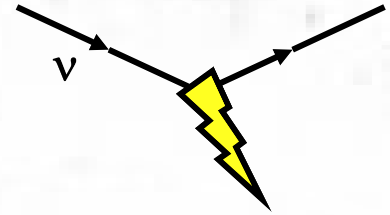
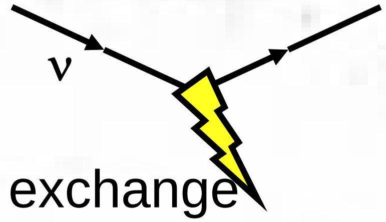
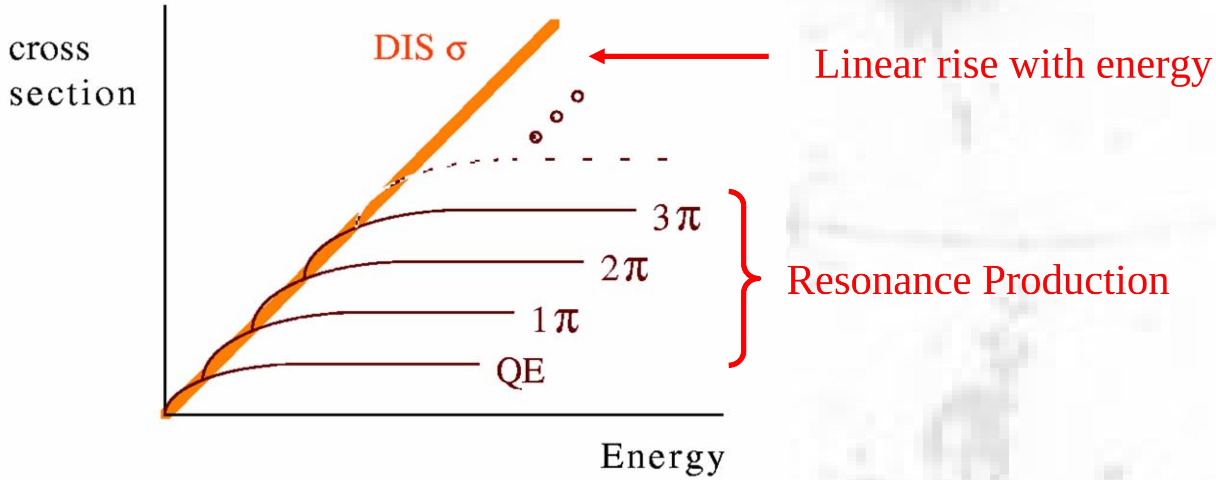


Neutrino-Nucleon
Deep Inelastic Scattering

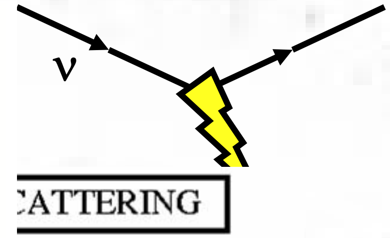
Neutrino-Nucleon 'n a Nutshell



- Charged - Current: $W^{\pm}$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N^* or Δ)
    $n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark'}$
- Neutral - Current: Z^0 exchange
  - Elastic Scattering:
    (Target unchanged)
    $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N^* or Δ)
  - Deep-Inelastic Scattering
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \nu_\mu + \text{quark}$

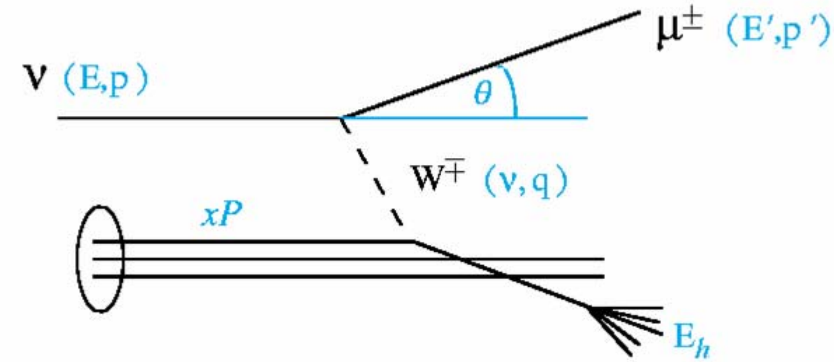


Scattering Variables



Scattering variables given in terms of invariants

•More general than just deep inelastic (neutrino-quark) scattering, although interpretation may change.



Measured quantities: E_h , E', θ

4-momentum Transfer^2: $Q^2 = -q^2 = -\left(p' - p\right)^2 \approx \left(4EE' \sin^2(\theta/2)\right)_{Lab}$

Energy Transfer: $\nu = \left(q \cdot P\right)/M_T = \left(E - E'\right)_{Lab} = \left(E_h - M_T\right)_{Lab}$

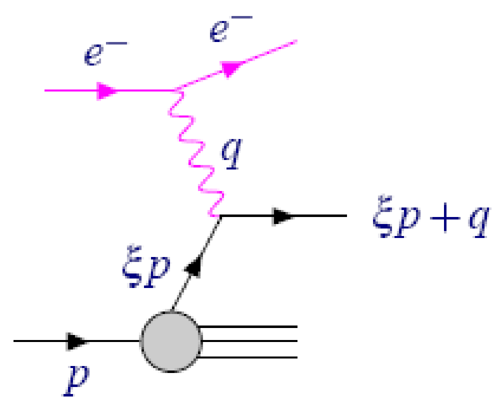
Inelasticity: $y = \left(q \cdot P\right)/\left(p \cdot P\right) = \left(E_h - M_T\right)/\left(E_h + E'\right)_{Lab}$

Fractional Momentum of Struck Quark: $x = -q^2/2\left(p \cdot q\right) = Q^2/2M_T\nu$

Recoil Mass^2: $W^2 = (q+P)^2 = M_T{}^2 + 2M_T\nu - Q^2$

CM Energy^2: $s = (p+P)^2 = M_T{}^2 + \dfrac{Q^2}{xy}$

Deep Inelastic Scattering Cont.

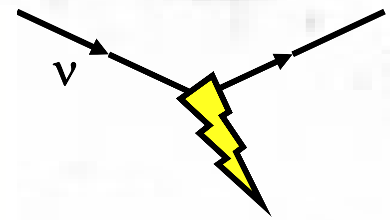


Much intuition was gained from the Feynman-Bjorken parton picture. Noting that the typical scale of strong-interactions is 1 fm or 200 MeV, consider a frame in which $|\vec{p}\,|$ is large

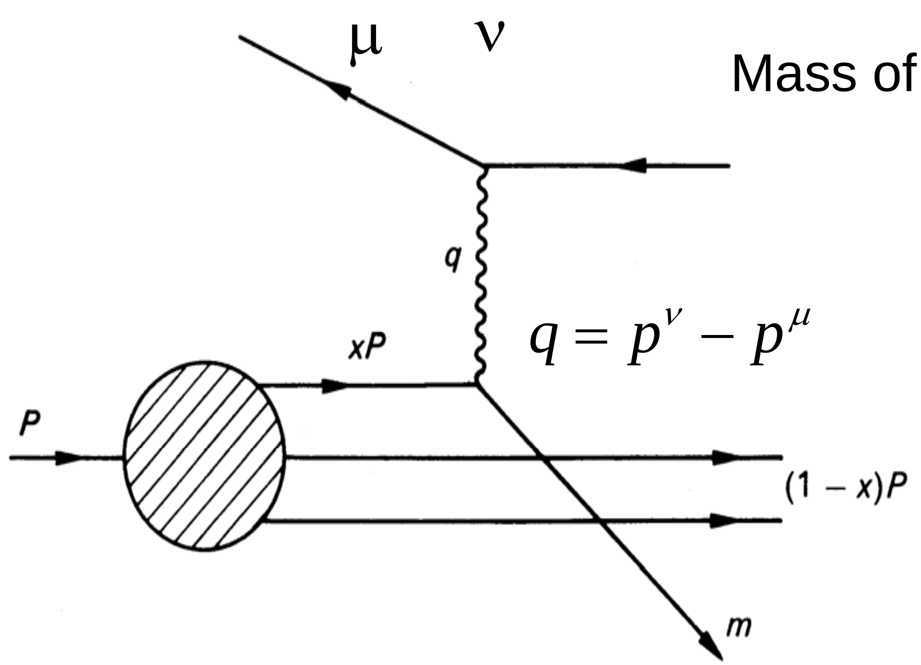
$$x \equiv \frac{-q^2}{2p \cdot q} \qquad (\xi p + q)^2 \simeq 0 \;\Rightarrow\; 2\xi p \cdot q + q^2 \simeq 0 \;\Rightarrow\; \xi = x\,.$$

The experimentally measurable quantity x gives the fraction of the proton's momentum carried by the struck quark (in the *infinite momentum* frame).

Parton Interpretation of DIS



Mass of target quark $m_q{}^2 = x^2 P^2 = x^2 M_T^2$



Mass of final state quark

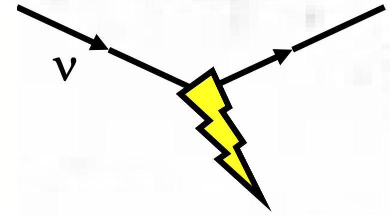
$$m_{q'}{}^2 = (xP + q)^2$$

In "infinite momentum frame", x is momentum of partons inside the nucleon

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M_T \nu}$$

Neutrino scatters off a parton inside the nucleon

So why is cross-section so large?



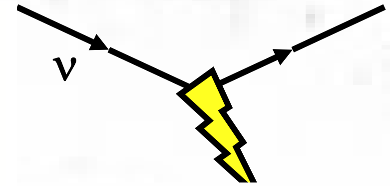
- (at least compared to νe^- scattering!)
- Recall that for neutrino beam and target at rest

$$\sigma_{TOT} \approx \frac{G_F^2}{\pi} \int_0^{Q^2_{\max} \equiv s} dQ^2 = \frac{G_F^2 s}{\pi}$$

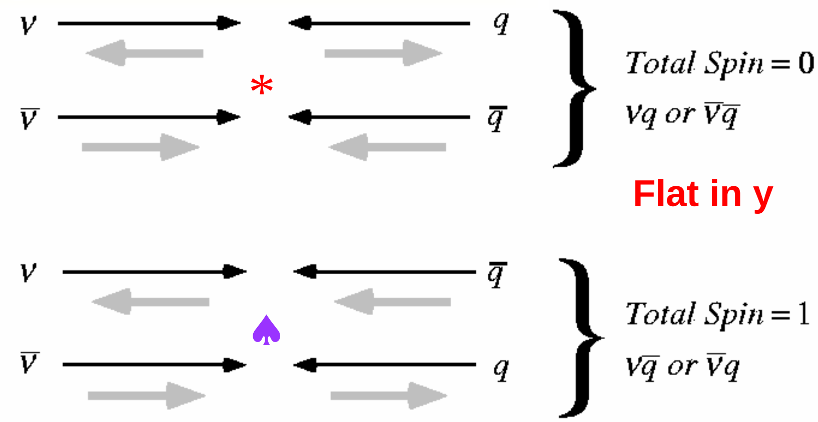
$$s = m_e{}^2 + 2 m_e E_\nu$$

- But we just learned for DIS that effective mass of each target quark is $m_q = x m_{\text{nucleon}}$
- So much larger target mass means larger σ_{TOT}

Chirality, Charge in CC ν-q Scattering



- Total spin determines inelasticity distribution
  - Familiar from neutrino-electron scattering



Flat in y

$1/4(1+\cos\theta^*)^2 = (1-y)^2$

$\int(1-y)^2 dy = 1/3$

point-like scattering implies linear with energy

$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(\overset{*}{x d(x)} + \overset{\spadesuit}{x\bar{u}(x)}(1-y)^2\right)$$

$$\frac{d\sigma^{\bar{\nu} p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(\overset{*}{x\bar{d}(x)} + \overset{\spadesuit}{x u(x)}(1-y)^2\right)$$

but what is this "q(x)"?

- Neutrino/Anti-neutrino CC each produce particular Δq in scattering

$$\nu d \rightarrow \mu^- u$$

$$\bar{\nu} u \rightarrow \mu^+ d$$

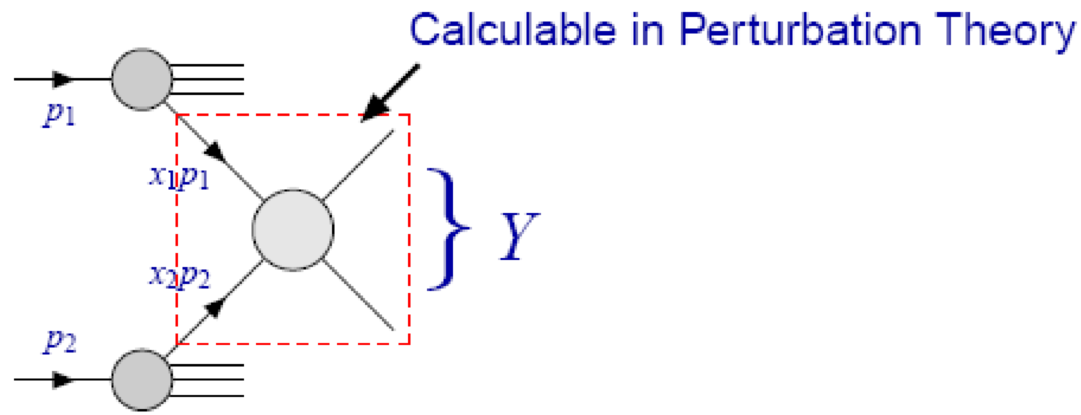
Factorization and Partons

- Factorization Theorem of QCD allows amplitudes for hadronic processes to be written as:

$$A(l+h \rightarrow l+X) = \sum_q \int dx A(l+q(x) \rightarrow l+X) q_h(x)$$

  - Parton distribution functions (PDFs) are universal
  - Processes well described by single parton interactions
  - Parton distribution functions not (yet) calculable from first principles in QCD
- "Scaling": parton distributions are largely independent of Q^2 scale, and depend on fractional momentum, x.

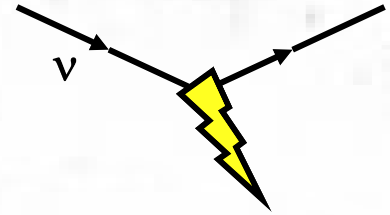
Hard Scattering Processes in Hadronic Collisions



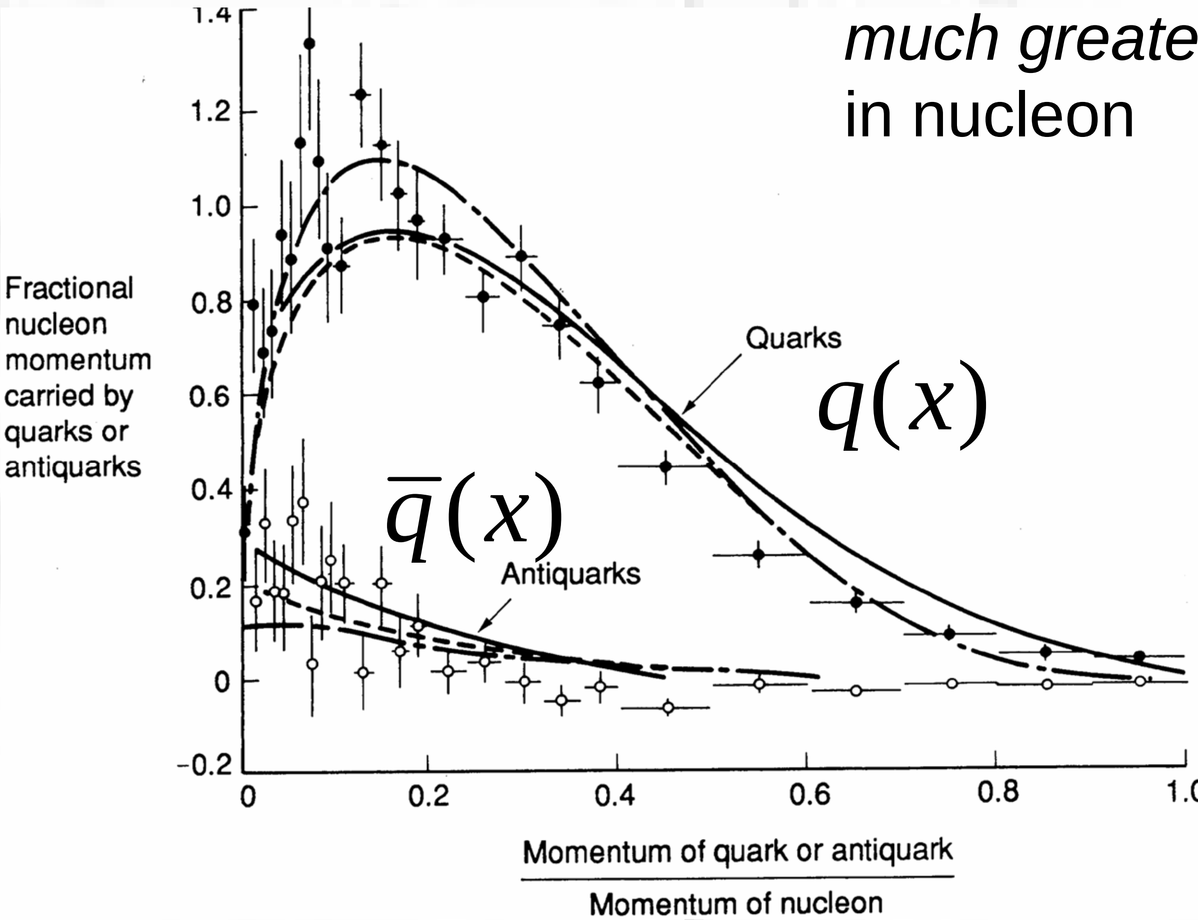
$$\sigma(h_1(p_1)+h_2(p_2) \to Y+X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{f_1,f_2} f_{f_1}(x_1) f_{f_2}(x_2) \sigma(f_1+f_2 \to Y)\,.$$

- The f_{f_i} s are "known" from Deep Inelastic Scattering.
- It is in this way (modified to take QCD corrections into account) that we were able to make predictions for the cross sections for W and Z production at the SPS or are able to make predictions for Higgs Boson production at the LHC.

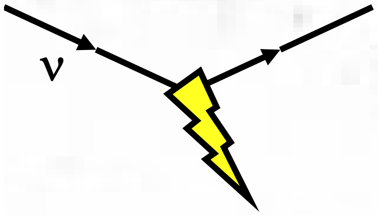
Momentum of Quarks & Antiquarks



- Momentum carried by quarks *much greater* than anti-quarks in nucleon



y distribution in Neutrino CC DIS



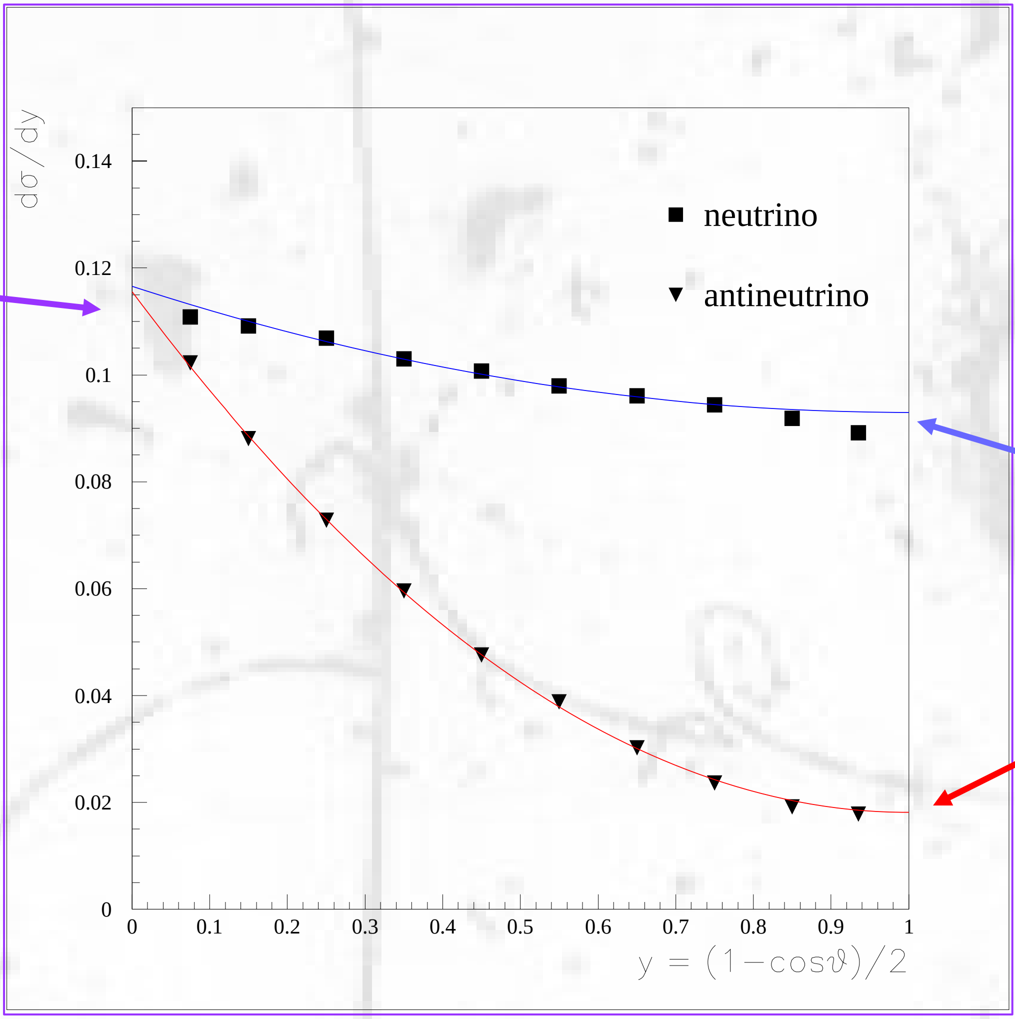
$$\frac{d\sigma(\nu q)}{dxdy} = \frac{d\sigma(\bar{\nu}\bar{q})}{dxdy} \propto 1$$

$$\frac{d\sigma(\nu \bar{q})}{dxdy} = \frac{d\sigma(\bar{\nu} q)}{dxdy} \propto (1-y)^2$$

y=0:

Quarks & anti-quarks

Neutrino and anti-neutrino identical



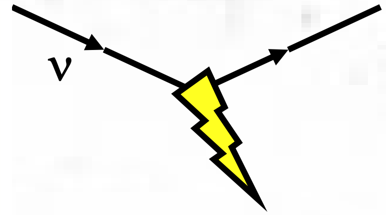
y=1:

Neutrinos see only quarks.

Anti-neutrinos see only anti-quarks

$$\sigma^{\bar{\nu}} \approx \frac{1}{2}\sigma^{\nu}$$

Touchstone Question #4: Neutrino and Anti-Neutrino $\sigma^{\nu N}$



- **Given:** $\sigma_{CC}^{\bar{\nu}} \approx \frac{1}{2}\sigma_{CC}^{\nu}$ **in the DIS regime (CC)**

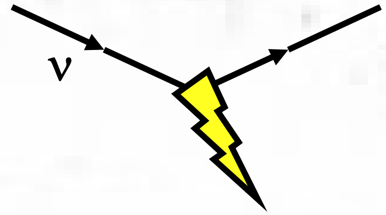
  and $$\frac{d\sigma(\nu q)}{dx} = \frac{d\sigma(\bar{\nu}\bar{q})}{dx} = 3\frac{d\sigma(\nu\bar{q})}{dx} = 3\frac{d\sigma(\bar{\nu}q)}{dx}$$

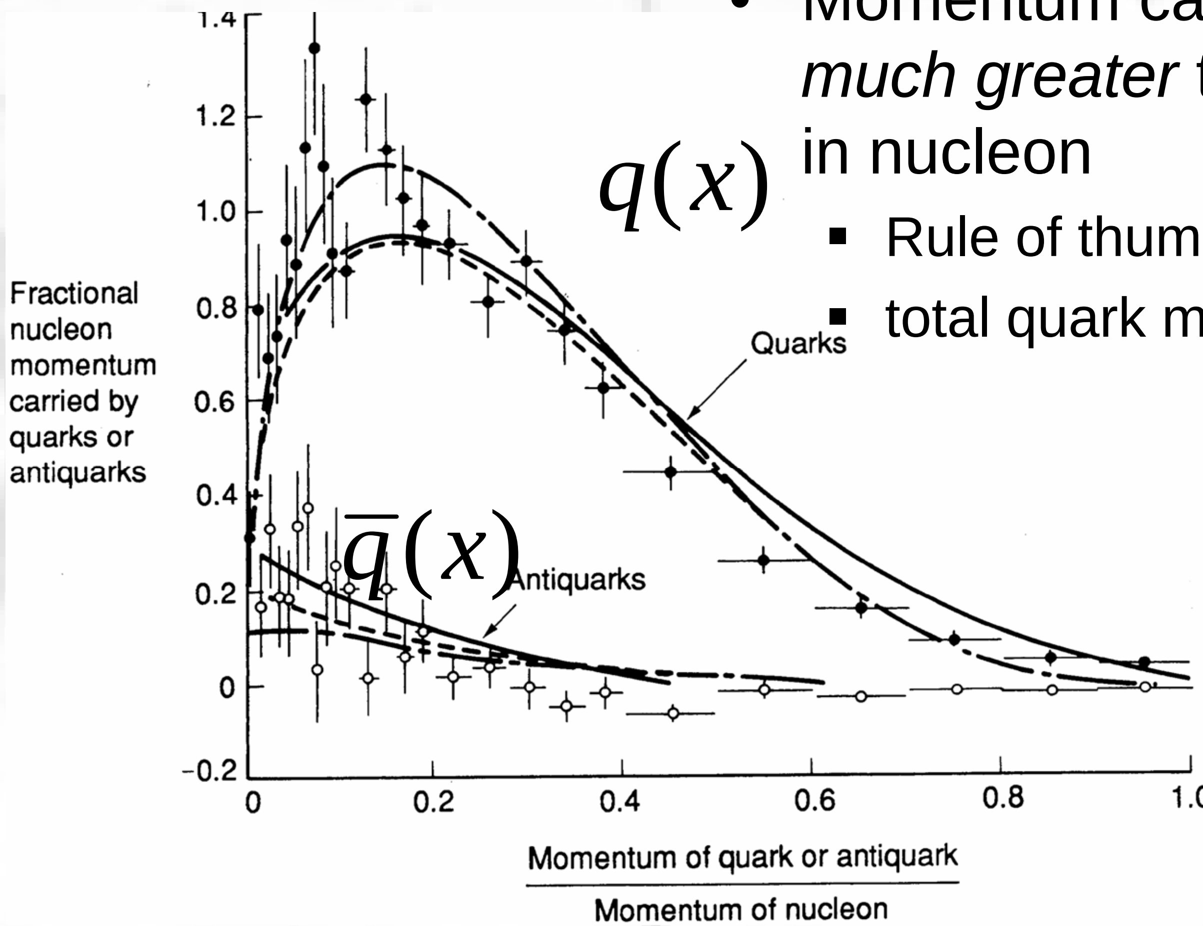
  for CC scattering from quarks or anti-quarks of a given momentum,

  and that cross-section is proportional to parton momentum, what is the approximate ratio of anti-quark to quark momentum in the nucleon?

(a) $\bar{q}/q \sim 1/3$ **(b)** $\bar{q}/q \sim 1/5$ **(c)** $\bar{q}/q \sim 1/8$

Momentum of Quarks & Antiquarks

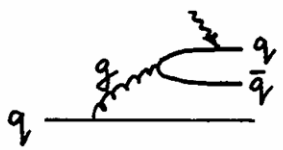




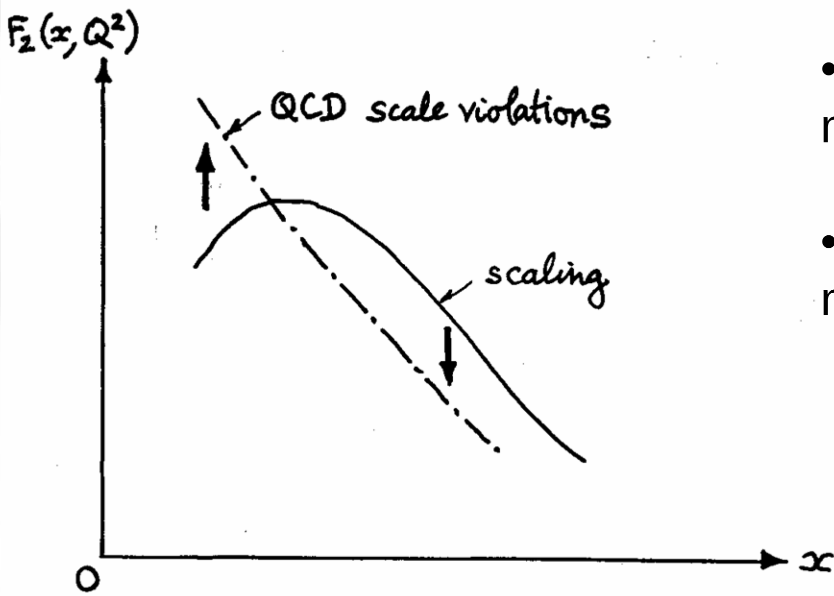
- Momentum carried by quarks *much greater* than anti-quarks in nucleon
  - Rule of thumb: at Q^2 of 10 GeV^2:
  - total quark momentum is 1/3

Strong Interactions among Partons

Q[2] Scaling fails due to these interactions



$$\frac{\partial q(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)q(y,Q^2) + P_{qg}\left(\frac{x}{y}\right)g(y,Q^2)\right]$$



•Pqq(x/y) = probability of finding a quark with momentum x within a quark with momentum y

•Pqq(x/y) = probability of finding a q with momentum x within a gluon with momentum y

$$P_{qq}(z) = \frac{4}{3}\frac{1+z^2}{(1-z)} + 2\delta(1-z)$$

$$P_{gq}(z) = \frac{1}{2}\left[z^2 + (1-z)^2\right]$$

Deep Inelastic Scattering and QCD Cont.

- I refer to the standard textbook for the use of the Operator Product Expansion (OPE) to determine the q^2 behaviour of the structure functions.
- The same results can be obtained from the DGLAP equations (let $t = \log(q^2/q_0^2)$):

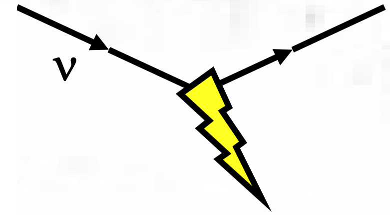
$$\frac{dq^{\mathrm{NS}}(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y} q^{\mathrm{NS}}(y,t)\, P_{q\to q}\left(\frac{x}{y}\right)$$

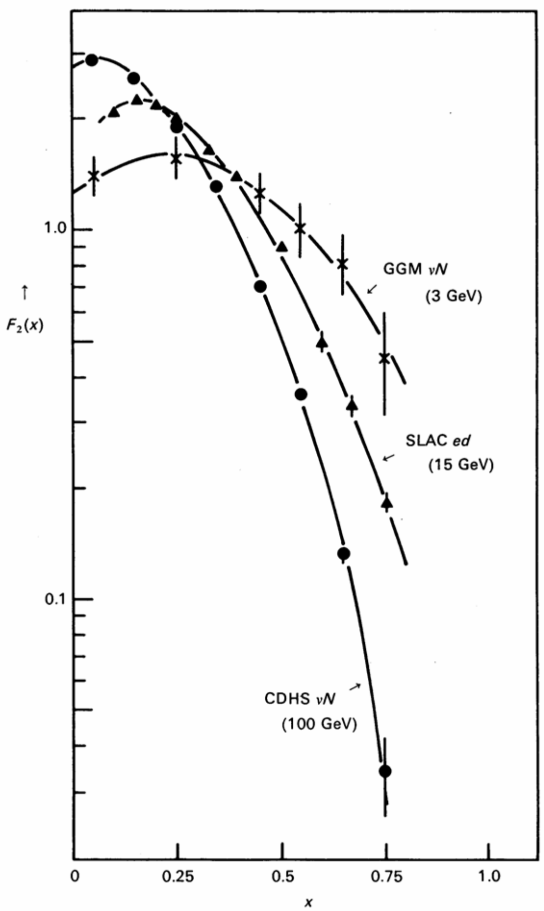
$$\frac{dq^{\mathrm{S}}(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left\{q^{\mathrm{S}}(y,t)\, P_{q\to q}\left(\frac{x}{y}\right) + g(y,t)\, P_{g\to q}\left(\frac{x}{y}\right)\right\}$$

$$\frac{dg(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left\{q^{\mathrm{S}}(y,t)\, P_{q\to g}\left(\frac{x}{y}\right) + g(y,t)\, P_{g\to g}\left(\frac{x}{y}\right)\right\}$$

$P_{q\to q}(x/y)$ $P_{q\to g}(x/y)$ $P_{g\to q}(x/y)$ $P_{g\to g}(x/y)$

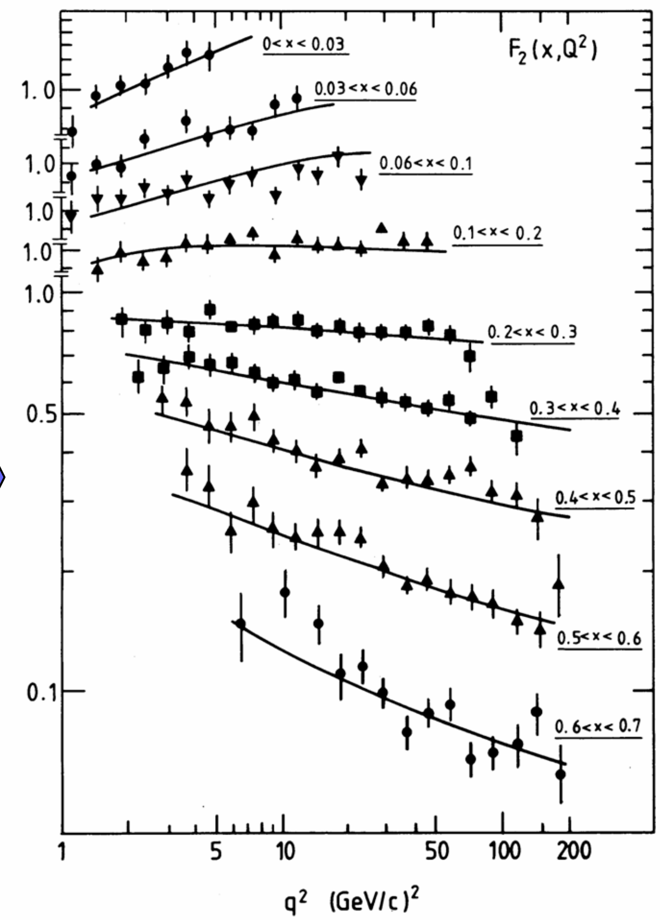
Scaling from QCD





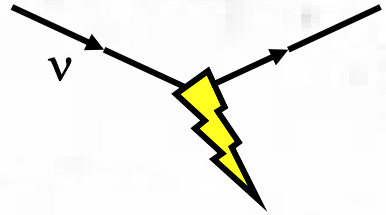
Observed quark distributions vary with Q^2

Scaling well modeled by perturbative QCD with a single free parameter (α_s)



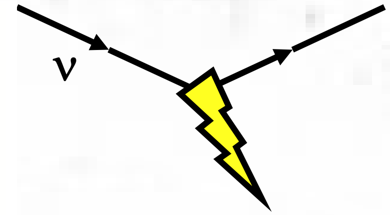
If you find this difficult to remember…

- It may help you to imagine scaling up a mountain
- Perhaps after yesterday it is more intuitive that as you go up in scale
  - the average momentum of each hiking group decreases
  - and the number of hiking groups increases…



DIS: Relating SFs to Parton Distributions

Structure Functions (SFs)



- A model-independent picture of these interactions can also be formed in terms of nucleon "structure functions"
  - All Lorentz-invariant terms included
  - Approximate zero lepton mass (small correction)

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} \propto \left[y^2 2xF_1(x,Q^2) + \left(2 - 2y - \frac{M_T xy}{E} \right) F_2(x,Q^2) \pm y(2-y) xF_3(x,Q^2) \right]$$

- For massless free spin-1/2 partons, one simplification…
  - Callan-Gross relationship, $2xF_1 = F_2$
  - Implies intermediate bosons are completely transverse

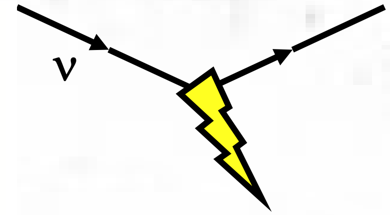
Can parameterize transverse cross-section by R_L.

•Callan-Gross violations, M

•NLO pQCD, $g \to q\bar{q}$

$$R_L = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}\left(1 + \frac{4M_T^2 x^2}{Q^2}\right)$$

SFs to PDFs



- Can relate SFs to PDFs in naïve quark-parton model by matching y dependence
  - Assuming Callan-Gross, massless targets and partons…
  - F_3: $2y-y^2=(1-y)^2-1$, $2xF_1=F_2$: $2-2y+y^2=(1-y)^2+1$

$$2xF_1^{\nu p,CC} = x\left[d_p(x)+\overline{u_p}(x)+s_p(x)+\overline{c_p}(x)\right]$$

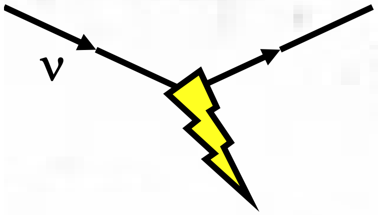
$$xF_3^{\nu p,CC} = x\left[d_p(x)-\overline{u_p}(x)+s_p(x)-\overline{c_p}(x)\right]$$

- In analogy with neutrino-electron scattering, CC only involves left-handed quarks
- However, NC involves both chiralities (V-A and V+A)
  - Also couplings from EW Unification
  - And no selection by quark charge

$$2xF_1^{\nu p,NC} = x\left[(u_L^2+u_R^2)\left(u_p(x)+\overline{u_p}(x)+c_p(x)+\overline{c_p}(x)\right)+(d_L^2+d_R^2)\left(d_p(x)+\overline{d_p}(x)+s_p(x)+\overline{s_p}(x)\right)\right]$$

$$xF_3^{\nu p,NC} = x\left[(u_L^2-u_R^2)\left(u_p(x)-\overline{u_p}(x)+c_p(x)-\overline{c_p}(x)\right)+(d_L^2-d_R^2)\left(d_p(x)-\overline{d_p}(x)+s_p(x)-\overline{s_p}(x)\right)\right]$$

Isoscalar Targets



- Heavy nuclei are roughly neutron-proton isoscalar
- Isospin symmetry implies $u_p = d_n, d_p = u_n$
- Structure Functions have a particularly simple interpretation in quark-parton model for this case…

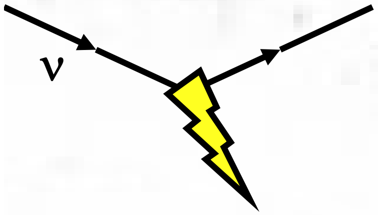
$$\frac{d^2\sigma^{\nu(\bar{\nu})N}}{dxdy} = \frac{G_F^2 s}{2\pi}\left\{ \left(1+(1-y)^2\right) F_2(x) \pm \left(1-(1-y)^2\right) xF_3^{\nu(\bar{\nu})}(x) \right\}$$

$$2xF_1^{\nu(\bar{\nu})N,CC}(x) = x(u(x)+d(x)+\bar{u}(x)+\bar{d}(x)+s(x)+\bar{s}(x)+c(x)+\bar{c}(x)) = xq(x)+x\bar{q}(x)$$

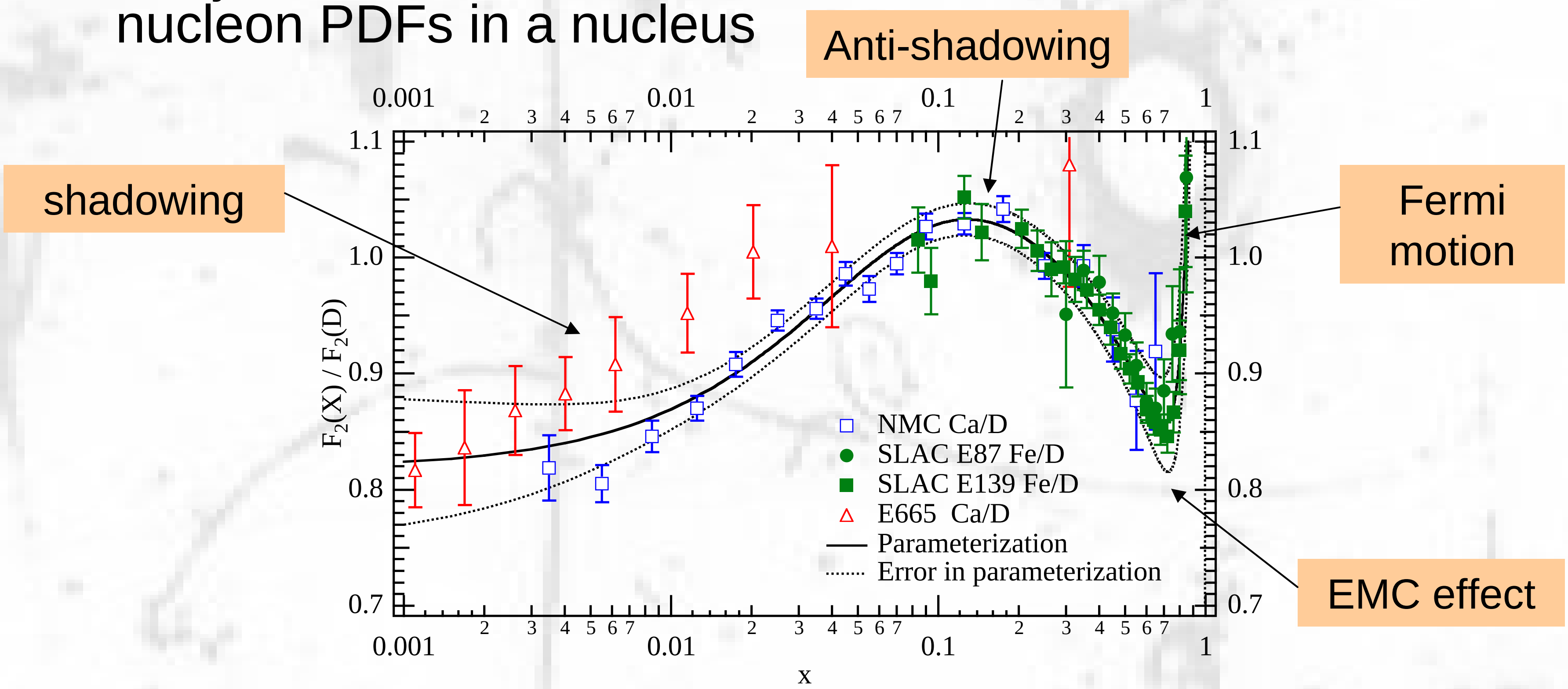
$$xF_3^{\nu(\bar{\nu})N,CC}(x) = xu_{Val}(x)+xd_{Val}(x) \pm 2x(s(x)-c(x))$$

$$\text{where } u_{Val}(x) = u(x)-\bar{u}(x)$$

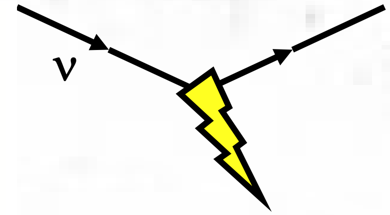
Nuclear Effects in DIS



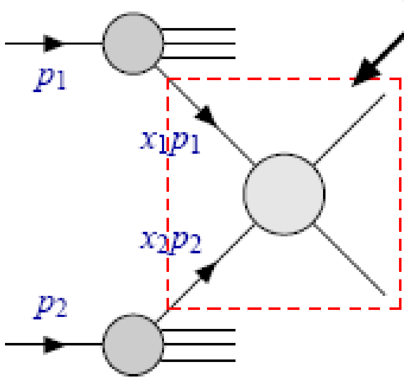
- Well measured effects in charged-lepton DIS
  - Maybe the same for neutrino DIS; maybe not… all precise neutrino data is on Ca or Fe targets!
  - Conjecture: these can be absorbed into effective nucleon PDFs in a nucleus



From SFs to PDFs



- As you all know, there is a large industry in determining Parton Distributions
  - to the point where some of my colleagues on collider experiments might think of parton distributions as an annoying piece of FORTRAN code in their C++ software
- The purpose, of course, exactly related to Chris' point about factorization in his Friday lecture



Calculable in Perturbation Theory

$$\sigma(h_1(p_1)+h_2(p_2)\to Y+X)=\int_0^1 dx_1\int_0^1 dx_2\sum_{f_1,f_2} f_{f_1}(x_1) f_{f_2}(x_2)\,\sigma(f_1+f_2\to Y)$$

- The f_{f_i} s are "known" from Deep Inelastic Scattering.

From SFs to PDFs (cont'd)

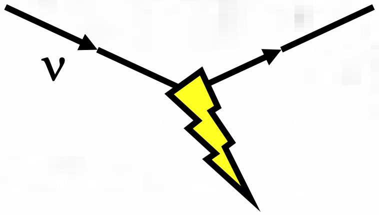
- We just learned that…

$$2xF_1^{\nu(\bar{\nu})N,CC}(x) = xq(x) + x\bar{q}(x)$$
$$xF_3^{\nu(\bar{\nu})N,CC}(x) = xu_{Val}(x) + xd_{Val}(x) \pm 2x(s(x) - c(x))$$
$$\text{where } u_{Val}(x) = u(x) - \bar{u}(x)$$

- In charged-lepton DIS

$$2xF_1^{\gamma p}(x) = \left(\tfrac{2}{3}\right)^2 \sum_{\text{up type quarks}} q(x) + \bar{q}(x)$$
$$+ \left(\tfrac{1}{3}\right)^2 \sum_{\text{down type quarks}} q(x) + \bar{q}(x)$$

- So you begin to see how one can combine neutrino and charged lepton DIS and separate
  - the quark sea from valence quarks
  - up quarks from down quarks

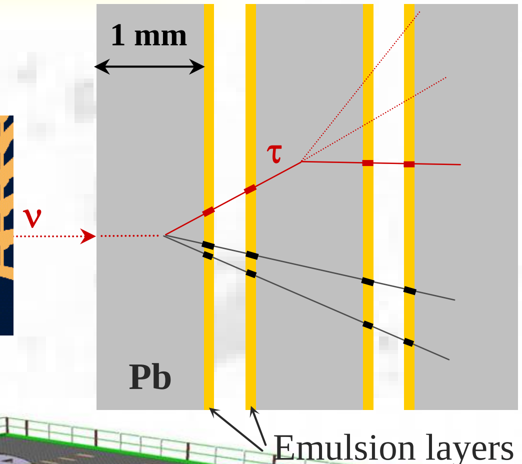


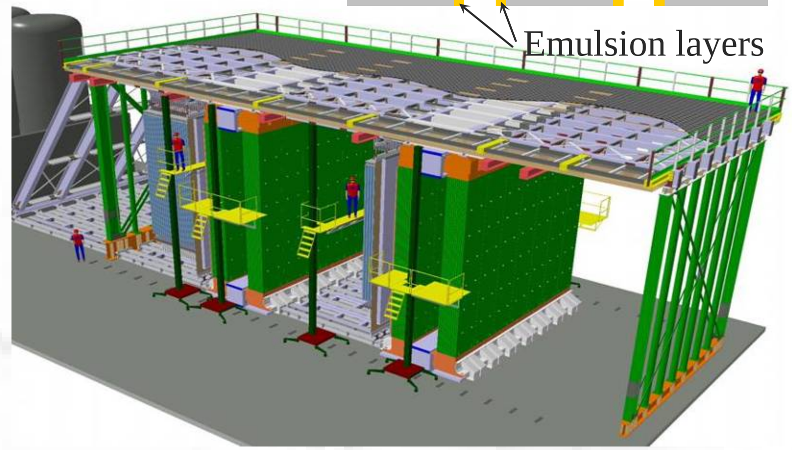
DIS: Massive Quarks and Leptons

Opera at CNGS

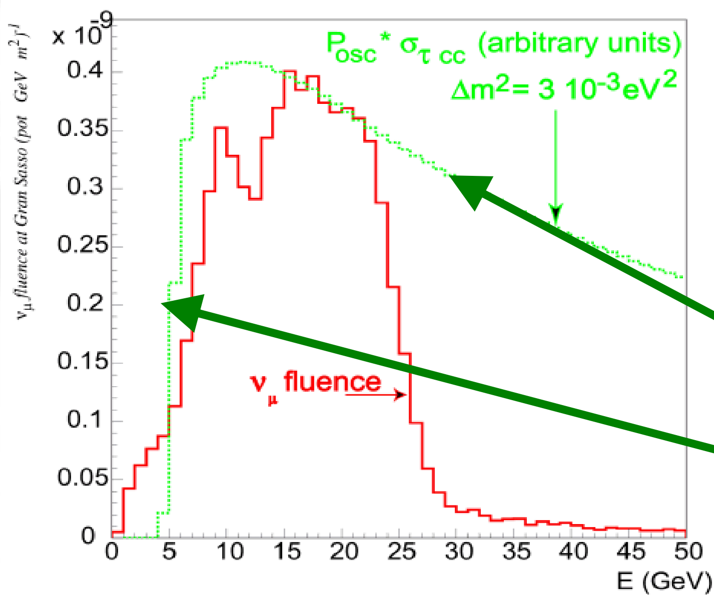
Goal: ν_τ appearance
- 0.15 MWatt source
- high energy ν_μ beam
- 732 km baseline
- handfuls of events/yr

1.8kTon





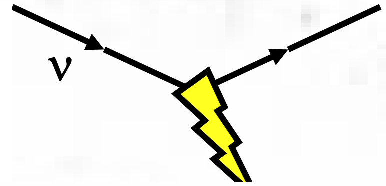
figures courtesy D. Autiero



oscillation probability

but what is this effect?

Lepton Mass Effects in DIS



- Recall that final state mass effects enter as corrections:

$$1 - \frac{m_{\text{lepton}}^2}{s_{\text{point-like}}} \quad \rightarrow \quad 1 - \frac{m_{\text{lepton}}^2}{x s_{\text{nucleon}}}$$

  - *relevant center-of-mass energy is that of the "point-like" neutrino-parton system*
  - *this is high energy approximation*
- For ν_τ charged-current, there is a threshold of

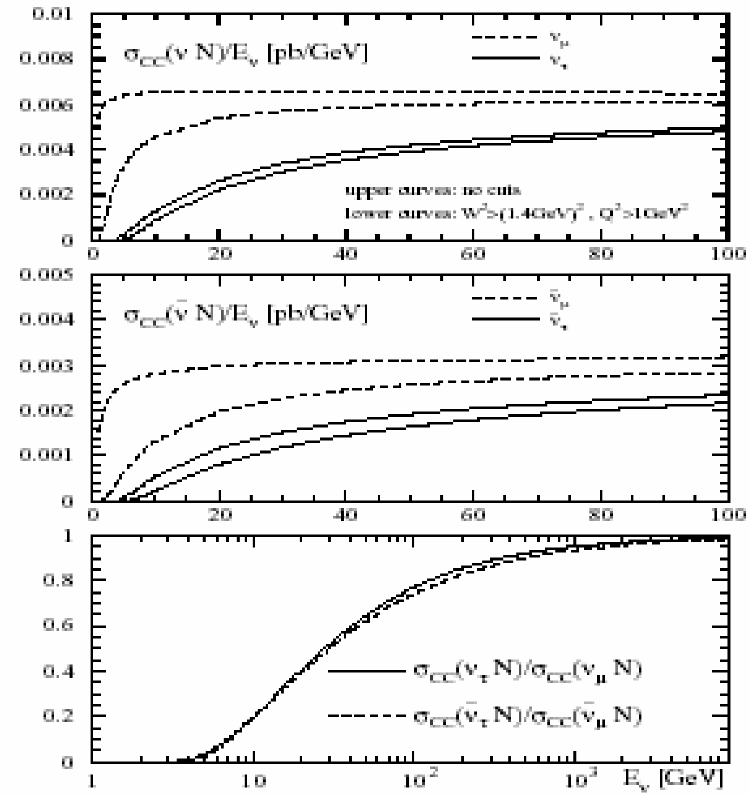
$$s_{\min} = (m_{\text{nucleon}} + m_\tau)^2$$

where

$$s_{initial} = m_{\text{nucleon}}^2 + 2E_\nu m_{\text{nucleon}}$$

$$\therefore E_\nu > \frac{m_\tau^{\,2} + 2m_\tau m_{\text{nucleon}}}{2m_{\text{nucleon}}} \approx 3.5 \text{ GeV}$$

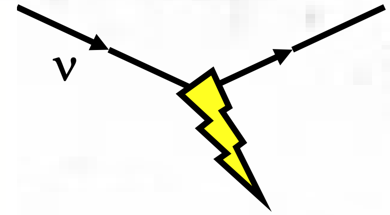
"m_{nucleon}" is M_T elsewhere, but don't want to confuse with m_τ...



(Kretzer and Reno)

- This is threshold for partons with *entire* nucleon momentum
  - effects big at higher E_ν also

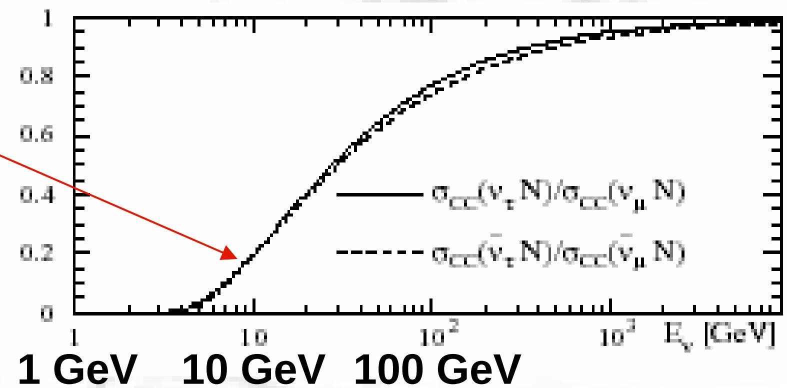
Touchstone Question #5: What if Taus were Lighter?



- Imagine we lived in a universe where the tau mass was not 1.777 GeV, but was 0.888 GeV
- By how much would the tau appearance cross-section for an 8 GeV tau neutrino increase at OPERA?

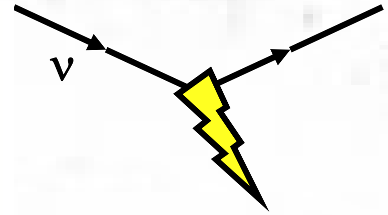
mass suppression: $1-\dfrac{m^2_{\text{lepton}}}{xs_{\text{nucleon}}}$

$$s_{\text{nucleon}} = m^2_{\text{nucleon}} + 2E_\nu m_{\text{nucleon}}$$

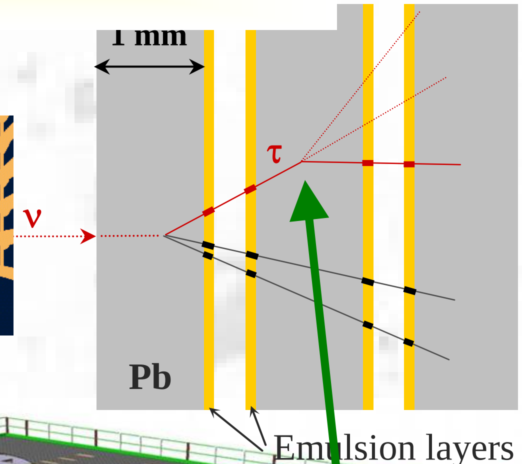


(a) $\dfrac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 1.4$ **(b)** $\dfrac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 2$ **(c)** $\dfrac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 3$

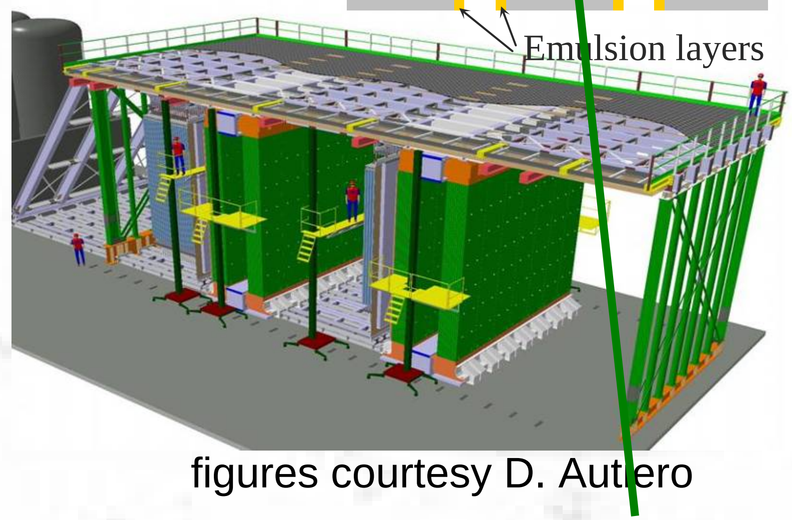
Opera at CNGS



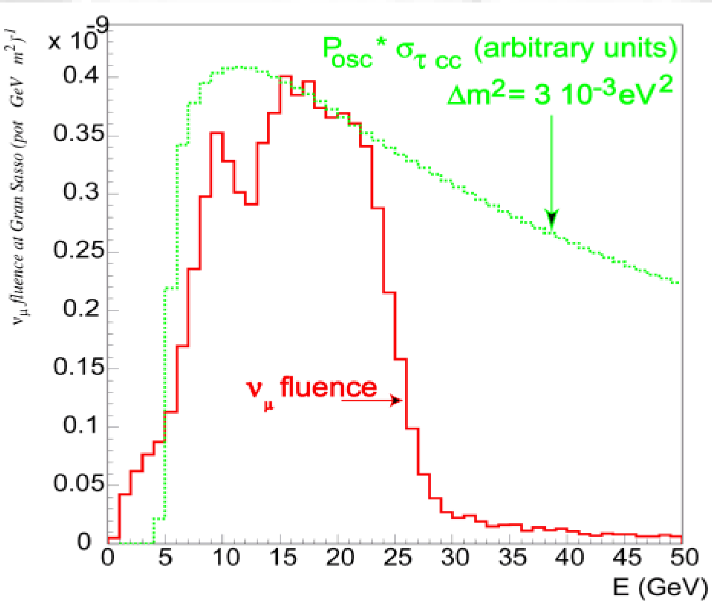
Goal: ν_τ appearance
- 0.15 MWatt source
- high energy ν_μ beam
- 732 km baseline
- handfuls of events/yr



1.8kTon

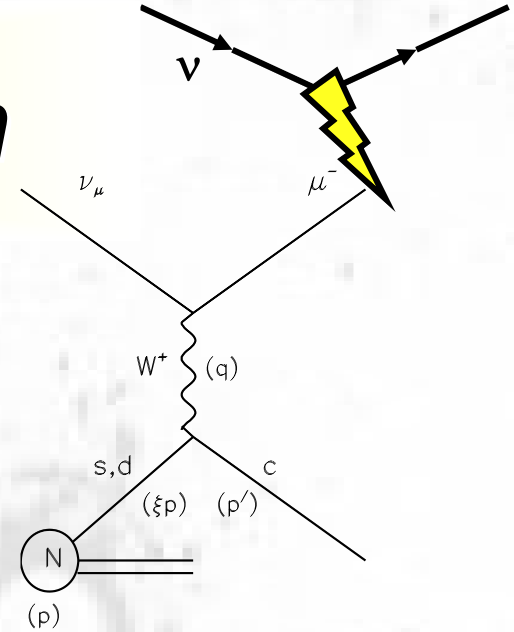


figures courtesy D. Autiero



what else is copiously produced in neutrino interactions with cτ ~ 100μm and decays to hadrons?

Heavy Quark Production



- Scattering from heavy quarks is more complicated.
  - Charm is heavier than proton; hints that its mass is not a negligible effect…

$$(q+\zeta p)^2 = p'^2 = m_c^{\ 2}$$

$$q^2 + 2\zeta p \bullet q + \zeta^2 M^2 = m_c^{\ 2}$$

Not your father's fractional momentum

$$\text{Therefore } \zeta \cong \frac{-q^2 + m_c^{\ 2}}{2p \bullet q}$$

$$\zeta \cong \frac{Q^2 + m_c^{\ 2}}{2M\upsilon} = \frac{Q^2 + m_c^{\ 2}}{Q^2 / x}$$

$$\zeta \cong x\left(1 + \frac{m_c^{\ 2}}{Q^2}\right)$$

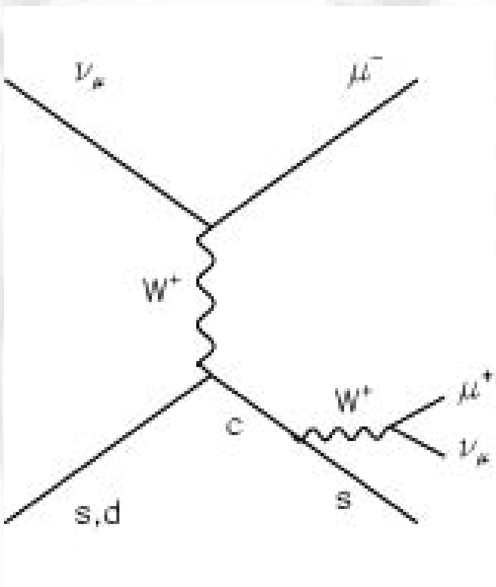
"slow rescaling" leads to kinematic suppression of charm production

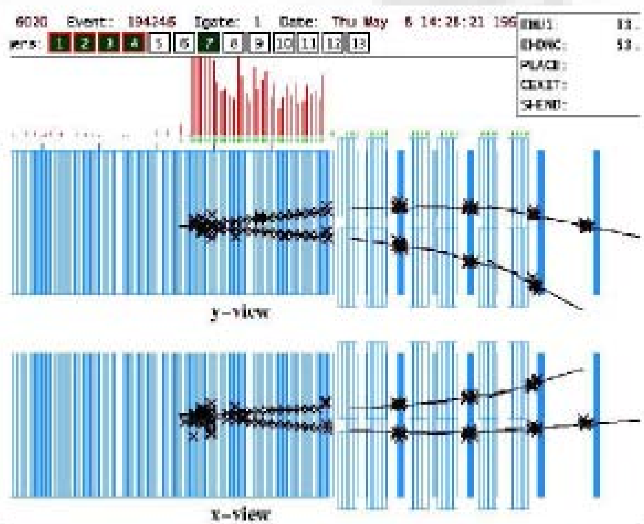
Neutrino Dilepton Events

- Neutrino induced charm production has been extensively studied
  - Emulsion/Bubble Chambers (low statistics, 10s of events). Reconstruct the charm final state, but limited by target mass.
  - "Dimuon events" (high statistics, 1000s of events)

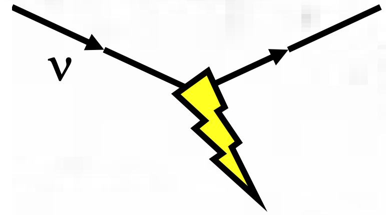
$$\nu_\mu + \begin{pmatrix} d \\ s \end{pmatrix} \rightarrow \mu^- + c + X, \qquad c \rightarrow \mu^+ + \nu_\mu + X'$$

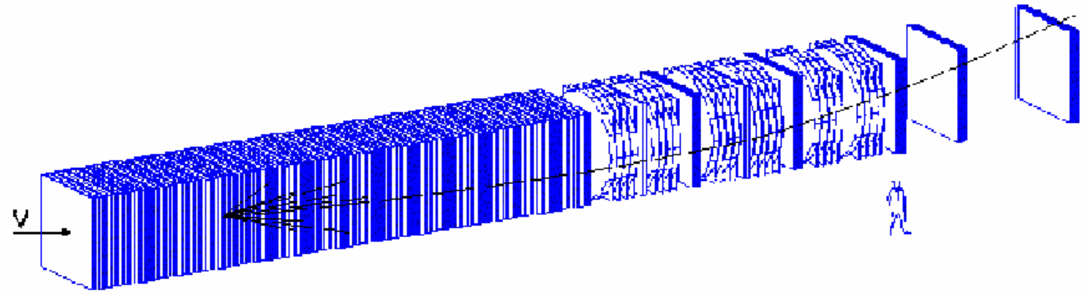
$$\bar{\nu}_\mu + \begin{pmatrix} \bar{d} \\ \bar{s} \end{pmatrix} \rightarrow \mu^+ + \bar{c} + X, \qquad \bar{c} \rightarrow \mu^- + \bar{\nu}_\mu + X'$$

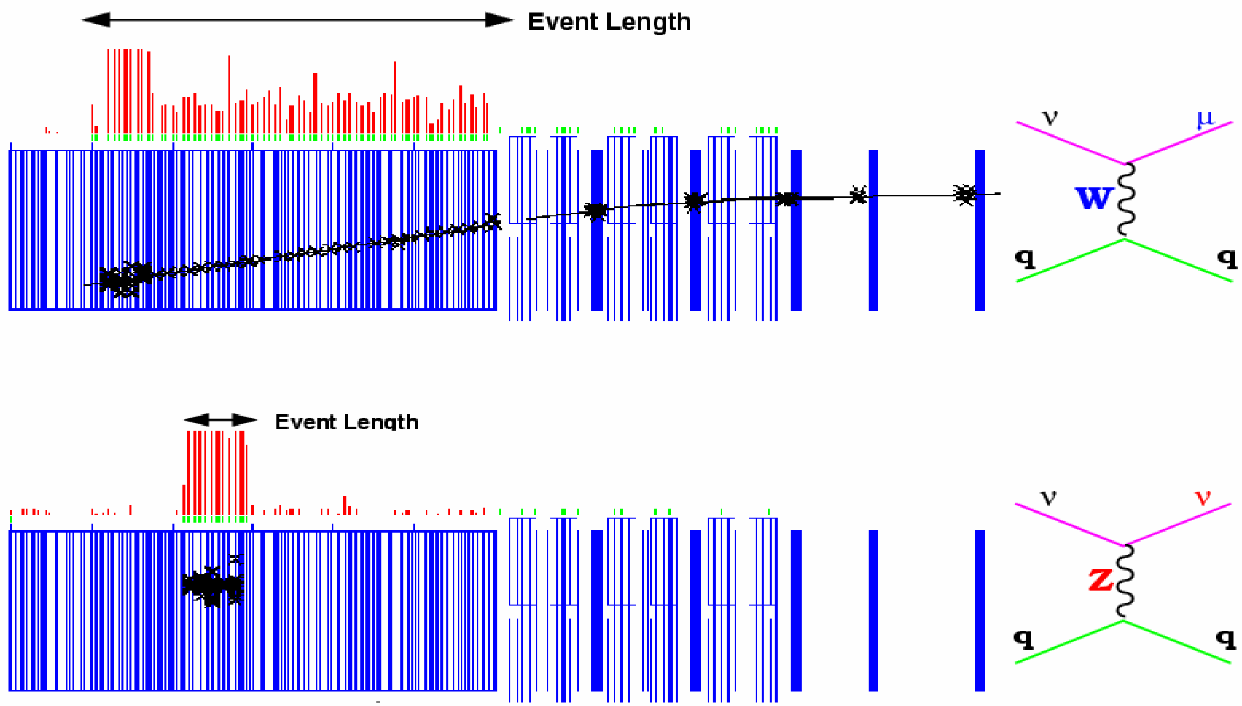




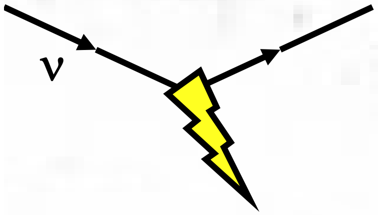
NuTeV at Work…







Neutrino Dilepton Events



- Rate depends on:
  - d, s quark distributions, $|V_{cd}|$
  - Semi-leptonic branching ratios of charm
  - Kinematic suppression and fragmentation

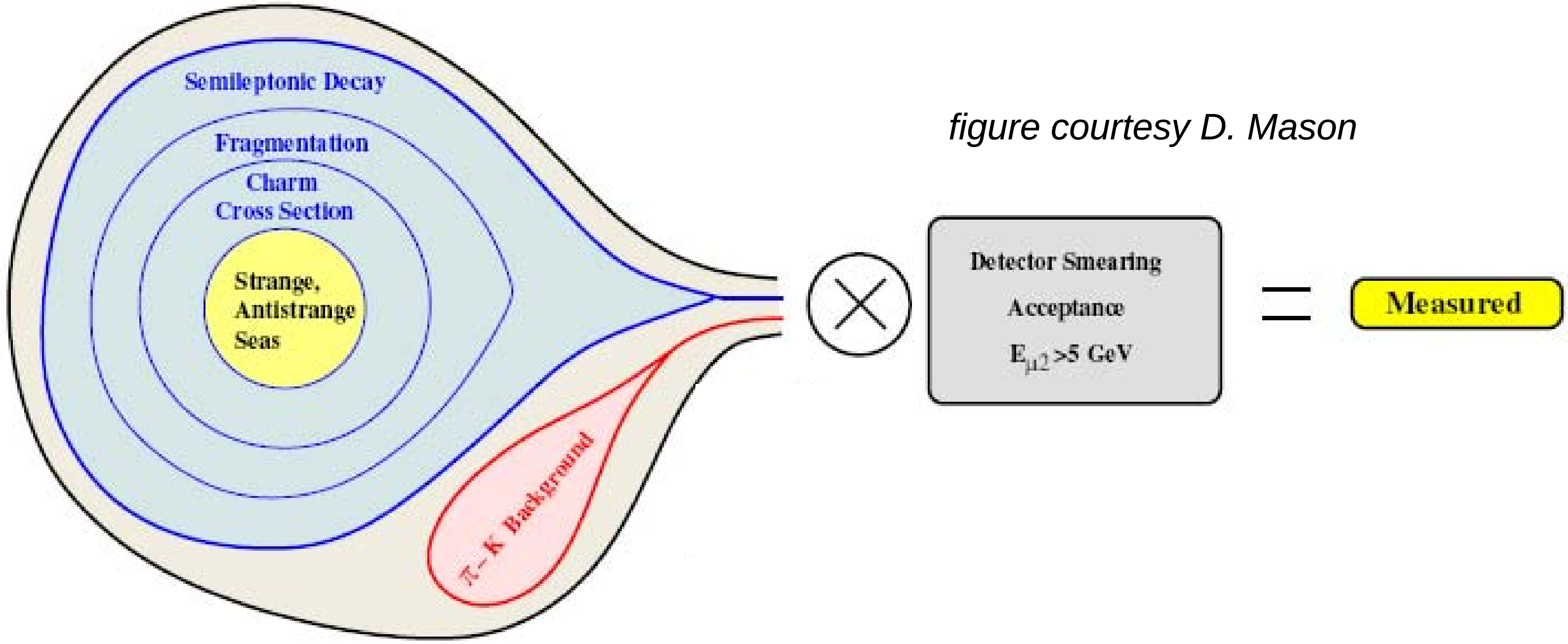
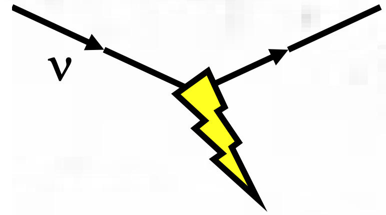
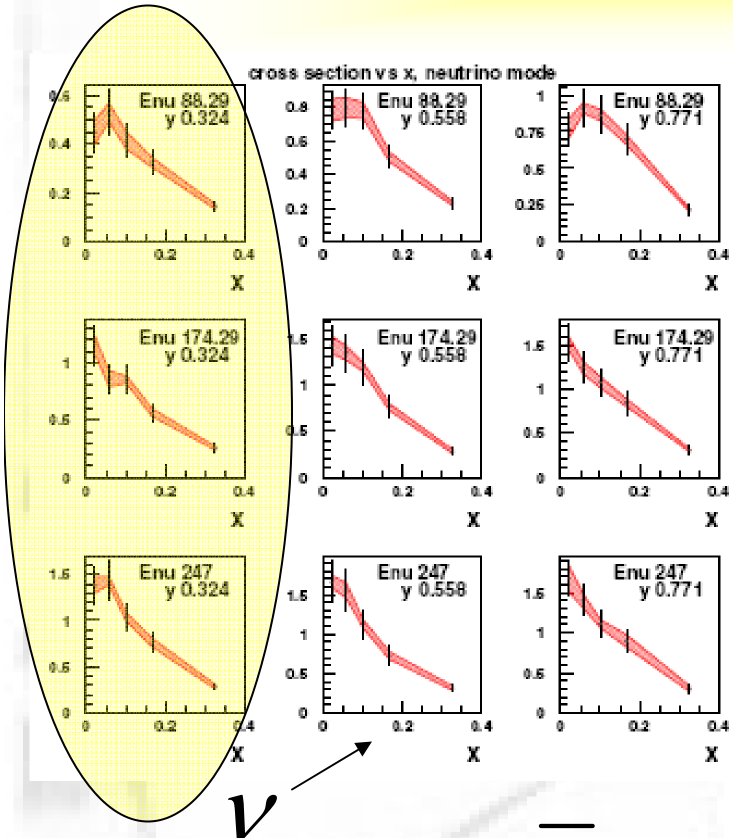


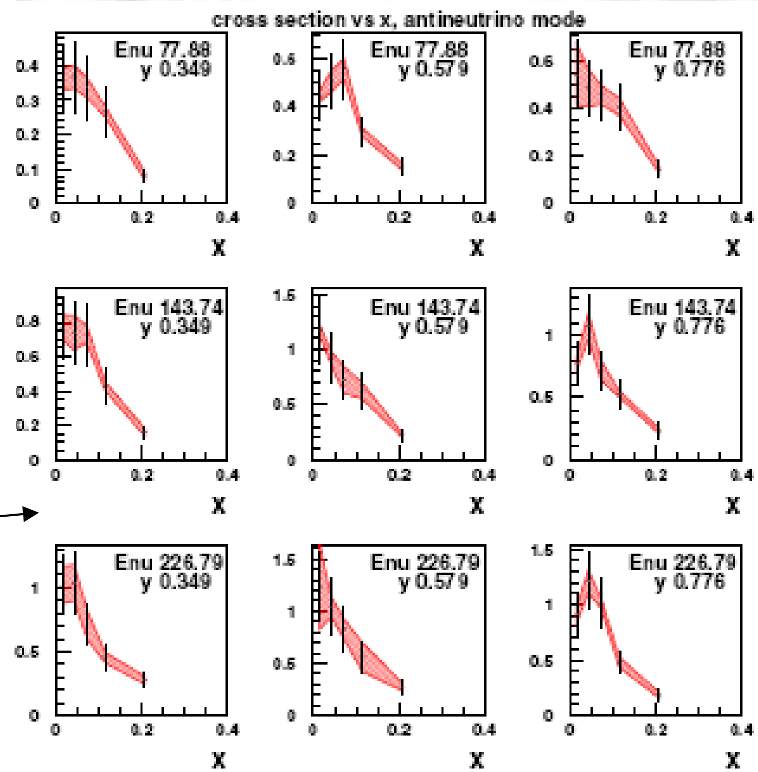
figure courtesy D. Mason

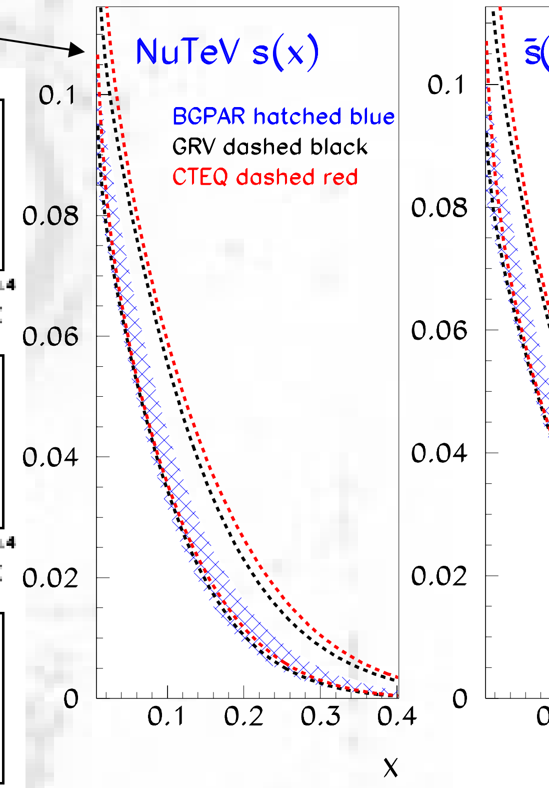
NuTeV Dimuon Sample



- Lots of data!
- Separate data in energy, x and y (inelasticity)
  - Energy important for charm threshold, m_c
  - x important for s(x)



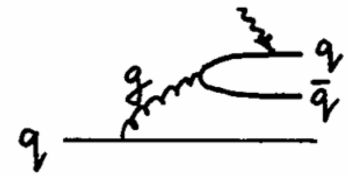


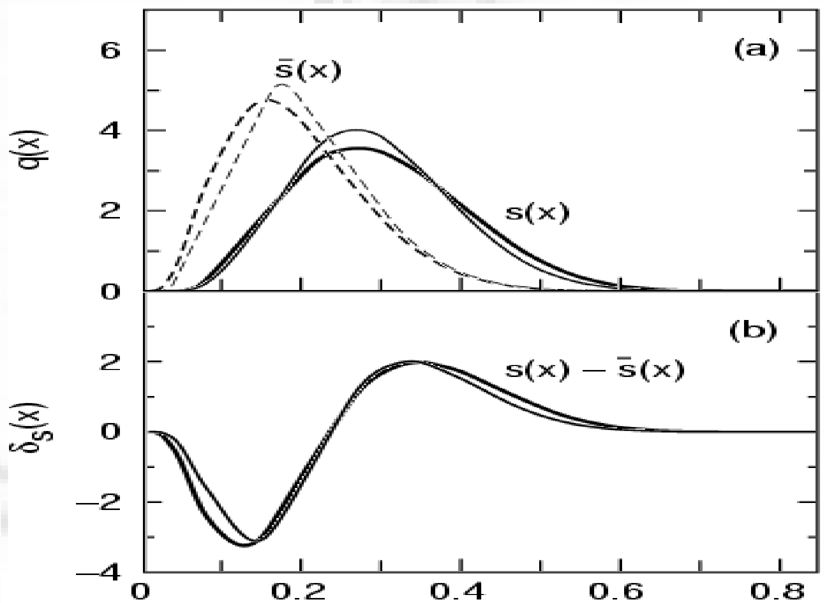


$$\frac{\pi \times \dfrac{d^2\sigma(\nu N \to \mu\mu X)}{dxdy}}{G_F^2 M_N E_\nu}$$

QCD at Work: Strange Asymmetry?

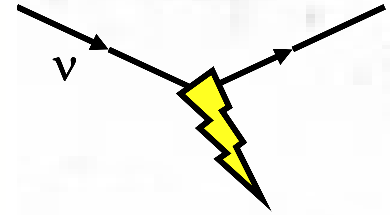
- An interesting aside…
  - The strange sea can be generated perturbatively from g→s+sbar.
  - BUT, in perturbative generation the momenta of strange and anti-strange quarks is equal
    - o well, in the leading order splitting at least. At higher order get a vanishingly small difference.
  - SO s & sbar difference probe non-perturbative ("intrinsic") strangeness
    - o Models: Signal&Thomas, Brodsky&Ma, etc.





(Brodsky & Ma, s-sbar)

NuTeV's Strange Sea



- NuTeV has tested this
  - NB: very dependent on what is assumed about non-strange sea
  - Why? Recall CKM mixing…

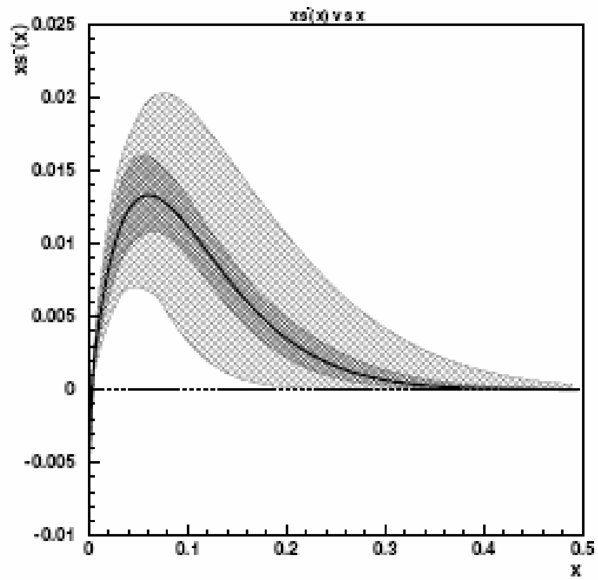
$$V_{cd}\,d(x)+V_{cs}\,s(x)\rightarrow s'(x)$$
$$V_{cd}\,\bar{d}(x)+V_{cs}\,\bar{s}(x)\rightarrow \bar{s}'(x)$$

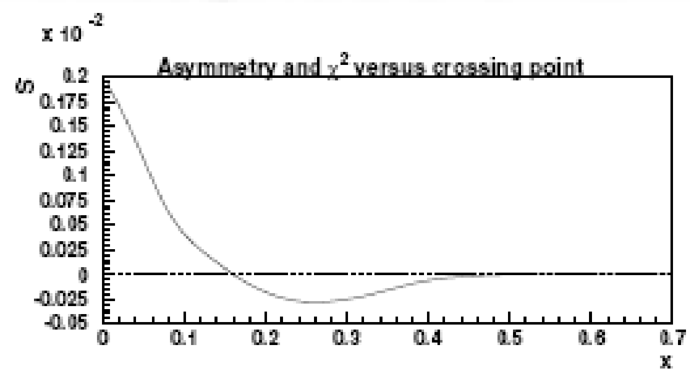
small *big*

  - Using CTEQ6 PDFs…

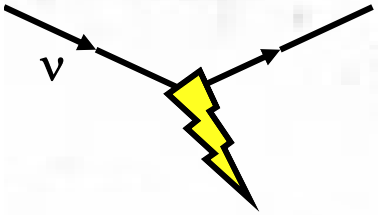
$$\int dx\left[x\left(s-\bar{s}\right)\right]=0.0019\pm0.0005\pm0.0014$$

$$\text{c.f., }\int dx\left[x\left(s+\bar{s}\right)\right]\approx 0.02$$

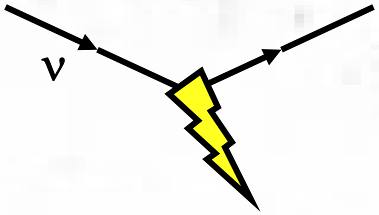




Deep Inelastic Scattering: Conclusions and Summary

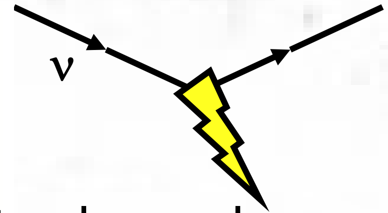


- Neutrino-quark scattering is elastic scattering!
  - complicated by fact that quarks live in nucleons
- Important lepton and quark mass effects for tau neutrino appearance experiments
- Neutrino DIS important for determining parton distributions
  - particularly valence and strange quarks

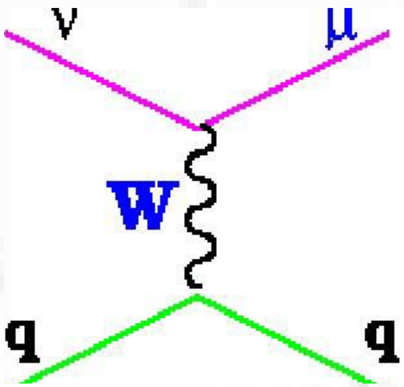


Neutrino-Nucleon Deep Inelastic Scattering Applied…

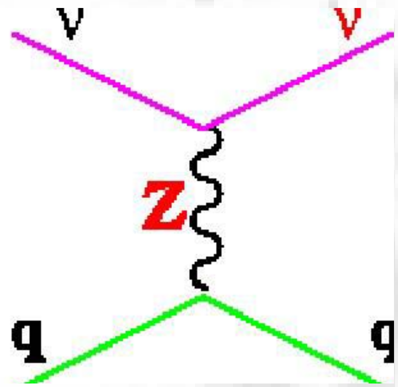
DIS NC/CC Ratio



- Experimentally, it's "simple" to measure ratios of neutral to charged current cross-sections on an isoscalar target to extract NC couplings



W-q coupling is I_3



Z-q coupling is $I_3\text{-}Q\sin^2\theta_W$

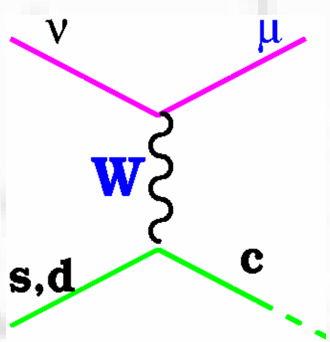
Llewellyn Smith Formulae

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \left(\left(u_L^2 + d_L^2\right) + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}} \left(u_R^2 + d_R^2\right) \right)$$

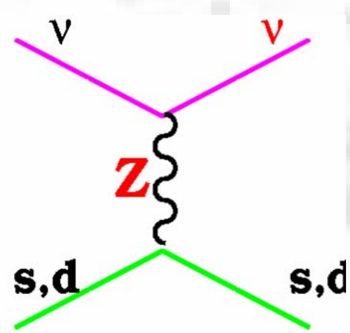
- Holds for isoscalar targets of u and d quarks only
  - Heavy quarks, differences between u and d distributions are corrections
- Isospin symmetry causes PDFs to drop out, even outside of naïve quark-parton model

Touchstone Question #6: Paschos-Wolfenstein Relation

Charged-Current

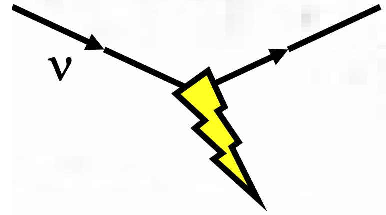


Neutral-Current



- If we want to measure electroweak parameters from the ratio of charged to neutral current cross-sections, what problem will we encounter from these processes?

Touchstone Question #6: Paschos-Wolfenstein Relation



- The NuTeV experiment employed a complicated design to measure

Paschos - Wolfenstein Relation

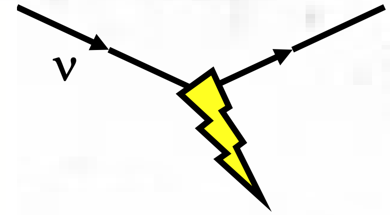
$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left(\tfrac{1}{2} - \sin^2 \theta_W \right)$$

- How did this help with the heavy quark problem of the previous question?

Hint: what to you know about the relationship of:

$$\sigma(\nu q) \text{ and } \sigma(\overline{\nu}\,\overline{q})$$

NuTeV Fit to R^{ν} and $R^{\bar{\nu}}$



- NuTeV result:

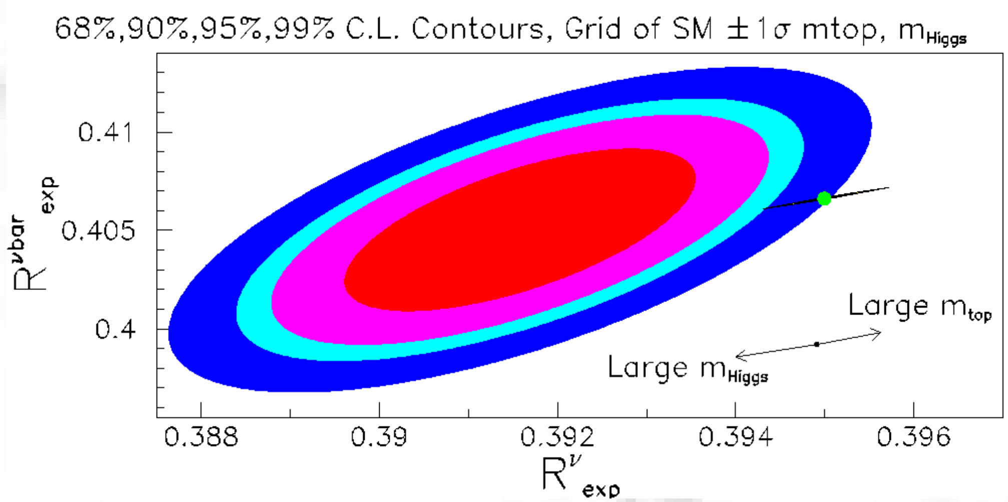
$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$
$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

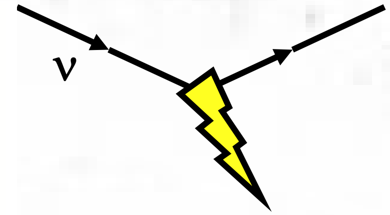
- Standard model fit (LEPEWWG): 0.2227 ± 0.00037

A 3σ discrepancy…

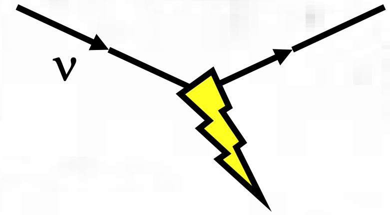
$$R^{\nu}_{\exp} = 0.3916 \pm 0.0013$$
$(SM : 0.3950)$ $\Leftarrow 3\sigma$ *difference*
$$R^{\bar{\nu}}_{\exp} = 0.4050 \pm 0.0027$$
$(SM : 0.4066)$ $\Leftarrow$ *Good agreement*



NuTeV Electroweak: What does it Mean?



- If I knew, I'd tell you.
- It could be BSM physics. Certainly there are no limits on a Z' that could cause this. But why?
- It could be the asymmetry of the strange sea…
  - it would contribute because the strange sea would not cancel in
  - but it's been measured; not anywhere near big enough
- It could be very large isospin violation
  - if $d_p(x) \neq u_n(x)$ at the 5% level… it would shift charge current (normalizing) cross-sections enough.
  - no data to forbid it. any reason to expect it?



Next Lecture:

GeV cross-sections, application to $\nu_\mu \rightarrow \nu_e$, other energy regimes