Hadronization Model for MINOS

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Introduction

- Hadronization (or fragmentation) model – the model that determines the final state particles and 4-momenta given a neutrino-nucleon interaction (CC/NC, nu/nubar, n/p) and the event kinematics (W^2, Q^2,x,y etc.).
- Candidate models:
  - Resonance models: isospin Clebsch-Gordon coefficients
    $W<1.7$ GeV/c^2
  - String models (JETSET)
    $W>4$GeV/c^2
  - Empirical models (e.g. NEUGEN's KNO-based model) – was used in the MINOS simulation
    intermediate W

MINOS Experiment

- MINOS is a long baseline neutrino experiment using the NuMI neutrino beam to study neutrino oscillations.
- We have two functionally identical detectors.
  - Near Detector at Fermilab to measure the flux and the background
  - Far Detector at Minnesota to measure the oscillation signal
- We use iron/scintillator tracking calorimeter to measure the neutrino energy.
  - 2.54cm steel planes
  - 5.95cm spacing between two consecutive planes
  - 1.0×4.1cm extruded polystyrene scintillator strips, up to 8m long

Impact on MINOS Measurement

- The hadronization model is important for the MINOS experiment:
  - ν_μ disappearance measurement – Δm_{32}^2, θ_{23}
    - Reconstructed shower energy
  - ν_e appearance measurement – θ_{13}
    - Event topology
    - Background estimation
  - Neutral current measurement – sterile neutrinos
    - Event topology

Improvements on the Hadronization Model

- Retuned the hadronization model in July/06 based on external data from bubble chamber experiments: 15ft-FNAL, BEBC, GGM and SKAT – mainly high energy
- Focused on the following quantities:
  - Charged/neutral pion multiplicity and dispersion
  - Forward/backward fragments
  - Fragmentation functions
  - Transverse momentum (p_t)

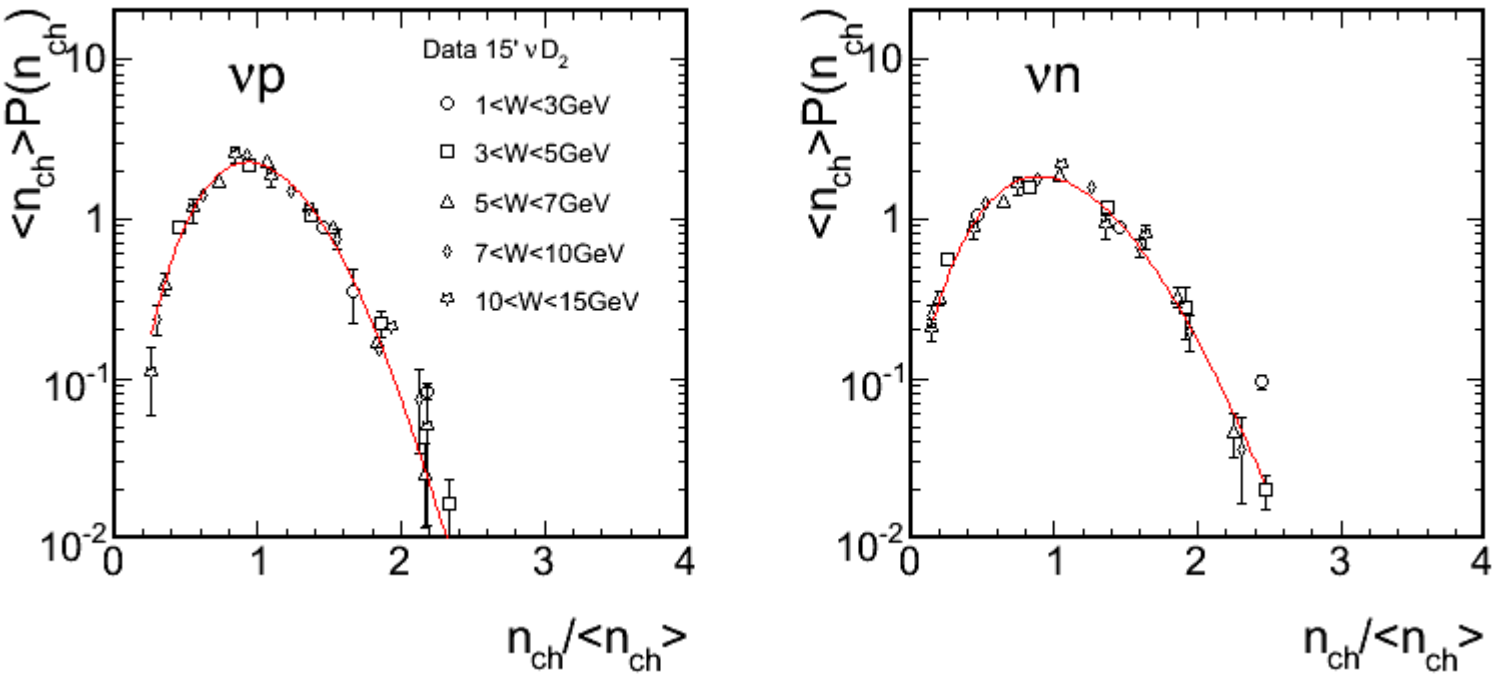
DIS Hadronization Model

- In MINOS, we combine a low energy hadronization model with a standard “high-energy” package - JETSET.
- At low invariant mass ($W<2.3 GeV/c^2$), we use our empirical model (modified KNO-based model).
- At high invariant mass ($W>3 GeV/c^2$), we use the tuned JETSET.
- Smooth transition between KNO-based model and JETSET over values from $2.3 GeV/c^2$ and $3 GeV/c^2$.

Low-W: KNO-based Model

- Select particles
  - Decide hadron multiplicity based on W and KNO-distributions. $\langle n_{ch} \rangle = a + b \ln W^2$
- Determine 4-momenta for particles
  - Select baryon 4-momentum from proton PDF (x_F,p_T)
  - Decay remaining hadronic system
  - Phase space decay with p_t reweighting
  - Rotate/boost hadronic system to lab frame

KNO Distributions



- W^2 independent charged pion multiplicity distributions
- Can be well fitted by Levy function: $\Psi = 2\frac{e^{-c}c^{cz+1}}{\Gamma(cz+1)}$
- Use KNO for charged pions, what about neutral pions?

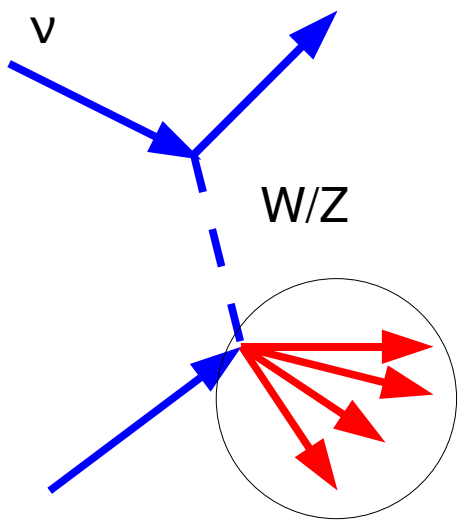
Forward/backward Hemispheres

In the hadronic CM frame:

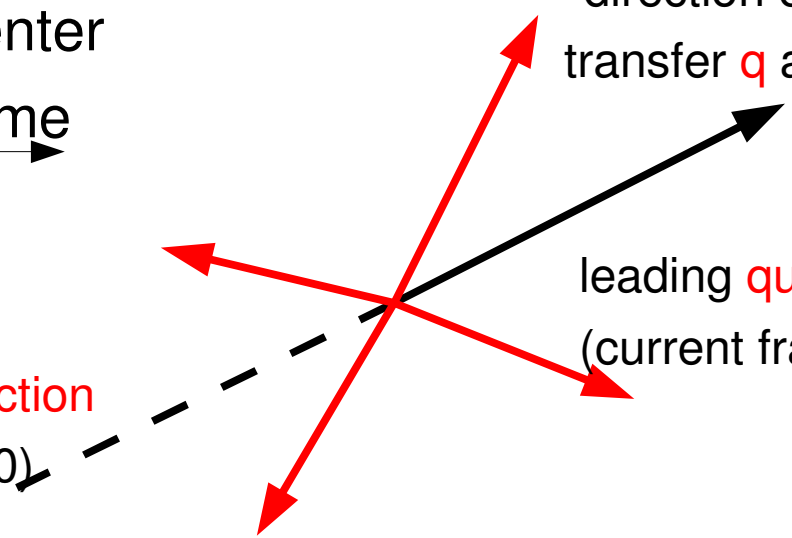
$x_F = P^*_L / P^*_{Lmax}$ = Feynman-x

P^*_L is the longitudinal momentum

P^*_{Lmax} is its max kinematical value (W/2)



boost to hadronic center of mass frame



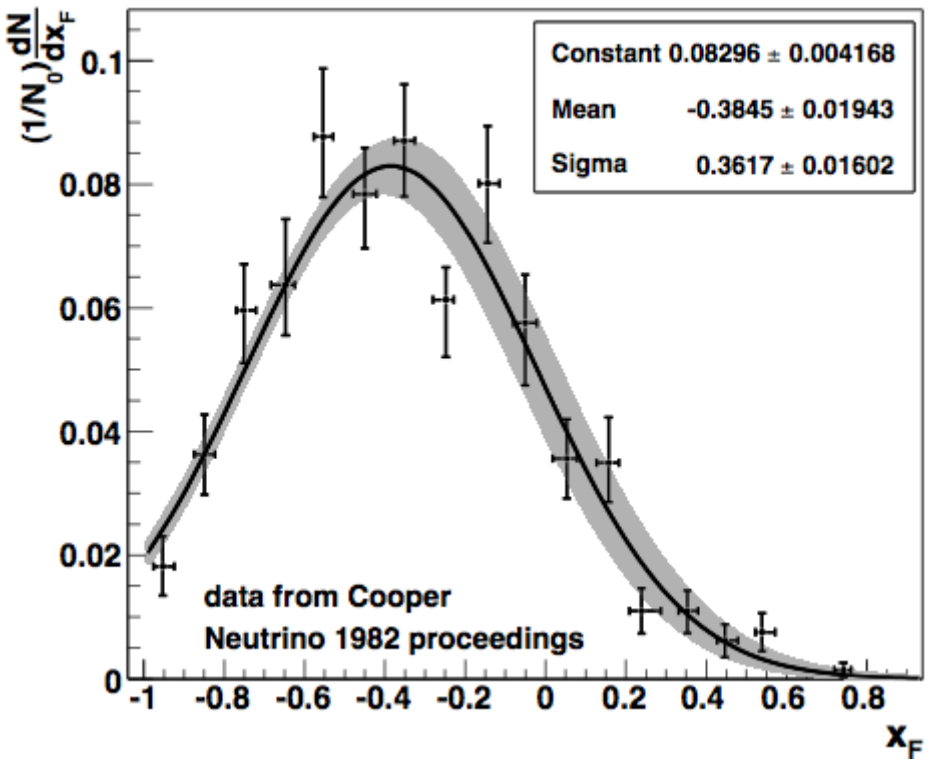
direction of the momentum transfer q at the hadronic CM

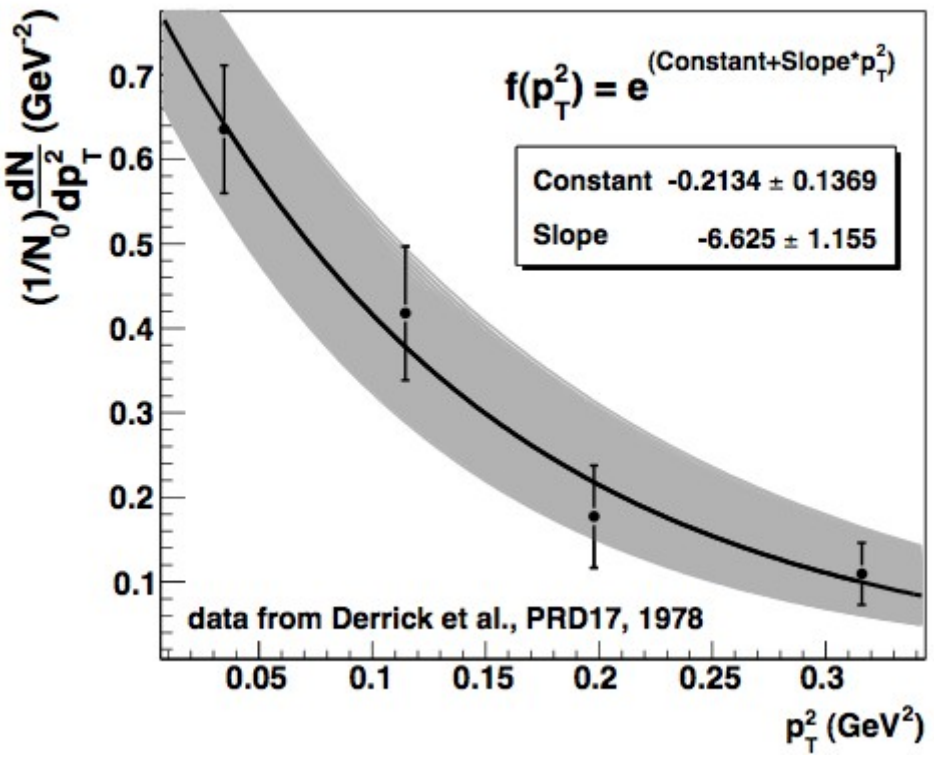
leading quark direction (current fragment, x_F>0)

remnant diquark direction (target fragment, x_F<0)

Select baryon 4-momentum from proton PDF (x_F,p_T)

Nucleon x_F and p_T





Building in experimental data on nucleon x_F and p_T

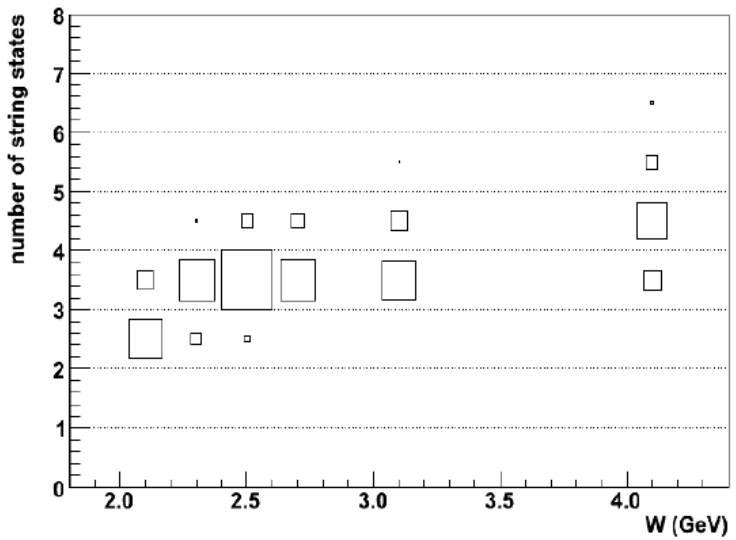
High-W: PYTHIA/JETSET

- Using PYTHIA/JETSET model for W>3GeV/c^2
- Including NUX's PYTHIA tuning (NOMAD exp. A.Rubbia's talk @ NuINT01)

	current PYTHIA defs	NUX/NOMAD tuning
ssbar suppression	0.30	0.21
gaussian $<p_T^2>$(GeV^2)	0.36	0.44
non gaussial p_T^2 tail	0.01	0.01
remaining energy cutoff (GeV)	0.80	0.20

How Low can JETSET go?

- Costas discussed with Tobjorn Sjostrand, author of JETSET/Pythia.
- It was suggested that using JETSET at 2GeV is pretty aggressive.
- "However you could never get around facts like that Pythia does not know about the isospin quantum number....So therefore, **at energies where twobody string states dominate...you should not use Pythia**"



at least:

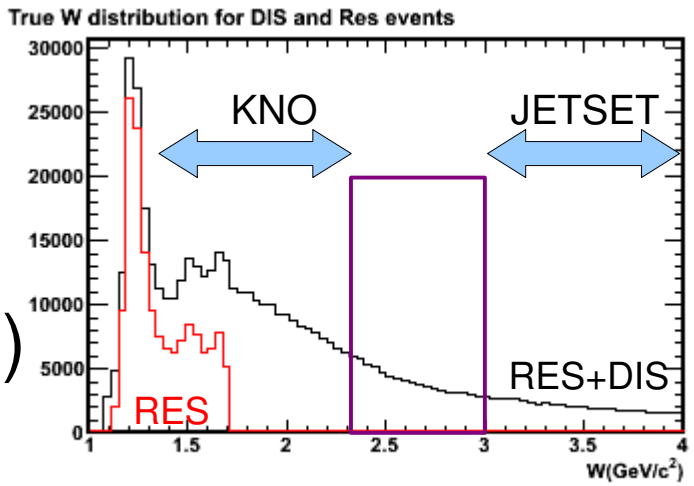
Wmin (JETSET) > 2.2 GeV

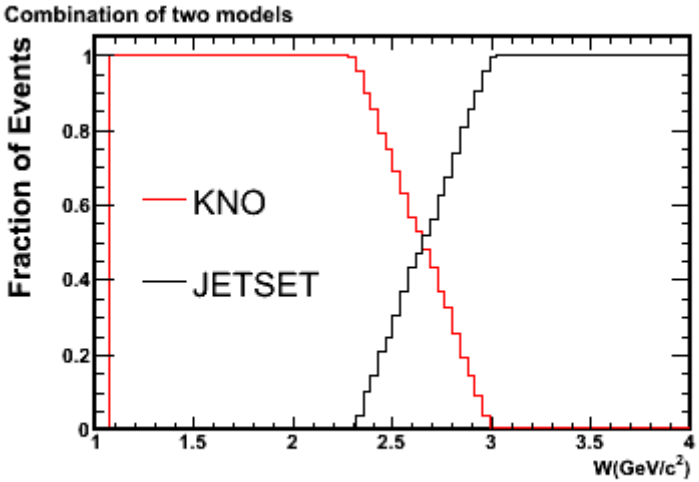
better:

Wmin (JETSET) > 2.5 GeV

The Final Model - AGKY

- R/S model used for RES events
- KNO-based model used for low-W DIS events (W<2.3GeV/c^2)
- JETSET used for high-W DIS events (W>3GeV/c^2)
- Smooth transition from 2.3GeV/c^2 to 3GeV/c^2

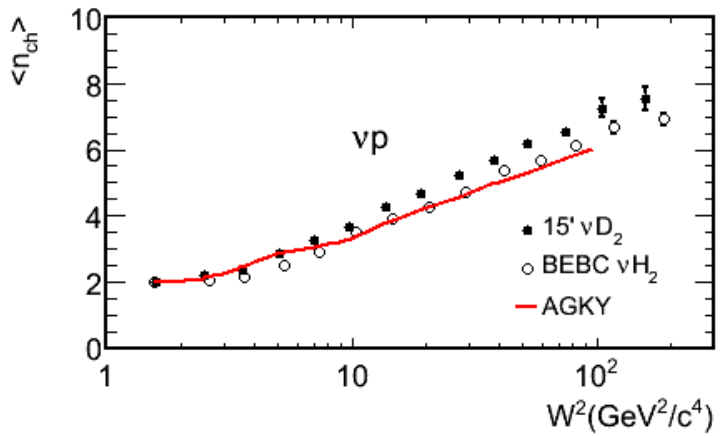


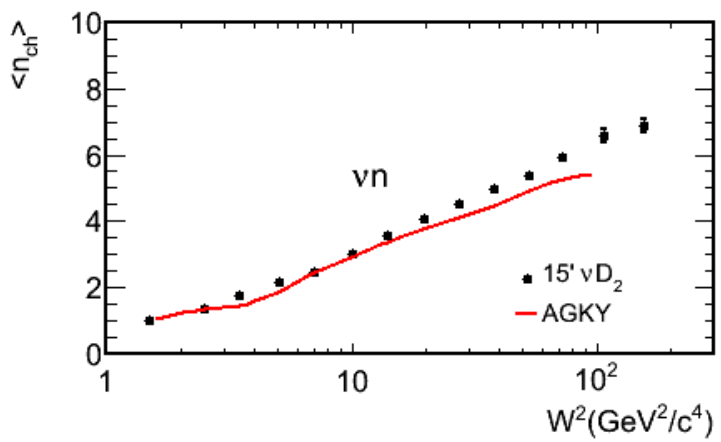


Compared with External Data

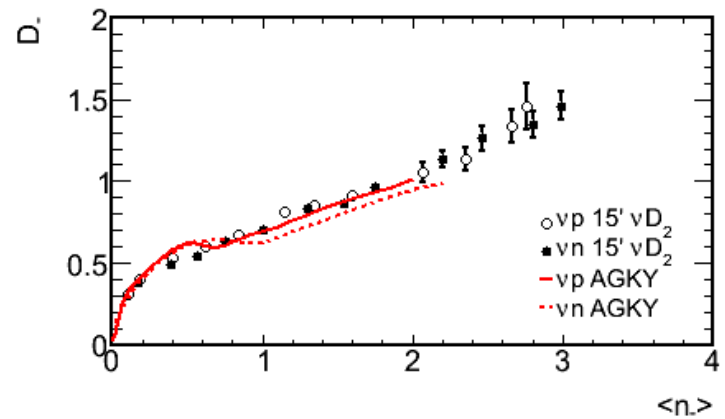
- We compared our model predictions with a lot of bubble chamber experiment data - 15ft-FNAL, BEBC, GGM and SKAT.
- Hadron multiplicity (n) – number of hadrons generated
- Dispersion - sqrt($\langle n^2 \rangle - \langle n \rangle^2$)
- $z = \frac{\nu}{E}$, *where* $\nu = E_\nu - E_\mu$ = *lab energy of the exchanged vector boson W*
- p_T = transverse momentum with respect to the current direction
- $x_F = P^*_L / P^*_{Lmax}$ = Feynman-x
- "Forward" – $x_F > 0$ – current fragment. "Backward" – $x_F < 0$ – target fragment.

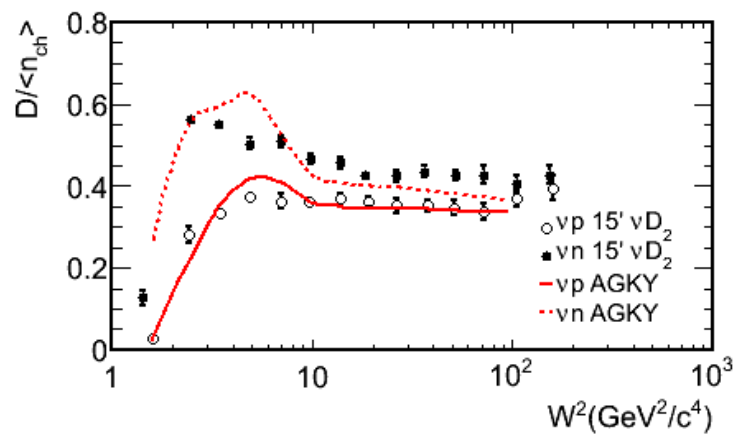
Charged Hadron Multiplicity and Dispersion





Multiplicity

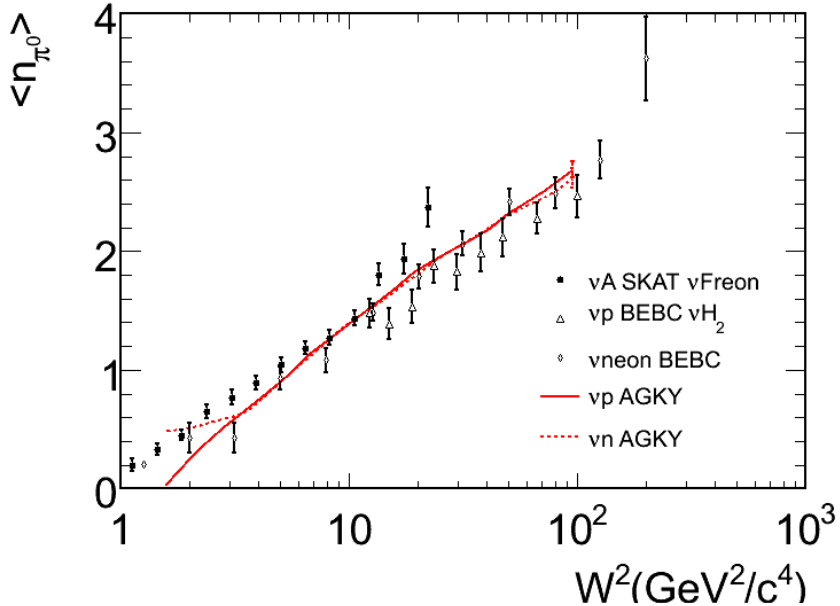




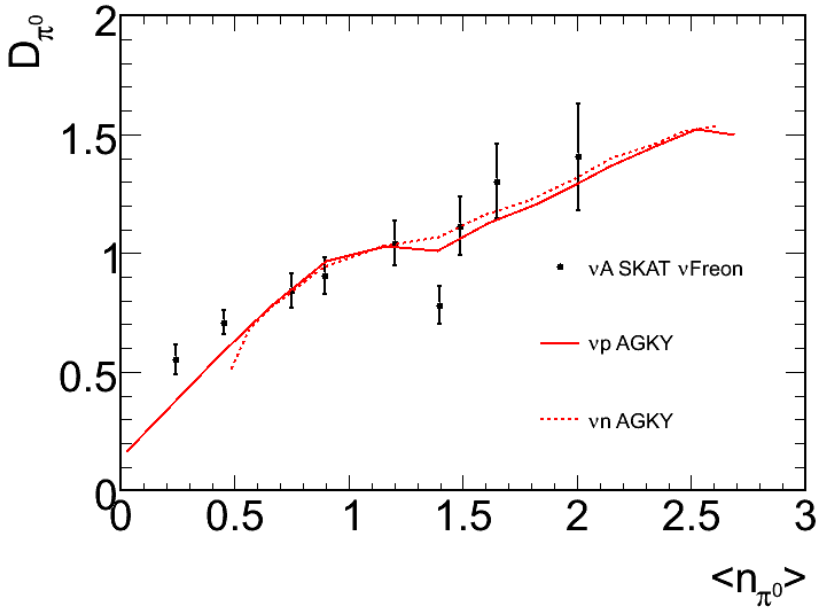
Dispersion

Pi0 Multiplicity and Dispersion

Multiplicity

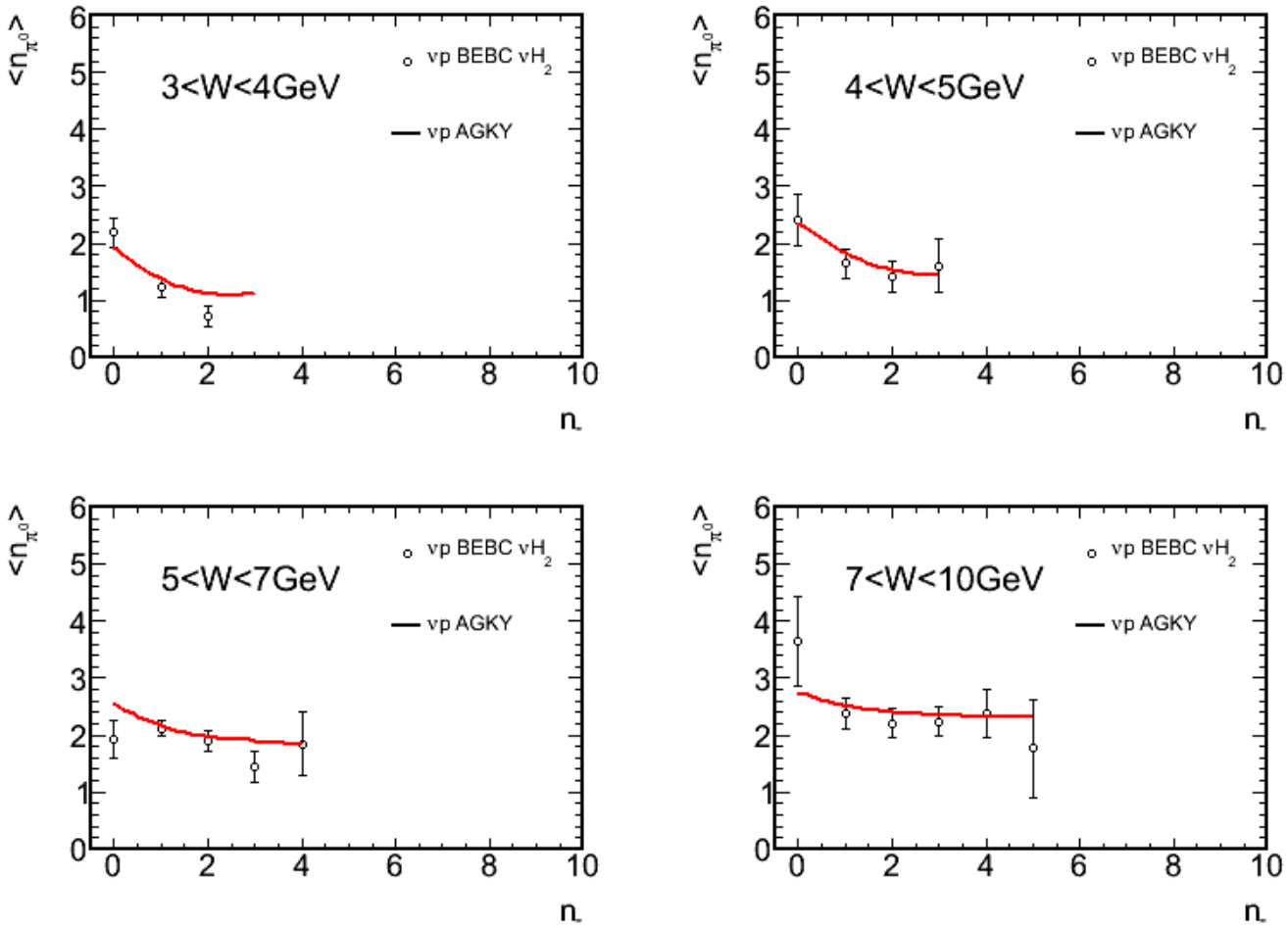


Dispersion



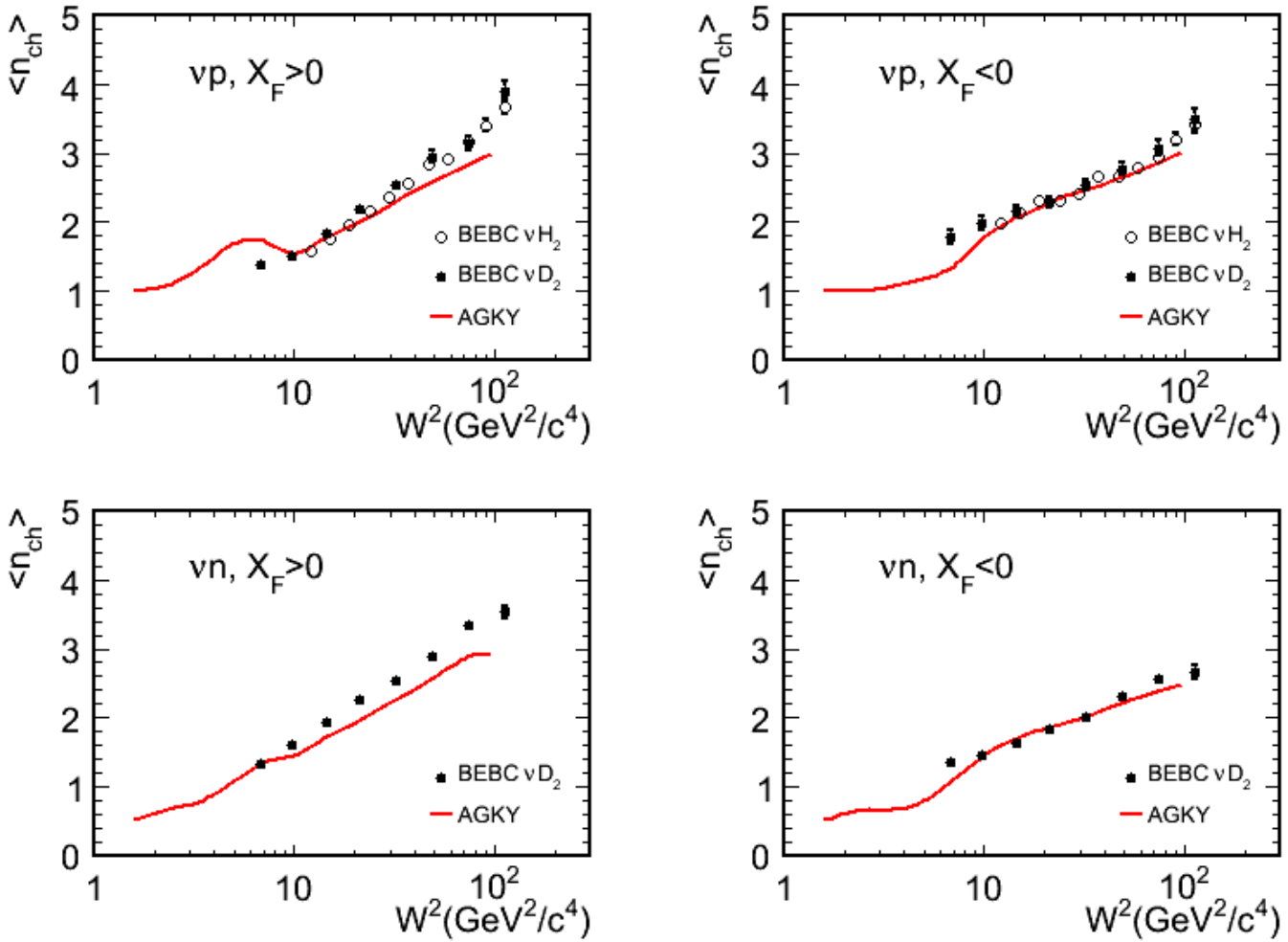
It was hard to make the pi0 measurements in the light target experiments. The interaction length was long so photons would escape the chamber easily.

Correlation between Charged Pions and Neutral Pions



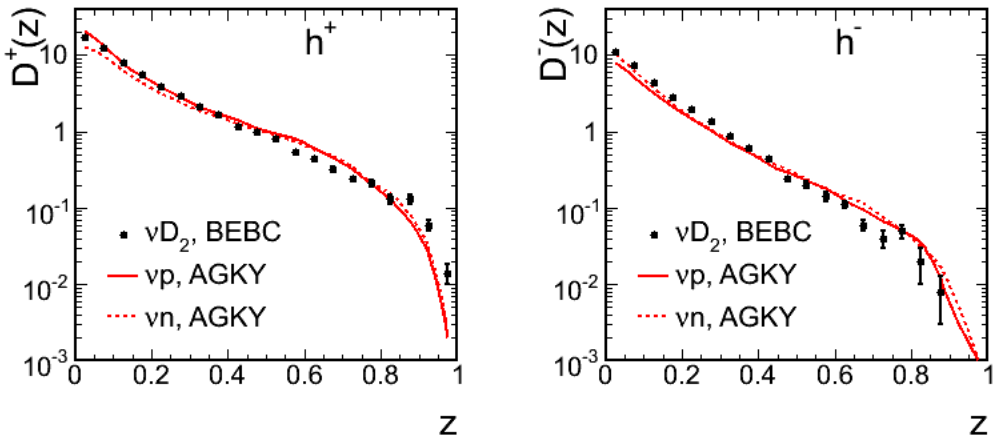
F/B Charged Hadron Multiplicity

- Forward Hemisphere: $x_F>0$
- Backward Hemisphere: $x_F<0$



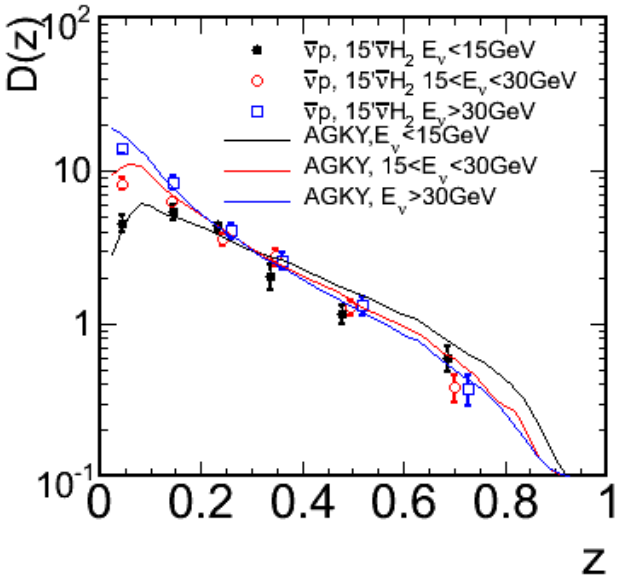
z Distributions

$$z = \text{energy fraction} = \frac{\nu}{E}, \text{ where } \nu = E_\nu - E_\mu = \text{lab energy of the exchanged vector boson } W$$



$$D^h(z) = \frac{1}{N}\frac{dN^h}{dz}(z)$$

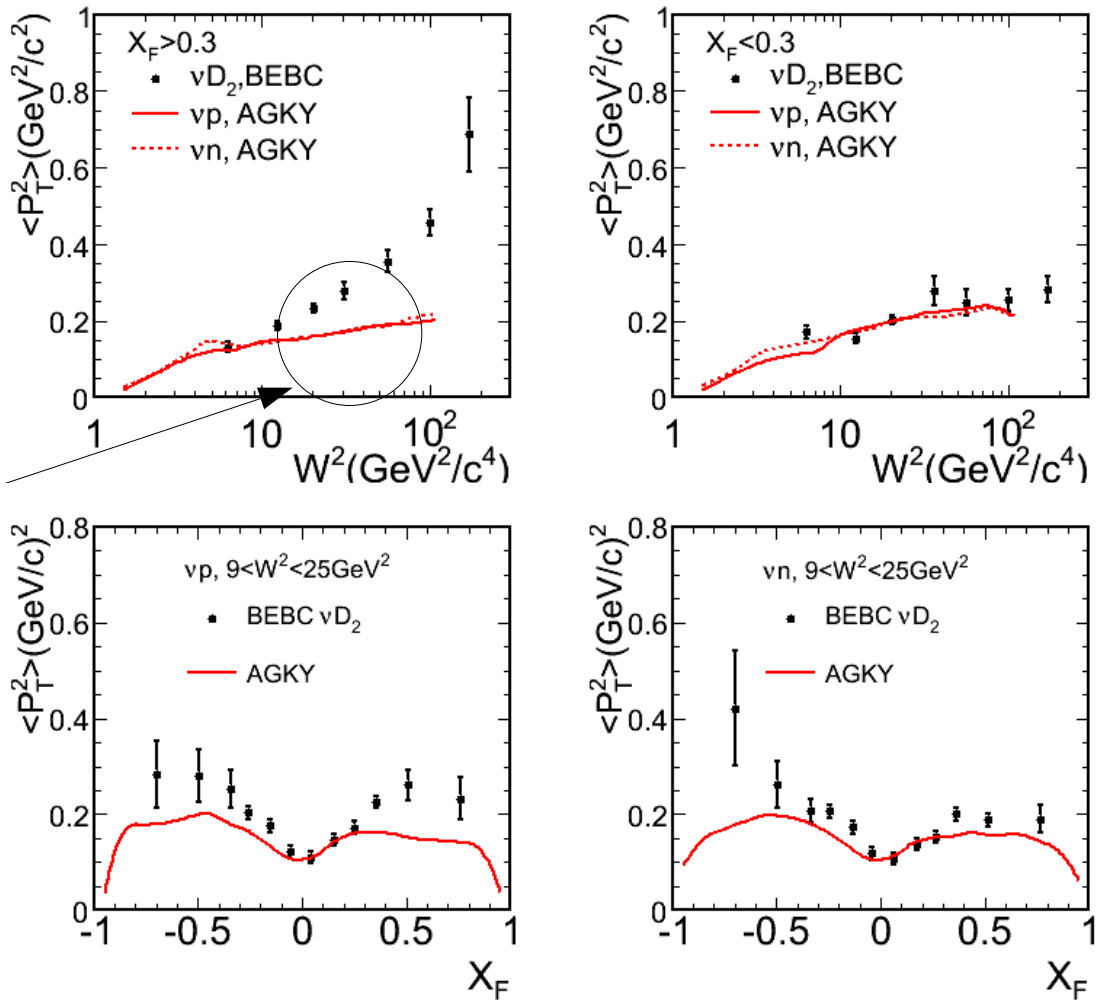
$Q^2 > 1(\text{GeV}/c)^2$, $W^2 > 5(\text{GeV}/c^2)^2$



Valuable low energy anti-neutrino data

Scaling is observed for z>0.3

p_t Distributions



p_t too low

"Seagull" plot

Summaries

- We have tuned the MINOS hadronization model based on external bubble chamber experiments data.
- Good agreement between our model and external data.
- Improvement on the MINOS data/MC agreement is achieved (not shown here).