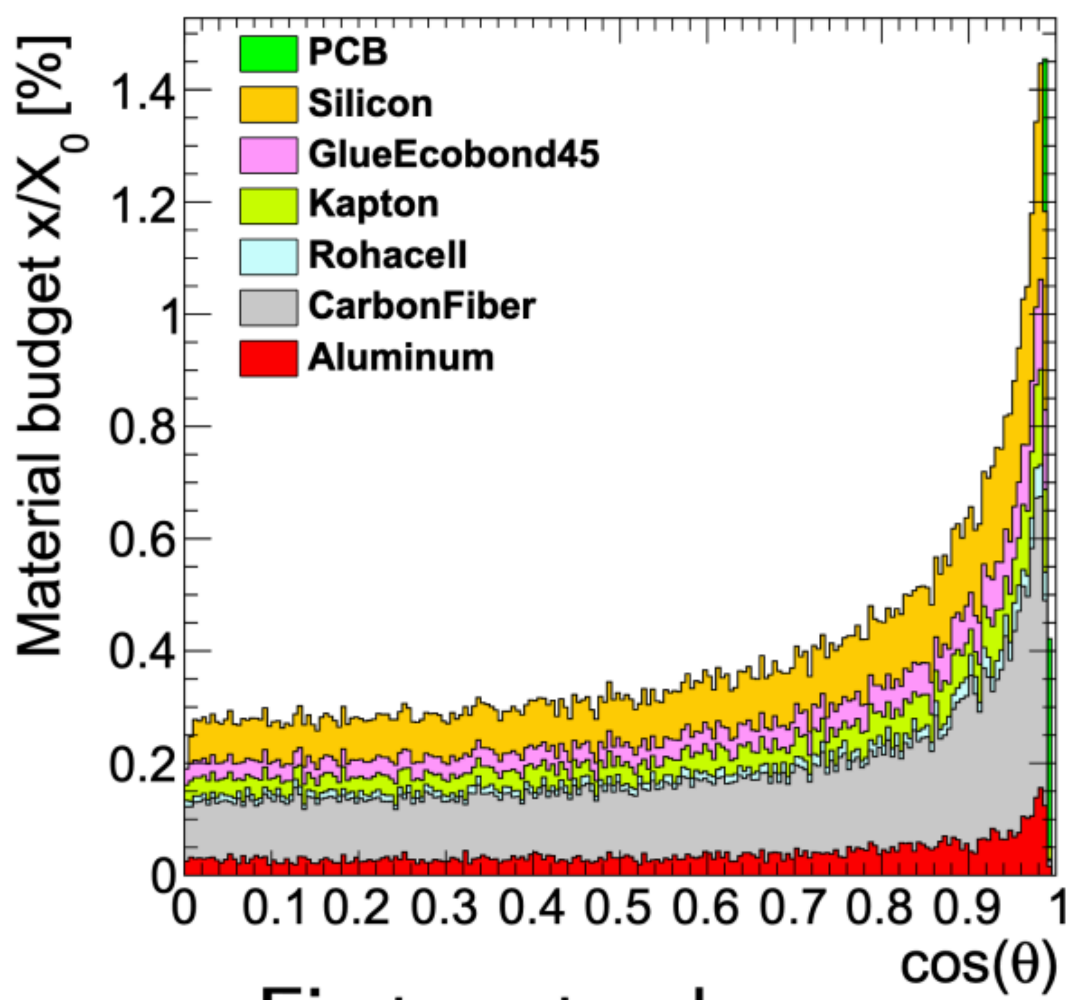
Bent silicon sensors (ALICE ITS3 R&D)



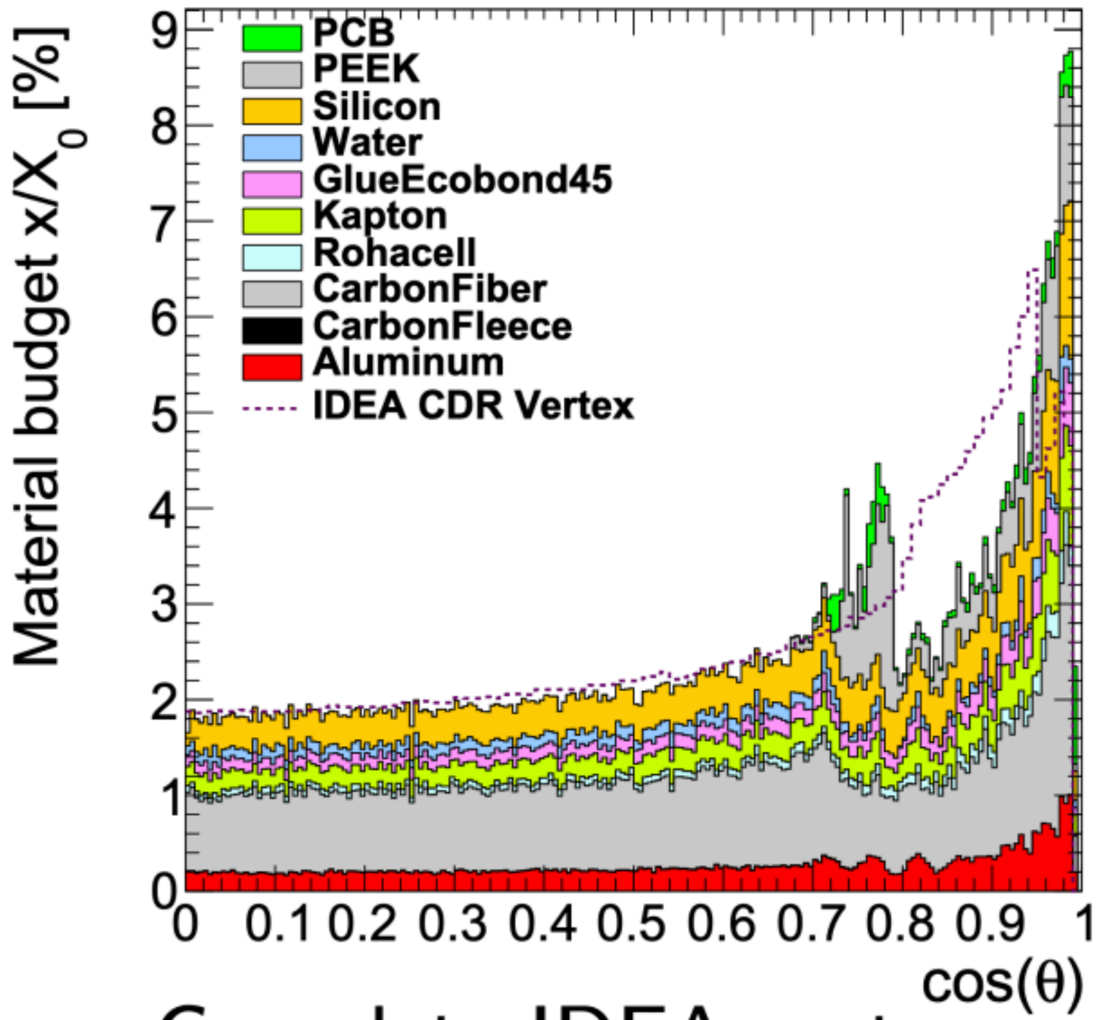
The IDEA vertex detector



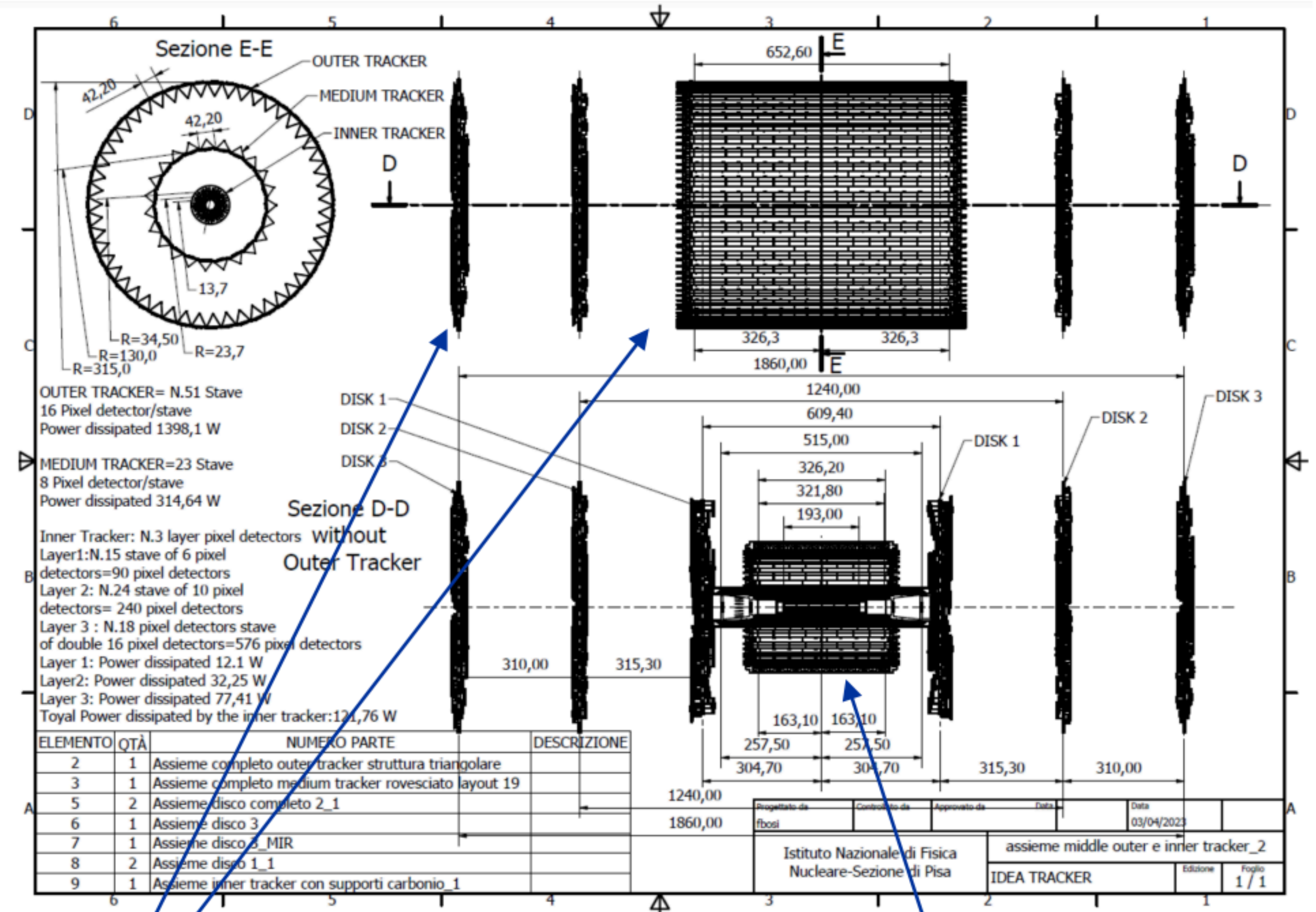
Complete vertex detector simulation



First vertex layer



Complete IDEA vertex



Outer vertex tracker

- intermediate layer at 13 cm radius
- outer layer at 31.5 cm radius
- 3 disks on each side

based on the ATLASPix3 sensors with modules of 50 x 150 μm^2 pixel size

Inner vertex tracker

- three layer at 13.7, 23.7 and 35.8 mm radius

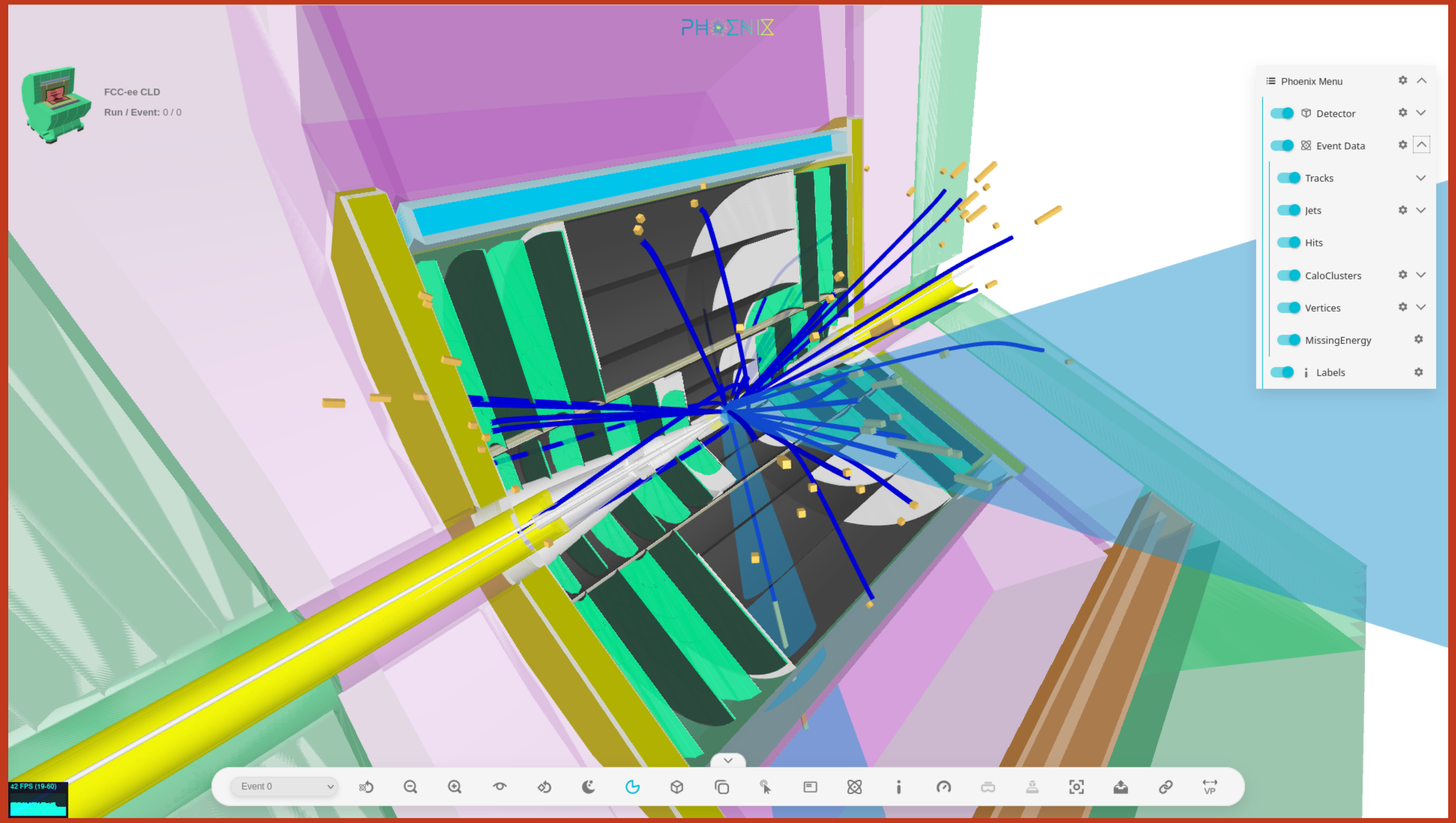
based on the ARCADIA sensors with modules of 25 x 25 μm^2 pixel size

Synergies: Common tools

- Nice sub-products of these collaborations already widely used

Key4HEP

A **common software framework** used for FCC, but also for many of the other future collider projects. Includes a common **event data model**, tools for easy and portable **detector geometry handling**, a consistent set of tags of **the most used HEP softwares**.



EUDAQ

A **common data acquisition software**, often used in conjunction with **common hardware** for beam monitor (EUDET), and data quality tools