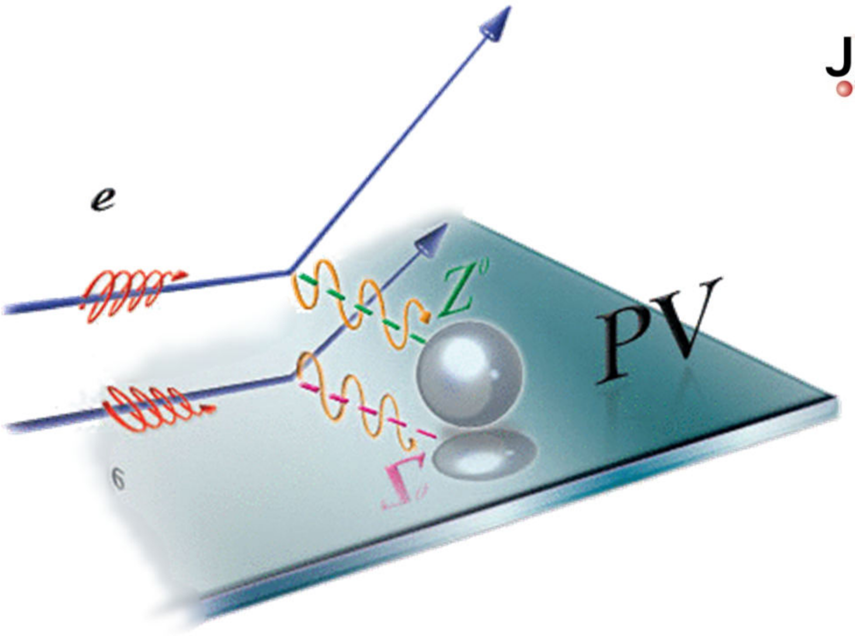
1. Using SBS for new C-REx
2. Strange Quark Program
3. Parity-Violating Deep Inelastic Scattering

Robert Michaels

Jefferson Lab
Thomas Jefferson National Accelerator Facility

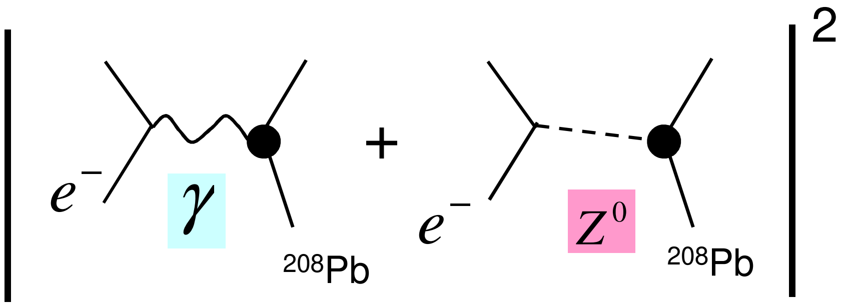


INT Workshop, 2019
Weak Elastic Scattering

Parity Violating Asymmetry

Electron scattering

$\sigma \approx$



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6}$$

Applications of A_{PV} at Jefferson Lab

- Nucleon Structure

  Strangeness $s\,\bar{s}$ in proton (HAPPEX, G0 expts)

- Test of Standard Model of Electroweak $\sin^2\theta_W$

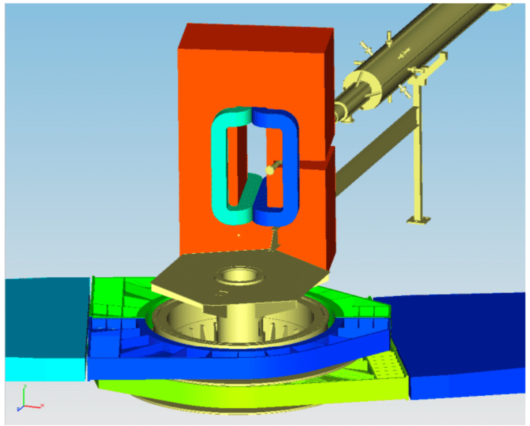
  e – e (MOLLER) or e – q (PVDIS)

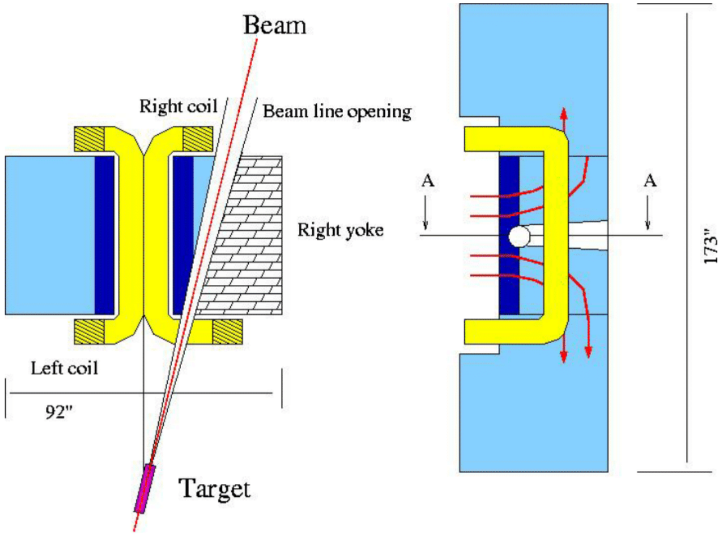
  elastic e – p at low Q^2 (QWEAK)

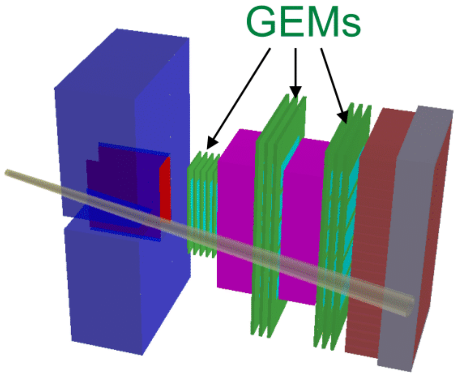
- Nuclear Structure (neutron density) : PREX, CREX

For a possible future C-REX at higher Q^2

Super Bigbite Spectrometer







- Magnet: 48D48 - 46 cm gap, 2-3 Tesla*m
- Solid angle is 70 msr at angle 15 deg.
- GEM chambers with 70 μm resolution
- momentum resolution is 0.5% for 5 GeV/c
- angular resolution is 0.5 mr

Parameters of SBS

Solid angle

$\theta_{central}$, degree	Ω, msr	D, meter	Hor. range, degree	Vert. range, degree
3.5	5	9.5	± 1.3	±3.3
5.0	12	5.8	± 1.9	±4.9
7.5	30	3.2	± 3	±8
15	72	1.6	± 4.8	±12.2
30	76	1.5	± 4.9	±12.5

Resolution:

Momentum =>

$$\frac{\sigma_p}{P} = 0.0029 + 0.0003 \times p[\mathrm{GeV}]$$

Angular =>

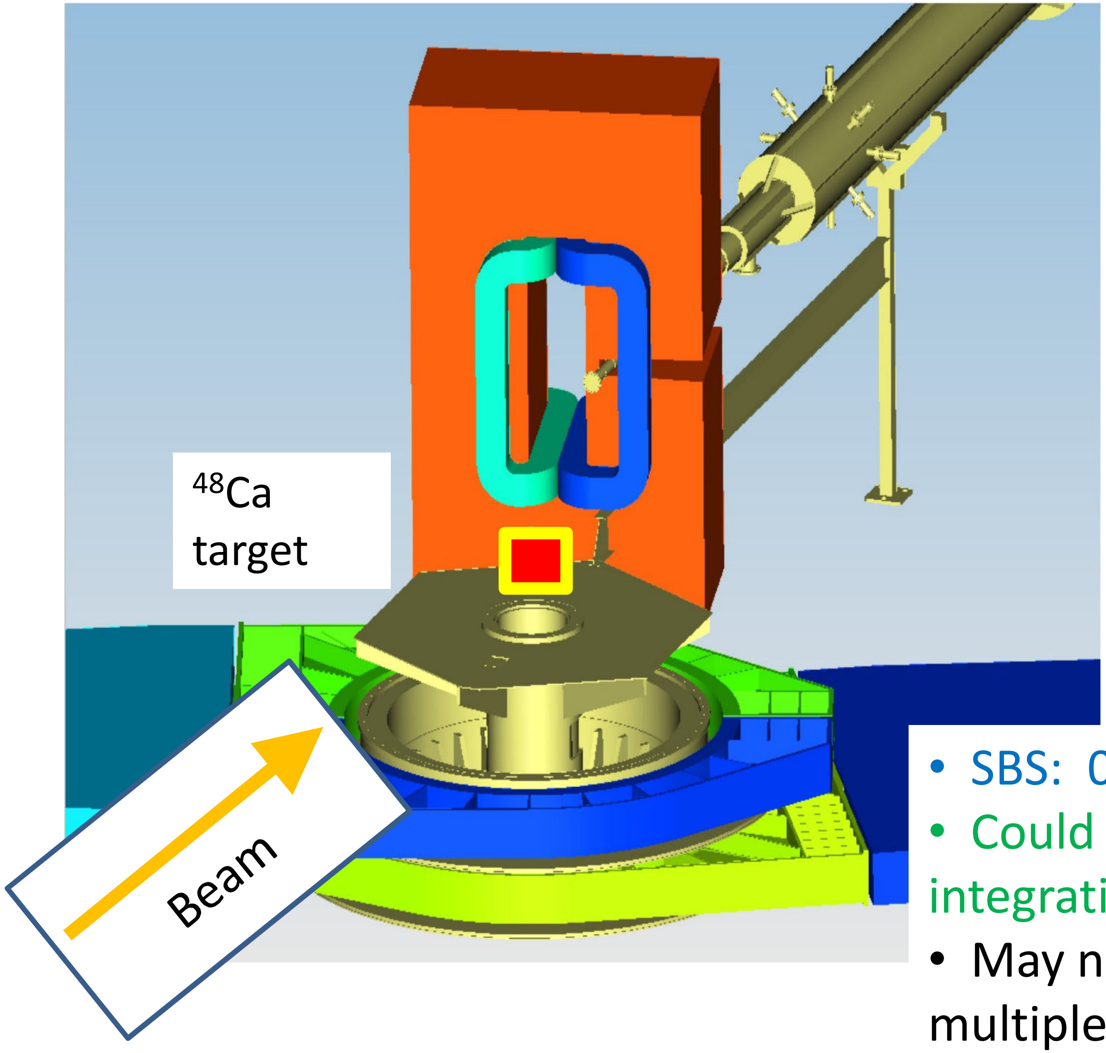
$$\sigma_\theta = 0.14 + 1.3/p \ [\mathrm{GeV}], \mathrm{mrad}$$

Momentum
acceptance =>

$$P \text{ range from } 2 - 10 \quad , \mathrm{GeV/c}$$

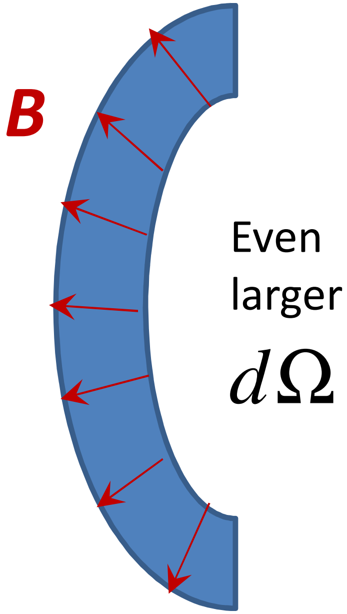
Using SuperBigBite Spectrometer

$d\Omega$ large, but varies with angle setting



or a new Crescent - shaped Spectrometer

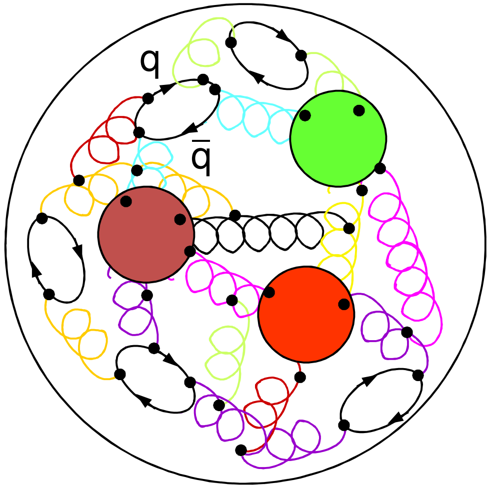
(Bogdan Wojtsekhowski)



- SBS: 0.35% momentum resolution
- Could be improved (~1/2) by putting integrating detector near wall of hall A.
- May need helium bag to reduce multiple scattering.

Historical Review: Strange Quarks in Nucleons

What is a proton made of ?



- Parity violating electron scattering provides a third, independent constraint on the vector form factors of the nucleon.

- Early theoretical motivations to look for strangeness effects ($s\bar{s}$), for example:

D.B. Kaplan, A. Manohar Nucl. Phys. **B310** (1988) 527

- Here I briefly summarize the experimental and theoretical conclusions that the strangeness form factors are “small”, i.e. at most a few percent of the electromagnetic FF.

Quark Currents in the Nucleon

R.D. McKeown, Phys. Lett. B **219** (1989) 140

D.H. Beck, PRD **39** (1989) 3248.

Measure $G^{\gamma,p}, G^{Z,p}, G^{\gamma,n}$:

$$G \sim \left\langle N \middle| \sum_i e_i \bar{q}_i \Gamma_\mu q_i \middle| N \right\rangle$$

e.g.

$$G^{\gamma,p}_{E,M} = \frac{2}{3} G^{u,p}_{E,M} - \frac{1}{3}\left(G^{d,p}_{E,M} + G^{s,p}_{E,M}\right)$$

Assume charge symmetry

$$\left.\begin{aligned} G^{u,p} &= G^{d,n} \\ G^{d,p} &= G^{u,n} \\ G^{s,p} &= G^{s,n} \end{aligned}\right\}$$

G. A. Miller PRC **57** (1998) 1492.

R. Lewis, N. Mobed PRD **59** (1999) 073002

B. Kubis, R. Lewis PRC **74** (2006) 015204

therefore

$$G^{u}_{E,M} = \left(3 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{Z,p}_{E,M}$$

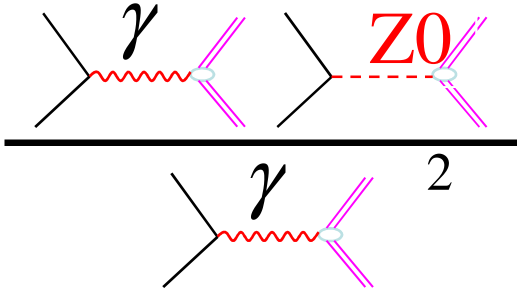
$$G^{d}_{E,M} = \left(2 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} + G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}$$

$$G^{s}_{E,M} = \left(1 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}$$

dropping the *p* superscripts on the left

Measuring Strange Vector Form Factors

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$



$$\sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

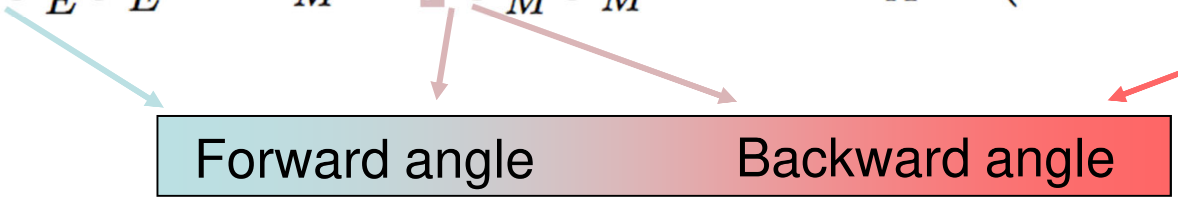
Interference with EM amplitude makes Neutral Current (NC) amplitude accessible

For a proton:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

~ few parts per million

$$A_E = \epsilon G_E^p G_E^Z \qquad A_M = \tau G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$



Forward angle

Backward angle

For spin=0,T=0 ^{4}He:

G^s_E only !

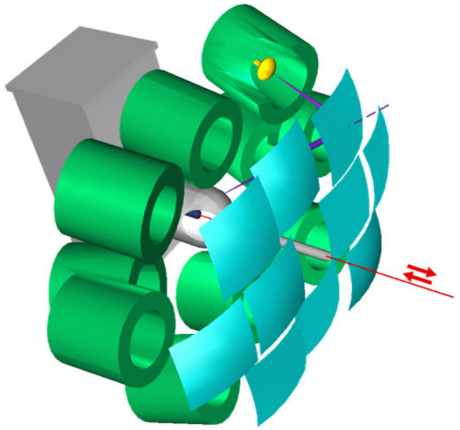
nuclear corrections: forward angle, low Q^2 only

For deuterium:

Enhanced G_A

Back-angle quasi-elastic.

20 year World-Wide Effort on Strange Quarks



SAMPLE

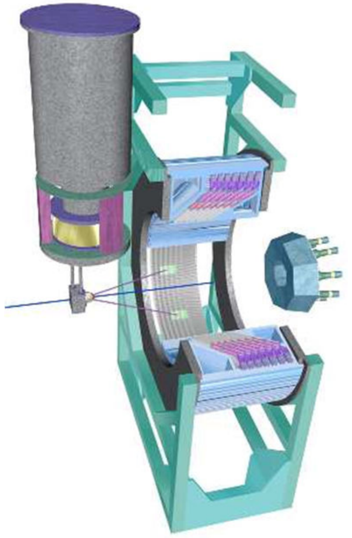
open geometry,
integrating,
back-angle only

A4

Open geometry

Fast counting calorimeter for background rejection

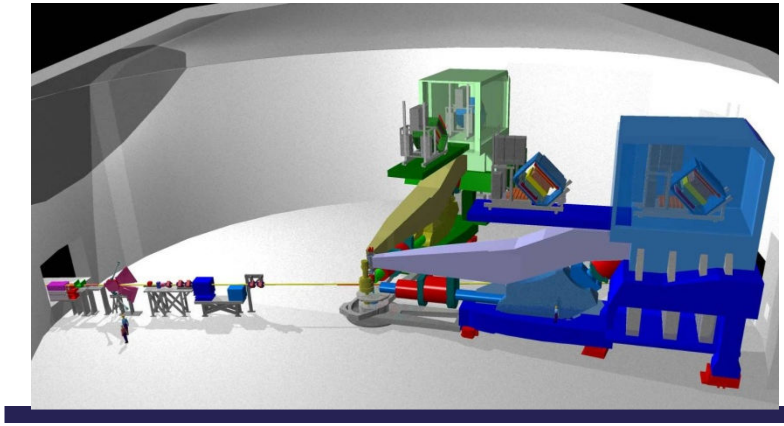
Forward and Backward angles



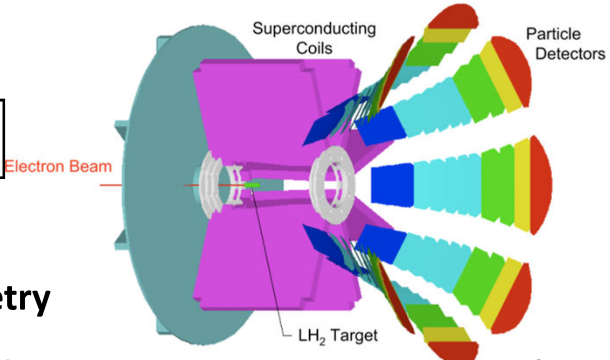
HAPPEX

Precision spectrometer, integrating

Forward angle, also ^{4}He at low Q^2



G0

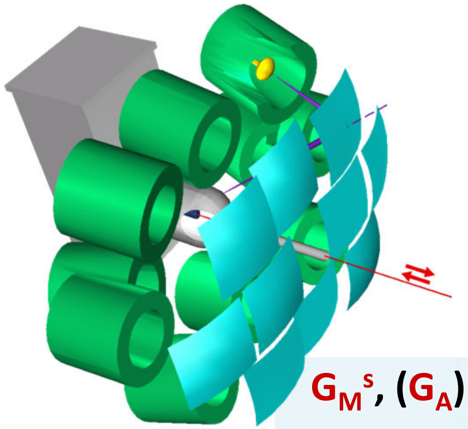


Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

Forward and Backward angles over a range of Q^2

Kinematics of World Data



SAMPLE

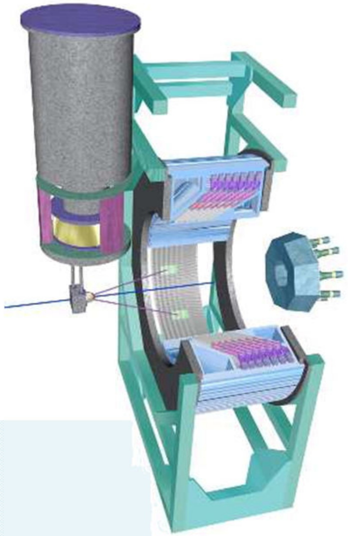
open geometry, integrating

G_M^s, (G_A) at $Q^2 = 0.1$ GeV^2

A4

Open geometry

Fast counting calorimeter for background rejection



$G_E^s + 0.23\ G_M^s$ at $Q^2 = 0.23$ GeV^2

$G_E^s + 0.10\ G_M^s$ at $Q^2 = 0.1$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23$ GeV^2

HAPPEX

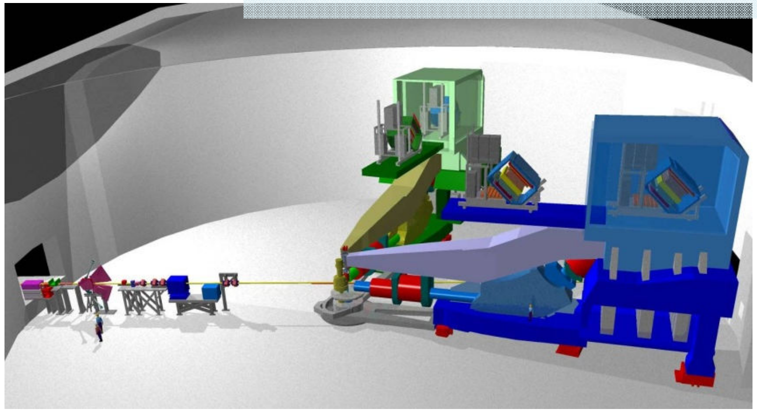
Precision spectrometer, integrating

$G_E^s + 0.39\ G_M^s$ at $Q^2 = 0.48$ GeV^2

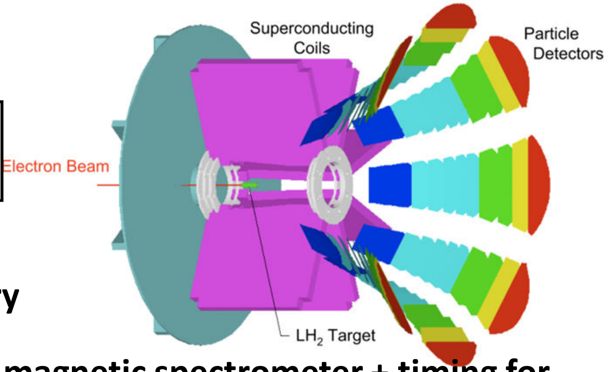
$G_E^s + 0.08\ G_M^s$ at $Q^2 = 0.1$ GeV^2

G_E^s at $Q^2 = 0.1$ GeV^2 (^{4}He)

$G_E^s + 0.48\ G_M^s$ at $Q^2 = 0.62$ GeV^2



G0



Open geometry

Fast counting with magnetic spectrometer + timing for background rejection

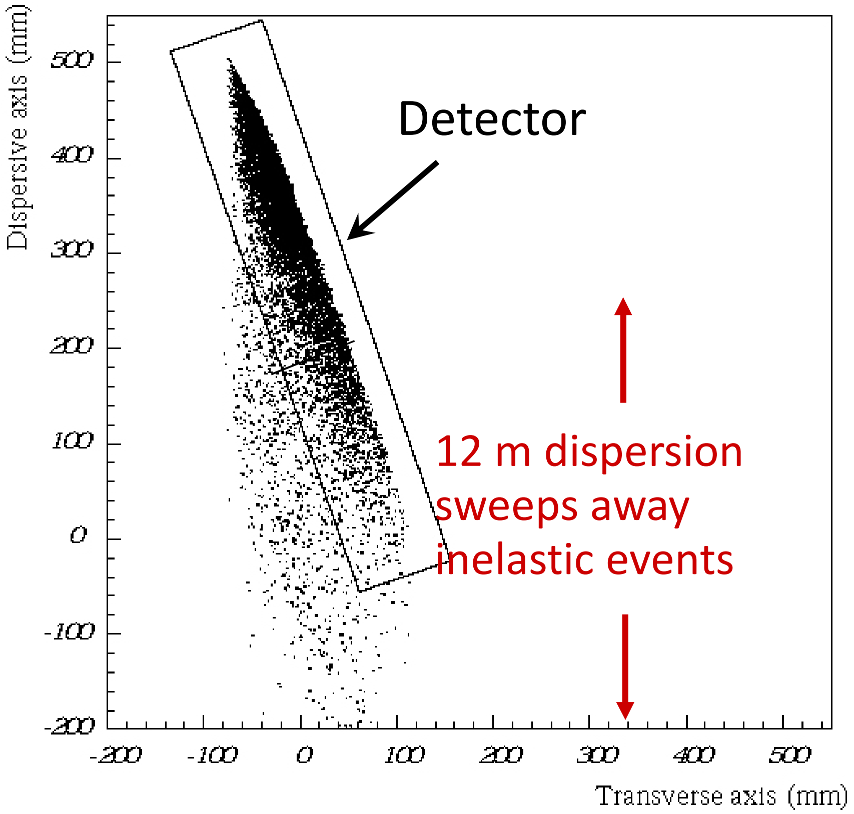
$G_E^s + \eta\ G_M^s$ over $Q^2 = [0.12,1.0]$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23, 0.62$ GeV^2

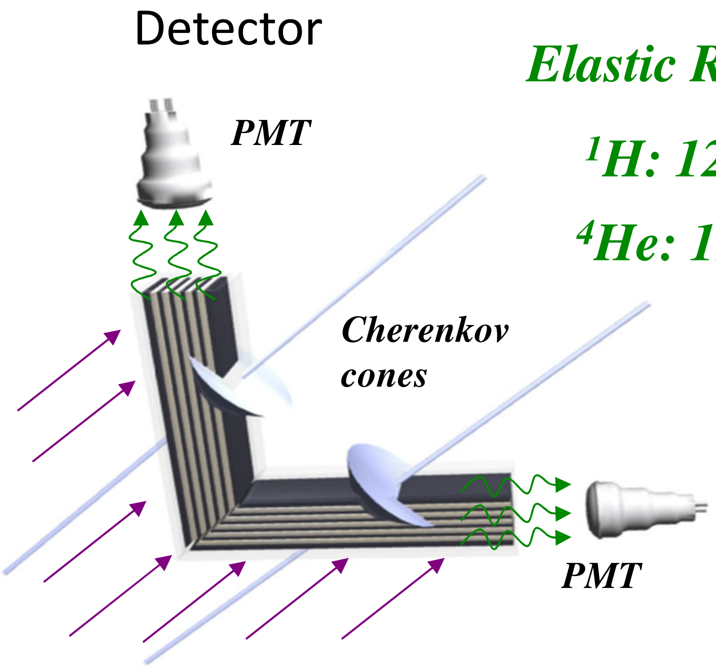
Example: HAPPEx

Clean separation of elastic events by HRS optics

→ **Locate detector over elastic line and integrate the flux**



12 m dispersion sweeps away inelastic events



Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz

Large dispersion & heavy shielding reduce backgrounds at focal plane

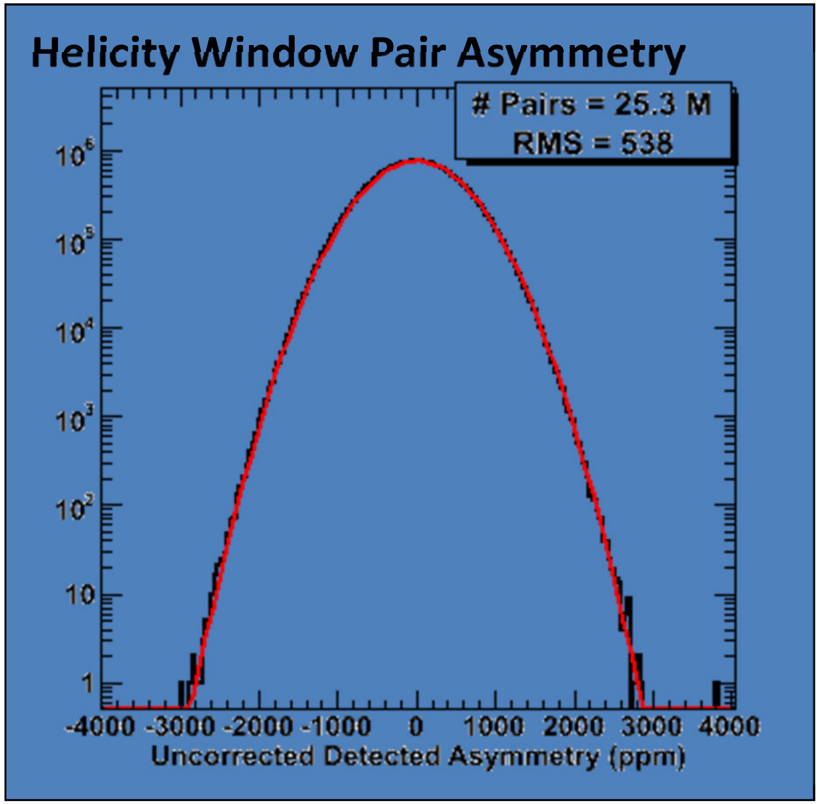
Brass-Quartz Integrating Cerenkov Shower Calorimeter

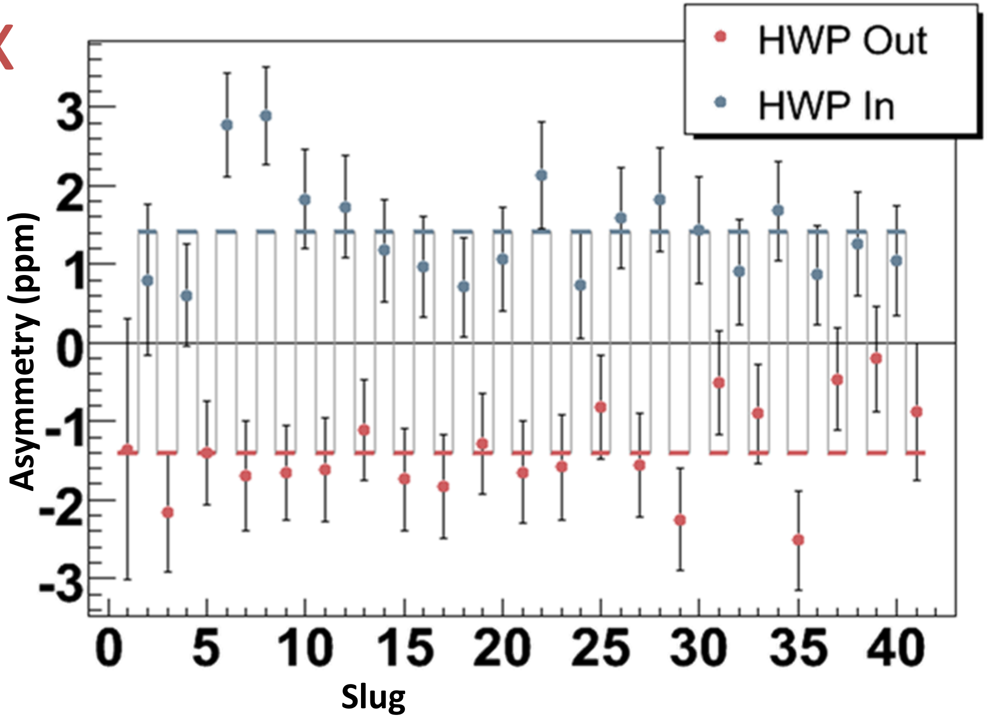
Example: HAPPEx

^{1}H Results (2005)

Parity Violating Asymmetry

A_{raw} correction ~3 ppb





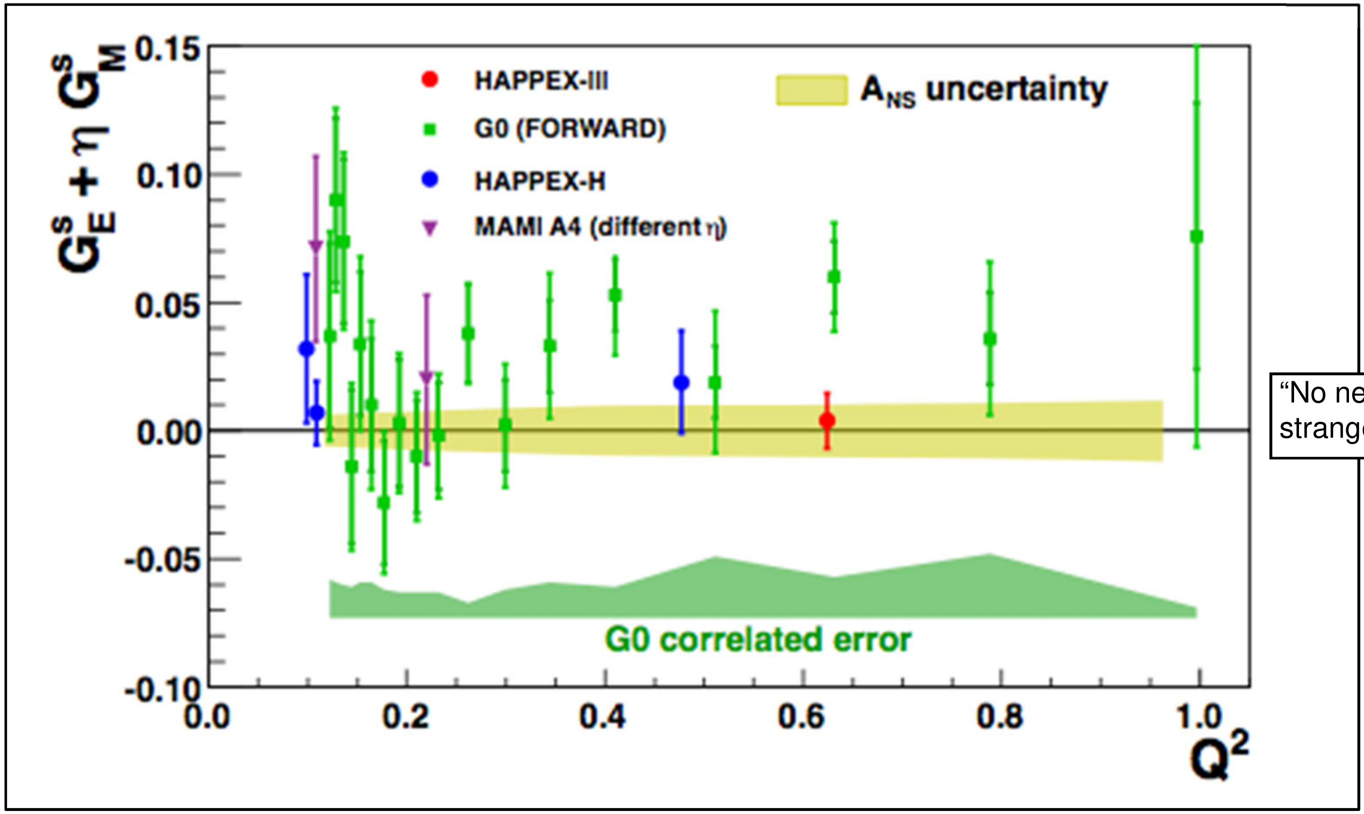
$Q^2 = 0.1089 \pm 0.0011 GeV^2$

A_{raw} = -1.58 ppm ± 0.12 (stat) ± 0.04 (syst)

Forward-angle proton scattering

world data prior to Qweak

$$\eta = \frac{\tau\, G_M^p}{\epsilon\, G_E^p} \sim Q^2$$



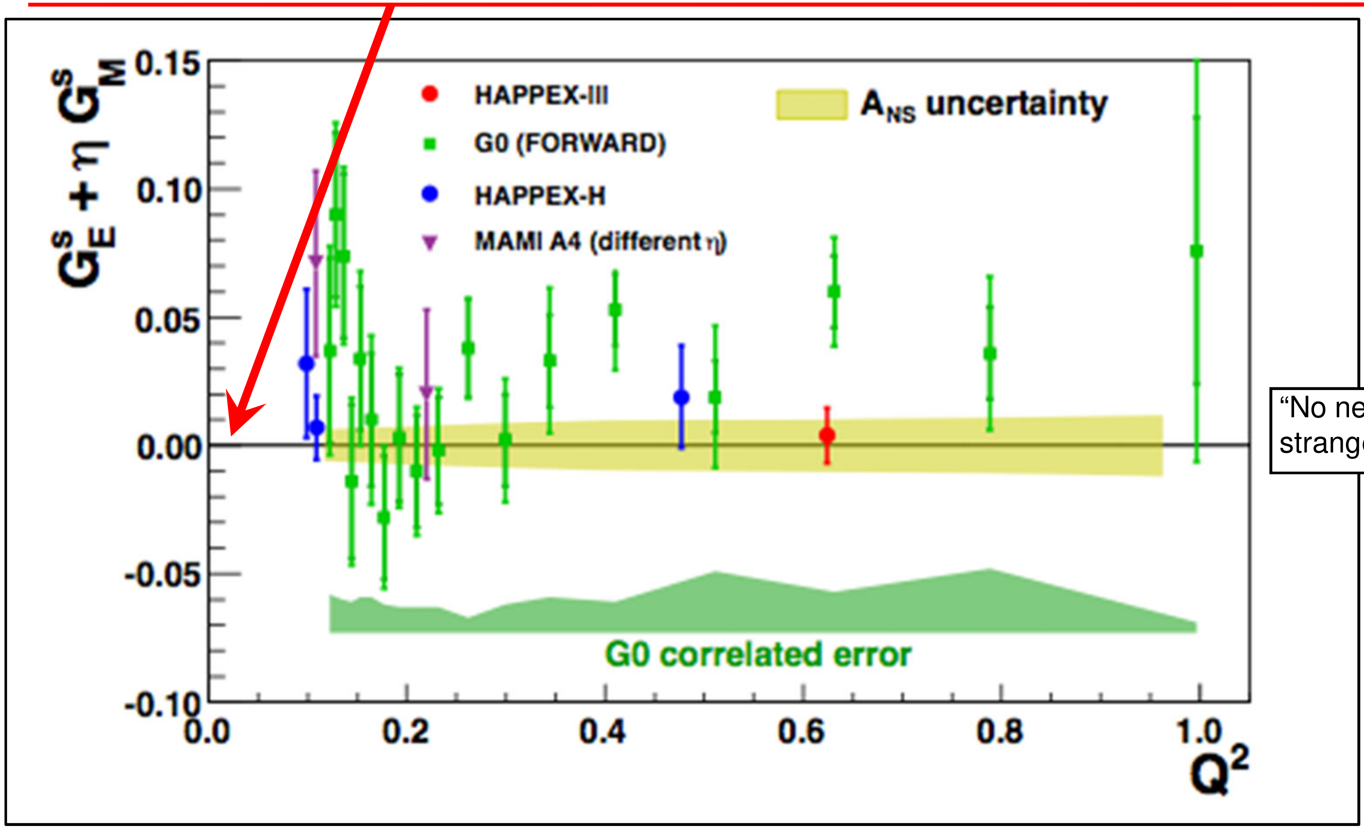
“No net vector strangeness” line

Combining results from forward-angle proton scattering (similar beam energies)

- Additional data at backward angles, and ^{2}H and ^{4}He target

Qweak result consistent with Std. Model w/ no strangeness

$$A_{EXP} = -226.5 \pm 7.3 \pm 5.8\ ppb,\ \ at < Q^2 > = 0.0248$$



“No net vector strangeness” line

Combining results from forward-angle proton scattering (similar beam energies)

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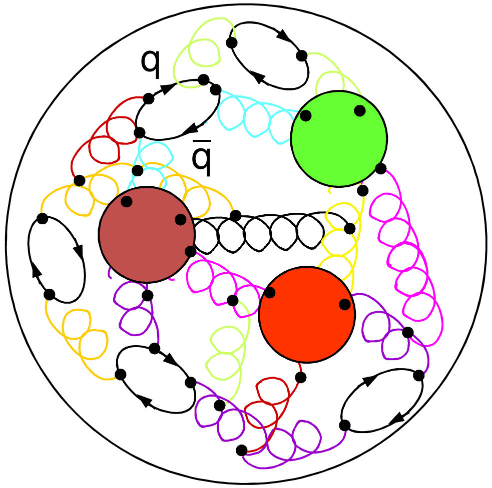
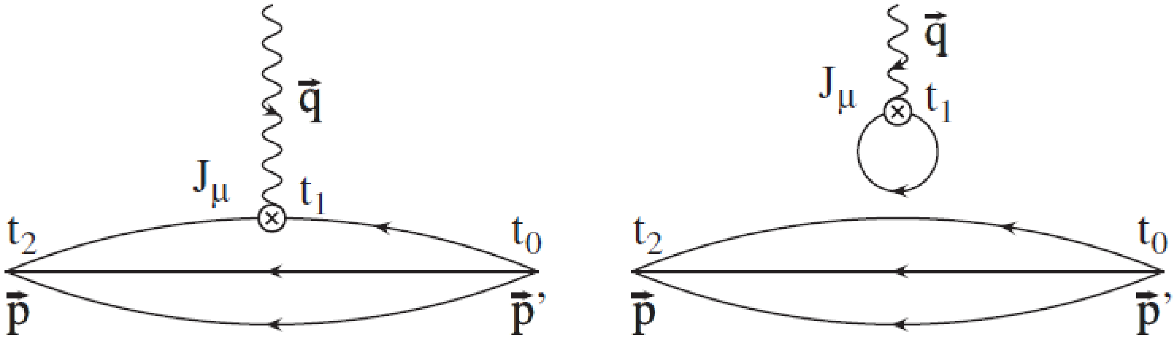
Summary: Strange Quarks in Protons



- Strange form factors arise from quantum fluctuations: $s\bar{s}$ pairs

- Experimentally, these form factors are small, less than a few percent of proton EM FF.

- Precise, direct lattice QCD agree (T. Doi, et al) agree with earlier "lattice + chiral extrapolation" (Leinweber and Thomas) and with experiment.



T. Doi, *et.al.* Phys Rev D **80** (2009) 094503
(xQCD Collaboration)

Deep Inelastic Scattering

- Parity violation arises from axial couplings either at the electron or at the quark.

- PVDIS emphasizes the latter: the quark’s chirality preference when participating in the in the weak force.

$$2C_{2u} - C_{2d}$$

- This has been measured twice in 40 years.
    - SLAC E122
    - JLAB 2009 -- factor of 5 improvement

PVDIS Formalism

For deuterium (isoscalar), neglecting sea quarks.

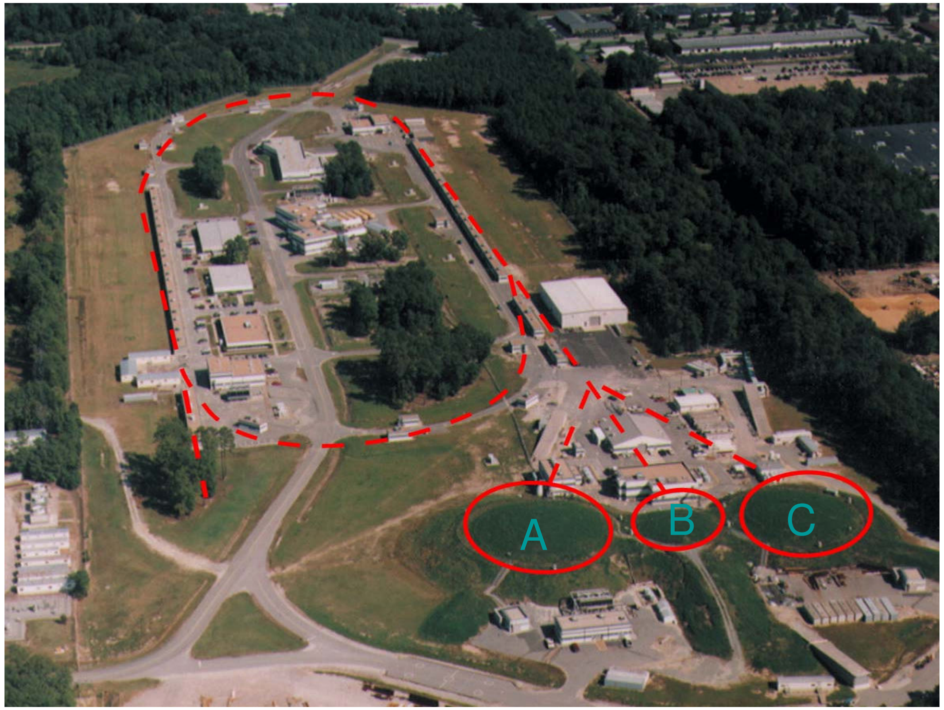
$$A_{PV} = \left(\frac{3G_F Q^2}{10\sqrt{2}\,\pi\alpha} \right) \left[(2C_{1u} - C_{1d}) + Y_3 \overbrace{(2C_{2u} - C_{2d})}^{\text{Unique sensitivity to these}} \right]$$

$$C_{1u} = 2 g_A^e g_V^u \qquad C_{1d} = 2 g_A^e g_V^d$$

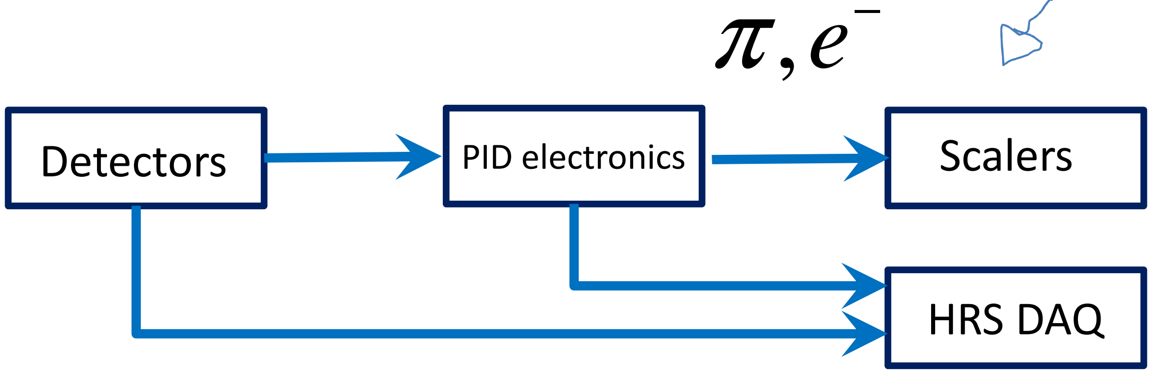
$$C_{2u} = 2 g_V^e g_A^u \qquad C_{2d} = 2 g_V^e g_A^d$$

PVDIS at 6 GeV (Jefferson Lab)

Spokespersons: Xiaochao Zheng, Paul Reimer, and Bob Michaels



- 100uA, 90% polarized beam on a 20cm liquid deuterium target
- Measured two DIS points: Q^2=1.085 and 1.901 GeV^2
- Ran in Nov-Dec. 2009
- four publications
  - Nature (main result)
  - Archival paper
  - Resonances
  - Specialized DAQ



π, e^-

Detectors

PID electronics

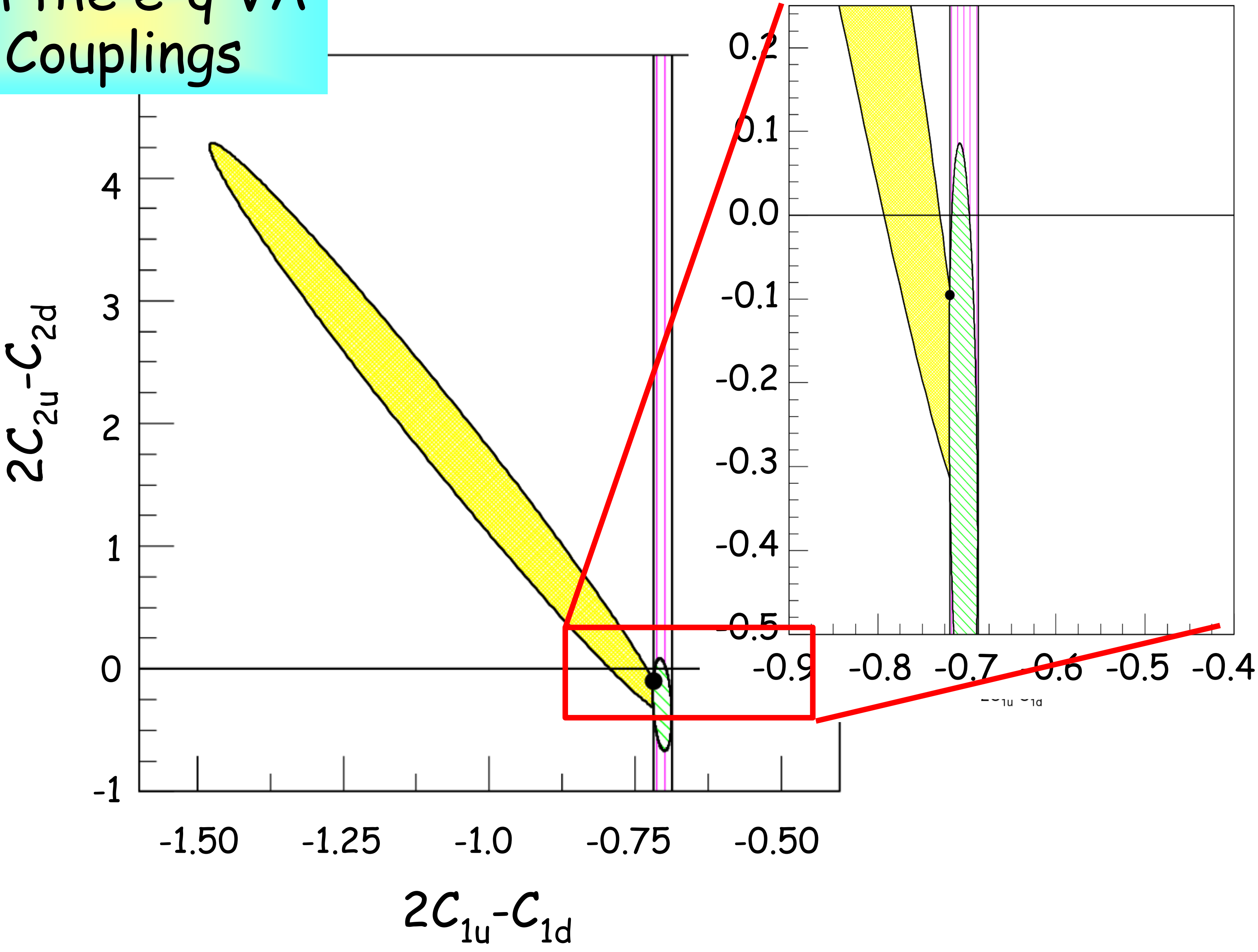
Scalers

HRS DAQ

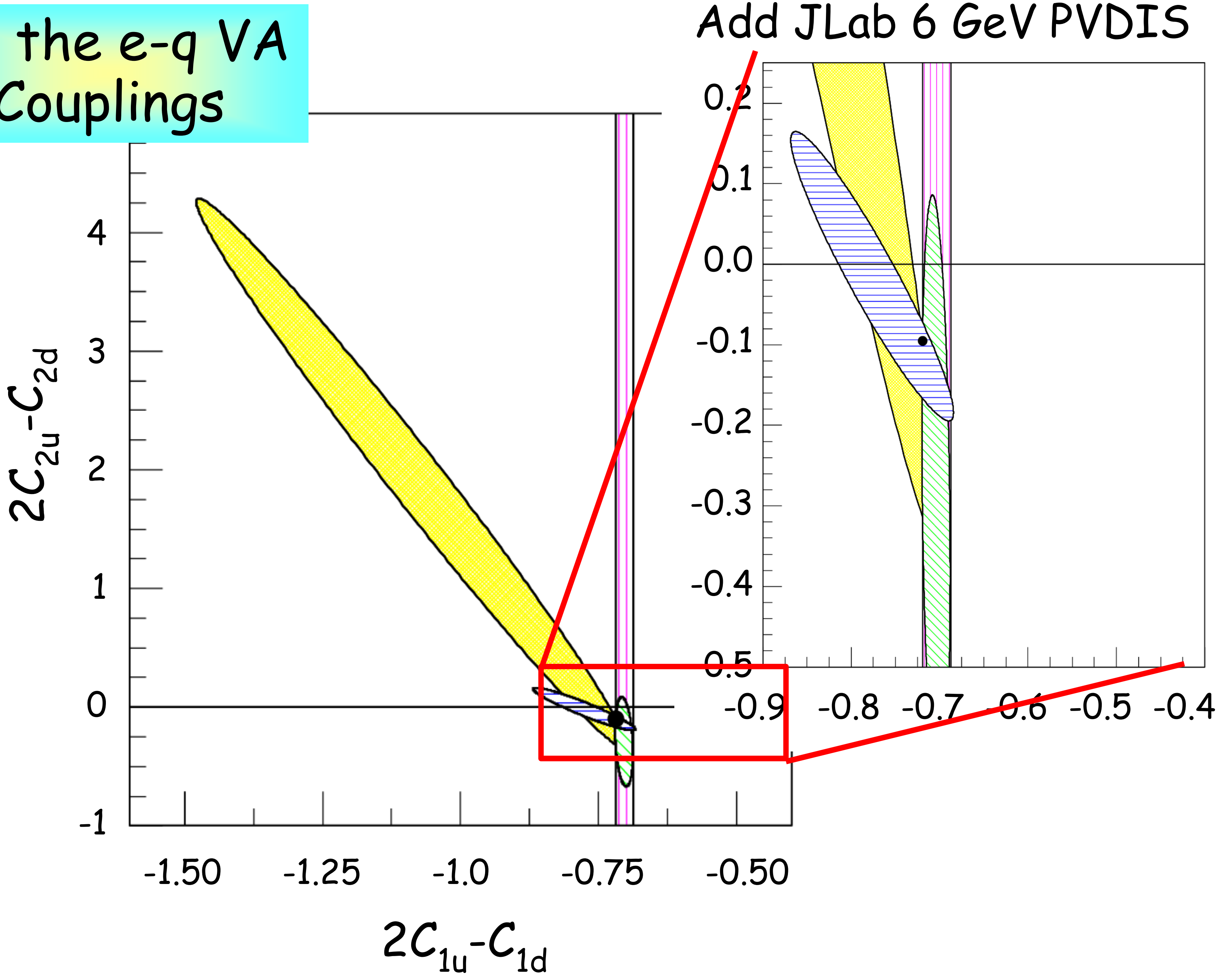
Part of Parity DAQ

On the e-q VA Couplings

Previous data: E122, Elastic PVES + APV

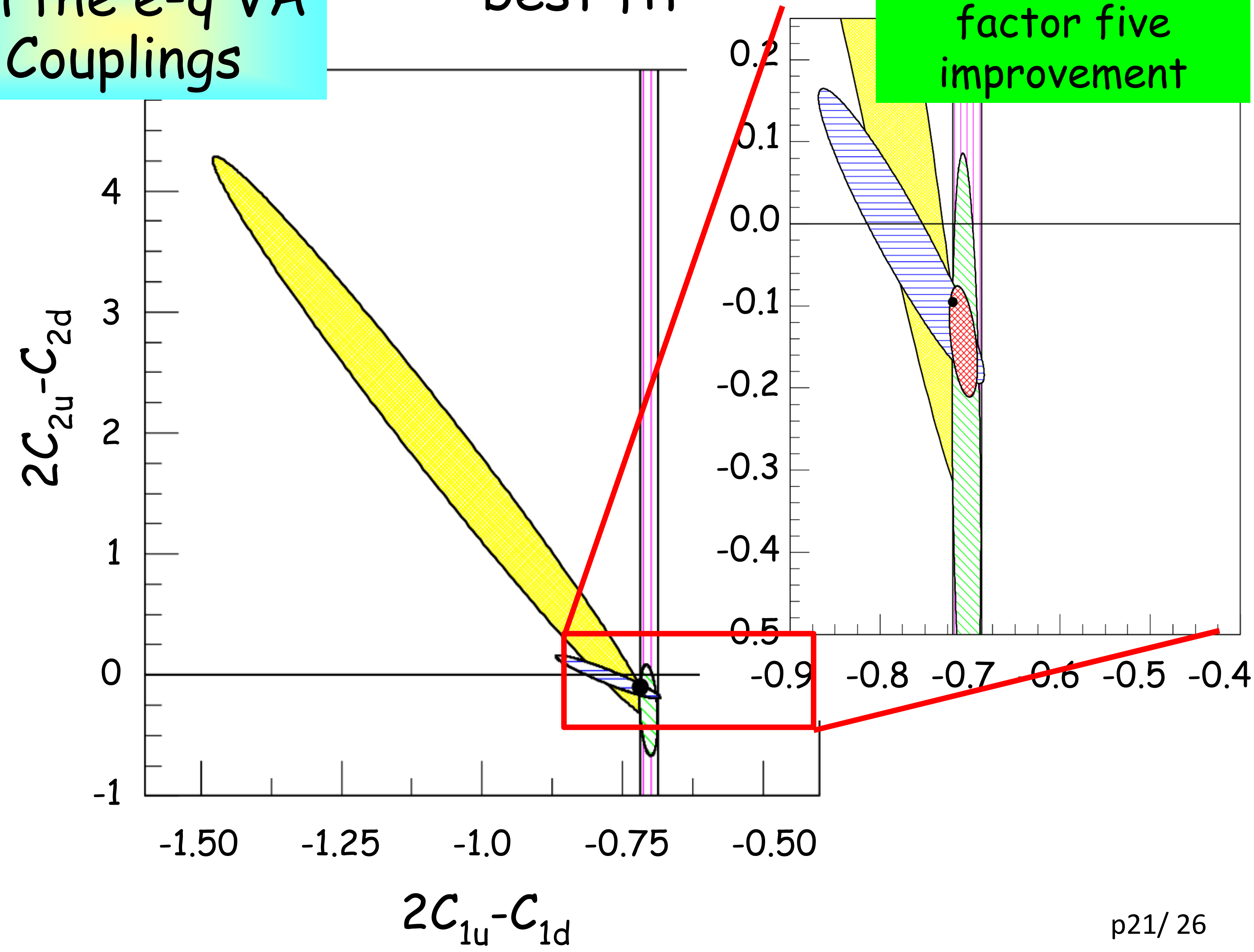


On the e-q VA Couplings



On the e-q VA Couplings

best fit

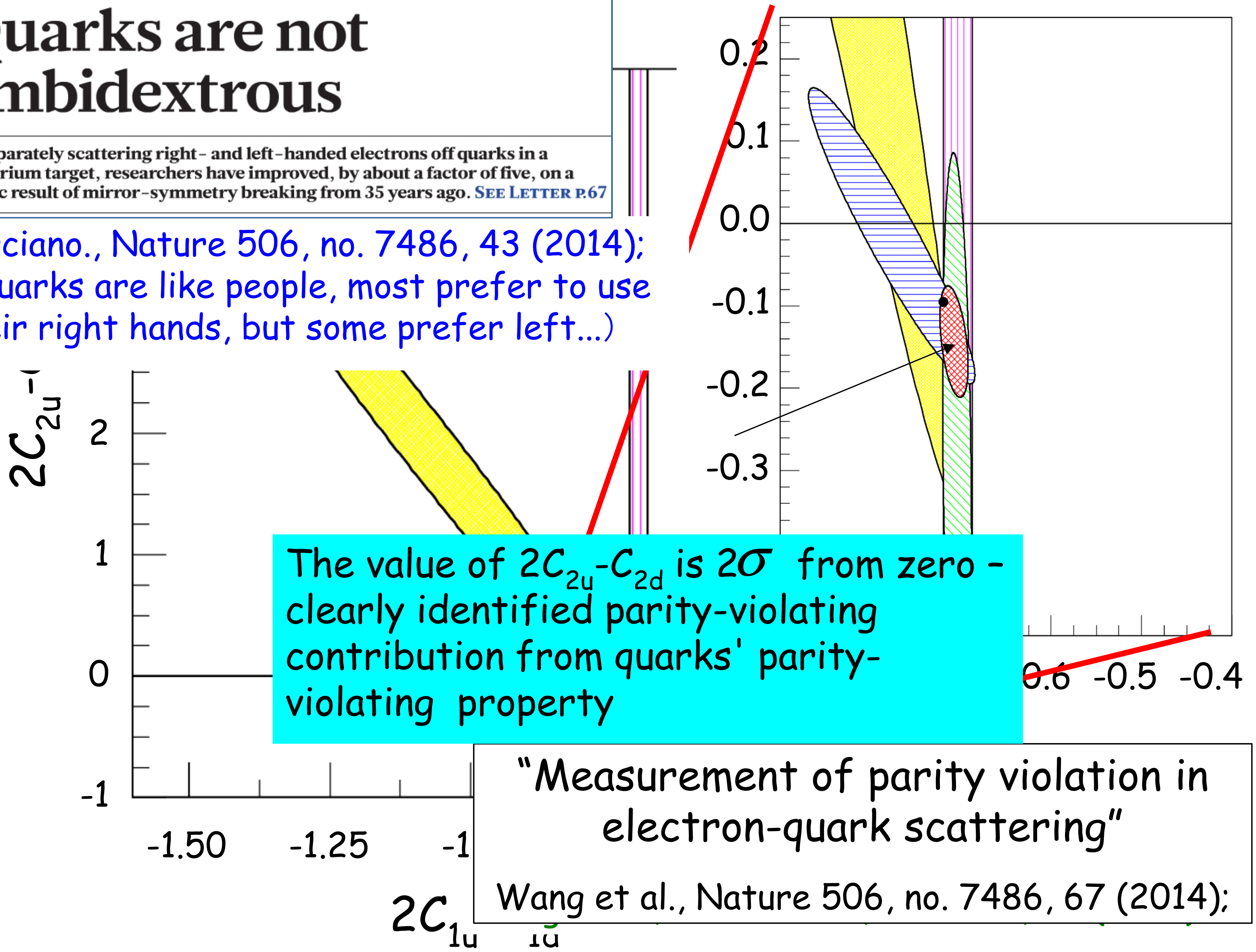

factor five improvement

PARTICLE PHYSICS

Quarks are not ambidextrous

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. SEE LETTER P.67

Marciano., Nature 506, no. 7486, 43 (2014);
(Quarks are like people, most prefer to use their right hands, but some prefer left...)



The value of $2C_{2u}$-C_{2d} is 2σ from zero – clearly identified parity-violating contribution from quarks' parity-violating property

"Measurement of parity violation in electron-quark scattering"

Wang et al., Nature 506, no. 7486, 67 (2014);

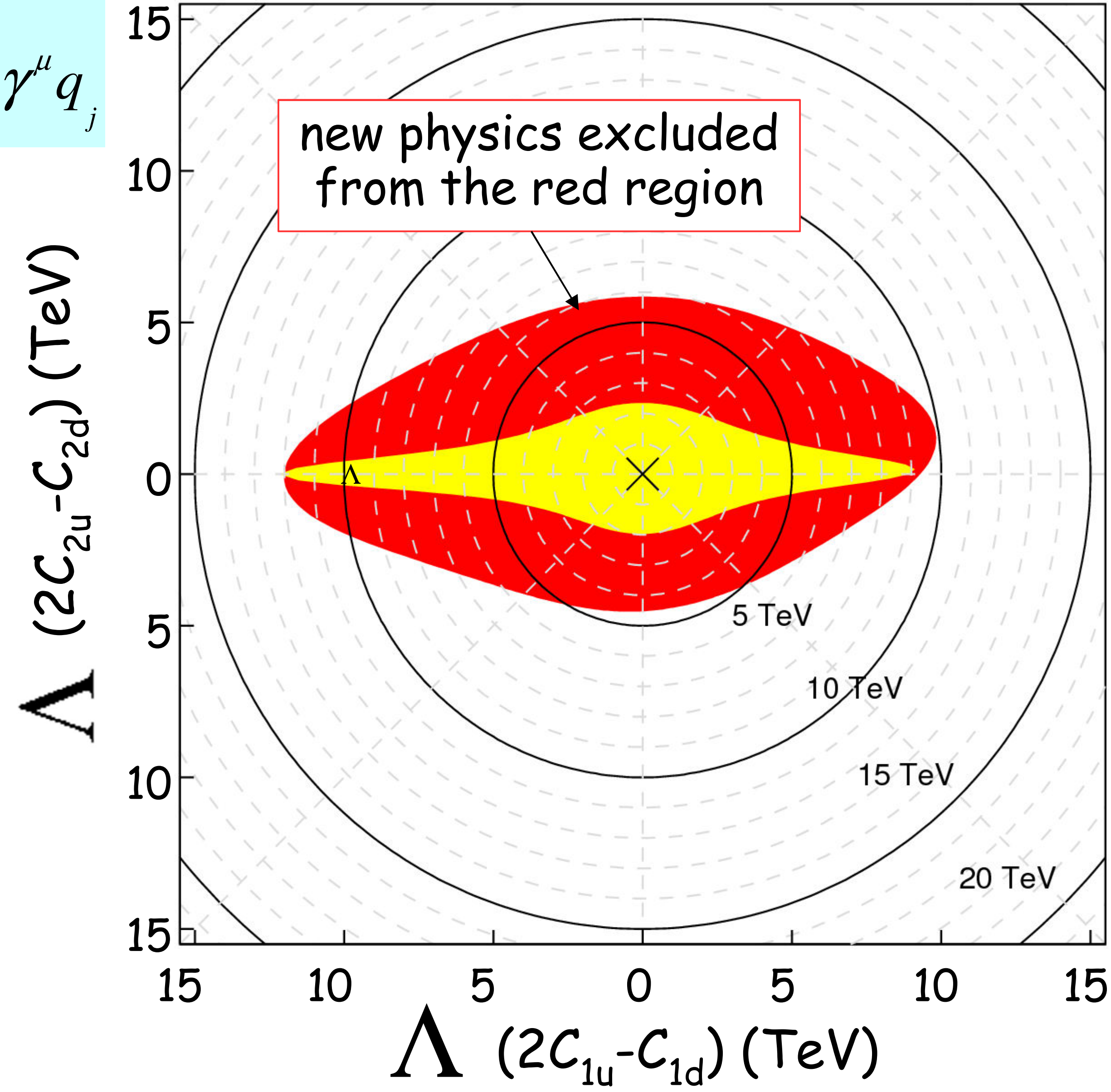
Limit on new eq VA contact interactions

$$L_{eq} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \bar{e}_i \gamma_\mu e_i \bar{q}_j \gamma^\mu q_j$$

Mass Scale

$$\Lambda$$

$$(g^2 = 4\pi)$$

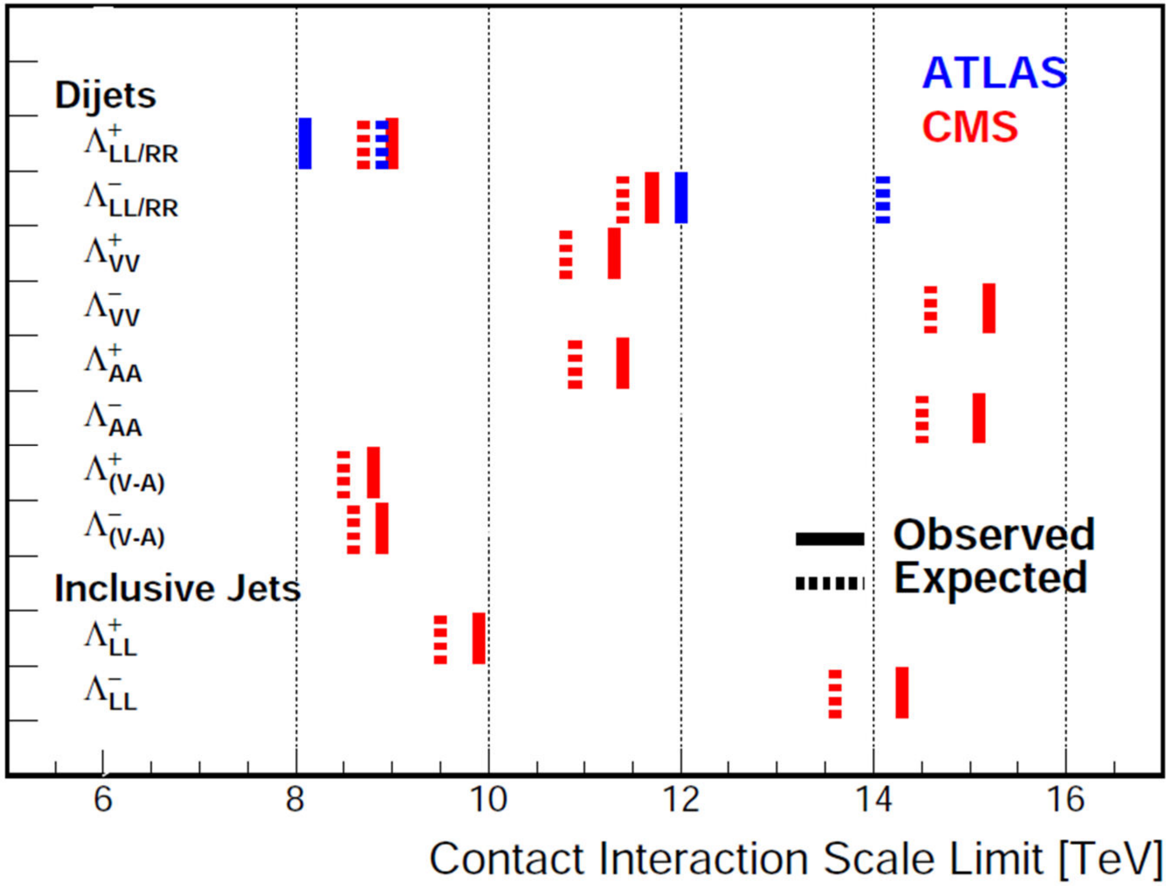


new physics excluded from the red region

Contact Interaction Limits from LHC (PDG)

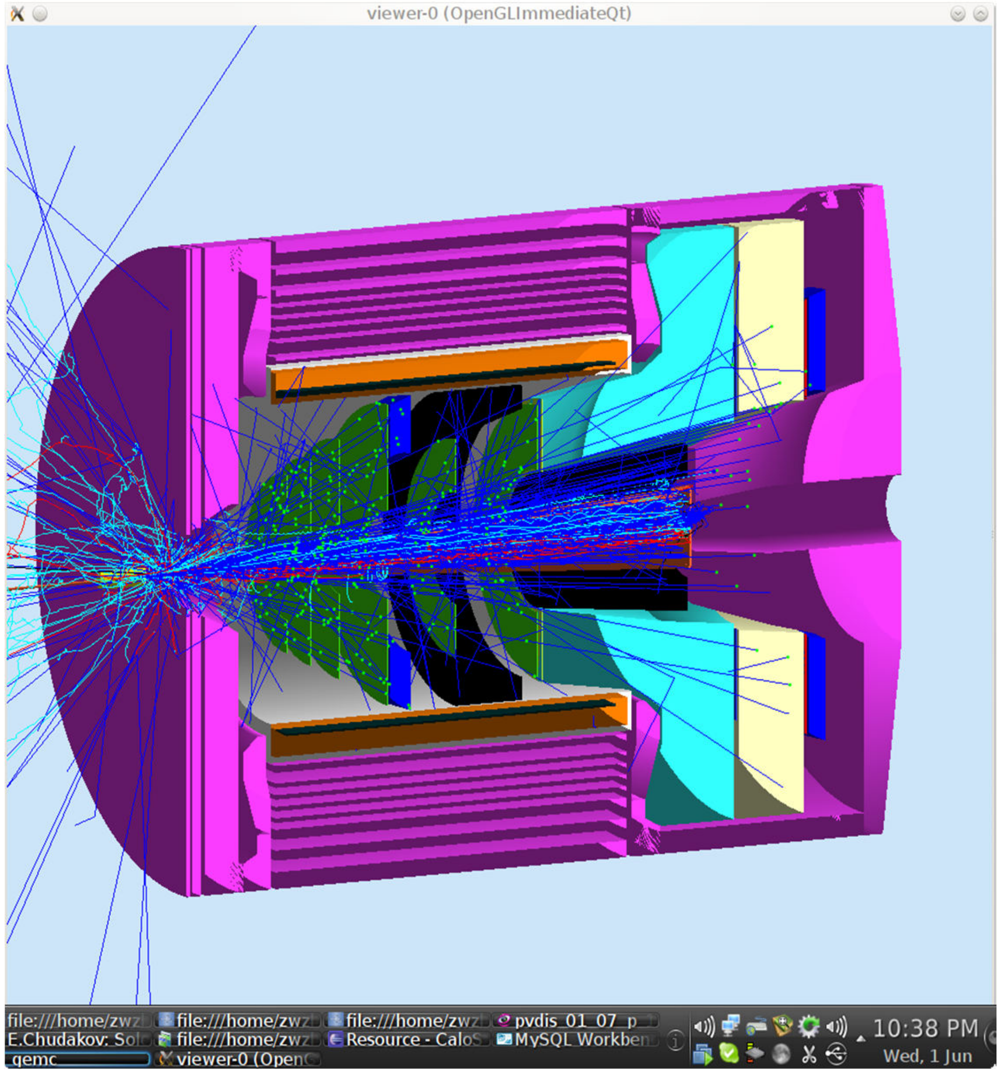
No access to AV or VA terms

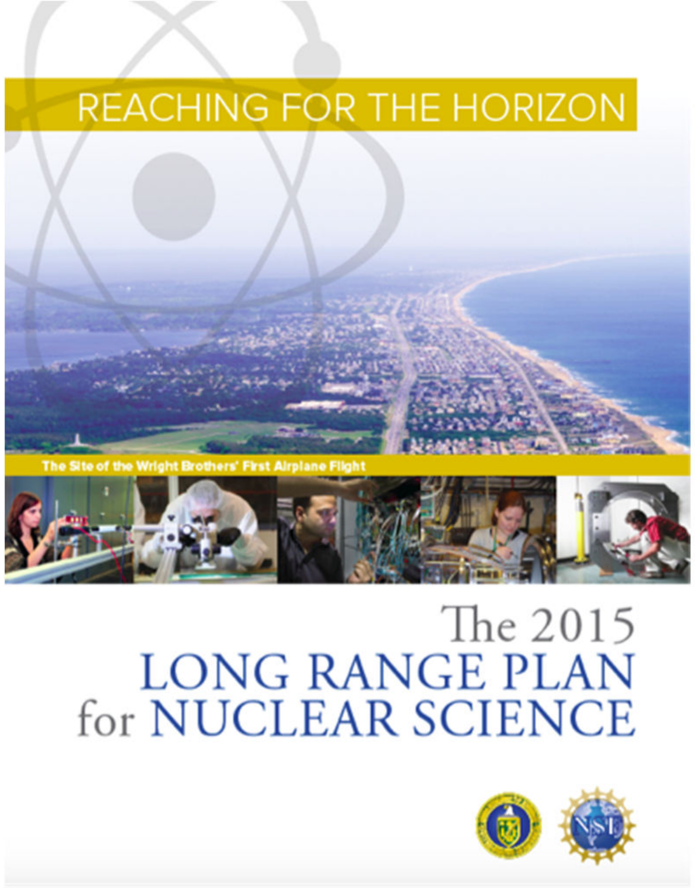
PVES is complementary to collider searches



Future: PVDIS Program with SoLID @ 12 GeV

"Solenoid Large Intensity Device"



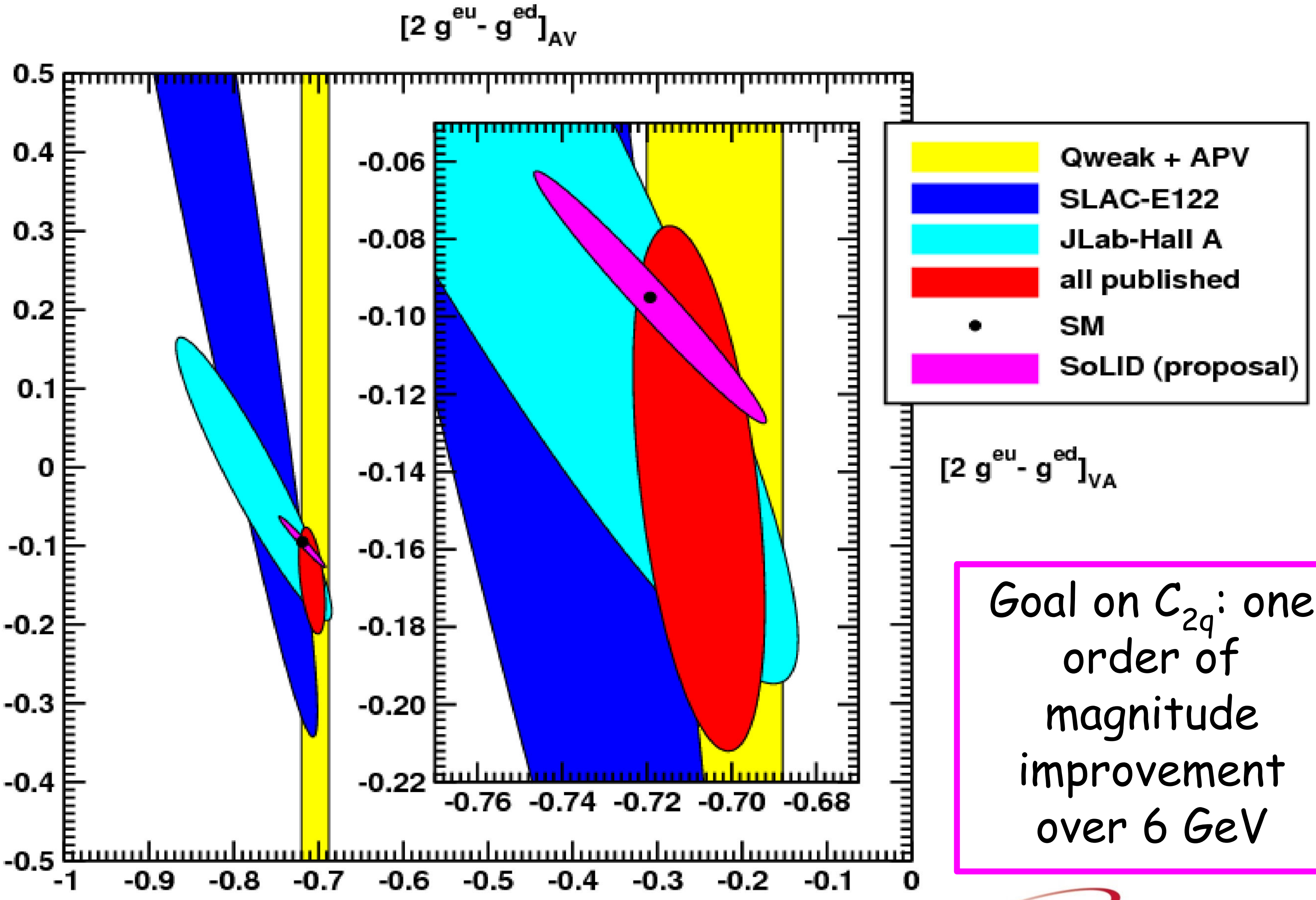


REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Future: PVDIS Program with SoLID @ JLab 12 GeV



Goal on C_{2q}: one order of magnitude improvement over 6 GeV

Robert Michaels, JLAB

Jefferson Lab
Thomas Jefferson National Accelerator Facility