Neutrino detection techniques from MeV to EeV

David Seckel
Univ. of Delaware
May 22, 2018

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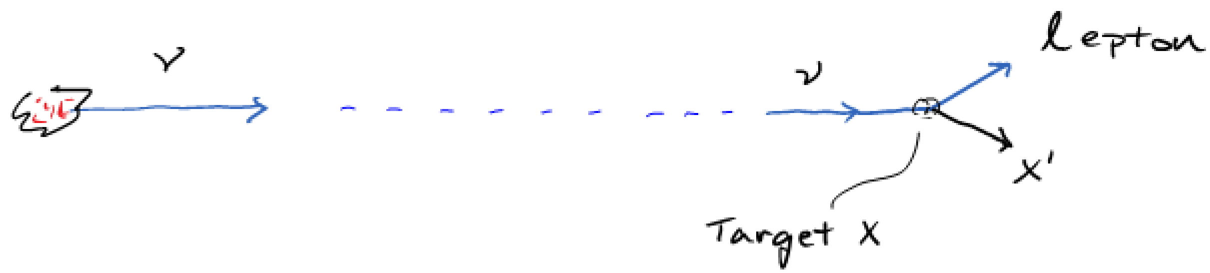
What does it mean to “detect a neutrino” ?



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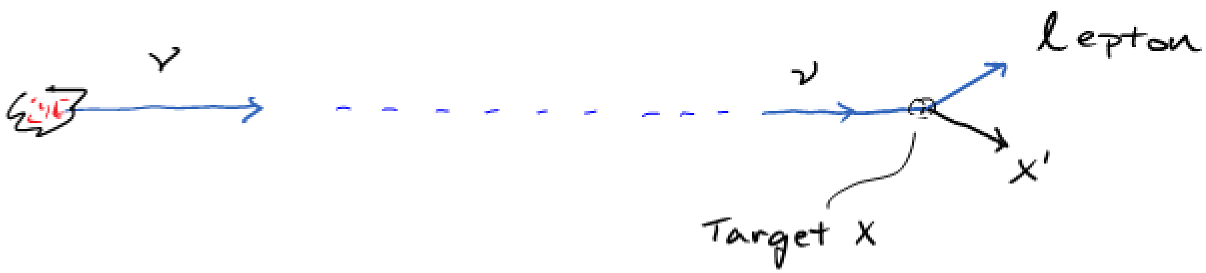

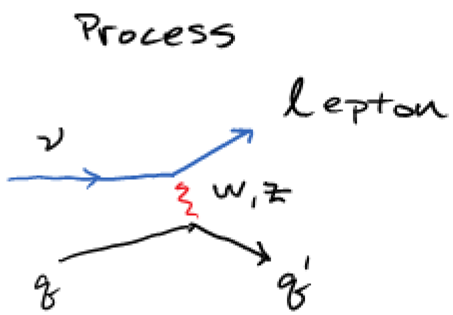

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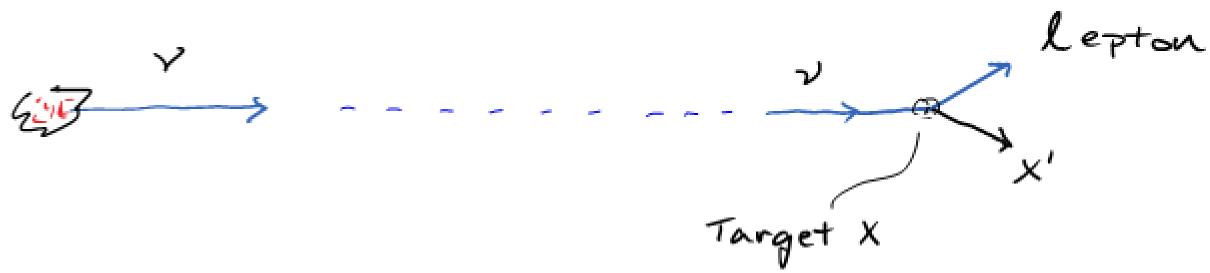

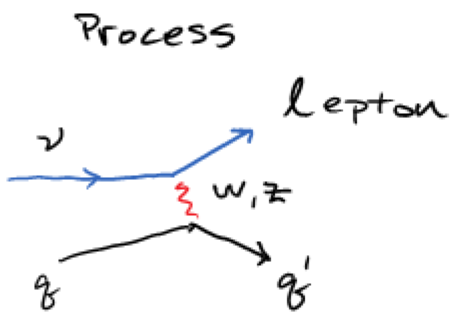

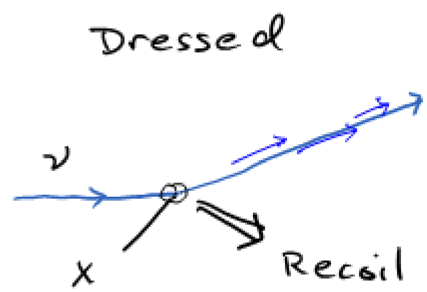

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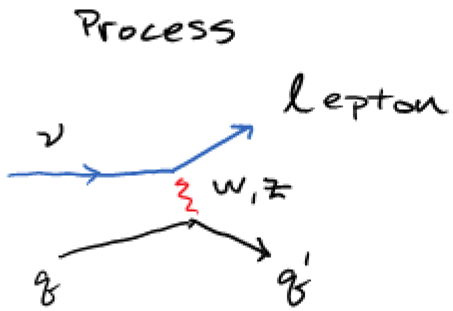
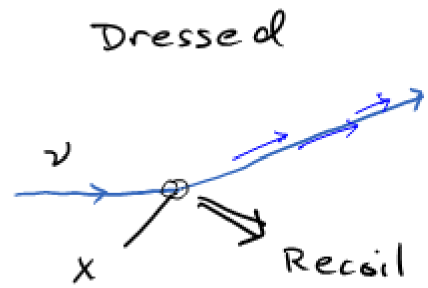
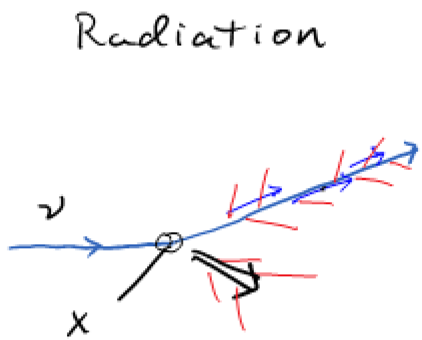
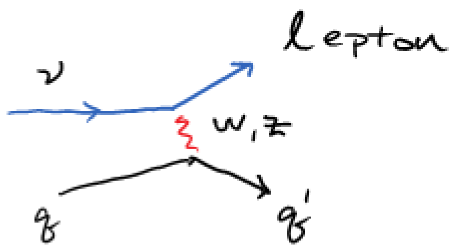




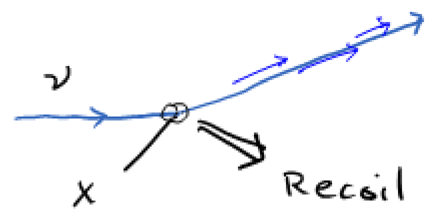


What does it mean to "detect a neutrino" ?

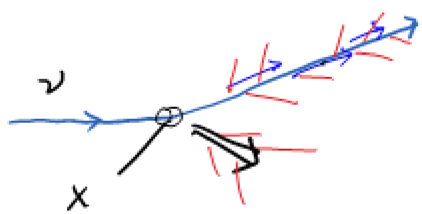
Process



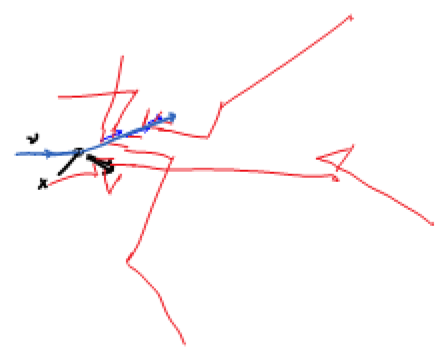
Dressed



Radiation



which propagates



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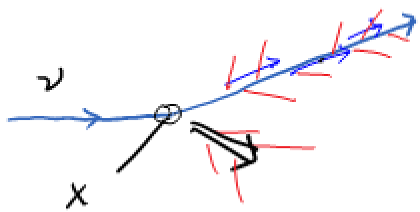
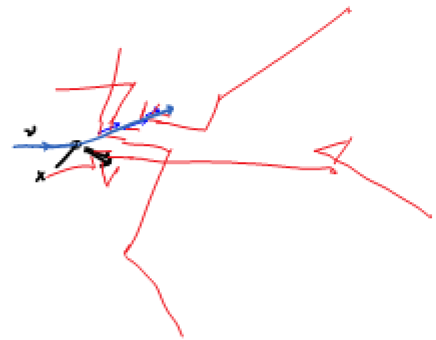
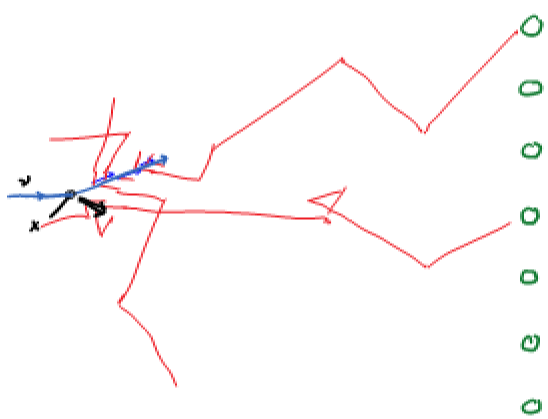
Radiation



which propagates

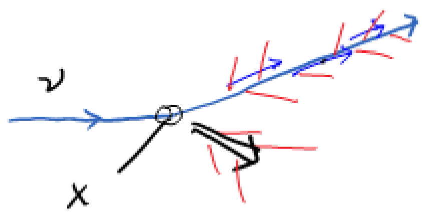


and some is detected

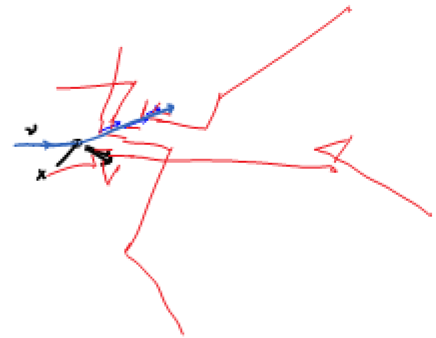


What does it mean to “detect a neutrino” ?

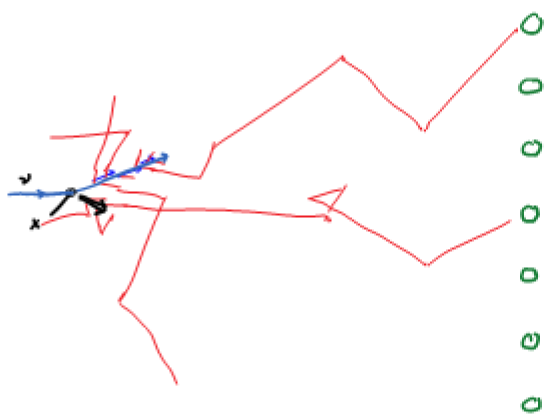
Radiation

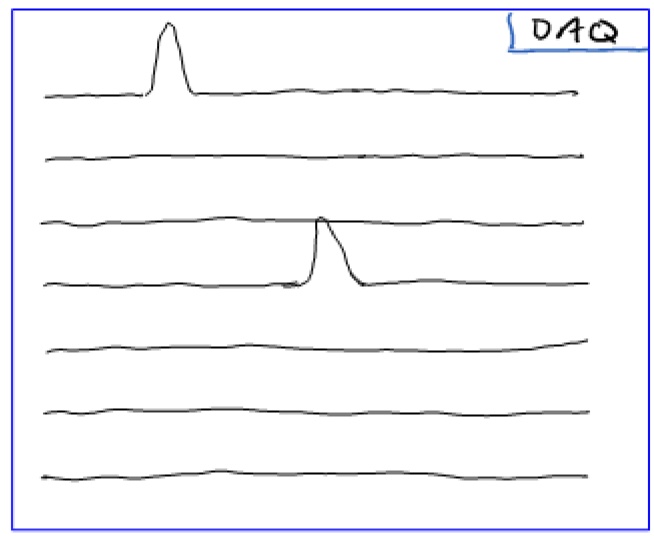


which propagates



and some is detected





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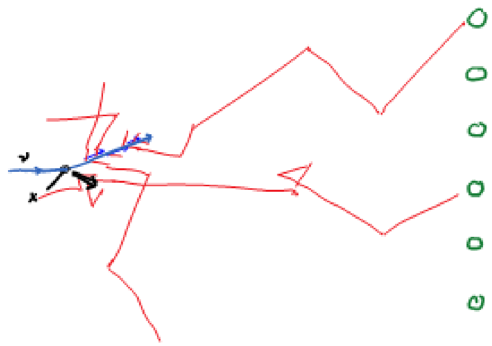
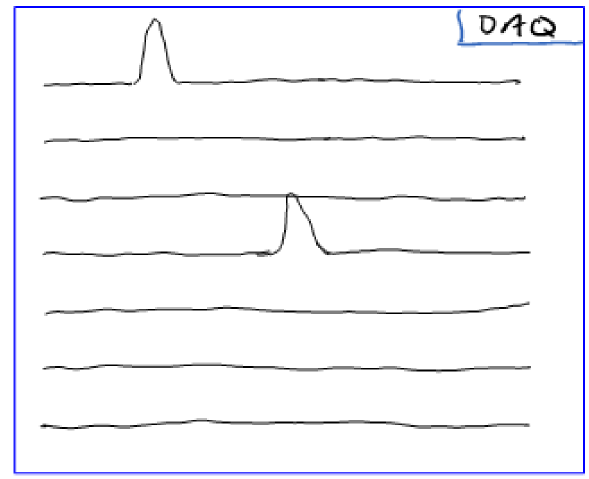
and some is detected





Analysis – Does it look like a neutrino ?

... Simulation – what should it look like

Backgrounds – ?

Extract
- Rate
- E
- $\hat{\Omega}$
- topology → particle id

Outline

- Lots of moving parts
- Intro and basics
  - Science goals
  - Neutrino properties
  - Requirements
  - Cases
- Strategies
- Cascades and tracks
  - EM cascades
  - Hadronic Cascades
  - Tracks
  - Air/dense
- Imaging cascades & tracks
  - Radiation, Propagation, "Camera"
- Optical techniques
- Radio techniques

Science Goals

- Man made
  - reactor
  - accelerator/beam
  - Red October

- Study neutrino properties
- Monitor sources

- Natural
  - relics of BB
  - radioactive decays
  - solar
  - supernovae
  - natural beams
    - atmospheric
    - astrophysical

- Study neutrino properties
- Source properties
  - internal properties
  - source distributions and evolution
- Propagation probes (MSW, Γ)
- Study neutrino flux as background

Different from γ

Astrophysical neutrinos

- SM particle astrophysics
  - extreme objects (multi-messenger …)
  - acceleration processes within source
  - propagation, e.g. flavor mixing

- SM cosmology
  - evolution of sources
  - propagation, e.g. cosmogenic production

- Particle physics
  - probe higher energies
    - Standard model (σ), new interactions
    - particles other than SM neutrinos?
  - Lorentz invariance
  - is $U_{\alpha i}$ universal?

Neutrino properties: SM

$$\mathscr{L}_F = \sum_i \overline{\psi}_i \left(i\,\partial\!\!\!/ - m_i - \frac{m_i H}{v} \right) \psi_i$$ mass

$$- \frac{g}{2\sqrt{2}} \sum_i \overline{\Psi}_i \, \gamma^\mu \, (1-\gamma^5)(T^+ \, W_\mu^+ + T^- \, W_\mu^-) \, \Psi_i$$ CC

$$- e \sum_i Q_i \, \overline{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu$$ charge

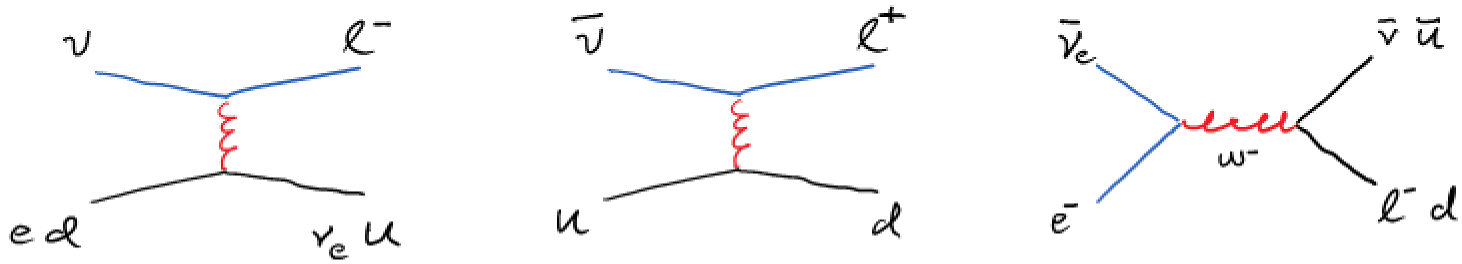
$$- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \, \gamma^\mu (g_V^i - g_A^i \gamma^5) \, \psi_i \, Z_\mu \, .$$ NC

$$g_V^i \equiv t_{3L}(i) - 2Q_i \sin^2\theta_W,$$
$$g_A^i \equiv t_{3L}(i),$$

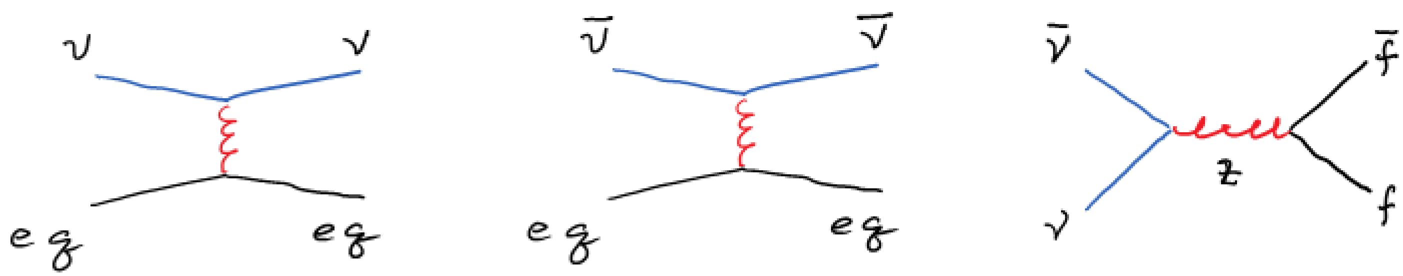
Defines most interactions of neutrinos with matter. Also $WWZ, WW\gamma$

Processes

- Charged current

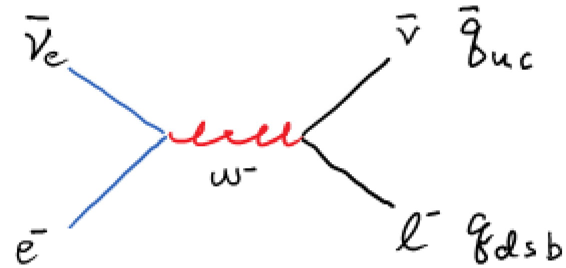


- Neutral current

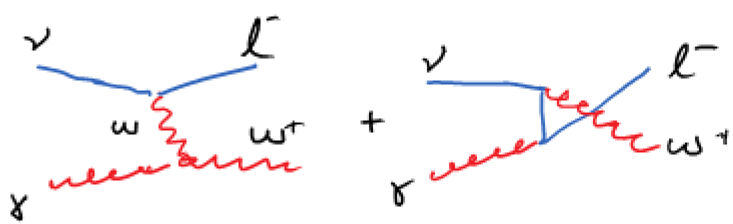


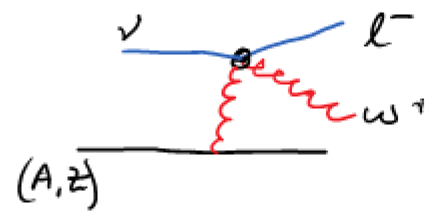
HE Processes

- Glashow resonance



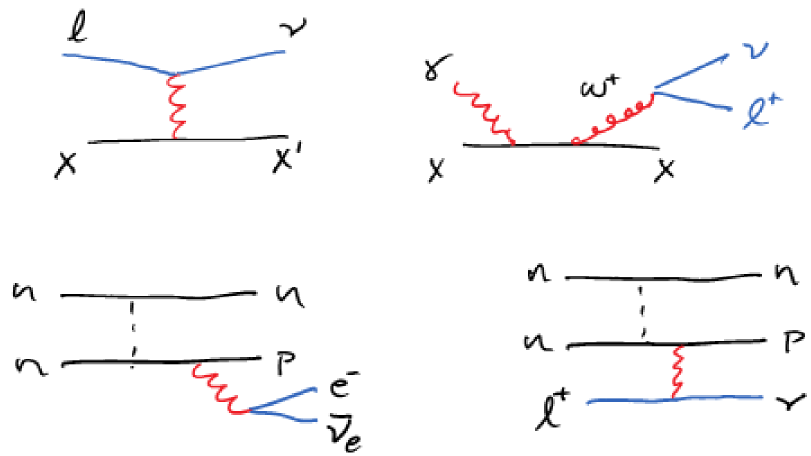
- $\gamma\nu$ and "W – bremsstrahlung"



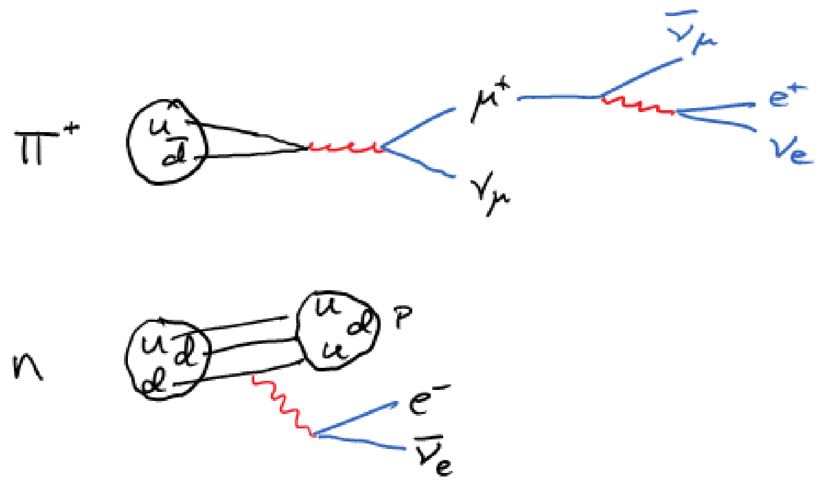


ν –production

- Scattering

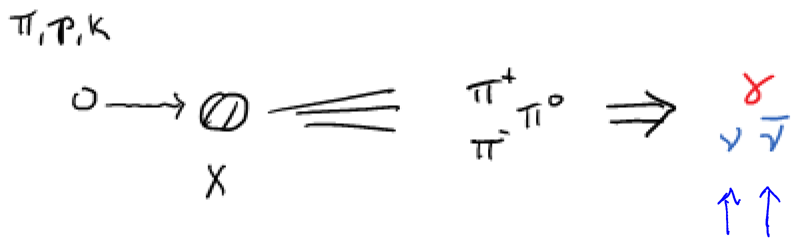


- Decays

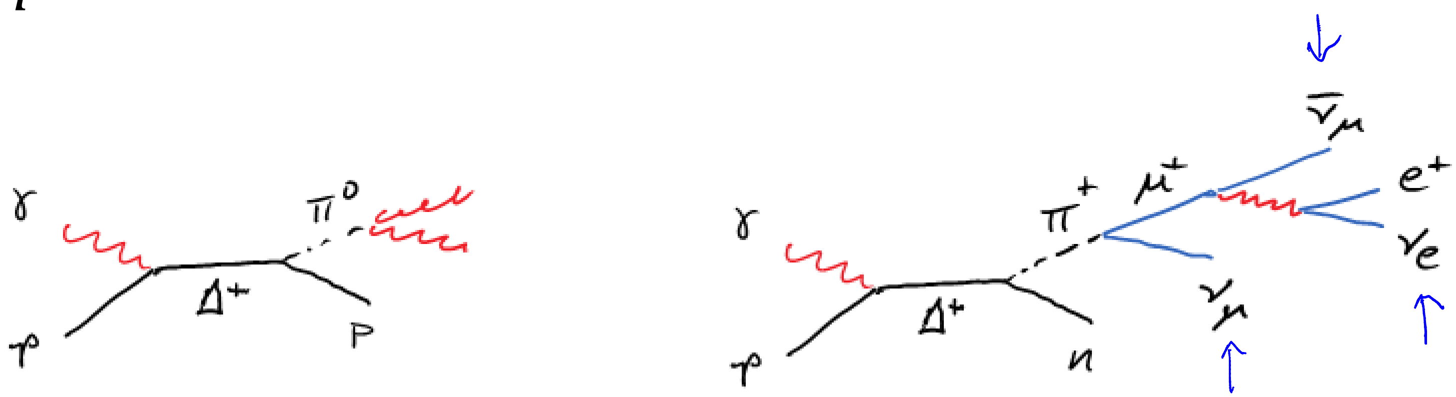


HE Production

- hadronic cascades

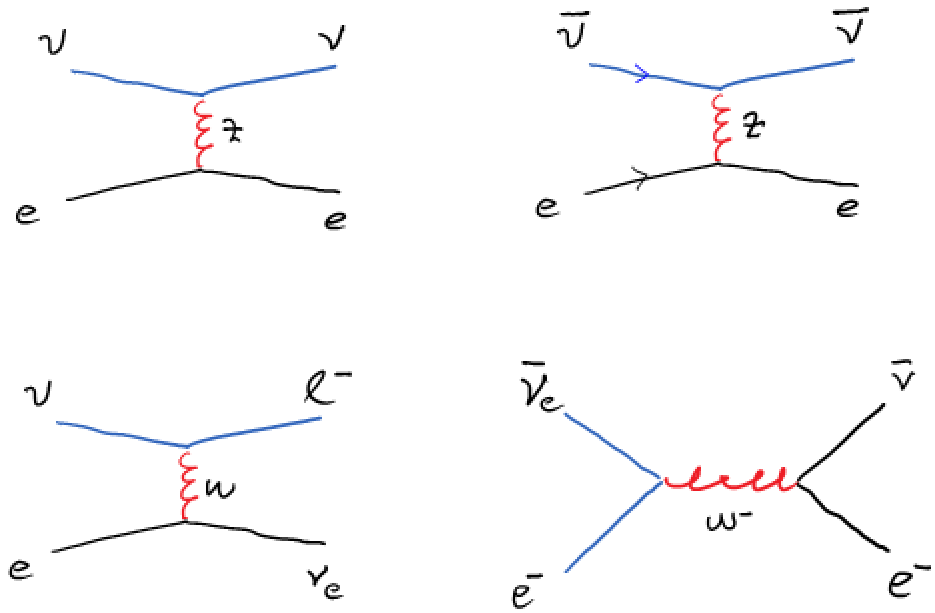


- γp- reactions



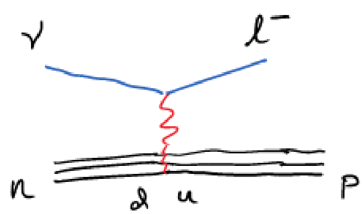
ν –interactions

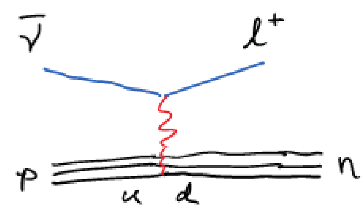
- electron scattering

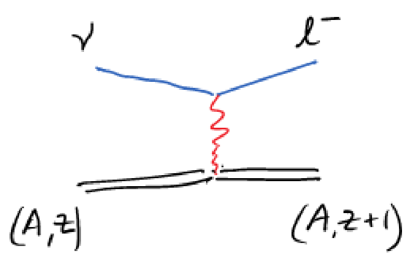


ν –interactions

- Charged current in nuclei

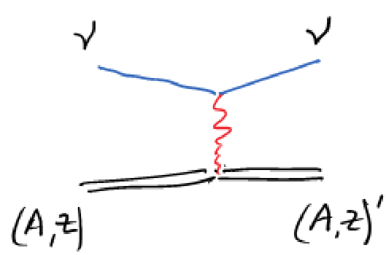






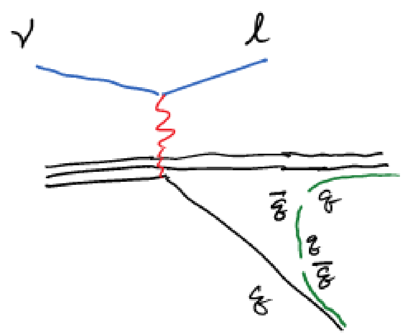
$$\langle A\, Z{+}1 | \left(\sum | \quad \rangle \langle \quad | \right) T^{+} \left(\sum | \quad \rangle\langle \quad | \right) | A, Z \rangle$$

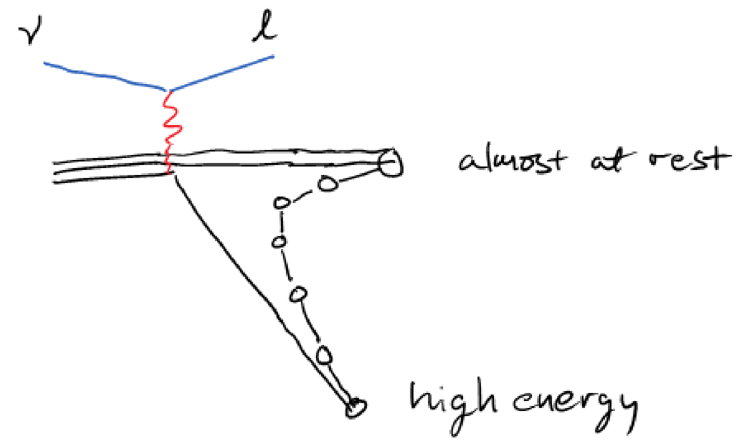
- Neutral currents



HE ν –interactions

- Deep inelastic CC & NC





- Heavy quarks
  - valence

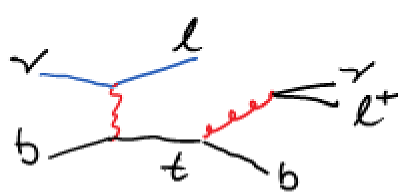
    $\nu: \quad d \to u\, c$

    $\bar\nu: \quad u \to d\, s$

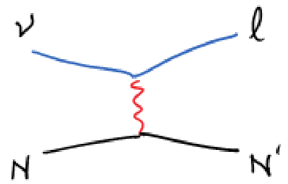
  - sea quarks

    $\nu \begin{cases} d\,s \to u\,c \\ \bar u\,\bar c \to d\,s \end{cases} \qquad \bar\nu \begin{cases} u\,c \to d\,s \\ \bar d\,\bar s \to \bar u\,\bar c \end{cases}$

  - top



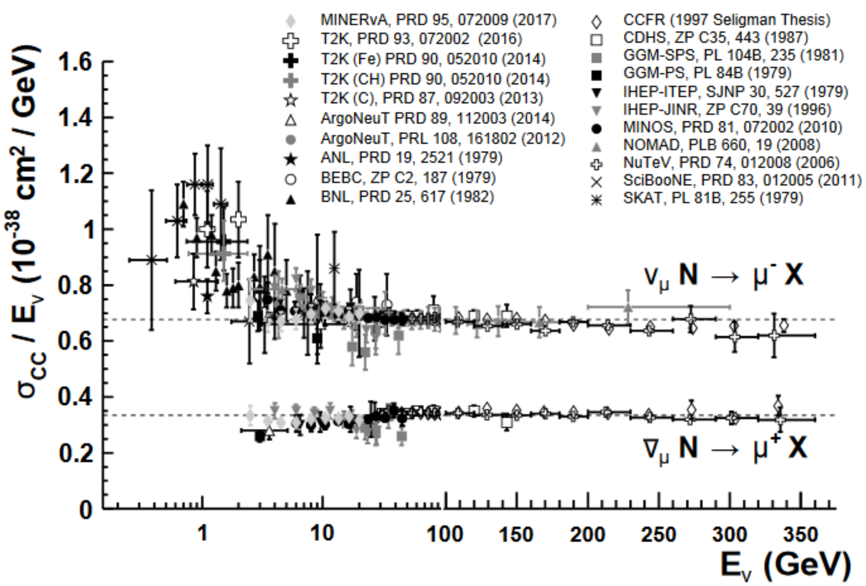
Cross-sections



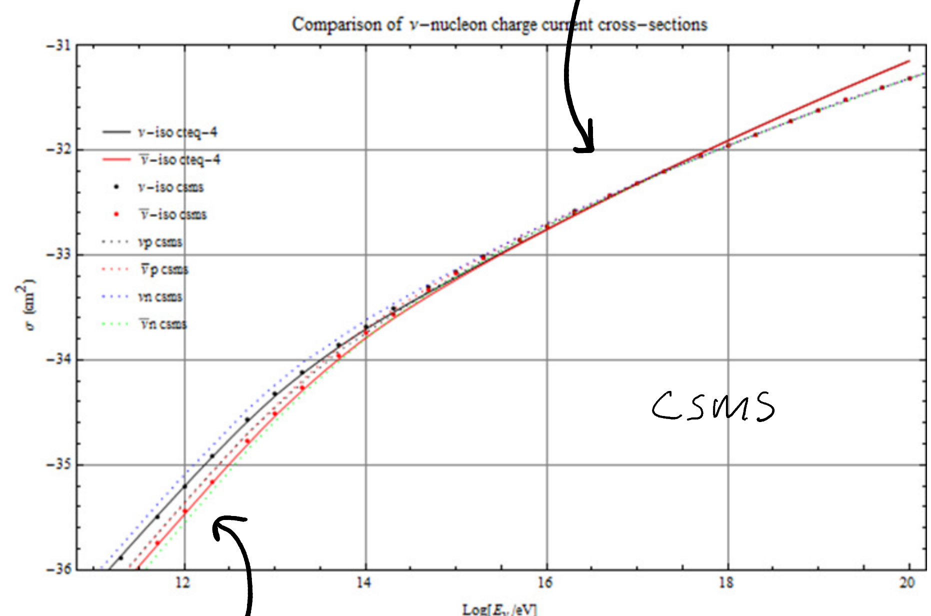
$$\sigma \sim \left(\frac{1}{M_W^2}\right)^2 s \sim \frac{m_N E}{M_W^4}$$

until $s \sim m_W^2$

still growing!



PDG



CSMS

~E different p, n, ν, $\bar{\nu}$

More on HE cross-sections

uncertainties

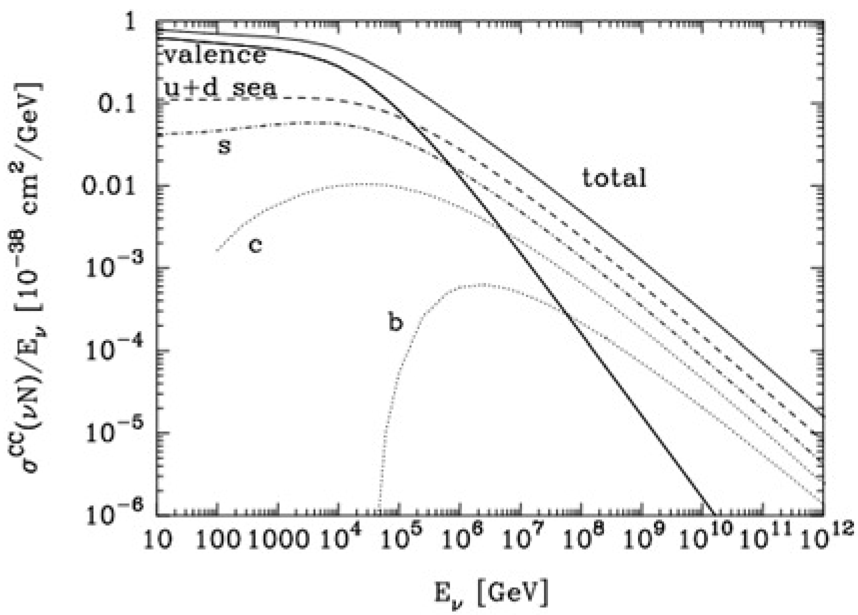
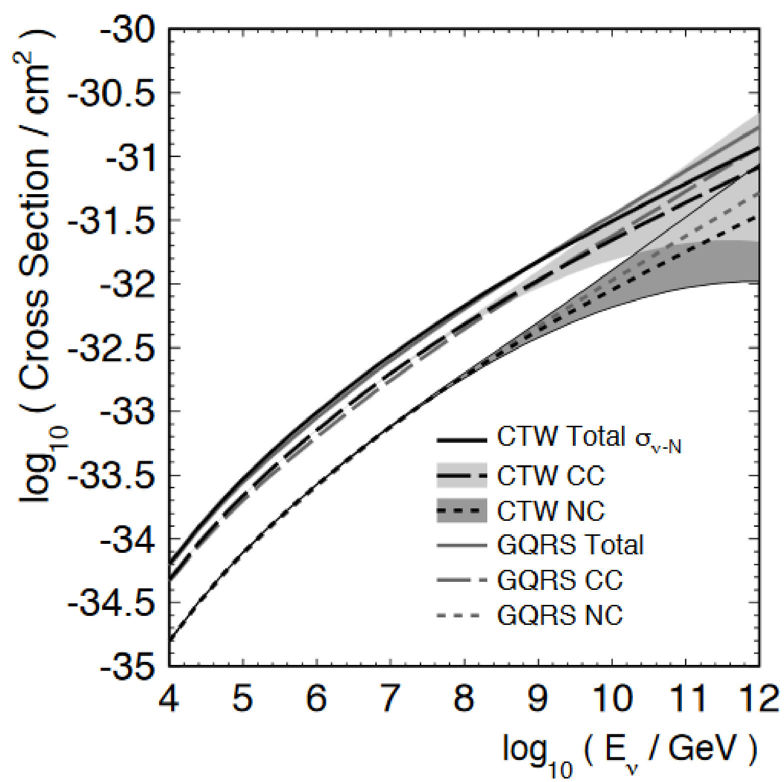


Fig. 2. Components of the νN charged-current cross section as functions of the neutrino energy for the CTEQ3 distributions.



QGRS

CTW

Propagation

- mass ≠ flavor

$$A_{\alpha\beta} = \sum_i U^*_{\alpha i} \, A_{ii}(t) \, U_{i\beta}$$

- detected flavor mix ≠ source flavor mix

- attenuation in the earth

Strategies

- “requirements”
- rates
- Comments on HE and ME case

Requirements

- events $N = \Gamma t$
- E – spectrum $E \pm \delta E$
- $\hat{\Omega}$ - direction $\hat{\Omega} \pm \delta\hat{\Omega}$
- event topology: particle-id

	e	μ	τ
ν			
$\bar{\nu}$			

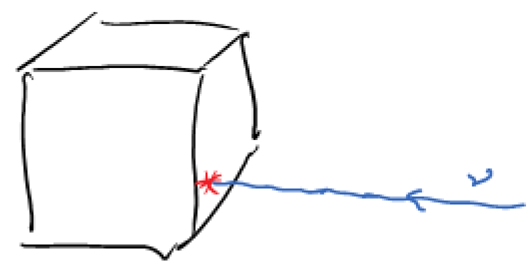
- backgrounds: events are significant
  - radioactivity
  - cosmic ray muons
  - “other” neutrinos

Event rates

- $N_{ev} = \int \Gamma \, dt$ $\qquad$ $\Gamma = \phi A$ $\quad$ Point source
  $\qquad\qquad\qquad\qquad\qquad$ $\Gamma = \phi A \Omega$ $\quad$ Diffuse

- $\Gamma = \phi A \;\Rightarrow\; \Gamma = \int \frac{d\phi}{dE} A(\hat{\Omega}, E)\, \varepsilon(\hat{\Omega}, E)\, dE$

- $A = N_t \sigma = n_t V \sigma$
  $= \int d^3\vec{x}\; n(\vec{x})\, \varepsilon(\hat{\Omega}, \vec{x})\, \sigma$



- $\Gamma = \phi A \Omega \;\Rightarrow\; \int \frac{d\phi}{dE\, d\hat{\Omega}} A(\hat{\Omega}, E)\, \varepsilon(\hat{\Omega}, E)\, d\hat{\Omega}\, dE$

Event rates

- Estimate analytically or simple simulation

… BUT … real work needs monte carlo including event simulation, radiation and propagation, detector response, background estimation, and prototype analysis

$$A = N_t \sigma = n_t V \sigma$$

$$= \int d^3\vec{x}\; n(\vec{x})\, \varepsilon(\hat{\Omega}, \vec{x})\, \sigma$$

ME and HE case

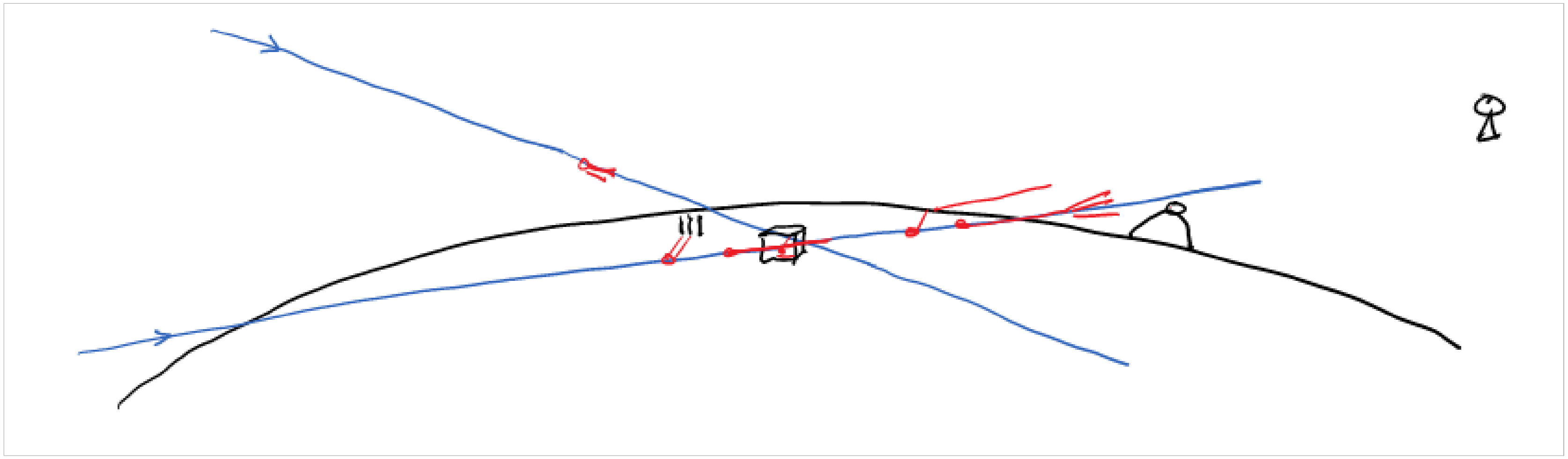
- Backgrounds
  - cosmic ray muons   2 khz @ icecube
  - atmospheric neutrinos   70,000/yr @ icecube
  - detector noise (PMT or other sensor)   500 hz per DOM

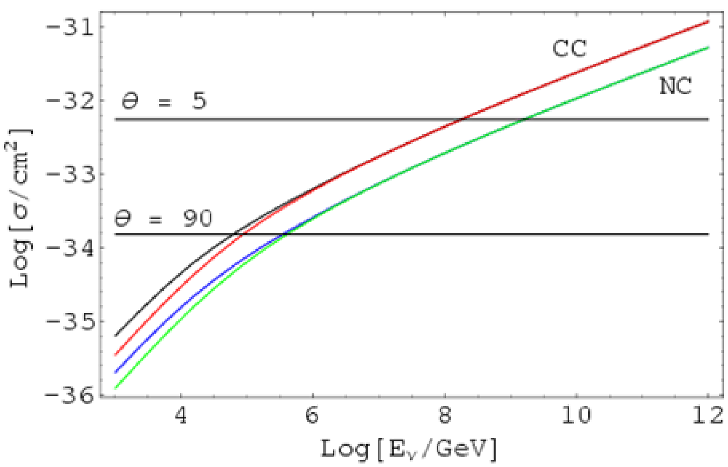
- Low to medium energies
  - cr muons … only upward events

- ME to HE
  - cr muons can be vetoed … contained events

- HE – better vetos, can eliminate atmospheric neutrino from upward sky.

HE strategy





$$N = \phi A \Omega t$$

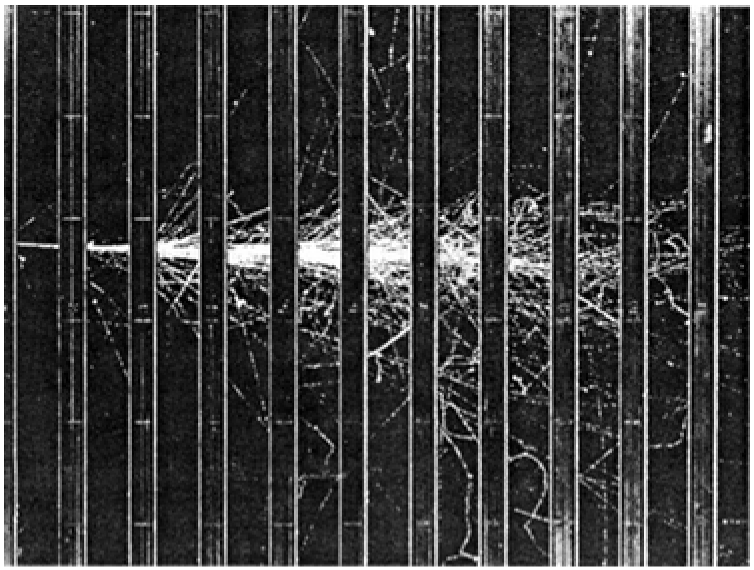
$$A = N_t \sigma$$

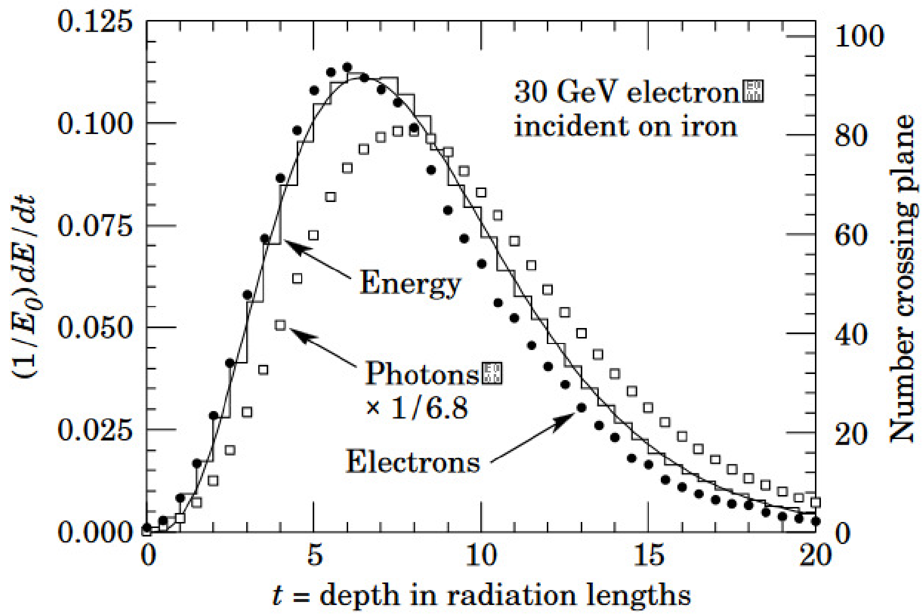
$$N_t = n V = n A_0 \ell$$

Cascades and tracks

- Image cascades and tracks to reconstruct event
- Cascades
  - Electromagnetic
  - Hadronic
  - Separating em and hadronic
- Tracks
  - mu
  - tau
- Density
  - water, air

em cascades

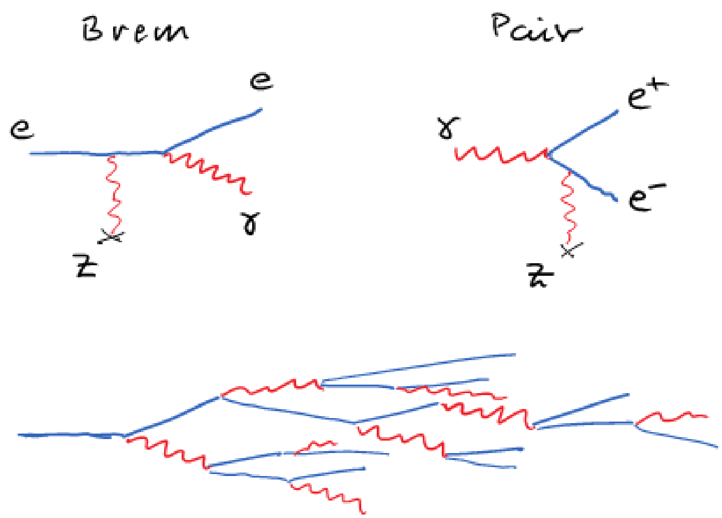




0.125
0.100
0.075
0.050
0.025
0.000
(1/E₀) dE/dt
100
80
60
40
20
0
Number crossing plane
30 GeV electron
incident on iron
Energy
Photons
× 1/6.8
Electrons
0
5
10
15
20
t = depth in radiation lengths

Electromagnetic cascades: longitudinal

- early - $E_s > E_c$ - critical energy ~ 80 MeV



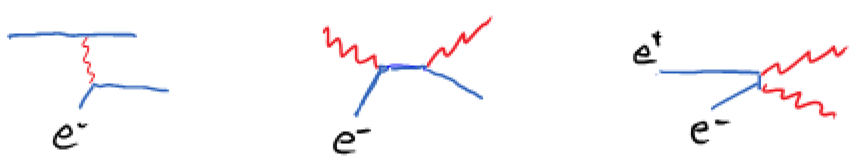
σ ~ constant

X_0

Air	36.66	gm/cm²
Water	36.08	

X_0 radiation length

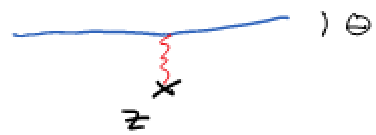
- late - $E_s < E_c$



$\sigma \sim \frac{1}{E}$

Electromagnetic cascades: profiles

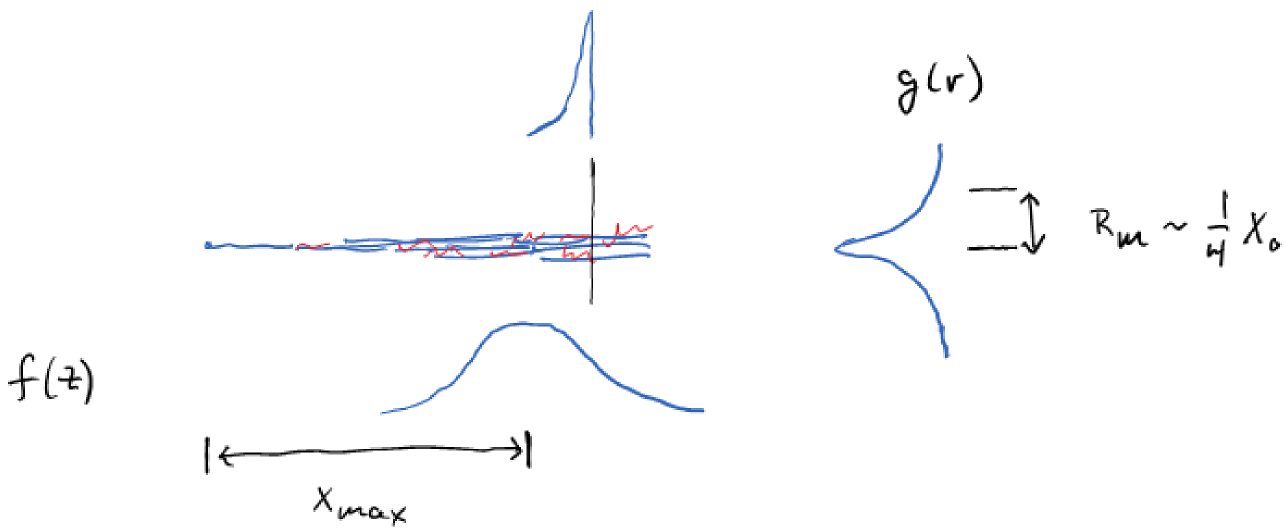
- Coulomb scattering



- Profiles

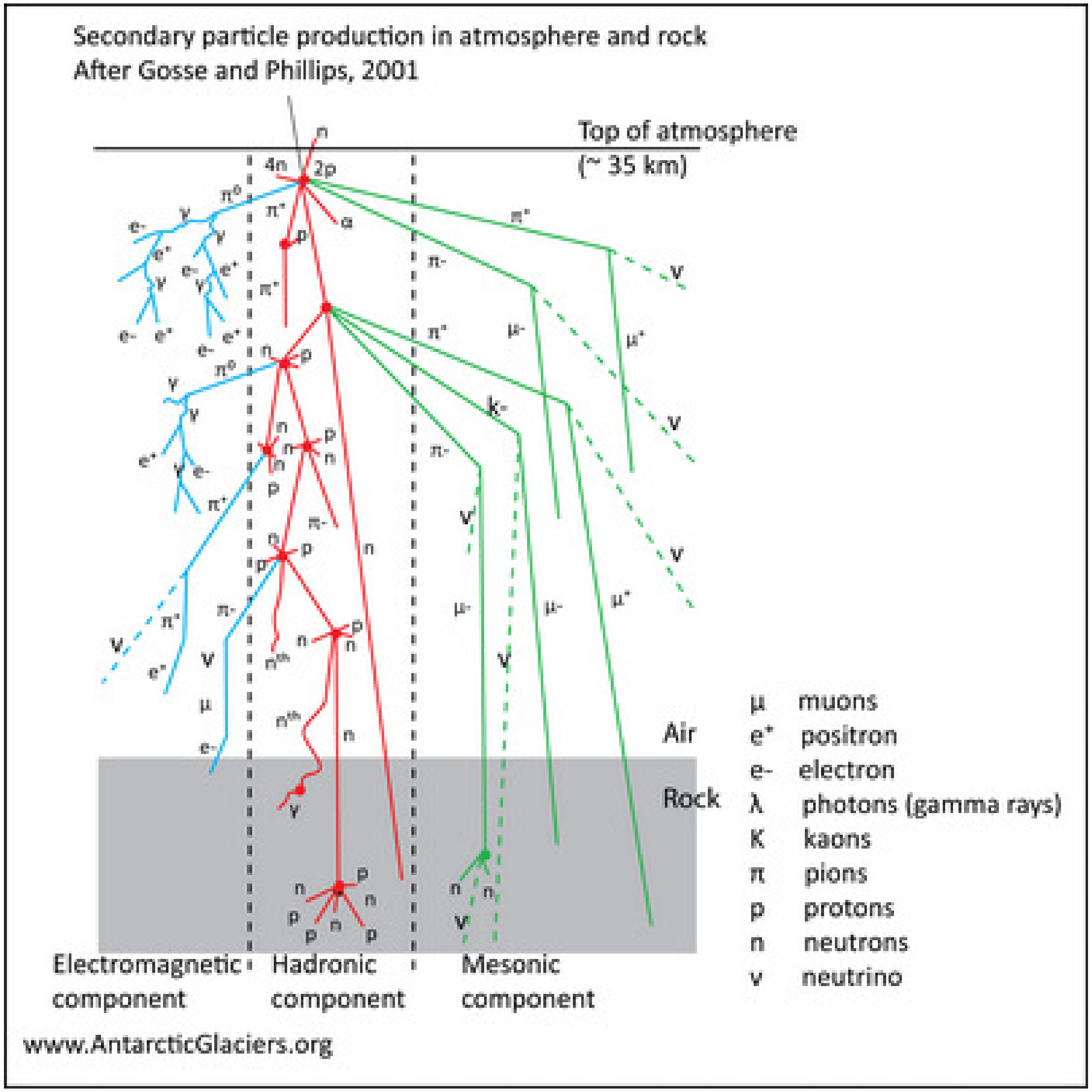
$$\rho(\vec{x}, t) = f(z)\, g(r)\, h(z - ct)$$

$$h(z-ct) \sim \delta(z-ct)$$



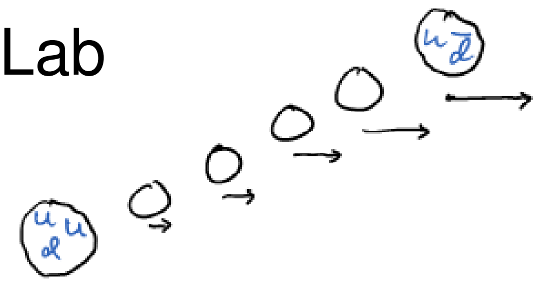
$$X_{max} = \ln(E/E_c)\, X_0 \approx 6\ \text{m} \quad \text{PeV-ice}$$

hadronic cascade



Hadronic cascades

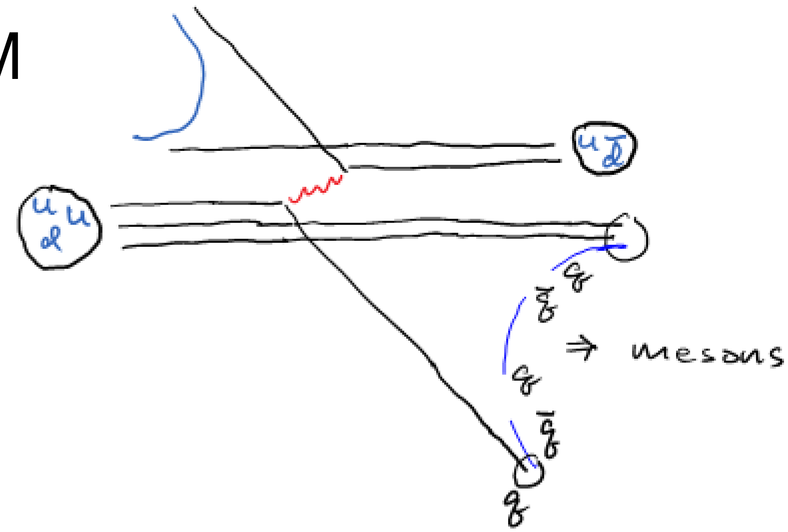
Lab



$\pi\ K\ \ N\bar{N}\ \ \Lambda\bar{\Lambda}\ \ldots$

$D\ \ \phi,\ \omega$

CM



Decay?

Critical energy $\ell\gamma = c\tau\frac{E}{m} = \lambda_{int}$

$\ell_{\pi^0} \simeq 2.5\ 10^{-8}\ m$ $\sigma(1\ PeV) \sim 60\ mb$

$\ell_{\pi^+} \simeq 7.8\ m$ $E_{\pi_0} \simeq 2\ PeV$ water

$\ell_K \simeq 3.7\ m,\ 15.3\ m$ $E_{\pi K} < M_{\pi K}$

$\ell_{K_s} \simeq 2.7\ 10^{-2}$ $E_{K_S} = 3\ GeV$

$\ell_c \ell_b \sim$ few 10^{-4} $E_{cb} \simeq 1-3\ TeV$

Hadronic cascades in water/ice

- For $E_s >$ PeV, almost all particles interact, energy remains hadronic
- For $E_s <$ PeV, π^0 decays – most energy transforms to an electromagnatic shower, but still a lot of hadrons
- Heavy quarks, slow to few TeV, and then decay. May lengthen shower. May provide “prompt” μ.
- Charged mesons below inelastic threshold stop and produce muons
- Target nuclei produce neutrons

Identifying hadronic cascades

- Hard … X_{max} and sensor spacing ?

- Prompt light from μ
  - Heavy Q at neutrino vertex
  - prompt Q from hadronic processes
  - conventional μ

Direct charm production

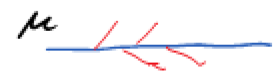
$\nu d \to l^-(u,\ c \cdot sin^2\theta_C)$ … 5% low energy
$\nu s \to l^-(c,\ u \cdot sin^2\theta_C)$ … 40% high energy
$\nu c \to \nu\ c$ … 10% high energy
$\nu b \to l^- t$ … 10% very high energy

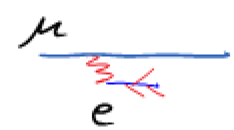
- echo's
  - μ: decay 2.2 μs delay
  - n: $np \to D\gamma$ 2.2 MeV ~ms delay
  - luminescence (efficiency e vs had)

Tracks

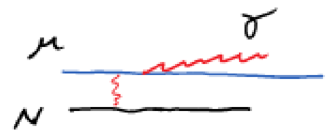
$$\frac{dE}{dx} = \alpha + \beta E$$

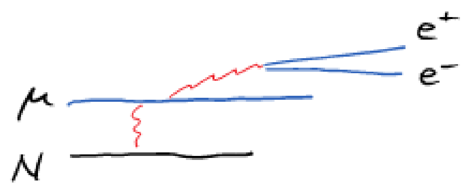
α $\begin{cases} \text{direct Č light} \\ \text{ionization} \Rightarrow \text{secondary Č light} \end{cases}$

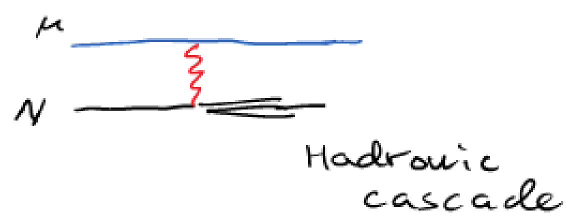




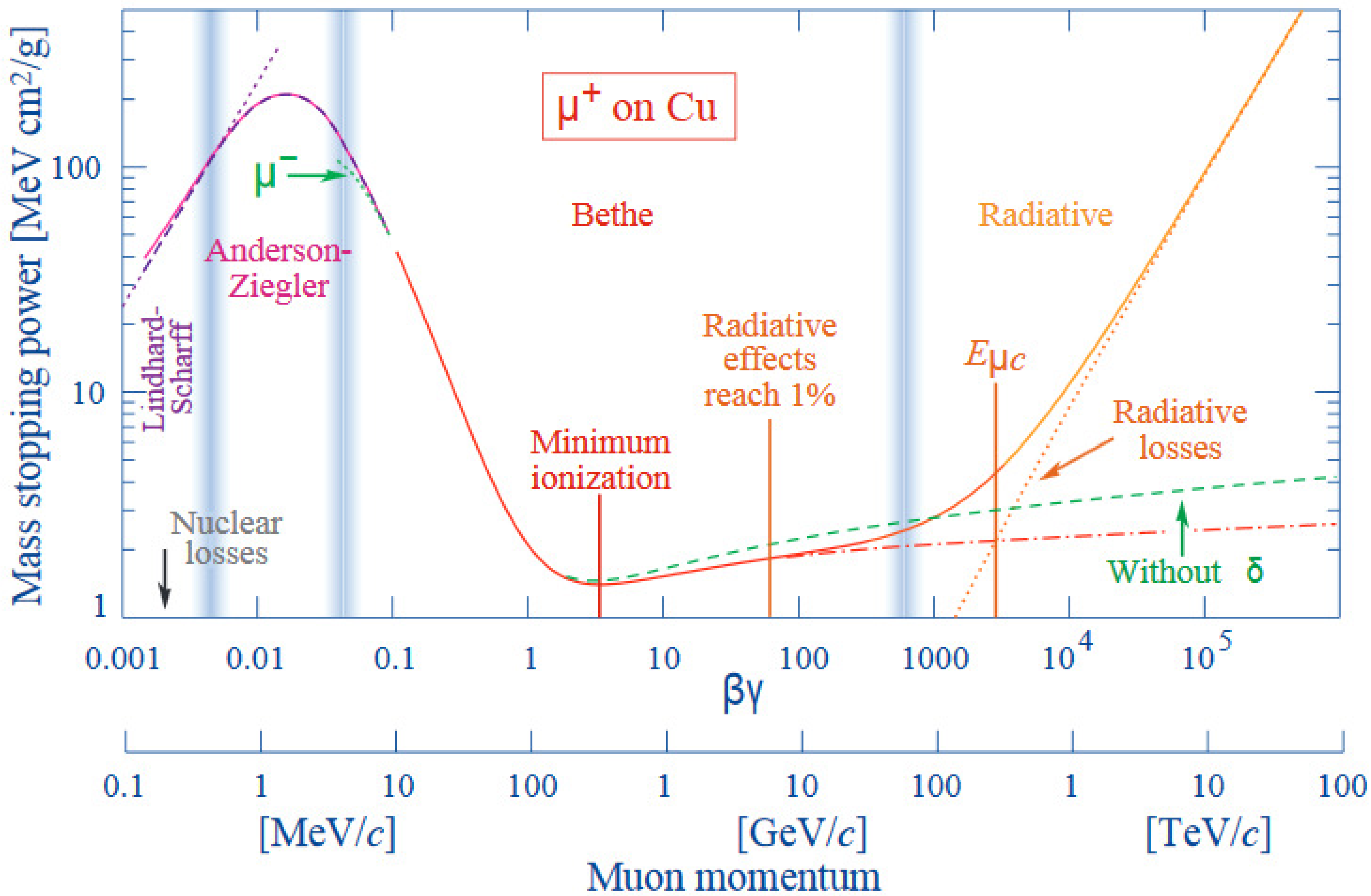
β $\begin{cases} \text{brems} \\ \text{pair production} \\ \text{photo-nuclear.} \end{cases}$





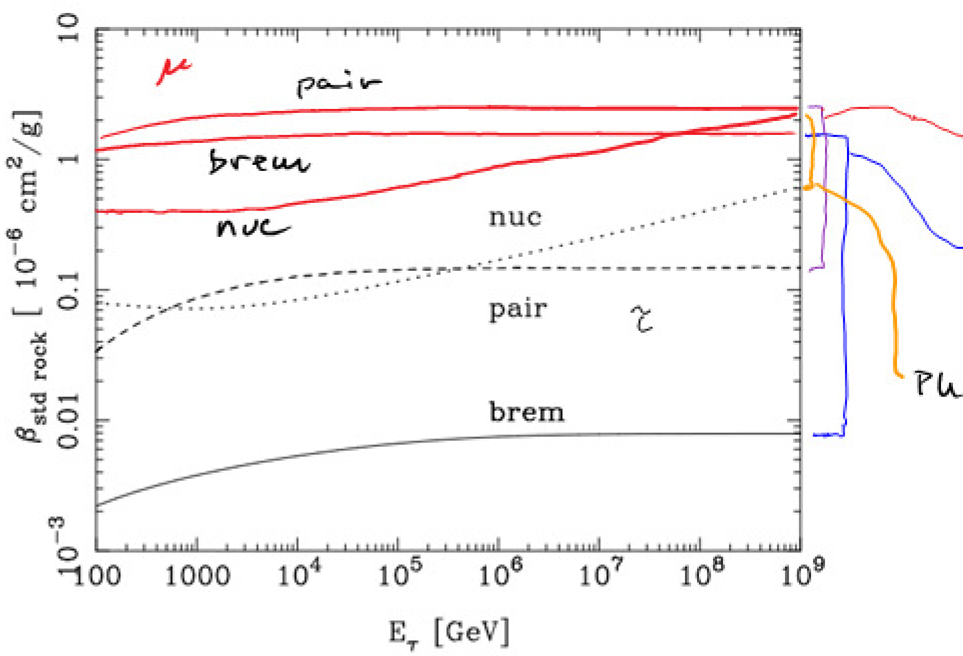


from the PDG …



μ+ on Cu
Mass stopping power [MeV cm²/g]
100
10
1
μ−
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe
Radiative
Radiative
effects
reach 1%
Eμc
Radiative
losses
Minimum
ionization
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

mu v tau



β_τ / β_μ

Pair $\sim \frac{1}{m}$ $\quad \frac{1}{17}$

Brem $\sim \frac{1}{m^2}$ $\quad \frac{1}{250}$

Photo nuc $\sim \frac{1}{m+\Lambda}$ $\quad \frac{1}{5}$

$\beta_\mu(100\text{ PeV}) \sim 6\cdot 10^{-6}$

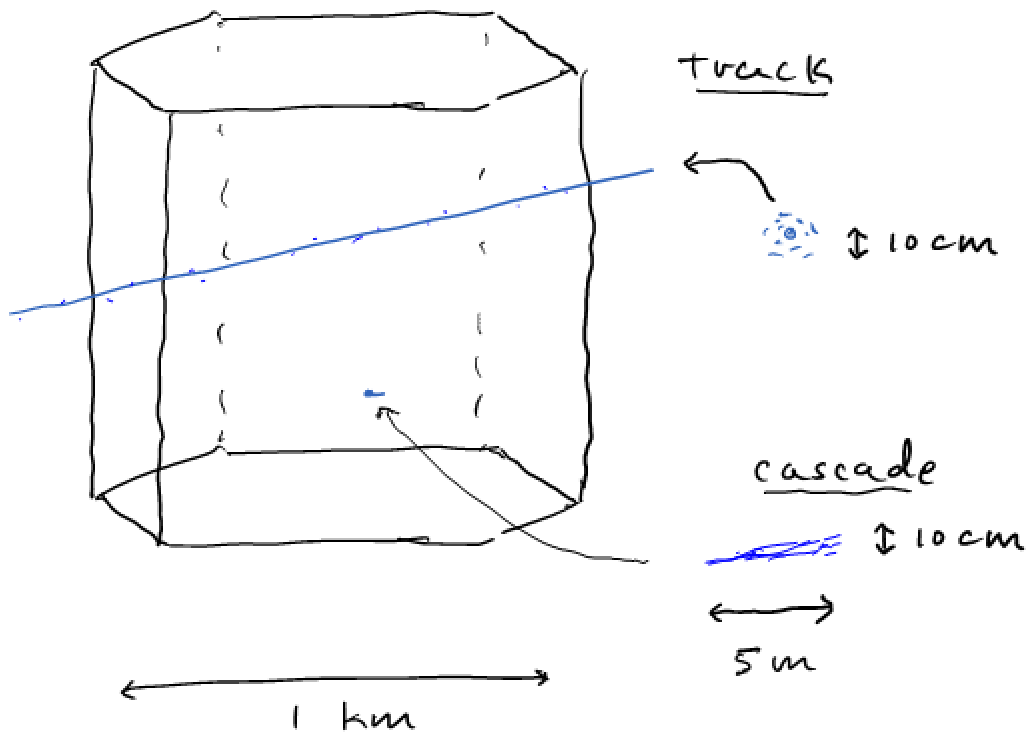
$\lambda^\mu_{ice} \sim 3$ km

$\beta_\tau(100\text{ PeV}) \sim 5\cdot 10^{-7}$ cm^2/g

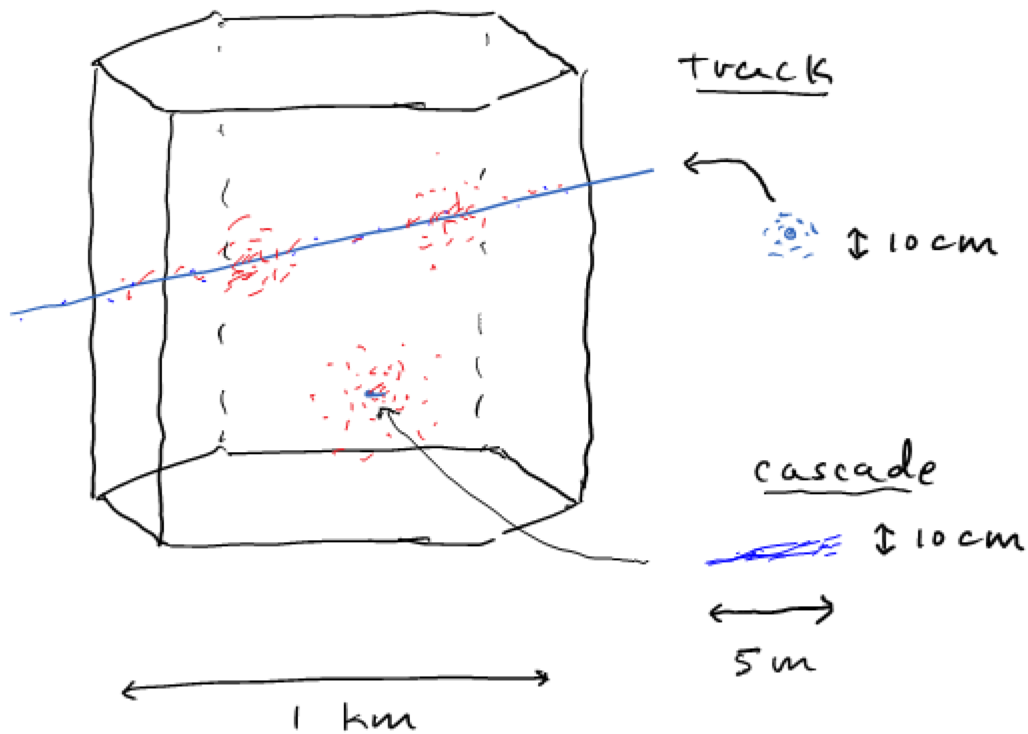
$\lambda^\tau_{ice} \sim 20$ km

$E_{crit} \equiv 400$ PeV

icecube sketch



icecube sketch



Material density

- Scale to X_0

- Physical size of showers in ice ~ few m. Difficult to image – often treated as point source. 10 cm radius, pancake is good approximation.

- Air $X_0 = 300$m at STP, longer at altitude. Showers are many km in length. Important for radio detection of showers. Transverse dimensions are 100's of m, shower curvature is important.

End of first day