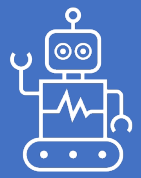
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Expected Performance of RPWELL-DHCAL

Dan Shaked Renous

RD51 Collaboration Meeting - 15.06.2021



Future Lepton Collider Experiments Require E_{Jet} Resolution of $\frac{\sigma}{E} \leq \frac{30\%}{\sqrt{E}}$

Jet energy resolution is limited by high dependence on the HCAL

- 70% of the jet energy is carried by hadrons

Intrinsic limitation of hadronic calorimeters (HCAL)

- Large fluctuations in the fraction of the EM and Hadronic component
  - Non-compensation: different response to EM and hadronic components
- Large jet-by-jet energy deposition fluctuations
- Large fluctuations in the fraction of the 'invisible energy' - deposited energy not contributing to the measured signal

Two possible solutions:

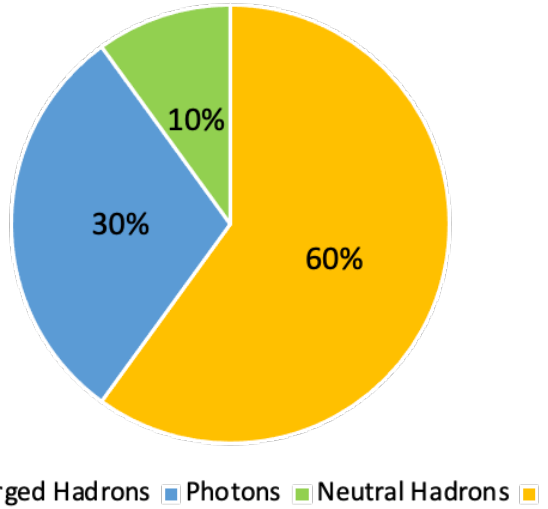
- Build compensating calorimeters ⇒ Dual readout
- **Reduce the dependency on the HCal ⇒ Particle flow calorimeters**

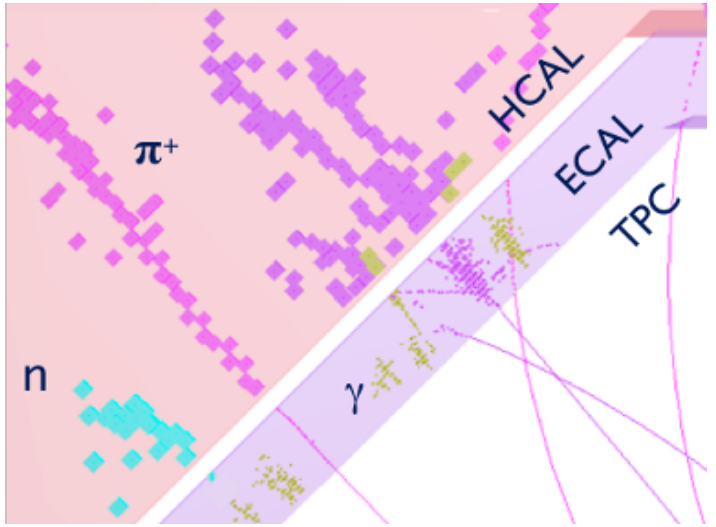
Particle Flow Calorimetry

- **Traditionally: Jet-energy is measured as a whole**
  - Measured in ECAL/HCAL
  - ~70% of the energy is measured in HCAL with $\frac{\sigma}{E} \approx \frac{60\%}{\sqrt{E[GeV]}}$
- **High granularity Particle Flow: Reconstruct individual particles**
  - Charged particle momentum is measured precisely in tracking system
  - Neutral hadrons (10%) energy is measured in HCAL

Perfect PFA can yield $\sim \frac{19\%}{\sqrt{E[GeV]}}$

using HCAL with $\frac{55\%}{\sqrt{E[GeV]}}$ energy resolution *





Marshall et. al. arXiv: 1308.4537

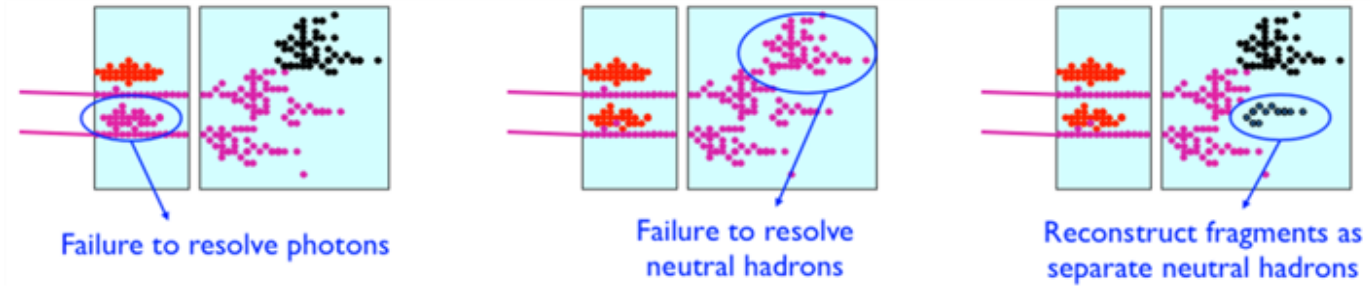
* M. Thomson, 2009
doi:http://dx.doi.org/10.1016/j.nima.2009.09.009

The Largest contributions to Jet Energy Resolution

Neutral hadron energy resolution (HCAL)

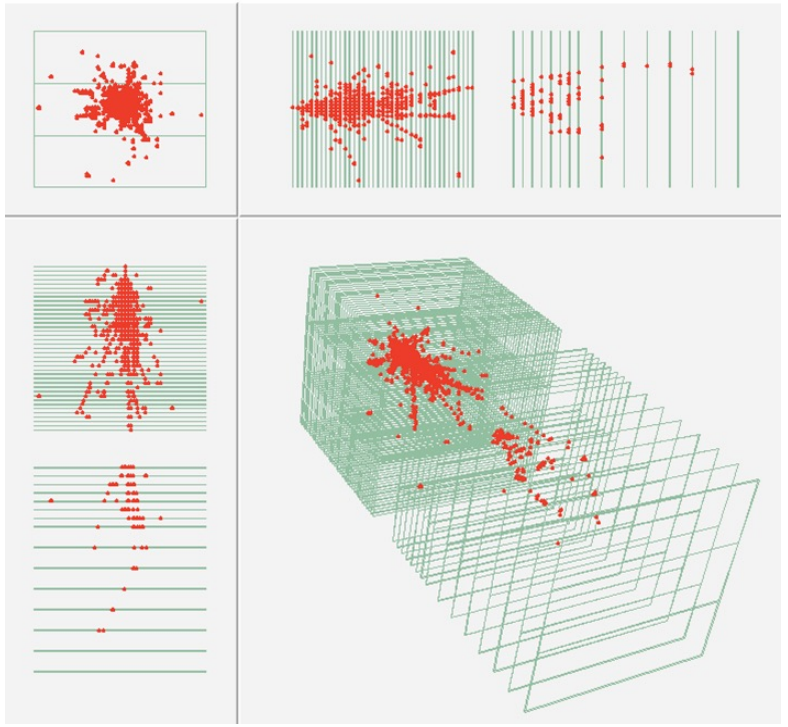
Confusion term – deposited energy can be assigned to more than particle.

Marshall et. al. arXiv: 1308.4537



(S)DHCAL: Requirements

- (Semi) Digital readout
- 1 cm^2 granularity
- 40-50 layers of sampling element with absorbers in between
- As thin as possible
  - minimizing cost of the magnet system
- High detection efficiency
- Low pad multiplicity – one pad fire per track
- For SDHCAL: Proportional response



Repond, CHEF 2013

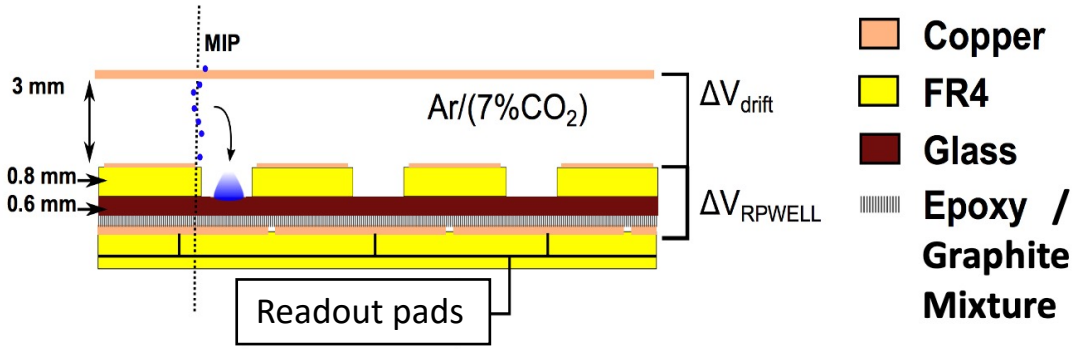
The RPWELL

Advantages:

- Strong discharge energy quenching
  - A few nA compared to 50-500 nA in other WELL-like structures*
- Environmental friendly gas mixture
- Charge evacuation through the bulk – lowering the pad multiplicity

Disadvantage:

- Thickness
  - 3.8 mm gas gap (drift+WELL) compared to 1.15 mm for the GRPC*
- Uniformity limited by quality of raw material



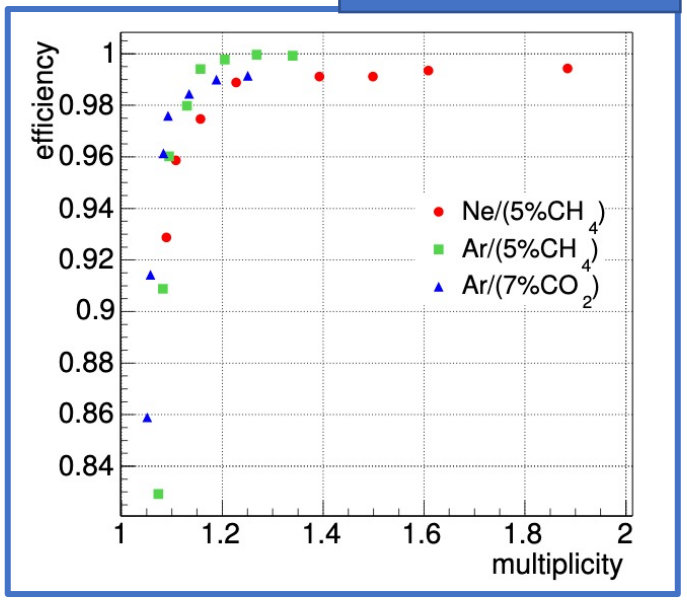
- Silicate glass resistive plate (~10^{10} Ωcm)
- Resistive plate coupled to anode through graphite-epoxy layer (~ MΩ)

*Bencivenni, JINST P05014, 2019
**CALICE: arXiv:1901.08818

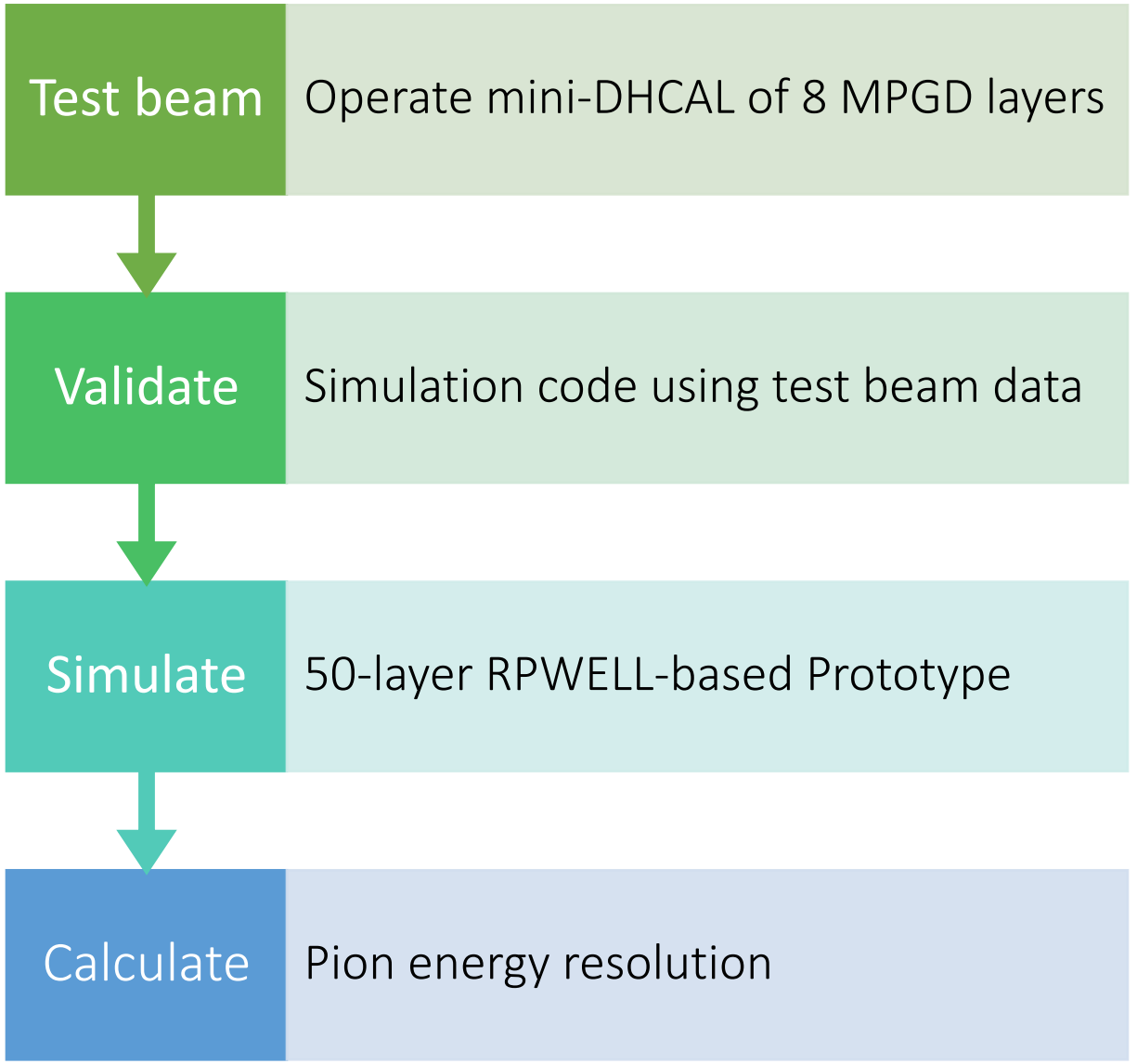
RPWELL - a Possible Technology for SDHCAL

- High granularity:
  - 1x1 cm^2 semi-digital readout pads
  - 1.4-cm-thick sampling elements
- Excellent response of single sampling element
  - ~98% efficiency
  - 1.3 average pad-multiplicity

L. Moleri, 2016



Work Flow


Test beam
Operate mini-DHCAL of 8 MPGD layers
Validate
Simulation code using test beam data
Simulate
50-layer RPWELL-based Prototype
Calculate
Pion energy resolution

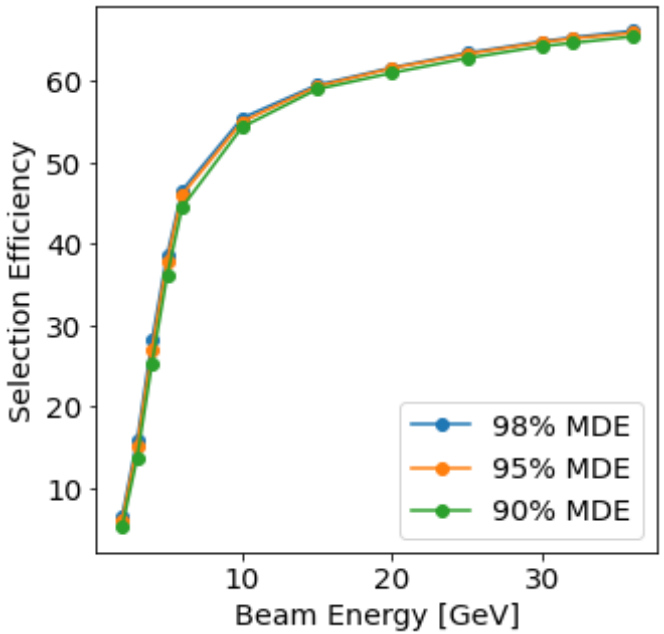
Simulated 50-layers RPWELL Fe-DHCAL

- Pions beam energy values:
  2, 3, 4, 5, 6, 10, 15, 20, 25, 30, 32, and 36 GeV
- 50k events per energy value
- 98%, 95% and 90% uniform MIP detection efficiency
- 1.37 average pad multiplicity (TB Jul. ’15)

Event Selection

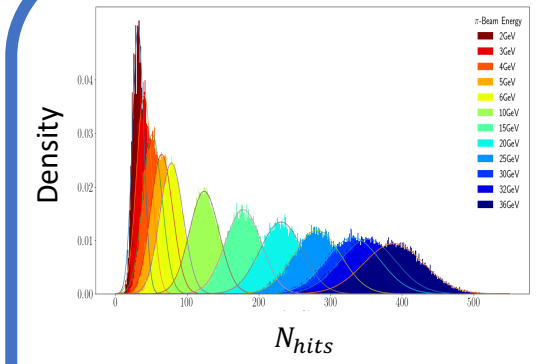
Suppress energy leakage:

- Select only showers that start in layers 1-10
  - Shower start definition following CALICE*
  - Expected efficiency 64%
    - 10 layers ≅ $\lambda_{i,\pi}$
- The following results are for 6-36 GeV

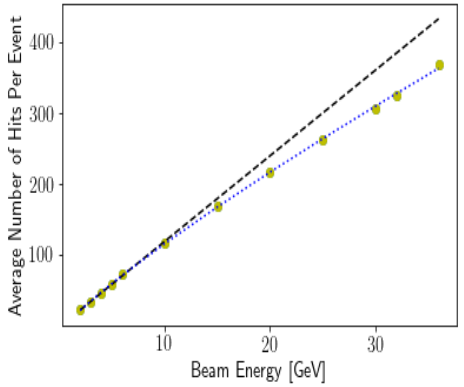


* Based on C. G. Reichelt, Particle ID Studies in a Highly Granular Hadron Calorimeter (September 2013)

Energy Reconstruction and Resolution



Extract $\langle N_{hits} \rangle$ per E_{beam}



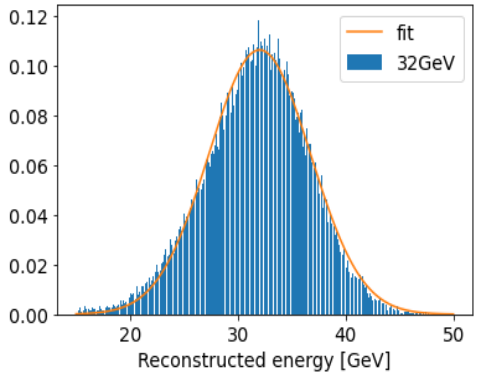
Fit a response function to the described data

$$[1]\ \langle N_{hits} \rangle = a \cdot E_{beam}^{b}$$

$$[2]\ \langle N_{hits} \rangle = a \cdot E_{beam}^{b} - c$$

$$[3]\ \langle N_{hits} \rangle = \frac{a}{b} \log(1 + bE_{beam})$$

[1] CALICE, 2019
[2] Repond, CHEF 2013
[3] Chefdeville, CHEF 2013



Reconstructed energy using the inverse response function

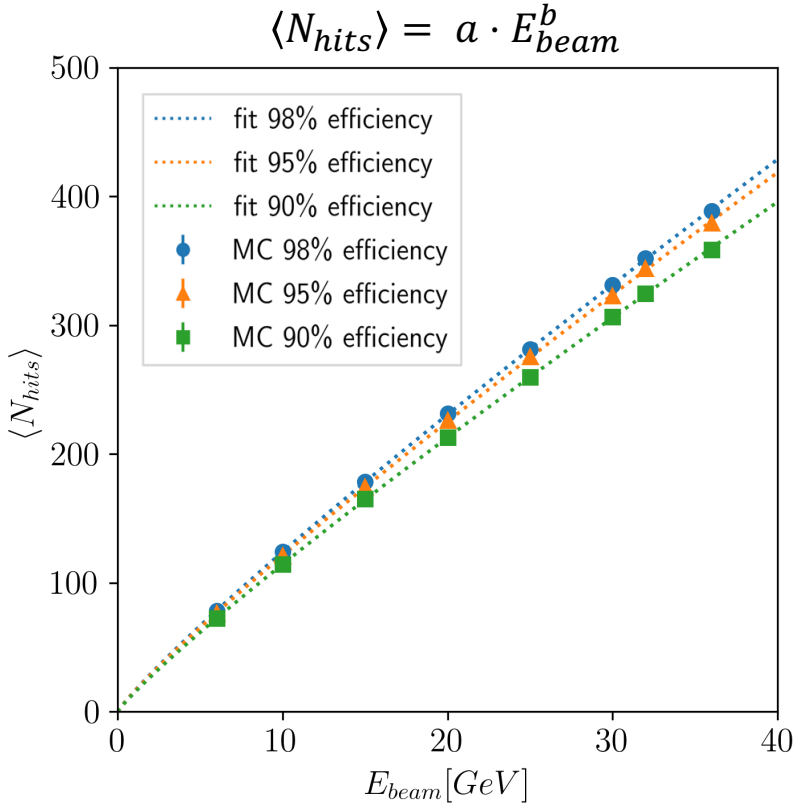
Fit the energy resolution

$$\frac{\sigma}{E[GeV]} = \frac{S}{\sqrt{E[GeV]}} \oplus C$$

to the relation $\frac{\sigma_{rec}}{\langle E_{rec} \rangle}$ as a function of E_{beam}

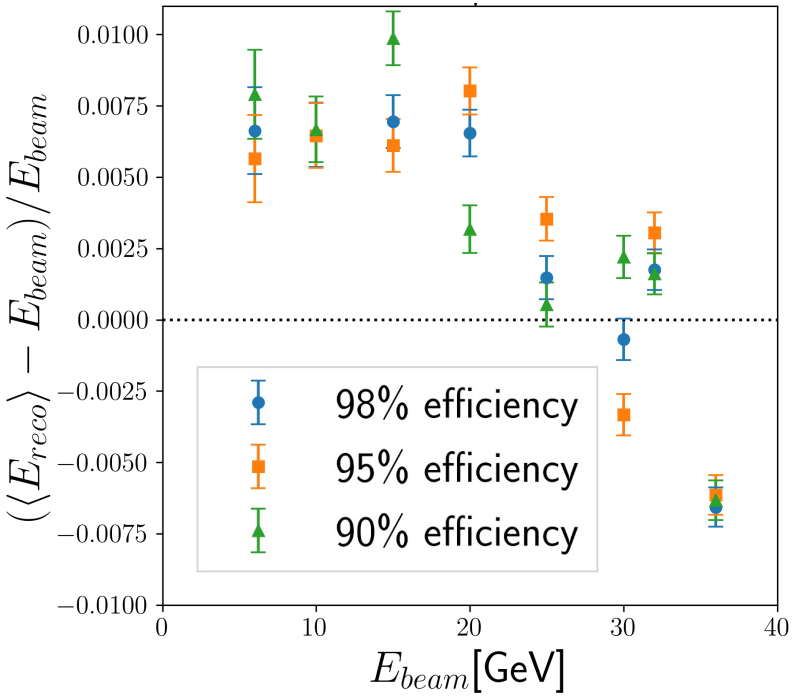
Calorimeter Response

- The response is describe by $\langle N_{hits} \rangle = a \cdot E_{beam}^{b}$
- Less efficiency => Less hits a
  - The importance performance uniformity



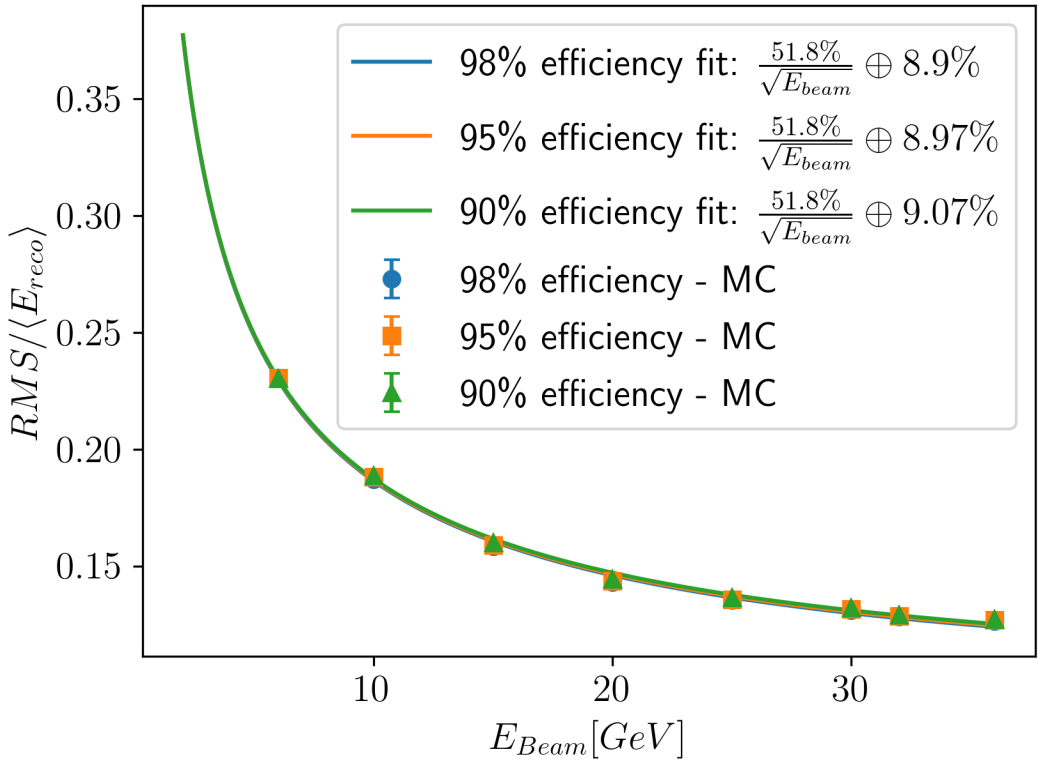
Reconstruction Bias

- All the configurations yield less then 1% bias
- No significant effect for detection efficiency



π^- Energy Resolution

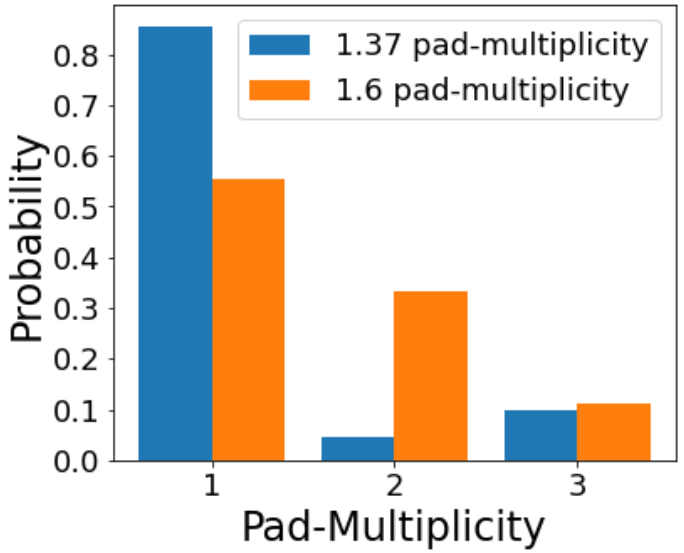
- No effect for MIP detection efficiency
  - Assuming uniformity
  - The effect might be in confusion term
- All results are less than $\frac{52\%}{\sqrt{E[GeV]}}$
  - Reminder: a perfect PFA + HCAL with $\frac{55\%}{\sqrt{E[GeV]}} \Rightarrow \frac{\sigma_{jet}}{\sqrt{E[GeV]}} = \frac{19\%}{\sqrt{E[GeV]}}$ *

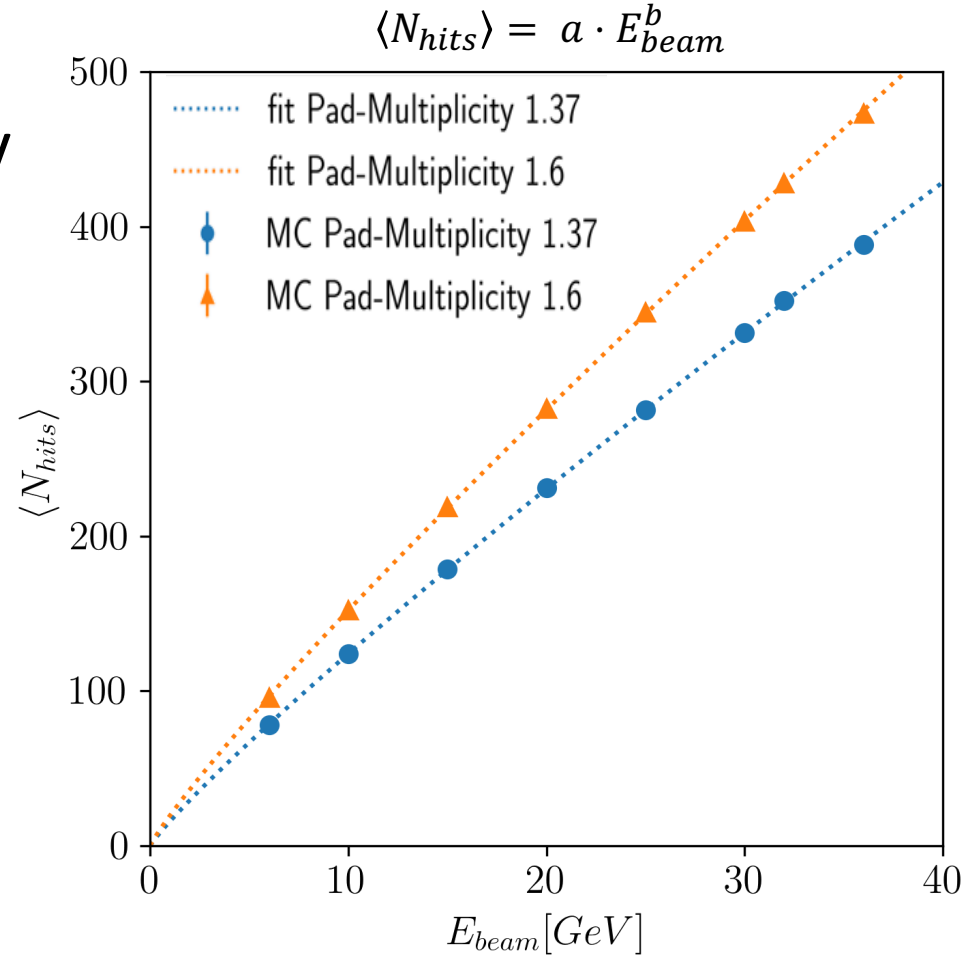


* M. Thomson, 2009
doi:http://dx.doi.org/10.1016/j.nima.2009.09.009

Effect of Pad-Multiplicity – part I

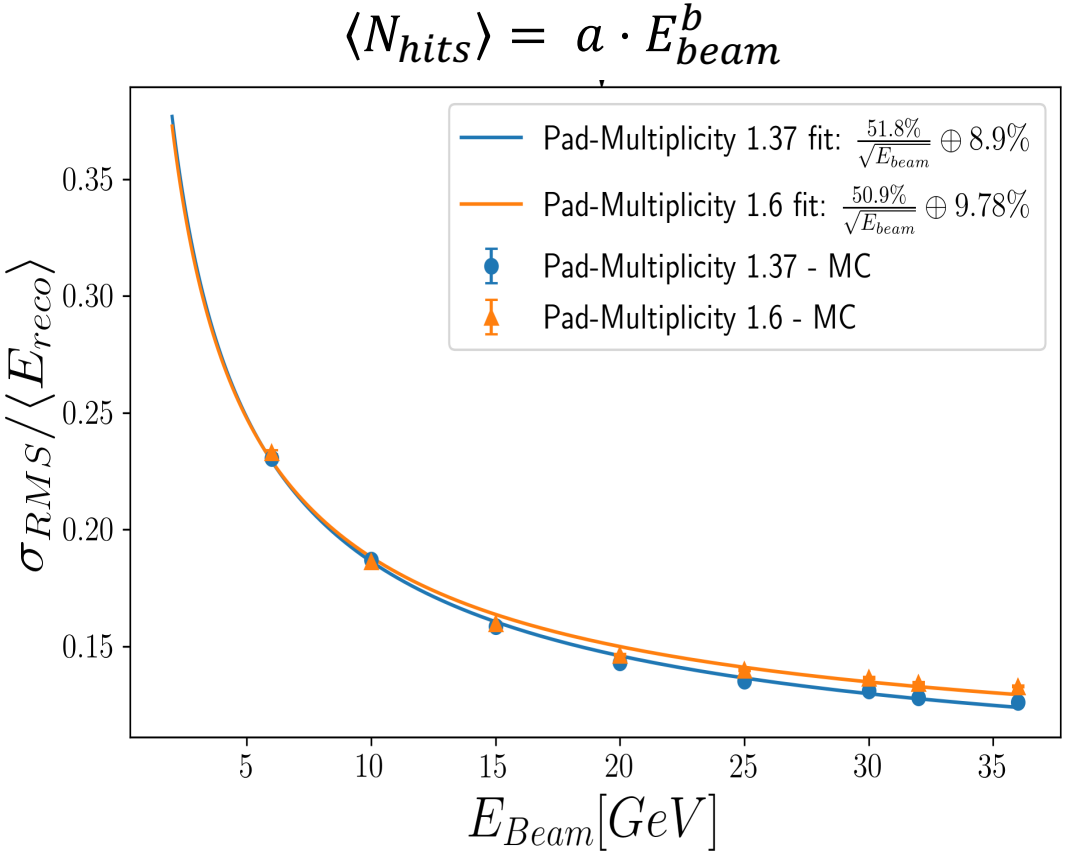
- Testing for 1.6 average pad-multiplicity
- Ratio of $\langle N_{hits} \rangle$ = ratio of pad-multiplicity





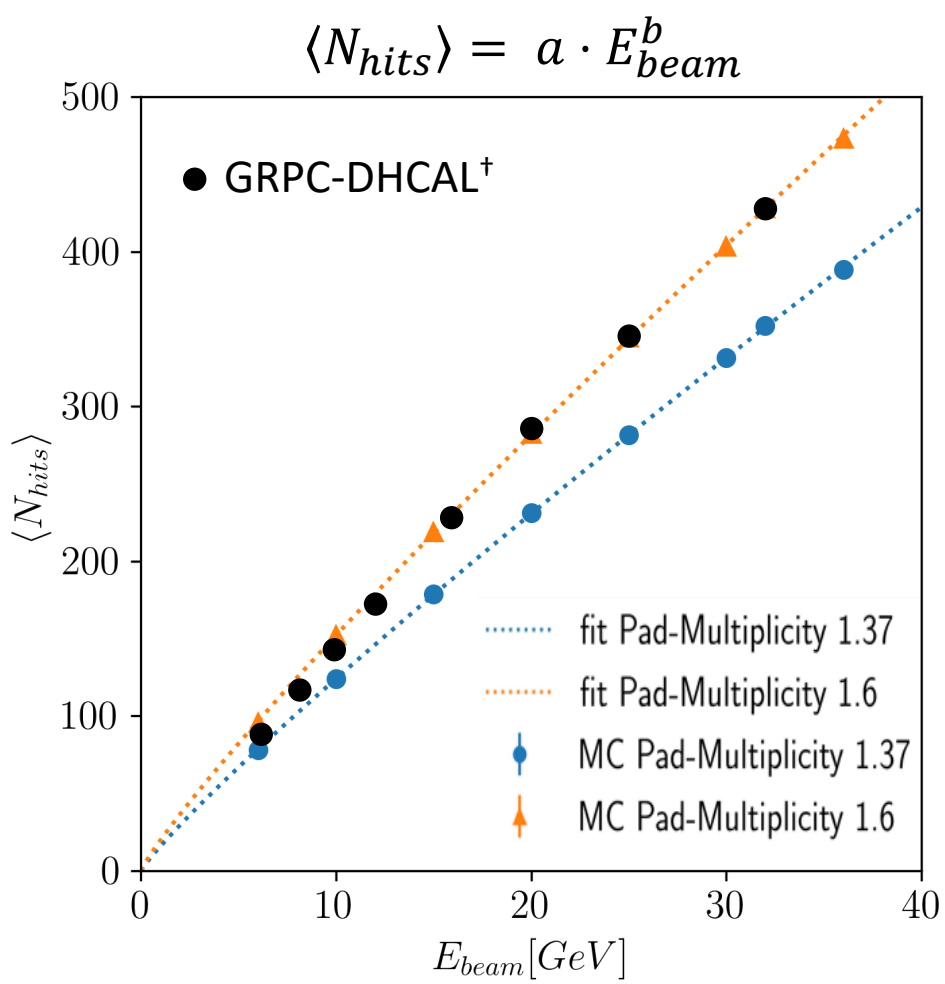
Effect of Pad-Multiplicity – part II

- Minor difference in energy resolution
- High pad-multiplicity is contributes to confusion.



Comparison to Other Technologies

- Comparable to GRPC-DHCAL*
- Validated by Data
- Pad-multiplicity 1.6
- Software compensation



Term	RPWELL [1.37 PM]	GRPC [1.6 PM]
Stochastic [% GeV]	51.8 ± 0.1	51.5 ± 1.5
Constant [%]	8.9 ± 0.02	10.6 ± 10.5

*CALICE: arXiv:1901.08818

Conclusions & Outlook

RPWELL-based DHCAL was simulated

Provides insights on requirements of DHCAL Sampling Elements

- Stable and uniform operation is desired
- High MIP detection efficiency and low Pad-multiplicity
  - At the level of π energy resolution – less crucial
  - Confusion term – more essential (to be tested using PFA)

Next steps:

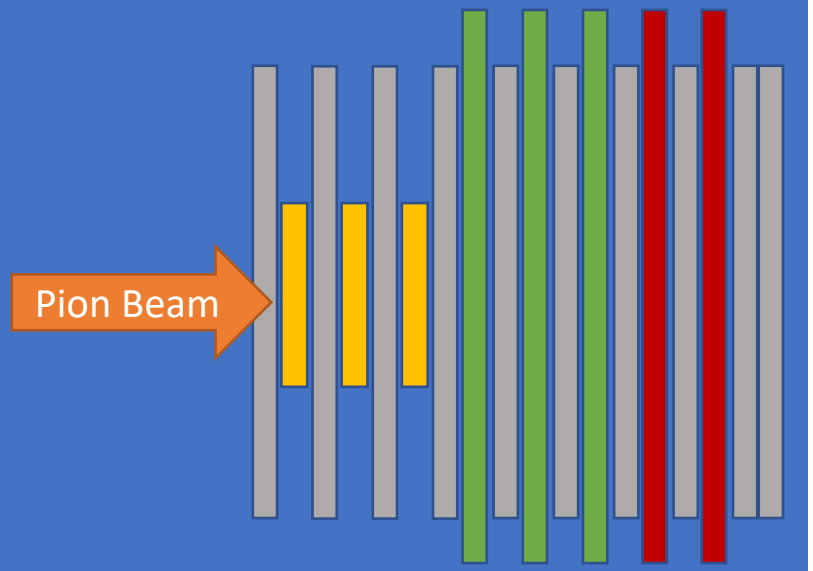
- Test effects of detection efficiency and pad-multiplicity as part of PFA
- Improve event selection to include results of low-energy pions

Thank you!

Questions?

Back up slides

Experimental Setup



Source pion-beam (2-6 GeV/c) – CERN/PS/T10

Single DAQ system – based on MICROROC chip

8 layers

- 2 cm Steel absorbers between layers
- λ_{int} = 20 cm: 45% chance of shower inside our setup
- X_0 = 1.8 cm: 99.9% chance of EM shower inside our setup

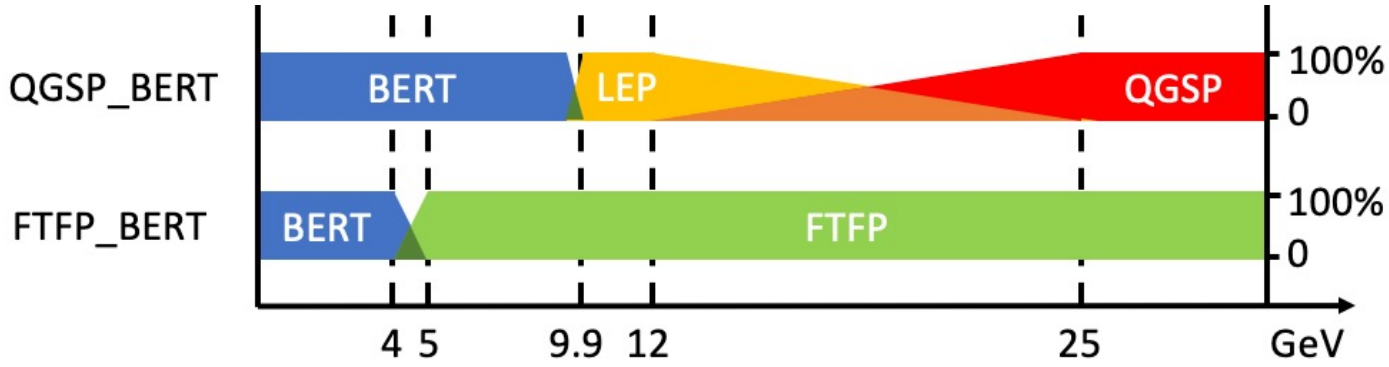
Sampling elements:

- 2+1 16x16 cm^2 bulk + resistive bulk µM
- 3 48x48 cm^2 resistive bulk µM
- 2 48x48 cm^2 RPWELL

Simulation: GEANT4 Physics Lists

3 different physics lists: QGSP_BERT, QGSP_BERT_EMZ, FTFP_BERT_EMZ

- QGSP – Quark-Gluon String Pre-compound model
- BERT – Bertini cascade model
- FTFP – Fritiof Pre-compound model
- LEP – Low Energy Parametrized model



Simulation: Digitization

Assigning hits to corresponding 1×1 cm^2 readout pads

Apply detection efficiency:

- Each hit gets a number in [0,1] (uniform distribution)
- Keeping only those below the given detection efficiency input value.

Apply pad-multiplicity:

- Random sampling of pad-multiplicity distribution
- Adding randomly edge-sharing pads to the event

Digitize

- Count one hit per pad

Error Estimation

- Entering standard erorr of $\langle N_{hits} \rangle$ to the fit of the response
- Calculating the “up” nad “down” versions of the response fit
  - Over- and under-estimation
- Energy is reconstructed by nominal, “up” and “down” versions
- Errors are propagated along the calculation: $\varepsilon_{res} = \frac{\sigma_{rec}}{\langle E_{rec} \rangle^2} \varepsilon_{\langle E_{rec} \rangle}$
- Differences between the versions and the nominal estimation are considered
- $\varepsilon_v = \frac{\sigma_{rec}}{\langle E_{rec} \rangle} - \frac{\sigma_{rec,v}}{\langle E_{rec} \rangle_v} \quad ; \; v \in \{up, down\}$
- $\varepsilon_{res}^{v} = \varepsilon_{\mathrm{v}} \oplus \varepsilon_{res} \; ; \; v \in \{up, down\}$