Integration of a high EM resolution crystal calorimeter within the IDEA DRO calorimeter

3rd FCC-France / Higgs&ElectroWeak Factory Workshop, Annecy
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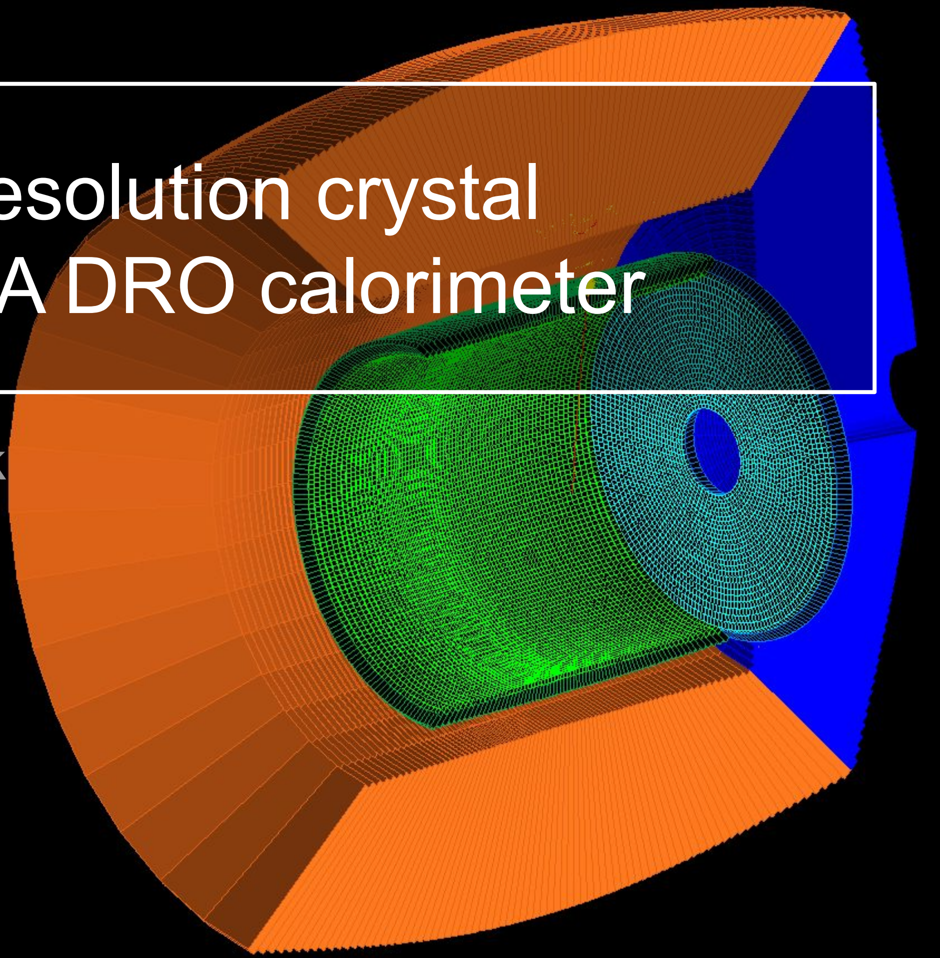
A growing effort within the
IDEA DRO Calorimeter group



“**Maximum information** crystal calorimetry” for a **hybrid dual-readout calorimeter system** at e^+e^- colliders

Design drivers:

Excellent energy resolution to photons and neutral hadrons
(~3%/√E and ~30%/√E respectively)

Separate readout of scintillation and Cherenkov light
(for integration with a dual-readout hadron calorimeter)

Longitudinal and transverse segmentation
(to provide more handles for particle flow algorithms and achieve 30%/√E energy resolution for jets)

Precise time tagging for both MIPs and EM showers
(time resolution better than 30 ps)

More details in:
2020 *JINST* **15** P11005

Performance highlights at an e^+e^- collider

Highlights **summary**:

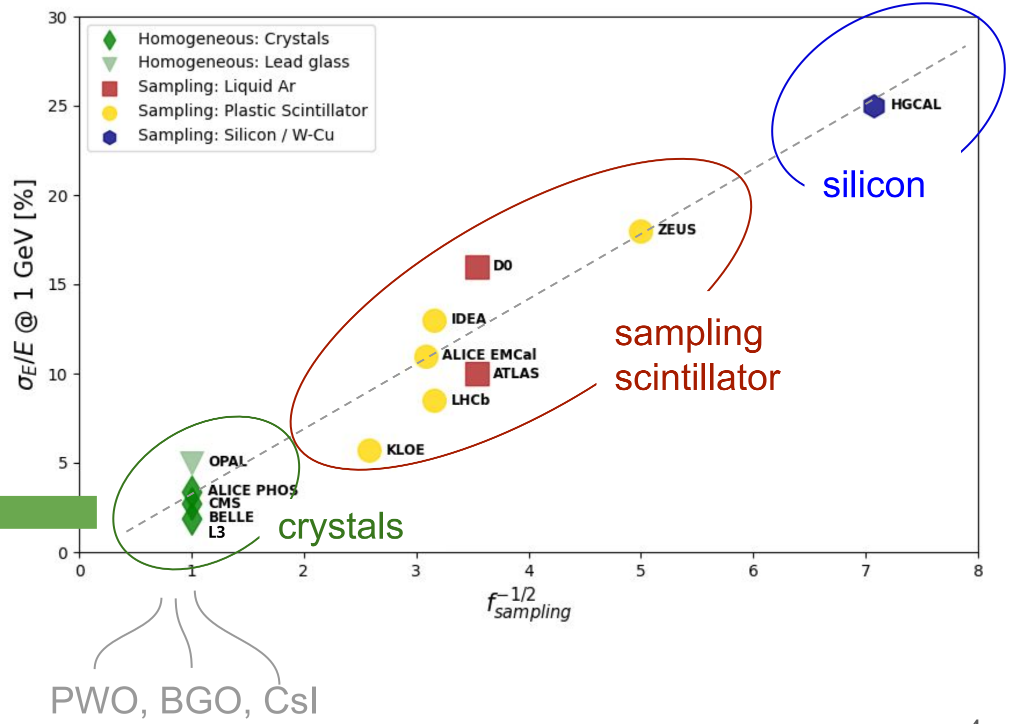
- Recovery of **bremsstrahlung photons** to improve the resolution of the **recoil mass signal in Higgstralhung events from Z→ee decays** to about 80% of that from Z→ μμ decays
- **Clustering of π^0 photons** ahead of jet clustering algorithms
  to reduce angular spread of jet particles in 4-6-jet event topologies
- Use of **dual readout in particle flow algorithm**
  to achieve ~3% jet energy resolution at the Z/W boson masses
- Extend the coverage for physics studies to include **final states with low energy photons** (e.g. B-physics, see today's talk from E.Perez)

Crystals in **calorimetry**

- Homogenous crystal calorimeters have a long **history** of **pushing the frontier of high EM resolution**
  - The entire EM shower is sampled
  - Large light signals are produced

$$\frac{\sigma_E}{E} \sim \frac{3\%}{\sqrt{E}}$$

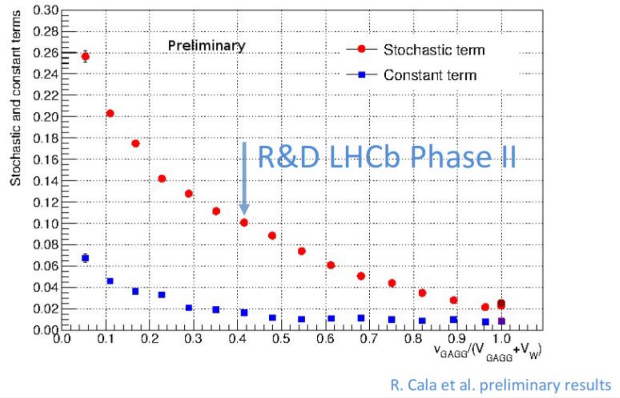
A sample of existing and future calorimeters

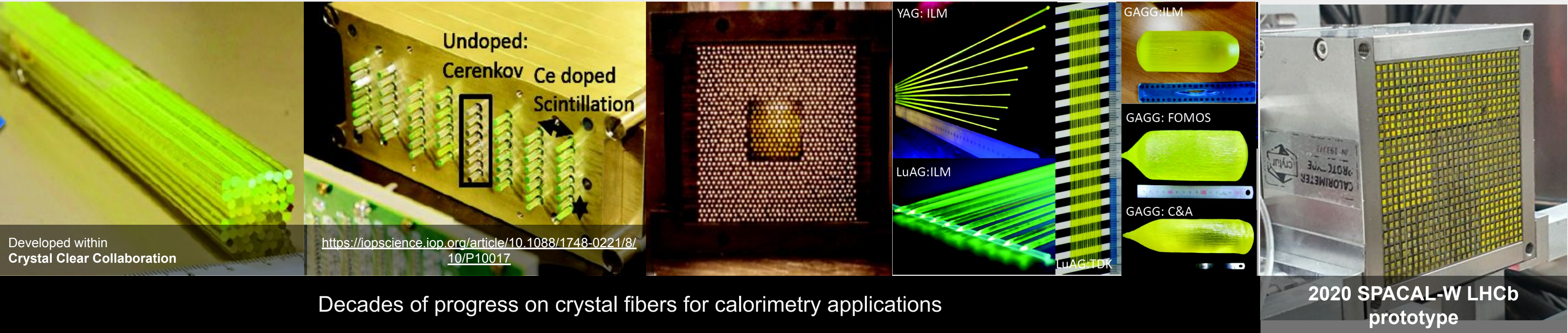


Possible approach for DRO crystal EM calorimetry?

- Exploit a mixture of scintillation and cherenkov **crystal fibers** (e.g. LuAG, YAG, GAGG)
- **Tune the sampling fraction to achieve the desired energy resolution**
- See ongoing R&D for LHCb Upgrade SPACAL
  L.Martinazzoli, Prototyping and Testbeam Results of a Tungsten-Crystal Spaghetti Calorimeter, IEEE 2021
- See also progress on the manufacturing side in C.Dujardin's talk on Thursday

E.Auffray @ FCC July WS





Developed within **Crystal Clear Collaboration**

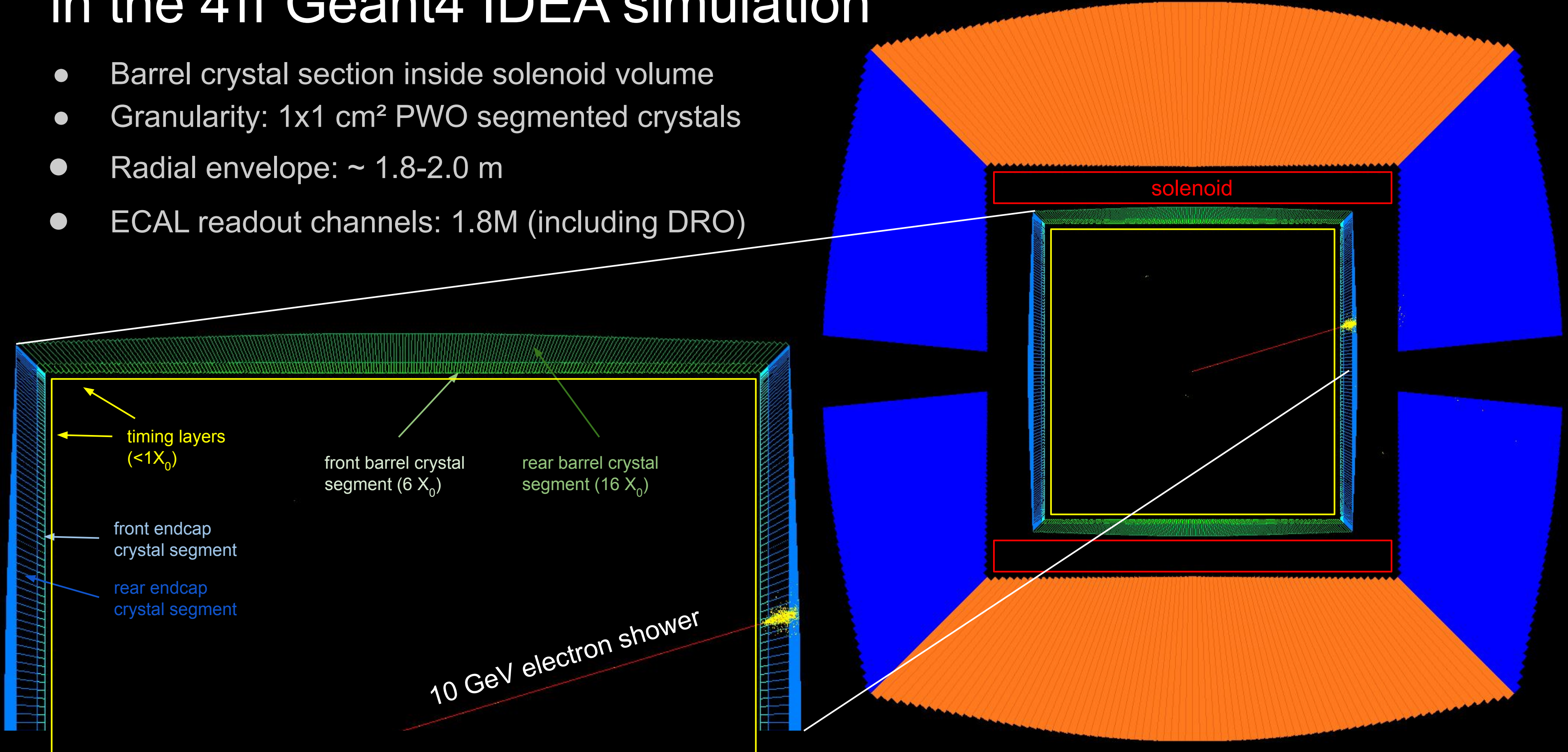
https://iopscience.iop.org/article/10.1088/1748-0221/8/10/P10017

Decades of progress on crystal fibers for calorimetry applications

2020 SPACAL-W LHCb prototype

Integration of a crystal calorimeter option in the 4π Geant4 IDEA simulation

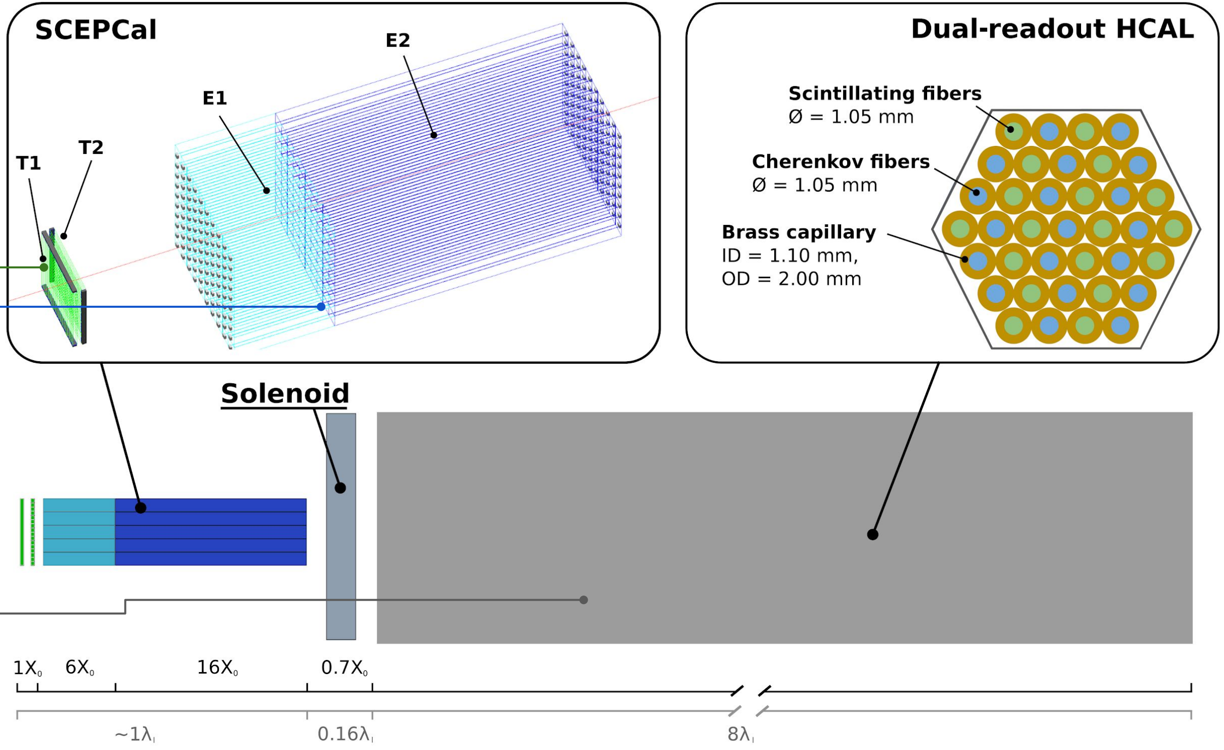
- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: 1.8M (including DRO)



Layout overview

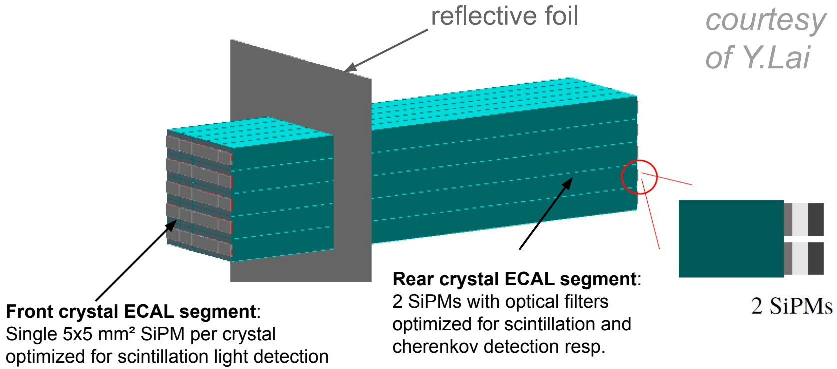
- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **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



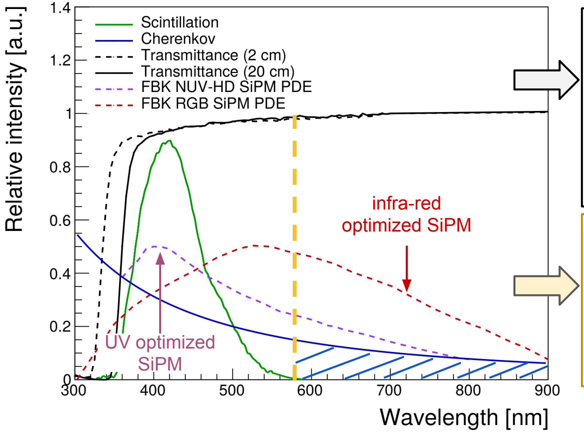
Dual-readout in PWO and BGO/BSO crystals

- **Dual readout needed only on rear segment**
- **Strategy can be customized for a given crystal choice** (e.g. 2 SiPMs + optical filters on the rear crystal segment)
- Sensitivity to cherenkov photons in both the UV and infrared region with Silicon Photomultipliers



courtesy of Y.Lai

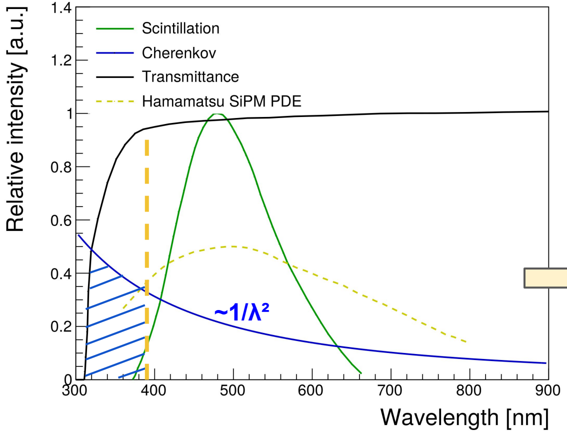
PWO



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



See R.Calà et al, *Characterization of BGSO for crystal calorimetry of future colliders* @ IEEE2021

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

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

1. Apply the DRO correction on the energy deposits in the crystal and fiber segments first
2. Sum up the corrected energy from both segments

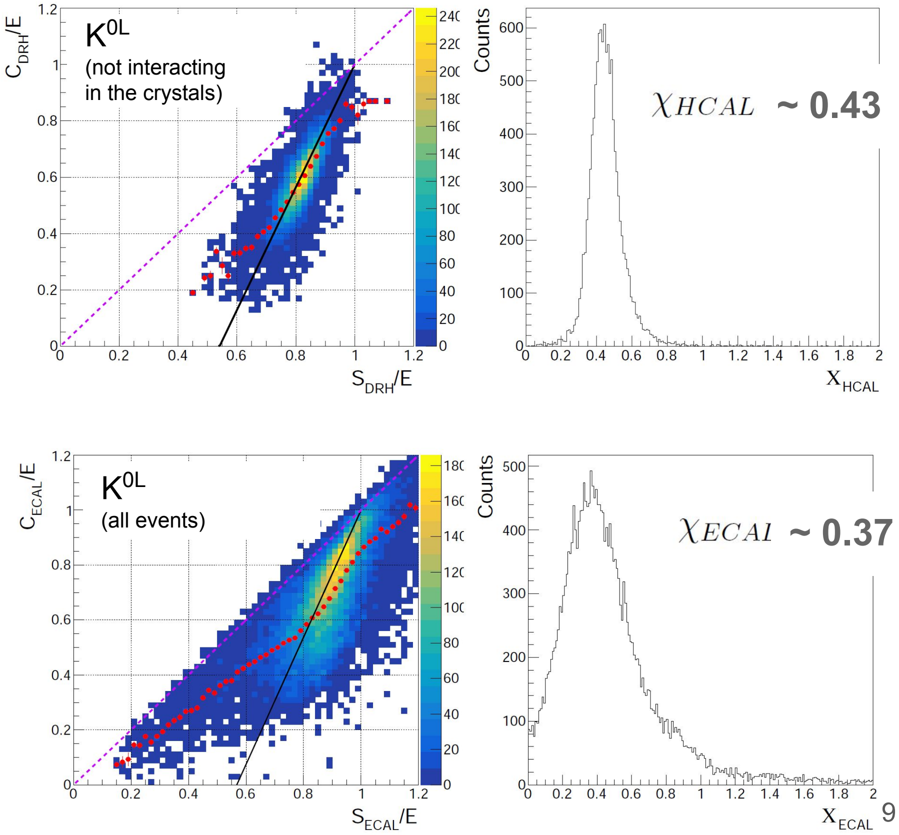
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$

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

$$E_{total} = E_{HCAL} + E_{ECAL}$$

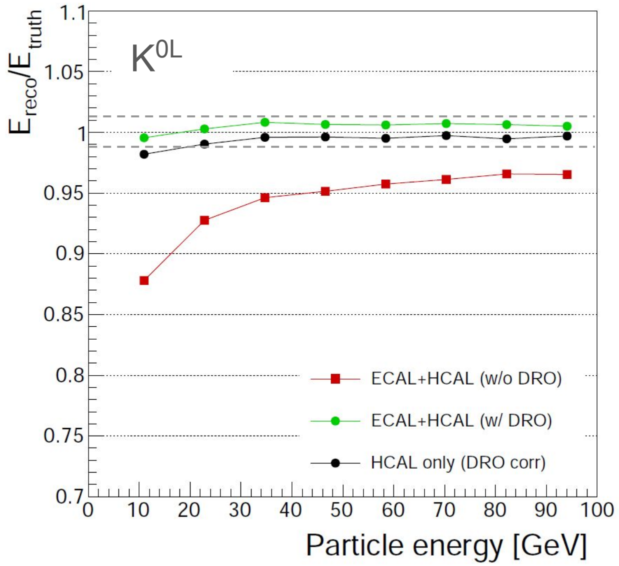
$$\chi_{HCAL} = \frac{1 - (h/e)_s^{HCAL}}{1 - (h/e)_c^{HCAL}}$$

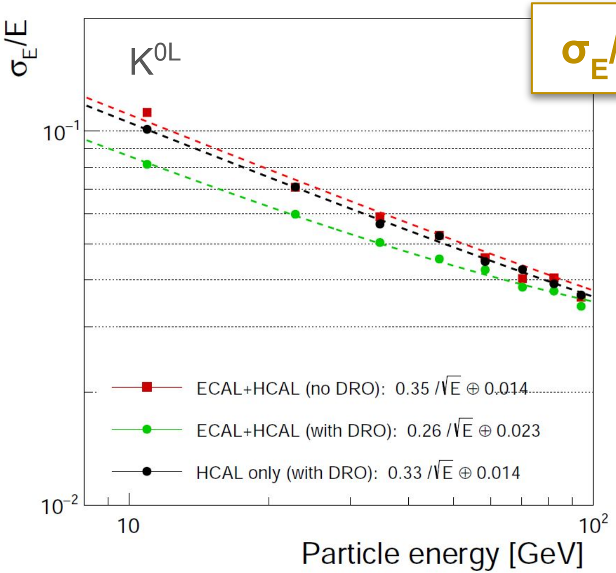
$$\chi_{ECAL} = \frac{1 - (h/e)_s^{ECAL}}{1 - (h/e)_c^{ECAL}}$$



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

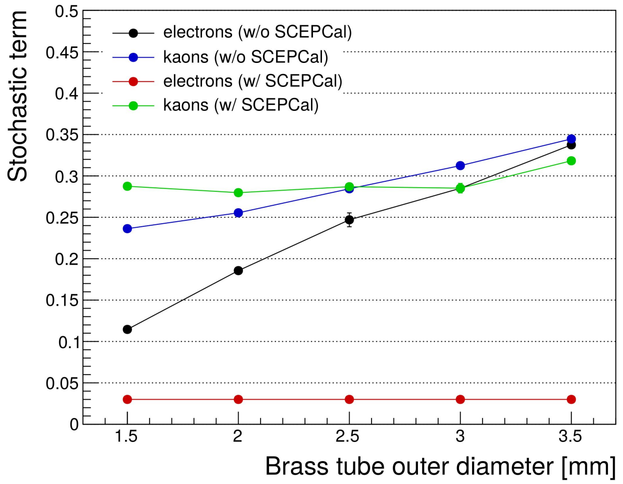


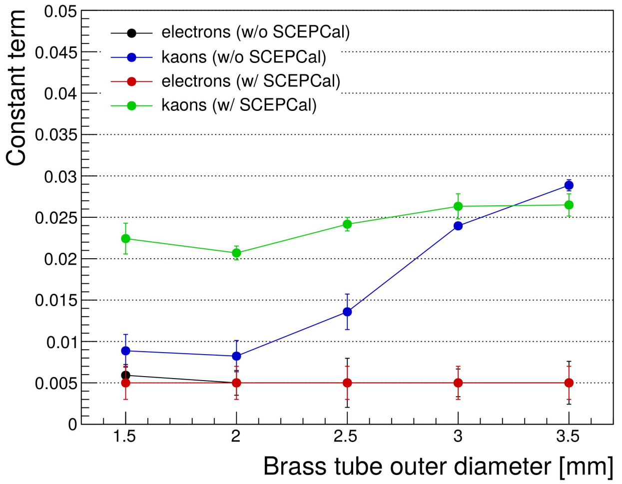


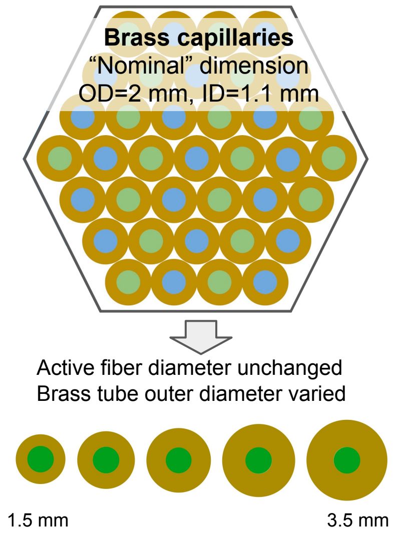
σ_E/E_{HAD} ~ 27%/√E ⊕ 2%

Calorimeter **cost/performance optimization**

- **Integration of crystals section for EM particles with IDEA calorimeter offers room for overall detector cost optimization**
  - Reduce sampling fraction and readout granularity in the hadronic segment (fibers-absorber sampling calorimeter) with limited impact on hadron resolution [e.g. increase of the brass tube outer diameter (OD) to 3-3.5 mm]
  - Relative channel reduction and cost decrease approximately with $\sim 1/OD^2$







Jet reconstruction with a dual-readout calorimeter

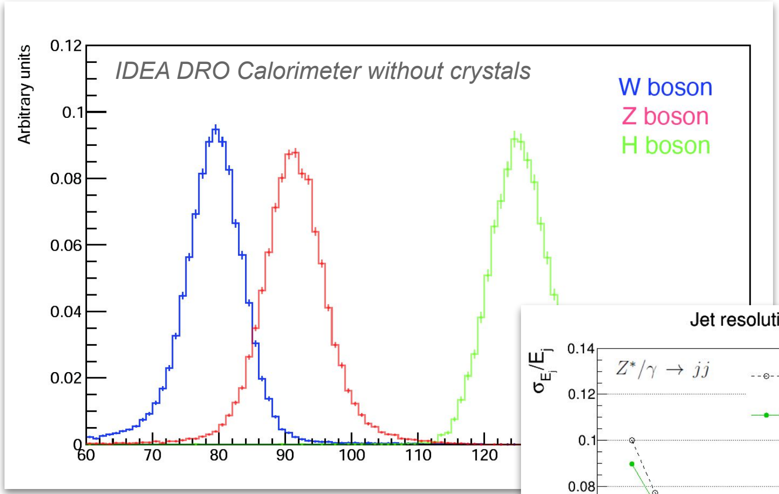
$e^+e^- \to HZ \to \tilde{\chi}^0\tilde{\chi}^0 jj$ → Decays to u,d,s,c, c semileptonic decays excluded

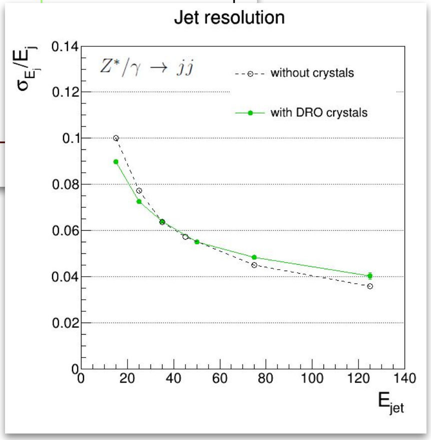
$e^+e^- \to WW \to \nu_\mu \mu jj$ → Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal, c semileptonic decays excluded

$e^+e^- \to HZ \to bb\nu\nu$ → b semi-leptonic decays excluded

‘Calorimeter only’ approach:

- Jet clustering (*FASTJET* Durham k_T) using all calorimeter hits:
  - 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

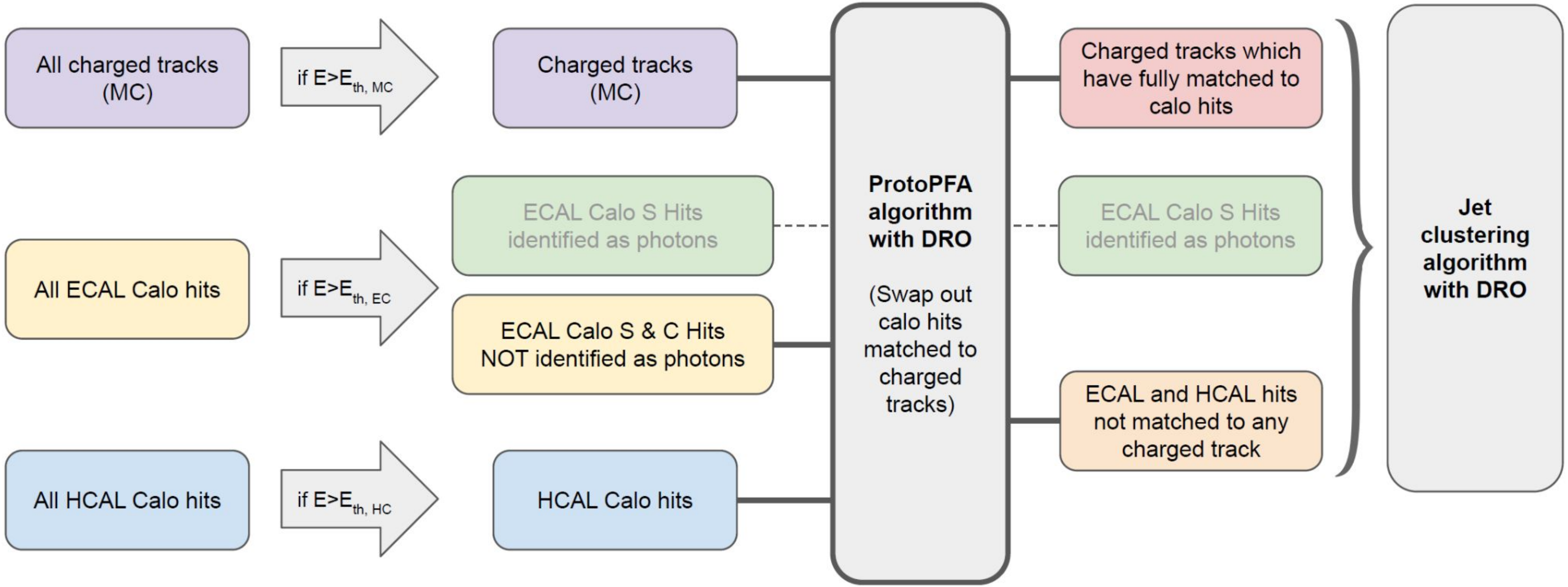




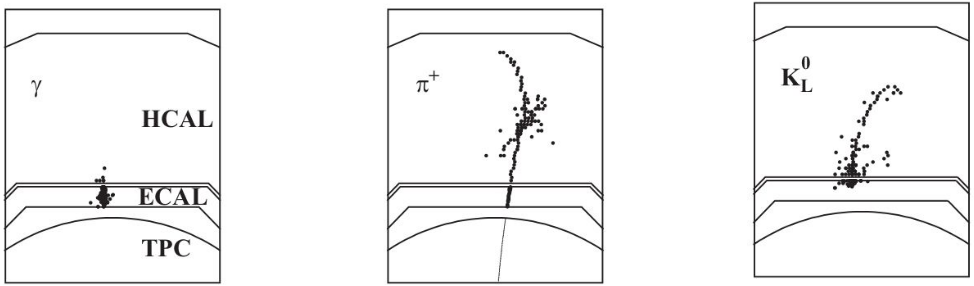
Comparable “calorimeter only” jet resolution of ~5.5% at 50 GeV achieved with the baseline IDEA calorimeter and with the addition of a dual-readout segmented crystals section

Dual-Readout Particle Flow Algorithm for jet reconstruction

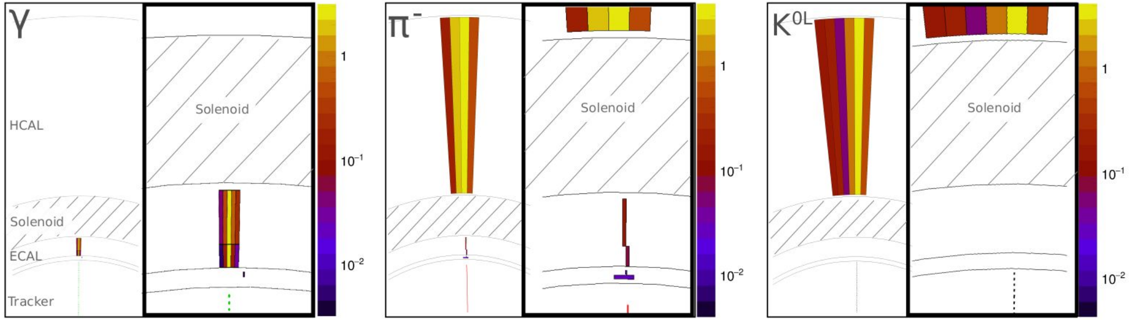
- Maximally exploit the information from the **crystal ECAL** for classification of EM clusters and use it **as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter hits
- Exploit the **high resolution and linear response** of the hybrid **dual-readout** calorimeter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



Single particle identification through ‘hits-topology’



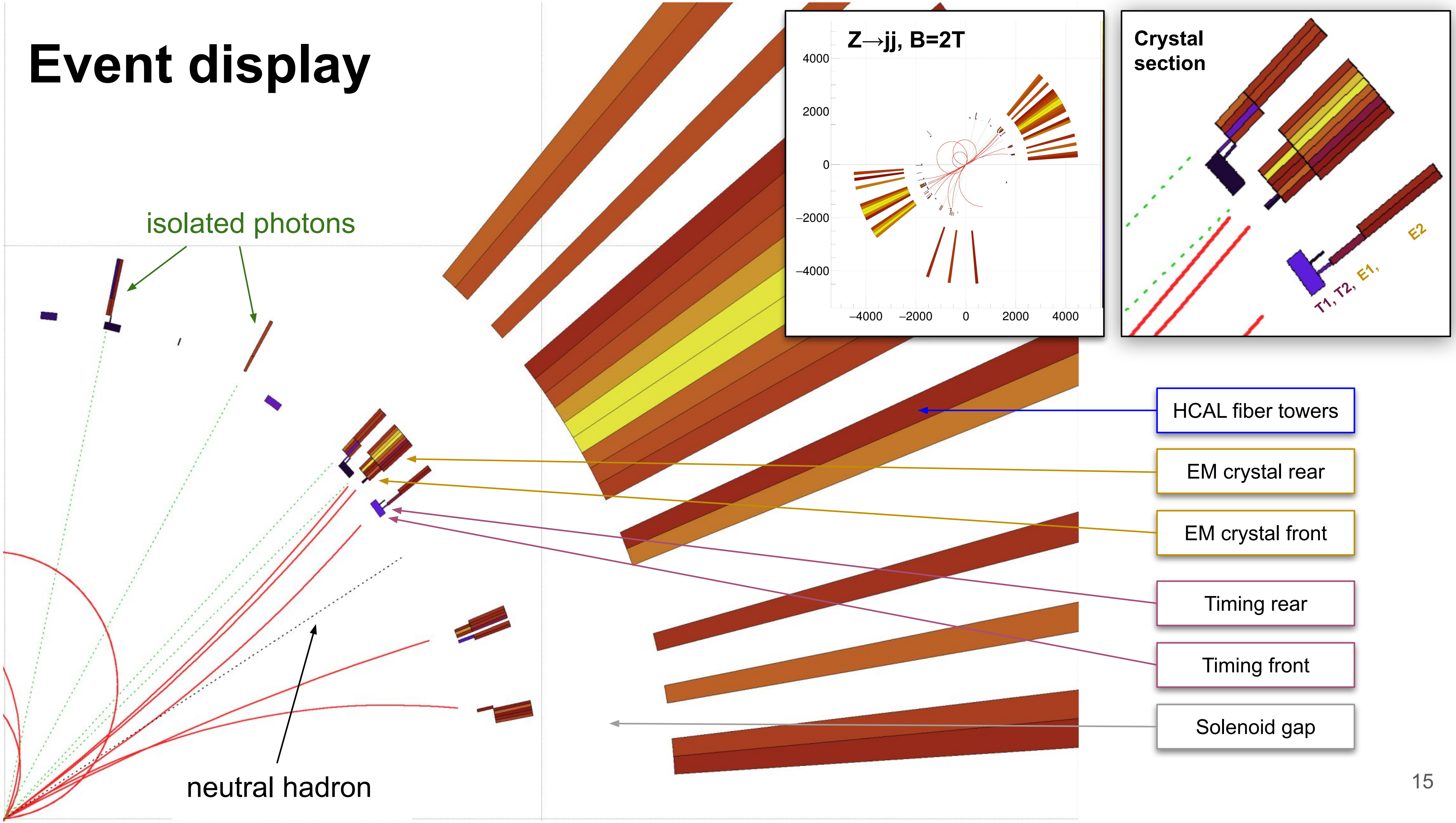
Typical PFA with Si-W high granularity calorimeter



DR-pPFA with high resolution DRO calorimeter

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

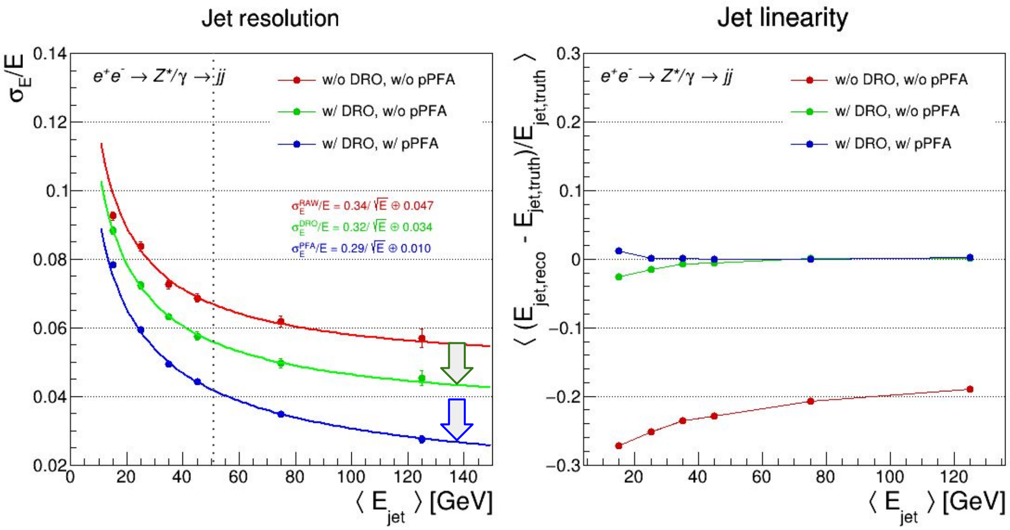
Event display



Jet resolution: with and without DR-pPFA

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

Summary

- A cost-effective integration of a segmented dual-readout crystal calorimeter within the IDEA fiber calorimeter results in **a highly performant hybrid calorimeter system suitable for future e^+e^- colliders**

- **Performance studies show promising results**:
  - **Excellent EM, HAD and jet resolution** by combining the DRO information from different calorimeter segments (homogeneous crystals & sampling fibers)
  - **Particle identification capabilities enhanced** by the longitudinal segmentation in the crystal section and by the dual-readout information
  - Combination of the DRO information with a simplified **particle flow algorithm shows additional improvement to the jet energy resolution achieving 3-4% for E_{jet} > 50 GeV**

- **Outlook and ongoing work**
  - Further optimization of the DR-pPFA algorithm and of the detector design accordingly
  - Planning for prototypes for validation of detector simulation inputs

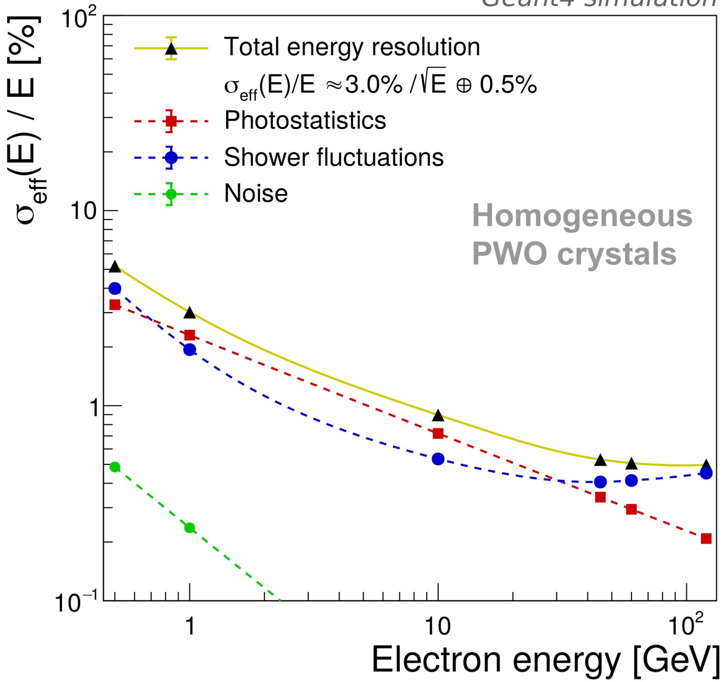
Additional material

Energy resolution 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

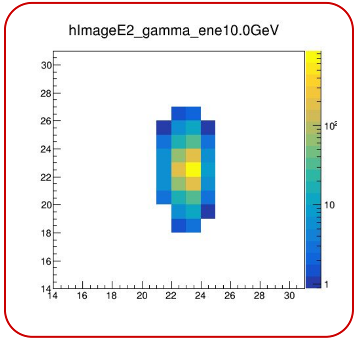
$\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$

Geant4 simulation

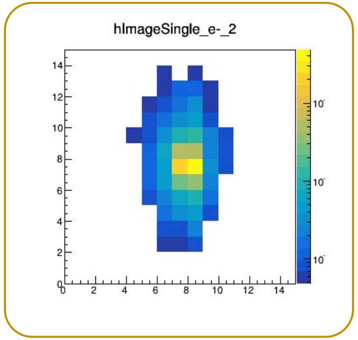


CNNs for **particle ID** with segmented crystal calorimeter

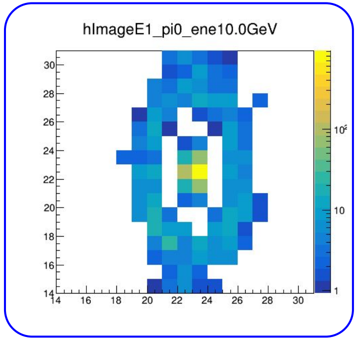
single γ event



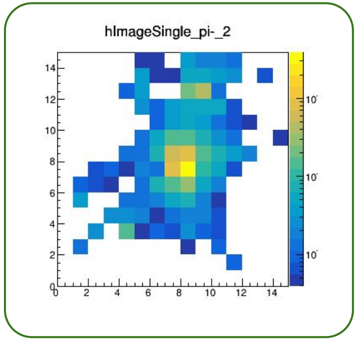
single e^- event



$\pi^0 \rightarrow \gamma\gamma$ 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

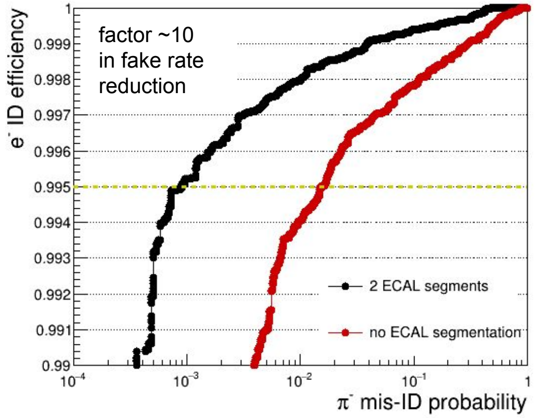
- Using the crystal EM section only, a good classification of EM clusters can be achieved:
  - $\pi^\pm$ / $e^\pm$
    - $e^\pm$ ID with ~99.9% efficiency at 0.4% $\pi^\pm$ mis-ID probability
  - π^0 / γ
    - Distinguish photons from π^0 with an efficiency higher than 95% at mis-ID probability smaller than 5%
  - $K^{0,L}$ / γ
    - 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**

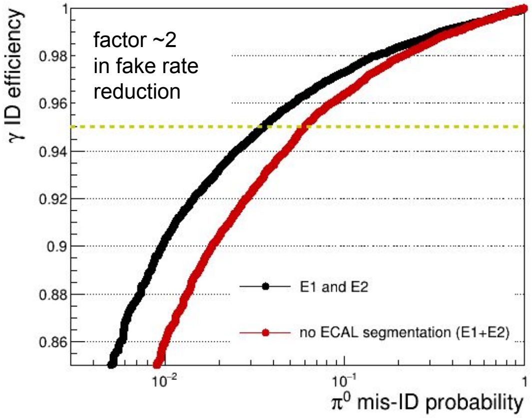
- Tangible improvements in particle ID from the longitudinal ECAL segmentation, i.e. **two crystal segments** (front and rear) instead of a single crystal cell

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

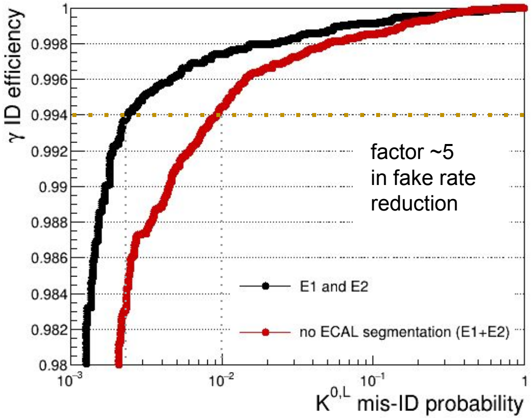
$\pi^{\pm} / e^{\pm}$



π^0 / γ

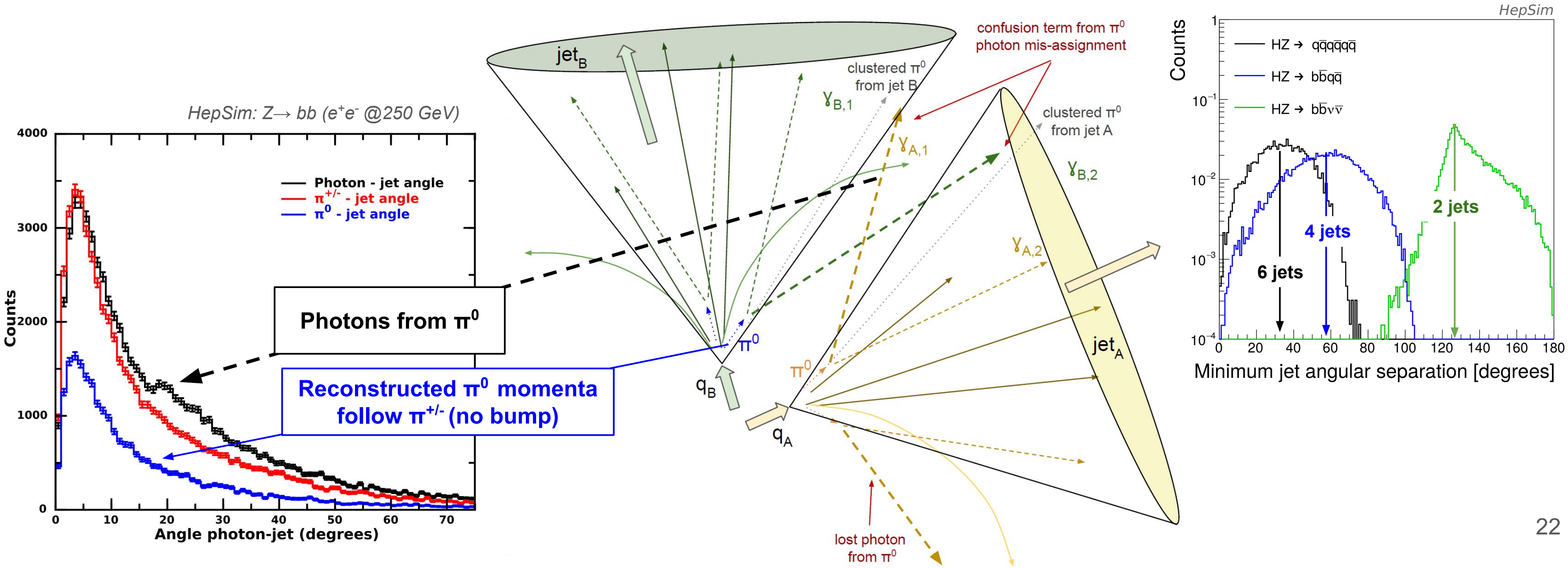


K^{0L} / γ



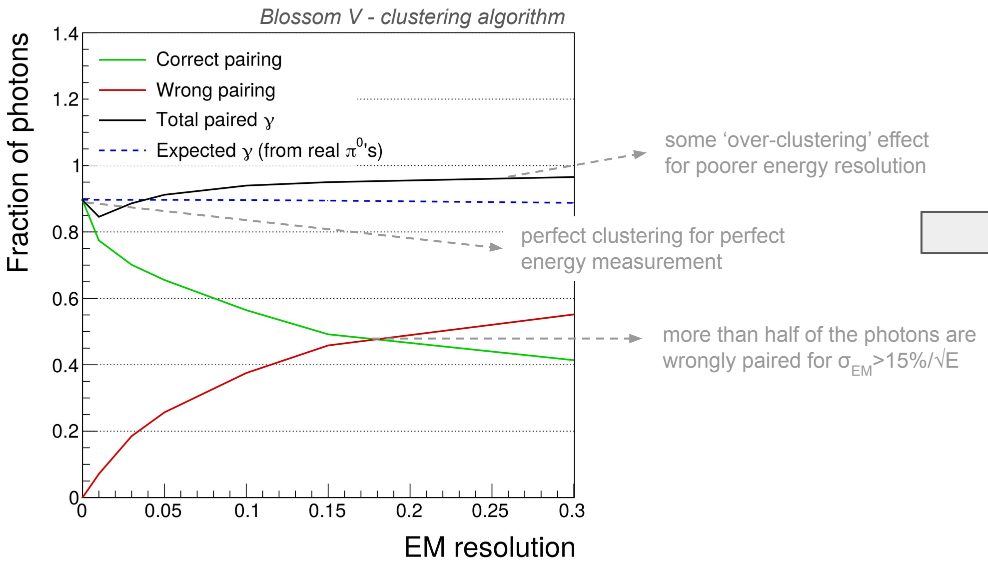
π^0 photon splitting across jets

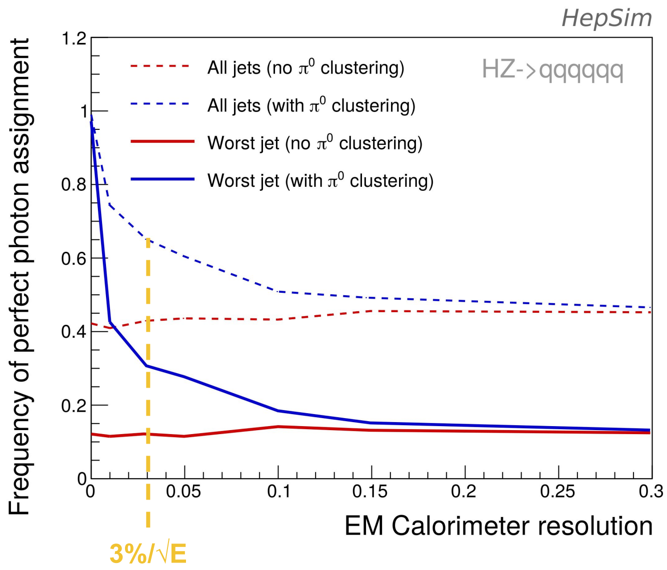
- **Many photons from π^0 decay** are emitted **at a ~20-35° angle** wrt to the jet momentum and can get scrambled across neighboring jets
- Effect is **particularly pronounced in 4 and 6 jets topologies**



Efficiency and purity of the **π^0 clustering algorithm**

- **A high EM energy 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**)



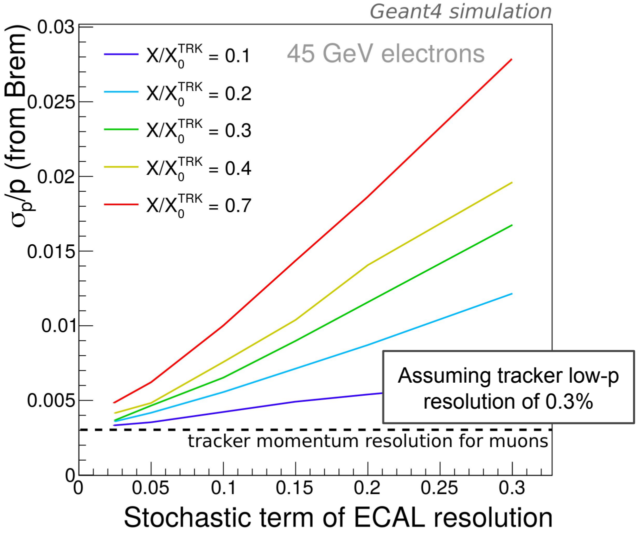


More details in https://doi.org/10.1088/1748-0221/15/11/P11005

This procedure improves the efficiency of jet clustering algorithms to correctly assign photons to the corresponding jet

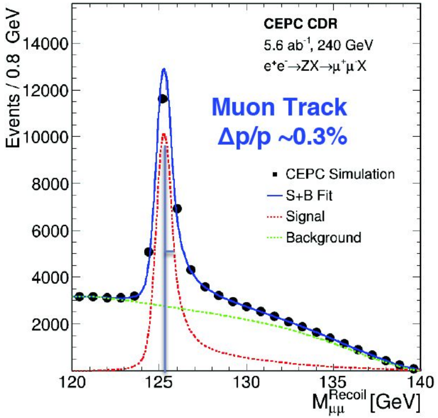
Recovery of Bremsstrahlung photons

- 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]

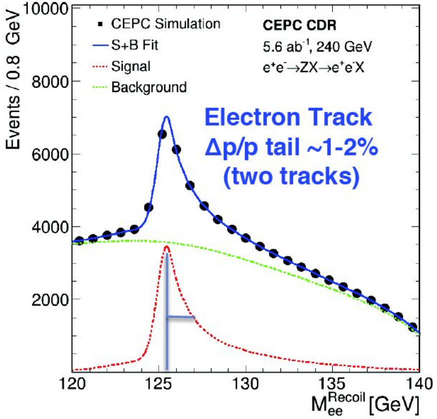


Example from CEPC CDR

Z→μ⁺μ⁻ Recoil



Z→e⁺e⁻ Recoil



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

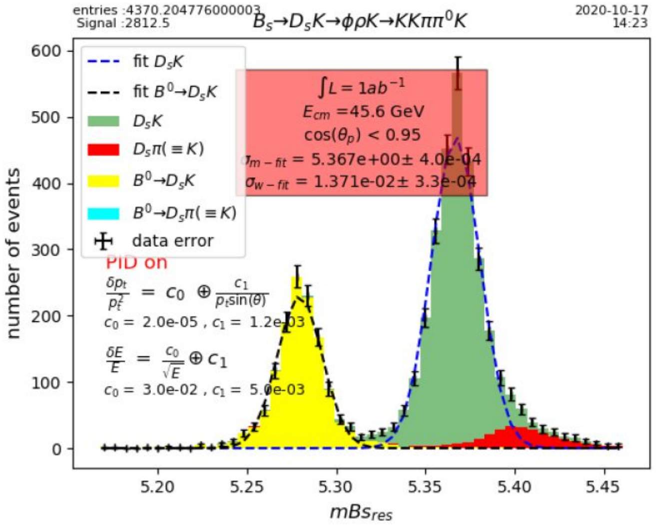
Studies of CP violation and EW physics at e^+e^- colliders

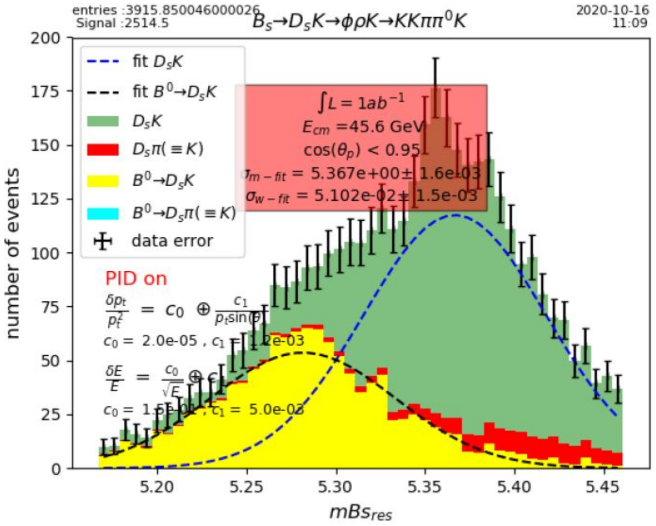
$\overline{\mathrm{B_s}}$ decay Mode	Decay Mode	Final State	Number of $\overline{\mathrm{B_s}}$ decays
$D_s^+ K^-$	$\mathrm{D_s^+} \to \phi\pi$	$\mathrm{K^+K^-\pi^+K^-}$	$\sim 5.2\ 10^5$
$D_s^+ K^-$	$\mathrm{D_s^+} \to \phi\rho$	$\mathrm{K^+K^-\pi^+K^-\pi^0}$	$\sim 9.8\ 10^5$

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]

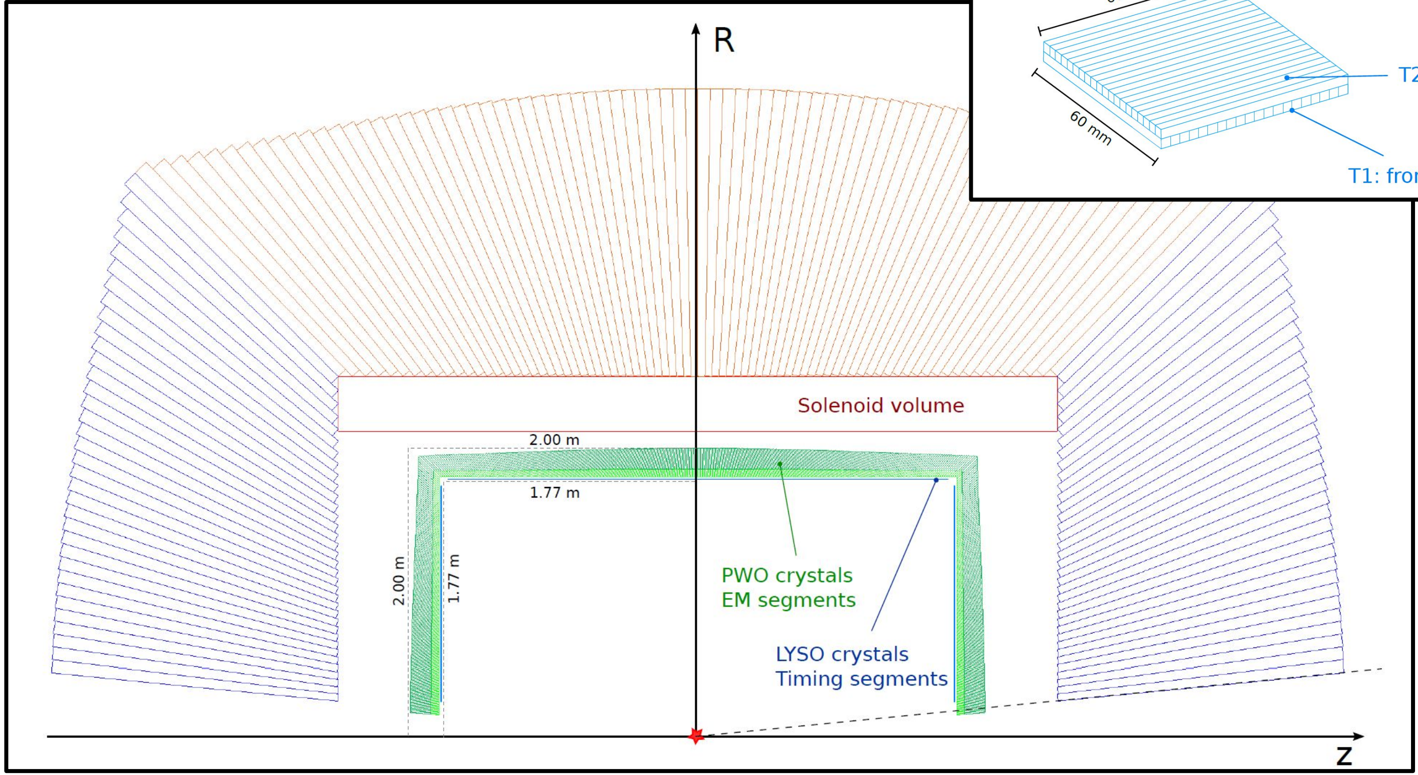
More on calo geometry and single particle performance

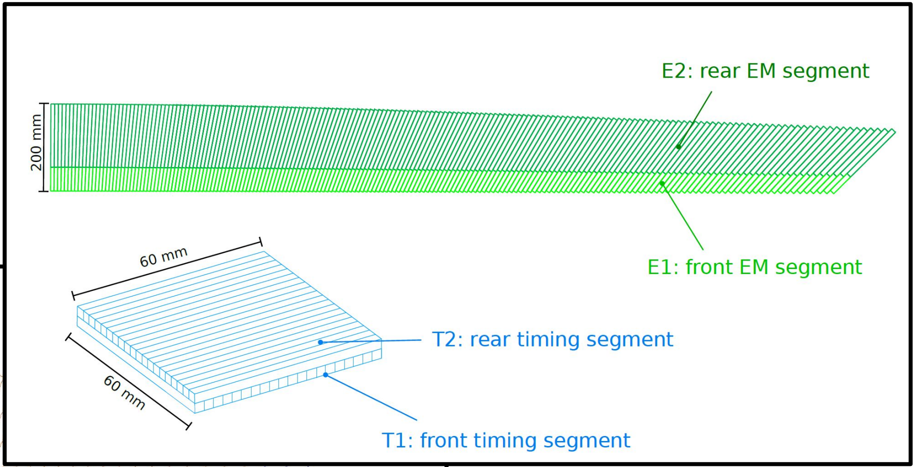
Segmentation of calorimeter

- ECAL
  - Radius: 1800-2000 mm
  - Segmentation in theta:
    - barrel: 2x180 = 360
    - endcap: 179 rings
  - Segmentation in phi:
    - barrel: 1360 rotations around the beam axis
    - endcap: tuned for each ring to have ~1x1 cm^2 crystals

- HCAL
  - Radius: 2500-4500 mm
  - Segmentation in phi: 252
  - Segmentation in theta: nominal

Geometry





- Just inside the solenoid
  ~22 cm of radial space
  ~22 X_0 ~ 1 λ_I

- 2 MIP timing layers as a planar XY grid
- 2 EM shower layers with projective geometry

Signals

- Hits in MIP timing layers:
    - t1, t2, E1, E2

Scintillation signal and time stamp from both layers

- Hits in EM shower layers:

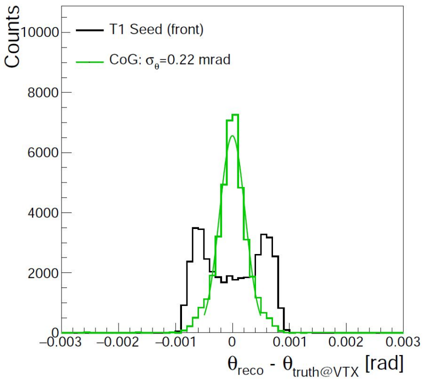
$$S_F = \mathcal{P}(E_{dep,F} \cdot LY \cdot \epsilon_S)$$
$$S_R = \mathcal{P}(E_{dep,R} \cdot LY \cdot \epsilon_S)$$
$$S = S_F + S_R$$
$$C = C_R = \mathcal{P}(N_{cher,prod,R} \cdot \epsilon_C)$$

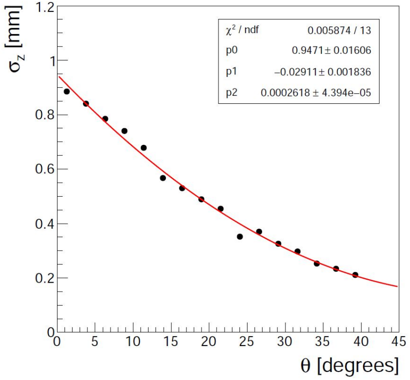
Scintillation signal from both front and rear segments

Cherenkov signal from only the rear segment

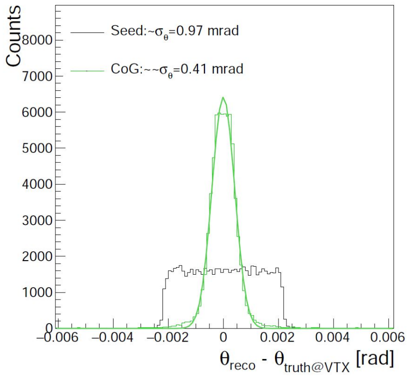
Angular resolution

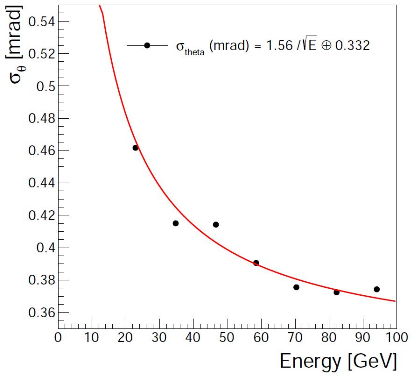
- **T1+T2:** 0.3-1.0 mm spatial resolution along z with the MIP timing layer grid (muons)





- **E1+E2:** 0.3-0.45 mrad angular resolution for EM particles using center of gravity of the shower (photons)





Energy resolution for EM particles

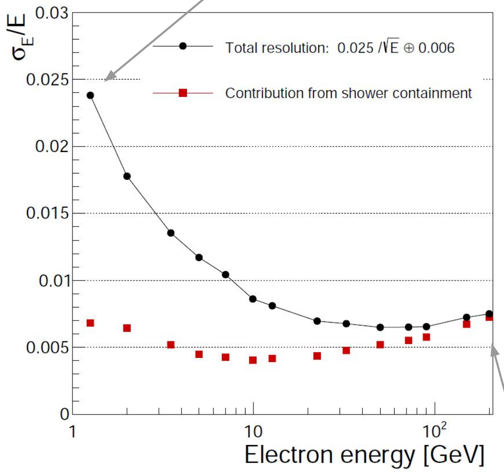
***With no tracker or dead material in front**

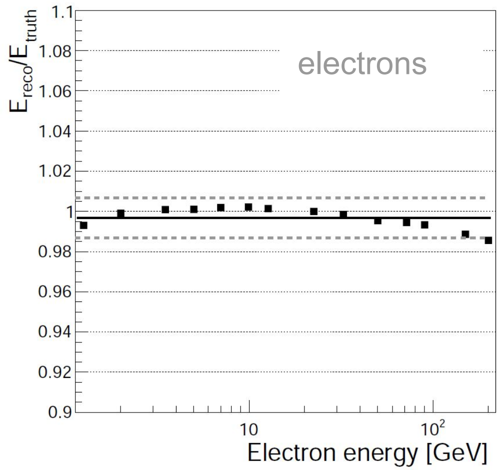
- Energy resolution:

$$\frac{\sigma_E}{E} \sim \frac{2.5\%}{\sqrt{E}} \oplus 0.6\%$$

- Linearity within ±1%

Driven by photostatistics as no tracker/dead material currently in simulation

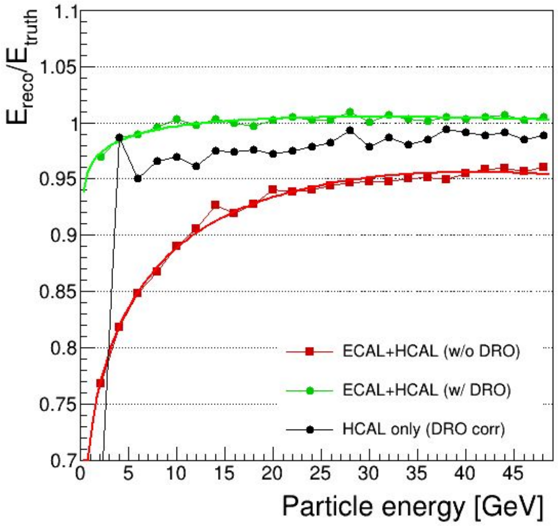


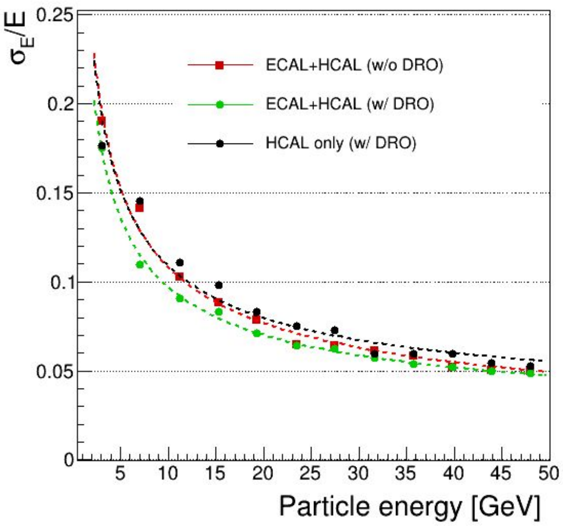


Some shower leakage beyond 200 GeV

Response to single charged pions

- Sample of charged pions of "low energy" to understand the expected calorimeter response to the charged pions within the jets
- Strong non-linearity without DRO correction
- Some residual non-linearity for very low energies after DRO





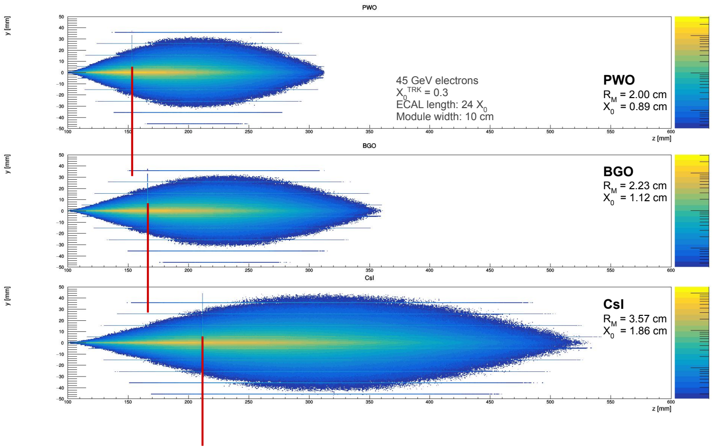
Some crystal options

- **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



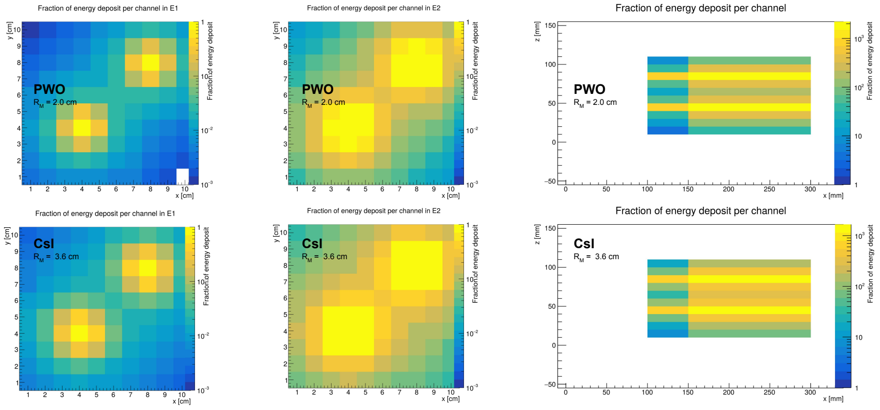


Photo-statistic requirements for S and C

- 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
- **SCEPCal layout choices** (granularity and SiPM size) **provide sufficient light collection efficiency**
  - Need experimental validation with lab and beam tests

Smearing according to Poisson statistics