Characterization of a PbWO4 crystal using Geant4 simulations for single particle collisions

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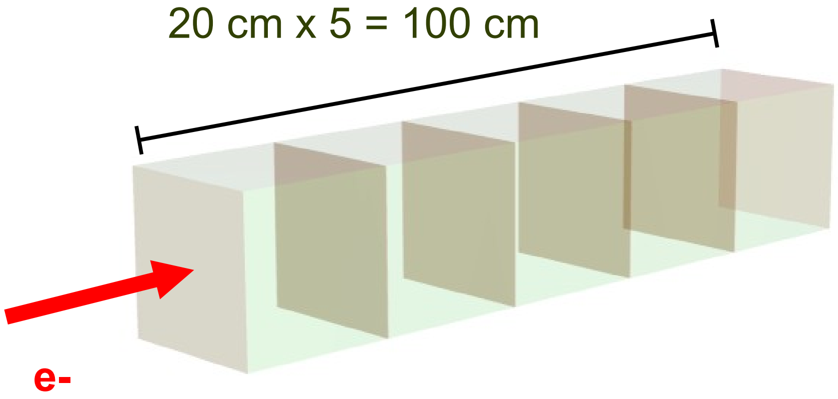
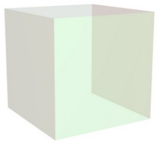
CalVision meeting

Feb 9, 2022

Simulation of a simple HCAL tower using PbWO4





20 cm x 20 cm ~ 21 X_0 ~ 1 λ_I

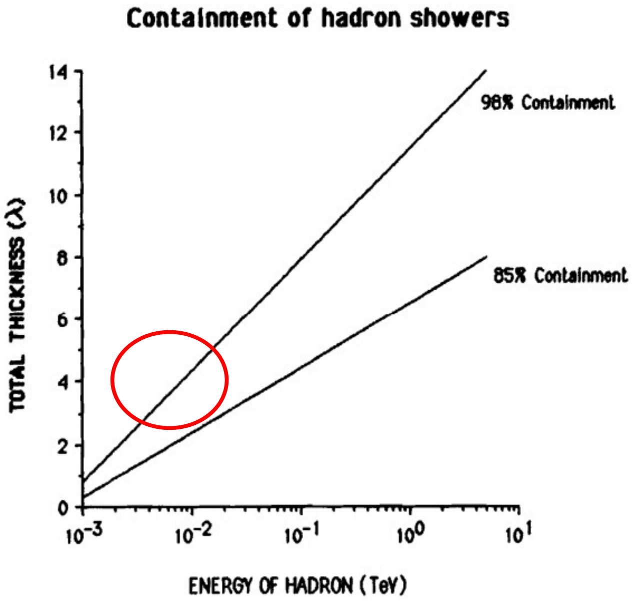
Simulate hits, N(scinitillation), N(cherenov) for particles of different types between 0.5 – 20 GeV

Challenging! 20 GeV particles produces 4 million photons (on average)

21 X0 (typical width for ECAL FCCee)

5 interaction length
~98% containment of hadronic shower for 1 GeV particles

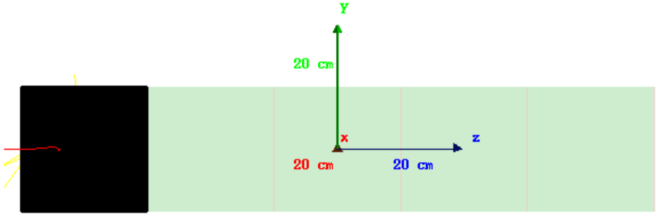
http://lss.fnal.gov/conf/C860623/p355.pdf



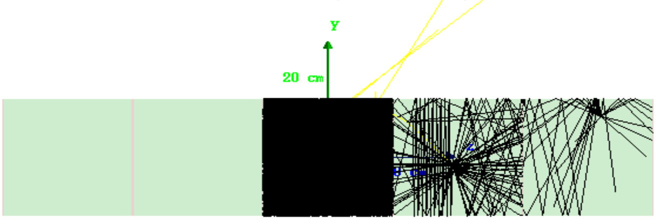
Examples of collisions

- Simulation have been created for 8 particles. 1000 events per particle type
- (e, gamma, pi, pi0, p, proton, neutron, mu, K-)
- Keep optical photons with wavelength 300 nm – 1000 nm
- All files are stored in HepSim: https://atlaswww.hep.anl.gov/hepsim/info.php?item=362

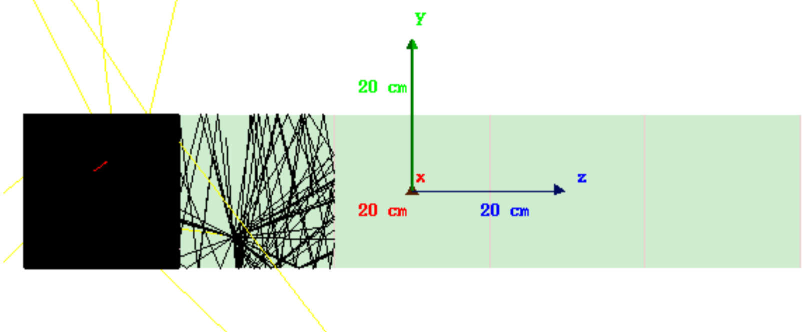
Electron (1 GeV)



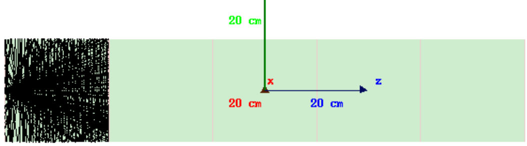
Neutron (5 GeV)



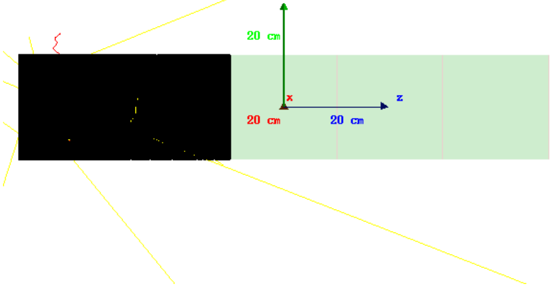
K- 5 GeV



Proton 0.5 GeV (Bragg effect)

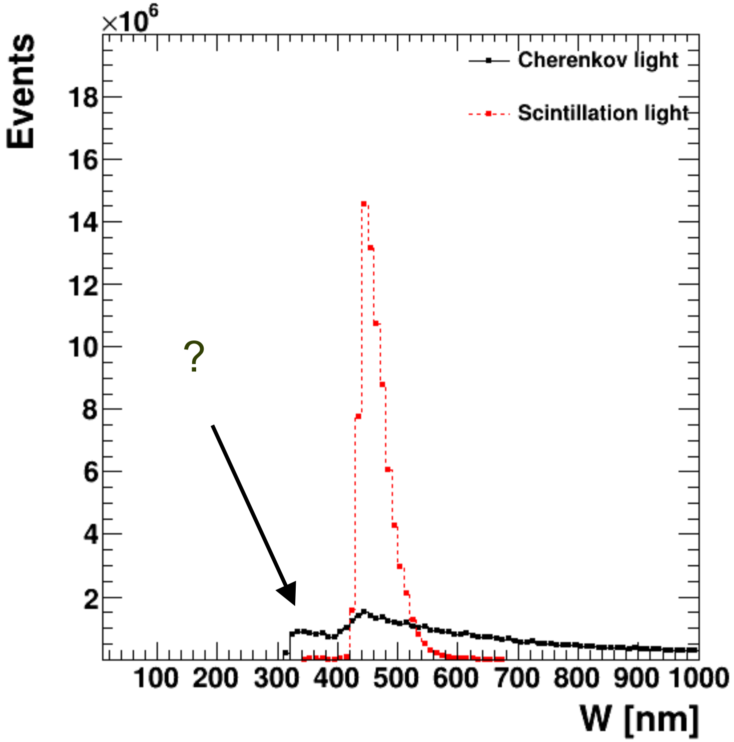


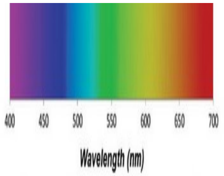
Proton 5 GeV



Photons are shown with black lines
(dark area – too many to show!)

Wavelength for Cherenkov and Scintillation light





Scintillation light peak: ~460 nm

Wavelength for 1000 injected electrons (1 GeV)

Counting of photons in [300-1000] nm range

No any instrumental filter, efficiency of SiPMT etc.

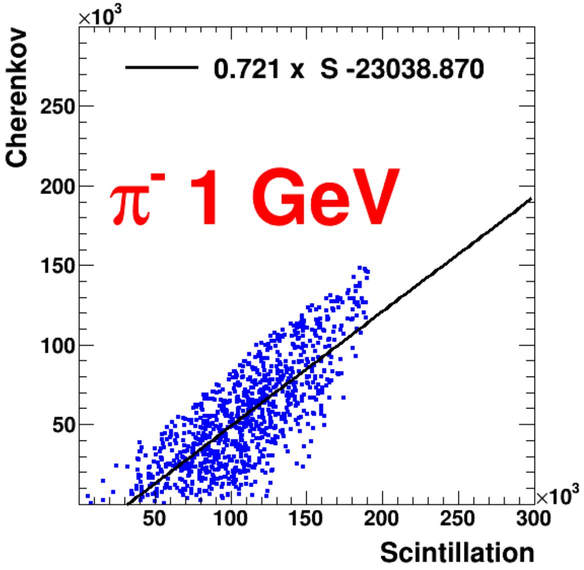
“**Luminosity per MeV**” calculated as the average number of photons per MeV (for e-):

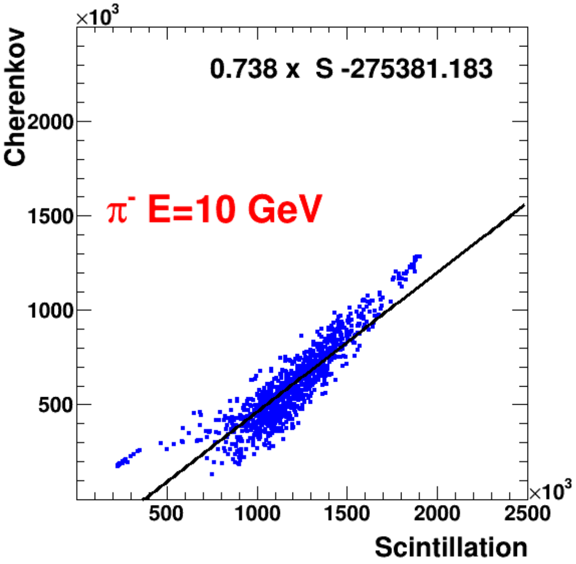
Scintillation light:
193 + -1 per MeV
Agrees with expectations for PbWO4
see http://scintillator.lbl.gov/

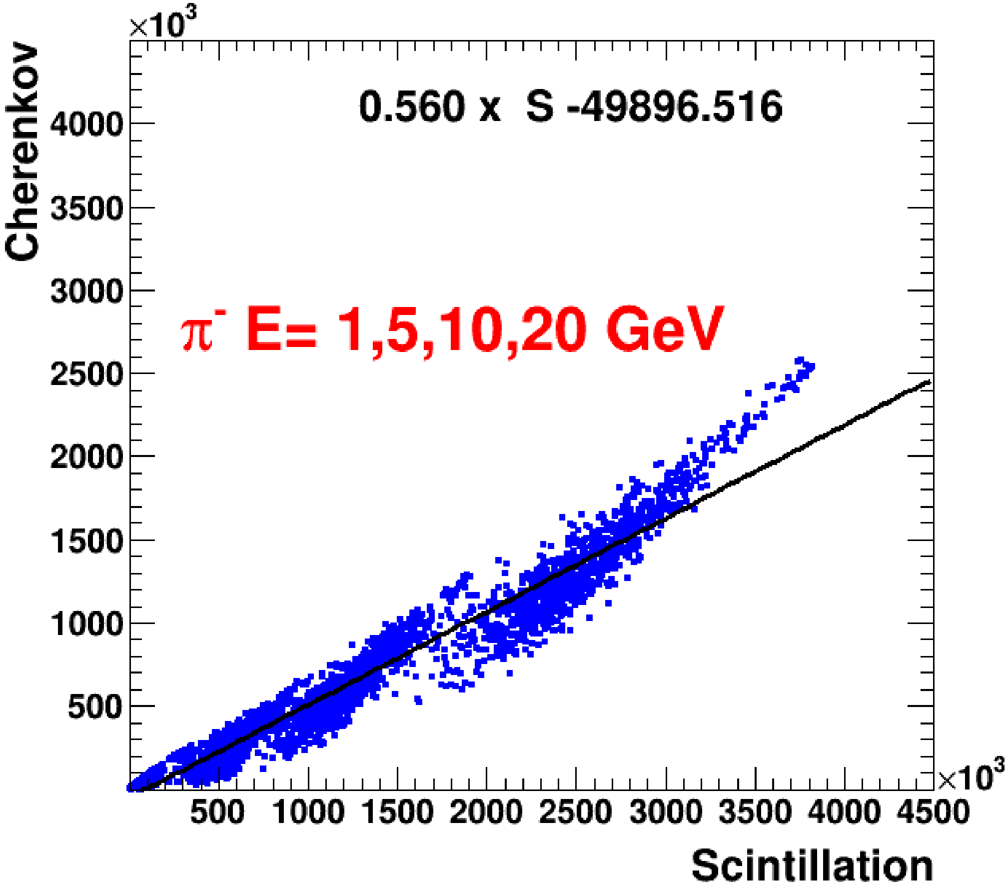
Cherenkov light:
127 +- 3 per MeV

Problem:
Expect Cherenkov peak below 300 nm.
The code has 200 nm cut, but optical properties are tabulated starting from 300 nm

Scintillation light vs Cherenkov

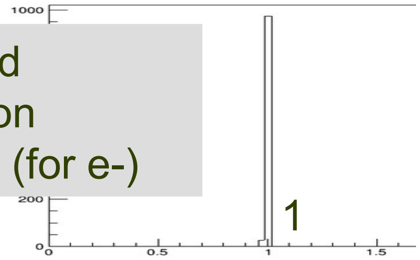






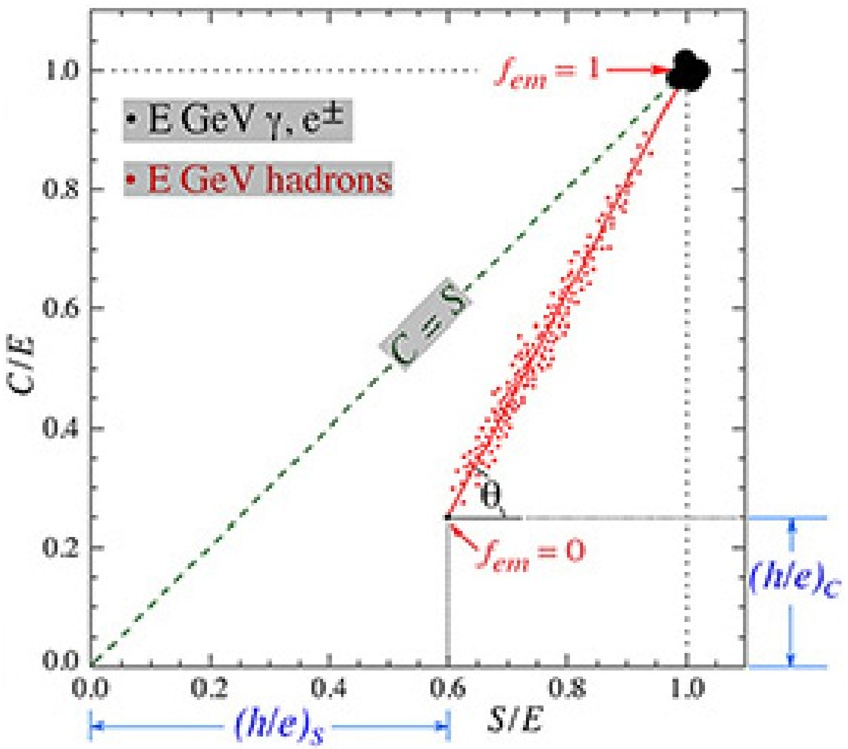
Calibrated Scintillation vs Cherenkov

- calibrate Scintillation and Cherenkov light to electrons:
N(optical photons)/E(beam) =1 using 20 GeV electrons



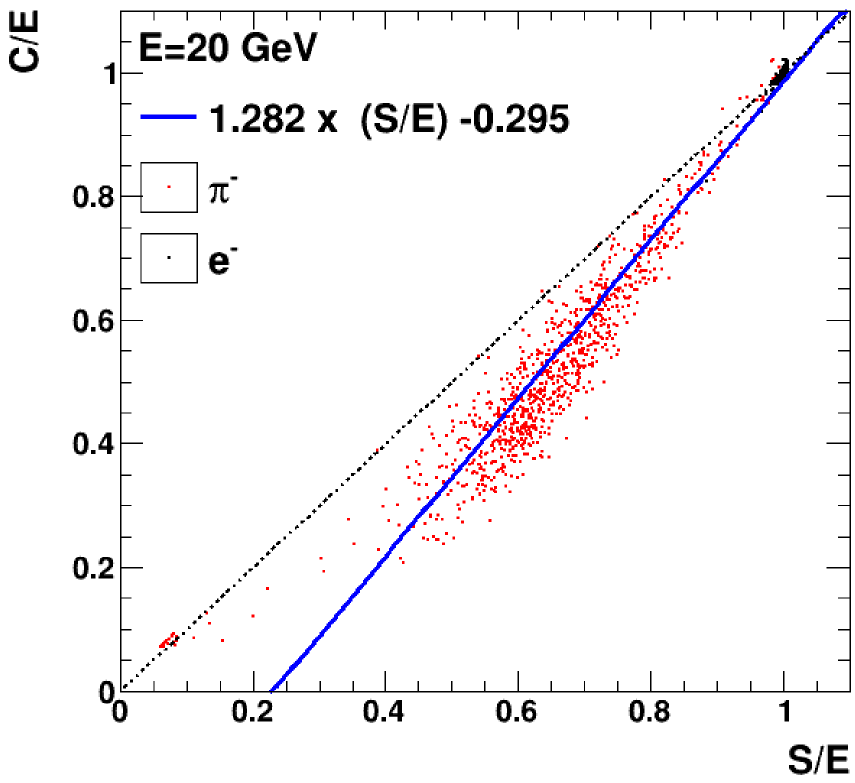
Calibrated scintillation light to 1 (for e-)

DREAM: 200 GeV



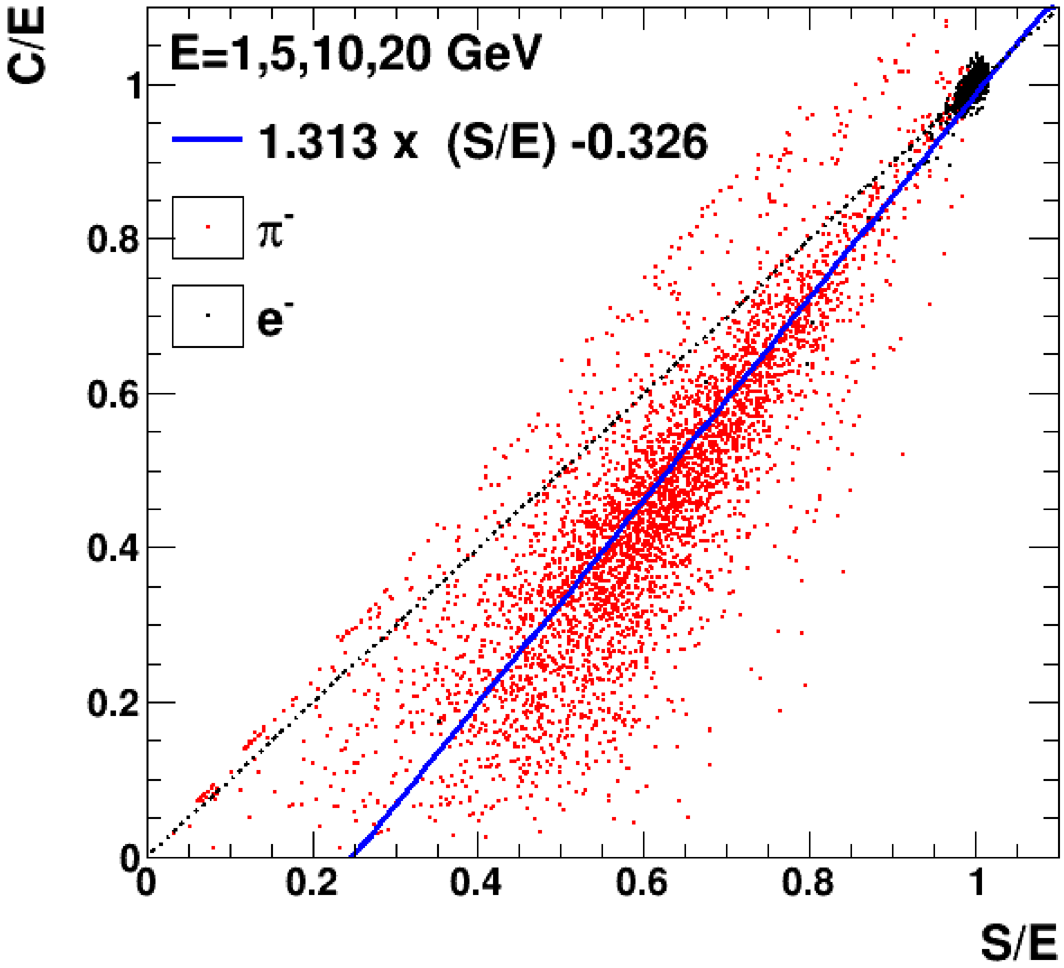
Dual-Readout Calorimetry
Sehwook Lee, Michele Livan, Richard Wigmans
Fig. 8: https://arxiv.org/pdf/1712.05494.pdf

20 GeV simulations



Fit includes electrons to force the fit to cross (1,1)

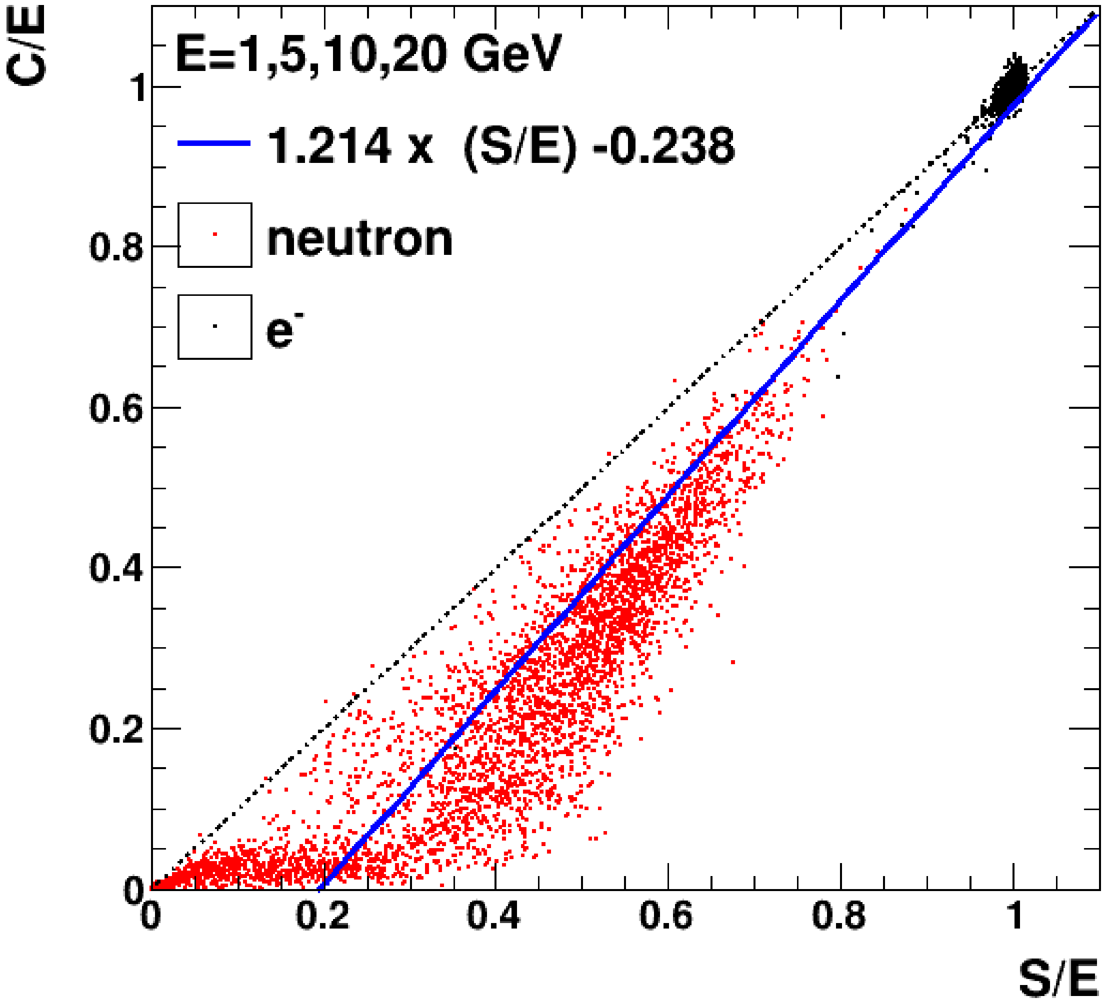
Pions: Scintillation light vs Cherenkov after calibration to electrons (all energies)



All energies from 1 to 20 GeV

1000 events per energy

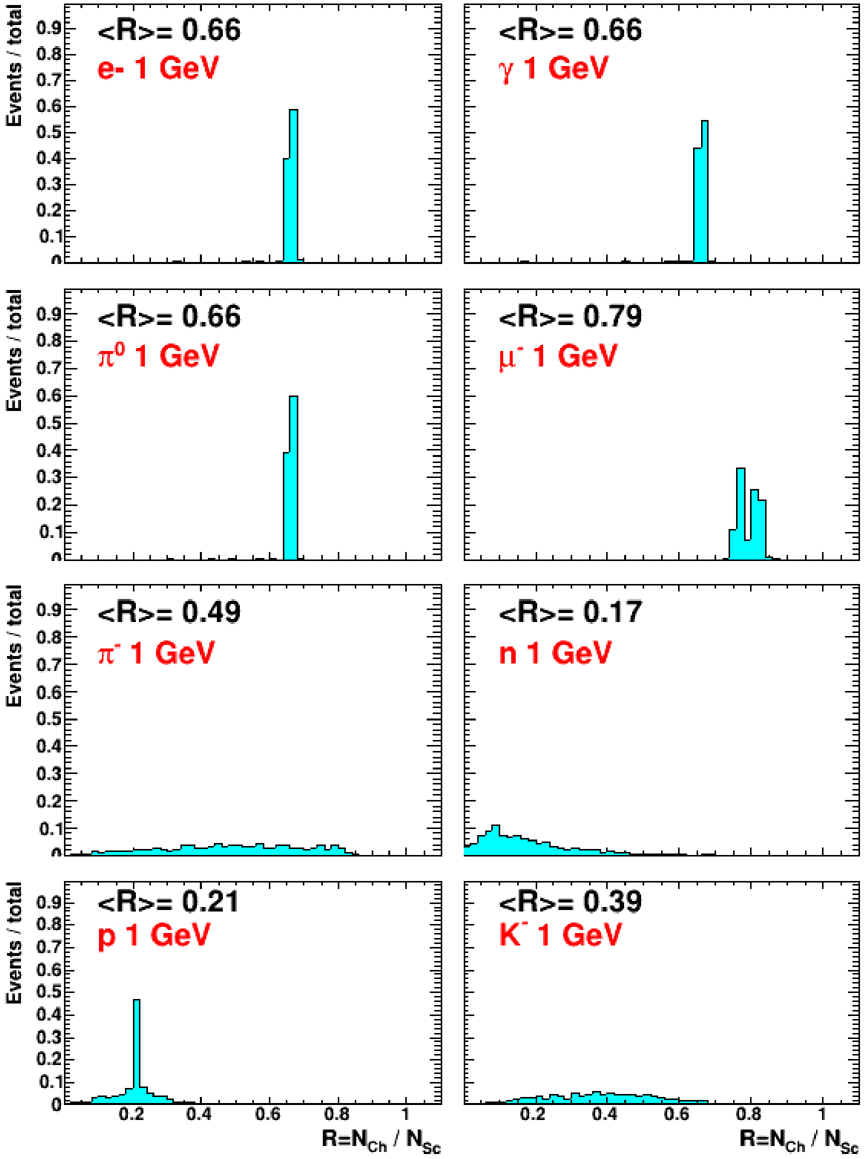
Neutrons: Scintillation light vs Cherenkov after calibration



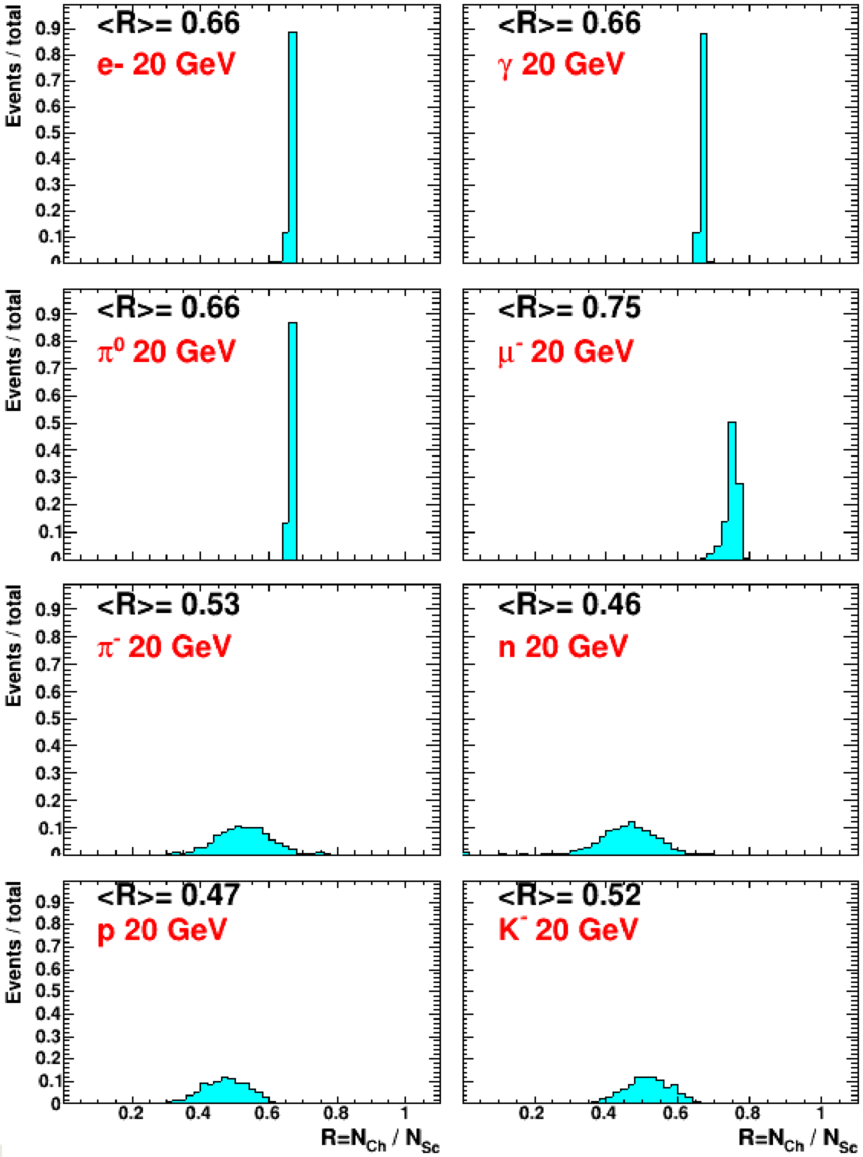
Neurons have many events with almost no Cherenkov light

Ratio of Cherenkov / Scinitillation photons

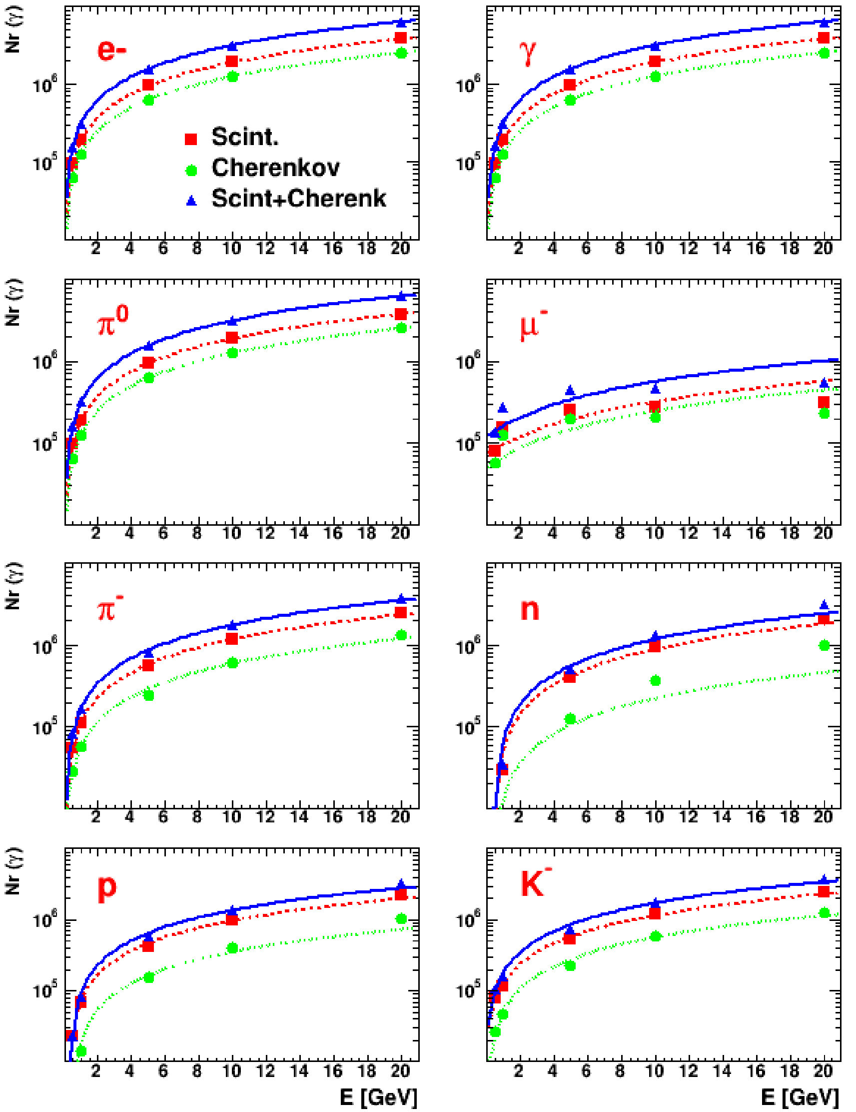
1 GeV



20 GeV



Rate of optical photons



Rate of Scintillation+Cherenkov
Fit with straight lines
e-: **191049 x E - 385**

h/e = 0.58 for Scintillation light
h/e = 0.39 for Cherenkov light
(calculated using e- and **pi-** at 5 GeV)

h/e = 0.45 for Scintillation light
h/e = 0.25 for Cherenkov light
(calculated using e- and **protons** at 5 GeV)

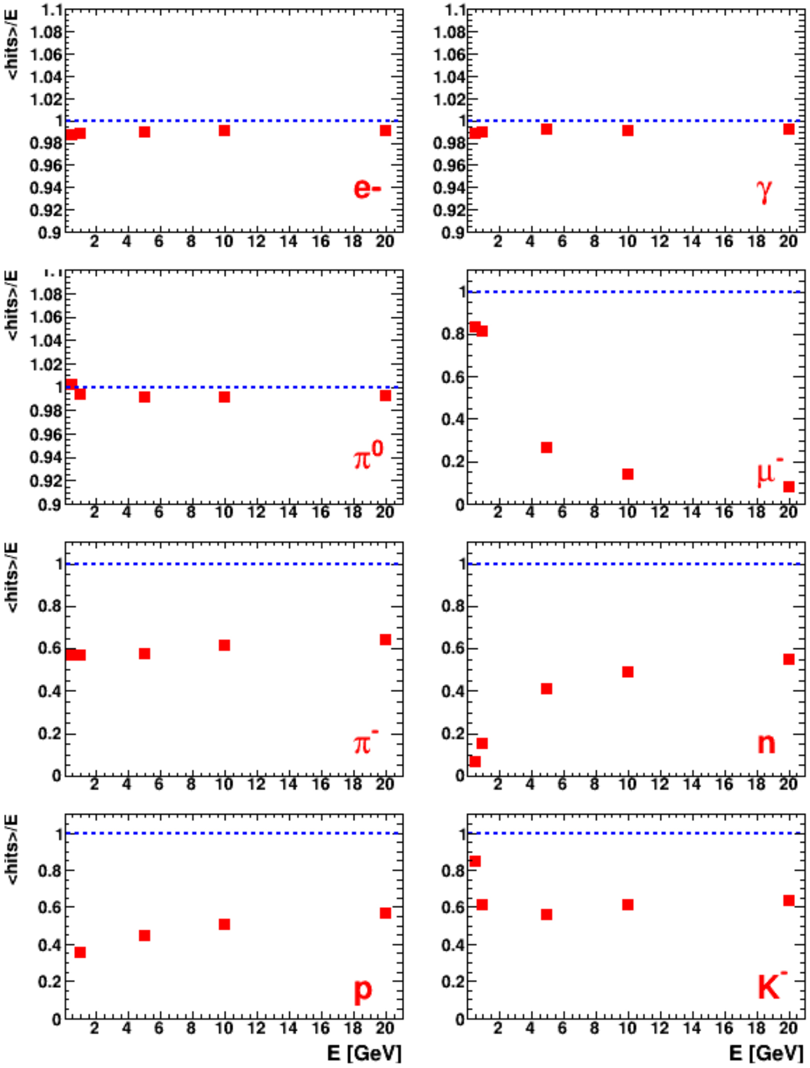
$$\chi = \frac{1-\eta_S}{1-\eta_C} = 0.68$$

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

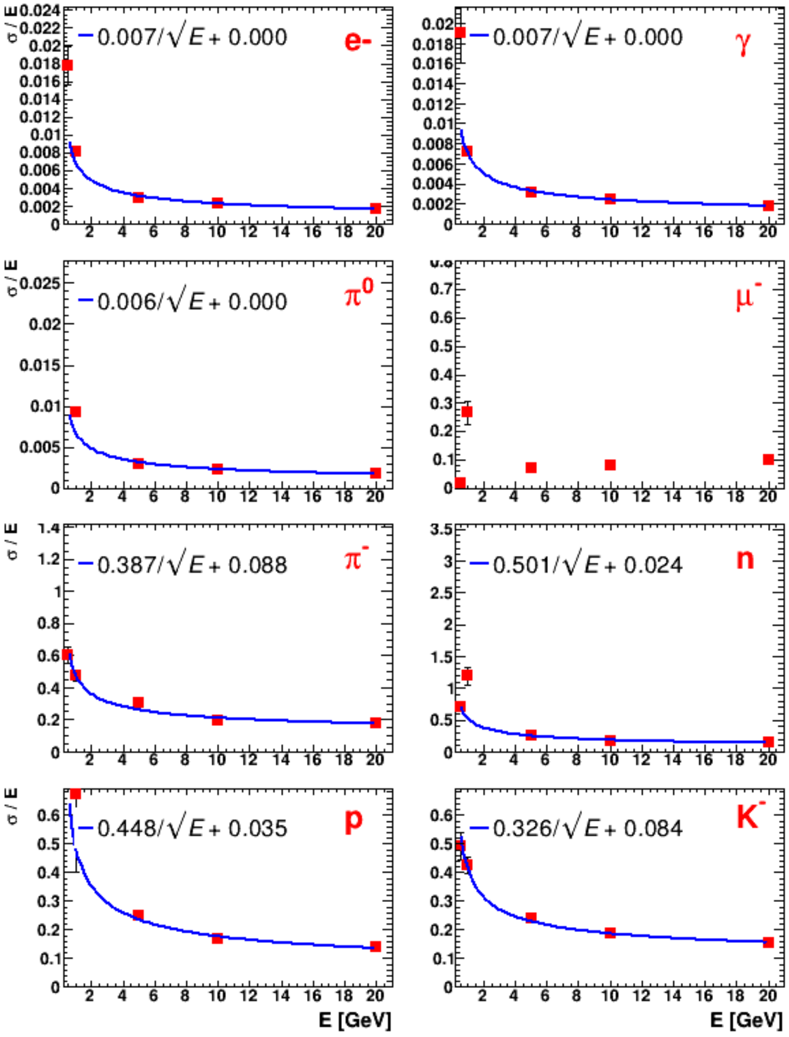
← correction formula

https://arxiv.org/pdf/1712.05494.pdf

Response and energy resolution of hits



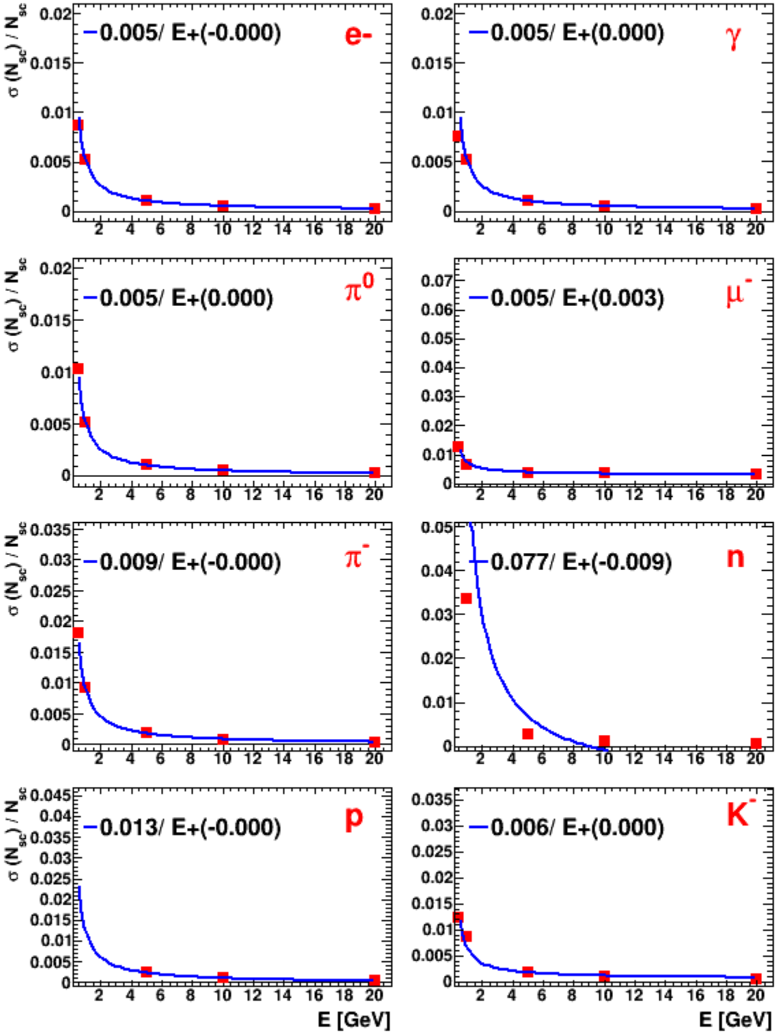
Response



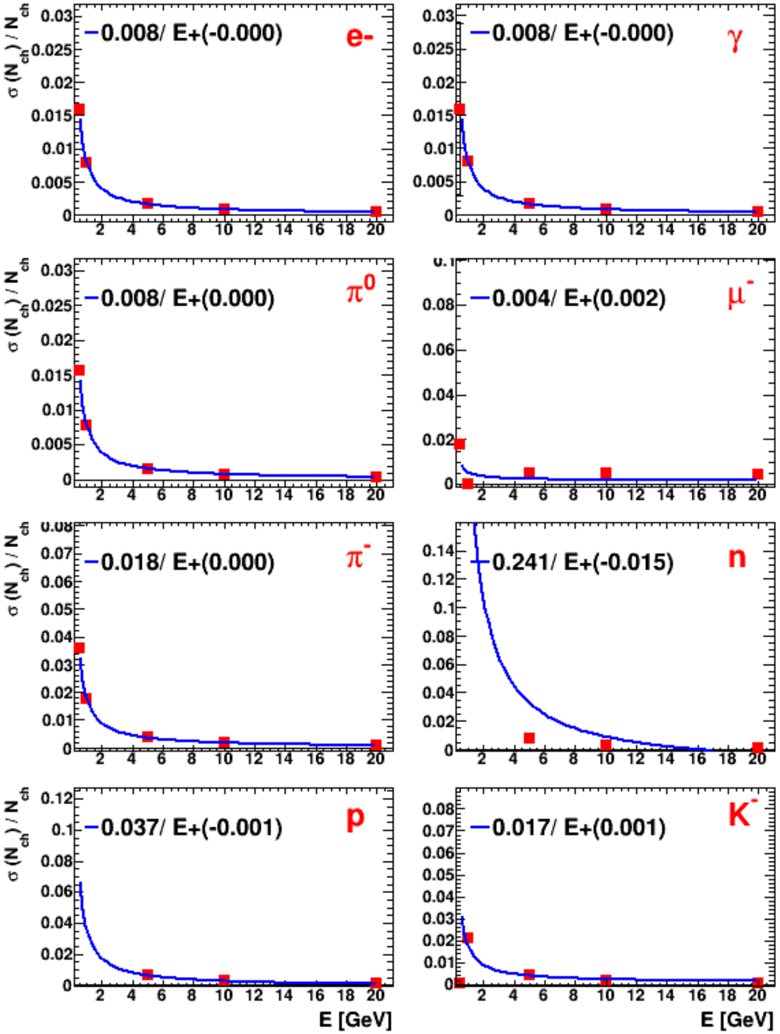
Resolution

Resolution of Scintillation and Cherenkov γ

Scintillation



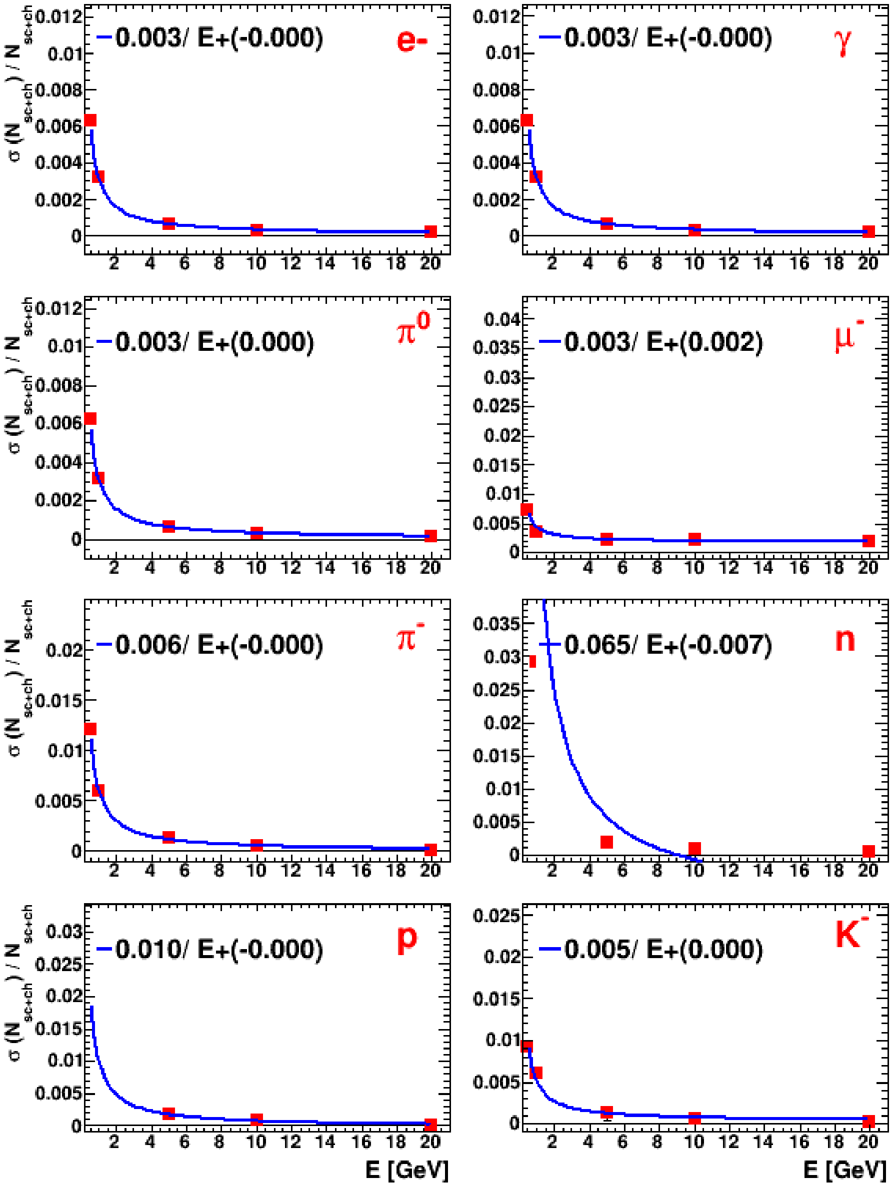
Cherenkov

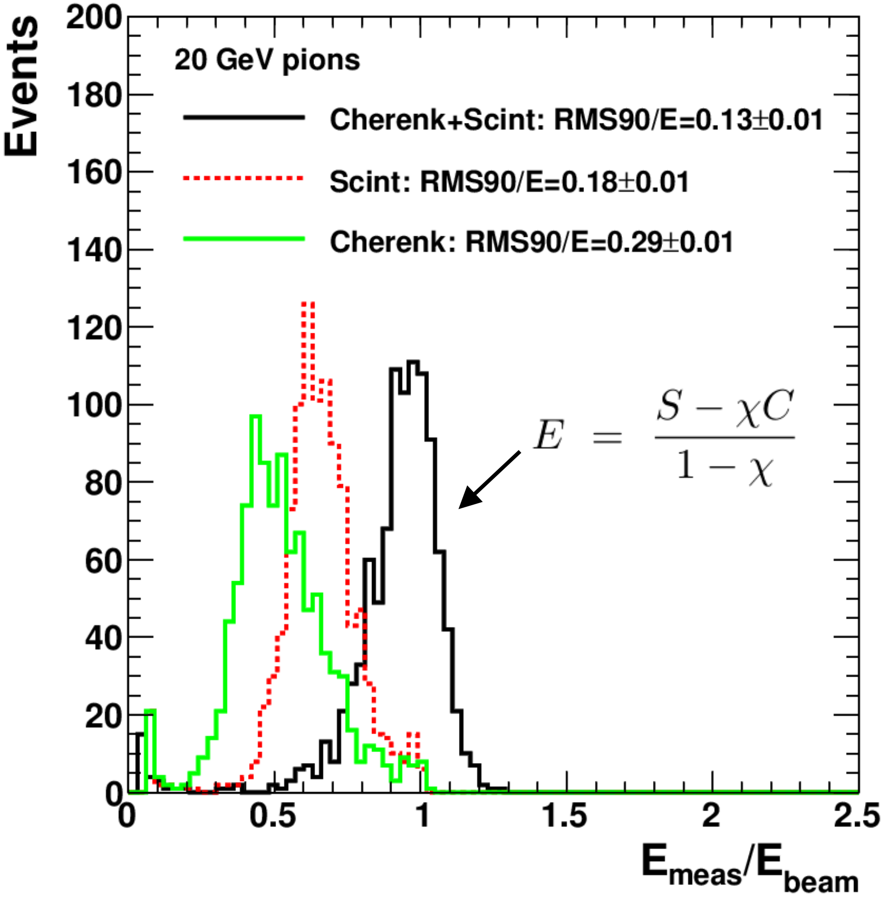


Cherenkov light has larger relative resolution (especially for hadrons)

1/E describes the light better than 1/sqrt(E)

Resolution of Scintillation + Cherenkov photons

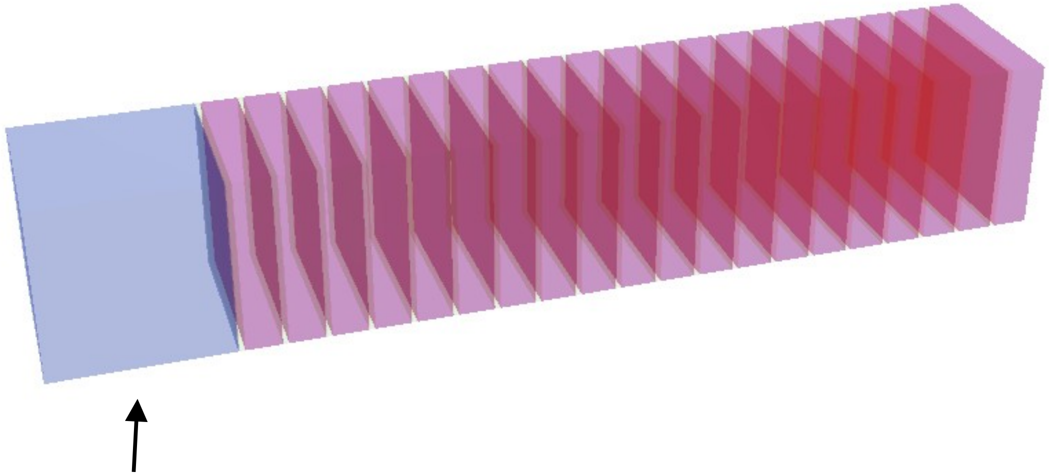




Some improvements
in the resolution

Simplified sampling HCAL

What about sampling option?



Place for ECAL
("vacuum")

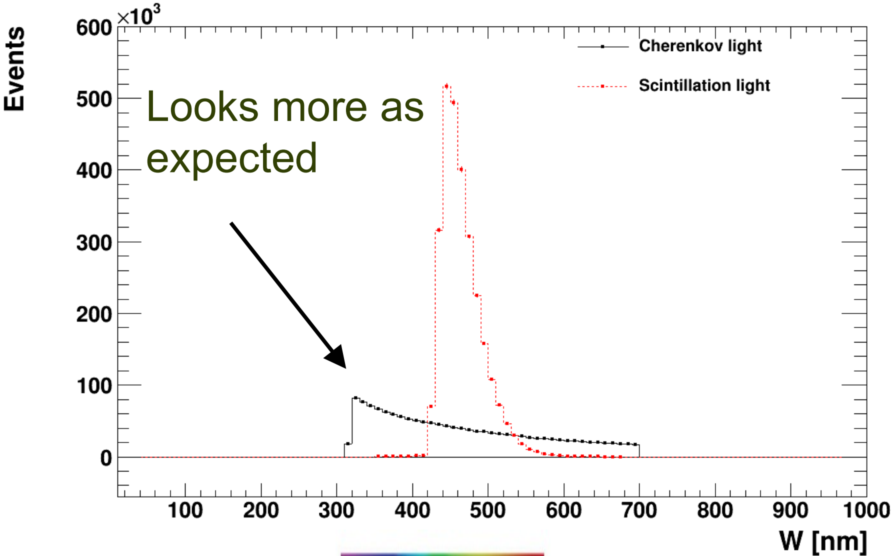
20 layers
→ 5.2 interaction lengths

Each layer has

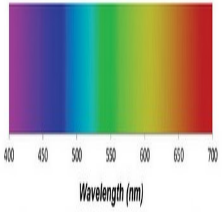
- *4 cm steel (red color)*
- *0.5 cm of PbWO4 surrounded by kill media*
- *Sampling fraction ~0.11*

- Geant4 is about a factor 10 faster than for the solid crystals since photons are created in the thin active layers
- "killing" optical photons after simulation may not be needed

Wavelength for Cherenkov and Scintillation light



Looks more as expected



Counting of photons in [300-700] nm range

No any instrumental filter, efficiency of SiPMT etc.

“**Luminosity per MeV**” calculated as the average number of photons per MeV (for e-):

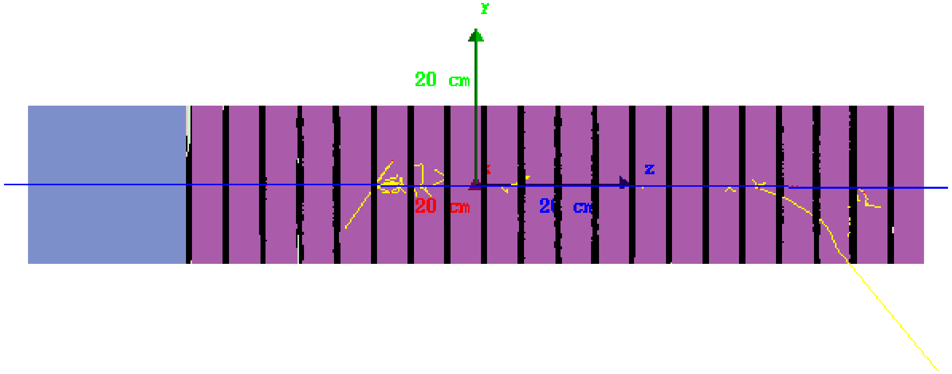
Scintillation light:
193 + -1 per MeV
Agrees with expectations for PbWO4
see http://scintillator.lbl.gov/

Scintillation light peak: ~460 nm

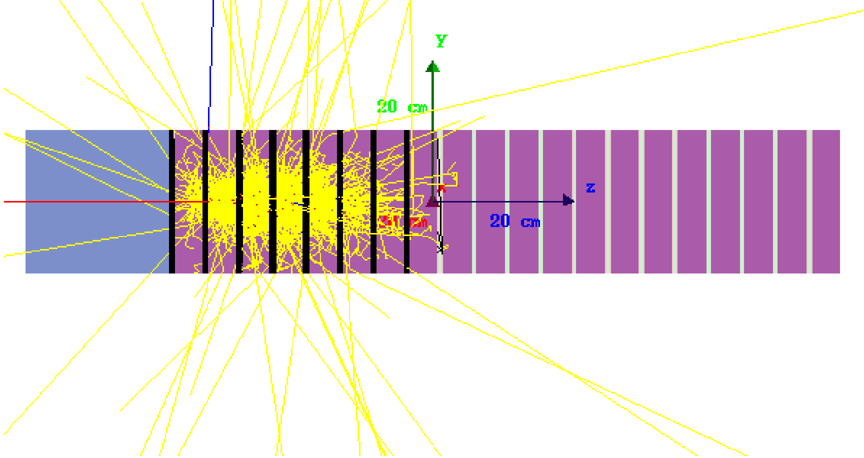
Problem: Cherenkov cannot be generated below 300 since optical properties are not defined

Simplified sampling HCAL: Examples

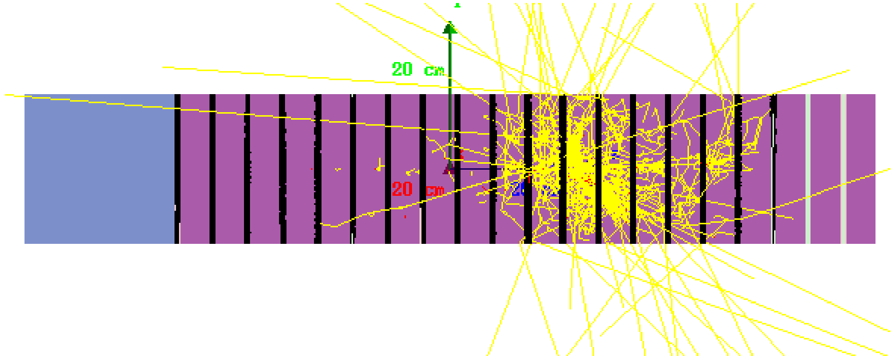
Muons 10 GeV



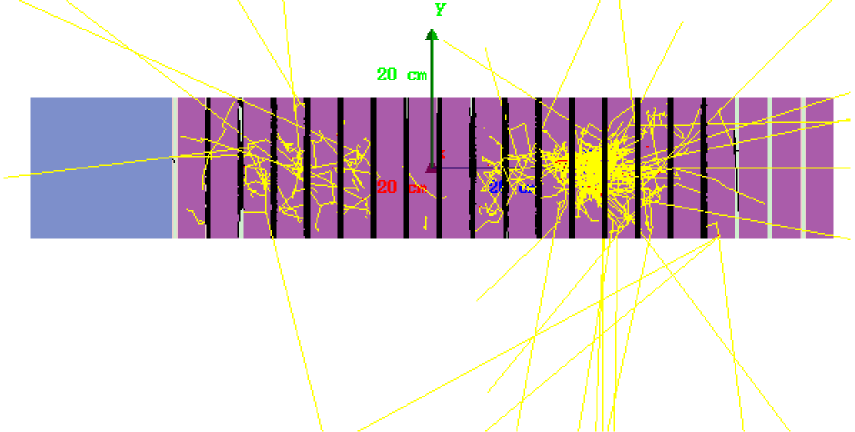
Electron 10 GeV



Pion 10 GeV



Neutron 10 GeV

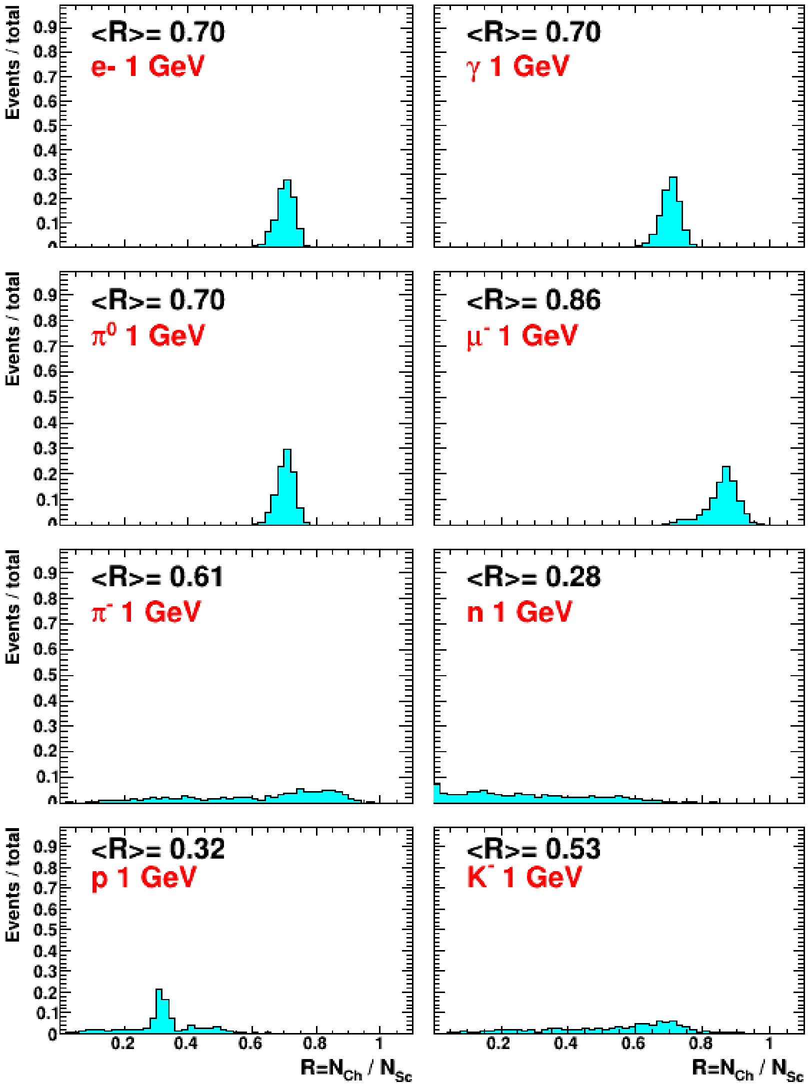


Optical photons are shown with black lines
(dark area – too many to show!)

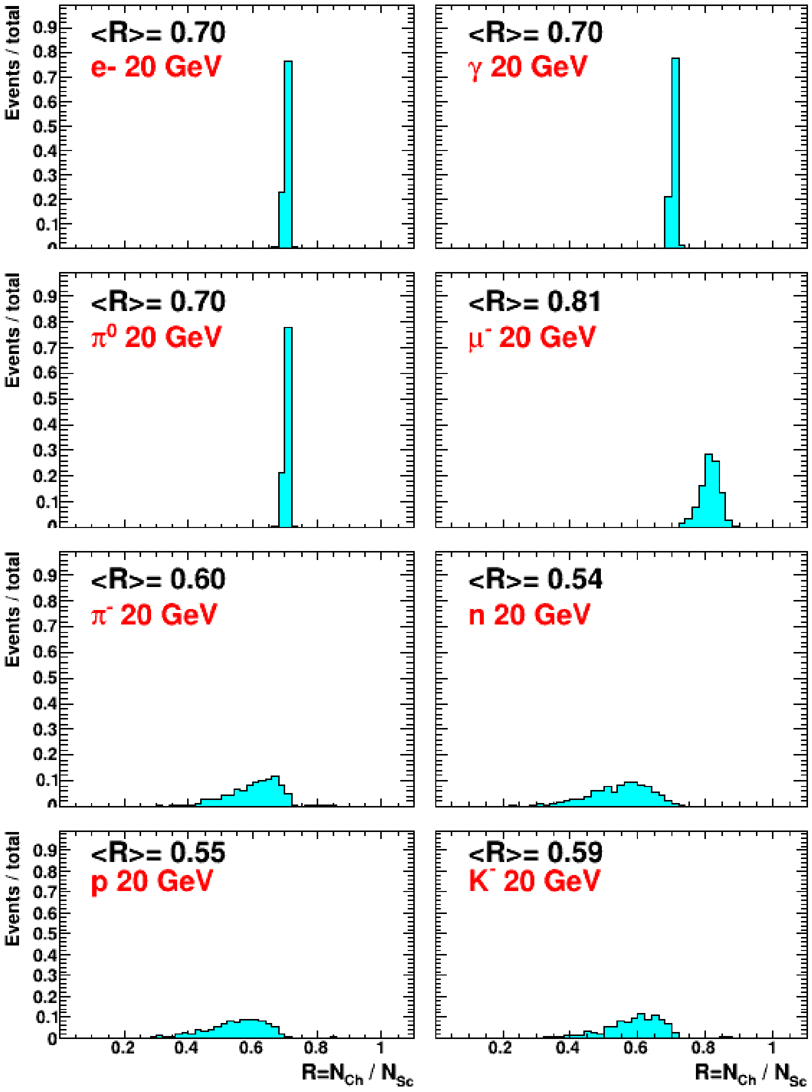
Yellow: Photons

Simplified sampling HCAL: cherenkov/scintillation

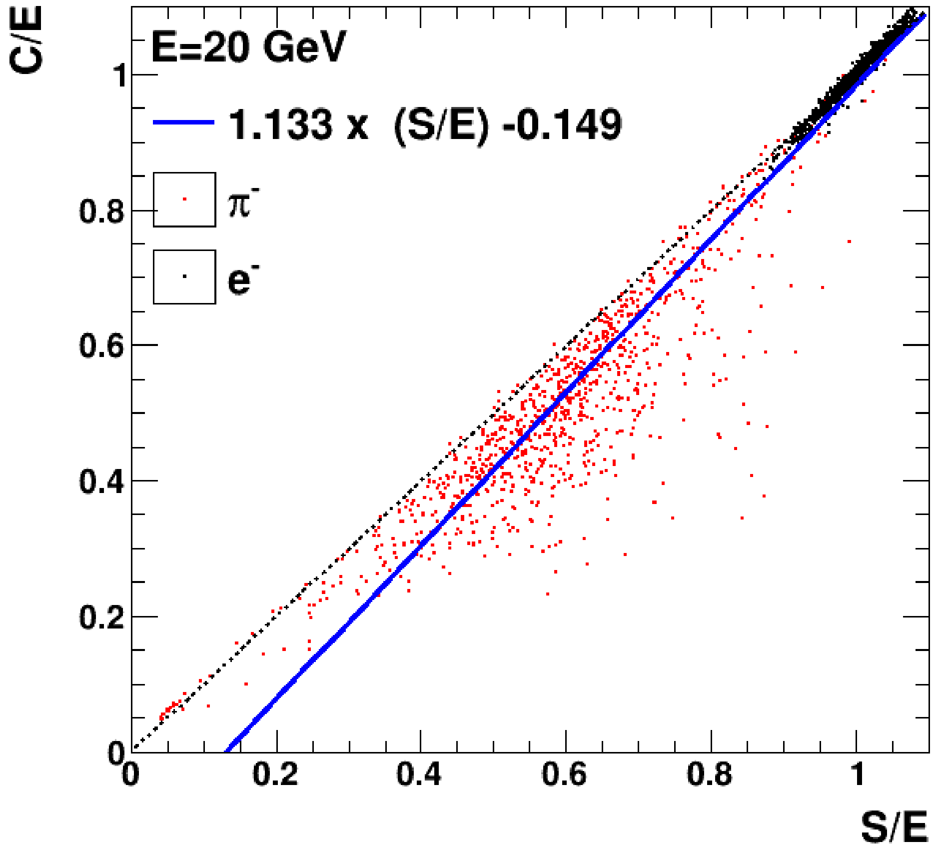
1 GeV

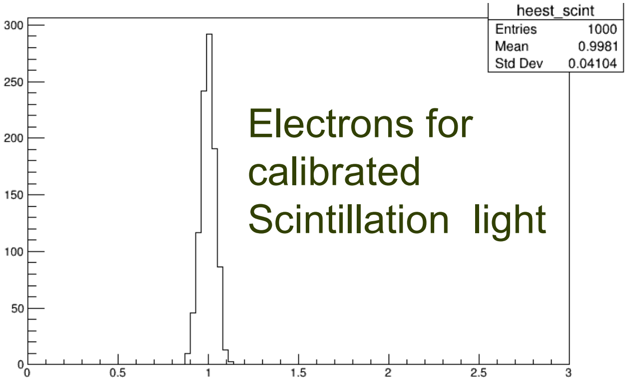


20 GeV

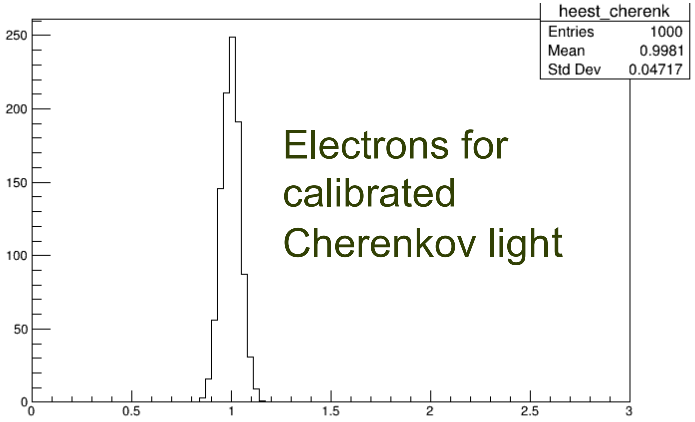


Scintillation light vs Cherenkov after calibration





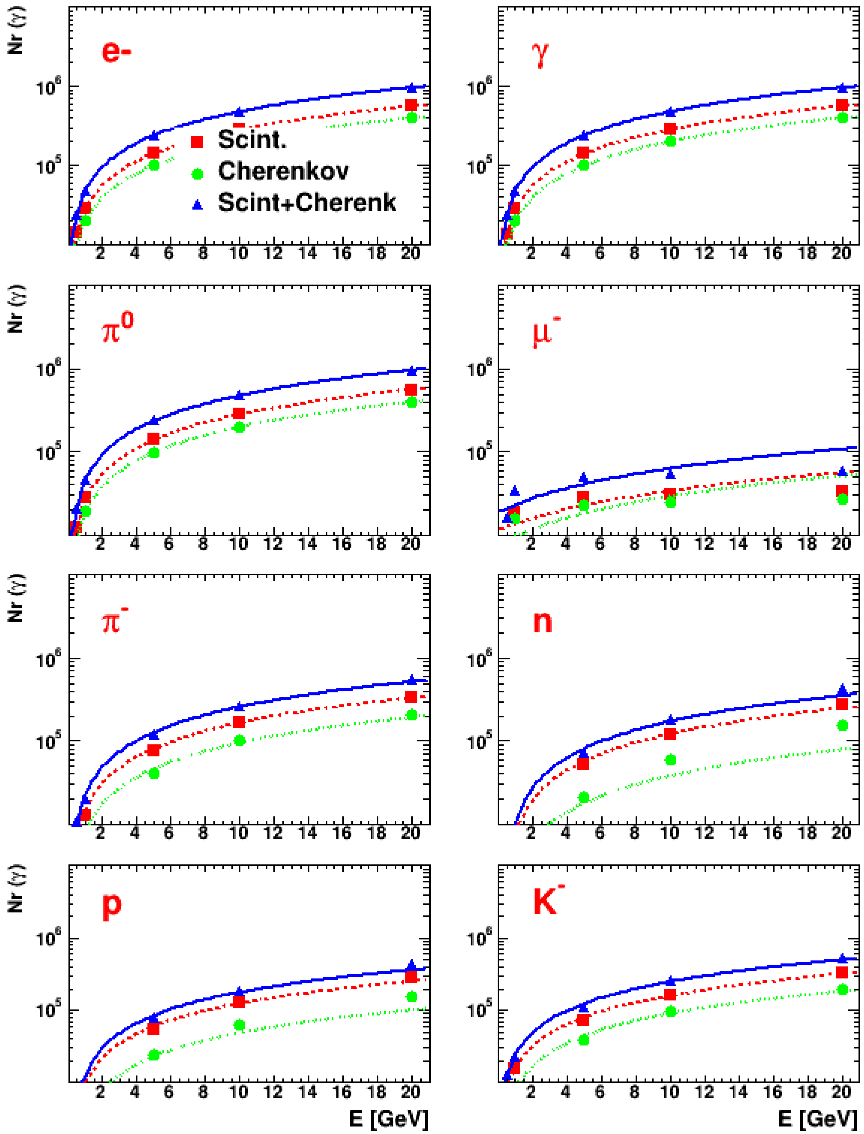
Electrons for calibrated Scintillation light



Electrons for calibrated Cherenkov light

- Larger spread for electrons (expected)
- Slope for pions is weaker than for pure crystal “HCAL”

Rate of optical photons



Rate of Scintillation+Cherenkov
Fit with straight line:
e-: **28236 x E -227**
(6.7 times lower than for pure crystals)

h/e = 0.53 for Scintillation light
h/e = 0.40 for Cherenkov light

(calculated using e- and **pi-** at 5 GeV)

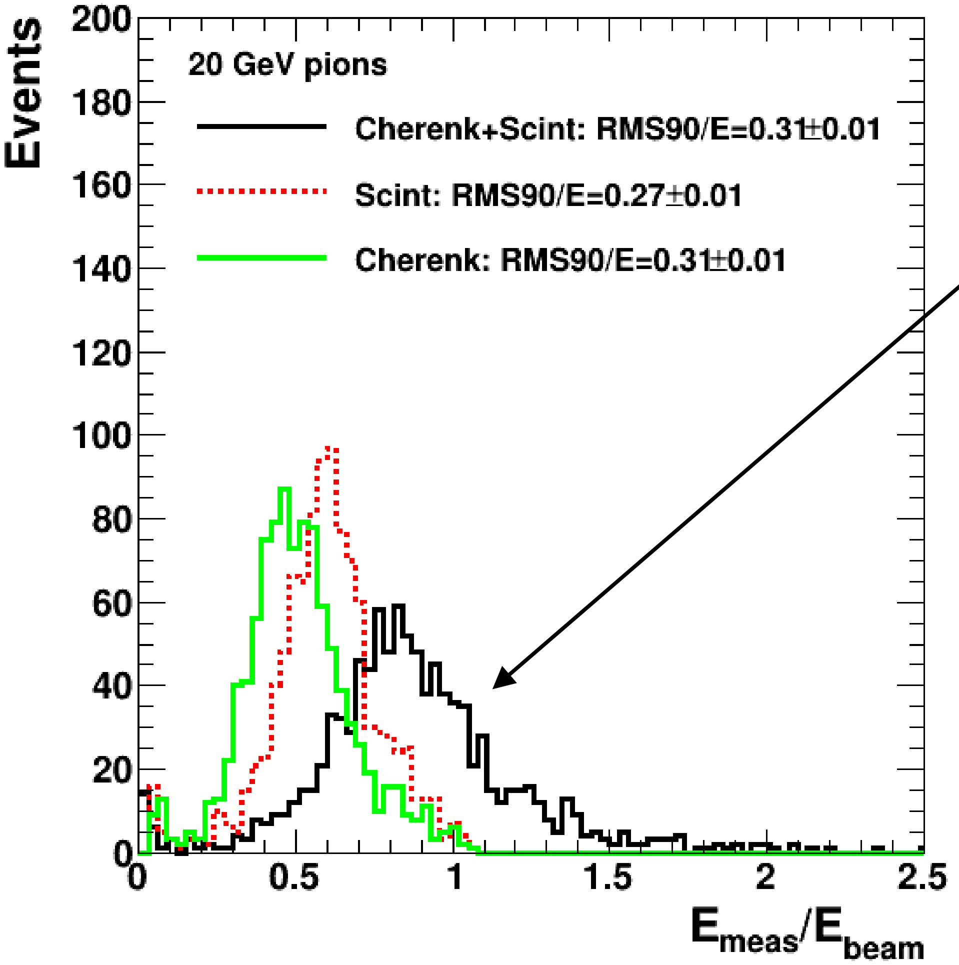
$$\chi = \frac{1-\eta_S}{1-\eta_C} = 0.79$$

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

Corrected energy

https://arxiv.org/pdf/1712.05494.pdf

20 GeV pions for calibrated response



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

No improvement in resolution

Similar conclusions for 50 GeV, protons, neutrons…

Will try to make a few variations in the simulations..