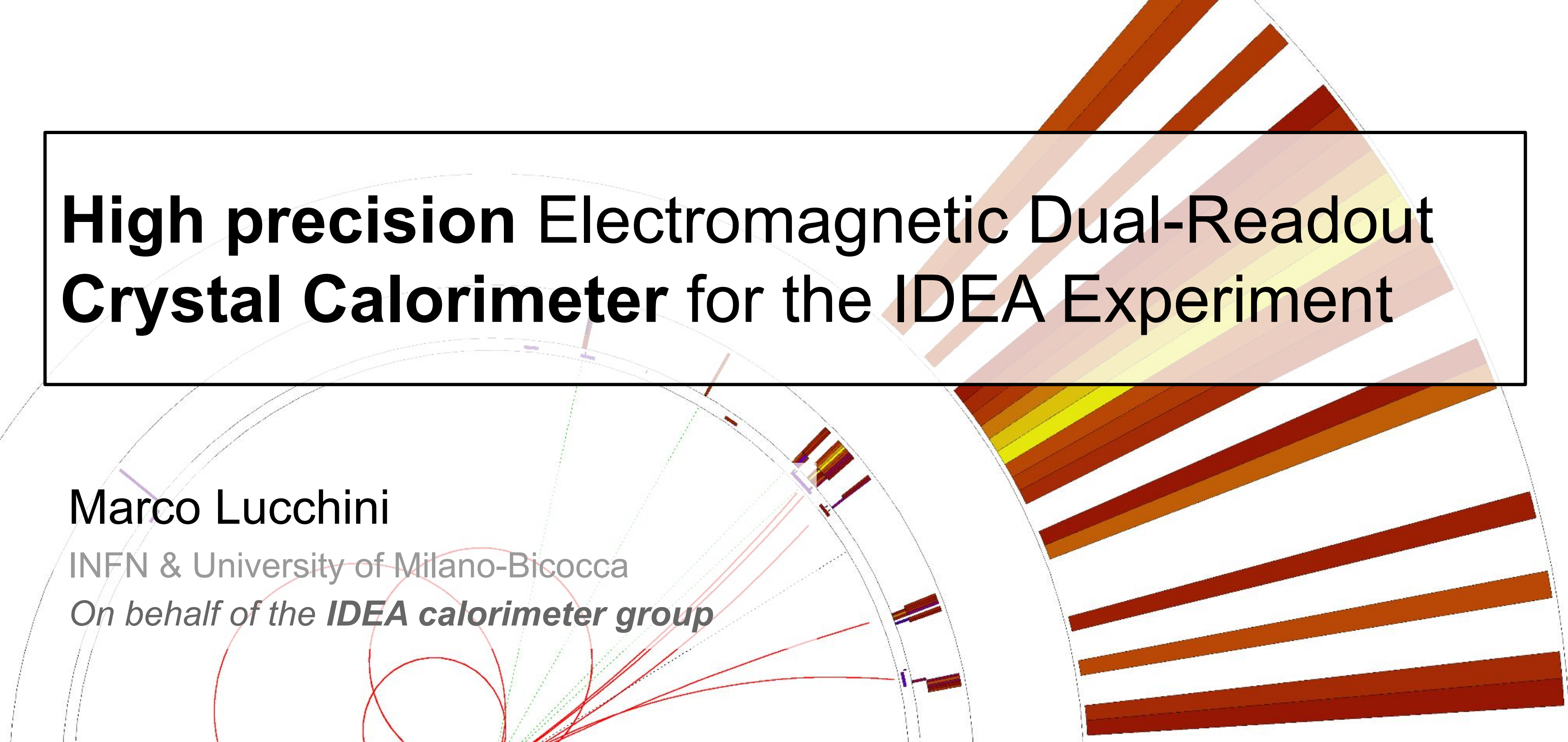


High precision Electromagnetic Dual-Readout **Crystal Calorimeter** for the IDEA Experiment

Marco Lucchini

INFN & University of Milano-Bicocca

*On behalf of the **IDEA calorimeter group***

FCC-France & Italy Workshop on Higgs,Top, EW, HF Physics in Lyon

21-23 November 2022

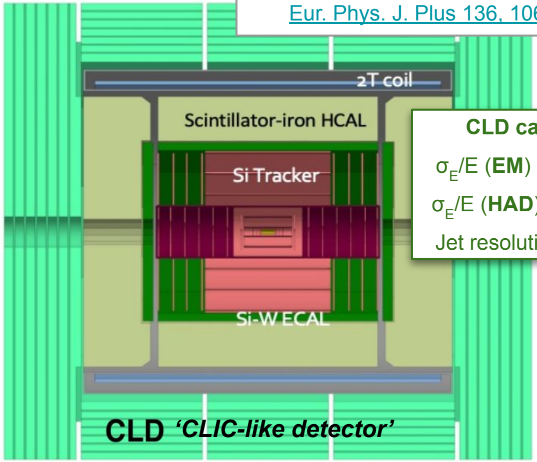
Current baseline detector concepts for future **e^+e^- colliders**

M.Aleksa et al., *Calorimetry at FCC-ee*, Eur. Phys. J. Plus 136, 1066 (2021)

Two main baseline concepts for general purpose detectors at future e^+e^- colliders:

- **CLD**: Sampling calorimeters with silicon / plastic scintillators active elements interleaved with tungsten / steel
  - Exploiting high granularity for particle flow algorithms (combining tracker and calorimeter exploiting topological information)
- **IDEA**: Sampling calorimeters with ~2 m long scintillating (plastic) and cherenkov fibers inside absorber groove
  - Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)

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

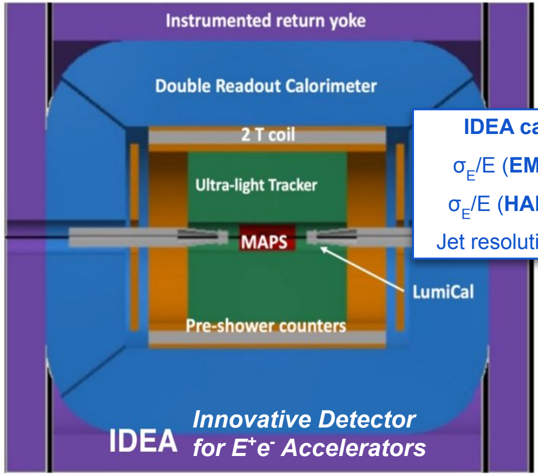


CLD calorimeter

σ_E/E (**EM**) ~15-17%/√E

σ_E/E (**HAD**) ~45-50%/√E

Jet resolution ~ 30%/√E



IDEA calorimeter

σ_E/E (**EM**) ~11%/√E

σ_E/E (**HAD**) ~30%/√E

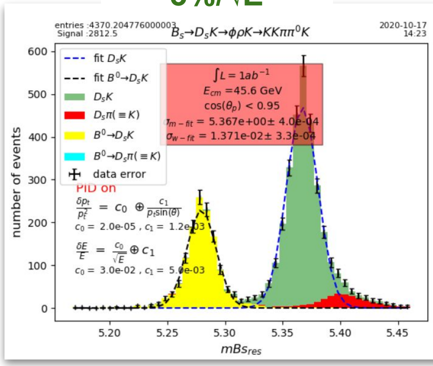
Jet resolution ~ 30%/√E

Potential for high EM energy resolution

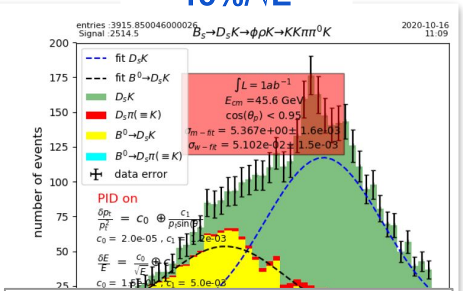
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

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

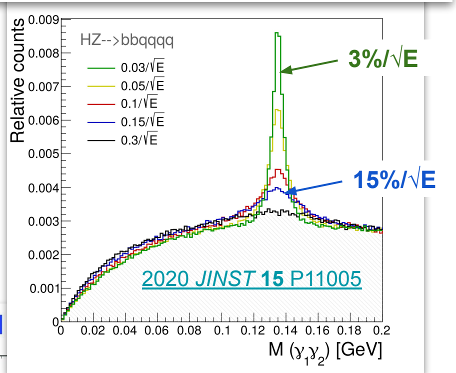
3%/√E

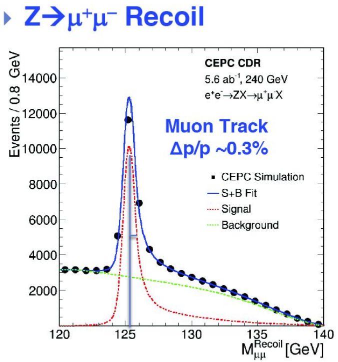


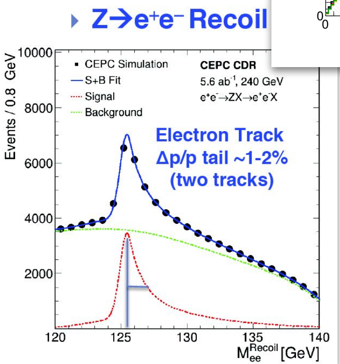
15%/√E



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







Example from CEPC CDR

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

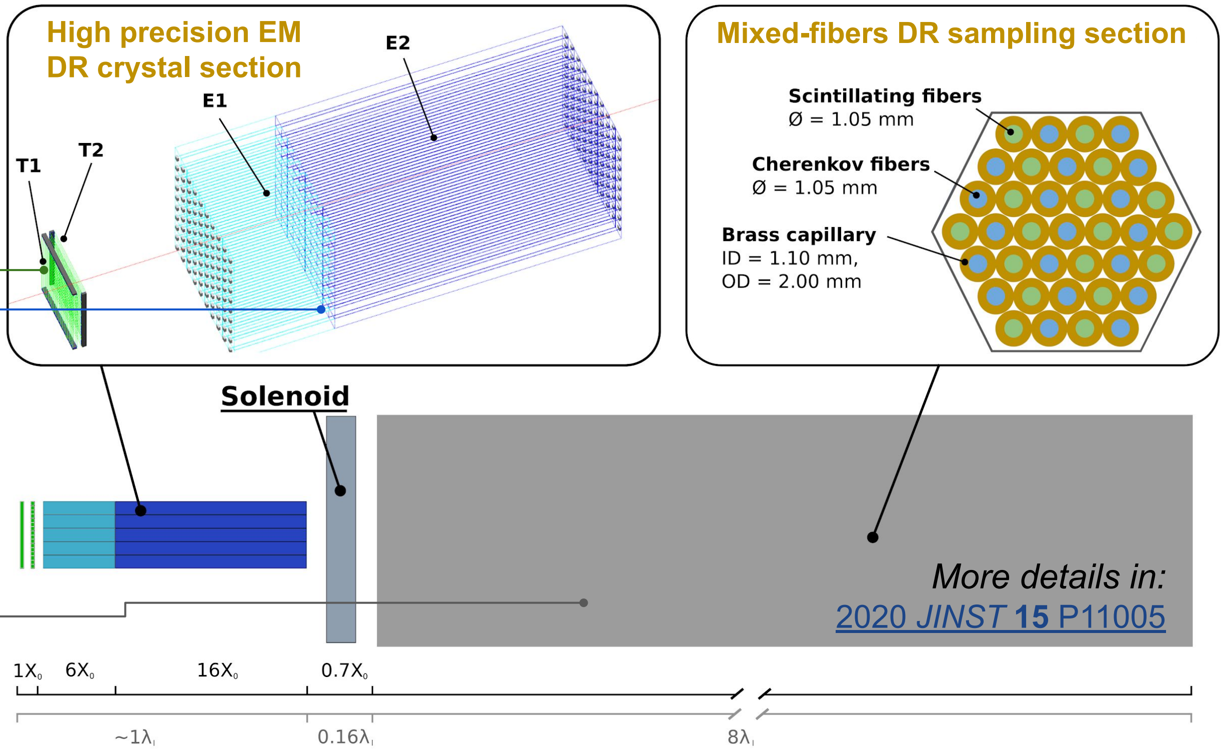
- **Excellent energy resolution to photons and neutral hadrons**
  (~3%/√E and ~30%/√E respectively)
- **Separate readout of scintillation and Cherenkov light**
  (to exploit dual-readout technique for hadron resolution and linearity)
- **Longitudinal and transverse segmentation**
  (to provide more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

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

Conceptual layout

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

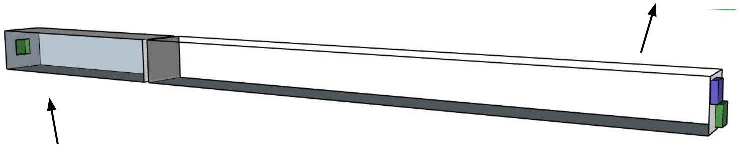
- **Timing layers** — **$\sigma_t \sim 20$ ps**
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — **$\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$**
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal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



Implementation of dual-readout in the crystal section

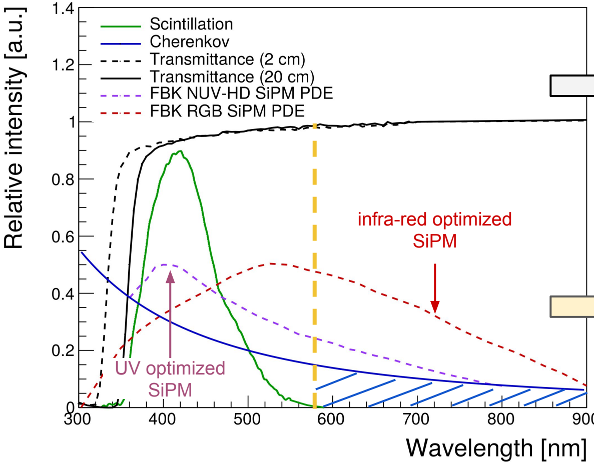
- Simultaneous readout of scintillation and Cherenkov light from the rear segment with dedicated SiPMs+wavelength filters

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



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

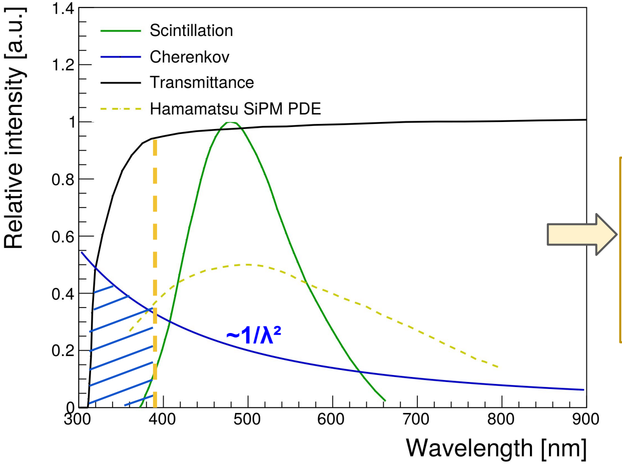
PWO



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



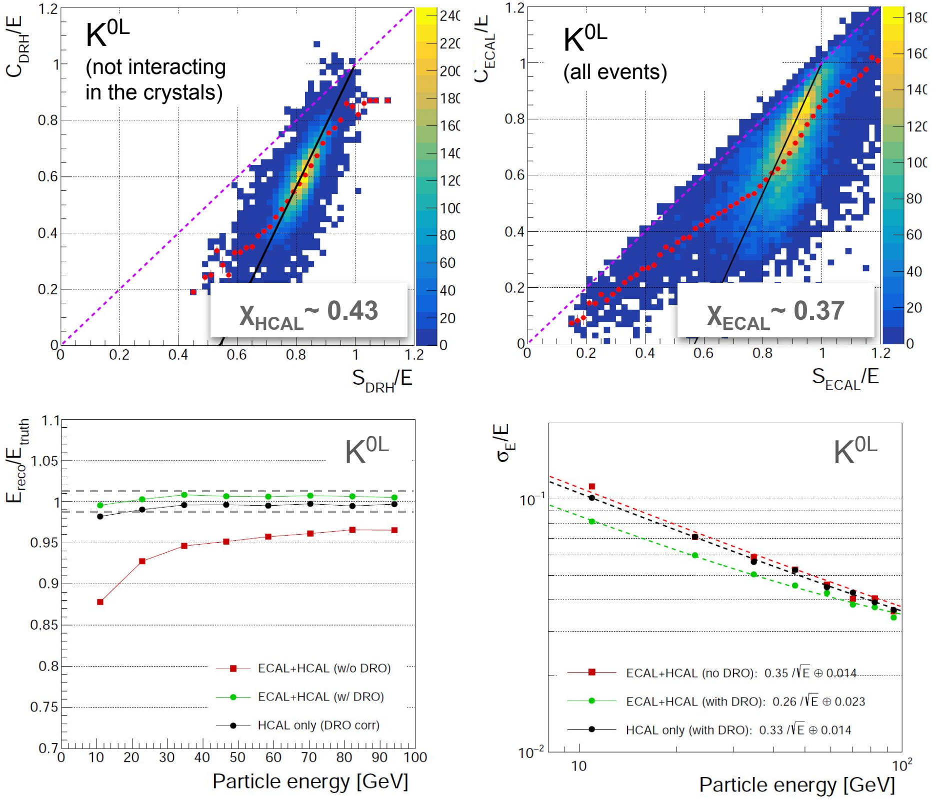
BGO/BSO have larger stokes shift, i.e. a wider range of transparency for 'UV Cherenkov'

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

- Apply the DR correction on the energy deposits in the crystal and fiber segments first and then s um up the corrected energy from both segments

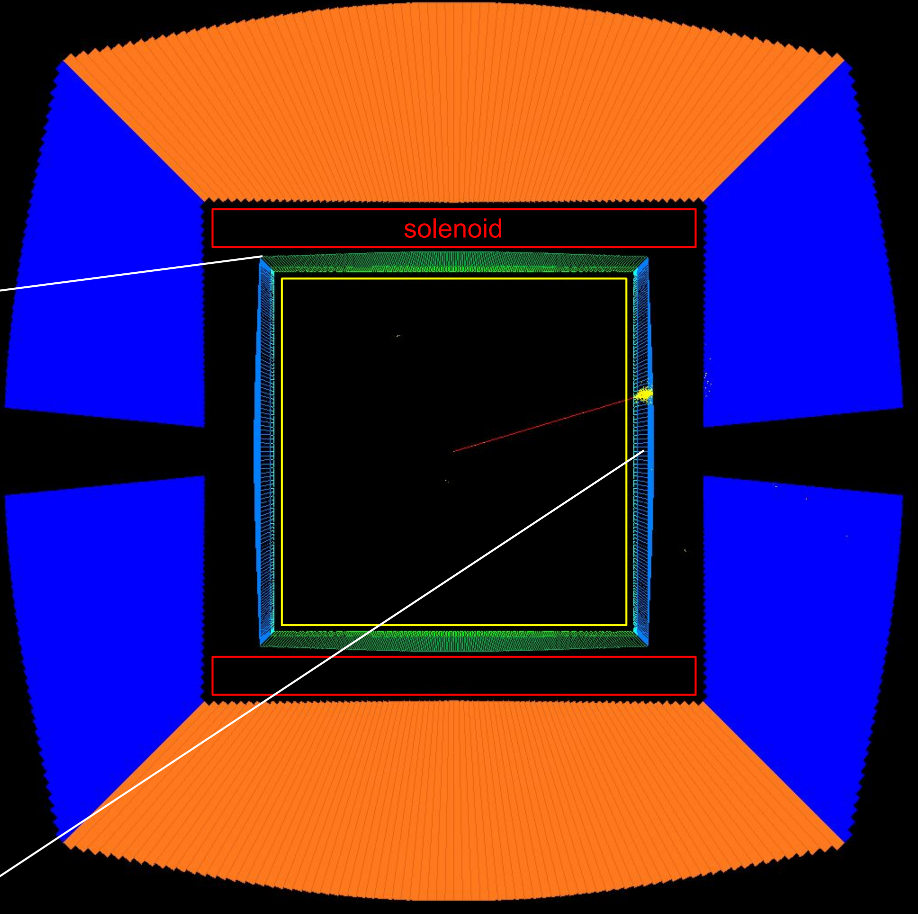
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

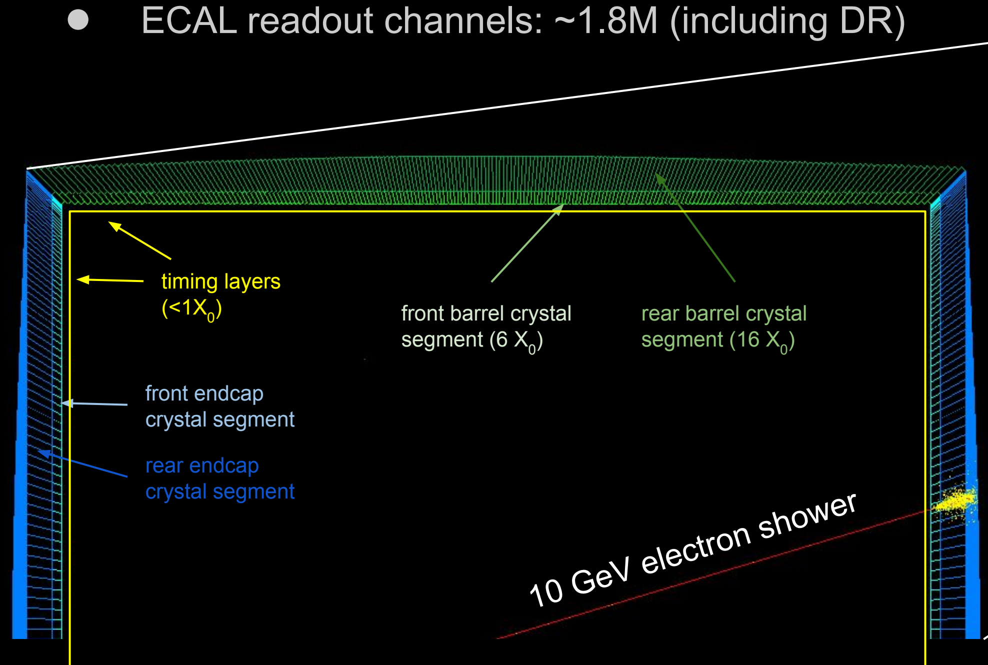
- **Dual-readout method confirms its applicability in a hybrid calorimeter**
    - Response linearity to hadrons restored within ±1%
    - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter



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

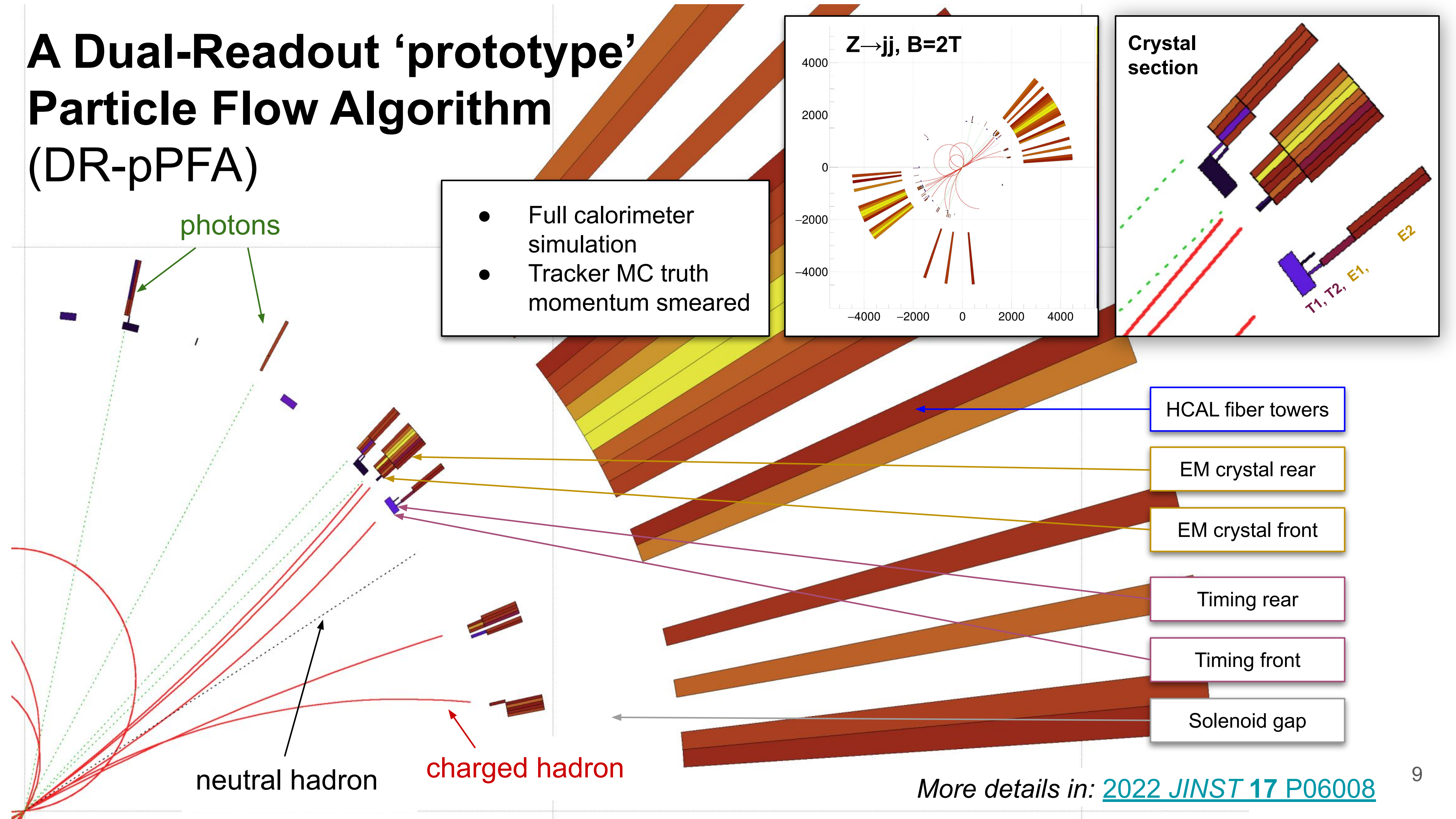
- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: ~1.8M (including DR)





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

- Full calorimeter simulation
- Tracker MC truth momentum smeared



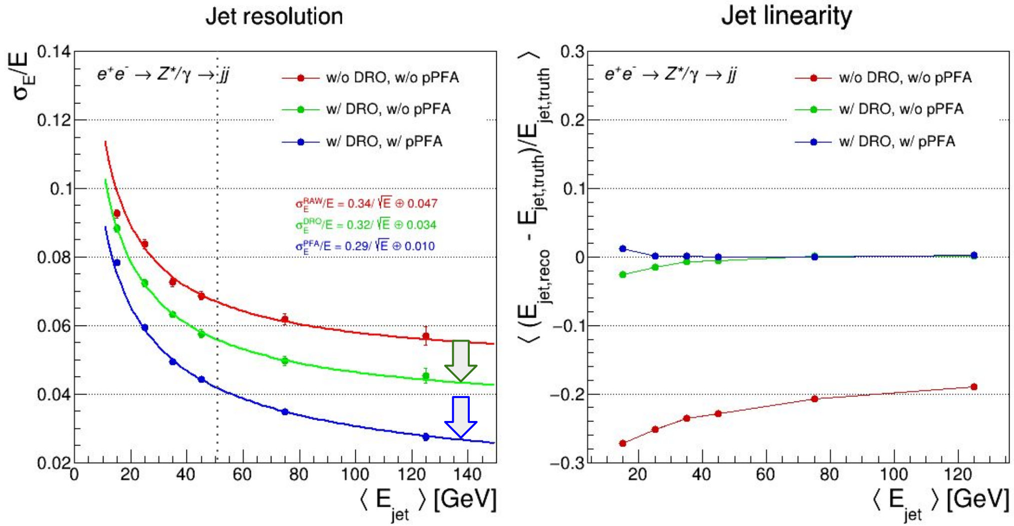
More details in: [*2022 JINST* **17** P06008]

Jet resolution: with and without DR-pPFA

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

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

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

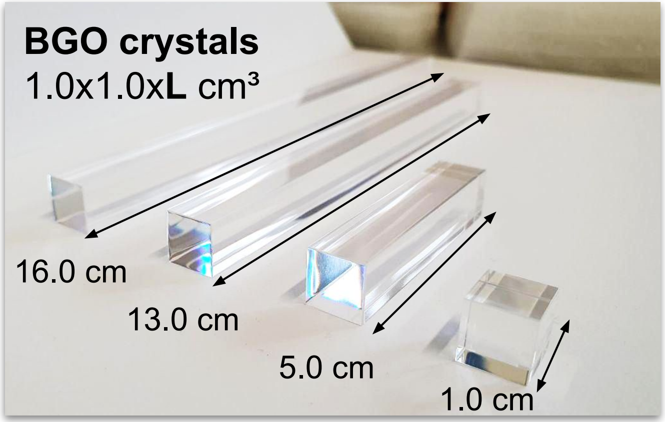


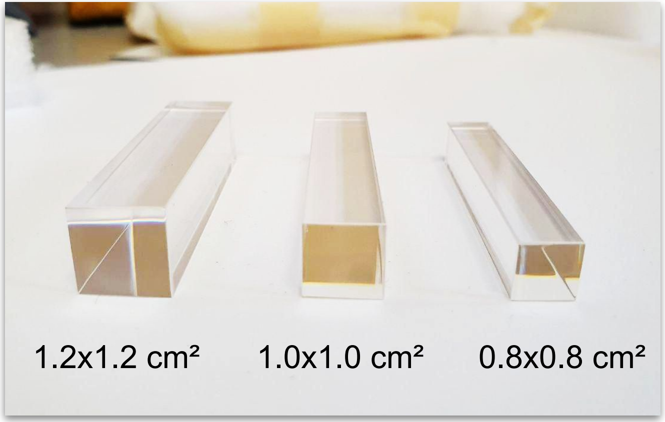
Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

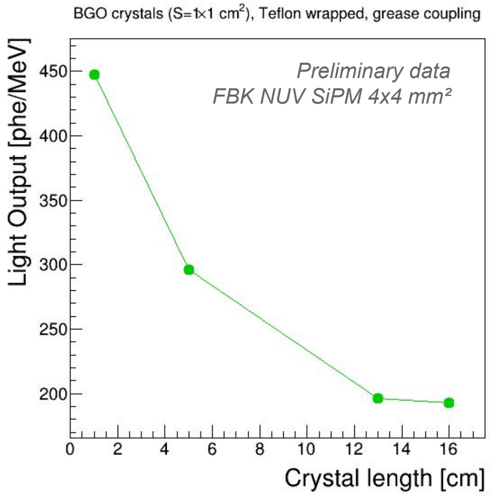
Ongoing effort to repeat the study with full simulation including tracker and with edm4hep data format: see talk from A.D'Onofrio in the afternoon

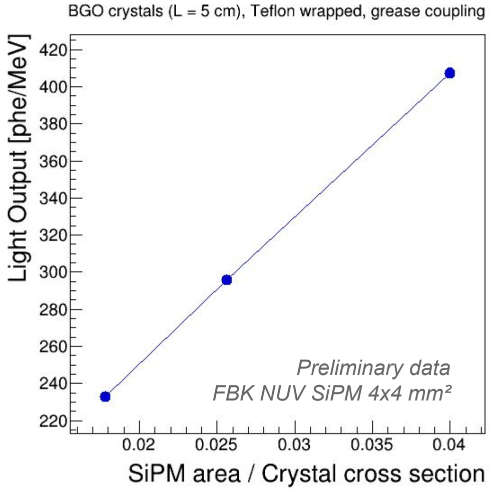
Ongoing R&D: calorimeter cell optimization

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









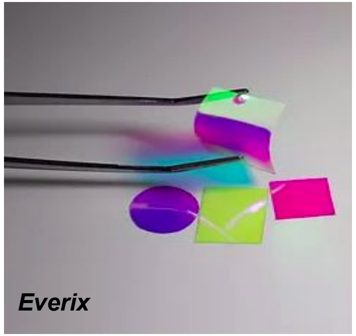
Ongoing R&D: dual-readout challenge

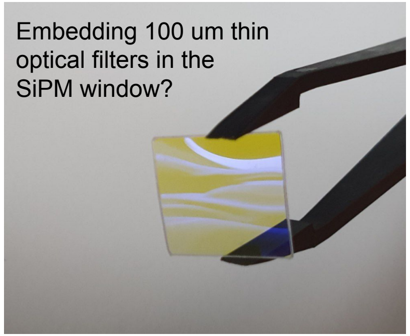
Multi-signal readout challenges:

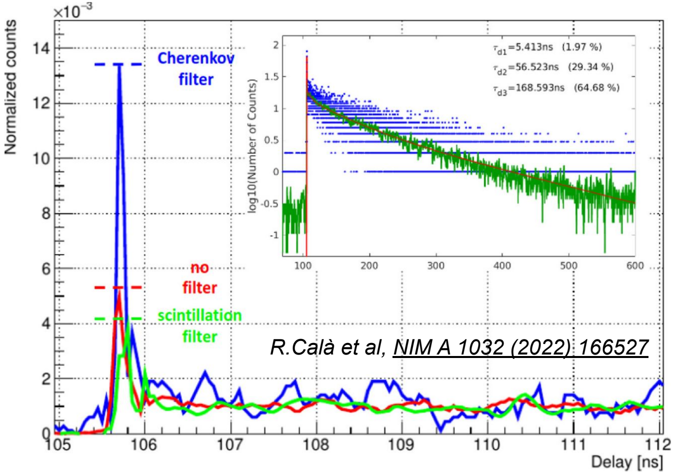
- Challenging dynamic range and photon sensitivity with SiPMs
- Reasonable **scintillation** and **cherenkov** light yields (>2000 phe/GeV and >100 phe/GeV resp.)
- **Good separation of scintillation and cherenkov signals** (e.g. based on thin wavelength filters)

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

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







Summary

- EM energy resolution at the 1-3%/$\sqrt{E}$ level can **expand the physics potential of e^+e^- collider experiments** providing enhanced sensitivity to low energy photons

- A **dual-readout hybrid calorimeter** (homogeneous crystals + fibers in brass tubes) **can meet the requirements of EM, HAD and jet energy resolution** (through the development of dedicated dual-readout particle flow algorithms)

- **Growing national and international efforts** (INFN MiB&Napoli, Calvision in US, Lab27 at CERN) to address **R&D challenges** and development of simulation tools to optimize a cost-effective calorimeter design

Additional material

Outlook and next steps

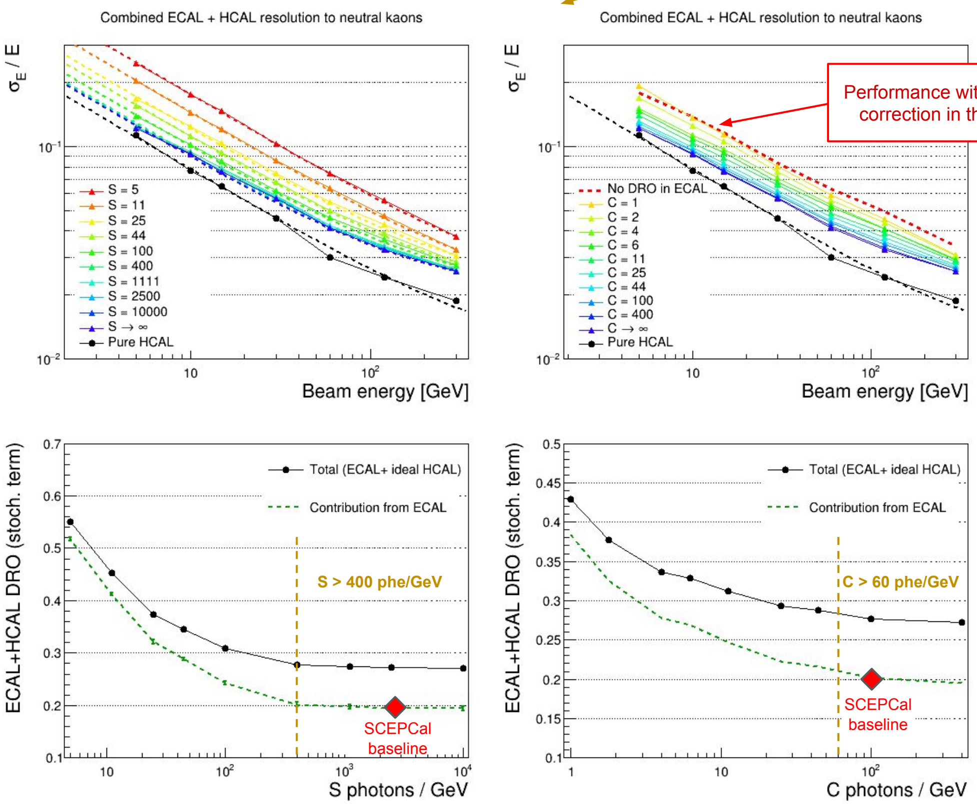
- Hardware / prototyping:
  - Identification of best crystal and SiPM candidates (+ wavelength filters)
  - Optimization of calorimeter cell design (geometry)
  - Demonstration of S and C light outputs
  - Proof-of-concept of dual-readout functionality with cosmic ray bench
  - Towards EM calorimeter module prototype for beam test

- Software / simulation
  - Migration of crystal calorimeter simulation in the latest IDEA Geant4 simulation with the edm4hep data format
  - Development of a DD4HEP version of the crystal geometry
  - Continue development of dedicated **DR-PFlow algorithms** with full detector simulation
  - Explore physics benchmarks benefiting from high energy resolution for photons

Photo-statistic requirements for S and C

Smearing according to Poisson statistics

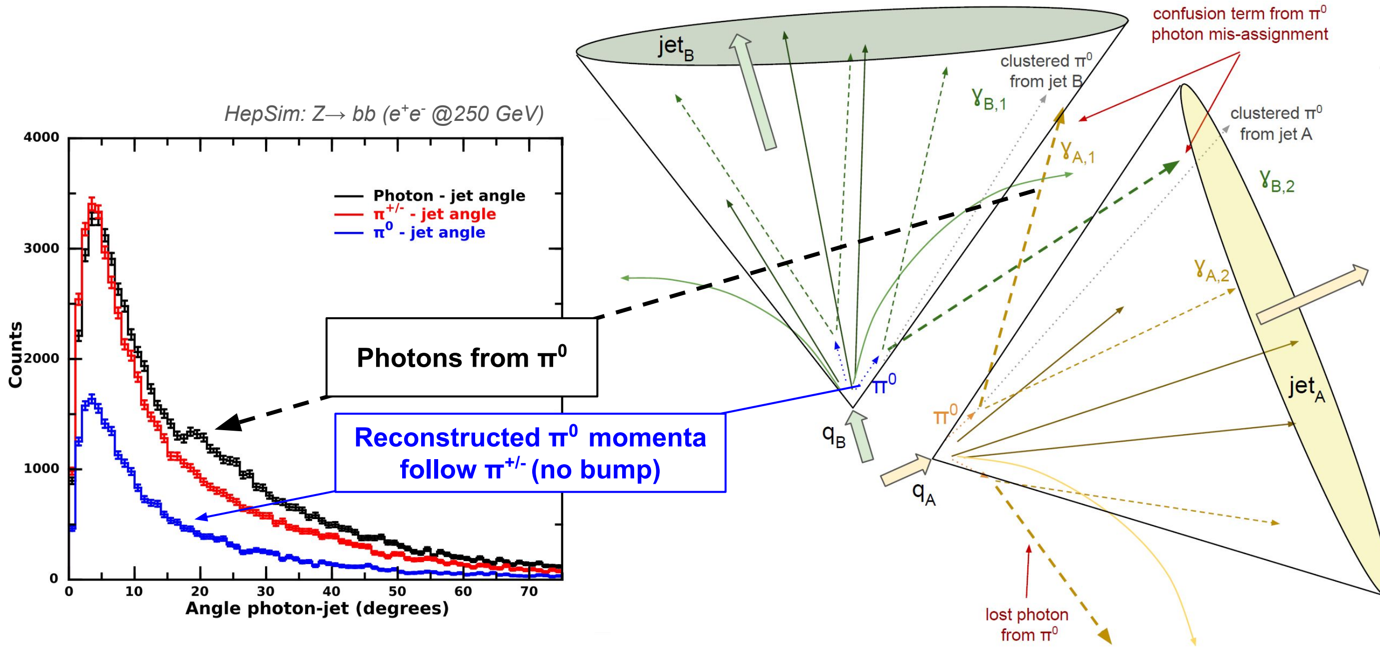
- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV
- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV
- **SCEPCal layout choices** (granularity and SiPM size) **provide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

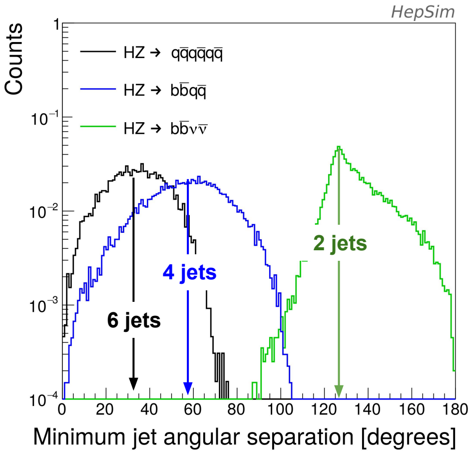


Impact of high EM resolution on reconstruction and physics

High photon resolution potential for PFA

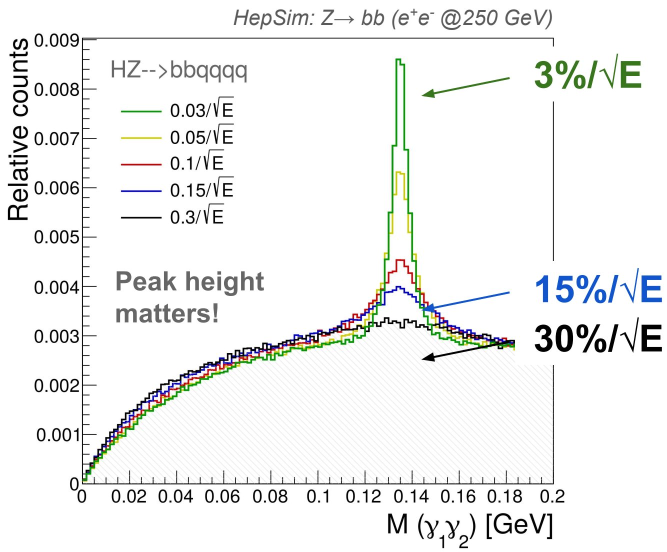
- **Many photons from π^0 decay** are emitted **at a ~20-35° angle** wrt to the jet momentum and can get scrambled across neighboring jets
- Effect **particularly pronounced in 4 and 6 jets topologies**

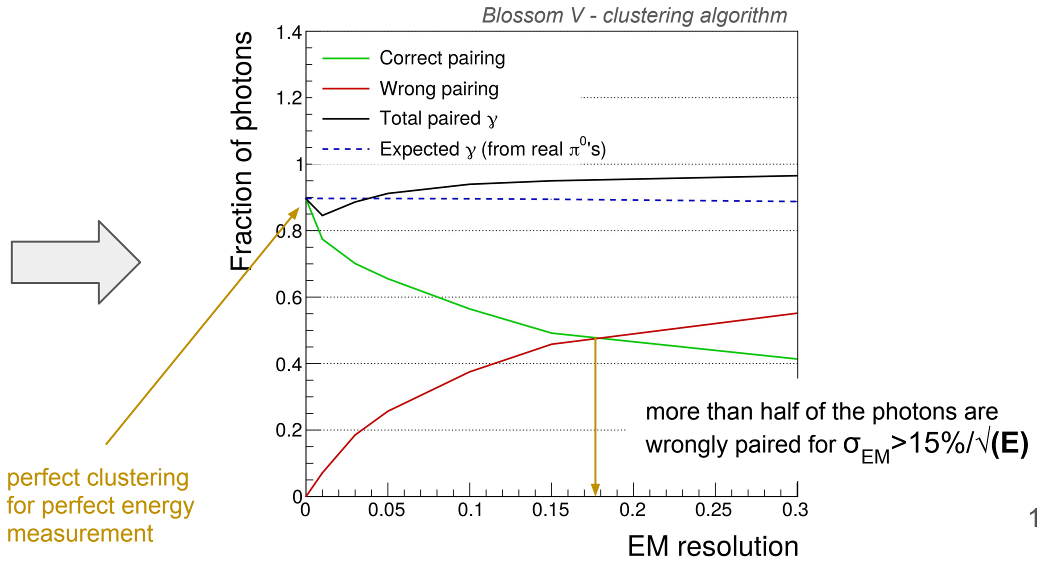




A graph-based algorithm for π^0 clustering

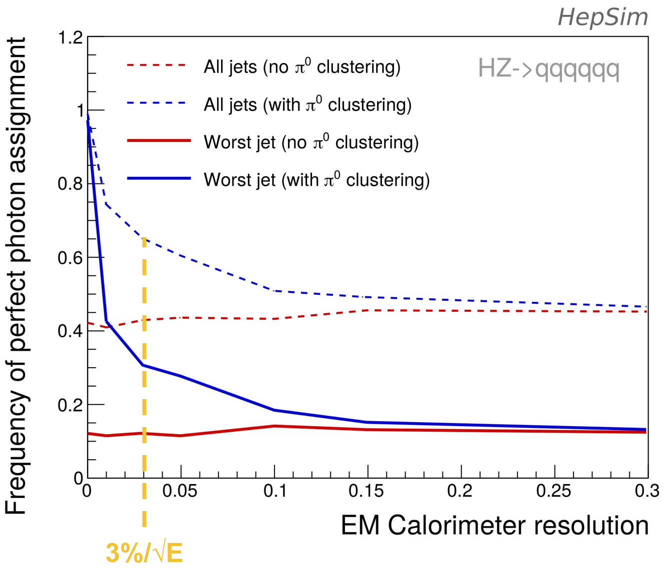
- **A high EM resolution enables efficient clustering of photons from π^0's**
  - Large fraction of π^0 photons correctly clustered with good σ_{EM}
    → **~90% for ~3%/√(E)** vs **50% for ~30%/√(E)**
  - Large fraction of "**fake π^0's**"reconstructed with poor σ_{EM}
    → ~50% for ~30%/√(E) vs 10%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

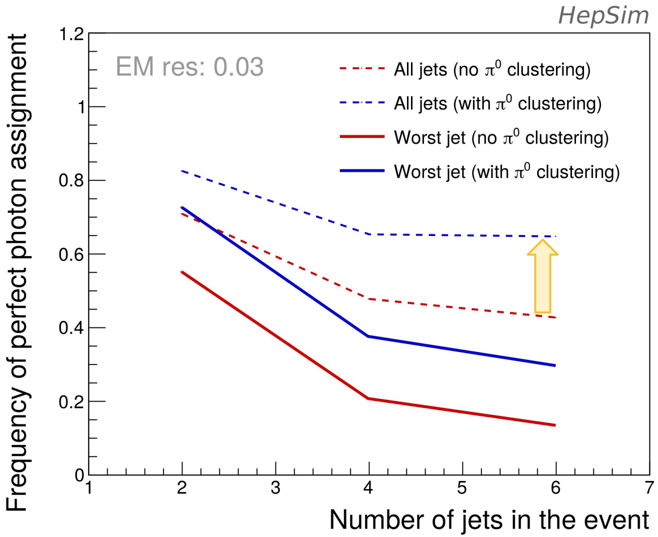




Improvements in photon-to-jet correct assignment

- **High e.m. resolution enables** photons **clustering into π⁰'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)

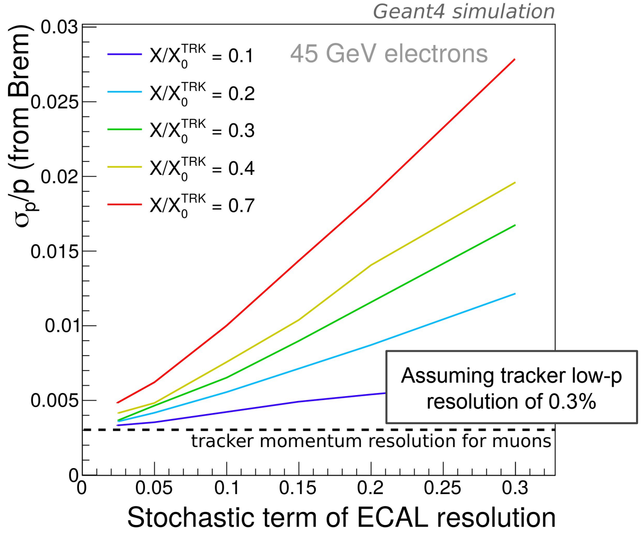




More details in:
https://doi.org/10.1088/1748-0221/15/11/P11005

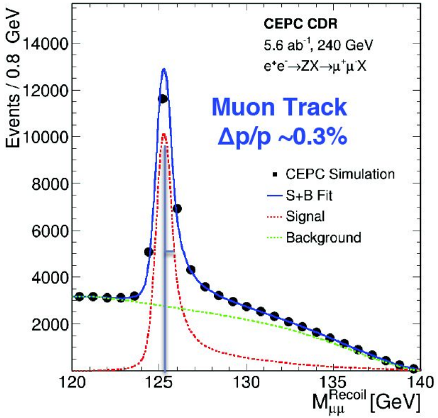
Recovery of Bremsstrahlung photons

- 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]

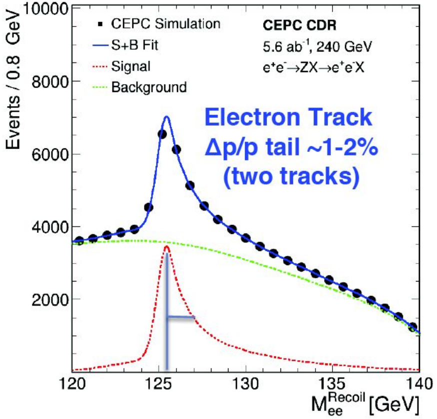


Example from CEPC CDR

Z→μ⁺μ⁻ Recoil



Z→e⁺e⁻ Recoil



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

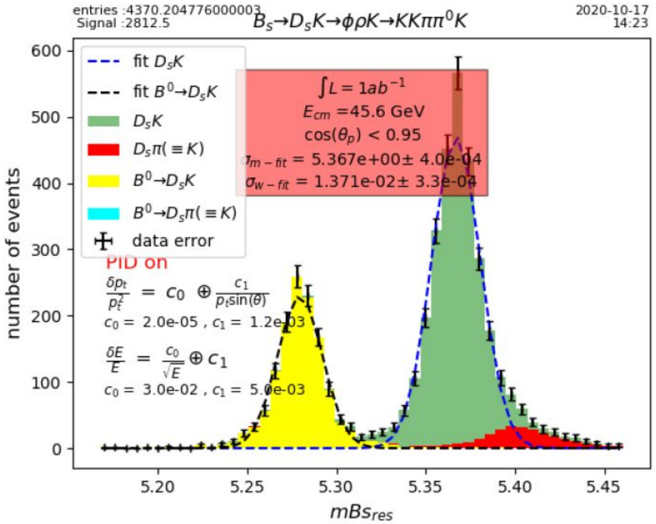
Studies of CP violation and EW physics at e^+e^- colliders

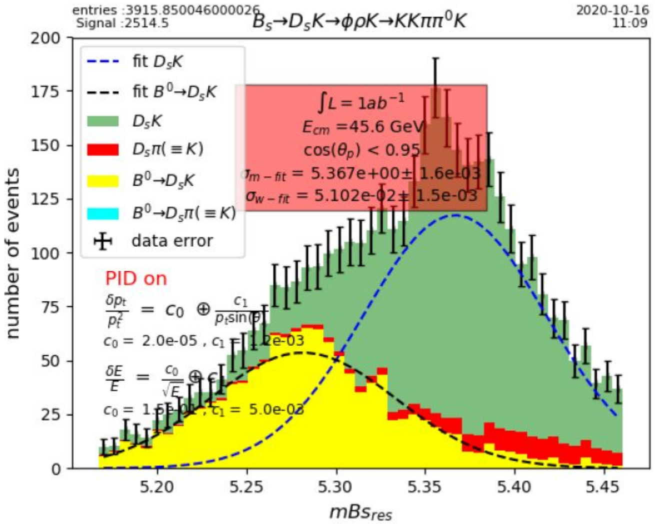
$\overline{B}_s$ decay Mode	Decay Mode	Final State	Number of $\overline{B}_s$ decays
$D_s^+ K^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+K^-$	$\sim 5.2\ 10^5$
$D_s^+ K^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+K^-\pi^0$	$\sim 9.8\ 10^5$

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

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

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

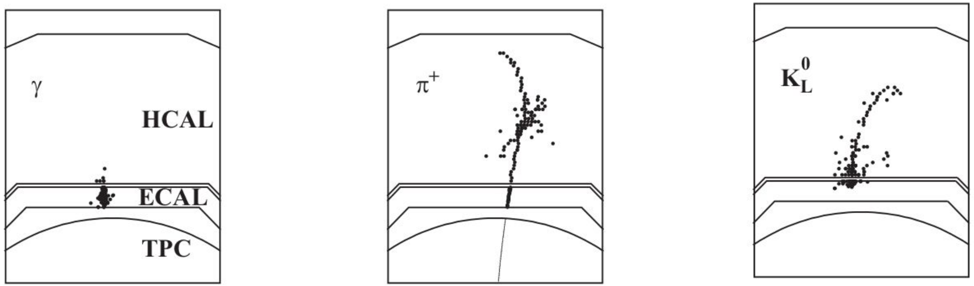




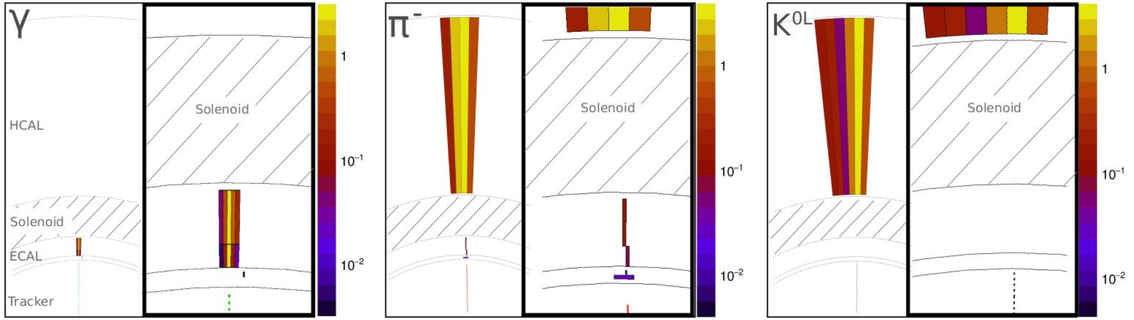
See **R. Aleksan's** talk @ 4th FCC Physics and Experiments Workshop

More on DR-pPFA

Single particle identification through 'hits-topology'



Typical PFA with Si-W high granularity calorimeter



DR-pPFA with high resolution DRO calorimeter

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

A different basis for a DR-oriented PF algorithm

- Could the **better energy linearity and resolution** offset the coarser longitudinal segmentation?

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

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

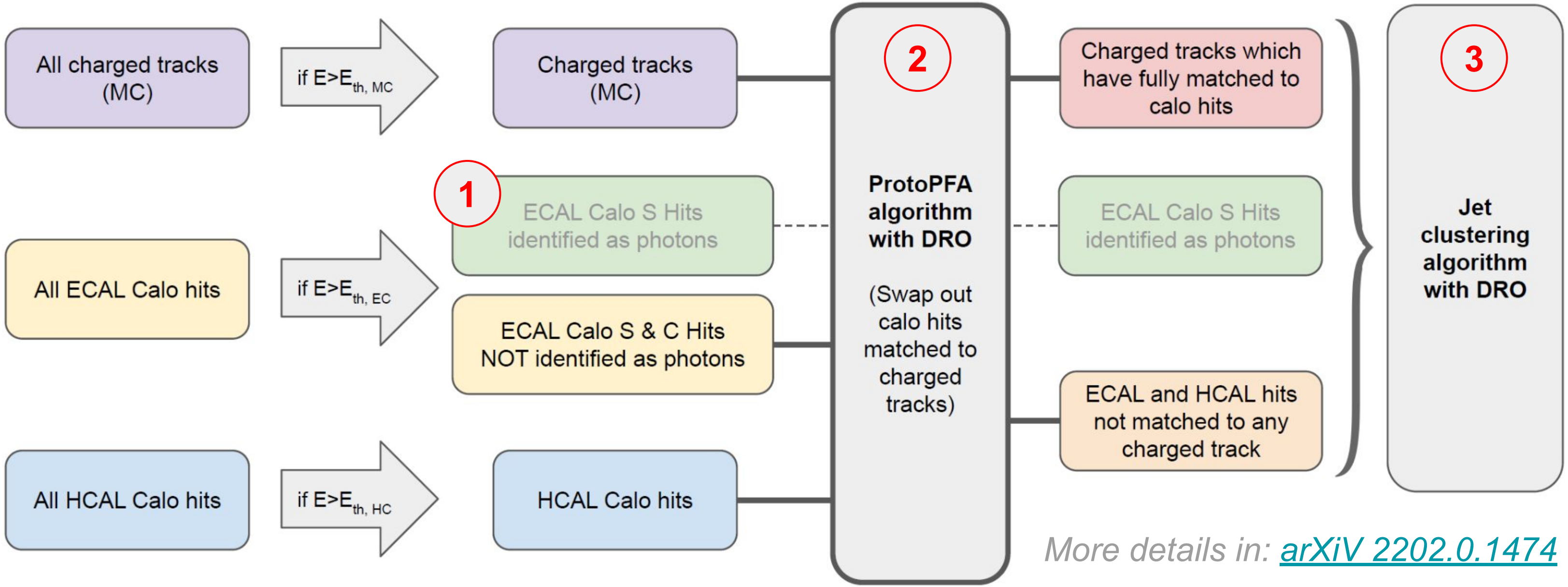
Highest energy resolution and linearity

Highest longitudinal segmentation

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

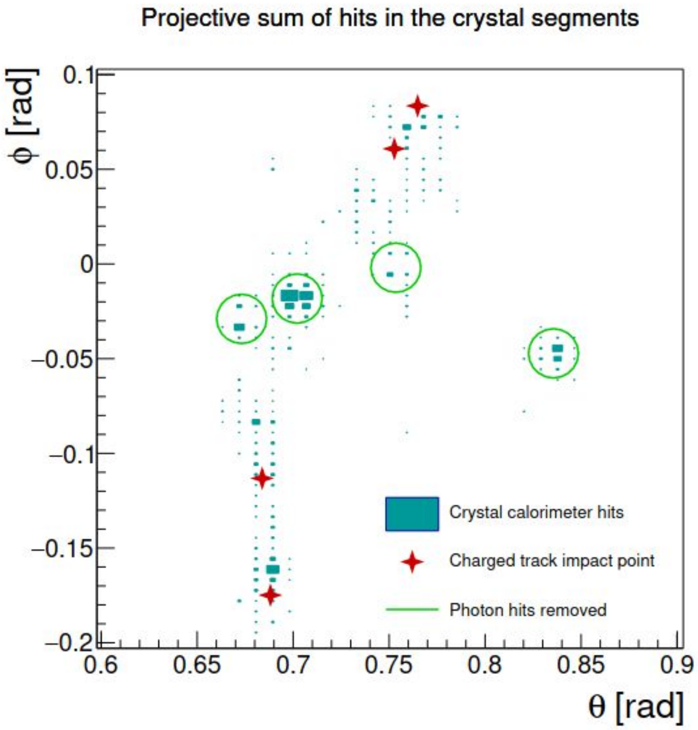
Dual-**R**eadout **P**article **F**low **A**lgorithm for jet reconstruction

- 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



More details in: arXiV 2202.0.1474

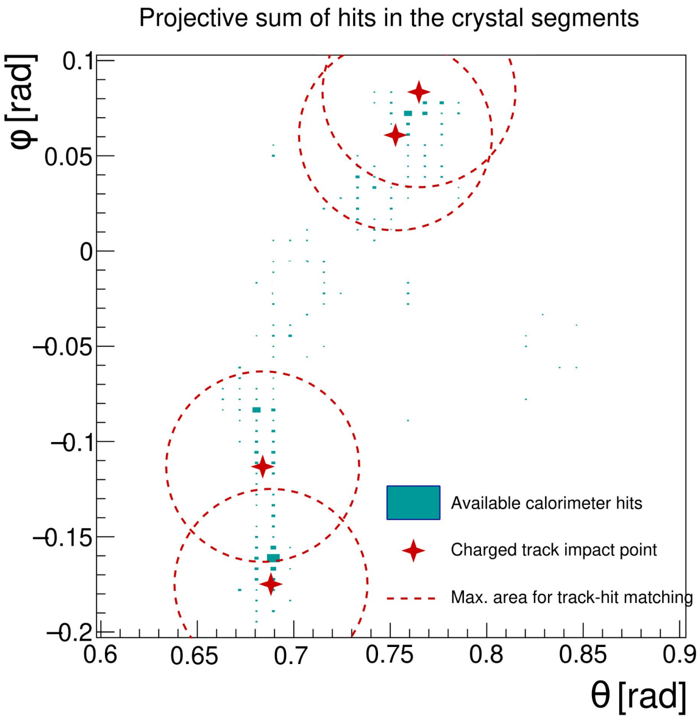
Step 1) Identification of photon hits



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

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

Step 2) Association of calorimeter hits to charged tracks



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

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

Step 3) Jet clustering

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

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

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

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