Particle Shower Simulation Studies for IceCube

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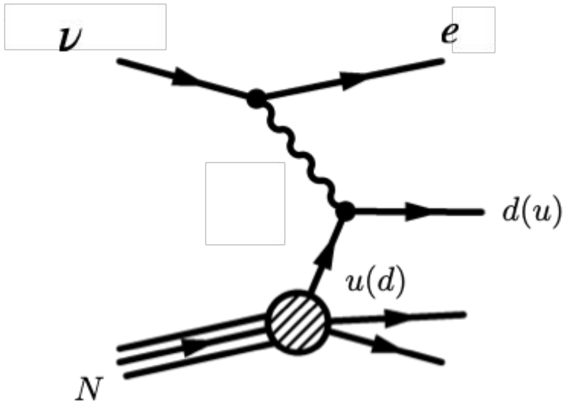
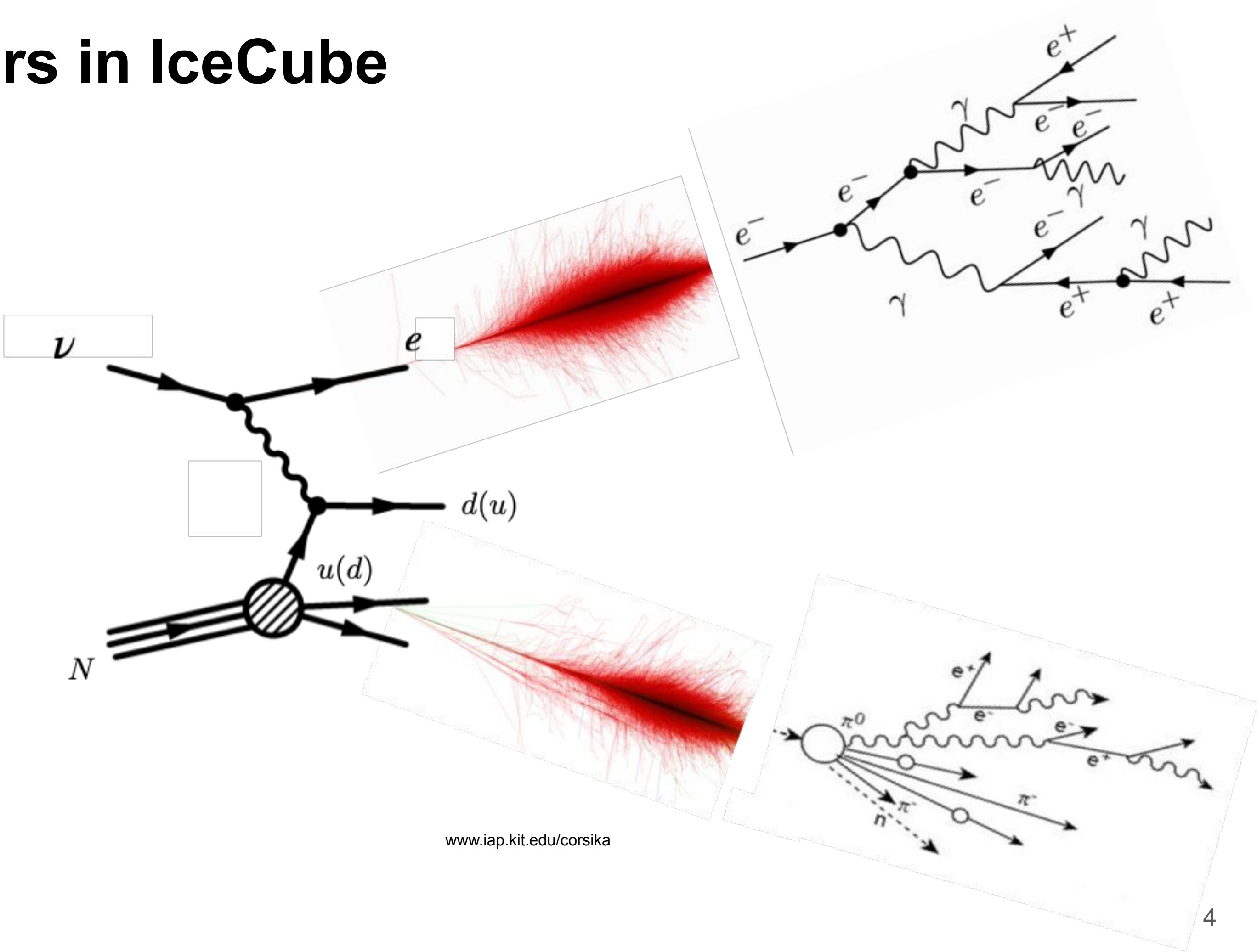
Outline

- **What are particle showers?**
- More realistic particle shower simulations
- Future studies using differences between EM and Hadronic showers

Particle showers in IceCube



Particle showers in IceCube

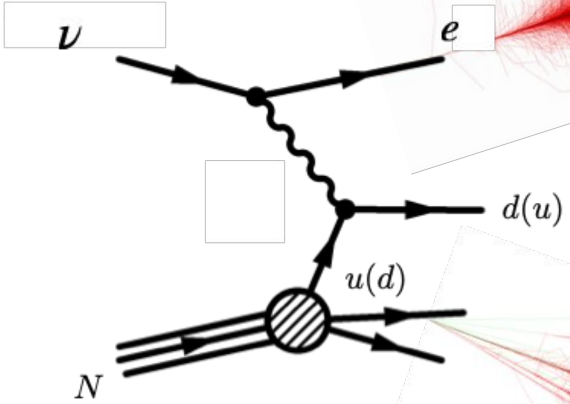


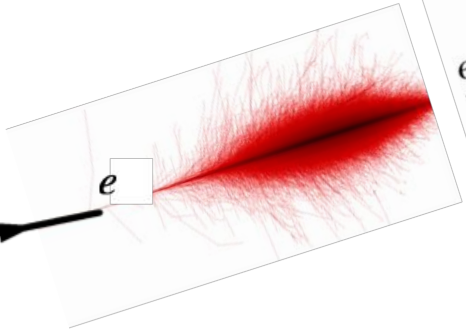
www.iap.kit.edu/corsika

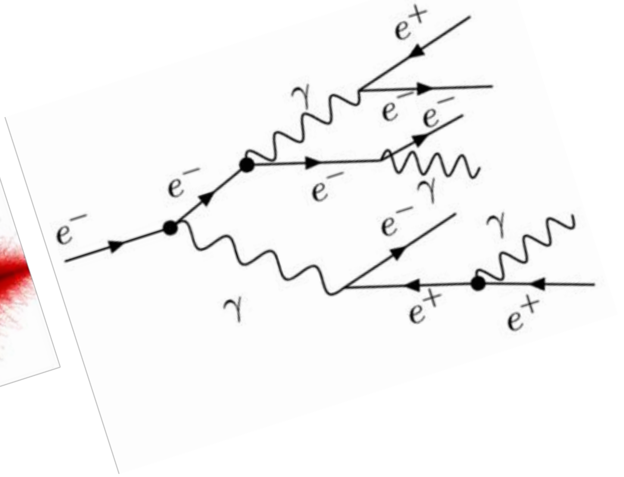
Particle showers in IceCube

Electromagnetic (in nuE CC interactions)

- Only photons, electrons, and positrons
- Simpler physics (EM)

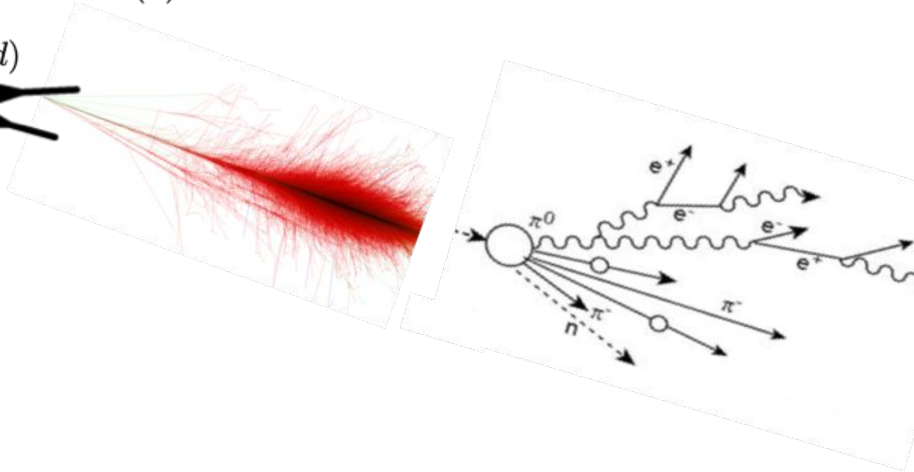






Hadronic (all interactions)

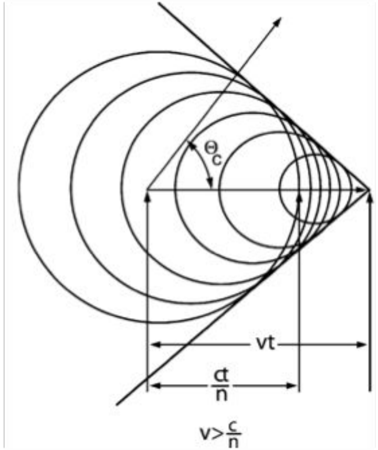
- Initiated by hadrons, but involves other particles (including electromagnetic) as well
- Much more complex to model



Particle showers in IceCube - Cherenkov Emission

- Charged particles traveling faster than speed of light in a medium (c/n) emit **cherenkov light**

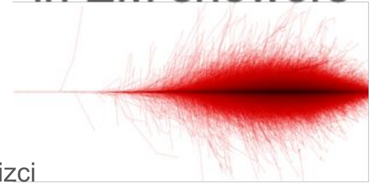
$$\frac{d^2E}{d\hbar\omega . dx} = \hbar\omega \frac{Z^2\alpha}{\hbar c}\left[1 - \frac{c^2}{n^2 v^2}\right]$$



- In particle showers $(v \approx c)$:

  Cherenkov light ∝ # of charged particles ∝ # of particles

- Gamma distribution is a good approximation for # of particles in EM showers

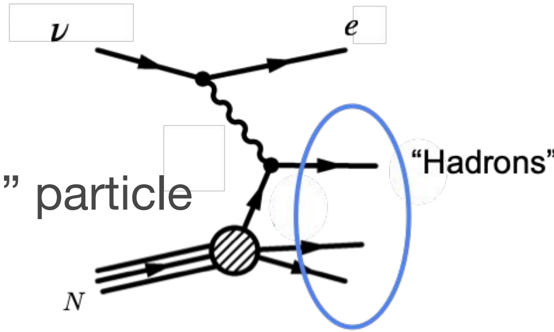


$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

Outline

- What are particle showers?
- **More realistic particle shower simulations**
- Future studies using differences between EM and Hadronic showers

IceCube shower simulations



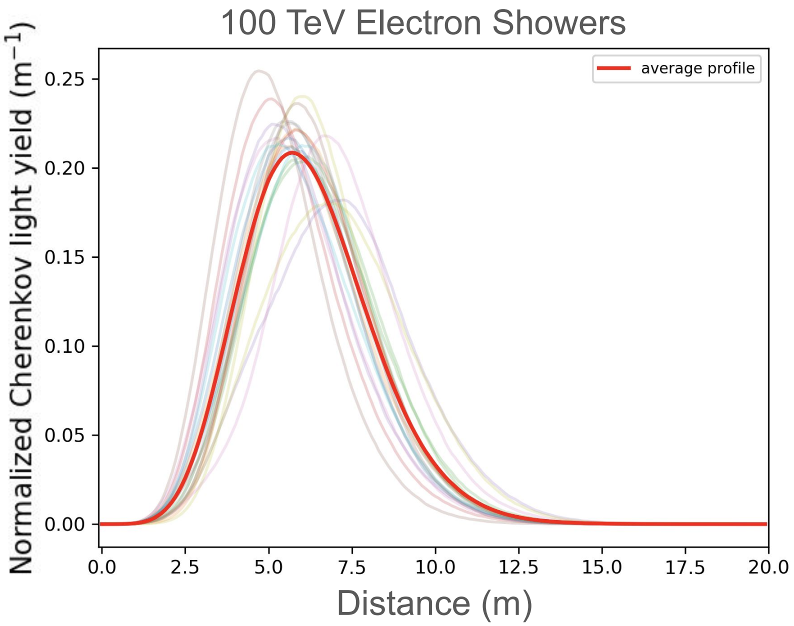
- Neutrino interaction is simulated but hadronization is not
    - Final state hadrons are replaced by generic "Hadrons" particle
- Shower to shower fluctuations in shape is ignored
- Lateral development never explored

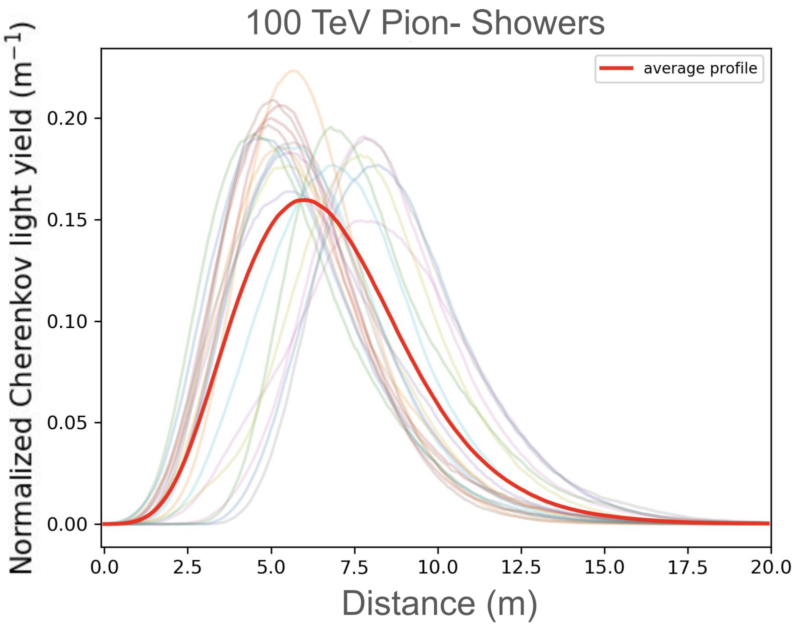
FLUKA simulations

- FLUKA is a tool for calculations of particle **transport** and their **interactions** with matter
- Can be linked with **DPMJET** (3.19) for high energy hadronic interactions
- Able to simulate **neutrino interactions**, including charm production (for CC only)

More realistic shower simulations for IceCube

Shower profiles - EM & Hadronic





First glance observations

- Average shower is not a perfect fit
- Hadronic showers fluctuate more than EM showers

Next: Peak distribution

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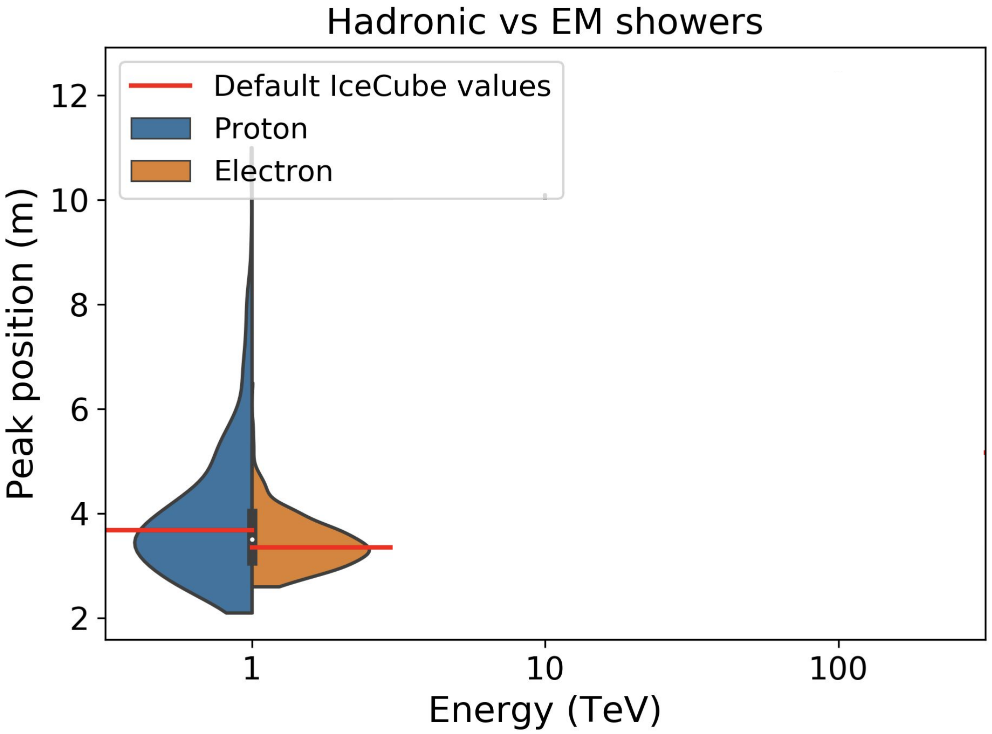
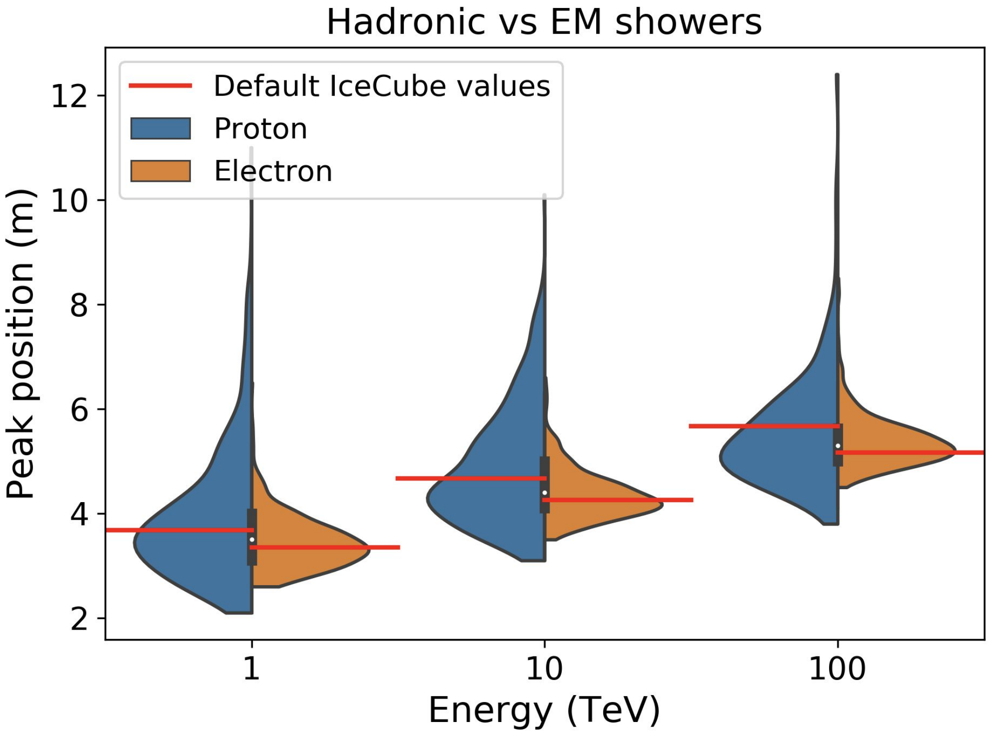
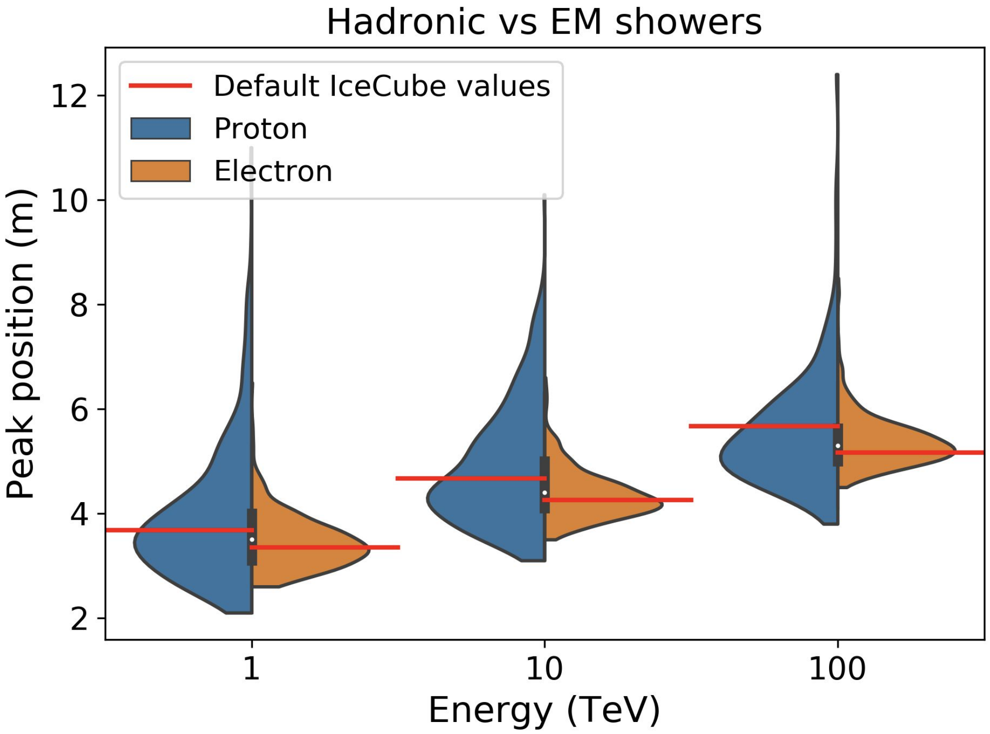
Shower Profiles - Peak position distribution



Shower Profiles - Peak position distribution



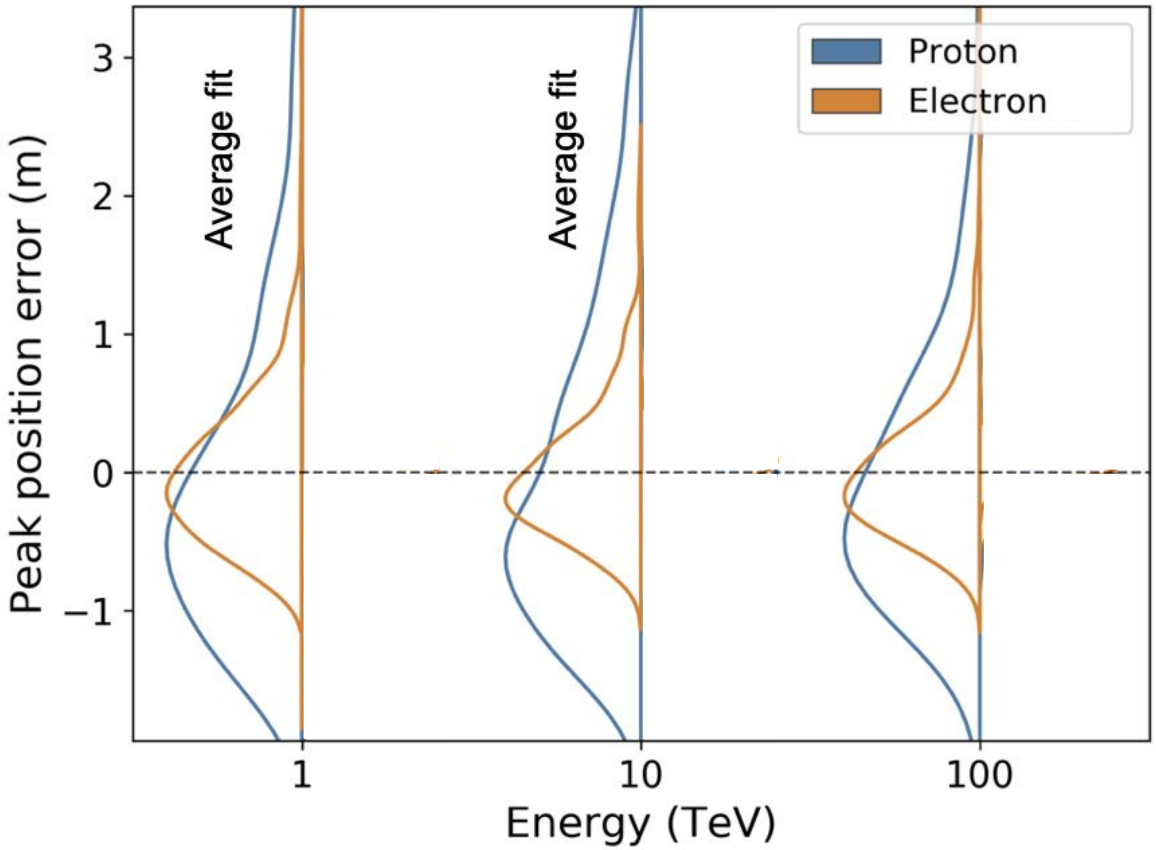
Shower Profiles - Peak position distribution



- Peak position cannot be well described by a single value from average fit
- Hadronic showers have wider distribution
- **Next**: Try gamma fits to individual showers

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

Shower Profiles - Peak position error



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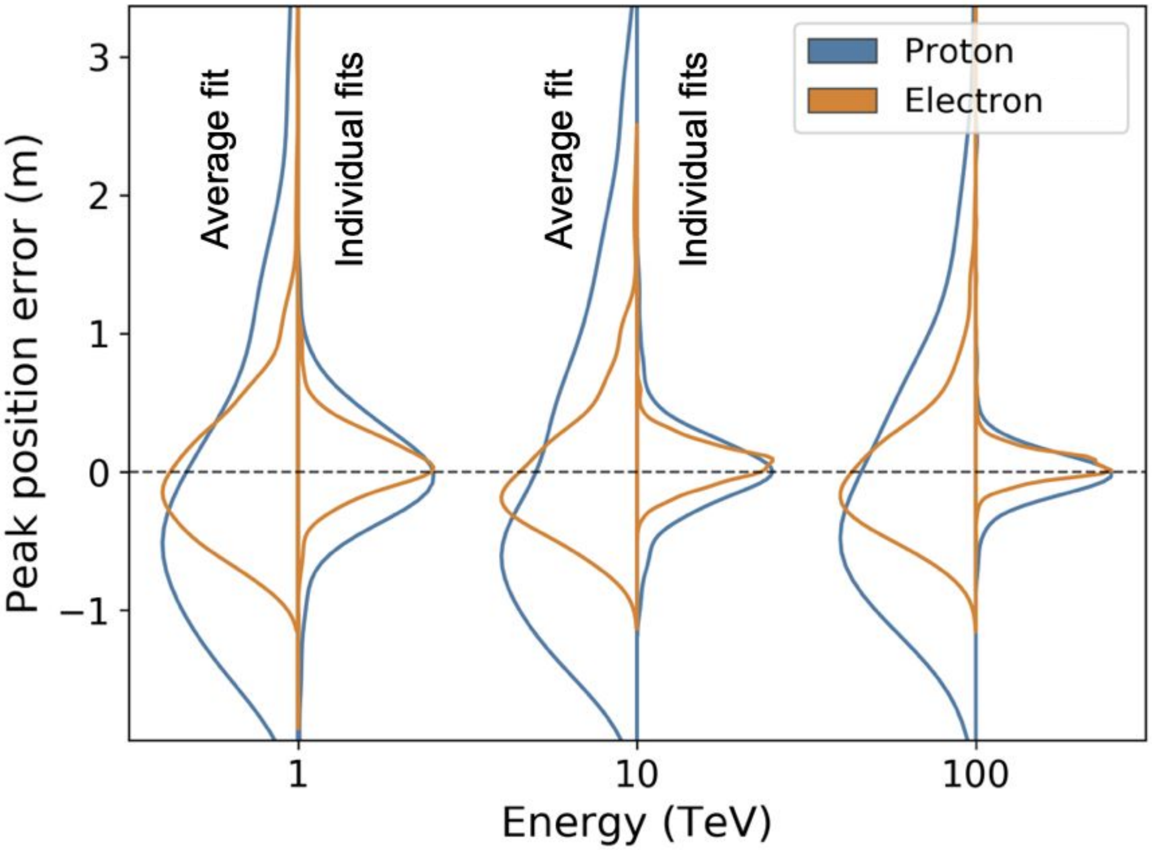
Shower Profiles - Peak position (Average fit vs Individual fits)



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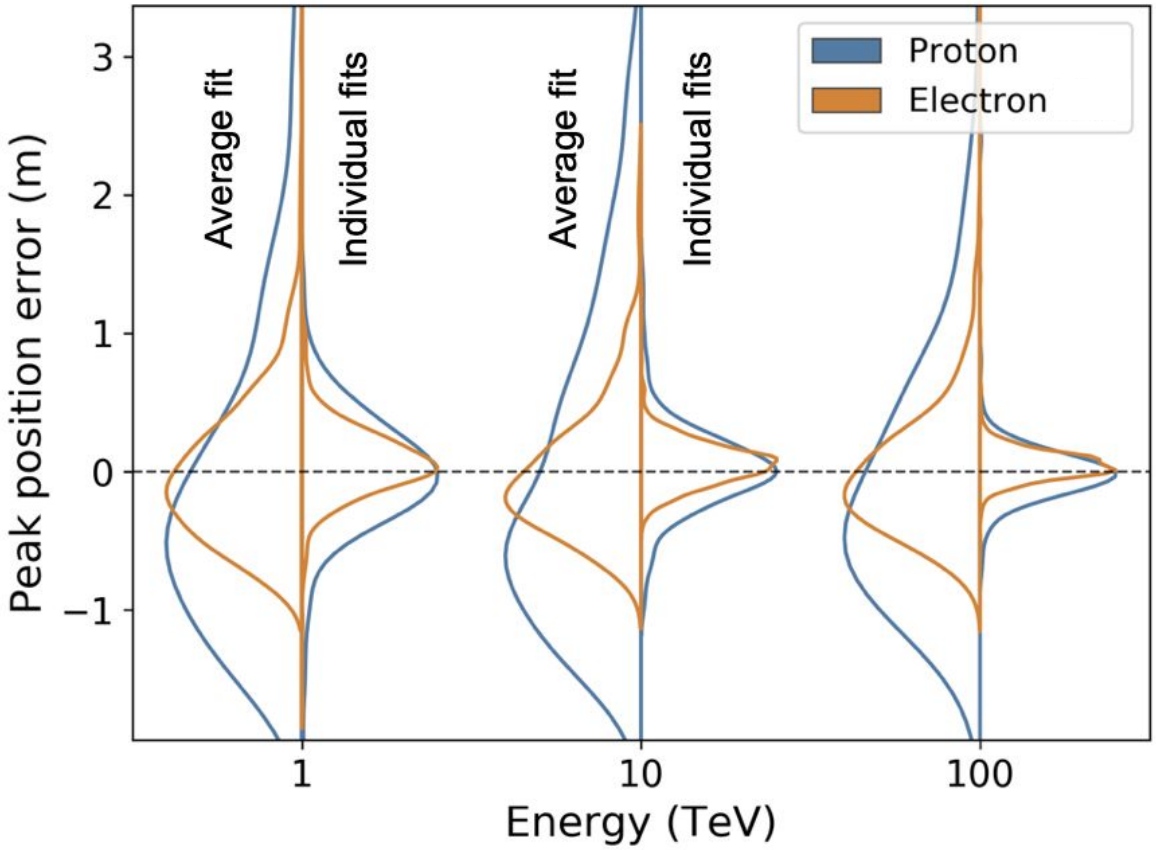
Shower Profiles - Peak position (Average fit vs Individual fits)



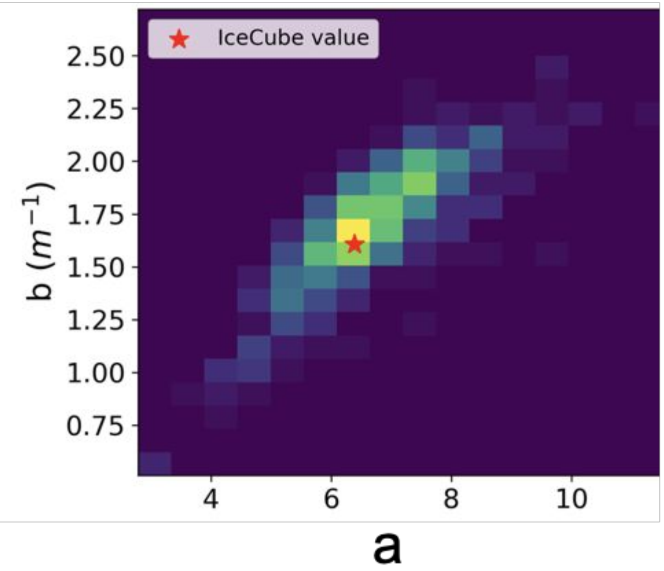
- Significant improvement
- Hadronic showers still have wider distribution
- Individual fits perform better at higher energies for both EM and hadronic
- **Next**: parameter distribution

EM Showers - Parametrization

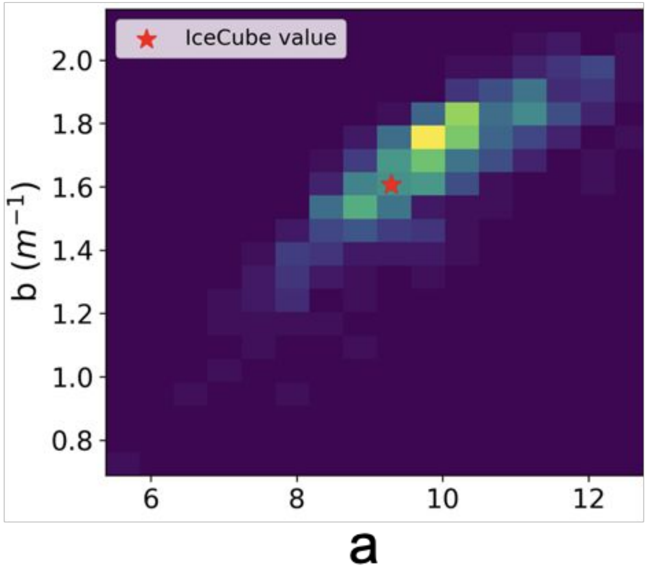
$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- a&b strongly correlated
- No correlation with total energy
- IceCube values (extrapolated) are a little off for high energies

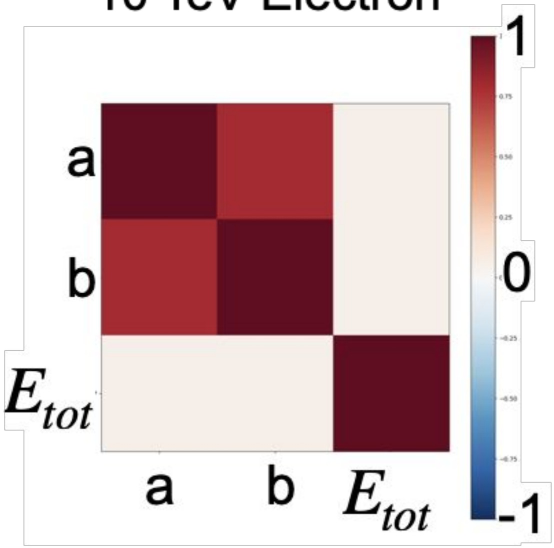
1 TeV Electron



100 TeV Electron



10 TeV Electron



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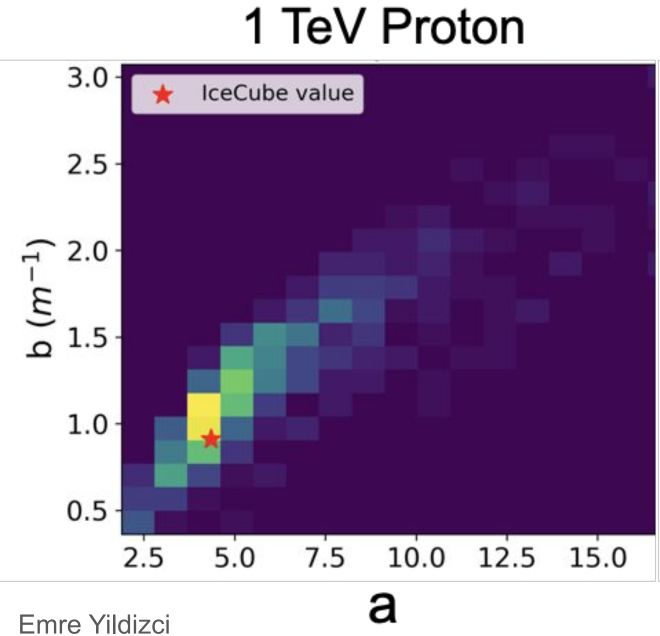
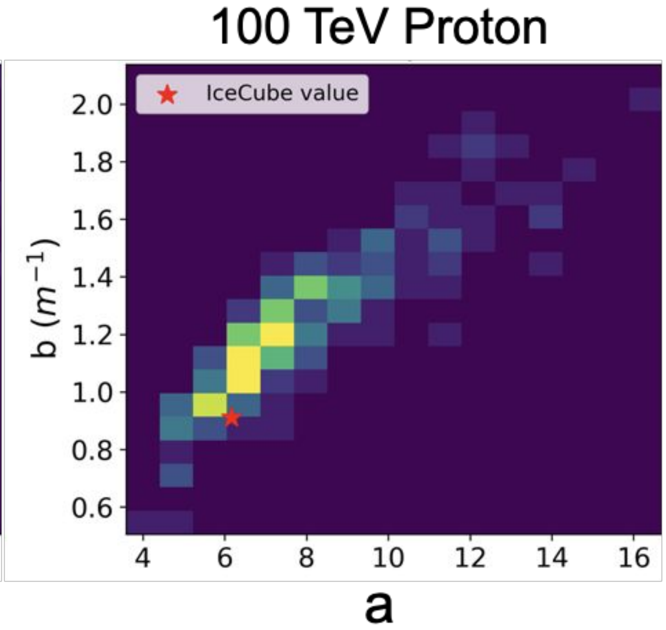
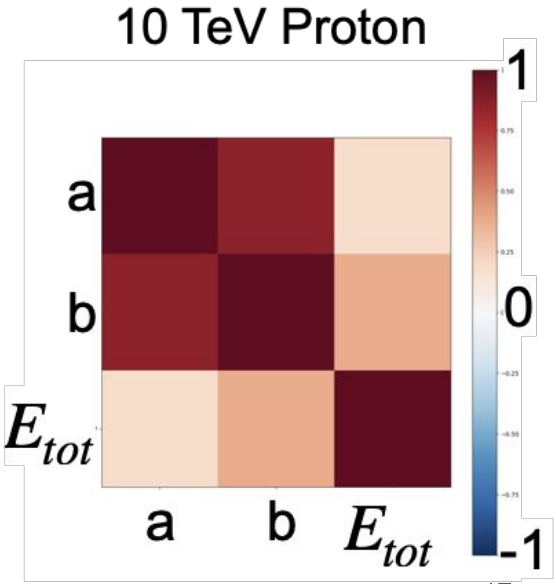
Hadronic Showers - Parametrization

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- a&b strongly correlated
- Small correlation with total energy
- IceCube values (extrapolated) are a little off for high energies
- Variations in a&b are larger than EM showers







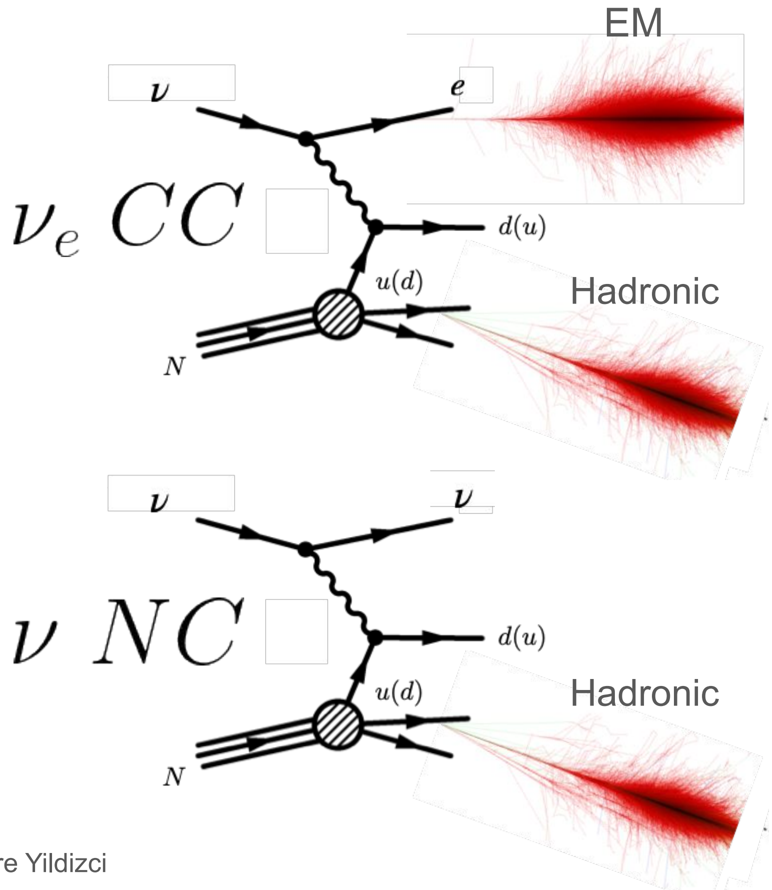
Next

- Get the a&b distribution at many energy levels and fit splines
- It is a significant improvement to get the fluctuations in shower shape over using an average profile
  - We also investigated some subtle features that couldn't be captured by parametrization

Outline

- What are particle showers?
- More realistic particle shower simulations
- **Future studies using differences between EM & Hadronic showers**

Future studies using differences between EM & Hadronic

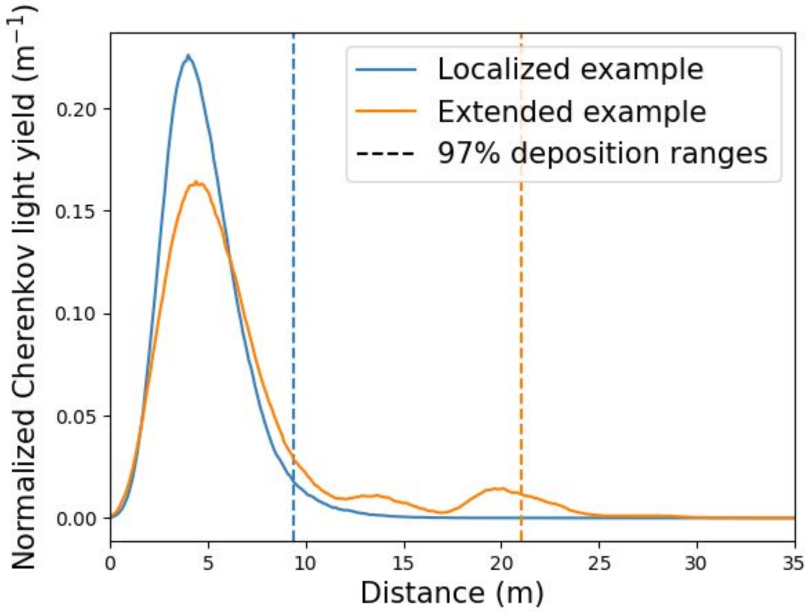


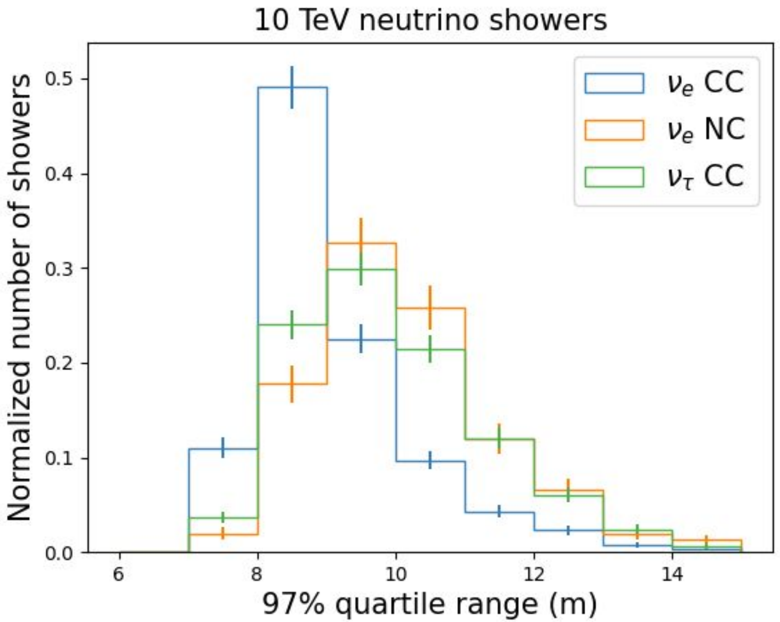
- nuE CC: EM + Hadronic
- All NC: Hadronic
- nuTau CC: Hadronic + (Tau decay)

- Shower properties to be explored
  - Shower extension
  - Lateral shower development

Shower extension

- Signals from extended showers could be separated from localized showers
- We use the last 3% energy deposition position as proxy for shower extension

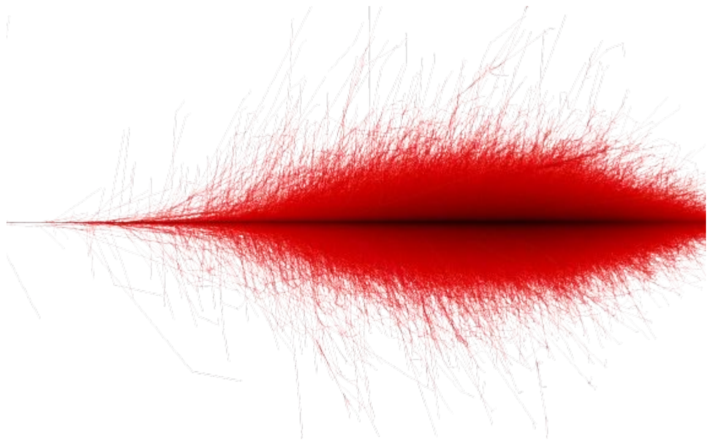




- NC showers and nuTau CC showers have larger extensions

2D shower profile

- Most of the emitted Cherenkov photons are very close to the shower axis
- But, information could be obtained from the off-axis photons



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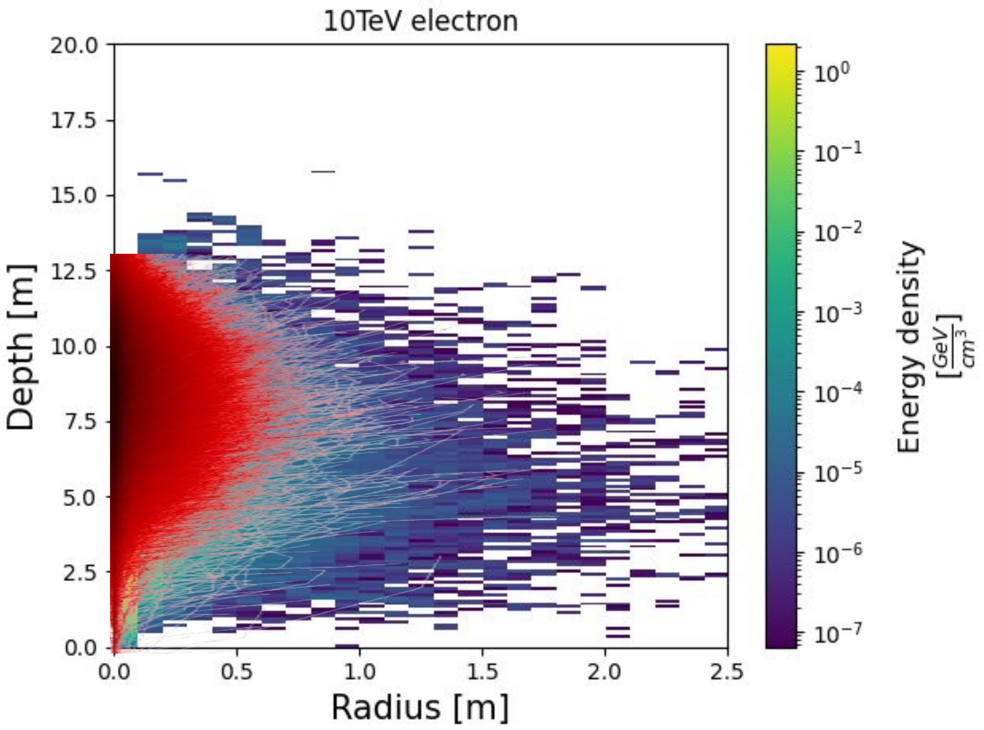

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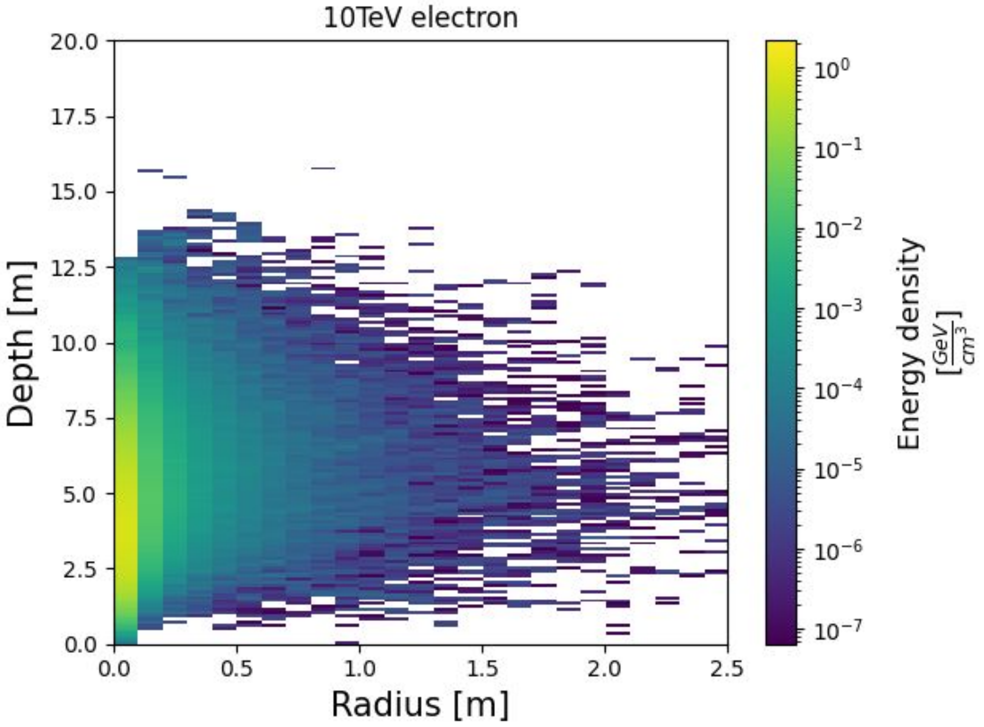
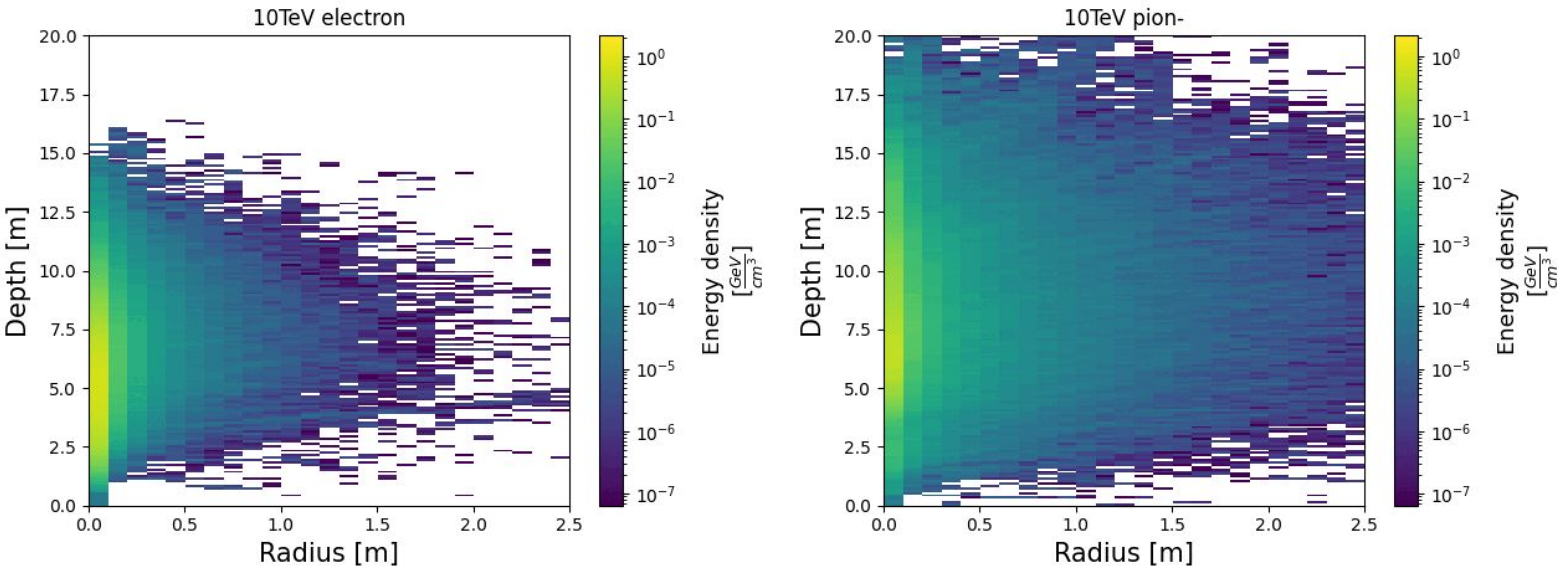


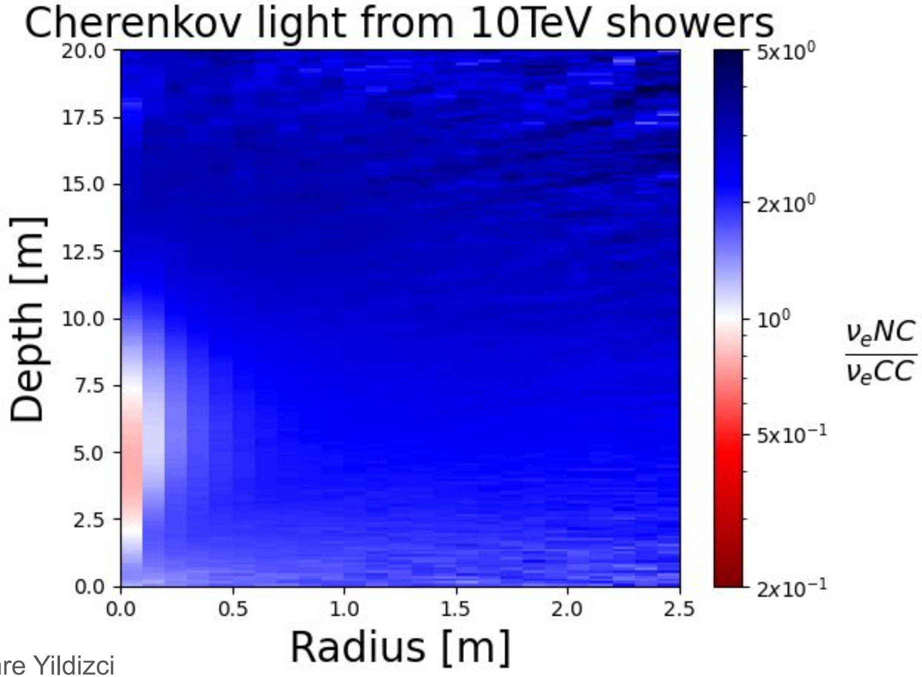
2D shower profile



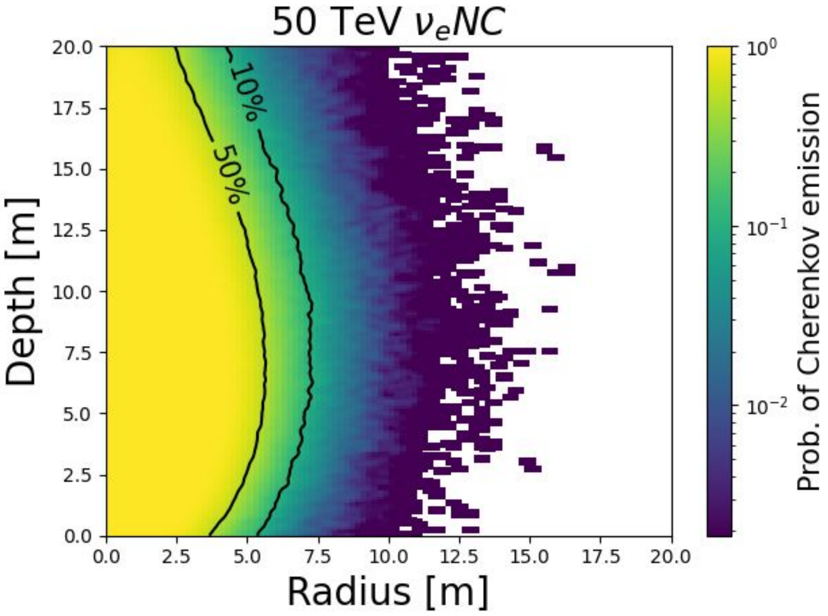
- EM showers are more localized than hadronic showers
  - Muons and other particles in hadronic showers
- How does it translate into the NC showers and nuE CC showers?

2D shower profile

- NC showers have more off-axis photons than CC showers



- How frequent are these off-axis photons?



Summary

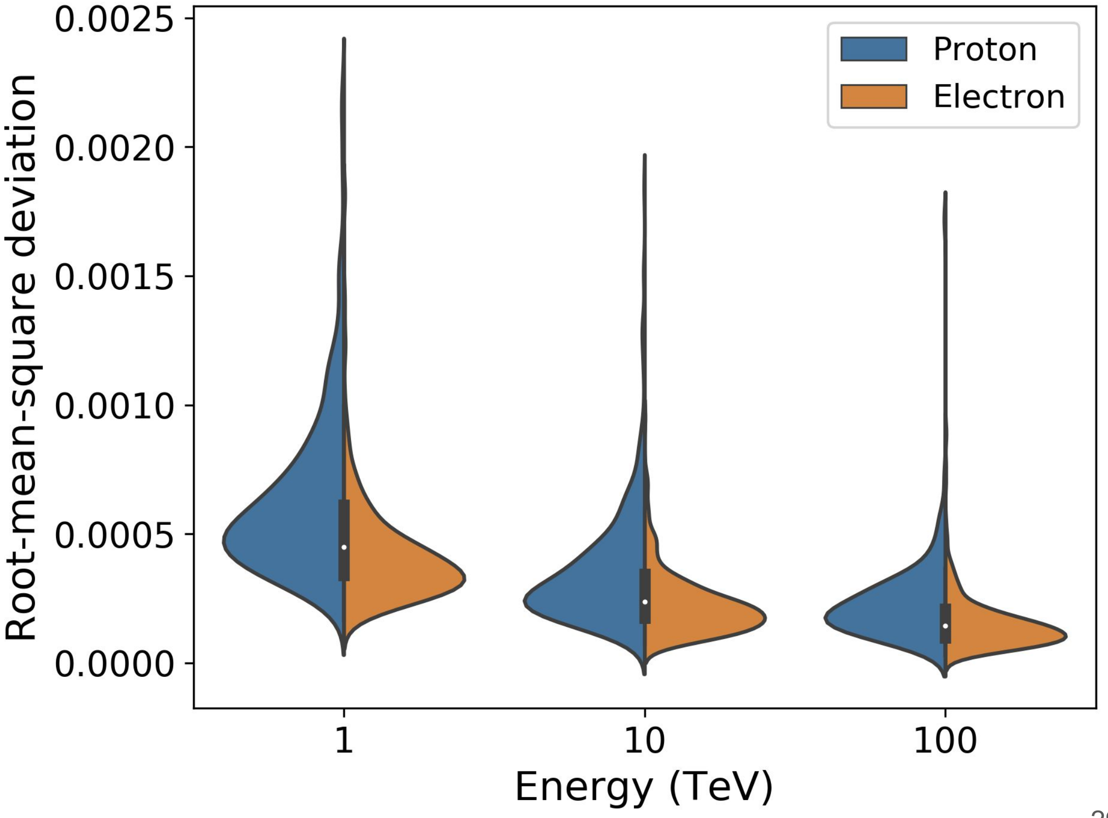
- We are working on a more detailed parametrization of EM and hadronic showers that could introduce fluctuations in shape
- We are studying the possibility of using differences of EM and hadronic showers to distinguish nuE CC events, all flavor NC events and nuTau CC events

Thanks!

Backup

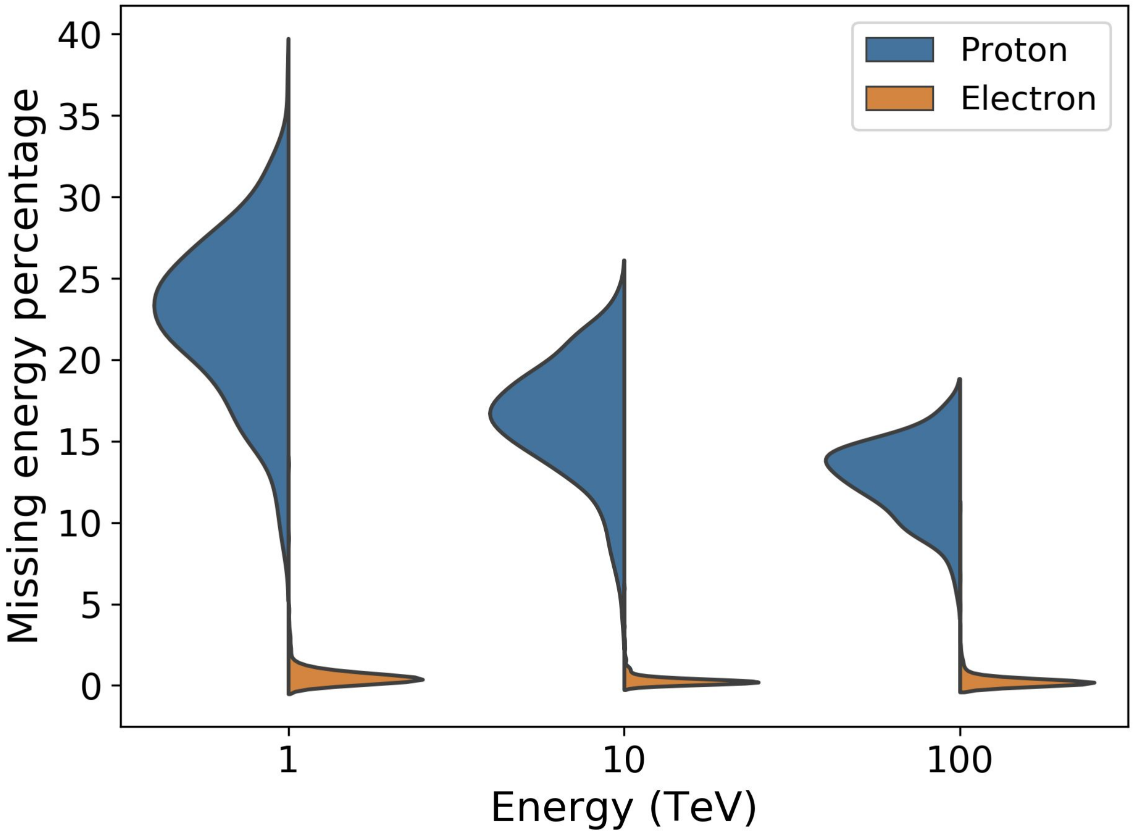
Shower Profiles - Profile shape

- RMS deviation as a proxy for how well the fits describe the shape
- EM showers have smaller deviations from the gamma fits
- Individual fits perform better at higher energies for both EM and hadronic showers



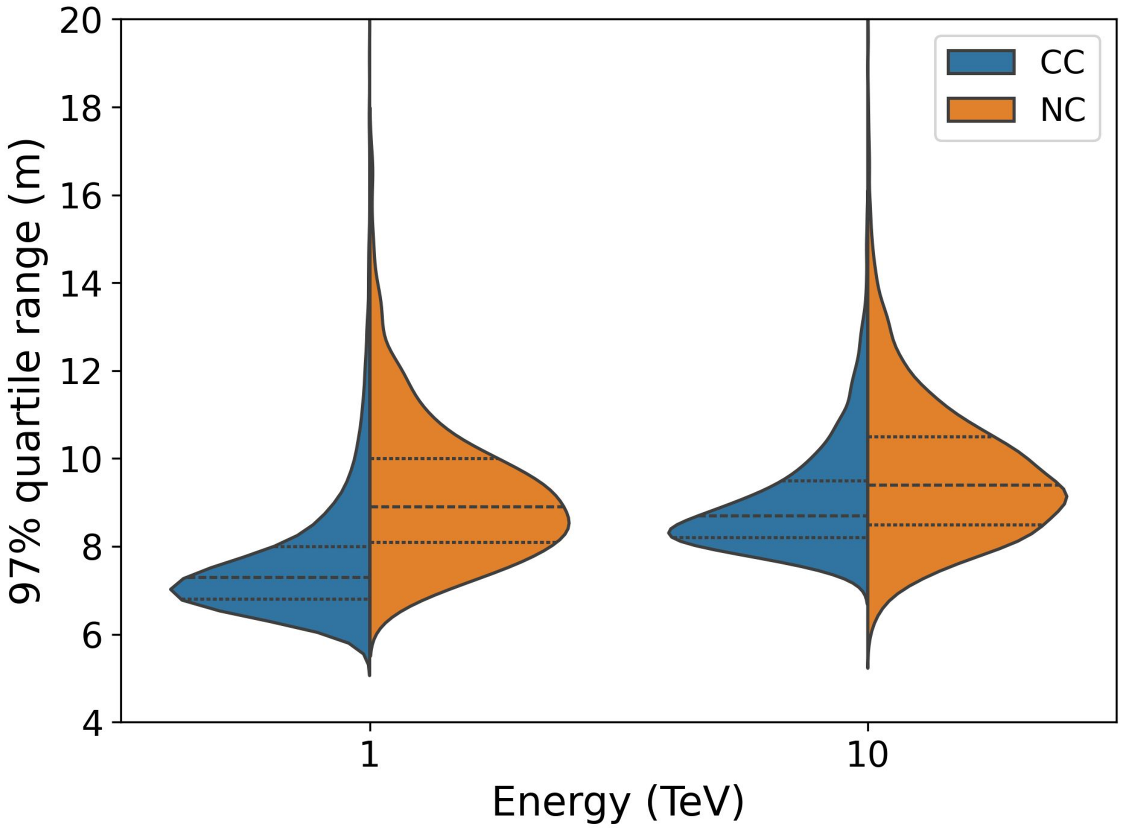
Shower Profiles - Missing energy

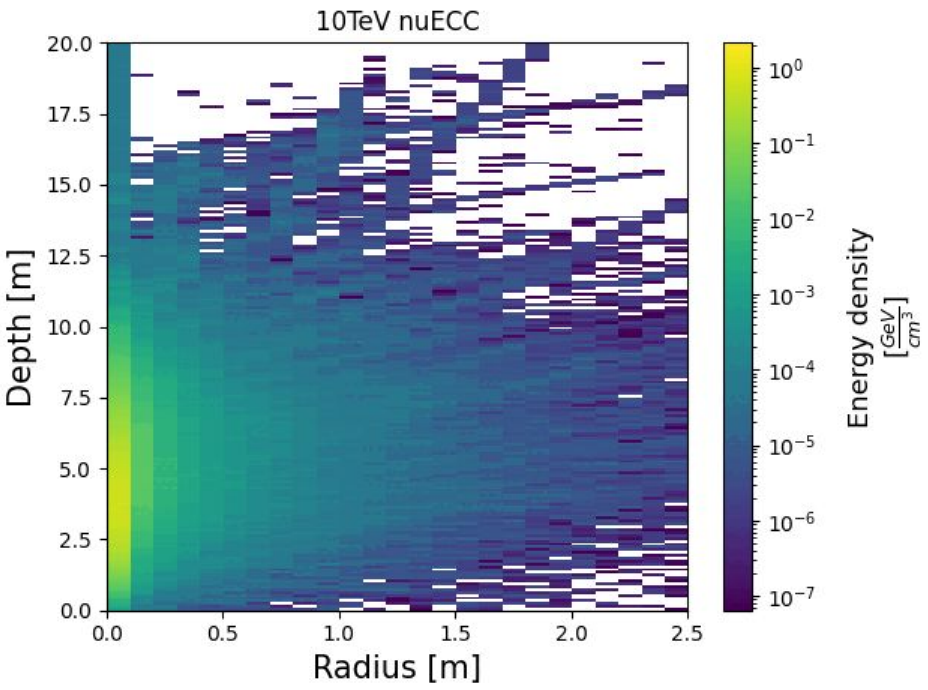
- Fraction of hadronic showers are “invisible” (recoil, neutrinos etc.)
- Total cherenkov yield from EM showers also not constant (~1% effect)
- Missing energy fraction decreases at higher energies



Shower extension

- NC showers deposit the last 3% of the energy far later than CC showers on average




10TeV nuECC
Depth [m]
Radius [m]
Energy density [GeV/cm^3]
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
0.5
1.0
1.5
2.0
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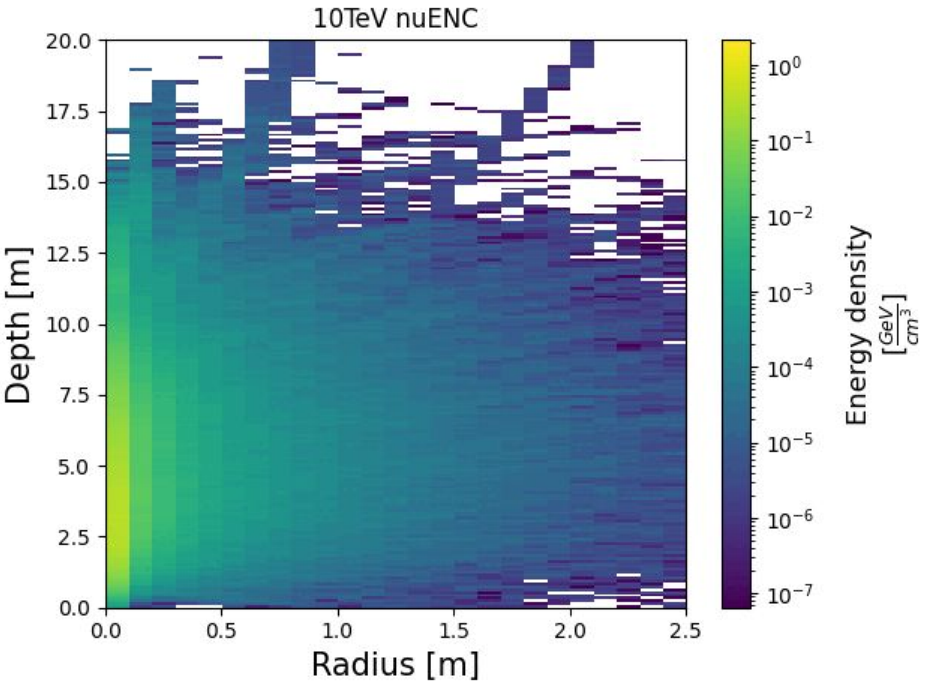
10^-3
10^-4
10^-5
10^-6
10^-7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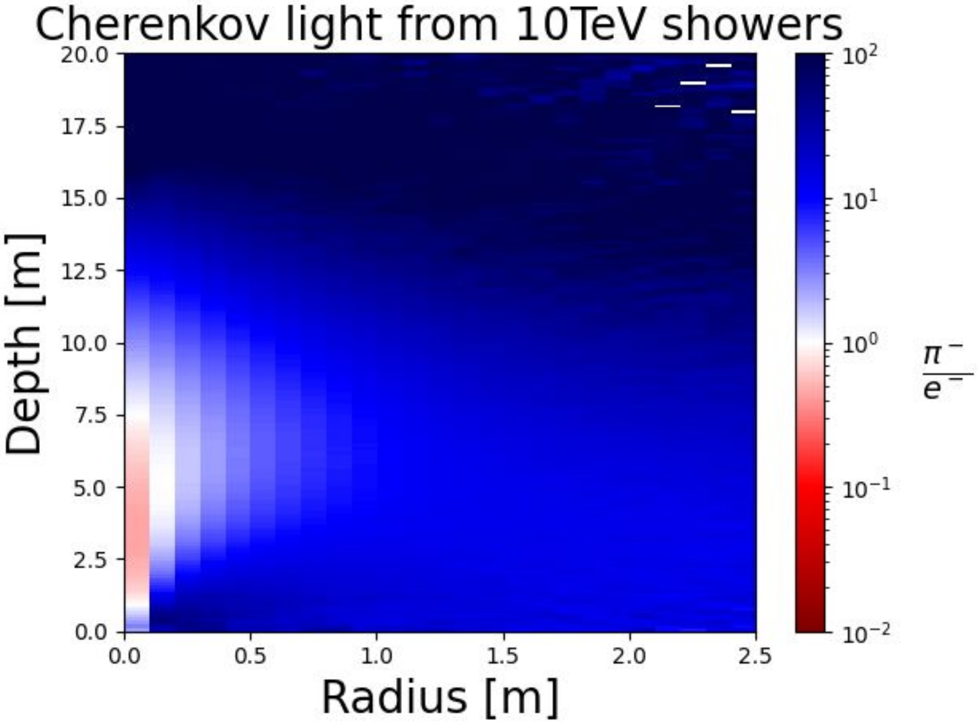
1.0
1.5
2.0
2.5
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7

2D shower profile

- NC showers have more off-axis photons than CC showers



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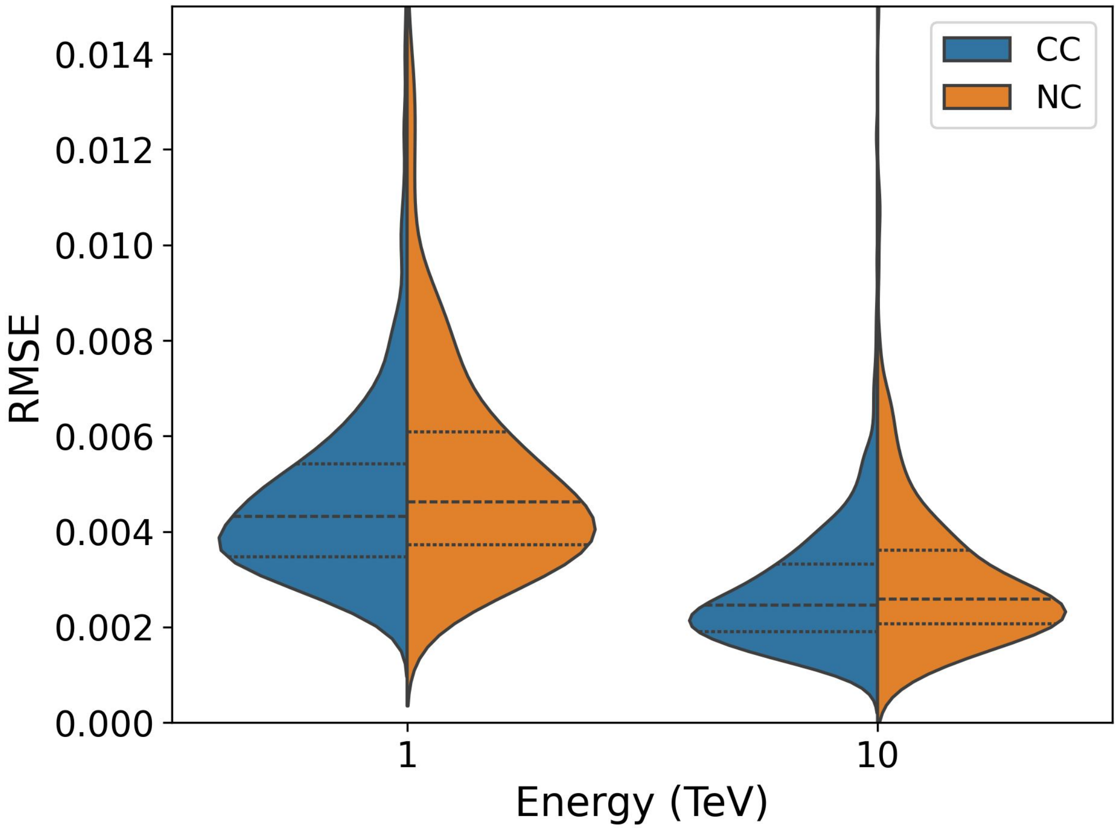
1D Shower Profiles - Root Mean Square Error

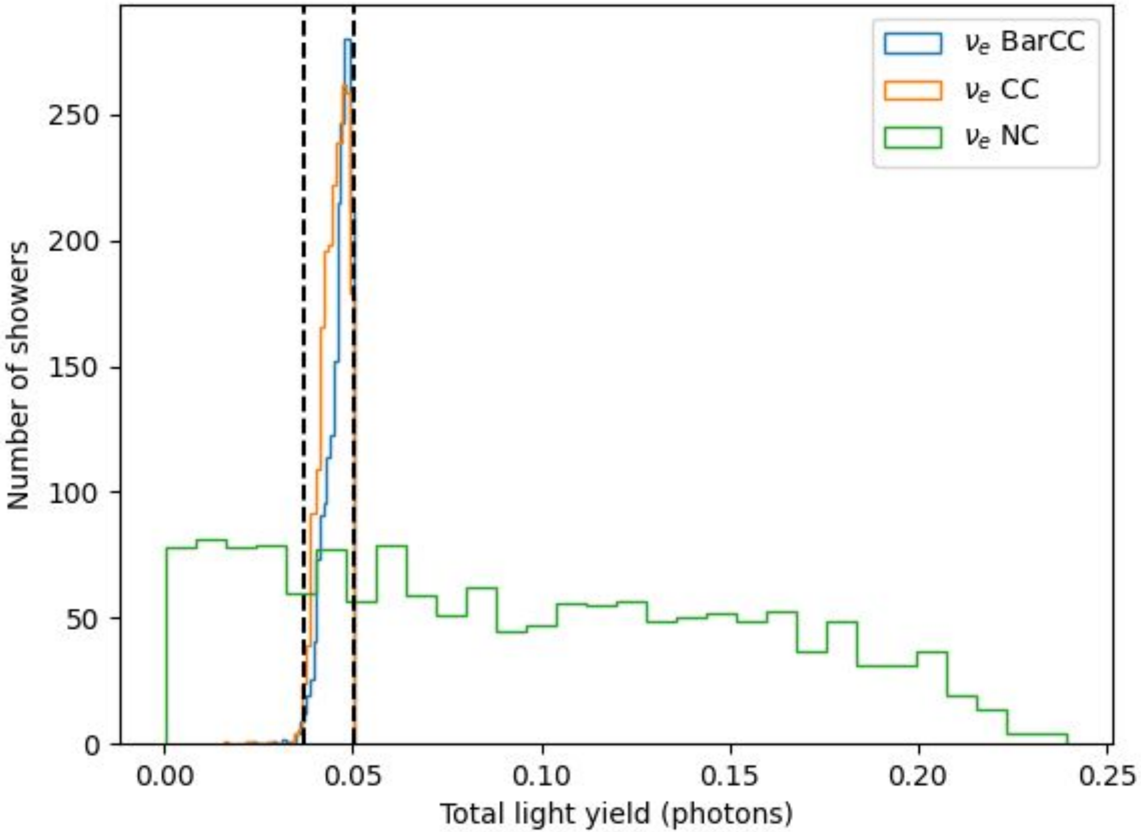
- RMS error as a proxy for how well the fits describe the shape
- CC events have smaller deviations from the gamma fits compared to NC events
- Errors are smaller at higher energies



Technical details

Simulated

- 1 TeV nuE CC
- 1 TeV nuEBar CC
- 5 TeV nuE NC
  - **Choose only events that deposit 1TeV energy**

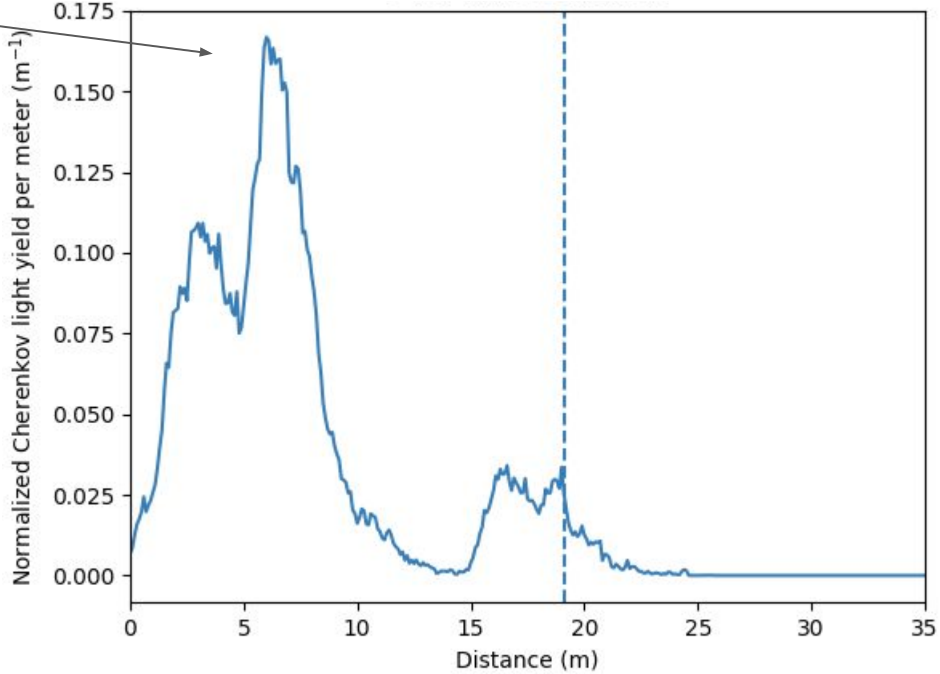


Potential method - 1D shower profile

Peak positions

Energy depositions away from the interaction vertex (double pulse/cascade method)

Lateral distribution



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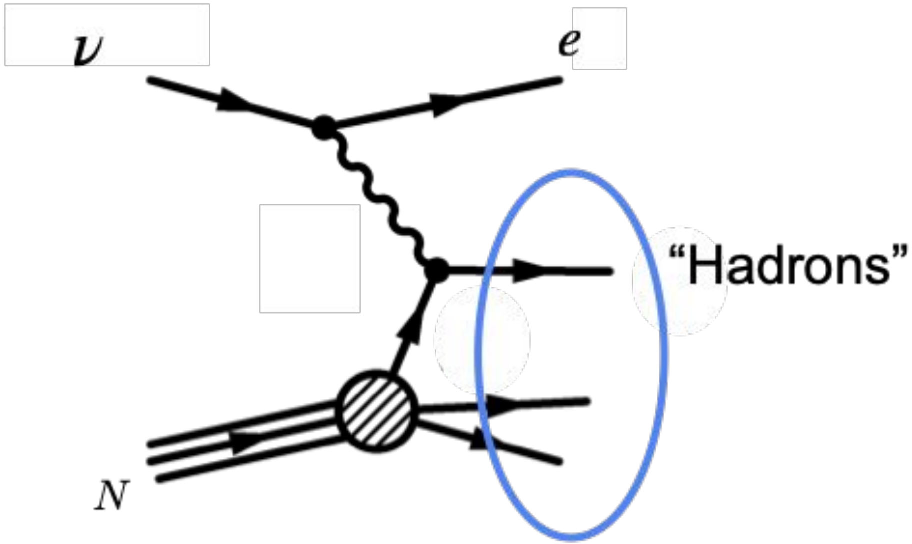
Particle showers in IceCube - Current state

- Neutrino interaction is simulated but hadronization is not
  - Final state hadrons replaced by generic “hadrons” particle (nugen)
- Shower to shower fluctuations in shape are ignored
- Parametrization is old
  - Pre-LHC models
  - Energy up to 10 TeV



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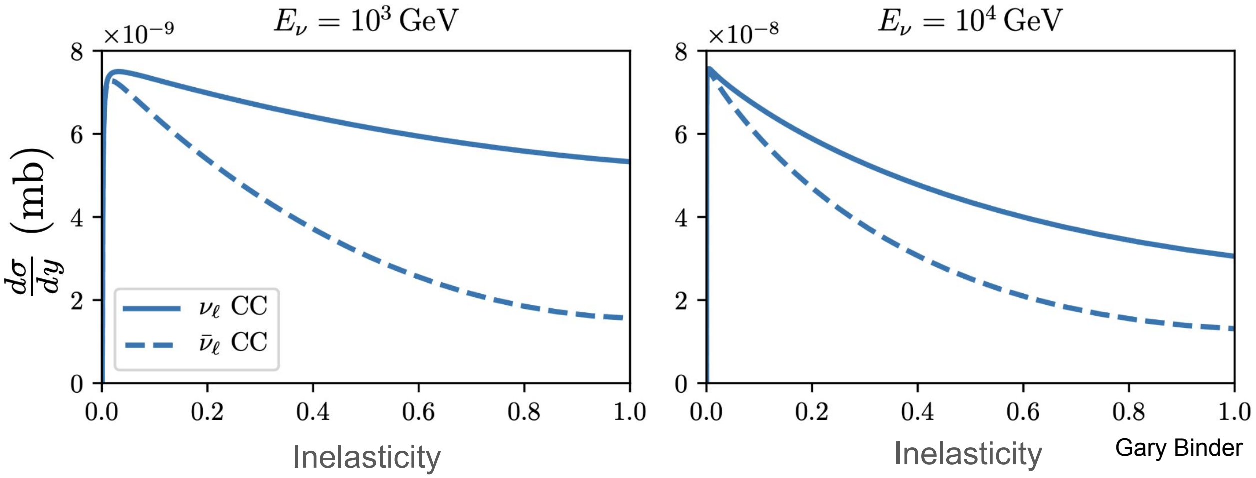
Neutrino Showers
Inelasticity distribution

Theoretical calculation cross section as a function of inelasticity



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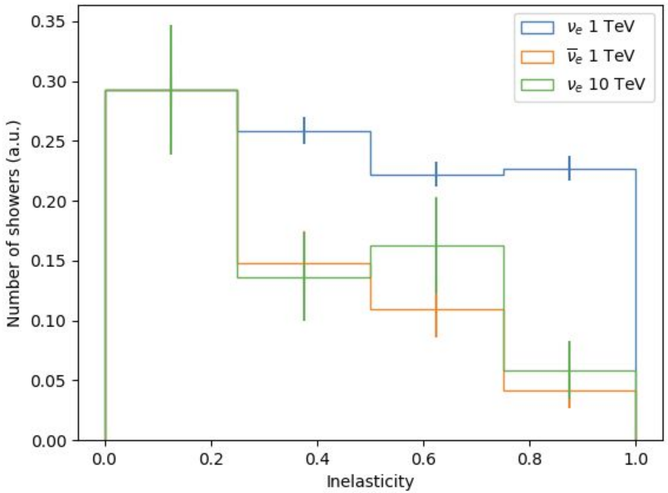
Probability distribution of inelasticity from Fluka

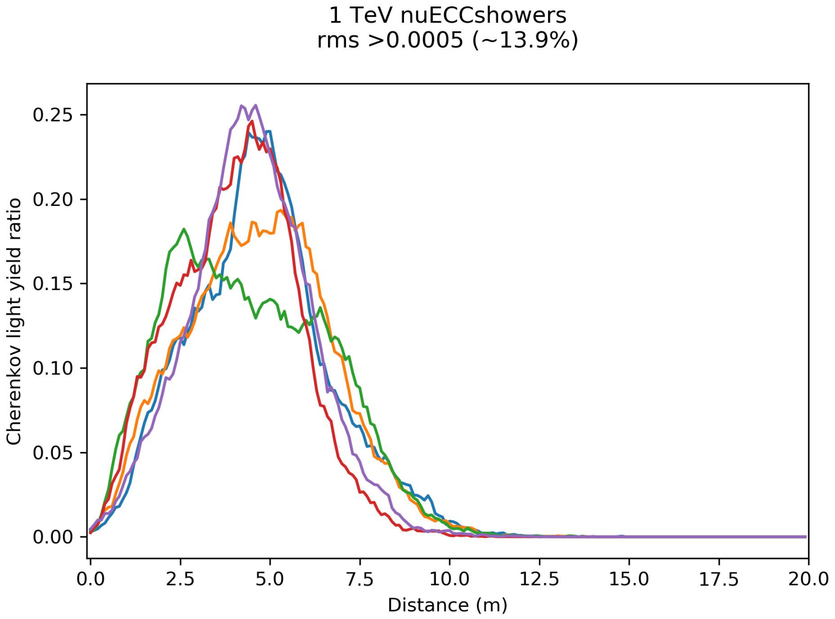
arbitrary y-axis scaling for easier comparison



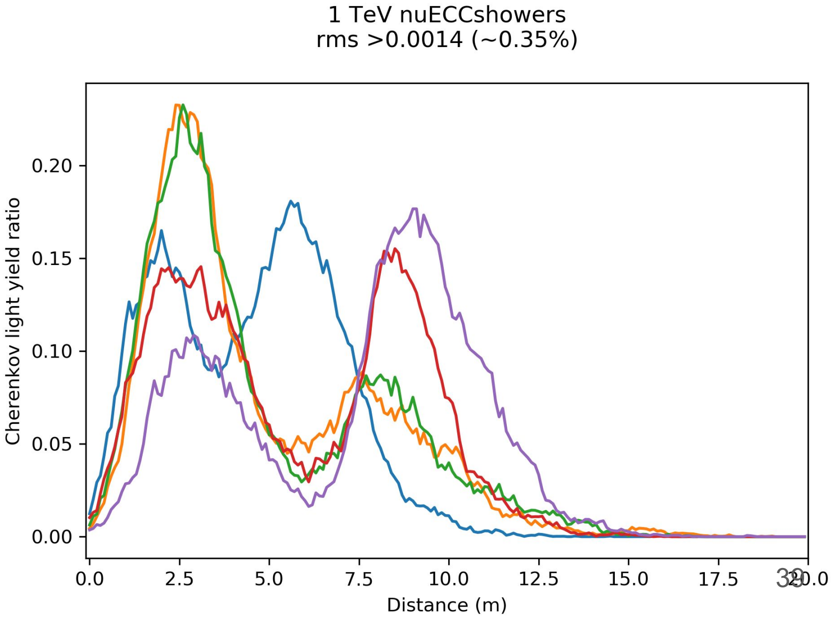
How frequent are “interesting” neutrino showers?

- Fit a gamma function to shower profiles and use RMS error as a proxy for how “anomalous” the profile is

Low RMSE



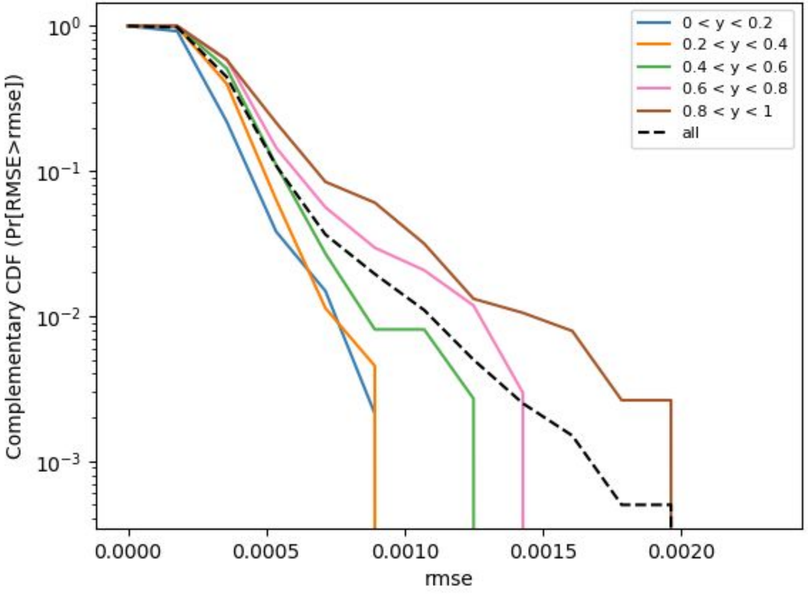
High RMSE



How frequent are “interesting” neutrino showers?

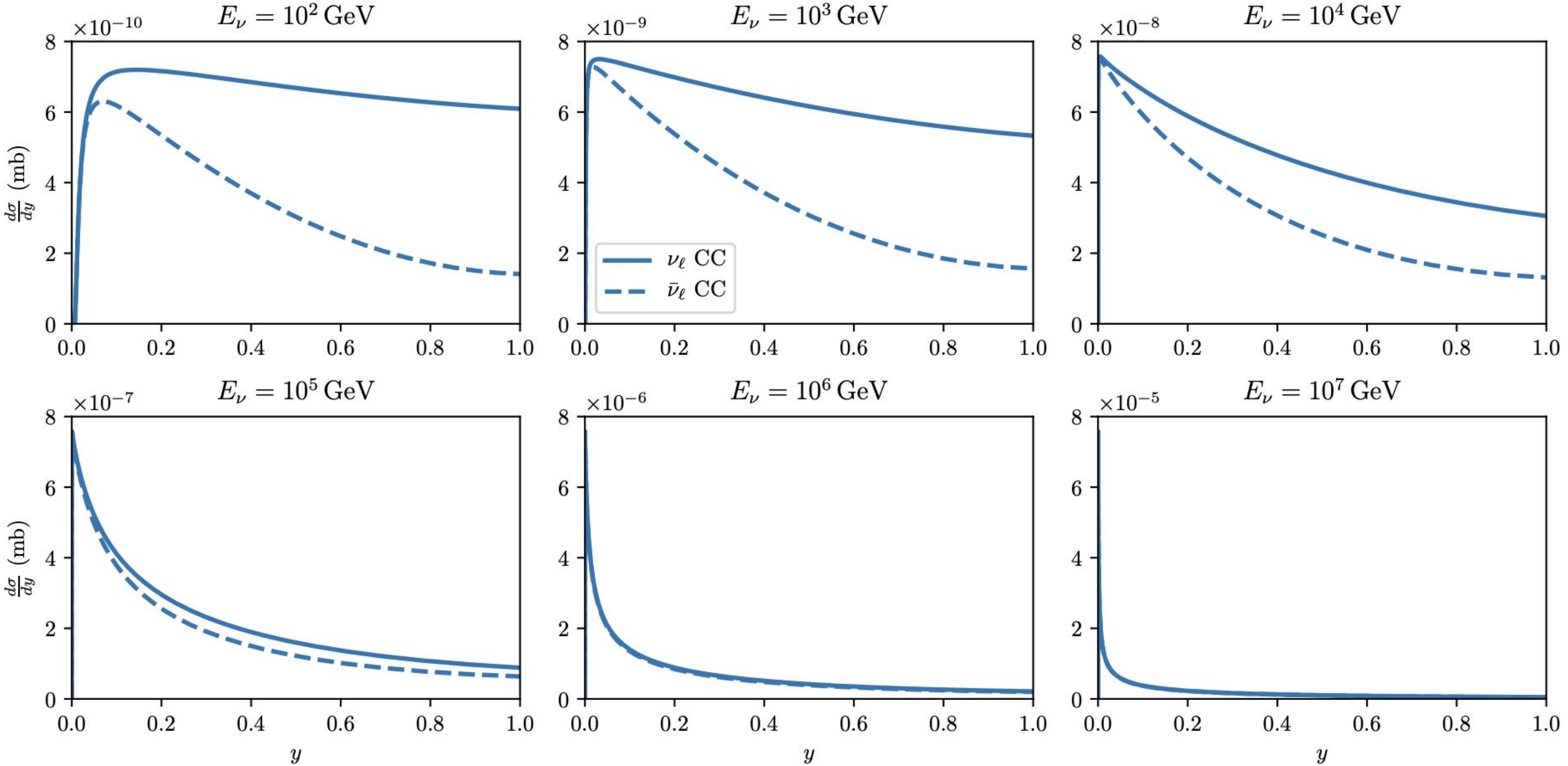
- Complementary CDF distribution of RMSE, Pr(RMSE>rmse), for different inelasticity values

High RMSE -> More deviation from gamma function



High inelasticity -> More hadronic energy -> More “interesting” showers

Inelasticity (y) = Hadronic / (Hadronic + EM) for **nuECC**



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