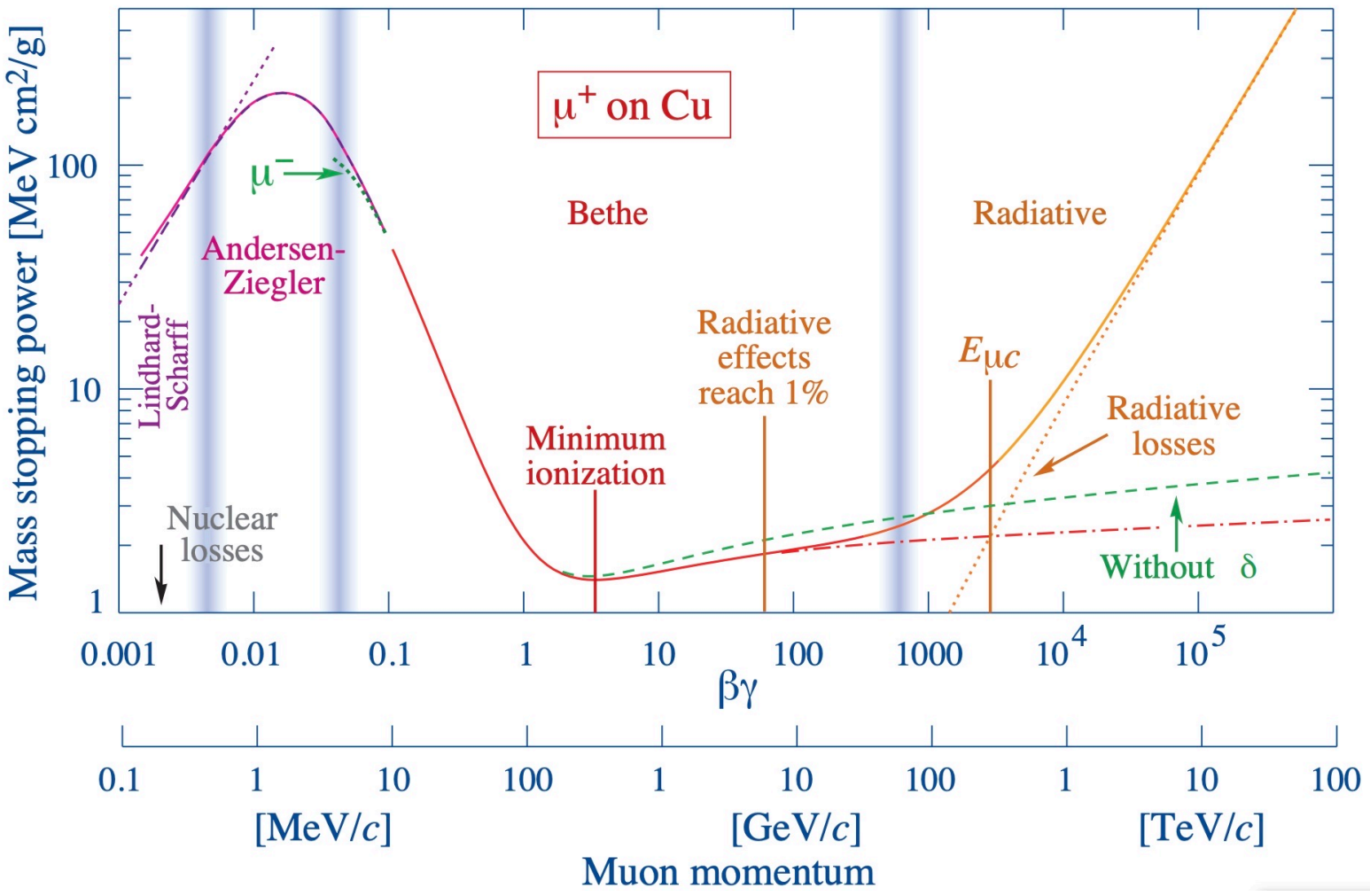
Neutrino Interactions, Simulation, and Event Generation

Lecture 2: What happens after a neutrino interacts?

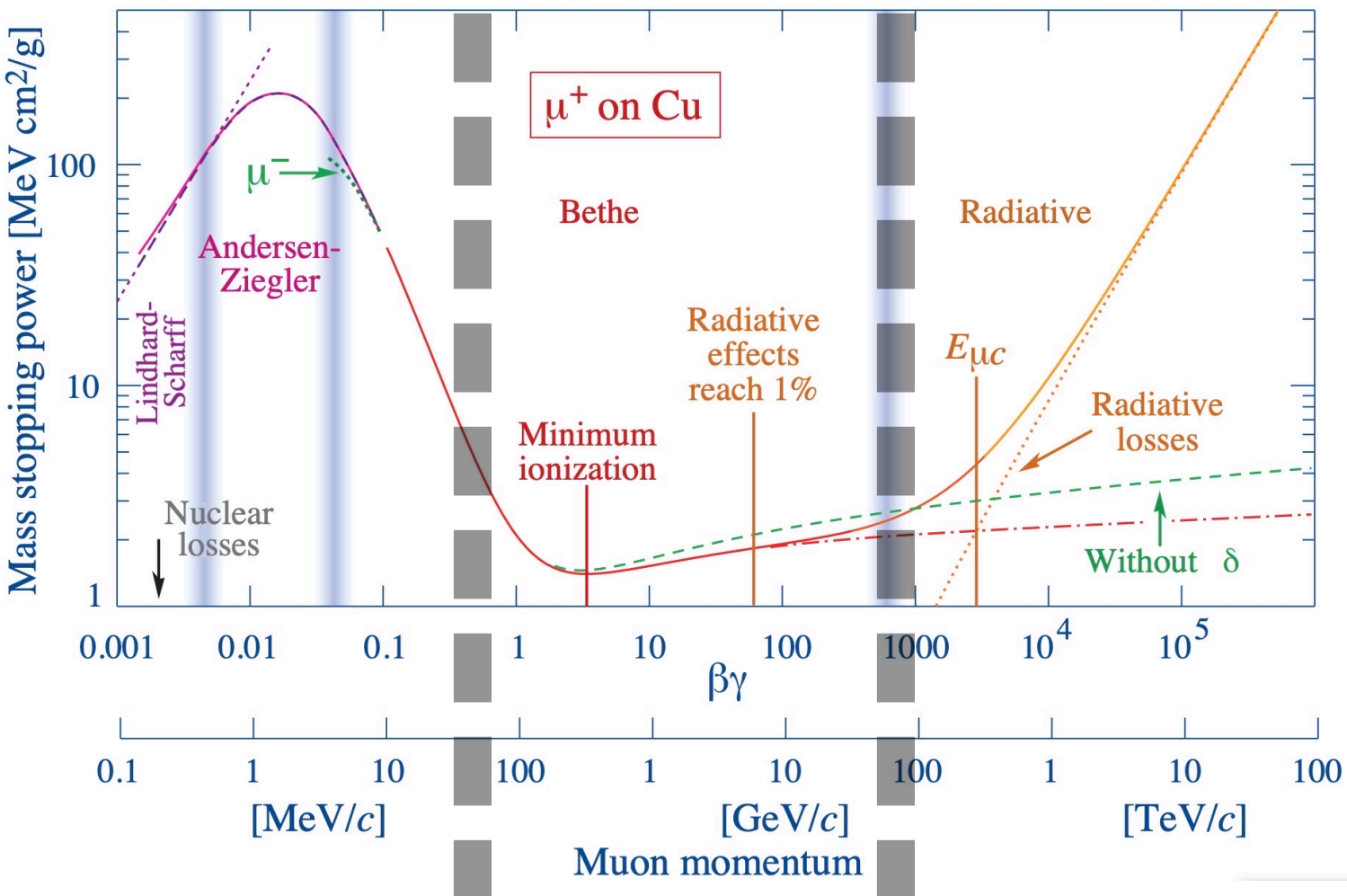
note: ✡ "...?" correspond to discussion questions throughout this lecture.

Let's start with one,

✡ What particles can be produced in a high energy (DIS) neutrino interaction? Which do you think are visible and why?



Particle Data Group, "Passage of Particles through Matter"


μ+ on Cu
Mass stopping power [MeV cm²/g]
100
10
1
μ−
Andersen-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
Radiative
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Muons

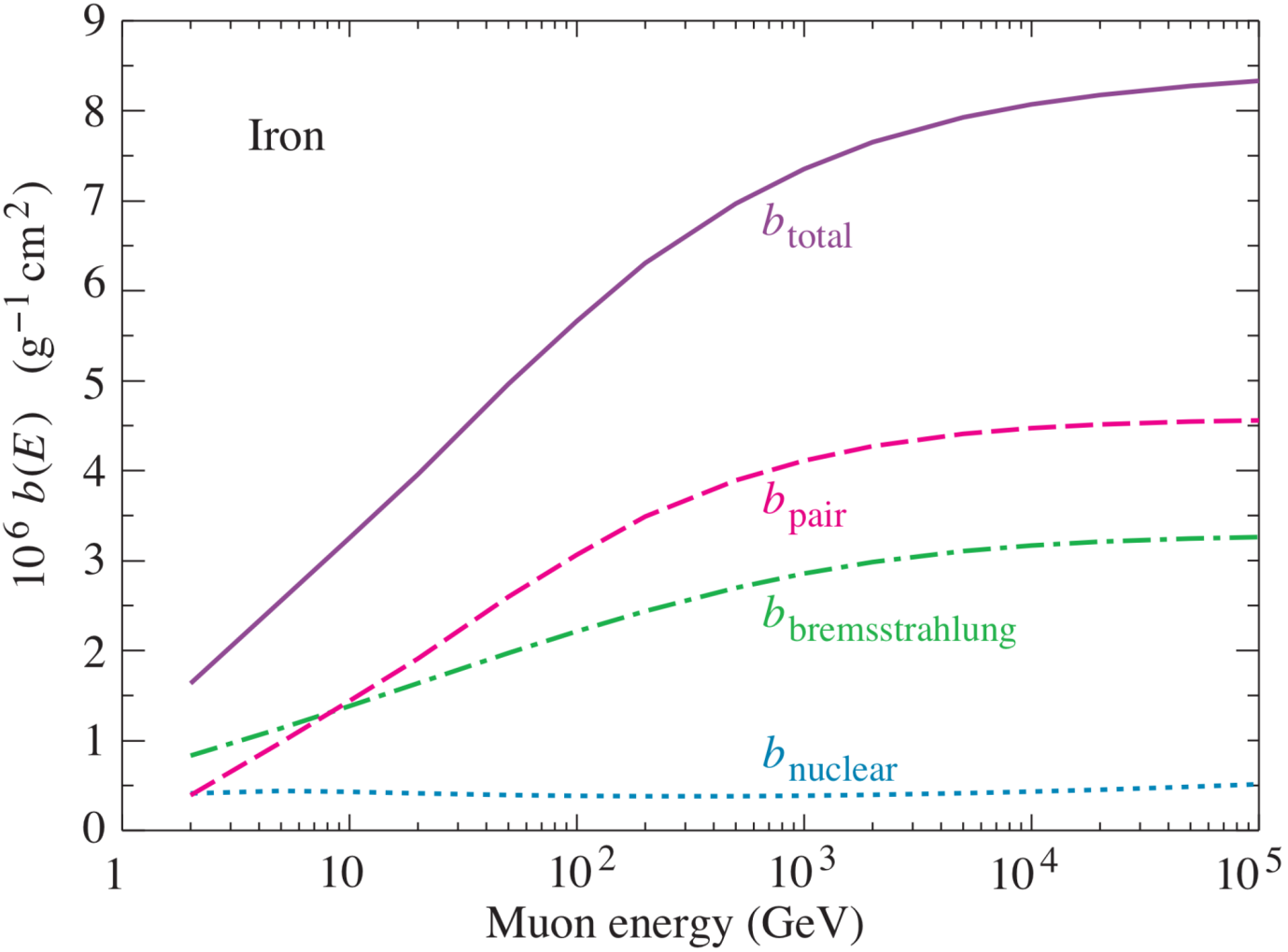
★ Given this, what is the most physically-motivated description of $\left\langle \frac{dE}{dx} \right\rangle$ for a muon?

a) $\left\langle \frac{dE}{dx} \right\rangle = a$

b) $\left\langle \frac{dE}{dx} \right\rangle = bE$

c) $\left\langle \frac{dE}{dx} \right\rangle = a + bE$

d) $\left\langle \frac{dE}{dx} \right\rangle = a + bE + cE^2$



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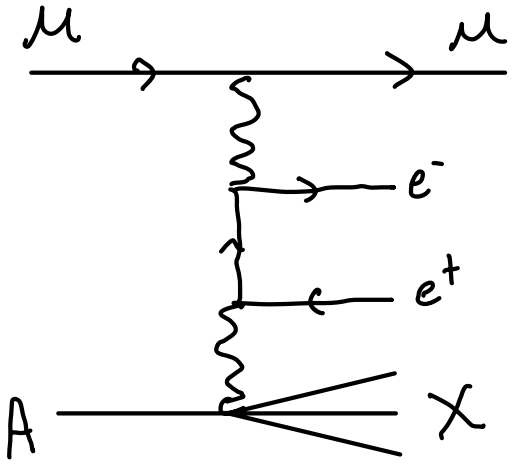
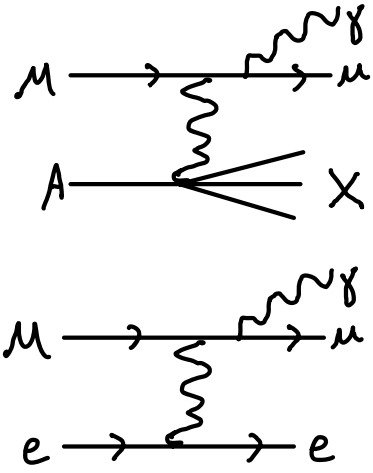
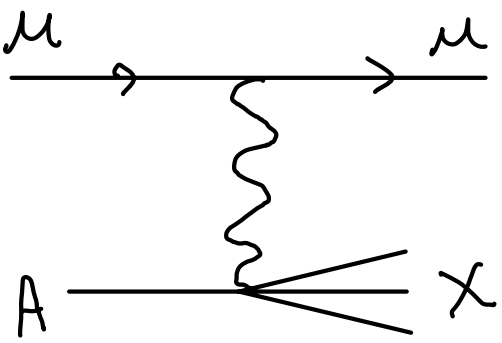
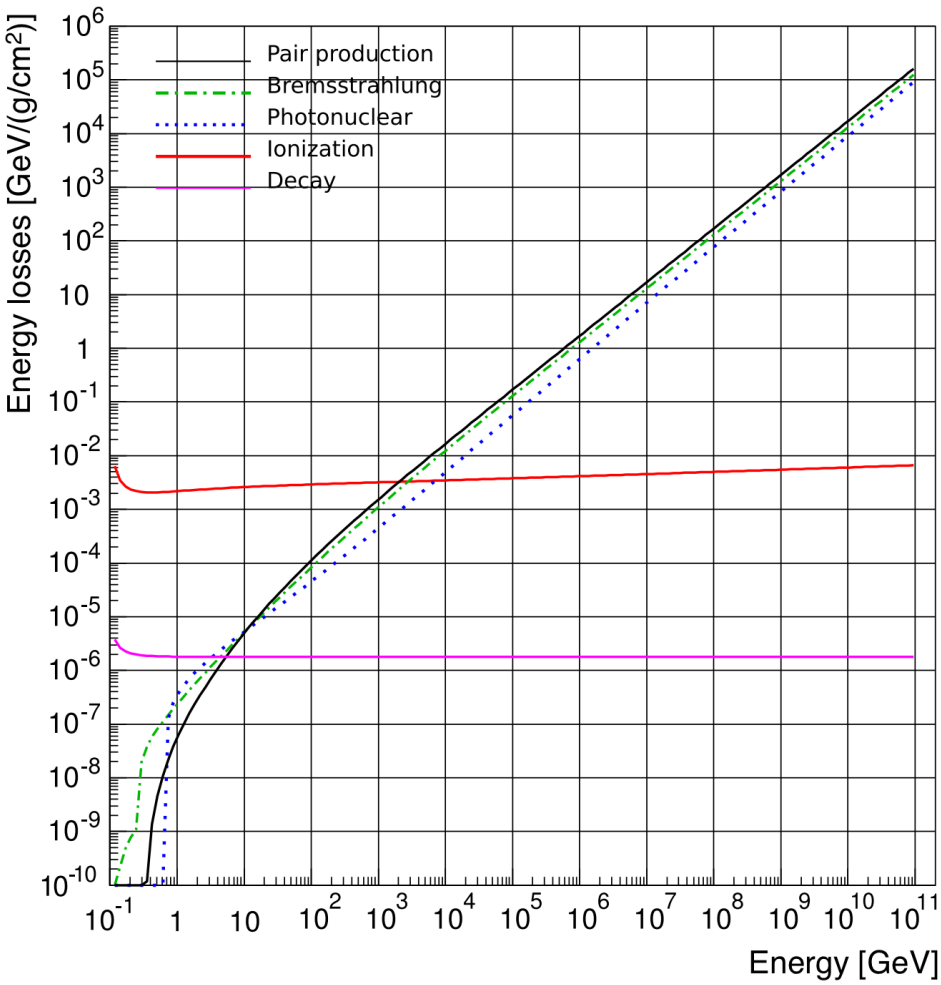
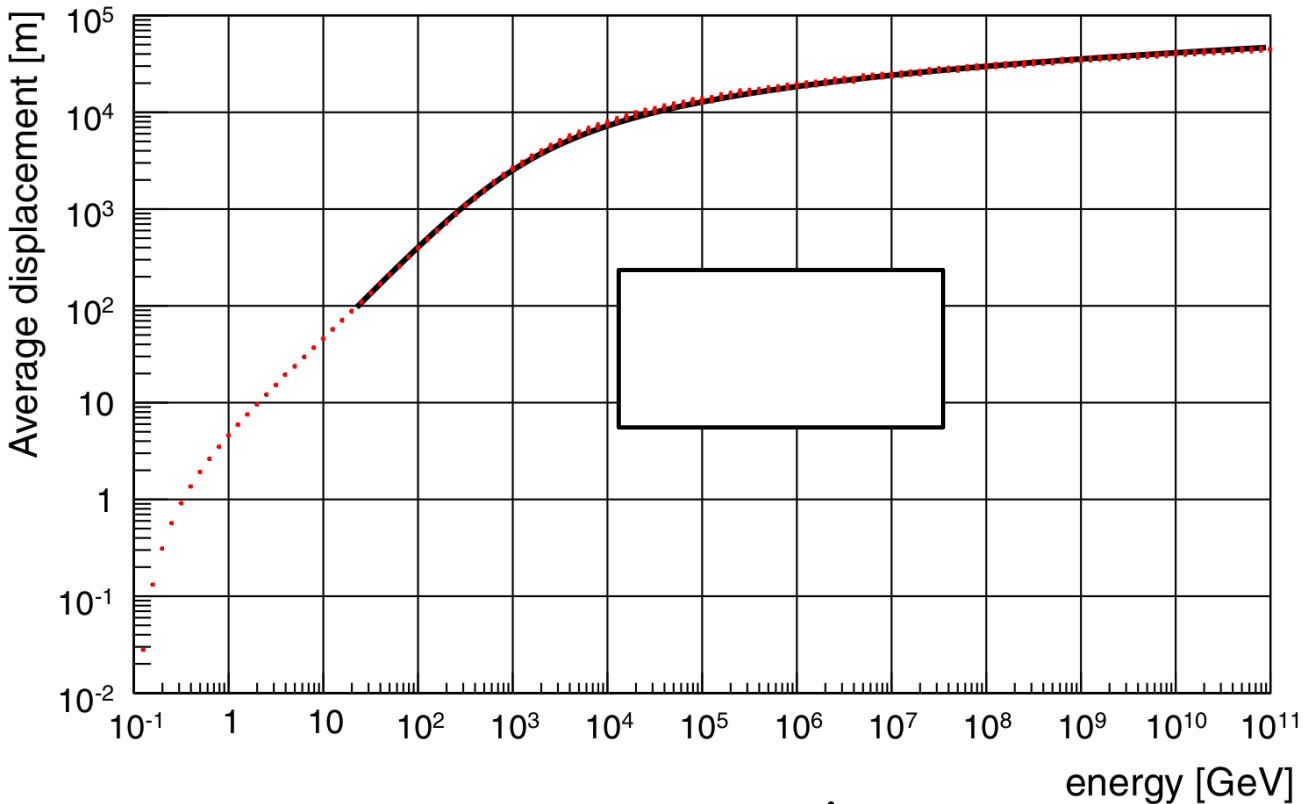








Muon energy losses in ice, Koehne et al. PROPOSAL (2013)



Muon range in ice, Koehne et al. PROPOSAL (2013)

Electrons

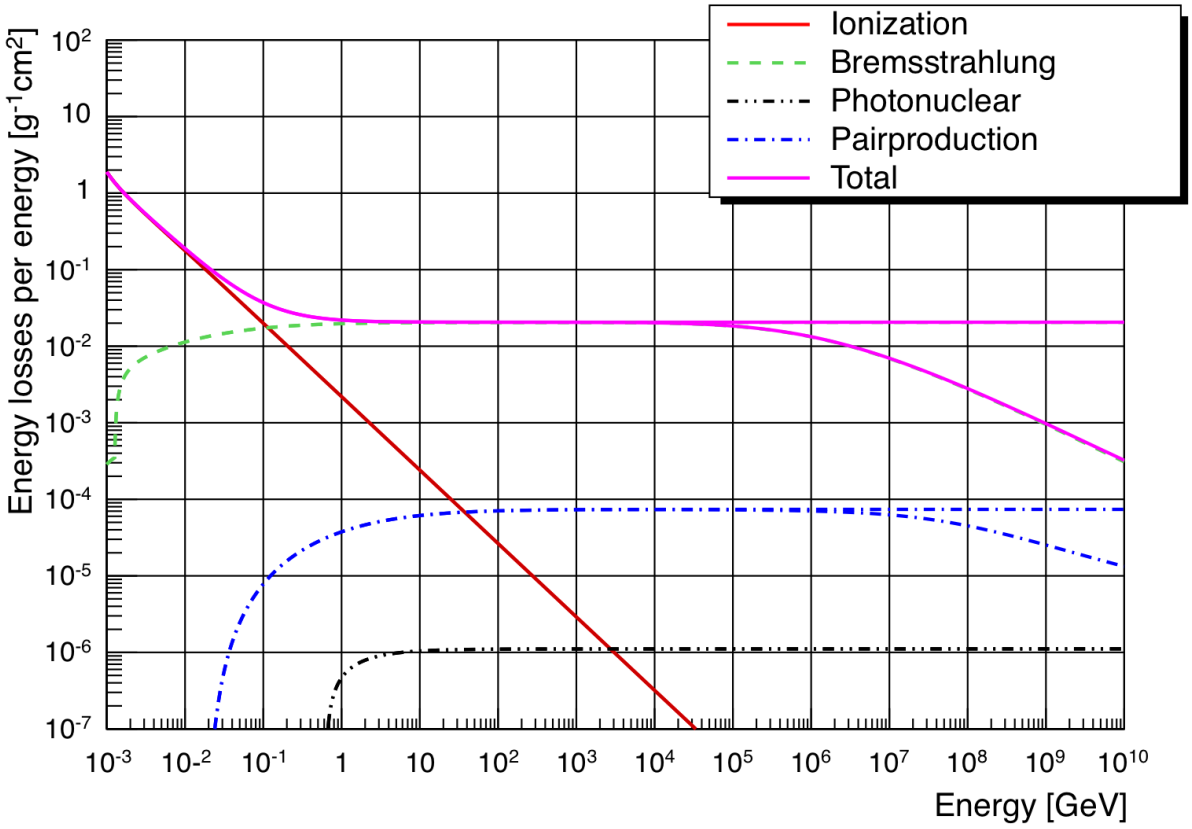
☆ How do you think electrons will behave in IceCube compared to muons?

a) similarly → they are stable leptons

b) they will ~always be MIPs

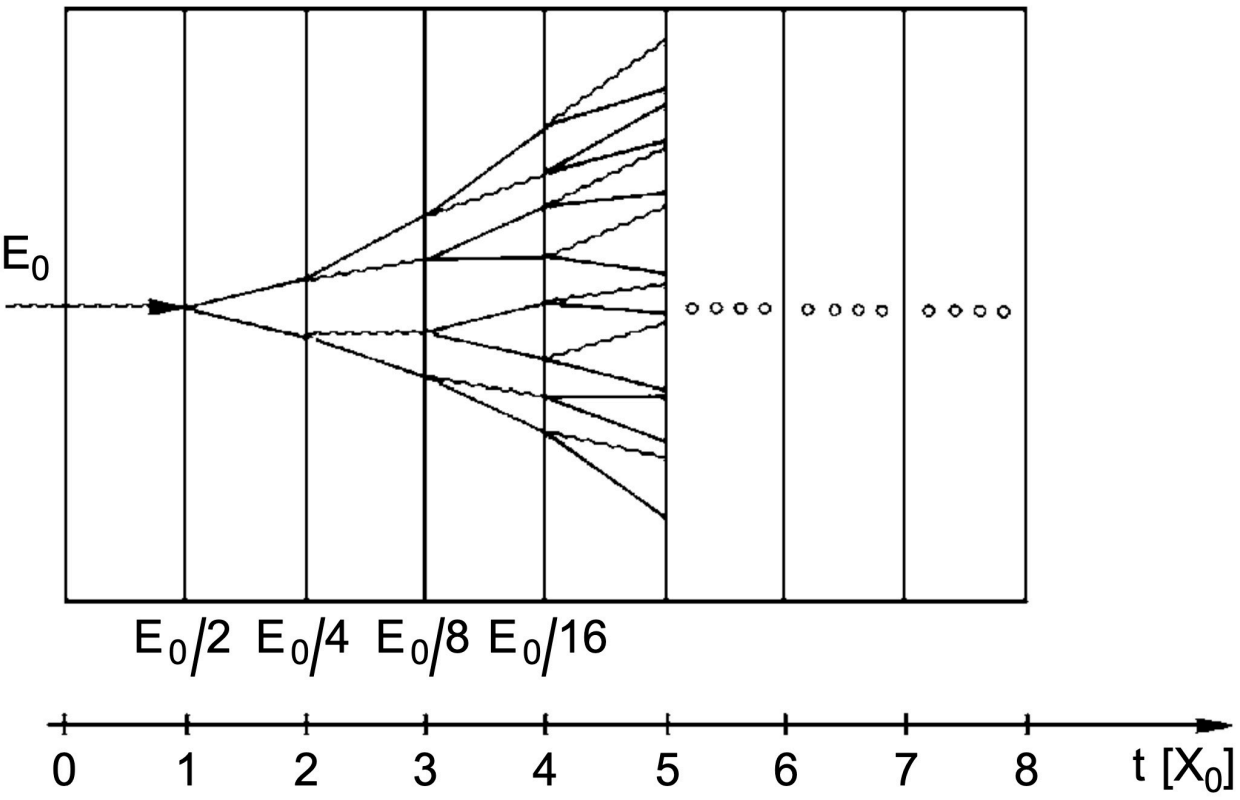
c) they will ~always be in the radiative regime

$$\left\langle \frac{dE}{dx} \right\rangle \Big/ E$$

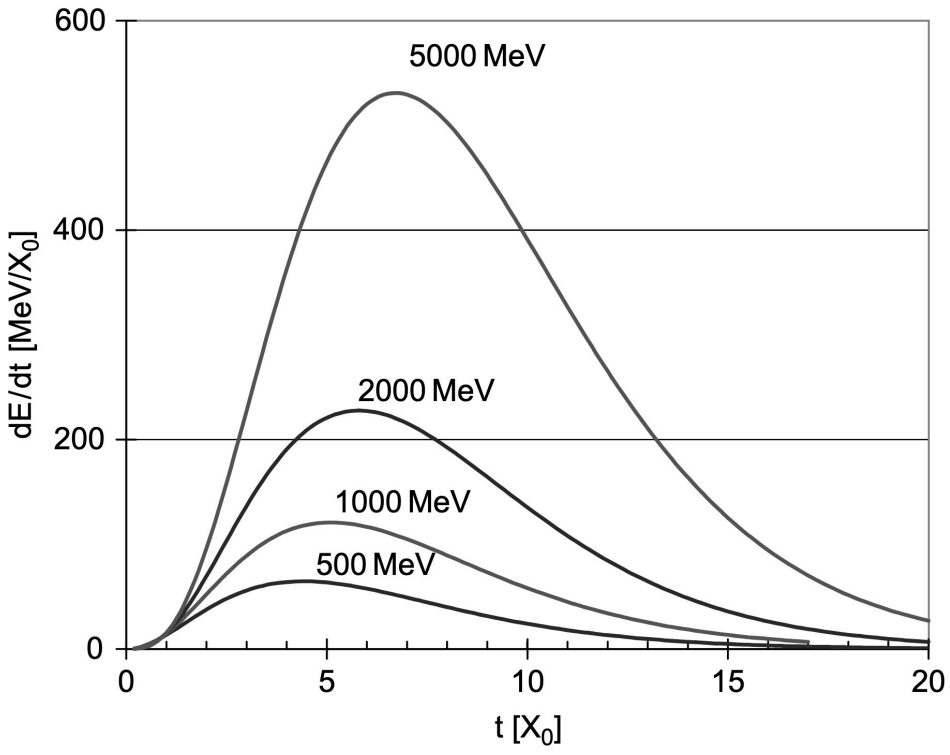


Electron energy losses in ice

Koehne et al. PROPOSAL (2013)



Grupen + Shwartz 2008



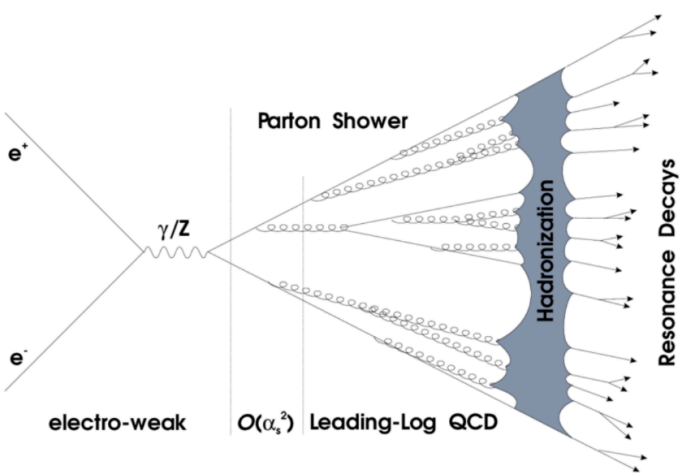
Grupen + Shwartz 2008

☆ Between muons (tracks) and electrons (cascades), which do you think has better

- energy reconstruction?

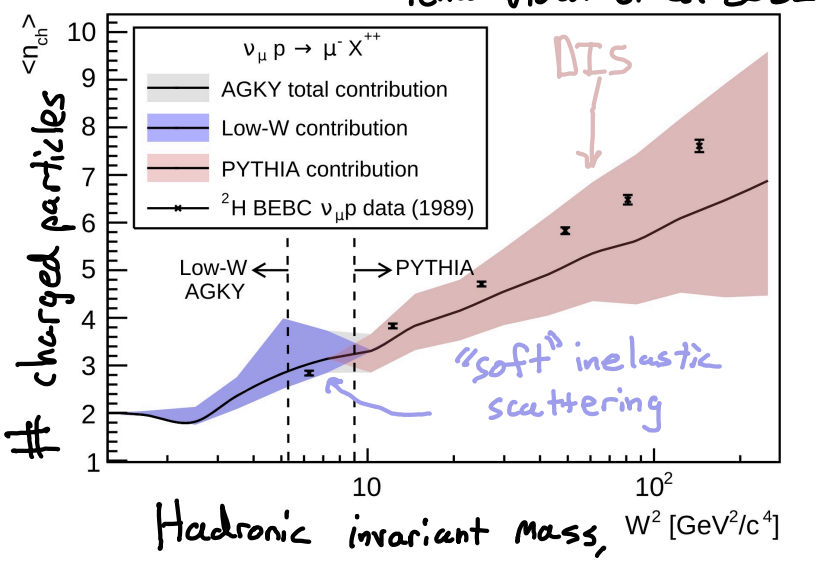
- directional reconstruction?

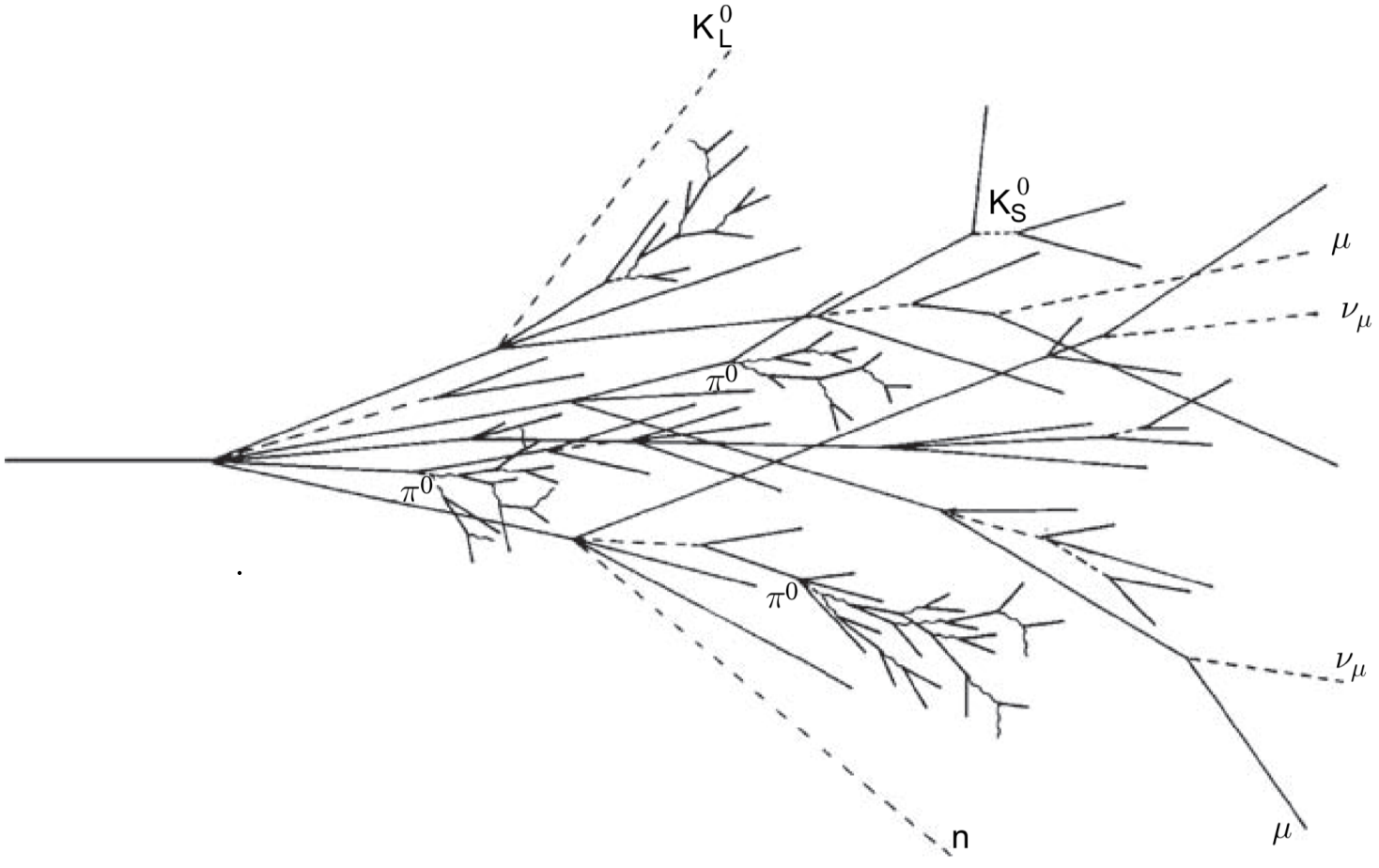
Hadrons



Sarkar 2000

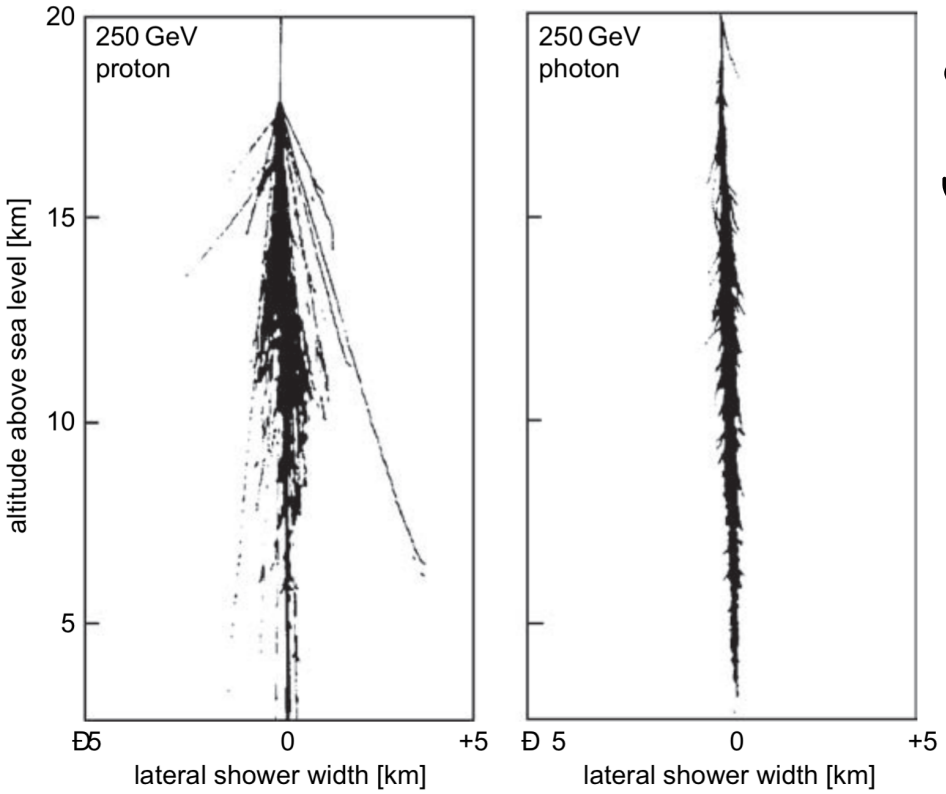
Tena-Vidal et al 2022





Hadronic shower, Grupen + Shwartz 2008

Important aspects of hadronic cascades:

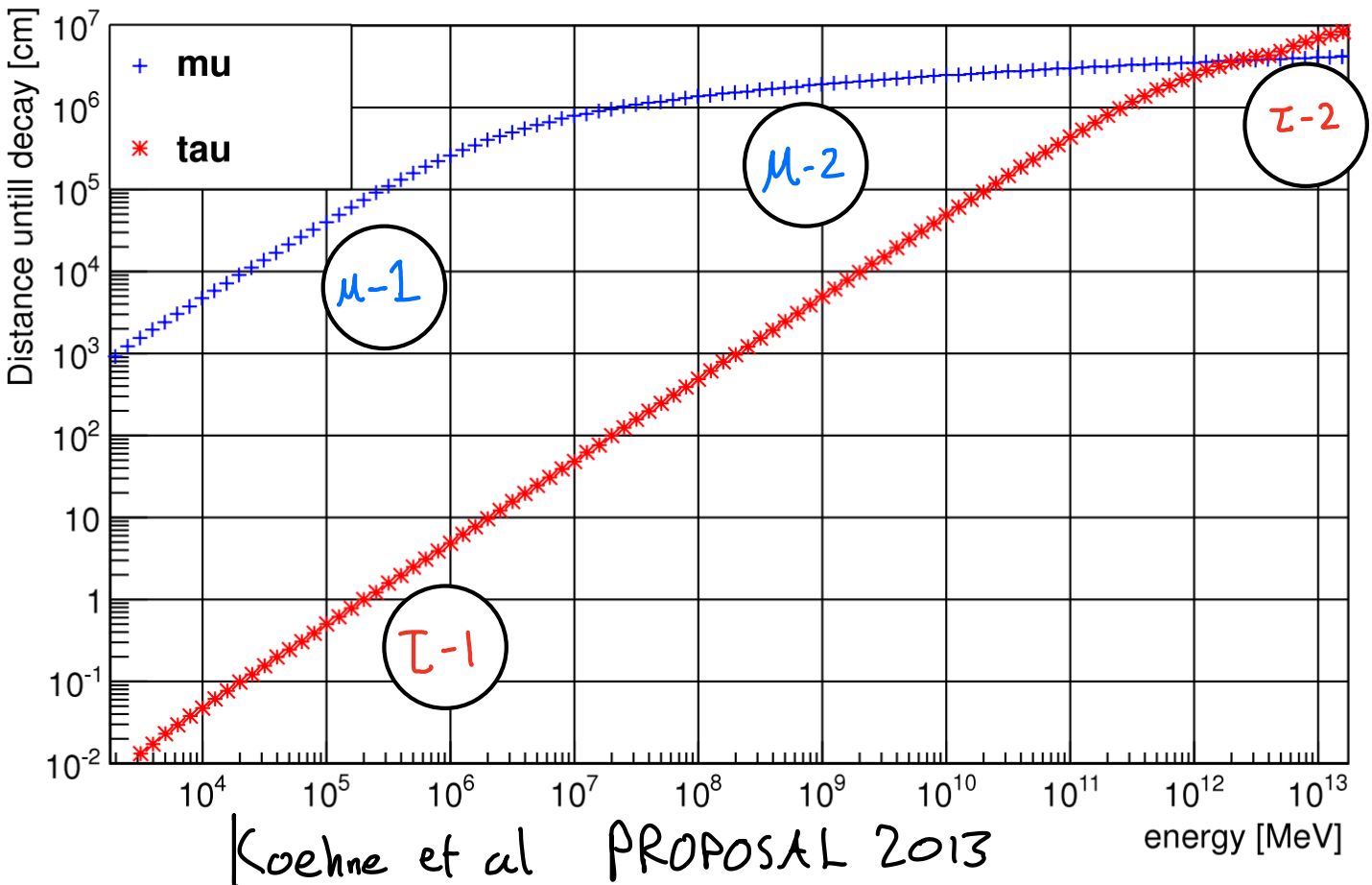


Simulated hadronic v.s. EM showers in the atmosphere, Gaisser & Shwartz 2008

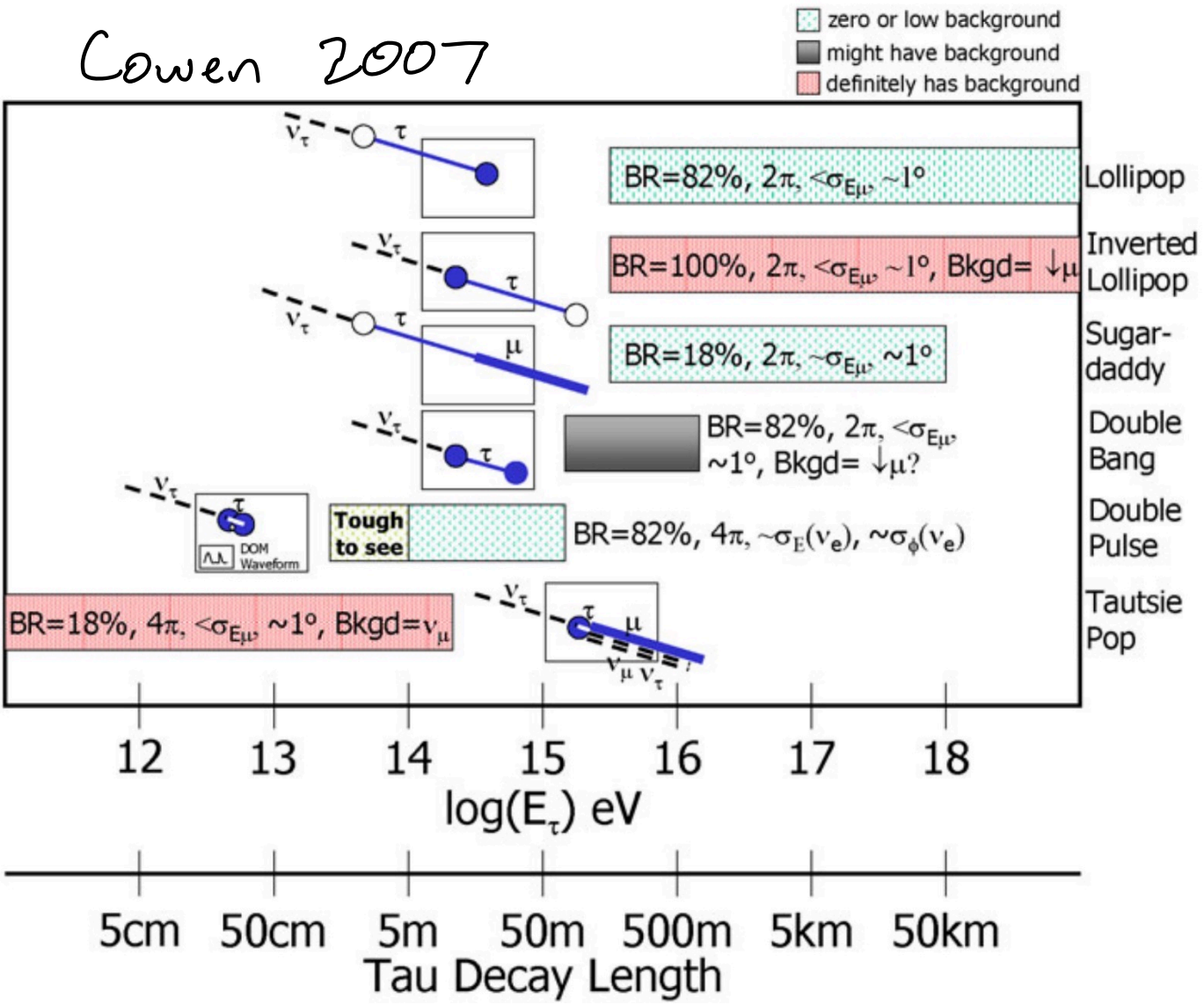
(note $\lambda_{int}^{air} \gg \lambda_{int}^{ice}$)

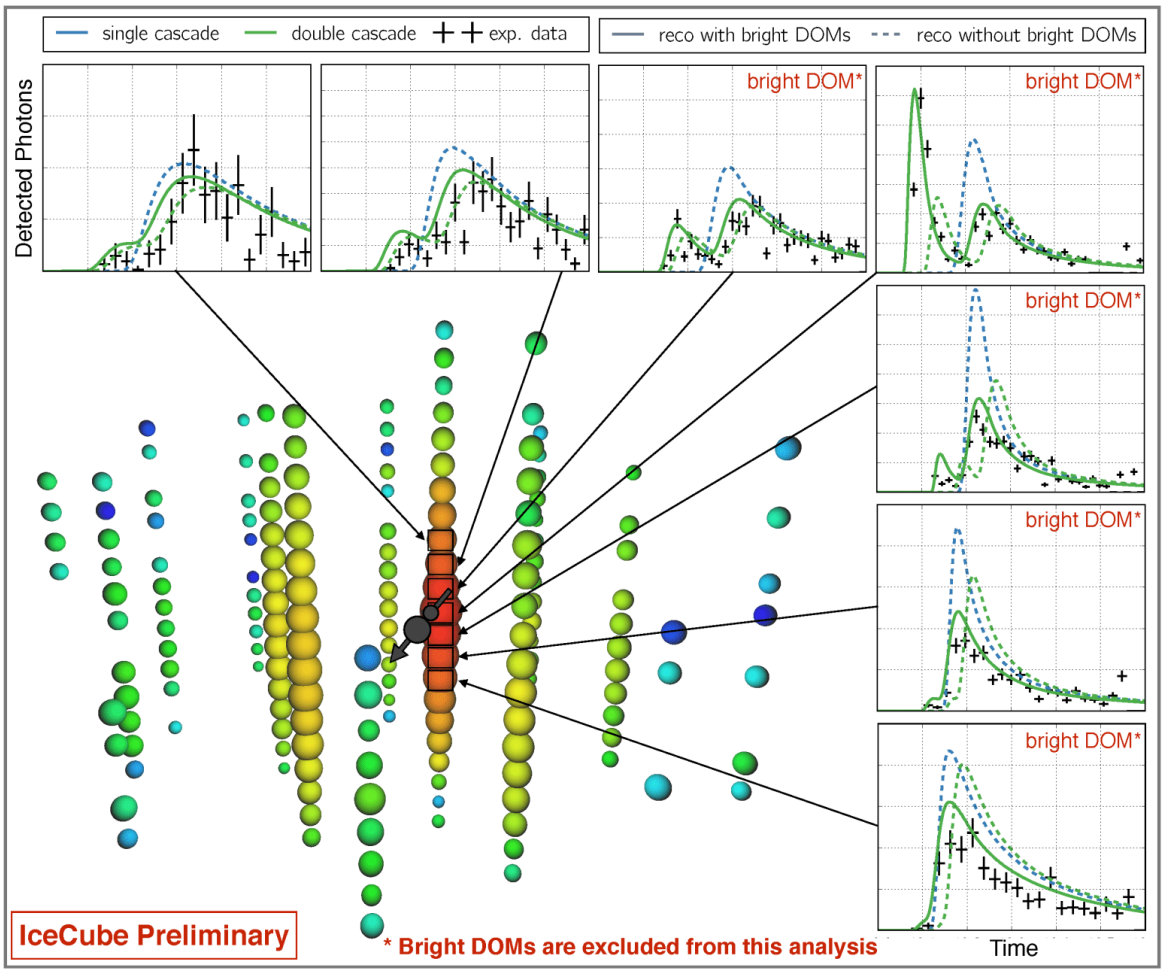
Taus

☆ What is limiting the range of muons and taus at each point; ionization, radiative losses, or decay? Bonus: how does the range scale with energy in each region?



Cowen 2007


zero or low background
might have background
definitely has background
BR=82%, 2π, <σEμ, ~1°
Lollipop
BR=100%, 2π, <σEμ, ~1°, Bkgd= ↓μ
Inverted Lollipop
BR=18%, 2π, ~σEμ, ~1°
Sugar-daddy
BR=82%, 2π, <σEμ, ~1°, Bkgd= ↓μ?
Double Bang
DOM Waveform
Tough to see
BR=82%, 4π, ~σE(νe), ~σφ(νe)
Double Pulse
BR=18%, 4π, <σEμ, ~1°, Bkgd=νμ
Tautsie Pop
12
13
14
15
16
17
18
log(Eτ) eV
5cm
50cm
5m
50m
500m
5km
50km
Tau Decay Length

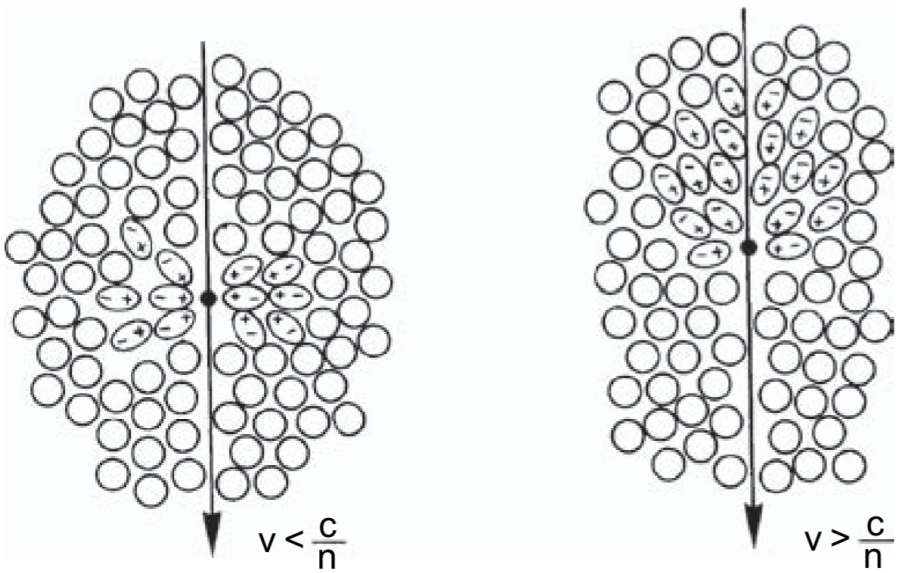


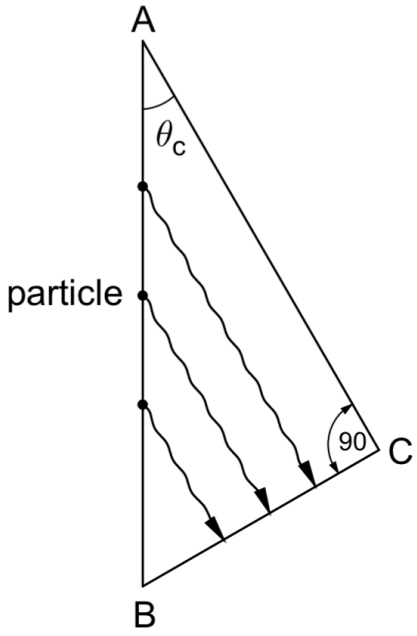
IceCube 2022

First ν_τ candidate

"Double Double"

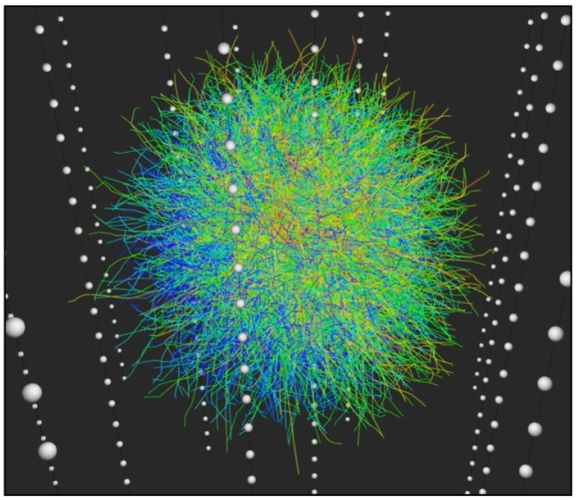
So how do we detect charged particles?





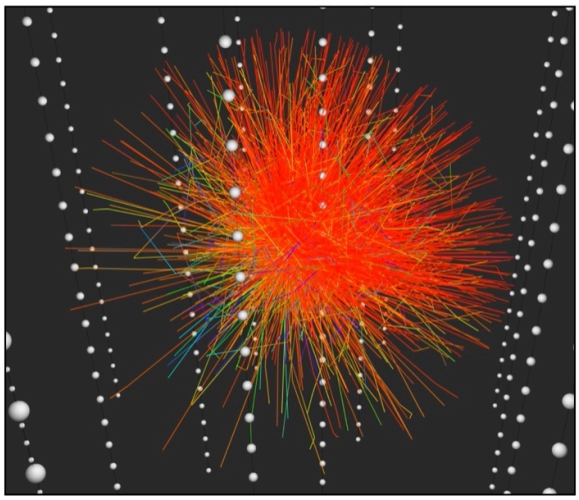
Grupen + Shwartz 2008

Short scattering length, long absorption length



10 TeV in ice

Short absorption length, longer scattering length



10 TeV in water

☆ Between ice and water, which do you expect to have better...

angular reconstruction?

energy reconstruction?

Other high energy neutrino detection techniques