Nucleon-Structure Studies from Lepton Scattering

Workshop on J-PARC Hadron Physics
Feb 10-12, 2014

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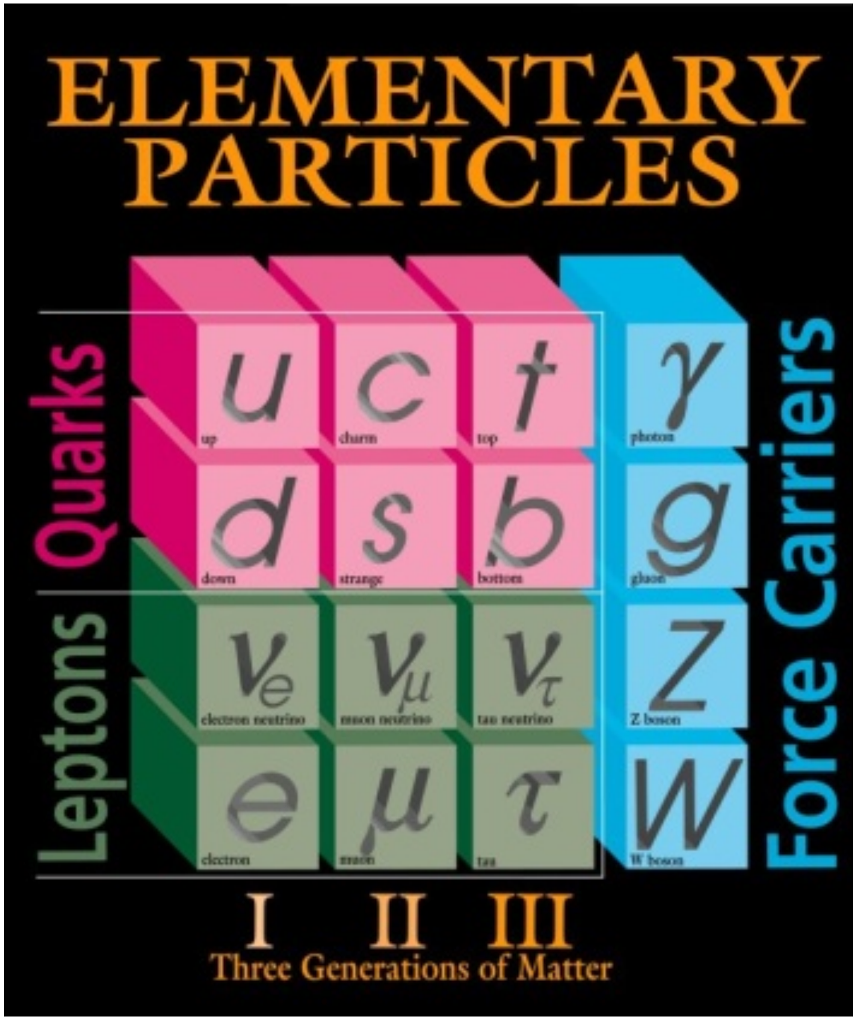
Outline

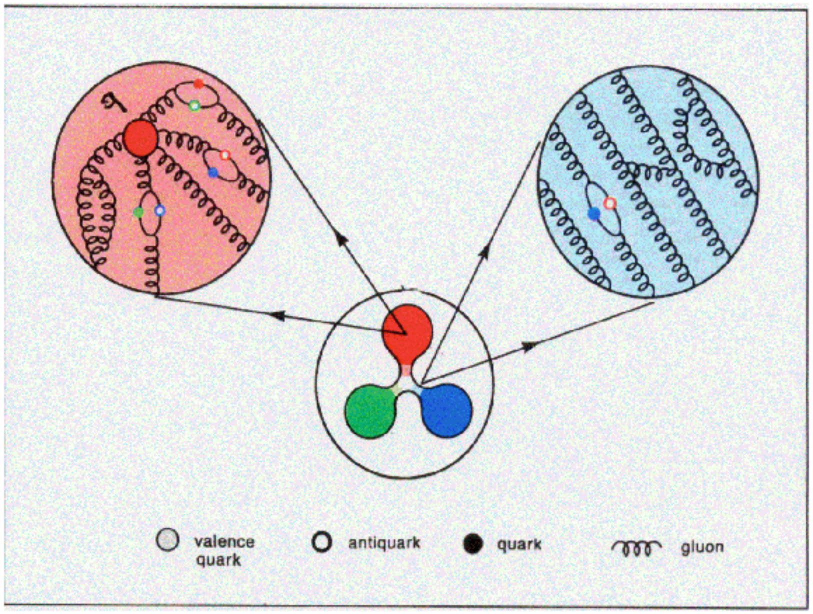
- ***Introduction***
- ***Few selected examples***
  - ***Proton charge radius***
  - ***Proton spin: imaging in momentum space***
  - ***Parity-violating electron scattering***
    - ***Strangeness contribution to the EM structure of the nucleon***
    - ***The weak charge of the proton***
- ***Summary***

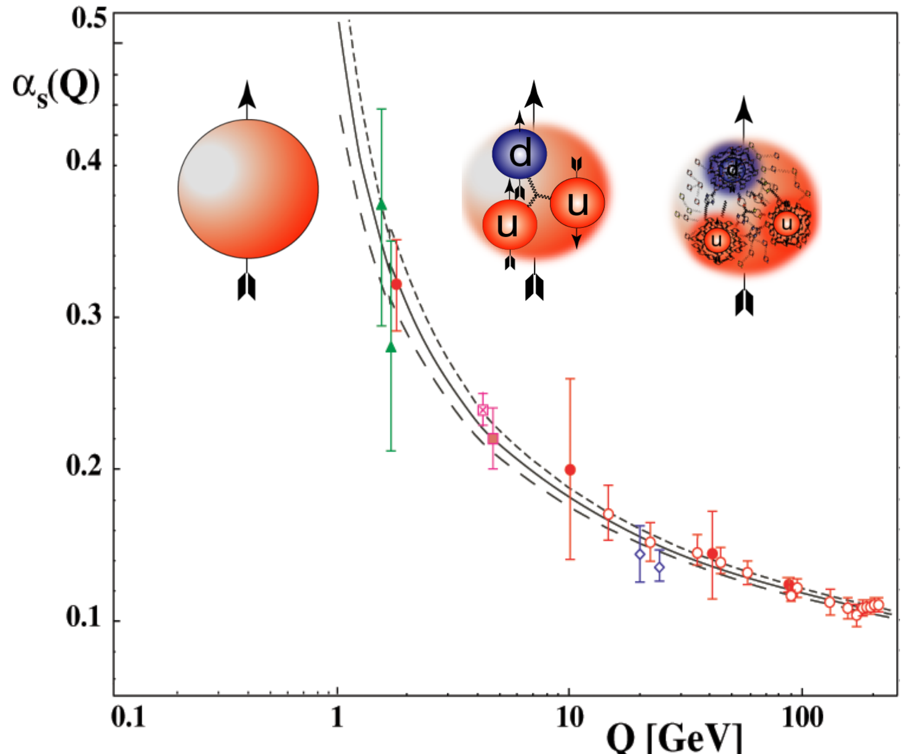
Standard Model (SM) of Particle Physics



- **SM very successful (no gravity)**
- **New physics exists (neutrino mass, dark matter, baryon number asymmetry of universe,….)**
- **Discovery of Higgs particle at LHC**
  - **almost irrelevant to nucleon mass**
- **Low-energy and precision frontier important and timely**
- **Strong interaction, QCD (quarks and gluons)**
  - **Remaining frontier of SM?**

QCD: still unsolved in non-perturbative region

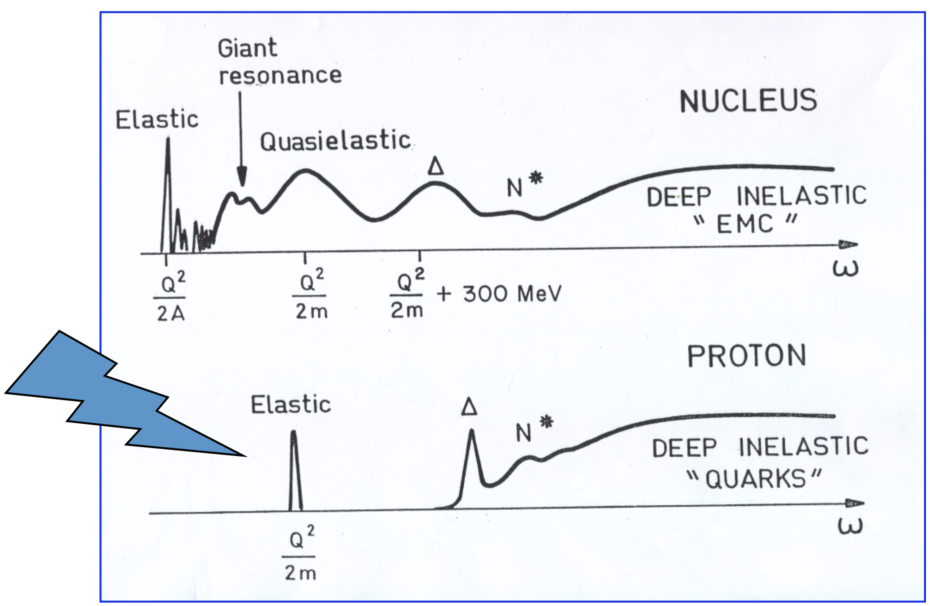




- *2004 Nobel prize for ``asymptotic freedom”*
- *Non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *Nucleon structure is one of the most active areas*
  - Nucleon anomalous magnetic moment ***(Stern, Nobel Prize 1943)***
  - Electromagnetic form factors of proton ***(Hofstadter, Nobel Prize 1961)***
  - Deep-inelastic scattering, quark underlying structure of the nucleon ***(Friedman, Kendall, Taylor, Nobel Prize 1990)***

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed (two-photon physics)***
- ***One can vary the wave-length of the probe to view deeper inside the hadron***

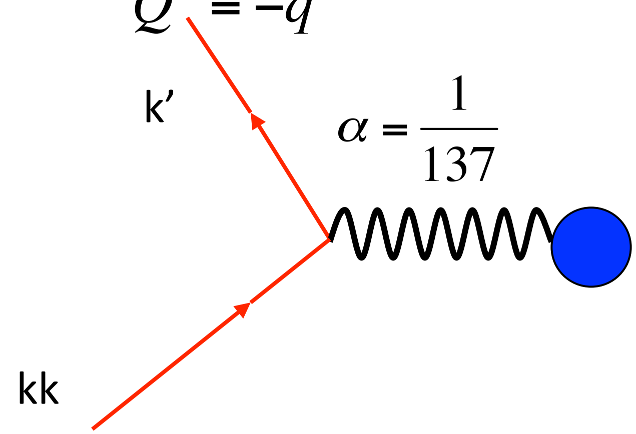


Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$

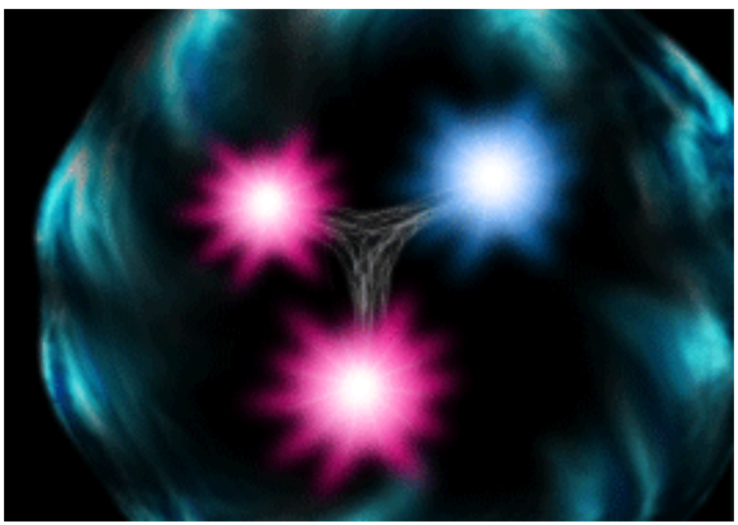
$$\alpha = \frac{1}{137}$$

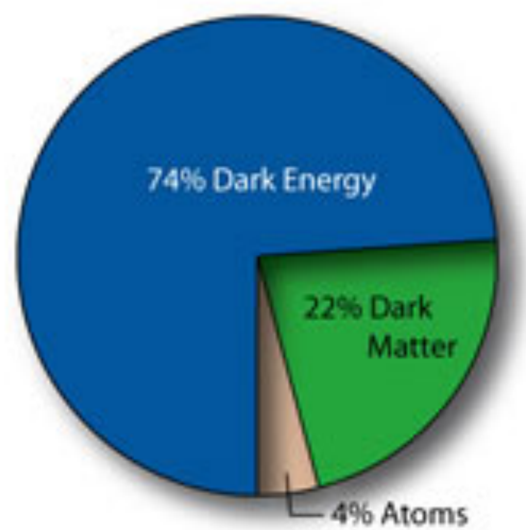


Proton – ``Hydrogen atom" to QCD

质子是量子色动力学的``氢原子";质量，带电半径，自旋，奇异夸克效应和弱电荷

- **Proton mass (Higgs discovery almost irrelevant)**
- **Proton Charge Radius**
- **Proton Spin**
- **Strangeness and proton weak charge**





Motivation for precise information on proton charge radius

- A fundamental static property of the nucleon
  - Important for understanding how QCD works
  - Challenge to Lattice QCD
- An important physics input to the bound state QED calculations, affects muonic H Lamb shift

  ($2S_{1/2} - 2P_{1/2}$) by as much as 2%
- Lamb Shift ($2S_{1/2} - 2P_{1/2}$) measurements are becoming more and more precise
- High precision tests of QED?
- Turning things around one can determine proton radius using QED and Lamb shift measurements

Methods for measuring proton charge radius

- Electron-proton elastic scattering to determine electric form factor

$$\sqrt{< r^2 >} = \sqrt{-6 \frac{dF(\vec{q})}{dq^2}) |_{q^2=0}}$$

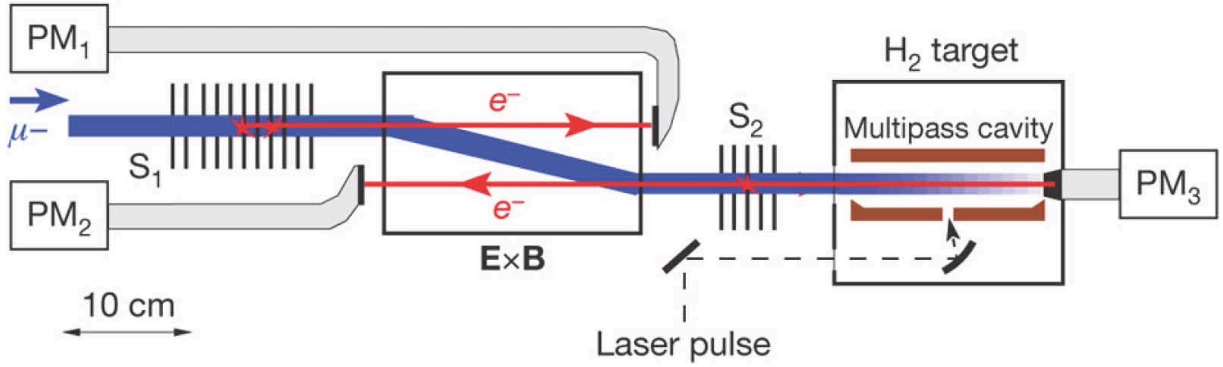
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left(\frac{{G_E^p}^2 + \tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2 \frac{\theta}{2} \right)$$

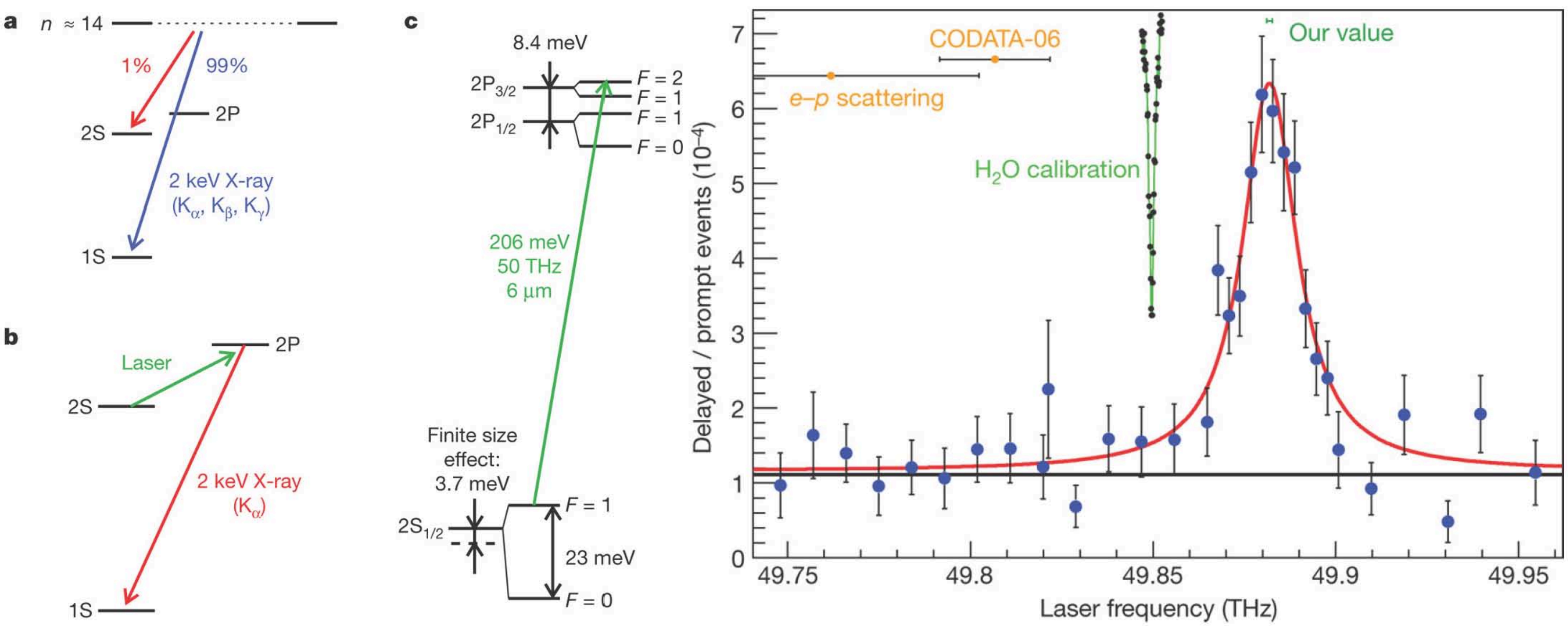
- Hydrogen spectroscopy (CODATA) (Lamb shift)

- Muonic Hydrogen (spectroscopy) (Lamb shift)

Muonic hydrogen Lamb shift experiment at PSI

Nature **466**, 213-216 (8 July 2010)



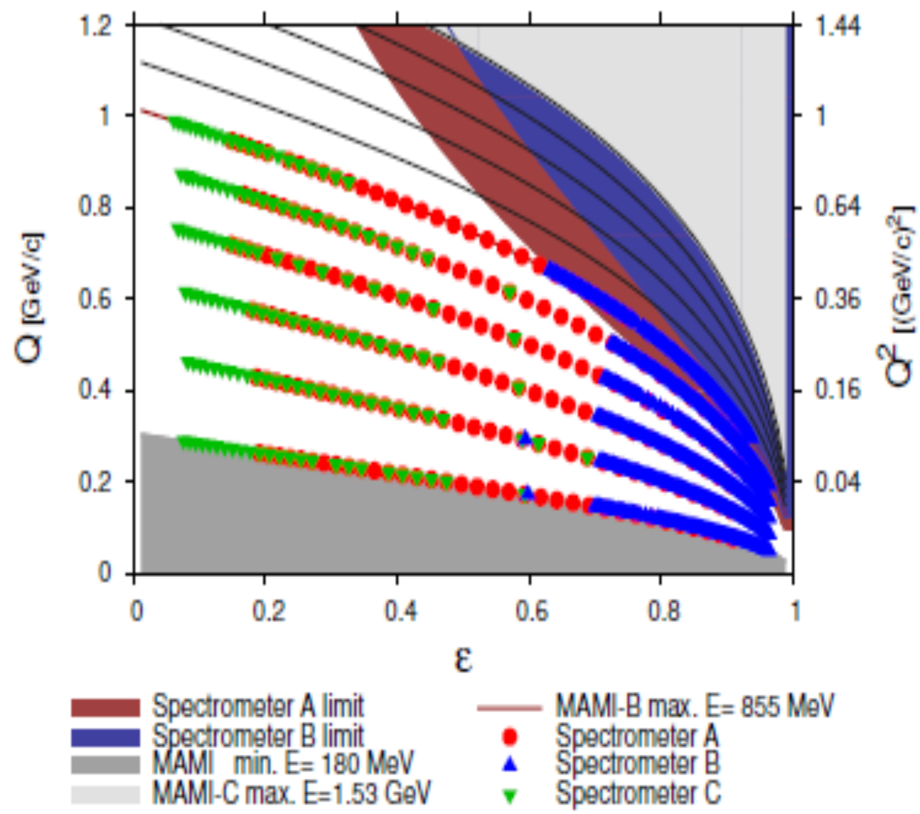


2010: new value is r_p = 0.84184(67) fm

Recent ep Scattering Experiments

Three spectrometer facility of the A1 collaboration:

Measurements @ Mainz



– Large amount of overlapping data sets
– Statistical error ≤ 0.2%
– Luminosity monitoring with spectrometer

- $Q^2 = 0.004 – 1.0\ (GeV/c)^2$

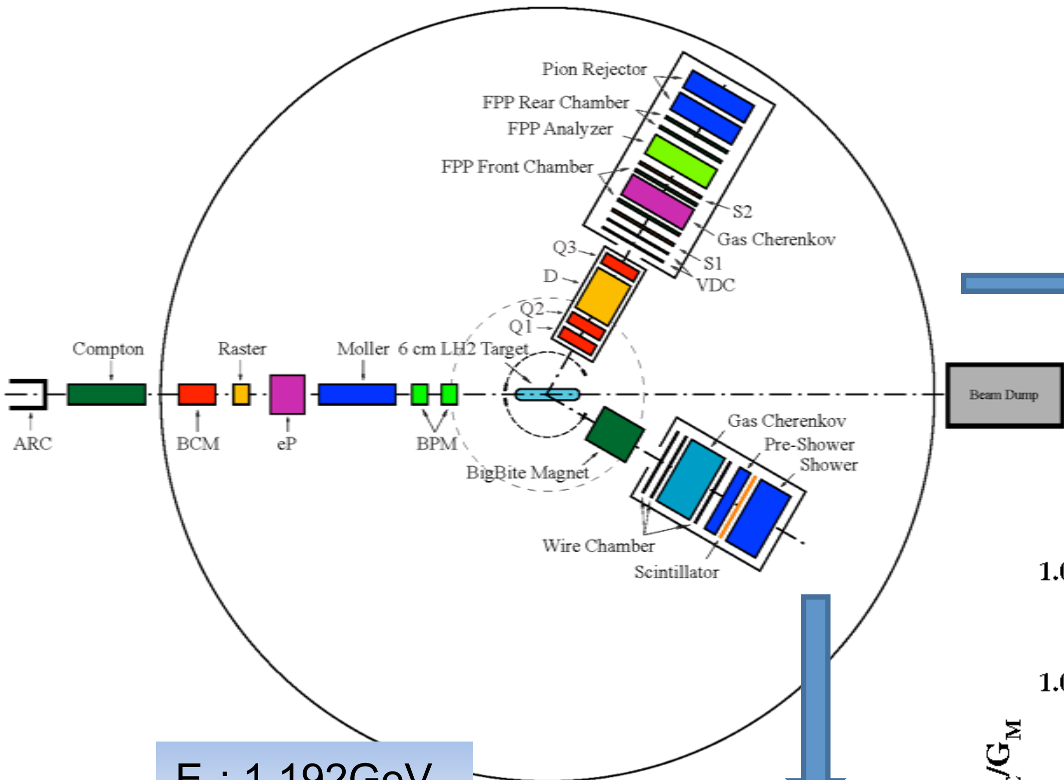
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

Jlab Recoil Proton Polarization Experimental



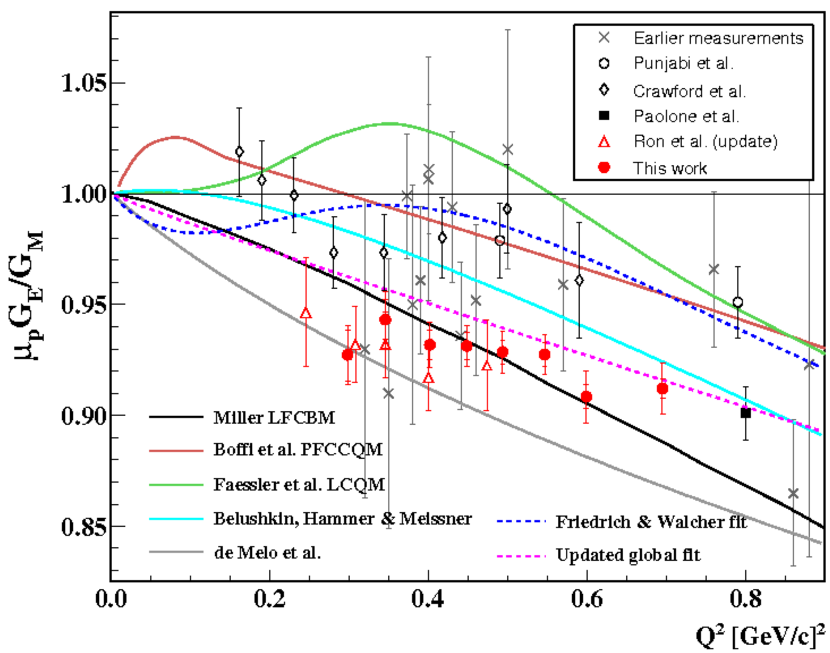
LHRS

- $\Delta p/p0$: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- $\Delta\Omega$: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

E_e: 1.192GeV
P_b: ~83%

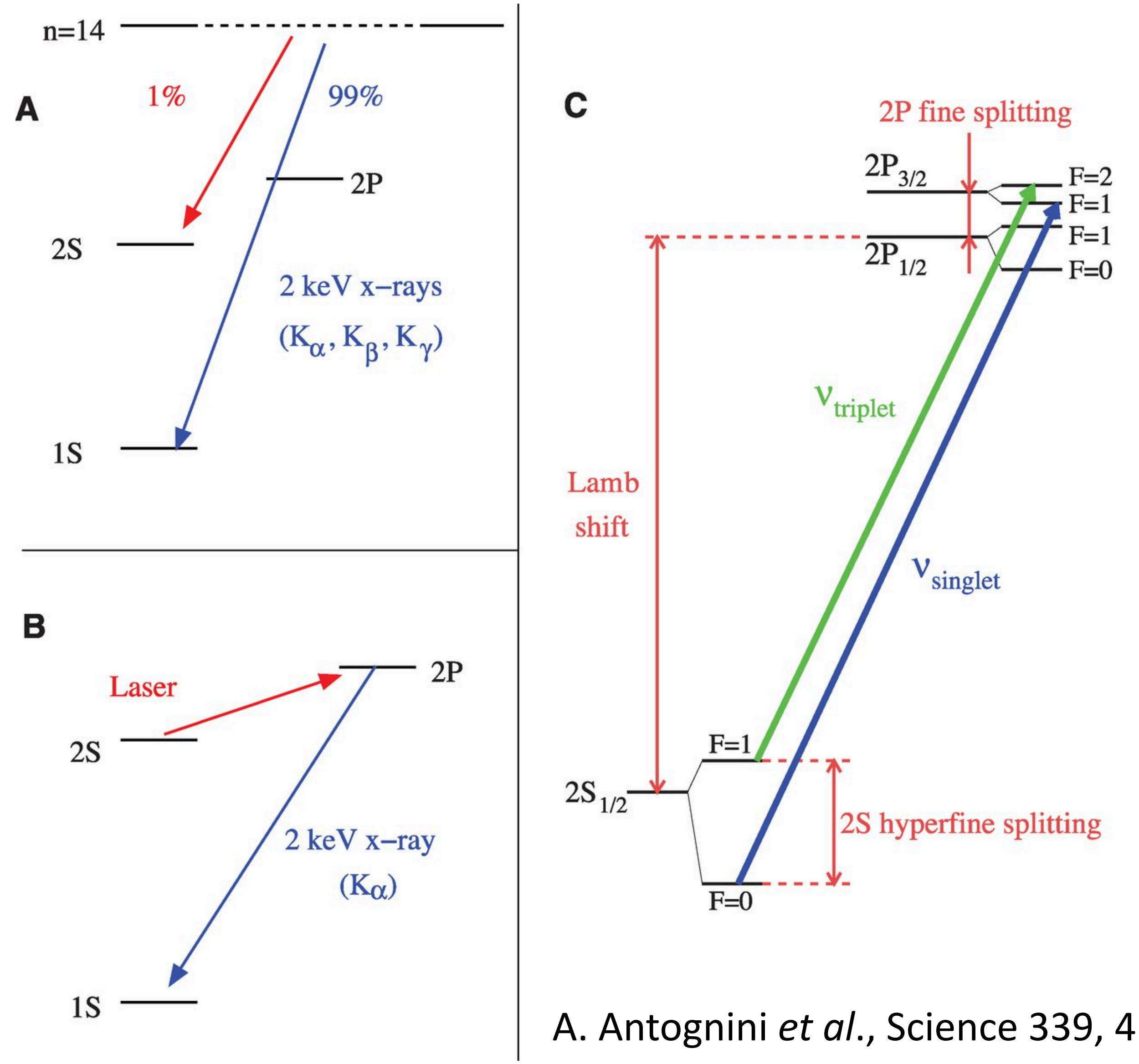
BigBite

- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - $\Delta\Omega$: 96msr
- PS + Scint. + SH



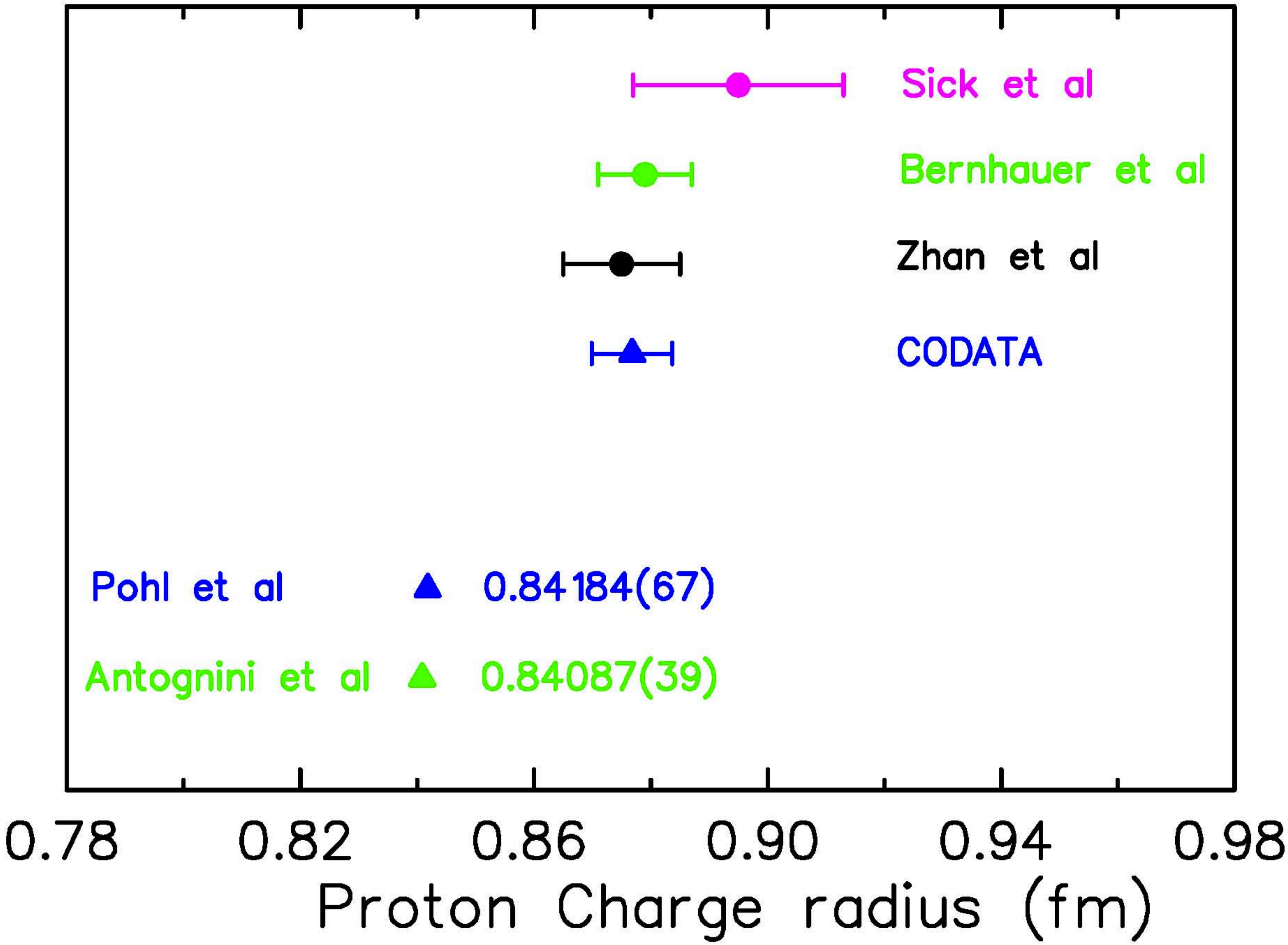
X. Zhan et al. Phys. Lett. B 705 (2011) 59-64
C. Crawford et al. PRL98, 052301 (2007)

New PSI results reported in Science 2013



A. Antognini *et al.*, Science 339, 417 (2013)

The proton radius puzzle intensified



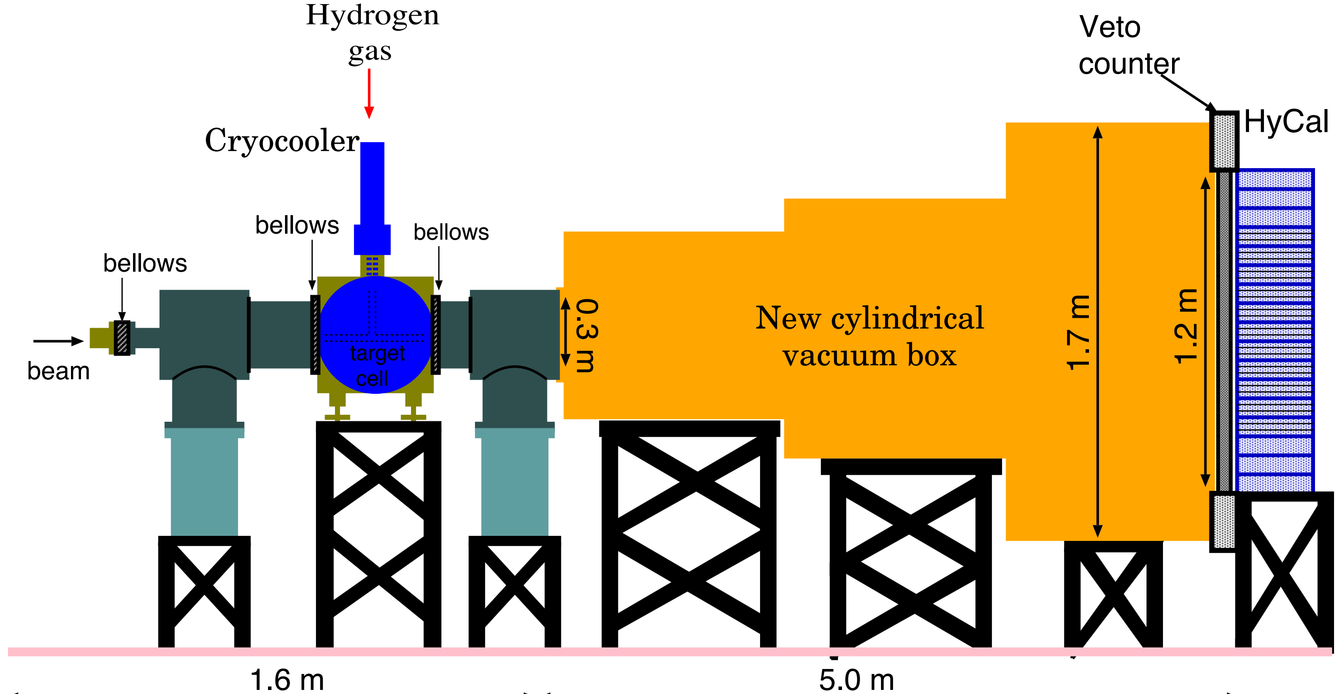
Partial Summary

- New physics: new particles, Barger et al. PRL106,153001 (2011), Carlson and Rislow, arXiv:1206.3587;

  New PV muonic force, Batell et al. PRL 107 (011803) 2011; Quantum gravity at the Fermi scale, R. Onofrio, arXiv:1312.3469;…….
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen, arXiv:1101.5965, arXiv:1109.3779; Jentschura, Annals Phys. 326, 500 (2011), Borie, arXiv:1103:1772, Carroll et al, arXiv:1108.5785, Hill and Gaz, PRL107, 160402(2011); Birse and McGovern, arXiv1206.3030, G.A. Miller 1209.4667, J.M. Alarcon, et al. 1312.1219,….
- Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher, PLB696, 343(2011),..
- Dispersion relations: Lorentz et al. arXiv:1205.6628
- ……………
- New experiments: Mainz (e-d, ISR, Jlab (PRad), PSI (Lamb shift, mu-p scattering), H Lamb shift, ***PRad*** …

PRad Experimental Setup in Hall B

Side View

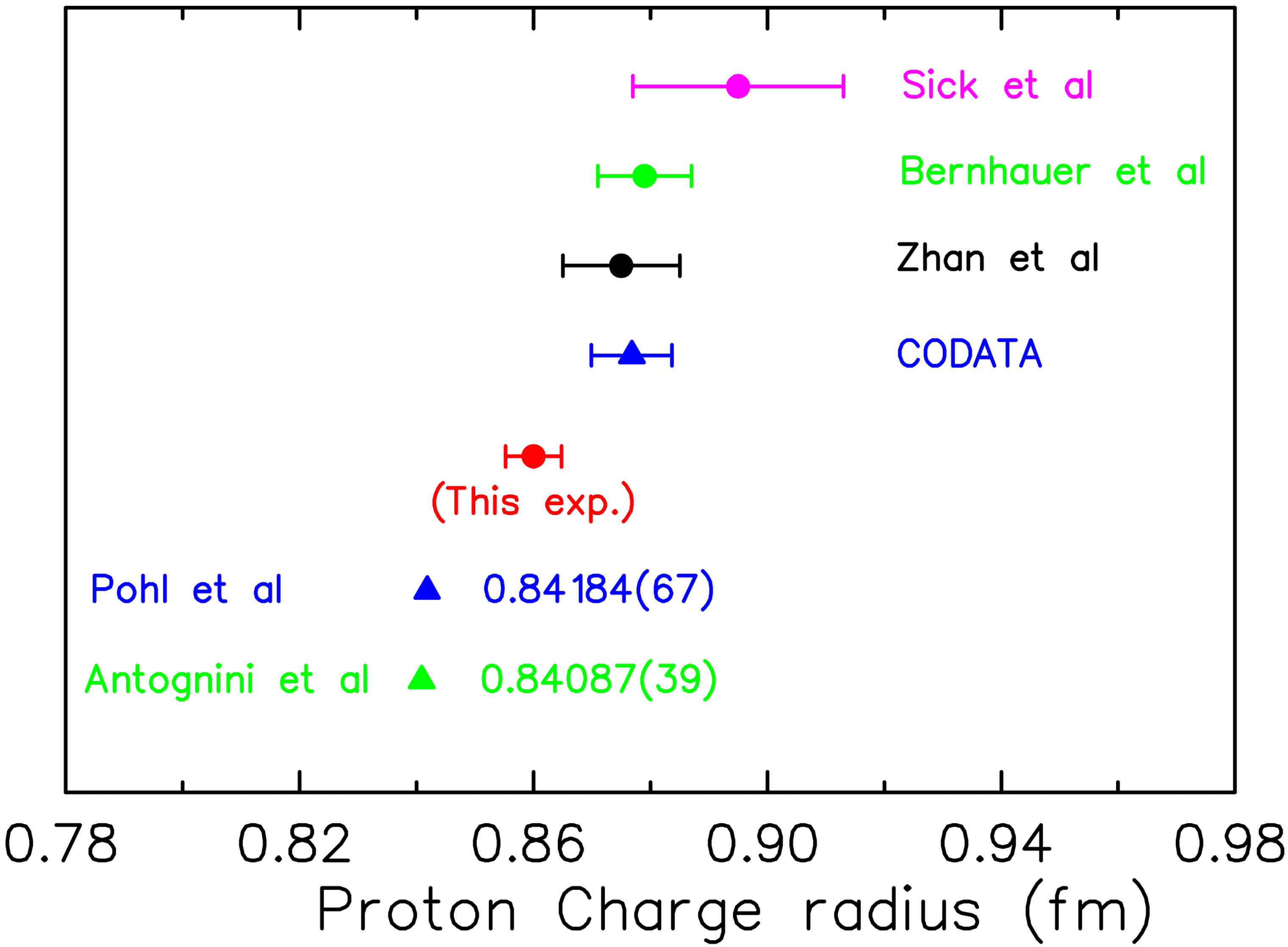


- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of $2x10^{-4} – 2.0x10^{-2}$ GeV^2** (lower than all previous electron scattering expts.)
- **XY – veto counters**
- **Vacuum box, one thin window at HyCal only**

Spokesperson: A. Gasparian, Co-spokespersons: D. Dutta, H. Gao, M. Khandaker

Approved with A rating

Projected Result



Spin as a knob （自旋在物理学中的重要性）

- Spin Milestones: (Nature)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - 1980s: "Proton spin crisis"
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: "New breakthrough in spin physics"?

Recent discovery of Topological insulator

Pauli and Bohr watch a spinning top

Nature: http://www.nature.com/milestones/milespin/index.html

The Incomplete Nucleon: Spin Puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

[X. Ji, 1997]

Jaffe-Manohar 1990

Chen *et al*. 2008

Wakamatsu 2009,2010

- DIS → $\Delta\Sigma \cong 0.30$
- RHIC + DIS → Δg not small
- → L_q

Orbital angular momentum of quarks and gluo
is important

Understanding of spin-orbit correlations
(atomic hydrogen, topological insulator…..)

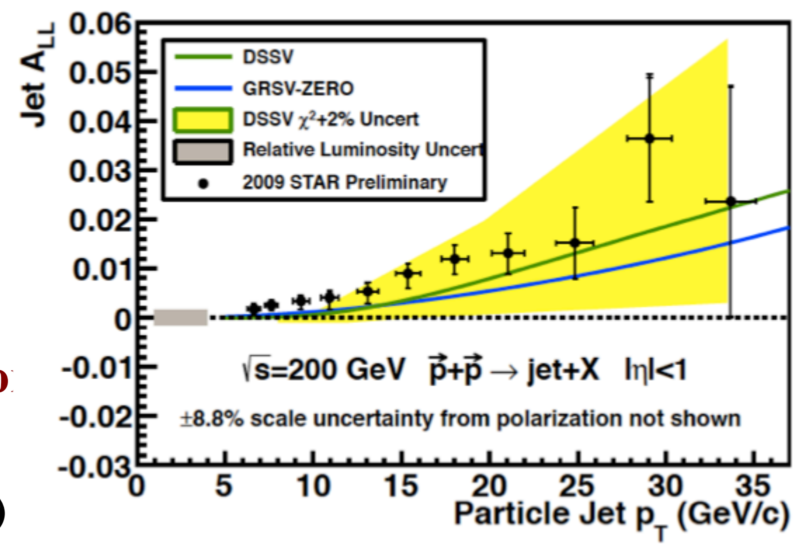


Figure credit to STAR Collaboration

How to access OAM?

Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} = \; - \;$ Boer-Mulders
	L		$g_1 = \; - \;$ Helicity	$h_{1L}^{\perp} = \; - \;$ Long-Transversity
	T	$f_{1T}^{\perp} = \; - \;$ Sivers	$g_{1T} = \; - \;$ Trans-Helicity	$h_1 = \; - \;$ Transversity $h_{1T}^{\perp} = \; - \;$ Pretzelosity

Leading-Twist TMD PDFs

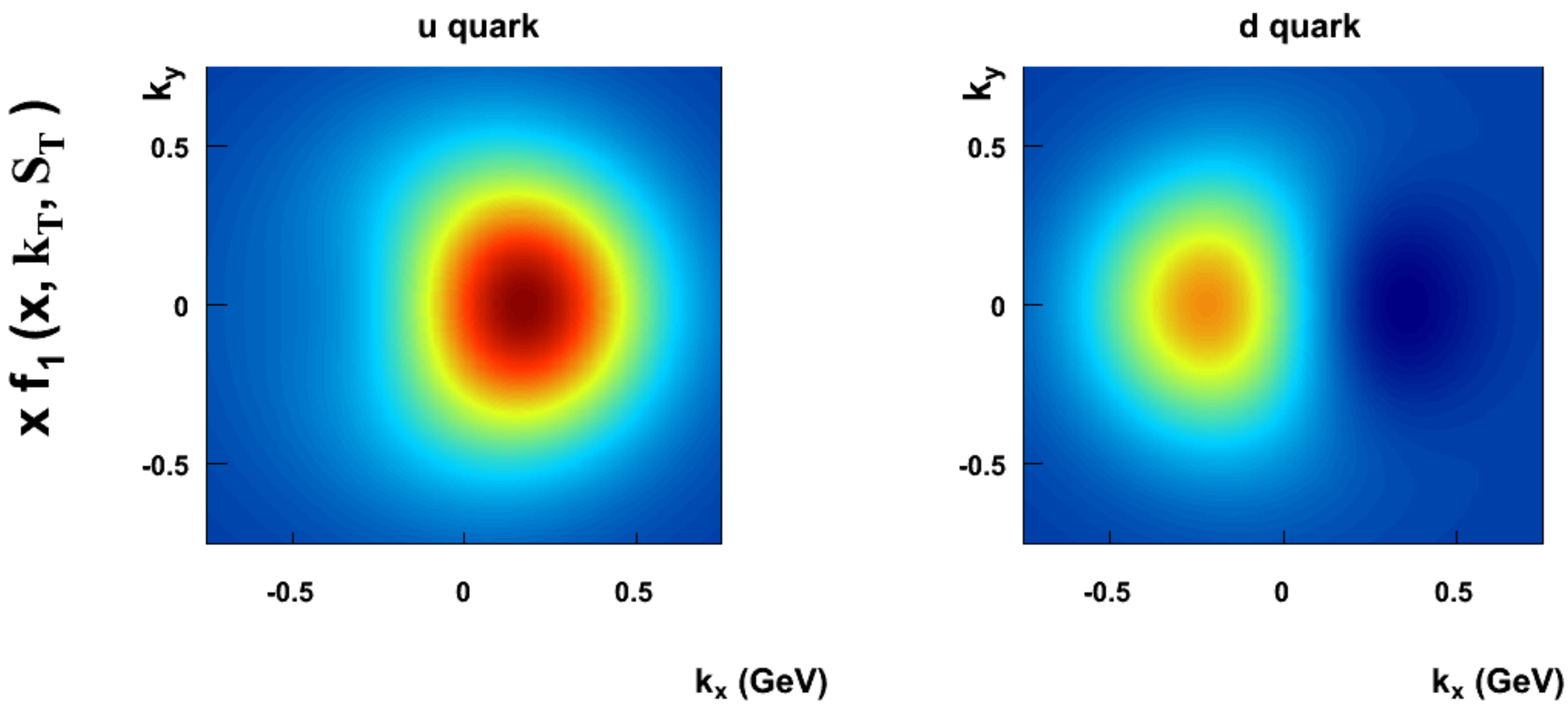
Nucleon Spin
Quark Spin

Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
	L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Long-Transversity
	T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Trans-Helicity	h_1 = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

Nucleon structure in 3-D momentum space!

Sivers $f_{1T}^{\perp}(x, Q^2, k_T)$ *as example @ fixed x, Q^2*

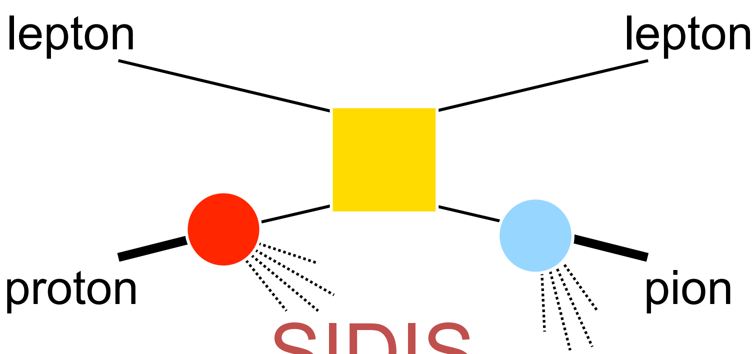
Unpolarized quark distribution in a proton moving in z dir and polarized in y-direction



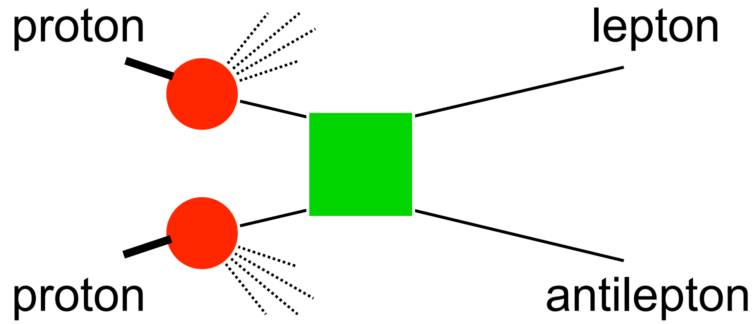
GRV98LO as input x=0.1

http://arxiv.org/pdf/0805.2677v2.pdf **A. Prokudin**

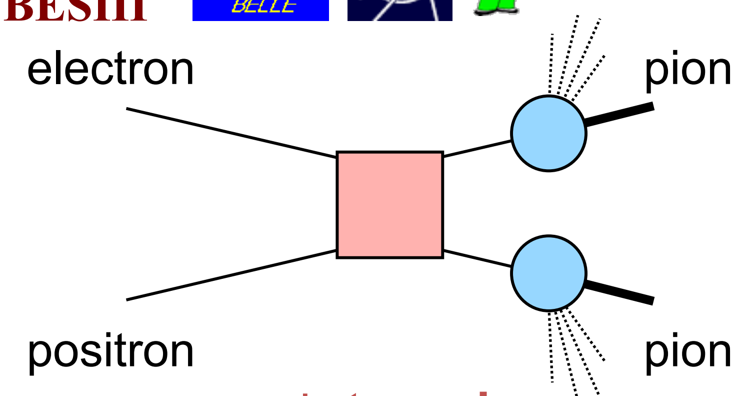
Access TMDs through Hard Processes



SIDIS



Drell-Yan



$e^- e^+$ to pions

- Yellow square: Partonic scattering amplitude
- Light blue circle: Fragmentation amplitude
- Red circle: Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

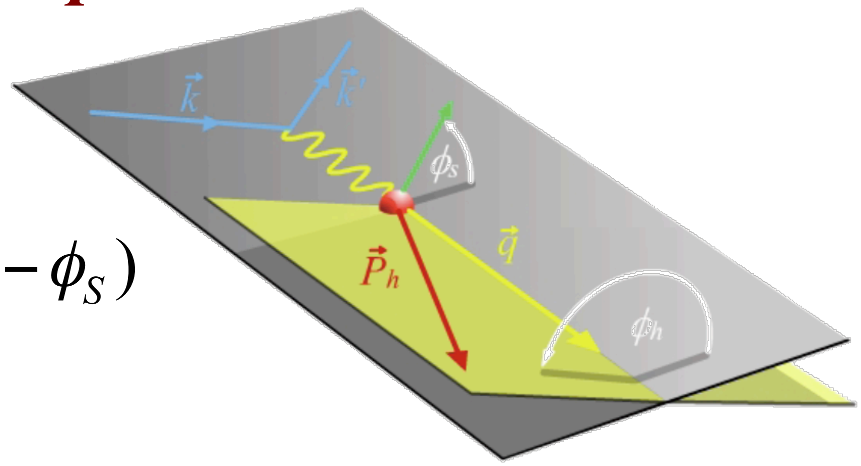
$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l,\varphi_S^l)=\frac{1}{P}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

$$=A_{UT}^{Collins}\sin(\phi_h+\phi_S)+A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

$$+A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S)$$



$$A_{UT}^{Collins}\propto\left\langle\sin(\phi_h+\phi_S)\right\rangle_{UT}\propto h_1\otimes H_1^{\perp}$$

$$A_{UT}^{Sivers}\propto\left\langle\sin(\phi_h-\phi_S)\right\rangle_{UT}\propto f_{1T}^{\perp}\otimes D_1$$

$$A_{UT}^{Pretzelosity}\propto\left\langle\sin(3\phi_h-\phi_S)\right\rangle_{UT}\propto h_{1T}^{\perp}\otimes H_1^{\perp}$$

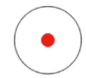
Collins frag. Func. from e^+e^- collisions

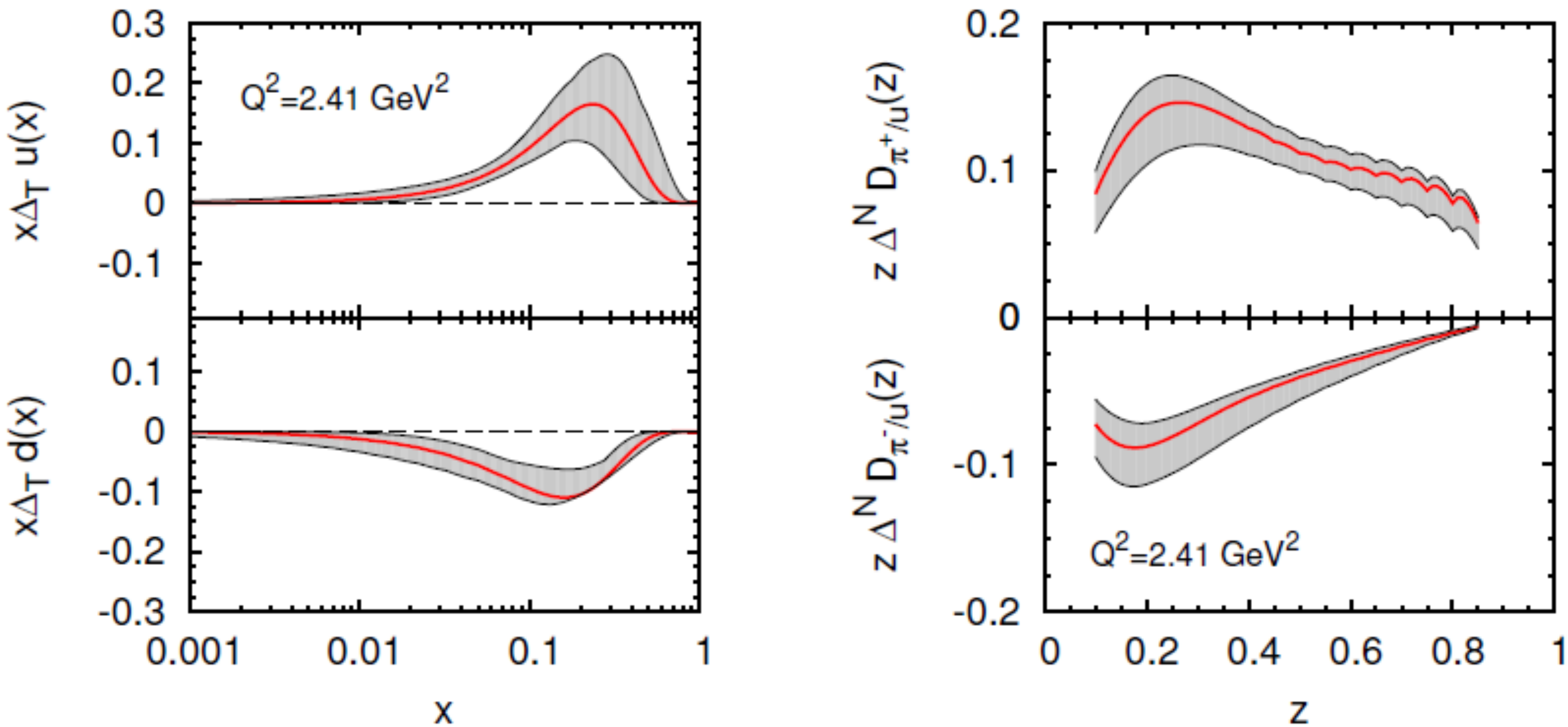
SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

Transversity

h_{1T} = 

- The third PDFs in addition to f_1  and g_{1L} 



$\Delta_T = h_{1T}$

A global fit to the HERMES, COMPASS and BELLE e+e- data
Anselmino et al., arXiv:1303.3822

Transversity

h_{1T} = 

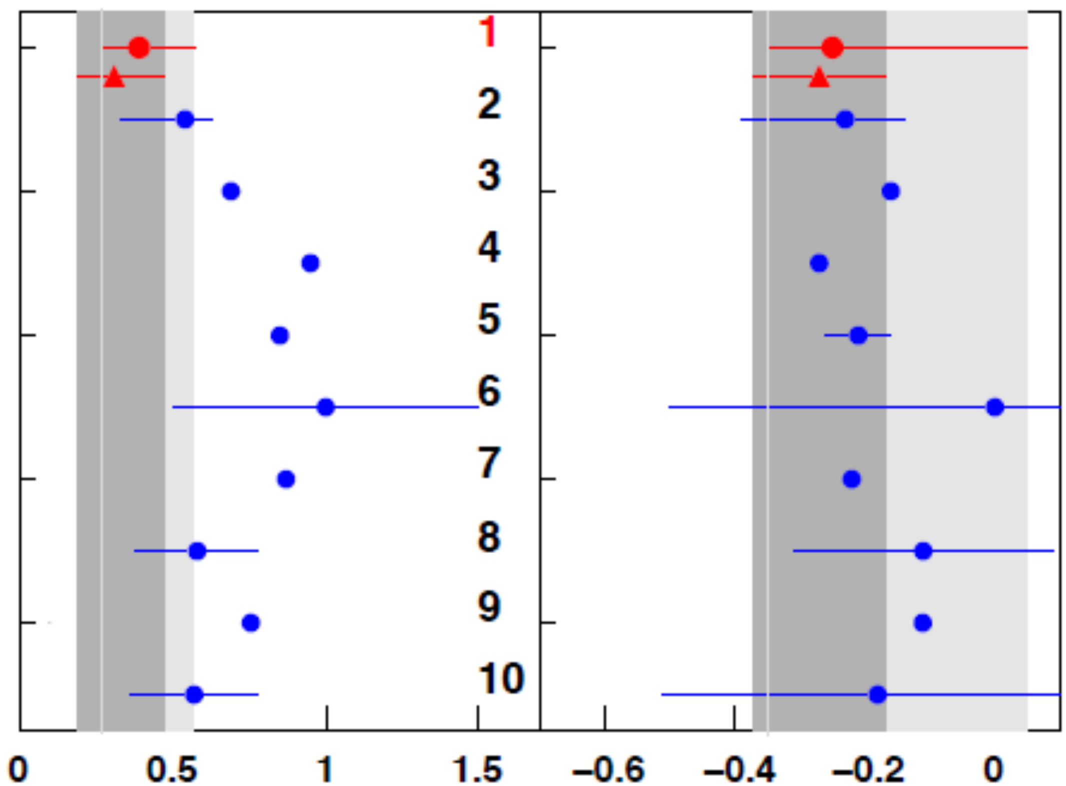
- Lowest moment gives tensor charge

$$\delta q^a = \int_0^1 (h_{1T}^a(x) - h_{1T}^{\bar{a}}(x))dx$$

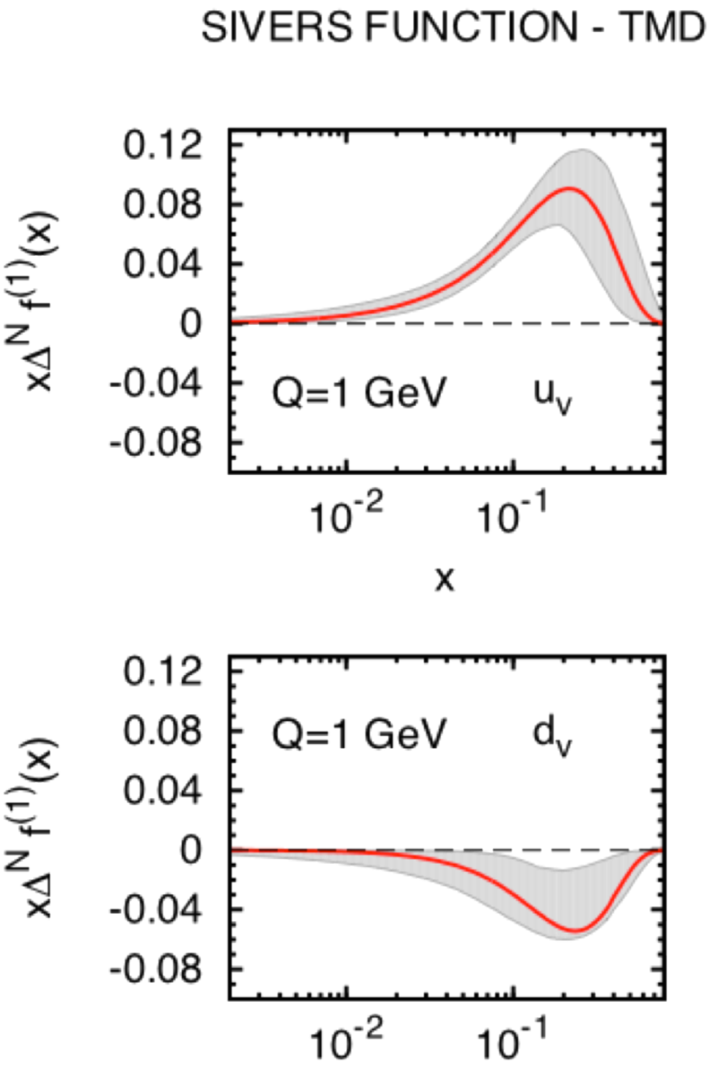
  - Fundamental property, benchmark test of Lattice QCD

● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

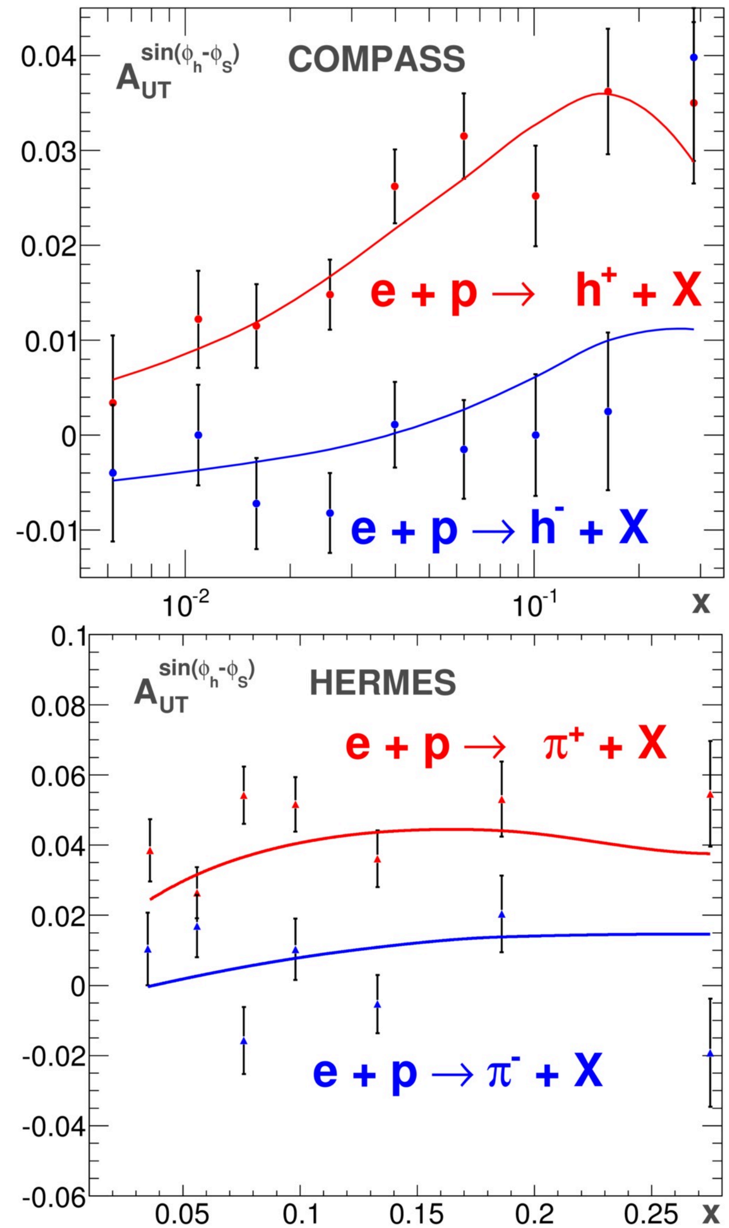
▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$



Anselmino et al., arXiv:1303.3822

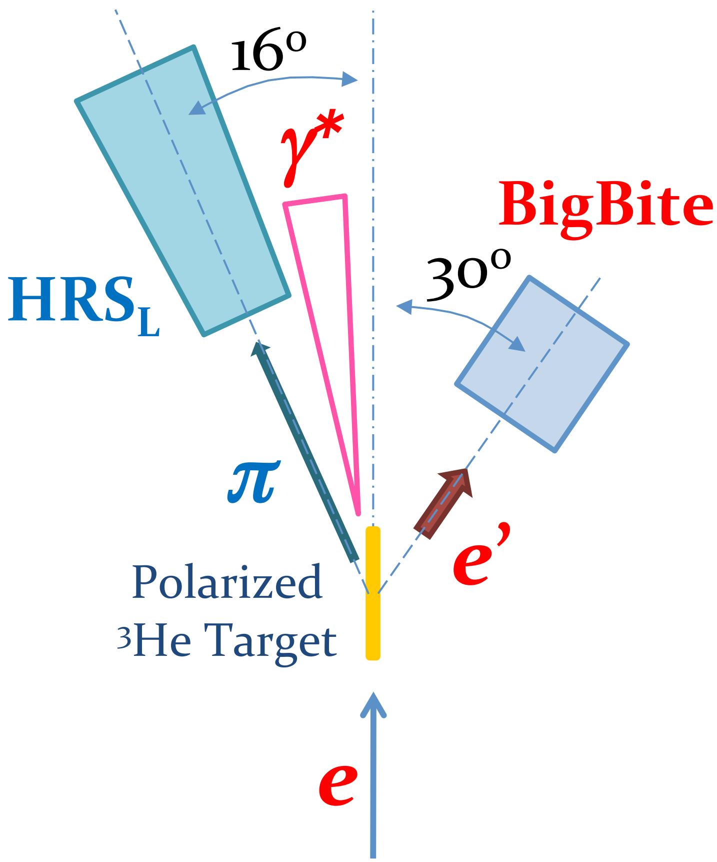


Extraction based on HERMES, COMPASS data arXiv:1204.1239 including TMD evolution



Energy evolution in SIDIS and D-Y
Sun and Yuan, arXiv:1304.5037

$E06\text{-}010$: neutron $A_{(U/L)T}(\pi^+K^+, \pi^-K^-)$



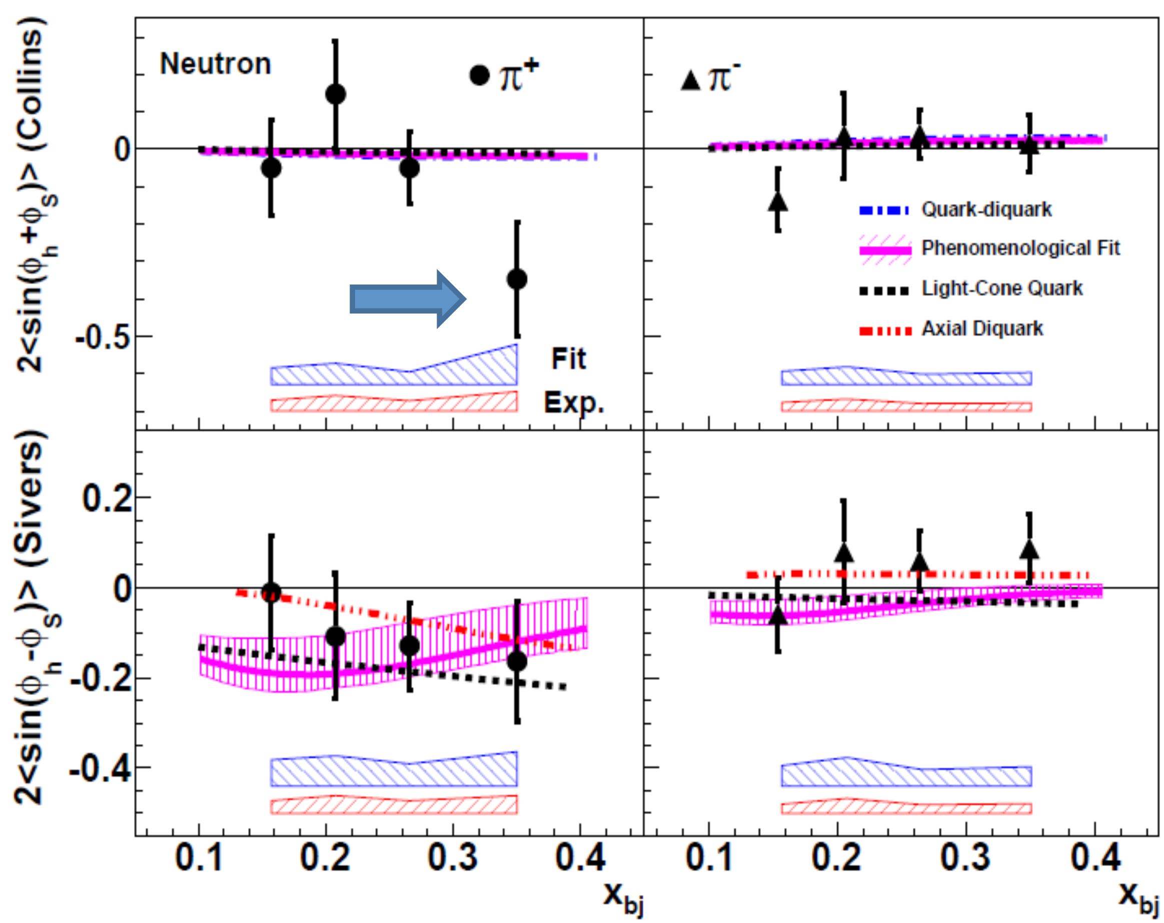
- ***First*** **neutron** data in SIDIS SSA&DSA
  – Similar Q^2 as HERMES experiment
- Disentangle Collins/Sivers effects

- Electron beam: E = 5.9 GeV
- High luminosity L ~ 10^{36} $cm^{-2}s^{-1}$
  - 40 cm transversely polarized ^3He target
  – Average beam current 12 uA (max: 15 uA as in proposal)

- BigBite at 30° as **electron** arm:
  P_e = 0.6 ~ 2.5 GeV/c
- HRSL at 16° as **hadron** arm: P_h = 2.35 GeV/c

Results on Neutron

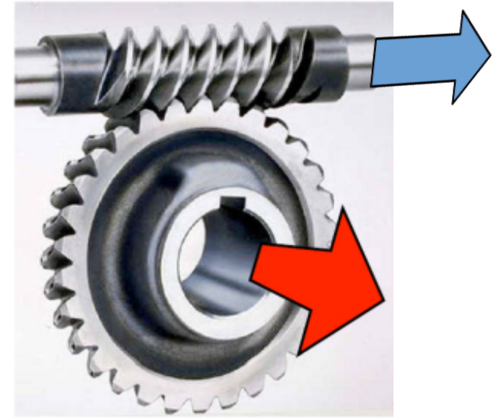
- Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**
- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/ COMPASS
  - **Independent**
  - **demonstration of negative d quark Sivers function.**



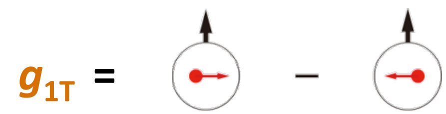
Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

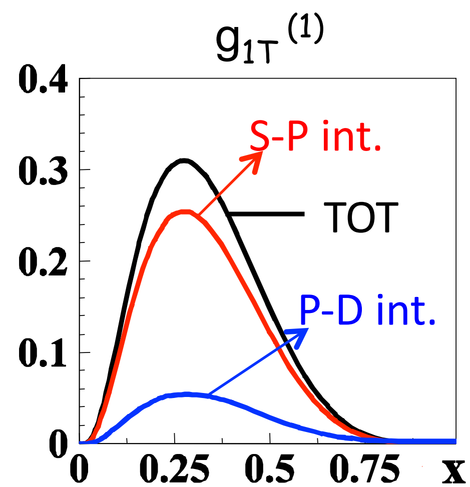
Double Spin Asymmetry: g_{1T}

- $A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$
  - Leading twist TMD PDFs
  - T-even, Chiral-even
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- First TMDs in Pioneer Lattice calculation
  - arXiv:0908.1283 [hep-lat], Europhys.Lett.88:61001,2009
  - arXiv:1011.1213 [hep-lat] , Phys.Rev.D83:094507,2011

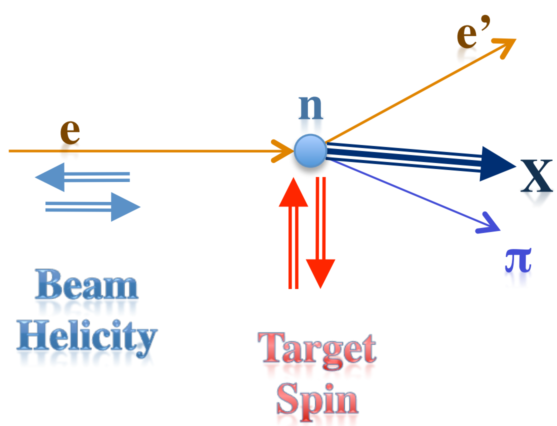


Worm Gear





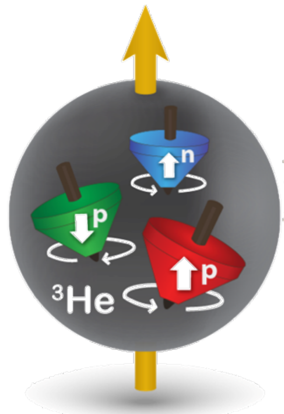
Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008



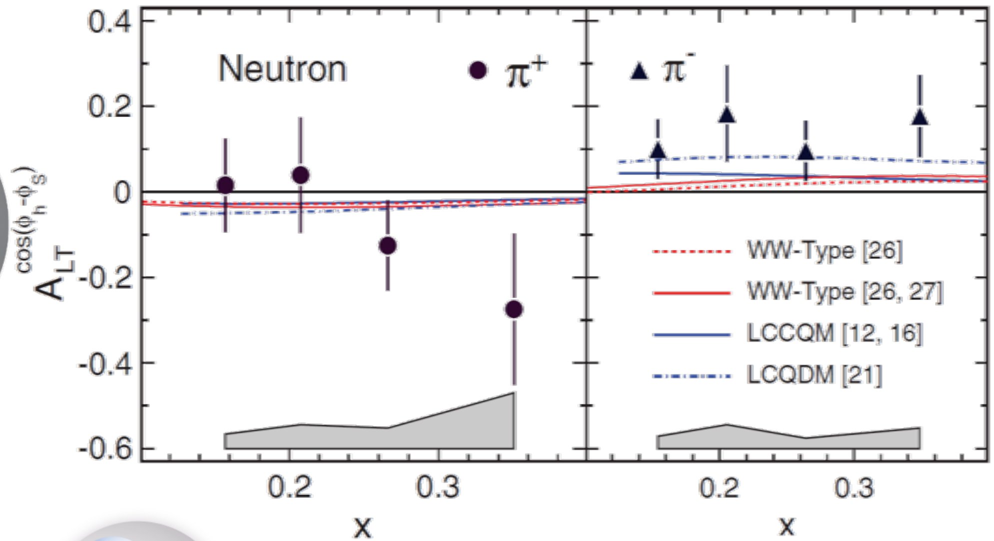
New Observable Reveals Interesting Behaviors of Quarks

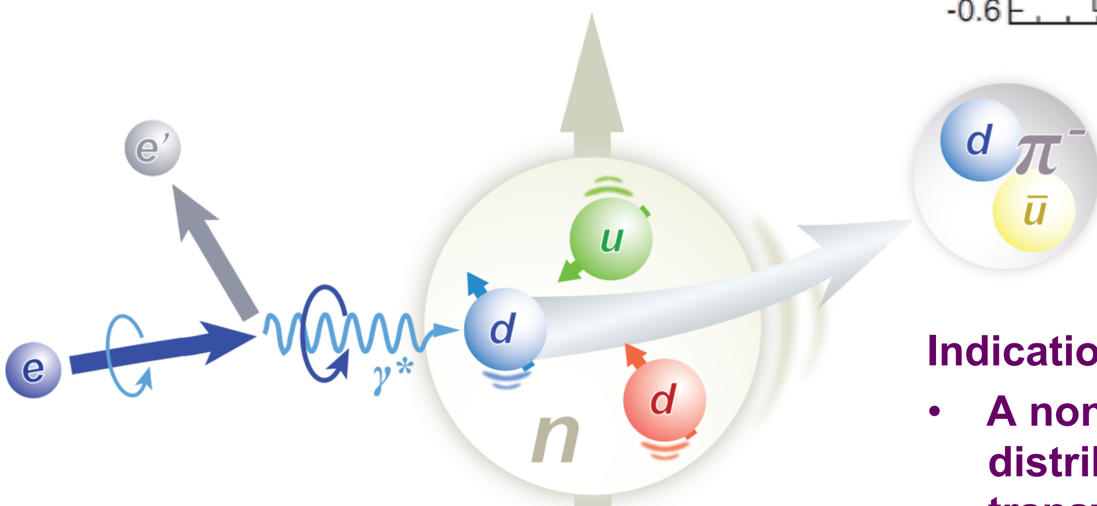
$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Target:
polarized ^{3}He => polarized neutron



Huang, *et. al.* PRL. 108, 052001 (2012)





First measurement of A_{LT}
beam-target double-spin asymmetry

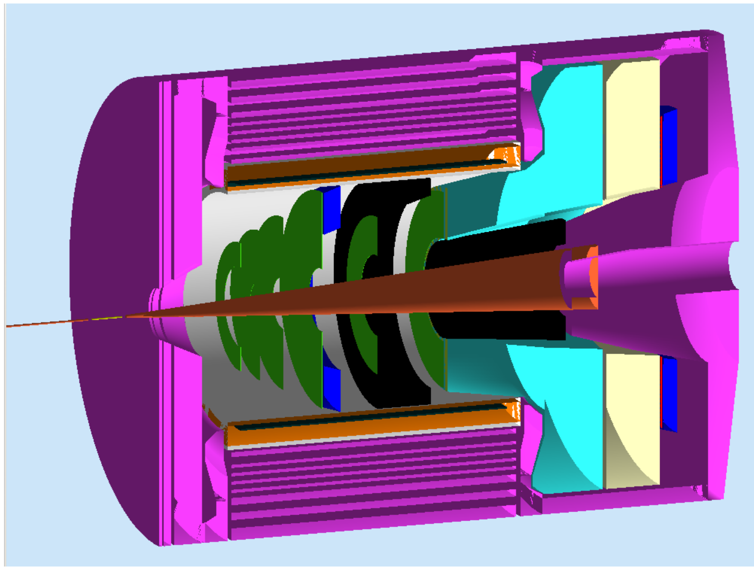
Indications:

- **A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction**
- **Quark orbital motions**

Hermes showed preliminary results from the proton

J. Huang et al., PRL108, 052001 (2012)

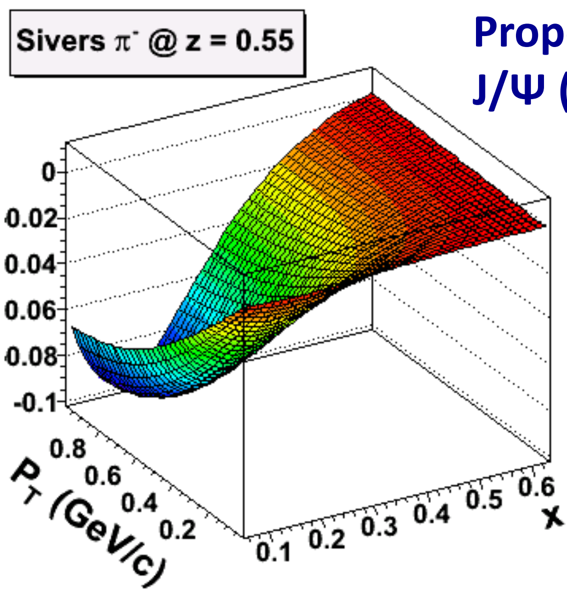
SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV



E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

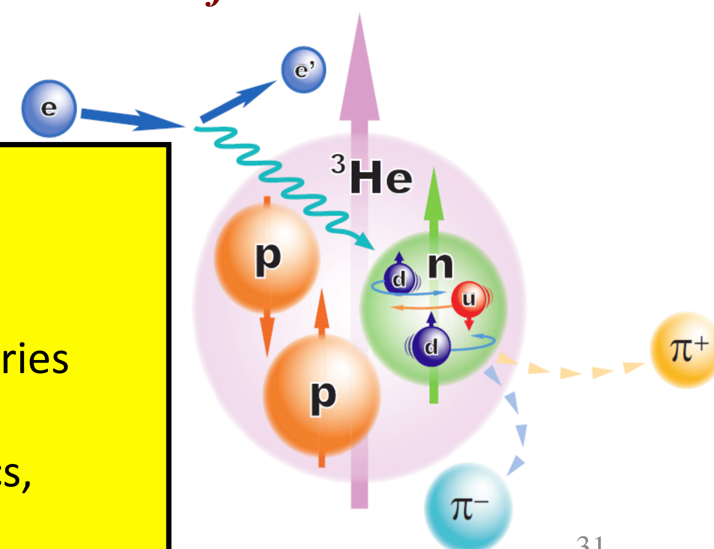
E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**



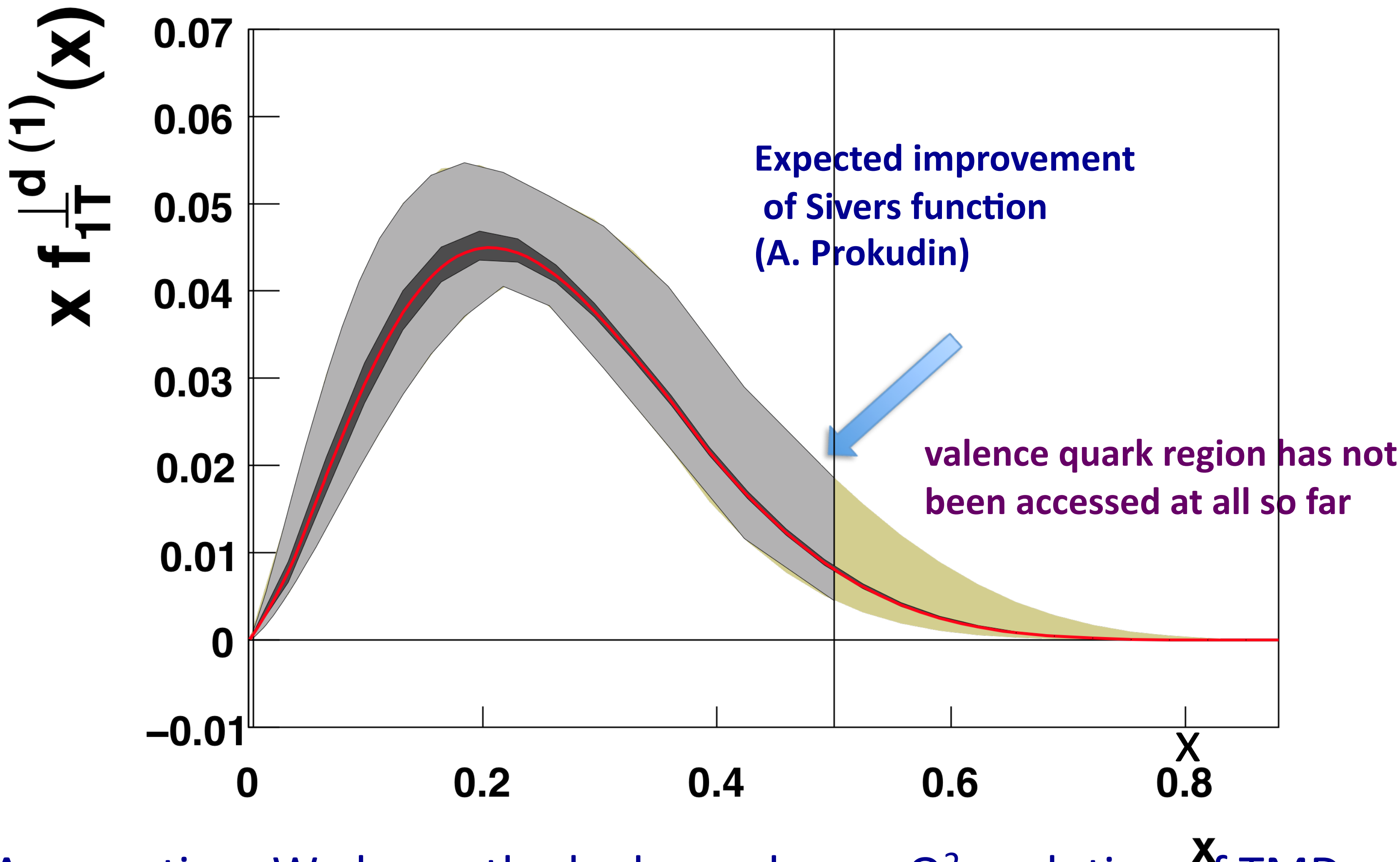
Proposals on PVDIS (A), J/Ψ (A$^-$) approved

International collaboration with 180 Collaborators from 8 countries

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.



Projected measurements in 1-D (x)



Assumption: We know the k_T dependence, Q^2 evolution of TMDs. Also knowledge on TMFF → project onto 1-D in x to illustrate the power of SoLID-^{3}He.

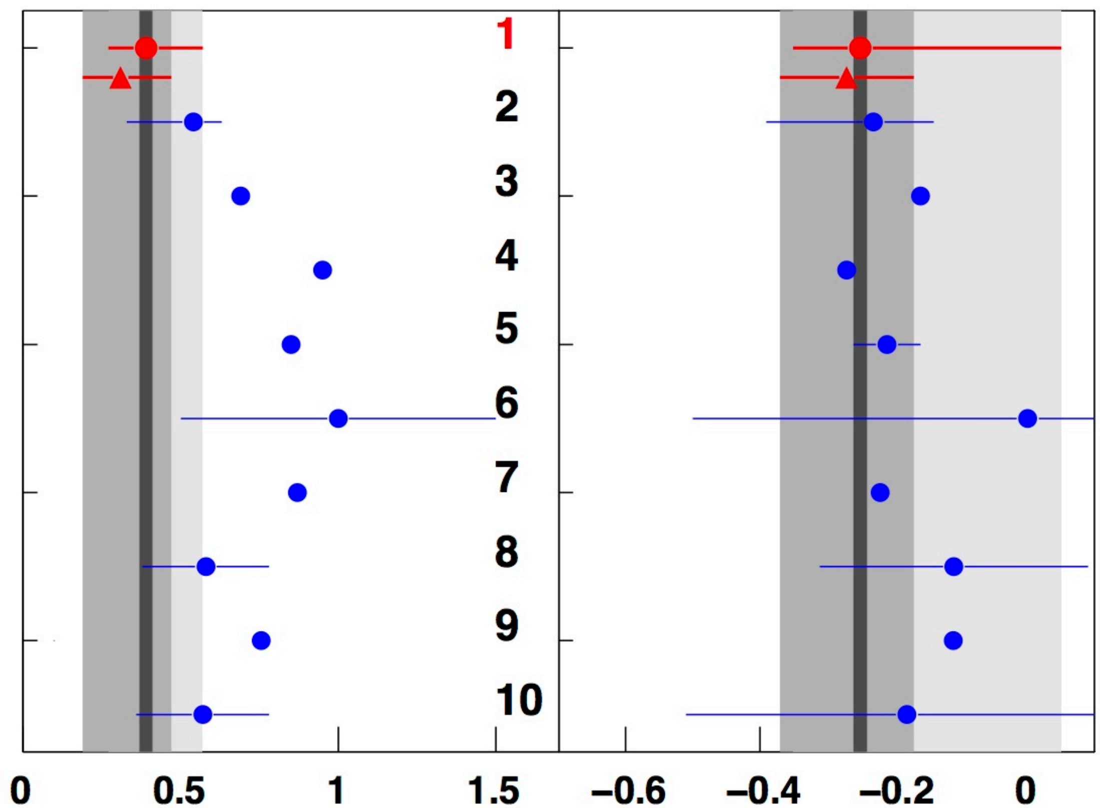
Jlab 12 GeV Program has major impact on Tensor Charge

1 – Anselmino et al (2013)
2 – Anselmino et al., Nucl. Phys. Proc. Suppl. (2009)
3 – Cloet, Bentz and Thomas, Phys. Lett. B (2008)
4 – Wakamatsu, Phys. Lett. B (2007)
5 – Gockeler et al., Phys. Lett. B (2005)
6 – He and Ji, Phys. Rev. D (1995)
7 – Pasquini et al, Phys. Rev. D (2007)
8 – Gamberg and Goldstein, Phys. Rev. Lett. (2001)
9 – Hecht, Roberts and Schmidt, Phys. Rev. C (2001)
10 – Bacchetta, Courtoy, Radici, arXiv:1212.3568

$$\delta q = \int_0^1 dx\, (h_1^q(x) - h_1^{\bar{q}}(x))$$

● $\delta u = 0.39^{+0.18}_{-0.12}$, $\delta d = -0.25^{+0.3}_{-0.1}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$, $\delta d = -0.27^{+0.1}_{-0.1}$



Statistics only

δ u

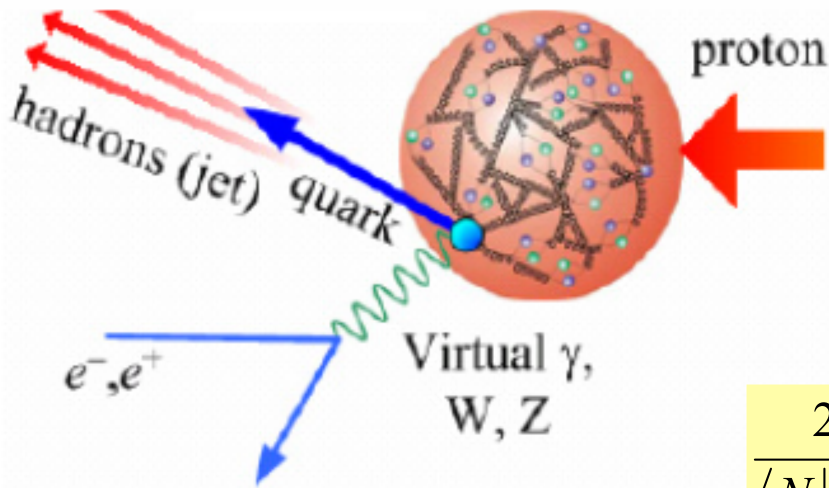
δ d

Thanks to
A. Prokudin

Strange Form Factors

$$J_\mu^{EM} = \sum_q Q_q \langle \overline{N} | \overline{u}_q \gamma_\mu u_q | N \rangle = \overline{N}\left[\gamma_\mu F_1^\gamma + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N} F_2^\gamma\right] N$$

Adopt the Sachs FF: $G_E^\gamma = F_1^\gamma + \tau F_2^\gamma \qquad G_M^\gamma = F_1^\gamma + F_2^\gamma$



Strange quark effect in nucleon structure: momentum, mass, spin, form factor,..

$$\frac{2\int_0^1 [s + \bar{s}]dx}{\int_0^1 [u + \bar{u} + d + \bar{d}]dx} = 0.42 \pm 0.07 \pm 0.06$$

$$\frac{2\langle N | m_s \bar{s}s | N \rangle}{\langle N | \hat{m}(u\bar{u} + d\bar{d}) | N \rangle} \approx 0.4$$

$$\Delta u + \Delta d + \Delta s = 0.20 \pm 0.10$$

$$\Delta s = -0.1 \pm 0.1$$

$$G_{E/M}^\gamma = \frac{2}{3}G_{E/M}^u - \frac{1}{3}G_{E/M}^d - \frac{1}{3}G_{E/M}^s$$

NC probes same hadronic flavor structure, with different couplings:

$$G_{E/M}^Z = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G_{E/M}^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right)G_{E/M}^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right)G_{E/M}^s$$

$G^Z_{E/M}$ provide an important new benchmark for testing non-perturbative QCD structure of the nucleon

PV Electron Scattering and Charge Symmetry

One expects the neutron to be an isospin rotation of the proton :

$$G_{E/M}^{p,u} = G_{E/M}^{n,d}, \qquad G_{E/M}^{p,d} = G_{E/M}^{n,u}, \qquad G_{E/M}^{p,s} = G_{E/M}^{n,s}$$

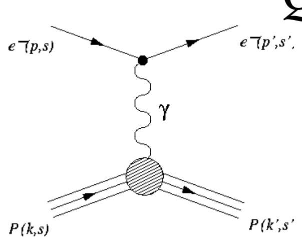
$$G_{E/M}^{\gamma,p} = \frac{2}{3}G_{E/M}^{u} - \frac{1}{3}G_{E/M}^{d} - \frac{1}{3}G_{E/M}^{s} \rightarrow G_{E/M}^{\gamma,n} = \frac{2}{3}G_{E/M}^{d} - \frac{1}{3}G_{E/M}^{u} - \frac{1}{3}G_{E/M}^{s}$$

$G^{\gamma,p}_{E,M}$, $G^{\gamma,n}_{E,M}$, $G^{Z,p}_{E,M}$	Charge symmetry →	$G^{u}_{E,M}$, $G^{d}_{E,M}$, $G^{s}_{E,M}$	Shuffle →	$G^{p}_{E,M}$, $G^{n}_{E,M}$, $G^{s}_{E,M}$

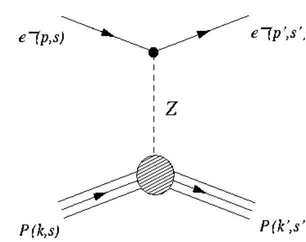
Well Measured ($G^{p}_{E,M}$, $G^{n}_{E,M}$)

$\langle N | \, s\gamma^{\mu} s \, | N \rangle$ ($G^{s}_{E,M}$)

$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q \, \ell^{\mu} J_{\mu}^{EM} \qquad M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}}\left[g_A \ell^{\mu 5} J_{\mu}^{NC} + g_V \ell^{\mu} J_{\mu 5}^{NC} \right]$$

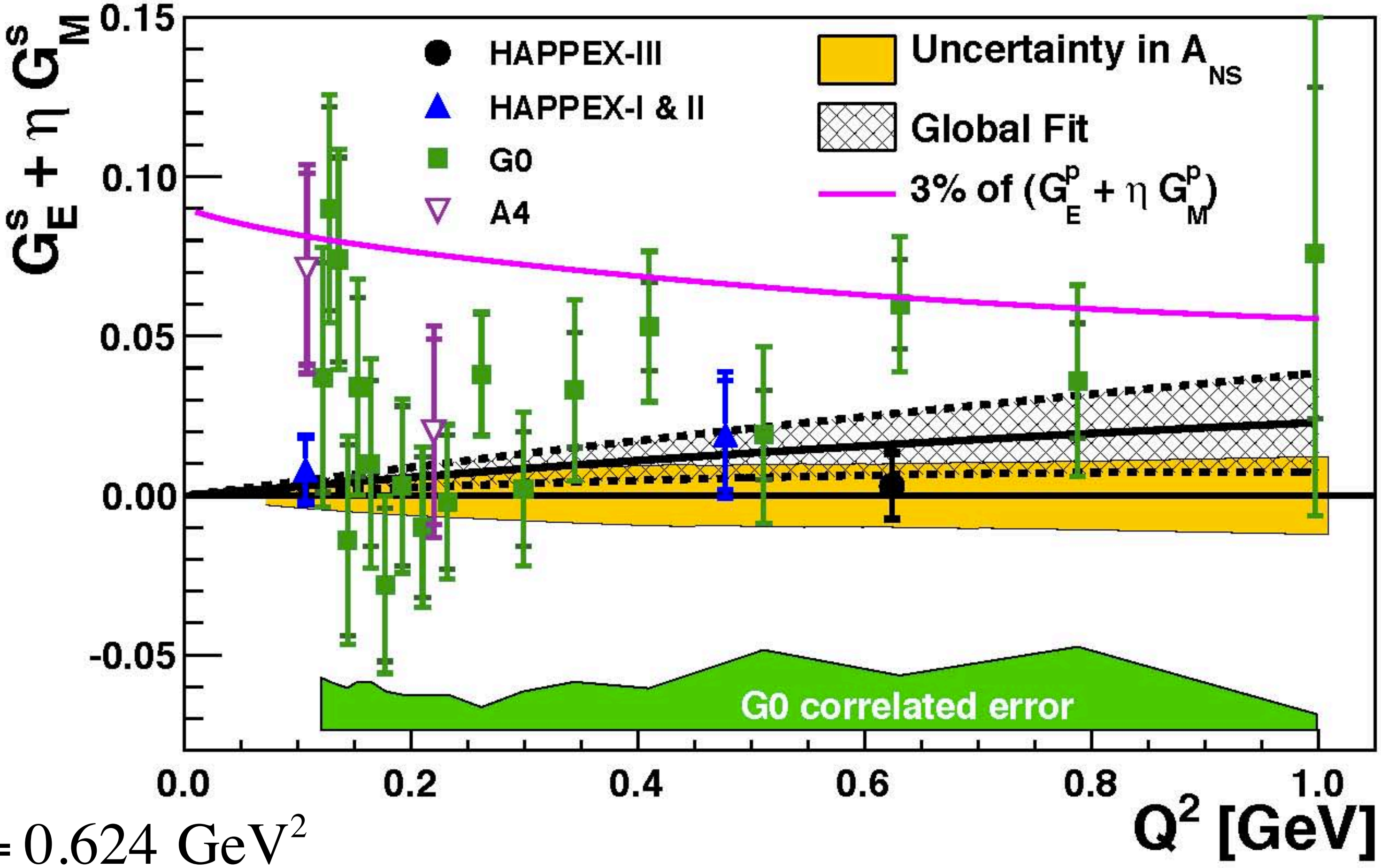


Interference with EM amplitude makes Neutral Current (NC) amplitude accessible



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_\gamma}{|M_\gamma|^2} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha} F\left(G_{E/M}^{p}, G_{E/M}^{n}, G_{E/M}^{s}, G_A\right)$$

Latest from HAPPEX-III together with world results



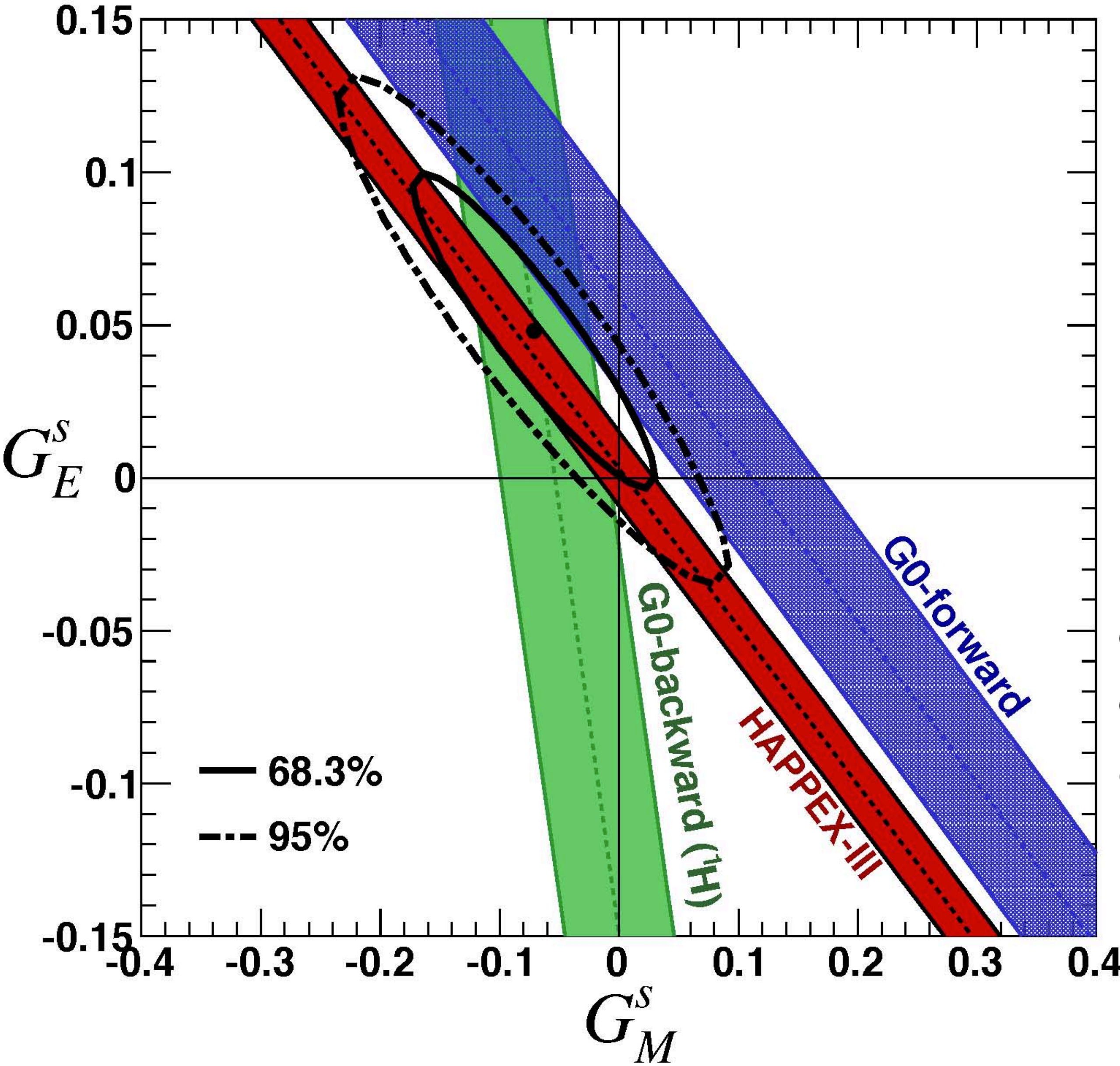
$$Q^2 = 0.624\ \text{GeV}^2$$

$$A_{PV} = -23.80 \pm 0.78(\text{stat}) \pm 0.36(\text{syst})$$

$$G_E^s + 0.517 G_M^s = 0.003 \pm 0.010(\text{stat}) \pm 0.004(\text{syst}) \pm 0.009(\text{ff})$$

The HAPPEX Collaboration, arXiv:1107.0913

Constraints on strange electric and magnetic form factors



$$G_E^s = 0.047 \pm 0.034$$

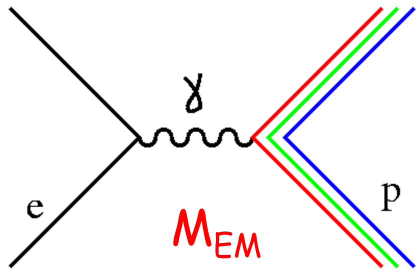
$$G_M^s = -0.070 \pm 0.067$$

correlation coefficient -0.93

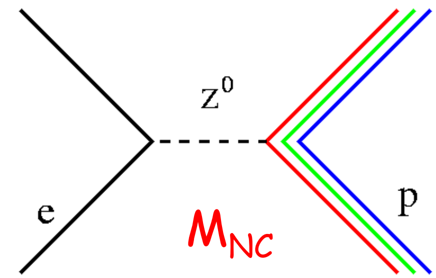
consistent with

$G_E^s = G_M^S = 0$

Q^p_{Weak} : Extract from Parity-Violating Electron Scattering



As $Q^2 \rightarrow 0$



measures Q^p – proton's electric charge

measures Q^p_{Weak} – proton's weak charge

$$A = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + F^p(Q^2,\theta)\right]$$

$$\xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B(Q^2)\right]$$

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$$ (at tree level)

- Q^p_{weak} is a well-defined experimental observable
- Q^p_{weak} has a definite prediction in the electroweak Standard Model

Q^e_{weak} : electron's weak charge is measured in PV Moller scattering (E158)

Slide credit: Stan Kowalski

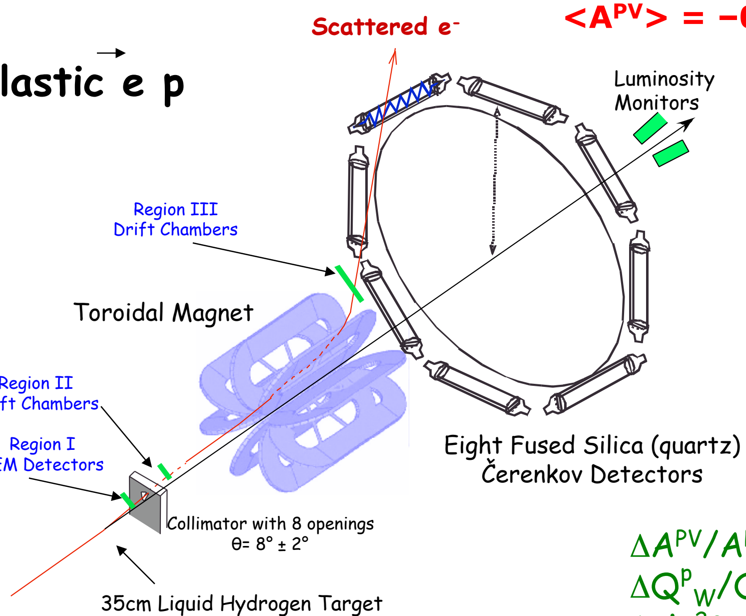
Qweak

Kinematics:

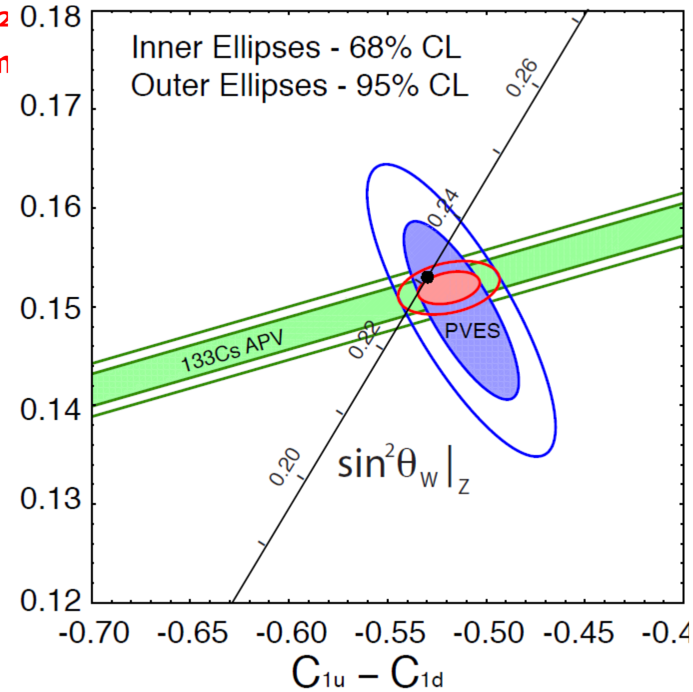
Int. Rate = 6.4 GHz
$\langle Q^2 \rangle$ = 0.030 GeV²
$\langle A^{PV} \rangle$ = −0.29 ppm

Phys. Rev. Lett. 111, 141803 (2013)

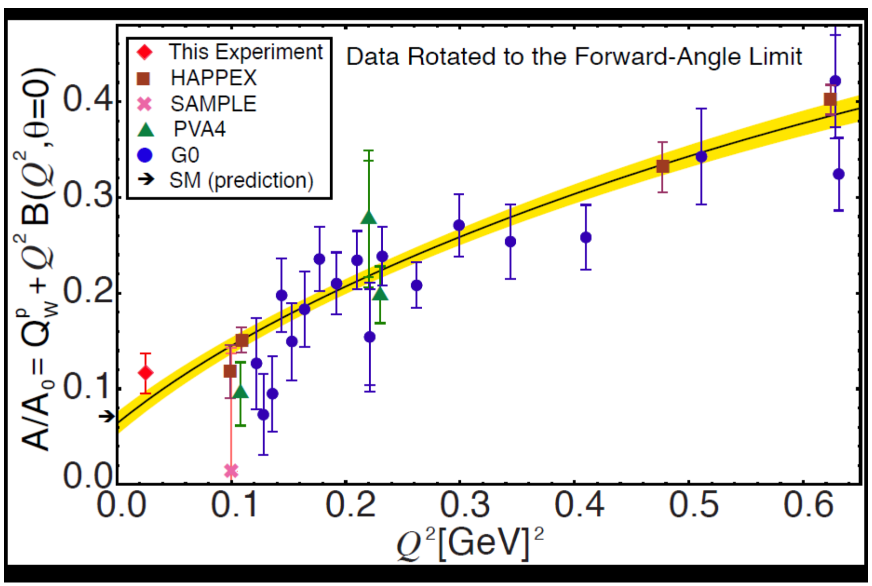
PV in elastic $\vec{e}$ p

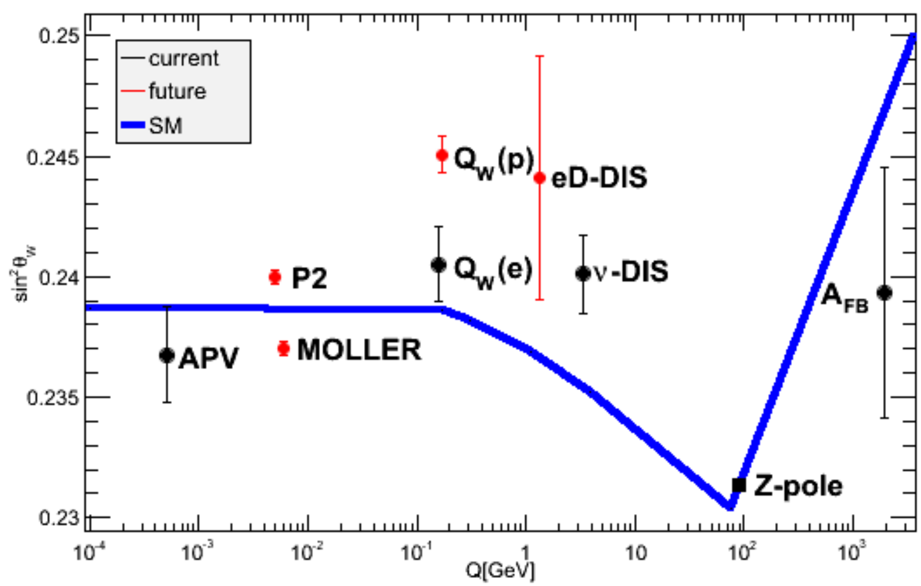


Beam:
E = 1.165 GeV
I = 180 μA
P_e = 85%
LH_2 = 2.5 kW



$\Delta A^{PV}/A^{PV}$=2.2%
$\Delta Q^p_W/Q^p_W$=4%
$\Delta \sin^2\theta_W$=0.0007





Summary

- Lepton scattering is a powerful tool to probe the rich internal structure of the nucleon
- Proton charge radius puzzle prompts intensive theoretical and experimental efforts
  - PRad Experiment (other new experiments)
- Three-dimensional imaging of nucleon helps solve remaining puzzle to proton spin
  - TMDs
    - Three-dimensional description of nucleon in momentum space
    - Transverse motion: spin-orbit correlations, multi-parton correlations, dynamics of confinement and QCD
    - Major advancement has been made both in theory and in experiments – first look at TMDs from SIDIS
- PV electron scattering probing internal structure of the nucleon, testing SM and searching for new physics

Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231