(Anti)-Neutrino DIS Measurements

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OUTLINE

I *Role of the Neutrino Probe*

- *The Ideal Case: Scattering off Free Nucleon;*
- *The Real Case: Existing Data.*

II *Understanding (Anti)-Neutrino Deep Inelastic Scattering*

- *The Axial-Vector Current;*
- *High Twist Contributions to Structure Functions;*
- *Nuclear Effects.*

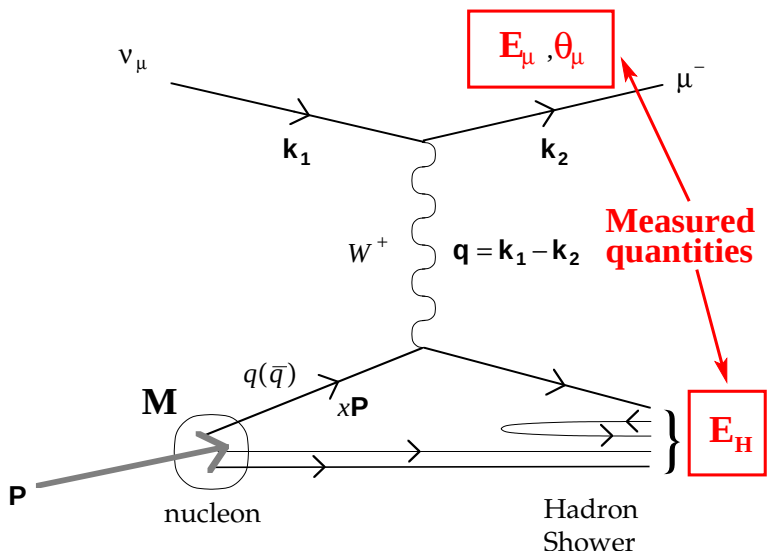
III *Determination of Strange Sea Distributions*

- *(Anti)-Neutrino Induced Charm Dimuon Production;*
- *Extraction of the Strange Sea Parameters;*
- *The NOMAD measurements.*

IV *Future measurements*

- *The MINERνA Experiment;*
- *The LBNE Project.*

THE NEUTRINO PROBE (IDEAL CASE)



$$Q^2_{\rm vis} = 4(E_\mu + E_H)E_\mu \sin^2(\theta_\mu/2)$$
$$x_{\rm vis} = Q^2_{\rm vis}/2M(E_H - M)$$
$$y_{\rm vis} = E_H/(E_\mu + E_H)$$

$$\frac{1}{E}\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M}{\pi(1+Q^2/M_W^2)^2}\left[y^2 xF_1 + \left(1 - y - \frac{Mxy}{2E_\nu}\right)F_2 \pm \left(y - \frac{y^2}{2}\right)xF_3\right]$$

- BOTH ν AND $\bar{\nu}$ DIS *off FREE nucleon ideal probe of nucleon structure:*
  - *Isospin relations* $F_2^{\bar{\nu},p}(x,Q^2) = F_2^{\nu,n}(x,Q^2)$ *(Adler sum rule);*
  - $\sigma^{\nu N} + \sigma^{\bar{\nu} N} \simeq F_2 \sim 2\sum(xq + x\bar{q})$; $\sigma^{\nu N} - \sigma^{\bar{\nu} N} \simeq xF_3 \sim 2\sum(xq - x\bar{q})$
  - *Small radiative corrections.*
- *Complete flavor separation in Charged Current interactions* (d/u, $s/\bar{s}$, $\bar{d}/\bar{u}$)
- *Separation of valence* (xF_3) *and sea* (F_2) *distributions*

$\Longrightarrow$ *We want to measure differential cross-sections and/or structure functions off p,D*

THE NEUTRINO PROBE (REAL CASE)

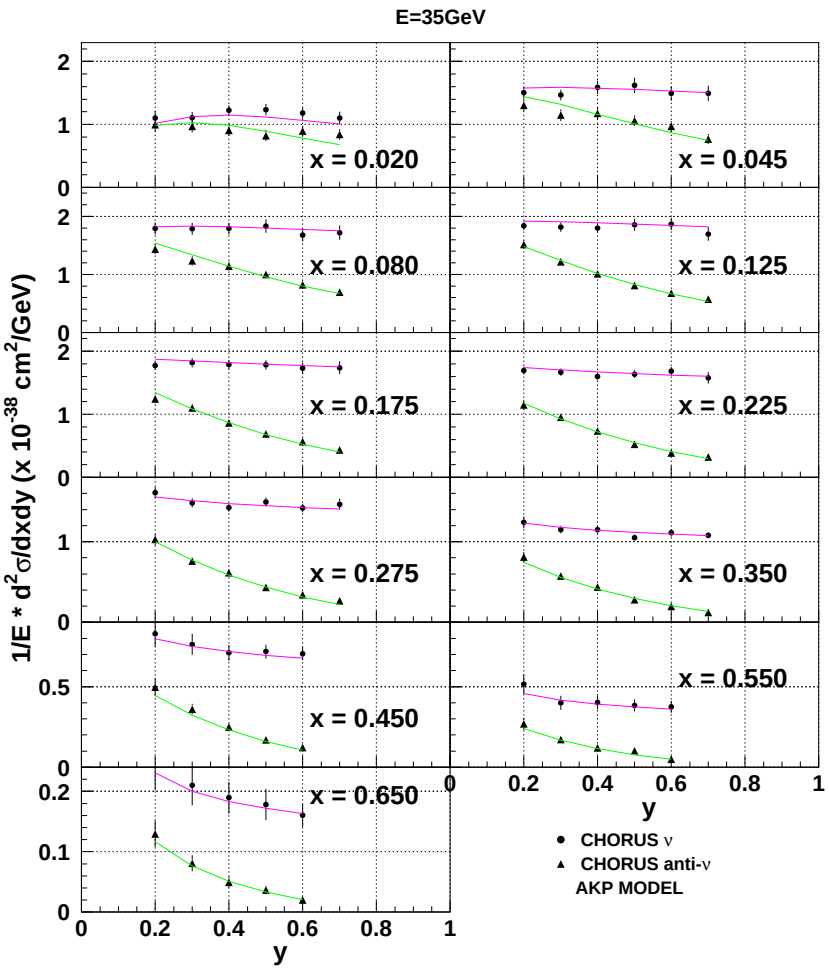
- *Potential of the $\nu(\bar{\nu})$ probe still limited by experimental factors:*
  - BEAM TECHNOLOGY: *beam intensity and knowledge of fluxes;*
  - DETECTOR RESOLUTION: *event reconstruction and energy scales.*

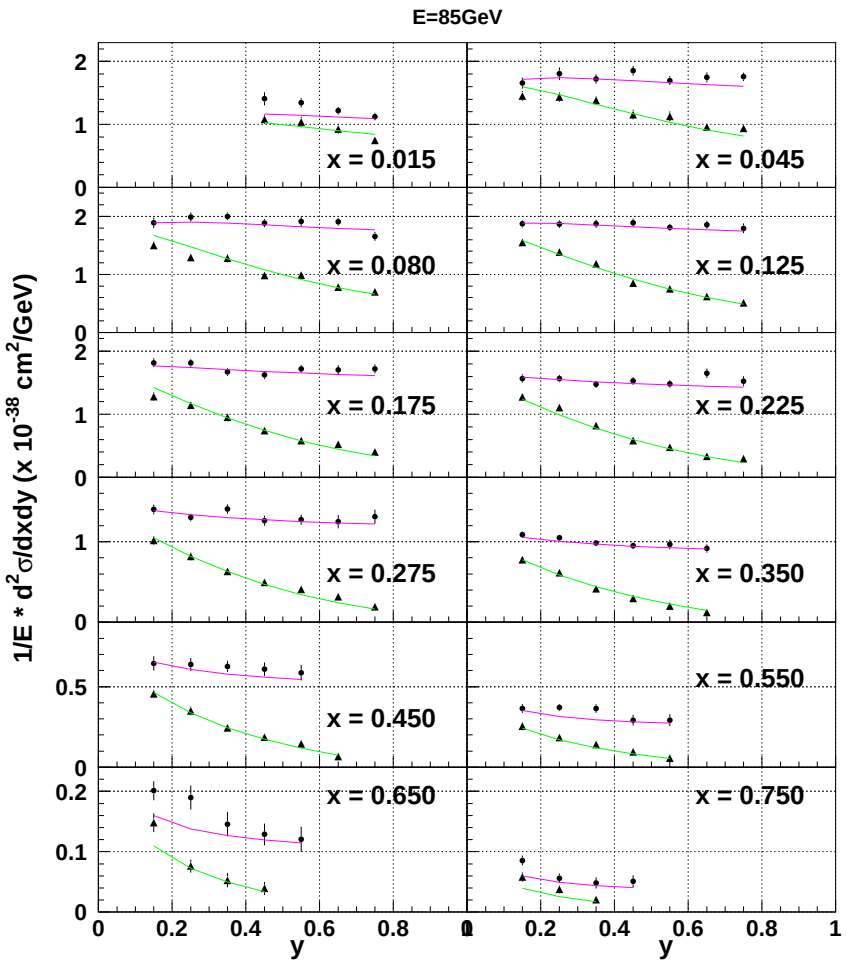
- *Existing measurements of $d^2\sigma/dxdy$ and structure functions use NUCLEAR targets and are significantly affected by systematics on E_μ, $E_{\rm H}$ energy scales and flux*

Experiment	Mass	ν_μ CC Stat.	Target	E_ν (GeV)	ΔE_μ	$\Delta E_{\rm H}$
CDHS	750 t	10^7	p,Fe	20-200	2.0%	2.5%
BEBC	various	5.7×10^4	p,D,Ne	10-200		
CCFR	690 t	1.0×10^6	Fe	30-360	1.0%	1.0%
NuTeV	690 t	1.3×10^6	Fe	30-360	0.7%	0.43%
CHORUS	100 t	3.6×10^6	Pb	10-200	2.5%	5.0%
NOMAD	2.7 t	1.3×10^6	C	5-200	0.2%	0.5%
	18 t	1.2×10^7	Fe	5-200	0.2%	0.5%
MINOS ND	980 t	3.6×10^6	Fe	3-50	2-4%	5.6%

$\Longrightarrow$ *Next generation experiments need high resolution detectors and $\geq 10^7$ CC events*

RECENT MEASUREMENTS OF $d^2\sigma/dxdy$





CHORUS (Pb) *PLB 632 (2006) 65-75.*

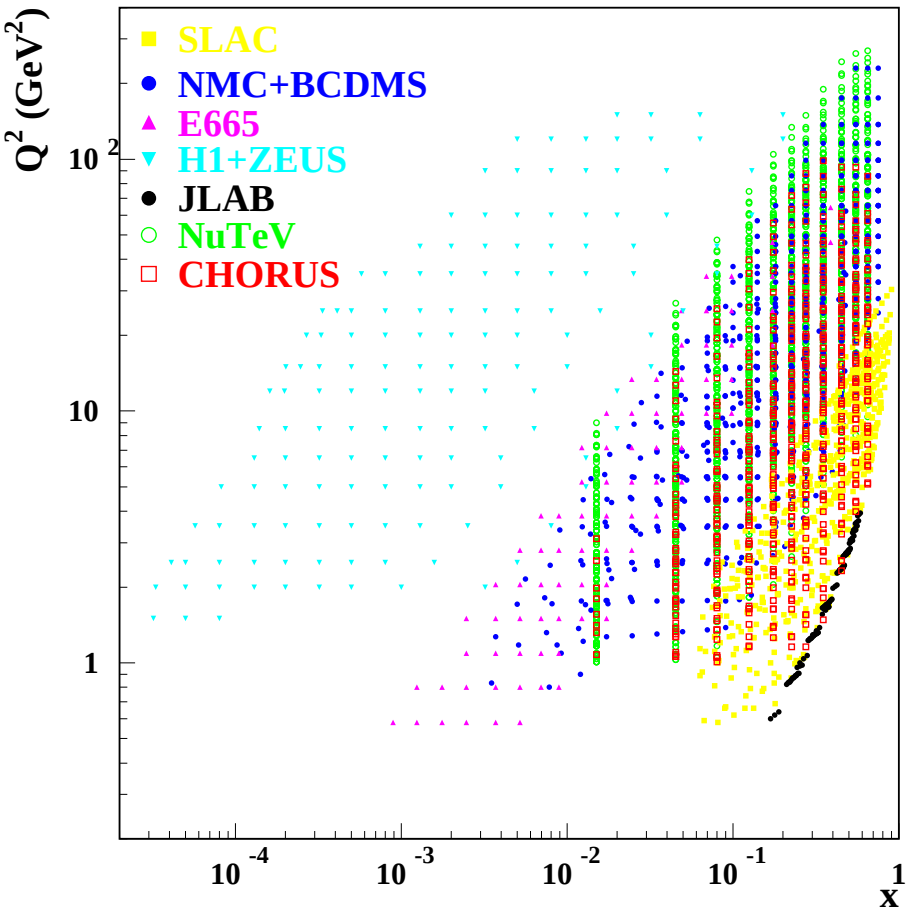
$\Delta E_\mu = 2.5\%, \Delta E_{\rm H} = 5.0\%$

Selected $\nu_\mu(\bar{\nu}_\mu)$CC: *870k (146k)*

NuTeV (Fe) *PRD 74 (2006) 012008.*

$\Delta E_\mu = 0.7\%, \Delta E_{\rm H} = 0.42\%$

Selected $\nu_\mu(\bar{\nu}_\mu)$CC: *860k (240k)*



- *(Anti)-Neutrino Charged Current (CC) DIS complementary to charged lepton (NC) DIS and Drell-Yan processes*

  $\Longrightarrow$ *Fixed target kinematics*

- *Need to address several model uncertainties in order to benefit from the addition of $\nu(\bar{\nu})$ CC data in global QCD fits:*
  - *Role of the Axial-Vector current;*
  - *High Twist corrections;*
  - *Nuclear effects.*

  $\Longrightarrow$ *Higher complexity with respect to charged lepton scattering off p,D*

PECULIARITY OF THE WEAK CURRENT

- *Neutrino scattering is characterized by the* AXIAL-VECTOR CURRENT *(V-A):*

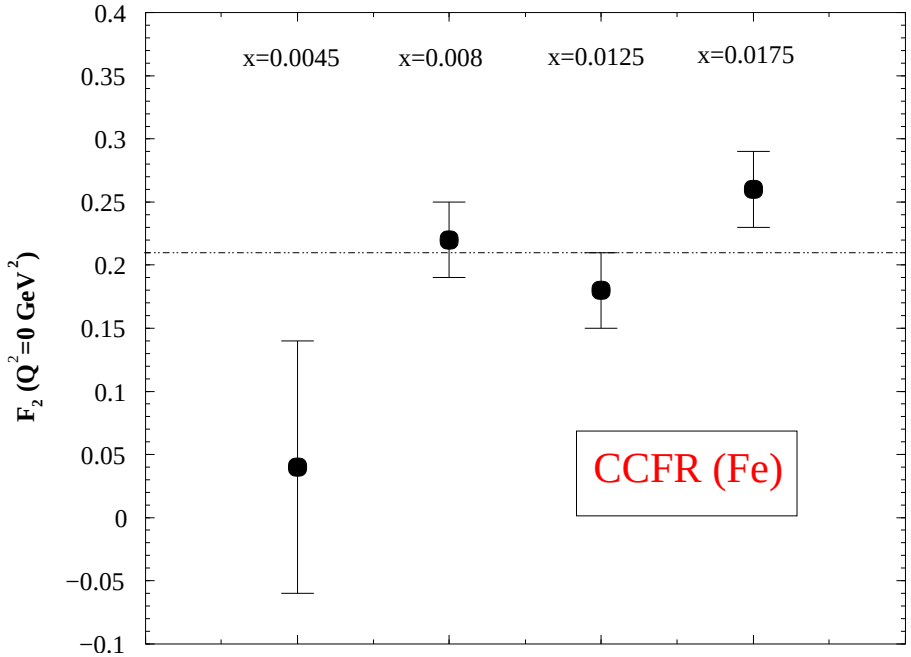
$$VV, AA \implies F_{1,2} \quad (or\ F_L,\ F_T)$$
$$VA \implies F_3$$

- *Conservation of Vector Current (CVC), in analogy to the charged leptons, implies:*

$$F_2, F_T \sim Q^2 \qquad F_{\rm L} \sim Q^4 \qquad for \quad Q^2 \to 0$$

- *Axial Current is only Partially Conserved (PCAC) and dominates F_L at low Q^2:*

$$\partial A = f_\pi m_\pi^2 \varphi \quad \implies \quad F_L = \frac{f_\pi^2 \sigma_\pi}{\pi}$$



- *Transition scale between low and high Q^2 is* NOT m_π^2 *but rather $M_{\rm PCAC} \sim 1\ GeV^2$, since direct pion contribution $\partial_\mu \varphi$ cancels out. Non vanishing constribution to F_2:*

$$F_2 = (F_L + F_T)/(1 + 4x^2 M^2/Q^2) \to (f_\pi^2 \sigma_\pi)/\pi \qquad Q^2 \to 0$$

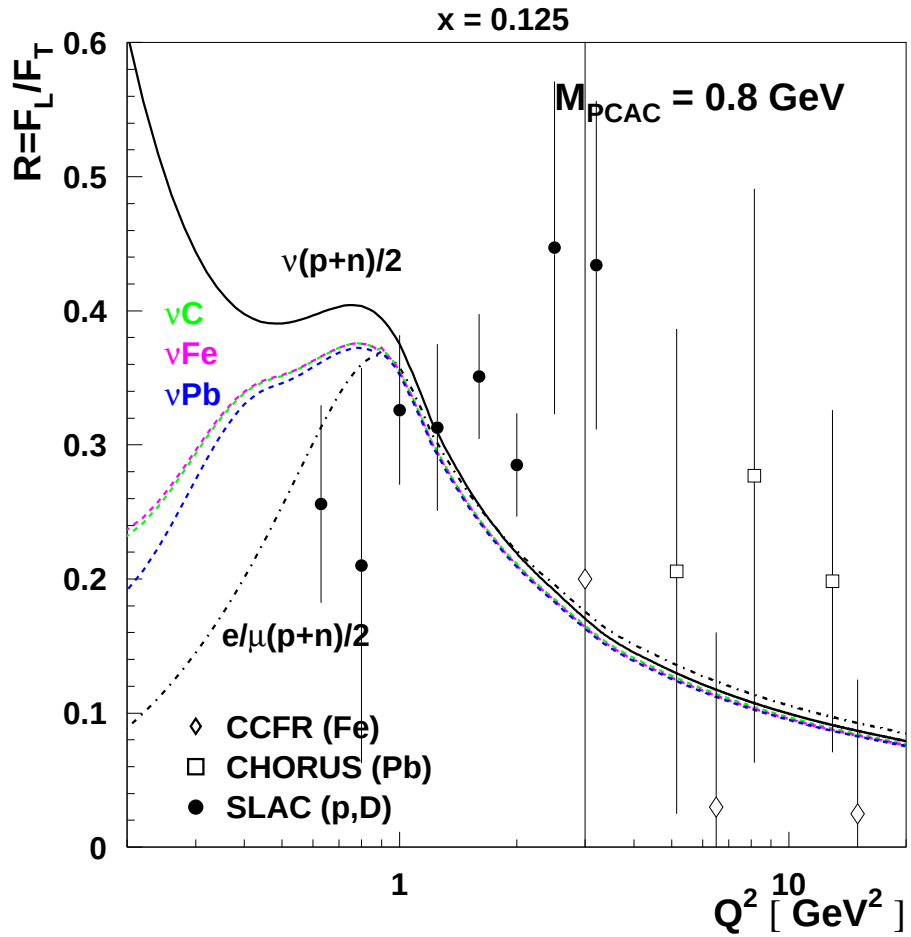
$\implies$ *CCFR determination on Fe target 0.210 ± 0.02* *(CCFR Coll., PRL 86 (2001) 5430).*

- *The finite PCAC contribution to F_L strongly affects the asymptotic behaviour of* $\boxed{R = \sigma_L/\sigma_T}$ *for* $Q^2 \to 0$*:*

$$F_T \sim Q^2$$
$$F_L \sim \frac{f_\pi^2 \sigma_\pi}{\pi} > 0$$

so that R is divergent for vanishing Q^2

$\Longrightarrow$ *Substantial difference with respect to charged lepton scattering.*



S. Kulagin and R.P., PRD 76 (2007) 094023

HIGH TWIST CONTRIBUTIONS

$$F_{T,2,3}(x,Q^2) = F^{\tau 2}_{T,2,3}(x,Q^2) + \frac{H^{\tau 4}_{T,2,3}}{Q^2} + ... \qquad \text{(OPE)}$$

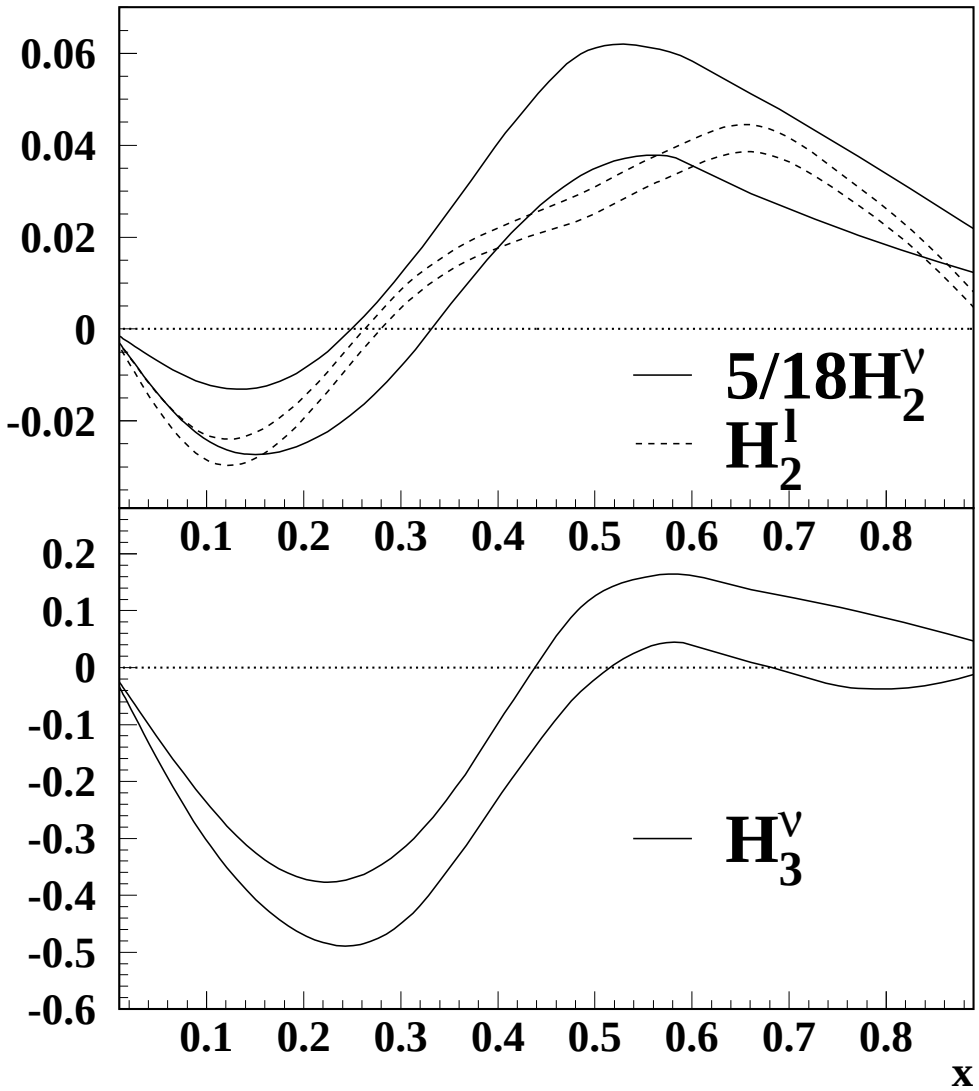
- *High Twists (HT) non-perturbative terms* $\tau = 4, 6, ...$ *reflecting the strength of the multi-parton correlations* (qq *and* qg) *and suppressed by powers of* $1/Q^2$
  $\Longrightarrow$ *Important at low and moderate* Q^2 (< 10 *GeV*^{2}) *where most* $\nu(\bar{\nu})$ *data*

- *Kinematical High Twists associated with finite mass of target nucleon relevant at large* x^2M^2/Q^2 *values. Corrections usually incorporated into the leading twist (LT) term* ($\tau = 2$) *following Georgi and Politzer (1976):*

  $$F^{\rm LT}_{T,2,3}(x,Q^2) \to F^{\rm LT,TMC}_{T,2,3}(x,Q^2)$$

  where the calculation involves the Nachtman variable $\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$. *Difficulty for* $x \to 1$ *due to wrong threshold behaviour* ($F^{\rm LT}_i(\xi,Q^2) > 0$).

- *Dynamical High Twists* ($\tau > 2$) *related to multi-parton correlations can be determined phenomenologically from data by exploiting their specific* Q^2 *dependence.*



- *No evidence for sizeable twist-6 terms from global fit to e, μ DIS and DY data (upper limit ~ 0.02 well below twist-4)*
- *HT similar in F_T and F_2 indicate HT contributions to F_L very small*
- *HT on F_2 and F_T from CHORUS $\nu(\bar{\nu})$ cross-section data consistent with charged leptons after charge rescaling.*
- *Simultaneous extraction of HT in xF_3 from neutrino data*

S. Alekhin, S. Kulagin and R.P., arXiv:0710.0124 [hep-ph], arXiv:0810.4893 [hep-ph]

EFFECTIVE LEADING ORDER APPROACH

- *Use Leading Order GRV98 PDFs and introduce scaling variable ξ_w and empirical K-factors to account for High Twists, missing high order QCD, etc.*

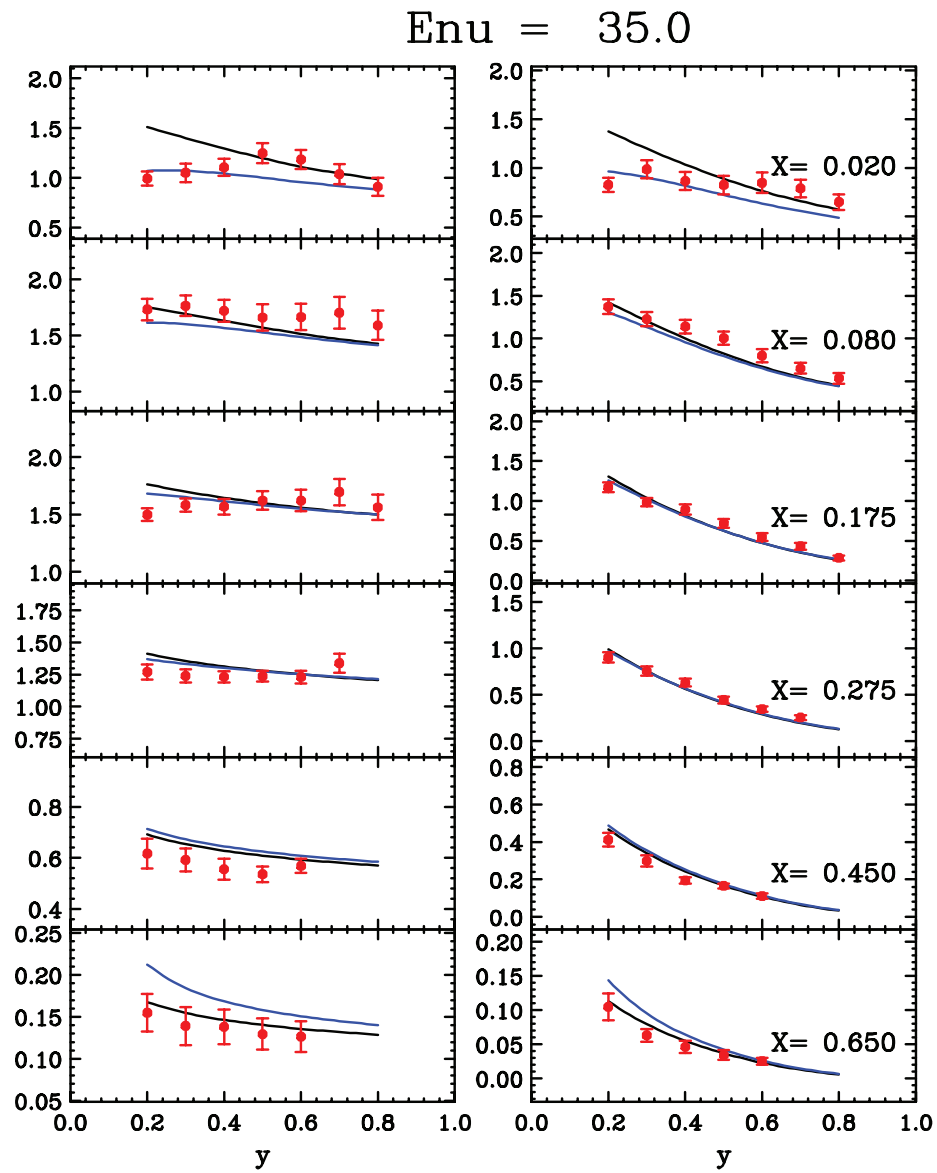
$$x \to \xi_w = \frac{Q^2+M_f^2+B}{M\nu\left[1+\sqrt{1+Q^2/\nu^2}\right]+A}$$
$$f(x,Q^2) \to K_f \times f(\xi_w, Q^2)$$

(*A. Bodek and U. Yang, arXiv hep-ex/0308007; 1011.6592 [hep-ph]*)

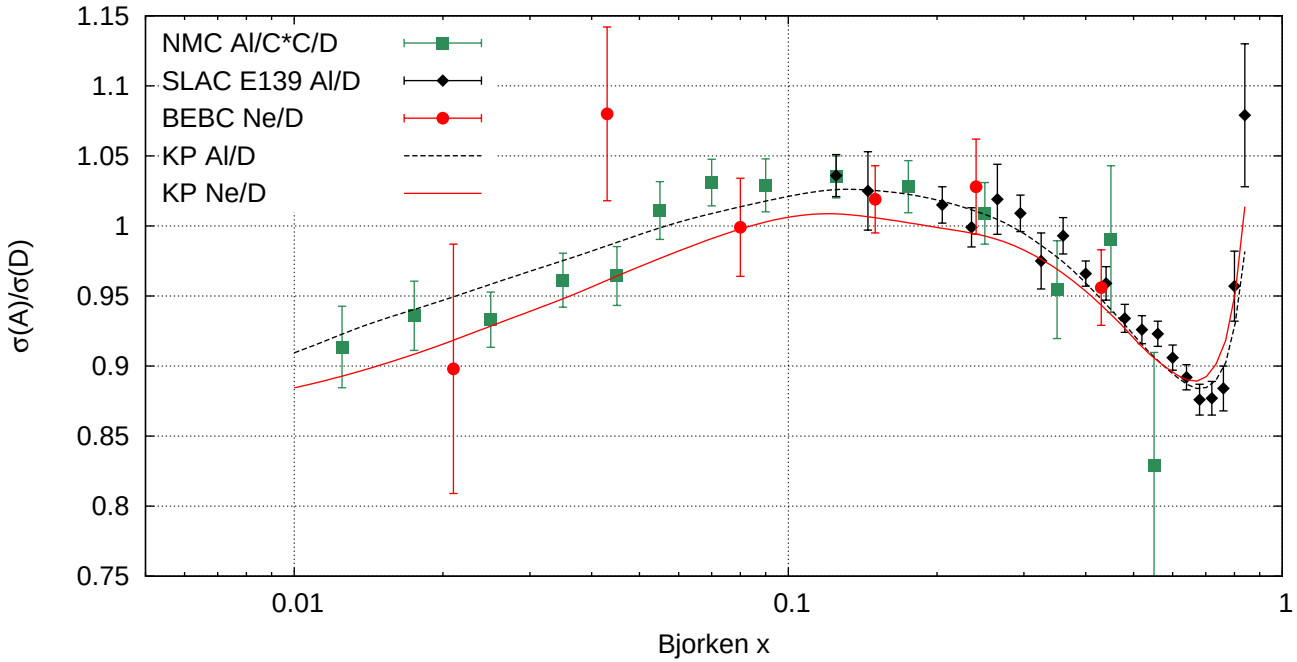
- *For $\nu(\bar{\nu})$ interactions use separate Vector and Axial K-factors*
  - *Vector K_f same as for e, μ data;*
  - *Axial K_f constrained by Adler sum rule.*

- *Results show significant contributions from effective HT*

  $\Longrightarrow$ *See talk by U. Yang in parallel session*



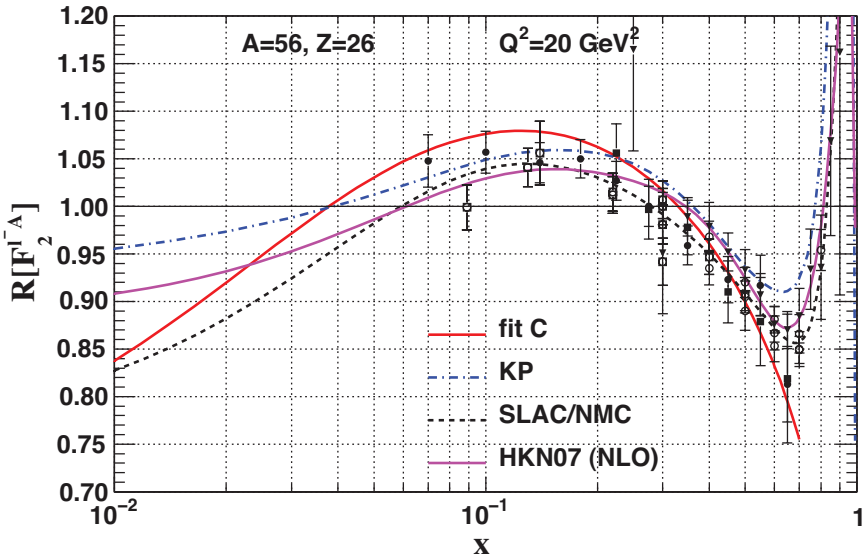
NUCLEAR EFFECTS



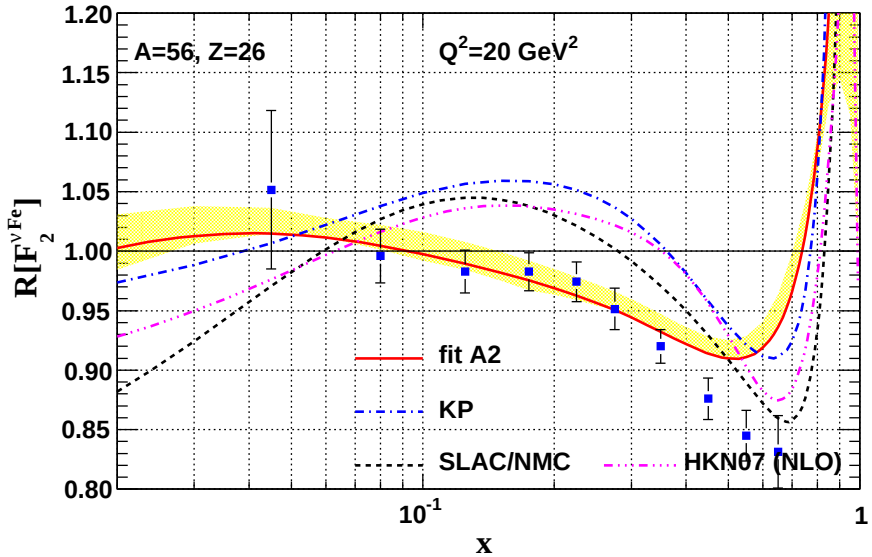
BEBC Coll., ZPC 36 (1987) 337; PLB 232 (1989) 417.

- *Nuclear corrections are crucial in order to use $\nu(\bar{\nu})$ data in global QCD fits since virtually all existing data on heavy targets*
  $\Longrightarrow$ *Significant uncertainties on nuclear corrections in $\nu(\bar{\nu})$ interactions*
- *Only DIRECT measurement of nuclear effects in $\nu(\bar{\nu})$ SFs from ratio ^{20}Ne/D in BEBC*
  - *Consistent with shadowing at small x_{Bj} but large uncertainties;*
  - *Consistent with the EMC effect measured from e, μ DIS.*
- *Differences with respect to e, μ DIS expected due to the axial-vector current and to the flavor selection*

CTEQ FITS TO $\nu(\bar{\nu})$ DATA



Fit to e, μ DIS + DY



Fit to $\nu + \bar{\nu}$ DIS

- *Within the CTEQ analysis introduce nuclear PDFs as modifications of nucleon PDFs:*

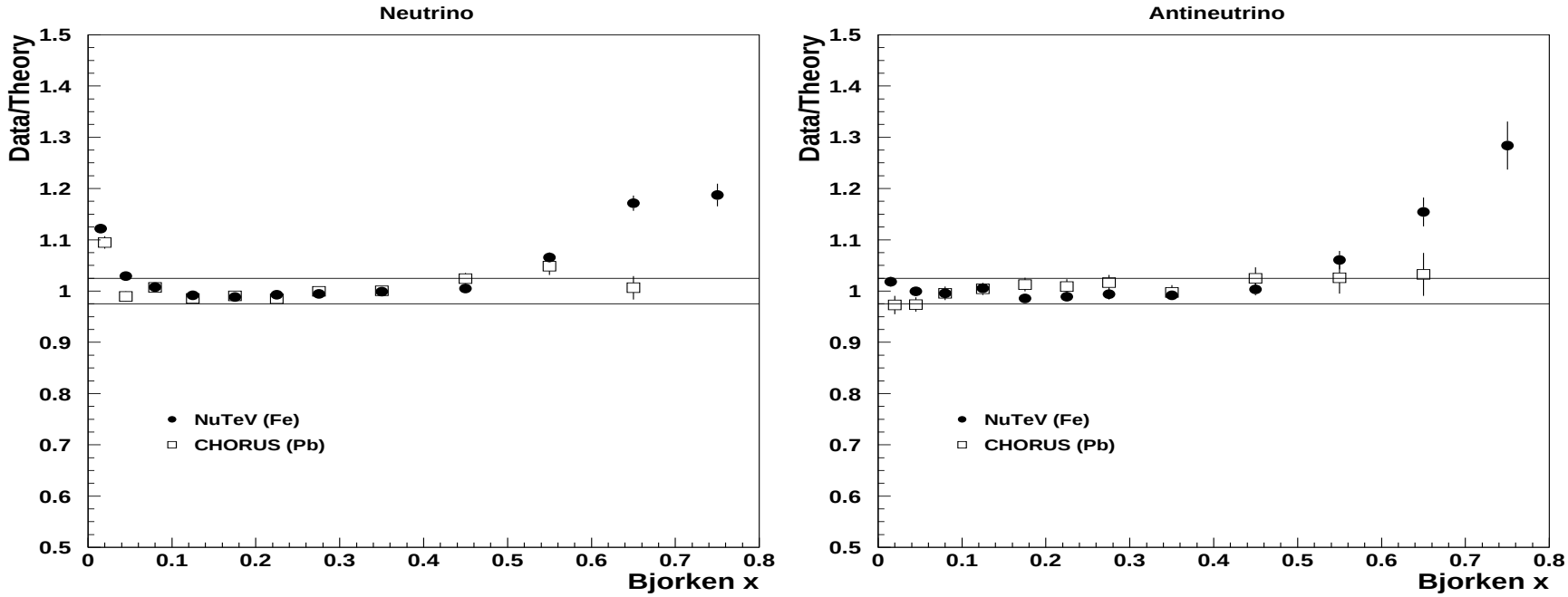
$$xf(x, Q_0) = f(x, c_0, c_1, ...c_n); \qquad c_k \to c_k(A)$$

(*I. Schienbein at al., PRD 80 (2009) 094004; PRL 106 (2011) 122301*).

- *Perform separate global fits to $\nu(\bar{\nu})$ DIS data and e, μ DIS + Drell-Yan nuclear data*
- *Results show CHORUS+NuTeV $\nu(\bar{\nu})$ data not consistent with e, μ DIS:*
  - *No shadowing observed at small $x_{\rm Bj}$;*
  - *Different EMC slope.*

$\Longrightarrow$ *See talk by K. Kovarik in parallel session*

KP PREDICTIONS FOR CHORUS AND NuTeV



- *Detailed phenomenological model* *including Fermi motion and binding energy, off-shell effect of bound nucleons, nuclear pion excess and shadowing correction* (*S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023, PRC 82 (2010) 054614*).

- *Comparison with NuTeV (Fe) and CHORUS (Pb)* *cross-section data (band* $\pm 2.5\%$*):*
  - *Systematic excess observed for* $x > 0.5$ *in both* ν *and* $\bar{\nu}$ *NuTeV data on Fe*
  - *CHORUS data on Pb target consistent with predictions at large x;*
  - *Discrepancy between NuTeV and old CCFR data at large* x *on Fe target.*

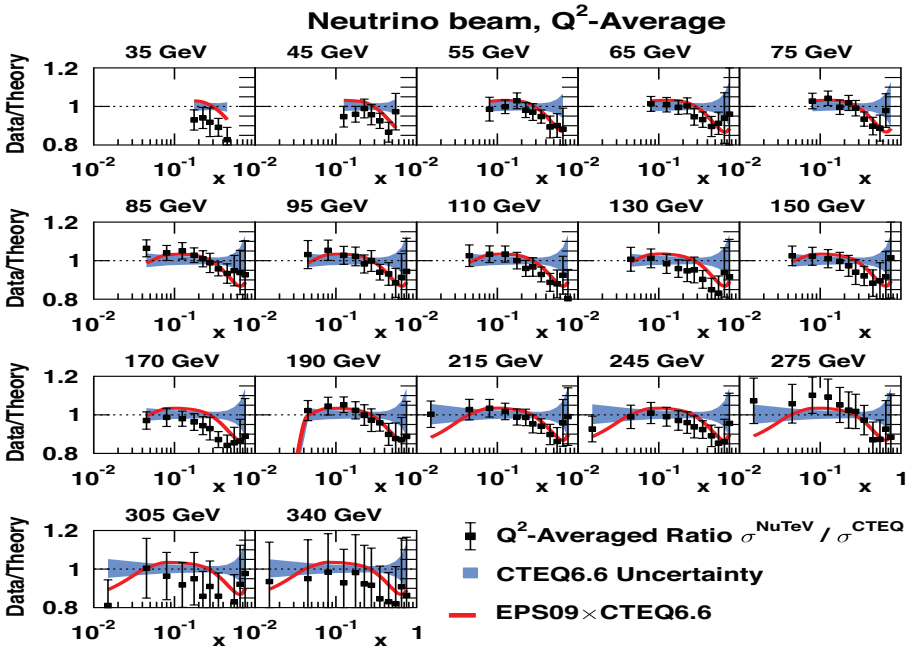
Cut	# of points		χ^2/dof	
	Neutrino	Antineutrino	Neutrino	Antineutrino
NuTeV (Fe)				
No cut	1423	1195	1.36	1.10
$x > 0.015$	1324	1100	1.15	1.08
$x < 0.55$	738	671	1.16	1.02
$0.015 < x < 0.55$	**686**	**620**	**0.97**	**1.01**
CHORUS (Pb)				
No cut	**607**	**607**	**0.68**	**0.84**
$x > 0.02$	550	546	0.55	0.83
$x < 0.55$	506	507	0.74	0.83
$0.02 < x < 0.55$	449	447	0.60	0.83

Fully independent model predictions, NOT FIT

- *Good agreement of predictions with the CHORUS differential cross-sections on Pb in the whole kinematic range*
- *Good agreement of predictions with the NuTeV differential cross-sections on Fe in the main kinematic region* $0.015 < x < 0.55$

$\Longrightarrow$ *See talk by S. Kulagin in parallel session*

RESULTS BY EPS



Experiment	χ^2/dof	
	CTEQ6.6	*CTEQ×EPS09*
NuTeV	*1.51*	**1.05**
CHORUS	*1.15*	**0.79**
CDHSW	*1.10*	*0.71*

- *Use nuclear corrections to PDFs from EPS09 fit to nuclear e, μ DIS and Drell-Yan* (*K. Eskola, H. Paukkunen and C. Salgado, JHEP 0904 (2009) 065; JHEP 1007 (2010) 032*).
- *Analysis of CHORUS, NuTeV and CDHSW $\nu(\bar{\nu})$ differential cross-sections and comparison with calculations based upon CTEQ6.6 + EPS09*
- *Results indicate CHORUS and CDHSW data are in agreement with calculations, but in disagreement with NuTeV data*

  $\Longrightarrow$ *Anomalous E_ν-dependent fluctuations in NuTeV data*

NEW MEASUREMENT FROM NOMAD

- *High resolution spectrometer with low density tracking,* $\rho \sim 0.1 g/cm^3$ *and* $B = 0.4\ T$
  - *Momentum calibration from* K^0_S *mass constraint;*
  - $\Delta E_\mu = 0.2\%$, $\Delta E_{\rm H} = 0.5\%$.

- *Measurement of* $d^2\sigma/dxdy$ *cross-section on Carbon in the energy range* $5 < E_\nu < 200$ *GeV*

  $\Longrightarrow$ *First measurement on C target*

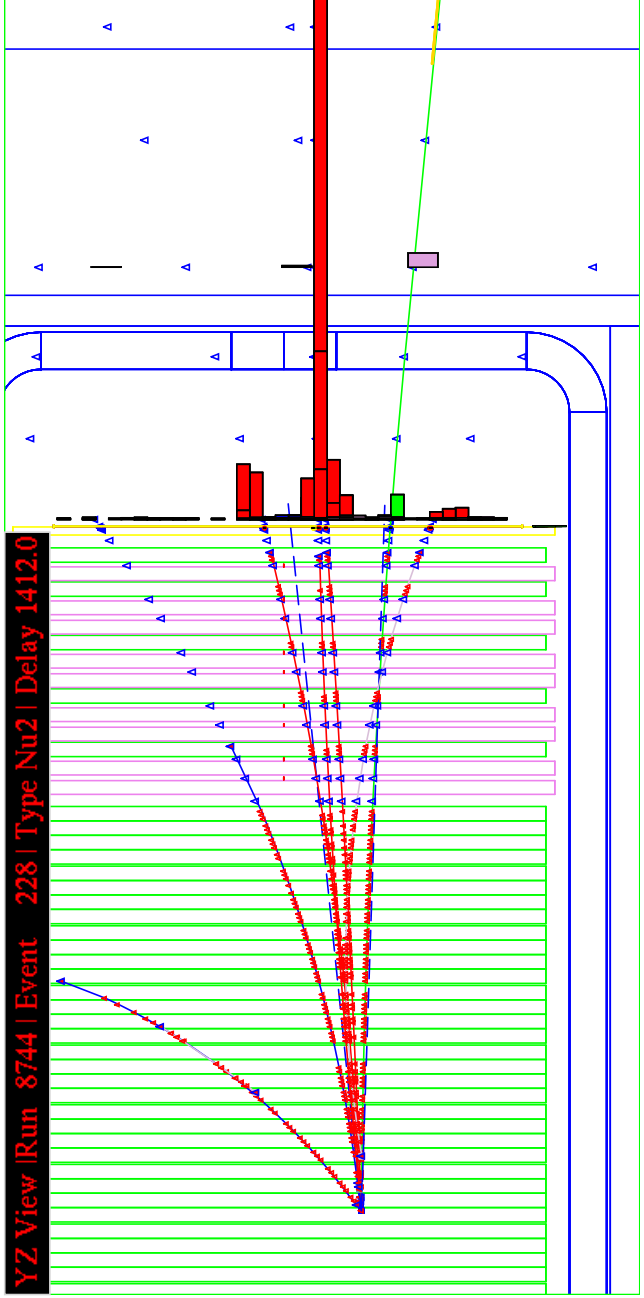
- *Absolute cross-section normalization to the world average value on isoscalar target:*

$$\sigma^\nu/E_\nu \ = \ 0.677 \pm 0.014 \times 10^{-38}\ \frac{cm^2}{GeV}$$

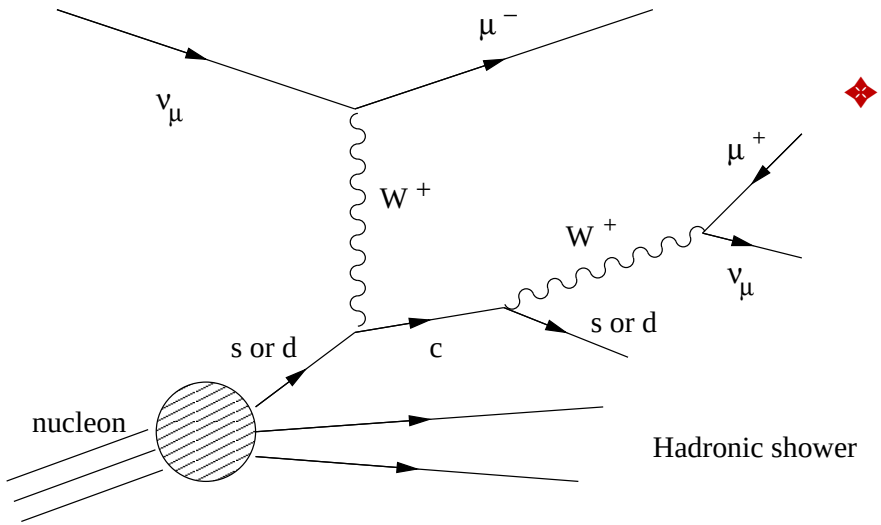
  in the energy range $40 < E_\nu < 80$ *GeV.*

- *Independent cross-check of NuTeV and CHORUS measurements*

  $\Longrightarrow$ *Preliminary results on C*
  do not show the NuTeV excess at large $x_{\rm Bj}$



A DIRECT PROBE OF STRANGE SEA



- *Charm dimuon production in $\nu(\bar{\nu})$ DIS*

$$\frac{d^2\sigma_{\mu\mu}}{dxdydz} = \frac{d^2\sigma_c}{dxdy} D_c(z) B_\mu; \qquad z = \frac{P_L(h_c)}{P_L^{\max}}$$

$$B_\mu = \sum_h f_h Br(h \to \mu^+ X); \; h = D^0, D^+, D_s^+, \Lambda_c^+$$

$D_c(z)$ *average fragmentation function*

- *Charm production in ν and $\bar{\nu}$ DIS provides a clean and direct access to $s(x)$ and $\bar{s}(x)$*

$$F_{2,c}(x,Q) = 2\xi \left[|V_{cs}|^2 s(\xi,\mu) + |V_{cd}|^2 \frac{u(\xi,\mu) + d(\xi,\mu)}{2} \right]$$

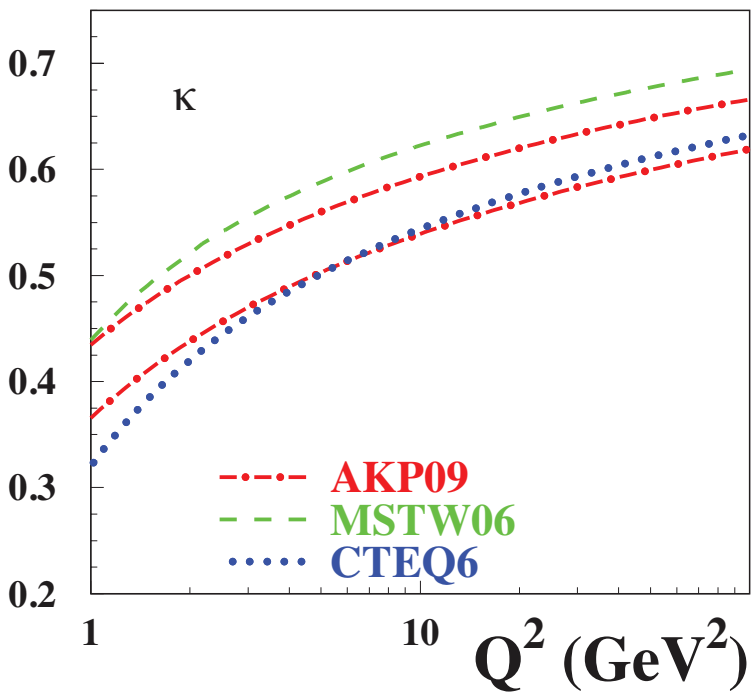
$$\xi = x\left(1 + m_c^2/Q^2\right), \; \mu = \sqrt{Q^2 + m_c^2}$$

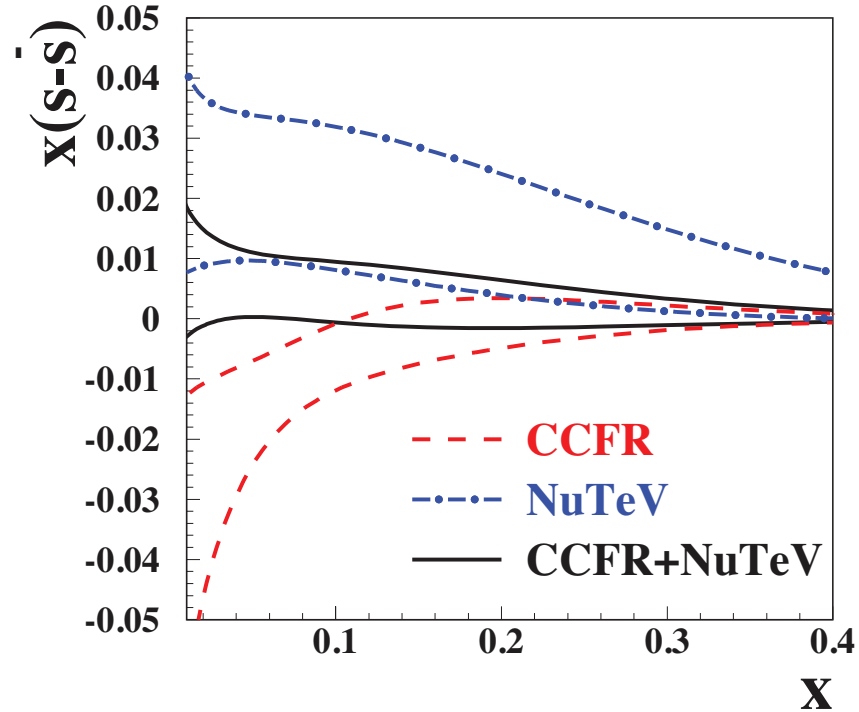
where simple LO approximations are given for illustration purpose

$$\begin{cases} \nu: & s/(d_v + d_s) \to c & \simeq 50\% \\ \bar{\nu}: & \bar{s}/\bar{d}_s \to \bar{c} & \simeq 90\% \end{cases}$$

Exp.	Publ.	Stat. ($N_{\mu\mu}$)	E_ν (GeV)
Charm dimuons in νN			
CDHS	1982	9922	$30-250$ (20)
CHARM II	1999	3100	$35-300$ (24)
NuTeV	2001	5102	$20-400$ (157.8)
CCFR	2001	5030	$30-400$ (150)
CHORUS	2008	8910	$15-240$ (27)
NOMAD	2011	15344	$6-300$ (27)
Charm dimuons in $\bar{\nu} N$			
CDHS	1982	2123	$30-250$
CHARM II	1999	700	$35-300$
NuTeV	2001	1458	$20-400$
CCFR	2001	1060	$30-600$
CHORUS	2008	430	$15-240$

- *The NuTeV and CCFR data are used in global QCD fits and provide the only information about $\bar{\nu}$-induced charm dimuons*
- *The new NOMAD measurement has the largest sample of ν-induced charm dimuons and can reach energies closer to the charm production threshold*





- *Global PDF fits with NuTeV and CCFR dimuon data:*

$\kappa_s = \frac{\int_0^1 x\left[s(x,Q^2)+\bar{s}(x,Q^2)\right]dx}{\int_0^1 x\left[\bar{u}(x,Q^2)+\bar{d}(x,Q^2)\right]dx} = 0.62 \pm 0.04 \pm 0.03(\mathrm{QCD})$ *(AKP09, PLB 675 (2009) 433)*

$S^- = \int_0^1 x\left[s(x) - \bar{s}(x)\right]dx = 0.0013 \pm 0.0009 \pm 0.0002(\mathrm{QCD})$ *(AKP09, PLB 675 (2009) 433)*

$S^- = 0.0016^{+0.0011}_{-0.0009}$ *(MSTW, EPJC 63 (2009) 189)*

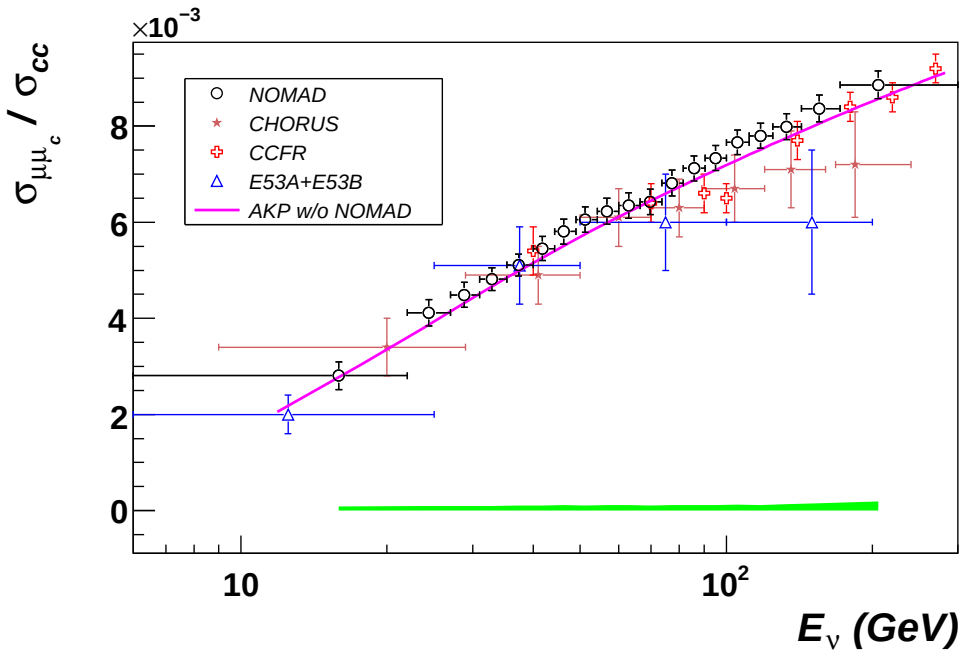
$S^- = 0.0018 \pm 0.0016$ *(CTEQ, JHEP 0704 (2007) 089)*

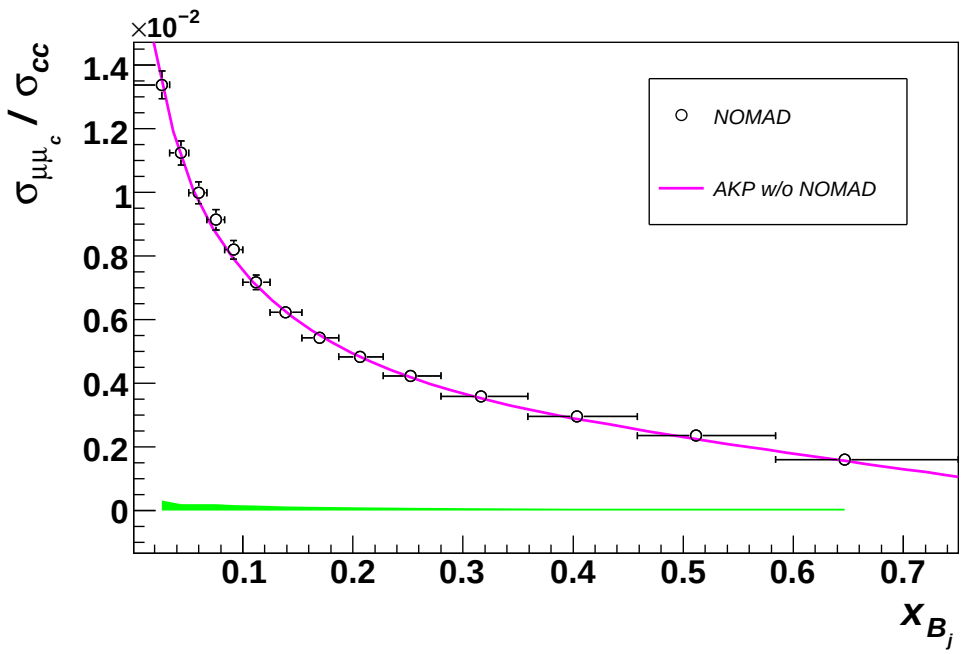
$S^- = 0.0005 \pm 0.0086$ *(NNPDF, NPB 823 (2009) 195)*

$S^- = 0.00196 \pm 0.00046^{+0.00155}_{-0.00116}(syst)$ *(NuTeV, PRL 99 (2007) 192001)*

$S^- = 0.0018 \pm 0.0038$ *(BPPZ, JHEP 0601 (2006) 006)*

CHARM DIMUON PRODUCTION FROM NOMAD





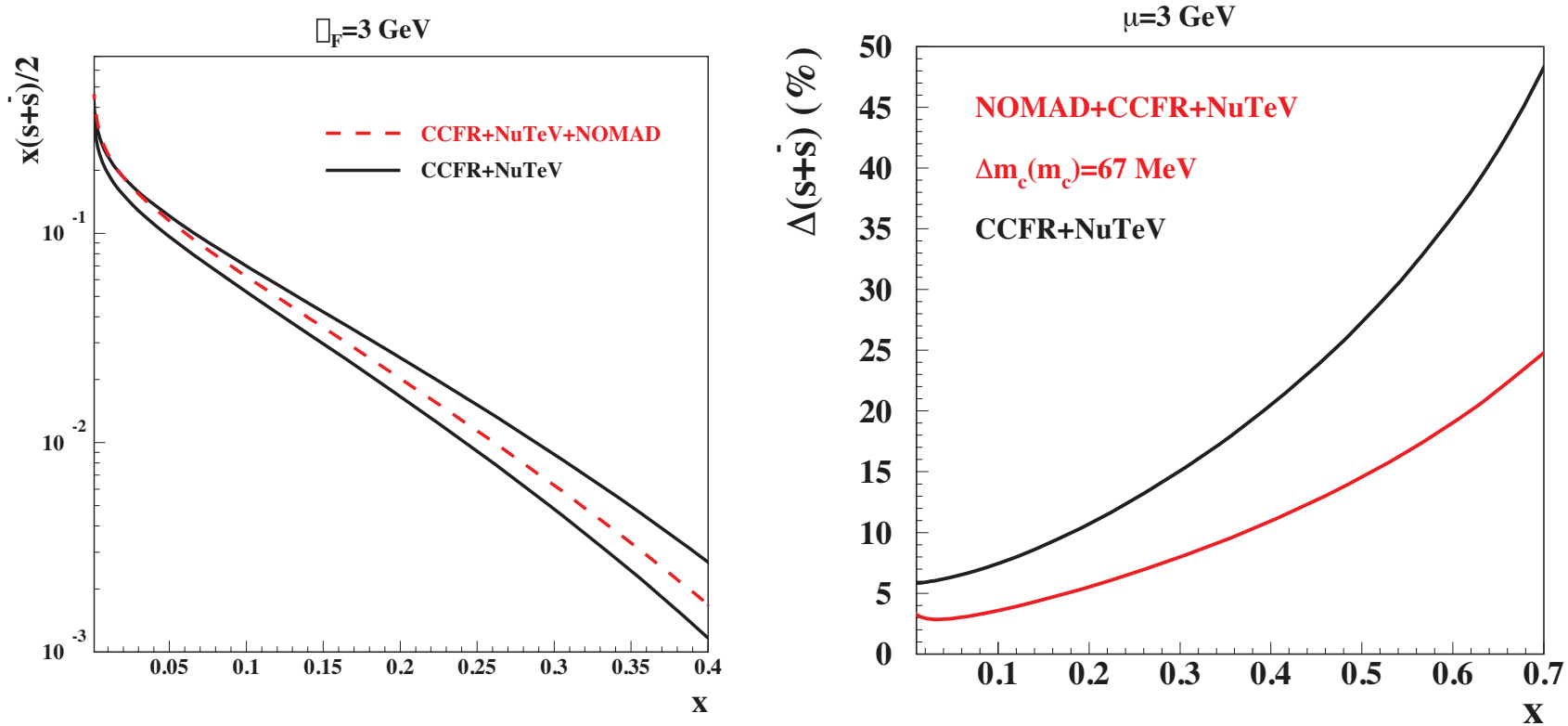
- *Measure* **RATIO** *of cross-sections to reduce systematics:*

$$\mathcal{R}_{\mu\mu} \equiv \sigma_{\mu\mu_c}/\sigma_{cc} \simeq N_{\mu\mu_c}/N_{cc}(x); \quad x = E_\nu, x_{B_j}, \sqrt{\hat{s}}$$

- *Require leading* μ^- *and* $Q^2 \geq 1$ *GeV*^{2}

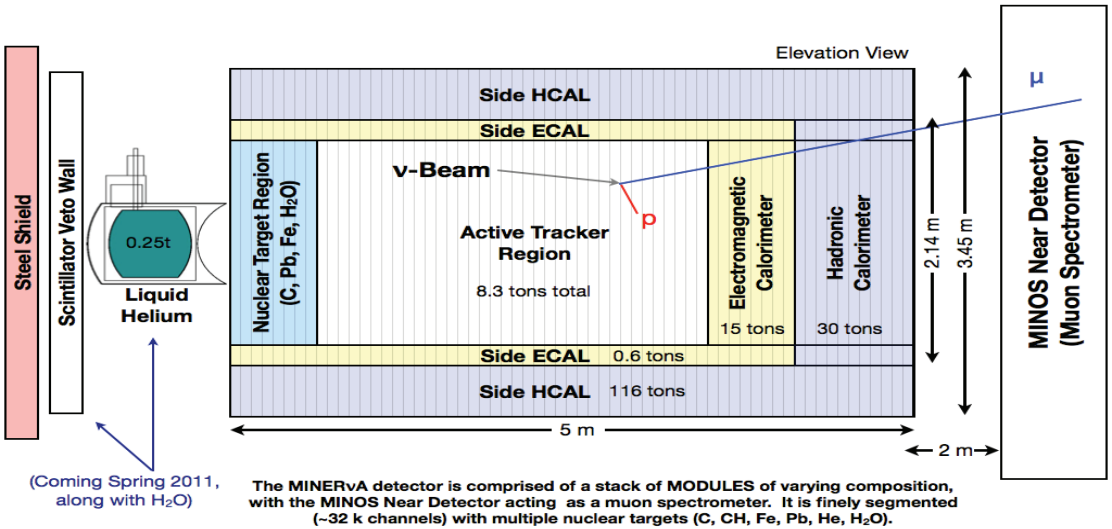
$$\int \sigma_{\mu\mu_c}\phi \; dx \; dy \; dE_\nu \quad = \quad 5.15 \pm 0.05 \times 10^{-3} \; \nu_\mu \mathrm{CC}$$

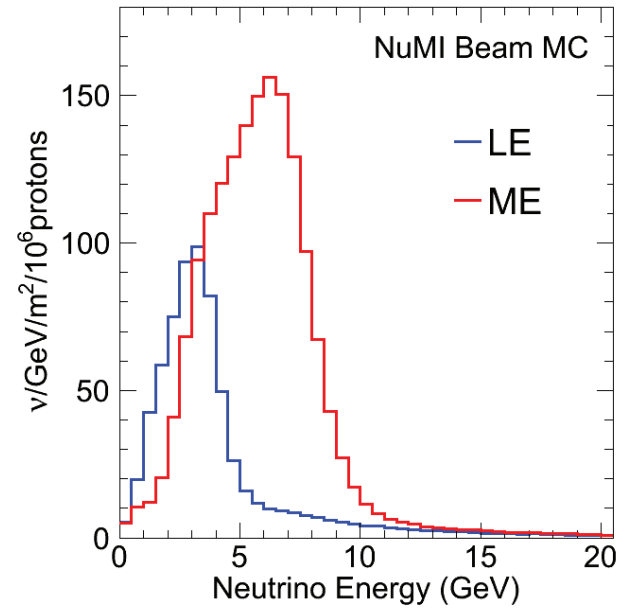
- *Total systematic uncertainty (17 different sources)* $\sim 2\%$
- *Agreement with model calculation based upon global fits with NuTeV+CCFR only*



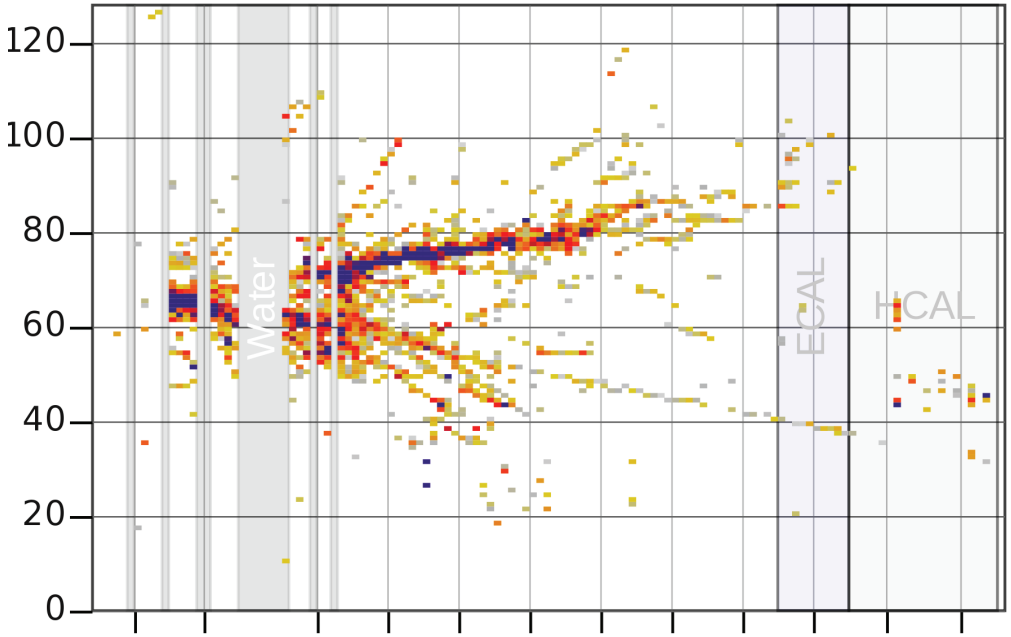
- *Add NOMAD $\sigma_{\mu\mu}/\sigma_{\rm CC}$ data to global PDF fit with NuTeV and CCFR dimuon data* (*S. Alekhin, S. Kulagin and R.P.; PLB 675 (2009) 433*)
- *Consistency of central values*
- *Reduction of $s(x)$ uncertainty by a factor 2 down to $\sim 3\%$: $\kappa_s = 0.61 \pm 0.02$*
- *Improved determination of the $\overline{\rm MS}$ mass* (*S. Alekhin, S. Moch; arXiv:1011.5790 [hep-ph]*) $m_c(m_c) = 1.070 \pm 0.067 \pm 0.050({\rm QCD})$

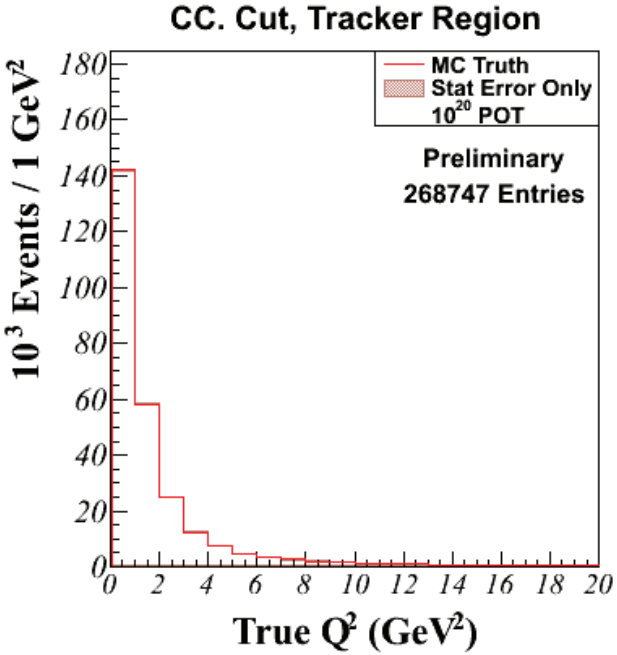
THE MINERνA EXPERIMENT





- *New neutrino scattering experiment currently taking data, with plastic scintillator tracker followed by the MINOS Near Detector as Muon spectrometer*
- *Nuclear targets of CH_2 (5 t), Fe (1 t), Pb (1 t), H_2O (0.35 t), He (0.25 t) and C (0.17 t) provide many A-dependent physics measurements*
- *Movable target and horns in NuMI beam line allow runs with Low (LE) and Medium (ME) energy spectrum:*
  - *Target esposure 4×10^{20} pot $(\nu + \bar{\nu})$ with LE, 12×10^{20} pot $(\nu + \bar{\nu})$ with ME (from 2012)*
  - *Collected exposure (so far) 1.2×10^{20} pot with LE for each ν and $\bar{\nu}$*





- *Charged Current events with resolvable muon track and characteristic hadron shower*

  $\Longrightarrow$ *Definition of DIS interactions: $Q^2 > 1$ GeV^2 and $W > 2$ GeV*

- *Beam studies and MIPP hadro-production measurements provide fluxes with a precision between 5% and 10% (E-dependent)*

- *Measure differential cross-sections and structure functions on different nuclear targets*
  - *Expect a total of 1.76×10^6 CC events and $460k$ DIS events in LE beam run (sum of all targets)*
  - *Expect one order of magnitude more DIS events in ME beam run*

  $\Longrightarrow$ *See talk by J. Mousseau in parallel session*

THE LBNE PROJECT

- *The Long-Baseline Neutrino Experiment (LBNE) designed for high sensitivity measurements of $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ with $\nu_e(\bar{\nu})$ appearance and $\nu_\mu(\bar{\nu}_\mu)$ disappearance*
  $\Longrightarrow$ *Next generation after MINOS and NOνA*

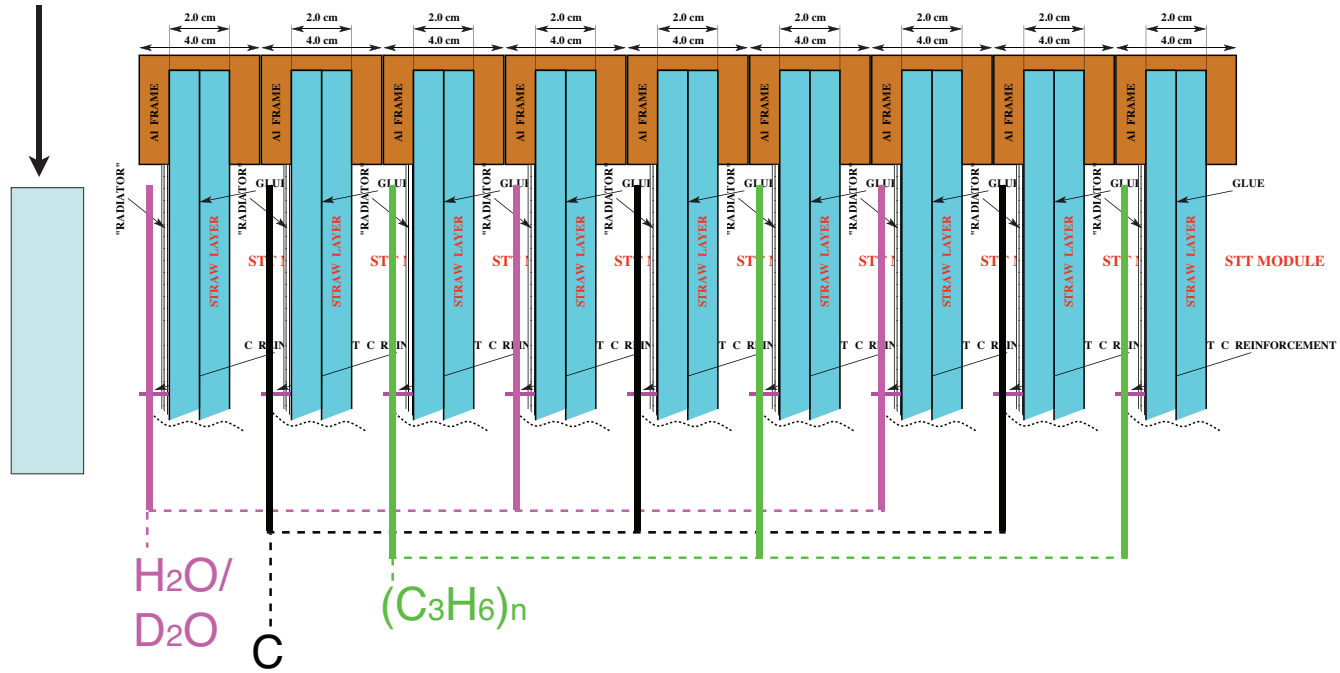
- *High intensity ν and $\bar{\nu}$ beams from Fermilab to Homestake mine in SD ($L \sim 1300$ km)*
  - *Default configuration with NuMI 700 kW proton beam;*
  - *Potential upgrade with new 8 GeV Linac (Project-X) up to 2.3 MW proton beam;*
  - *Different options for beam spectra considered (default LE).*

- NEAR DETECTOR *complex at ~ 500 m from target with fine-grained detectors*
  - *Service measurements (fluxes, backgrounds, cross-sections, etc.) for LBL studies*
  - *Precision measurements of neutrino interactions*

  $\Longrightarrow$ *Complementary physics programs*

- *One of the reference ND configurations includes a high resolution tracker in B field*
  - $\Delta E_\mu < 0.2\%$, $\Delta E_{\rm H} < 0.5\%$;
  - *Fiducial mass ~ 7 tons, run 5 year ν + 5 year $\bar{\nu}$;*
  - *Expect about 4.5×10^7 CC events with 700 kW beam ($\sim 1.8 \times 10^8$ with Project-X)*

Possible to have additional external target



- *Possible to install multiple nuclear targets in the fine-grained ND tracker*
- *In-situ determination of fluxes to* $\sim 2\%$
- *Subtraction of C target from polypropylene* $(C_3H_6)_n$ *target provides free proton*
  - *Collect* $\mathcal{O}(10^6)$ ν *CC events and* $\mathcal{O}(10^6)$ $\bar{\nu}$ *CC events with the 700 kW NuMI beam*
  - *Complete flavor and valence/sea separation (d/u at large* x*)*
  - *Precision test of Adler sum rule (current algebra)*

$$S_A = \int_0^1 \frac{dx}{x} \left(F_2^{\bar{\nu}p} - F_2^{\nu p}\right) = 2$$

- *Subtraction of* H_2O *target from* D_2O *target gives interactions on neutron (in D)*

SUMMARY

- *Power of $\nu + \bar{\nu}$ DIS as a probe of nucleon structure still limited by the beam technology and by the resolution of detectors*

  $\Longrightarrow$ *Some inconsistencies among existing data samples*

- *Recent progress in understanding $\nu(\bar{\nu})$ interactions to include $\nu(\bar{\nu})$ DIS into global QCD fits (Axial-Vector current, High Twists, nuclear corrections)*

- *New NOMAD measurement of ν-induced charm dimuon production allows a substantial reduction of the uncertainties on the strange sea distribution*

- *Many new results from neutrino scattering experiments are expected in the near future (NOMAD, MINERνA)*

  $\Longrightarrow$ *Stay tuned!*

- *The future LBNE project coupled with high intensity neutrino beams (Project X) would finally allow to exploit the physics potential of the (ideal) $\nu(\bar{\nu})$ probe*