Neutrino nucleon and neutrino nucleus elastic scattering

Y. Miyachi, Yamagata University

Contents

- Neutrino-nucleon or Neutrino-nucleus ?
  - Connection to **spin structure of the proton**
- Spin structure of the proton
  - Role of strange quark spin, Δs
  - Form factors, axial charge and strangeness

What we learned from DIS.

- Experimental results
  - E734, SciBooNE*, MiniBooNE, T2K*
- Feasibility study done at pre-T2K era (~2007).
- Summary in 2007 and now

Proton spin problem and Δs

Polarized DIS: $\vec{\mu} + \vec{N} \rightarrow \mu' + X$

Inclusive measurement

$d\sigma(x, Q^2)$

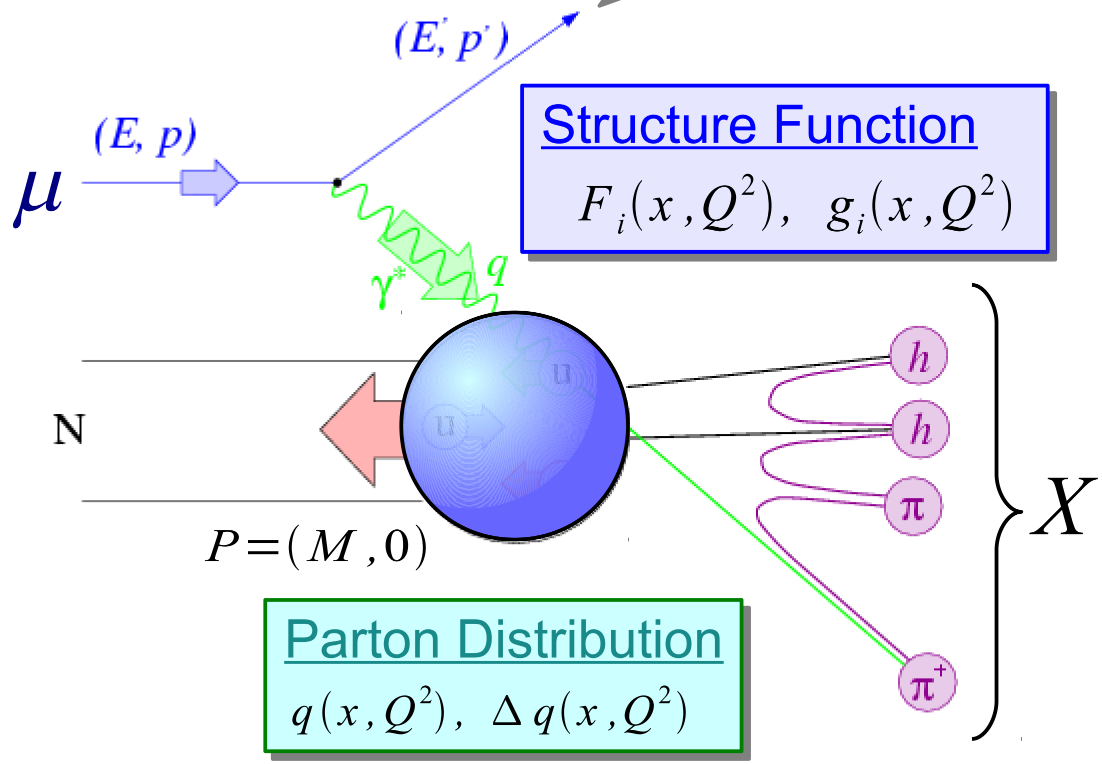
Double spin asymmetry

$$A_1 \sim \frac{g_1}{F_1}$$

From unpol. DIS

$$g_1 \sim A_1 F_1$$

$$= \frac{1}{2} \sum_q e_q^2 \Delta q(x)$$



$$\int dx\, g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q$$

Proton spin problem and Δs

$$\int dx\, g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q$$

Δq includes anti-q $= \Delta q + \Delta \bar{q}$

$$= \frac{1}{2}\left\{\left(\frac{2}{3}\right)^2 \Delta u + \left(\frac{1}{3}\right)^2 \Delta d + \left(\frac{1}{3}\right)^2 \Delta s\right\}$$

$$= \frac{1}{9} a_0 + \frac{1}{12} a_3 + \frac{1}{36} a_8$$

Proton spin budget

$$\frac{1}{2} = \frac{1}{2} a_0 + \Delta G + L$$

$$a_0 = \Delta u + \Delta d + \Delta s \quad = ?.??$$

polDIS

$$a_3 = \Delta u - \Delta d \quad = 1.26$$

β-decay

$$a_8 = \Delta u + \Delta d - 2\Delta s \quad = 0.86$$

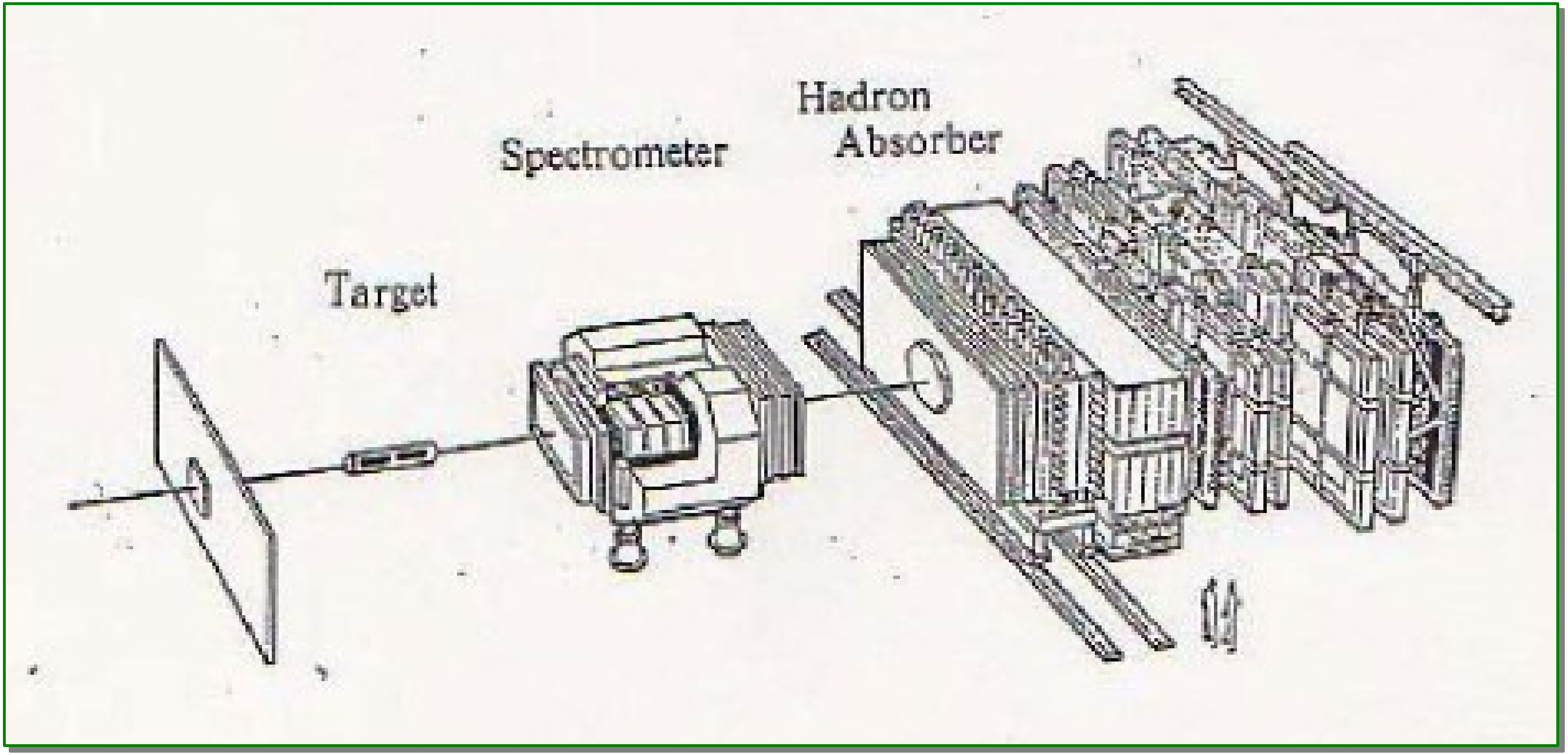
hyperon-decay

Δu

Δd

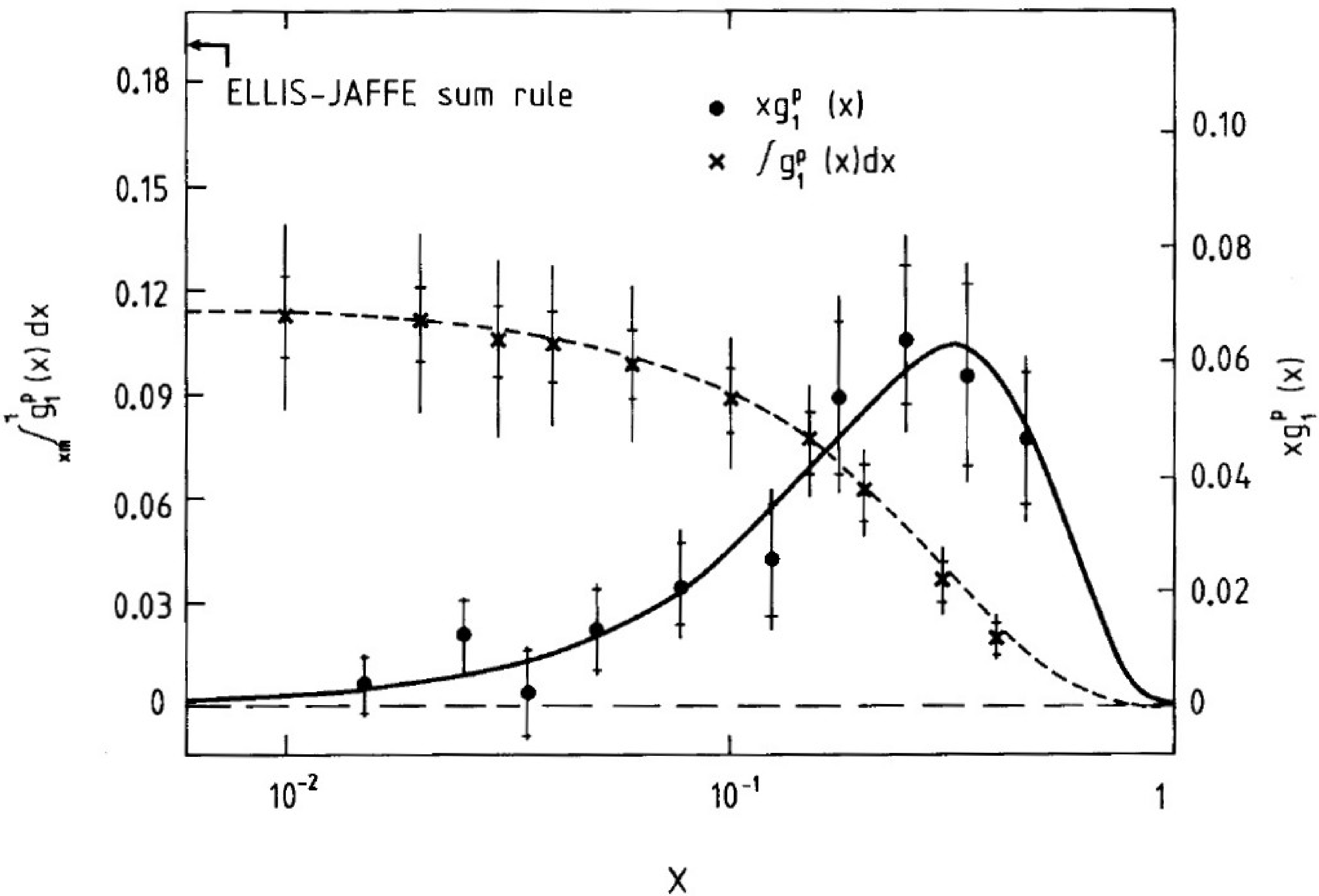
Δs

CERN-EMC experiment



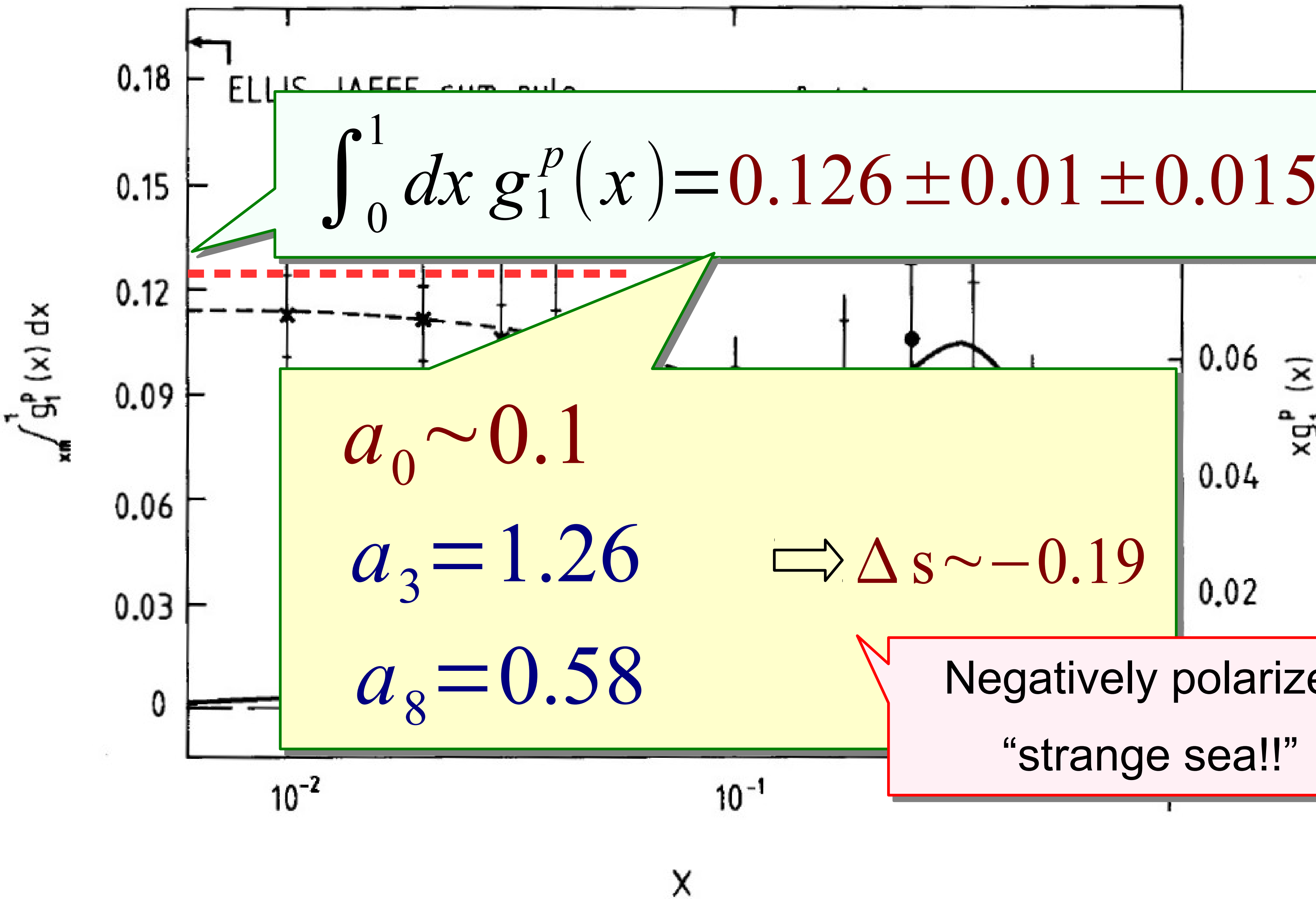
Proton spin problem and Δs - EMC results -

Nucl. Phys. B328 (1989) 1, Phys. Lett. B206 (1988) 364



Proton spin problem and Δs - EMC results -

Nucl. Phys. B328 (1989) 1, Phys. Lett. B206 (1988) 364



$$\int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.01 \pm 0.015$$

$$a_0 \sim 0.1$$

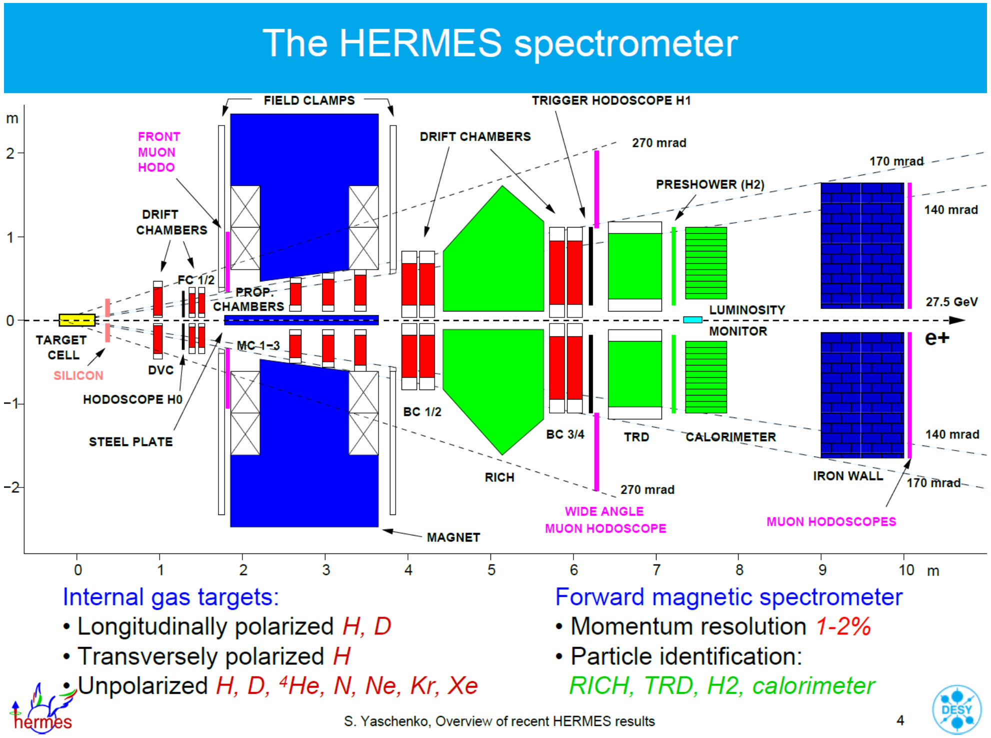
$$a_3 = 1.26 \qquad \Rightarrow \Delta s \sim -0.19$$

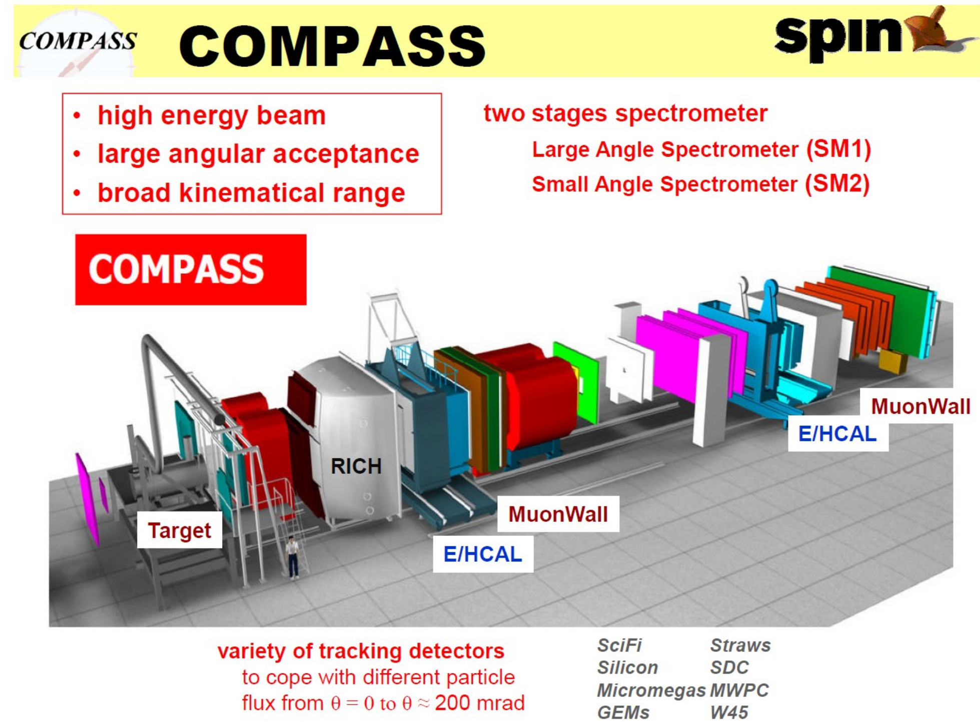
$$a_8 = 0.58$$

Negatively polarized

"strange sea!!"

Polarized DIS experiment





Beam 26.7 GeV pol. electron/positron

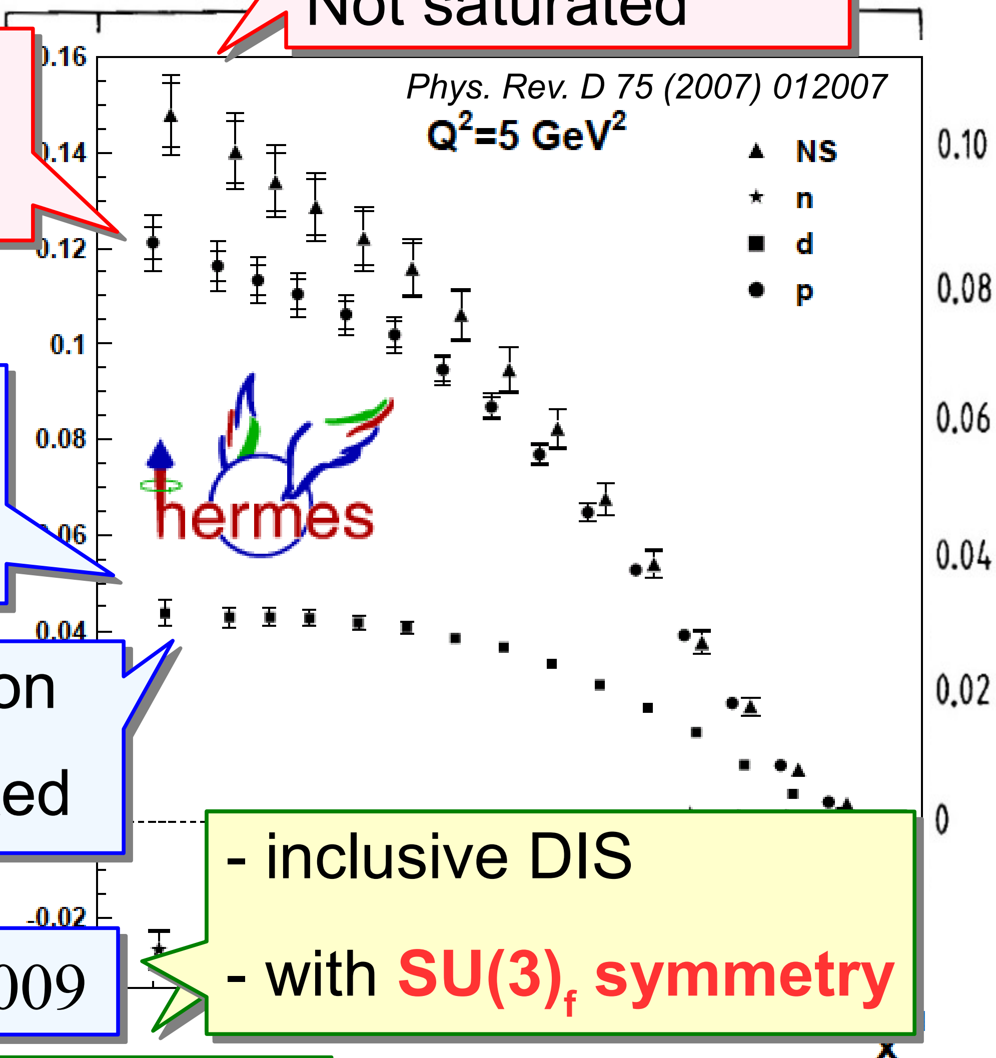
Target
1996-1997 Long. H
1998-2000 Long. D
2002-2005 Trans. H
2006-2007 unpol. H

Beam 160 GeV pol. muon

Target
2002 - 2006 Long. + Trans. ^{6}LiD.
2007 Long. + Trans. NH_3
2010 Trans. NH_3
2011 Long. NH_3

+ JLab experiments

Updated results on g_1 and Δs



$NS \propto a_3 = \Delta u - \Delta d$

Not saturated

Proton

Not saturated

$$\int_{0.021}^{0.9} g_1^d(x)\,dx = 0.0436 \pm 0.0012 \pm 0.018 \pm 0.0008 \pm 0.0026$$

Deuteron

Saturated

- inclusive DIS
- with **SU(3)$_f$ symmetry**

hermes $\Delta s = -0.085 \pm 0.013 \pm 0.008 \pm 0.009$

COMPASS $\Delta s = -0.08 \pm 0.01 \pm 0.02$ *Phys. Lett. B 647 (2007) 8*

- from global QCD analysis

We now know Δs with its uncertainty **$\delta(\Delta s) \sim 0.02$**

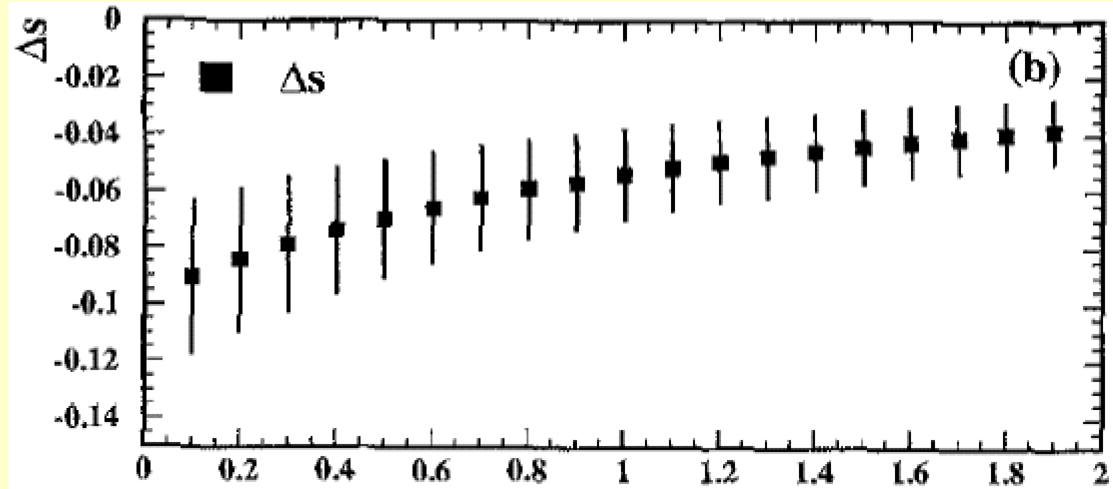
SU(3)$_f$ violation and impact on Δs

E. Leader et. al.,

Phys. Lett. B488 (2000) 283

a_8	$-(\Delta s + \Delta\bar{s})$
0.40	0.02 ± 0.01
3F − D	0.06 ± 0.01
0.86	0.15 ± 0.02

J. Lichtenstadt and H. J. Lipkin, Phys. Lett. B353 (1995) 119



SU(3): symmetric ↔ violated

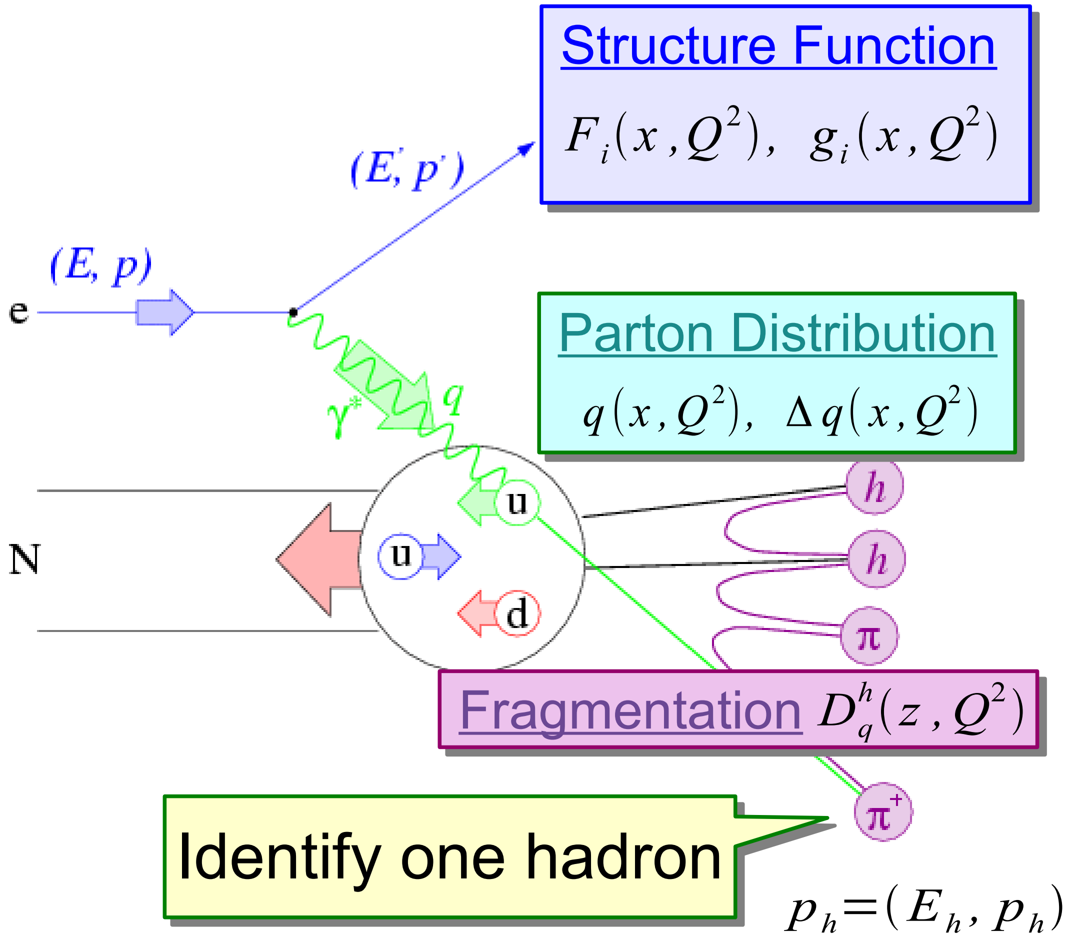
<u>χQM calculation: *(X. Song et. al, Phys. Rev. D55 (1997) 2624-2629)*</u>

SU(3) symmetry: Δs = -0.1

SU(3) breaking: Δs = -0.05

Possible large contribution from SU(3)$_f$ breaking ⇔ **δ(Δs) ~ 0.02**

Flavor tagging in DIS $\vec{l}+\vec{N}\rightarrow l'+h+X$



Flavor Tagging:

Hadron carries information on

quark flavor

through fragmentation function

$$\frac{d^3\Delta\sigma^h}{dx\,dz\,dQ^2}\propto\sum_i e_q^2\,\Delta q(x,Q^2)\,D_q^h(z,Q^2)$$

$$z=\frac{P\cdot p_h}{P\cdot q}=\frac{E_h}{\nu}$$

Δs determination with SIDIS data

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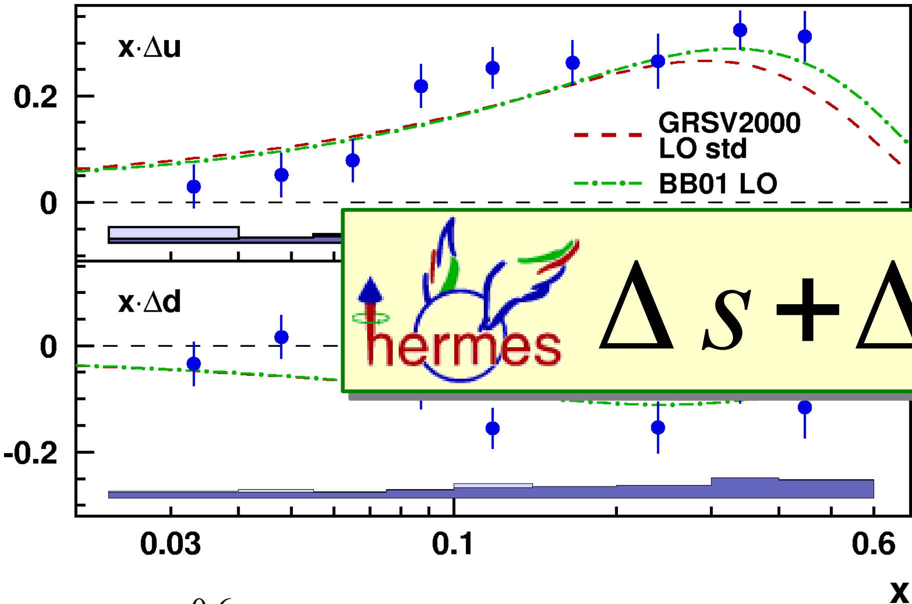
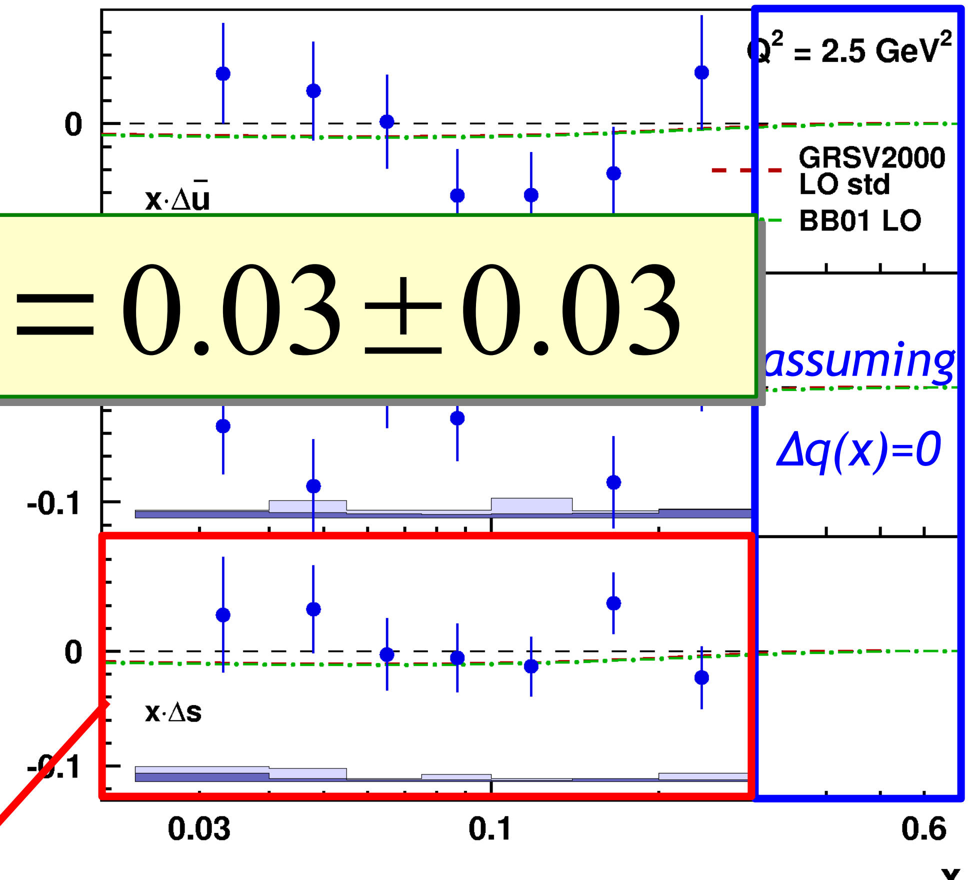
Phys. Rev D 71 (2005) 012003

$\Delta\bar{s}(x)=0$ assumed





$$\Delta s+\Delta\bar{s}=0.03\pm 0.03$$

$$\Delta q=\int_{0.023}^{0.6} dx\,\Delta q(x) \qquad Q^2=2.5\,GeV^2$$

$$\Delta u=0.601\pm 0.039\pm 0.049$$

$$\Delta d=-.226\pm 0.039\pm 0.050$$

$$\Delta\bar{u}=-.002\pm 0.036\pm 0.023$$

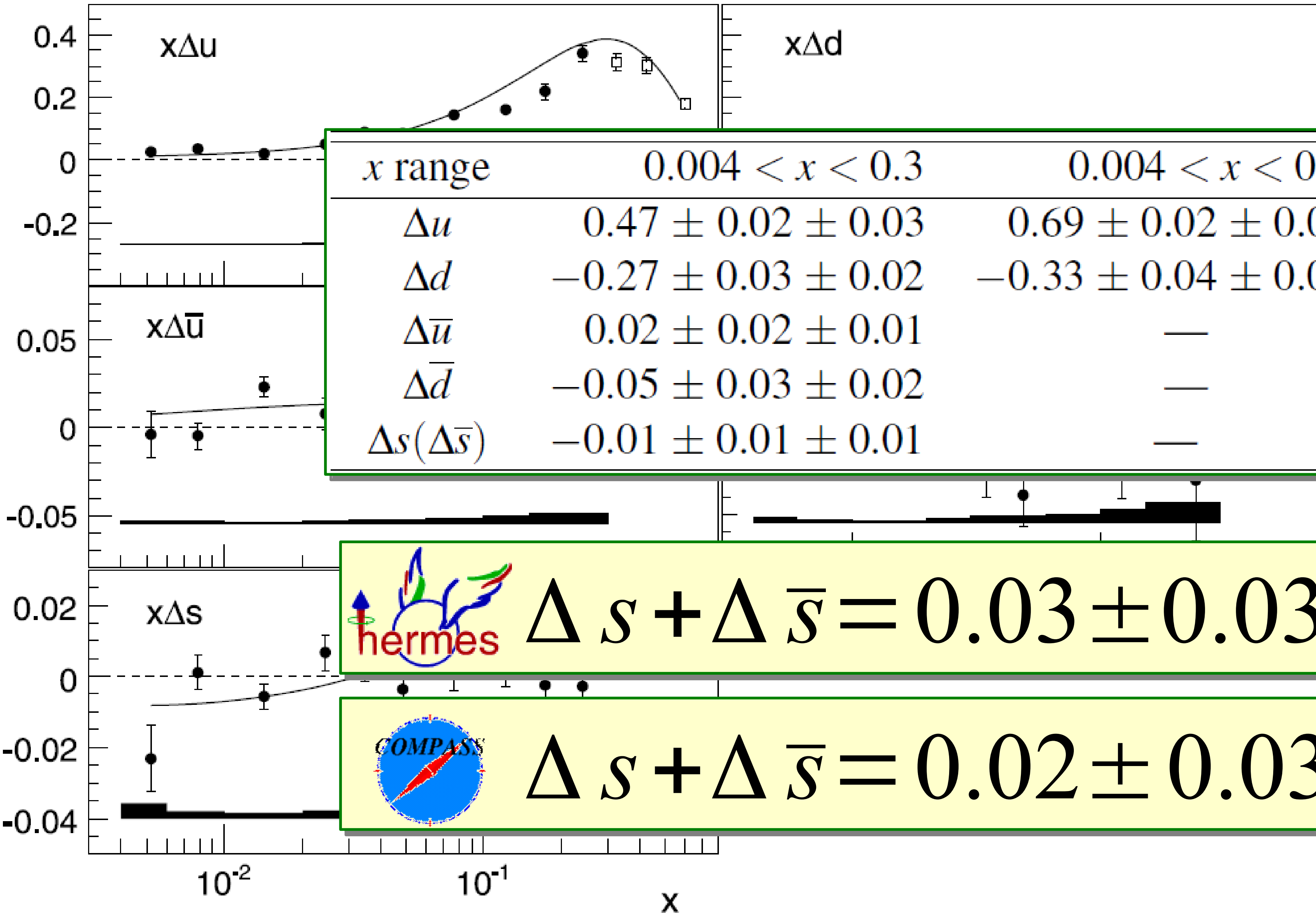
$$\Delta\bar{d}=-.054\pm 0.033\pm 0.011$$

$$\Delta s=0.028\pm 0.033\pm 0.009$$

- without SU(3) symmetry assumption
- only partial moments are available
- “LO” extraction

Δs determination with SIDIS data

COMPASS PRLB693(2010)227



x range	$0.004 < x < 0.3$	$0.004 < x < 0.7$
Δu	$0.47 \pm 0.02 \pm 0.03$	$0.69 \pm 0.02 \pm 0.03$
Δd	$-0.27 \pm 0.03 \pm 0.02$	$-0.33 \pm 0.04 \pm 0.03$
$\Delta\bar{u}$	$0.02 \pm 0.02 \pm 0.01$	—
$\Delta\bar{d}$	$-0.05 \pm 0.03 \pm 0.02$	—
$\Delta s(\Delta\bar{s})$	$-0.01 \pm 0.01 \pm 0.01$	—

hermes $\Delta s + \Delta\bar{s} = 0.03 \pm 0.03$

COMPASS $\Delta s + \Delta\bar{s} = 0.02 \pm 0.03$

Δs measured in DIS

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Inclusive measurement:

$\Delta s = -0.08 \pm 0.02$

SU(3)$_f$ symmetry

Semi-inclusive measurement:

$\Delta s = 0.03 \pm 0.03$

Flavor tagging

Without SU(3)$_f$

Limited x range

Nucleon Form Factors

Axial charge, and Δs

$$a_0 = \Delta u + \Delta d + \Delta s \quad = \mathbf{0.3}$$

polDIS

$$a_3 = \Delta u - \Delta d \quad = 1.26$$

β-decay

$$a_8 = \Delta u + \Delta d - 2\Delta s \quad = 0.86$$

hyperon-decay

Nucleon form factors

D. H. Beck and B. R. Holstein, J. Mod. Phys. E10 (2001) 1

form fac	ame	low momentum transfer limit
$G_E(Q^2)$		$\chi_f^\dagger \chi_i (F_1 - \frac{Q^2}{4M^2} F_2)$
$G_M(Q^2)$	$-\frac{}{2\lvert\vec{q}\rvert e}\langle N \rvert J_+ \lvert N\rangle$	$\chi_f^\dagger \vec{\sigma} \chi_i \times \vec{q} \frac{F_1+F_2}{2M}$
$G_A(Q^2)$	$\langle N \rvert \vec{A} \lvert N\rangle$	$\chi_f^\dagger \vec{\sigma} \chi_i G_A$

Electric charge

Magnetic moment

Spin: Δq

Strange contribution:

$$G_A^s(Q^2) = \frac{G_A^s(0)}{(1+Q^2/M_A^2)^2}$$

$$G_A^s(0) = \Delta s$$

Neutrino-Nucleon scattering

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$$\frac{d\sigma}{dQ^2} = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW \pm CW^2\right)$$

$$W = \frac{4E_\nu}{m_p} - \frac{Q^2}{m_p^2}$$

$$A = \frac{1}{4}\left[G_1^2(1+\tau) - \left(F_1^2 - \tau F_2^2\right)(1-\tau) + 4\tau F_1 F_2\right]$$

$$\tau = \frac{Q^2}{4\mathrm{m}_p^2}$$

$$B = -\frac{1}{4}G_1\left(F_1 + F_2\right)$$

$$C = \frac{1}{16}\frac{m_p^2}{Q^2}\left(G_1^2 + F_1^2 + \tau F_2^2\right)$$

NC-EL/CC-QE

Neutral Current

$$F_{1,2} = \left[\left[\frac{1}{2} - \sin^2\theta_W\right]\left[F^p_{1,2} - F^n_{1,2}\right] - \sin^2\theta_W\left[F^p_{1,2} + F^n_{1.2}\right] + \boxed{\frac{1}{2}F^s_{1,2}}\right]$$

$$G_1 = \left[-\frac{G_A}{2}\tau_z + \boxed{\frac{G_A^s}{2}}\right] \Longrightarrow G_A^s\left(Q^2 = 0\right) = \Delta s$$

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Experimental results on neutral current ν-N(A) cross section

E734, SciBooNE*, MiniBooNE, T2K*

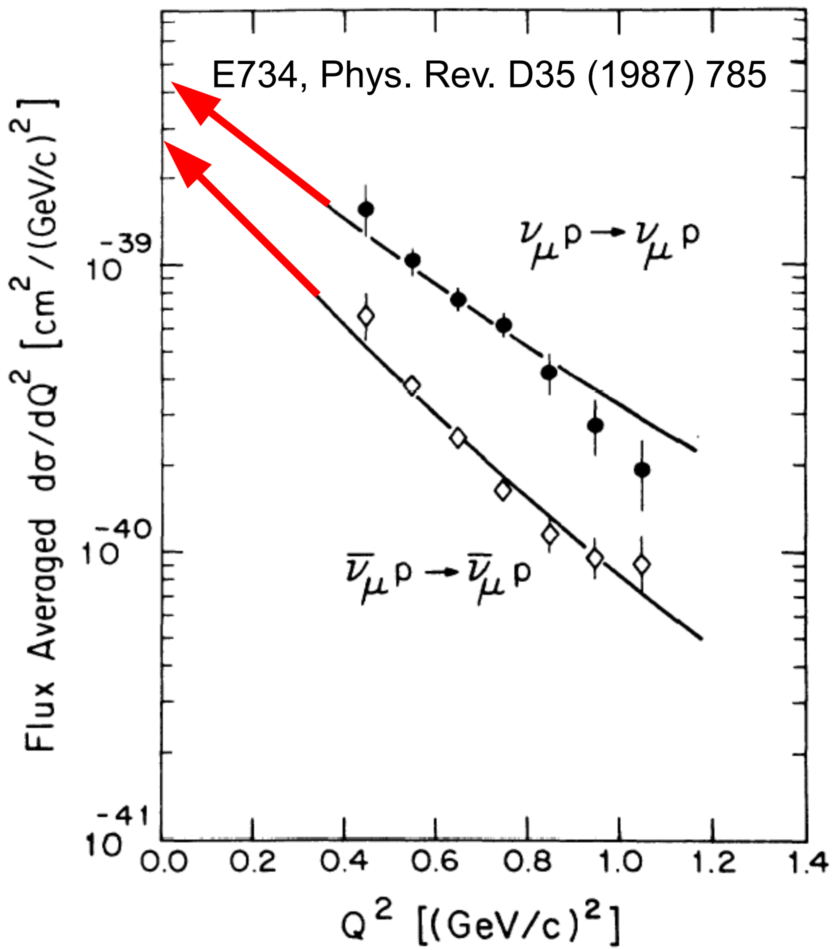
Neutrino scattering and Δs
- E734 results -

Neutral current elastic scattering cross section

Liquid scintillator + Drift Tube 170 t

0.5E19 POT for neutrino

2.5E19 POT for anti-neutrino



From $G_A^s(Q^2)$ to Δs

$$G_A^s(Q^2 \rightarrow 0) = \Delta s = -0.21 \pm 0.10$$

Further analysis based on E734

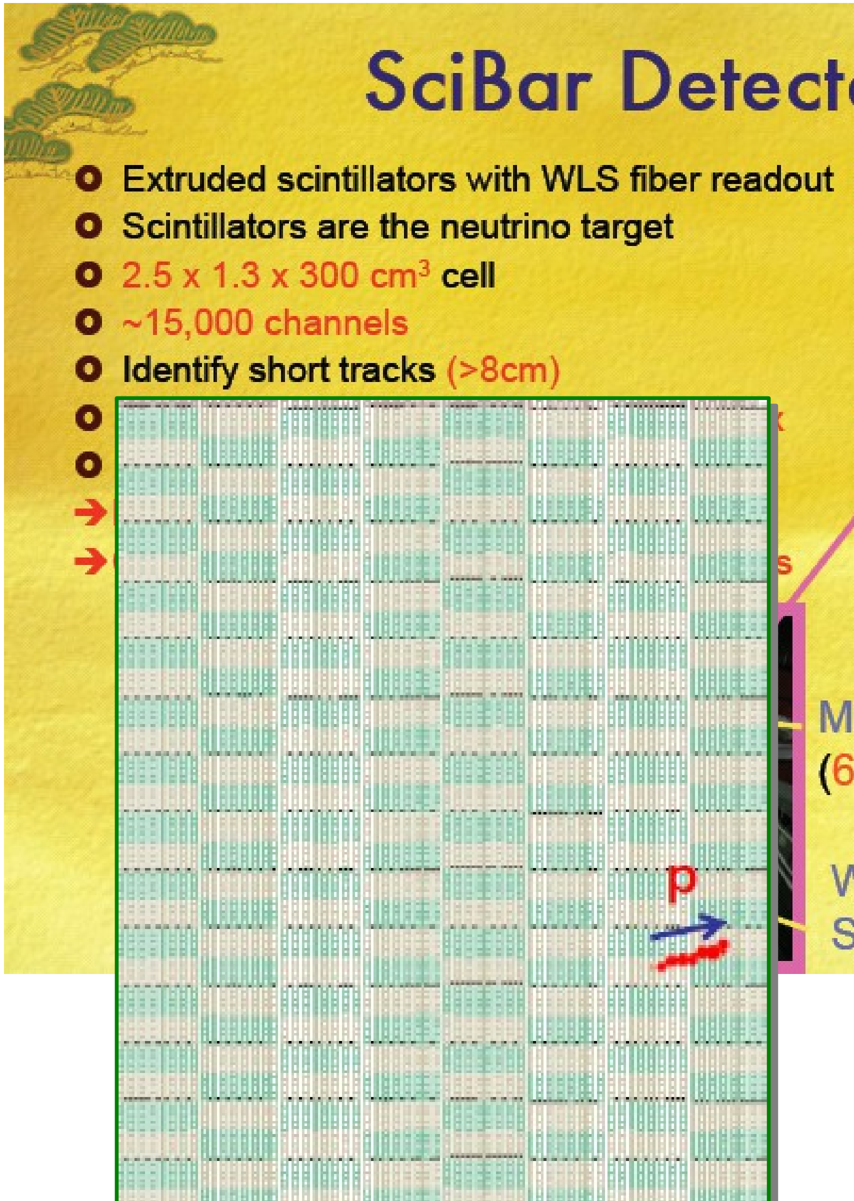
$$R_{NC/CC}^{\nu} = 0.152 \pm 0.007 \pm 0.017$$
$$R_{NC/CC}^{\bar{\nu}} = 0.218 \pm 0.012 \pm 0.023$$
$$R_{NC}^{\nu/\bar{\nu}} = 0.302 \pm 0.019 \pm 0.037$$

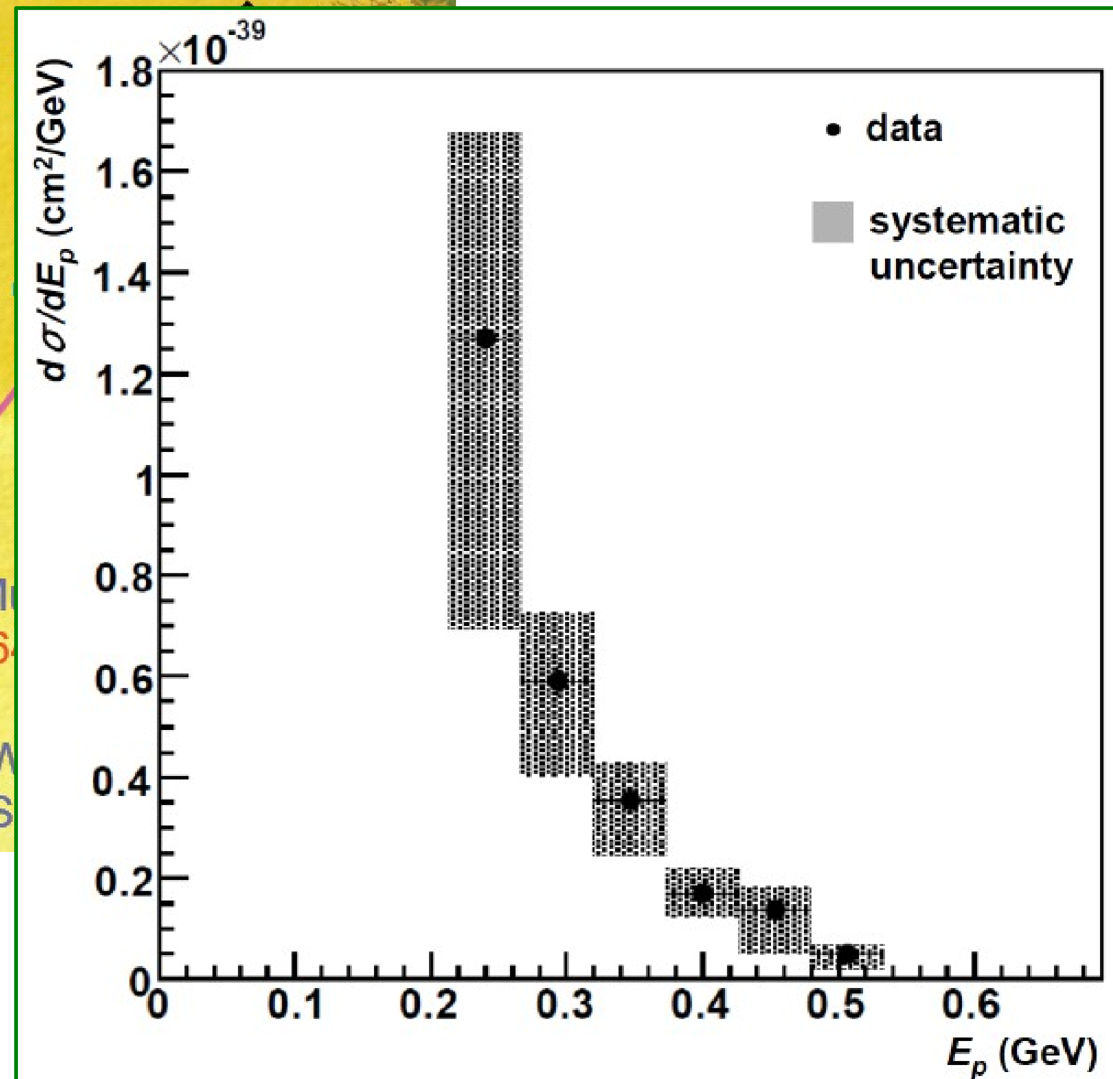
$-0.21 < \Delta s < 0$

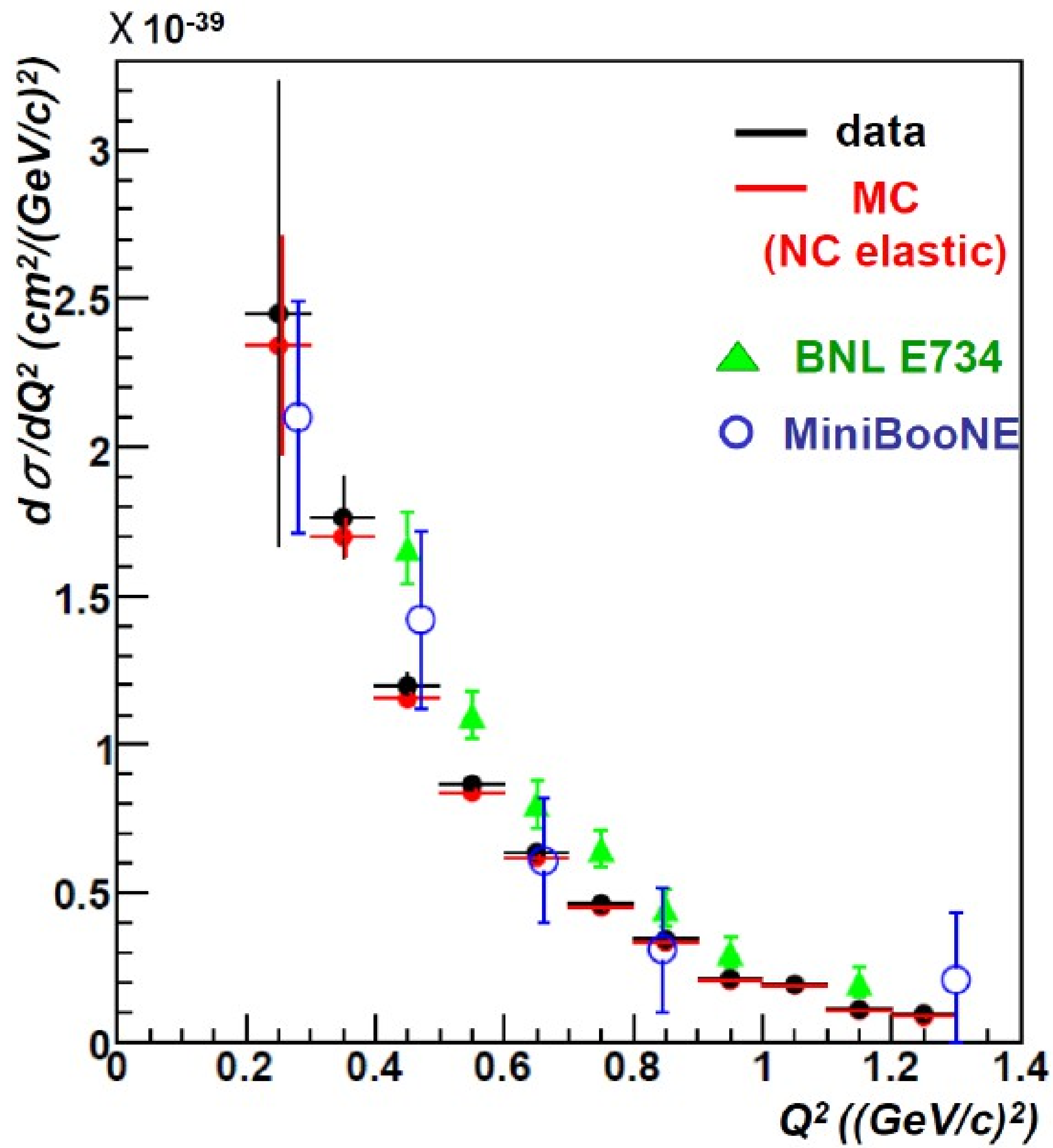
strong correlation with the axial mass M_A

Q^2 dependence of G_s^A

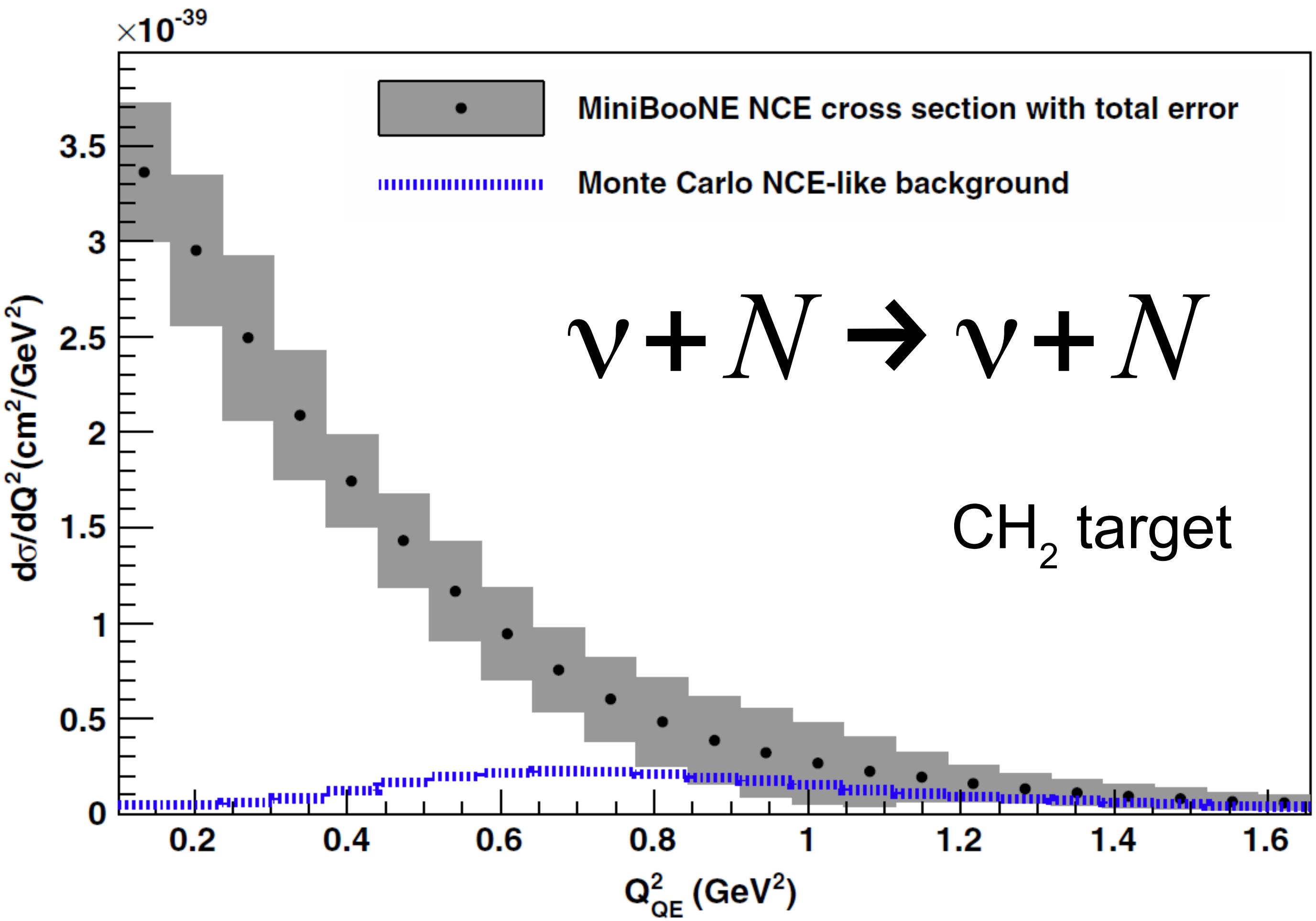
(NuFact06, H. Tanaka)






X 10^{-39}
$d\sigma/dQ^2$ ($cm^2/(GeV/c)^2$)
3
2.5
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Q^2 $((GeV/c)^2)$
data
MC
(NC elastic)
BNL E734
MiniBooNE

PRD82 (2010) 092005
ArXiv:1309.7257

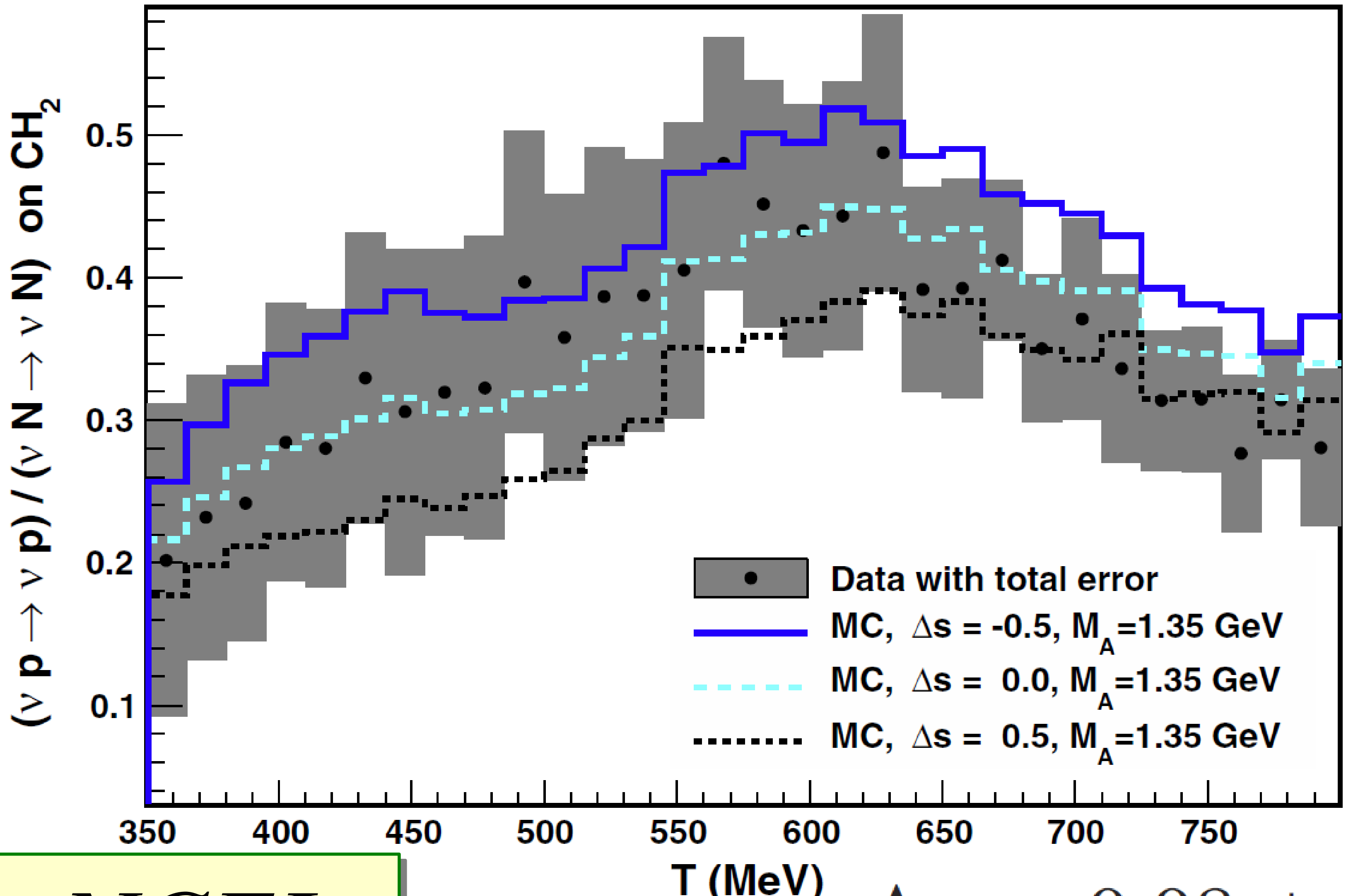


$$\Delta s = 0 \rightarrow M_A = 1.39 \pm 0.11 \text{ GeV}$$

$$\Delta s = -0.2 \rightarrow M_A = 1.35 \pm 0.11 \text{ GeV}$$

Determination of Δs at MiniBooNE

PRD82 (2010) 092005



$\bar{\nu} - NCEL$

arXiv:1309.7257

$$\Delta s = 0.08 \pm 0.26$$

$$\chi^2_{\min}/\mathrm{DOF} = 34.7/29$$

T2K results on neutral ~~current elastic scattering~~

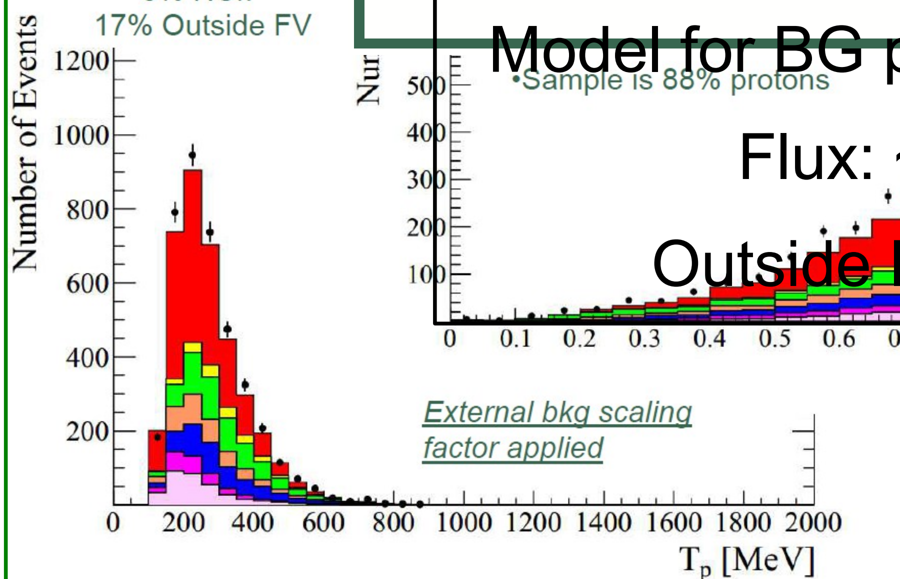
⇔ Stat.: ~10% (MiniBooNE)

Stat.: 3%

Final Sample

$$<\sigma>_{flux} = 2.24\times10^{-39} \pm 0.07(\text{stat.})\,^{+0.53}_{-0.63}(\text{sys.})\,\frac{\text{cm}^2}{\text{nucleon}}$$

Bkg by FSI category
29% CCQE
25% Outside/Sand
21% Other
8% NCπ^0
17% Outside FV



Model for BG process: ~ 15%

Flux: ~ 20%

Outside BG: 6.4%

Flux averaged cross section

$$<\sigma>_{flux} = \frac{N_{data} - B_{mc}}{T\Phi\varepsilon}$$

N_{data}	selected number of events in data
B_{MC}	background prediction from MC
T	total number of target nucleons
Φ	Neutrino flux
ε	Selection efficiency correction

- Uses data with water in the P0D
- Reported as cross section per nucleon
  - Averages over carbon, brass, water
- Background subtracted result
- Using 9.918 x 10^{19} POT select 3936 events with a predicted background of 2016 events

$$<\sigma>_{flux} = 2.24\times10^{-39} \pm 0.07(\text{stat.})\,^{+0.53}_{-0.63}(\text{sys.})\,\frac{\text{cm}^2}{\text{nucleon}}$$

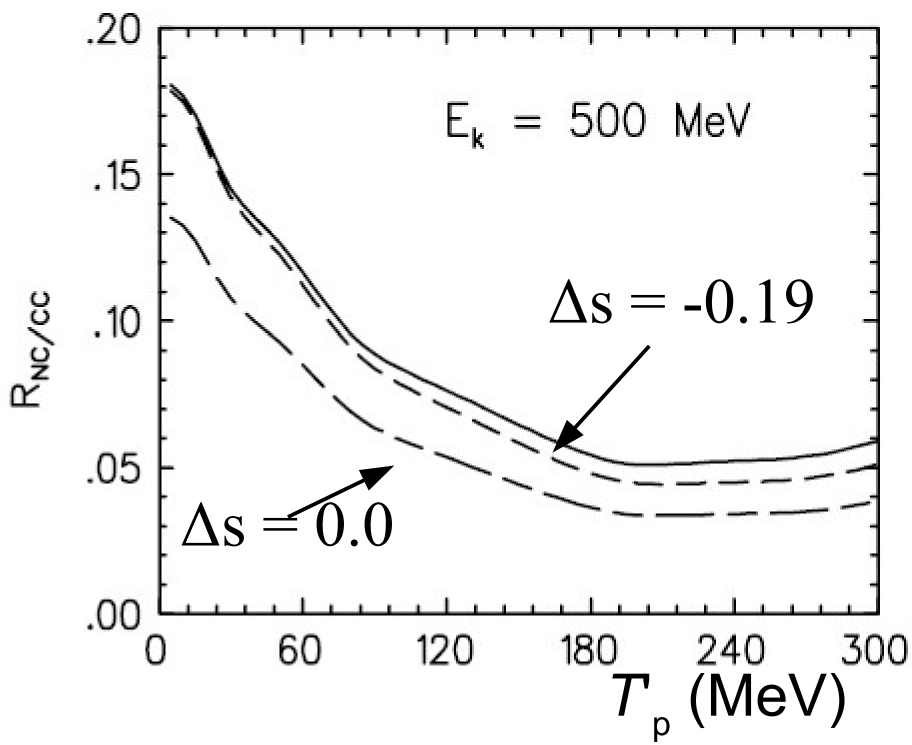
$$\text{NEUT}: <\sigma>_{flux} = 2.02\times10^{-39}\,\frac{\text{cm}^2}{\text{nucleon}} \qquad \text{GENIE}: <\sigma>_{flux} = 1.78\times10^{-39}\,\frac{\text{cm}^2}{\text{nucleon}}$$

D. Ruterbories @NuFact 2013

Is it really possible to extract Δs from R(NC/CC) measurement with NUCLEAR target?

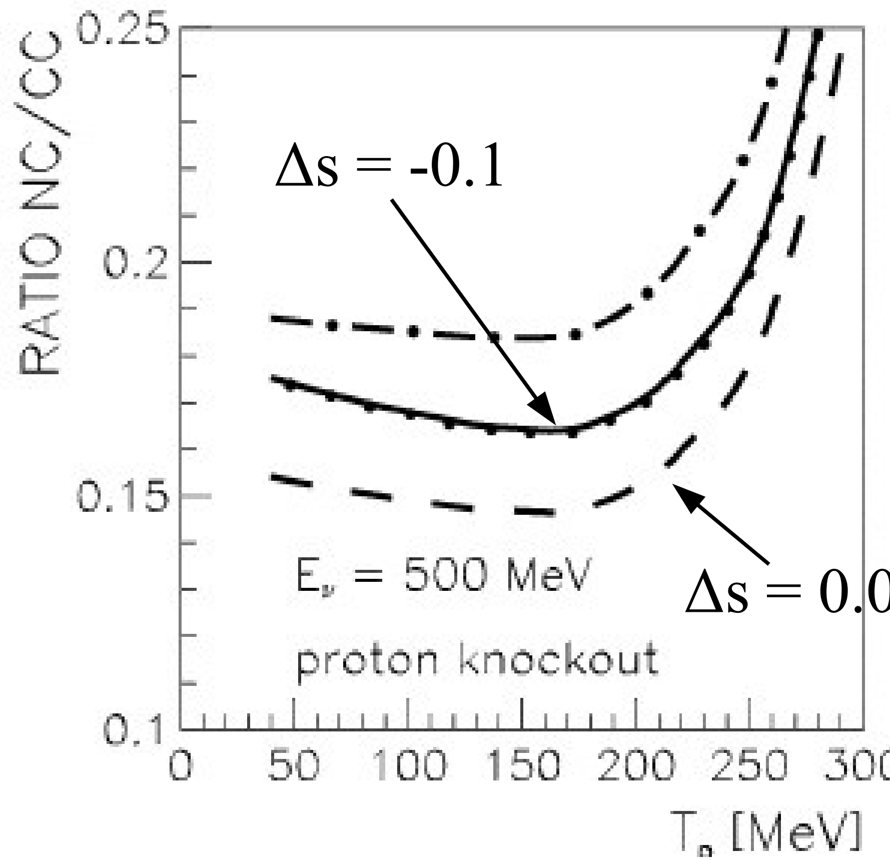
R(NC/CC) and Δs

B. I. S. van der Ventel and J. Piekarewicz, Phys. Rev. C73 (2006) 025501



a relativistic <u>plane-wave</u> impulse-approximation.

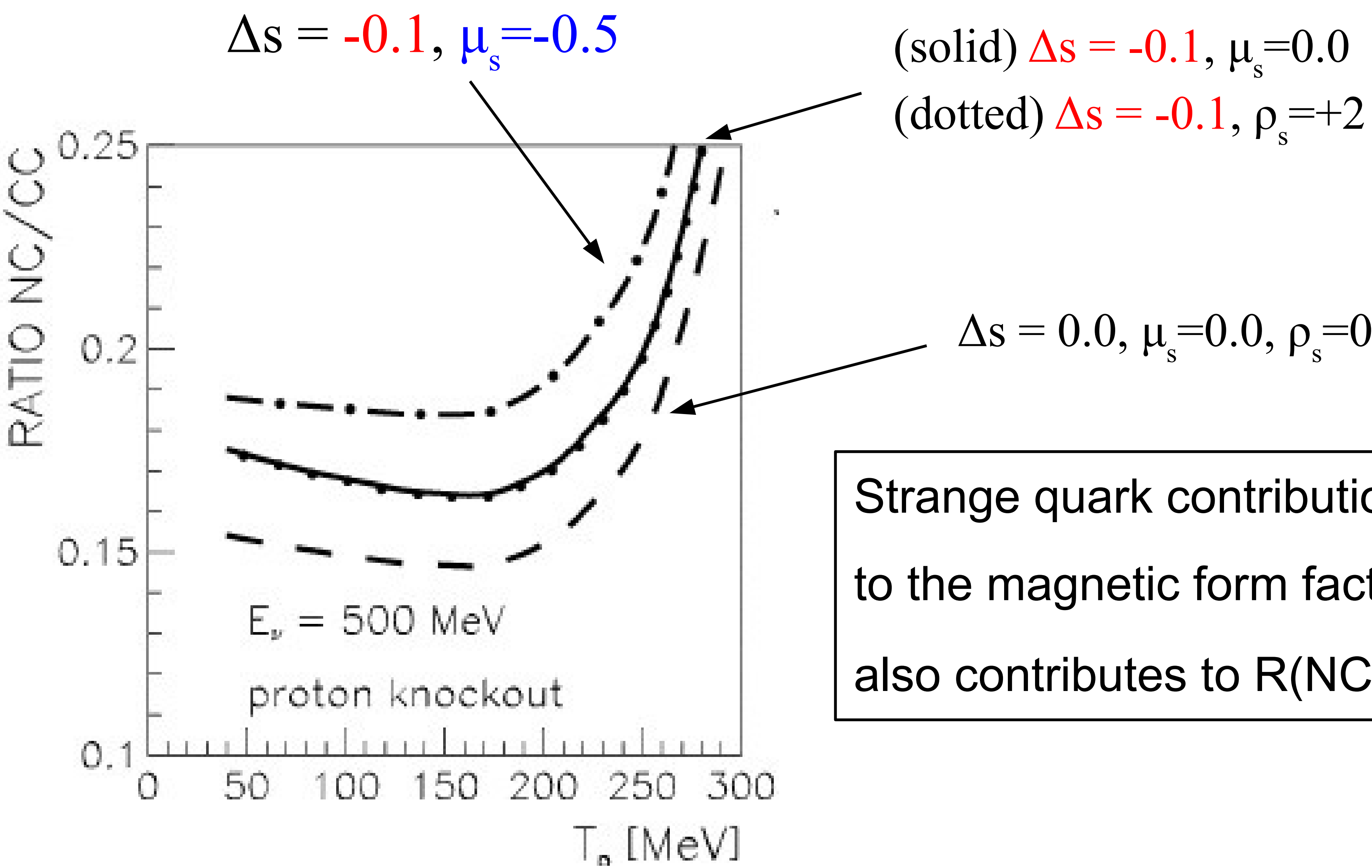
A. Meucci et al., Nucl. Phys. A 773 (2006) 250



a relativistic <u>distorted-wave</u> impulse-approximation

Both were calculated for ^{12}C.

R(NC/CC) and strange form factors



Strange quark contribution

to the magnetic form factor G_M^s

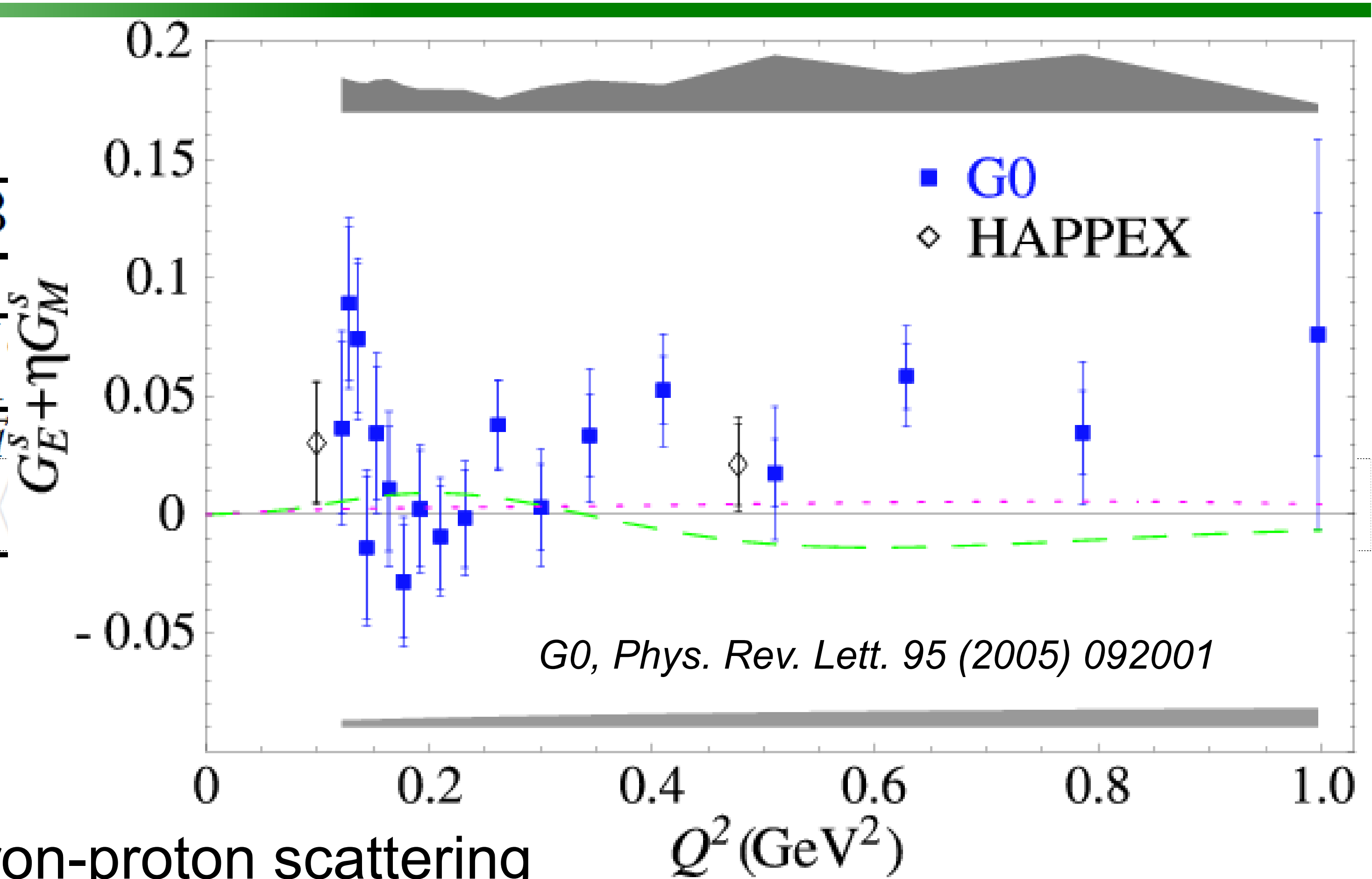
also contributes to R(NC/CC)

Global analysis of strange form factors

$$G_E^s \qquad G_M^s \qquad G_A^s$$

Strange from factors: G_E^s and G_M^s

form factor	B
$G_E(Q^2)$	$\frac{1}{2M}$
$G_M(Q^2)$	$-\frac{1}{2\lvert\vec{q}\rvert}$
$G_A(Q^2)$	



Parity violating electron-proton scattering

$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

$$= \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\varepsilon G_E G_E^Z + \tau G_M G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M G_A^e}{\varepsilon (G_E)^2 + \tau (G_M)^2}$$

Global analysis of the strange form factors

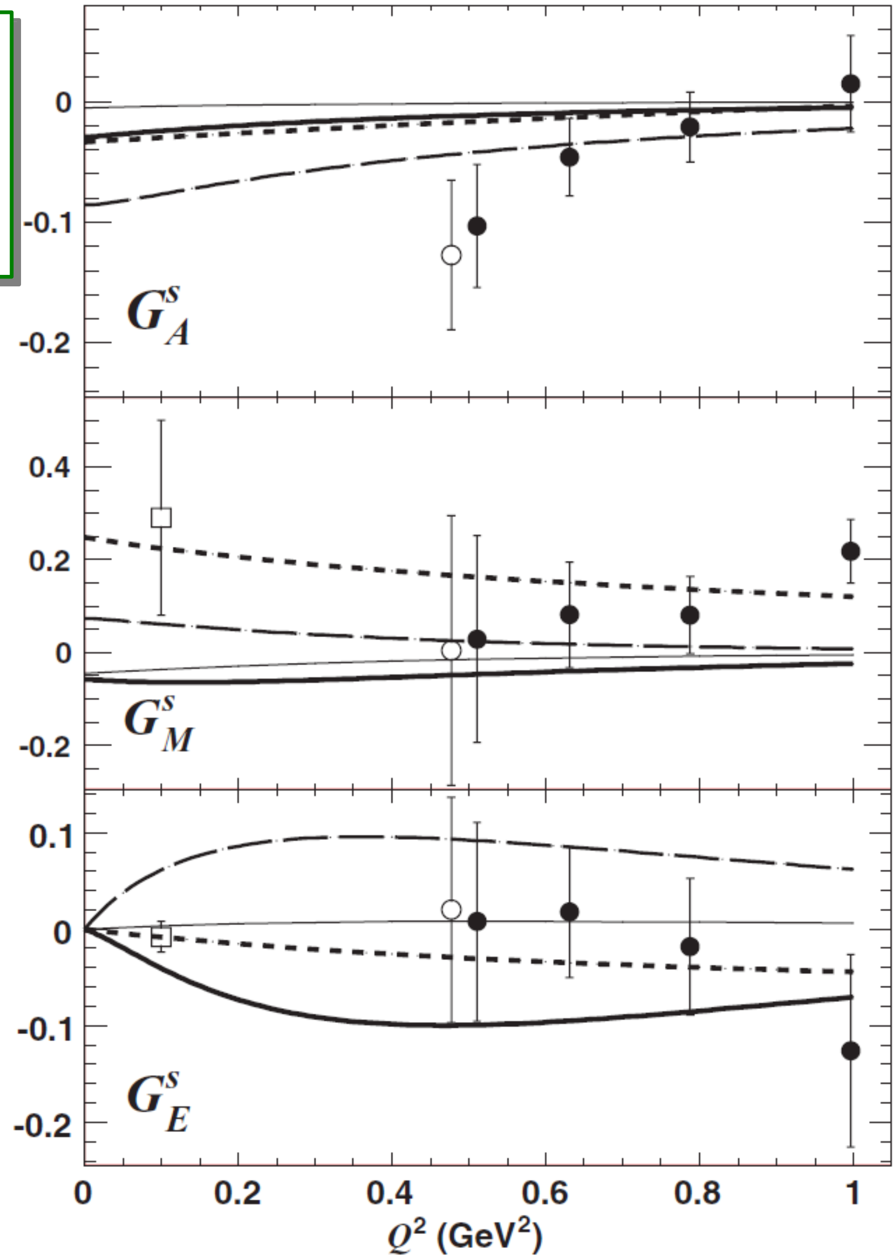
PHYSICAL REVIEW C **78**, 015207 (2008)

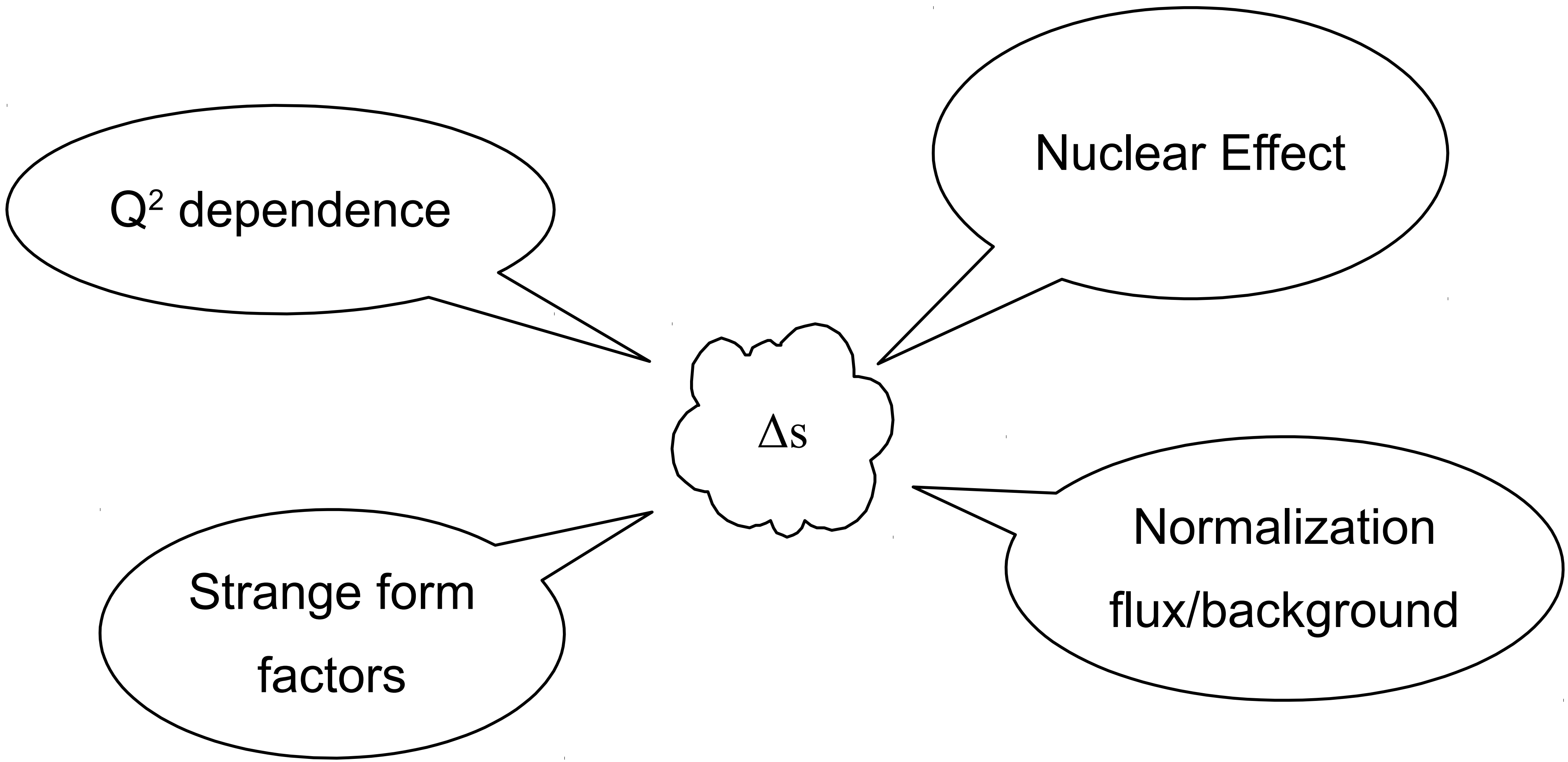
Strange quark contribution to the vector and axial form factors of the nucleon: Combined analysis of data from the G0, HAPPEx, and Brookhaven E734 experiments

Stephen F. Pate,[*] David W. McKee,[†] and Vassili Papavassiliou
Physics Department, New Mexico State University, Las Cruces, New Mexico 88003, USA
(Received 27 May 2008; published 29 July 2008)

Q^2 (GeV^2)	Solution 1		
	G_E^s	G_M^s	G_A^s
0.477	0.02 ± 0.12	0.00 ± 0.29	-0.127 ± 0.062
0.511	0.01 ± 0.10	0.03 ± 0.22	-0.103 ± 0.051
0.631	0.02 ± 0.07	0.08 ± 0.11	-0.046 ± 0.032
0.788	-0.02 ± 0.07	0.08 ± 0.08	-0.021 ± 0.029
0.997	-0.13 ± 0.10	0.22 ± 0.07	0.015 ± 0.040

Solution 2		
G_E^s	G_M^s	G_A^s
0.39 ± 0.06	-0.94 ± 0.15	0.266 ± 0.127
0.37 ± 0.05	-0.81 ± 0.12	0.257 ± 0.102
0.31 ± 0.03	-0.47 ± 0.06	0.221 ± 0.060
0.25 ± 0.03	-0.31 ± 0.05	0.180 ± 0.050
0.23 ± 0.06	-0.17 ± 0.06	0.225 ± 0.045





Accurate measurement of **NC ν-H** in $0.1 < Q^2 < 0.4$ GeV^2 which is covered by the electron scattering.

Methods of Δs measurement

R(NC/CC) measurements

Neutrino flux should be canceled.

It also suppresses the nuclear effect.

Is there any model dependence uncertainty?

ν-H scattering extraction

Using two targets with different mixture of H and C

Separation of ν-H and ν-C scattering becomes possible

Neutrino flux information is needed to extract the cross section.

J-PARC ν-beam line

- Feasibility study done for T2K in 2007

Beam flux

1 GeV for "on-axis"

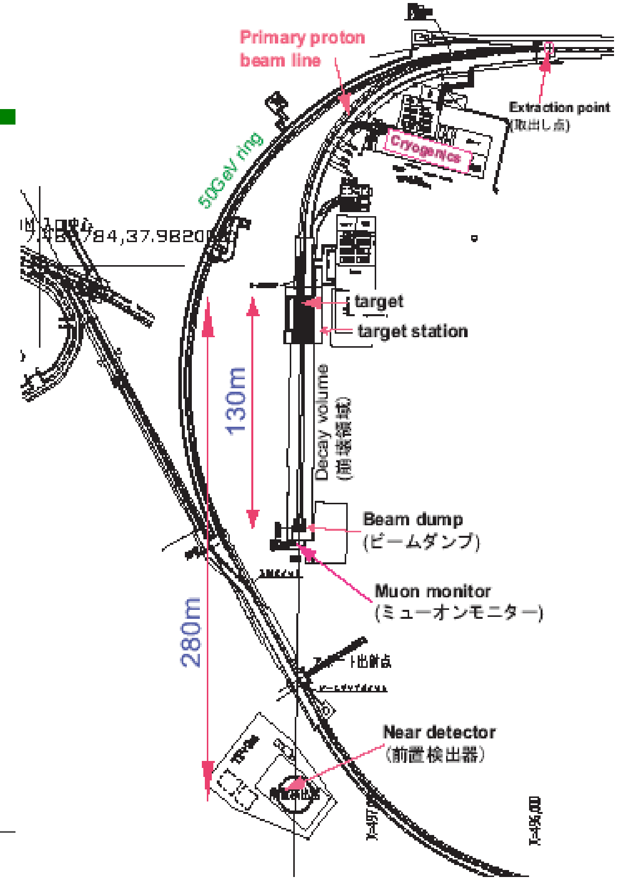
< 1GeV for "off-axis"

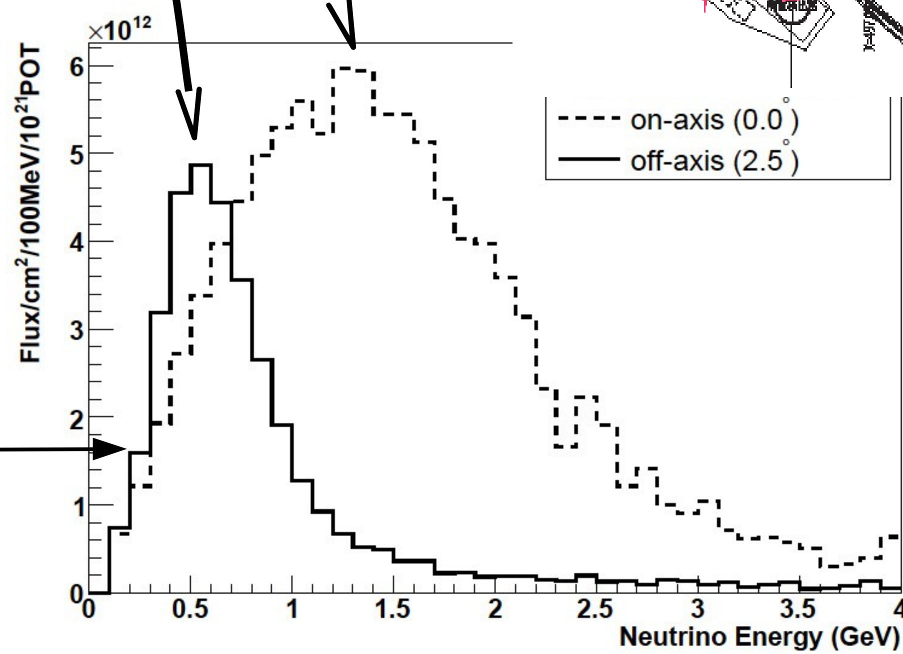
10^{21} POT/year (130 days)

anti-neutrino beam

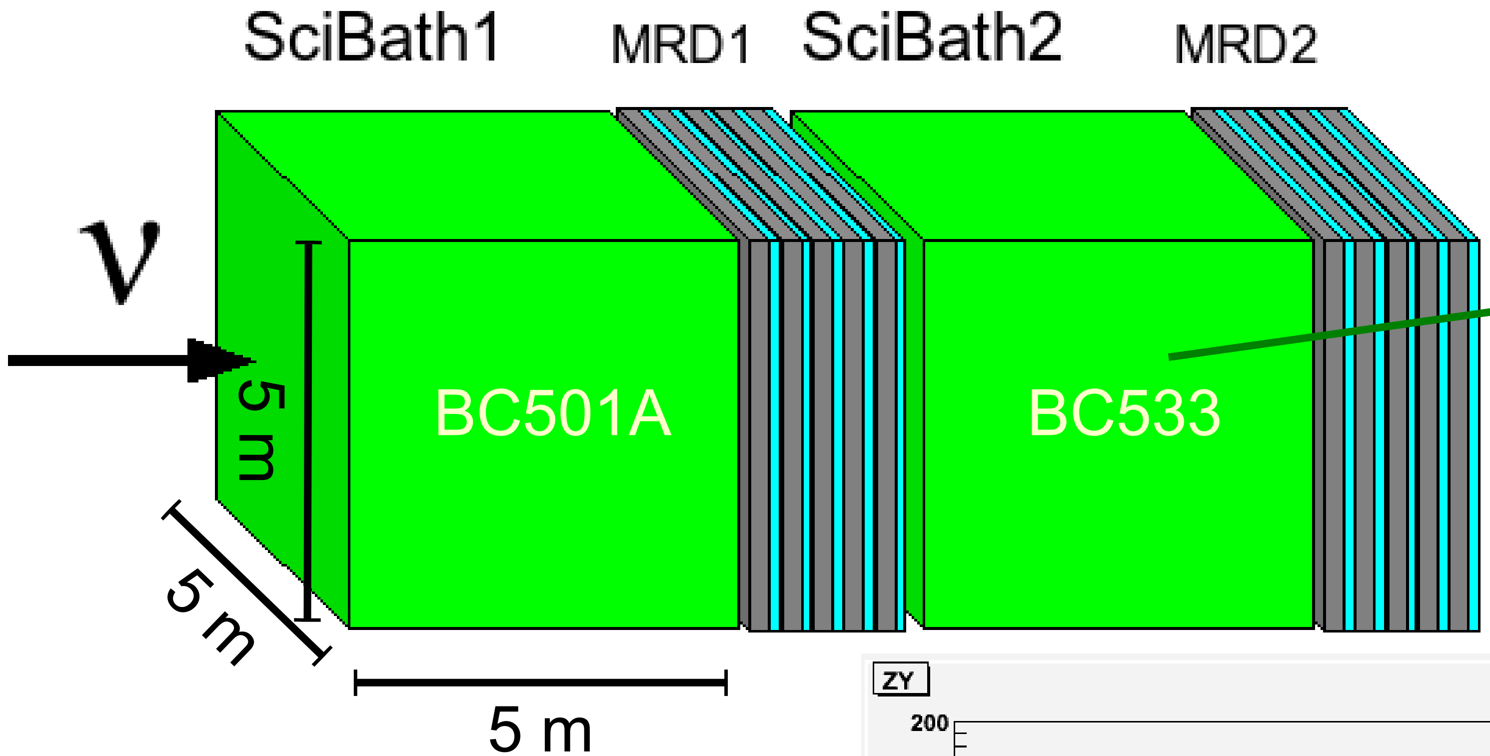
neutrino anti-neutrino asymmetry measurement

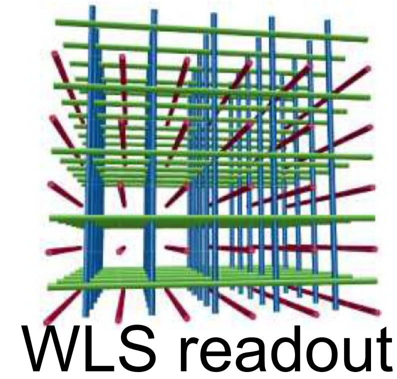
Expected ν flux (MC data)





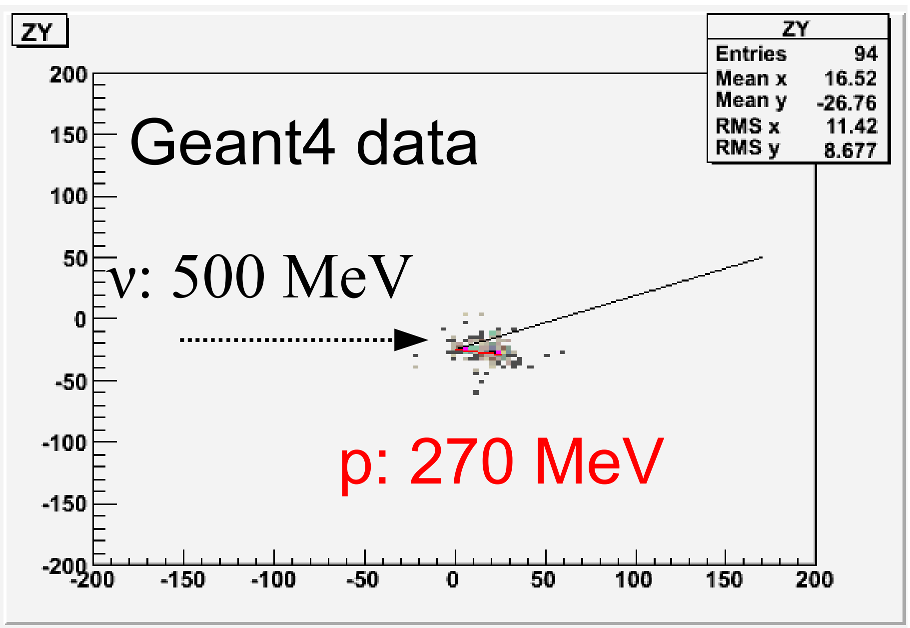
Dual SciBath configuration





Fiducial volume:

3x3x3 m^3



Extraction of N_{NC}^{H}

Nuclear effect free extraction:

Using two liquid scintillators with different mixture of H and C:

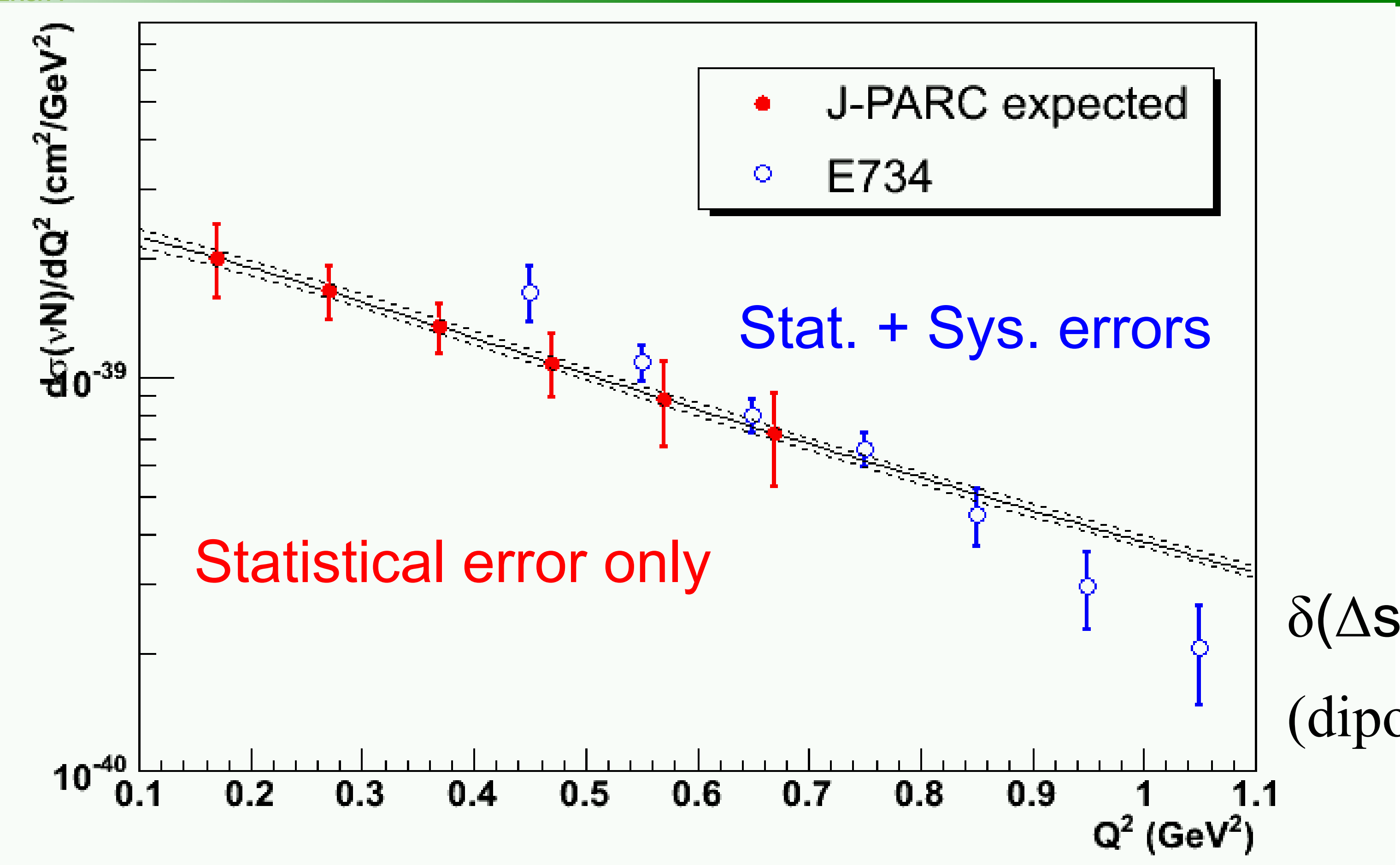
BICRON:	H/C	ρ(g/cm³)	ρ^H(g/cm³)	ρ^C(g/cm³)
BC501A	1.212	0.874	0.112	0.688
BC533	1.96	0.8	0.080	0.794

$$N_{NC}^{H} = 23.4 \times N_{NC}^{BC533} - 20.3 \times N_{NC}^{BC501A}$$

(~ 15% *N_{NC})

$$N_{NC}^{C} = -2.36 \times N_{NC}^{BC533} + 3.30 \times N_{NC}^{BC501A}$$

Expected sensitivity



$\delta(\Delta s) = 0.03$

(dipole form factor)

Expected sensitivity assuming the dipole approximation:

$$\delta(\Delta s) = 0.03$$

Systematic errors must be studied carefully. (Normalization, Background)

Summary

given at workshops in 2007

Proton spin problem

Δs is a key for understanding of sea quark contribution

HERMES, COMPASS: $\Delta s = -0.08 \pm 0.02$ with SU(3) symmetry

HERMES SIDIS: $\Delta s = 0.03 \pm 0.03$ (partial, no SU(3) symmetry)

Strange nucleon form factor constrains Δs first moment

Neutrino scattering: NC elastic scattering

E734 NC cross section measurements : $-0.2 < \Delta s < 0.0$

FINeSSE proposed R(NC/CC) measurement : $\delta(\Delta s) = 0.04$

SciBooNE: Data taking was started in 2007

Done | MiniBooNE | T2K | ・・・

Key points: nuclear effects in R(NC/CC), Q^2 extrapolation

Summary

given at workshops in 2007

YAMAGATA UNIVERSITY

Δs measurement at J-PARC

- Aim to measure NC cross section on H, not R(NC/CC)
- Sensitivity study based on
  - 1E21POT neutrino off-axis beam at 280m away from the production target
  - Dual SciBath detector (BC501A and BC533)
  - **δ(Δs) ~ 0.03** expected (with dipole form factor assumption)
  - Normalization and background contributions to the systematic error to be studied.
  - Q^2 extrapolation (Q^2 dependence) also has to be carefully studied.

Normalization, Background (especially "Dirt") has to be under control. Systematic is Key!