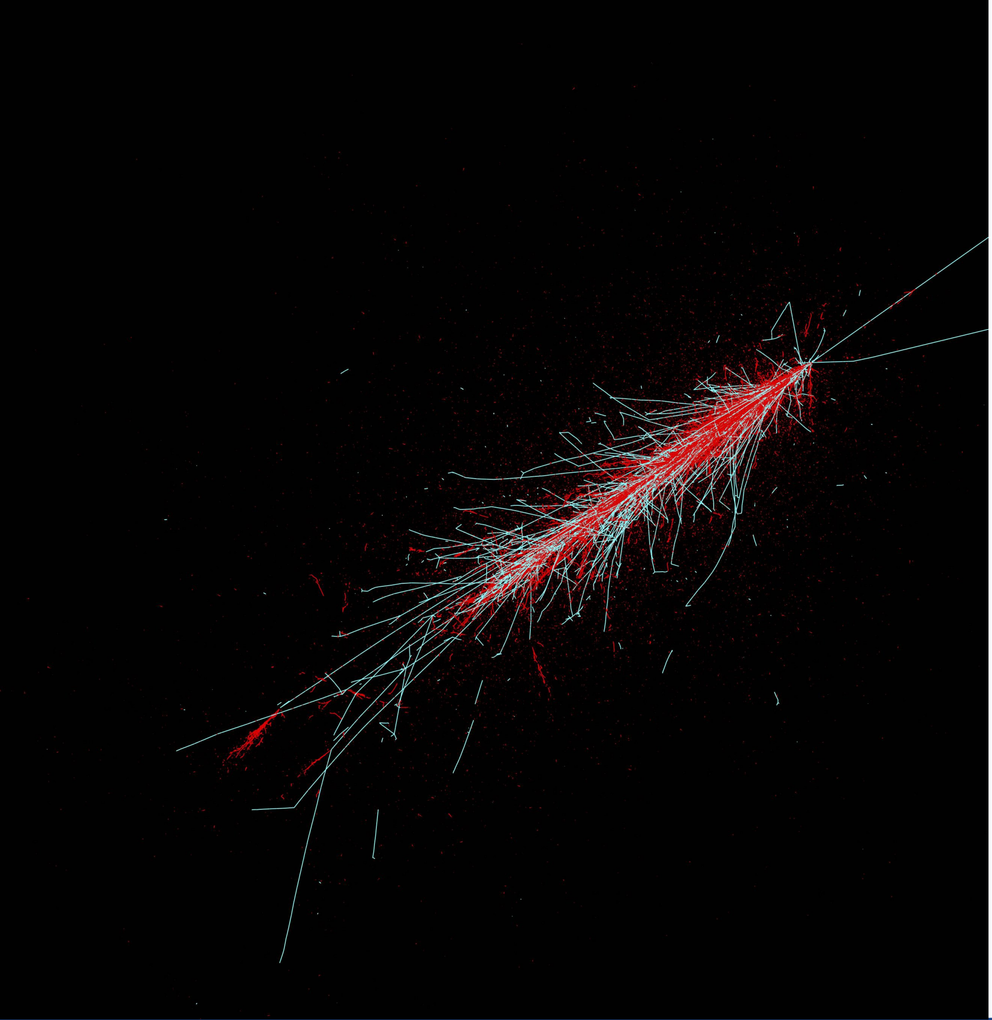
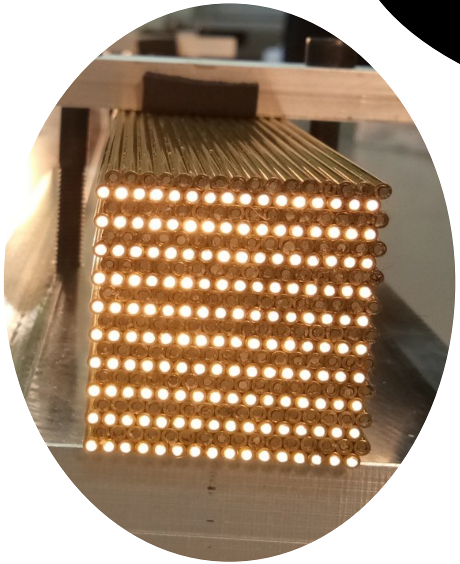


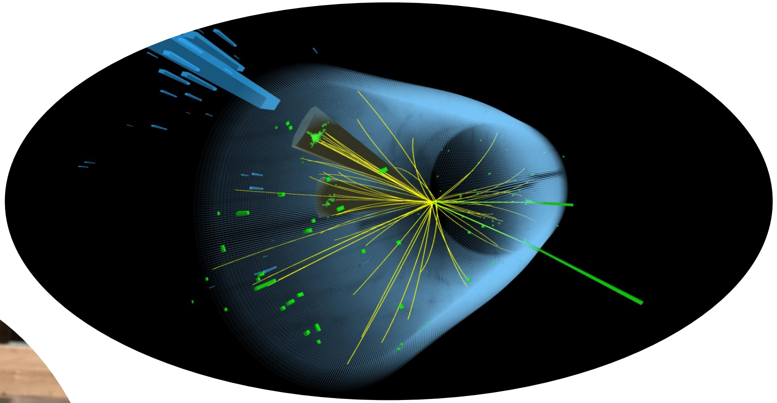
Dual-Readout Calorimetry for future HEP Experiments

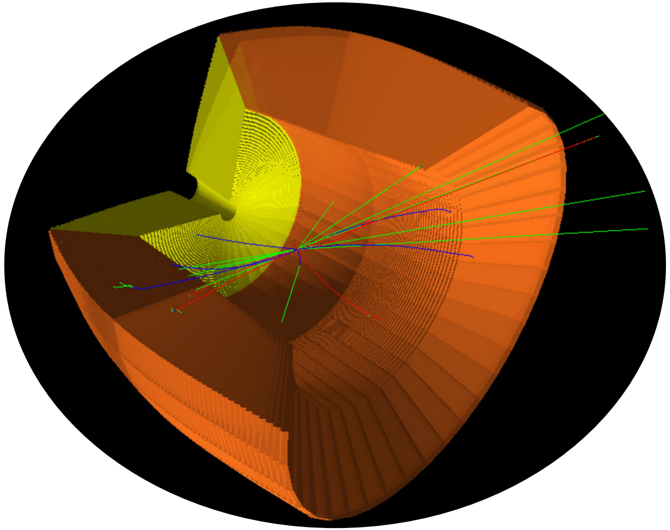
Andrea Pareti – INFN and Università di Pavia
Workshop on Future Accelerators - 25/04/2023

Topics

Future e^+e^- colliders
Experimental Challenges
Dual-Readout Calorimetry
Current and expected results
Outlook





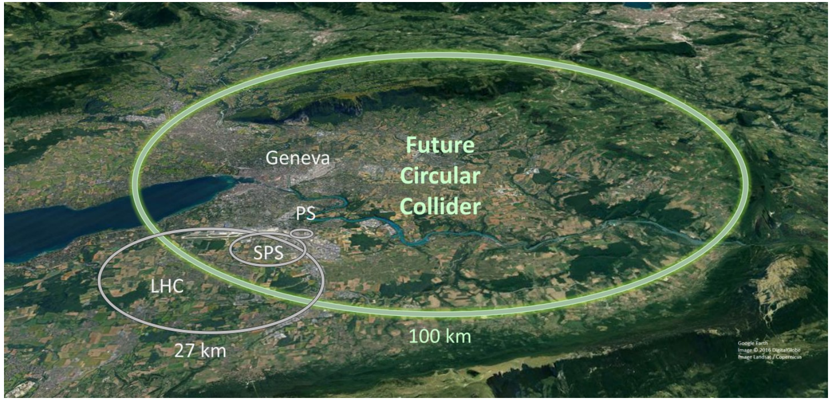


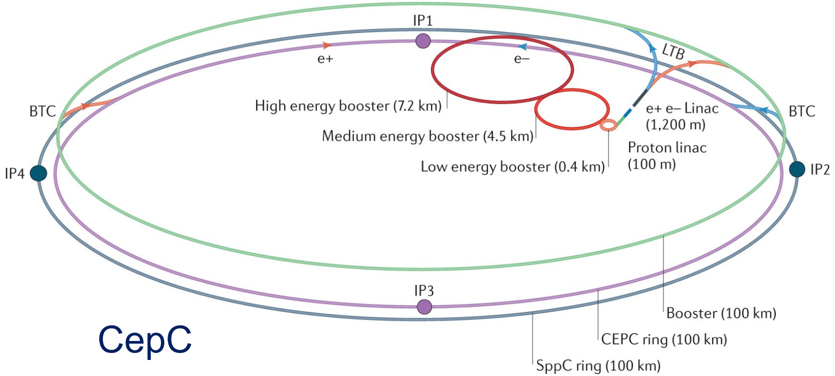
Searches at e^+e^- colliders

Two main projects for future e^+e^- colliders:
FCC at CERN, CepC (China)
Energies in the Center of mass frame:
[90, 160, 240, 365] GeV

Broad physics potential:

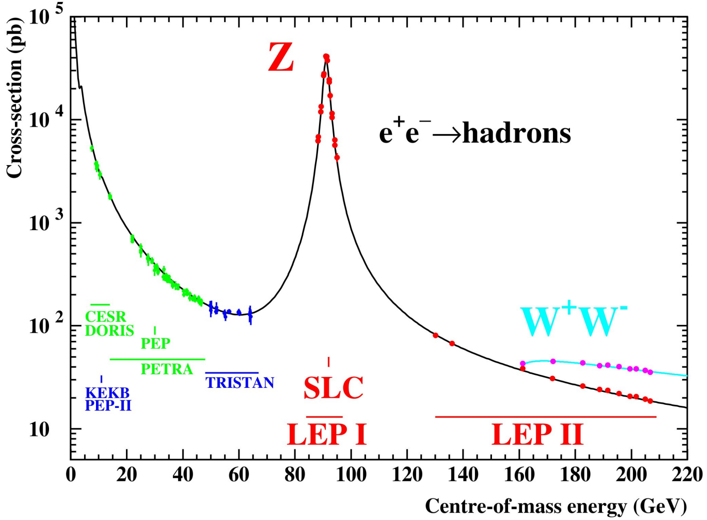
- ElectroWeak physics at Z pole and WW threshold
- Higgs precision measurements
- Direct searches for new physics
- Heavy Flavour Physics





CepC

Searches at e^+e^- colliders

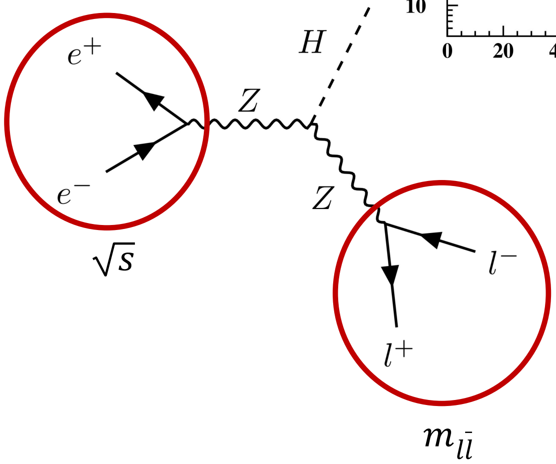


Two main projects for future e^+e^- colliders:
FCC at CERN, CepC (China)
Energies in the Center of mass frame:
[90, 160, 240, 365] GeV

Broad physics potential:

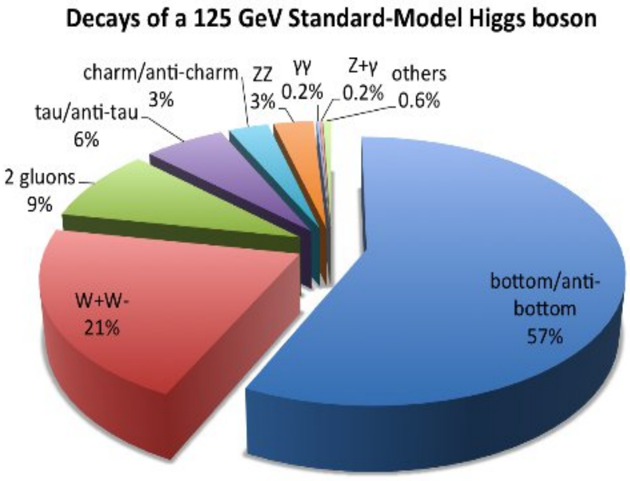
- ElectroWeak physics at Z pole and WW threshold
- Higgs precision measurements
- Direct searches for new physics
- Heavy Flavour Physics

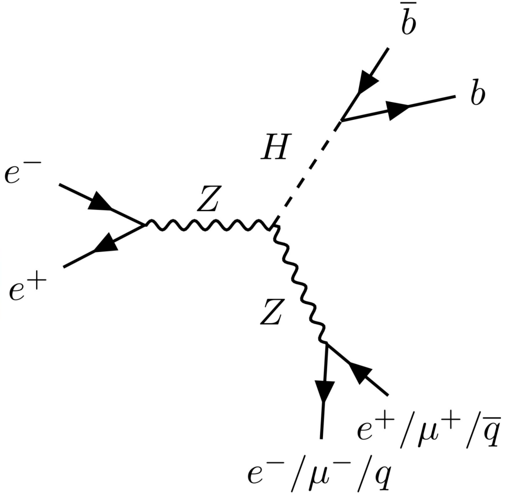
Very tight requirements on detector performance for precision physics

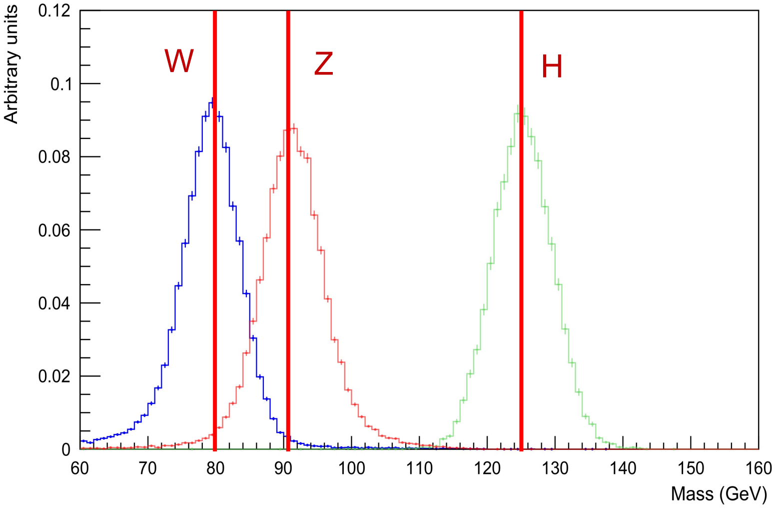


Exploit recoil method:

$$m^2_{recoil} = \left(\sqrt{s} - E_{l\bar{l}}\right)^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$







Jet measurement benchmarks

Large W/Z/H hadronic branching ratio: High jet energy resolution is fundamental for future colliders measurements

Benchmark: distinguish W and Z bosons hadronic decays through the jet invariant mass

W/Z **separation** $= (m_Z - m_W)/\sigma_m$

Target resolution: $\frac{\sigma}{E} = \frac{30\%}{\sqrt{E}}$

Experimental Challenges

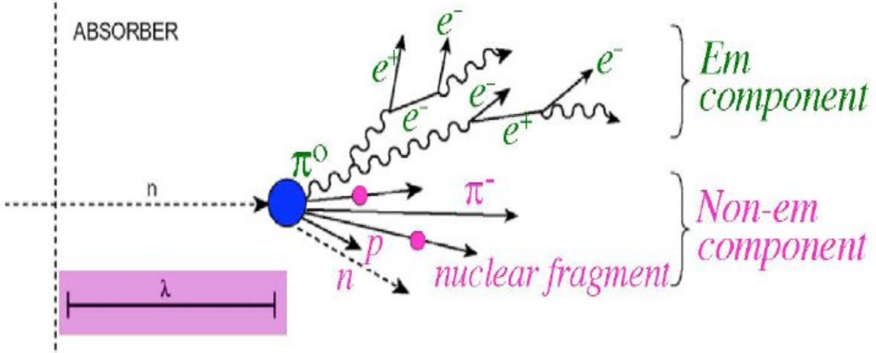
Any hadronic shower has two components
Electromagnetic fraction f_{em}: fraction of primary jet energy contained in the *em* component

Calorimeter response to the *em* and *non-em* components is very different: $\boldsymbol{e/h \neq 1}$

Hadronic jet reconstruction problems:

1. Large event-per-event fluctuations in f_{em}
2. f_{em} increases with energy (non-linearity)
3. Large event-per-event fluctuations in the invisible energy

electrons, positrons, photons, π^0



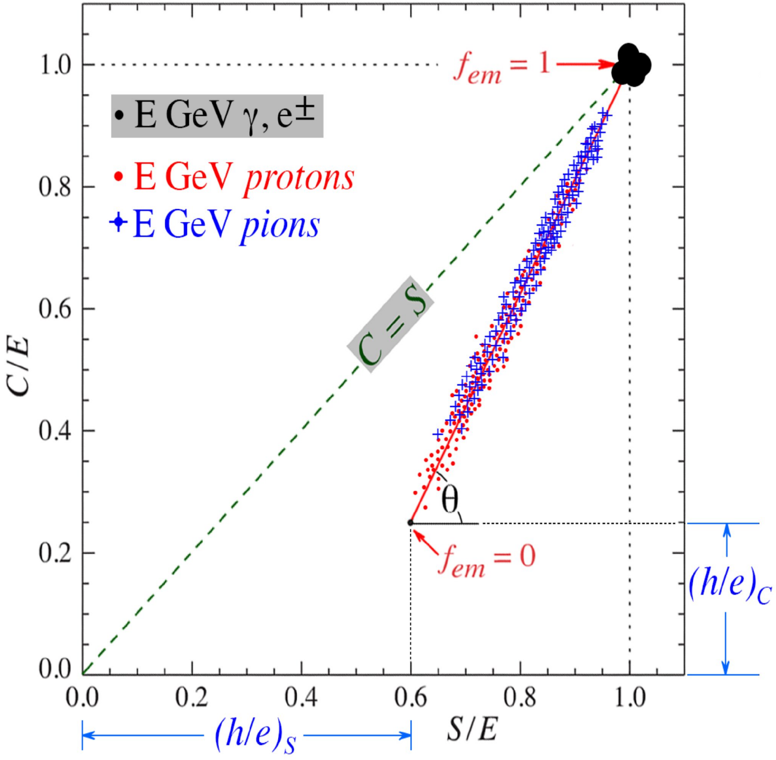
Charged hadrons (π,k…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Dual-Readout calorimetry

Idea:
Use two different physical processes to better sample each incoming object → evaluate shower f_{em}

- Cerenkov light:
  - sensitive to relativistic particles, mostly due to the *em* component of the shower
- Scintillation light:
  - measure total energy deposition

The responses to hadronic and electromagnetic objects $\left(\frac{h}{e}\right)_S, \left(\frac{h}{e}\right)_C$ are detector-dependent parameters to be measured



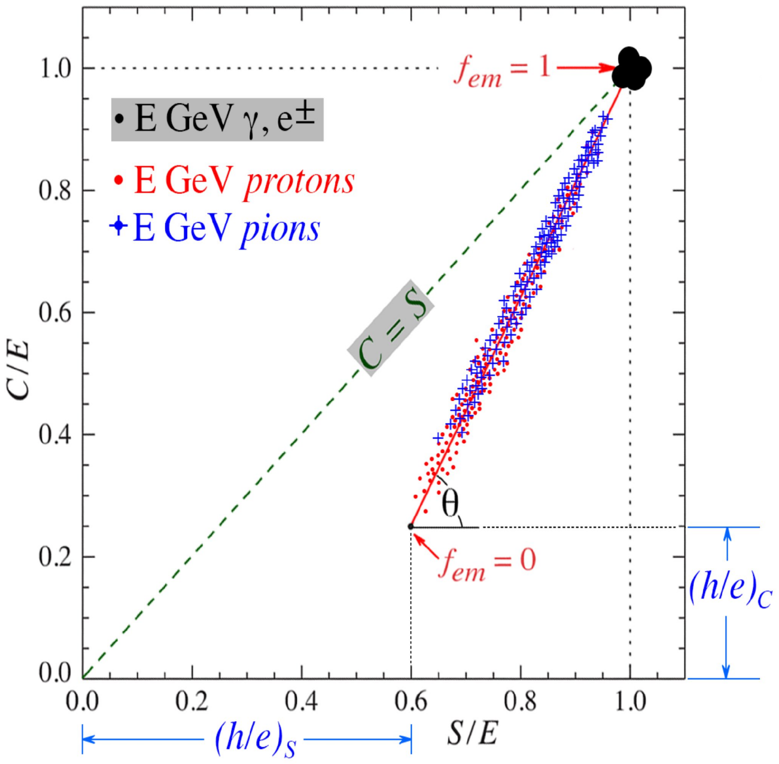
Dual-Readout calorimetry

$$\chi = cotg(\vartheta) = \frac{1-(h/e)_S}{1-(h/e)_C}$$

independent on particle type and energy

Given particle energy estimated by scintillation (S) and Cerenkov emission (C), one can correct the reconstructed energy

$$E = \frac{S-\chi C}{1-\chi}$$

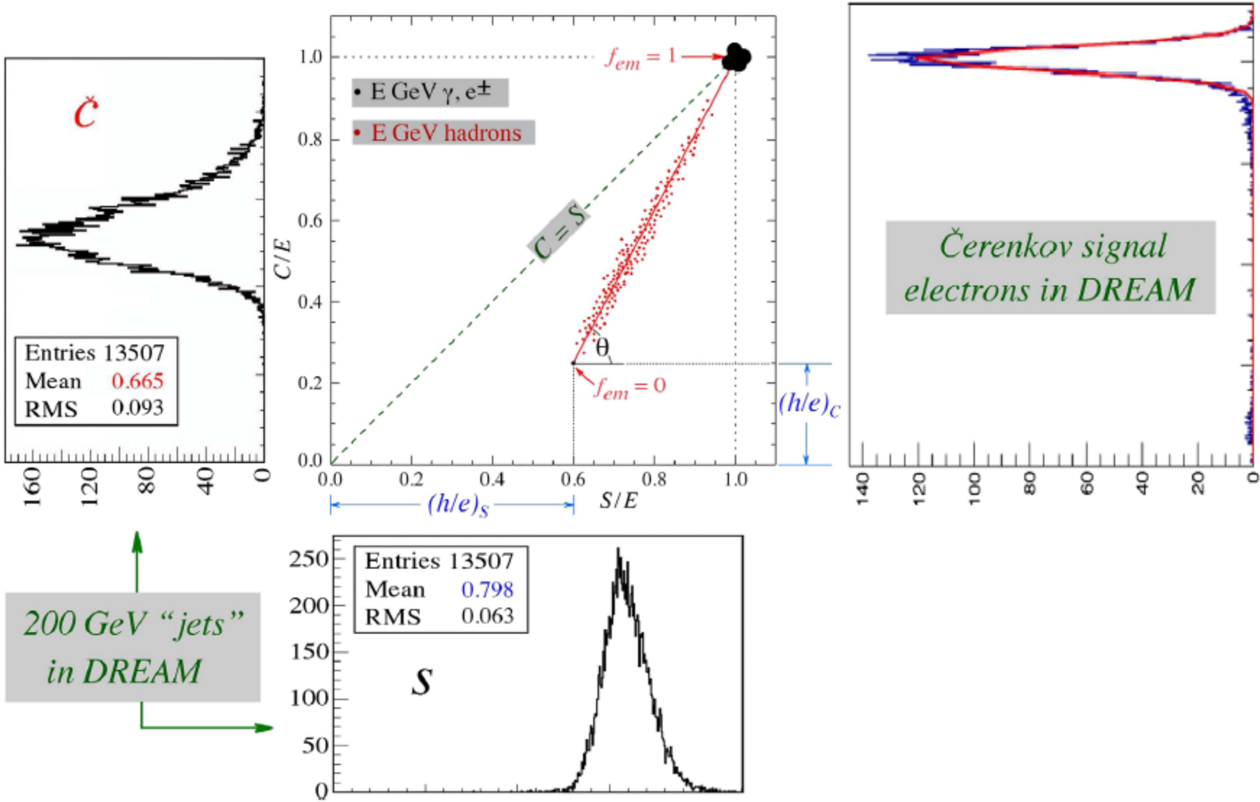


Dual-Readout calorimetry

Before Dual-Readout correction:
Scintillation and Cerenkov independent signals do not correctly match the true energy

$$\frac{S}{E} \neq 1, \frac{C}{E} \neq 1$$

Non-linearity of the reconstructed energy due to the f_{em} dependence on E



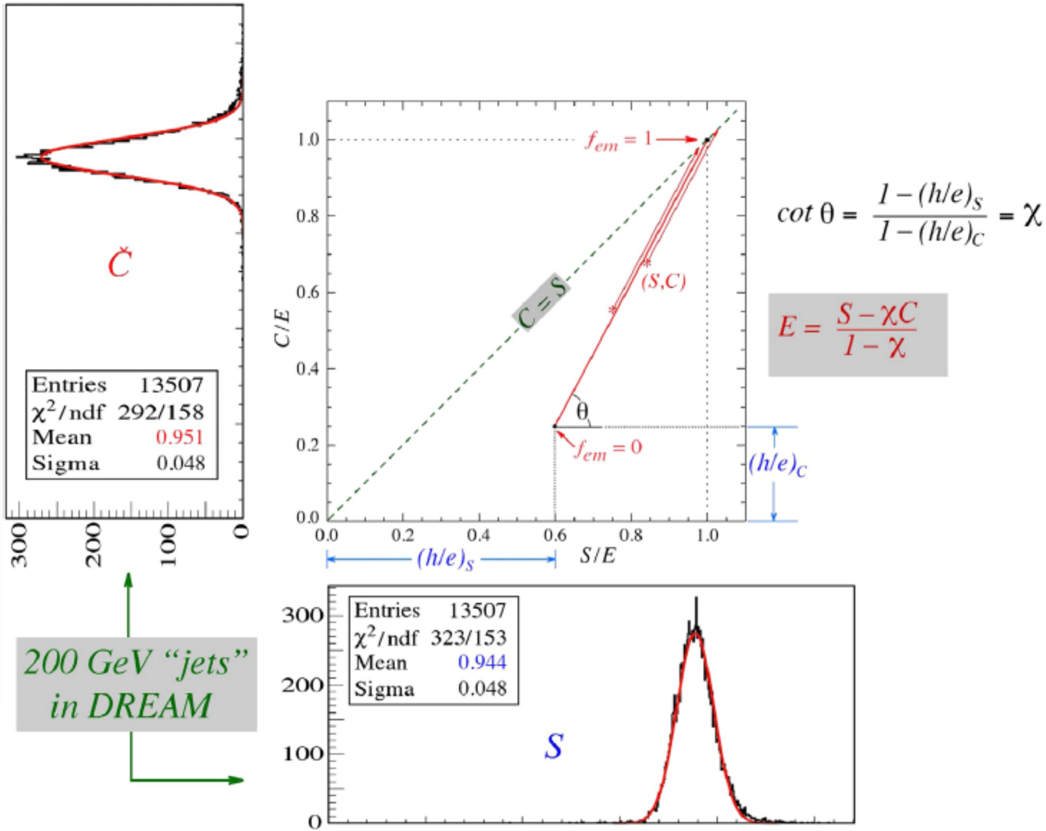
Dual-Readout calorimetry

After Dual-Readout correction:
Reconstructed energy much closer to the true one

$$\frac{S}{E} \simeq 1, \frac{C}{E} \simeq 1$$

Estimating the f_{em} on event basis we can restore the linearity of the reconstructed energy

Proof of principle prototypes built and tested within the RD52 collaboration

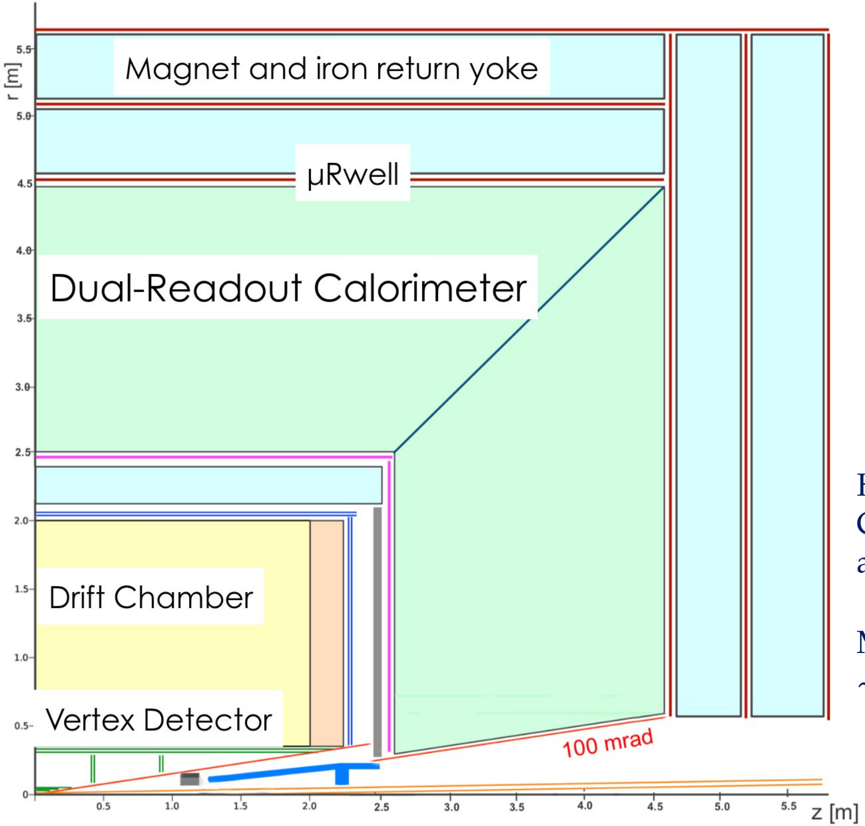


IDEA Detector

2T magnetic field solenoid located between tracking and calorimeter volumes

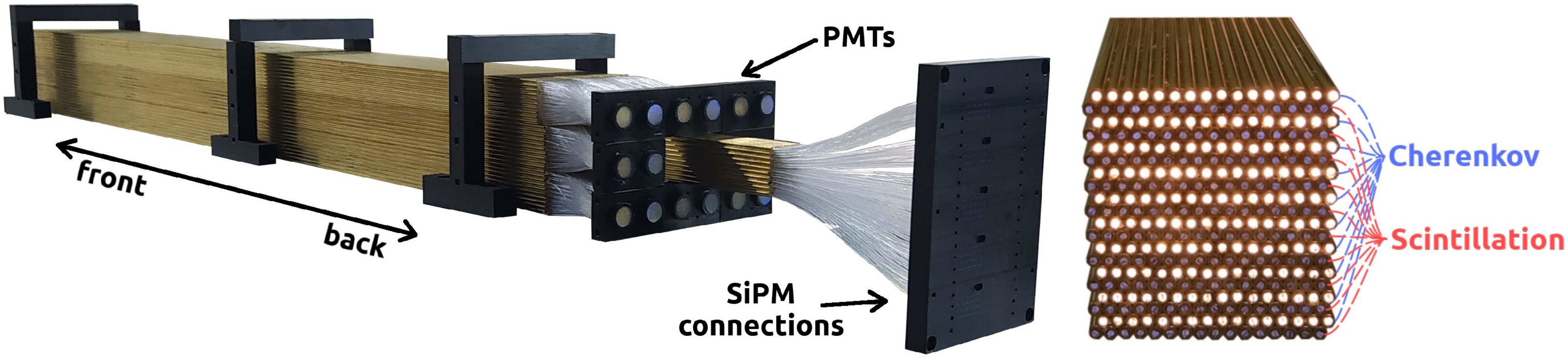
Dual-Readout calorimeter for both EM and hadronic showers
Also crystal-based DR ECAL section taken into consideration

Vertex Detector based on pixel sensors, targeting few micron resolution



μ-RWELL MicroPattern Gas Detector stages for muon ID and momentum measurement located before and after the calorimeter

High-transparency Drift Chamber for excellent PId and spatial resolution
($\sigma_x < 100\ \mu m$)
Momentum resolution:
~ 0.28% for 100 GeV tracks



Dual-Readout Calorimetry: How?

Drive towards highly-granular design:
- Particle Identification
- Heavy-Flavour jet tagging

IDEA detector @ FCC-ee/CepC:
Fiber-based calorimeter with single-fiber SiPM readout
Alternating rows of scintillating and Cerenkov fibers in capillary tubes of absorber material

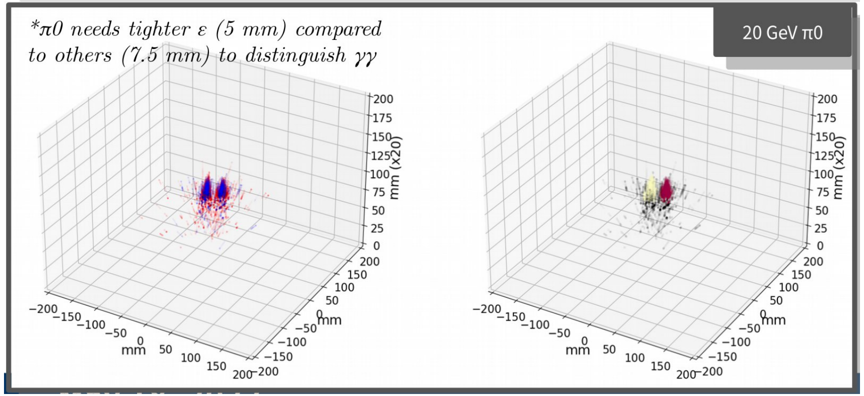
SiPM readout

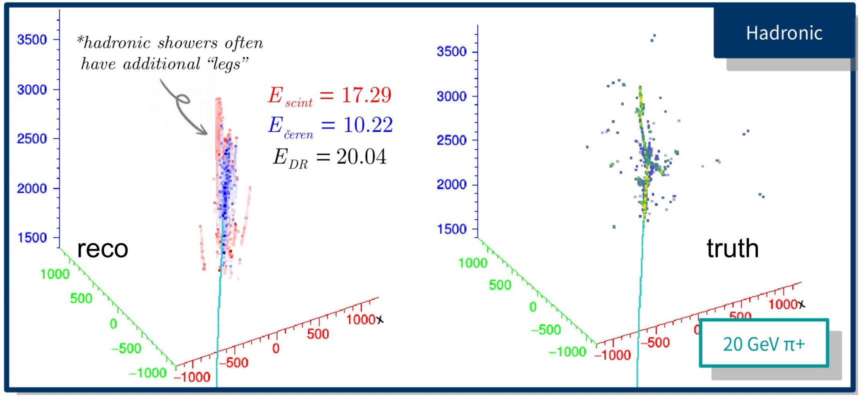
Key to achieve high-granularity
Drastically improve the particle identification and the tagging of heavy-flavour object initiated jets

Lateral segmentation with 2mm capillaries
Exploit timing information to also access longitudinal segmentation

Allows 3D event reconstruction and unveiling of shower sub-structures
Huge number of data to deal with

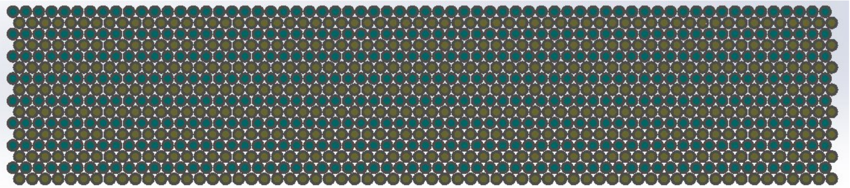
→ **Particle-Flow friendly calorimeter**





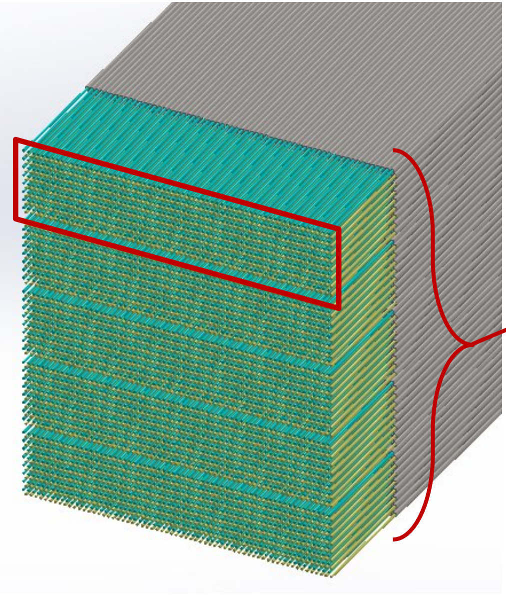
Pictures taken from Ko's talk

HiDRa Prototype

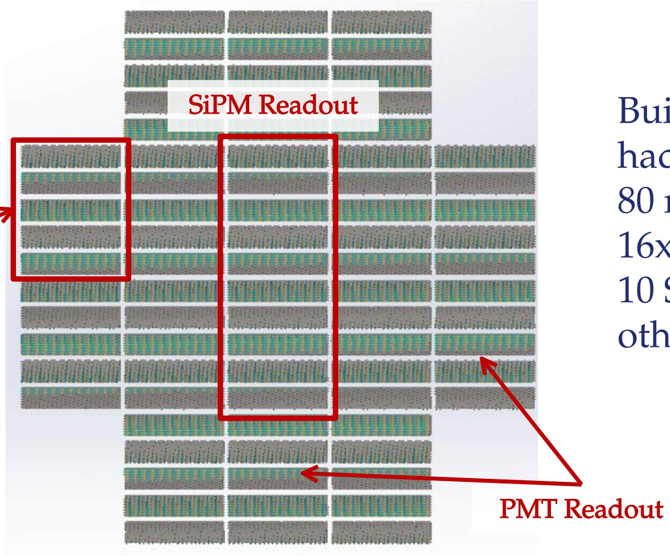


1 Mini-Module: 64 × 16 capillaries

Demonstrate the feasibility of the DR technique in association with SiPM readout, with high-energy test beams



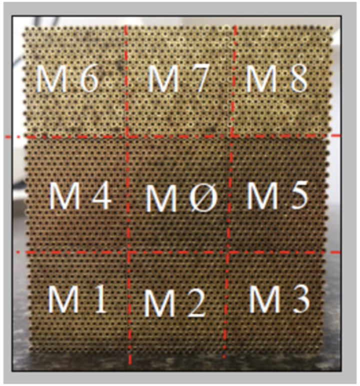
1 Module: 5 Mini-Modules

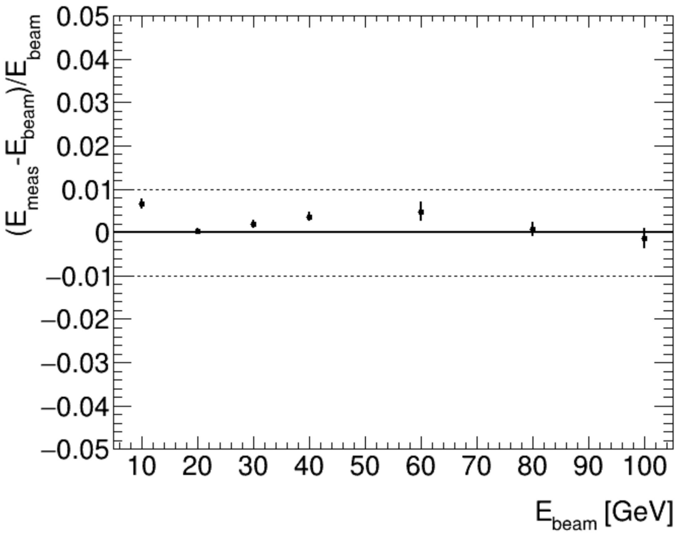


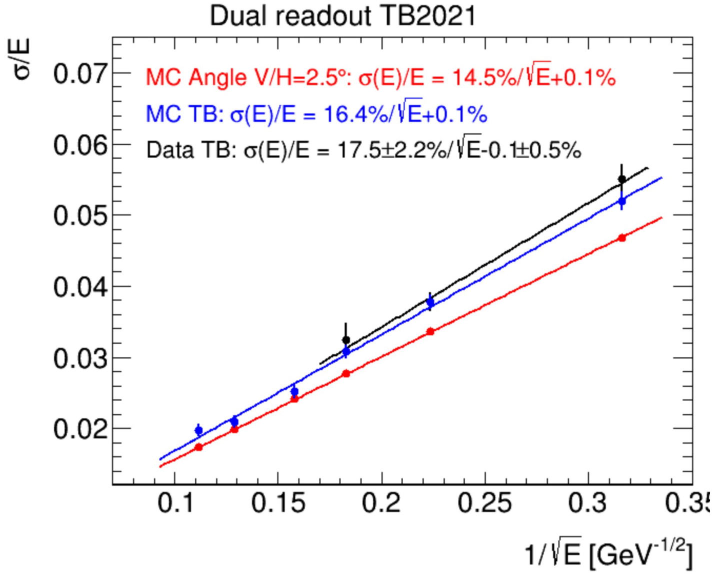
Build a (almost) fully-containing hadron shower calorimeter:
80 mini-modules, each made of 16x64 capillaries
10 SiPM readout mini-modules, the others with PMTs

2021 Prototype

First small-scale (electromagnetic shower sized, $10 \times 10 \times 100\ cm^3$) prototype built and tested at SPS
Central module M0 mounted with SiPM, modules [1..8] with PMTs



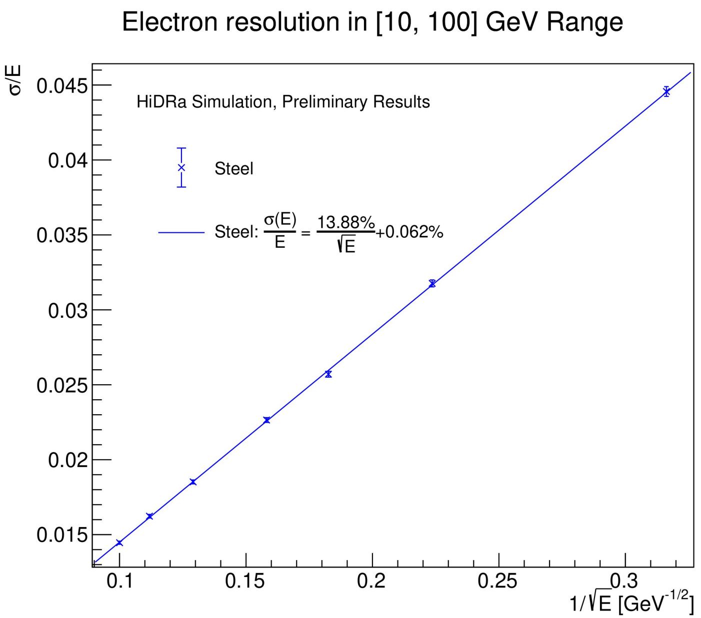


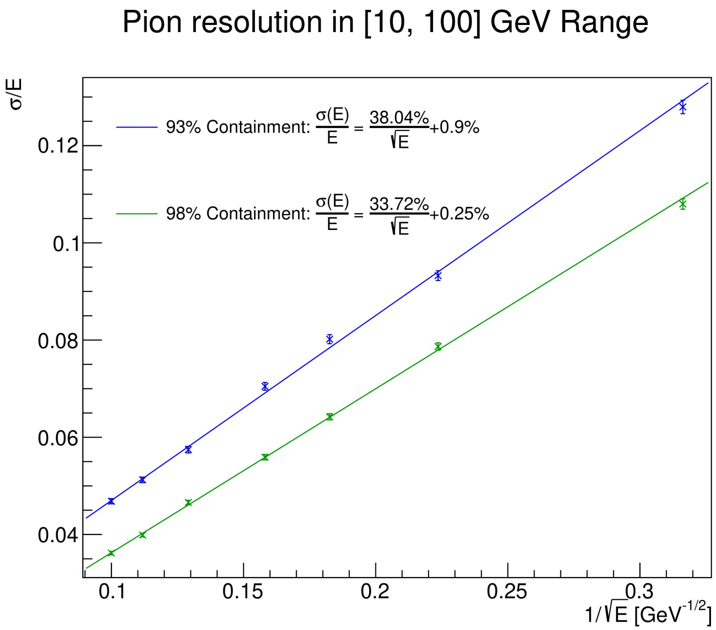


HiDRa Prototype

Baseline simulation resolution results for the HiDRa prototype
Large impact of containment on hadron resolution
Add new modules in simulation to evaluate full calorimeter performance

First mini-module construction started to get acquaintance with production
Similar prototype in development also by the Korean team colleagues
Pion performance $\sim (2 - 2.5\%)/(\sqrt{E})$ better with brass, but steel was chosen due to lower price





Conclusions

- ✓ Dual-Readout is a well understood technique, with experience in development and construction
- ✓ Test beam prototypes look promising for target resolution
- ✓ Now focus is on SiPM readout implementation

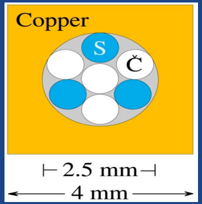
- ➢ Vigorous research activity to reach a realistic and tested proposal for a full detector at FCC/CepC
- ➢ Deep Learning implementation to unleash full potential of the Dual Readout + High Granularity combination

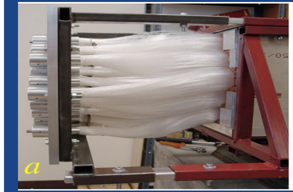
Backup

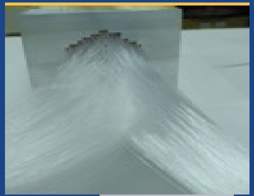
Long story short

DREAM (2003),
Texas Tech Uni

Copper, 2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%

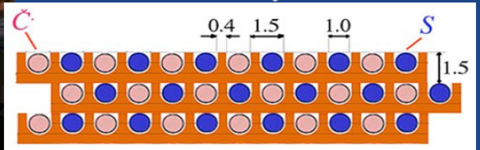






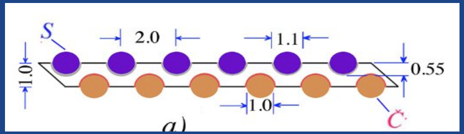
RD52 (2012),
INFN Pisa

Copper, 2 modules,
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT.
Sampling fraction: 4.5%, 10 λ_{int}



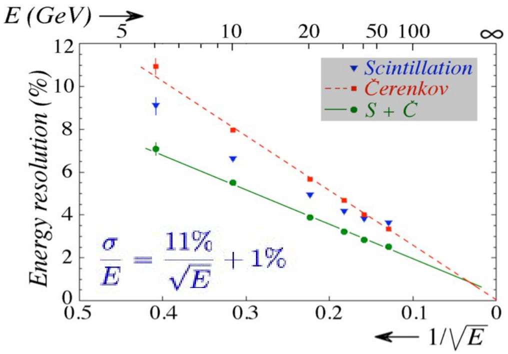
RD52 (2012),
INFN Pavia

Lead, 9 modules,
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}

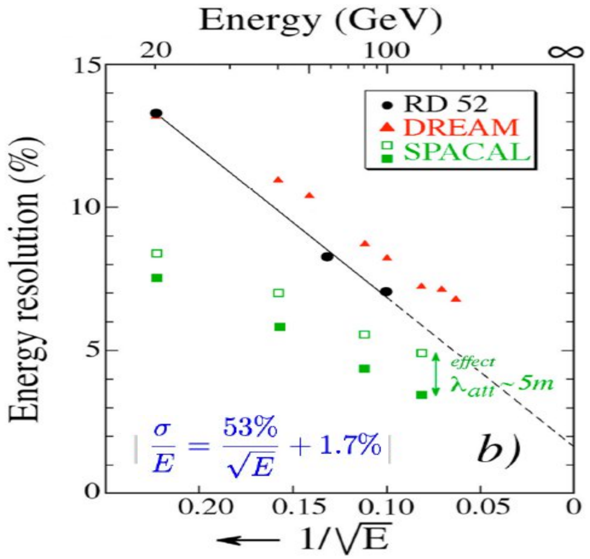


A few results from RD52

Test beam (em) data: Copper Module

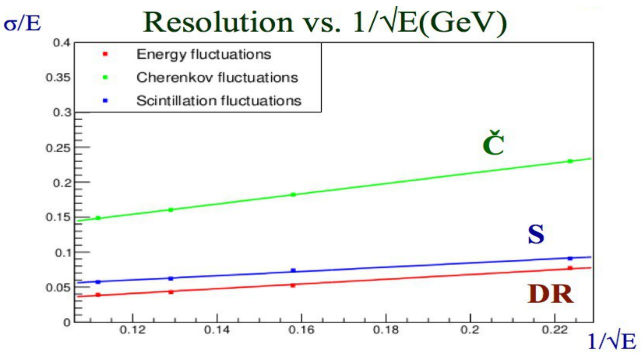


Test beam (pion) data: Lead Module



Not corrected for non-containment (94%) and attenuation length effect

Simulation (pion): Lead Module



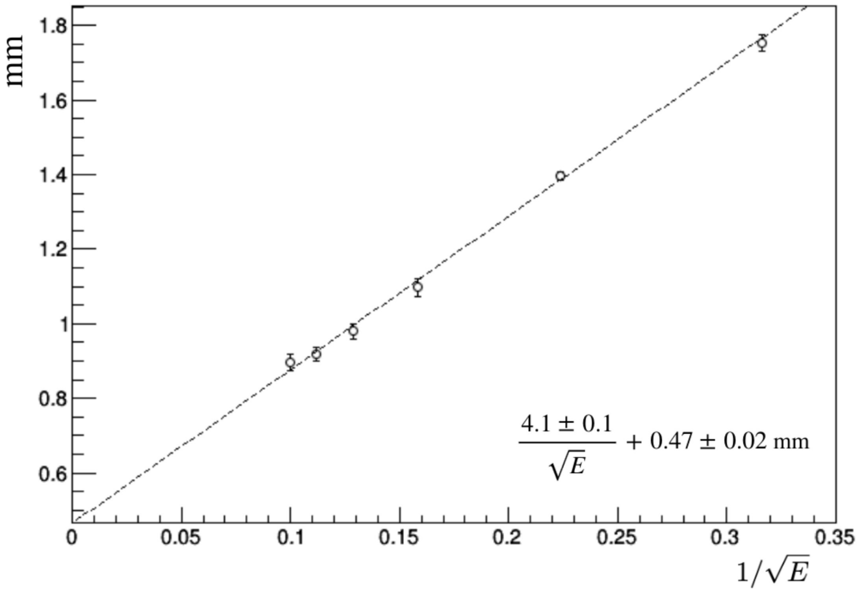
S: $30\%/\sqrt{E} + 2.4\%$

C: $73\%/\sqrt{E} + 6{,}6\%$

DR: $34\%/\sqrt{E}$

SiPM readout:

Predicted position resolution for electrons in the current IDEA detector calorimeter Geant4 full-simulation

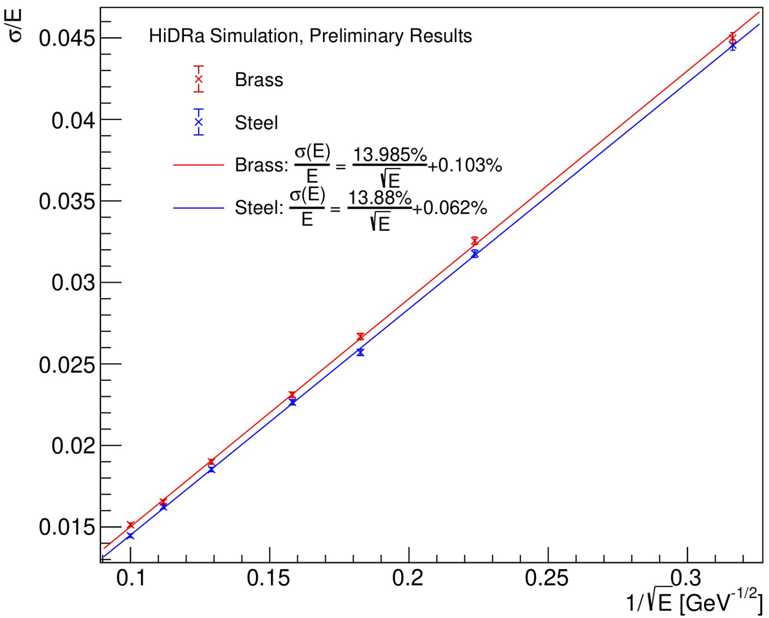


HiDRa Prototype

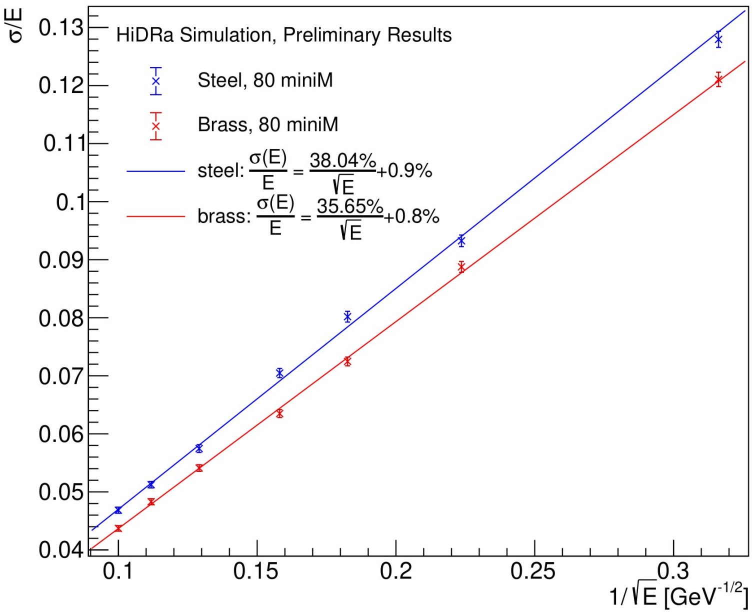
Baseline simulation resolution results for the HiDRa prototype

First mini-module construction started to get acquaintance with production
Steel was chosen as absorber material (less expensive)

Electron resolution in [10, 100] GeV Range

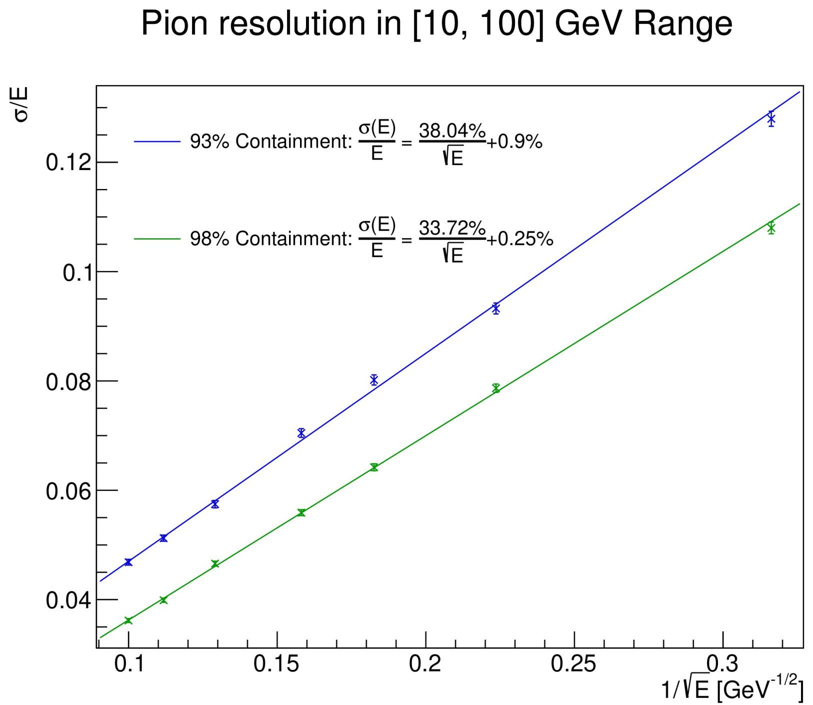


Pion resolution in [10, 100] GeV Range

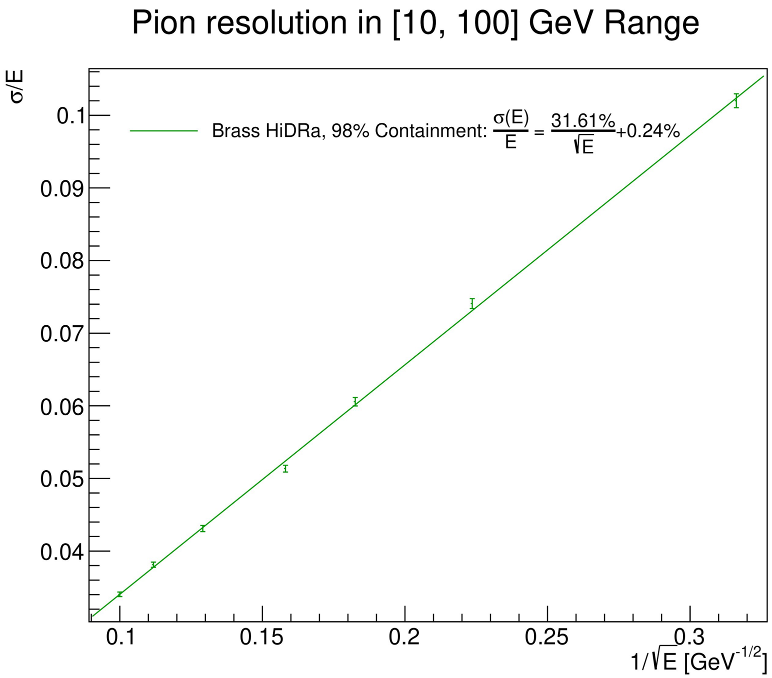


HiDRa Prototype

Steel Absorber, effect of increasing containment



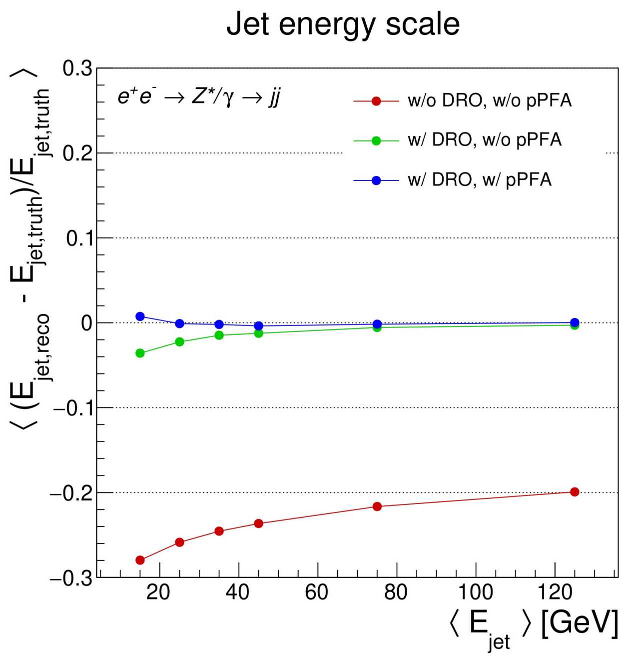
Brass absorber, expected result with full containment

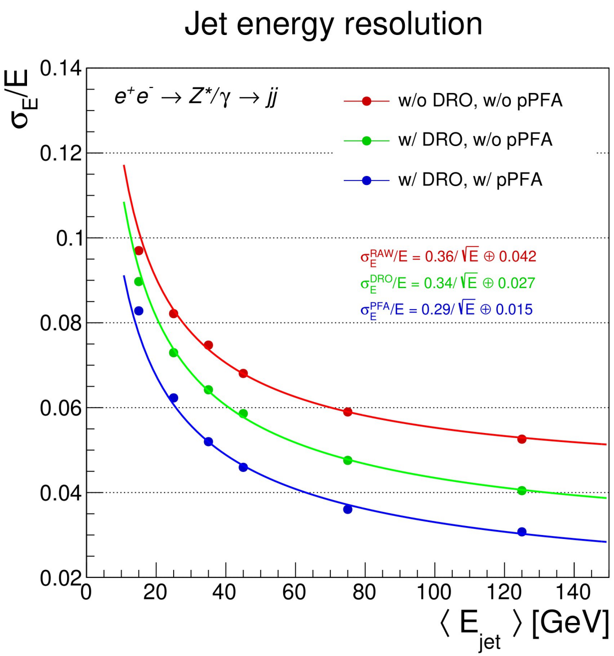


PFA in Fiber Calorimeter

https://arxiv.org/pdf/2202.01474.pdf

Particle Flow Analysis: exploit outstanding tracking capability to reconstruct charged tracks in the ID. Leave calorimeter to measure neutral components





Dual-Readout calorimetry

The responses to hadronic and electromagnetic objects $\left(\frac{h}{e}\right)_S, \left(\frac{h}{e}\right)_C$ are detector-dependent parameters to be measured

$$\chi = cotg(\vartheta) = \frac{1-(h/e)_S}{1-(h/e)_C}$$

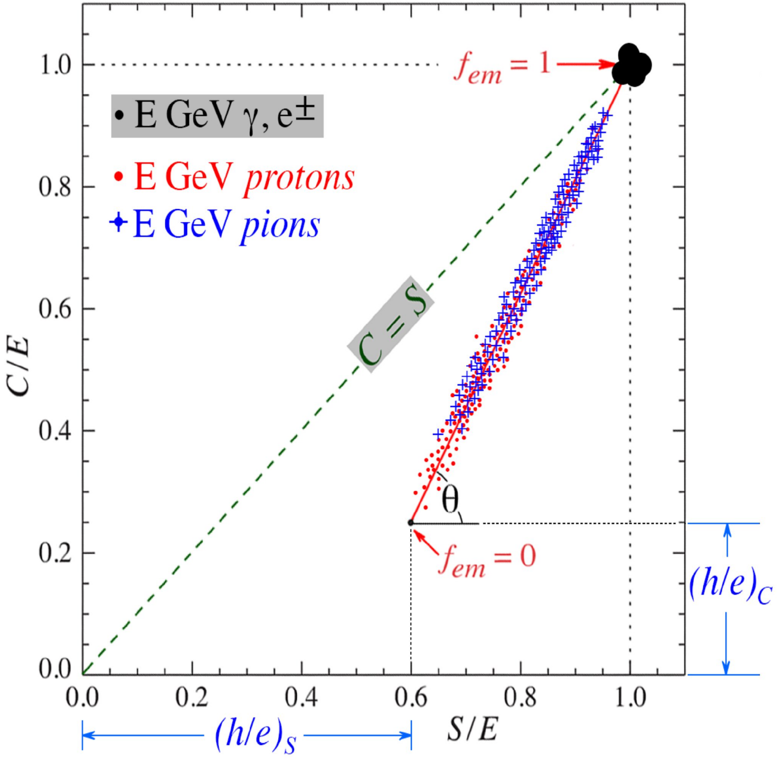
independent on particle type and energy

Given particle energy estimated by scintillation (S) and Cerenkov emission (C), one can correct the reconstructed energy

$$E = \frac{S-\chi C}{1-\chi}$$

Estimate electromagnetic fraction:

$$f_{em} = \frac{\left(\frac{h}{e}\right)_C - \left(\frac{h}{e}\right)_S \left(\frac{C}{S}\right)}{\left(\frac{C}{S}\right)\left(1-\left(\frac{h}{e}\right)_S\right) - \left(1-\left(\frac{h}{e}\right)_C\right)}$$



EW Observables

From Gabriella Gaudio, LFC2022

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times 10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times 10^4$)	1196	±	30	0.1	1.6
R_b ($\times 10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41 541	±	37	0.1	4
N_ν($\times 10^3$)	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}$($\times 10^6$)	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

+FCC-ee