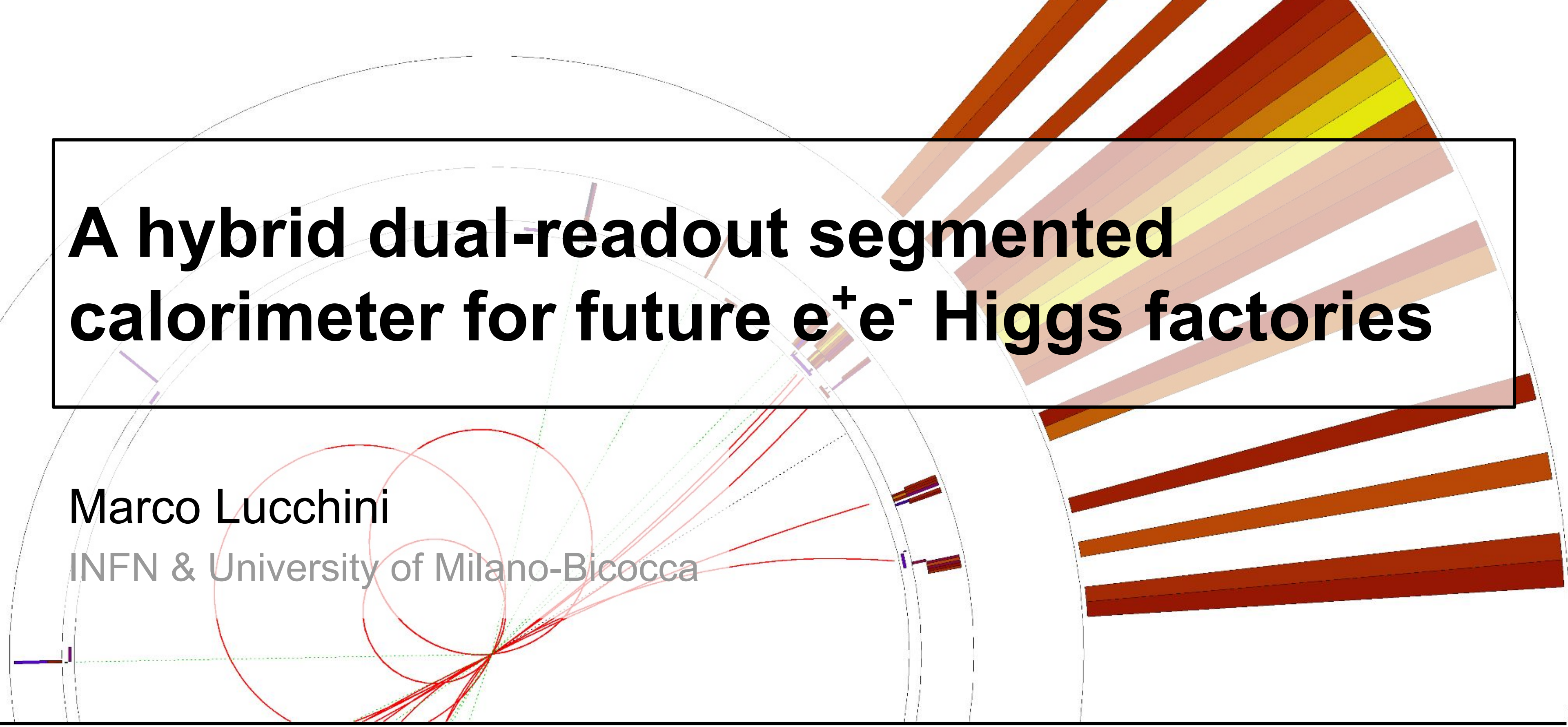

A hybrid dual-readout segmented calorimeter for future e^+e^- Higgs factories

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INFN & University of Milano-Bicocca

Seminar on *Calorimetry at Future Colliders*

25th May 2023

INFN NAPOLI

Calorimetry at Future Colliders

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

INFN

Disclaimer

- Far from a comprehensive review of crystal calorimetry for future colliders
- **Biased by my expertise and most recent research in the field**
  [CMS Electromagnetic Calorimeter, CMS Mip Timing Detector,
  R&D on scintillators and calorimeter prototypes for future colliders]

2011 – 2018

2018 – 2020

2020 – present

Outline

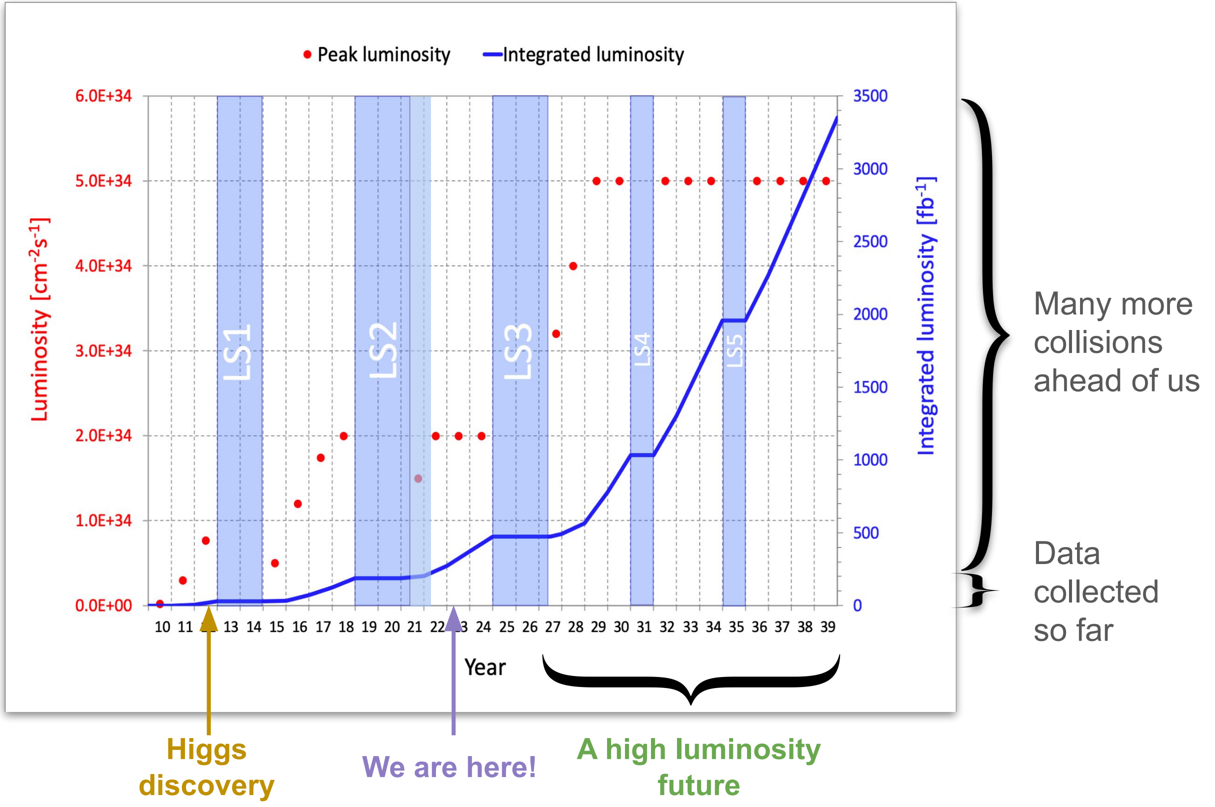
- **Context** - future colliders
- **The physics case** for precision (EM) calorimetry at e^+e^- Higgs factories
- A hybrid dual-readout **calorimeter concept**
- **R&D challenges** and outlook

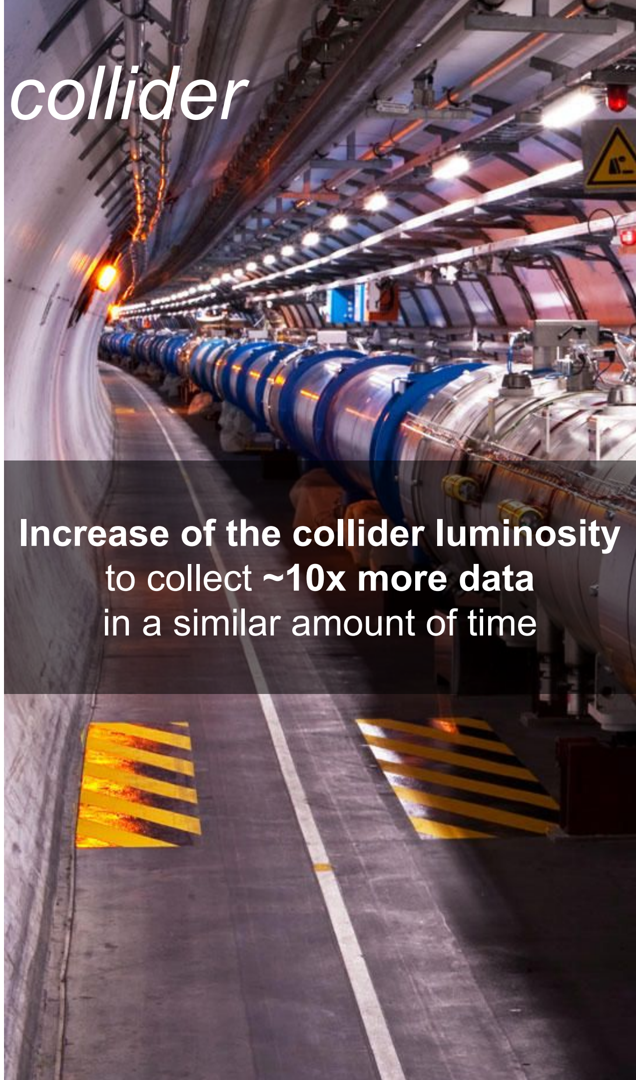
Context and physics case

colliders remain a powerful to address open fundamental questions

High Luminosity LHC: *the next future collider*

The best opportunity and highest priority for the next decade





Increase of the collider luminosity
to collect **~10x more data**
in a similar amount of time

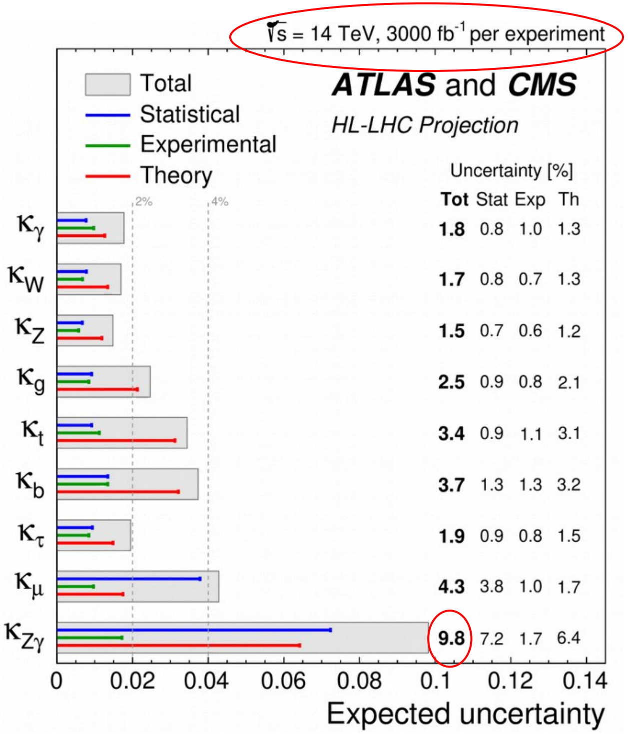
The physics reach of **HL-LHC**

170 million Higgs bosons
120 thousand Higgs-boson pairs

An example: *Higgs stoichiometry*
entering the era of precision Higgs physics

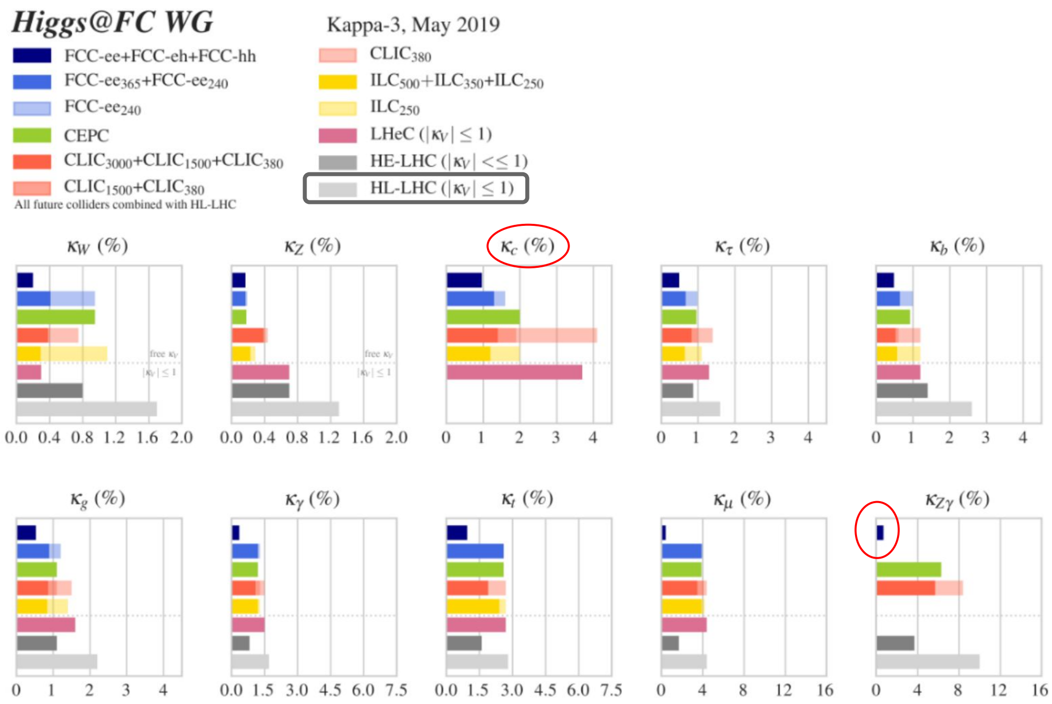
- **Estimated precision at the end of HL-LHC**
  - **O(2−4%) precision** on the couplings to W, Z, and 3rd generation fermions
  - **Higgs width** indirectly measurable at **~17%** (ZZ → 4 lepton channel)
  - Higgs-boson **self-coupling** probed with **O(50%)** precision

- **What will not be achieved**
  - Couplings to u, d, s, c quarks still not accessible at the LHC directly



CERN Yellow Report on the Physics at the HL-LHC:
https://cds.cern.ch/record/2703572?ln=en

Further improving precision with a **Higgs factory**

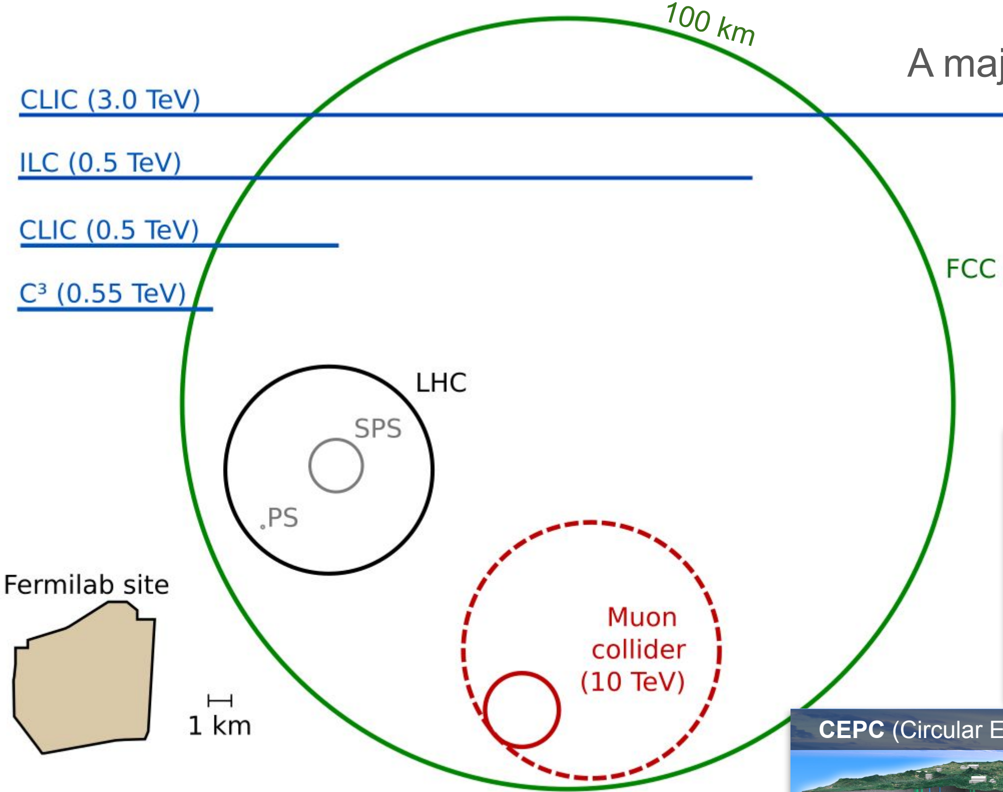


- **An e^+e^- Higgs factory can measure these couplings with smaller uncertainties** than HL-LHC due to:
  - Better knowledge of the momentum of the incoming particles
  - Smaller background environments
  - Better detector resolutions

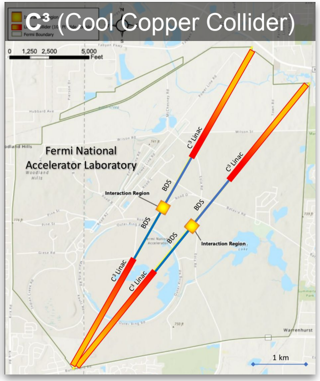
- Model-independent measurements of the **Higgs boson width to the 1% level** (invariant mass of $Z \rightarrow e^+e^-$ recoil in Higgsstralhung)

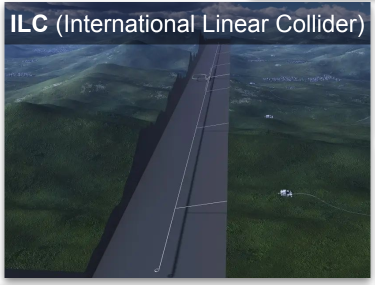
- **Higgs self-coupling below 10%**

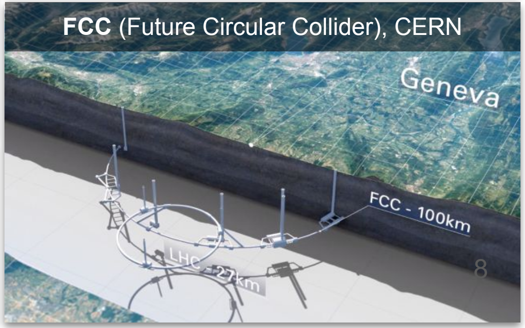
Future collider options on the table (for the XXI century)

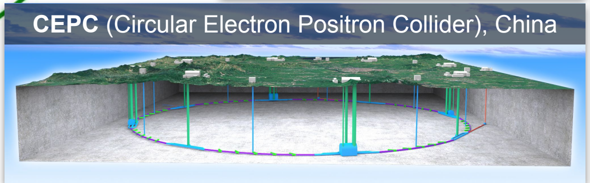


A major **civil engineering** challenge!









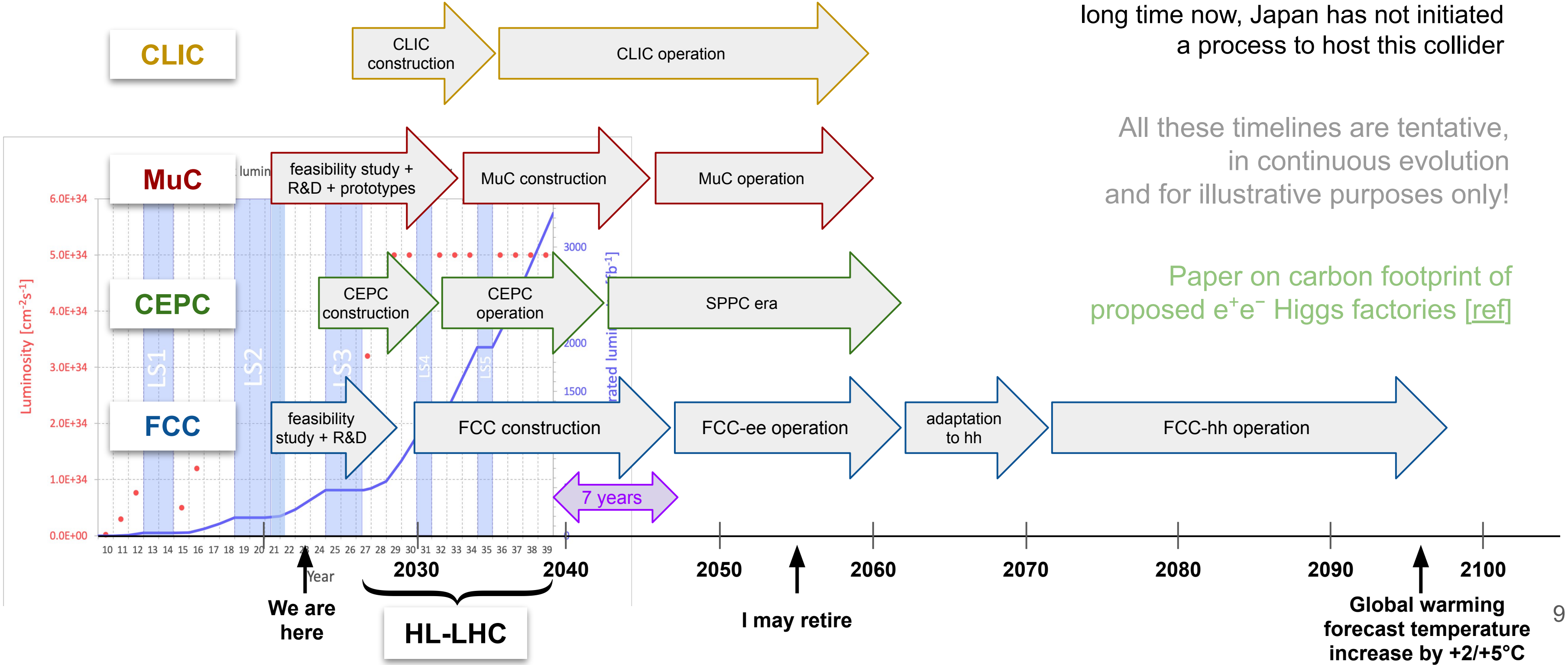
Proposed future collider timelines

- Project timelines spanning over many decades (operation should start around end of HL-LHC)
- **Intense R&D phase on detectors in the next 5+ years!**

ILC is ready for construction but for a long time now, Japan has not initiated a process to host this collider

All these timelines are tentative, in continuous evolution and for illustrative purposes only!

Paper on carbon footprint of proposed e^+e^- Higgs factories [ref]



Defining a strategy

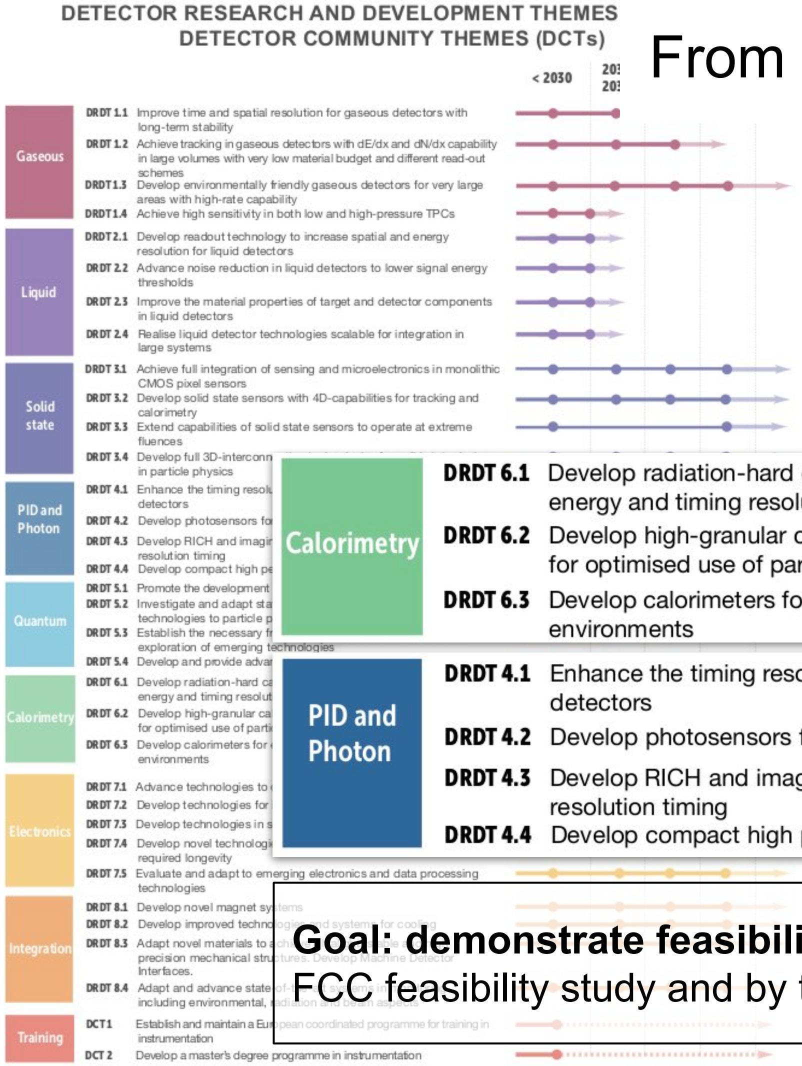
- From the 2020 Update of the European Strategy for Particle Physics (ESPPU):

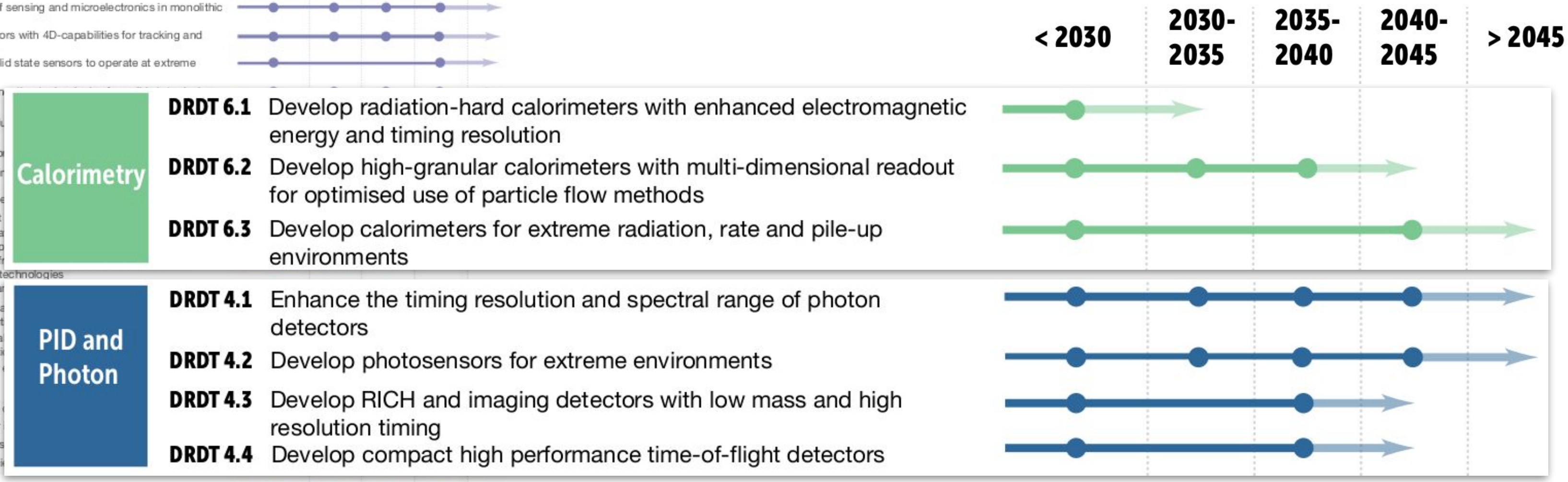
  *“**An electron-positron Higgs factory is the highest priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”*

- Ongoing processes in the HEP international community to **identify the detector requirements** for future collider experiments

From the 2021 **ECFA Detector R&D Roadmap**

https://cds.cern.ch/record/2784893





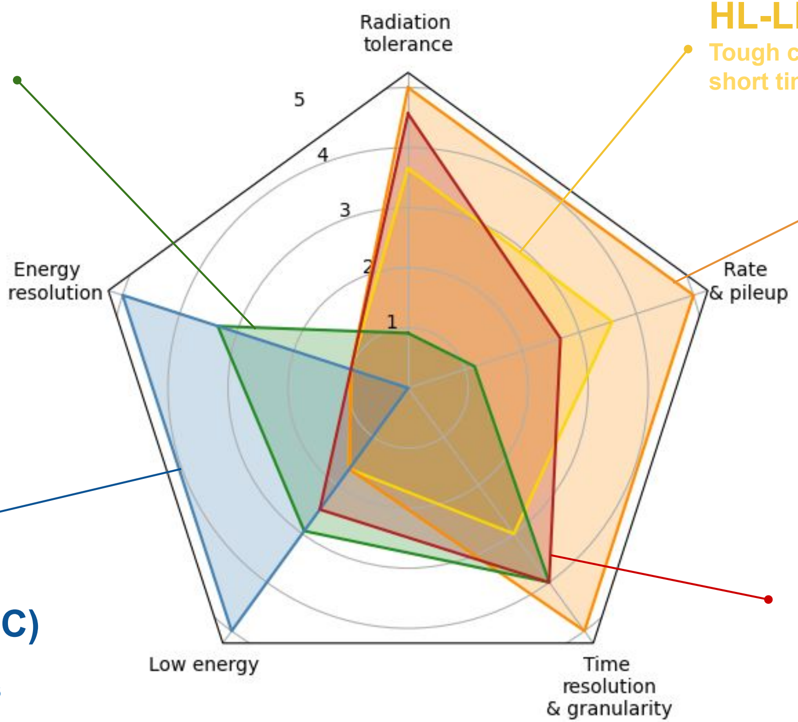
Goal: demonstrate feasibility of detector concepts for future colliders as part of the FCC feasibility study and by the next update of the ESPP **(2026-2027)**

Qualitative representation of **requirements** for calorimeters **at future colliders**

e^+e^- colliders
Precision physics benefits from exploiting the best possible energy and time resolution

HL-LHC
Tough challenges on a short timescale

FCC-hh
Setting the toughest challenge on radiation tolerance and pileup conditions



Strong interaction experiments (e.g. EIC)
Requiring the highest energy resolution for low energy photons

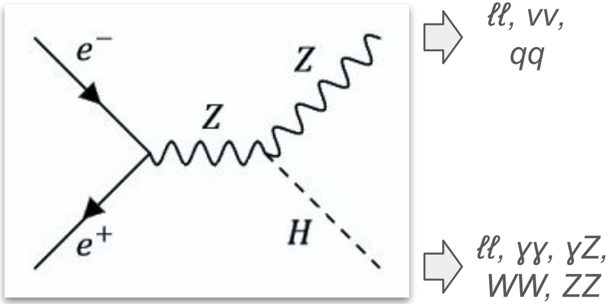
$\mu^+\mu^-$ colliders
High beam induced background and radiation levels, need for ambitious time resolution

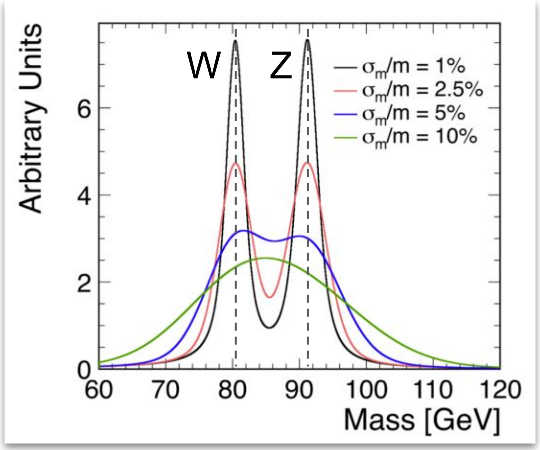
Inspired from https://indico.cern.ch/event/994685/

Jet energy resolution as a key benchmark for future **e⁺e⁻ colliders**

- Higgs production **at e^+e^- colliders** (@$\sqrt{s}$~250 GeV) is mainly through Higgsstrahlung
- **97% of the Standard Model Higgsstrahlung signal has jets in the final state**
  - **~32%** with 2 jets
  - **~55%** with 4 jets
  - **~11%** with 6 jets
- A typical jet resolution of ~30%/$\sqrt{E}$ (~3-4% @90 GeV) is required (e.g. to distinguish jets from W or Z bosons)
  - **Why is this so challenging?** [R.Ferrari seminar]
    [CMS jet energy resolution ~80%/$\sqrt{p_T}$]

Higgsstrahlung



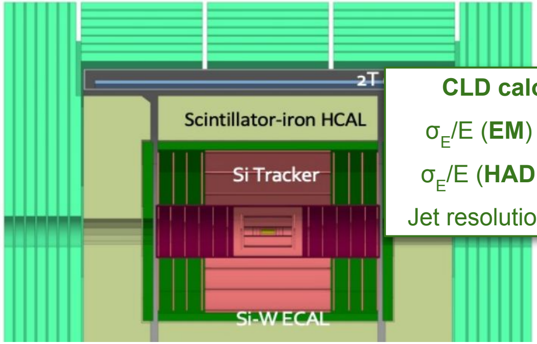


Baseline detector concepts for future e^+e^- colliders

General purpose detector concepts at future e^+e^- colliders:

- **CLD**: Exploiting high granularity for particle flow algorithms (combining tracker and calorimeter exploiting topological information)
- **IDEA**: Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)
- **Noble Liquid:** large(r) sampling fraction and light yield combined with reasonable granularity

- **EM energy resolution is far from that of state-of-the-art homogeneous crystal calorimeters (1-3%/√E)**

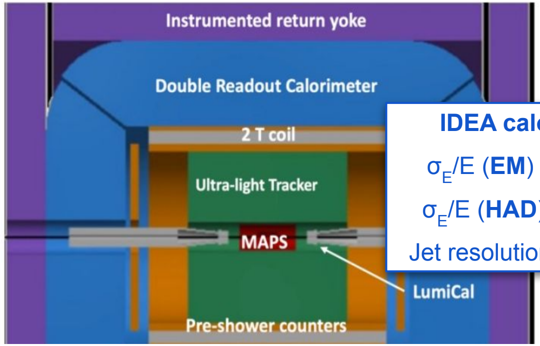


CLD calorimeter

σ_E/E (**EM**) ~16%/√E

σ_E/E (**HAD**) ~45%/√E

Jet resolution ~ 30%/√E

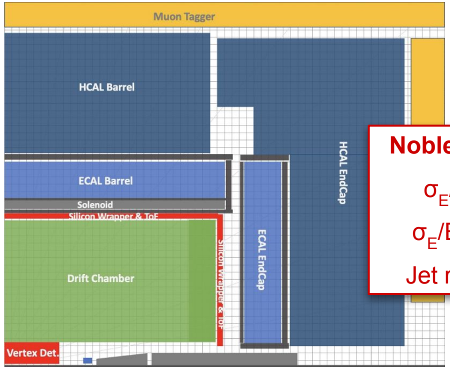


IDEA calorimeter

σ_E/E (**EM**) ~13%/√E

σ_E/E (**HAD**) ~31%/√E

Jet resolution ~ 30%/√E



Noble liquid calorimeter

σ_E/E (**EM**) ~8%/√E

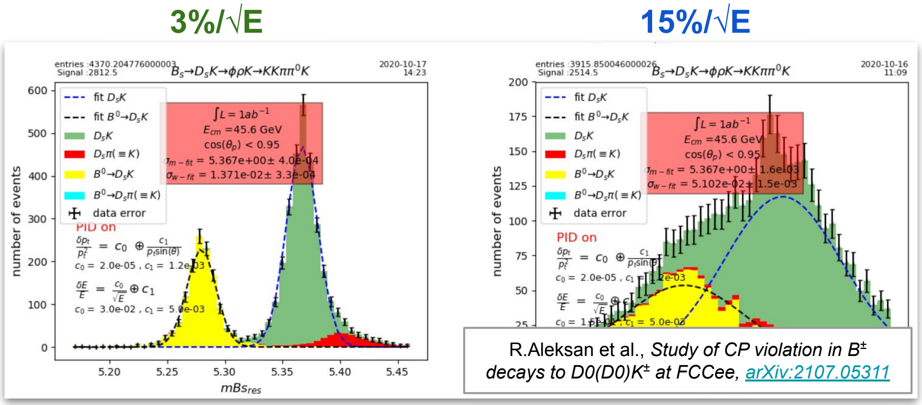
σ_E/E (**HAD**) ~37%/√E

Jet resolution ~ ?%/√E

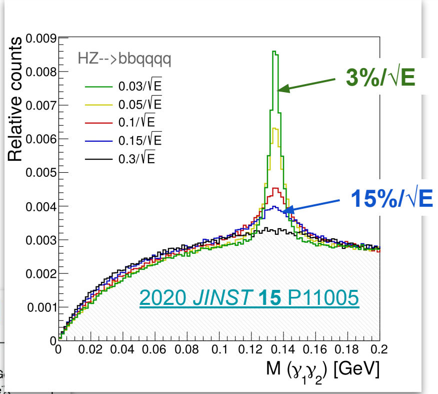
Potential for **high EM energy resolution**

A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)



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



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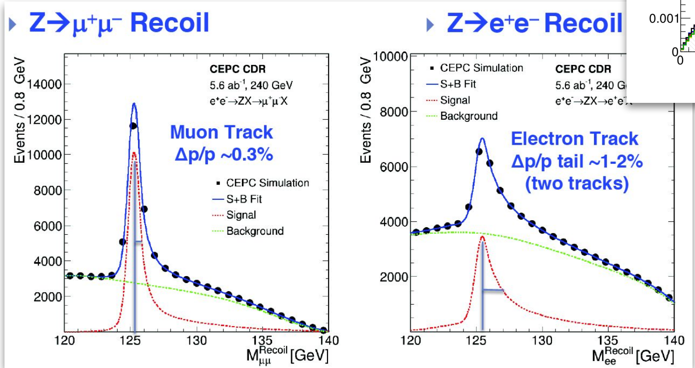
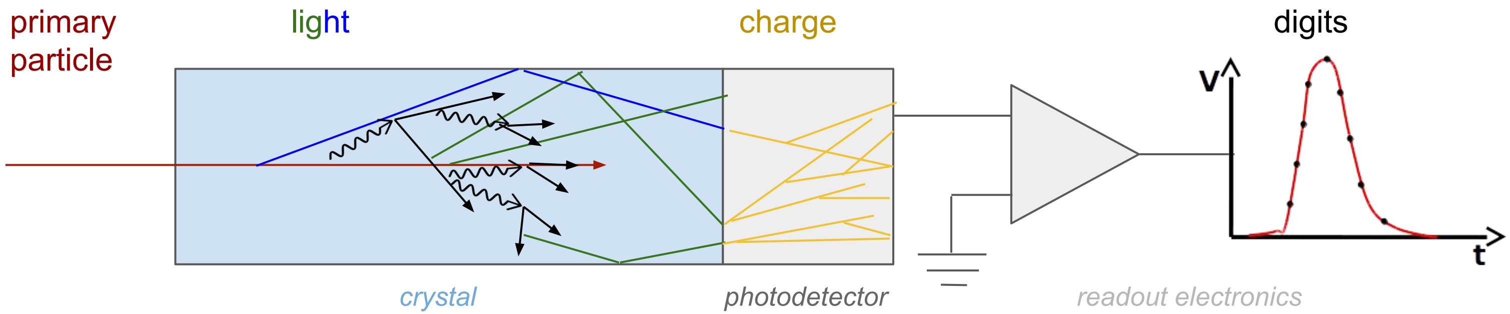


Example from CEPC CDR

Calorimeter concept

Calorimetry with scintillating crystals



Electromagnetic Shower

Primary particle creates a **EM shower of secondary particles ($\gamma \rightarrow e^+e^-$)** in the crystal, losing its entire energy inside the medium

Generation of light signal

Energy deposits are converted into optical photons in **scintillators**
Charged particles also create **Cherenkov** photons

Light transport and detection

Optical photons travel through the transparent medium until they reach a photodetector

Conversion to electrical signal

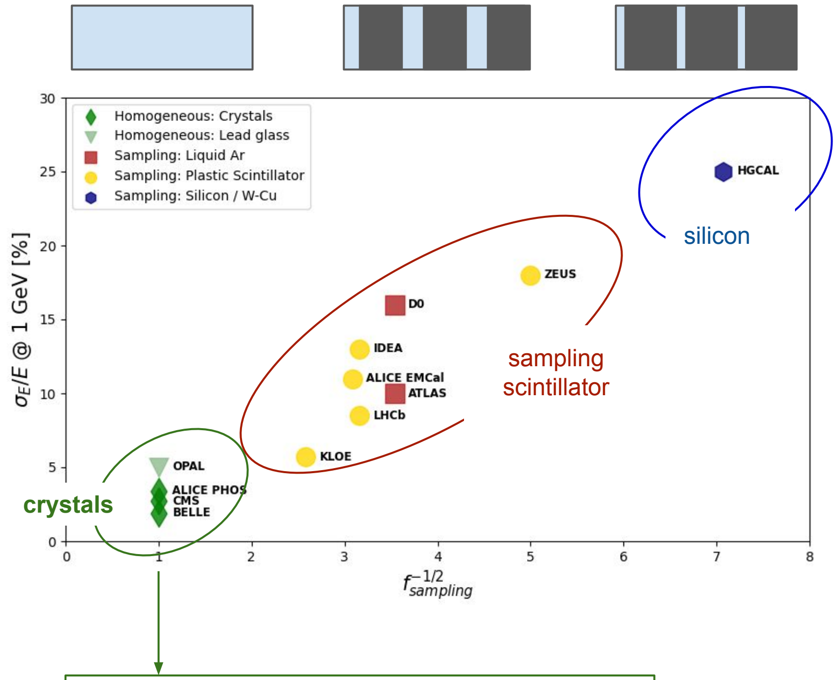
Optical photons are converted into **charge** and the signal is amplified by dedicated electronics and eventually digitized

Homogeneous crystal calorimetry

- A long history of **pushing the frontier of high EM resolution and** the **only way to get a 1-3%/√(E) energy resolution for photons** (and thus π^0's)

- Future e^+e^- Higgs Factories set **no stringent requirements on radiation tolerance** and pileup (an opportunity to aim for the best possible precision of event reconstruction)

A sample of existing and future calorimeters



The entire EM shower is sampled, large light signals are produced

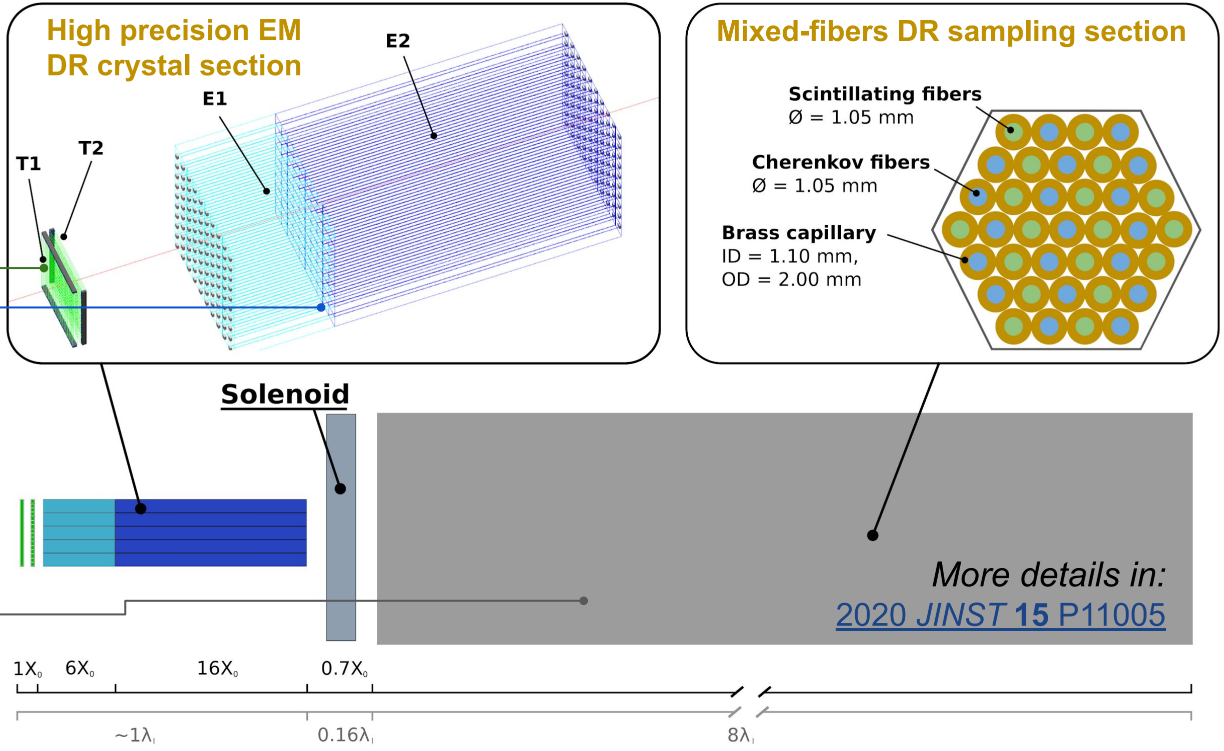
Technological progress in the field of scintillators and photodetectors has **enabled** the design of **a cost-effective and highly performant calorimeter**

- **Excellent energy resolution to photons and neutral hadrons**
  (~3%/√E and ~30%/√E respectively)
- **Separate readout of scintillation and Cherenkov light**
  (to exploit dual-readout technique for hadron resolution and linearity)
- **Longitudinal and transverse segmentation**
  (to provide more handles for PID and particle flow algorithms)
- **Energy resolution at the level of 4-3% for 50-100 GeV jets**
- **Precise time tagging for both MIPs and EM showers**
  (time resolution better than 30 ps)

"Maximum information" calorimetry
(**6D**: x,y,z,t,E,C/S)

Conceptual layout

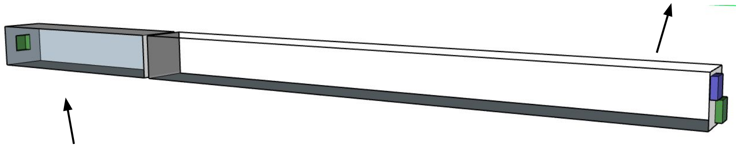
- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs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



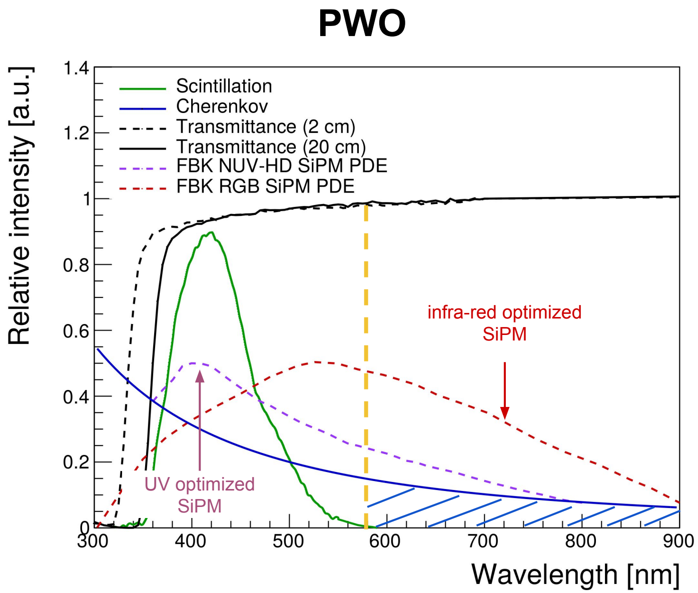
Implementation of dual-readout in the crystal

- **Simultaneous readout of scintillation and Cherenkov light from the same active element** with dedicated SiPMs+wavelength filters to enable dual-readout correction of hadronic shower fluctuations

Rear crystal ECAL segment:
Two 4x4 mm² SiPMs with optical filters optimized for scintillation and cherenkov detection resp.

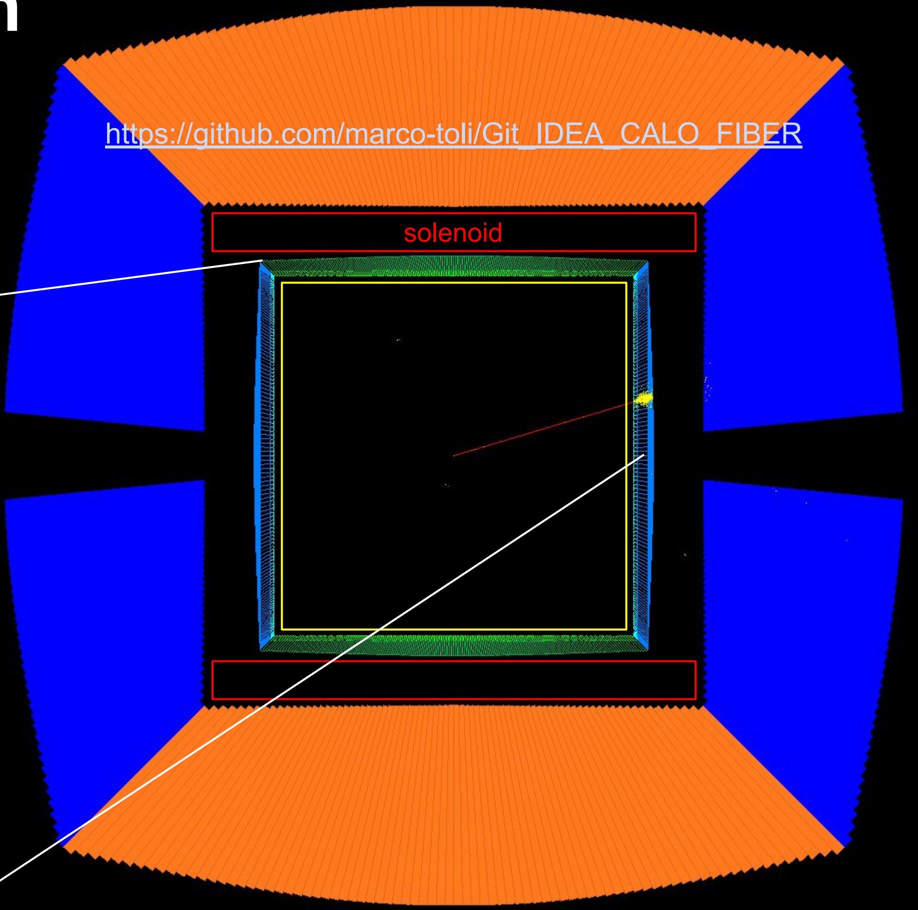


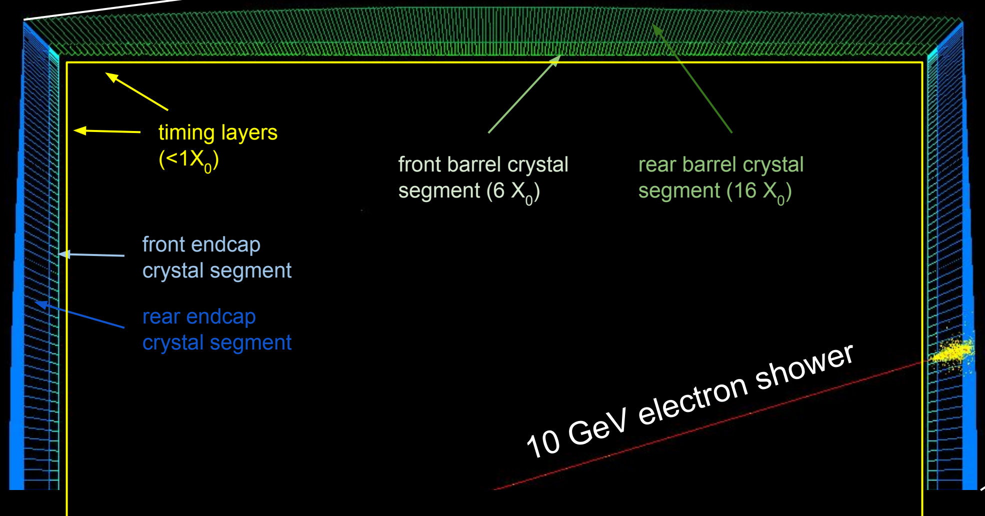
Front crystal ECAL segment:
Single 5x5 mm² SiPM per crystal optimized for scintillation light detection



Integration of crystal EM calorimeter in 4π Geant4 IDEA **simulation**

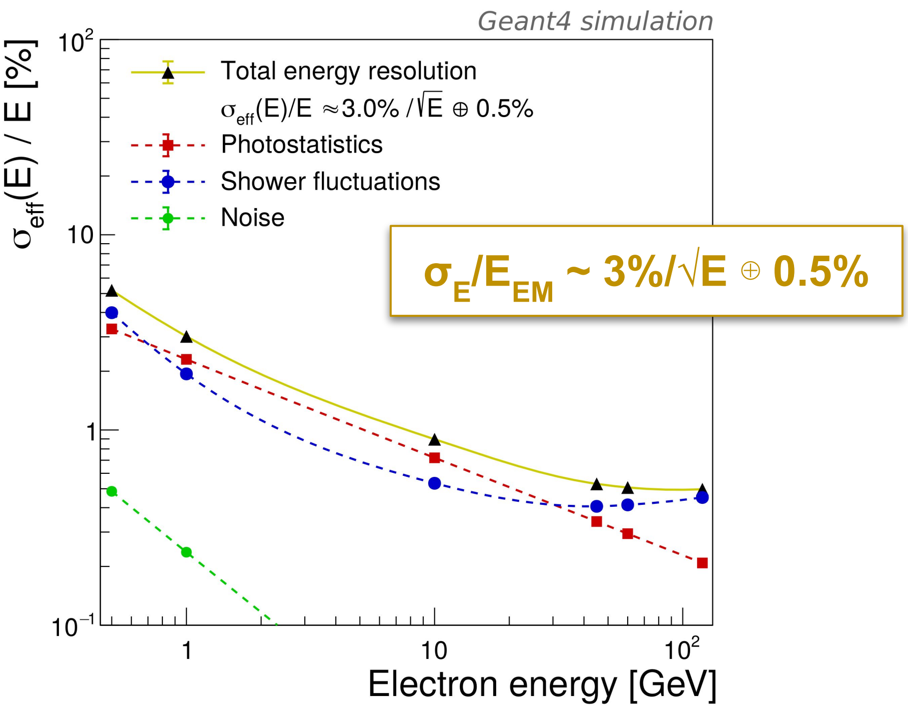
- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: ~1.8M (including DR)





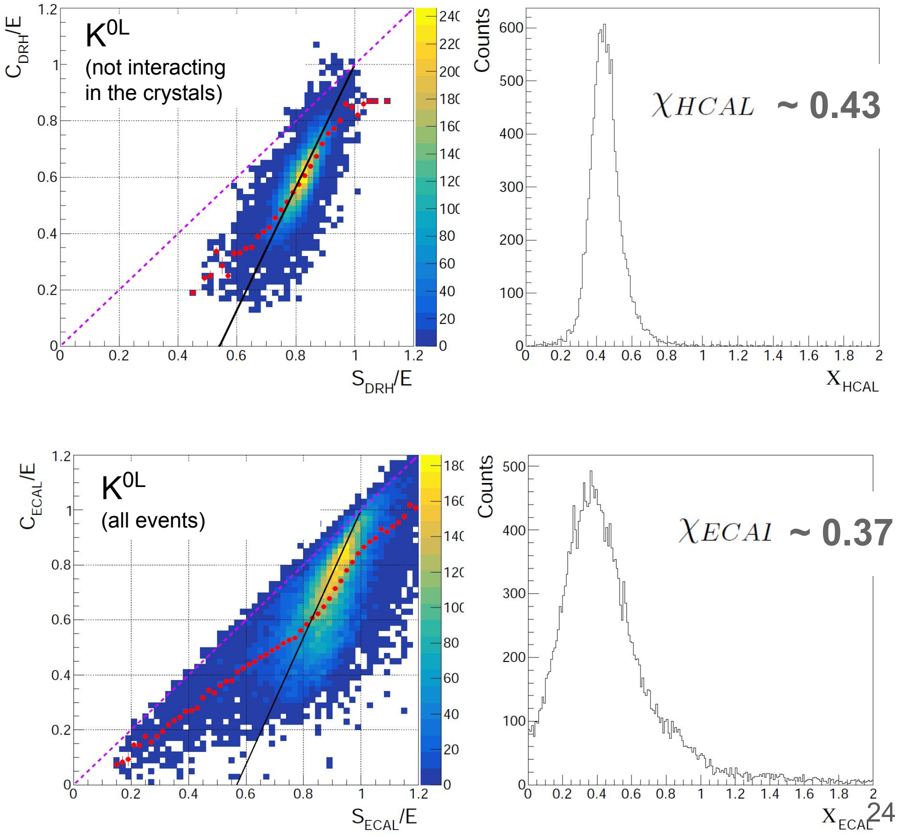
Energy resolution drivers for **EM particles**

- Contributions to energy resolution:
  - Shower fluctuations
    - Longitudinal leakage
    - Tracker material budget
    - Services for front layers readout
  - Photostatistics
    - Tunable parameter depending on:
      - SiPM choice
      - Crystal choice
  - Noise
    - Negligible with SiPMs
      - High gain devices (~10^5)
      - Small dark count rate within signal integration time window



The **dual-readout method** in a hybrid calorimeter

1. Evaluate the χ-factor for the crystal and fiber section
2. Apply the DRO correction on the energy deposits in the crystal and fiber segment independently
3. Sum up the corrected energy from both segments

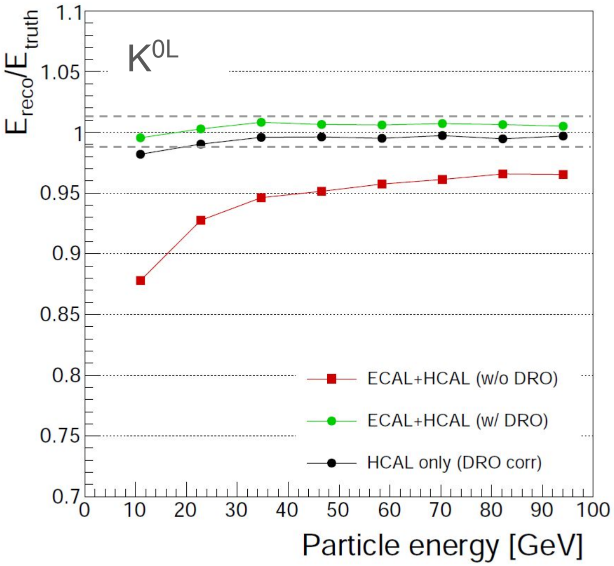


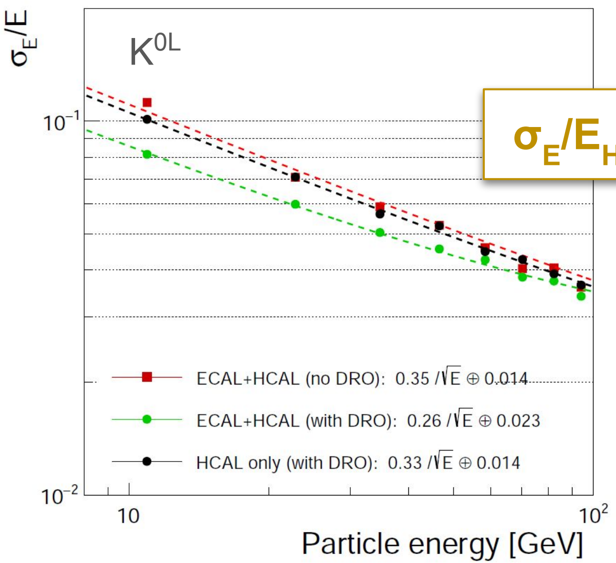
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$
$$\chi_{ECAL} = \frac{1-(h/e)_s^{ECAL}}{1-(h/e)_c^{ECAL}}$$

$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1-\chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1-\chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

Energy resolution for **neutral hadrons**

- **Dual-readout method confirms its applicability to a hybrid calorimeter system**
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter

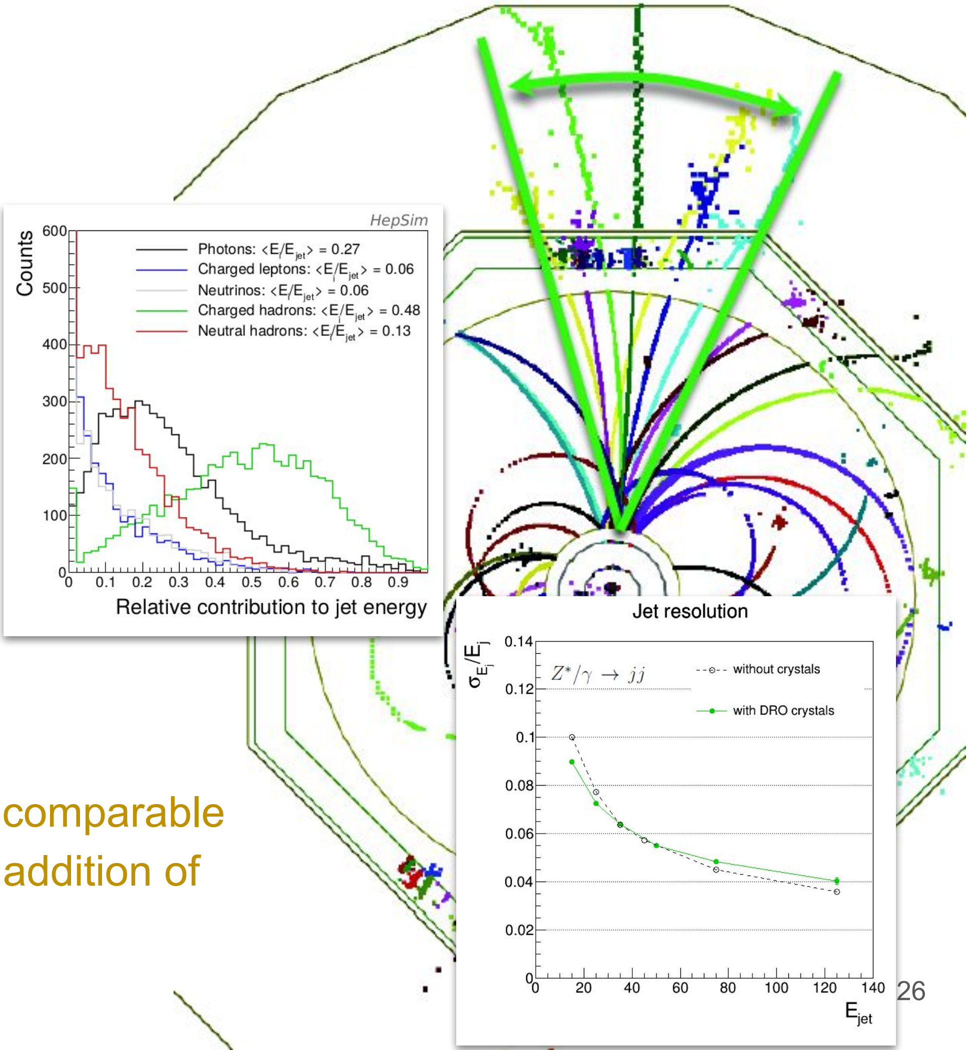




$\sigma_E/E_{HAD} \sim 27\%/\sqrt{E} \oplus 2\%$

Jet reconstruction

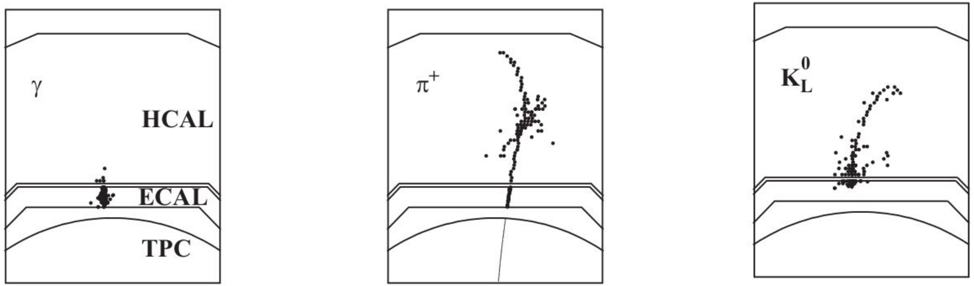
- Jets are complex objects, a cocktail of particles typically within a cone-like structure
- **Calorimeter only approach**: cluster all calorimeter hits within a certain cone (using the *FASTJET* Durham k_T):
  - Both Scintillation and Cherenkov signals
  - Both for the ECAL (crystals) and the HCAL (fiber sampling)
- Apply a dual-readout correction based on the S and C components clustered within each jet



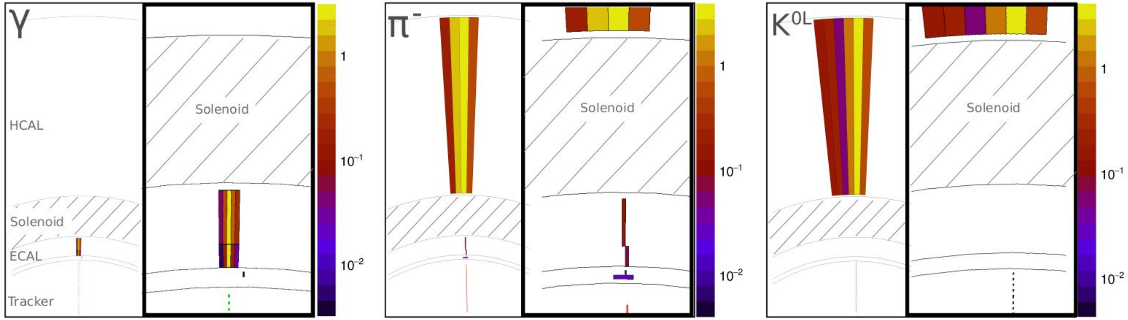
Jet resolution of ~5.5% at 50 GeV achieved, comparable with the baseline IDEA calorimeter without the addition of crystal EM section

But **<u>can we do better?</u>**

Single particle identification through ‘hits-topology’



Typical PFA with Si-W high granularity calorimeter



DR-pPFA with high resolution DRO calorimeter

A moderate longitudinal segmentation, fine transverse granularity and the highest energy resolution for single particle identification

A different basis for a DR-oriented PF algorithm

- A **different optimization** of particle flow algorithm **is required** for a coarsely segmented calorimeter
- Could the **better energy linearity and resolution** offset the coarser longitudinal segmentation?

	High granularity Si/W ECAL and scintillator based HCAL	Fiber-based dual-readout calorimeter	Hybrid crystal and dual-readout calorimeter
N. of longitudinal layers	> 40	1	5
ECAL cell cross-section	25–100 mm^2	2–144 mm^2	100 mm^2
HCAL cell cross-section	100–900 mm^2		400–2500 mm^2
EM energy resolution	$15 - 25\%/\sqrt{E}$	$10 - 15\%/\sqrt{E}$	$\approx 3\%/\sqrt{E}$
HAD energy resolution	$45 - 55\%/\sqrt{E}$	$25 - 30\%/\sqrt{E}$	$\approx 25 - 30\%/\sqrt{E}$

Moderate longitudinal segmentation (helpful to identify and measure the π^0 component of jets)

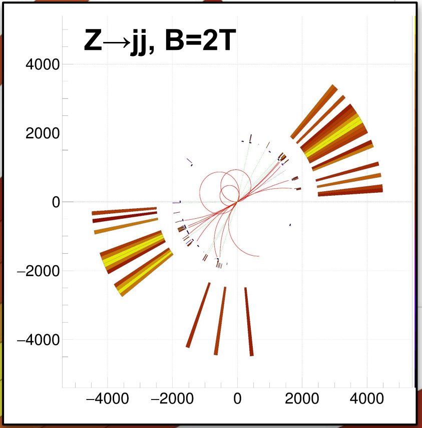
Highest energy resolution and linearity

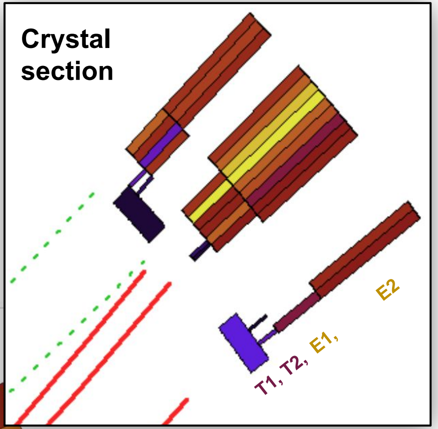
Highest transverse segmentation: full potential (e.g. using neural networks) yet unexplored

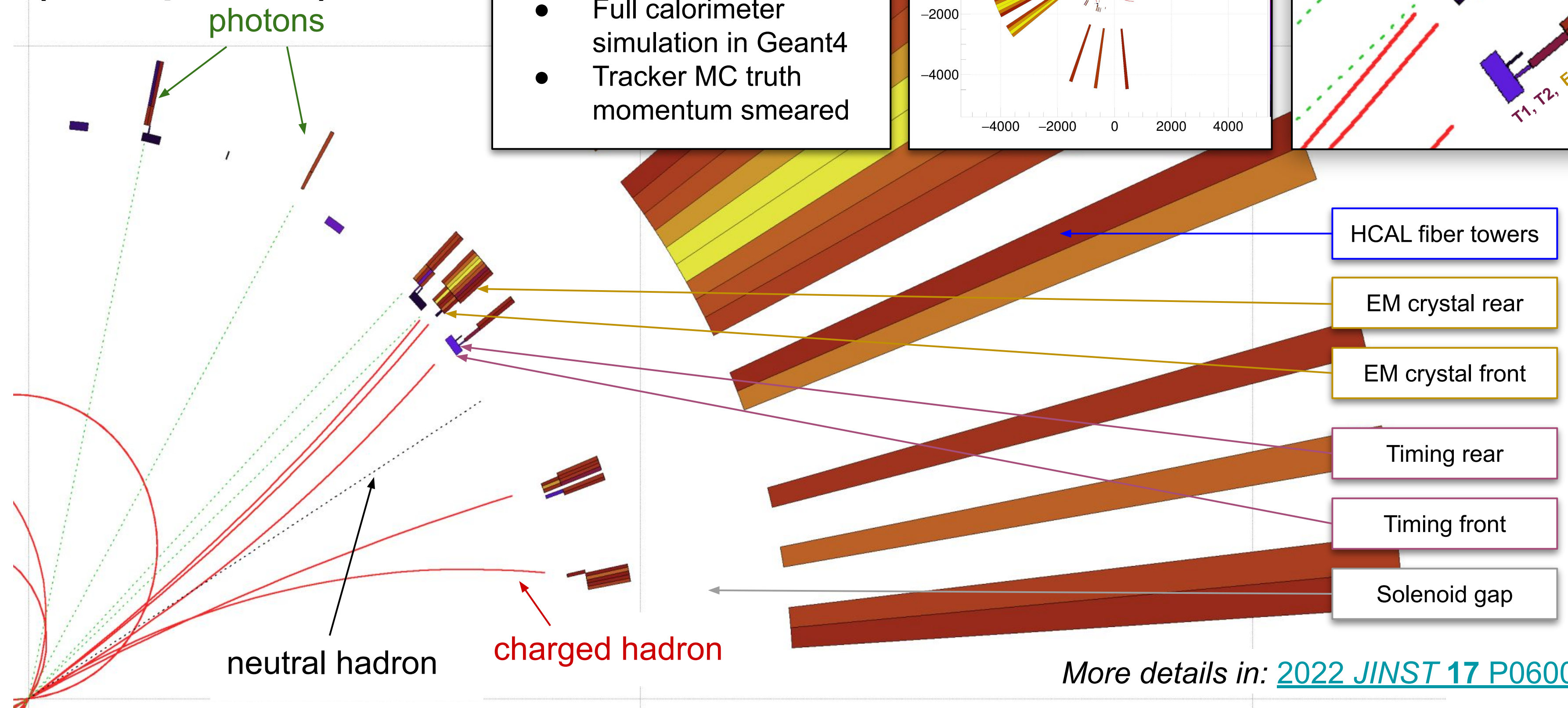
Highest longitudinal segmentation

A Dual-Readout ‘prototype’ Particle Flow Algorithm (DR-pPFA)

- Full calorimeter simulation in Geant4
- Tracker MC truth momentum smeared



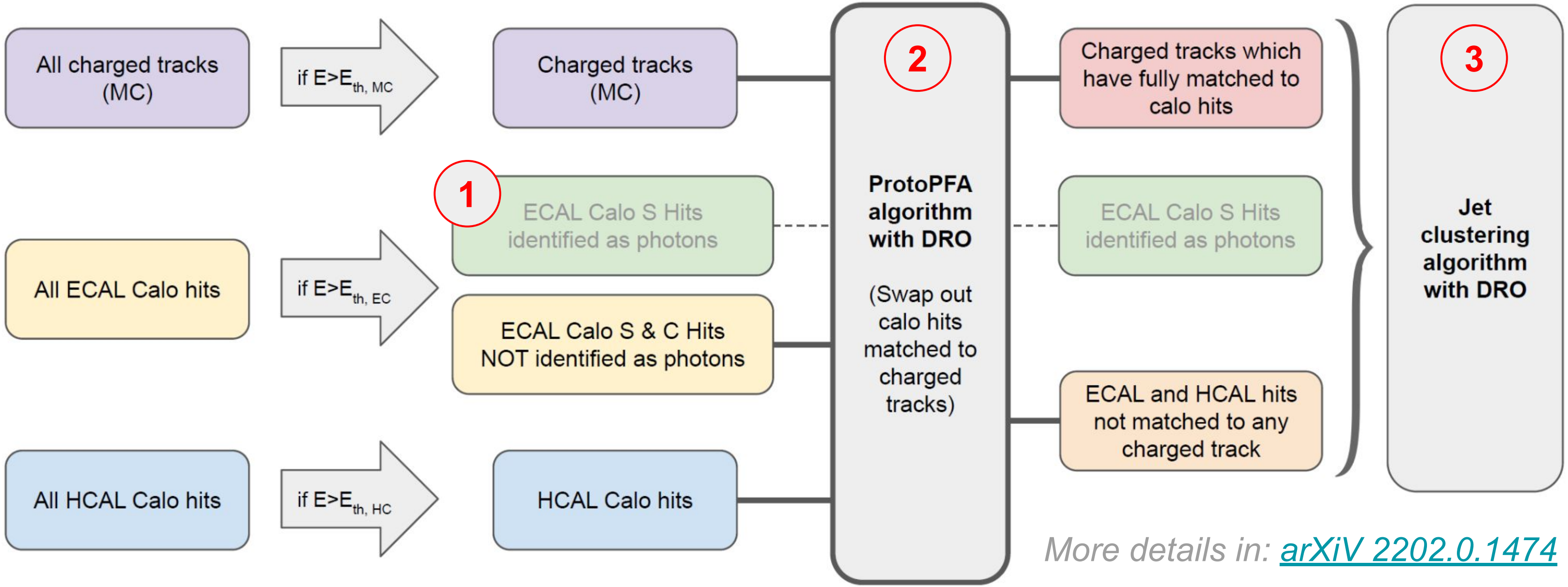




More details in: [*2022 JINST* **17** P06008]

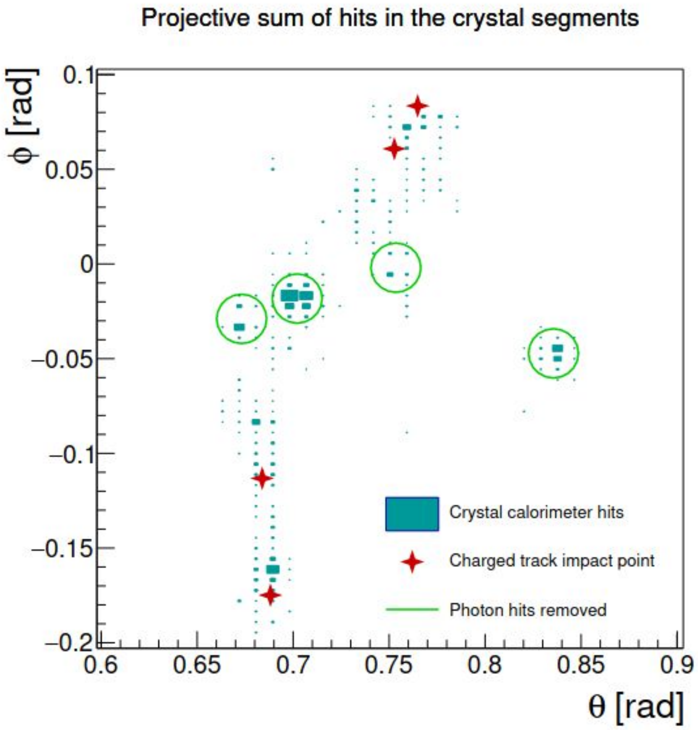
Dual-Readout Particle Flow Algorithm for jet reconstruction

- Maximally exploit the information from the **crystal ECAL** for classification of EM clusters and use it **as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter hits
- Exploit the **high resolution and linear response** of the hybrid **dual-readout** calorimeter to improve precision of the track-calo hits matching in a particle flow approach



More details in: arXiV 2202.0.1474

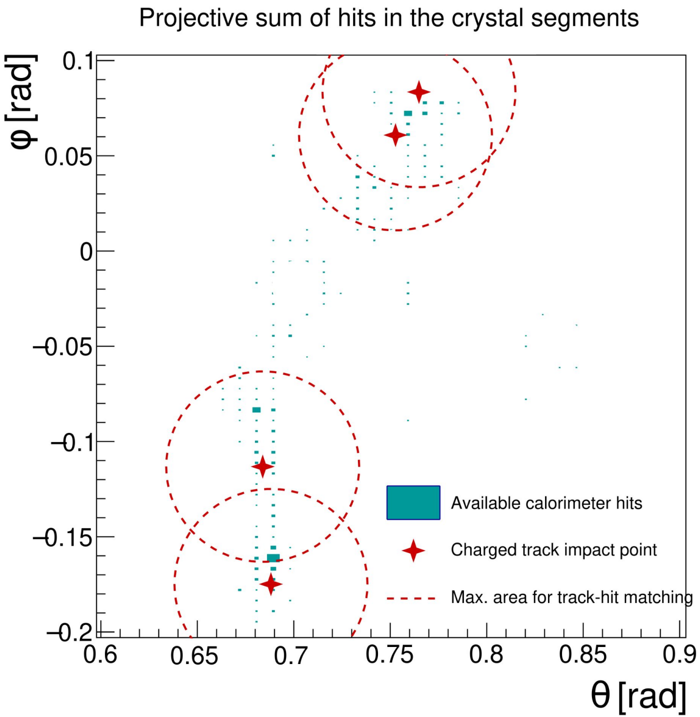
Step 1) Identification of photon hits



- Calorimeter hits **in the crystal segments** are analyzed
- Neutral seeds are identified as hits above a certain threshold and which have no charged track pointing to them
- Hits within a cone of R<0.013 are clustered around the "**photon seeds**"
- Such **"photon hits"** do not take part to step 2 (association of calorimeter hits with charged tracks)

**longitudinal segmentation (EM crystal section) is crucial for this step*

Step 2) Association of calorimeter hits to charged tracks



- Calorimeter hits **in both calorimeter segments** are parsed
- Hits are associated to tracks based on their distance from a certain track
- **Successful match**: if the sum of the energy of hits associated to a track is within ±1σ from the expected track signal the calorimeter hits are replaced with the track momentum

**dual-readout is used here to correct energy of clustered calorimeter hits and improve track-hit matching*

Step 3) Jet clustering

- The jet clustering algorithm* is fed with the collection of
  - All photon hits (from step 1)
  - A collection of tracks
    - charged particles not reaching the calorimeter
    - tracks that were swapped with calorimeter hits at step 2
  - All the other calorimeter hits (both ECAL and HCAL) that have not been swapped out
- The algorithm clusters the 4-momentum vectors into two jets
- The jet energy ("non-swapped hadron" component) is corrected with DRO**

$$E_{jet} = C_{PFA} \cdot \left[\sum E_{hits,\gamma} + \sum E_{tracks} + \sum E_{hits,leftover,DRO} \right]$$

FASTJET package: generalized k_T algorithm with $R=2\pi$ and $p=1$ (*ee_genkt_algorithm*), force number of jets to 2

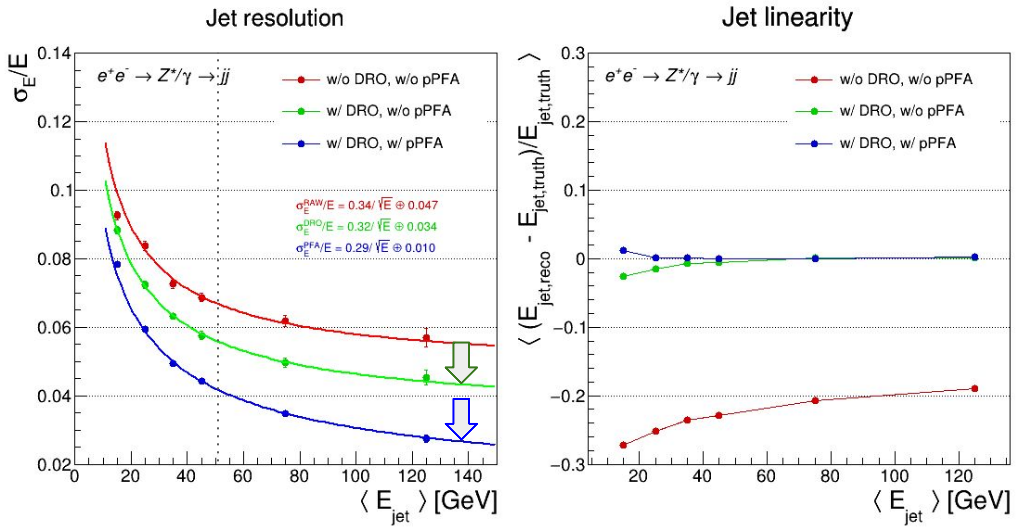
***dual-readout is used here to correct energy of calorimeter hits which have not been matched to tracks (e.g. neutral hadrons)*

Jet resolution: with and without DR-pPFA

More details in:
[2022 *JINST* **17** P06008]

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \rightarrow Z^* \rightarrow jj$ events (at different center-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

R&D challenges

Implementing dual-readout in crystals

- First test of combination of a DRO crystal ECAL with DREAM HCAL back in 2009 with BGO modules ([N.Ackurin et al., NIM A 610 (2009) 488-501]())

Successful demonstration that DRO principles also apply to a hybrid calorimeter system (despite many experimental limitations!)

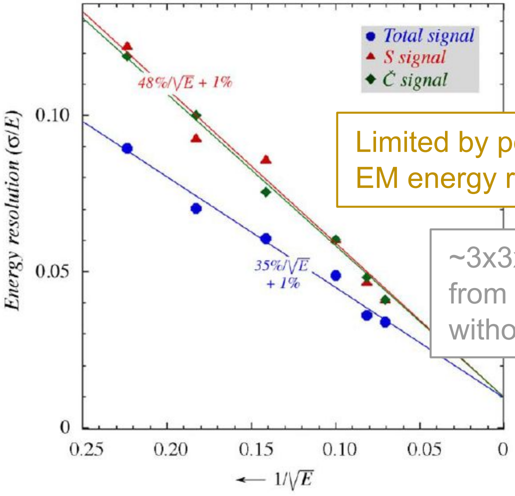
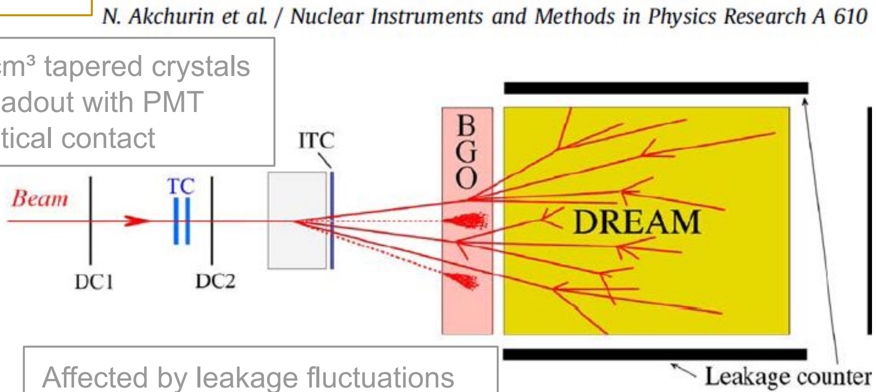


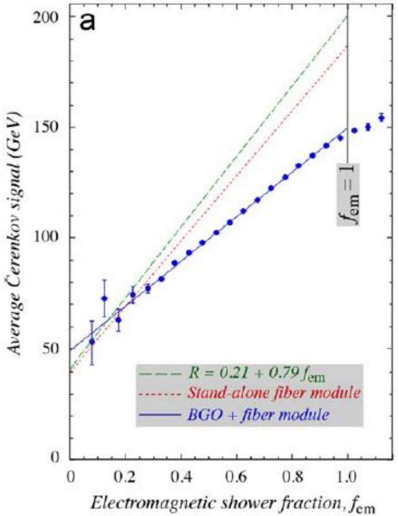
Fig. 8. The energy resolution of the BGO ECAL as a function of energy, for electrons with energies ranging from 20 to 200 GeV. The relative width of the distribution, σ/mean, is plotted versus the beam energy, separately for the scintillation and Cherenkov components of the signals, and for the total signal, integrated over the first 115 ns. See text for details.

Limited by poor ECAL EM energy resolution

~3x3x24 cm³ tapered crystals from L3 readout with PMT without optical contact



Affected by leakage fluctuations



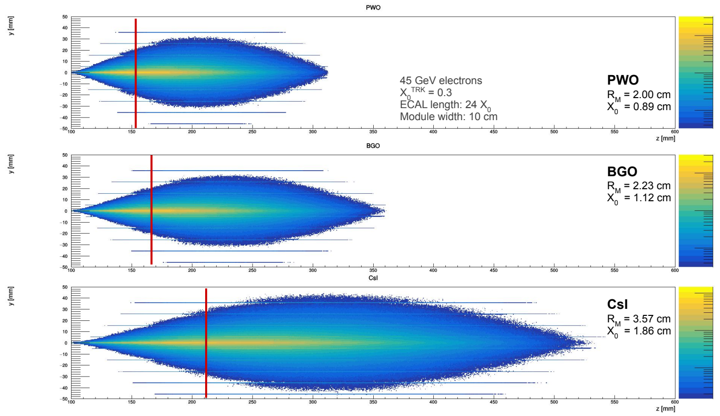
Some crystal options

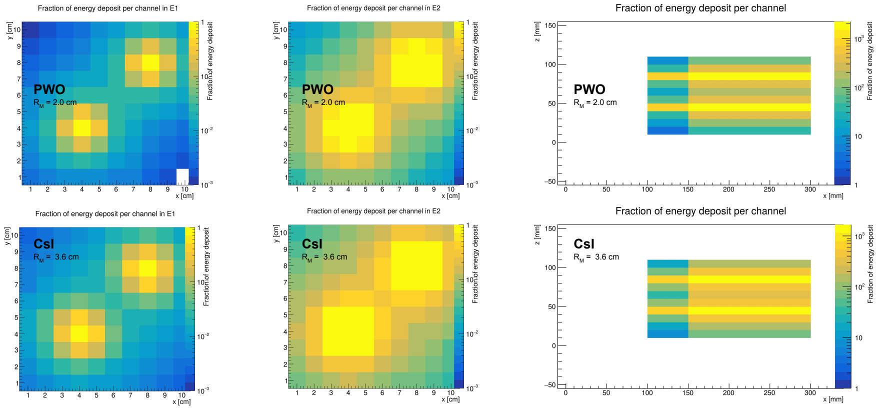
- **PWO**: the most compact, the fastest
- BGO/BSO: parameters tunable by adjusting the Si-fraction
- CsI: the less compact, the slowest, the brightest

better for PFA

better stochastic term

Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Refractive index, n	Relative LY @ RT	Decay time ns	Photon density (LY / τ_D) ph/ns	dLY/dT (% / °C)	Cost (10 m³) Est. \$/cm³	Cost*X_0 Est. \$/cm²
PWO	8.3	20.9	0.89	2.00	2.2	1	10	0.10	-2.5	8	7.1
BGO	7.1	22.7	1.12	2.23	2.15	70	300	0.23	-0.9	7	7.8
BSO	6.8	23.4	1.15	2.33	2.15	14	100	0.14	--	6.8	7.8
CsI	4.5	39.3	1.86	3.57	1.96	550	1220	0.45	+0.4	4.3	8.0

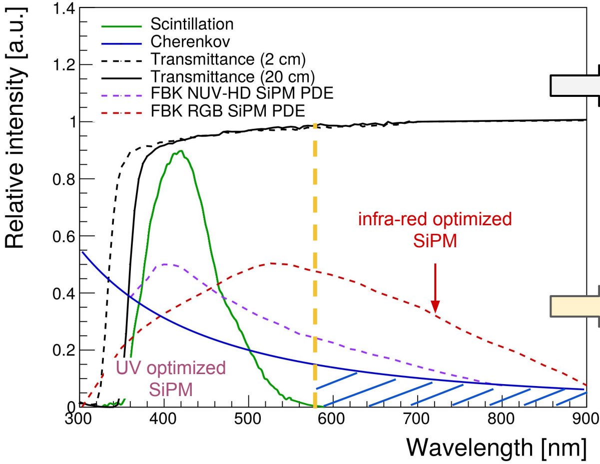




The dual-readout challenge

- Quality of the S and C signals in terms of **light yield** and **purity** is likely to be a key discriminant between crystal options
- Different strategies could be pursued for different scintillators

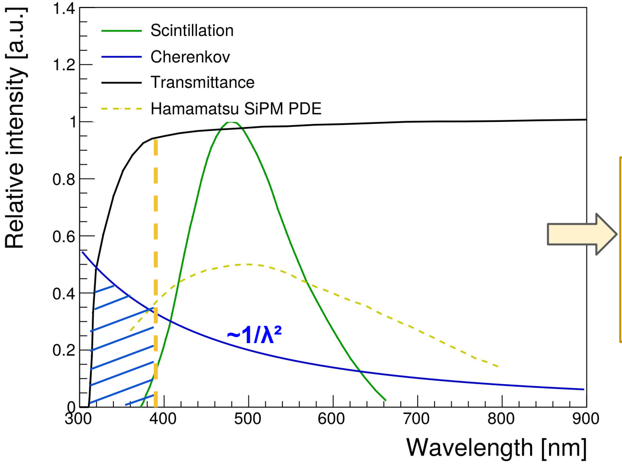
PWO



Estimated:
- >2000 phe/GeV for scintillation photons
- >100 phe/GeV for Cherenkov photons

Cherenkov photons above scintillation peak are much less affected by self-absorption

BGO / BSO

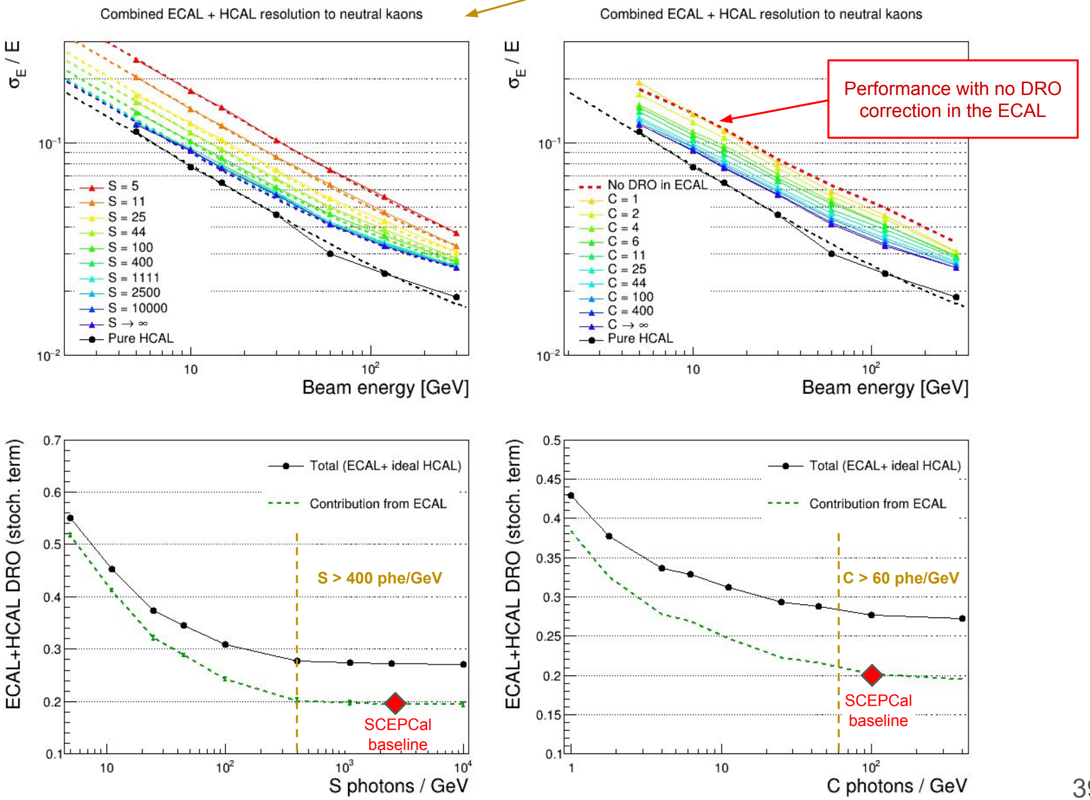


BGO/BSO have larger stokes shift, i.e. a wider range of transparency for 'UV Cherenkov'

Photo-statistic requirements for S and C

- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV
- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV
- **Baseline layout choices** (granularity and SiPM size) to **provide sufficient light collection efficiency** in Geant4
  - Need experimental validation with lab and beam tests

Smearing according to Poisson statistics



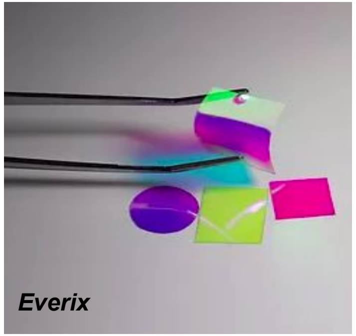
Ongoing R&D: separation of S and C signals

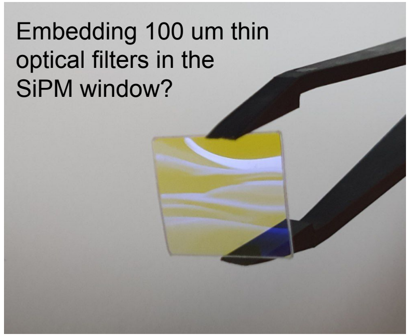
Multi-signal readout challenges:

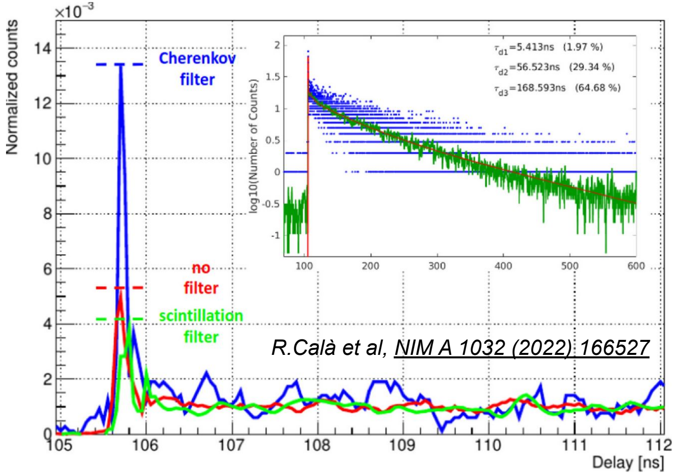
- Challenging dynamic range and photon sensitivity with SiPMs
- Reasonable **scintillation** and **cherenkov** light yields
- **Good separation of scintillation and cherenkov signals** (e.g. based on thin wavelength filters)

Exploring crystal candidates with high Cherenkov yield and density (PWO, BGO, BSO)

- See also optimization study of BGSO crystals *R.Calà et al, NIM A 1032 (2022) 166527*

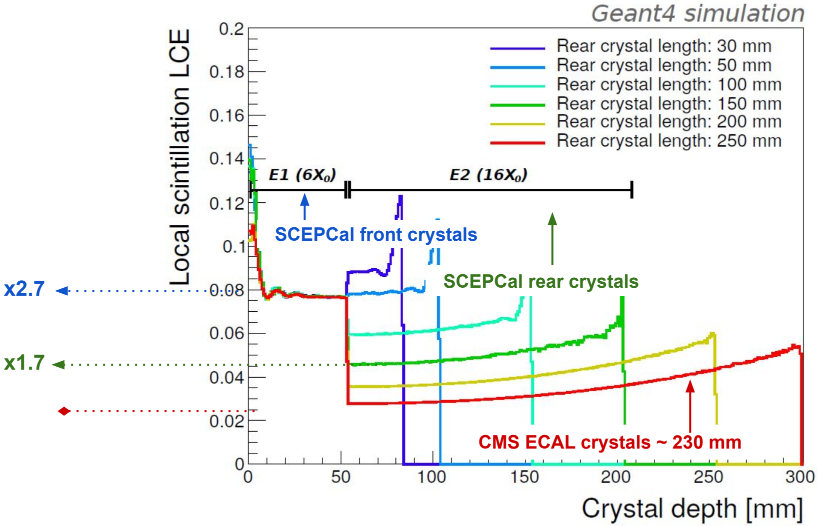






Layout optimization

- **High granularity increases light collection efficiency** (both C and S)
  - 1 cm² cross section compared to ~ 3 cm² in L3/CMS and crystal length reduced by ~2x
- **SiPM active area can be tuned** to achieve target resolution (stoch. term)
  - Light collection efficiency increasing linearly with SiPM area
- SiPM with smaller dynamic range but high PDE can be selected for C-detection



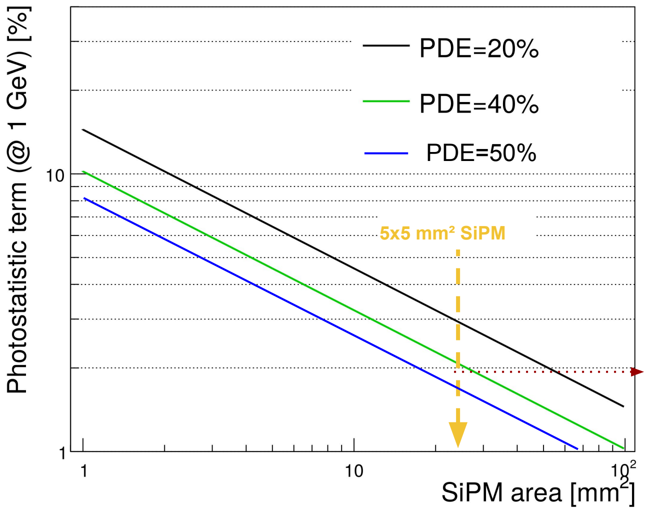
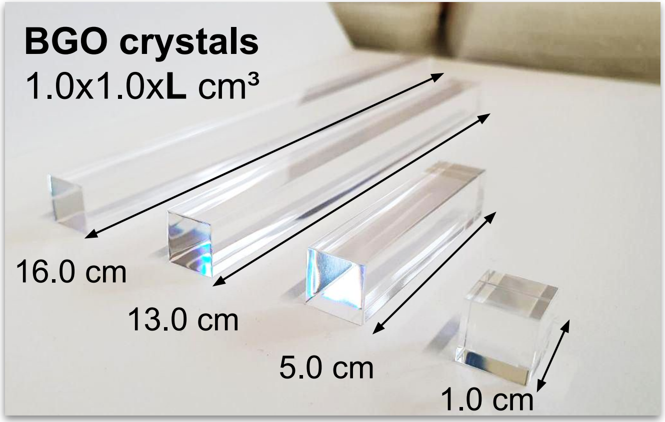
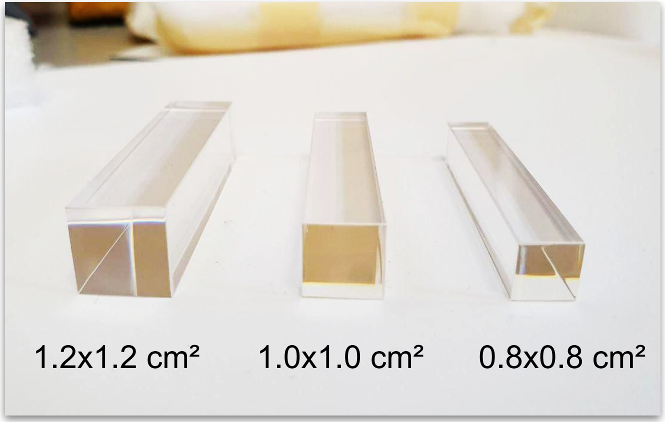


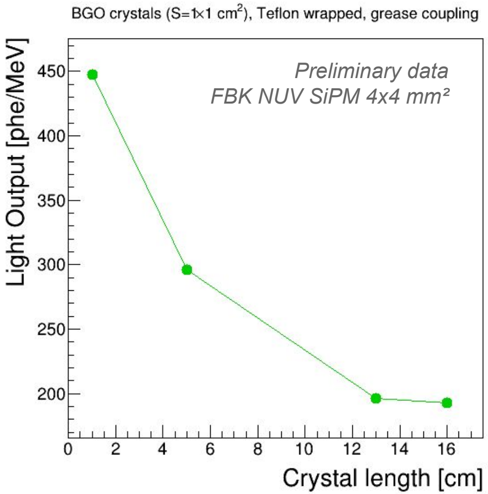
Photo-statistics term for S can be tuned by increasing the SiPM active area down to <**2%**

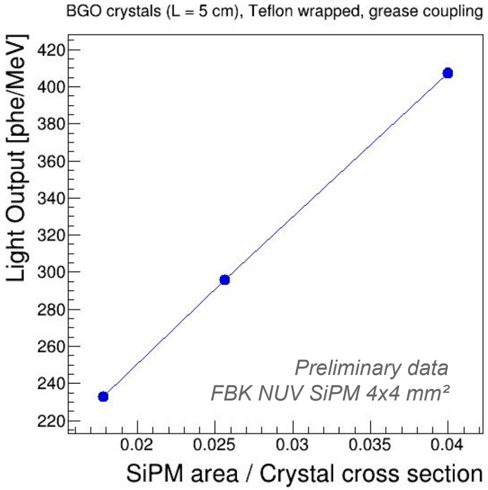
Layout optimization: **first studies**

- Optimization of crystal cross section (granularity) and longitudinal segmentation
- Evaluation of light output for different crystal and SiPM geometries
- First experimental results available to validate expectations from Geant4 ray-tracing simulation









Outlook and opportunities

- **An innovative hybrid dual-readout calorimeter** concept was proposed to enhance the physics reach of future e^+e^- colliders but proof-of-principle, R&D, prototyping and simulation **efforts and ideas are required on several fronts**

- Collaborative frameworks / resources
  - There is a DOE funded R&D consortium in the US: Calvision
  - There is a proposed R&D inside the ECFA DRD6
  - RD_FCC (IDEA DR calorimetry) within INFN
  - Waiting for evaluation on a PRIN 2022

- Ongoing activities
  - Crystal, filters and SiPM characterization
  - Laboratory tests with radioactive sources and cosmics
  - Prototyping and test beams (within Calvision @FNAL)

Additional material

Useful links

- Calvision webpage [link]

CALVISION consortium

CALorimetry using cherenko**V** and **I**norganic **S**cintillation Inn**O**vatio**N**

New proposal for
U.S. DOE FOA DE-FOA-0002424

Project Summary/Abstract

Application Title: Maximal Information Calorimetry

Sarah Eno, the University of Maryland (Principal Investigator)
A. Belloni, University of Maryland (Co-Investigator)
C.G. Tully, Princeton University (Co-Investigator)
R. Hirosky, University of Virginia (Co-Investigator)
S. Chekanov, Argonne National Laboratory (Co-Investigator)
S. Magill, Argonne National Laboratory (Co-Investigator)
N. Akchurin, Texas Tech University (Co-Investigator)
H. Newman, Caltech (Co-Investigator)
R.-Y. Zhu, Caltech (Co-Investigator)
J. Hirschauer, Fermi National Accelerator Laboratory (Co-Investigator)
H. Wenzel, Fermi National Accelerator Laboratory (Co-Investigator)
J. Qian, University of Michigan (Co-Investigator)
B. Zhou, University of Michigan (Co-Investigator)
J. Zhu, University of Michigan (Co-Investigator)
M. Demarteau, Oak Ridge National Laboratory (Co-Investigator)
P. Harris, MIT (Co-Investigator)

In the past, homogeneous electromagnetic calorimeters have allowed precision measurements of electrons and photons, while high granularity, dual-readout, and compensating calorimeters are considered promising paths for improving hadronic measurements. We propose to form a consortium of Universities and Department of Energy laboratories to conduct a program of work that should allow state-of-the-art calorimetric measurements of all particles by emphasizing incorporation of homogeneous calorimetry that makes maximal use of available information. A phased program of work is described, starting with an electromagnetic calorimeter with maximal information usage that would be suitable for future lepton colliders. On a longer timescale, this program is expected to lead to a broader research program aimed at the development of an ultimate hadron calorimeter for the best high energy particle measurements. Collaboration will be strengthened via regular in-person meetings of the consortium.

More on the physics case

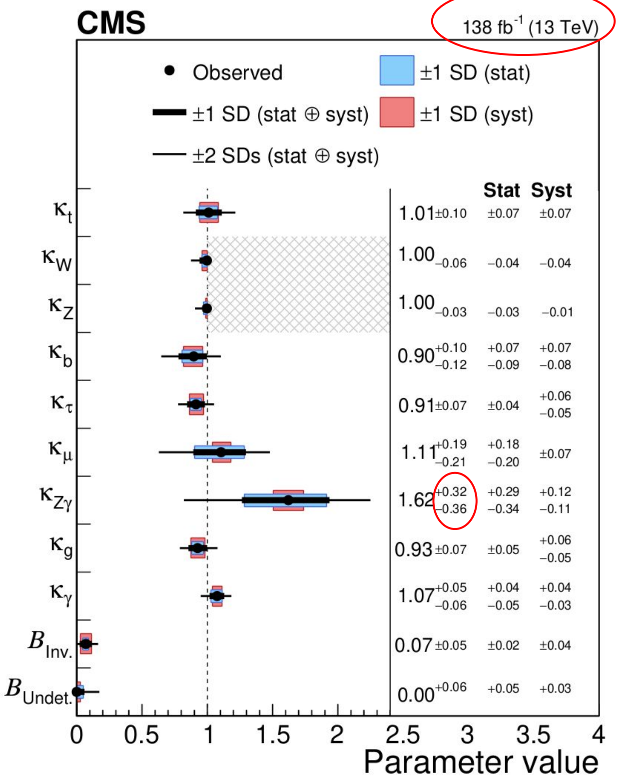
The physics reach of HL-LHC

5% of LHC data delivered
(~8 million Higgs/experiment)

An example: *Higgs stoichiometry*

entering the era of precision Higgs physics

- Only 5% of total LHC dataset delivered (138 fb^{-1})
  - Already ~8 million Higgs bosons per experiment
- After 10 years from Higgs discovery:
  - All main production modes observed
  - Couplings measured with **6-30%** precision
- Run 3 started in April 22
  - Expected integrated luminosity of ~350 fb^{-1}
  - 5σ observation for H→μμ at ~300 fb^{-1} (now at ~3σ)



The Higgs Factory Physics Menu

The Starting Point

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

Flavour Physics

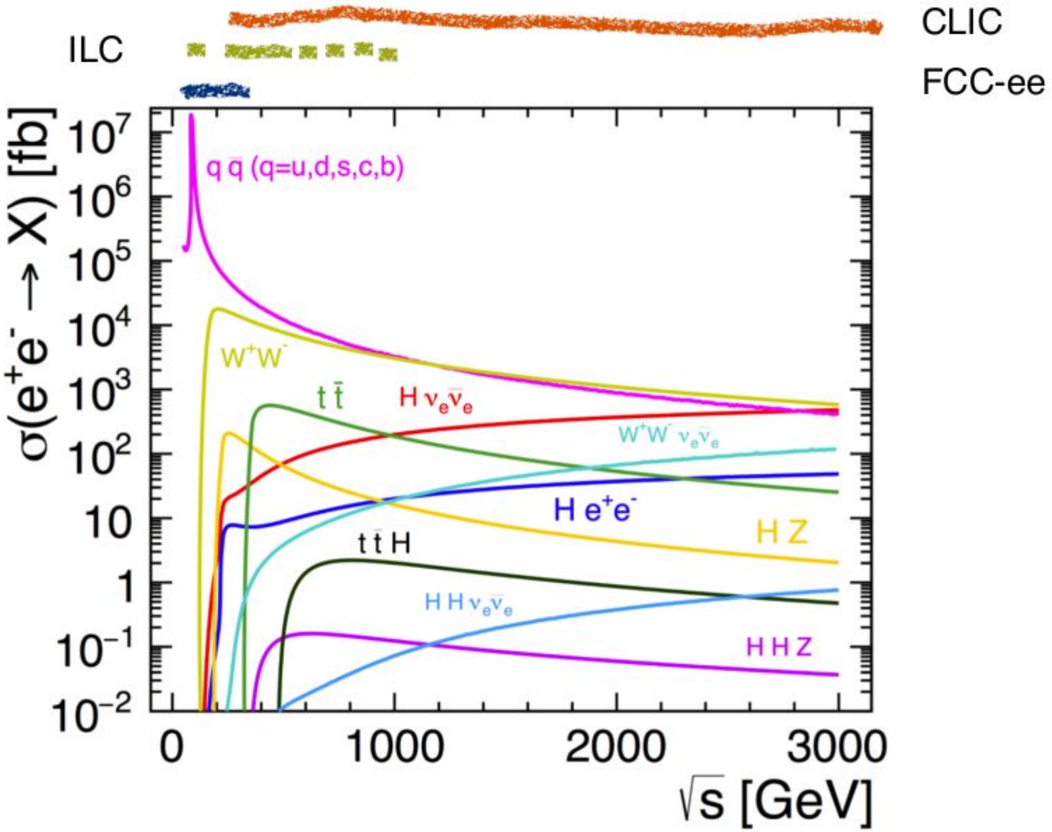
use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

New Particles

searches for weakly coupled new particles with high luminosity / high energy in a clean environment

Cross Sections and Processes

Interesting Physics from 91 GeV into the multi-TeV regime



Main SM processes of Higgs-Top-EWK factories

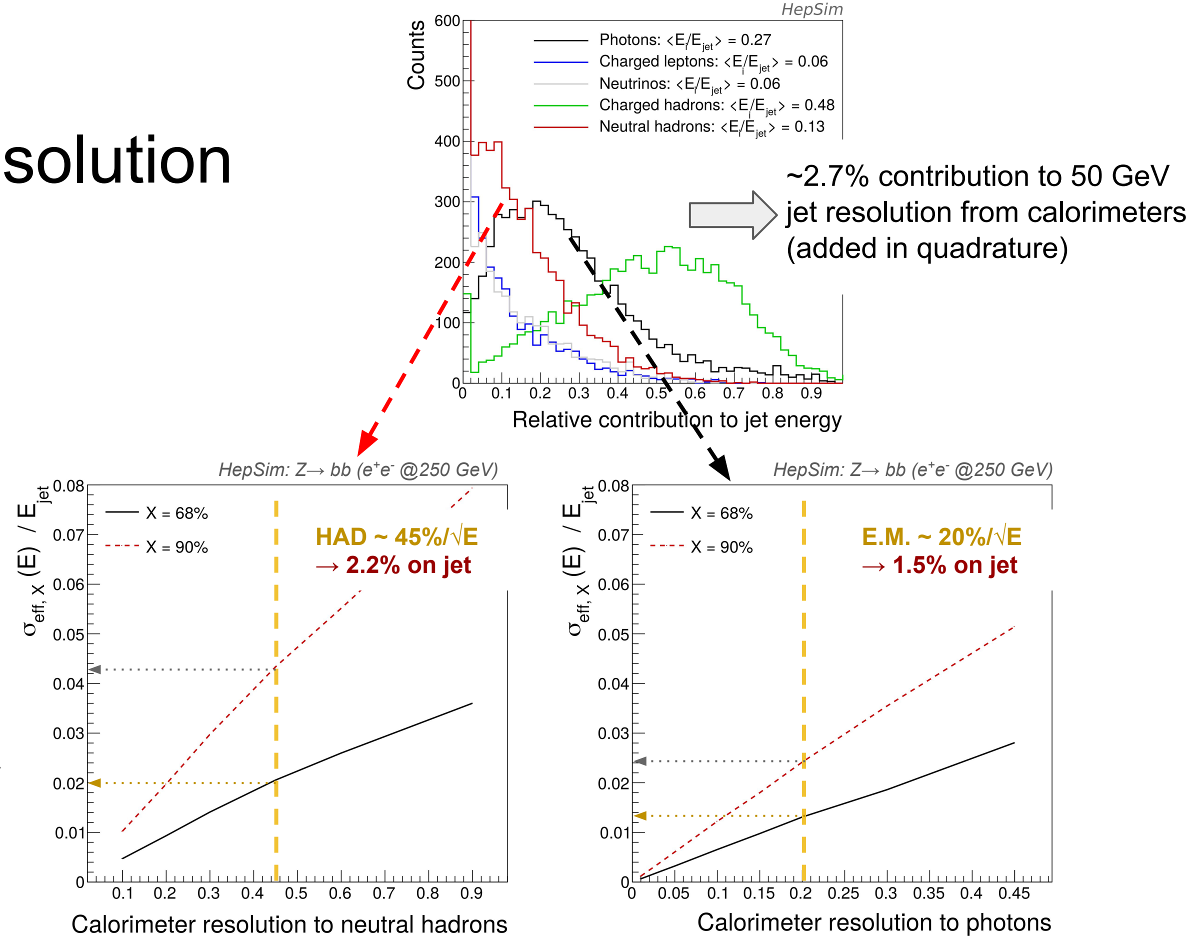
Cross sections low compared to hadron colliders.

Z-pole 3+ orders of magnitude higher than everything else.

Traditional impact of calorimeters on jet resolution

- Baseline jet performance depends on particle composition and the relevant sub-detector resolutions

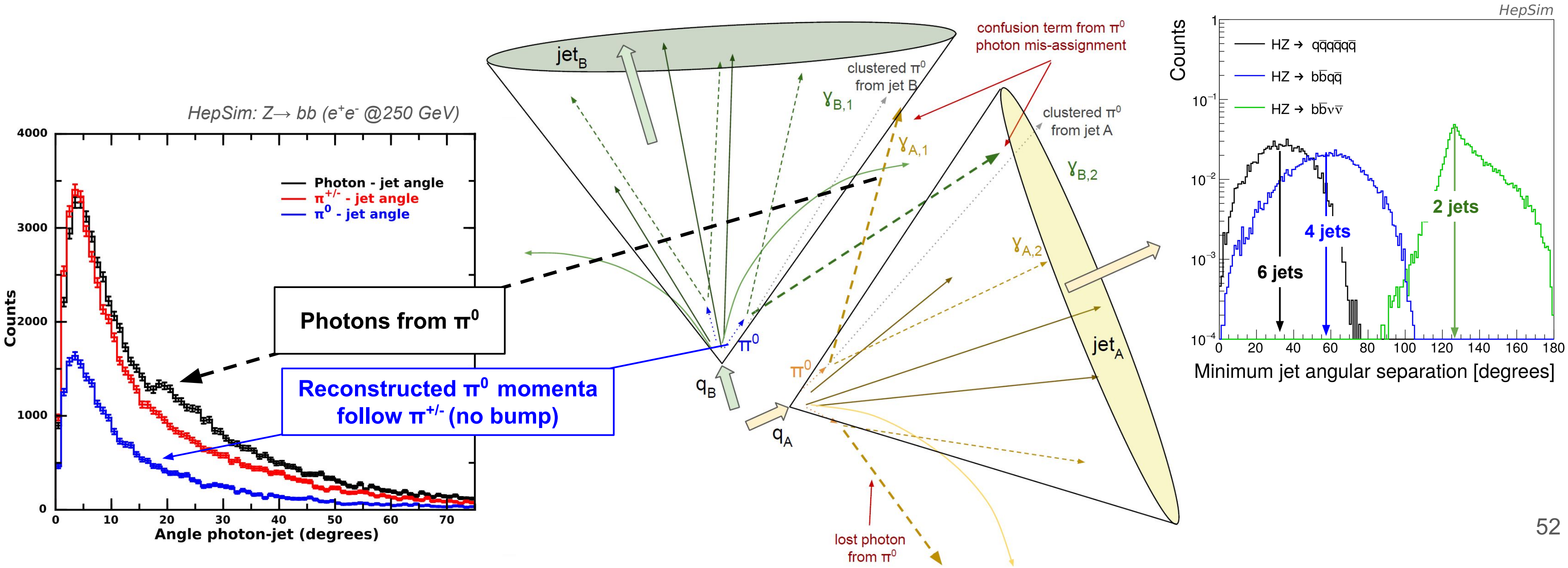
- Calorimeter resolution on neutral particles required to achieve target jet resolution of ~3%
  - Photons
    better than 20%/√E
  - Neutral hadrons
    (mostly $K^{0,L}$ of <E>~5 GeV) better than 45%/√E



But the role of calorimeters in jet reconstruction spans beyond the direct impact on energy resolution...

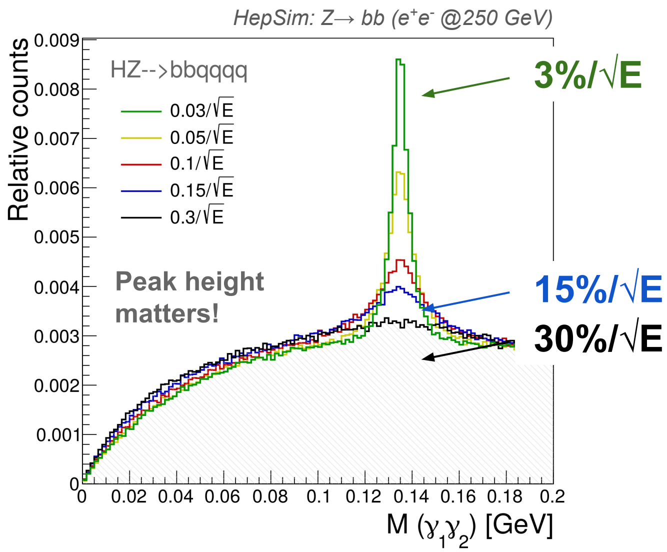
High photon resolution potential for PFA

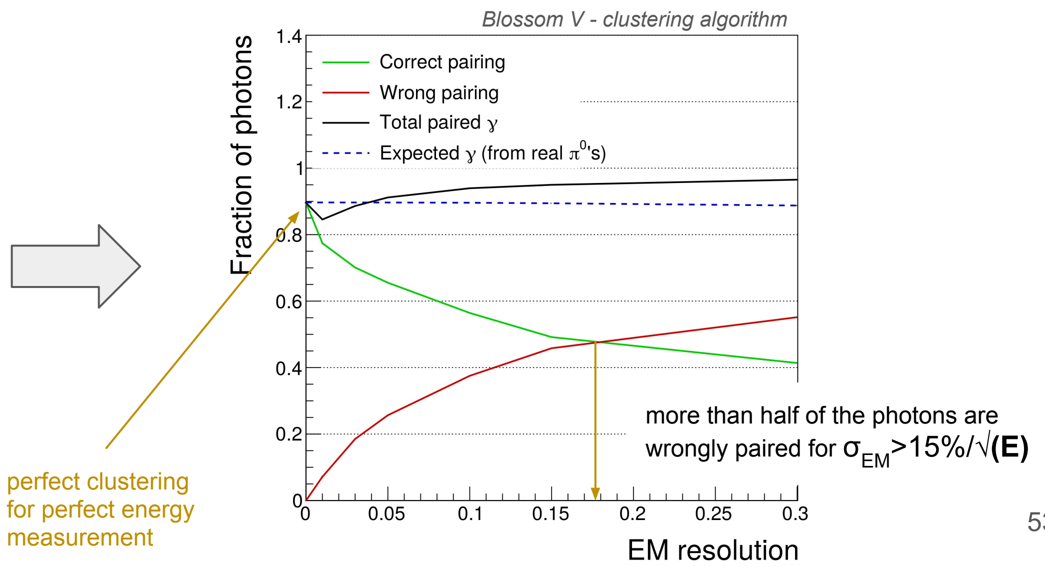
- **Many photons from π^0 decay** are emitted **at a ~20-35° angle** wrt to the jet momentum and can get scrambled across neighboring jets
- Effect **particularly pronounced in 4 and 6 jets topologies**



A graph-based algorithm for **π^0 clustering**

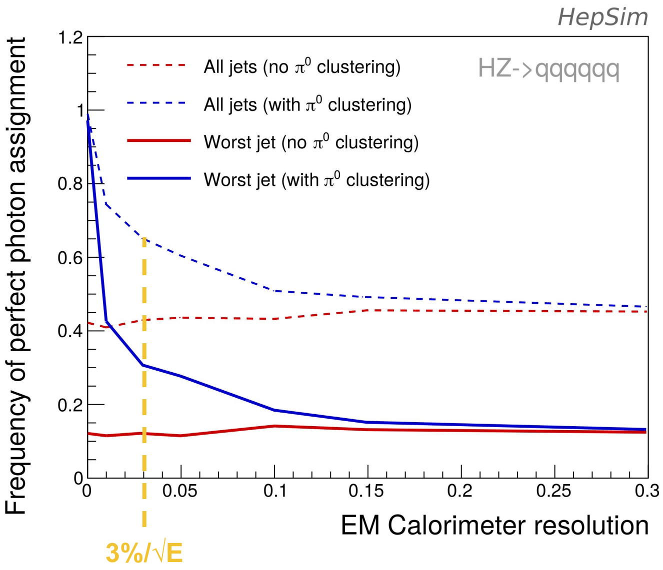
- **A high EM resolution enables efficient clustering of photons from π^0's**
  - Large fraction of π^0 photons correctly clustered with good σ_{EM}
    → **~90% for ~3%/√(E)** vs **50% for ~30%/√(E)**
  - Large fraction of "**fake π^0's**"reconstructed with poor σ_{EM}
    → ~50% for ~30%/√(E) vs 10% with ~3%/√(E)

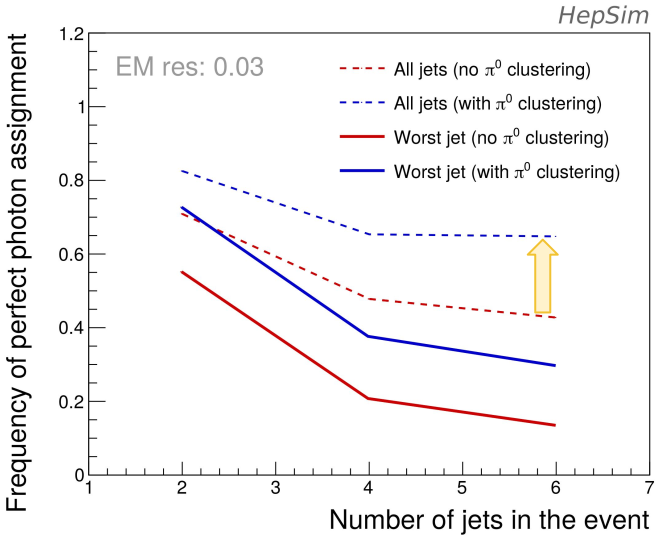




Improvements in photon-to-jet correct assignment

- **High e.m. resolution enables** photons **clustering into π^0's** by reducing their angular spread with respect to the corresponding jet momentum
- **Improvements in the fraction of photons correctly clustered to a jet** sizable only for e.m. resolutions of ~3%/√(E)

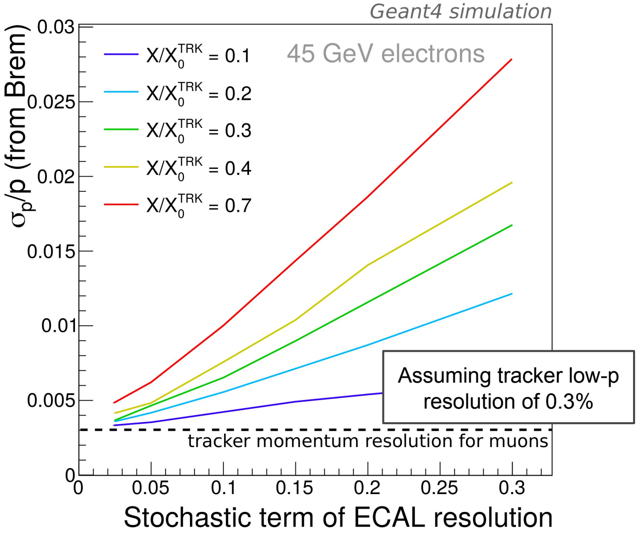




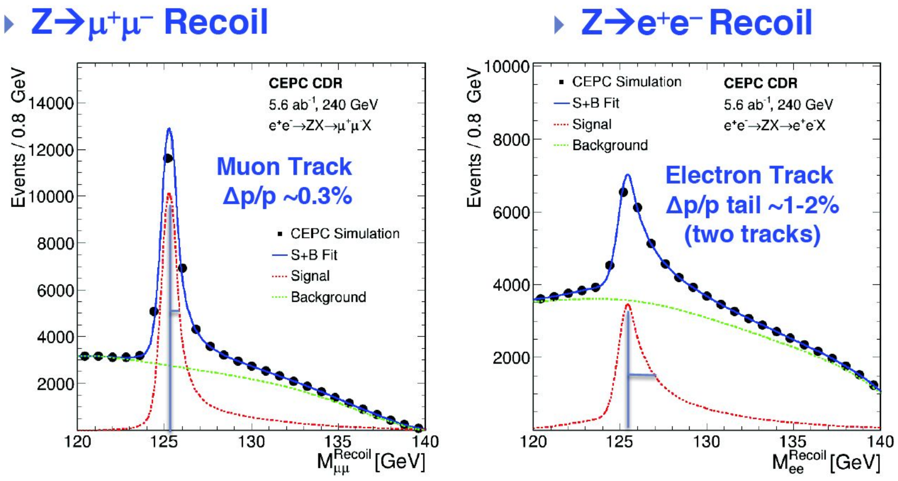
More details in:
https://doi.org/10.1088/1748-0221/15/11/P11005

Recovery of Bremsstrahlung photons

- Reconstruction of the Higgs boson mass and width from the recoil mass of the Z boson is a key tool at e^+e^- colliders
- Potential to **improve the resolution of the recoil mass signal from Z→ee decays** to about 80% of that from Z→ μμ decays [with Brem photon recovery at EM resolution of 3%/√E]



Example from ***CEPC CDR***



~80% of resolution recovery with 3%/√(E)

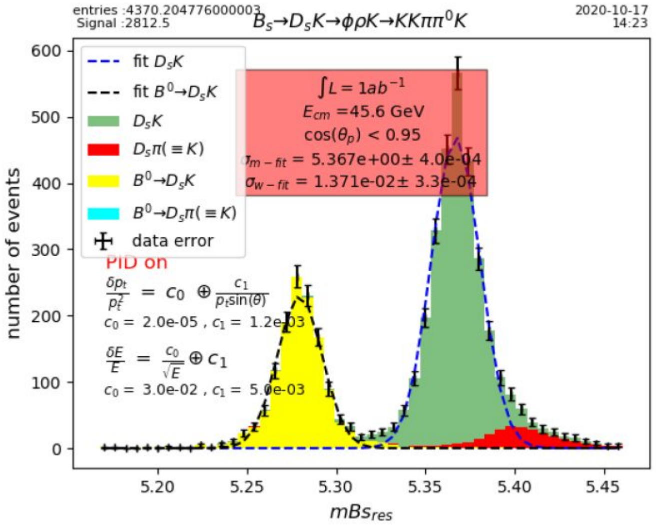
Studies of CP violation and EW physics at e^+e^- colliders

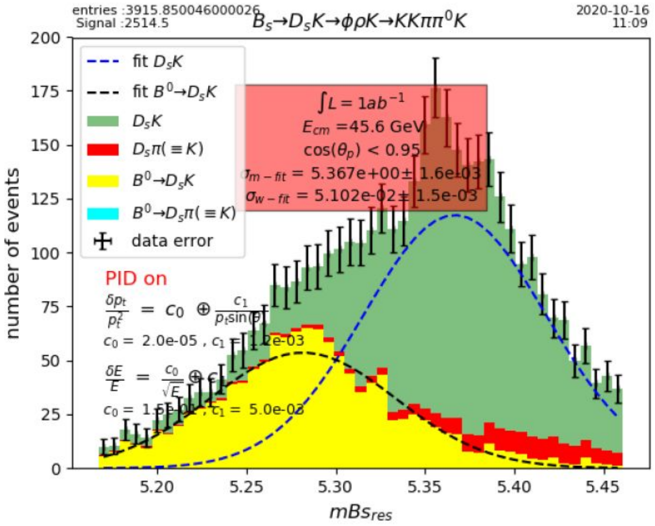
$\overline{B_s}$ decay Mode	Decay Mode	Final State	Number of $\overline{B_s}$ decays
$D_s^+K^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+K^-$	$\sim 5.2\ 10^5$
$D_s^+K^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+K^-\pi^0$	$\sim 9.8\ 10^5$

EM energy resolution at 3%/√E is required to study B_s decay final states with multiple neutrals

$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$$

$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$$

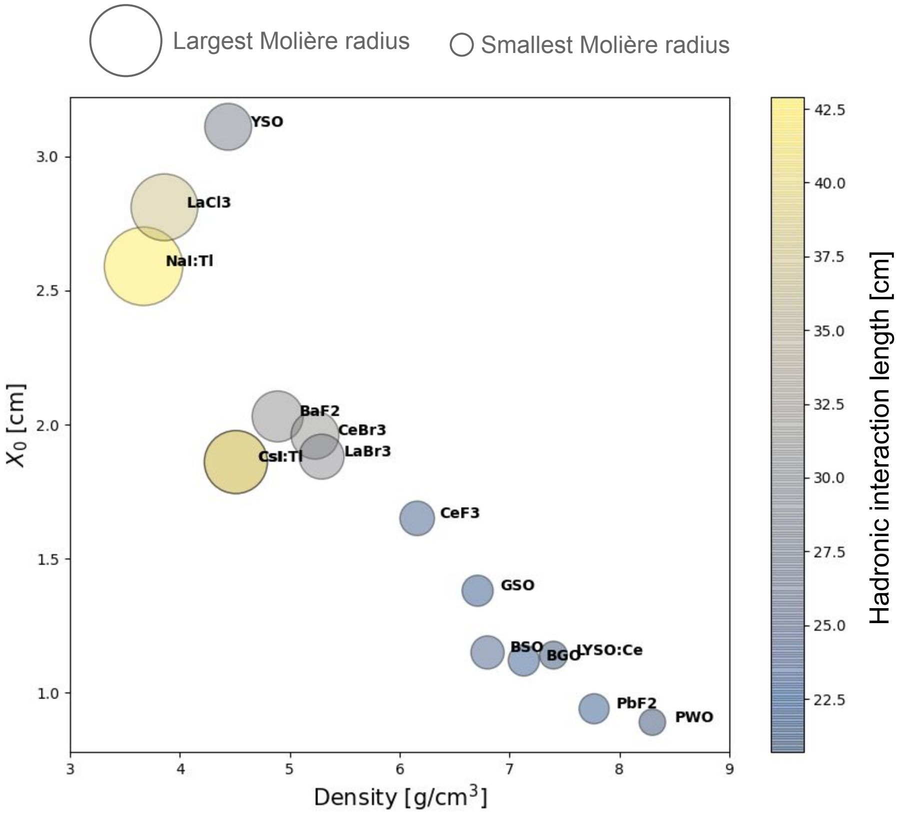


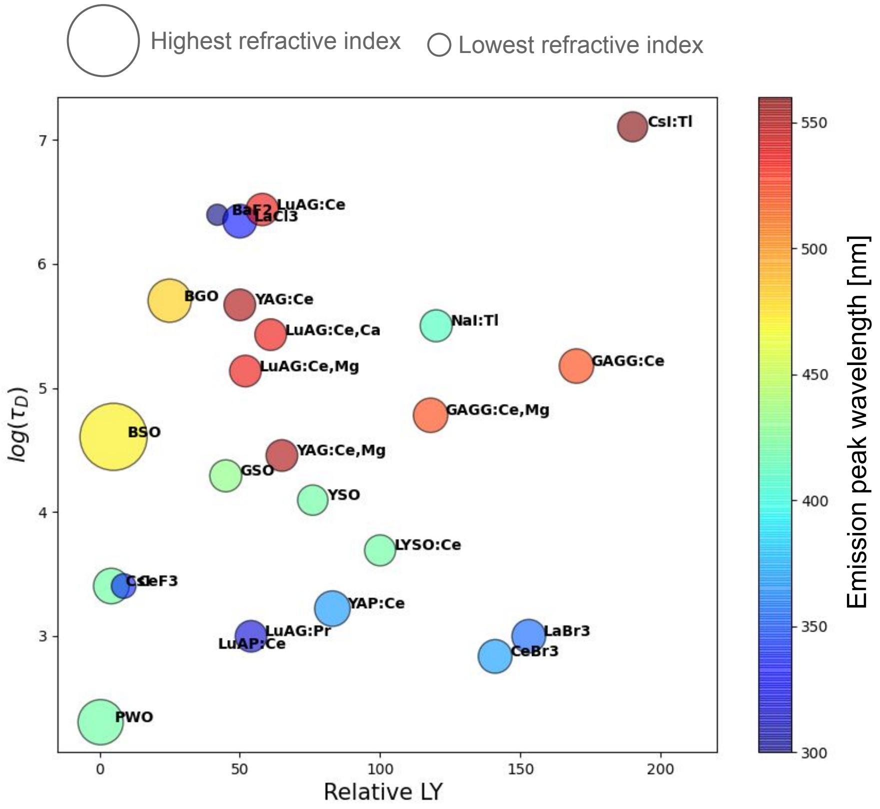


See **R. Aleksan's** talk @ [4th FCC Physics and Experiments Workshop]

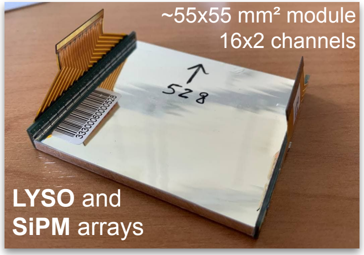
More on technology

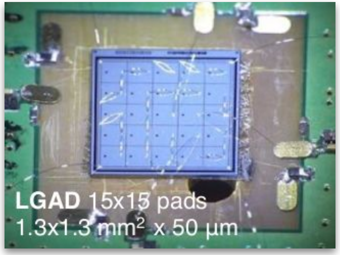
Crystal portraits





Rough comparison of technologies



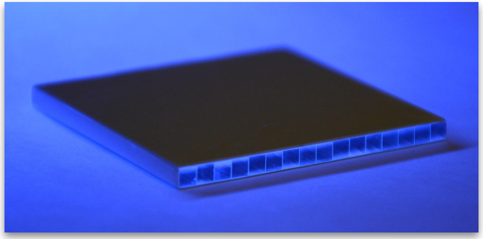


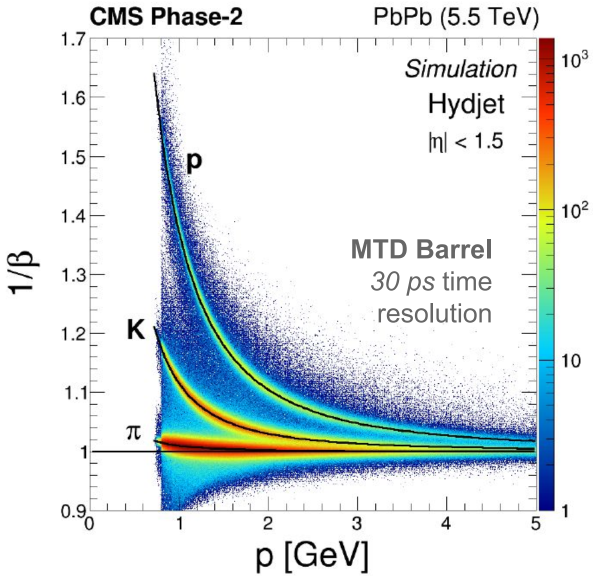
[from MTD TDR]	**Barrel region**	**Endcap region**
Total surface	38 m²	16 m²
Sensor technology	LYSO+SiPMs	LGADs
Highest radiation level [1 MeV n.eq./cm²]	2e14	2e15
Cost / m²	**~250 k€**	**~700 k€**
Power consumption / m²	**~1 kW** (50% from radiation damage)	**~5 kW**
Channel count / m²	**~9k**	**~530k**
Radiation length [X0]	0.3-0.5 (dominated by sensors)	0.15 (dominated by mechanics/services)
Time resolution (before/after irrad.)	30 / 60+ (limited by radiation damage)	40 / 40 (contribution from electronic noise)

- Different technologies are best suited for different environments/constraints
- In the absence of heavy radiation damage LYSO+SiPM offer a viable option for the instrumentation of **large surfaces with contained cost, channel count and power budget**

Timing in crystal based particle detectors

- **Two examples from CMS**:
  - Time tagging of **MIPs with ~30 ps** time resolution with single LYSO layer
    - See MTD in CMS Phase 2 upgrade
  - Time resolution of ~**30 ps for EM showers** with the PWO ECAL
    - See CMS ECAL in Phase 2 Upgrade
- **An additional powerful handle for event reconstruction** (time-of-flight for heavy ions, search for long lived particles, pileup mitigation)

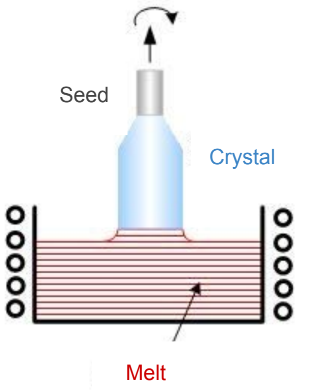




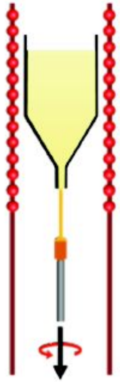
Progress in crystal **manufacturing**

opens new ways for designing crystal based (segmented) calorimeters

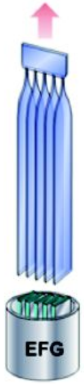
Czochralski method



Micro-Pulling Down technique

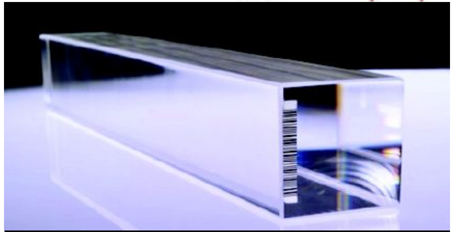


Edge-Defined Film-Fed Growth (EDG)

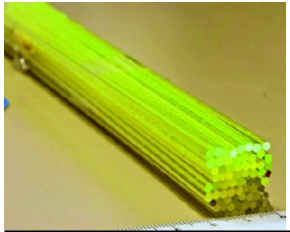


3D printing

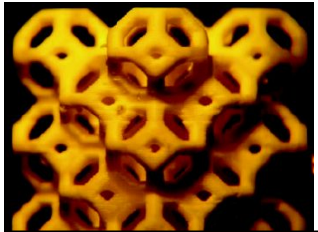
G. A. Dosovitskiy et al., **First 3D-printed complex inorganic polycrystalline scintillator** (link)

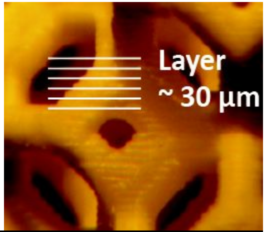


CMS PWO bulk crystals



Crystal fibers for high granularity





3D printed micro structures (for dreaming)

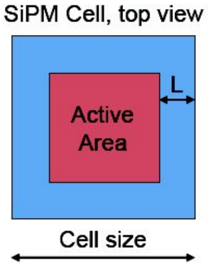
Technological advancements in **Silicon Photomultipliers**

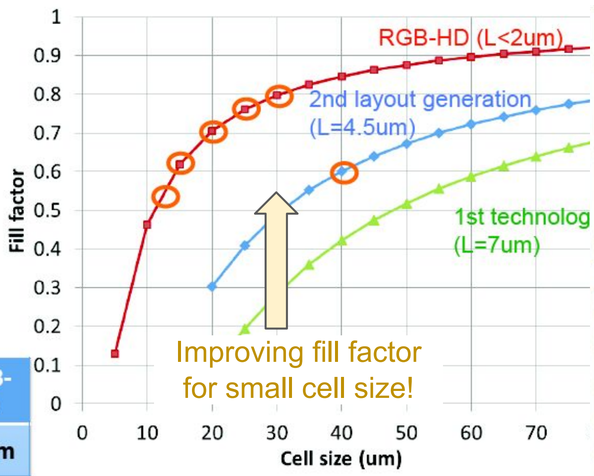
- Many technological advancements in the field of photodetectors
- Compact and robust SiPMs with **small cell size and fast recharge time** (~4 ns) **extending the dynamic range and enhancing sensitivity** in a wide range of wavelengths

FONDAZIONE BRUNO KESSLER

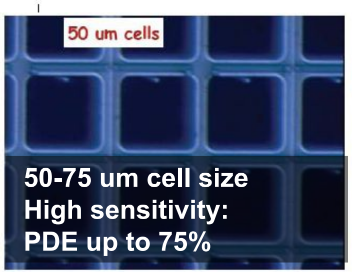
FBK

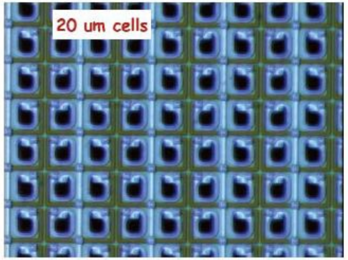
RGB-HD SiPM technology

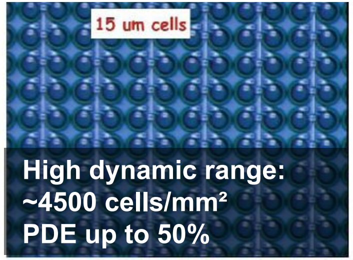


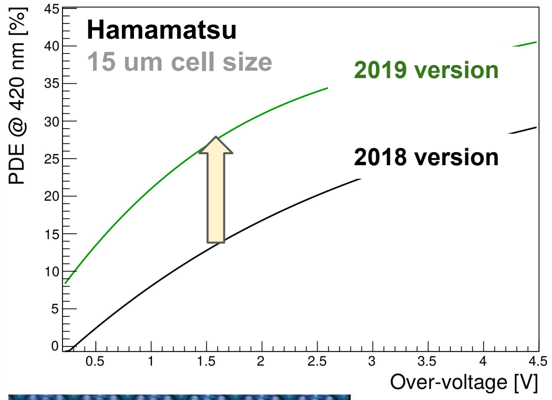


	Std. SiPM RBG	RGB-HD
CS	40 μm	15 μm
FF	60 %	62 %





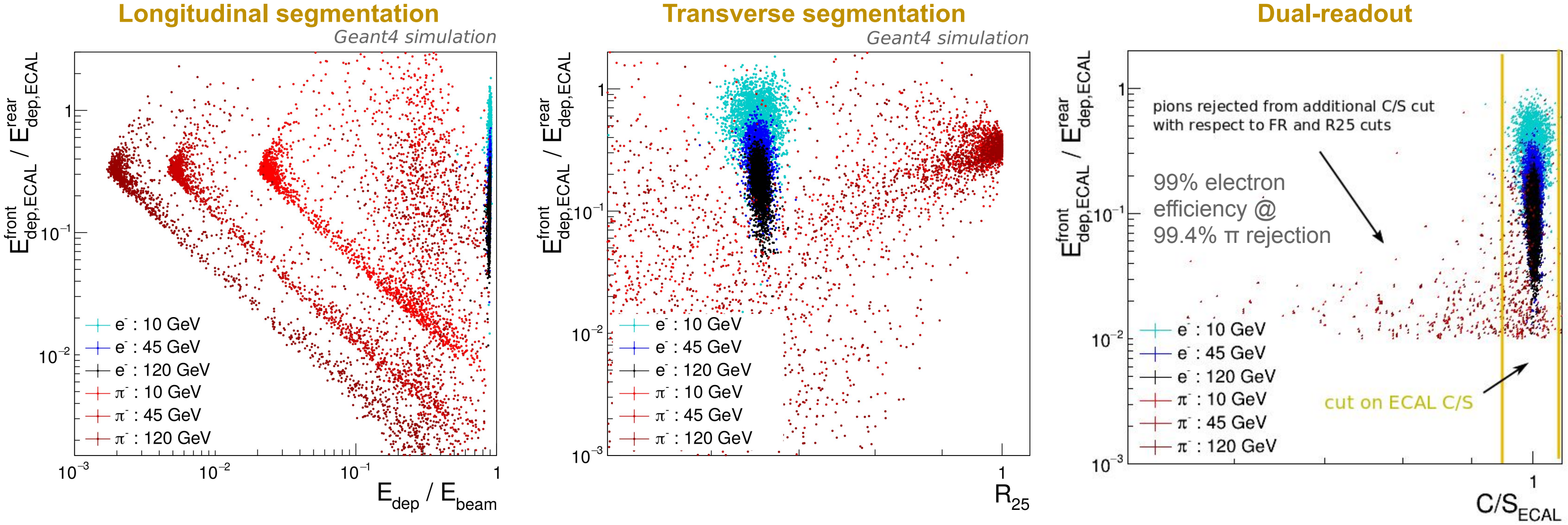




More on Geant4 simulation

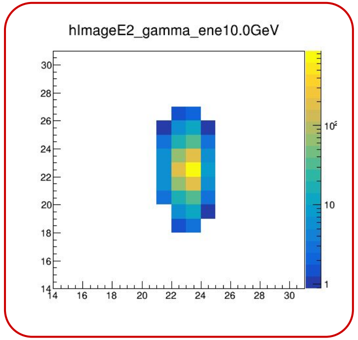
Particle ID with crystal segmentation

- Topology of longitudinal/transverse energy deposits in crystals provides a **clear $e^{+/-}/\pi^{+/-}$ discrimination**→better than 99% electron efficiency at 99% pion rejection (with simple cuts)
- **Large potential for improvement with the addition of dual-readout information** and use of more sophisticated pattern recognition algorithm

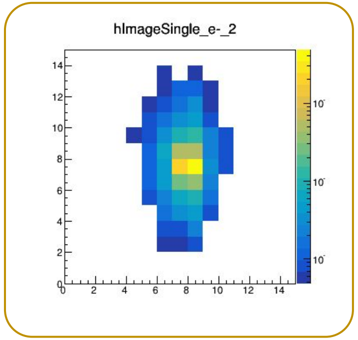


CNNs for **particle ID** with segmented crystal calorimeter

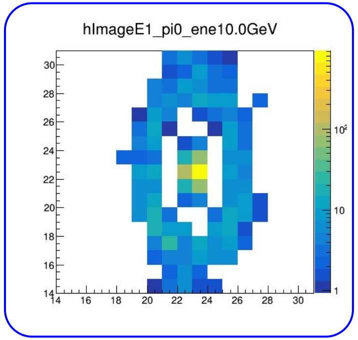
single ɣ event



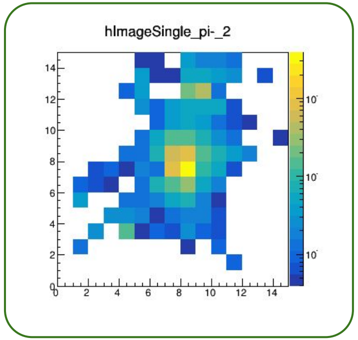
single e^- event



$\pi^0 \rightarrow$ ɣɣ events



single π^- event



- Use Convolutional Neural Networks to exploit the **crystal transverse + longitudinal segmentation** and the **high sampling fraction** (=1 in a homogenous calorimeter) for classification of EM clusters

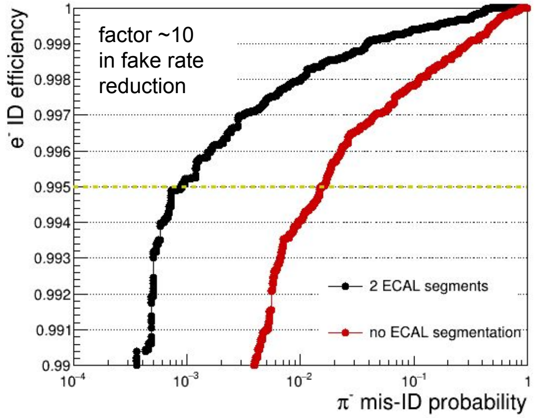
- Using the crystal EM section only, a good classification of EM clusters can be achieved:
  - $\pi^\pm$ / $e^\pm$
    - $e^\pm$ ID with ~99.9% efficiency at 0.4% $\pi^\pm$ mis-ID probability
  - π^0 / ɣ
    - Distinguish photons from π^0 with an efficiency higher than 95% at mis-ID probability smaller than 5%
  - $K^{0,L}$ / ɣ
    - Distinguish EM and HAD neutral clusters in crystal section (i.e. clusters with no charge track pointing to it) as an early step in particle flow algorithm

Crystal longitudinal **segmentation matters**

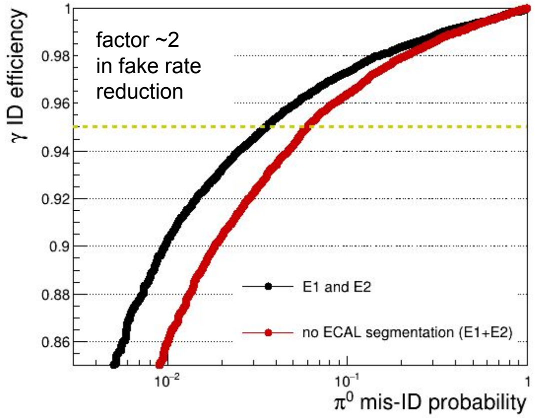
- Tangible improvements in particle ID from the longitudinal ECAL segmentation, i.e. **two crystal segments** (front and rear) instead of a single crystal cell

Single particle gun events with uniform energy distribution in the range 1-100 GeV, 100k events for each type of particle

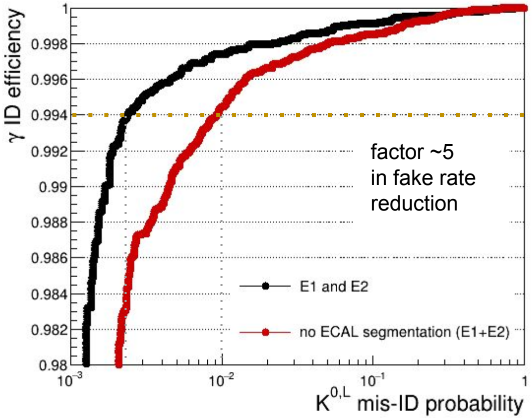
$\pi^{\pm} / e^{\pm}$



π^0 / γ

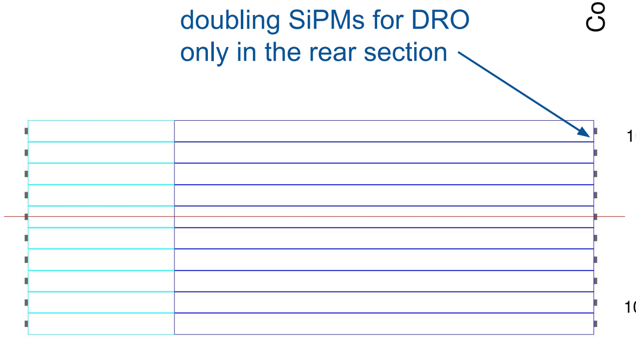


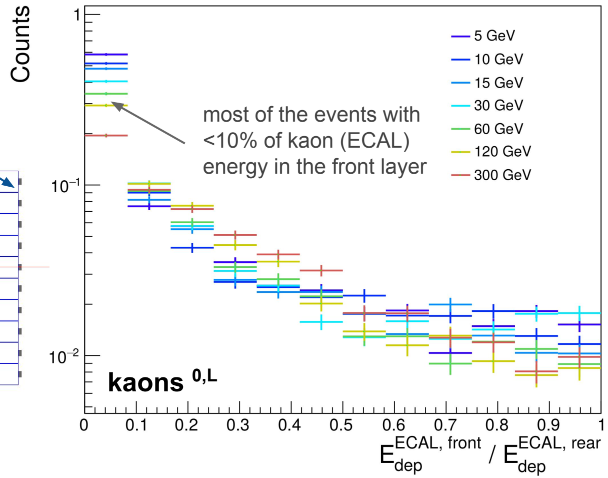
K^{0L} / γ

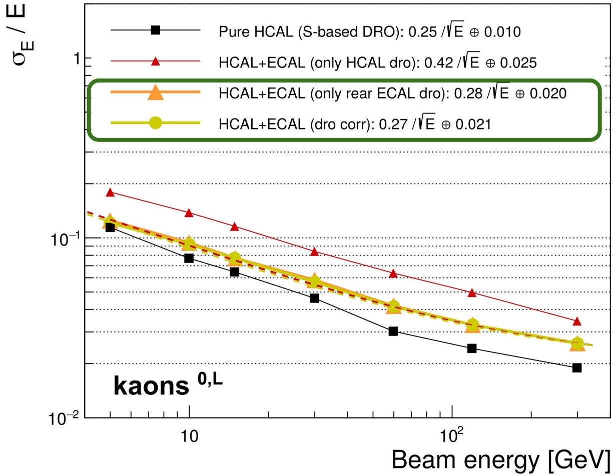


DRO in the **rear** SCEPCal segment **only**

- Majority of the energy deposit from hadron is in the rear ECAL section
- **Dual readout can be implemented in the rear section only**
  - No degradation in performance wrt a full (front+rear) DRO ECAL
  - +50% in channel count wrt to non-DRO ECAL can be mitigated by decreasing granularity in the rear compartment where shower radius is larger

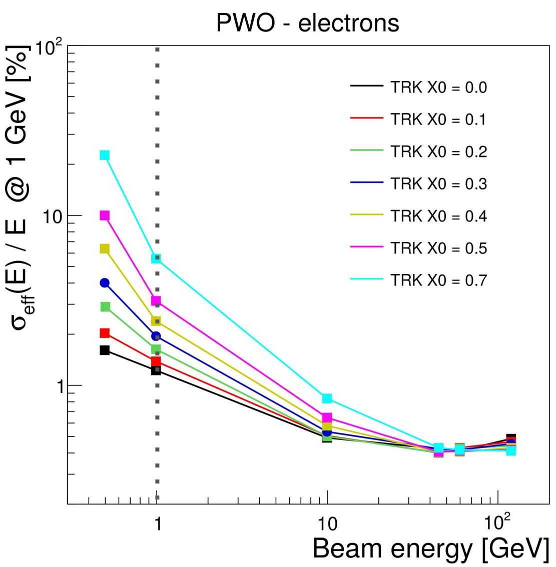


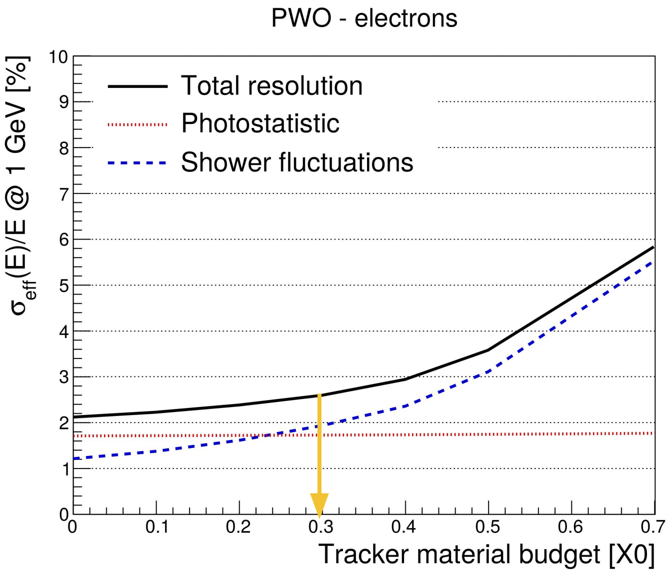




Impact of tracker and dead **material budget**

- Tracker material budget <0.3X_0 for <2% impact on stoch. term
  - Well within the target of the CEPC and IDEA reference tracker designs
- Dead material for services <0.3X_0 for impact on stoch. term < 2%
  - Compatible with estimated material budget from cooling (5 mm Al plate) and readout electronics





Photon mixing - confusion term for C and S

- In some cases, the two measured S and C signals are actually a linear combination of the true ones:

$$\begin{cases} S_{meas} = S_{true} + k_S \cdot C_{true} \\ C_{meas} = C_{true} + k_C \cdot S_{true} \end{cases}$$

$$\begin{cases} S_{true} = \frac{S_{meas} - k_S C_{meas}}{1 - k_C k_S} \\ C_{true} = \frac{C_{meas} - k_C S_{meas}}{1 - k_C k_S} \end{cases}$$

$$\frac{C_{true}}{S_{true}} = \frac{C_{meas} - k_C S_{meas}}{S_{meas} - k_S C_{meas}}$$

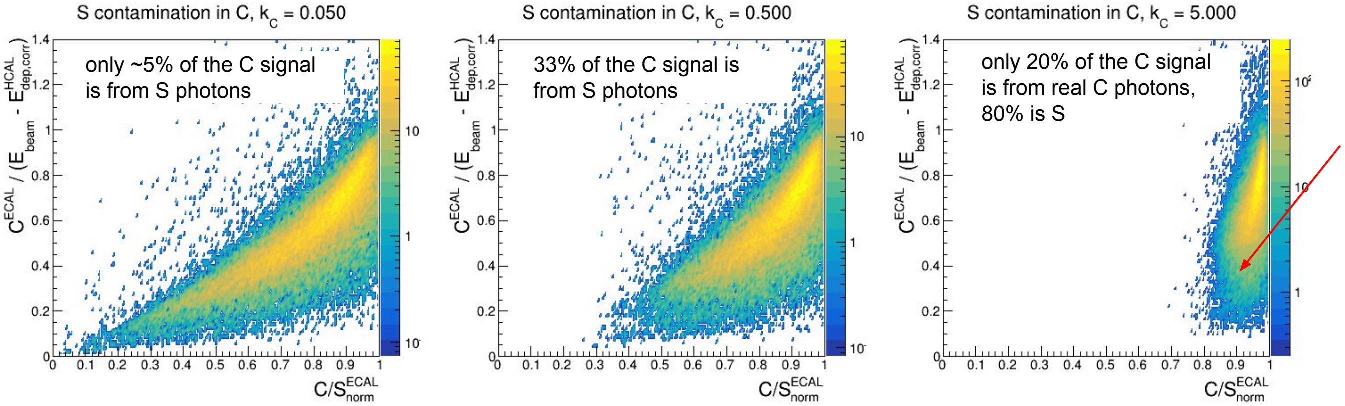
We can see 3 limit cases where the DRO correction will not work since C_{meas}/S_{meas} ~ 1:

- k_s>>1, the measured S signal is dominated by Cherenkov photons
- k_c>>1, the measured C signal is dominated by scintillation photons
- k_s ~ k_c ~ 1, the measured S signal is equal to the measured C signal

Comments on the impact of S-C mixing on DRO

- In addition to the previous scenarios where a good C/S contrast could not be achieved, with S-C mixing, the following occurs:
  - the k_S*C_{true} fraction (f(C)) inside S fluctuates as the C signal according to a Poissonian statistics
  - the k_C*S_{true} fraction (f(S)) inside C fluctuates as the S signal according to a Poissonian statistics
  - it C and S are both relatively large signals (small photo-statistic fluctuations) this effect is negligible

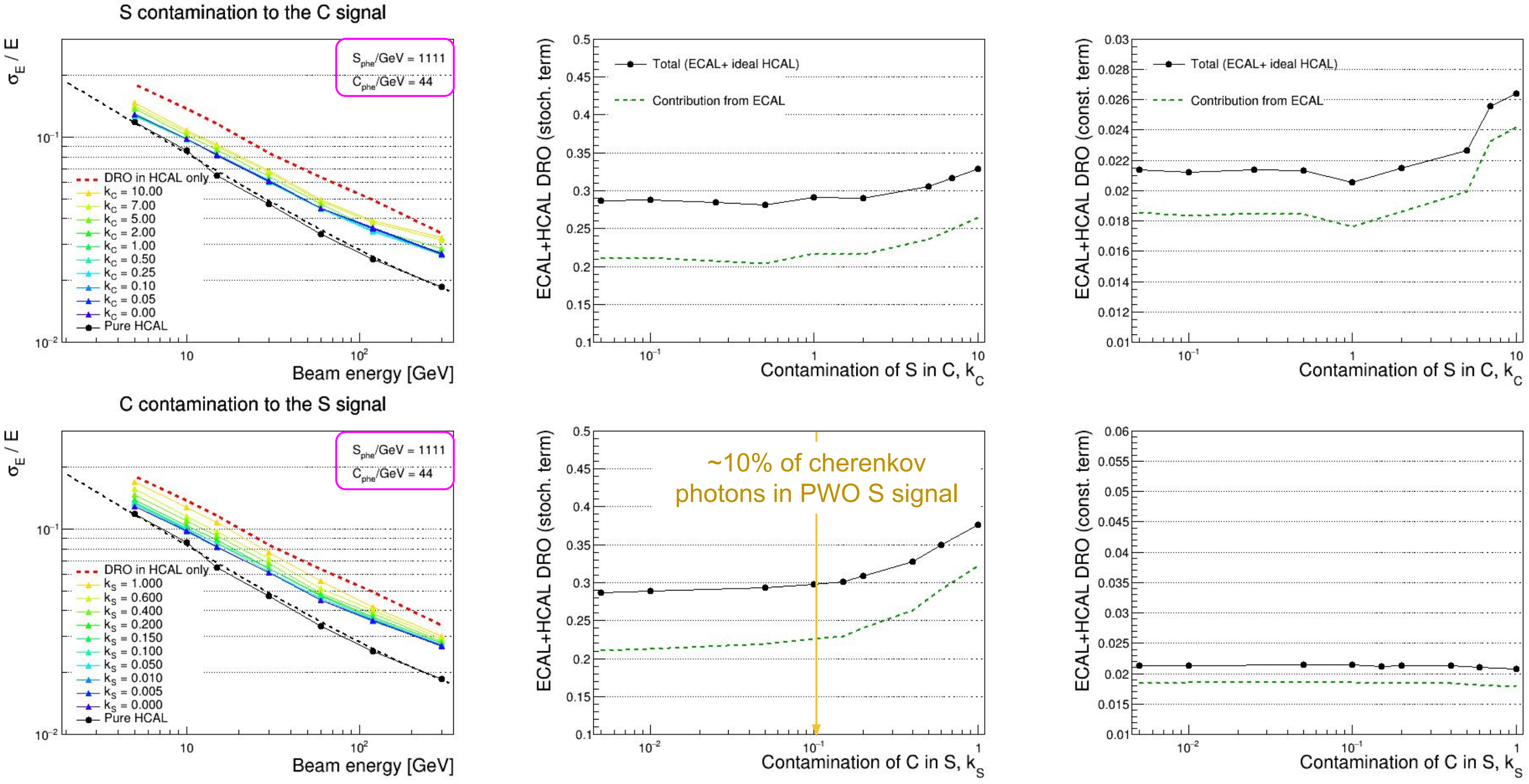
- k_S (k_C) is the C (S) contamination to S (C) , defined as a fraction of the S_{true} (C_{true}),
  - thus k_S = 0.1 means that an amount of C photons corresponding to 10% of the S_{true} average signal is added to the S_{meas} (equivalent to saying that the S signal contains a 10% contamination from C signal)
  - k_S = 1 means that an amount of C photons equal to the amount of the S_{true} average signal is added to the



DRO correction seems still possible in these conditions, the correlation is steeper but still present with simply a different slope

Impact of mixing term on energy resolution

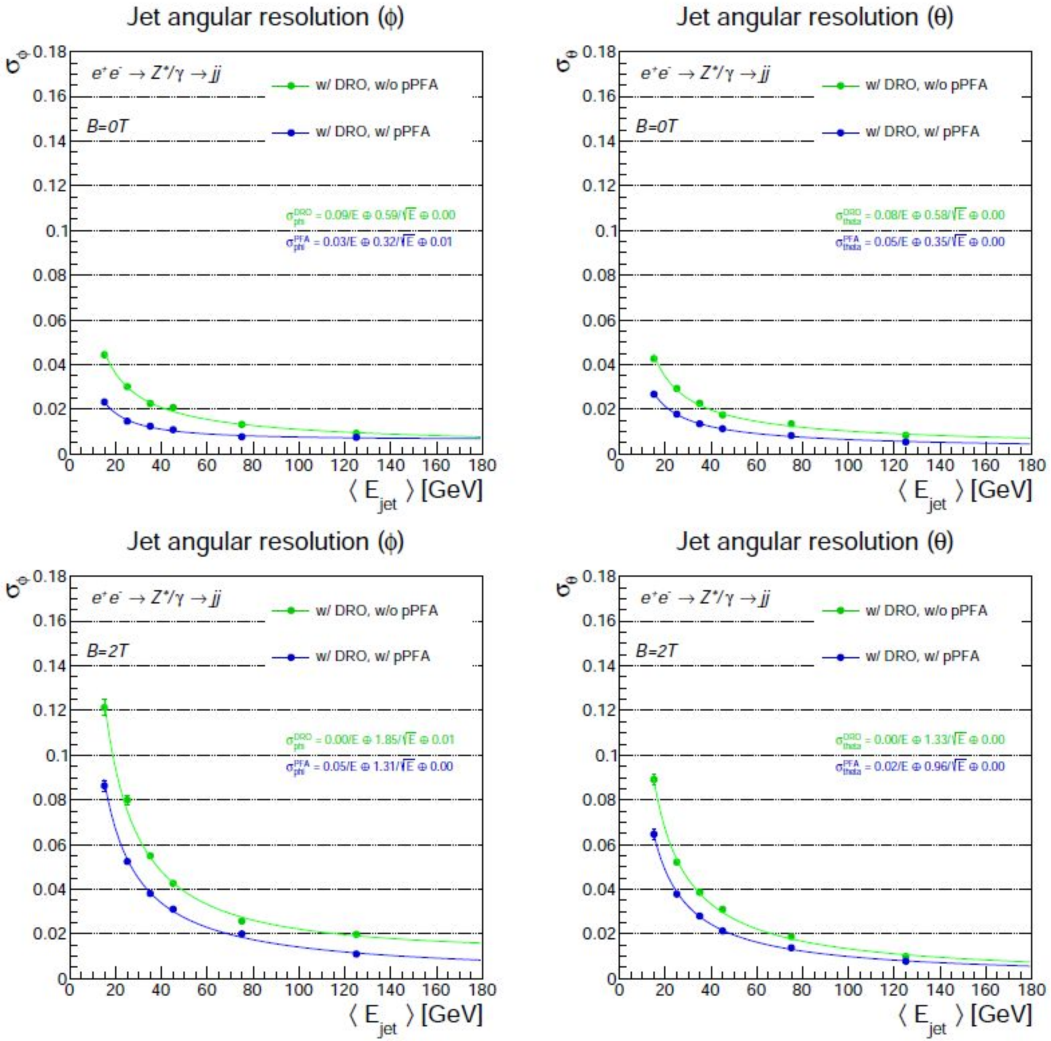
for certain (realistic) values of S and C photostatistics



Jet angular resolution

- Improvements in the jet angular resolution using the DR-PFA

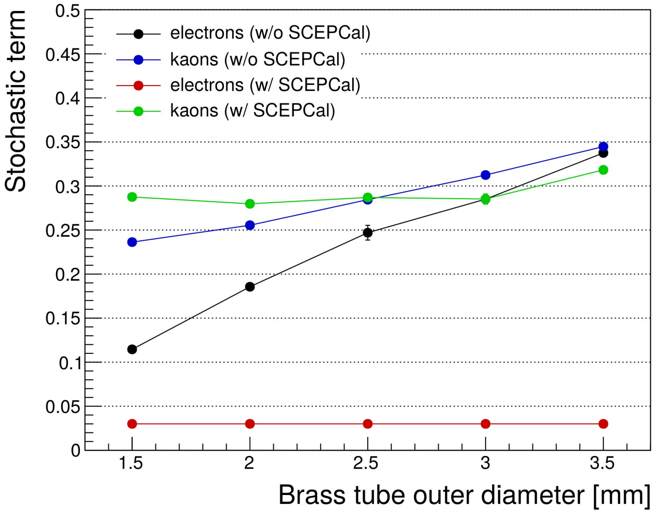
- Angular resolution at the level of ~0.01-0.02 mrad for >80 GeV jets

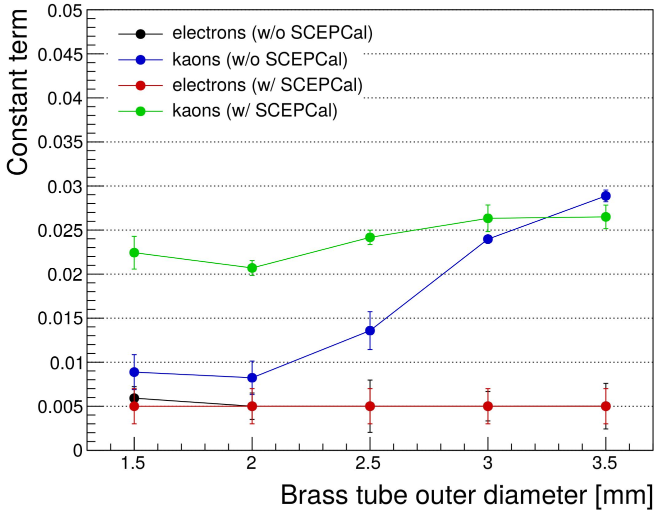


More on cost/performance optimization

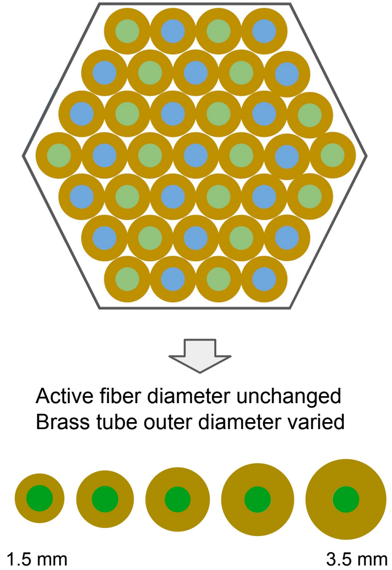
Example of calorimeter cost/performance optimization

- **Brass tube outer diameter** (OD) **can be increased to 3/3.5 mm with marginal impact on the hadron resolution**
- Relative channel reduction and cost decrease approximately with ~$1/OD^2$



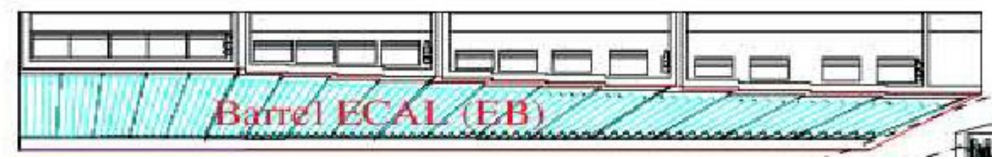


Brass capillaries
"Nominal" dimension
OD=2 mm, ID=1.1 mm

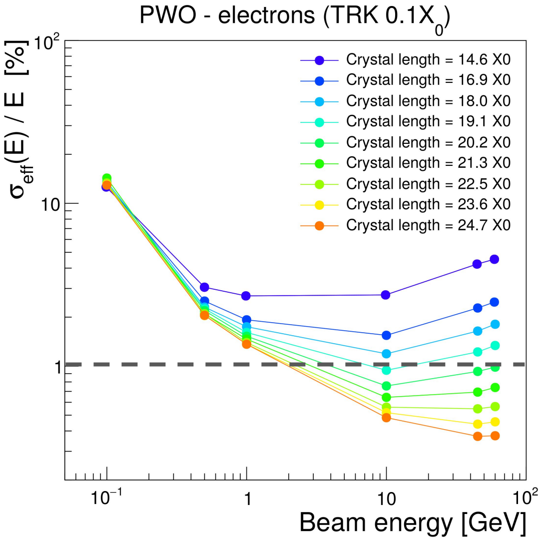


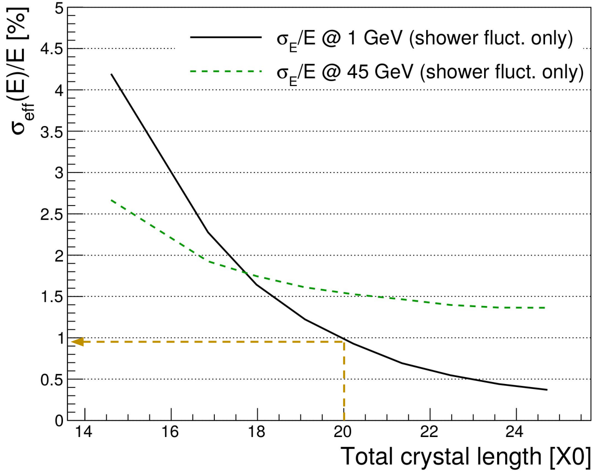
Optimization of crystal volume

- Crystal pointing geometry
  →reduce by ~20% crystal volume and channel count



- Optimizing crystal length vs energy resolution
  - with 20 X_0 contribution to constant term from shower leakage comparable to intercalibration precision: O(1%)
  - no substantial impact on stochastic component (negligible wrt photo-statistics term of ~4-5%)



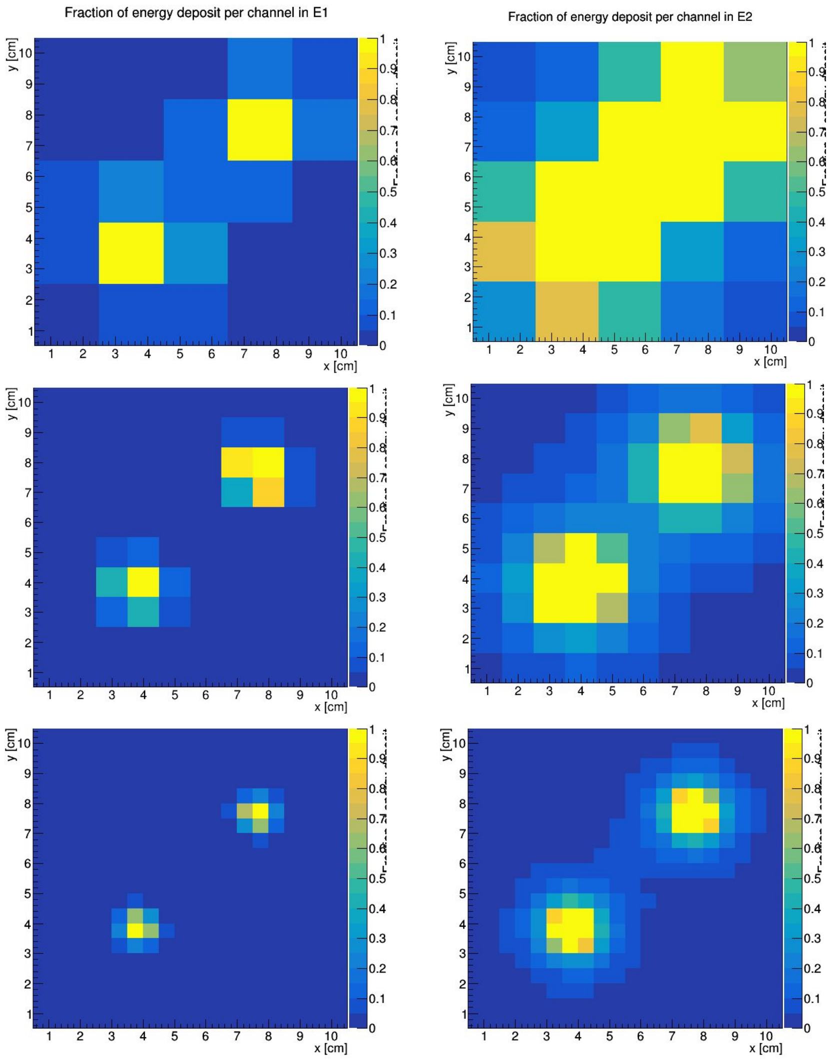


Transverse segmentation (visual impact)

cell size: 2x2 cm²

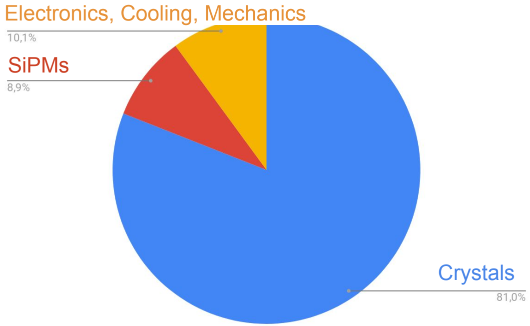
cell size: 1x1 cm²

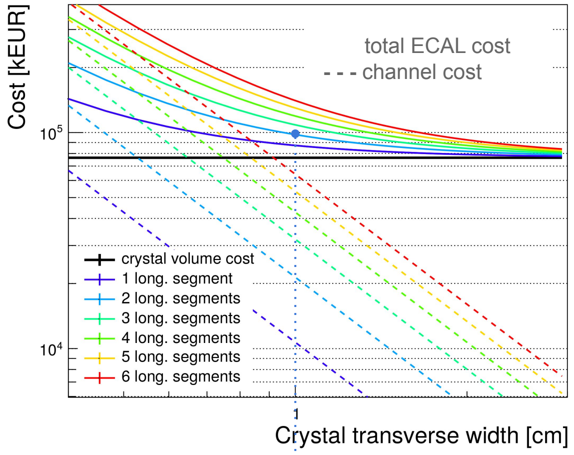
cell size: 0.5x0.5 cm²



Cost-power drivers and optimization

- **Channel count** in **SCEPCal** is limited to **~2.5M**
  - 625k channels/layer (2 “timing layers” + “ECAL layers”)
- Cost drivers in **ECAL** layers (tot ~95M€):
  - **~81% crystals**, **9**% SiPMs, **10**% (electronics+cooling+mechanics)
  - **~19% of cost scales with channel count**
- Power budget driven by electronics: ~74 kW
  - 18.5 kW/layer
- Room for fine tuning of the segmentation and of the detector performance/cost optimization (see backup)





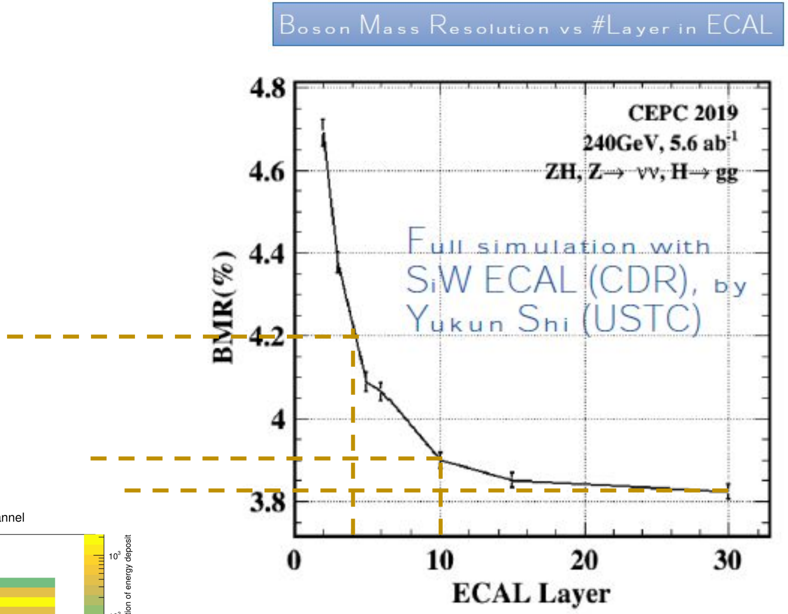
Reference design:
1 cm², 2 segments
cost ~ 95M€

Longitudinal segmentation in SCEPCal

Y.Liu, Detector concept with crystal calorimeter @IAS Conference 2021

- The benefit for PFA from longitudinal segmentation saturates quickly

- **A non-uniform longitudinal segmentation** (finer at the beginning of the EM shower where R_M is smaller) may better exploit the number of readout layers for PFA



Sampling fraction of the SiW ECAL is fixed, but longitudinal number of layers is varied