Potential of high resolution EM calorimetry for particle flow algorithms

LCWS 2021

International Workshop on Future Linear Colliders

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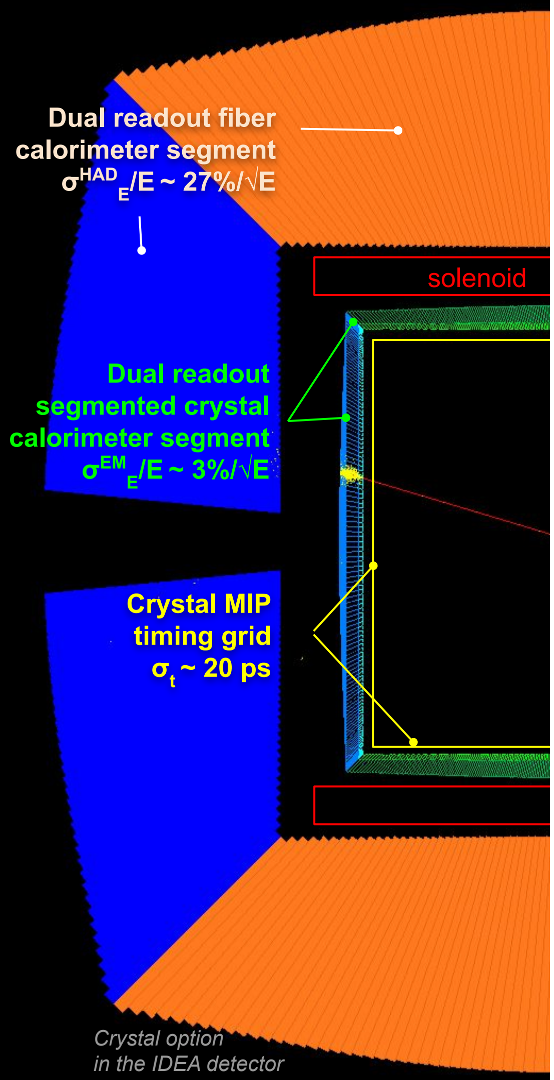


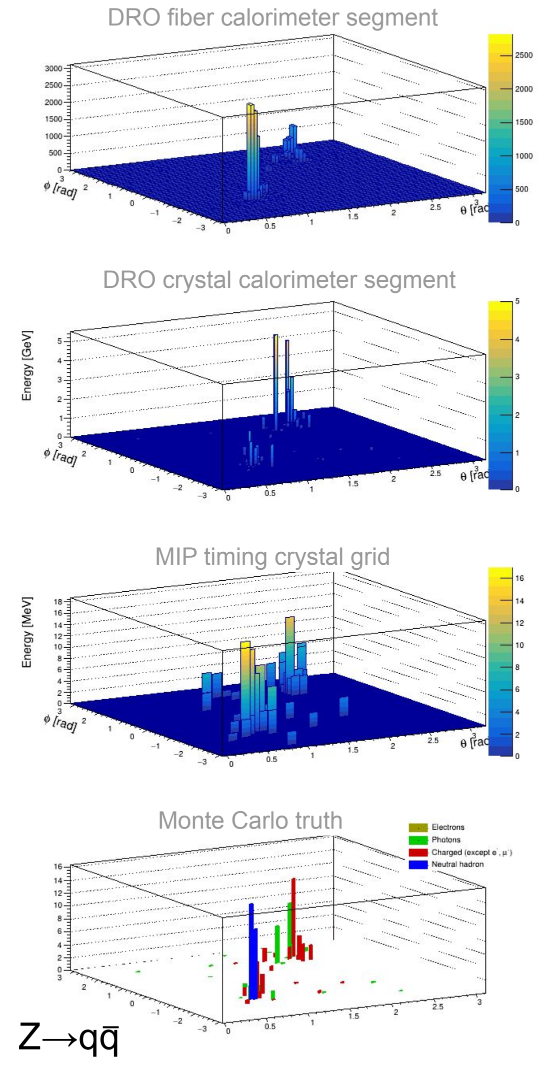
Dual readout fiber calorimeter segment
$\sigma^{HAD}_E/E \sim 27\%/\sqrt{E}$

solenoid

Dual readout segmented crystal calorimeter segment
$\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$

Crystal MIP timing grid
$\sigma_t \sim 20$ ps

Crystal option in the IDEA detector



DRO fiber calorimeter segment

DRO crystal calorimeter segment

MIP timing crystal grid

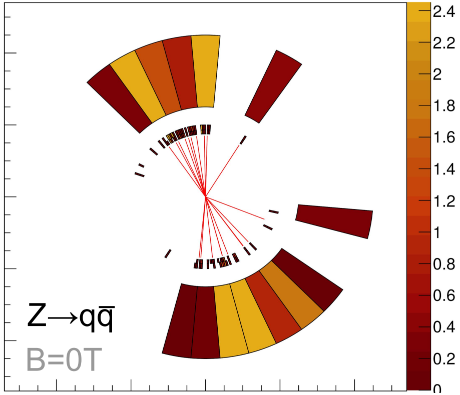
Monte Carlo truth

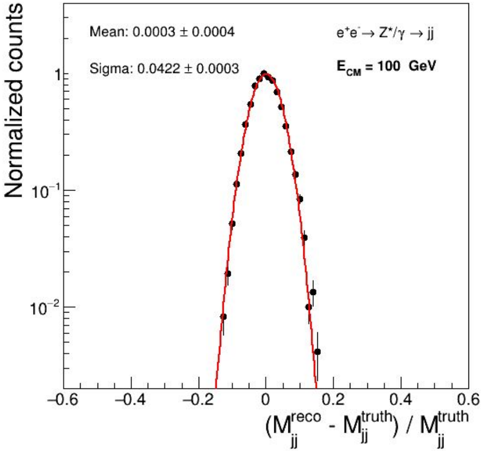
$Z \to q\bar{q}$

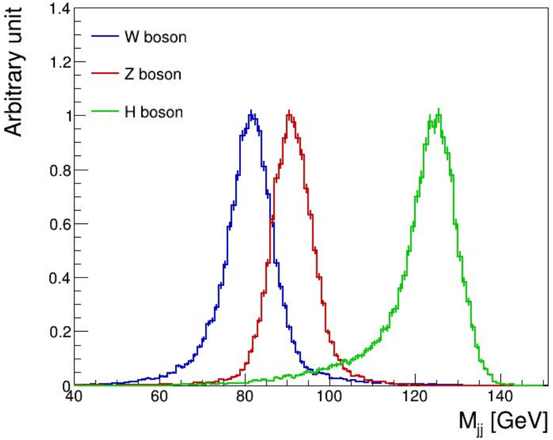
Jets reconstruction with hybrid dual-readout calorimeter

- Jet reconstruction with hybrid dual-readout calorimeter working well for first attempt
→ ~ 4% dijet invariant mass resolution (with calo-only information, 2-jet topologies)

- **Expected improvement by** addition of **tracking resolution** and by exploiting enhanced **calo-track matching performance from calo-based single particle measurements**





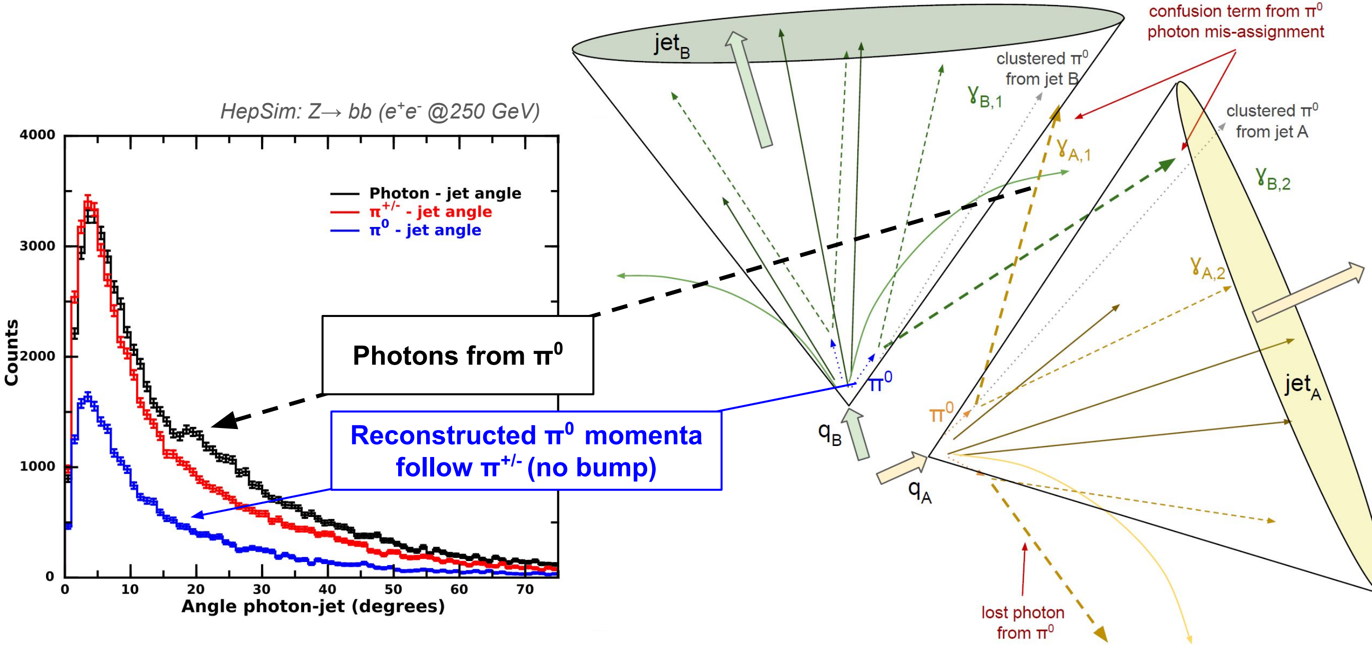


ee→WW→jjμν
ee→HZ →*XX*jj
ee→HZ →jjνν

Hepmc files courtesy of L.Pezzotti

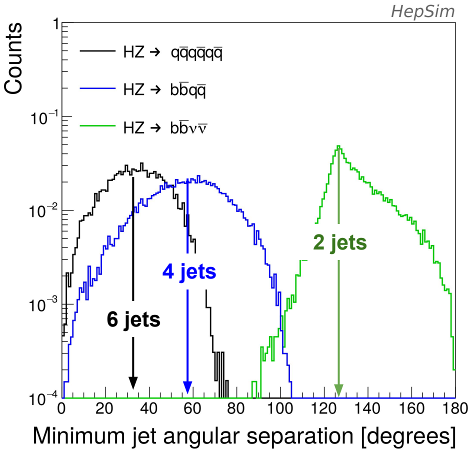
π^0 photon splitting across jets

- **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**


HepSim: Z→ bb (e^+e^- @250 GeV)

Photons from π^0

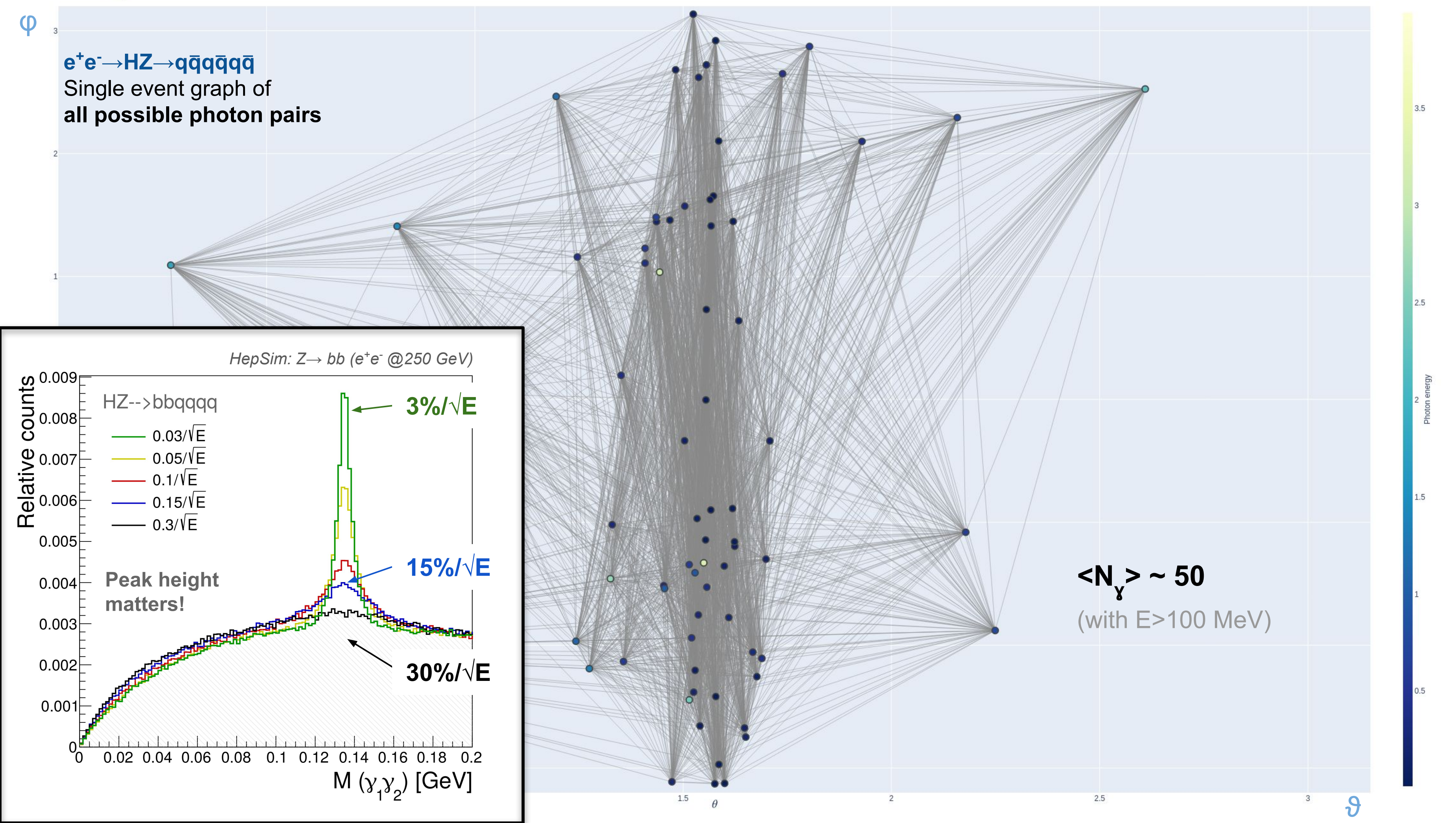
Reconstructed π^0 momenta follow $\pi^{+/-}$ (no bump)


HepSim

$e^+e^-\rightarrow HZ\rightarrow q\bar{q}q\bar{q}q\bar{q}$

Single event graph of

all possible photon pairs



$\langle N_\gamma \rangle \sim 50$

(with E>100 MeV)

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

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

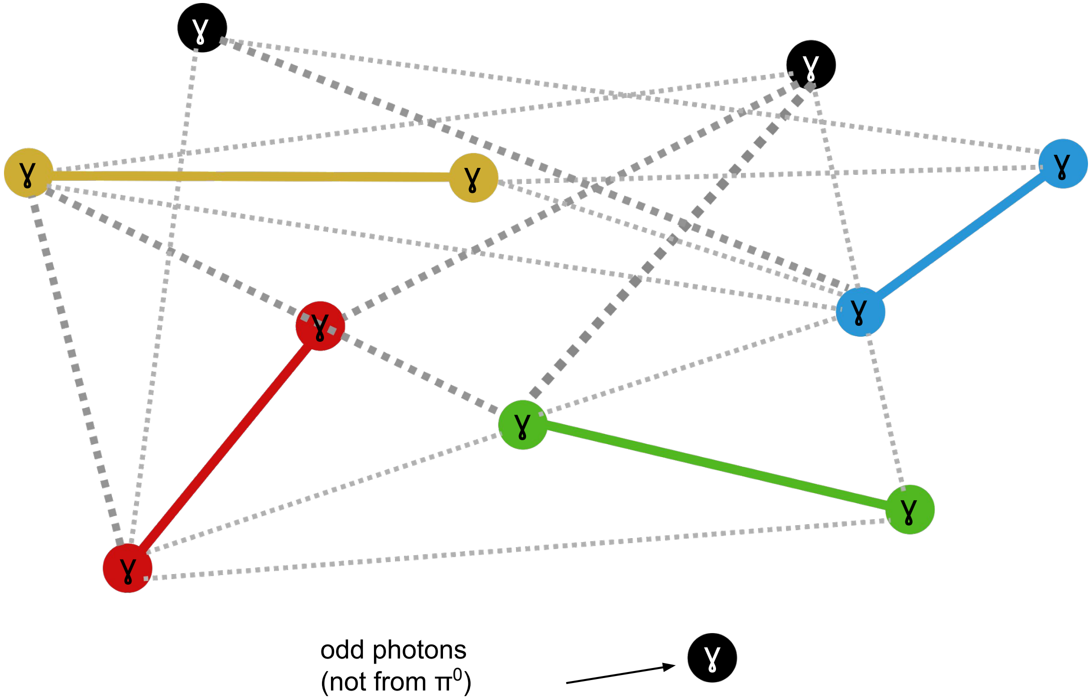
- **Node** = photon
- **Edge** = pair of photons

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

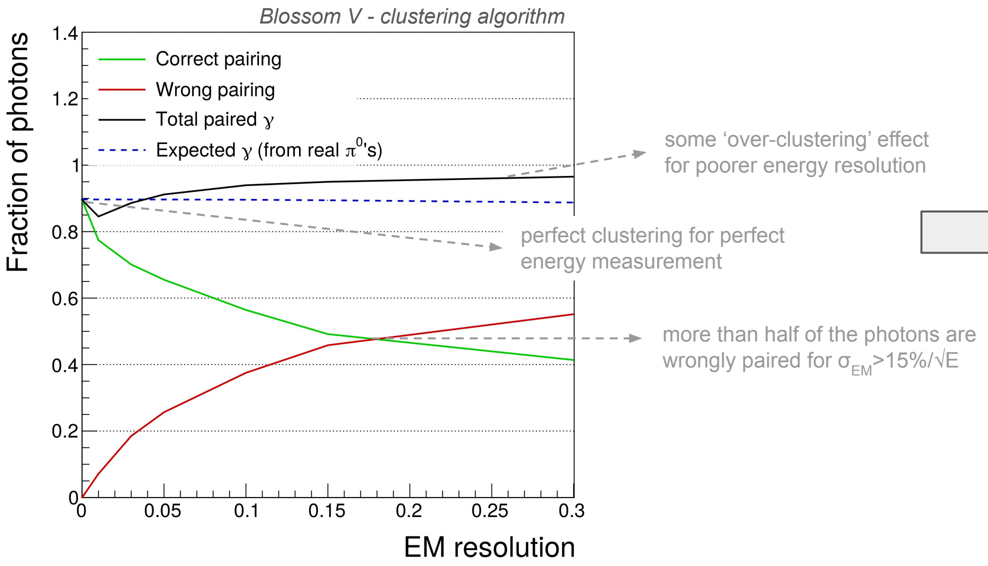


odd photons
(not from π^0)
can be left unpaired

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

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

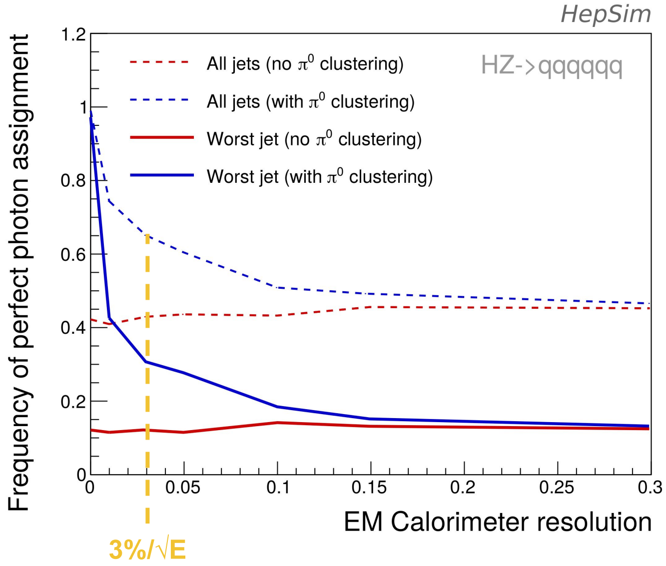
- **A high EM energy resolution enables efficient clustering of photons from π^0's**
  - Large fraction of π^0 photons correctly clustered with good σ_{EM} **(>90% for ~3%/√E)**



some 'over-clustering' effect for poorer energy resolution

perfect clustering for perfect energy measurement

more than half of the photons are wrongly paired for σ_{EM}>15%/√E

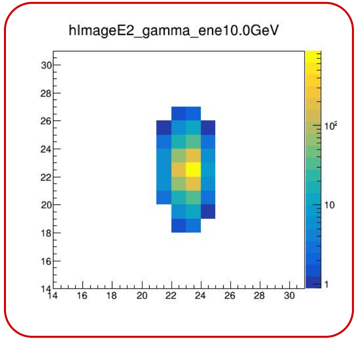


More details in https://doi.org/10.1088/1748-0221/15/11/P11005

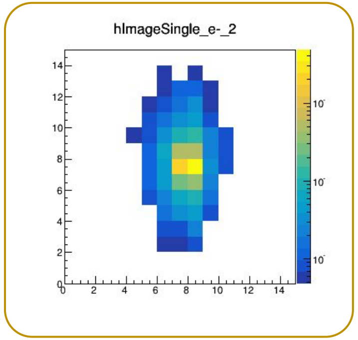
This procedure improves the efficiency of jet clustering algorithms to correctly assign photons to the corresponding jet

Particle ID with segmented crystal calorimeter and CNNs

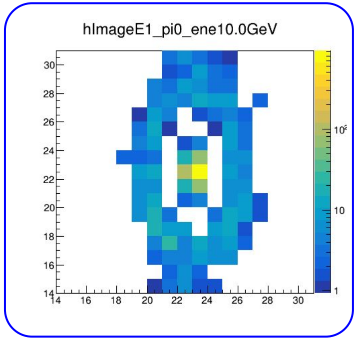
single γ (15x15 grid)



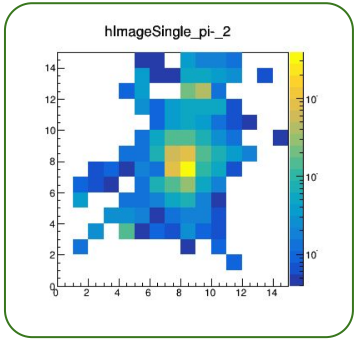
single e^- (15x15 grid)



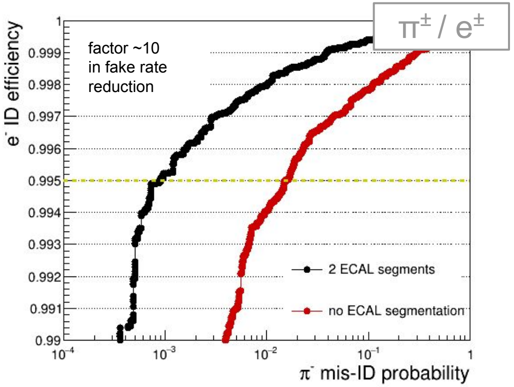
$\pi^0 \to \gamma\gamma$ (15x15 grid)

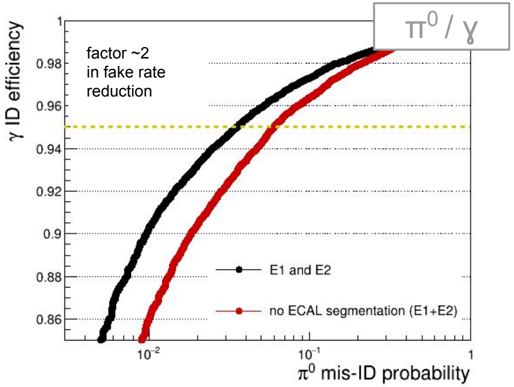


single π^- (15x15 grid)



- Exploit Convolutional Neural Networks with the **crystal segmentation** and **high sampling fraction** (=1) for classification of EM clusters
- Exploit maximum information (**dual-readout**, **time** information and high **energy resolution)** from the **crystals as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter measurements

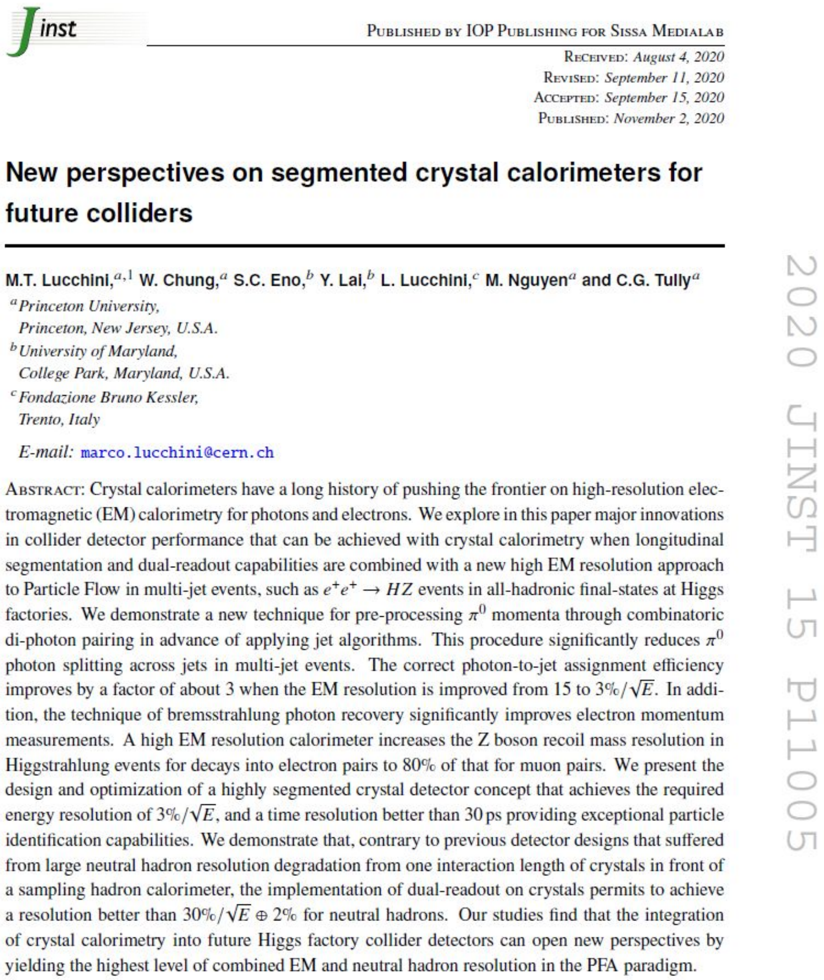




Additional material

More details in

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



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New perspectives on segmented crystal calorimeters for future colliders

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Abstract: Crystal calorimeters have a long history of pushing the frontier on high-resolution electromagnetic (EM) calorimetry for photons and electrons. We explore in this paper major innovations in collider detector performance that can be achieved with crystal calorimetry when longitudinal segmentation and dual-readout capabilities are combined with a new high EM resolution approach to Particle Flow in multi-jet events, such as $e^+e^+ \to HZ$ events in all-hadronic final-states at Higgs factories. We demonstrate a new technique for pre-processing π^0 momenta through combinatoric di-photon pairing in advance of applying jet algorithms. This procedure significantly reduces π^0 photon splitting across jets in multi-jet events. The correct photon-to-jet assignment efficiency improves by a factor of about 3 when the EM resolution is improved from 15 to $3\%/\sqrt{E}$. In addition, the technique of bremsstrahlung photon recovery significantly improves electron momentum measurements. A high EM resolution calorimeter increases the Z boson recoil mass resolution in Higgsstrahlung events for decays into electron pairs to 80% of that for muon pairs. We present the design and optimization of a highly segmented crystal detector concept that achieves the required energy resolution of $3\%/\sqrt{E}$, and a time resolution better than 30 ps providing exceptional particle identification capabilities. We demonstrate that, contrary to previous detector designs that suffered from large neutral hadron resolution degradation from one interaction length of crystals in front of a sampling hadron calorimeter, the implementation of dual-readout on crystals permits to achieve a resolution better than $30\%/\sqrt{E} \oplus 2\%$ for neutral hadrons. Our studies find that the integration of crystal calorimetry into future Higgs factory collider detectors can open new perspectives by yielding the highest level of combined EM and neutral hadron resolution in the PFA paradigm.

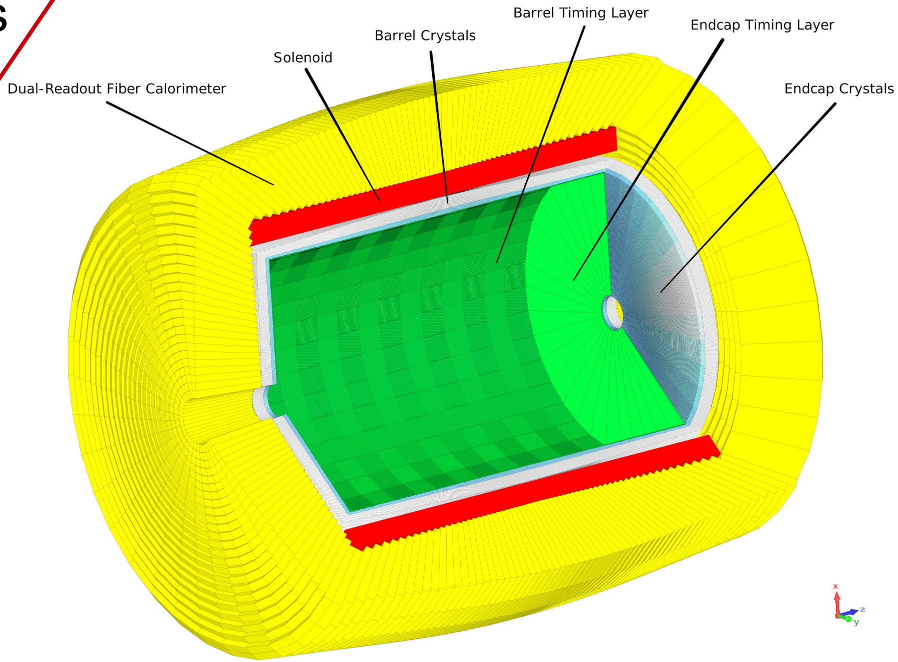
2020 JINST 15 P11005

More on detector geometry

The combination of a **segmented crystal high precision EM calorimeter** (*SCEPCal*) **with a dual-readout hadron calorimeter** would be *IDEA*L to take up the challenge of precision physics at future e^+e^- colliders

- Design optimization of a segmented crystal ECAL
- Effective integration with a dual-readout HCAL
- Global cost-performance optimization

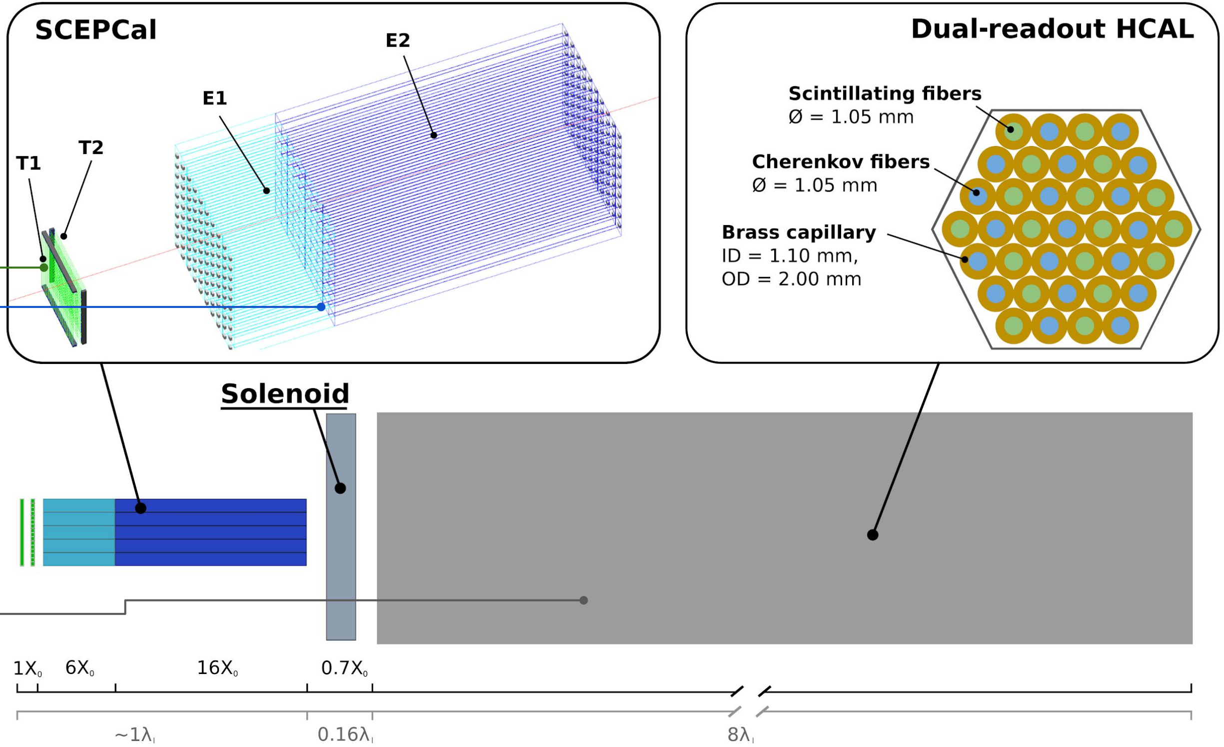
W.Chung



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** $\sigma^{HAD}_E/E \sim 27\%/\sqrt{E}$
  - Scintillating and quartz fibers inserted in brass capillaries



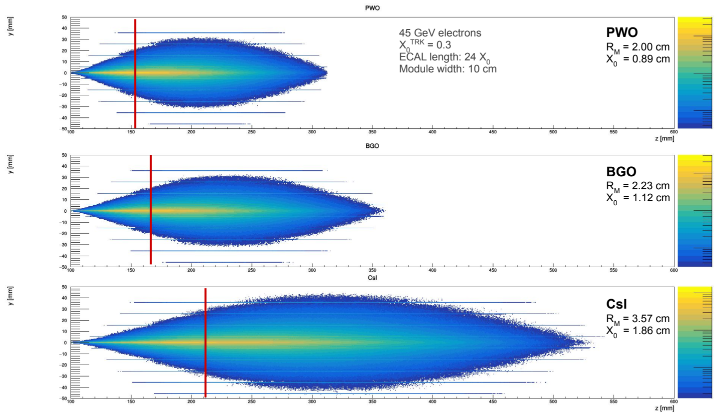
Some crystal options for EM shower detection

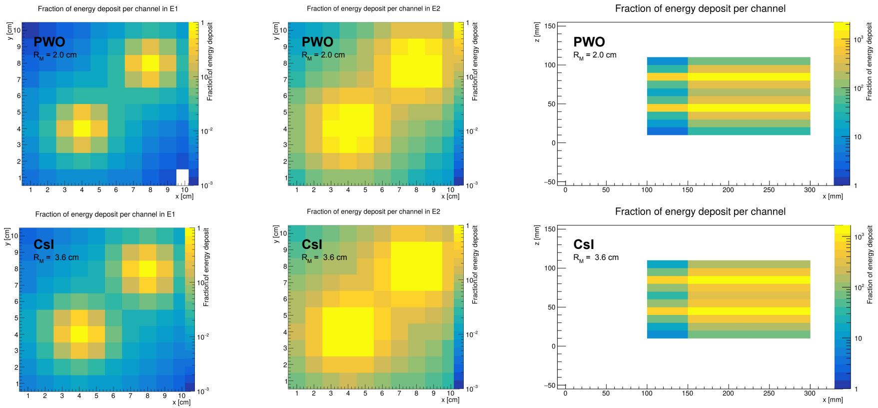
- **PWO**: the most compact, the fastest
- BGO/BSO: parameters tunable by adjusting the Si-fraction
- CsI: the less compact, the slowest, the brightest

better for PFA ⇧

⇩ better stochastic term

Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Relative LY	Decay time ns	Refractive index	Melting point (°C)	Cost (10 m³) Est. $/cm³	Cost*X_0 Est. $/cm²
PWO	8.3	20.9	0.89	2.00	1	10	2.20	1123	8	7.1
BGO	7.1	22.7	1.12	2.23	70	300	2.15	1050	7	7.8
BSO	6.8	23.4	1.15	2.33	14	100	2.68	1030	6.8	7.8
CsI	4.5	39.3	1.86	3.57	550	1220	1.95	621	4.3	8.0



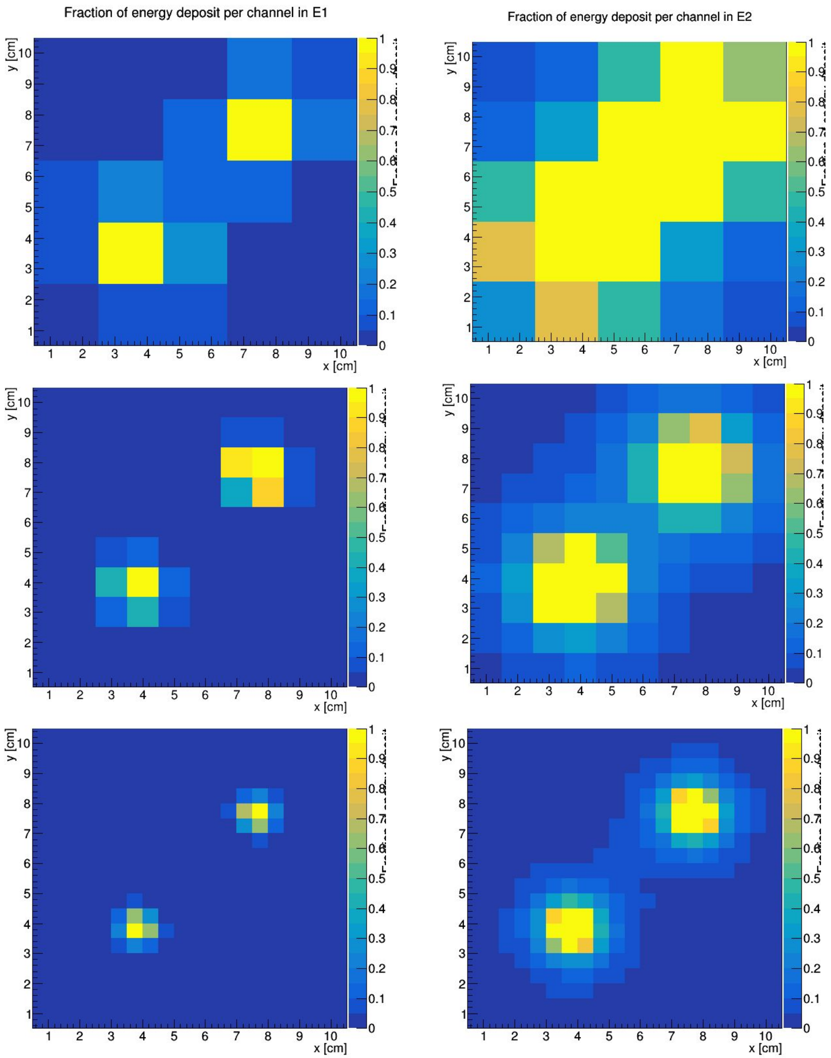


Transverse segmentation (visual impact)

cell size: 2x2 cm²

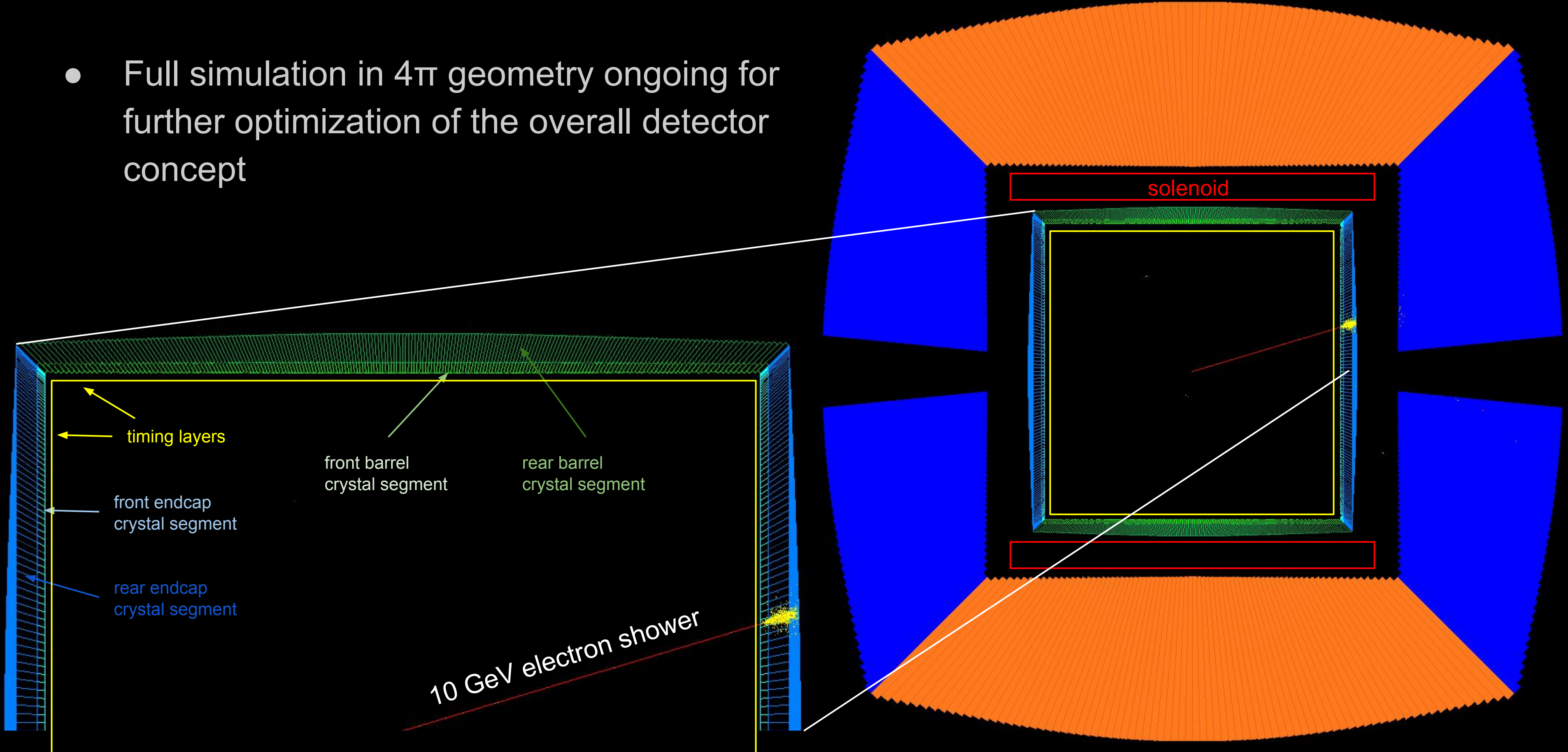
cell size: 1x1 cm²

cell size: 0.5x0.5 cm²

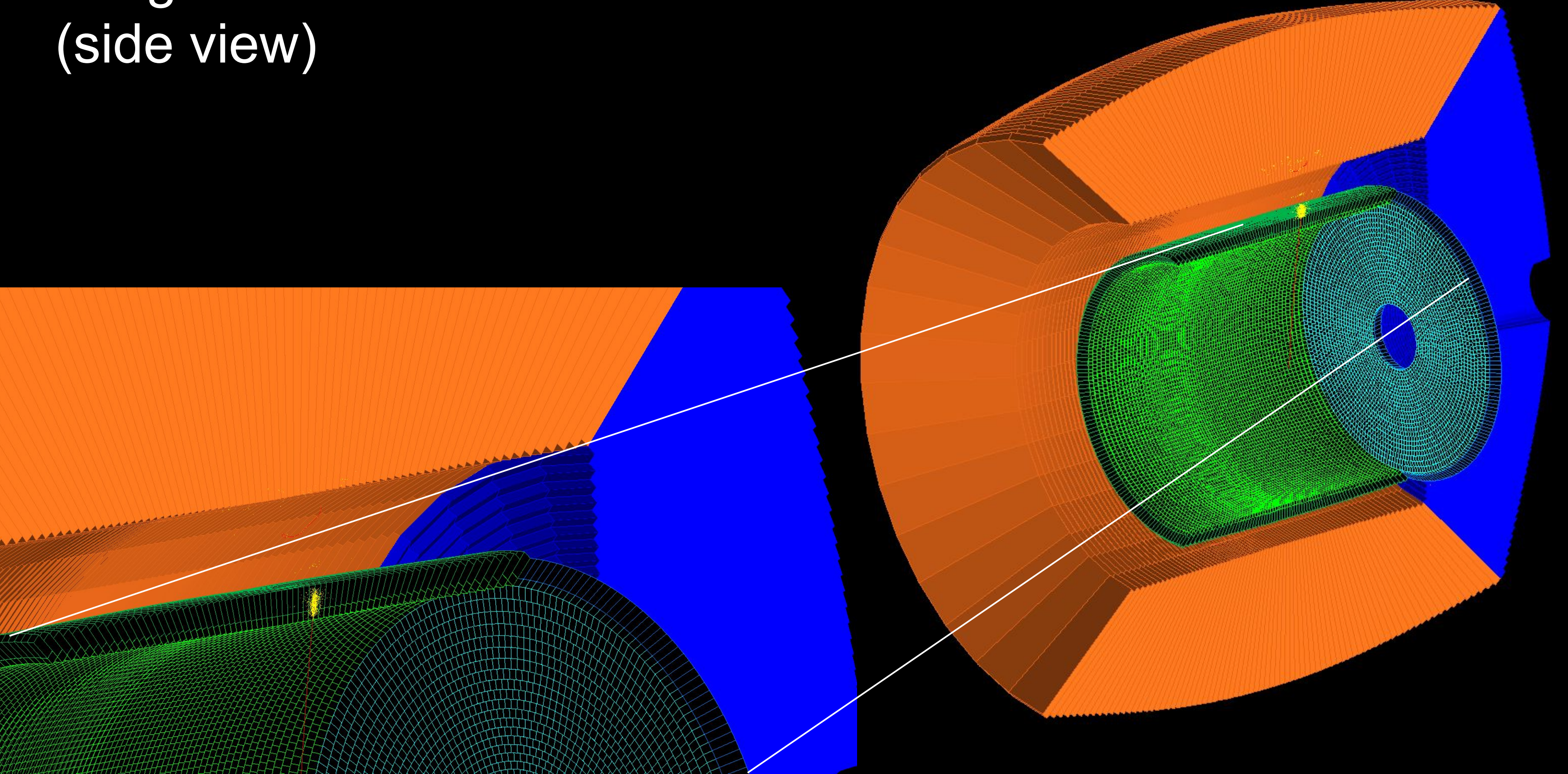


Ongoing integration in 4π Geant4 IDEA simulation

- Full simulation in 4π geometry ongoing for further optimization of the overall detector concept

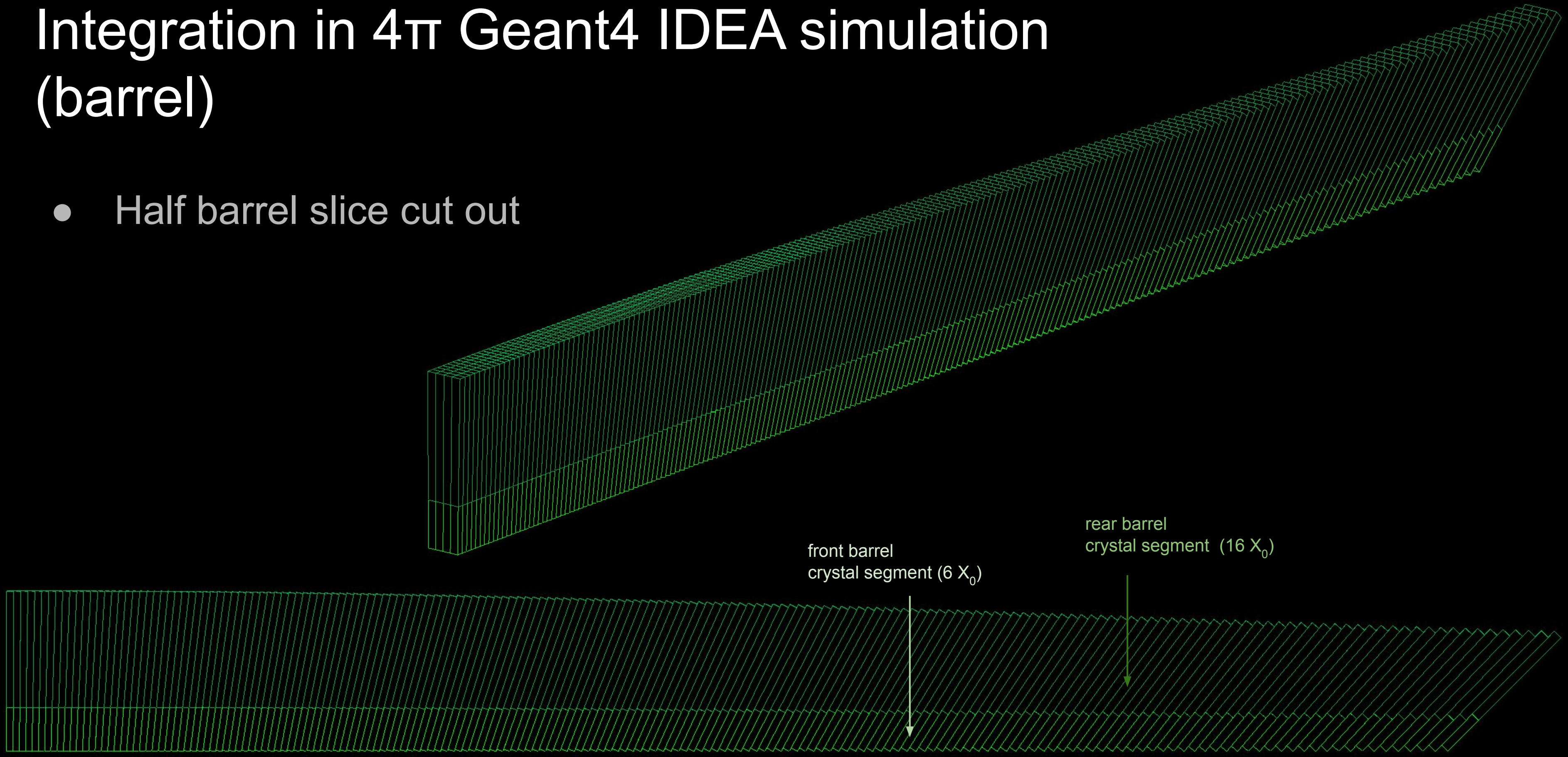


Integration in 4π Geant4 IDEA simulation (side view)



Integration in 4π Geant4 IDEA simulation (barrel)

- Half barrel slice cut out

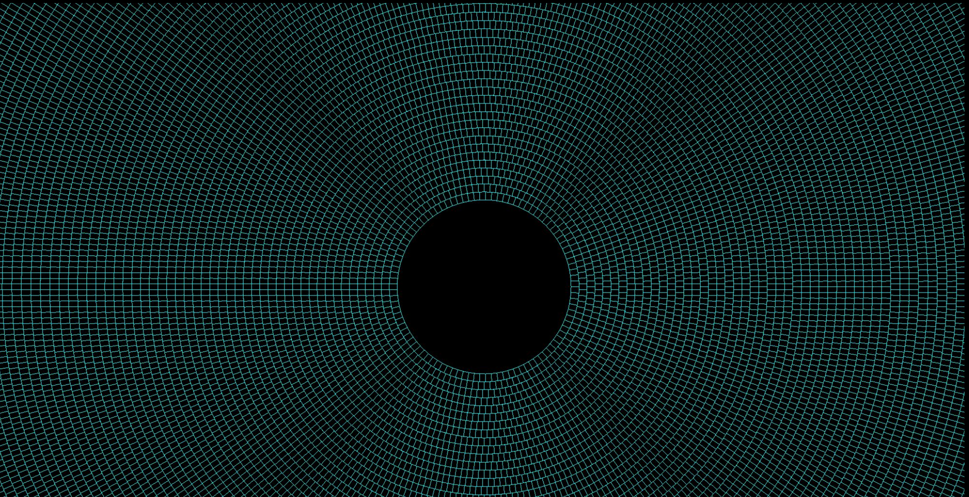


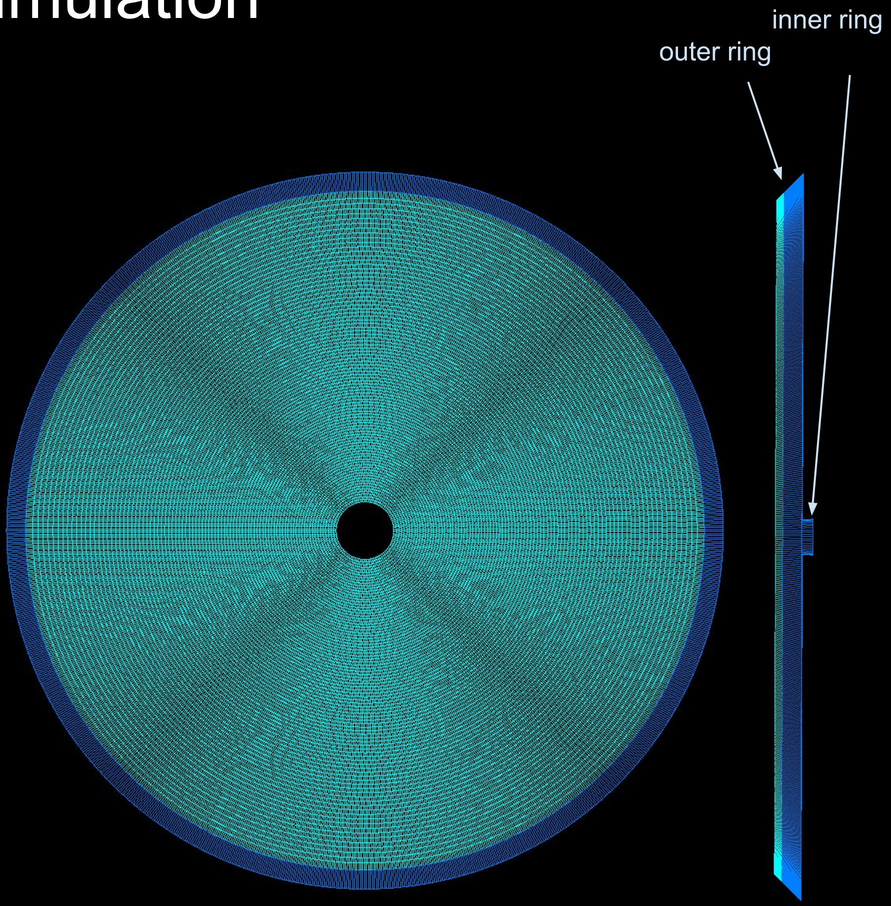
front barrel
crystal segment (6 X_0)

rear barrel
crystal segment (16 X_0)

Integration in 4π Geant4 IDEA simulation (endcap)

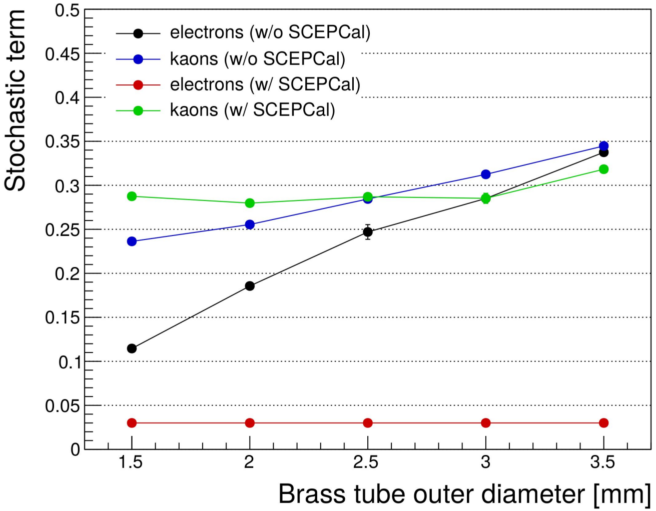
- Concentric pointing rings
- Each ring divided in replicas to yield similar crystal dimensions

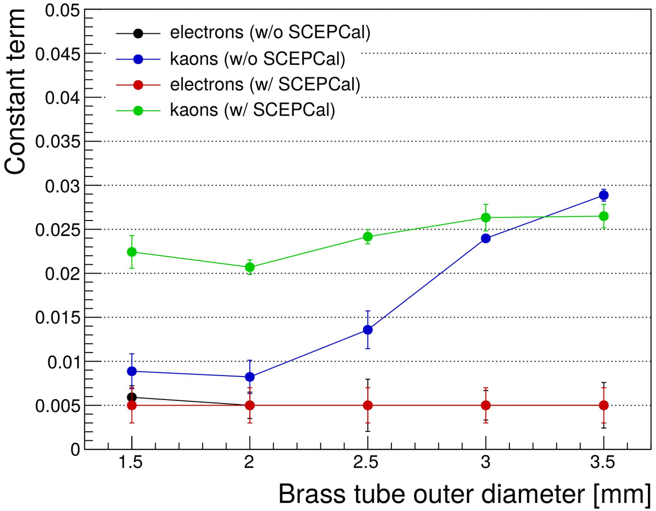




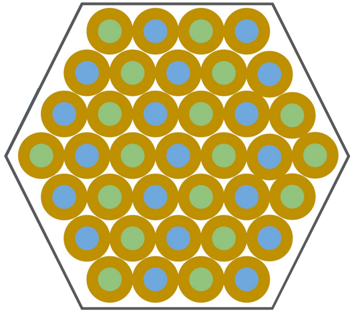
Example of calorimeter cost/performance optimization

- **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

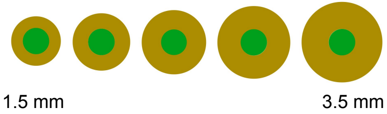




Brass capillaries
“Nominal” dimension
OD=2 mm, ID=1.1 mm



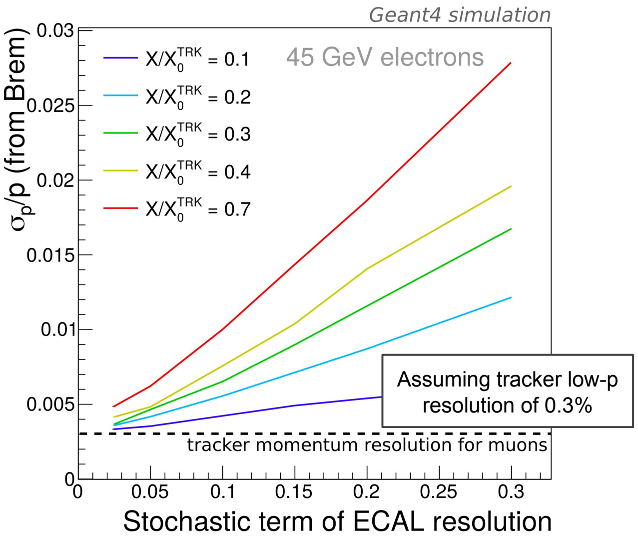
Active fiber diameter unchanged
Brass tube outer diameter varied



More on high EM energy resolution potential

Recovery of Bremsstrahlung photons

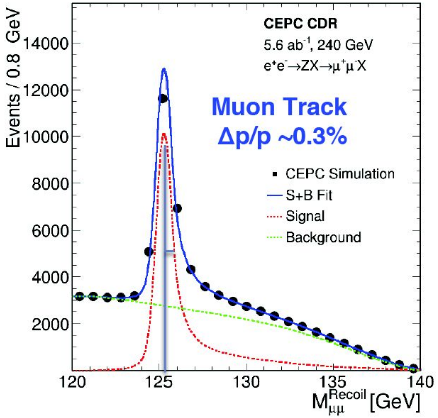
- Reconstruction of the Higgs boson mass and width from the recoil mass of the Z boson is a key tool at e^+e^- colliders
- Potential to **improve the resolution of the recoil mass signal from Z→ee decays** to about 80% of that from Z→ μμ decays [with Brem photon recovery at EM resolution of 3%/√E]



Assuming tracker low-p resolution of 0.3%

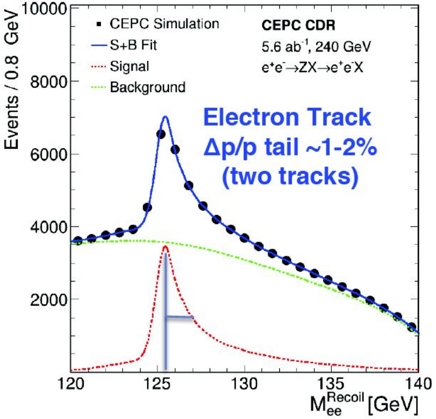
Example from [CEPC CDR]

Z→$\mu^+\mu^-$ Recoil



Muon Track
Δp/p ~0.3%

Z→e^+e^- Recoil



Electron Track
Δp/p tail ~1-2%
(two tracks)

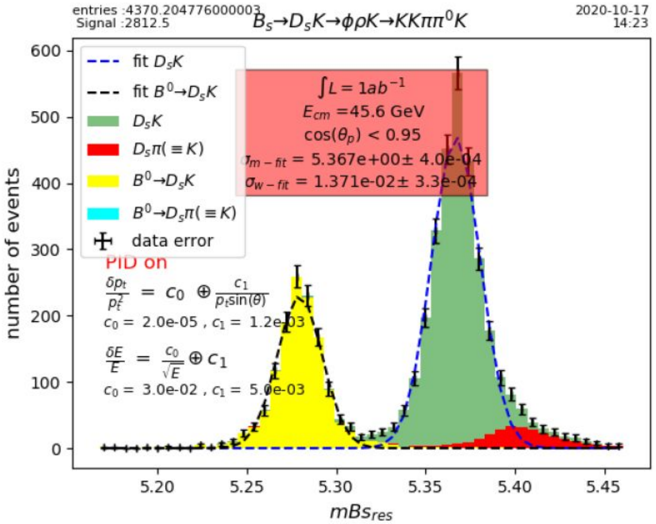
~80% of resolution recovery with 3%/√(E)

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

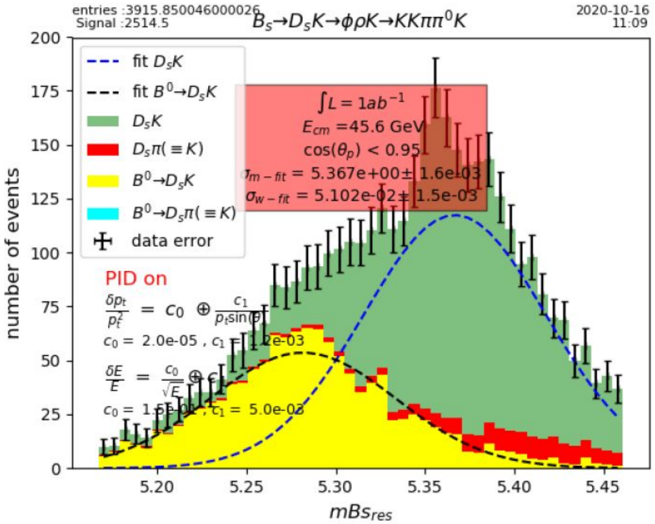
$\overline{\mathrm{B}}_s$ decay Mode	Decay Mode	Final State	Number of $\overline{\mathrm{B}}_s$ decays
$D_s^+K^-$	$\mathrm{D_s^+} \to \phi\pi$	$\mathrm{K^+K^-\pi^+K^-}$	$\sim 5.2\ 10^5$
$D_s^+K^-$	$\mathrm{D_s^+} \to \phi\rho$	$\mathrm{K^+K^-\pi^+K^-\pi^0}$	$\sim 9.8\ 10^5$

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

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



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

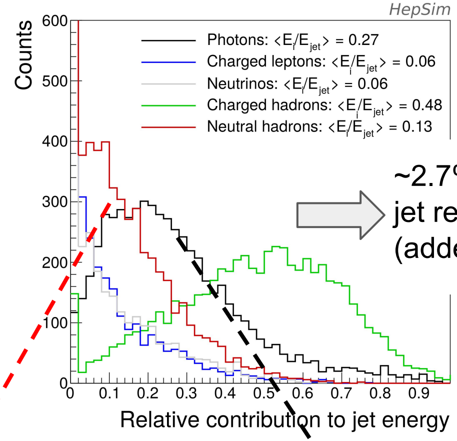


See **R. Aleksan's** talk @ [4th FCC Physics and Experiments Workshop]

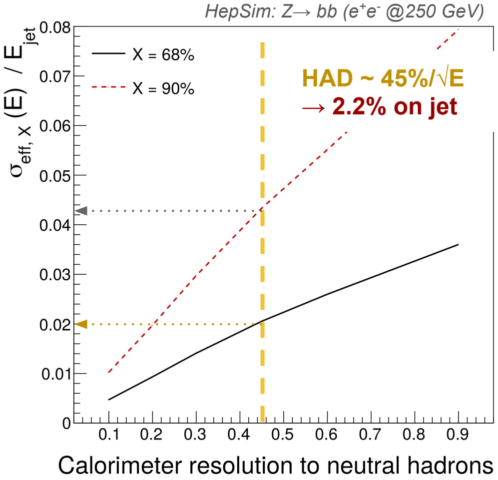
Traditional impact of calorimeters on jet resolution

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

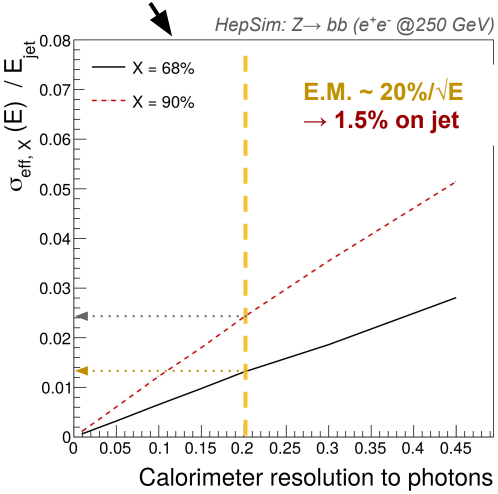
- Calorimeter resolution on neutral particles required to achieve target jet resolution of ~3%
  - Photons
    better than 20%/√E
  - Neutral hadrons
    (mostly $K^{0,L}$ of <E>~5 GeV) better than 45%/√E



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



HAD ~ 45%/√E
→ 2.2% on jet



E.M. ~ 20%/√E
→ 1.5% on jet

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

More on particle identification

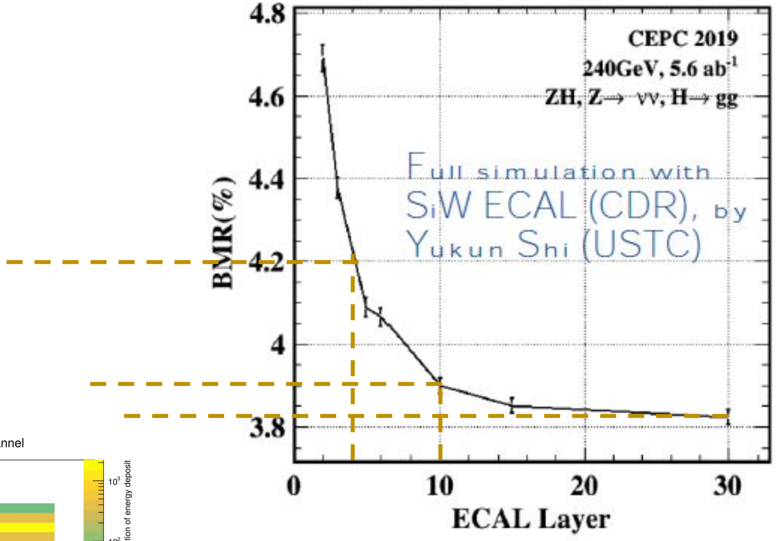
Longitudinal segmentation in SCEPCal

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

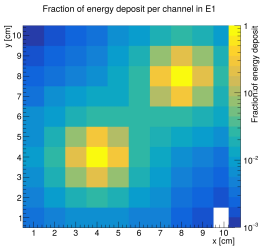
- The benefit for PFA from longitudinal segmentation saturates quickly

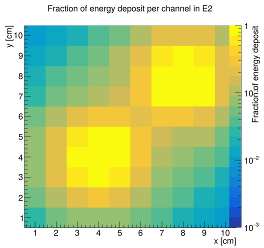
- **A non-uniform longitudinal segmentation** (finer at the beginning of the EM shower where R_M is smaller) may better exploit the number of readout layers for PFA

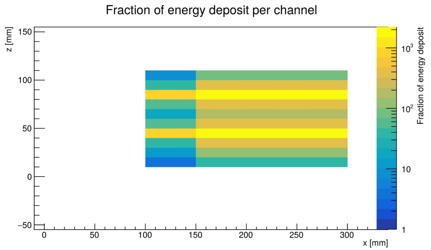
Boson Mass Resolution vs #Layer in ECAL



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

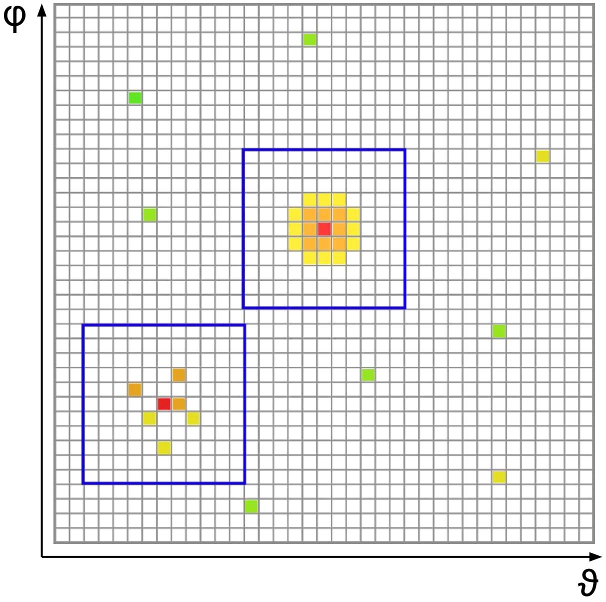






Exploiting CNN for particle ID

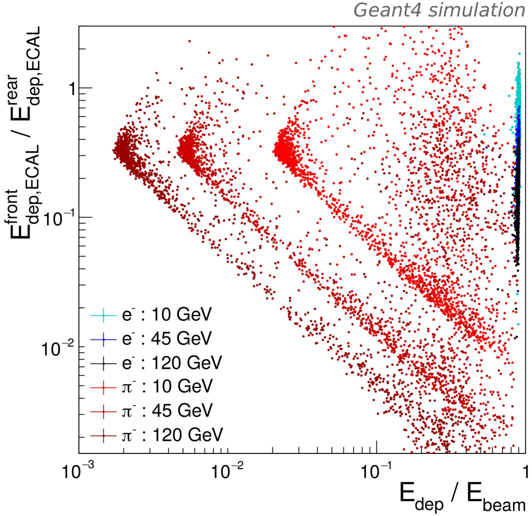
- Single particle gun events **(e^-, γ, π^0, π^-, K^{0L}) isotropically**
- Flat energy distribution in **1-100 GeV range**
- Process data to:
    - Find ‘**seed ECAL crystal’** in the full calorimeter (i.e. crystal with the highest energy deposit)
    - Select a square image of **45x45 pixels** (=crystals) around the seed crystal (→ **45x45** cm²)
    - 10 MeV energy cut on ECAL hits (hits in ECAL crystals with total energy lower than 10 MeV are not used to build the images)
- **Train a convolutional neural network for particle discrimination:**
    - **e^- / π^-**
    - **γ / π^0**
    - **γ / K^{0L}**



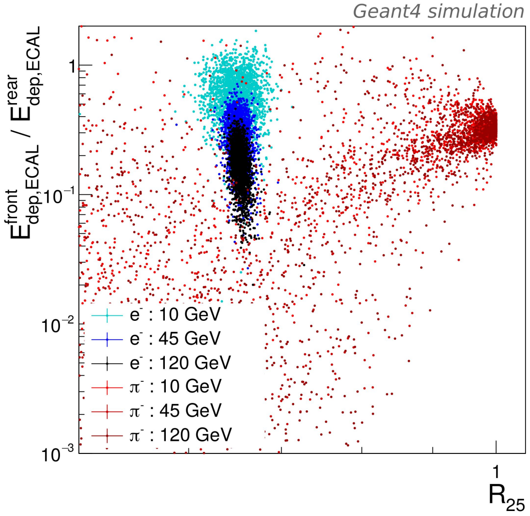
Particle ID with crystal segmentation

- 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

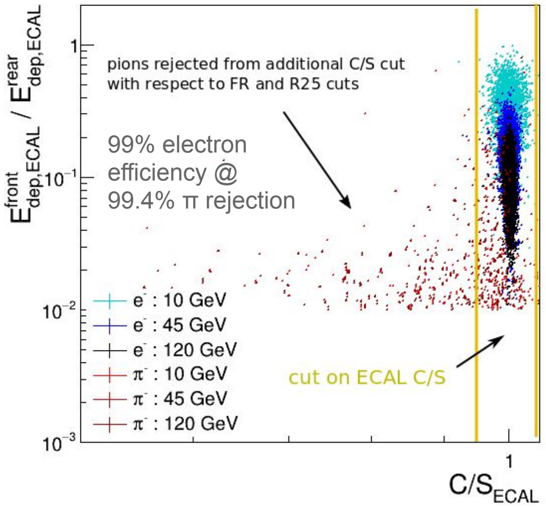
Longitudinal segmentation



Transverse segmentation



Dual-readout



pions rejected from additional C/S cut with respect to FR and R25 cuts

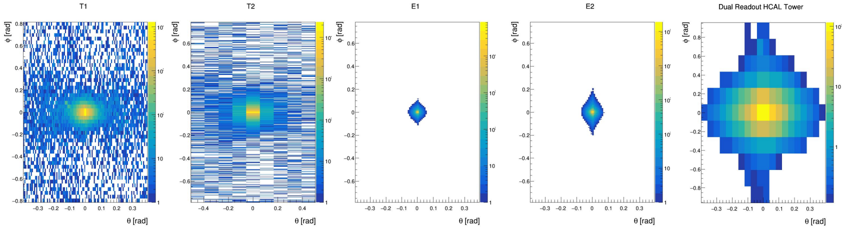
99% electron efficiency @ 99.4% π rejection

cut on ECAL C/S

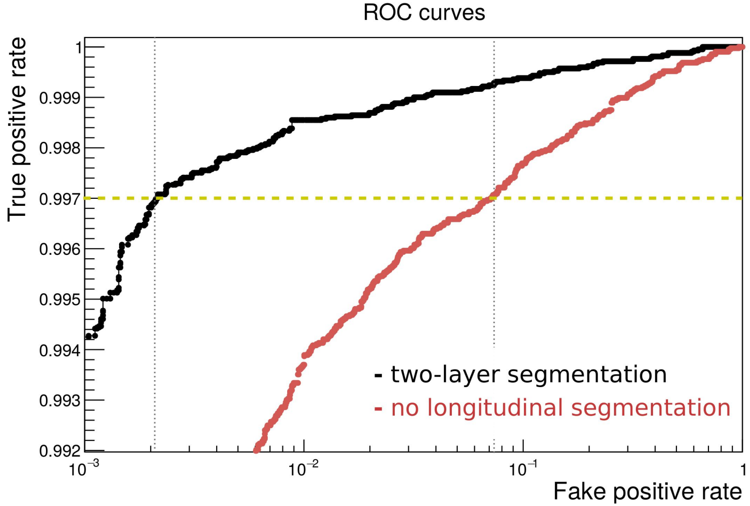
Exploiting segmentation for PID using CNNs

- Exploit the 5 calorimeter longitudinal layers:
  - For each layer the transverse segmentation combined with the additional information (e.g. dual readout and timing) can be treated as a colored image
  - Extract features from each image with convolutional filters
  - Combine features to identify particle patterns to achieve particle discrimination

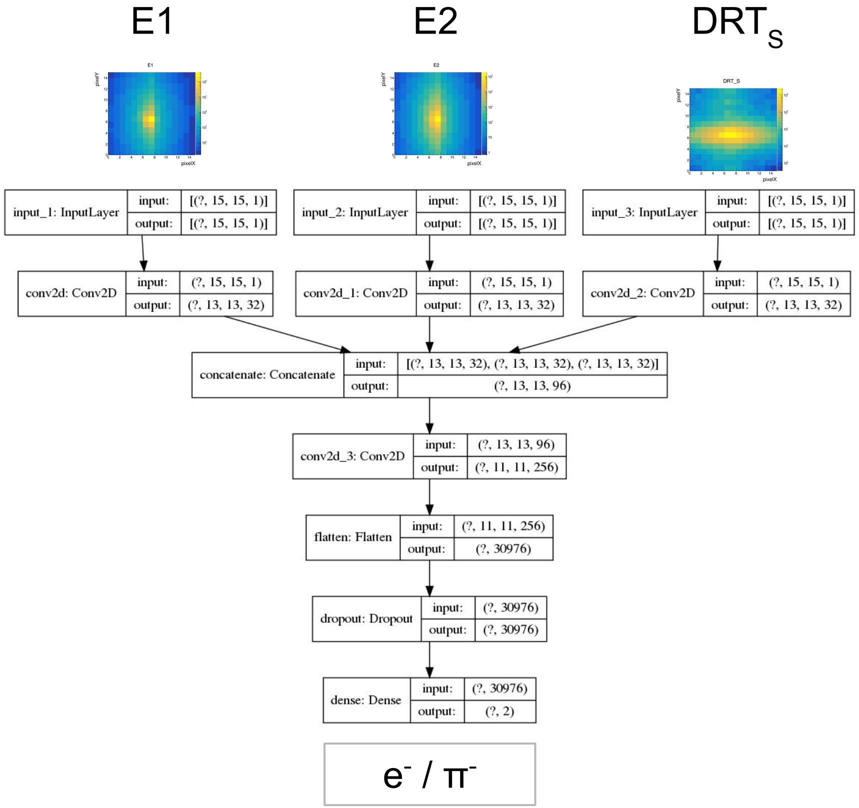
- Preliminary results: **longitudinal segmentation in the crystal EM section substantially reduces pion mis-identification rate**



e^-/ π^- discrimination with ECAL only

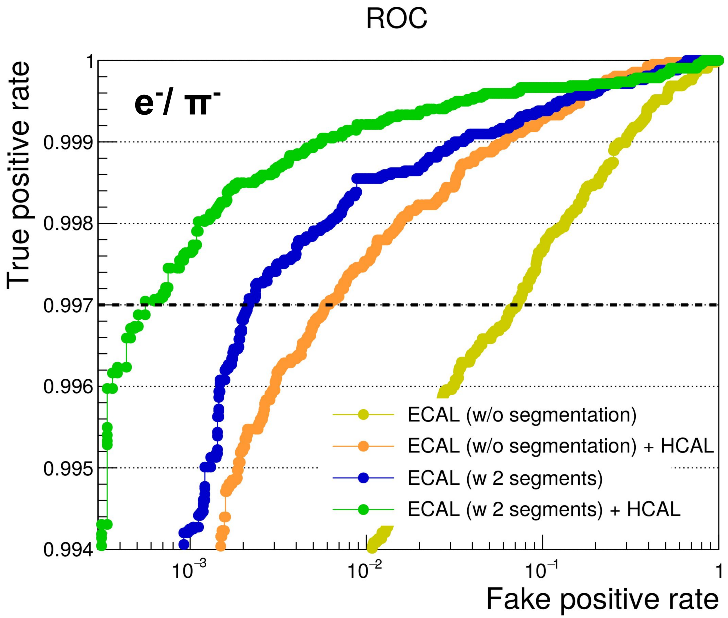


Example of CNN structure with 3 longitudinal layers



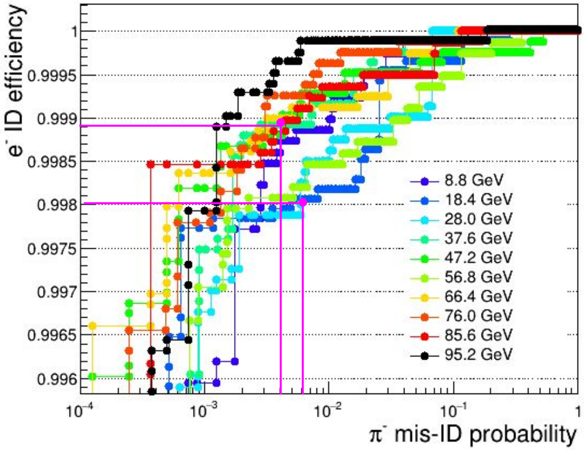
input_1: InputLayer — input: [(?, 15, 15, 1)] — output: [(?, 15, 15, 1)]
input_2: InputLayer — input: [(?, 15, 15, 1)] — output: [(?, 15, 15, 1)]
input_3: InputLayer — input: [(?, 15, 15, 1)] — output: [(?, 15, 15, 1)]
conv2d: Conv2D — input: (?, 15, 15, 1) — output: (?, 13, 13, 32)
conv2d_1: Conv2D — input: (?, 15, 15, 1) — output: (?, 13, 13, 32)
conv2d_2: Conv2D — input: (?, 15, 15, 1) — output: (?, 13, 13, 32)
concatenate: Concatenate — input: [(?, 13, 13, 32), (?, 13, 13, 32), (?, 13, 13, 32)] — output: (?, 13, 13, 96)
conv2d_3: Conv2D — input: (?, 13, 13, 96) — output: (?, 11, 11, 256)
flatten: Flatten — input: (?, 11, 11, 256) — output: (?, 30976)
dropout: Dropout — input: (?, 30976) — output: (?, 30976)
dense: Dense — input: (?, 30976) — output: (?, 2)

e^- / π^-



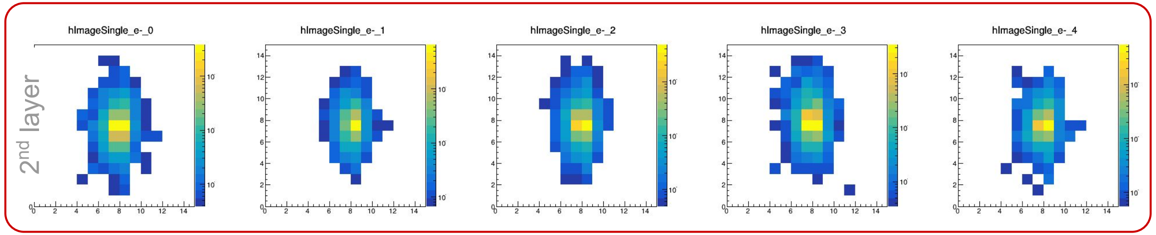
$\pi^\pm$ / $e^\pm$ identification with CNN

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

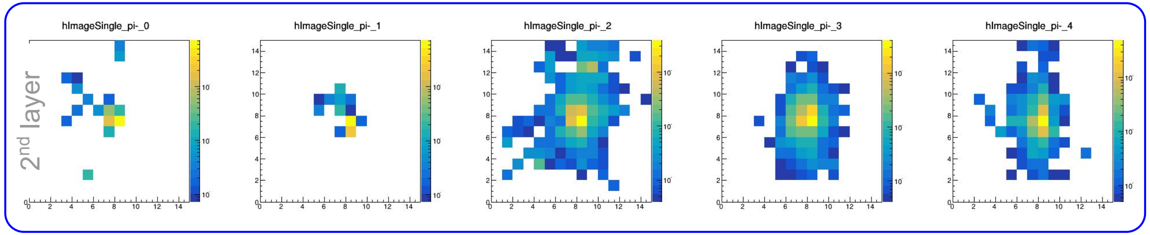


	IDEA Pb only		Crystal calo only	
	e^- ID	π^- mis-ID	e^- ID	π^- mis-ID
20 GeV	99.4%	0.8%	99.8%	0.6%
60 GeV	99.8%	0.4%	99.9%	0.4%

single e^- events



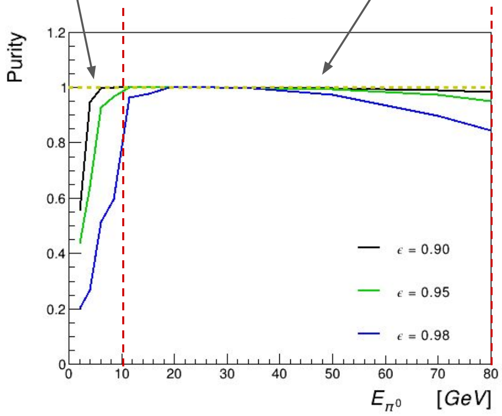
single π^- events

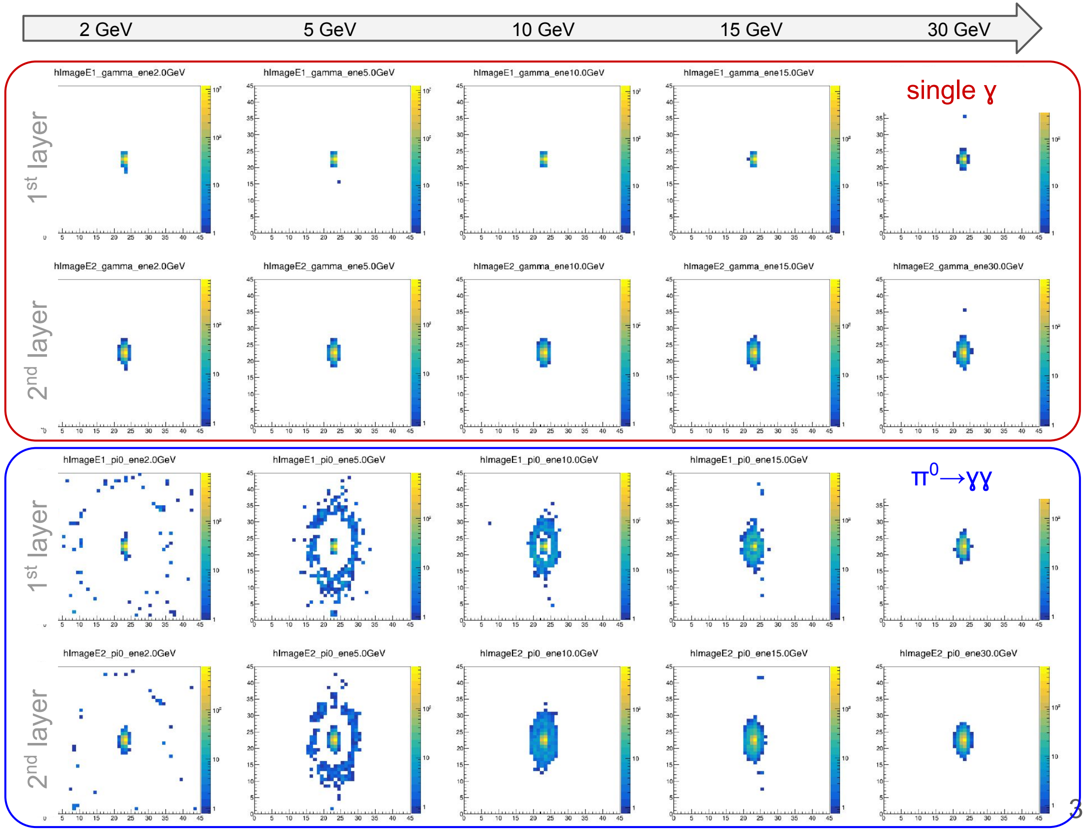


π^0 / γ identification with CNN

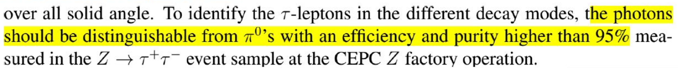
One photon with very low energy can be missed

Good separation in range 10-80 GeV





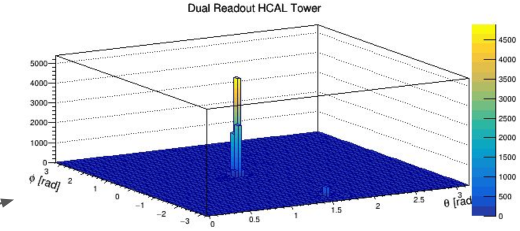
- In CEPC CDR requirement:


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.

Jets (event display)

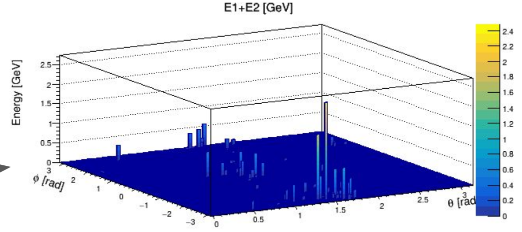
WW→jjμν

Hadron showers



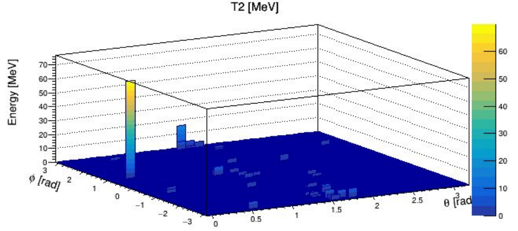
Fiber calo towers

Mainly **photon** and **electron** showers but also half of the **hadrons start showering**



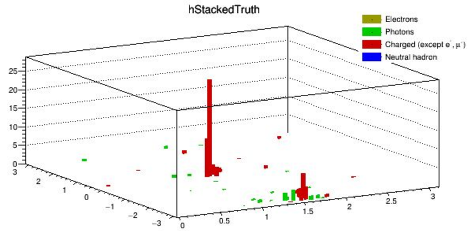
Crystal EM shower layers (E1+E2)

All MIPs leave a track here



Crystal timing layer (T1)

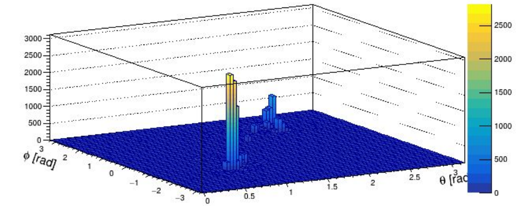
- **Charged hadrons (mainly π±)**
- **Neutral hadrons (mainly K^{0L})**
- **Photons (mainly from π^0)**
- **Electron**
- **(Muons and neutrinos not displayed on truth graph)**



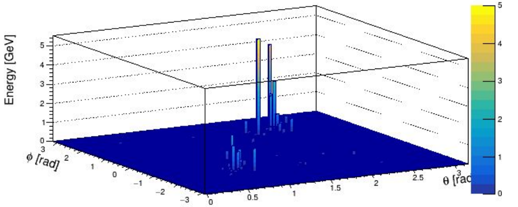
MC truth

Z→qq **(event display)**

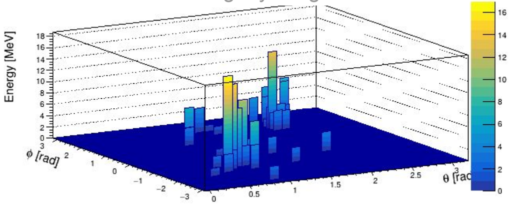
DRO fiber calorimeter segment



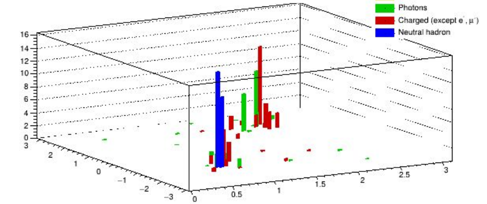
DRO crystal calorimeter segment

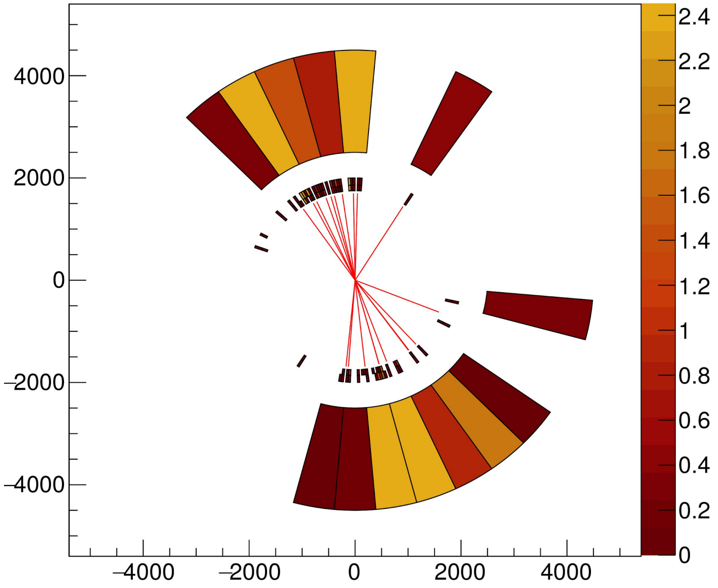


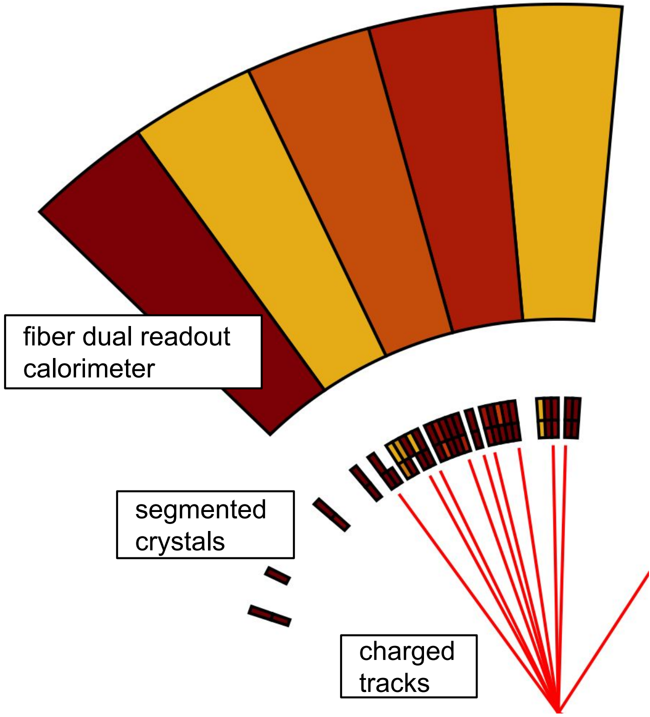
MIP timing crystal grid



Monte Carlo truth







fiber dual readout calorimeter

segmented crystals

charged tracks

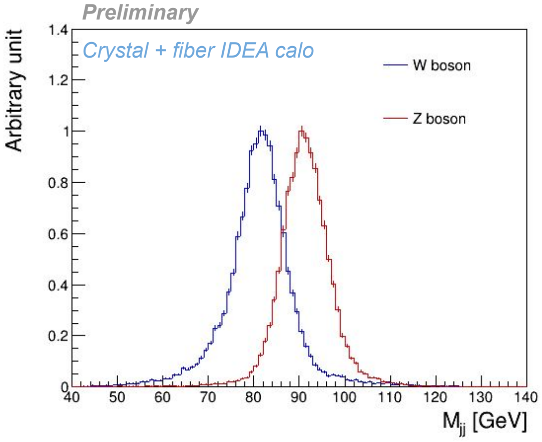
Hybrid dual-readout in jets

Running on same hepmc files from L.Pezzotti

- Run jet clustering algorithm using all crystal and fiber calo hits
- For each jet create a sub-jet with the contribution from the:
    - Fiber calo scintillation hits only
    - Fiber calo Cherenkov hits only
    - Crystal calo scintillation hits only
    - Crystal calo Cherenkov hits only

- Reconstruct the dual readout corrected jet energy by correcting the crystal and fiber jet component based on the respective DRO signals (as for single hadrons)

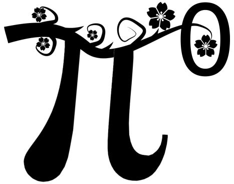
- **Room to improve the jet DRO correction algorithm**
  + expected improvement by exploiting PFA
  (identify single particles belonging to the jet)



- **ee→WW→jjμν**
- **ee→HZ**
  →□□jj

Maximum weight matching via Blossom V algorithm

for π^0 reconstruction in multi-jet events



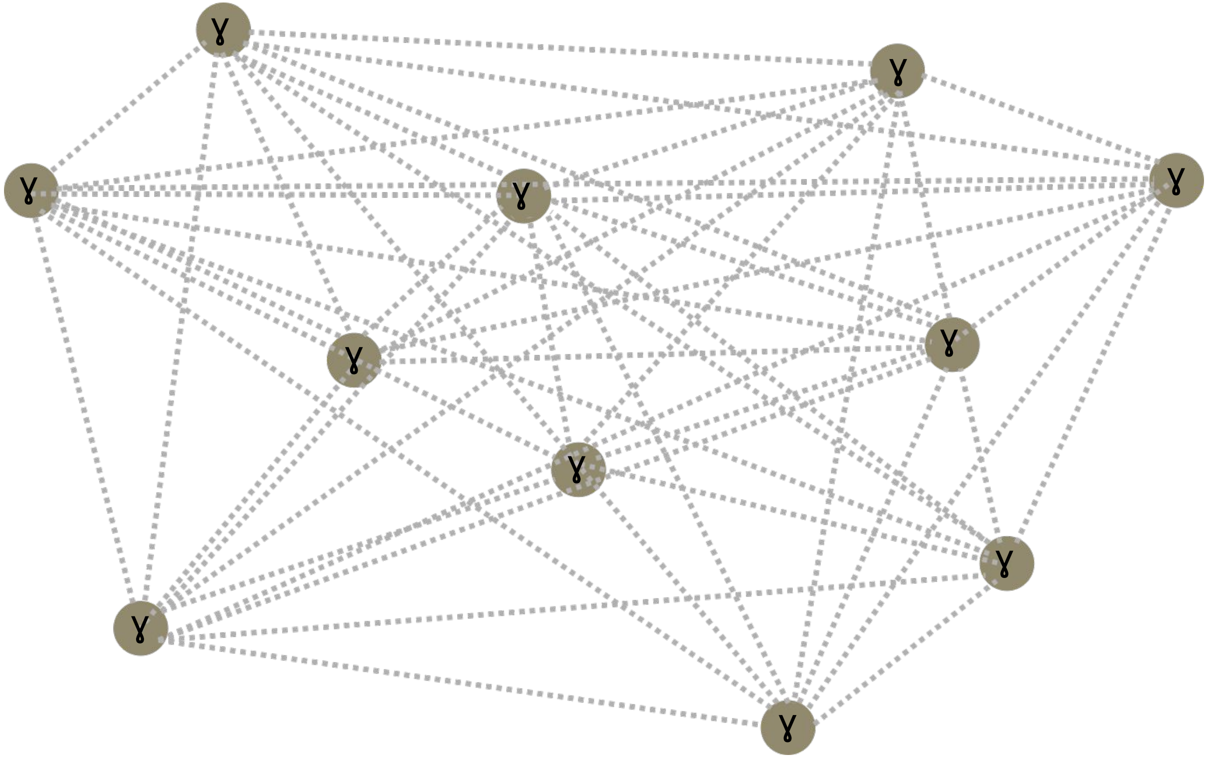
Algorithm

- max_weight_matching (*G*, *maxcardinality=False*, *weight='weight'*)
- Compute a maximum-weighted matching of G.
  - A matching is a subset of edges in which no node occurs more than once.
  - The weight of a matching is the sum of the weights of its edges.
  - A maximal matching cannot add more edges and still be a matching.
  - The cardinality of a matching is the number of matched edges.
- If G has edges with weight attributes the edge data are used as weight values else the weights are assumed to be 1.
- This function takes time O(number_of_nodes ** 3).

- This method is based on the “blossom” method for finding augmenting paths and the “primal-dual” method for finding a matching of maximum weight, both methods invented by Jack Edmonds [1].

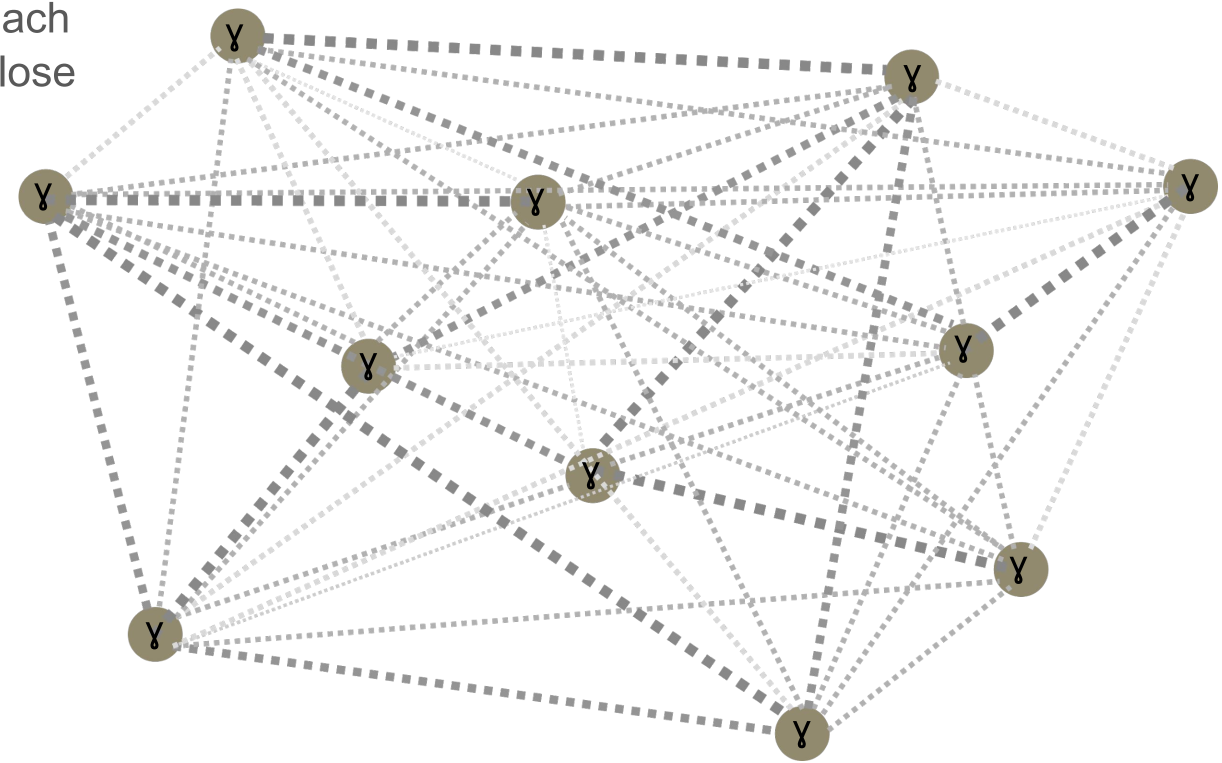
A graph-based approach for π^0 clustering

- **Build a graph with all photons in the event**
  - **Node** = photon
  - **Edge** = pair of photons
  - Node properties
    - px, py, pz, E
  - Edge properties
    - invariant mass
    - boost
    - angle

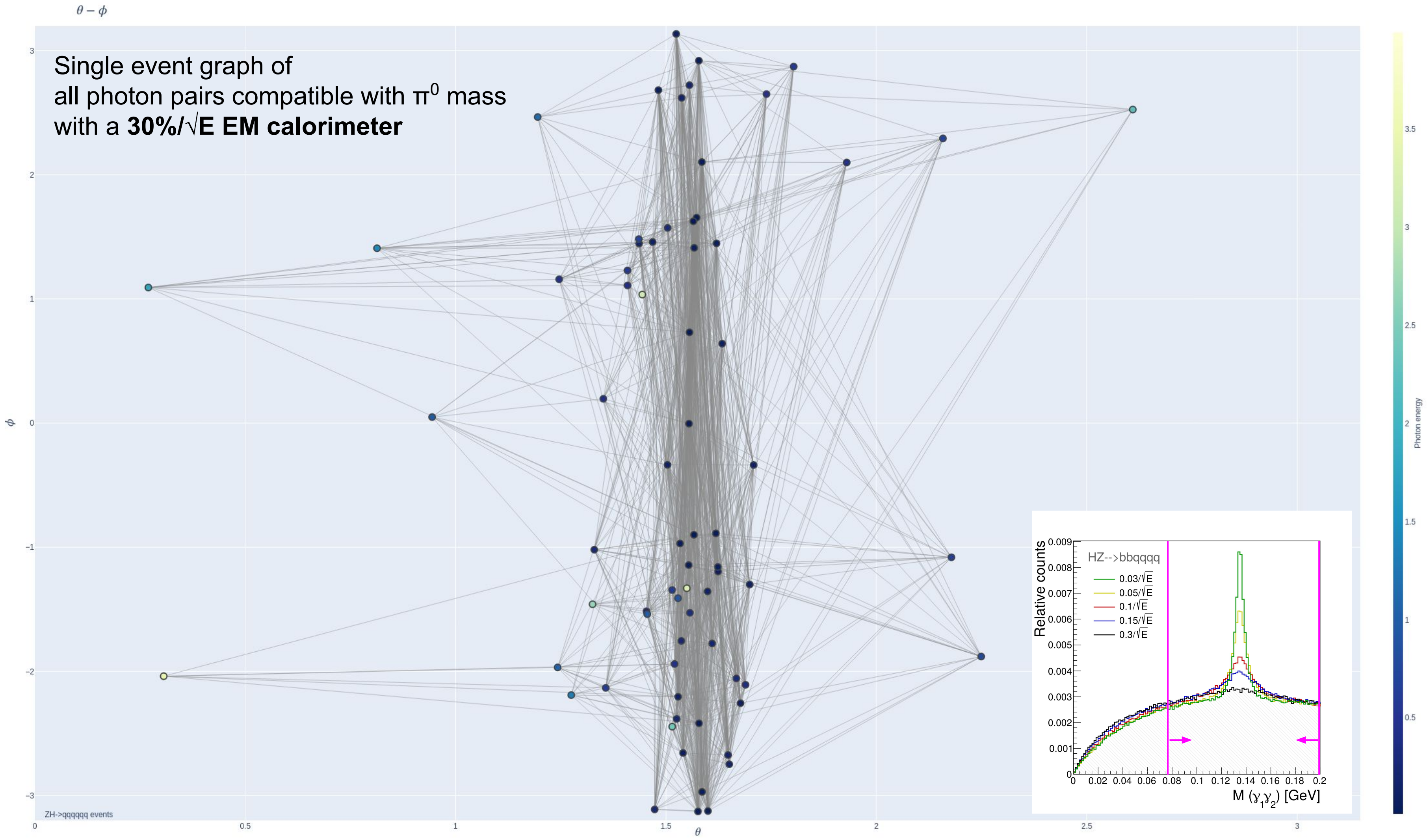


Assign weights to the graph edges

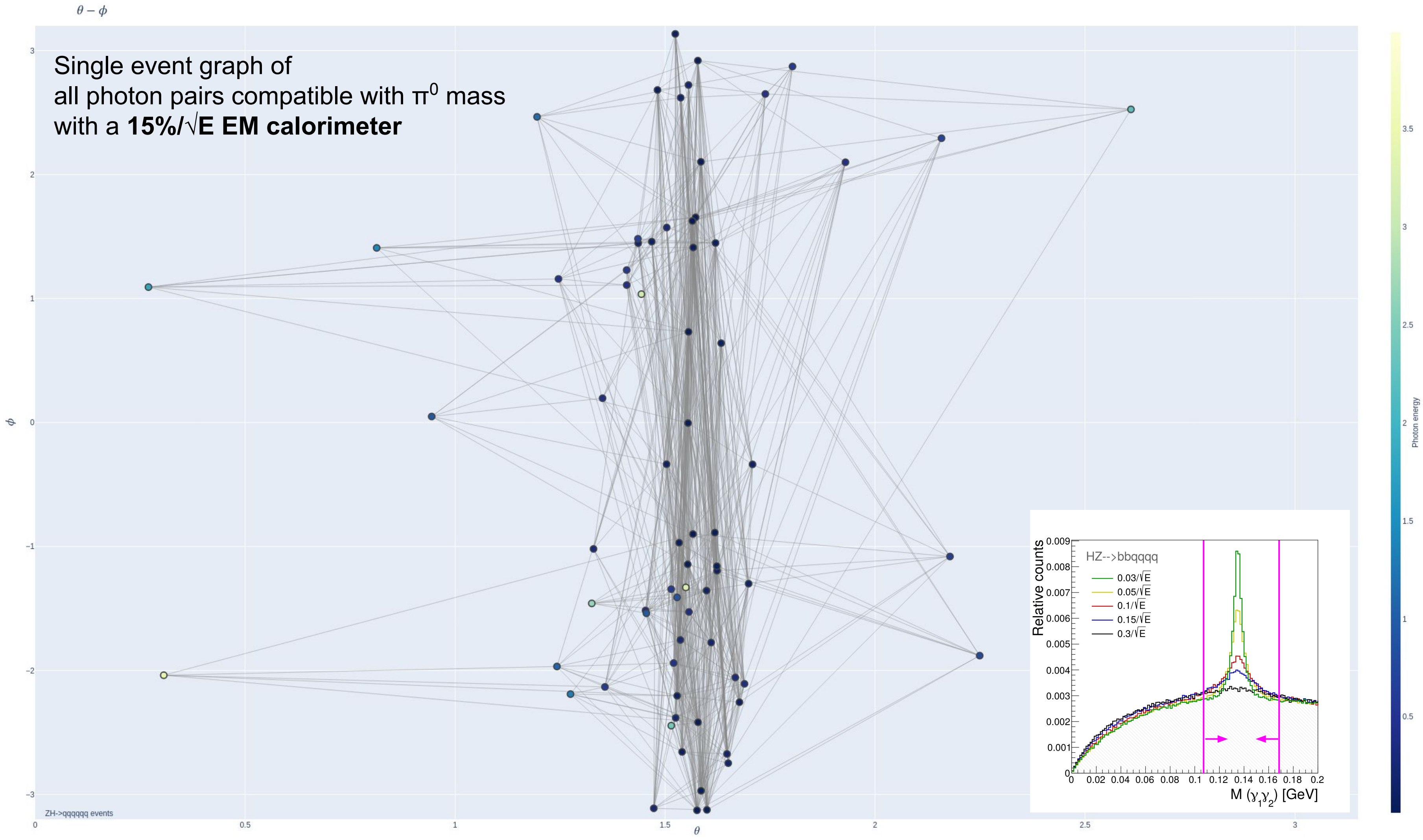
- **Assign a weight, w_{ij}**, to each edge depending on how close is the di-photon invariant mass to the π^0 mass
- $\chi^2_{ij} = (M_{\gamma,i\,\gamma,j} - M_\pi)^2 / M_\pi$
- $w_{ij} = 1 - \chi^2_{ij} / \chi^2_{max}$
- $\chi^2_{max} = \max(\chi^2_{ij})$
- $w_{ij} \in [0,1]$

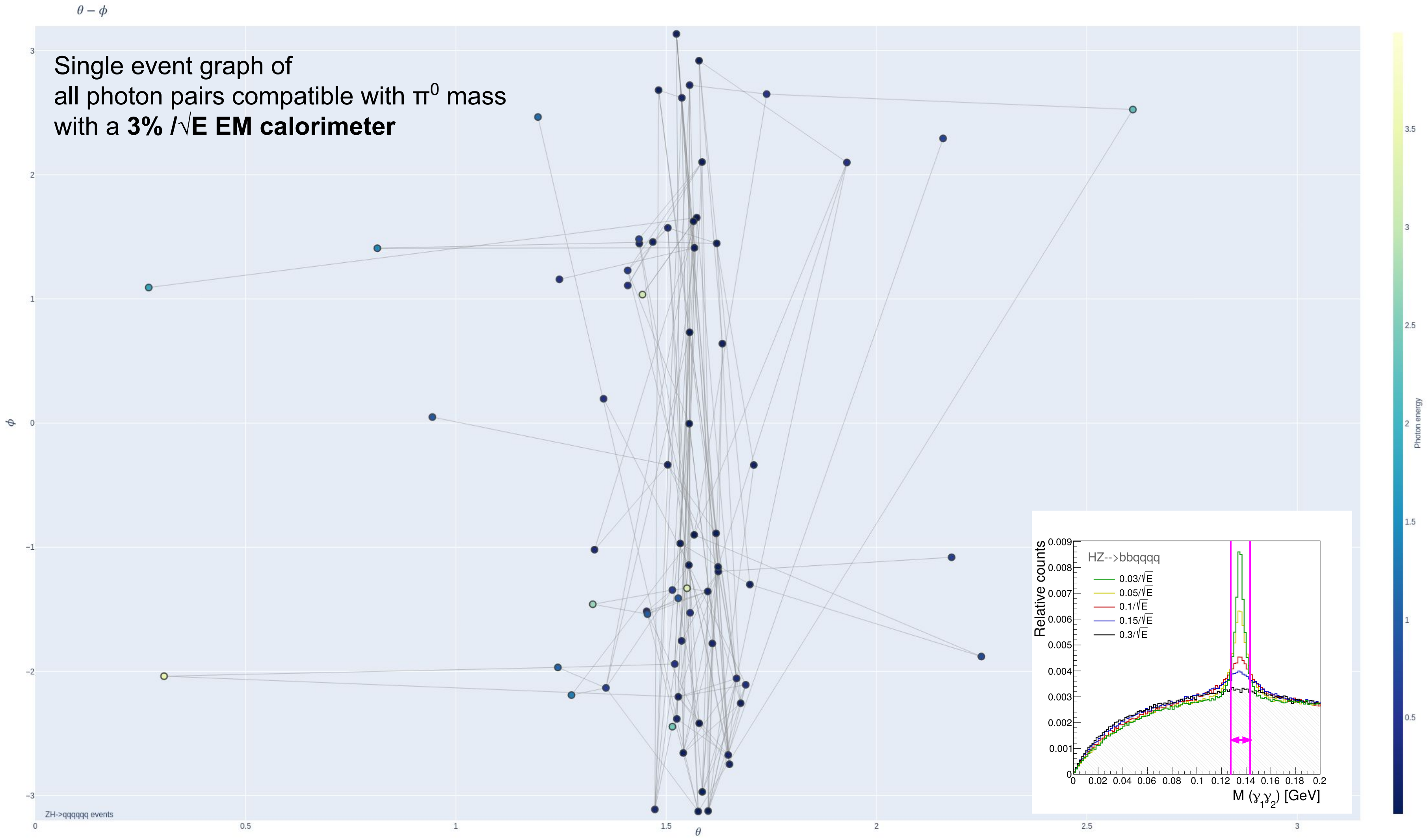


Single event graph of
all photon pairs compatible with π^0 mass
with a **30%/√E EM calorimeter**



Single event graph of
all photon pairs compatible with π^0 mass
with a **15%/√E EM calorimeter**



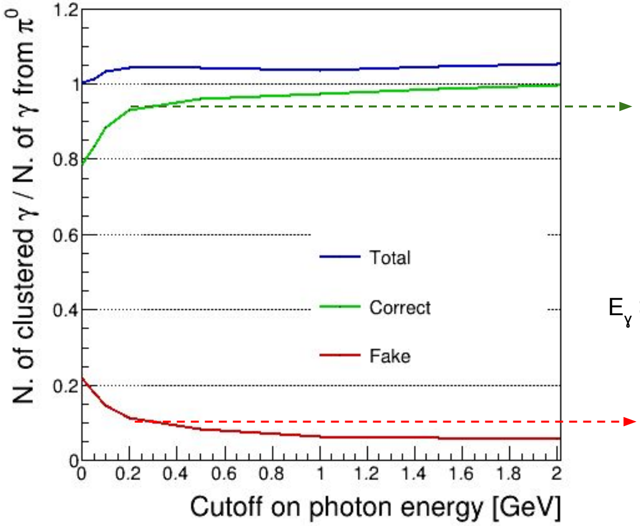


Single event graph of
all photon pairs compatible with π^0 mass
with a **3% /√E EM calorimeter**

Algo performance vs photon energy cut (results)

- Close to 100% of π^0's with both photons with energy >200 MeV correctly reconstructed with 3%/√(E) resolution

3% / √E

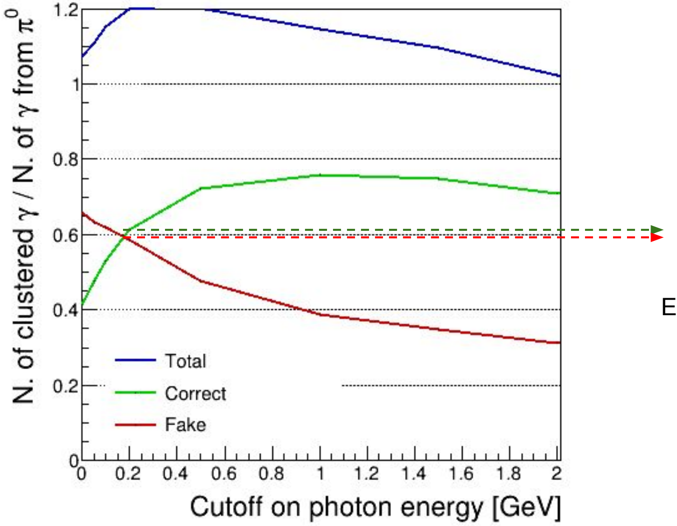


95%

10%

For
E_γ > 200 MeV

30% / √E



60% / 60%

For
E_γ > 200 MeV