

Parity-Violating Deep Inelastic Scattering (PVDIS) at JLab 6 and 12 GeV

Xiaochao Zheng (Univ. of Virginia)

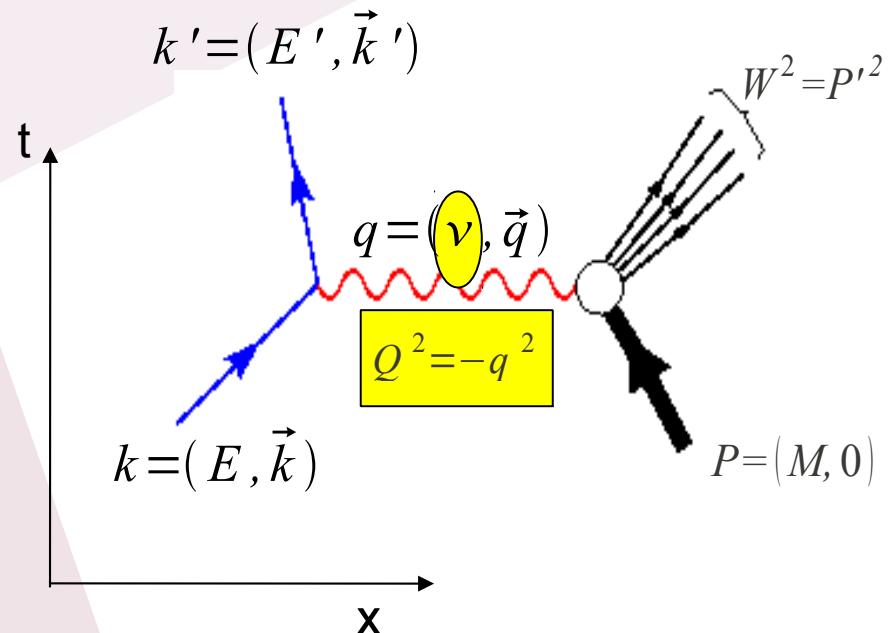
November 21, 2014

- PVDIS and electron-quark effective couplings
- The 6 GeV PVDIS experiment
 - DIS results - electron-quark effective VA couplings
 - Resonance results - duality in EW sector?
- Outlook for the 12 GeV Program - PVDIS with SoLID

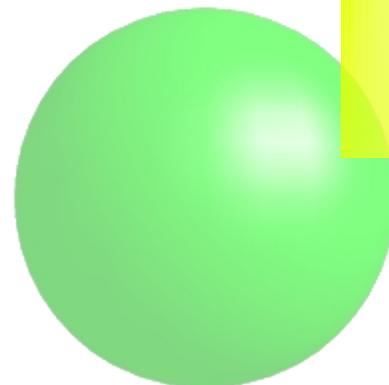


Inclusive Electron Scattering Basics

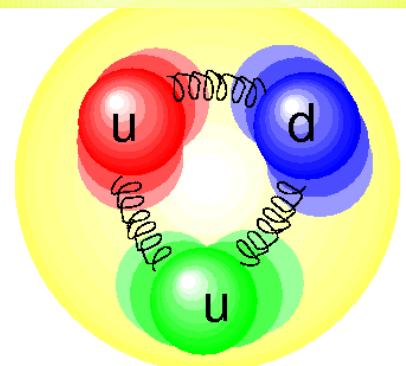
Inclusive: only scattered electron is detected



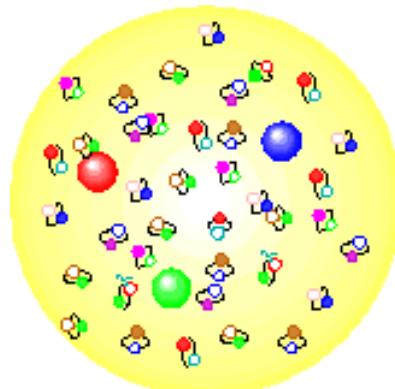
"Elastic": $W=M_p$
(form factors)



"Resonance": $1 < W < 2 \text{ GeV}$
(structure functions)

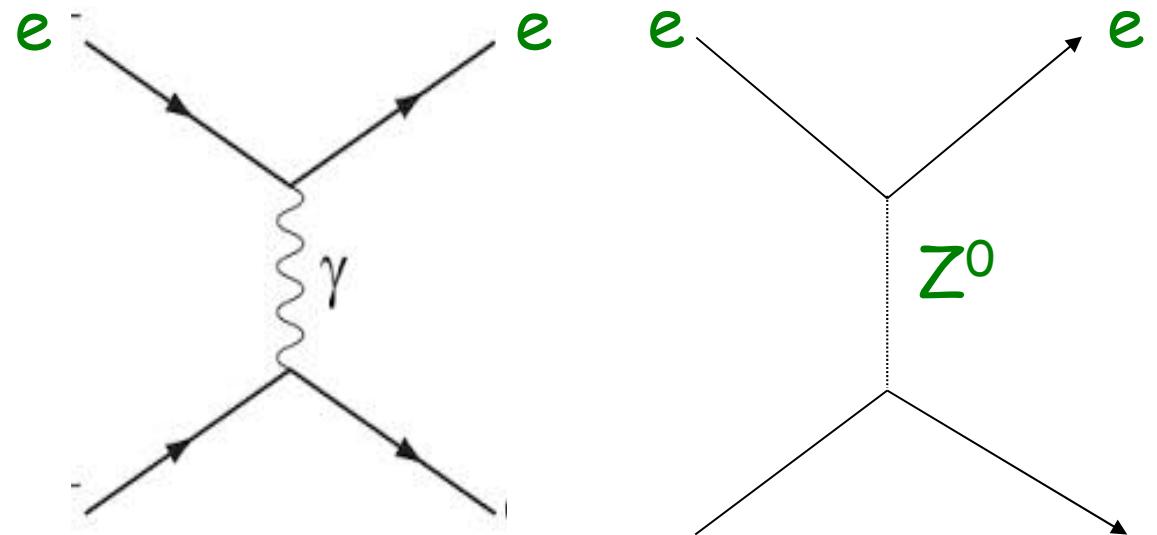


"Deep Inelastic": $W > 2 \text{ GeV}$,
(structure functions, parton distribution functions)

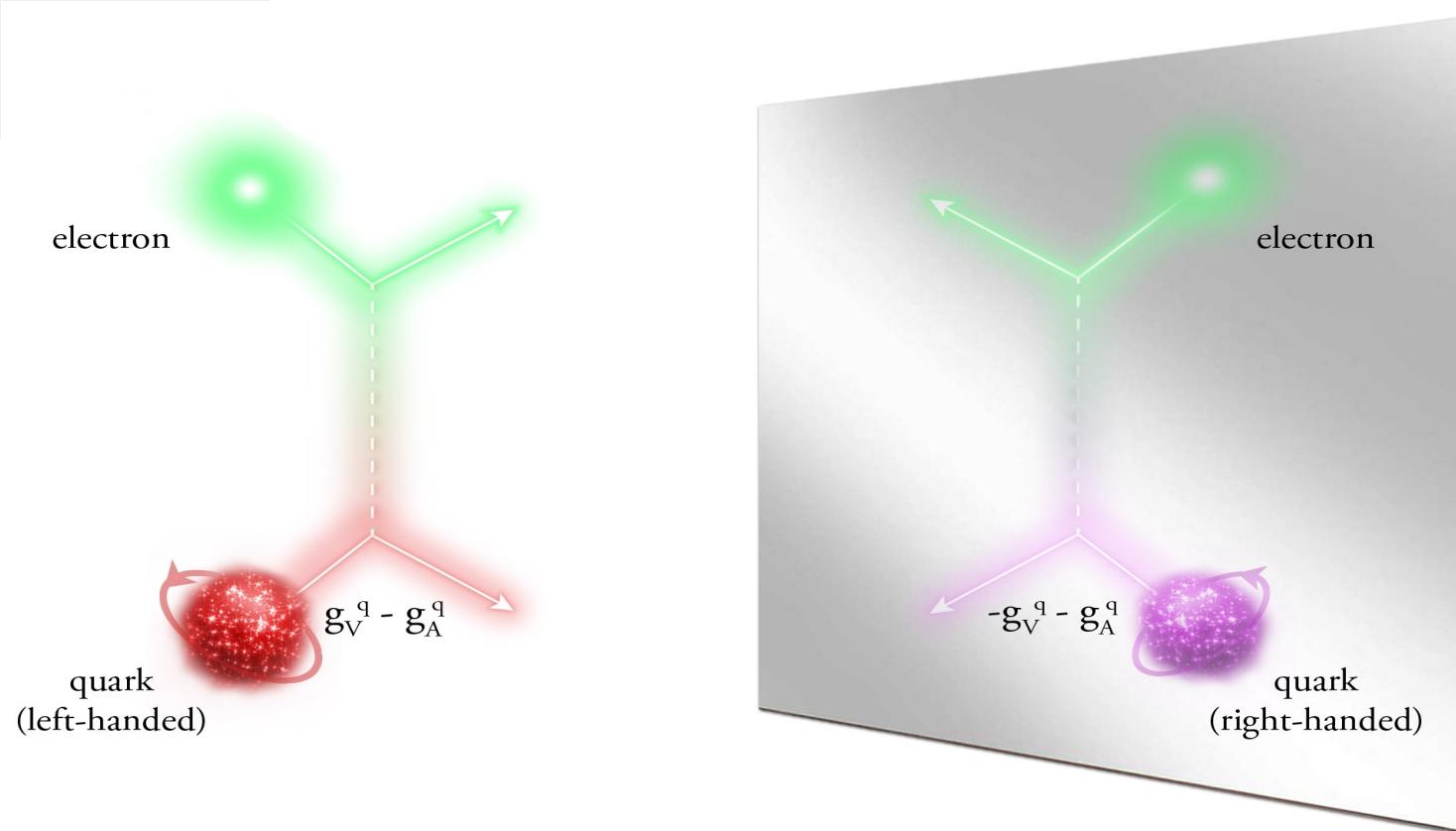


Parity-Violating Electron Scattering

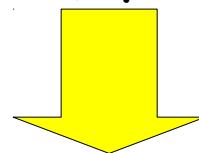
- To study nucleon structure not accessible in electromagnetic interaction:
 - + elastic PVES: nucleon strange form factors; "neutron skin" in heavy nucleus
- To test the electroweak Standard Model:
 - + Moller - E158
 - + PVDIS



Parity Violation in the Standard Model

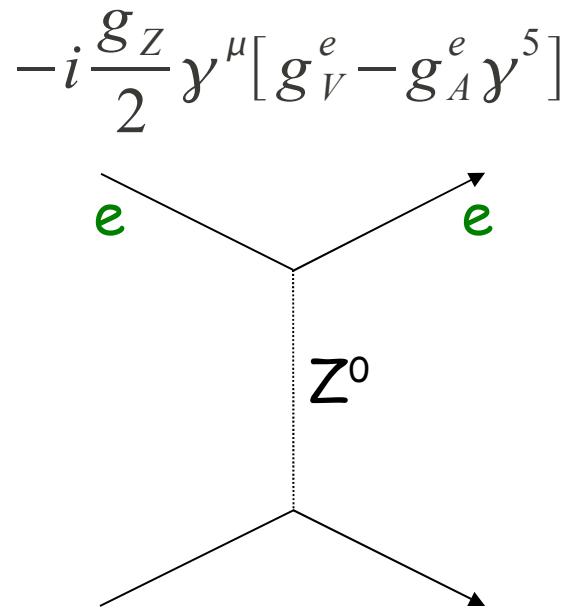


- In weak interaction, all elementary fermions behave differently under parity transformation
- They have a preferred chiral state when coupling to the Z^0



Parity Violation in the Standard Model

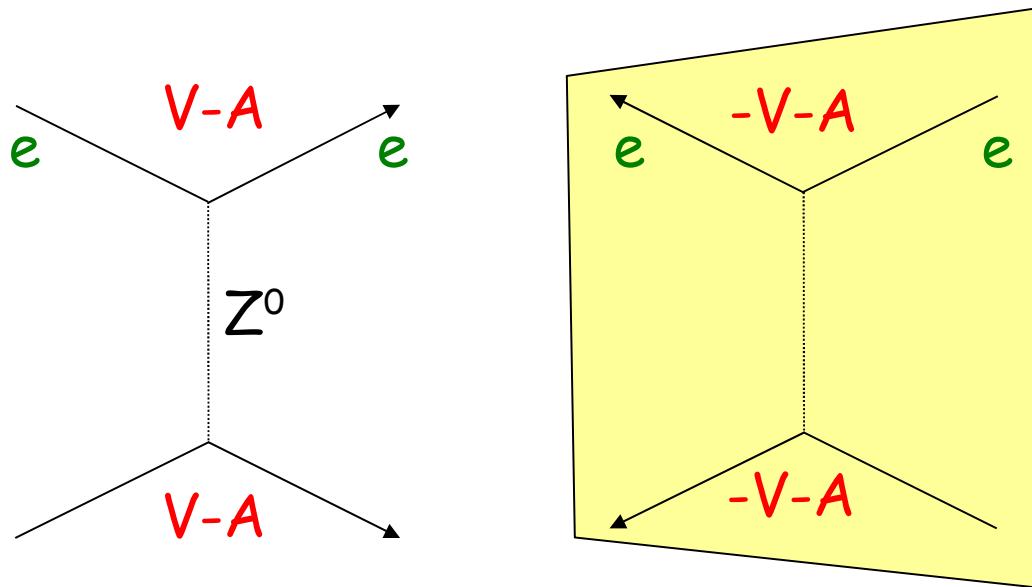
- Unlike electric charge, need two charges (couplings) for weak interaction: g_L, g_R
 or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$



fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q \sin^2 \theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-	$-\frac{1}{2}$	$-\frac{1}{2} + 2 \sin^2 \theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3} \sin^2 \theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W$

Parity Violation in the Standard Model

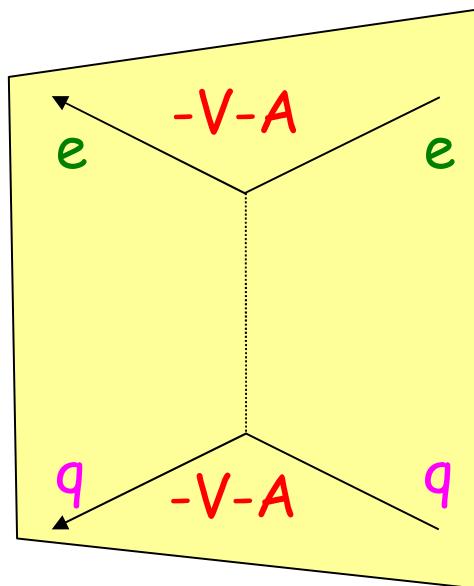
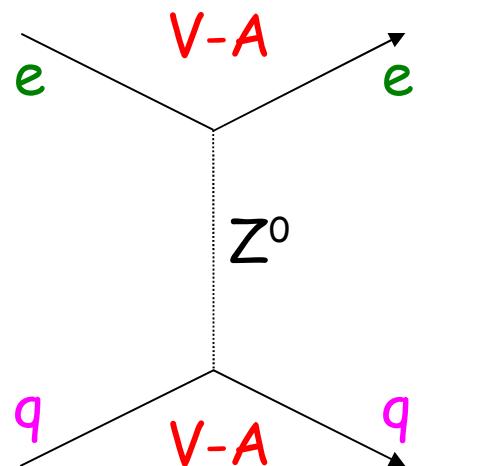
- Unlike electric charge, need two charges (couplings) for weak interaction: g_L, g_R
or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$
- PVES asymmetry comes from $V(e) \times A(\text{targ})$ and $A(e) \times V(\text{targ})$



Effective Couplings in the Standard Model

- Unlike electric charge, need two charges (couplings) for weak interaction: g_L, g_R
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- PVDIS asymmetry comes from:

$$C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q$$



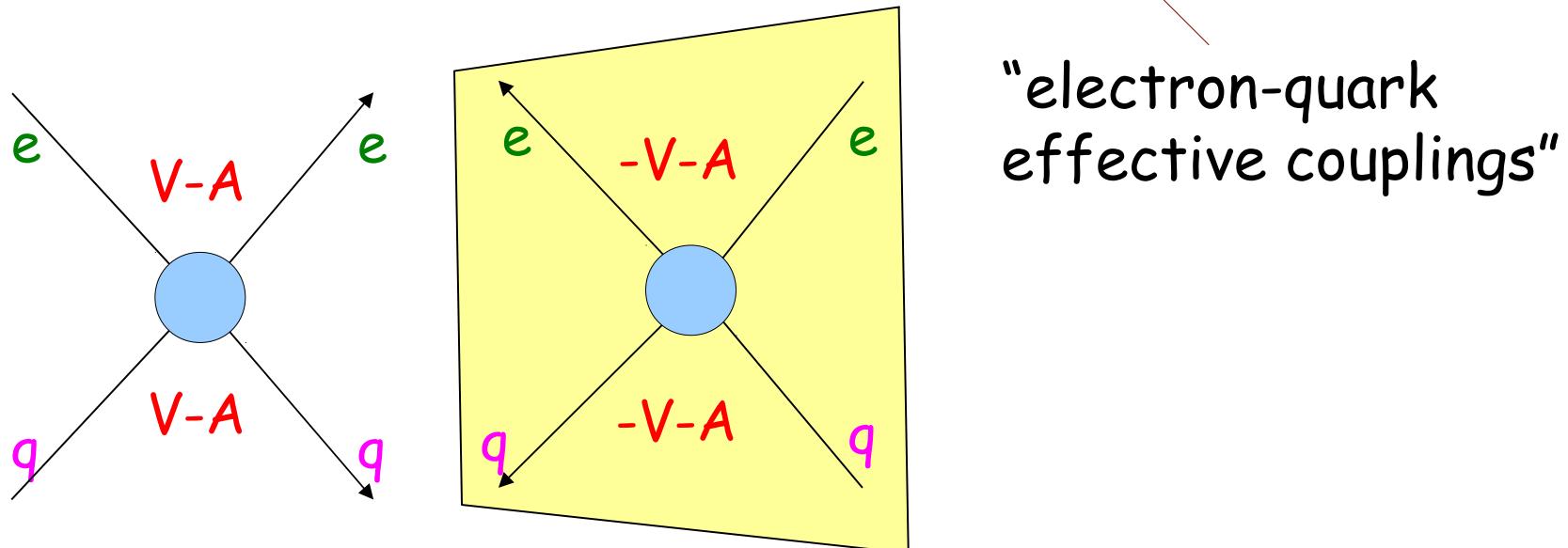
"electron-quark
effective couplings"

Effective Couplings and New Contact Interactions

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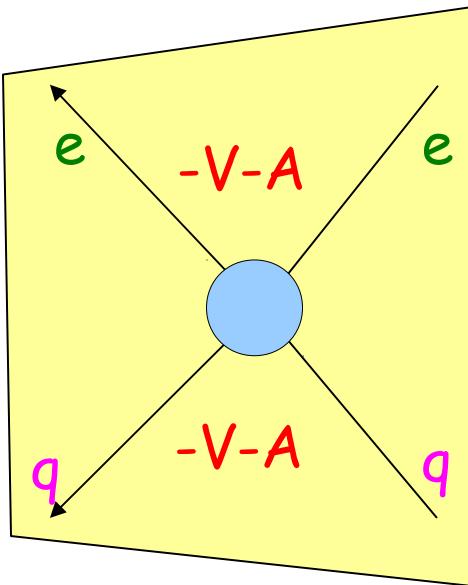
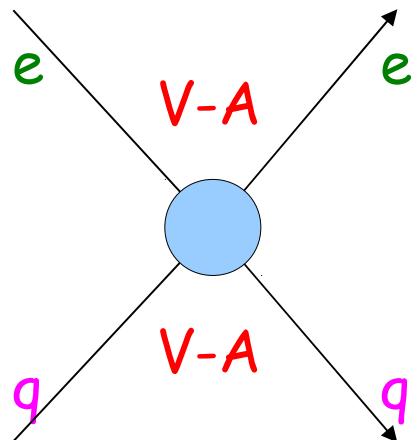


Effective Couplings and New Contact Interactions

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- PVDIS asymmetry comes from:

$$C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q$$



"electron-quark
effective couplings"

$$C_{1q} = g_{AV}^{e q}, \quad C_{2q} = g_{VA}^{e q}$$

Erler&Su, Prog. Part. Nucl.
Phys. 71, 119 (2013)

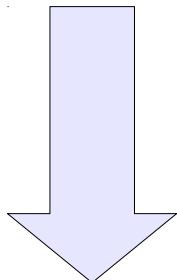
Accessing $C_{1q,2q}$

- Need electron beam on hadronic target
- In elastic PVES
 - directly probes C_{1q} , electrons' parity-violating property;
 - quarks' parity-violation is represented by the nucleon axial form factor G_A , and extracting C_{2q} from G_A is model-dependent
- Only in PVDIS, electron probes the quark and PVDIS asymmetry depends on C_{2q} directly.

Formalism for Parity Violation in DIS

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} [a(x) + Y(y) b(x)]$$

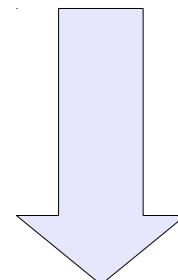
$$a(x) = \frac{1}{2} g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} = \frac{1}{2} \frac{\sum_i C_{1i} Q_i q_i^+ (x)}{\sum_i Q_i^2 q_i^+ (x)}$$



For an isoscalar target (${}^2\text{H}$), structure functions largely simplifies:

$$a(x) = \frac{3}{10} (2C_{1u} - C_{1d}) \left(1 + \frac{0.6 s^+}{u^+ + d^+} \right)$$

$$b(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^\gamma} = \frac{1}{2} \frac{\sum_i C_{2i} Q_i q_i^- (x)}{\sum_i Q_i^2 q_i^+ (x)}$$



$$b(x) = \frac{3}{10} (2C_{2u} - C_{2d}) \left(\frac{u_V + d_V}{u^+ + d^+} \right)$$

Formalism for Parity Violation in DIS

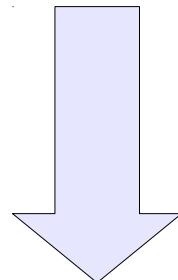
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} [a(x) + Y(y) b(x)]$$

$$x \equiv x_{Bjorken} = \frac{Q^2}{2 M \nu}$$

$$q_i^+(x) \equiv q_i(x) + \bar{q}_i(x)$$

$$q_i^-(x) = q_i^V(x) \equiv q_i(x) - \bar{q}_i(x)$$

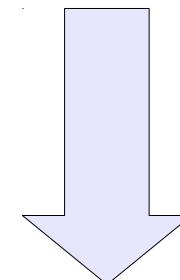
$$a(x) = \frac{1}{2} g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} = \frac{1}{2} \frac{\sum_i C_{1i} Q_i q_i^+(x)}{\sum_i Q_i^2 q_i^+(x)}$$



For an isoscalar target (${}^2\text{H}$), structure functions largely simplifies:

$$a(x) = \frac{3}{10} (2C_{1u} - C_{1d}) \left(1 + \frac{0.6 s^+}{u^+ + d^+} \right) \downarrow 0$$

$$b(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^\gamma} = \frac{1}{2} \frac{\sum_i C_{2i} Q_i q_i^-(x)}{\sum_i Q_i^2 q_i^-(x)}$$



$$b(x) = \frac{3}{10} (2C_{2u} - C_{2d}) \left(\frac{u_V^+ + d_V^+}{u^+ + d^+} \right) \downarrow 1$$

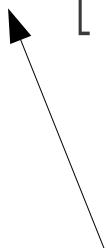
If neglecting sea quarks, asymmetry is no longer sensitive to PDFs \rightarrow "static limit"

Still, C_{2q} are more difficult to access than C_{1q}

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} [a(x) + Y(y) b(x)]$$

$$y \equiv \frac{E - E'}{E} = \frac{\nu}{E}$$

$$r^2 = 1 + \frac{Q^2}{\nu^2}$$

$$Y = \left[\frac{r^2}{1+R} \right] \frac{1 - (1-y)^2}{1 + (1-y)^2 - y^2 \left[1 - \frac{r^2}{1+R} \right] - xy \frac{M}{E}}$$


- The term sensitive to the quark spin is kinematically suppressed due to angular momentum conservation.
- C_{2q} are much smaller than C_{1q} :

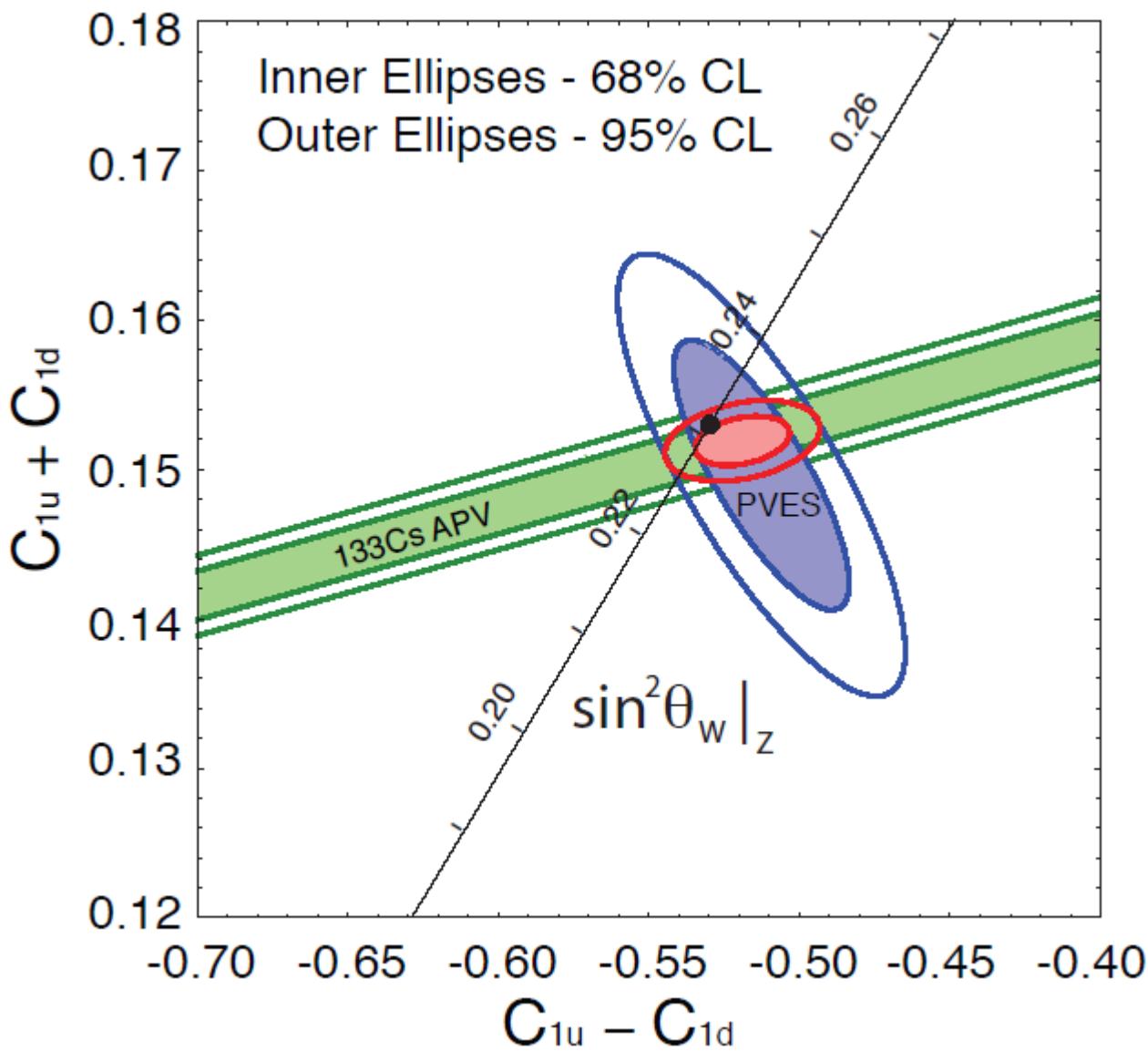
$$C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W$$

$$C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W$$

$$C_{2u} = -\frac{1}{2} + 2 \sin^2 \theta_W$$

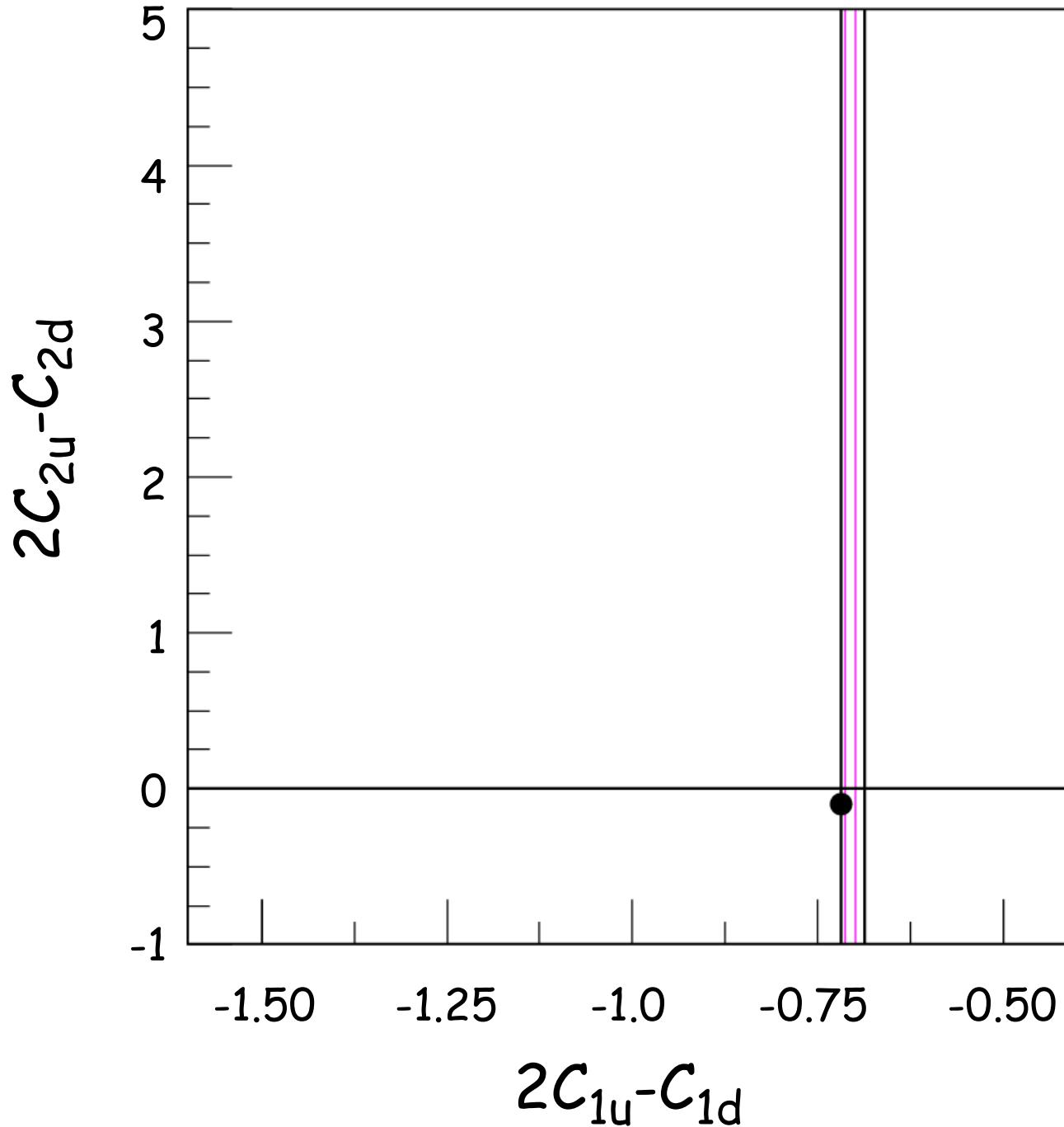
$$C_{2d} = \frac{1}{2} - 2 \sin^2 \theta_W$$

Best Data on C_{1q} (eq AV couplings) from PVES+APV

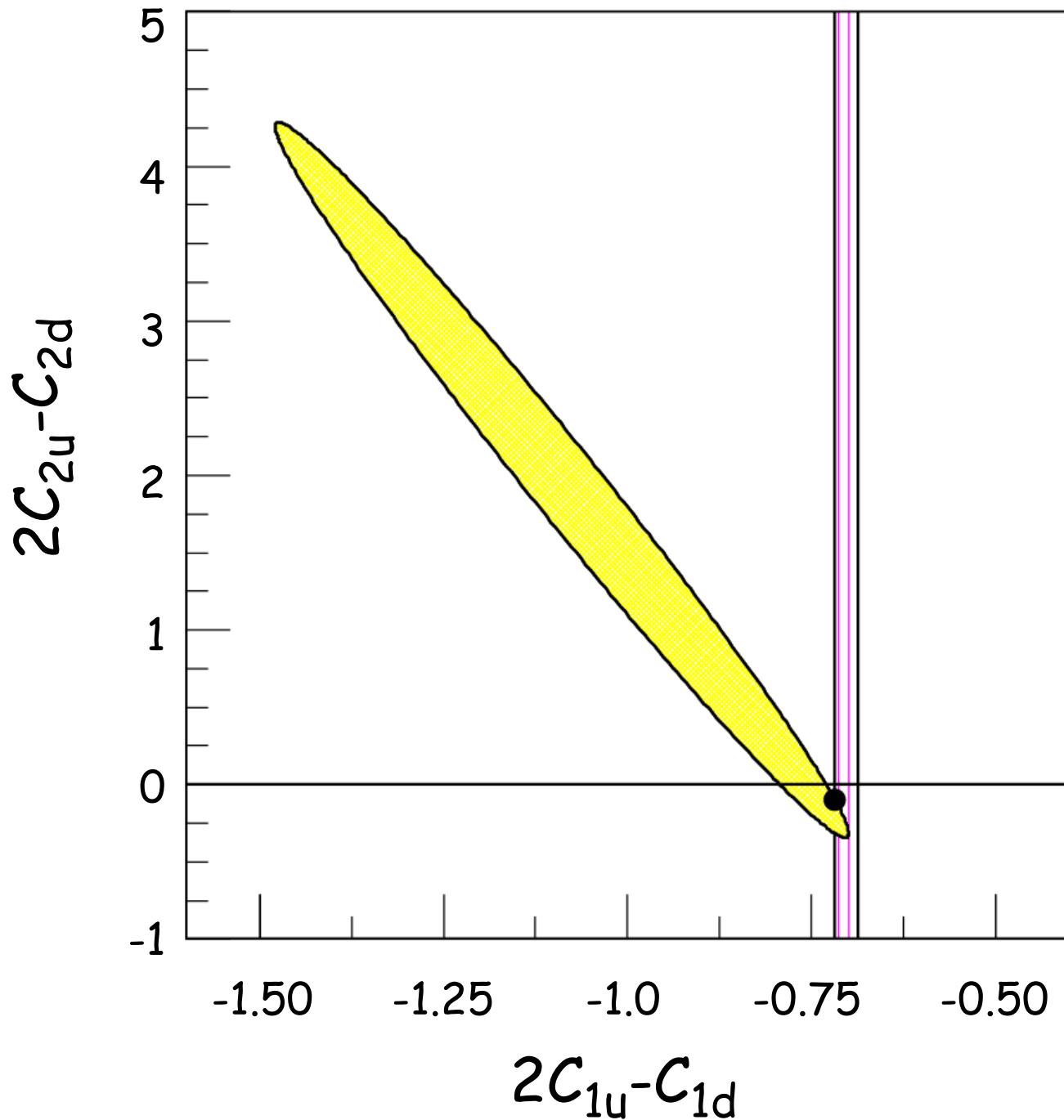


Androic et al., PRL 111, 141803 (2013);

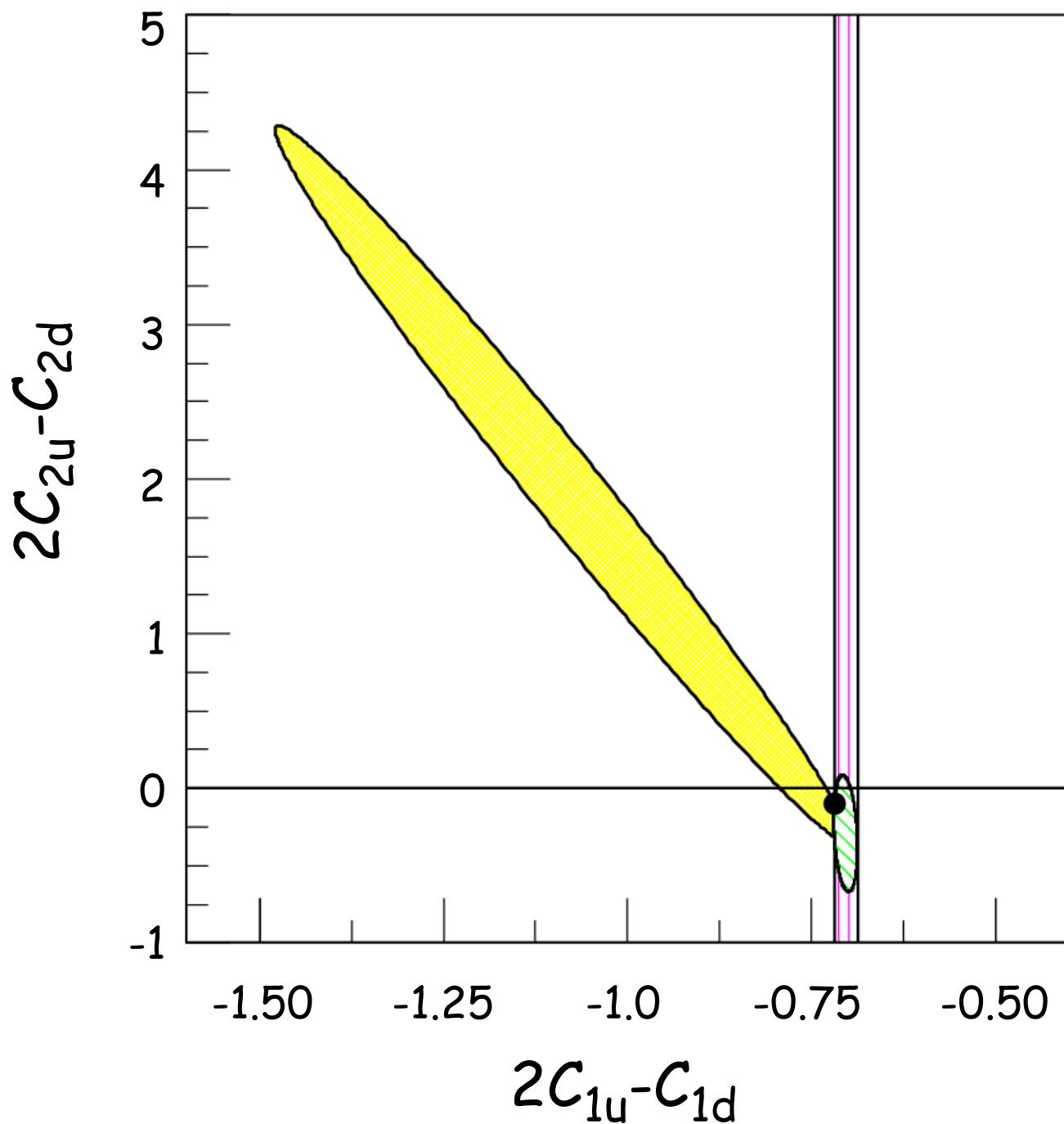
Projecting to C_{1q} vs C_{2q} (e-q AV vs. VA couplings)



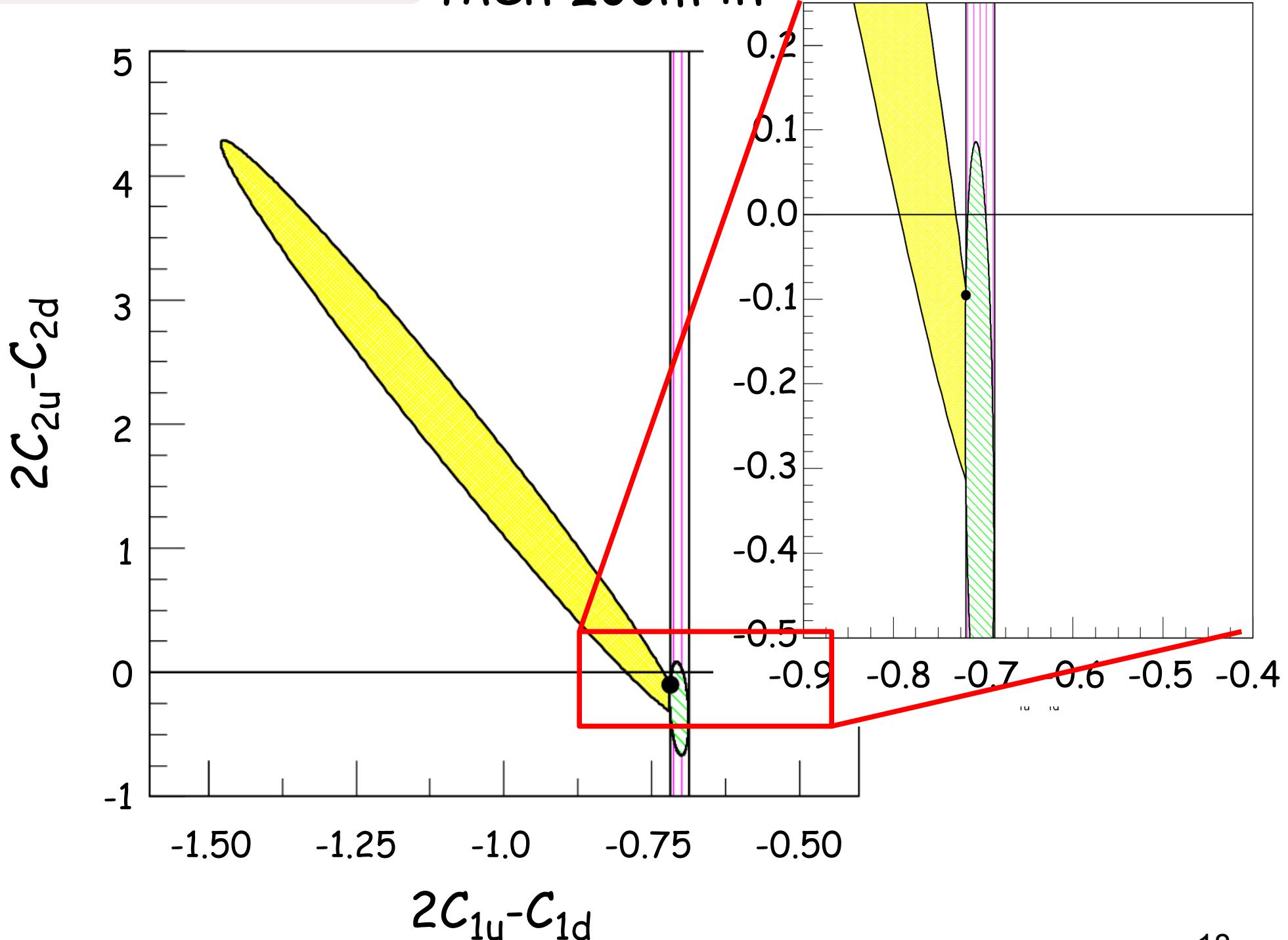
Add E122 - the first PVES (1978)



and combine them



then zoom in



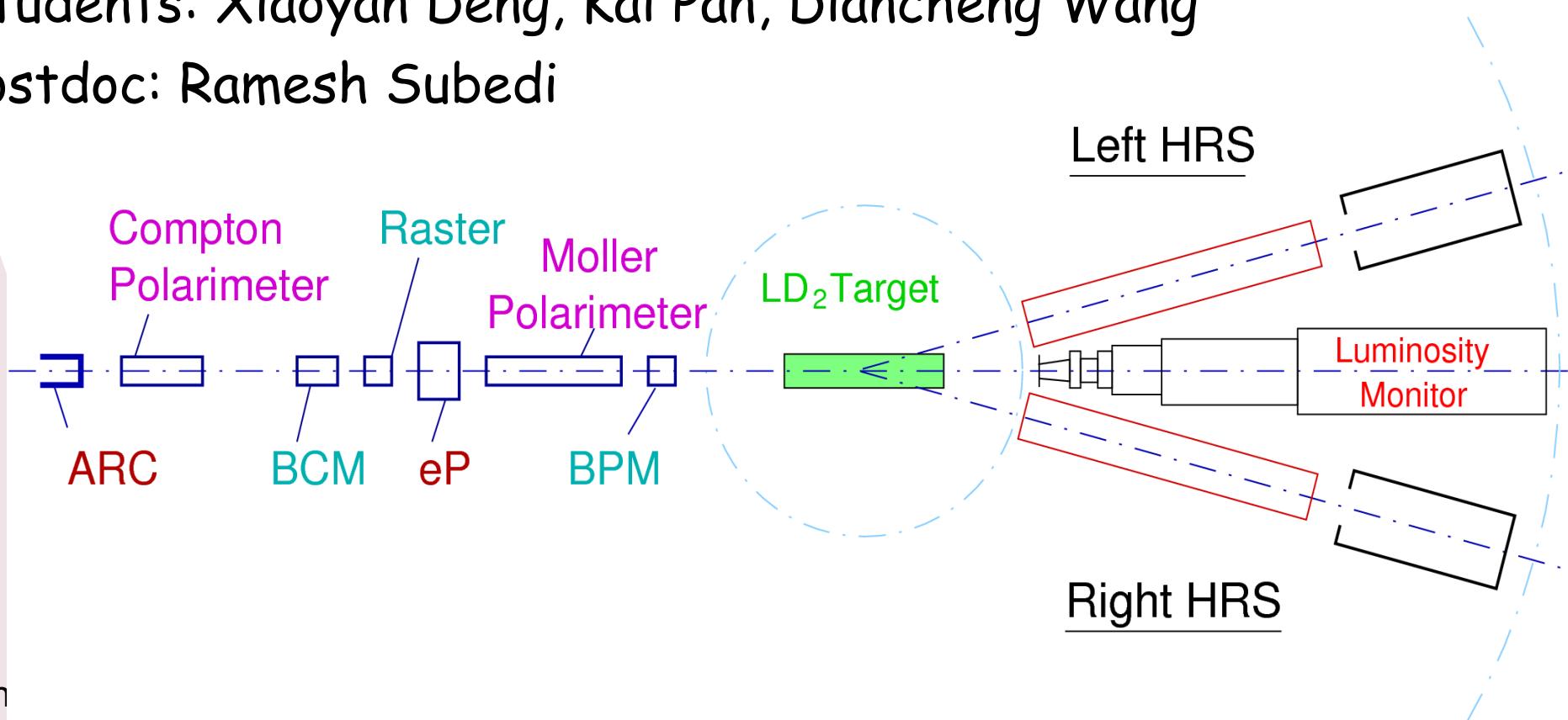
PVDIS at 6 GeV (JLab E08-011)



- Staff: ~700
- User community: ~1300
- Beam first delivered in 10/95
- In full operation since 11/97
- ~ 10^2 PhDs to date (~1/3 of US PhDs in Nuclear Physics)
- 6 GeV until 2012, 12 GeV - 2014
- “Continuous beam”, provides the highest polarized luminosity of the world

PVDIS at 6 GeV (JLab E08-011)

- Ran in Oct-Dec 2009, 100uA, 90% polarized electron beam, 20-cm liquid deuterium target
- Two High Resolution Spectrometers (HRS pair) detected electrons in the inclusive mode at DIS $Q^2=1.1$ and 1.9 GeV^2 , and five resonance kinematics.
- Spokespersons: Robert Michaels, Paul Reimer, X. Z.
- Students: Xiaoyan Deng, Kai Pan, Diancheng Wang
- Postdoc: Ramesh Subedi



E08-011 Kinematics

Kine#	HRS	E_b (GeV)	θ_0 (deg)	E'_0 (GeV)	R_e (kHz)	R_{π^-}/R_e
DIS#1	Left	6.067	12.9	3.66	≈210	≈0.5
DIS#2	Left & Right	6.067	20.0	2.63	≈18	≈3.3
RES I	Left	4.867	12.9	4.0	≈300	<≈0.25
RES II	Left	4.867	12.9	3.55	≈600	<≈0.25
RES III	Right	4.867	12.9	3.1	≈400	<≈0.4
RES IV	Left	6.067	15	3.66	≈80	<≈0.6
RES V	Left	6.067	14	3.66	≈130	<≈0.7

DIS Asymmetry Results

$$A_{Q^2=1.085, x=0.241}^{phys} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm}$$

$$A^{SM} = (1.156 \times 10^{-4}) [(2C_{1u} - C_{1d}) + 0.348(2C_{2u} - C_{2d})] = -87.7 \text{ ppm}$$


uncertainty due to PDF: 0.5% 5%

uncertainty due to HT: 0.5%/Q², 0.7ppm

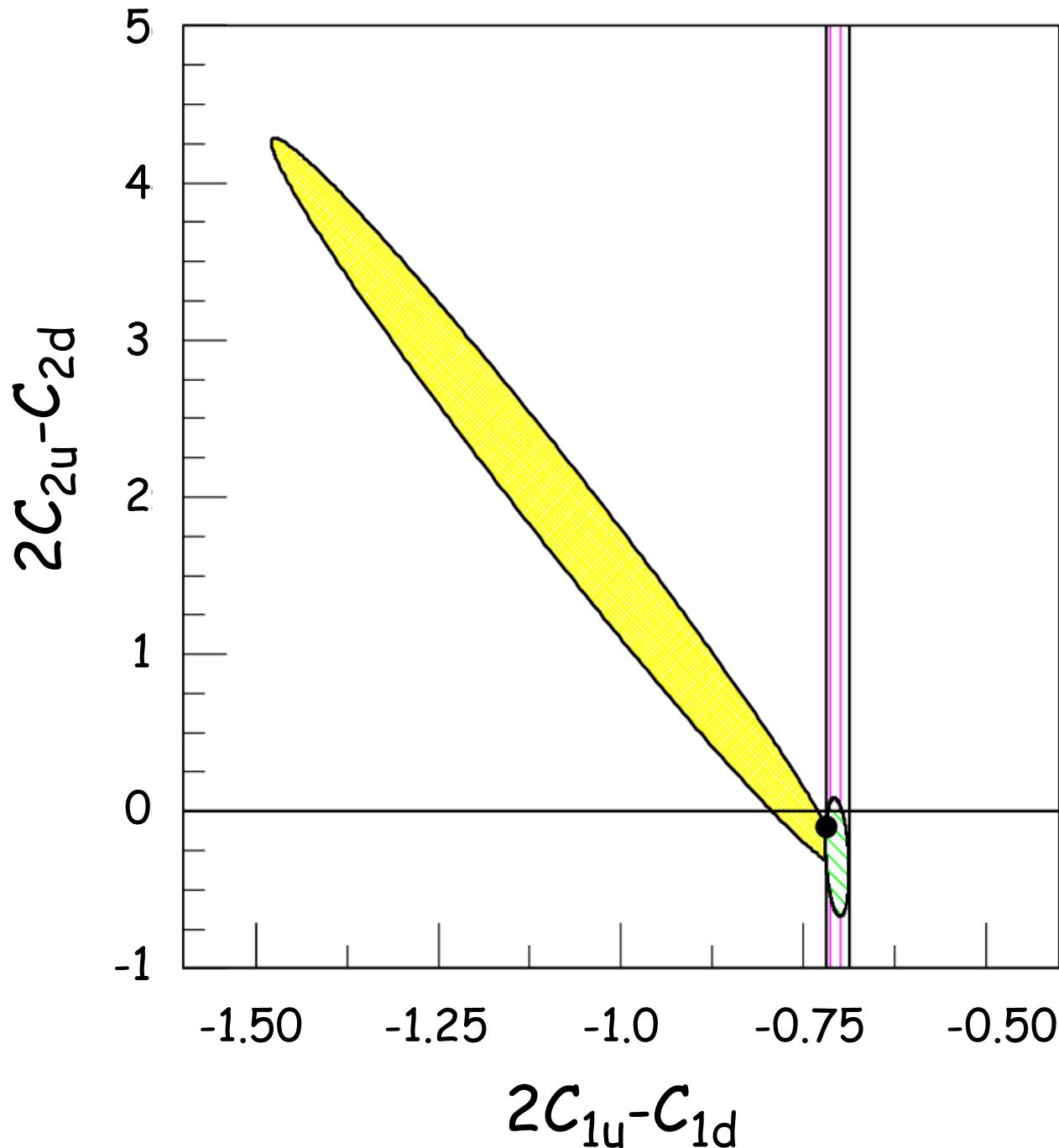
$$A_{Q^2=1.901, x=0.295}^{phys} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm}$$

$$A^{SM} = (2.022 \times 10^{-4}) [(2C_{1u} - C_{1d}) + 0.594(2C_{2u} - C_{2d})] = -158.9 \text{ ppm}$$

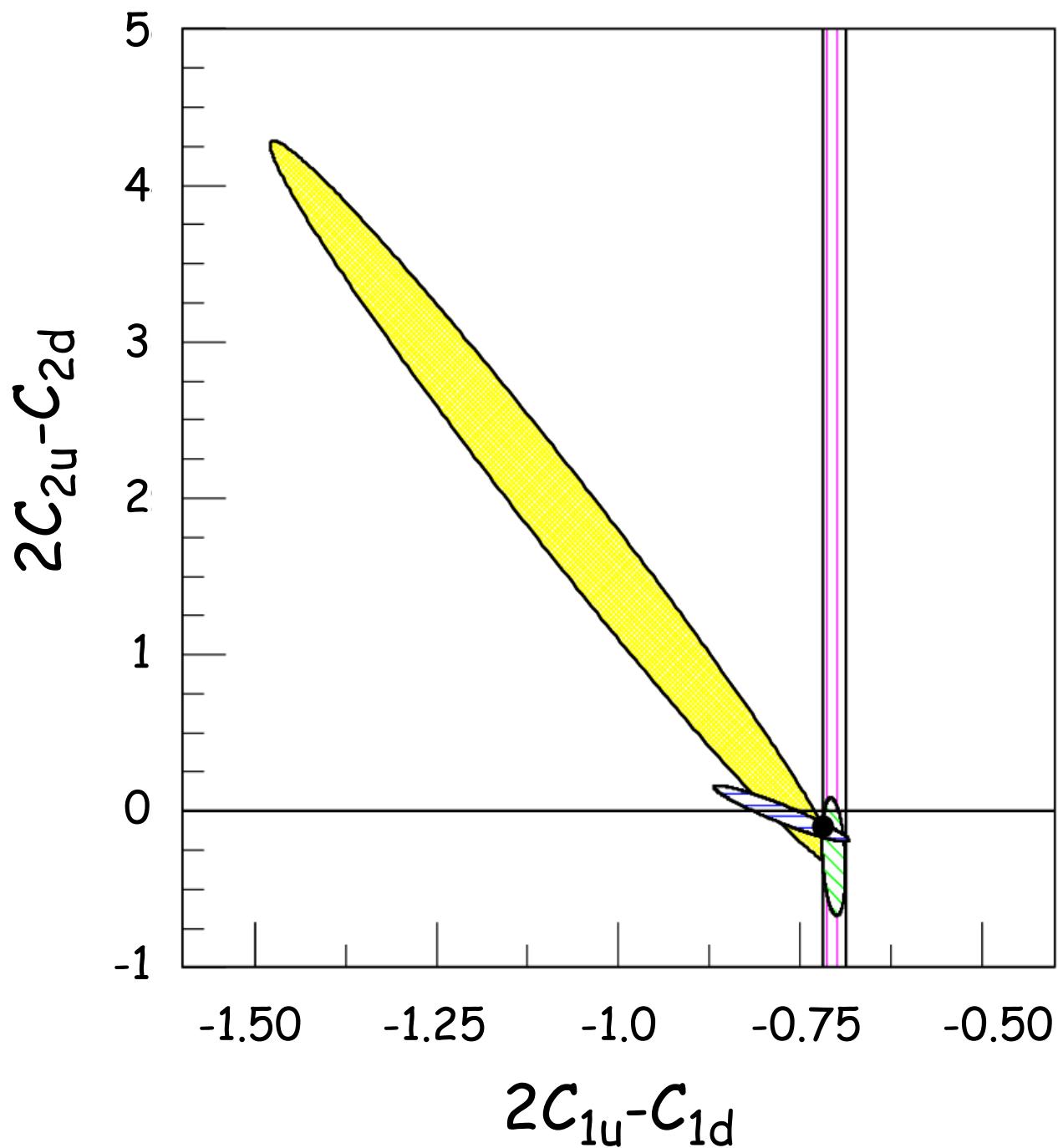

uncertainty due to PDF: 0.5% 5%

uncertainty due to HT: 0.5%/Q², 1.2ppm

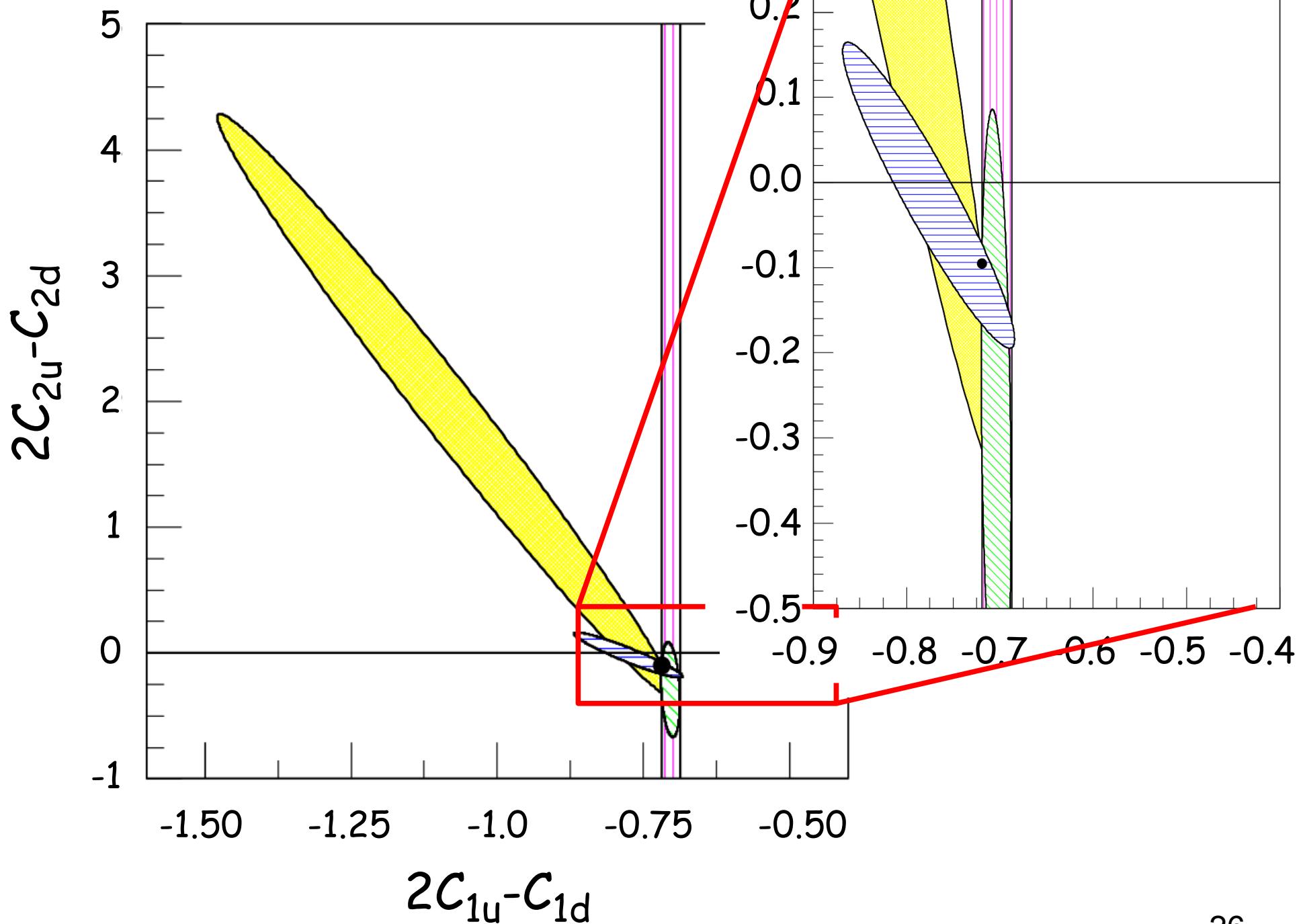
Previous data: Elastic PVES + APV



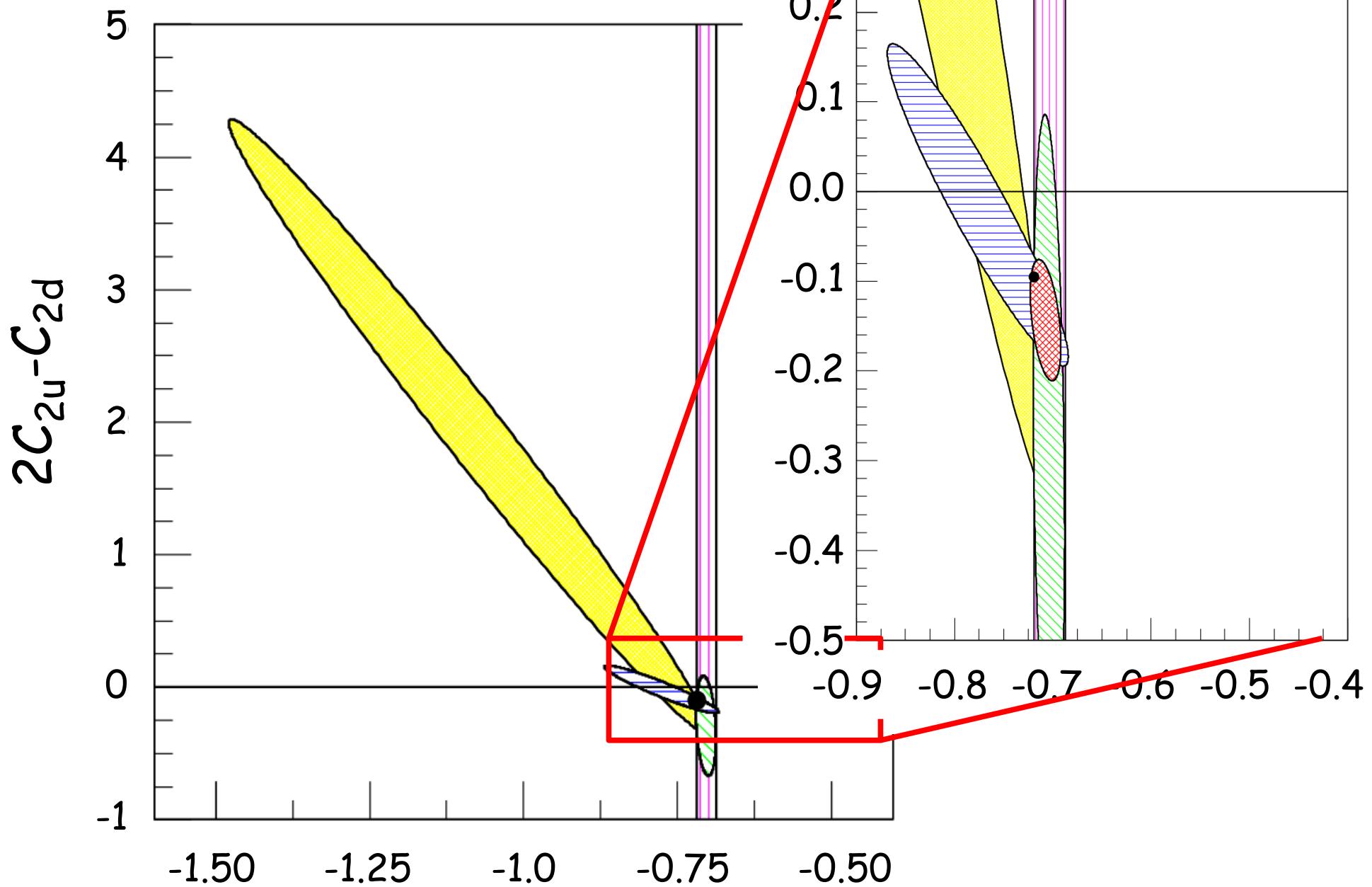
Add JLab PVDIS



zoom in



best fit



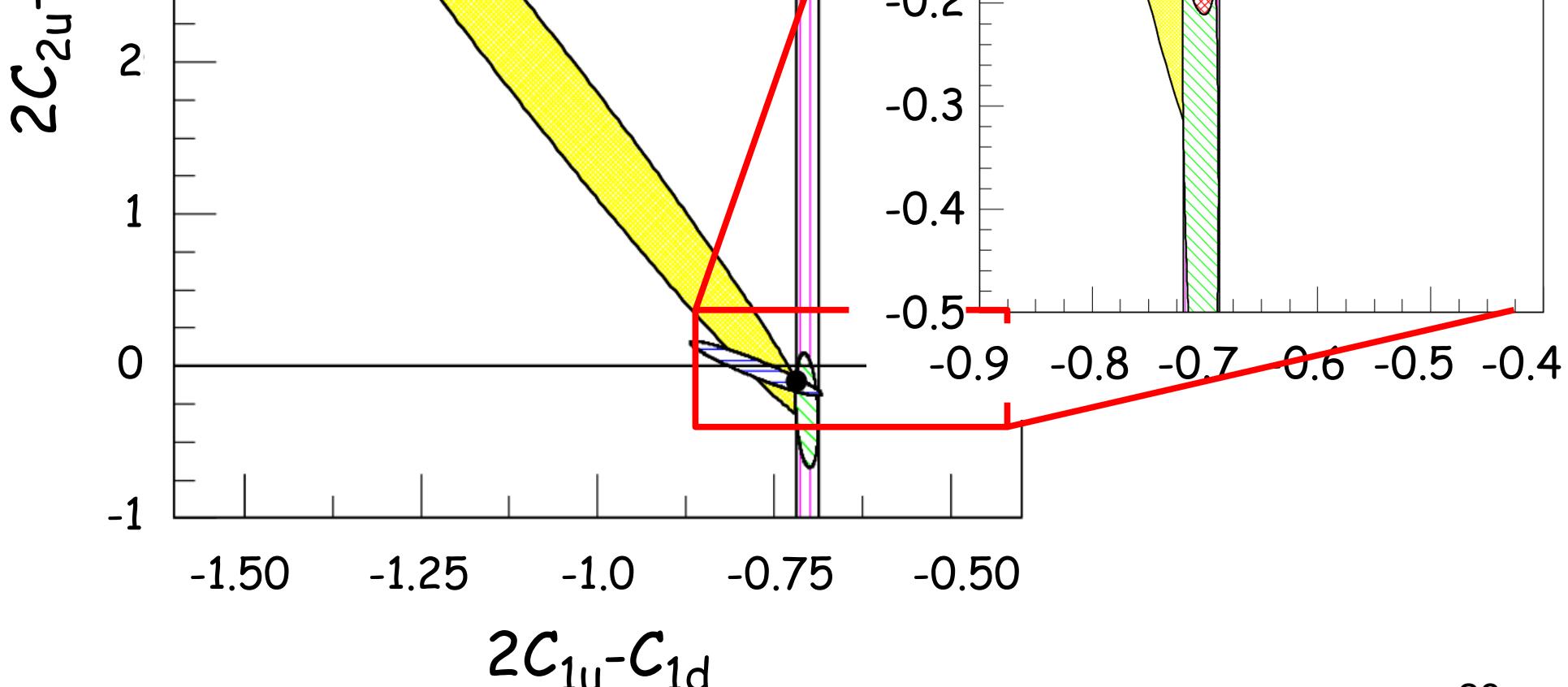
$2C_{1u}$ Wang et al., Nature 506, no. 7486, 67 (2014);

best fit

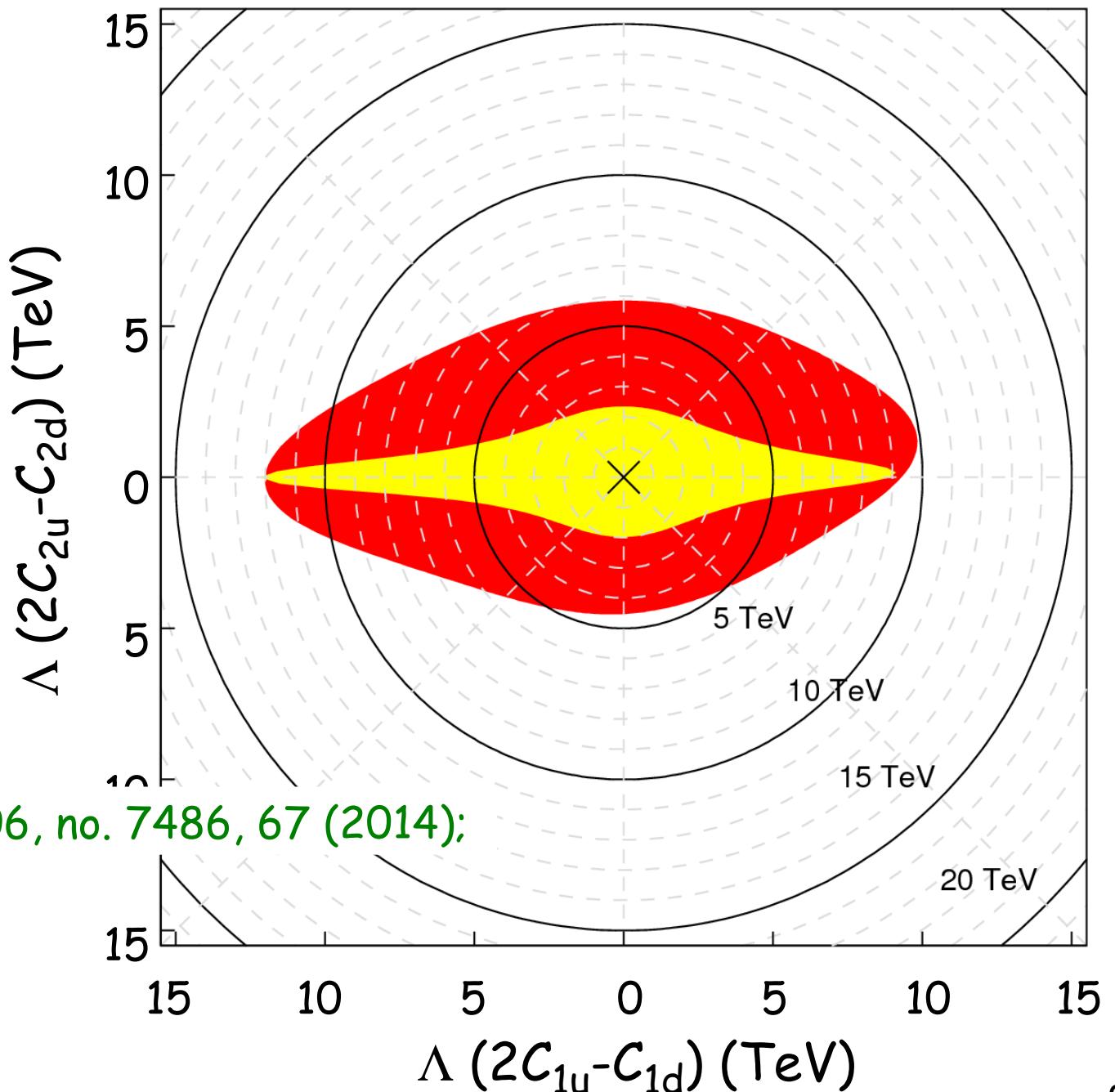
Quarks are not ambidextrous

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](#)

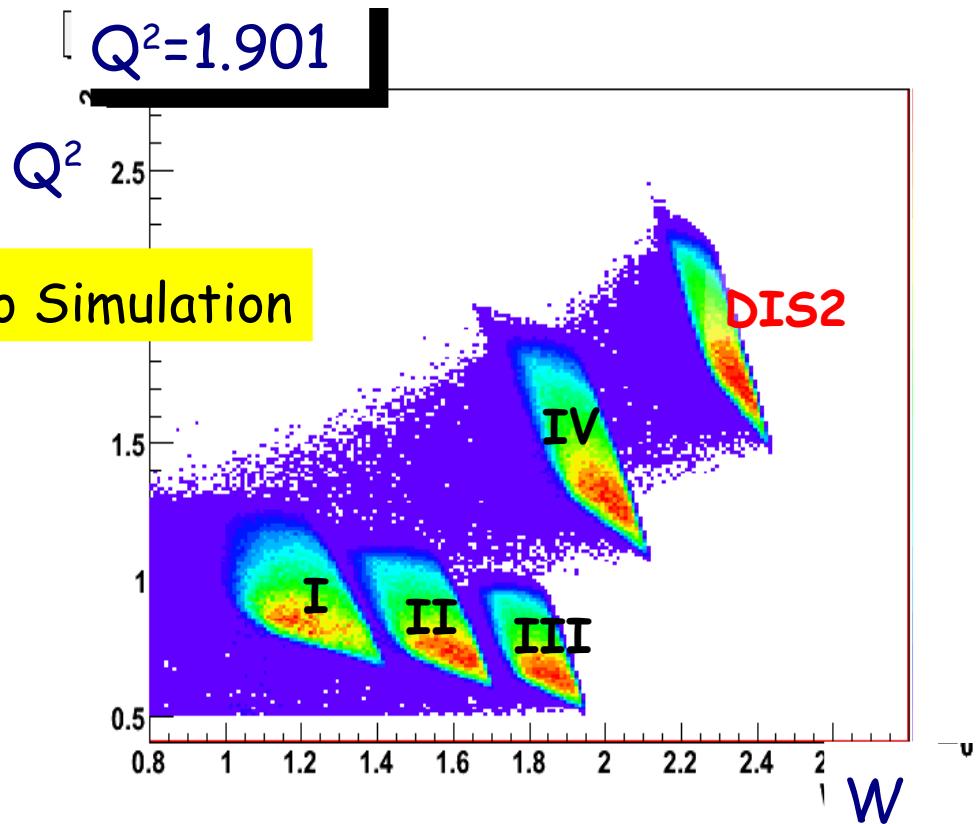
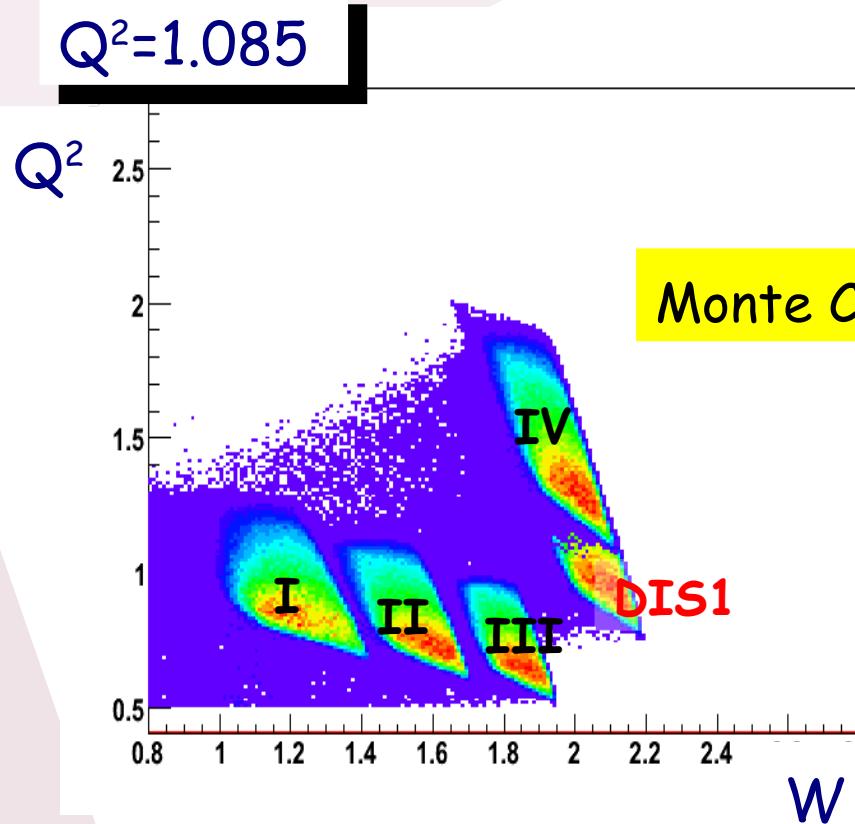
Marciano., Nature 506, no. 7486, 43 (2014);



BSM Mass Limit on eq VA contact interaction



Resonance Background Data Coverage



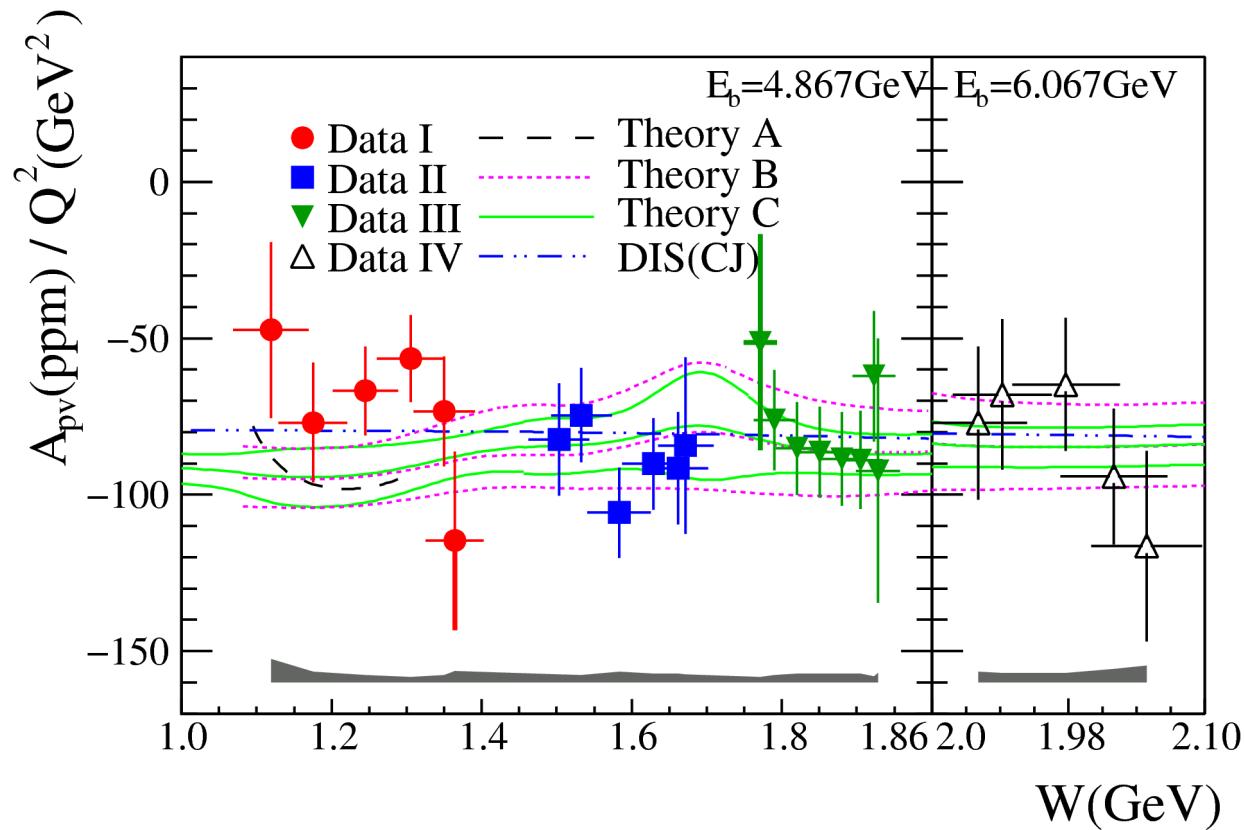
- Four setting covered the full resonance region;
- "Grouping" of lead glass blocks allowed a reasonable study of the W -dependence;

Resonance PV Asymmetry Results

A: Matsui, Sato, Lee, PRC72,025204(2005)

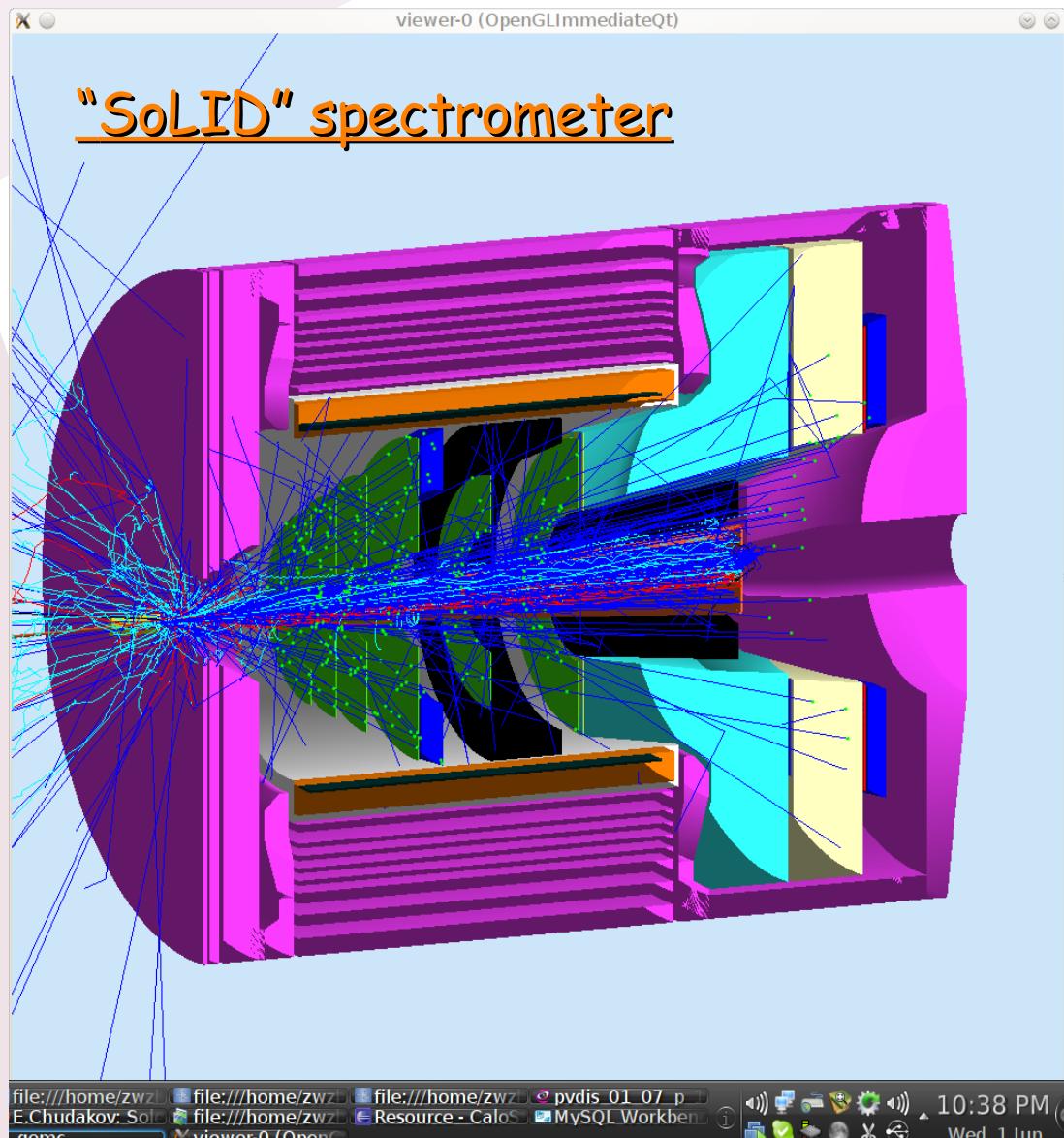
B: Gorchtein, Horowitz, Ramsey-Musolf, PRC84,015502(2011)

C: Hall, Blunden, Melnitchouk, Thomas, Young, PRD88, 013011 (2013)



Wang et al., PRL 111, 082501 (2013);

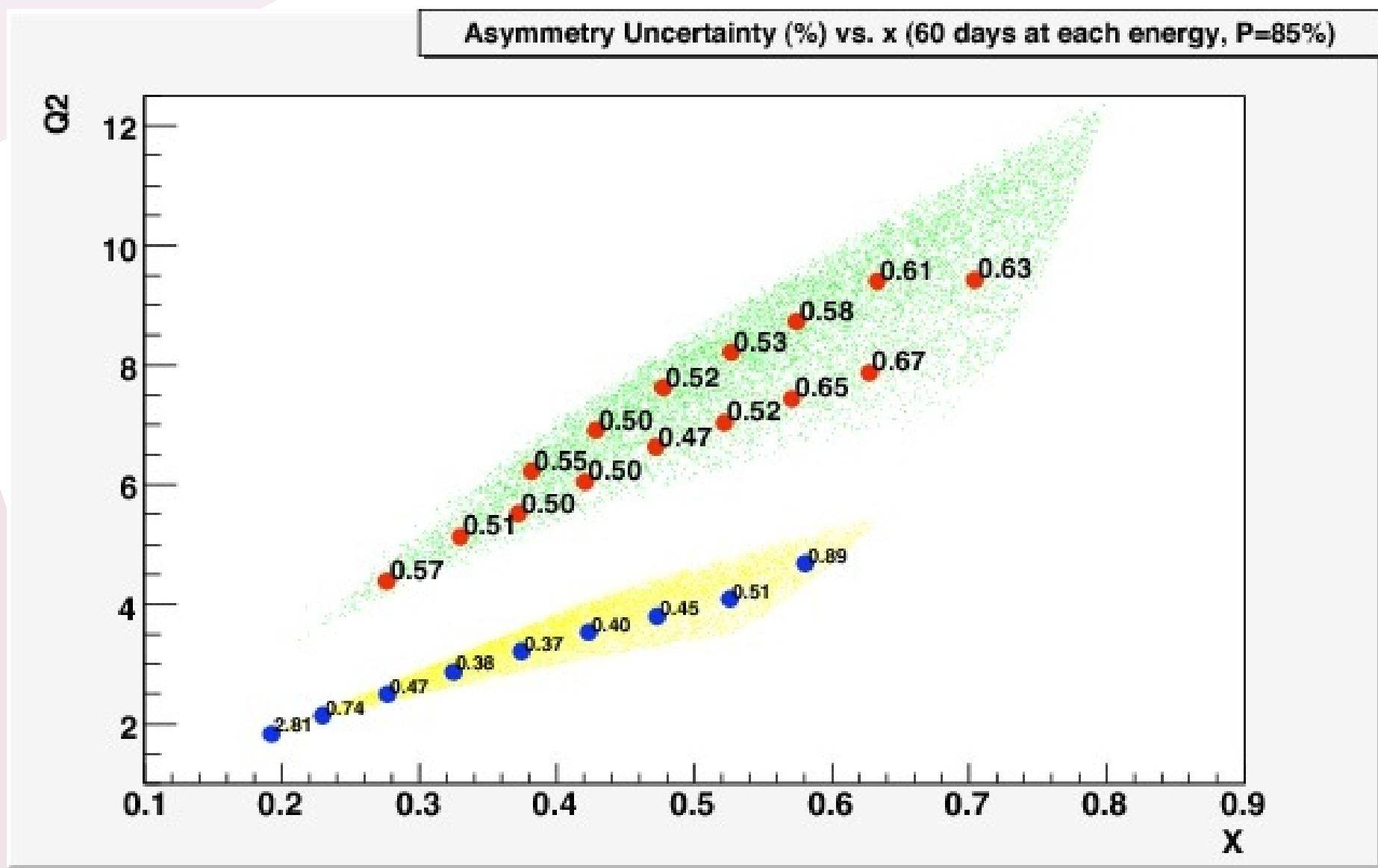
Coherent PVDIS Program with SoLID @ 11 GeV



SoLID Physics topics:

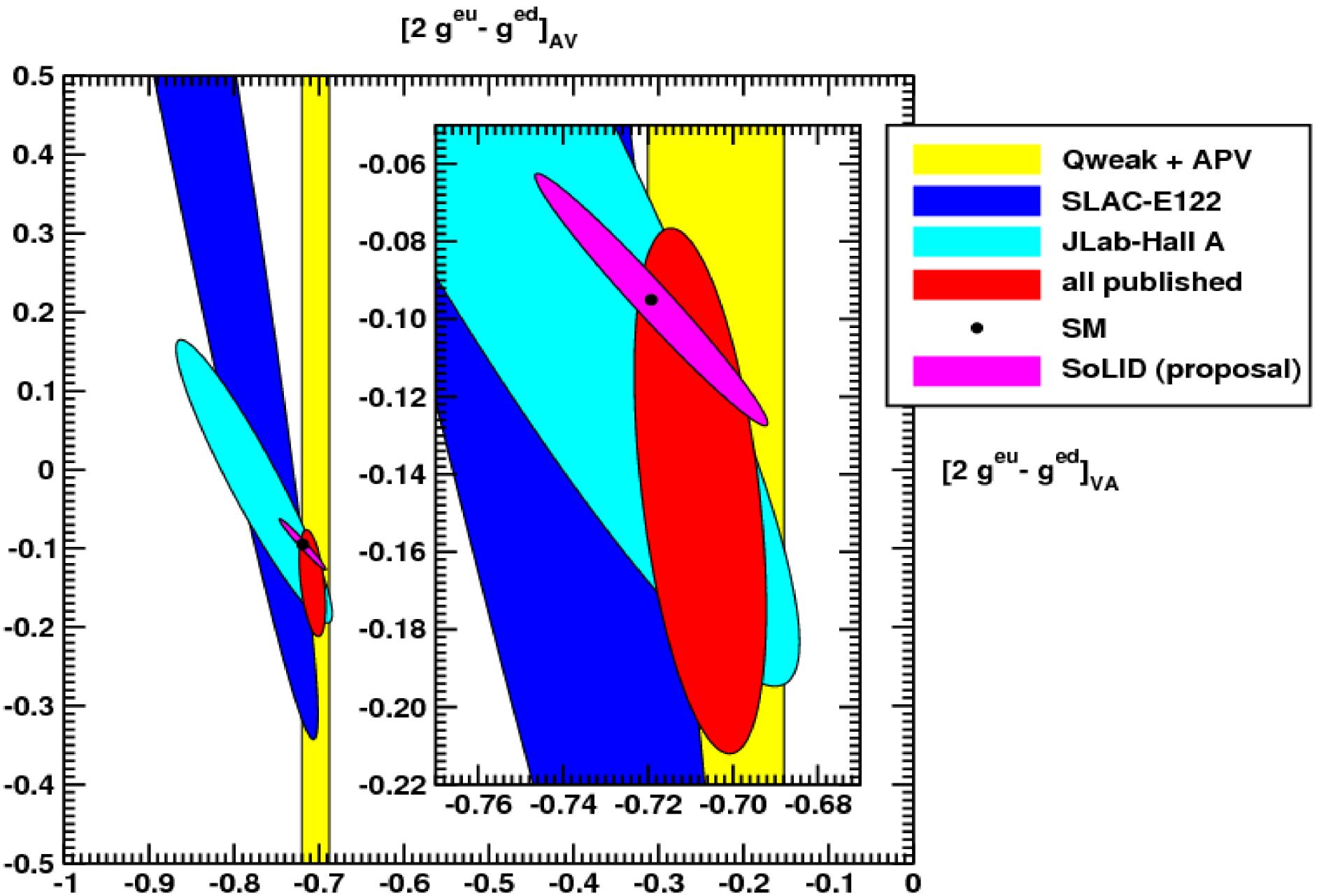
- PVDIS deuteron (180 days) - C_2 , $\sin^2\theta_W$, CSV, diquarks,
- PVDIS proton (90 days) - d/u
- PV with ${}^3\text{He}$ (LOI)
- SIDIS
- J/ψ

Coherent PVDIS Program with SoLID @ 11 GeV

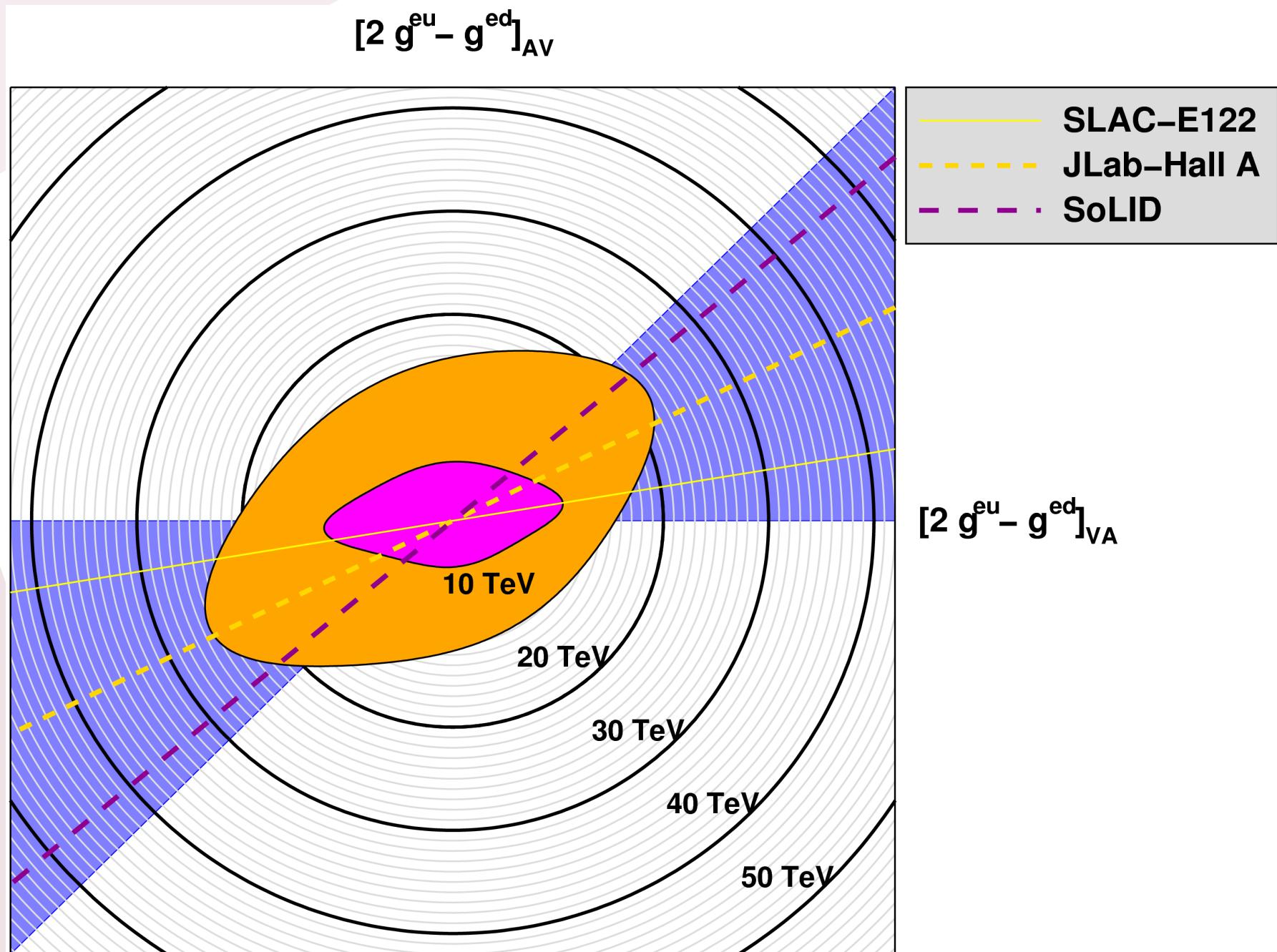


Goal on C_{2q} : one order of magnitude improvement over 6 GeV

Coherent PVDIS Program with SoLID @ 11 GeV



Coherent PVDIS Program with SoLID @ 11 GeV



Summary and Perspectives

The 6 GeV PVDIS from JLab:

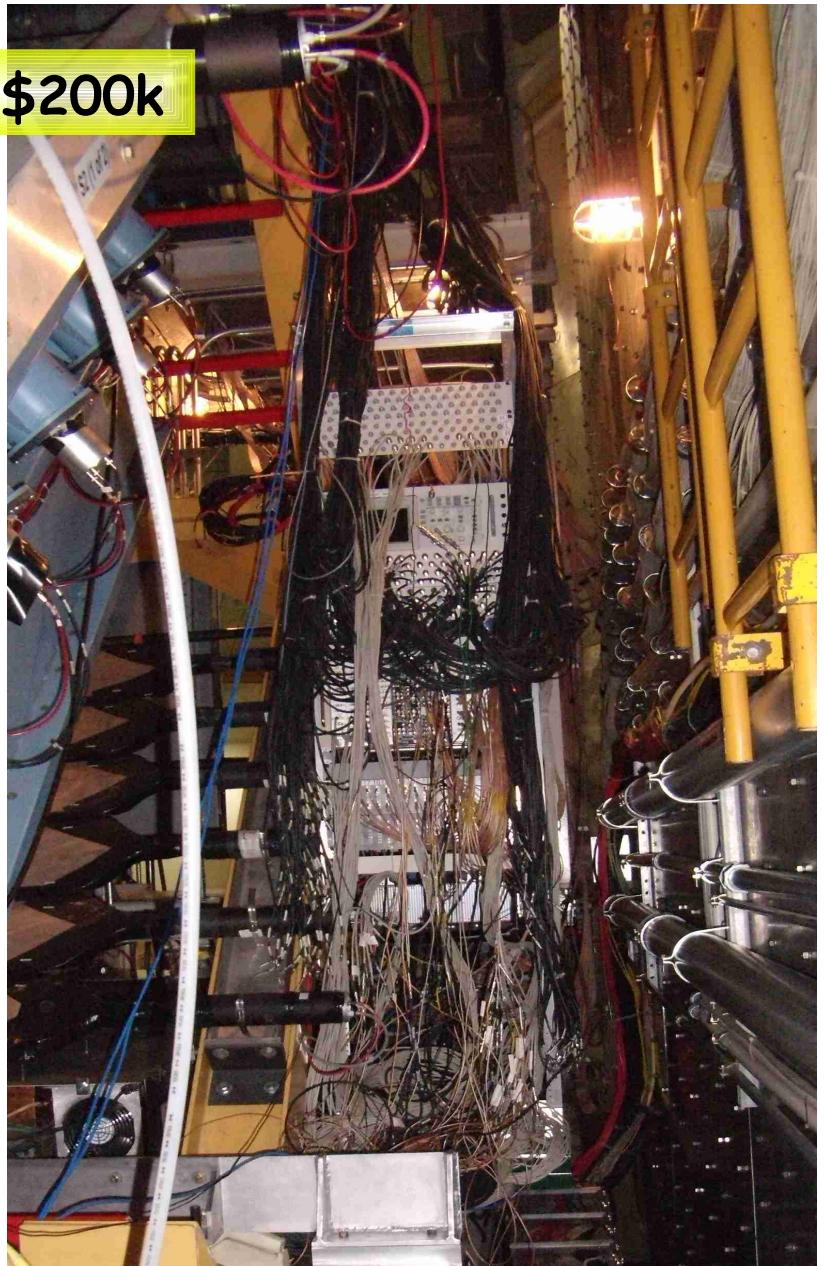
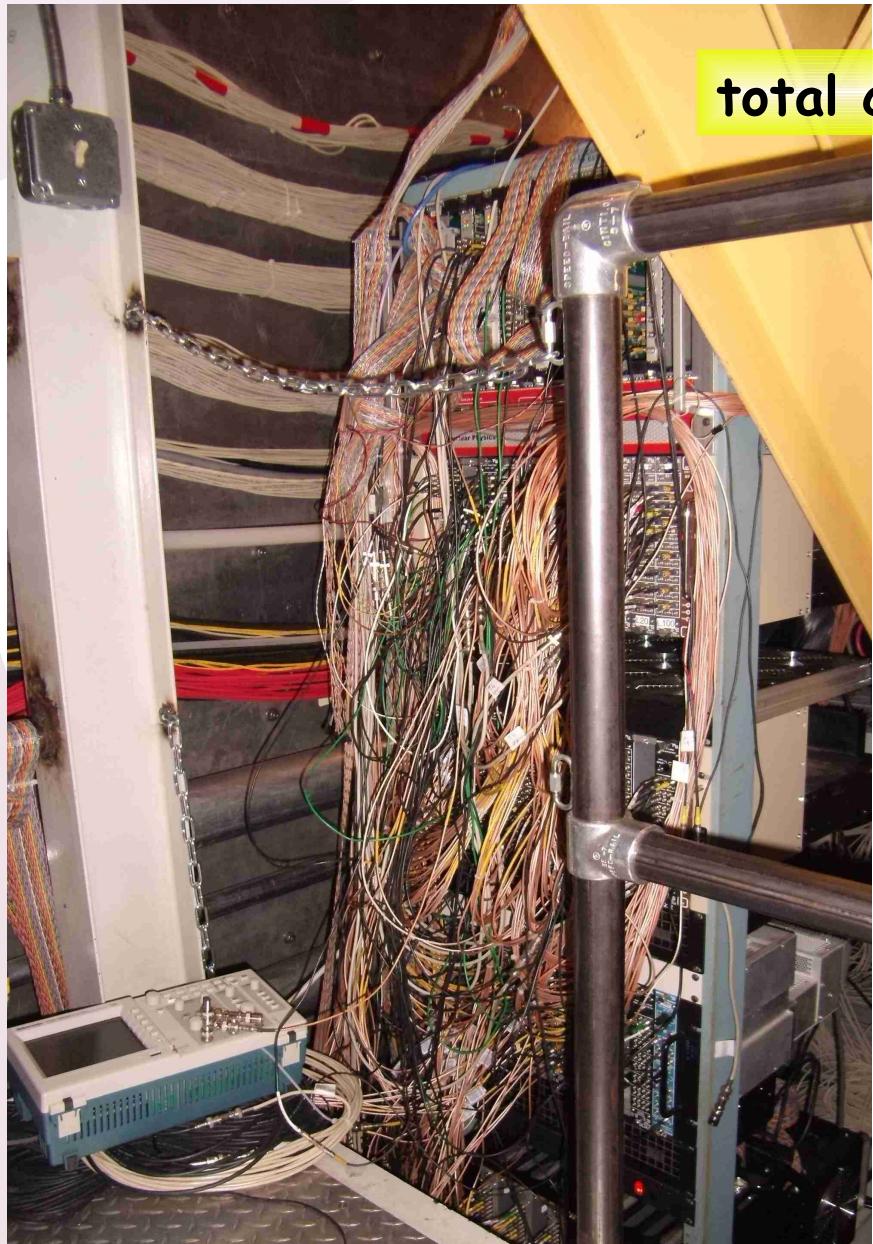
- Improved world data on the eq VA effective coupling term $2C_{2u}-C_{2d}$ by factor of five; agrees with the SM; and showed $2C_{2u}-C_{2d}$ is 2σ from zero - indicating a nonzero contribution to PVDIS asymmetry due to quark's chirality preference; BSM mass limits complimentary to collider experiments.
- Resonance PV asymmetries seem to indicate duality in the electroweak observables for the first time.

"New construction" experiments at JLab 12 GeV:

- PVDIS @ 11 GeV (SoLID) will improve C_{2q} by another order of magnitude.

Subedi et al, NIM-A724, 90 (2013); Wang et al., PRL111, 082501 (2013);
Wang et al., Nature506, no.7486, 67 (2014); Want et al., arXiv:1411.3200 (nucl-ex)

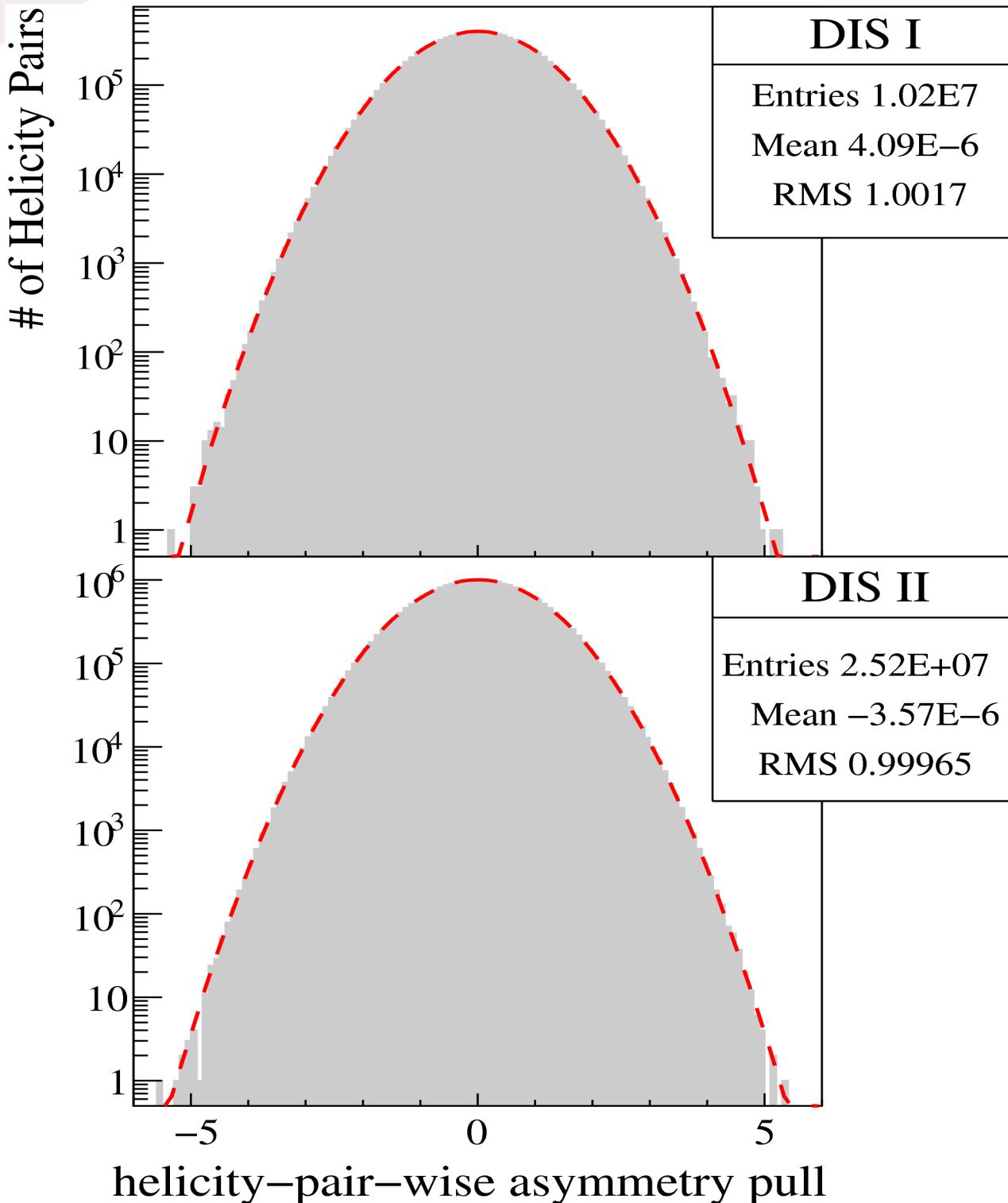
It's not easy to count electrons! – Our customized fast counting DAQ with online particle identification



Data Quality

(pair-wise
asymmetry pull plots):

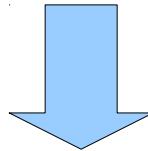
$$pull = \frac{A_i - \langle A \rangle}{\Delta A_i}$$



From Measured to Physics Asymmetry

correcting for background f_i with asymmetry A_i :

$$A^{phys} = \frac{\left(\frac{A^{raw}}{P_b} - \sum_i A_i f_i \right)}{1 - \sum_i f_i}$$



$$A^{phys} \approx \frac{A^{raw}}{P_b} \prod_i (1 + \bar{f}_i)$$

$$\bar{f}_i \equiv f_i \left(1 - \frac{A_i}{A^{raw}} P_b \right)$$

From Measured to Physics Asymmetry

$$A_{Q^2=1.085, x=0.241}^{raw} = -78.45 \pm 2.68 \pm 0.07 \text{ ppm}$$

P_b	88.18%
ΔP_b	$\pm 1.76\%$
$1 + f_{\text{depol}}$ (syst.)	1.0010 $< 10^{-4}$
$1 + f_{\text{Al}}$ (syst.)	0.9999 ± 0.0024
$1 + f_{dt}$ (syst.)	1.0147 ± 0.0009
$1 + f_{rc}$ (syst.)	1.015 ± 0.020
$1 + \bar{f}_{\gamma\gamma, \gamma Z \text{ boxes}}$ (syst.)	0.998 — ± 0.002

Δf_{π^-}	$\pm 0.009\%$
$\Delta \bar{f}_{\text{pair}}$	$\pm 0.04\%$
Δf_{A_n}	$\pm 2.5\%$
ΔQ^2	$\pm 0.85\%$
rescatt bg	$\ll 0.2\%$
target impurity	$\pm 0.06\%$

A^{phys} (ppm)	-91.10
(stat.)	± 3.11
(syst.)	± 2.97
(total)	± 4.30

From Measured to Physics Asymmetry

$$A_{Q^2=1.901, x=0.295}^{raw} = -140.30 \pm 10.43 \pm 0.16 \text{ ppm (LHRS)}$$

$$A_{Q^2=1.901, x=0.295}^{raw} = -139.84 \pm 6.58 \pm 0.46 \text{ ppm (RHRS)}$$

P_b	89.29	88.73%	Δf_{π^-}	$\pm 0.006\%$	$\pm 0.003\%$
ΔP_b	1.19%	$\pm 1.50\%$	$\Delta \bar{f}_{\text{pair}}$	$\pm 0.4\%$	$\pm 0.2\%$
$1 + f_{\text{depol}}$ (syst.)	1.0021 $< 10^{-4}$		$\Delta \bar{f}_{A_n}$	$\pm 2.5\%$	$\pm 2.5\%$
$1 + f_{\text{Al}}$ (syst.)	0.9999 ± 0.0024	0.9999 ± 0.0024	ΔQ^2	$\pm 0.64\%$	$\pm 0.65\%$
$1 + f_{dt}$ (syst.)	1.0049 ± 0.0004	1.0093 ± 0.0013	rescatt bg	$\ll 0.2\%$	$\ll 0.2\%$
$1 + f_{rc}$ (syst.)	1.019 ± 0.004		target impurity	$\pm 0.06\%$	$\pm 0.06\%$
$1 + f_{\gamma\gamma\text{box}}$	0.997	—	Asymmetry		
$1 + \bar{f}_{\gamma\gamma, \gamma Z\text{boxes}}$ (syst.)	— ± 0.003	1.005 ± 0.005	$A^{\text{phys}} \text{ (ppm)}$ (stat.)	-160.80 ± 6.39	
			(syst.)	± 3.12	
			(total)	± 7.12	

Pion Asymmetries

HRS, Kinematics	Left DIS#1	Left DIS#2	Right DIS#2
narrow path			
$A_\pi^{\text{meas}} \pm \Delta A_\pi^{\text{meas}}$ (total) (ppm)	-48.8 ± 14.0	-22.0 ± 21.4	-20.3 ± 6.0
$A_{e,\text{dit}}^{\text{bc,raw}} \pm \Delta A_{e,\text{dit}}^{\text{bc,raw}}$ (stat.) (ppm)	-78.5 ± 2.7	-140.3 ± 10.4	-139.8 ± 6.6
$f_{\pi/e} \pm \Delta f_{\pi/e}$ (total) ($\times 10^{-4}$) $\left(\frac{\Delta A_e}{A_e} \right)_{\pi^-, n}$	(1.07 ± 0.24) 0.89×10^{-4}	(1.97 ± 0.18) 0.63×10^{-4}	(1.30 ± 0.10) 0.27×10^{-4}
wide path			
$A_\pi^{\text{meas}} \pm \Delta A_\pi^{\text{meas}}$ (total) (ppm)	-41.3 ± 12.8	-23.7 ± 21.4	-20.3 ± 6.0
$A_{e,\text{dit}}^{\text{bc,raw}} \pm \Delta A_{e,\text{dit}}^{\text{bc,raw}}$ (stat.) (ppm)	-78.3 ± 2.7	-140.2 ± 10.4	-140.9 ± 6.6
$f_{\pi/e} \pm \Delta f_{\pi/e}$ (total) ($\times 10^{-4}$) $\left(\frac{\Delta A_e}{A_e} \right)_{\pi^-, w}$	(0.72 ± 0.22) 0.54×10^{-4}	(1.64 ± 0.17) 0.55×10^{-4}	(0.92 ± 0.13) 0.21×10^{-4}

Pair Production Background

- Took reversed-polarity runs, mostly to determine e^+/e^- ratio.
Positron asymmetry from those runs have very large error;
- Assumed positron asymmetry to be similar to π^- asymmetry;
- Effect on the measurement is about 10 times larger than π^- background.

SLAC E122 vs. JLab E08-011

	SLAC E122 (1978)	JLab E08-011 (2009)
Beam	37%, 16.2-22.2 GeV	90%, 6.0674 GeV, 100uA
Target	30-cm LD2, LH2	20-cm LD2
Spectrometer	4°	12.9° and 20°
Q ²	1-1.9 GeV ²	1.1 and 1.9 GeV ²
Data collection	Integrating gas Cerenkov and lead glass detectors, independently	Counting DAQ using both GC and lead glass for PID at the hardware level
Deuteron results	(two highest energies only) $A/Q^2 = (-9.5 \pm 1.6) \times 10^{-5} \text{ (GeV/c)}^{-2}$ $\pm 0.86 \times 10^{-5} \text{ (stat)} \pm 5\% \text{ (Pb)} \pm 3.3\% \text{ (beam)}$ $\pm 2\% \text{ (\pi contamination)}$	$\pm (3-4)\% \text{ (stat)}$ $\pm \text{syst.}$
$\sin^2 \theta_W = 0.20 \pm 0.03$		
Proton results	$\pm 3\% \text{ (radiative corrections)}$ $A/Q^2 = (-9.7 \pm 2.7) \times 10^{-5} \text{ (GeV/c)}^{-2}$	