R&D towards future Higgs factories

Higgs 2023 (Beijing) - 1/12/2023

Giovanni Marchiori (APC-Paris)

Introductory remarks

- *Many thanks to the organisers for the invitation and the extremely interesting and well organised conference*

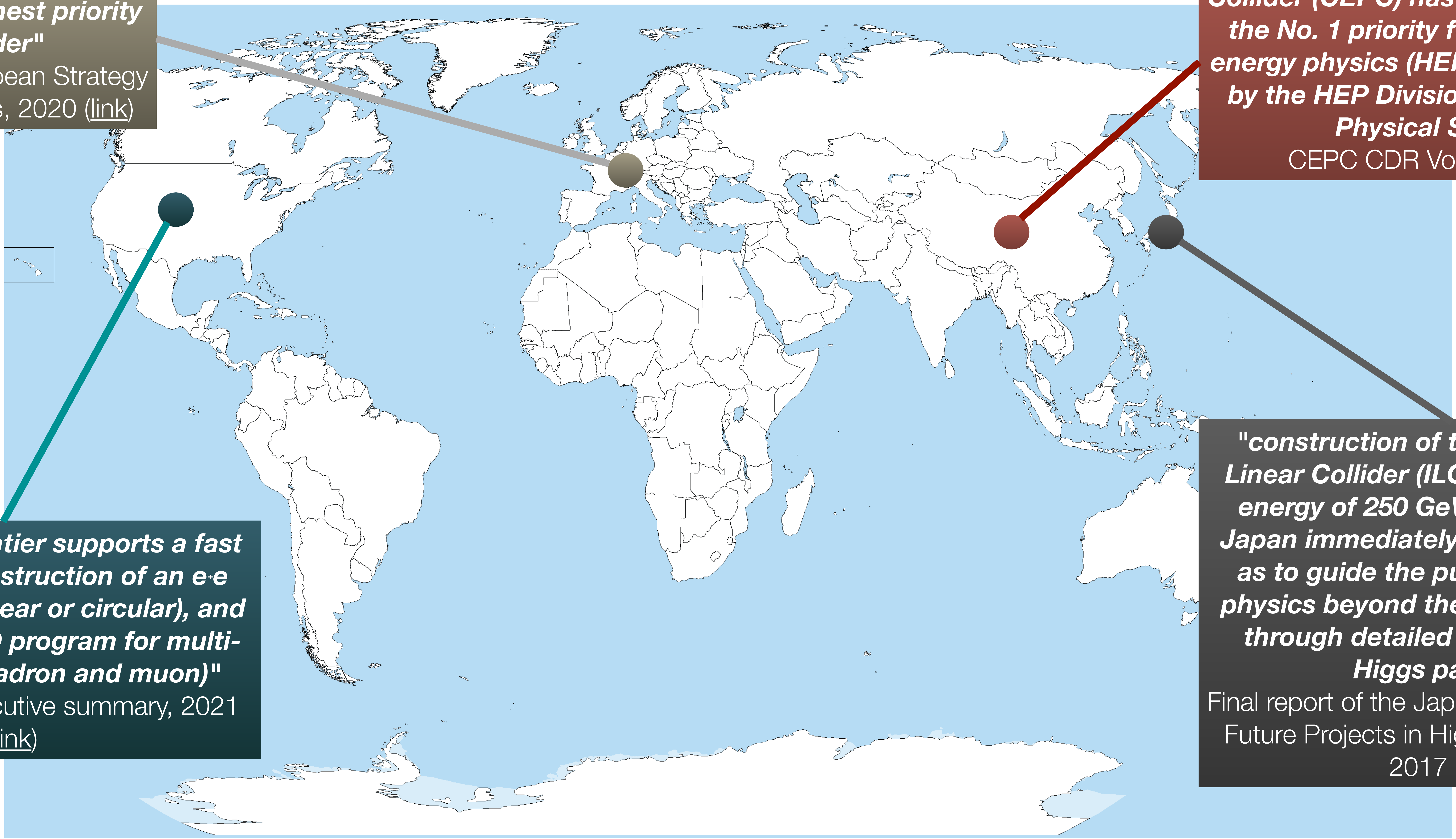
- *Huge amount of R&D on accelerators and detectors towards Higgs factories*
  - *impossible to cover in one talk, I will show you a personal selection of recent activities*

- *There are more details in the slides than I can cover in 25'*
  - *I won't go through everything, but slides are available offline!*

Higgs factories are the highest-priority next collider in HEP

"An electron-positron Higgs factory is the highest priority next collider"
Update of the European Strategy for Particle Physics, 2020 (link)

"The Chinese Electron Positron Collider (CEPC) has been identified as the No. 1 priority for the next high-energy physics (HEP) project in China by the HEP Division of the Chinese Physical Society."
CEPC CDR Vol1, 2018 (link)

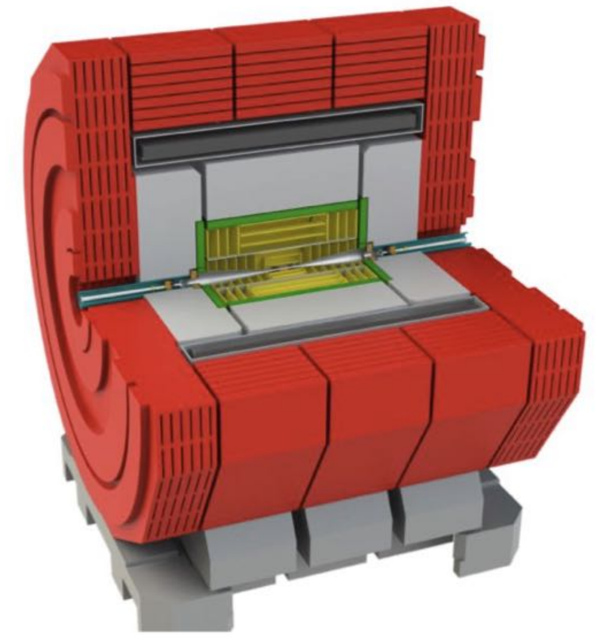
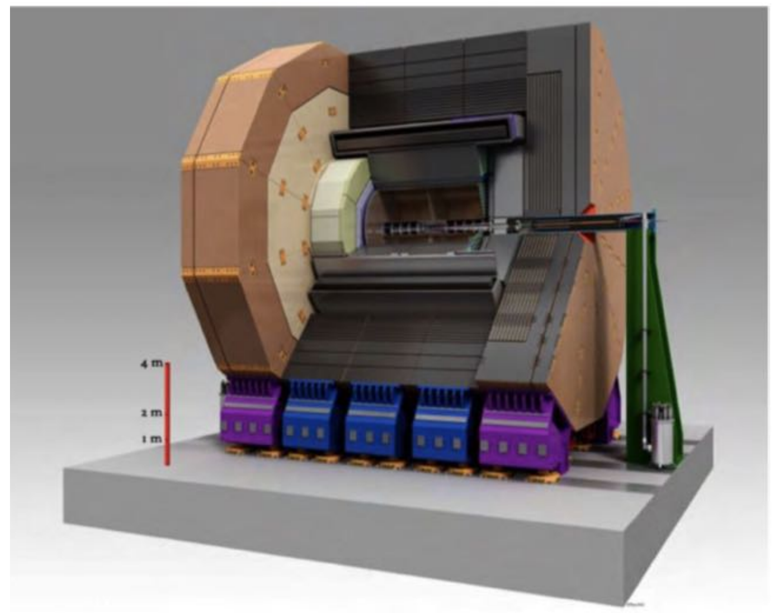
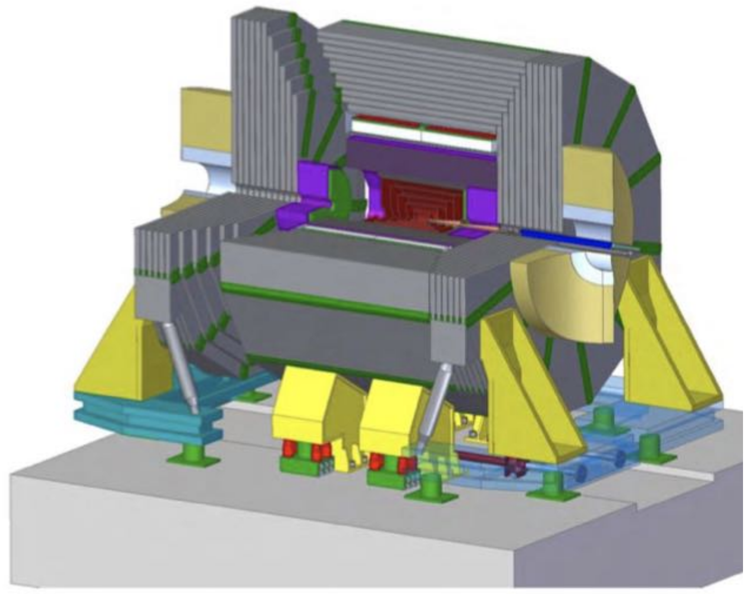


"The Energy Frontier supports a fast start for the construction of an e^+e^- Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon)"
Snowmass21 executive summary, 2021 (link)

"construction of the International Linear Collider (ILC) with a collision energy of 250 GeV should start in Japan immediately without delay so as to guide the pursuit of particle physics beyond the Standard Model through detailed research of the Higgs particle"
Final report of the Japanese committee on Future Projects in High Energy Physics, 2017 (link)

Higgs factory proposals

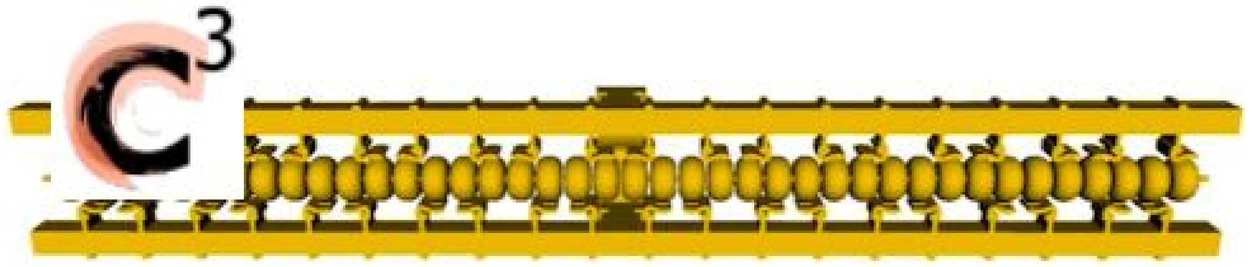
e^+e^- Linear (10-50 km)

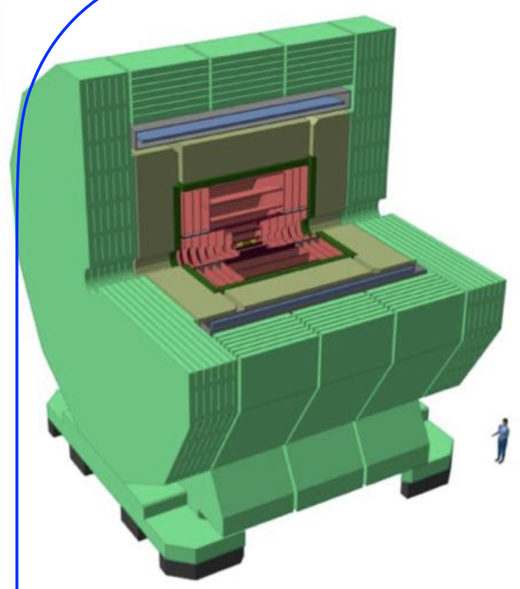
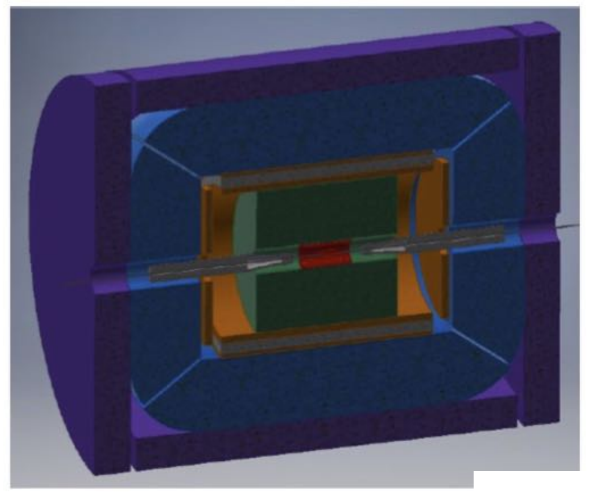
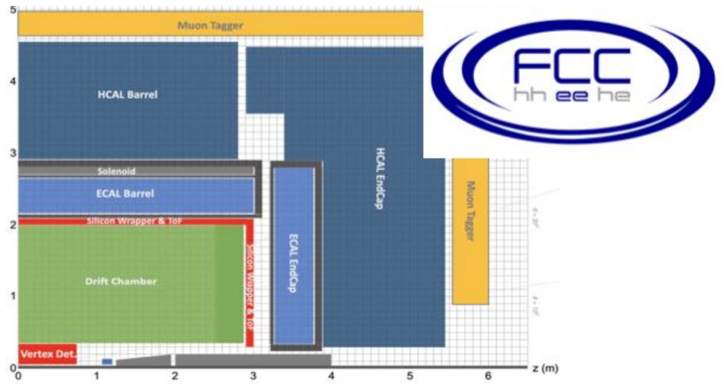
CLIC => **CLICdet**,
√s: 380 GeV, 1.5 TeV, 3 TeV

ILC => **ILD** and **SiD**:
√s: 250 – 500 GeV (1 TeV)

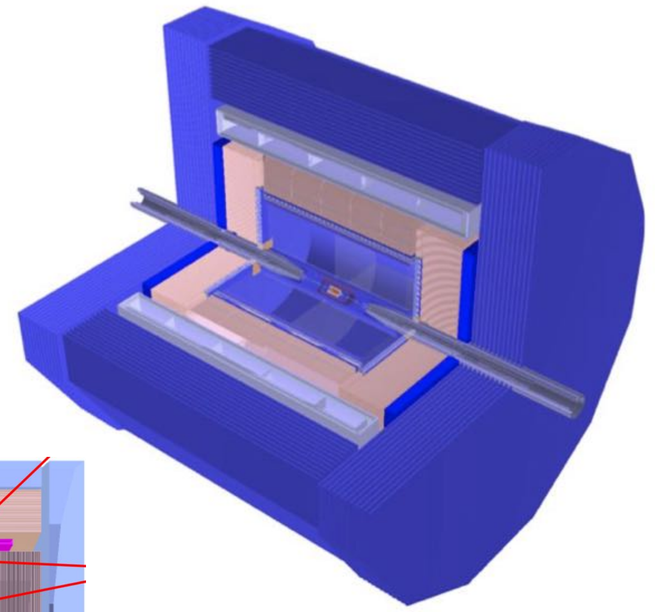
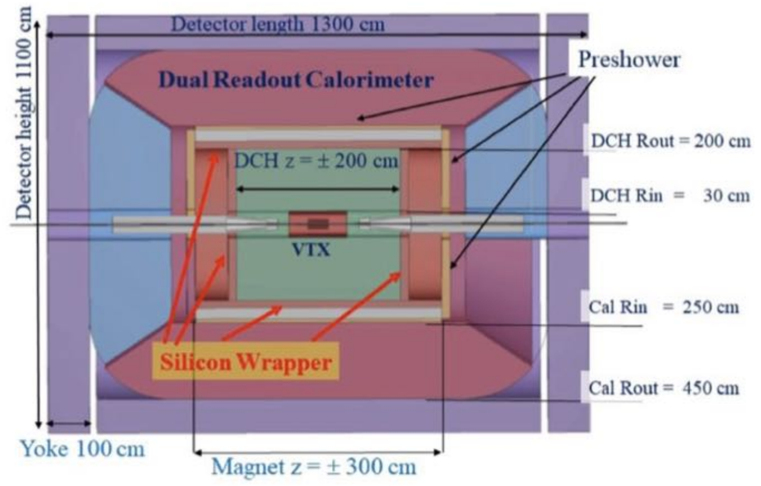
+ C3 ..

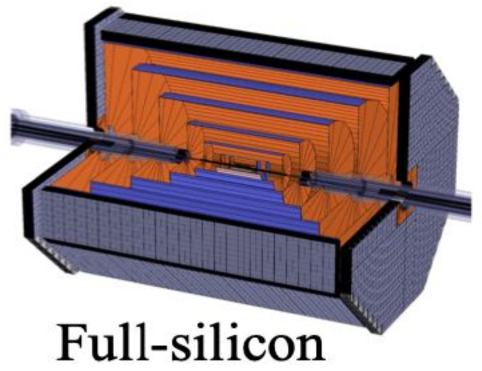


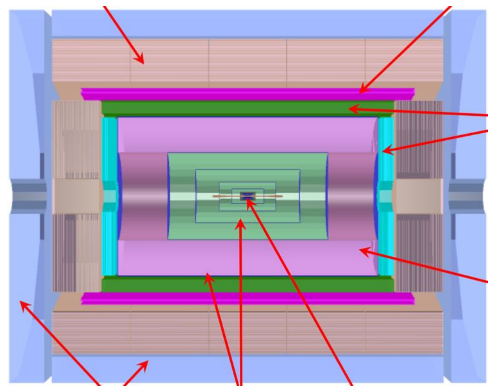
e^+e^- Circular (~100 km)

FCC-ee => **ALLEGRO, CLD, IDEA**
√s : 90 - 365 GeV

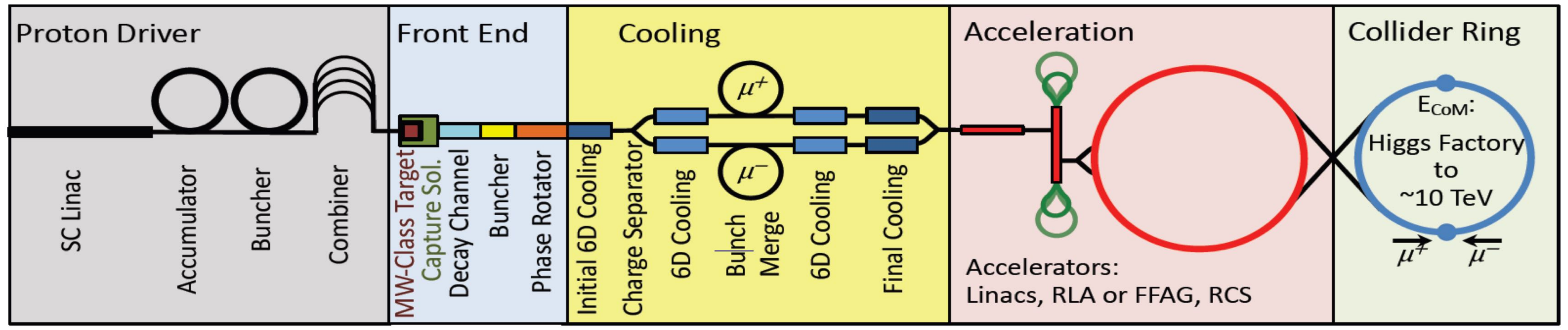




CEPC => **baseline, FST, low-B, 4th**
√s : 90 - 365 GeV

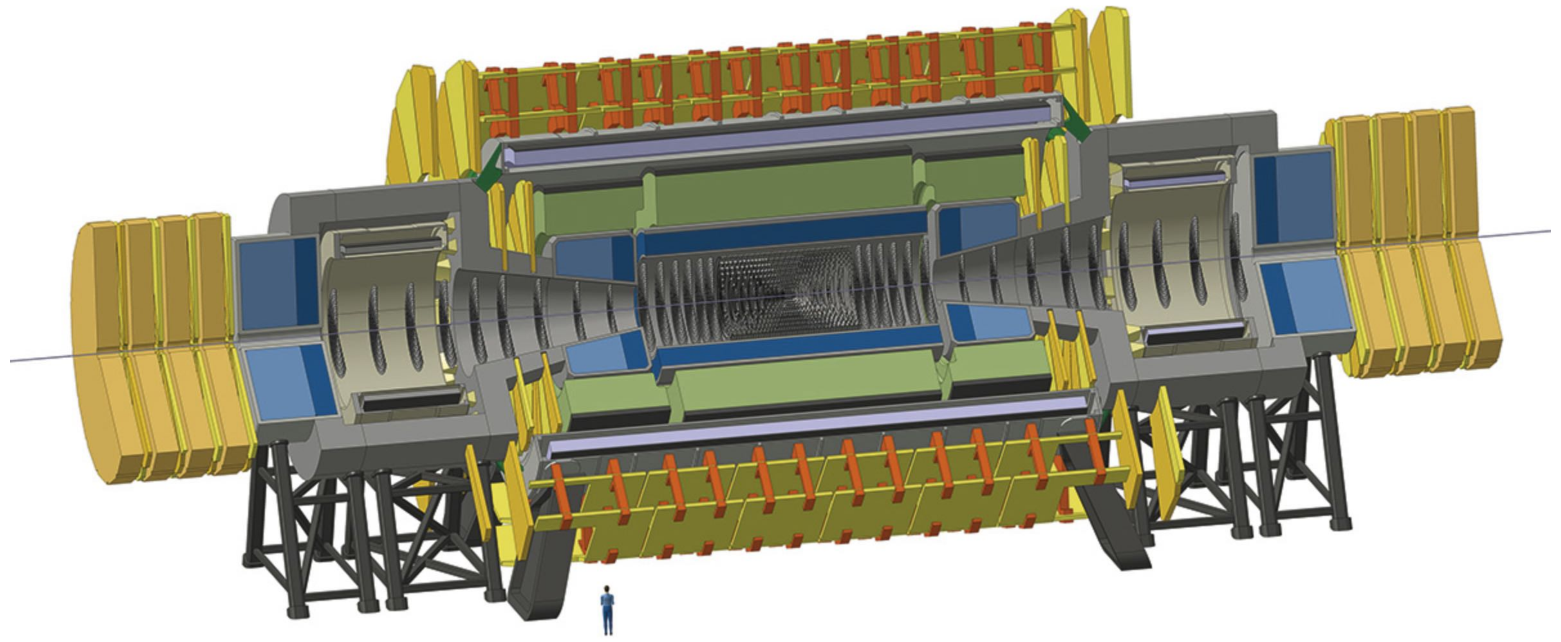
$\mu^+\mu^-$ Circular (5-10 km)

MuCol
√s = 3, 10 TeV



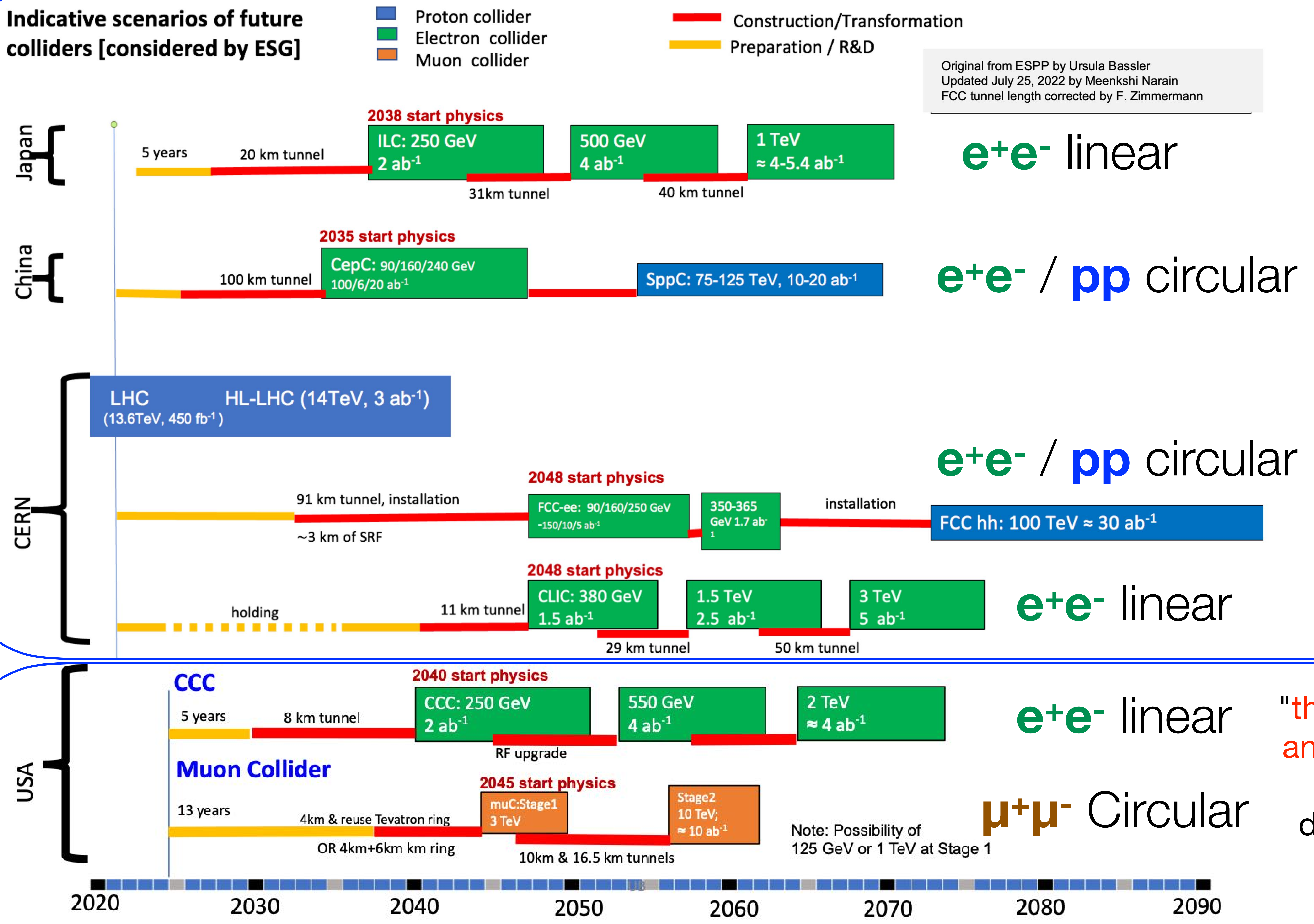
pp Circular (~100 km)

FCC-hh, SppC
√s > 100 TeV



Project timescales

K. Jakobs



Comments:

- e^+e^- timelines are limited by approval processes
- CEPC and ILC projects need to get approval in the near future to maintain these schedules
- CERN projects are linked to completion of the HL-LHC
- hh timelines are limited by technology issues, costs, proceeding e^+e^- projects

"the timelines shown are technologically limited, and some challenges need to be sorted out, for example, successful R&D and feasibility demonstrations for C3 and Muon Collider are essential at a short timescale."

Snowmass21 Energy Frontier Report

Though a **O(100TeV) pp collider (FCC-hh, SppC)**
and a **multi-TeV lepton collider (muon collider or CLIC)**
are also Higgs factories,
they are either less mature solutions and/or longer term projects
compared to e^+e^- colliders at $\sqrt{s}$~250 GeV

In the following, also for the sake of time,
I will highlight some recent R&D activities on shorter term projects
with more mature studies: ILC, CEPC, FCC-ee

Apologies if your favourite R&D topic is not covered!

Ingredients for a successful e^+e^- Higgs factory

- **A powerful accelerator/collider**
  - **Energy**: beam energies of ~120 GeV (240 GeV ~peak of ZH cross-section) and beyond
    - Linear: ~250 GeV => open ZHH process, for self-coupling measurement from HH production
    - Circular: limited by synchrotron radiation, ~175-180 GeV => self-coupling study from electroweak corrections to ZH production at two different CM energies (+ top physics at ttbar threshold)
    - Also crucial to go down to 45 GeV (=> Z pole run to disentangle effect of H and EW operators), possibly run @62.5 GeV (ee->H)
  - **Luminosity**: as high as possible to deliver O(1M) of Higgs over (few) years of data-taking
    - Beam current as large as possibly allowed by power budget
    - Beam size at interaction point (IP) as small as possible

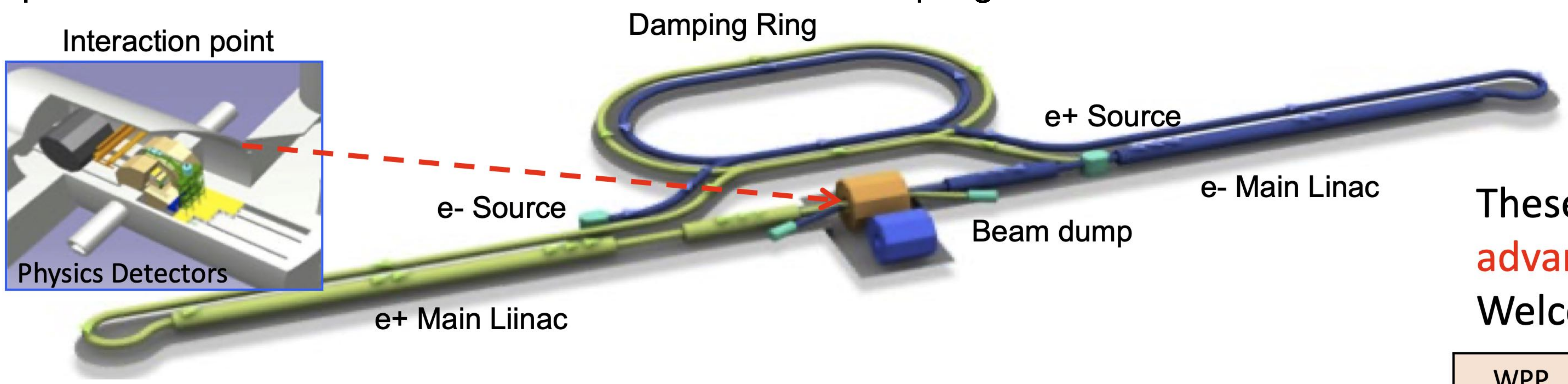
- **A detector with unprecedented performance**
  - Full **coverage**
  - High **efficiency**
  - Excellent particle **reconstruction** (resolution) and **identification**

- **A big, reliable, stable - and sometimes very thin - solenoid magnet** to provide the field for charged track p_T measurements

Accelerator

Key areas of accelerator R&D

- Example from the ILC technical network accelerator R&D programme



These WPs can be applied to various advanced accelerators.
Welcome to join!

- Creating particles — ***Sources***
  - polarized elections / positrons
- High quality beams — ***Damping ring***
  - Low emittance beams
    - Small beam size (small beam spread)
    - Parallel beam (small momentum spread)
- Acceleration — ***Main linac***
  - superconducting radio frequency (SRF)
- Getting them collided — ***Final focus***
  - nano-meter beams
- Go to ***Beam dumps***

SRF

e-, e+ Sources

Nano-Beam

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

Key aspects of accelerator R&D

- Example from the ILC technical network accelerator R&D programme

Sources
Acceleration
Focusing

(+ many more: injection, backgrounds, logistics, power consumption & cost reduction, …)

Only a few selected highlights in the following

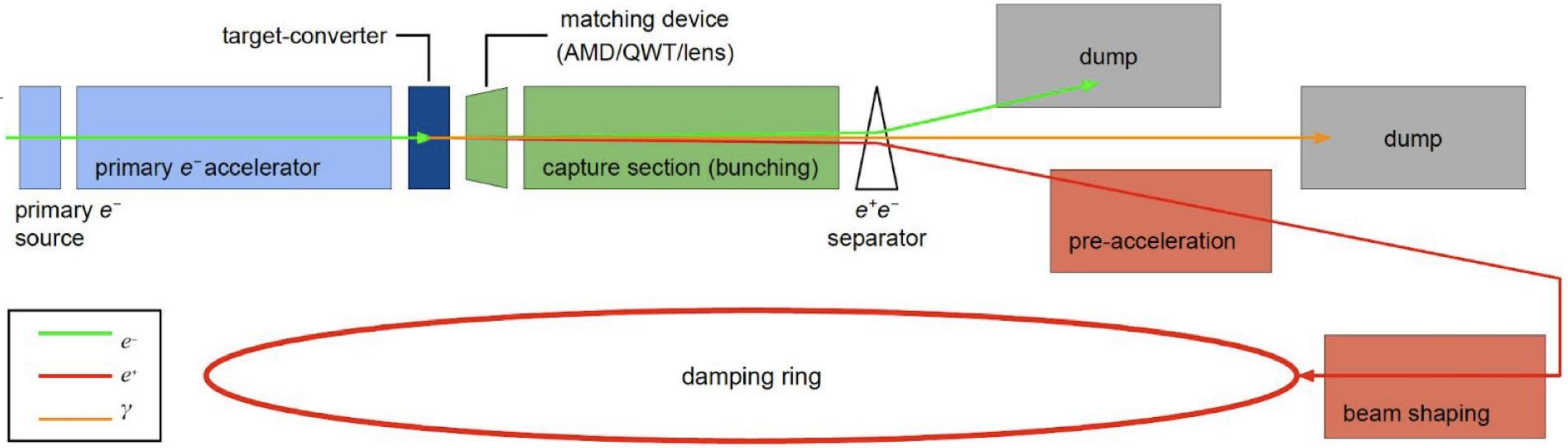
…applied to various …tors.

•Creating part…
•polarized…
•High quality b…
•Low emit…
•Small b…
•Paralle…
•Acceleration
•supercon…
•Getting them collided – *Final focus*
•nano-meter beams
•Go to *Beam dumps*

Beam

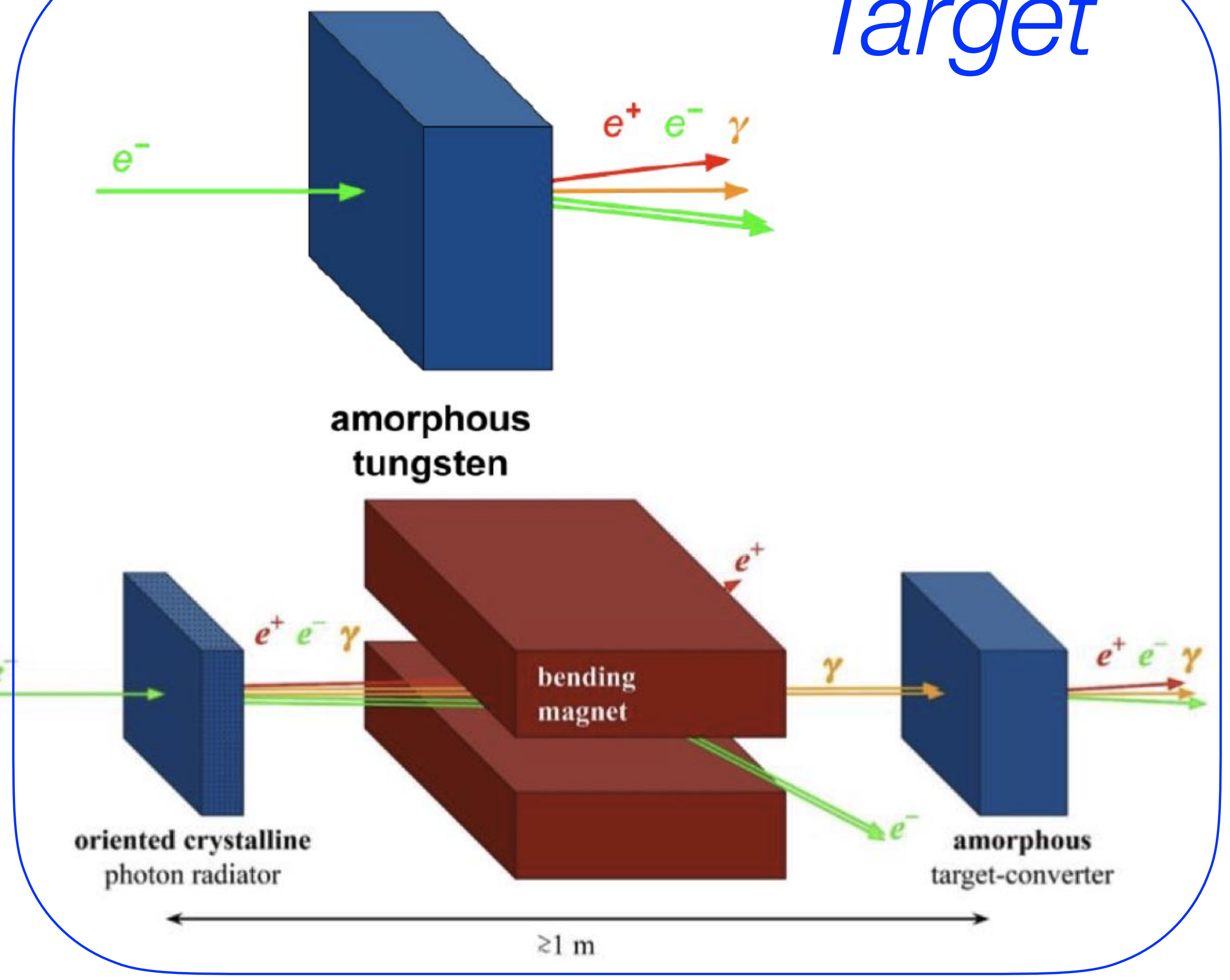
		…ty production
		…M design
		…rab cavity
		…E- source
		…ulator target
		…lator focusing
		…riven target
		…iven focusing
		…iven capture
		…t replacement
		…ystem design
		…ction/extraction
WP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

Sources

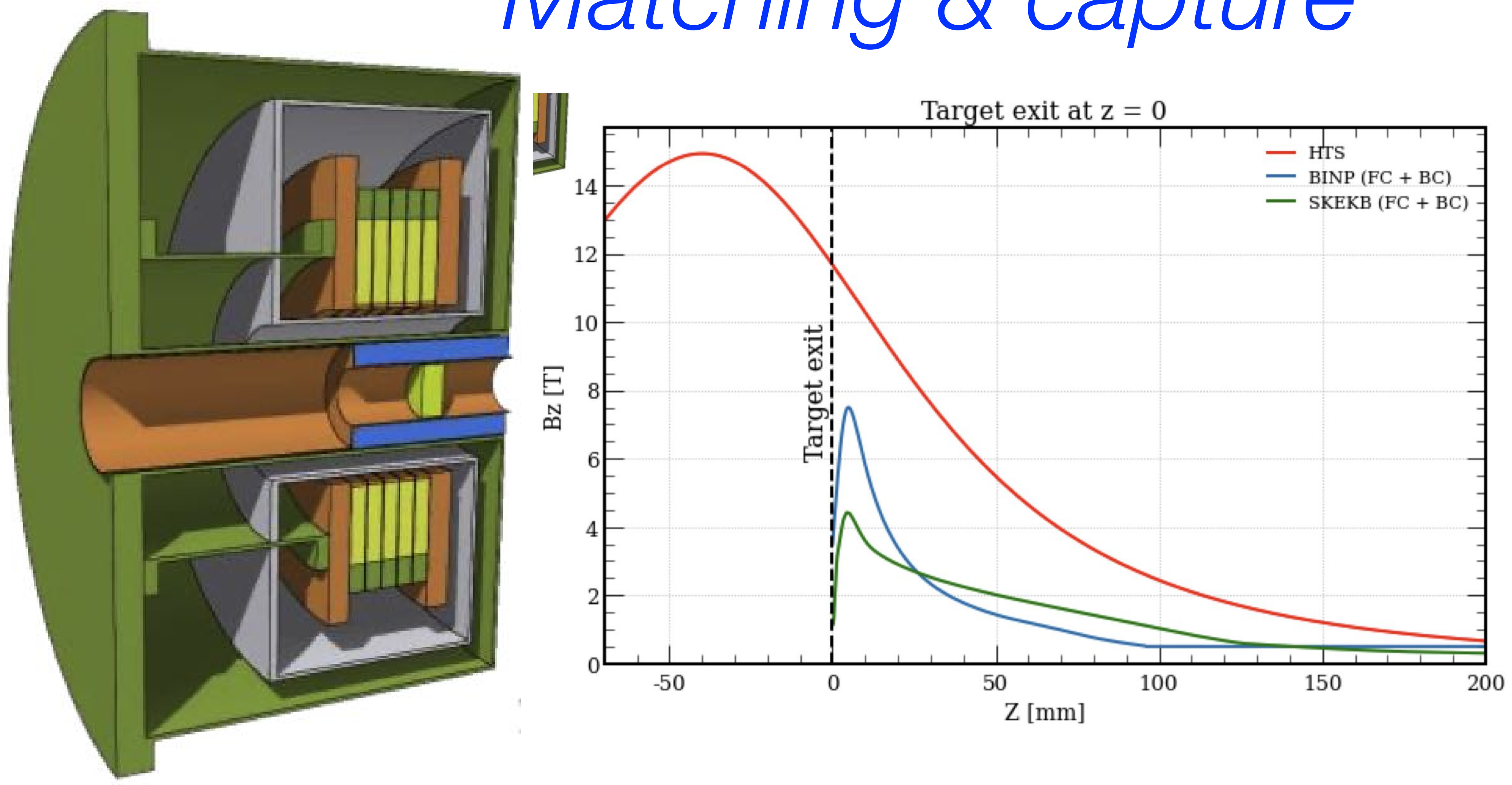


- All e^+e^- Higgs factories require an intense **positron source** and have thus a vigorous positron R&D programme
- Examples of R&D for FCC-ee:
  - production **target**: conventional vs hybrid scheme (comparable production rate but lower thermal load)
  - **matching device** (fast phase space rotation to transform small size, high divergence -> big size, low divergence) & **capture system**
    - High-temperature superconducting (HTS) solenoid being investigated as more flexible alternative to current solutions (higher peak field & aperture, DC operation, flexibility on field profile and target position) - ongoing, no showstopper found so far
  - **Pre-acceleration**: e^+ linac designed, full tracking simulations from production target to damping ring using the realistic field maps

Target

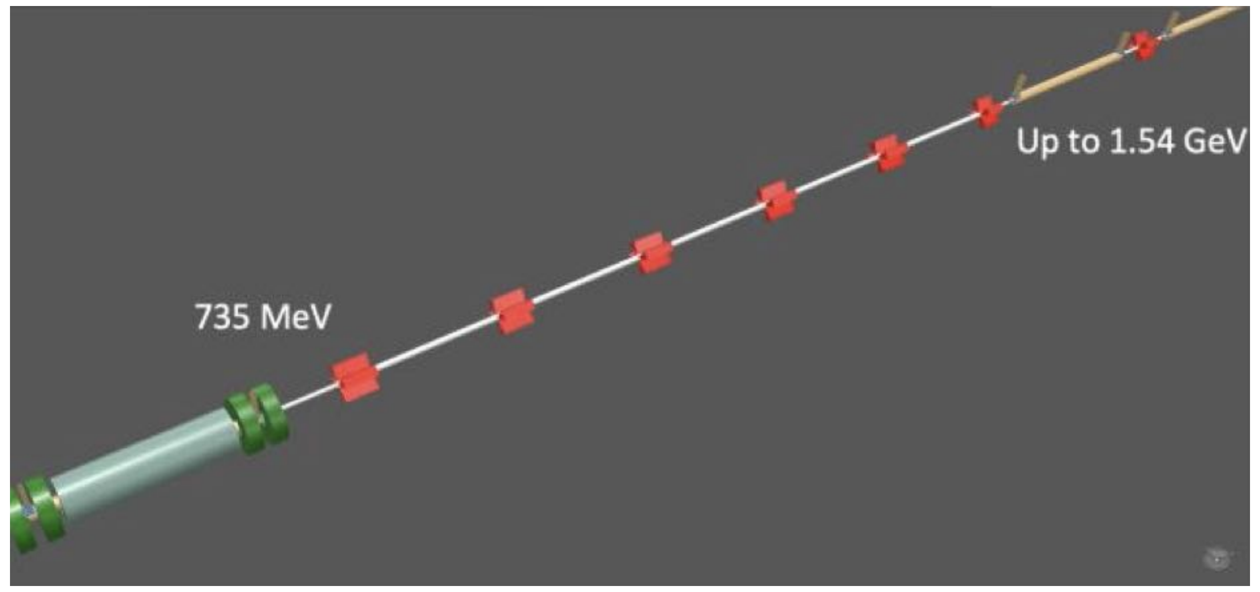


Matching & capture



HTS solenoid designed by PSI

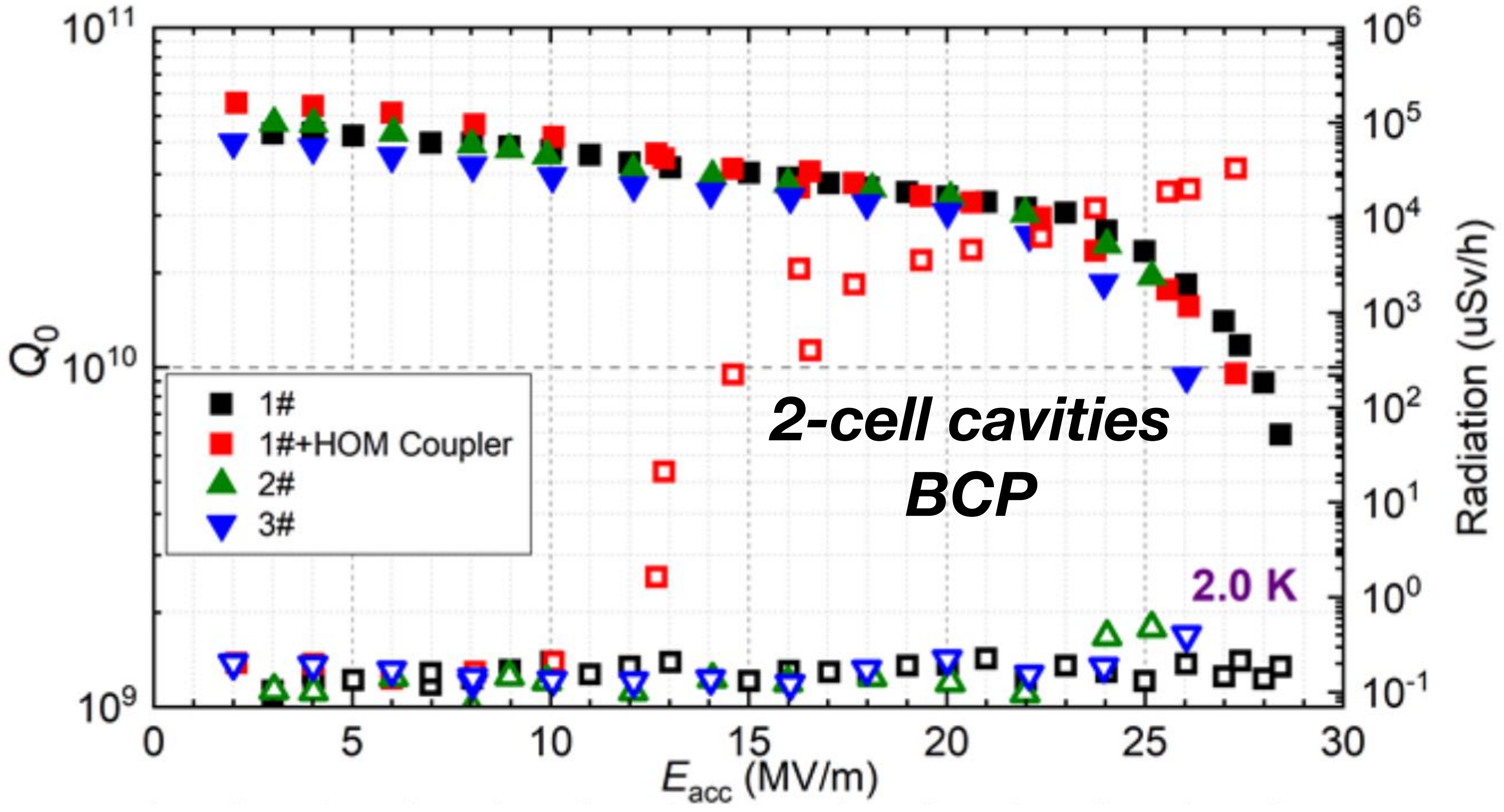
Pre-acceleration

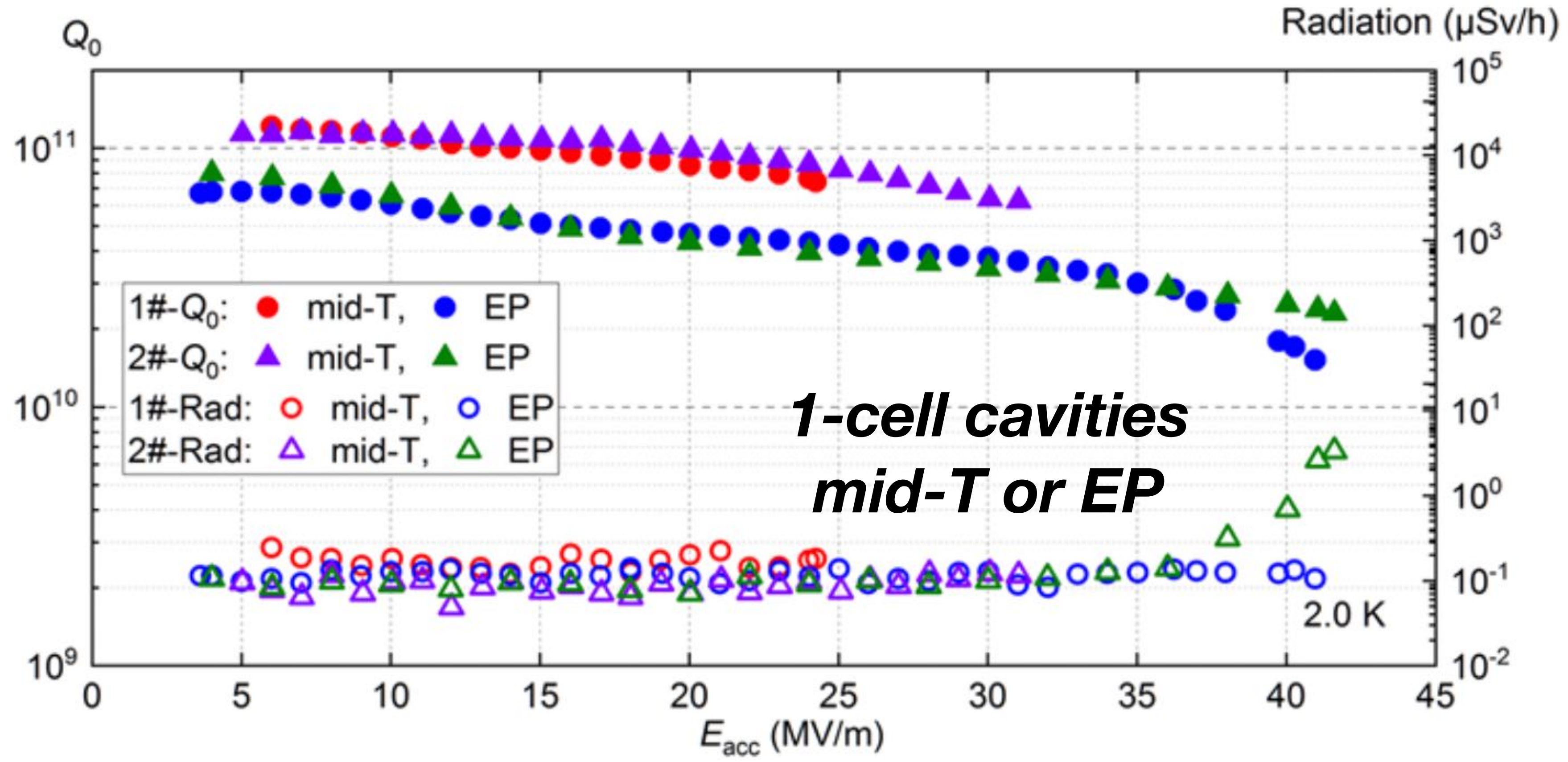


I. Chaikovska

Acceleration

- Provided by **superconducting radio-frequency (SRF) cavities**. Key aspects: field (->energy), quality factor Q_0 (->efficiency)
- CEPC target: 2-cell (1-cell) cavities for collider ring for H (Z) running => 25 MV/m (17 MV/m) and Q_0 = 3e10 (2e10) at 2K
- Three prototypes of 2-cell cavities manufactured and treated with buffered chemical polishing (BCP) => 25 MV/m, Q_0=2.5e10
- Electropolishing and mid-T baking promise higher Q_0: 8e10 @ 25MV/m in single-cell cavities. To be tested on 2-cell cavities
- R&D on new design of 1-cell cavity applicable to all beam energies of Higgs, Z, and W on-going



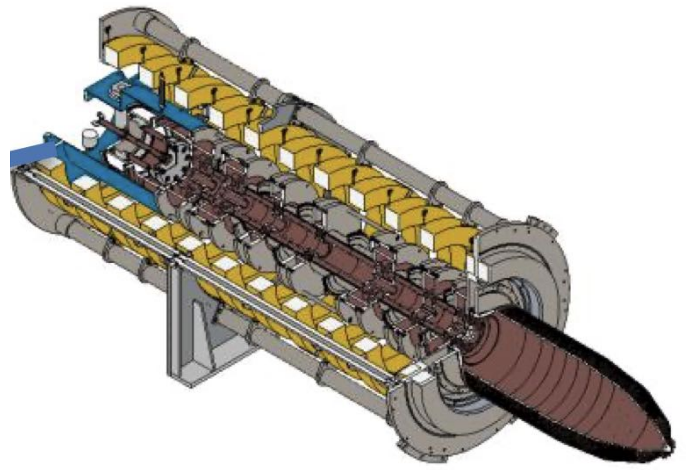


- R&D also ongoing on **klystrons** that power the SRFs to increase their efficiency (typical: 40-45%; CEPC target: 80%)

Klystron No. 2

Klystron No. 3
Efficiency 80.5%

(in fabrication)

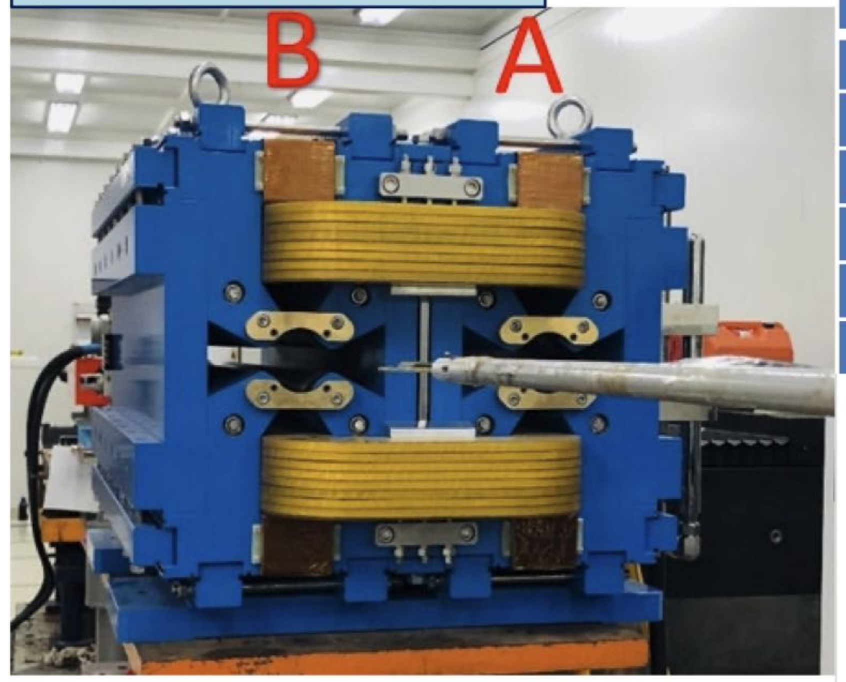


N. Wang

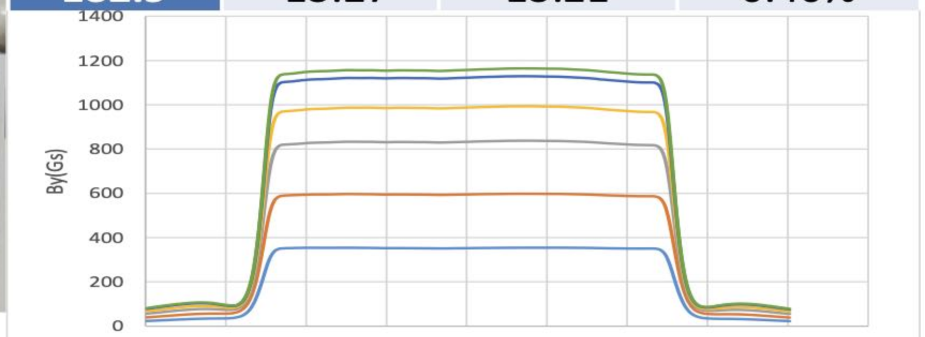
Focusing & low emittance beams

- **CEPC arc quadrupoles:** dual-aperture configuration => 50% less power consumption (~3000 quads in full ring)
  - QUAD for CEPC fabricated, meet requirements
- **CEPC quadrupoles for final focus:** short-length, high gradient (up to 140 T/m). Single-aperture magnet fabricated and OK (reaching needed gradient), next step = dual-aperture quadrupole

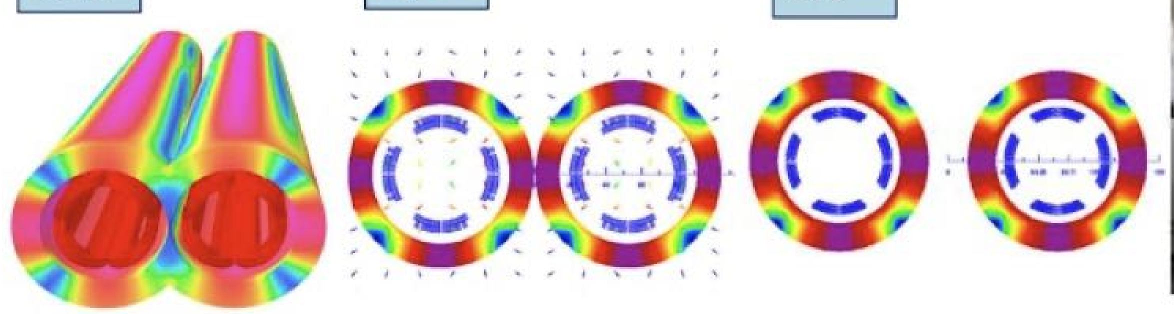
Dual aperture QUAD



E(GeV)	GL(T)-A	GL(T)-B	difference
45	-3.36	3.35	0.40%
80	-5.91	5.88	**0.59%**
120	-8.89	8.85	0.49%
148	-10.93	10.89	0.40%
175	-12.77	12.73	0.30%
182.5	-13.27	13.21	0.40%



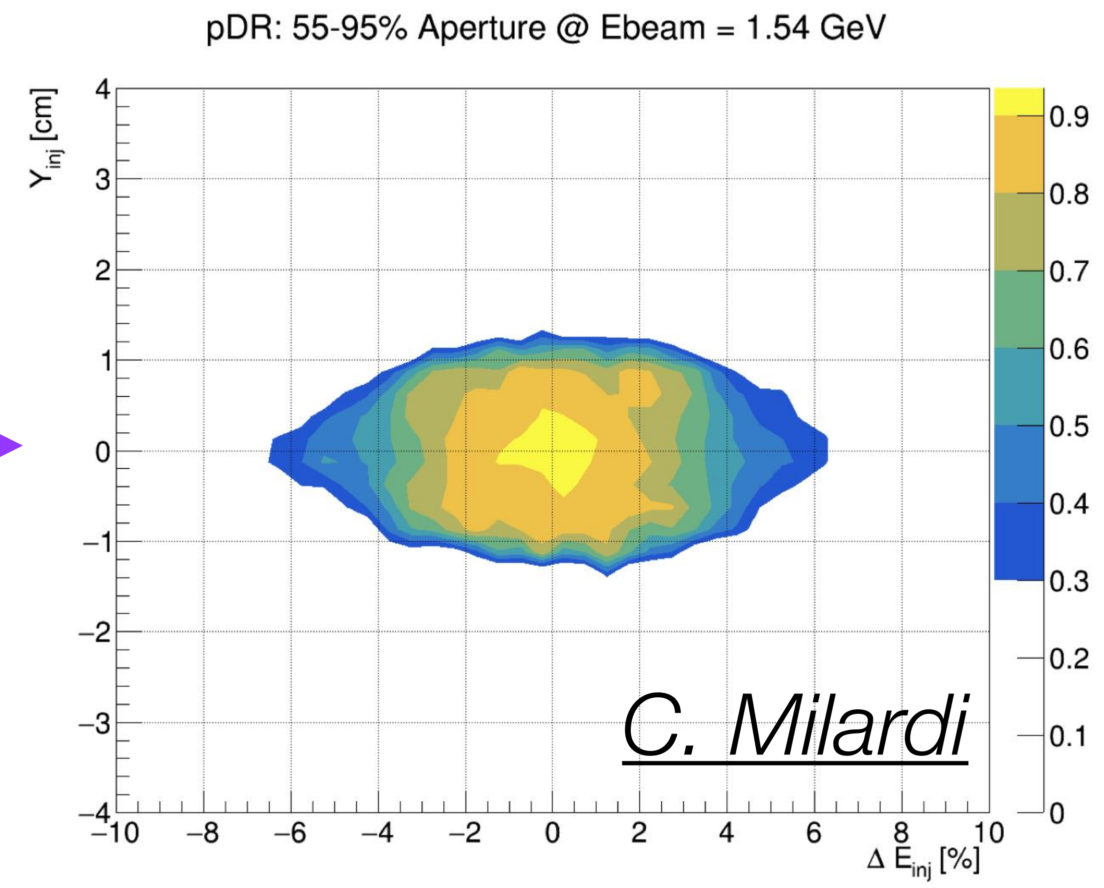
SCQ Specifications	Q1a	Q1b	Q2	
Field gradient	142.3	85.4	96.7	T/m
Magnetic length	1210	1210	1500	mm
Reference radius	7.46	9.085	12.24	mm
Mini. distance between aperture center	62.71	105.28	155.11	mm
High order field harmonics	≤5×10^{-4}	≤5×10^{-4}	≤5×10^{-4}	
Dipole field	≤3	≤3	≤3	mT



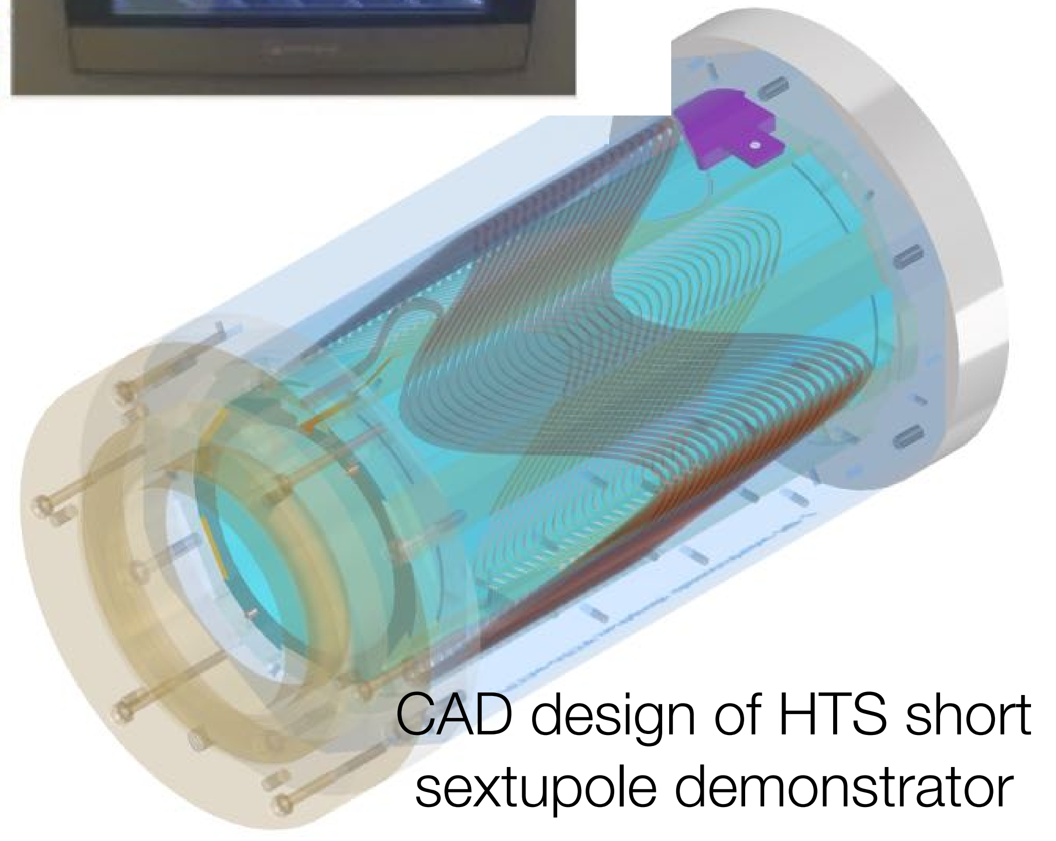
0.5m single-aperture Cos2θ SCQ

N. Wang

- **FCC-ee arc quads and sextupoles:** R&D ongoing on use of HTS magnets
  - power saving (T~40K, cryo-cooler supplied cryostat) and reduced length/increased dipole filling factor (sextupole nested inside quadrupole)
  - Plan to produce 1m prototype by 2026
- **Damping ring**: FCC-ee damping ring and transfer line design completed & simulated (2000 turns have been tracked - ~15% damping time)
  - R&D ongoing on alternative design, with significantly less elements and lower design complexity => lower cost, higher reliability
- **Booster**: CEPC new design => -60% emittance wrt CDR



C. Milardi



CAD design of HTS short sextupole demonstrator

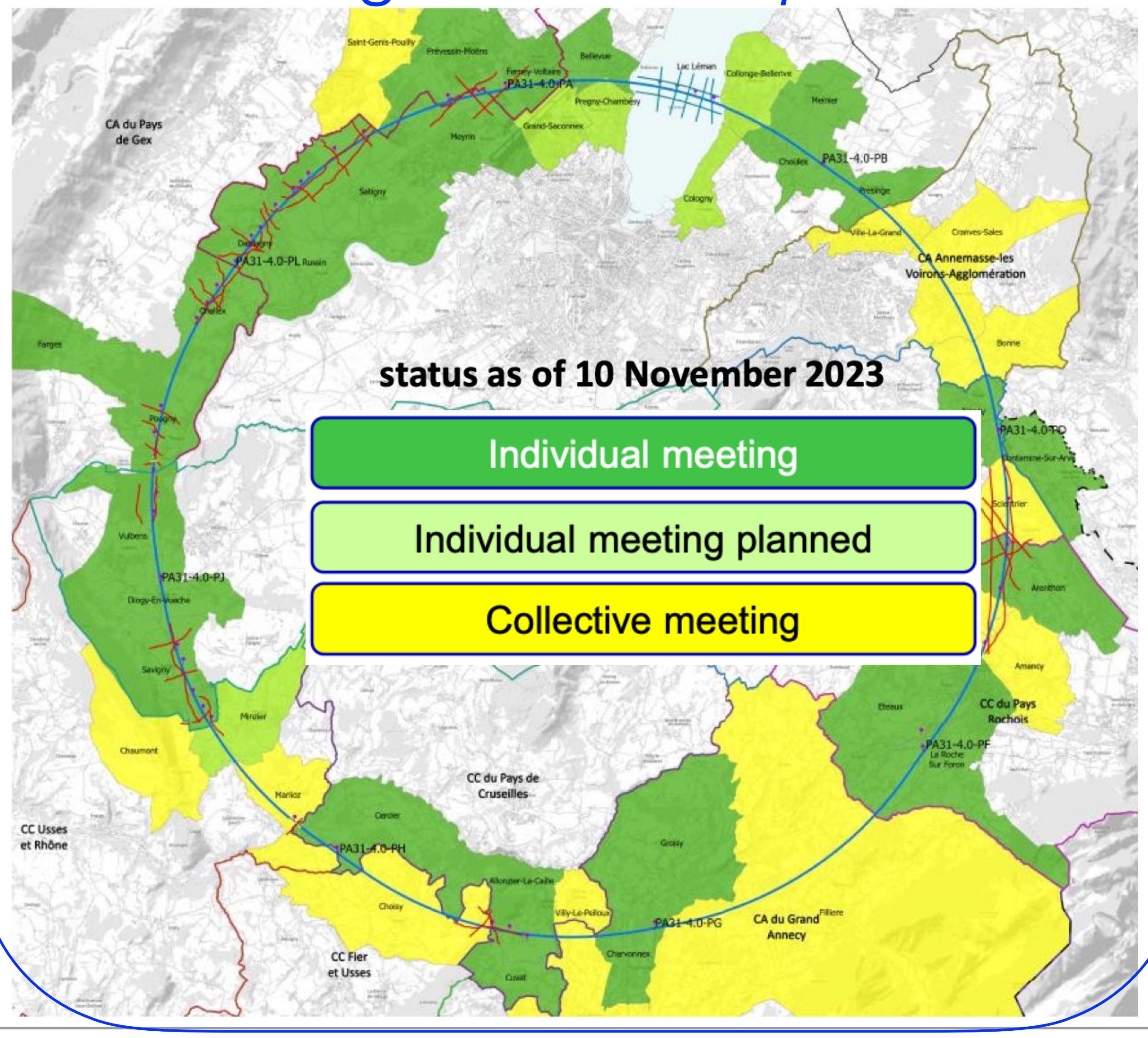
M. Benedikt

Logistic aspects

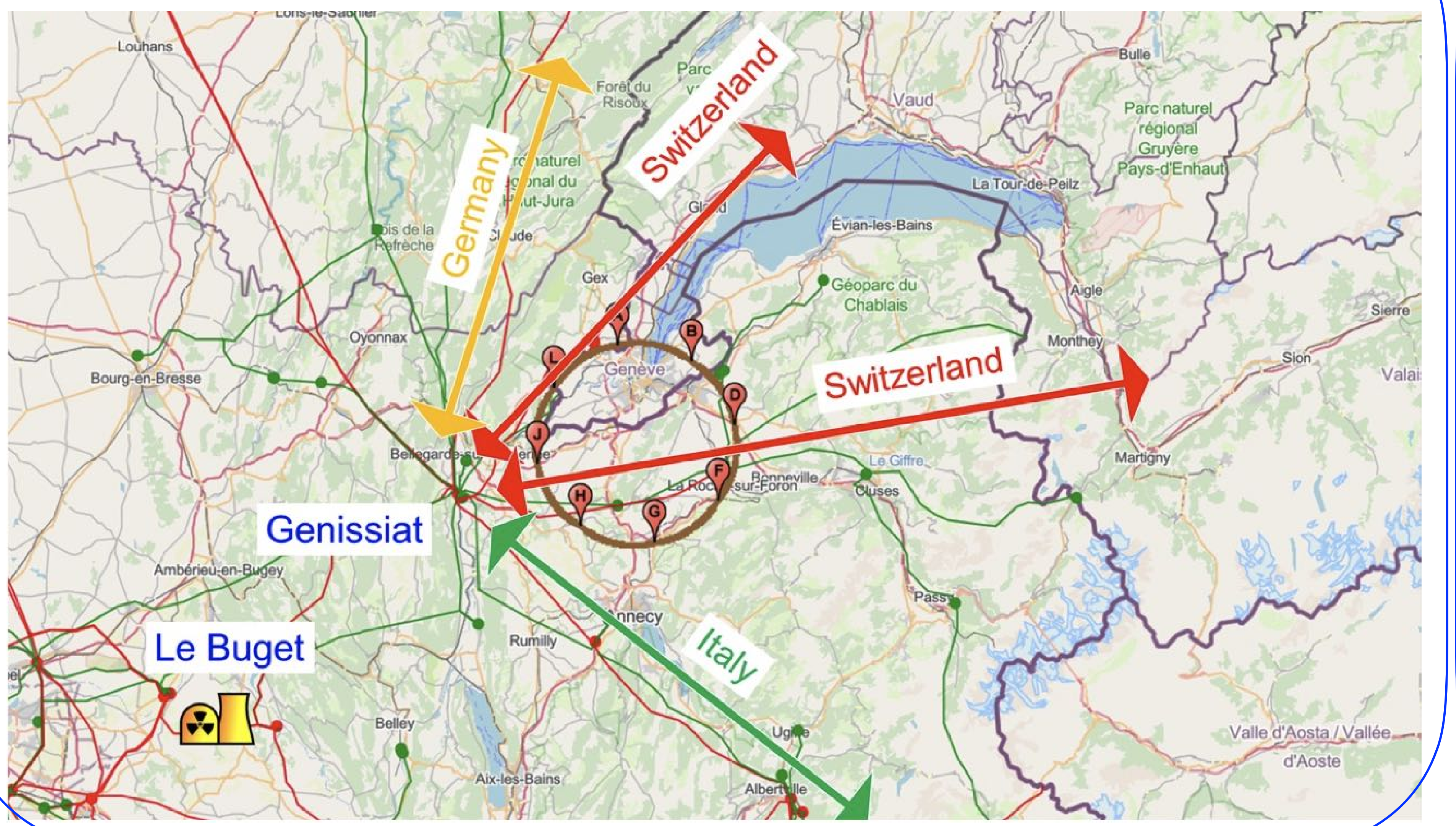
- **Geology & surface constraints / connection to electrical grid & transport infrastructures / resistance from local communities ..**
- Good progress on all these points from FCC-ee
  - Layout chosen out of ~100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment, (protected zones), infrastructure (water, electricity, transport), machine performance etc.
  - Environmental studies and preparation of geological investigations ongoing since Feb 2023, working with FR and CH to get authorisations for start of seismic investigations and drillings in Q2 2024
  - Several meetings with municipalities concerned either done or scheduled
  - Electrical connection concept was studied and confirmed by the French electrical grid operator (RTE)
  - Detailed road & highway access/creation study carried out by public expertise agency, including regulatory requirements

M. Benedikt

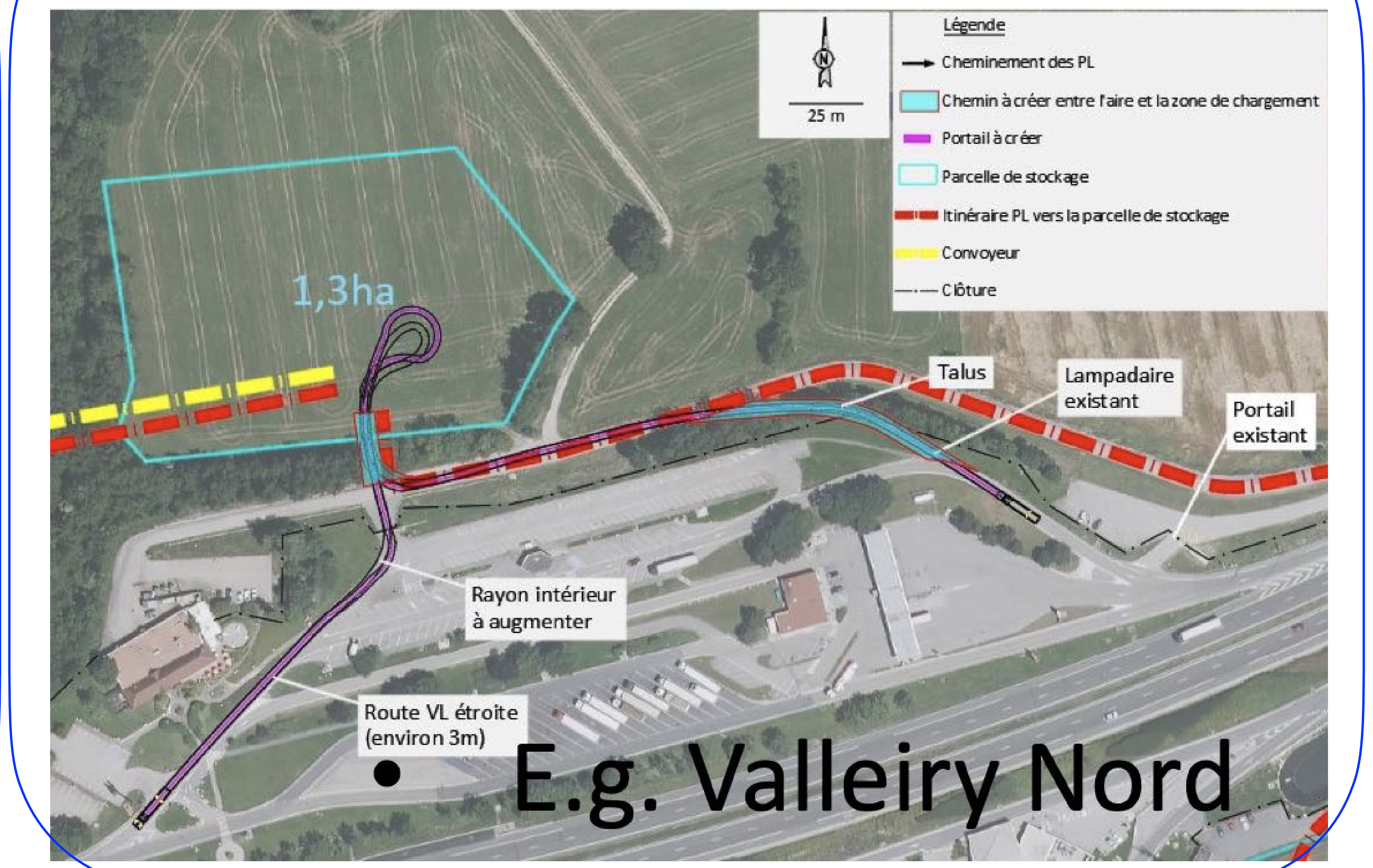
Meetings w/ municipalities



Electrical connection studies



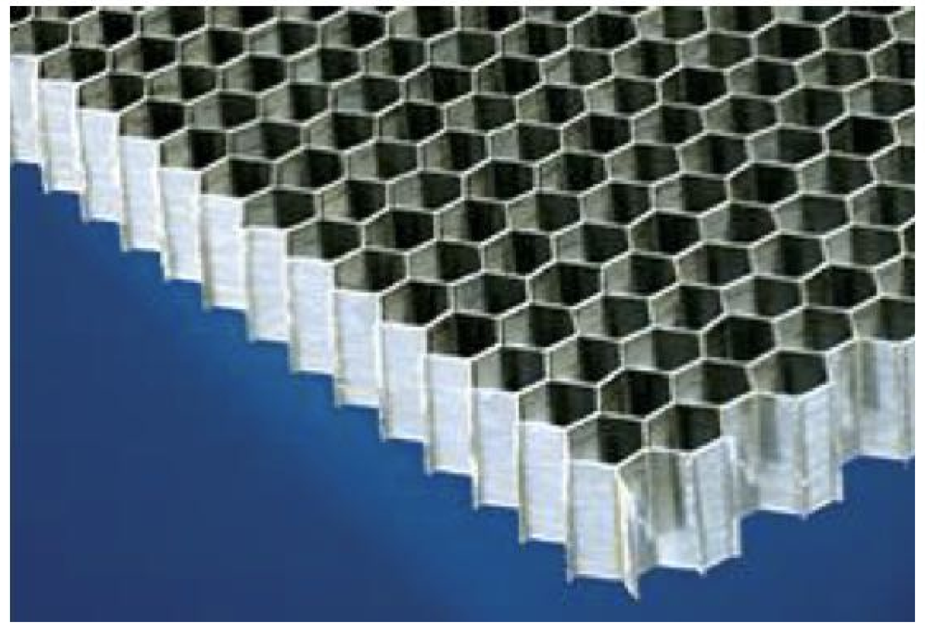
Road access studies

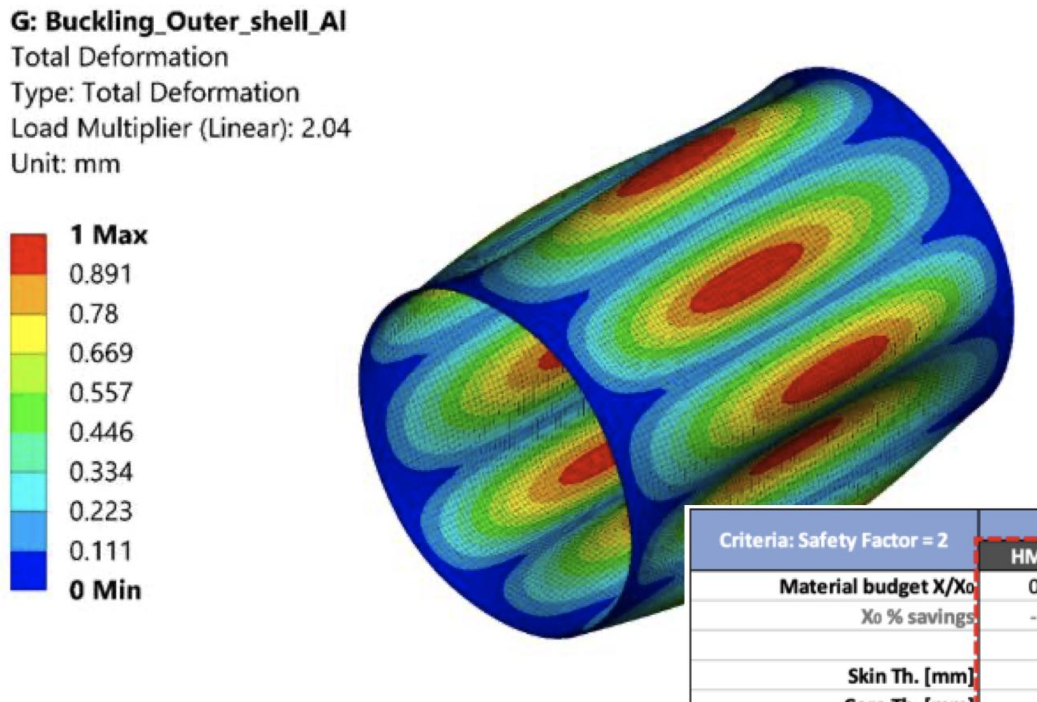


Detector magnet

Detector magnet R&D

- H-factory experiments will feature **big superconducting solenoids providing few T fields for charged particle tracking**
- Main lines of R&D (in sparse order):
  - **Vacuum vessel technology:**
    - For ultra-transparent magnets for detectors (e.g. IDEA @FCC) with magnet inside calorimeter
    - Effort within CERN EP R&D WP4 to optimise transparency through smart geometries (such as honey-comb structure) and novel materials (carbon-fibre vacuum-vessel wall) => 1/10th wrt solid Al vessel

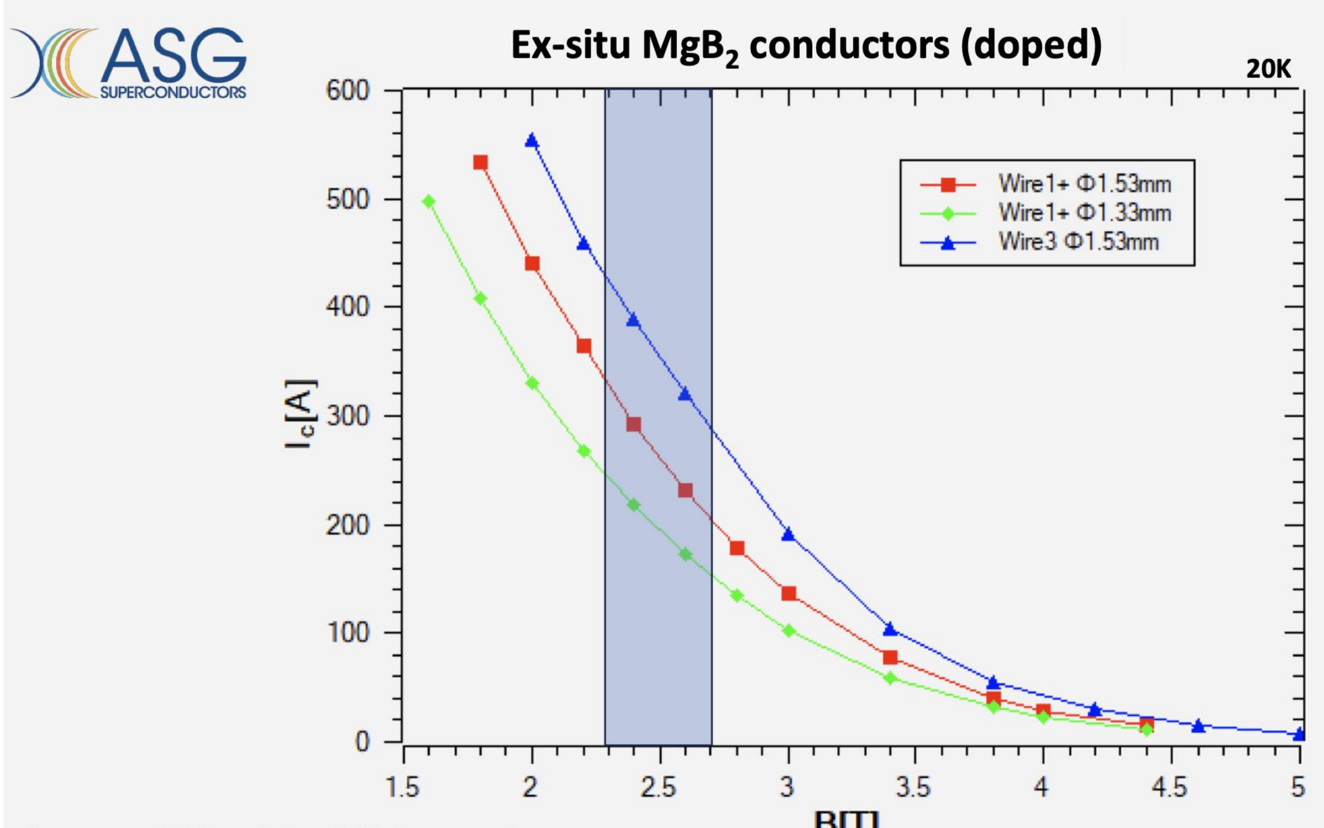




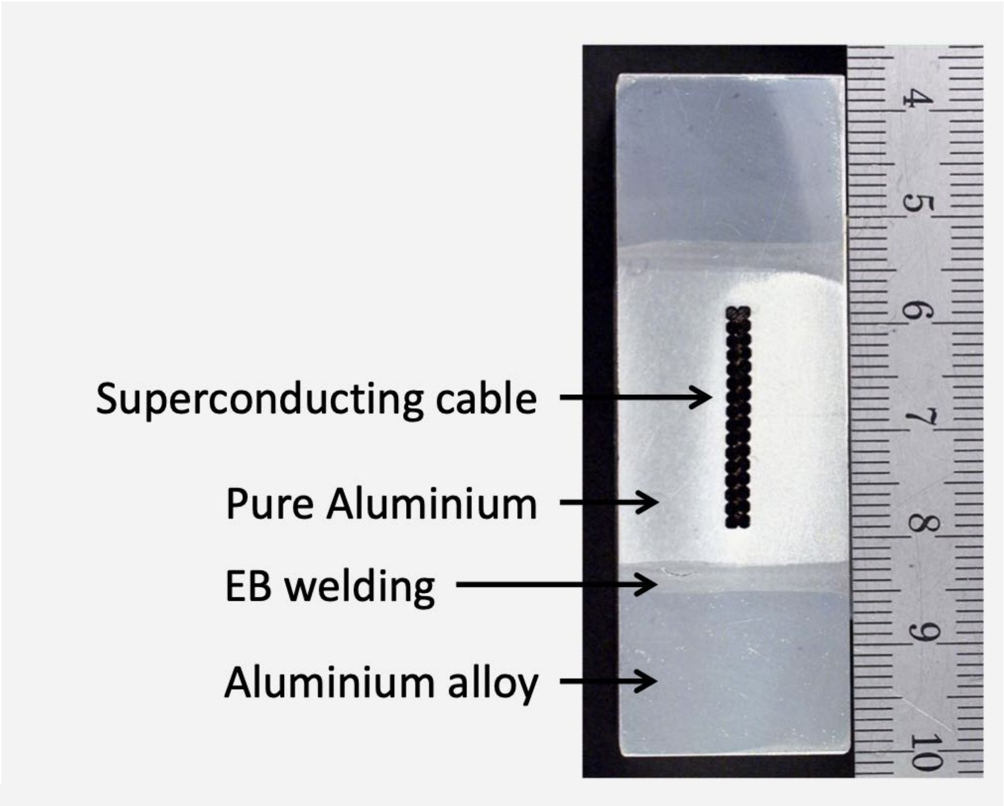
Criteria: Safety Factor = 2	Honeycomb Al		Solid shell	
	HM CFRP	Al	HM CFRP	Al
Material budget X/Xo	0.017	0.045	0.065	0.24
Xo % savings	-62%	REF	44%	433%
Skin Th. [mm]	1.6	1.7		
Core Th. [mm]	26	40		
Total Th. [mm]	29.2	43.4	16.8	20.9
Thickness % savings	-33.00%	REF	-61%	-52%

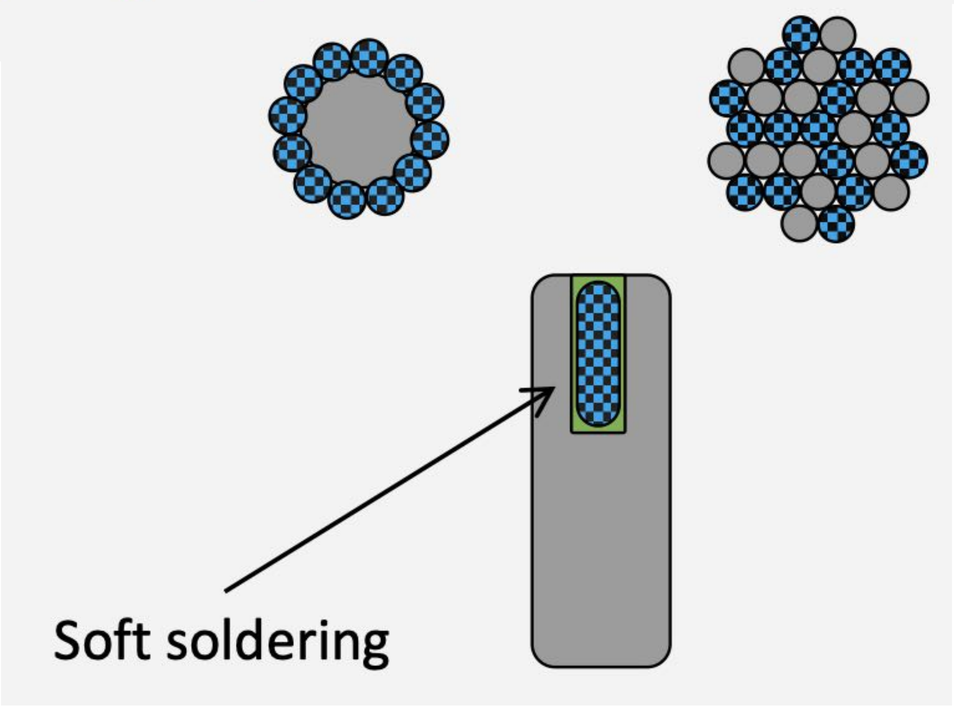
Transparency comparison of different materials for FCC-ee IDEA Solenoid (Courtesy M. Barba [15])

  - **Conductor technology:**
    - Commercial availability of Al-stabilised Nb-Ti conductor used in all modern experiments has been an issue in recent years => joint CERN+KEK effort to see how to re-establish availability
    - New types of conductor being investigated e.g. magnesium-diboride (MgB_2) for IDEA solenoid (Rare-earth barium copper oxide for CEPC)
      - T_C=39K, would allow operating the magnet at T>10K
        - => lower costs: more efficient cryogenics -> less power needed; higher adiabatic stability -> no need for Al matrix as stabiliser, just for protection -> less demanding in terms of Al purity and of quality of bonding between cable and Al (cabling/soft soldering)



Courtesy of Tiziana Spina, ASG-Superconductors

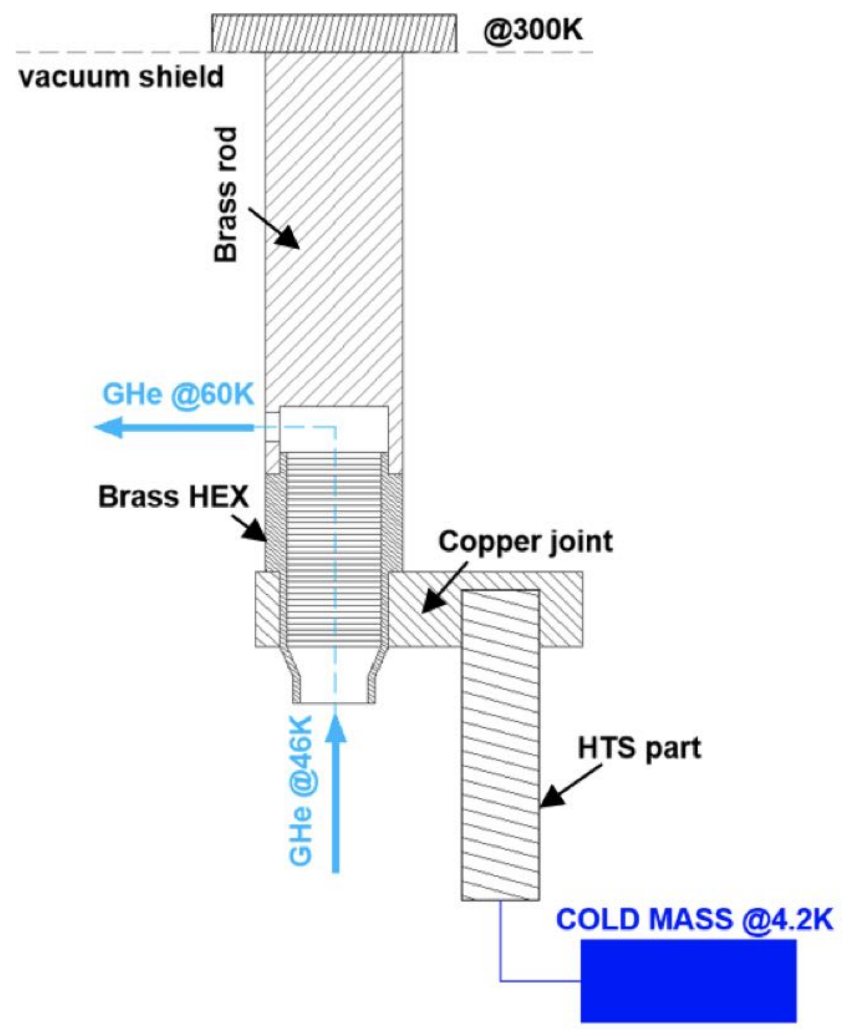




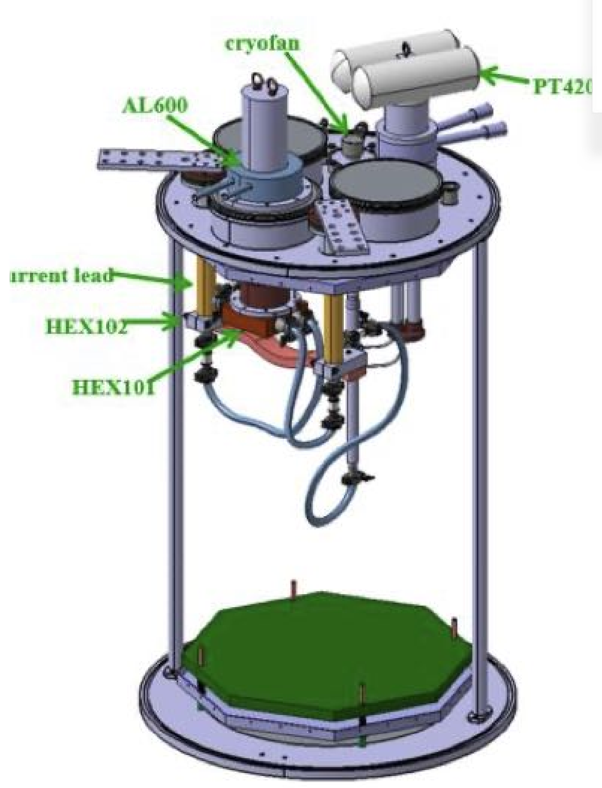
M. Mentink, M. Bracco

Detector magnet R&D

- Main lines of R&D (continued from previous slide):
  - **Cryogenics**:
    - "standard" solution based on gravity-powered circulation of 4.2K liquid helium well understood & reliable, but
      - Liquid helium price increasing fast and future availability a concern
      - Requires big cryogenic plant with long transmission lines
      - Power consumption not negligible: ATLAS ~3MCHF/year => >50% of magnet cost after 30 yrs of running
    - Novel solutions under study
      - HTS intermediate section so that >99% of the dissipation between power converters at room temperature and magnet at 4.2K takes place at ~50K => 10x less power
      - Use of cryocoolers closer to magnets => only modest amount of He needed, liquified locally => more redundancy, higher efficiency, lower costs
  - **Quench detection and protection**:
    - Well-understood and works well for Al-NbTi magnets, more challenging for HTS magnets
    - CERN EP R&D WP8 has developed concepts that tackle both issues
      - demonstration with demonstrator coil planned



Concept of an HTS-based current lead (Courtesy W. Gluchowska)



Demonstrator setup, featuring cryo-coolers, cryofan, heat exchangers, HTS-based current leads (CERN EP WP8, Courtesy W. Gluchowska)

M. Mentink

Detector

Physics drivers and target performance

The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e+e-

- Advancing HEP detectors to new regimes of sensitivity
- Building next-generation HEP detectors with novel materials & advanced techniques

C. Vernieri

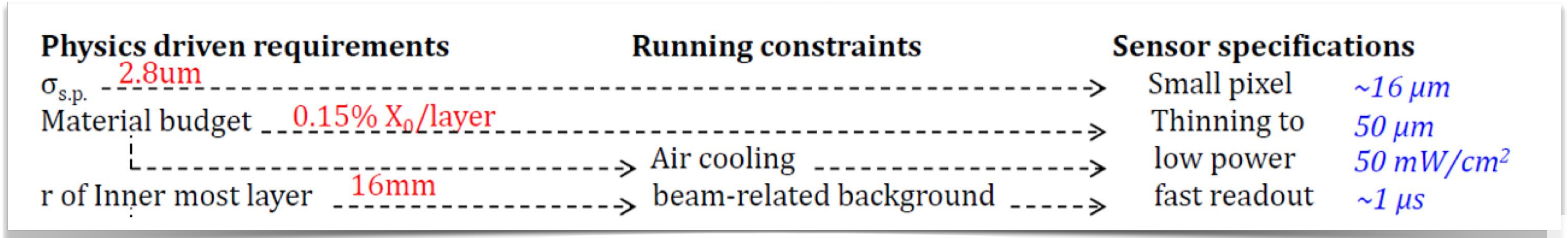
Initial state	Physics goal	Detector	Requirement	
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV	Track momentum resolution
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV	
		Calorimeter	4% particle flow jet resolution	Jet energy resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2	EM energy resolution
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$	Timing
			shower timing resolution 10 ps	
	$hb\bar{b}/hc\bar{c}$	Tracker (vertex)	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu$m	Impact parameter resolution
			5μm single hit resolution	

Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

Additional requirements on particle identification (PID):
desirable for Higgs physics (further improve precision in some channels), crucial for flavour physics

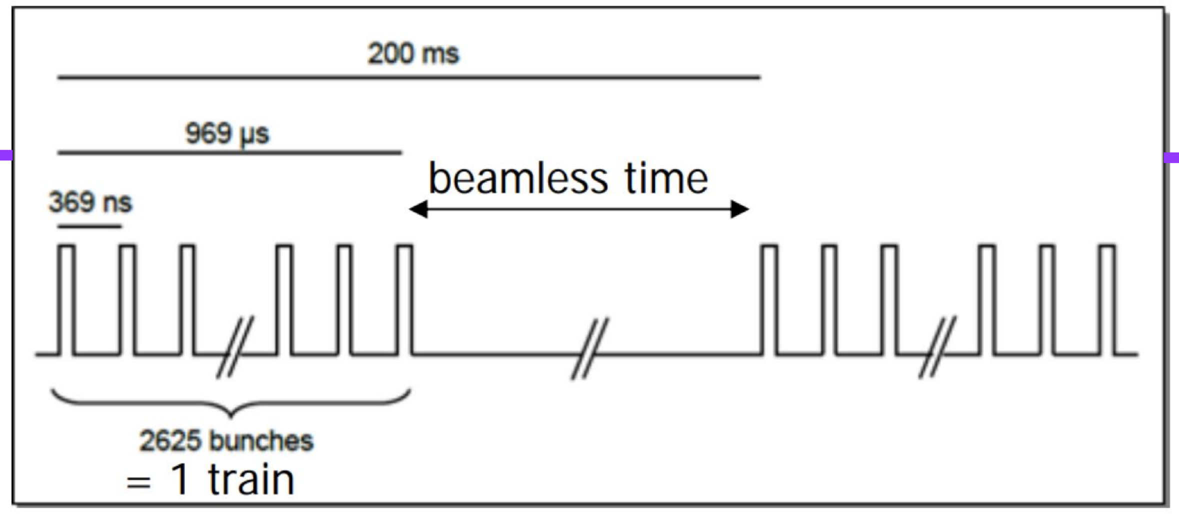
Vertexing with Si detectors

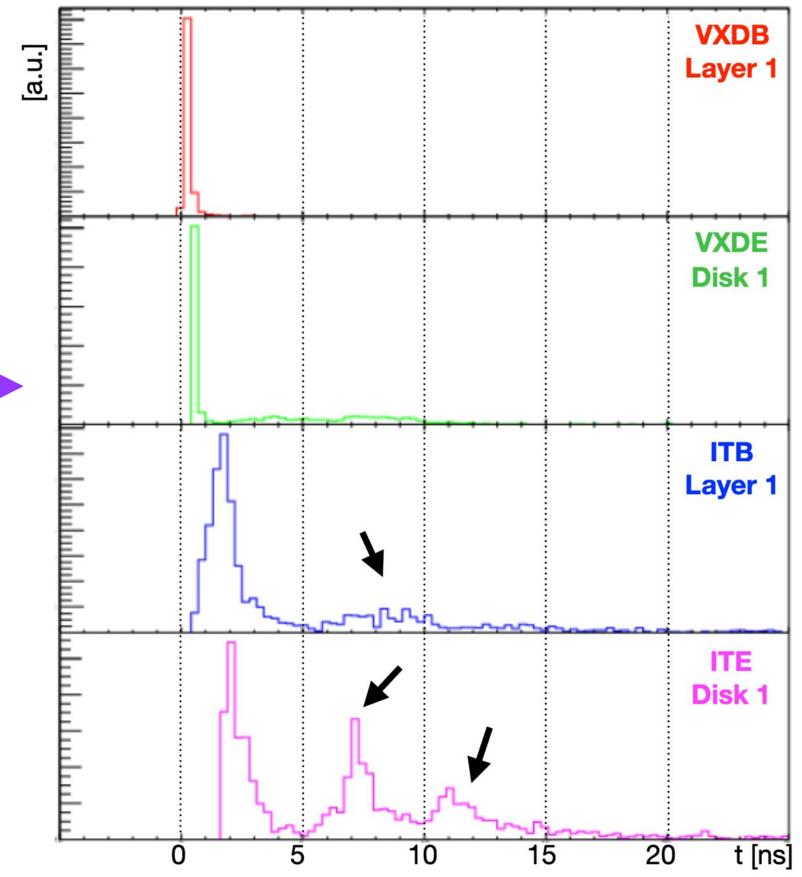
- Jet flavour tagging (for e.g H->bb/cc/ss..) => very precise track impact parameter resolution => low-mass Si trackers near IP
  - 5 μm hit resolution or better, with <~0.15% X_0 per layer for vertex detector



- Good timing resolution can be an additional handle for improved performance
  - 1-500 ns: bunch identification
  - 1-10 ns: bkg rejection
  - 10-100 ps: PID with time-of-flight (TOF)

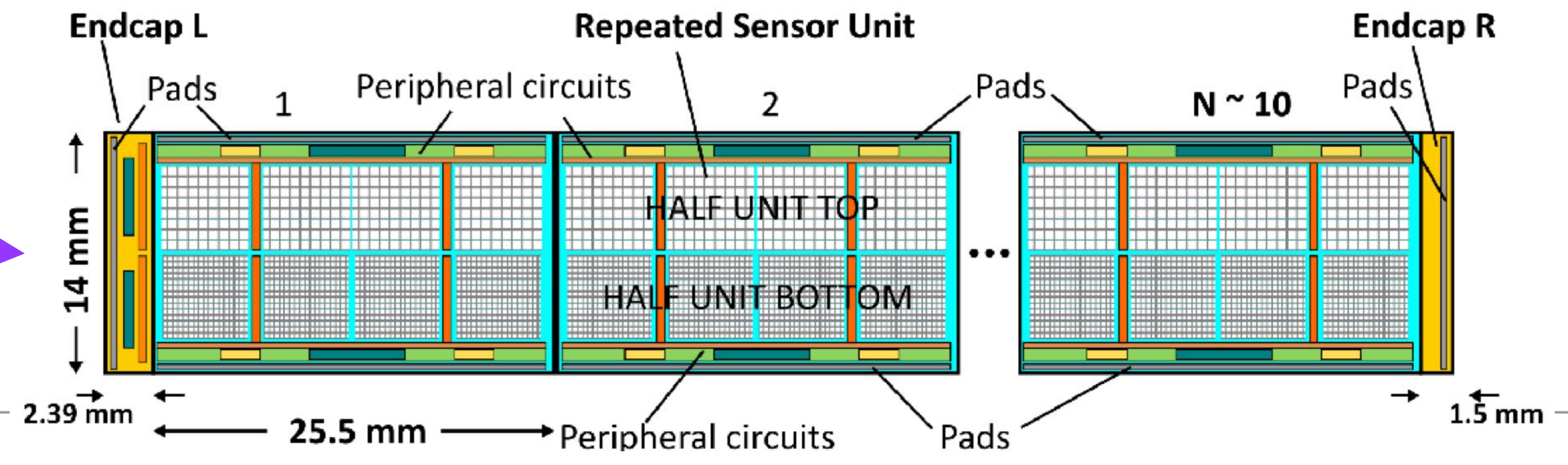
ILC Timing Structure





Bkg hits from incoherent pair creation in FCC-ee CLD detector

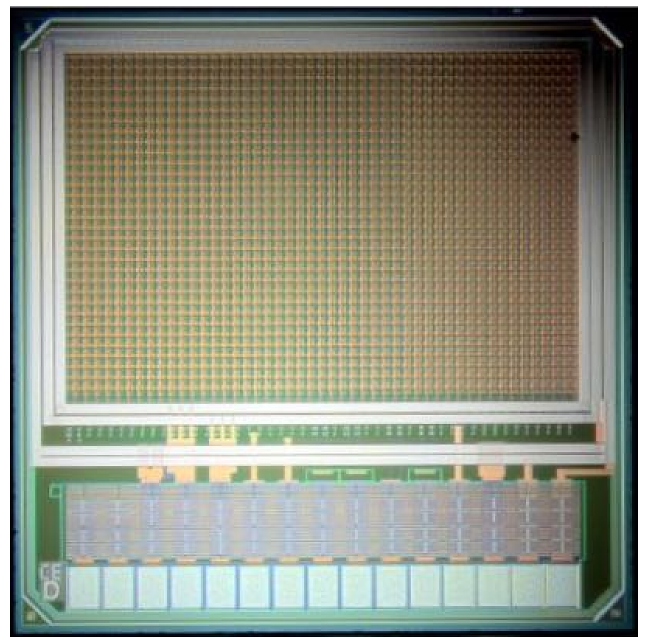
- A lot of R&D ongoing for Higgs factories as well as other future projects e.g. ALICE ITS3
  - all based on **M**onolithic **A**ctive **P**ixel **S**ensors (electronics and sensor on same wafer => can be extremely thin, ~50um or even less)
  - general trends: use technologies with small feature size (65-110 nm) to reduce power consumption or add more features; target big sensors (up to wafer size) through use of "stitching" (step-and-repeat of reticles) to reduce further the overall material budget



Vertexing with Si detectors

CE65 project: MAPS in 65nm process towards ALICE ITS3 and Higgs factories

Z. El Bitar

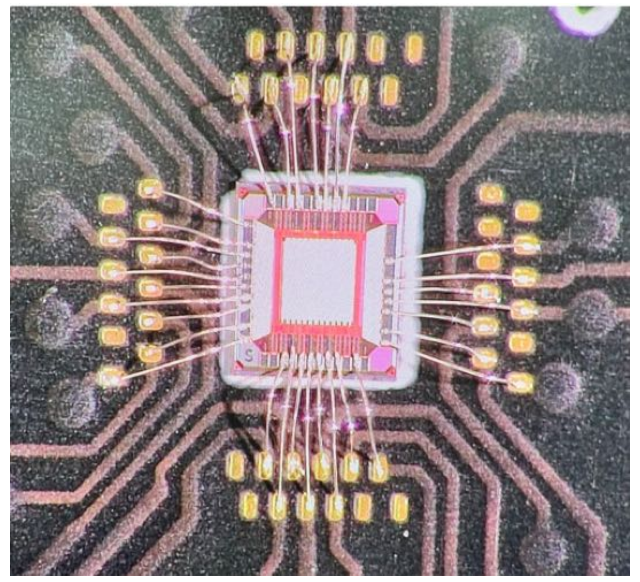


Various designs (different pitch, in-pixel architecture, ..) tested with beam: **3-4 μm resolution** (15-25) μm pitch, >99% efficiency

NAPA: MAPS with **ns timing**

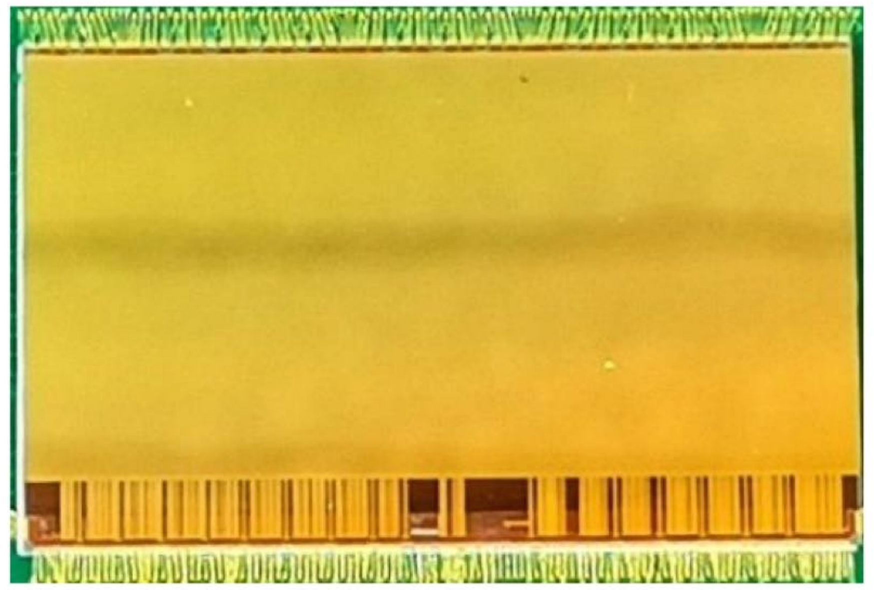
C. Vernieri

	Specification	Simulated NAPA-p1	
Time resolution	1 ns-rms	0.4 ns-rms	✓
Spatial Resolution	7 μm	7 μm	✓
Noise	< 30 e-rms	13 e-rms	✓
Minimum Threshold	200 e-	~ 80 e-	✓
Average Power density	< 20 mW/cm²	0.1 mW/cm² for 1% duty cucle	✓



First prototype (p1) produced in 65 nm process
5x5 mm², 25 μm pitch
Chip characterization ongoing
Design of large sensor prototype (5x20 cm²) ongoing

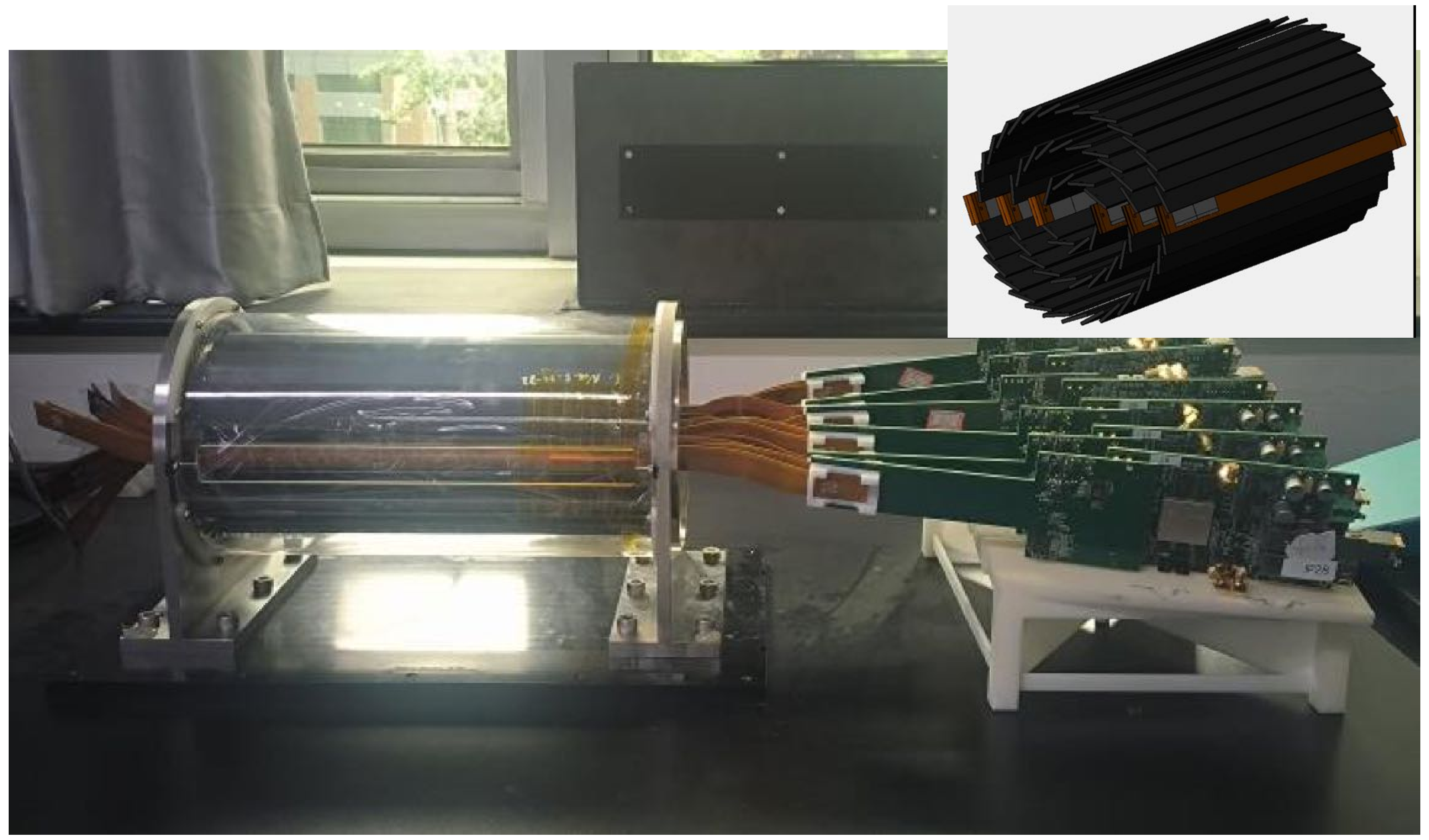
TaichuPix: MAPS in 180 nm process for CEPC



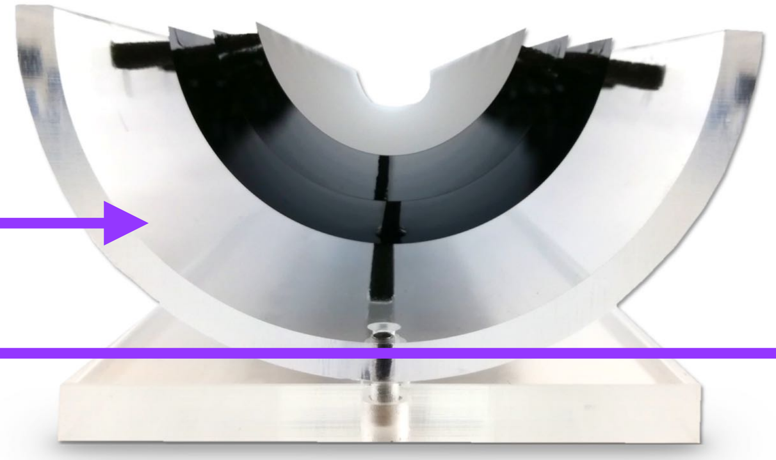
TaichuPix-3
(15.9 × 25.7 mm²)

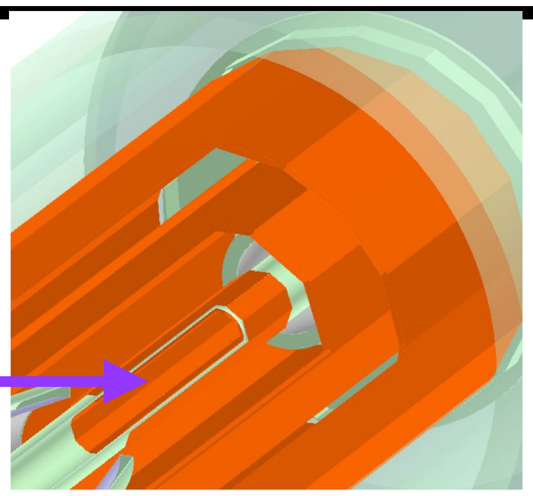
Z. Liang

16x26 mm² with 25 μm pitch
Thinned to 150 μm
Tested with beam: **4.5 μm hit resolution**, >99% efficiency, **35 ns track time resolution** @20 MHz clock
6-layer detector prototype assembled and tested, with **air cooling** on => 60 mW/cm², 41C ->27 C with 2m/s flux, resolution unaffected
Further work to reduce material budget: thinner sensor (150->50 μm), replace Cu->Al in flex



- Further directions of R&D:
  - Bent sensors to reduce material budget (currently planned for ALICE ITS3)
  - A layer-0 inside the beam pipe being investigated by CEPC





Tracking with Si detectors

- Thin Si detectors (with looser requirements than for the vertex) can also be used for the main tracker (or part of it)
- Possibly use Si detectors for wrapper around a gaseous main tracker (TPC, drift chamber) => high-res point for extrapolation to calo
- Timing with few 10 ps resolution for TOF could be provided in Si wrapper or in dedicated layers of full-Si tracker — without compromising other requirements especially for inner layers (material budget, granularity)

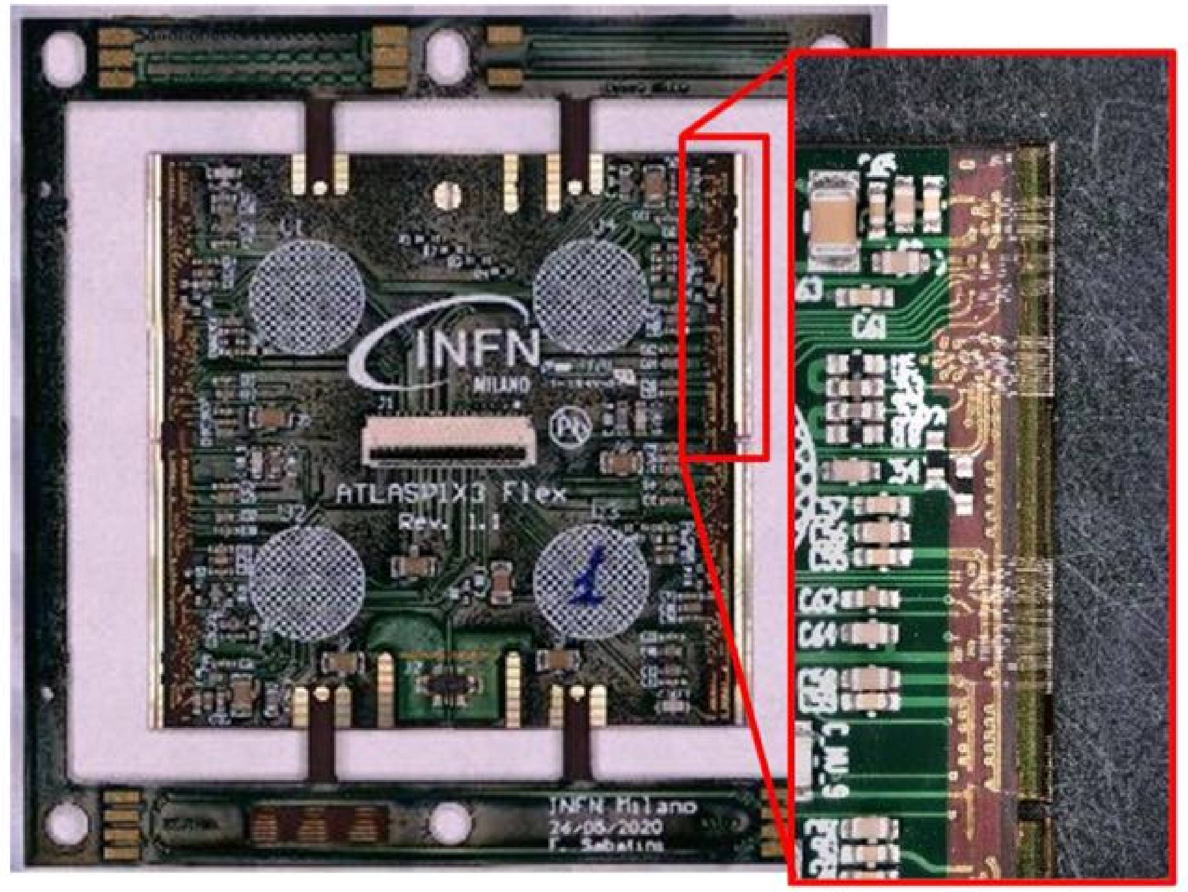
ATLASPIX3 (KIT, China, INFN, UK)

full reticle size detector, implementing most features needed for Internal Tracker and Si Wrapper

- 180 nm HVCMOS monolithic sensor
- 20×21 mm^2, assembled in quad modules
- pixel size 50×150 μm^2 (25×150 on recent proto)
- 25 ns timestamping

Tested with beam: > 99% eff, resolution **~10 μm**

Latest version can be biased by **serial powering** => less cables/power losses



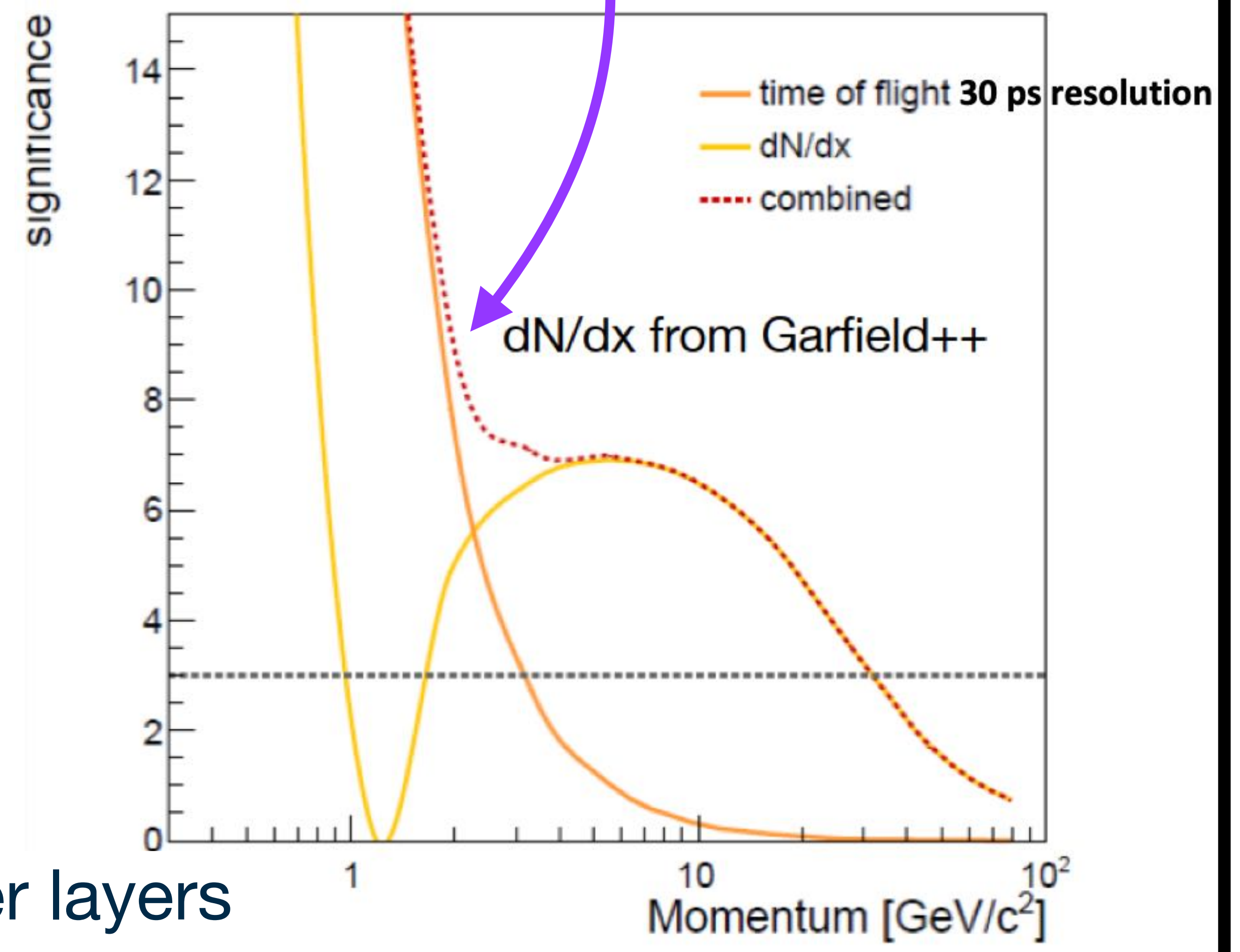
A. Andreazza

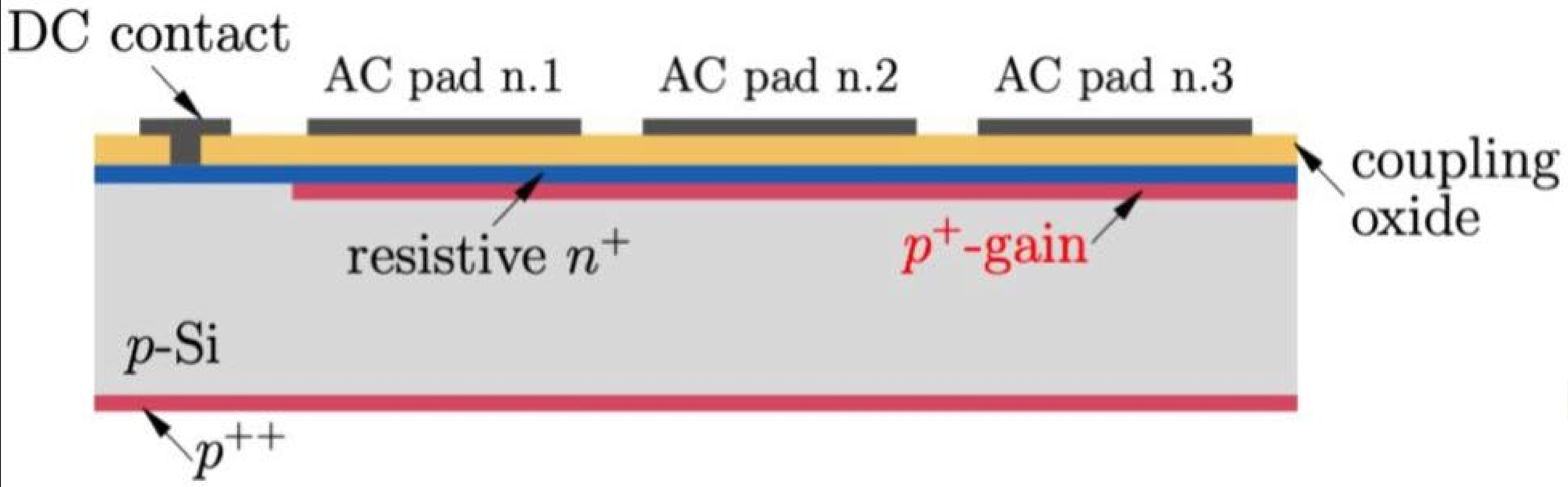
Timing layer with **resistive silicon detectors (RSD)**

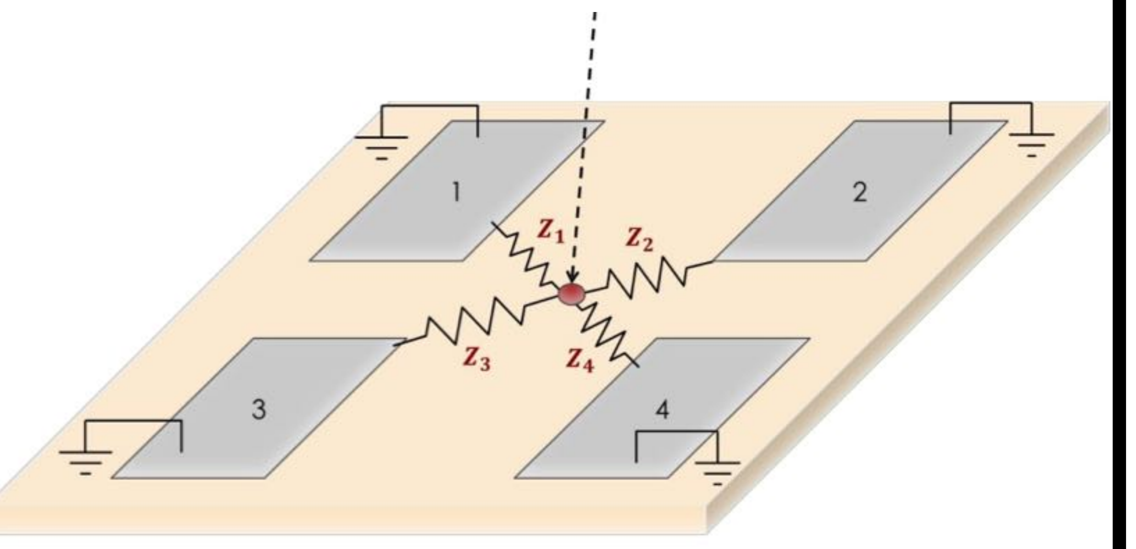
- LGAD sensors with continuous gain layer, charge collection through resistive n-layer, readout on AC-coupled pads
- Position of track determines charge sharing on pads (impedance of path between charge deposition and electrodes)

  good resolution even with large pitch (**10 μm** achieved in lab with 200 μm pitch)
- More space in readout pixel cell to implement precision TDC (**35 ps** time resolution so far)
- Hybrid detector => more material => OK in outer layers

A. Andreazza

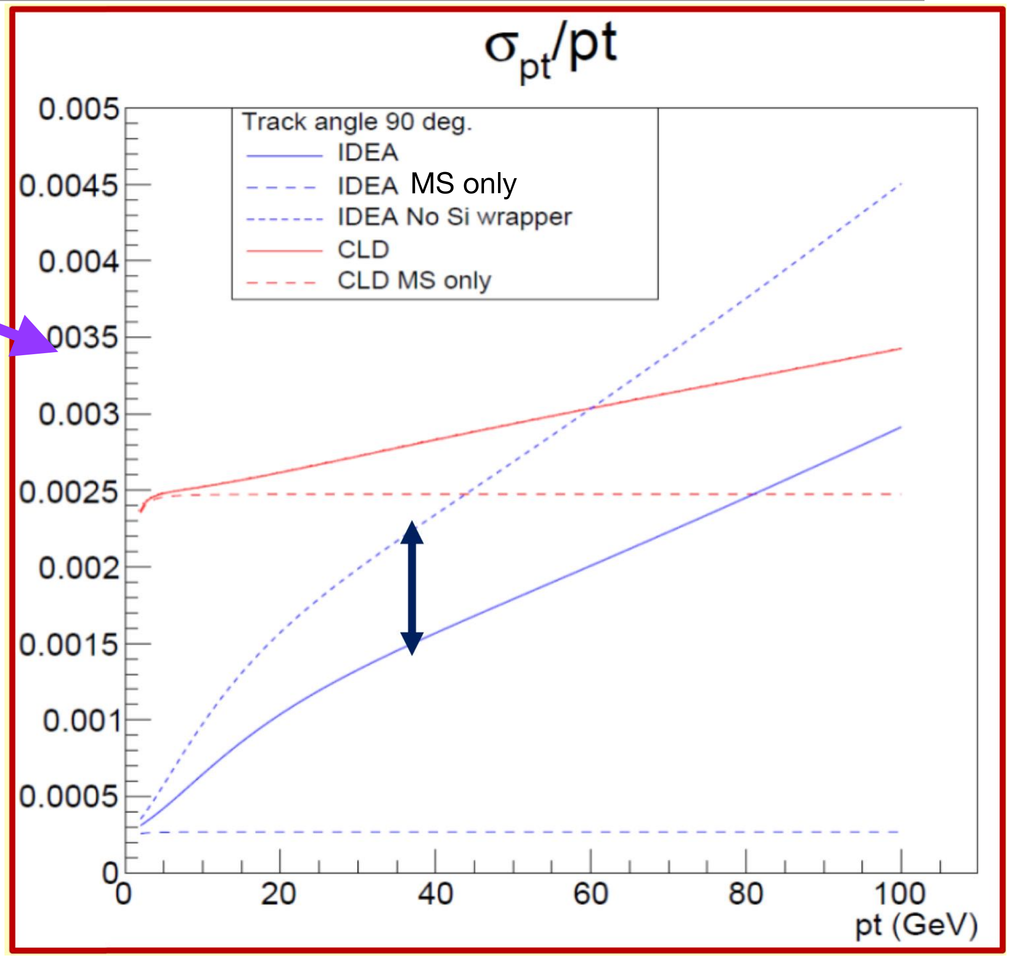




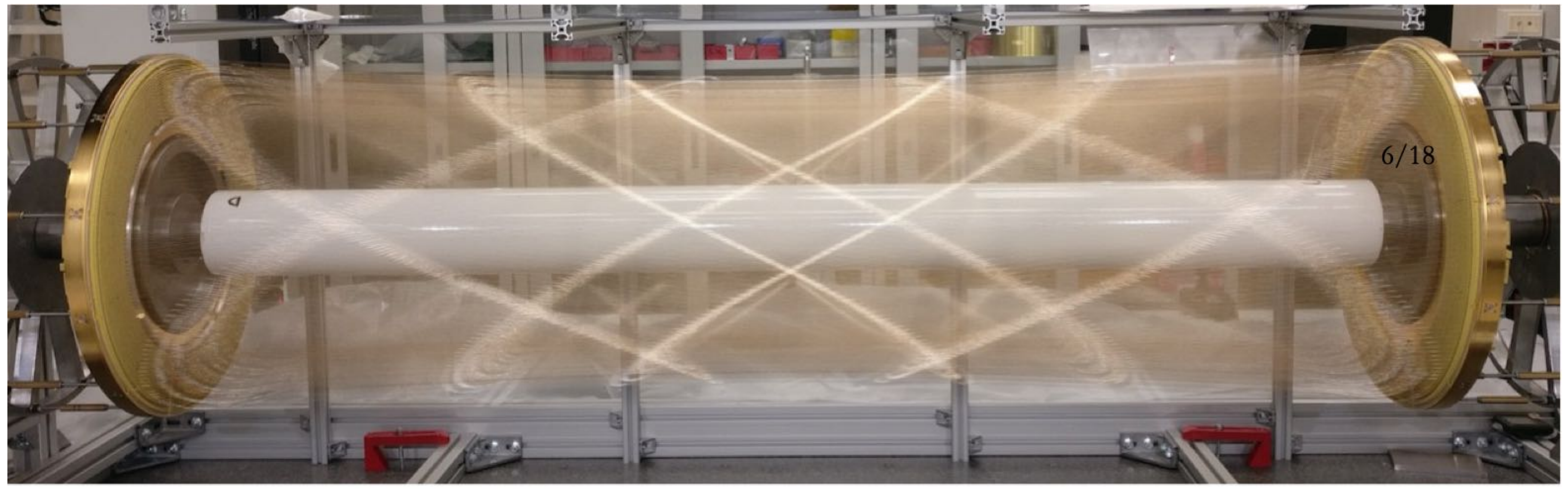


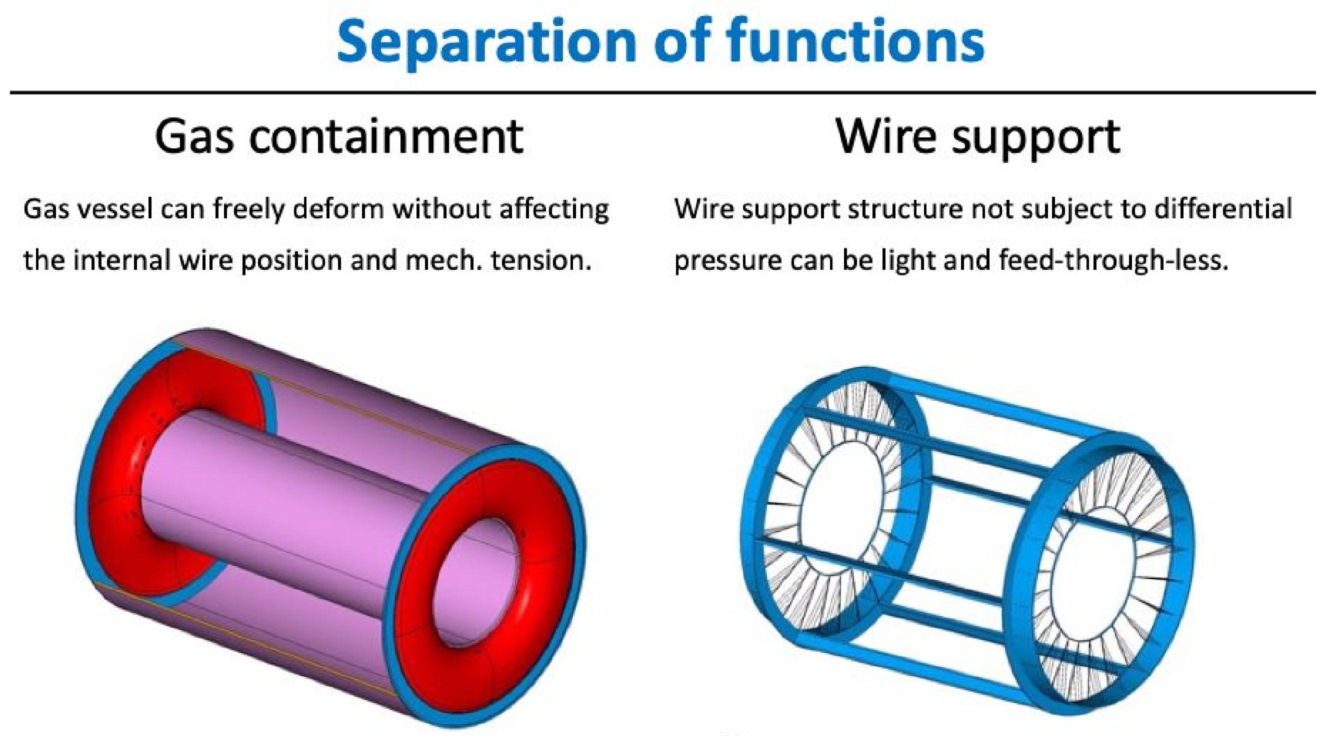
Tracking with gas detectors: drift chambers

- Despite intrinsic hit resolution is smaller wrt Si, gas detectors with many dense sampling layers can provide similar track momentum resolution, and much smaller material budget => better overall resolution at low p_T
- Gaseous tracker can also provide PID at p>few GeV via ionisation loss measurement (dE/dx or dN_{cl}/dx)
- Drift chamber proposed for FCC-ee IDEA detector, evolution of MEG2 design - 1.6% X_0 at 90 degrees

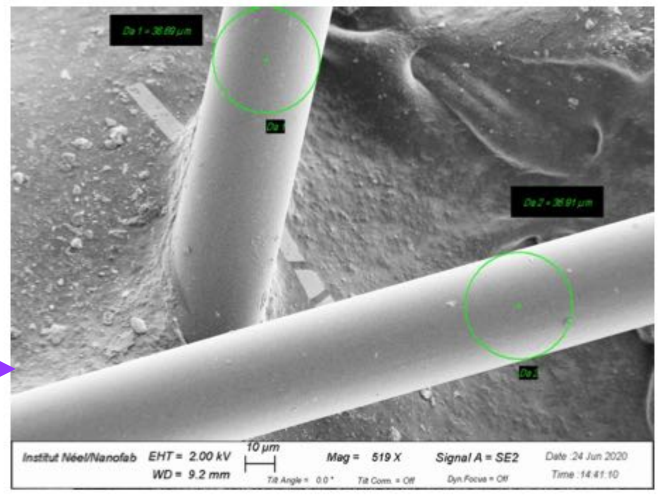


F. Grancagnolo

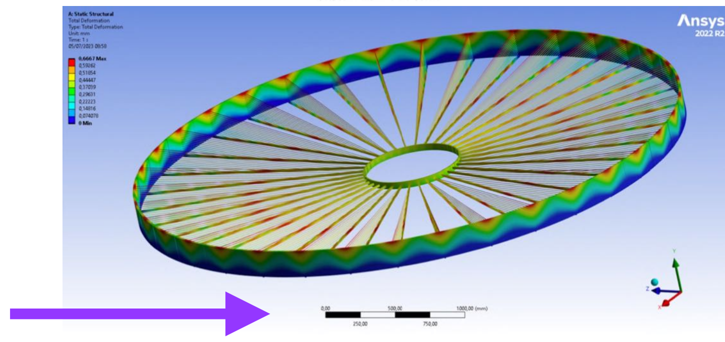


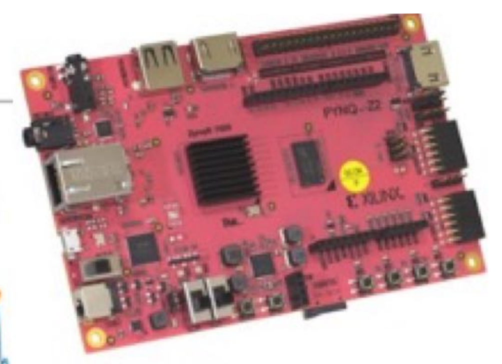


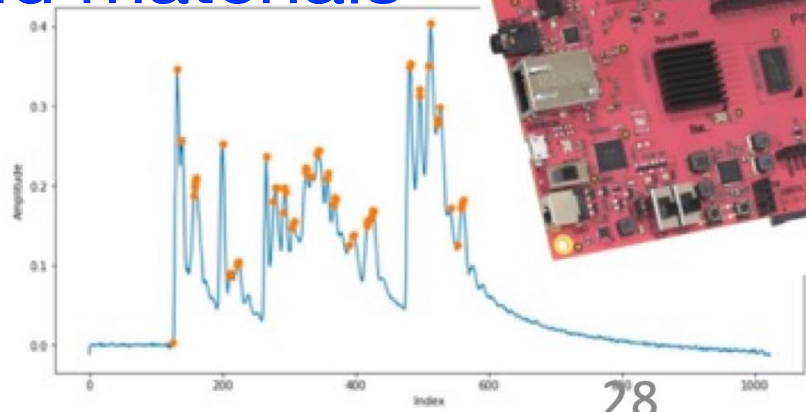
- Significant **challenges** being addressed by current R&D activities:
  - **Wires** (material/radius/number..): in baseline design with 20 μm W and 40-50 μm Al wires and cell size ~1.2 cm, very little margin for wire tension T_c to satisfy both electrostatic stability and elastic limit conditions (Al: 26< T_c <36g) => R&D on (2 μm) Ag coated 35 μm C wires (30<T_c<87g with 10% larger cell and ~60% more wires, but -40% X0)
  - **Overall mechanical structure**:
    - huge number of wires (N_W~400k) + avoid massive feed-through => R&D on (feed-through-less) wiring with robot
    - support structure: huge load (10-20 tons depending on N_W and T_c) w/ little deformation (<200 μm on spokes) to avoid spoiling resolution (100 μm), studied w/ FEM analysis (600 μm achieved) => R&D on structure and materials
  - **Data reduction** (crucial @Z pole): full detector >1 TB/s, only amplitude & time of each peak 25 GB/s => R&D on readout with ADC+FPGA/multichannel board with real-time peak-finding algorithm



Carbone wires seen from SEM

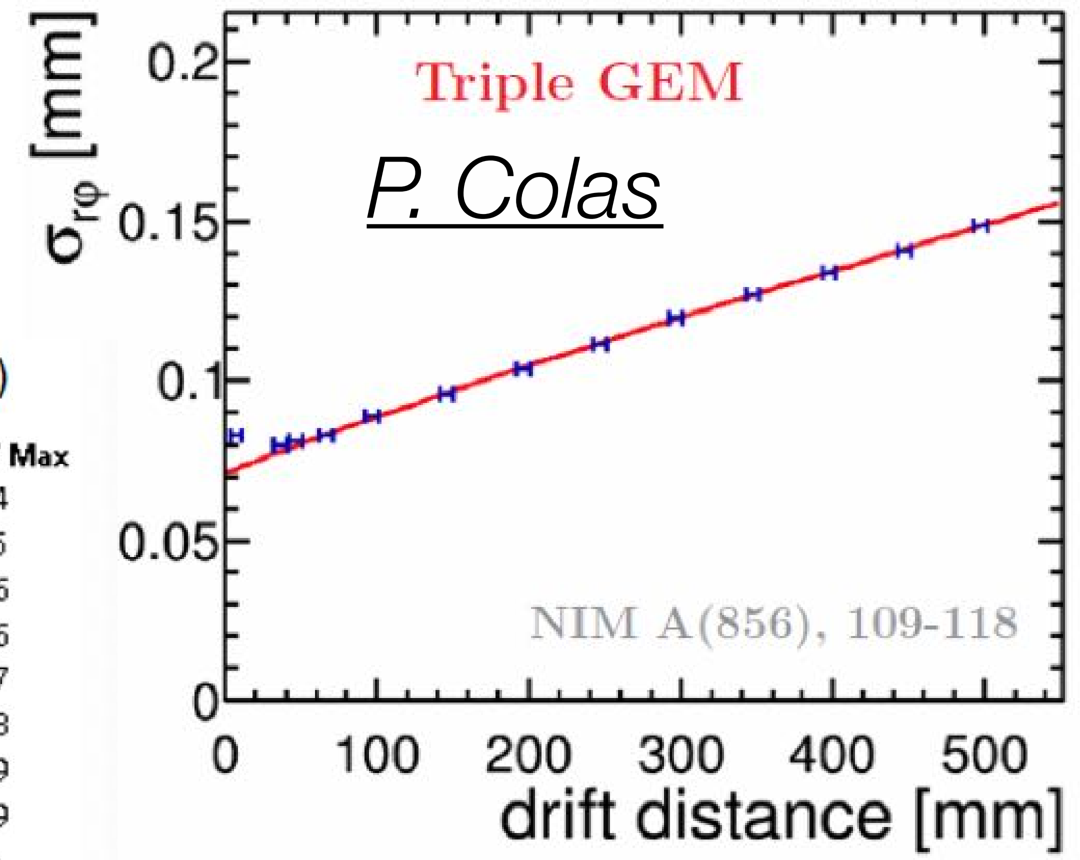


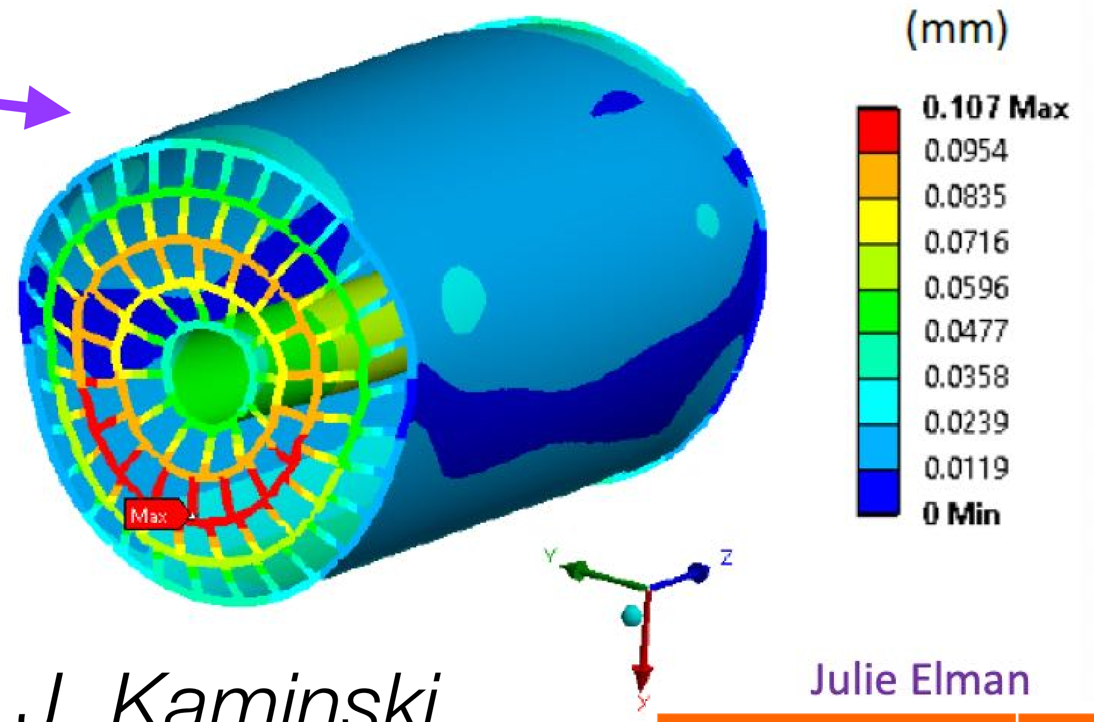




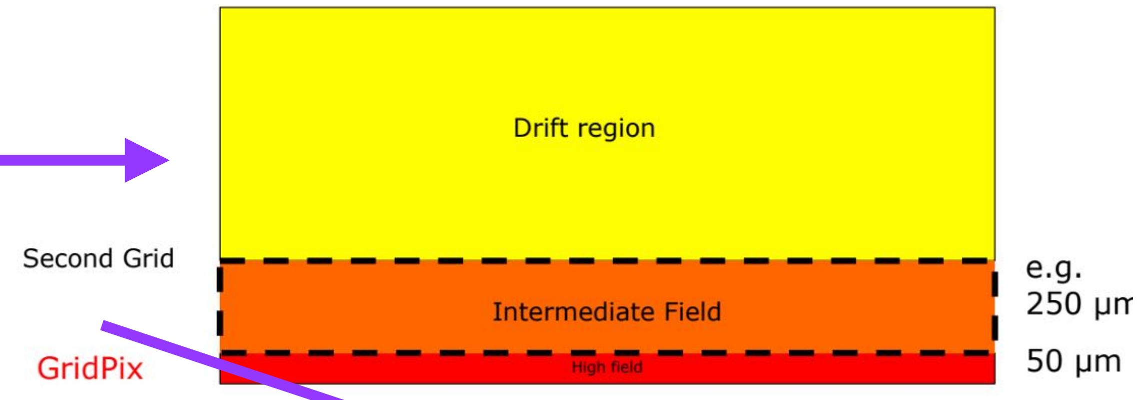
Tracking with gas detectors: TPCs

- A TPC is the main tracking detector for ILD @ILC and for baseline detector for CEPC (though new concept uses DCH instead)
- Provides 3D track reconstruction exploiting timing of drift, with much lower material budget than Si detector
- Pad (GEM or Micromegas) or pixelated (Gridpix) readout both achieve desired resolution
- Mechanical studies indicate that deformations are under control
- Power consumption not an issue for pad readout (6 kW/endplate), but large (~60 kW/endplate) with pixelated readout => R&D on 65 nm electronics at low voltage with low-consumption ADC
- **Main issue** (@Z pole): **I**on-**B**ack**F**low (positive ions going back to drift volume, creating space charge that distorts electric field) => significant R&D
  - MPGD combining GEMs + Micromegas
  - GridPix with second grid
  - Graphene layer (transparent to electrons, but not to larger ions)
  - Either of these could lead to large IBF suppression and small distortions from ee->Z events at Z pole. Beamstrahlung background more challenging (200x hit rate), requires further R&D
    - Optimise shielding in MDI region
    - Develop techniques to map E field distortions using silicon detectors (vertex detector and internal/external tracker)





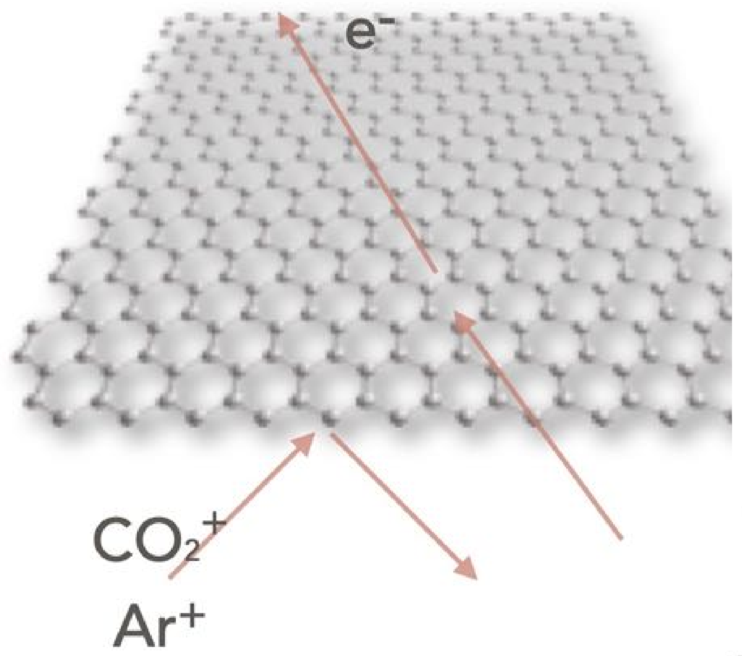
J. Kaminski

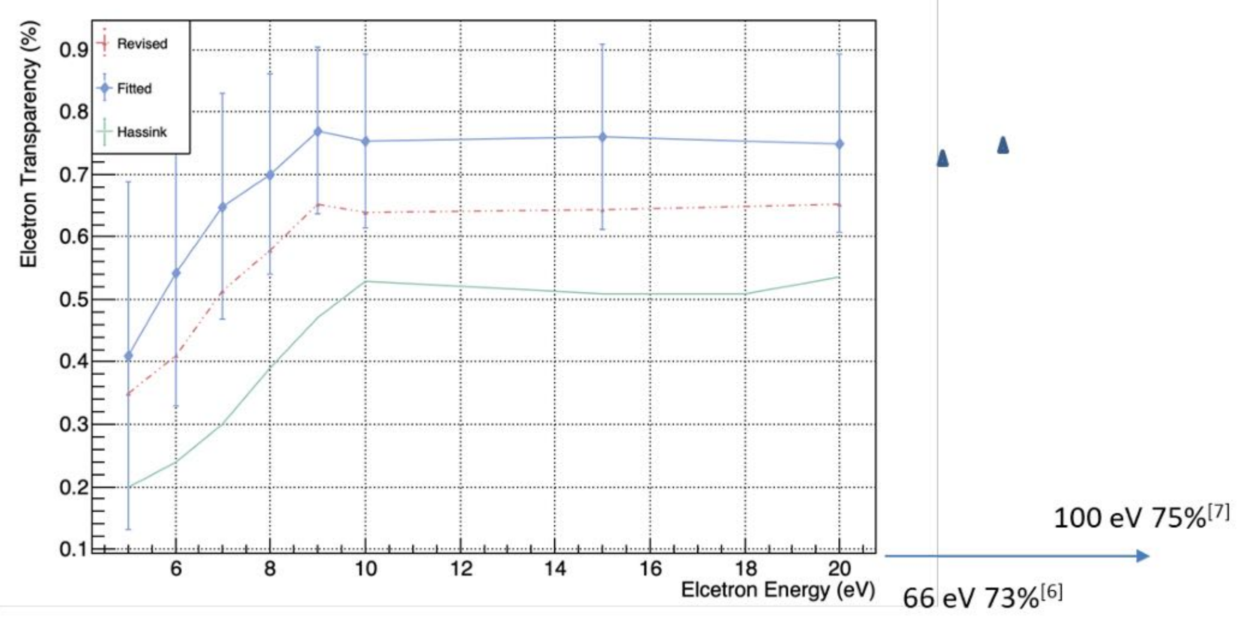


Julie Elman

Ion backflow	Hole 30 µm	Hole 25 µm	Hole 20 µm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	12 10^{-4}	3 10^{-4}	1 10^{-4}
transparancy	100%	99.4%	91.7%

K. Ja

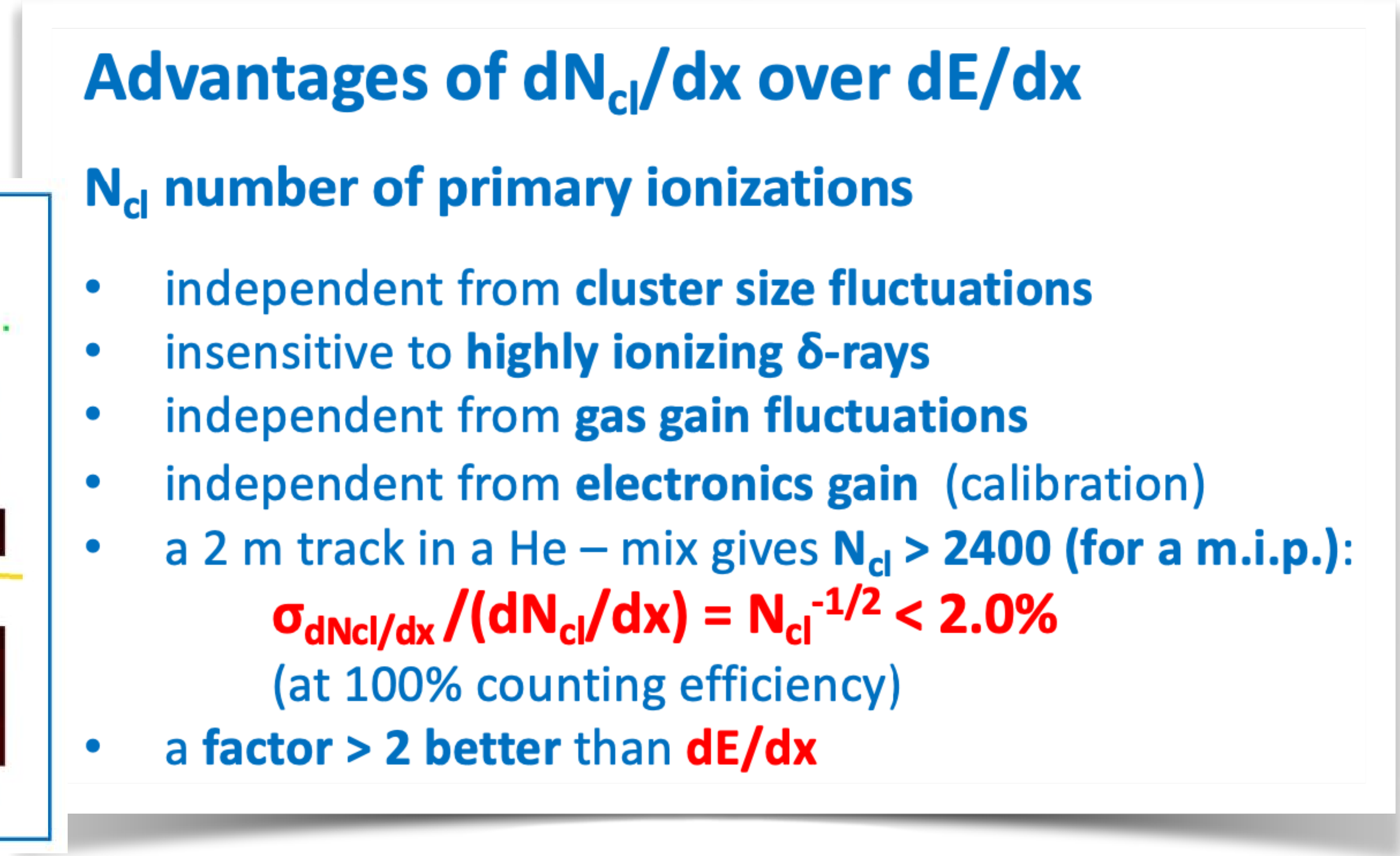




PID with gaseous detectors

- Traditional approach (since late 70's): dE/dx from total ionisation Δ (per unit length) => β
  - In the relativistic rise region: [Δ(π) – Δ(K)] / Δ(π) ≈ 10-15% => π/K separation requires resolutions better than few %
  - Resolution obtained in ~40 years saturates at ~4-4.5% — despite different gases/technologies/geometries
    - largely due to long tail in energy loss distribution from secondary interactions
    - maybe improvable with finer (x2) granularity/higher pressure/machine learning algorithms

F. Grancagnolo

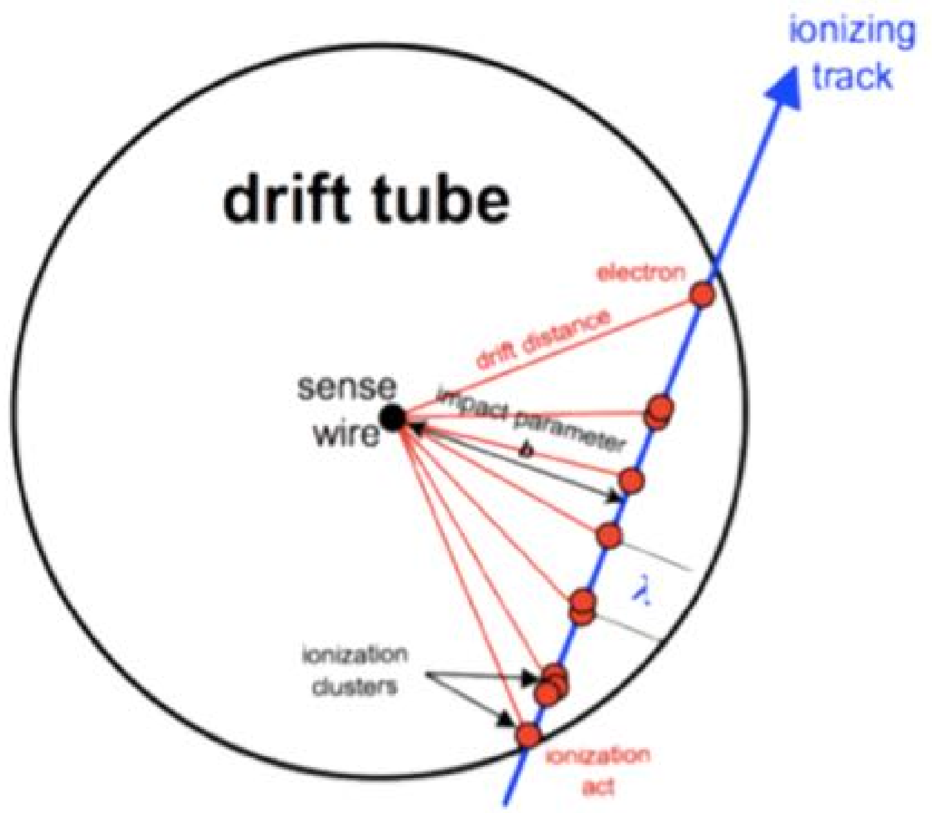


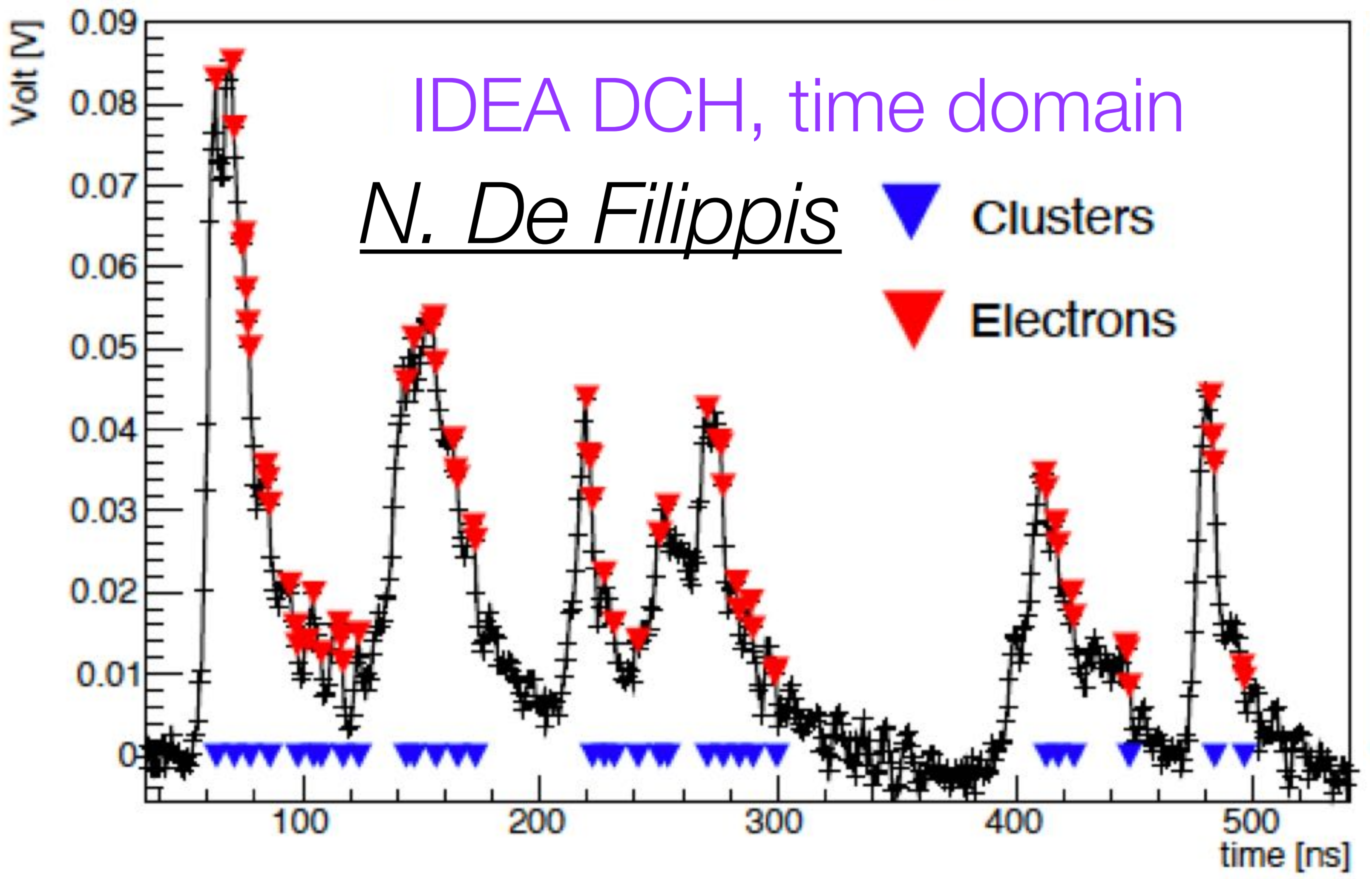
Advantages of dN_{cl}/dx over dE/dx

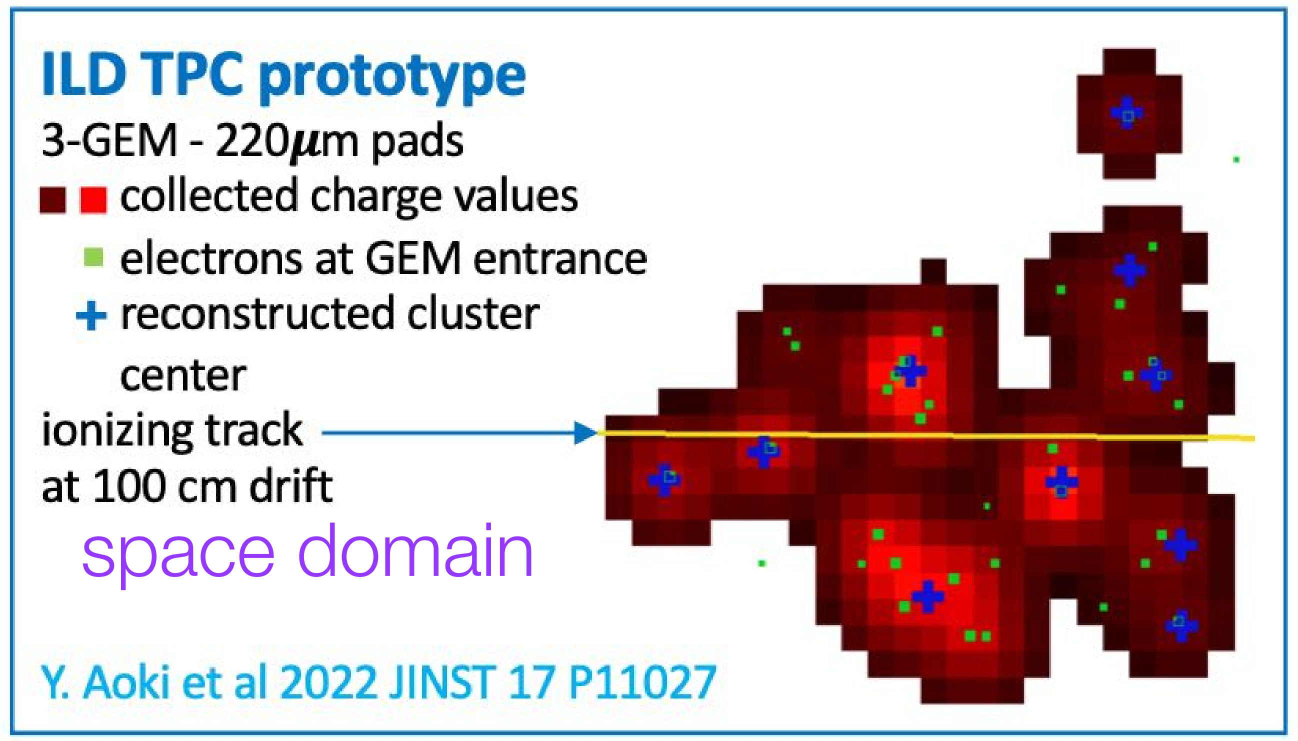
N_{cl} number of primary ionizations

- independent from **cluster size fluctuations**
- insensitive to **highly ionizing δ-rays**
- independent from **gas gain fluctuations**
- independent from **electronics gain** (calibration)
- a 2 m track in a He – mix gives **N_{cl} > 2400 (for a m.i.p.)**:
  $\sigma_{dNcl/dx} / (dN_{cl}/dx) = N_{cl}^{-1/2} < 2.0\%$
  (at 100% counting efficiency)
- a **factor > 2 better** than **dE/dx**

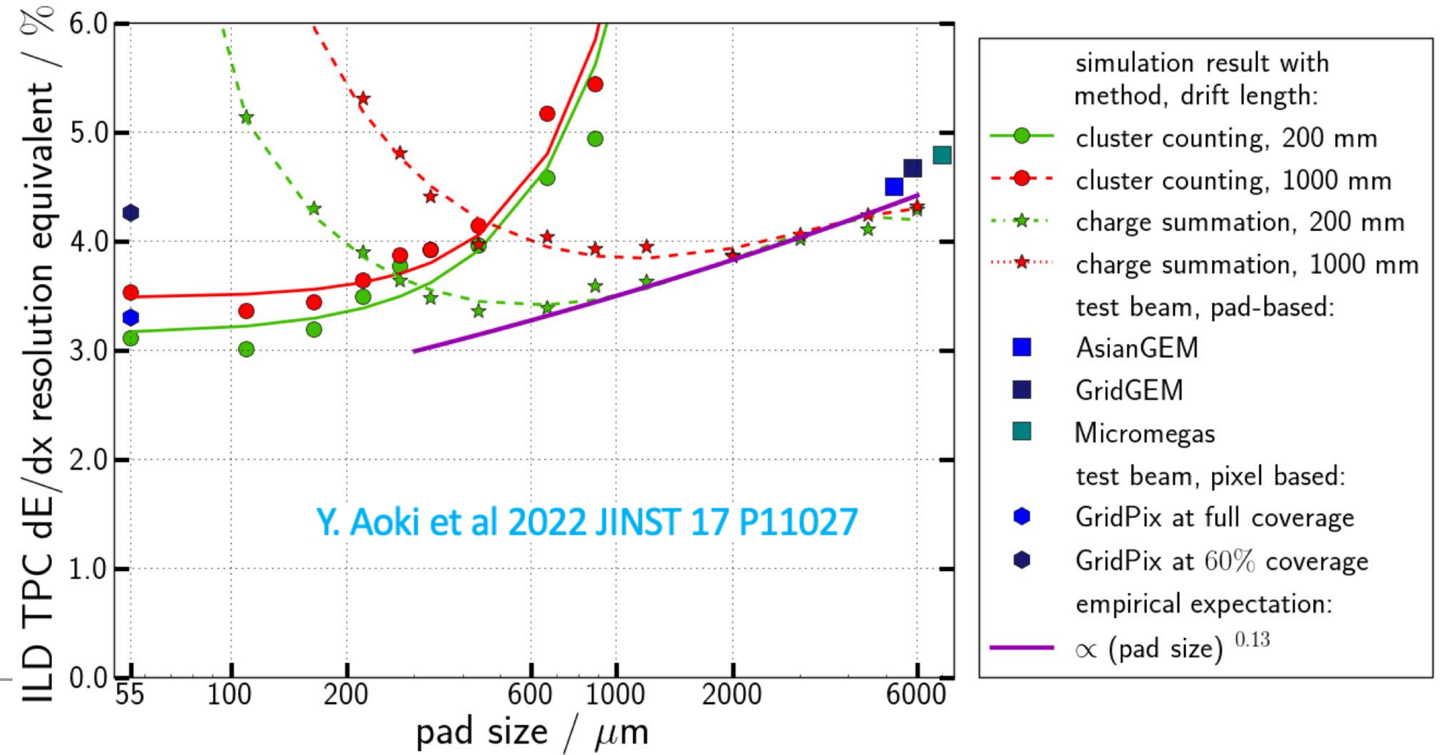
- Alternative technique: cluster counting (in time and/or space domain)



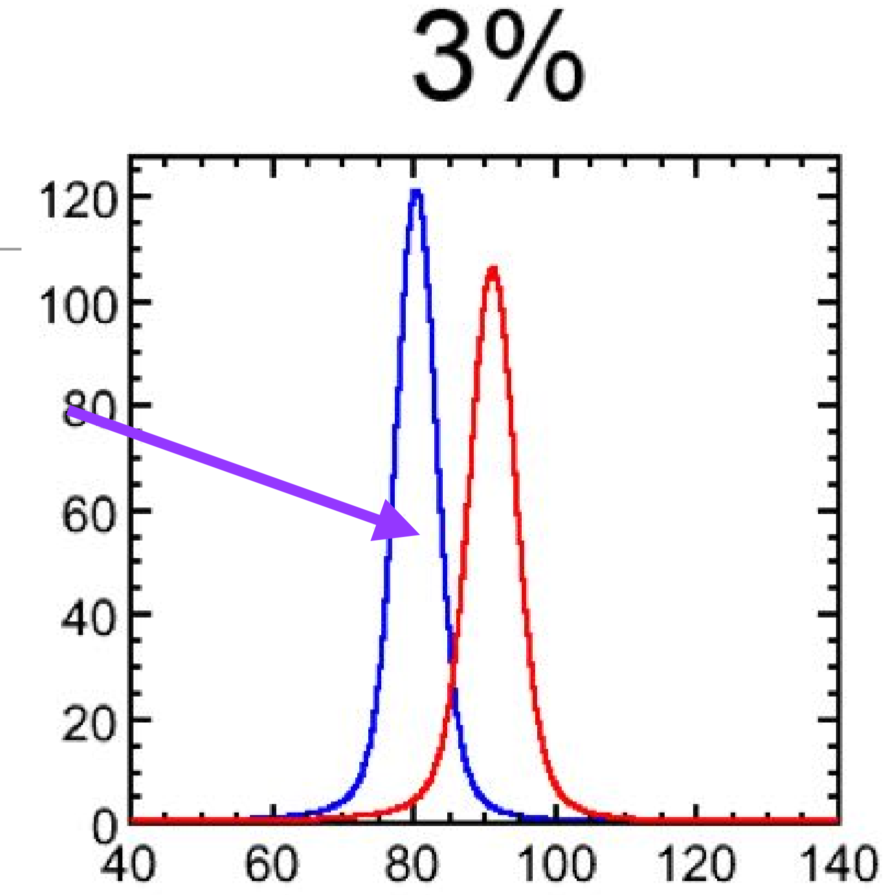




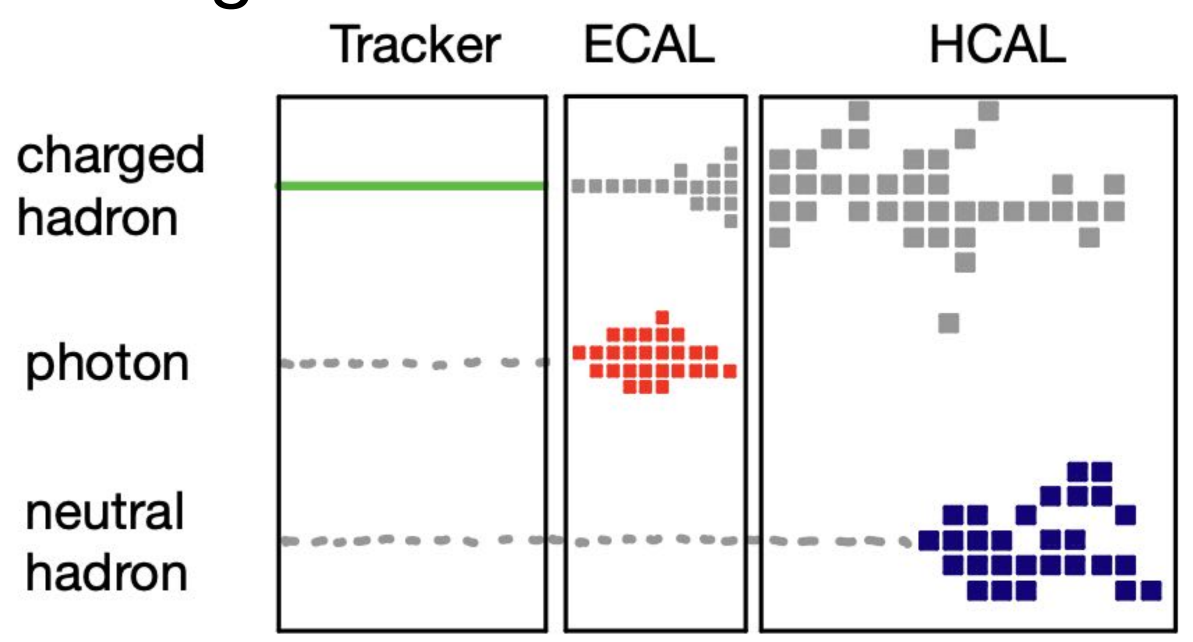
- dN_{cl}/dx in time domain for IDEA: peak-finding algo developed and tested on prototype drift tubes at testbeam
  - Observed N_{cl} distribution in good agreement with Poisson with μ = expected N_{cl} => 2.5% resolution extrapolated to IDEA
- dN_{cl}/dx in space domain for ILD TPC with pixelated readout (55 μm pitch) => 3.3% achieved in testbeams



Calorimetry - some general considerations

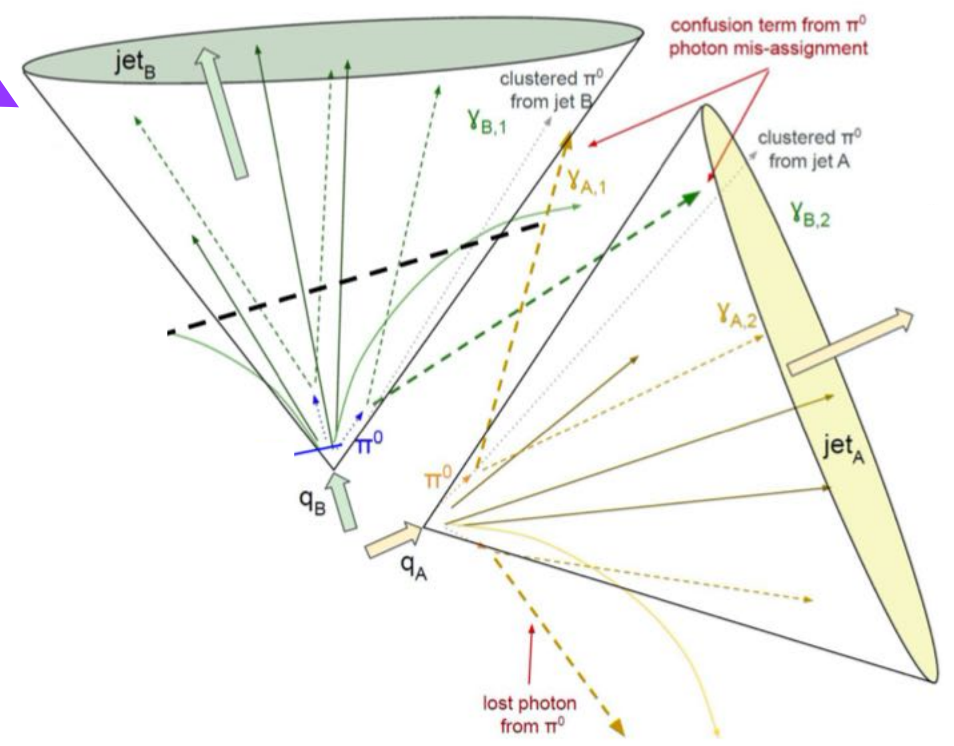


- Target jet energy resolution ~3-4% (or better) at E_{jet}~ 30-100 GeV for e.g. separation of W/Z/H->qq peaks
- Typical jet energy composition: 30% photons / 70% hadrons (60% charged / 10% neutral)
- To get to desired resolution, either have both ECAL and HCAL with excellent EM and hadron energy resolution
  - E.g. 40 GeV jet, ECAL with $5\%/\sqrt{E}$ and HCAL with $30\%/\sqrt{E}$ => 4%
- Or, use particle-flow algorithm (PFA) to leverage excellent momentum resolution from tracker to measure charged hadron contribution
  - Same 40 GeV jet, and 2x worse resolutions - HCAL with $60\%/\sqrt{E}$, ECAL with $10\%/\sqrt{E}$ => 3%



F. Simon

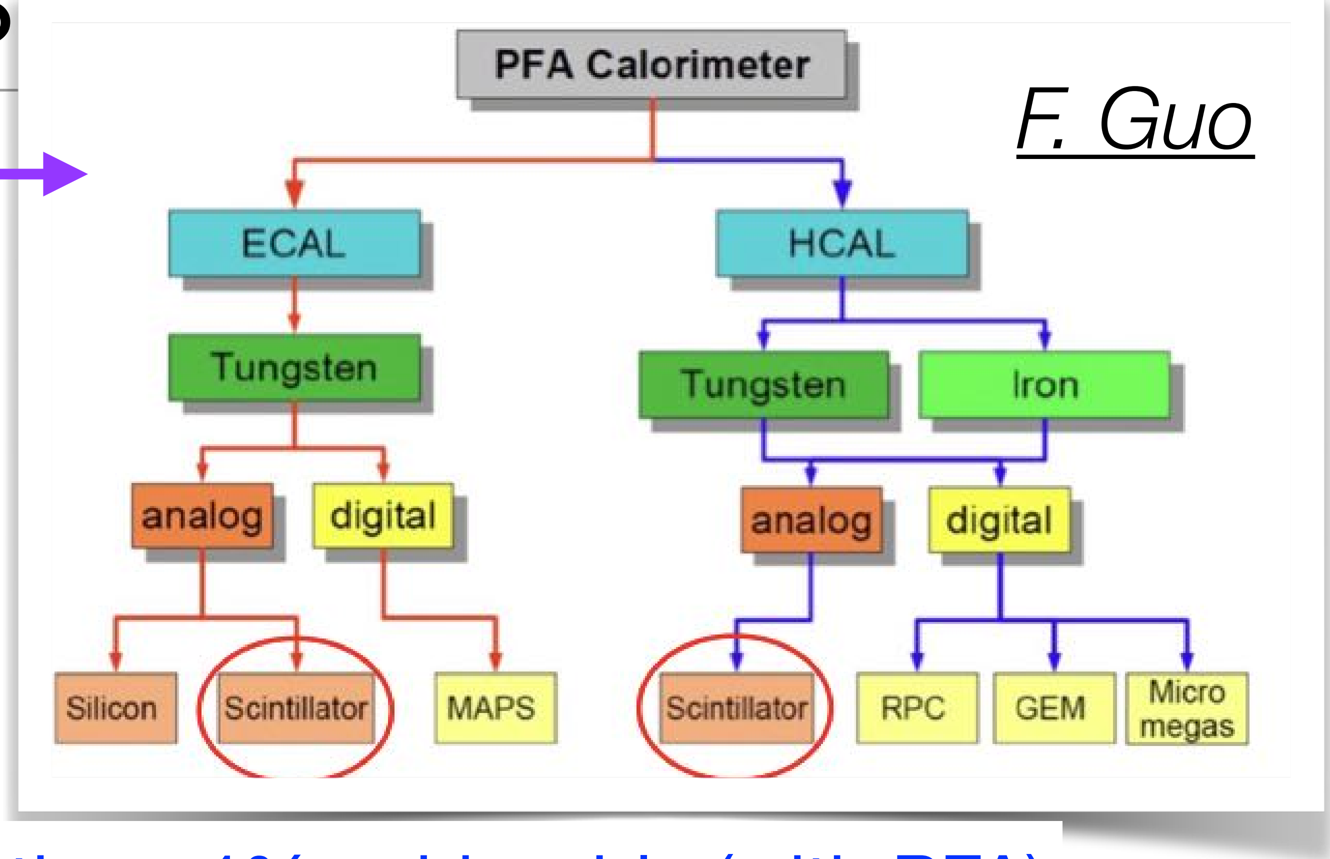
- Or, correct HCAL event-by-event through measurement of EM fraction with dual readout calorimeter, even with relatively modest EM resolution ($15\%/\sqrt{E}$)
- Photons from π^0 increase confusion between jets - could be addressed by π^0 reconstruction in PFA, requires excellent γ energy resolution (also desirable for heavy flavour physics)



- Some type of calorimeters could implement timing info => potential for PID with TOF, but also supplemental info for PFA and hadronic energy reconstruction
- Three different types of calorimeter proposals:
  - High-granularity "sandwich" sampling calorimeters (10-15%/$\sqrt{E}$ EM resolution)
  - Optical calorimeters (crystal/fiber w/ dual read-out) - more emphasis (for crystal option) on EM resolution (1-2/%/$\sqrt{E}$)
  - Noble liquid calorimeters (for EM section) - interpolate a bit between previous two cases (~5%/$\sqrt{E}$)

R&D on sandwich high-granularity sampling calorimeters

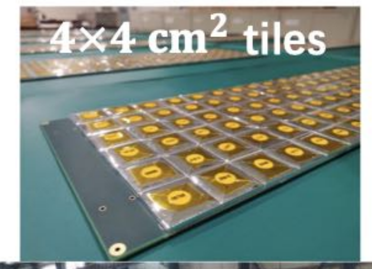
- A lot of R&D performed on various hardware options by CALICE collaboration for ILC

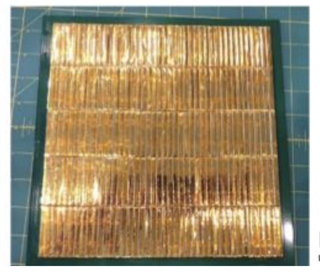


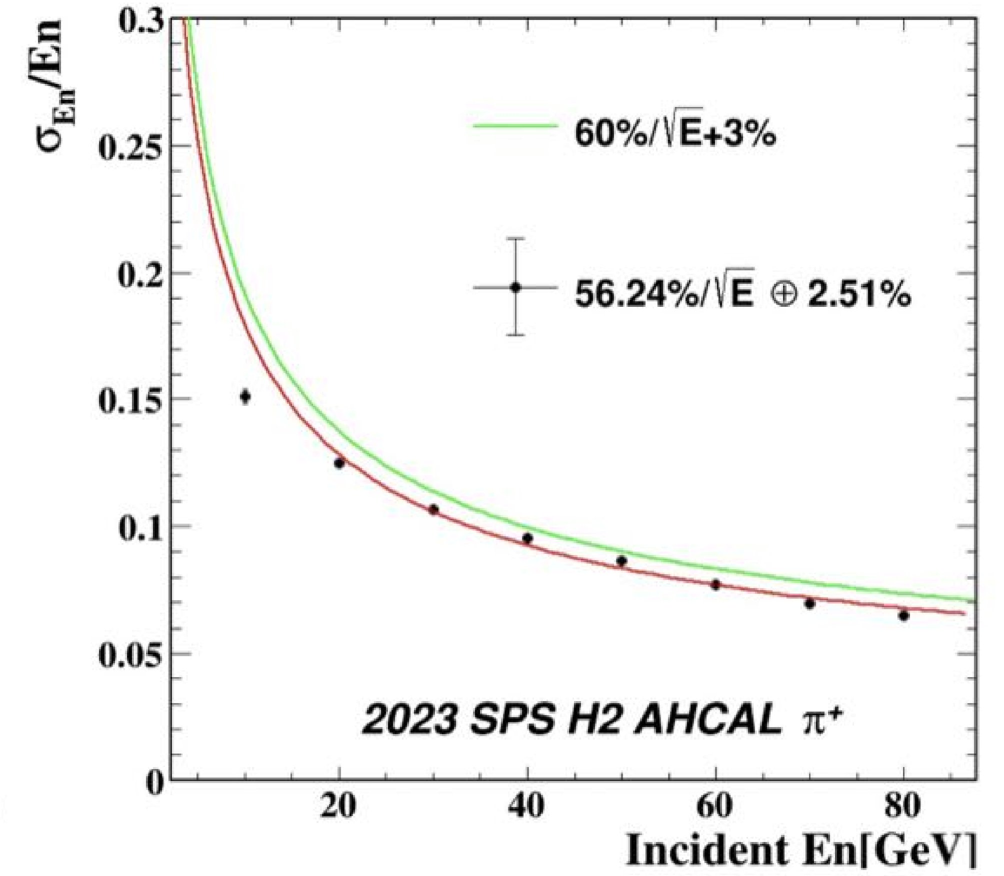
- also the technology chosen for some concepts for CEPC/FCCee, e.g. CEPC baseline detector

ECAL prototype: scintillator strip + SiPM + CuW (ScW)

HCAL prototype: scintillator tile + SiPM + steel (AHCAL)



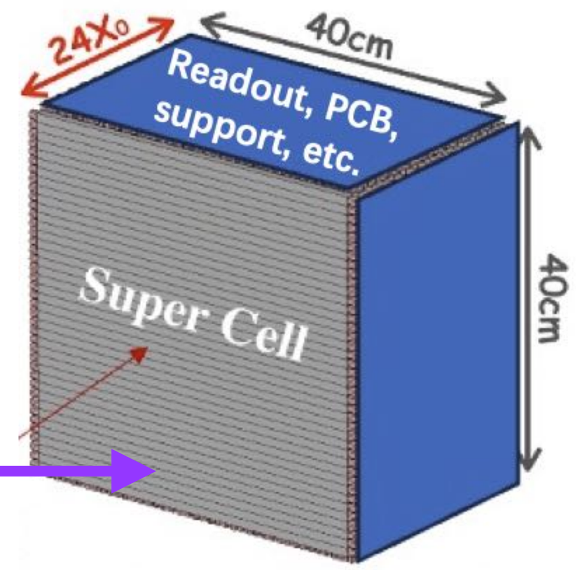


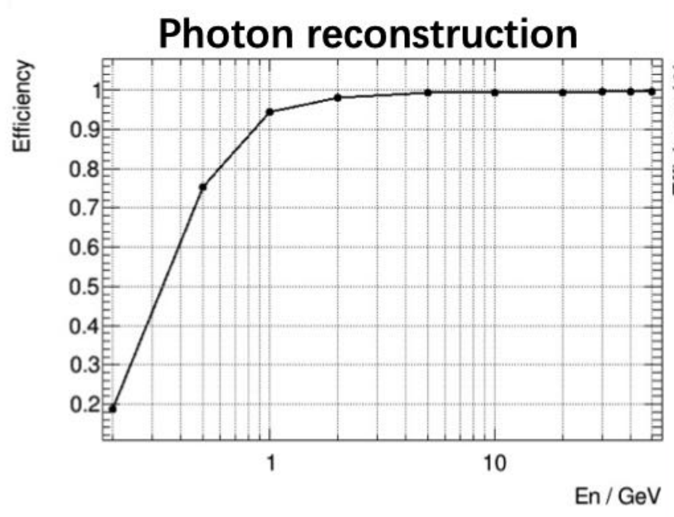


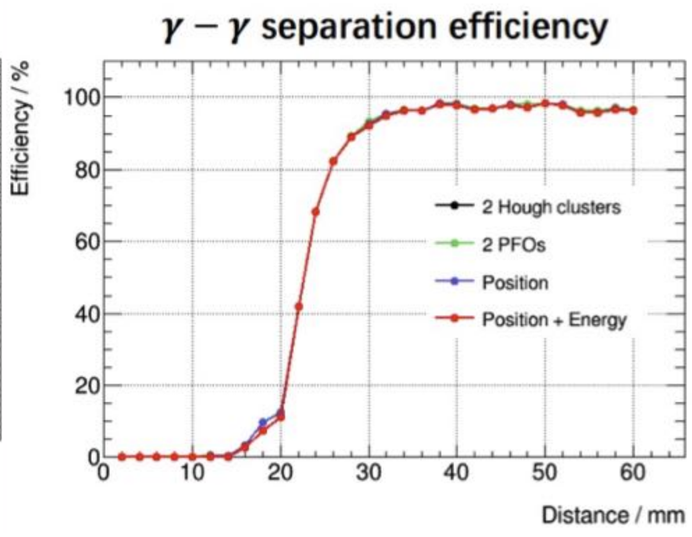
Boson mass resolution ~4% achievable (with PFA)

Under study: need for cooling @Z pole; timing

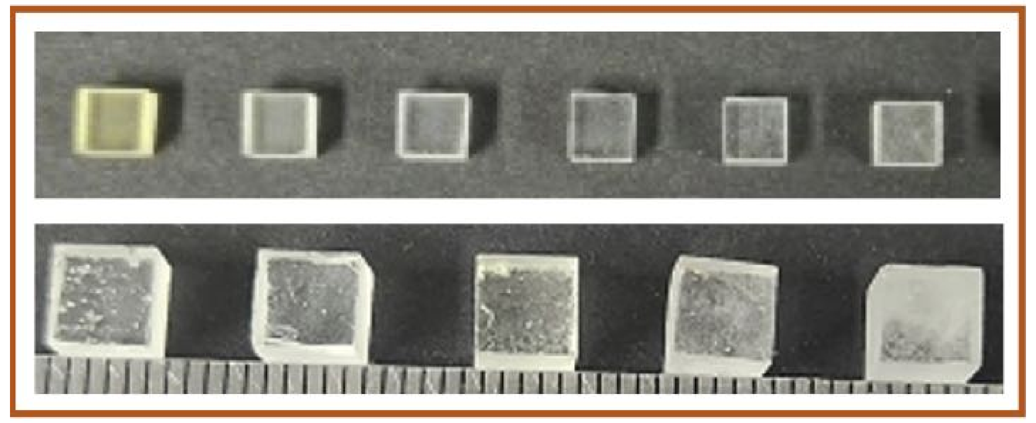
- New concept under study: homogeneous crystal ECAL + scintillating glass HCAL
  - ECAL: transverse crystal bars + SiPM => x,y,z,t,E ; EM resolution $3\%/\sqrt{E}$

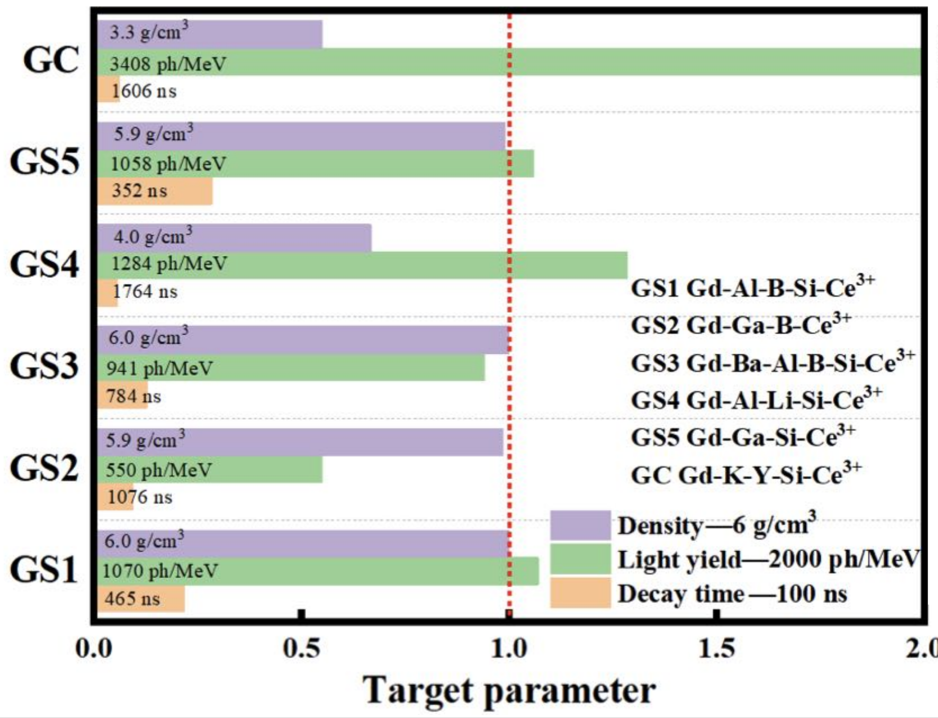


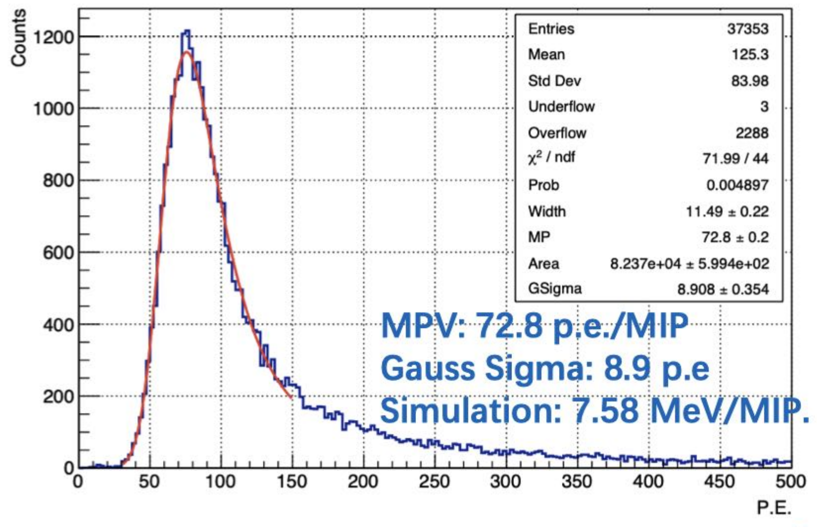




    - Large light yield measured in BGO crystals, 1 ns timing (100ps with Cherenkov?)
    - But ~25% larger R_M (2.3 cm) => more shower overlap/ambiguity => R&D on software for PFA reconstruction
  - HCAL: R&D on high-density glass (higher sampling fraction => less fluctuations in response, smaller stochastic term)
    - With 6 g/cm³ (R&D target) expect $30\%/\sqrt{E}$ => boson mass resolution ~3% within reach



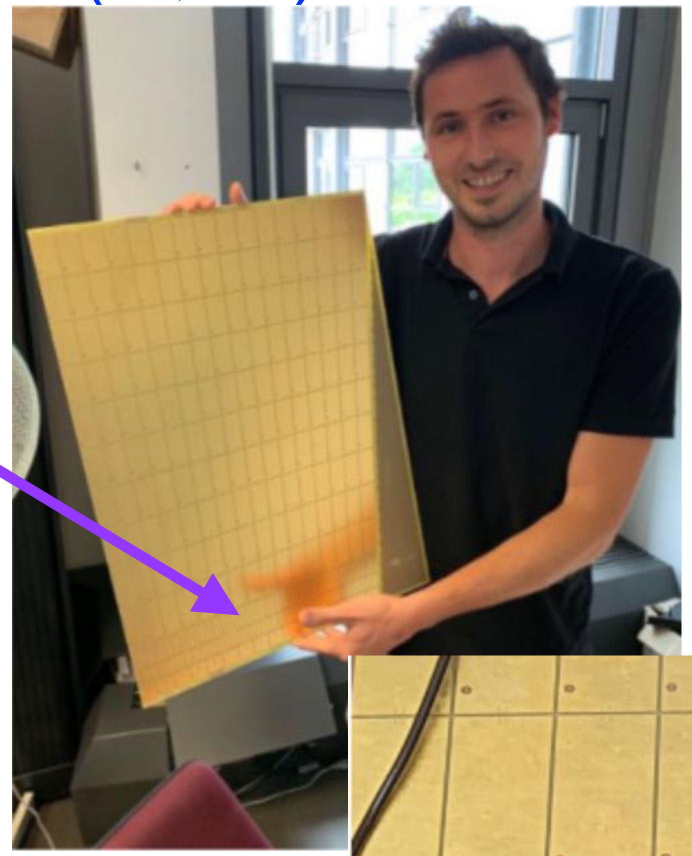


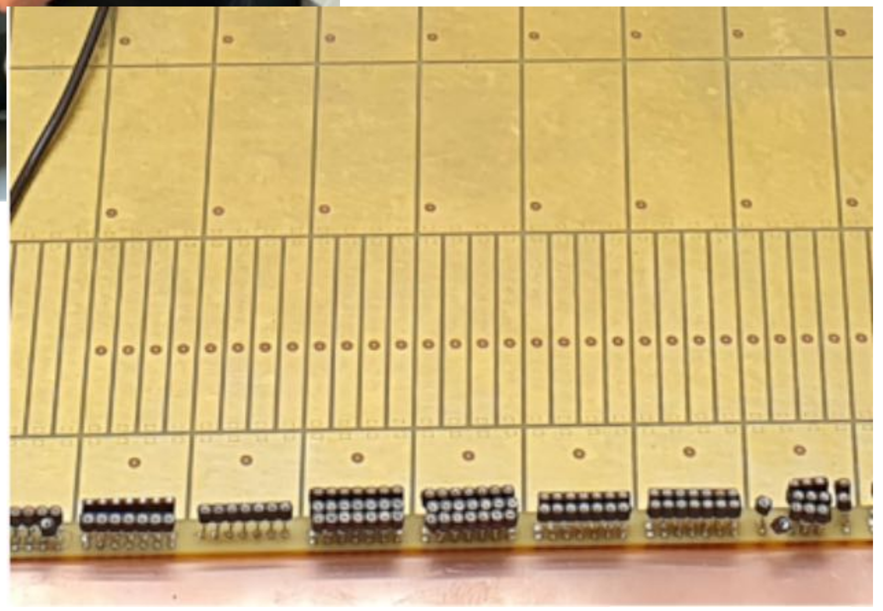


Glass scintillator tile #11: 30.5×30.0×8.7 mm³

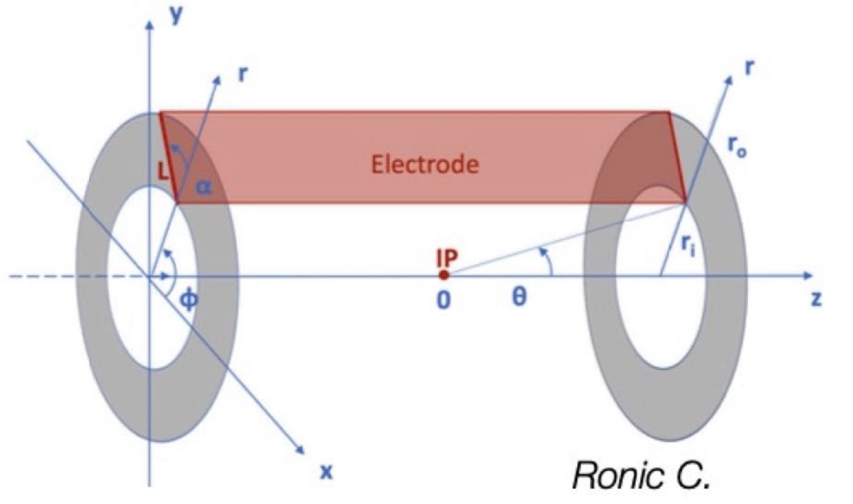
R&D on noble liquid calorimeters

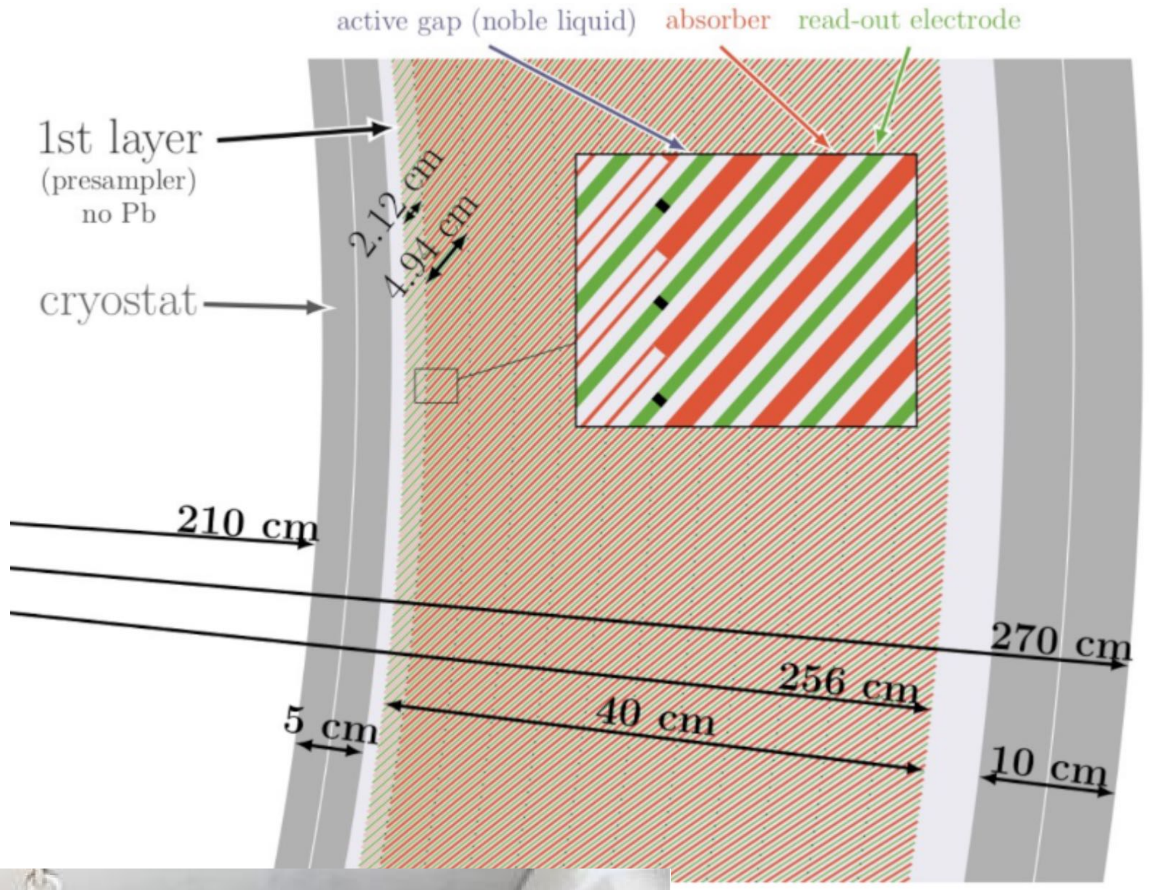
- ALLEGRO concept for FCC-ee built around highly granular noble-liquid (Ar, Kr) ECAL with Pb or W absorbers
- Multi-layer PCB as read-out electrode with “arbitrary granularity”
  - Signal traces inside the electrode
- Prototype for PCBs produced and tested, x-talk negligible thx to shielding inside PCB + shaping
  - Simulation studies ongoing to optimise granularity for next proto
- Prototype of two absorbers and one electrode built ant tested in liquid nitrogen bath, no damages found
- FEM analysis performed for structural element design
- Work ongoing:
  - Geant4 simulation implemented, performance studies in progress
  - Test-beam prototype with 64 layers in development planned
    - Design ready by 9/2024, then need to build it
  - Design of end-cap section

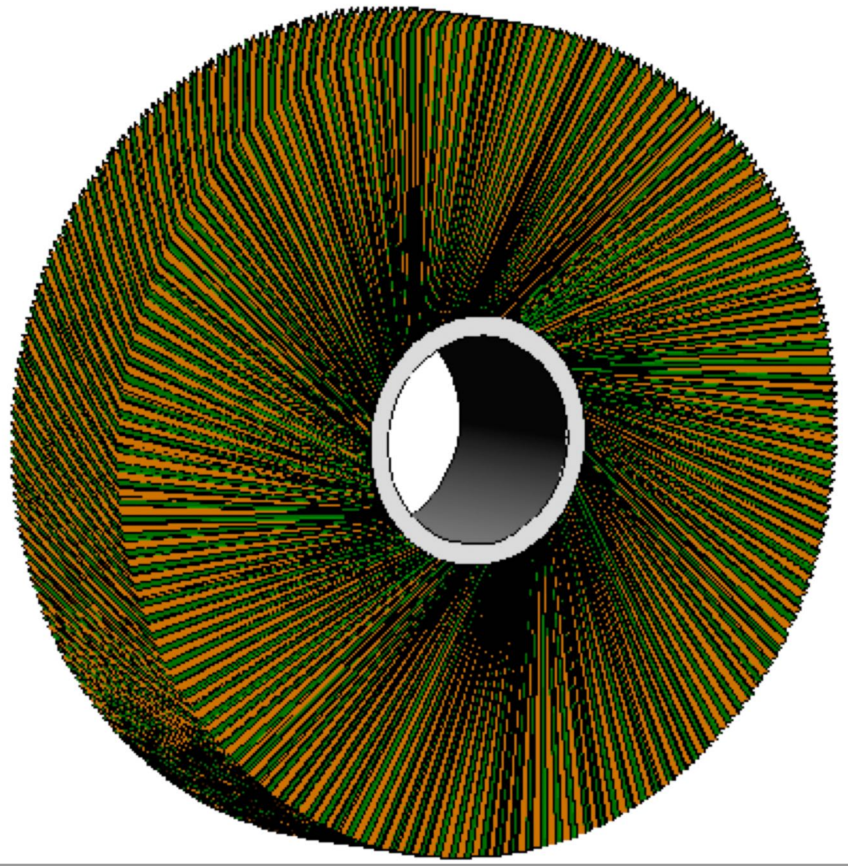




J. Pekkanen

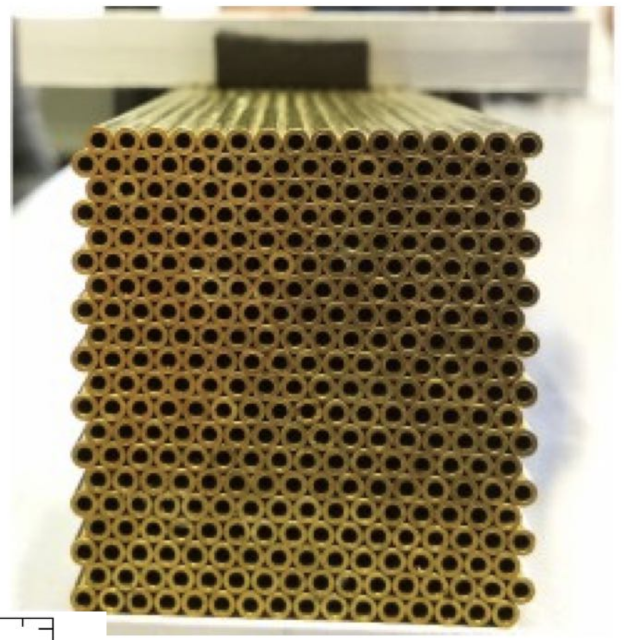






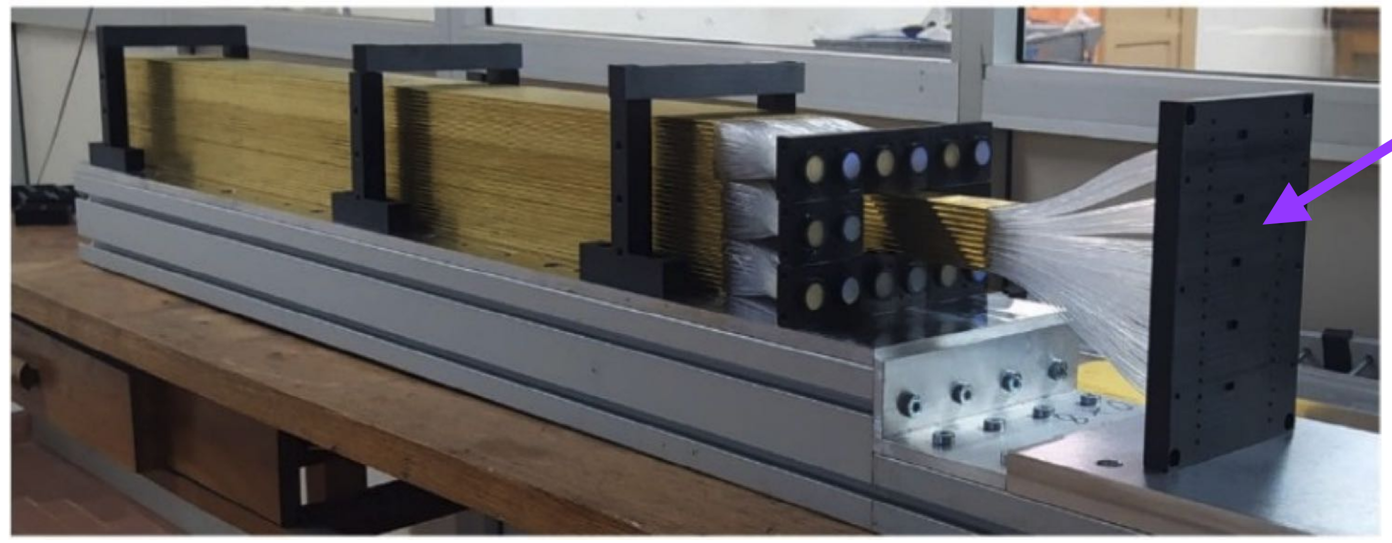
R&D on dual readout calorimeters

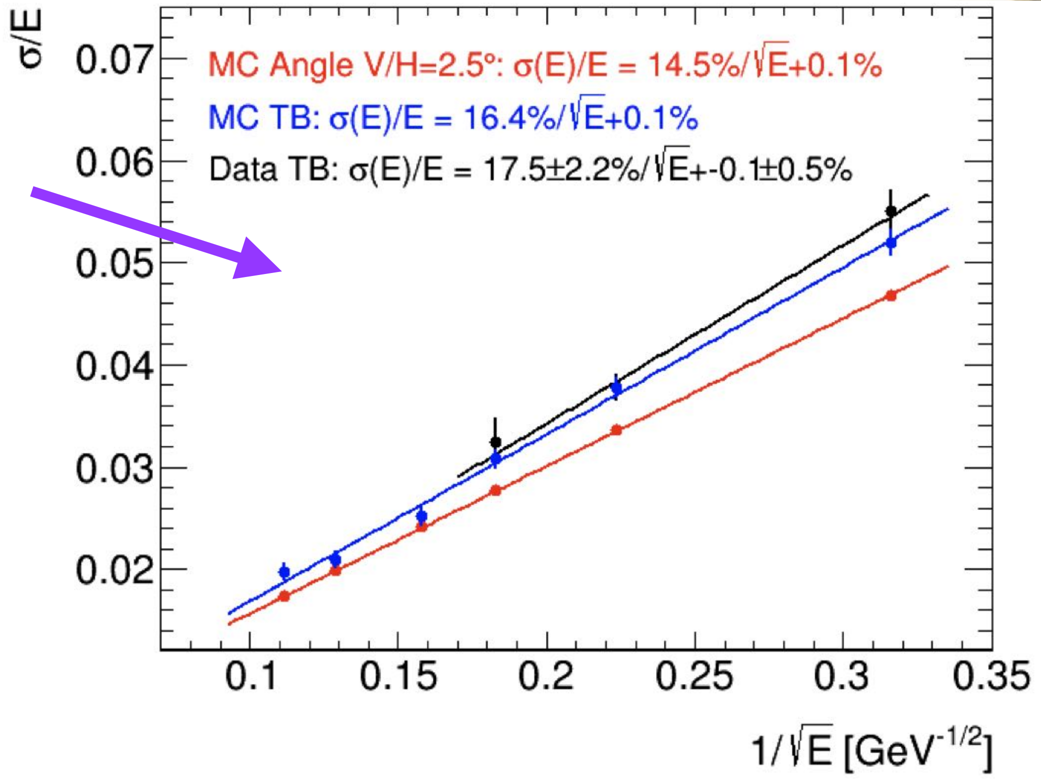
- Improve energy measurement of hadronic showers using two sampling processes => event-by-event EM fraction calculation
  - Scintillation light (total deposited energy)
  - Cherenkov light (mainly EM shower component)
- IDEA calorimeter: highly granular fibre-based dual-readout calorimeter
  - 130M fibres, 1 mm diameter, 1.5 mm pitch
  - Metal capillaries containing fibres act as absorbers



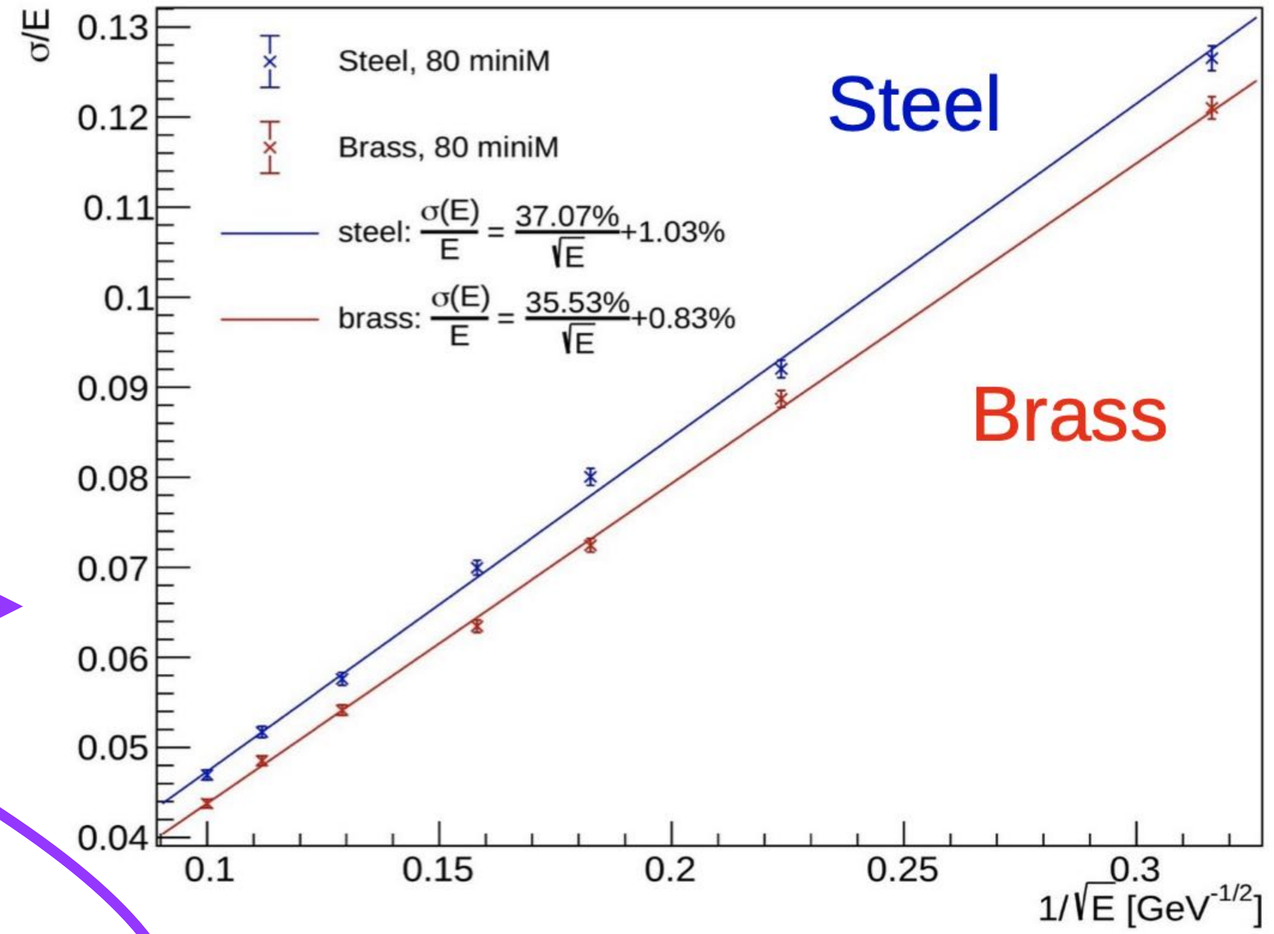
G. Polesello

- Tested small EM-size module to understand construction issues + integration with SiPMs

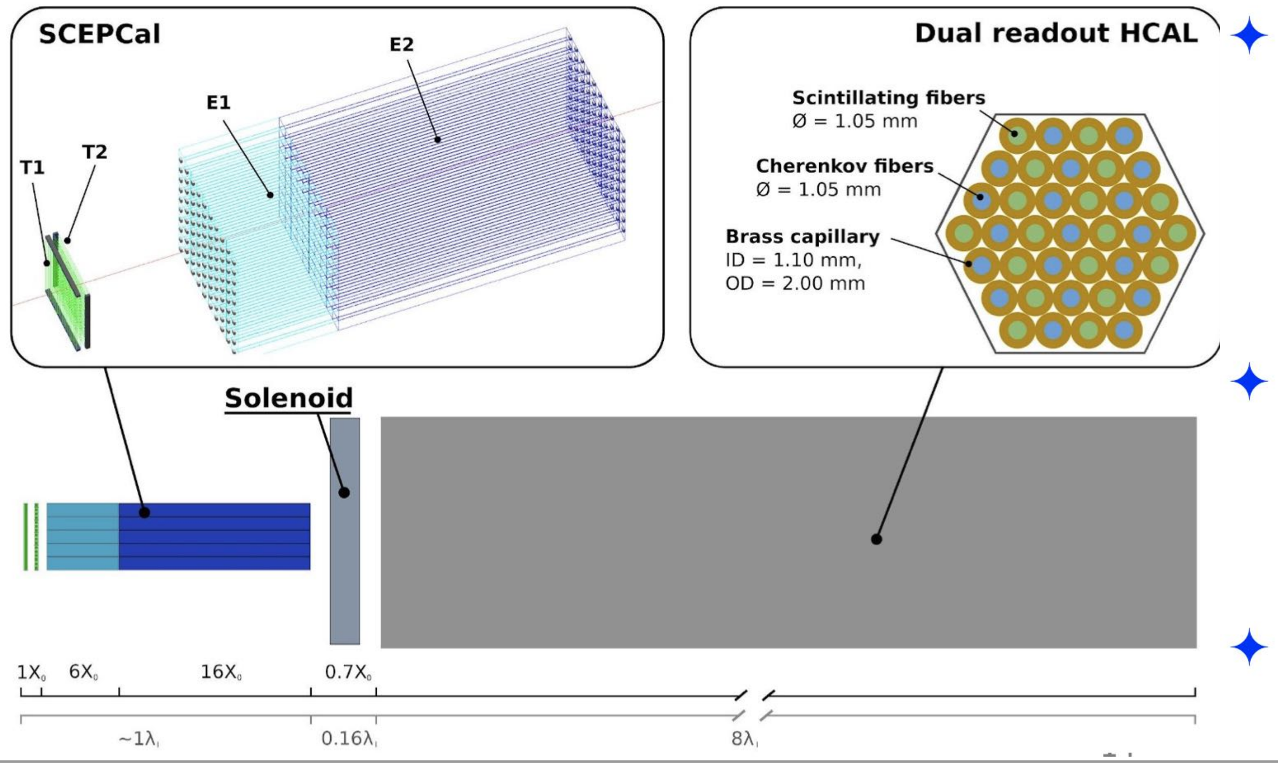




- Hadronic-size module funded and under construction, expected pion resolution ~35%/√E



- IDEA++: DR crystal inside solenoid + DR fibre outside => EMER ~3%/√E, had ER ~29%/√E



- ECAL ~20 cm $PbWO_4$
  - 2 layers: 6+16 X_0
  - DR with filters
  - $\sigma_{EM} \approx 3\% /\sqrt{E}$
- timing layer
  - LYSO:Ce crystals
  - $\sigma_t \sim 20$ ps
- HCAL layer
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$

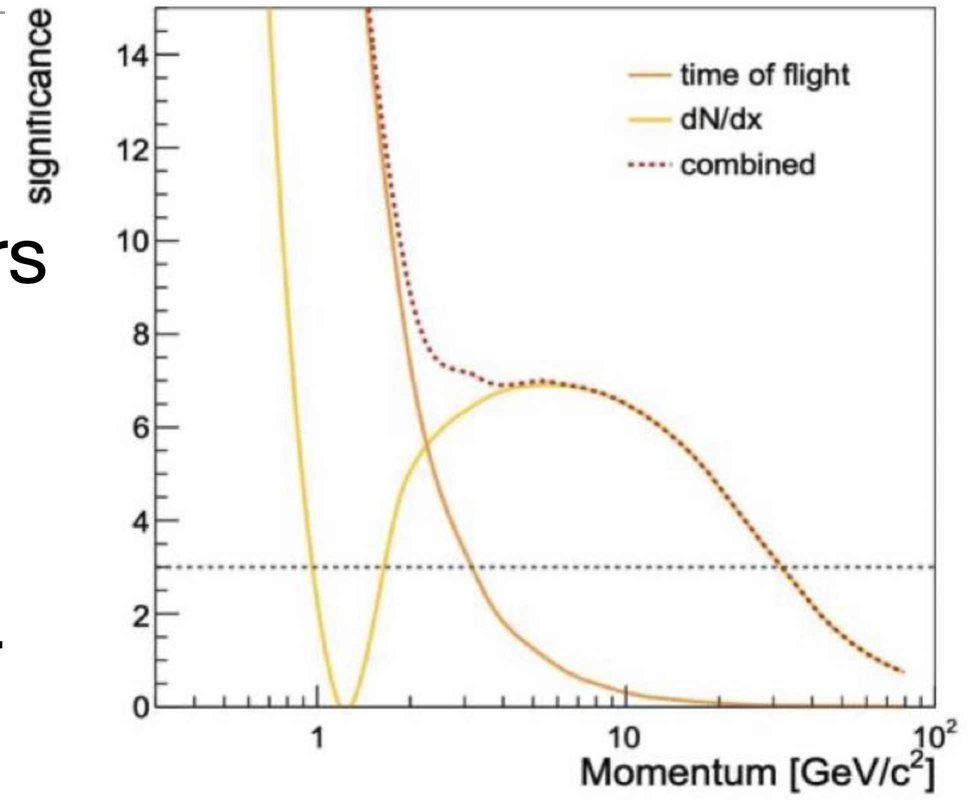
R&D activities:

- Crystals:
  - Optimisation of crystal cross section and longitudinal segmentation
  - Choice of materials → prominent candidates are BGO, BSO, PWO due to high density, small R_M and X_0, high refractive index (Cherenkov yield)
- Filters:
  - Development/identification of custom thin wavelength filters to separate S & C components with sufficient light yield and purity
- SiPM readout:
  - Dynamic range, linearity, etc
  - Explore very small cell size SiPMs (<10 um)

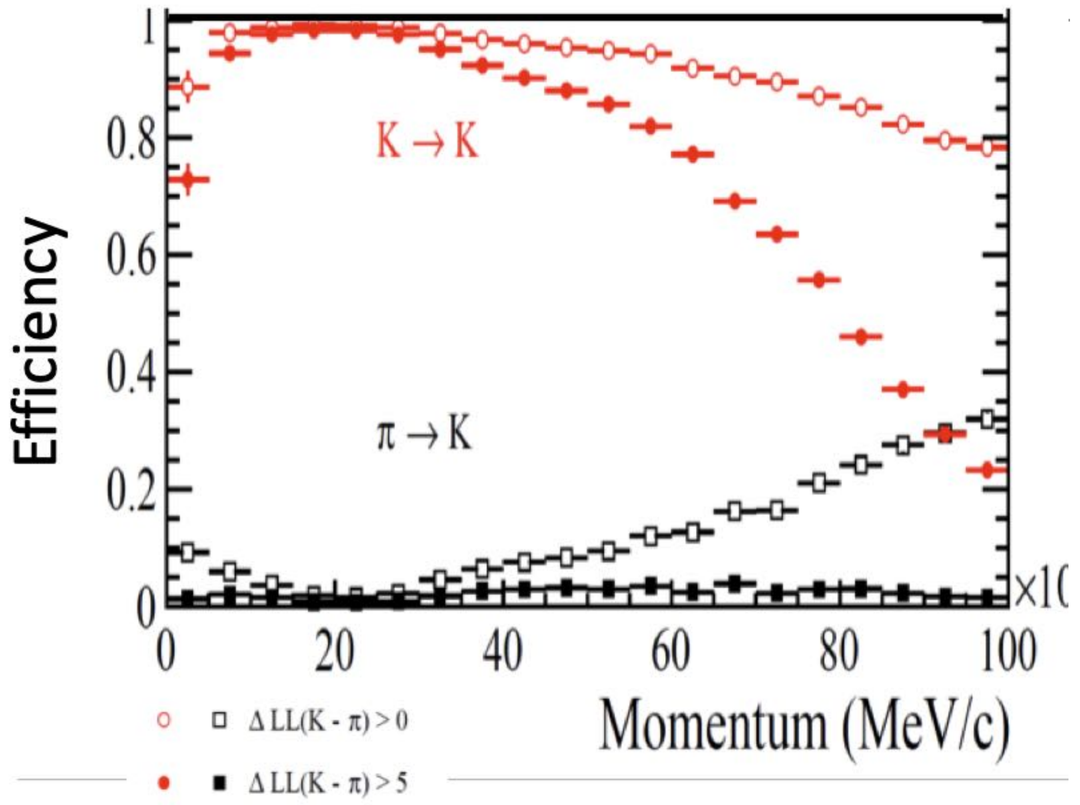
Particle identification

- Two possibilities discussed already
  - TOF in external layers of Si detector or (some) layers of imaging calorimeters equipped with Si sensors (MAPS)
  - dE/dx or dN/dx with TPC/DCH
- Third option being investigated: Cherenkov detectors (considered in particular for experiments with Si trackers)
- ARC: array of RICH cells - tile the plane with many separate cells, each with its own mirror and sensor array.
  - Compact (target radial depth of 20 cm and few $\%X_0$) with dual aerogel + gas radiators
  - Use spherical focusing mirrors (R~30 cm for radiator thickness ~15cm)
  - Performance studied (simulations) varying the gas type and pressure
    - C_4F_{10} at atmospheric pressure gives good momentum range for K-π separation, with acceptable photon yield

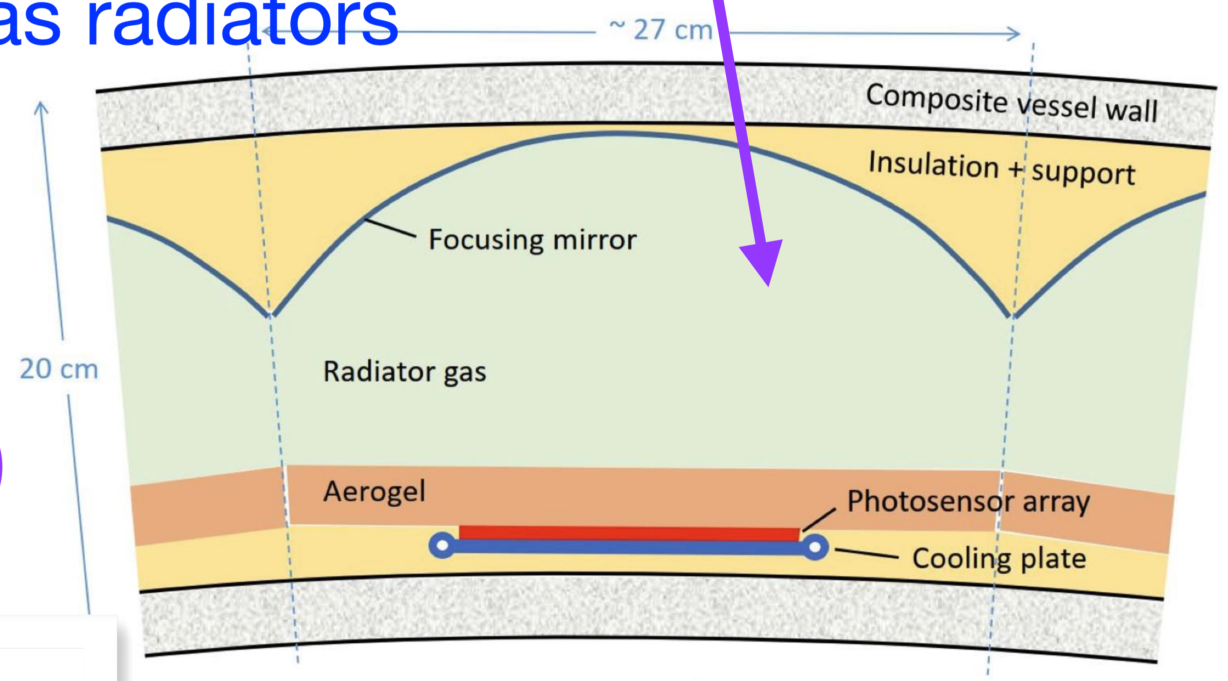
dN/dx + TOF (IDEA simulation)



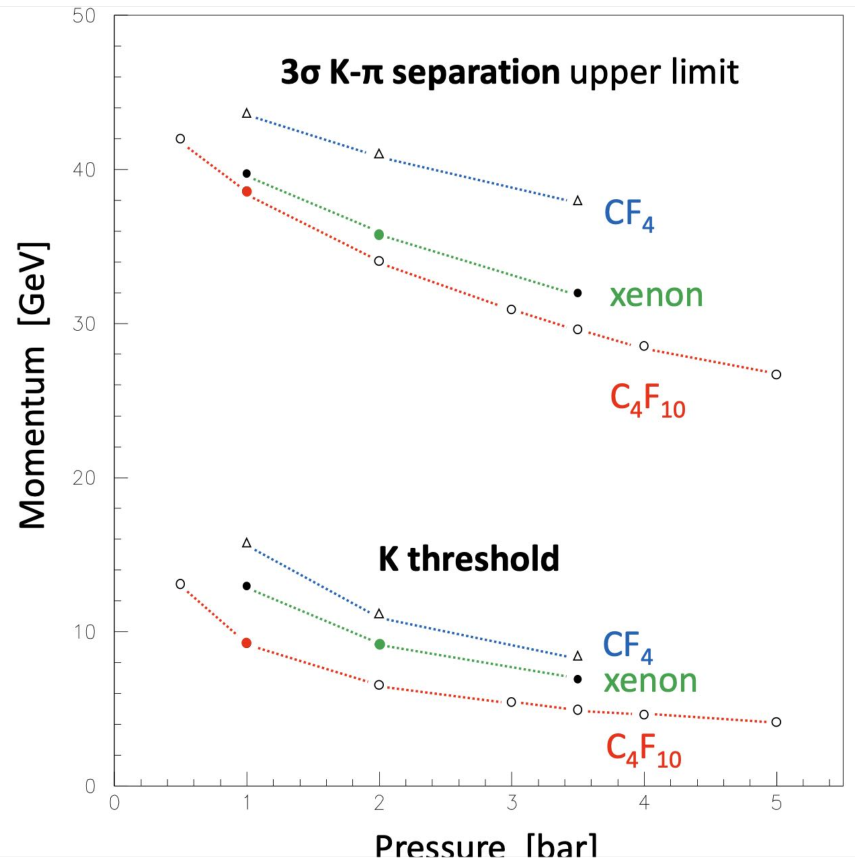
RICH performance (LHCb)

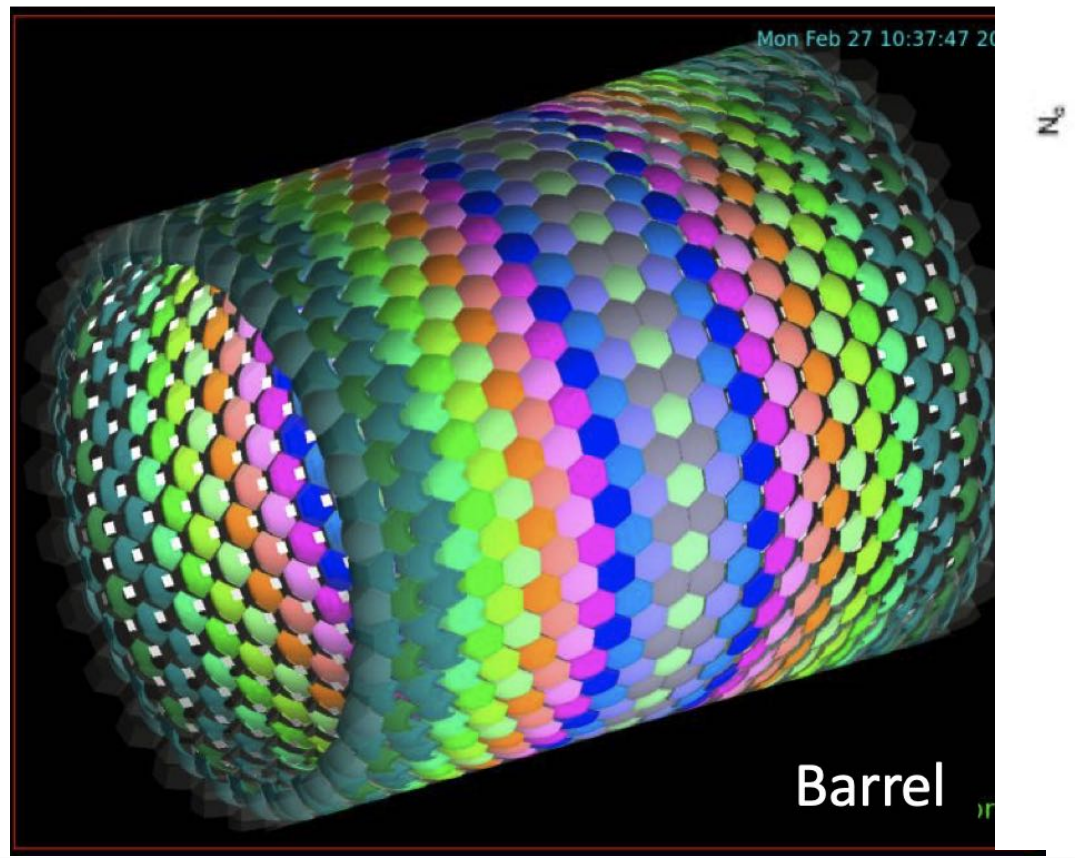


R. Forty

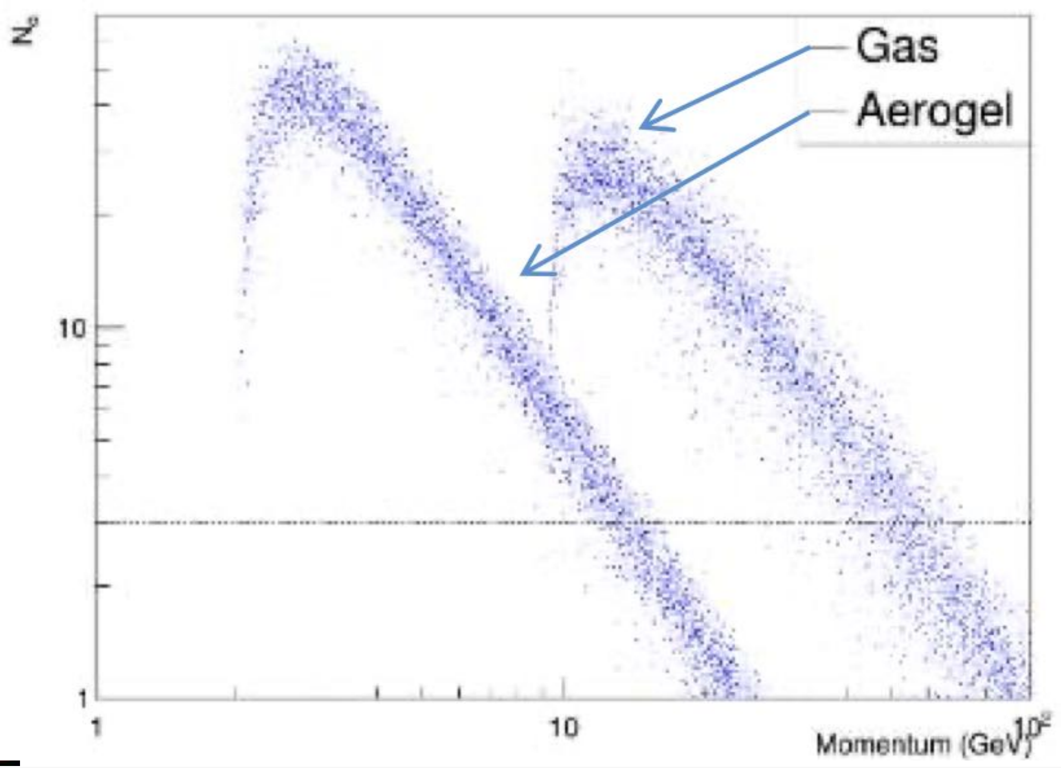


ARC detector (one cell)





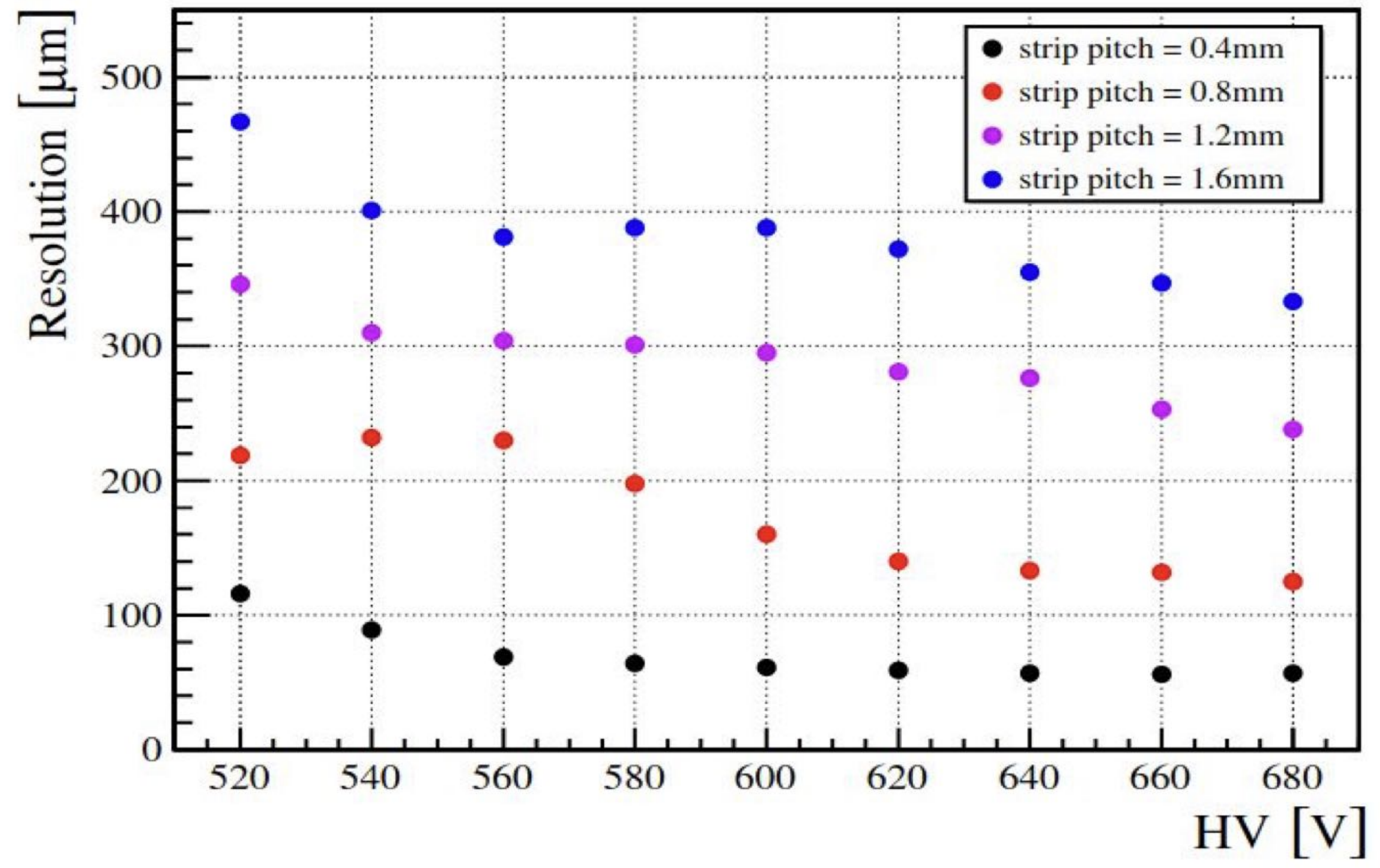
K-π separation

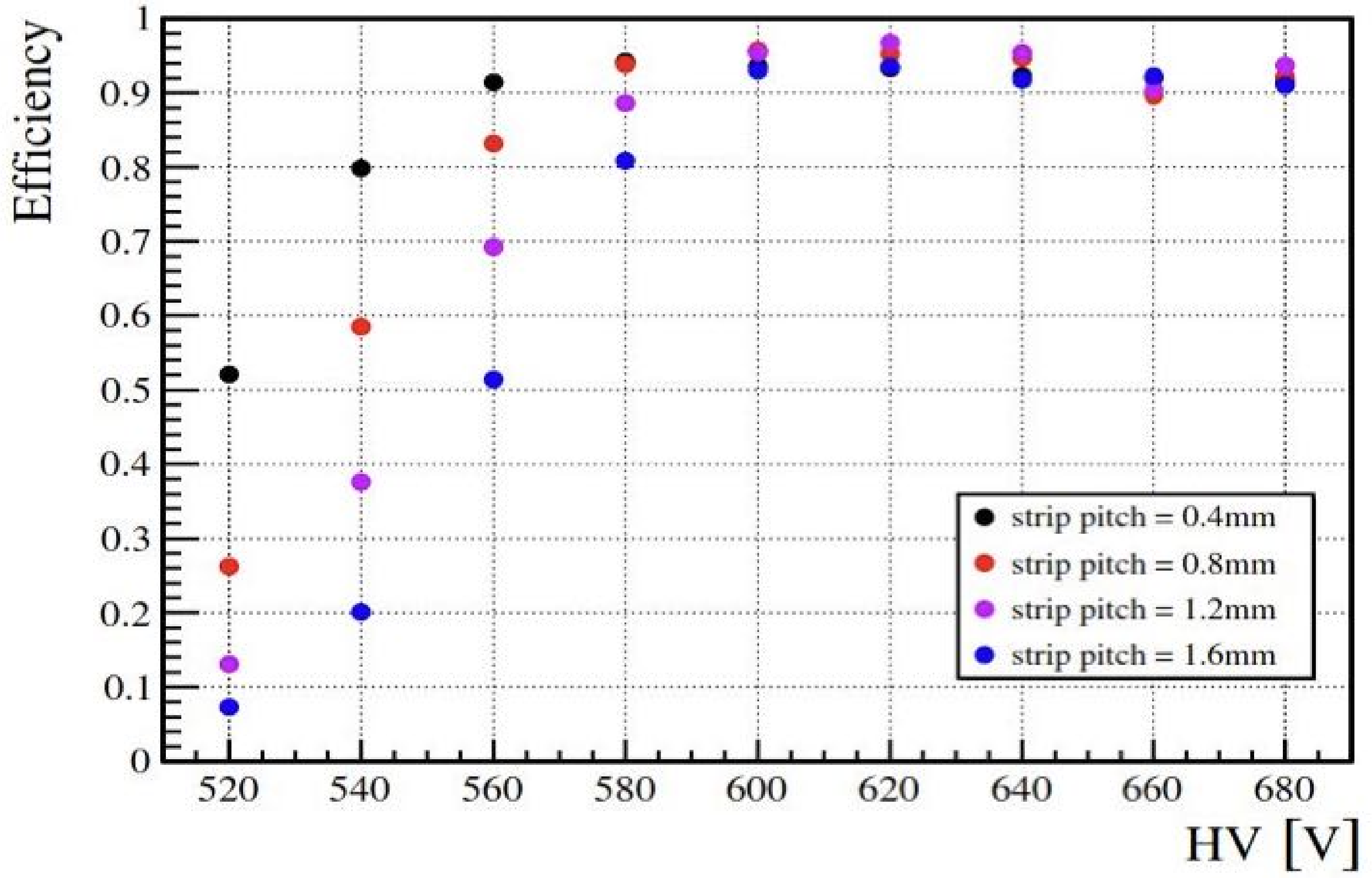


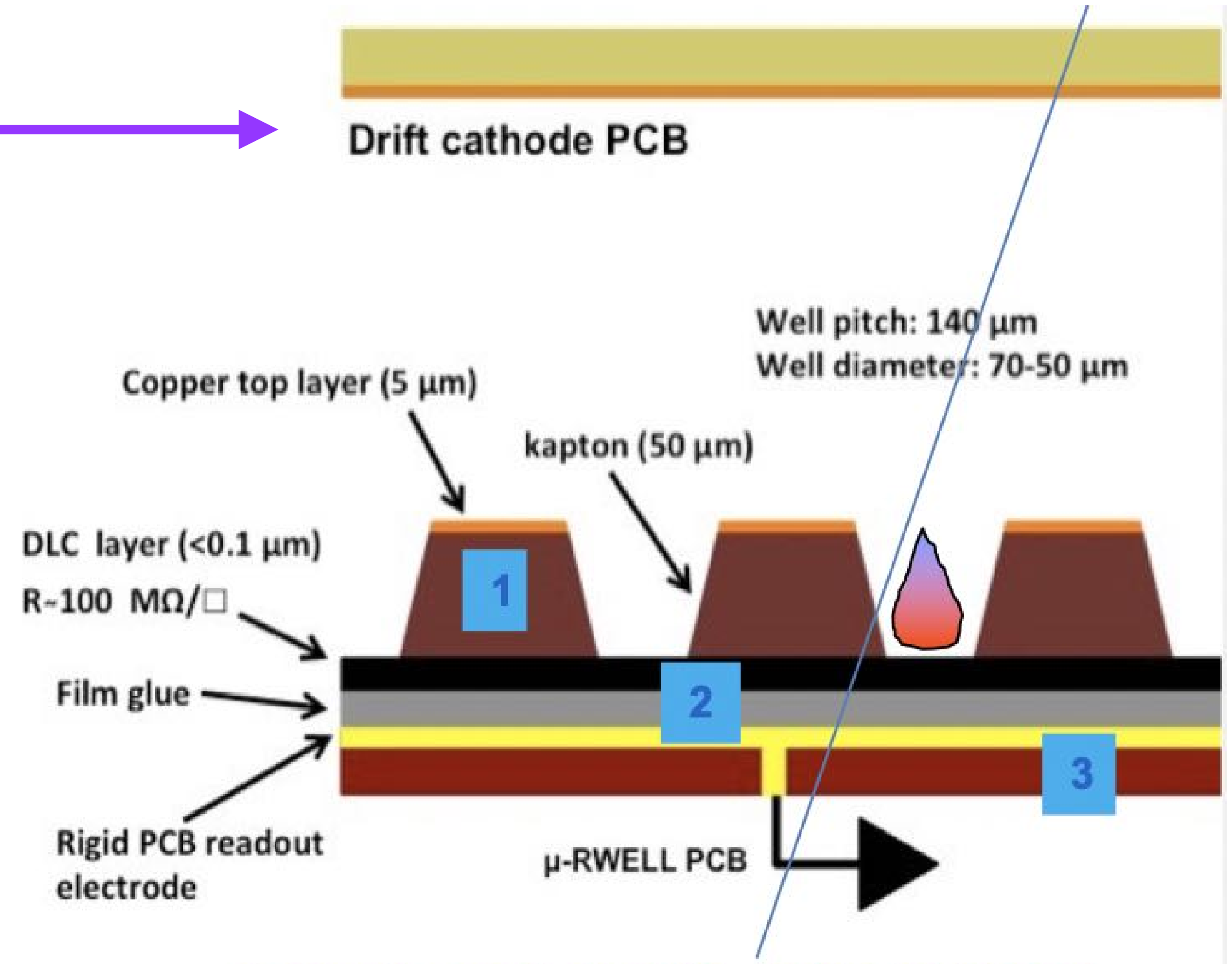
Lots of R&D and prototyping to do, eg
* transparent but leak-tight vessel
* eco-friendly gas for radiator (pressurised Ar/Xe?)
* SiPM photosensors: performance/cooling/..
* aerogel: develop larger & thinner tiles, use as thermal insulator, …

Muons

- Large distance from IP and granularity achievable with current technologies => less critical constraints / R&D needs *R. Farinelli*
- Large R => large surface => effort to simplify design / reduce costs
  - e.g. μ-Rwells for IDEA: cheap & can sustain high rates
- 2021 beam test confirms good performance (140-180 GeV μ/π beam, $Ar/CO_2/CF_4$ 45/15/40)

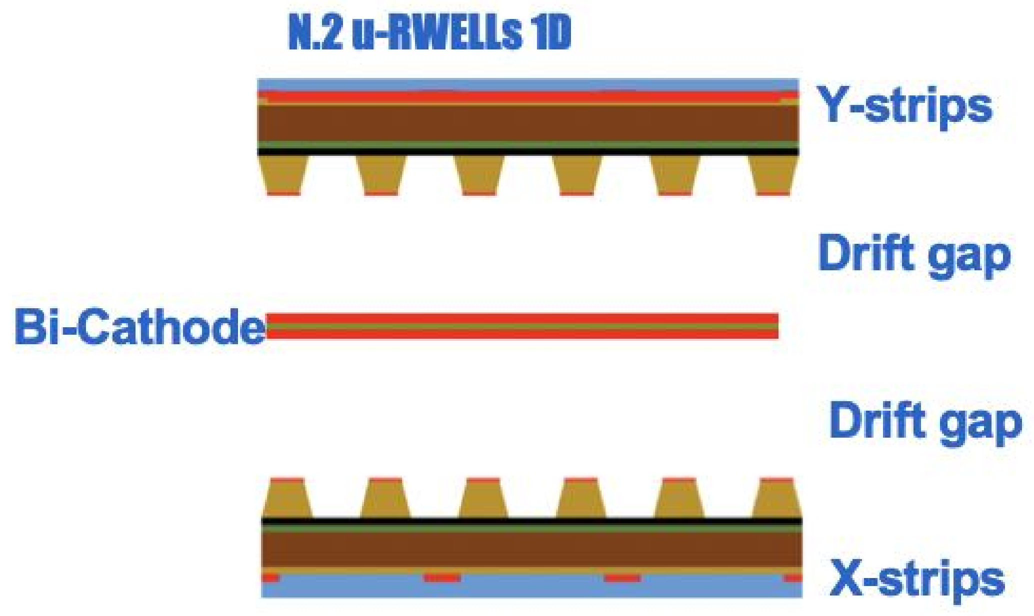


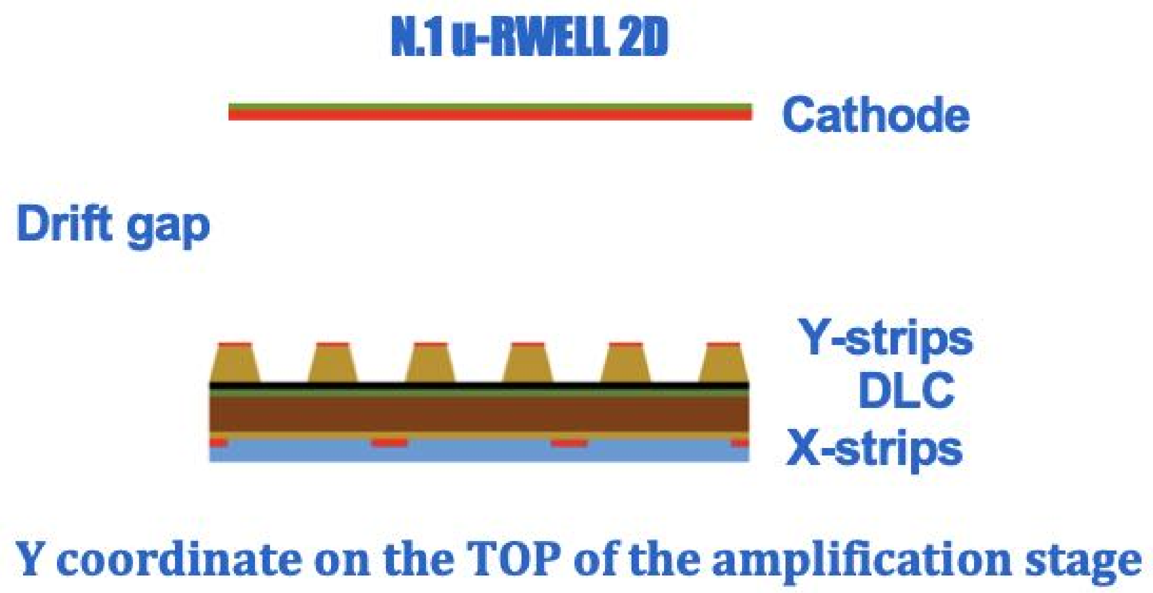




G. Bencivenni et al., 2015_JINST_10_P02008

- Studies ongoing to optimise geometrical and electrical parameters (e.g. pitch)
- Work ongoing on 2D readout - next years
- Industrialisation / full layout / gas mixture : few years





Conclusion

Beyond the success of the HL-LHC phase,
the top priority for the future of our community is a Higgs factory.
It might not be ready tomorrow, but we need to prepare for it today.
Vigorous R&D has tackled many issues, but others still remain

The future cannot be predicted,
but futures can be invented.

(Dennis Gabor, Nobel Prize in Physics 1971 for the invention of the holographic method)

I don't know which Higgs factory accelerator and detectors will be built, but they will be those that we will have invented.

If you want a future Higgs factory tomorrow, get involved in R&D today*

**or as soon as possible*

FCC feasibility study (2021—2025) status summary

The first half of the FCC Feasibility Study will soon be completed with the mid-term review

- End October 2023: Review committee reports available to Scientific Policy Committee and Finance Committee
- 20 – 22 November 2023: SPC and FC review meetings on mid-term review
- 2 February 2024: CERN Council meeting on mid-term review

Focus 2021 - 2023:

- identifying best placement & layout and adapting entire project to new placement
- this provided the input for the mid-term review

Fruitful collaboration between scientific & technical actors, in close cooperation with the host state services concerned, at departmental/cantonal and local level. Direct exchange in place with communes concerned by surface sites. Environmental studies ongoing.

Focus 2024 - 2025:

- Subsurface investigations, further optimization of implementation, surface sites, synergies, etc.
- Full design iteration in view of technical and cost optimisation of entire project

M. Benedikt

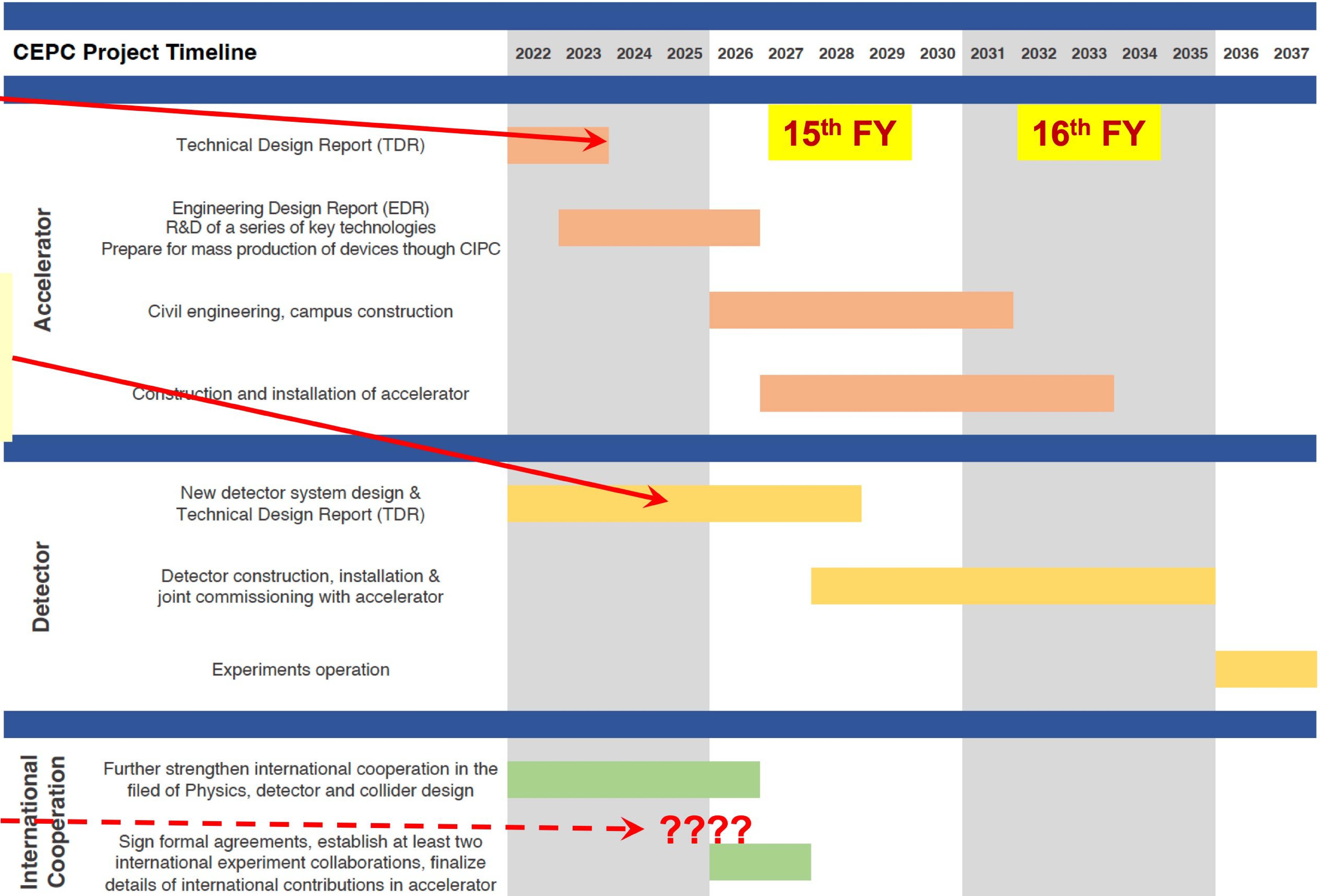
CEPC timeline

Completion of Accelerator TDR

Goal

TDR of a Reference Detector @ June 30, 2025

International Collaborations



Muon collider

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

D. Schulte

- Main challenges
  - Dense neutrino flux
  - Beam induced background
  - Beam quality
- Critical beam complex with new technologies required

- Lots of R&D planned towards addressing these issues and building a demonstrator to prove that it can work by ~2045
  - Ambitious goal: 3 TeV collider on same timescale

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

5 yrs/energy point

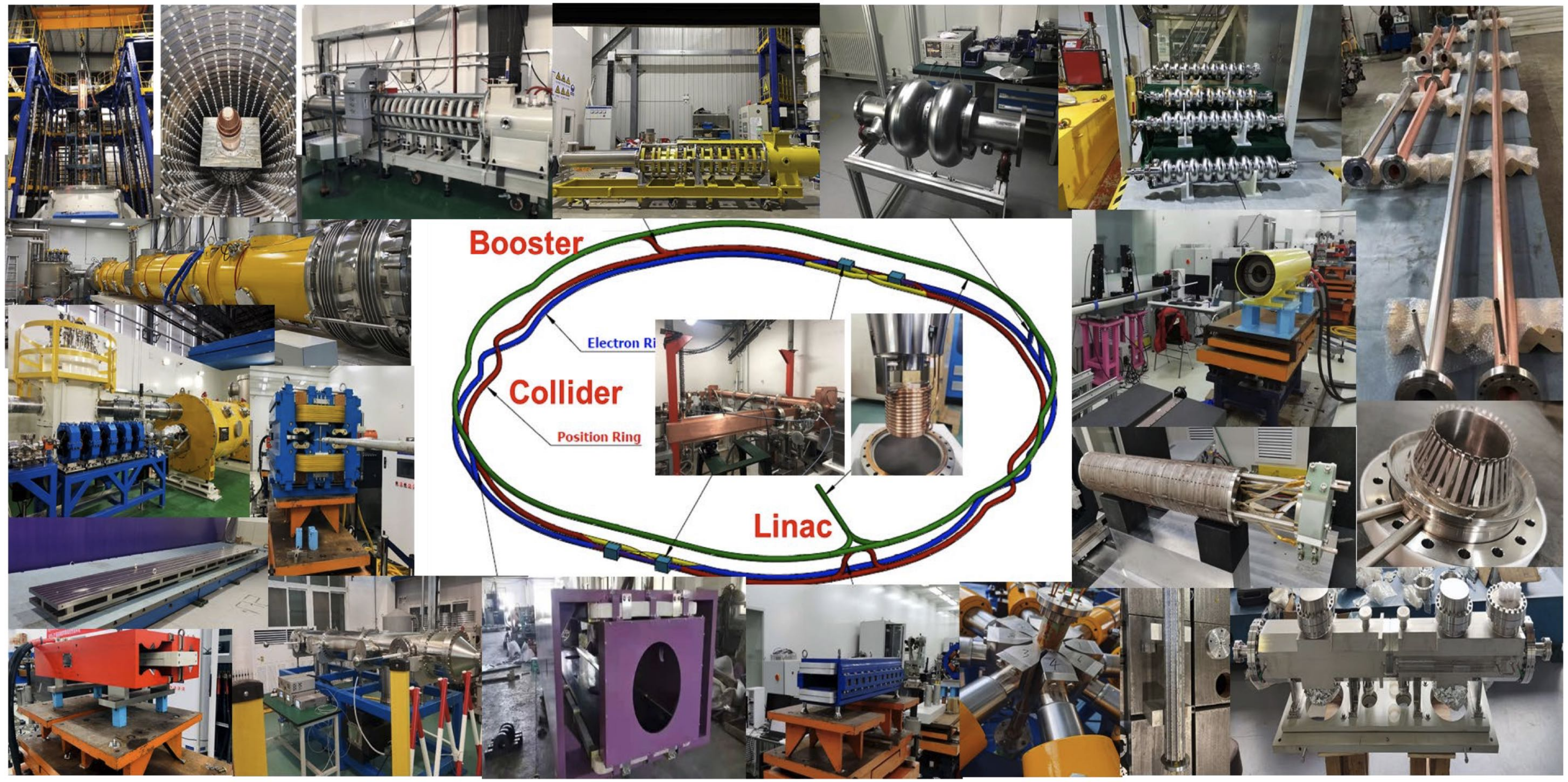
More accelerator R&D activities

- Other elements of CEPC (electron guns, all types of magnets, beam diagnostics, vacuum beam pipes with NEG coating, electro-static separators, alignment apparatus, as well as high efficiency klystrons) in progress. Many were already tested to have satisfied design specifications
- Lattice and IR design, overall collider layout optimisation (optics/SRF) to e.g. reduce synchrotron radiation and power consumption
- MDI design => bkg shielding, ..
- Accelerator placement
- Continuous Injection: FCC-ee, CEPC require top-up injection for collider rings to keep luminosity high => Continuing efforts on start-to-end simulations
- Bending
- Beamstrahlung Photon Dump
- …

CEPC hardware R&D progress

representative Key Technologies for the CEPC

Specification Met ✓ Prototype Manufactured ✓



	Accelerator	Fraction
✓	Magnets	27.3%
✓	Vacuum	18.3%
✓	RF power source	9.1%
✓	Mechanics	7.6%
✓	Magnet power supplies	7.0%
✓	SC RF	7.1%
✓	Cryogenics	6.5%
✓	Linac and sources	5.5%
✓	Instrumentation	5.3%
✓	Control	2.4%
✓	Survey and alignment	2.4%
✓	Radiation protection	1.0%
✓	SC magnets	0.4%
✓	Damping ring	16 0.2%

Key technology R&D spans all component lists in CEPC CDR

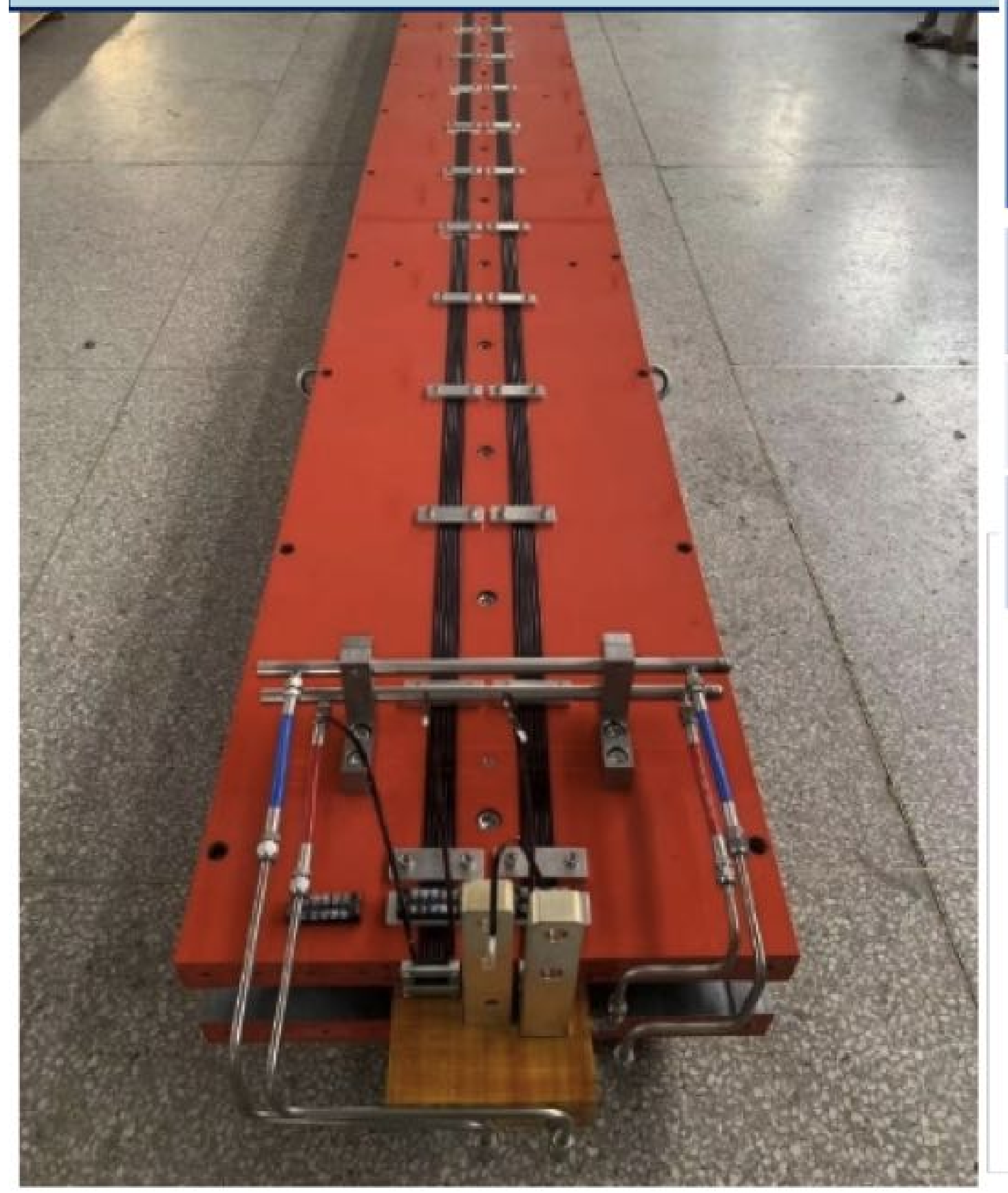
EPS-HEP2023 conference

- Prototypes built for almost all parts, with specifications met for many of them

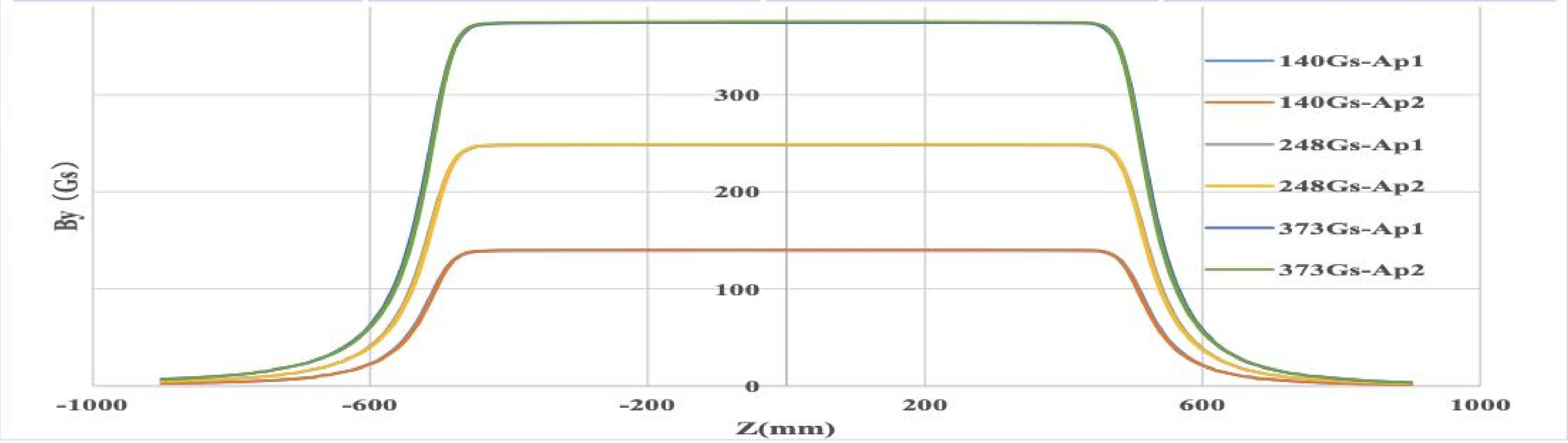
Bending

- **CEPC** R&D:
  - **Dual-aperture** configuration for **arc dipoles** => 50% less power consumption
  - Full-length dual-aperture dipoles for collider **fabricated and meet requirements**

Full-length Dual aperture dipole



E(GeV)	Ap1 ByL(T.mm)	Ap2 ByL(T.mm)	Differ
45	15.3972	15.3765	-0.13%
80	27.3358	27.3199	-0.06%
120	41.2001	41.1810	-0.05%

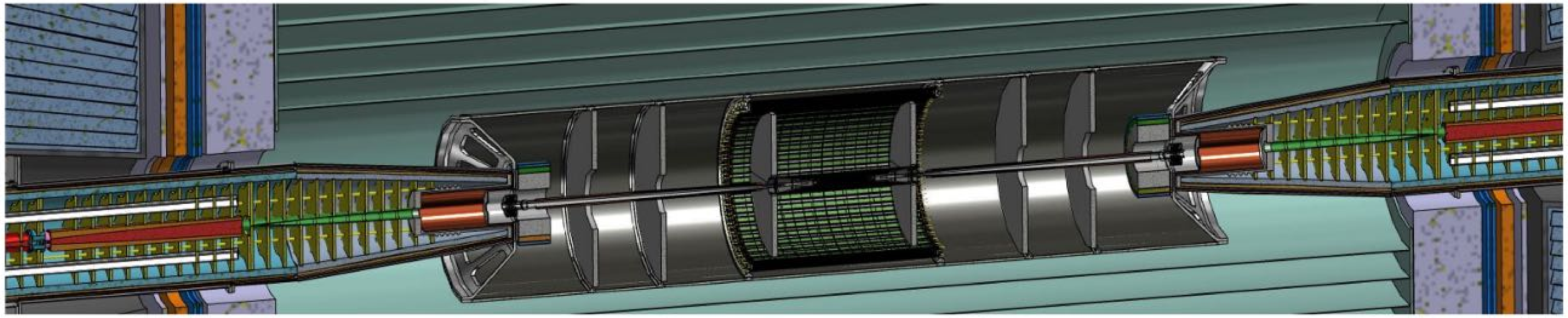


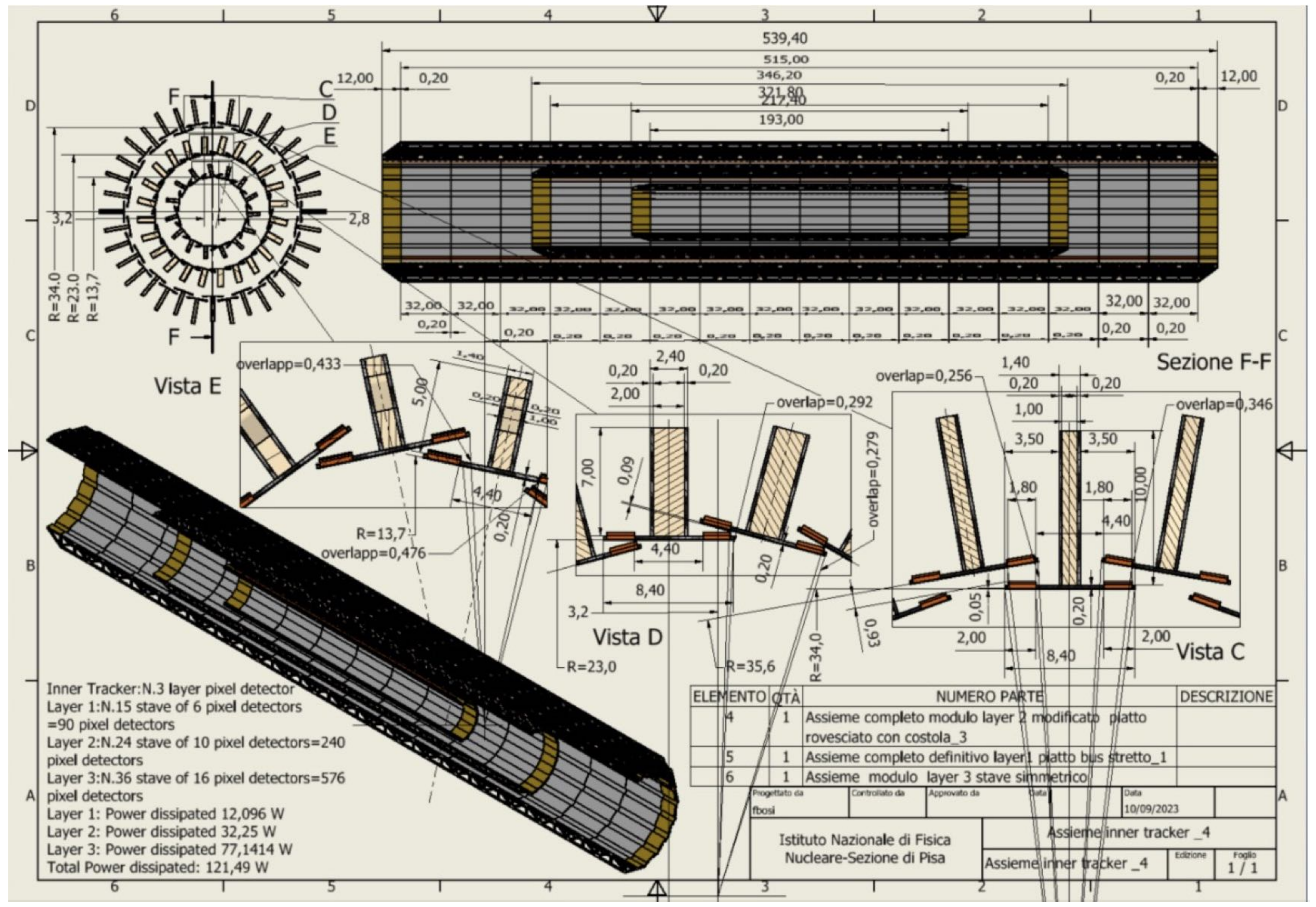
- Further **power savings / cost reduction**
  - Ongoing R&D to replace Cu with **Al for coils** (or dilute Cu)
  - Ongoing R&D to operate at **higher V / lower I** to reduce power loss in cables

Machine-detector interface

- High luminosity -> high currents -> high backgrounds -> **shielding**
- Also, nanobeams -> focusing magnets close to IP -> very compact MDI region -> **geometrical constraints**
- Novel outer support tube for central beam pipe and vertex detector designed, as part of **full engineering study of the interaction region** with LumiCal and vertex trackers of the IDEA detector

F. Palla





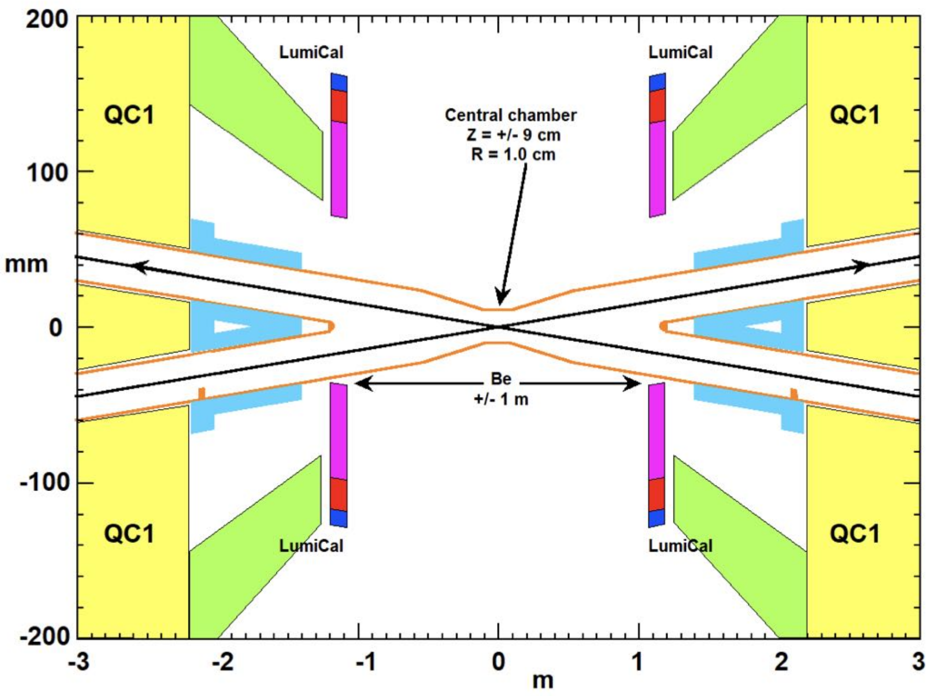
- Inside the same volume of the support tube that holds also the LumiCal
  - Vertex detector supported by the beam pipe
  - Outer Tracker (1 barrel and 6 disks) fixed to the support tube

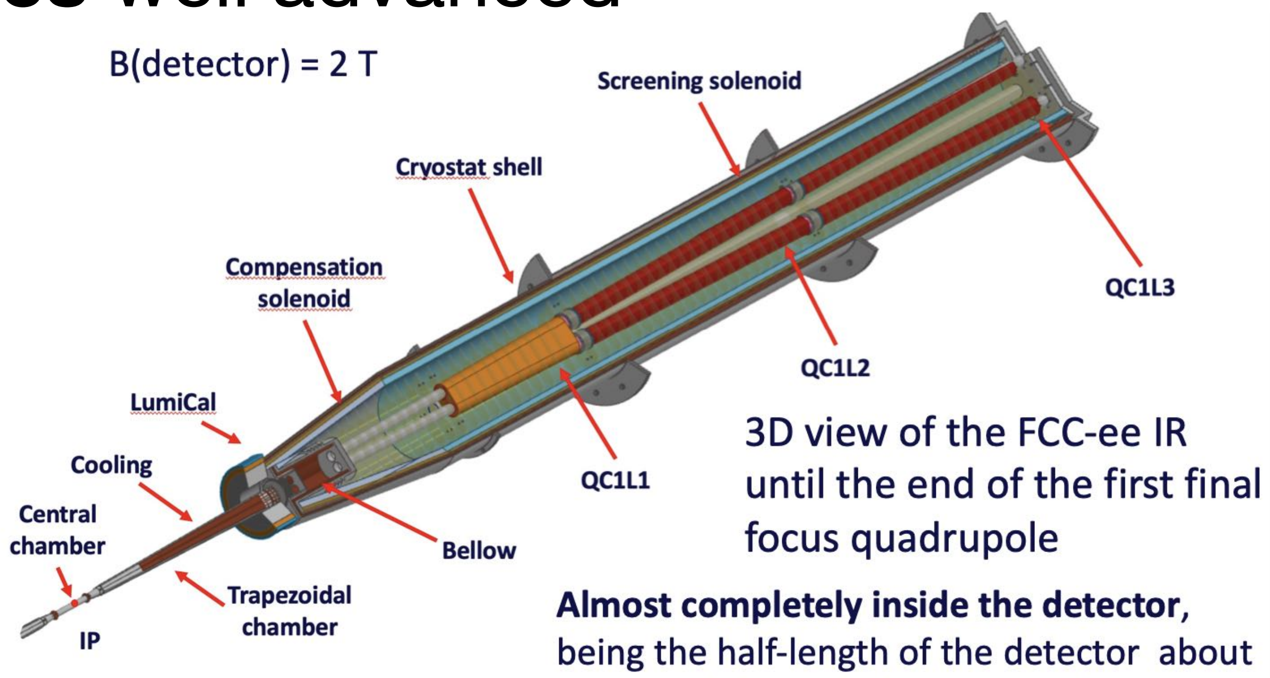
Inner vtx: Total power ~120 W Total weight ~230 g

- Ongoing studies: **thermal isolation** from beampipe takeout / **routing of services**

- **IR design / bkg studies** well advanced

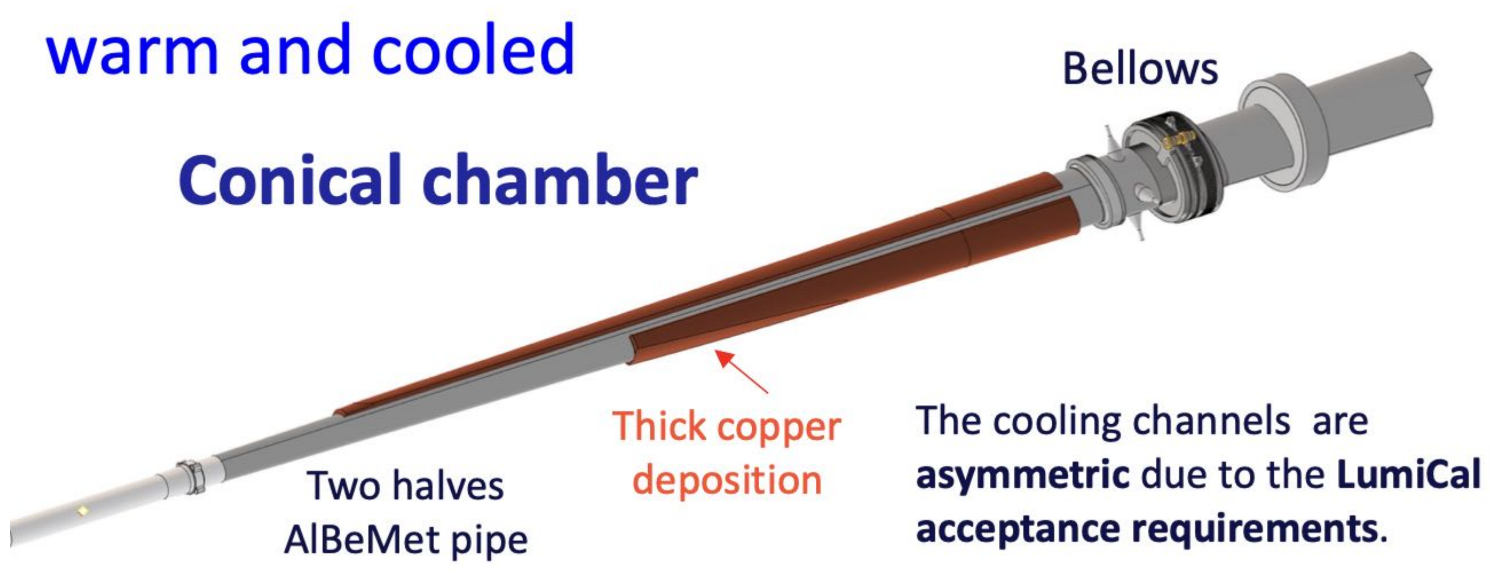
M. Boscolo





3D view of the FCC-ee IR until the end of the first final focus quadrupole

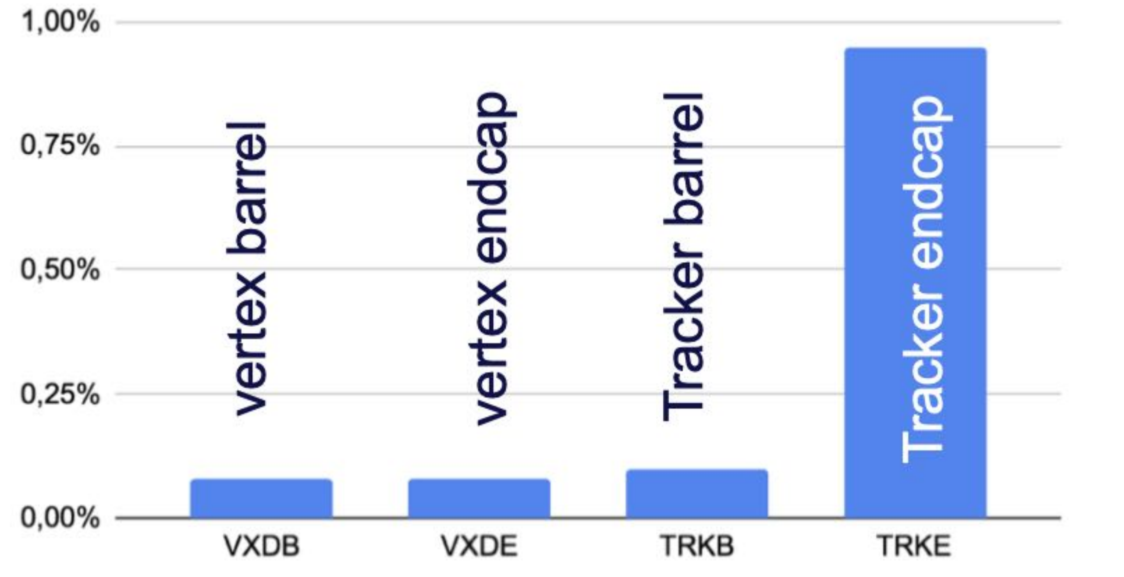
Almost completely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at about 8.4 m.



The cooling channels are **asymmetric** due to the **LumiCal acceptance requirements.**

Synchrotron Radiation backgrounds

Maximum occupancy in subdetector/BX

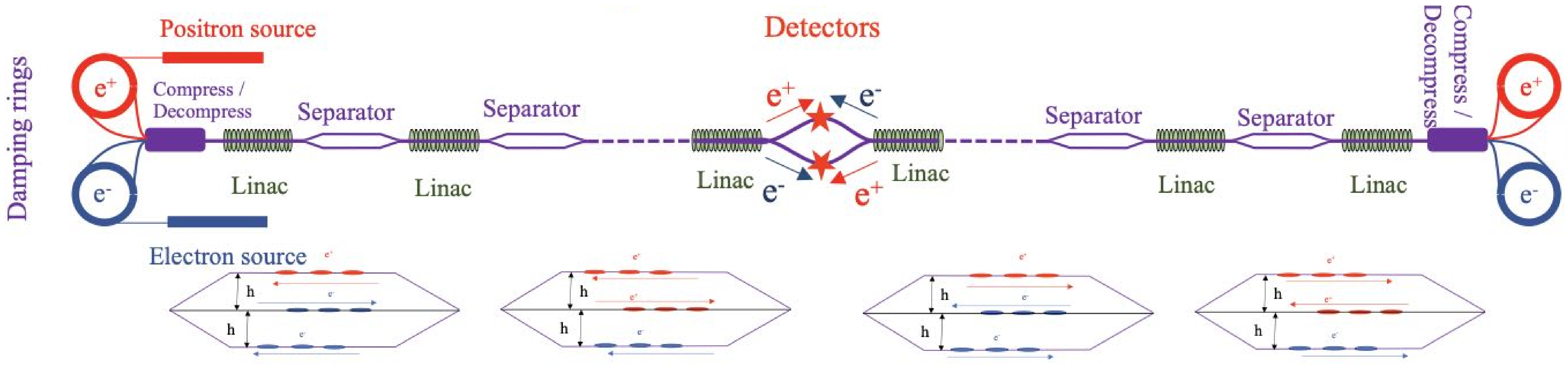


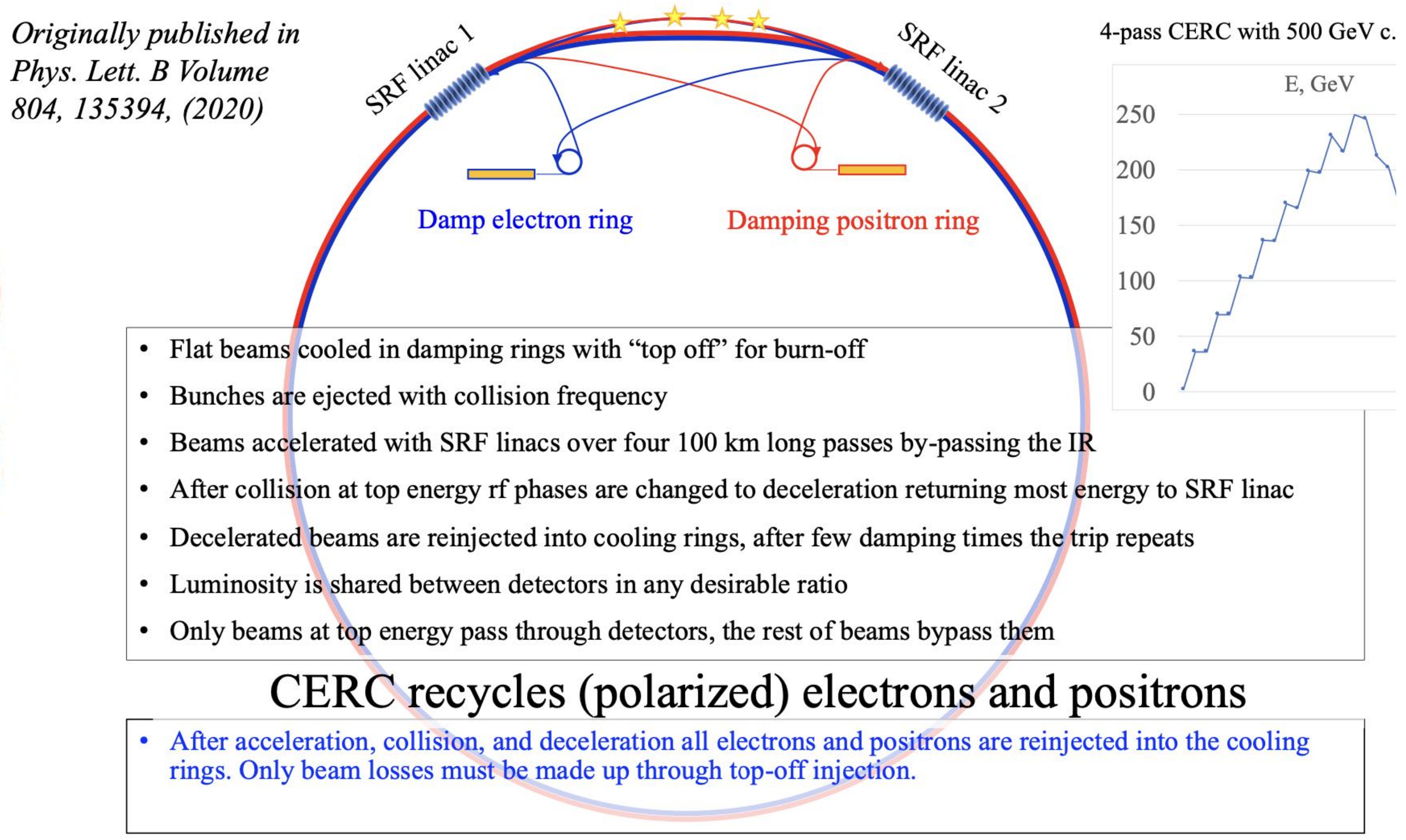
($t\bar{t}$ threshold - CDR beam parameters CLD detector - NO shieldings)

Recycling energy-recovery linacs

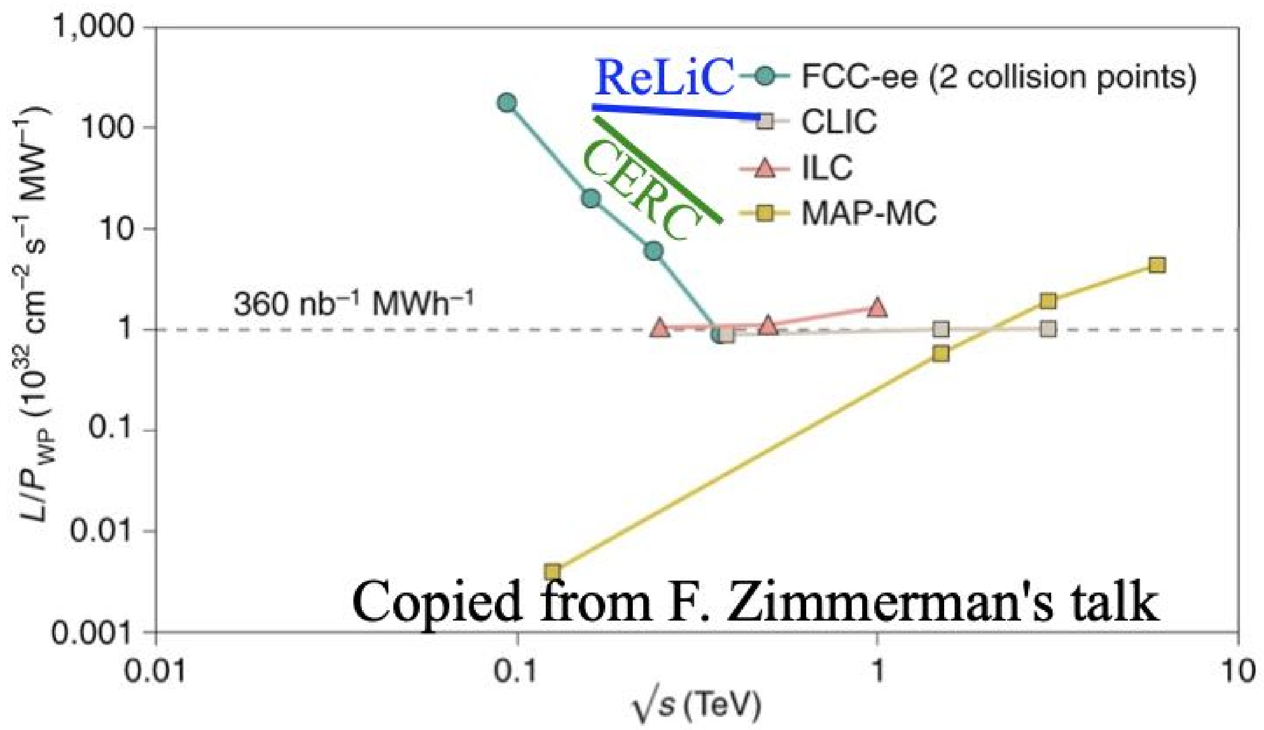
V. Litvinenko

- In **principle**, the idea is very simple : return energy from used beam back to the RF cavity and use it to accelerate fresh beam
- Extremely low losses of Superconducting RF linacs making this process very efficient
- **Concepts developed for linear and circular machines**





Collider efficiency : L/P



Challenges

- Eliminating particles loss caused by low energy tail induces by the beamstrahlung
- Damping rings with large energy acceptance
- Bunch compressing and decompression to fit into the damping ring energy acceptance
- High rep-rate injection and ejection kickers

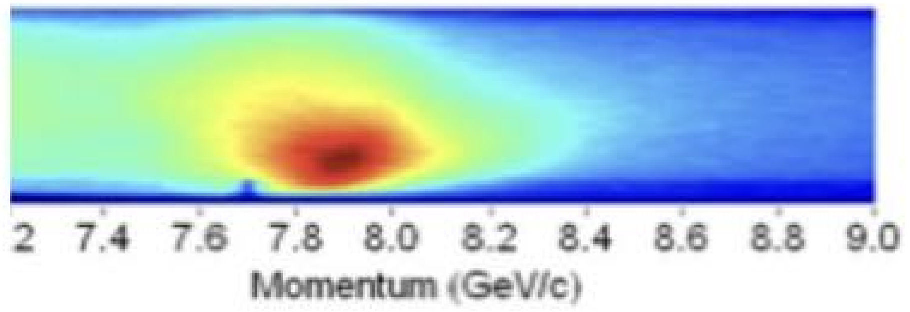
- High efficiency LiHe refrigerators
- 1.5 GHz SRF cavities with quality factor $Q > 10^{11}$ at 1.5 K (or 2 K)
- N_3Sb 4K SRF cavities with quality factor
- Reactive tuners to reduce power to suppressing microphonics
- Damping rings with very flat beams ($\varepsilon_h/\varepsilon_v$ ~2,000-4,000)
- Damping rings with 10% energy acceptance
- 10-to-40 fold bunch decompressors
- MHz scale rate injection/ejection kickers
- Vertical beam stabilization at the Ips

Plasma-based acceleration

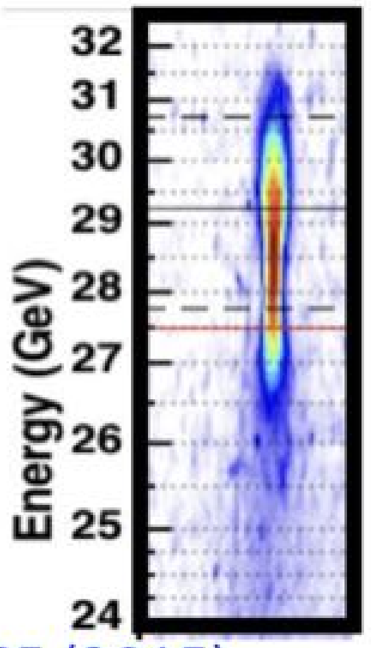
Plasma based accelerator

- Acceleration gradient:
  - Laser Wake Field Acceleration (LWFA)
    - 8GeV energy gain in 20cm plasma with 3x10^{17} cm^{-3} was achieved at BELLA, LBL

A. J. Gonsalves et al. PRL (2019)



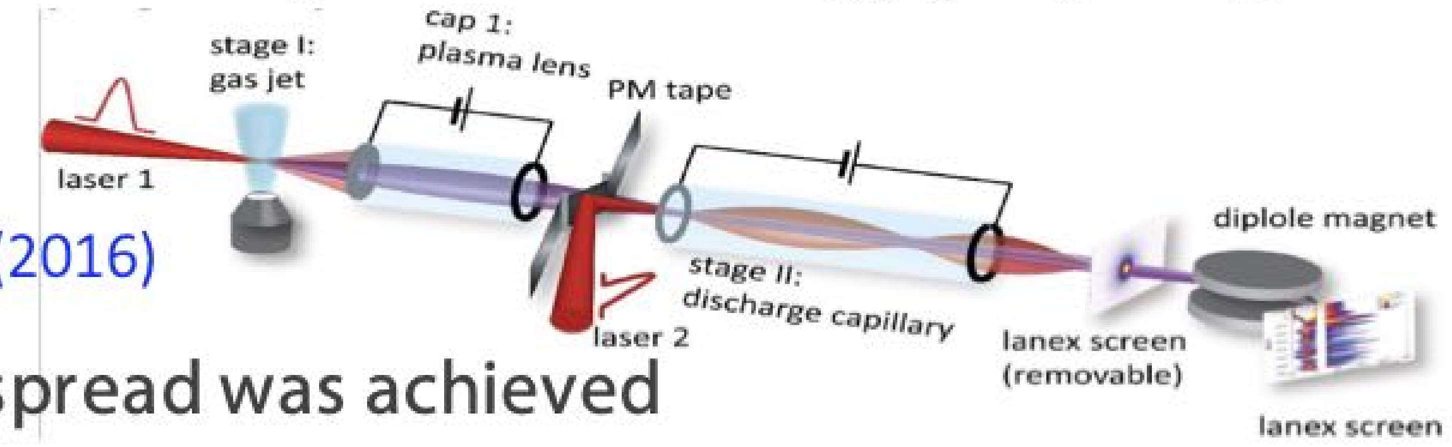
  - Beam driven plasma wakefield(PWFA)
    - 9GeV energy gain in 1.3m was achieved at FACET SLAC



M. Litos et al. PPCF (2015)

- Staging:
  - Proof-of-principle staging of LWFAs (~100 MeV energy gain) using high gradient plasma-lenses

S. Steinke et al. Nature (2016)



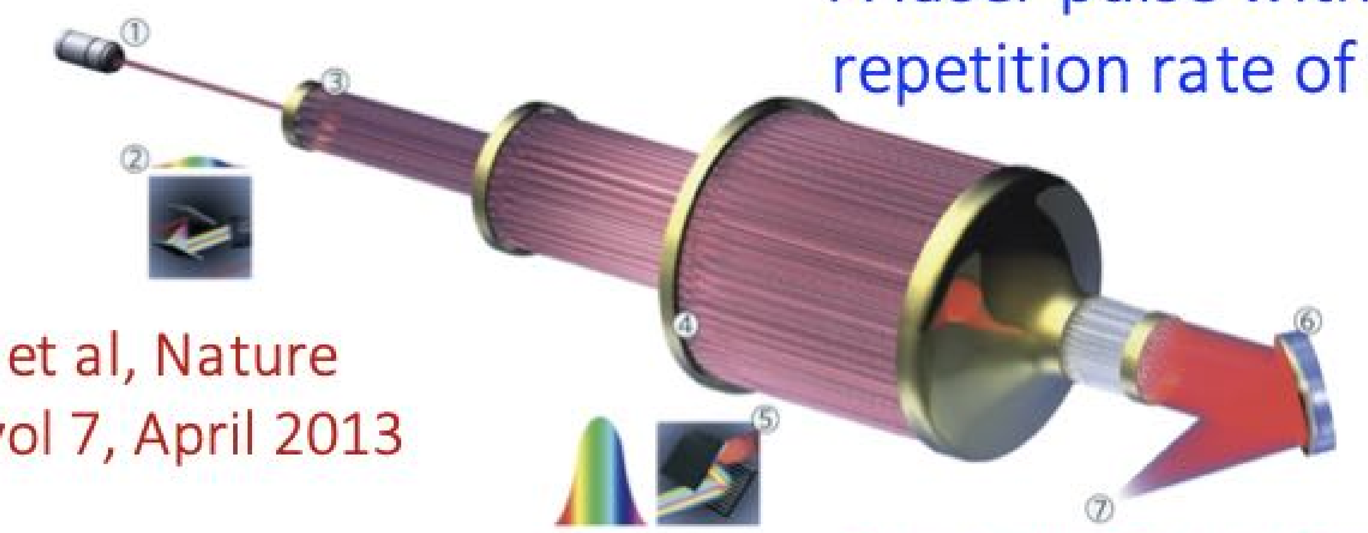
- Beam quality: ~10^{-3} energy spread was achieved
- Plasma recovery at high repetition rate was recent observed at FLASH Forward, R. D'Arcy et al., Nature (2022)

Challenges towards collider

M. Bai

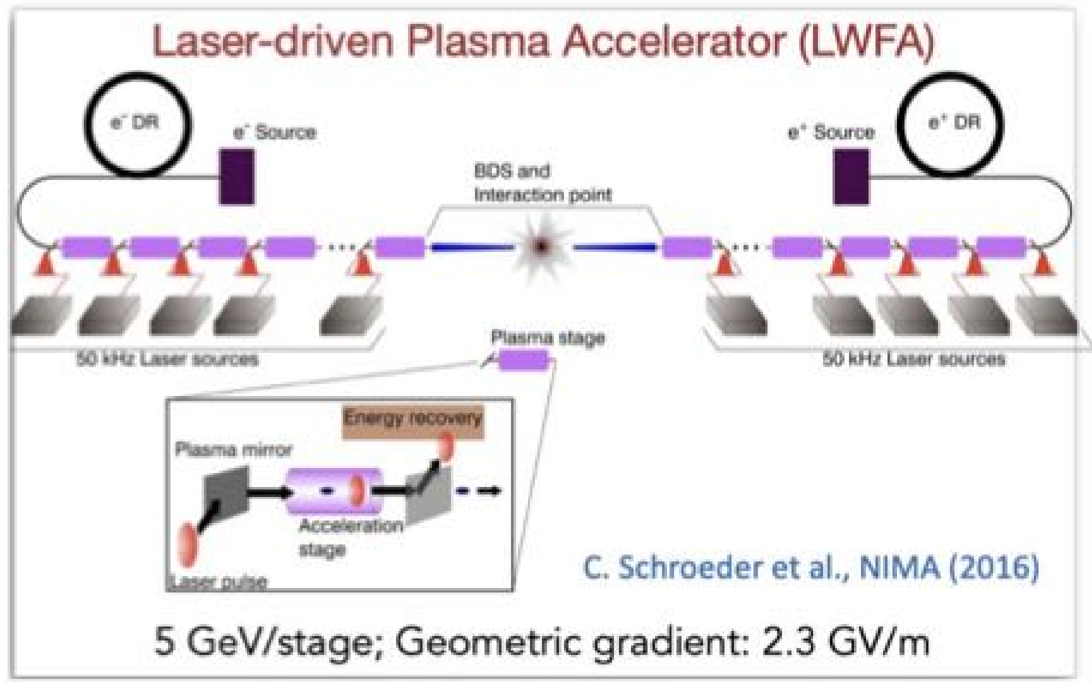
- Beam quality
  - Bunch intensity, momentum spread, emittance
- High average power laser at high repetition rate
  - Promising new technology: fiber laser

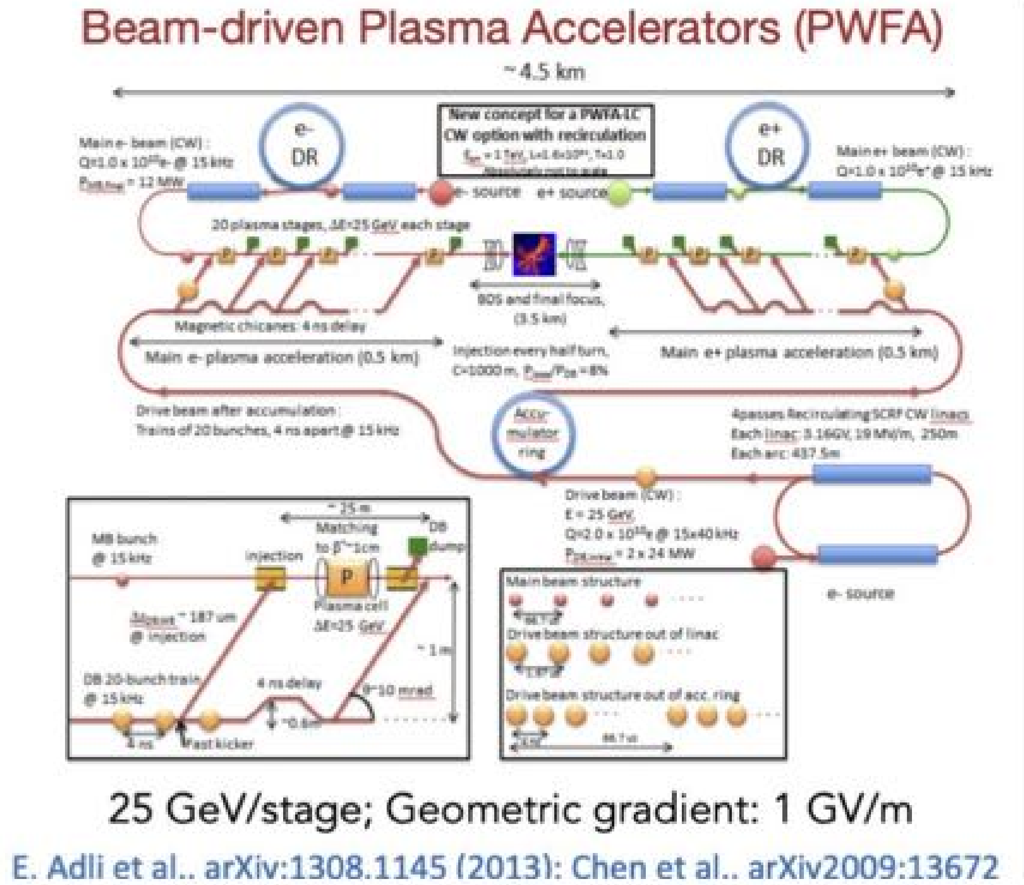
A laser pulse with >10J at a repetition rate of ~10kHz



G. Mourou, et al, Nature Photonics, vol 7, April 2013

- Multiple staging





- Positron beam for e+e- collider
- Beamstrahlung

10

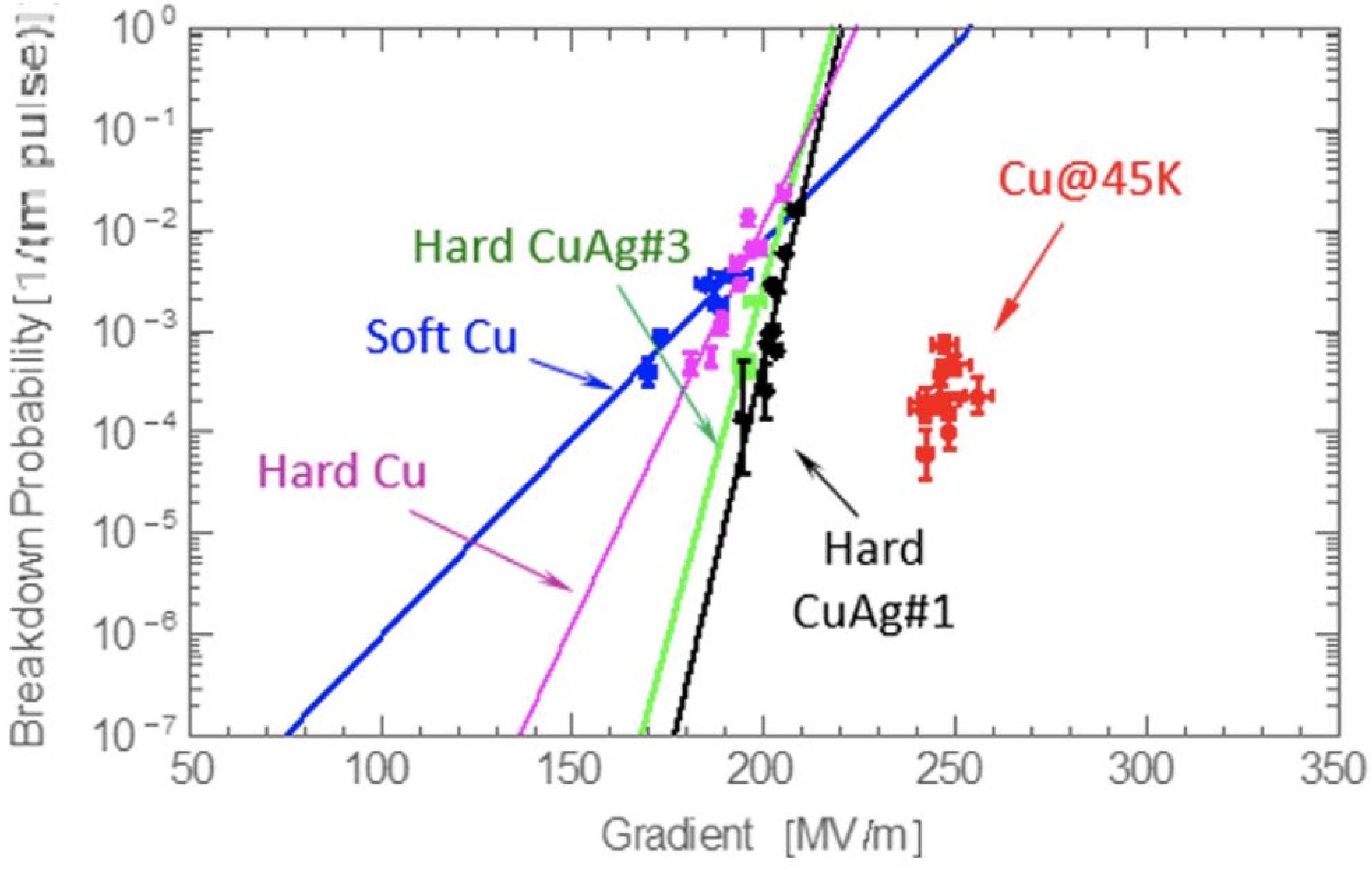
SLAC

C3

Cryogenic temperature elevates performance in gradient

- Increased material strength is key factor
- Increase electrical conductivity reduces pulsed heating in the material

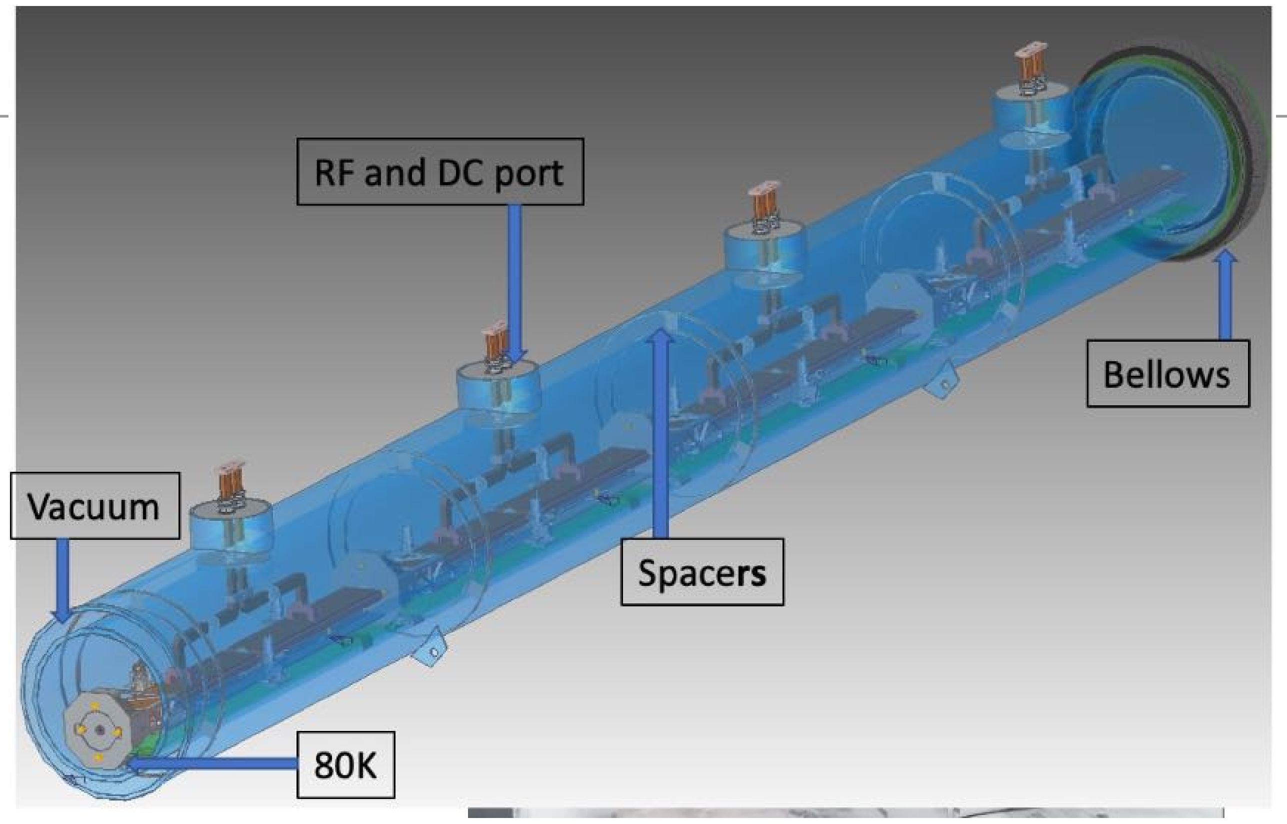
Operation at 77 K with liquid nitrogen is simple and practical



Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [$x10^{34}$]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

Cryomodule Concept



Accelerator Design

- Engineering and design of prototype cryomodule underway

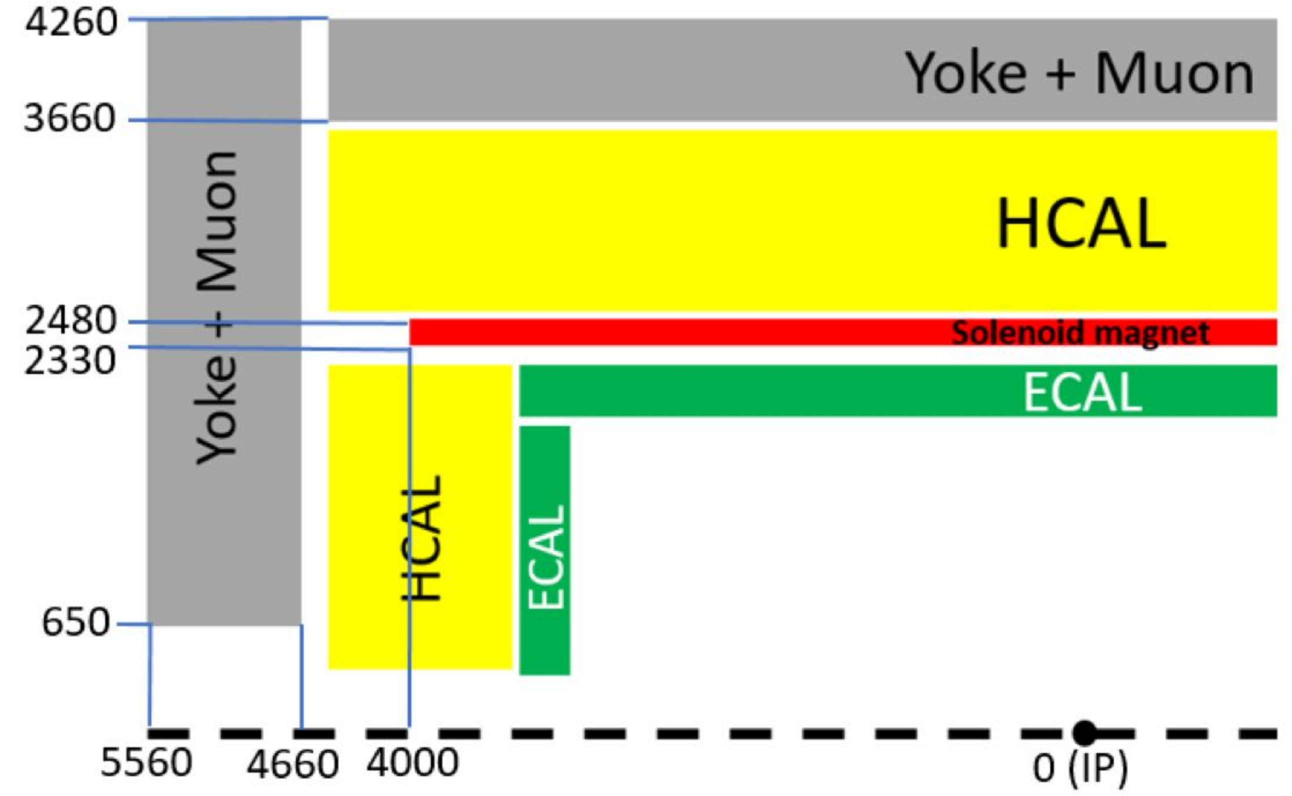
E. Nanni

Focused on challenges identified with community through snowmass (all underway)

- Gradient – Scaling up to meter scale cryogenic tests
- Vibrations – Measurements with full thermal load
- Alignment – Working towards raft prototype
- Cryogenics – Two-phase flow simulations to full flow tests
- Damping – Materials, design and simulation
- Beam Loading and Stability - Thermionic beam test
- Scalability – Cryomodules and integration

Laying the foundation for a demonstration program to address technical risks beyond RDR (CDR) level

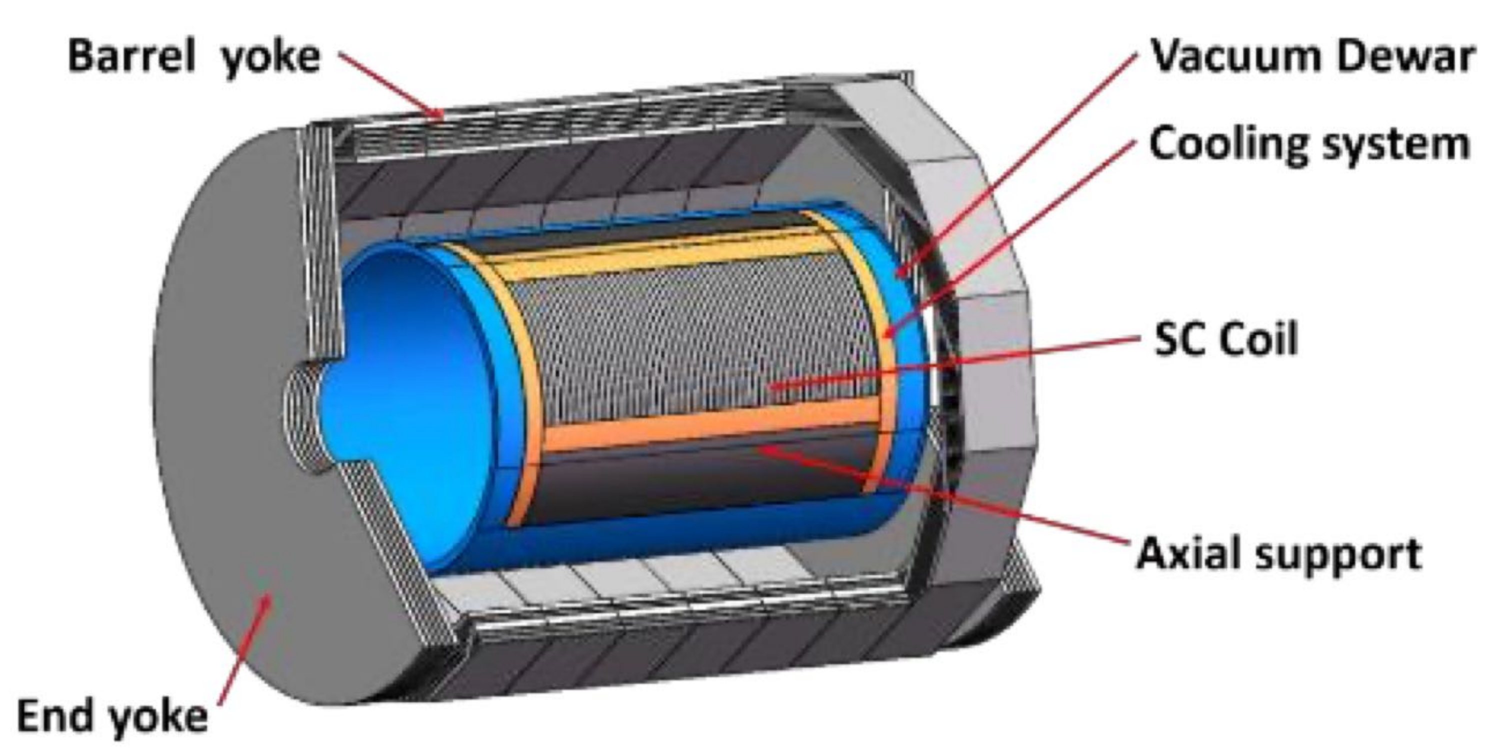
CEPC solenoid R&D



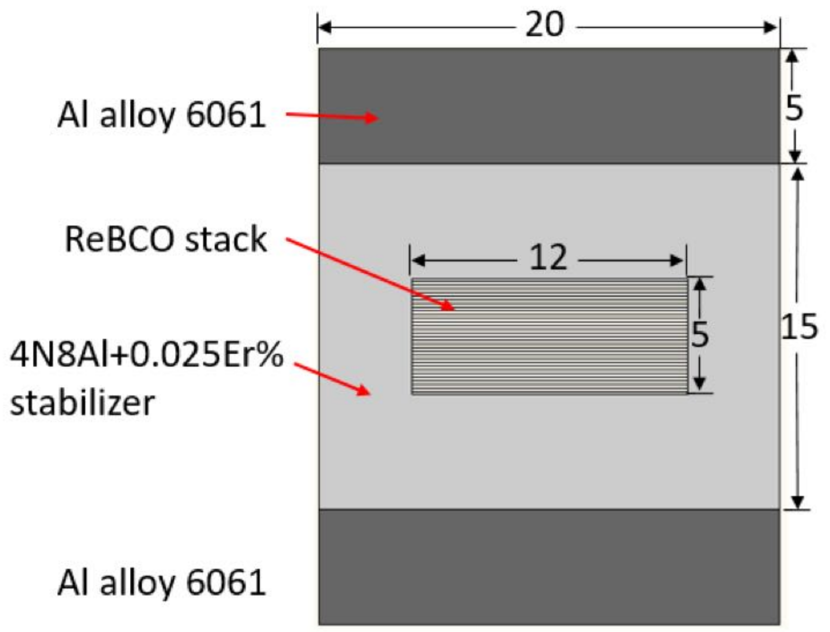
Challenges

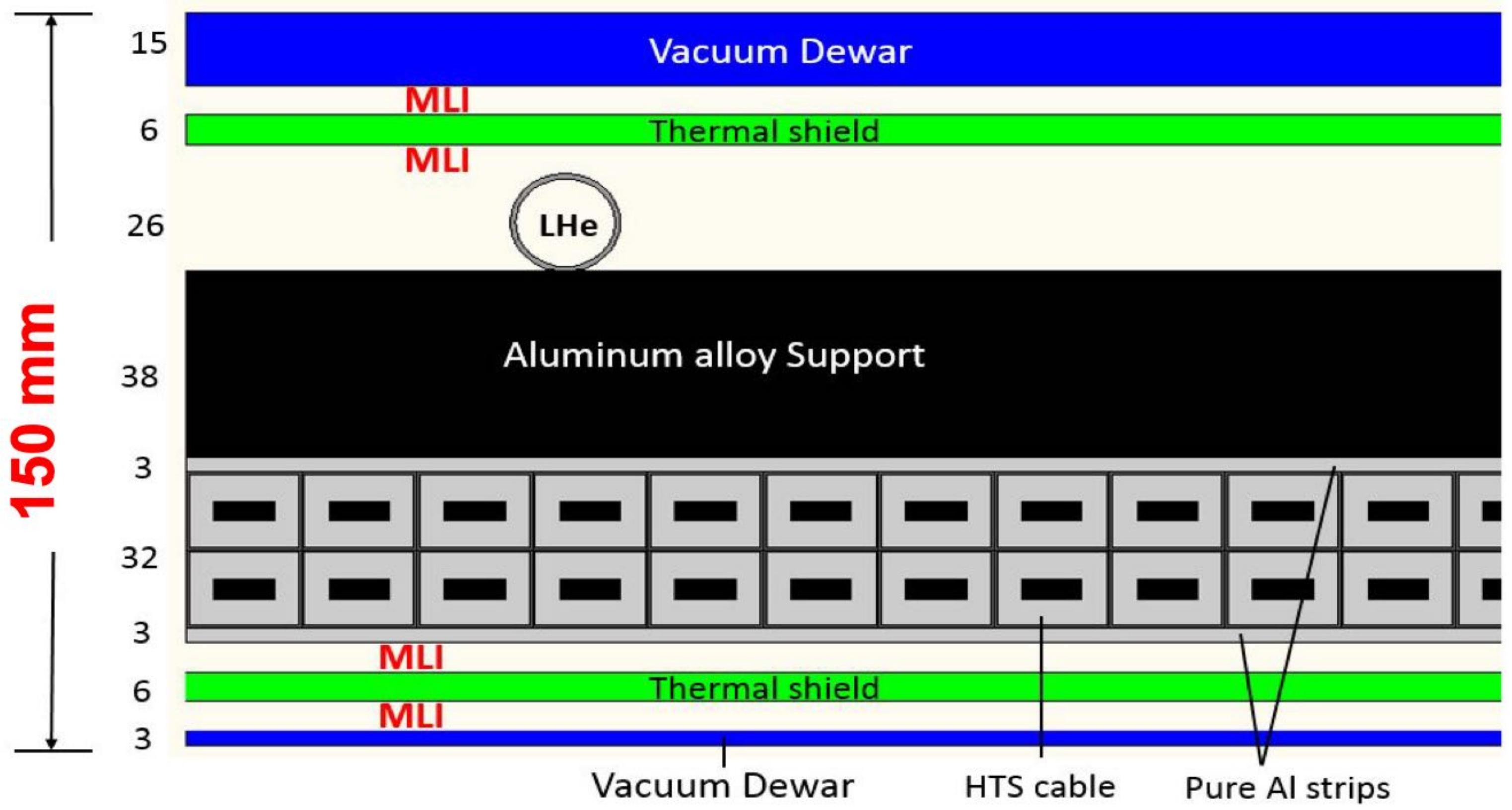
Low mass <1.5X_0
ultra-thin <150 mm
high strength cable

R&D: high strength HTS cable, ultra-thin cryostat.

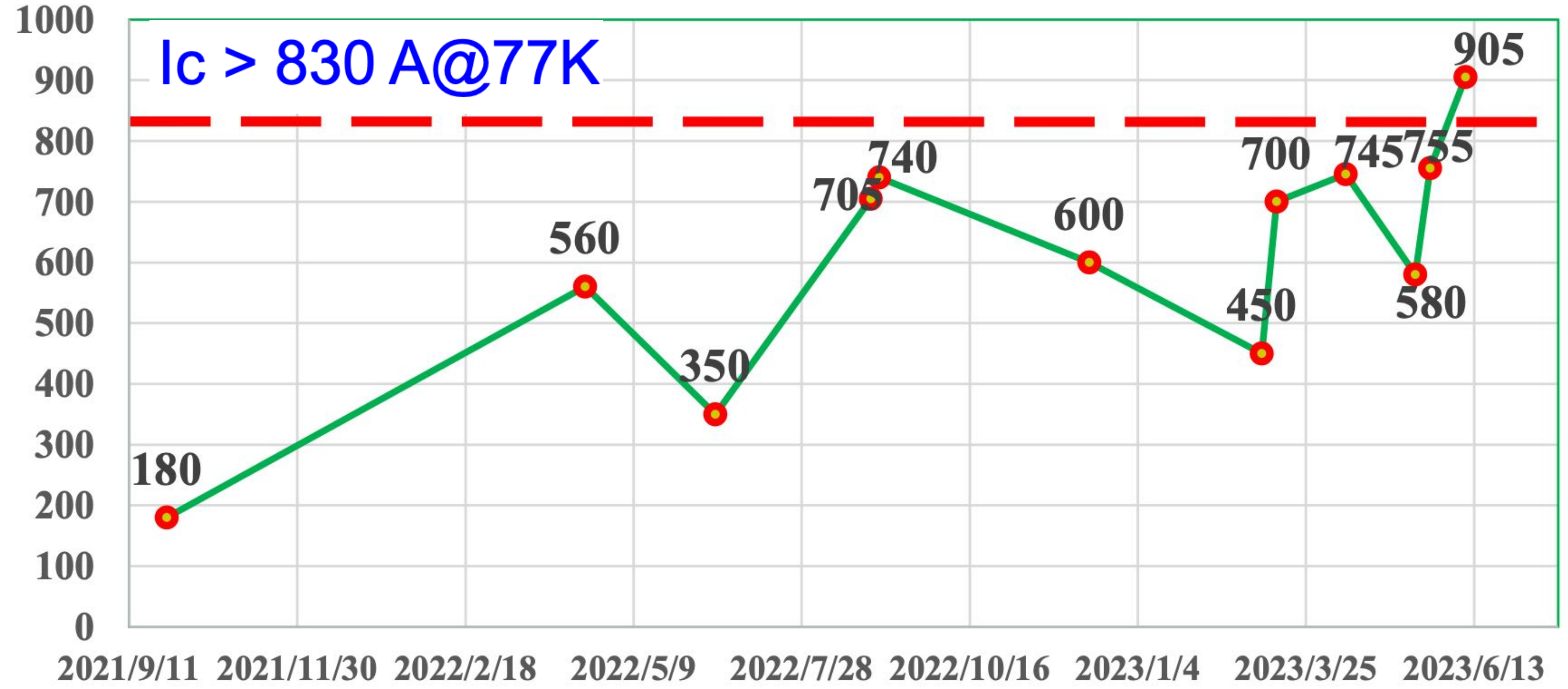


Al stabilized ReBCO stacked tape conductor (ASTC) cable



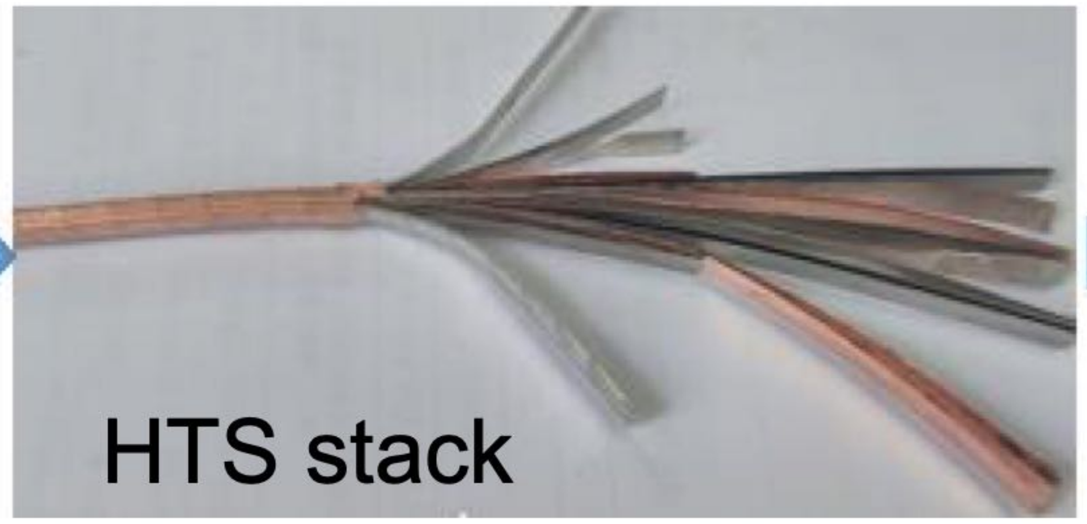


Magnetic field	3 T	Current	28000 A
Inner diameter	4660 mm	Inductance	1.27 H
Outer diameter	4960 mm	Stored energy	500 MJ
Magnet thickness	150 mm	Cold mass	27 ton
Length	8000 mm	HTS cable length	10.7 km
Total weight			

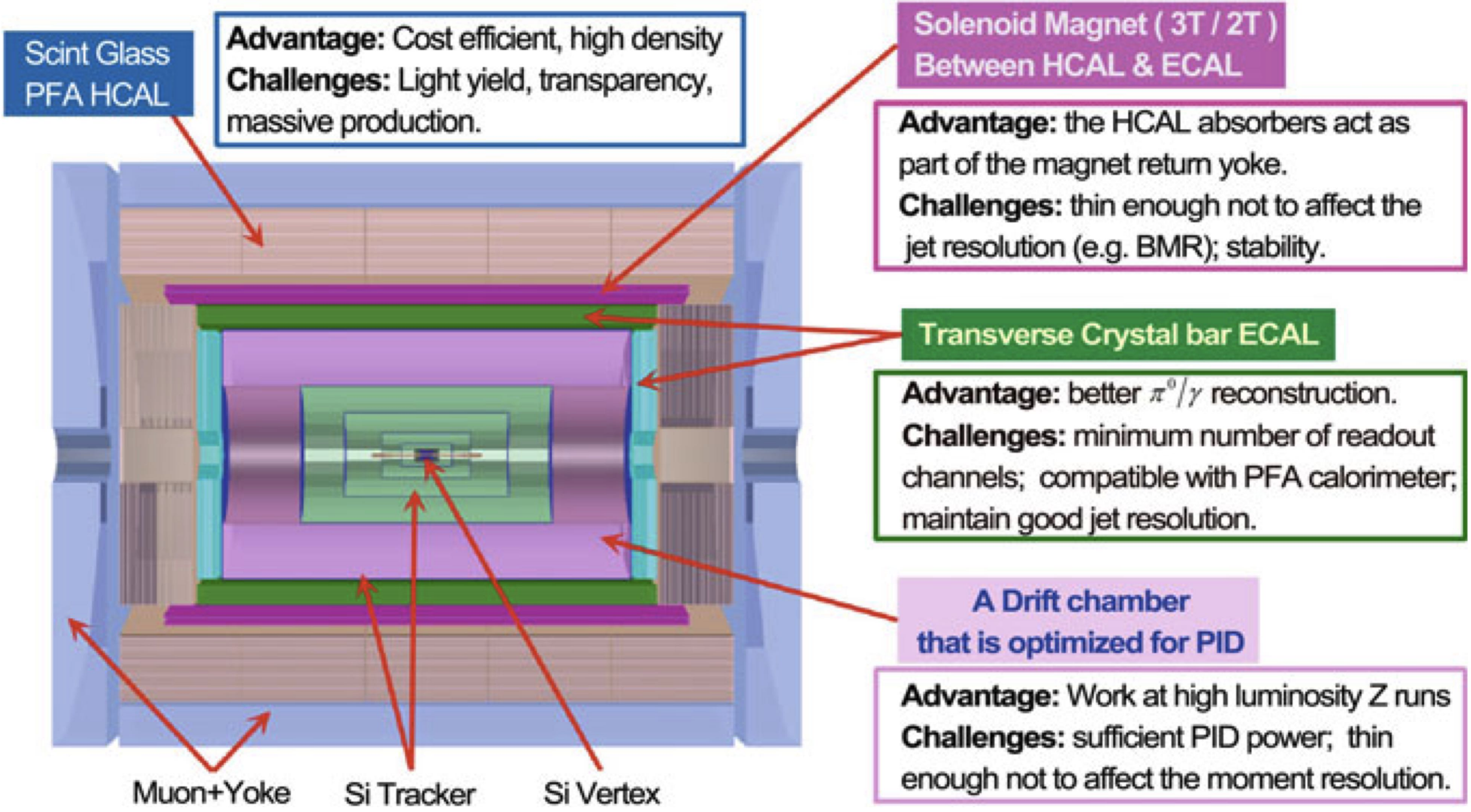


Significant progress !


HTS tape



CEPC new detector concept



IDEA detector concept

P. Giacomelli

Beam pipe: R~1.0 cm

Vertex:

5 MAPS layers

R = 1.2-34 cm

Drift Chamber: 112 layers

4 m long, R = 35-200 cm

Outer Silicon wrapper:

Si strips

Superconducting solenoid coil:

2 T, R ~ 2.1-2.4 m

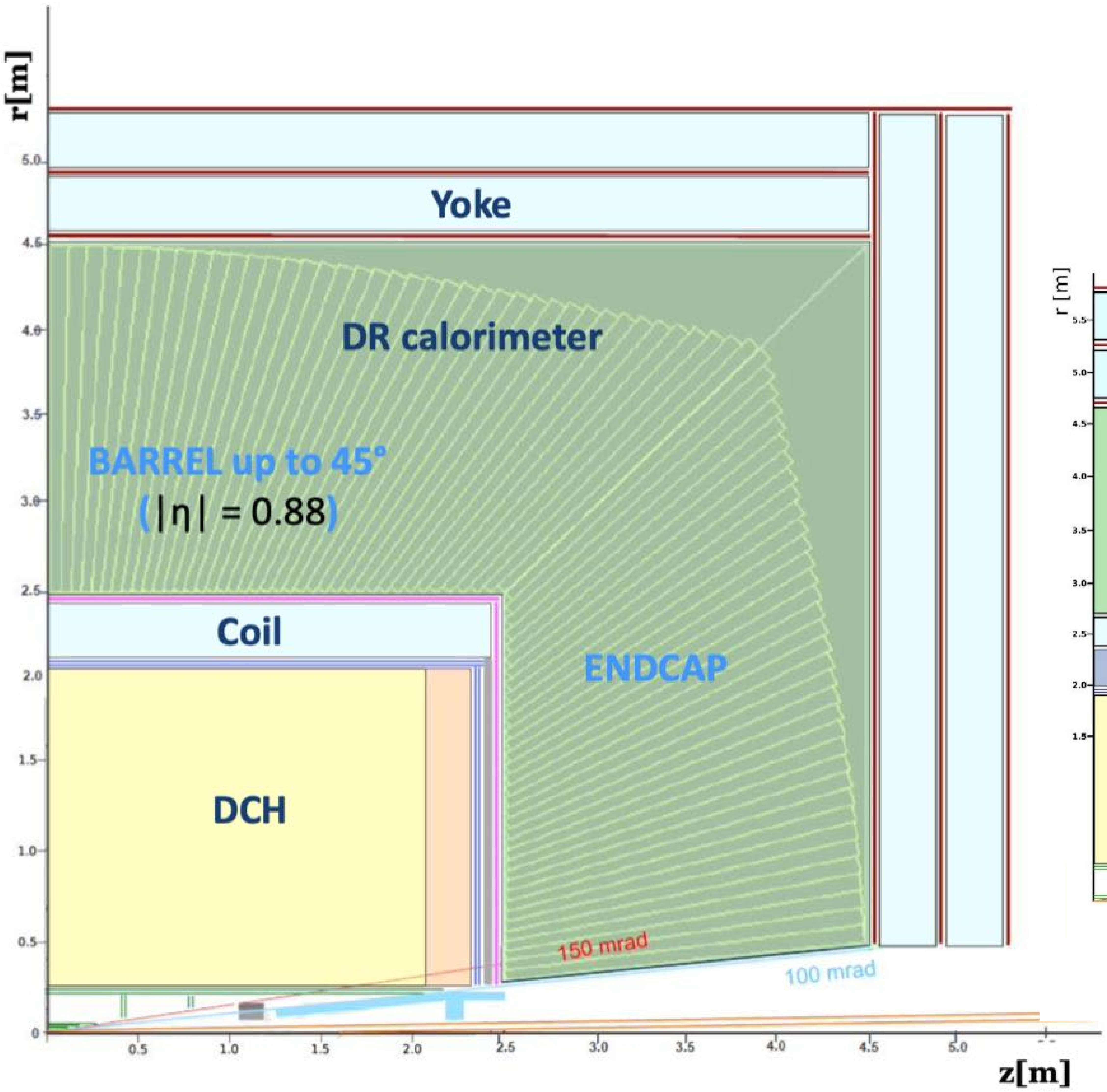
0.74 X_0, 0.16 λ @ 90°

Preshower: ~1 X_0

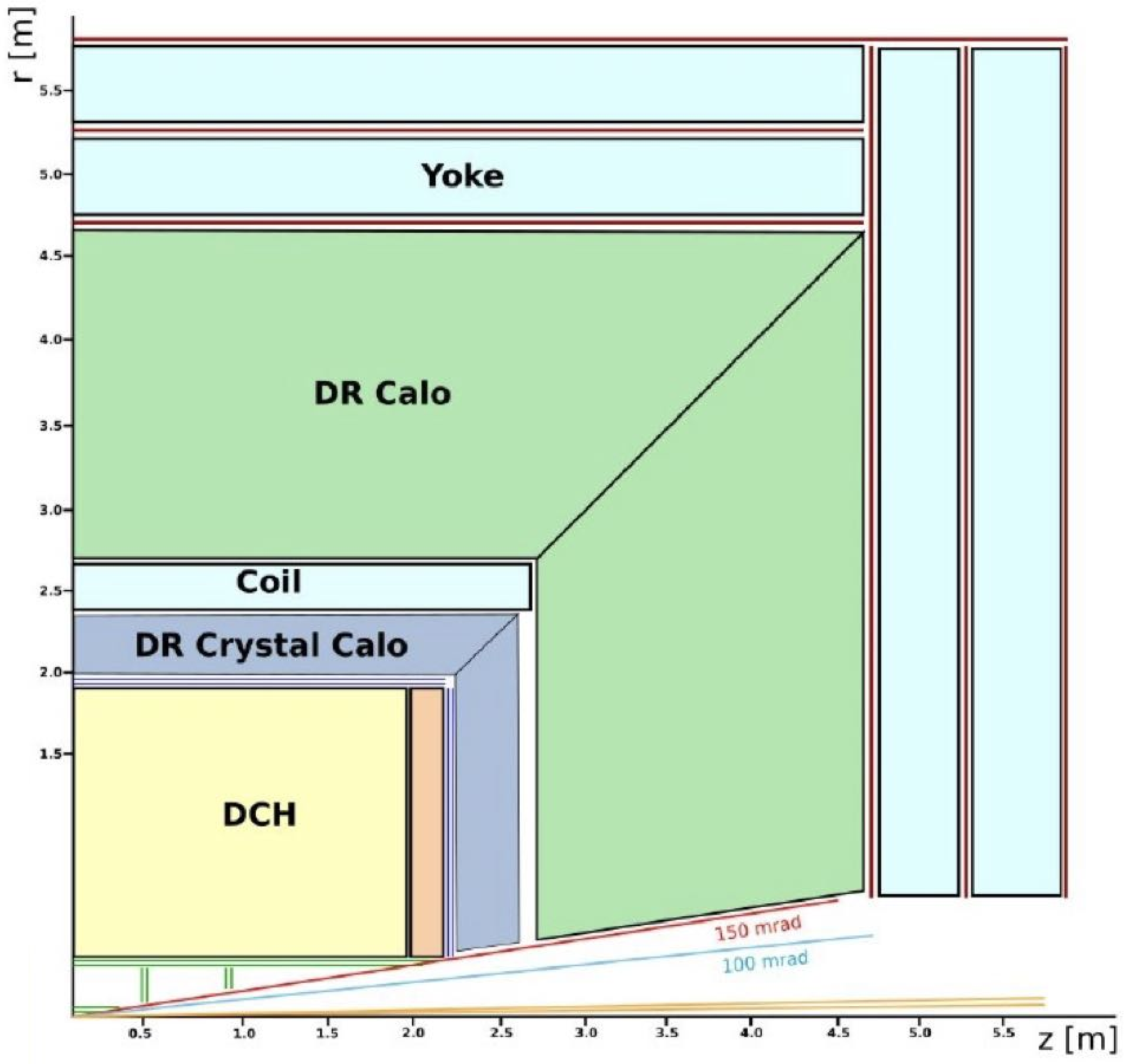
Dual-Readout Calorimeter:

2m / 7 λ_{int}

Yoke + Muon chambers

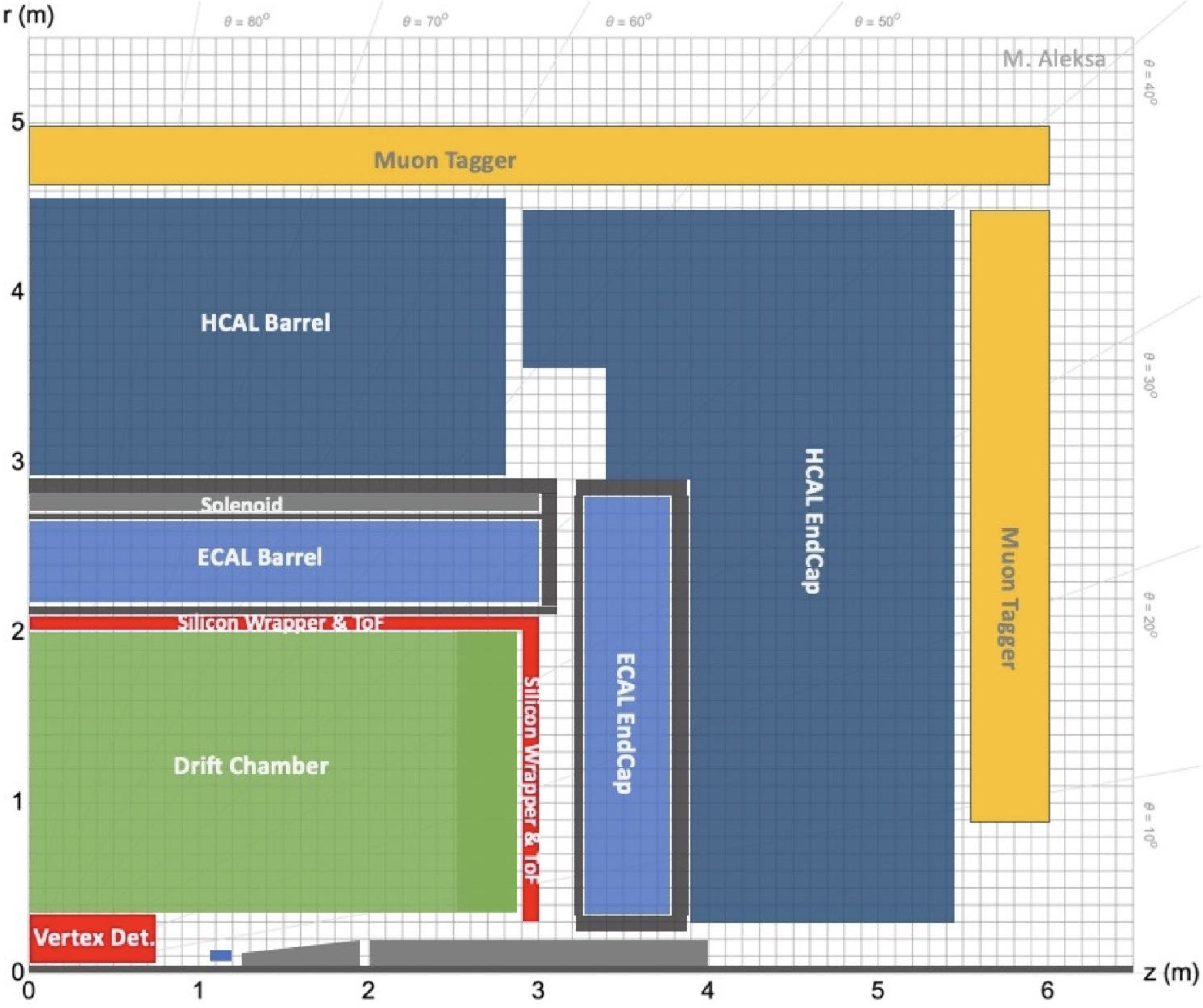


IDEA++ (w/ crystal DR calo)



Allegro detector concept

M. Aleksa



ALLEGRO

- **A** **L**epton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut

Vertex Detector:

- MAPS or DMAPS possibly with timing layer (LGAD)
- Possibly ALICE 3 like or similar to Belle II VTX upgrade

Drift Chamber (±2.5m active) similar to IDEA

Silicon Wrapper + ToF:

- MAPS or DMAPS possibly with timing layer (LGAD), Monolithic CMOS (see talk by P. Schwemling this morning)

High Granularity ECAL:

- Noble liquid + Pb or W
- Particle Flow reconstruction

Solenoid B=2T, sharing cryostat with ECAL, between ECAL and HCAL

- Light solenoid coil ≈ 0.76 X_0 (see back-up)
- Low-material cryostat < 0.1 X_0 (see back-up)

High Granularity HCAL / Iron Yoke:

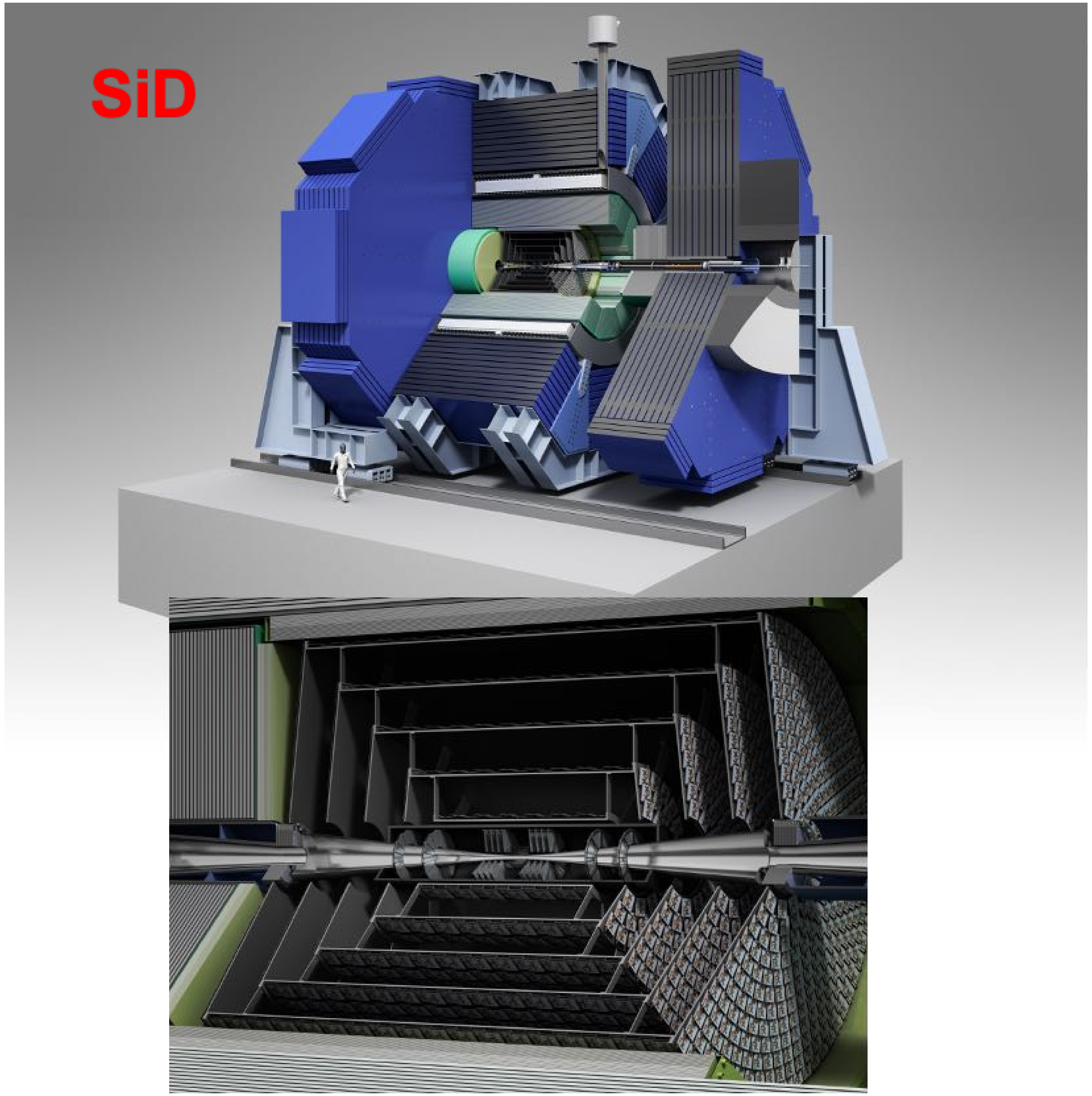
- Scintillator + Iron (particle flow reconstruction)
  - SiPMs directly on Scintillator or
  - TileCal: WS fibres, SiPMs outside

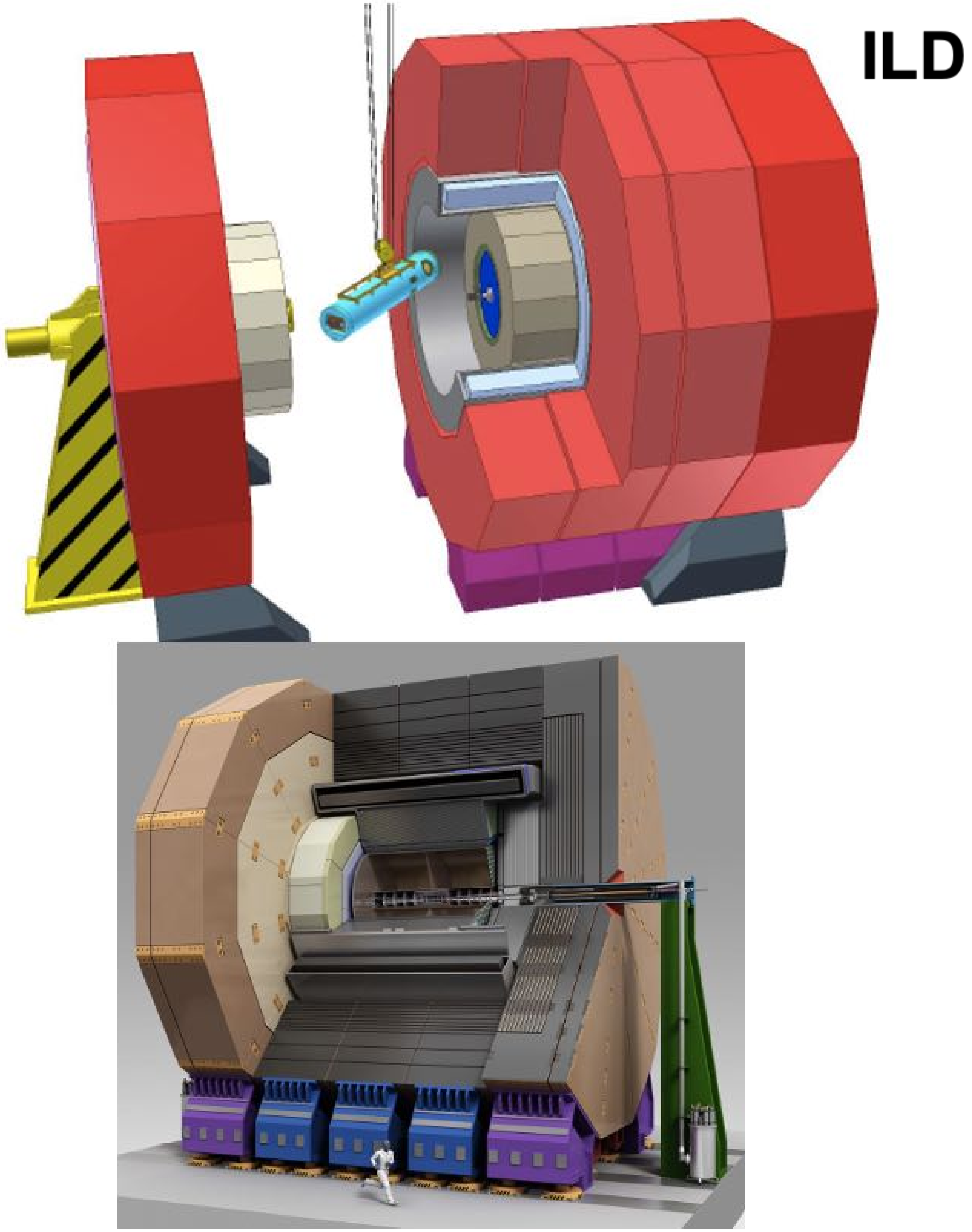
Muon Tagger:

- Drift chambers, RPC, MicroMegas

See talk at FCC Week 2022 in Paris

ILC detectors





CEPC layer-0 inside beampipe

Tr(MM) in the barrel

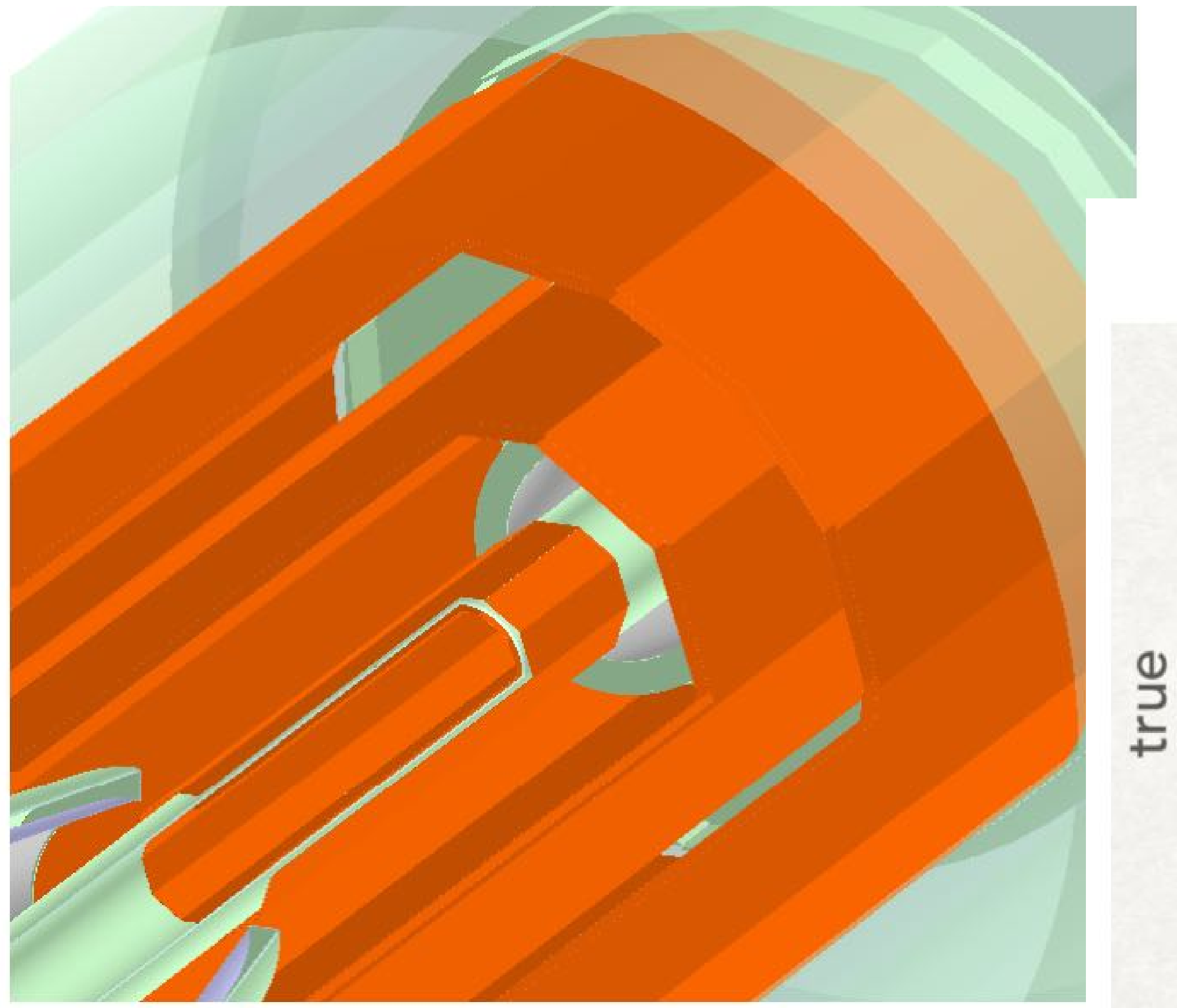
- 2.45 for baseline (?)
- 2.55 for 8 mm inner radius (9 mm)

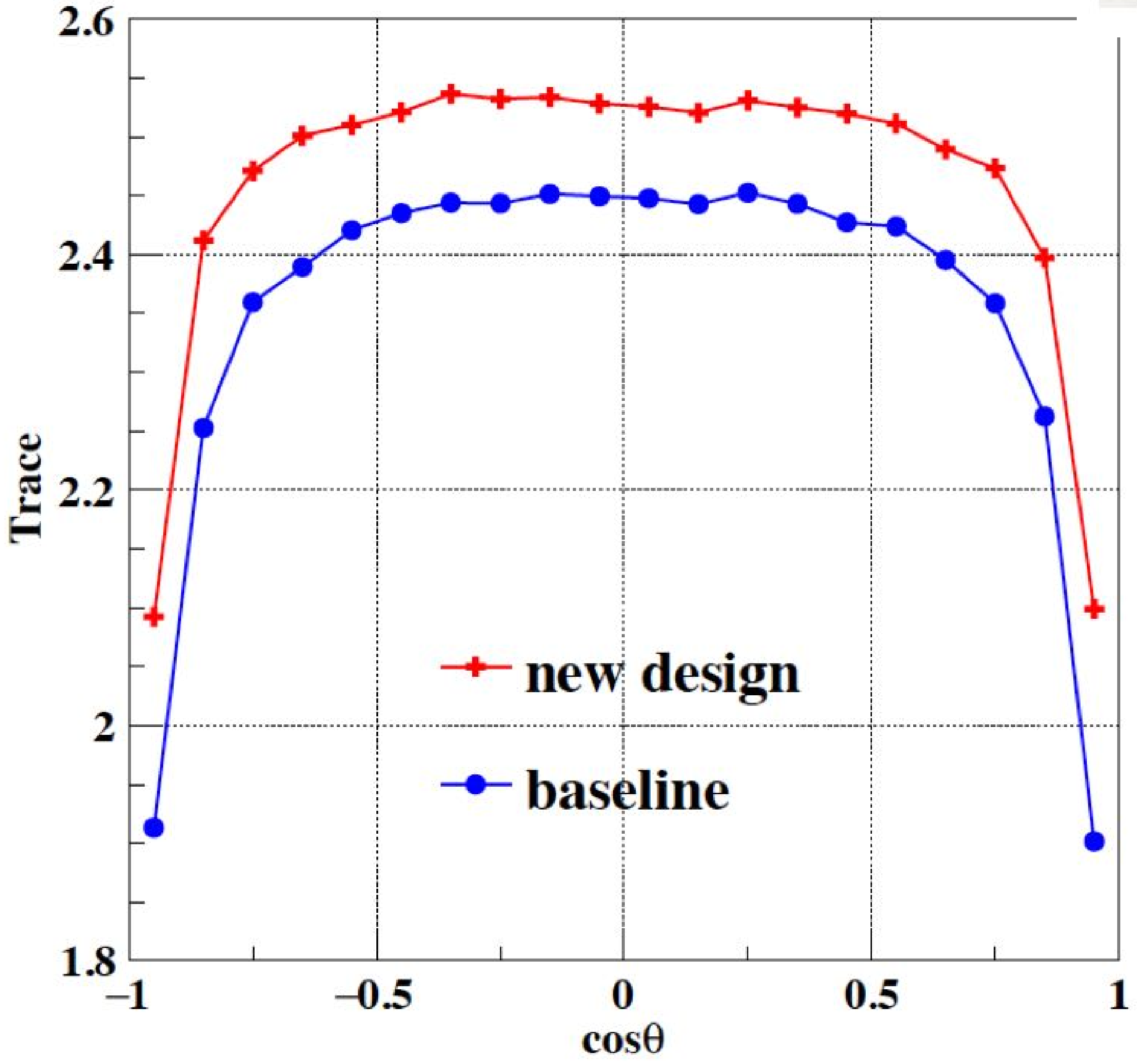
Compared to Baseline:

- 10 mm beam pipe with silicon outside/inside improves the accuracy of g(Hcc) and |Vcb| measurement by ~20%

Vin:

- Pro:
  - Closer to the IP with same beam pipe radius
  - No multiple scattering to the 1st layer
  - Loose the material constrain of beam pipe: more efficient cooling, etc
- Challenges:
  - Vacuum level
  - Radiation tolerance
  - Power & Signal → Wireless?





H->qq Migration Matrix

Perfect

true \ identified as	b	c	g
b	1	0	0
c	0	1	0
g	0	0	1

Worst

true \ identified as	b	c	g
b	1/3	1/3	1/3
c	1/3	1/3	1/3
g	1/3	1/3	1/3

M. Ruan

Drift chamber wire material

F. Grancagnolo

Electrostatic stability condition

$$T_c \geq \frac{C^2 V_0^2}{4\pi\epsilon w^2} L^2$$

T_c wire tension
w cell width
L wire length

C capacitance per unit length
V_0 voltage anode-cathode

For w = 1 cm, L = 4 m:

T_c > 26 g for 40 µm Al field wires (δ_{grav} = 260 μm)

T_c > 21 g for 20 µm W sense wires (δ_{grav} = 580 μm)

Elastic limit condition

T_c < YTS × π ·r_w^2 *YTS = 750 Mpa* for W, *290 Mpa for Al*

T_c < 36 g for 40 µm Al field wires (δ_{grav} = 190 μm)

T_c < 24 g for 20 µm W sense wires (δ_{grav} = 510 μm)

The drift chamber length (**L = 4 m**) imposes strong constraints on the drift cell size (**w = 1 cm**)

Very little margin left ⇒ increase wires radii or cell size

⇒ use different types of wires

But cell size not too big => occupancy

Increase cell size to *w > 1.5 cm (+10%)*

(56,448 → 45,700 cells, 112 → 100 layers, 340,000 → 500,000 wires, 9 → 18 Ton)

and **replace 20 µm W and 40-50 µm Al** (5:1) with

(2 (0.5) µm Ag coated) **35 µm C wires** (10:1). Stability condition:

30 g < T_c < 87 g corresponding to ***270 (158) µm > δ_{grav} > 93 (54) µm***

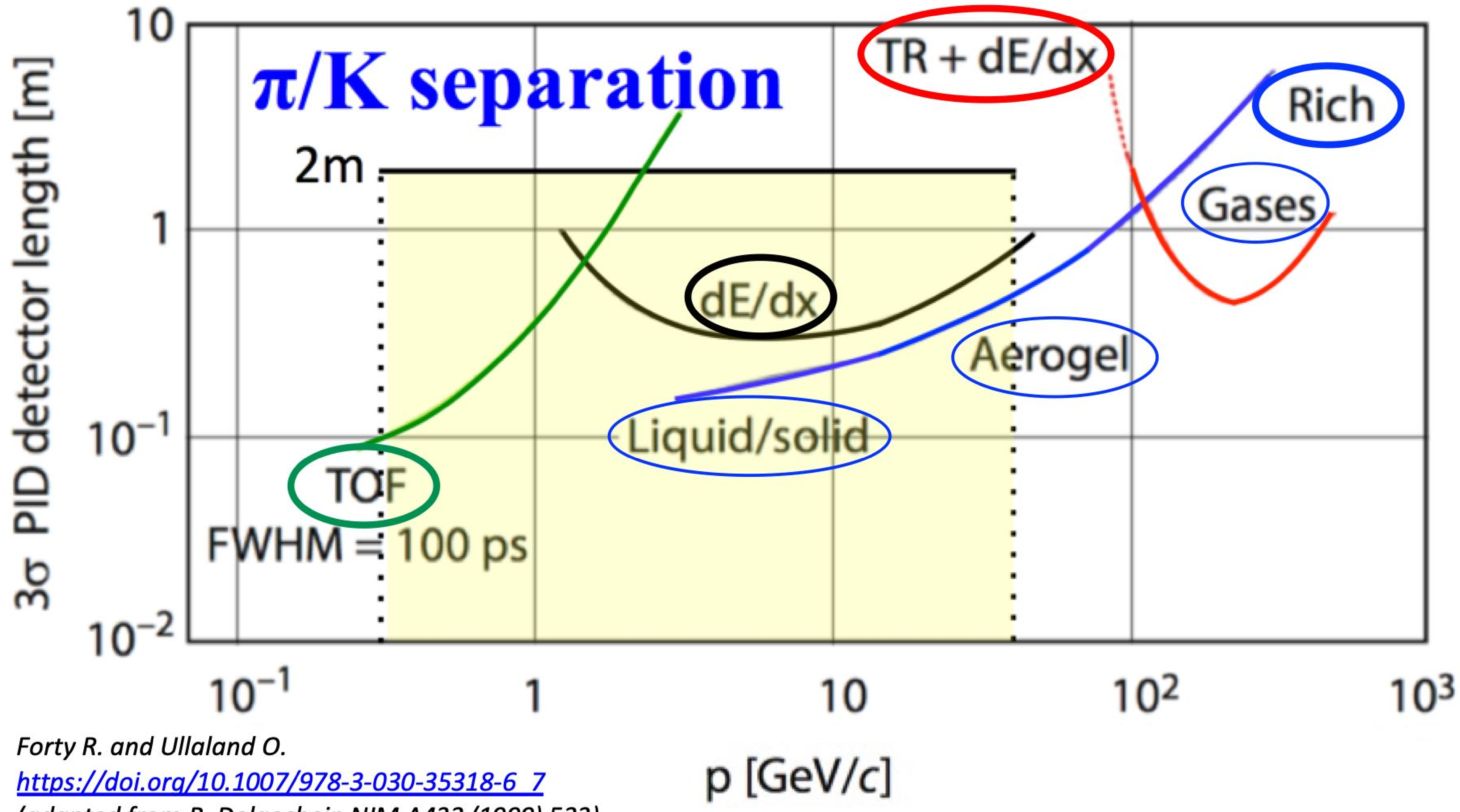
(safety factor within ample margin!)

Contribution to m. scatt. from wires: 1.3×10^{-3} X_0 → 0.9×10^{-3} X_0

Particle identification technologies

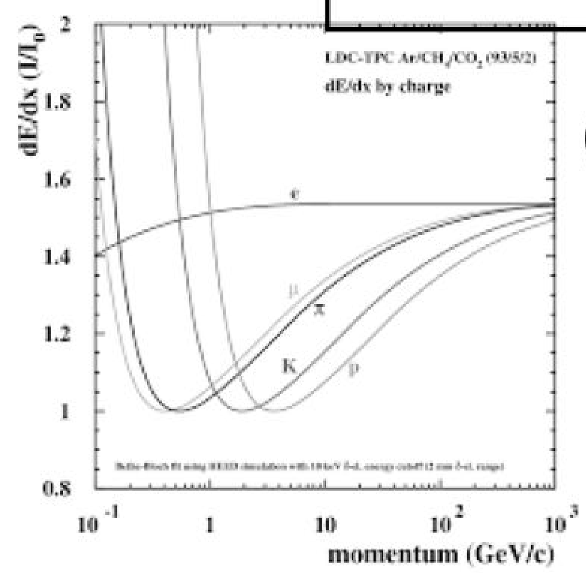
F. Grancagnolo

$$\frac{m^2}{p^2} = \frac{1}{\gamma^2 - 1} = \frac{1-\beta^2}{\beta^2}$$



Forty R. and Ullaland O.
https://doi.org/10.1007/978-3-030-35318-6_7
(adapted from B. Dolgoshein NIM A433 (1999) 533)

dE/dx



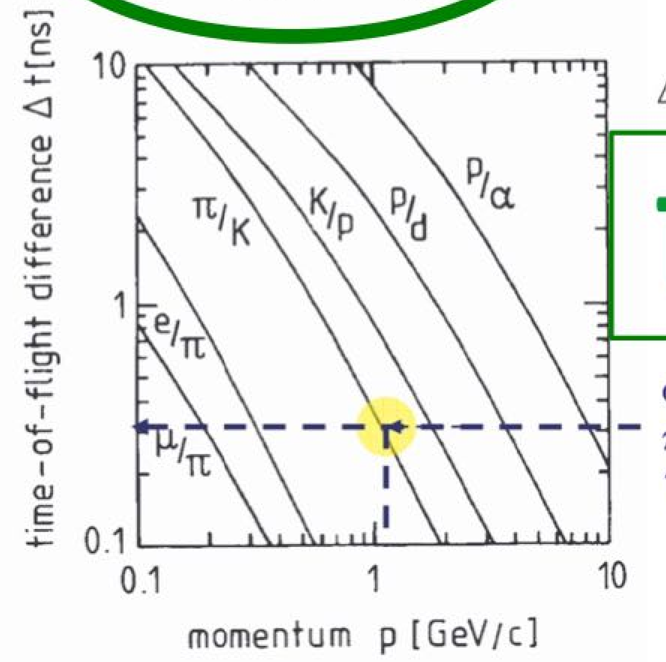
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1+\frac{2\gamma m_e}{M}+\left(\frac{m_e}{M}\right)^2}$$

$$N_{cluster} = \int_0^L \frac{1}{w(x)}\frac{dE}{dx}dx$$

$dN_{cluster}/dx$

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1}-\frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1+m_1^2c^2/p^2}-\sqrt{1+m_2^2c^2/p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2-m_2^2\right)$$



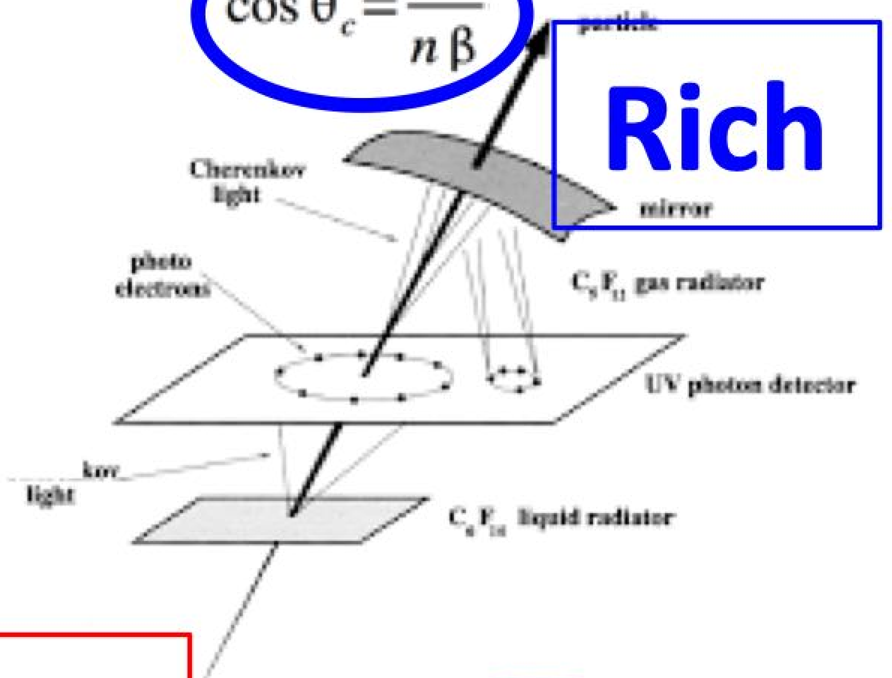
Δt for L = 1 m path length

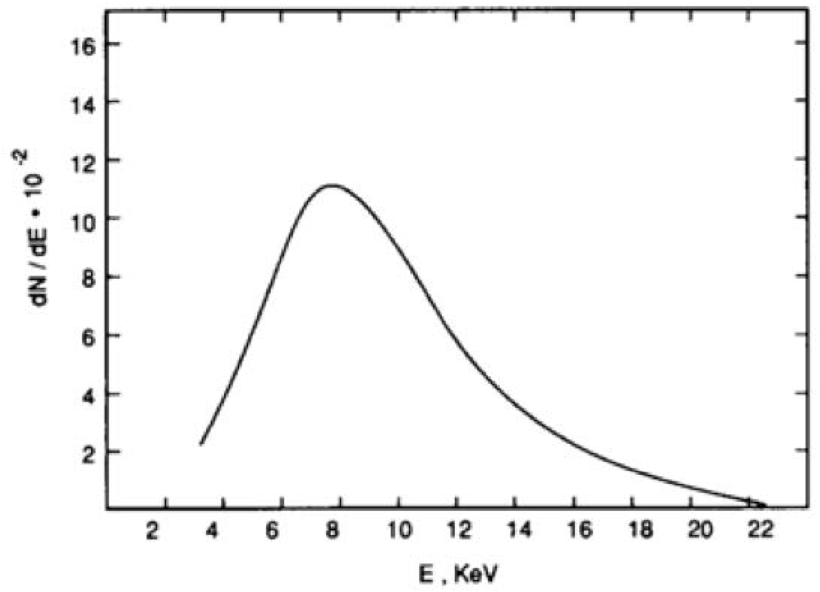
TOF

σ_t = 300 ps
π/K separation up to 1 GeV/c

$$\cos\theta_c = \frac{1}{n\beta}$$

Rich





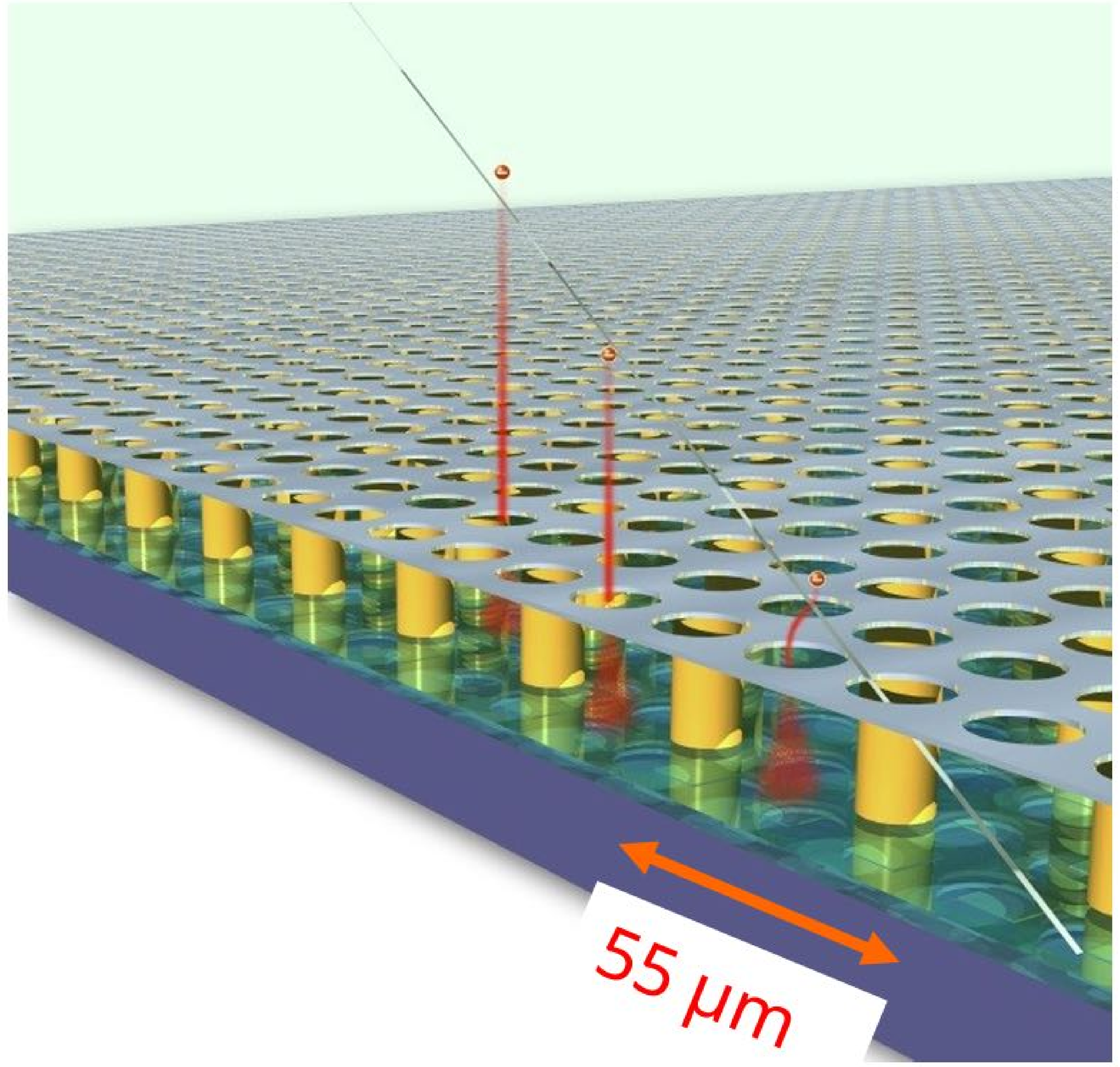
TR

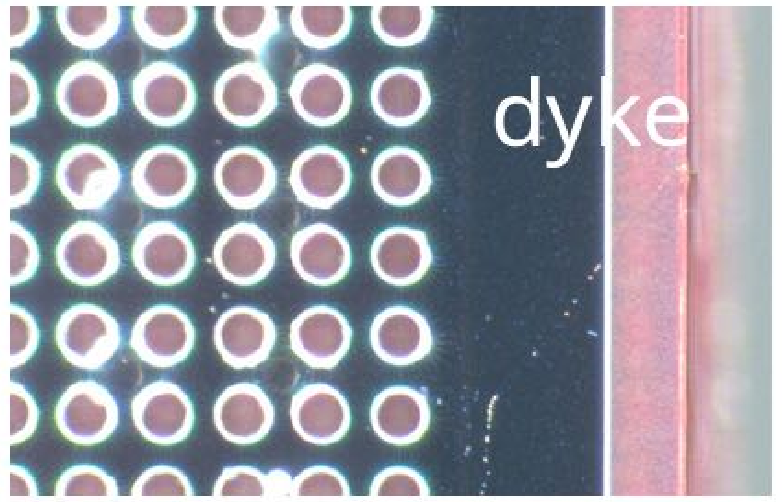
$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma$$

$$\omega_p = \sqrt{\frac{N_e e^2}{\epsilon_0 m_e}} \qquad \hbar\omega_p = 20\,eV$$

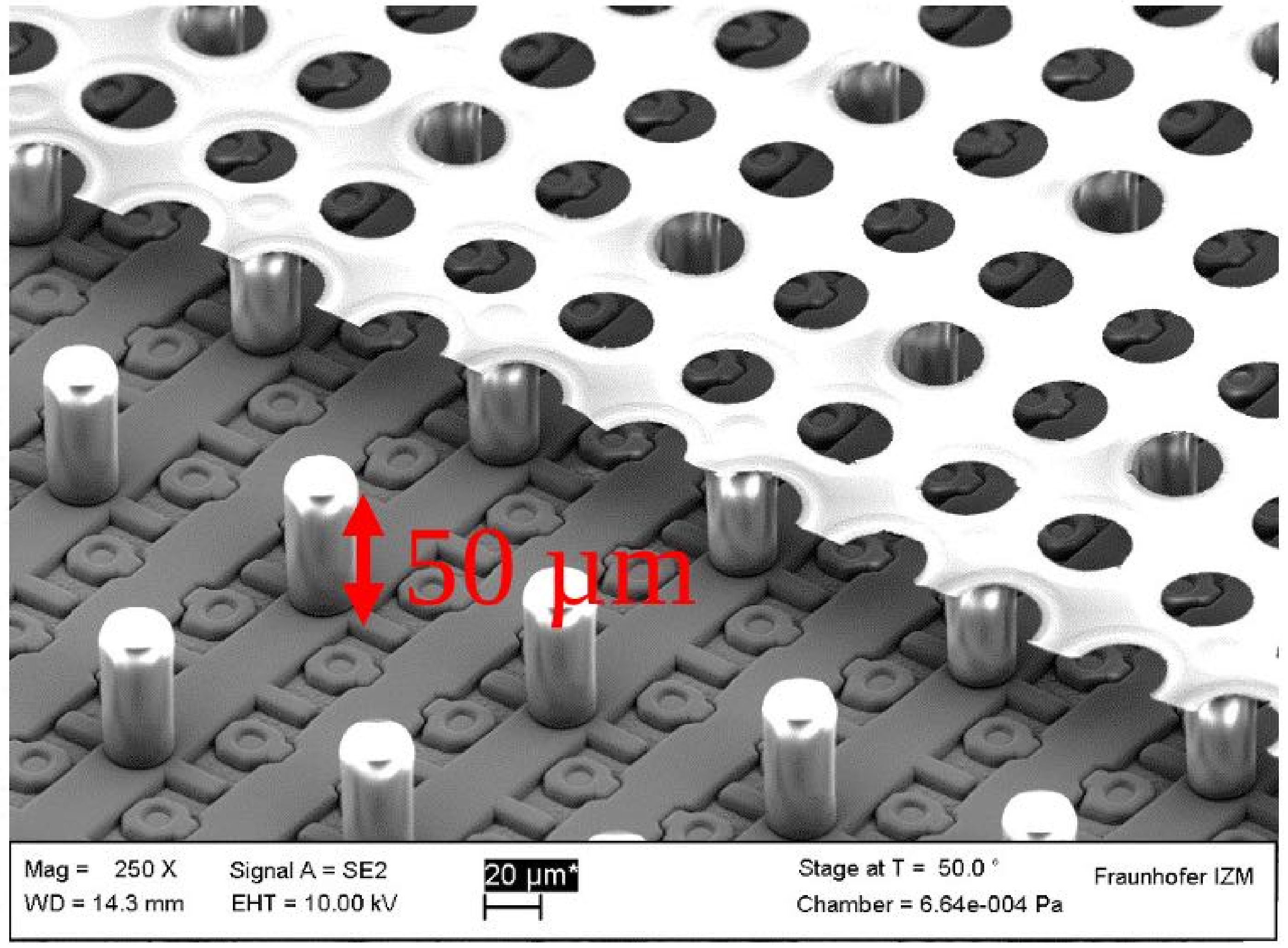
GridPix technology

- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 μm)
- detecting individual electrons





- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability



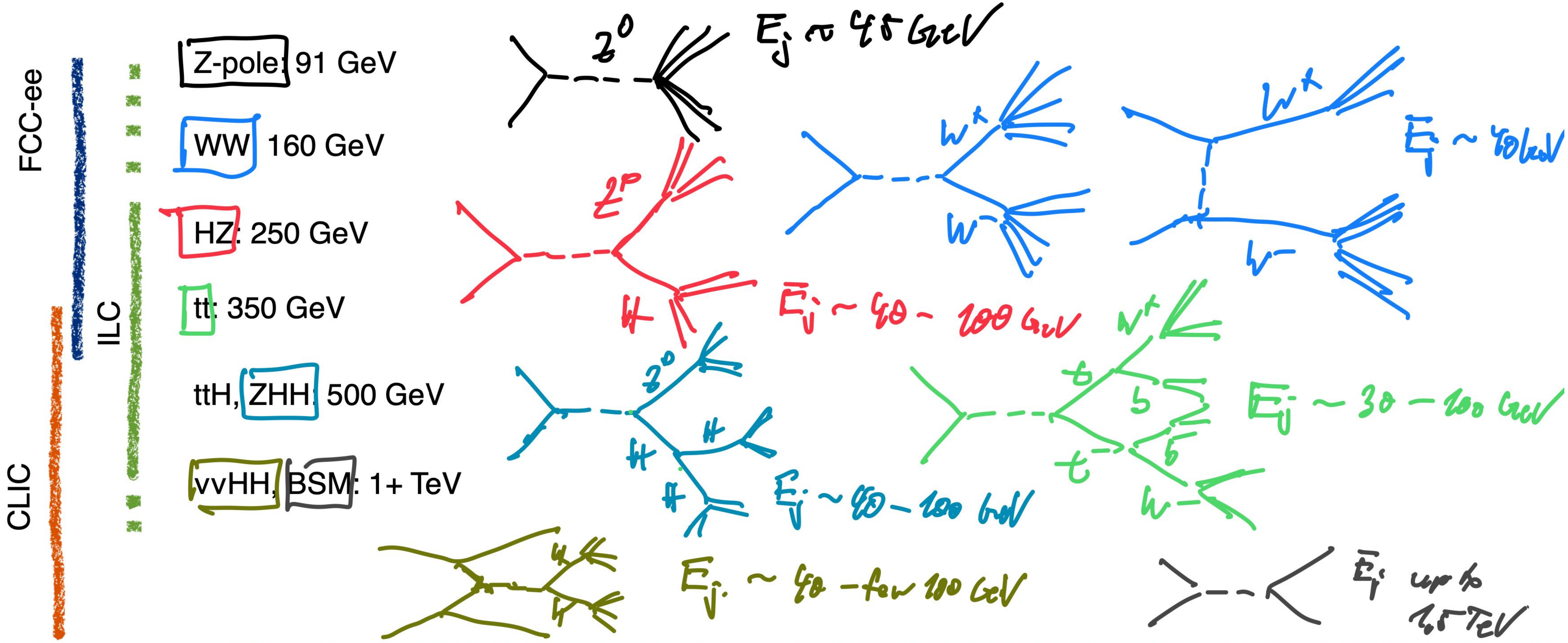
Typical jet energies at Higgs factories

F. Simon

Energy

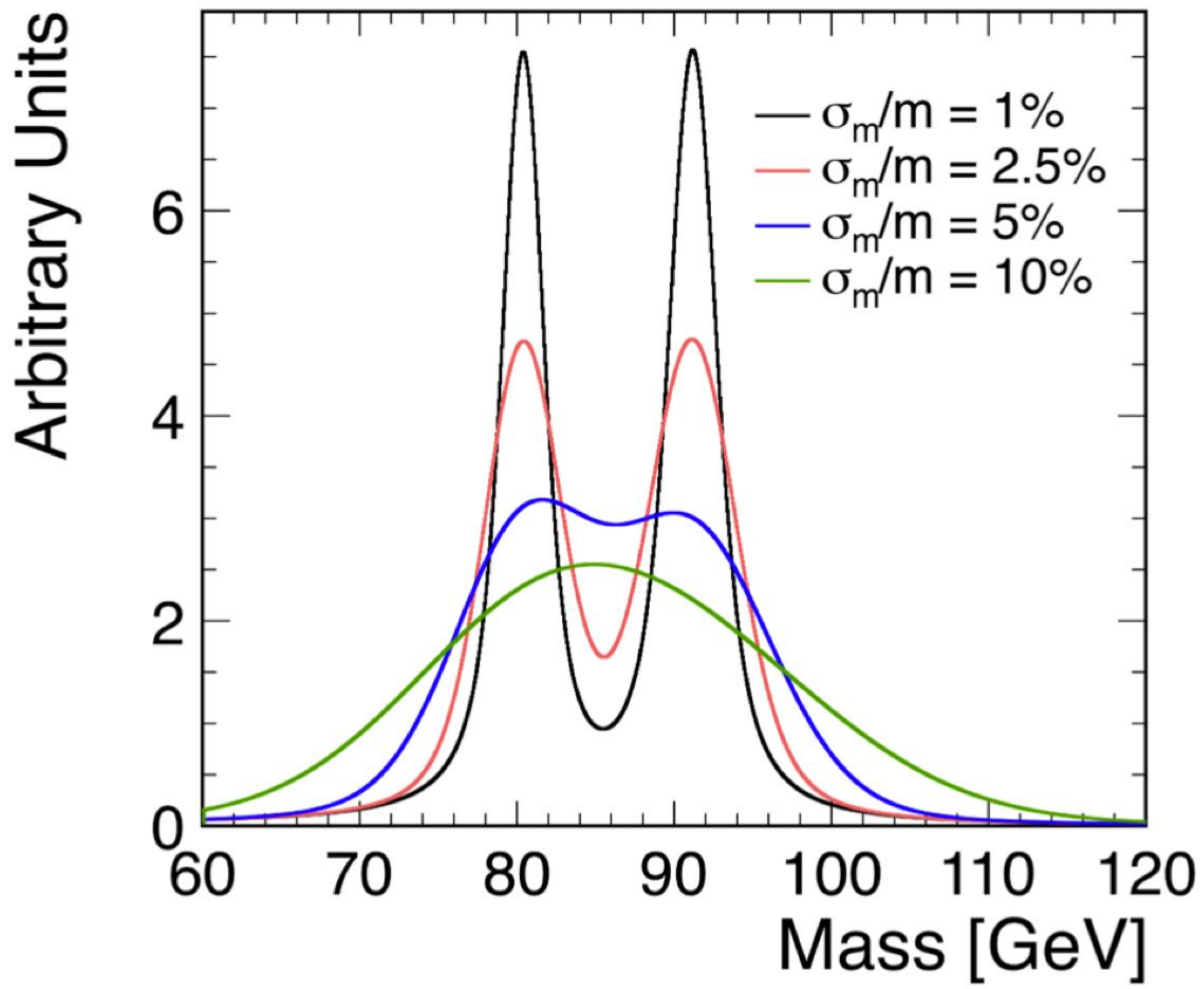
Initial and Final States

- Collider dependent - but often less than you naively assumed



Jet performance - physics drivers

F. Simon



want:

JER 3 - 5%

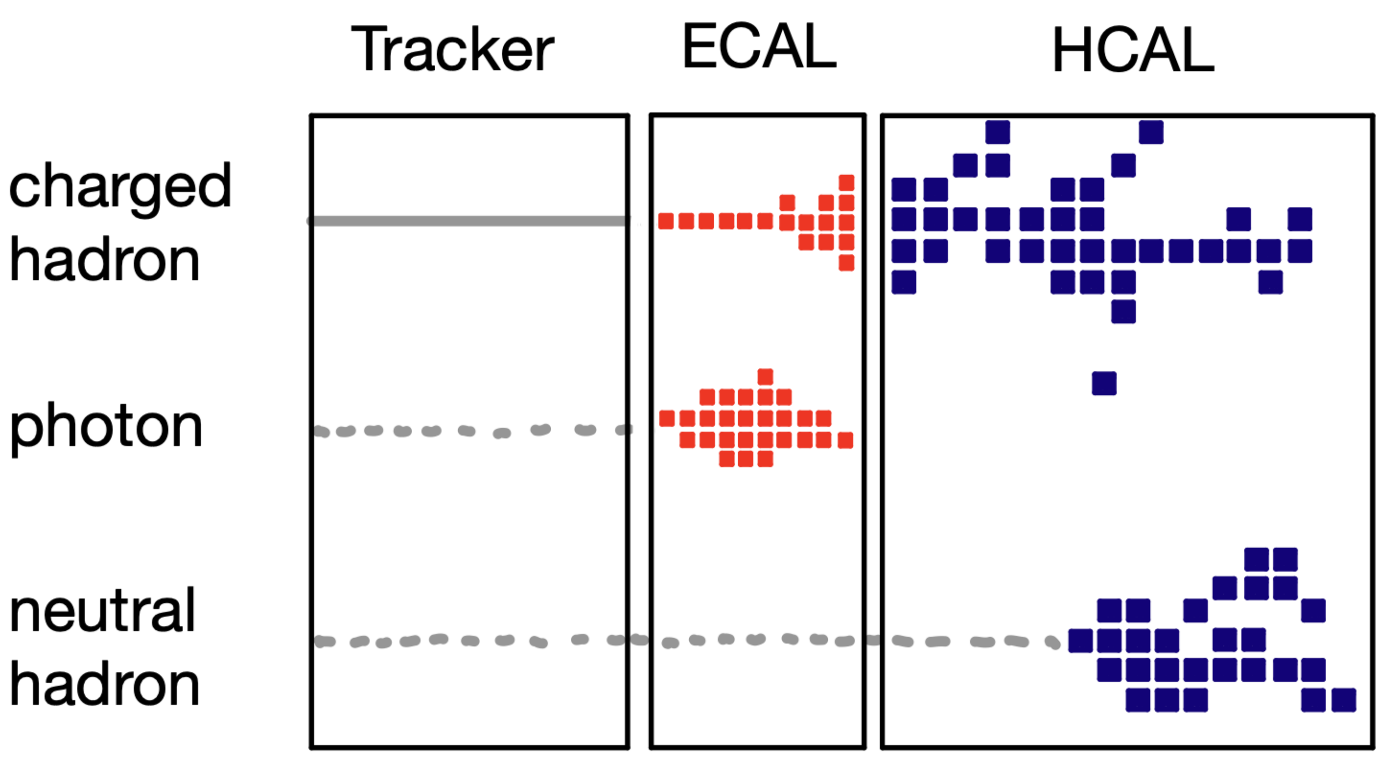
- The typical jet composition:
  - 60% charged (primarily $\pi^{+/-}$)
  - 30% photons (from π^0 decay)
  - 10% neutral hadrons (n, K_L)

Jet reconstruction with *calorimeters only*

~ 60% - 100+% / Sqrt(E)

~ 10% - 20% / Sqrt(E)

~ 60% - 100+% / Sqrt(E)



Jet reconstruction with *Particle Flow*

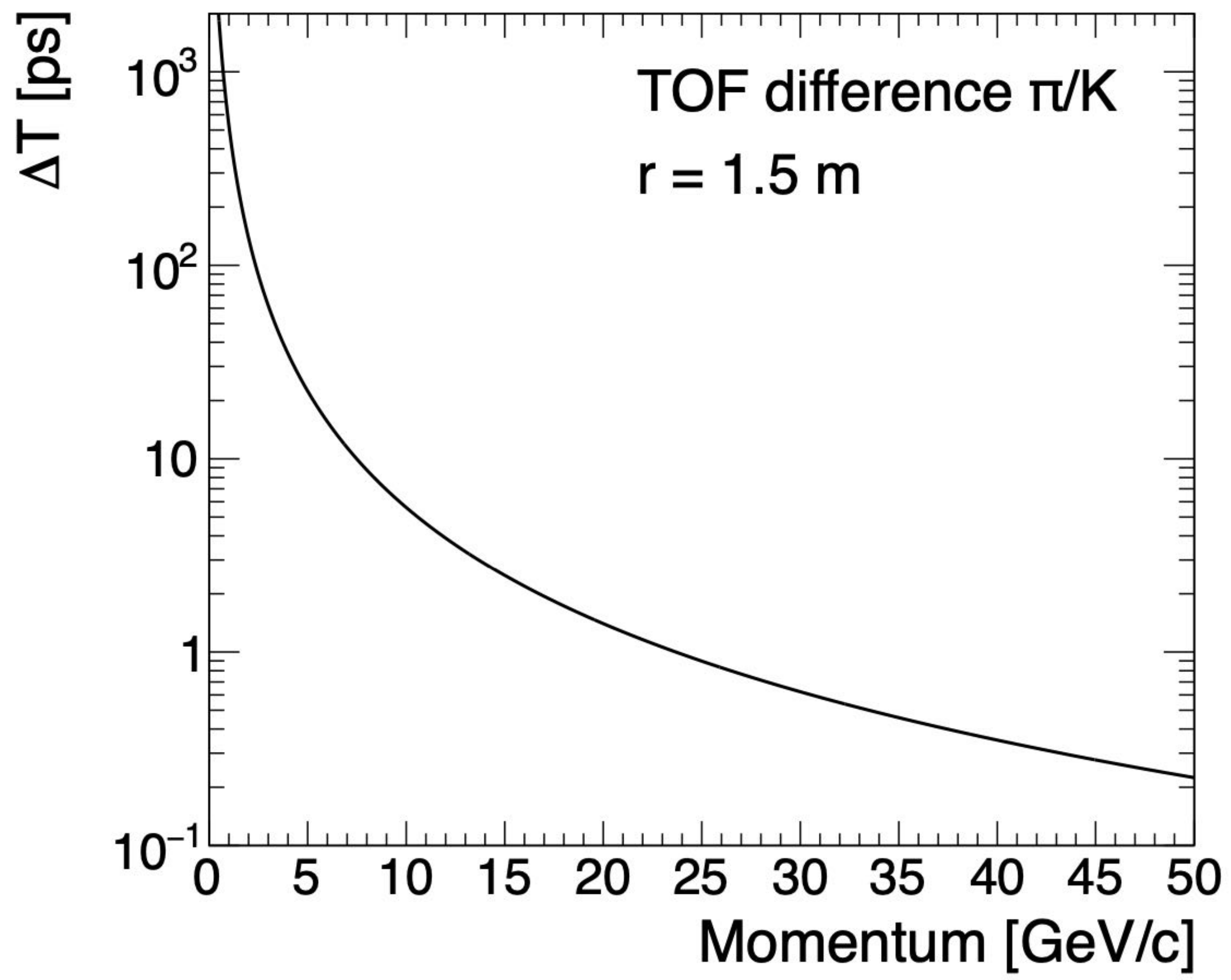
excellent measurement in tracker, negligible resolution

~ 10% - 20% / Sqrt(E)

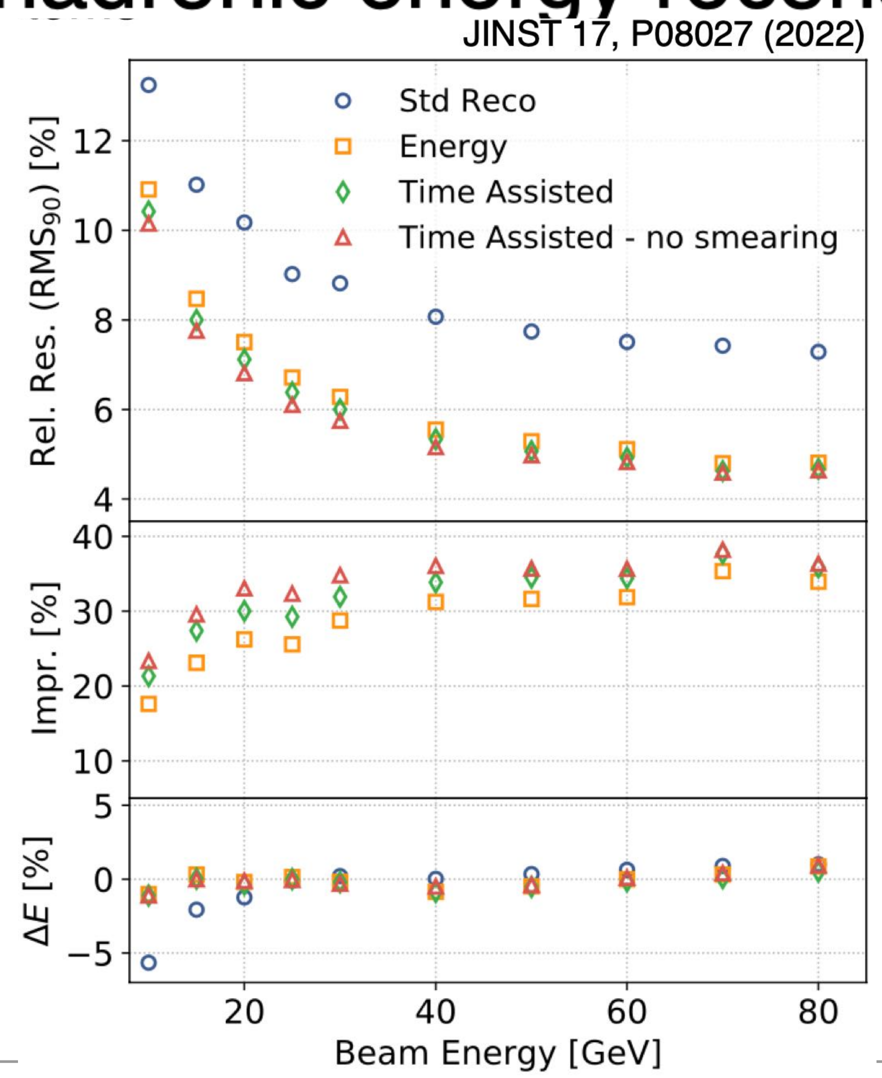
~ 60% - 100+% / Sqrt(E)

When using PFA, confusion (= shower separation, pattern recognition) and intrinsic energy resolution of the calorimeter system drive performance

TOF for PID



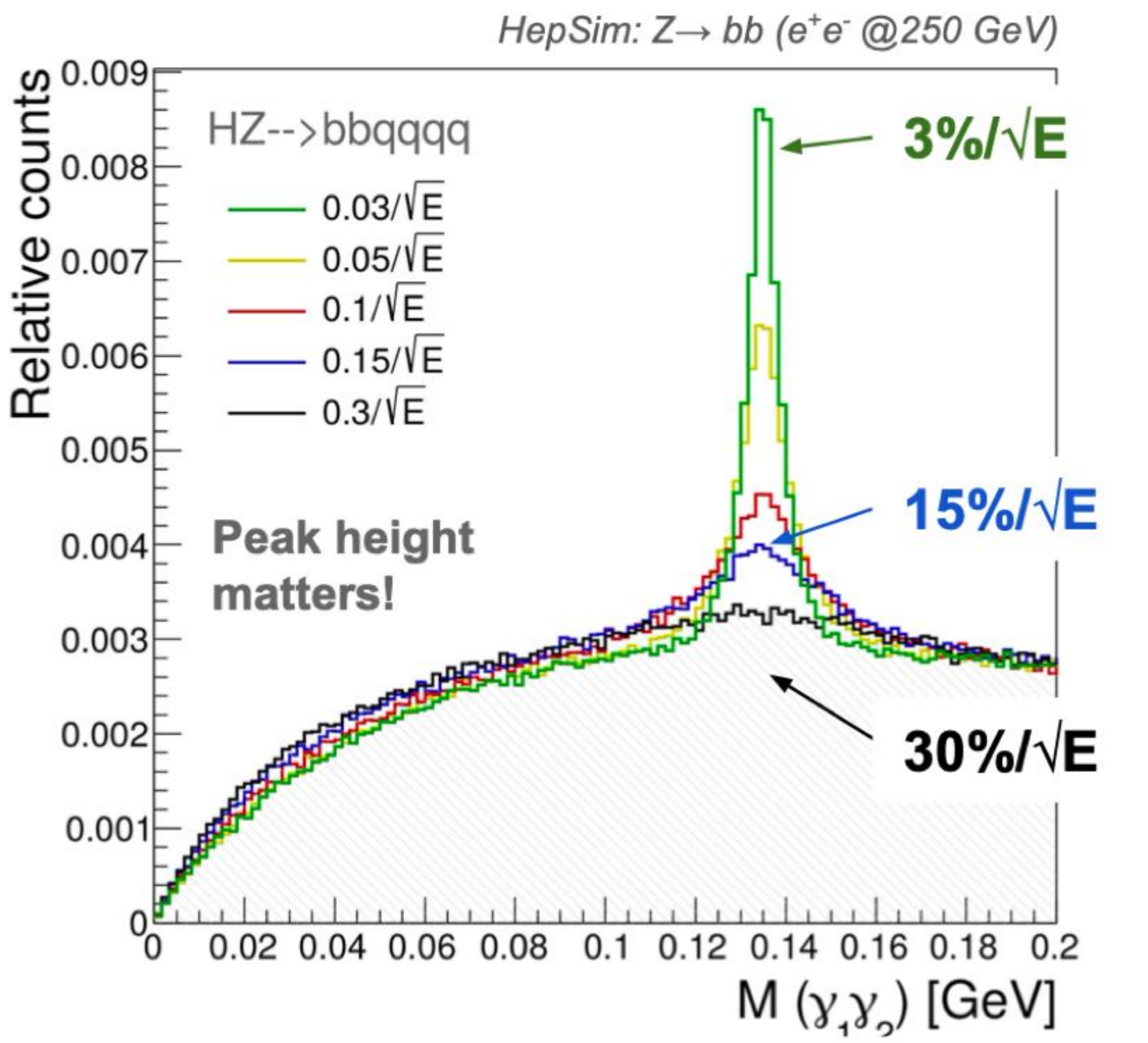
Timing also beneficial for hadronic energy reconstruction



Possible benefit of timing for pattern recognition in PFA calorimeters, ...

Photons from π^0 increase confusion between jets.

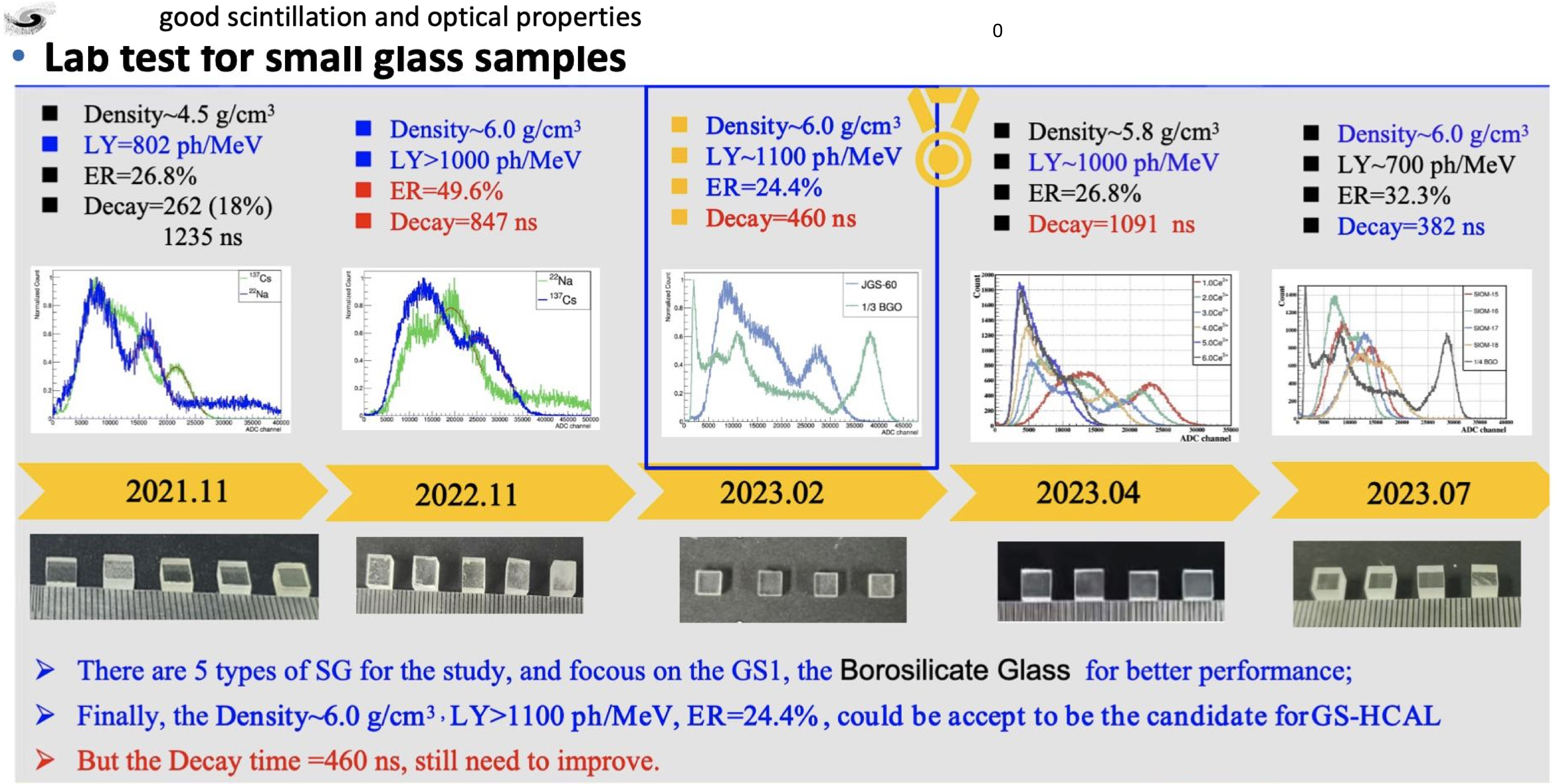
Could be addressed by explicit π^0 reconstruction in PFA. Requires excellent γ energy resolution.



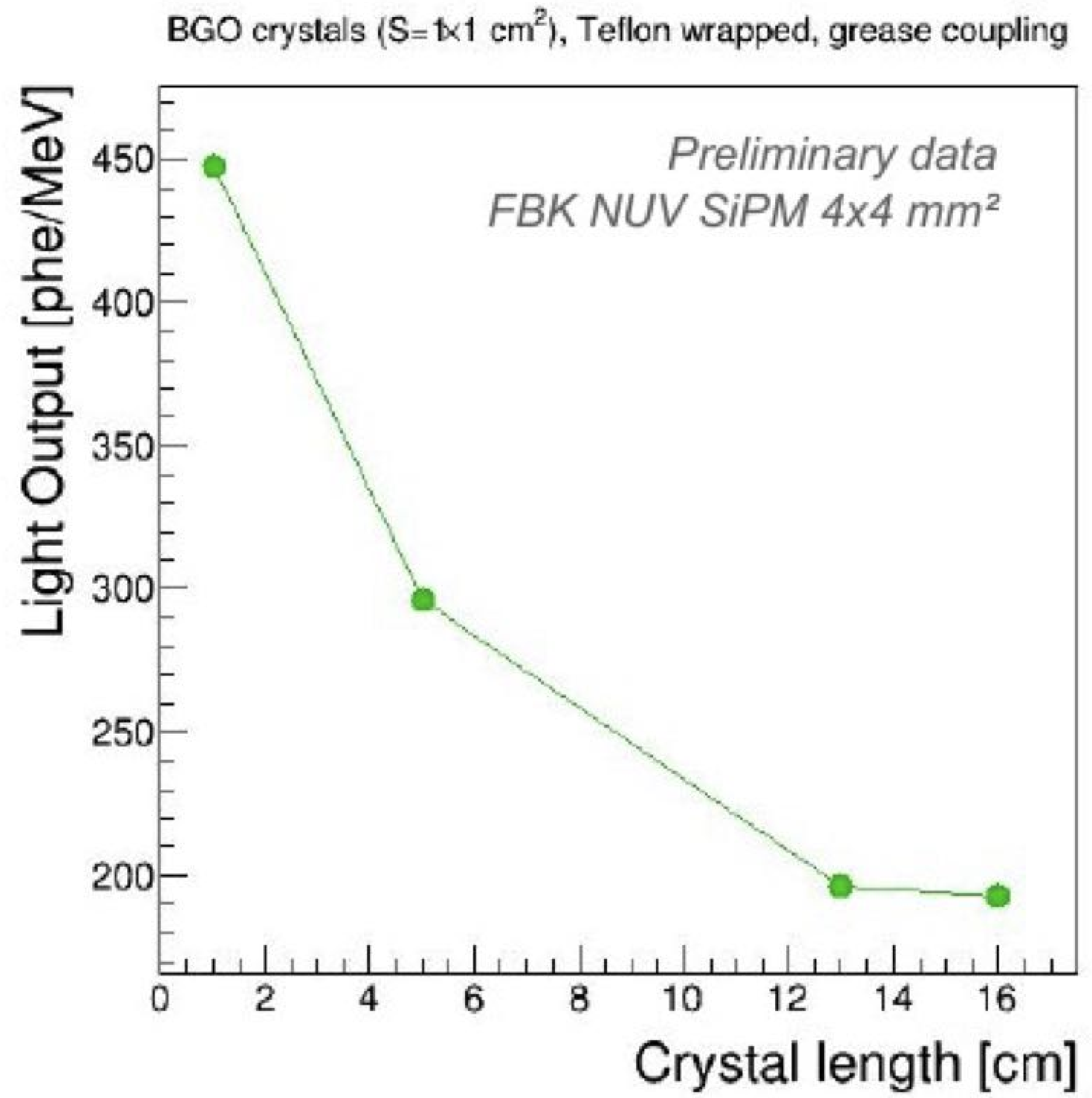
Glass scintillator HCAL

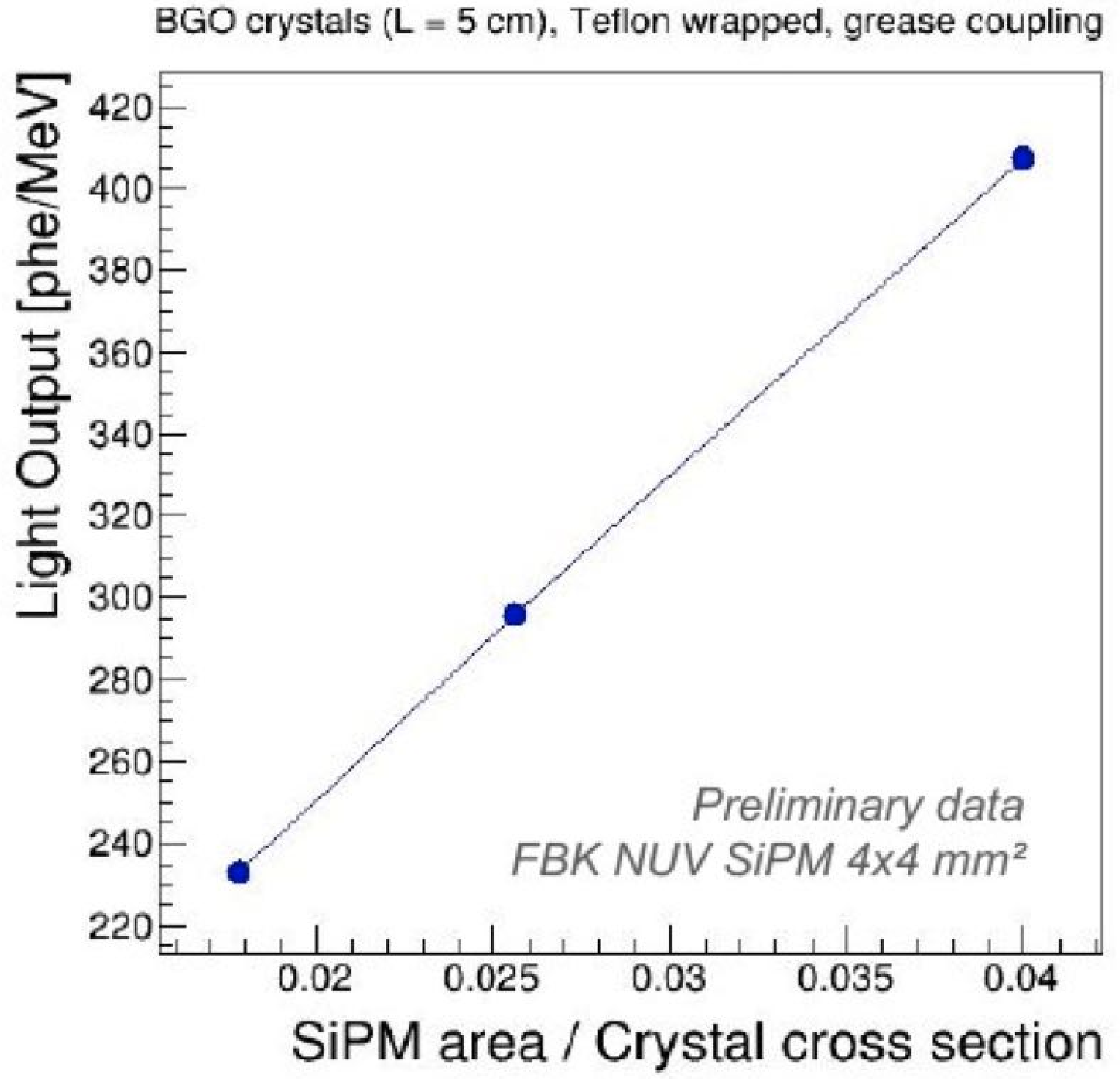
- Challenges
  - Increase density while keeping high light yield and transparency
  - Synthesizing large cm-scale glass tiles with good scintillation and optical properties

0



Dual readout calorimeter: EM section with crystals



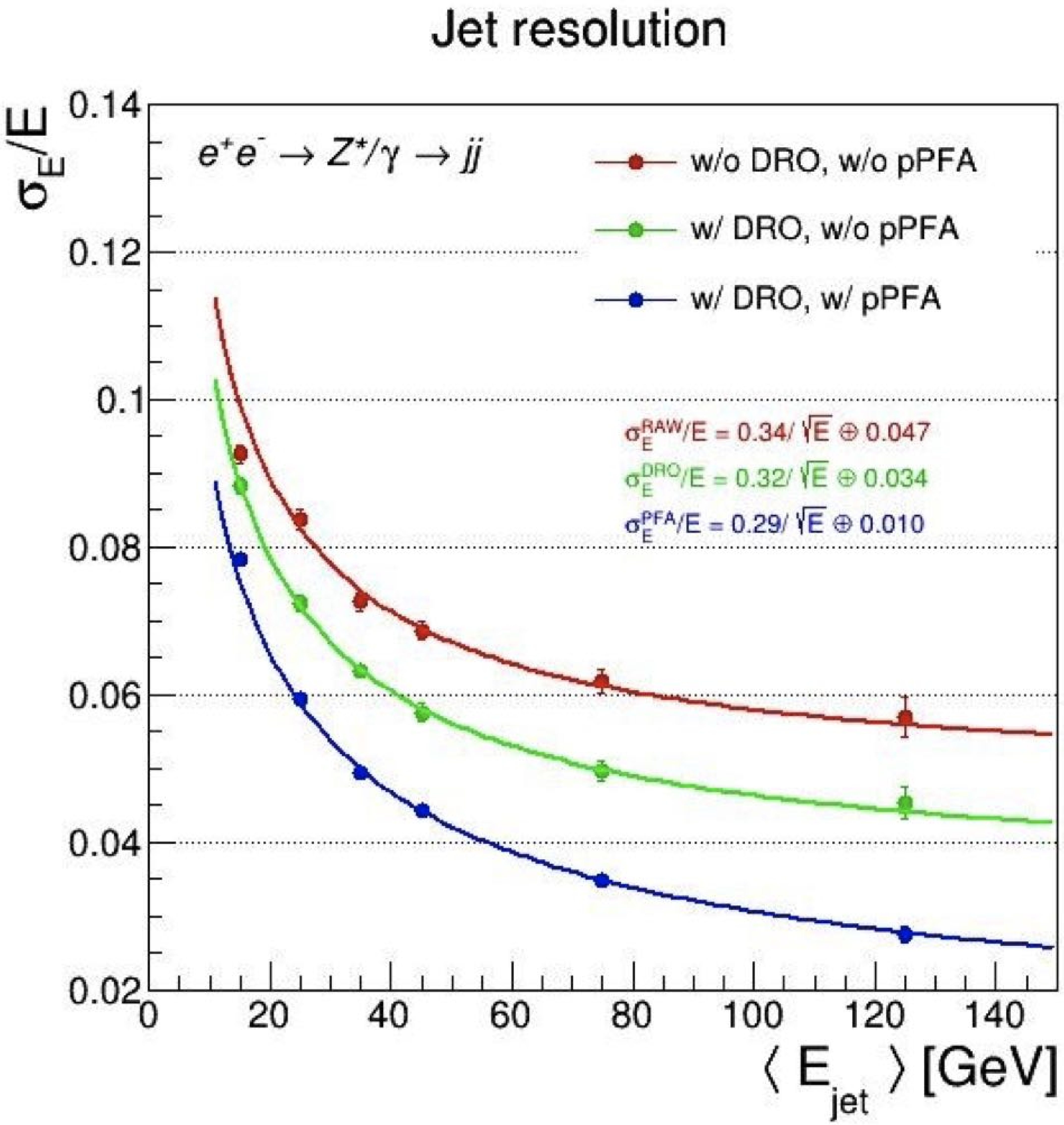


Light yield measurements in Mi-Bicocca

16

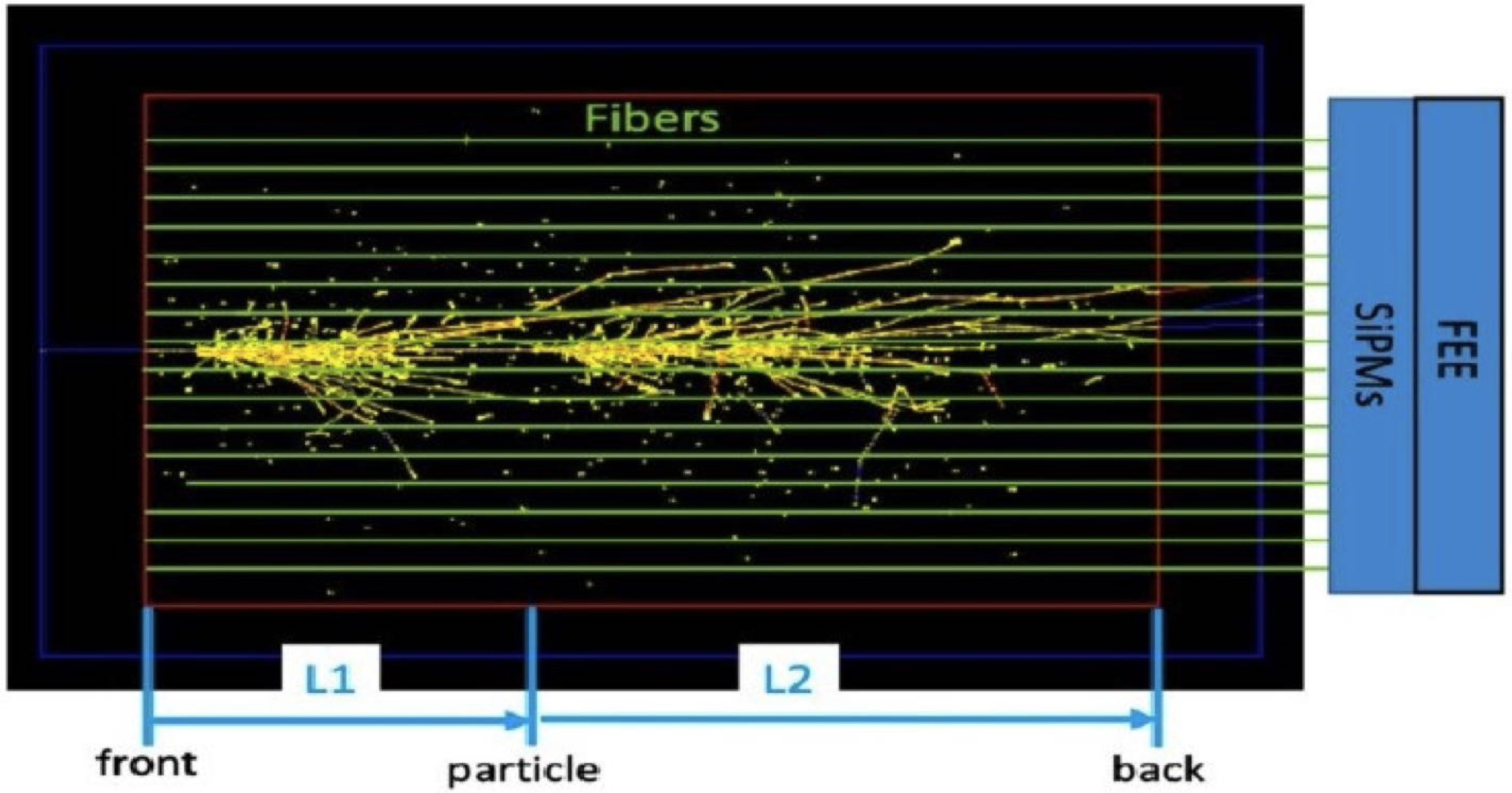
JINST 17 (2022) 06, P06008

G. Polesello



Calorimeter simulation

Dual readout calorimeter: longitudinal segmentation with timing



Preliminary results
No optimisation

Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

Timing Resolution $\Delta(t)$, ps	Position Resolution $\Delta(z)$, cm	Energy Resolution σ/E, %
0	0.0	3.6
100	5.0	3.9
150	7.5	4.0
200	10.0	4.2

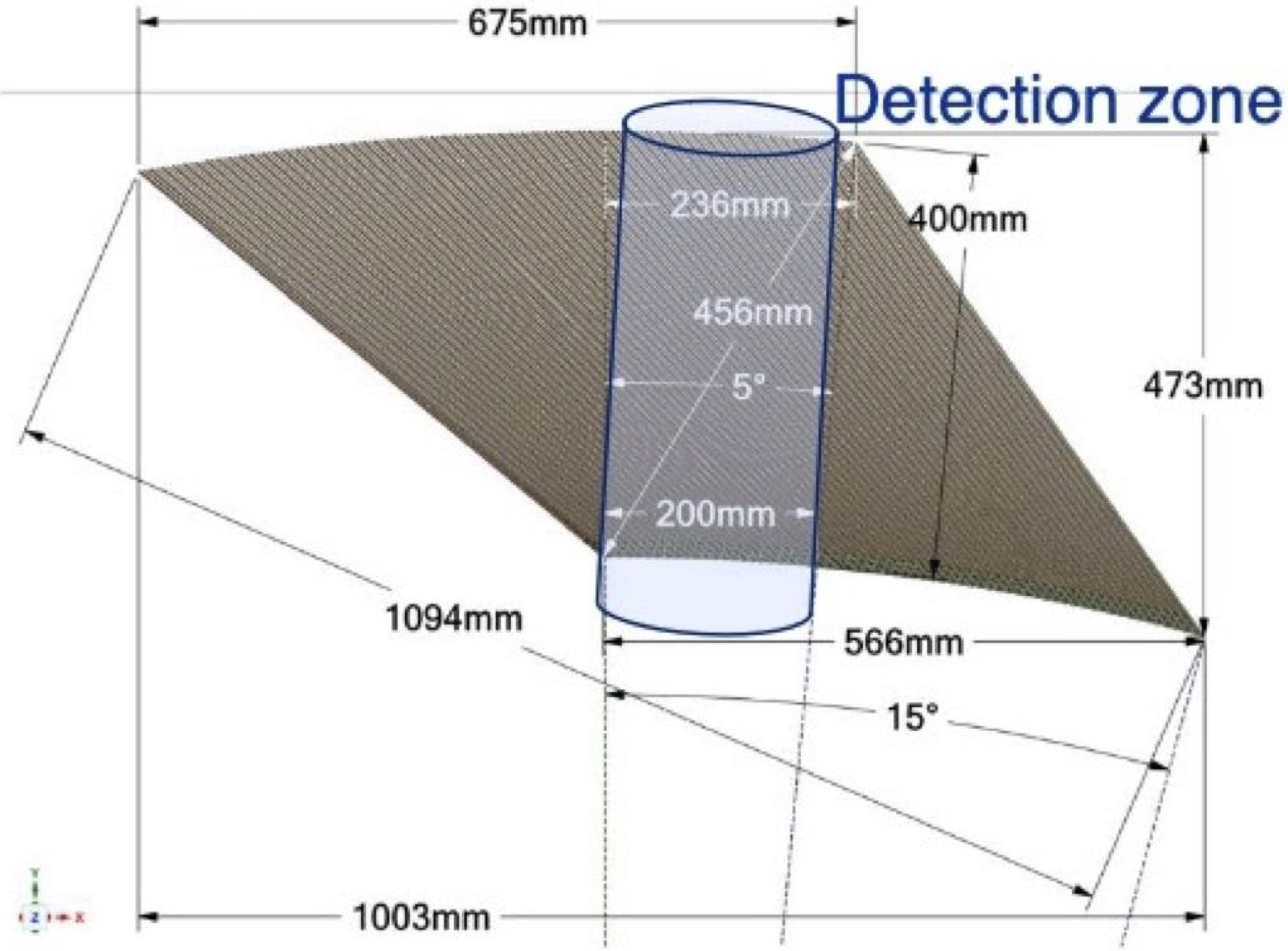
@ 100 GeV

only cherenkov fibres

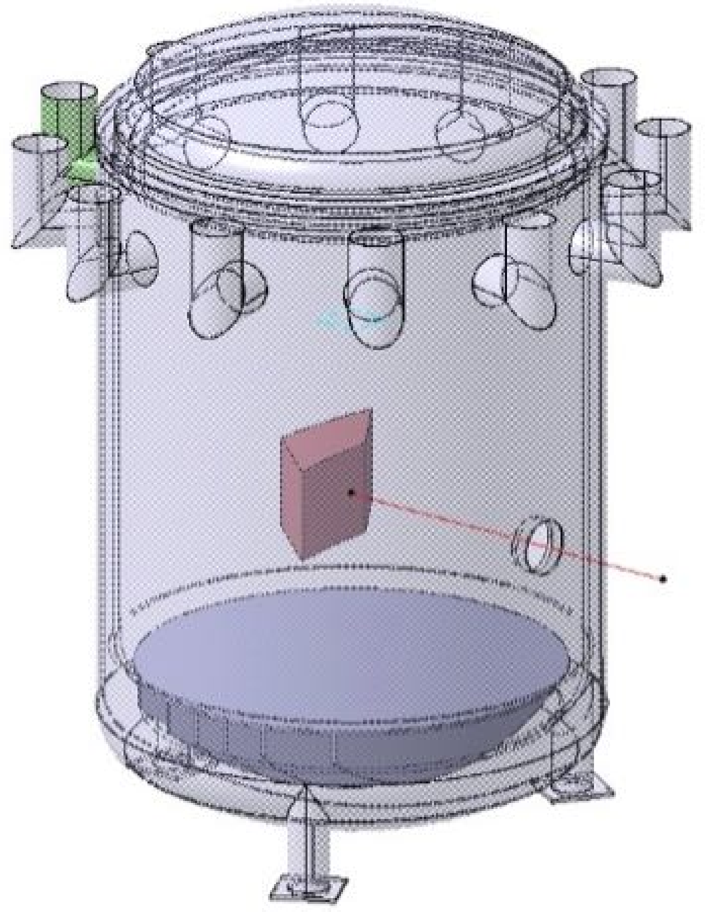
Allegro testbeam module

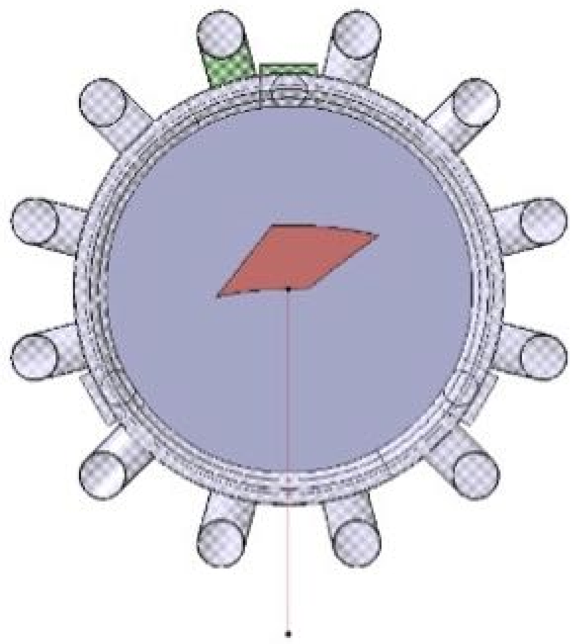
M. Aleksa

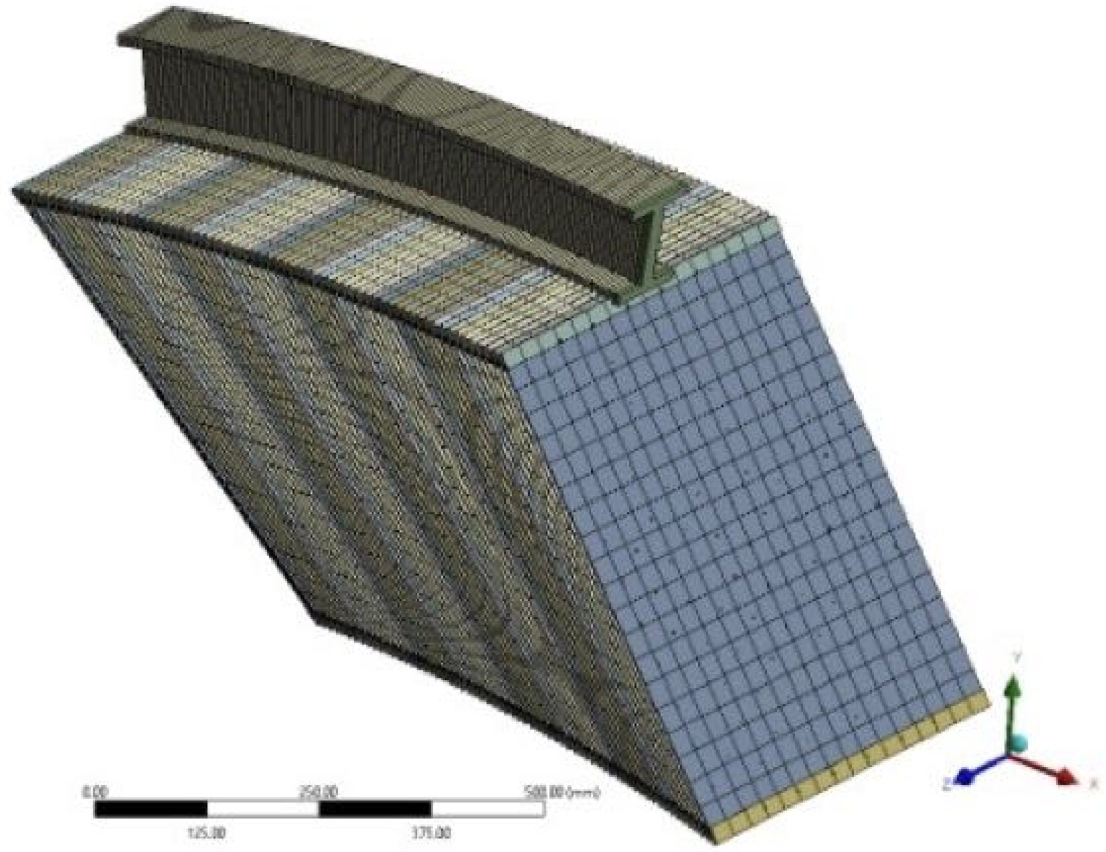
- Mechanical design of **testbeam module** (64 absorbers) has started
- **Finite element calculations** including
  - Rings and G10 bars
  - Absorbers and electrodes as shell (2D) elements using layers
  - Distance pins
  - Six M5 beams join electrodes and absorbers in each side (inner-outer)
- In parallel work on finding/adapting **testbeam cryostat**
- Plan to **produce testmodule** in the next four years

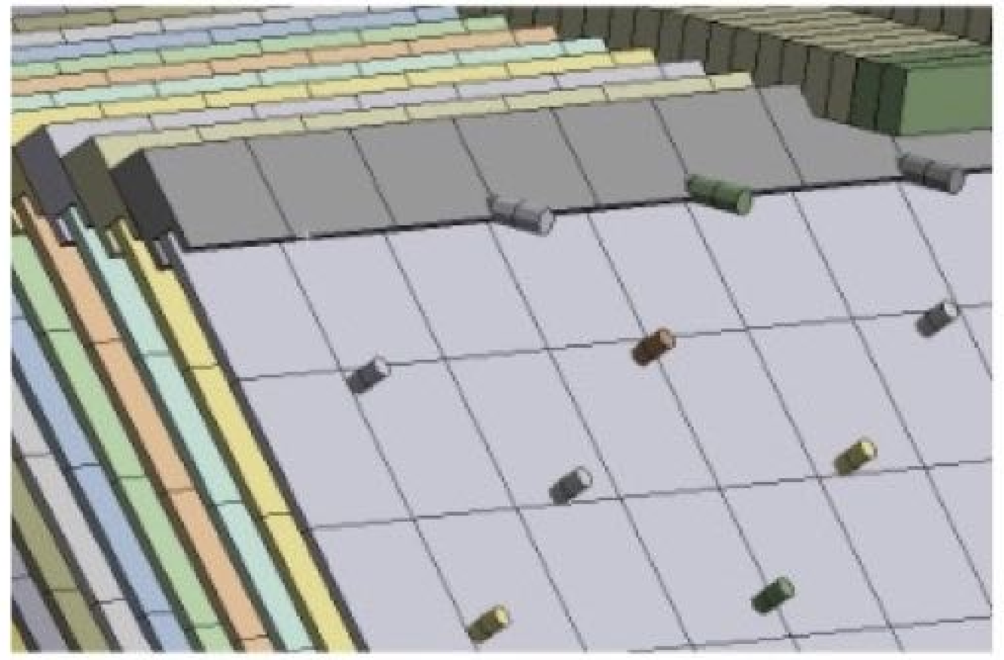


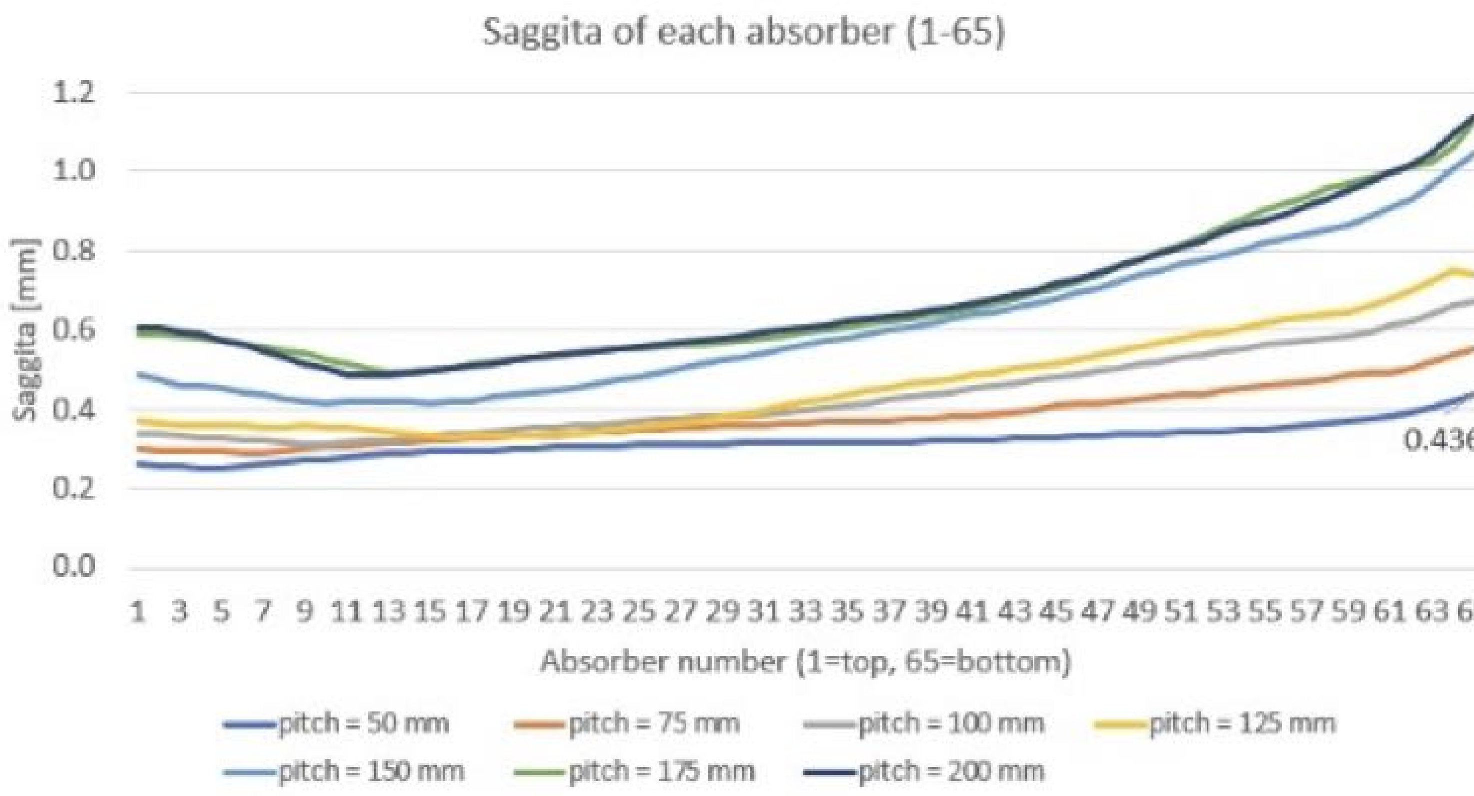
The cryostat available to make the test beam is the CRRP-00563.







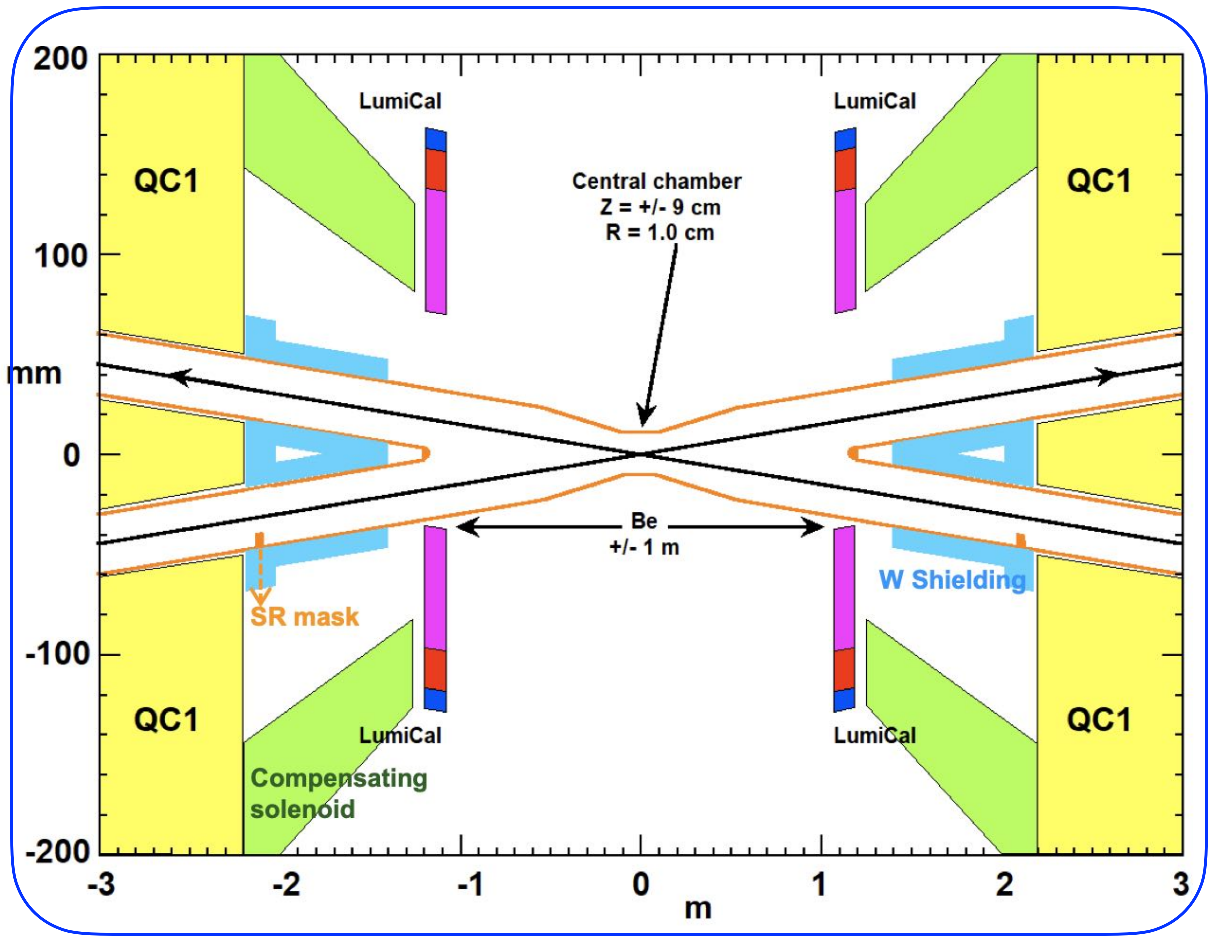




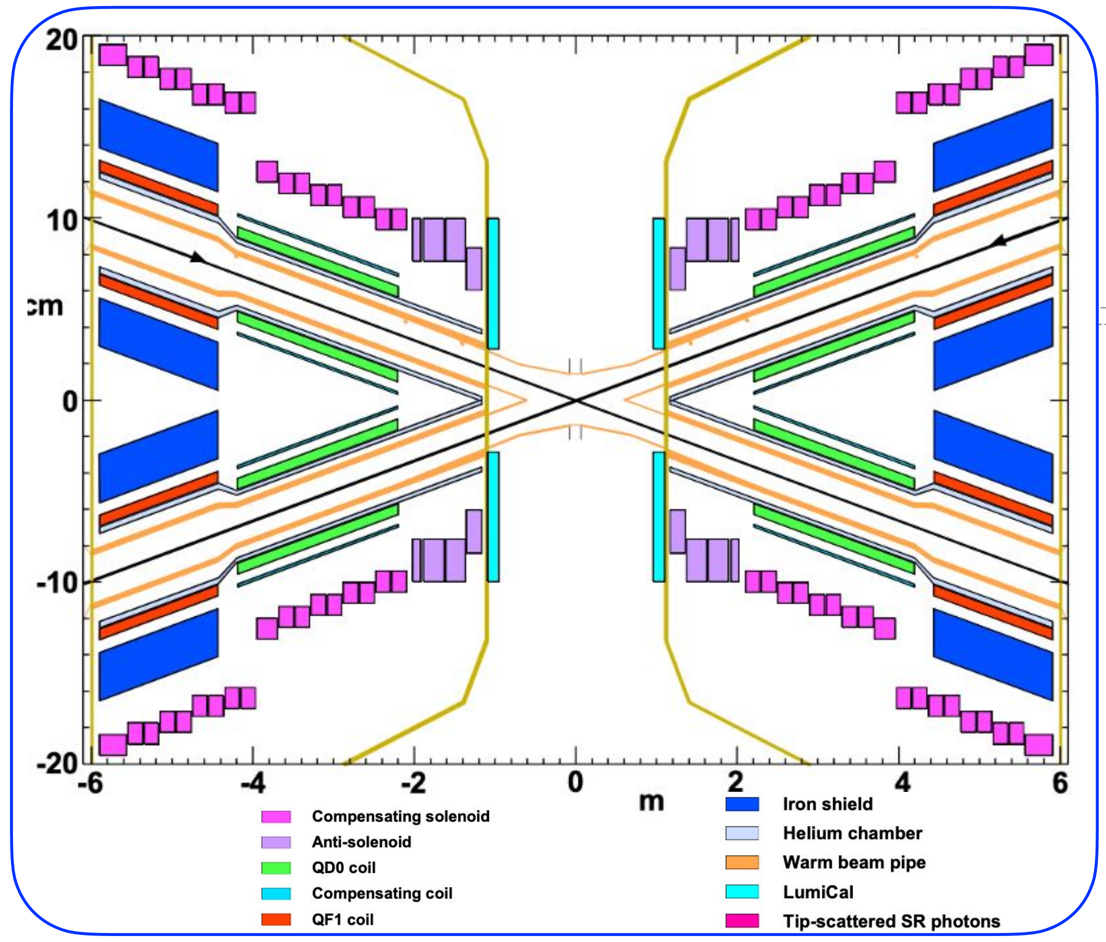
Interaction regions

FCC-ee	CEPC	ILC	CLIC

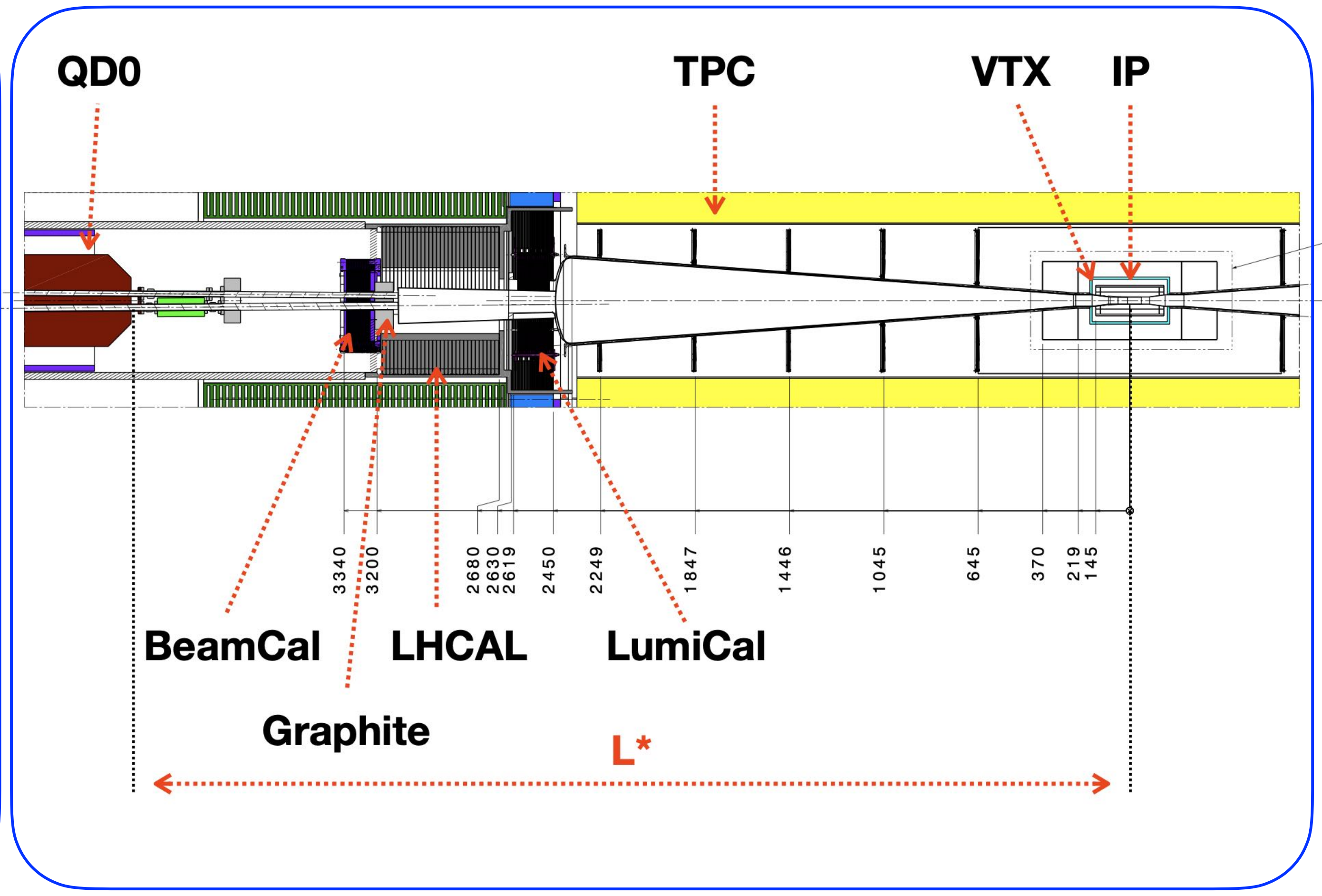
FCC-ee



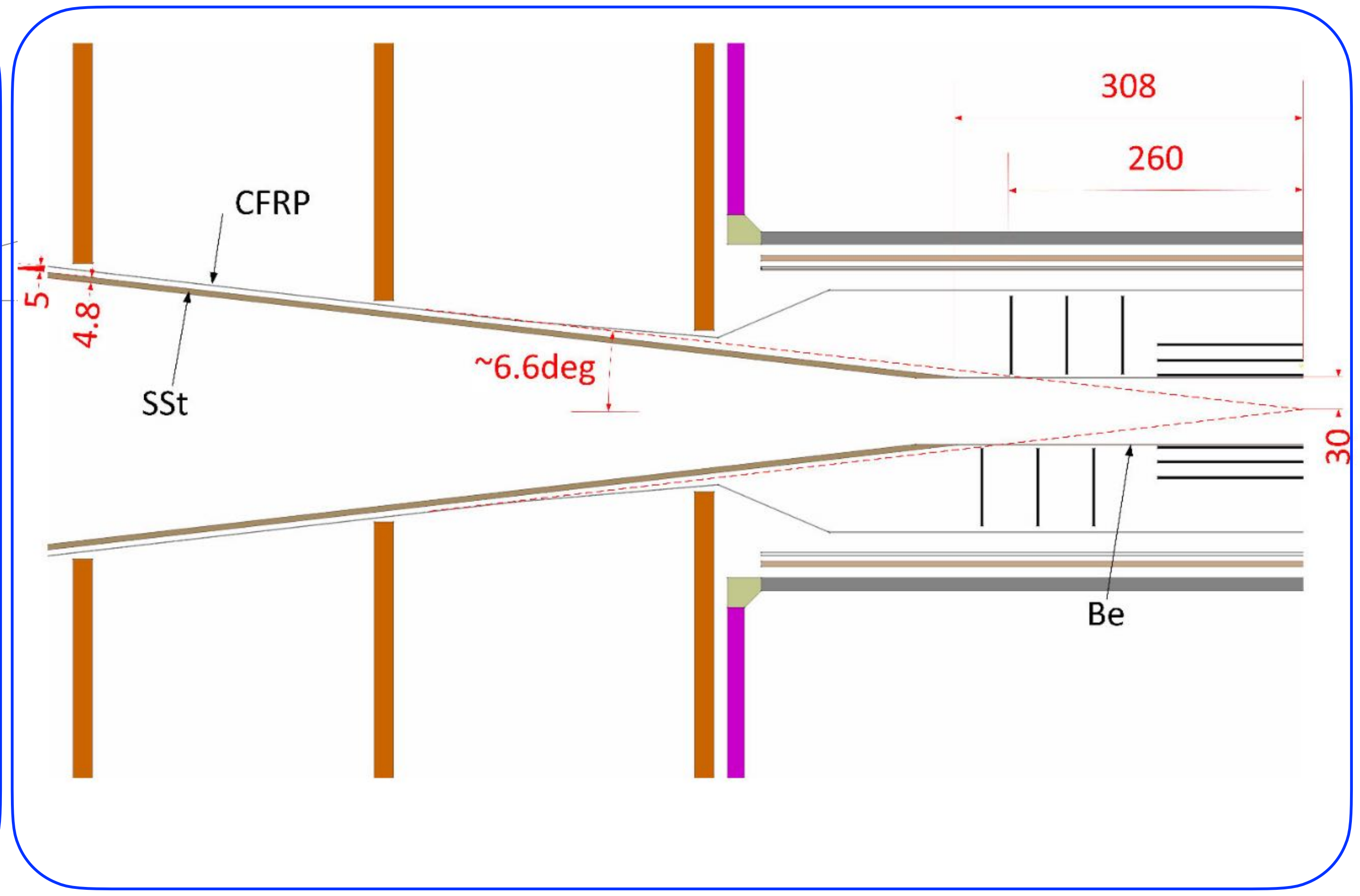
CEPC



ILC

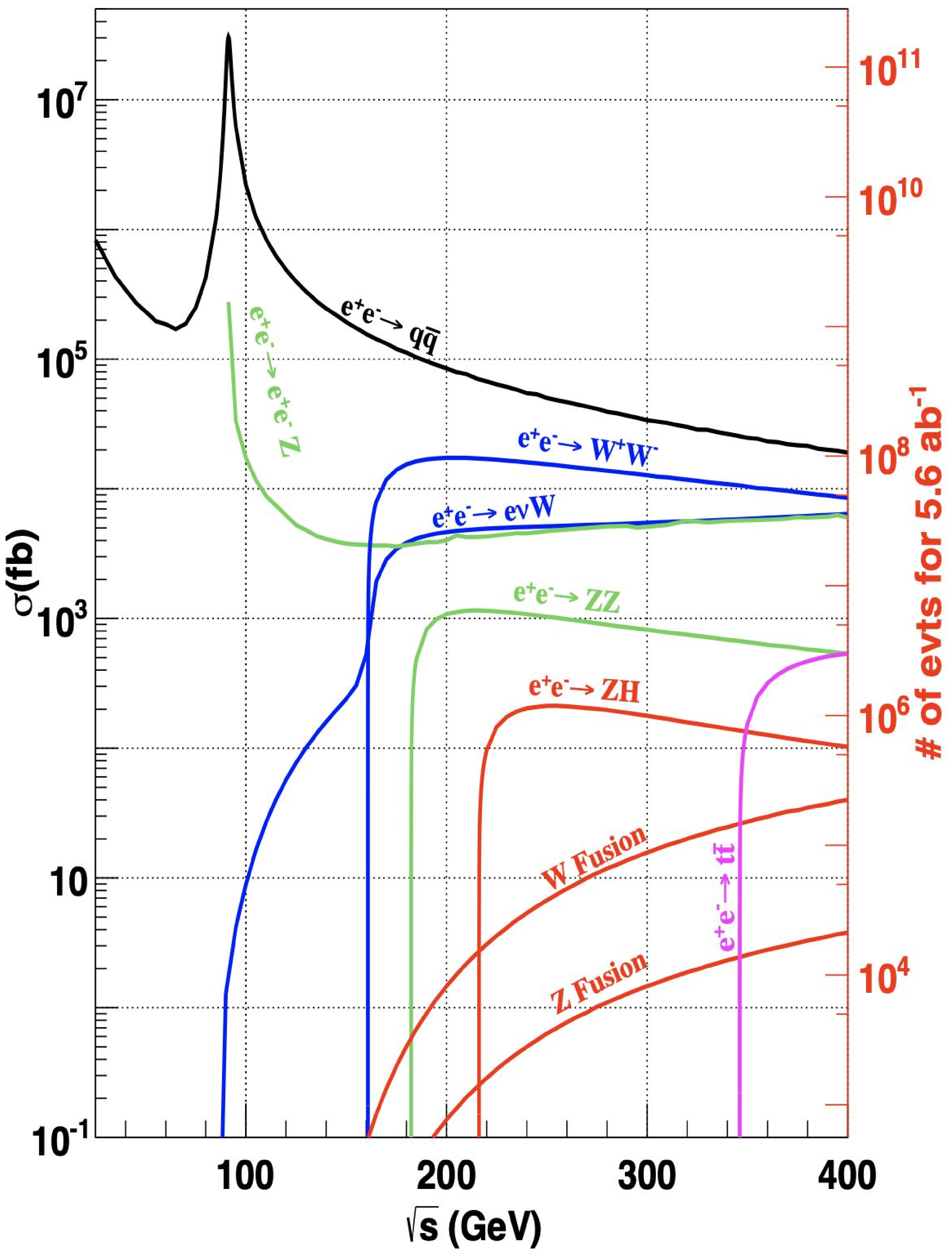


CLIC



	FCC-ee	CEPC	ILC	CLIC
L* (Δz between IP and first	2.2 m	2.2 m	4.1 m	6 m
Position of final quadrupole	Inside detector	Inside detector	Outside detector	Outside detector
LumiCal position	z=1m, ~50-100 mrad (Constrained by compensating solenoid)	z~0.95~1.11m 26-105 mrad (fiducial volume 53-79 mrad)	z=2.5m, 33-80 mrad	z=2.5m, 39-134 mrad
Tracker acceptance	Down to ~9 degrees (defined by luminometer)	Down to ~8 degrees	Down to ~6° (defined by conical beam pipe)	Down to ~7° (defined by conical beam pipe)
Inner beam pipe radius	10 mm	10 mm	16 mm	29.4 mm
Crossing angle	30 mrad	33 mrad	14 mrad	20 mrad
Main solenoid B field	2T	3T (2T at Z pole)	3.5-5T	4T

Physics rates



- In central detector
  - At Z resonance:
    - ~80 kHz for L = 180*10^{34}/cm^{2}s (FCC-ee, CEPC)
      - includes O(10) kHz from ee→ee and O(100 Hz) from ee→γγ in detector acceptance (θ ~9–171°)
    - ➡ fast **detector response** to minimise dead time
    - ➡ **zero-suppression** to reduce data transfer/output rate
    - ➡ **trigger-less design** (preferable to avoid trigger efficiency systematic uncertainties) **could be challenging**
  - At $\sqrt{s}$ >= 160 MeV: L<10^{35}/cm^{2}s, σ≲1 nb ⇒ rate ≲ 100 Hz

- In forward luminosity calorimeters
  - sustained rate due to large Bhabha xsections at small angles: ~80 kHz for L = 180*10^{34}/cm^{2}s (FCC-ee, CEPC)
  - ➡ **radiation hardness** in very forward region

Backgrounds at e^+e^--factories

- **All projects**: very small beams ⇒ high EM fields ⇒ bend the trajectories of the opposite bunch particles
  - ➡ **beamstrahlung** ⇒ photons
    ⇒ increase of IP size / center-of-mass energy spread. Impact on physics but not on detector (but requires measurement in situ of luminosity profile vs $\sqrt{s}$)
  - ➡ **Incoherent pair creation** (IPC) ⇒ $e^\pm$
  - ➡ **$\gamma\gamma \to$qqbar** ⇒ hadrons (jets)

    ⇒ can lead to large occupancy and energy deposited in detector

    ⇒ space granularity / time resolution for use of timing in offline reconstruction

    ⇒ very large $e^\pm$ rate at low p_T => impact on design of inner region and on forward region (envelope around IR limits beam pipe and inner detector radii)
- **Circular colliders**: bending of charged beam particles in dipole magnetic field
  - ➡ **Synchrotron radiation** ⇒ photons

    ⇒ can lead to energy deposited in the detector if unshielded

    ⇒ SR in solenoid due to x-ing angle limits B field to minimise impact on luminosity
- **Increase with energy**: most significant at 365 GeV (FCC-ee) / 500 GeV (ILC) / 3 TeV (CLIC)
- **Mitigated** through machine-detector-interface (**MDI**) design, but pose **constraints** on **detector** design too