PHYS 5326 – Lecture #10, 11, 12.5

Friday, Mar. 30, 2007
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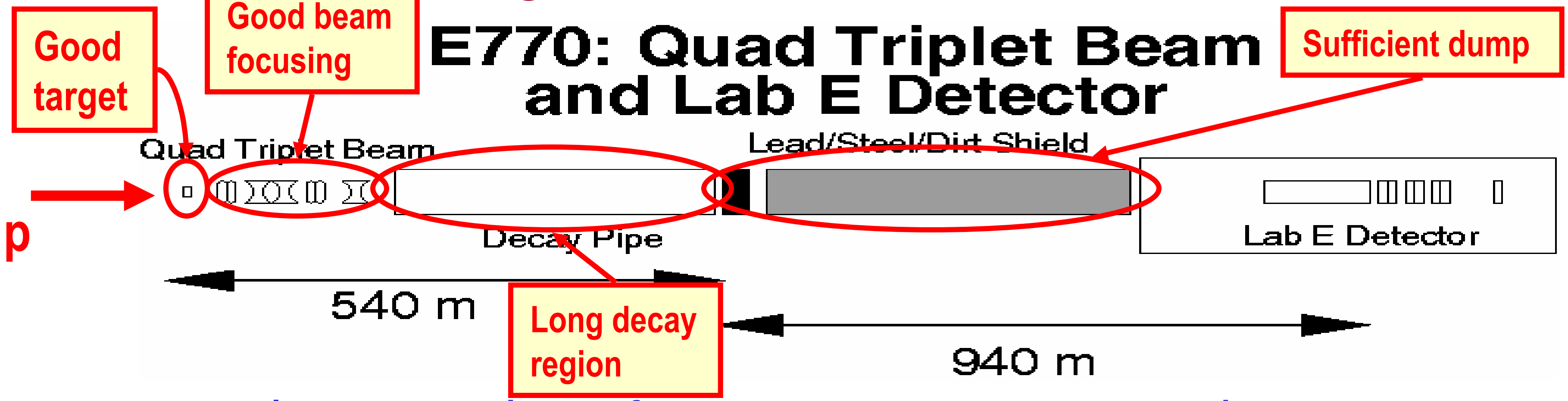
1. Exam review
2. Local Gauge Invariance
3. Introduction of Massless Vector Gauge Fields

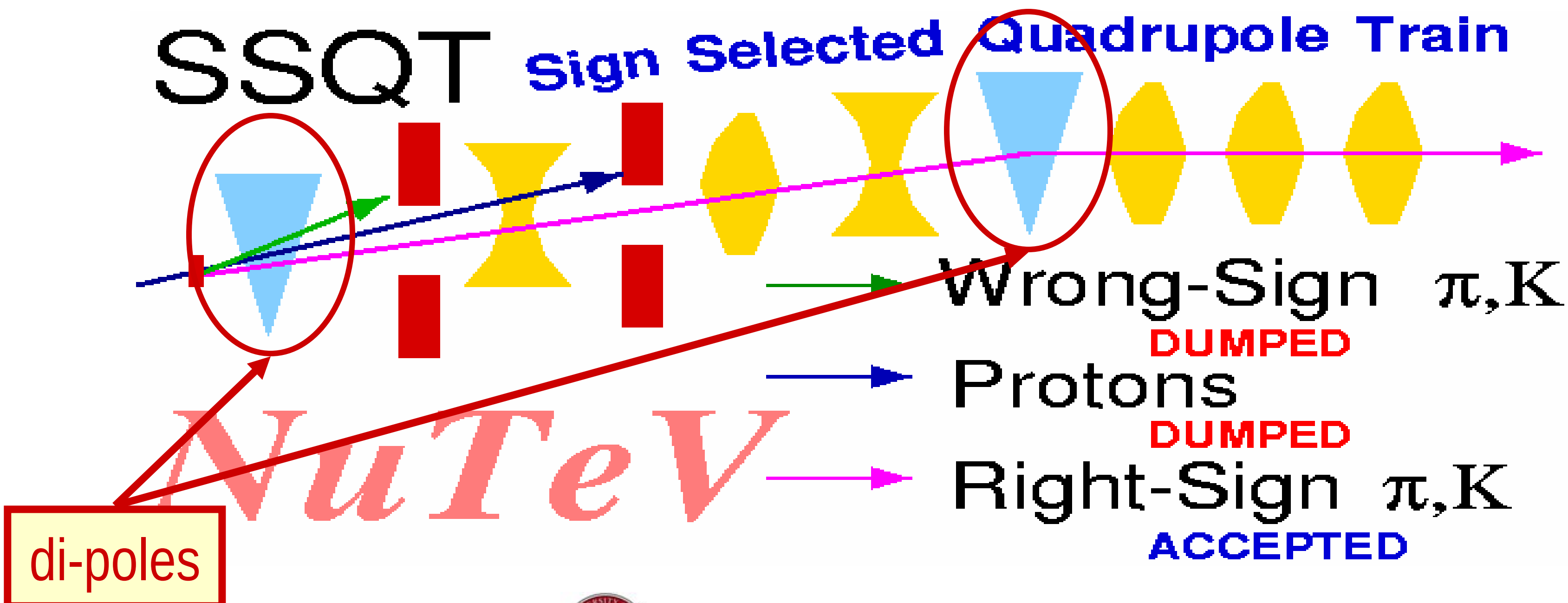
1. Design a sign selected neutrino beamline.



- Use large number of protons on target to produce many secondary hadrons (π, K, D, etc)
- Let π and K decay in-flight for ν_μ beam
  - $\pi \rightarrow \mu + \nu_\mu$ (99.99%), $K \rightarrow \mu + \nu_\mu$ (63.5%)
- Other flavors of neutrinos are harder to make
- Let the beam go through shield and dirt to filter out μ and remaining hadrons, except for ν
  - Dominated by ν_μ

1. Design a sign selected neutrino beam?

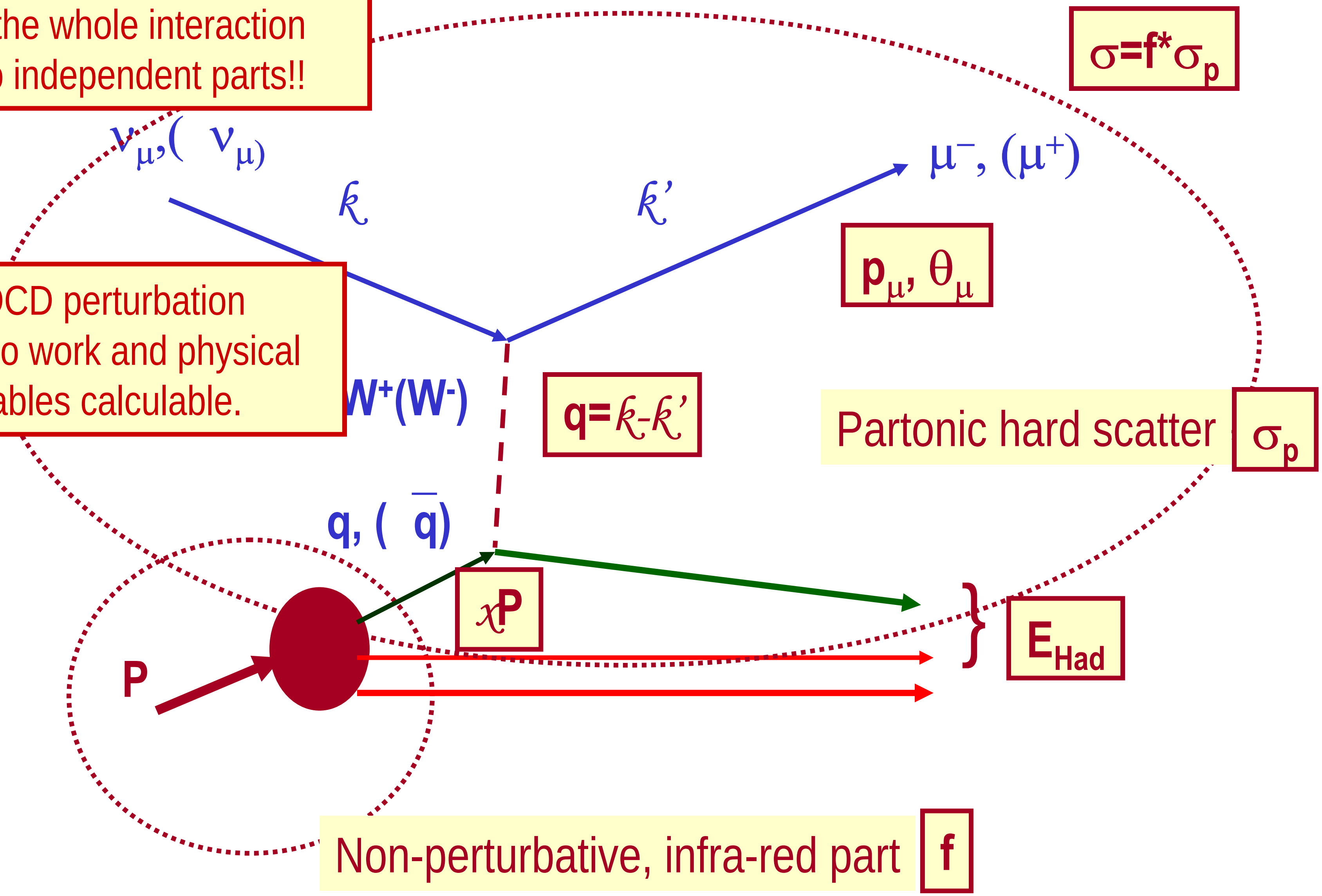
- Neutrinos are electrically neutral
- Need to select the charge of the secondary hadrons from the proton interaction on target
- Sets of Dipoles are used to select desired charges of the secondary hadrons
- Proton incident to the target with an upward angle of 7mrad
- The target is then followed by a dipole to deflect the correct sign secondary mesons
- Strategically placed particle dumps absorbs incorrect signs, neutrals and protons
- Second set of dipole deflects correct sign mesons to the decay pipe and to the experiment



2. QCD Factorization Theorem

Factor the whole interaction into two independent parts!!

Allow QCD perturbation theory to work and physical observables calculable.



3. Structure Functions and PDF's

SF is the description of the collection of point-like particles that forms nucleons while PDF's provide momentum distributions of individual partons within the collection.

- Assuming parton model, ν-N cross section can be rewritten in terms of point-like particle interactions

$$\frac{d^2\sigma^{\nu T}}{dxdy} = \frac{G_F^2 xs}{\pi\left(1+Q^2/M_W^2\right)^2}\left[q^{\nu T}(x)+\left(1-y^2\right)\bar{q}^{\nu T}+2(1-y)k^{\nu T}(x)\right]$$

Spin 0 partons

$$\frac{d^2\sigma^{\bar{\nu} T}}{dxdy} = \frac{G_F^2 xs}{\pi\left(1+Q^2/M_W^2\right)^2}\left[\bar{q}^{\bar{\nu} T}(x)+\left(1-y^2\right)q^{\bar{\nu} T}+2(1-y)k^{\bar{\nu} T}(x)\right]$$

- Comparing the parton-neutrino to proton-neutrino SF and PDF's are related as

$$2xF_1^{\nu(\bar{\nu})T} = 2\left[xq^{\nu(\bar{\nu})T}(x)+x\bar{q}^{\nu(\bar{\nu})T}(x)\right]$$

$$F_2^{\nu(\bar{\nu})T} = 2\left[xq^{\nu(\bar{\nu})T}(x)+x\bar{q}^{\nu(\bar{\nu})T}(x)+2xk^{\nu(\bar{\nu})T}\right]$$

$$xF_3^{\nu(\bar{\nu})T} = 2\left[xq^{\nu(\bar{\nu})T}(x)-x\bar{q}^{\nu(\bar{\nu})T}(x)\right]$$

Parity violating components

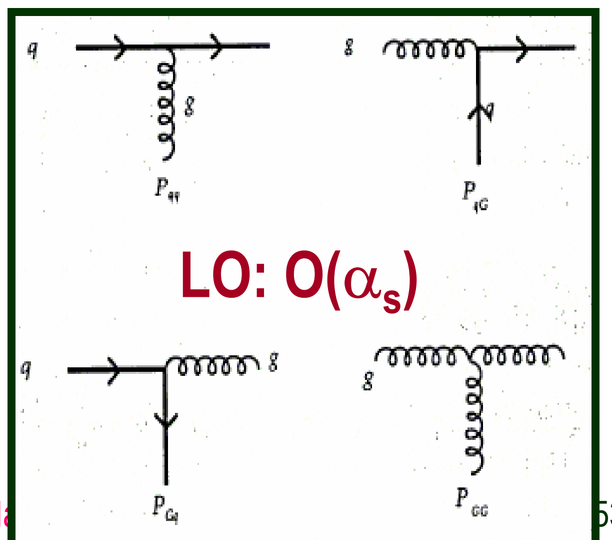
If no spin 0, 2xF1=F2

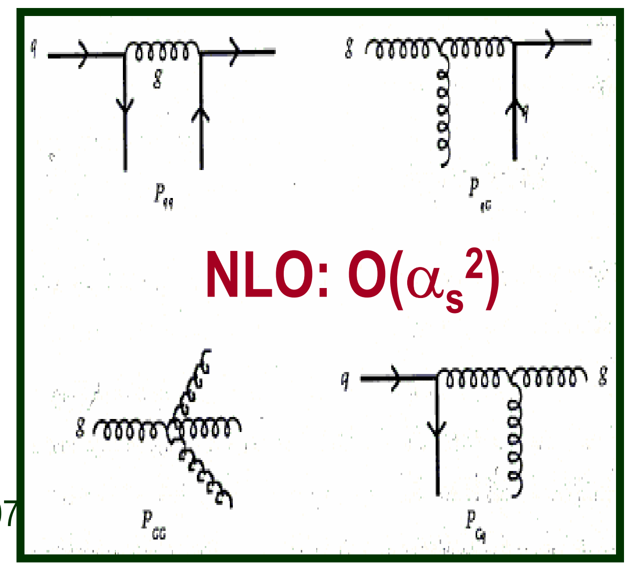
4. PDF Evolution: DGLAP Equations

- The evolution equations by **D**okshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi provide mechanism to evolve PDF's to any kinematic regime or momentum scale, as a function of momentum transfer scale of the interactions

$$\frac{dG(x,M^2)}{d\ln M^2}=\frac{\alpha_s(\mu^2)}{2\pi}\int_x^1\frac{dy}{y}\left[q^S(y,M^2)P^S_{Gq}\left(\frac{x}{y}\right)+G(y,M^2)P_{GG}\left(\frac{x}{y}\right)\right]$$

$P_{ij}(x/y)$: Splitting function that is the probability of parton i with momentum y get resolved as parton j with momentum x<y

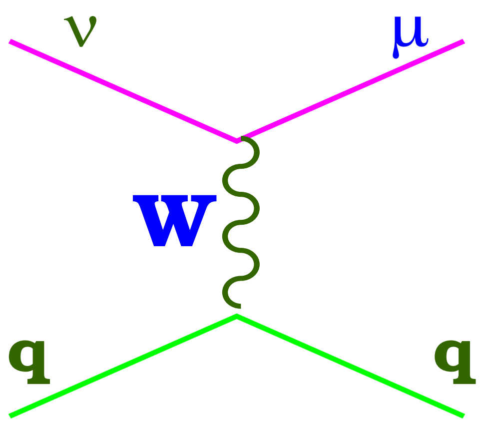




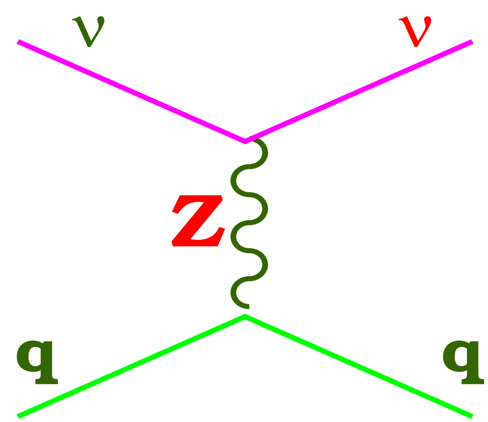
What can PDF's depend on?

- Different functional forms of PDF and SF's
- Order of QCD calculations
  – Higher order (NLO) calculations require higher order PDF's
- Different assumptions in the nucleon
  – No intrinsic sea quarks
  – Fixed flavors only
- Approximation at non-perturbative regime
  – Different method of approximating low x behavior

5. How is $\sin^2\theta_W$ measured?



$$coupling \propto I^{(3)}_{weak}$$



$$coupling \propto I^{(3)}_{weak} - Q_{EM}\sin^2\theta_W$$

- Cross section ratios between NC and CC proportional to $\sin^2\theta_W$
- Llewellyn Smith Formula:

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right)\right)$$

- Define experimental variable to distinguish NC and CC
- Compare the measured ratio with MC prediction

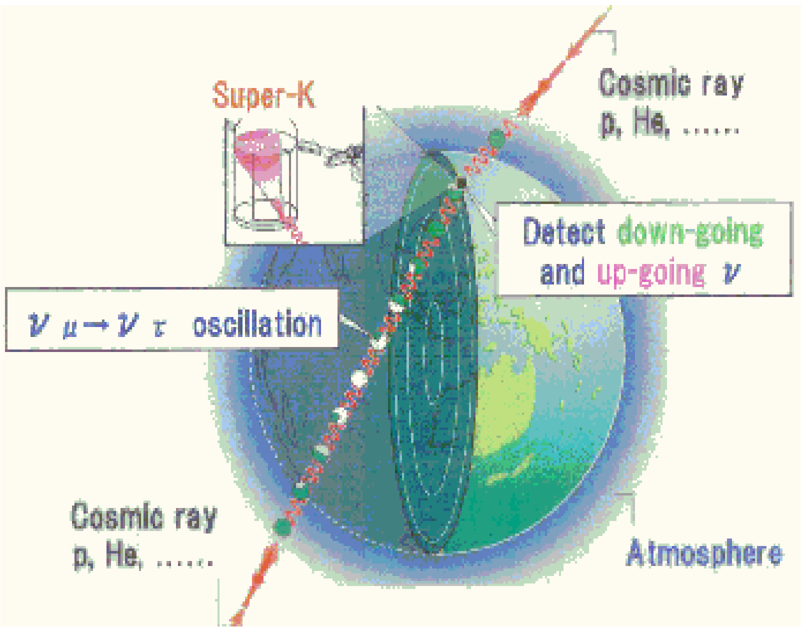
6. Neutrino Oscillation & Its importance

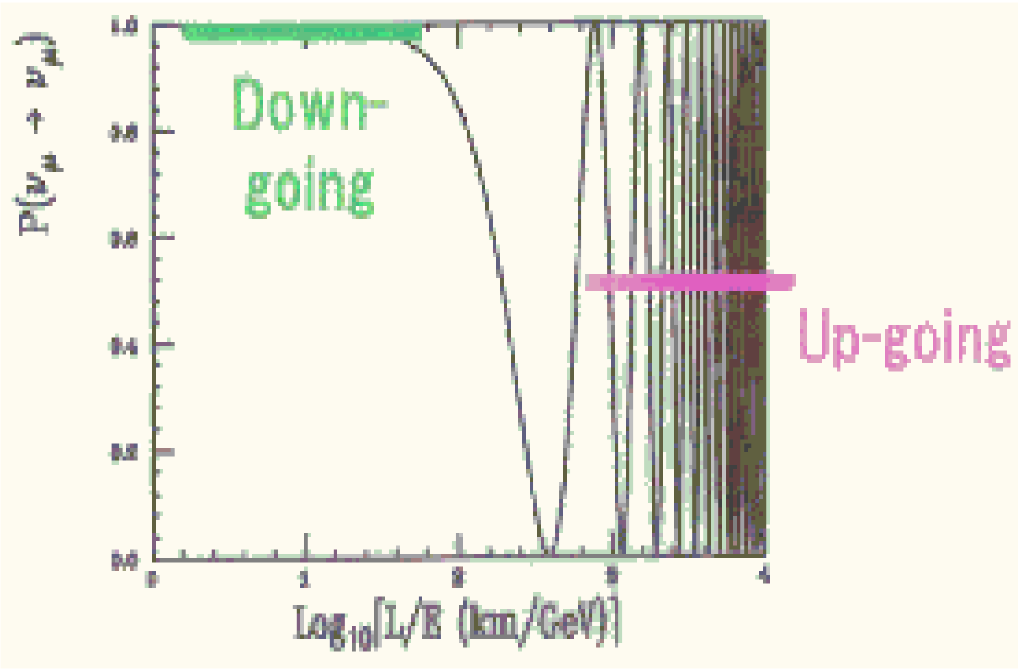
- Caused by the fact that there are two different eigenstates for mass and weak flavors
- The weak eigenstates are expressed as a linear combination of mass eigenstates with time phase and mixing angle
- Neutrinos are one of the fundamental constituents in nature
  - Three weak eigenstates based on SM
- Left handed particles and right handed anti-particles only
  - Violates parity ➔ Why only neutrinos?
  - Is it because of its masslessness?
- SM based on massless neutrinos
- SM inconsistent

7. Importance of Zenith Angle

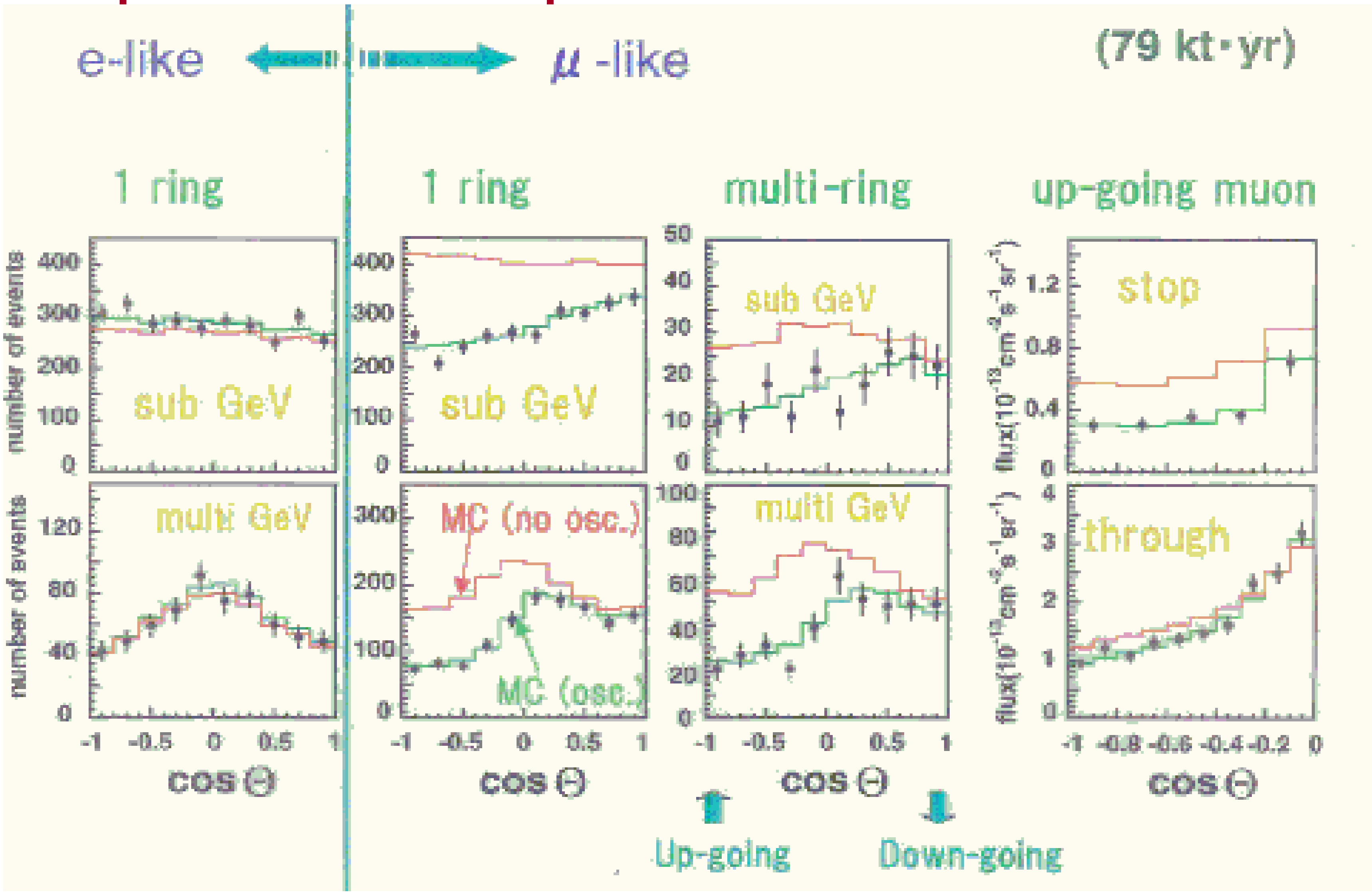
- The Zenith angle represents the different distance the neutrinos traveled through the earth
- The dependence to the angle is a direct proof of the oscillation probability

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$





Super-K Atmospheric Neutrino Results



8. Atmospheric Neutrinos & Their Flux

- Neutrinos resulting from the atmospheric interactions of cosmic ray particles
  - He, p, etc + N → π,K, etc
    - $\pi \rightarrow \mu+\nu_\mu$
    - $\mu \rightarrow e+\nu_e+\nu_\mu$
  - This reaction gives 2 ν_μ and 1 ν_e
- Expected flux ratio between ν_μ and ν_e is 2 to 1
- Give a predicted ratio of $\boxed{\left(\frac{N_{\nu_e}}{N_{\nu_\mu}}\right) \approx \frac{1}{2}}$