FCC - Detectors

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Università di Bologna

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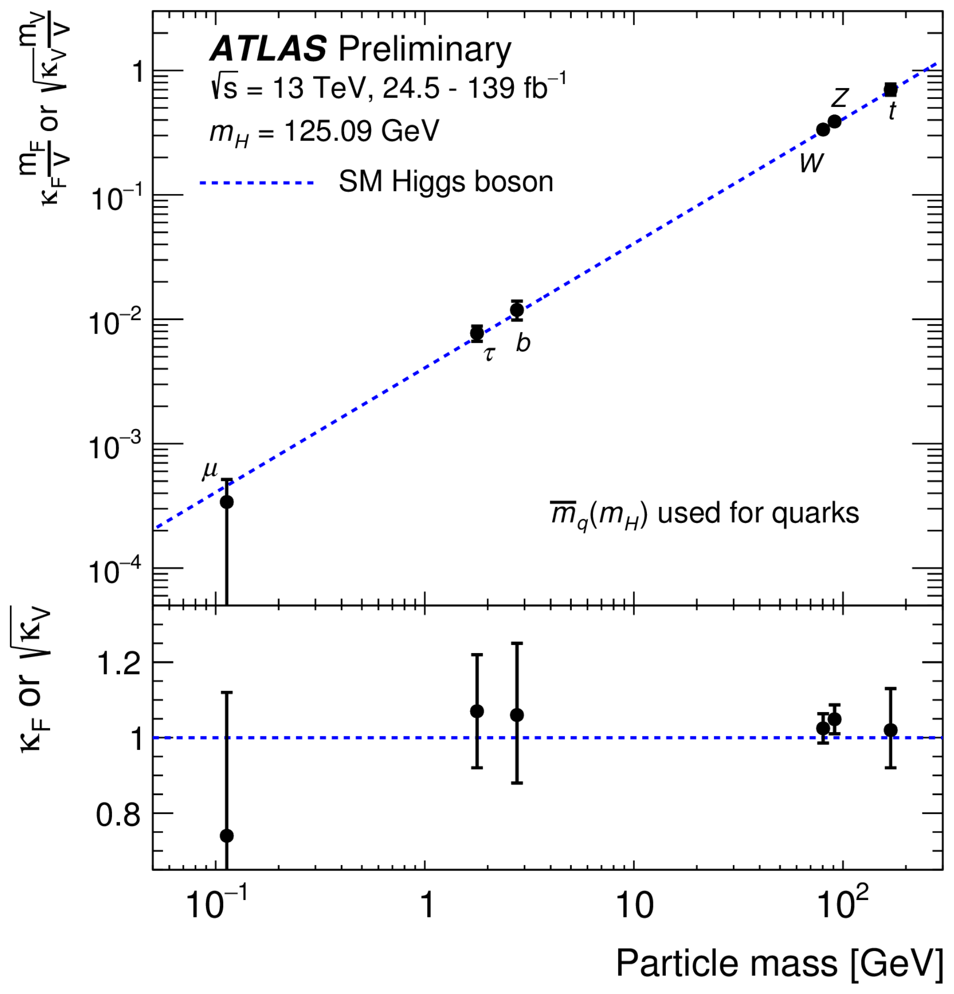
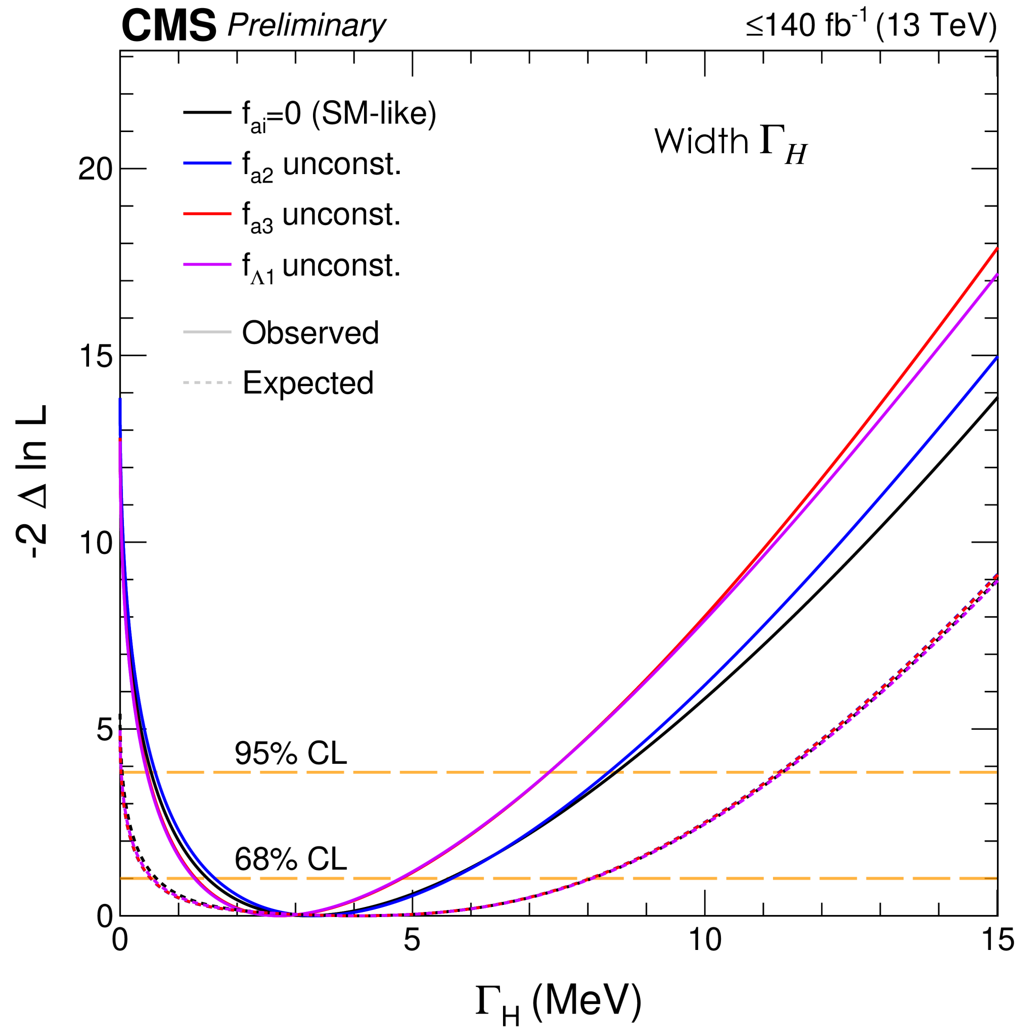
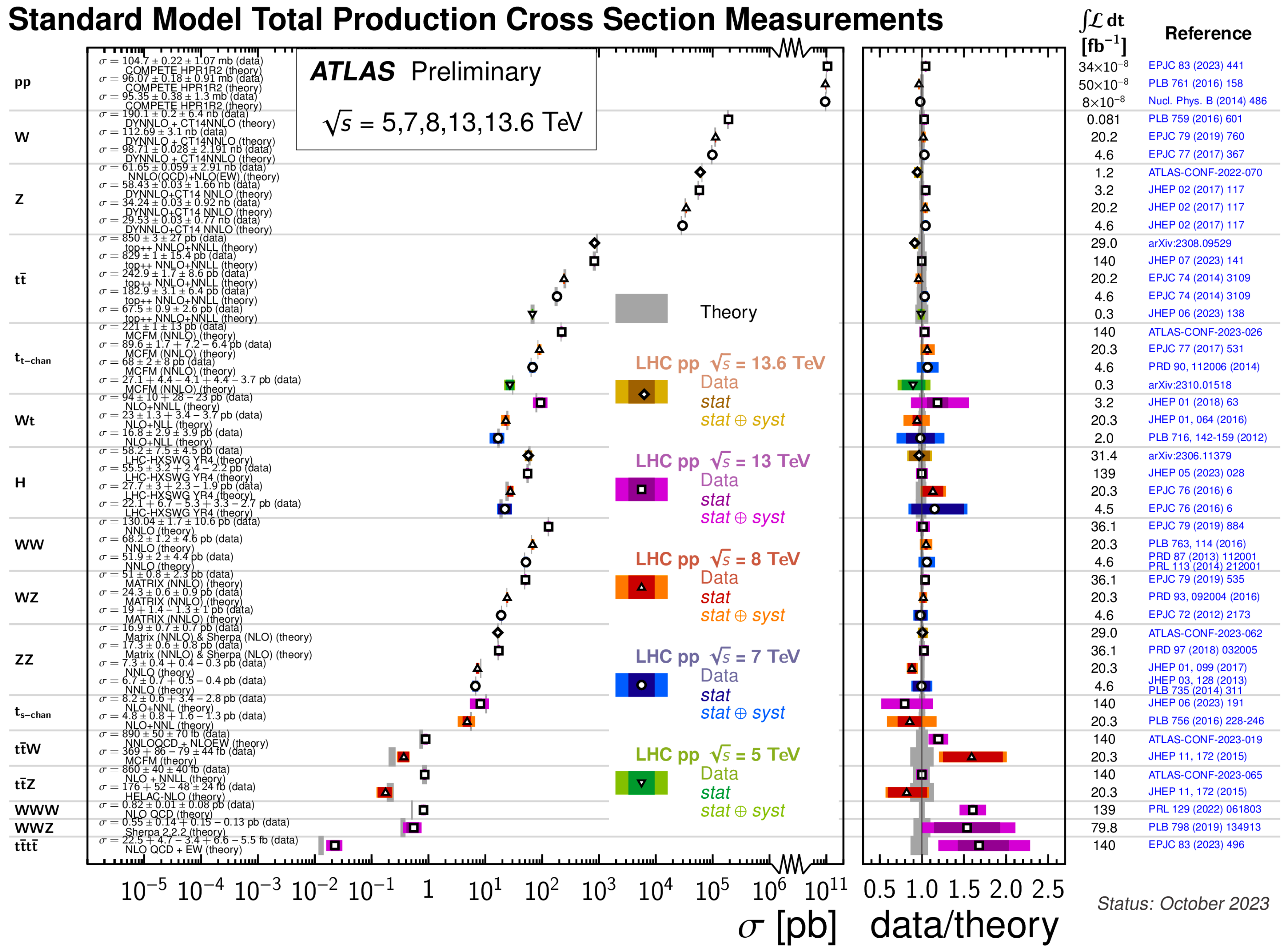
The physics we have

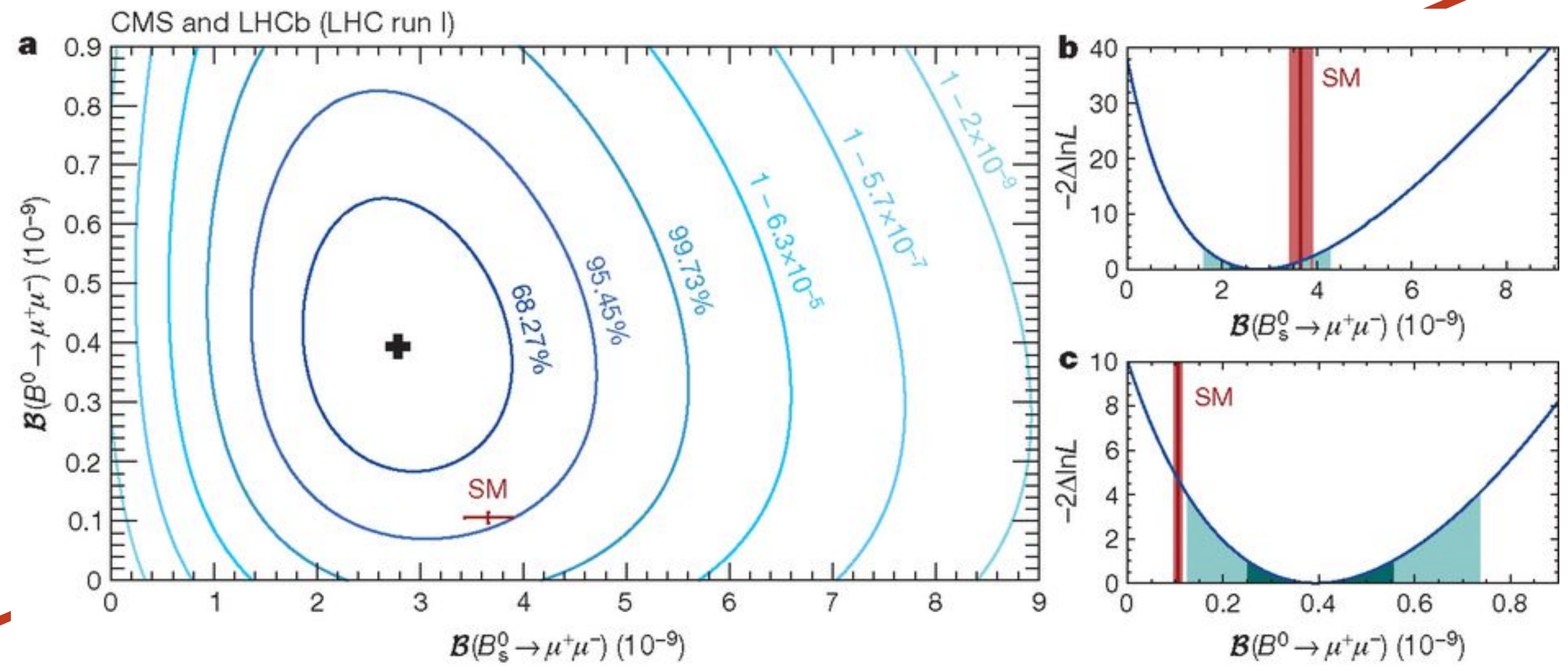
- The take-home message from the LHC so far: **this universe is very SM-like.**



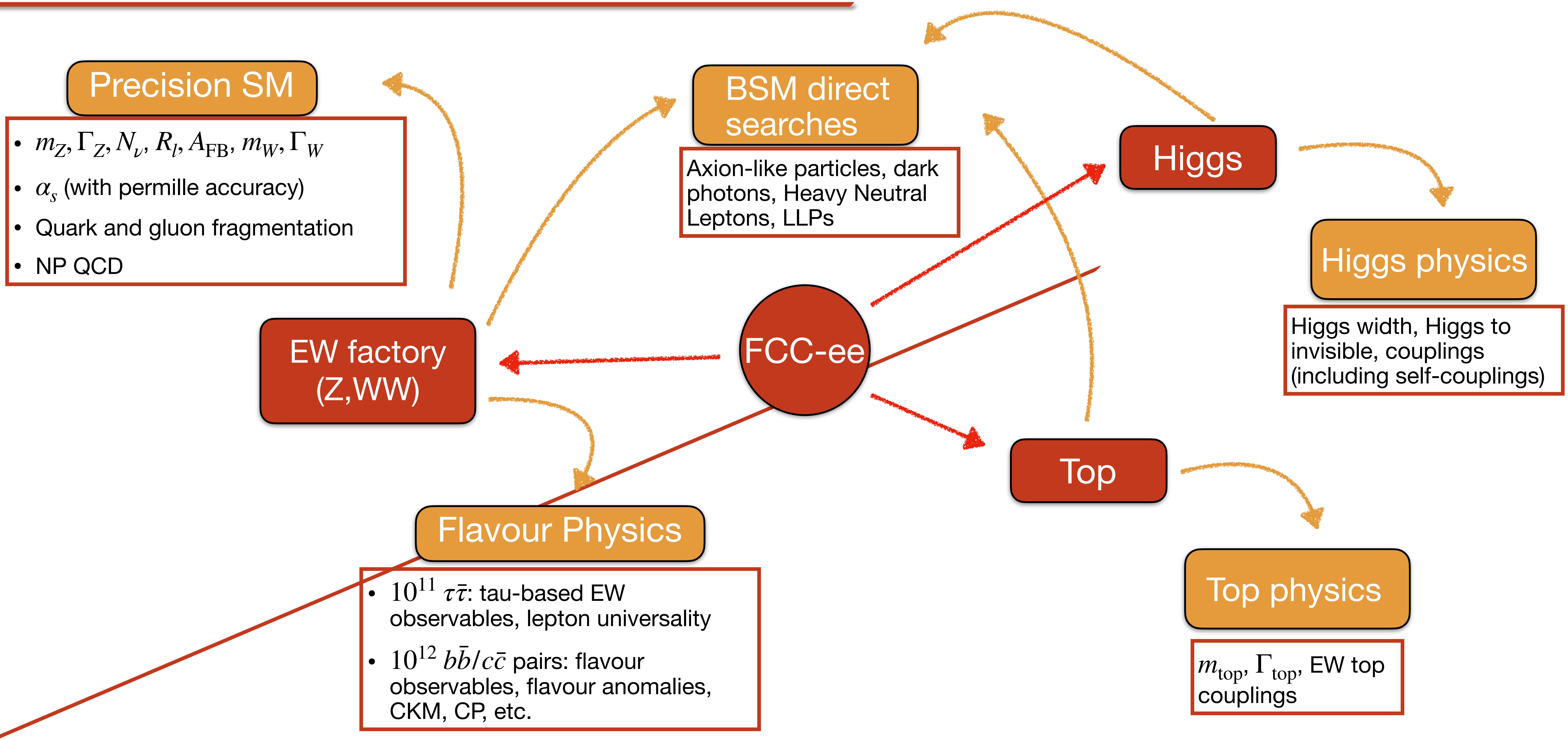


No significant deviation from SM with 140 fb^{-1} of pp collisions (not promising for BSM at HL-LHC)





The physics we need



Original idea/slide from C. Grojean

FCC-ee in pills

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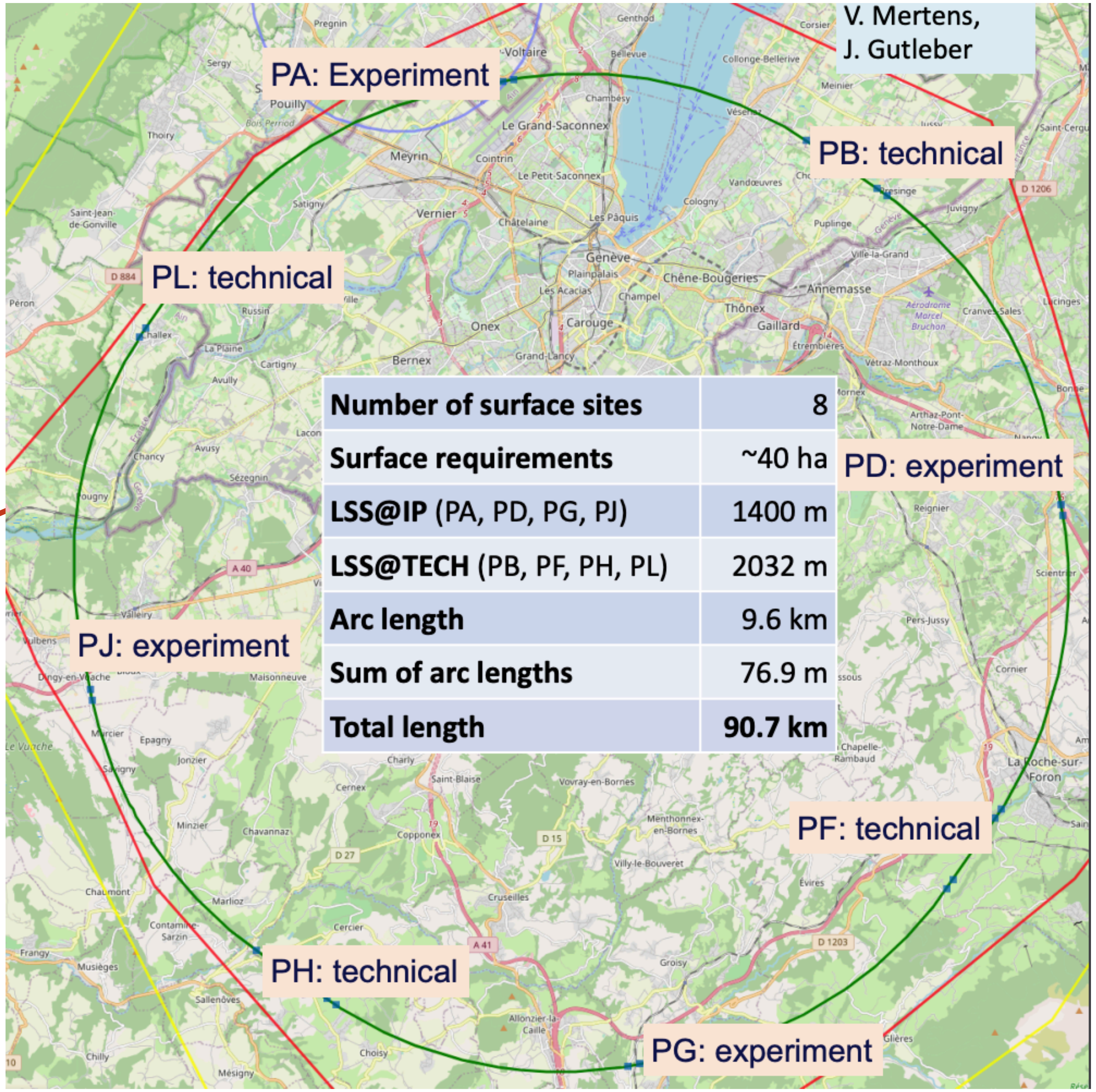
	Z pole	WW pole	ZH pole	Top pair pole
Beam energy (GeV)	45.6	80	120	182.5
Beam current (mA)	1270	137	26.7	4.9
Number of bunches	11200	1780	440	60
Luminosity (per IP - 10^{34} cm^{-2} s^{-1})	140	20	5	1.25
Integrated luminosity (per IP - ab^{-1}/year)	17	2.4	0.6	0.15
Planned running time (years)	4	2	3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

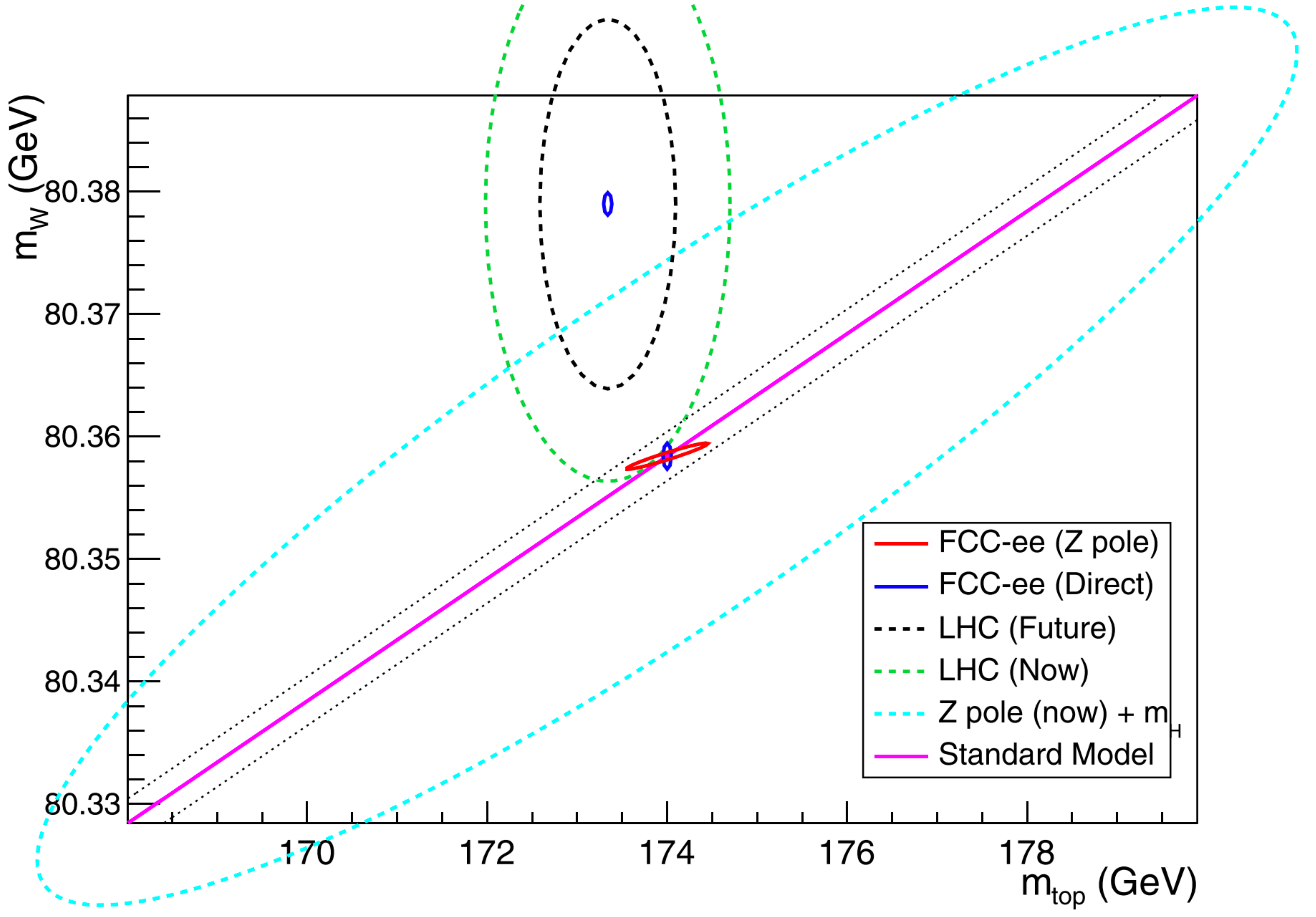
Which translates in

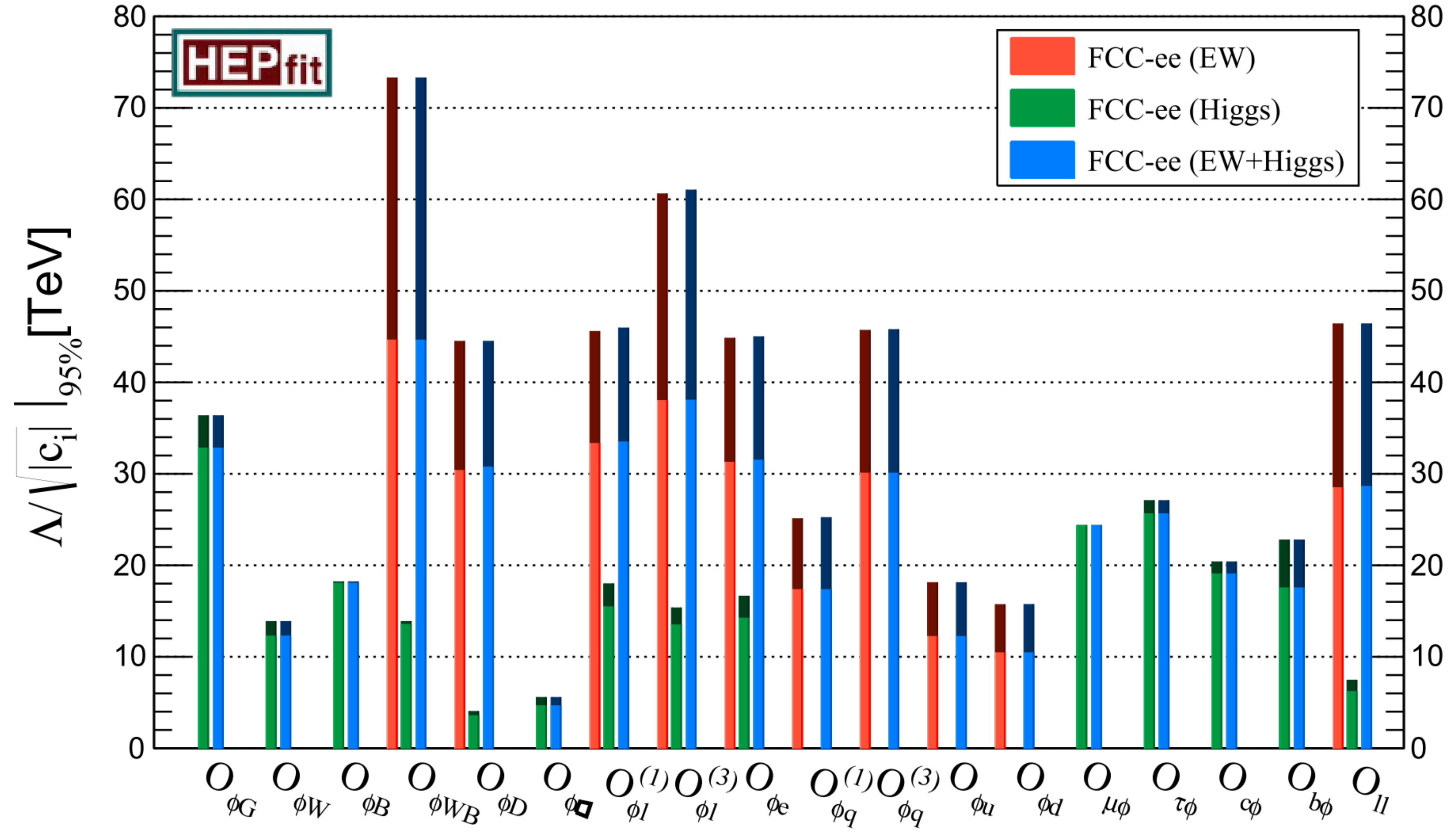
- 5×10^{12} Z (LEP $\times 10^5$)
- $\sim 10^8$ WW (LEP $\times 10^4$)
- 2×10^6 H unprecedented at e^+e^-
- 2×10^6 $t\bar{t}$ unprecedented at e^+e^-



The physics we need

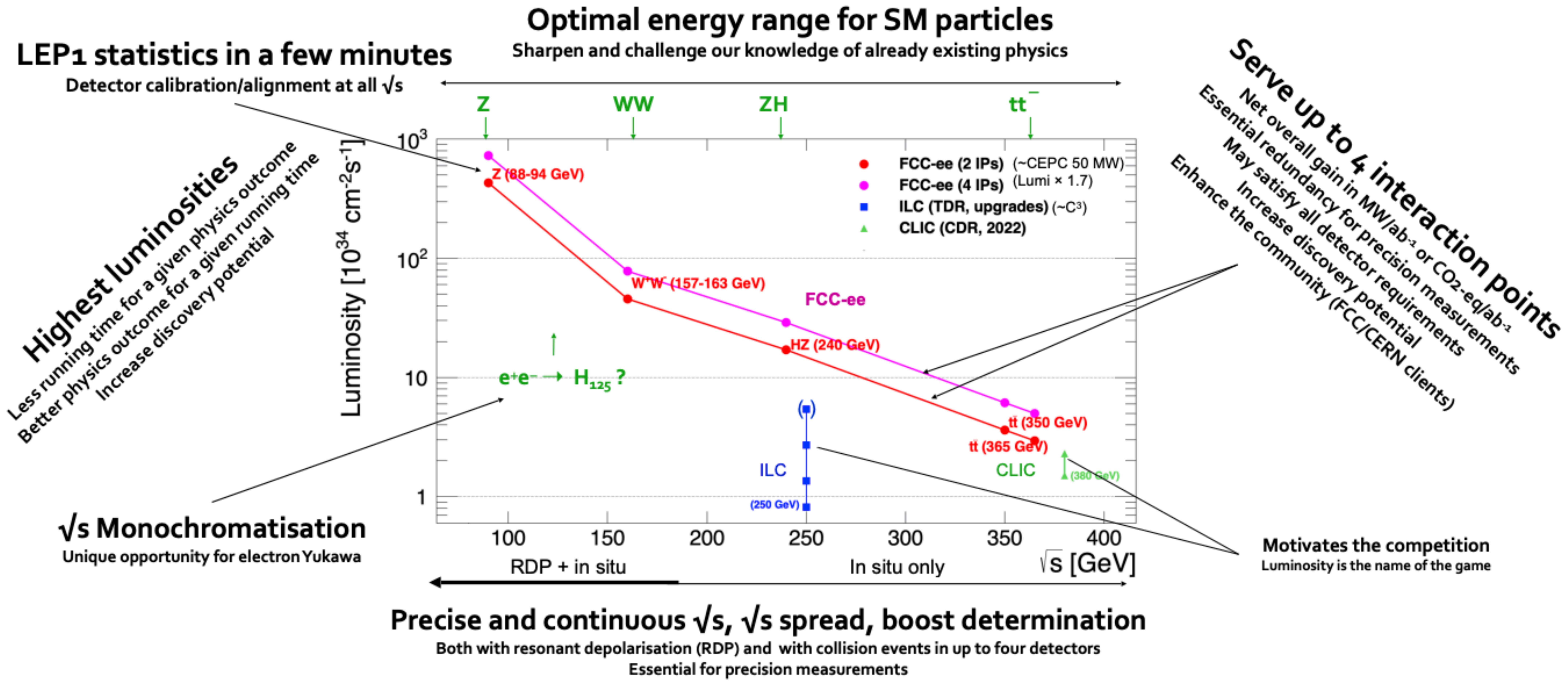
- The **whole physics programme** (not just the "Higgs factory") makes the difference
  - $\sin^2\theta_W^{\mathrm{eff}}$, mainly from $A_{\mathrm{FB}}^{\mu\mu}$.
  - m_W and width to $o(1\ \mathrm{MeV})$.
  - m_{top} and width at $o(10 - 50\ \mathrm{MeV})$.
  - Auxiliary measurements ($\alpha_{\mathrm{QED}}(m_Z^2)$, Z boson mass and width, $\alpha_S^2(m_Z^2)$).
  - Model-independent Γ_H, Higgs couplings and Higgs to invisible.
  - BSM models (ALPs, dark photon, light dark matter, ….).





Taken from FCC-ee CDR

A little bit of advertisement

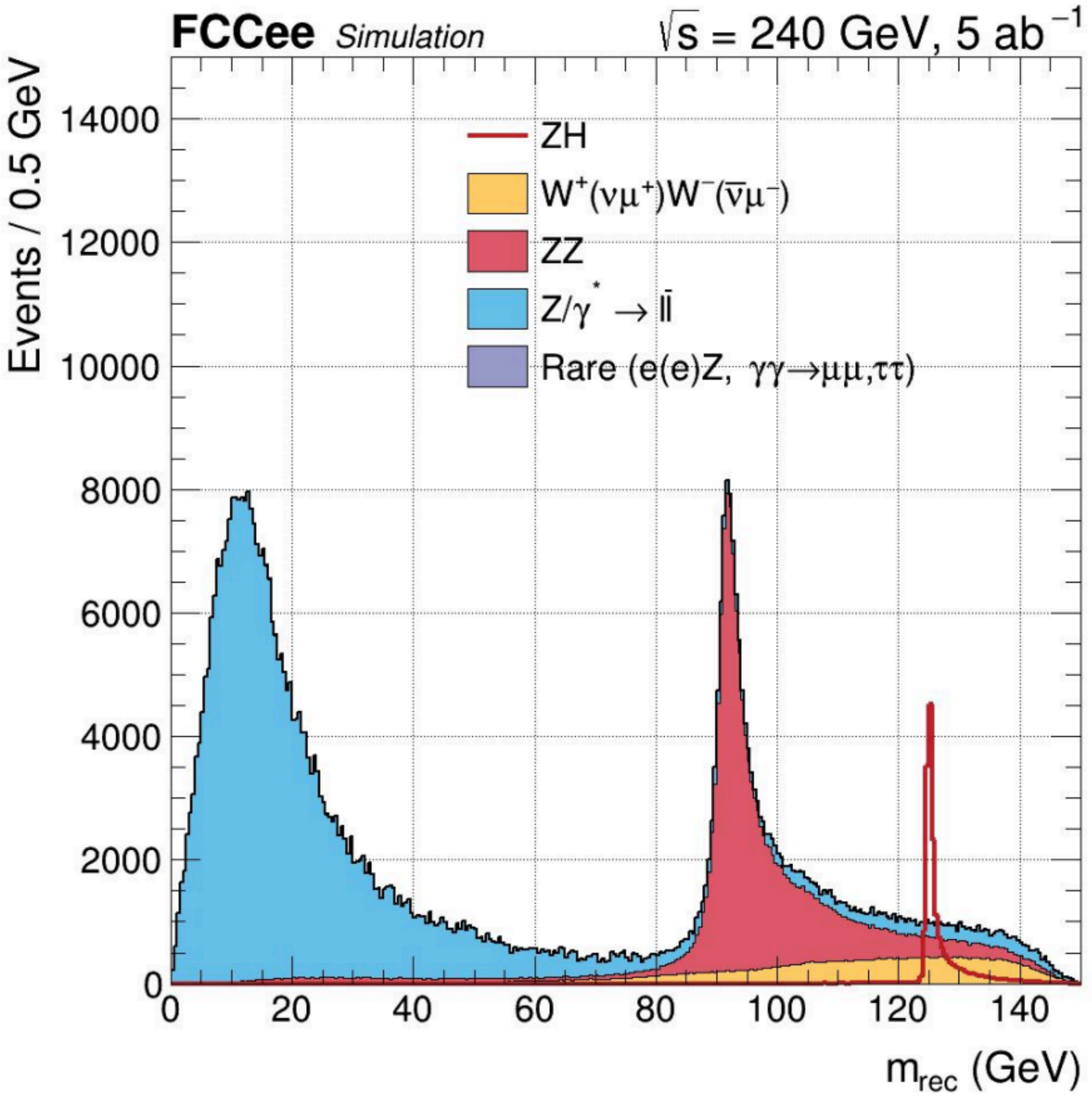


The physics we need

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.

	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	$\sigma_{r\phi} \sim 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}[\mu\text{m}]$	Additional case study: B→K*ττ
$H \to gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{jet})}{E_{jet}} \sim 4\,\%$ (at $E_{jet} \sim 50$ 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



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

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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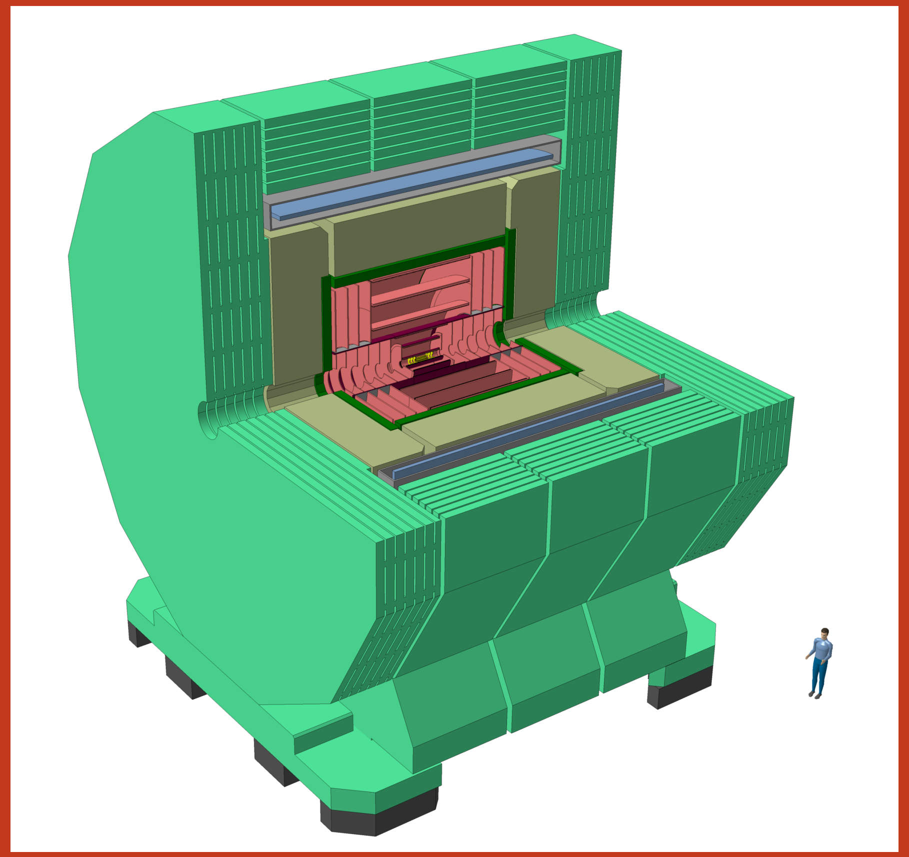
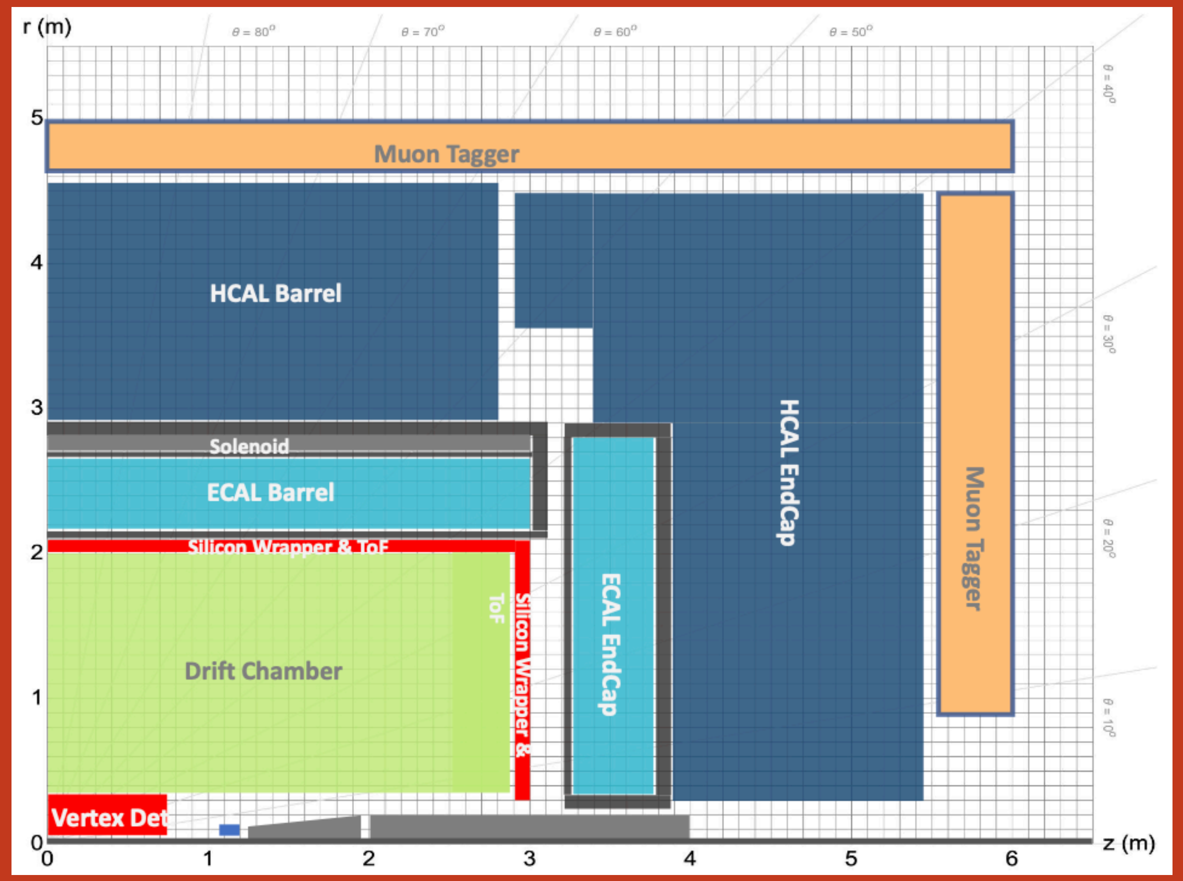
CLD (CLIC-like Detector)



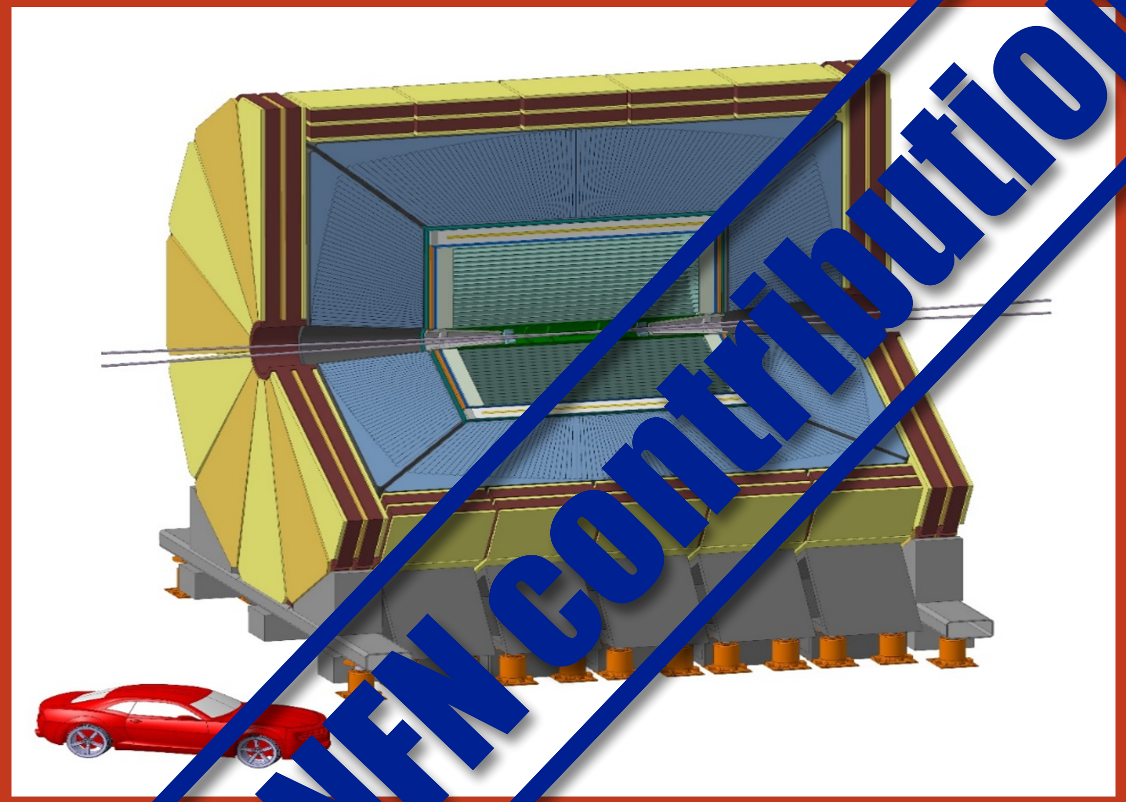
2 T solenoid **outside calo**
Full silicon tracker
SiW high-granularity EM Calo
Sci-steel high-granularity HAD Calo
RPC-based Muon detector

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

IDEA (Innovative Detector for e+e- Accelerators)



Large INFN contribution

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

Not discussed further in this talk

- 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.

Vertex detectors

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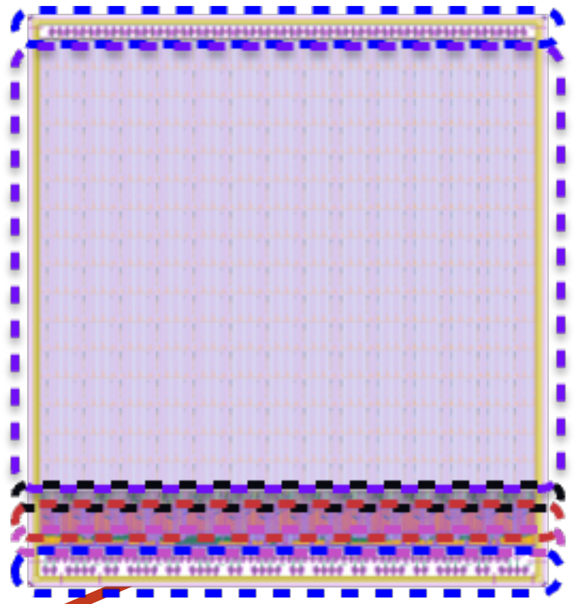
General requirements

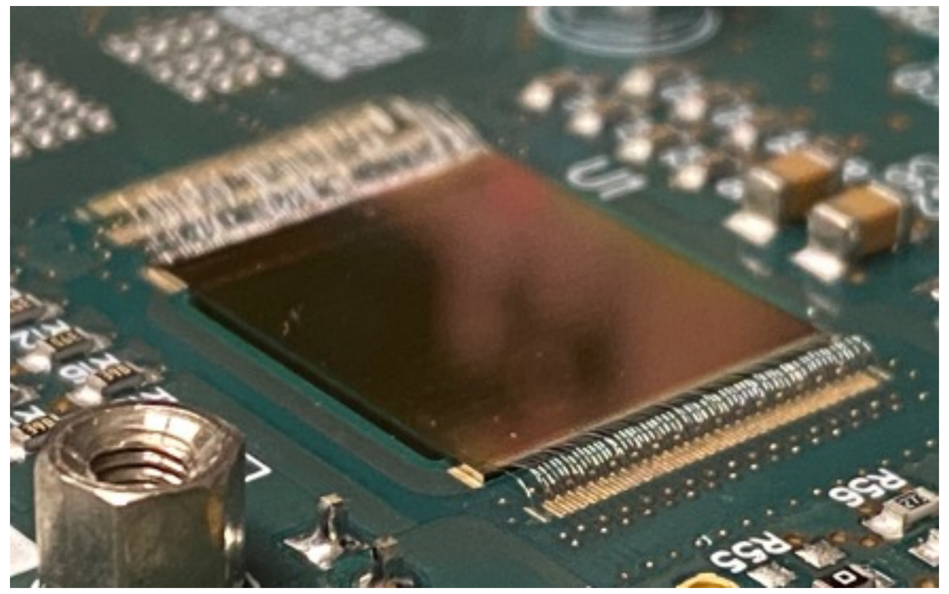
Flavour physics and tagging requires 3-5 μm → pixel size ~15 μm.
Small material budget (0.1% of X_0/layer) → Thickness ~ 50 μm.
Low power consumption (especially inner layers) → 10-30 mW/cm^2.

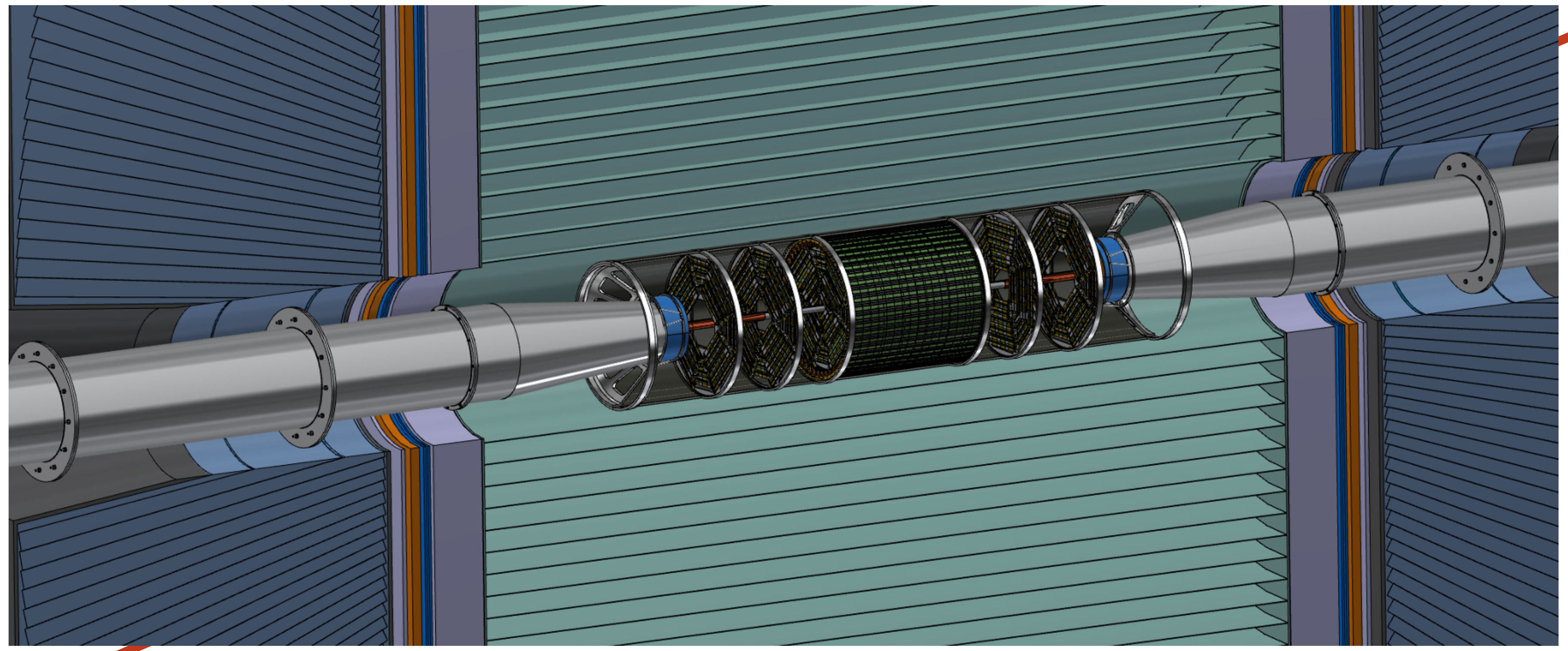
Solution: CMOS MAPS

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

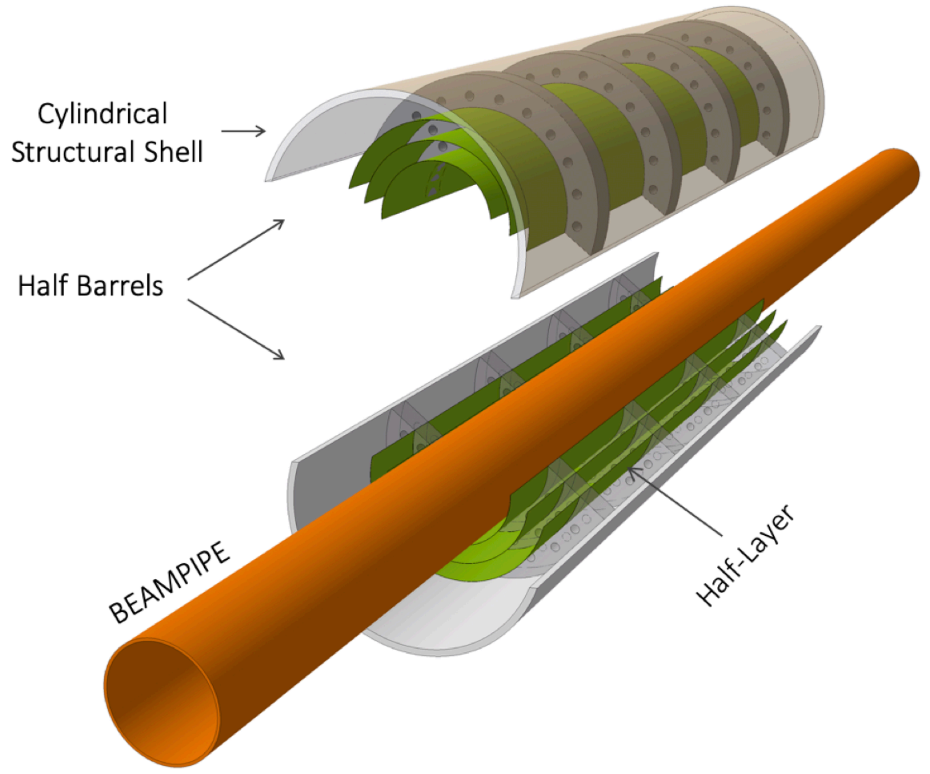






The IDEA design (see G. Gaudio's talk)

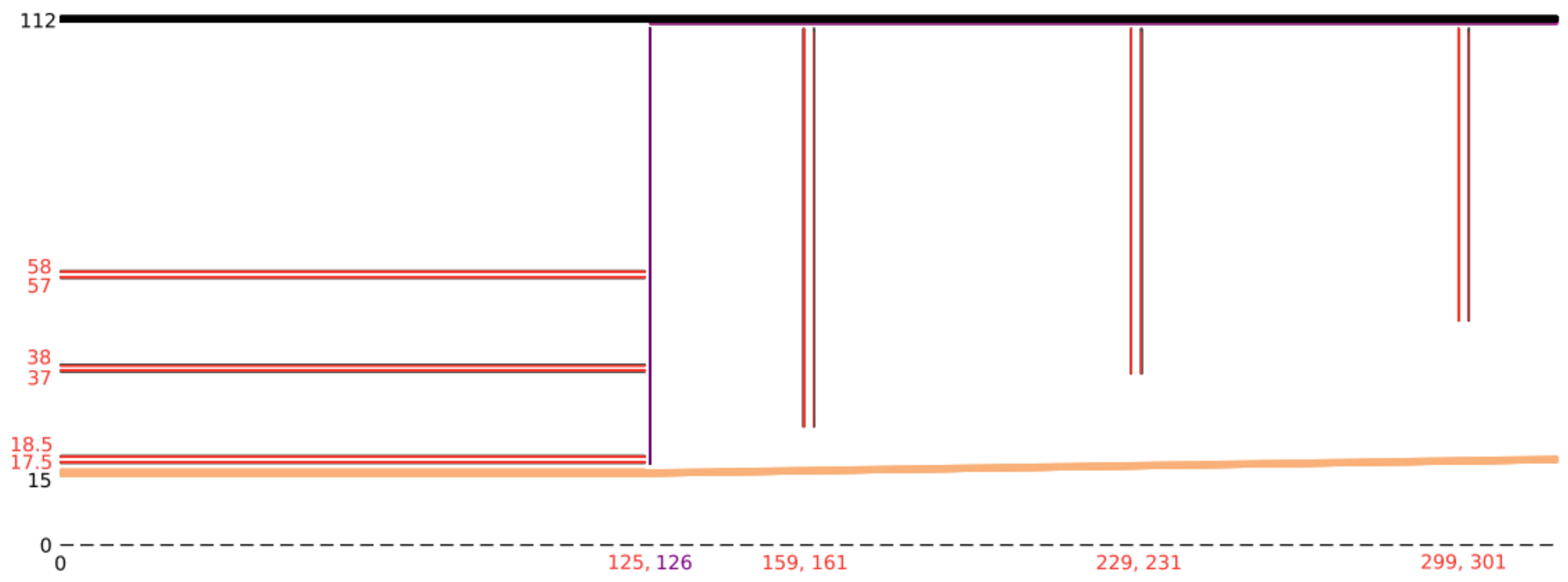
Bent silicon sensors (ALICE ITS3 R&D)

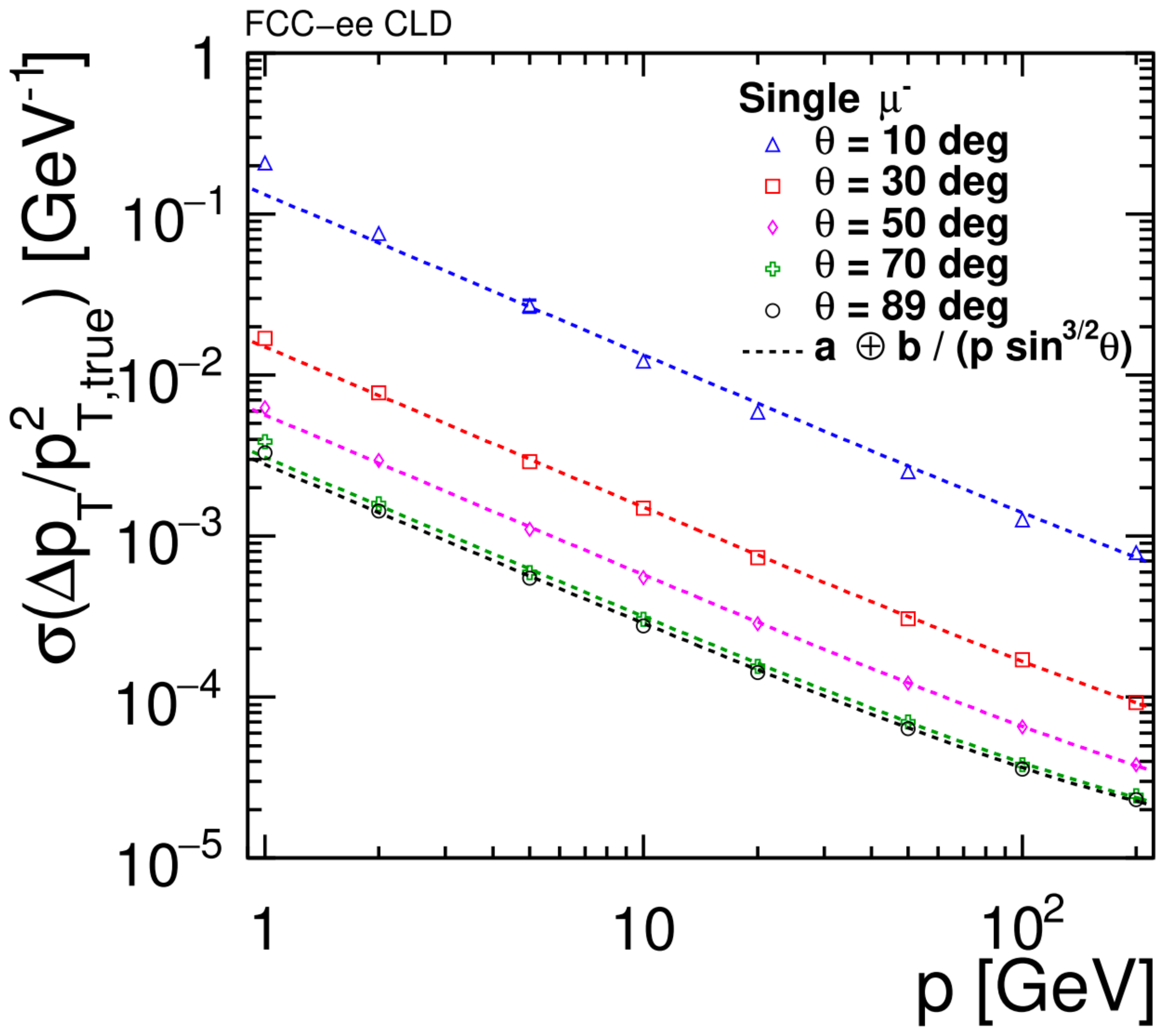


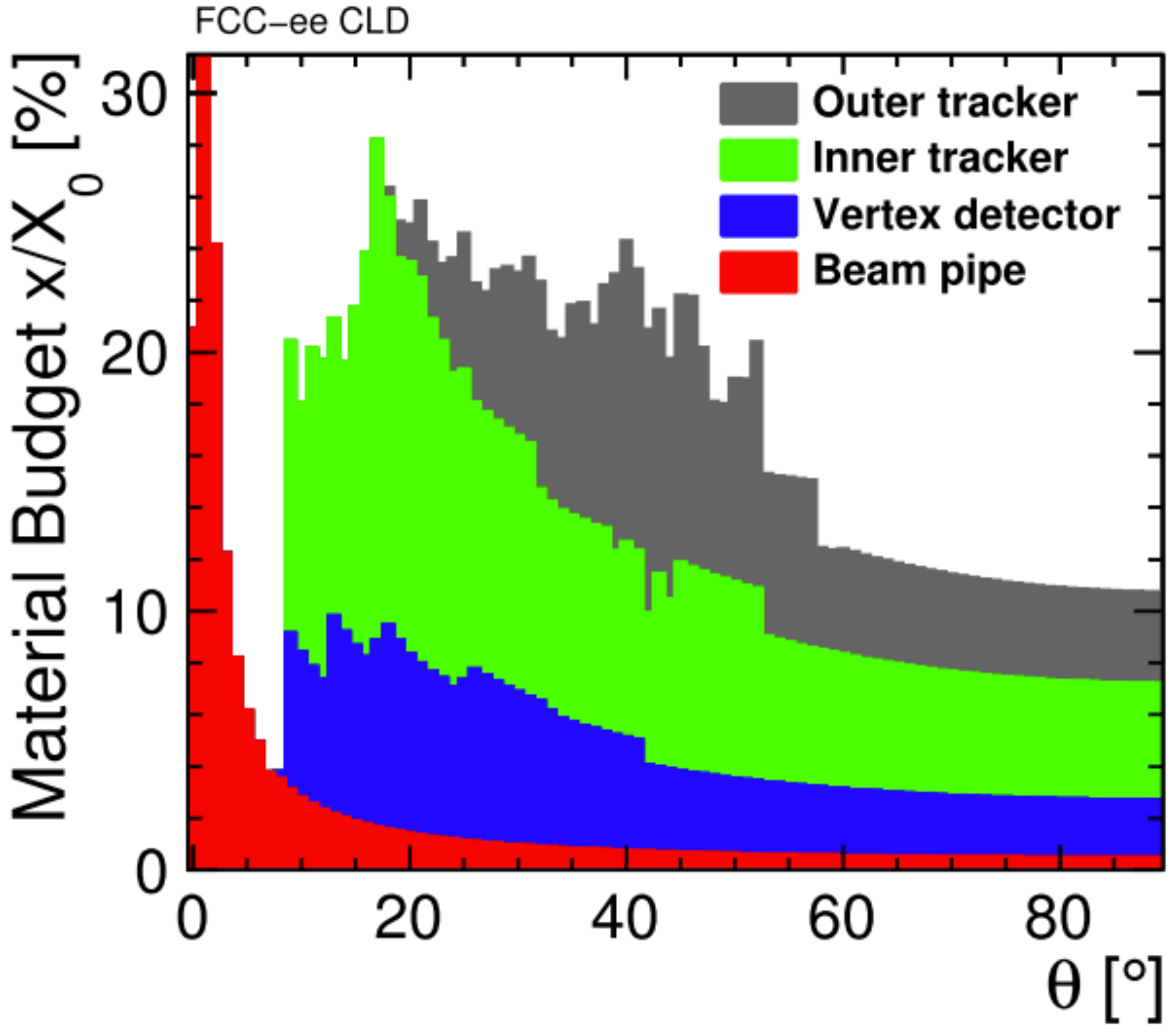
All-silicon tracking - the CLD approach

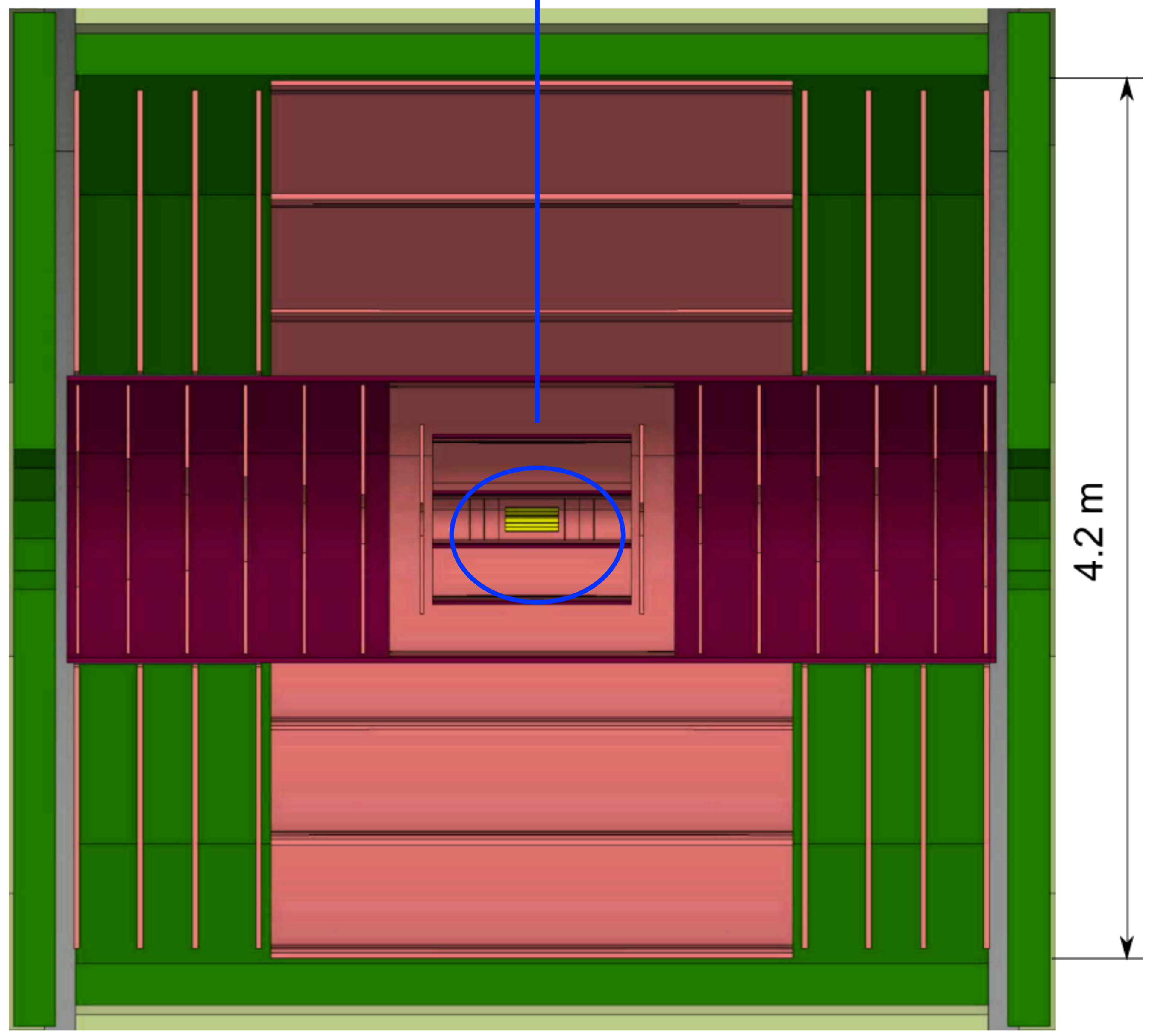
VTX:
- Pixel size 25x25 μm² - 50 μm sensor thickness - aiming at 3 μm resolution.
- Material and cooling benchmarked on ALICE ITS (LS2) upgrade design.
- Power dissipation: 40 mW/cm² - water cooled.

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

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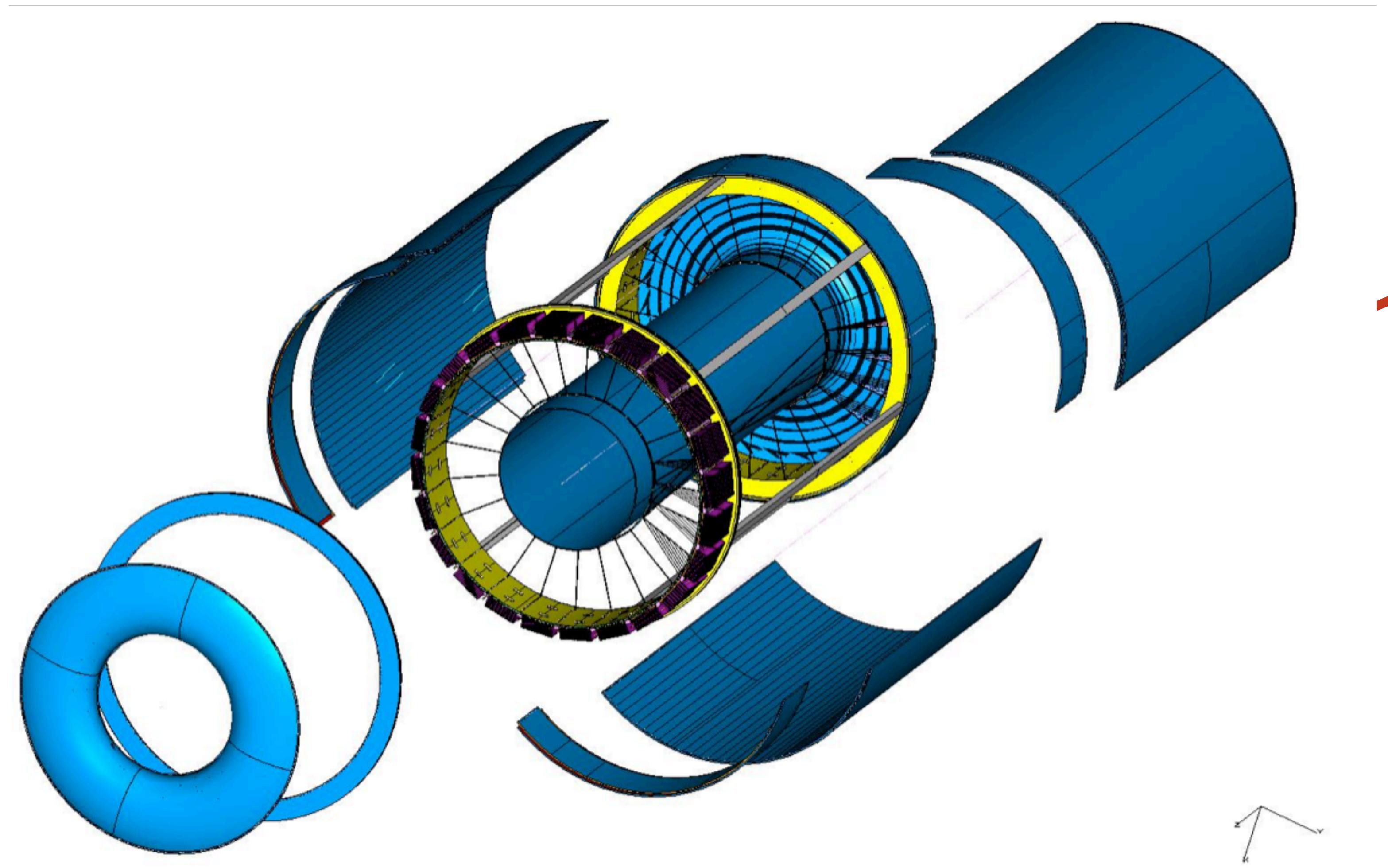
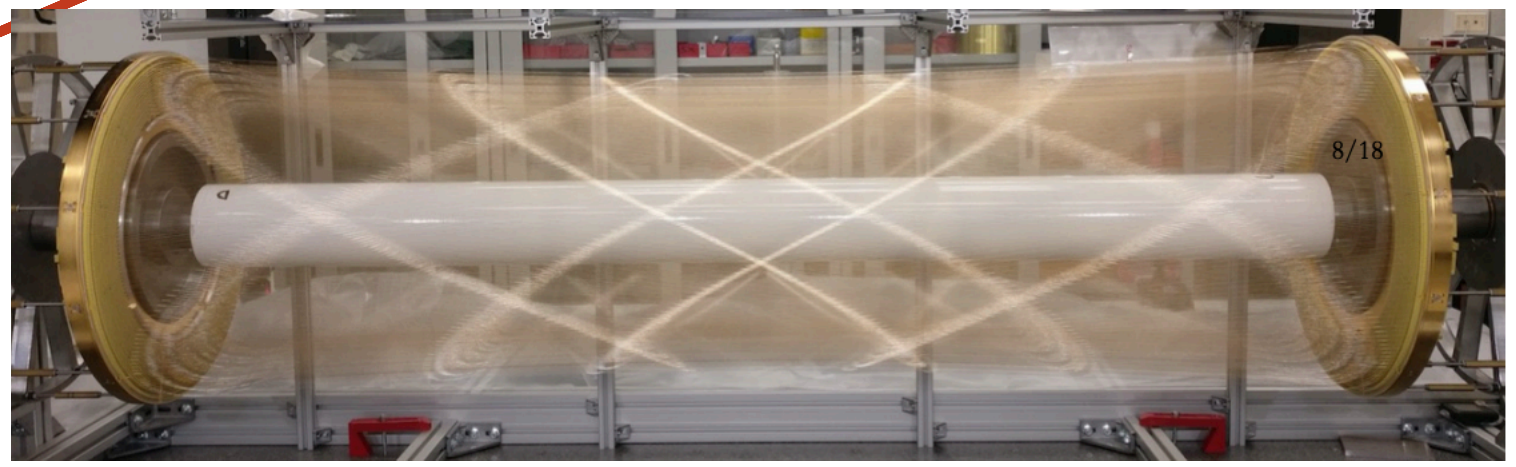
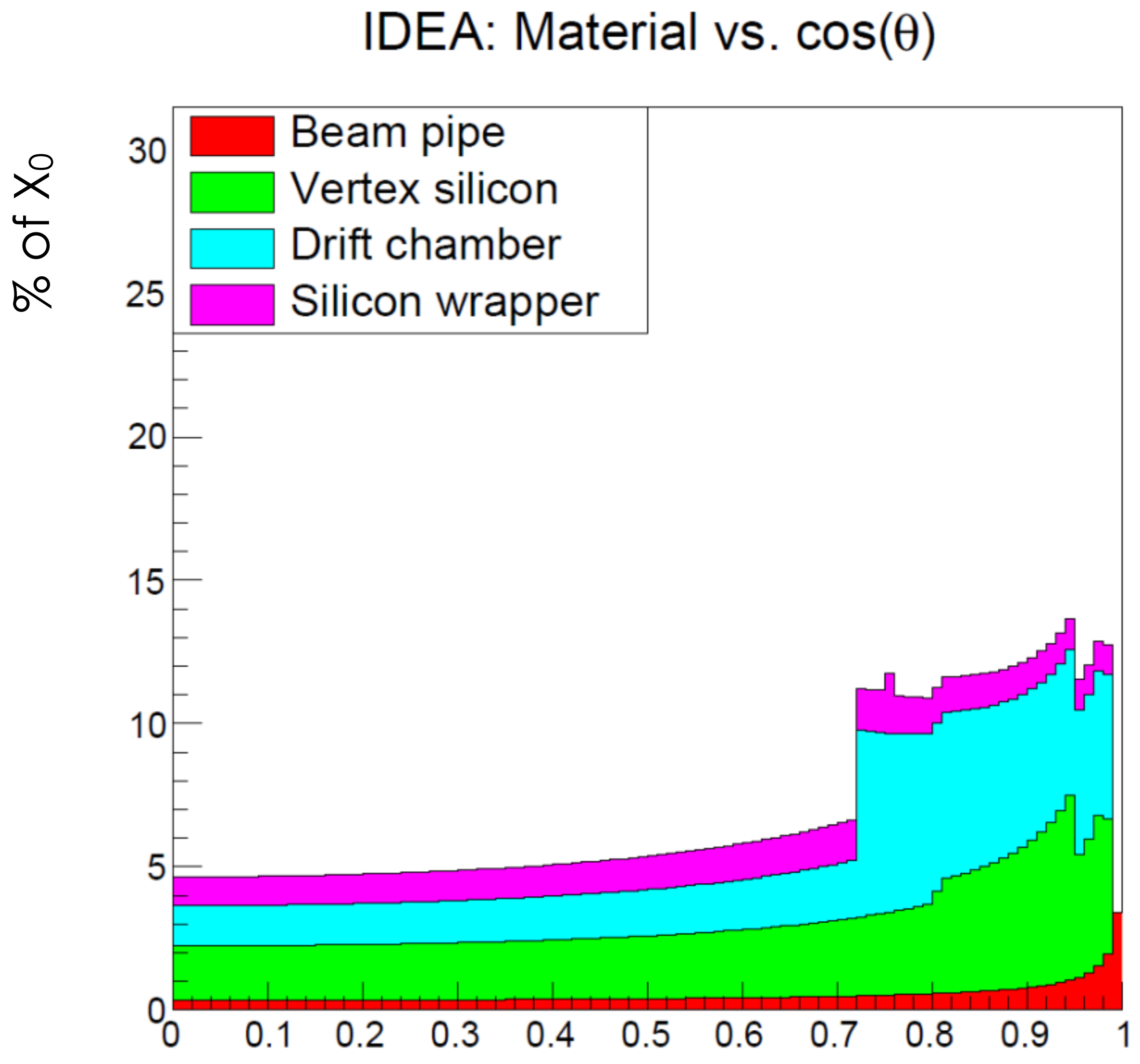
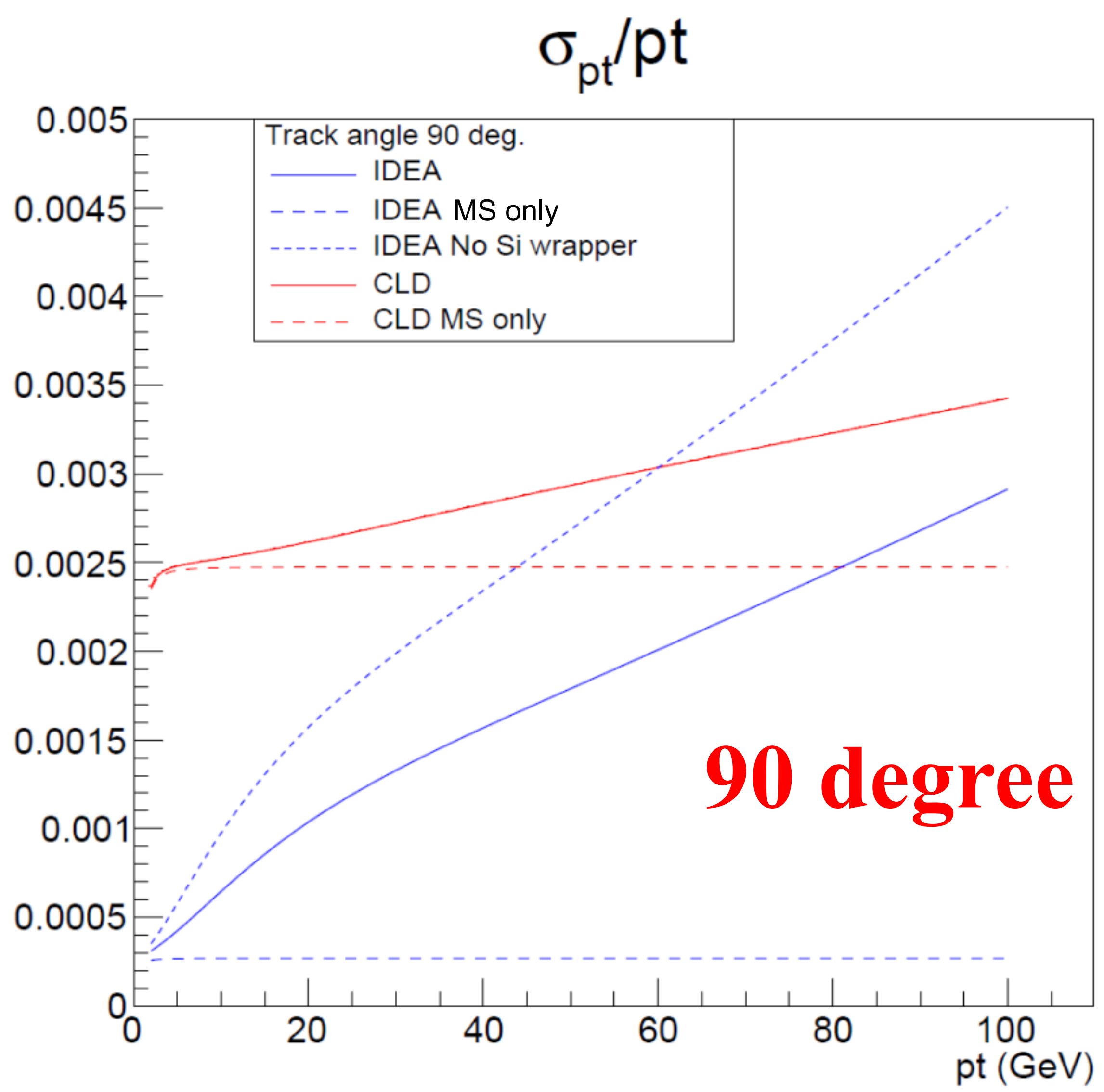
ALLEGRO: VTX similar to CLD

- Tracking with **drift chamber** (As in IDEA - similar in concept to MEG II chamber).
- Minimising multiple scattering, adding **only 2%** X_0 to material in front of calorimeter.
- Drift time o(300 ns).
- Cluster counting (12.5 cm^{-1} clusters) **improves spacial resolution and dE/dx measurement.**
- Single point precision (with cluster counting) better than ~ 100 μm. Many points on each track.





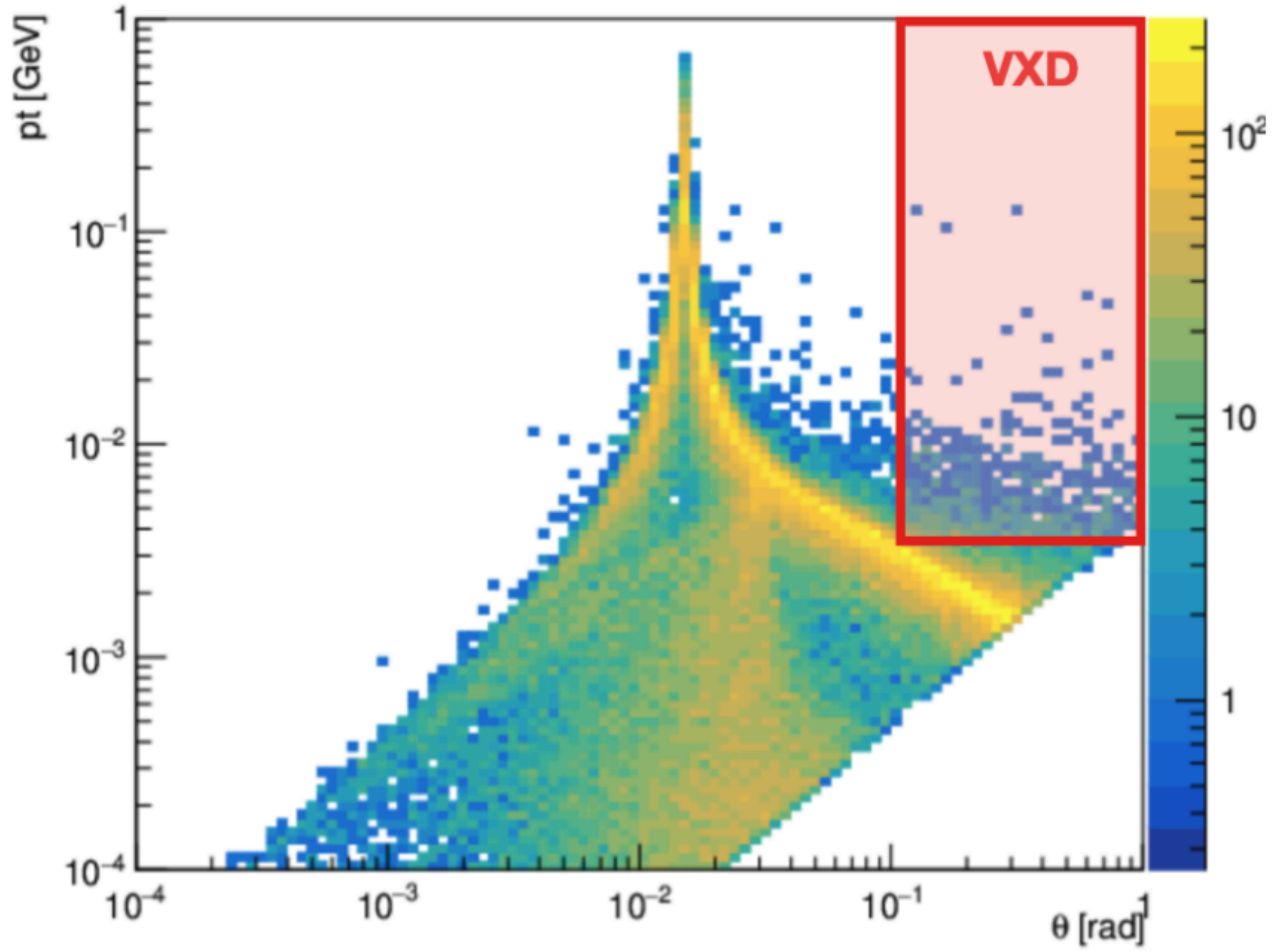


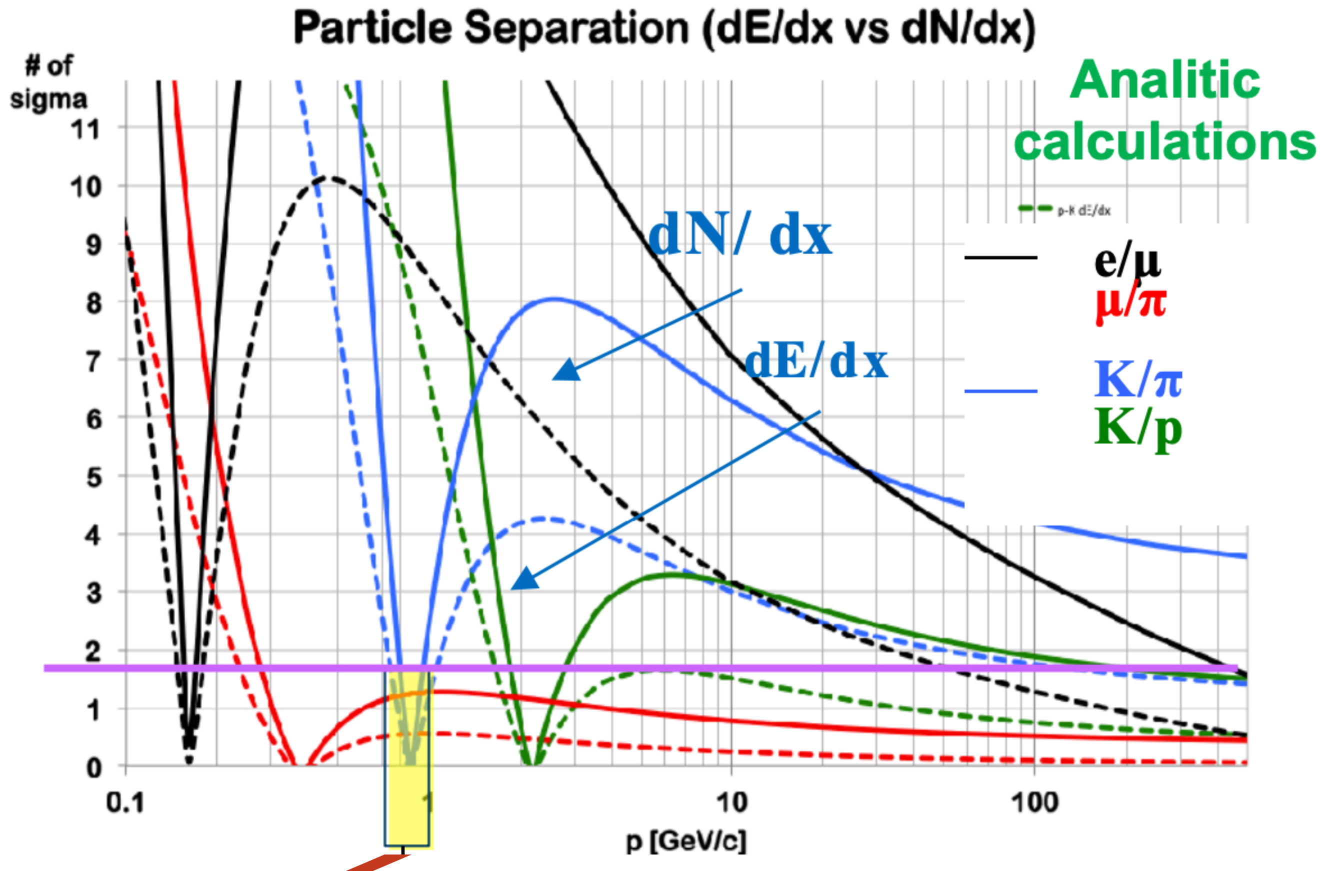


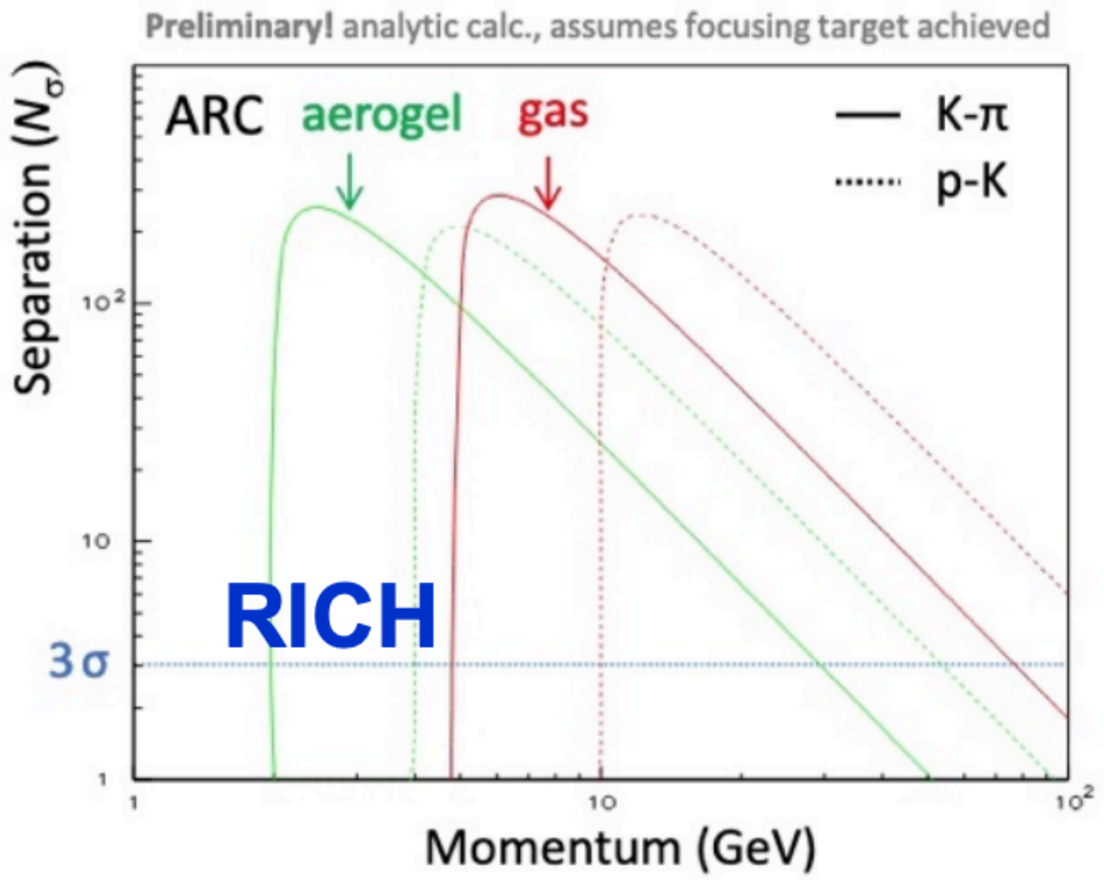
Challenges

- 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.

Particle-flow oriented calorimeters

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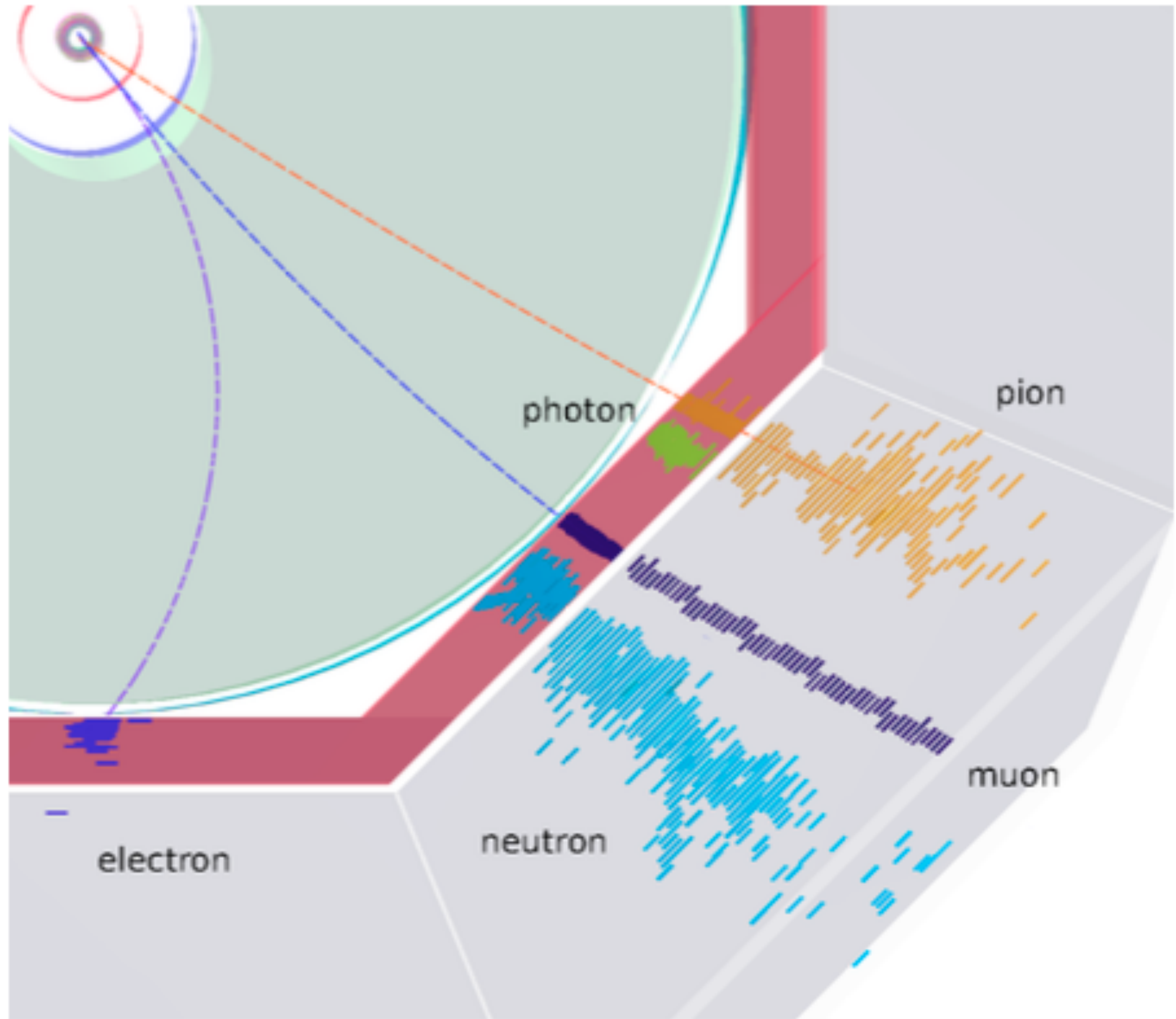
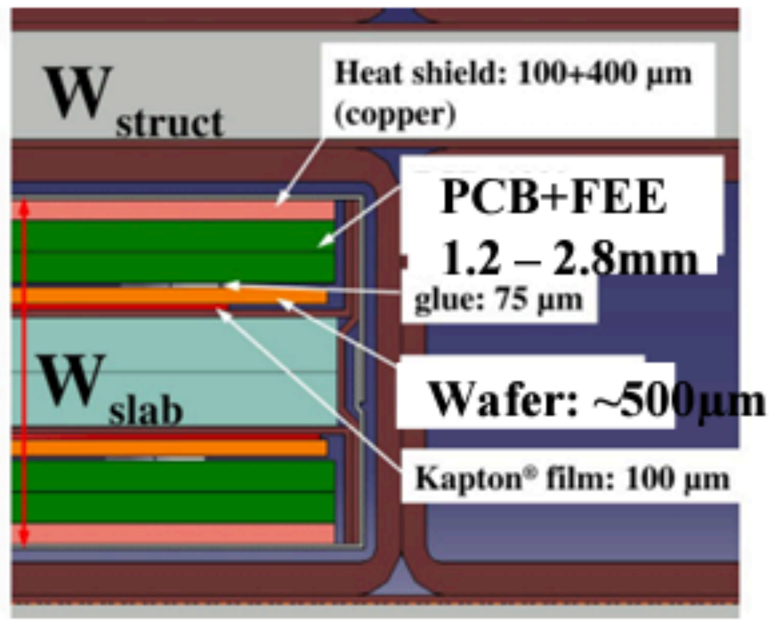
- Basic idea: for charged particles, measure their contribution to jets by **using tracker rather than calorimeter**.
- Requirements: High granularity - compactness (small Moliere radius).
- Drawbacks: confusion term (when the calorimeter subtraction goes wrong - produces tails in jet energy distributions).
- Studied in detail for linear colliders.

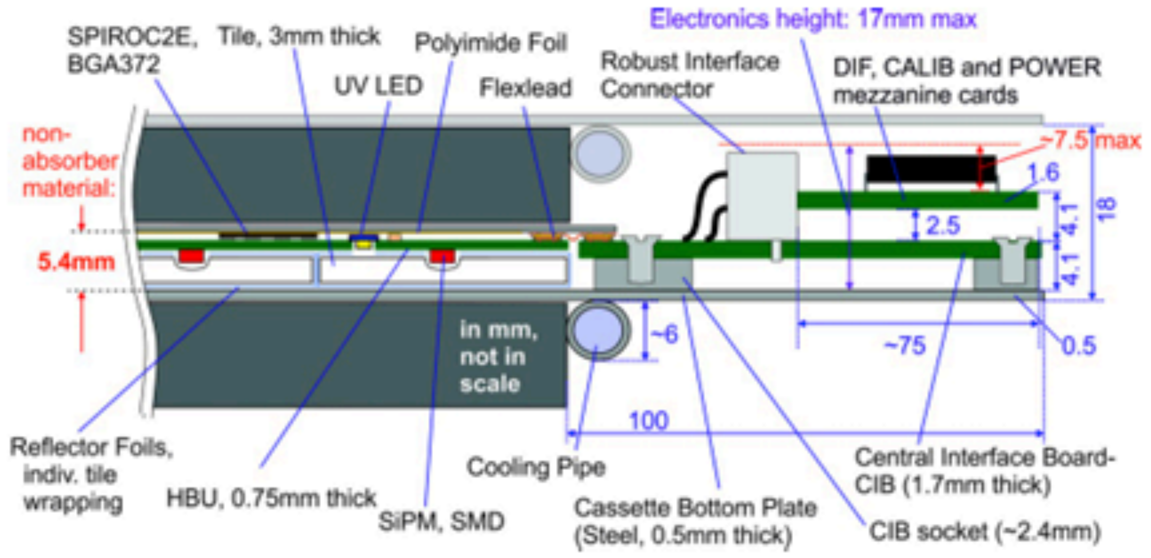


SiW ECAL



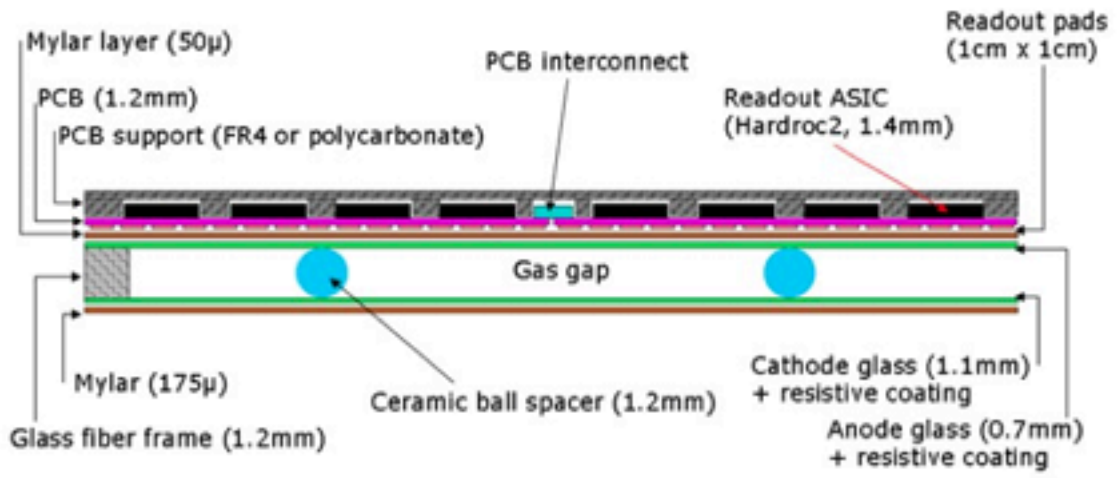
Active area: silicon PiN Diodes
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



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

Semi Digital HCAL



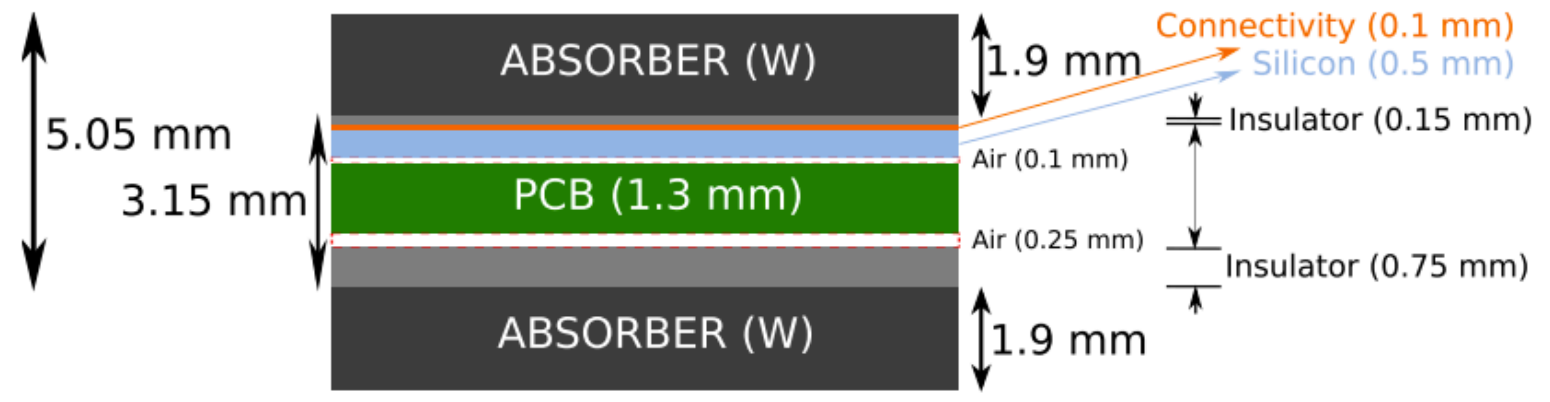
Gas RPCs
Typical segmentation: 1x1cm^2

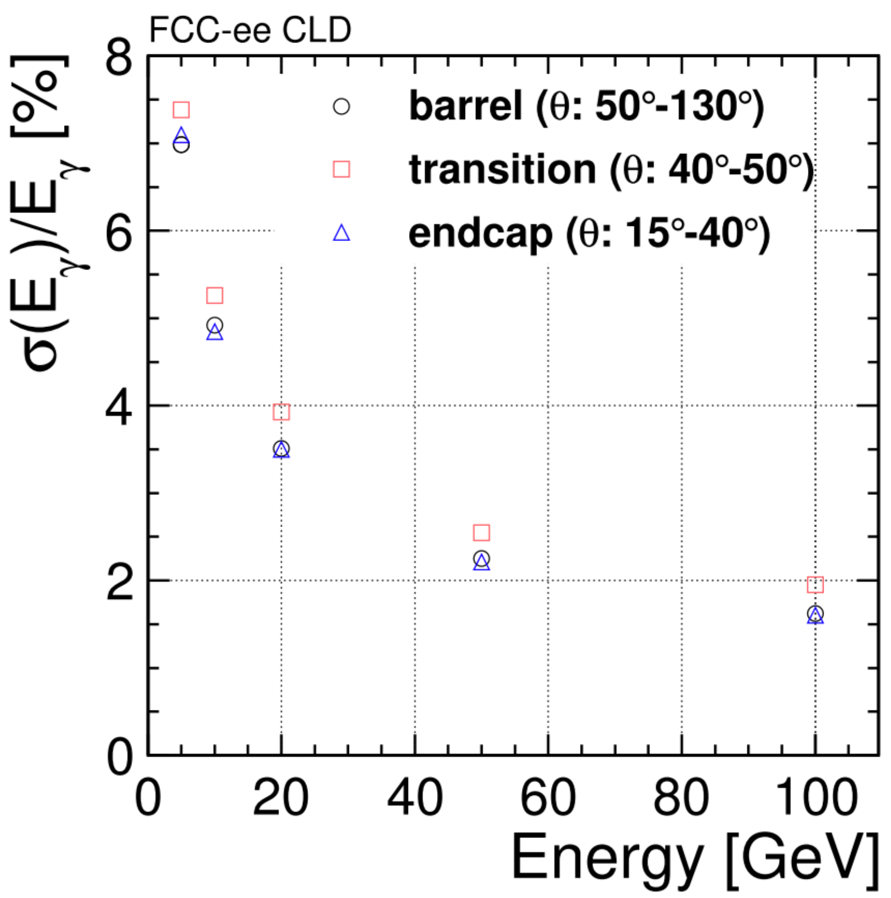
Challenges:
- Cooling despite challenging environment (no power pulsing possible)
- Timing for particle flow?
- AI-boosted particle flow?

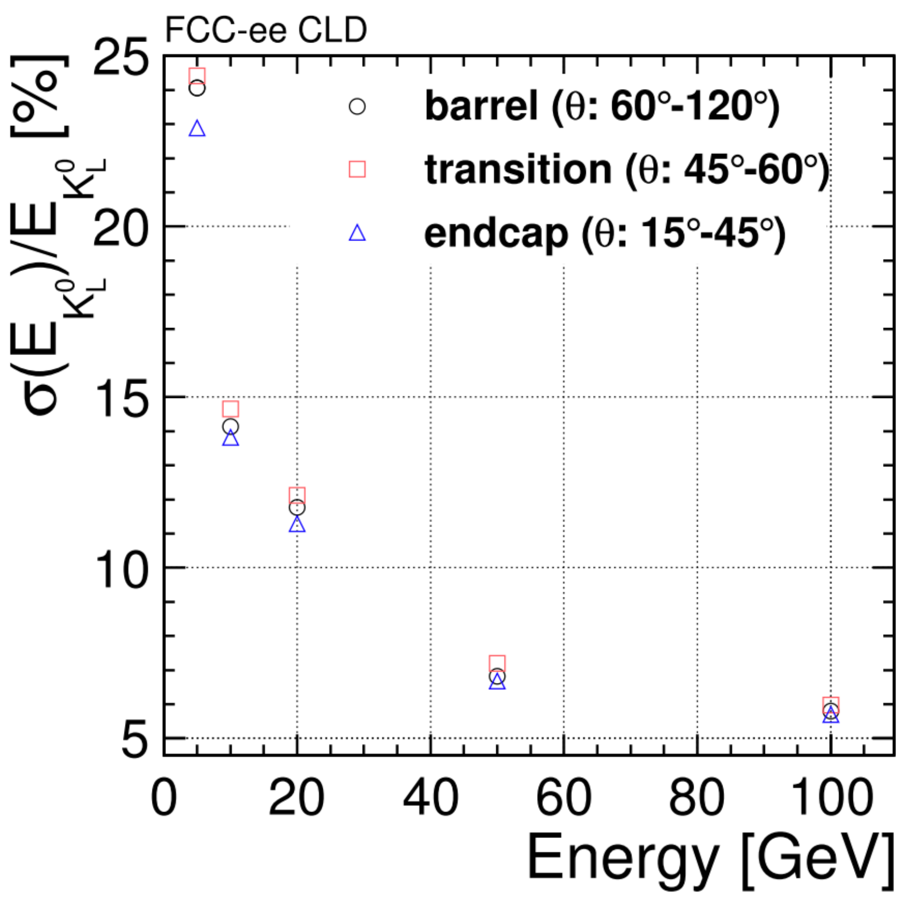
Calorimeters (CLD)

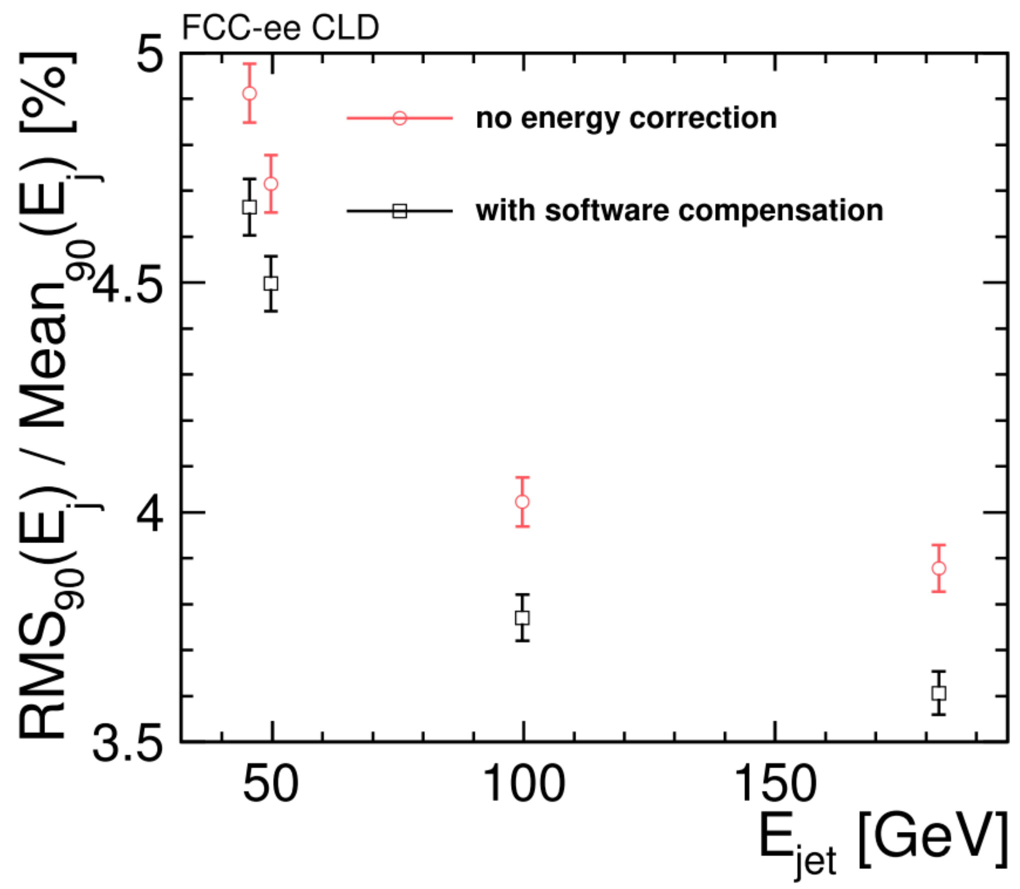
- CLD paradigm: calorimeter **optimised for particle flow** (emphasis on **granularity** rather than **quality of the energy measurement**)

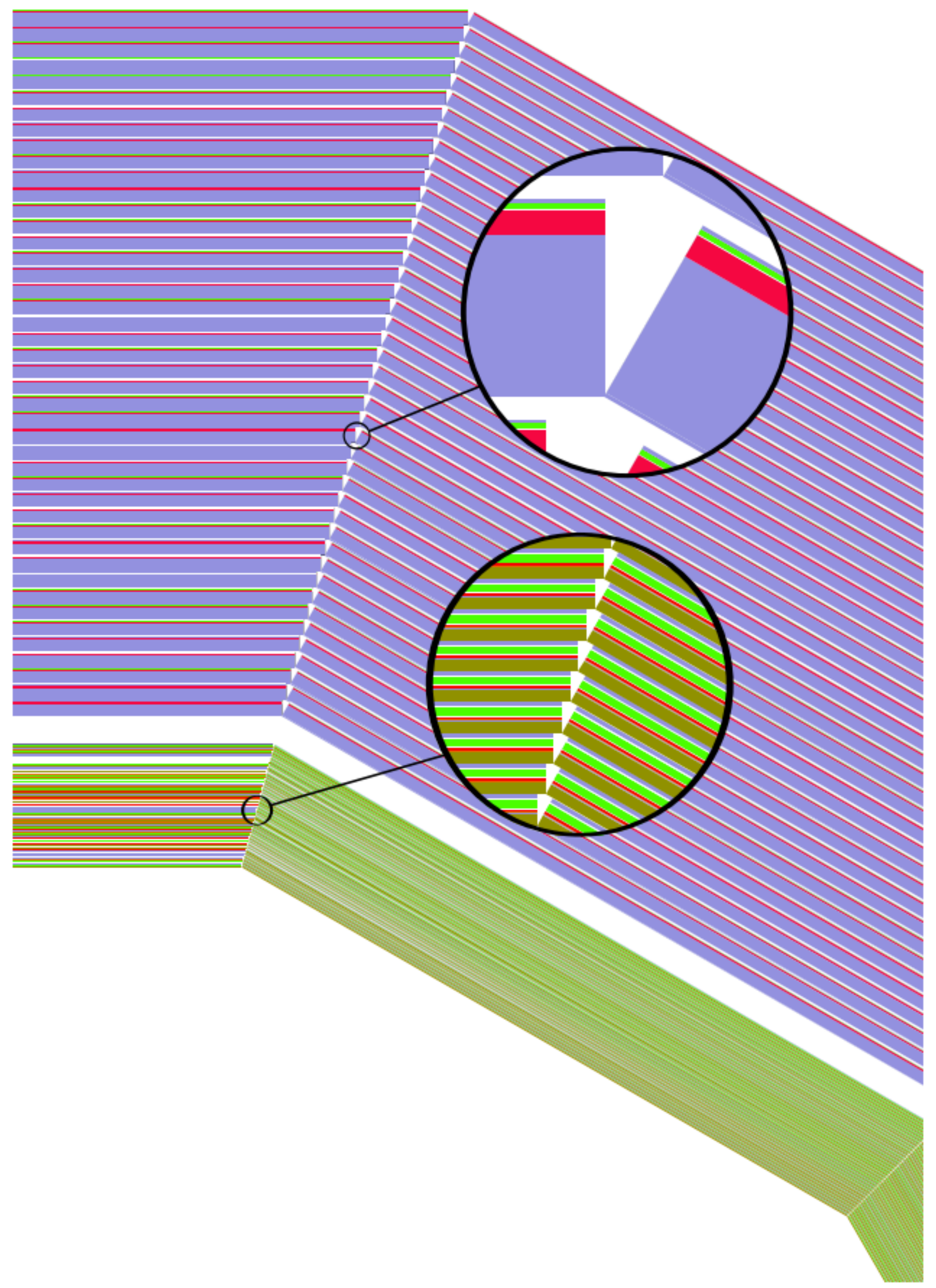
ECAL (CDR numbers - See here for optimisation studies):
  Cell size 5x5 mm^2 with Si-W.
  40 layers - 5.05 mm thickness each.
  Total 20 cm, 22 X_0, ~ 1 λ_I.
  No power pulsing - cooling is an issue - part of the optimisation process.
HCAL:
  Cell size 30x30 mm^2 scintillator-steel.
  44 layers - 26.5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









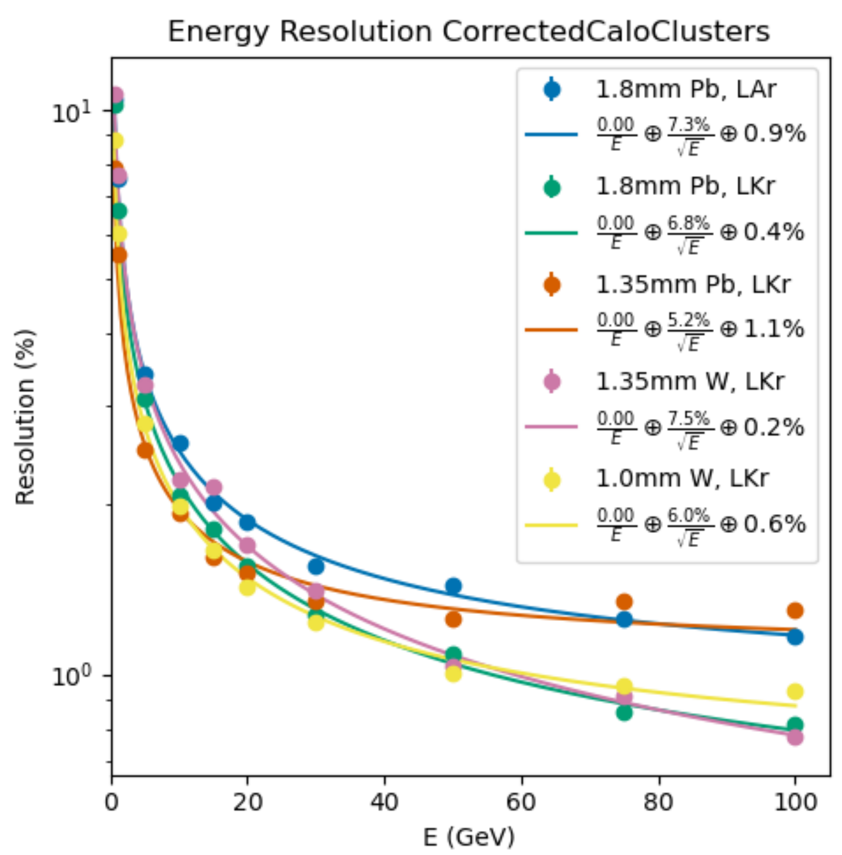


Calorimeters (ALLEGRO)

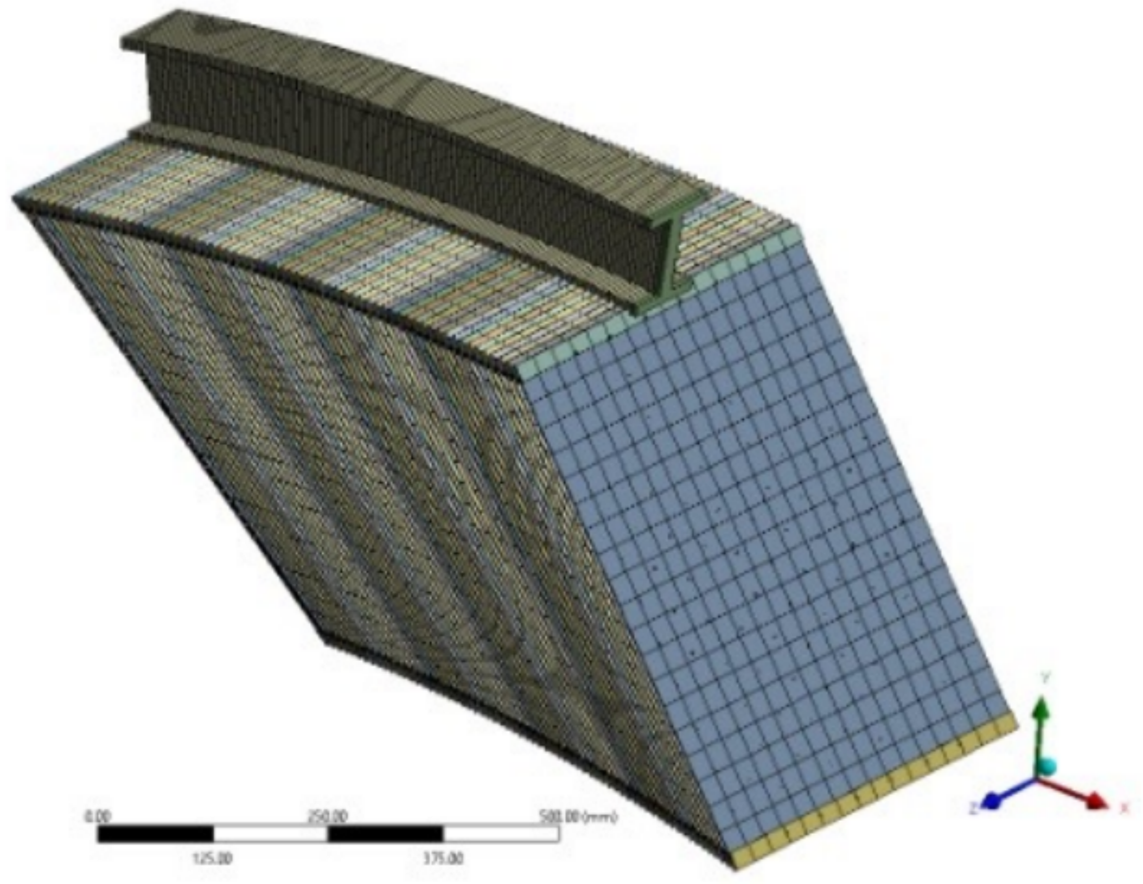
EM Calorimeter:

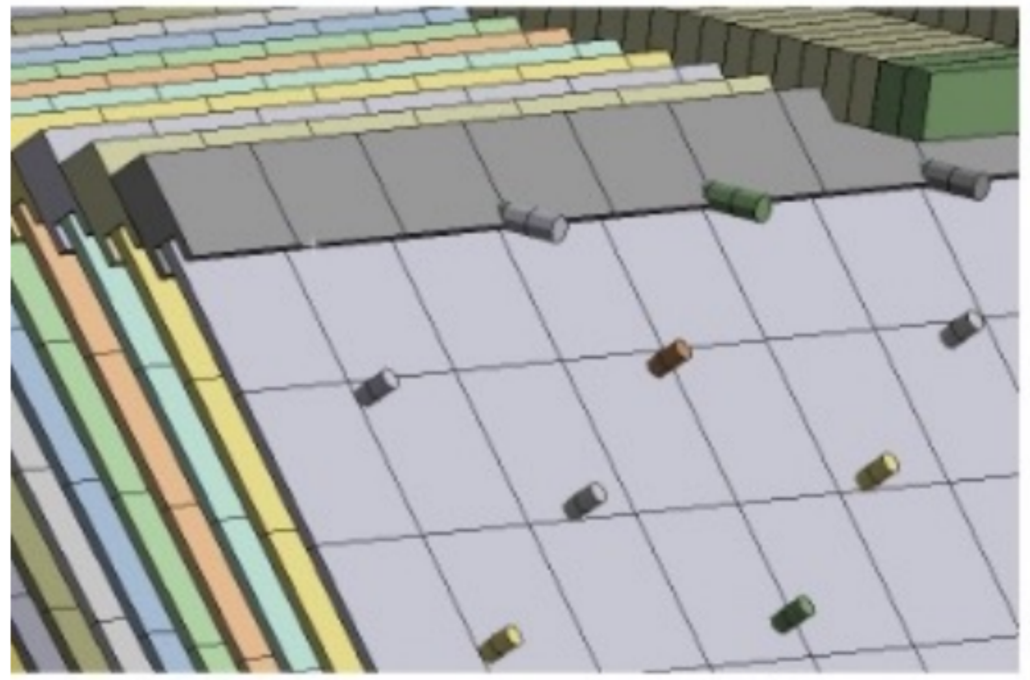
- Noble liquid calorimeters: good energy resolution, long-term stability, easy to calibrate.
    - Ideas to **achieve high granularity** targeting particle flow.
- Solution heavily inspired to ATLAS: LAr + copper - but different geometry.

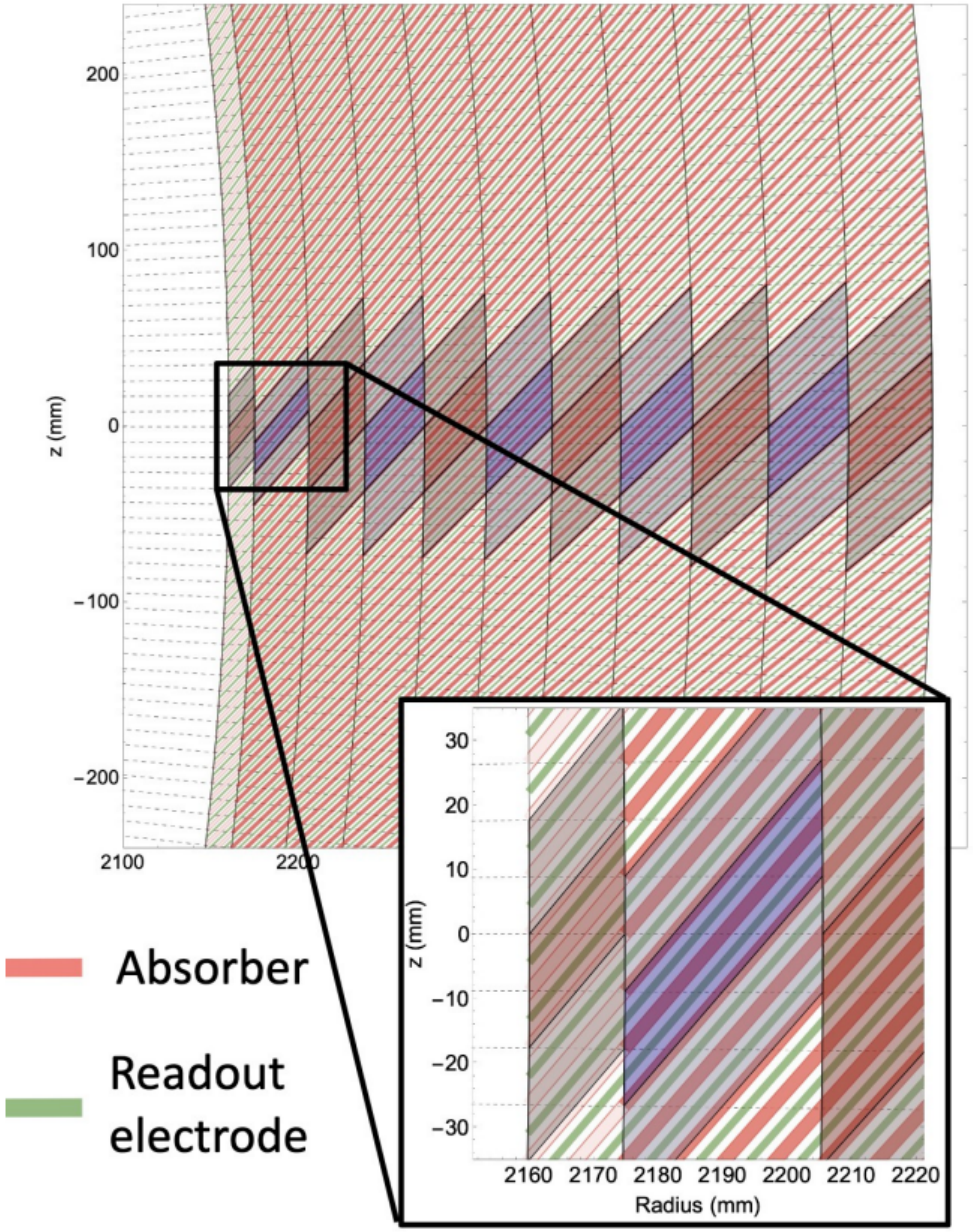
Hadronic section with an increased granularity scintillator tile + steel (a la TileCal).



Example optimisation of material







Calorimeters (other ongoing R&Ds)

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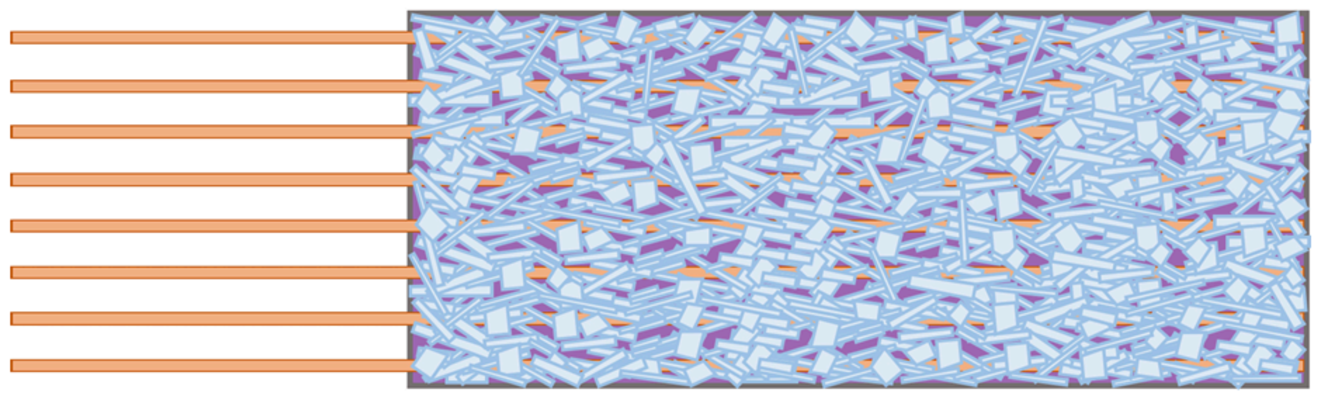
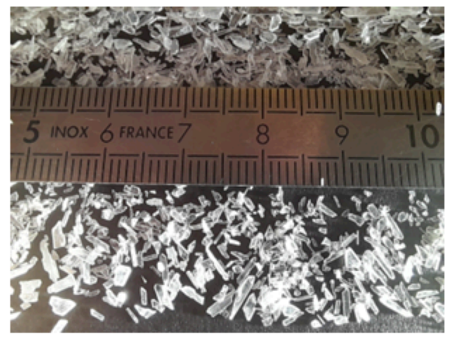
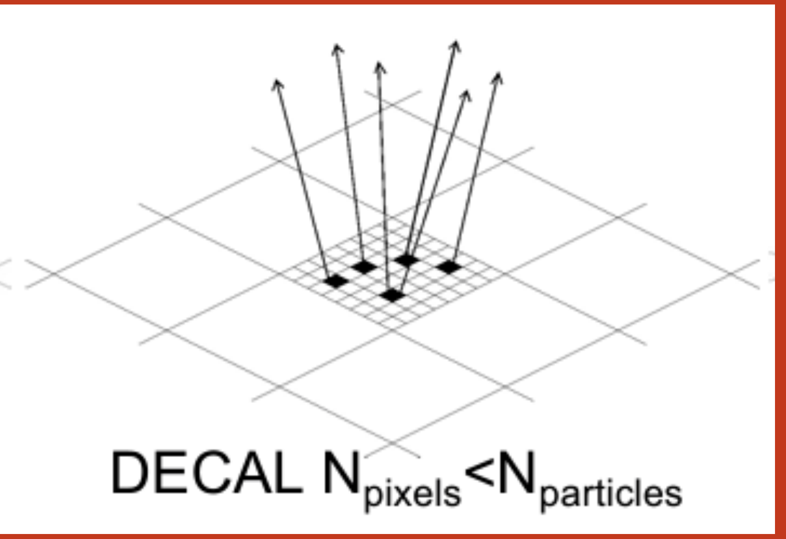
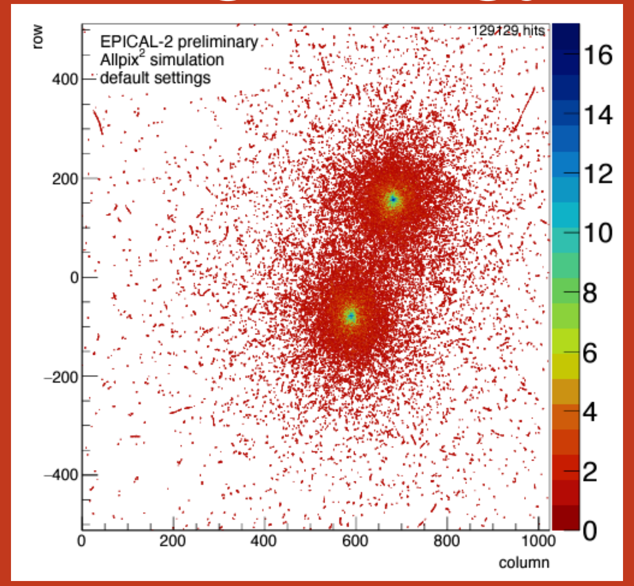
GRAiNITA
scintillator grains and absorber suspended in a liquid. Trapped light extracted with WLS fibres - high density EM calorimeter.



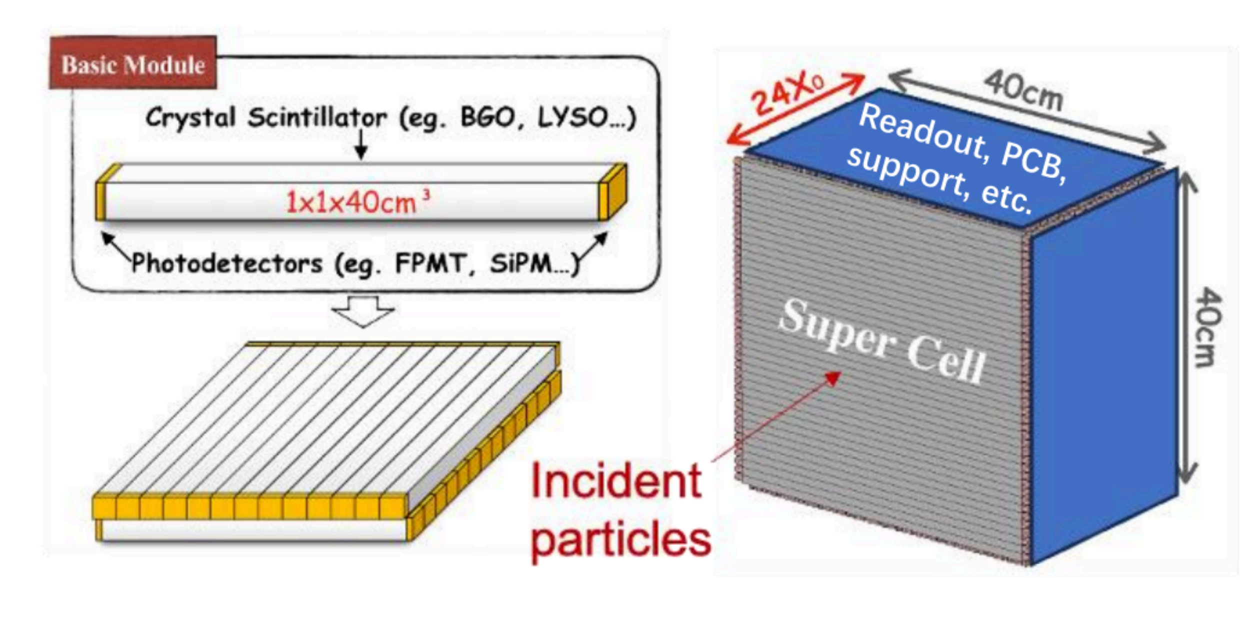


DECAL - Ultra-high granularity CMOS Ecal
High-density digital CMOS readout - count hits rather than measuring energy





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

Synergies: Consortia and ECFA DRD

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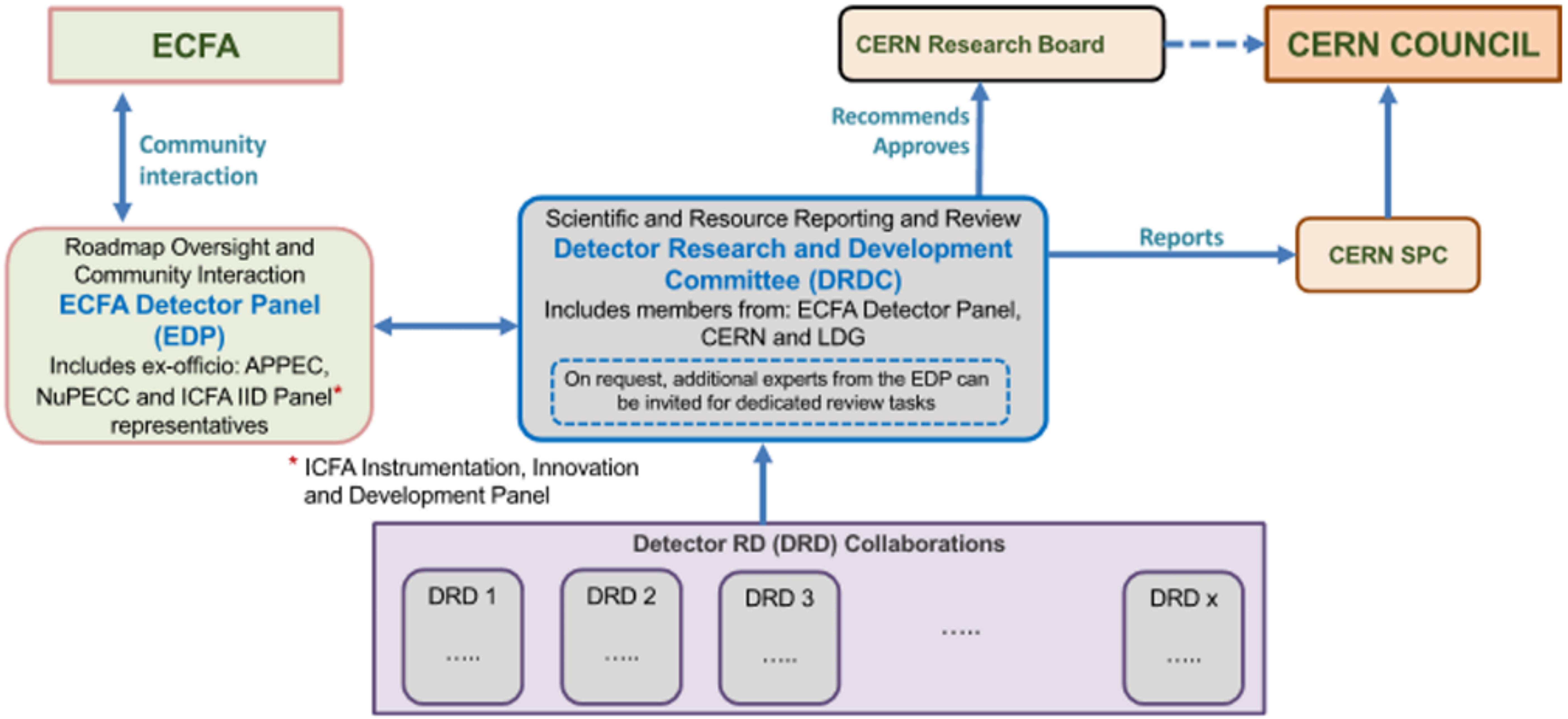
- A lot of leverage done in the past within **consortia and proto-collaborations.**
- Challenges connected with detector R&D find **a common framework** (aimed at increasing coherence and optimising resources) with ECFA DRD.
- **INFN positioning for many of these items is strategic**.



EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

CRYSTAL CLEAR

RD51 Collaboration

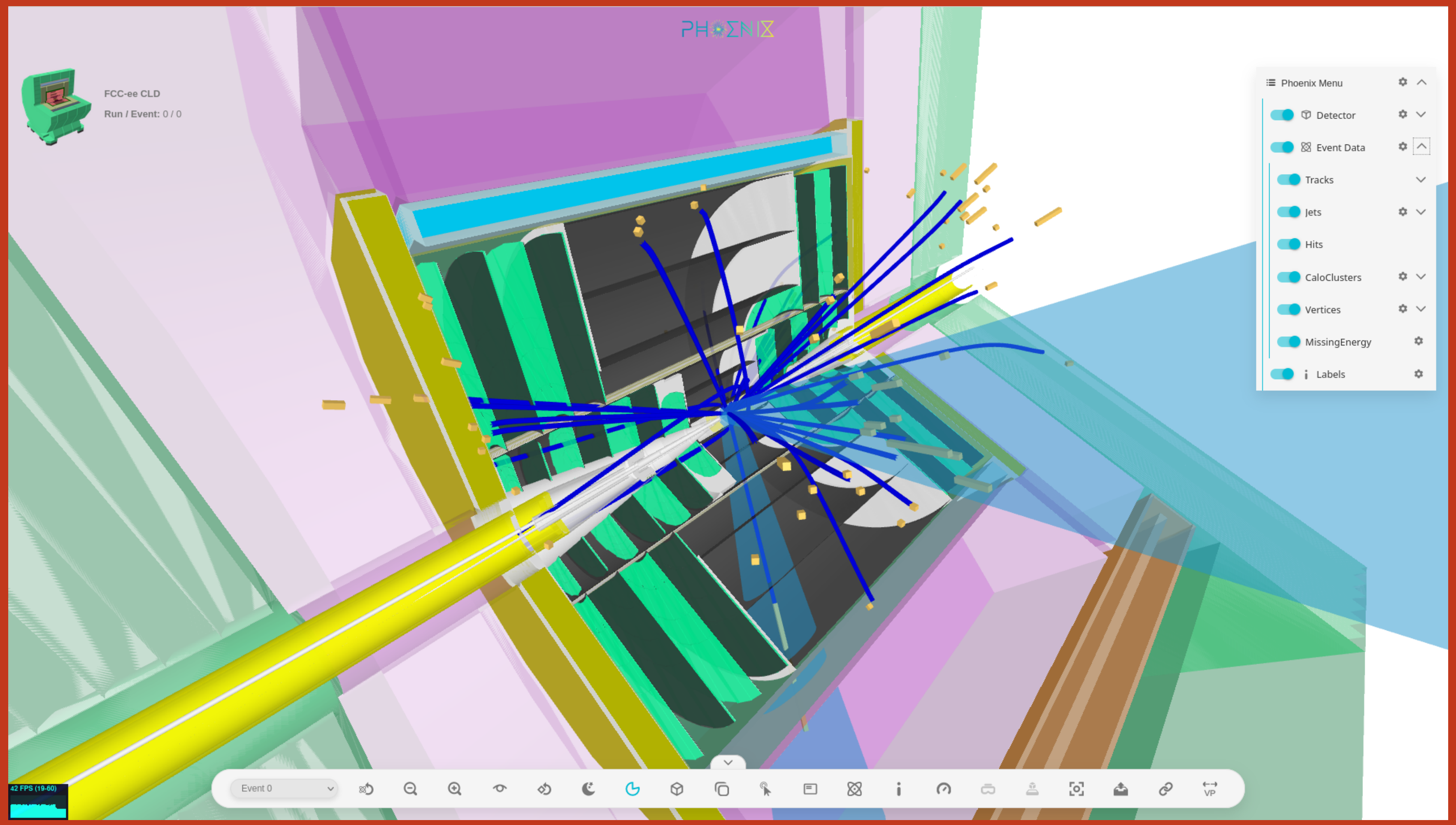
AIDA innova

Synergies: Common tools

- Nice sub-products of these collaborations already widely used

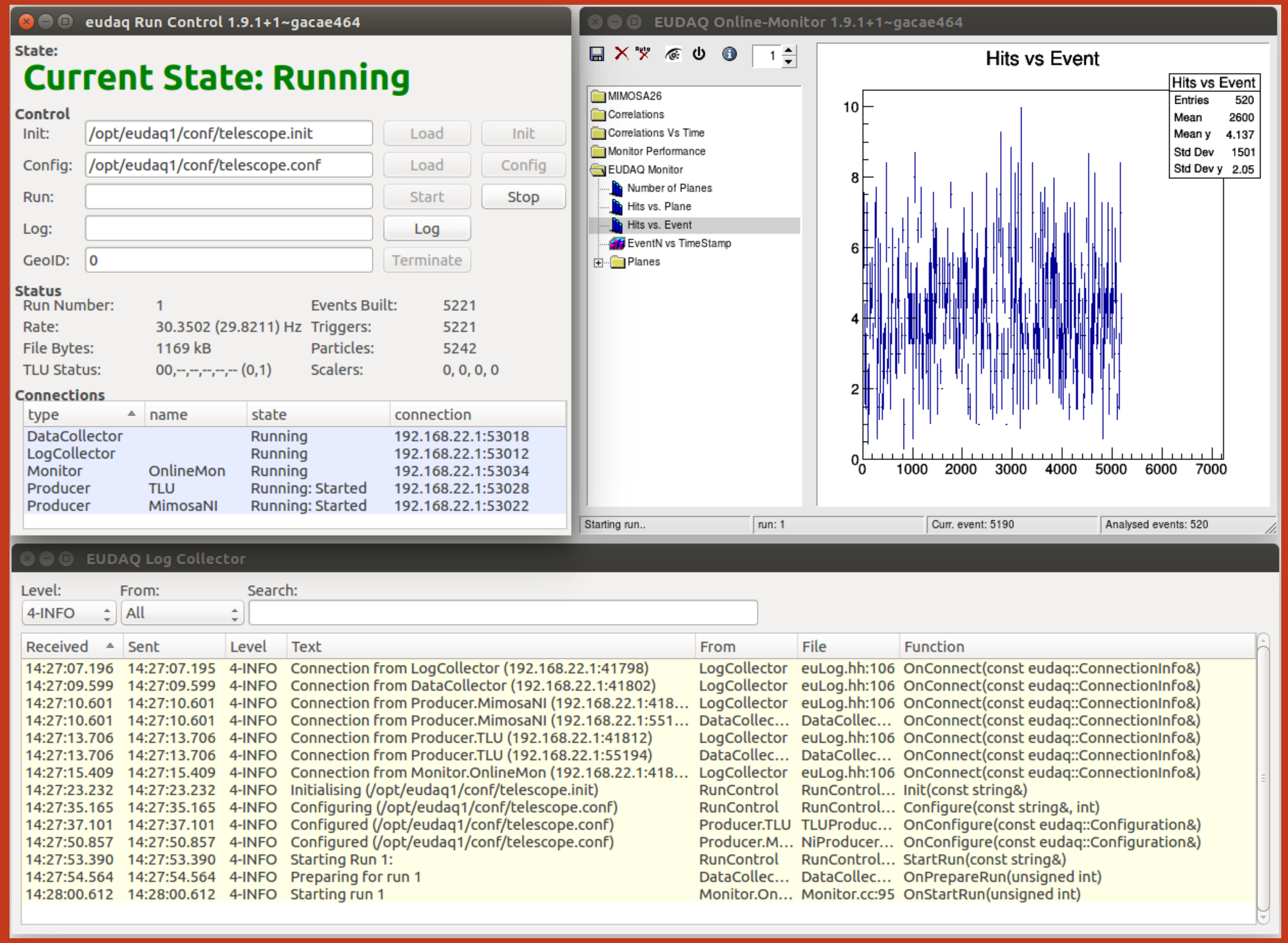
Key4HEP

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



So…is everything done already?

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- Indeed, a lot of work done, but way more ahead
  - 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 for optimal particle flow? UV/digital light sensors for crystals/fibres?).
  - **Software is in development** (starting from detector simulations) - better software means more opportunities for improved physics requirements.
  - Etc..
- "Detector 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

- Work for the definition of the detectors for FCC-ee **in full swing**.
- A game of ideas (already at play):
    - **Full-silicon** or **ultra-low material** tracking? Calorimeter with **high granularity** or **high energy resolution**?
- International collaboration in detector R&D being shaped by **ECFA DRD initiative**.
    - INFN **strategically placed** in many of the key R&Ds.
- It is a long time to FCC-ee
    - …but a **big push is happening now**! Feasibility study + European Strategy update key ingredients for council approval.
    - Some very important signals at international level (including P5 endorsement and signing of SoI from US).