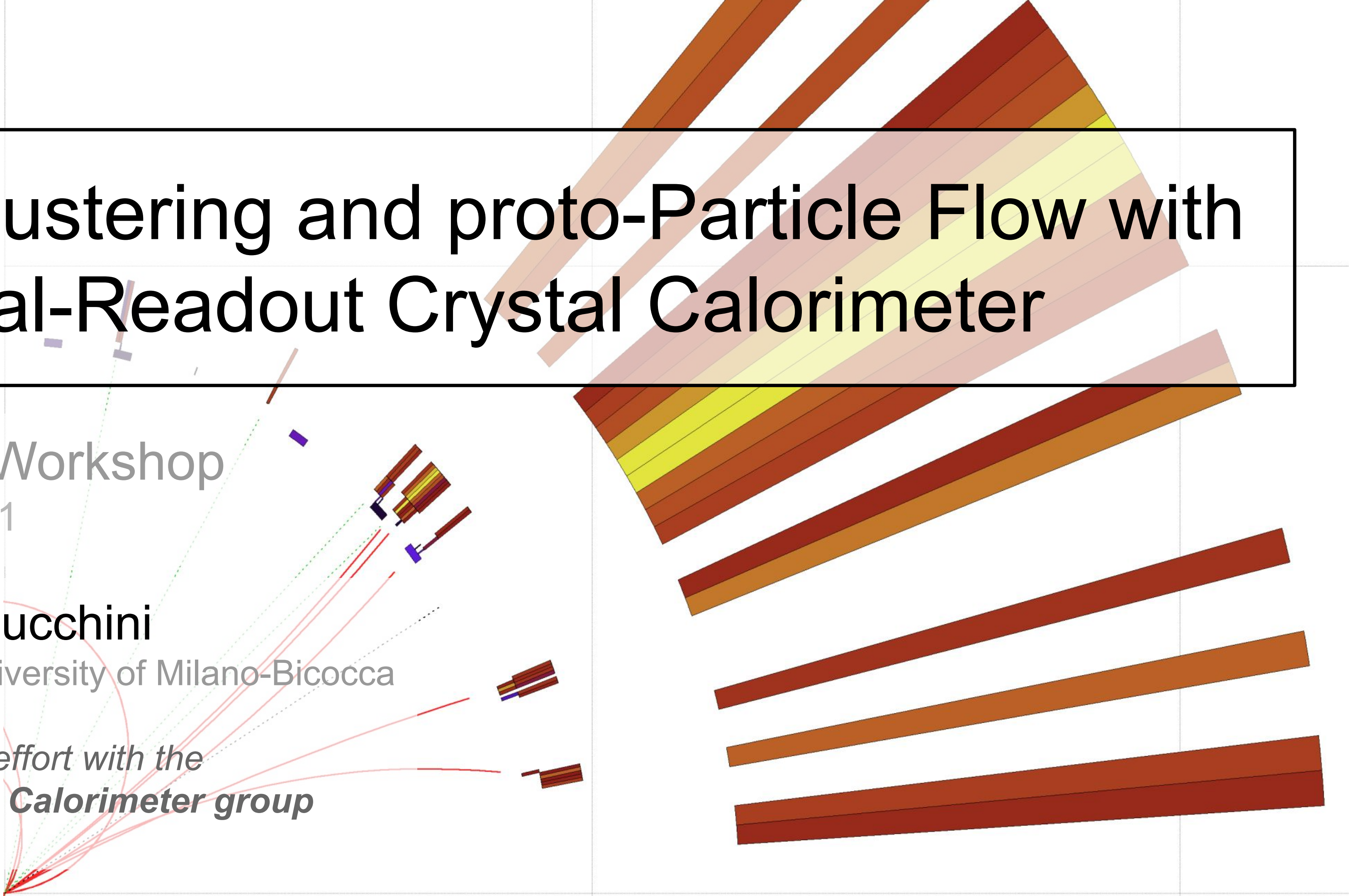
π^0 Clustering and proto-Particle Flow with a Dual-Readout Crystal Calorimeter



CEPC Workshop

11/11/2021

Marco Lucchini

INFN & University of Milano-Bicocca

A growing effort with the

IDEA DRO Calorimeter group

Context …

- **Jet energy and angular resolution are key detector requirements to achieve accurate reconstruction of multi-jet final states at future e^+e^- colliders**

Context …

- **Jet energy and angular resolution are key detector requirements to achieve accurate reconstruction of multi-jet final states at future e^+e^- colliders**

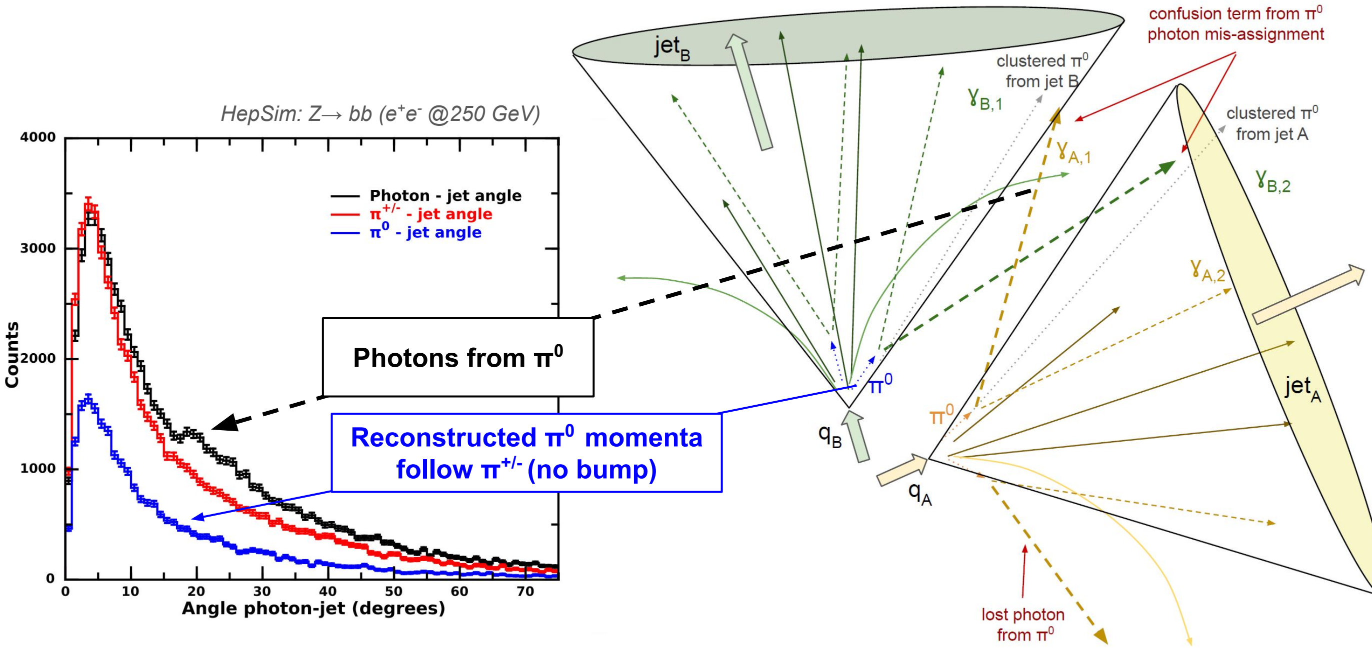
… and contents

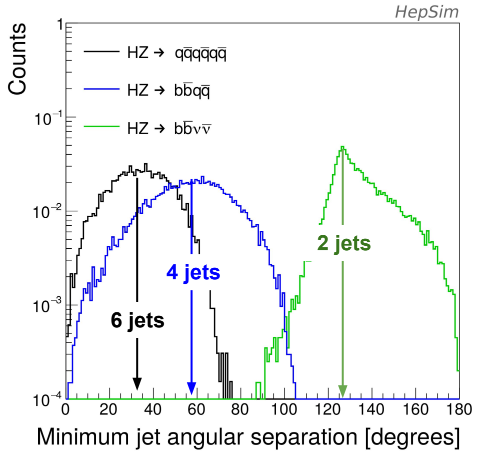
- Potential of a high EM resolution crystal calorimeter for **π^0 clustering** before applying traditional jet clustering algorithms
  - Using **HepSiM MC truth level particles with different level of smearing for photon energy** resolution and study graph-based π^0 clustering performance in 2, 4 and 6-jet events

- Integration of a segmented high EM resolution DRO crystal calorimeter with a fiber DRO hadron calorimeter to enhance jet resolution using a **Dual-Readout proto-Particle Flow Algorithm** (DR-pPFA)
  - Using **full detector simulation based on Pythia+Geant4**, and studying jet resolution with and without the DR-pPFA algorithm for dijet events

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**





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

1 **Build a graph with all photons in the event**

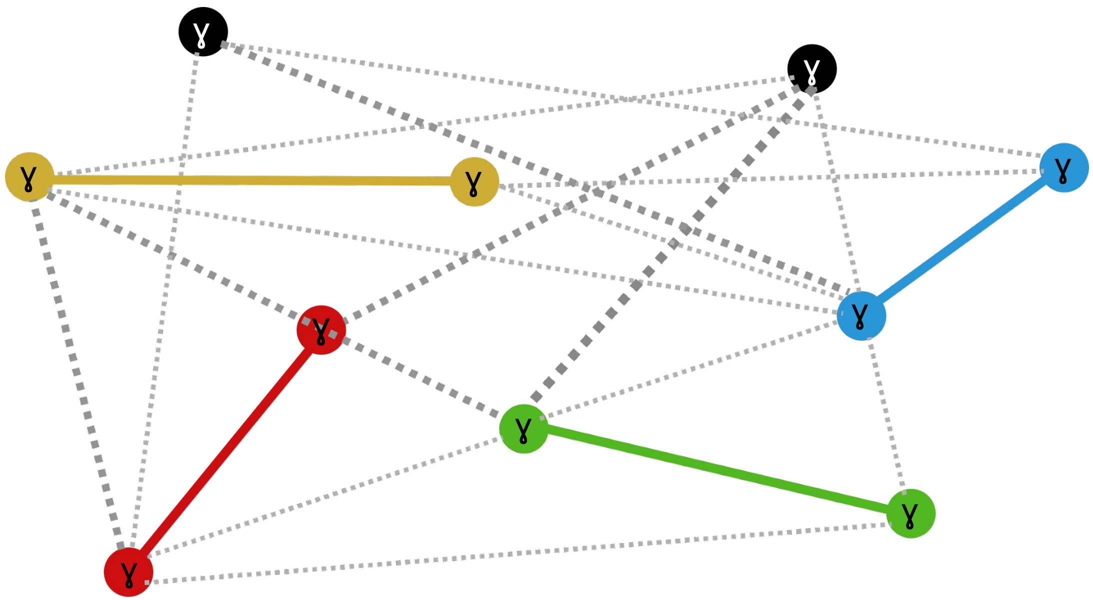
- **Node** = photon
- **Edge** = pair of photons

2 **Assign a weight, w_{ij}**, to each edge

- $\chi^2_{ij} = (M_{\gamma,i\,\gamma,j} - M_\pi)^2 / M_\pi$
- $w_{ij} = 1 - \chi^2_{ij} / \chi^2_{max}$

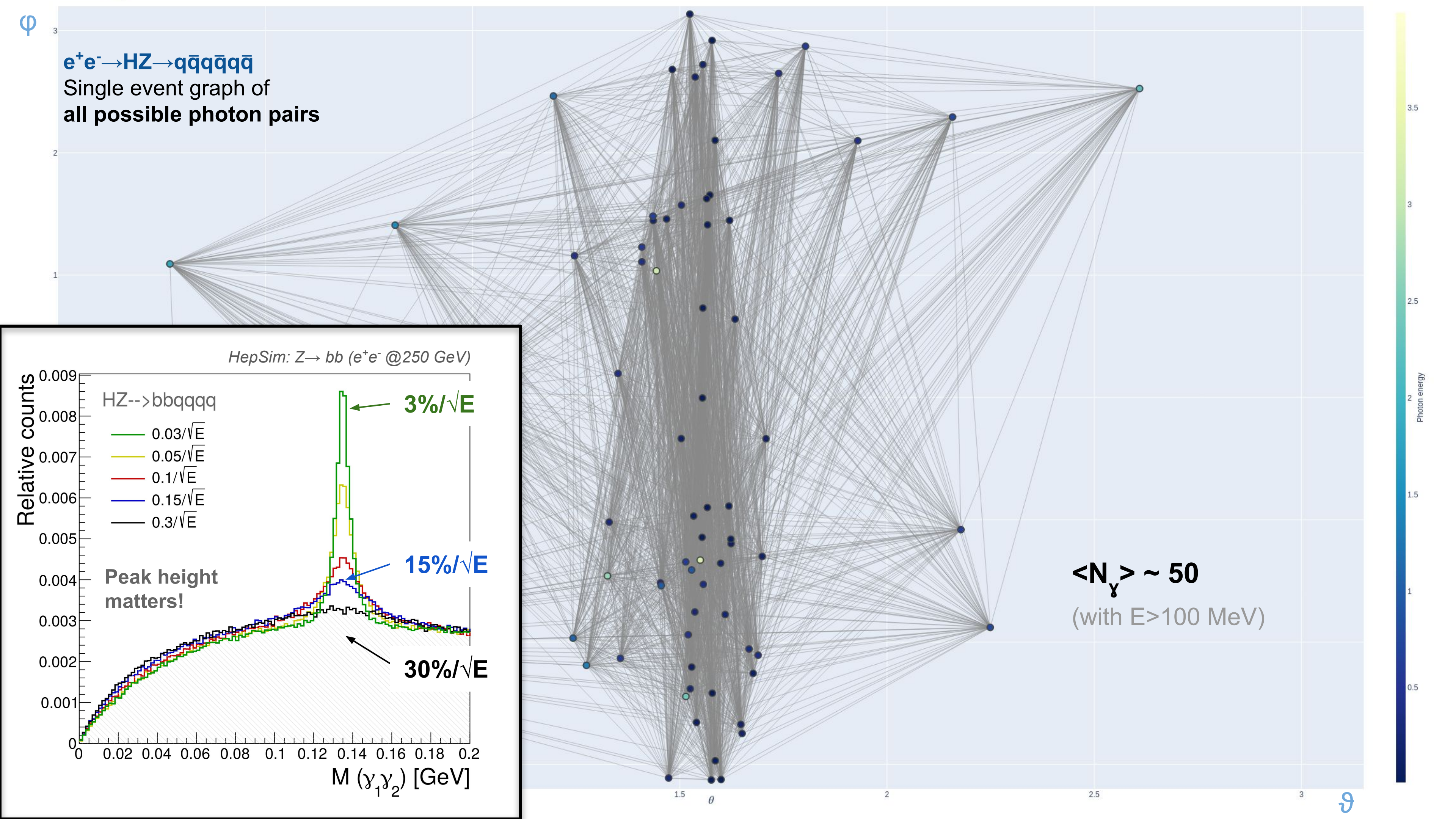
3 Use the **Blossom V algorithm to solve efficiently** the problem as a maximum weight matching

4 The best solution is the one that pairs all photons (passing selection cuts) while minimizing the total graph weight



odd photons
(not from π^0)
can be left unpaired

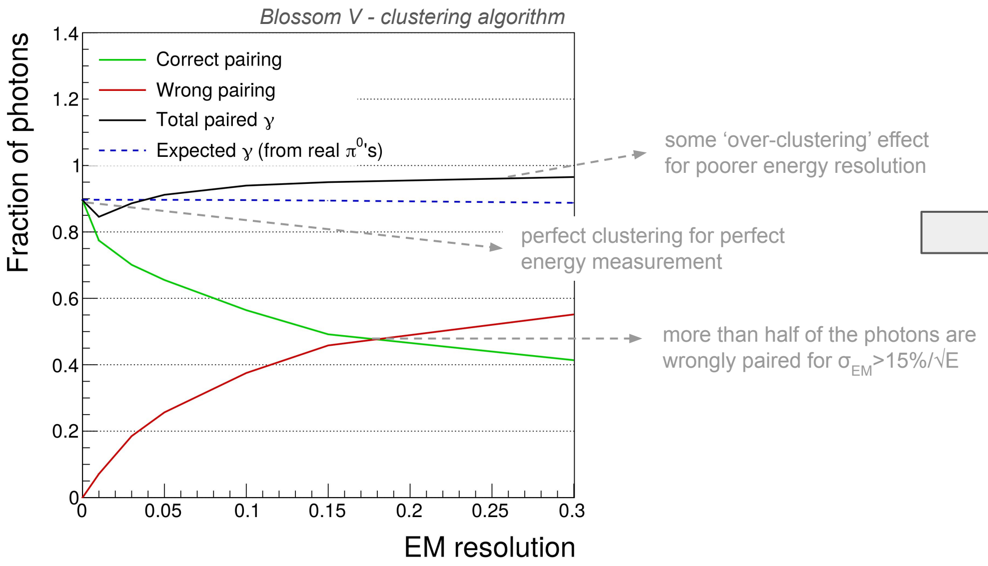
Similar method applied in B. van Doren, G. W. Wilson, [arXiv:1203.2577.](arXiv:1203.2577) Improving the prompt electromagnetic energy component of jet energy resolution with π^0 fitting in high granularity electromagnetic calorimeters

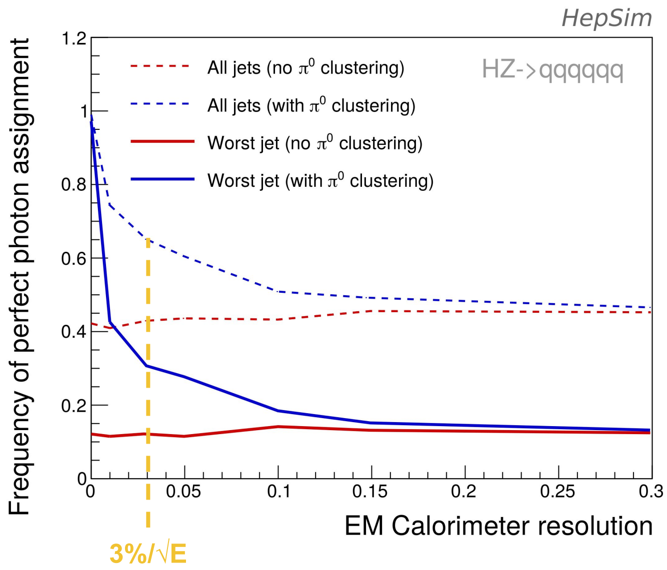


φ
$e^+e^- \to HZ \to q\bar{q}q\bar{q}q\bar{q}$
Single event graph of
all possible photon pairs
HepSim: Z→ bb (e+e- @250 GeV)
HZ-->bbqqqq
0.03/√E
0.05/√E
0.1/√E
0.15/√E
0.3/√E
3%/√E
15%/√E
30%/√E
Peak height matters!
Relative counts
M (γ1γ2) [GeV]
<Nγ> ~ 50
(with E>100 MeV)
θ
ϑ
Photon energy

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**)





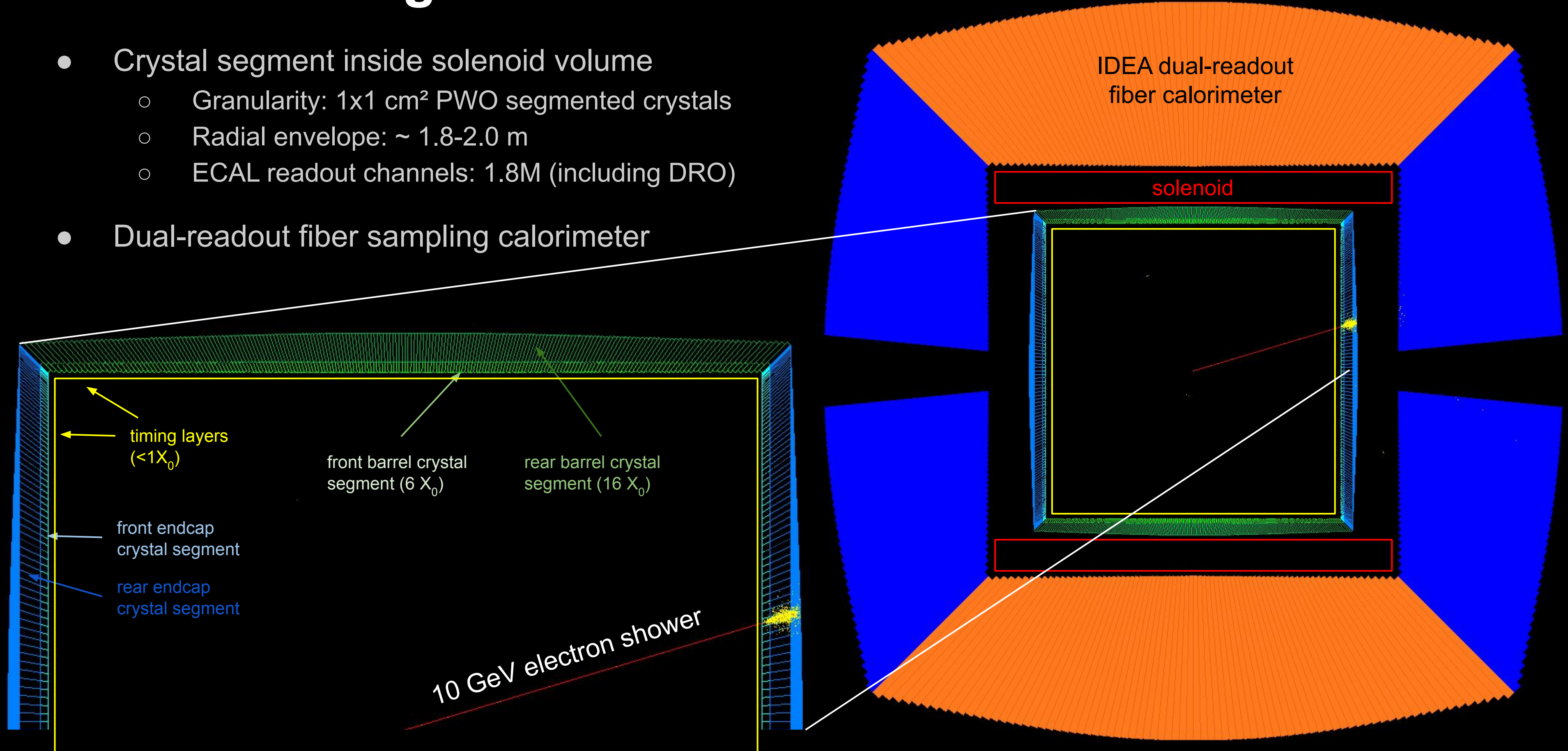
More details in https://doi.org/10.1088/1748-0221/15/11/P11005

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

[see dedicated talk at the "Calorimeter session" on Tuesday 9th]

Detector design overview

- Crystal segment inside solenoid volume
  - Granularity: 1x1 cm² PWO segmented crystals
  - Radial envelope: ~ 1.8-2.0 m
  - ECAL readout channels: 1.8M (including DRO)
- Dual-readout fiber sampling calorimeter



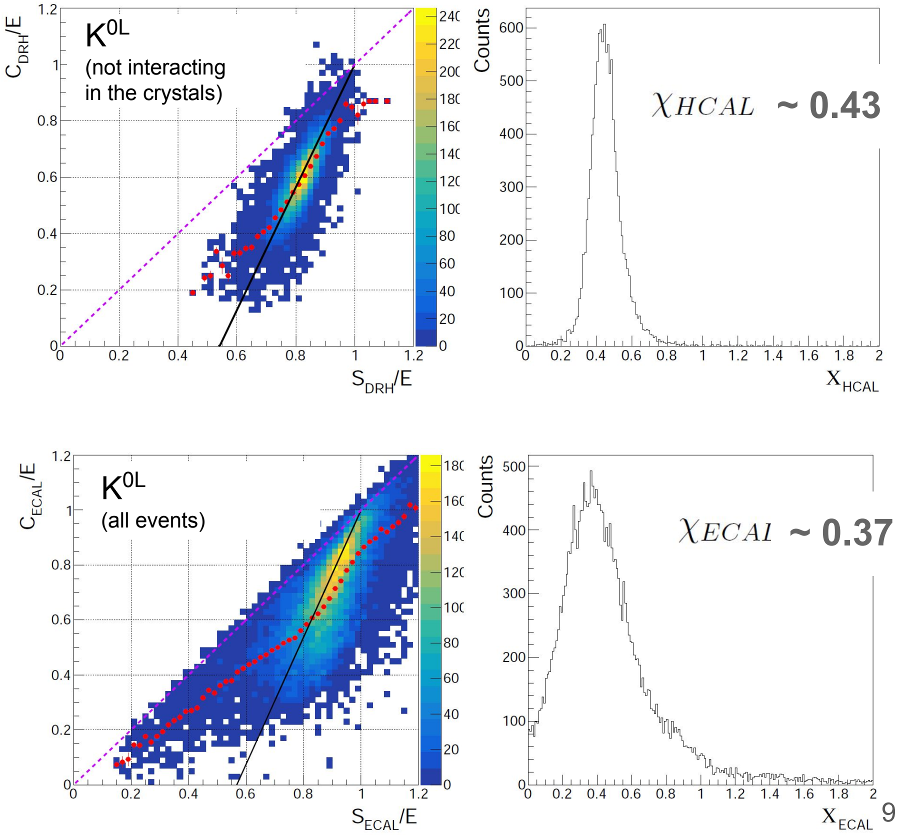
The **dual-readout method** in a hybrid calorimeter

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

$$\boxed{\begin{aligned} E_{HCAL} &= \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}} \\ E_{ECAL} &= \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}} \\ E_{total} &= E_{HCAL} + E_{ECAL} \end{aligned}}$$

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

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



Jet reconstruction with a dual-readout calorimeter

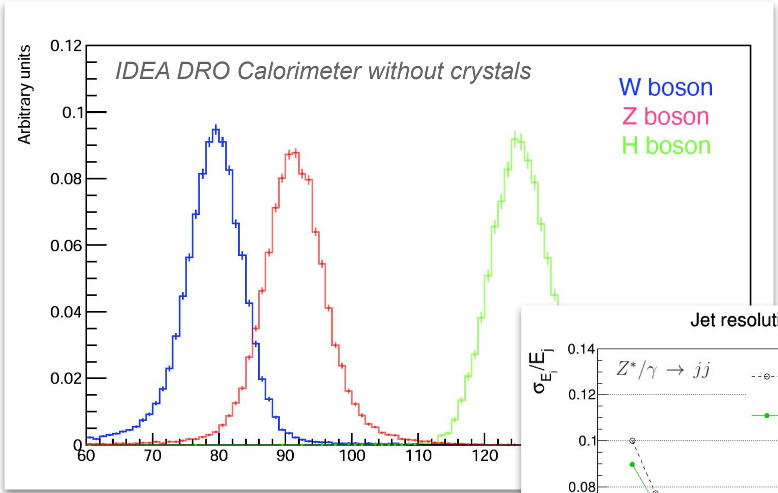
$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$ → Decays to u,d,s,c, c semileptonic decays excluded

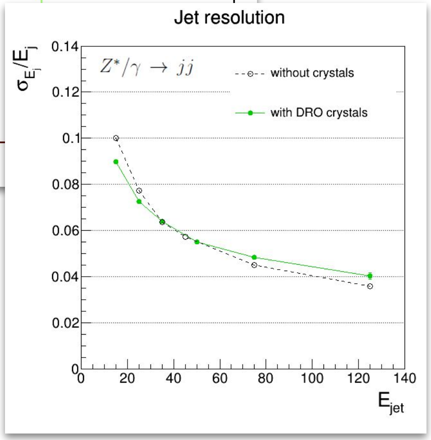
$e^+e^- \rightarrow WW \rightarrow \nu_\mu \mu jj$ → Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal, c semileptonic decays excluded

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



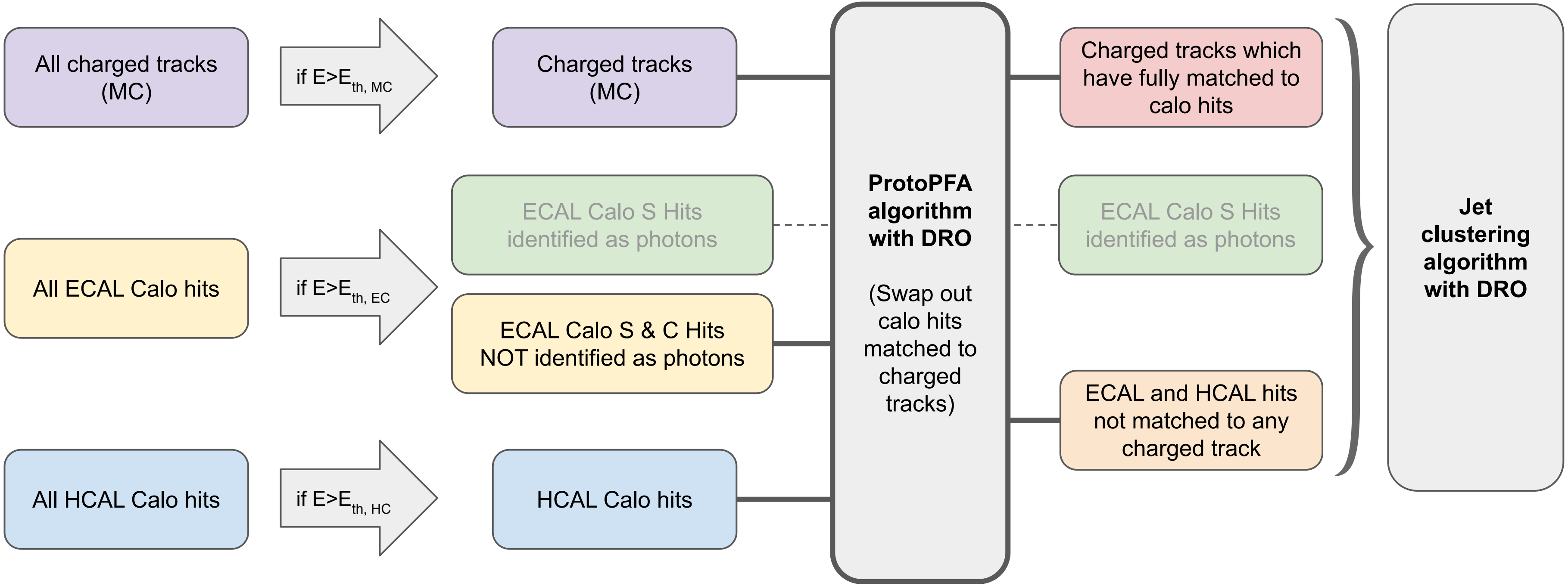


Comparable "calorimeter only" jet resolution of ~5.5% at 50 GeV achieved with the baseline IDEA calorimeter and with the addition of a dual-readout segmented crystals section

Dual-Readout proto Particle Flow Algorithm (**DR-pPFA**)

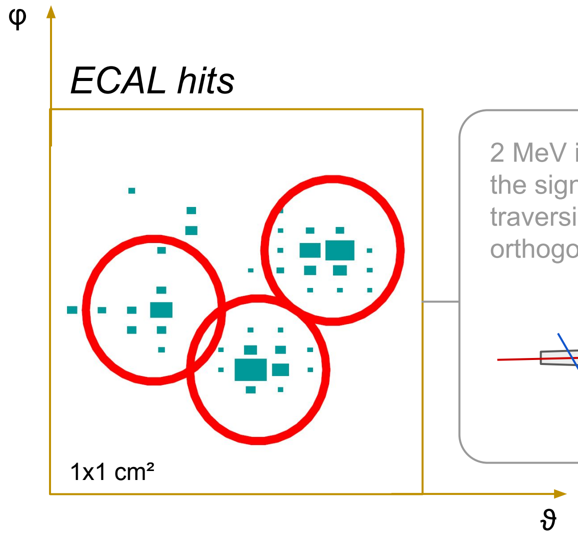
- **General strategy**: implement a particle flow approach in a high resolution dual-readout calorimeter with moderate longitudinal segmentation:
  - Maximally exploit the information from the **crystal ECAL** for classification of EM clusters and use it **as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter measurements
  - 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

DR-pPFA overview

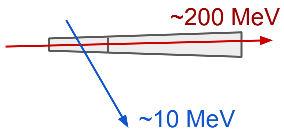


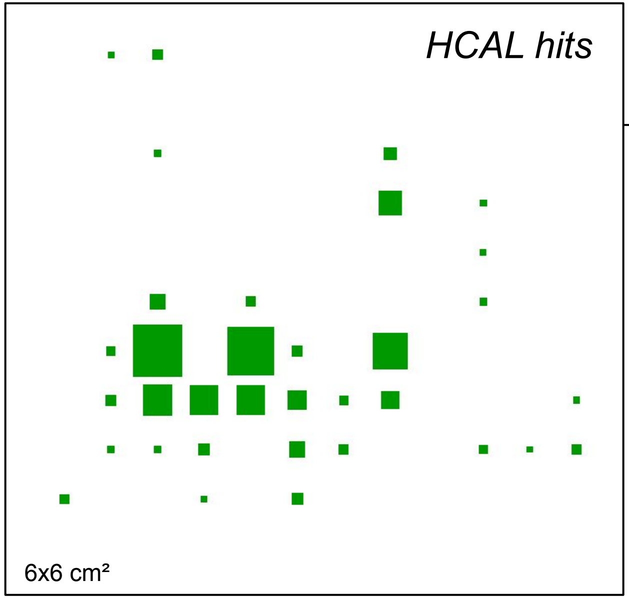
Readout granularity and calorimeter hits

- Readout granularity of fiber towers (~6x6 cm²), crystal granularity (~1x1 cm²)
- Consider all calorimeter hits with energy > 2 MeV
- Every hit 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)



2 MeV is about 20% of the signal from a MIP traversing a crystal orthogonally to its axis

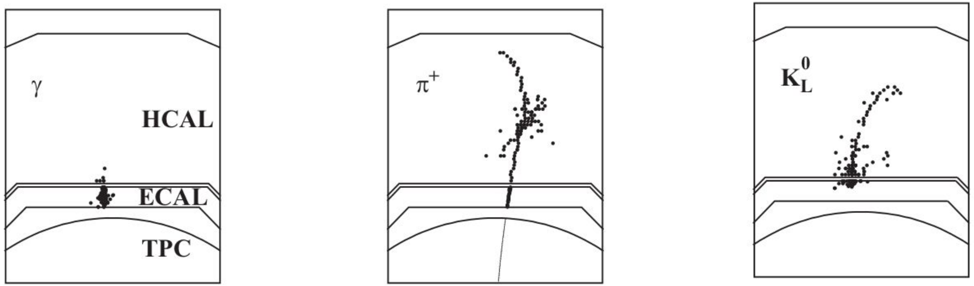




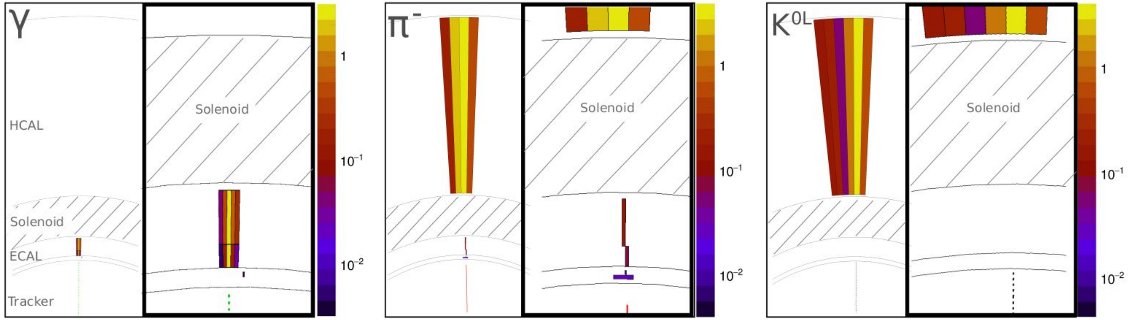
Readout granularity in the baseline IDEA DRO calorimeter is much finer:

- at single fiber level → O(mm)
- or grouping 8x8 fibers → O(cm)

Single particle identification through ‘hits-topology’



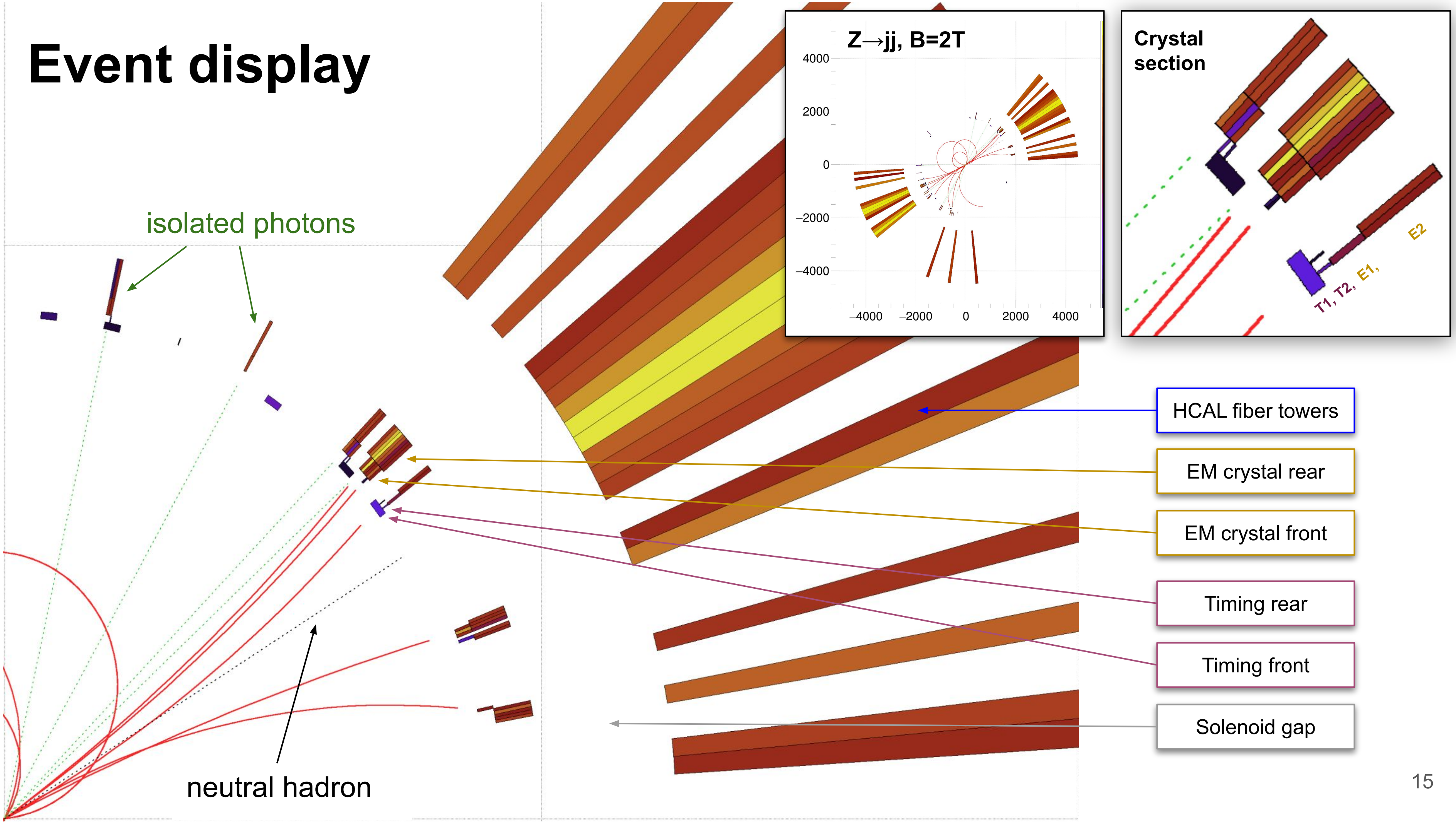
Typical PFA with Si-W high granularity calorimeter



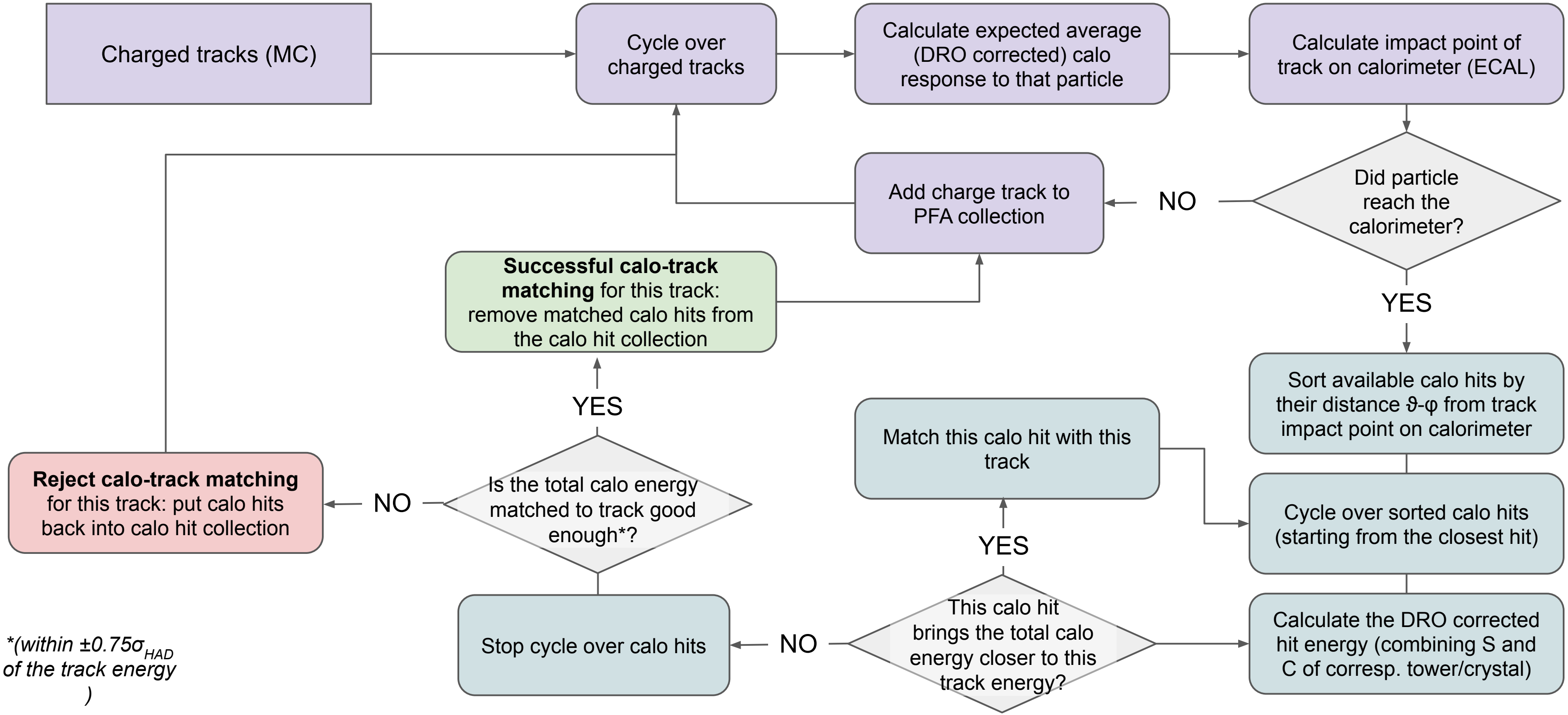
DR-pPFA with high resolution DRO calorimeter

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

Event display

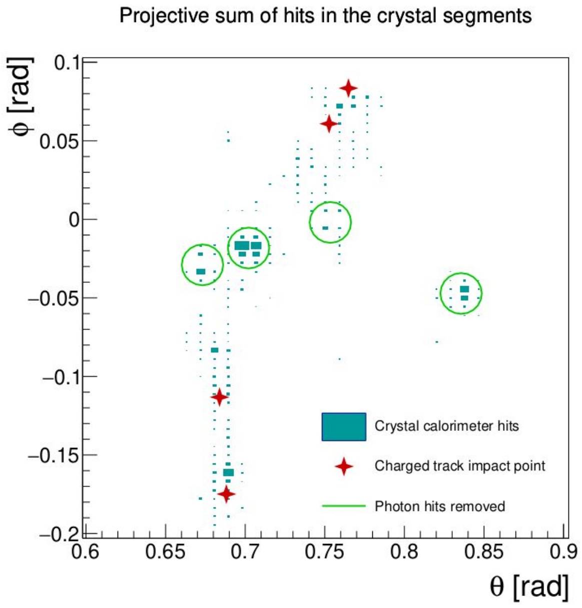


Track-hit matching algorithm



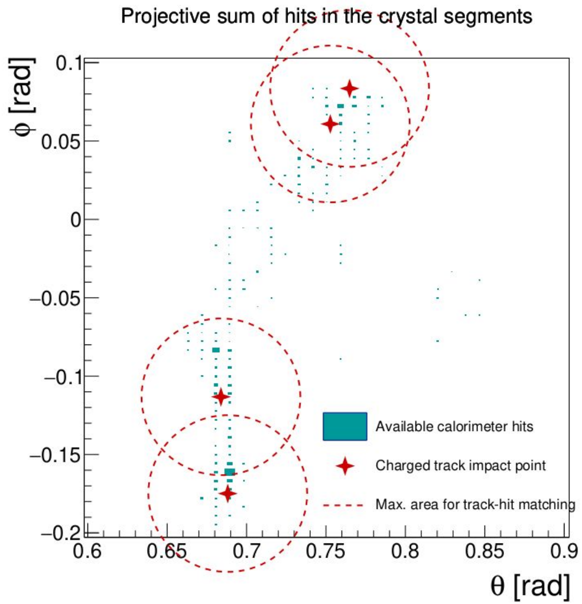
(within ±0.75σ_{HAD} of the track energy)

Step 1: identification of photon hits in crystal ECAL



- Identification of calorimeter hits in the crystal section associated with photons (and removal of such hits from collection)
- Currently done by selecting hits within a certain radius with respect to MC truth information of the photon hit position
- Working on a MC truth-independent photon seed algorithm

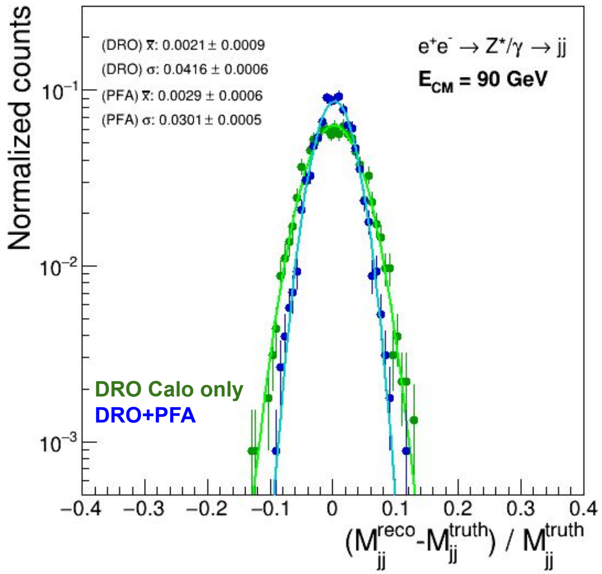
Step 2: matching tracks to calo-hits

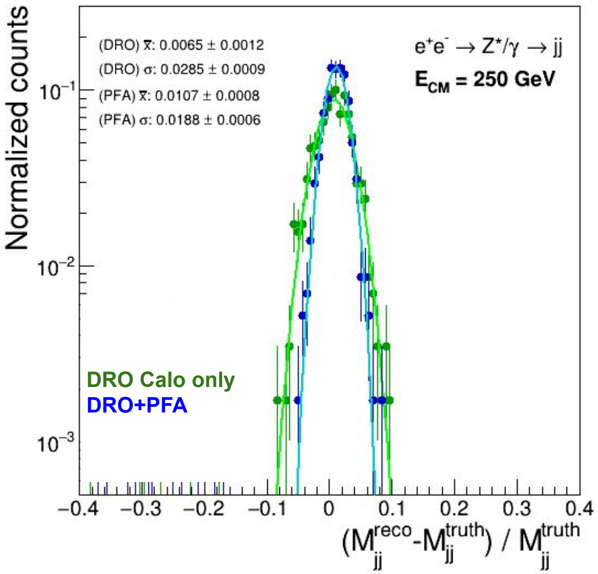


- Performing iterative search of hits collection to match calorimeter hit to a certain charged track (impact point of charged particle on calorimeter calculated analytically with helicoidal trajectory)
- Swapping out calo hits with charged tracks if the sum of energy from the hits matched to a certain track is close enough to expected energy
(~75% of tracks are “successfully matched”)
- Working on a neutral seed clustering algorithm for additional clean up of calorimeter hits from neutral hadrons

Dijet invariant mass distributions

- Reasonably Gaussian distributions: no need to use rms90 to estimate resolution

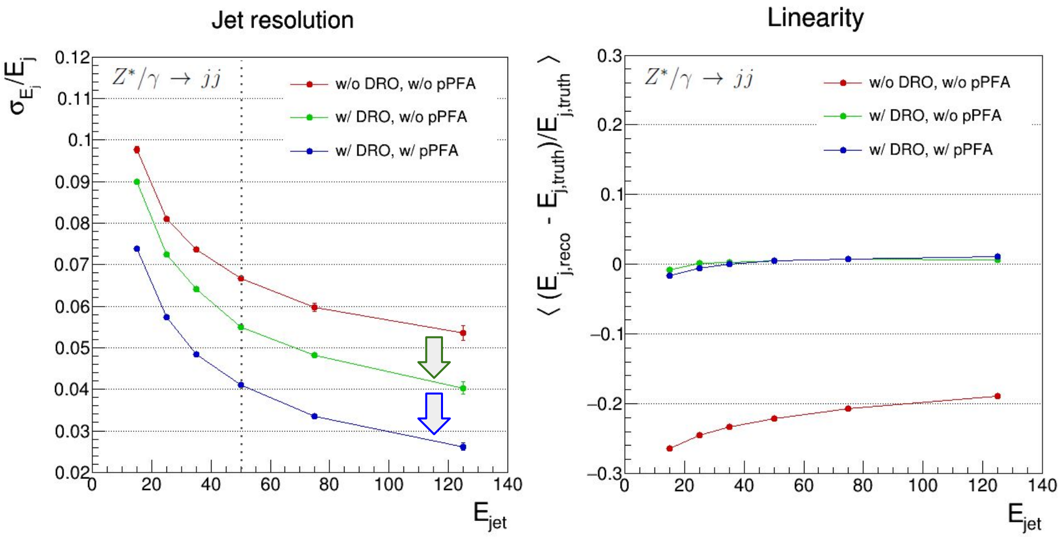




Jet resolution: with and without DR-pPFA

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 and outlook

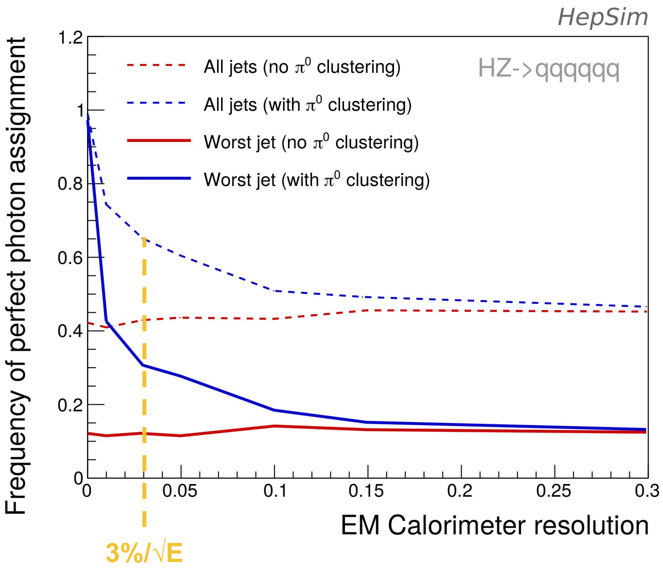
- Integration of a high EM resolution crystal calorimeter within the IDEA DRO calorimeter can open new possibilities to improve objects and jet reconstruction:
    - **π^0 clustering algorithm to enhance correct association of photons to the corresponding jet** in 4 and 6 jet event topologies
    - Implementation of a **simplified particle flow algorithm shows improvement of jet energy resolution** achieving ~3% for 50 GeV jets in dijet events reconstructed with crystals in front of the fiber calorimeter

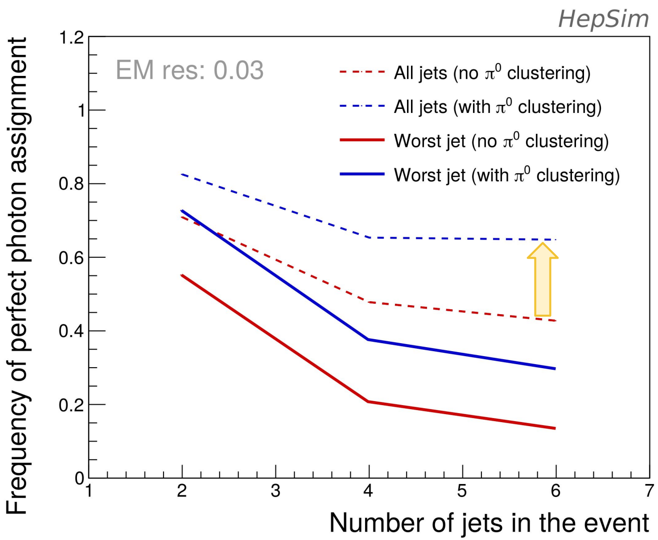
- **Outlook and ongoing work**
    - **Improve reconstruction of photons and neutral hadrons with ECAL seed based clustering**
    - **Implement clustering of photons into π^0** in full Geant4 simulation as a first step before the jet clustering algorithm (expected improvement only in 4/6 jet topologies)
    - 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)

Additional material

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)



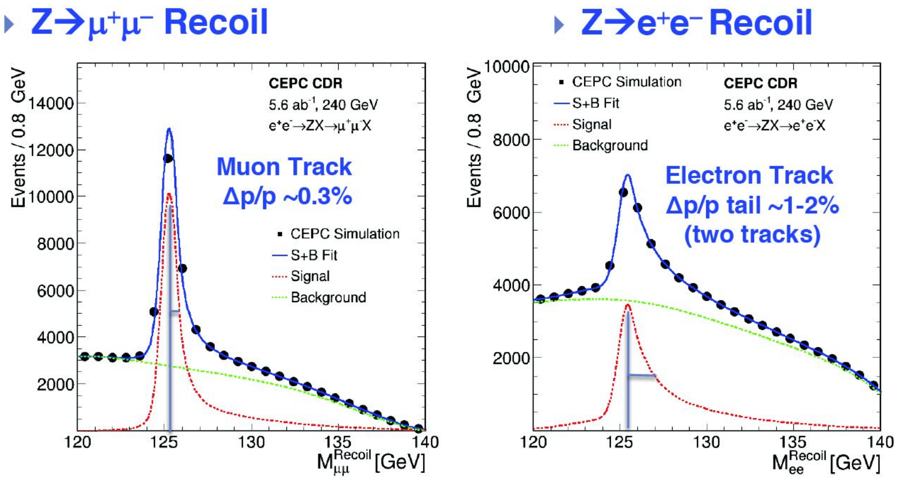


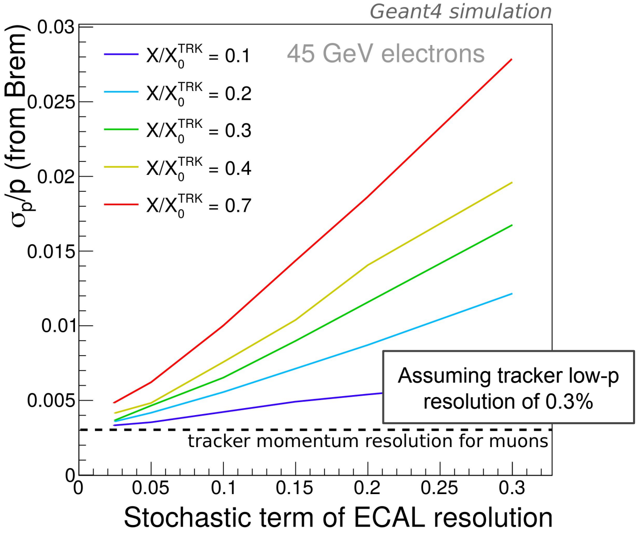
More details in:
https://doi.org/10.1088/1748-0221/15/11/P11005

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





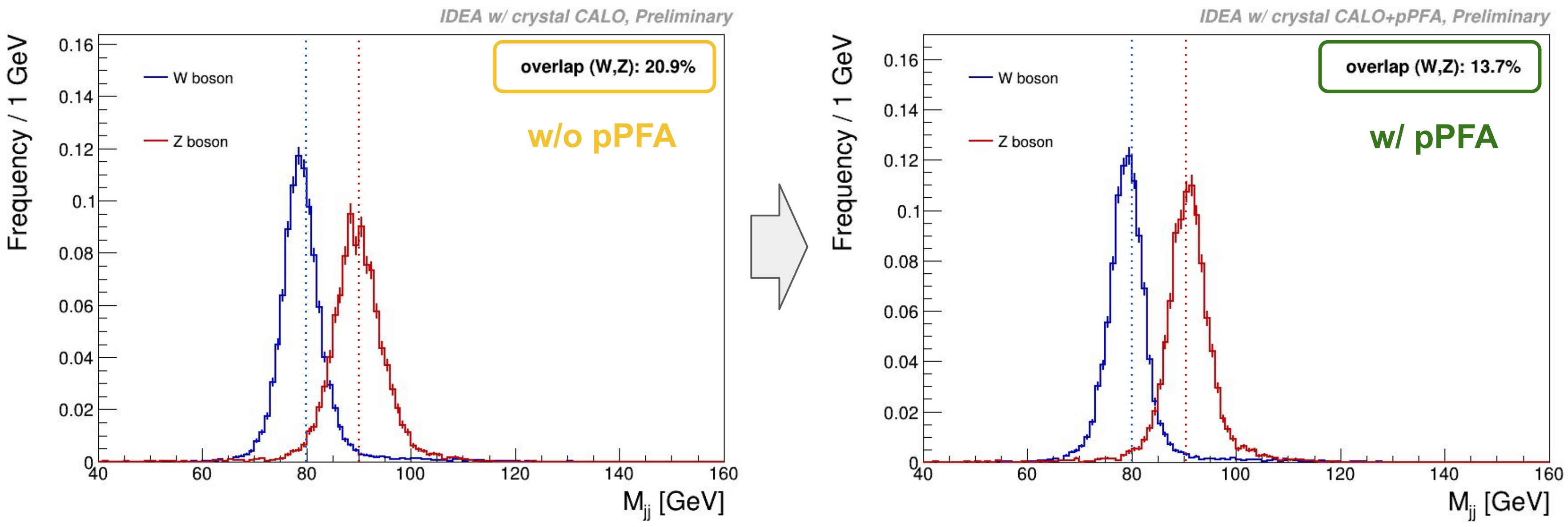
~80% of resolution recovery with 3%/√(E)

Boson dijet resonances

- Consistent improvement from pPF algorithm also in dijet boson resonances

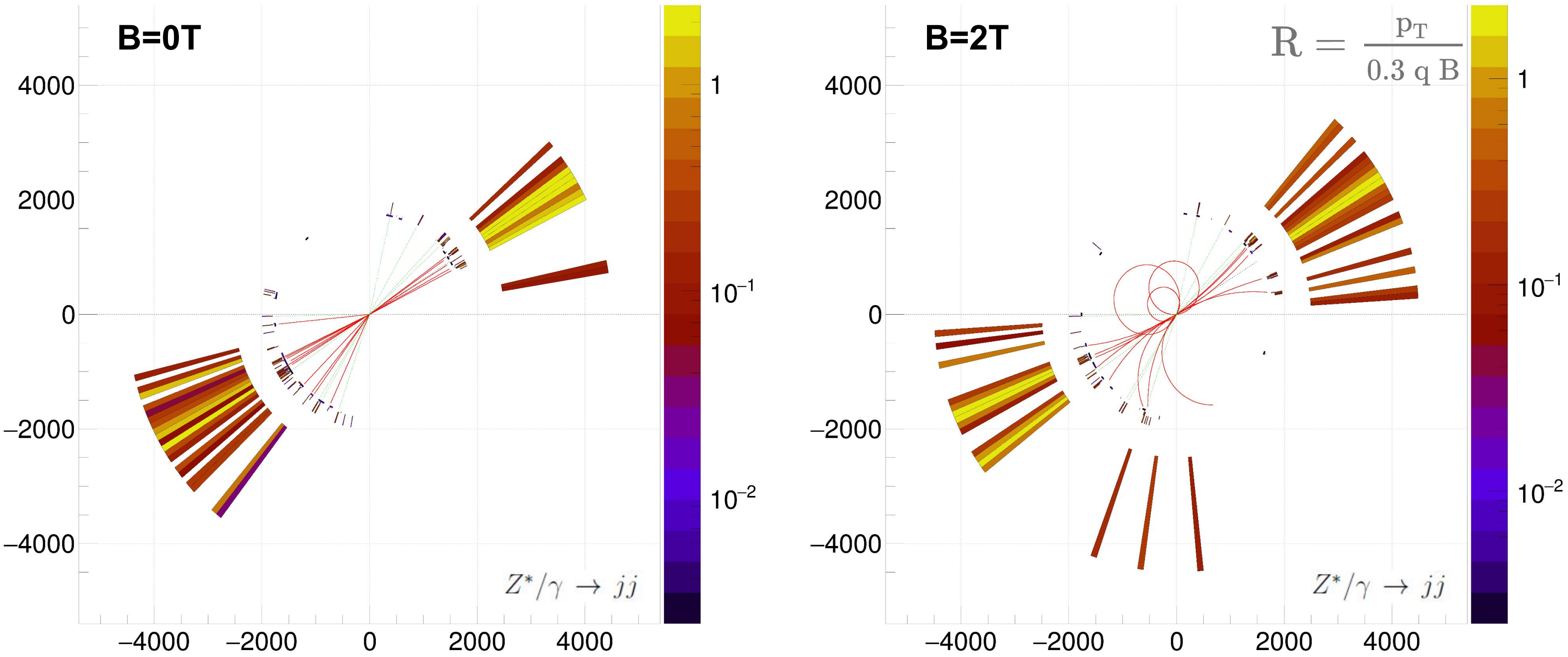
- $e^+e^- \to ZH,\ H \to \chi_1^0\chi_1^0,\ Z \to jj$
- $e^+e^- \to W^+W^-,\ W^+ \to \mu\nu,\ W^- \to jj$

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



Implementation of DR-pPF algorithm

Z→jj, event display



Introduction

- Goal:
  - Explore the potential for jet reconstruction from combining the performance of the dual-readout hybrid calorimeter (segmented crystals + the fiber sampling IDEA calorimeter) with a particle flow approach

- Tools:
  - Use HepMC samples from L.Pezzotti
  - Run through the Geant4 simulation with crystals (code on github)
  - Use MC-truth momentum at vertex and extrapolate impact point of track on calorimeter (start with B=0T first, then try with B=2T)

$Z^*/\gamma \to jj$

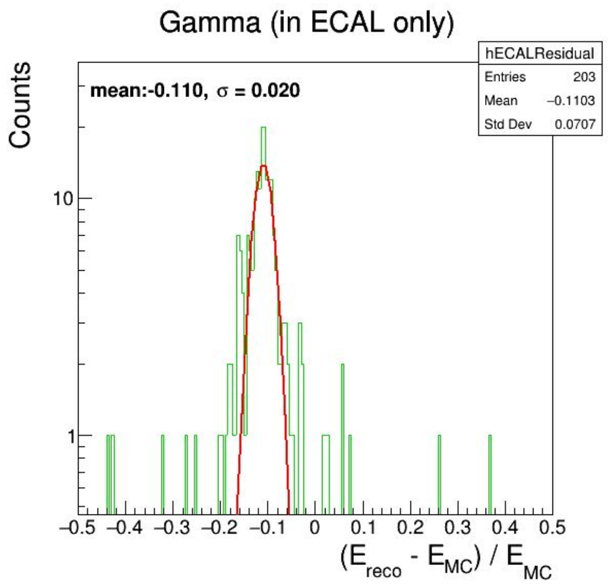
- $e^+e^- \to ZH,\ H \to \chi_1^0\chi_1^0,\ Z \to jj$
- $e^+e^- \to W^+W^-,\ W^+ \to \mu\nu,\ W^- \to jj$
- $e^+e^- \to ZH,\ H \to b\bar{b},\ Z \to \nu\nu$

1. Identify calo hits from photons

- **Swap out all ECAL hits identified as belonging to a photon** in a separate collection
  - i.e. all hits within $\Delta R_{ECAL} < 0.013$ within a MC photon
  - *in reality: hits not matched to a charged track, with shower shape compatible with EM particle*

- The total energy of hits swapped out in this way, $\mathbf{E_{gamma,filtered}}$ corresponds to about 90% of all the photon energy in the event (with a good resolution), the other 10% of photon hits are passed as calo hits to the pPF algorithm

- *Assuming photons entirely contained in ECAL, valid for photons within jet with MPV at 1-2 GeV*



2. Swap out charged calo hits with tracks

- **Feed the remaining ECAL + HCAL hits (C+S) and charged tracks from MC truth to the proto pfa algorithm**

1. For each charge track, T_i, run through the calo hits sorted by their distance from the track impact point on the calorimeter (ECAL) in increasing order, i.e. start with the closest hits and accept only hits within loose $\Delta R_{ECAL,HCAL}$ cuts (0.05, 0.3 resp.)

2. Consider the calo hit energy as the dual-readout corrected one: $\mathbf{E_{hit}} = (S_{hit}-\square*C_{hit})/(1-\square)$

3. **If** the energy clustered so far (E_{calo}) is smaller than the target energy (expected DRO corrected calo response for MC truth energy of T_i, $\mathbf{E_{target}}$) and if the addition of E_{hit} brings $\mathbf{E_{calo}}$ closer to E_{target} than add the hit (E_{calo} += E_{hit}) **otherwise** stop clustering

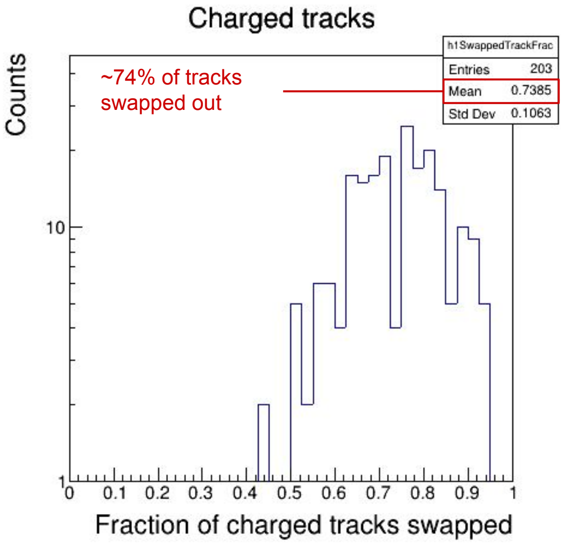
4. Once the clustering cycle over calo hits is over for a given track, T_i,
   a. **if** the clustering was “good enough” (**E_{calo} within ±0.75σ from E_{target}**, where σ is the expected single hadron energy resolution at that energy):
   → swap out all the clustered calo hits and this MC truth track to the PFA collection
   b. **else**:
   → do not swap out these calo hits and do not add this charged track to the PFA collection

5. After running over all MC truth charged tracks the algorithm returns two collections:
   a. the charged tracks for those particles that have been swapped out
   b. the ‘leftover’ calo hits (should be only the neutral component in the ideal case but has remnants from charged hadr. too)

pPFA control plots (1)

Fraction of charged tracks swapped out by the algorithm

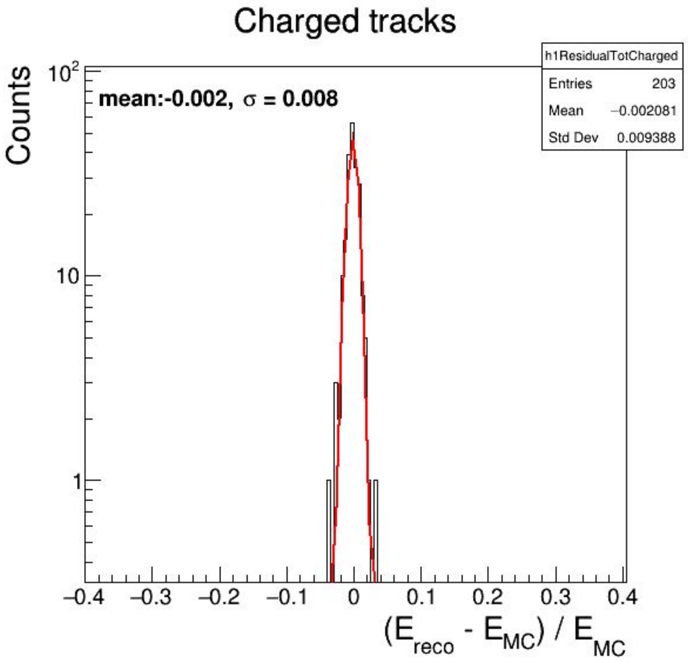
Residual of energy of swapped out charged tracks $(E_{calo} - E_{MC}) / E_{MC}$



Sum of hits clustered as belonging to a certain charged track minus the MC truth particle energy (only for those particles that get swapped out)

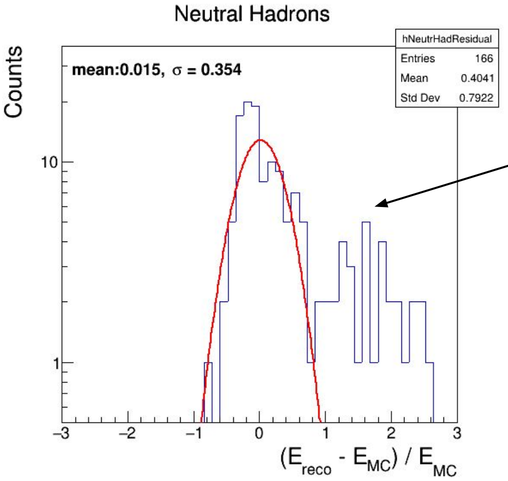
pPFA control plots (2)

Total energy of calo hits that are swapped out as belonging to MC charged particles minus the total MC truth energy of those charged particles

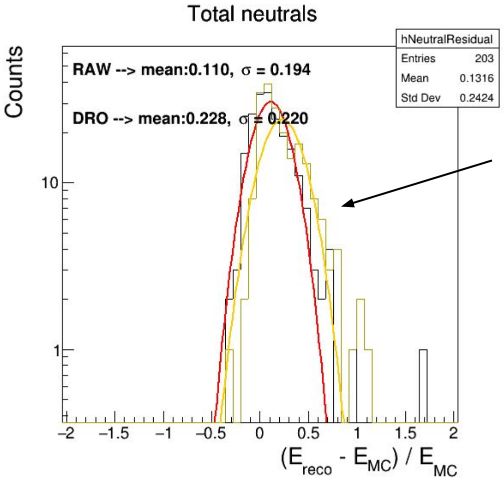


3. Neutral residuals

- The calo hits ‘leftover’ returned from the pPF algorithm contains a mixture of:
  - ~10% of the total photon energy
  - Some hits from charged particles (not swapped out)
  - Hits from neutral hadrons (mainly neutrons and K^{0L})
- A dual readout correction is applied to this energy contribution:
  - $E_{neutral,DRO} = (S_{neutral} - X*C_{neutral}) / (1-X)$



Total energy of ‘leftover’ calo hits returned from the pPF algorithm minus the total expected energy of neutral hadrons (tails come from 10% residual photons and non-swapped charged hits)



Total energy of leftover calo hits returned from the pPF algorithm + the photon hits filtered out at step 1 minus the total expected energy of neutrals (photons+neutral hadrons)

Resolution comparable with expected neutral hadron resolution?

4. Jet clustering

Jet clustering algorithm (FASTJET, generalized k_t algorithm with R = 2, p = 1 and forcing the number of jets to two → similar to Durham) is run over the collection of 4D-vectors returned from the pPFA and consisting of:

- Calo hits from photons, filtered out (at step 1) → only the ***S*** calo hits
- Swapped-out charged tracks (step 2) → MC-truth momentum vector
- 'Leftover' calo hits (step 3) → both ***C*** and ***S*** calo hits

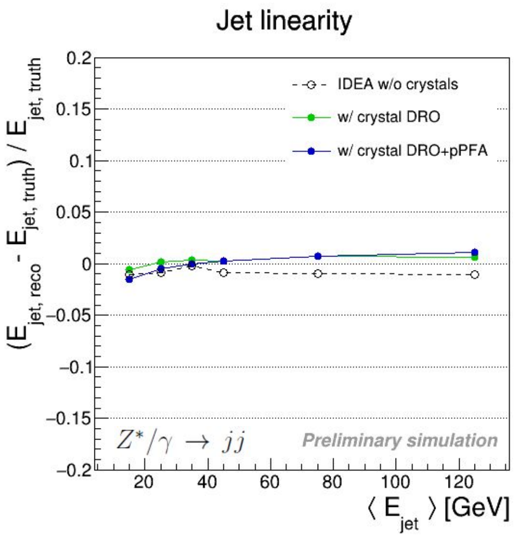
The total jet energy is then defined as the sum of three contributions clustered within the jet and multiplied by a scale factor k_{PFA}~ 1.027:

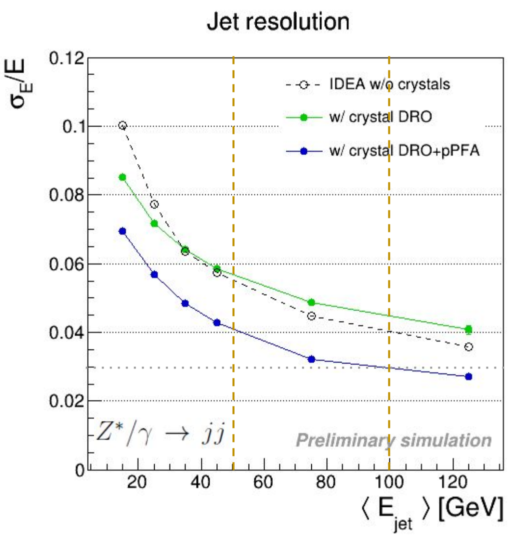
$$\mathrm{E_{jet}} = \mathrm{k_{PFA}} \cdot (\mathrm{E}\gamma + \mathrm{E_{track}} + \mathrm{E_{leftover,DRO}})$$

Results: comparison with IDEA fiber calo only

Dijet invariant mass resolution*sqrt(2) and linearity as a function of average jet energy energy in $Z^* \rightarrow jj$ events

- IDEA w/ DRO (data analysis from L.Pezzotti)
- crystals + IDEA w/ DRO (same samples and similar procedure/cuts as used for IDEA only results)
- crystals + IDEA w/ DRO + pPFA

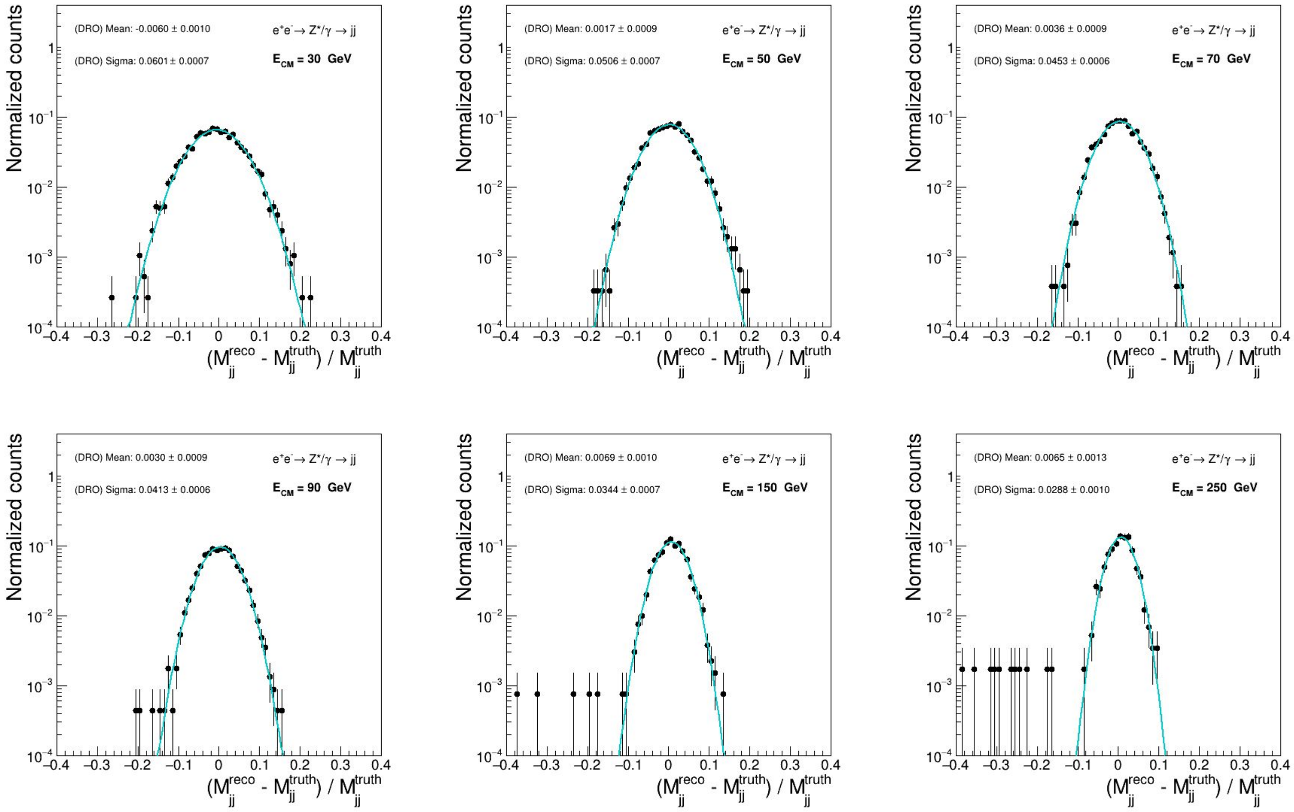




better than 4% jet energy resolution for 50 GeV jets

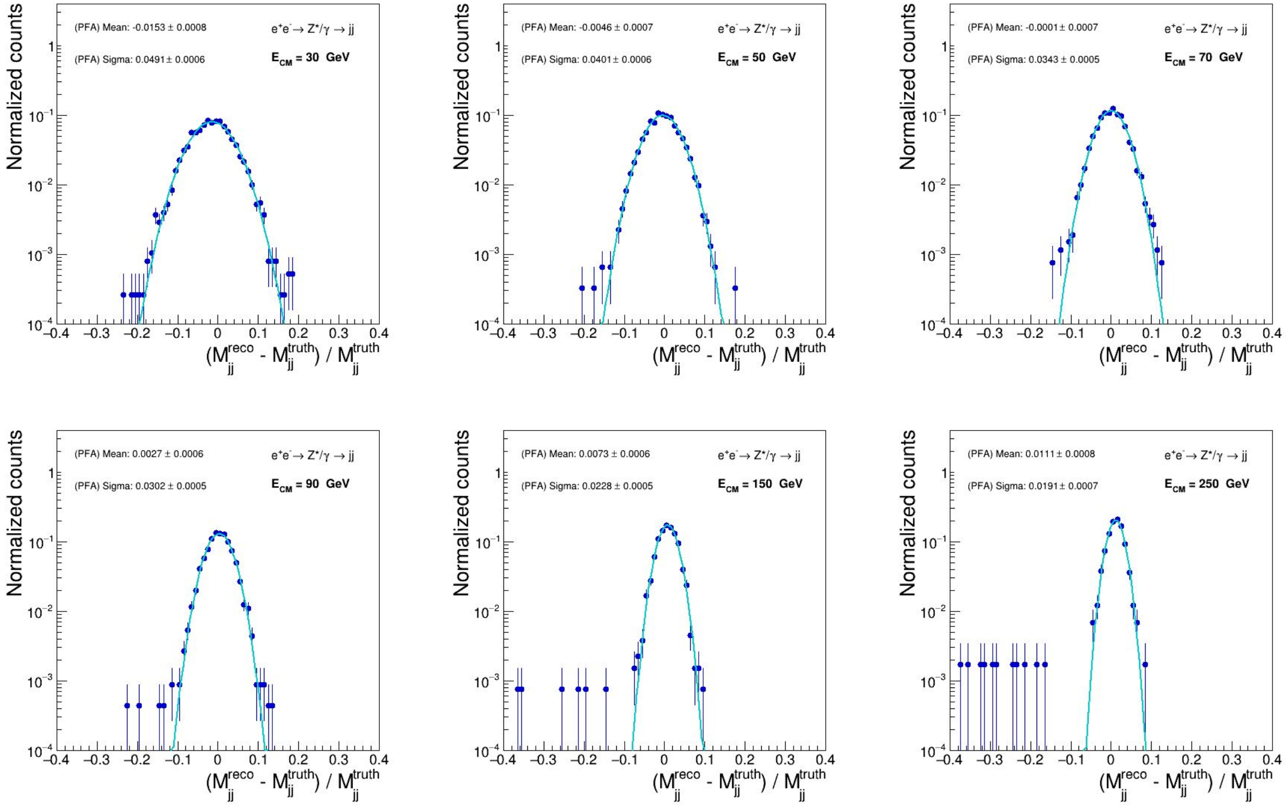
better than 3% jet energy resolution above 100 GeV

With crystal calo DRO



$Z^*/\gamma \to jj$

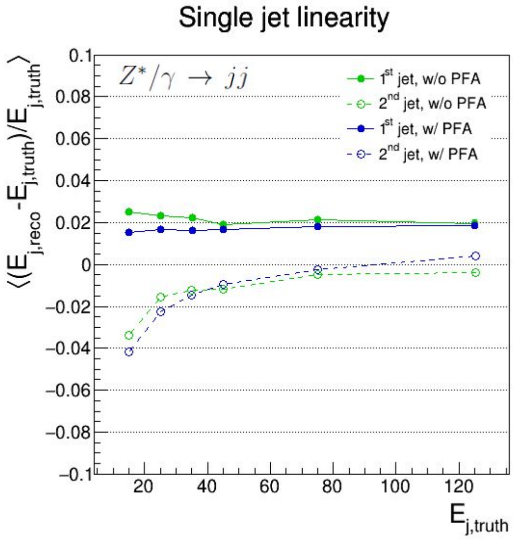
With crystal calo DRO + PFA

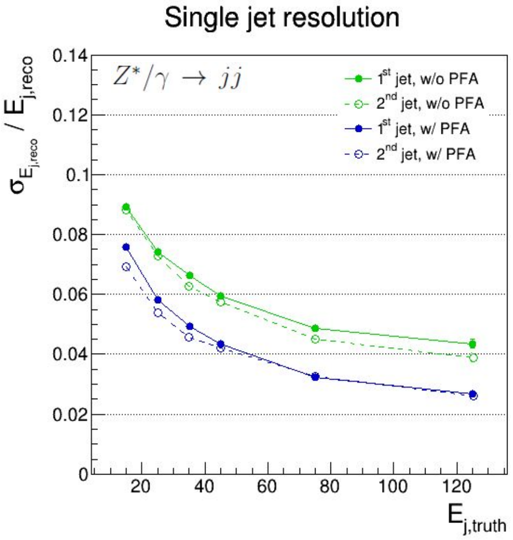


$Z^*/\gamma \to jj$

Single jet linearity and resolution

- Single jets have comparable energy resolution, also consistent with $M_{jj}*\sqrt{2}$
- Leading jet tends to cluster 2% energy from sub-leading one
- Second jet more sensitive to non linearity effects below 30 GeV

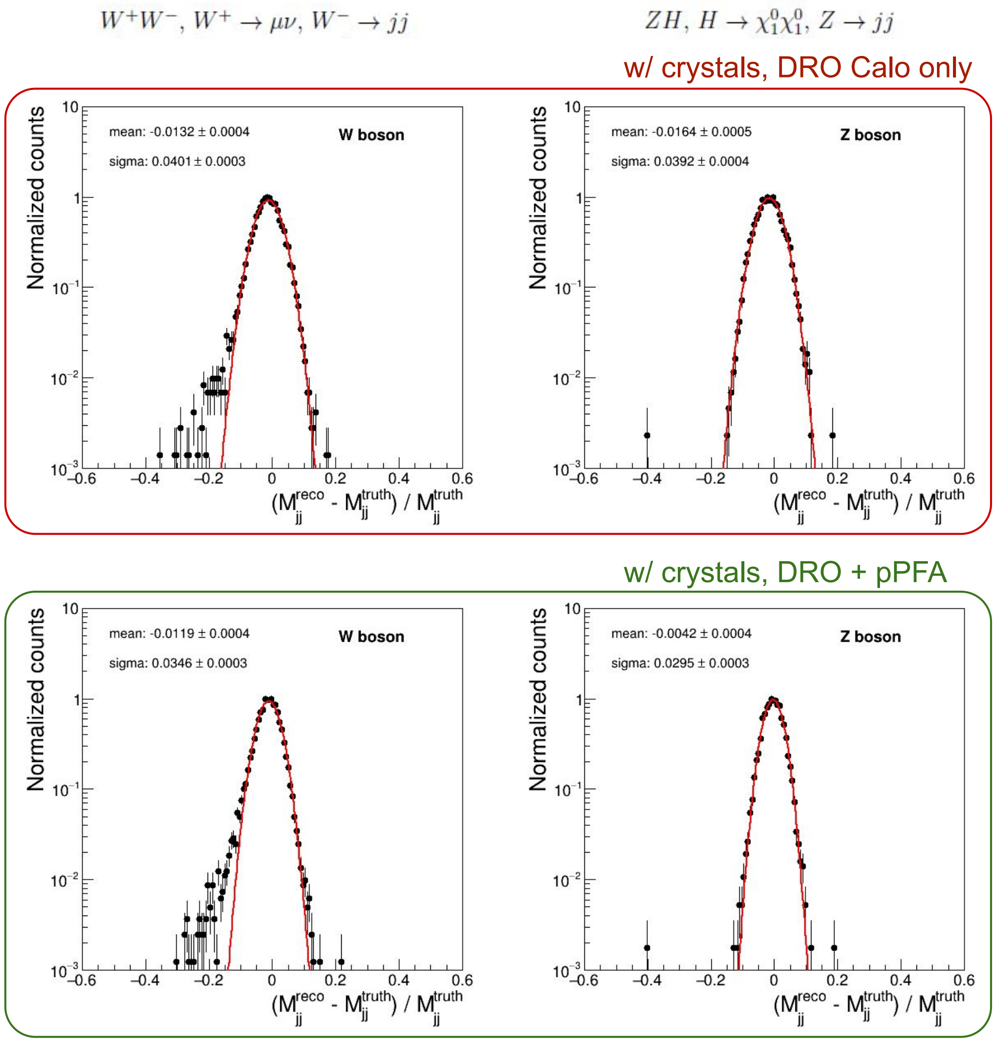




Energy resolution

- Consistent improvement from pPF algorithm also in dijet boson resonances

- Gaussian distributions
    - low energy tail in W events attributed to leakage and/or overlap of the muon energy with one of the jets

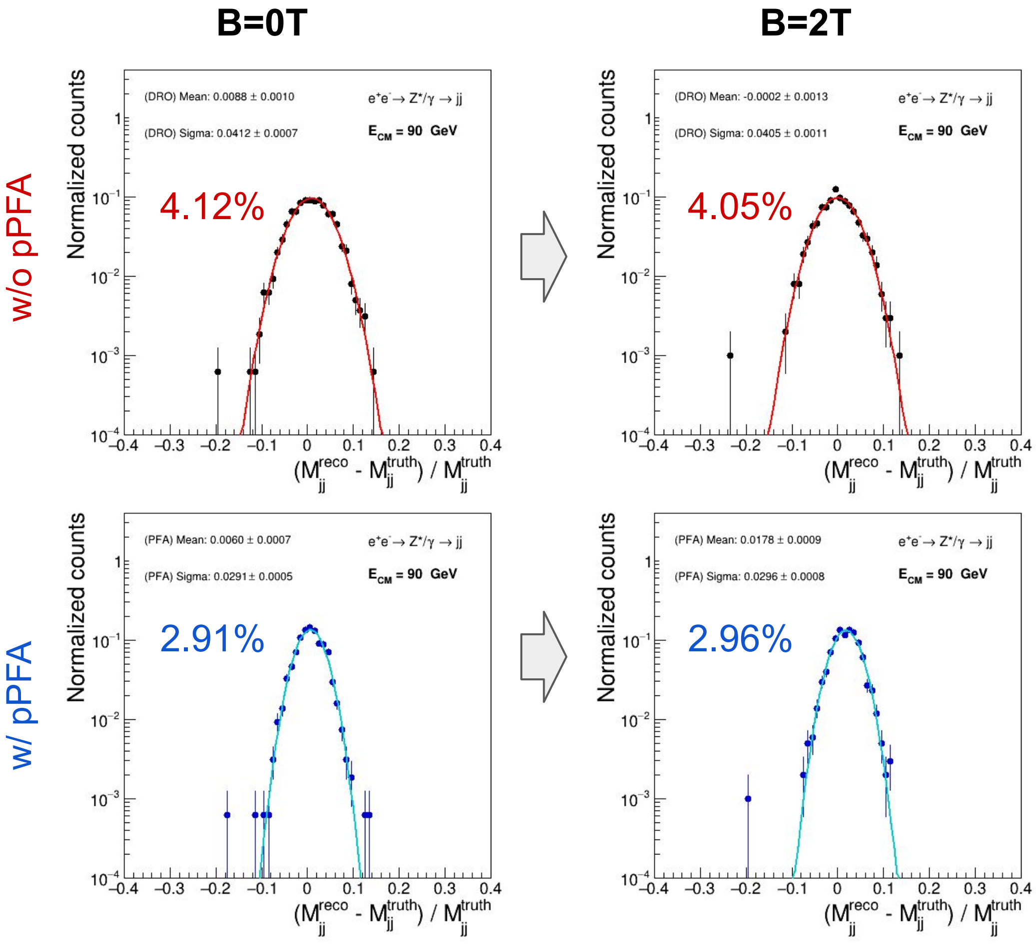


Impact of magnetic field

- Low energy charged pions are bent by the magnetic field (2T)
  - If $p_T \lesssim 2$ GeV they do not reach the calorimeter (R_{ECAL}~1.8 m)
  - Low p_T that reach calorimeter cause hits in more crystals/towers (curved trajectories)

- Preliminary results show negligible impact of magnetic field on performance
  - Low p_T particles (not reaching the calo) are assumed to be measured by the tracker

E_{leak}< 0.1 GeV



More on jet studies with pPFA

Event cleaning in Z*→jj samples

Cuts used for IDEA Calo only	Cuts used for crystal+IDEA Calo

Event cleaning Before studying the jet calibration and the calorimeter energy reconstruction performance, we need to select jets such that all of the particles contributing to the jets are fully or, at least, largely absorbed in the calorimeter. We define therefore the following cleaning cuts:

- reject events containing muons or neutrinos among the final states passed to GEANT4,
- require that the pseudorapidity of each of the two jets is within $|\eta| < 2$ to ensure a good lateral containment, → Restrict to barrel region → |eta| < 1.4
- reject events in which the kinetic energy carried by escaping particles (except neutrinos) from the back of the calorimeter is in excess of 0.1 GeV. The cut value was chosen by studying the spectrum of the particles escaping the calorimeter from the back as provided by GEANT4, → Looser cut on leakage energy at 0.3 GeV
- reject events where the sum of the energies measured by the scintillating fibers is below a fixed value, dependent on the center-of-mass energy. → This cut is not applied
    - why would it be justified?
    - how could it be implemented in the real detector?
    - what would be the equivalent cut in the hybrid calorimeter?

The last cut is justified by the fact that we want to exclude the small fraction of events where the total visible energy deposited into the calorimeter is too small compared to the sum of the energies of the particles being absorbed into it. The visible energy deposited in

Event cleaning in dijet boson resonances

Cuts used for IDEA Calo only

- $e^+e^- \to ZH$, $H \to \chi_1^0\chi_1^0$, $Z \to jj$
The Z is required to decay only in u,d,s,c quark pairs. The events are cleaned requiring that no neutrinos or muons enter the calorimeter, that the two reconstructed jets are within 2 in pseudorapidity, and that the energy leaked behind the calorimeter is smaller than 1 GeV.

- $e^+e^- \to W^+W^-$, $W^+ \to \mu\nu$, $W^- \to jj$
The cleaning requirements are the same as for the Z, except that one muon and one neutrino are admitted, and, given the presence of the muon, the requirement on the leakage is modified into the requirement that the difference between the energy of the muon, as assumed to be measured in the inner detector, and the sum of the leaked energy and the scintillating-fiber energy deposited in the calorimeter, in a cone of $\Delta R = 0.1$ around the muon direction, is smaller than 1 GeV.

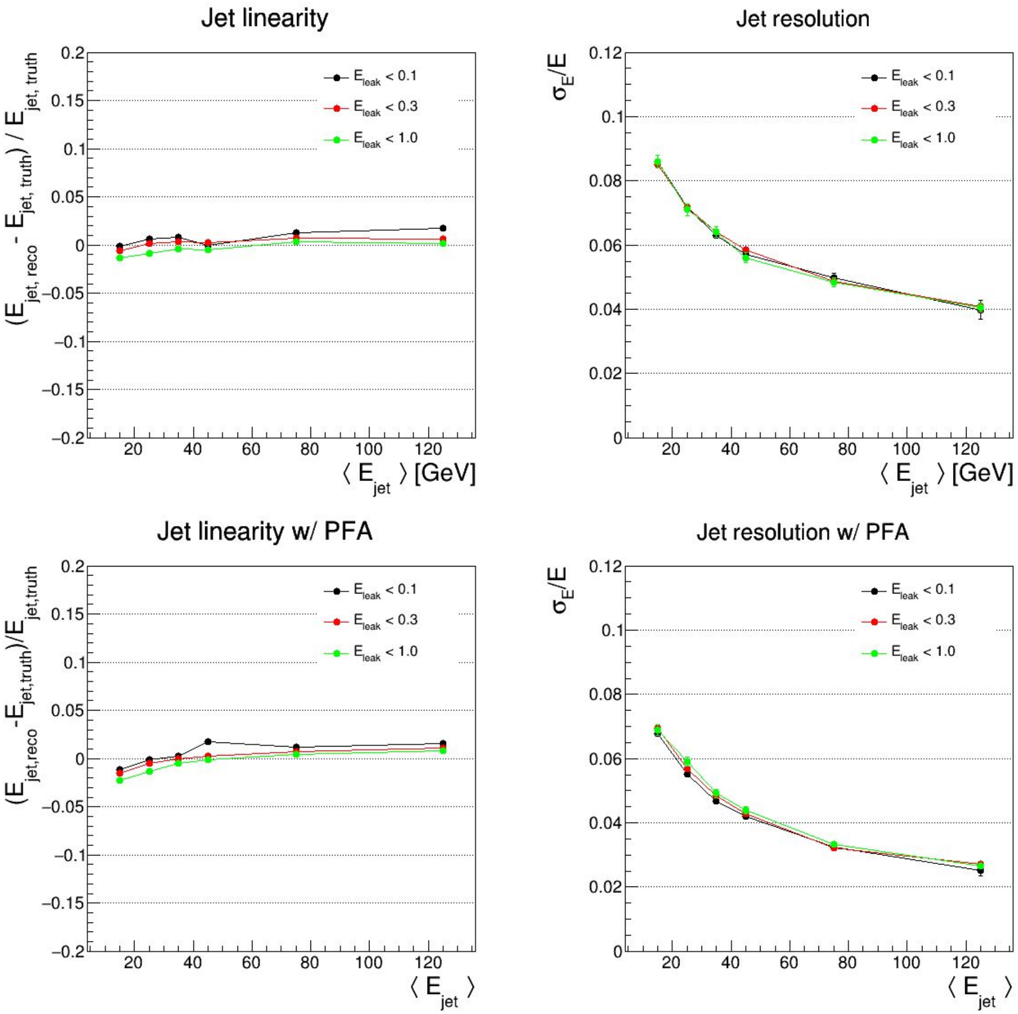
- $e^+e^- \to ZH$, $H \to b\bar{b}$, $Z \to \nu\nu$
The cleaning requirements are the same as for the Z, except that no neutrinos beyond the ones from the Z decay are accepted. Since the Higgs decay into $b\bar{b}$ has a large semileptonic branching ratio, the requirement of no neutrinos strongly reduces the statistics. We also looked at the distribution obtained while including the semileptonic decays.

Cuts used for crystal+IDEA Calo

- Same cuts but restrict to barrel, |eta| < 1.4
- Cut on energy deposited by the muon to account for energy deposited in the crystals
- Same cuts

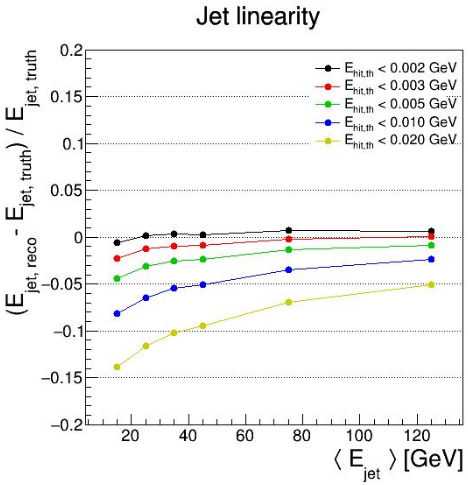
Impact of energy leakage cut on jet resolution

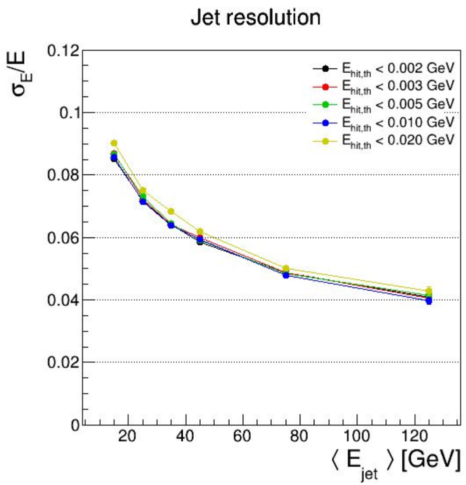
- Negligible impact on the jet resolution from a variation of the cut on leakage energy in the 0.1 - 1 GeV range



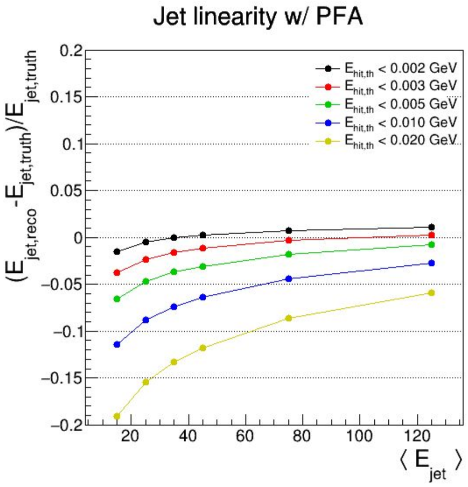
Impact of hit energy threshold on jet resolution

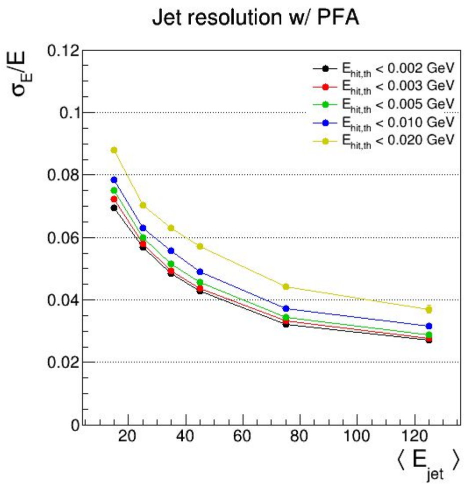
- $E_{hit,threshold}$: **2**, 3, 5, 10, 20 MeV
- Work in progress





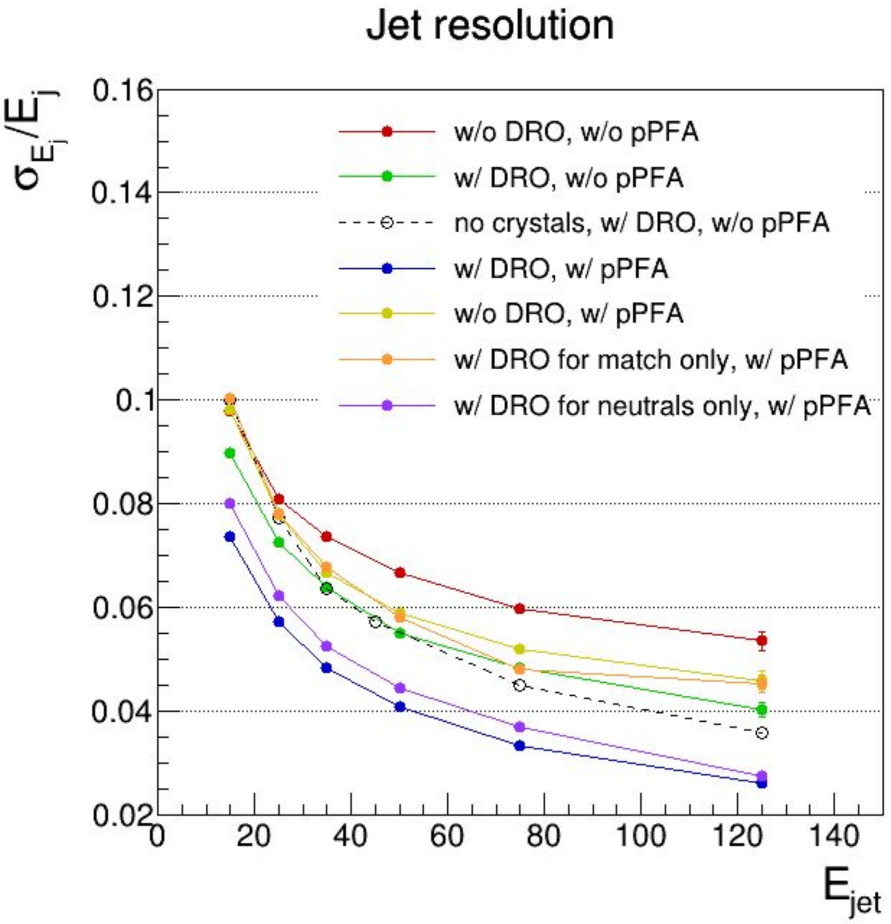
Target calo energy used for track matching is not re-calibrated to account for lower calo response with higher E_{hit} threshold → could explain stronger non linearity and degradation of resolution



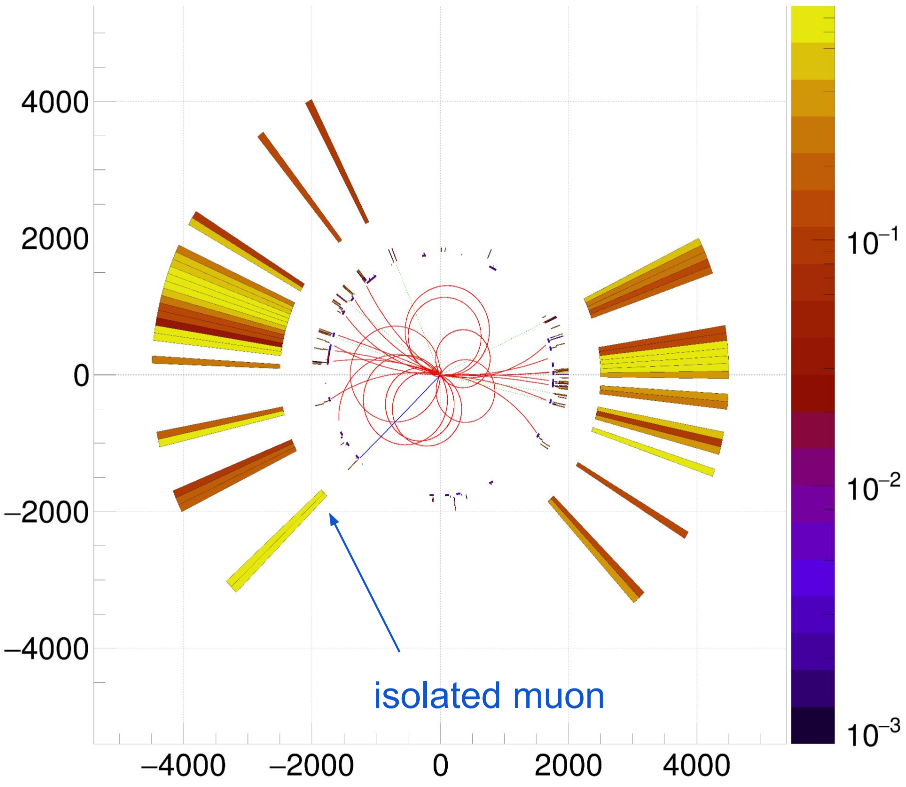


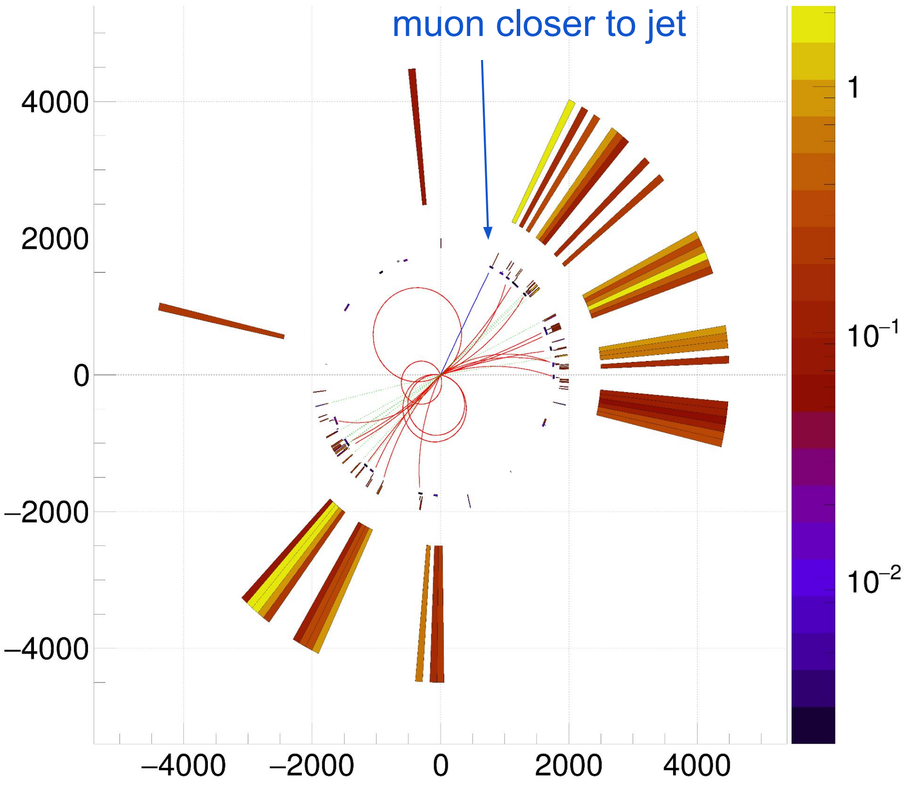
Jet resolution

- IDEA no crystal, calo only performance with DRO
- With crystals
  - Raw calorimeter response (no DRO, no pPFA)
  - Dual readout corrected calorimeter response
- With crystals and pPFA
  - Only pPFA (no DRO)
  - pPFA and DRO used to correct neutral component only
  - pPFA and DRO used for the track-hit matching
  - pPFA and DRO used for both track-hit matching and correction of neutral component



Event display, **WW → μvjj**

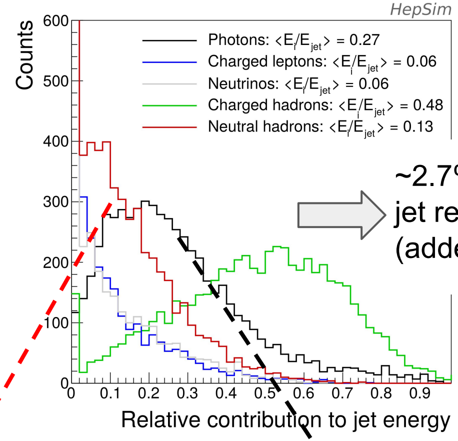




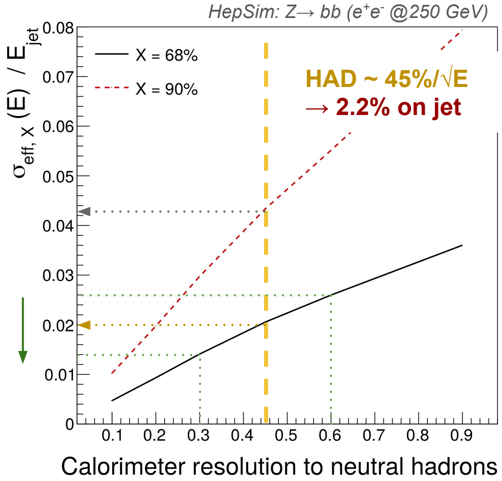
Traditional impact of calorimeters on jet resolution

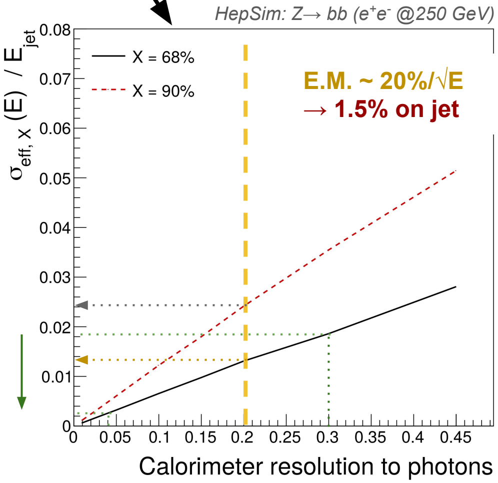
- Baseline jet performance depends on particle composition and the relevant sub-detector resolutions

- 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



~2.7% contribution to 50 GeV jet resolution from calorimeters (added in quadrature)

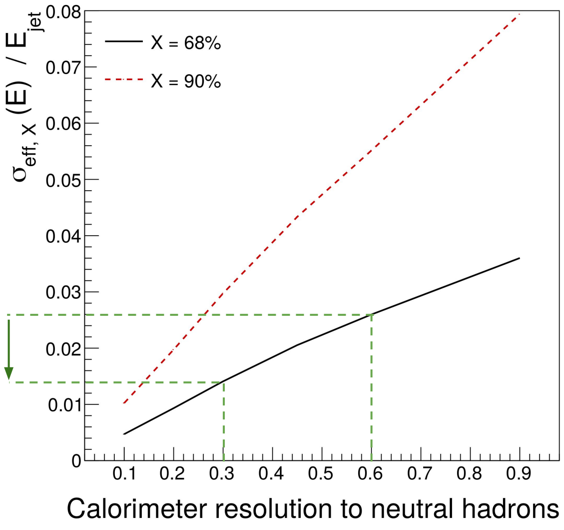


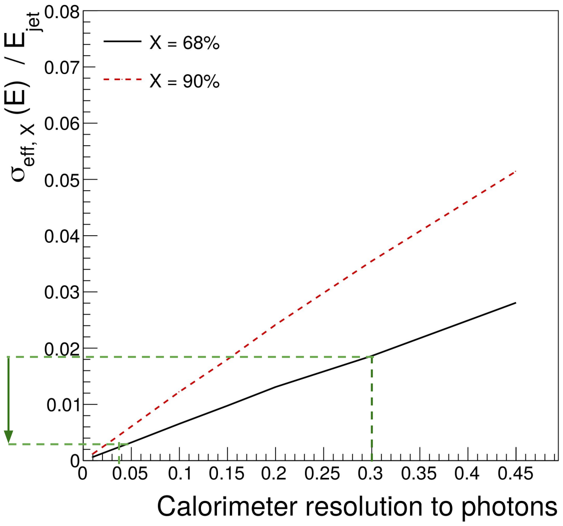


But the role of calorimeters in jet reconstruction spans beyond the direct impact on energy resolution...

Improvement of jet resolution from neutral component

- A calorimeter with **3%/√E** resolution for photons and **30%/√E** resolution for neutral hadrons can reduce the contribution of the "neutrals component" to the jet energy resolution from 1.8% to 0.5% and from 2.5% to 1.5 % respectively compared to a calorimeter with **30%/√E** resolution for photons and **60%/√E** resolution for neutral hadrons



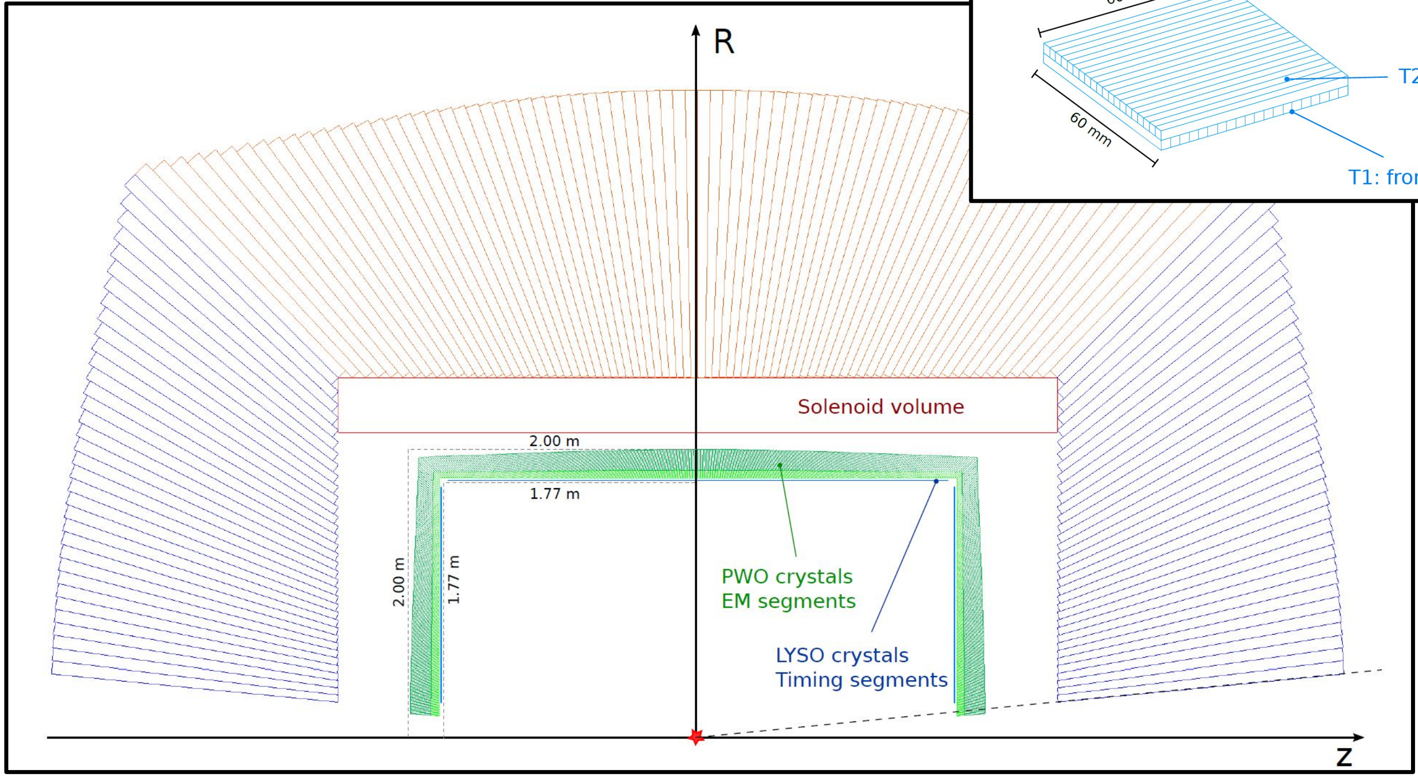


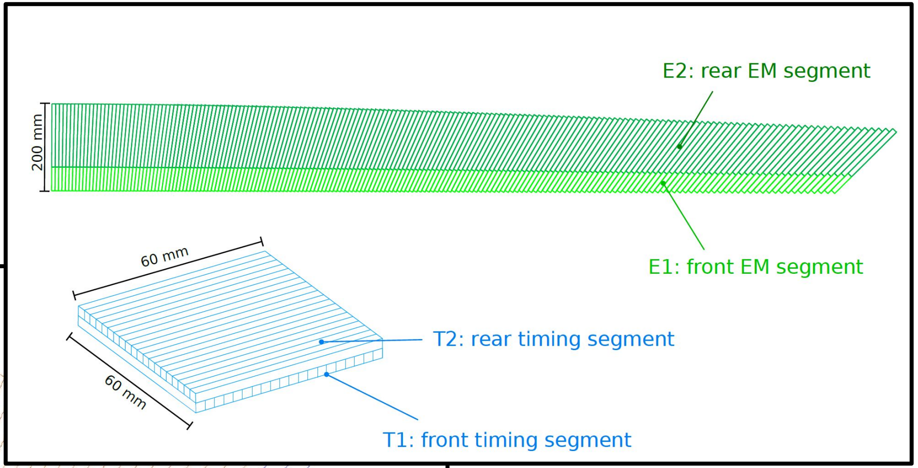
More on calo geometry and single particle performance

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 cm² 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:

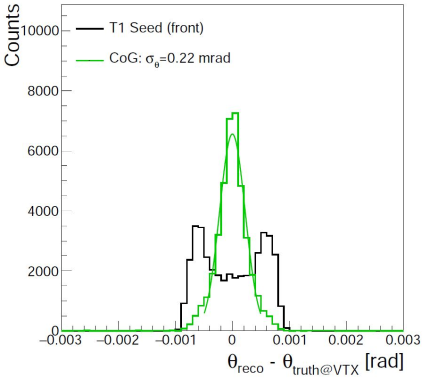
$$S_F = \mathcal{P}(E_{dep,F} \cdot LY \cdot \epsilon_S)$$
$$S_R = \mathcal{P}(E_{dep,R} \cdot LY \cdot \epsilon_S)$$
$$S = S_F + S_R$$
$$C = C_R = \mathcal{P}(N_{cher,prod,R} \cdot \epsilon_C)$$

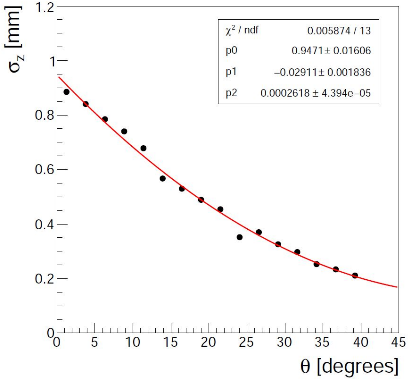
Scintillation signal from both front and rear segments

Cherenkov signal from only the rear segment

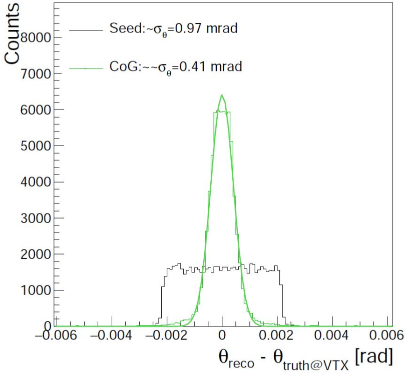
Angular resolution

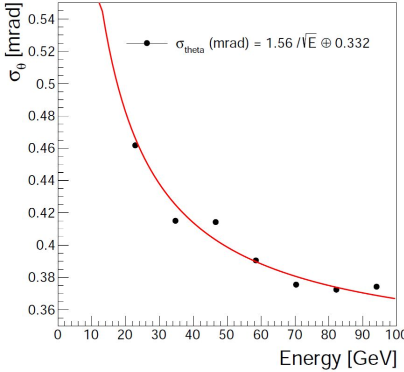
- **T1+T2:** 0.3-1.0 mm spatial resolution along z with the MIP timing layer grid (muons)





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





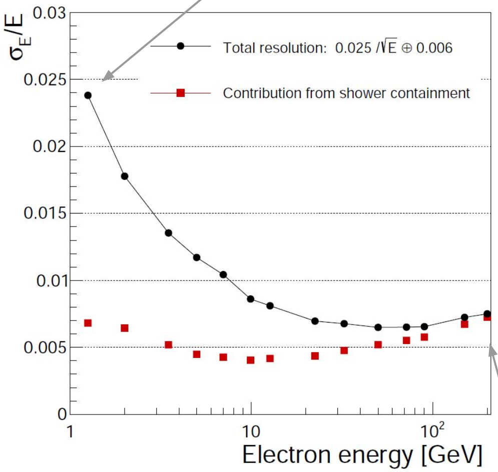
Energy resolution for EM particles

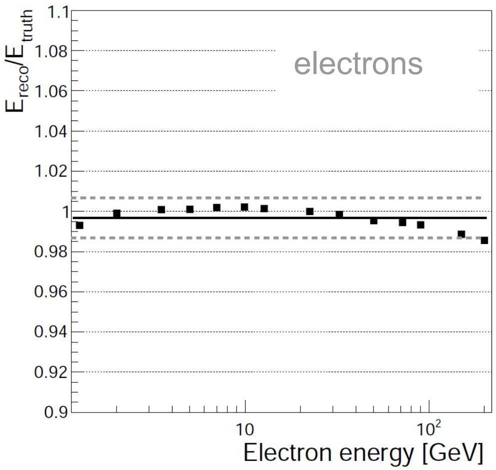
- Energy resolution:

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

- Linearity within ±1%

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

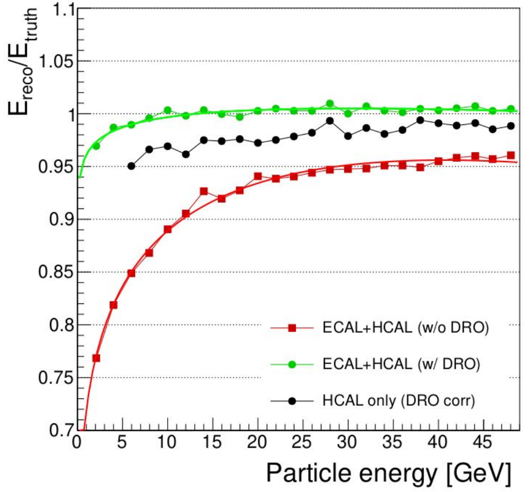


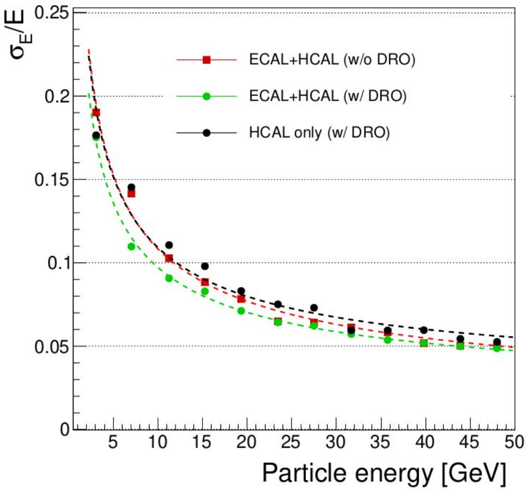


Some shower leakage beyond 200 GeV

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

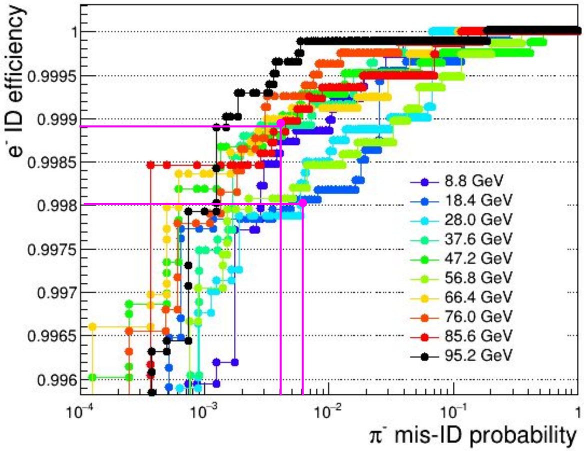




Particle identification with segmented crystals

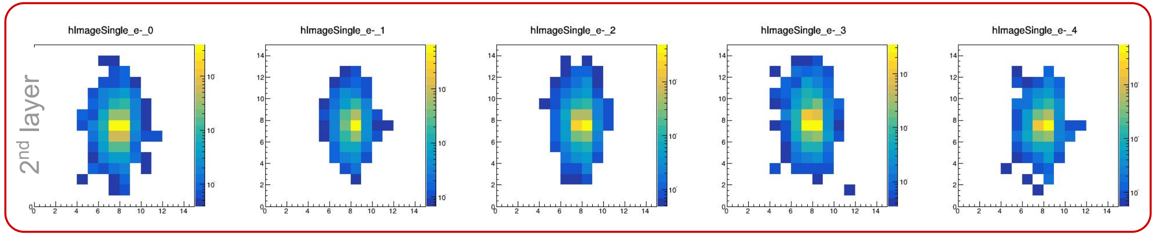
π± / e± identification with CNN

- Crystal calo only performance comparable to fiber calo only
- Further improvement by combining both calorimeter segments

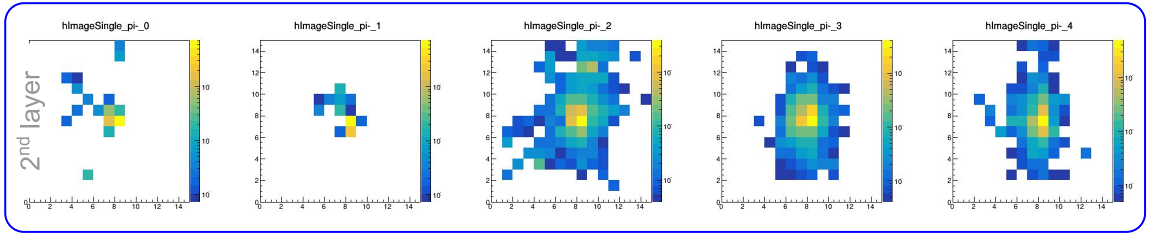


	IDEA Pb only		Crystal calo only	
	e⁻ ID	π⁻ mis-ID	e⁻ ID	π⁻ mis-ID
20 GeV	99.4%	0.8%	99.8%	0.6%
60 GeV	99.8%	0.4%	99.9%	0.4%

single e⁻ events



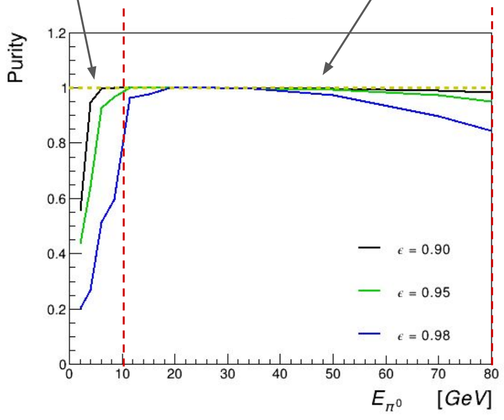
single π⁻ events

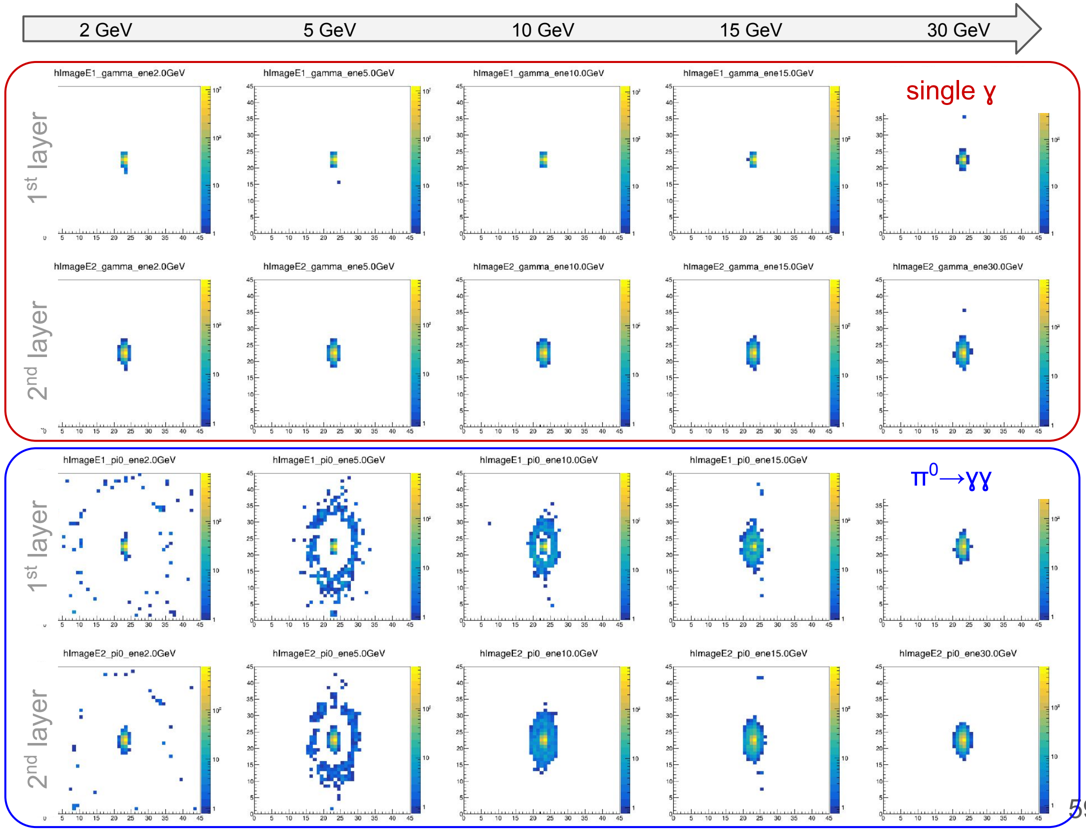


π^0 / γ identification with CNN

One photon with very low energy can be missed

Good separation in range 10-80 GeV



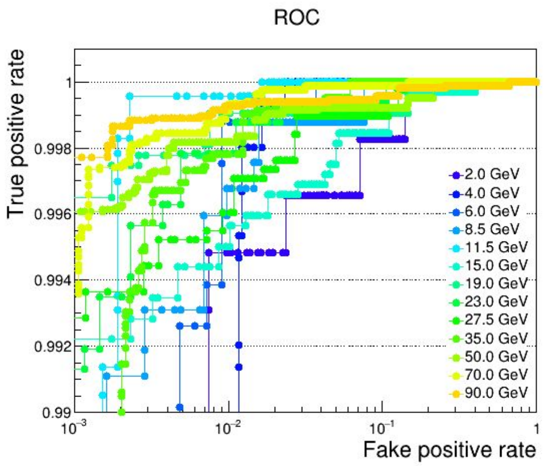


- In CEPC CDR requirement:

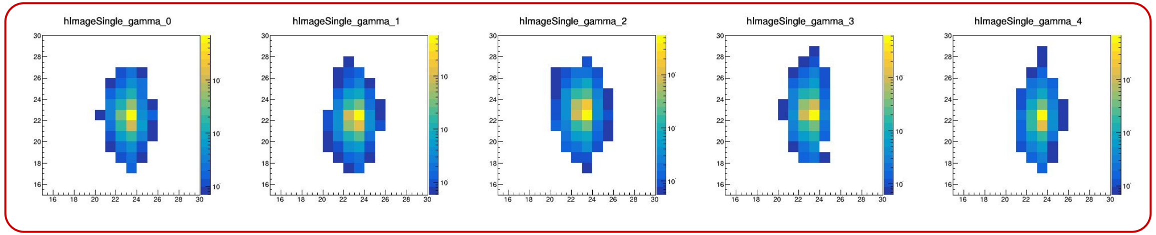
over all solid angle. To identify the τ-leptons in the different decay modes, the photons should be distinguishable from π^0's with an efficiency and purity higher than 95% measured in the $Z \to \tau^+\tau^-$ event sample at the CEPC Z factory operation.

K^{0L} / ɣ identification with CNN

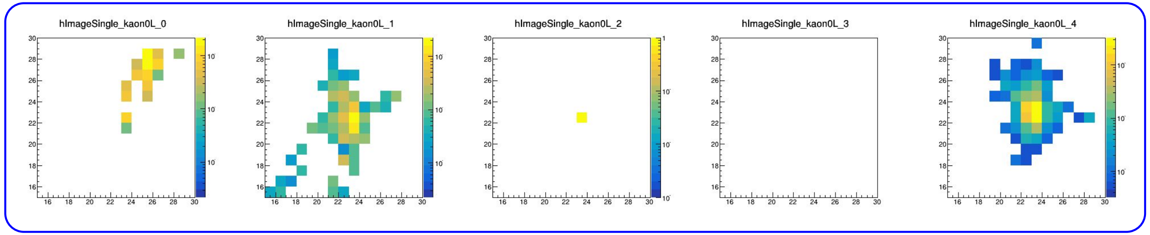
- Considering all events and all kaons (even those not interacting with the ECAL)



single ɣ events

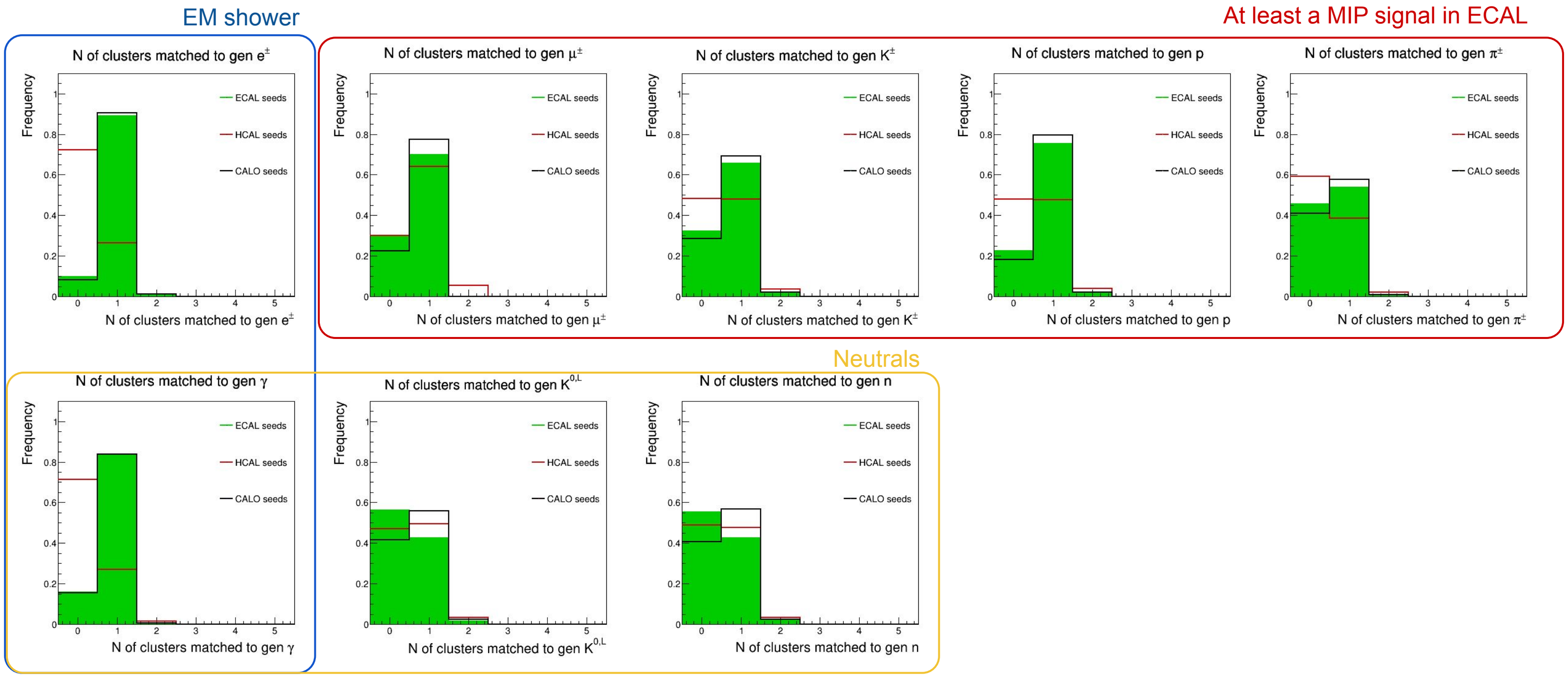


single K^{0L} events



ECAL/HCAL/Calo cluster-to-MC truth matching

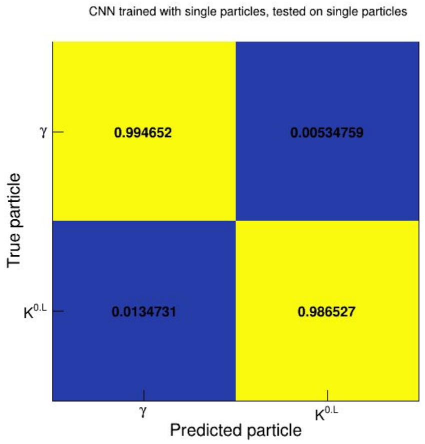
- $E_{MC\ truth} > 200$ MeV
- $E_{seed,3x3} > 200$ MeV



K^{0L} / γ discrimination with CNN

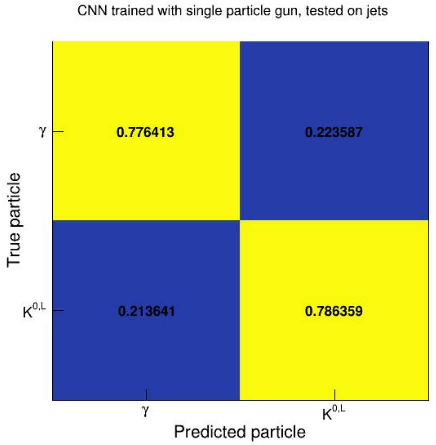
single particles

training on single particles (3k K^{0L} +3k γ, flat energy distribution in 1-5 GeV)
testing on single particles (3k K^{0L} +3k γ, flat energy distribution in 1-5 GeV)



option A

training on single particles (3k K^{0L} +3k γ, flat energy distribution in 1-5 GeV)
testing on jet particles (8k K^{0L} +190k γ, 0.01-100 GeV, steep energy dependence)



Possibly suboptimal because of different energy spectra between training and testing?

option B

training on jet particles (4k K^{0L} +10k γ, 0.01-100 GeV, steep energy dependence)
testing on jet particles (4k K^{0L} +10k γ, 0.01-100 GeV, steep energy dependence)