Optimisation and software tools
Common items

Roman Pöschl

Supported by

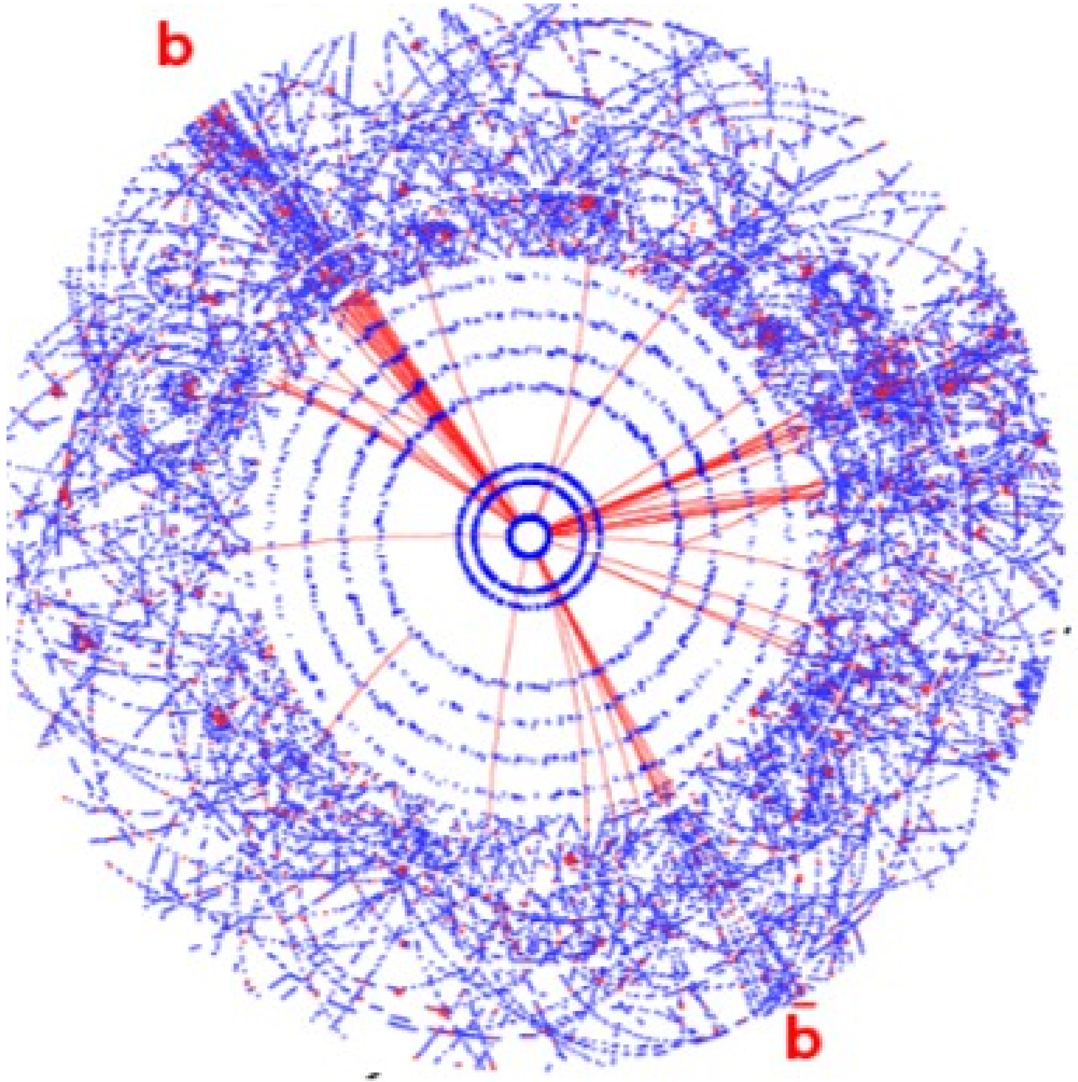
ECFA WG3 Workshop – May 2023 CERN

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

ECFA

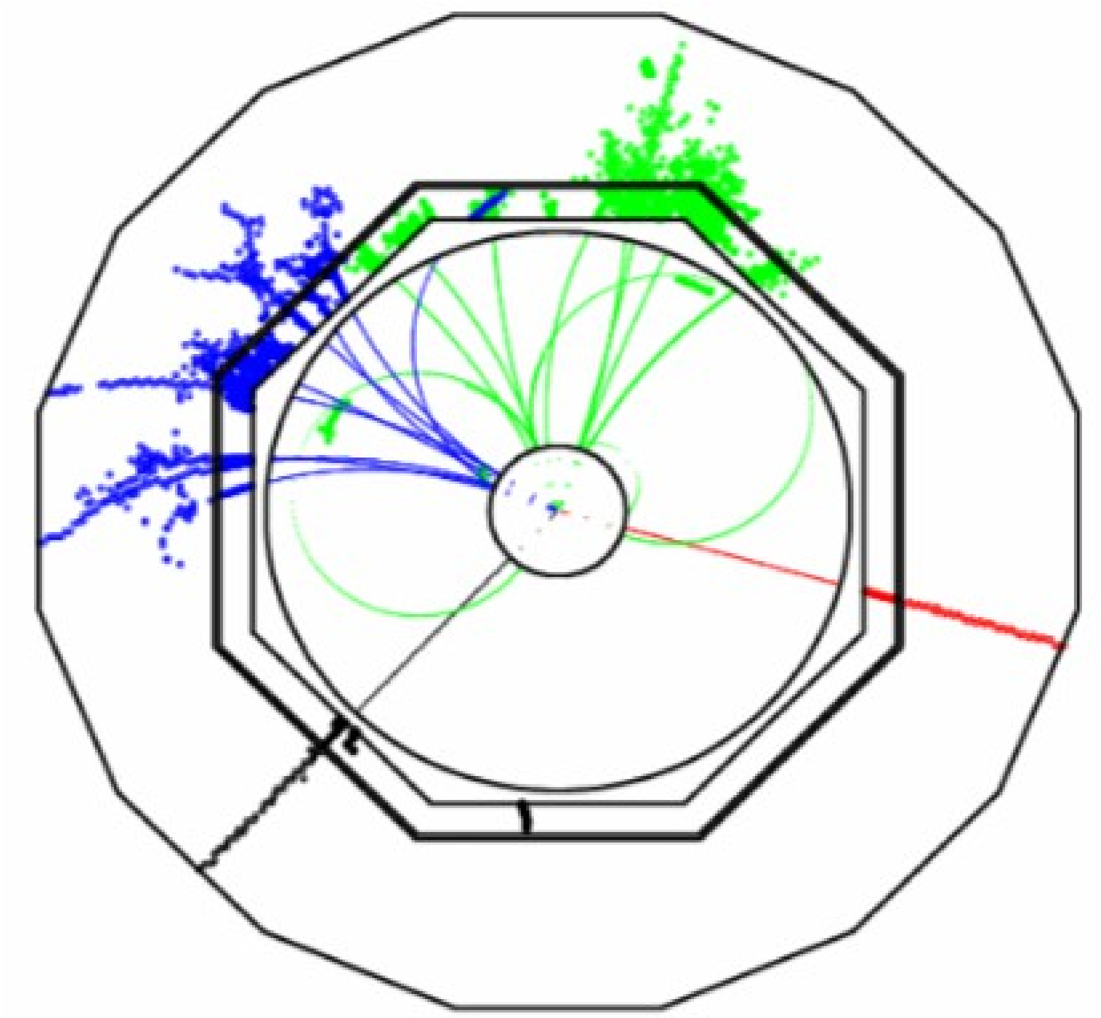
European Strategy Update

Hadron-hadron collisions e.g. LHC



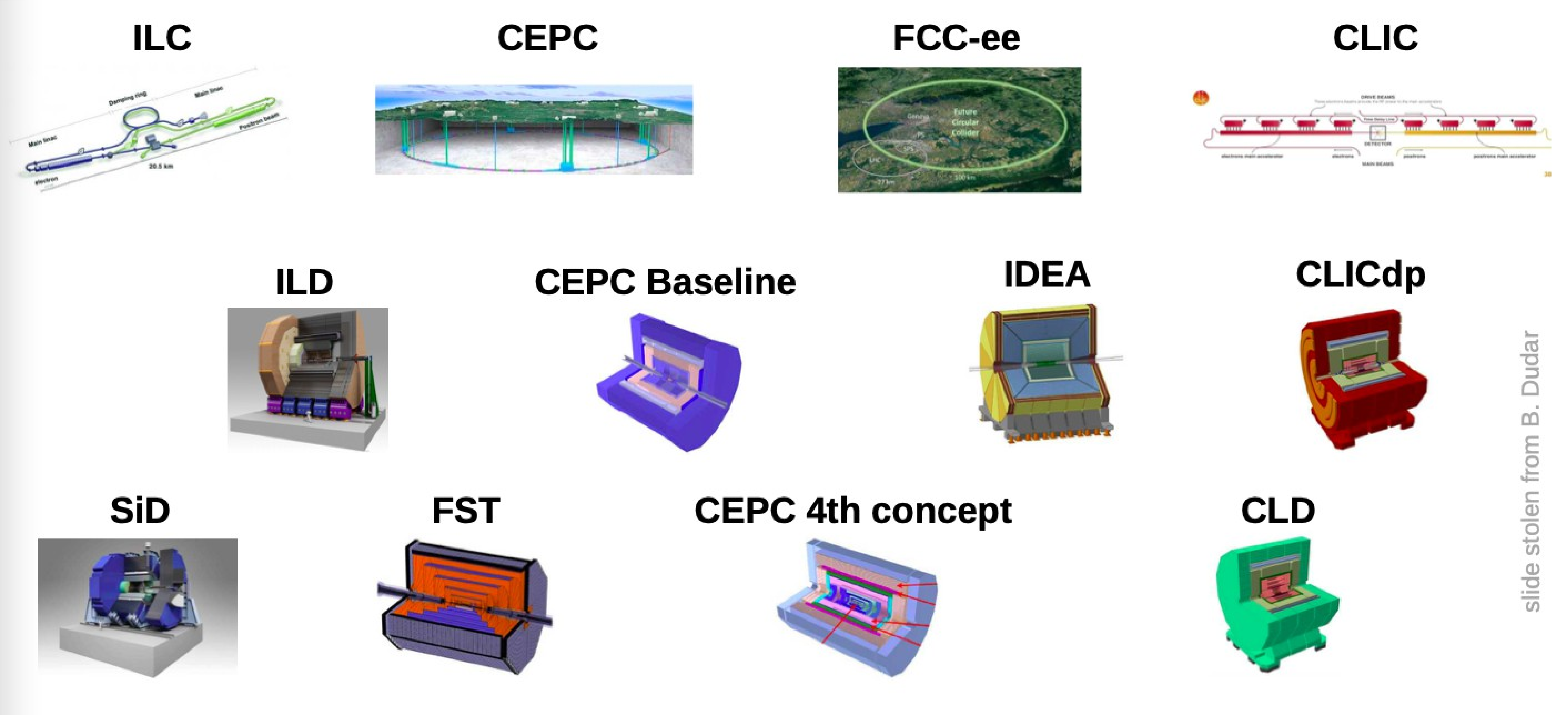
- Busy events
- Require hardware and software triggers
- High radiation levels

e^+e^--collisions



- Clean events
- No trigger
- Full event reconstruction

Detector systems – Target projects



Uli Einhaus, this morning

Detector Optimisation – Software Tools studied in WG2

- GENERATORS
- SIMULATION
- RECONSTRUCTION
- ALGORITHMS & TOOLS
- SOFTWARE ECOSYSTEM

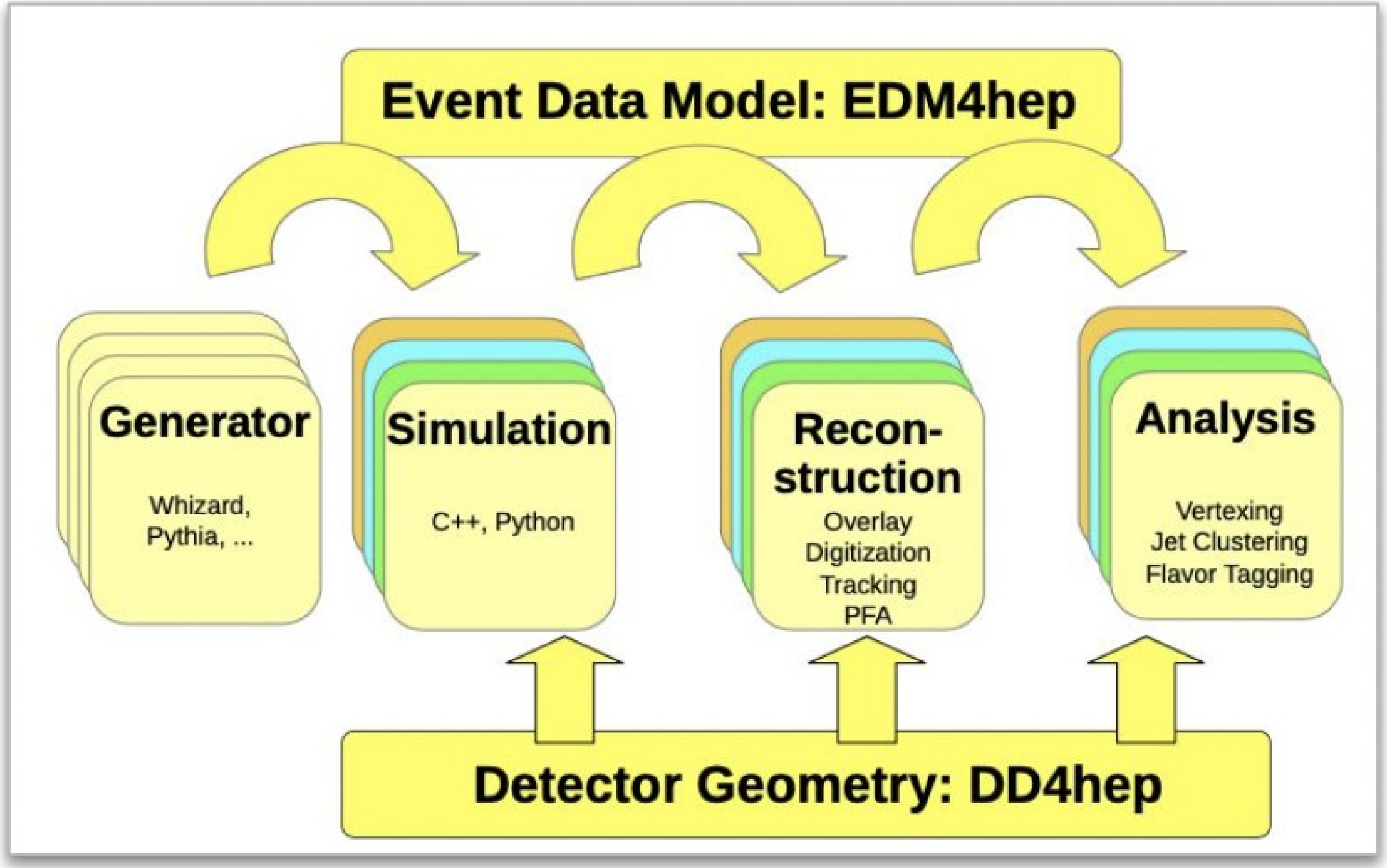
- Monte Carlo generators for e+e- precision EW, Flavour, Higgs, and top physics,
- Luminosity measurements
- Software framework
- Fast simulation and the limitations of such techniques
- Full Simulation
- Track and vertex reconstruction algorithms
- Jet algorithms / jet reconstruction
- Particle-flow reconstruction and global event description
- Requirements on particle identification
- Flavour tagging algorithms
- Importance of timing information
- Constrained fit

Slide courtesy by D. Zerwas

Detector Optimisation – Software Ecosystem Key4HEP

Create a software ecosystem integrating in optimal way various software components to provide a ready-to-use full-fledged solution for data processing of HEP experiments

- *Key4hep* federates FCC, ILC, CLIC , CEPC and other experiments
- In use or medium term migration plan
- Supported by R&D efforts (AIDA, CERN EP etc.)
- KEY4HEP coordinators consulted and involved in the the organisation of all WG2 meetings
  Frank Gaede
  Gerardo Ganis
  Andrè Sailer



Slide courtesy by D. Zerwas

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

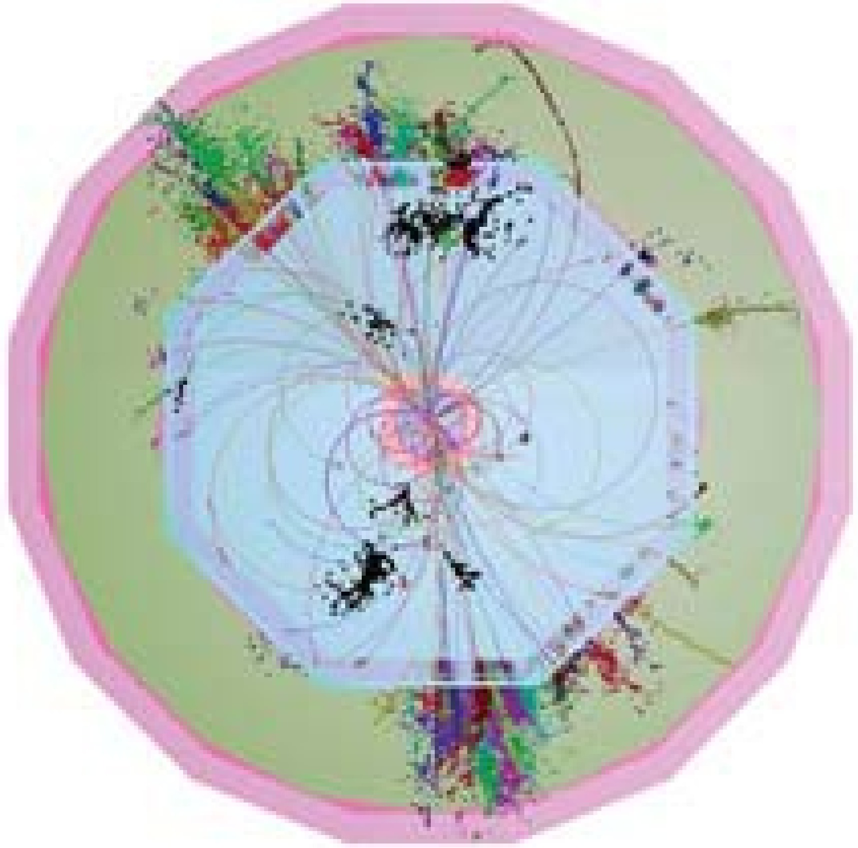
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(GeV))^{1/2}$ (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+)

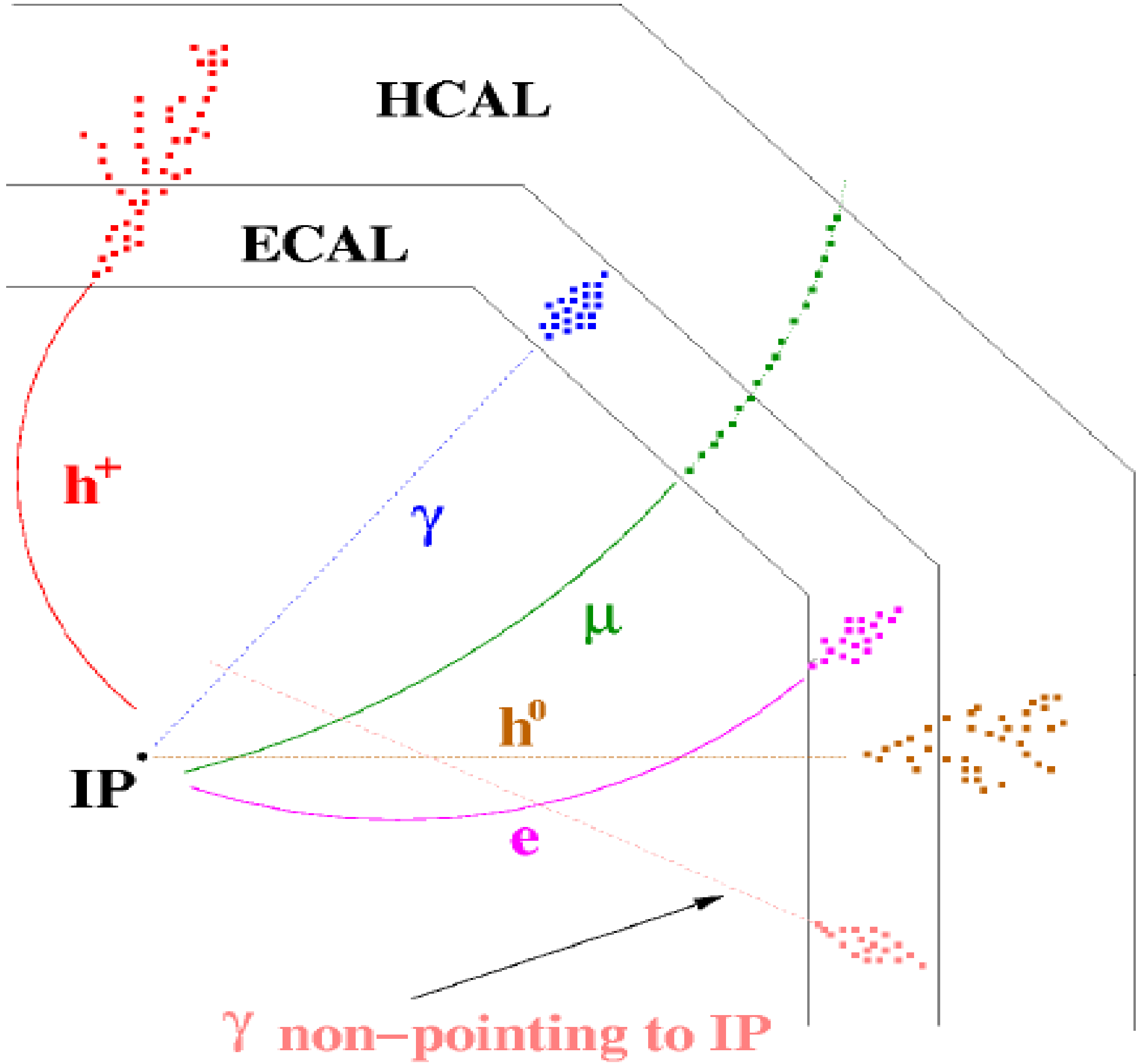
- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Particle Flow Detector Layout

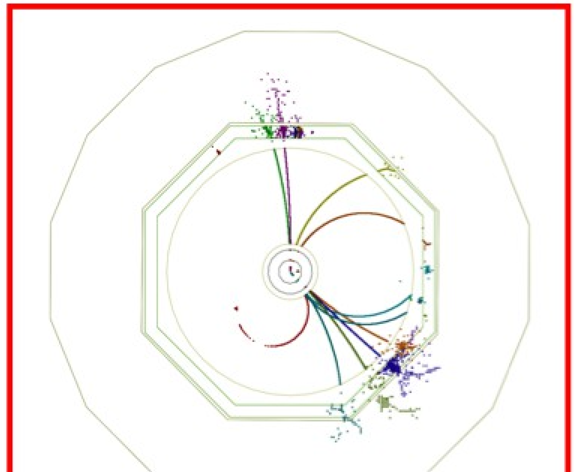
- Jet energy measurement by measurement of **individual particles**
- Maximal exploitation of precise tracking measurement

- 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



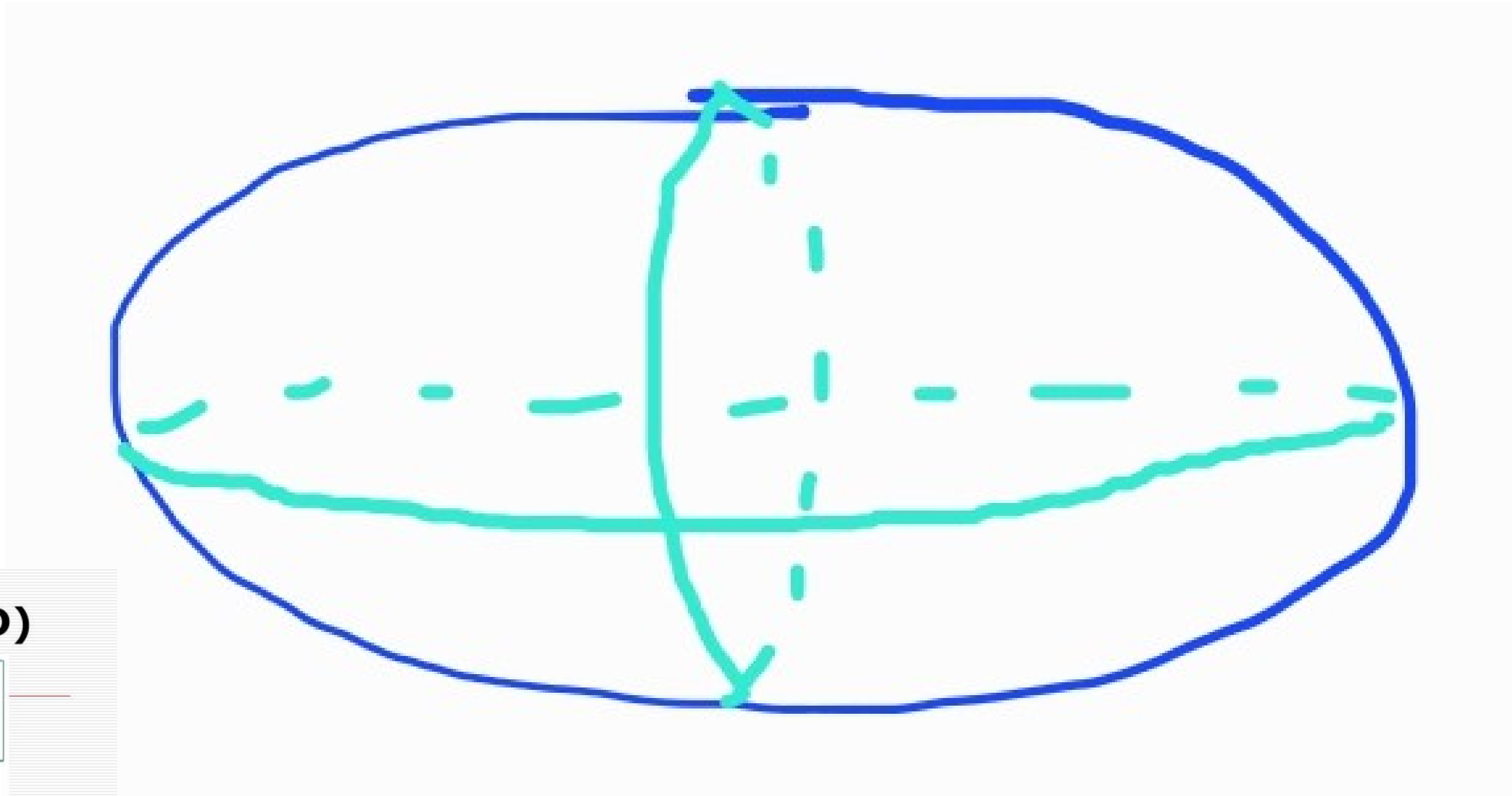
Detector Hermeticity

Invisible Higgs decays

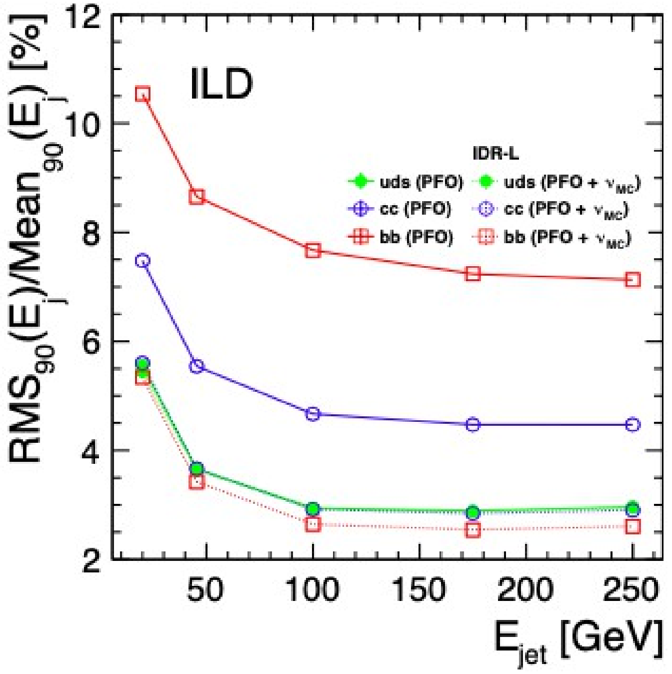


e+e- → qq H → qq inv in ILD detector

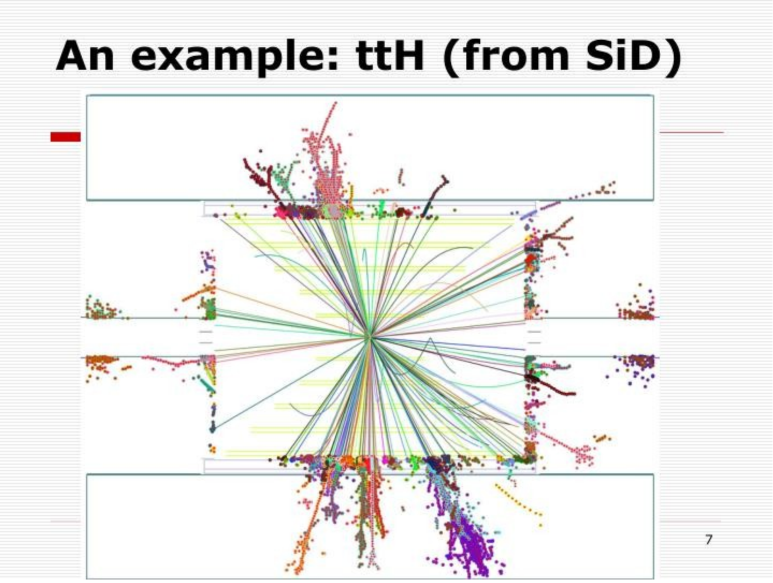
Hermeticity = Acceptance down to the beam pipe and no acceptance holes!



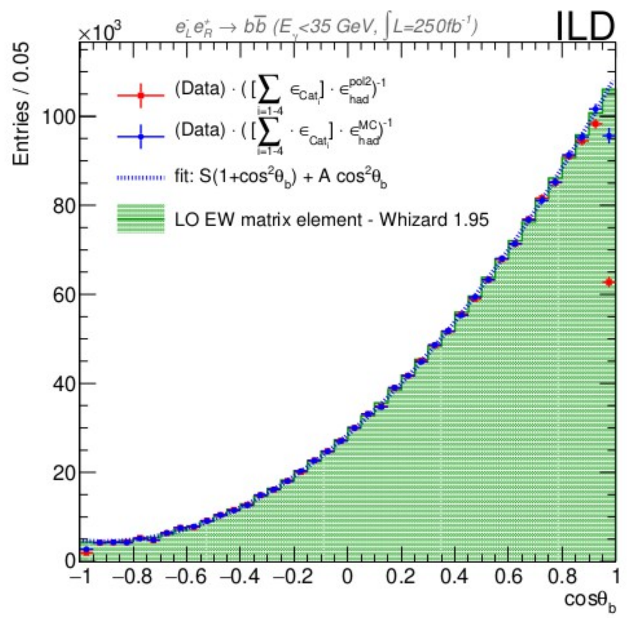
Missing Energy



Rich events:



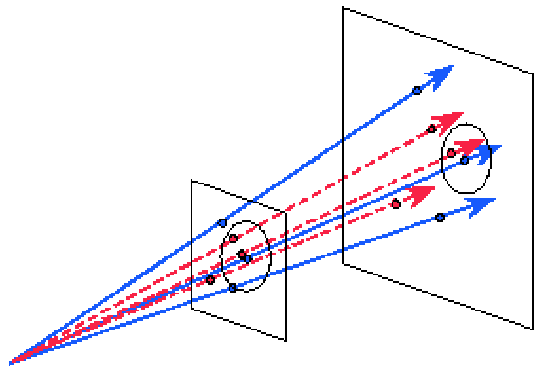
Heavy Quark asymmetries



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

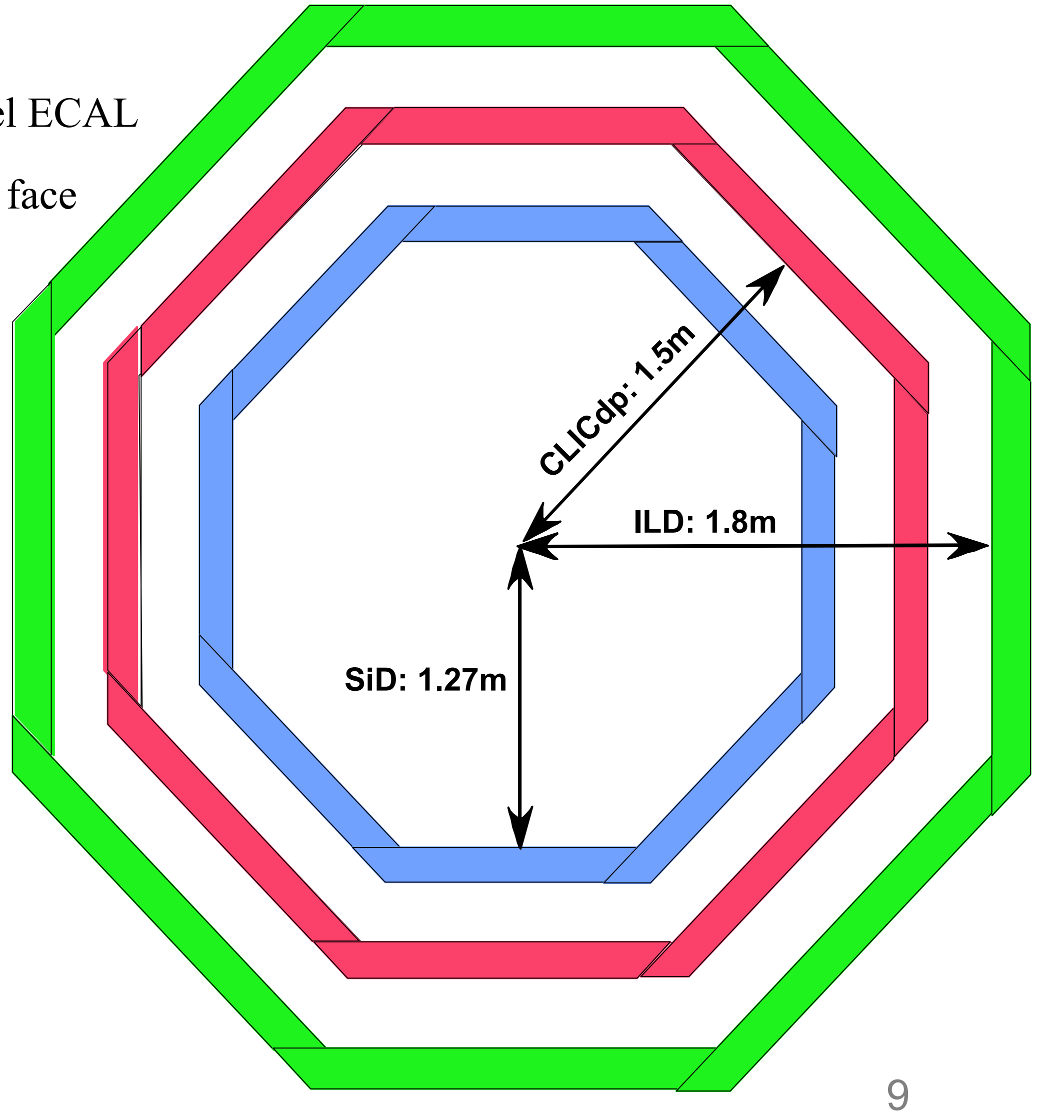
Detectors for e+e- Colliders – Main Parameters

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

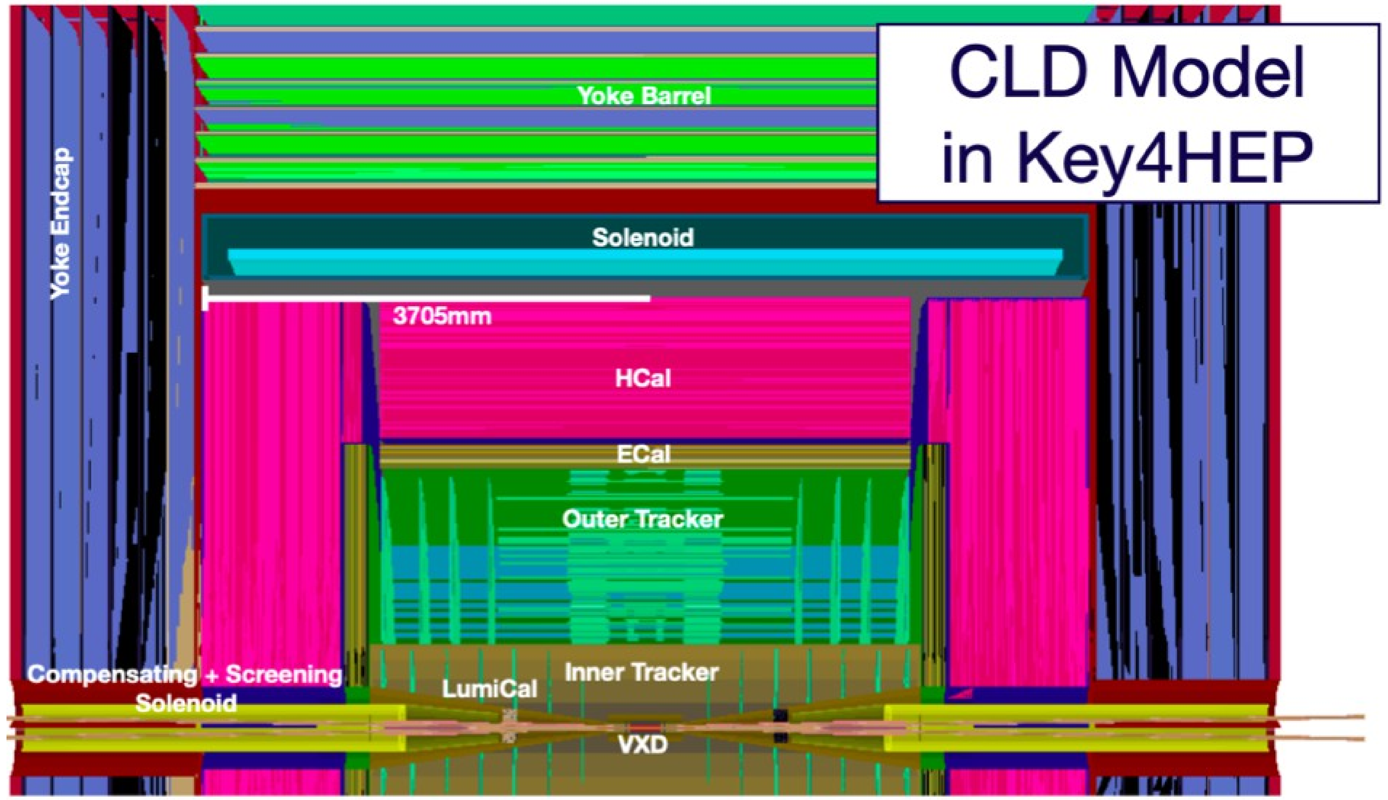
- Figure of merit (ECAL):
  - Barrel: $B R_{in}^2 / R_m^{effective}$
  - Endcap: "B" $Z^2 / R_m^{effective}$
    - R_{in} : Inner radius of Barrel ECAL
    - Z : Z of EC ECAL front face
- Different approaches
  - SiD: $B R_{in}^2$
  - CLICdp: $B R_{in}^2$
  - ILD $B R_{in}^2$
  - CLD: $B R_{in}^2$



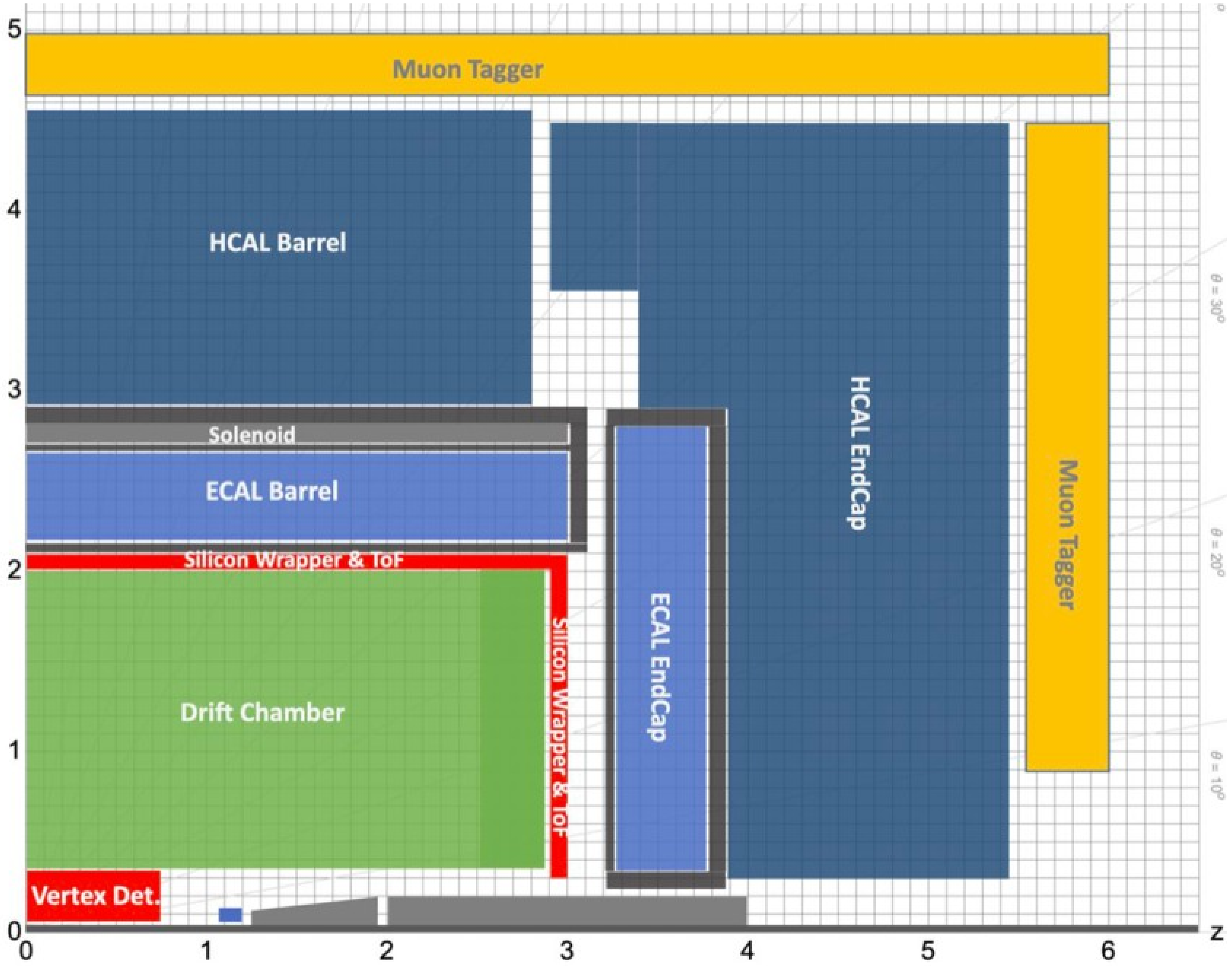
- Roughly: The smaller B the bigger $R_{in,Ecal}$ has to be
- Overall outer radius will depend on required Hcal thickness
- ... and details of return yoke design
  - Cost, safety considerations ...

Detectors for e+e- Colliders – Main Parameters

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



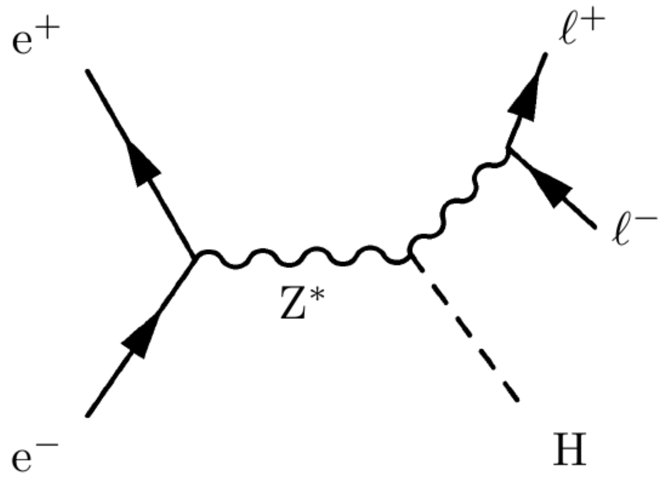
FCC-ee detector Model with Lar Ecal
Solenoid **between** Ecal and HCAL

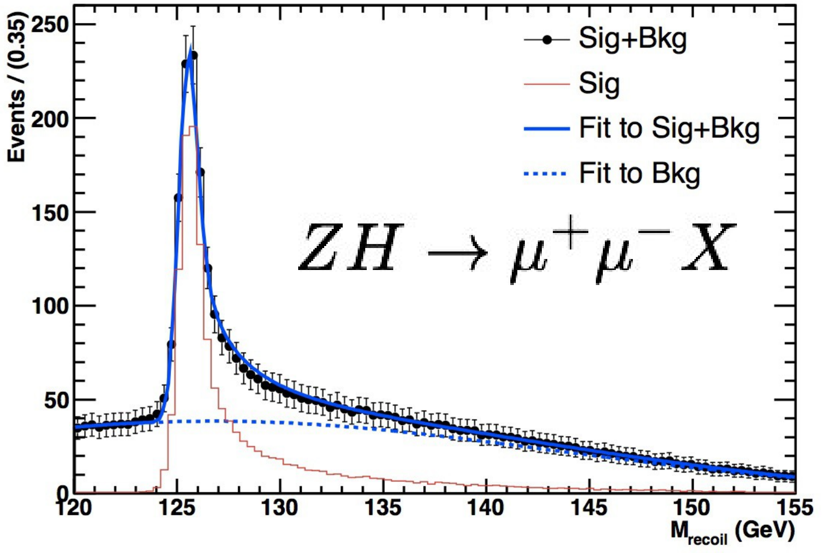


- The position of the solenoid is an obvious topic of study (if not done yet)
  - Comparison has to be carried out at equal footing
  - Definition of benchmarks, detail of detector simulation

Central Tracking

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



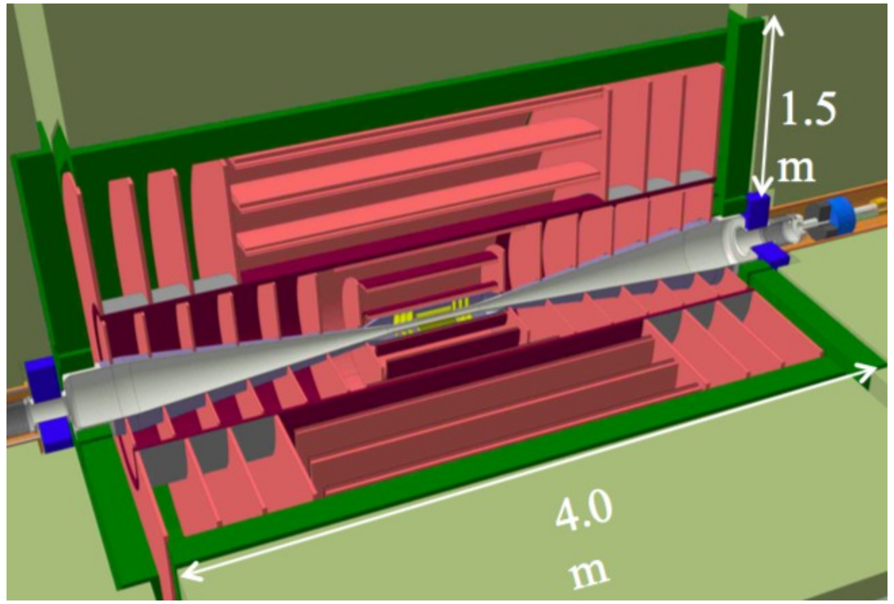


Gluckstern Formula:

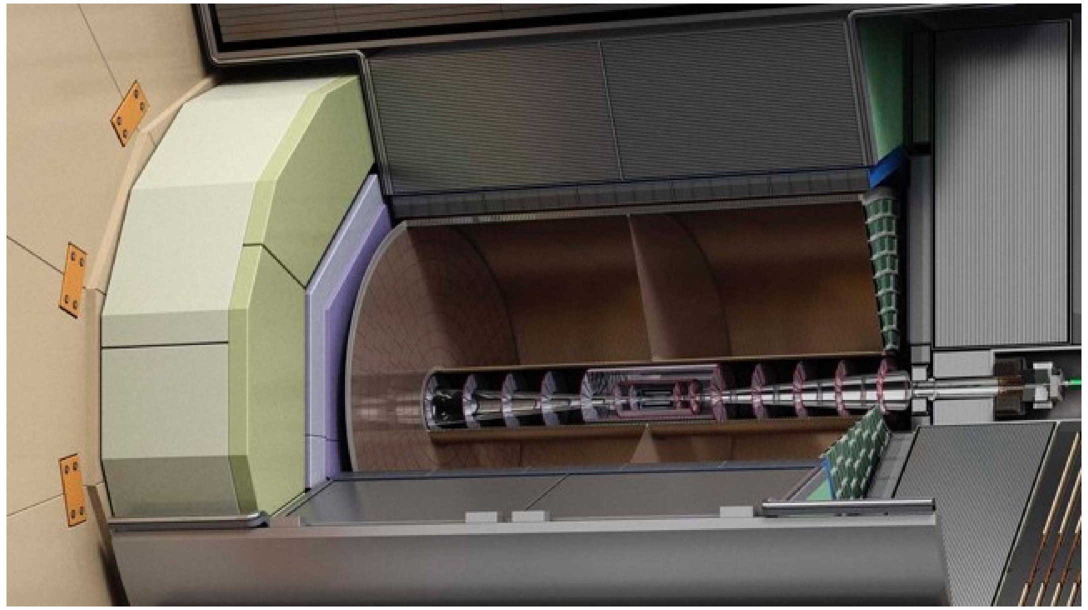
$$\frac{\Delta p_t}{p_t^2} = \frac{\sigma_{r\phi}}{0.3\, L^2 B} \sqrt{\frac{720}{N+4}}$$

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

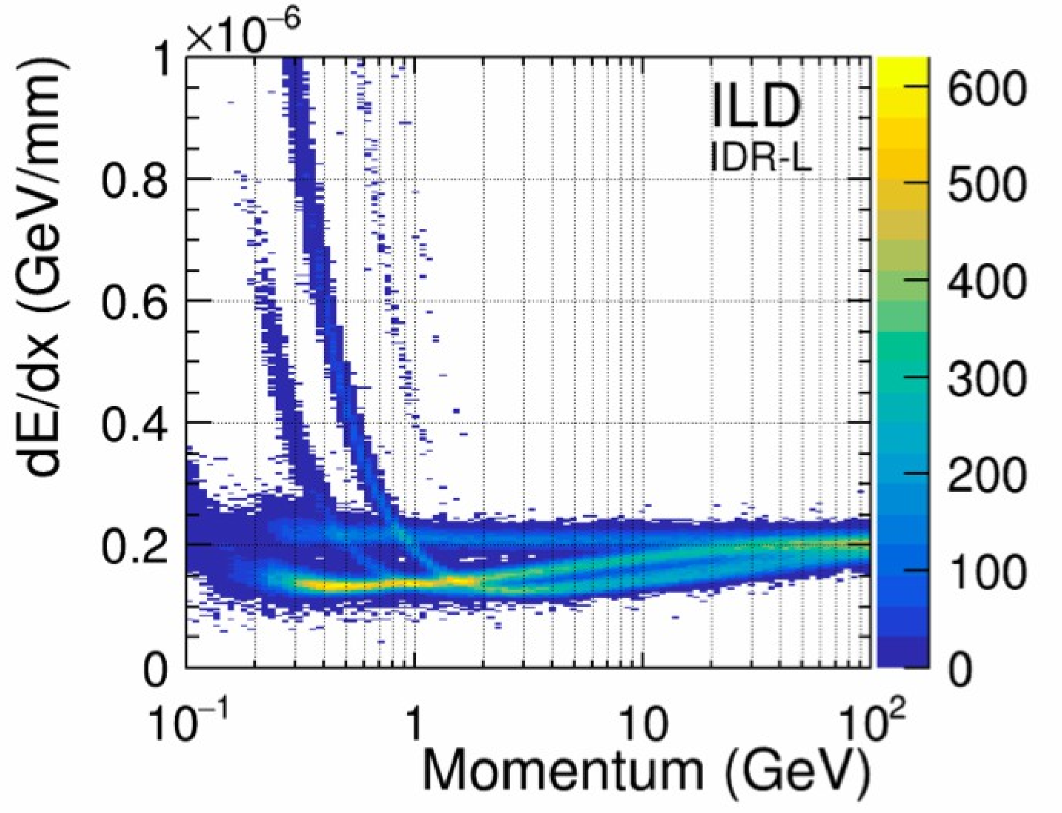
Option 1: All silicon tracking



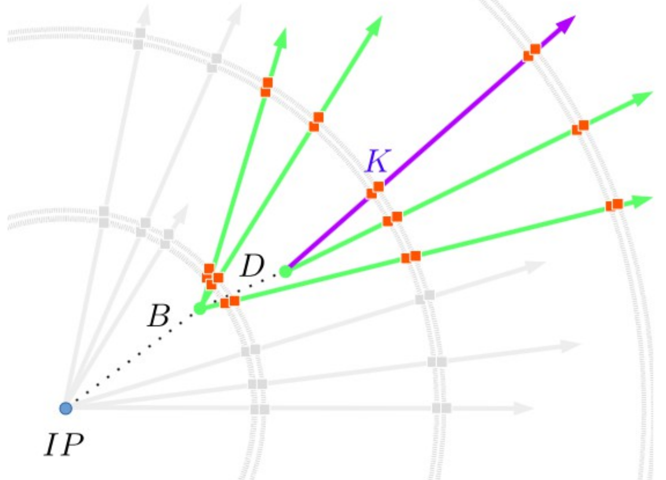
Option 2: Gaseous tracking

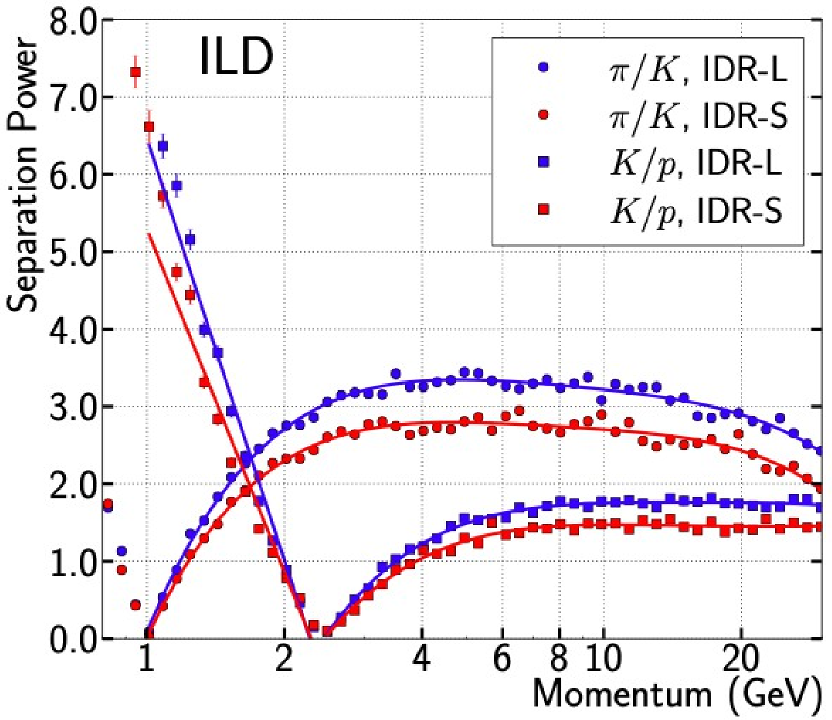


Gaseous Tracking – dE/dx in ILD



- 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:

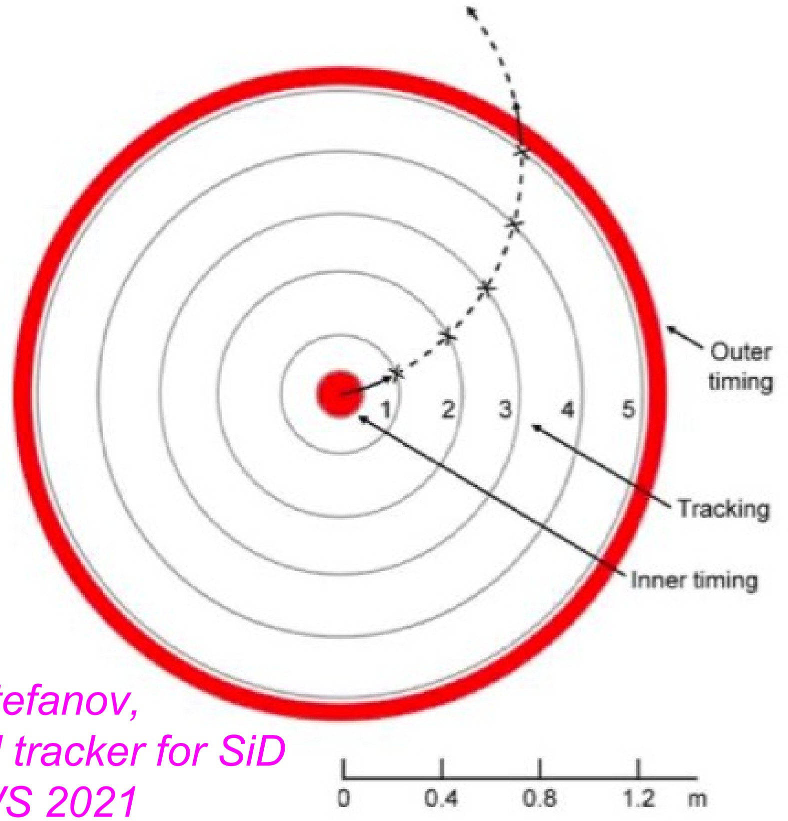
- Kaon identification in ee->tt, ee->bb, ee->cc, ee->ss
  - •Supplementary to vertex charge measurement for heavy quarks
    - •Increases statistics by a factor of two
  - •Backbone of ee->ss
- Separation of W->ud and W->cs

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

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

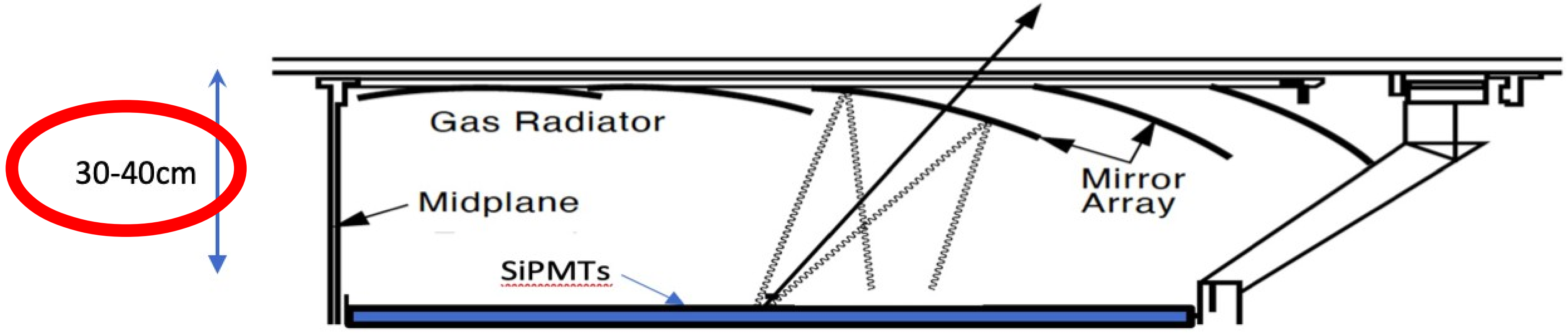
Cerenkov Detector

à la J. Vavra

Three options:

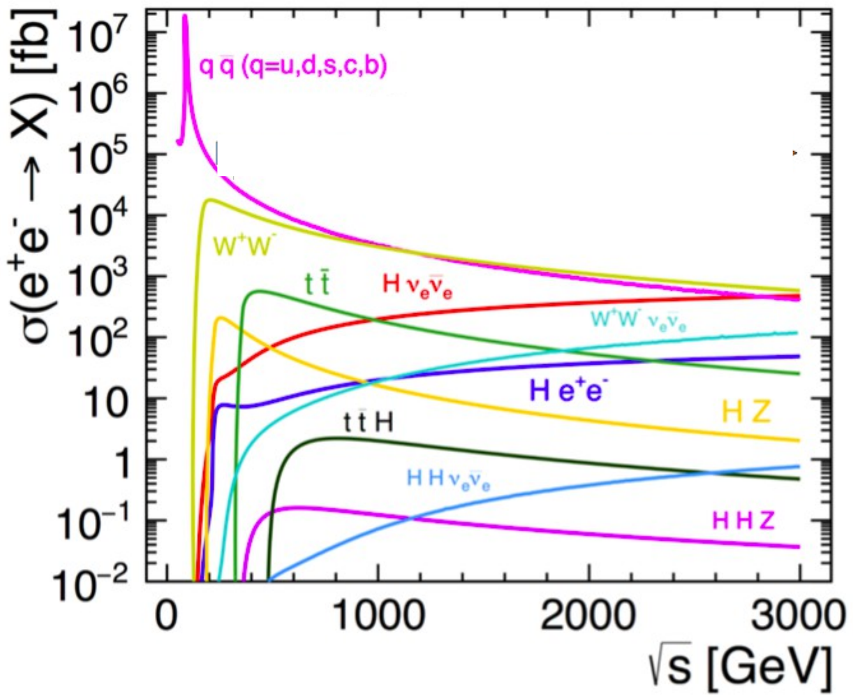
- DIRC: 6- 7 GeV/c
- Focusing Aerogel RICH: 9-10 GeV/c
- Gaseous RICH: 10-30 GeV/c

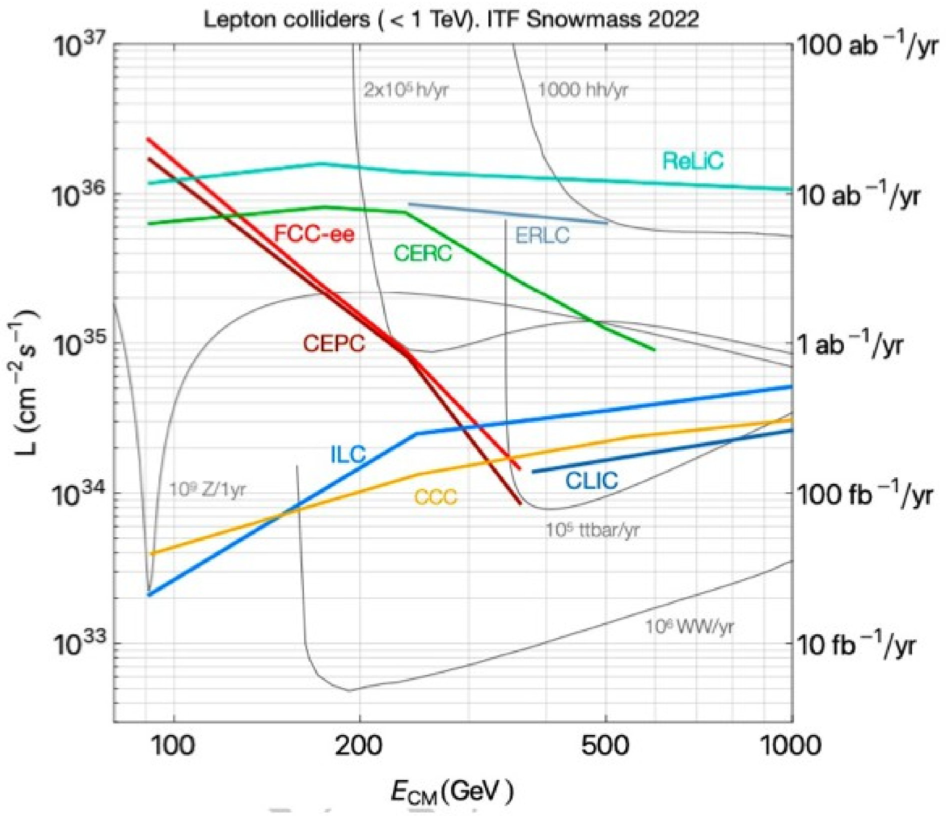
Gaseous RICH looked at for SiD:



- 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

Future direction of R&D - Impact of event rates





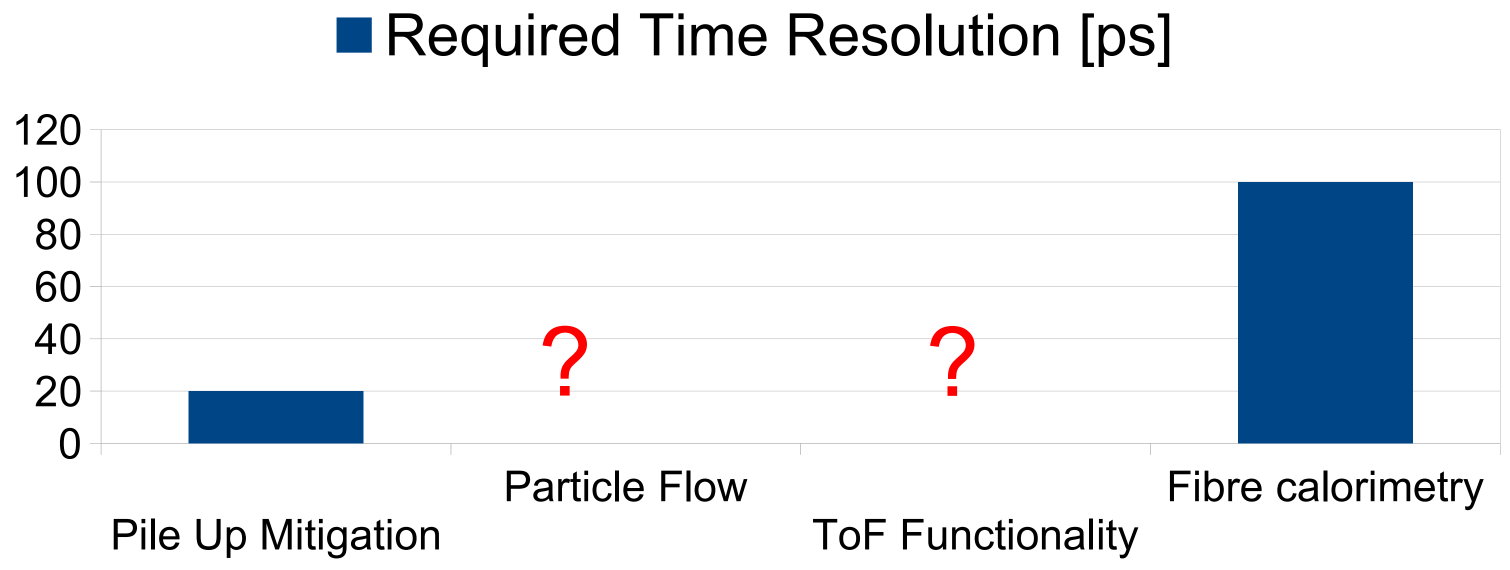
High energy e+e- colliders:

- 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

Timing ?

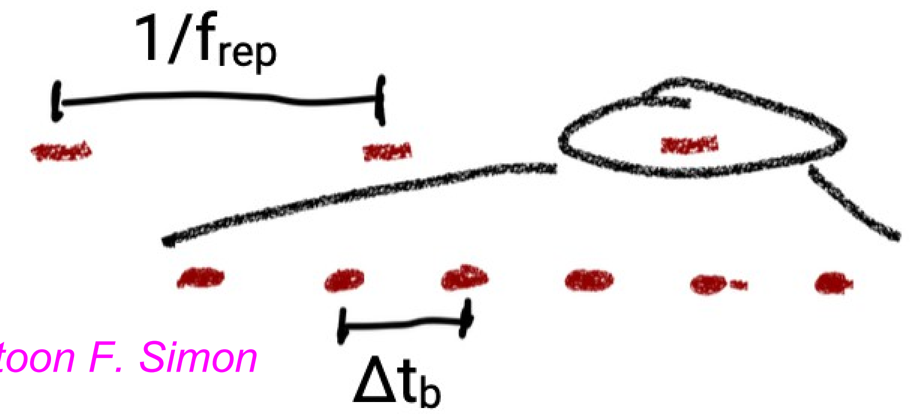
- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters 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

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

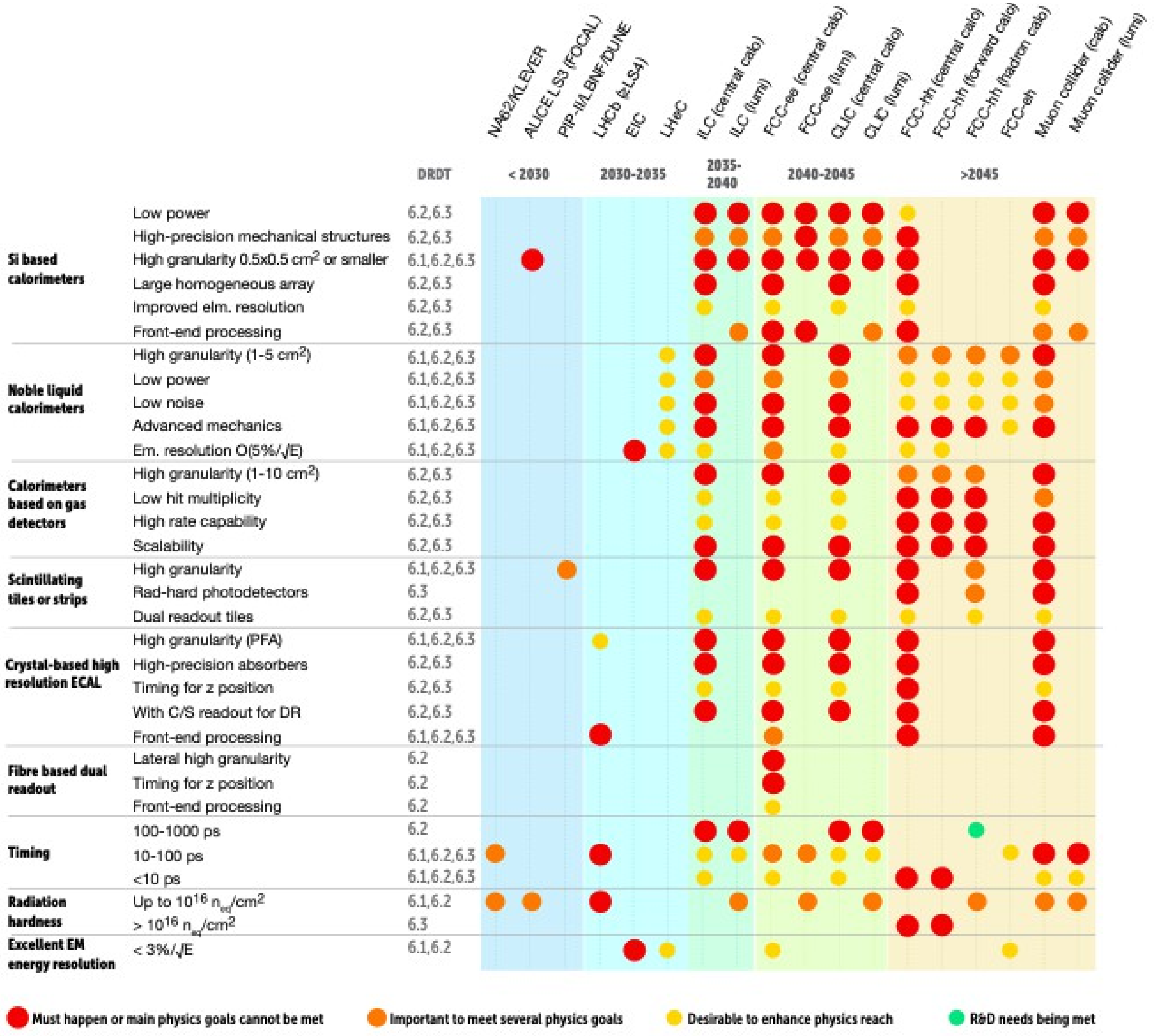
- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in “continuous” mode
  - R&D Goal: Avoid/minimise active cooling in also continuous mode
  - Challenge differs depending on where the electronics will actually be located

ECFA

Calorimetry- Identified Key Technologies and R&D Tasks

European Strategy Update

- 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



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

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)

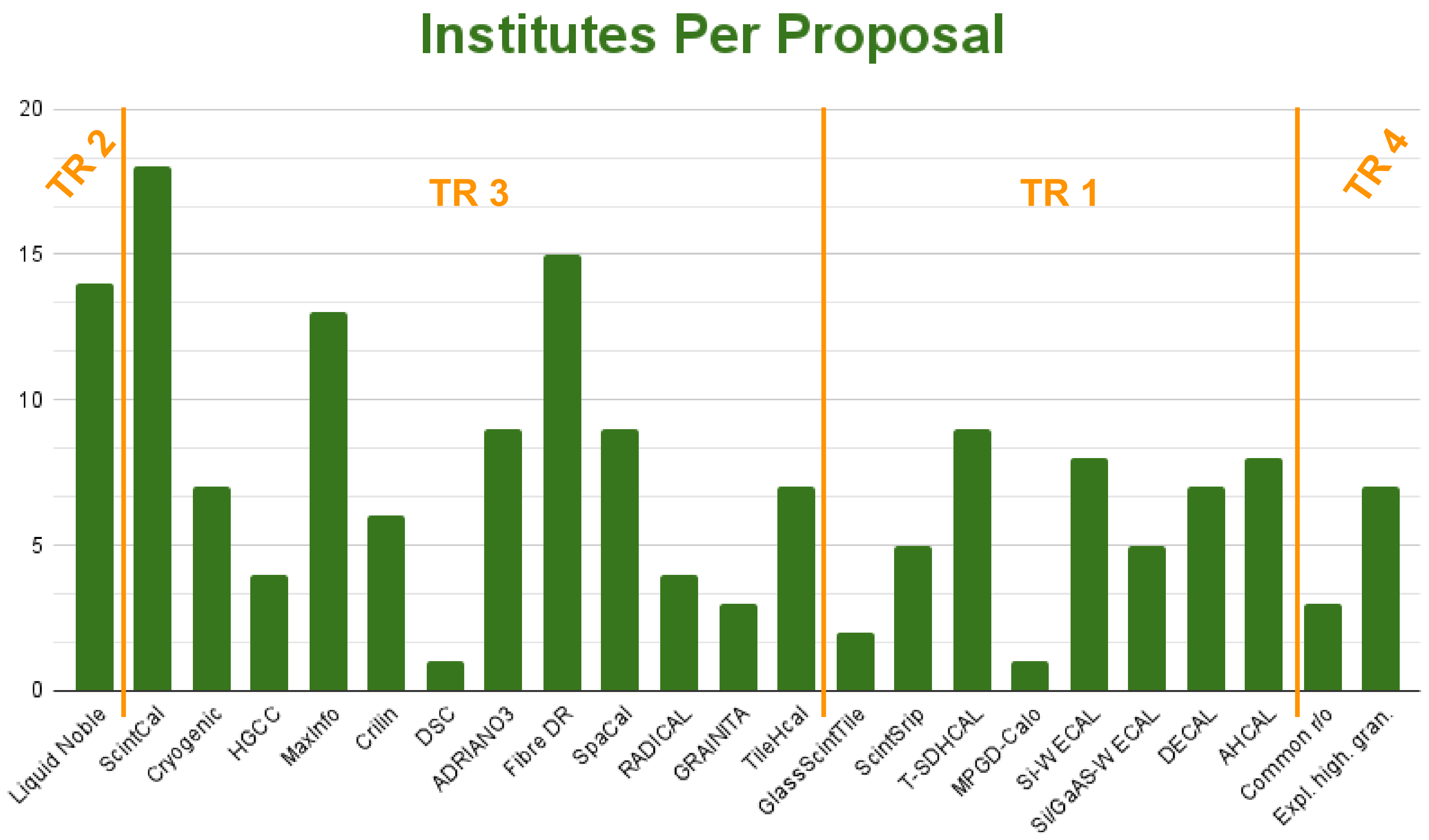
Track 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
Track Conveners:
Etiennette Auffray (CERN), **Gabriella Gaudio** (INFN-Pavia), **Macro Lucchini** (U. and INFN Milano-Bicocca), **Philipp Roloff** (CERN), **Sarah Eno** (U. of Maryland), **Hwidong Yoo** (Yonsei Univ.)

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

G. Gaudio
2^{nd} Calorimeter Community Meeting

Input proposals

23 comprising 110 institutes/labs received



DRD Calo – Basic structure

Management: Gouvernmental and executive bodies including Speakers Bureau (→ Dissemination)

Work Areas: Will deliver monitorable results and enable R&D with shared interest

- Technologies will emerge from input-proposals
  - Maybe after some minor regrouping

Full integrated sampling Calorimeters ~Track 1
- Technology 1
- Technology 2
- ….

Liquified Noble Gas Calorimeters ~Track 2

Optical Calorimeters ~Track 3
- Technology 1
- Technology 2
- ….

Transversal Activitites (common collaboration interests):

- Materials
- Photodetectors, Electronics and DAQ
- Testbeam Facilities snd Infrastructure
- Detector Physics, simulation, algorithms and s/w tools
- Industrial connection + technological transfer

DRD Calo – Basic structure

Management: Gouvernmental and executive bodies including Speakers Bureau (→ Dissemination)

Work Areas: Will deliver monitorable results and enable R&D with shared interest

- Technologies will emerge from input-proposals
  - Maybe after some minor regrouping

Full integrated sampling Calorimeters ~Track 1

- Technology 1
- Technology 2
- ….

Liquified Noble Gas Calorimeters ~Track 2

Optical Calorimeters ~Track 3

- Technology 1
- Technology 2
- ….

Transversal Activitites (common collaboration interests):

- Materials
- Photodetectors, Electronics and DAQ
- Testbeam Facilities snd Infrastructure
- Detector Physics, simulation, algorithms and s/w tools
- Industrial connection + technological transfer

- Transversal Activities are vital for the success of the collaboration
- Transversal Activities will also ensure relations with other DRD

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
- I^2C 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	I^2C
FCC	LAR	Lar	50-200 pF	200 ns	<1 mW	Gb/s	TSMC 130n	1.2 V	I^2C
SKIROC3	CALICE	Si	50 pF	200 ns	<1 mW	Mb/S	TSMC 130n	1.2 V	?

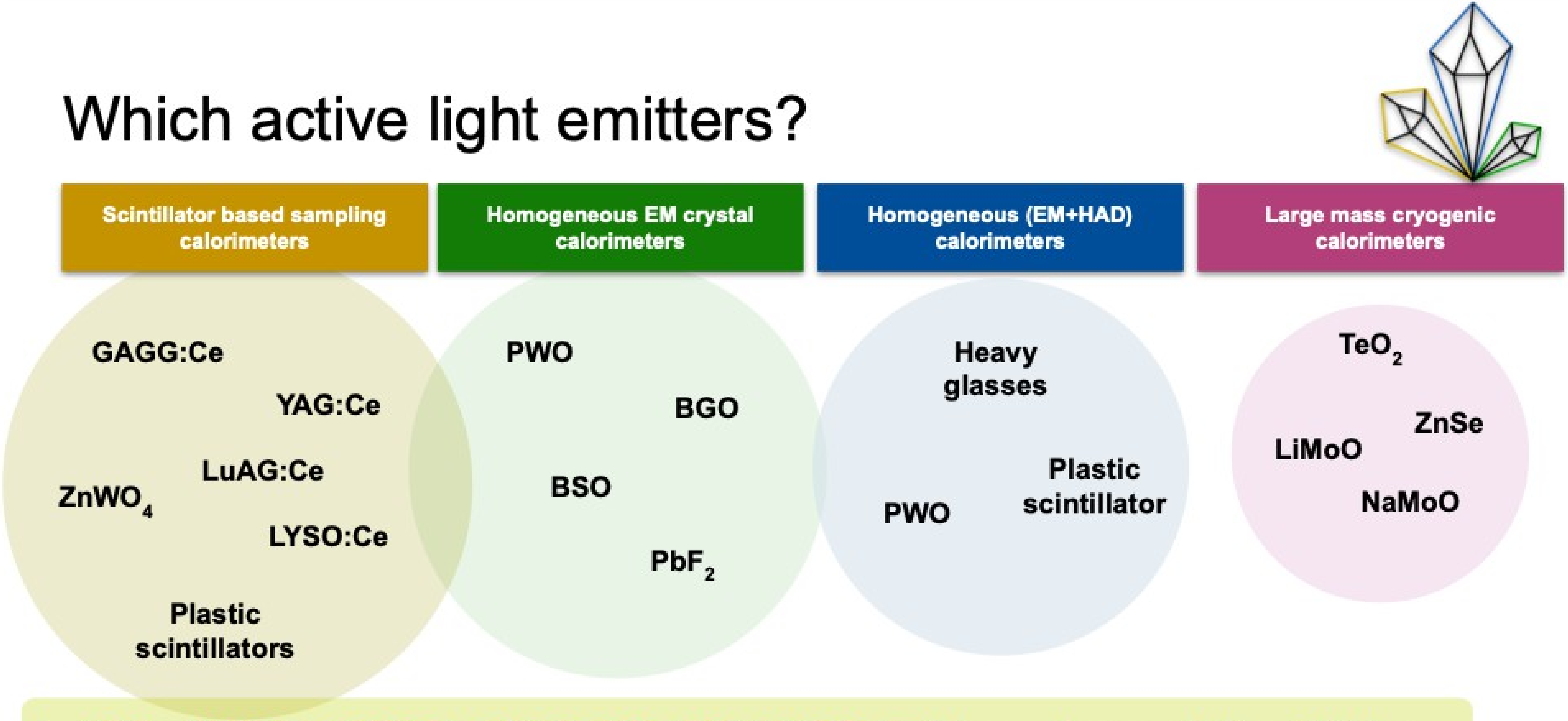
CdLT CALICE meeting 20 apr 2022

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

Materials for optical calorimeters

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

Which active light emitters?



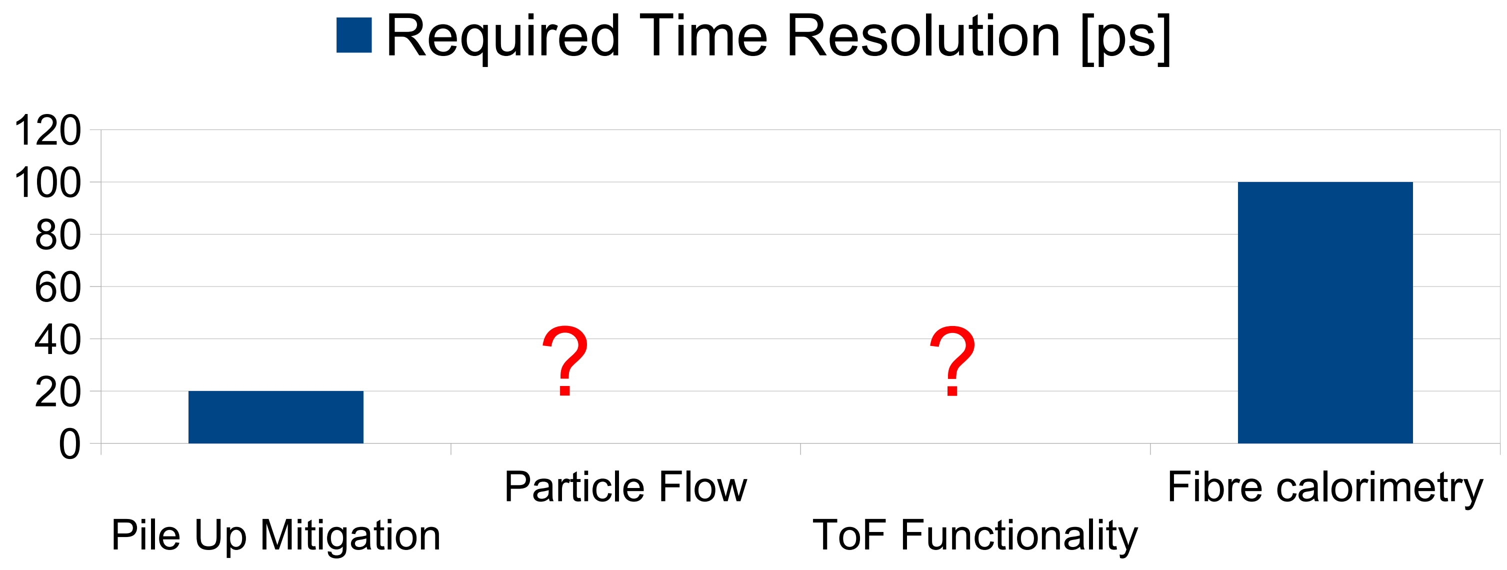
LuAG:Ce, LYSO:Ce, GAGG:Ce, BGSO, BGO, BSO, PWO, BaF_2:Y, heavy glasses, plastic scintillators

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!

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

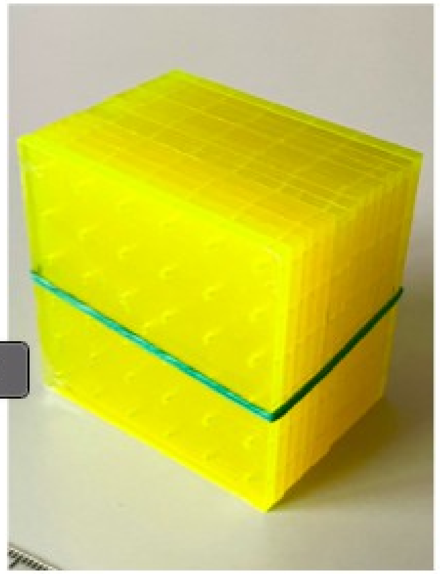


- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

Materials for optical calorimeters

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)

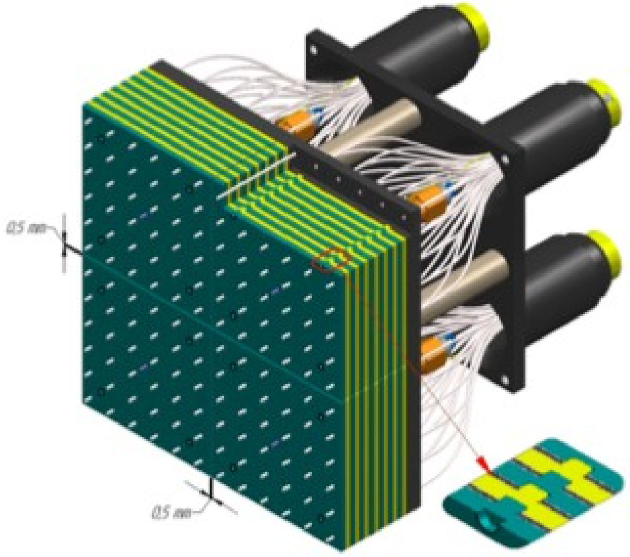
R&D on material has
Overlap with DRD 5

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:

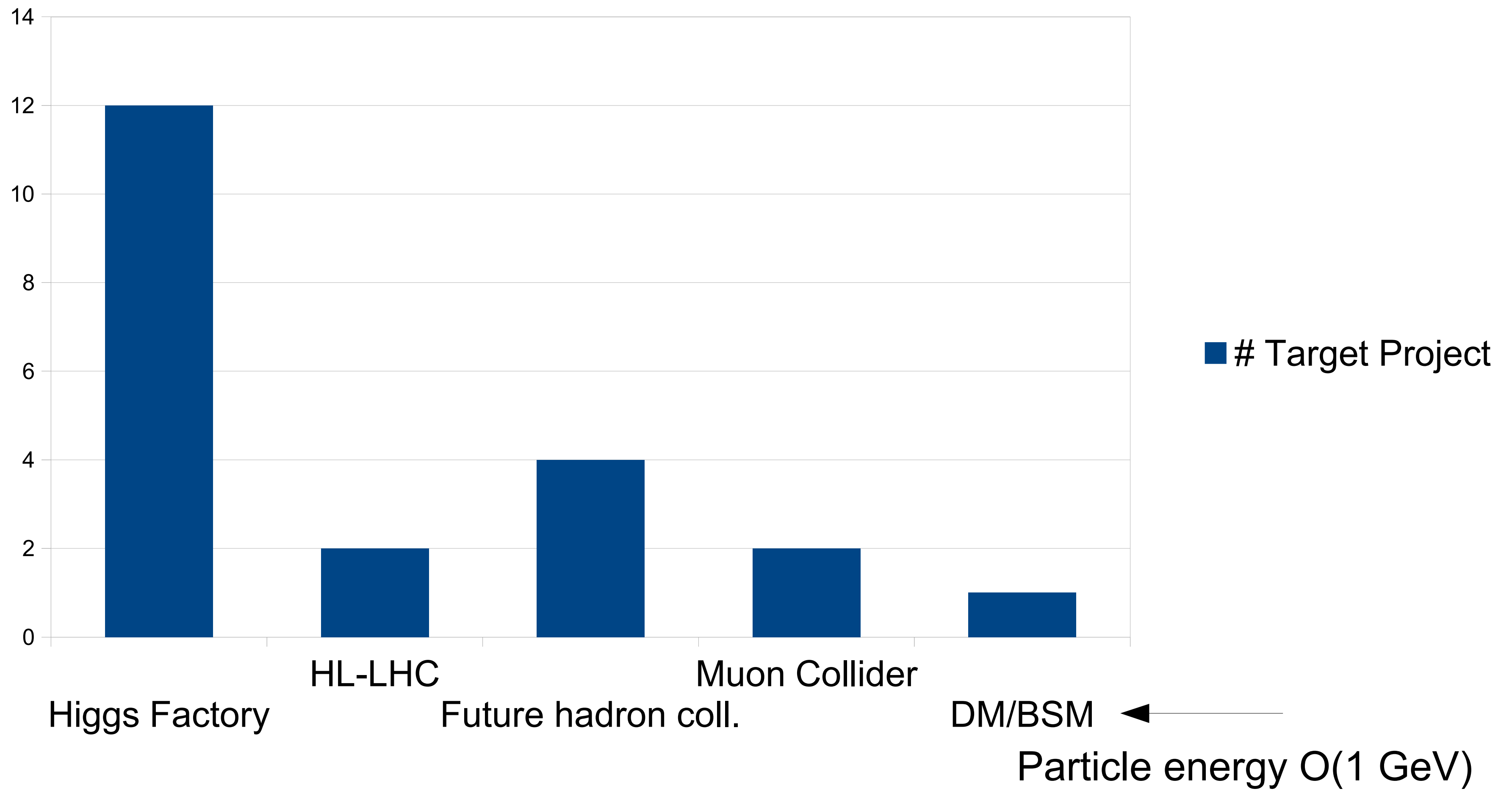
- Easy to construct a shashlyk calorimeter with very fine sampling
- Primary scintillator and WLS materials required: both can be optimized using NC technology



KOPIO/PANDA design
Fine-sampling shashlyk

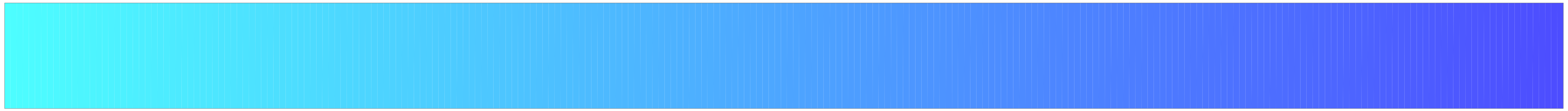
DRD Calo - Input proposals and beam tests

- 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”



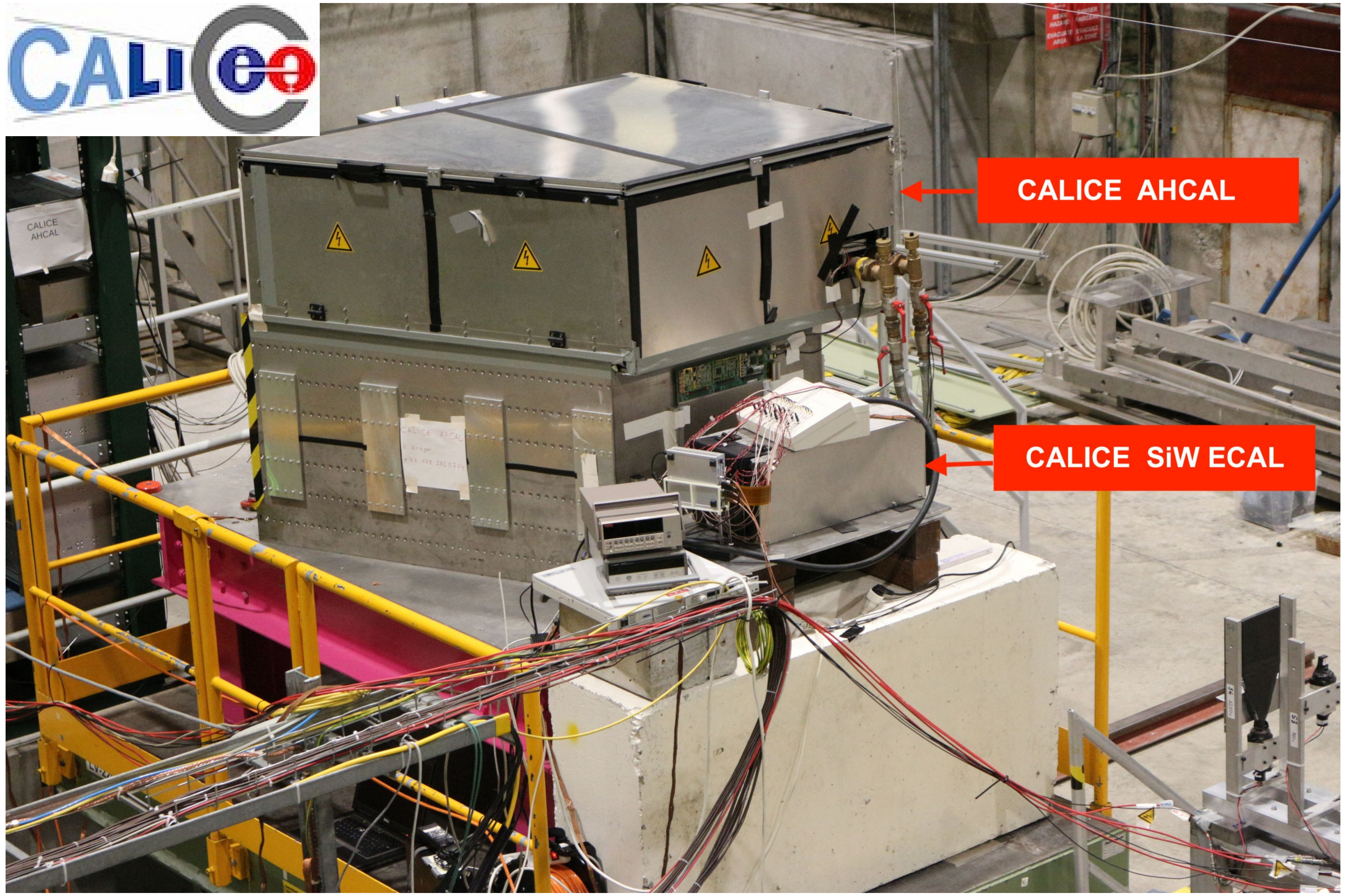
2024 2027 2030

- 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

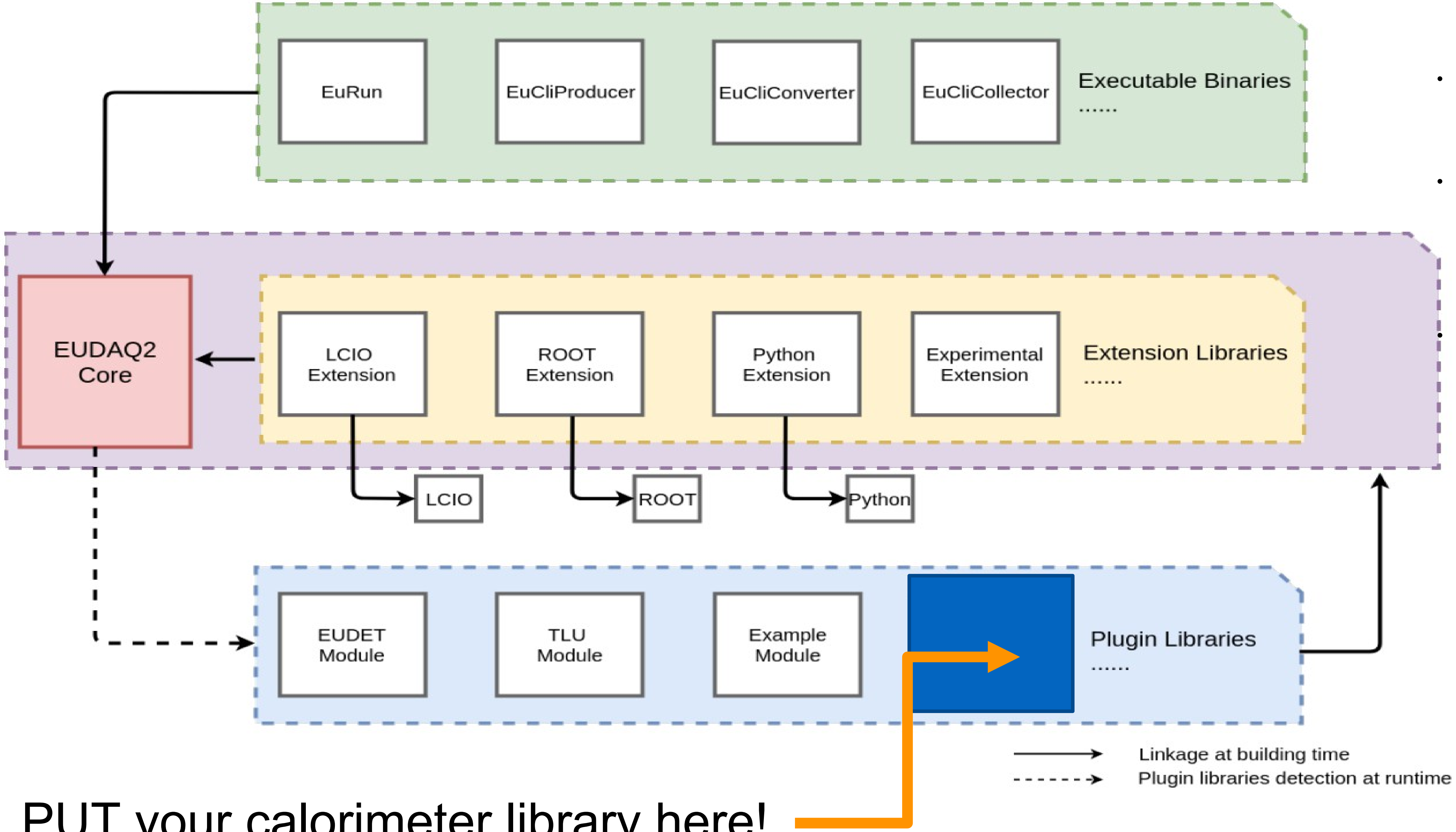
Dedicated Calorimeter Beamline?



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

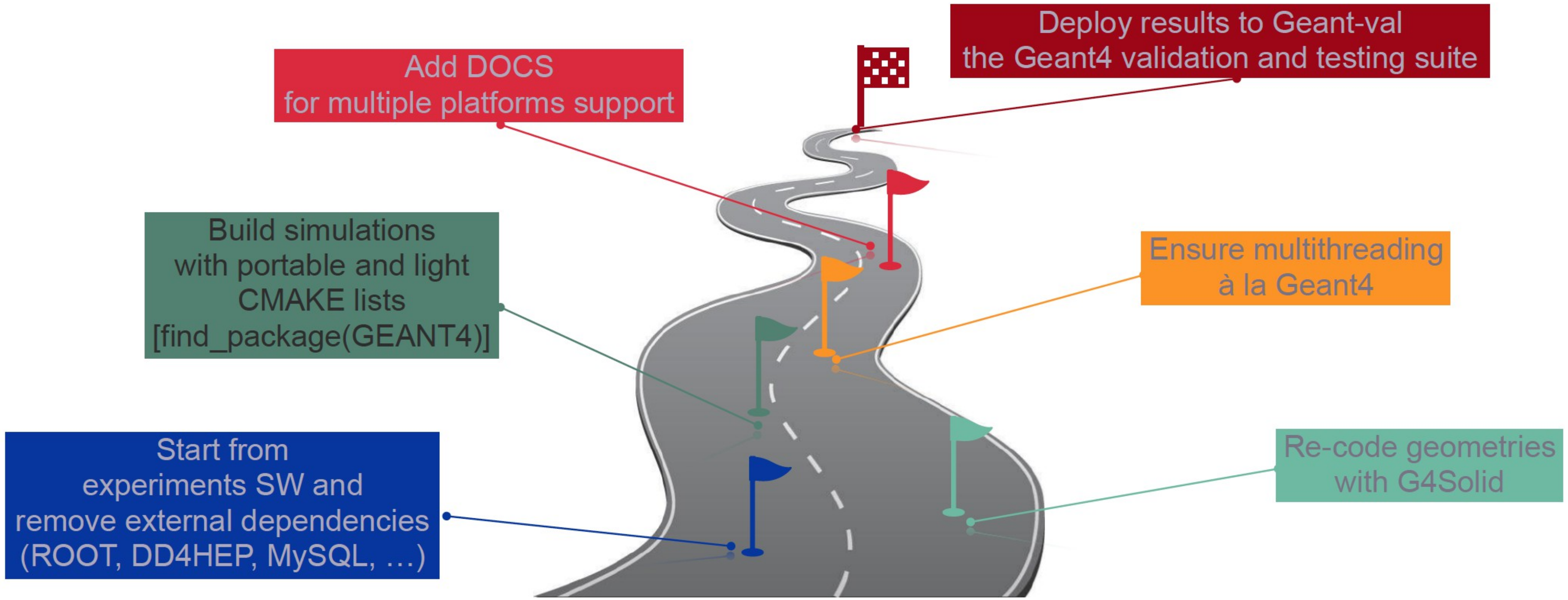
EUDAQ Data Acquisition Systems



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, ...

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

Complex Calorimeters – A playground for modern algorithms

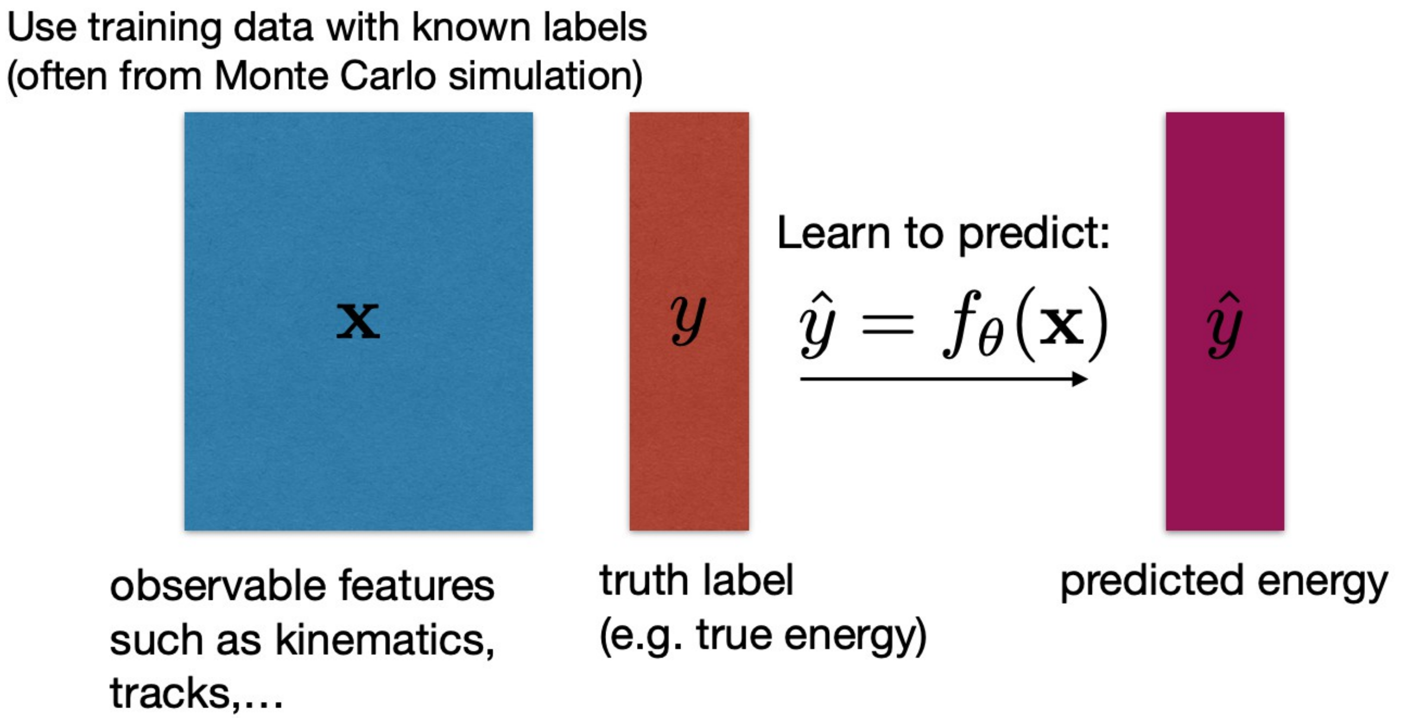
Tommaso Dorigo and MODE Collaboration

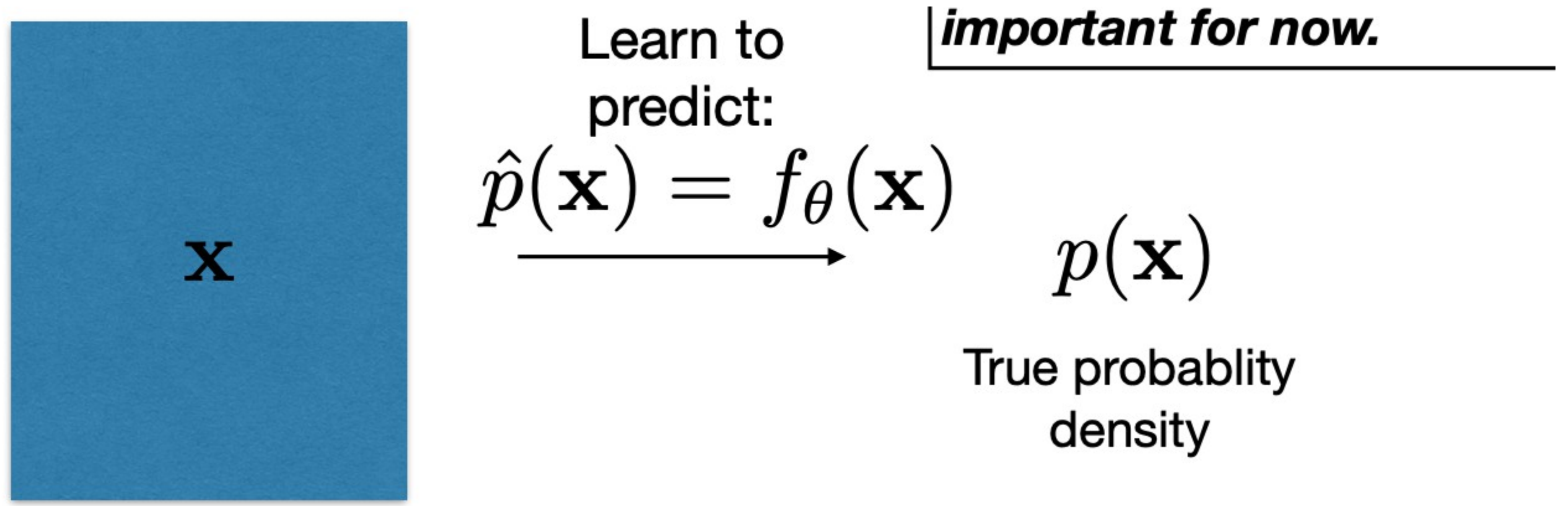
Machine Learning approach is gaining more and more importance in HEP and in calorimetry in particular

highly complex data with large number of detailed information

Simulation provides tagged data for supervised learning

Tracking, clustering, particle ID ...





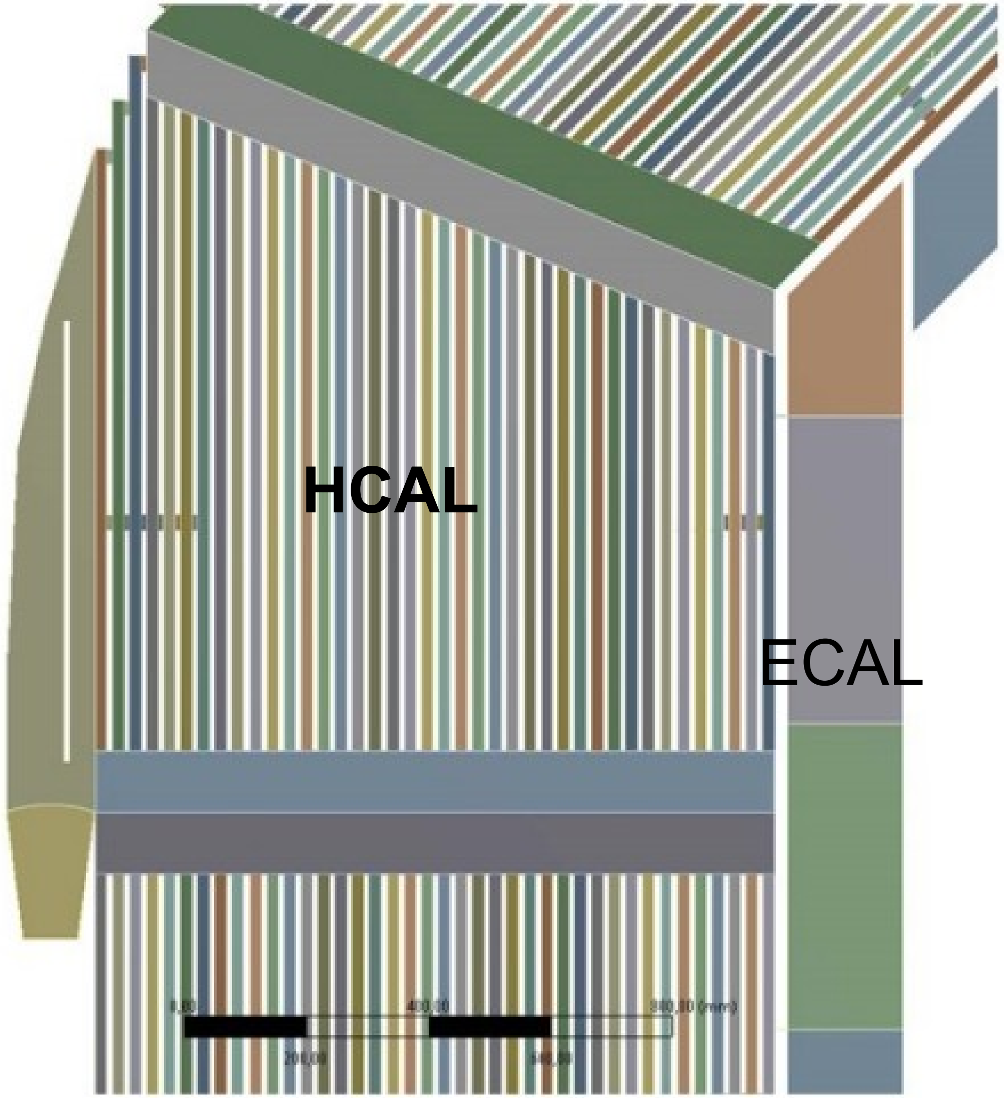
ECFA

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**

Backup

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