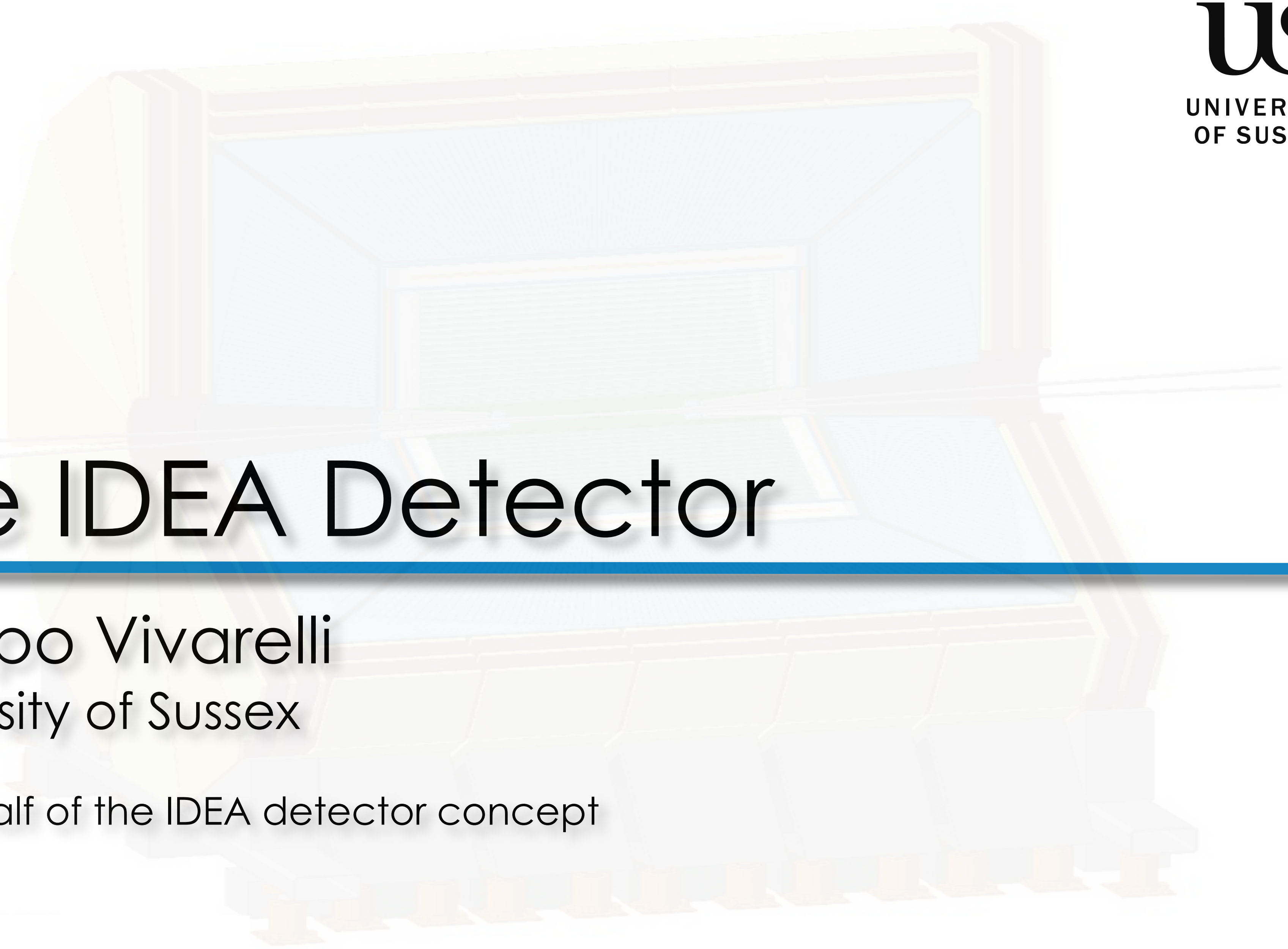


The IDEA Detector

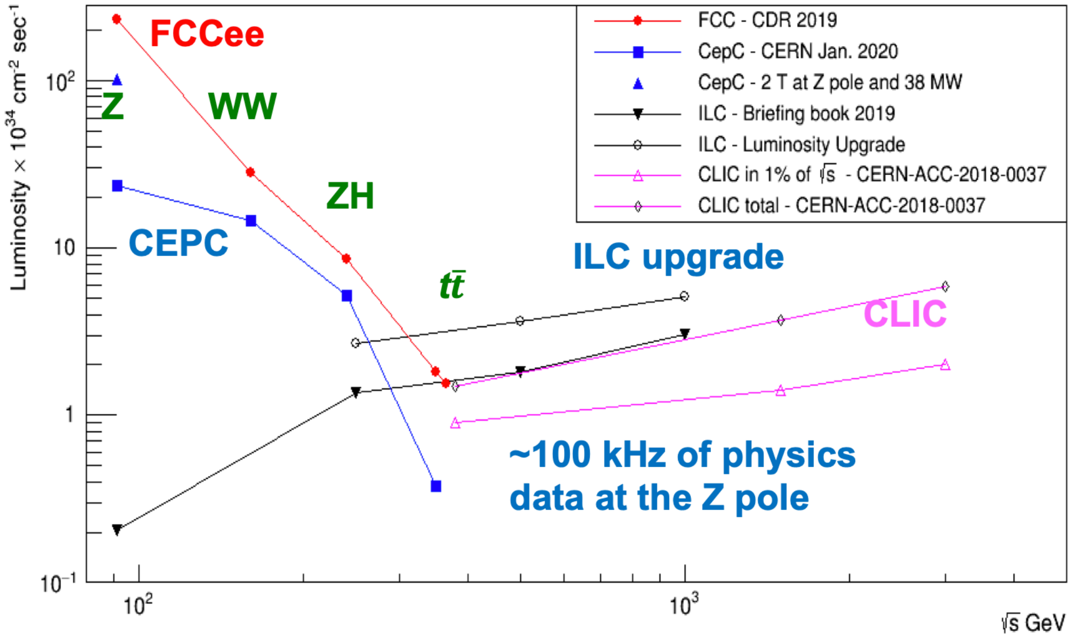
Iacopo Vivarelli

University of Sussex

On behalf of the IDEA detector concept

Machine/detector environment

- **5x10^{12} Z, 10^8 WW pairs, 10^6 Higgs** bosons and **10^6 top pairs** expected.
- Different **running conditions** depending on beam energy:
  - High-intensity machine at the Z-pole, high-current machine at the top threshold



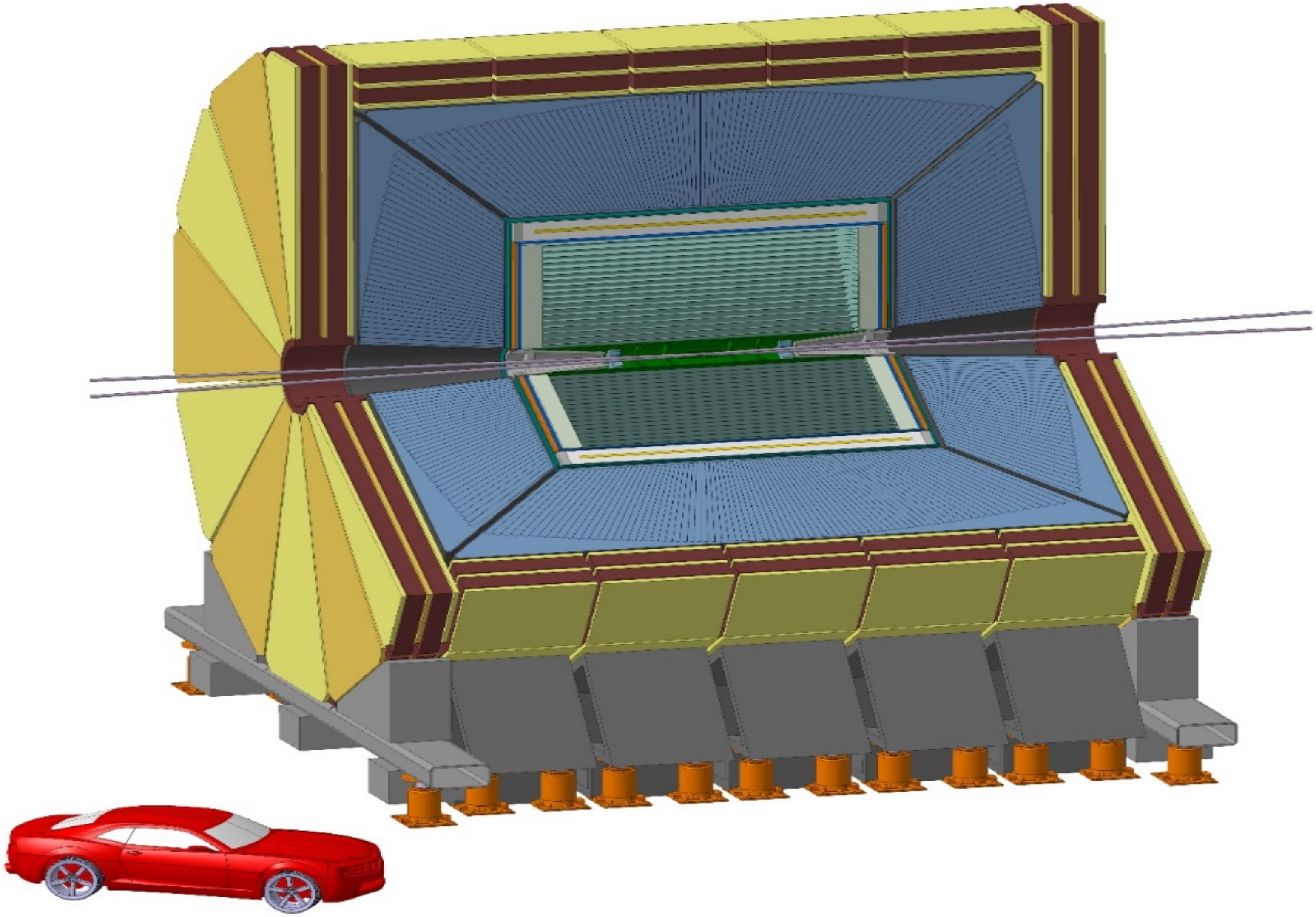
- Bunch spacing ranging from **20 ns (Z) to 7 μs (top)**
  - No power-pulsing.
  - Need fast detectors.
- Large (30 mrad) crossing angle between beams + low beam emittance $\Longrightarrow$ detector **magnetic field** 2 T max.
- Machine-detector interface structure (large angle + shielding + compensating magnets + luminometer) limit **detector acceptance to ±150 mrad (100 mrad for calo)**

Physics requirements

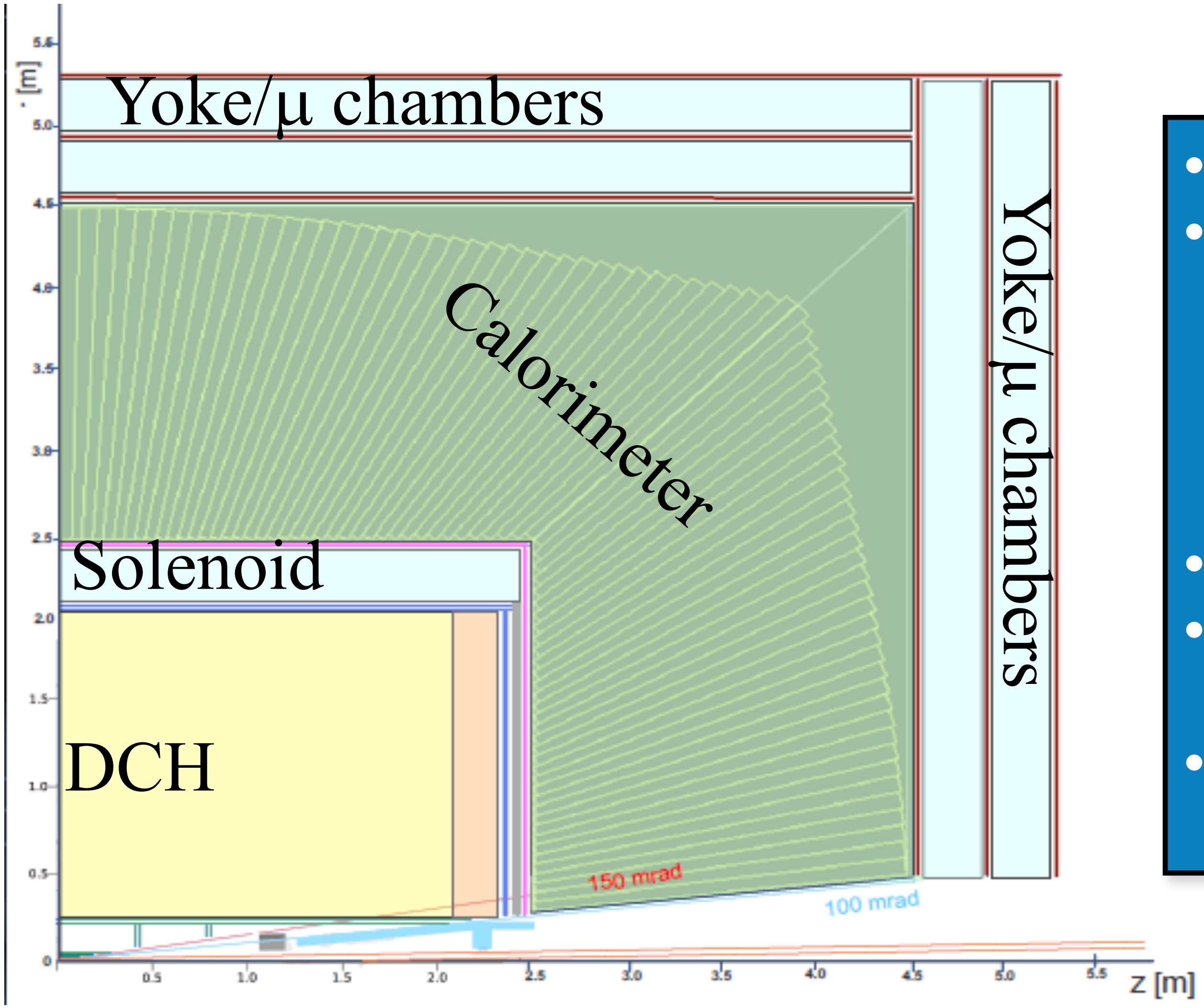
Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_{\mathrm{T}}) \sim 2 \times 10^{-5}$ $\oplus 1 \times 10^{-3}/(p_{\mathrm{T}} \sin\theta)$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

- Higgs sector definition imposes strict requirements on hadronic resolution, tracking and vertexing.
- On top of that:
  - Excellent PID for flavour physics.
  - Tau polarisation measurement capabilities.
  - …..

Innovative Detector for E^+e^- Accelerators (IDEA)



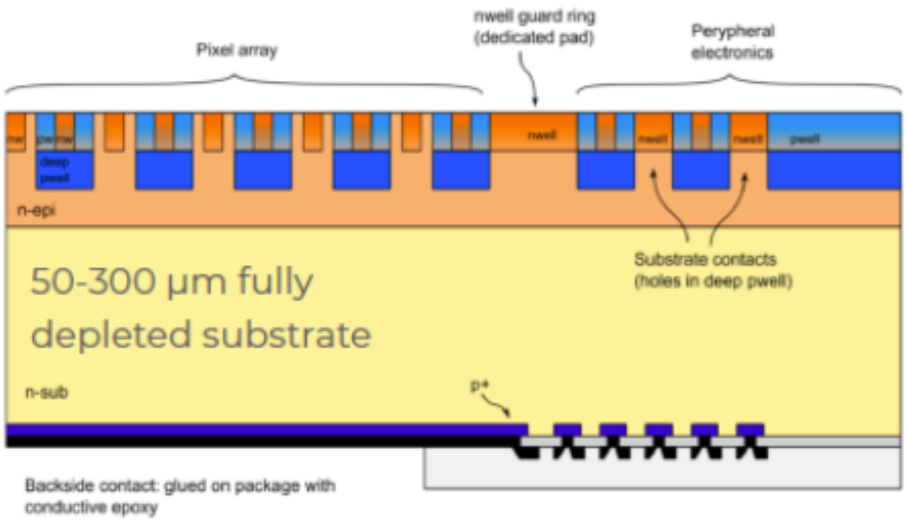
IDEA - overview

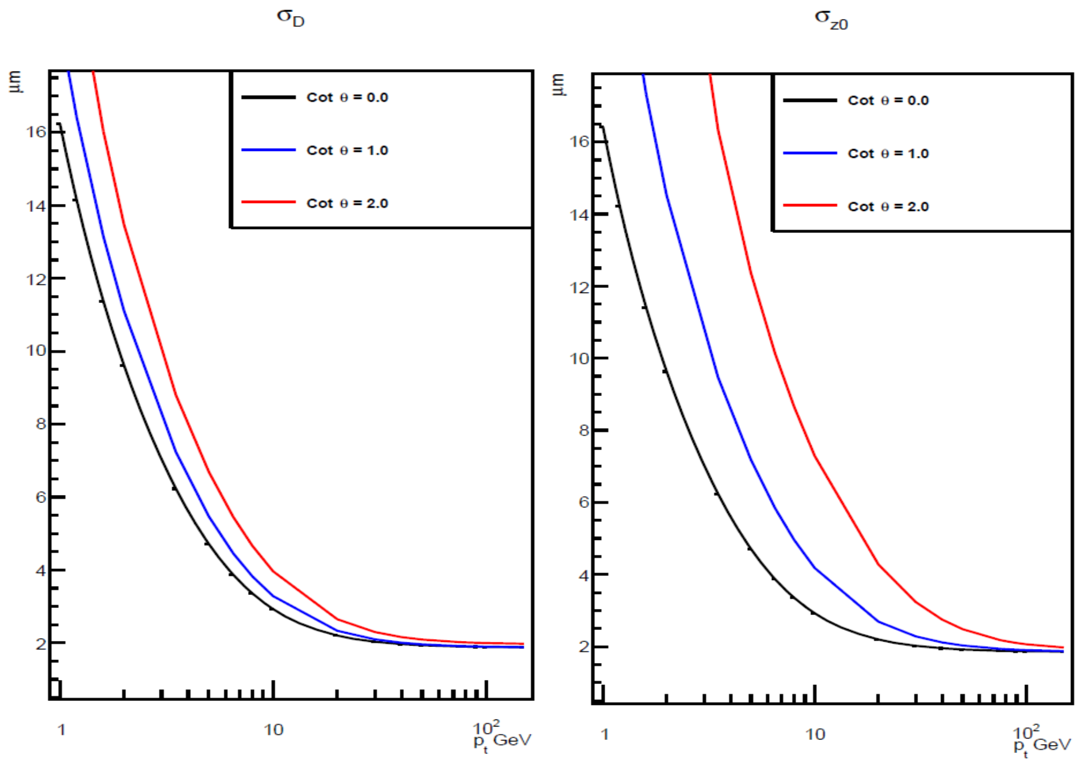


- Silicon vertex detector
- **Low material** in the tracking volume to **minimise multiple scattering.**
  - Tracking with **ultra-light drift chamber.**
- 2 T **thin solenoid** within calo.
- **Dual-readout calorimeter** + pre-shower.
- MPGD (μRwell) based Muon detector.

Vertex detector

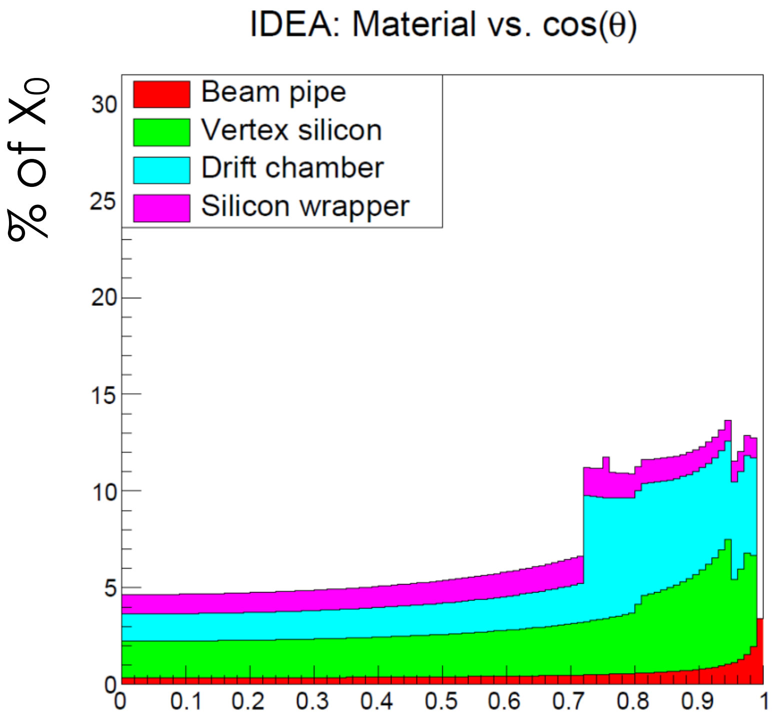
- Low power (< 20 mW/cm^2) / high-resolution pixel detector
  - R&D performed within the ARCADIA framework
  - Monolithic sensors (MAPS) to provide **20 µm pixel for ~ 3 µm single point resolution**
    - Current ALICE ITS pixel size 30 µm for 5 µm single point resolution
  - Target hit efficiency - 99.9%

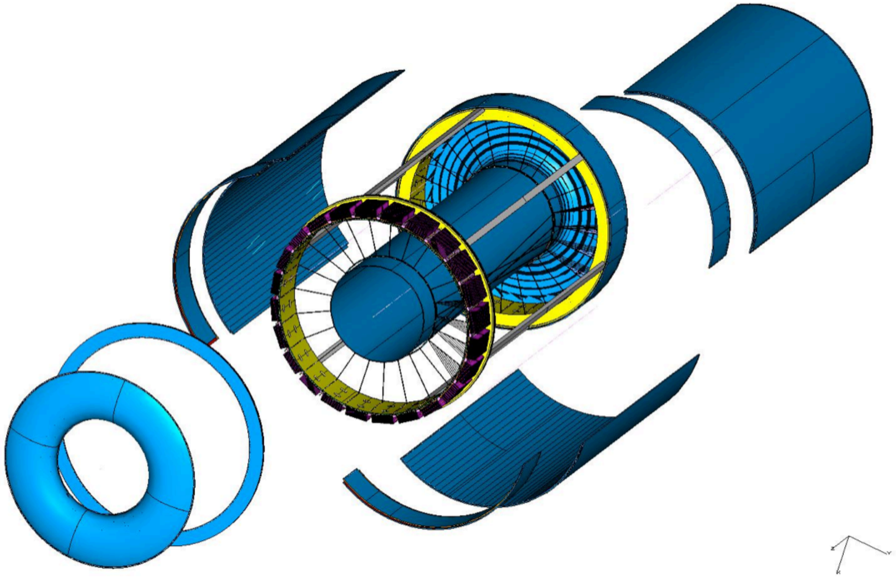


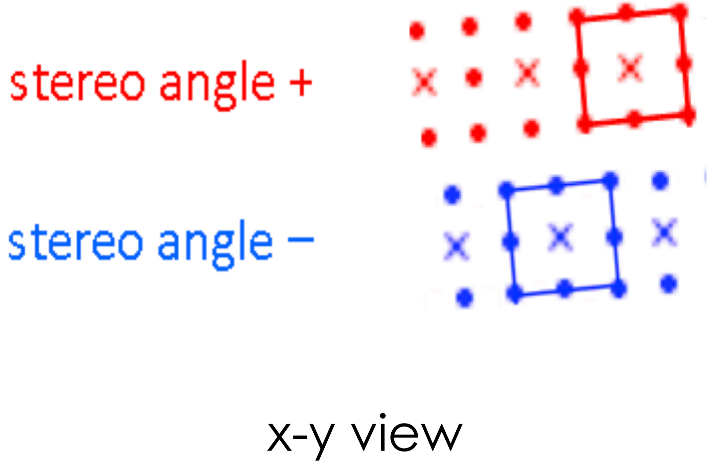


Tracking

- Tracking with drift chamber (similar in concept to MEG II chamber)
  - Minimising multiple scattering, adding only **2% X_0 to material in tracking volume**
  - R_{in} = 35 cm, R_{out} = 200 cm, L = 400 cm, drift time o(300 ns)
  - 90% He - 10% iC_4H_{10} - max drift time 360 ns, Stereo angle 30°
  - **Cluster counting (12.5 cm^{-1} clusters)** improves spacial resolution and dE/dx measurement
  - Single point precision (with cluster counting) **better than ~ 100 μm**.



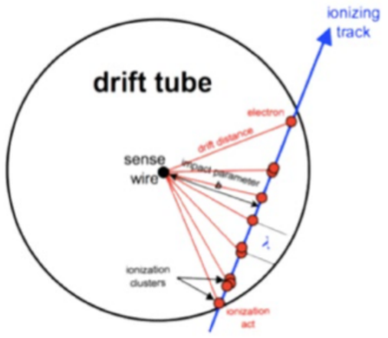


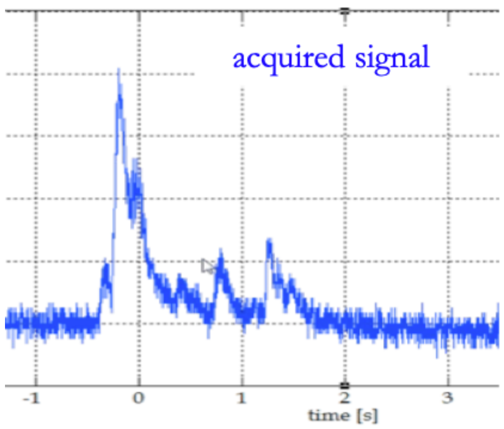


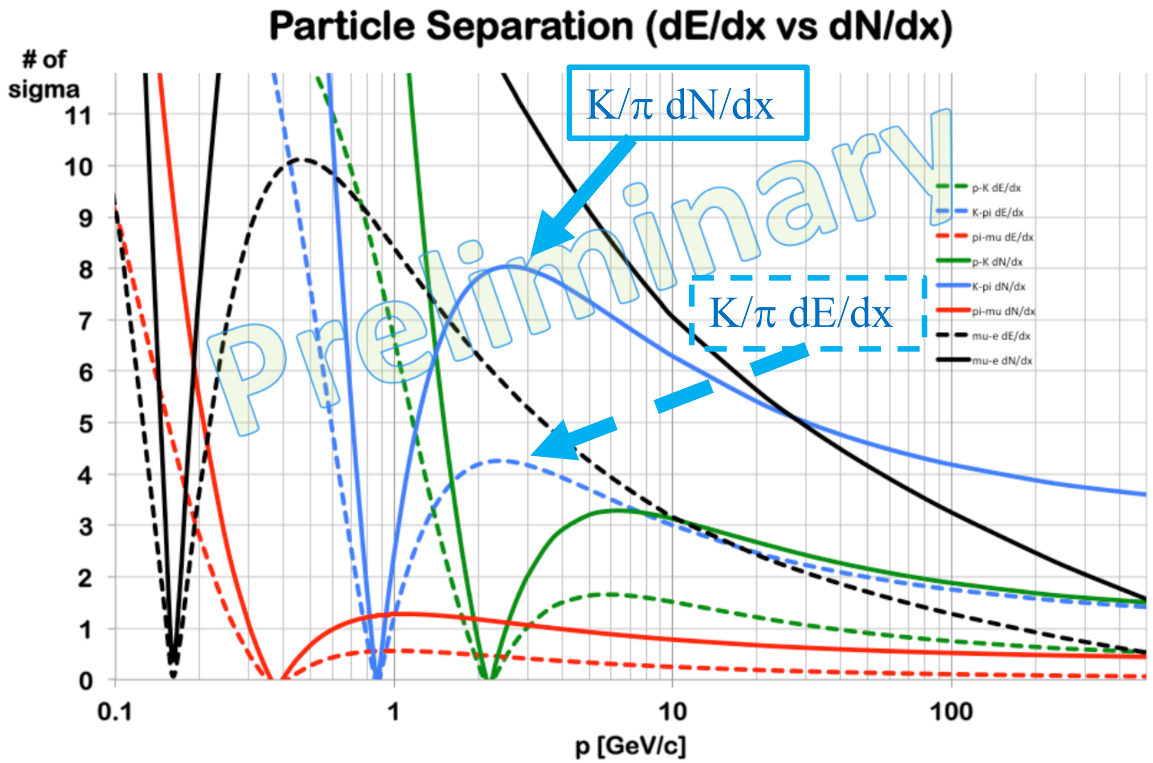
See here and talk from M. Primavera at this workshop for more details

Cluster counting

- Number of ionisation clusters along track **proportional to the energy loss**.
- With ~ 1 ns time resolution **waveform sensitive to individual clusters**.
  - Requires ~ GHz sampling and on-detector feature extraction.
- Excellent K/π separation for most momenta. TOF could help recover missing ranges.

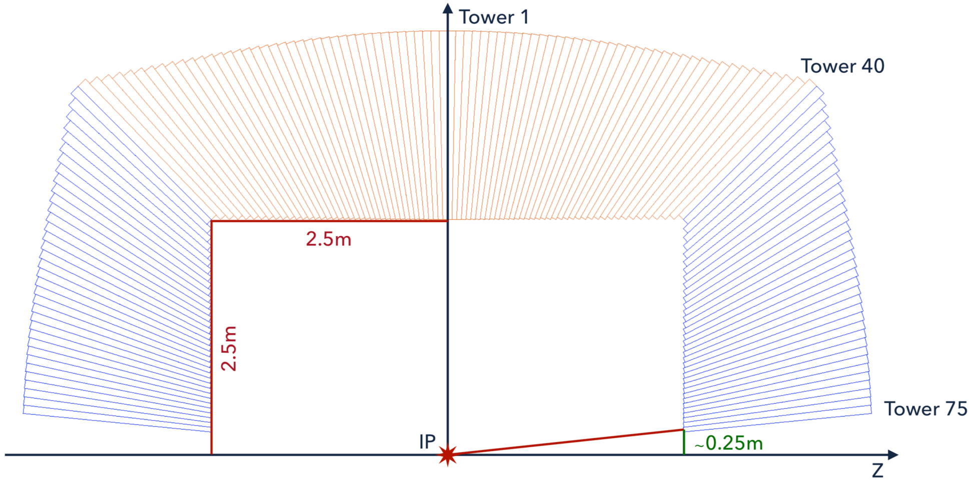


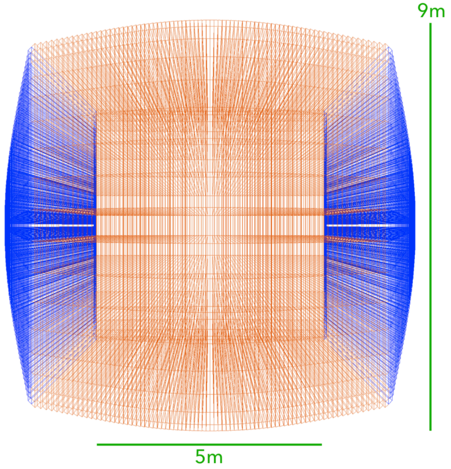


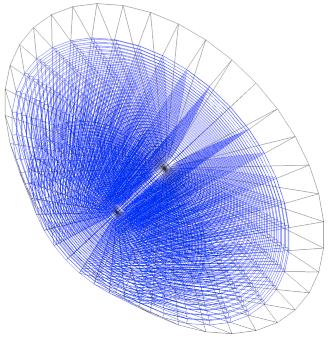


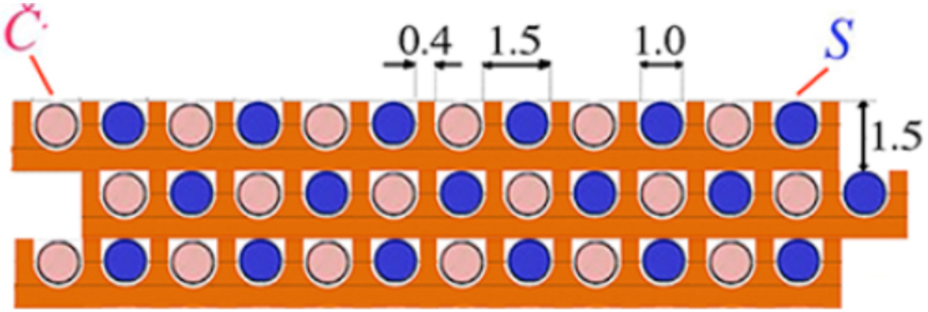
Calorimetry+preshower

- Preshower under optimisation, using μ-RWELL
- Single EM+HAD sampling calorimeter, with **1.5 mm fiber pitch** and Cherenkov/Scintillation dual-readout.
  - For details about dual-readout, see here
- No mechanical **longitudinal segmentation**, ~ 7 λ_I length.
- Good **EM intrinsic** energy resolution, excellent **hadronic** resolution









The dual-readout principle in a nutshell

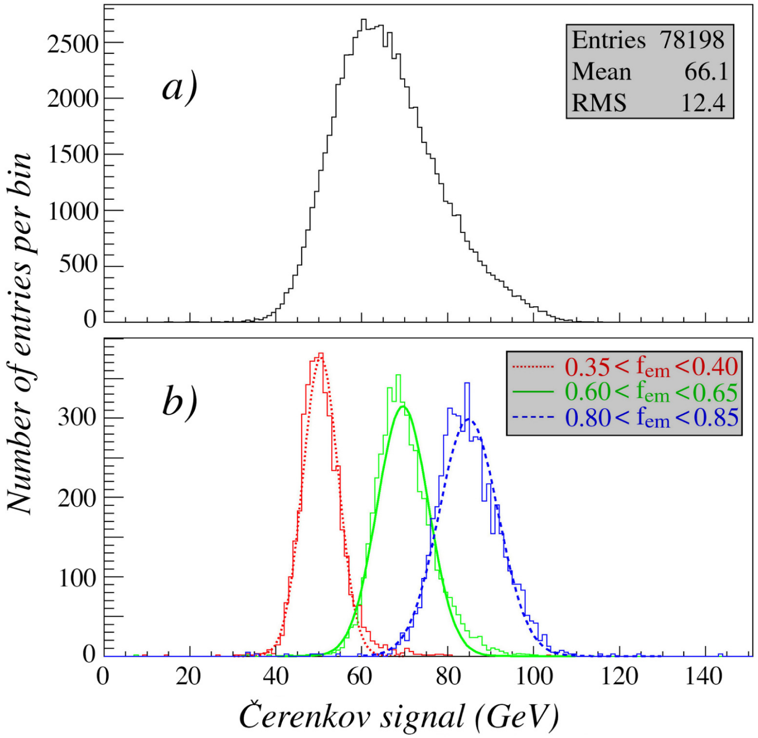
- Sampling the **hadronic shower** with two readouts of **different e/h factor** allows to correct event by event for non-compensation.
- Cherenkov (C) channel mostly sensitive to the em shower component, Scintillation (S) sensitive to all.

$$\begin{cases} E_S = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right) \\ E_C = E\left(f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right) \end{cases}$$

Two equations in two unkowns (f_{em} and E)

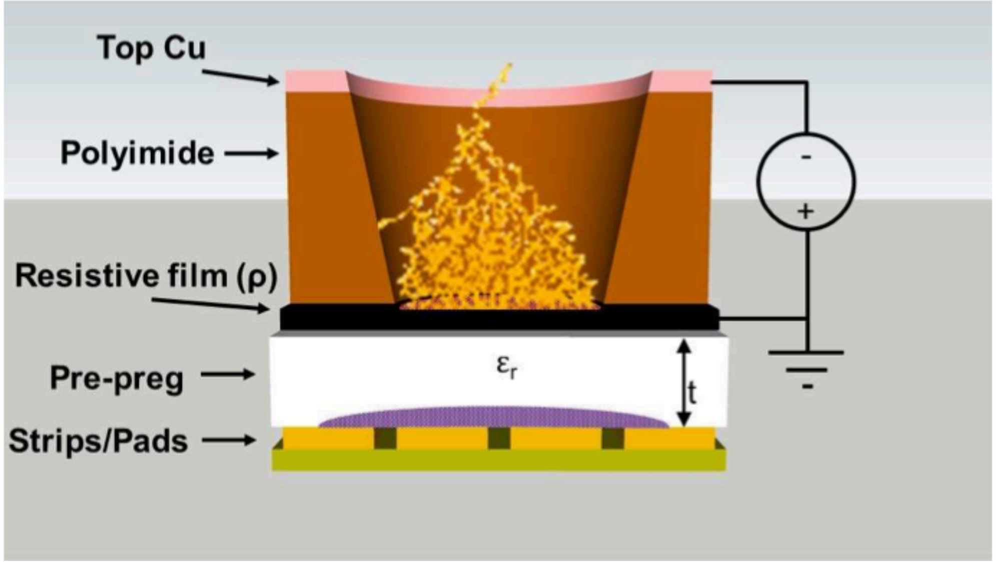
$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

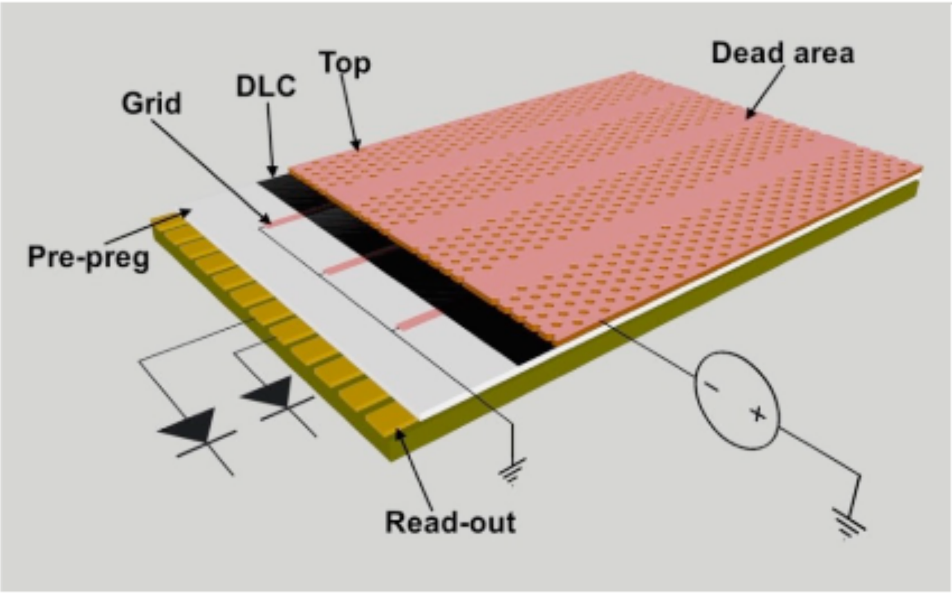


Magnet and muon system

- Thin superconducting solenoid within the calorimeter volume (0.46 X_0 cold mass, 0.28 X_0 cryostat)
- Current design: NbTi/Cu conductor + high strength aluminum for cryostat - 8 ton total
- Muon spectrometer using Micropattern Gaseous Detectors (μ-RWELL)



Taken from arXiv:1903.11017

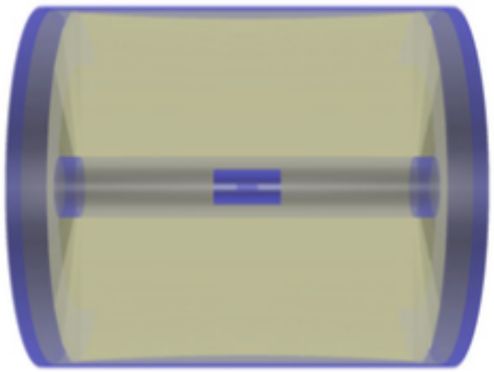


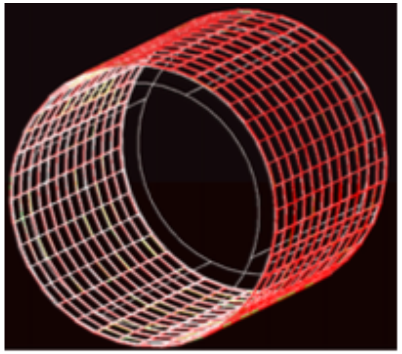
Detector elements principle:

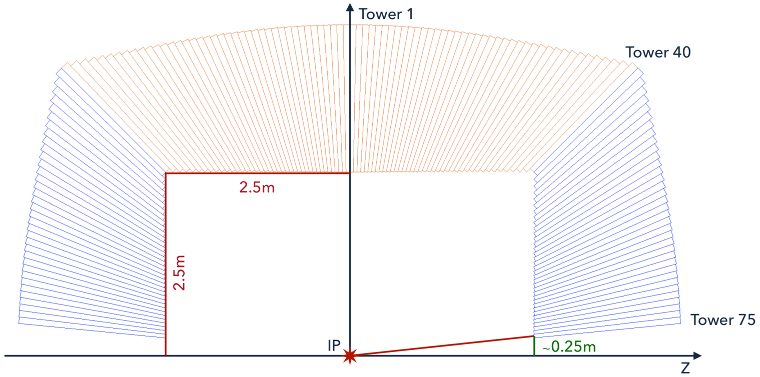
- Amplification stage
- Resistive layer to quench the multiplication
- Patterned PCB for readout

Performance

Simulation

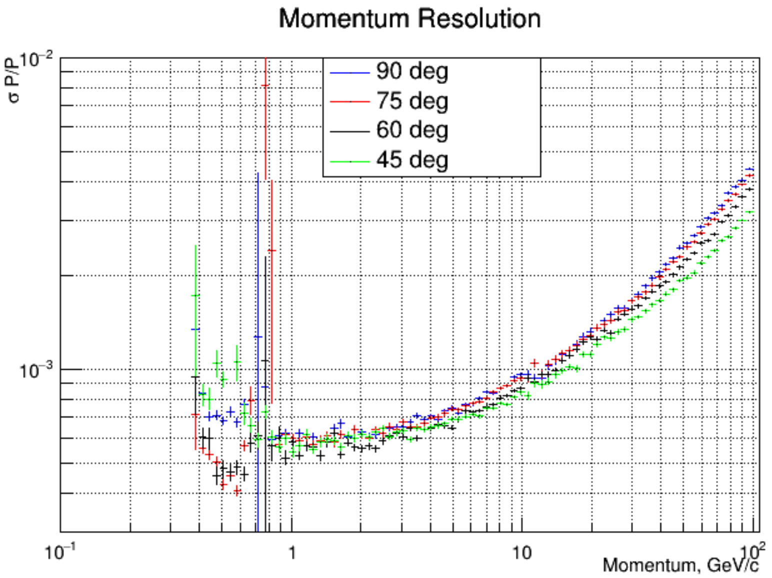


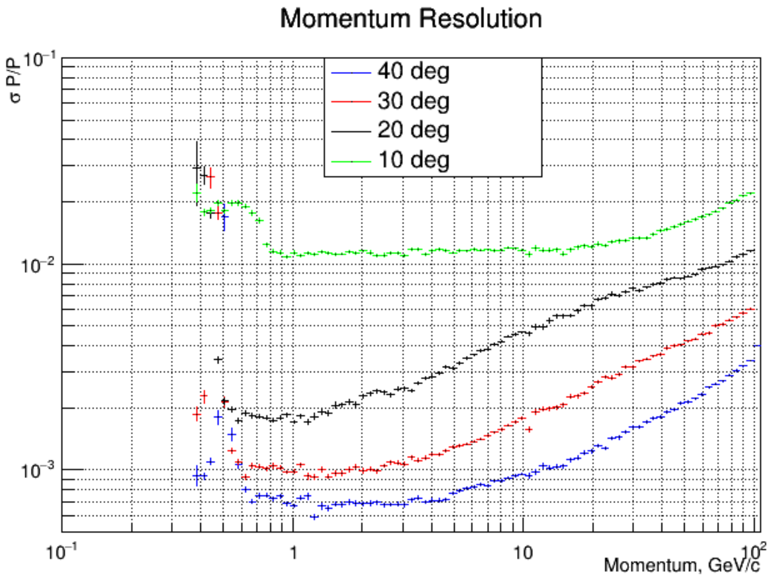


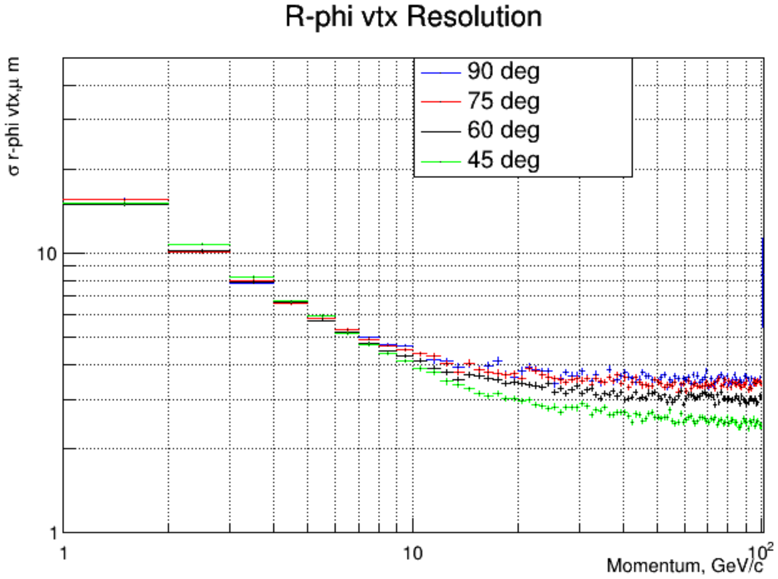


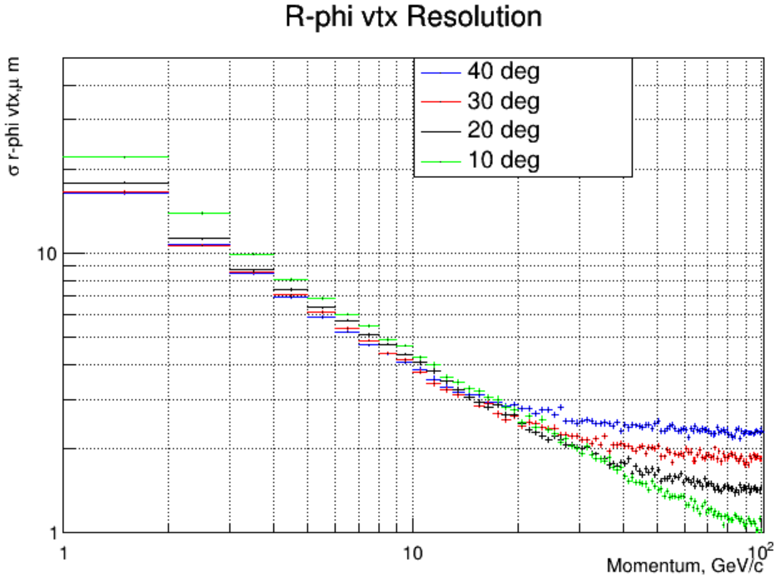
- Full **G4 standalone simulation** of each of (simplified) Silicon Vertex and preshower, Drift Chamber, Calorimeter detector existing.
- Integration among sub-detectors and with FCC software ongoing.
  - See talk from Sanghyun Ko at this workshop.
  - See also twiki
- Studies in the next slides use either **full simulation or a Delphes fast simulation**

Tracking


Momentum Resolution


Momentum Resolution


R-phi vtx Resolution


R-phi vtx Resolution

Tracking

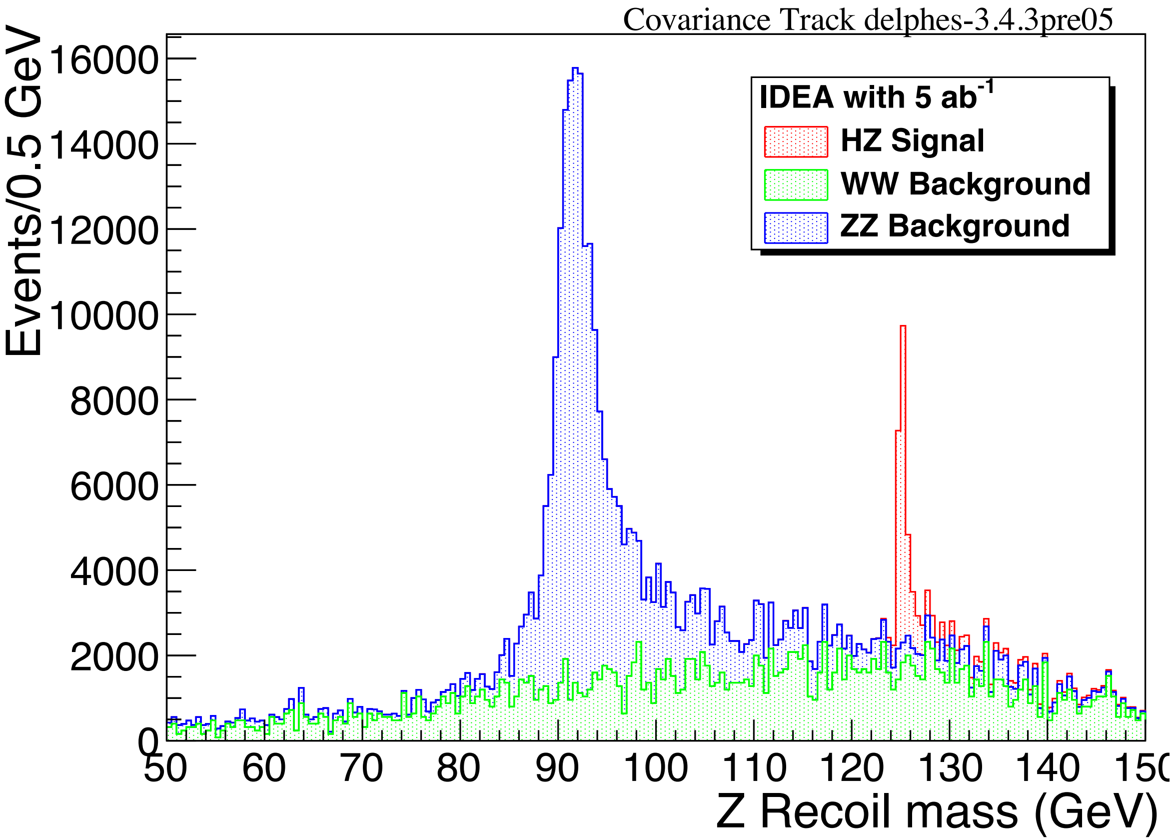
- Use of fast simulation comes handy for physics studies
  - Fast tracking simulation validated against full simulation and then used to measure, e.g., Z recoil mass distribution

Di-muon events, selected if:

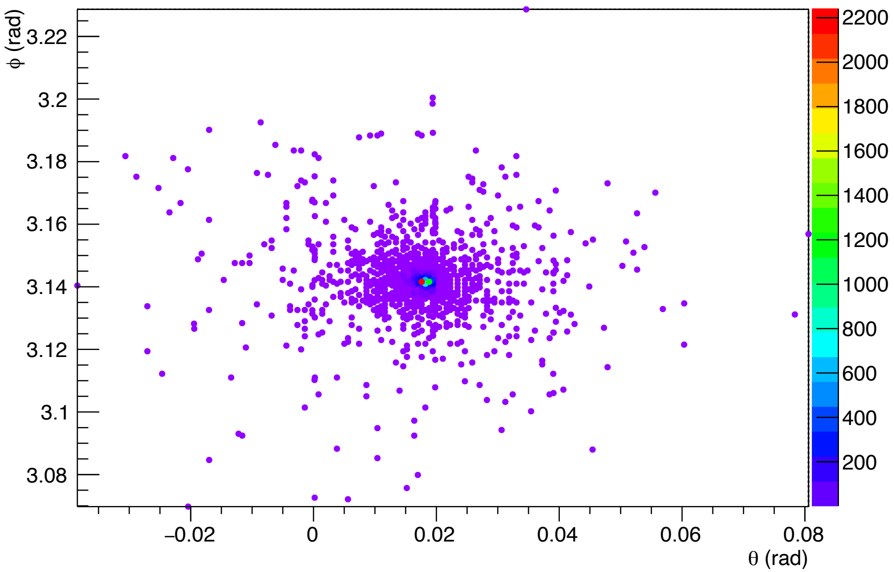
$p_T^{\mu} > 1$ GeV and $|\eta| < 2.44$

$|m_{\mu\mu} - m_Z| < 20$ GeV

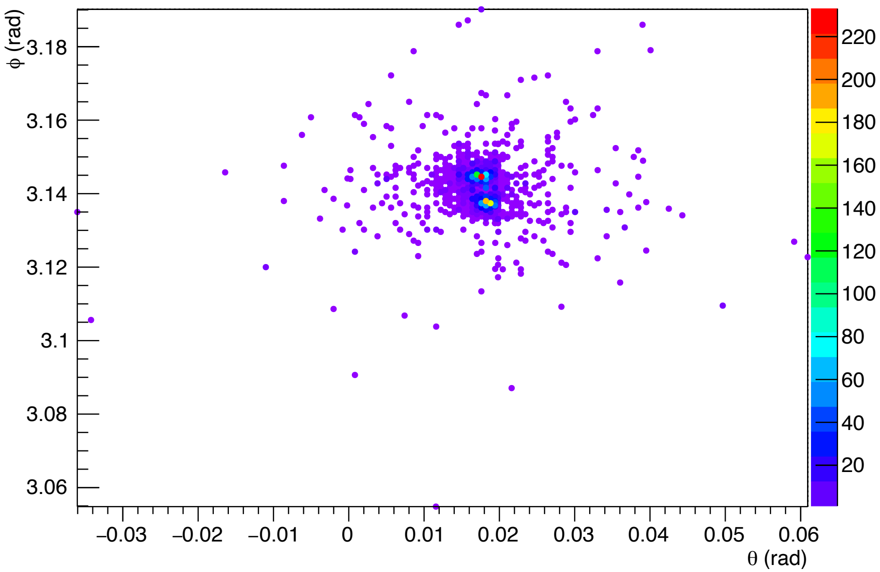
- Similar studies using $Z \rightarrow jet\ jet$ ongoing



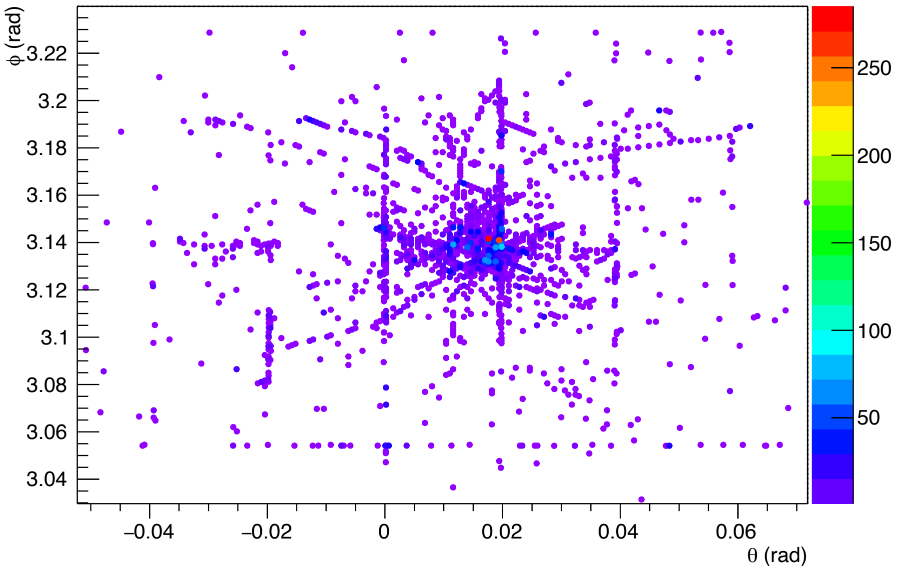
Calorimeter - Full granularity



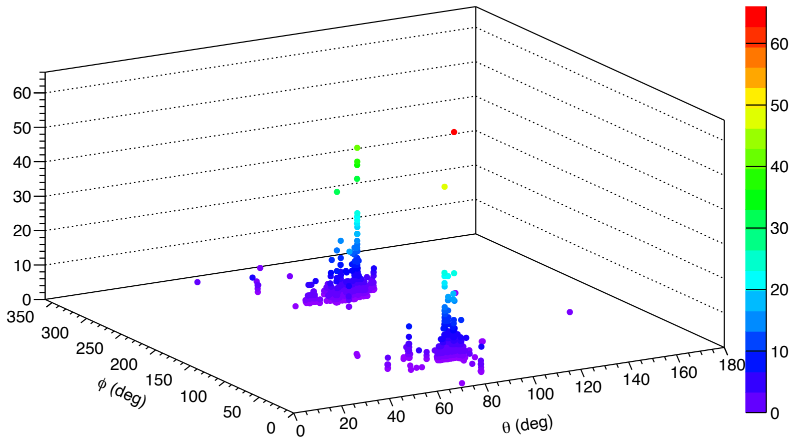
e- 40 GeV



π^0 40 GeV



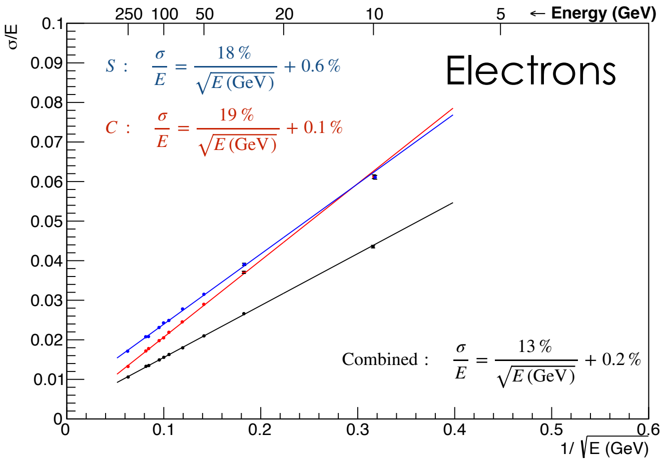
π^- 40 GeV

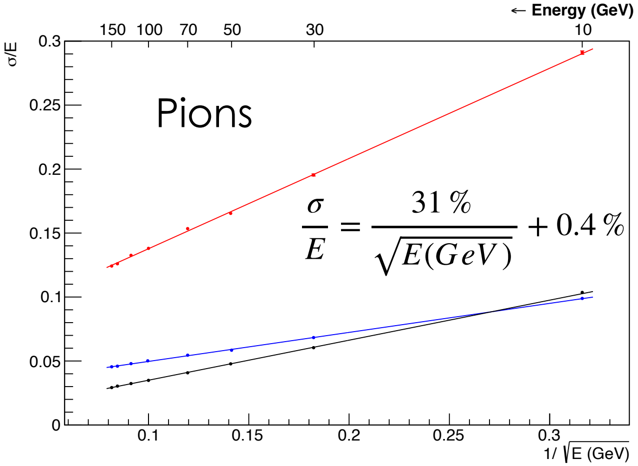


Di-jet

Calorimeter - single particle response

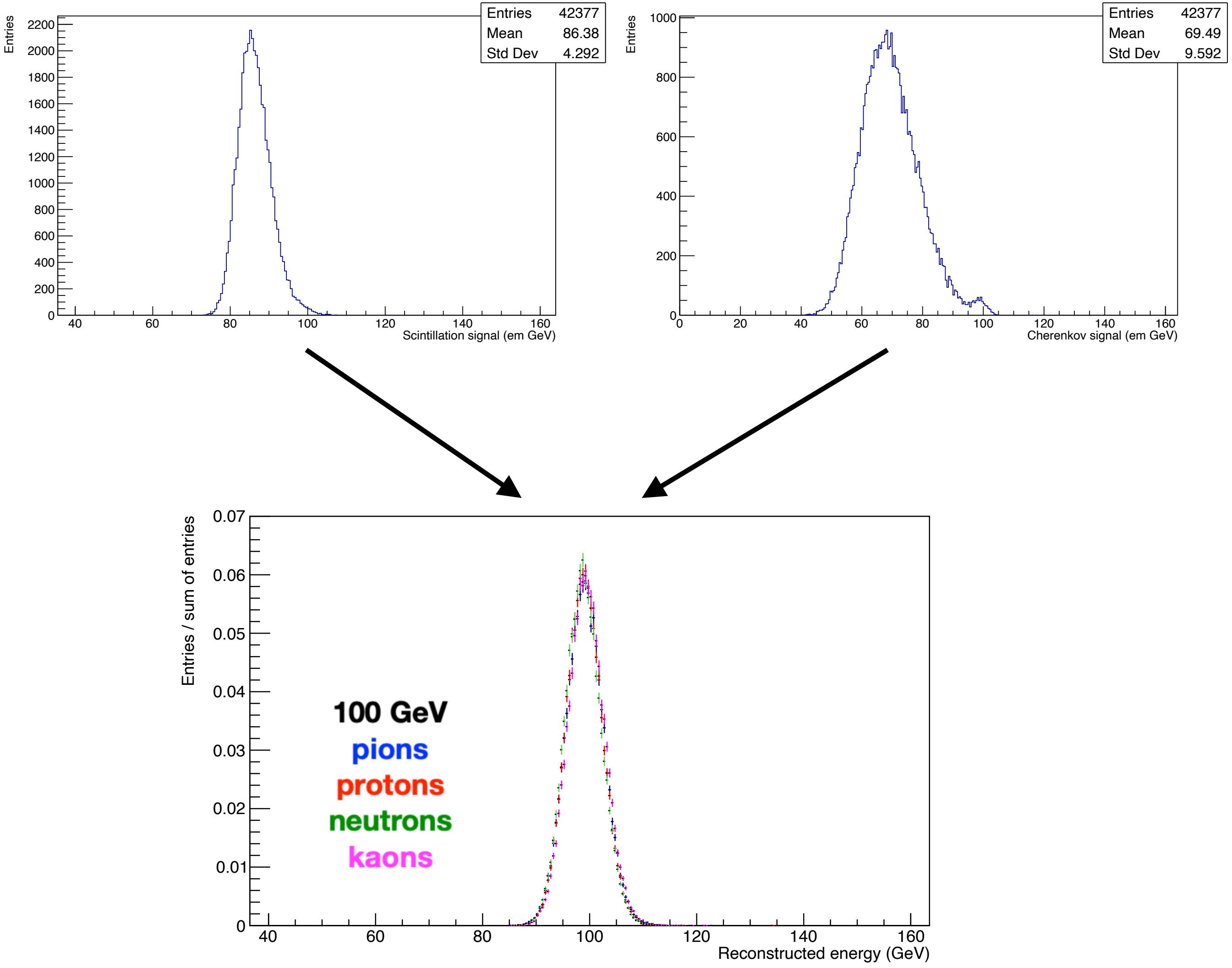
- Single particle response evaluated with calo-only IDEA-geometry G4 simulation





Scintillation signal - 100 GeV pions

Cherenkov signal - 100 GeV pions

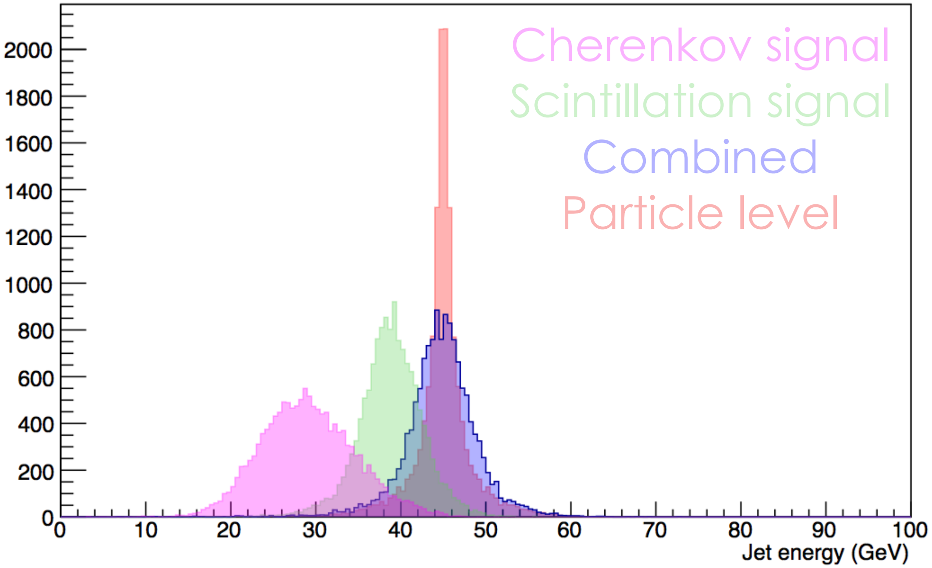


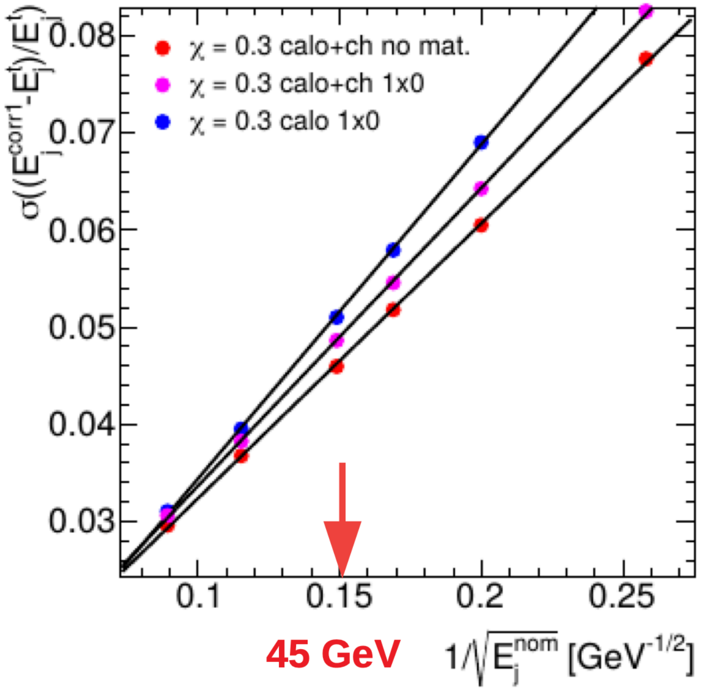
Calorimeter - jets

- IDEA: pure calorimetric measurement compared with a “track aided” calibration

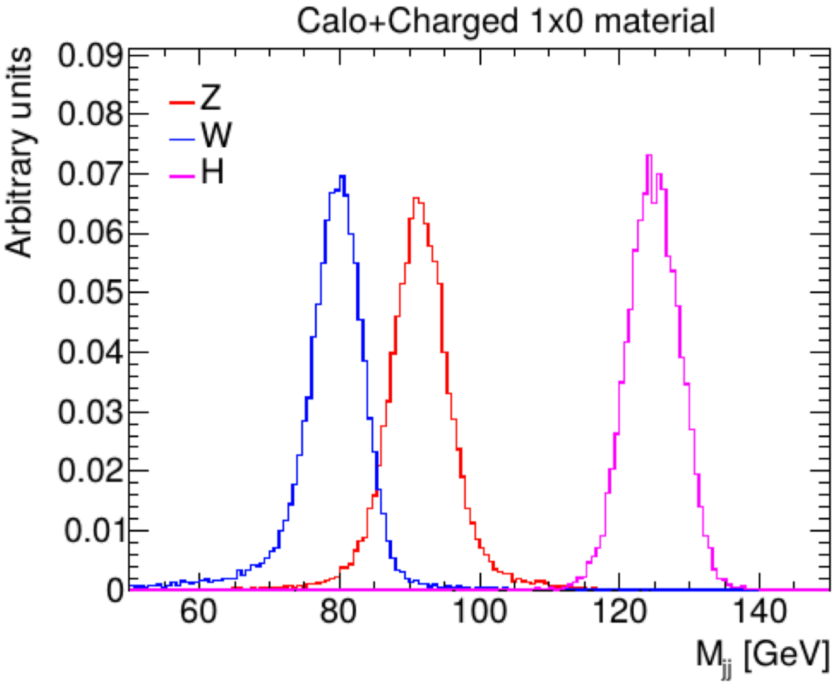
- Full collision events used

$$e^+e^- \to ZH \to jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \to WW \to jj\mu\nu$$
$$e^+e^- \to ZH \to \nu\nu bb$$

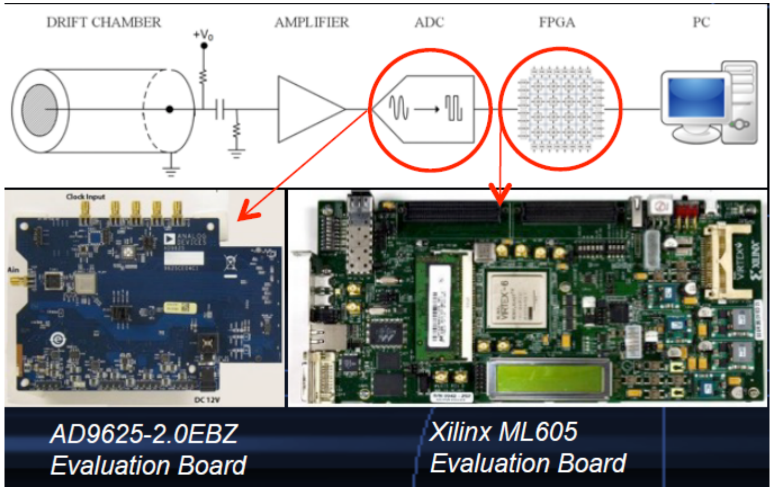




45 GeV

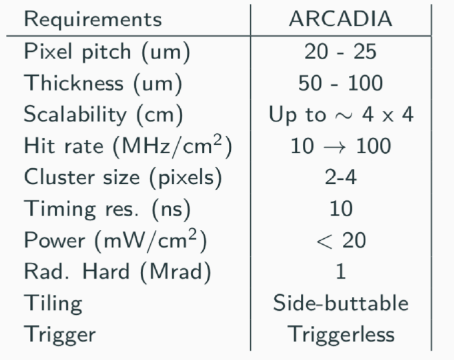


R&D and ideas



Drift chamber - ongoing development:
- Light mechanics and new wire technology
- Cluster counting electronics

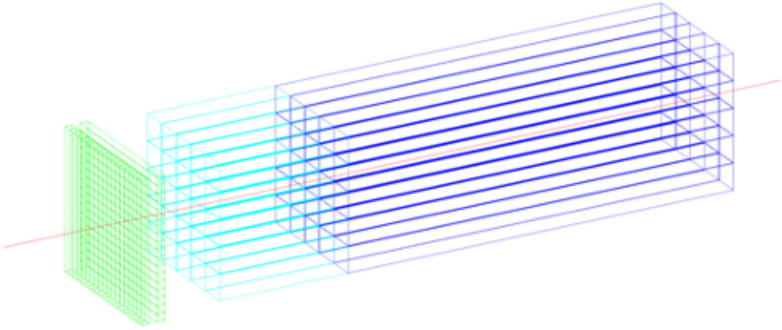
- Low-power, high speed MAPS within ARCADIA
- Large-area silicon sensors developments based on AtlasPix3



Requirements	ARCADIA
Pixel pitch (um)	20 - 25
Thickness (um)	50 - 100
Scalability (cm)	Up to ∼ 4 x 4
Hit rate (MHz/cm^2)	10 → 100
Cluster size (pixels)	2-4
Timing res. (ns)	10
Power (mW/cm^2)	< 20
Rad. Hard (Mrad)	1
Tiling	Side-buttable
Trigger	Triggerless

First Implementation

- Target hit rate: 100MHz/cm^2
- Target efficiency: 99.9% (in every regard)
- Pixel size: 20μm × 20 μm
- Double column arrangement
- Support for 2048 pixels in column (4cm)



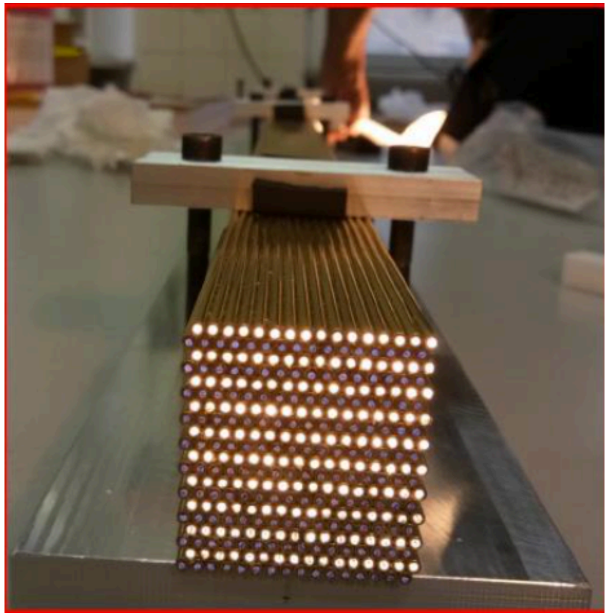
Calorimetry: considering an option with crystals in front

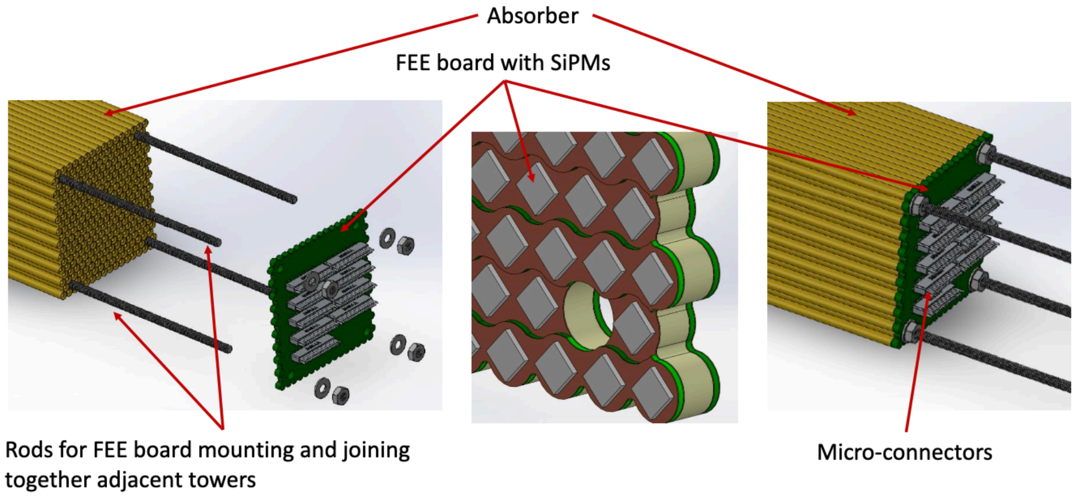
2 segments of 5 and 15 cm of $PbWO_4$, EM resolution ~ 3%/√E + timing layer

See talk from M. Lucchini in this workshop

2021 calorimeter test-beam

- “Bucatini” calorimeter being assembled t**o be put on beam at DESY** in February 2020 (COVID permitting)
- Scalable mechanical option - **brass tubelets with 2 mm (1.1 mm) outer (inner) diameter**
- 9 towers 3.3 x 3.3 x 100 cm^3, **central one read with SiPM** (15 μm pitch), the others with ordinary PMTs





Absorber

FEE board with SiPMs

Rods for FEE board mounting and joining together adjacent towers

Micro-connectors

- Readout of SiPMs with 5 readout boards (A5202)
  - Ad-hoc solution for Test beam
- R&D for full-scale production under active investigation

See talk from A. Karadzhinova-Ferrer at this workshop

Summary

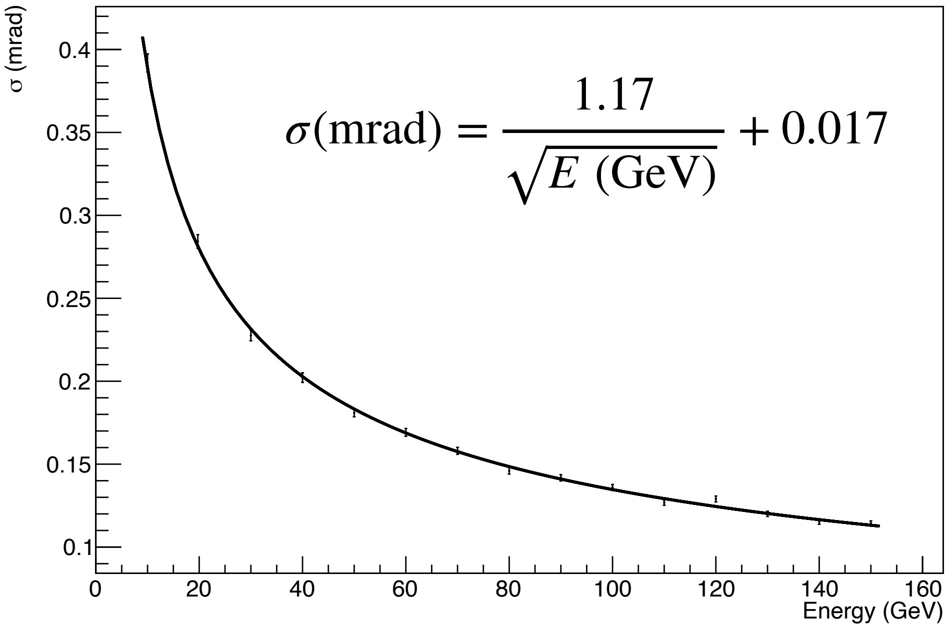
- I outlined a few ongoing activities on many fronts:
  - But **a lot more** on the table:
    - Exploration of Digital Photon Counters, 3D printing for calorimeter, MAPS R&D, etc.
    - Particle flow, ML for simulation and reconstruction, particle ID, 4- and 6-jets events, etc.
  - IDEA receiving **significant funding under AIDAinnova** - further significant funds on dual-readout calorimeter in Korea (PI: H. Yoo)
- **Room for collaboration** and new ideas on many fronts.

Backup

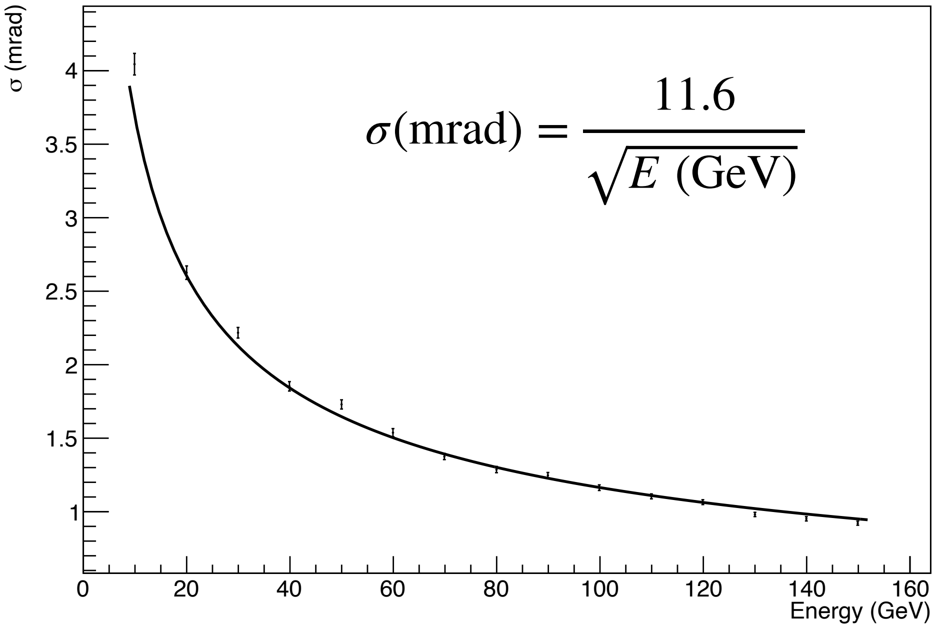
Angular resolutions

- The use of the **single-fibre granularity** yields the ultimate angular resolution of the calorimeter.
- Position obtained as the **energy-weighted fibre mean.**

Electrons



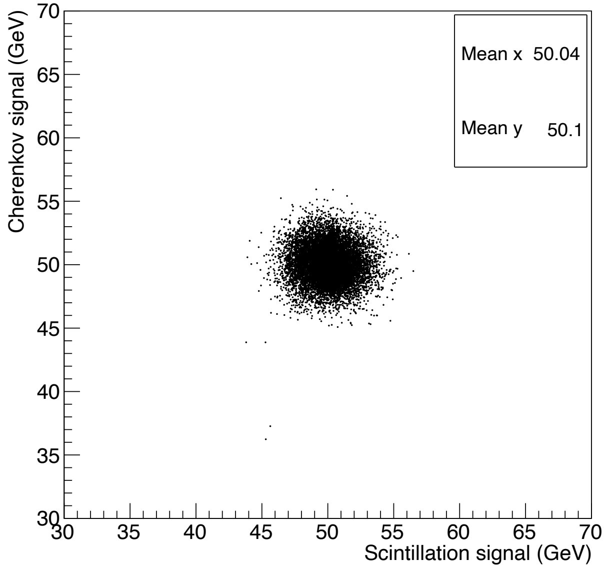
Pions



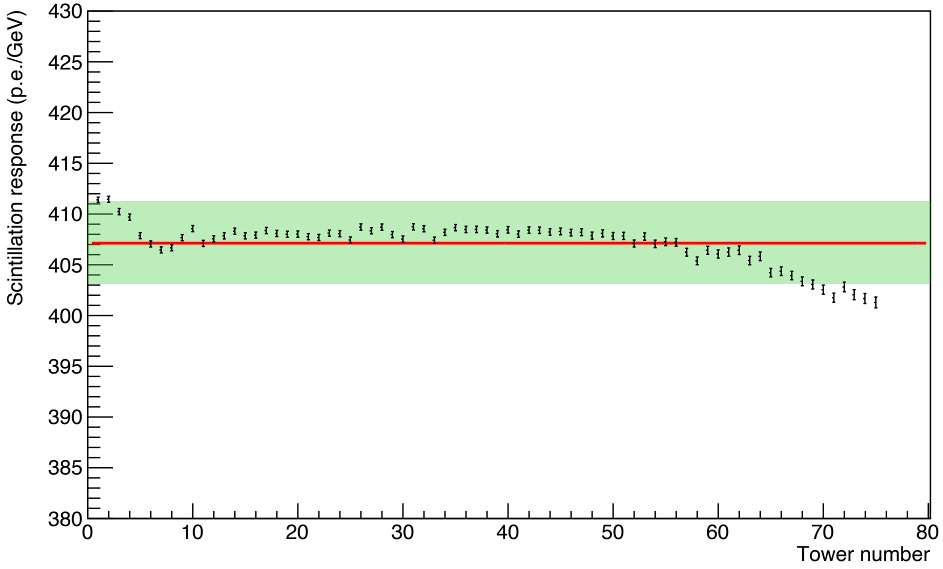
Calibration with electrons

- From now on using tower granularity.
- Light yield tuned **according to Test Beam results.**
- **After tower equalisation,** energy deposited by electrons used as pe/GeV calibration factor.

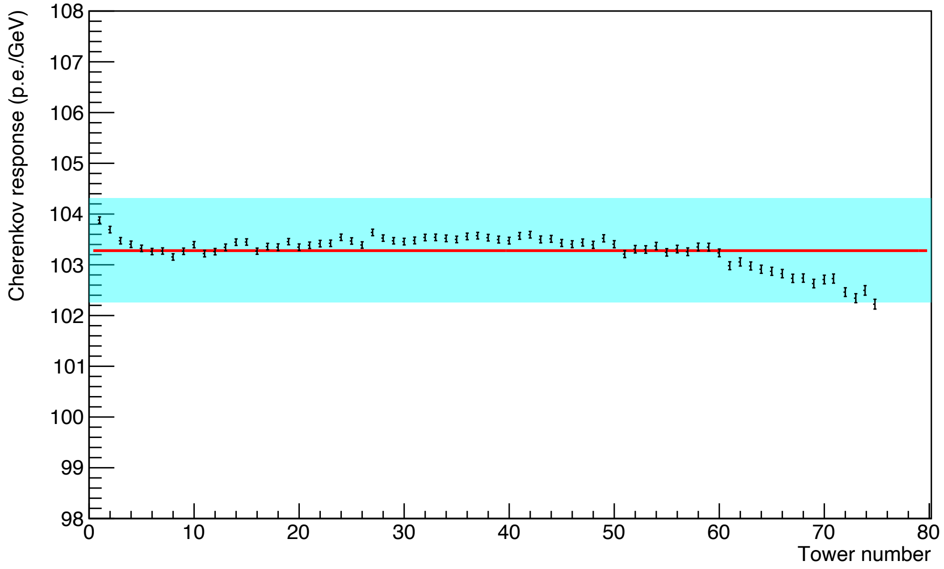
50 GeV electrons



40 GeV electrons - S channel



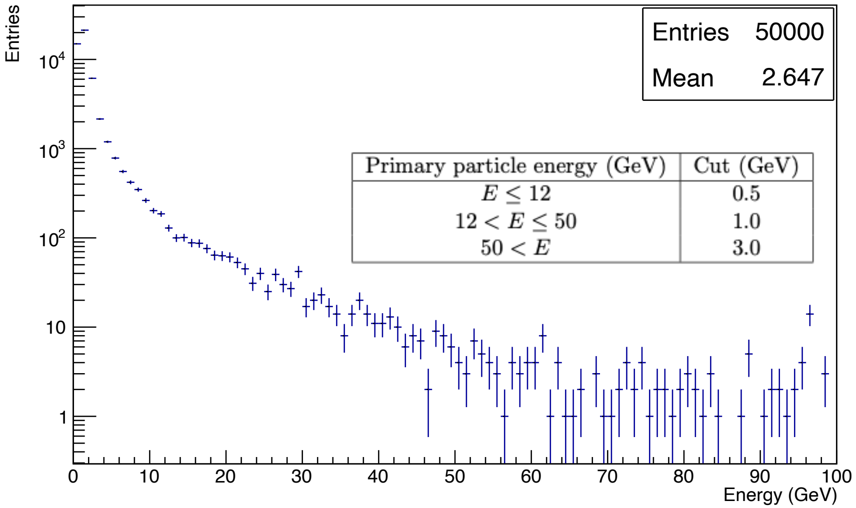
40 GeV electrons - C channel



Single pion response

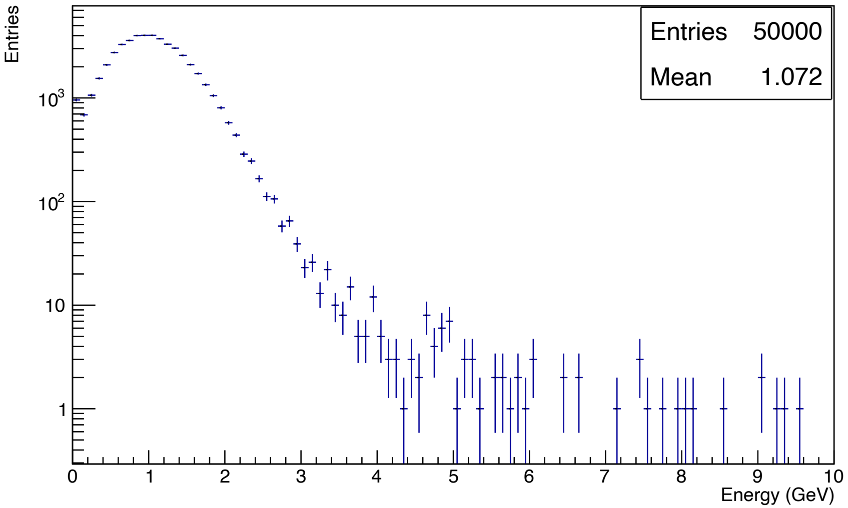
- Current IDEA calorimeter inner radius 2.5 m; outer radius 4.5.
  - **Reject events with poor containment** to focus on performance
- Evaluating performance using coarse granularity.

Kinetic energy escaped from calorimeter surface, 100 GeV pions



Primary particle energy (GeV)	Cut (GeV)
$E \leq 12$	0.5
$12 < E \leq 50$	1.0
$50 < E$	3.0

Energy carried away by neutrinos only, 100 GeV pions



Jet response

- Studied in **di-jet events so far** (reconstructed with ee_genkt algorithm in two exclusive jets).
- Separately reconstructing **S, C and truth-level jets**.
- Event cleaning: **central jets only** considered; reject events with **muons or neutrinos or poor containment**.
- Two options considered (with and without 1X$_0$ of additional "tracker" material):

Calo only

$$E^r_j = \frac{E^s_j - \chi E^c_j}{1-\chi}$$ + dedicated calibration

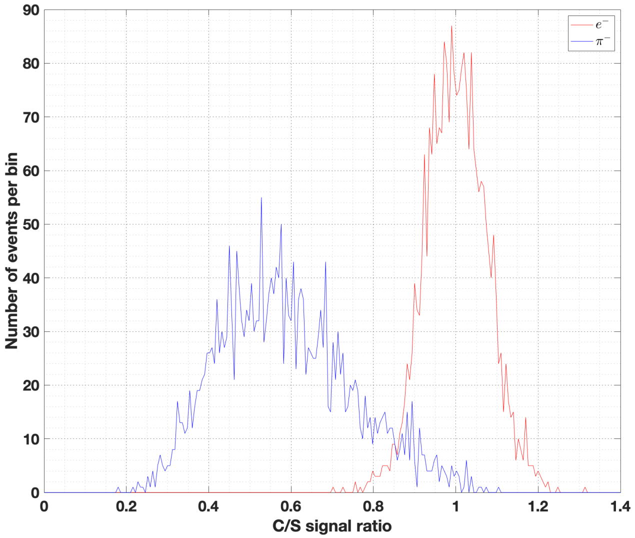
Calo + charged

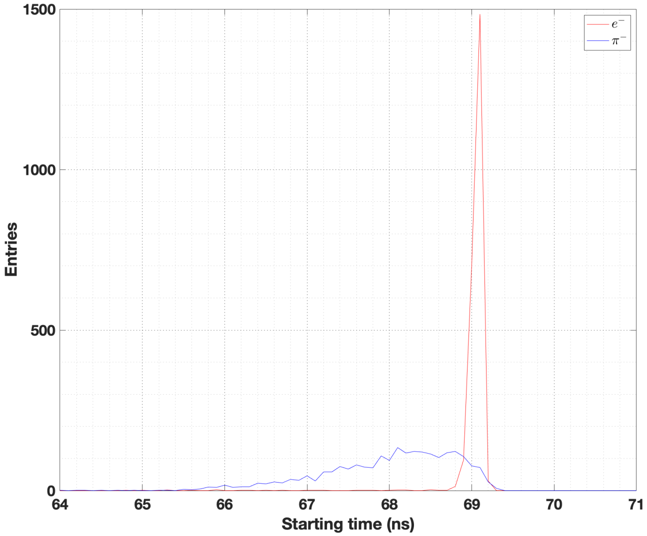
$$E^{r*}_j = E^{ch}_j + E^s_j - \frac{E^s_j E^{ch}_j}{E^r_j}$$ + dedicated calibration

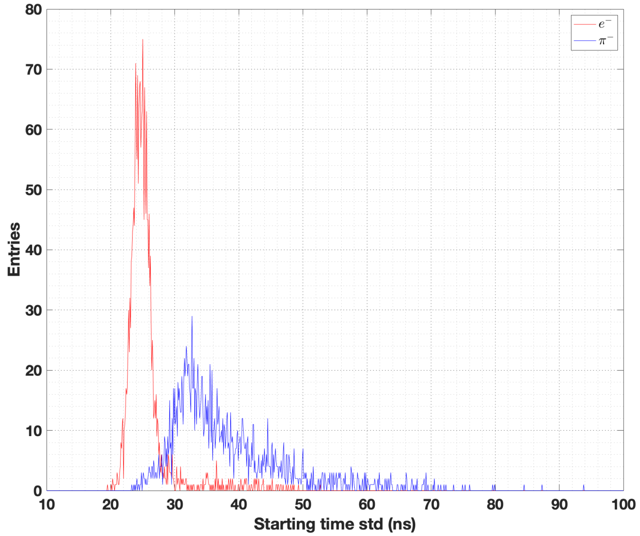
(Sum charged component and total energy, then correct for double counting)

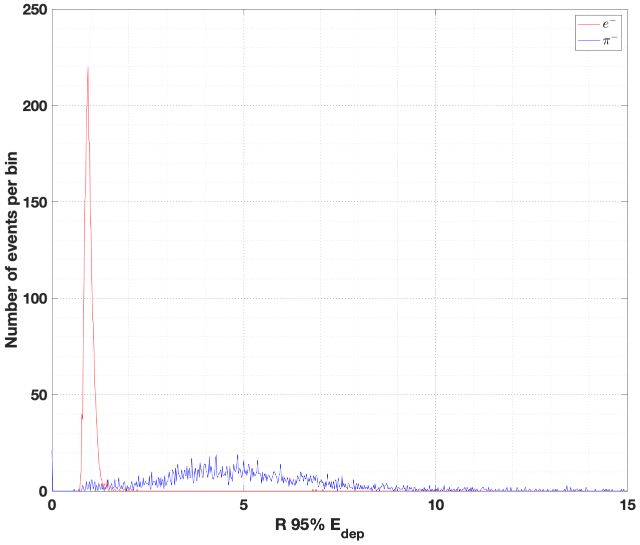
Particle identification

- Compare **electron and pion** shower shapes (20 GeV).
- Consider also **Time of arrival** of signal to SiPM (fiber propagation and SiPM + electronics time response parametrised in full sim).
- Combined performance: ε = 99.5%, fake ~1%.

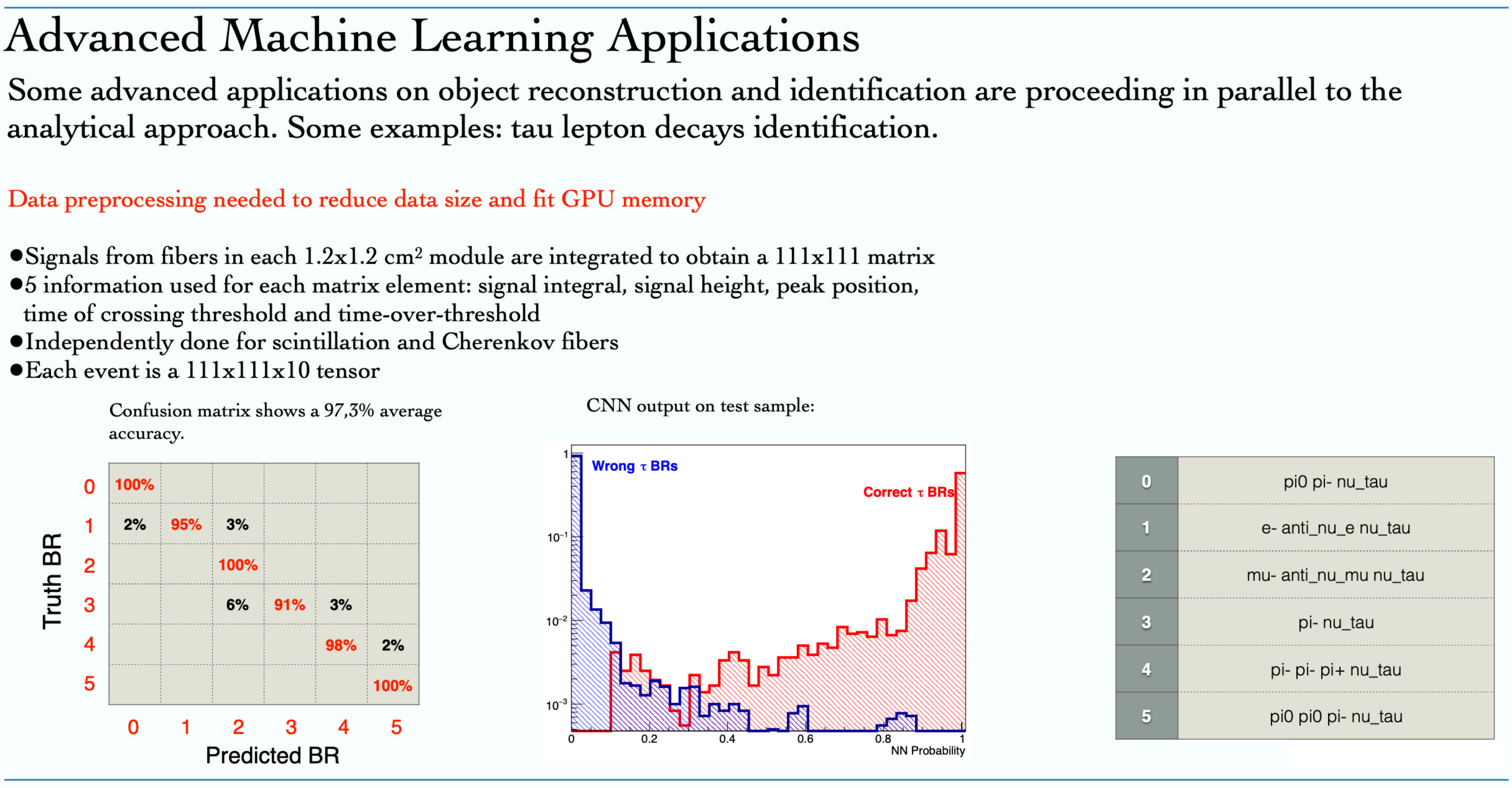








Tau decay identification



Advanced Machine Learning Applications

Some advanced applications on object reconstruction and identification are proceeding in parallel to the analytical approach. Some examples: tau lepton decays identification.

Data preprocessing needed to reduce data size and fit GPU memory

- Signals from fibers in each 1.2x1.2 cm^2 module are integrated to obtain a 111x111 matrix
- 5 information used for each matrix element: signal integral, signal height, peak position, time of crossing threshold and time-over-threshold
- Independently done for scintillation and Cherenkov fibers
- Each event is a 111x111x10 tensor

Confusion matrix shows a 97,3% average accuracy.

Truth BR \ Predicted BR	0	1	2	3	4	5
0	100%					
1	2%	95%	3%			
2			100%			
3			6%	91%	3%	
4					98%	2%
5						100%

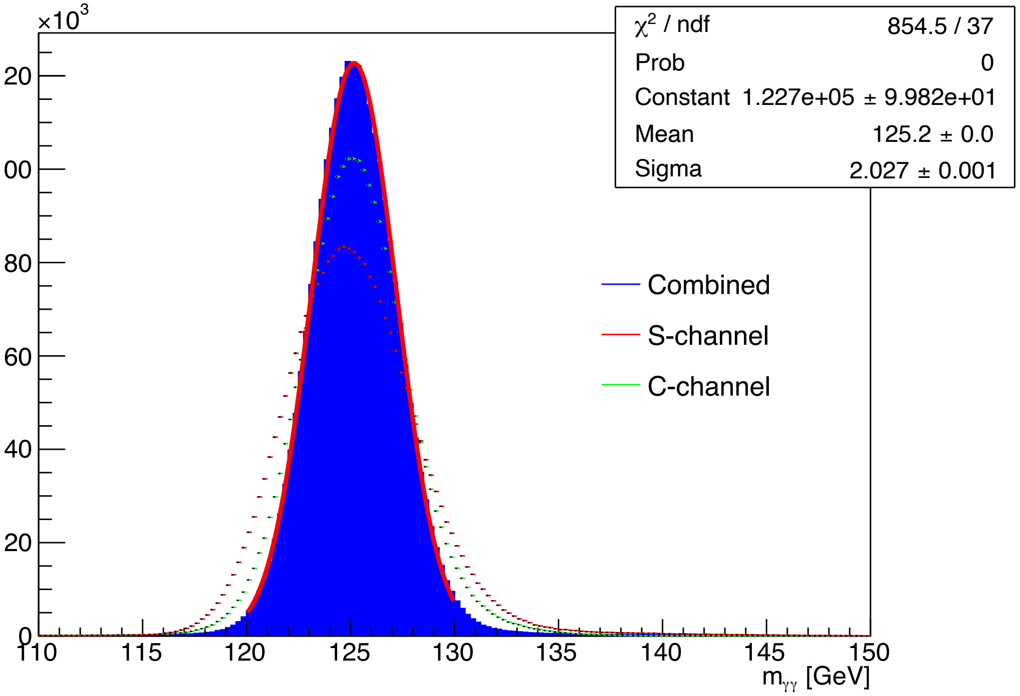
CNN output on test sample:

0	pi0 pi- nu_tau
1	e- anti_nu_e nu_tau
2	mu- anti_nu_mu nu_tau
3	pi- nu_tau
4	pi- pi- pi+ nu_tau
5	pi0 pi0 pi- nu_tau

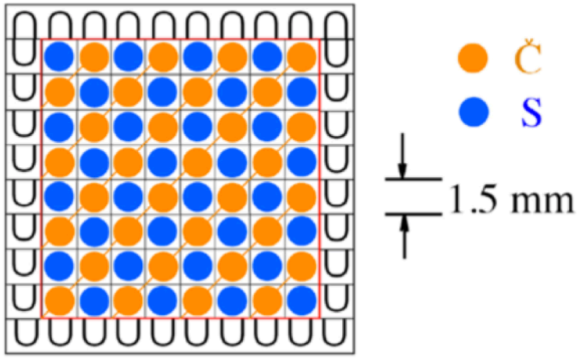
$H \rightarrow \gamma\gamma$ as a photon candle

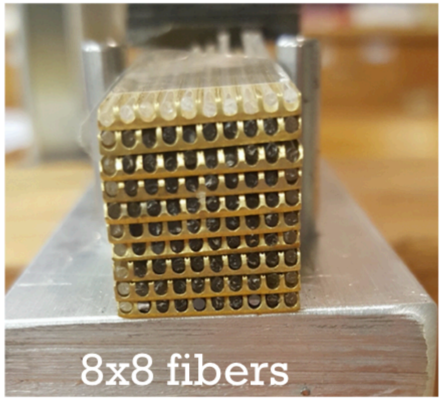
- Using 5M $e^+e^- \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$ events and clustering opposite calorimeter hemispheres as photons.
- Dedicated calibration corrections for impact point on tower

- Using tower granularity (estimated use of full granularity further improves mass resolution by 20%)
- Combined mass resolution ~ 2 GeV



SiPM dual readout





- Single fibre readout with **HAMAMATSU SiPM.**
- Readout for Cherenkov and Scintillation light **separated to minimise cross talk** (the latter expected to be ~ 50 times larger if not attenuated).