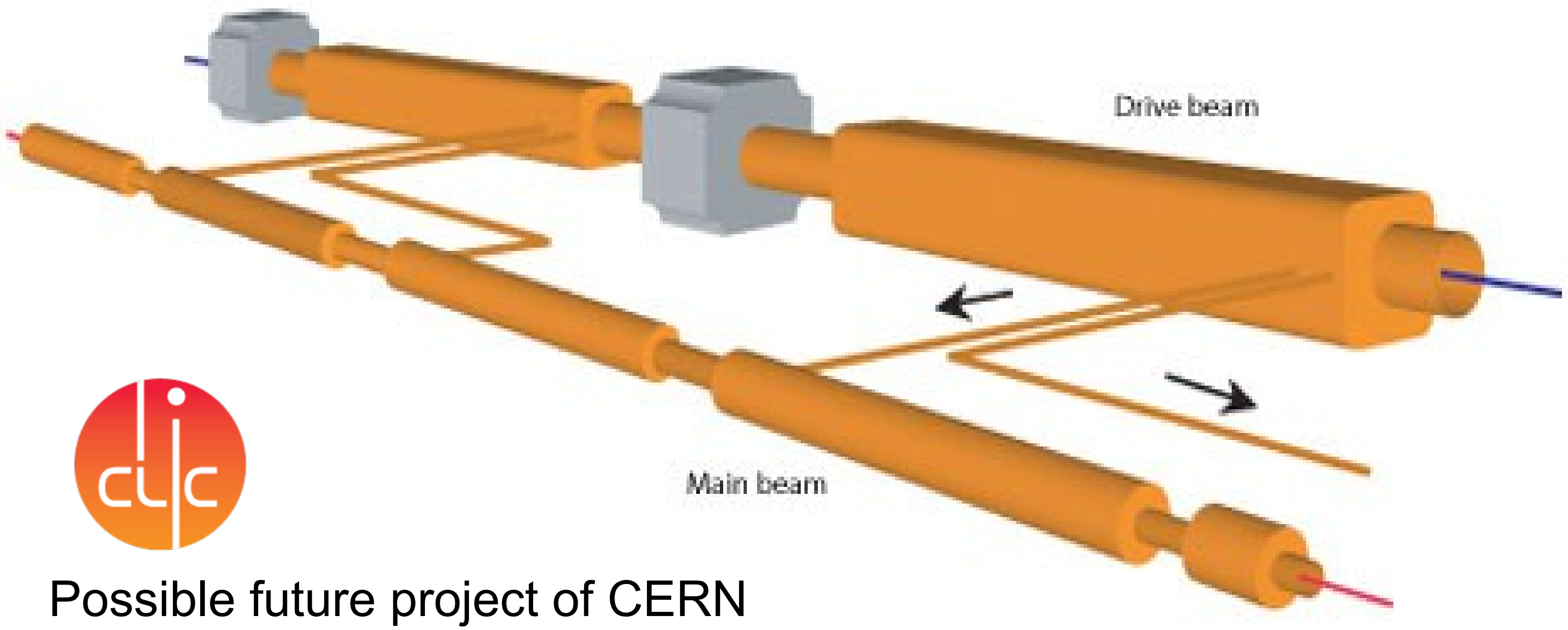
Detector Challenges at Future Higgs Factories and formation of Detector R&D (DRD) Collaborations (with focus on calorimetry)

Roman Pöschl

Supported by AIDA innova

Seminar ICEPP University of Tokyo – December 2023

Linear Electron Positron Colliders



Possible future project of CERN

Energy: 0.4 - 3 TeV

CDR in 2012
Update 2016

Footprint 48km

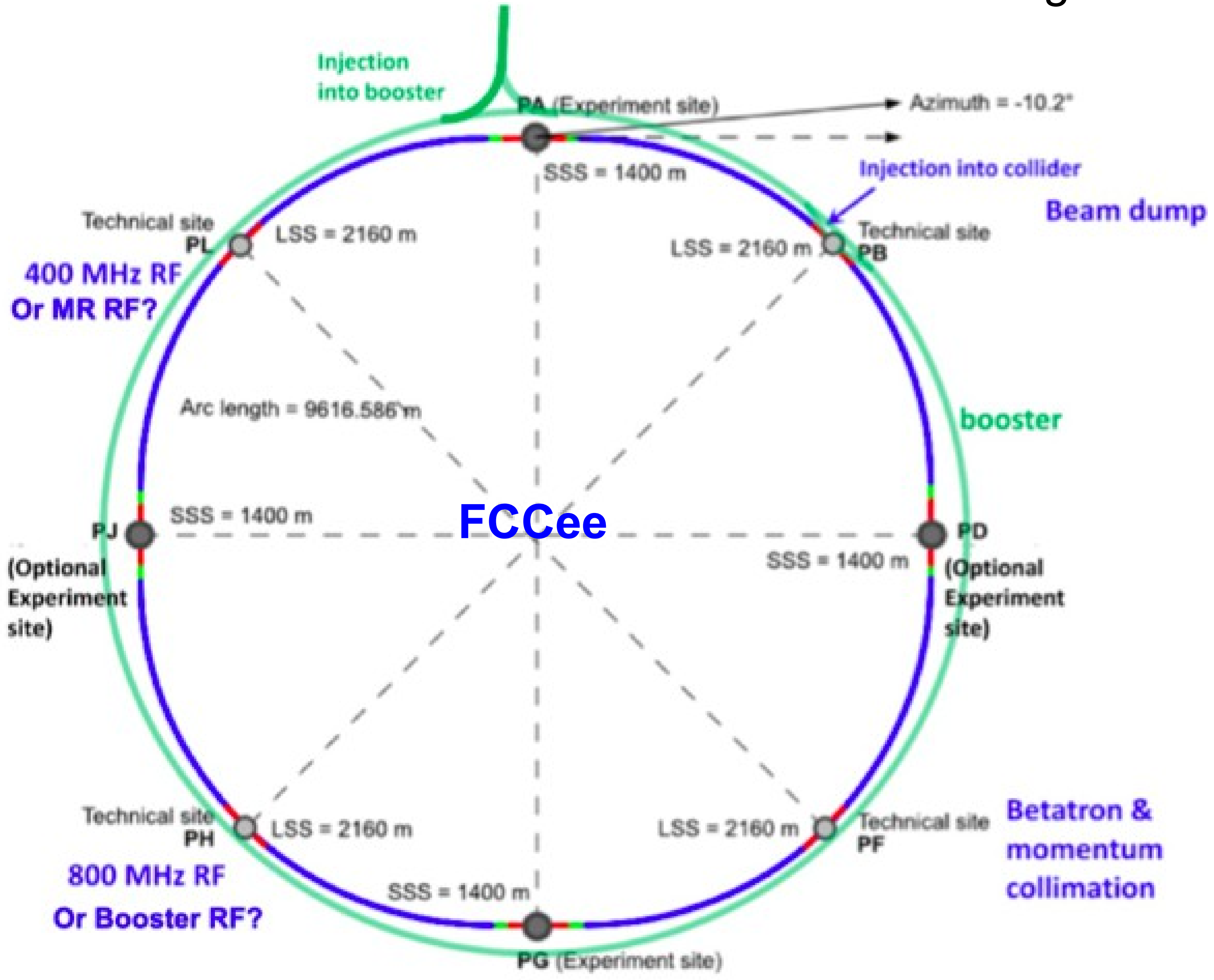
Initial Energy 380 GeV

Cool Copper Collider

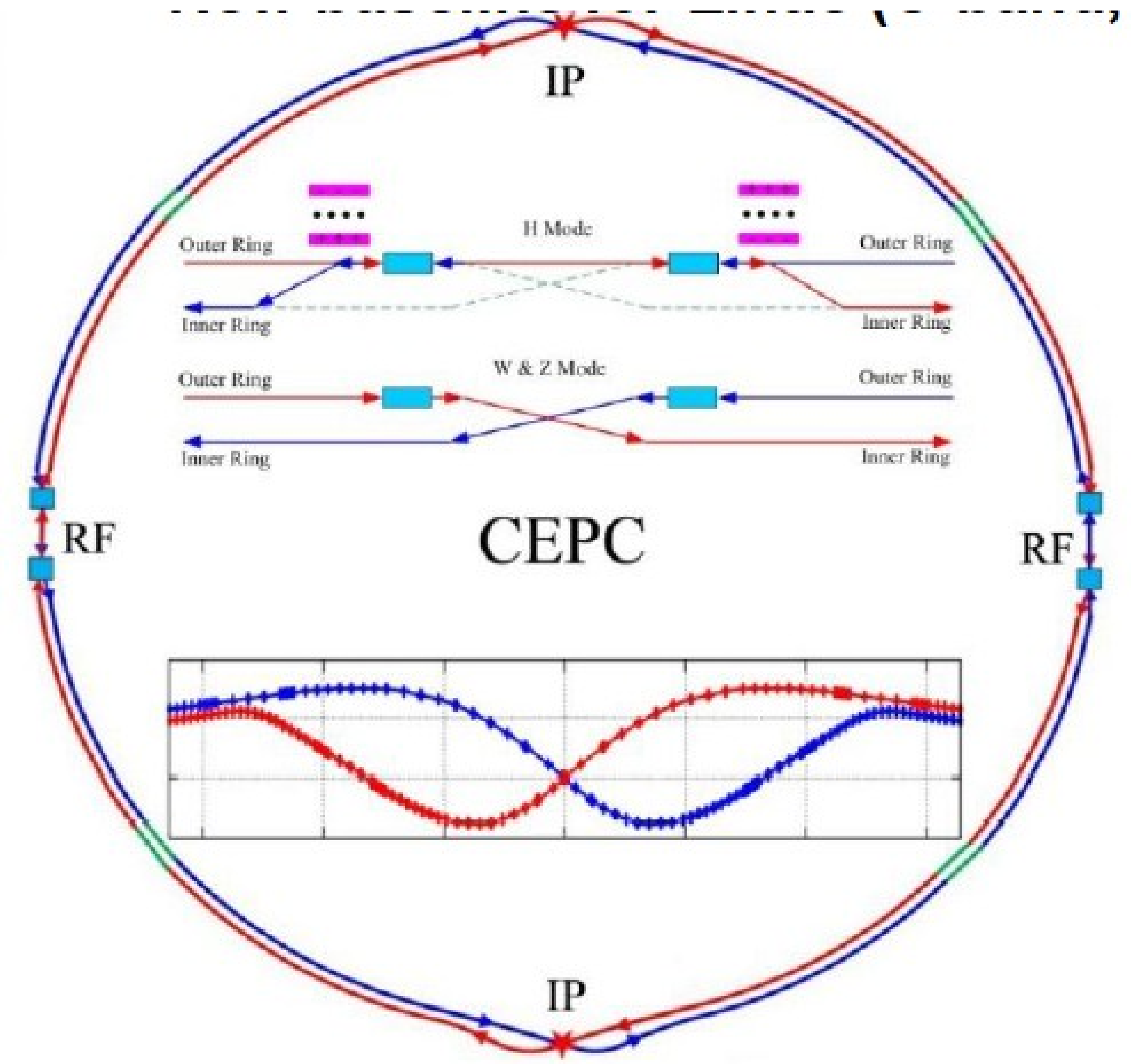
Based on new RF Technology
Operation at Cryogenic temperature (LN2 ~ 80K)
Aiming at gradients of 120 MV/m

Circular Electron Positron Colliders

Centre of Mass energies: Z-mass – tt threshold



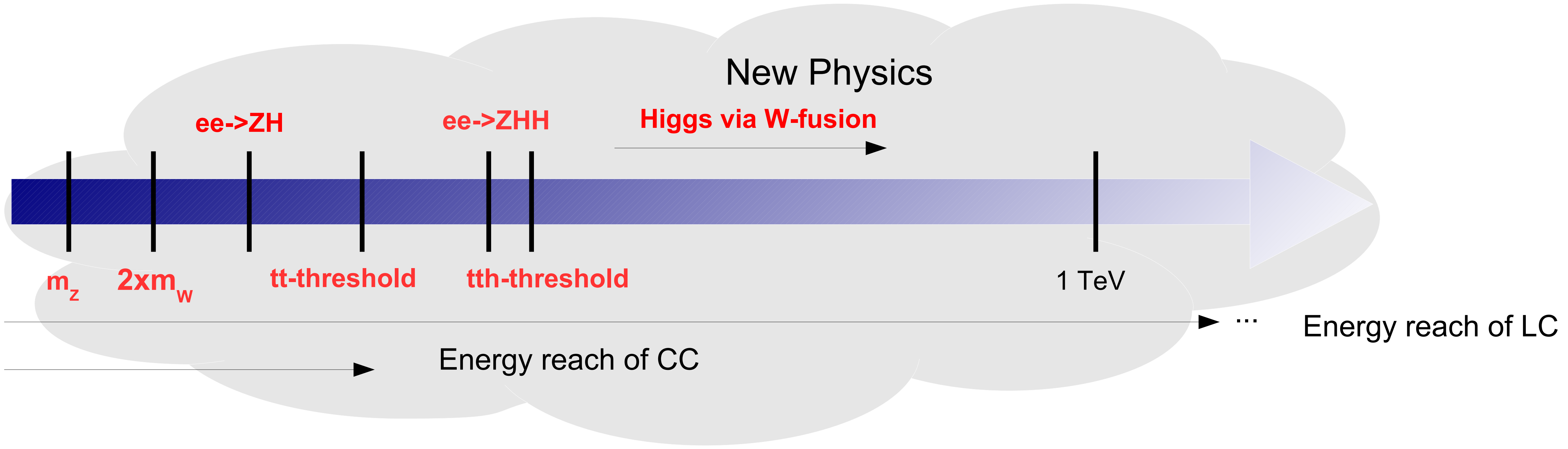
Circumference: 90.6 km



Circumference: 100 km

3

e+e- Physics program



All Standard Model particles within reach of planned e+e- colliders

High precision tests of Standard Model over wide range to detect onset of New Physics

Machine settings can be “tailored” for specific processes

- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL}) + (P-P')(\sigma_{RL}-\sigma_{LR})\right]$$

Background free searches for BSM through beam polarisation

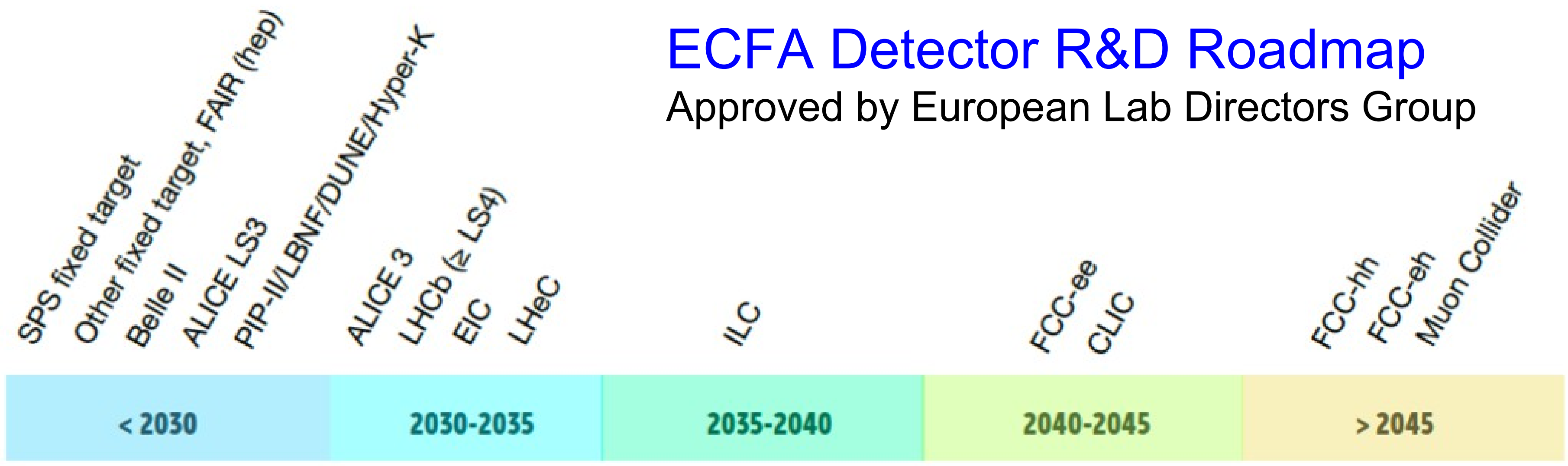
Time Scale of Future Projects

Snowmass EF-Vision (L. Reina)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

ECFA Detector R&D Roadmap

Approved by European Lab Directors Group



Linear vs. circular e+e- machines – Instantaneous luminosities

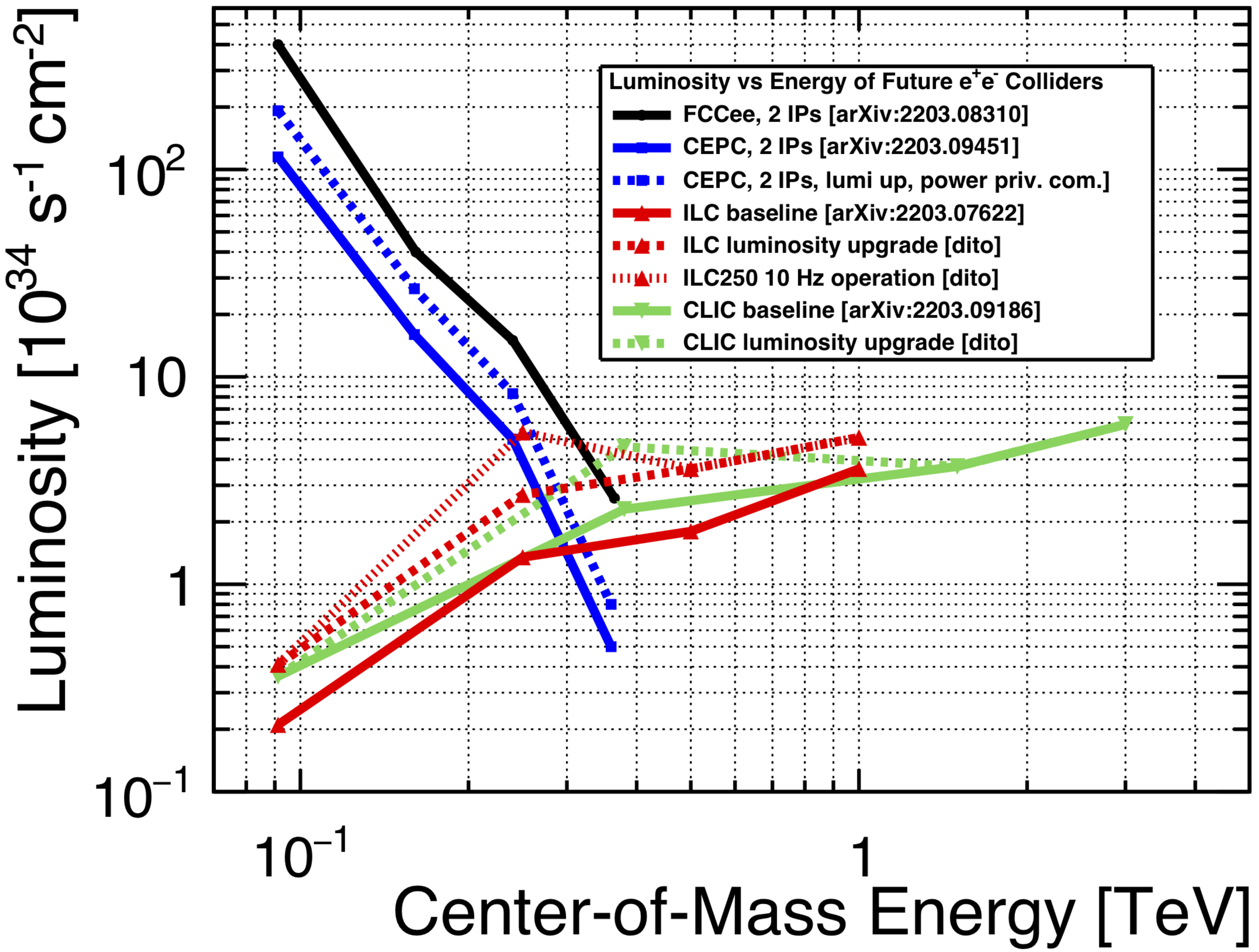


Figure J. List

High energies ~above tt-threshold
Domain of linear colliders

Low energies e.g. Z-pole
Domain of circular machines
However, see later ...

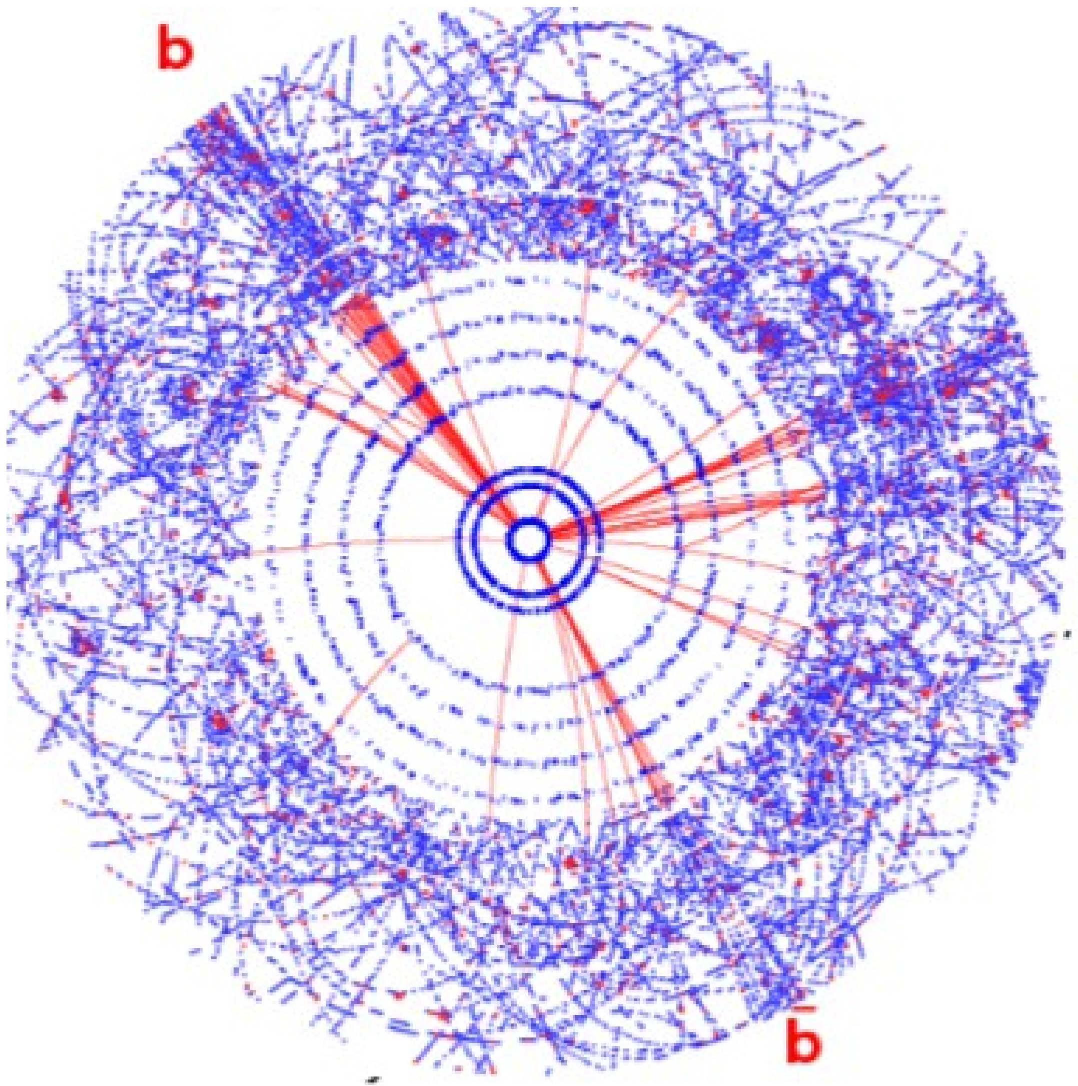
Transition region, i.e. HZ threshold
… not so clear
Comparable numbers for all proposals and N = σL

Linear colliders are more versatile to test chiral theory due to polarised beams

Plot on power consumption see backup

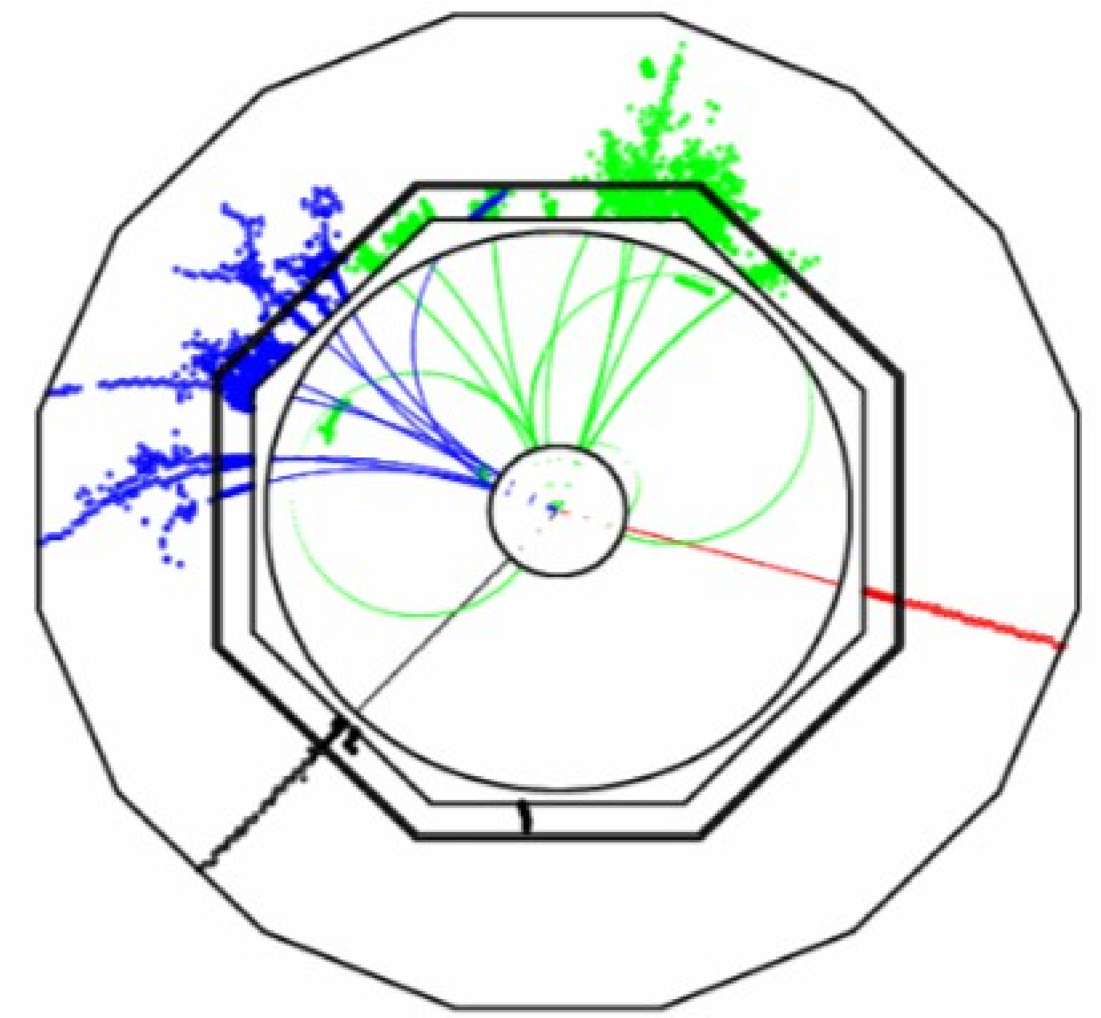
(Rough) Comparison – Hadron collisions ↔ e^+e^- collisions

Hadron-hadron collisions e.g. LHC



- Busy events
- Require hardware and software triggers
- High radiation levels

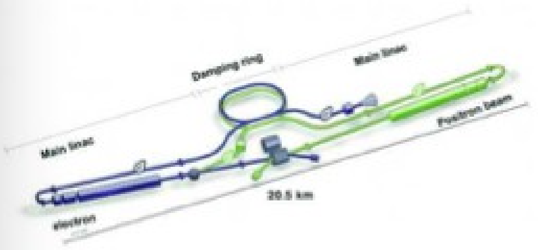
e^+e^--collisions



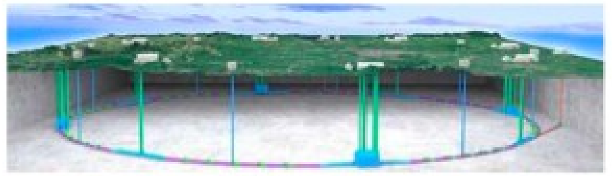
- Clean events
- No trigger
- Full event reconstruction

Detector systems – Target projects

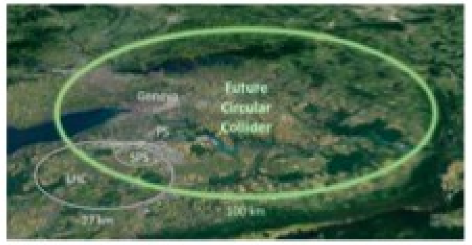
ILC



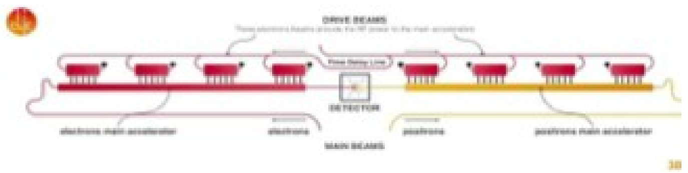
CEPC



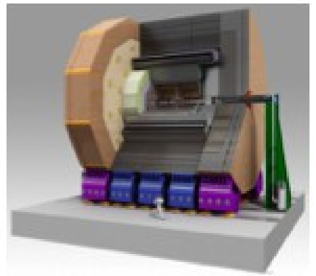
FCC-ee



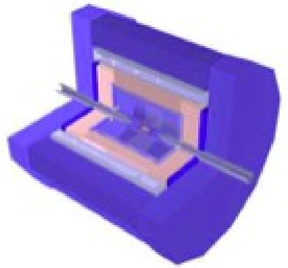
CLIC



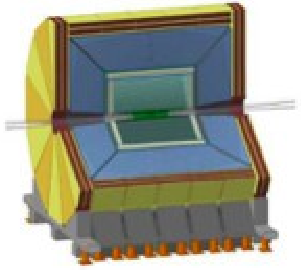
ILD



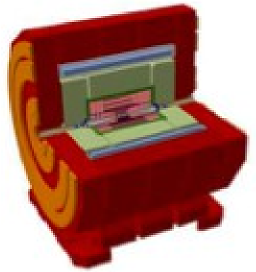
CEPC Baseline



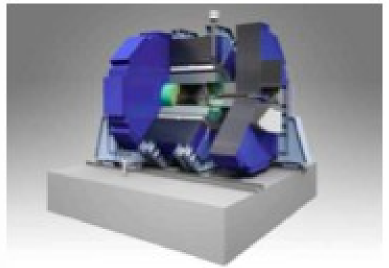
IDEA



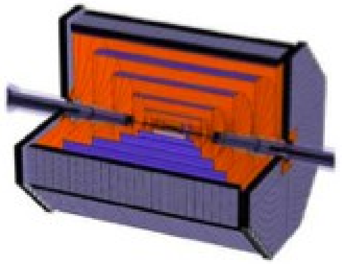
CLICdp



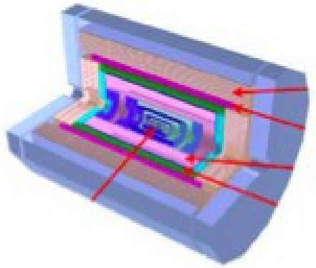
SiD



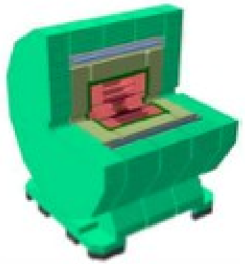
FST



CEPC 4th concept



CLD



slide stolen from B. Dudar

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

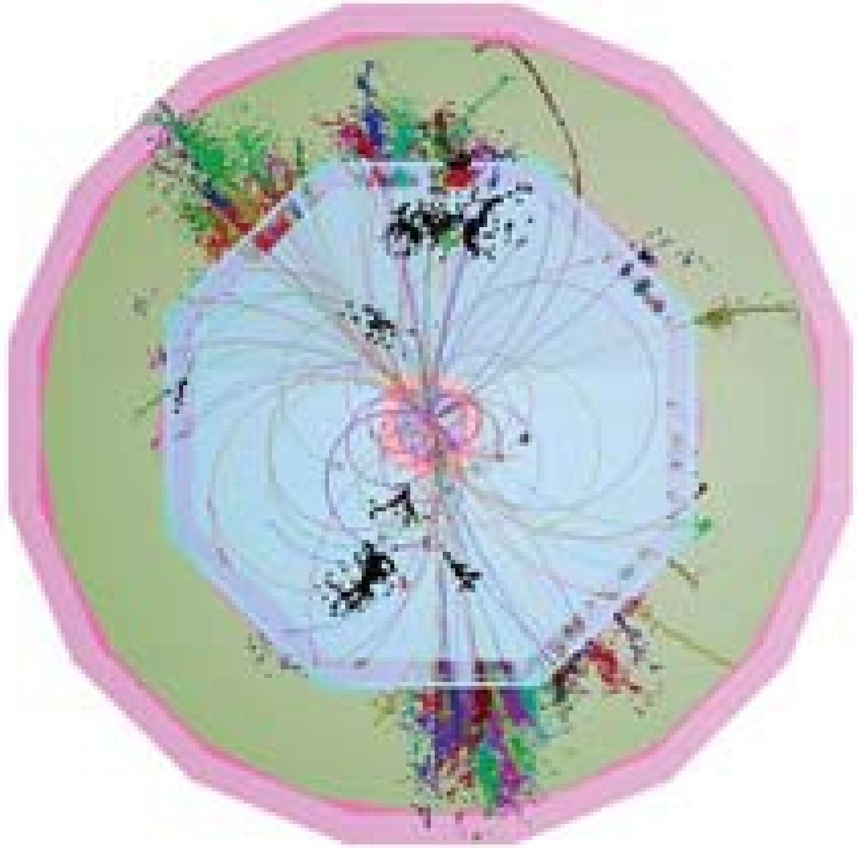
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\mathrm{GeV}))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : … well as hermetic as possible, LC Detectors require θ_{min} = 5 mrad

(for events with missing energy e.g.dark sector/ invisible decays)



Final state will comprise events with a large number of charged tracks and jets(6+)

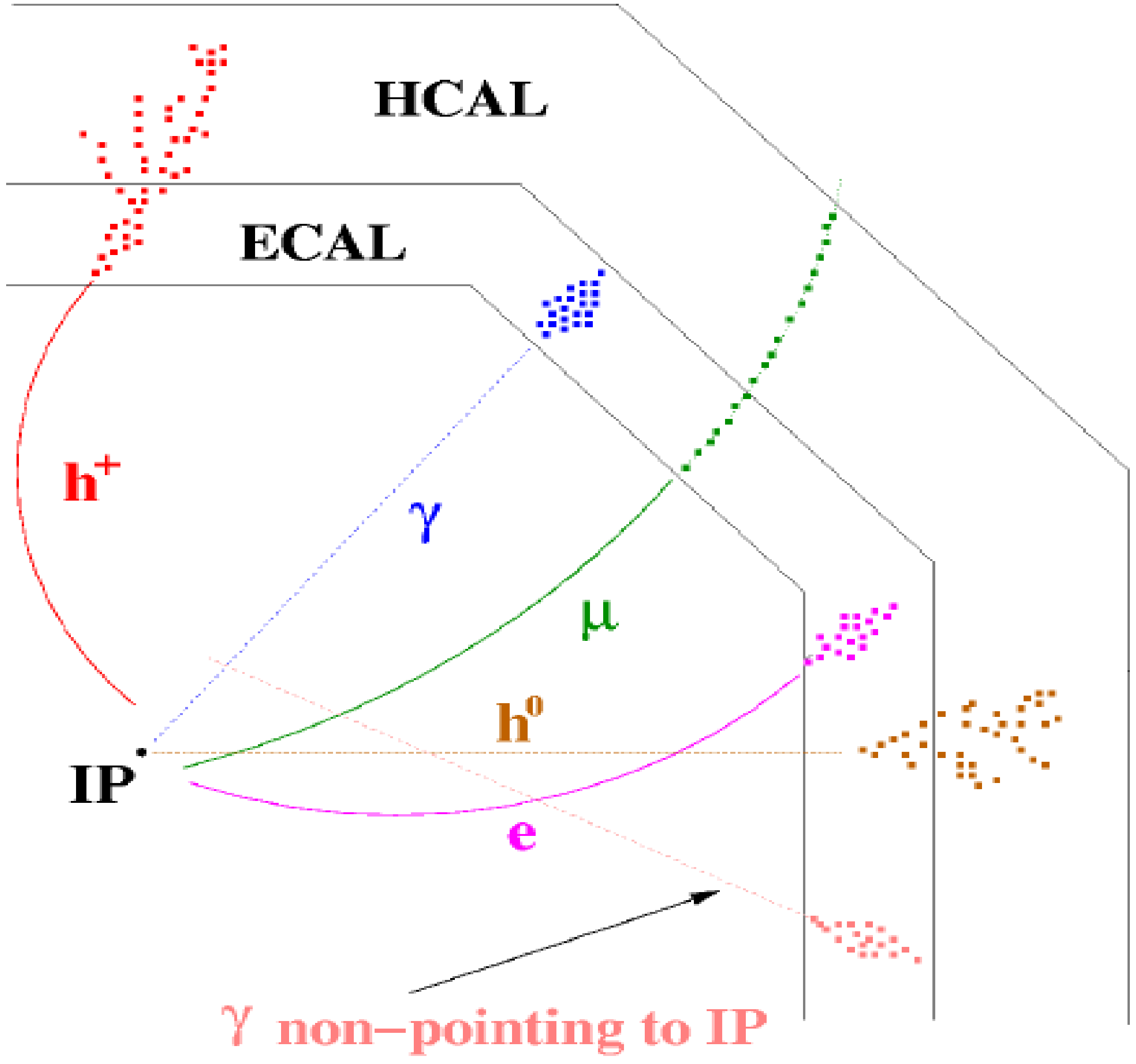
- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Particle Flow Detector Layout

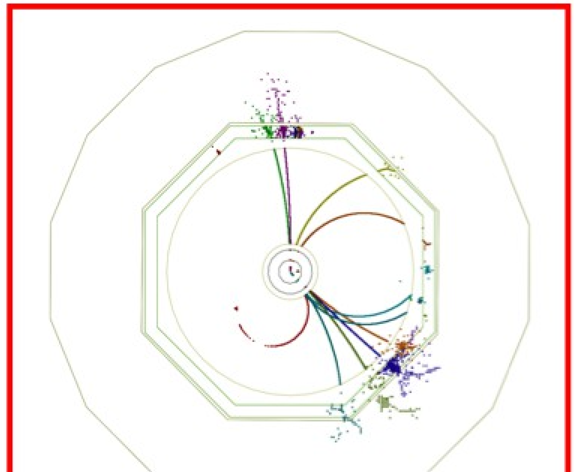
- Jet energy measurement by measurement of **individual particles**
- Maximal exploitation of precise tracking measurement

- Large radius and length
  - ➔ to separate the particles
- Large magnetic field
  - ➔ to sweep out charged tracks
- “no” material in front of calorimeters
  - ➔ stay inside coil (the puristic viewpoint)
  - ➔ see later discussion
- Minimize shower overlap
  - ➔ Small Molière radius of calorimeters
- **high granularity of calorimeters**
  - ➔ to separate overlapping showers



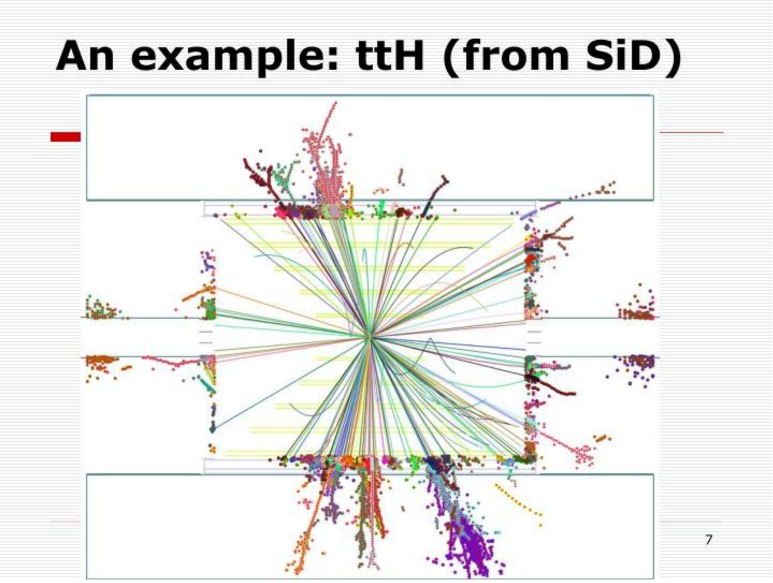
Detector Hermeticity

Invisible Higgs decays

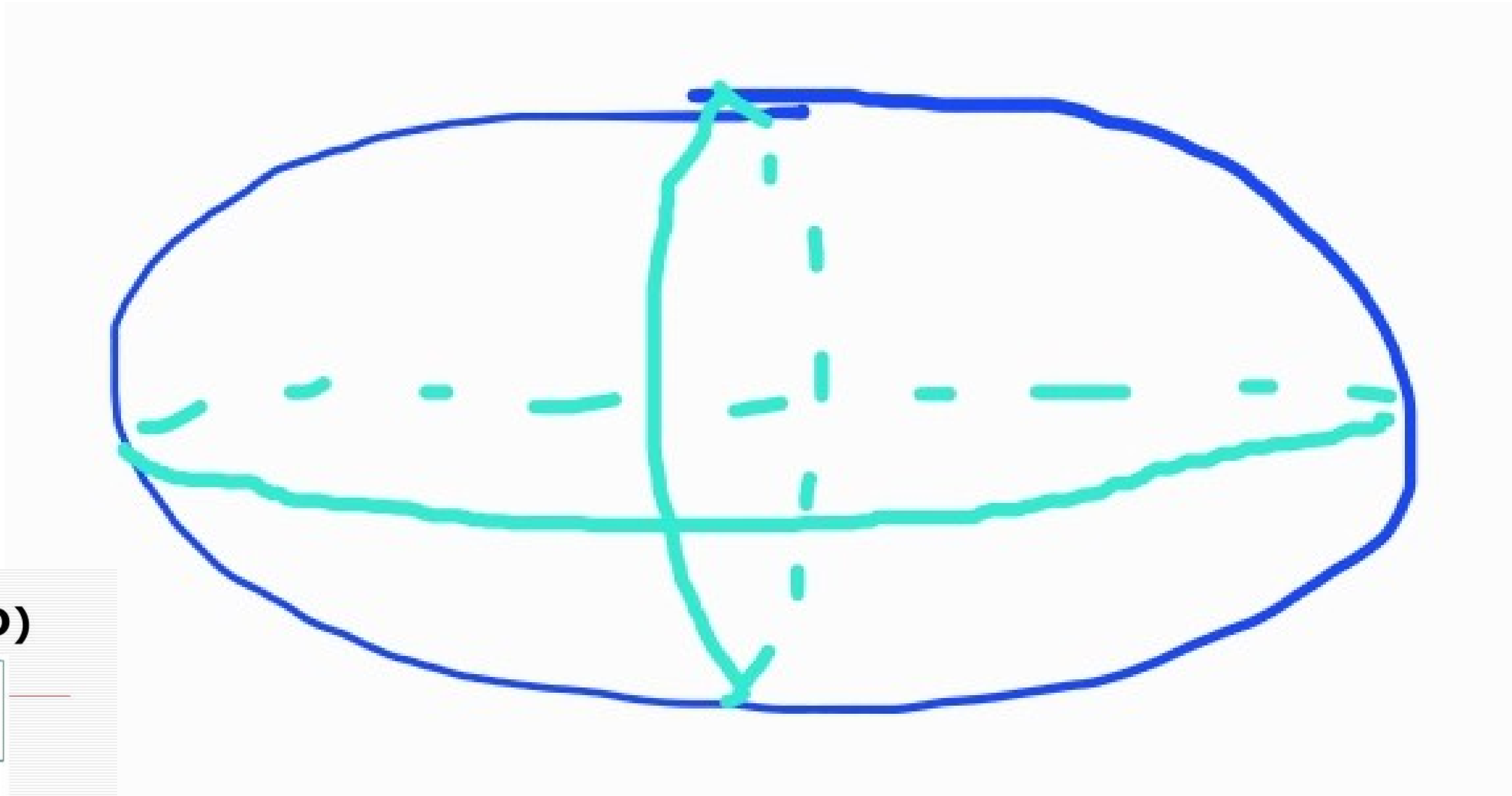


e⁺e⁻ → qq H → qq inv in ILD detector

Rich events:

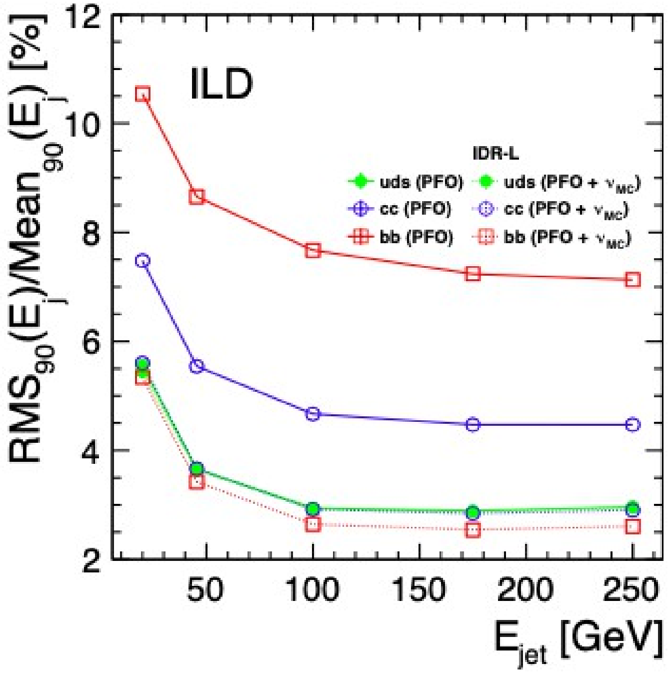


Hermeticity = Acceptance down to the beam pipe and no acceptance holes!

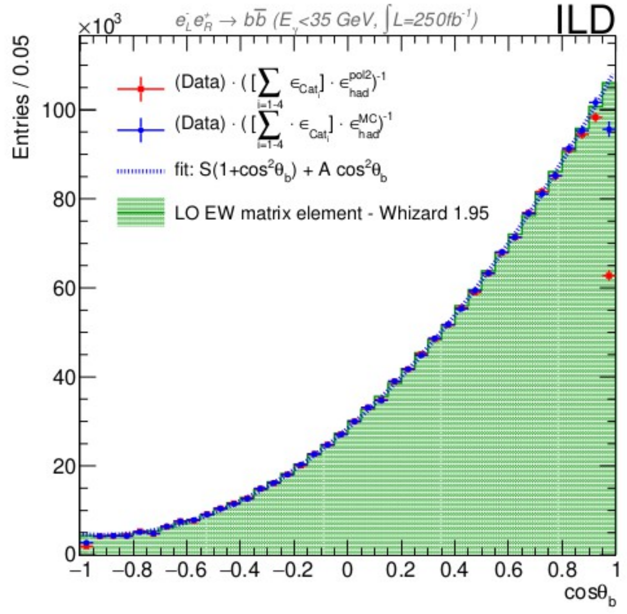


Detector Hermeticity requires is team effort
Vertex Detectors, Central Tracking and
of course
calorimeters

Missing Energy

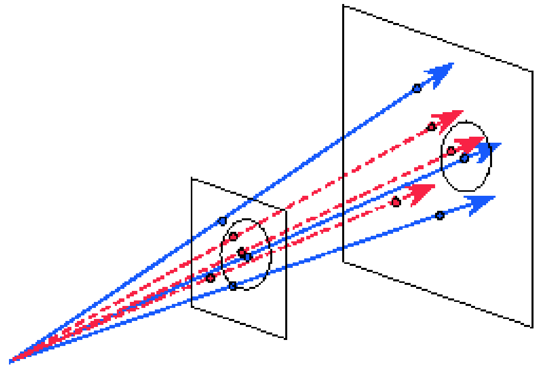


Heavy Quark asymmetries



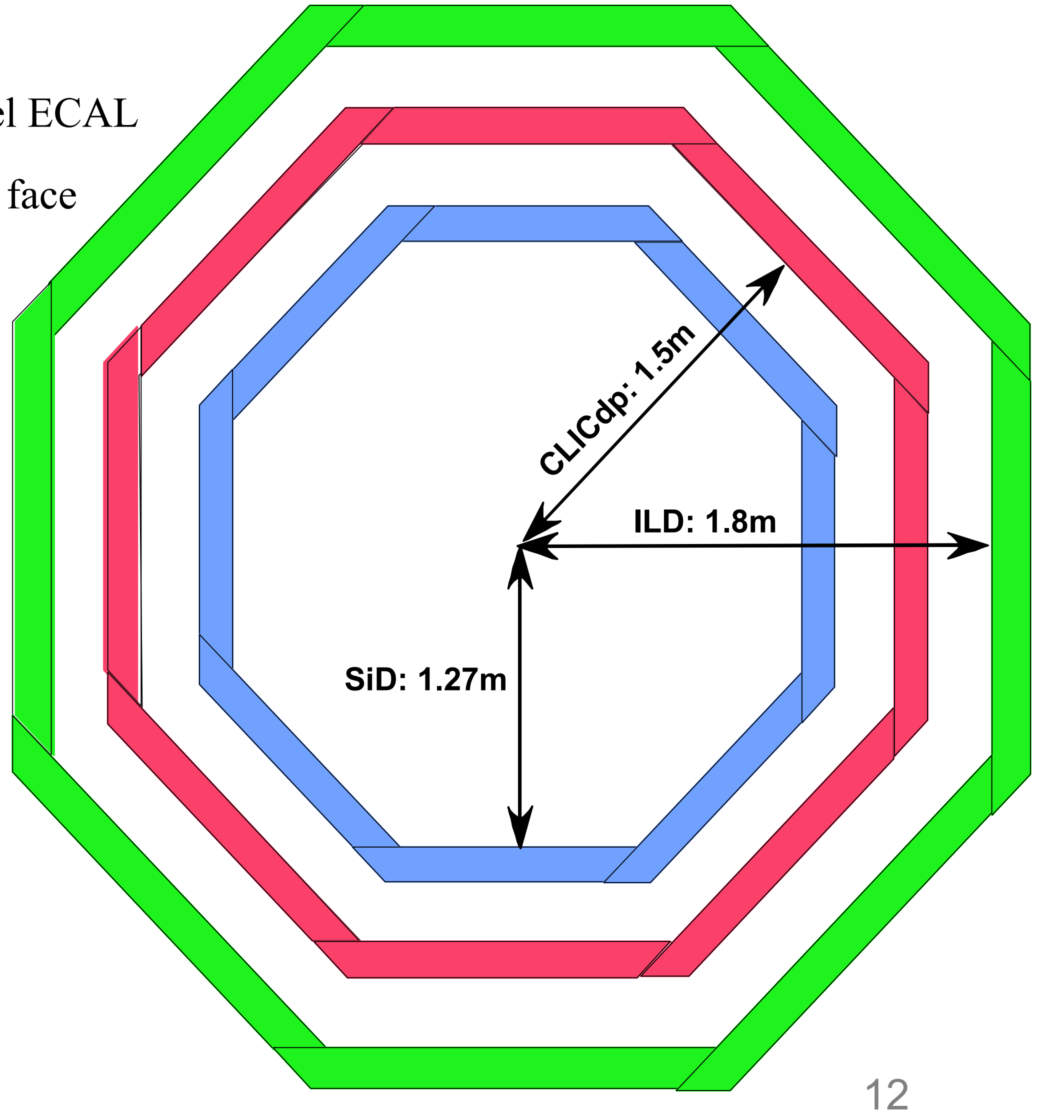
Detectors for e+e- Colliders – Main Parameters

Concepts currently studied differ mainly in SIZE and aspect ratio



	ILD	SiD	CLICdp	CLD
Rin [mm] Vertex Detector	16	14	31	17.5
$R_{in,\ Ecal}$ [mm]	1805	1270	1500	2150
$R_{out,tot}$ [mm]	7755	6042	6450	6000
$Z_{min,\ ECAL}$ [mm]	2411	1657	2310	2310
$Z_{max,tot}$ [mm]	6712	5763	5700	5300
B [T]	3.5	5	4	2

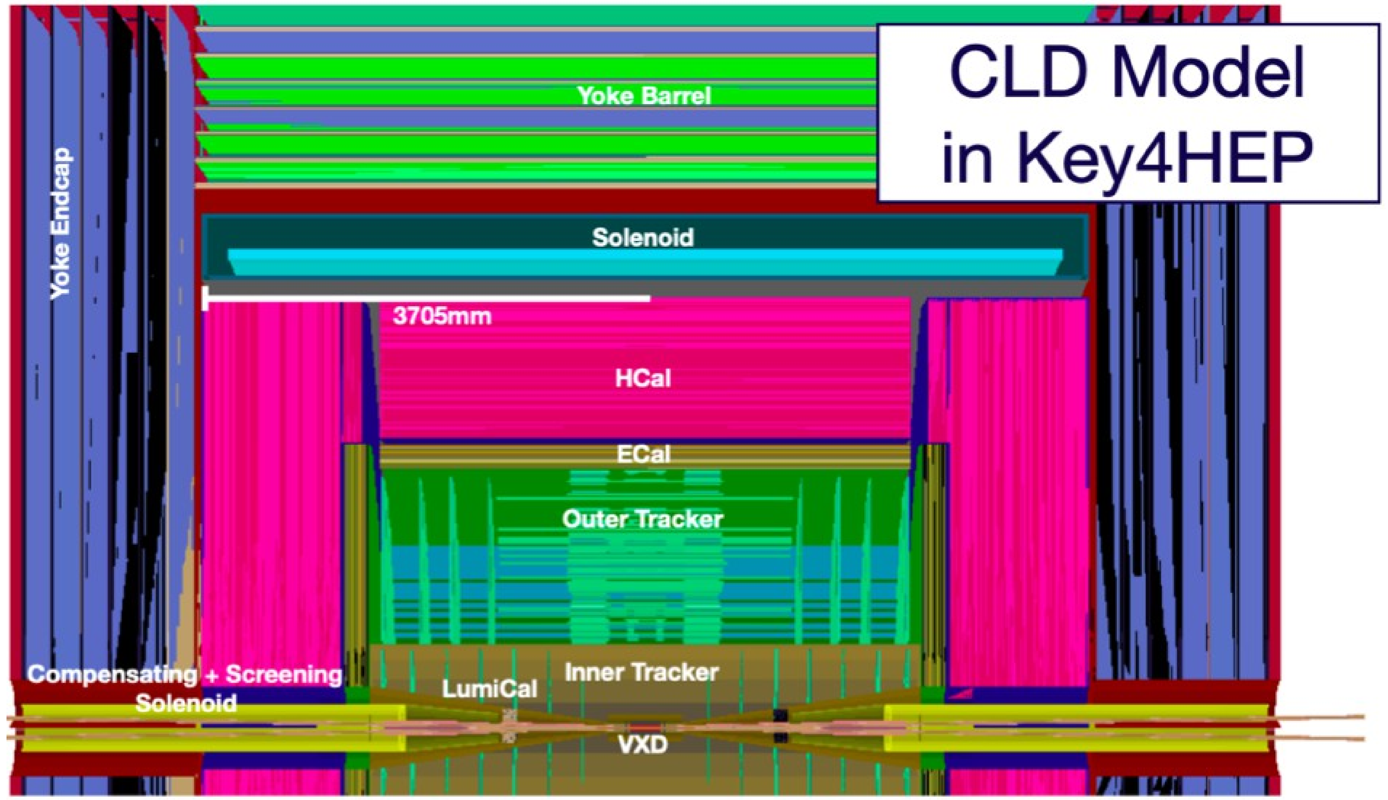
- Figure of merit (ECAL):
  - Barrel: $B\ R_{in}^2 / R_m^{effective}$
  - Endcap: "B" $Z^2 / R_m^{effective}$
    - R_{in} : Inner radius of Barrel ECAL
    - Z : Z of EC ECAL front face
- Different approaches
  - SiD: $B\ R_{in}^2$
  - CLICdp: $B\ R_{in}^2$
  - ILD $B\ R_{in}^2$
  - CLD: $B\ R_{in}^2$



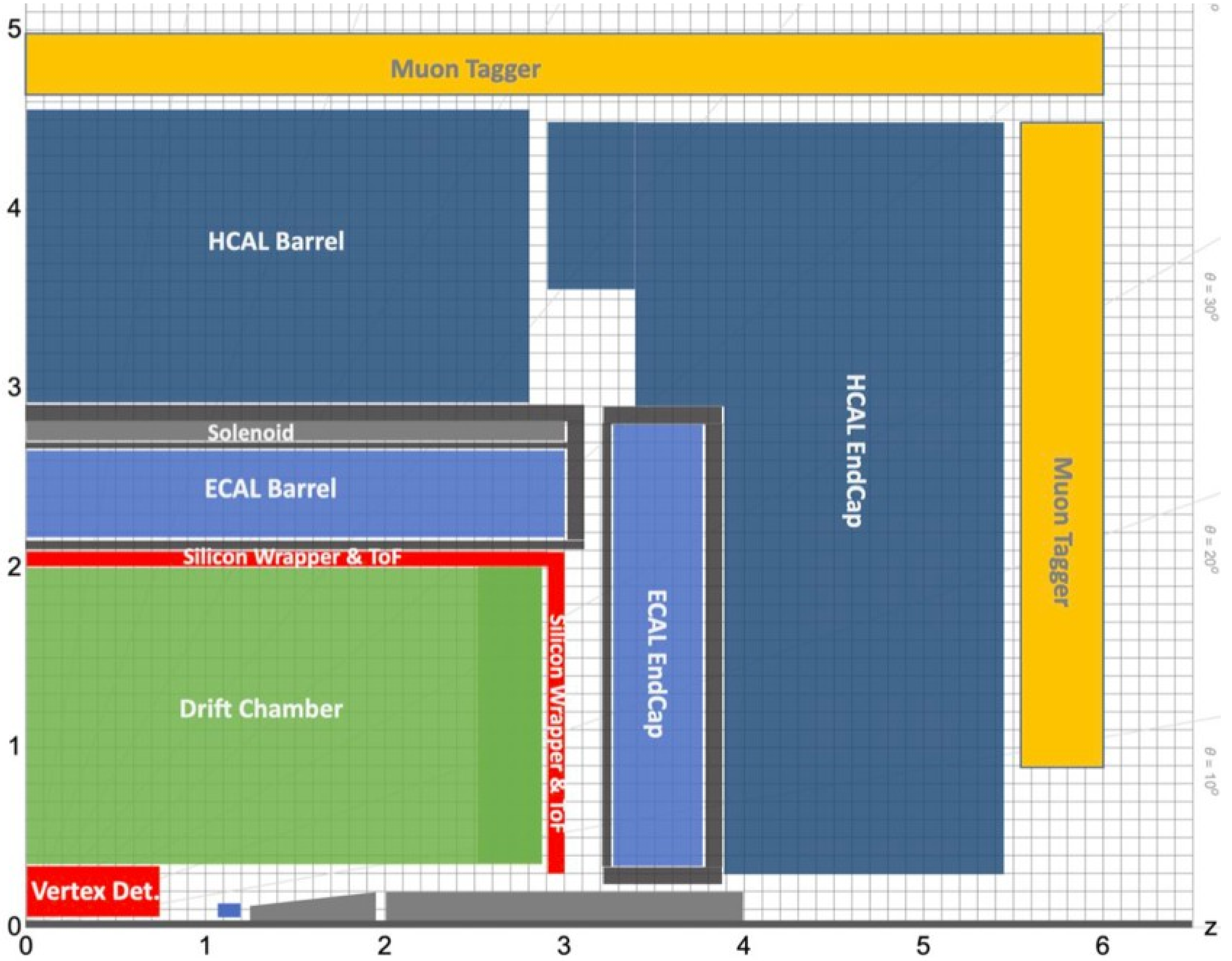
- Roughly: The smaller B the bigger $R_{in,Ecal}$ has to be
- Overall outer radius will depend on required Hcal thickness
- ... and details of return yoke design
  - Cost, safety considerations ...

Detectors for e+e- Colliders – Main Parameters

CLD Detector Model
Solenoid **outside** of imaging alorimeter



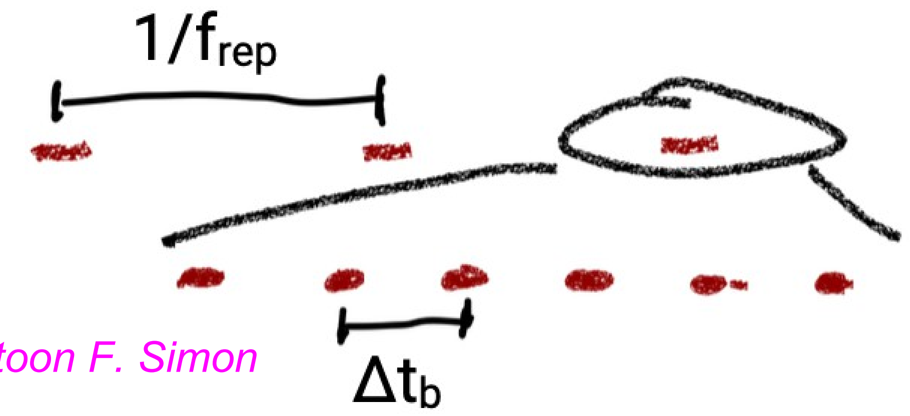
FCC-ee detector Model with Lar Ecal
Solenoid **between** Ecal and HCAL



- The position of the solenoid is an obvious topic of study (if not done yet)
  - Comparison has to be carried out at equal footing
  - Definition of benchmarks, detail of detector simulation

Operation mode- pulsed or continous

- Linear Colliders operate in bunch trains



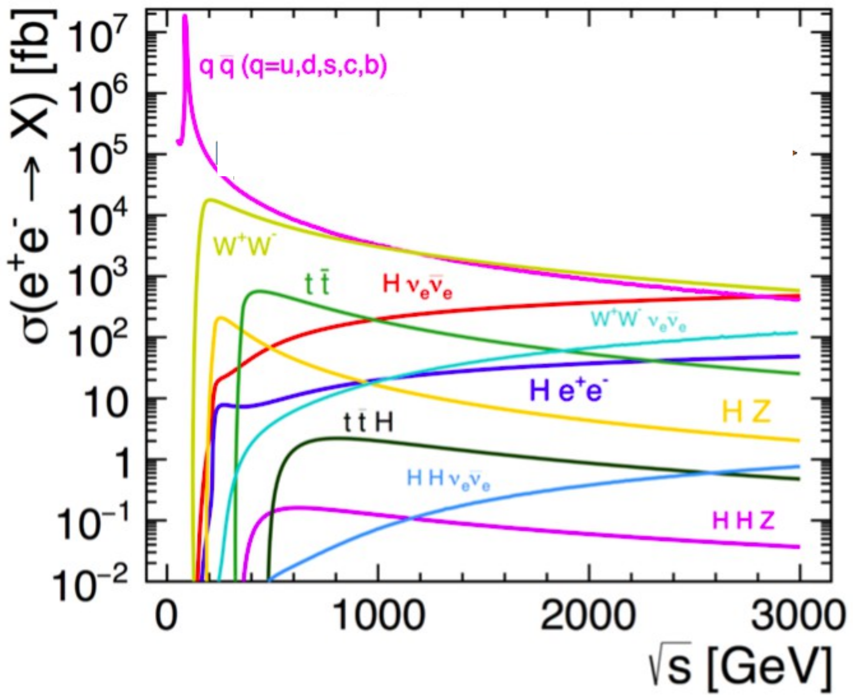
Cartoon F. Simon

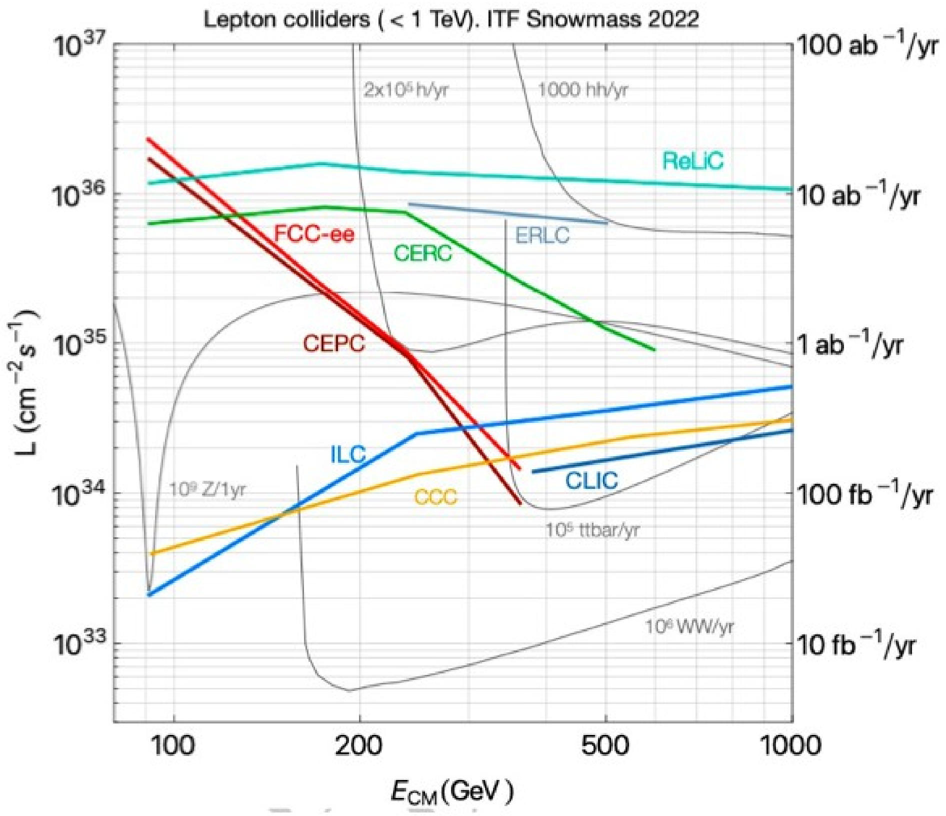
CLIC: Δt_b ~ 0.5ns, frep = 50Hz
ILC: Δt_b ~550ns, frep = 5 Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with 10^8 cells
- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Supports compact and hermetic detector design

- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in "continuous" mode
  - R&D Goal: Avoid/minimise active cooling also in continuous mode
  - Challenge differs depending on where the electronics will actually be located

Future direction of R&D - Impact of event rates





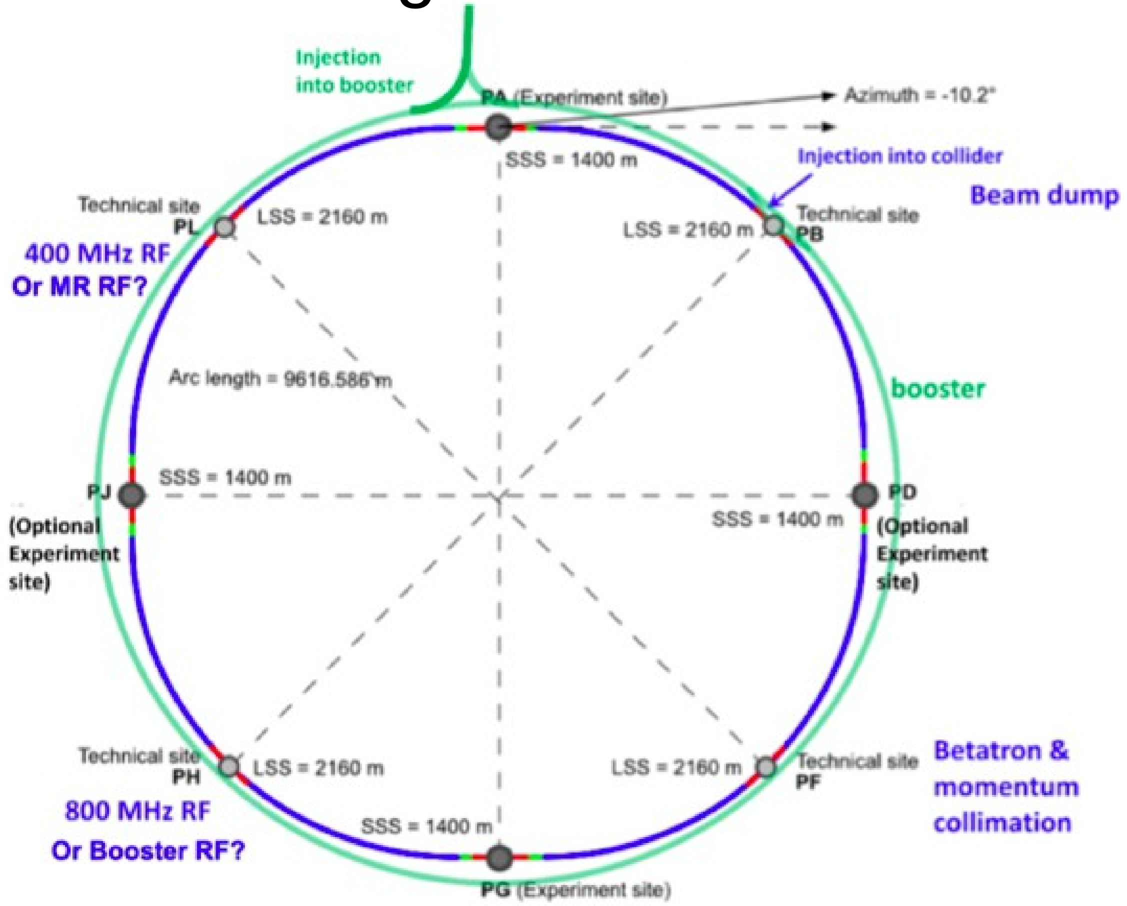
High energy e+e- colliders:

- Physics rate is governed by strong variation of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee) to few Hz above Z-Pole
- (Extreme) rates at pole may require other solutions than rates above pole

- Event and data rates have to looked at differentially
  - In terms of running scenarios and differential cross sections
  - Optimisation is more challenging for collider with strongly varying event rates
    - Z-pole running must not compromise precision Higgs physics

FCC MDI Nutshell (and poor man's) Introduction

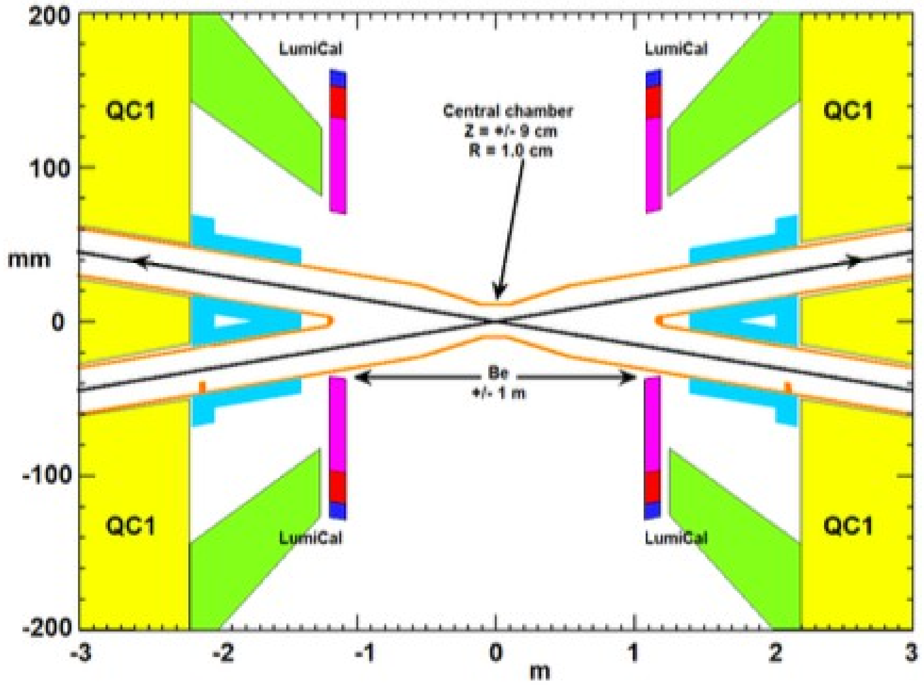
Machine layout
as shown during FCC Week 2023 Cracow



- Circumference 90,6 km
- 4IP (FCC-ee = FCC-hh)

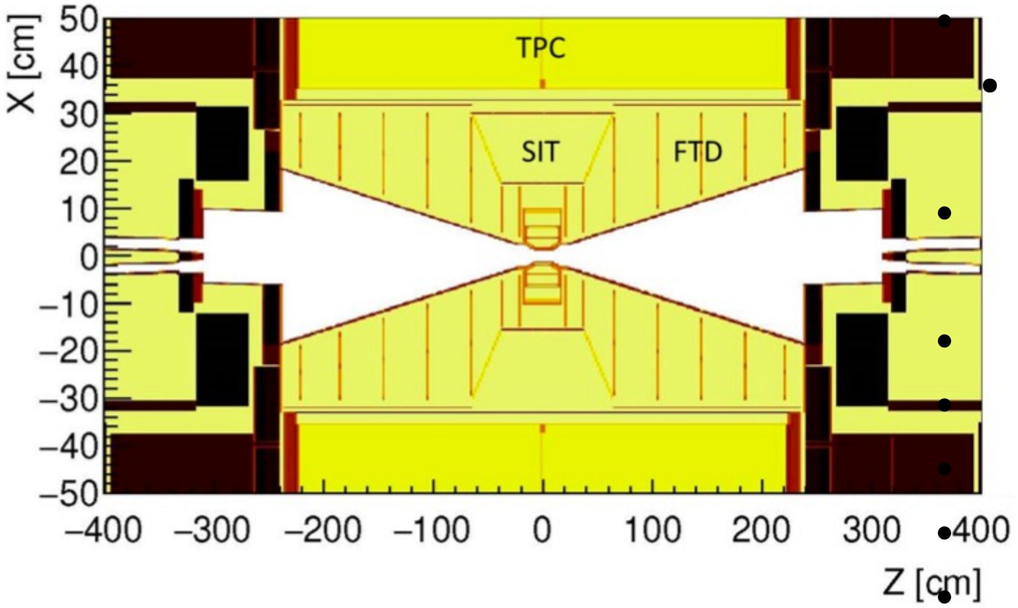
M. Boscolo, FCC Week Cracow

Typical MDI



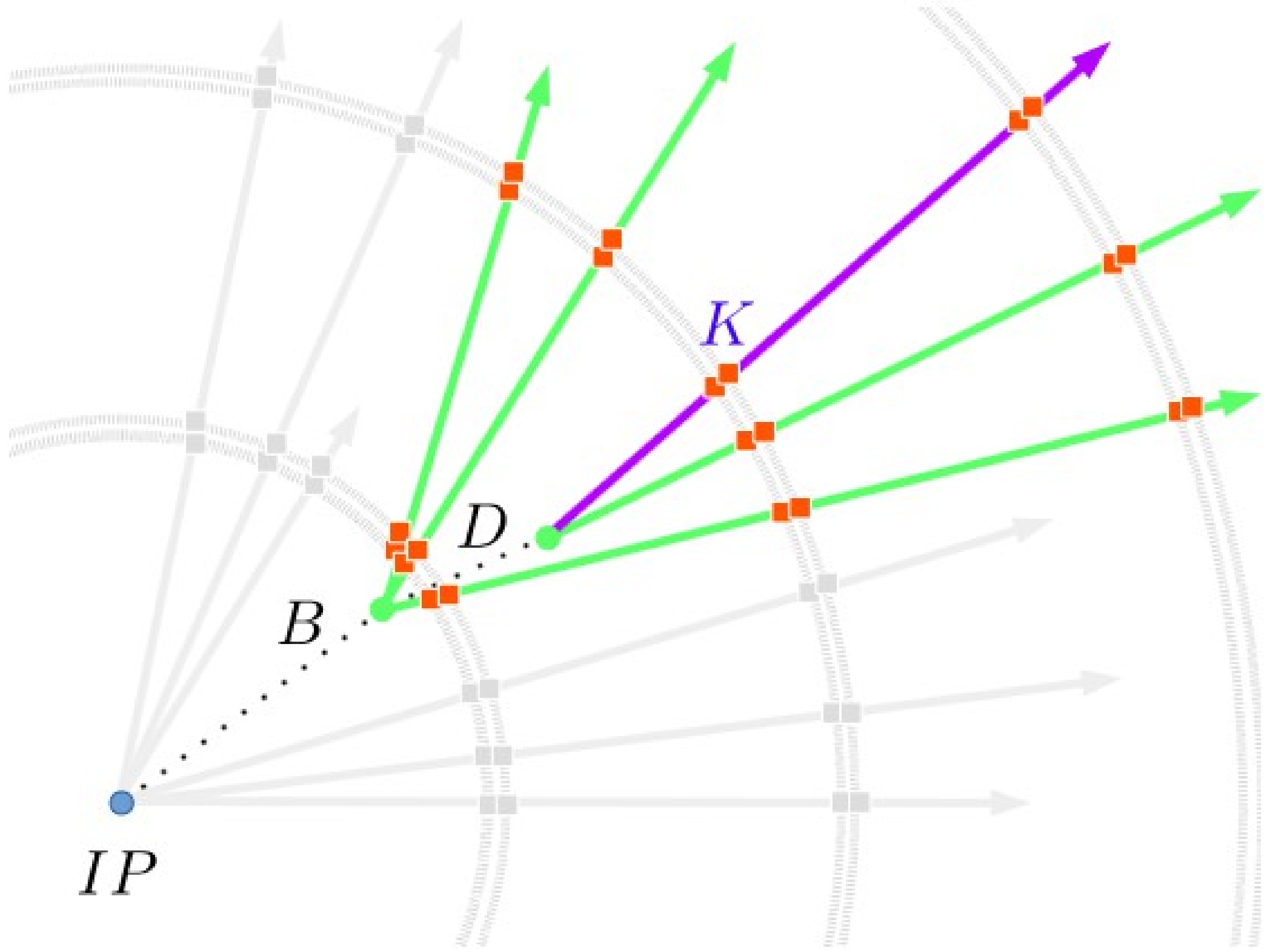
- L* = 2.2m
- Final quadropole inside detector region
(and is background source)
- LumiCal at 1000mm
- => defines tracker acceptance cos ~0.984
- Inner beampipe radius 10mm
- Magnetic Field 2 T
- Crossing angle ~30 mrad

Compare with ILC MDI region



- L* = 4.1m
- Final quadropole outside of detector region
- Tracker Acceptance defined by conical beam pipe(due to blown-up beam)
- cos ~0.995
- LumiCal at ~2500mm
- Inner beampipe radius 16 mm
- Magnetic Field 3.5-4 T
- Crossing angle 14 mrad

Vertexind and Tracking



PhD thesis: S. Bilokin
A. Irles

- Determination of primary vertex
- Flavor tagging
  - Indispensable for analyses with final state quarks
- Quark charge measurement
  - Important for top quark studies,
  - indispensable for ee->bb, cc, ss, ...
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification by dE/dx (and more)
- Future detectors can base the entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and semi-leptonic events

Central Tracking

Collider	ILC		CLIC	FCC-ee			CEPC	
Detector Concept	SiD	ILD	CLICdet	CLD	FCC-ee IDEA	Noble LAr/LKr	CEPC baseline	CEPC IDEA
B-field [T]	5	4	4	2	2	2	3	2
Vertex inner radius [mm]	14	14	31	17 → 12	17 → 12	17 → 12	16	16
Tracker out. radius [m]	1.25	1.8	1.5	2.2	2.0	2.0	1.81	2.05
Vertex	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel
Tracker	Si-strips	TPC/ Si-strips	Si-pixel	Si-pixel	DC/ Si-strips	DC/Si-strips or Si-pixel	TPC/Si-strips or Si-strips	DC/ Si-strips

Ziad El Bitar
2nd ECFA Higgs/top/elw. Workshop

Vertex Detectors - Constraints

Physics O(Hz/cm²)

Physics
- ➪ Flavour tagging
- ➪ Low pT tracks
- ➪ Vertex/Jet charge determination

Vertex reconstruction
- ➪ granularity
- ➪ Pitch ~17-20 µm
- ➪ (σ_{sp} ~3-4 um)

Material Budget
- ➪ ~ 0.15% X_0 / layer
- ➪ < 1% X_0 for the whole VTX
- + ~0.3 % X_0 for the beam pipe
- + 0.15% X_0 for 5 µm Gold coating

Low material detectors & supports structures

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

$a \simeq 5\mu m$ $\quad b \sim 15\mu m.GeV$ @FCCee

$b \sim 10\mu m.GeV$ @ILC

Cooling
Stiffness / Alignment

Beam background O(10-50 MHz/cm²)

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Rad.Tol. devices

Time resolution
O(1 µs)

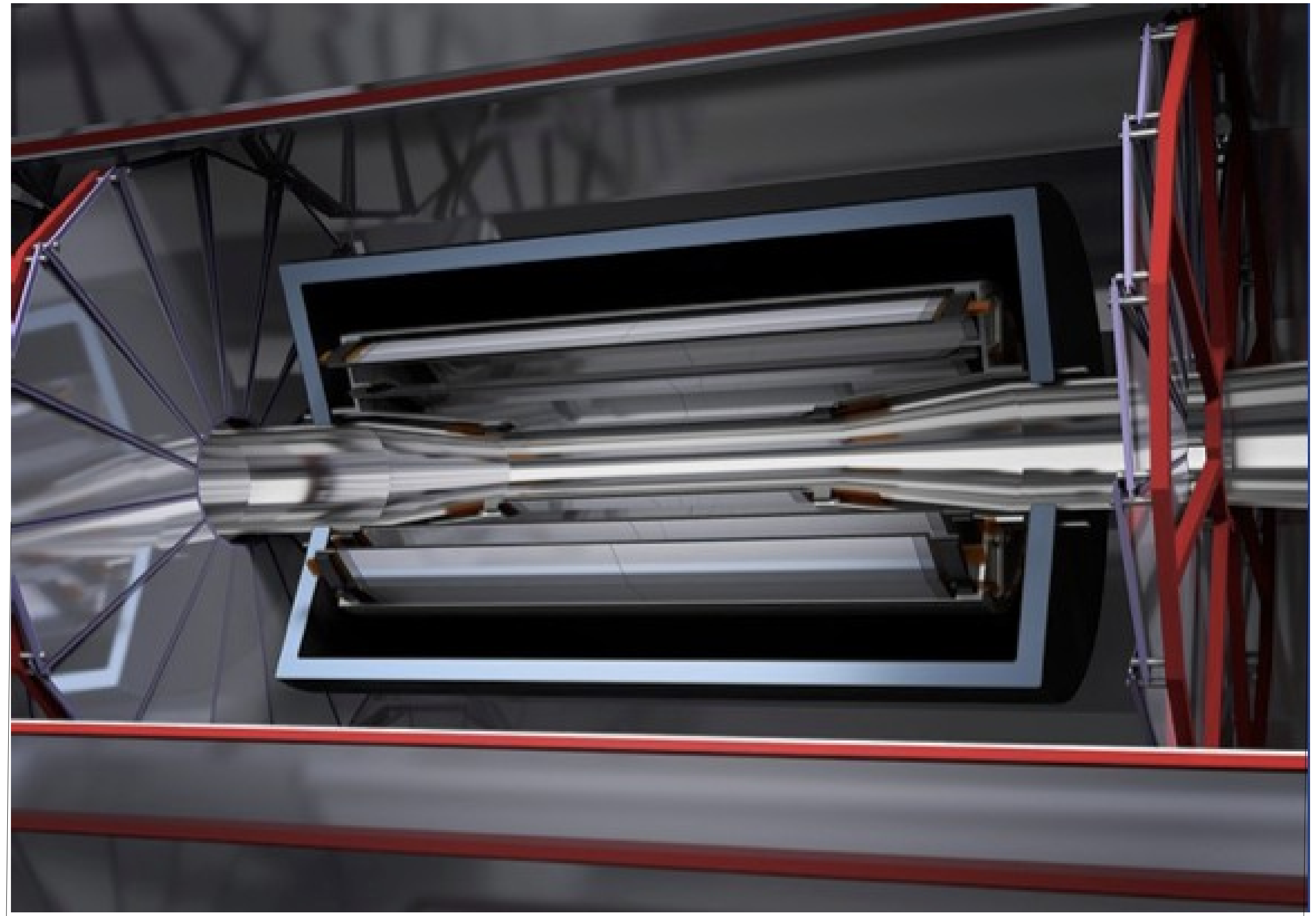
Power consumption ~< 50mW/cm²

Fast read-out & low Power Architectures (~ 20 mW/cm²)

Power pulsing (ILC) vs continuous beam (FCCee)

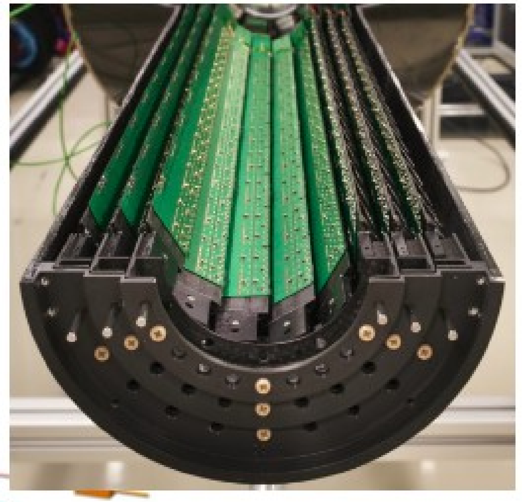
Ziad El Bitar
2nd ECFA Higgs/top/elw. Workshop

Vertex Tracking



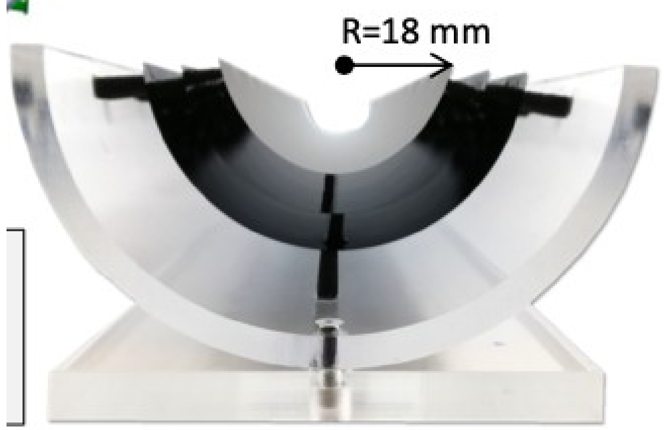
Big question: Radius of beam pipe

- Low material budget is overall challenge
  - Major step through ALICE upgrade (?)



ITS2:
(S.Beolé, iWoRiD 2022)

- 7 layers of MAPS
- TJ 180 nm CMOS
- 12.5 Giga pixels
- Pixel size: $27 \times 29\ \mu m^2$
- Water cooling
- **0.3 % X_0 / inner layer**



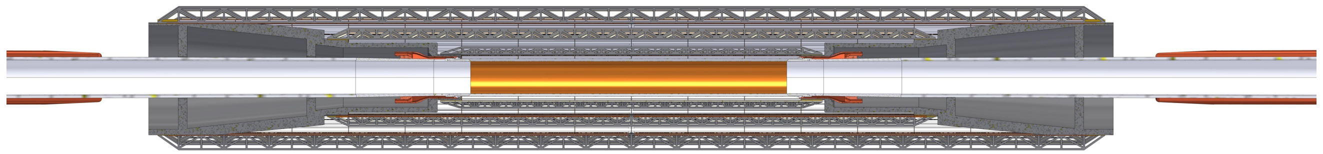
ITS3
(M. Šuljić, iWoRiD 2023)

- 4 outer layers of ITS2
- 3 new fully cylindrical inner layers
  - Sensor size up to 27×9 cm
  - Thickness 30-40 µm
  - No FPCs
  - Air cooling in active area
- **0.05 % X_0 / inner layer**

Considerable material reduction by application of **bent** layers
=> No carrier structures

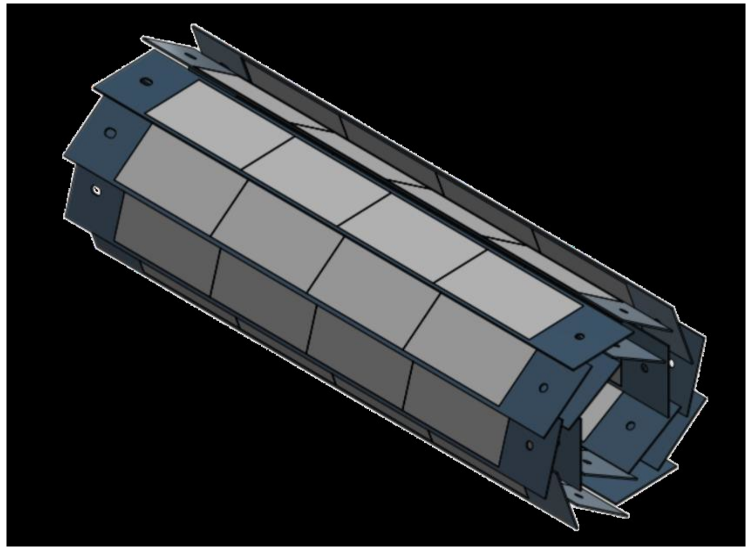
Vertex Tracking - Synergies

IDEA Vertex Detector

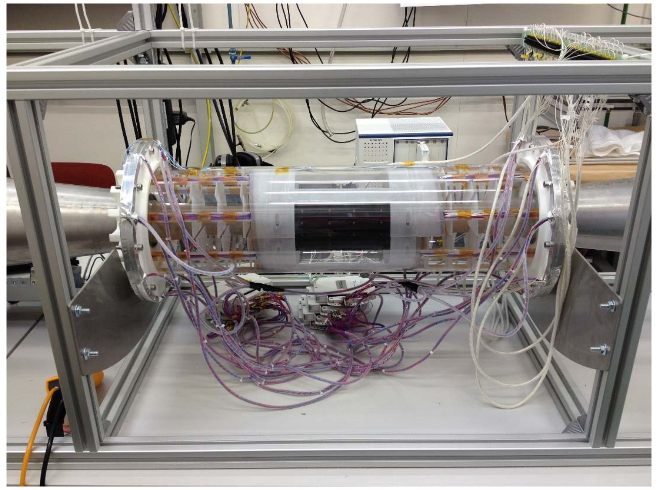


CLD – IDEA – ILD' – Belle-II vertex detectors

?



iVTX



CLICdp Wind Tunnel

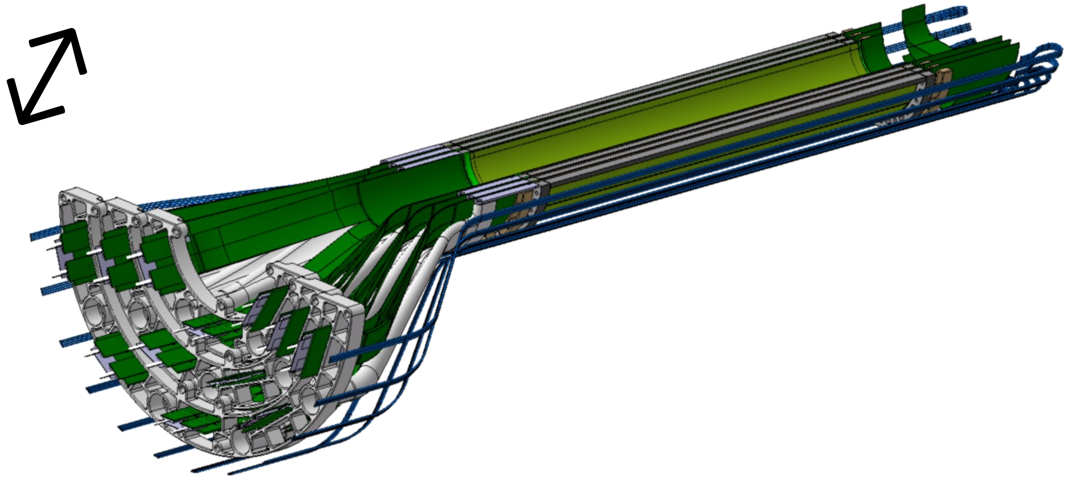
↕

CLICdp – ILD vertex detectors

↔

ALICE ITS3

⤢



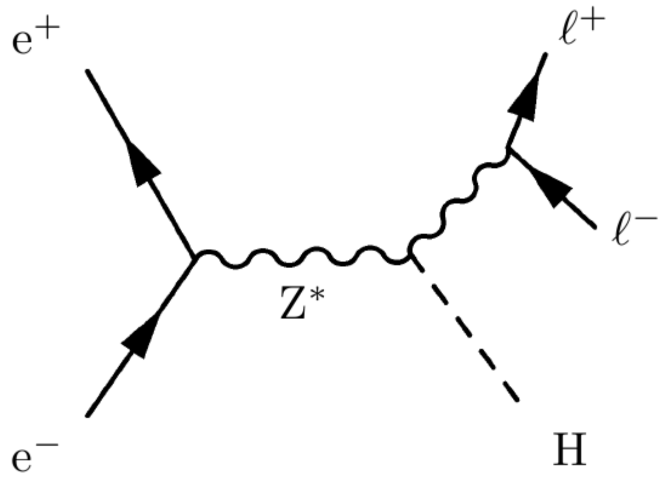
Numerous similarities in their vertex detector requirements (conflicts !), concepts & design:

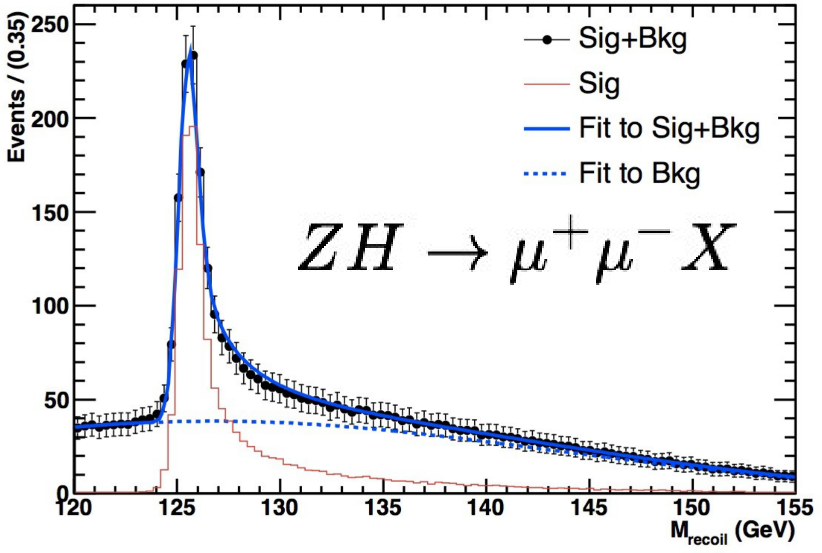
- inner layer & beam pipe radii, spacial & time resolution, radiation load, etc.
- **power consumption / mass budget / warm cooling / cooling service path-bulk**

M. Winter
4th French FCC Meeting

Central Tracking

"Royal" task of central tracking system
Precise measurement of charged particles in e.g.



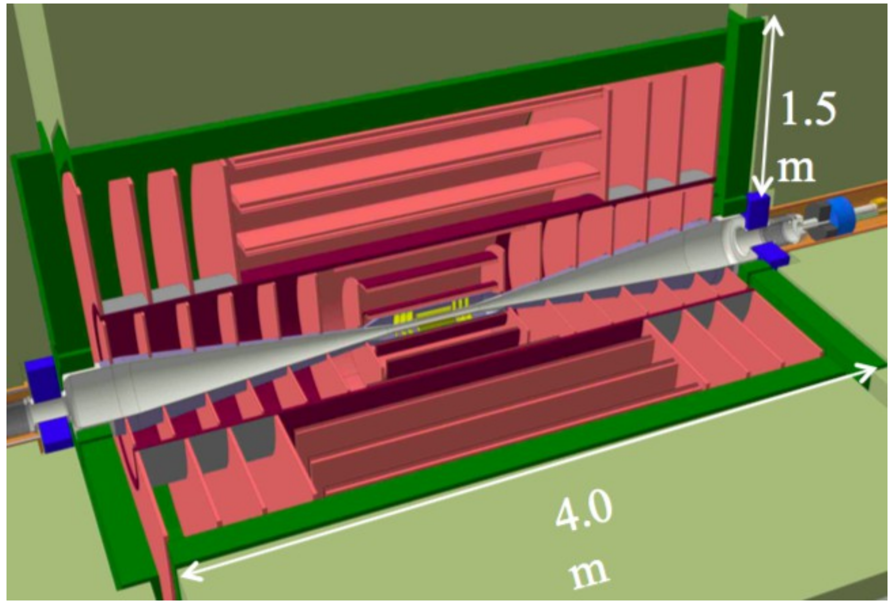


Gluckstern Formula:

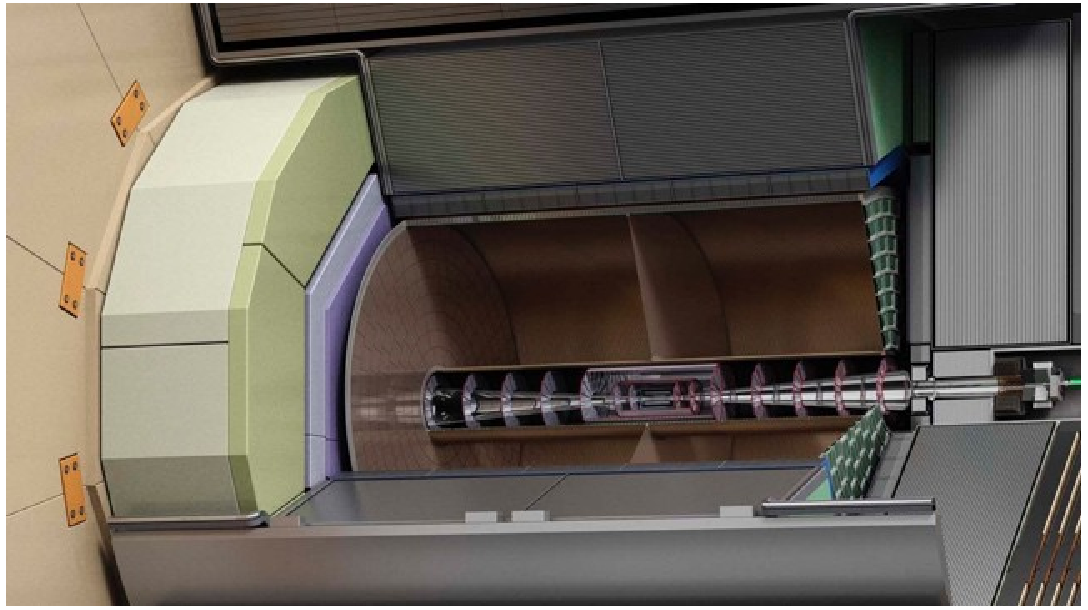
$$\frac{\Delta p_t}{p_t^2} = \frac{\sigma_{r\phi}}{0.3\, L^2\, B}\sqrt{\frac{720}{N+4}}$$

Relates track momentum resolution with single point resolution **σ** with **N**umber of hits and track length **L** and magnetic Field **B**

Option 1: All silicon tracking



Option 2: Gaseous tracking



IDEA Drift Chamber

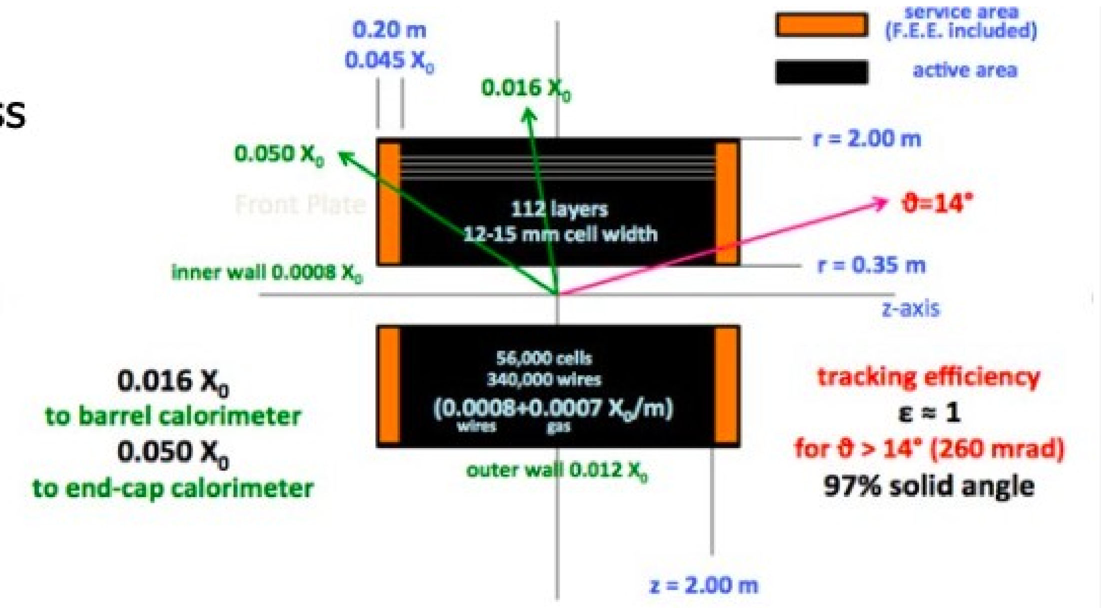
The DCH is:

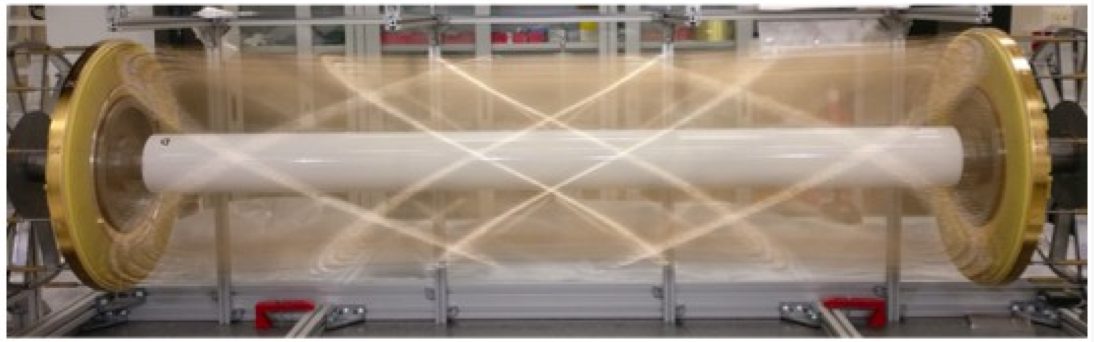
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm
- drift time ~150ns
- σ_{xy} < 100 μm, σ_z < 1 mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires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

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

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

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



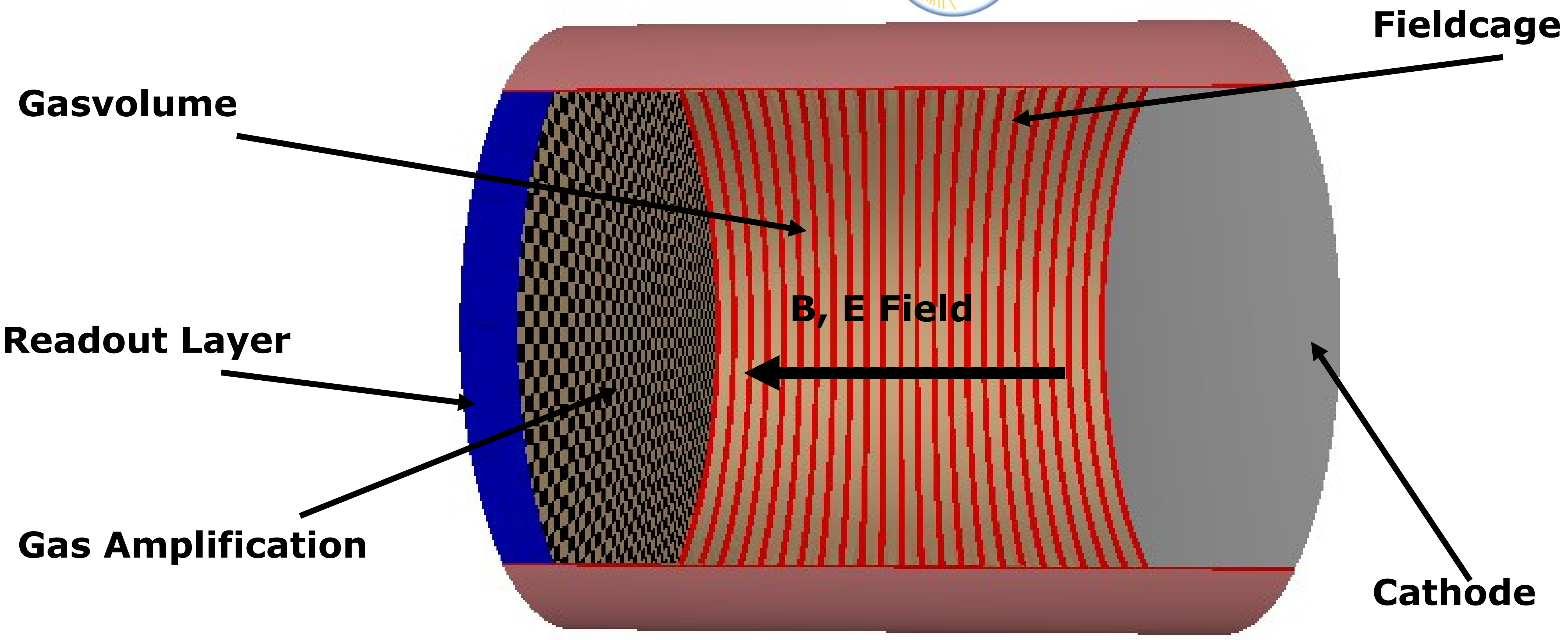


- the wire net created by the combination of + and – orientation generates a more uniform equipotential surface → better E-field isotropy and smaller ExB asymmetries)

- thin wires → increase the chamber granularity → reducing both multiple scattering and the overall tension on the endplates

Central Tracking – Gaseous Tracking - TPC

R&D for LC TPC is organised in LC TPC Collaboration



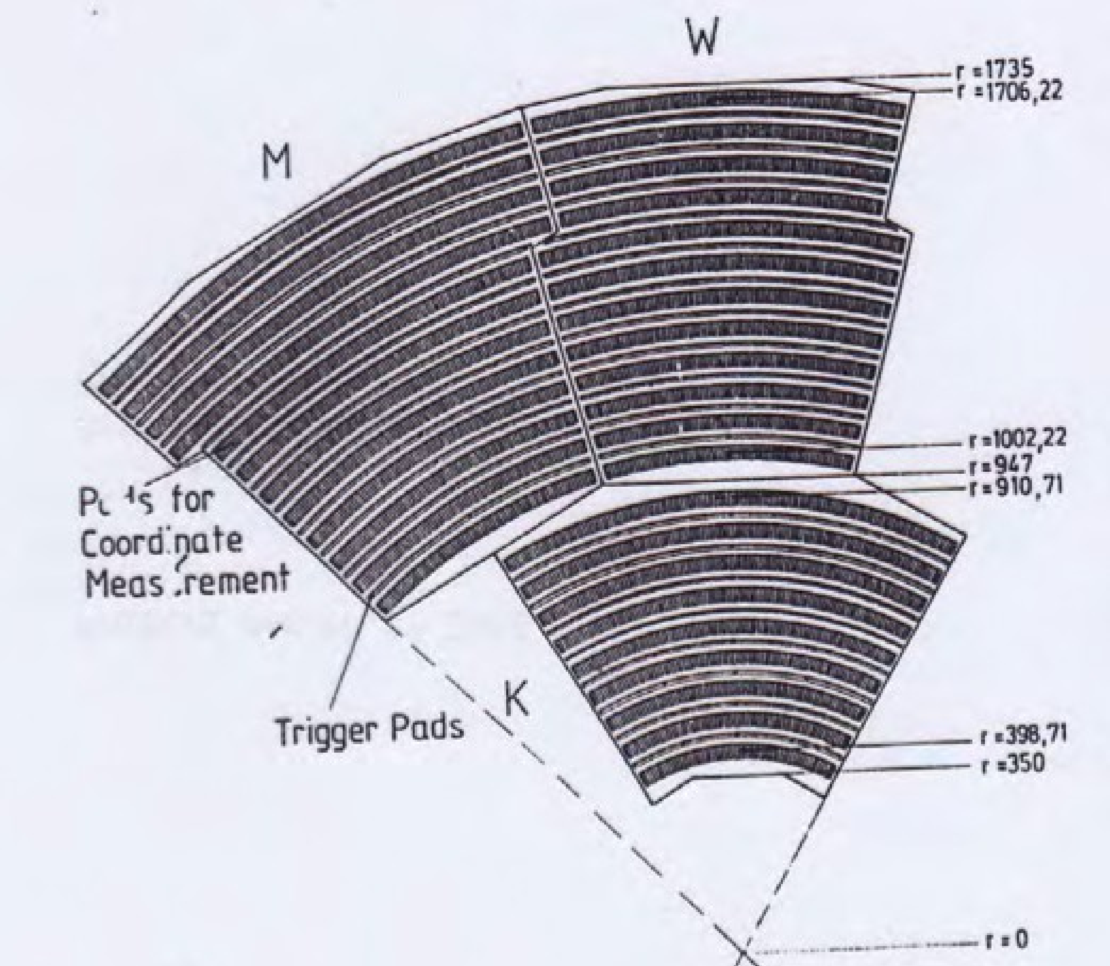
- Charged particle ionizes Gas
- Electron cloud drifts to Anode (Readout layer)
- Transversal diffusion is largely suppressed since E || B

z Coordinate: $z = v_d \cdot t_d$ (vd, td drift velocity and drifttime,respectively

- $r\phi$ Coordinate by segmented Readout layer

TPC – From ALEPH to ILD

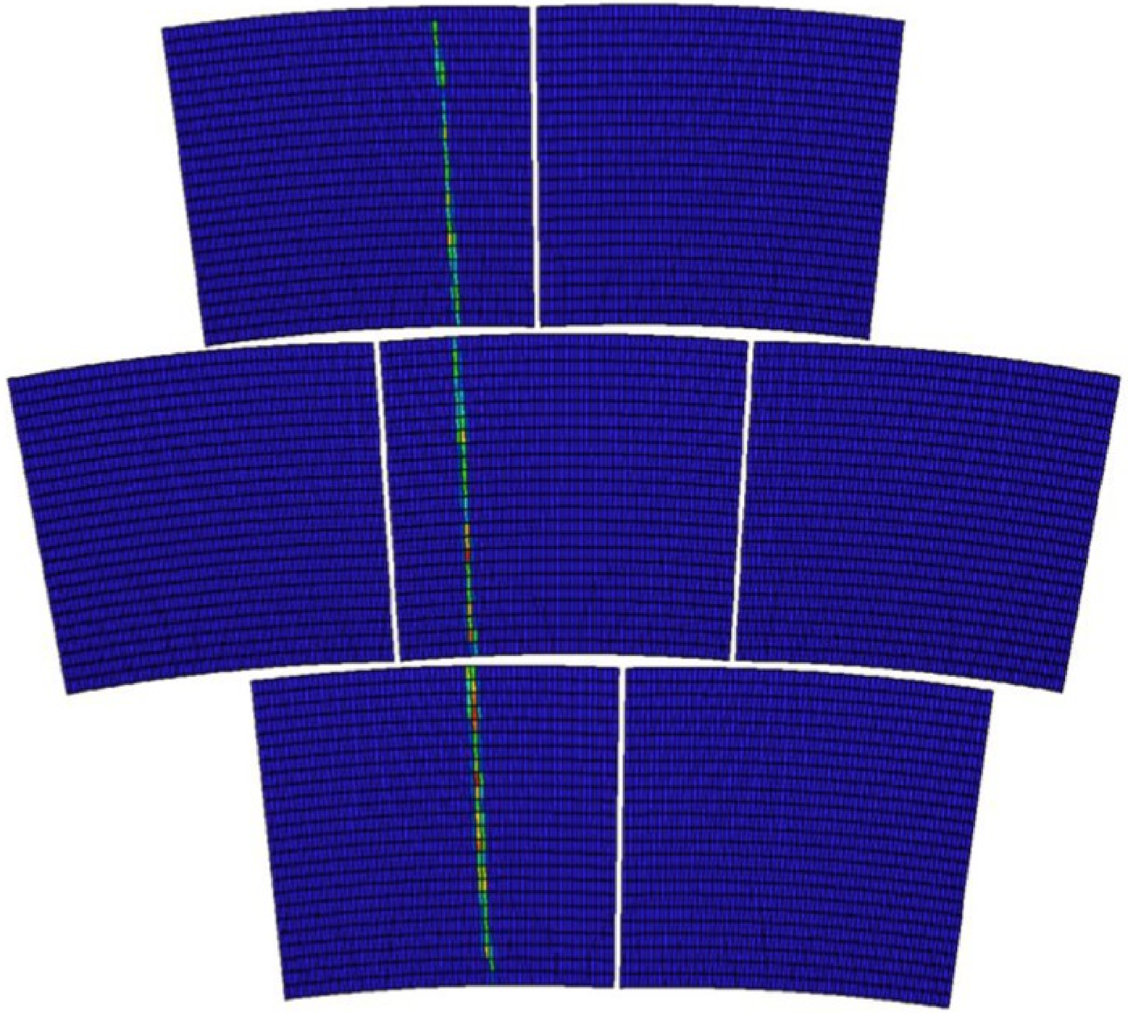
ALEPH (LEP Experiment)



Lecture Uni Freiburg

- 22 pad rows for 22 space points in rφ
- Typical pad pitch 6.2x30mm^2
- N.B.: Signal collection with help of 334 sense wires

ILD



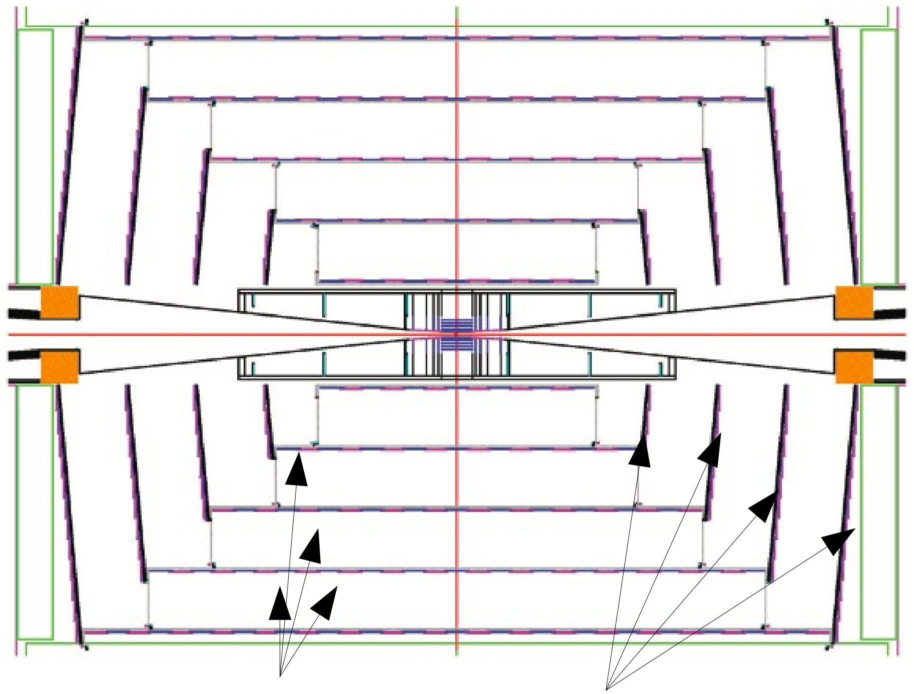
K. Fujii, TYL Meeting 2011

- 220 pad rows for 220 space points in rφ
- Typical pad size 1x6 mm^2 => O(10^6) Pads
- Readout with Micro Pattern Gas Detectors (MPGD)

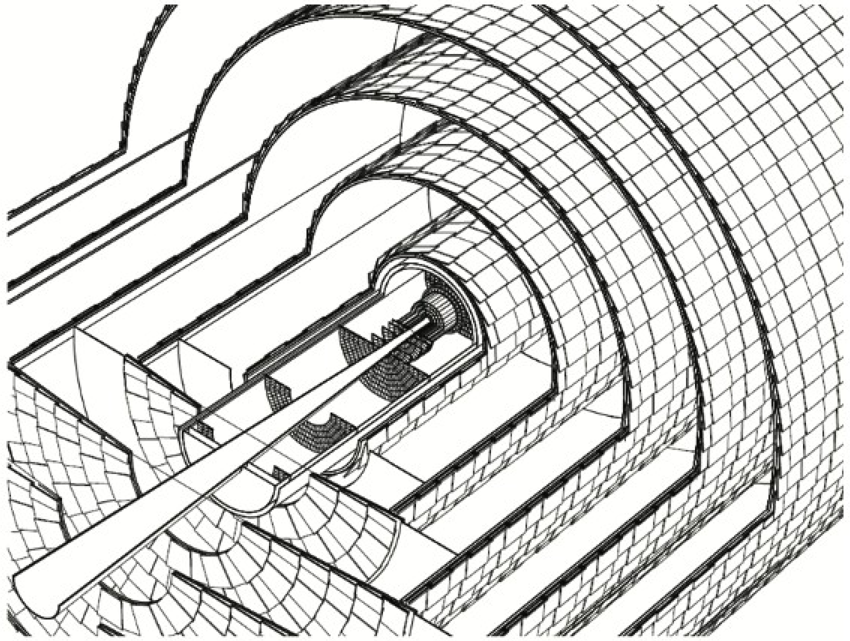
Central Tracking – All Silicon

SiD and CLICdp have chosen all silicon tracking for the central tracking

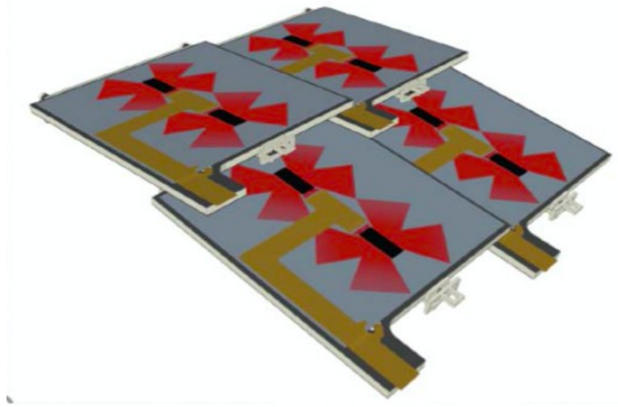
The concept is based on a few layers with excellent position resolution: Typically 5-10 μm



Barrel layers and forward disks



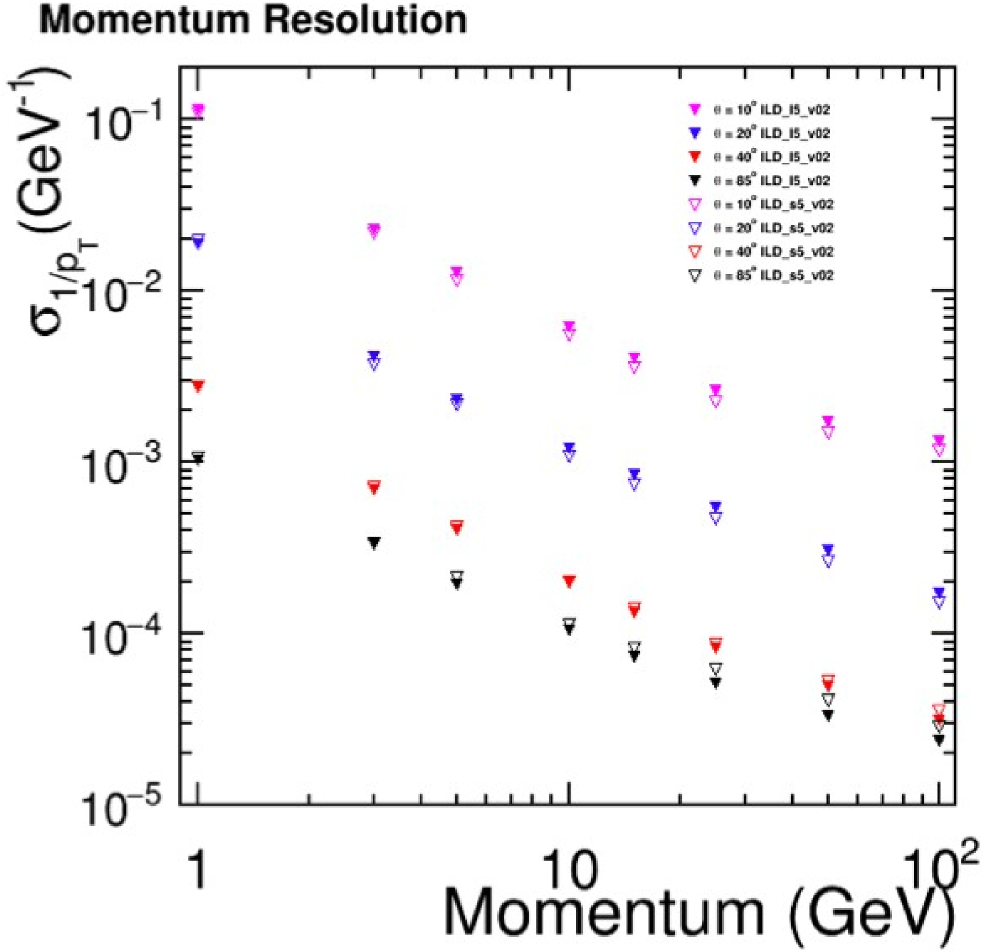
3D Cut view



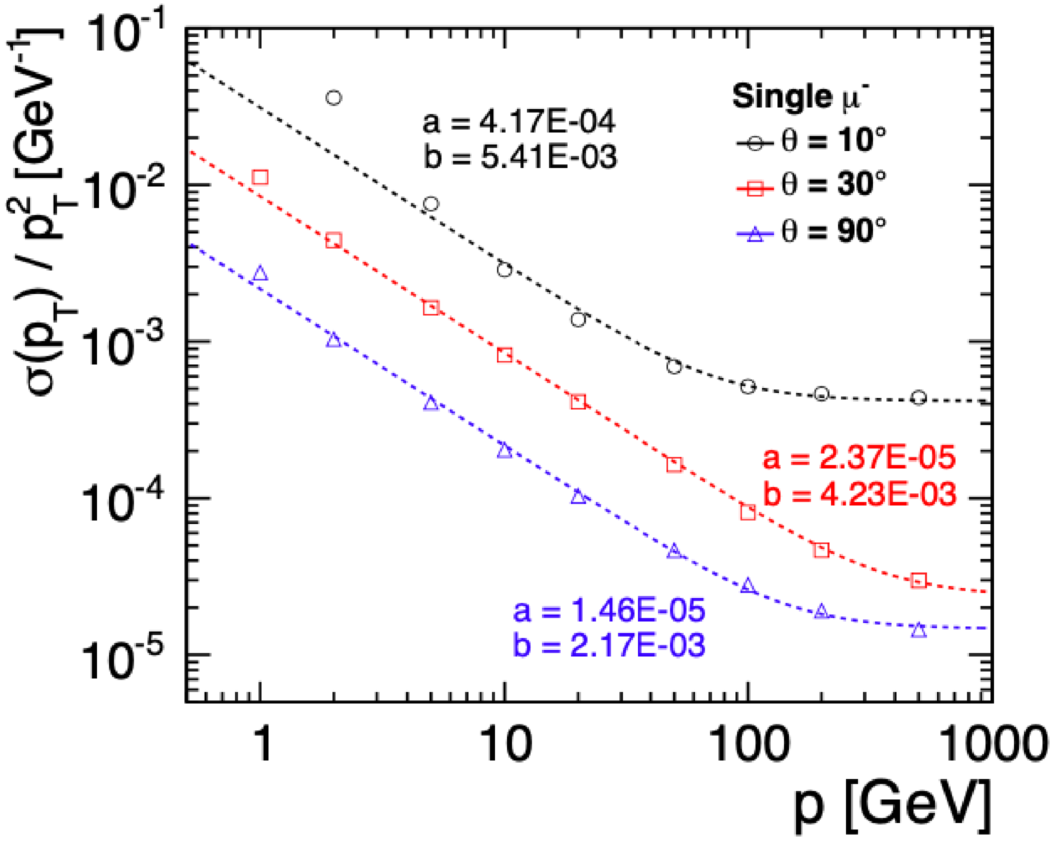
SiD: Sensor overlap allow for full coverage in R and φ

Track Momentum Resolution - Comparison

ILD with gaseous Tracking



SiD with "All Silicon Tracking"



Momentum resolution: $\sigma_{1/p_T} = \frac{\sigma_{p_T}}{p_T^2} = a \oplus b/p_T$

Both approaches achieve desired asymptotic momentum resolution a = 2×10^{-5} GeV^{-1}

A TPC at FCCee?

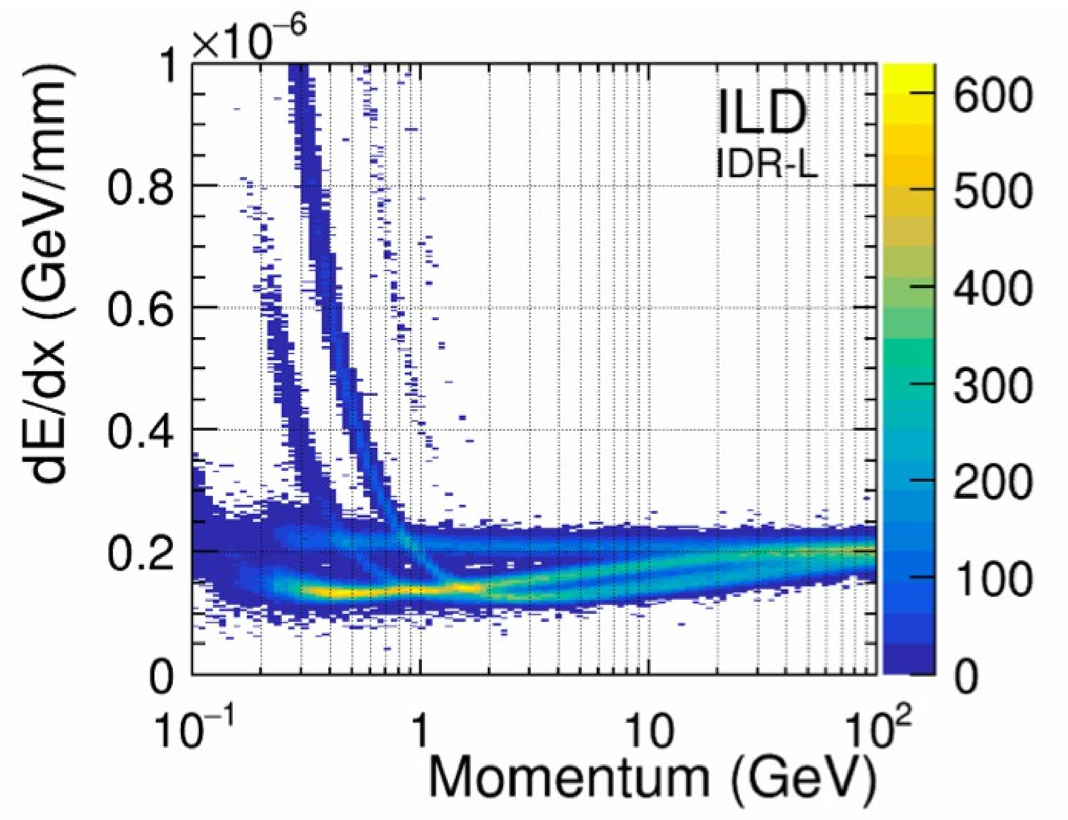
- Count number of primary ions (that stay in TPC for long time, ~0.44s)
- Main source of background: Beamstrahlung many low energy e+e- pairs due to quadropole moment of beam => focusing effect
- Per bunch crossing more for more (more focusses) Linear Collider, here ILC
- Accumulation due to high repetition frequency at circular colliders

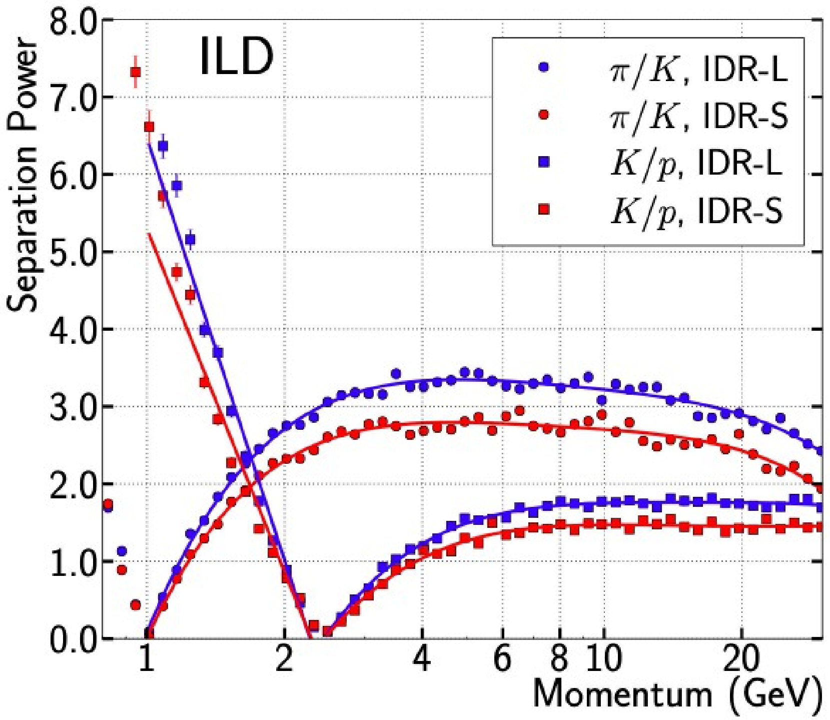
			FCCee-91	FCCee-240	ILC-250
model	B-field	MDI	thousand ions / bunch crossing		
ILD_l5_v02	3.5 (uniform)	ILC	6.5	14	960
ILD_l5_v02_2T	2.0 (uniform)	ILC	6.9	15	4700
ILD_l5_v03	3.5 (map)	ILC	5.7	14	1100
ILD_l5_v05	3.5 (map, anti-DID)	ILC	0.6	3.7	450
ILD_l5_v11	2.0 (uniform)	FCCee	390	1000	110000

- MDI for FCC increase background significantly compared to MDI for ILC

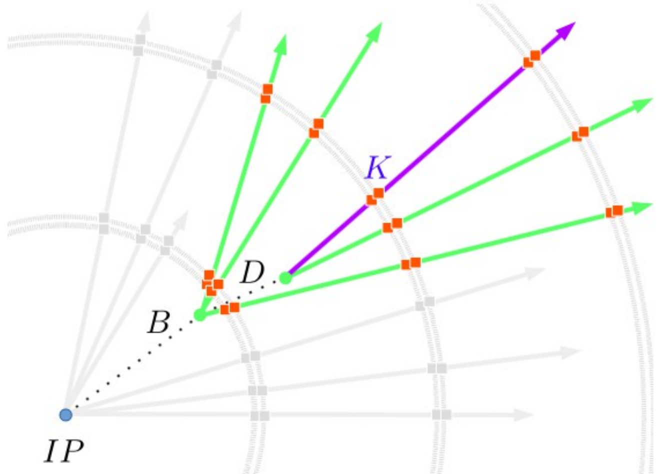
Daniel Jeans
Preliminary results

Gaseous Tracking – dE/dx in ILD





- Up to 220 points for dE/dx in ILD
- ILD targets resolution of at least 5% on dE/dx,
- Fine pixels avoid ambiguities
  - => most of the time all 220 Hits are available
  - Big difference to e.e. ALEPH
- Test beam results are encouraging



Applications of dE/dx:

- Kaon identification in ee->tt, ee->bb, ee->cc, ee->ss
  - •Supplementary to vertex charge measurement for heavy quarks
    - •Increases statistics by a factor of two
  - •Backbone of ee->ss
- Separation of W->ud and W->cs

- Separation power pi/K 2-3 sigma at momenta above 2 GeV
  - Degradation towards higher momenta

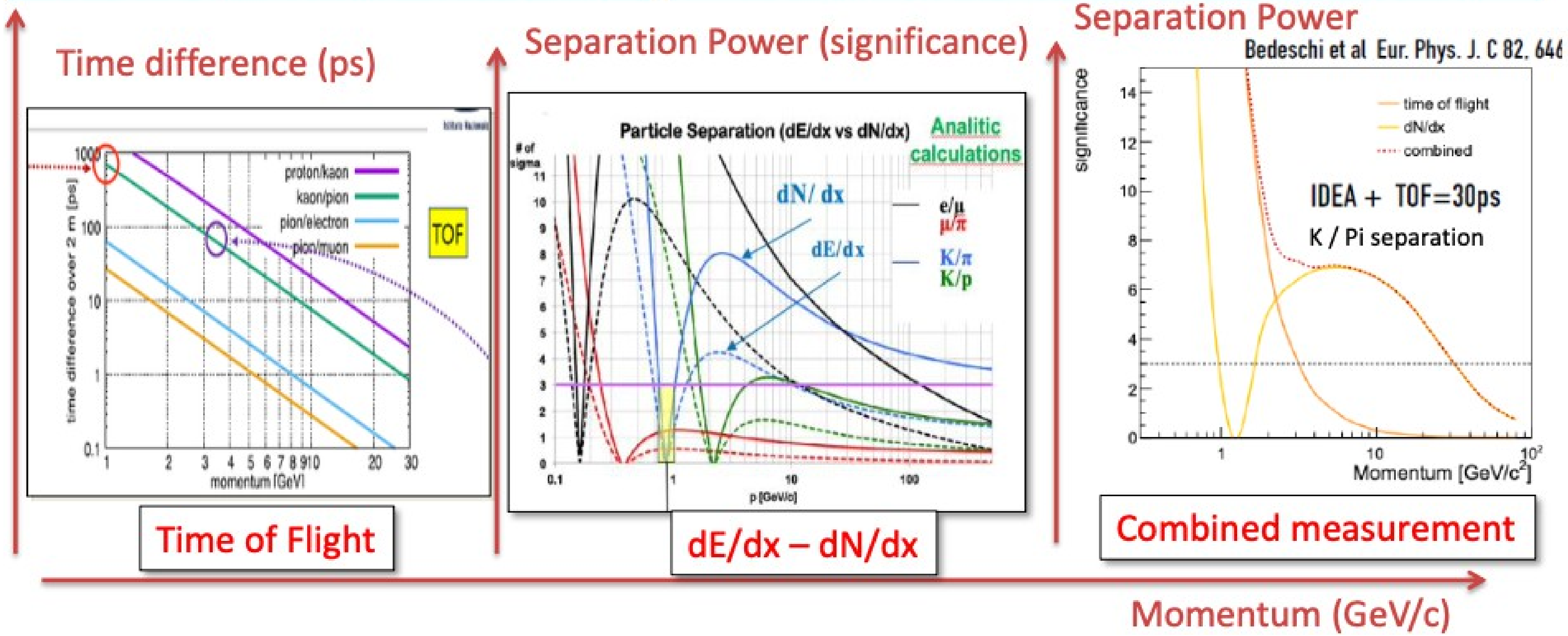
Gaseous Tracking – dE/dx → dN/dx and timing

Particle ID and time resolution DRD4 & 1/3

More details here: https://indico.cern.ch/event/1202105/contributions/5402790/attachments/2662086/4612032/FCC-DRD4.pdf

- Goal:
  - ✓ K/π, π/e⁻ separation, etc. ⇨ Interest to push beyond 10 ps resolution
  - ✓ Even more important for the physics program @ Z peak

Fast timing (<100 ps) Solid state (pixelated) detector (DRD3)	dE/dx + dN/dx Mainly gazeous detector, e.g. TPC, DC, RICH (DRD1)

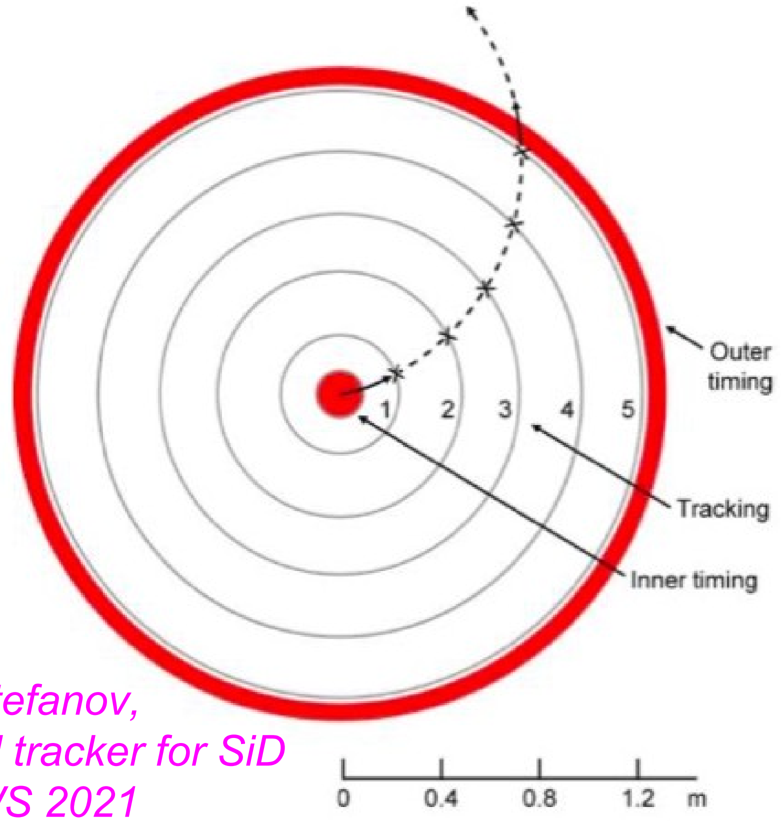


A. Besson
4th French FCC Meeting

In absence of gaseous tracking

Two options (not mutually exclusive)

ToF System



K. Stefanov,
Pixel tracker for SiD
LCWS 2021

(With two closed eyes)
ToF systems might work
up to 10 GeV

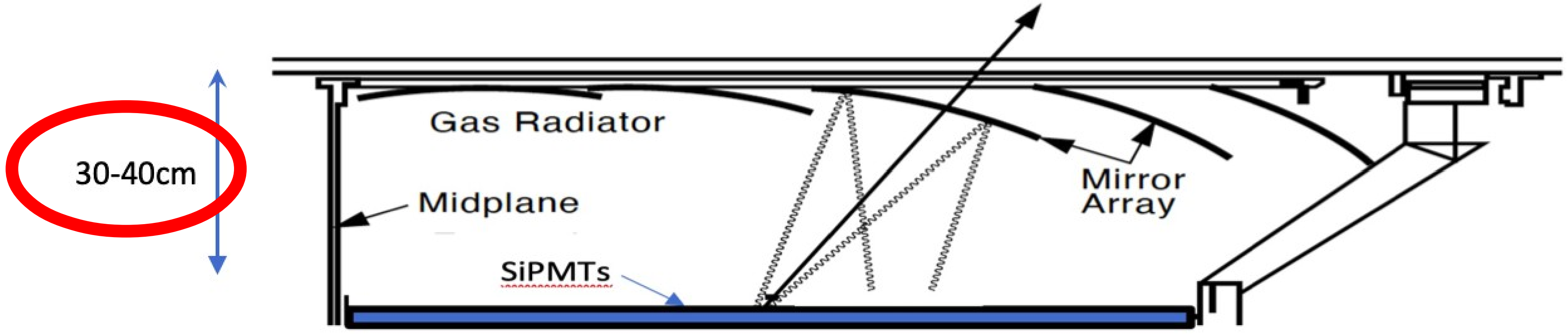
Cerenkov Detector

à la J. Vavra

Three options:

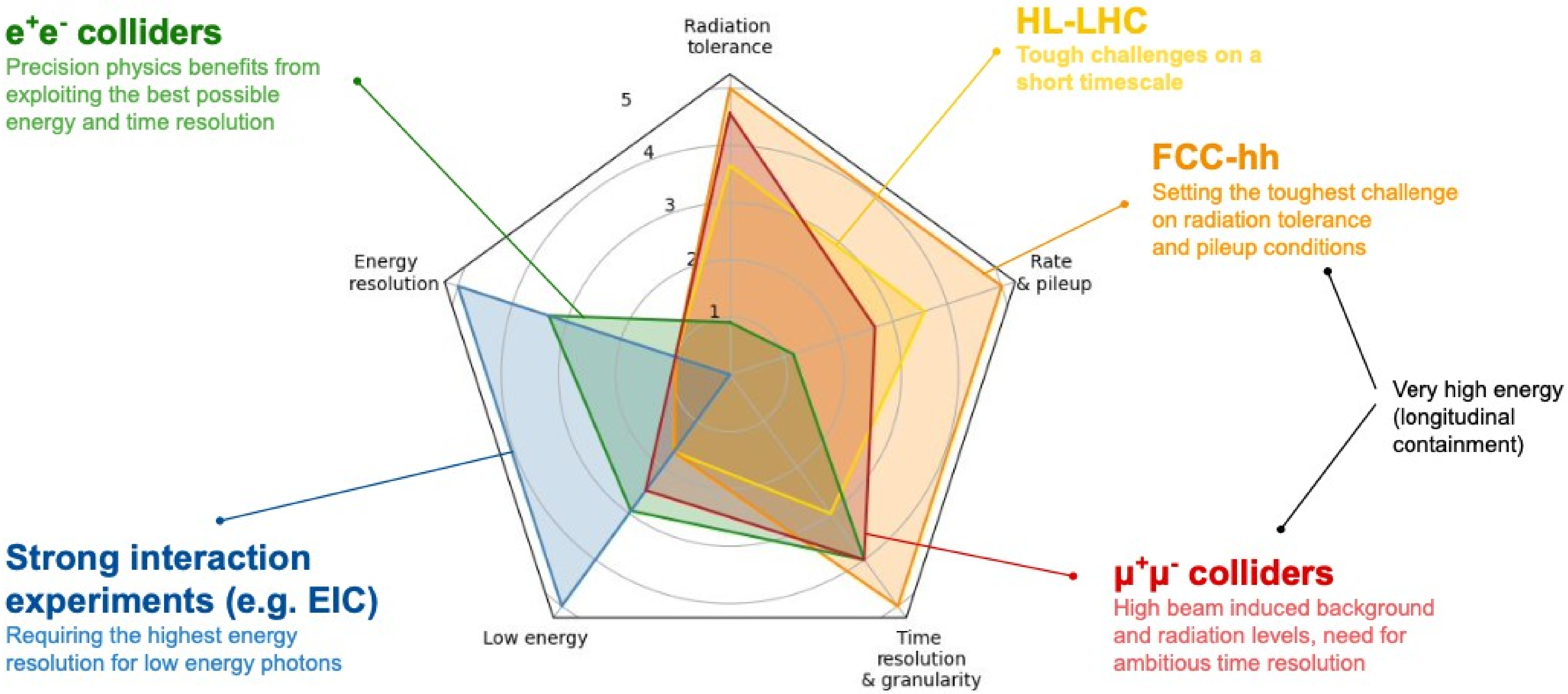
- DIRC: 6- 7 GeV/c
- Focusing Aerogel RICH: 9-10 GeV/c
- Gaseous RICH: 10-30 GeV/c

Gaseous RICH looked at for SiD:



- ToF and Cherenkov are options for PiD systems
- Cherenkov most likely needed to go to high momenta
- Both lead to ” compressed tracking systems
- New ideas to minimise this compression might be needed
- ... and material is added in front of the calorimeter

Requirements for calorimetry at future colliders



Inspired from https://indico.cern.ch/event/994685/

M. T. Lucchini, 1^{st} Calo Community Meeting

Calorimetry - General guidance of R&D

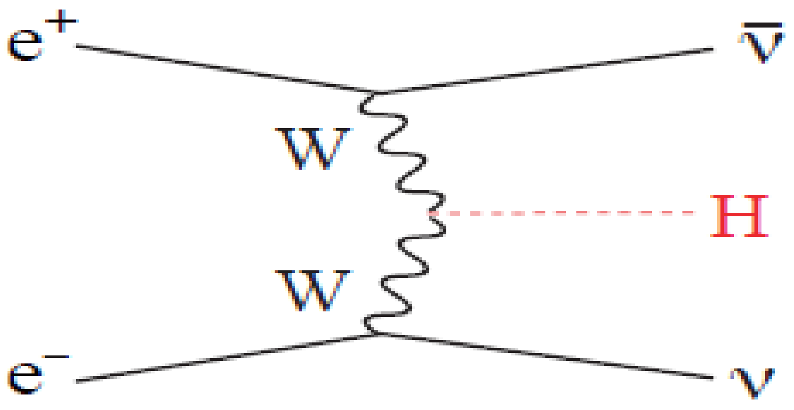
- Calorimeters in no longer a detector to measure only Energy (1D)
- High granularity is recurrent topic in all the proposals (+ 3D)
  - 2D-segmentation
  - 3rd dimensions achieved either by physical segmentation or by timing information
- Timing is also additional “dimension” of the calorimeter (+1D)
  - pile-up rejection (μ-collider, FCC-hh, ...)
  - better track/particle matching
  - **tens of ps** is the current paradigm for timing application

G. Gaudio
2nd Calorimeter Community Meeting

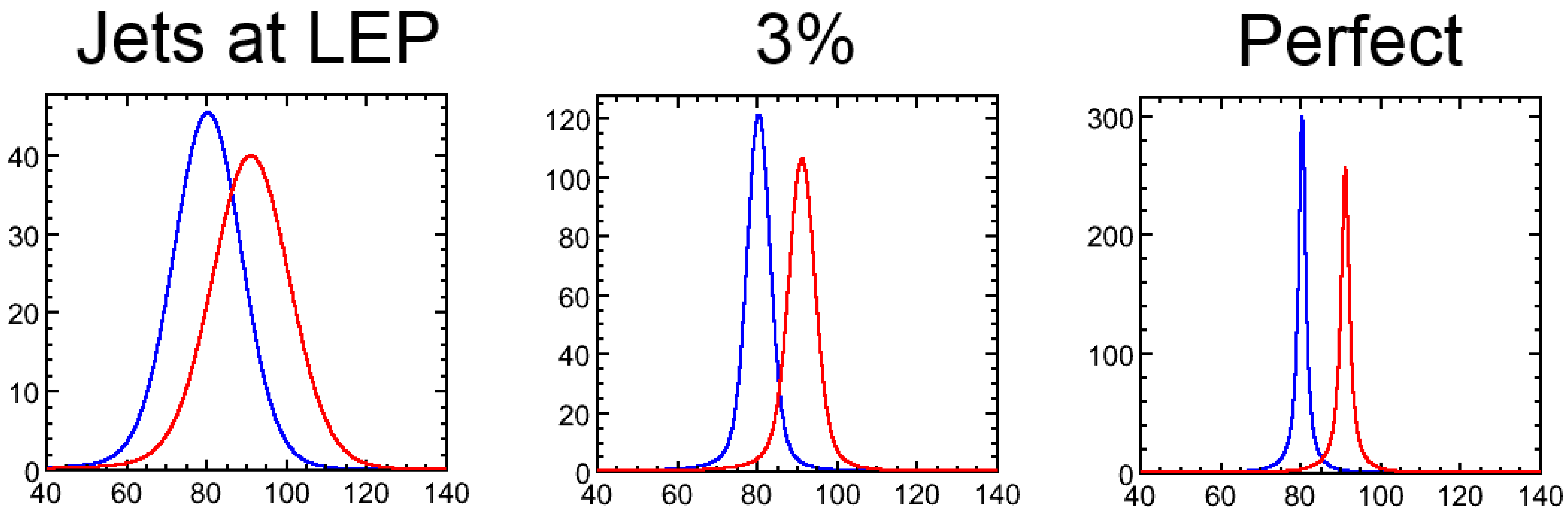
Granular calorimeters – Use case

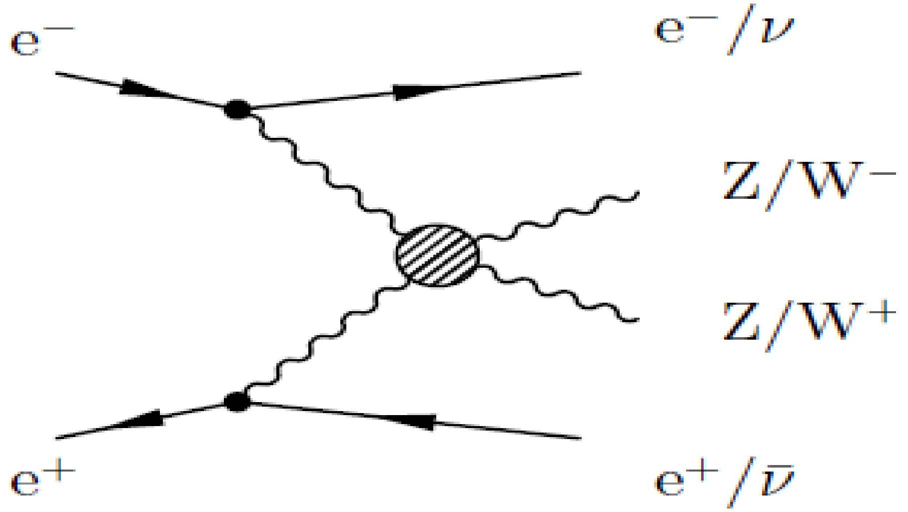
Examples:

W Fusion with final state neutrinos requires reconstruction of H decays into jets



Jet energy resolution of ~3% for aclean W/Z separation



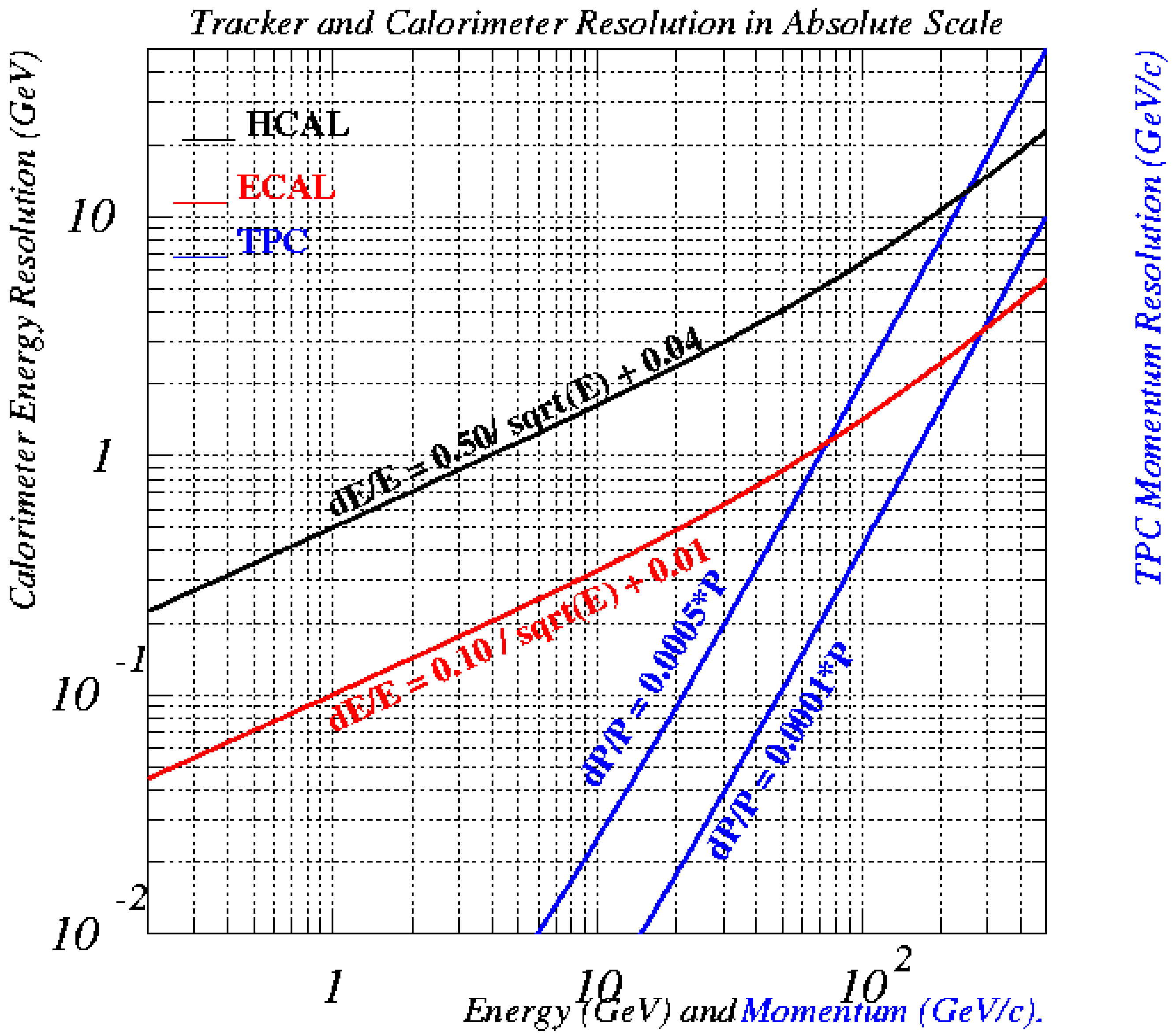


M. Thomson

Slide: F. Richard at International Linear Collider – A worldwide event

Jet energy resolution

Final state contains high energetic jets from e.g. Z,W decays
Need to reconstruct the jet energy to the utmost precision !
Goal is around dE_{jet}/E_{jet} - 3-4% (e.g. 2x better than ALEPH)



Jet energy carried by …

- Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$): 65%
  Most precise measurement by Tracker
  Up to 100 GeV
- Photons: 25%
  Measurement by Electromagnetic
  Calorimeter (ECAL)
- Neutral Hadrons: 10%
  Measurement by Hadronic
  Calorimeter (HCAL) and ECAL

$$\boxed{\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}}$$

Jet energy resolution – Different approaches

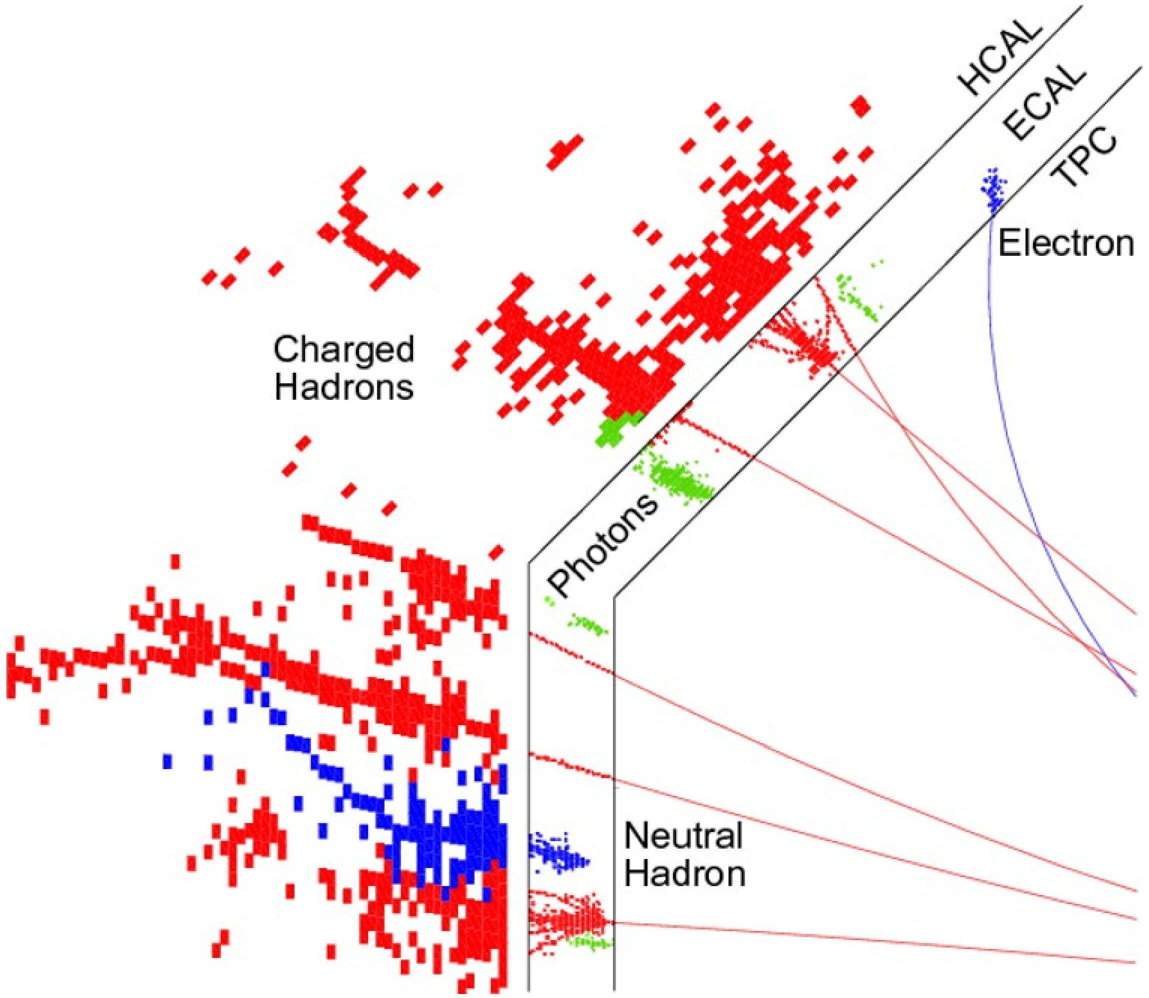
High pixelisation to exploit tracking as much as possible

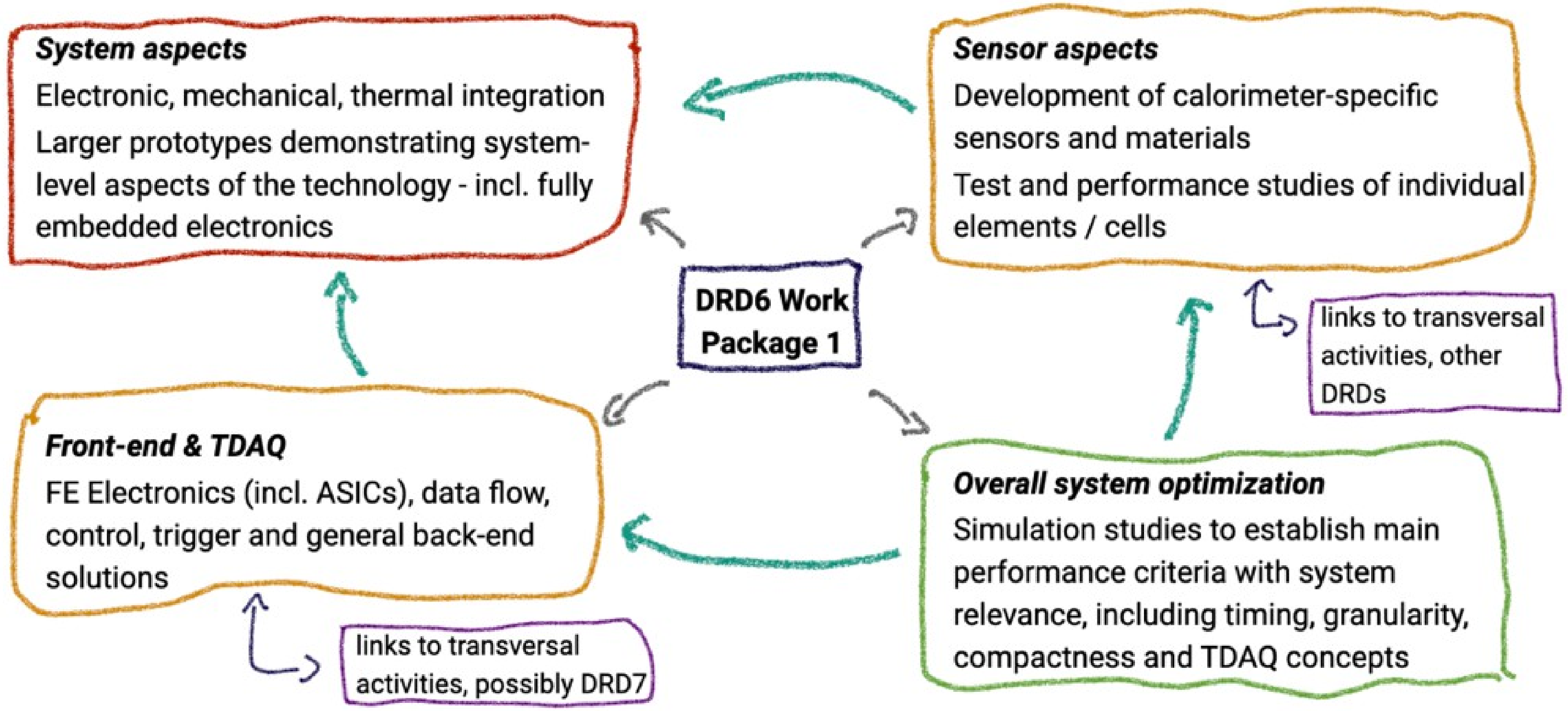
$$\boxed{\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}}$$

Optimise for hadronic energy resolution

Optimise for electromagnetic energy resolution

Imaging calorimeters



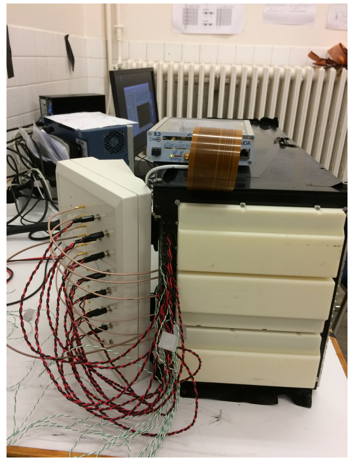


Imaging calorimeters live on the high separation power for Particle Flow

- Challenges:
  - High pixelisation, 4pi hermetic -> little room for services
    - Detector integration plays a crucial role
- New strategic R&D issues
  - Detector module integration
  - Timing
  - High rate e+e- collider (such as FCCee)

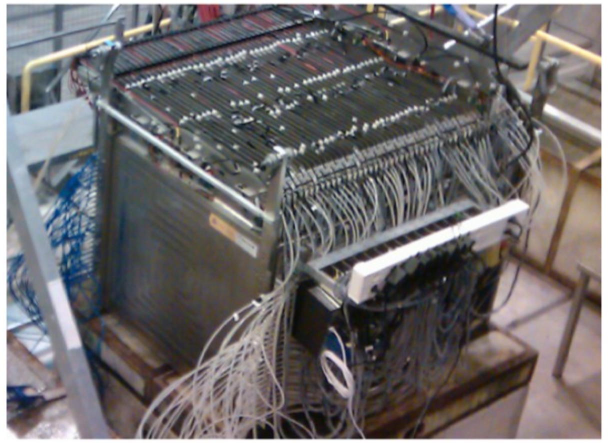
CALICE (Technological) Prototypes

ScECAL



SiECAL

AHCAL



SDHCAL

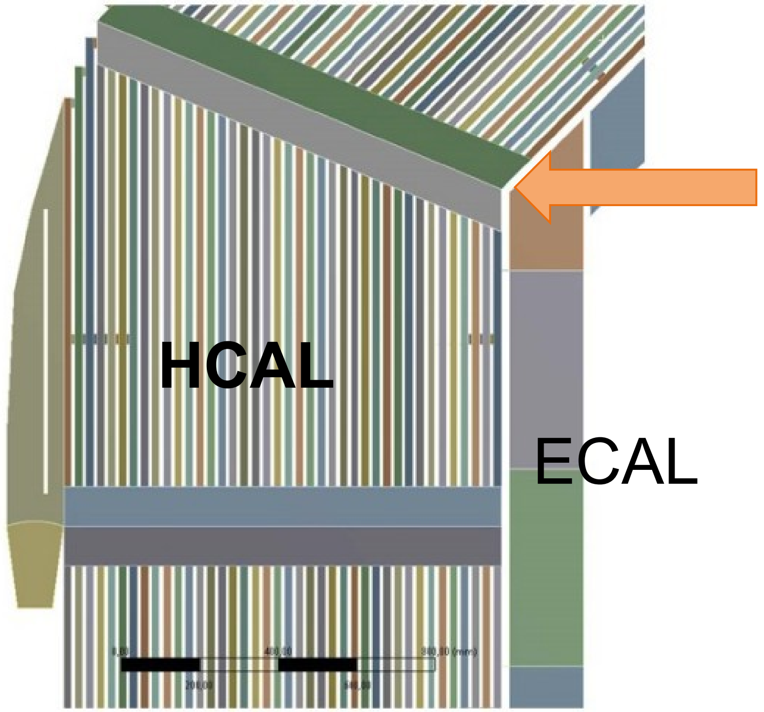
Name	Sensitive Material	Absorber Material	Resolution	Pixel size/mm^3	~Layer size**/cm^3	~Layer depth/X_0	~Layer depth/λ_I	# of Pixels/ layer	# of layers	Comment
ScECAL	Scintillator	W-Cu Alloy	Analogue, 12bit	5x45x2	23x22x0.5	0.73	0.03	210	32	2x16 x and y strips
SiECAL	Si	W	Analogue, 12bit	5.5x5.5x 0.3 (0.5, 0.65)	18x18x 0.24 (- 0.63)	0.6-1.6	0.02-0.06	1024	≥22	Can be run in different configs.
AHCAL	Scintillator	Fe*/W	Analogue, 12bit	30x30x3	72x72x2/ 1.4	1/2.9	0.11	576	38	Running with Fe and W
SDHCAL	Gas	Fe*	Semi-digital 2bit	10x10x6	100x100x 2.6	1.1	0.12	9216	48	

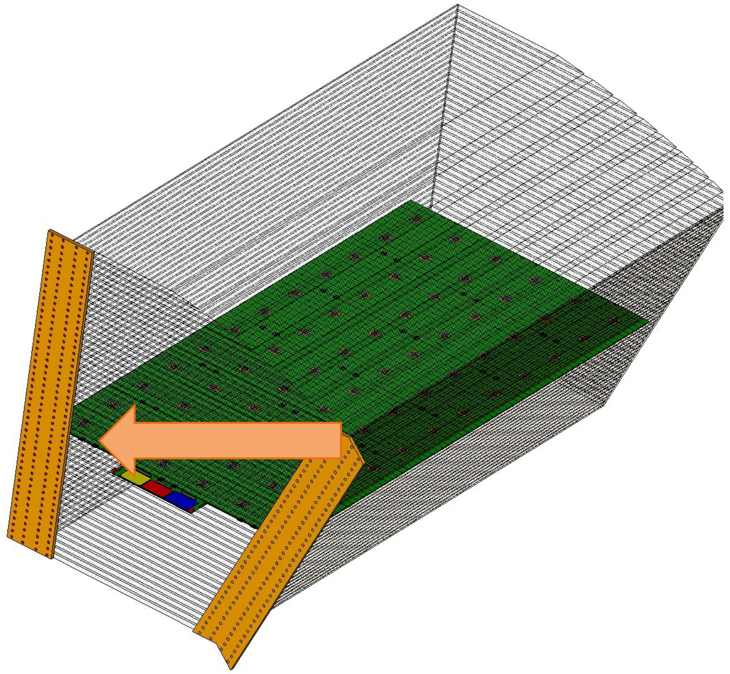
*Stainless Steel

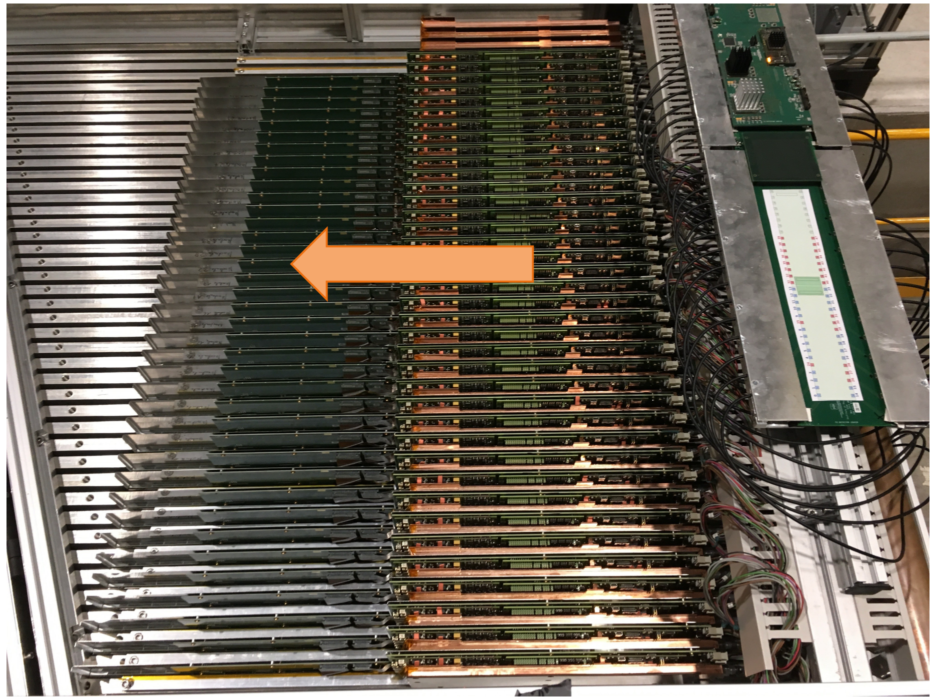
**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)

Space

- Successful application of PFA requires calorimeters to be inside the magnetic coil
- => Tight lateral and longitudinal space constraints
- Both for readout components and services (power, cooling)

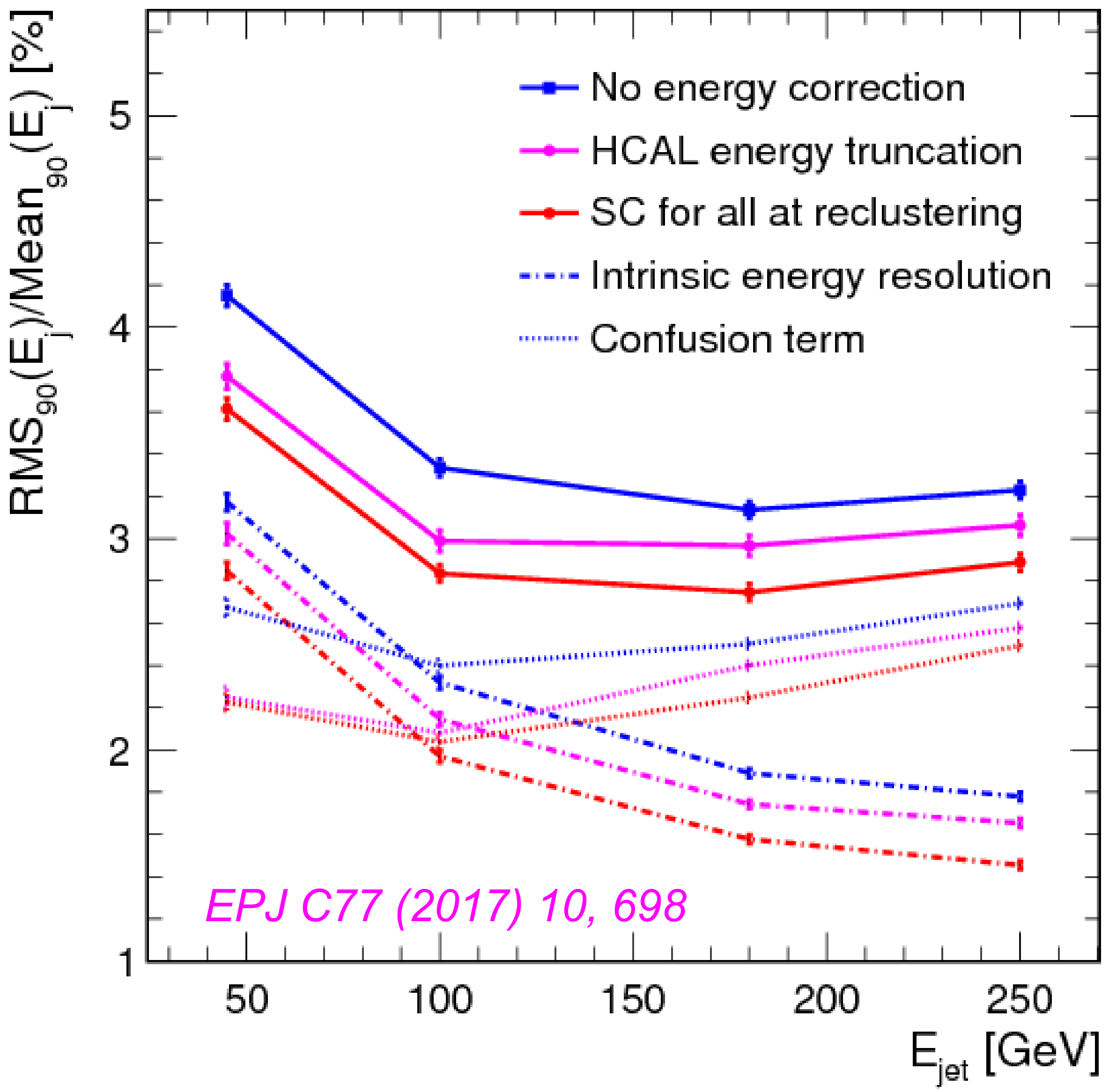






Jet energy resolution

Pandora PFA jet energy resolution



Study within ILD Concept

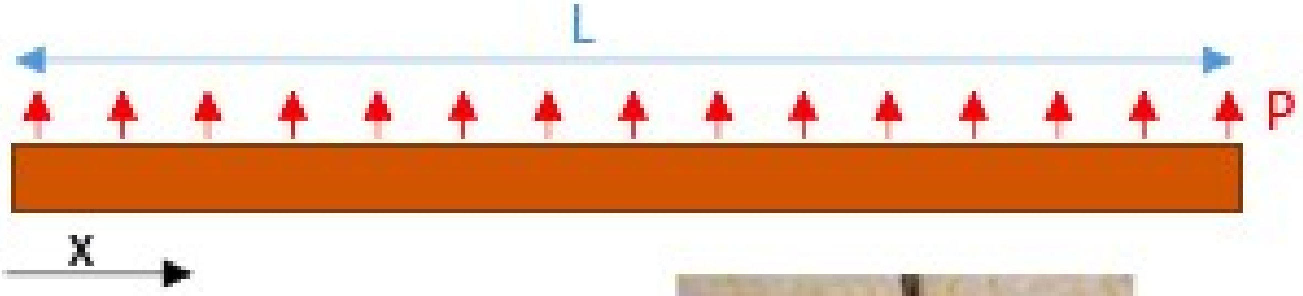
- Design goal: 30%/√E at 100 GeV
  - ~3-4% over entire jet energy range
- At lower energies < 100 GeV resolution is dominated by intrinsic calorimeter resolution
- At higher energies have more particles and higher boost
  - Smaller distance between particles
  - More overlap between calorimeter showers
  - Pattern recognition becomes more challenging

  => Confusion
- Note particularly the gain by software compensation
  - i.e. exploiting the wealth of information available through high granularity

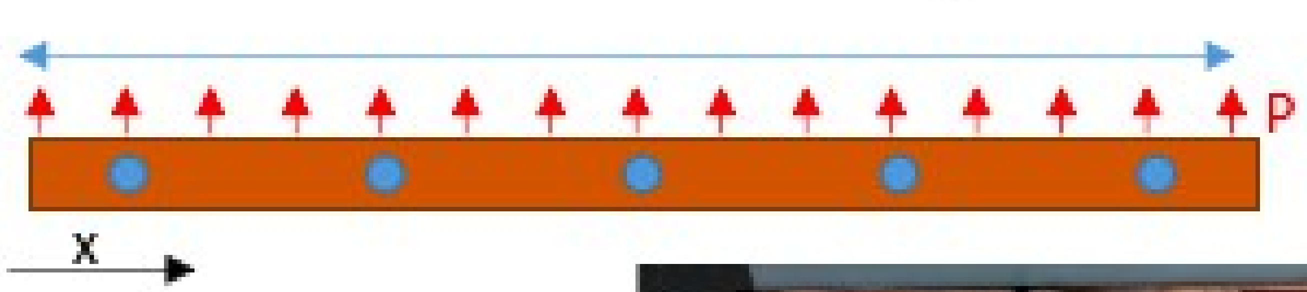
PFAs ARBOR and APRIL are alternatives with similar performance

Active cooling?

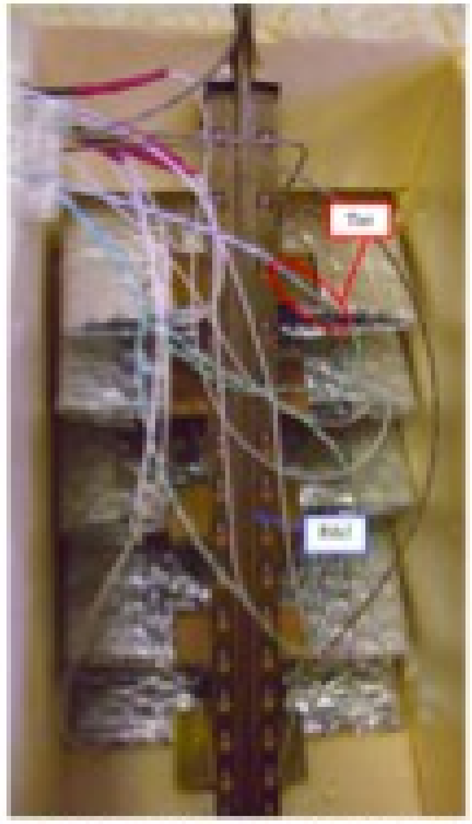
Passive cooling



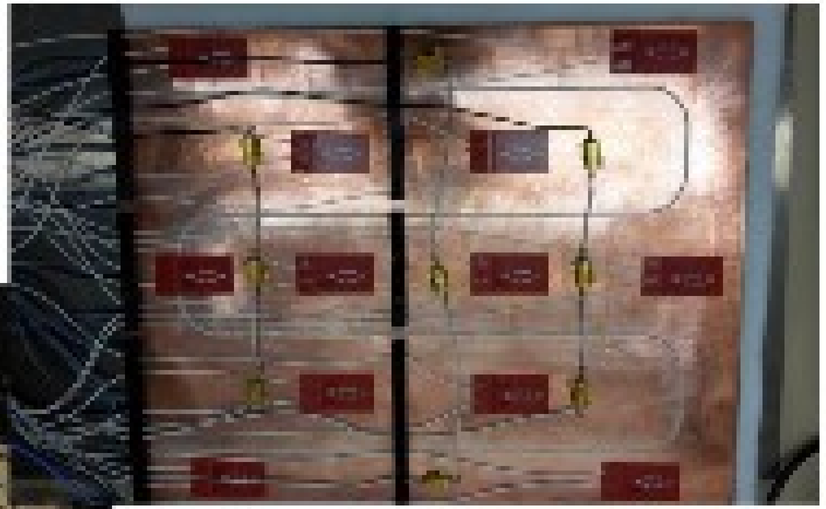
Active cooling



Passive cooling ramp example



Passive cooling ramp set up test



Active cooling test layout (400mm x 300mm x 3mm thick copper plate with 1,8OD pipes embedded)

Active cooling set up test with water at room temperature

Future Noble Gas Calorimeters

- LAr Calorimetry is proven technology since a few decades ATLAS, H1, DO, NA31

- Challenge is to make the technology “fit” for future hadron and lepton machines

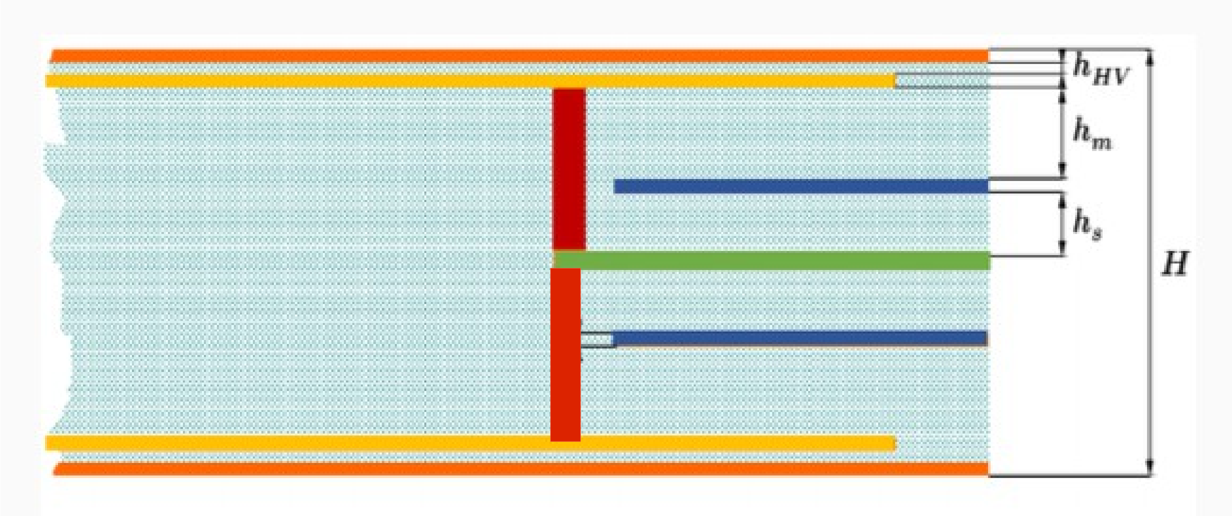
- Design is driven by particle flow
  - ATLAS Jet-Energy resolution based on PFA
  - ~24% at 20 GeV and 6% at 300 GeV

- => Increase of granularity
  - Goal: Factor ~10 w.r.t. ATLAS LAr Calorimeter
  - 220 kCells -> ~2 MCells

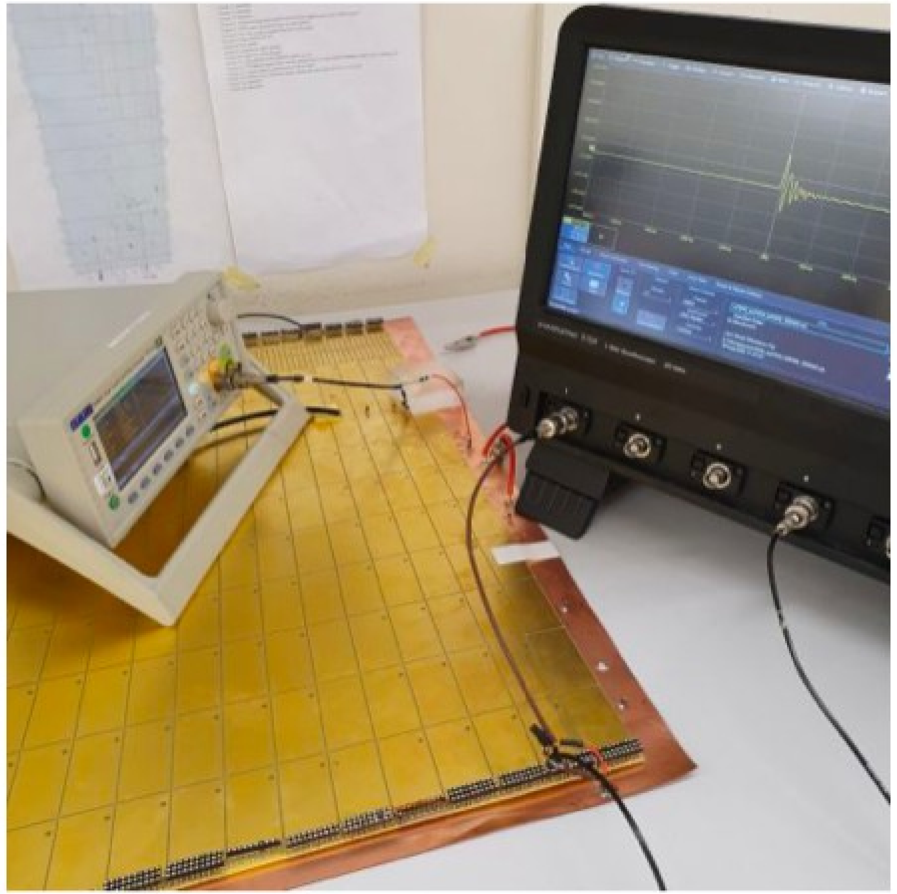
ATLAS LAr calorimeter

Future Noble Gas Calorimeters – How to increase the granularity

- Development of a multilayer PCB
  - HV Layer on both sides
  - Readout layer on both sides
  - Connected to signal trace



- One signal trace is economical solution to reduce signal traces
- Pick-up of signal from both sides increases S/N



Challenges:

- Control number of signal traces
- Big number of capacitanes => Noise
  - Goal is 300 keV Noise for 200 pF cell (S/N > 5)
  - FCCee allows for higher integration times
  - Cold electronics?

Work Package 2 – Liquid Noble Gas Calorimeters

- Develop the calo design
  - Study design solutions for endcaps
  - Study general performance in simulation, in combination with some HCAL concept
  - Optimize granularity
- Build a first prototype and measure performance in testbeam
  - Need to design and optimize electrodes, absorbers
  - Readout electronics
  - Can then be refined to test further developments / new ideas

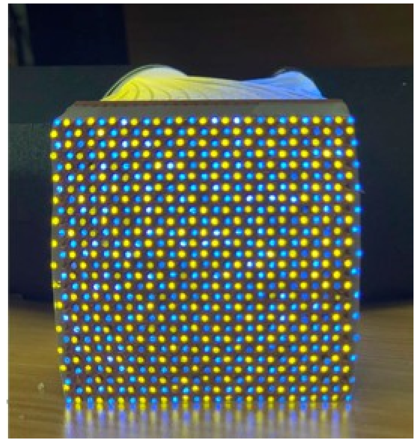
4 Work Areas

1. General design and expected performance
2. Readout electrodes
3. Readout electronics
4. Mechanical studies and prototype

Dual readout calorimetry – Building Blocks

Fast signals

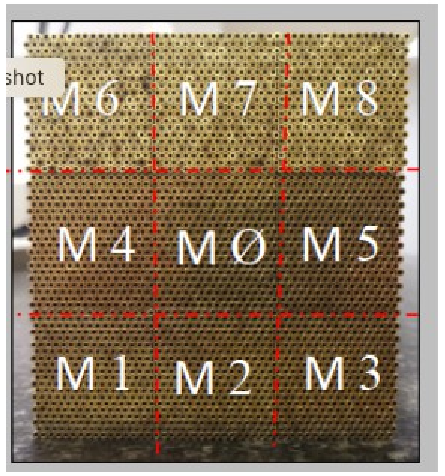
Slow signals



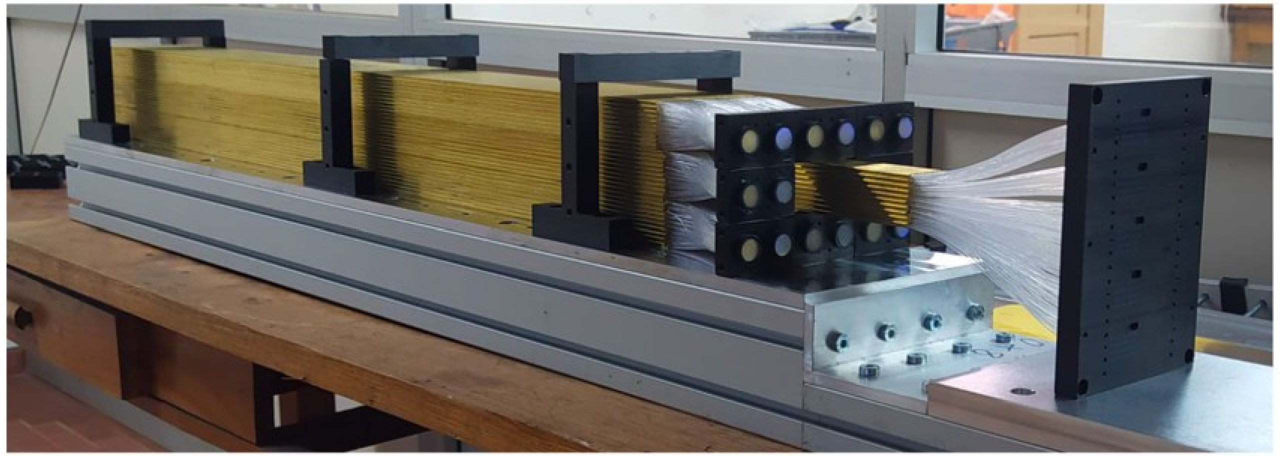
Dual readout to capture
Electromagnetic and hadronic
components of shower

Prototype development

- First step “electromagnetic prototype” 10x10x100cm^3
  - Qualification of
    - Assembly procedure
    - Readout systems

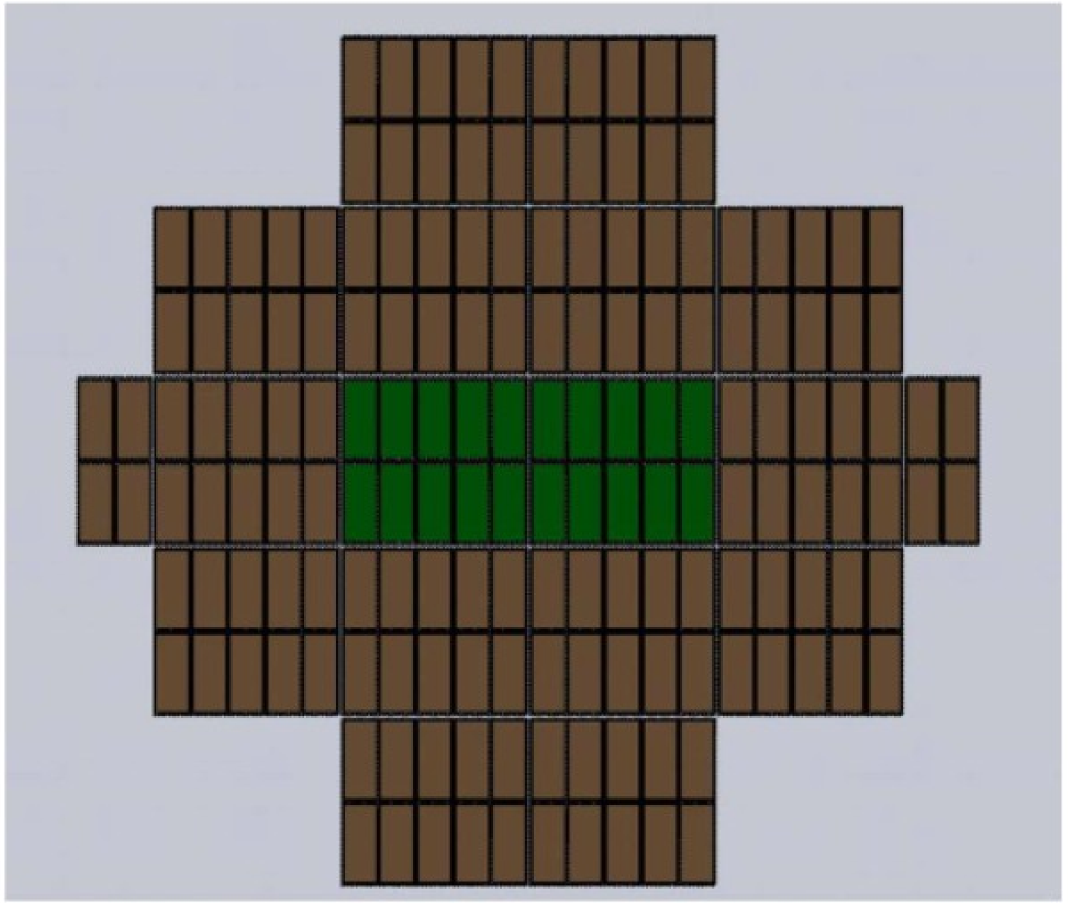


Stack of capillaries

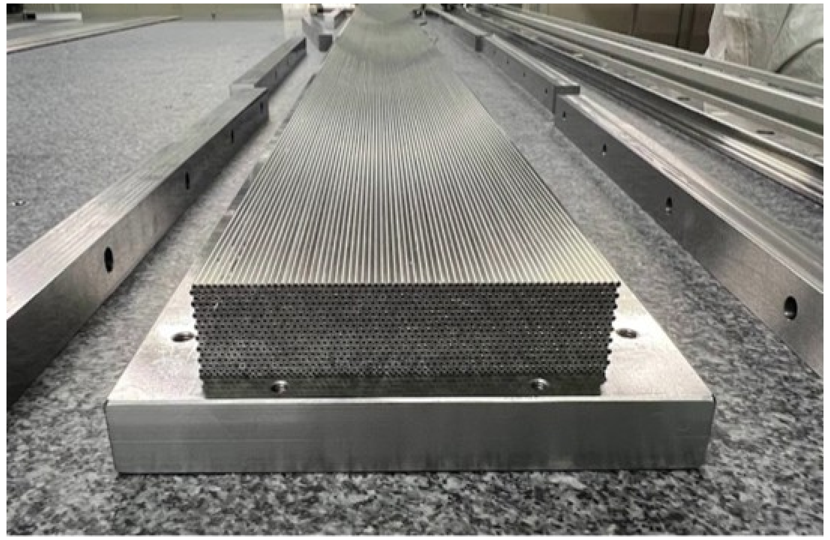


Outgoing fibres guided to readout plane

Prototype with hadronic containment

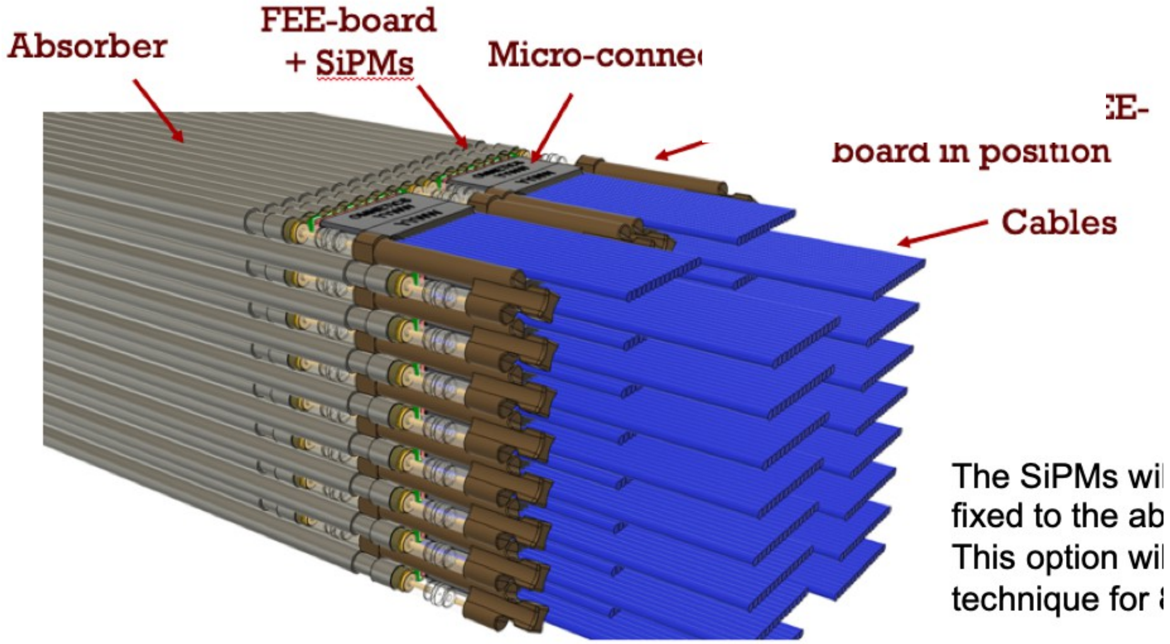


- 65x65x200 cm^3
- 17 modules in total
- 2 central modules equipped with SiPMs
- 15 modules equipped with PMTs



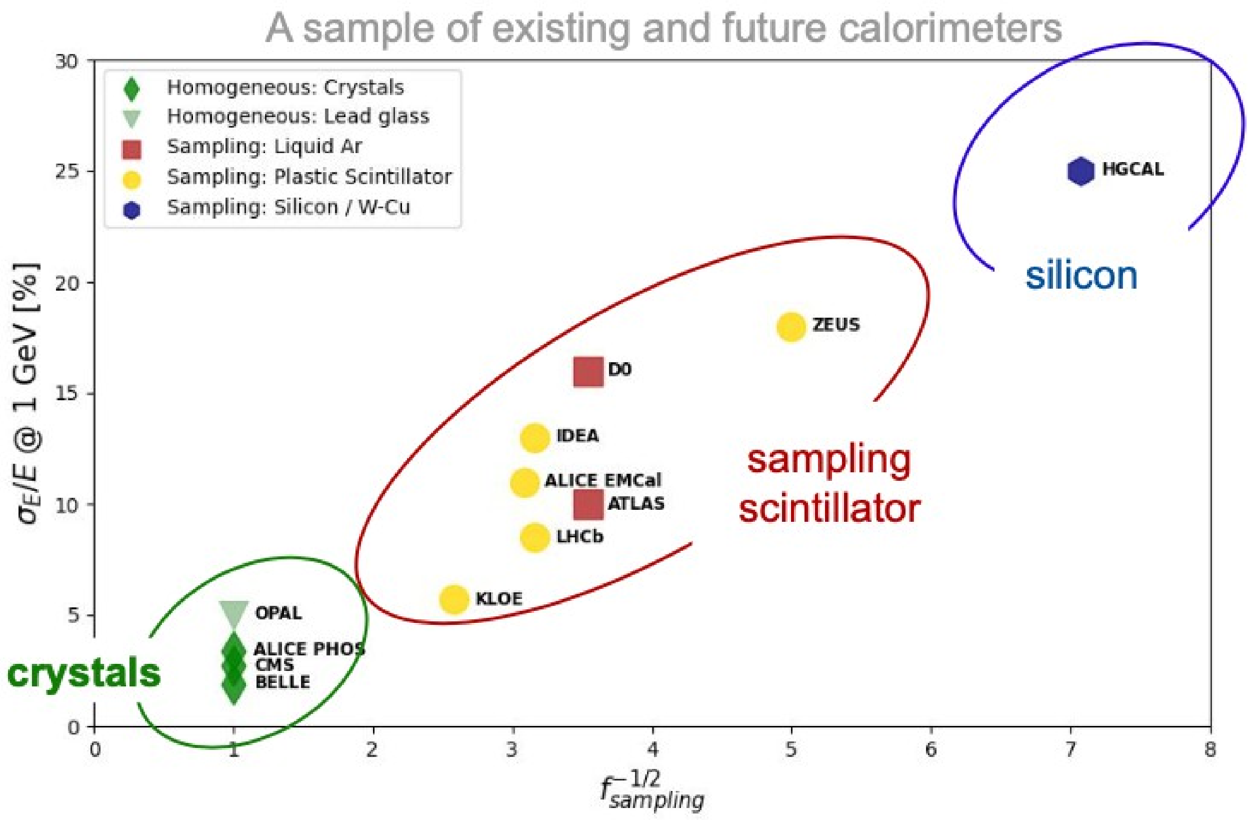
Under construction as we speak

Major challenge SiPM integration

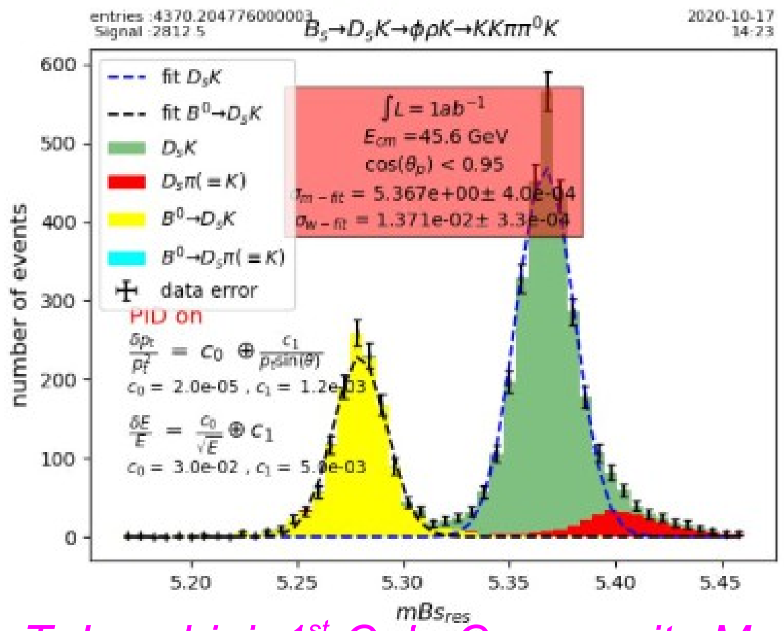


Sampling and Homogeneous Calorumeters

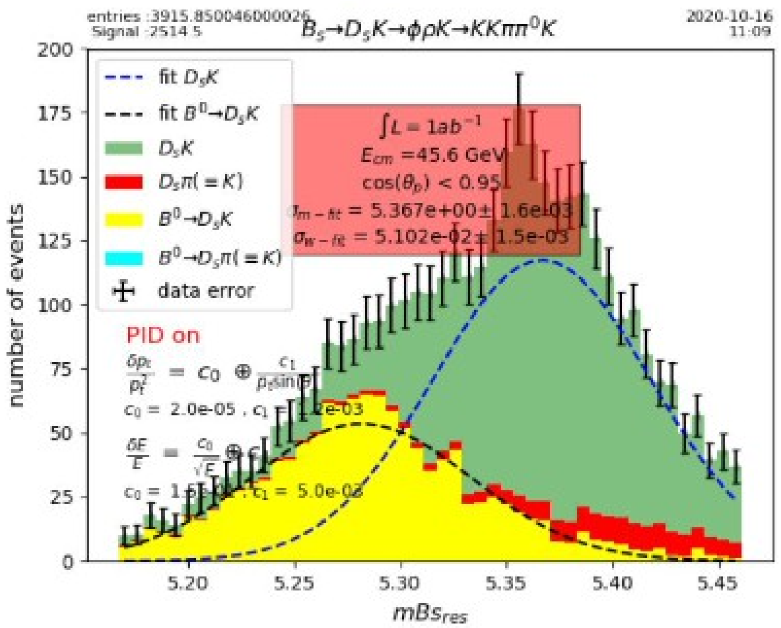
- Many proposals are based on sampling calorimeters
  - i.e. Separation of sensitive and absorber medium
- Sampling leads to limitations in elm. energy resolution 10-15%/√E
- (Most likely) homogeneous calorimeters remain the only way to get to energy resolutions of 1-5%/√E



3%/√E



15%/√E



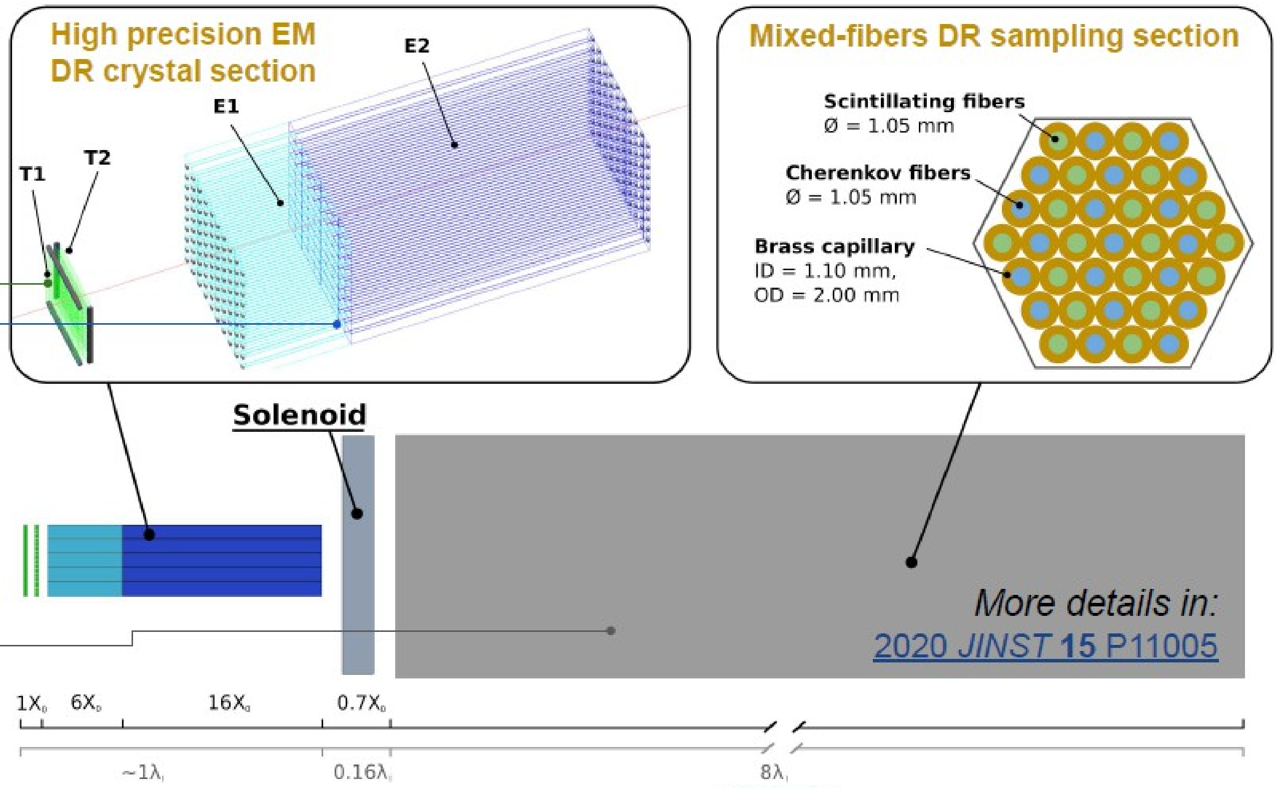
CP violation studies with B_s decay to final states with low energy photons

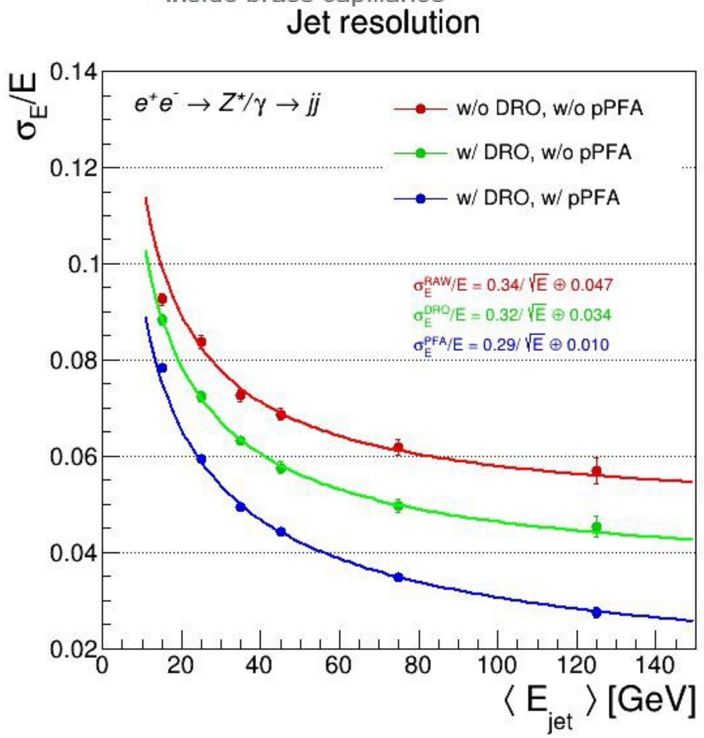
[R.Aleksan et al., *Study of CP violation in B± decays to D0(D0)K± at FCCee*, arXiv:2107.05311]

M. T. Lucchini, 1st Calo Community Meeting

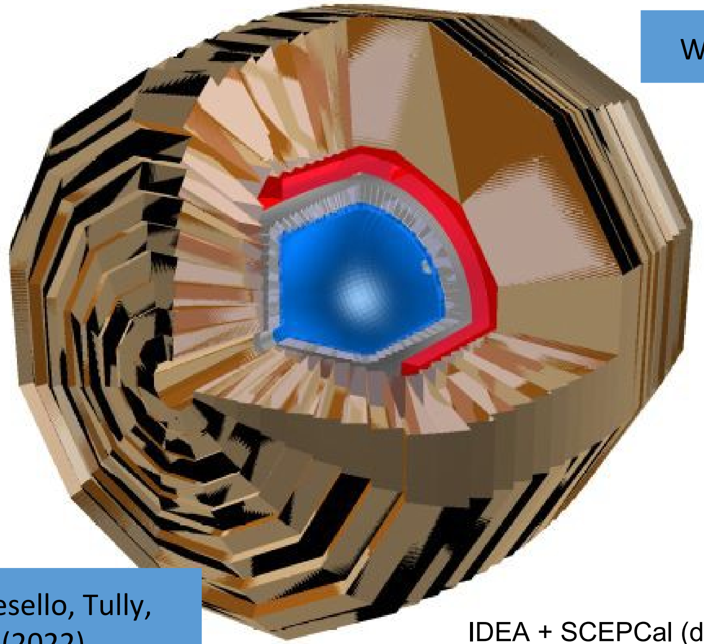
Combination crystal calo and DR Calo

- **Timing layers** — $\sigma_t \sim 20$ ps
    - LYSO:Ce crystals ($\sim 1X_0$)
    - 3x3x60 mm³ active cell
    - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
    - PWO crystals
    - Front segment ($\sim 6X_0$)
    - Rear segment ($\sim 16X_0$)
    - 10x10x200 mm³ crystal
    - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
    - $\sim 0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
    - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries





❖ Transition of simulation to key4hep in progress



W. Chung

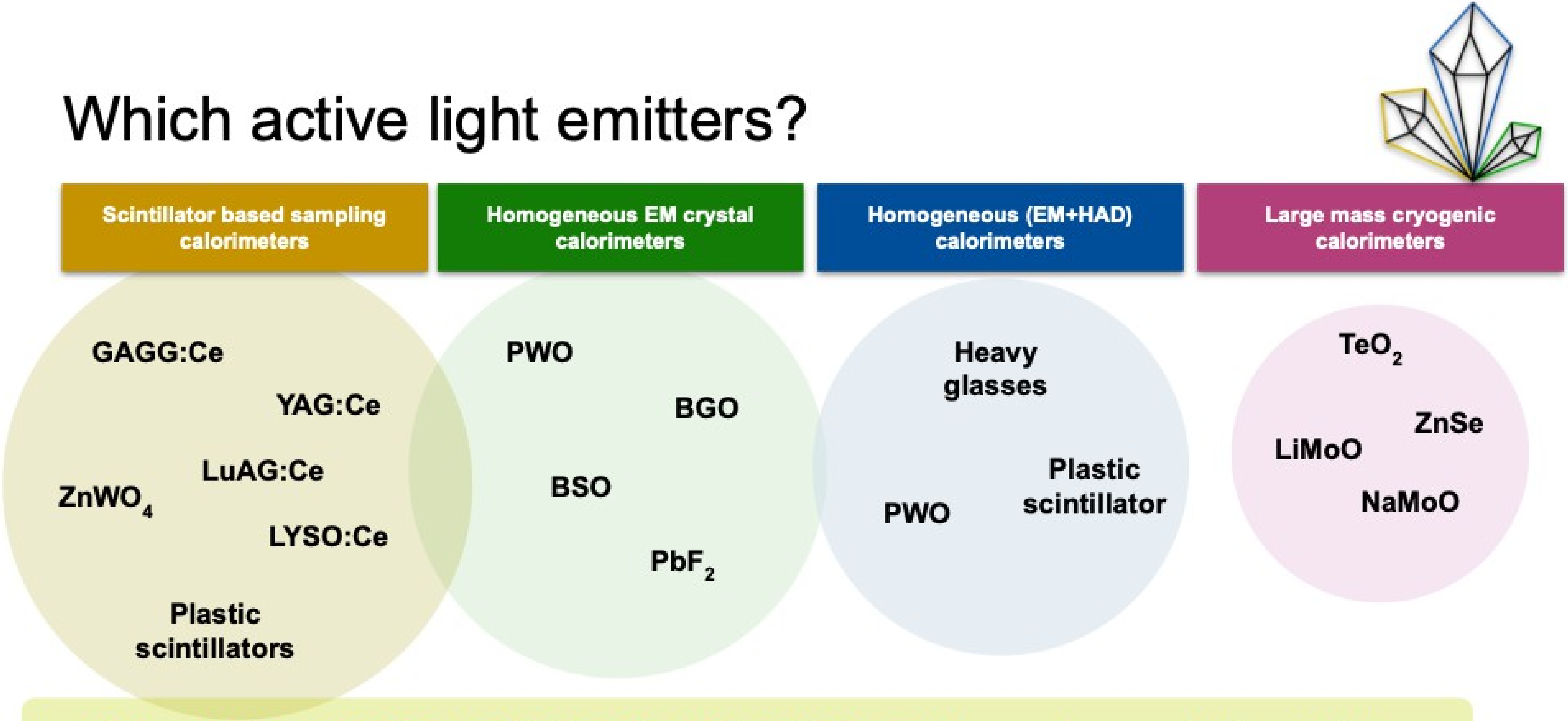
Lucchini, Pezzotti, Polesello, Tully, JINST 17 P06008 (2022)

IDEA + SCEPCal (detector element sizes exaggerated for visibility)

Materials for optical calorimeters

P. Roloff, M. Lucchini
2nd Calo Community Meeting

Which active light emitters?



LuAG:Ce, LYSO:Ce, GAGG:Ce, BGSO, BGO, BSO, PWO, BaF_2:Y, heavy glasses, plastic scintillators

Optimization and customization of active materials, light collection and readout is **common to all proposals** 5

- R&D will have to break down the plethora of materials to few on which the R&D will focus on
- Definition of criteria needed!

Novel optical materials

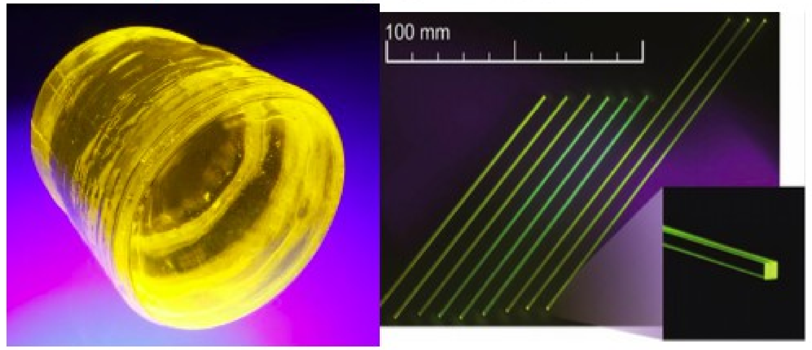
- Radiation hard optical materials with ultrafast timing response are required for new detectors in HEP, nuclear medicine and industry

- A time resolution below 30 ps or even in the sub ps domain requires a better understanding of the fast signal production mechanisms in detection materials

- Innovative test suites required for the combination of fast timing and radiation tolerance will be developed for the characterisation and classification of materials

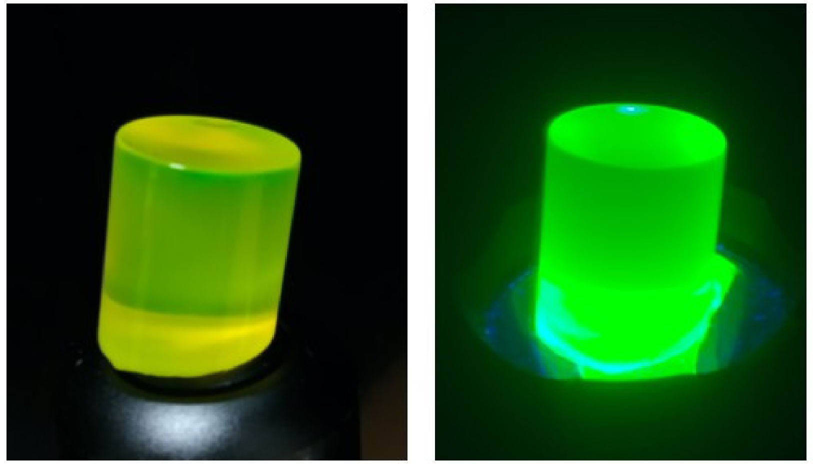
- Scalable and cost effective production techniques for the novel materials have to be explored together with the industrial partners

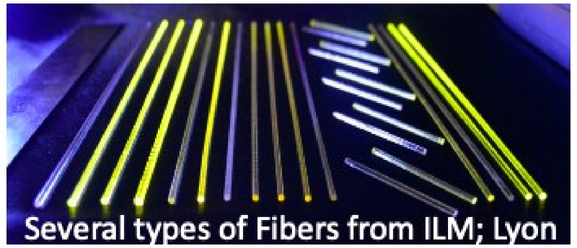
Crytur YAG ingots => fibers



Crytur PWO crystals

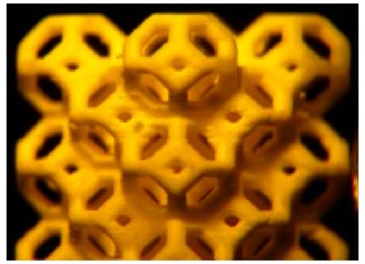
GlasstoPower development on quantum materials





Several types of Fibers from ILM; Lyon

3 D printed garnet Crystals



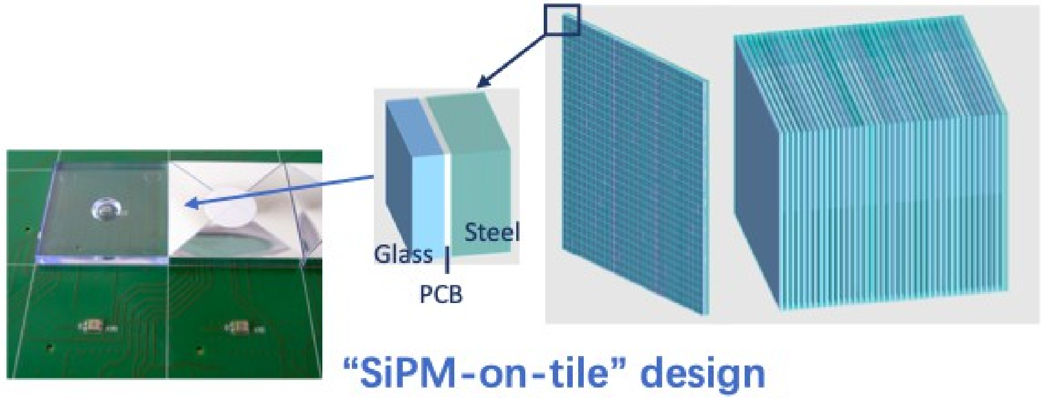
Courtesy G. Dosovitskyi, Kurchatov Institute

Glass Scintillators – The bright future?

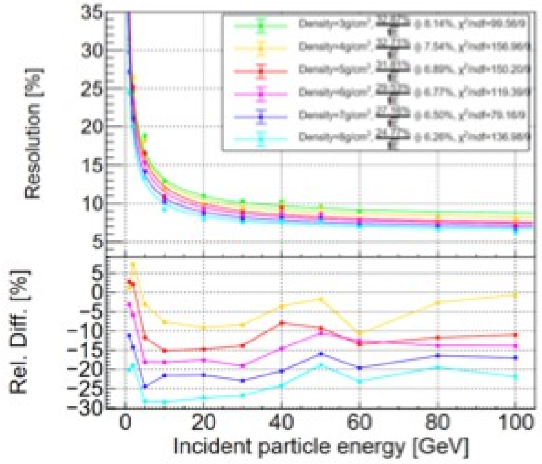
Glass scintillator HCAL

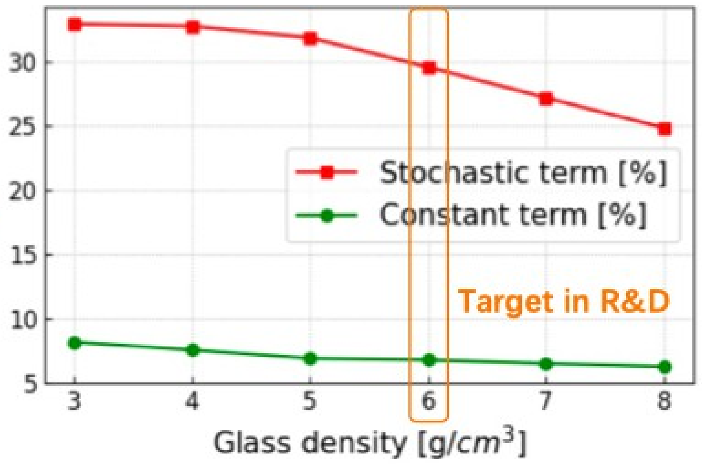
- **Motivation: better energy resolution**
  - Higher density ➡ higher sampling fraction.
- **Validate with standalone simulation:**
  - $\lambda_I = 23.83$ cm, MIP response ~7 MeV/cm.
  - Standalone simulation of glass-steel:
    - 40 layers, total depth 5λ.

Sen & Dejing, TIPP 2023



"SiPM-on-tile" design
AHCAL-like glass HCAL





- HCAL resolution can be improved with higher density.
- Consider $6\ \mathrm{g/cm^3}$ as glass scintillator R&D target (a balance with the light yield).

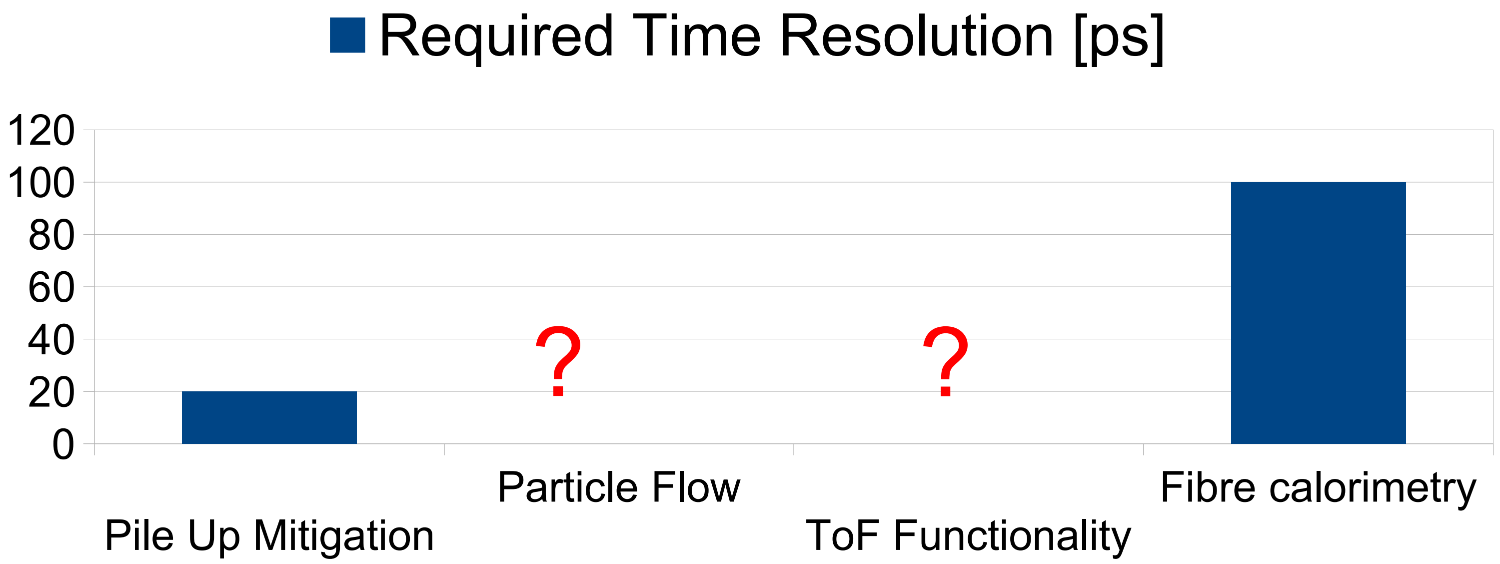
2023/10/11 Fangyi Guo | Second ECFA Workshop, 2023 16

Two points to take home (my understanding):

- Would be relatively cheap
- Problem is optimal doping to achieve transparency

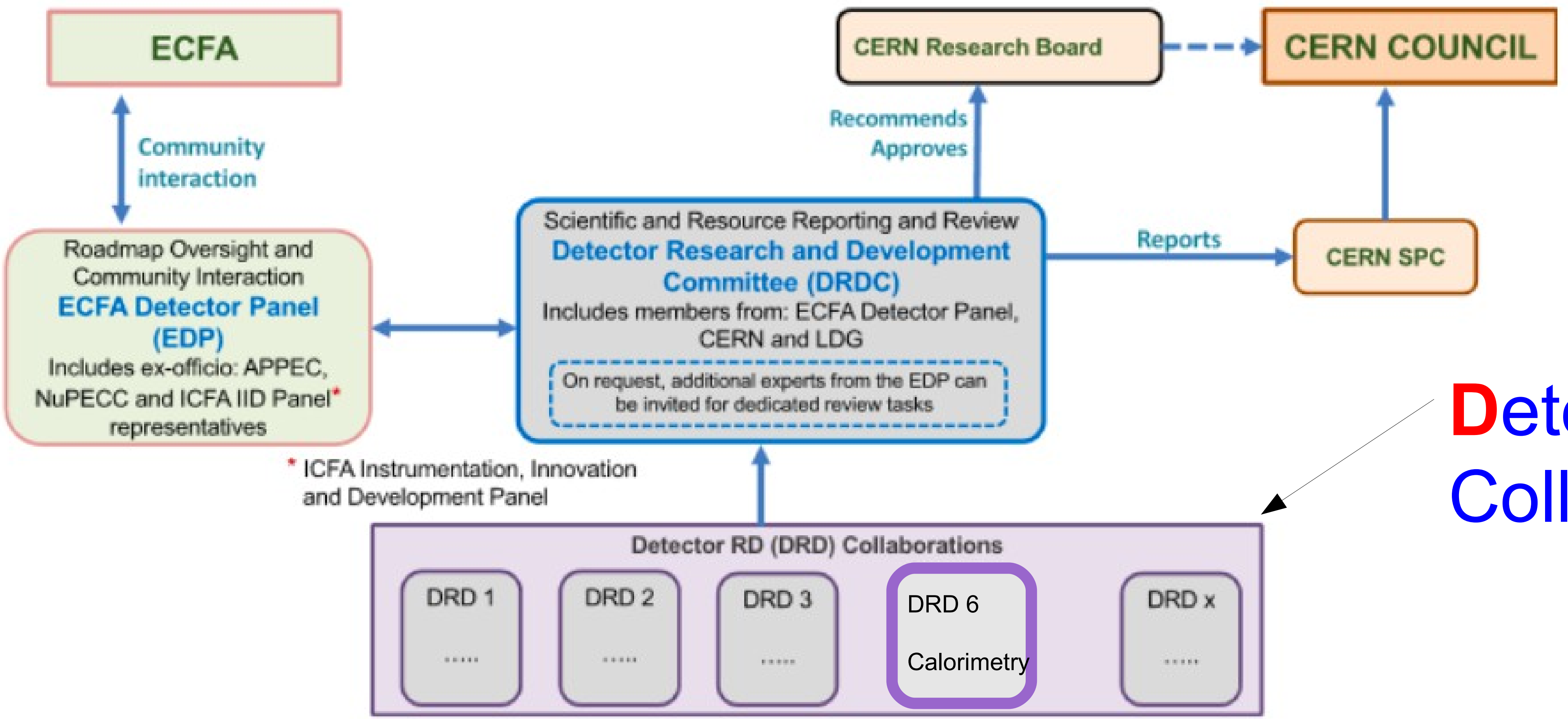
Timing ?

- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters



- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

Future Organisation of Detector R&D (in Europe)



Detector R&D Collaborations

- Current model: DRD will be hosted by CERN and therefore become legally CERN collaborations
  - Significant participations by non-European groups is explicitly welcome and needed
  - World wide collaborations!
- The progress and the R&D will be overseen by a DRDC that is assisted by ECFA
  - https://committees.web.cern.ch/drdc
  - Thomas Bergauer of ÖAW/Austria appointed as DRDC-Chair
- The funding will come from national resources (plus eventually supranational projects)

Categories of R&D

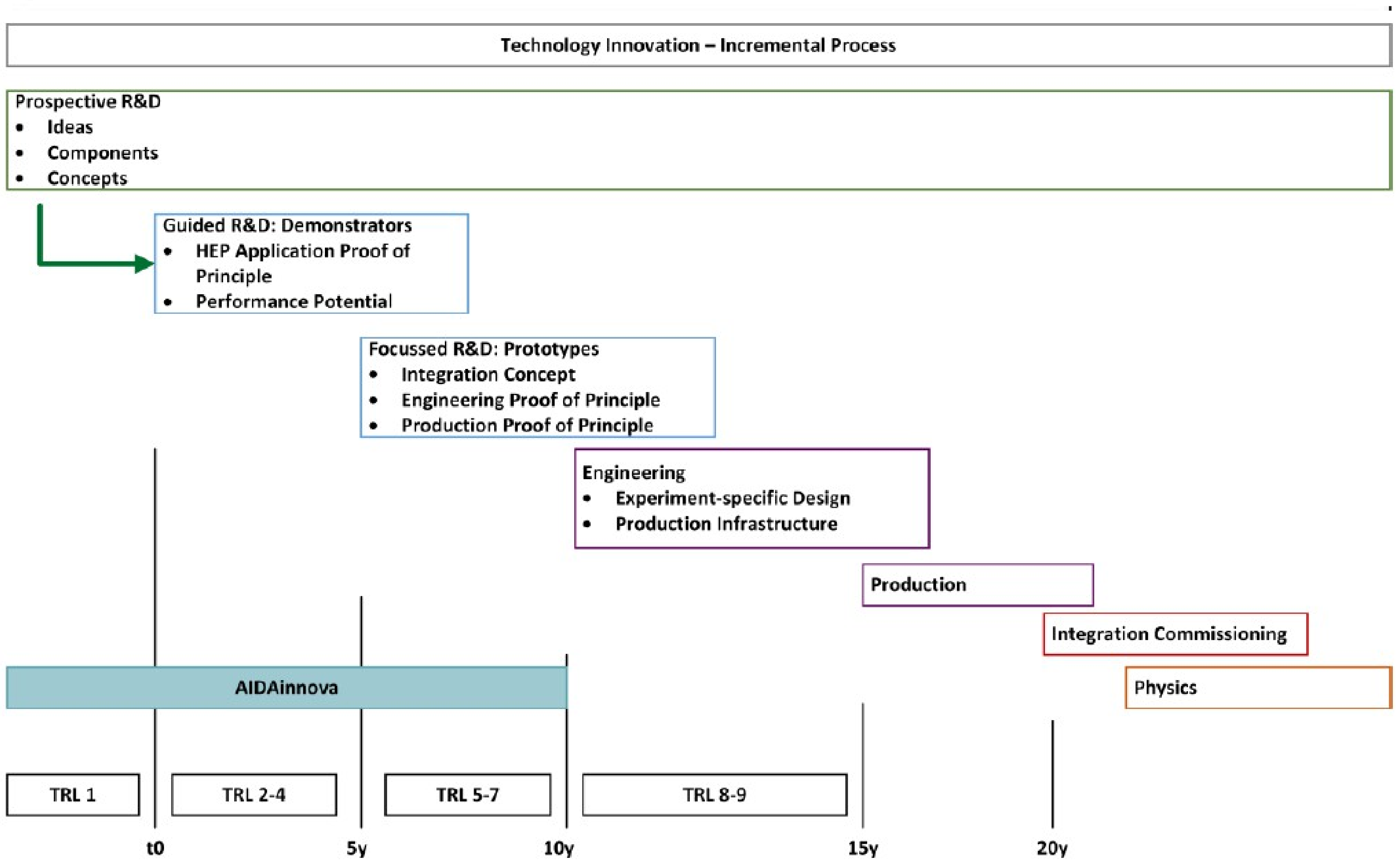
1. Strategic R&D via DRD Collaborations
   (long-term strategic R&D lines)
   (address the high-priority items defined in the Roadmap via the DRDTs)
2. Experiment-specific R&D
   (with very well defined detector specifications)
   (funded outside of DRD programme, via experiments, usually not yet covered within the projected budgets for the final deliverables)
3. "Blue-sky" R&D
   (competitive, short-term responsive grants, nationally organised)

vision

focus

agility

Transitions Blue-sky → Strategic → Specific expected
Cross-fertilisation desired

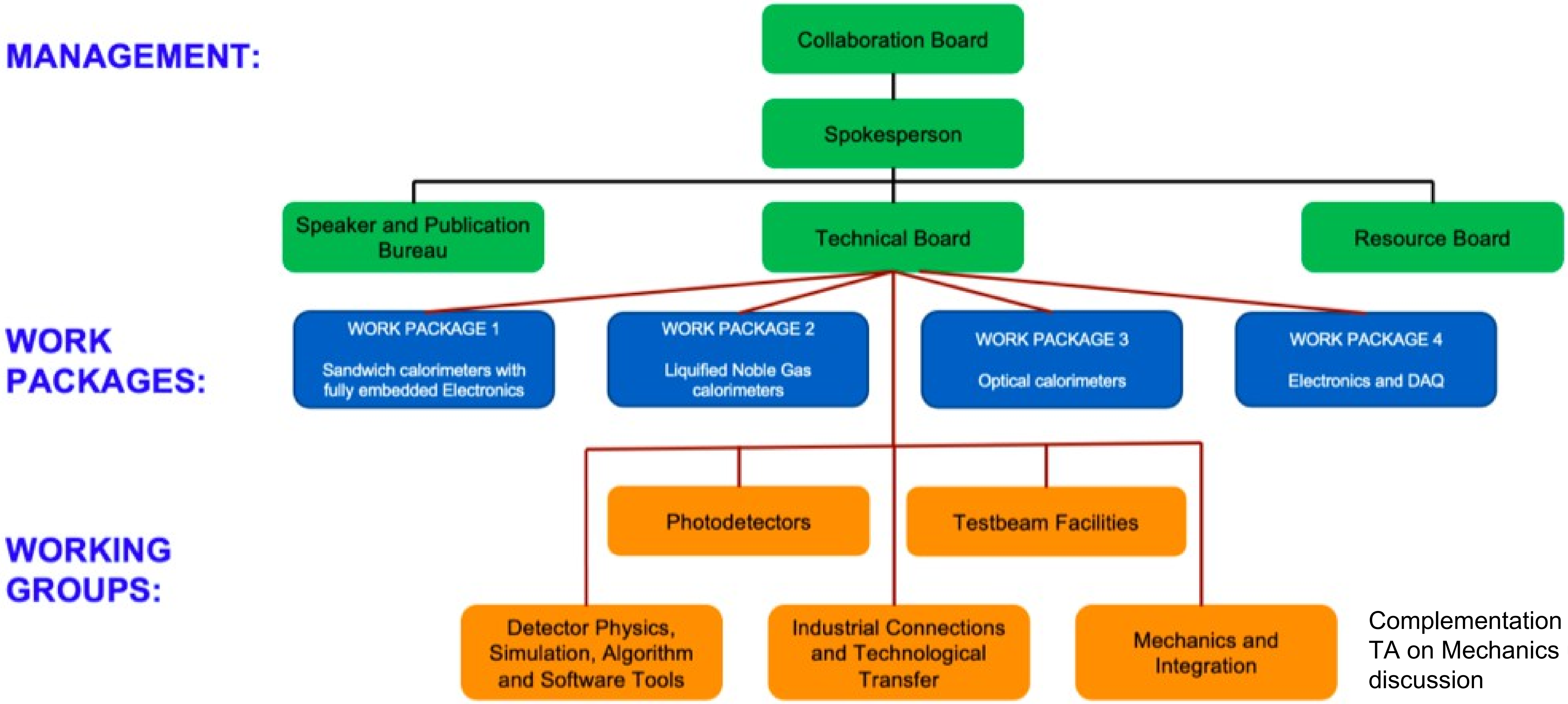


F. Sefkow, CALICE Meeting and ECFA Higgs/top/EW Factory Meeting

Status of DRDs

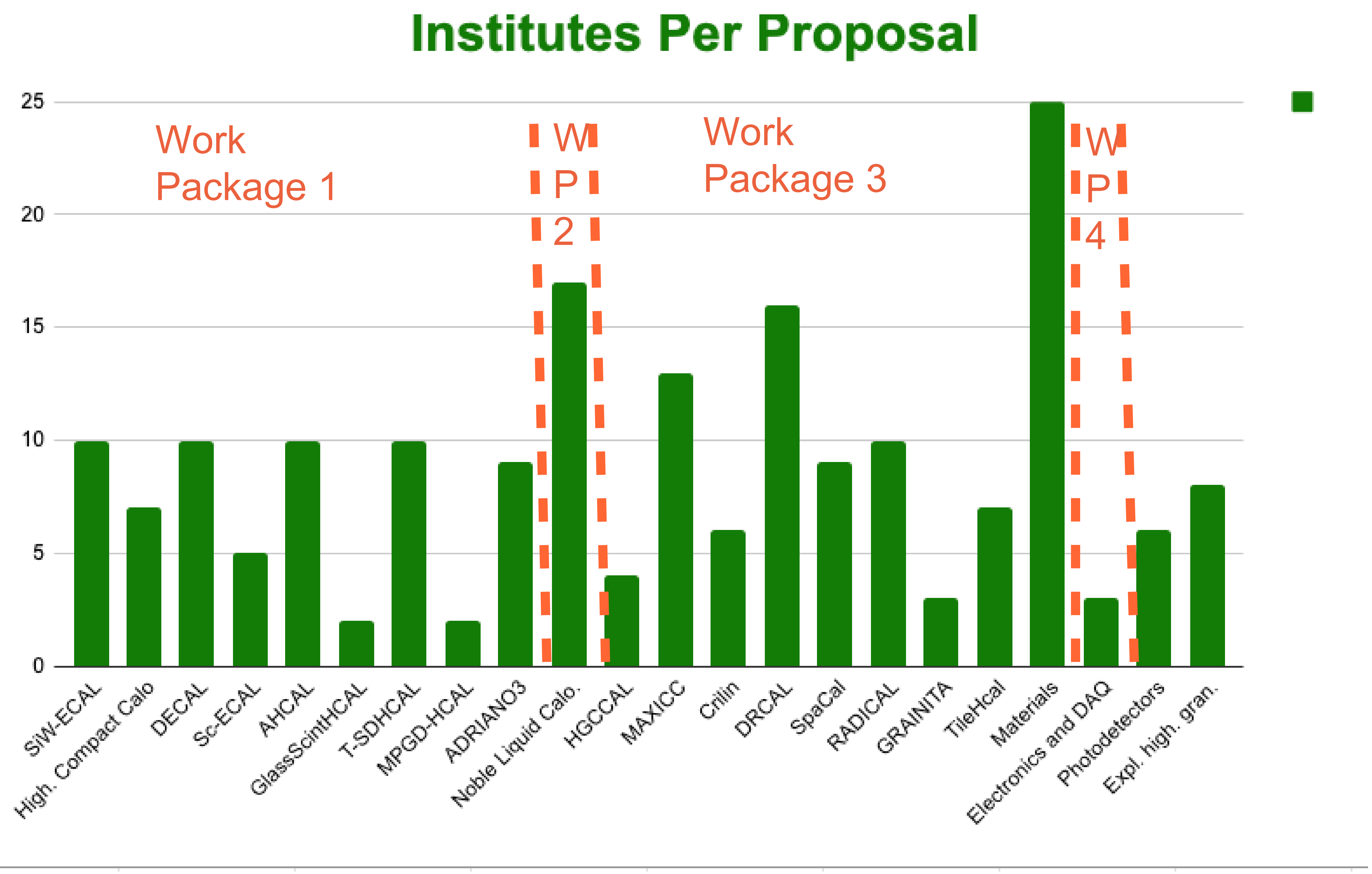
Collab.	Topic	Initial Proposal Submission	Seeking approval	comment
DRD 1	Development of Gaseous Detectors	July 2023	Dec. 2023	Former RD51
DRD 2	Liquid Detectors	July 2023	Dec. 2023	
DRD 3	Solid State Detectors	3 Oct. 2023	Dec. 2023	Former RD50
DRD 4	Photon Detectors and Particle Identification Techniques	July 2023	Dec. 2023	
DRD 6	Calorimetry	July 2023	Dec. 2023	CALICE, CrystalClear
DRD 5	Quantum and Emerging Technologies		later	
DRD 7	R&D Collaboration for Electronic Systems	LoI submitted	later	
TF 8	Integration	-	later	Workshop on 6th Dec.

DRD Calo – Basic structure

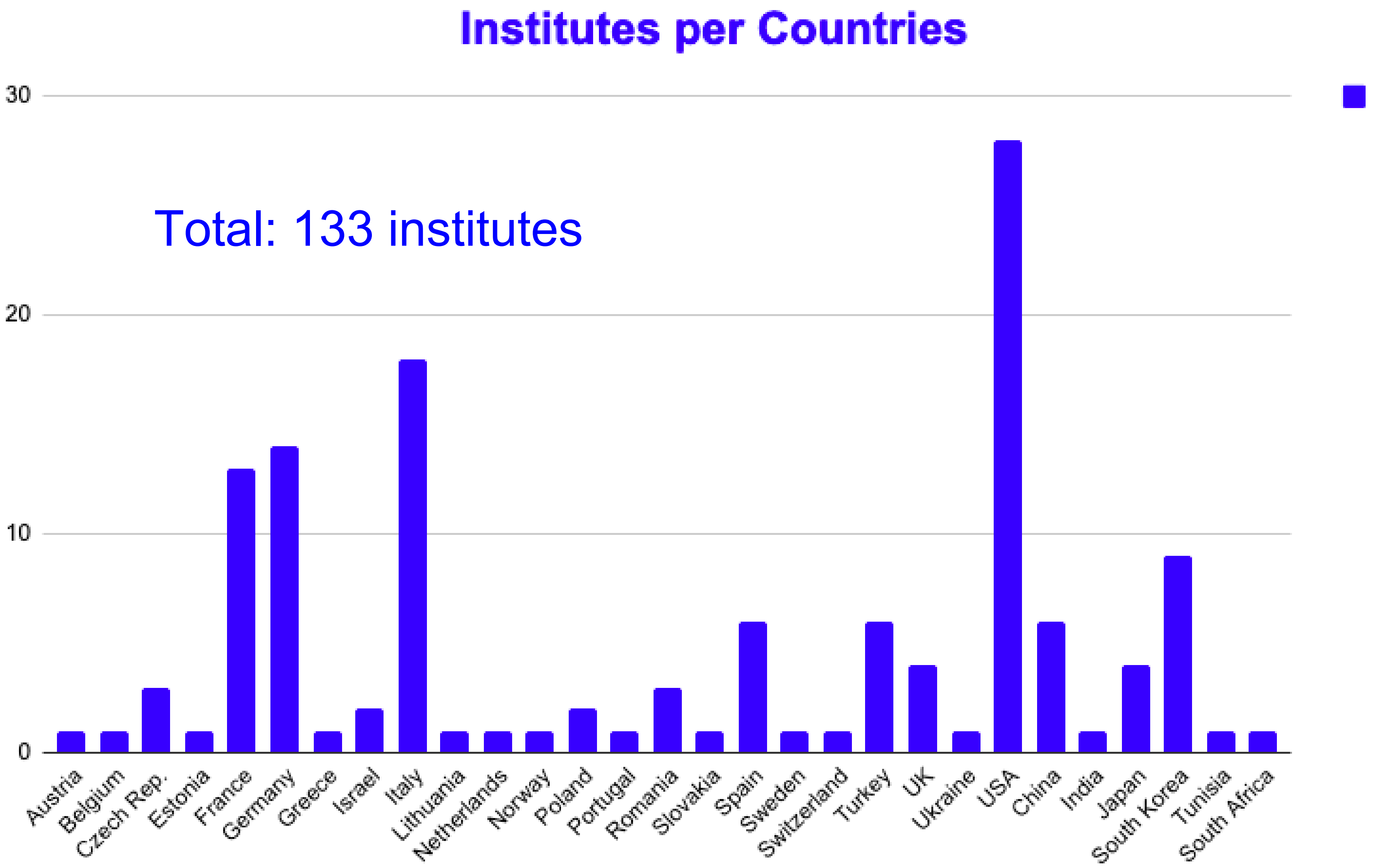


Complementation with TA on Mechanics under discussion

Drawing: G. Gaudi

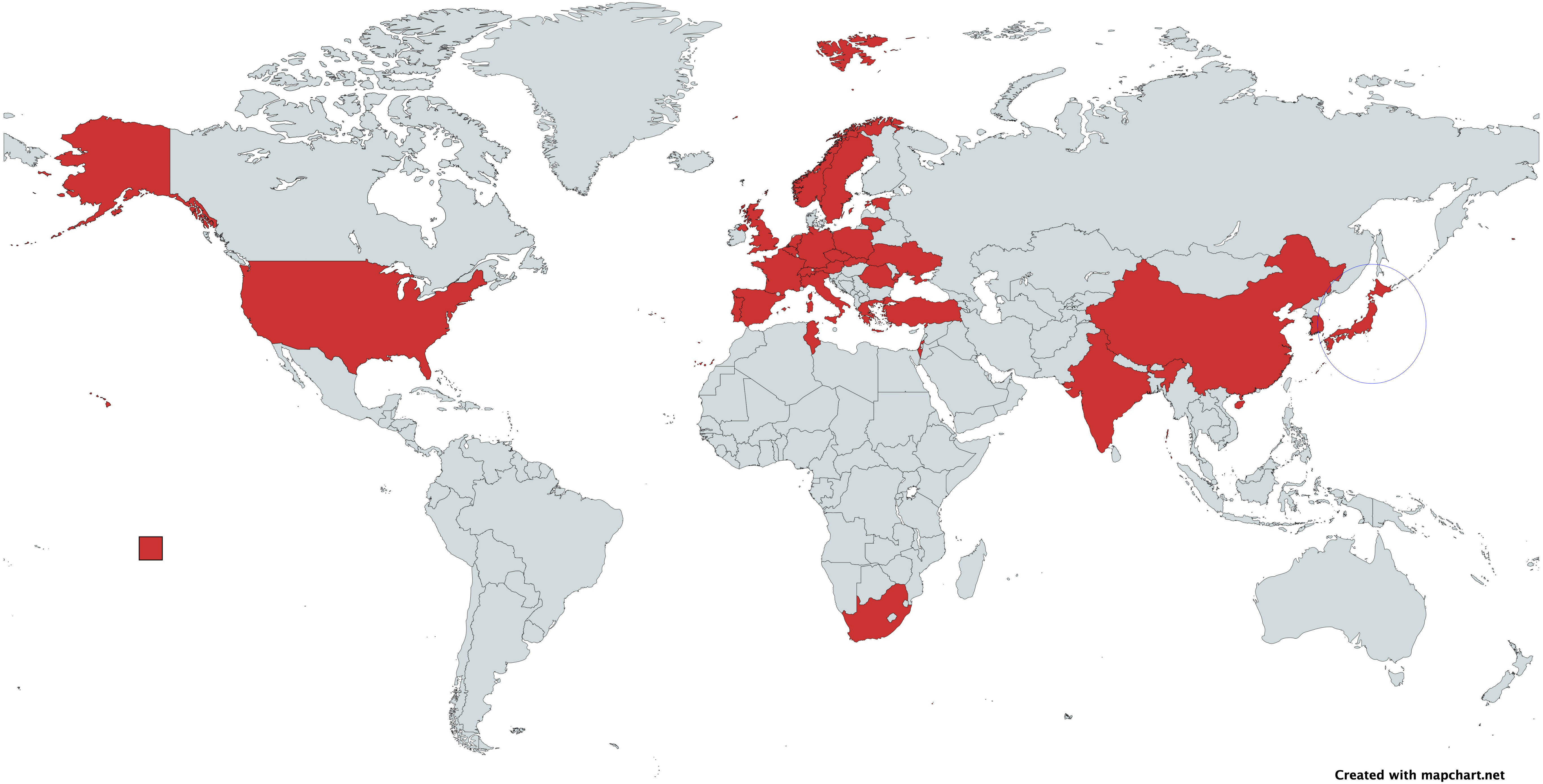

Institutes Per Proposal
25
20
15
10
5
0
Work
Package 1
W
P
2
Work
Package 3
W
P
4
SiW-ECAL
High. Compact Calo
DECAL
Sc-ECAL
AHCAL
GlassScintHCAL
T-SDHCAL
MPGD-HCAL
ADRIANO3
Noble Liquid Calo.
HGCCAL
MAXICC
Crilin
DRCAL
SpaCal
RADICAL
GRAINITA
TileHcal
Materials
Electronics and DAQ
Photodetectors
Expl. high. gran.

DRD Calo – Overall Interest



- Mainly European Groups but interest from all over the world (37%)
  - US biggest single participation -> close contact to emerging effort in US
  - Very visible Asian participation

DRD Calo – Where?



Summary and outlook

- Detector Optimisation is a wide field

- Several aspects are common across Higgs factories
  - Low material for vertex detectors
  - PID Capabilities
  - Granular calorimeters
  - Understanding the usefulness of time information

- Carrying detector requirements into Detector R&D require close communication between concepts and detector R&D Collaborations

- Detector R&D Collaborations allow for exploiting synergies between different proposals
  - Allow to carry out coordinated strategic R&D
  - DRDs are about to start
  - Worldwide participation

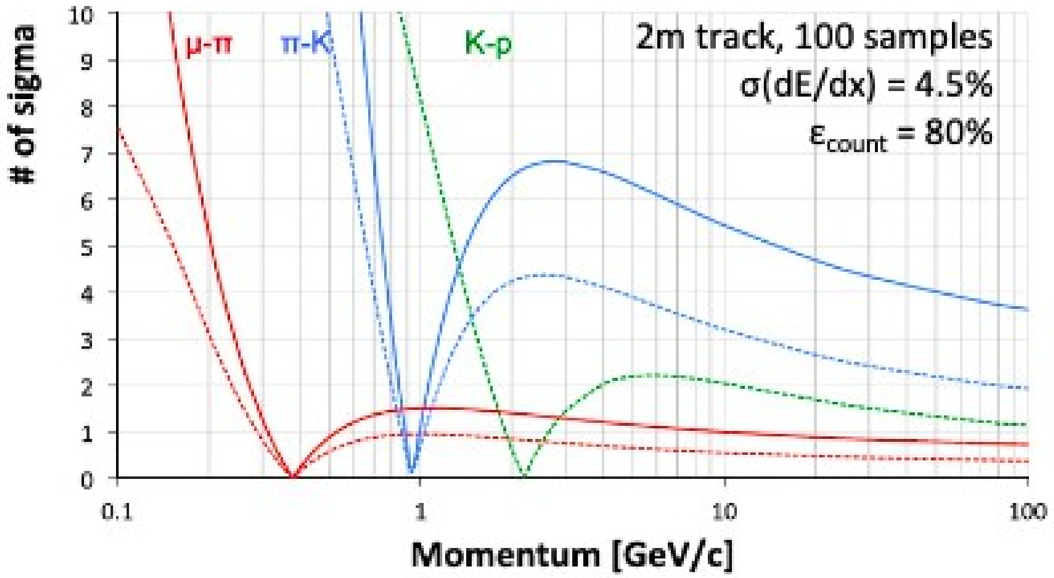
Backup

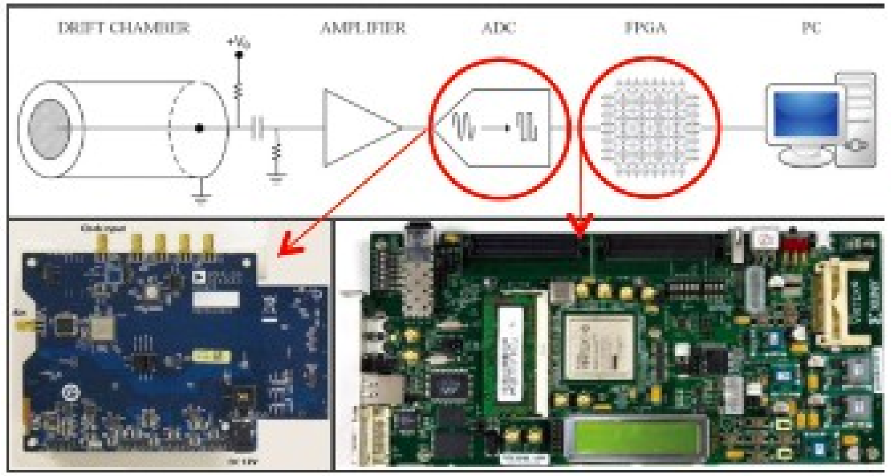
dE/dx → dN/dx – Cluster counting

- G. Chiarello et. al, NIM A 936 (2019) 503-504
- G. Cataldi et al. NIM A 386 (1997) 458
- F. Grancagnolo, AIDAinnova kickoff (link) + private communication
- J. Kaminski, "Electronics for cluster counting" RD51 workshop (link)

$$\frac{\sigma_{dN/dx}}{dN/dx} = (\varepsilon_{count}\delta_{clusters}L_{track})^{-0.5}$$

Particle Separation (dE/dx vs dN/dx)





- IDEA Drift Chamber PID resolution can be considerably improved using cluster counting:
  - Standard truncated mean dE/dx : σ ≃ 4.2%
  - Cluster counting : σ ≃ 2.5%
- FEE for cluster counting: till now, single channels solutions available, see e.g.:

  IEEE IWASI 2007 pp. 1-5, JINST 12 C07021 (2017), NIMA 735 (2014) 169

Further developments (R&D):

- Development of suitable FEE for IDEA and SCTF (INFN, BINP) - AIDAinnova Task 7.4.1

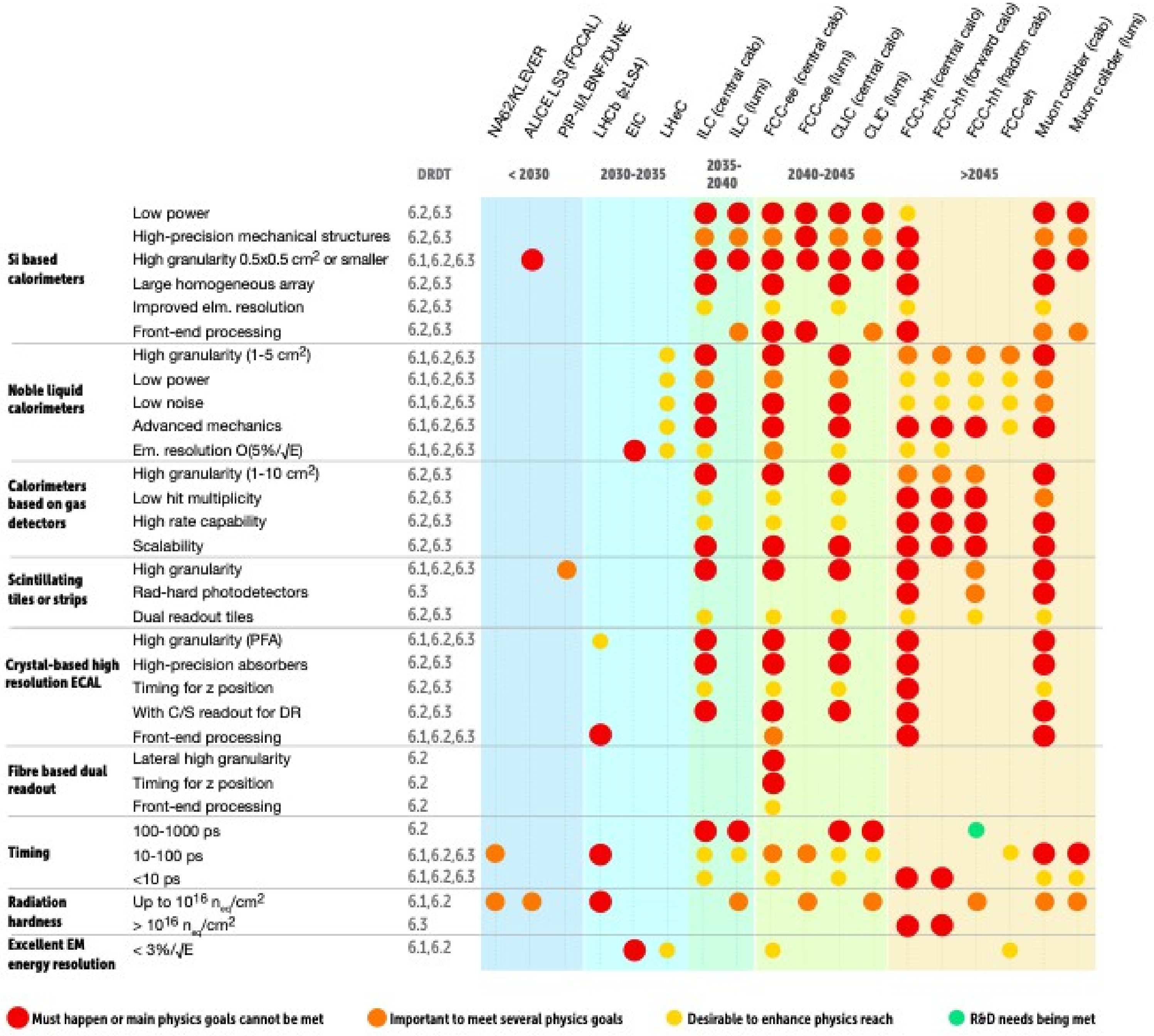
  - BW > 1 GHz, noise < 1 mV, gain > 10, power < 10 mW/ch,
- Data reduction (peak finder) and pre-processing at high-rates on FPGA

  (JINST 12 C07021 (2017))
- Experimental verification of dN/dx method with e, μ, π, K, p beams (ECFA input)

  → test beams at CERN (H8), He-based mixtures

Calorimetry- Identified Key Technologies and R&D Tasks

- Key technologies and requirements are identified in ECFA Roadmap
  - Si based Calorimeters
  - Noble Liquid Calorimeters
  - Calorimeters based on gas detectors
  - Scintillating tiles and strips
  - Crystal based high-resolution Ecals
  - Fibre based dual readout
- R&D should in particular enable
  - Precision timing
  - Radiation hardness
- R&D Tasks are grouped into
  - Must happen
  - Important
  - Desirable
  - Already met



DRD Calo – From input proposals to working structure

The Proposal Team

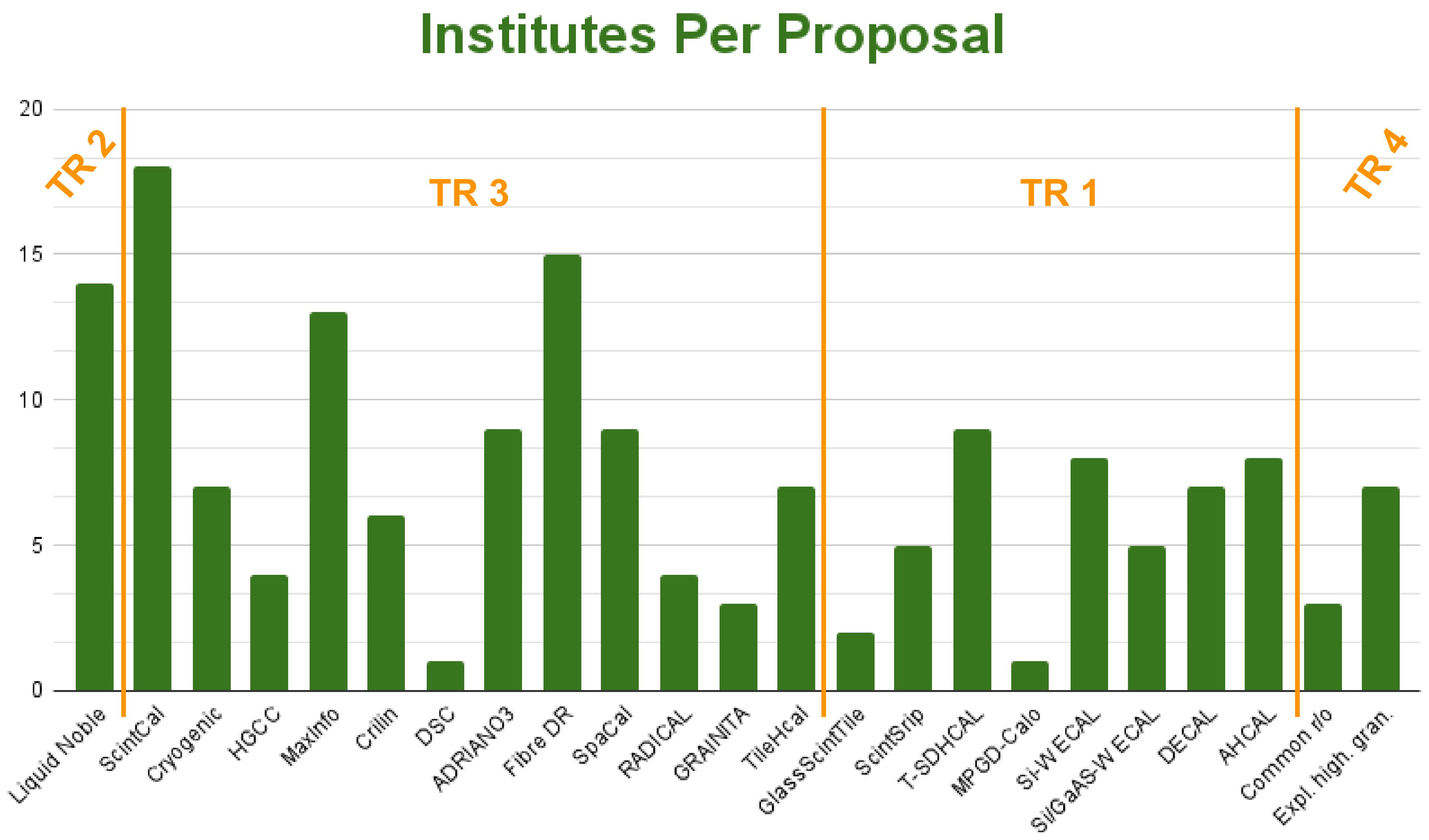
Track 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters
Track conveners:
Adrian Irles (IFIC), **Frank Simon** (KIT), **Jim Brau** (U. of Oregon), **Wataru Ootani** (U. of Tokyo)

Track 2: Liquified Noble Gas Calorimeters
Track Conveners:
Martin Aleksa (CERN), **Nicolas Morange** (IJCLab), **Marc-André Pleier** (BNL)

Track 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
Track Conveners:
Etiennette Auffray (CERN), **Gabriella Gaudio** (INFN-Pavia), **Macro Lucchini** (U. and INFN Milano-Bicocca), **Philipp Roloff** (CERN), **Sarah Eno** (U. of Maryland), **Hwidong Yoo** (Yonsei Univ.)

Track 4: Transversal Activities
Christophe de La Taille (Lab. Omega)

Input proposals
23 comprising 110 institutes/labs received



G. Gaudio
2nd Calorimeter Community Meeting

DRD6 - The “readout landscape”

Name	Track	Active media	readout
LAr	2	LAr	cold/warm elx"HGCROC/CALICElike ASICs"
ScintCal	3	several	SiPM
Cryogenic DBD	3	several	TES/KID/NTL
HGCC	3	Crystal	SiPM
MaxInfo	3	Crystals	SIPM
Crilin	3	PbF2	UV-SiPM
DSC	3	PBbGlass+PbW04	SiPM
ADRIANO3	3	Heavy Glass, Plastic Scint, RPC	SIPM
FiberDR	3	Scint+Cher Fibres	PMT/SiPM,timing via CAENFERS, AARDVARC-v3,DRS
SpaCal	3	scint fibres	PMT/SiPMSPIDER ASIC for timing
Radical	3	Lyso:CE, WLS	SiPM
Grainita	3	BGO, ZnWO4	SiPM
TileHCal	3	organic scnt. tiles	SiPM
GlassScintTile	1	SciGlass	SiPM
Scint-Strip	1	Scint.Strips	SiPM
T-SDHCAL	1	GRPC	pad boards
MPGD-Calo	1	muRWELL,MMegas	pad boards(FATIC ASIC/MOSAIC)
Si-W ECAL	1	Silicon sensors	direct withdedicated ASICS (SKIROCN)
Si/GaAS-W ECAL	1	Silicon/GaAS	direct withdedicated ASICS (FLAME, FLAXE)
DECAL	1	CMOS/MAPS	Sensor=ASIC
AHCAL	1	Scint. Tiles	SiPM
MODE	4	-	-
Common RO ASIC	4	-	common R/O ASIC Si/SiPM/Lar

Trends:

- On-detector embedded elx.
  - Challenges: #channels, Low power digital noise, data reduction
- Off-detector electronics: Fibre/crystal readout
  - Challenges:
  - Low power, data reduction
- Digital calorimetry:
  - Challenges:
  - (extreme) #channels, low power, data reduction

Different calorimeter types but similar challenges

Common ASIC development – One example

Ch. de la Taille
CALICE Meeting, Valencia

- Dynamic gain preamp or TOT ?
- 200 ns shaping, 10 MHz ADC, several samples on the waveform
- Timing capability ? Auto-trigger and zero suppression
- Target ~1 mW power/ch and possible power pulsing
- I²C slow control ? New readout protocol ?
- Include 2.5V LDO inside VFE ?
- Compatible with FCC LAr. SiPM/RPC tbd

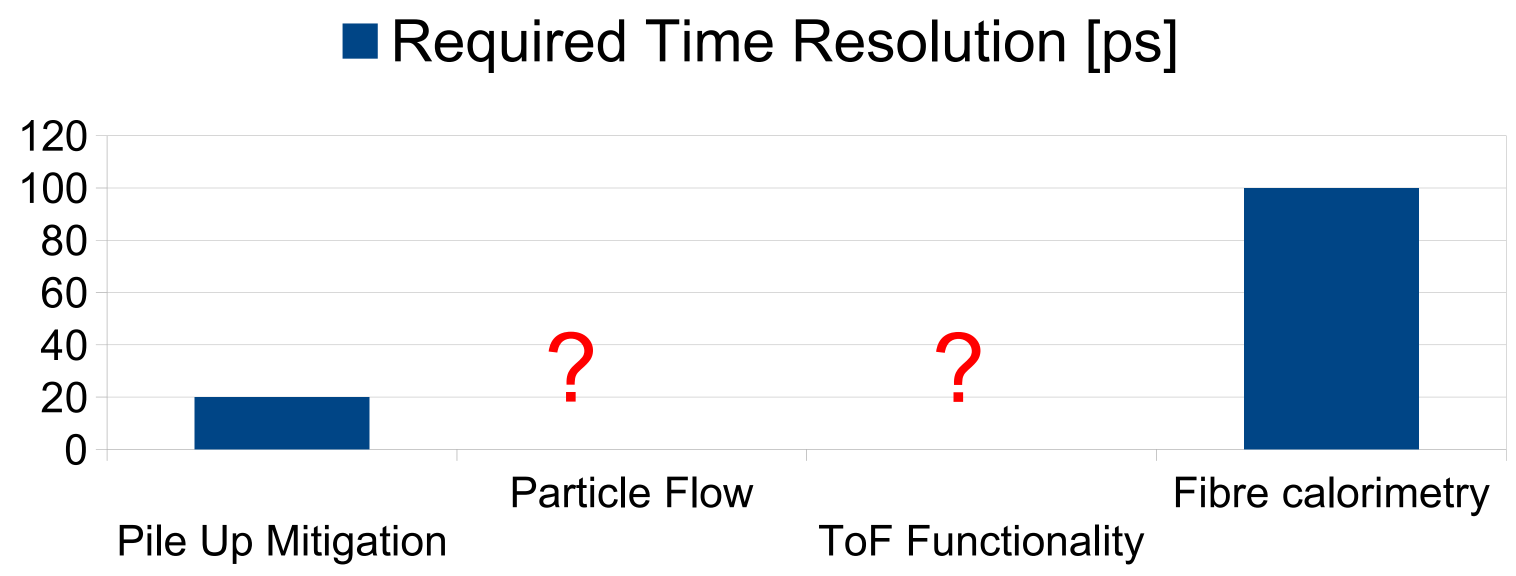
	experiment	Sensor	capacitance	shaping	power	data	techno	Vdd	slow control
SKIROC2	CALICE	Si	30 pF	300 ns	5 mW/ch	5 MHz	SiGe 350n	3.3 V	SPI
HGCROC	CMS	Si	50 pF	20 ns	20 mW/ch	1.2 Gb/s	TSMC 130n	1.2 V	I²C
FCC	LAR	Lar	50-200 pF	200 ns	<1 mW	Gb/s	TSMC 130n	1.2 V	I²C
SKIROC3	CALICE	Si	50 pF	200 ns	<1 mW	Mb/S	TSMC 130n	1.2 V	?

CdLT CALICE meeting 20 apr 2022

- The main goal will be to avoid parallel developments
- Requires close communication with DRD 3 and DRD 7

Timing ?

- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters



- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

V. Sola
AIDAinnova Meeting
Valencia

Nanomaterial composites (NCs)


Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

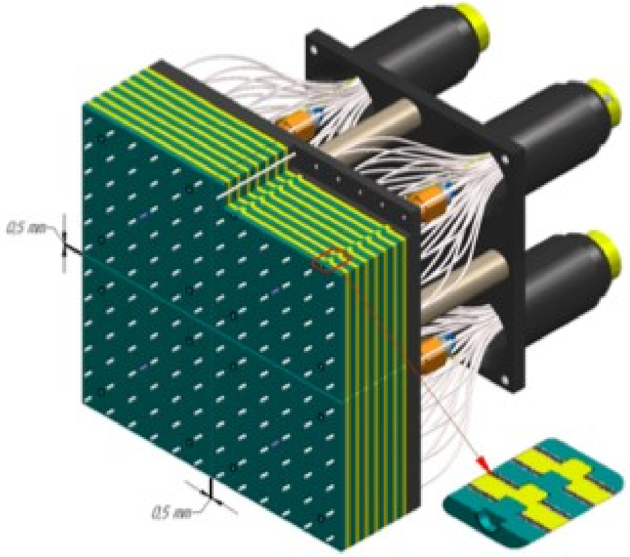
- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals
- Cast with polymer or glass matrix
- Decay times down to O(100 ps)
- Radiation hard to O(1 MGy)

Despite promise, **applications in HEP have received little attention to date**

No attempt yet to build a **real calorimeter with NC scintillator** and **test it with high-energy beams**

Shashlyk design naturally ideal as a test platform:

- Easy to construct a shashlyk calorimeter with very fine sampling
- Primary scintillator and WLS materials required: both can be optimized using NC technology

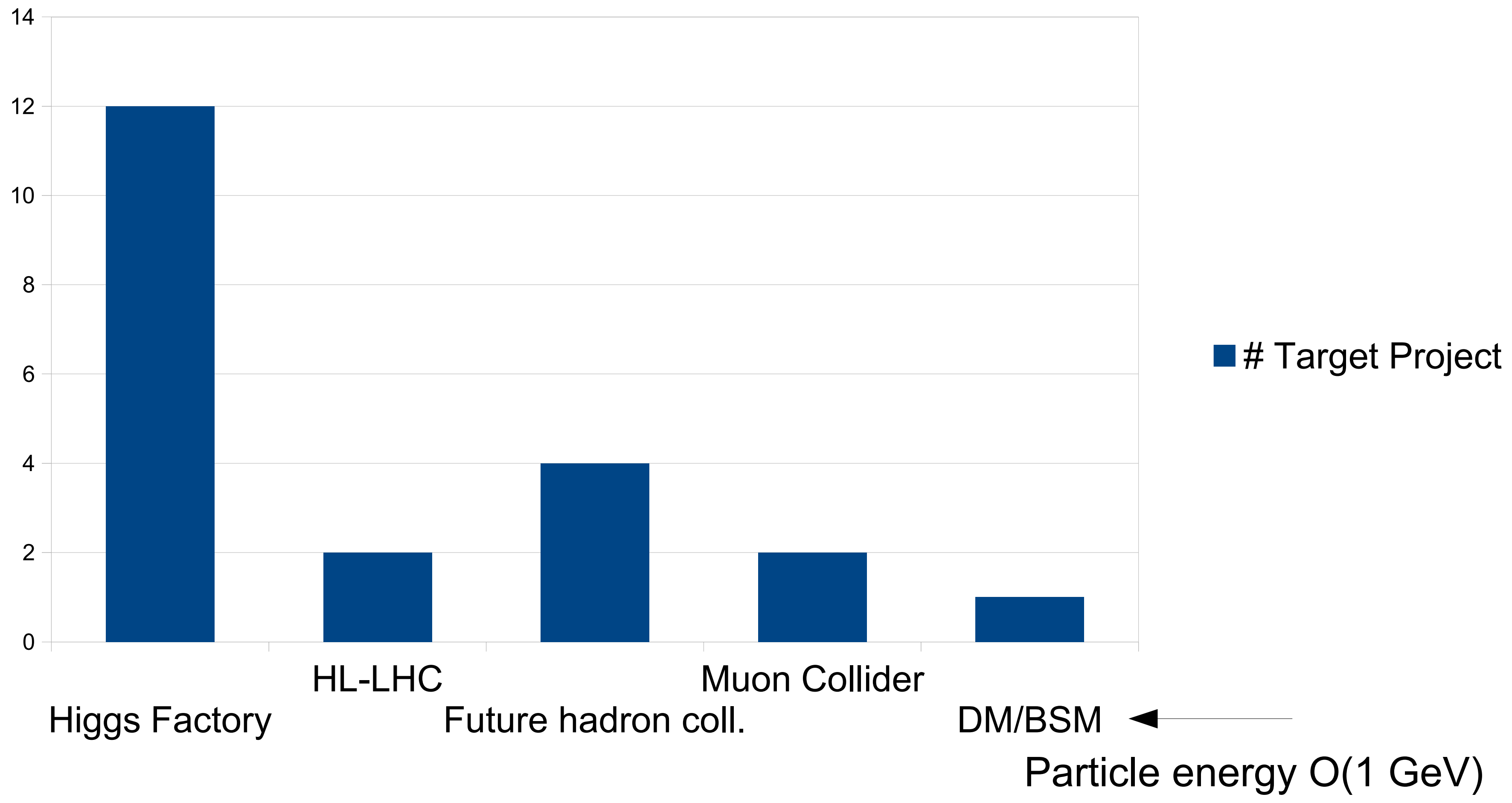


KOPIO/PANDA design
Fine-sampling shashlyk

R&D on material has Overlap with DRD 5

DRD Calo - Input proposals and beam tests

- 19 of 23 input proposals have declared that the devices are going to be tested in beam test (no surprise)
- (Main) target projects of input proposals (partially double counted, not mutually exclusive)



- Higgs factories dominate
  - HF includes heavy flavor that target superb elm. energy resolutions
- (Already now) orientation towards future hadron collider and muon collider

Input proposals - “Testbeam schedule”

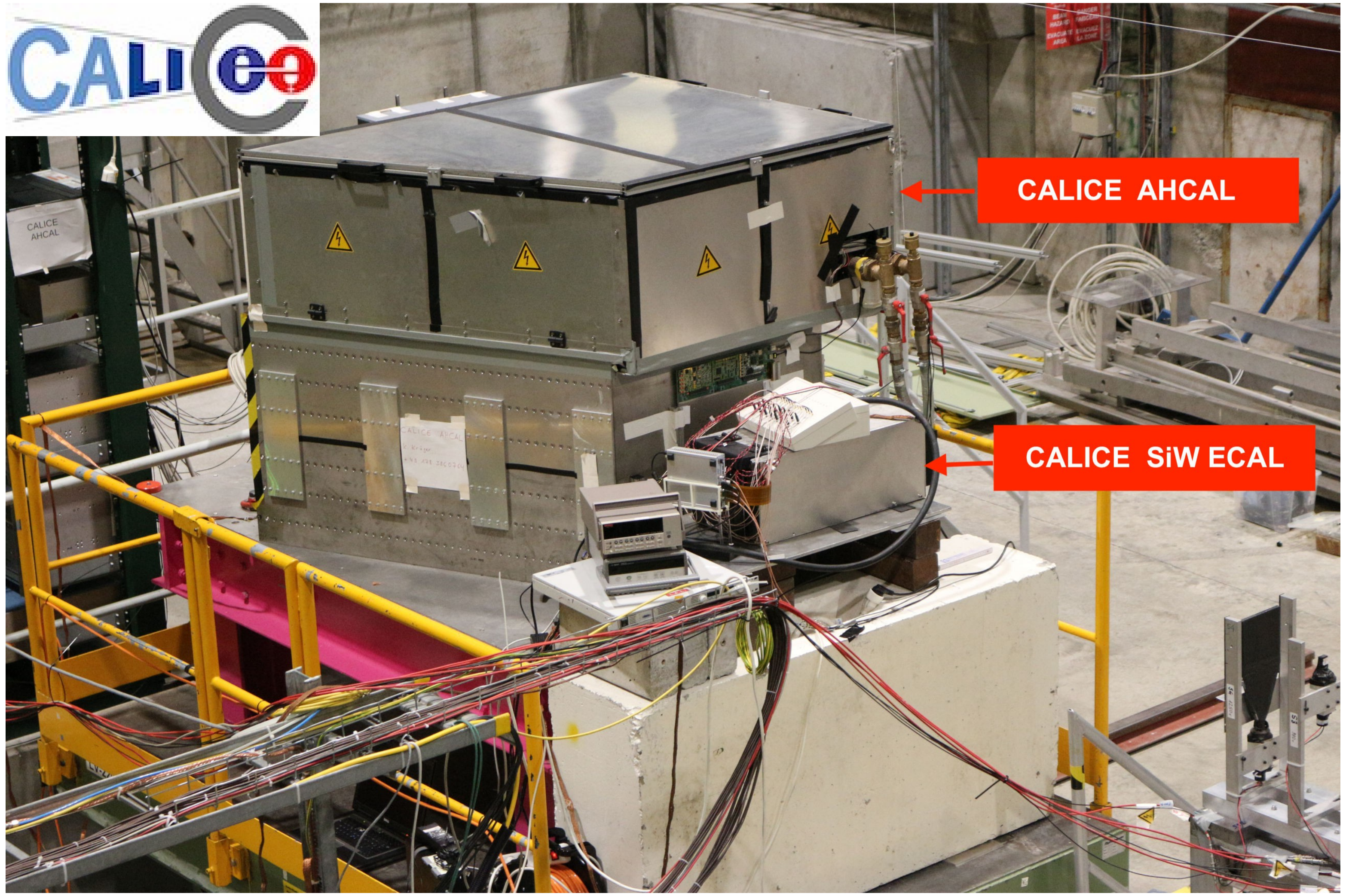
2024 2027 2030

- Input-proposals reveal (relatively) little need at the beginning
  - Start with prototypes that are either existing or currently under construction
  - Benefitting from AIDAinnova and EUROLABS funding
- Relatively high density of beam tests with new (large scale) prototypes after 2025
- The large scale beam tests will be preceded by smaller scale beam tests
  - Individual layers smaller systems before “mass production”

Match Irradiation/Beamtest Facilities Detector Needs

	Energy	Irradiation
Higgs Factory CMS energy 90-1 TeV Radiation <= 10^{14} n_{eq}/cm^2	✓	✓
HL-LHC CMS energy 14 TeV (shared by partons) Radiation ~10^{16} n_{eq}/cm^2	(✓)	✓
Muon Collider CMS energy 3-10 TeV Radiation ~HL-LHC	X	✓
Future Hadron Collider CMS energy 100 TeV (shared by partons) Radiation up to ~10^{18} n_{eq}/cm^2	X	X

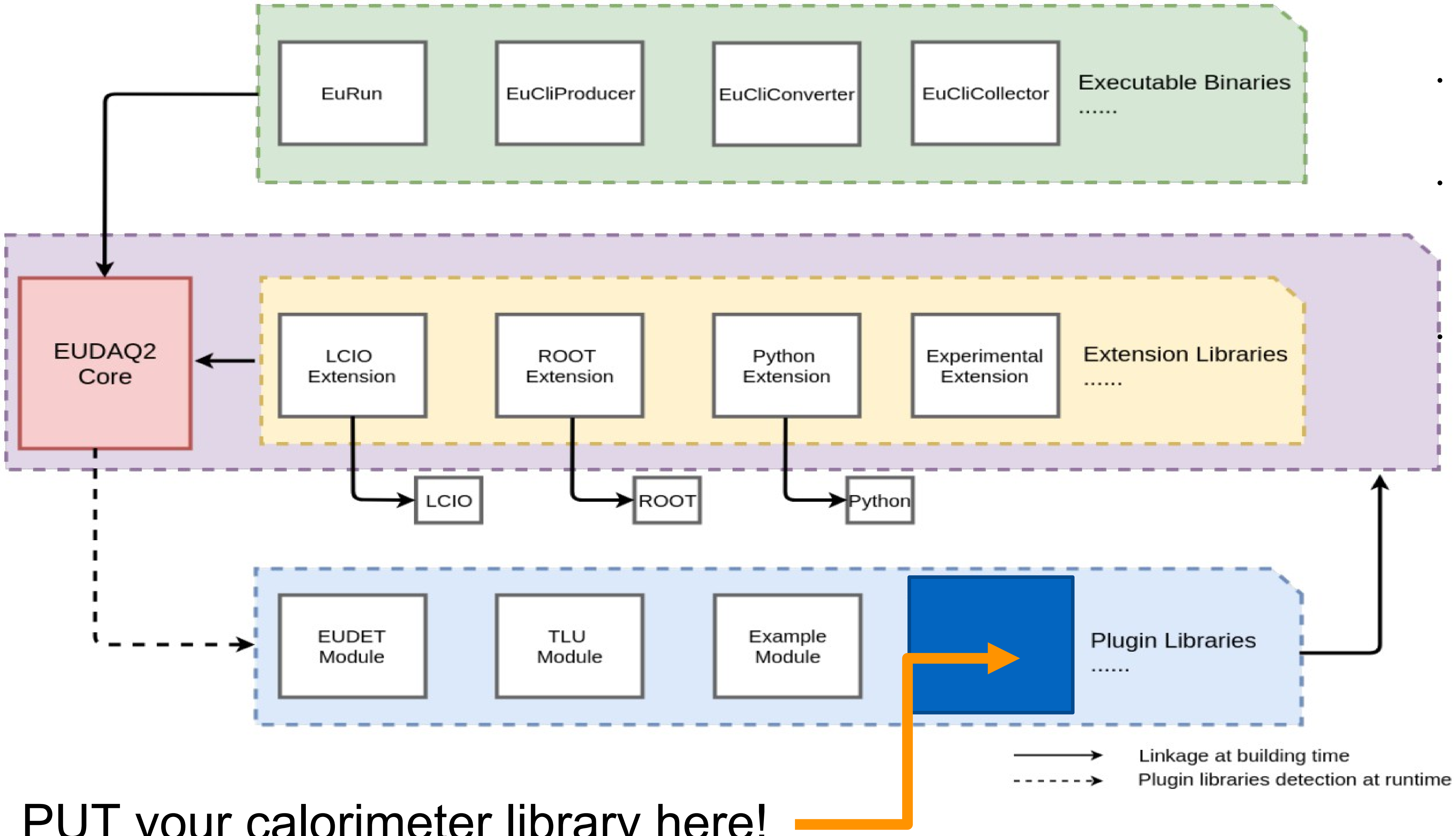
Dedicated Calorimeter Beamline?



Common setup at CERN June 2022

- Calorimeters are typically large objects
  - A beam test is similar to a small experiment
- Difficult for facility managers to schedule calorimeter beam tests
  - No concurring running with other devices possible
- Takes lots of expertise to carry out a successful beam test campaign
  - Implies use of infrastructure
- A dedicated beam line maybe with dedicated slots during a year may help curing these issues
  - Would need sustained expertise on the beamline

EUDAQ Data Acquisition Systems

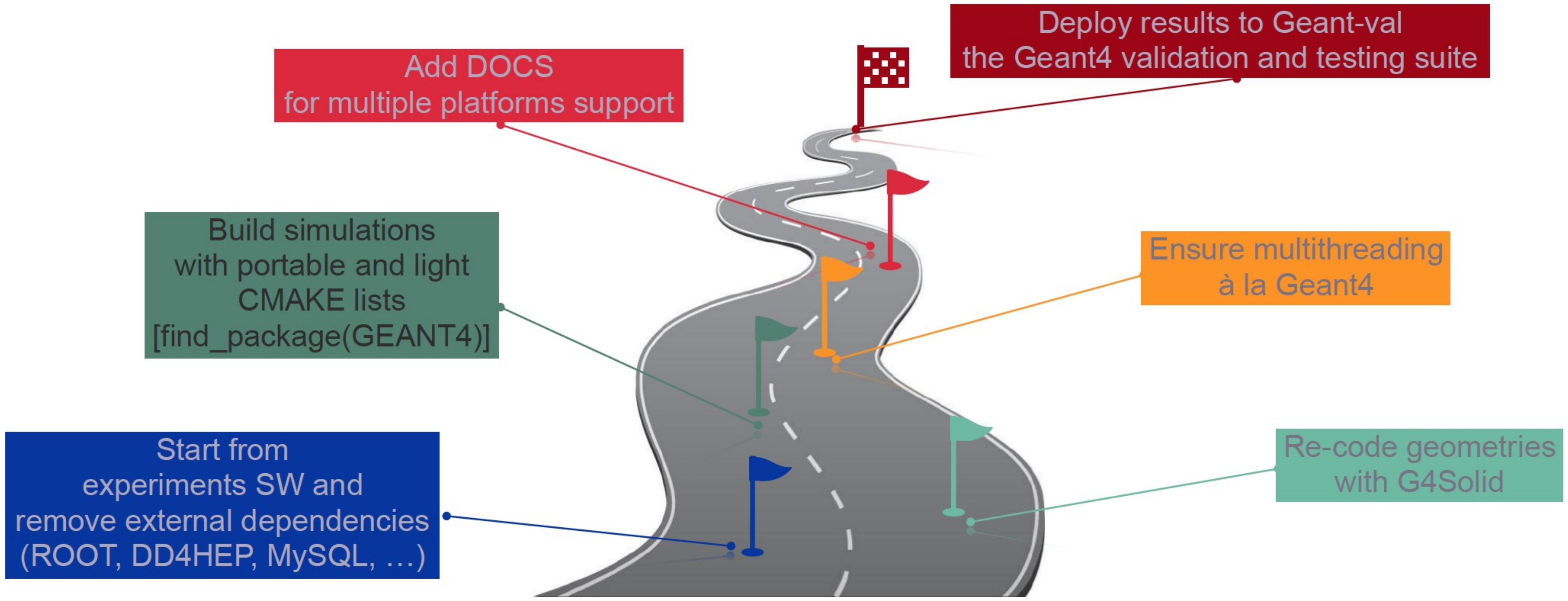


PUT your calorimeter library here!

- Implementation of custom producers is rather simple
- easier integration with other eudaq producers (TLU, Telescopes)
- Already a long list of custom producers integrated:
  - CALICE SiWECAL,
  - CALICE AHCAL,
  - CALICE SiWECAL + AHCAL,
  - CMS HGCAL silicon prototype + CALICE AHCAL, ...

... and once the data are recorded

From experiments to geant-val, a winding road



geant-val.cern.ch

Geant-val is the Geant4 validation and testing suite.

For the Community, it allows to deploy results on a common data-base and fetch the information via a web-interface.

For the developers, it allows to Create multiple jobs over beam energies, particle types, physics lists

Better to involve G4 collaboration at the beginning of the testbeam. G4 collaboration available to help with the geant4-val inclusion

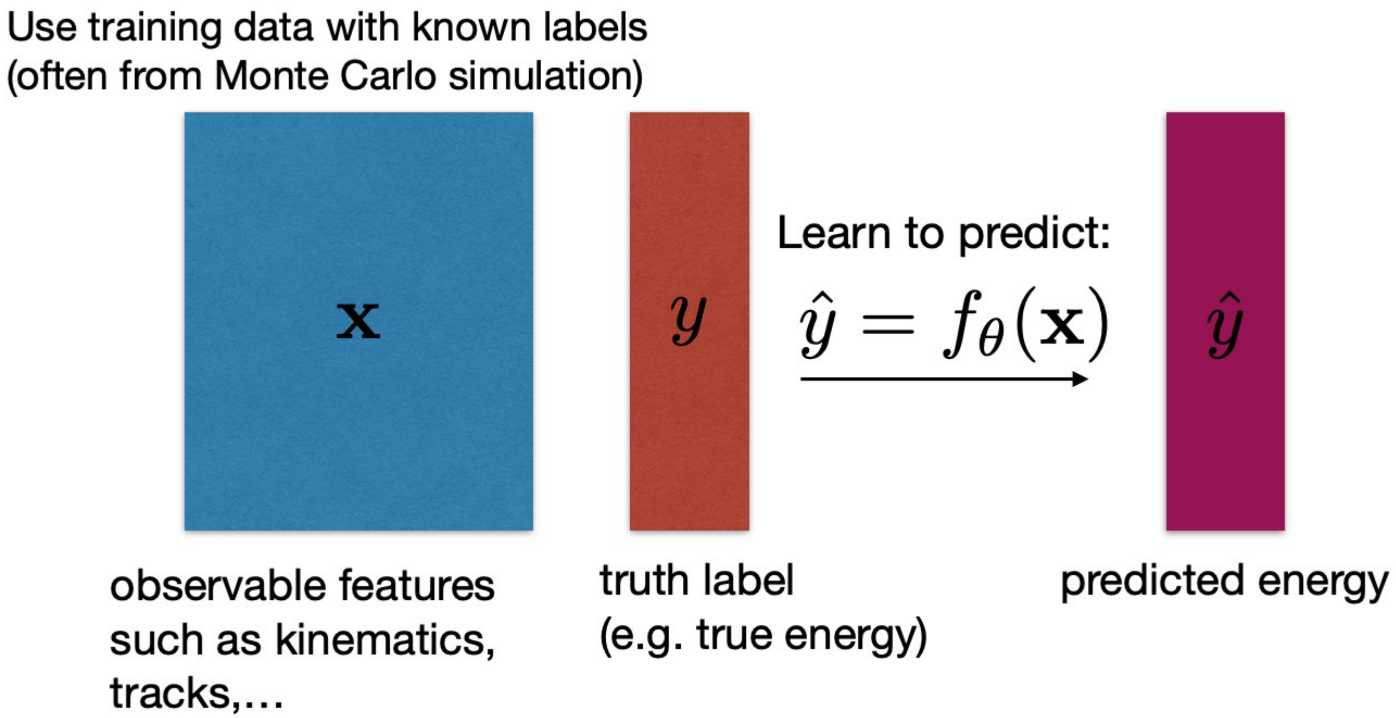
Tommaso Dorigo and MODE Collaboration

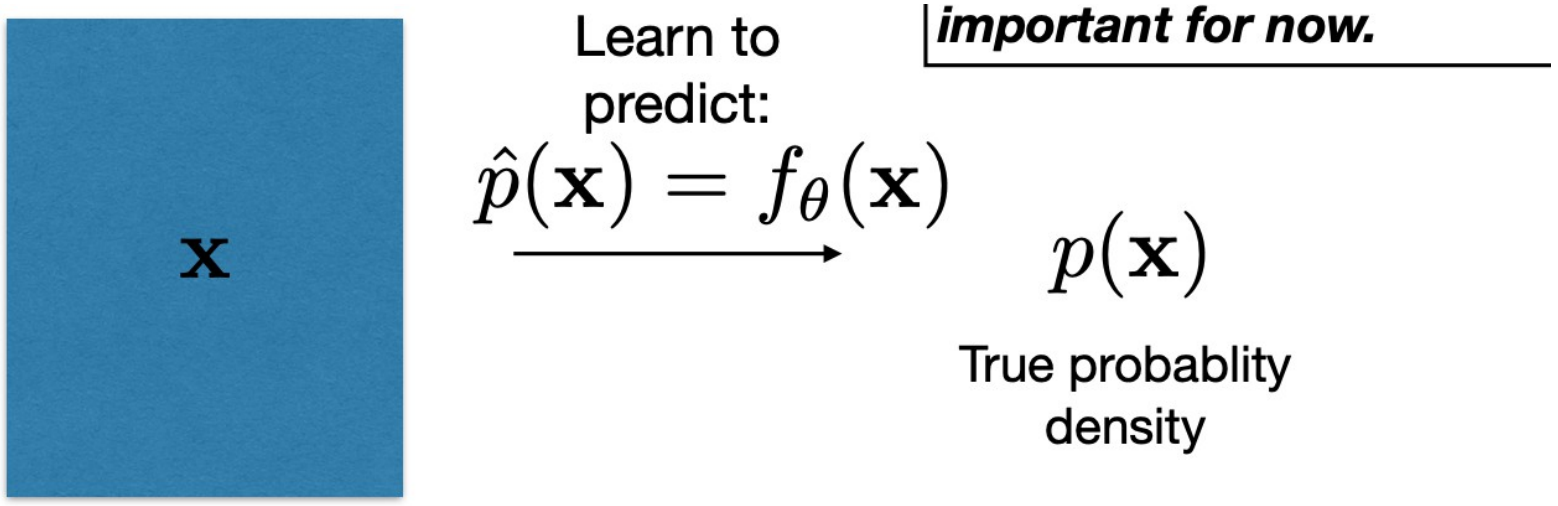
Machine Learning approach is gaining more and more importance in HEP and in calorimetry in particular

highly complex data with large number of detailed information

Simulation provides tagged data for supervised learning

Tracking, clustering, particle ID ...





Summary and outlook

- Detector Optimisation is a wide field

- Requires interplay between all components of a detector concept

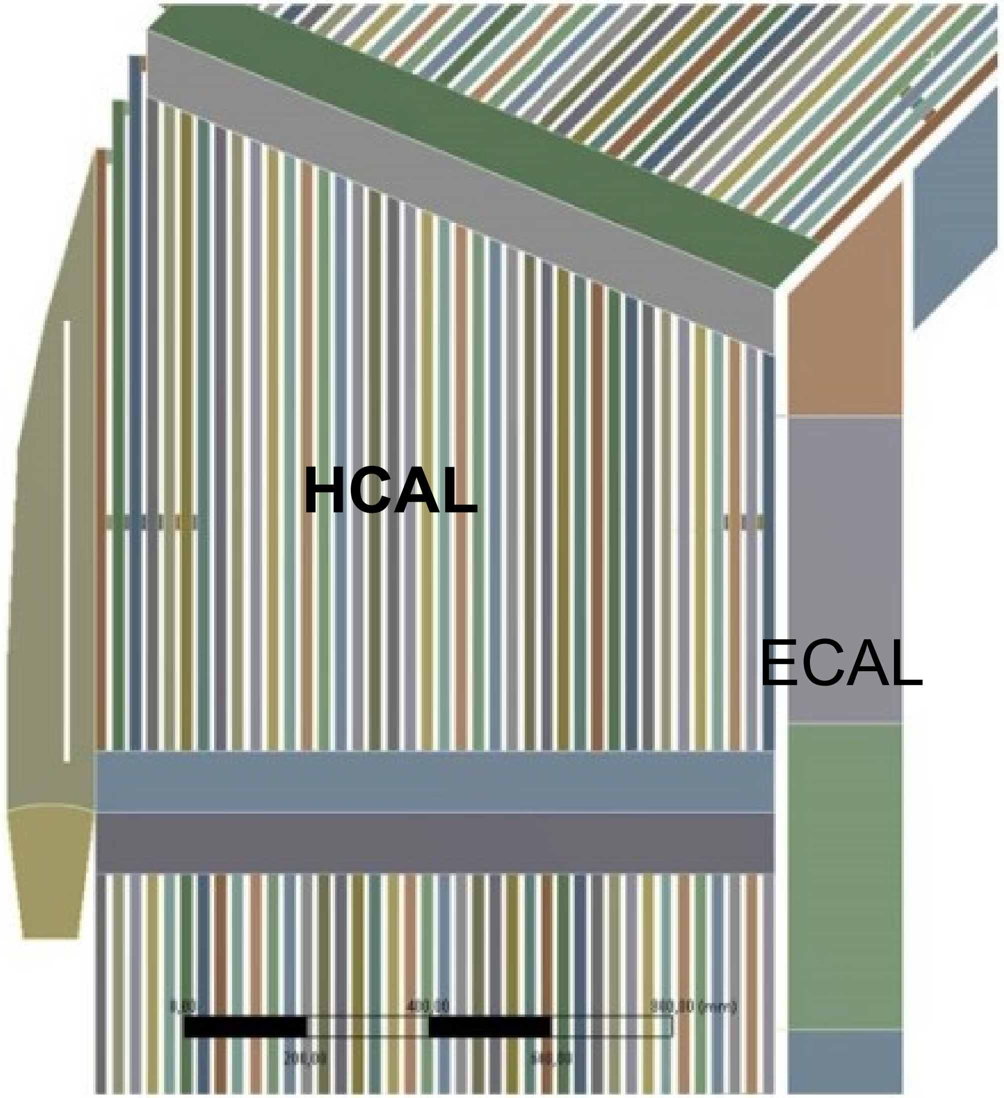
- During optimisation studies a working software system is of paramount importance
  - Should allow for comparing detecor concepts on equal footing

- Carrying detector requirements into Detector R&D require close communication between concepts and detector R&D Collaborations

- Detector R&D Collaborations allow for exploiting synergies between different proposals
  - DRD on Calo will give great importance to transversal aspects of R&D
    - Material
    - Electronics and DAQ
    - Beamtests and mutual support
  - Don't forget: Data analysis of recorded calo prototype data do have a scientific value on their own

- Funding should support thie wide range of topics: **It will pay off**

ILD concept and highly granular calorimeters



- ILD is particle flow detector
  - Implies goal to measure every particle of hadronic final state
  - Key components for PFA are highly granular calorimeters
- Calorimeter options in ILD
  - Silicon-Tungsten Ecal
    - 26-30 layers
    - Cell size 5.5x5.5mm^2, layer depth 0.6-1.6 X_0
  - Scintillator-Tungsten Ecal
    - 30 layers
    - Strip size 5x45 mm^2, layer depth 0.7 X_0
  - Analogue Hcal
    - 48 layers
    - Scintillating tiles: 30x30mm^2, layer depth 0.11λ_I
    - Absorber stainless steel
  - Semi-Digital Hcal
    - 48 layers
    - GRPC: 10x10mm^2, layer depth 0.12 λ_I
    - Absorber stainless steel