The (Un)reasonable Effectiveness* of Neural Network in Cherenkov Calorimetry

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(*) inspired by E. P. Wigner, 1960

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Challenge in Hadron Calorimetry

❖ Invisible energy:

In hadron-nuclei interactions, large fraction of hadron energy goes to nuclear dissociation and becomes invisible. We need to estimate the invisible energy from visible quantity.

- Compensation using slow neutrons
- Dual Readout using R=Scintillation/Cherenkov
- Vertex Imaging using ML technique in high granularity calorimeter

❖ Large volume:

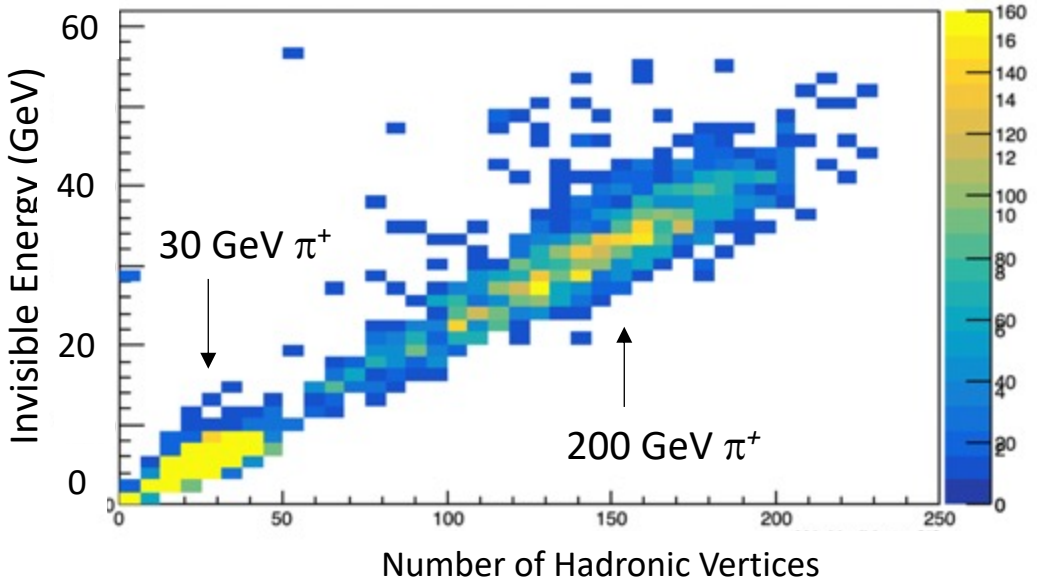
Very high granularity pushes the cost up quickly as the granularity increases.

- 3D readout: CMS HGCAL, CALICE
- 2D readout: Fiber calorimeter with longitudinal segmentation with timing

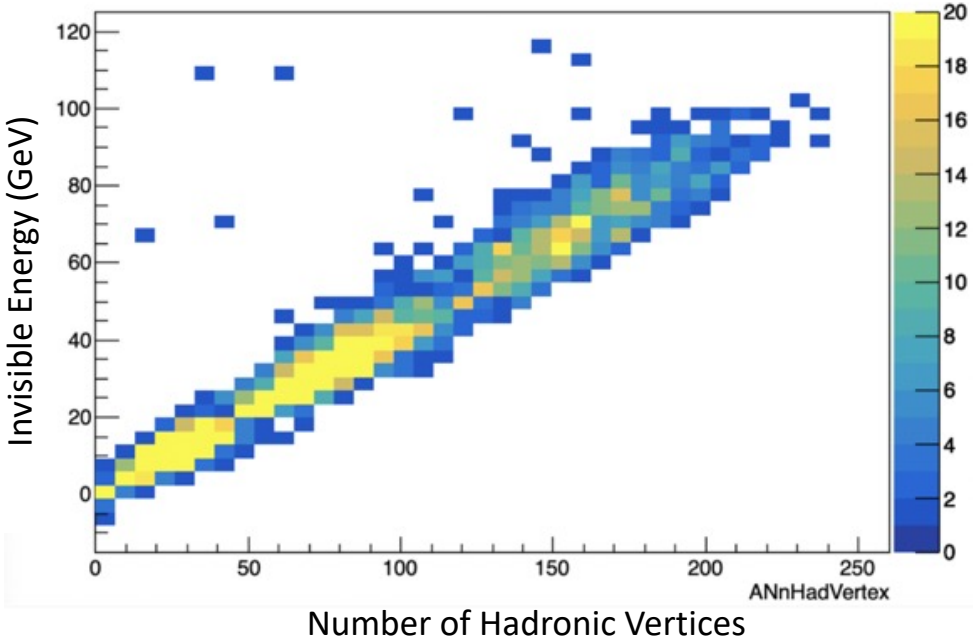
Invisible Energy in Cu vs Number of Hadron Vertices (G4 truth)

Total invisible energy of hadronic shower increases with the number of hadronic vertices, though the lost kinetic energy at each vertex varies and depends on the energy of parent particle (see next page).

dedx signal (silicon)



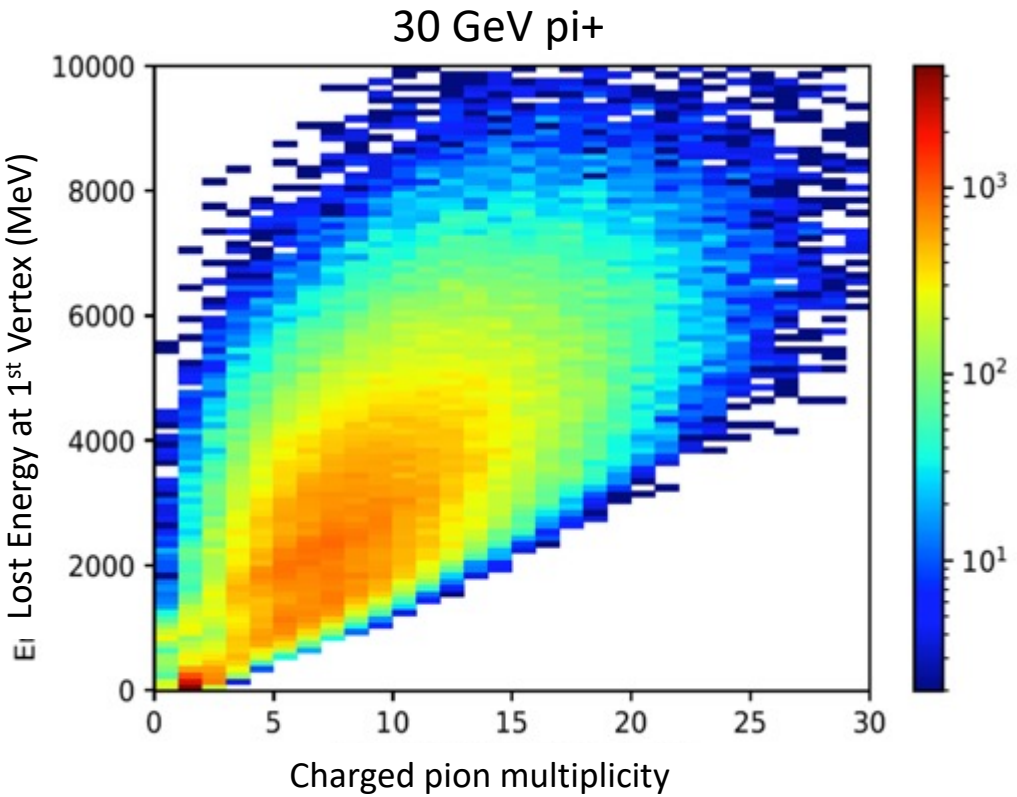
Cherenkov

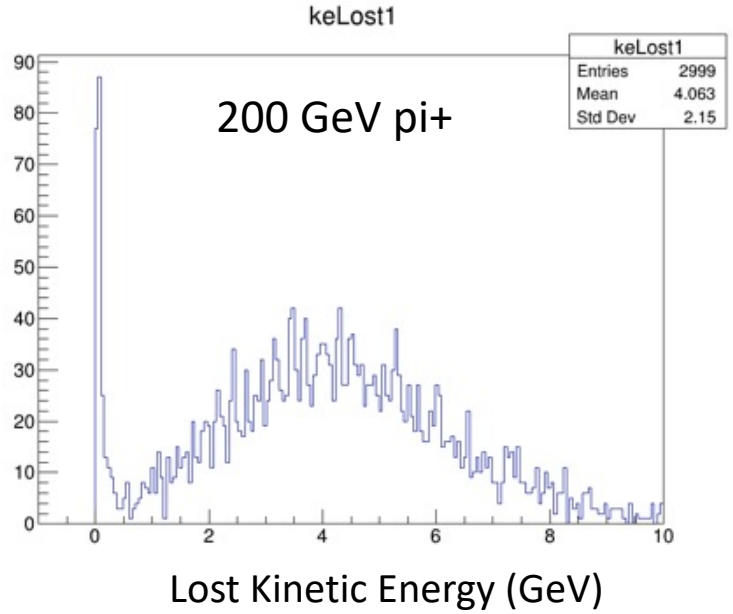


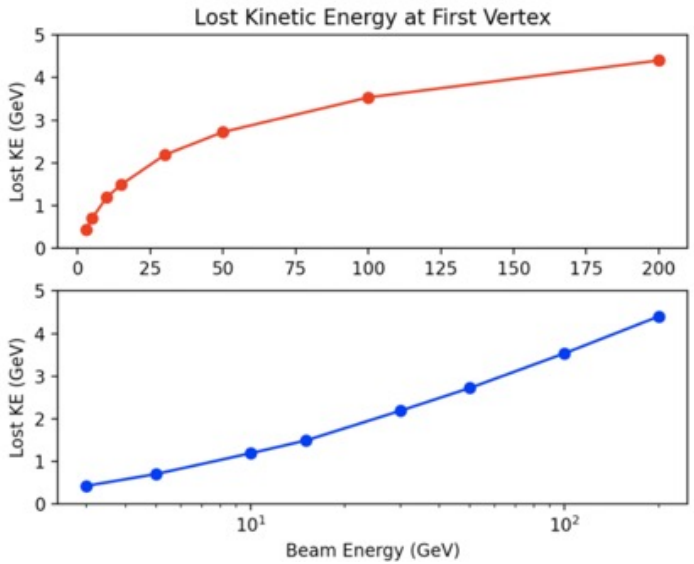
(Invisible Energy) = (Beam Energy) – (Observed Energy)

Pi+ on Cu: Lost Kinetic Energy at Vertex

(Lost energy = Beam Energy – Visible Kinetic Energy at Vertex (G4 truth))





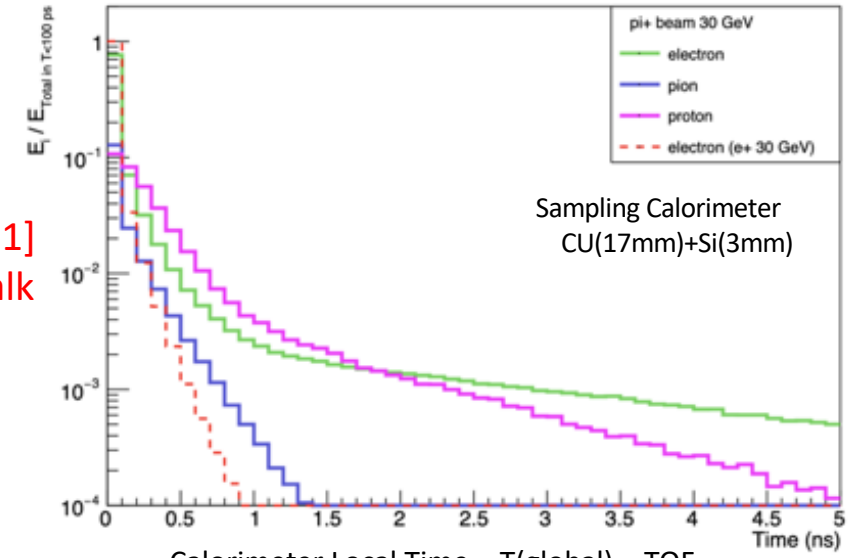


Let GNN use the image of vertices to estimate the lost energy.

Vertex Imaging using Fast Components of Shower

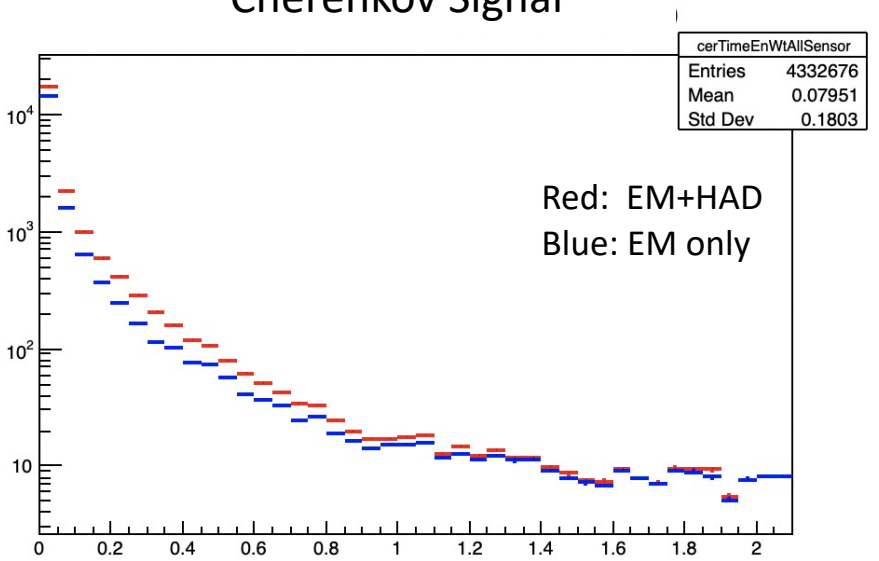
Previous study [1]
Adil Hussain's talk yesterday

dEdx (ionization) signal (< 5 ns)



Calorimeter Local Time = T(global) – TOF

Cherenkov Signal

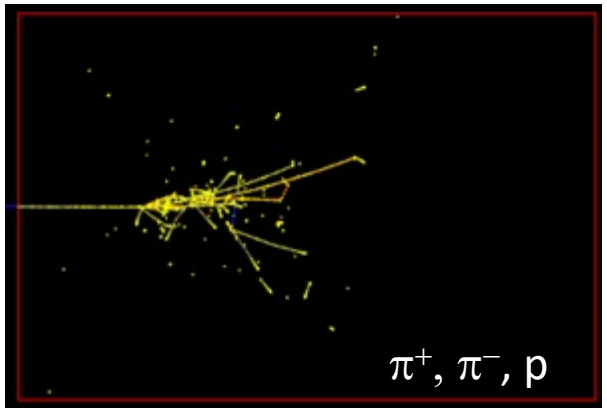


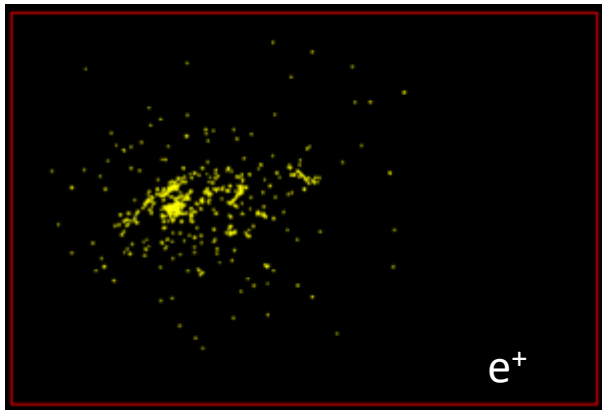
Calorimeter Local Time = T(global) – TOF

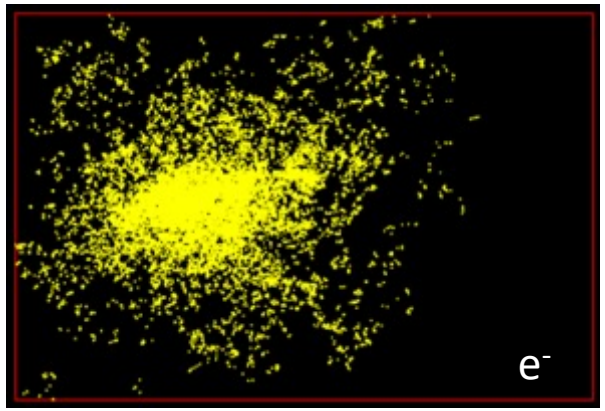
This study

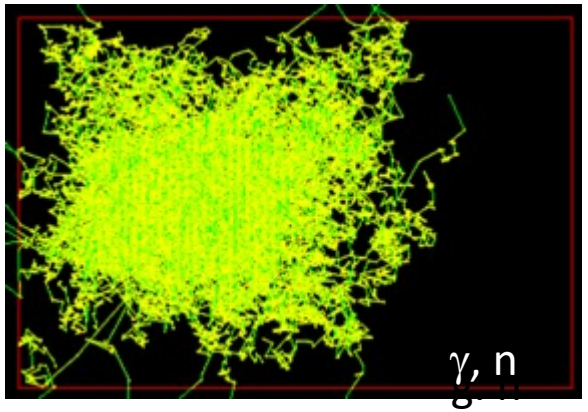
TOF = z/c

Particles in a hadronic shower in a solid Cu block (1x1x1.5 m^3) for 30 GeV π+









FAST components

SLOW components

Vertex Imaging

dE/dx (ionization) Calorimeter

20x20x20 mm3 Cube (Cu: 17 mm, Si: 3mm)

CNN: In: $(E, x, y, z)_{cube}$ 1 image: 0 - 5 ns

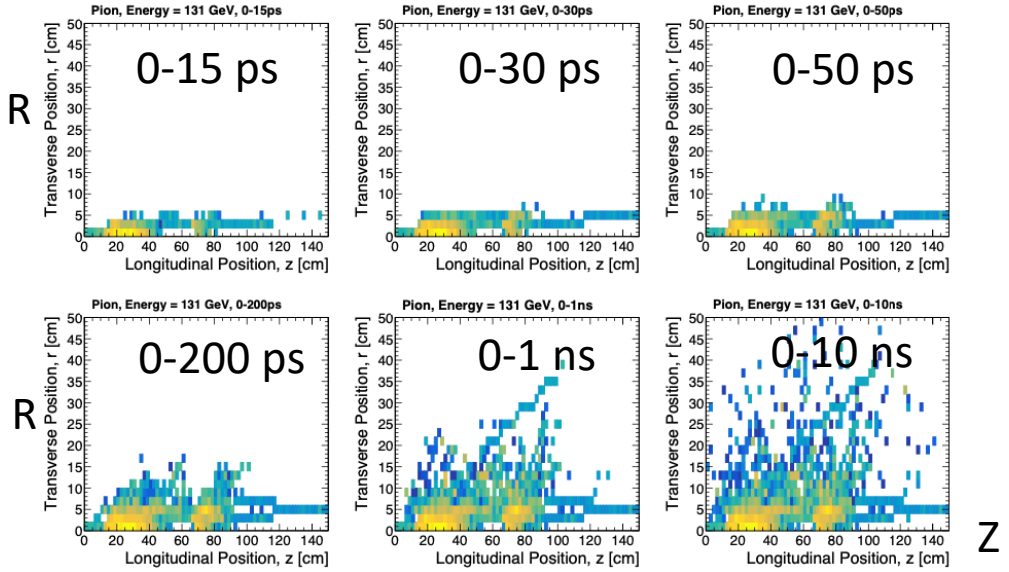
GNN: in: $(E, x, y, z)_{cube}$ base image: 0 - 10 ns
additional: up to 8 images

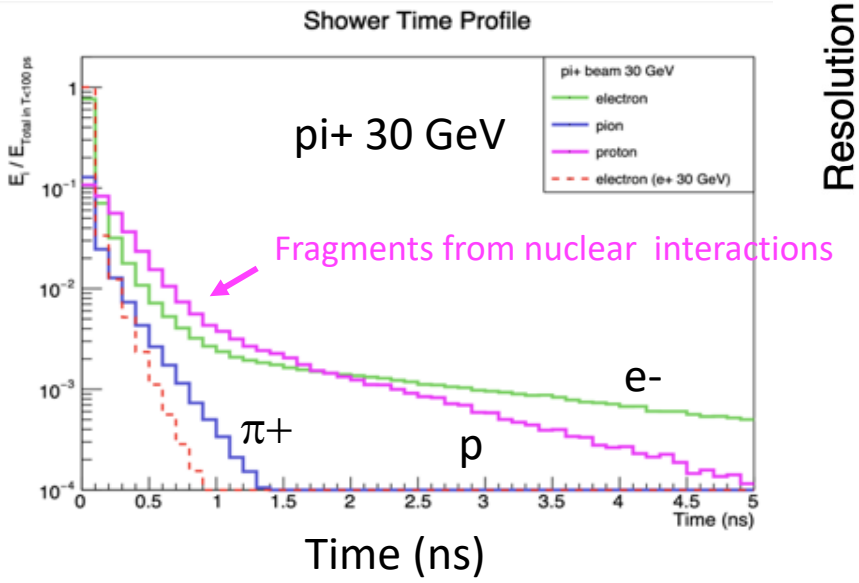
How about time widow → 0 ns ?

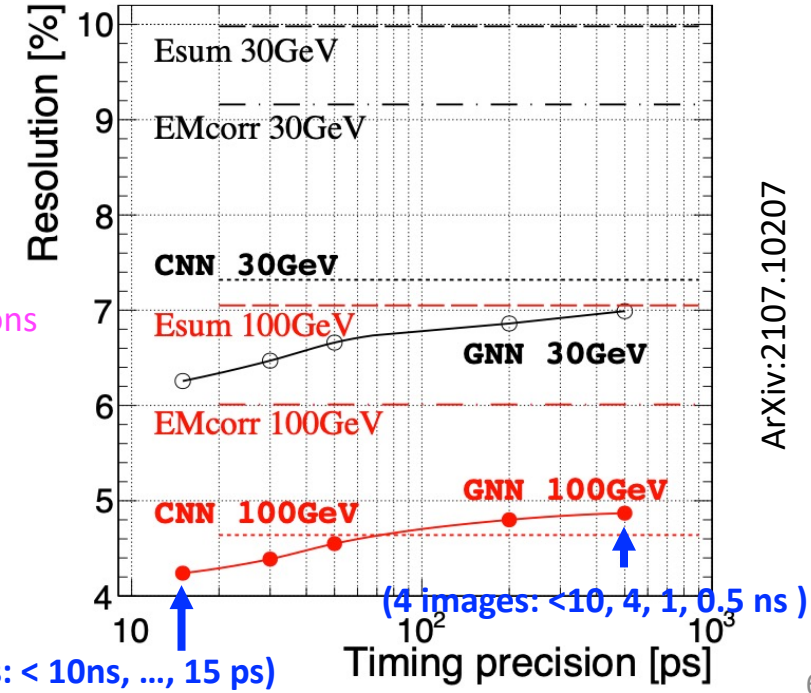
→ Cherenkov Calorimeter

(*) Need more analyses for better understanding of space-time structure of shower at vertex..

Shower images of 131 GeV π+ in R-Z and Time for GNN







Cherenkov Calorimeter

❖ Characteristic of Cherenkov signal in calorimeter

Very fast - < 50ps

Narrow transverse shower profile:

❖ Potential Benefits:

Radiation hard

Quartz fibers and tiles are more radiation resistant than scintillator.

Short signal integration to reduce out-of-time PU effect at collider

10 ns is enough in CMS HF today at LHC with beam spacing 25 ns at 40 MHz.

Longitudinal segmentation with timing of Cherenkov light

page 13 of this slide

Good jet substructure imaging for jetID for boosted W/Z/H/t at multi TeV (FCC-hh)

the narrow transverse show profile may give good jetID capability.

Least production of neutrons to reduce neutron background in Tracker and Muon system

Cu and Fe absorbers produce less neutrons than Pb, W and U absorbers

Good resolution for W/Z/H identification in hadronic mode (FCC-ee)

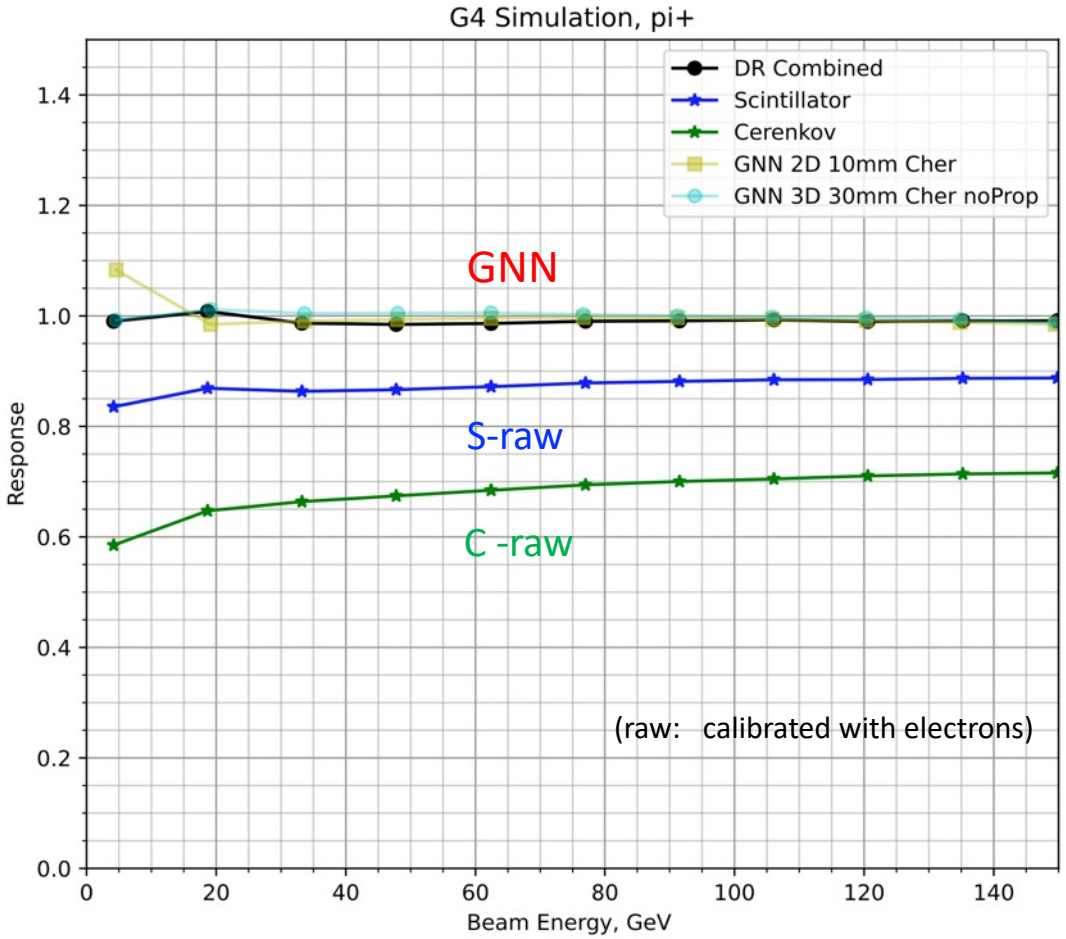
page-10 of this slide

GEANT4 Simulation of Fiber Calorimeter

- Dual Readout Fiber calorimeter
- Cu absorber (2 m deep)
- Transverse segmentation:
  - 1x1 cm^2 for 2D analysis, 3x3 cm^2 for 3D analysis
- Fibers along beam direction
  - 1 mm ϕ fibers, 1.5 mm spacing, 34% packing in volume
  - Cherenkov fibers: n(core) 1.49, n(clad) 1.42, 100 pe/G eV
  - Scintillation fiber: signal production t < 10 ns, 400 pe/GeV
- No SiPM and readout electronics simulation
- G4: FTFP-BERT (and QGSP-BERT)

GNN for Energy Reconstruction

- Dynamic Graph CNN is used in this study [4]:
- EdgeConv - incorporates local neighborhood information as it can be stacked or recurrently applied to learn global shape properties.
- Individual energy deposits are presented as points with their 2D(3D) coordinates and number of captured Cherenkov photons (in time-slices) as attribute(s).
- 3D case uses 50ps binning for the photon arrival time at the SiPM
- GNN is train to reproduce the incident particle energy
- Independent training(700k), validation(100k) and test(300k) samples are used.
- Sample of pions with uniform energy distribution in range of 0.5-150 GeV
- Linearity and resolution are evaluated with gaussian fit



1.0

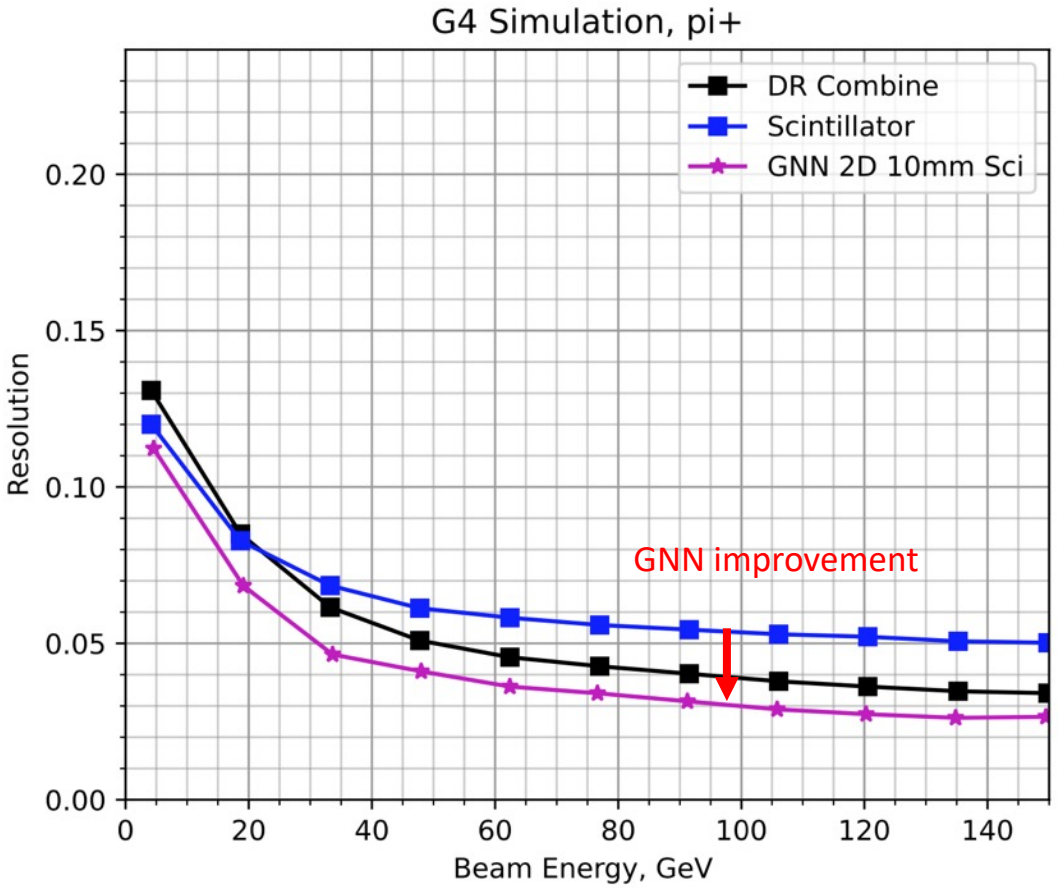
GNN trained with pions keeps the response for electrons = 1.0 (not shown in this plot)

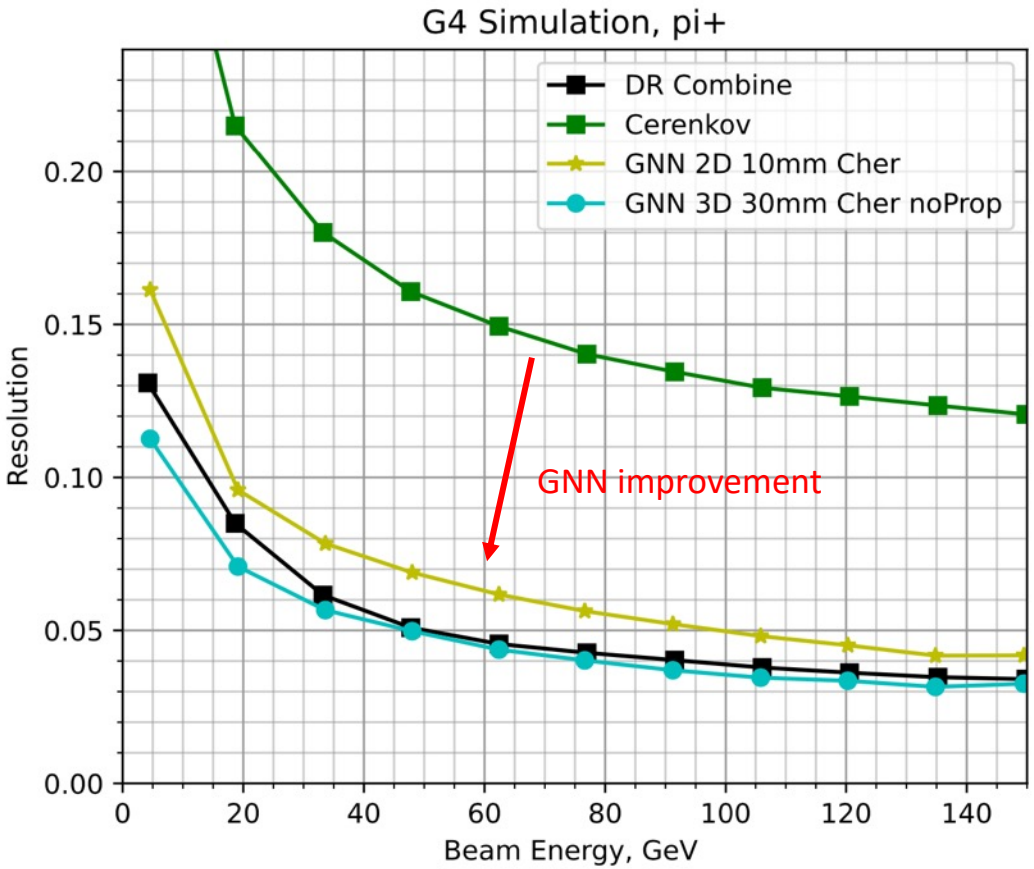
Results: Resolution with GNN

Scintillation Signal Only

Dual Readout (S+C): 31% (+) 0.8 %

Cherenkov Signal Only



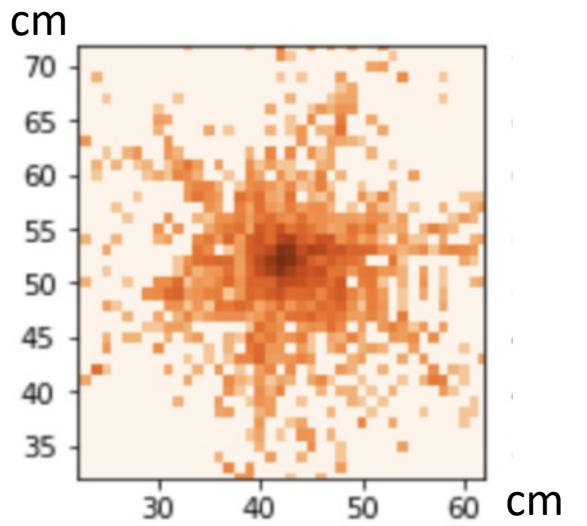


GNN improves the resolution for either cases.

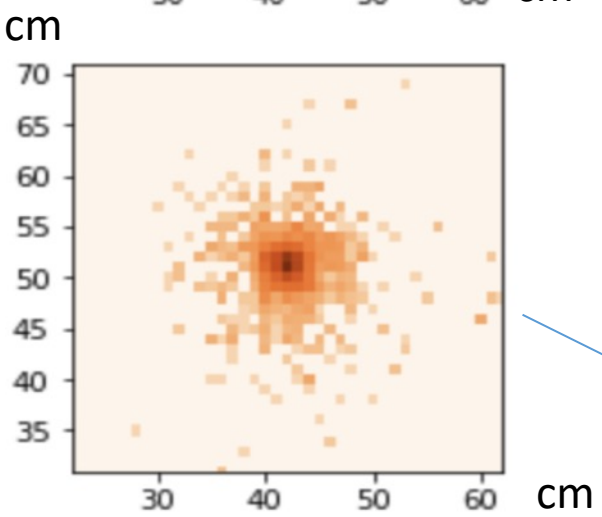
Invisible Energy vs Number of Cherenkov Hits in 2D (x,y)

Hit map of log(E)
In 40 x 40 cm^2 area
(grid 1 x 1 cm^2)

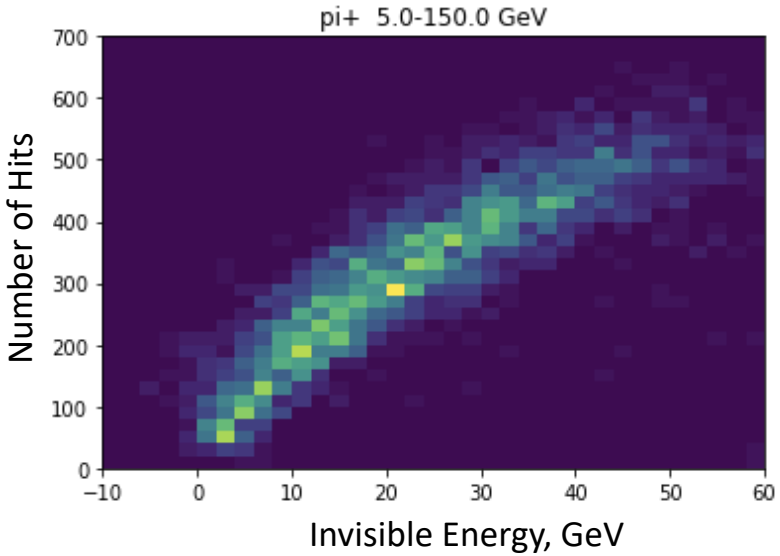
Beam 126 GeV
Inv. energy 53 GeV

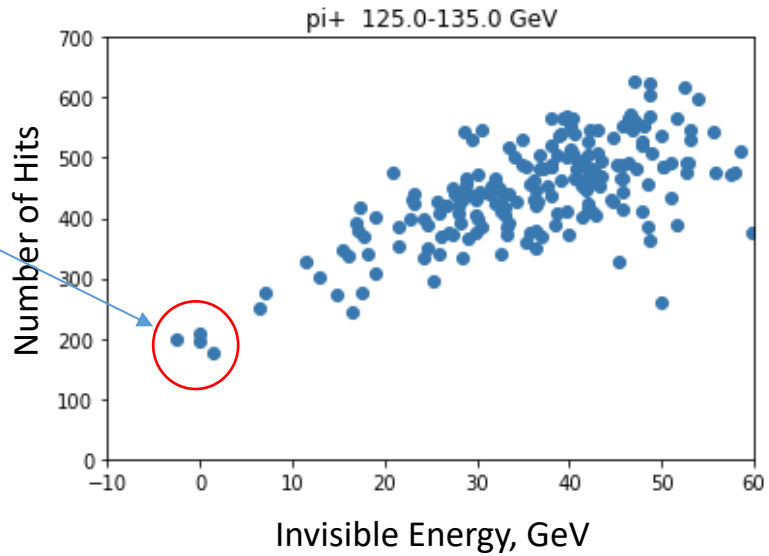


Beam 127 GeV
Inv. energy 1 GeV



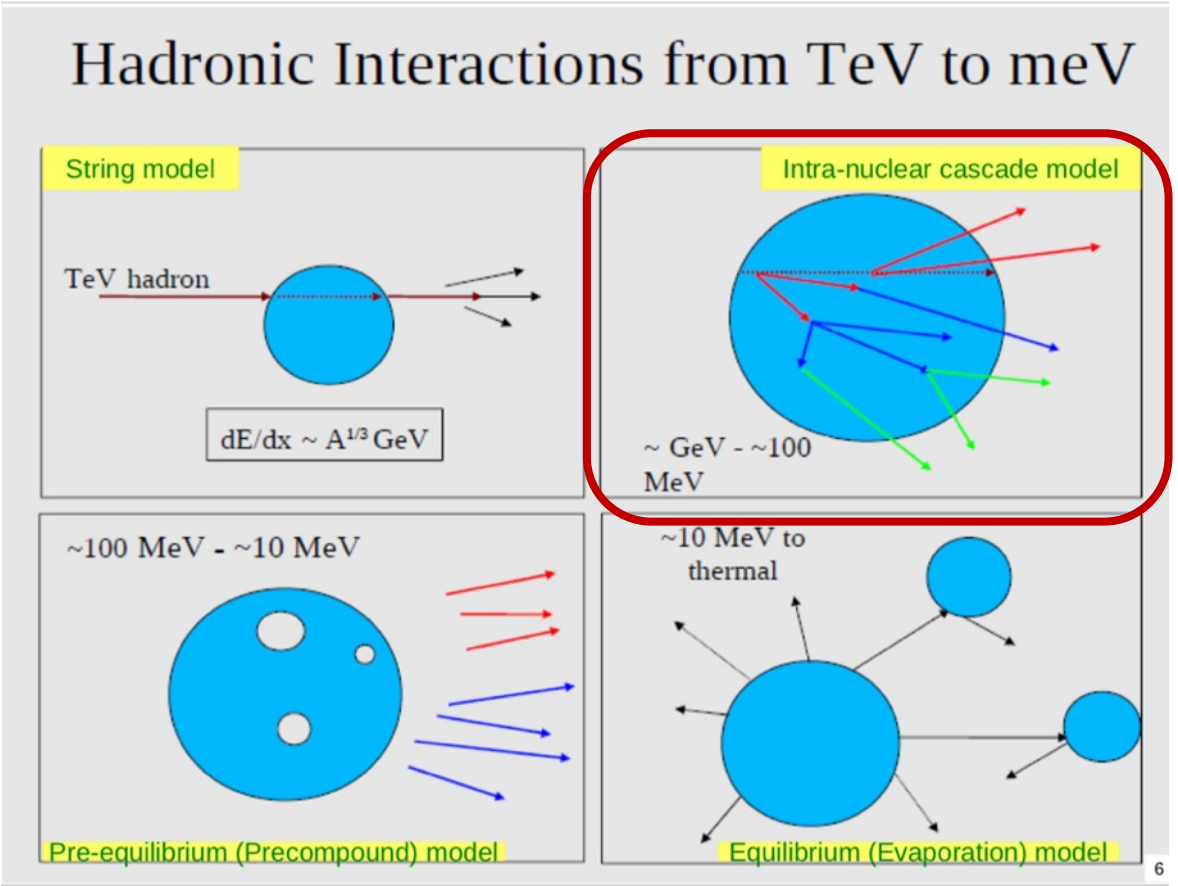
(Invisible Energy = Beam Energy – Cherenkov Signal)





Invisible energy depends on the number of hits in 2D hit map.

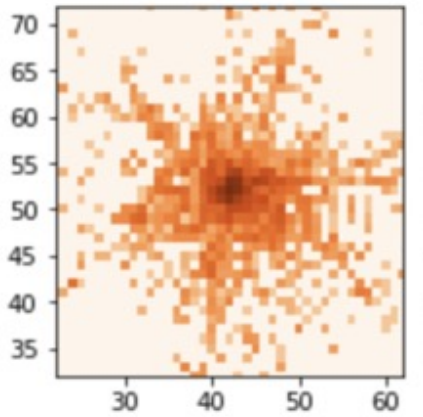
GNN analyzes this heat map (not only the hit counts) for estimation of the lost kinetic energy.



GNN analyzes activities around each vertex in 2D or 3D space, and estimates lost kinetic energy at each vertex.

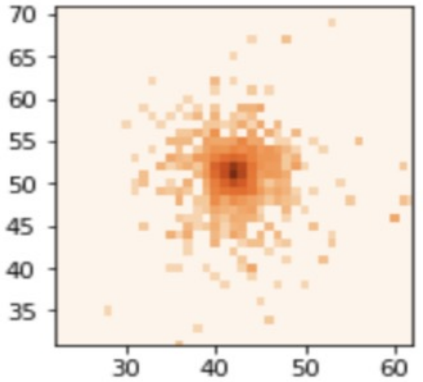
←Fast Components

←Slow Components



Invisible

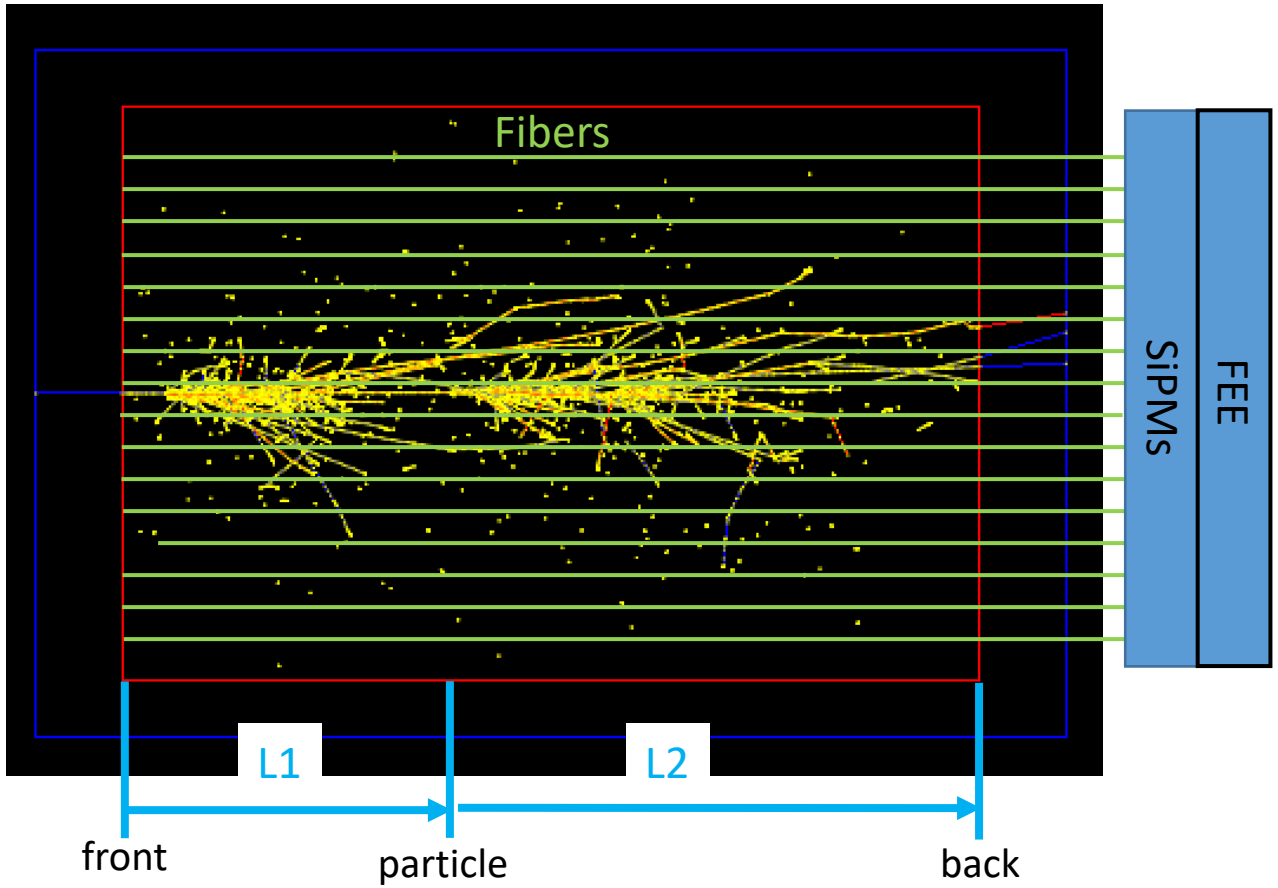
53 GeV



1 GeV

GEANT4 Hadronic Physics, Alberto Robin (2019)
https://indico.cern.ch/event/781244/contributions/3251933/attachments/1782461/2902499/HadronicPhysics.pdf

Cherenkov Fiber Calorimeter: Longitudinal Segmentation with Timing



Signal Time = L1/c + L2/kc,
c = velocity of particle
kc = velocity of light in fiber (k~0.6)

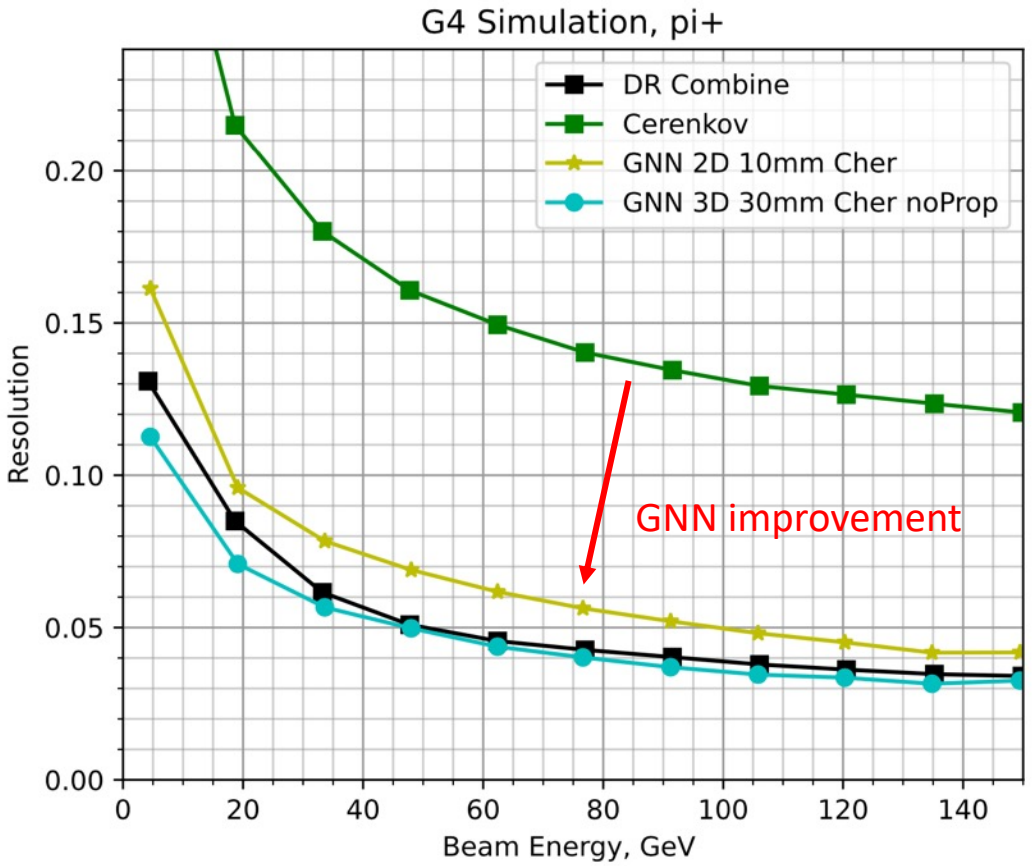
Adil Hussain's talk on Thursday

- 2D readout: Fewer readout channels
- SiPM, readout electronics on backside: Lower radiation environment
- Easier calibration, no need to calibrate in depth
- Longitudinal Segmentation:

Δt=150 ps, corresponding to Δz =7 cm along fibers. (~1/3 λ)

Timing Resolution	σ/E @ 100 GeV
0 ps	3.6 %
100 ps	3.9 %
150 ps	4.0 %
200 ps	4.2 %

Verification of Cherenkov Calorimetry with GNN



Prototype: Cherenkov Calorimeter

Depth:	200 cm
Transverse size:	50 x 50 cm^2
Transverse segmentation:	2x2 cm^2
SiPM readout	

No longitudinal segmentation with timing.

(Parameters need to be optimized.)

Use a prototype in testbeam to verify the improvement of resolution from GREEN to YELLOW.
A prototype calorimeter can be built with today's technology.

Conclusions

- ❖ High granularity Cherenkov calorimeter and ML technique provide very fast and excellent performance to future experiments.
  - Granularity: a Moliere radius (transverse) and 1/3 interaction length (longitudinal)
  - GNN training: Input (E_{Cher}, x, y, z) in cells and target (Ebeam)
- ❖ Longitudinal segmentation with timing of Cherenkov lights will be a cost-effective way to build a calorimeter for 3D GNN energy reconstruction.
  - Fast photo detectors (SiPM) and high-performance readout are required [2][3][5].
- ❖ Prototype calorimeter with 2D readout in beams verifies Cherenkov calorimetry with GNN.
- ❖ Vertex Imaging in space and time domain with NN techniques looks promising. CNN and GNN have been used so far. We continue studying NN technique for hadron calorimetry and develop calorimeter designs that match with the new technique.

References

[1] On the Use of Neural Networks for Energy Reconstruction in High-granularity Calorimeters
N. Akchurin, C. Cowden, J. Damgov, A. Hussain, S. Kunori
arXiv:2017.10207

[2] Value of Timing in Calorimetry
N. Akchurin, C. Cowden, J. Damgov**, A. Hussain**, S. Kunori
CALOR 2022, 19-May-2022, Thursday, 13:00

[3] 3D shower shape reconstruction with the dual-readout calorimeter
Sang Hyun Ko
CALOR 2022, 18-May-2022, Wednesday, 12:20

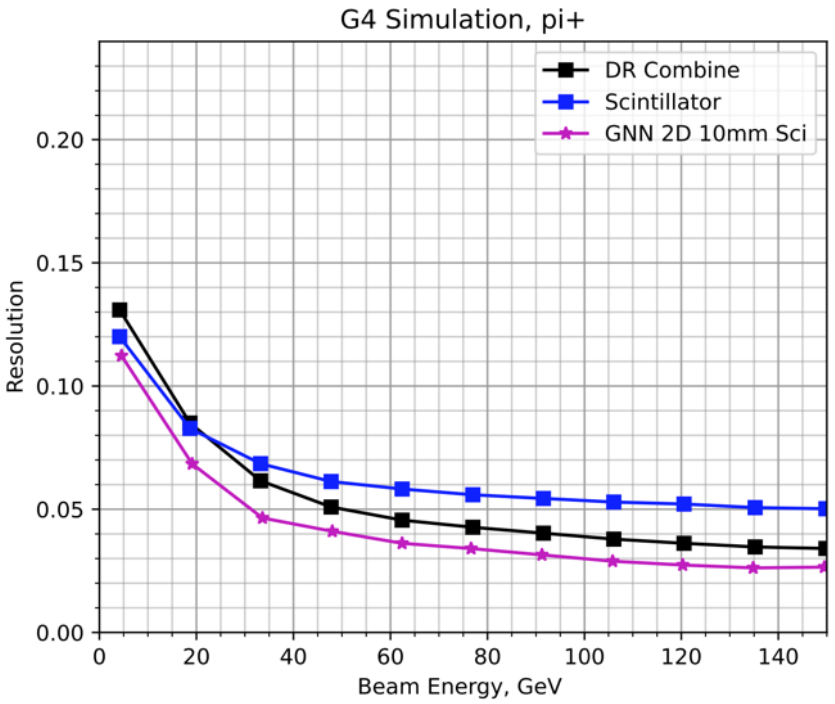
[4] Dynamic Graph CNN for Learning on Point Cloud
Y. Wang, Y. Sun, Z. Liu, S. E. Sarma, M. M. Bronstein, J. M. Solomon
arXiv:1801.07829

[5] Longitudinal Segmentation of Multi-readout Fiber Calorimeters by Timing for 3D Imaging Calorimetry
N. Akchurin, C. Cowden, J. Damgov, A. Hussian, **S. Kunori**
CPAD Instrumentation Frontier Workshop 2021, March 18-22, 2021
https://indico.fnal.gov/event/46746/contributions/210063/

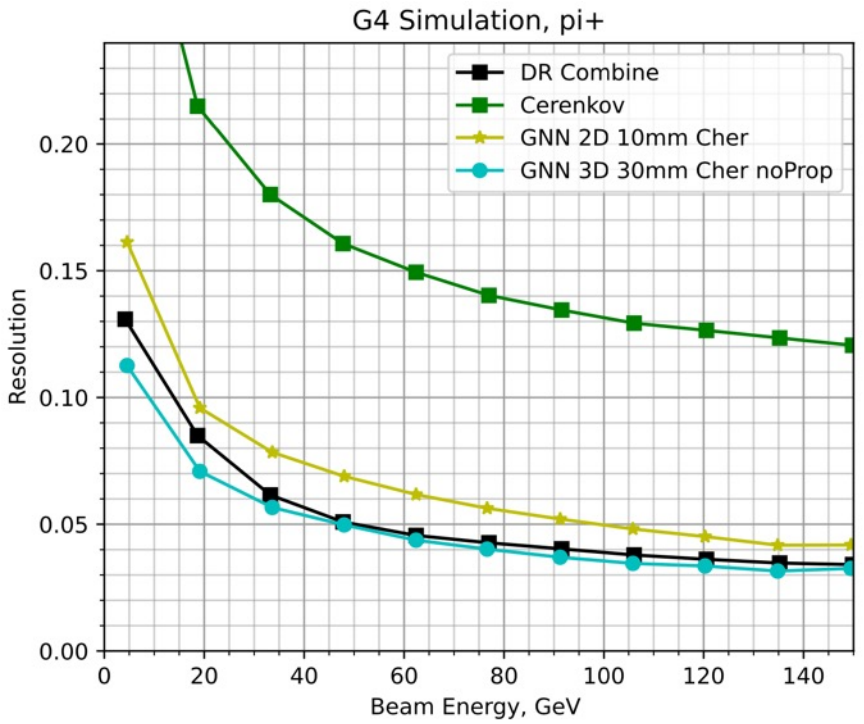
Additional slides

Results: Resolution with GNN

Scintillation Signal Only



Cherenkov Signal Only

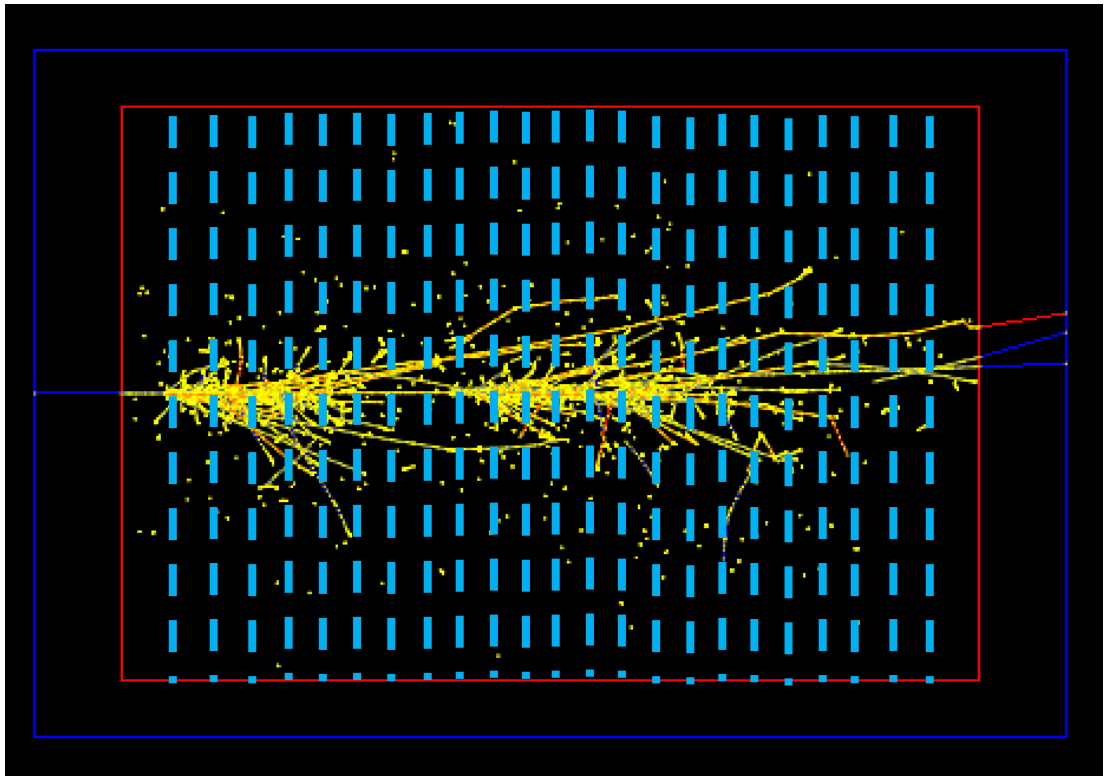


	a	b
Dual Readout	31.0 %	0.8 %
S (raw)	21.8	3.2
S (GNN-2D)	27.3	0.3
C (raw)	62.9	6.9
C (GNN-2D)	34.1	1.6
C (GNN-3D)	24.5	1.3

a: stochastic, b: constant

GNN improves the resolution for either cases.
Same DR curves are shown as reference.

Cherenkov Tile Calorimeter



- ❖ Large channel counts:
  3D Calo: Nx * Ny * Nz
- ❖ Small Cherenkov lights to SiPM:
- ❖ Possibility of good TOF measurement

Concept of Cherenkov Tile Calorimeter

- size: 3x3 cm^2
- finer transverse segmentation with timing

Quantities reflect invisible energy in hadronic showers

(not complete list)

C/S (DR)

vs

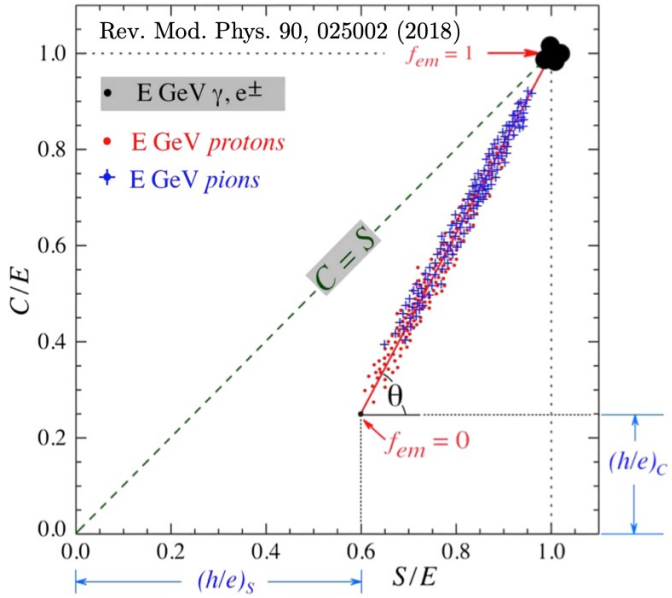
Number of clusters

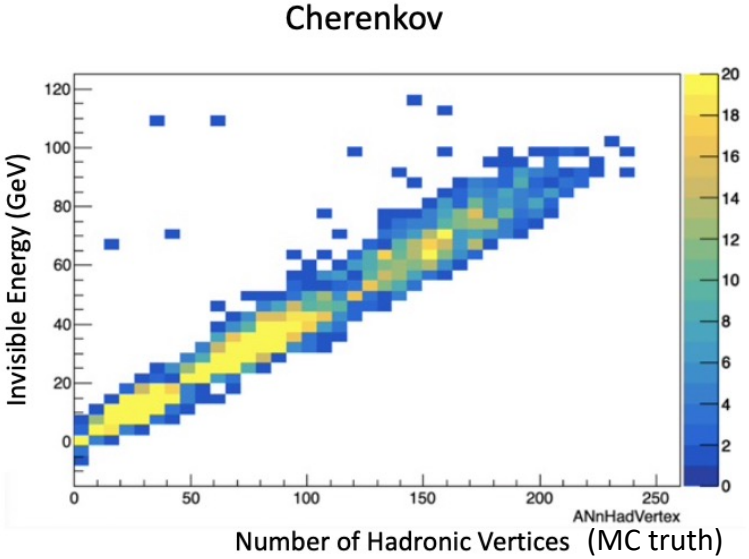
vs

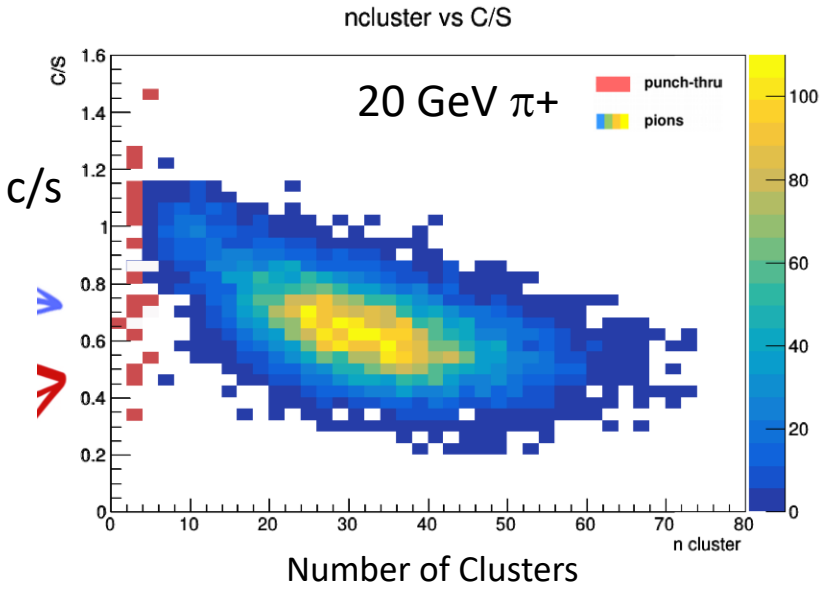
Number of vertices

vs

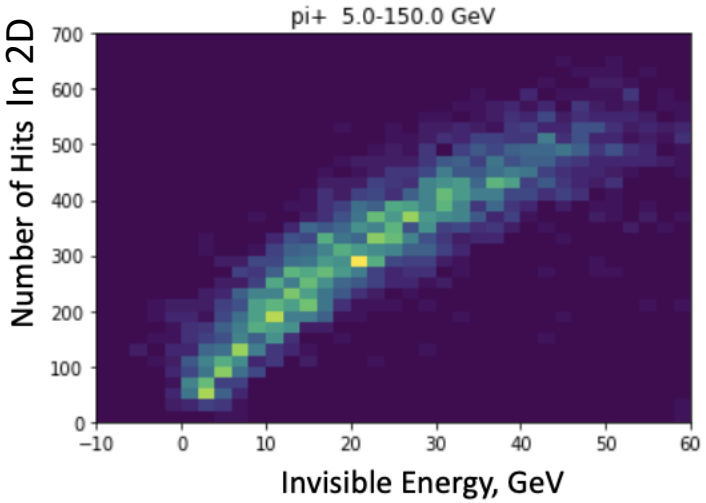
Number of hits in 2D







(Invisible Energy = Beam Energy – Cherenkov Signal)



Sang Hyun Ko, page 2 & 14, on Wednesday [3]

SK's slide: page 3 & 10