The JLab 6 GeV Parity Violation Deep Inelastic Scattering (PVDIS) Experiment

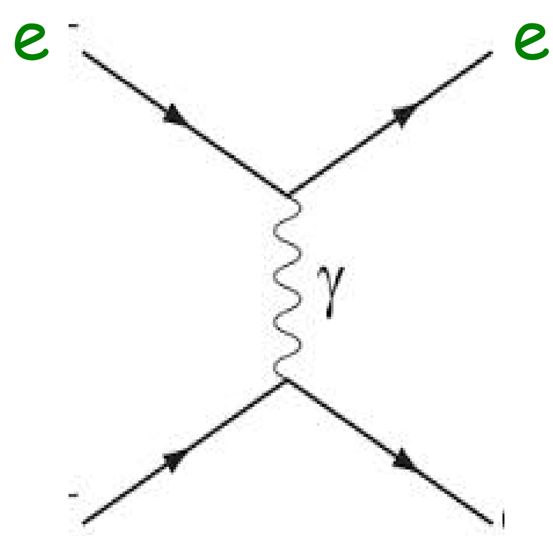
Xiaochao Zheng (Univ. of Virginia)

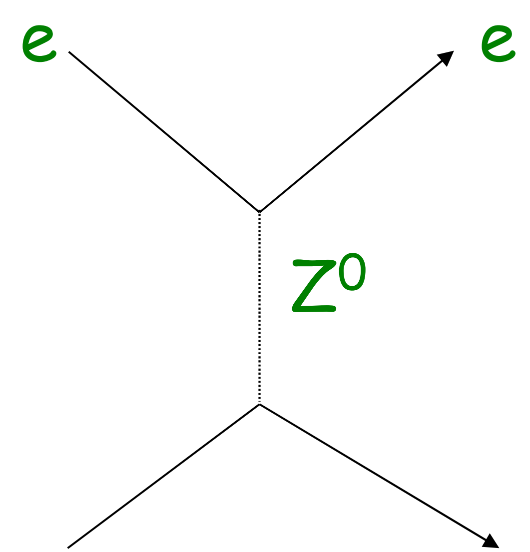
July 23rd, 2014

- 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

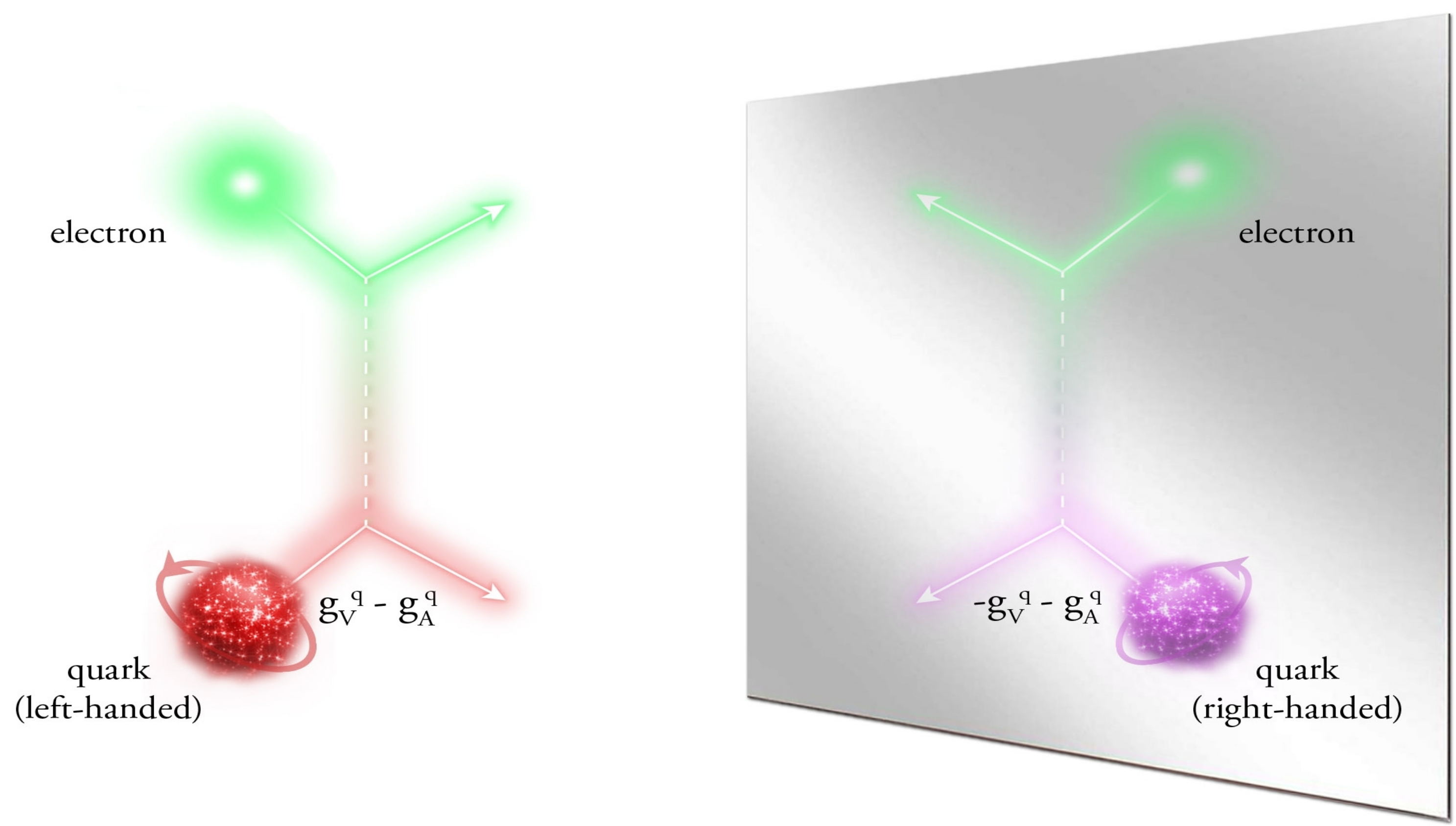
Parity-Violating Electron Scattering

- 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

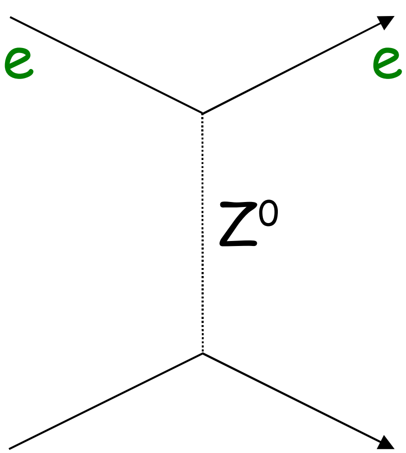
- They have a preferred chiral state when coupling to the Z^0

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: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$

$$-i\frac{g_Z}{2}\gamma^\mu[g_V^e - g_A^e\gamma^5]$$



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

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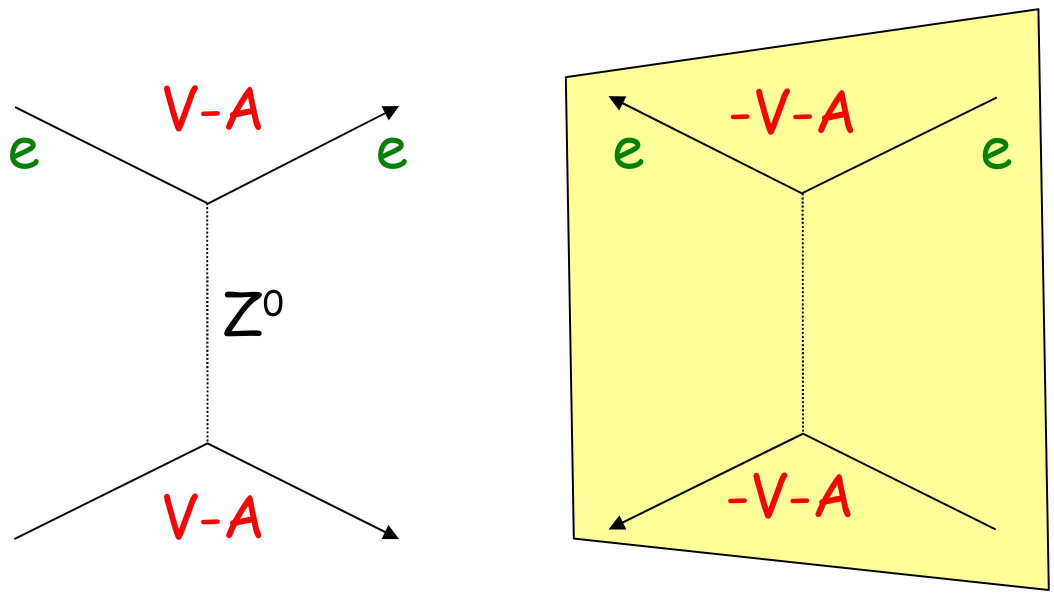
- PVES asymmetry comes from V(e)xA(targ) and A(e)xV(targ)



Effective Couplings in the Standard Model

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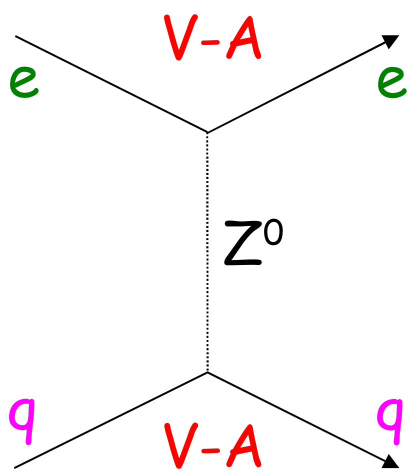
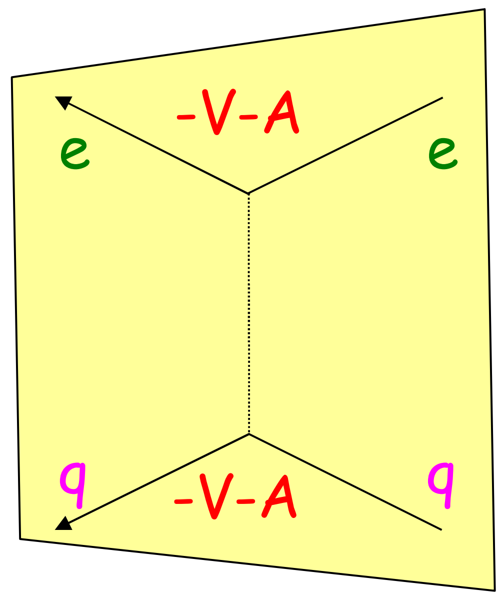
- PVDIS asymmetry comes from: $C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q$





"electron-quark effective couplings"

Effective Couplings and New Contact Interactions

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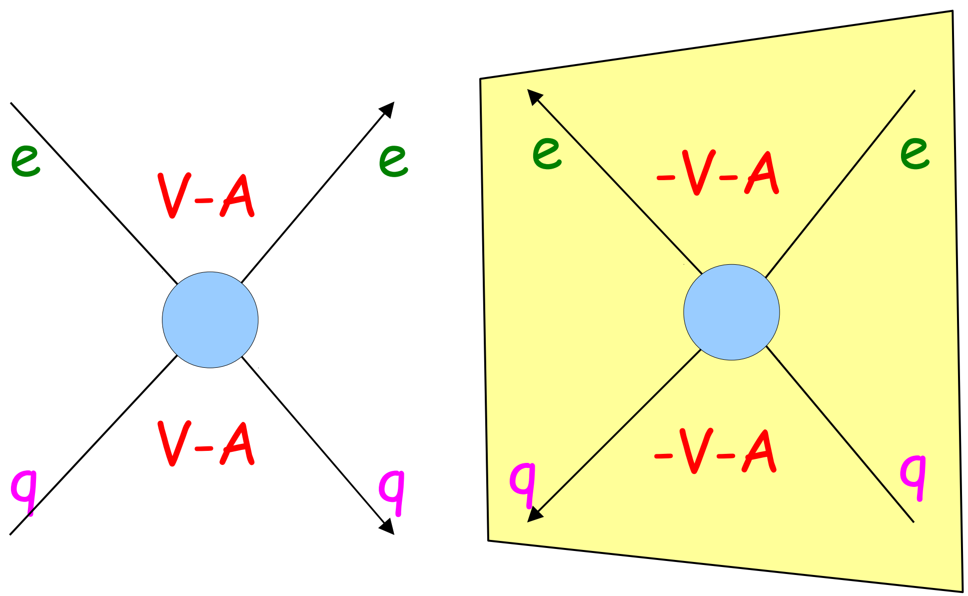

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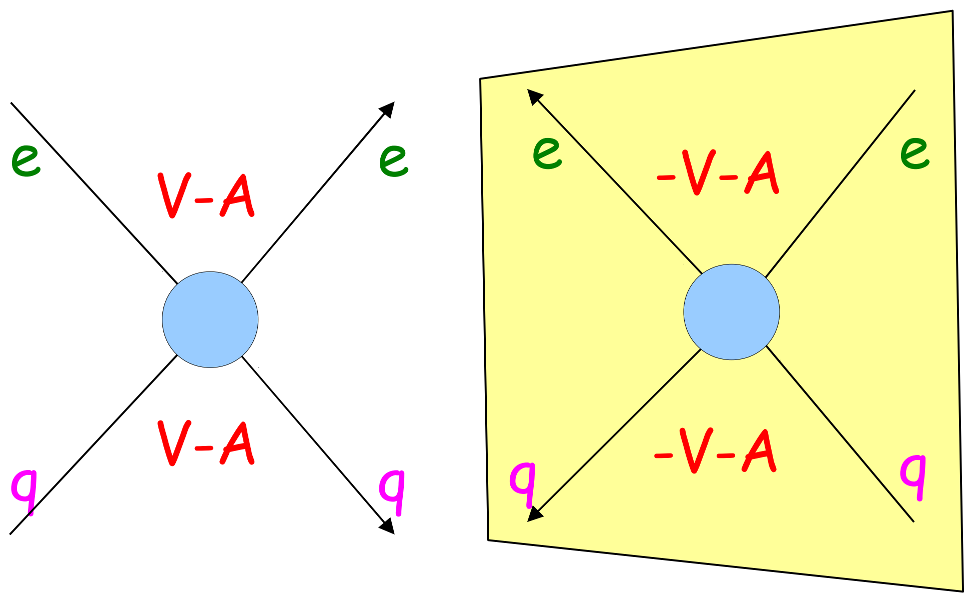

"electron-quark effective couplings"

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

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

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

$$x\equiv x_{Bjorken} \qquad y\equiv 1-E'/E$$

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

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

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

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

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

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

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

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$x \equiv x_{Bjorken} \qquad y \equiv 1 - E'/E$

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

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

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

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

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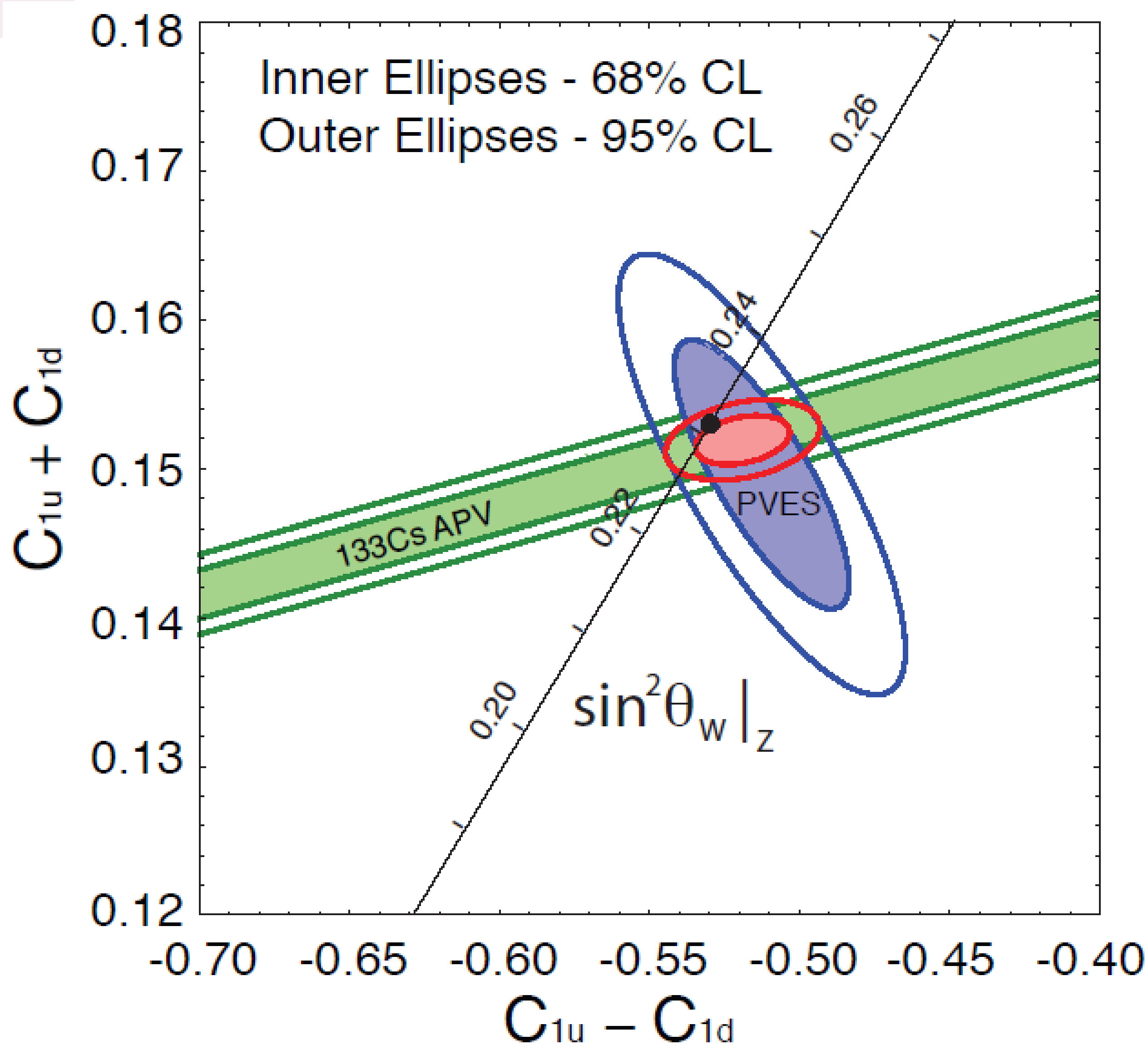
$\frac{0.6\, s^+}{u^+ + d^+} \rightarrow 0$

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

$\frac{u_V + d_V}{u^+ + d^+} \rightarrow 1$

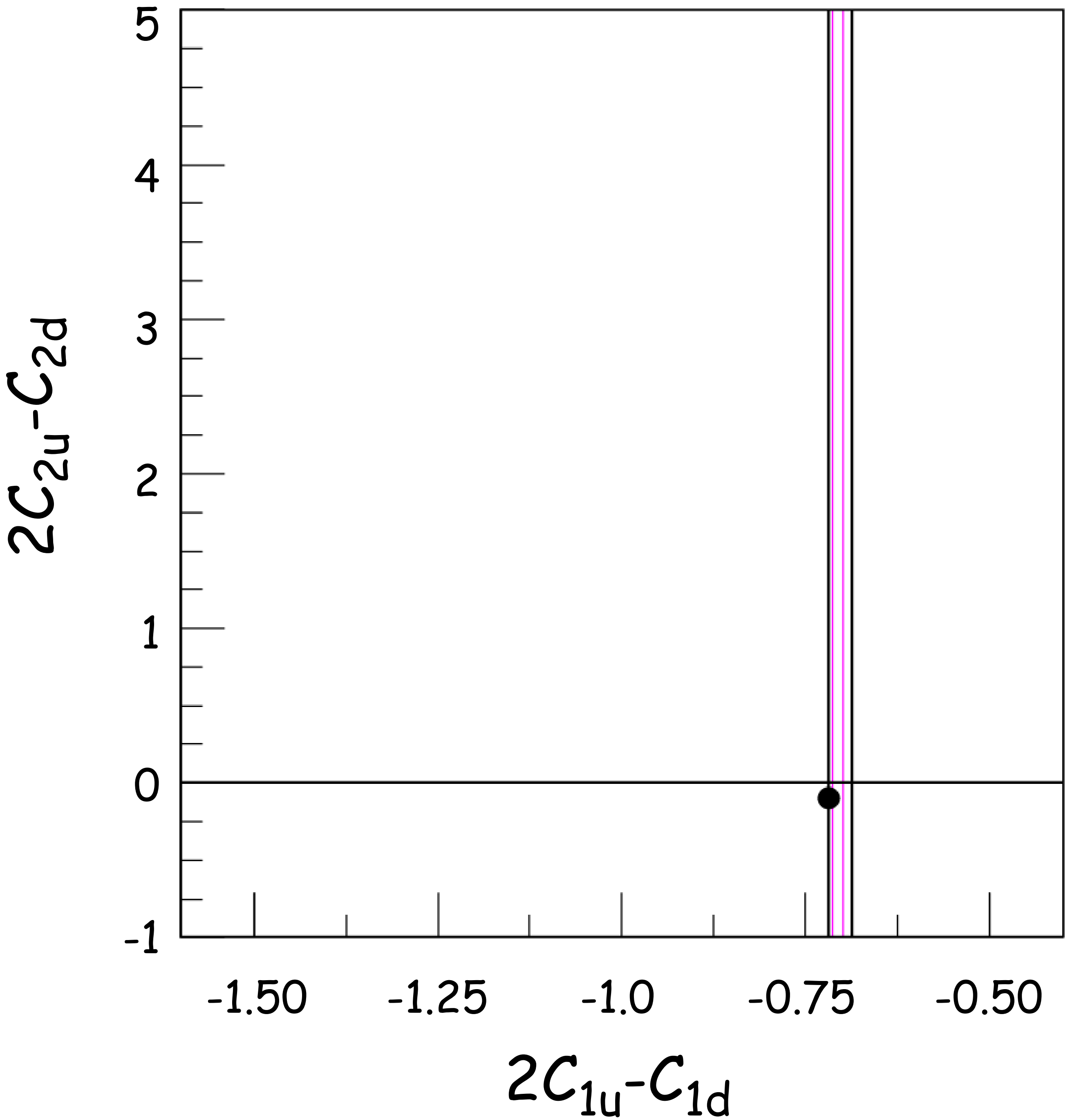
If neglecting sea quarks, asymmetry is no longer sensitive to PDFs → "static limit"

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

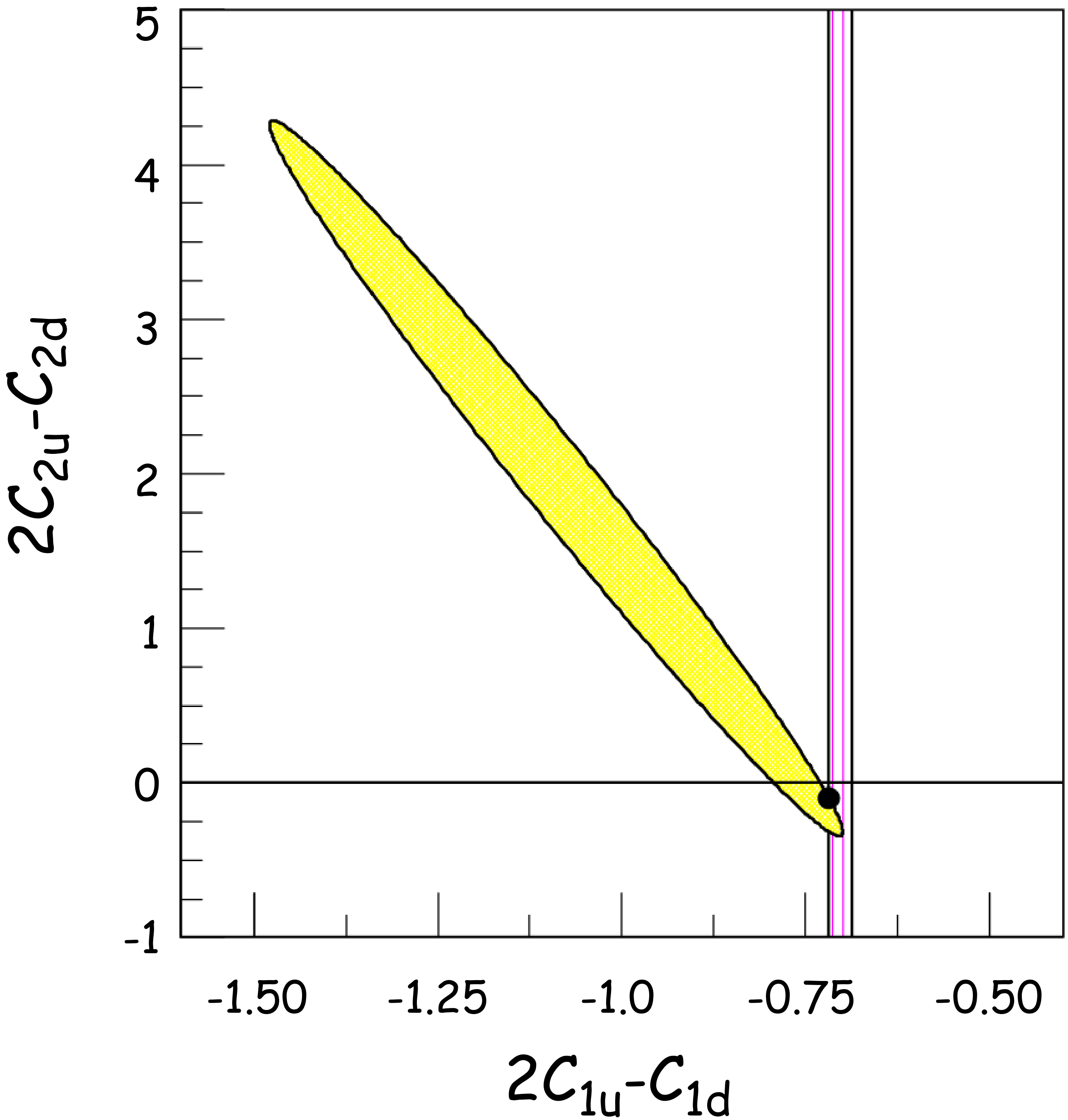


Androic et al., PRL 111, 141803 (2013);

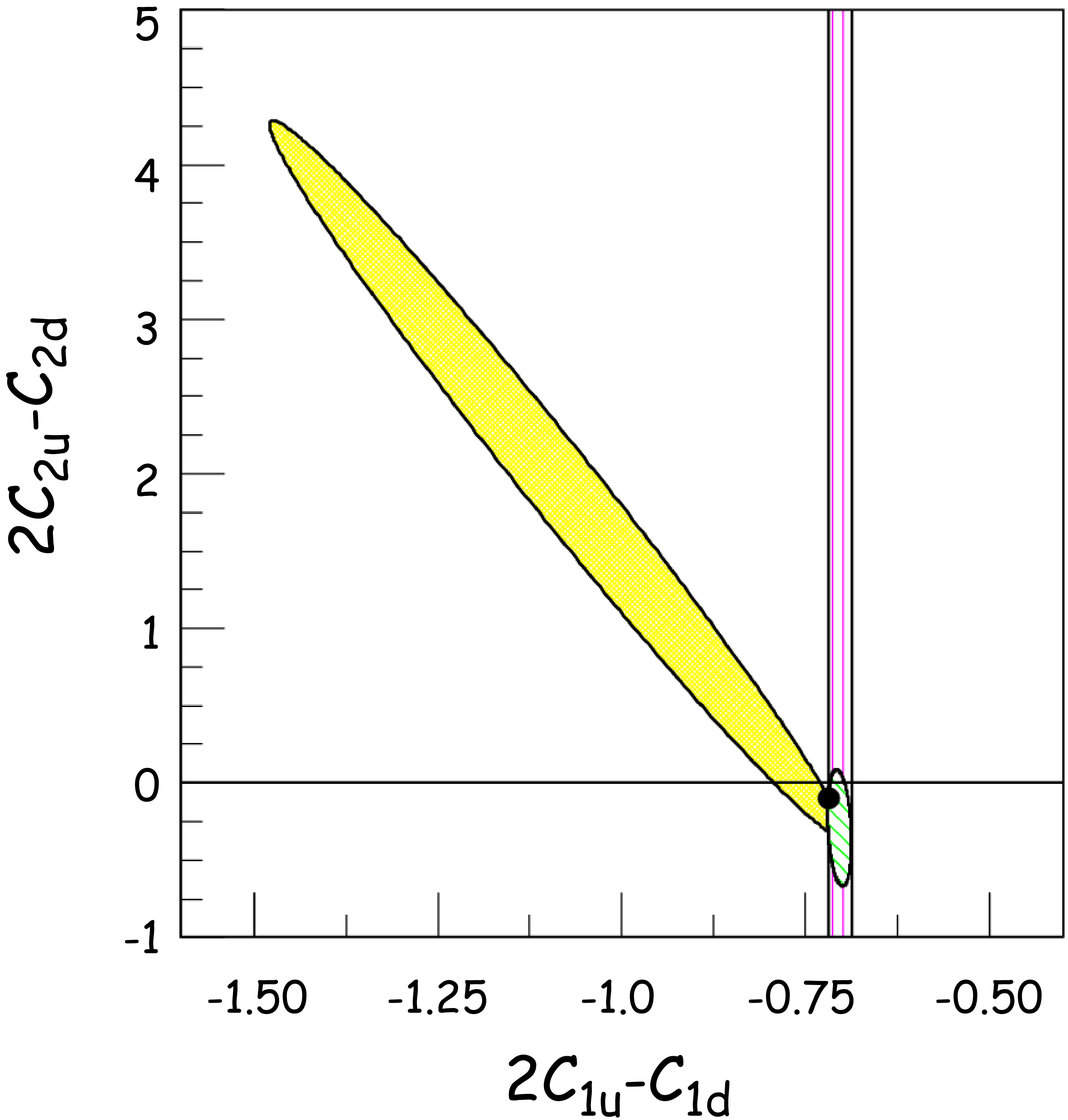
Projecting to C_{1q} vs C_{2q} (e-q AV vs. VA couplings)



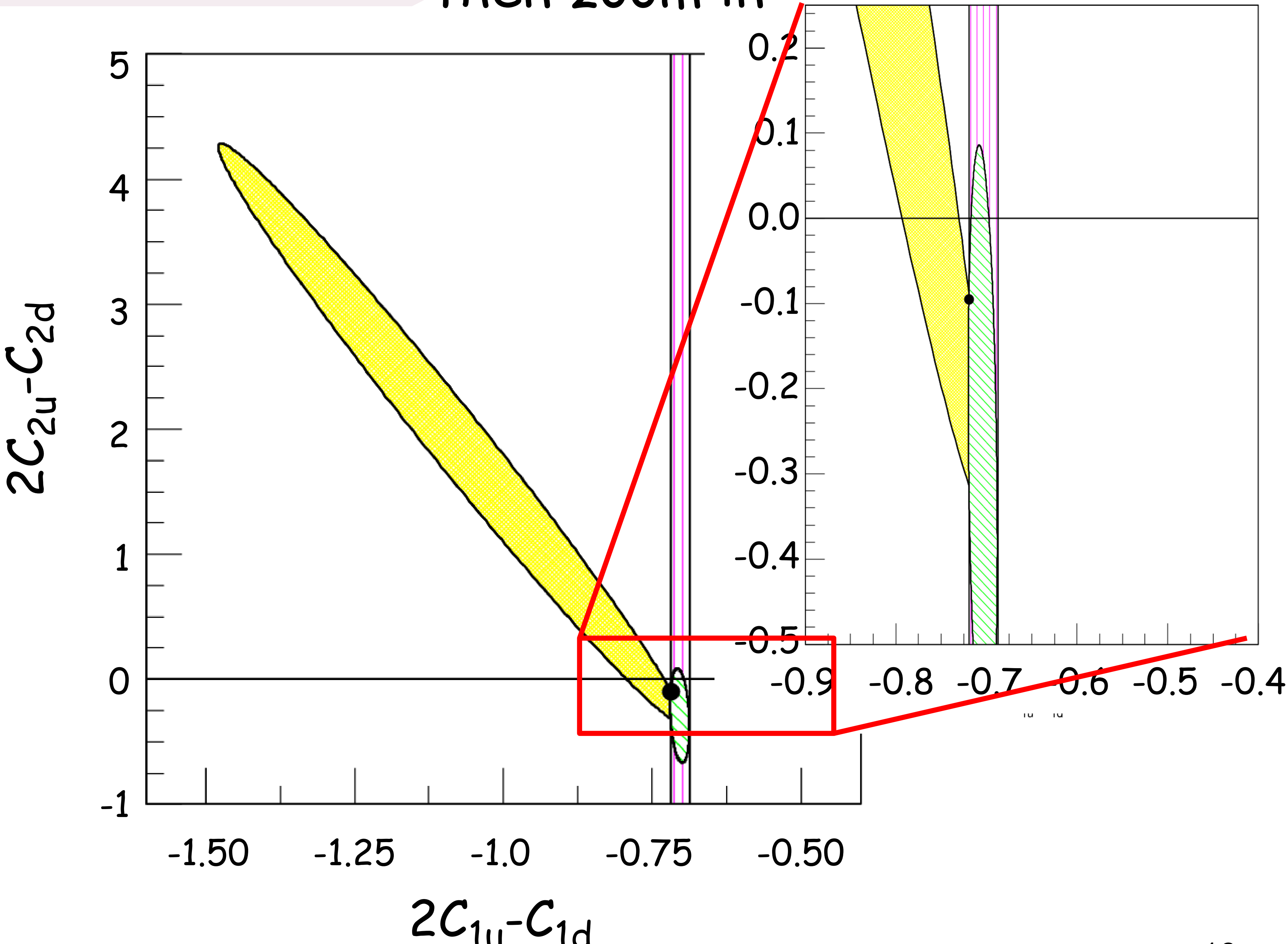
Add E122



and combine them



then zoom in



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$2C_{2u}-C_{2d}$
-1.50
-1.25
-1.0
-0.75
-0.50
$2C_{1u}-C_{1d}$
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4

PVDIS at 6 GeV (JLab E08-011)

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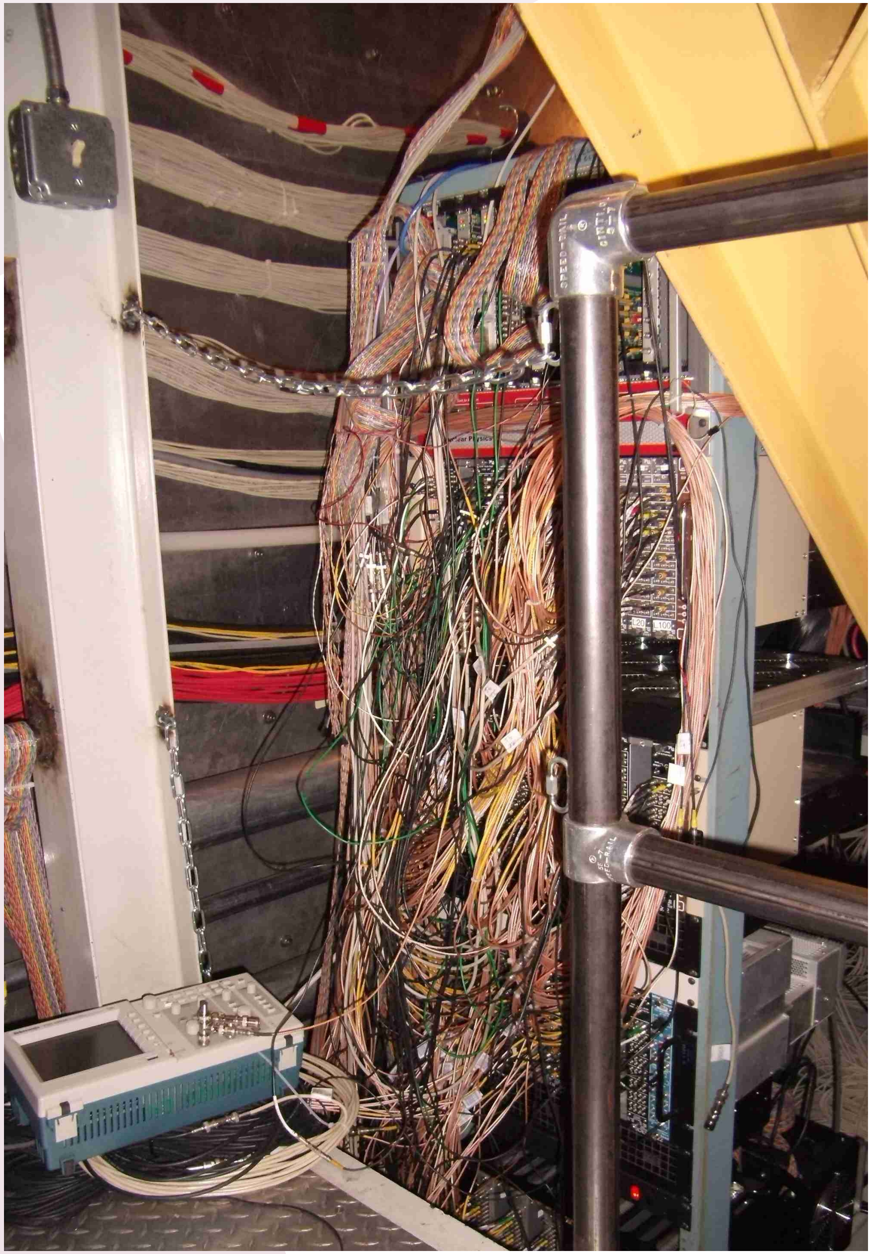


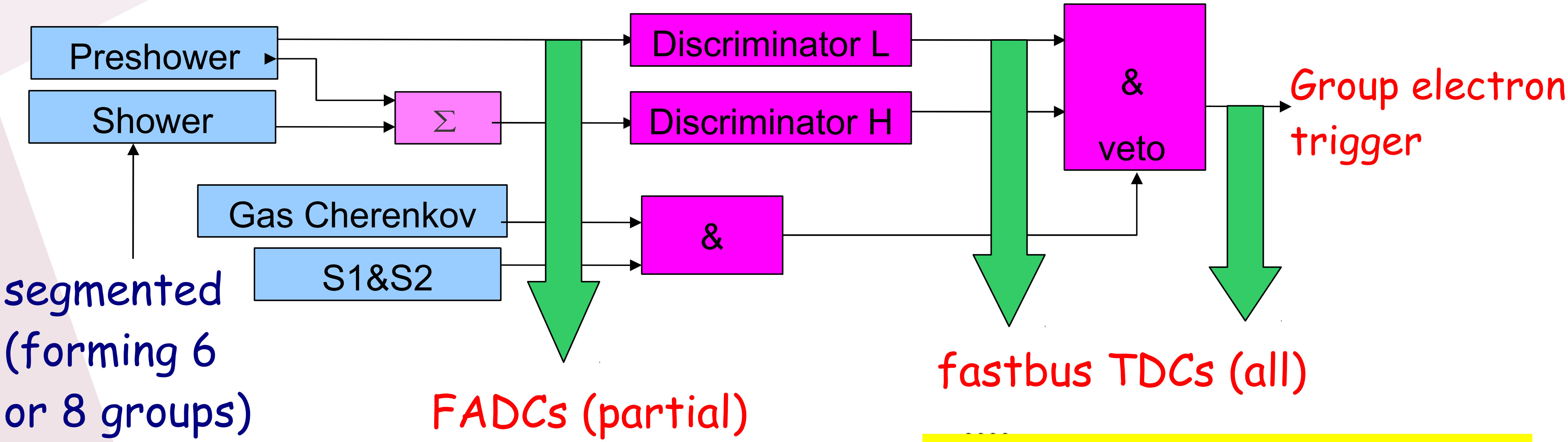
- Ran in Oct-Dec 2009, 100uA, 90% polarized electron beam, 20-cm liquid deuterium target
- Two High Resolution Spectrometers (HRS pair) detected electrons in the inclusive mode at DIS Q^2=1.1 and 1.9 GeV^2, and five resonance kinematics.
- Scaler-based fast counting DAQ specifically built for the 500kHz DIS rates w/ 10^4 pion rejection.
- Spokespeople: R. Michaels, P. Reimer, X. Z.
- Students:Xiaoyan Deng, Kai Pan Diancheng Wang.
- postdoc: Ramesh Subedi

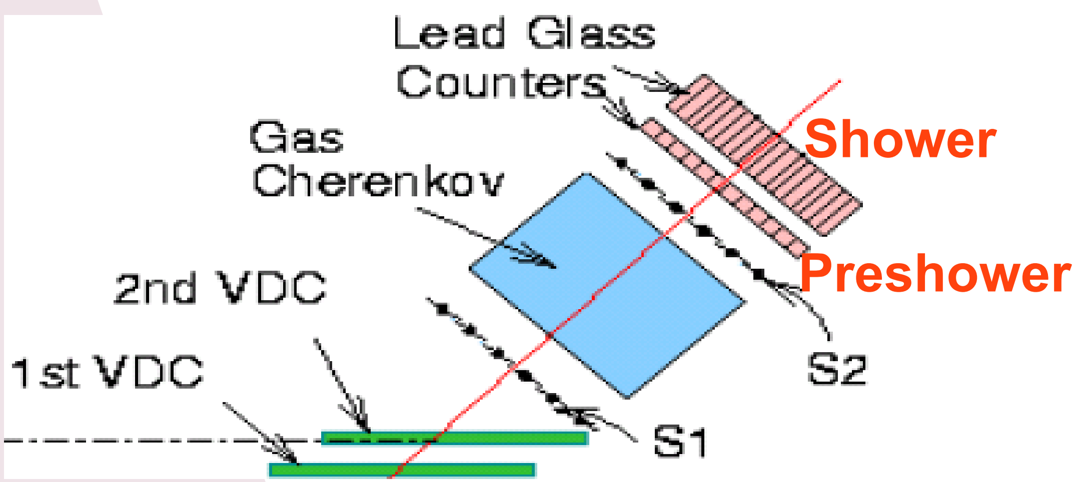
E08-011 Kinematics

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	$< \approx 0.25$
RES II	Left	4.867	12.9	3.55	≈600	$< \approx 0.25$
RES III	Right	4.867	12.9	3.1	≈400	$< \approx 0.4$
RES IV	Left	6.067	15	3.66	≈80	$< \approx 0.6$
RES V	Left	6.067	14	3.66	≈130	$< \approx 0.7$

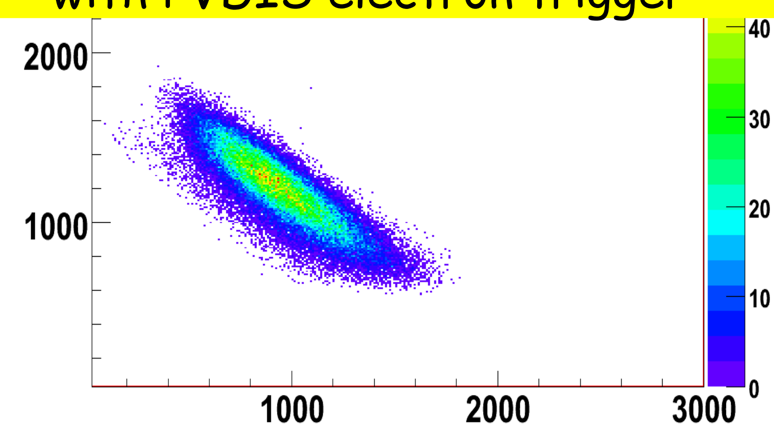
Scaler-Based Counting DAQ with online (hardware) PID

- DIS region, pions contaminate, can't use integrating DAQ.
- High event rate (~500KHz), exceeds Hall A regular DAQ's Limit (4kHz)





ADC spectrum from regular DAQ, with PVDIS electron trigger



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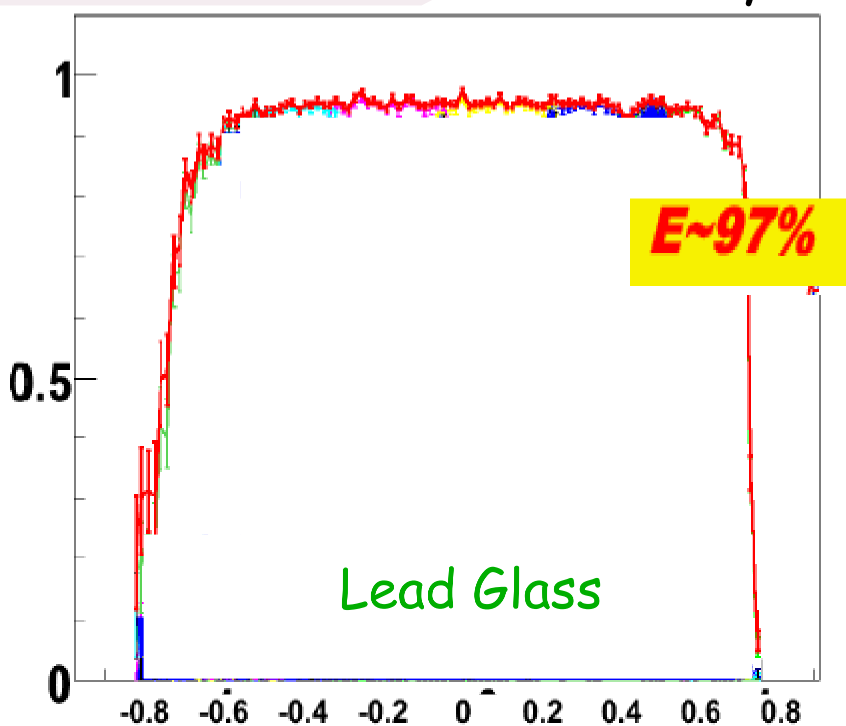
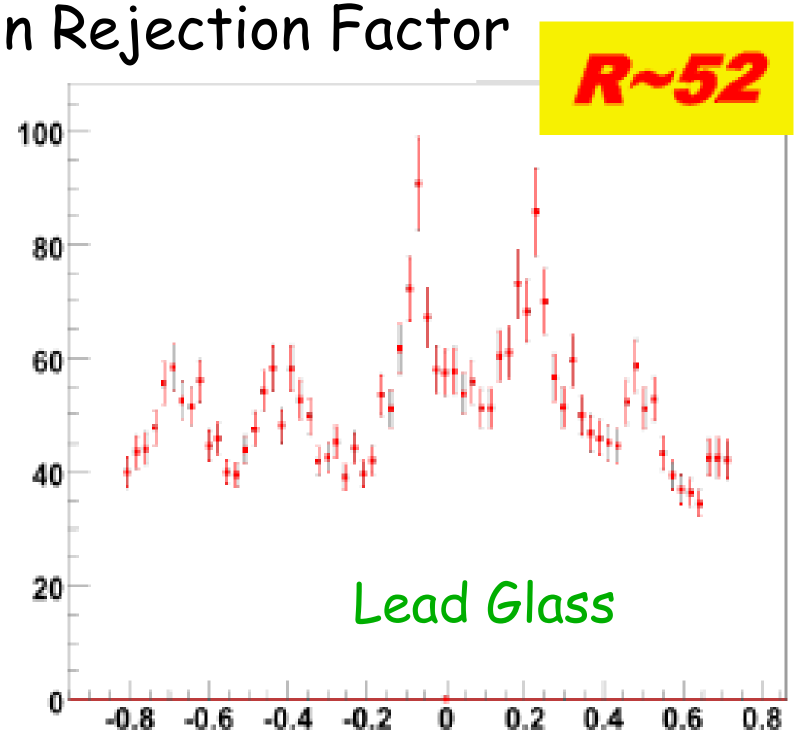
PID Performance - Single Run

Electron Detection Efficiency



Vertical hit position [m]

Pion Rejection Factor



Vertical hit position [m]

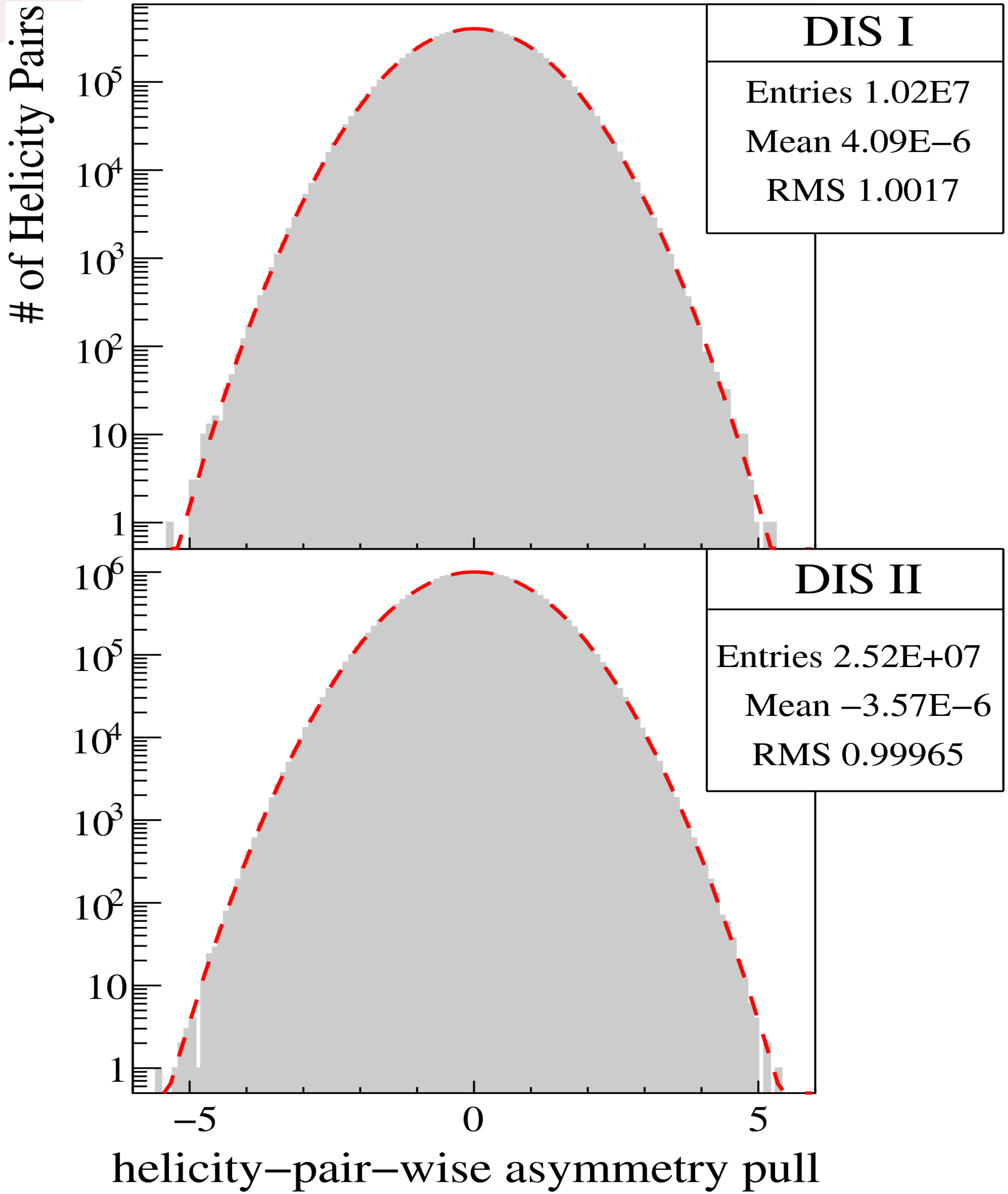
Affects measured asymmetry (Q^2) if it varies over the acceptance or if there are "holes"

<u>Combined with Cherenkov, pion contamination f < 2×10^{-4}.</u>

<u>Detector efficiencies extracted from VDC-on runs, taken daily</u>

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:

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

$$\Downarrow$$

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

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

Pion Asymmetries

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

From Measured to Physics Asymmetry

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

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

Δf_{π^-}	±0.009%
Δf_{pair}	±0.04%
Δf_{A_n}	±2.5%
ΔQ^2	±0.85%
rescatt bg	$\ll 0.2\%$
target impurity	±0.06%

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

From Measured to Physics Asymmetry

$$A^{raw}_{Q^2=1.901,\,x=0.295} = -140.30 \pm 10.43 \pm 0.16\ ppm\,(LHRS)$$
$$A^{raw}_{Q^2=1.901,\,x=0.295} = -139.84 \pm 6.58 \pm 0.46\ ppm\,(RHRS)$$

P_b	89.29	88.73%
ΔP_b	1.19%	±1.50%
$1+f_{\text{depol}}$	1.0021	
(syst.)	$<10^{-4}$	
$1+f_{\text{Al}}$	0.9999	0.9999
(syst.)	±0.0024	±0.0024
$1+f_{\text{dt}}$	1.0049	1.0093
(syst.)	±0.0004	±0.0013
$1+f_{\text{rc}}$	1.019	
(syst.)	±0.004	
$1+f_{\gamma\gamma\text{box}}$	0.997	
$1+f_{\gamma\gamma,\gamma Z\text{boxes}}$	–	
(syst.)	±0.003	

Δf_{π^-}	±0.006%	±0.003%
Δf_{pair}	±0.4%	±0.2%
Δf_{A_n}	±2.5%	±2.5%
ΔQ^2	±0.64%	±0.65%
rescatt bg	$\ll 0.2\%$	$\ll 0.2\%$
target impurity	±0.06%	±0.06%

	Asymmetry
A^{phys} (ppm)	−160.80
(stat.)	±6.39
(syst.)	±3.12
(total)	±7.12

Compare to Standard Model?

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

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

uncertainty due to PDF: 0.5% 5%

uncertainty due to HT: 0.5%/Q^2, 0.7ppm

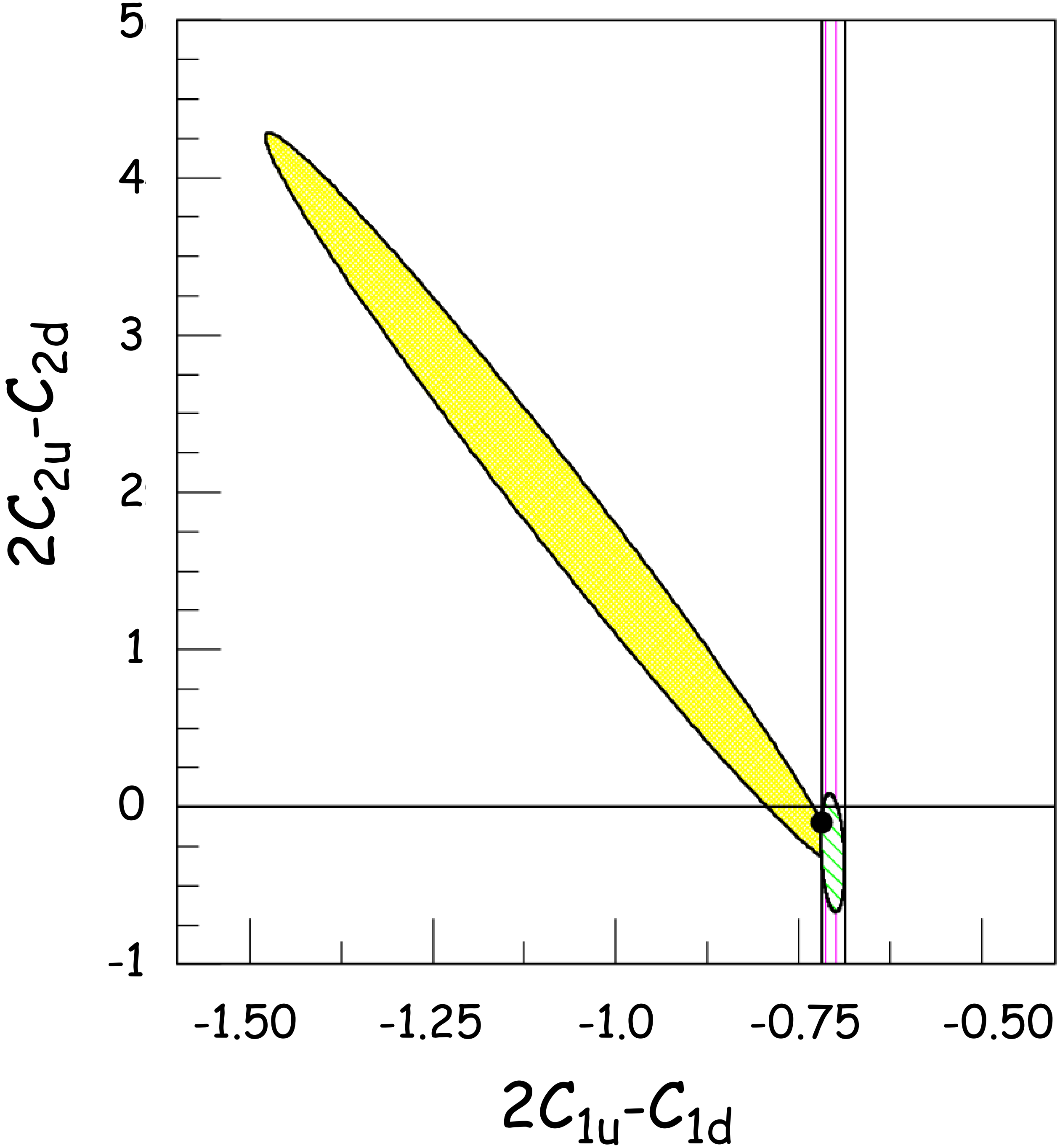
$$A^{phys}_{Q^2=1.901,\, x=0.295} = -160.80 \pm 6.39 \pm 3.12\ ppm$$

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

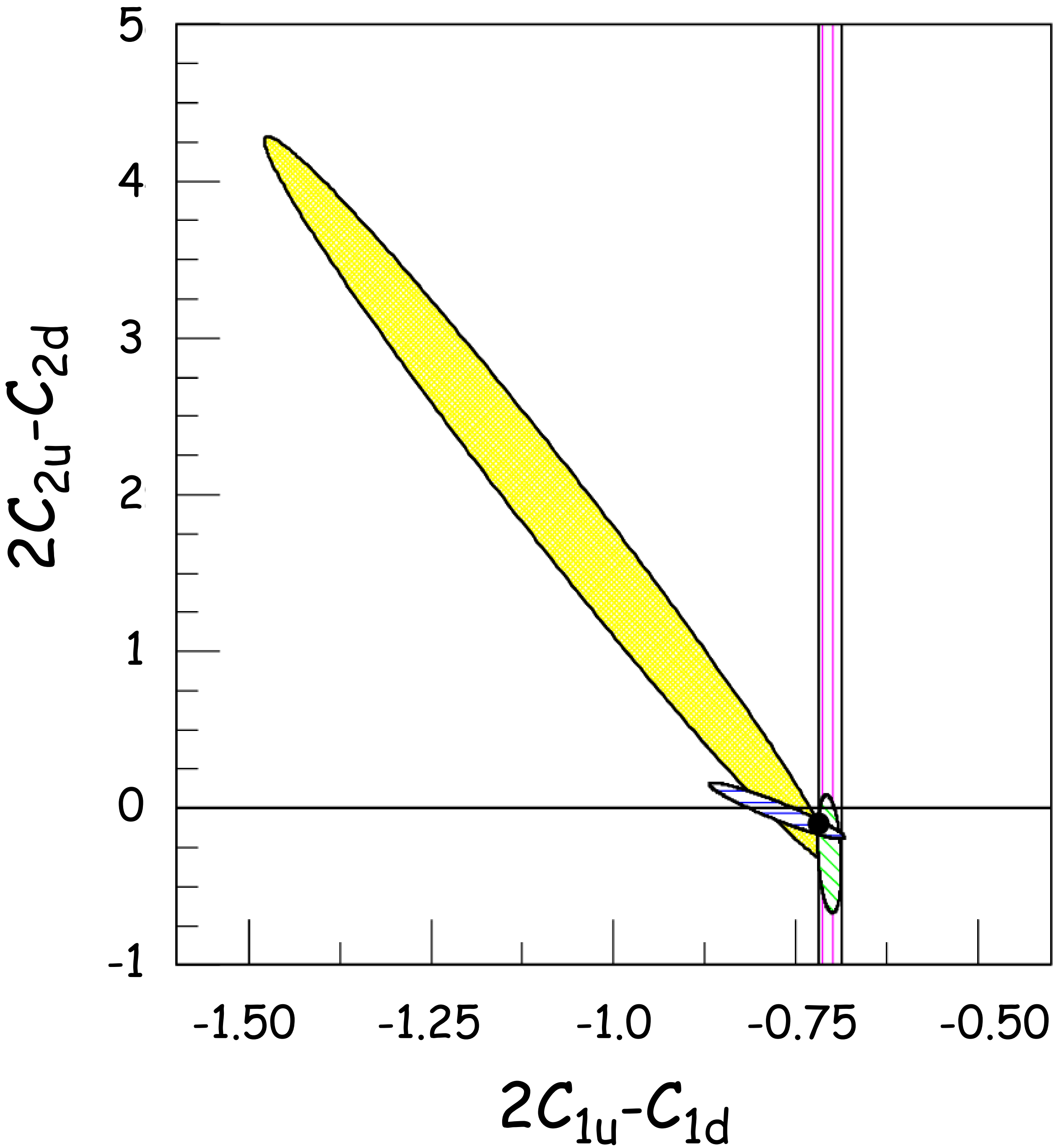
uncertainty due to PDF: 0.5% 5%

uncertainty due to HT: 0.5%/Q^2, 1.2ppm

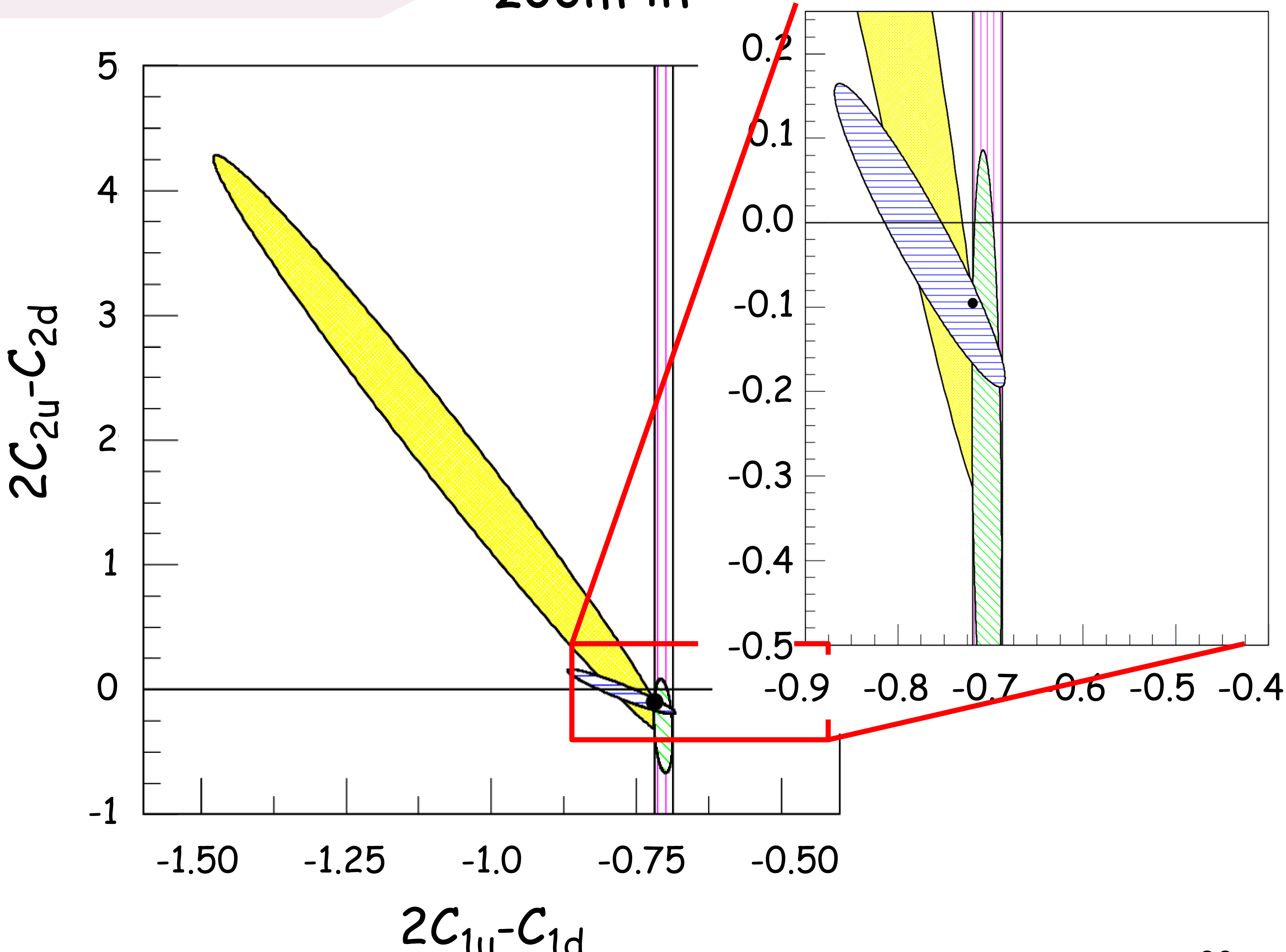
Previous data: Elastic PVES + APV



Add JLab PVDIS



zoom in



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-0.75
-0.50
$2C_{1u}-C_{1d}$
0.2
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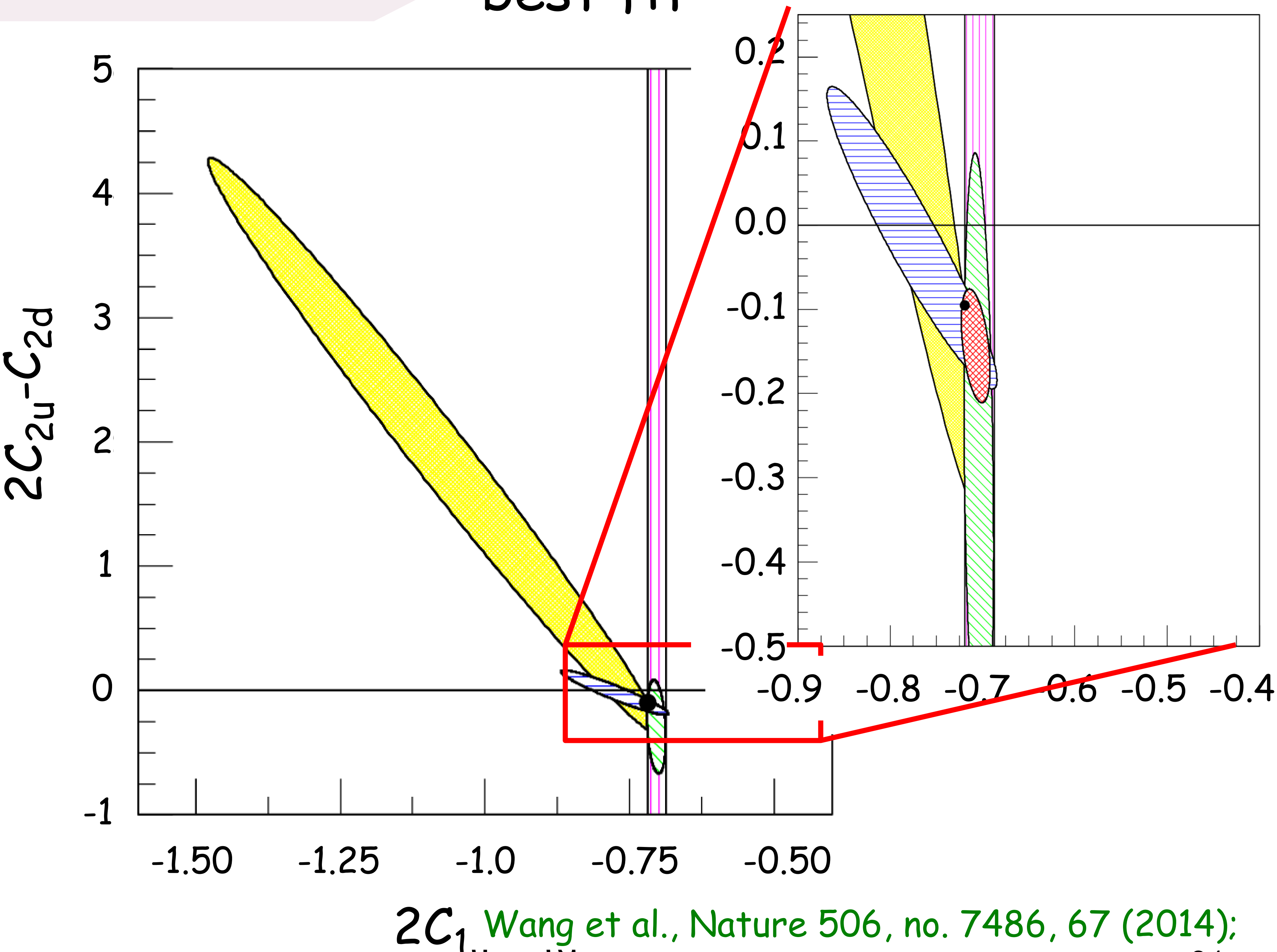
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4

best fit



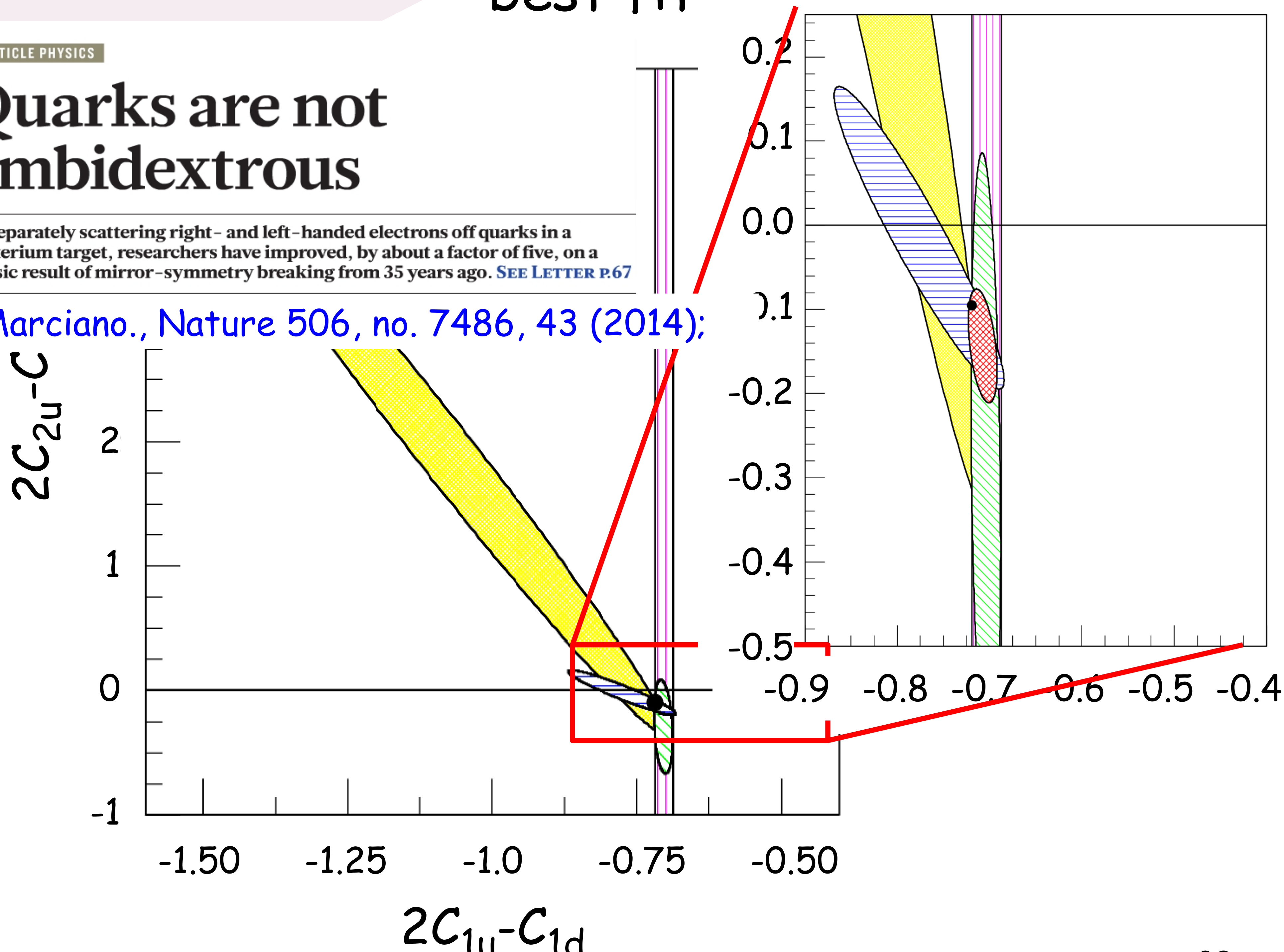
Wang et al., Nature 506, no. 7486, 67 (2014);

PARTICLE PHYSICS

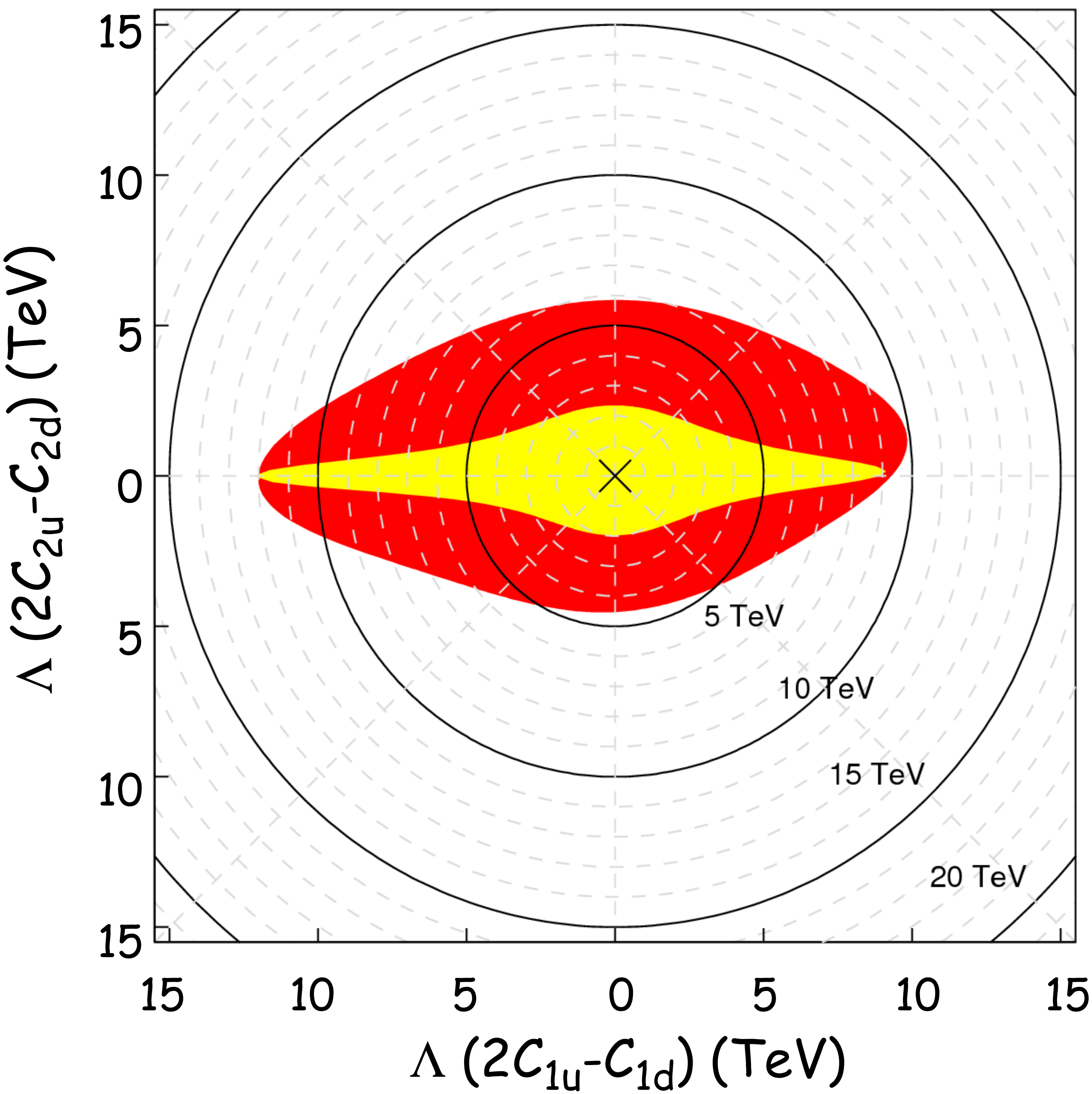
Quarks are not ambidextrous

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);

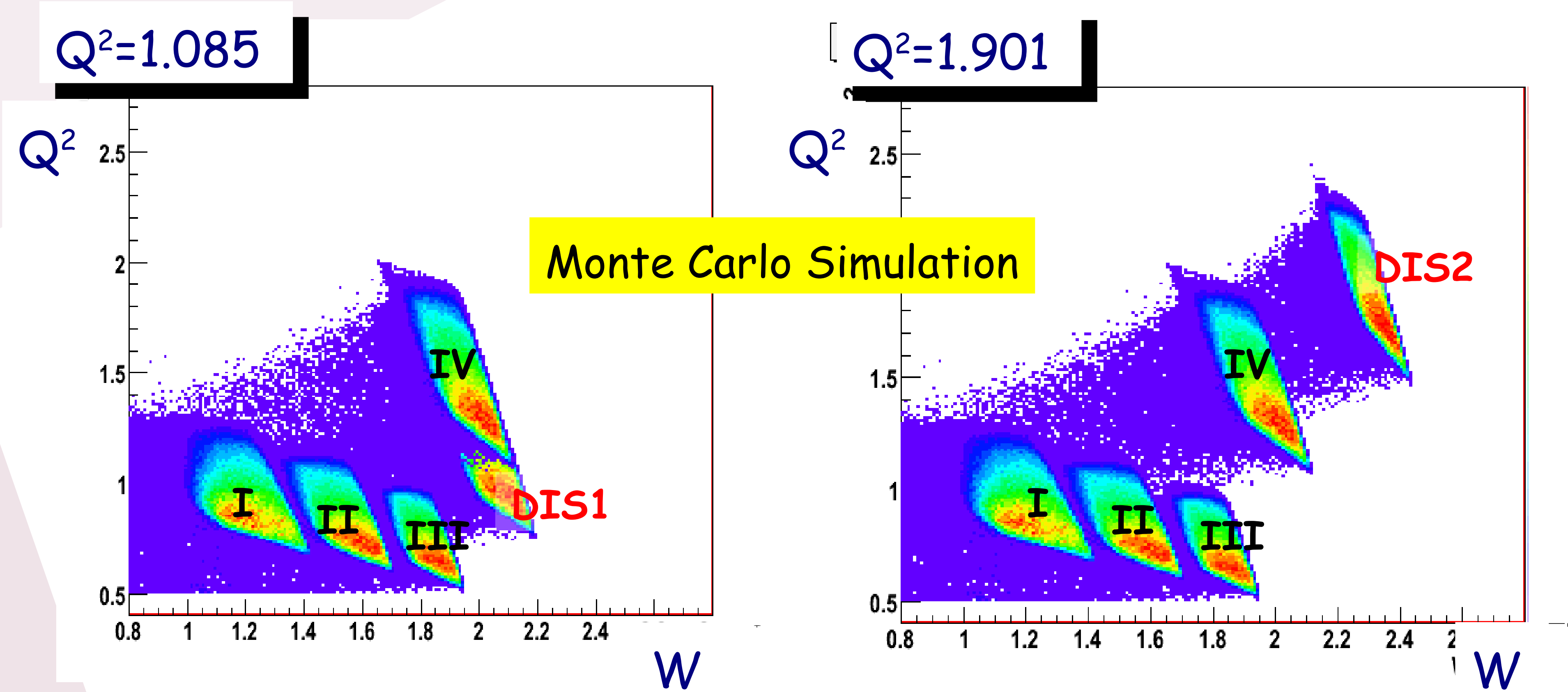


BSM Mass Limit on eq VA contact interaction



X. Zheng, Hadron 2014

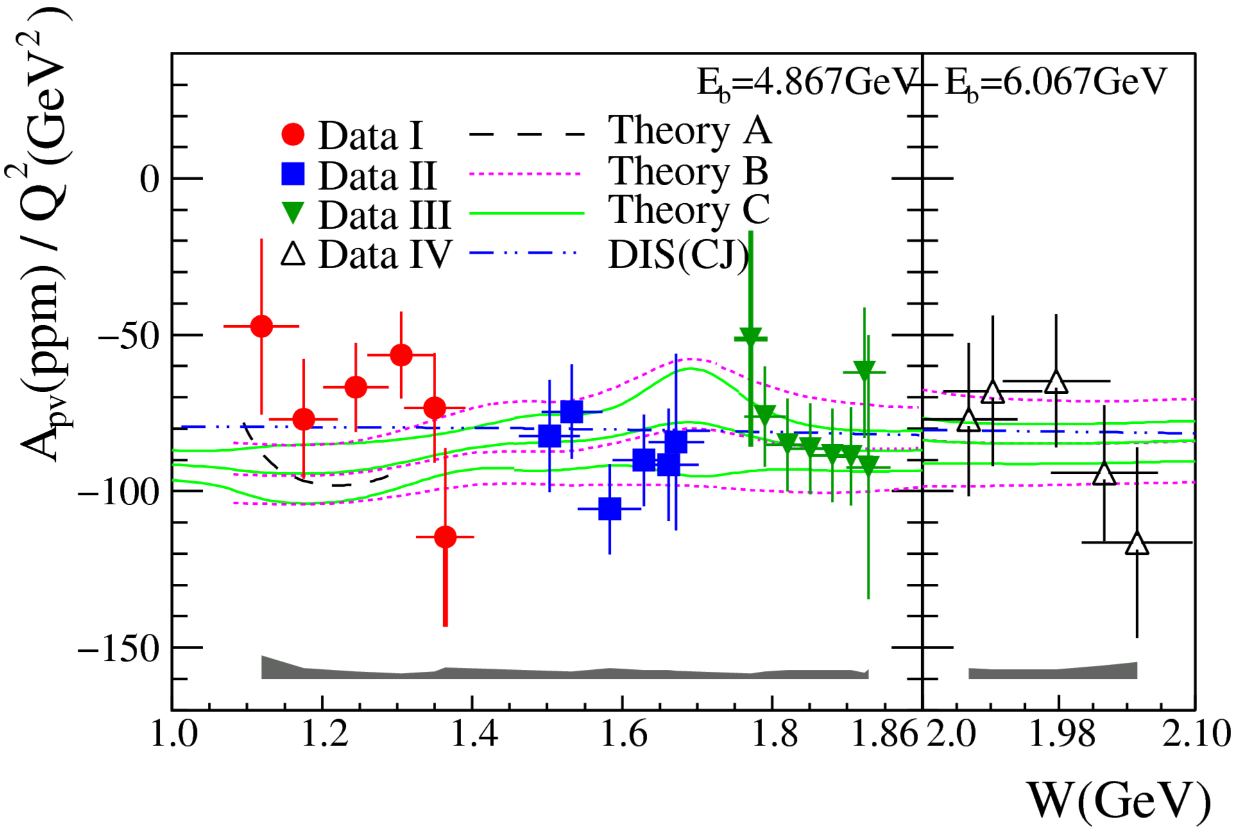
Resonance Background Data Coverage



- 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);

Summary and Perspectives

The 6 GeV PVDIS from JLab:

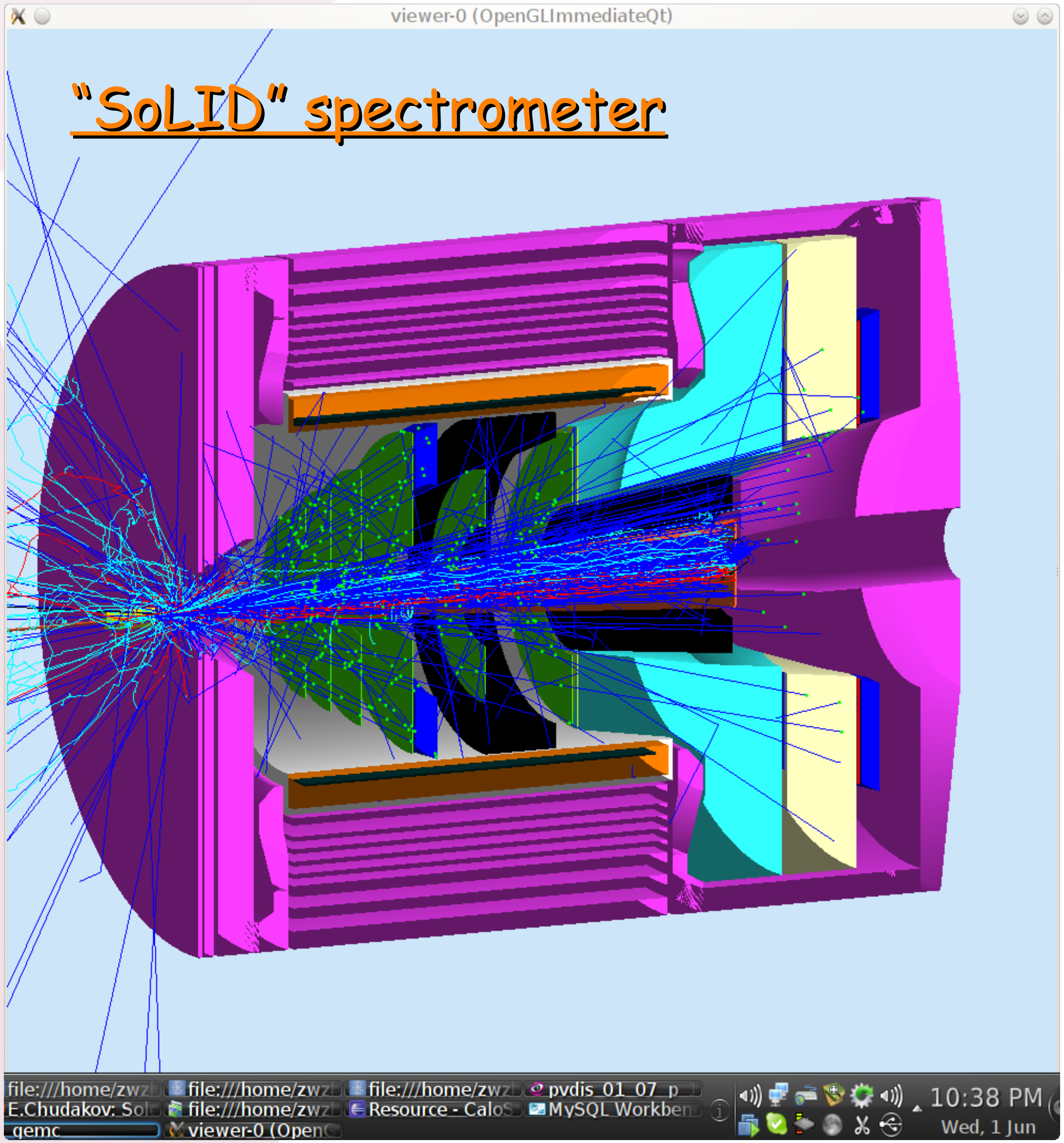
- Improved world data on the eq VA effective coupling term $2C_{2u}$-C_{2d} by factor of five; agrees with the SM; and showed $2C_{2u}$-C_{2d} is 2σ from zero – indicating a nonzero contribution to PVDIS asymmetry due to quark's chirality preference; BSM mass limits complimentary to collider experiments.
- 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-A 724, 90 (2013); Wang et al., PRL 111, 082501 (2013); Wang et al., Nature 506, no. 7486, 67 (2014); long paper draft available.

Coherent PVDIS Program with SoLID @ 11 GeV

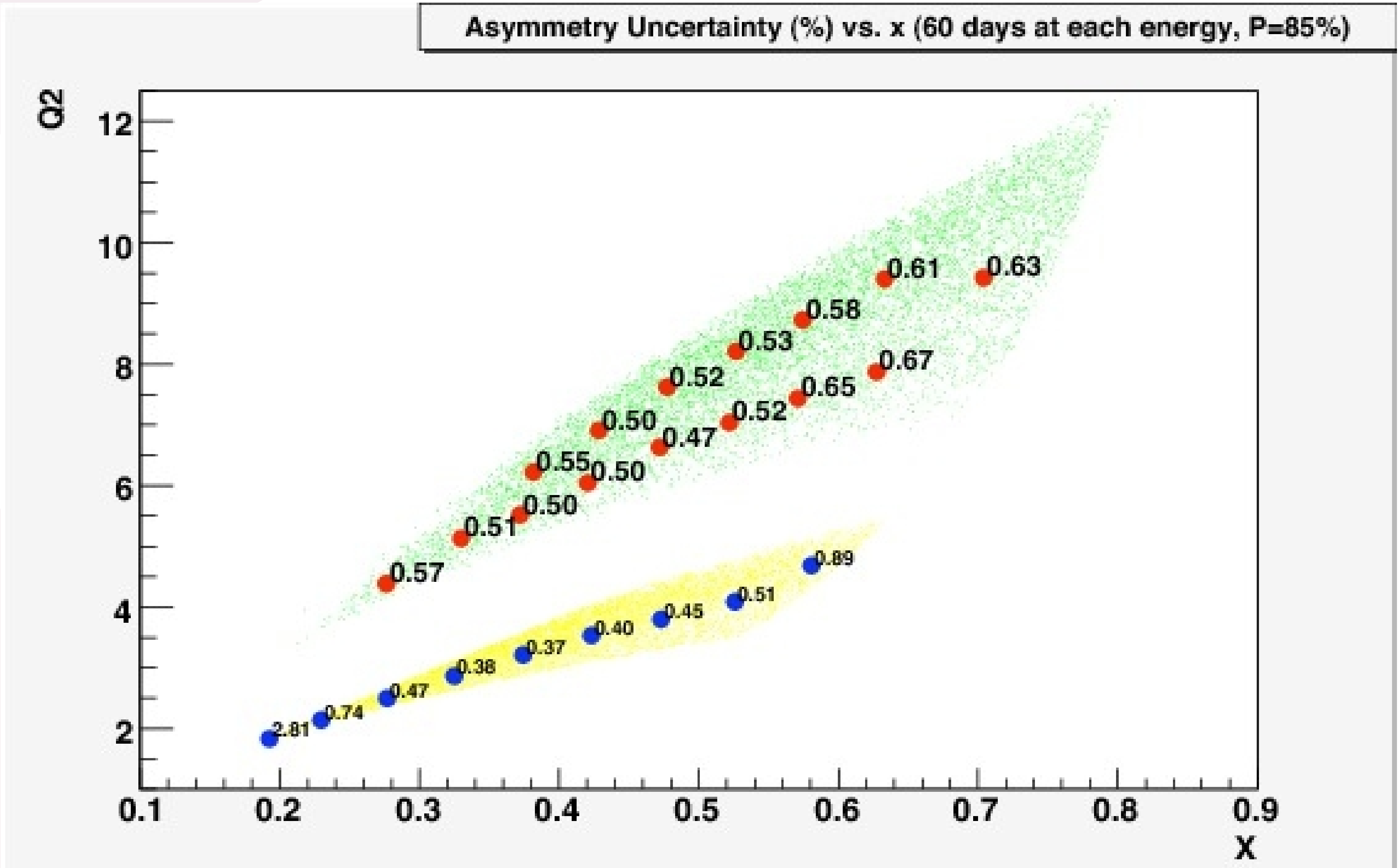


SoLID Physics topics:

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

X. Zheng, Hadron 2014

Coherent PVDIS Program with SoLID @ 11 GeV



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

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Beam-Normal Asymmetry Background

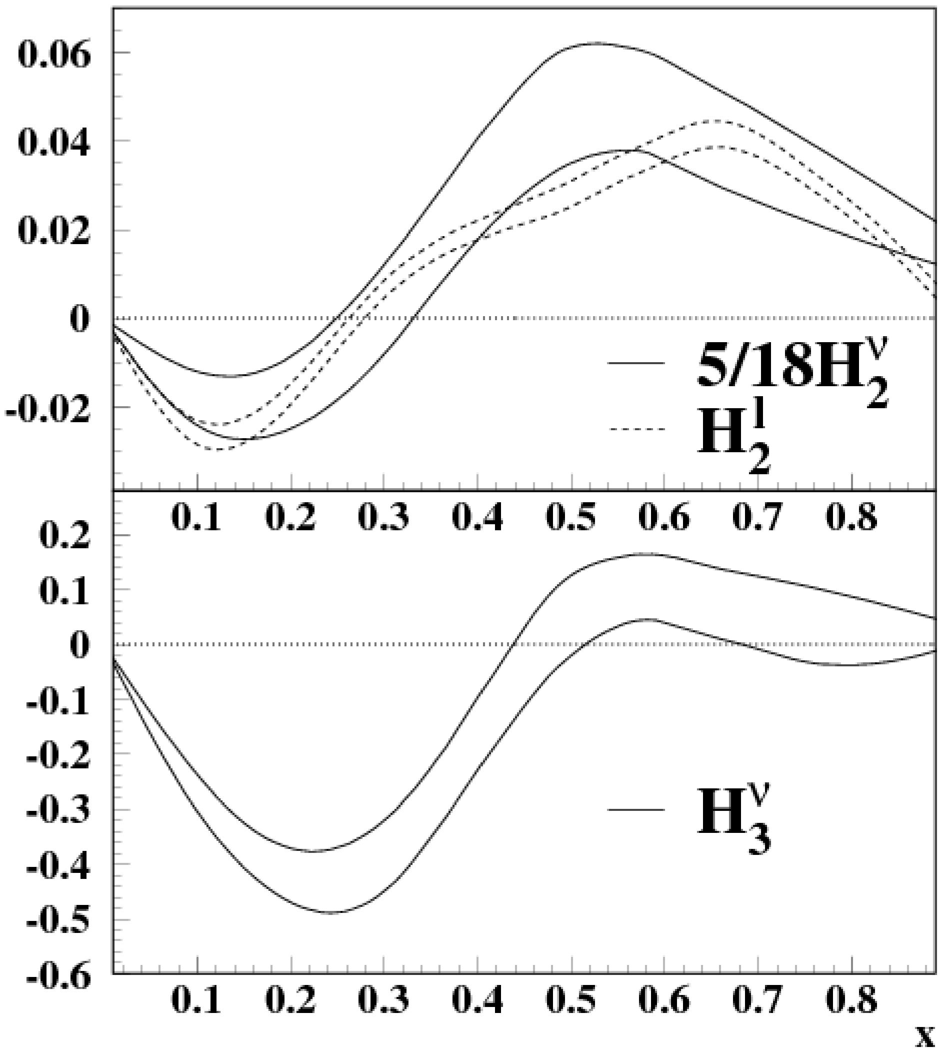
Kinematics Q^2 (GeV/c)^2	Left DIS#1 1.085	Right DIS#2 1.907
$A_n^{meas} \pm \Delta A_n^{meas}$ (stat.) (ppm, narrow)	-24.15 ± 15.05	23.49 ± 44.91
A_e^{meas} (ppm, narrow)	78.45	-139.97
$\left(\frac{\Delta A_e}{A_e}\right)_{A_n,\text{ narrow}}$	1.18%	0.76%
$A_n^{meas} \pm \Delta A_n^{meas}$ (stat.) (ppm, wide)	-24.66 ± 15.01	24.60 ± 44.90
A_e^{meas} (ppm, wide)	78.27	-140.67
$\left(\frac{\Delta A_e}{A_e}\right)_{A_n,\text{ wide}}$	1.20%	0.76%

Estimation of HT on the a_3 term

We could use HT results on $F_3^{\gamma Z}$ from neutrino data in 0710.0124(hep-ph) to correct the a_3 term:

$$F_{2,T,3}(x,Q^2) = F_{2,T,3}^{\tau=2}(x,Q^2) + \frac{H_{2,T,3}^{\tau=4}(x)}{Q^2} + \frac{H_{2,T,3}^{\tau=6}(x)}{Q^4} + \ldots\ldots$$

isoscalar target



for F_2^{ν} and F_2^{l}

for xF_3^{ν}

(not F_3^{ν})

for any target

$$F_3^{\nu} = 2\left[d + s - \bar{u} - c\right]$$

for deuteron

$$F_3^{\nu} = 2\left[u_V + d_V + 2s - 2\bar{c}\right]$$

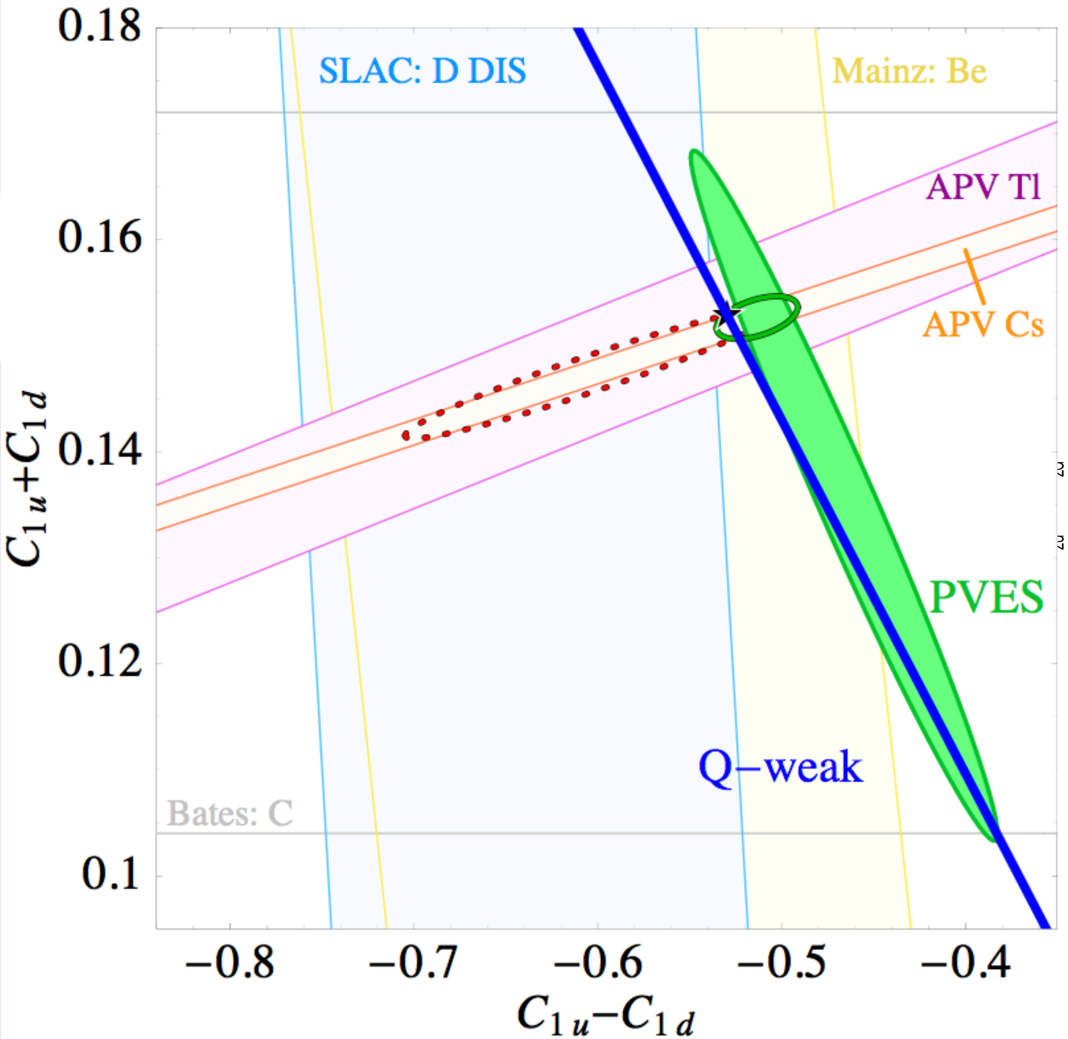
SLAC E122 vs. JLab E08-011

	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^{o}	12.9^{o} and 20^{o}
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) $A/Q^2=(-9.5\pm1.6)\times10^{-5}\,(GeV/c)^{-2}$ $\pm0.86\times10^{-5}$(stat)$\pm$5%(Pb)$\pm$3.3%(beam) $\pm$2%(π contamination) $\pm$3%(radiative corrections)	$\pm$(3-4)%(stat) $\pm$syst.
Proton results	$A/Q^2=(-9.7\pm2.7)\times10^{-5}\,(GeV/c)^{-2}$	

$\sin^2\theta_W=0.20\pm0.03$

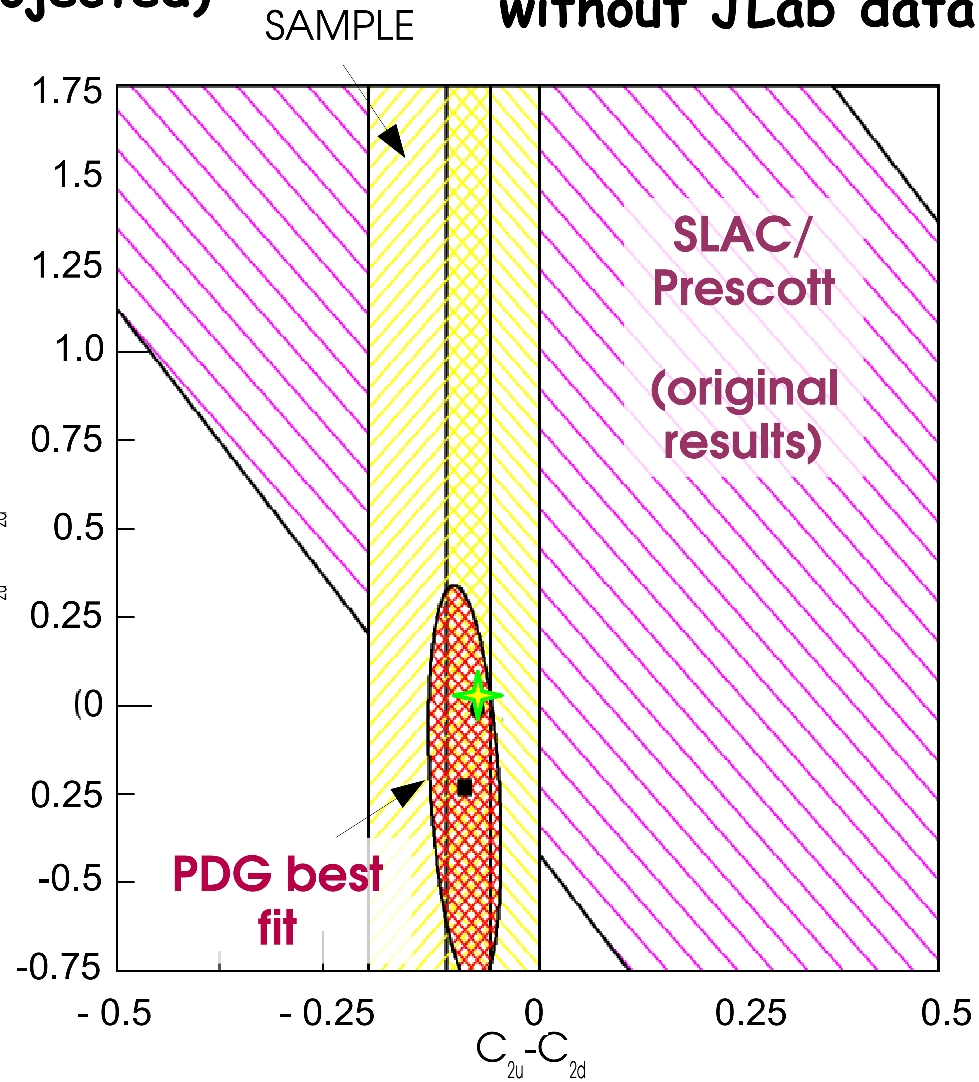
Some Older Plots

with recent PVES data and Qweak (projected)



all are 1 σ limit

without JLab data



Qweak in Hall C (2010-May 2012): $^1H + \vec{e} \rightarrow e' + p$ **factor of 5 improvement** in the proton weak (vector) charge $Q^p_W=-2(2C_{1u}+C_{1d})$

DAQ Deadtime Correction

(work of D. Wang)

Deadtime correction to asymmetry:

$A_{measured} = A_{phys}$ (1 – deadtime loss)

Deadtime Decomposition:

- Group Deadtime: proportional to group rate; narrow/wide.
- Veto Deadtime: T1/GC rate; the same for all groups.
- Final OR.
- Overall Deadtime: Veto DT + Group DT + Final OR DT