TESTS OF THE STANDARD MODEL WITH NEUTRINO BEAMS

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J-PARC Workshop KEK, Tsukuba, November 30, 2005

SUMMARY

- NEUTRINO BEAMS: WHY AND HOW
  - NEUTRINO FACTORIES, β BEAMS AND SUPERBEAMS
  - NEUTRINO SCATTERING
- AN EXAMPLE: THE STORY OF THE NUTEV ANOMALY
  - PROBING ELECTROWEAK COUPLINGS
  - PROBING THE STRUCTURE OF THE NUCLEON
- ELECTROWEAK INTERACTIONS: THE WEINBERG ANGLE
  - NEUTRINO-ELECTRON SCATTERING: HIGH AND LOW ENERGY
  - NEUTRINO-NUCLEON SCATTERING: DIS AT HIGH ENERGY
  - NEUTRINO-NUCLEON SCATTERING: LOW-ENERGY QUASIELASTIC INTERACTIONS
- STRONG INTERACTIONS: NUCLEON STRUCTURE
  - FLAVOR SEPARATION: UNPOLARIZED AND POLARIZED
  - NUCLEON STRANGENESS: HIGH AND LOW ENERGY

NEUTRINO BEAMS

NEUTRINOS INTERACT WEAKLY...

DIS X-SECT.: $\frac{\sigma^W}{\sigma^\gamma} \sim \frac{G_F Q^2}{8\pi\alpha} \frac{M_W^2}{Q^2+M_W^2} \approx 5 \cdot 10^{-5} Q^2/\mathrm{GeV}^2$ ($Q^2 << M_W^2$)

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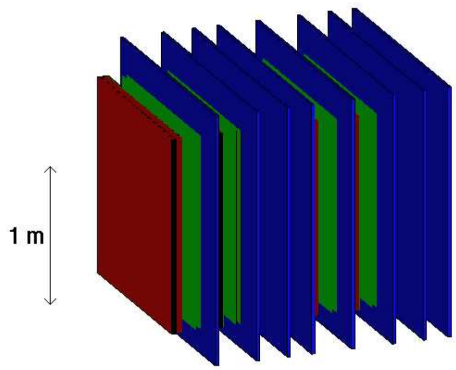
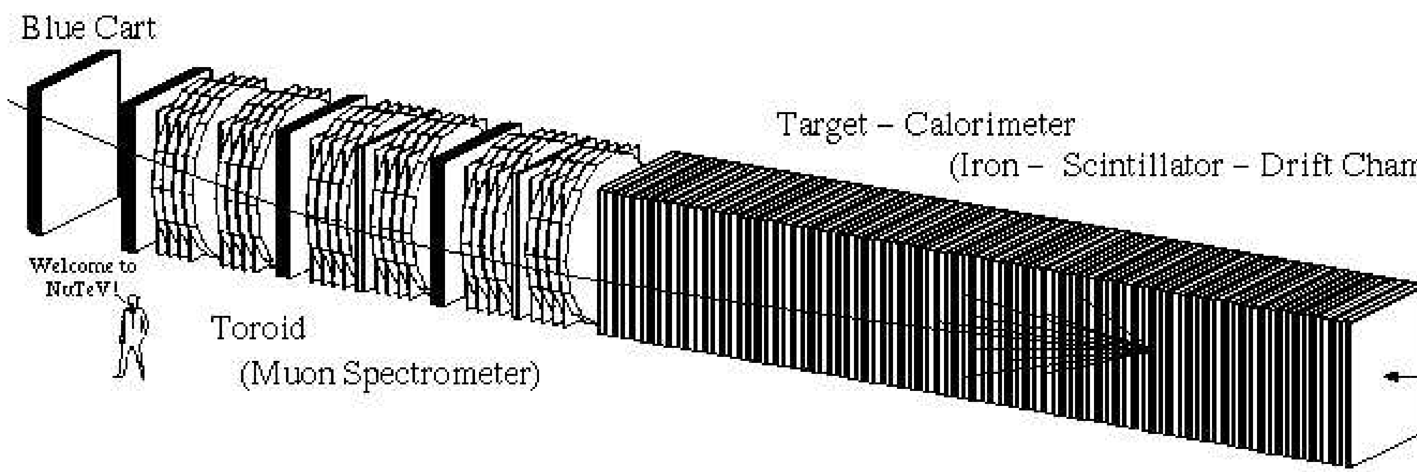
NEED A BIG TARGET! . . .





CHORUS

800 Kg EMULS. STACKS

$\sim 10^{19}$ POT/YR. $\Rightarrow$

10^{16} ν/YR.

$\sim 10^6$ DIS EVENTS/YR

$E_\nu = 10 \div 200$ GeV

NuTeV

84×3 m $\times 3$ m $\times 10$ cm

$690 \cdot 10^3$ Kg Fe PLATES

$\sim 10^{18}$ POT/YR.

$\sim 10^6$ DIS EVENTS/YR

$E_\nu = 20 \div 400$ GeV

NMC: 5 Kg, ~ 0.9 m^3, $\sim 10^6$ EV/YR

INTENSE NEUTRINO BEAMS: A VIEW FROM EUROPE

- May 2001 $\Rightarrow$ CERN Neutrino Factory report
- June 2001 $\Rightarrow$ Construction of JPARC begins in Tokai
- March 2002 $\Rightarrow$ CERN Neutrino Factory R&D cancelled
- September 2004 $\Rightarrow$ Villars Meeting of the SPSC

  Recommendations:

  – Future neutrino facilities offer great promise ...a post-LHC construction window may exist for a facility to be sited at CERN
  – CERN should arrange for budget and personnel..for the realization of such facilities
  – CERN should support the European Neutrino Factory initiative
  – we welcome the effort...concerned with the conceptual design of a beta beam
- November 2005 $\Rightarrow$ BENE (Beams for European Neutrino Experiments)

  interim report:

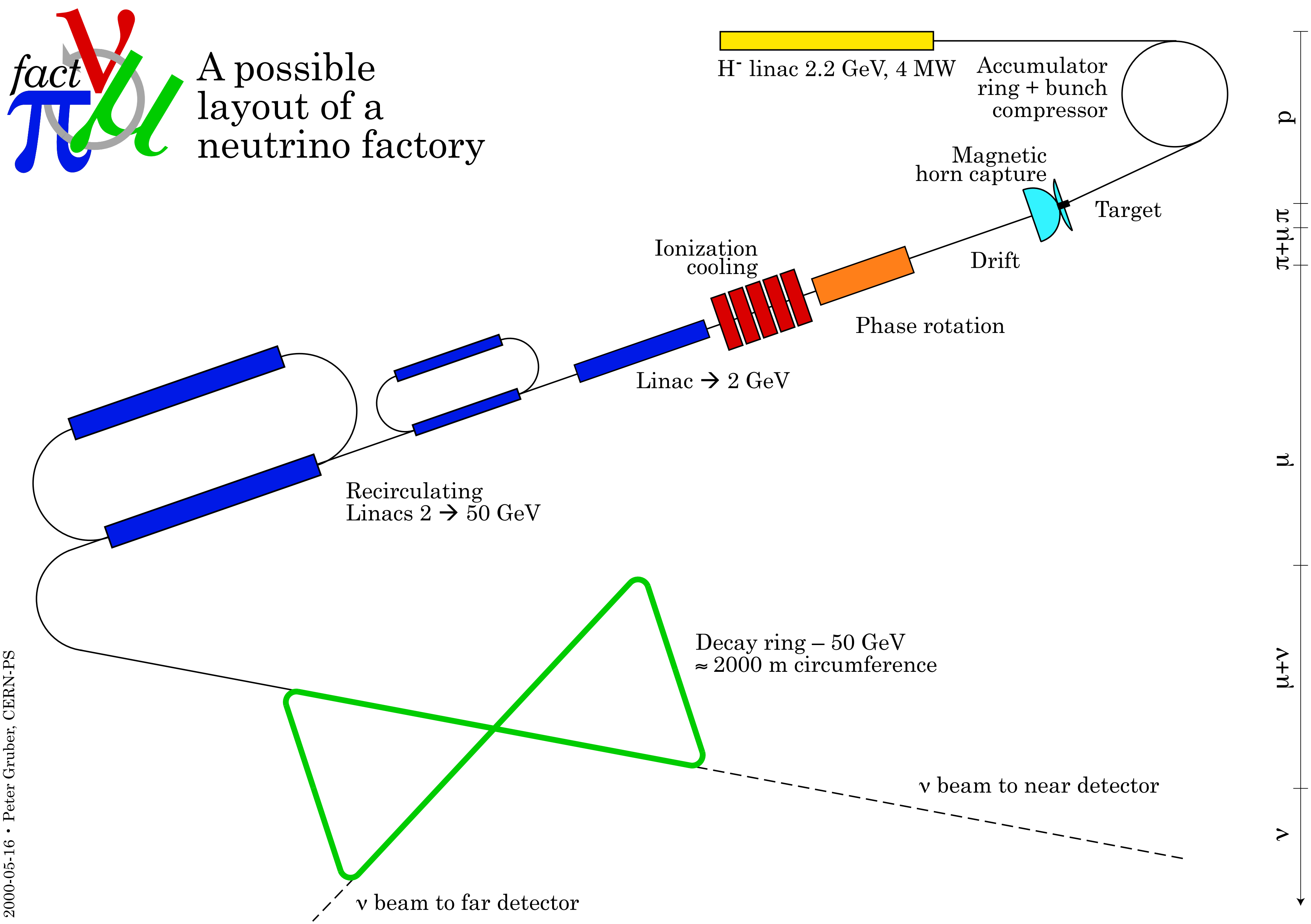
  Three candidate facilities: superbeams, a neutrino factory and a β beam.

THE NEUTRINO FACTORY

(CERN DESIGN)

MUON BEAM ENERGY	$E_\mu = 50$ GeV
LENGTH OF THE STRAIGHT SECTION	$L = 100$ m
DISTANCE OF DETECTOR FROM END OF THE STRAIGHT SECTN.	$d = 30$ m
NR. OF μ DECAYS PER YR. ALONG THE STRAIGHT SECTN.	$N_\mu = 10^{20}$
MUON BEAM ANGULAR DIVERGENCE	$0.1 \times m_\mu / E_\mu$
MUON BEAM TRANSVERSE SIZE	$\sigma_x = \sigma_y = 1.2$ mm
PROTON TARGET RADIUS (DIS)	$R = 50$ cm
PROTON TARGET EFF. DENSITY (UNPOL. DIS)	100 gr/cm^2
PROTON TARGET EFF. DENSITY (POL. DIS)	10 gr/cm^2
PROTON TARGET EFF. DENSITY (ELASTIC $\nu - e$)	1500 gr/cm^2
DIS EVENTS/YEAR (1 TON TARGET)	10^9
ELASTIC e EVENTS/YEAR (20 TON TARGET)	10^7

A possible layout of a neutrino factory

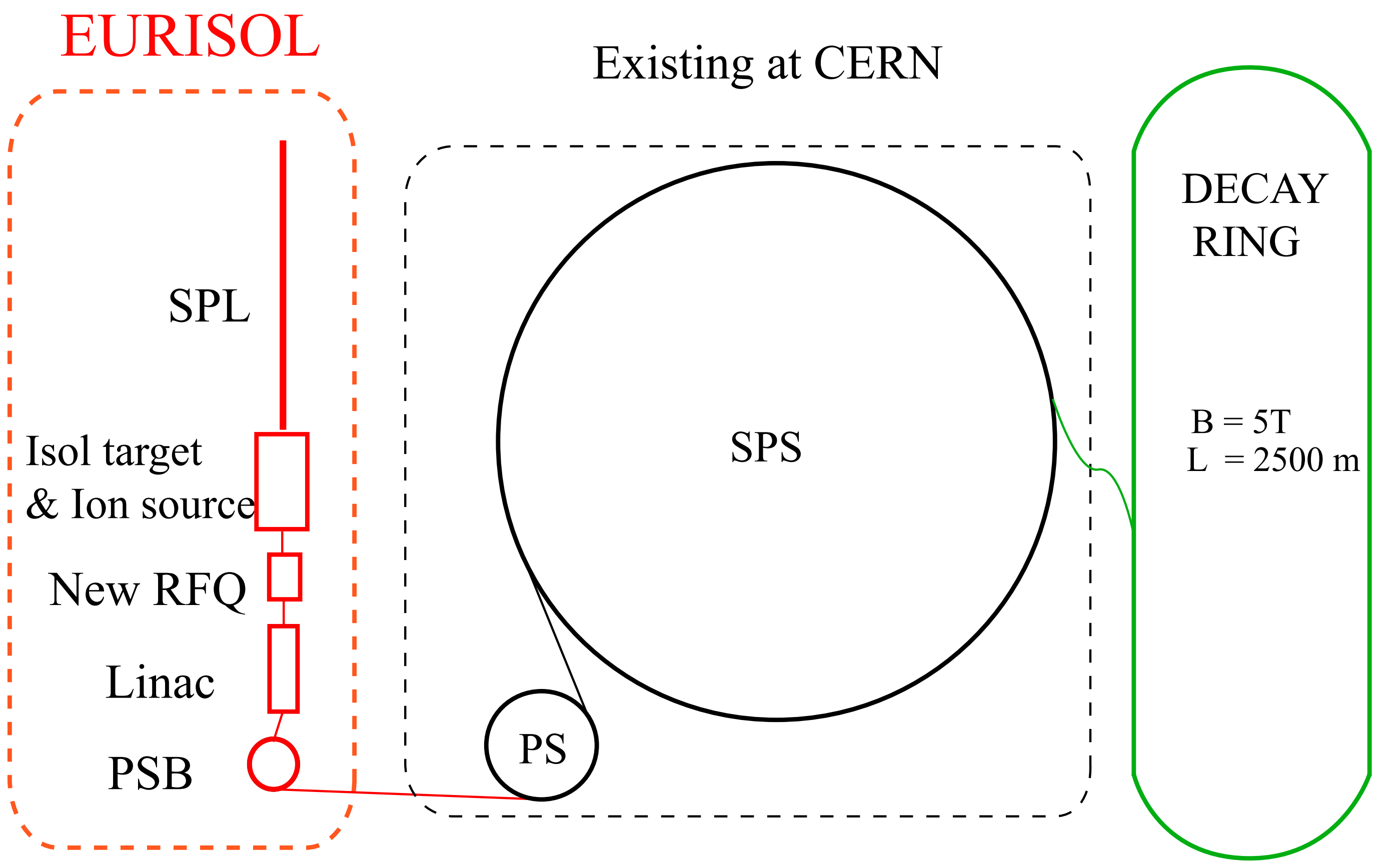


2000-05-16 • Peter Gruber, CERN-PS

THE SUPERBEAM & β BEAM:

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos et al., see http://beta-beam.web.ch/beta-beam



- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- The 4 targets could run in parallel, but the decay ring optics requires:

$$\gamma(Ne^{18}) = 1.67 \cdot \gamma(He^6).$$

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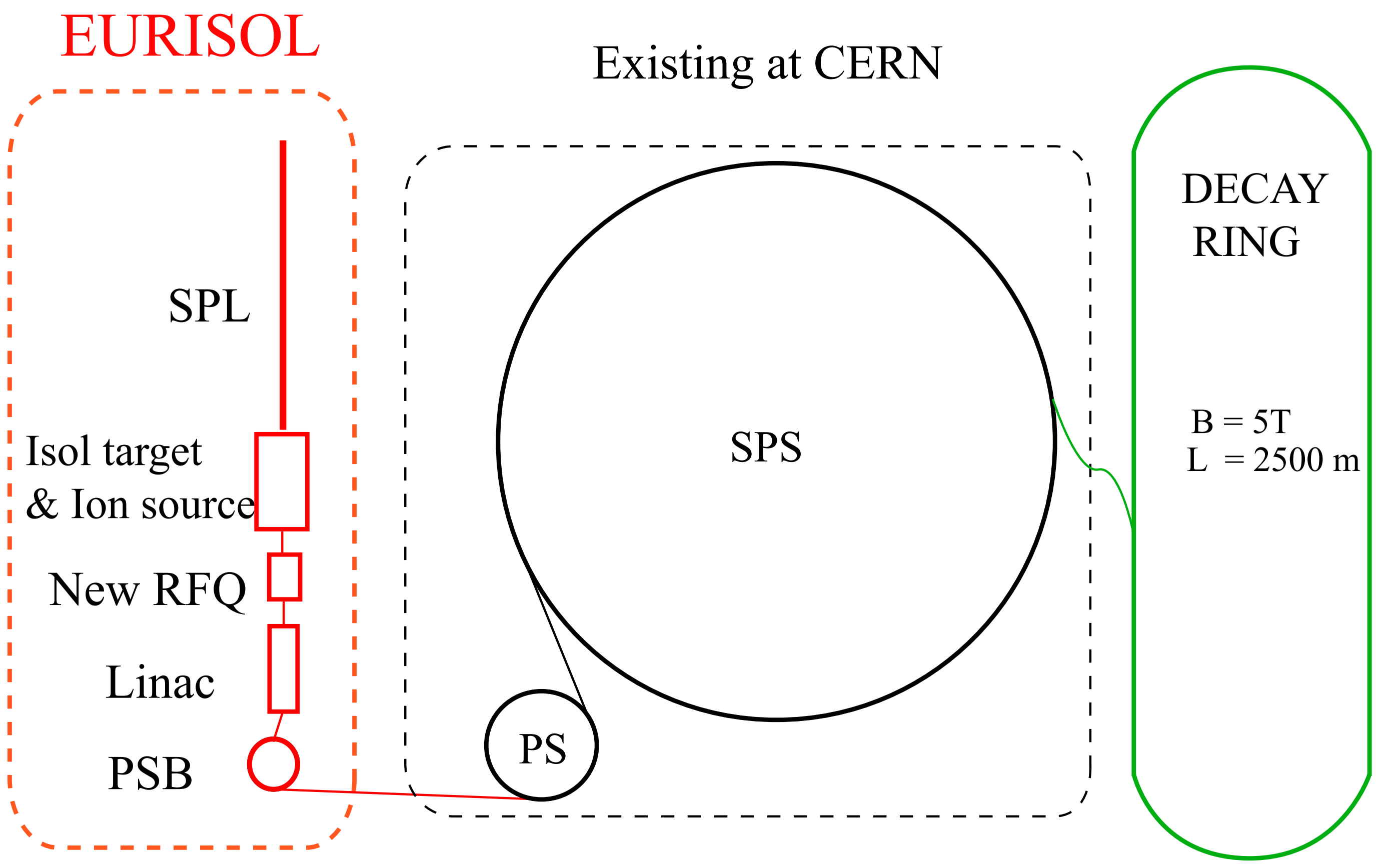

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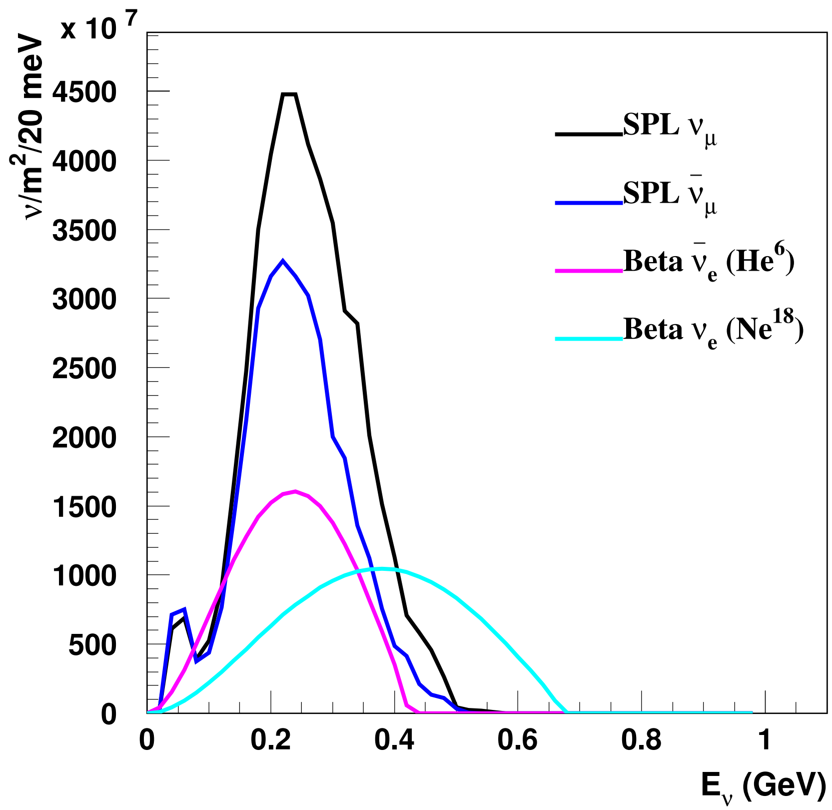
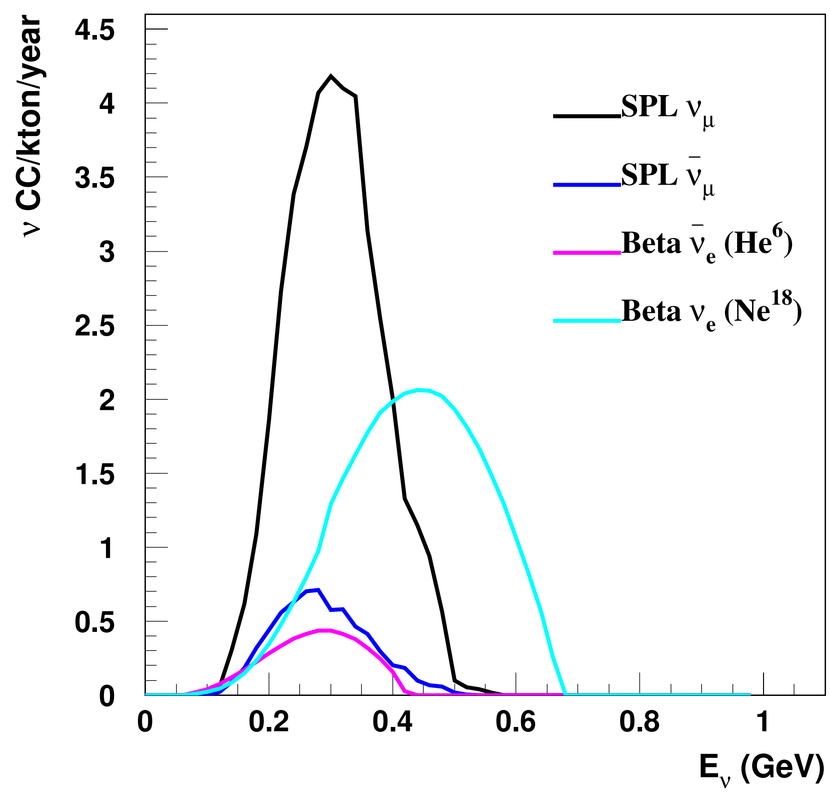
FLUXES AND SPECTRA: FROM LOW ENERGY...

Fluxes



CC Rates

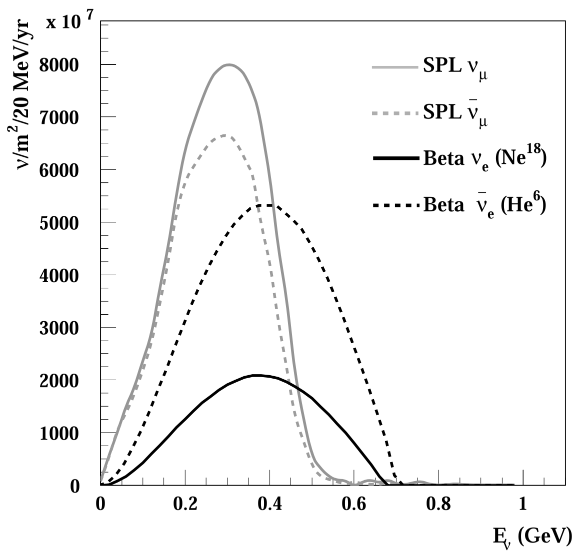


	Fluxes @ 130 km $\nu/m^2/yr$	$<E_\nu>$ (GeV)	CC rate (no osc) events/kton/yr	$<E_\nu>$ (GeV)	Years	Integrated events (440 kton × 10 years)
SPL Super Beam						
ν_μ	$4.78 \cdot 10^{11}$	0.27	41.7	0.32	2	36698
$\overline{\nu}_\mu$	$3.33 \cdot 10^{11}$	0.25	6.6	0.30	8	23320
Beta Beam						
$\overline{\nu}_e\ (\gamma = 60)$	$1.97 \cdot 10^{11}$	0.24	4.5	0.28	10	19709
$\nu_e\ (\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36	32.9	0.43	10	144783

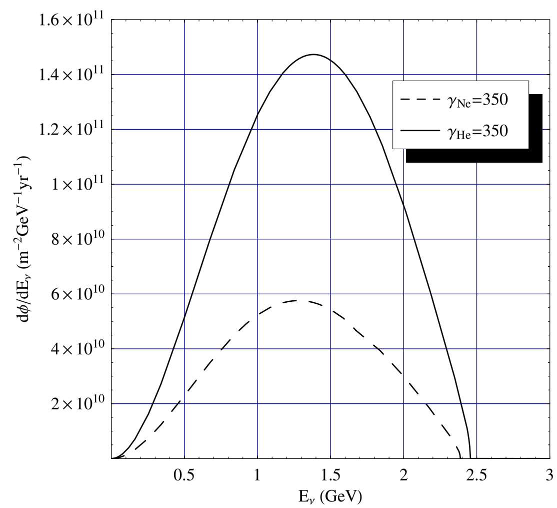
…TO HIGH ENERGY

FLUXES

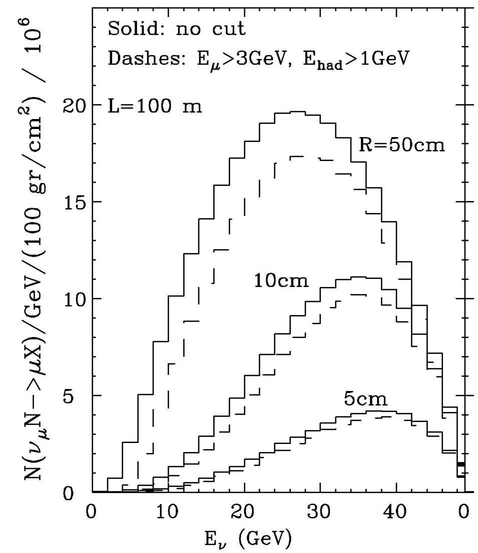
$\beta = 100\ ^3He$ Frejus



$\beta = 350\ ^3He$ Gran Sasso



NuFact front-end



COMPARISON OF BEAM OPTIONS

		T2K	T2K 2	PS++	SPL	SPL 3.5	βB	$\beta B_{100,100}$
p-driver	(MW)	0.75	4	4	4	4	0.4	0.4
p beam energy	(GeV)	50	50	20	2.2	3.5	1-2.2	1-2.2
$\langle E(\nu_\mu)\rangle$	(GeV)	0.7	0.7	1.6	0.27	0.35	0.3	0.4
L	(Km)	295	295	732	130	130	130	130
Off-Axis		2^0	2^0	-	-	-	-	-
ν_μ^{CC} (ν_e^{CC}) (no oscillation)	(Kt/year)	100	500	450	41	122	38	56
ν_e^{CC}/ν_μ^{CC}	(%)	0.4	0.4	1.2	0.4	0.7	0	0
Detector Fid. Mass	(kton)	22.5	540	2.2	440	440	440	440
Material		H_2O	LAr	H_2O	H_2O	H_2O	H_2O	H_2O
Signal efficiency	(%)	40	40	100	70	70	60	70
π°/ν_e (π/ν_e)	(%)	80	80	0	30	30	0.2	0.2
$\sin^2 2\theta_{13}\cdot 10^4$	(90% CL)	60	6	64	18	7	7	2

NOTE fluxes given at the respective distances:

$10^6 - 10^7\times$ higher flux at front end of $\beta 60 \Rightarrow 10^5$ DIS events/year with 1 ton detector

WHY NEUTRINOS?:

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THEY PROBE ELECTROWEAK COUPLINGS...

elastic ν-fermion scattering

$$\frac{d\sigma}{dy}(\nu f \to \nu f) = \frac{G_F^2 Q^2}{\pi y} \left[g_L^2 + g_R^2 (1-y)^2 \right];$$

$$Q^2 \equiv -(k_\nu - k'_\nu)^2, \quad y \equiv \frac{p_f \cdot q_\nu}{p_f \cdot k_\nu}$$

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...SPIN...

REACTION	g_L	g_R
$\nu_\mu e^- \to \nu_\mu e^-$ (NC)	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$
$\nu_\mu e^- \to \mu^- \nu_e$ (CC)	1	0
$\nu u \to \nu u$ (NC)	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$	$\frac{2}{3}\sin^2\theta_W$
$\nu d \to \nu d$ (NC)	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$
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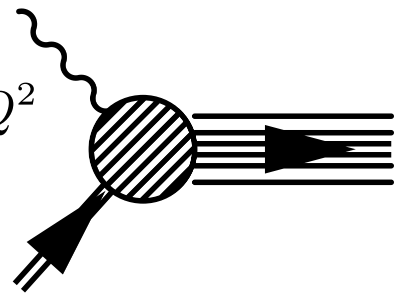
$\nu d \to \nu d$ (NC)	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$
$\nu_e d \to e^- u$ (CC)	1	0

AND FLAVOUR!

NEUTRINO-HADRON INTERACTIONS

DEEP-INELASTIC SCATTERING:. . .



Lepton fractional energy loss: $y = \frac{p\cdot q}{p\cdot k}$;

Bjorken x: $x = \frac{Q^2}{2p\cdot q}$

lepton-nucleon CM energy: $s = \frac{Q^2}{xy}$;

virtual boson-nucleon CM energy $W^2 = Q^2\frac{1-x}{x}$;

$$\frac{d^2\sigma^{\lambda_p\lambda_\ell}(x,y,Q^2)}{dxdy} = \frac{G_F^2}{2\pi(1+Q^2/m_W^2)^2}\frac{Q^2}{xy}\left\{\left[-\lambda_\ell\, y\left(1-\frac{y}{2}\right)xF_3(x,Q^2) + (1-y)F_2(x,Q^2)\right.\right.$$

$$\left.\left.+y^2xF_1(x,Q^2)\right] - 2\lambda_p\left[-\lambda_\ell\, y(2-y)xg_1(x,Q^2) - (1-y)g_4(x,Q^2) - y^2xg_5(x,Q^2)\right]\right\}$$

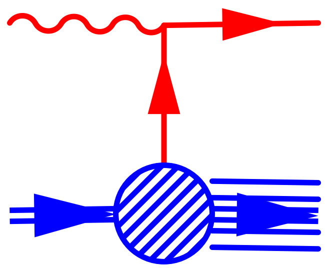
$\lambda_l \;\rightarrow$ lepton helicity

$\lambda_p \;\rightarrow$ proton helicity

	PARITY CONS.	PARITY VIOL.
UNPOL.	$F_1,\ F_2$	F_3
POL.	g_1	$g_4,\ g_5$

PARTON DISTRIBUTIONS

STRUCTURE FUNCTION=HARD COEFF.⊗PARTON DISTN.



$$F_2^{\rm NC}(x,Q^2) = x \sum_{\text{flav. } i} e_i^2 (q_i + \bar{q}_i) + \alpha_s \left[C_i[\alpha_s] \otimes (q_i + \bar{q}_i) + C_g[\alpha_s] \otimes$$

q_i quark, $\bar{q}_i$ antiquark, g gluon

LEADING PARTON CONTENT (up to $O[\alpha_s]$ corrections)

	$q_i \equiv q_i^{\uparrow\uparrow} + q_i^{\uparrow\downarrow}$	$\Delta q_i \equiv q_i^{\uparrow\uparrow} - q_i^{\uparrow\downarrow}$
NC	${F_1}^{\gamma,\,Z} = \sum_i e_i^2\,(q_i + \bar{q}_i)$	${g_1}^{\gamma,\,Z} = \sum_i e_i^2\,(\Delta q_i + \Delta\bar{q}_i)$
CC	$F_1^{W^+} = \bar{u} + d + s + \bar{c}$	$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c}$
CC	$-F_3^{W^+}/2 = \bar{u} - d - s + \bar{c}$	$g_5^{W^+} = \Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c}$
	$F_2 = 2xF_1$	$g_4 = 2xg_5$

$W^+ \to W^- \Rightarrow u \leftrightarrow d,\ c \leftrightarrow s$; more combinations using Isospin: $p \to n \Rightarrow u \leftrightarrow d$

ELASTIC & QUASI-ELASTIC SCATTERING

POINTLIKE CROSS SECTIONS CORRECTED BY FORM FACTORS:

neglecting terms $O(M_n/E)$, for the e.m. current

$$\langle p'|j^\mu|p\rangle = \bar u(p')\gamma^\mu u(p) G_M(Q^2) + \bar u(p') u(p)\left(\frac{p^\mu + p'^\mu}{2m}\right) G_E(Q^2);$$

axial current $\Rightarrow G_A$; define analogously strange form factors from strange current

$$\left[\frac{d\sigma}{dy}^{\rm NC}_{\nu} + \frac{d\sigma}{dy}^{\rm NC}_{\bar\nu}\right]_p = \frac{G_F^2 M_n E_\nu}{2\pi}\frac{1}{4}\left[2(1-y+y^2)\right]\left[(G_A - G^s_A)^2 + \left(G^p_M(1-4\sin^2\theta_W) - G^n_M - G^s_M\right)\right.$$

$$\left[\frac{d\sigma}{dy}^{\rm NC}_{\nu} - \frac{d\sigma}{dy}^{\rm NC}_{\bar\nu}\right]_p = \frac{G_F^2 M_n E_\nu}{2\pi}\frac{1}{2}(2-y)\left[G^p_M(1-4\sin^2\theta_W) - G^n_M - G^s_M\right](G_A + G^s_A)$$

$$\left[\frac{d\sigma}{dy}^{\rm NC}_{\nu} + \frac{d\sigma}{dy}^{\rm NC}_{\bar\nu}\right]_n = \frac{G_F^2 M_n E_\nu}{2\pi}14\left[2(1-y+y^2)\right]\left[(G_A + G^s_A)^2 + \left(G^n_M(1-4\sin^2\theta_W) - G^p_M - G^s_M\right)\right.$$

$$\left[\frac{d\sigma}{dy}^{\rm NC}_{\nu} - \frac{d\sigma}{dy}^{\rm NC}_{\bar\nu}\right]_n = \frac{G_F^2 M_n E_\nu}{2\pi}\frac{-1}{2}(2-y)\left[G^n_M(1-4\sin^2\theta_W) - G^p_M - G^s_M\right](G_A + G^s_A)$$

$$\left[\frac{d\sigma}{dy}^{\rm CC}_{\nu} + \frac{d\sigma}{dy}^{\rm CC}_{\bar\nu}\right] = \frac{G_F^2 M_n E_\nu}{2\pi}\left[2(1-y+y^2)\right]\left[G_A^2 - (G^p_M - G^n_M)^2\right]$$

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$M \to$ nucleon mass; form factors depend on $Q^2 = 2M_n(E_n - M_n)$ (nucl. rest frame)

NOTE NO DEP. ON G_E, ENTERS THROUGH $O(M_n/E)$ TERMS

AN EXAMPLE....

THE NUTEV ANOMALY

PW RATIO: DATA...

NuTeV 2001 $\sin^2\theta_W(\mathrm{OS}) = 0.2272 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst}) \pm 0.0002(M_t, M_H)$

Global Fit 2003 $\sin^2\theta_W(\mathrm{OS}) = 0.2229 \pm 0.0004$

...VS. THEORY

$$R^- = \frac{\sigma_{NC}(\nu) - \sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu) - \sigma_{CC}(\bar{\nu})}$$

$$= \left(\frac{1}{2} - \sin^2\theta_W\right)$$

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$$+ O(\delta(u-d)^2 \quad)$$

U,D...DENOTE MOMENTUM FRACTIONS CARRIED BY CORRESP. QUARK FLAVORS

- ISOSPIN VIOLATION $\longrightarrow$ corrn. for non-isoscalar target included, but not $u^p \neq d^n$

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$s - \bar s \approx 0.004$ (OR 2% ISOSPIN VLN.) ENOUGH TO REMOVE ANOMALY: CAN WE TEST IT?

Disentangling strangeness

Charm is copiously produced in $W^+ + s \to c$

easily tagged through dimuon signal, 2nd muon from subsequent c decay

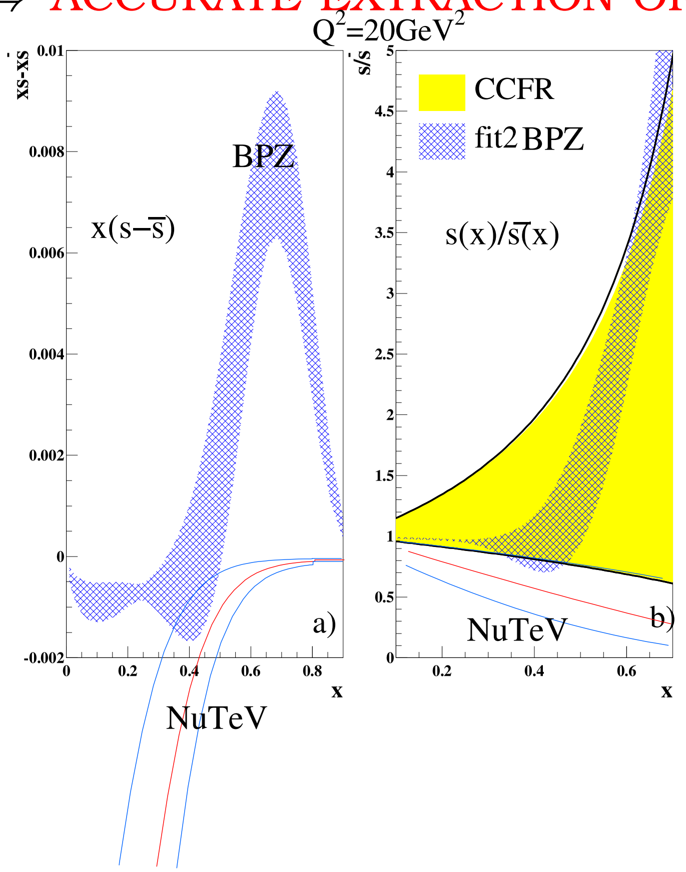
$\Rightarrow$ accurate extraction of the strange distribution

DISENTANGLING STRANGENESS

CHARM IS COPIOUSLY PRODUCED IN $W^+ + s \to c$

easily tagged through dimuon signal, 2nd muon from subsequent c decay

$\Rightarrow$ ACCURATE EXTRACTION OF THE STRANGE DISTRIBUTION



CCFR/NUTEV $s - \bar{s}$ DETERMINATION

5000 ν & 1500 $\bar{\nu}$ DIMUON EVENT SAMPLE:

ASSUMED PARM.: $s(x) = \kappa \frac{\bar{u}(x)+\bar{d}(x)}{2}(1-x)^\alpha$

NEGATIVE $s - \bar{s}$ AT SMALL x

$\Rightarrow$ MOM. FRACT. $s - \bar{s} = -0.003 \pm 0.001$

NUTEV ANOMALY WORSE!

DISENTANGLING STRANGENESS

CHARM IS COPIOUSLY PRODUCED IN $W^+ + s \to c$

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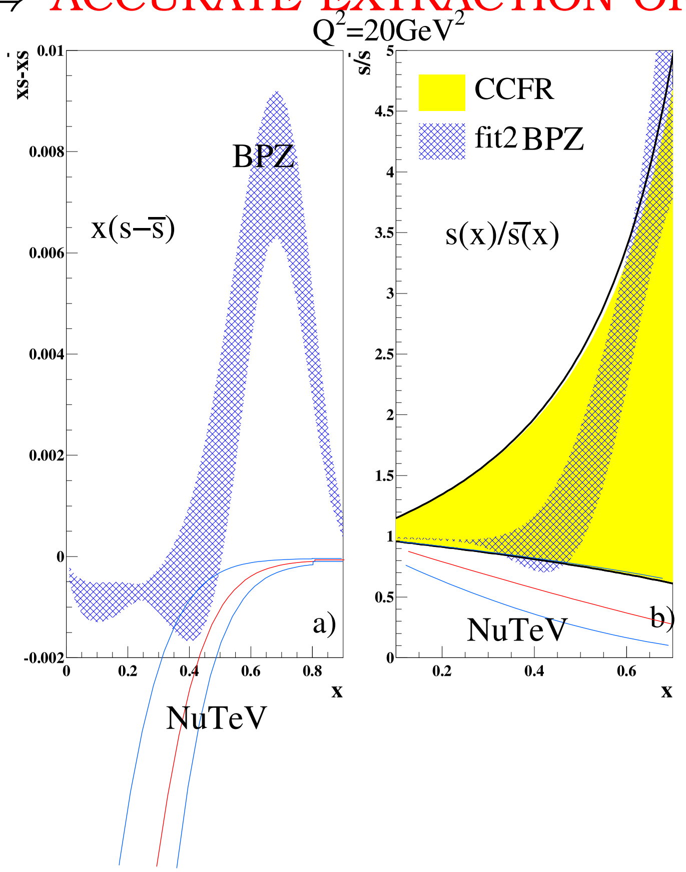

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NUTEV ANOMALY WORSE!

HOWEVER, BPZ GLOBAL FIT TO NEUTRINO INCLUSIVE DIS (Barone et al 2003) $\Rightarrow$

POSITIVE (TINY) ASYMMETRY

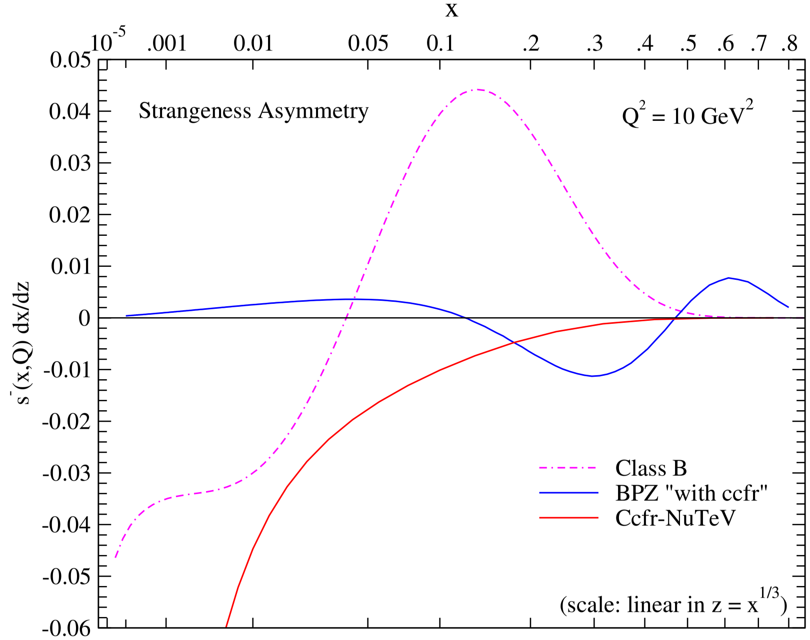
COMBINING INCLUSIVE AND EXCLUSIVE INFORMATION

CTEQ DEDICATED DIMUON ANALYSIS (April 2004)

- $\int_0^1 (s(x) - \bar{s}(x))dx = 0$ IN PROTON
  $\Rightarrow$ EITHER $s(x) - \bar{s}(x)$ HAS A NODE OR IT VANISHES EVERYWHERE

- $[s(x) - \bar{s}(x)] < 0$ FOR SMALL $x \lesssim 0.05$ CONSTRAINED BY DIMUON

strangeness asymmetry



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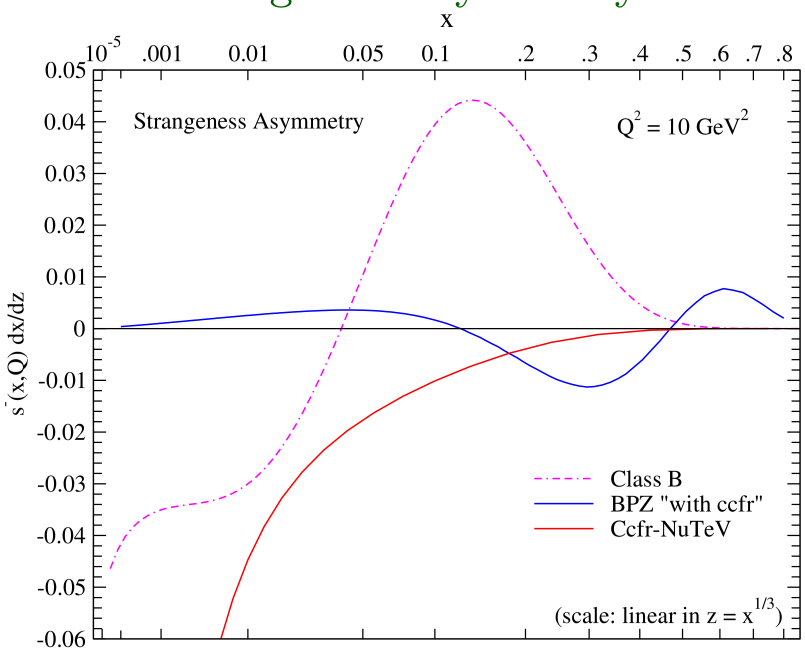
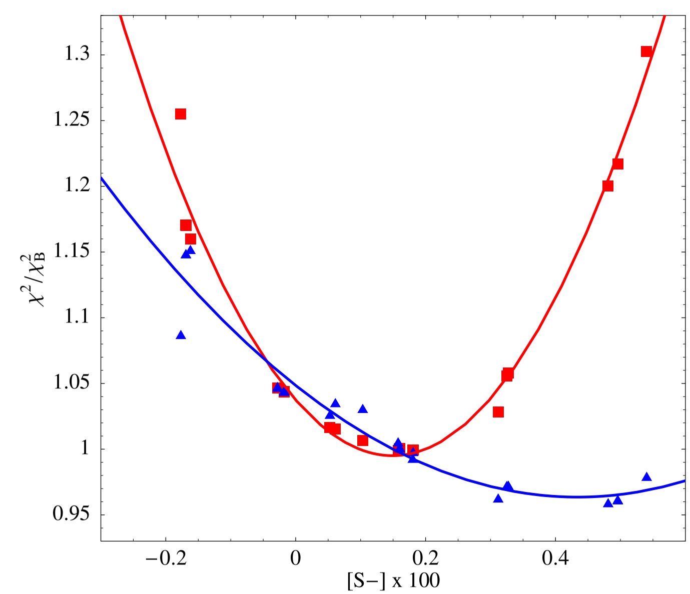
- $[s(x) - \bar{s}(x)] < 0$ FOR SMALL $x \lesssim 0.05$ CONSTRAINED BY DIMUON
- LARGE x REGION WEIGHS MORE IN MOMENTUM FRACTION
- POSITIVE MOM. FRACTION $s - \bar{s} \approx 0.02$: THE END OF THE STORY (?)

strangeness asymmetry



χ^2 dimuon vs. inclusive

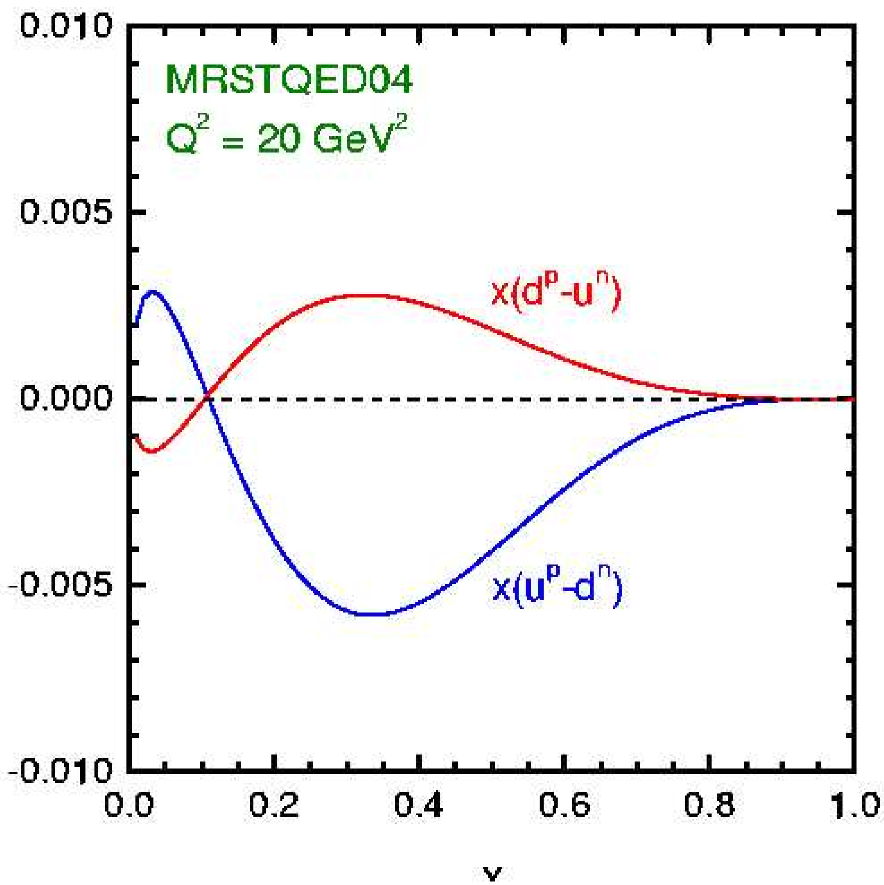


MORE... ISOSPIN VIOLATION!

QED EFFECTS LEAD TO ISOSPIN VIOLATION:
$u - \bar{u}$ radiate more photons than $d - \bar{d}$: $\frac{d}{dt}q_i \propto e_i^2 q_i$

$\Rightarrow$ MORE PHOTON MOMENTUM IN PROTON THAN NEUTRON

$\Rightarrow |u(x) - \bar{u}(x)| < |d(x) - \bar{d}(x)|$ AT LARGE x



- SIGN OF EFFECT AS REQUIRED TO EXPLAIN NUTEV
- SIZE OF EFFECTS WITH REASONABLE ASSUMPTIONS ABOUT 1/2 OF NUTEV ANOMALY
- THEORETICAL RESULTS AGREES WITH FIT IF ISOSPIN VIOLATION ALLOWED

MRST 2005

ELECTROWEAK INTERACTIONS

$\sin^2\theta_W$ FROM ELASTIC $e-\nu$ SCATTERING:

CLEAN PROBE OF THE ELECTROWEAK COUPLINGS,

.... BUT WITH SMALL CROSS SECTION: elastic/DIS $\sim m_e/m_p$

$$\frac{d\sigma}{dy}(\nu e^- \rightarrow \nu e^-) = \frac{2G_F^2 m_e E_\nu}{\pi}\left[g_L^2 + g_R^2(1-y)^2\right]; \quad y \equiv E_e/E_\nu$$

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AT NUFACT EXPECT $\sim 10^7$ EVENTS/YR. WITH μ^+ BEAM, HALF WITH μ^- BEAM
(2 ton CH_4 or 20 ton liquid Ar detect.; one yr.: $\int Ldt = 8.6 \cdot 10^{10}\mathrm{pb}^{-1}$);
NOTE: $\sigma \propto E_\nu$

$\sin^2\theta_W$ IS DETERMINED FROM g_A, g_V (OR g_L, g_R):

REACTION	g_L	g_R	$g_L^2 + \frac{1}{3}g_R^2$
$\nu_\mu e^- \to \nu_\mu e^-$ (NC)	$-\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$	0.091
$\overline{\nu_\mu} e^- \to \overline{\nu_\mu} e^-$ (NC)	$\sin^2\theta_W$	$-\frac{1}{2}+\sin^2\theta_W$	0.077
$\nu_e e^- \to \nu_e e^-$ (NC+CC)	$\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$	0.551
$\overline{\nu_e} e^- \to \overline{\nu_e} e^-$ (NC+CC)	$\sin^2\theta_W$	$\frac{1}{2}+\sin^2\theta_W$	0.231

CURRENT STATUS

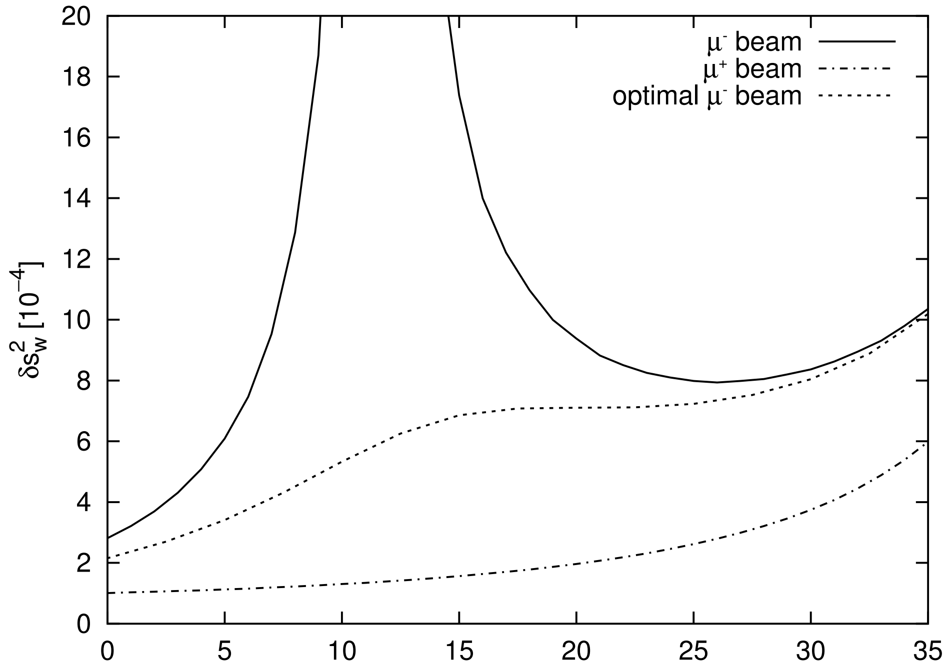
$\sin^2\theta_W = 0.2324 \pm 0.0058(\text{stat}) \pm 0.0059(\text{syst})$ (CHARMII, 1994)

HIGH ENERGY (NEUTRINO FACTORY)

UNCERTAINTIES: $(\times 10^{-4})$

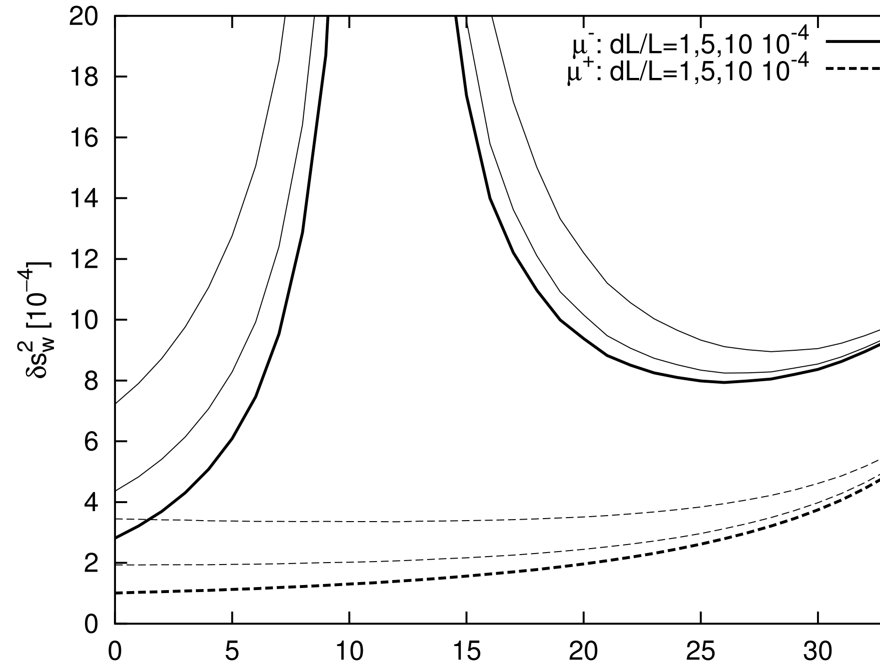
AT THE NUFACT, CANNOT DISENTANGLE ν_μ, $\bar{\nu}_e$ IN A μ^- BEAM

(UNLESS MUON IN FINAL STATE)



(a) $E_{min}(e^-)$ [GeV]

STAT. UNCERTAINTY



(b) $E_{min}(e^-)$ [GeV]

SYST. LUMI. UNCERTAINTY

- SIGNAL: FORWARD e TRACK WITH NO HADRONS, $E > E_{min}$
- BACKGROUND: QUASIELASTIC $\nu - p$ SCATTERING, REMOVE WITH p_T CUT

LOW ENERGY (?)

- THE CROSS SECTION AGAIN

$$\frac{d\sigma}{dy}(\nu e^- \to \nu e^-) = \frac{2G_F^2 m_e E_\nu}{\pi}\left[g_L^2 + g_R^2(1-y)^2\right]$$

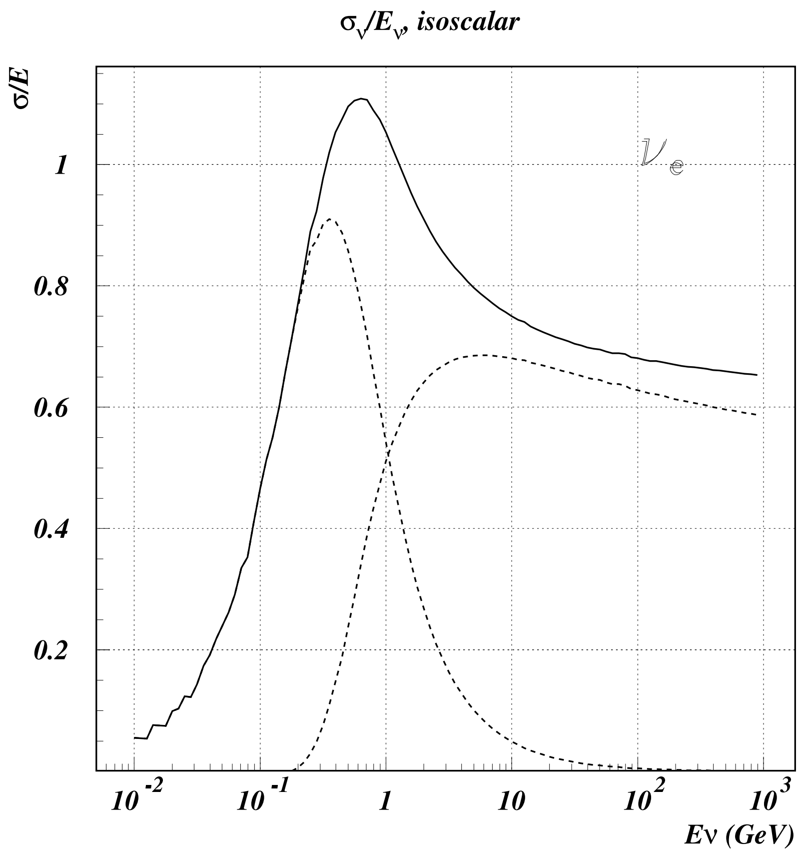
$\Rightarrow$ LOOSE FACTOR ~ 30 FROM ENERGY, & ~ 30 FROM FLUX

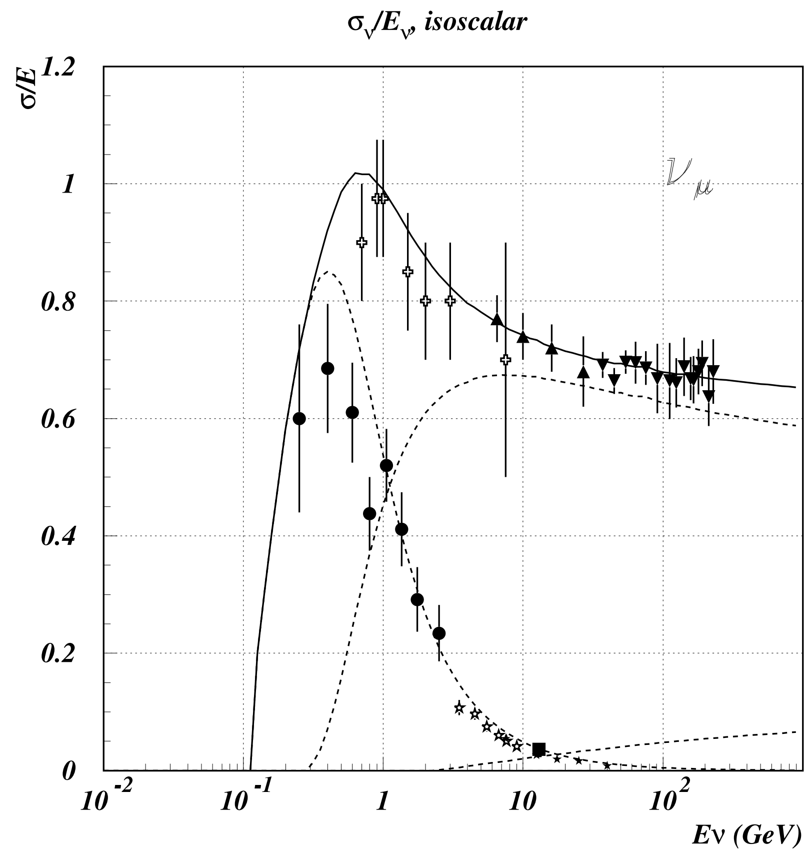
- PURE ν_e OR $\bar{\nu}_e$ BEAM $\Rightarrow$ NEED NOT CONSTRUCT "OPTIMAL" BEAM
- GOOD CONTROL ON FLUX NORMALIZATION (DOMINANT SYSTEMATICS)

$\delta \sin^2\theta_W$ PERHAPS $\sim 10^{-3}$ OR EVEN 10^{-4}?

MEASUREMENT AT LOW ENERGY $\Rightarrow$ TEST OF RADIATIVE CORRECTIONS

THE NEUTRINO-NUCLEON CROSS SECTION





$E_\nu \lesssim M_N \quad \Rightarrow$ QUASIELASTIC: σ/E_ν DROPS BECAUSE OF FORM FACTOR

$E_\nu \lesssim M_N \quad \Rightarrow$ DEEP-INELASTIC : $\sigma/E_\nu \sim$ CONSTANT

$\sin^2\theta_W$ FROM DIS AT THE ν FACTORY:

- CANNOT DISENTANGLE NC ν, $\bar{\nu}$ EVENT BY EVENT
- HOWEVER, CAN MEASURE NC/CC RATIOS

CONSTRUCT AN "IDEAL" OBSERVABLE:

$$R^{\mu^-} = \frac{\sigma_{NC}(\nu_\mu) + \sigma_{NC}(\bar{\nu}_e)}{\sigma_{CC}(\nu_\mu) + \sigma_{CC}(\bar{\nu}_e)}; \; R^{\mu^+} = \frac{\sigma_{NC}(\bar{\nu}_\mu) + \sigma_{NC}(\nu_e)}{\sigma_{CC}(\bar{\nu}_\mu) + \sigma_{CC}(\nu_e)}; \; P = \frac{\sigma_{NC}(\mu^-) - \sigma_{NC}(}{\sigma_{CC}(\mu^-) - \sigma_{CC}(}$$

OBSERVABLE	STAT. ERROR	PDF
R^{μ^-}	0.4	~ 12
R^{μ^+}	0.5	~ 15
$R^{\mu^-} - 0.8R^{\mu^+}$	2.2	~ 2
P	4.9	~ 4

UNCERTAINTIES ON $\sin^2\theta_W$ FROM ν DIS IN UNITS OF 10^{-4}

$\sin^2\theta_W$ FROM ELASTIC SCATTERING OFF NUCLEONS

- (QUASI)ELASTIC ν-NUCLEON CROSS SECTIONS DEPEND ON FIVE INDEP. FORM FACTORS (G_M^p, G_M^n, G_A, G_M^s, G_A^s) + THREE (G_E^p, G_E^n, G_E^s) WHEN $O(M_n/E)$ TERMS RETAINED
- WITH ν, $\overline{\nu}$ BEAMS & p, n TARGETS, SIX INDEP. CROSS SECTIONS

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- WITH ν, $\overline{\nu}$ BEAMS & p, n TARGETS, SIX INDEP. CROSS SECTIONS
  - $E >> M_n \Rightarrow$ FIVE XSECTS ARE LINEARLY INDEPENDENT $\rightarrow$ CAN DETERMINE WEINBERG ANGLE $\sin^2\theta_W$ & FOUR OUT OF FIVE FORM FACTORS (a linear combination of the three magnetic f.f. is undetermined)

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  - $E \lesssim M_n \Rightarrow$ ALL XSECTS LINEARLY INDEP., BUT EIGHT FORM FACTORS $\rightarrow$ NEED TO INPUT THREE FORM FACTORS

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- WITH ν, $\overline{\nu}$ BEAMS & NUCLEON TARGETS, (ONLY p, ISOSCALAR NUCLEI,...) FOUR INDEP. CROSS SECTIONS NEED TO INPUT STRANGE FORM FACTOR G_A^s

BEAM OPTIONS AND QUANTITATIVE ESTIMATES (P. Ferrario, S.F.)

- TWO EXTREME ENERGY SCENARIOS:

  $\beta 60 \longrightarrow \langle E_\nu \rangle \approx 200$ MEV (LOW ENERGY)

  $\beta 1500 \longrightarrow \langle E_\nu \rangle \approx 5$ GEV (HIGH ENERGY)

- COMPUTE RATES ON 4.4 MTON WATER AT 130 KM: $\Phi_\nu \sim \Phi_{\overline{\nu}} \sim 10^{11}/(m^2 yr)$
  - at low energy, $\sim 1.5 \times 10^5$ CC ν and as many $\overline{\nu}$ events; $\sim 3 \times 1.610^4$ NC proton ν and $\sim$ half $\overline{\nu}$ events, $\sim 3 \times 1.310^4$ NC neutron ν and $\sim$ half $\overline{\nu}$ events

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  - at high energy, $\sim 3 \times 10^6$ CC ν and as many $\overline{\nu}$ events; $\sim 3 \times 1.510^5$ NC proton ν and as many $\overline{\nu}$ events, $\sim 3 \times 1.310^5$ NC neutron ν and as many $\overline{\nu}$ events

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- BIN EVENTS W. XSECT APPROX CONSTANT IN BIN: ANG. RESOLUTION $\Delta\theta \sim 5^\circ$
  NOTE y DEPENDENCE DRIVEN BY FORM FACTOR THROUGH $Q^2 = 2M_p(yE_\nu - M_p)$
  - at low energy, rate uniformly distributed in ~ 20 bins of $0.003 < Q^2 < 0.1$ GeV^2
  - at high energy, rate concentrated in first two out of ~ 20 bins $Q^2 \lesssim 1$ GeV^2

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- ERROR ON $\sin^2\theta_W$: LOW ENERGY: $\delta =\sim 2 \times 10^{-3}$ (WITH P/N SEPARATION);
  $\delta =\sim 1 \times 10^{-2}$ (WITHOUT P/N SEPARATION)
  HIGH ENERGY: $\delta =\sim 5 \times 10^{-3}$ (WITH OR WITHOUT P/N SEPARATION)
  - no significant gain from p/n at high energy: dep. of xsect on G_A^s very weak
  - no significant gain from high energy: increased xsect in low-y where dep on $\sin^2\theta_W$ weak

DETECTION CONSTRAINTS (V. Antonelli, G. Battistoni, S.F.)

- In water Čerenkov, need $\frac{p}{E} > 0.75$ for recoiling proton $\Rightarrow p > 1.1$ GeV; Cannot detect recoiling neutron

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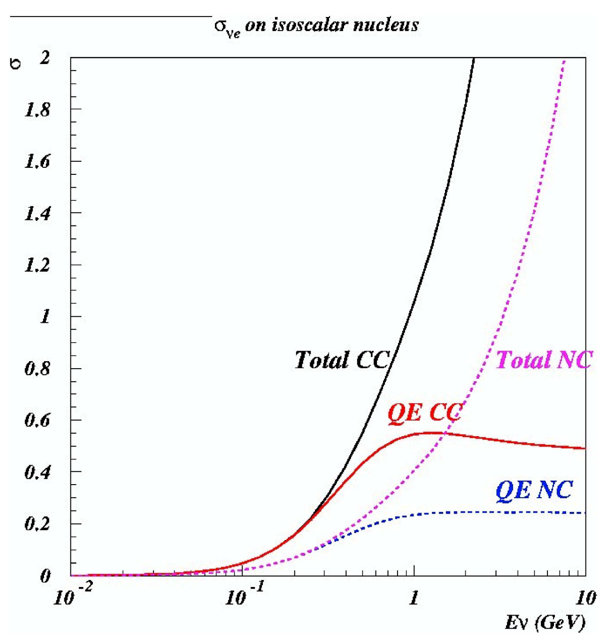
- IN LIQUID AR, NEED $p \gtrsim 300$ MEV ($E - m \gtrsim 50$ MEV) IN ORDER TO HAVE REASONABLE PROTON TRACK & NOT CONFUSE WITH NUCLEAR EFFECTS CANNOT DETECT RECOILING NEUTRON



- QUASIELASTIC CONTRIBN LARGE $\longrightarrow$ LOW ENERGY
- MAXIMIZE DETECTION EFFICIENCY $\longrightarrow$ HIGH ENERGY

$\Rightarrow$ OPTIMAL ENERGY AROUND 1 GEV

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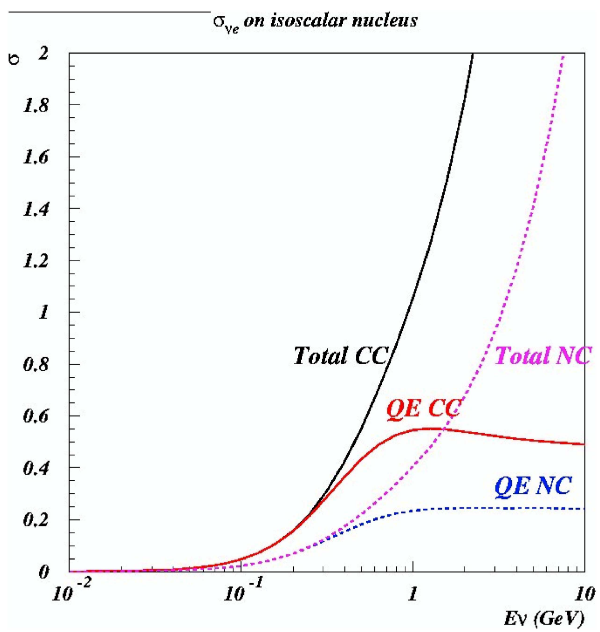
- PERHAPS NEUTRON DETECTION POSSIBLE THROUGH RECOIL AFTER DEUTERIUM BREAKUP (SNO)?



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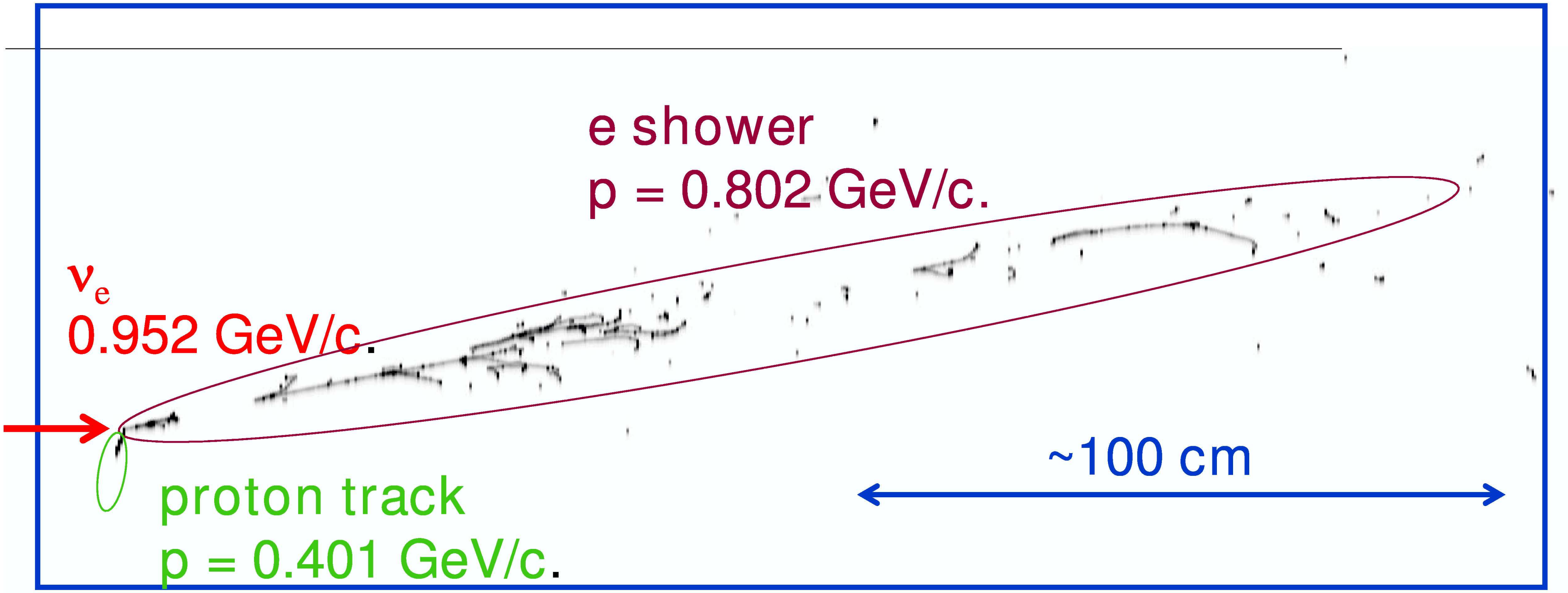
CC qe events for $E_\nu \lesssim 1.0$ GeV

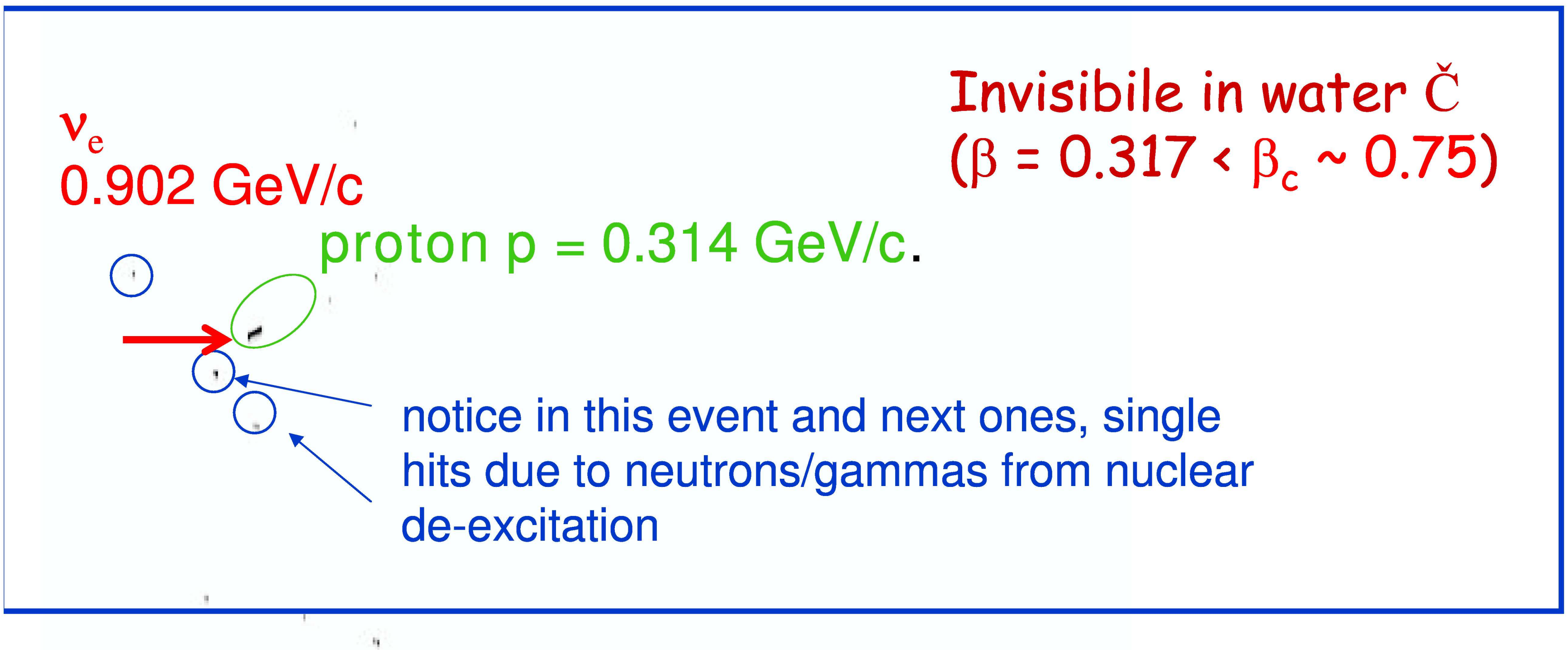


at this energy for ν_e:

$$\frac{\sigma_{NC}^{all}}{\sigma_{CC}^{all}} \sim 0.35 \qquad \frac{\sigma_{CC}^{qel}}{\sigma_{CC}^{all}} \sim 0.56 \qquad \frac{\sigma_{NC}^{qel}}{\sigma_{NC}^{all}} \sim 0.66$$

NC qe events for $E_\nu \lesssim 1.0$ GeV

~ 8 events out of 25 NC elastic events have a detectable/identifiable proton



$\sin^2\theta_W$ AT LOW ENERGY:

(TENTATIVE) QUANTITATIVE CONCLUSIONS

- MEASUREMENT WITH WATER ČERENKOV & PRESENT TECHNOLOGY NOT REALISTIC
- MEASUREMENT WITH PRESENT ICARUS TECHNOLOGY FEASIBLE

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- MEASUREMENT WITH PRESENT ICARUS TECHNOLOGY FEASIBLE
  - CUT $p_p \gtrsim 300$ MEV IMPLIES $Q^2 \gtrsim 0.1$ GEV^2
    $\Rightarrow$ LOSS OF 2/3 OF XSECT IN FIRST BIN, ABOUT 25% OF TOTAL
  - AT FAR DETECTOR, MEASUREMENT ONLY COMPETITIVE WITH LARGE VOLUME (5 MTON TO REACH 5×10^{-3} ACCURACY)
  - AT NEAR DETECTOR MEASUREMENT ALREADY COMPETITIVE WITH SMALL VOLUME (500 TON TO REACH 5×10^{-4} ACCURACY)

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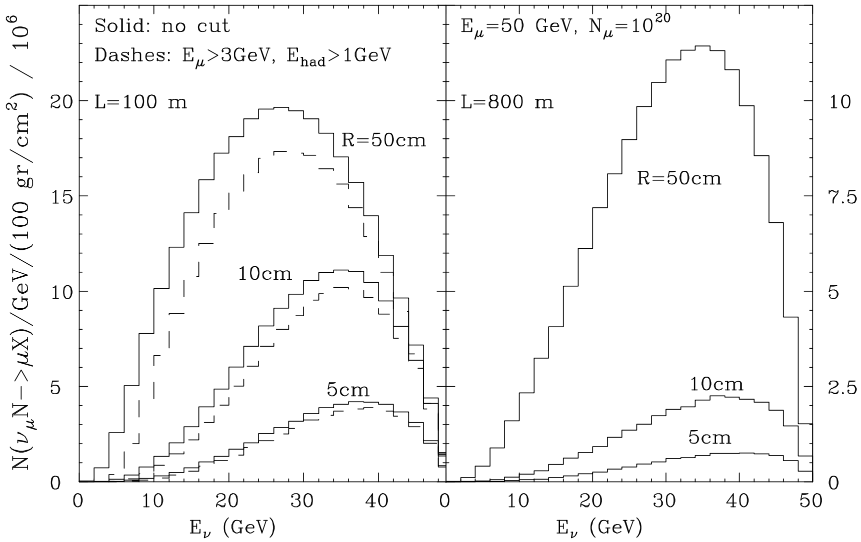
  - AT NEAR DETECTOR MEASUREMENT ALREADY COMPETITIVE WITH SMALL VOLUME (500 TON TO REACH 5×10^{-4} ACCURACY)
- SNO TECHNOLOGY MIGHT ENABLE LOW-ENERGY MEASUREMENT, MUST BE INVESTIGATED

STRONG INTERACTIONS

Flavour Separation at the Neutrino Factory



- Neutrino beam is wide band → can determine all F_i, g_i from $y = Q^2/(2xm_pE_\nu)$ dependence of (e.g.)

$$\frac{d^2\sigma^{\uparrow\lambda_\ell}}{dxdy} - \frac{d^2\sigma^{\downarrow\lambda_\ell}}{dxdy} = \frac{G_F^2}{8\pi(1+Q^2/m_W^2)^2}\frac{Q^2}{xy}\left[\lambda_\ell\, y(2-y)xg_1(x,Q^2) + (1-y)g_4(x,Q^2) + y^2 xg_5(x,Q\right.$$

- Can disentangle individual PDFs by linear combination: at LO

$$\tfrac{1}{2}\left(g_1^{W^-} - g_5^{W^-}\right) = \Delta u + \Delta c; \qquad \frac{1}{2}\left(g_1^{W^+} + g_5^{W^+}\right) = \Delta\bar{u} + \Delta\bar{c}$$

$$\tfrac{1}{2}\left(g_1^{W^+} - g_5^{W^+}\right) = \Delta d + \Delta s; \qquad \frac{1}{2}\left(g_1^{W^-} + g_5^{W^-}\right) = \Delta\bar{d} + \Delta\bar{s}$$

Δc, $\Delta\bar{c}$, Δs, $\Delta\bar{s}$ only present above charm threshold

STRUCTURE FUNCTIONS AT THE ν FACTORY:

UNPOLARIZED...

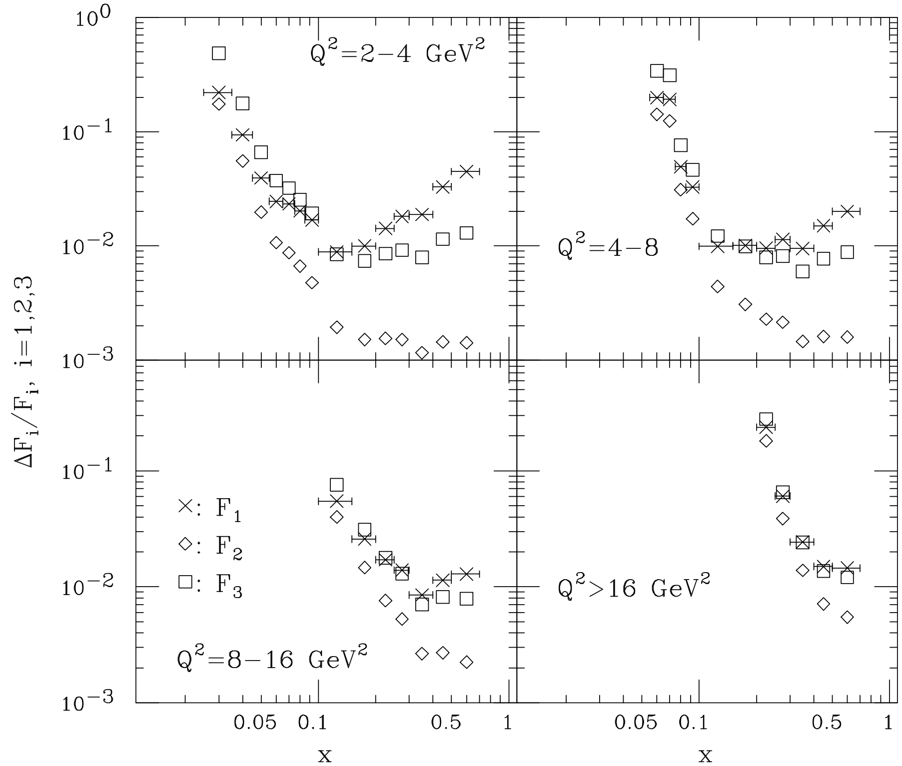
EVENT RATES
(DEFAULT BEAM AND DETECTOR)

x							
9.E−1	7.E+3	2.E+4	4.E+4	5.E+4	7.E+4	6.E+4	1.E+4
8.E−1	8.E+4	2.E+5	4.E+5	6.E+5	8.E+5	6.E+5	9.E+4
7.E−1	3.E+5	9.E+5	2.E+6	3.E+6	3.E+6	2.E+6	2.E+5
6.E−1	9.E+5	3.E+6	5.E+6	7.E+6	8.E+6	4.E+6	7.E+4
5.E−1	2.E+6	6.E+6	1.E+7	1.E+7	2.E+7	6.E+6	1.E+3
4.E−1	4.E+6	1.E+7	2.E+7	3.E+7	2.E+7	4.E+6	
3.E−1	7.E+6	2.E+7	3.E+7	4.E+7	2.E+7	6.E+5	
2.E−1	1.E+7	3.E+7	5.E+7	4.E+7	8.E+6		
1.E−1	1.E+7	3.E+7	3.E+7	1.E+7	3.E+4		
9.E−2	2.E+6	6.E+6	5.E+6	5.E+5			
8.E−2	3.E+6	6.E+6	4.E+6	2.E+5			
7.E−2	3.E+6	6.E+6	3.E+6	2.E+4			
6.E−2	3.E+6	5.E+6	2.E+6				
5.E−2	3.E+6	5.E+6	8.E+5				
4.E−2	3.E+6	4.E+6	2.E+5				
3.E−2	3.E+6	2.E+6					
2.E−2	2.E+6	2.E+5					
1.E−2	5.E+4						

Q^2 (GeV) axis: 0.5, 1, 5, 10, 50, 100

$N(\nu_\mu\ N \to \mu\ X)$/bin
E_μ=50 GeV, $N_\mu=10^{20}$
R=50cm Target=100 g/cm^2
L=100+30 meters

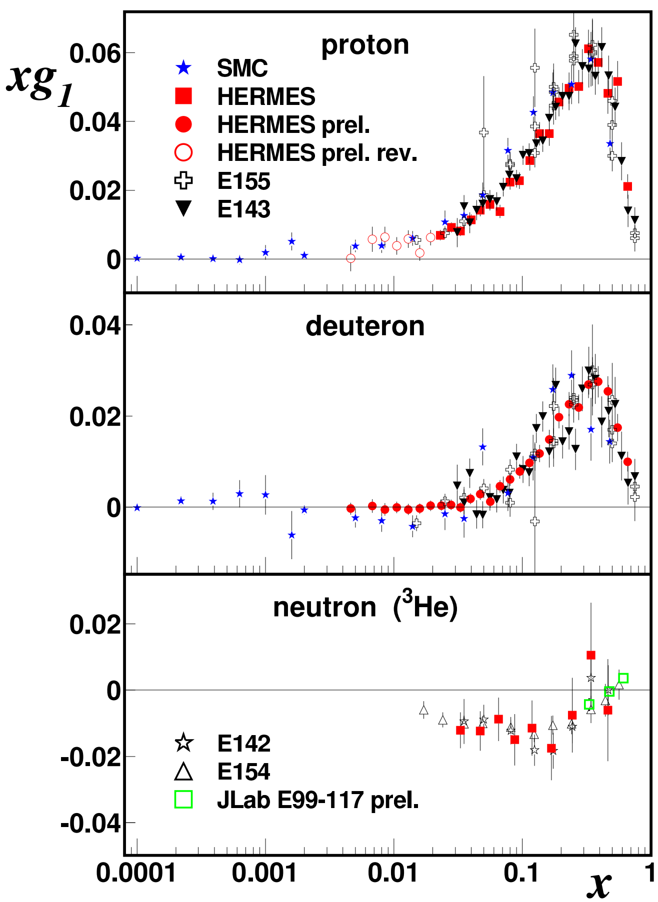
EXPECTED STAT. ERRORS



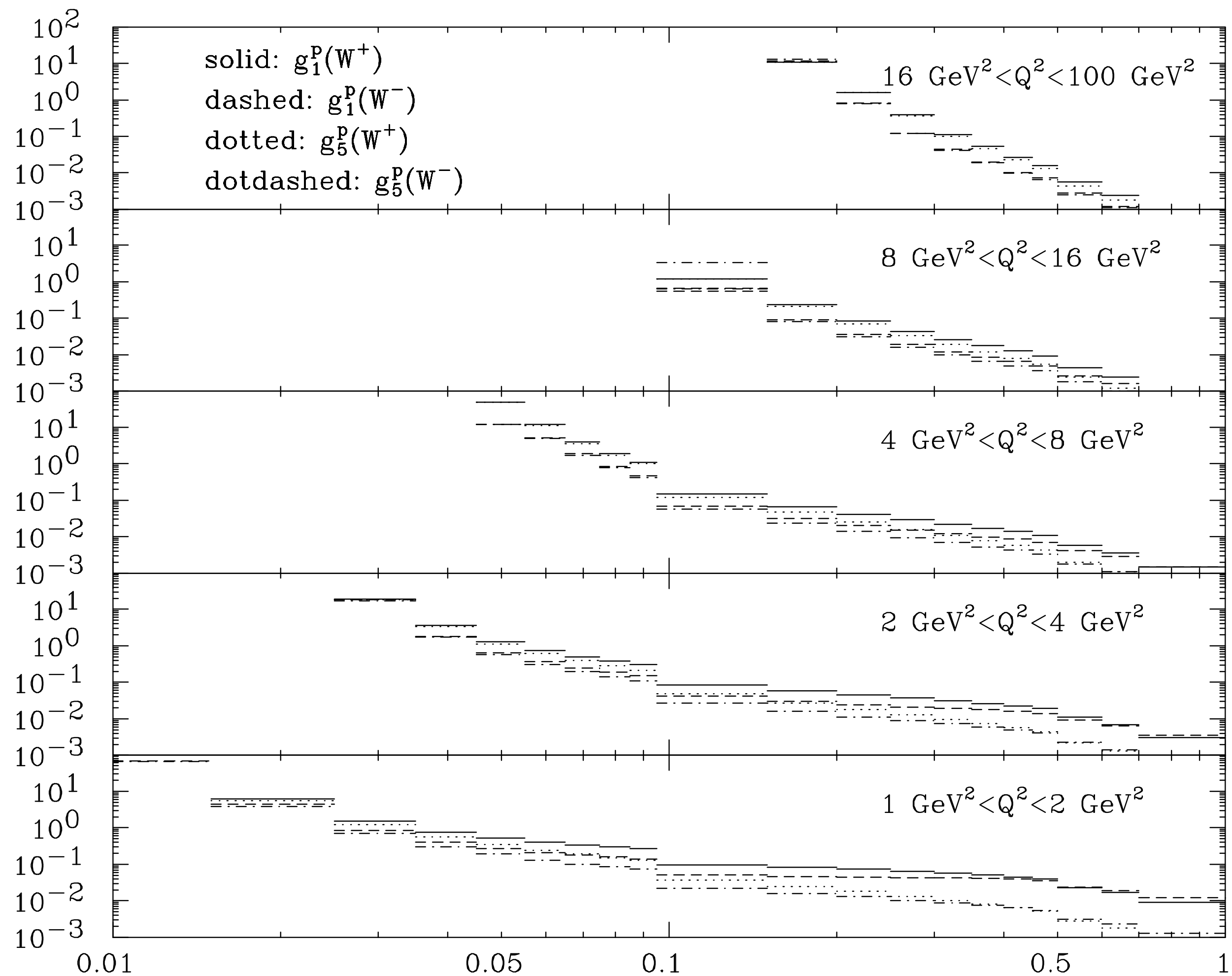
KINEMATIC COVERAGE AND ACCURACY RATHER BETTER THAN CURRENT CHARGED LEPTON EXPERIMENTS (E.G. NMC)

...AND POLARIZED

PRESENT



ABSOLUTE ν FACT ERRS.



STATISTICAL ACCURACY ABOUT ONE ORDER OF MAGNITUDE BETTER THAN CURRENT POLARIZED CHARGED-LEPTON EXPERIMENTS!

POLARIZED DIS AT A νFACT (S.F., M.L.Mangano, G.Ridolfi)

LIGHT FLAVOUR SEPARATION:

- PRESENT: TRIPLET $a_3 = 1.11 \pm 0.04$; NO INFO ON $\Delta q - \Delta \bar{q}$
- ν–FACT.: $a_3 = 1.107 \pm 0.006$; $\Delta(u - \bar{u}) = 0.764 \pm 0.006$; $\Delta(d - \bar{d}) = -0.320 \pm 0.008$

IS THE GLUON CONTRIBUTION “LARGE”? (w.r. to quark)
IS THE SCALE–INVARIANT QUARK “SMALL”? (w.r. to octet)

- PRESENT: GLUON: $\Delta g(1, 1\,\mathrm{GeV}^2) = 0.8 \pm 0.2$;
  SCALE–INV. QUARK $\Delta\Sigma(1) = 0.38 \pm 0.03$; OCTET $a_8 = 0.6 \pm 30\%$(?)
- ν–FACT.: “ANOMALY” $\Delta g = 0.9 \pm 0.1$; $\Delta\Sigma = 0.39 \pm 0.01$; $a_8 = 0.56 \pm 0.01$
  ‘INSTANTON” $\Delta g = 0.2 \pm 0.1$; $\Delta\Sigma = 0.32 \pm 0.01$; $a_8 = 0.57 \pm 0.01$

IS THE STRANGENESS “VALENCELIKE”?

- PRESENT: NO INFORMATION ON VALENCE–SEA SEPARATION
- ν–FACT.: ‘INSTANTON” $[\Delta s - \Delta \bar{s}]\,(1, 1\,\mathrm{GeV}^2) = -0.007 \pm 0.007$;
  ‘SKYRMION” $[\Delta s - \Delta \bar{s}]\,(1, 1\,\mathrm{GeV}^2) = -0.106 \pm 0.008$;

CAN EASILY TELL SCENARIOS FROM EACH OTHER BUT
ERROR ON SINGLET DRIVEN BY SYST ERROR ON GLUON:
ONLY OBSTACLE TO FULL SPIN STRUCTURE IS Δg!

THE PROTON SPIN STRUCTURE FROM LOW-ENERGY DATA

AXIAL CHARGES FROM ELASTIC ν-p SCATTERING

(Kaplan & Manohar, 1988):

$$\langle p'|j_5^s\mu|p\rangle = \bar{u}(p')\gamma^\mu\gamma_5 u(p) G_A^s(Q^2); \qquad G_A^s(0) = \Delta s$$

- CAN DETERMINE Δs FROM FORWARD STRANGE AXIAL FORM FACTOR
- DETERMINE FORM FACTOR AT SMALL Q^2 & EXTRAPOLATE TO $Q^2 = 0$
- CORRECTIONS FROM HIGHER DIMENSIONAL OPERATORS KNOWN & SMALL
- CAN EXTRACT G_A FROM UNPOLARIZED XSECT, BUT W. LARGE ERROR
  POLARIZED ELASTIC CASE WORTH INVESTIGATING

CONCLUSIONS

- NEUTRINO SCATTTERING EXPERIMENTS HAVE BEEN CRUCIAL IN ESTABLISHING THE STANDARD MODEL

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- AT PRESENT, THEY STRETCH THE BOUNDARIES OF THE STANDARD MODEL
- NEW PHYSICS IS BEHIND THE CORNER

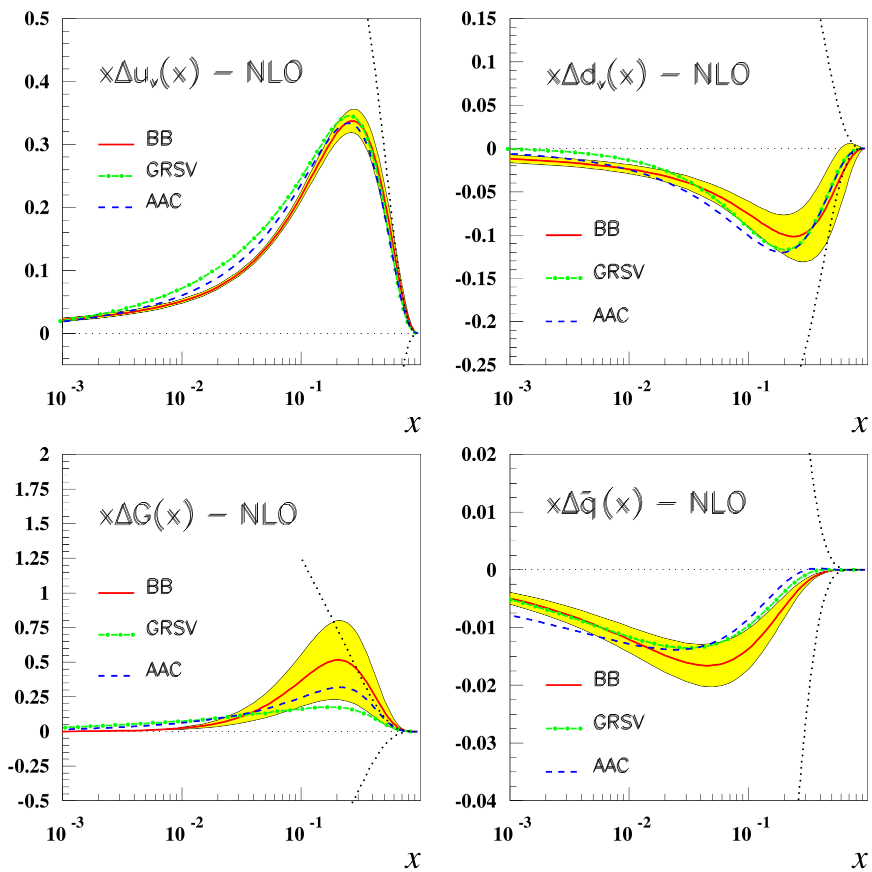
CAN MEASURE ACCURATELY SHAPE OF

LIGHT FLAVORS

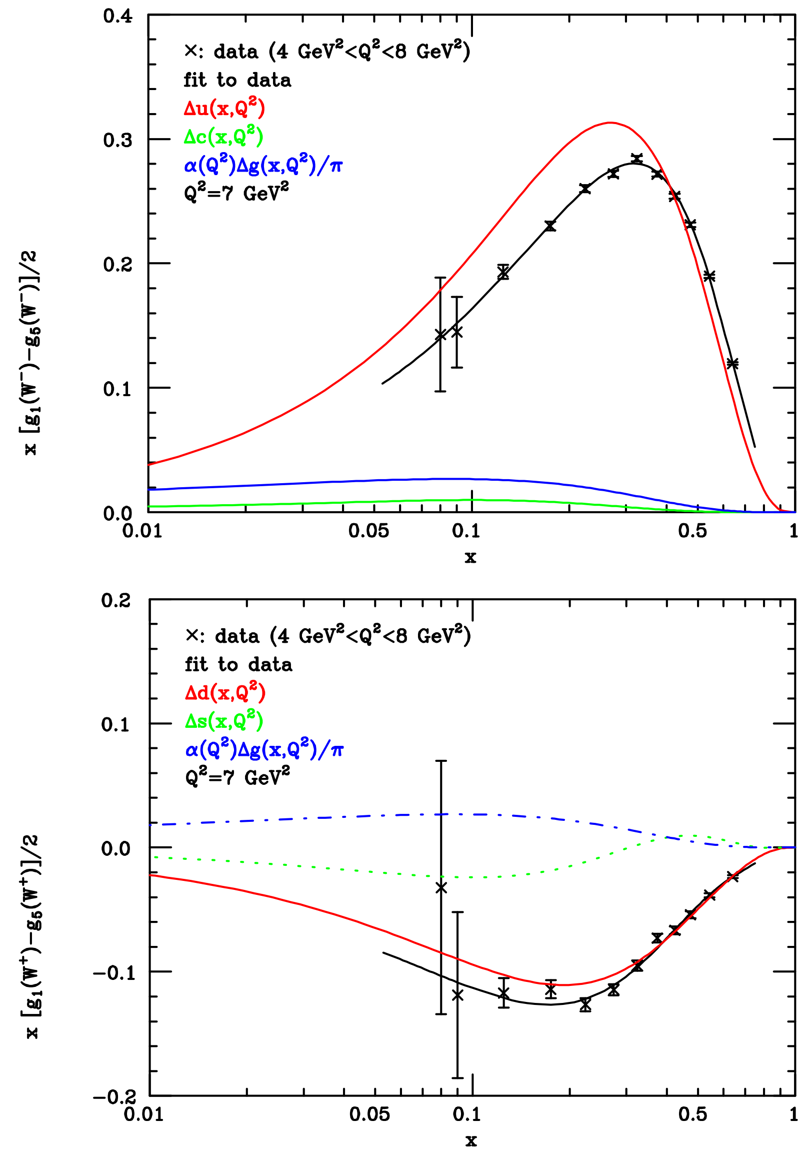
BUT NOT STRANGENESS OR CHARM

UNLESS THE GLUON IS KNOWN

(COMPASS, RHIC!)



BLÜMLEIN & BÖTTCHER, 2003



ν FACT PARTONS & DATA

$$g_1^{W^-} - g_5^{W^-} \sim \Delta u + \Delta c - \frac{\alpha_s}{4\pi}\Delta g$$

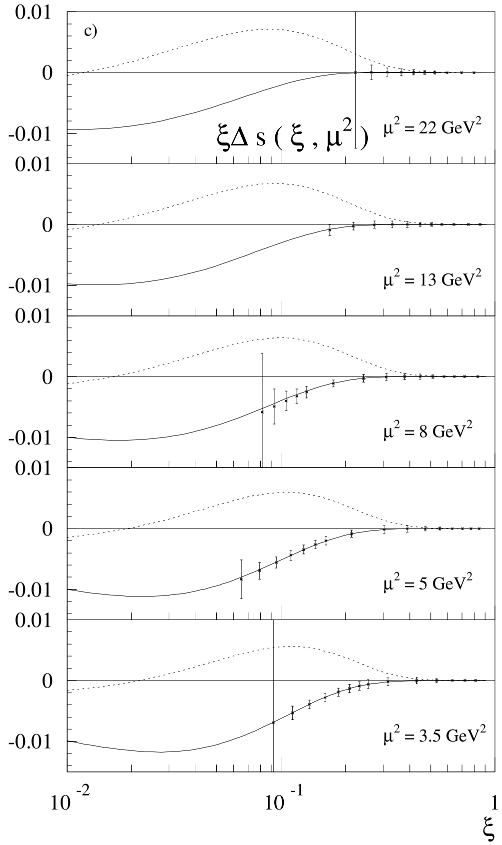
$$g_1^{W^+} - g_5^{W^+} \sim \Delta d + \Delta s - \frac{\alpha_s}{4\pi}\Delta g$$

- CHARM FACTORY PHYSICS: CHARM PRODUCED IN $W^+ + s \to c$
  easily tagged through dimuon signal, 2nd muon from subsequent c decay $\Rightarrow$ STRANGE QUARK

- Λ POLARIZATION IN THE CURRENT FRAGMENTATION REGION $\Rightarrow$ FRAGMENTATION FUNCTIONS

- ν–INDUCED EXCLUSIVE D_s PRODUCTION $\Rightarrow$ GENERALIZED PARTON DISTRIBUTIONS

AN EXAMPLE: POLARIZED STRANGENESS



Strange distn. at LO directly determined by tagged–charm structure function:

$$g_{1,c}^{W^+}(x, Q^2) = |V_{cs}|^2 \Delta s(\xi, \mu_c^2) + |V_{cd}|^2 \Delta d(\xi, \mu_c^2);$$

$\xi = x(1 + m_c^2/Q^2)$; $\mu_c^2 = Q^2 + m_c^2$

Statistical errors small; however large error induced by QCD corrns. due to uncertainty on gluon

EXCELLENT DETERMINATION OF SHAPE IF GLUON KNOWN (COMPASS, RHIC...)