Combining Dual-Readout Crystals and Fibers in a Hybrid Calorimeter for the IDEA Experiment

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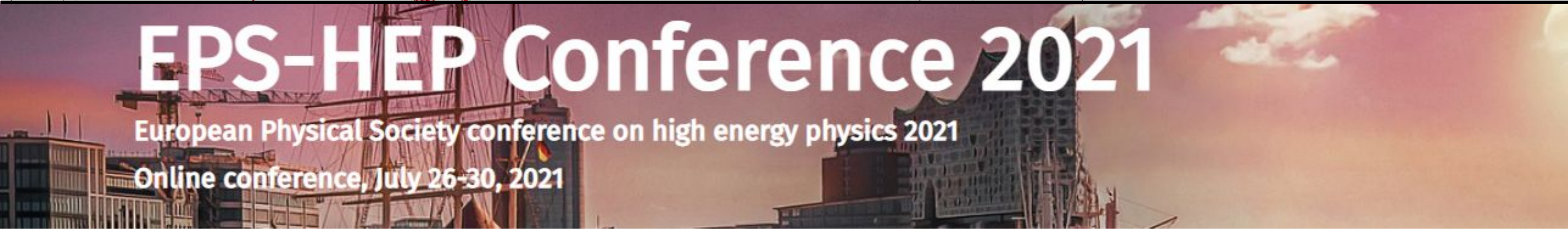
*On behalf of the **IDEA proto collaboration***



A cost-effective highly performant calorimeter system suitable for future e^+e^- colliders

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 particle flow algorithms)

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

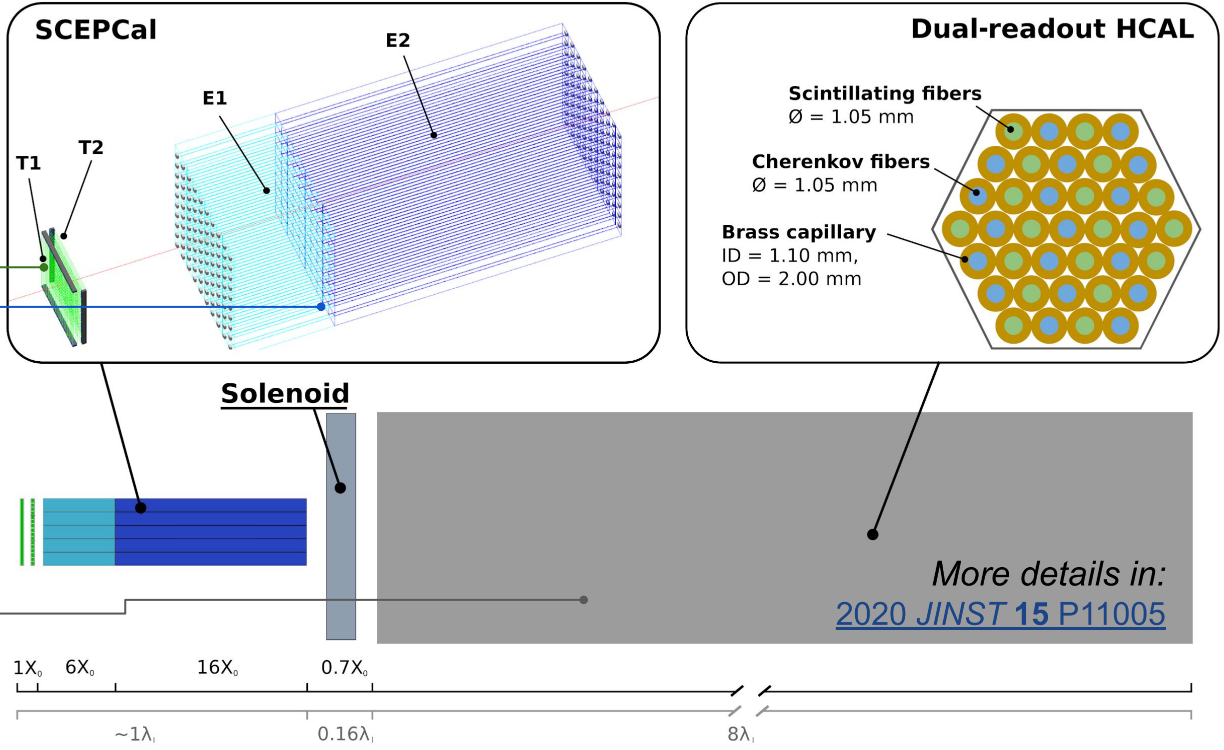
Energy resolution at the level of 4-3% for 50-100 GeV jets

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

Conceptual layout

- **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

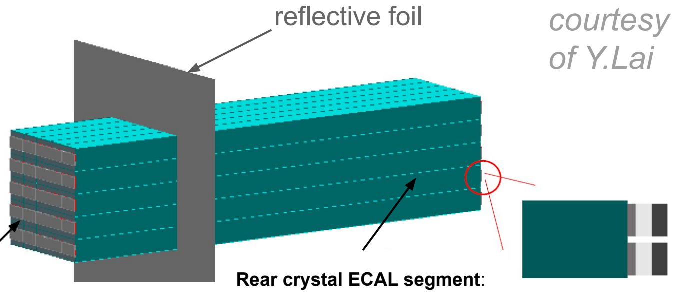


More details in:
2020 JINST **15** P11005

Dual-readout in PWO and BGO/BSO crystals

- **Dual-readout needed only on the rear segment** where hadrons more often start interacting
- **DR 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

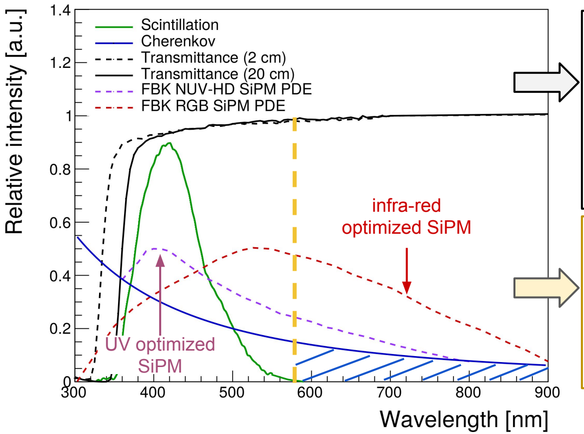
courtesy of Y.Lai



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

Rear crystal ECAL segment: 2 SiPMs with optical filters optimized for scintillation and cherenkov detection resp.

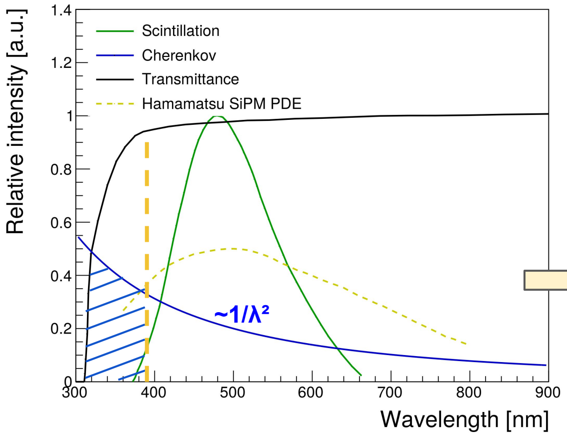
PWO



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

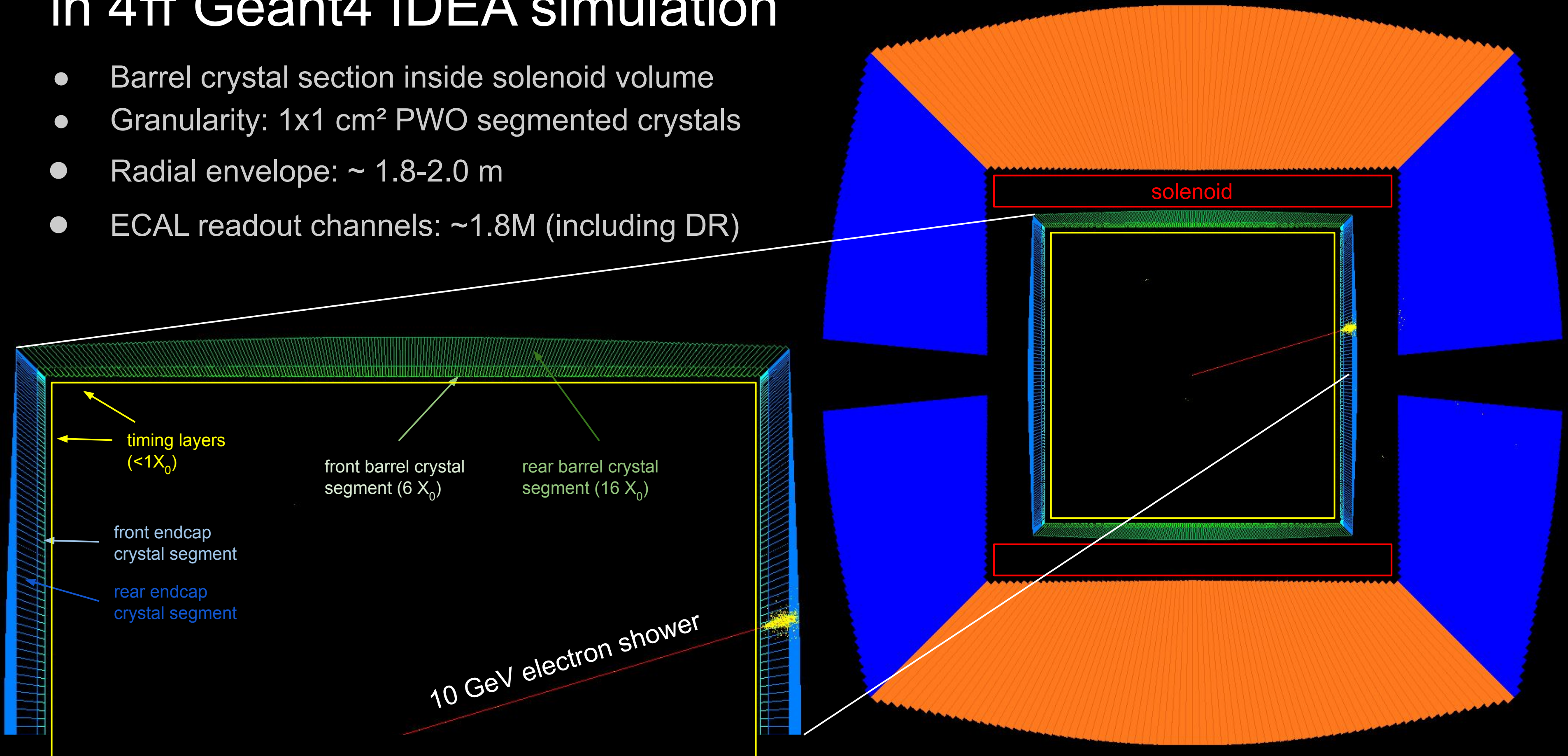
BGO/BSO



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

Integration of crystal calo option 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)



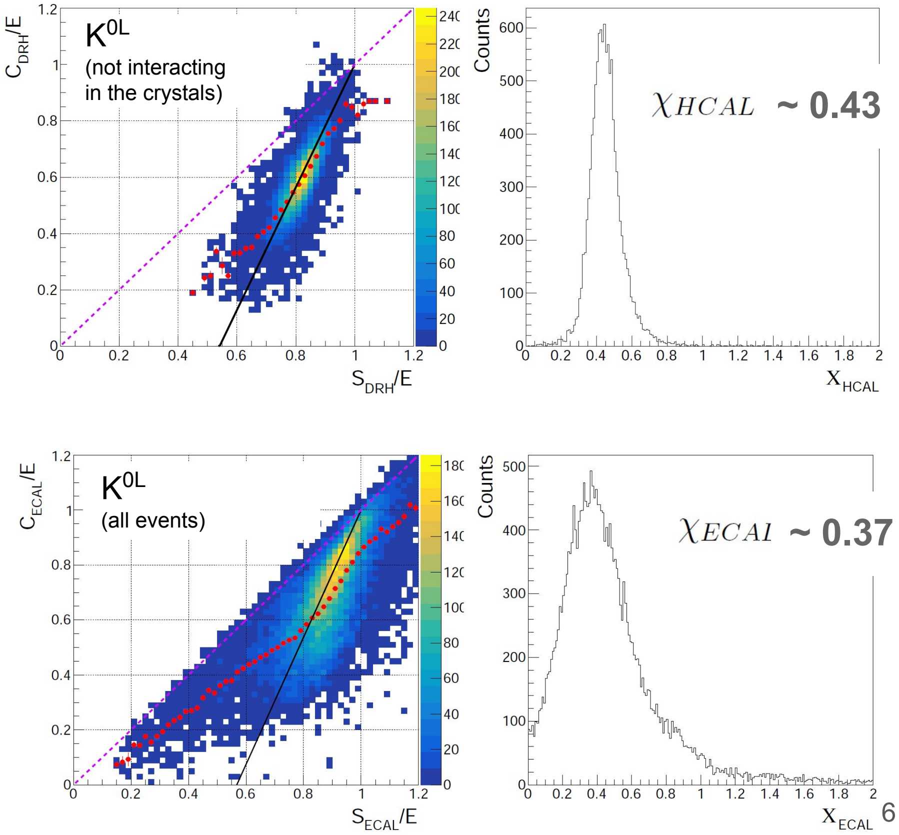
The **dual-readout method** in a hybrid calorimeter

1. Apply the DR correction on the energy deposits in the crystal and fiber segments first

2. Sum up the corrected energy from both segments

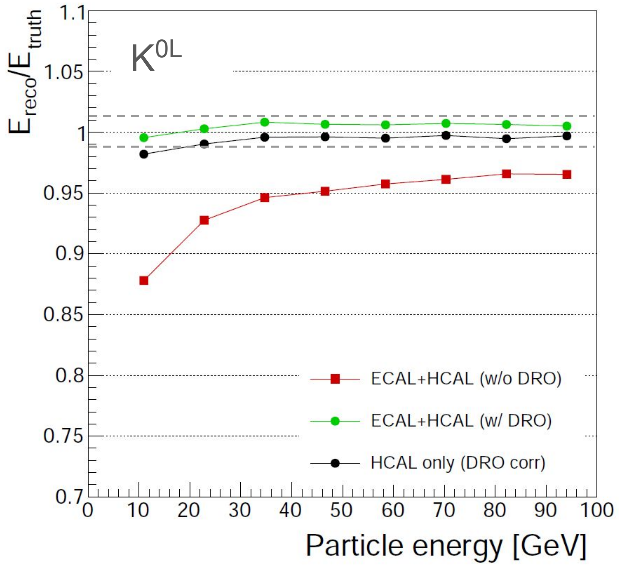
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

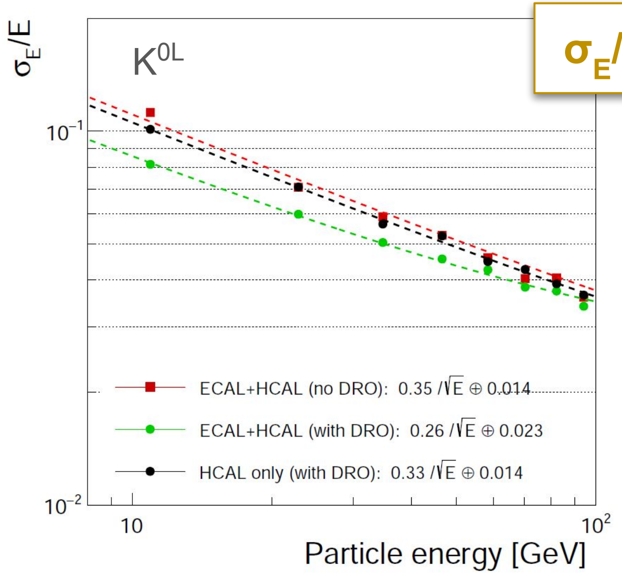
$$\chi_{HCAL} = \frac{1 - (h/e)_s^{HCAL}}{1 - (h/e)_c^{HCAL}}$$
$$\chi_{ECAL} = \frac{1 - (h/e)_s^{ECAL}}{1 - (h/e)_c^{ECAL}}$$



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} ~ 26%/√E ⊕ 2%

Jet reconstruction with a dual-readout calorimeter

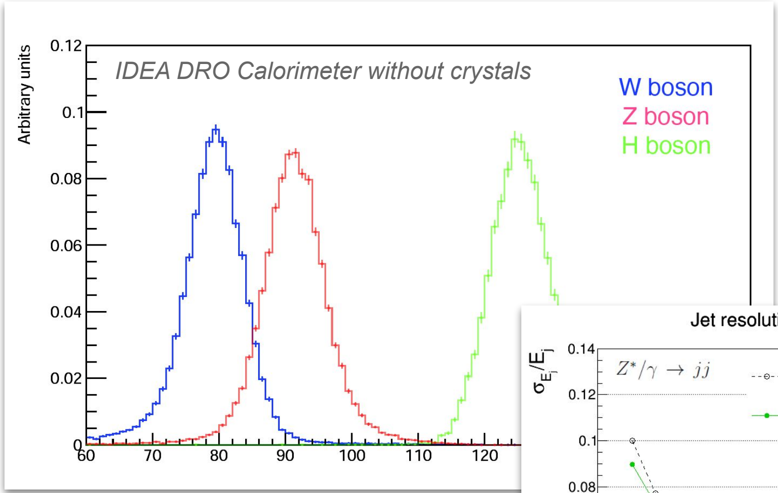
$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$ → Decays to u,d,s,c, c semileptonic decays excluded

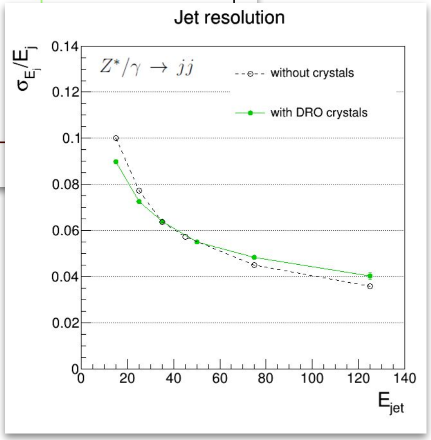
$e^+e^- \rightarrow WW \rightarrow \nu_\mu \mu jj$ → Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal, c semileptonic decays excluded

$e^+e^- \rightarrow HZ \rightarrow bb\nu\nu$ → 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

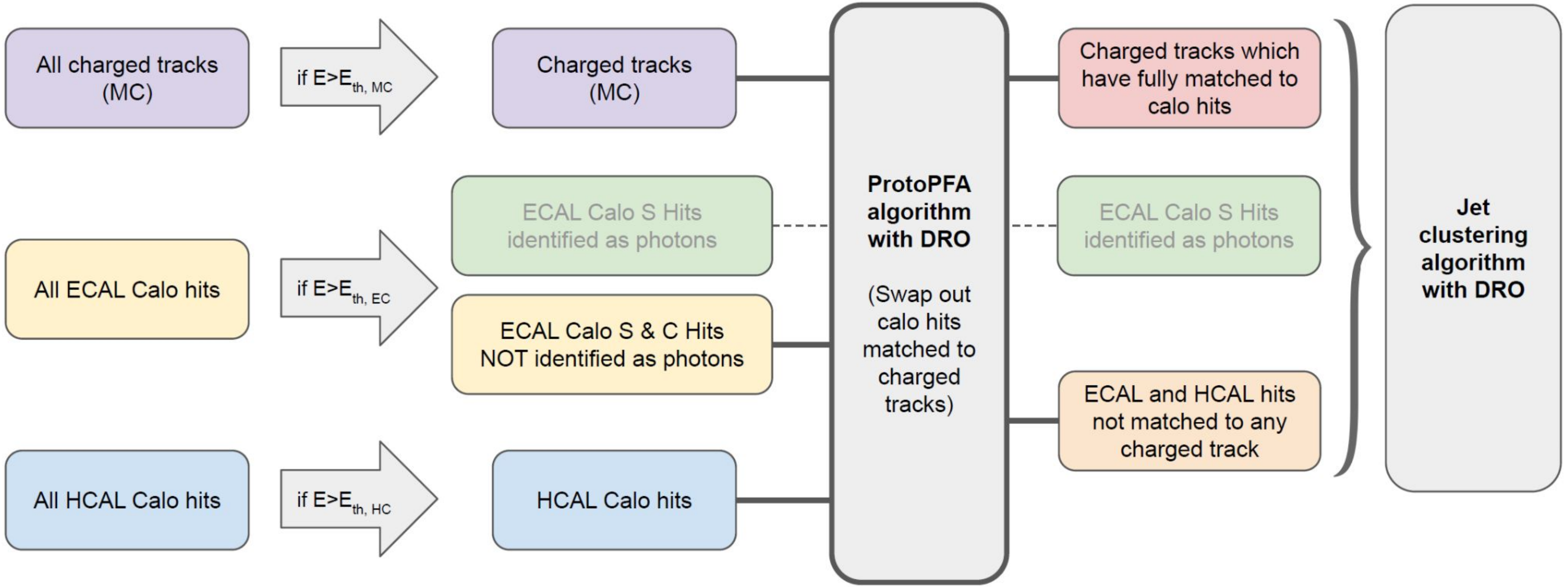




Comparable "calorimeter only" jet resolution of ~5.5% at 50 GeV achieved with the baseline IDEA calorimeter and with the addition of a dual-readout segmented crystals section

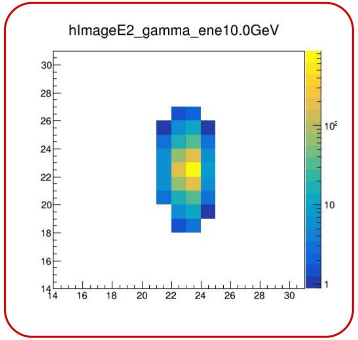
Dual-**R**eadout **P**article **F**low **A**lgorithm for jet reconstruction

- 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

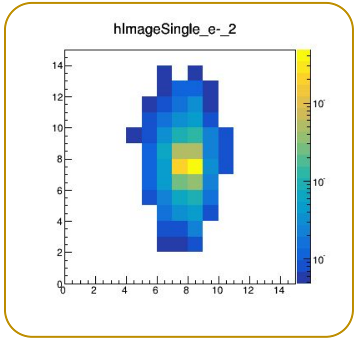


CNNs for **particle ID** with segmented crystal calorimeter

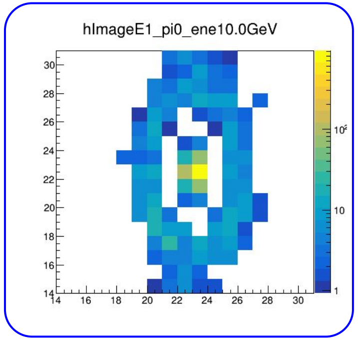
single ɣ event



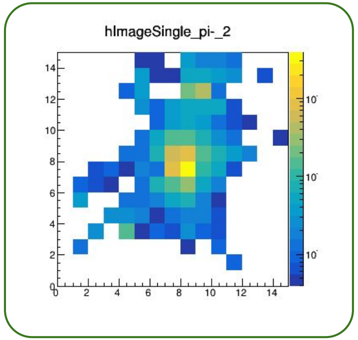
single e⁻ event



$\pi^0 \to \gamma\gamma$ events



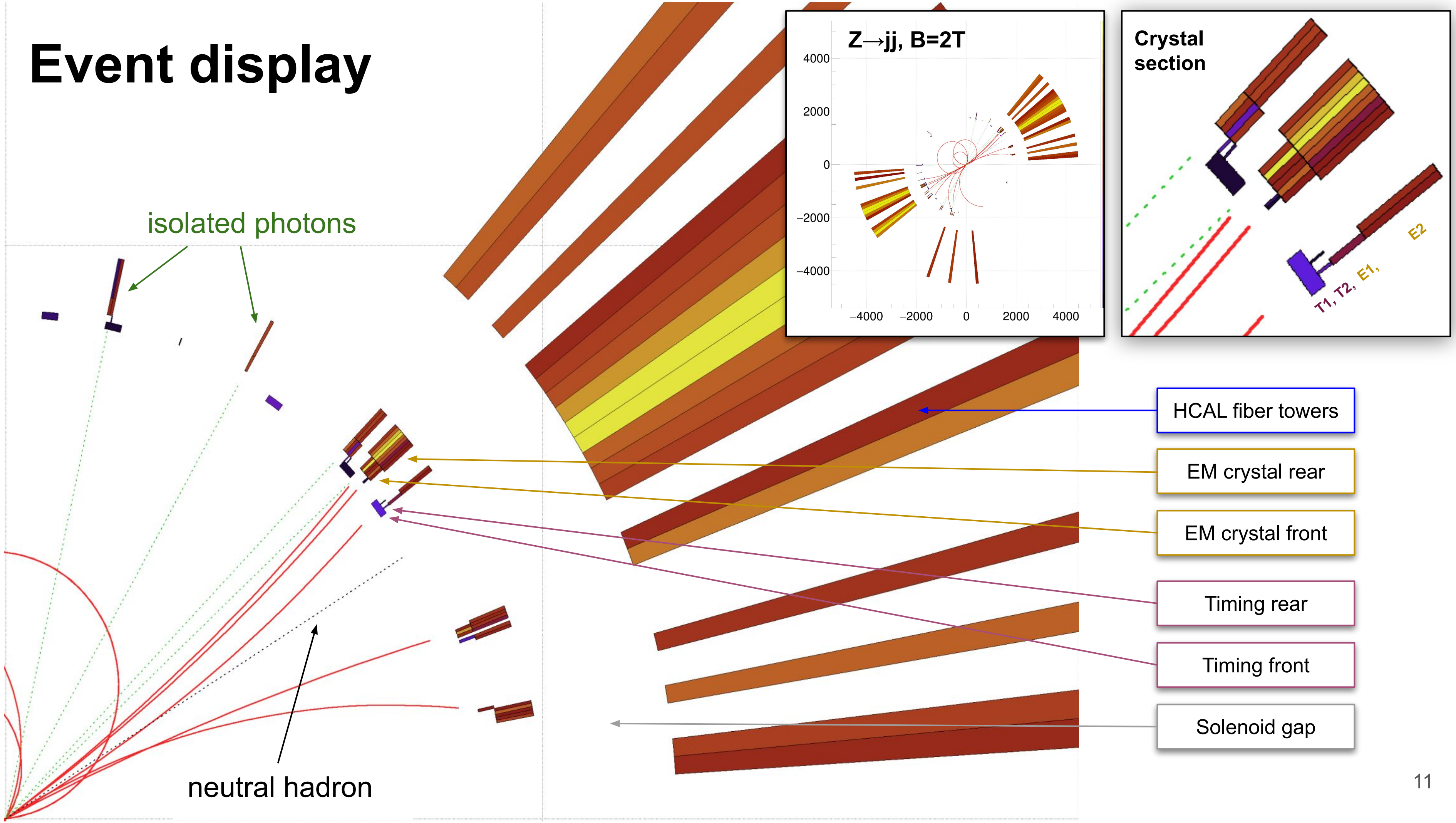
single π^- event



- 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 / 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

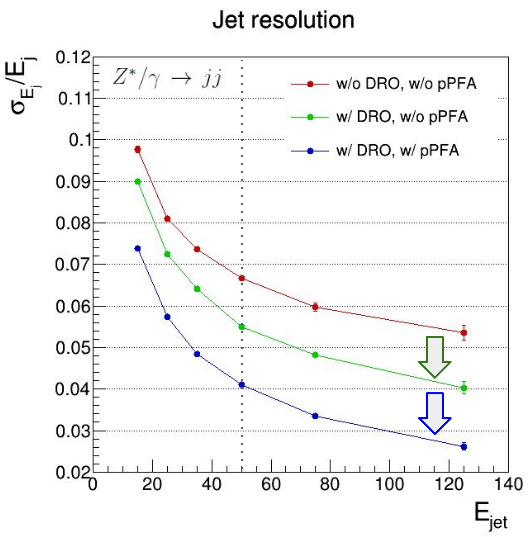
Event display

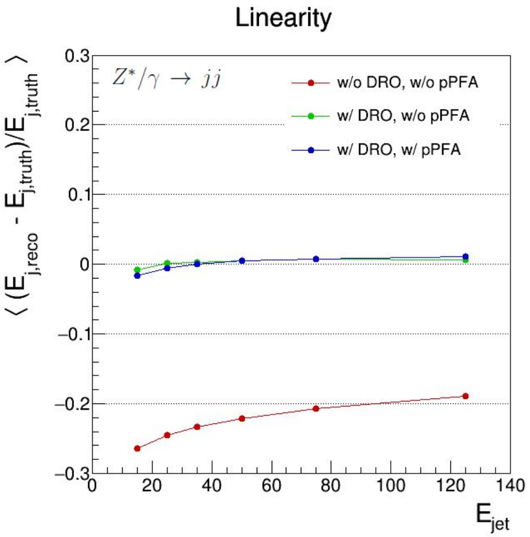


Jet resolution: with and without DR-pPFA

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \to Z^* \to jj$ 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**

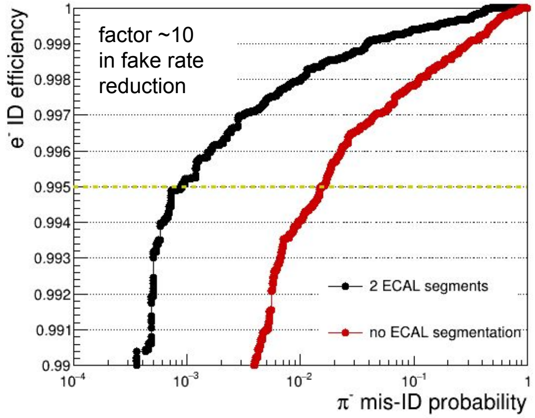
Additional material

Crystal longitudinal **segmentation matters**

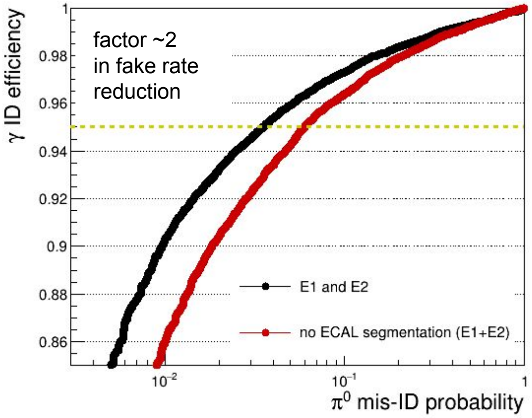
- Tangible improvements in particle ID from the longitudinal ECAL segmentation, i.e. **two crystal segments** (front and rear) instead of a single crystal cell

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

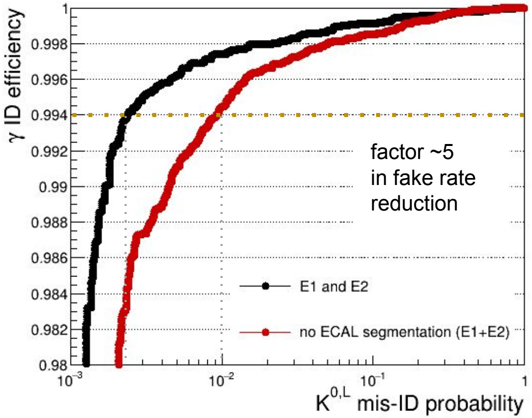
$\pi^{\pm} / e^{\pm}$



π^0 / γ

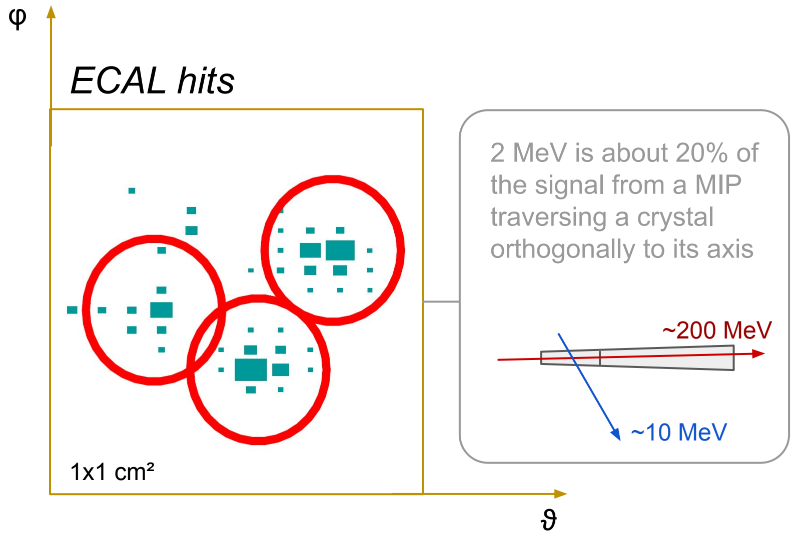


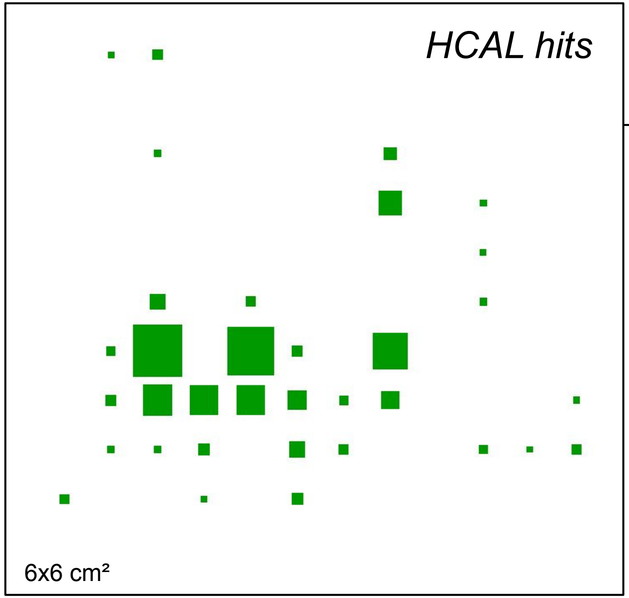
K^{0L} / γ



Readout granularity and calorimeter hits

- Readout granularity of fiber towers (~6x6 cm²), crystal granularity (~1x1 cm²)
- Consider all calorimeter hits with energy > 2 MeV
- Every hits corresponds to a crystal or to a HCAL tower and carry both the S and C signal (including effects of photostatistics for both ECAL and HCAL)





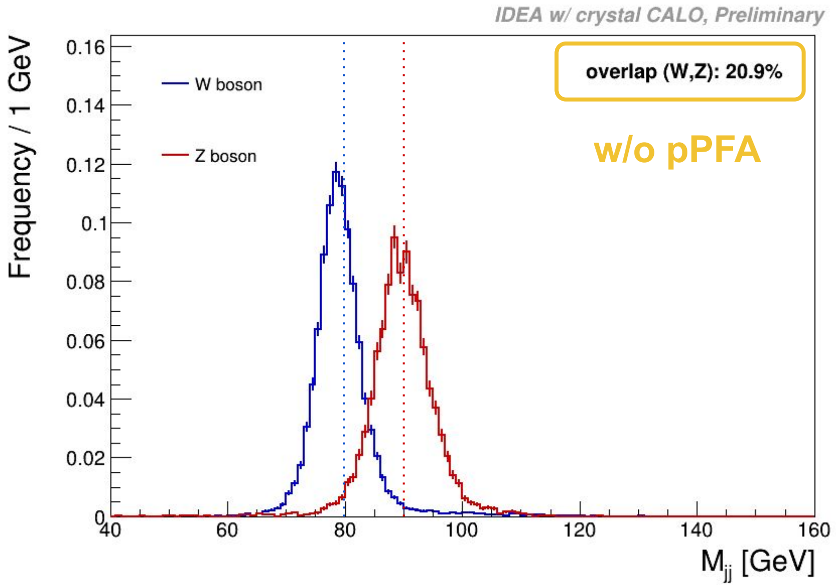
Readout granularity in the baseline IDEA DRO calorimeter is much finer:
- at single fiber level → O(mm)
- or grouping 8x8 fibers → O(cm)

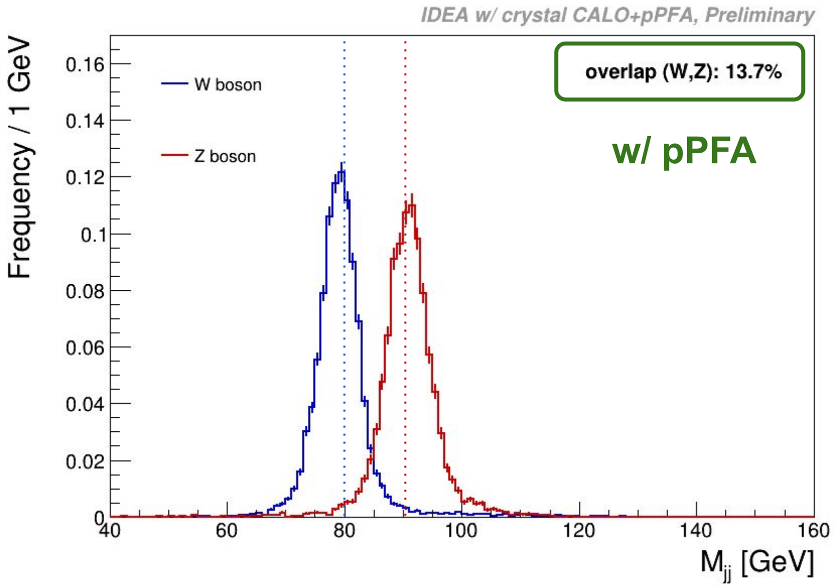
Boson dijet resonances

- Consistent improvement from pPF algorithm also in dijet boson resonances

- $e^+e^- \to ZH,\ H \to \chi_1^0\chi_1^0,\ Z \to jj$
- $e^+e^- \to W^+W^-,\ W^+ \to \mu\nu,\ W^- \to jj$

$$\text{Overlap} = \sum_i \min(\text{bin}_{i,W}; \text{bin}_{i,Z})$$





Comments and outlook on *"DR-pPFA"*

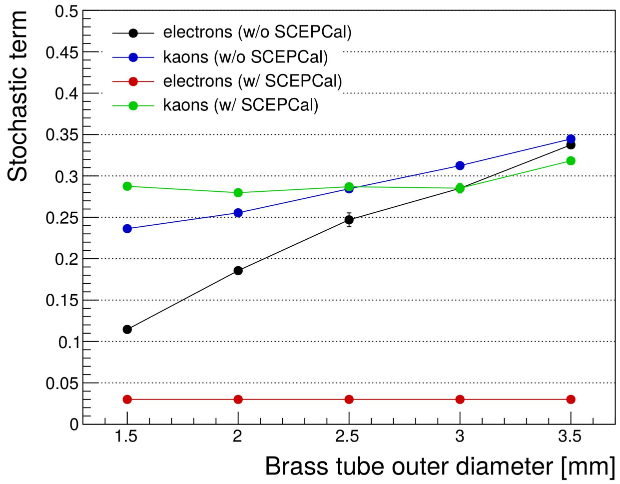
- Implementation of a **simplified particle flow algorithm improved jet energy resolution** in dijet events reconstructed with crystals in front of the fiber calorimeter

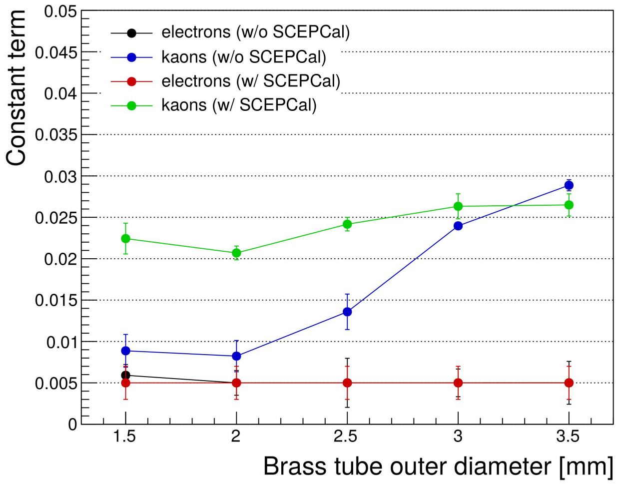
- **Some key differences with respect to standard PFA**:
  - Longitudinal segmentation strongly reduced: O(3) layers instead of O(40)
    →typical topological algorithms to separate neutral and charged hadrons hard to use **but…**
  - **Superior resolution** to photons: 3%/√E instead of ~30%/√E
  - Superior resolution to hadrons: 30%/√E instead of ~60%/√E
    - → direct improvement on the neutral hadron component of the jet
    - → simplified/improved matching of tracks to calo cluster based on energy

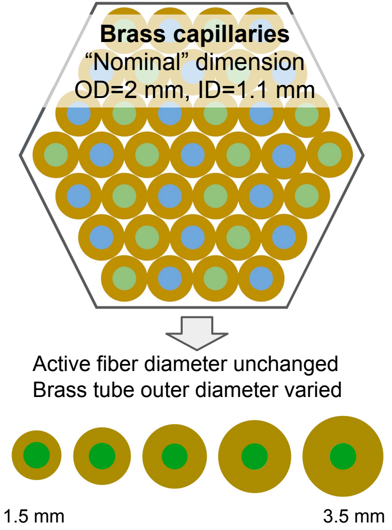
- **Room for improvement**
  - Improve step 1 reconstruction of photons with clustering
  - **Cluster photons into π^0** before the jet clustering algorithm (expected improvement in 4/6 jet topologies)
  - Target an **optimization of** step 2 for **calo hits to charge track matching** (e.g. graph-based approach)
  - **Better exploit longitudinal segmentation** in track-hit matching
    (both crystal segmentation and time information for virtual segmentation along the fibers)
  - Include information from two timing layers (currently simulated but neglected)

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 ~1/OD^2







R&D and prototyping

- **Short term goals** for validation of a segmented crystal DRO calorimeter:
  - Verification of DRO signals and timing with segmented crystals+optical filters+SiPMs and front-end electronics

- **Ongoing efforts**:
  - R&D on crystals and validation of scintillation and Cherenkov photon yield ongoing, synergies with ***Crystal Clear Collaboration***
  - Plans for prototyping of a segmented crystal calorimeter with dual-readout within the ***CALVISION*** (**CAL**orimetry using cherenko**V** and **I**norganic **S**cintillation **I**nn**O**vatio**N**) consortium
  - Ongoing effort for test beam of a full length fiber sampling ***IDEA*** calorimeter →will possibly allow in future a combined test of the hybrid calorimeter with crystals in front of a fiber tower

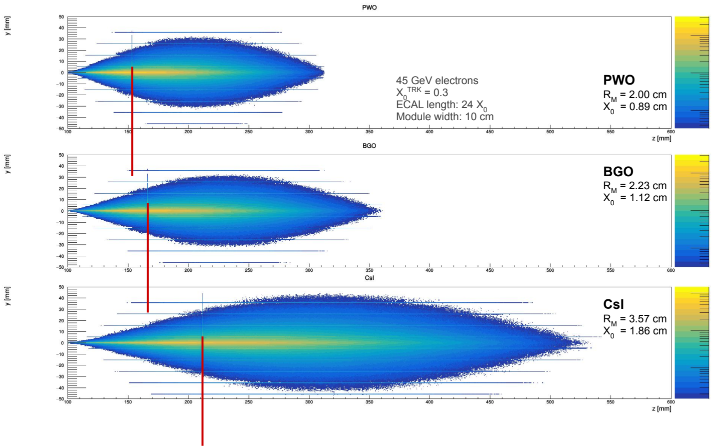
Some crystal options

- **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



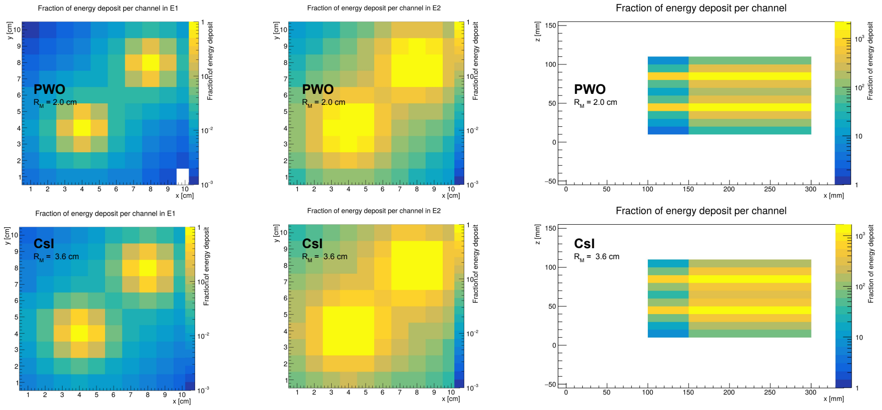
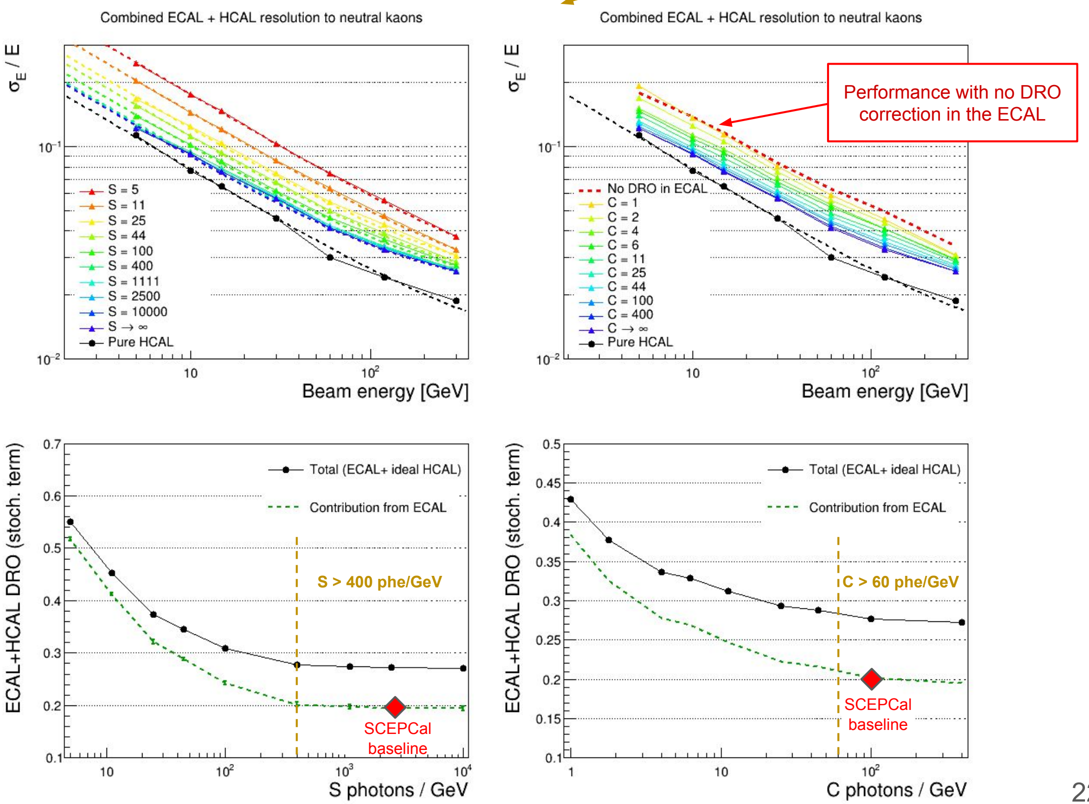


Photo-statistic requirements for S and C

Smearing according to Poisson statistics

- 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



Motivation

Performance potential at an e^+e^- collider

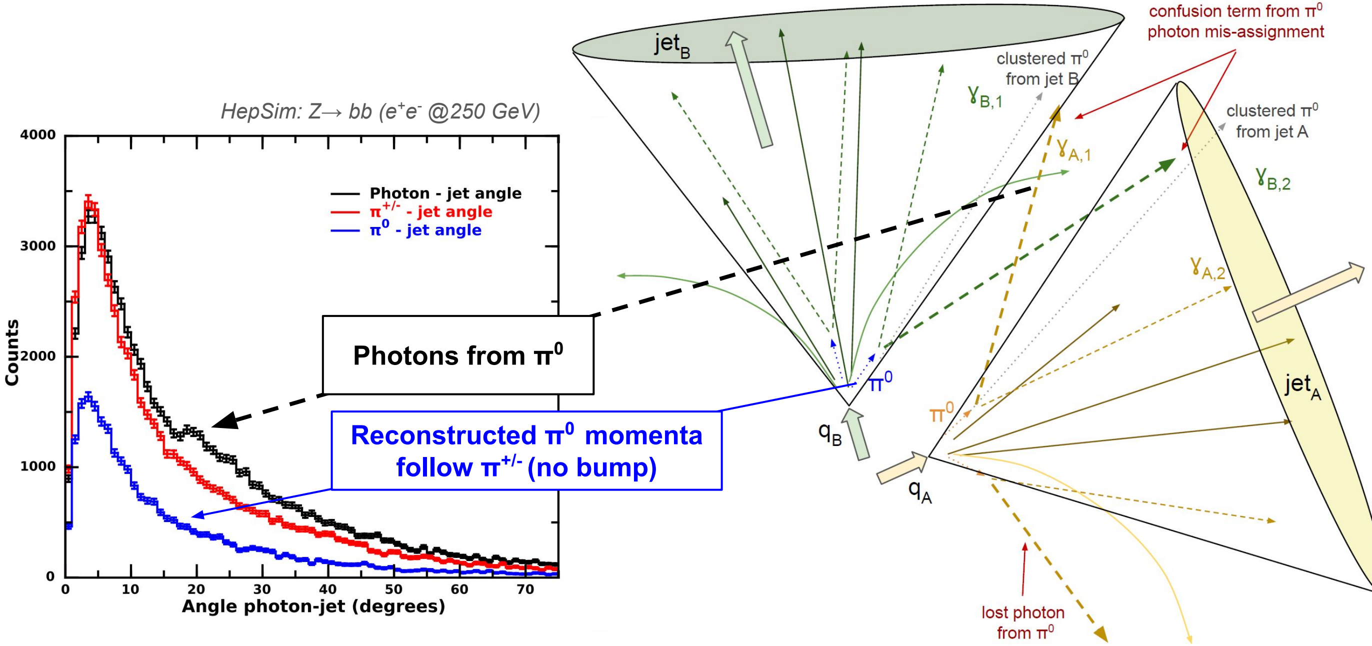
- Extend the coverage for physics studies to include final states with low energy photons (e.g. B-physics, see R.Aleksan's slides at 4th FCC workshop)

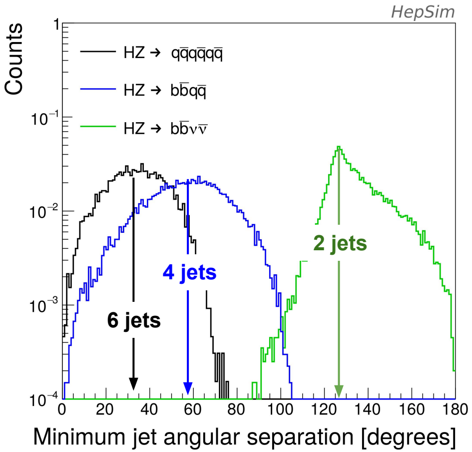
- Recover bremsstrahlung photons to increases the Z boson recoil mass resolution in Higgstrahlung events for decays into electron pairs to 80% of that for muon pairs

- Enable new techniques to improve jet reconstruction
    - Clustering of π^0 photons before applying jet algorithms to narrow the angular spread of jet particles → improves reconstruction for topologies with 4 and 6 jets in final state
    - Combine the dual-readout information with a particle flow approach to achieve jet energy resolution at the level of 3-4% for jets above 50 GeV

High photon resolution potential for PFA

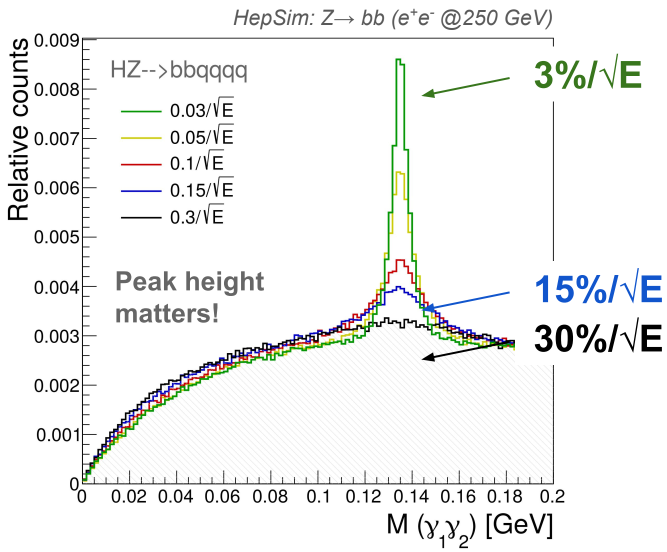
- **Many photons from π^0 decay** are emitted **at a ~20-35° angle** wrt to the jet momentum and can get scrambled across neighboring jets
- Effect **particularly pronounced in 4 and 6 jets topologies**

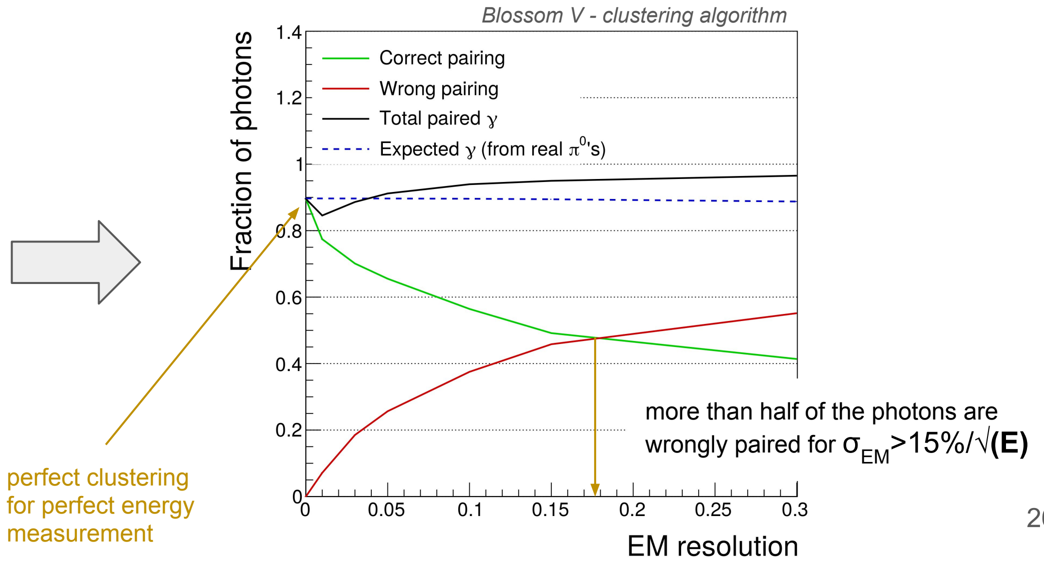




A graph-based algorithm for π^0 clustering

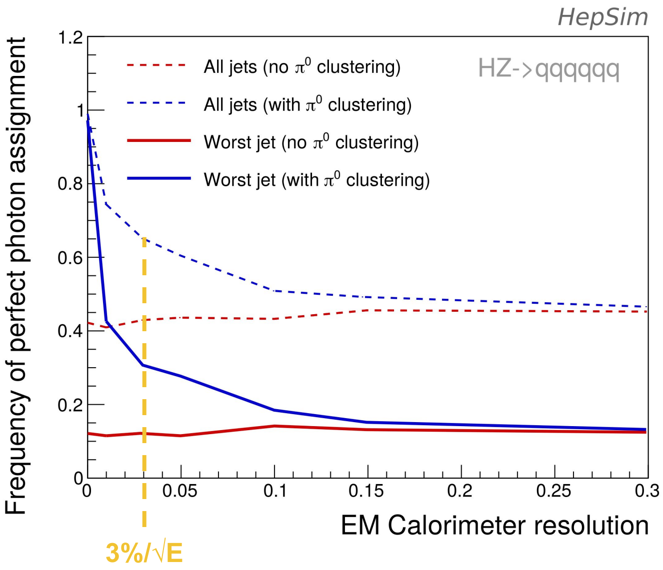
- **A high EM resolution enables efficient clustering of photons from π^0's**
  - Large fraction of π^0 photons correctly clustered with good σ_{EM}
    → **~90% for ~3%/√(E)** vs **50% for ~30%/√(E)**
  - Large fraction of "**fake π^0's**" reconstructed with poor σ_{EM}
    → ~50% for ~30%/√(E) vs 10%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

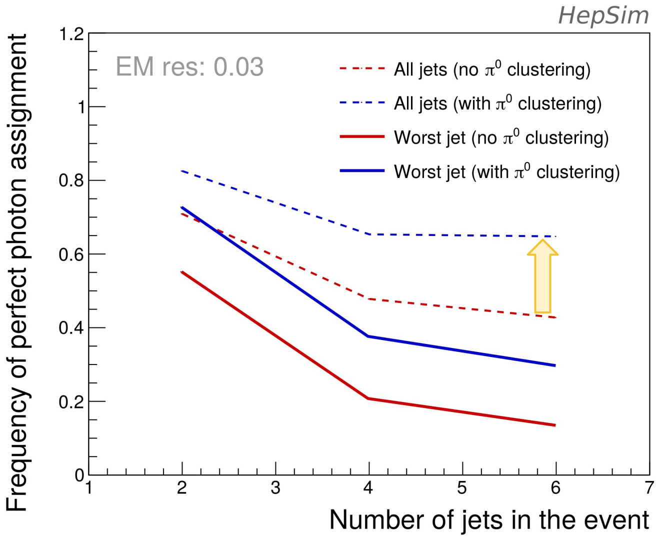




Improvements in photon-to-jet correct assignment

- **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)





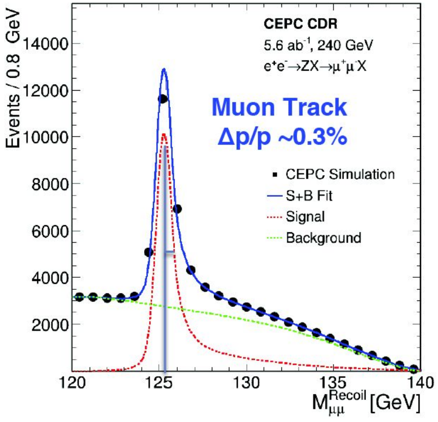
More details in:
https://doi.org/10.1088/1748-0221/15/11/P11005

Recovery of Bremsstrahlung photons

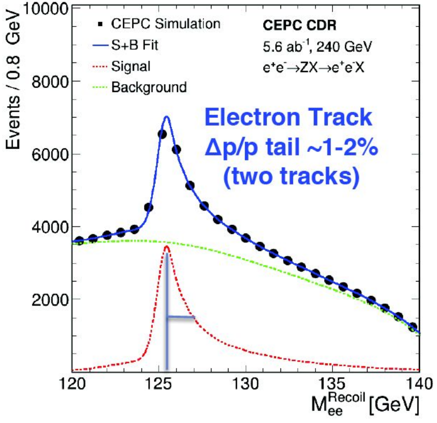
- Reconstruction of the Higgs boson mass and width from the recoil mass of the Z boson is a key tool at e^+e^- colliders
- Potential to **improve the resolution of the recoil mass signal from Z→ee decays** to about 80% of that from Z→ μμ decays [with Brem photon recovery at EM resolution of 3%/√E]

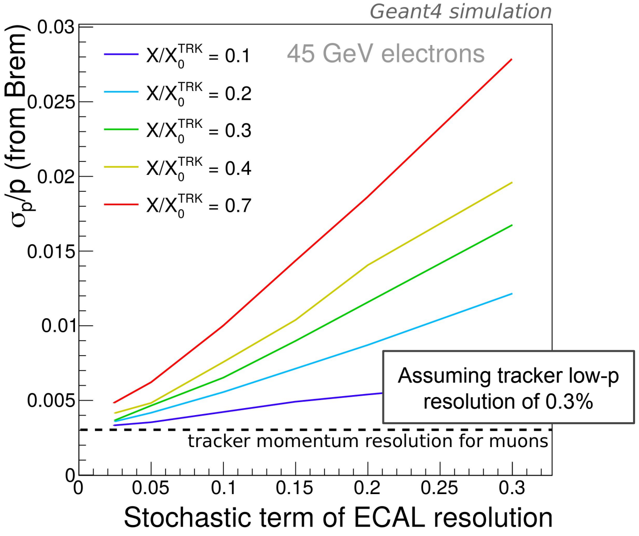
Example from CEPC CDR

▸ **Z→μ⁺μ⁻ Recoil**



▸ **Z→e⁺e⁻ Recoil**





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

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

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