POLARIZED STRUCTURE FUNCTIONS
AT A NEUTRINO FACTORY

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I.N.F.N. ROMA III

COMPASS WORKSHOP, TRIESTE, FEBRUARY 20, 2002

Q: WHAT IS A νFACT GOOD FOR?

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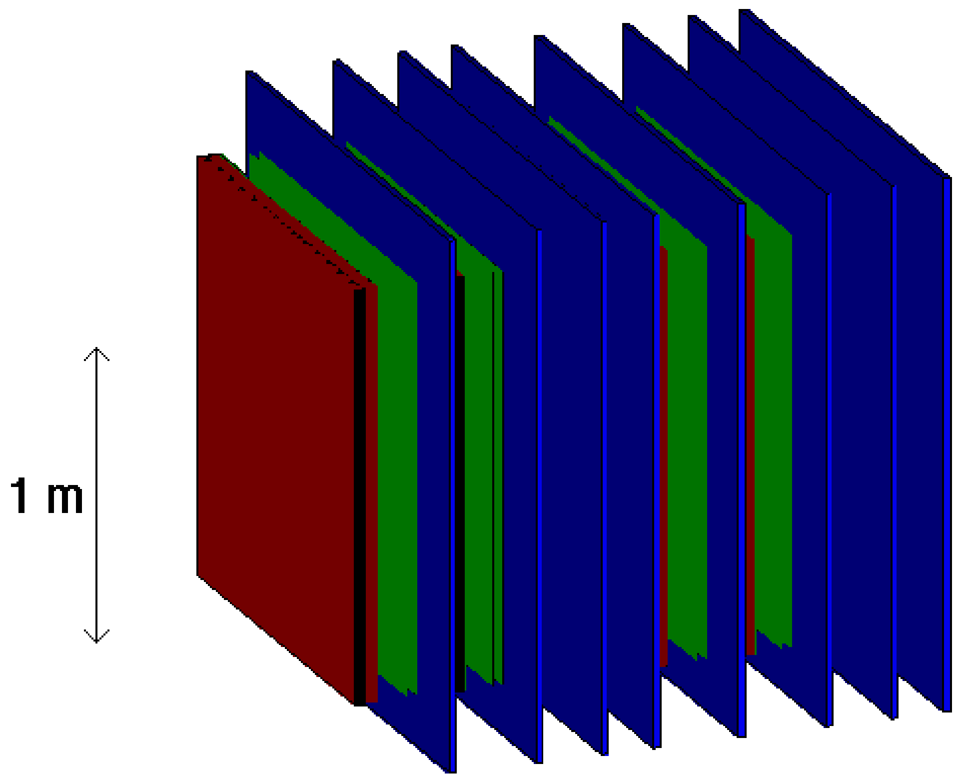
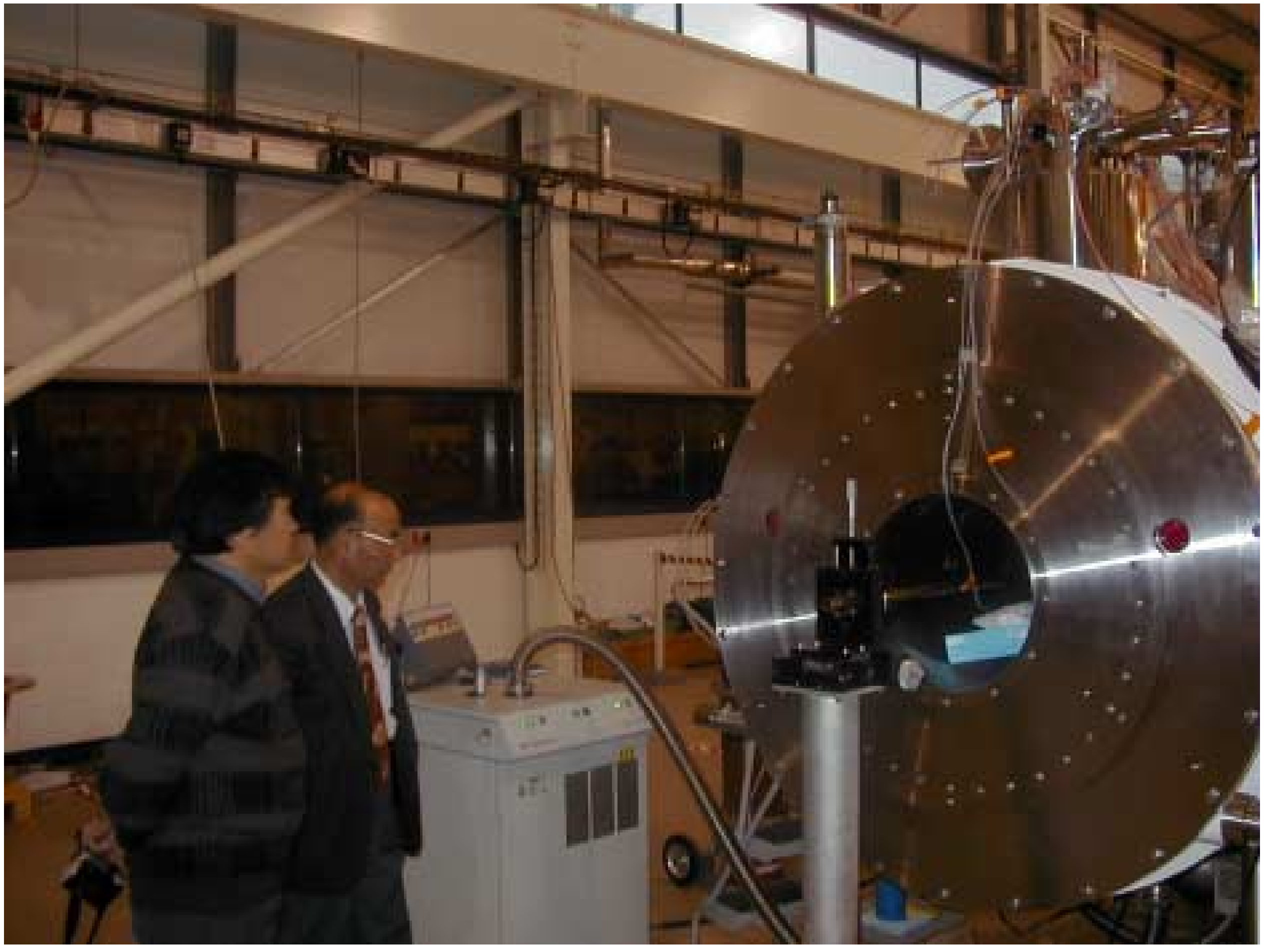
A: FOR FITTING THIS TARGET. . .



THE CHORUS TARGET

. . . INTO THIS MAGNET

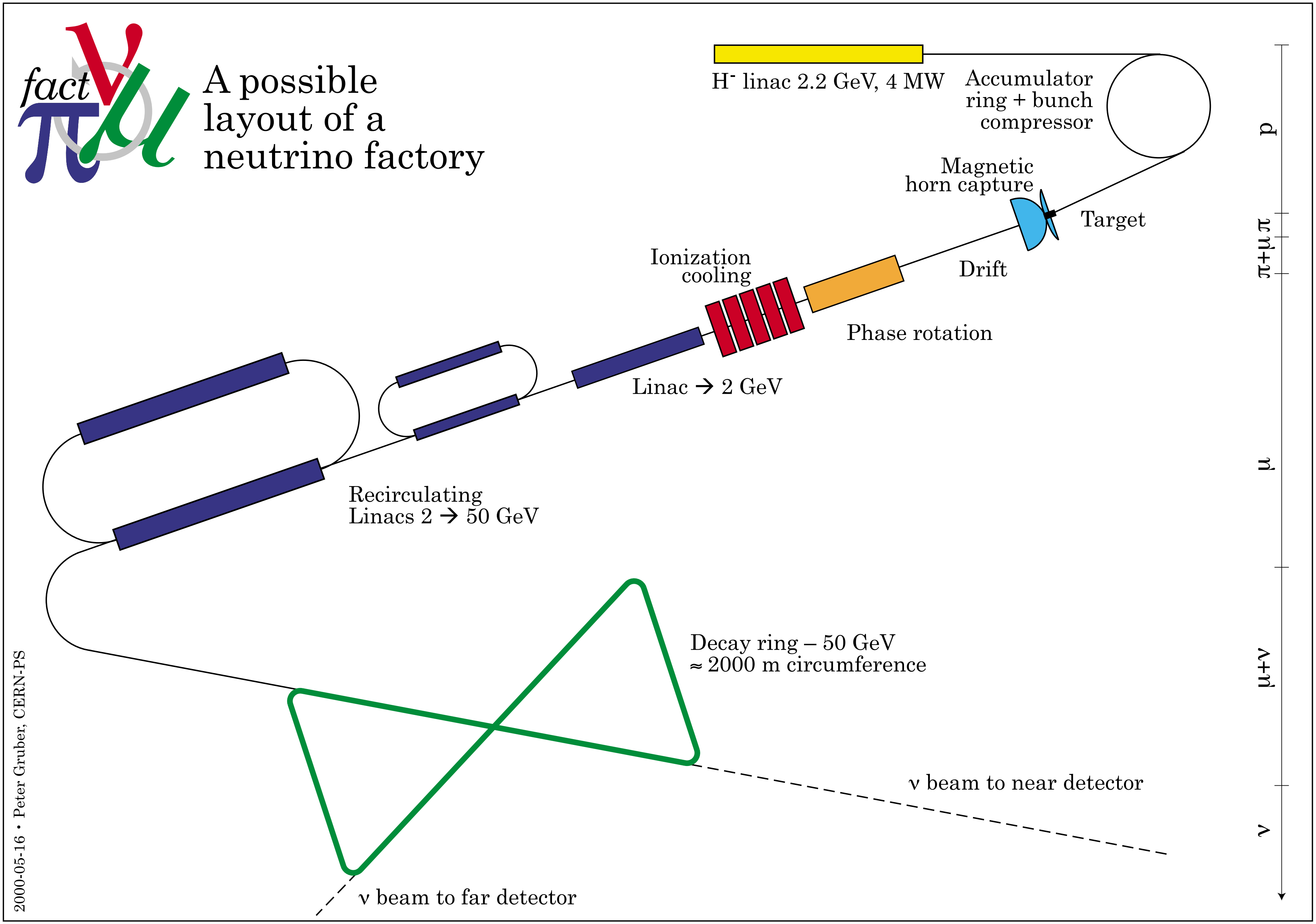


THE COMPASS TARGET MAGNET

THE CERN NEUTRINO FACTORY 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 RADIUS (ELASTIC)	$R = 20$ cm
PROTON TARGET EFF. DENSITY (UNPOL. TARGETS)	100 gr/cm^2
PROTON TARGET EFF. DENSITY (POL. TARGETS)	10 gr/cm^2

NUTEV, CHORUS: $\sim 10^6$ events; $E_\nu = 10 \div 200$ GeV CHORUS,
$E_\nu = 20 \div 400$ GeV NuTeV


fact
A possible
layout of a
neutrino factory
H⁻ linac 2.2 GeV, 4 MW
Accumulator
ring + bunch
compressor
Magnetic
horn capture
Target
Drift
Phase rotation
Ionization
cooling
Linac → 2 GeV
Recirculating
Linacs 2 → 50 GeV
Decay ring – 50 GeV
≈ 2000 m circumference
ν beam to near detector
ν beam to far detector
p
π
π+μ
μ
μ+ν
ν
2000-05-16 • Peter Gruber, CERN-PS

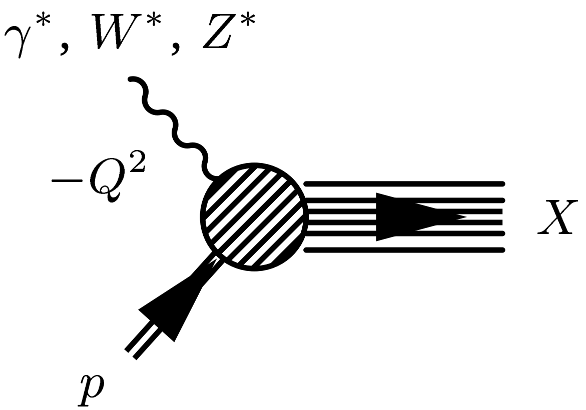
PHYSICS MOTIVATIONS

See M. L. Mangano et al. hep-ph/0105155; I. Bigi et al., hep-ph/0106177

- NEUTRINO OSCILLATIONS:
  - Observation of all three oscillations
  - Determination of θ_{13} & δm_{13}
  - CP violation in neutrino mixing
- PRECISION PHYSICS:
  - EW parameters ($\sin^2\theta_W$, CKM matrix elements, ...)
  - strong coupling constant (α_s)
  - parton distributions of the nucleon
- PROCESSES HITHERTO UNOBSERVED IN CC SECTOR:
  - polarized charged-current DIS: S.F., Mangano, Ridolfi, N.P. B602 (2001) 585
  - charm factory physics
  - ν–induced nuclear effects
- EXOTICA:
  - νe annihilation, neutrino structure functions
  - skewed parton distributions
  - new physics

D.I.S. with Parity Violation

Structure Functions...



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 $W^2 = Q^2\frac{1-x}{x}$;

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

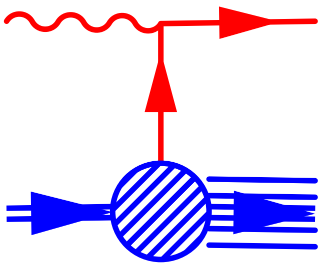
$$\left.\left. + y^2xF_1(x,Q^2)\right] - 2\lambda_p\left[-\lambda_\ell\, y(2-y)xg_1(x,Q^2) - (1-y)g_4(x,Q^2) - y^2xg_5(x,Q^2)\right]\right\}$$

$\lambda_l \rightarrow$ 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.



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

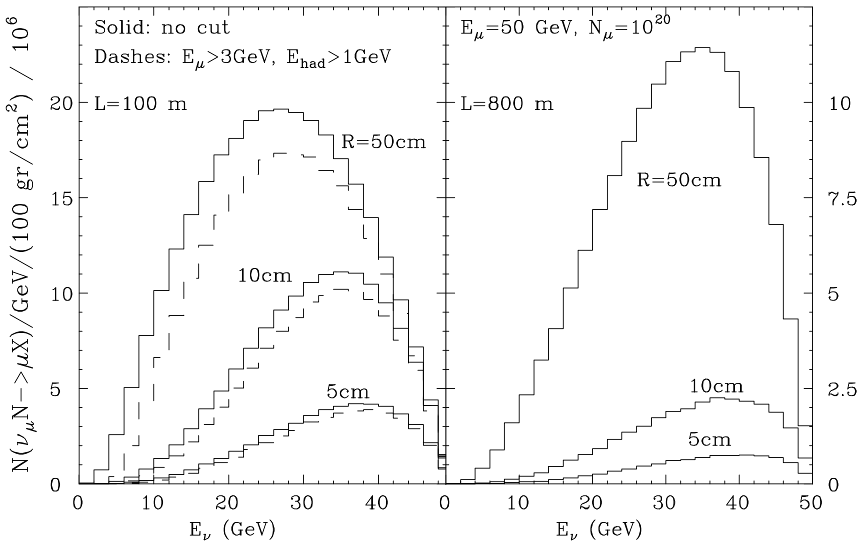
q_i quark, $\bar{q}_i$ antiquark, g gluon

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: $p \to n \Rightarrow u \leftrightarrow d$

Flavour Separation



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

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

- Can disentangle individual pdfs by linear combination: at LO

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

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

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

STRUCTURE FUNCTIONS AT THE ν FACTORY:

UNPOLARIZED...

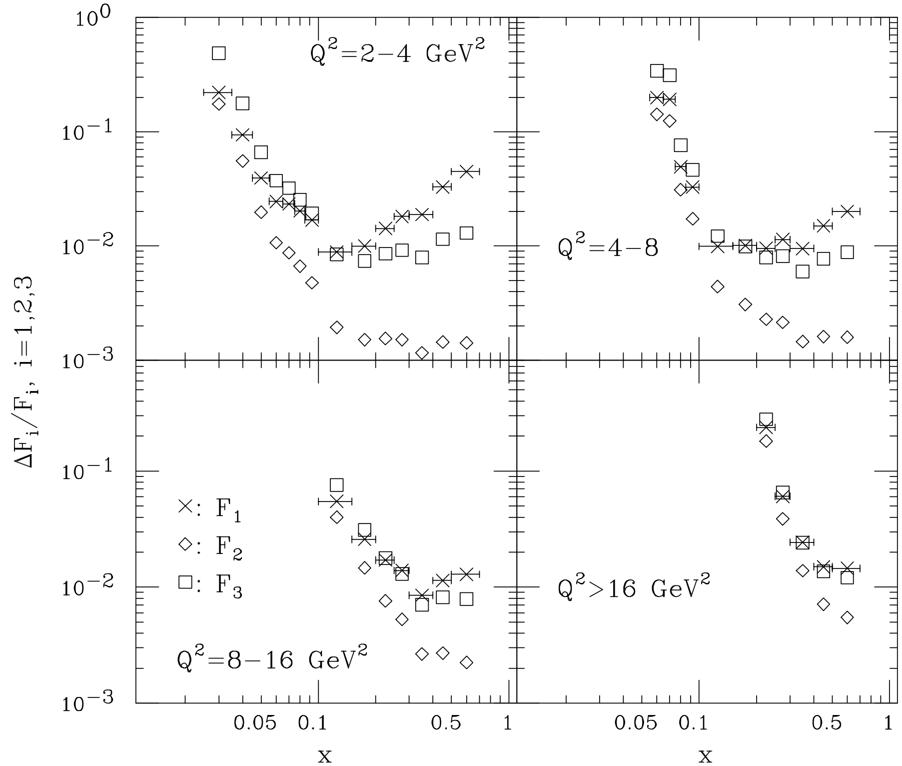
EVENT RATES (DEFAULT BEAM AND DETECTOR)

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

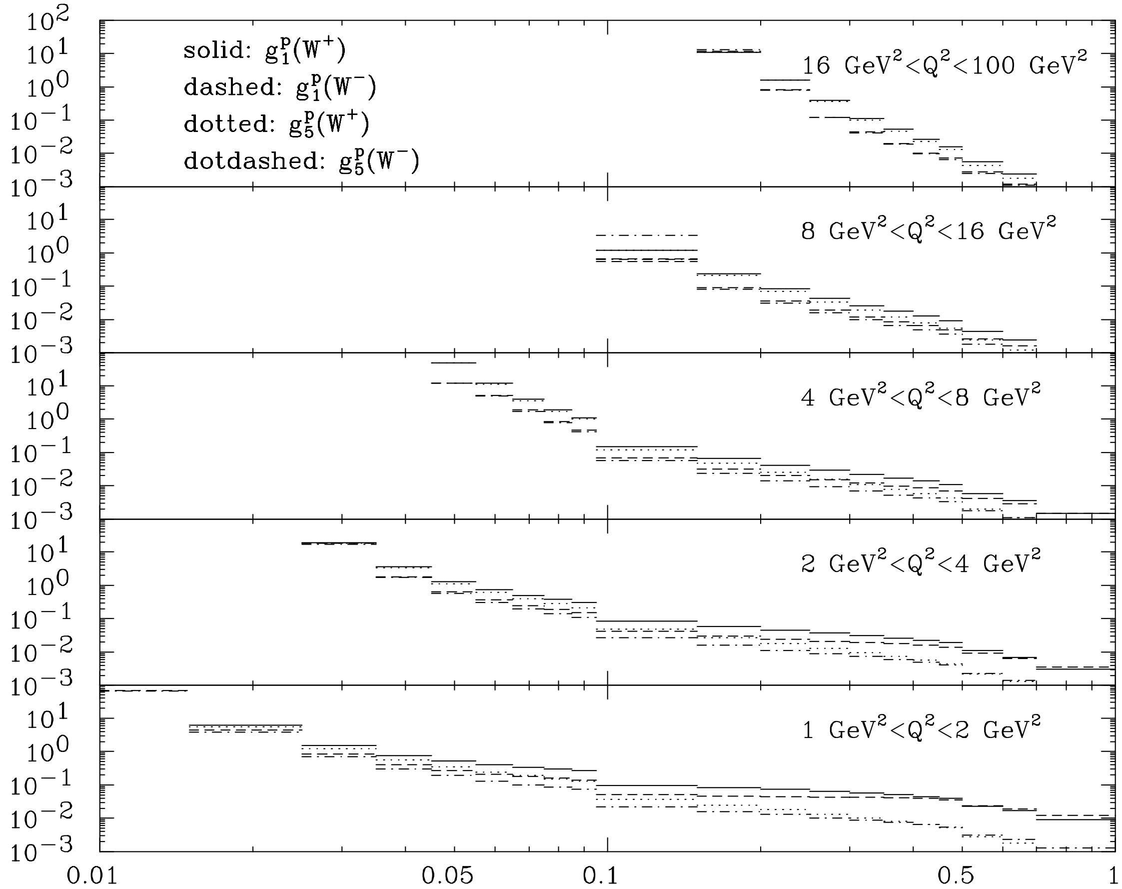
$N(\nu_\mu N \to \mu X)$/bin
E_μ=50 GeV, $N_\mu=10^{20}$
R=50cm Target=100 g/cm^2
L=100+30 meters

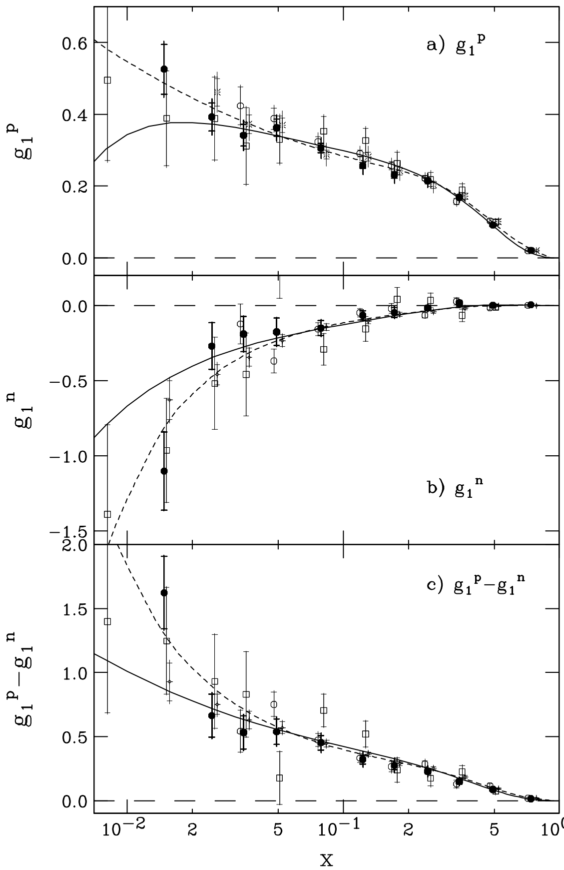
EXPECTED STAT. ERRORS



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

...AND POLARIZED



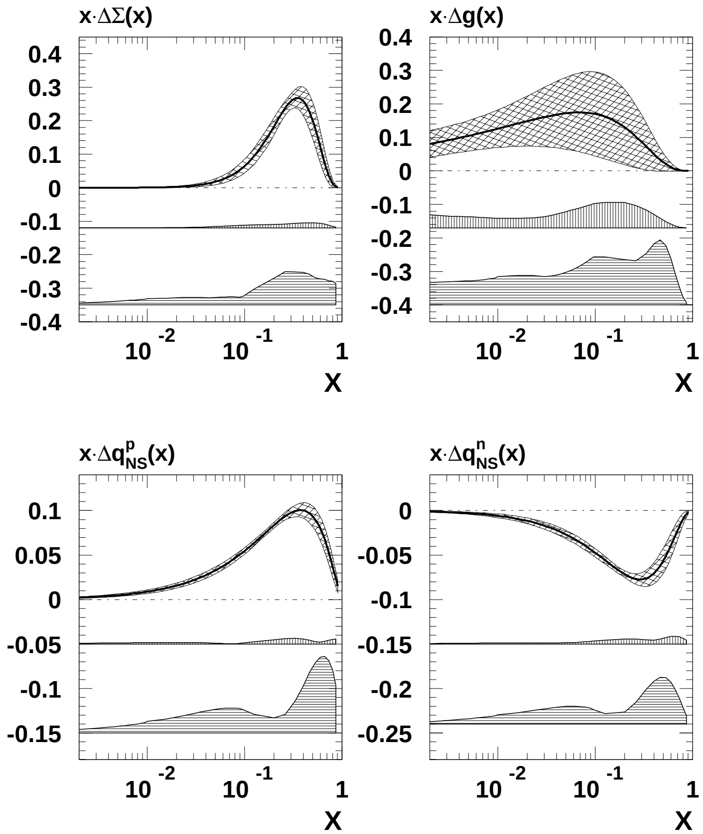


ABSOLUTE ν FACT ERRS.

SLAC E155 DATA (2000)

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

POLARIZED PARTON DISTRIBUTIONS:
WHAT DO WE KNOW?



WORLD DATA (SMC, 1999)

FIRST MOMENTS

- QUARK ISOTRIPLET: $\Delta q_3(1) = 1.11 \pm 0.04;$
- SCALE–INV. QUARK SINGLET: $\Delta\Sigma(1) = 0.38 \pm 0.03;$
- GLUON: $\Delta g(1, 1\,\mathrm{GeV}^2) = 0.8 \pm 0.2;$

[Altarelli, Ball, S.F., Ridolfi, 1998-2001]
stat. errors only; main syst: small x/shape

Note: quark SU(3) octet from β decays only; $\Delta q_8(1) = 0.6 \pm 0.2(?)$

- FIRST MOMENTS KNOWN BETTER THAN SHAPES: TRIPLET ACCURATE, QUARK SINGLET AVERAGE; GLUON SEMI-QUANTITATIVE
- SHAPES KNOWN VERY POORLY
- ONLY SINGLET/TRIPLET FLAVOUR SEPARATION POSSIBLE
- CANNOT DISENTANGLE QUARK FROM ANTIQUARK

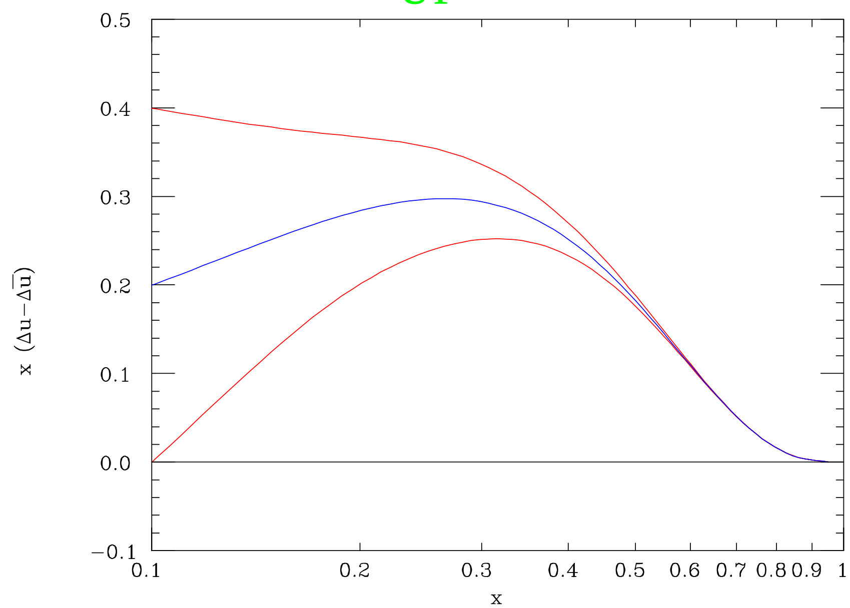
A THEORETICAL CONSTRAINT: POSITIVITY

POSITIVITY OF CROSS SECTION REQUIRES $|\Delta q \leq q$, $|\Delta \bar{q} \leq \bar{q}$
(up to small, computable NL correction [Altarelli, S.F., Ridolfi, 1998])

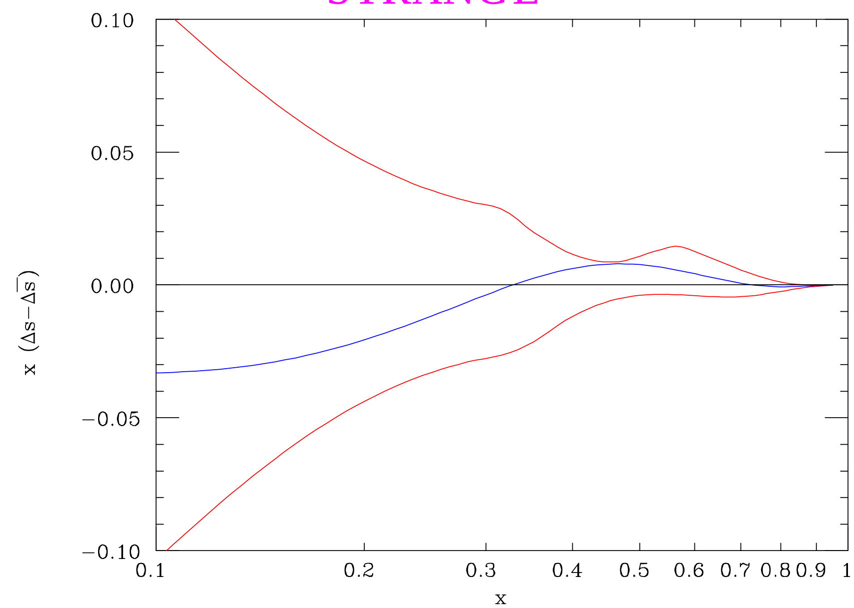
BOUNDS ON $\Delta q - \Delta \bar{q}$

BLUE: $\Delta q - \Delta \bar{q} = \Delta q$ RED: POSITIVITY BOUND ON $\Delta q - \Delta \bar{q}$

UP



STRANGE



unpolarized pdfs: CTEQ5+Barone et al. (strange); polarized pdfs: ABFR

- UP, DOWN: ANTIQUARK << QUARK $(\Delta \bar{u} \approx \Delta \bar{d} \approx 0)$
- STRANGE: ANTIQUARK CAN BE LARGE OR SMALL
  ($\Delta \bar{s} \approx \Delta s$ or$\Delta \bar{s} \approx 0$ both allowed)

The Spin Puzzle

Axial Charges (for flavor i): $\langle N;\, p, s | J^{\mu}_{5,\, i} | N;\, p, s \rangle = a_i M_N s^{\mu}$

Singlet Axial Charge $\Rightarrow$ Quark Spin Fraction (??)

$$a_0 \equiv \sum_{i=1}^{n_f} a_i = \int_0^1 dx \sum_{i=1}^{n_f} (\Delta q_i + \Delta \bar{q}_i) + O(\alpha_s)$$

EXPECT $a_0 \approx a_8 \equiv \Delta u + \Delta d - 2\Delta s$ (Zweig Rule $\rightarrow$ Ellis-Jaffe Sum Rule)

GET $a_0 = 0.10^{+0.17}_{-0.11}$ $(Q^2 = \infty)$ vs. $a_8 = 0.58 \pm 0.03$ [$\pm 30\%$ SU(3) violn. (?)]

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SCENARIOS

Define a scale-independent quark (by choice of facn. scheme):

$$a_0 = \int_0^1 dx \sum_{i=1}^{n_f} (\Delta q_i + \Delta \bar{q}_i) - \frac{\alpha_s}{2\pi} \int_0^1 dx\, \Delta g$$

- ANOMALY: $\frac{\alpha_s}{2\pi} \int_0^1 dx\, \Delta g \approx a_0 - a_8$,
  ZWEIG RULE RESPECTED BY SCALE–INVARIANT QUARK FIRST MOMENT
- INSTANTON: $\frac{\alpha_s}{2\pi} \int_0^1 dx\, \Delta g \ll a_8$, SCALE–INVARIANT QUARK $\approx a_0 \approx 0$
  effect can be induced by QCD vacuum on sea quarks (instantons)
- SKYRMION: $\Delta u_v + \Delta d_v = -\Delta s_v$, SMALL POLARIZATION OF VALENCE QUARKS
  hence unrelated to glue, happens in Skyrme or chiral models

What would we like to know?

Is the gluon contribution "large"? (w.r. to quark)
If not, refute the anomaly scenario
Is the scale–invariant quark "small"? (w.r. to octet)
If not, refute the instanton scenario

Is the strangeness "valencelike"?
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What would we learn at a νfact ?

- assume the validity of a scenario & fit to current data
- generate pseudo-data with realistic errors and binning for a nufact
- refit to current + pseudodata

What we would learn:

Light flavour separation:

- Present: triplet $a_3 = 1.11 \pm 0.04$; no info on $\Delta q - \Delta \bar{q}$
- ν–fact.: $a_3 = 1.107 \pm 0.006$; $\Delta(u - \bar{u}) = 0.764 \pm 0.006$; $\Delta(d - \bar{d}) = -0.320 \pm 0.008$

WHAT WE WOULD LEARN:

LIGHT FLAVOUR SEPARATION:

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IF NOT, REFUTE THE ANOMALY SCENARIO
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- ν–FACT.: "ANOMALY" $\Delta g = 0.9 \pm 0.1$; $\Delta\Sigma = 0.39 \pm 0.01$; $a_8 = 0.56 \pm 0.01$
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IS THE STRANGENESS "VALENCELIKE"?
IF NOT, REFUTE THE SKYRMION SCENARIO

- 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" $[\Delta s - \Delta\bar{s}]\,(1, 1\,\mathrm{GeV}^2) = -0.106 \pm 0.008$;

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

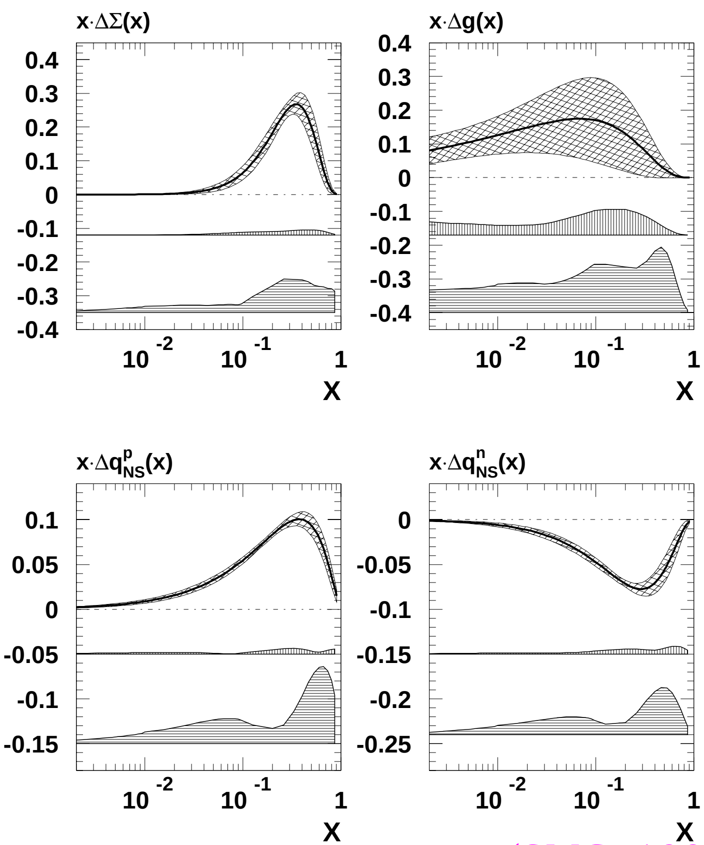
. . . What About Shapes?

Can measure accurately shape of light flavors

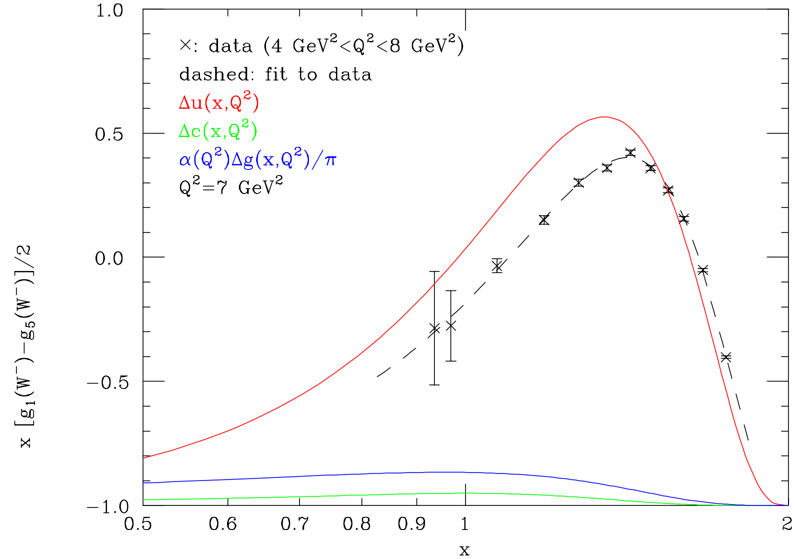
but not strangeness or charm

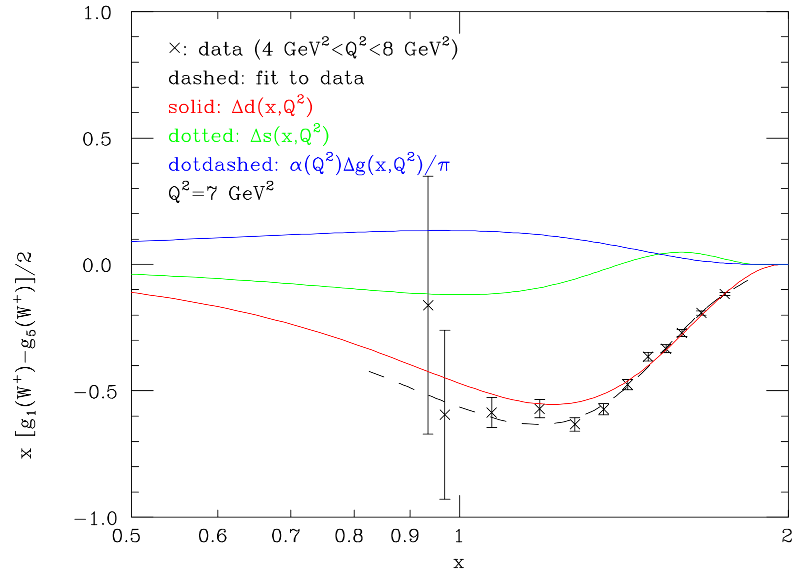
unless the gluon is known

(COMPASS, RHIC!)



world data (SMC, 1999)





ν fact partons & data

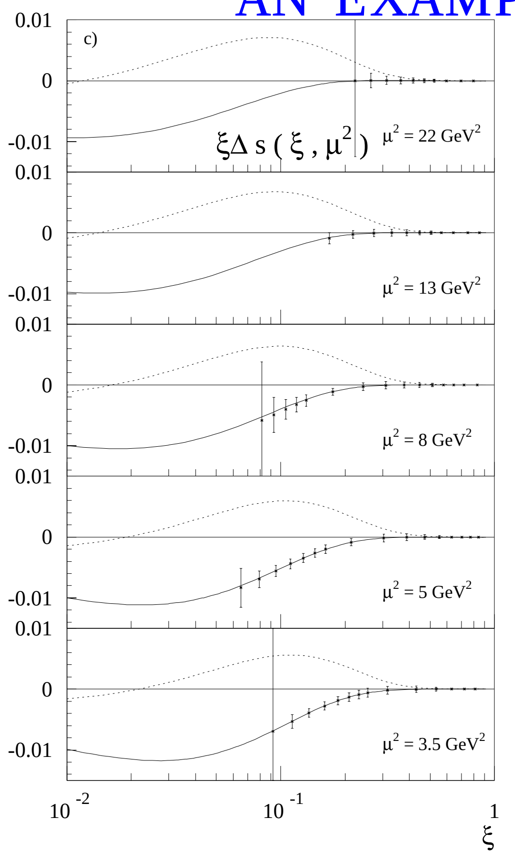
$$g_1^{W^-} - g_5^{W^-} \sim \Delta u + \Delta c - \frac{\alpha_s}{4\pi}\Delta g$$

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

More...

- CHARM FACTORY PHYSICS: CHARM PRODUCED IN $W^+ + s \to c$ easily tagged through dimuon signal, 2nd muon from subsequent c decay (Gehrmann) $\Rightarrow$ STRANGE QUARK
- Λ POLARIZATION IN THE CURRENT FRAGMENTATION REGION $\Rightarrow$ FRAGMENTATION FUNCTIONS (Anselmino et al.)
- ν–INDUCED EXCLUSIVE D_s PRODUCTION $\Rightarrow$ GENERALIZED PARTON DISTRIBUTIONS (Lehmann–Dronke and Schäfer)

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...)

CONCLUSIONS

- FULL FLAVOUR, ANTIFLAVOUR SEPARATION IS POSSIBLE
  PROVIDED THE GLUON DISTRIBUTION IS KNOWN
- NO OTHER EXPERIMENT CAN FULLY DISENTANGLE THE
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15 YEARS DOWN THE ROAD!