Challenges at Future HEP Experiments

- a (hopefully not too) personal selection -

Roman Pöschl

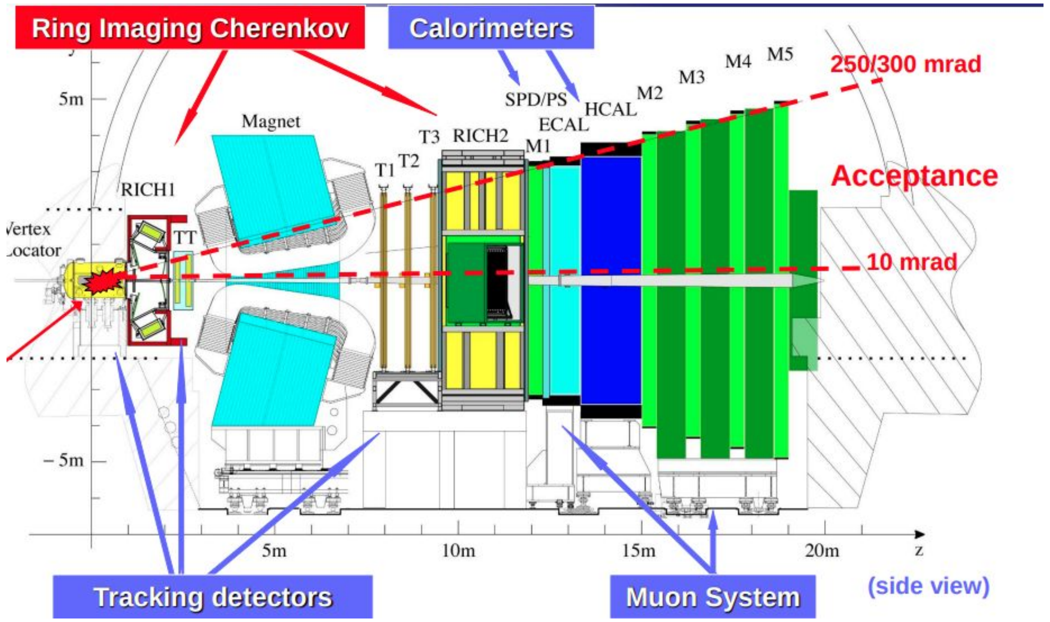
Supported by

R.P. Is indebted to a number of distinguished colleagues in particular **Marc Winter, Paul Colas, Marcel Dermarteau** and **David Rousseau** for having provided input to this talk

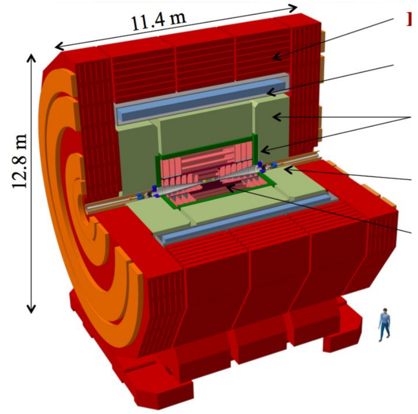
Inauguration Workshop RTG2994 – Würzburg March 2025

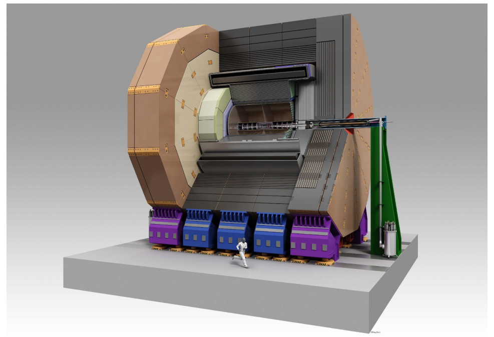
Detector R&D - Target Projects

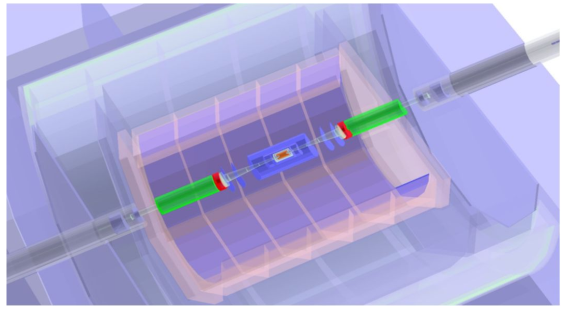
HL-LHC (mainly) after LS4

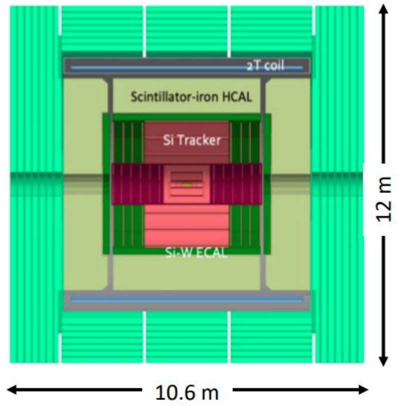


Higgs Factories

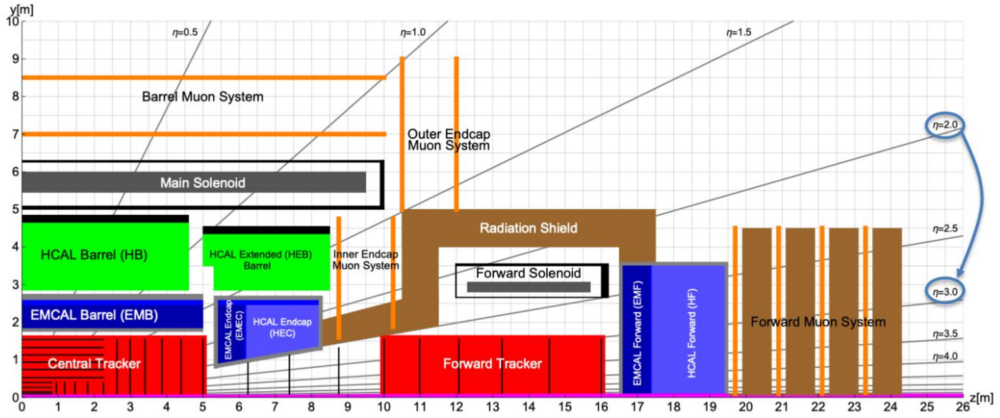




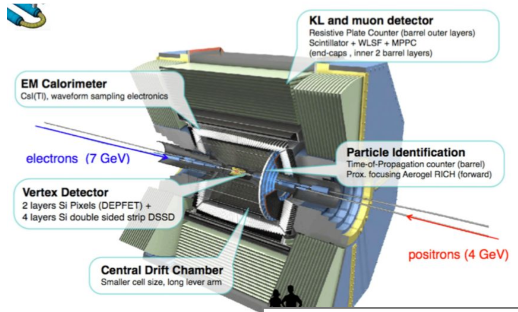


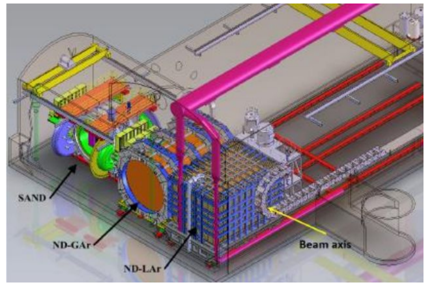


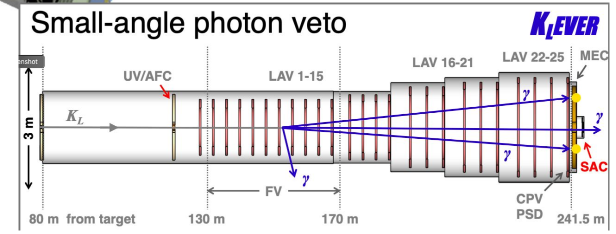
Future hadron colliders (including eh colliders)



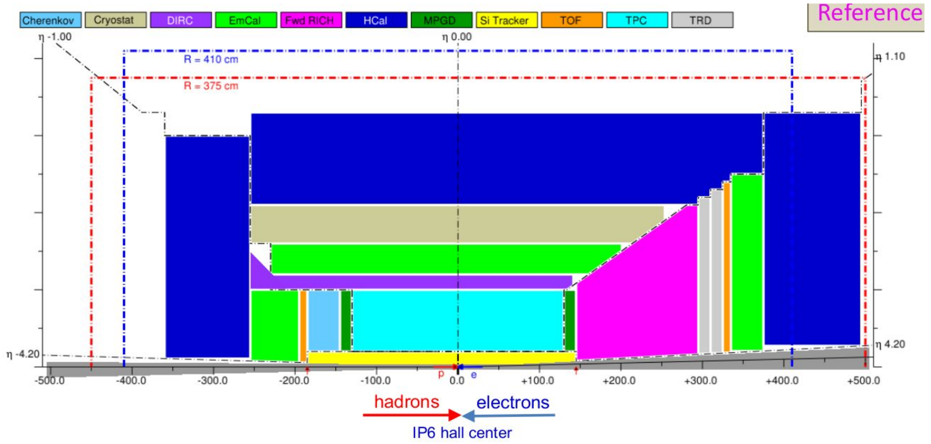
SuperKEKB, DUNE ND and Fixed Target



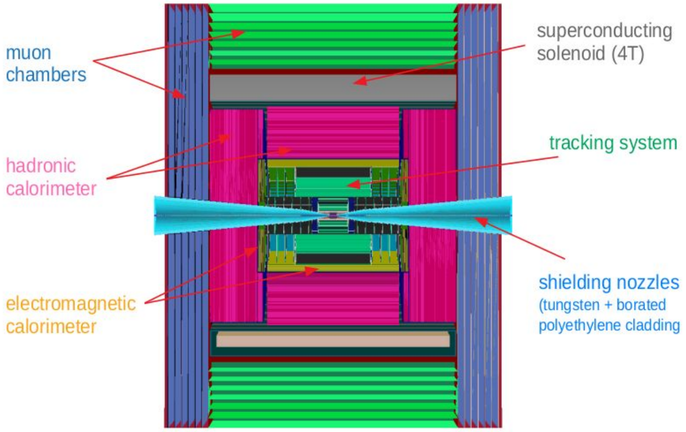




EiC



Muon Collider



Timescale of future (large scale) projects

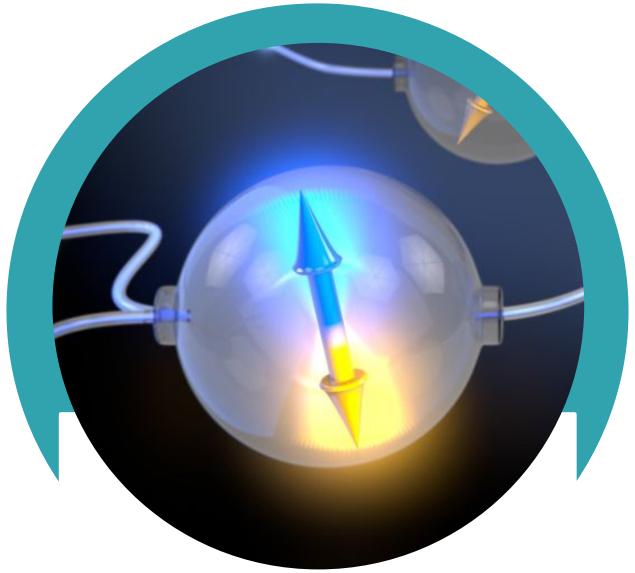
- … as approved by European Lab Director Group (LDG)

See backup for set of smaller scale projects

Pillars of successful experimental program

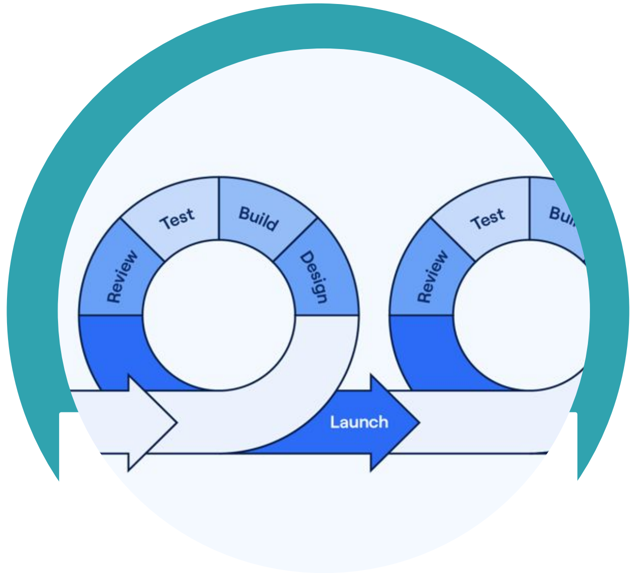
Revolutions

The Unexpected



Technologies

Current and future technologies and their challenges



Agility

Multi-decade Requirements

Summary

Learning from History

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Future Instrumentation - Driving Thoughts

- The next-generation experiments will not – and should not – be your grandfather's experiment!
- The time-scale of "many decades" provides for interesting challenges and opportunities.
  - Many decades of operation at different energies with different physics topologies creates tension with single detector design.
  - Many decades for technology development that is advancing at break-neck pace, needs to be followed and will impact the detector design.
  - The community needs to be nimble, creative and work towards experimental transformational developments.
- The "**many decades**" should provide for at least one "**revolution**". We could not be at a better time for transformational detector designs.

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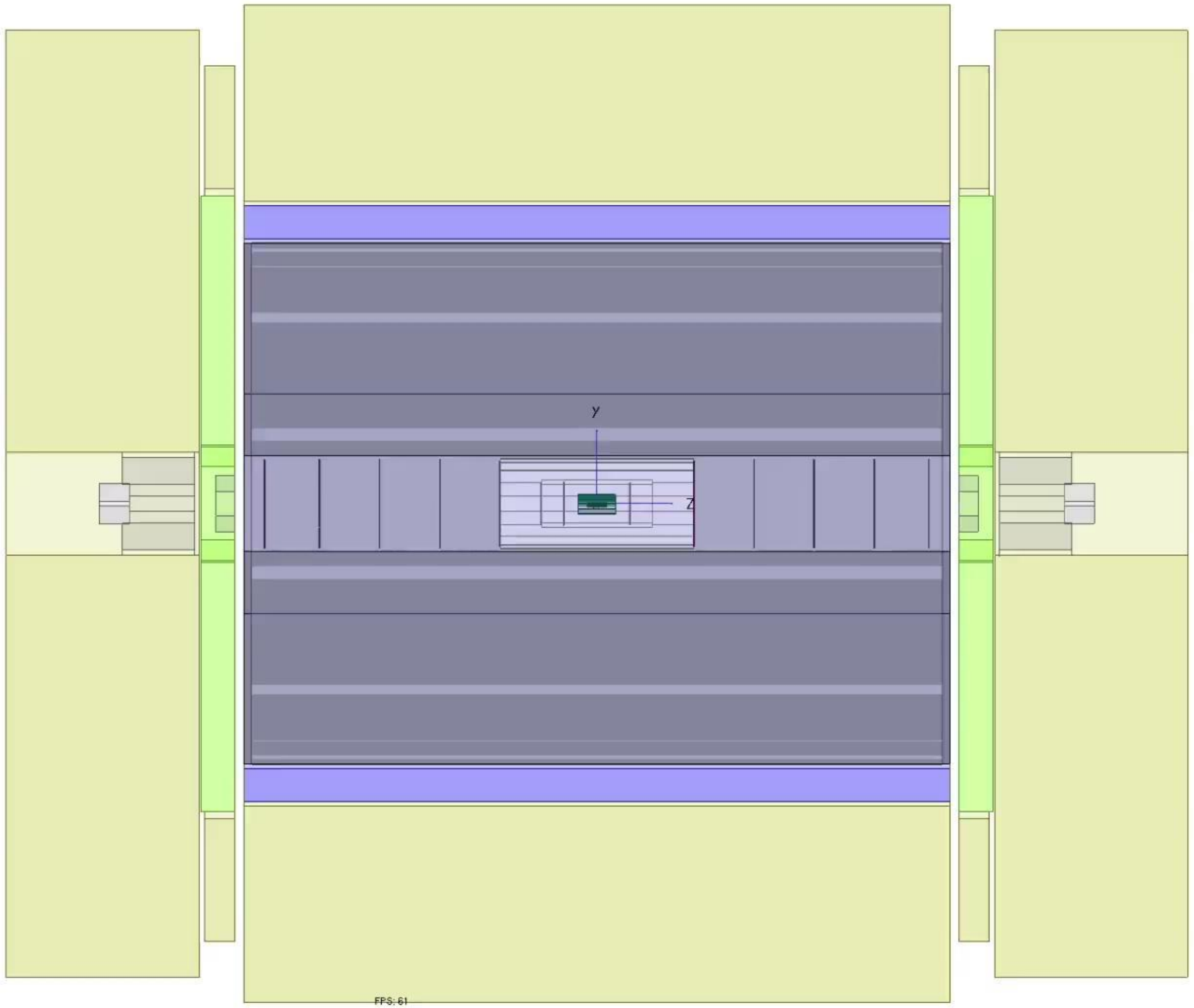
A typical HEP Event

Vertex Detectors
Reconstruction of interaction point and decay vertices

Tracking Detectors
Reconstruction of charged particles in central and forward part

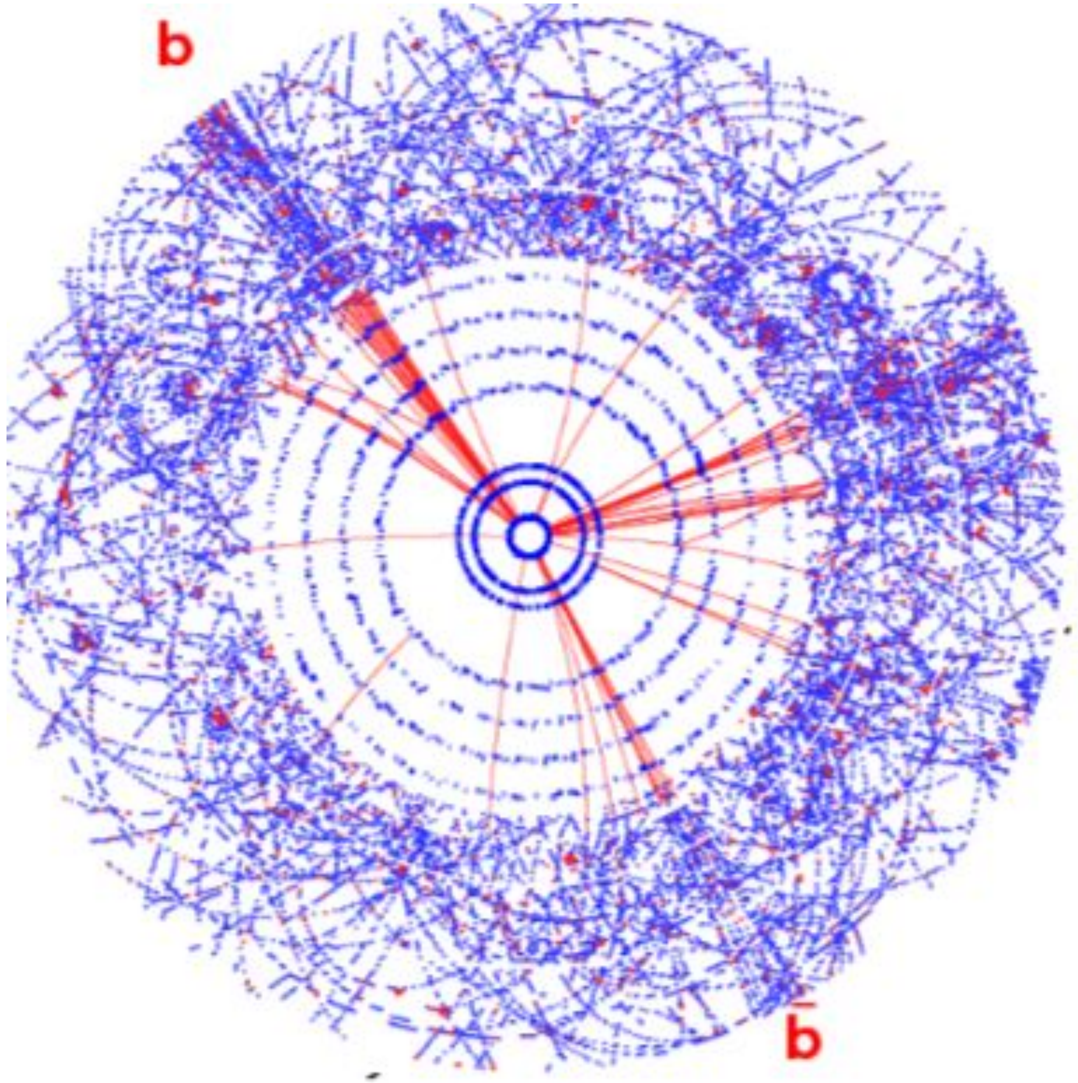
Calorimetry
Energy measurement in the outer (and forward) part
Subdivided in electromagnetic (ECAL) and Hadronic (HCAL) Calorimeters

B. Dudar



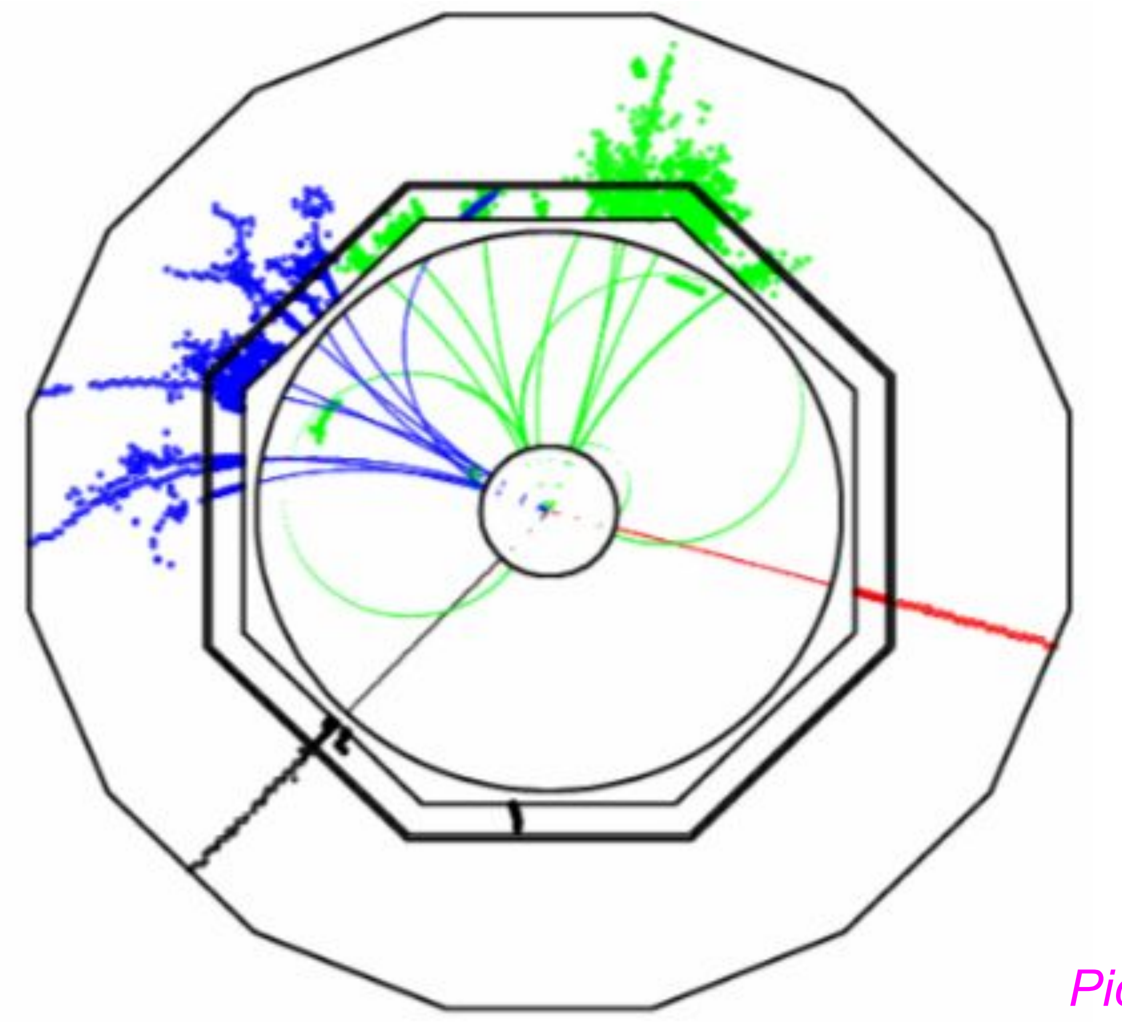
(Rough) Comparison – Hadron collisions ↔ e^+e^- collisions

Hadron-hadron collisions e.g. LHC



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

e^+e^--collisions

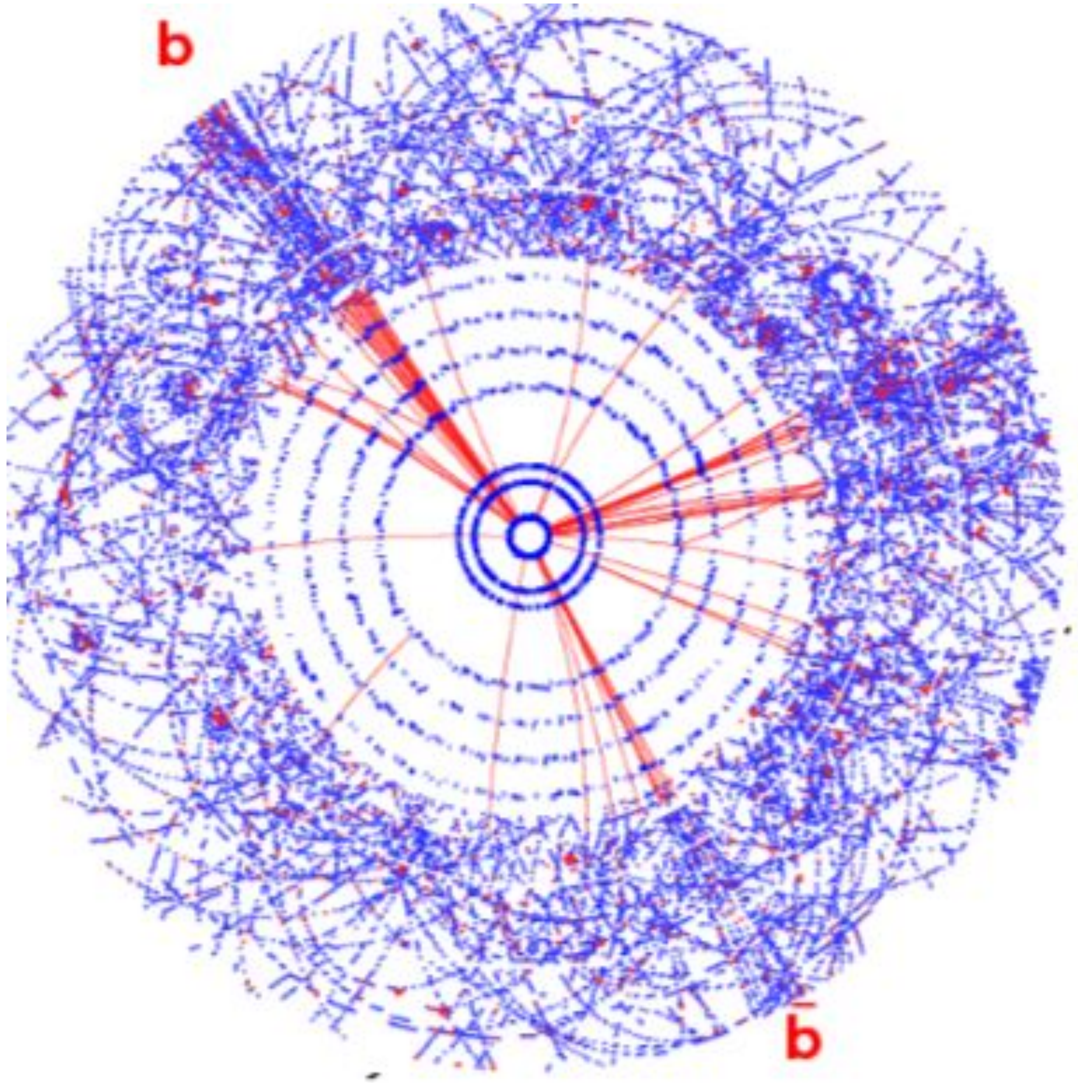


Picture Y. Sirois

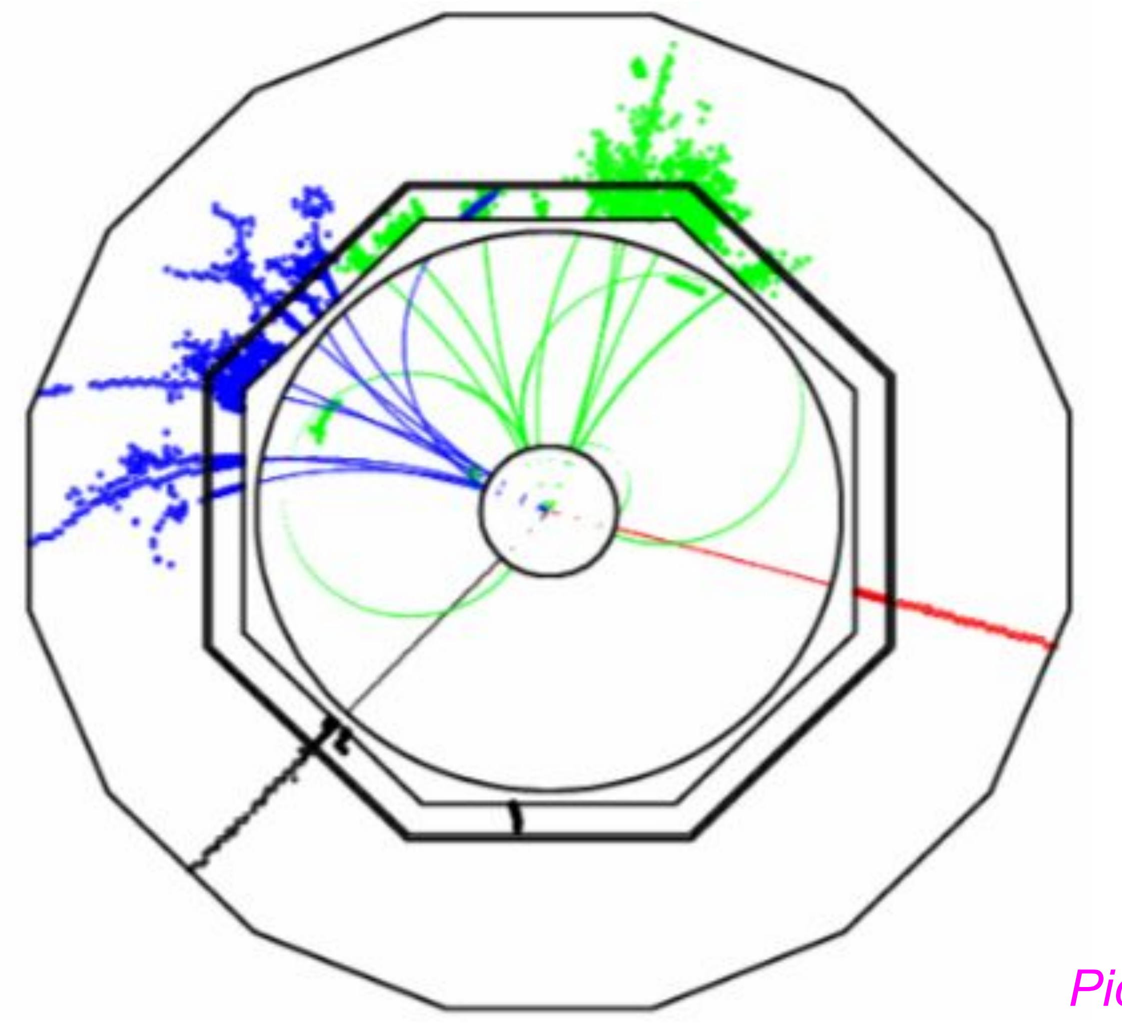
- Clean events
- No trigger
- Full event reconstruction

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

Hadron-hadron collisions e.g. LHC



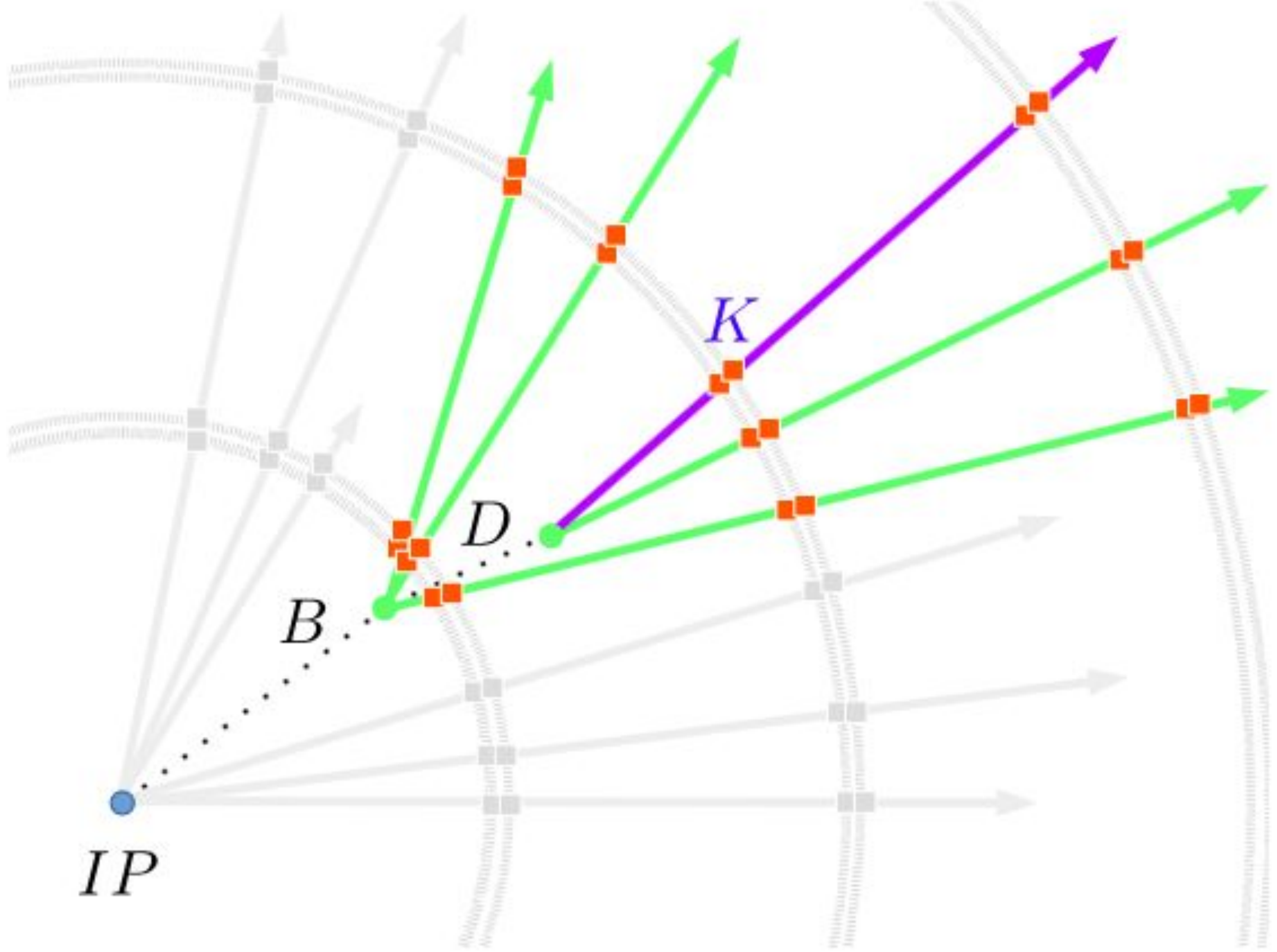
e^+e^--collisions



Picture Y. Sirois

- EPPSU 2020 named clearly an e+e- Higgs factory as priority after LHC
- Therefore many R&D activities have been targeted into this direction (and sets the priorities for this talk)
  - However, community keeps an eye on future hadron and muon colliders

Vertexing and Tracking - Tasks

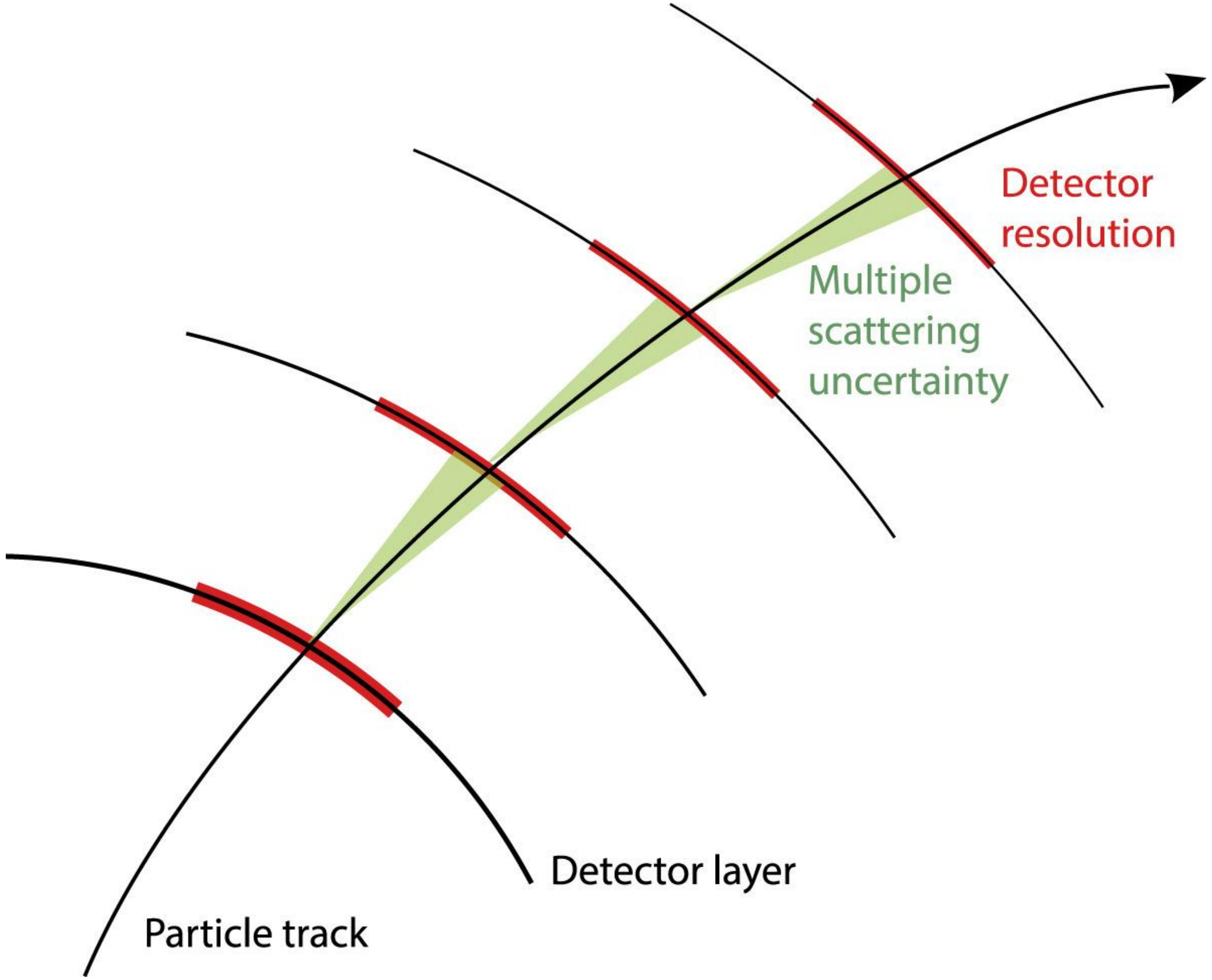


- Determination of primary vertex
- Flavor tagging
  - Indispensable for analyses with final state quarks
- Quark charge measurement
  - Important for top quark studies,
  - indispensable for ee->bb, cc, ss, ...
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification 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

PhD thesis: S. Bilokin
A. Irles

Transparency in Tracking

- Critical requirements:
  - High spatial resolution
  - Low mass budget
  - No active cooling
  - Low power
  - Hermetic with redundancy



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CMOS Sensors Silicon Tracking

Main asset: µ-circuits (steering, r.o., slow control) integrated on thin sensing substrate → **Monolithic & Thin** (& **T$_{room}$**)

Numerous developments of **custom design** CMOS Pixel Sensors (CPS) on-going for vertexing and tracking devices foreseen to equip experiments at existing infrastructures (LHC, KEK, PSI, …) and future colliders (eIC, FAIR, FCC$_{ee/hh}$, CEPC, ILC, C3, …)

Some R&D for ECAL

Optimisation imposes hierarchising conflicting requirements:

Spatial resol. / Timing / Mat. budget (power) / Rad. Tol. / Hit rate

- Dependence on CMOS process (foundry) characteristics

Frameworks: CERN-EP, DRD**, ITS3** (main driver for Higgs factories: 65 nm techno with **stitched curved sensors**)

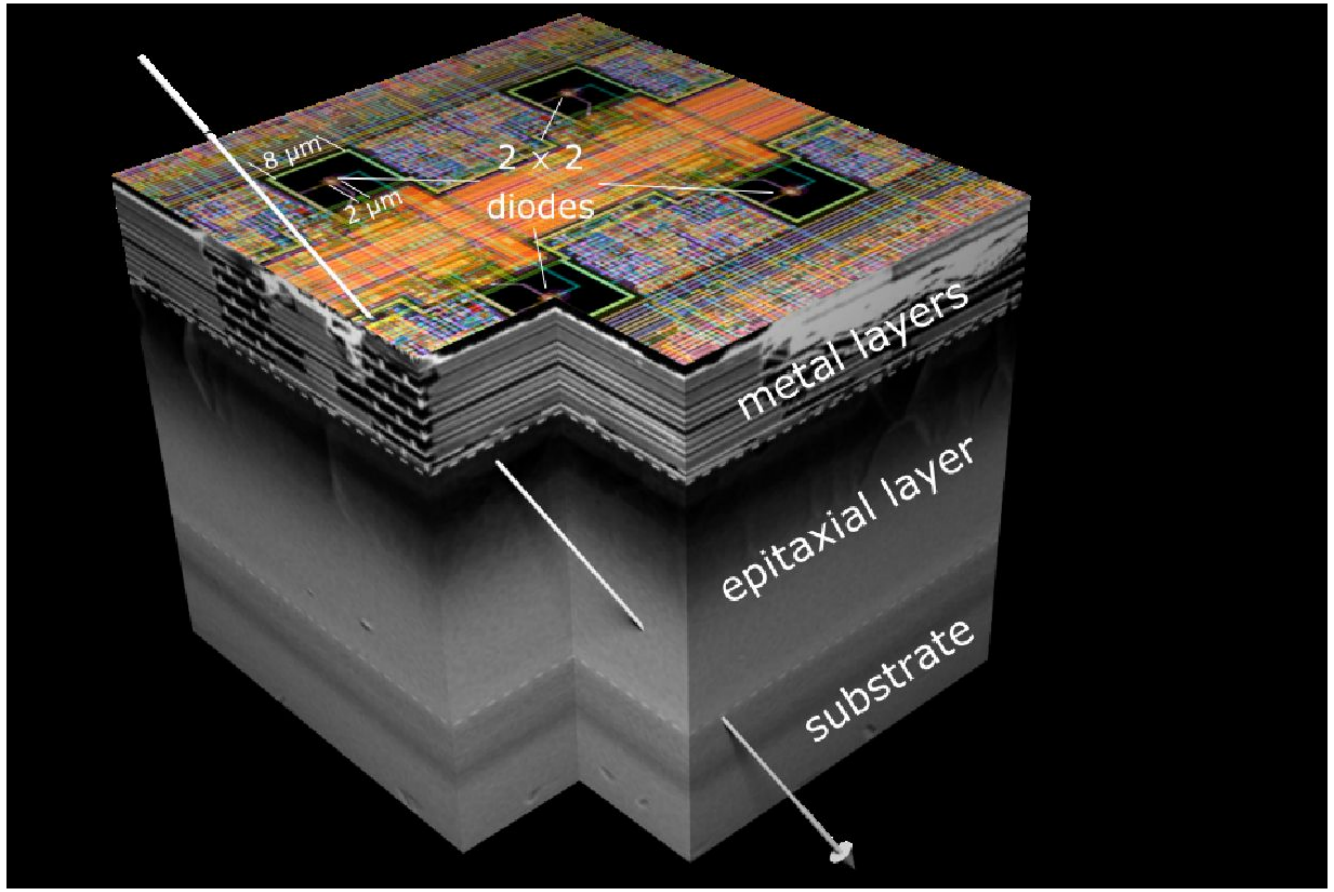
3 predominent foundries: TJsc, TPSCo, L Foundry

System Integration is crucial for realistic detector optimisation:

. Air cooling at which price ?

. Services → impact on FW region ?

. Impact on choice of sensor technology and design ?



Courtesy of Marc Winter

Ambitioned Performances

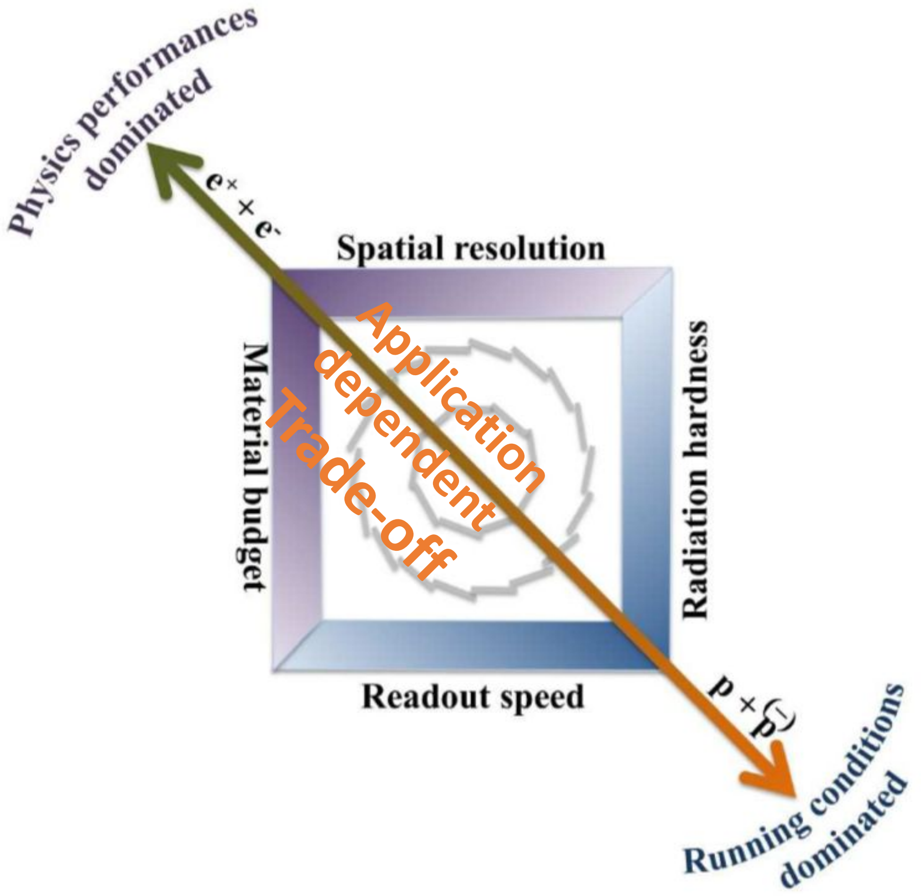
Spatial and pointing resolution : < 3 µm and R_{in} ≤ 15 mm

Time stamping :

- Z pole running: << 1 µs ?
- for $\sqrt{s}$ > 200 GeV : O(1) µs

Material budget / single layer: ≤ 0.15 % Xo

→ no active cooling inside sensitive volume (air flow only ?



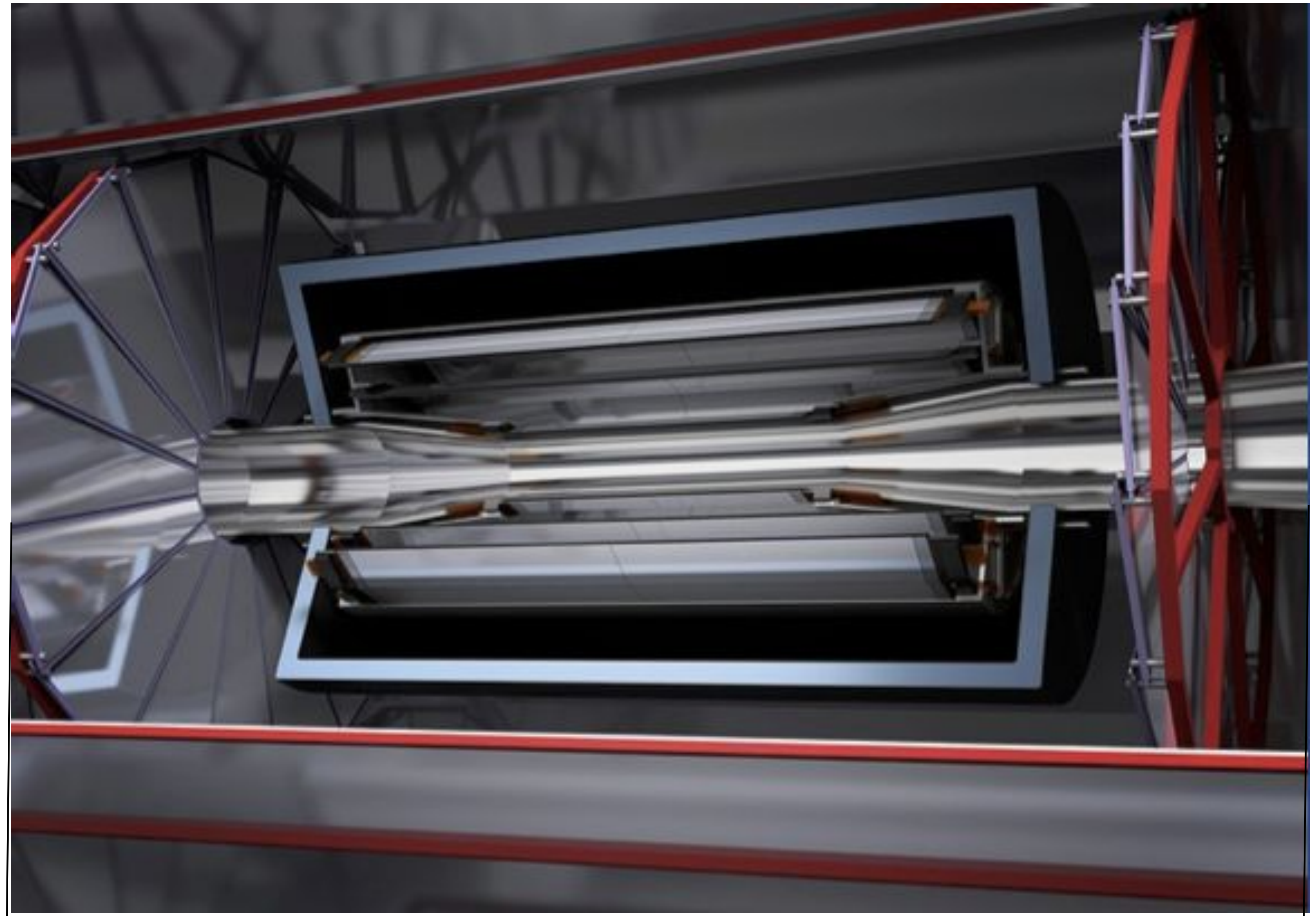
Remarks:

- minimise beam pipe material budget and radius
- exploit at best low radiation levels and backgrounds (as compared to LHC)
- system optimisation should minimise bulk of services (end-caps !)
- Z-pole and H-top operations could involve two different vertex detectors

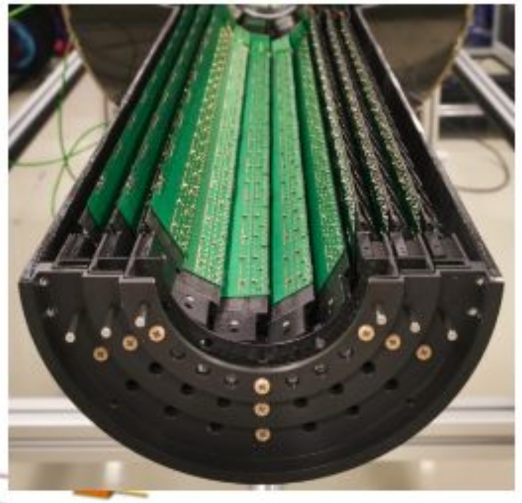
Courtesy of Marc Winter

Vertex Tracking for Higgs Factories

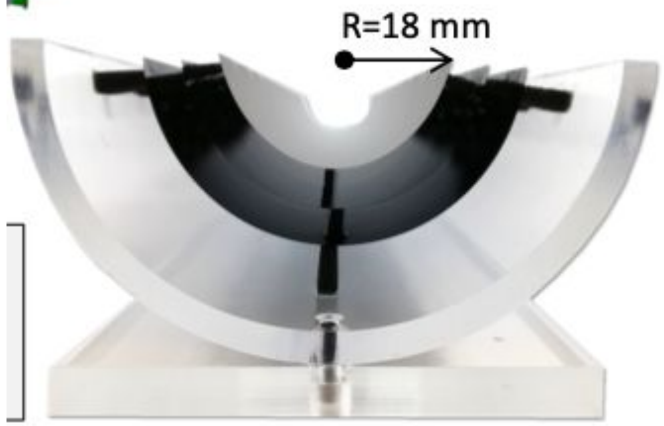
- Low material budget is overall challenge
  - Major step through ALICE upgrade



Big question: Radius of beam pipe



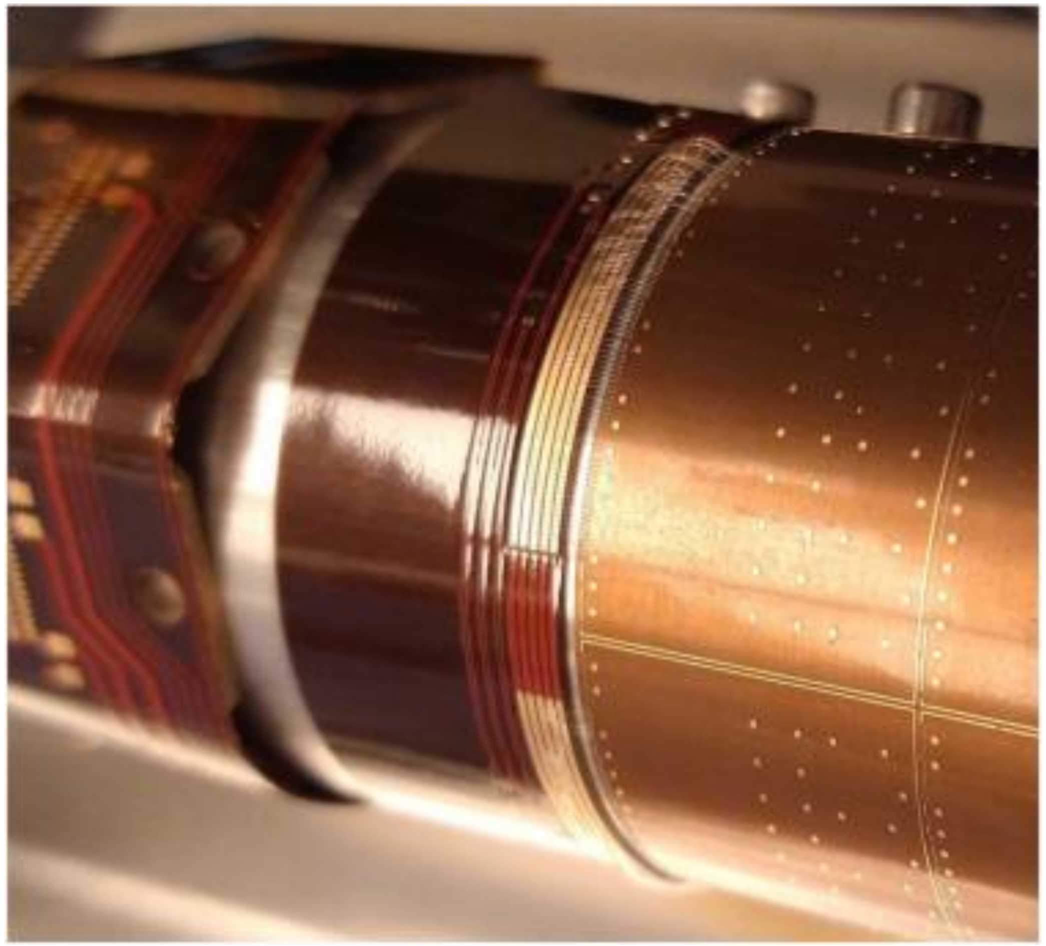
ITS2:
(S.Beolé, iWoRiD 2022)
- 7 layers of MAPS
- TJ 180 nm CMOS
- 12.5 Giga pixels
- Pixel size: 27×29 μm²
- Water cooling
- **0.3 % X_0 / inner layer**



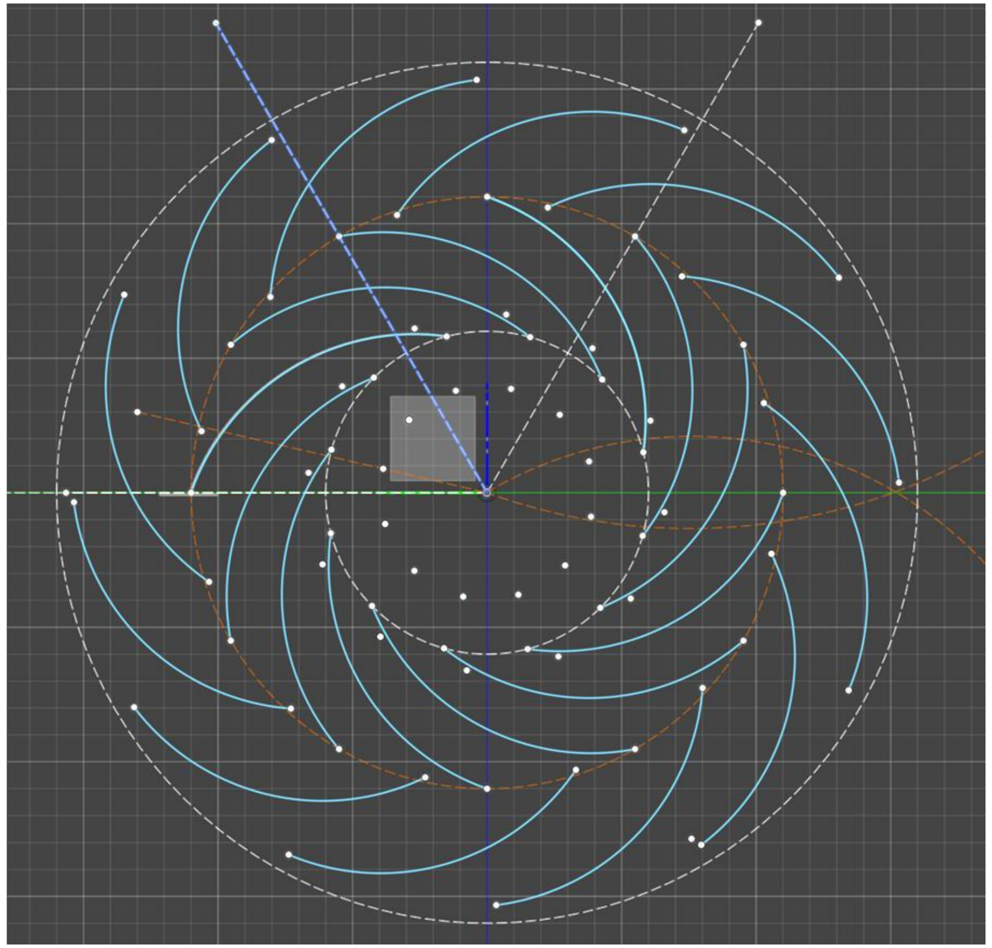
ITS3
(M. Šuljić, iWoRiD 2023)
- 4 outer layers of ITS2
- 3 new fully cylindrical inner layers
  - Sensor size up to 27×9 cm
  - Thickness 30-40 μm
  - No FPCs
  - Air cooling in active area
- **0.05 % X_0 / inner layer**

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

(Future) Vertex Detector Geometries



ALICE ITS3 mechanical bent prototype



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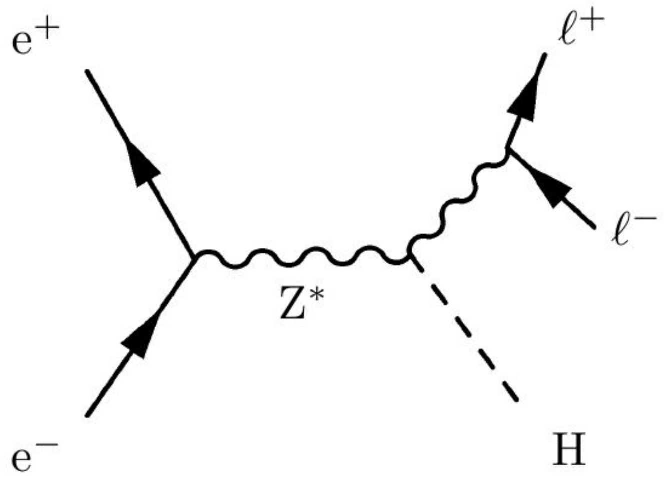
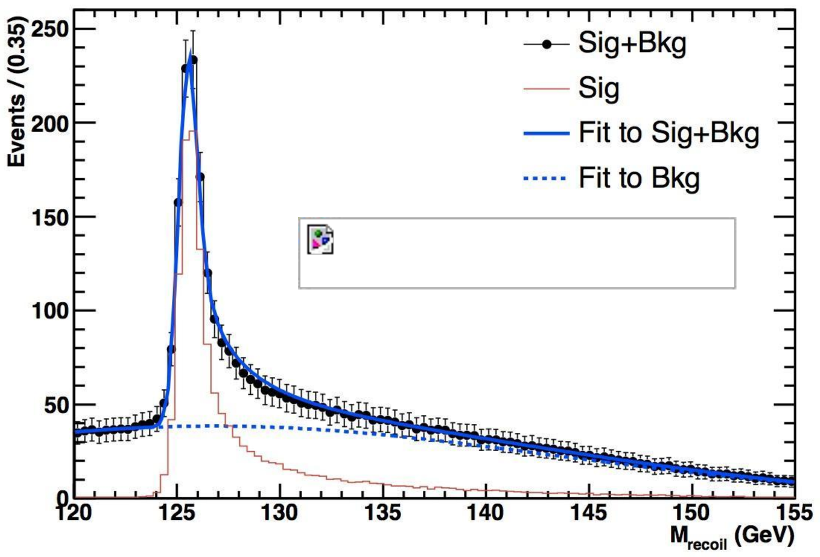
Central Tracking

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



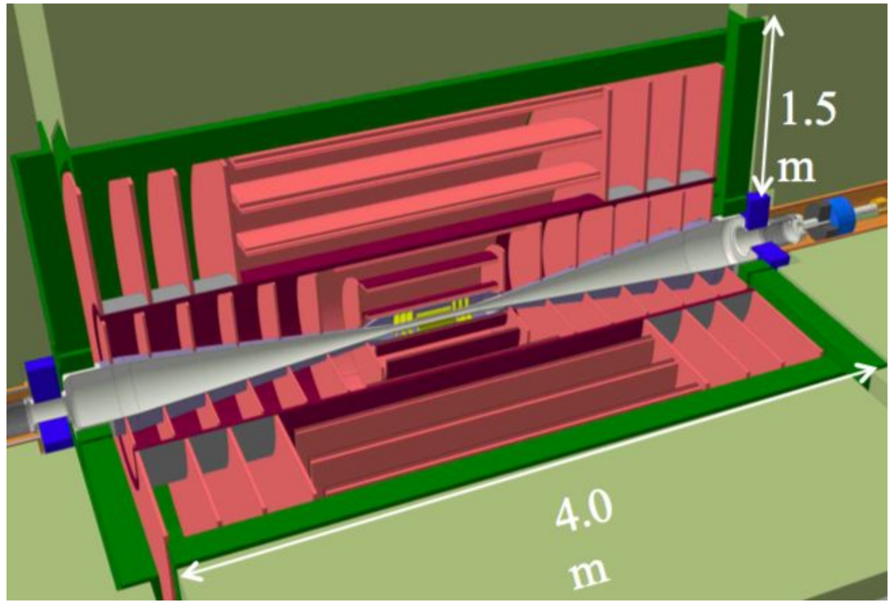


Gluckstern Formula:

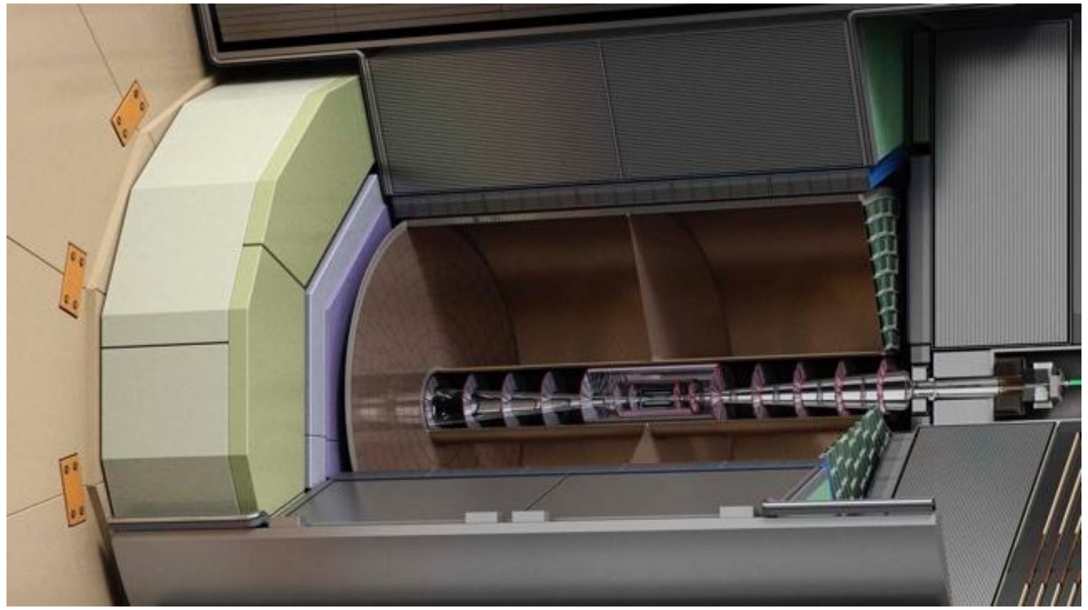
$$\frac{\Delta p_t}{p_t^2} = \frac{\sigma_{r\phi}}{0.3\, L^2 B} \sqrt{\frac{720}{N+4}}$$

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

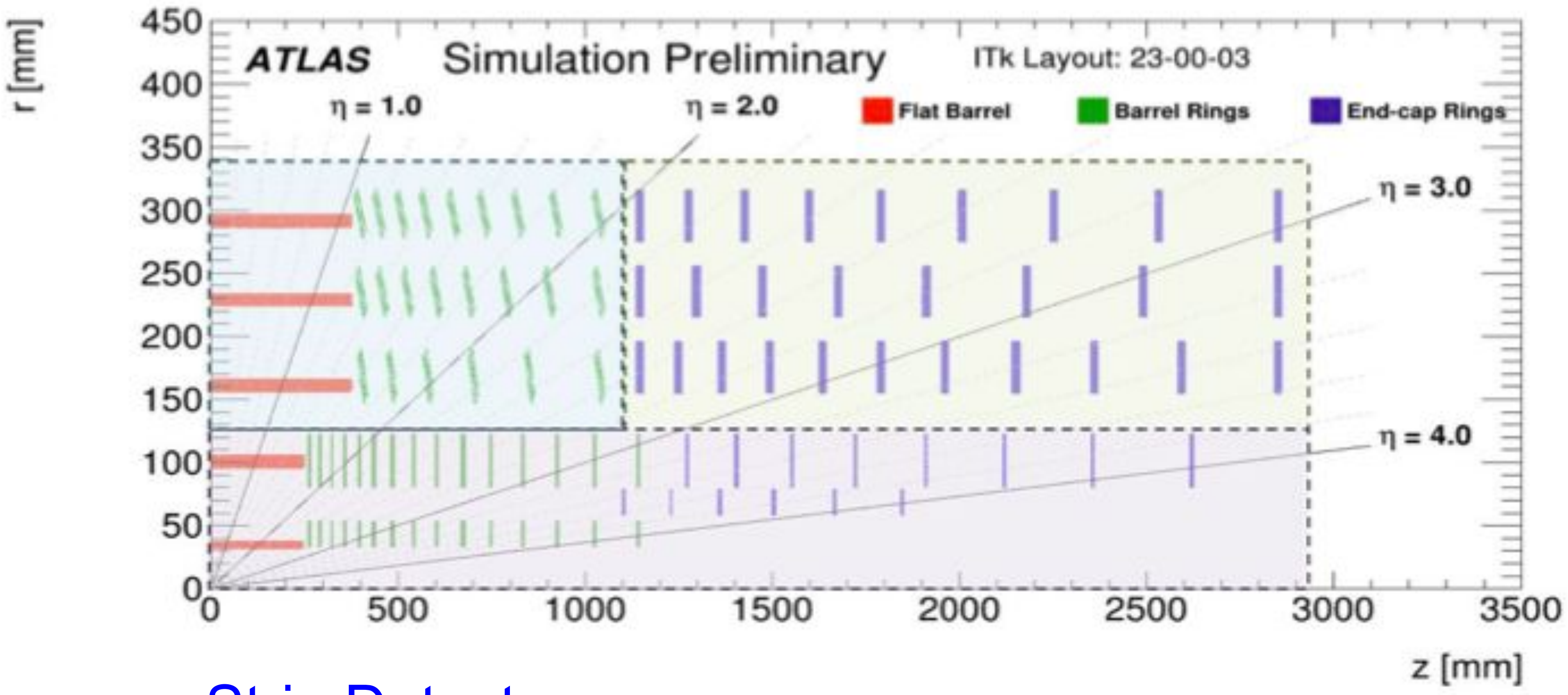


Option 2: Gaseous tracking

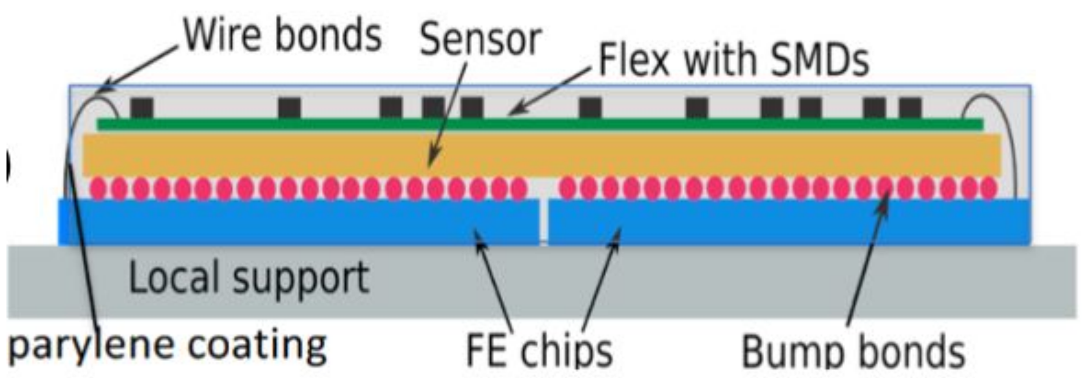


Central Tracking With Silicon – Example ATLAS ITK

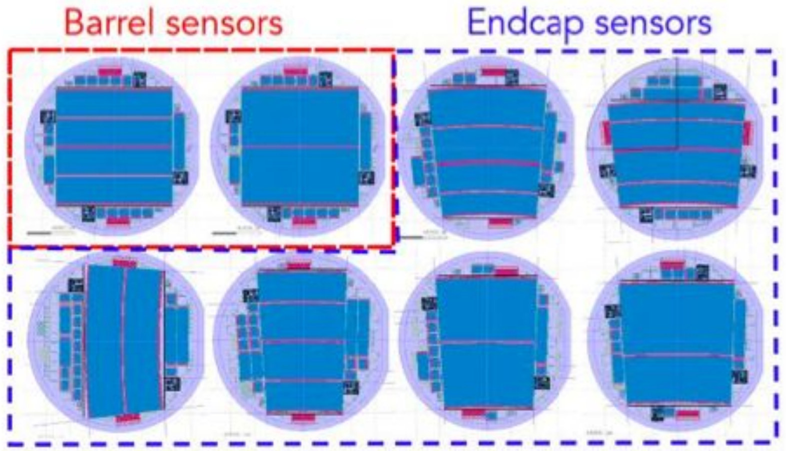
Pixel Detectors

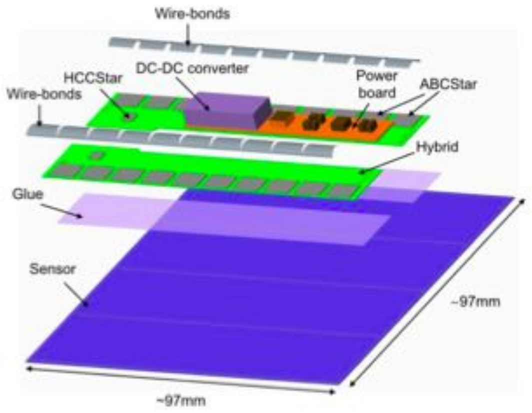


Structure of ITK Pixel Module



Strip Detectors



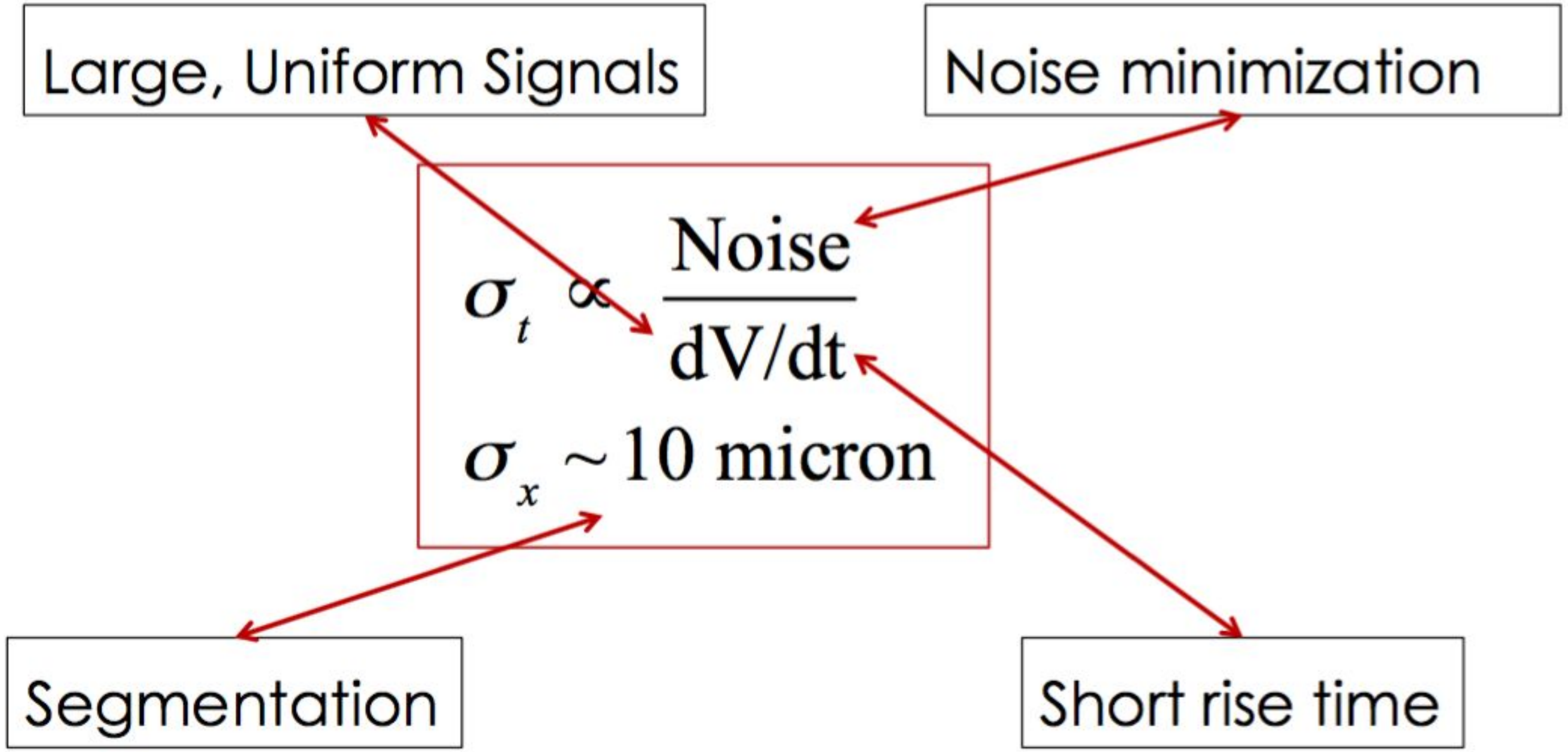


Short Strip Barrel module

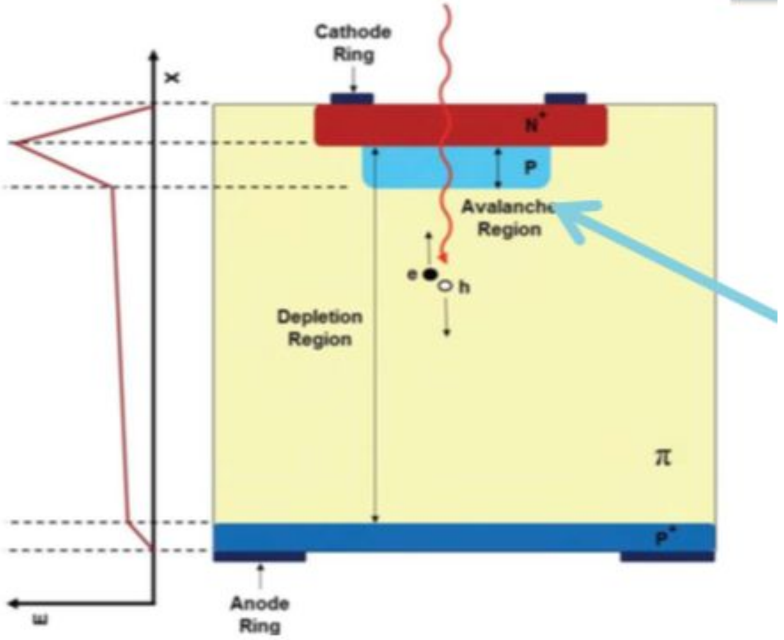
- Silicon tracking yield excellent single point resolution
  - Typically O(few µm)
- Less measurement points than gaseous tracking
- LHC Detectors feature large silicon tracking
  - ... that undergo currently a major upgrade
- Many proposals for future detectors will also feature a large silicon tracking volume

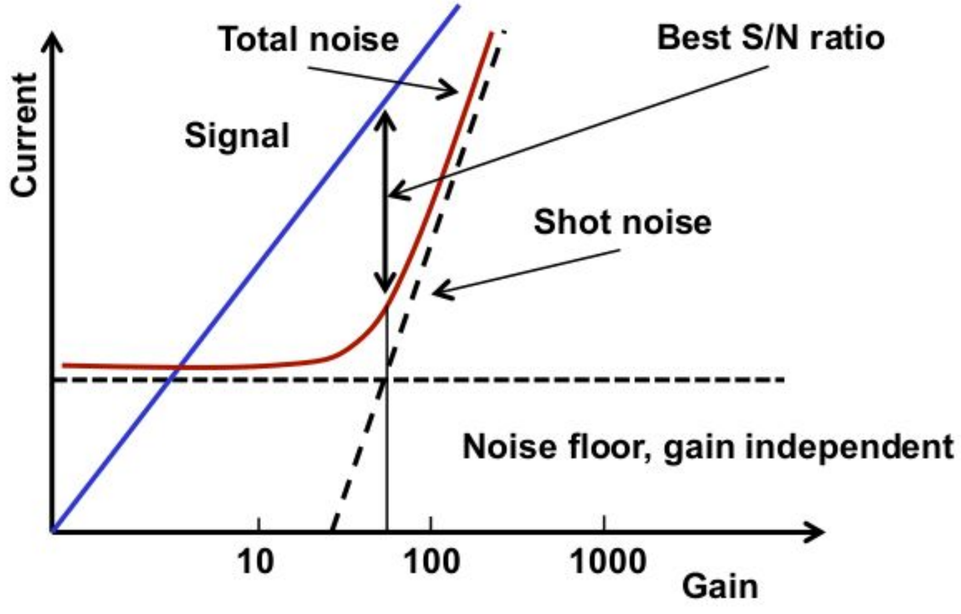
Timing (not only) for Tracking

Pioneered by LHC Experiments, timing detectors may require adaptation for Higgs Factory Experiments



Working horse LGAD

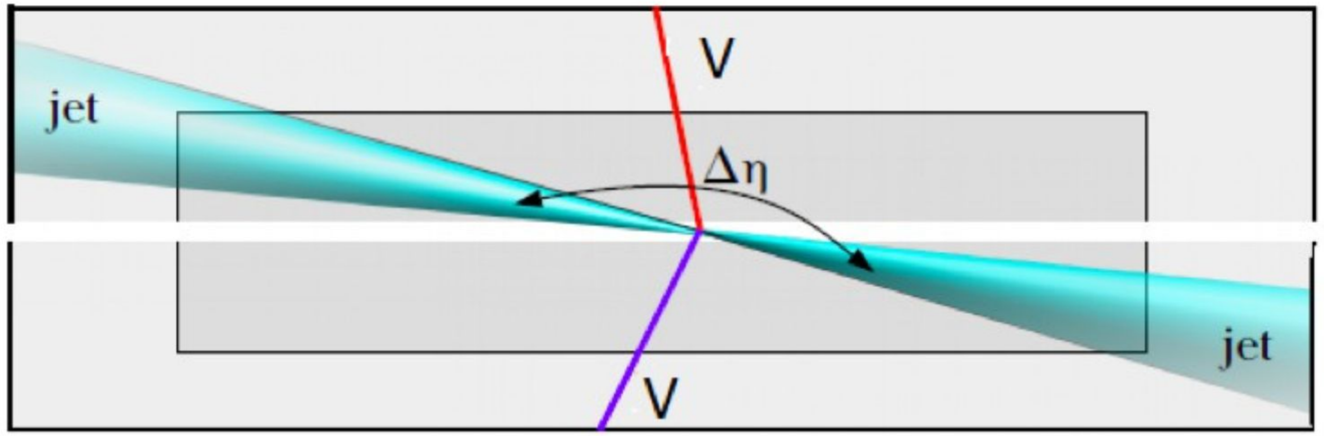




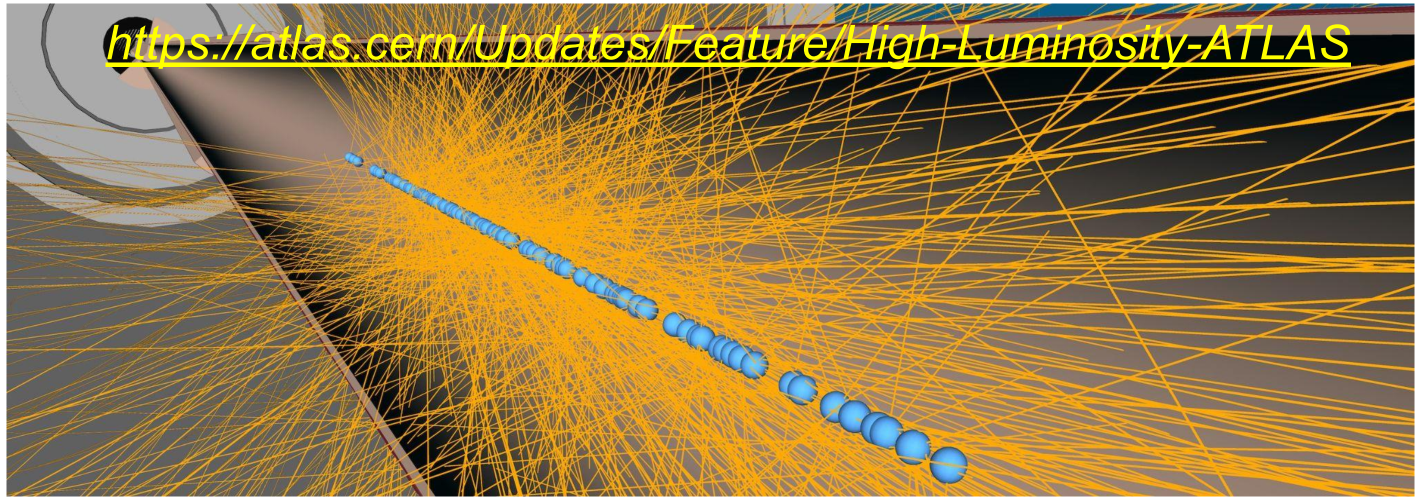
- Better dV/dt by “active” Si diodes ? => Low Gain Avalanche Detectors
  - LGADs applied for ATLAS HGTD and CMS ETD
  - Expect time resolution σ_t ~ 30-50ps
- Combining LGADs with tracking devices is current major R&D topic
- **=> 4D tracking**

Timing and pile-up mitigation

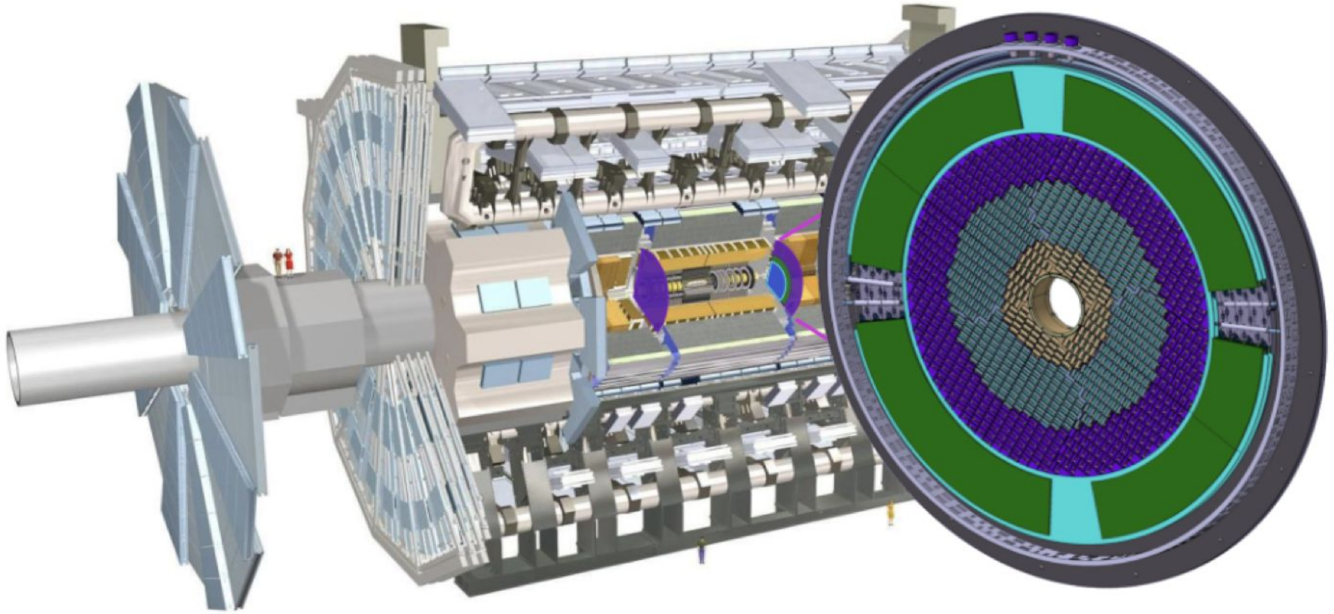
Vector Boson Scattering at HL-LHC …



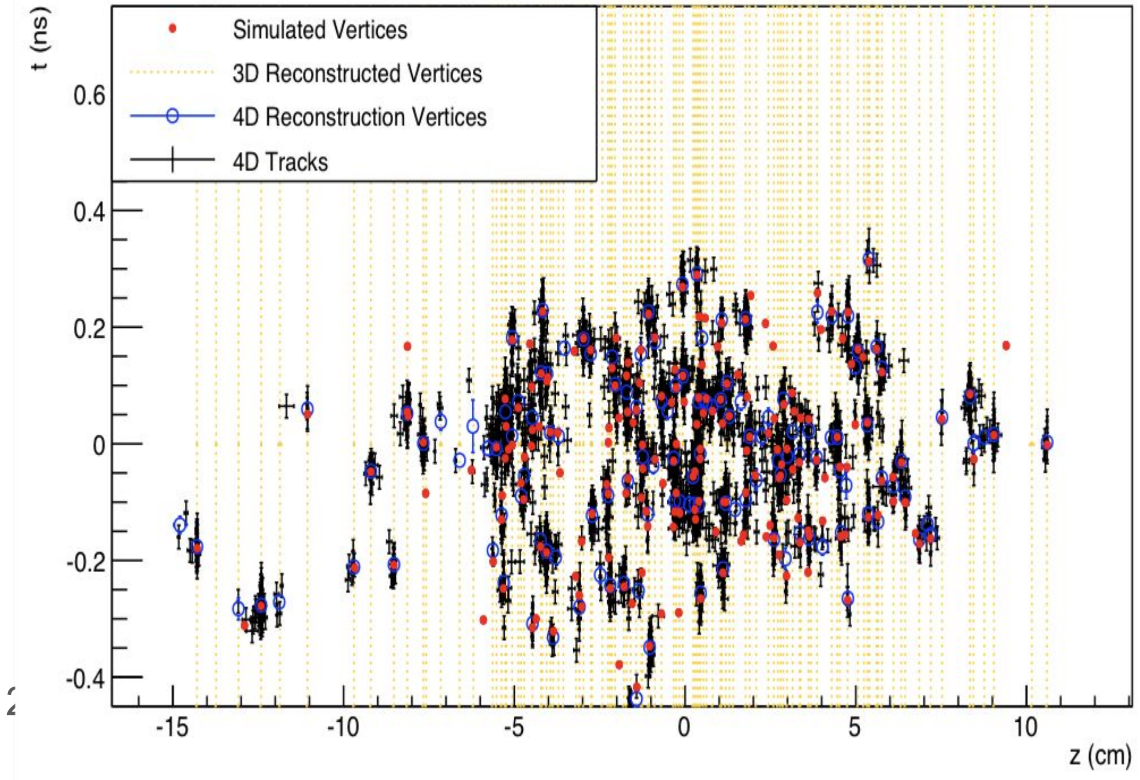
… compromised by pile-up (<μ> = 200)



ATLAS HGTD based on LGADs σ_t~30ps

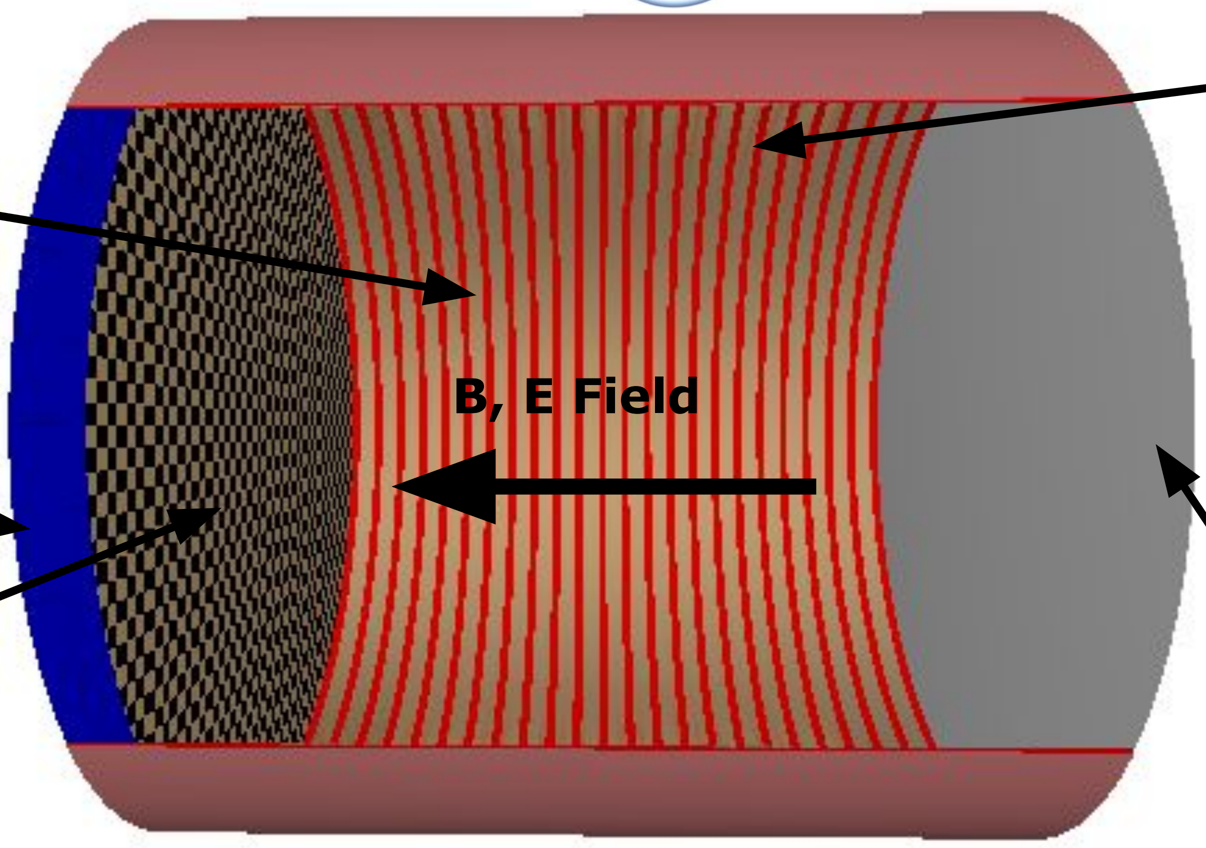


-> reconstruction of individual vertices



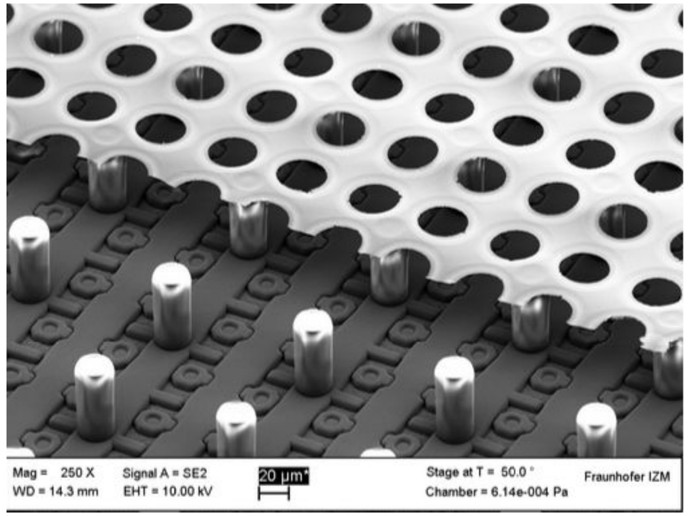
Gaseous Tracking Systems at Future Colliders

R&D for LC TPC is organised in LCTPC Collaboration

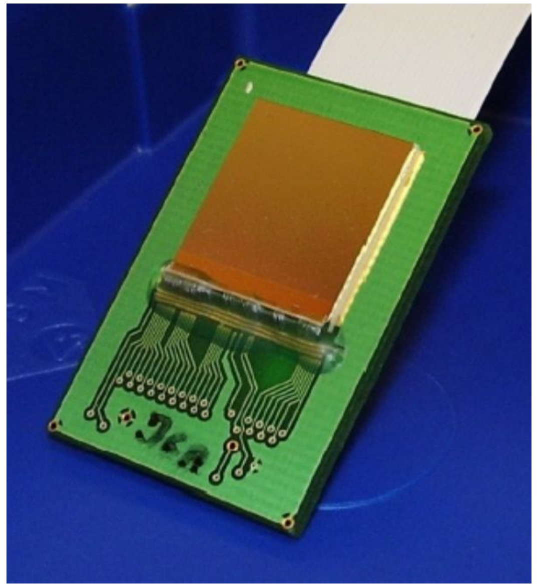


- Charged particle ionizes Gas
- Electron cloud drifts to Anode (Readout layer)
- Transversal diffusion is largely suppressed since E || B
  z Coordinate: $z = v_d \cdot t_d$ (vd, td drift velocity and drifttime,respectively
- $r\varphi$ Coordinate by segmented Readout layer

Central Tracking – Gaseous Tracking - TPC



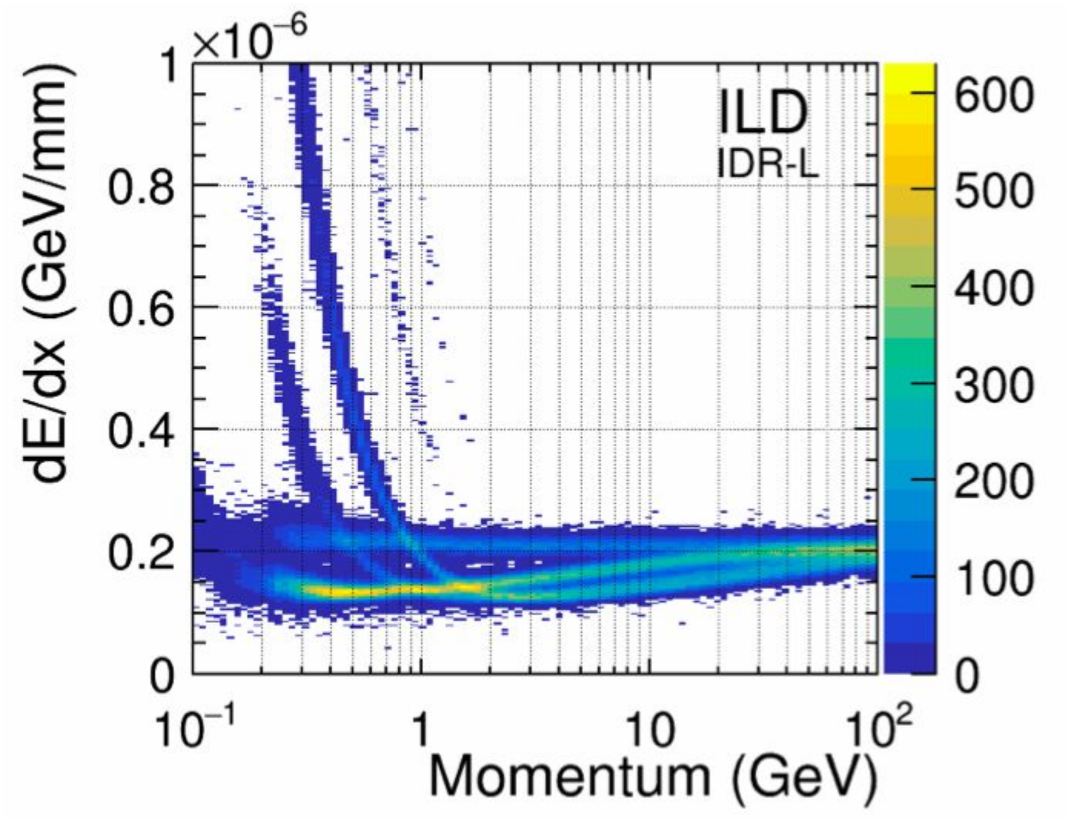
- Micropattern Gas Detectors - Pads :
  T2K/ND280 (near detector at JPARC neutrino oscillation experiment) started in 2023-24 using a technology envisaged for a pad TPC : resistive Micromegas. This allows developments relevant for a Higgs factory TPC : long term stability, algorithms for dE/dx measurements, gain calibration and charge spreading studies.



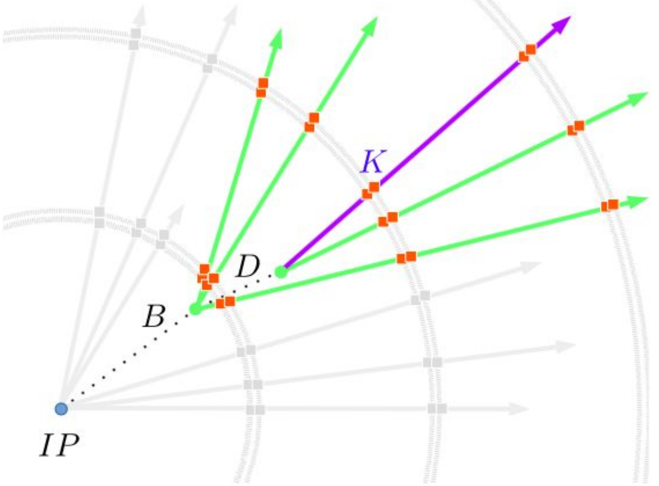
- Pixels : Performance studies going on using DESY 2021 test beam data and simulations. dE/dx, dN/dx, resolution, chip alignment, distortions.

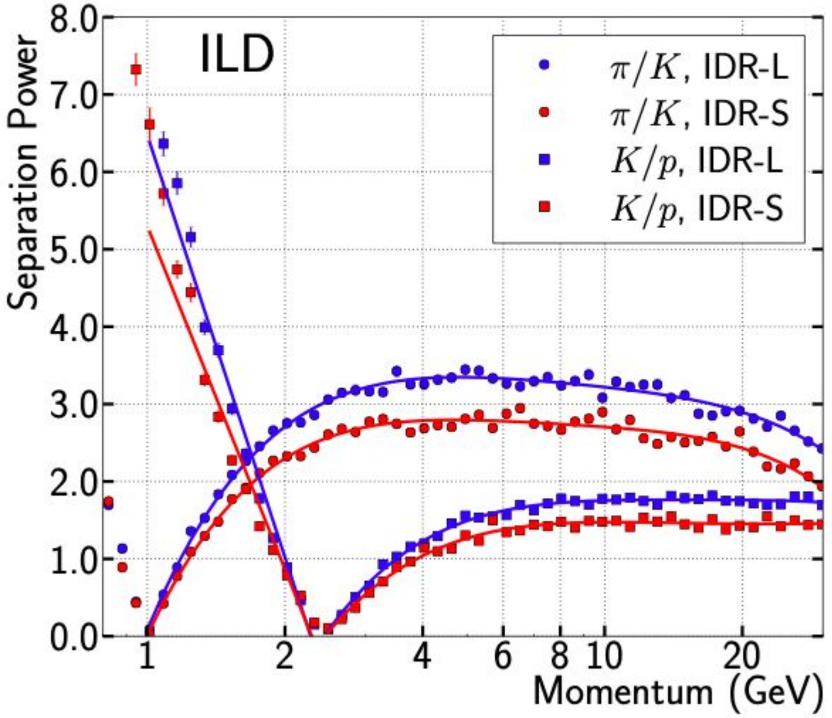
- Ion backflow and distortions from space charge (common to all readout options) :
  R&D necessary and in progress for TPC application at circular colliders, especially at the TeraZ. Here the ALICE Pb-Pb data are also useful. This also requires intense beam background simulations.

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
- Test beam results are encouraging





Applications of dE/dx:

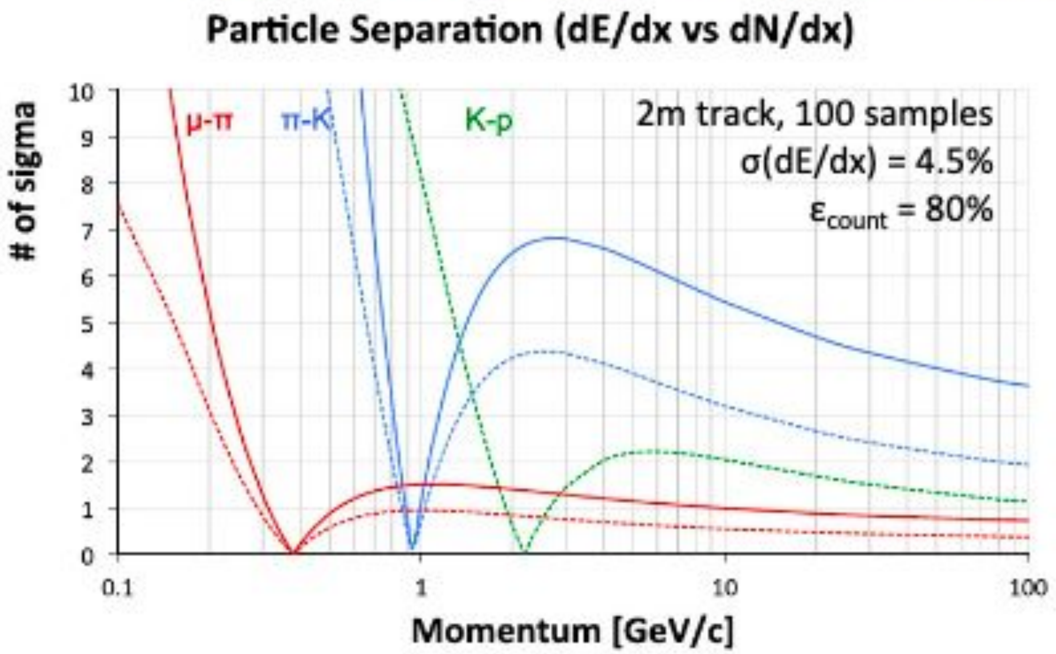
- Kaon identification in ee->tt, ee->bb, ee->cc, ee->ss
  - •Supplementary to vertex charge measurement for heavy quarks
    - •Increases statistics by a factor of two
  - •Backbone of ee->ss
- Separation of W->ud and W->cs

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

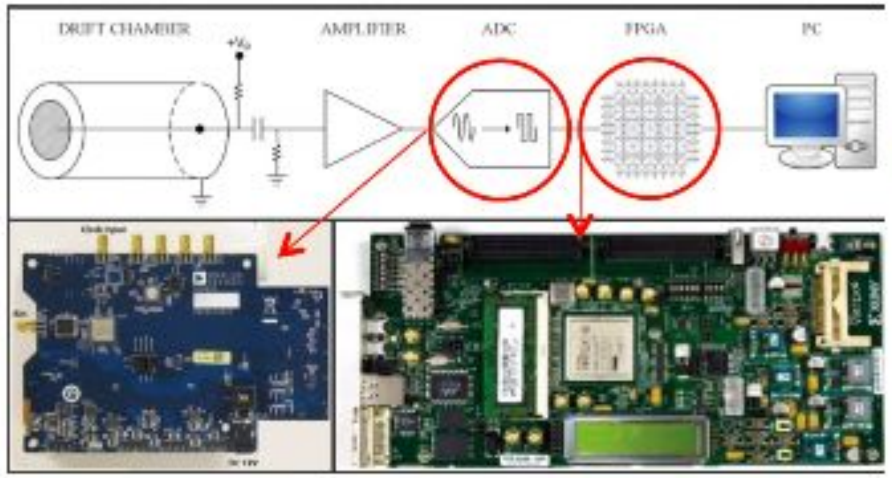
dE/dx → dN/dx – Cluster counting

- 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)

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



- 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



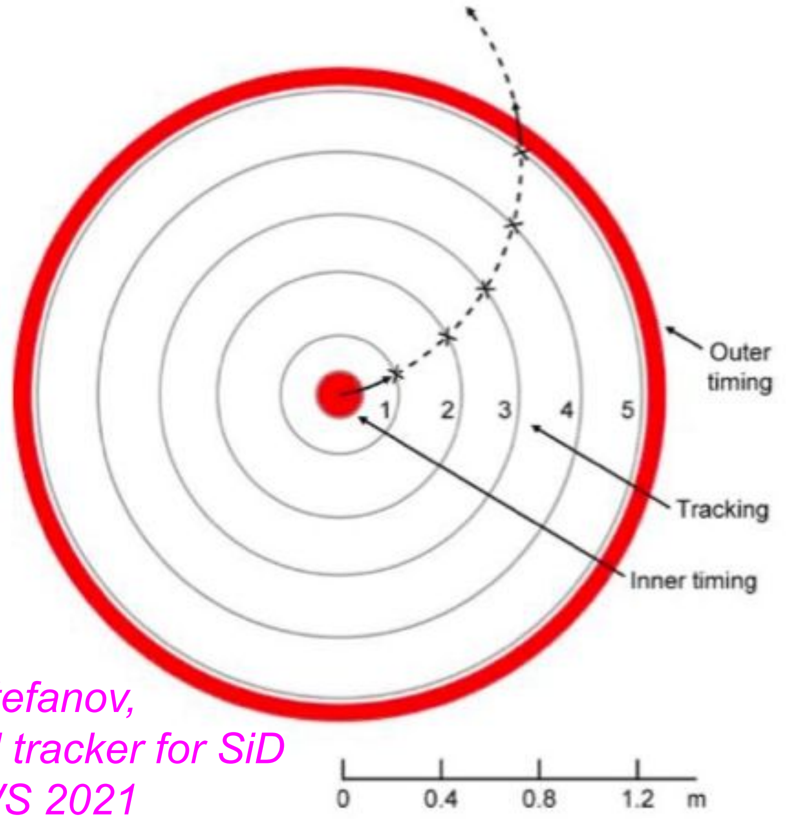
Further developments (R&D):

- 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

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

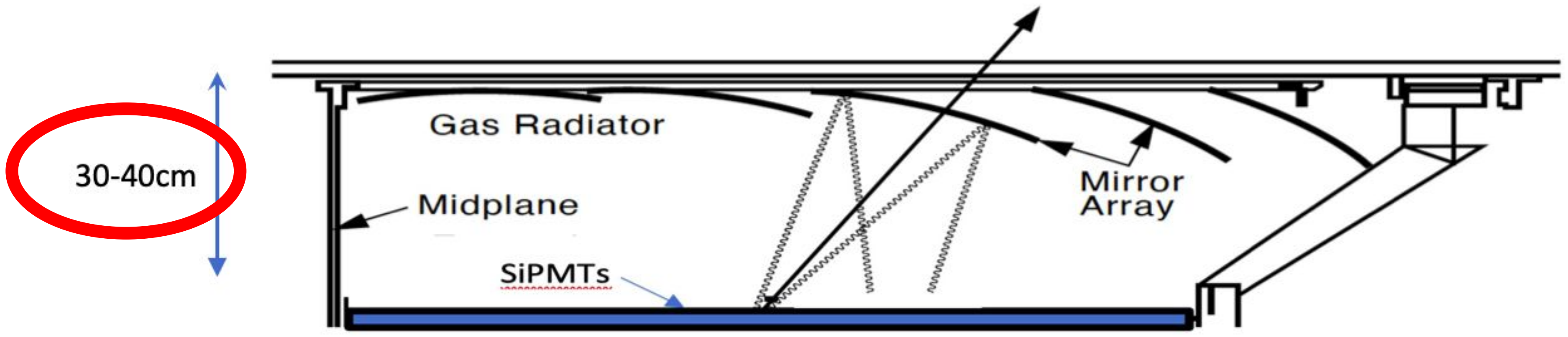
Cerenkov Detector

Three options:

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

à la J. Vavra

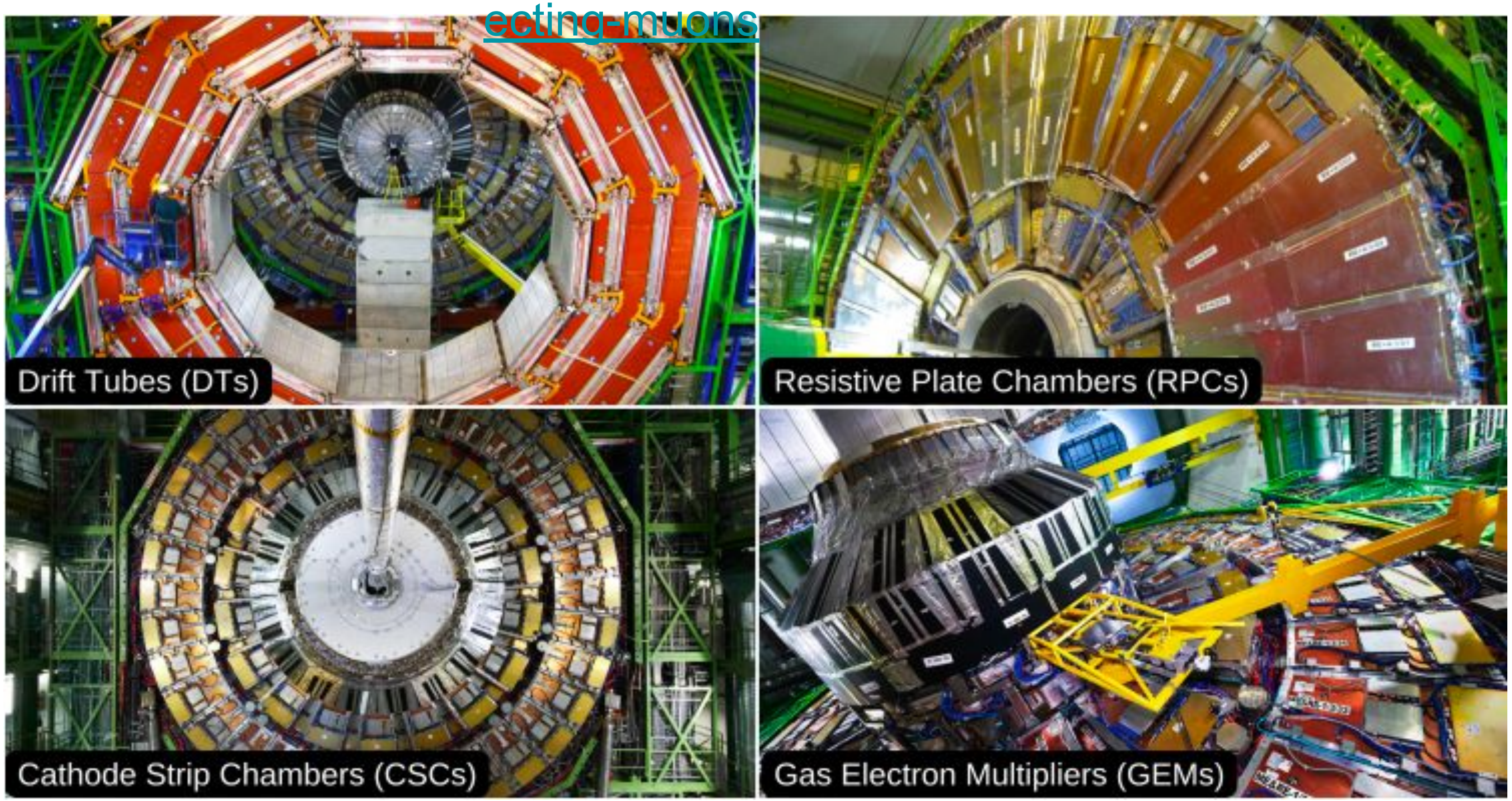
Gaseous RICH looked at for SiD:



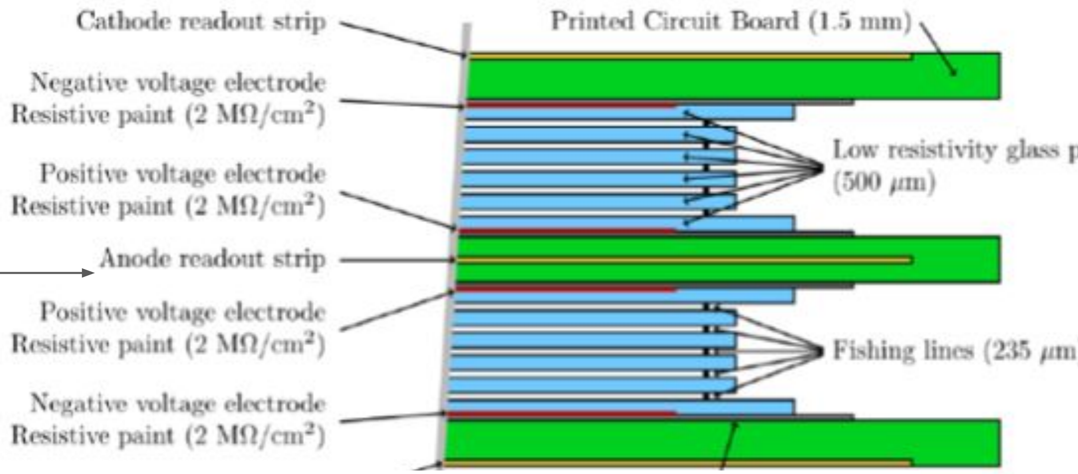
- ToF and Cherenkov are options for PiD systems
- Cherenkov most likely needed to go to high momenta
- Both lead to ”compressed” tracking systems
  - Ongoing R&D to minimise this compression

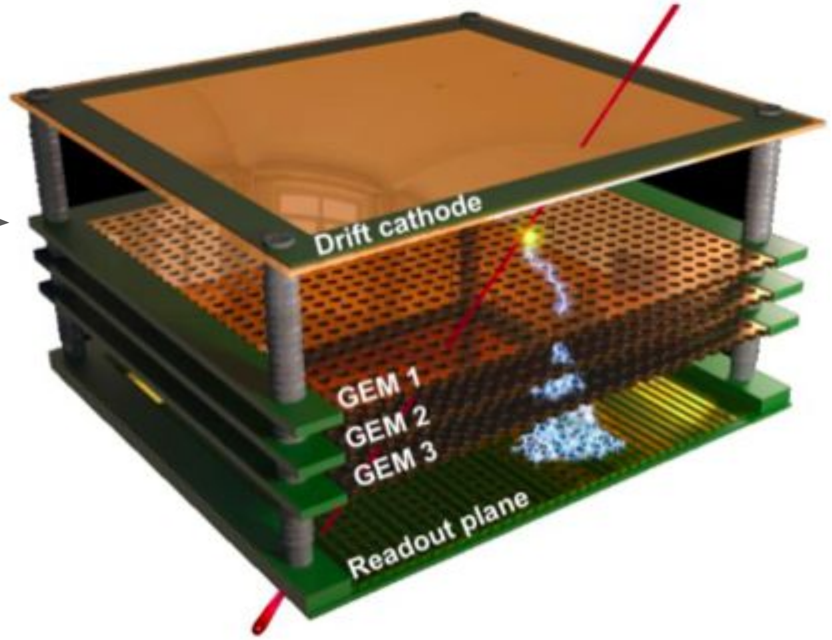
(Large scale) gas detectors

Example CMS Muon System
https://cms.cern/detector/detecting-muons



Trend: **Multi** Layer Chambers

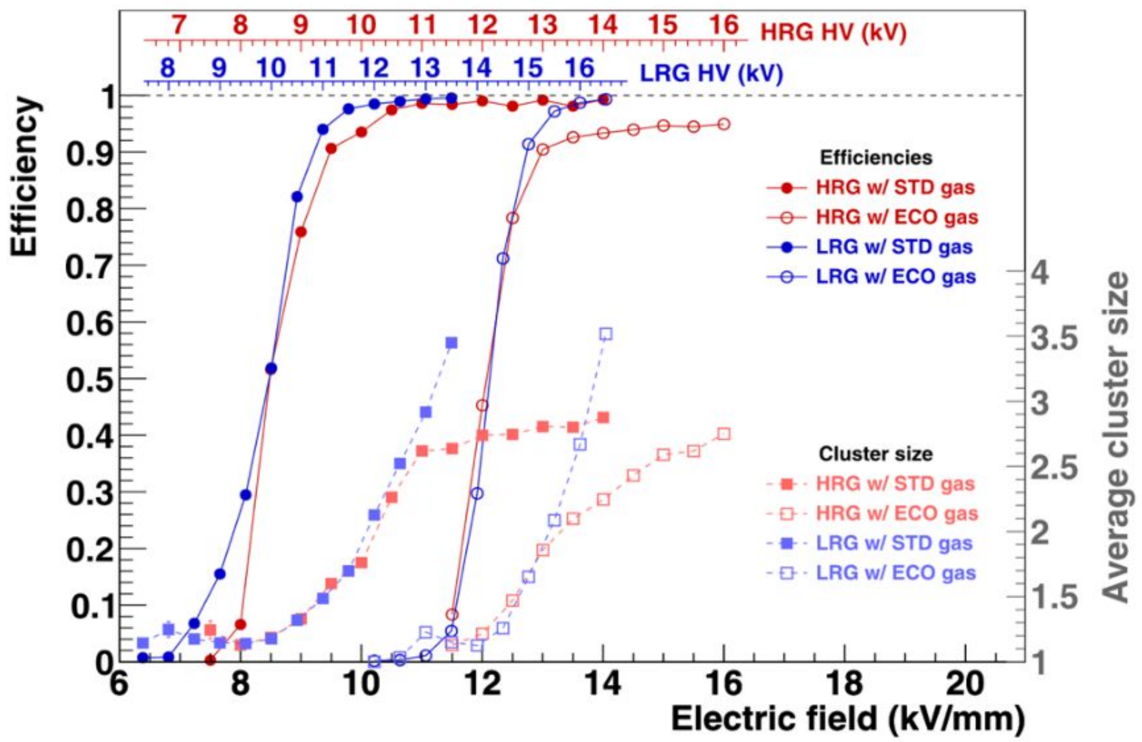




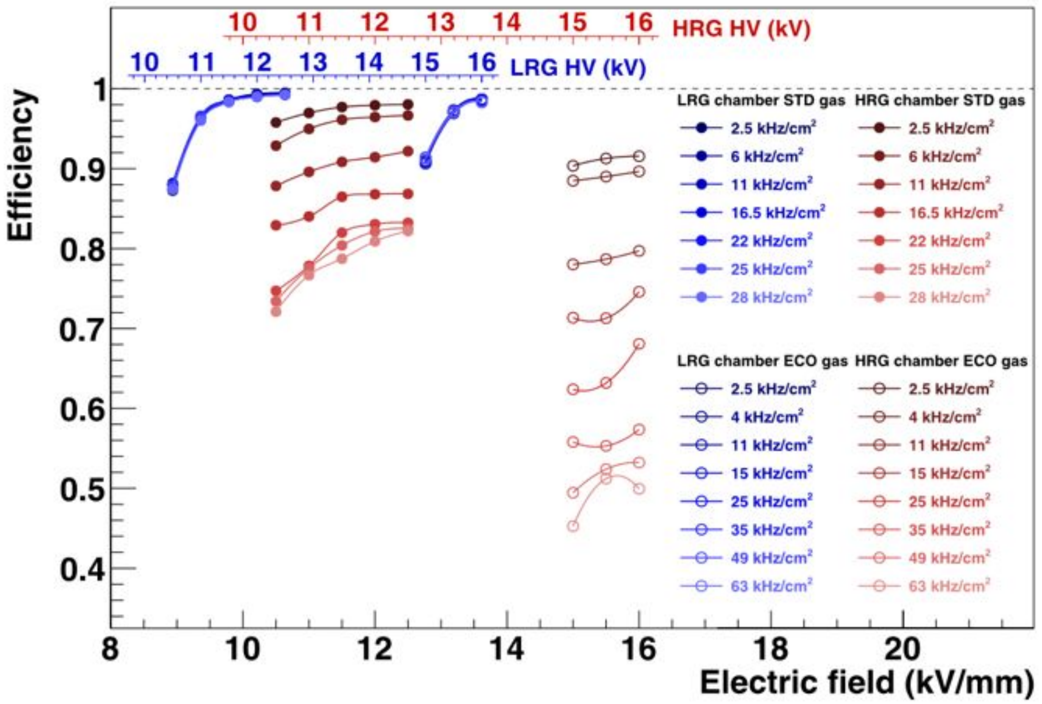
Gas chambers are also options for calorimetry

MRPCs for fast timing

- **MRPC developments for fast timing (D7.2)**:
  - MRPC with 10 layers and 230µm gaps.
  - Glass sheets with low-resistivity (LRG ~10^9 Ωcm), and high-resistivity glass (HRG ~10^{12} Ωcm) used.
  - Standard (98% $C_2H_2F_4$ 2% SF_6 GWP 2040) and ECO (100% HFO1234ze GWP 6) gas mixtures were used.
- **Good performance of LRG, even with ECO gas, but at much higher voltage (+4kV).**

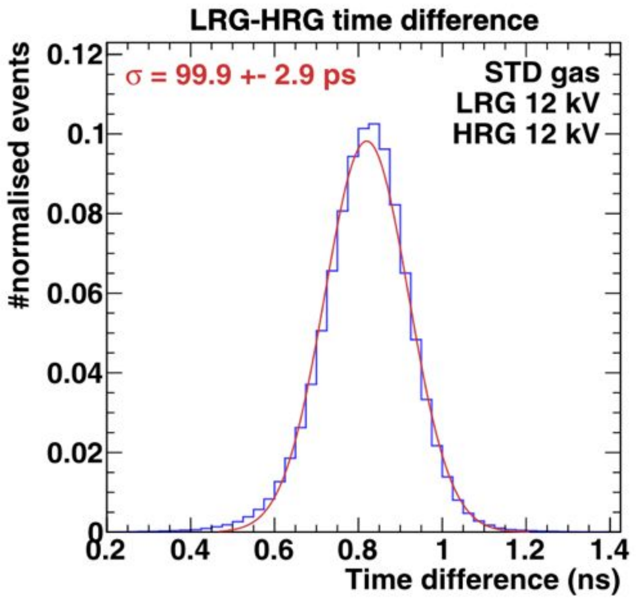


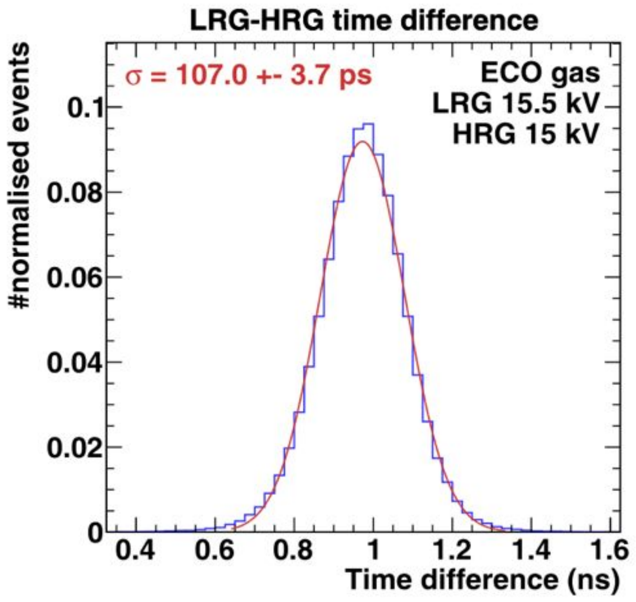
- **Rate performance with beam spot of 4 cm^2**



Inauguration RT

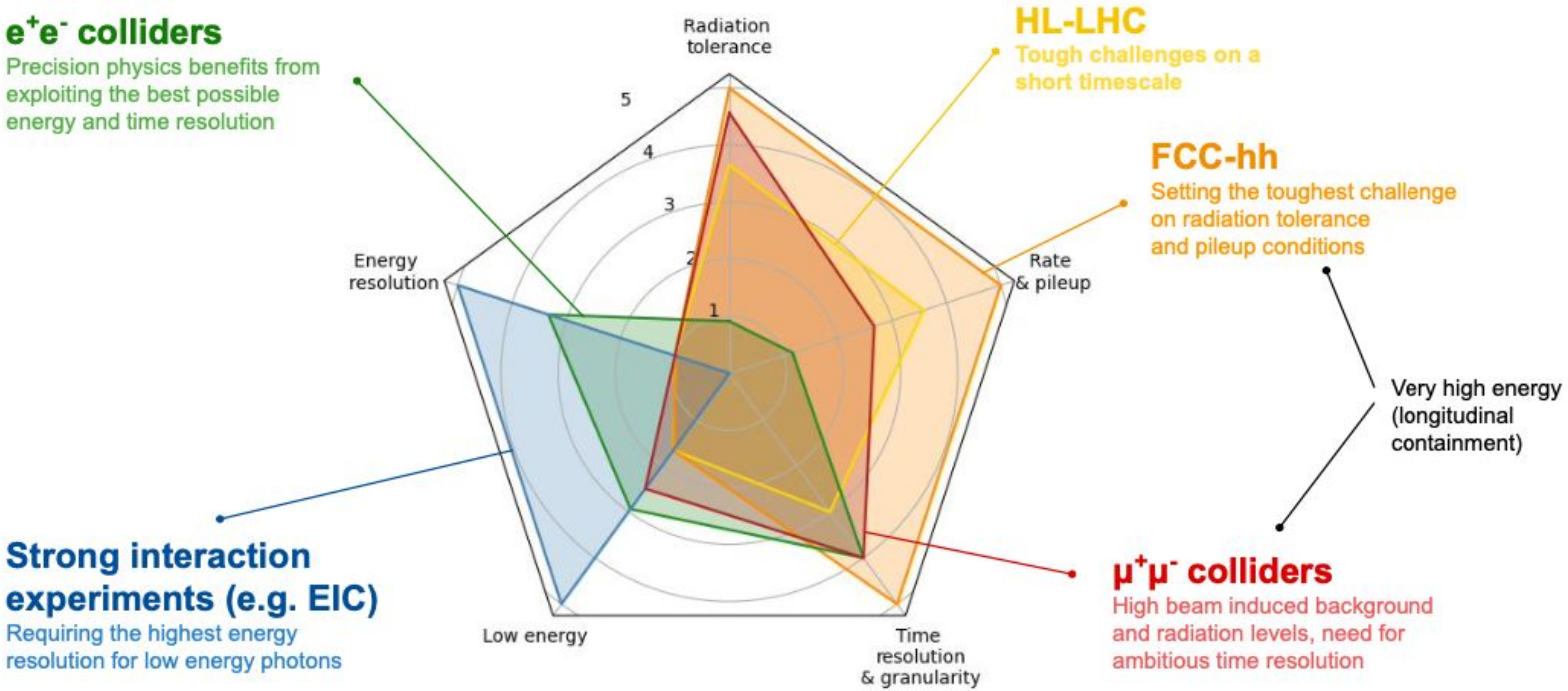
- **Time resolutions measure: ~100ps**





B. Schmidt, AIDAinnova Midterm Review

Requirements for calorimetry at future colliders

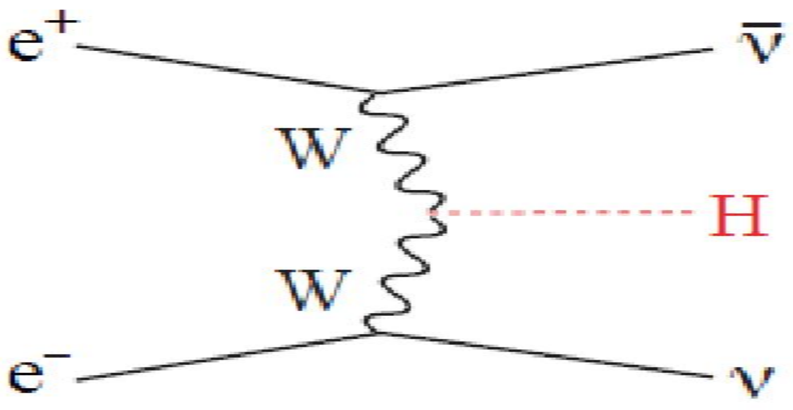


Inspired from https://indico.cern.ch/event/994685/

Motivation for excellent jet energy resolution

Examples:

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



- Jet energy resolution of ~3% for a clean W/Z separation

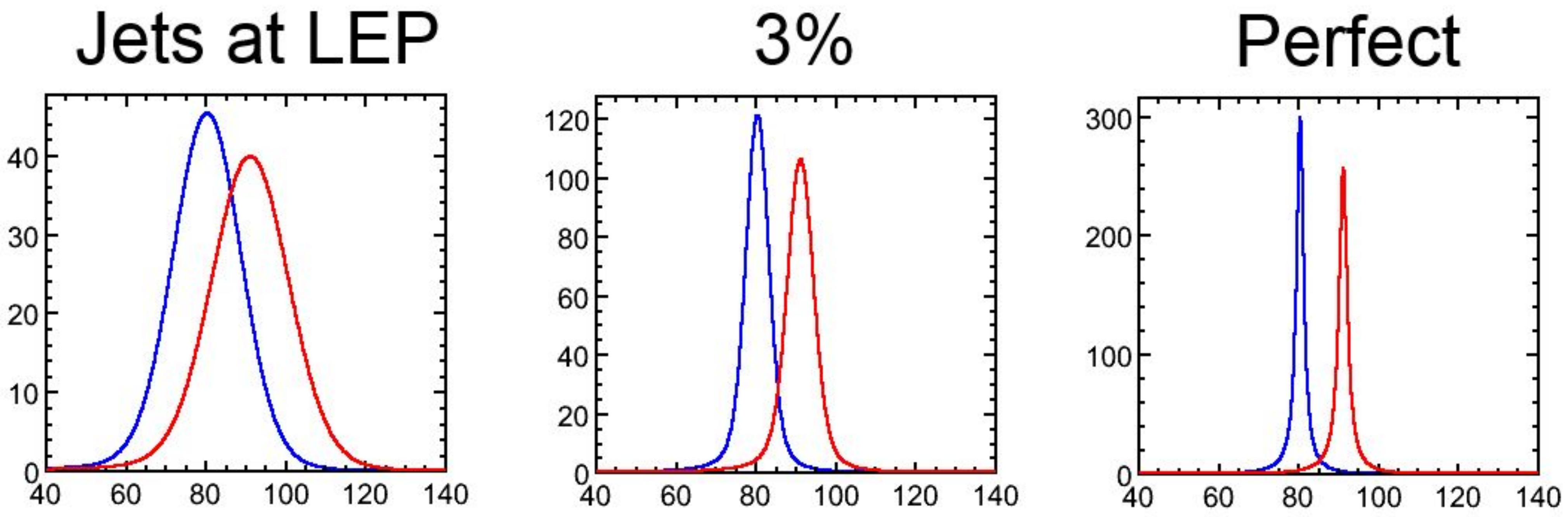
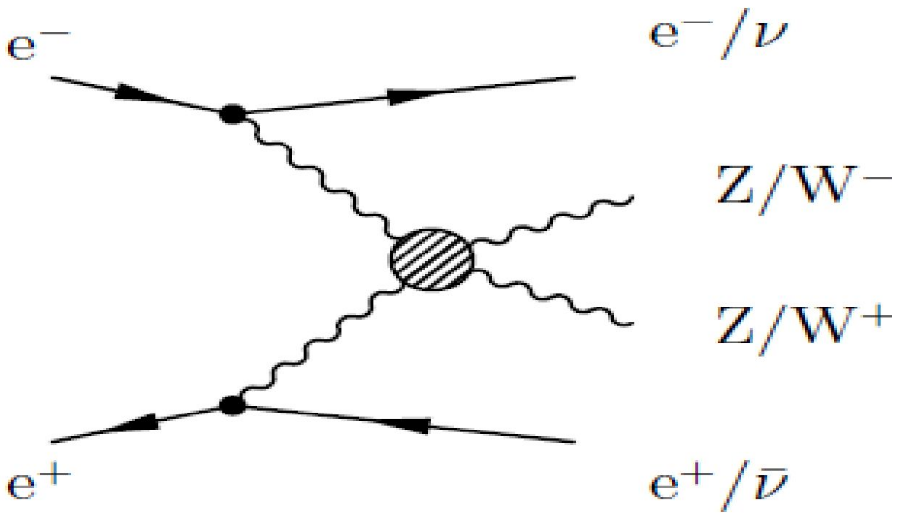


Figure by M. Thomson



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

27

Jet energy resolution – Different approaches

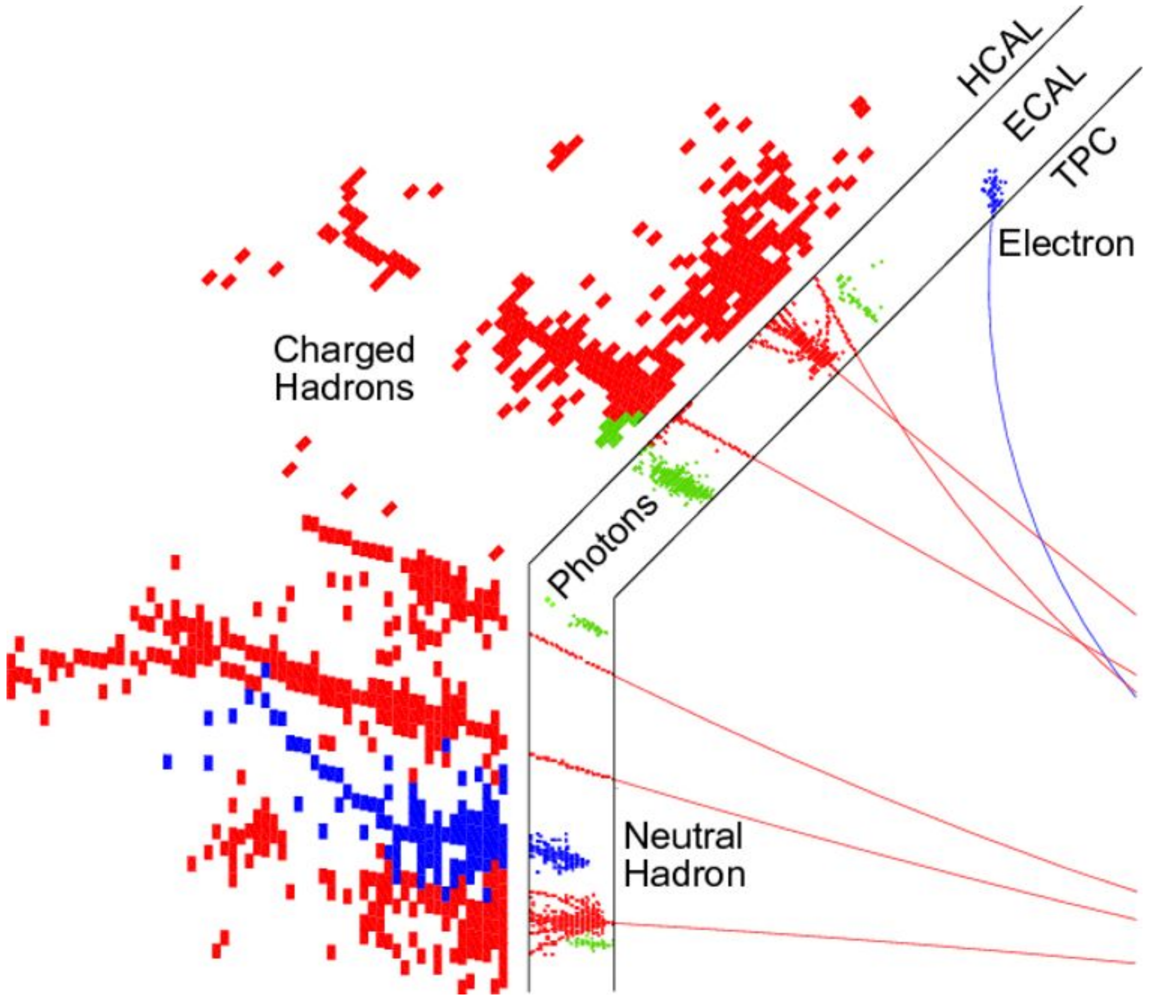
High pixelisation to exploit tracking as much as possible

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

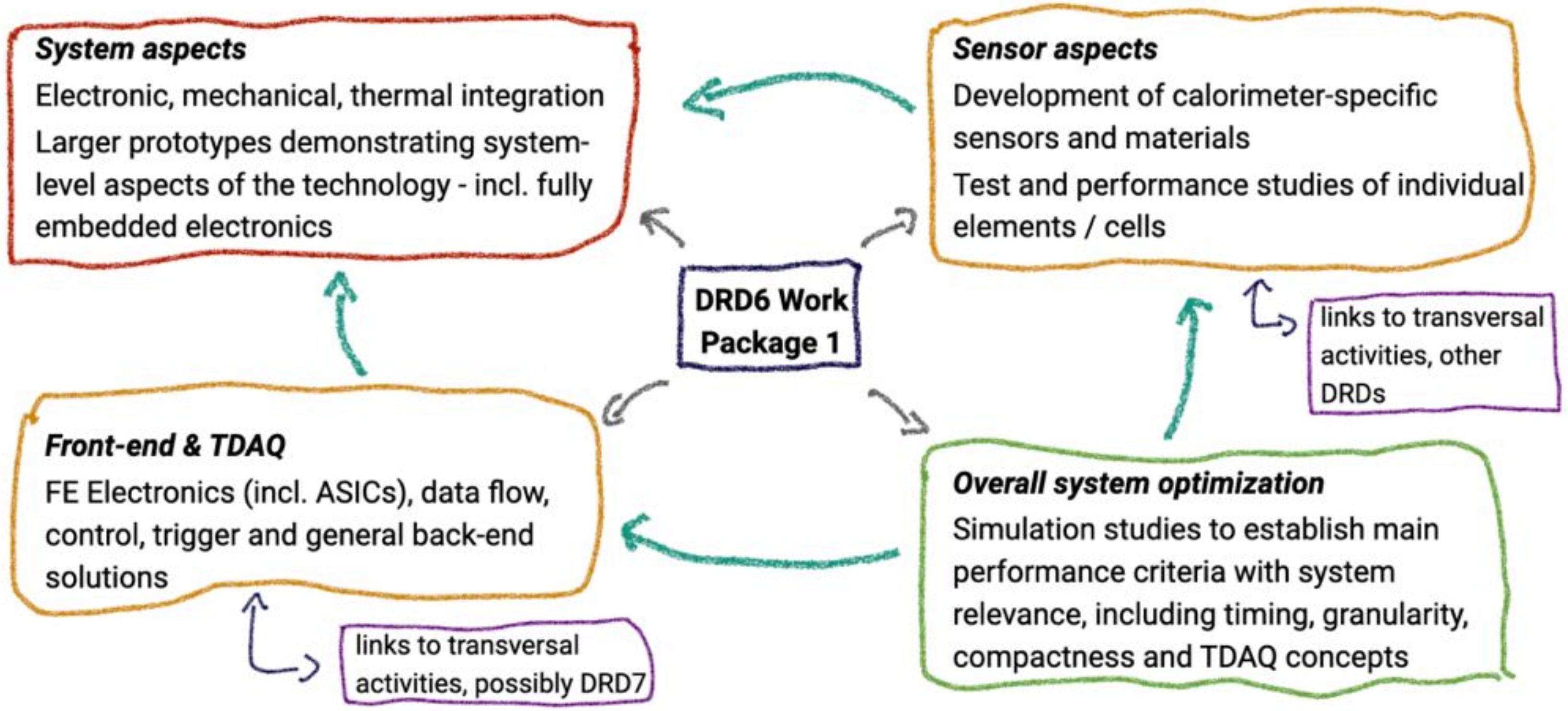
Optimise for hadronic energy resolution

Optimise for electromagnetic energy resolution

Imaging calorimeters



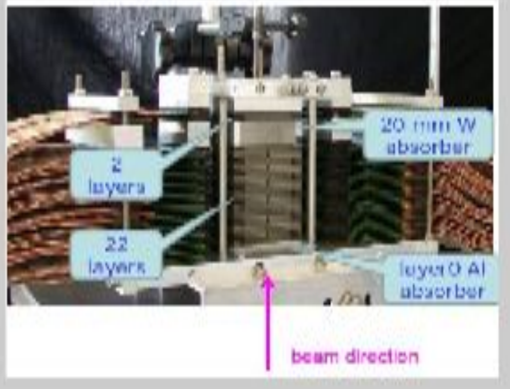
Imaging calorimeters provide the high separation power for **Particle Flow**



- 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)

Imaging Calorimeters - Prototyping

Si-W ECAL	(ALICE FoCAL)	Scint-W ECAL	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

From V. Boudry, Calor 2024

- Many technology options being pursued for imaging calorimeters, with analog, digital or semi-digital readout.
- First true fully imaging calorimeter is the HGCAL of CMS.

Future Noble Gas Calorimeters

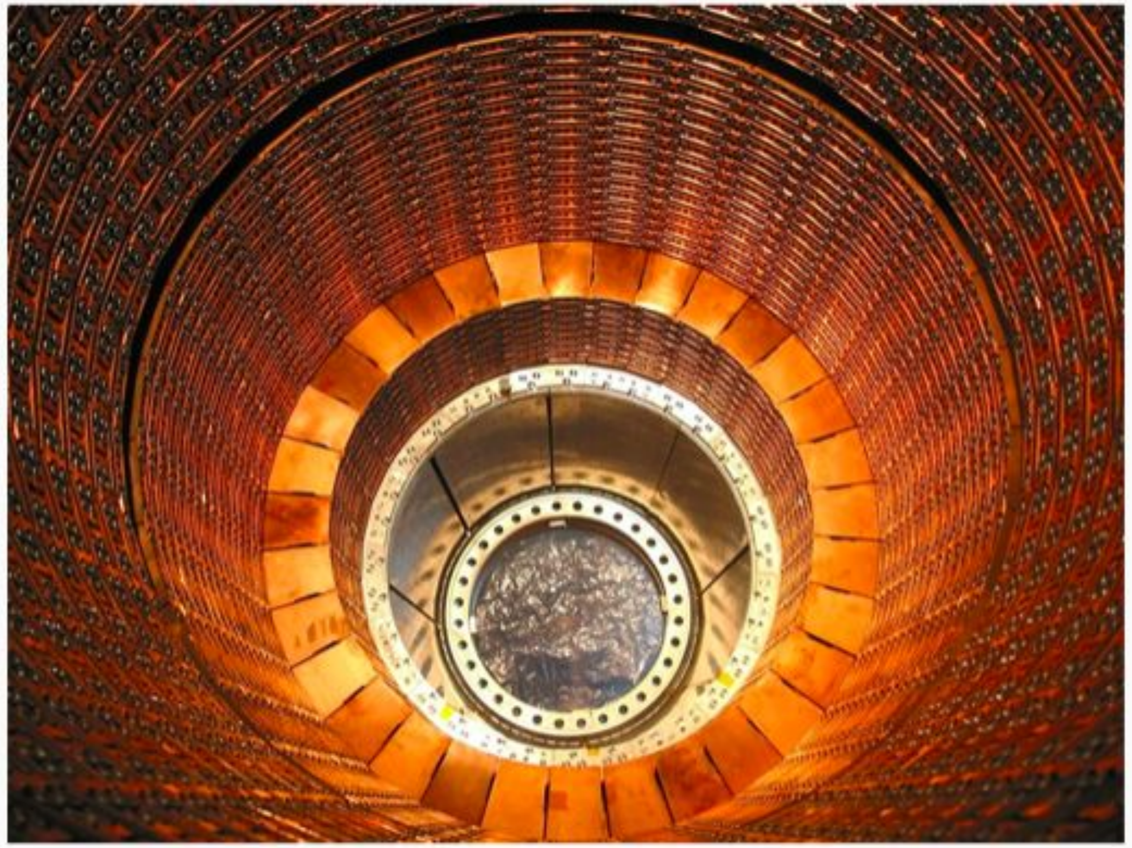
- LAr Calorimetry is proven technology since a few decades
  ATLAS, H1, DO, NA31

- 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

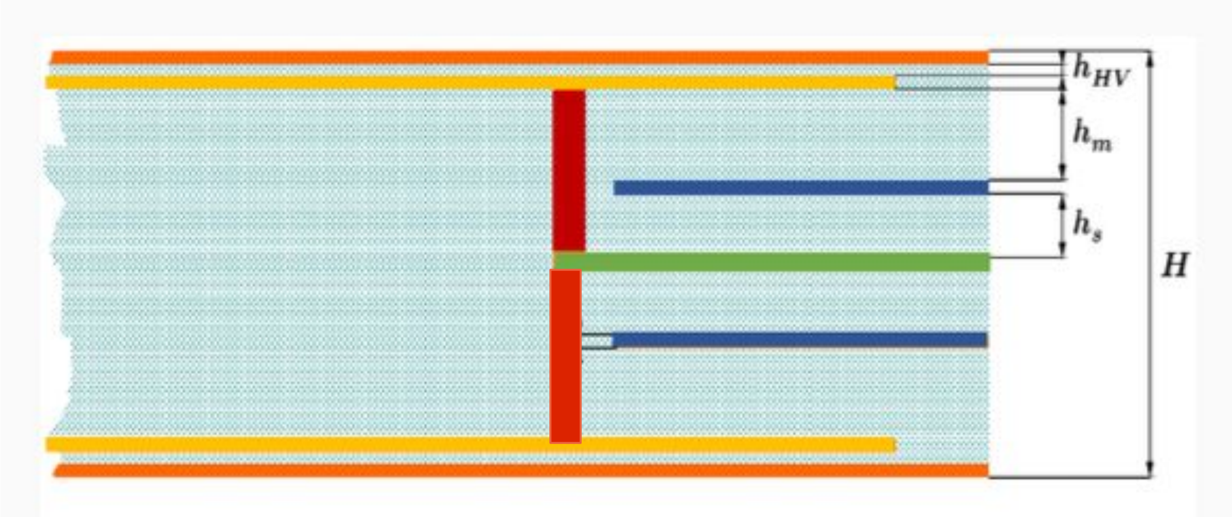
- => Increase of granularity
  - Goal: Factor ~10 w.r.t. ATLAS LAr Calorimeter
  - 220 kCells -> ~2 MCells

ATLAS LAr calorimeter

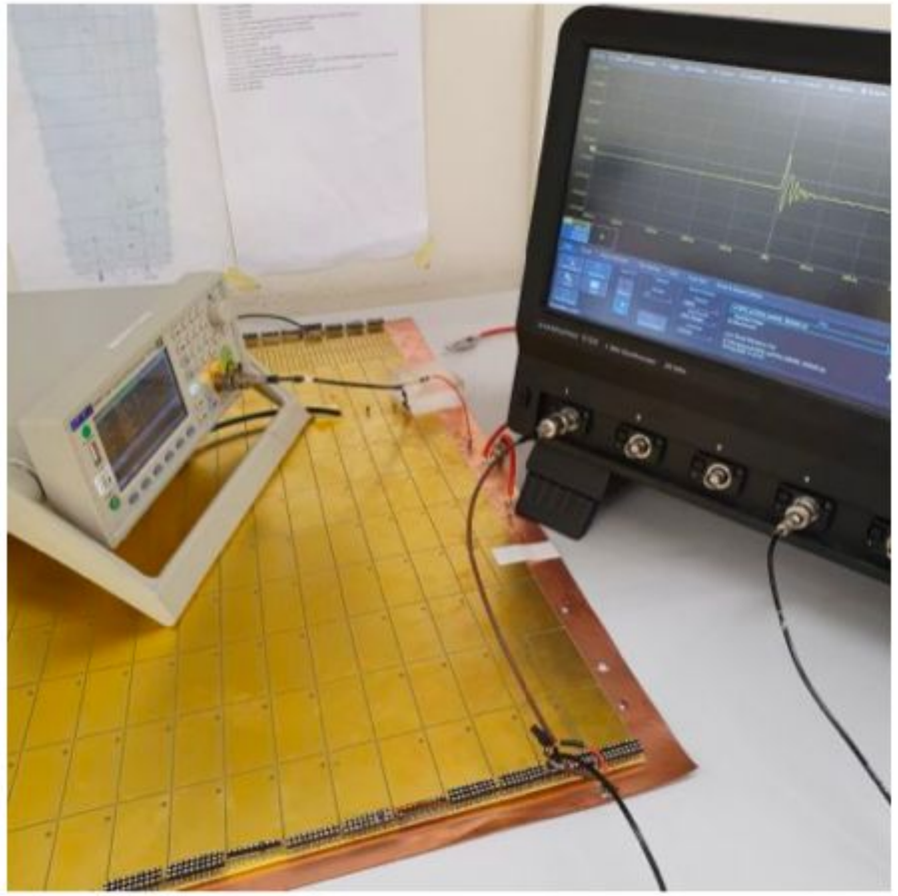


Future Noble Gas Calorimeters – How to increase the granularity

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



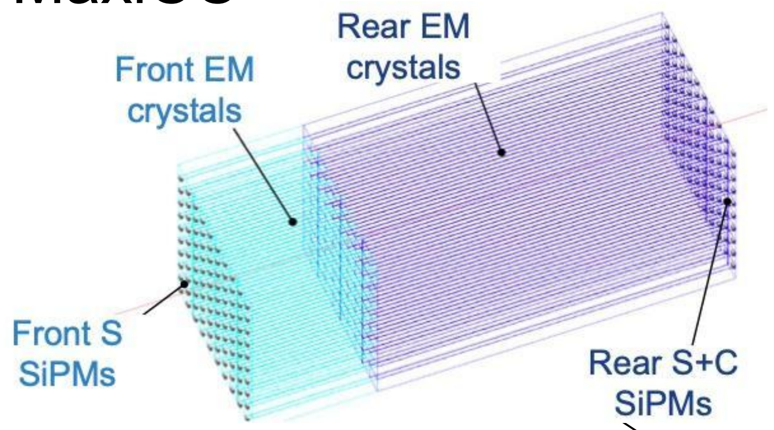
- One signal trace is economical solution to reduce signal traces
- Pick-up of signal from both sides increases S/N



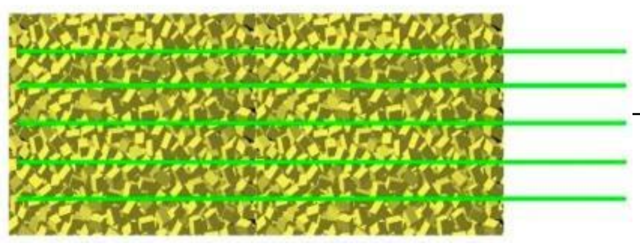
Challenges:

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

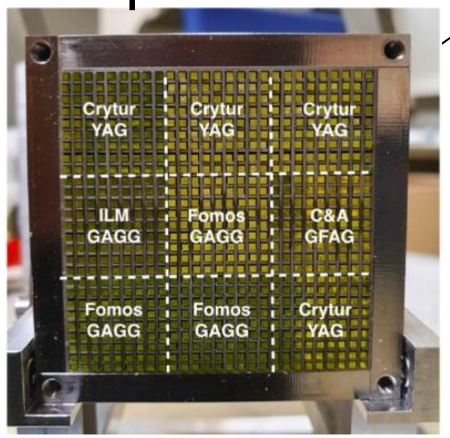
MaxiCC



GRAiNITA



SpaCal



- More than e.g. imaging calorimeters optical calorimeters put emphasis on the electromagnetic energy resolution
  - (Liquid Noble) interpolates a bit between these two cases
- Elm. resolutions down to 1-2%/√E are envisaged
  - Advantegeous for Higgs Factory, indispensable for Heavy Flavour

Table 2: Overview of R&D activities on optical calorimeter concepts.

Name	Calorimeter type	Application	Scintillator/WLS	Photodetector
HGCCAL	EM / Homogeneous	e^+e^- collider	BGO, LYSO	SiPMs
MAXICC	EM / Homogeneous	e^+e^- collider	PWO, BGO, BSO	SiPMs
CRILIN	EM / Quasi-Homog.	$\mu^+\mu^-$ collider	PbF_2, PWO-UF	SiPMs
GRAINITA	EM / Quasi-Homog.	e^+e^- collider	$ZnWO_4$, BGO	SiPMs
SPACAL	EM / Sampling	e^+e^-/hh collider	GAGG, organic	MCD-PMTs, SiPMs
RADICAL	EM / Sampling	hh collider	LYSO, LuAG	SiPMs
DRCAL	EM+HAD / Sampling	e^+e^- collider	PMMA, plastic	SiPMs, MCP
TILECAL	HAD / Sampling	e^+e^-/hh collider	PEN, PET	SiPMs

- Main challenges
  - Find the good optical material
  - Find the adequate photosensor
  - Move from table top to system
    - First project to fully make this step is SpaCal (LHCb)

Dual Readout Calorimetry

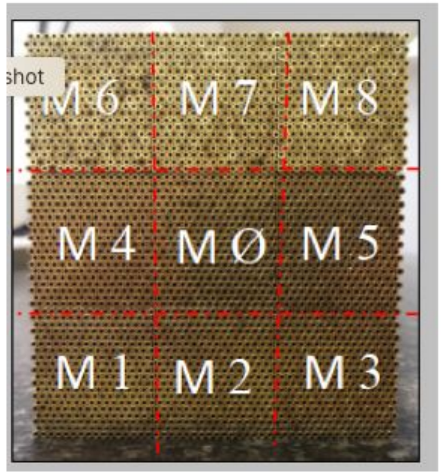
Fast signals

Slow signals

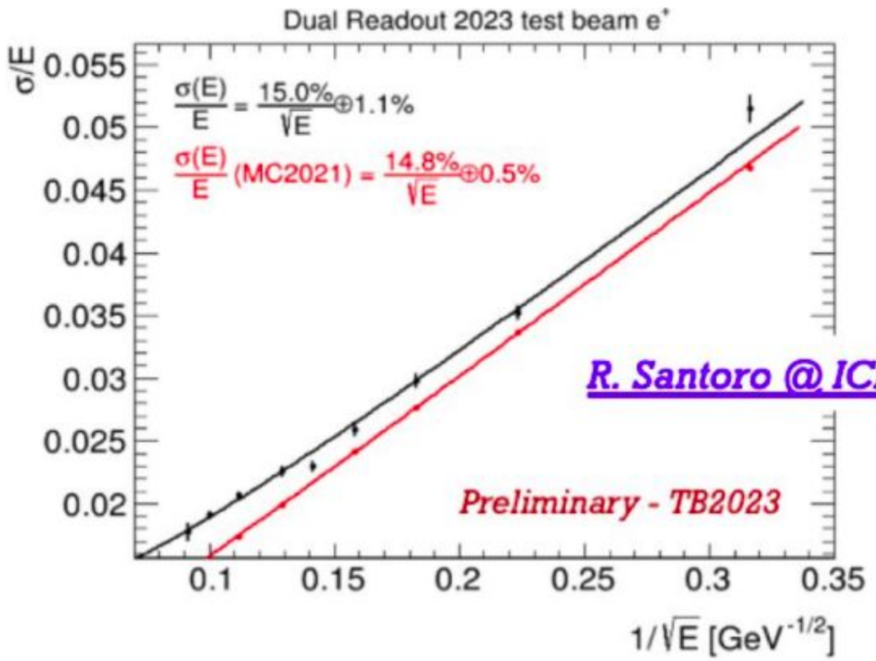
Dual readout to capture Electromagnetic and hadronic components of shower

Prototype development

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



Outgoing fibres guided to readout plane



R. Santoro @ ICHEP2024

Electromagnetic energy resolution
In beam test

$$\frac{\sigma}{E} = \frac{15\%}{E} \oplus 1.1\%$$

Novel optical materials

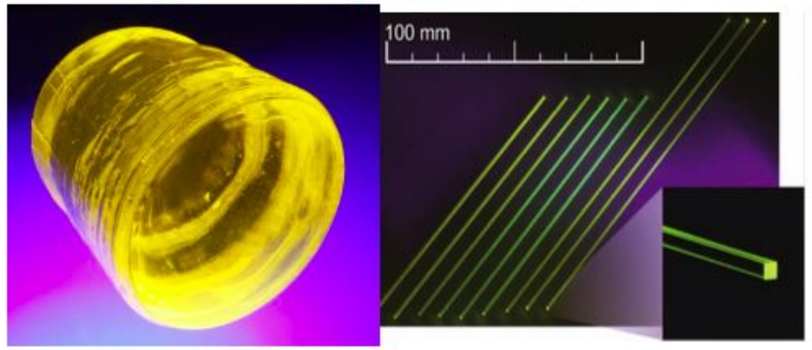
- Radiation hard optical materials with ultrafast timing response are required for new detectors in HEP, nuclear medicine and industry

- 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

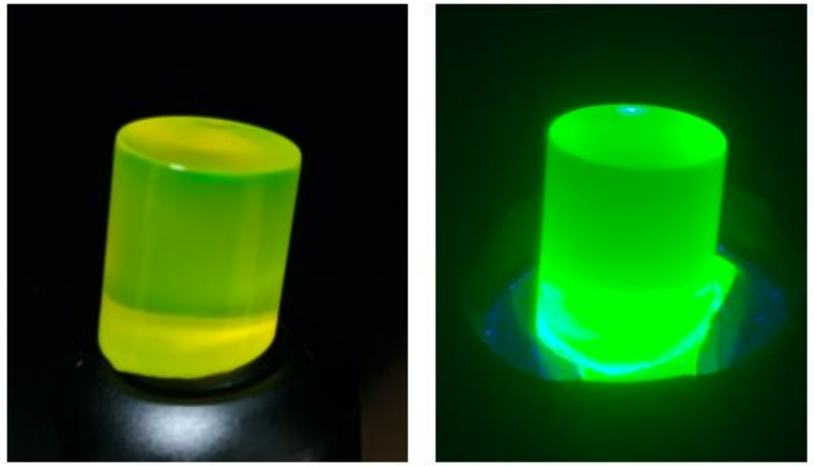
- Scalable and cost effective production techniques for the novel materials have to be explored together with the industrial partners

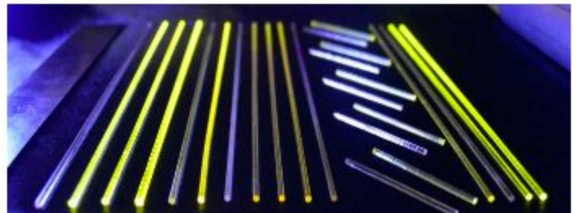
Crytur YAG ingots => fibers



Crytur PWO crystals

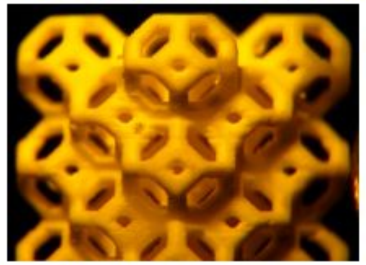
GlasstoPower development on quantum materials





Several types of Fibers from ILM; Lyon

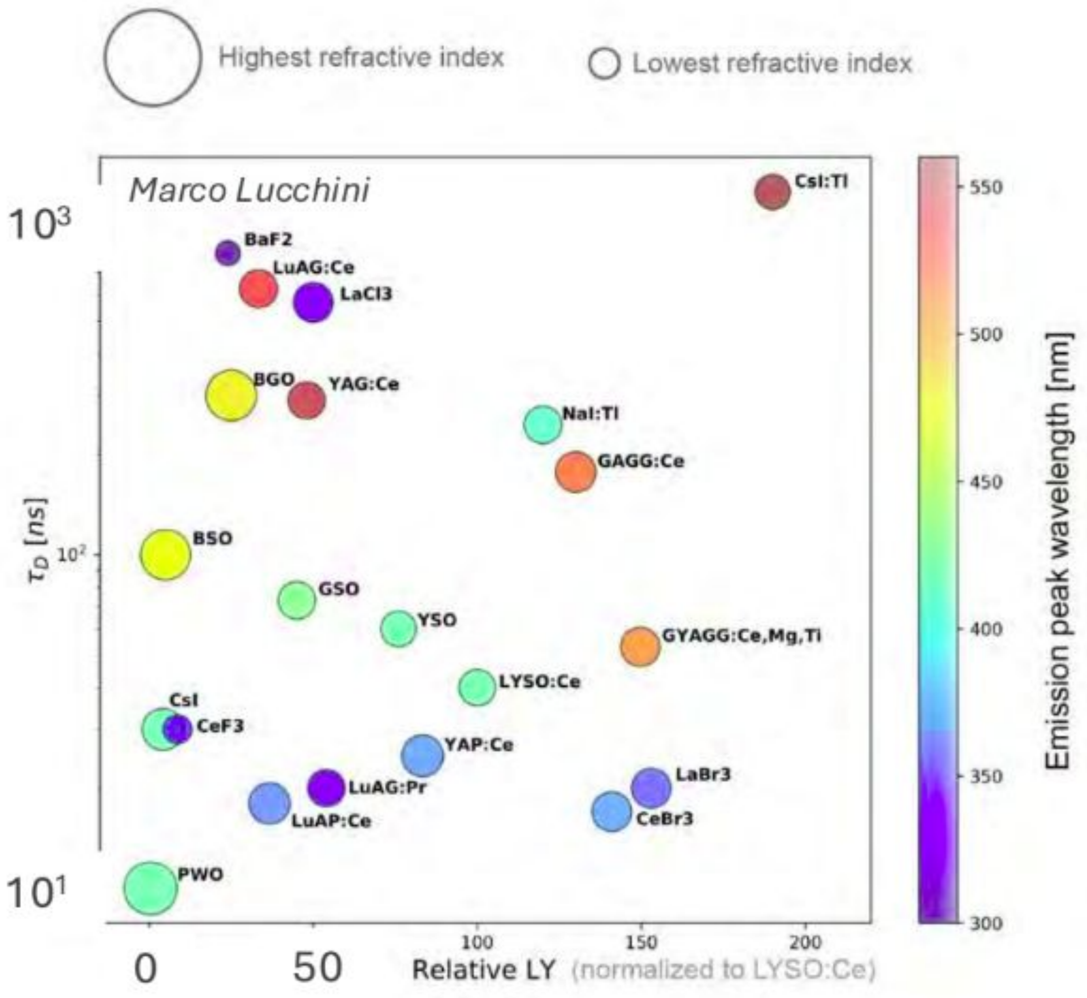
3 D printed garnet Crystals

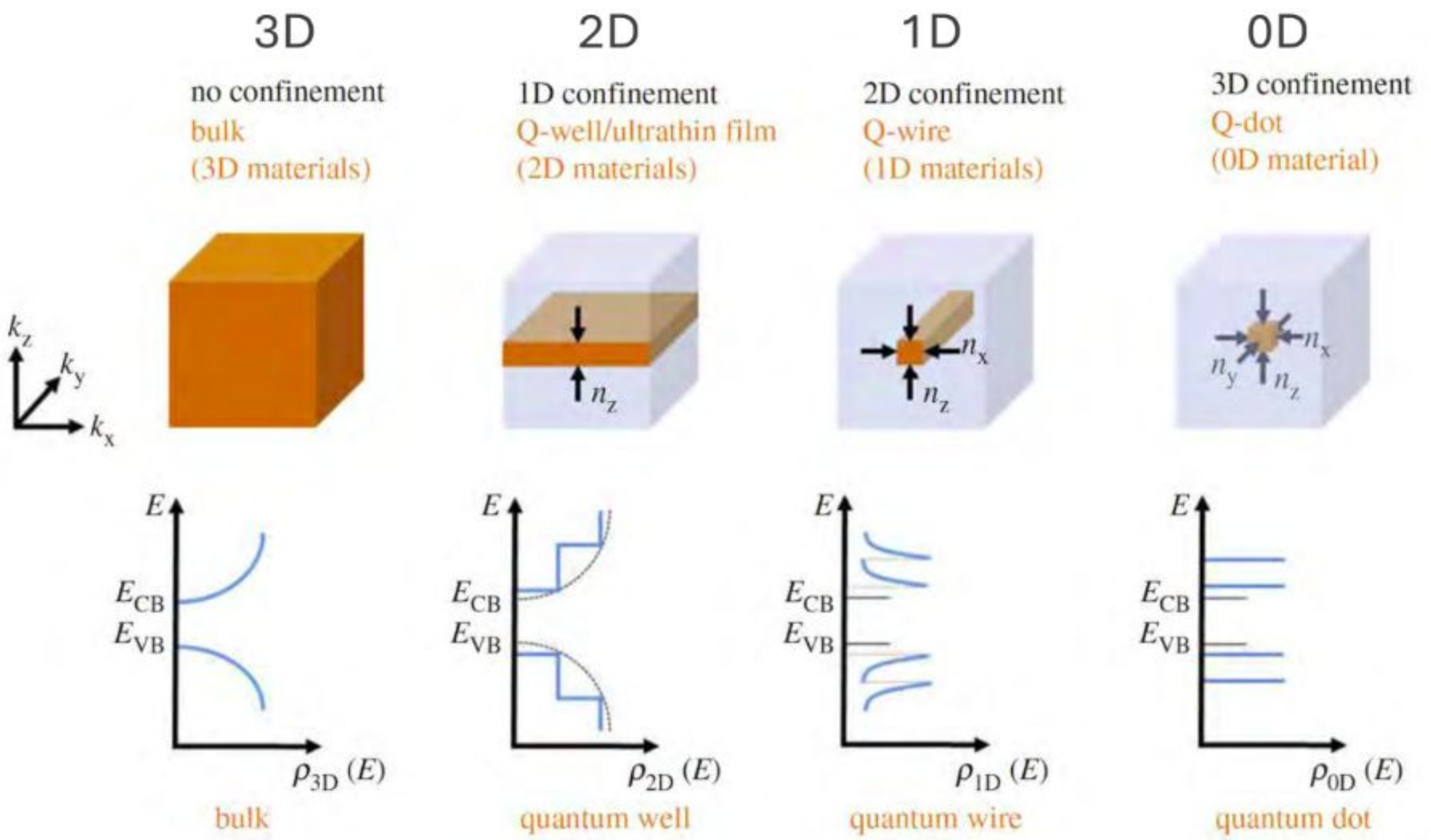


Courtesy G. Dosovitskyi, Kurchatov Institute

Quantum Dots

- Traditionally crystal - fully absorbing calorimetry - has obtained the best energy resolution



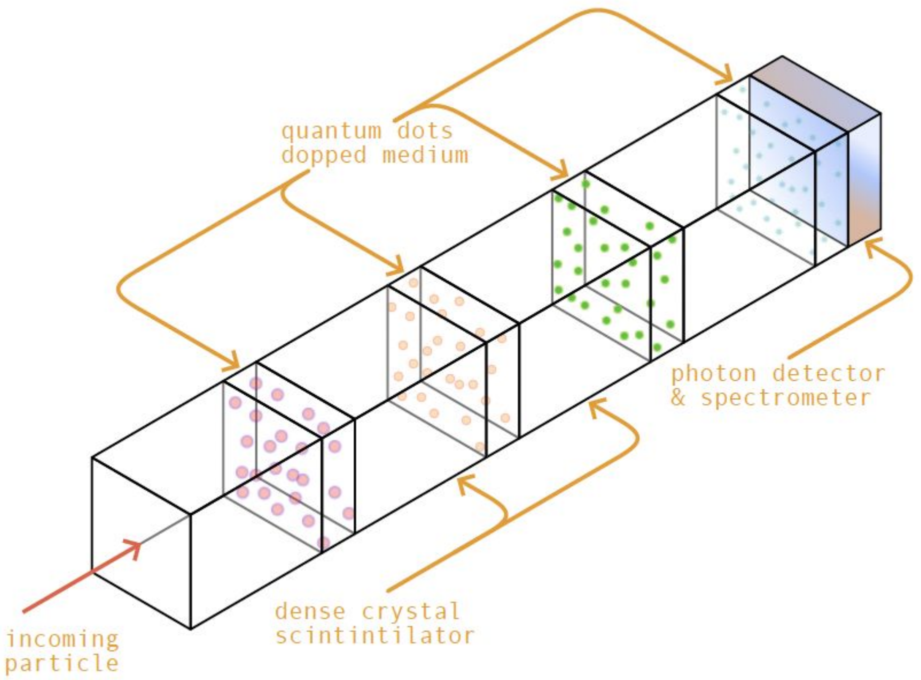


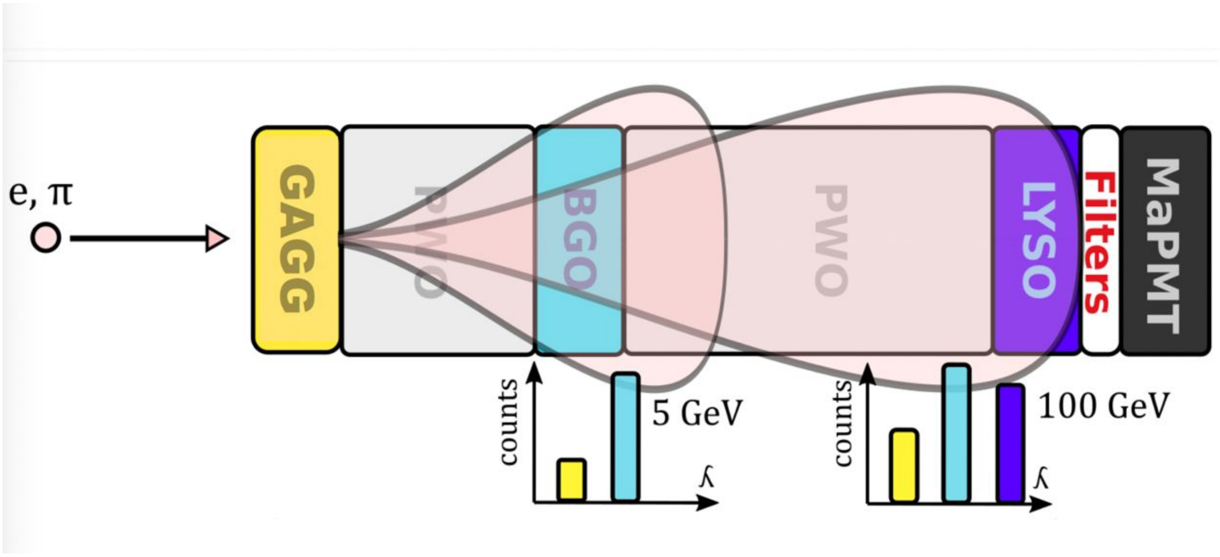
- Huge range of possibilities through **quantum engineering** of materials

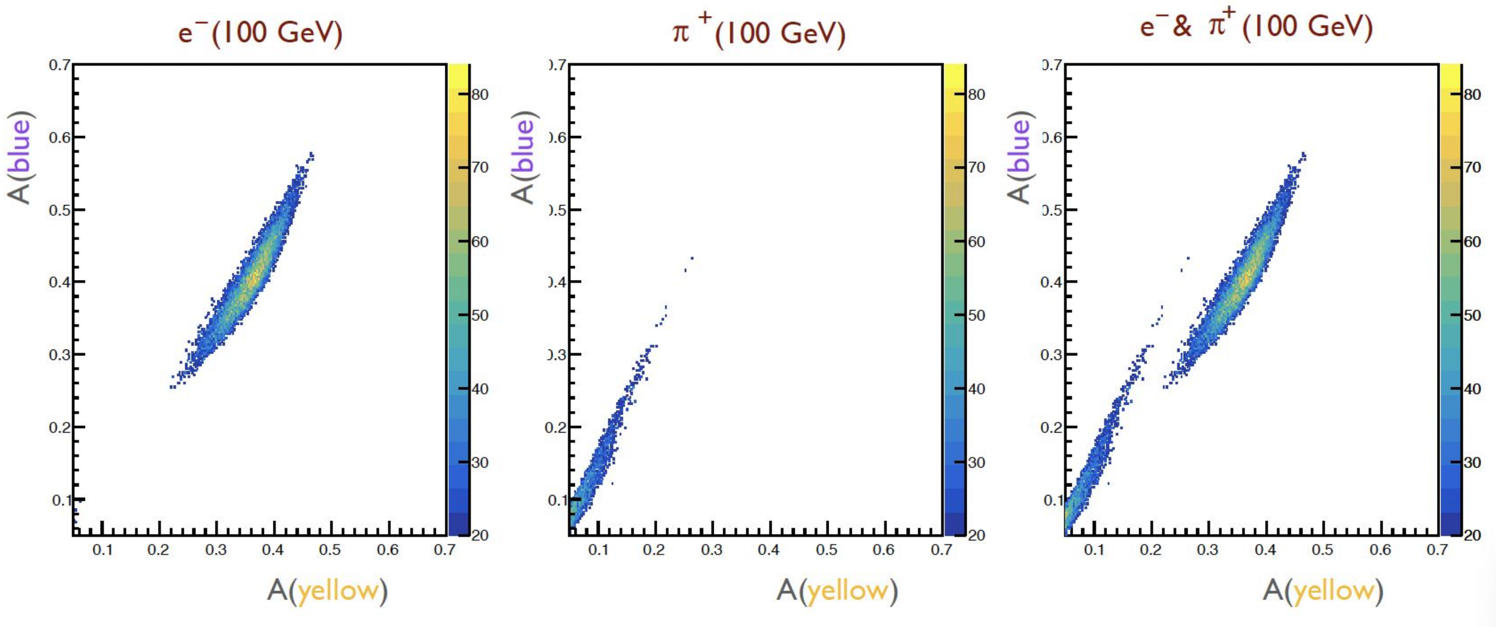
M. Demarteau, DRD Calo Meeting

36

Quantum Dot Crystal Calorimetry





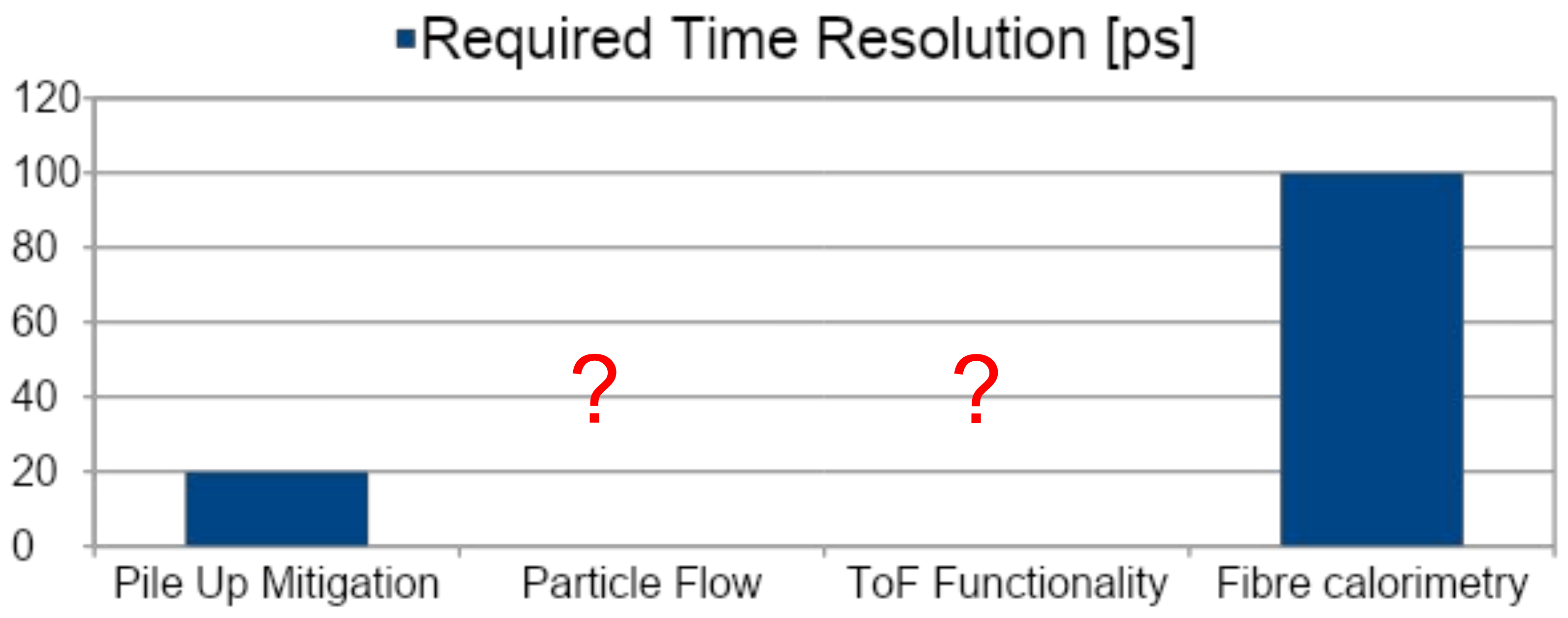


Chromatic Calorimetry

From: Devanshi Arora, CALOR'24

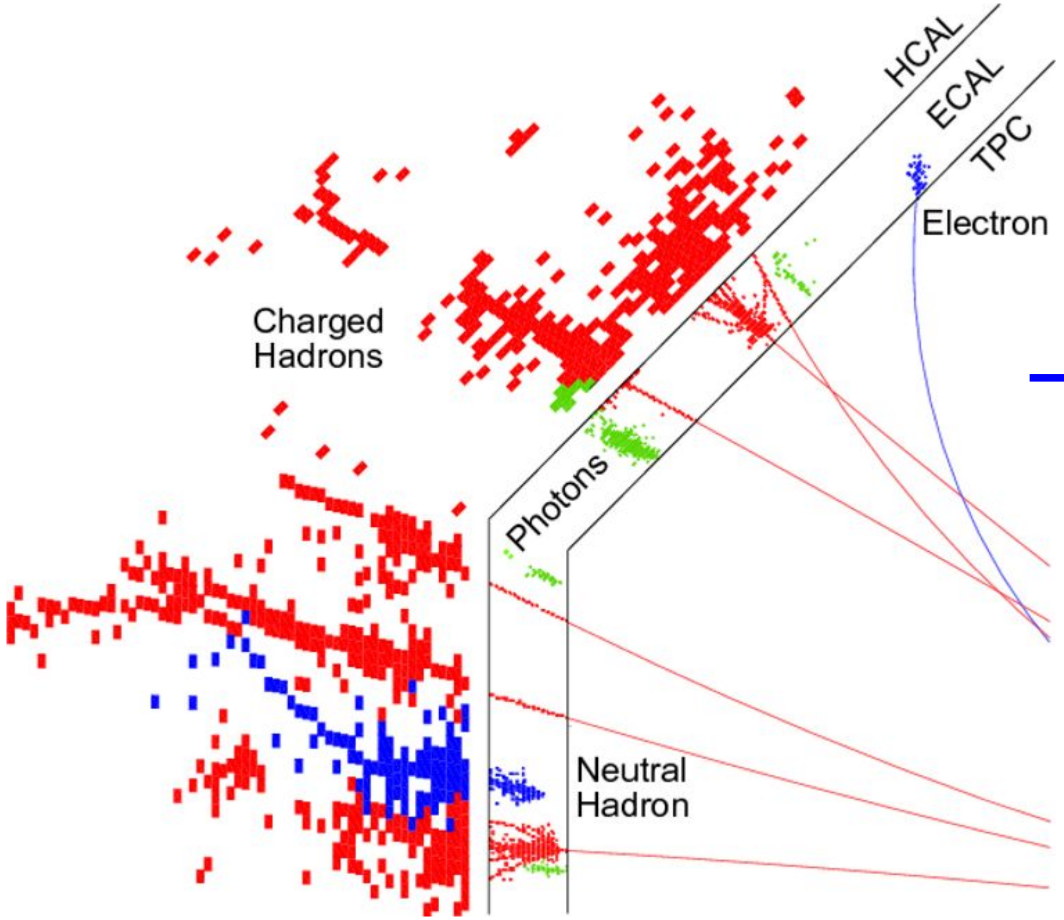
Timing ?

- 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

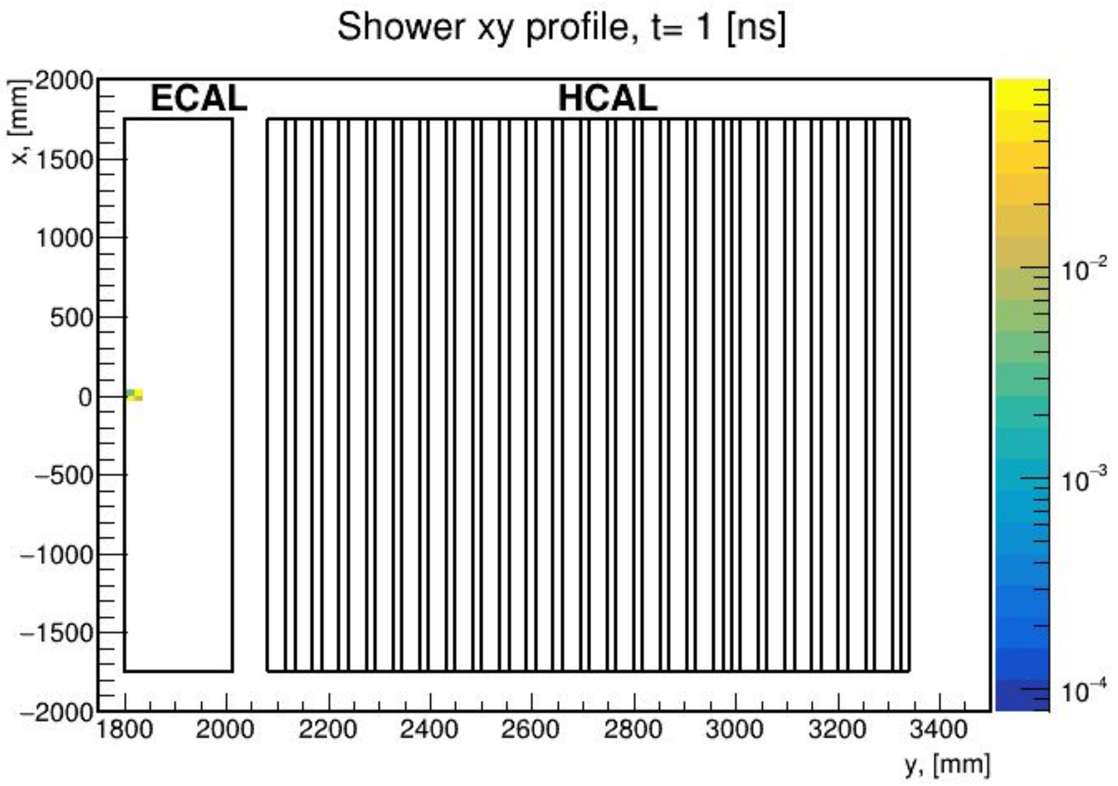


- A topic on which calorimetry has to make up its mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

Event Reconstruction



From static pictures to movies



Y. Padniuk, Master student
Technical University of Kiyv

- Can precise timing help for particle flow?
  - ANR-DFG project CALO5D
- Optimisation of Particle Flow Algorithms with help of Machine Learning Techniques
- Need early answers since a visible improvement would trigger intensive R&D

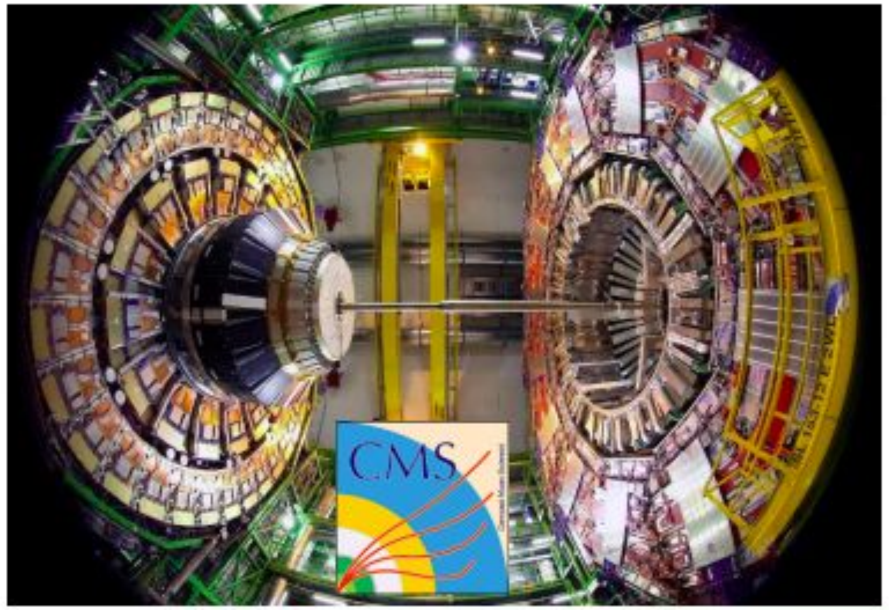
Electronics for Future Calorimeters

H2GCROC for the endcap calorimeter – Phase II

6M of Silicon channels
(+ 240k of SiPM)

Radhard (200 Mrad)
Low Power (15 mW per chn)
Precise timing (25 ps)

Total of 150k ASICs needed
Pre-prod this year



CALOROC for EIC

Same ASIC structure (floorplan)
Same ADC and TDC
Same readout

Common interfaces

HEP trend => imaging calorimetry

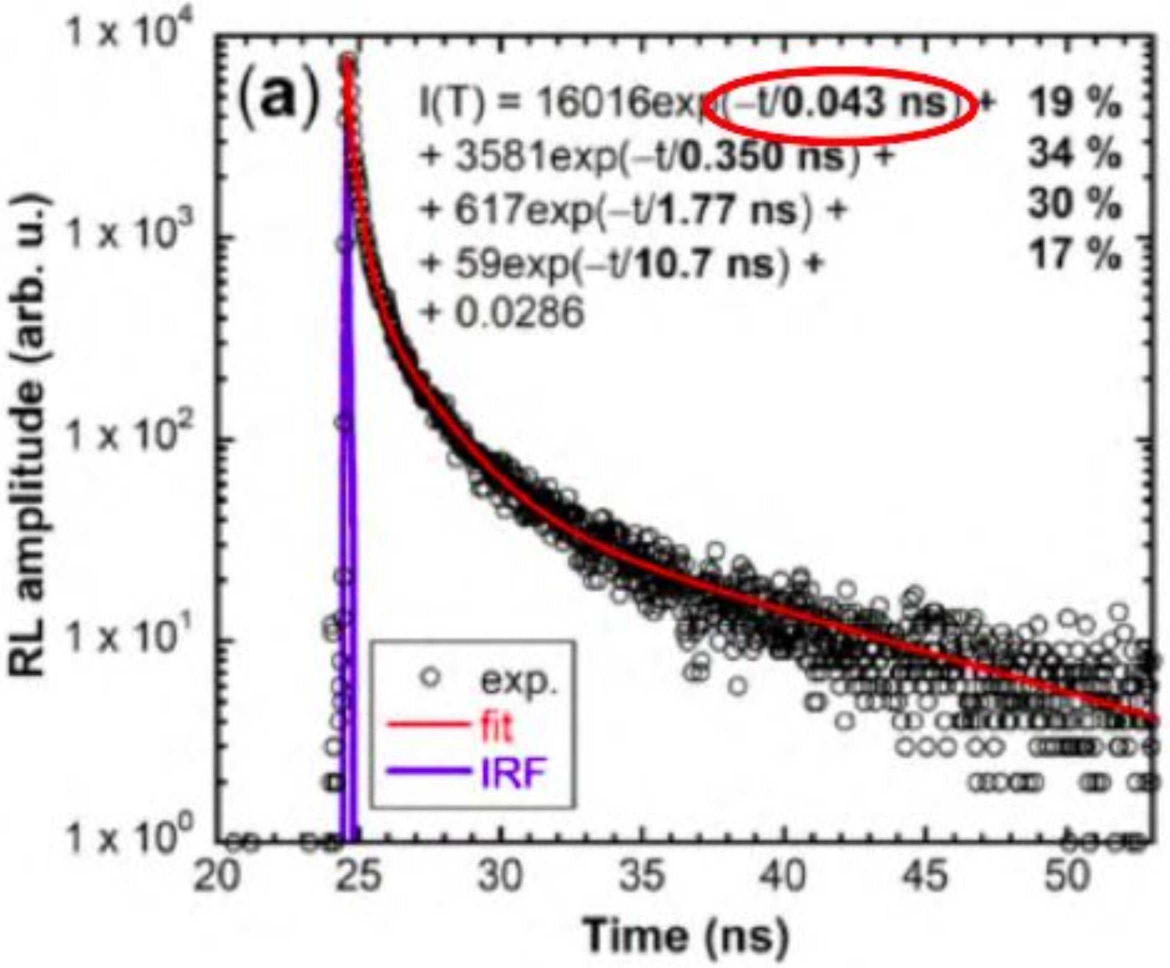
- High number of channels
- Charge and precise timing (<100 ps)
- Low power + System-On-Chip

Based on H2GCROC, CALOROC will provide a versatile and low-power solution for SiPM readout

C. de la Taille, DRD Calo Meeting

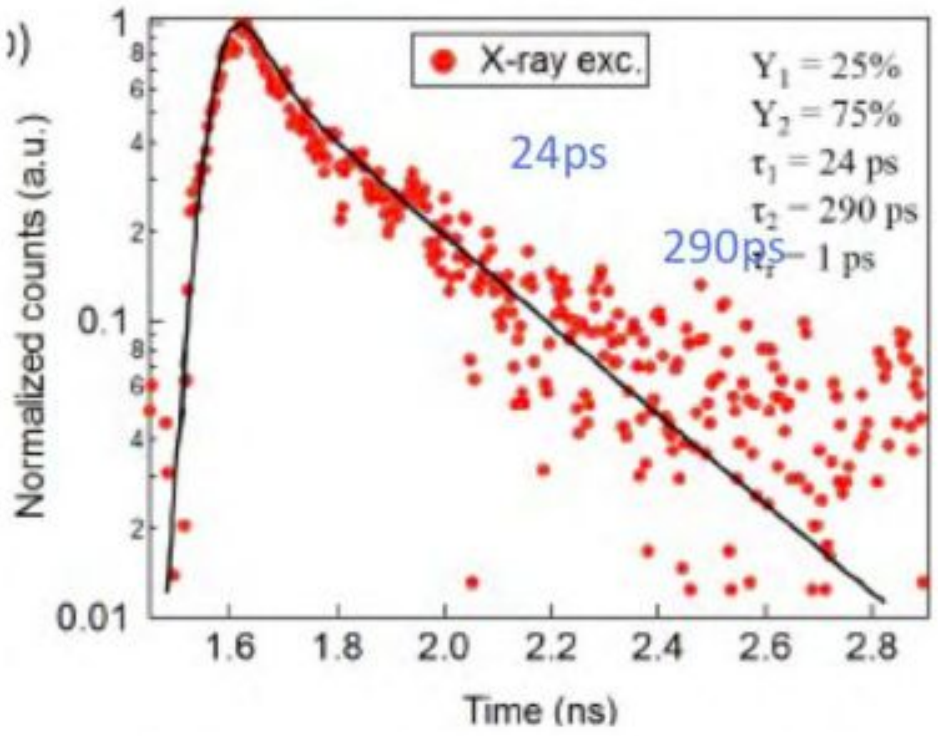
Quantum Dots for Timing

- Fast light emission through QD engineering



K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. Nanomaterials 2022, 12, 14. https://doi.org/ 10.3390/nano12010014

CdSe nanoplatelet,



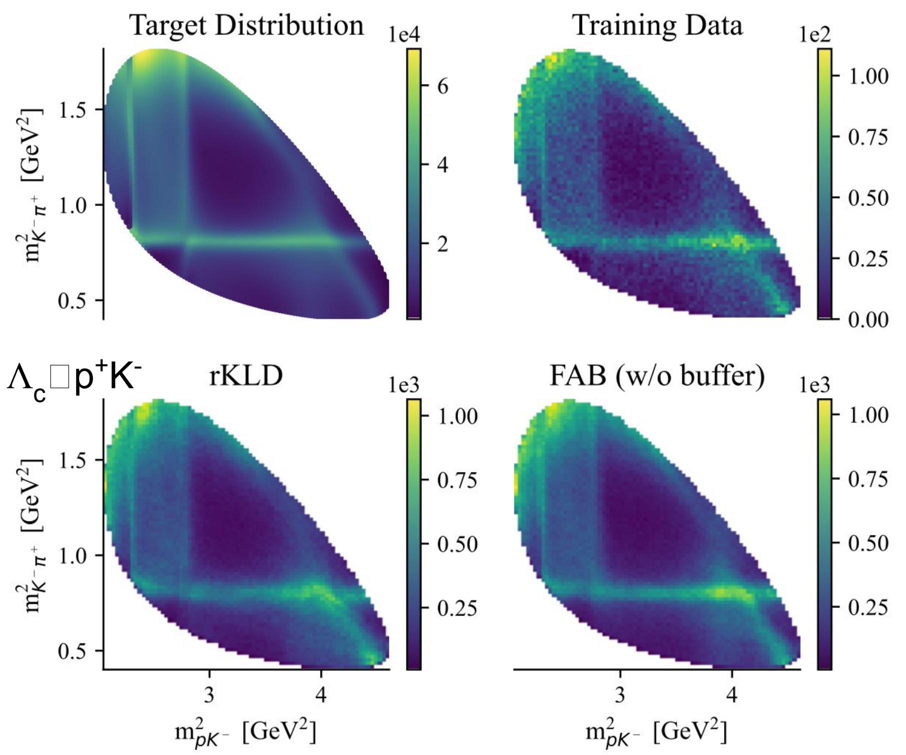
J. Grim et al., *Nature Nanotechnology*, **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

Simulation

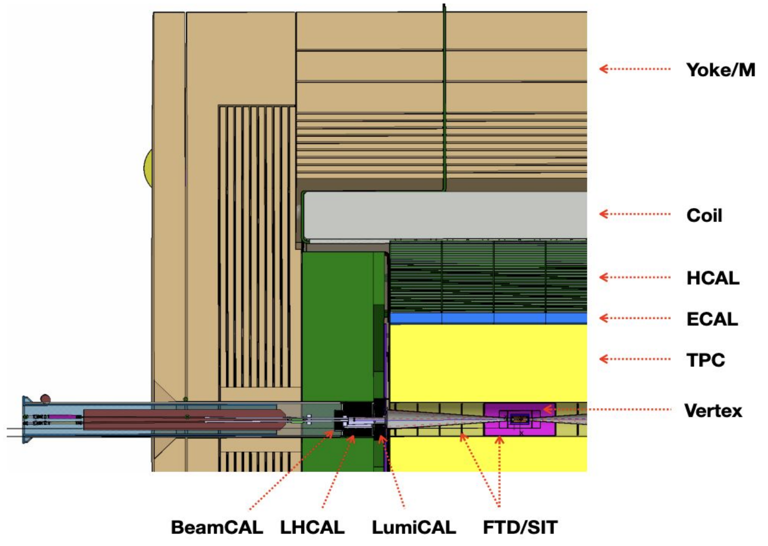
- Simulation needs ~ typically 50% of computation need
- Detector simulation (Geant4) but also event generation N$^{(p)}$LO
- More data, precision physics -> need for even more simulation
- Generative models to emulate event generator and detector simulation
- Physics simulator are still needed (keep them alive) to provide training data
- Several orders of magnitude speed-up, but accuracy ?

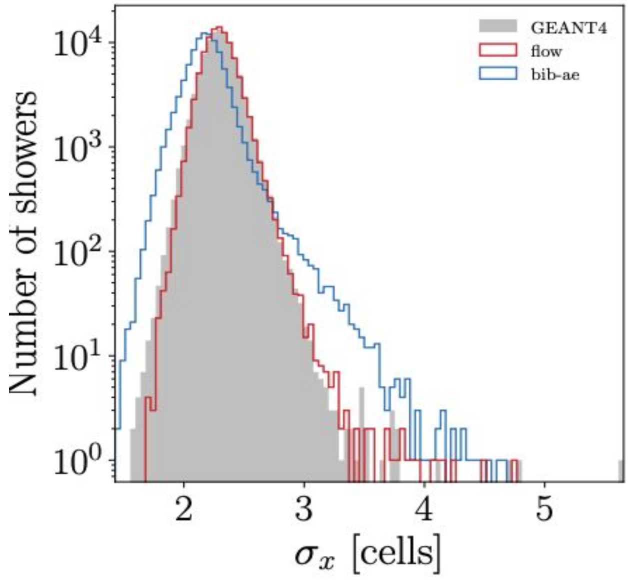
Flow Annealed Bootstrap Meets Differentiable Particle Physics

Emulation of Matrix Elements for : Λ_c□p$^+$K$^-$ π^+



Convolutional L2Flows : **Generating Accurate Showers in Highly Granular Calorimeters Using Normalizing Flows**

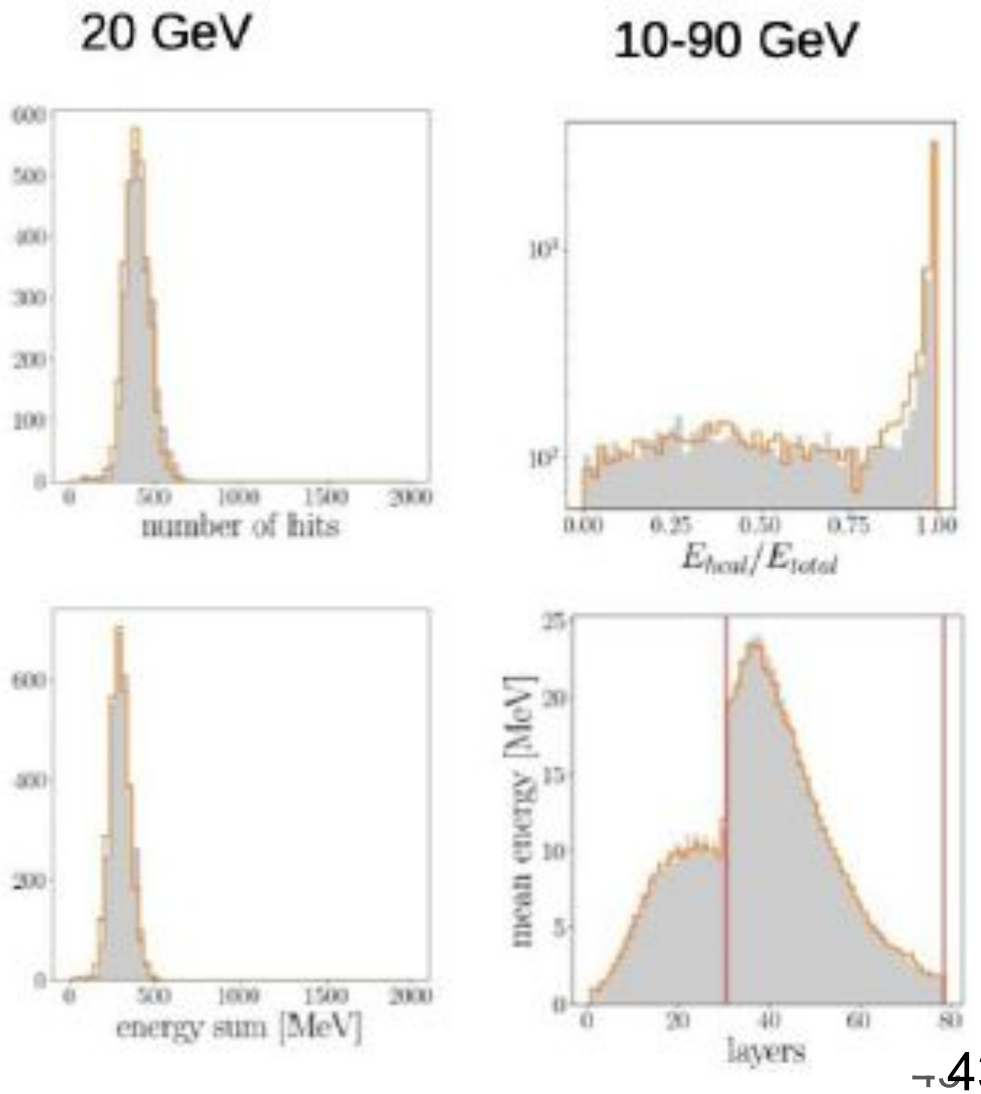


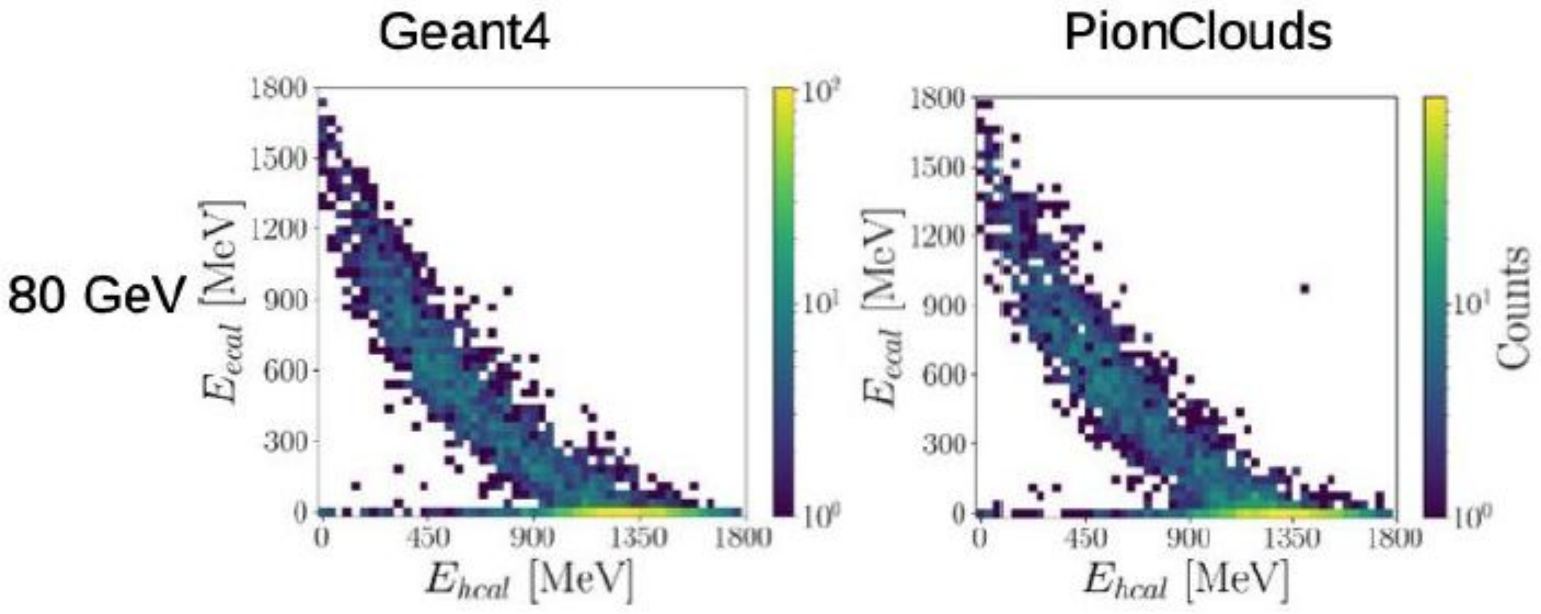


Machine Learning for Simulation

- Generating showers in highly granular calorimeters with GEANT is rather time-consuming
- Potential solution: ML models trained with (limited statistics) GEANT showers as truth
  - Should offer the possibility to condition on energy, angle, …
- Investigated many different architectures
  - Big step forward: diffusion models
    - Can cope with (almost) any geometry
      - But need very detailed info for this (individual GEANT steps)
    - Out-of-the-box: slow due to many diffusion step
- Now working mainly on
  - Making the diffusion models faster
  - Implementing the ML showers into full detector simulation&reconstruction chain
  - Finding metrics to judge if this is "good enough"

From arXiv:2103.01458

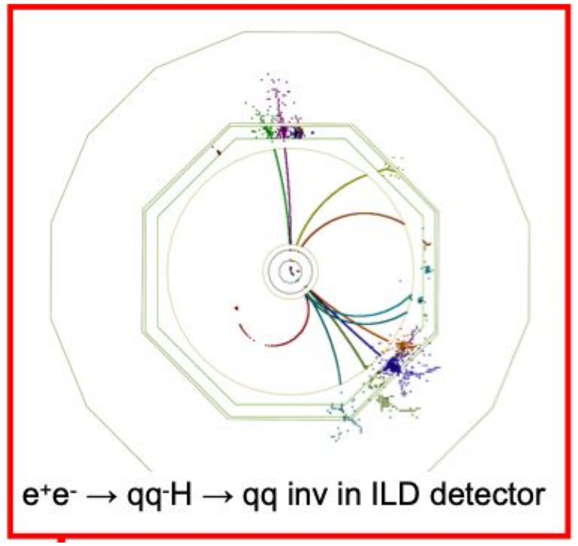




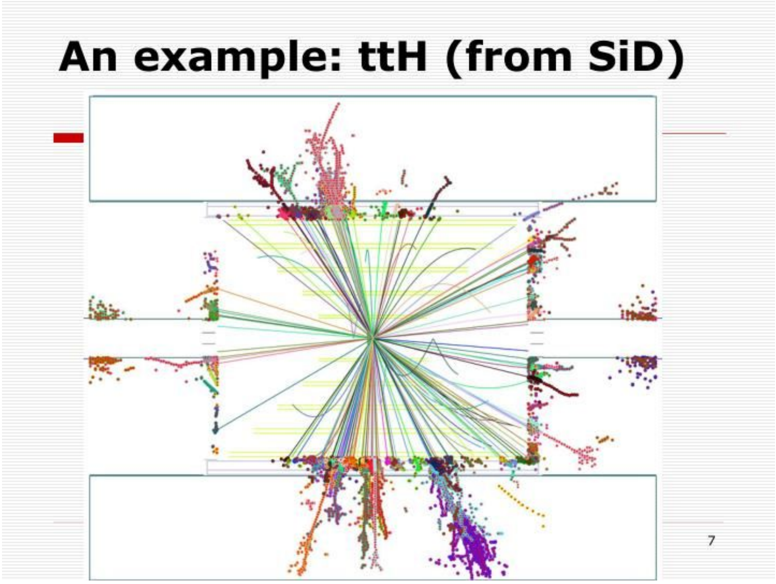
Slide by K. Krüger

Detector Design - Hermeticity

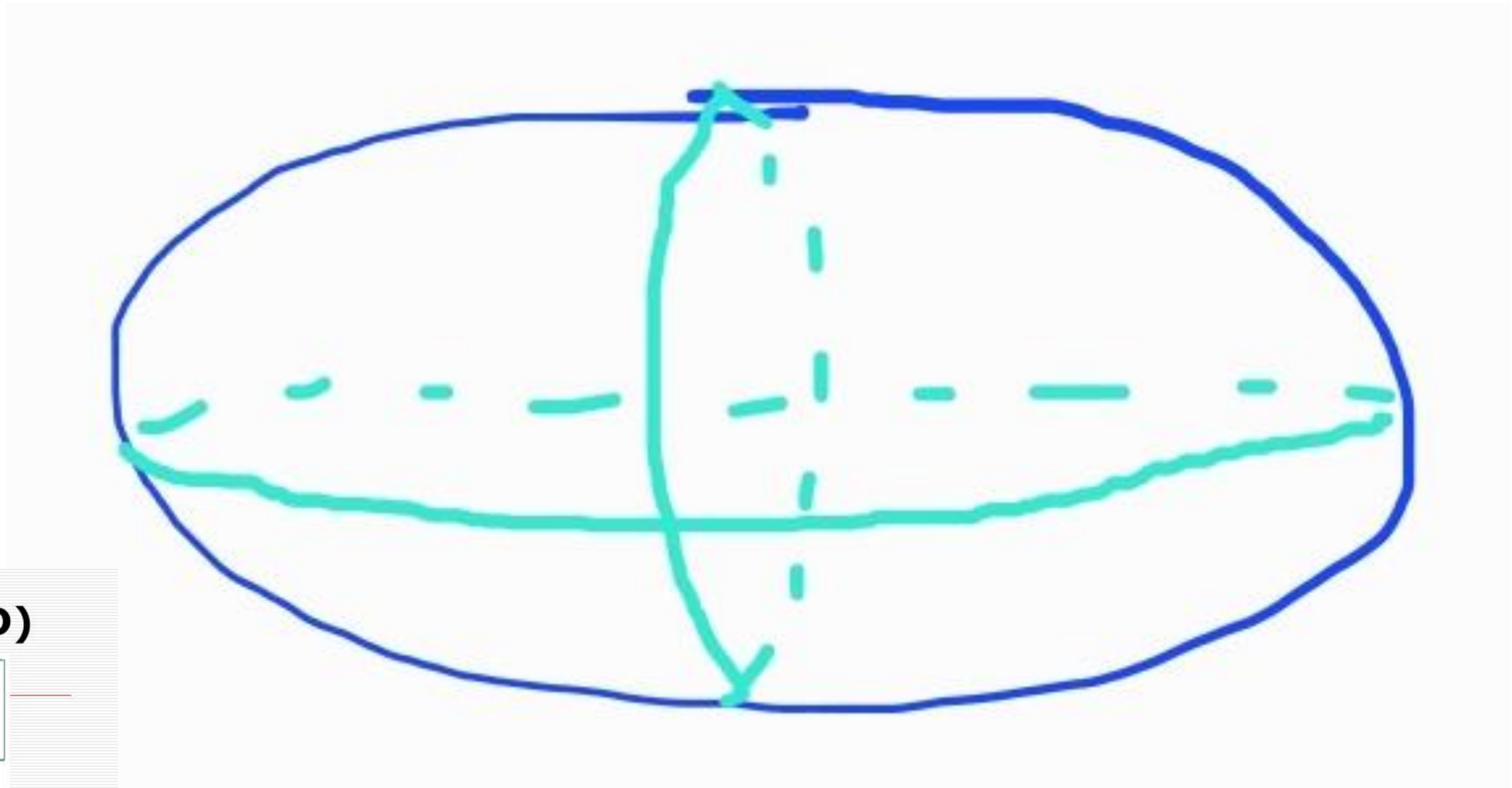
Invisible Higgs decays



Rich events:

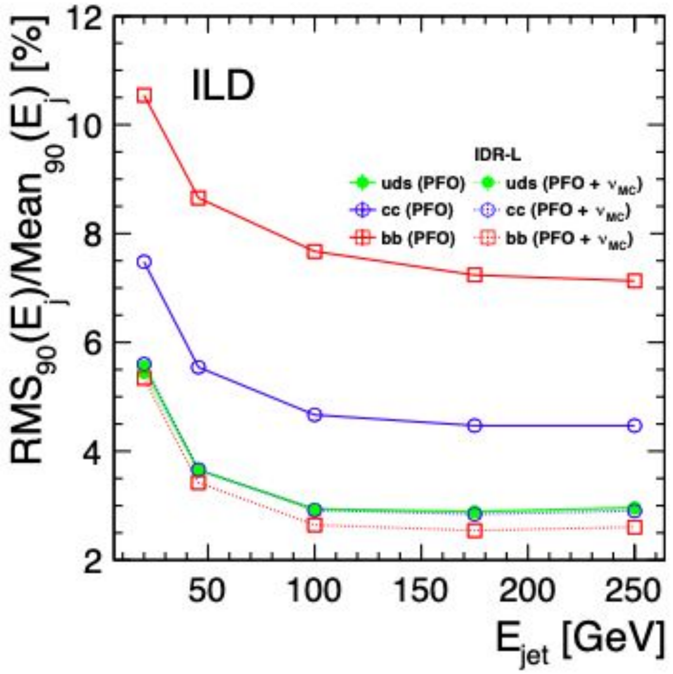


Hermeticity = Acceptance down to the beam pipe and no acceptance holes!

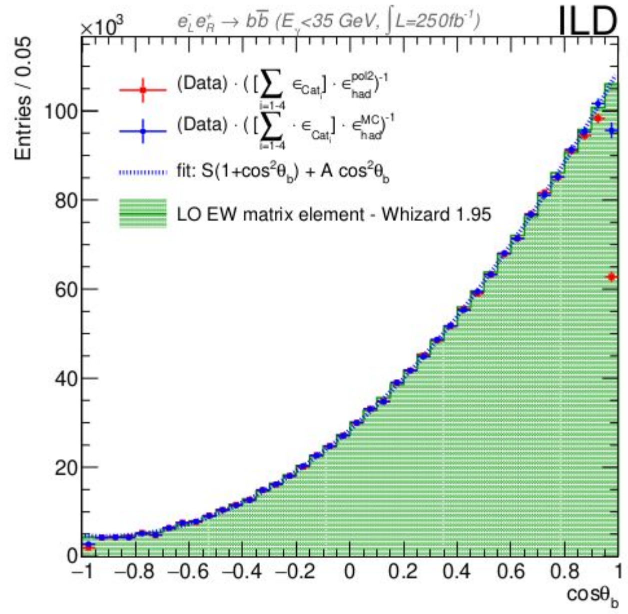


Detector Hermeticity requires is team effort Vertex Detectors, Central Tracking and Calorimeters

Missing Energy



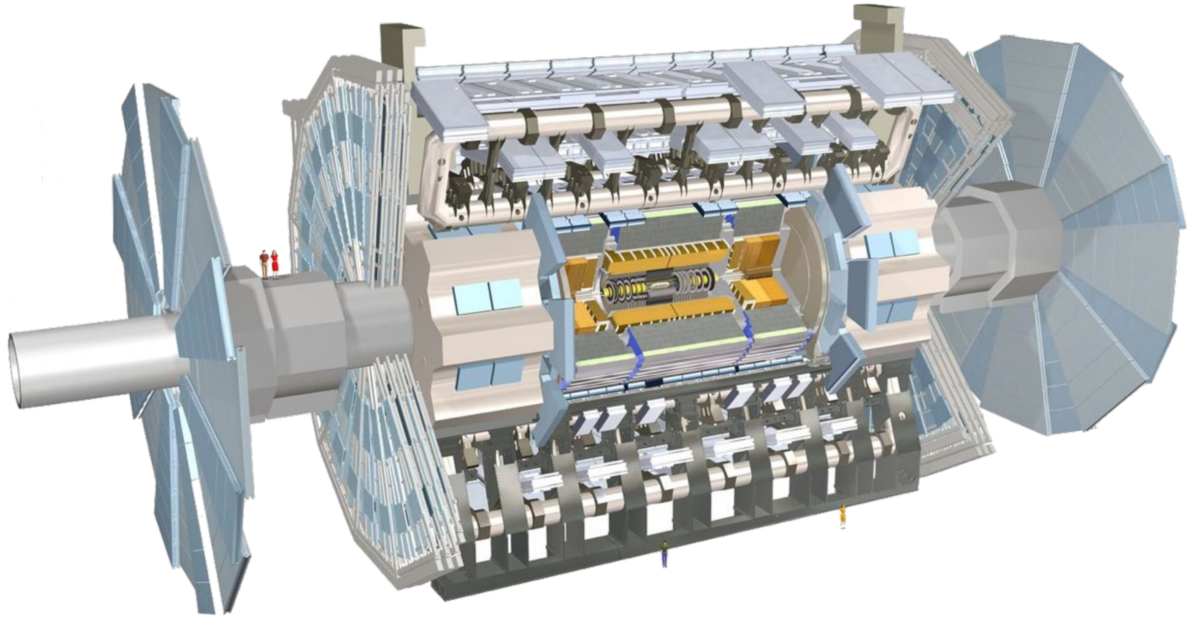
Heavy Quark asymmetries

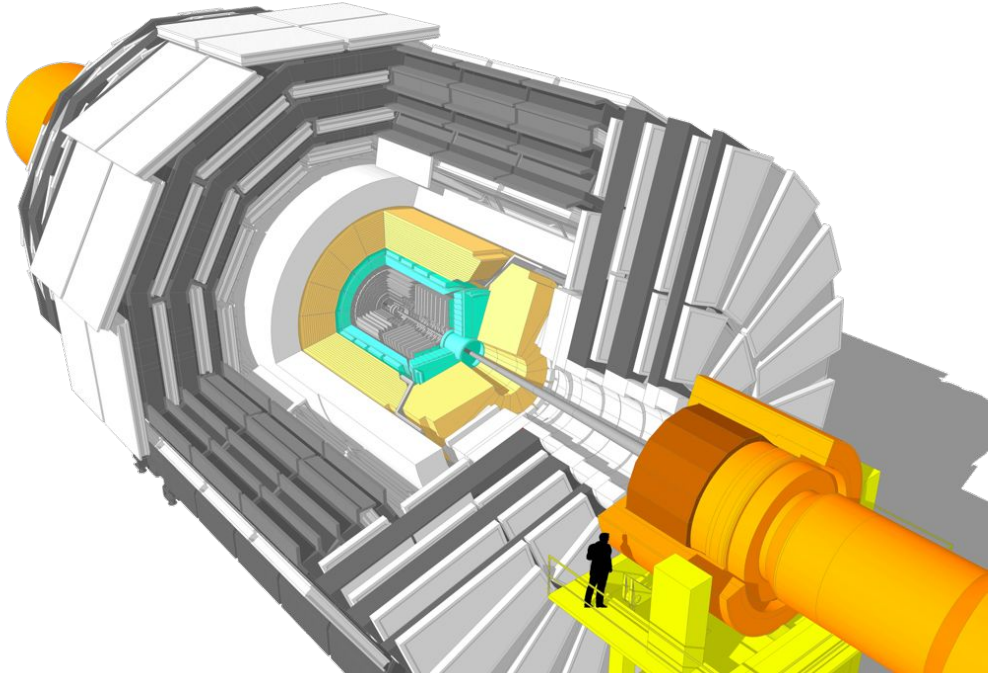


Detector Design - Modularity

Agile: the LHC Experiments

- Very different mechanical design philosophy, with CMS being much more ‘modular’ than the more monolithic ATLAS detector.





- Need to integrate substantial “upgrades” from the start.

Experiment design

- LHC experiments designed in the nineties, will take data well into thirties
- AI used more and more in the full pipeline data taking, reconstruction, simulation
- Can AI be used to design experiment ?
- Key ingredient : auto-differentiation, to obtain the gradients of the figure-of-merits wrt experiment design parameter
- Key difficulty (being overcome) inherent stochasticity of HEP detectors
- Active development, see in particular Mode workshops

Fourth MODE Workshop on Differentiable Programming for Experiment Design

23–25 Sept 2024
Valencia (Spain)
Europe/Paris timezone

Enter your search term

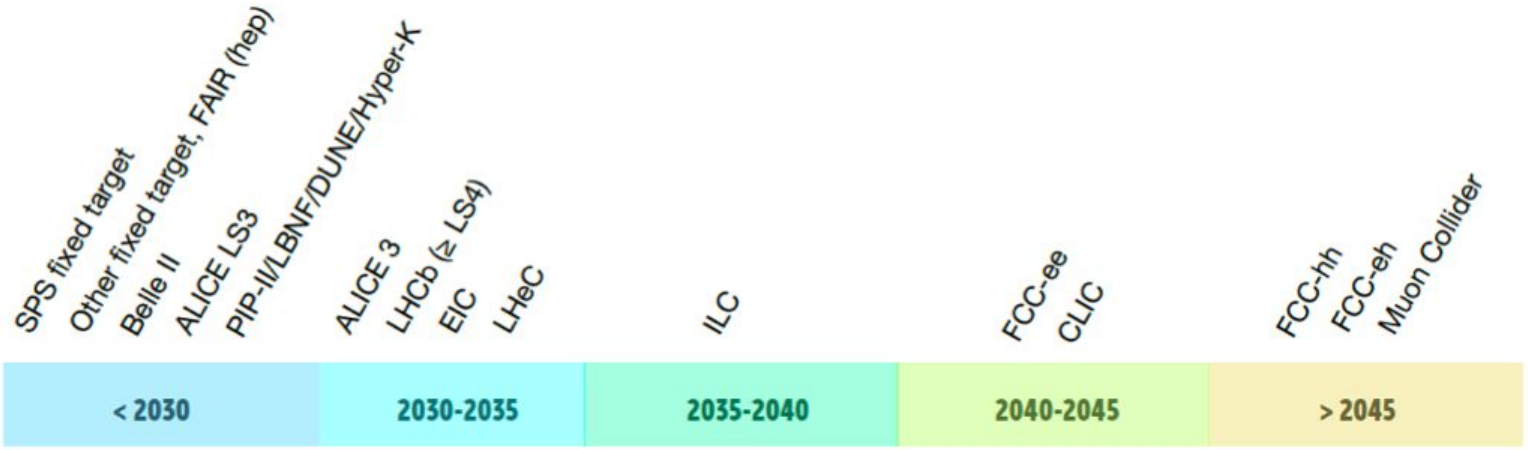
David Rousseau

ECFA Detector R&D Roadmap

- ECFA R&D Roadmap
  - CERN-ESU-017 https://cds.cern.ch/record/2784893
  - 248 pages full text and 8 page synopsis

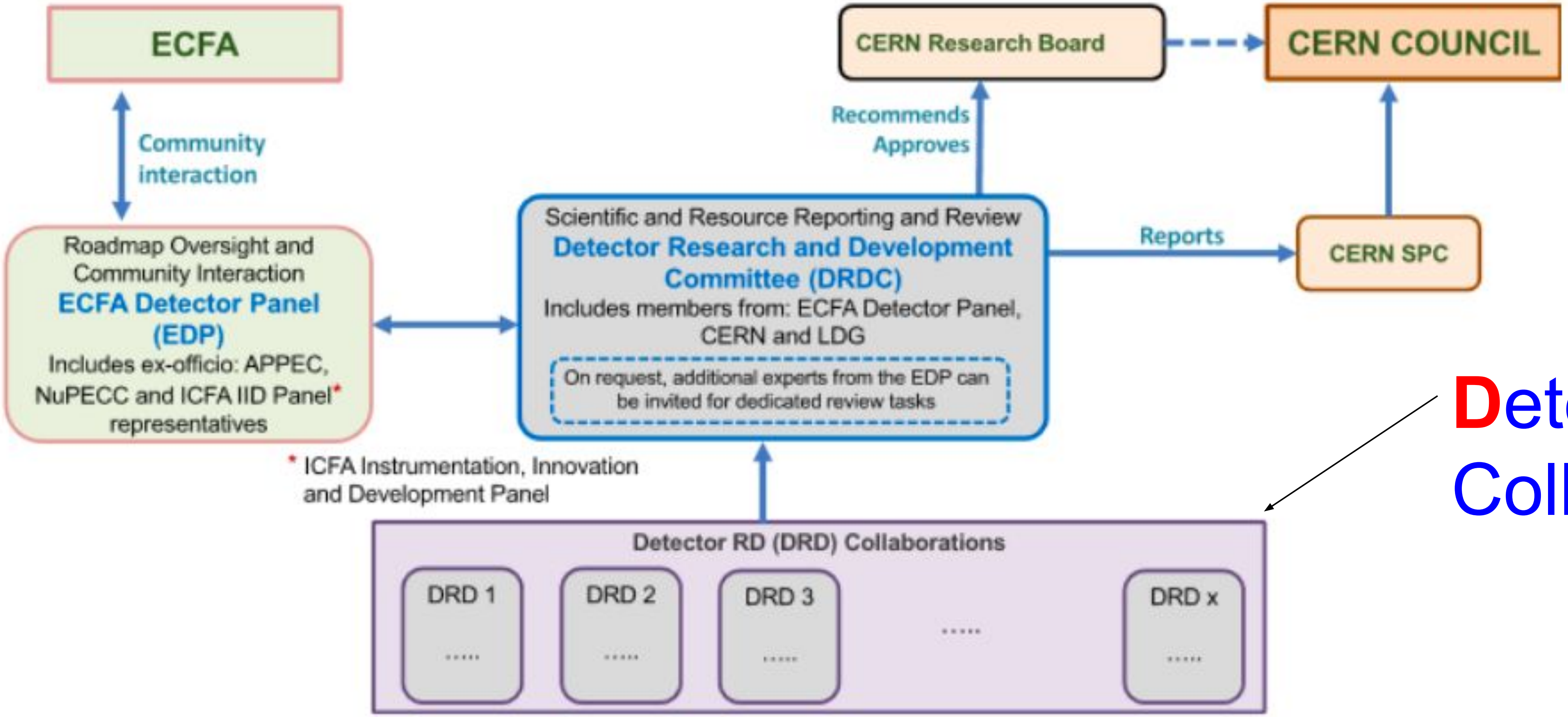
- Endorsed by ECFA and presented to CERN Council in December 2021

The Roadmap has identified
- General Strategic Recommendations (GSR)
- Detector R&D Themes (DRDT)
- Concrete R&D Tasks



Guiding principle: Project realisation must not be delayed by detectors

Future Organisation of Detector R&D (in Europe)



Detector R&D Collaborations

- DRDs are hosted by CERN and are therefore legally CERN collaborations
  - 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
  - Chair Thomas Bergauer of ÖAW/Austria
- The funding will come from national resources (plus eventually supranational projects)

Irène Joliot-Curie Laboratoire de Physique des 2 Infinis — CNRS IN2P3 Les deux infinis

The DRDs

Fully Approved for an initial period of 3 years by CERN Research Board in December 2023

- Gaseous Detectors (DRD1) [ex RD51]
- Liquid Detectors (DRD2)
- Photodetectors & Particle ID (DRD4)
- Calorimetry (DRD6)

Reports at March 2024 open DRDC session;
first review at Nov 2024 DRDC meeting

Fully Approved for an initial period of 3 years by CERN Research Board in June 2024

- Semiconductor Detectors (DRD3) [ex RD50, RD42,..]
- Quantum Sensors (DRD5)
- Electronics (DRD7)

Talks at open session June 3rd 2024
First review now!

Fully approved in Dec 2024

- Integration (DRD8)

Full Proposal submitted by 31 Oct 2024

Thomas Bergauer, Feb '25

Summary and outlook

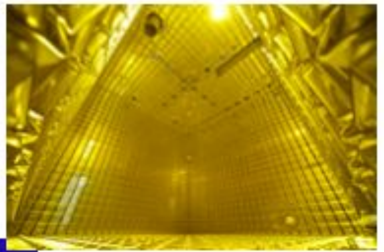
- EPPSU 2020 is about to be implemented
    - R&D needs and objectives have been summarised in the ECFA Detector Roadmap
    - The execution of the R&D programme will be (mainly) organised within DRDs
    - CERN Collaborations with worldwide participation
    - Goal is to achieve sustained funding for Detector R&D
- (An incomplete) overview on the concrete implementation has been given in this talk
- Current focus is on Higgs factories
    - Benefit from HL-LHC upgrades (e.g. vertex detectors and ALICE ITS3)
    - But HL-LHC LS4 in view (e.g. LHCb SpaCal)
        - CMS-HGCAL for granular calorimeters
    - Integrate engineering from the beginning in the R&D cycles
- Next years will see the full implementation of timing in many types of detectors
- Novel materials (Quantum Dots) will enter the game
- AI will play an ever increasing role
    - Simulation, reconstruction and even detector design
- Not covered but input for discussion
    - Instrumentation and computing should offer attractive career paths for ECR
        - Personal remark on AI:
        - It’s really fascinating but have to be careful to form physicists and not “machine learners”

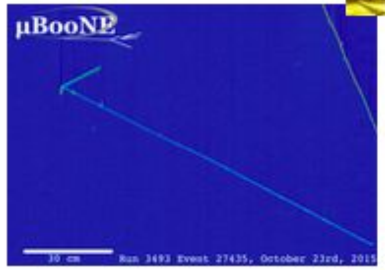
Backup

Liquid Detectors - Science Directions

Neutrinos

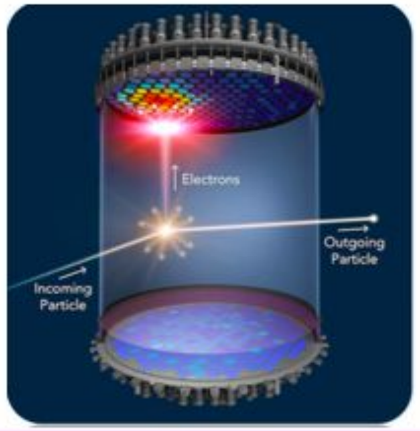
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEvNS to DIS)
- Astro neutrinos





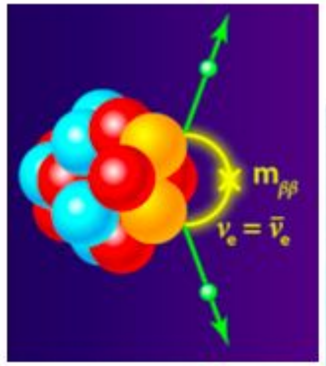
Dark Matter

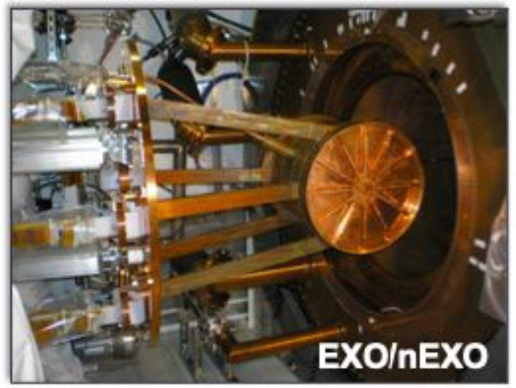
- Direct detection (WIMPs, …)



0νββ

- Search for Majorana neutrinos





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J.R. Monroe, DRD 2 talk, DRDC Meeting, March '24

Liquid Detectors - Requirements

Neutrinos	Dark Matter	0νββ
• **Push Energy thresholds down** to ~1MeV to enhance oscillation physics, supernovae νs study, to enable solar νs …	• **Push Energy thresholds down** to 1 meV/10 eV/1 keV to enable low mass DM/1 GeV DM/ WIMPs.	• **Improve Energy Resolution** to sub-% FWHM
• **Unambiguous readout**	• **Reduce background rates**	• **Reduce background rates**
• **Scalability**	• **Scalability**	• **Scalability**

3

J.R. Monroe, DRD 2 talk, DRDC Meeting, March '24

Calorimetry- Match Irradiation/Beam test 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

Message:

Beam test infrastructure is of vital need for detector R&D

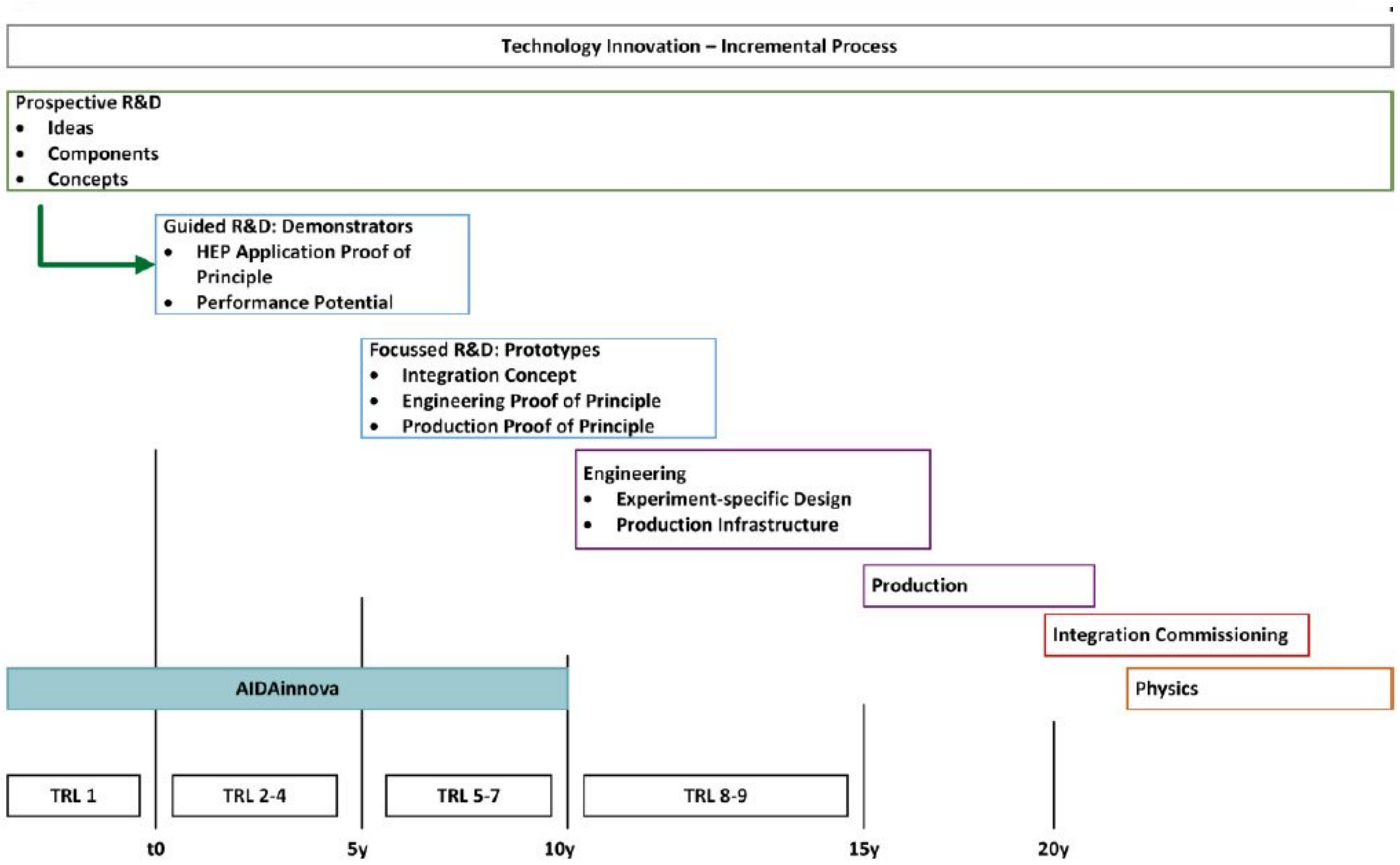
High quality detectors at future machines need sustained support of beam test facilities by lab managements

This costs money!

Categories of R&D

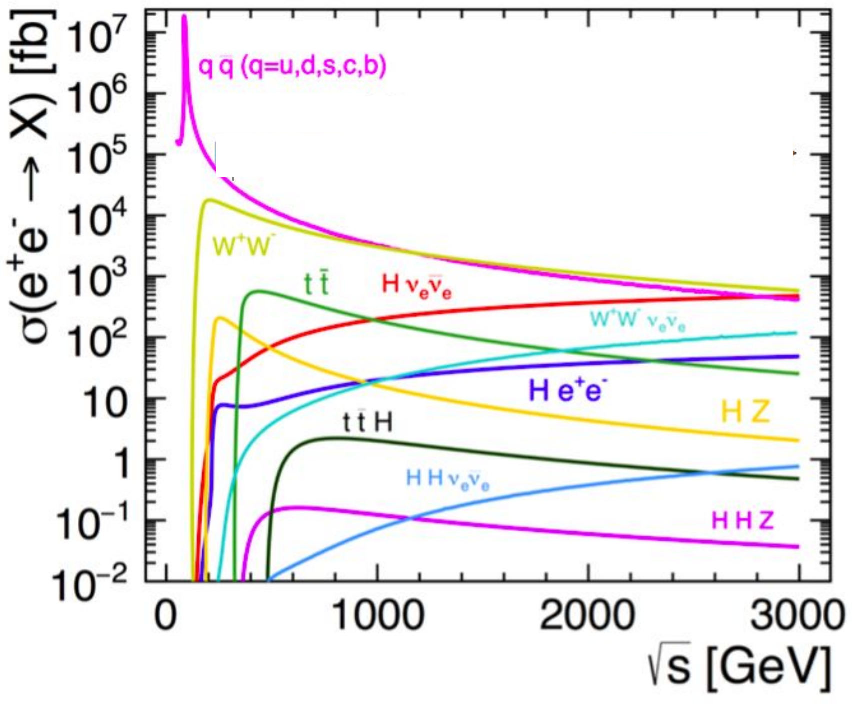
1. Strategic R&D via DRD Collaborations **vision**
   (long-term strategic R&D lines)
   (address the high-priority items defined in the Roadmap via the DRDTs)
2. Experiment-specific R&D **focus**
   (with very well defined detector specifications)
   (funded outside of DRD programme, via experiments,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

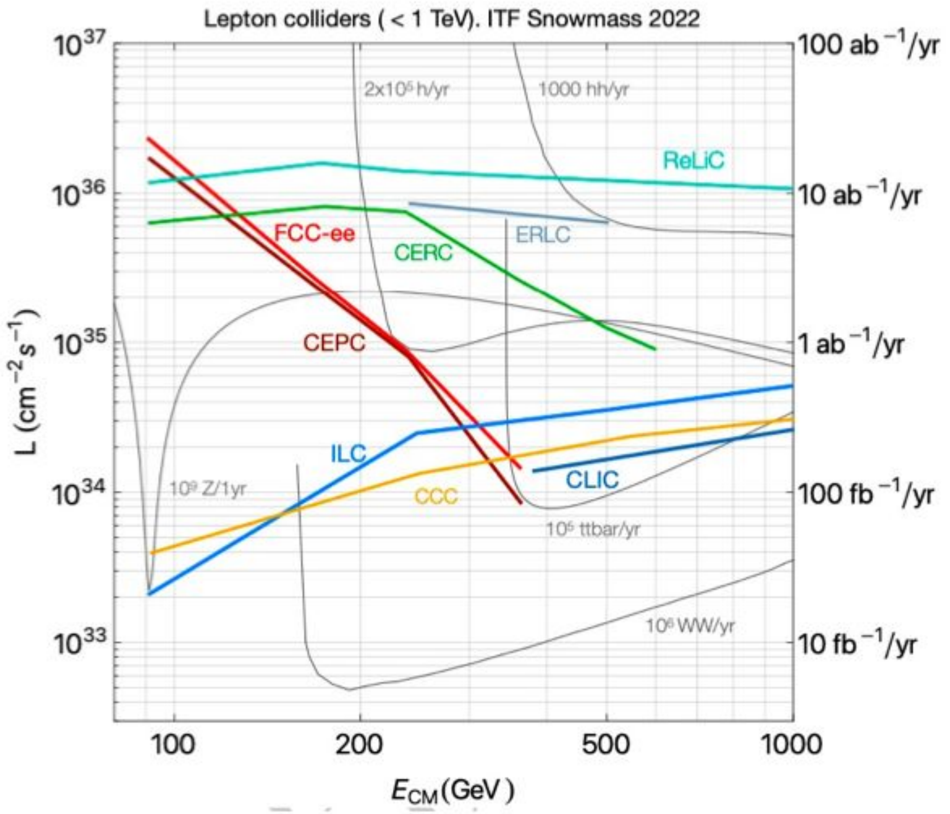
Transitions Blue-sky → Strategic → Specific expected
Cross-fertilisation desired



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

Future direction of R&D - Impact of event rates





High energy e+e- colliders:

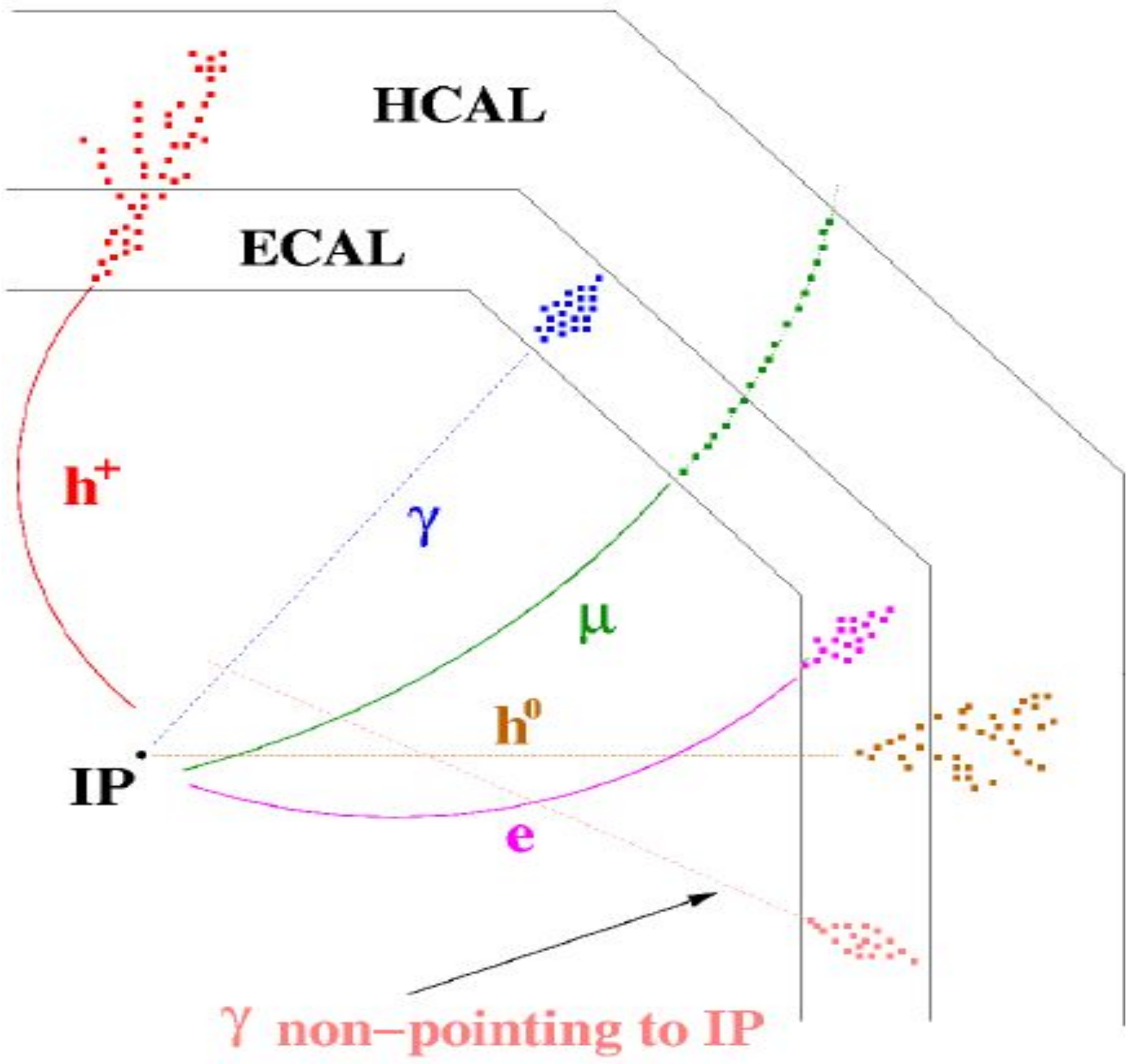
- Physics rate is governed by strong variation
- of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee)
- to few Hz above Z-Pole
- (Extreme) rates at pole may require other
- solutions than rates above pole

- 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

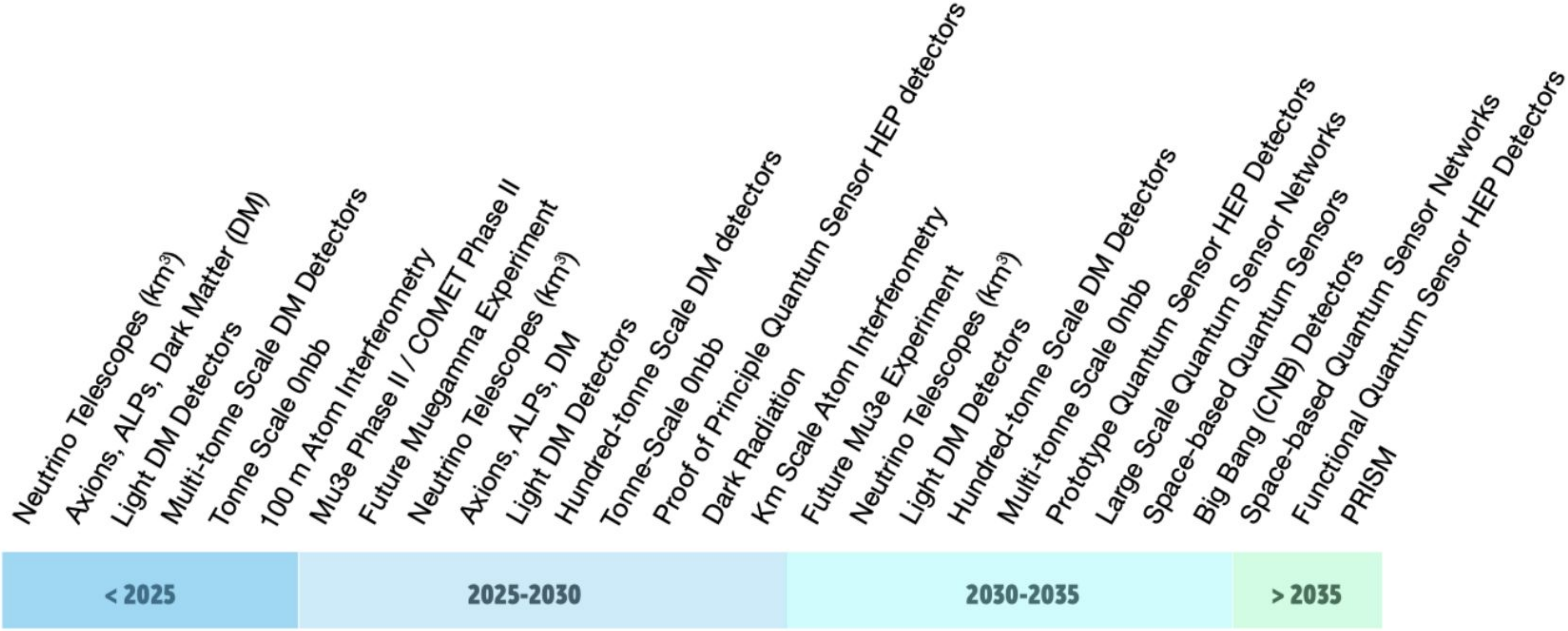
Particle Flow Detector Layout

- 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



ECFA Roadmap - Small(er) scale projects



Gaseous Tracking Systems at future colliders

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ILC TPC DETECTOR: STARTt: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 20 m2 Single unit detect: ~ 400 cm2 (pads) ~ 130 cm² (pixels)	**Max. rate**: < 1 kHz **Spatial res.:** <150μm **Time res.:** ~ 15 ns **dE/dx:** 5 %	Si + TPC Momentum resolution : dp/p < 9*10-5 1/GeV Power-pulsing
CEPC TPC DETECTOR START: > 2030	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 2x10 m2 Single unit detect: up to 0.04 m2	**Max.rate**:>100 kHz/cm2 **Spatial res.:** ~100μm **Time res.:** ~ 100 ns **dE/dx:** <5%	- Higgs run - Z pole run - Continues readout - Low IBF and dE/dx
FCC-ee and/or CEPC IDEA CENTRAL TRACKER START: >2030	e+e- Collider Tracking/ Triggering	He based Drift Chamber	Total volume: 50 m3 Single unit detect: (12 m2 X 4 m)	**Max. rate:** < 25 kHz/cm2 **Spatial res.:** <100 μm **Time res.:** 1 ns **Rad. Hard.:** NA	Particle sepration with cluster counting at 2% level
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Main Tracker	Drift Chamber	Total volume: ~ 3.6 m3	**Max. rate**: 1 kHz/cm2 **Spatial res.:** ~100 μm **Time res.:** ~ 100 ns **Rad. Hard.:** ~ 1 C/cm	
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Inner Tracker	Inner Tracker / (cylindrical μRWELL, or TPC / MPDG read.	Total area: ~ 2 - 4 m2 Single unit detect: 0.5 m2	**Max. rate**: 50-100 kHz/cm2 **Spatial res.:** ~<100 μm **Time res.:** ~ 5 -10 ns **Rad. Hard.:** ~ 0.1-1 C/cm2	Challenging mechanics & mat. budget < 1% X0
ELECTRON-ION COLLIDER (EIC) START: > 2025	Electron-Ion Collider Tracking	Barrel: cylindrical MM, μRWELL Endcap: GEM, MM, μRWELL	Total area: ~ 25 m2	Luminosity (e-p): 1033 **Spatial res.:** ~ 50- 100 um **Max. rate**: ~ kHz/cm2	Barrel technical challenges: low mass, large area Endcap: moderate technical challenges

CMOS Sensors in use or development

Name	Expt	Sub-syst	Area	Δ Pos., Time	Power (fid.)	Technology	Comment
ALPIDE	ALICE-ITS2	Vx & In. Trkr	10 m^2	5 µm, ≤ 10 µs	≤ 50 mW/cm^2	TJsc 180 nm EPI	In operation
MOSAIX	ALICE-ITS3	Vx only	0.12 m^2	5 µm, 2-10 µs	≤ 40 mW/cm^2 ?	TPSco 65 nm EPI	Wafer scale CPS
FASTPIX	→ HL-LHC	Demonstr.		≥ 1 µm, ≤ 100 ps	+++	TJsc 180 nm EPI	Timing & Rad. Tol.
MonoPix	→ ATLAS	ITk	few m^2	< 10 µm, ≤ 20 ns	> 0.5 W/cm^2	TJsc 180 nm EPI	Not retained
CACTUS	FCC, eIC, …	Timing det.	few m^2	< 100 ps	< 300 mW/cm^2	LF 150 nm	Proto., 1 mm^2 pixels
MALTA	HL-LHC, …	Fast det.	few m^2	36x40 $µm^2$, 25 ns	> 100 mW/cm^2	TJsc 180 nm EPI	512x512 pixels
MIMOSIS	CBM/FAIR	Vx & In. Trkr	0.16 m^2	5 µm, 5 µs	< 100 mW/cm^2	TJsc 180 nm EPI	Fixed target HI expt
TaichuPix	CEPC	Vx & In. Trkr		≤ 5 µm	90-160 mW/cm^2	TJsc 180 nm EPI	8x8 $µm^2$ n-well
NAPA	SiD/C3	Trkr, (calo.)		7µm pitch, O(ns)	20 mW/cm^2	TPSCo 65 nm EPI	Target values
ARCADIA	IDEA/FCCee	Vx & In. Trkr		10-50 µm		LF 110 nm	Working horse
CLICpix	CLICdp	Vx & In. Trkr		25 µm pitch, 10 ns		TPSCo 65 nm EPI	Follows TimePix
OBELIX	Belle-II	Vx (7 layers)	O(1) m^2	≤ 10 µm, ≤ 100 ns	≈ 200 mW/cm^2	TJsc 180 nm EPI	Follows MonoPix
MuPix	Mu3e expt	Vx & Trkr		≤ 30 µm, ≤ 20 ns	≤ 350 mW/cm^2	HV TJsc 180 nm	Fixed target expt

Courtesy of Marc Winter

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

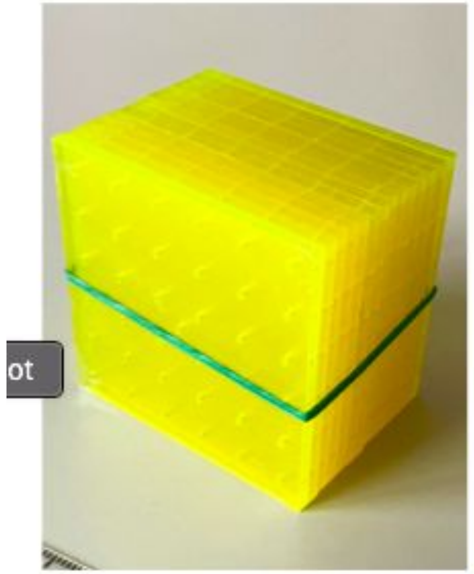
			FCCee-91	FCCee-240	ILC-250
model	B-field	MDI	thousand ions / bunch crossing		
ILD_l5_v02	3.5 (uniform)	ILC	6.5	14	960
ILD_l5_v02_2T	2.0 (uniform)	ILC	6.9	15	4700
ILD_l5_v03	3.5 (map)	ILC	5.7	14	1100
ILD_l5_v05	3.5 (map, anti-DID)	ILC	0.6	3.7	450
ILD_l5_v11	2.0 (uniform)	FCCee	390	1000	110000

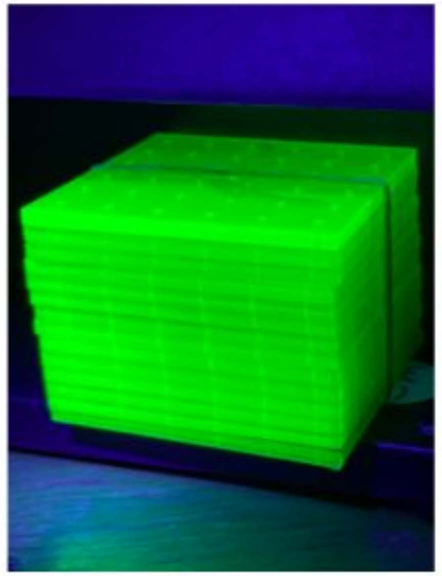
- MDI for FCC increase background significantly compared to MDI for ILC

Daniel Jeans
Preliminary results

V. Sola
AIDAinnova Meeting
Valencia

Nanomaterial composites (NCs)





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

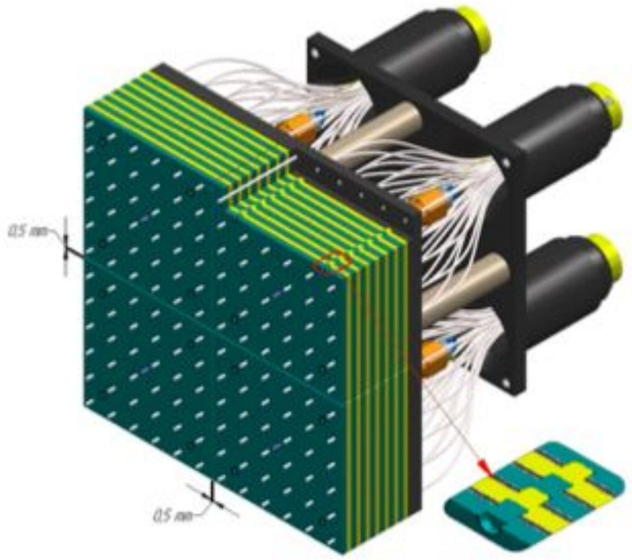
- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals
- Cast with polymer or glass matrix
- Decay times down to O(100 ps)
- Radiation hard to O(1 MGy)

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

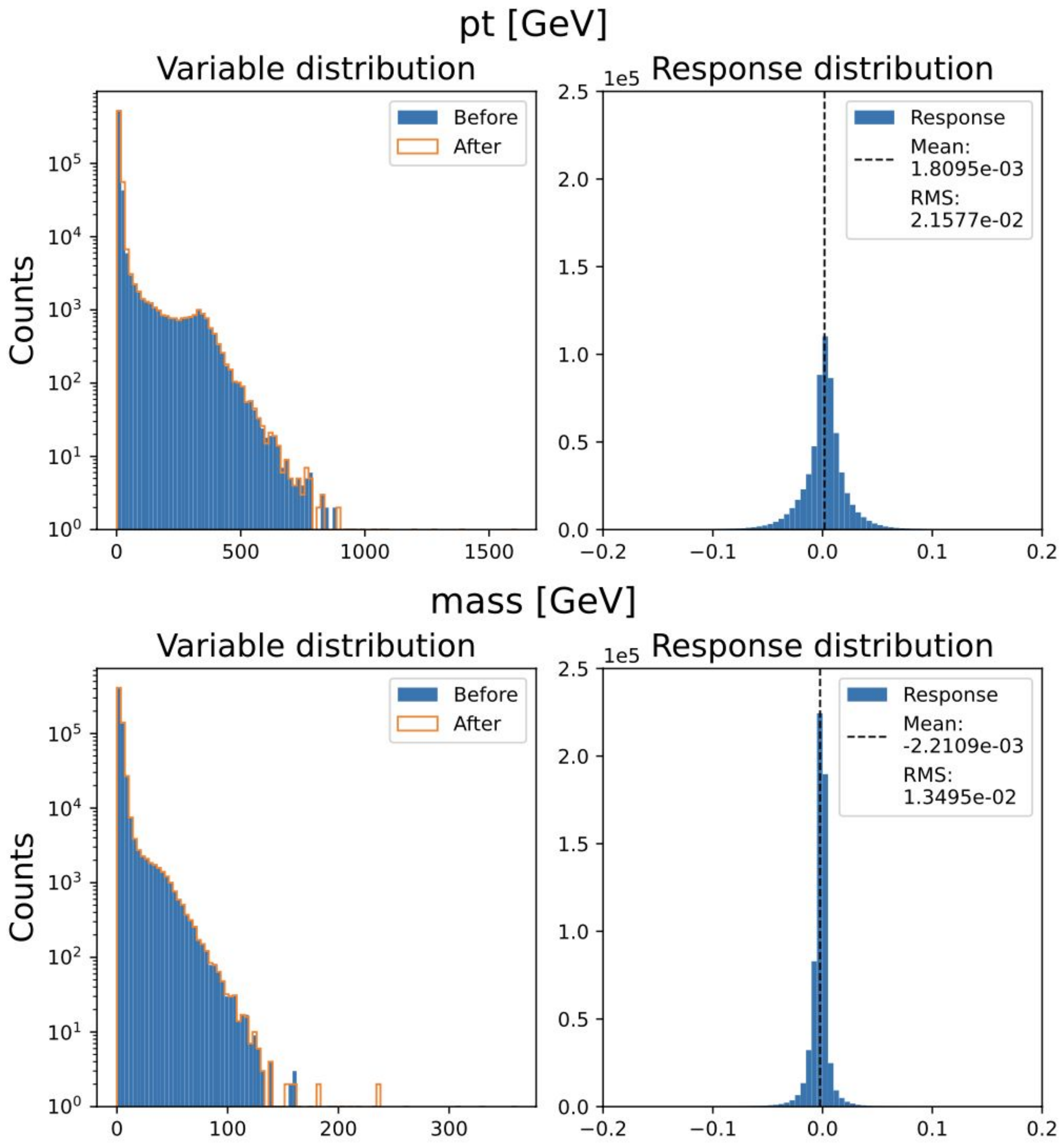


KOPIO/PANDA design
Fine-sampling shashlyk

R&D on material has Overlap with DRD 5

Dataset

- Persistent Dataset size challenge : AI can also be used for “intelligent” data compressing (allowing for losses).
- (g)zip : no loss compression
- mp3 : allow for losses that are inaudible to the human hear
- lossy compression for example Baler: Auto-encoder-based compression of scientific datasets
- To be tuned for almost zero impact on downstream physics analysis (which might not exist yet)



David Rousseau