The JLab Parity Violation Deep Inelastic Scattering (PVDIS) Experiment

Xiaochao Zheng (Univ. of Virginia)

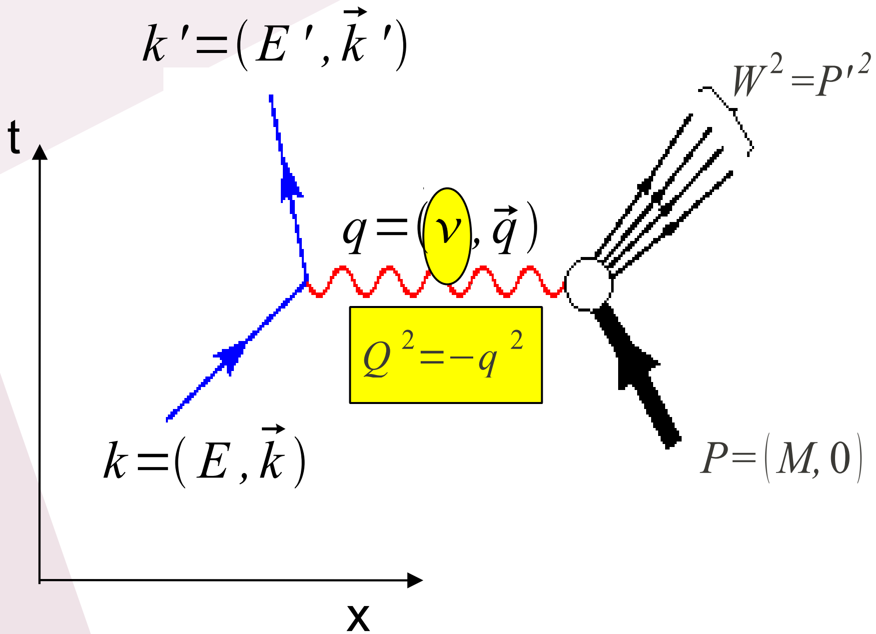
September 26, 2014

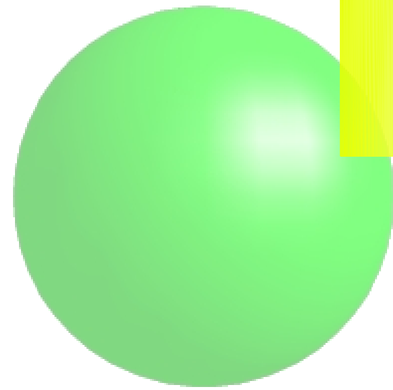
- Electron scattering basics – elastic, resonance, DIS
- PVDIS and electron-quark effective couplings
- The 6 GeV PVDIS experiment
  - DIS results – electron-quark effective VA couplings
  - Resonance results – duality in EW sector?
- Outlook for the 12 GeV Program – PVDIS with SoLID

Jefferson Lab

Inclusive Electron Scattering Basics

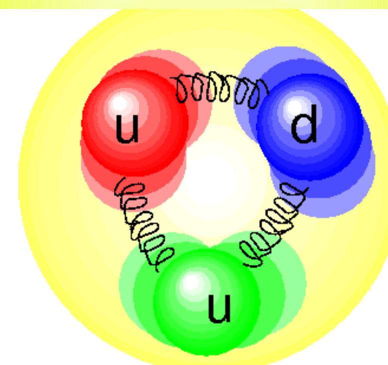
Inclusive: only scattered electron is detected



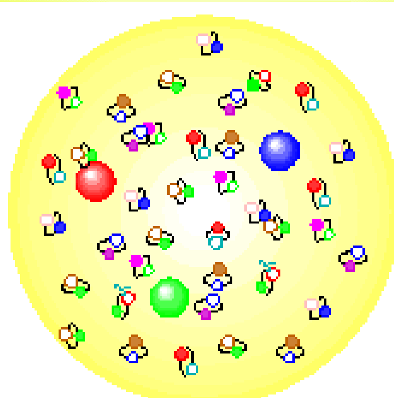


"Elastic": $W=M_p$
(form factors)

"Resonance": 1<W<2GeV
(structure functions)

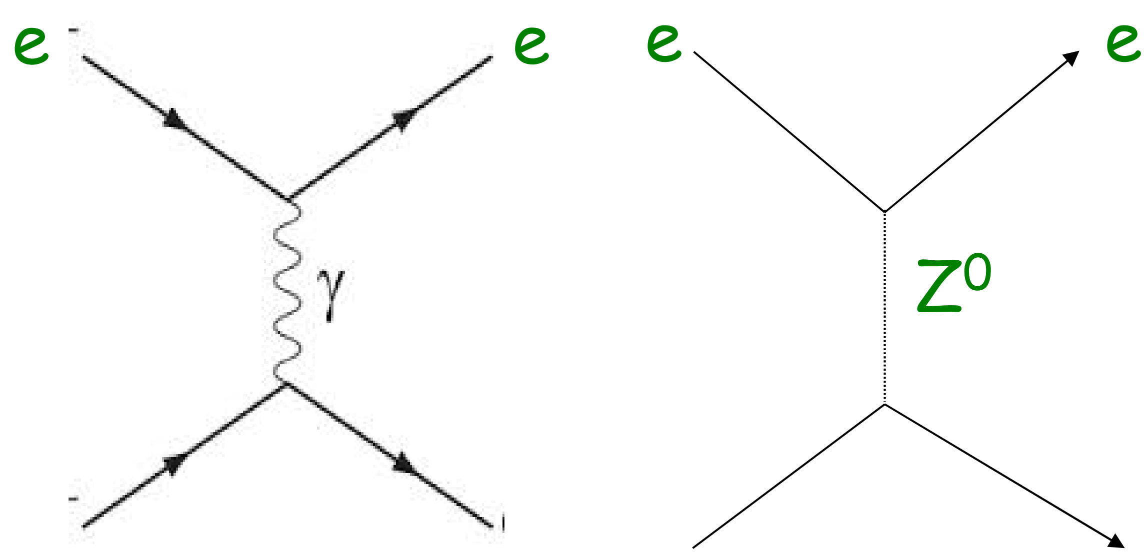


"Deep Inelastic": W>2 GeV,
(structure functions, parton distribution functions)

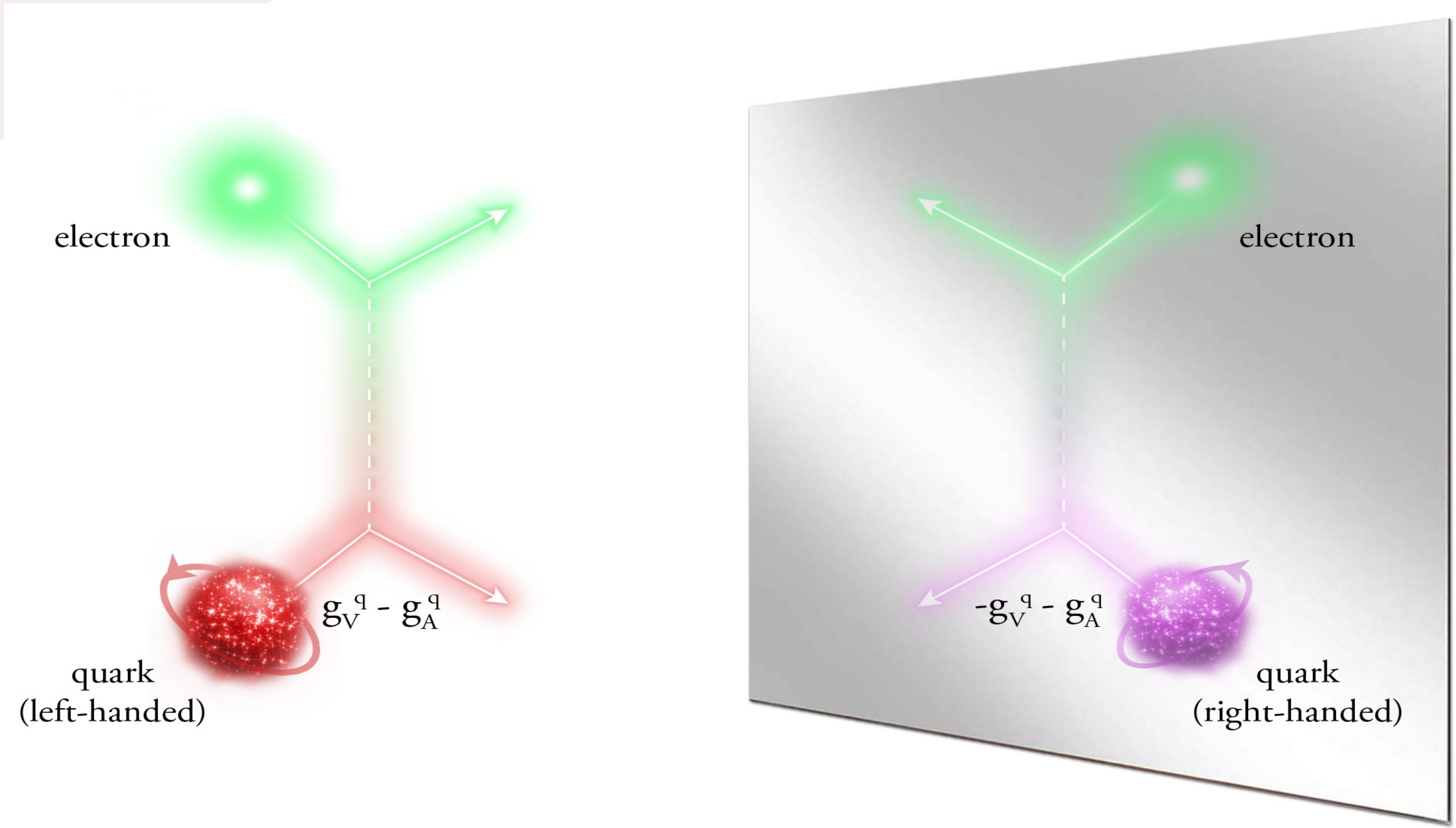


Parity-Violating Electron Scattering

- 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

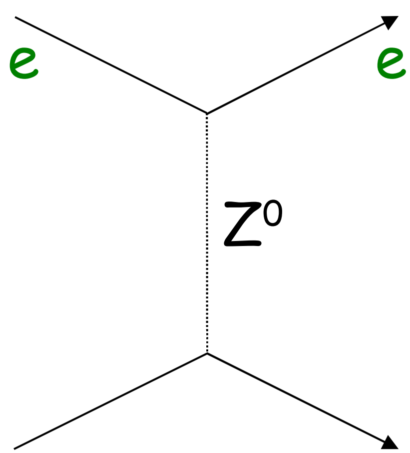
- They have a preferred chiral state when coupling to the Z^0

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~(g_L+g_R) g_A~(g_L-g_R)

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



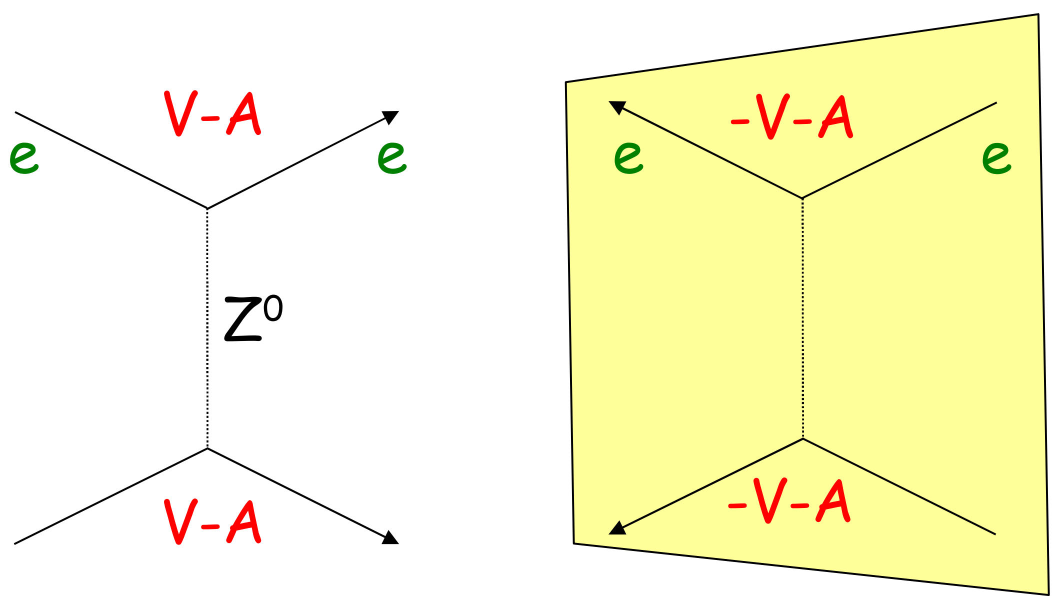
fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e-, μ-	$-\frac{1}{2}$	$-\frac{1}{2}+2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2}-\frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$

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)xA(targ) and A(e)xV(targ)

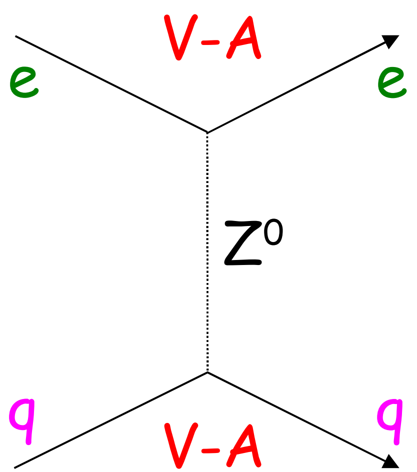


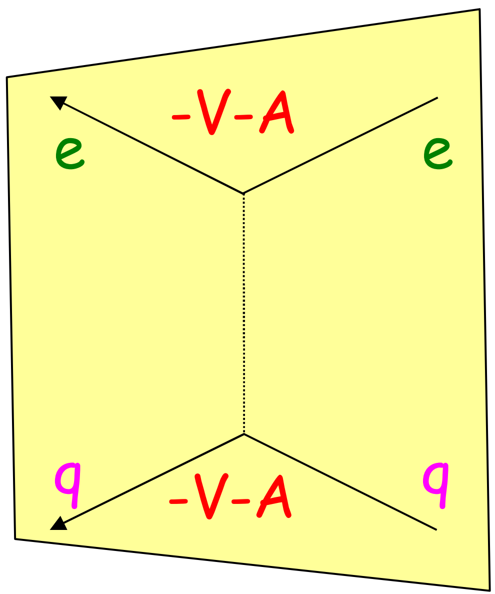
Effective Couplings in the Standard Model

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

  or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$

- 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"

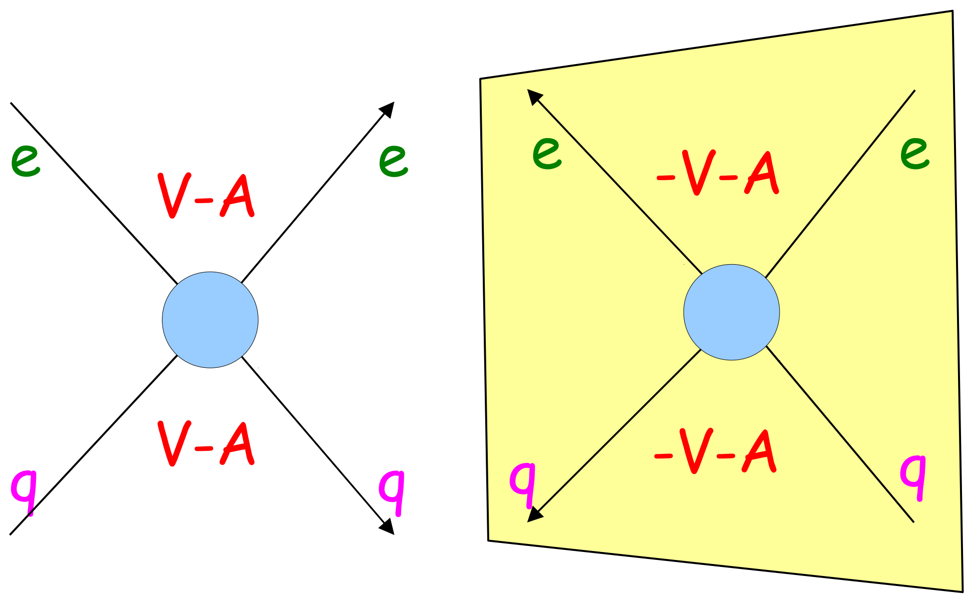
Effective Couplings and New Contact Interactions

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

  or "vector" and "axial" weak charges: $g_V \sim (g_L+g_R)$ $g_A \sim (g_L-g_R)$

- PVDIS asymmetry comes from: $C_{1q} \equiv 2 g^e_A g^q_V, \quad C_{2q} \equiv 2 g^e_V g^q_A$

"electron-quark effective couplings"

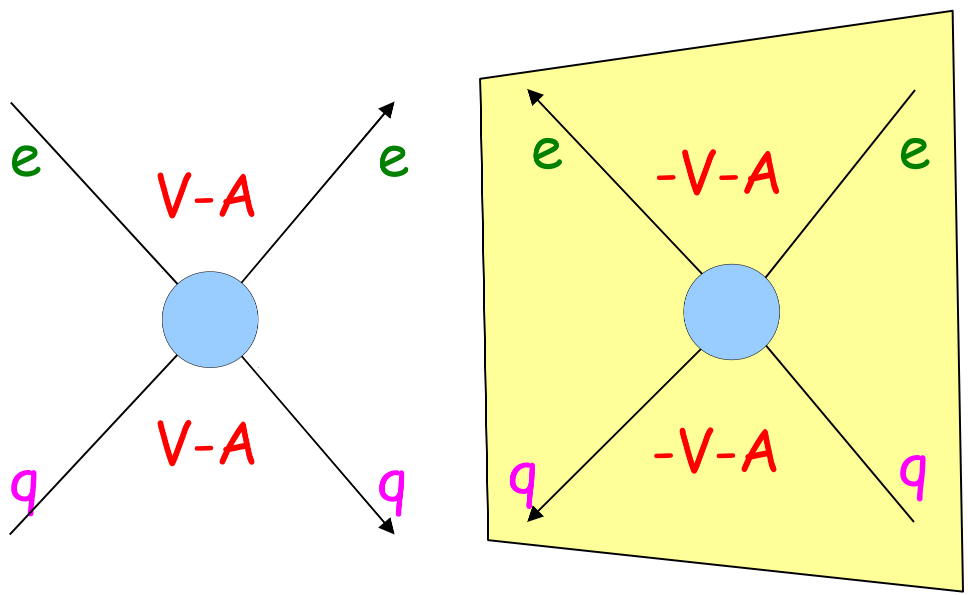


Effective Couplings and New Contact Interactions

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

  or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$

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



"electron-quark effective couplings"

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

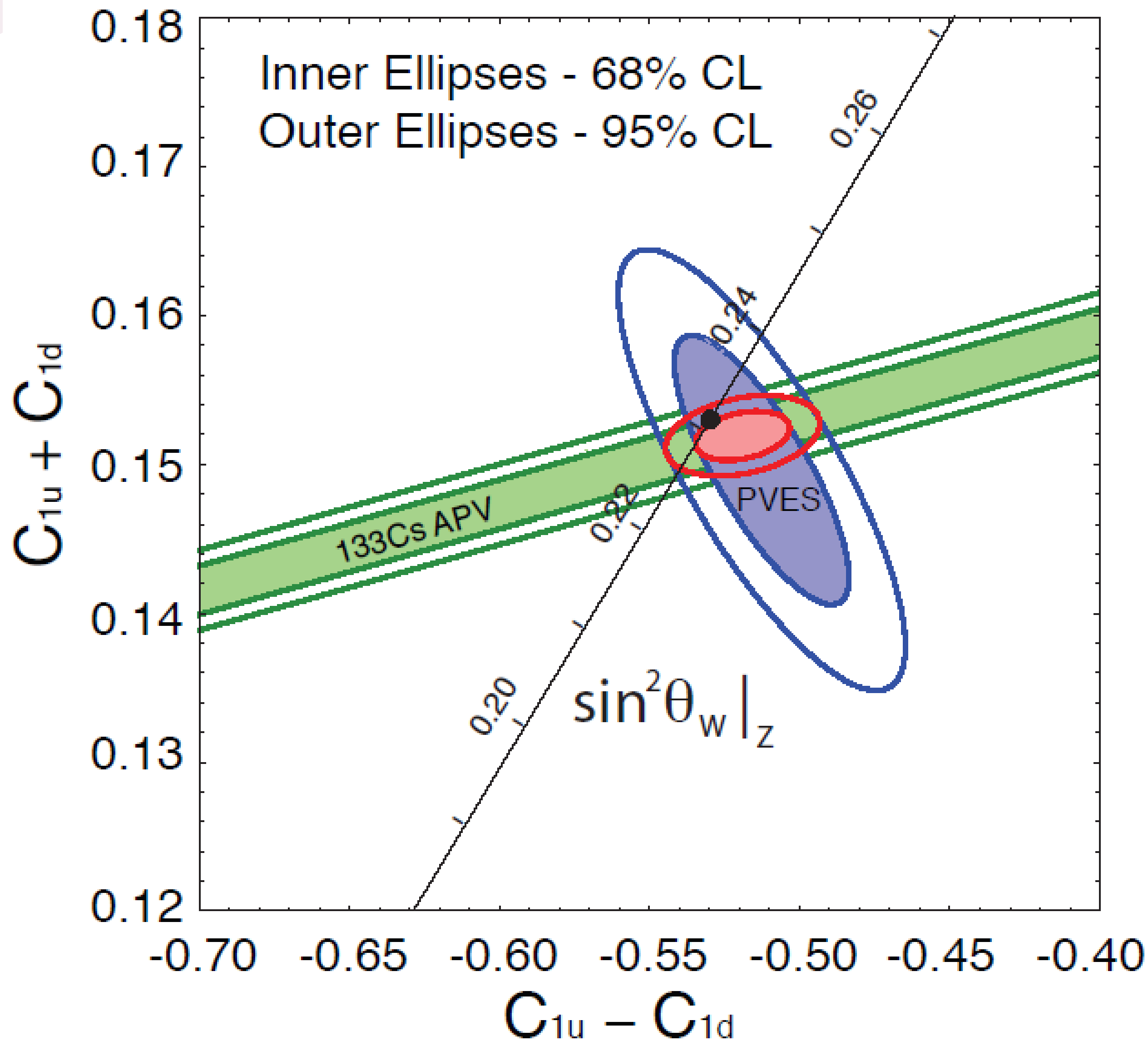
$$Y=\left[\frac{r^2}{1+R}\right]\frac{1-(1-y)^2}{1+(1-y)^2-y^2\left[1-\frac{r^2}{1+R}\right]-xy\frac{M}{E}}$$

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

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

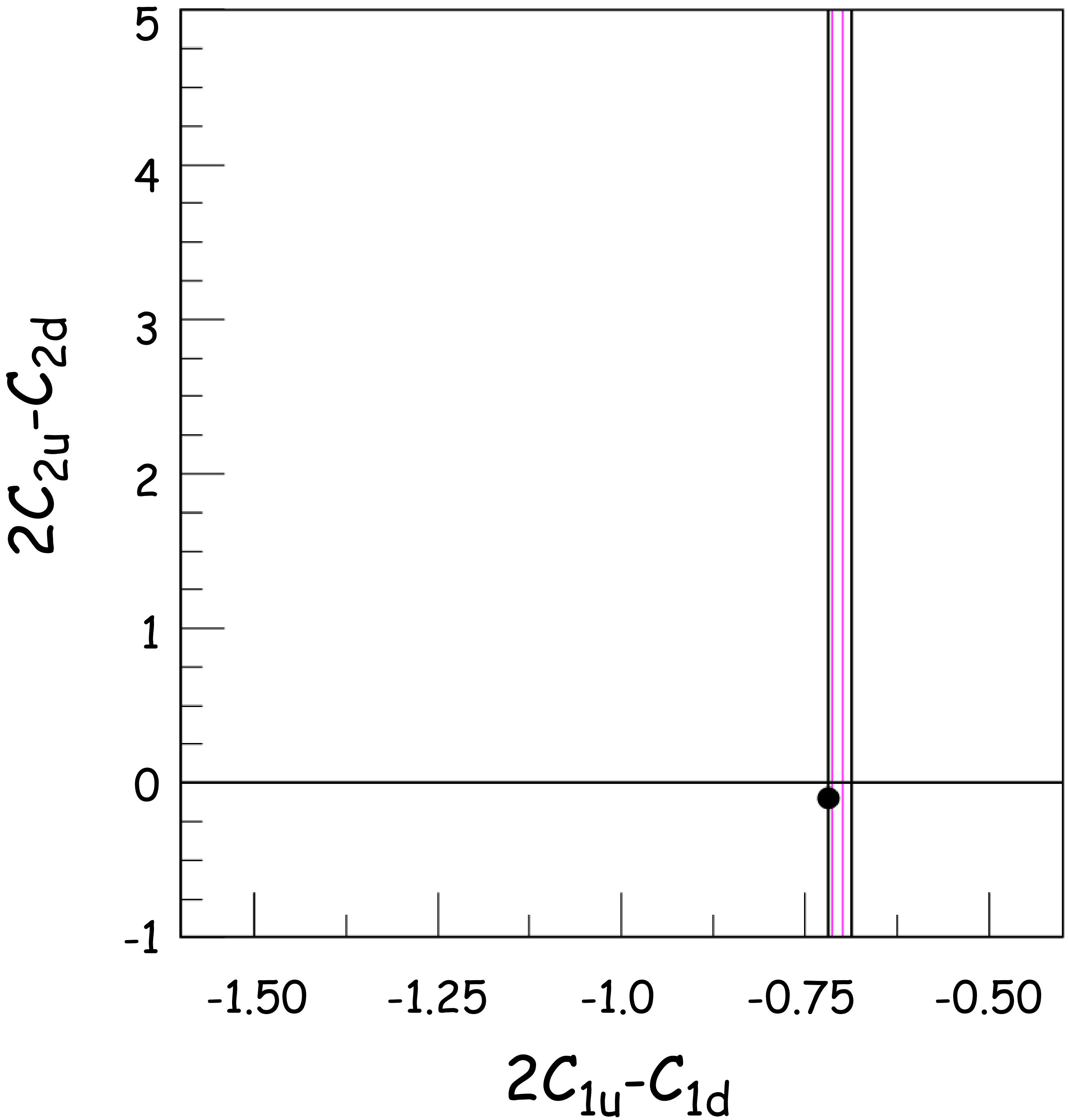
$$C_{1d}=\frac{1}{2}-\frac{2}{3}\sin^2\theta_W \qquad C_{2d}=\frac{1}{2}-2\sin^2\theta_W$$

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

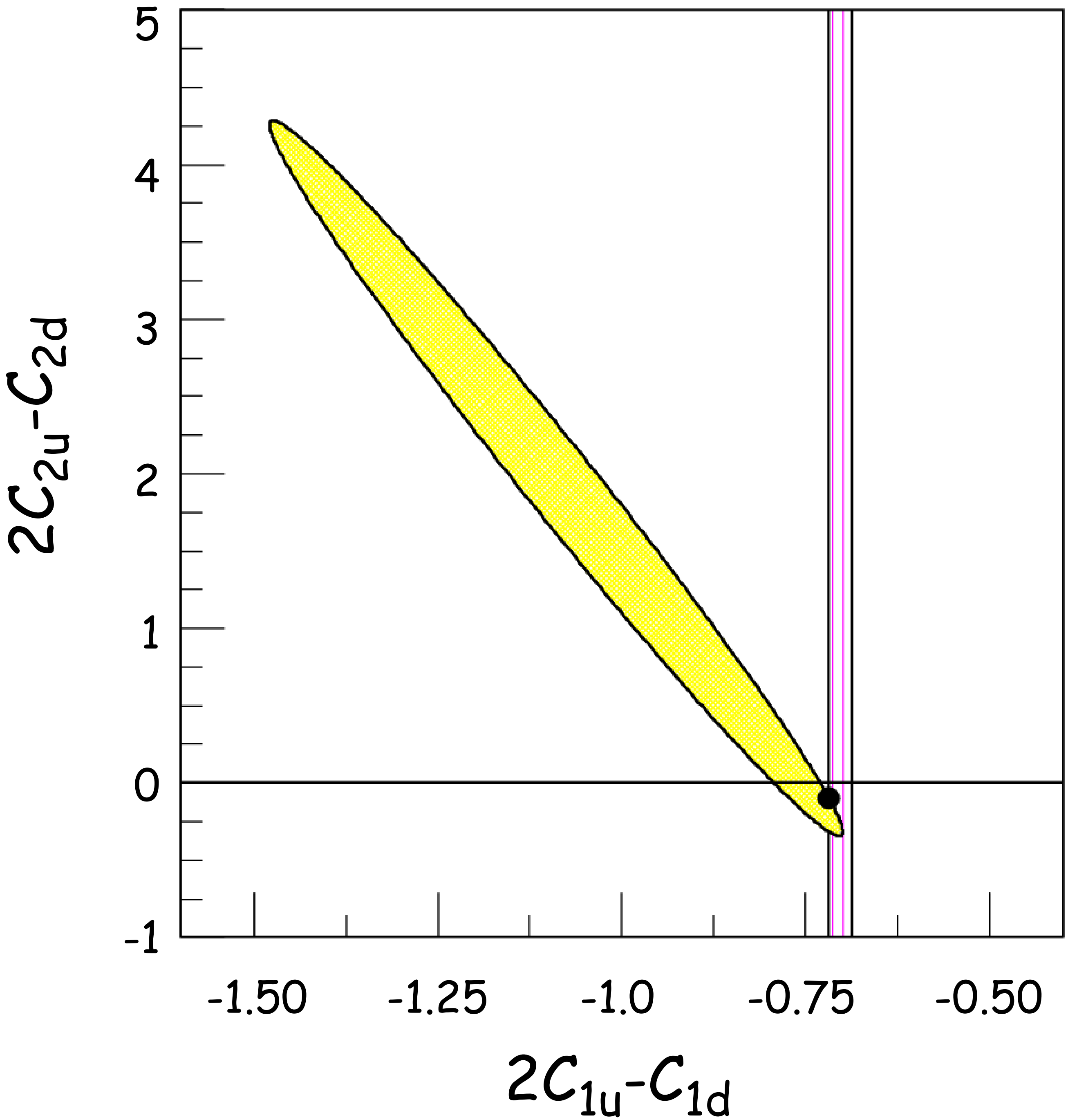


Androic et al., PRL 111, 141803 (2013);

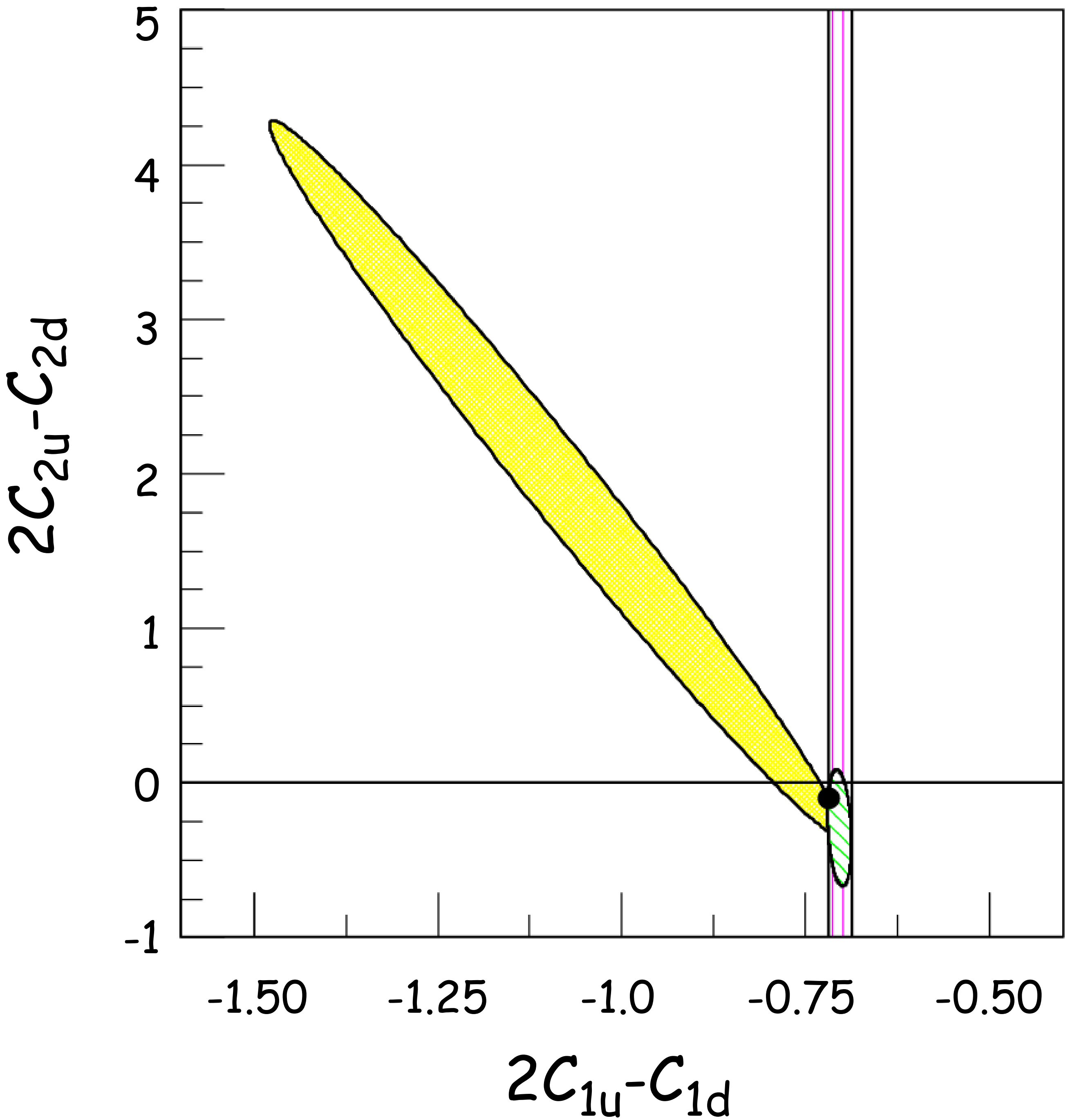
Projecting to C_{1q} vs C_{2q} (e-q AV vs. VA couplings)



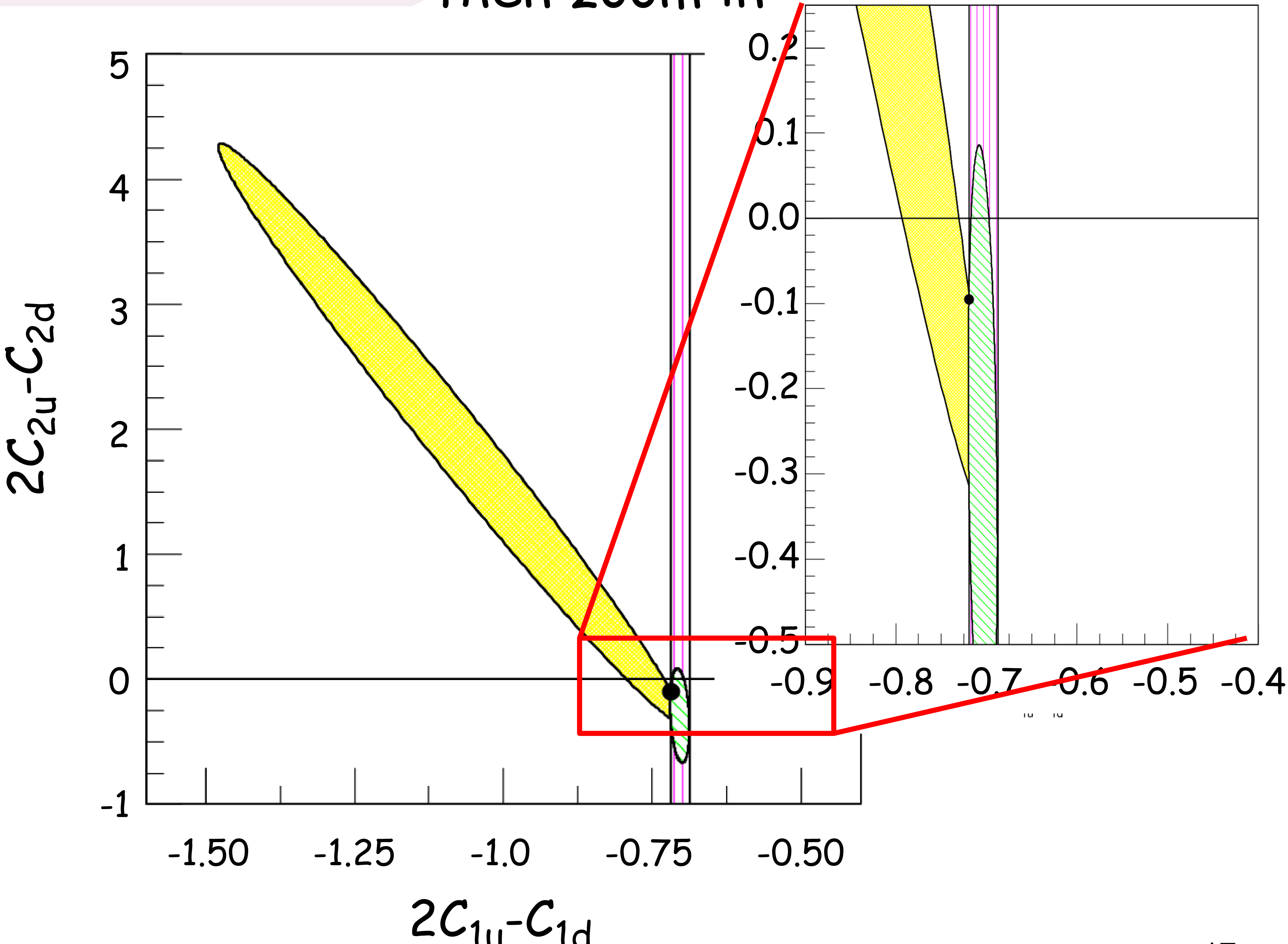
Add E122 – the first PVES (1978)



and combine them

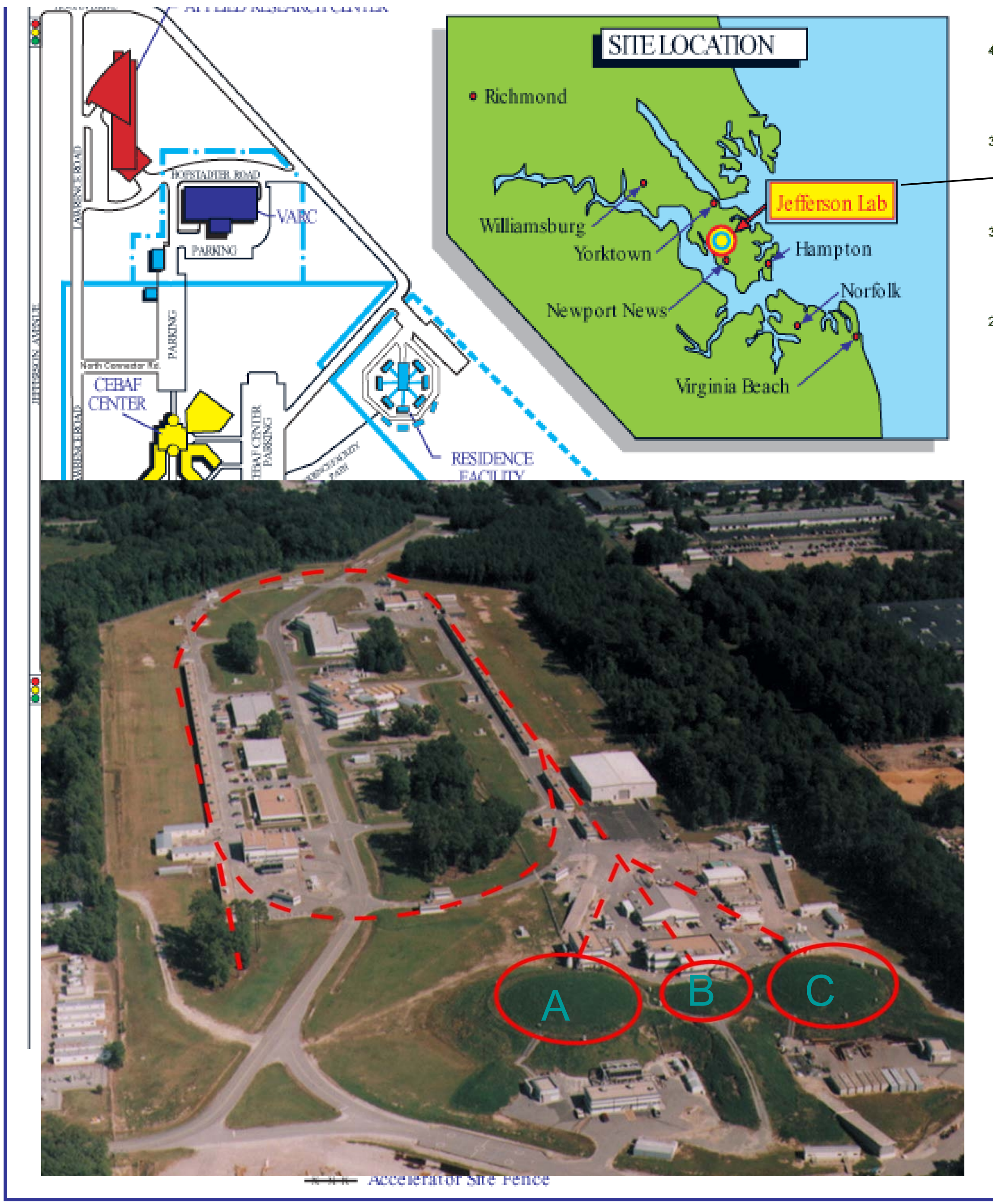


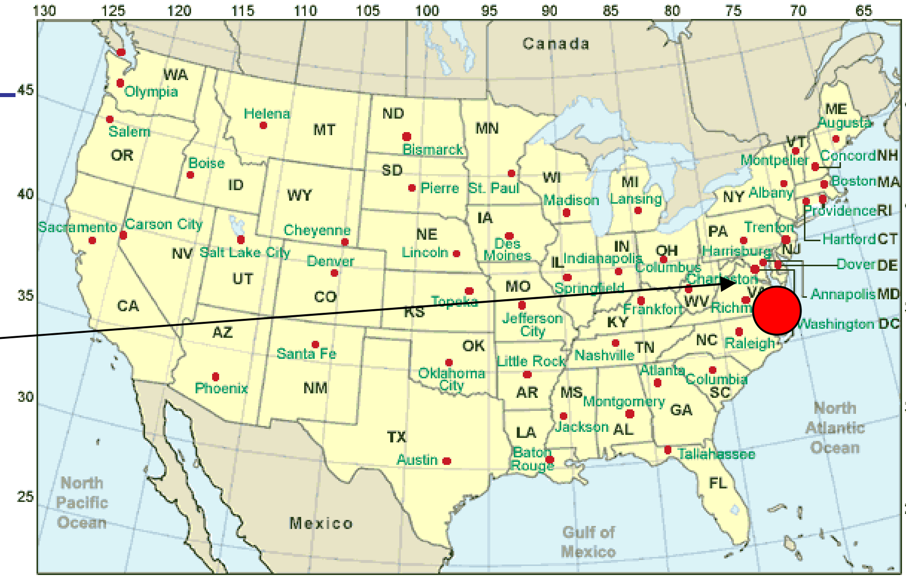
then zoom in



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
5
4
3
2
1
0
-1
-1.50
-1.25
-1.0
-0.75
-0.50
$2C_{2u}-C_{2d}$
$2C_{1u}-C_{1d}$

PVDIS at 6 GeV (JLab E08-011)



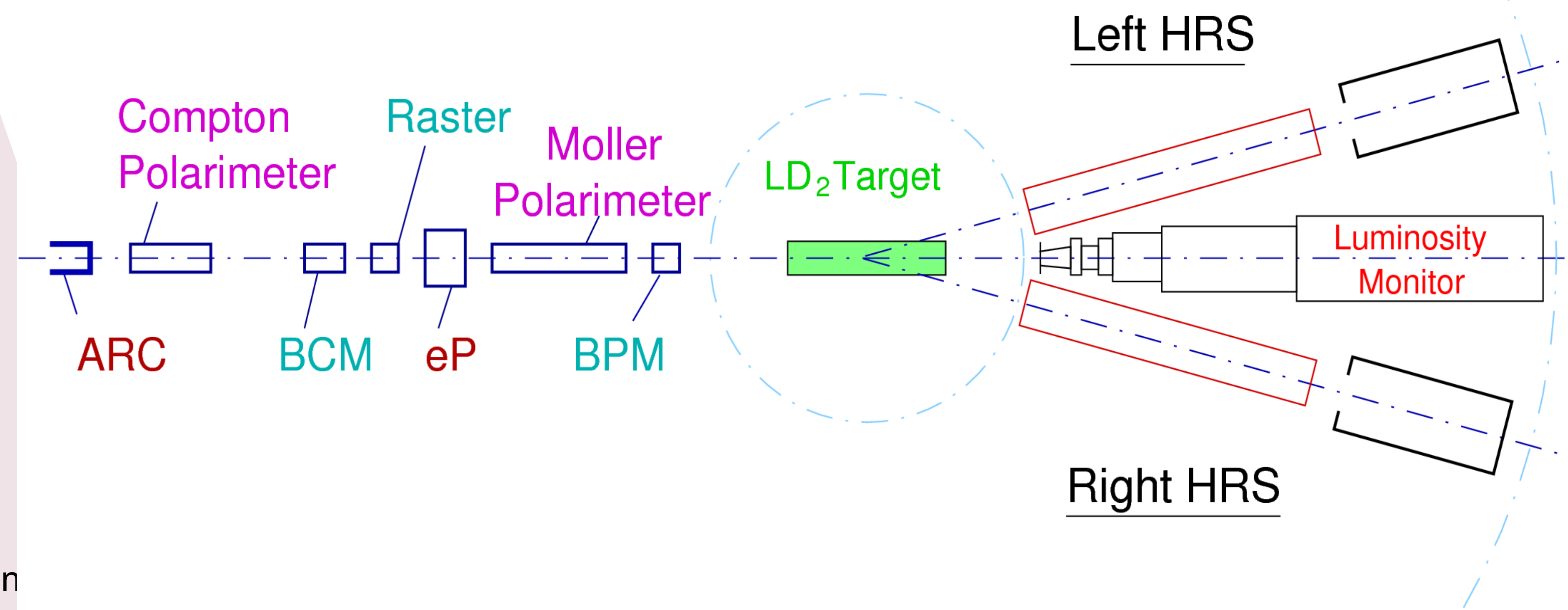


- **Staff: ~700**
- **User community: ~1300**

- Beam first delivered in 10/95
- In full operation for since 11/97
- >300 PhDs to date and >200 in progress (~1/3 of US PhDs in Nuclear Physics)
- Energy: 6 GeV, 12 GeV (starting 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

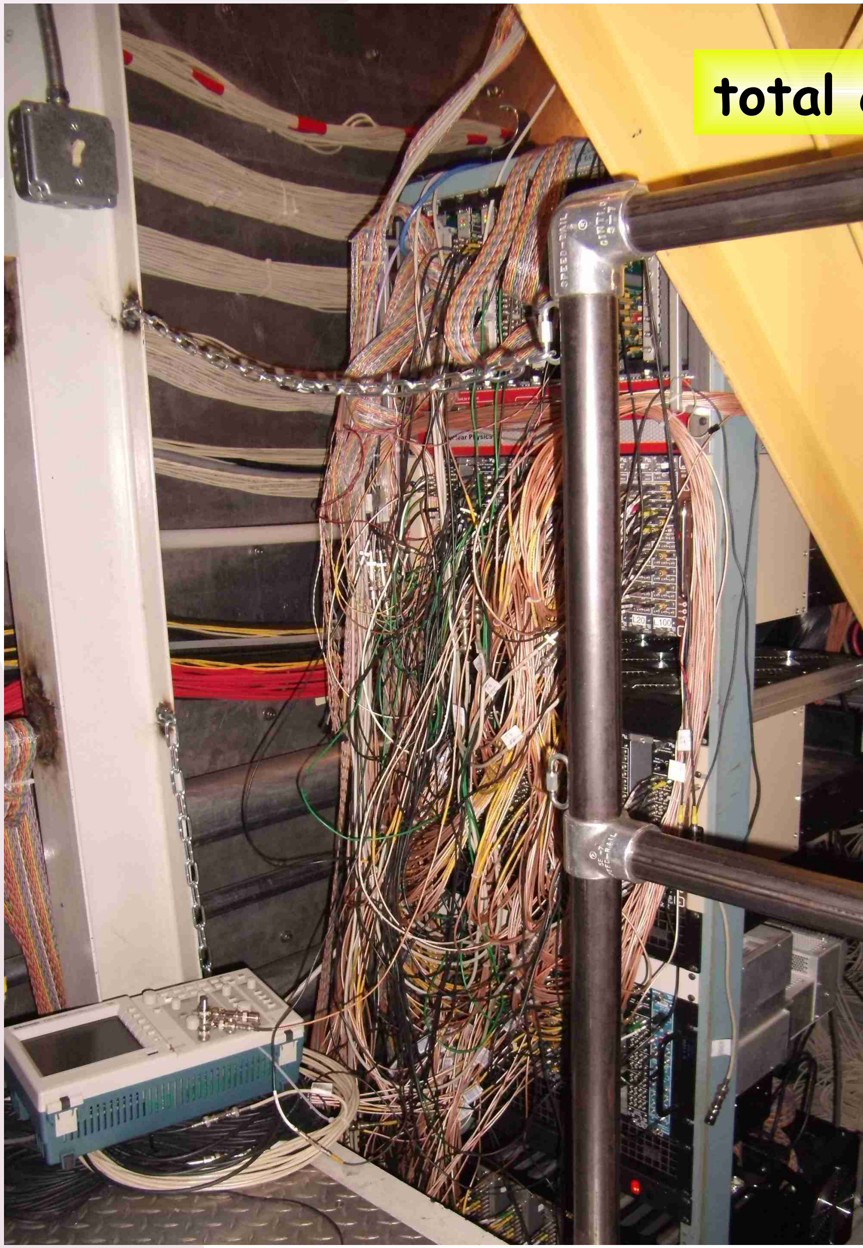


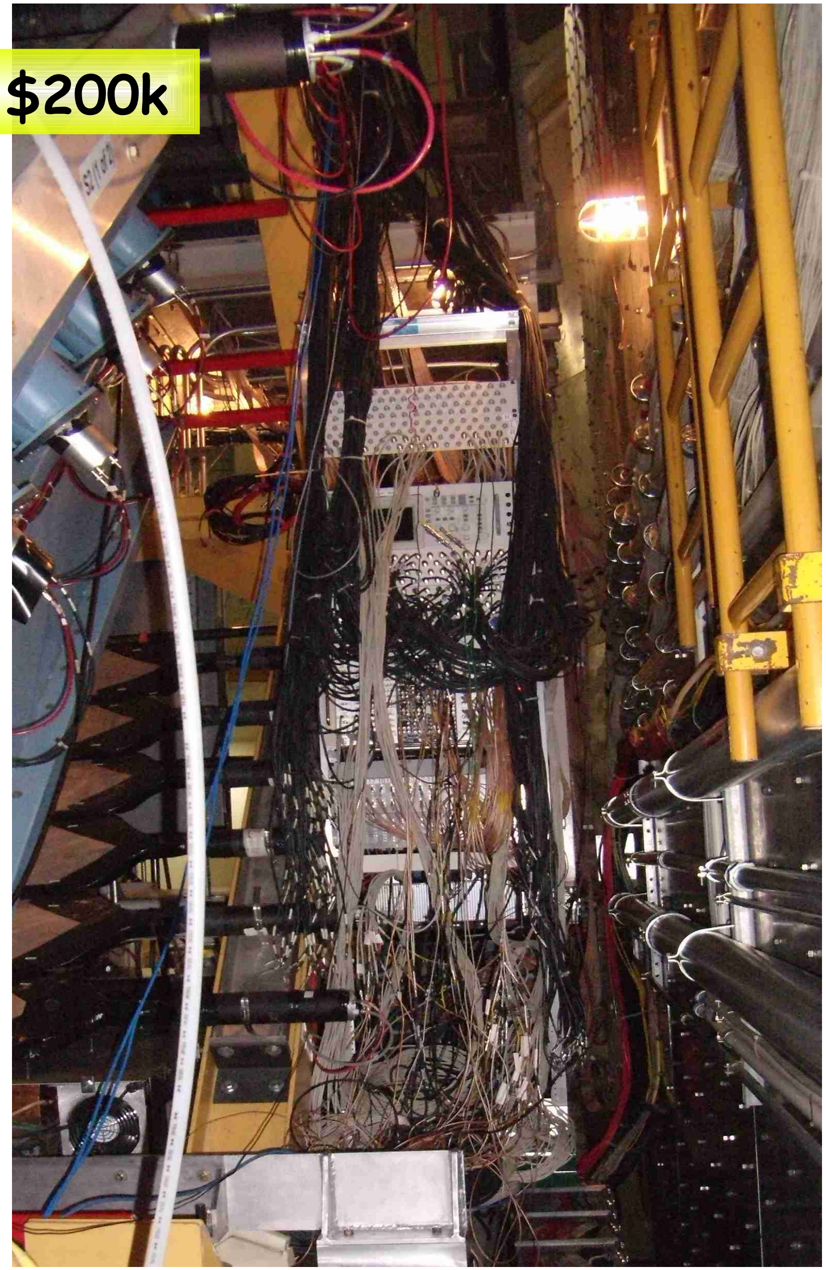
E08-011 Kinematics

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	$<\approx 0.25$
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	$<\approx 0.7$

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

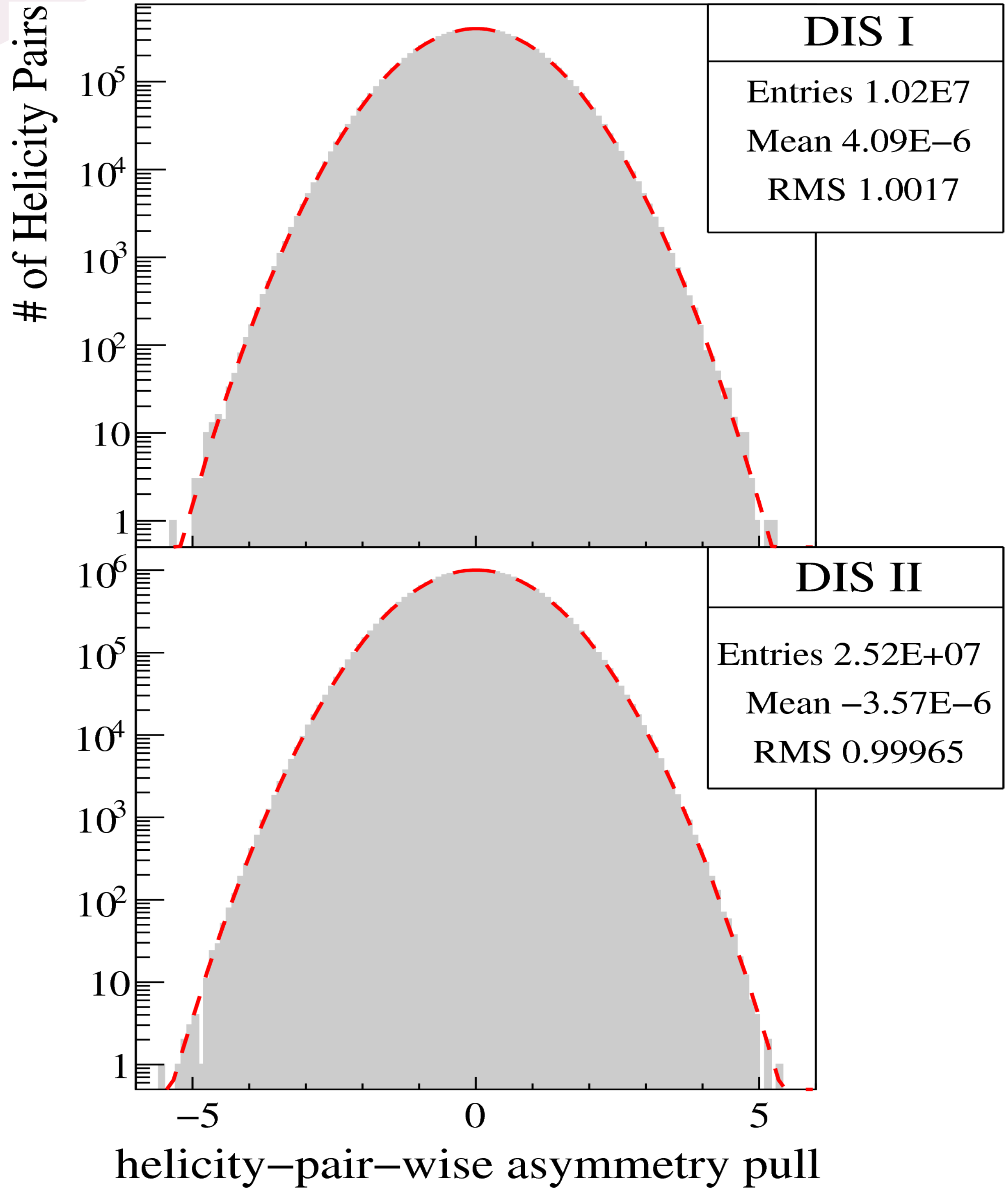
total cost: $200k





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:

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

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

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

From Measured to Physics Asymmetry

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

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

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

$A^{\rm phys}$ (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%	$\pm$1.50%
$1+f_{\rm depol}$	1.0021	
(syst.)	$< 10^{-4}$	
$1+f_{\rm Al}$	0.9999	0.9999
(syst.)	$\pm$0.0024	$\pm$0.0024
$1+f_{\rm dt}$	1.0049	1.0093
(syst.)	$\pm$0.0004	$\pm$0.0013
$1+f_{\rm rc}$	1.019	
(syst.)	$\pm$0.004	
$1+f_{\gamma\gamma{\rm box}}$	0.997	–
$1+f_{\gamma\gamma,\gamma Z{\rm boxes}}$	–	1.005
(syst.)	$\pm$0.003	$\pm$0.005

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

Asymmetry

$A^{\rm phys}$ (ppm)	$-$160.80
(stat.)	$\pm$6.39
(syst.)	$\pm$3.12
(total)	$\pm$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

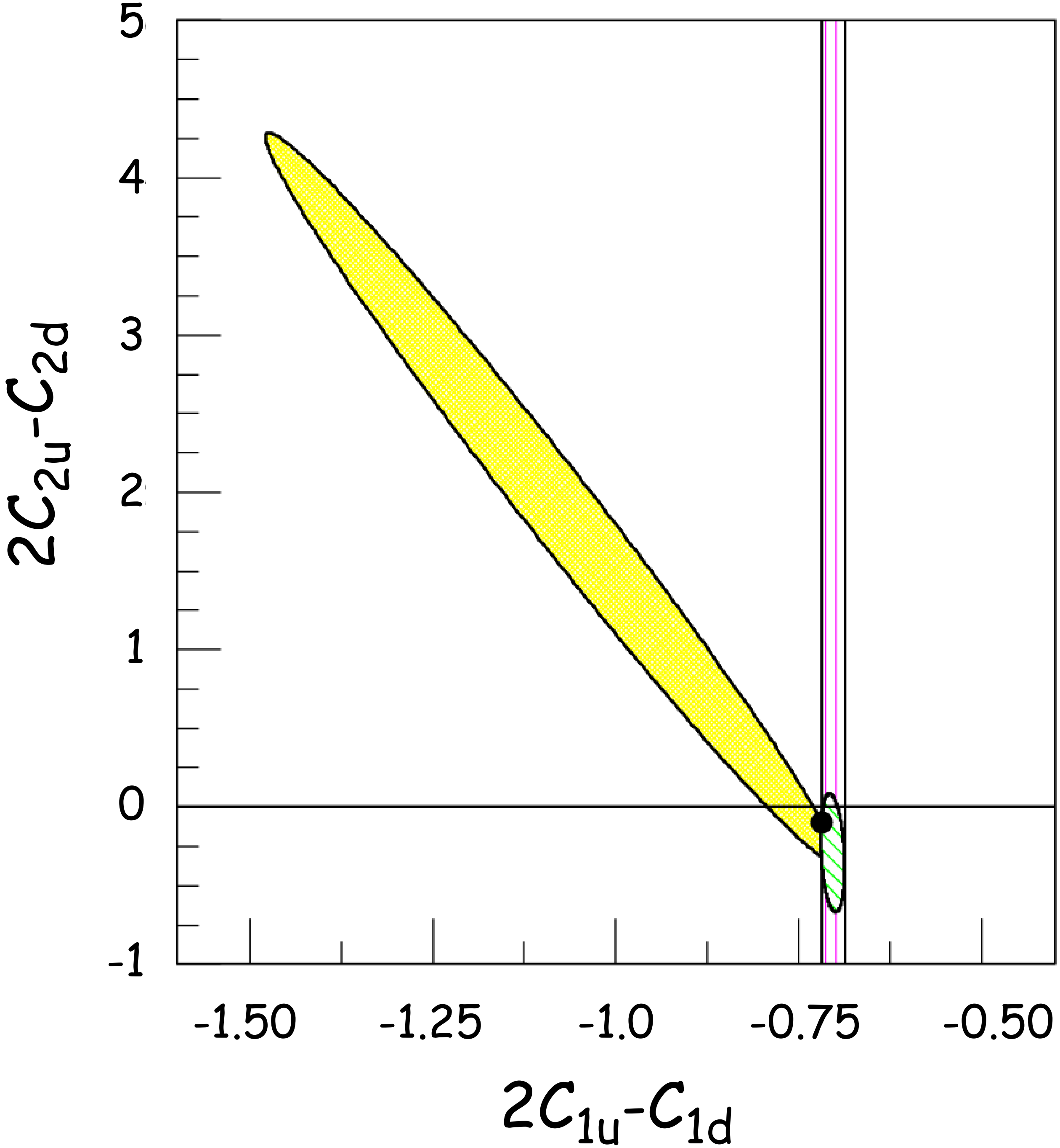
$$A^{phys}_{Q^2=1.901,\, x=0.295} = -160.80 \pm 6.39 \pm 3.12\ ppm$$

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

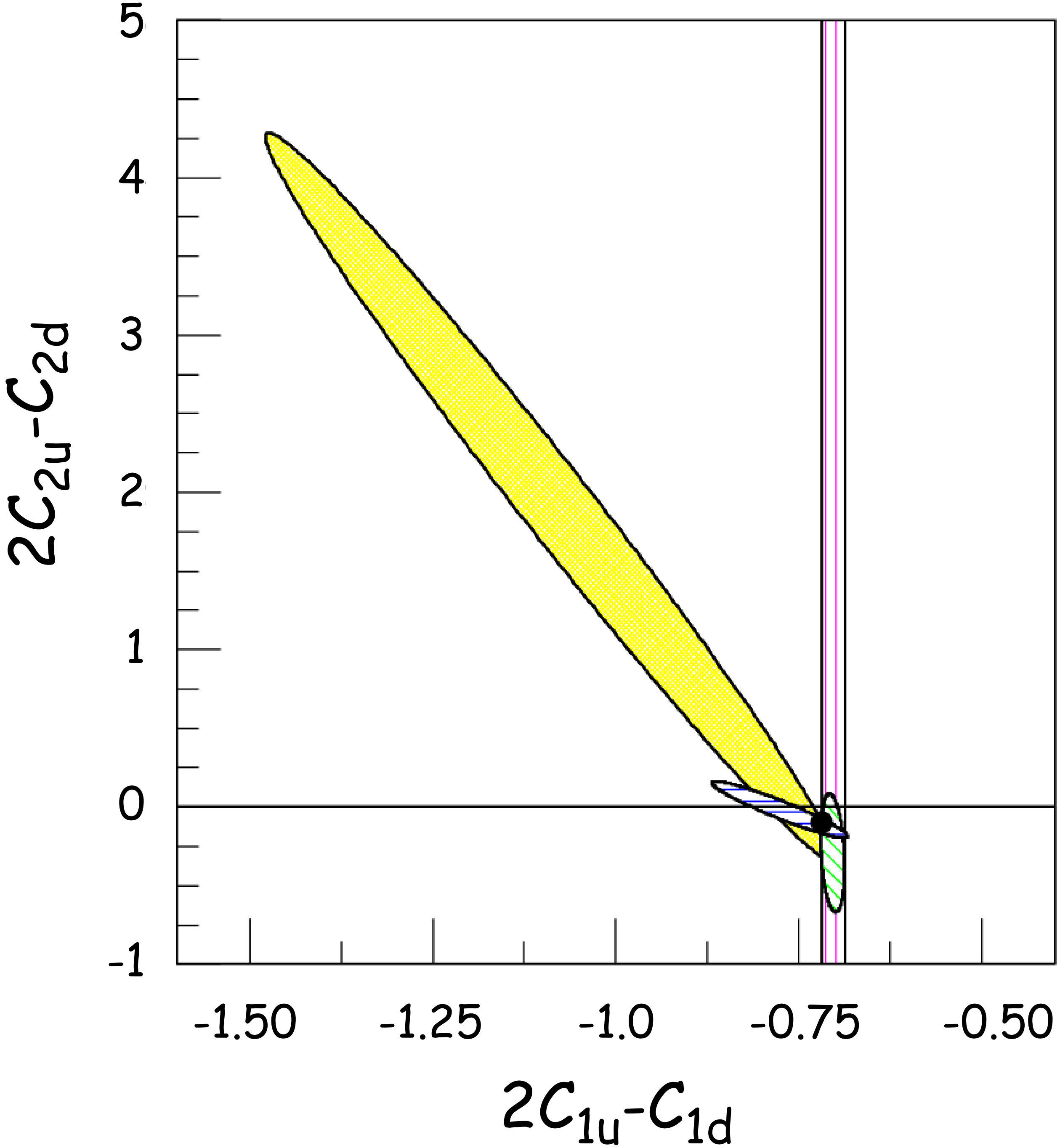
uncertainty due to PDF: 0.5% 5%

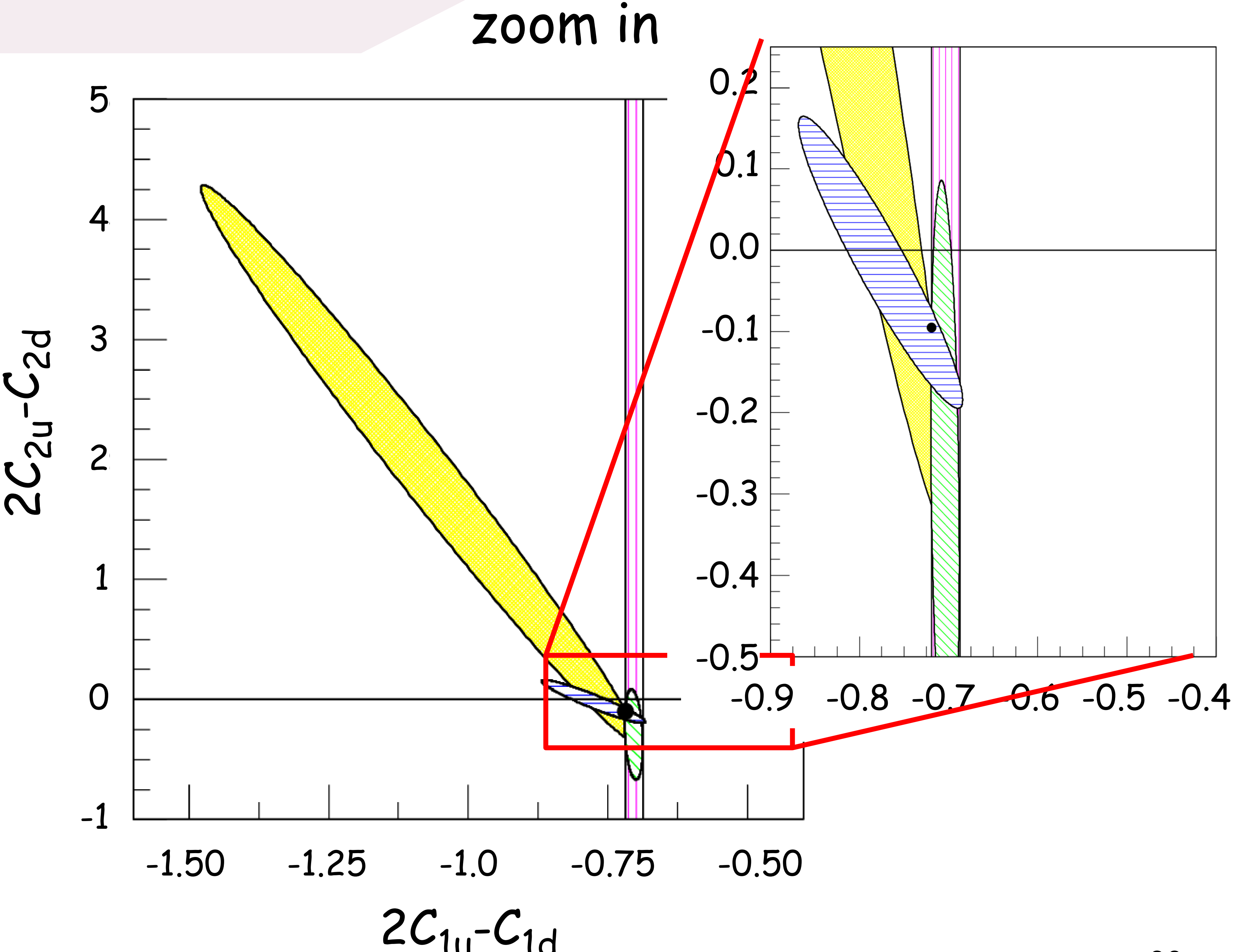
uncertainty due to HT: 0.5%/Q^2, 1.2ppm

Previous data: Elastic PVES + APV

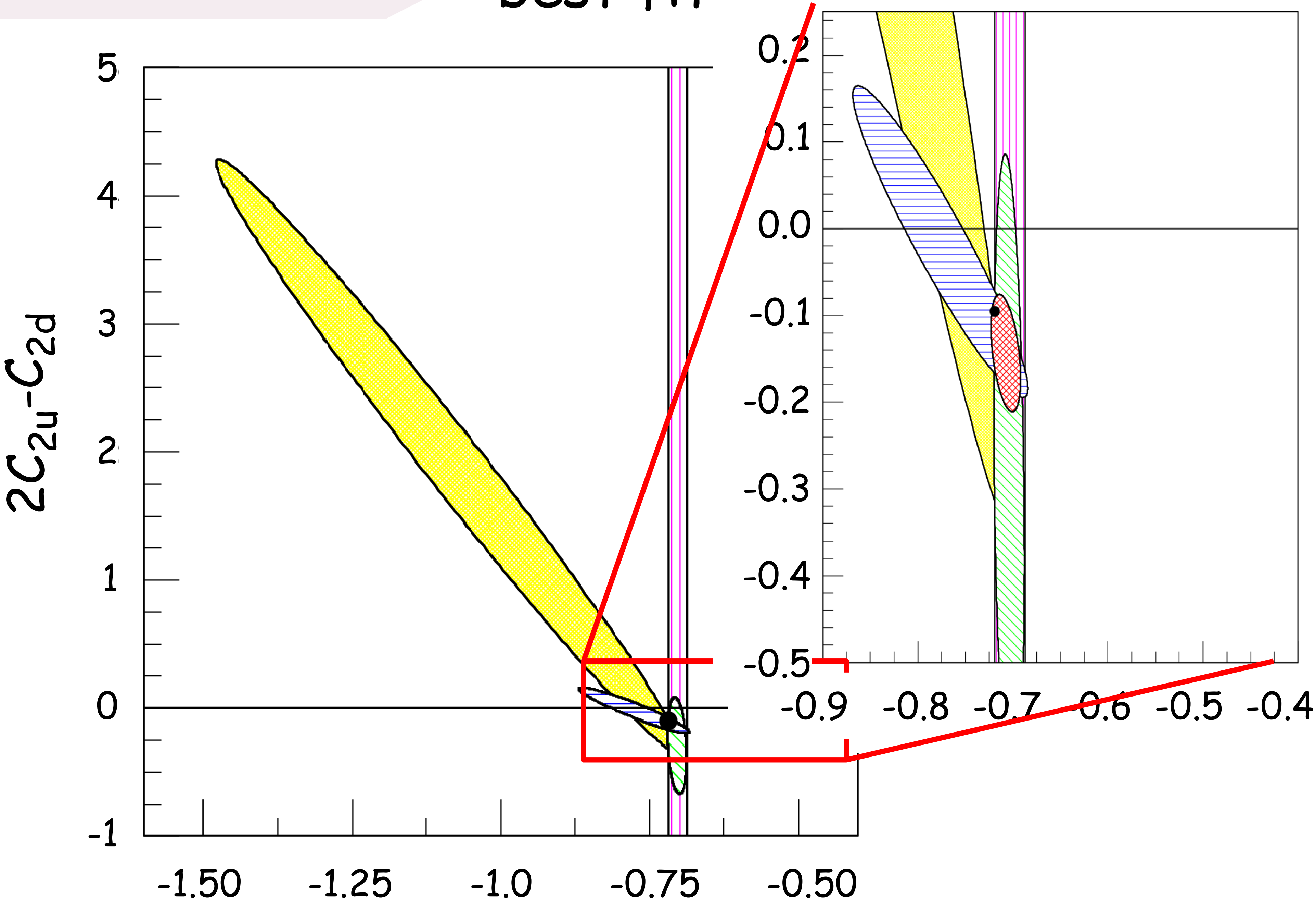


Add JLab PVDIS



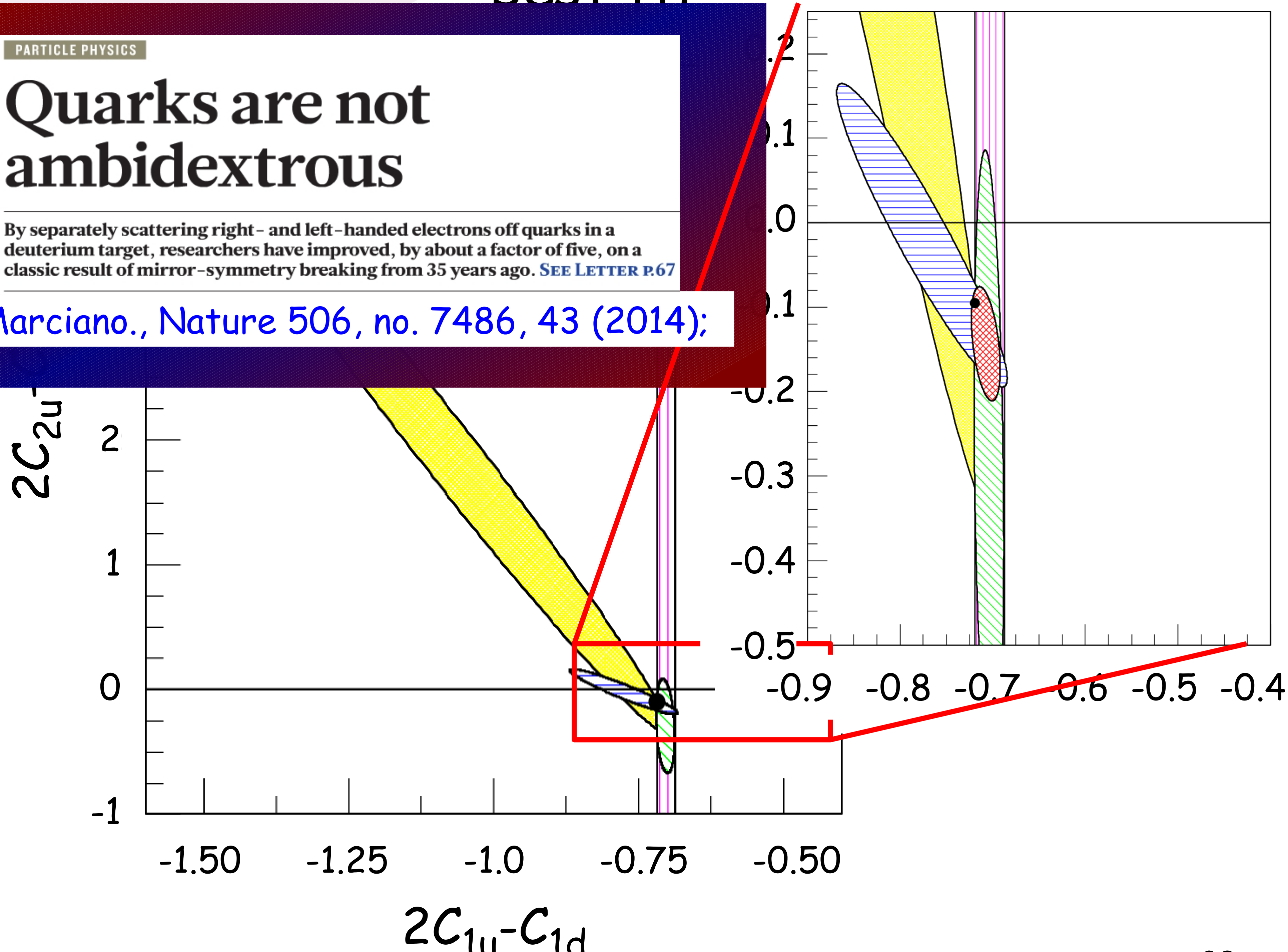

zoom in
5
4
3
2
1
0
-1
$2C_{2u}-C_{2d}$
-1.50
-1.25
-1.0
-0.75
-0.50
$2C_{1u}-C_{1d}$
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4

best fit



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

best fit



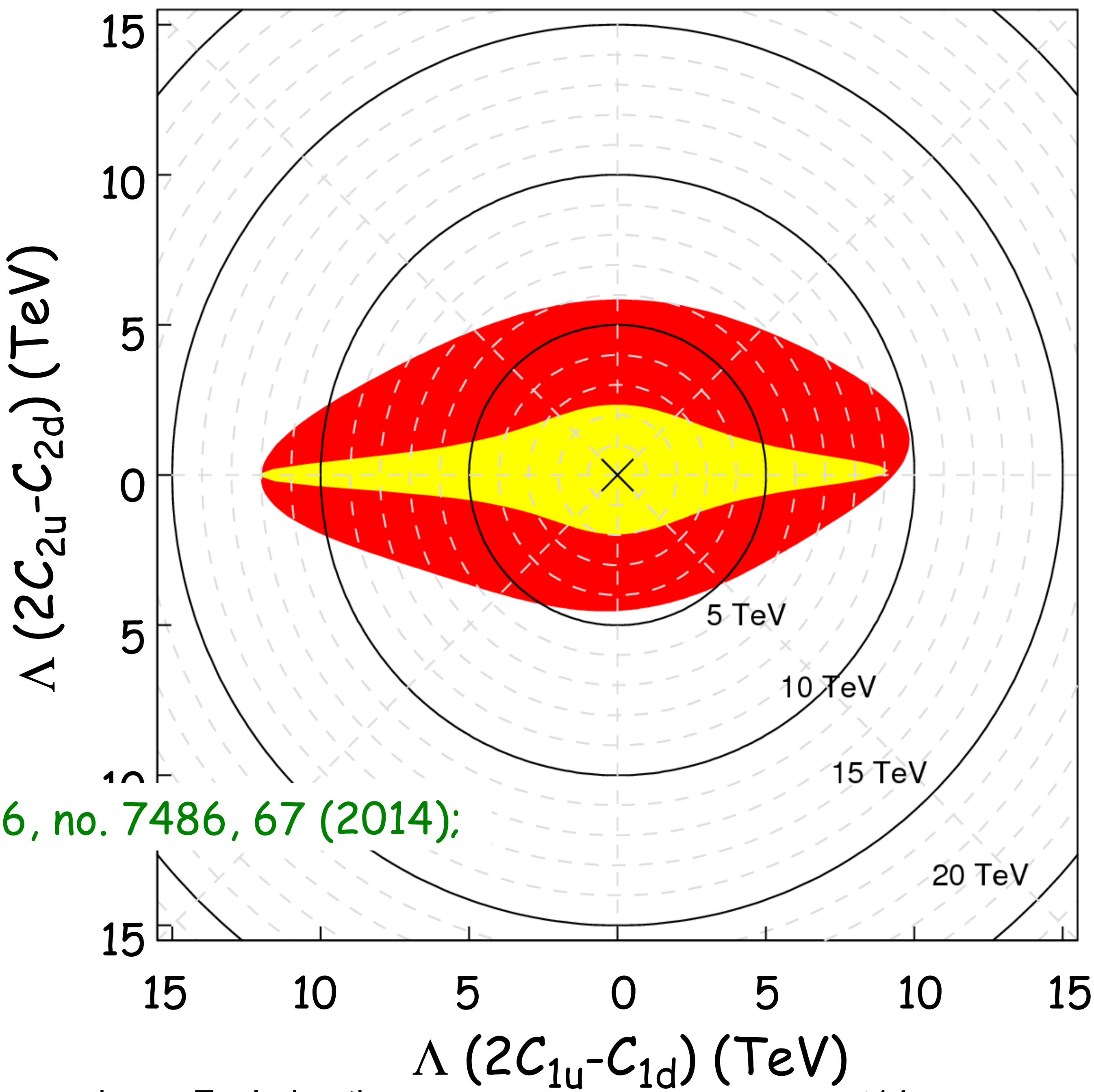
PARTICLE PHYSICS

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

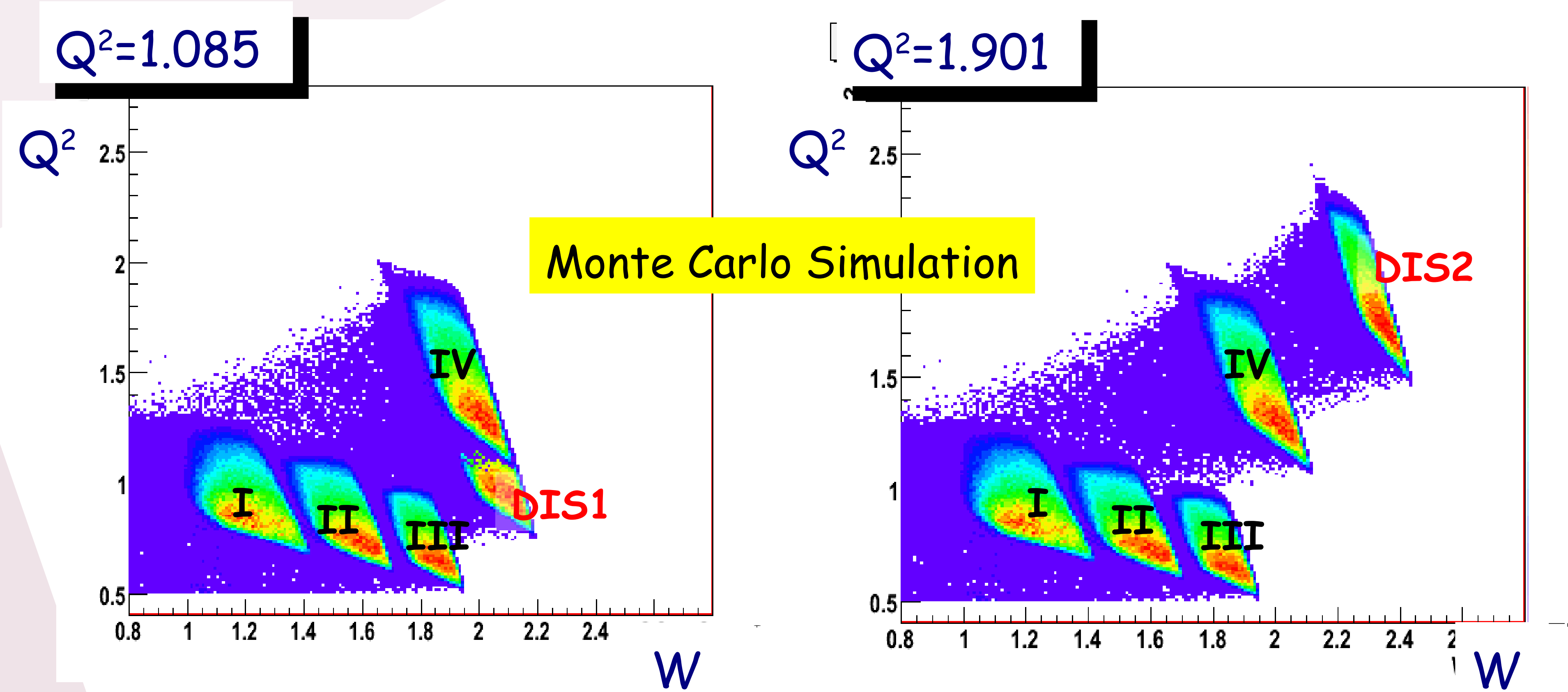
Marciano., Nature 506, no. 7486, 43 (2014);

BSM Mass Limit on eq VA contact interaction



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

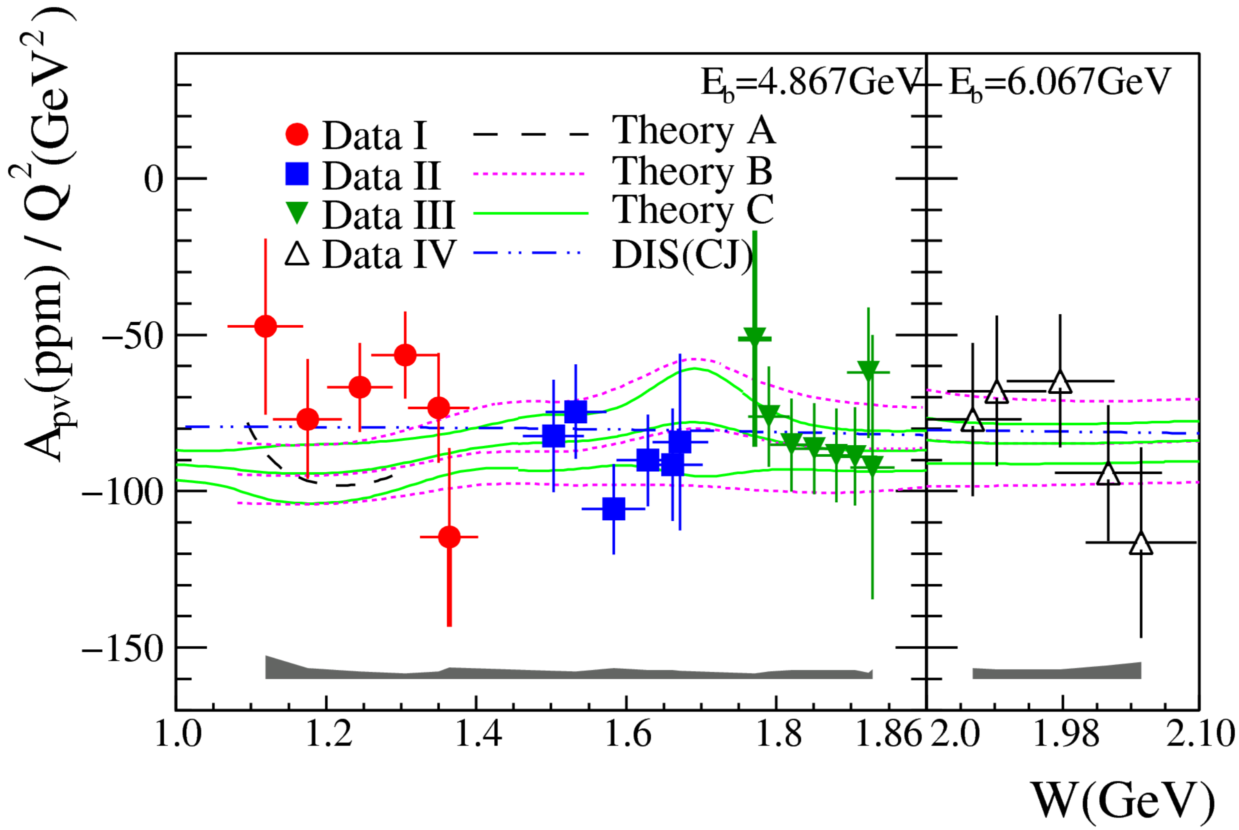
Resonance Background Data Coverage



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

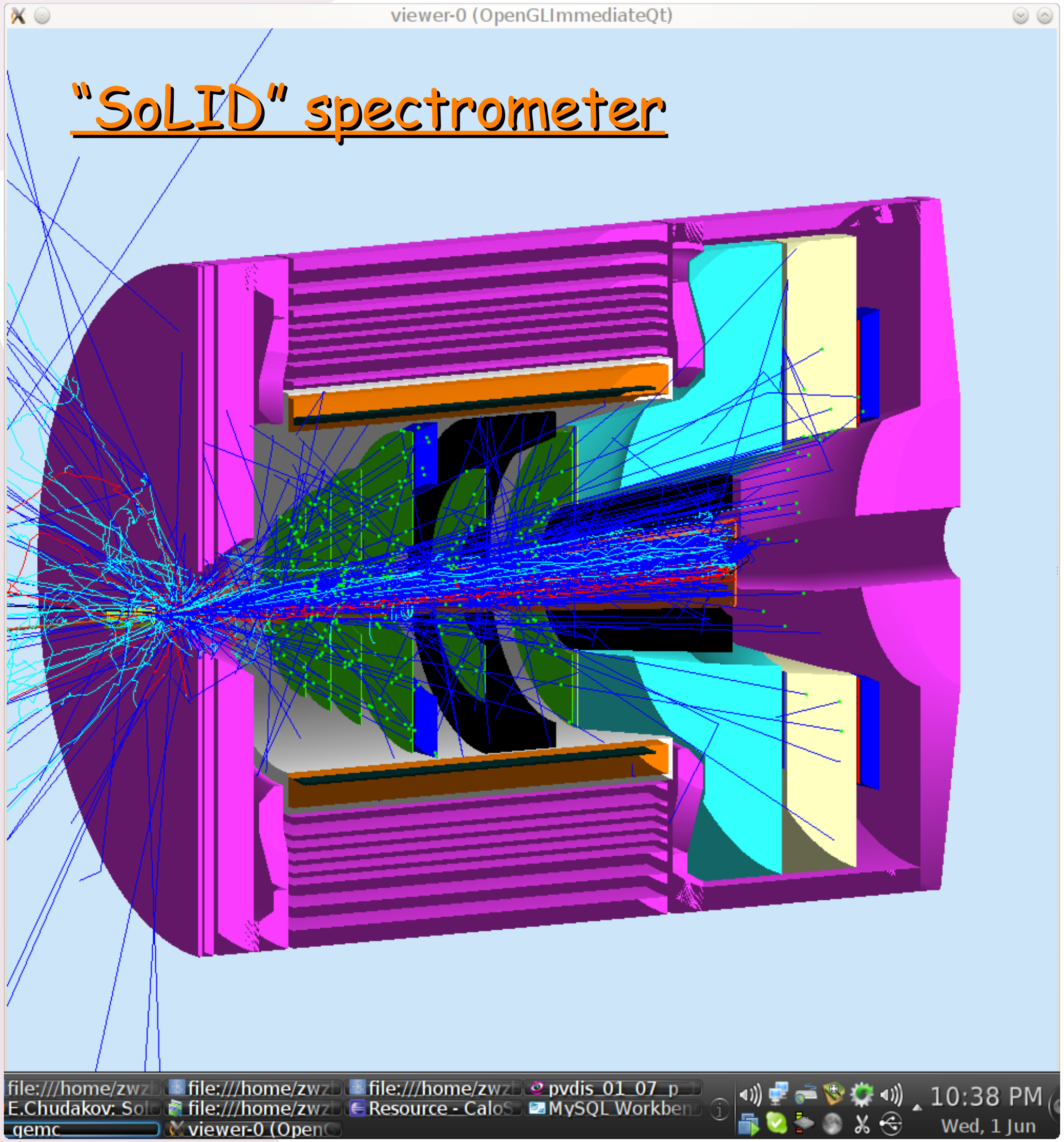
Resonance PV Asymmetry Results

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);

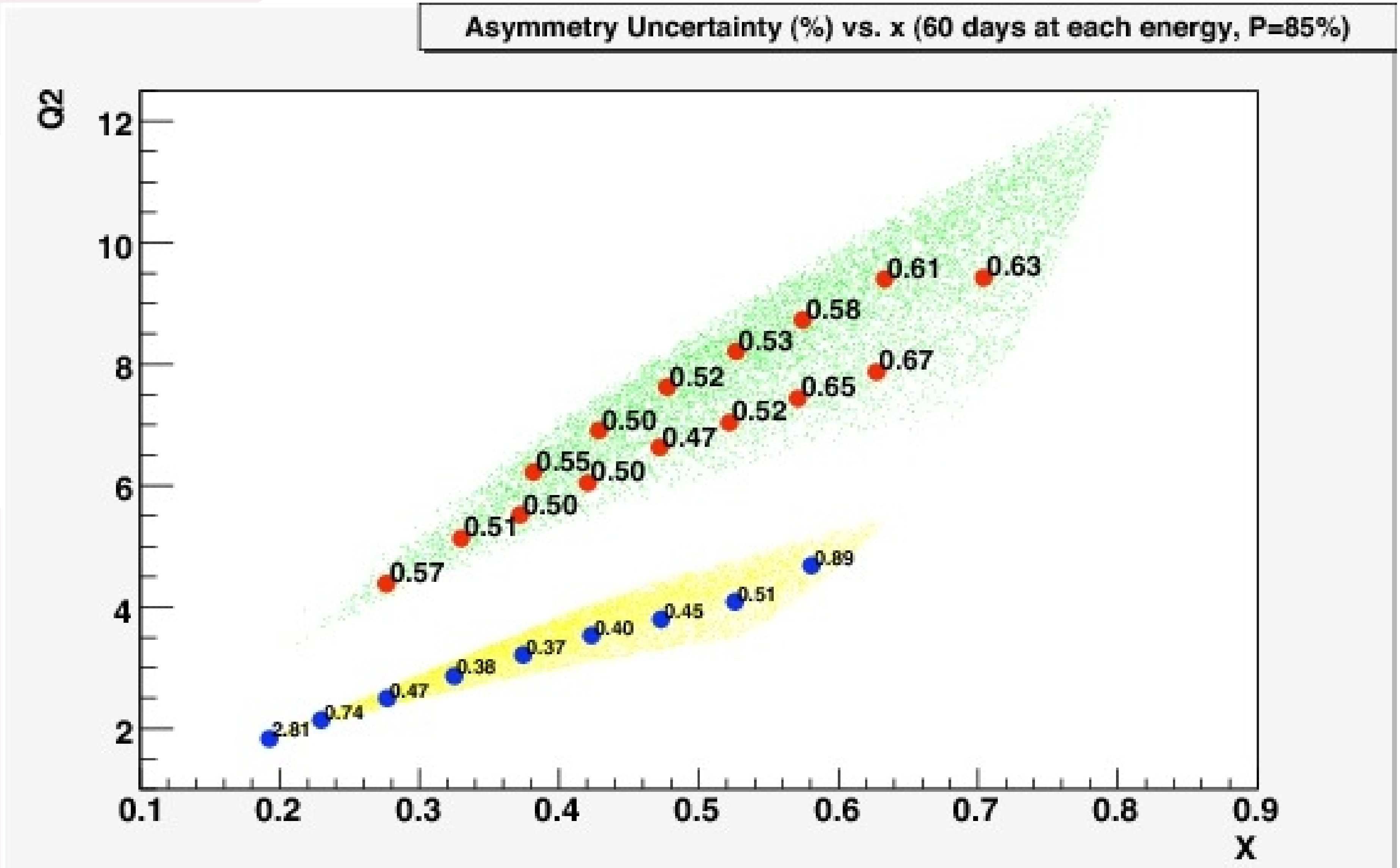
Coherent PVDIS Program with SoLID @ 11 GeV



SoLID Physics topics:

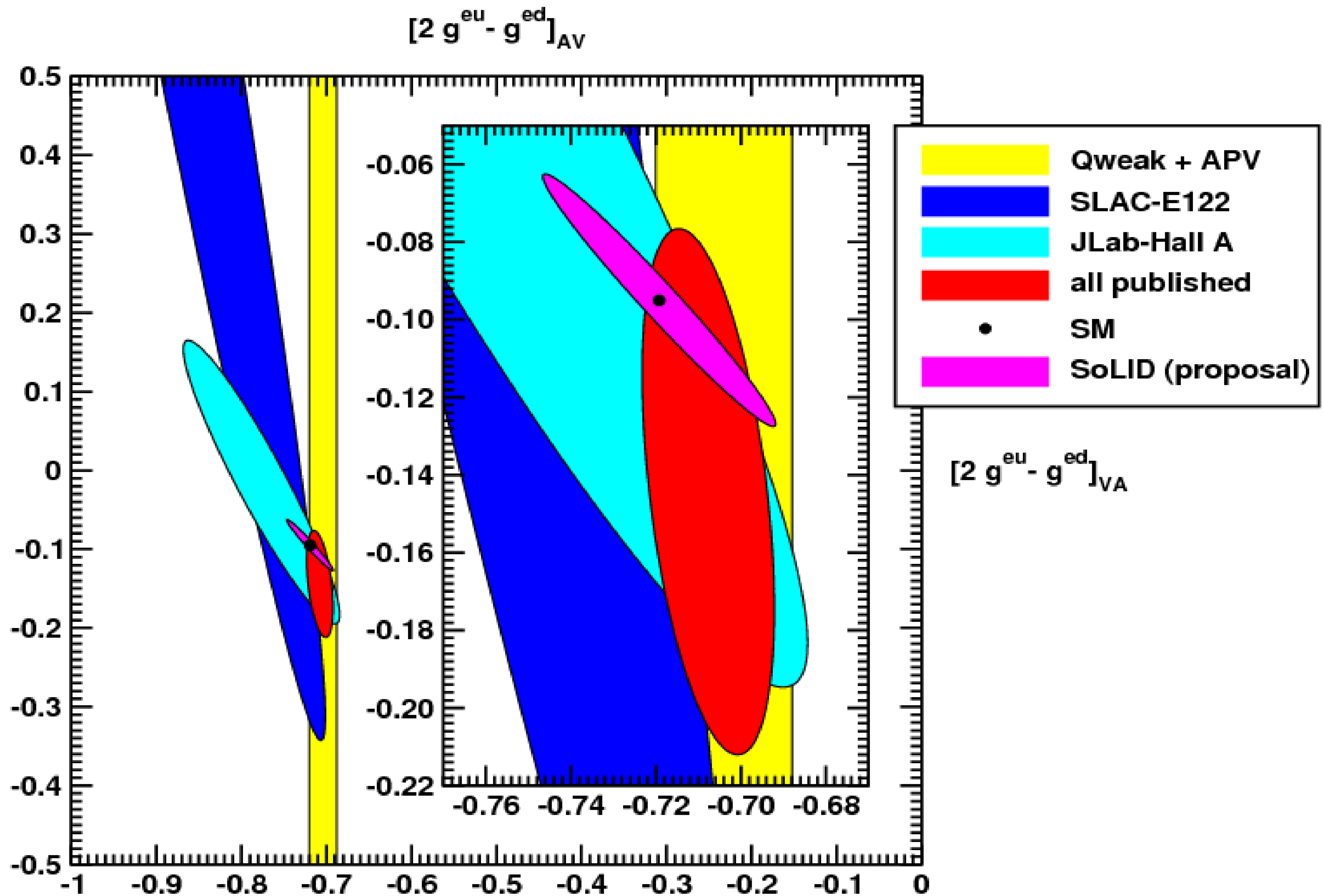
- PVDIS deuteron (180 days) – C_2, $\sin^2\theta_W$, CSV, diquarks,
- PVDIS proton (90 days) – d/u
- PV with $^3\vec{He}$ (LOI)
- SIDIS
- J/ψ

Coherent PVDIS Program with SoLID @ 11 GeV

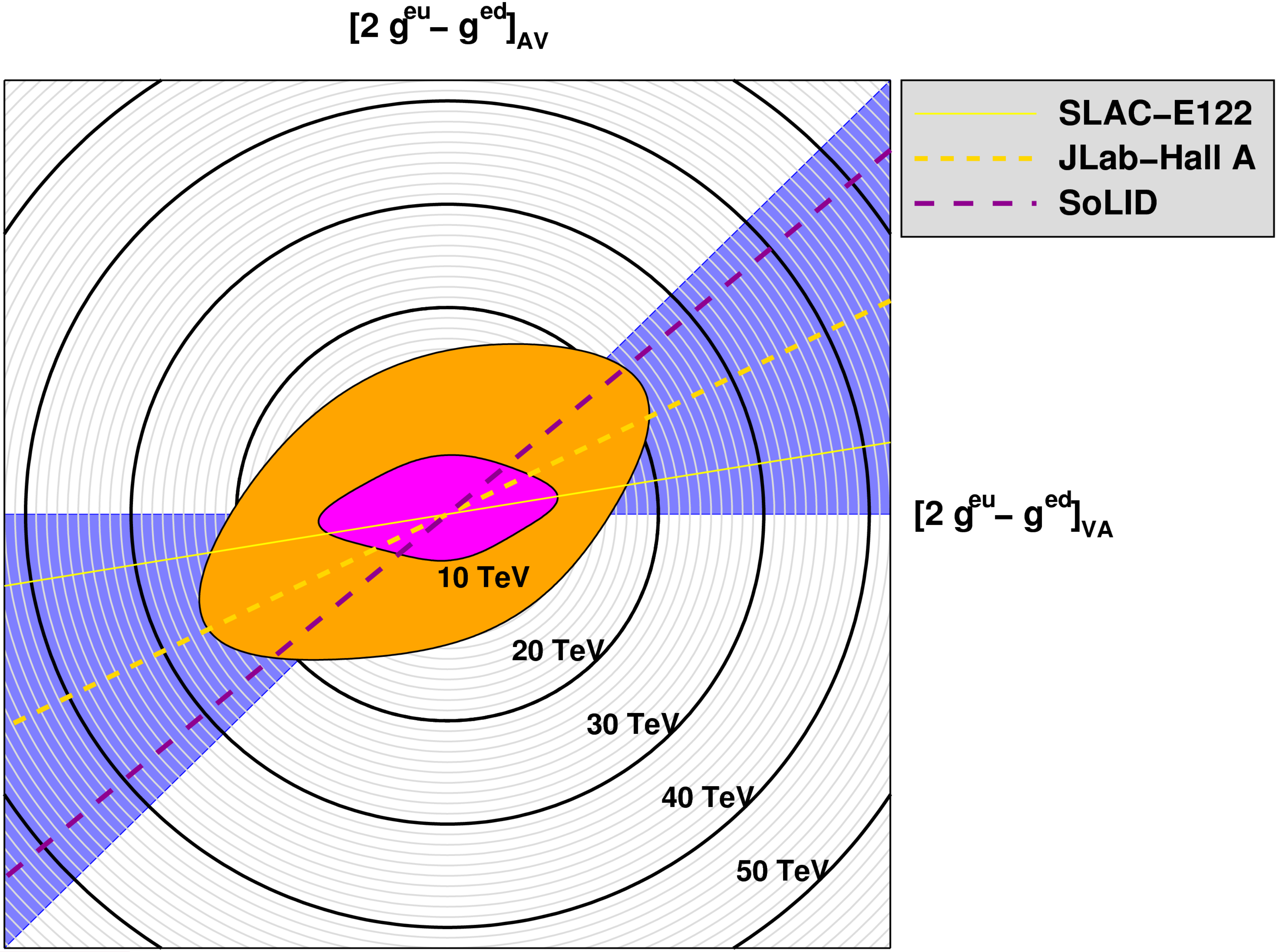


Goal on C_{2q}: one order of magnitude improvement over 6 GeV

Coherent PVDIS Program with SoLID @ 11 GeV



Coherent PVDIS Program with SoLID @ 11 GeV



6 GeV PVDIS Timeline

- 2003 – Letter of Intent to JLab PAC
- 2003-2005 – main proposer was distracted by other physics topics
- 2005 – Full proposal to JLab PAC, partially approved (E05-007) with A-rating
- 2008 – Jeopardy review, approved 32 days (E08-011) with A-rating
- 2009, Oct-Dec – Running of Experiment
- 2010-2013 – Data analysis
- 2013-present – publishing results (1 NIM, 1 PRL, 1 Nature, 1 PRC long paper ongoing)

6 GeV PVDIS Timeline

I was at ANL-MEP

- 2003 – Letter of Intent to JLab PAC
- 2003-2005 – main proposer was distracted by other physics topics
- 2005 – Full proposal to JLab PAC, partially approved (E05-007) with A-rating
- 2008 – Jeopardy review, approved 32 days (E08-011) with A-rating
- 2009, Oct-Dec – Running of Experiment
- 2010-2013 – Data analysis
- 2013-present – publishing results (1 NIM, 1 PRL, 1 Nature, 1 PRC long paper ongoing)

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.

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}

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

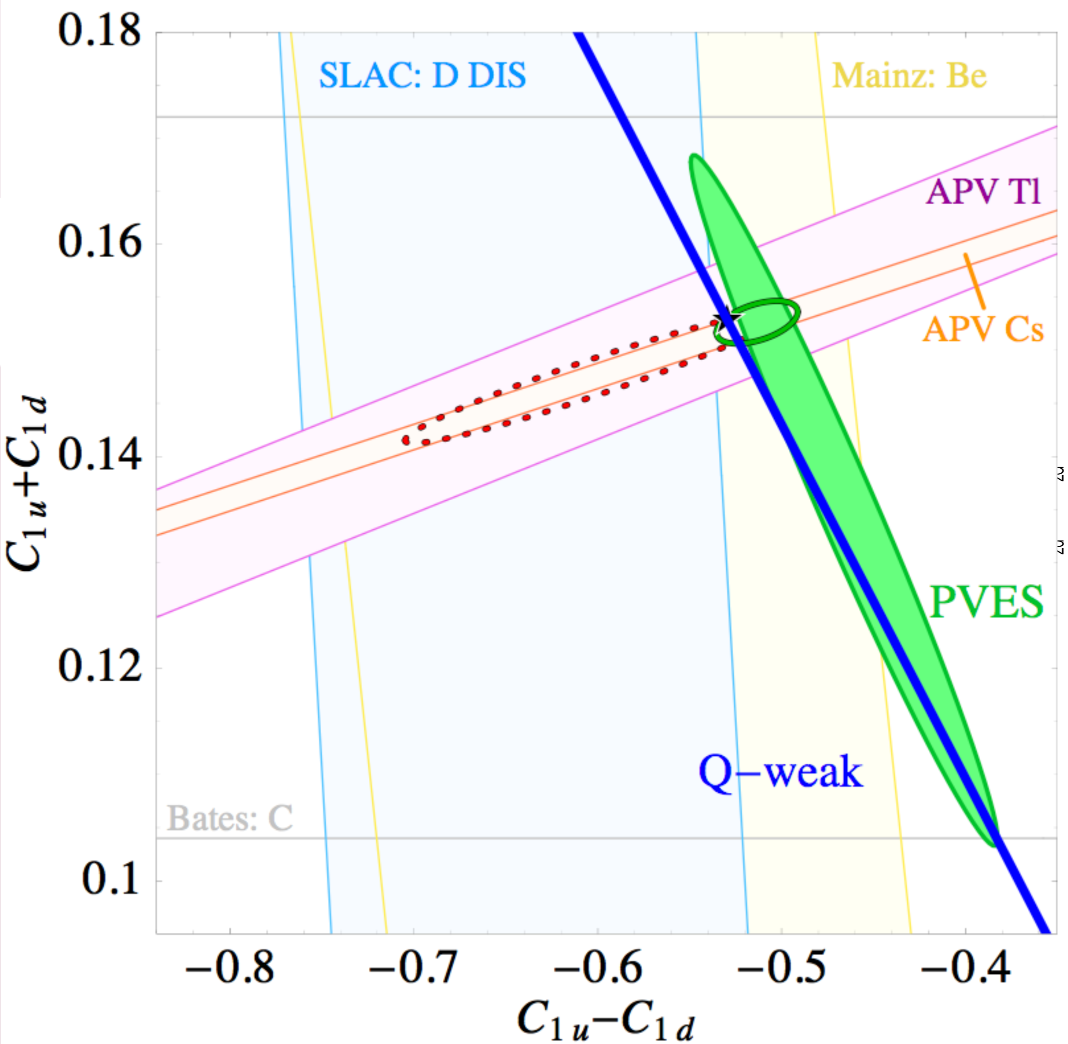
	SLAC E122 (1978)	JLab E08-011 (2009)
Beam	37%, 16.2-22.2 GeV	90%, 6.0674 GeV, 100uA
Target	30-cm LD2, LH2	20-cm LD2
Spectrometer	4^{o}	12.9^{o} and 20^{o}
Q^2	1-1.9 GeV^2	1.1 and 1.9 GeV^2
Data collection	Integrating gas Cerenkov and lead glass detectors, independently	Counting DAQ using both GC and 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)±5%(Pb)±3.3%(beam) ±2%(π contamination) ±3%(radiative corrections)	±(3-4)%(stat) ±syst.
Proton results	$A/Q^2=(-9.7\pm2.7)\times10^{-5}\ (GeV/c)^{-2}$	

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

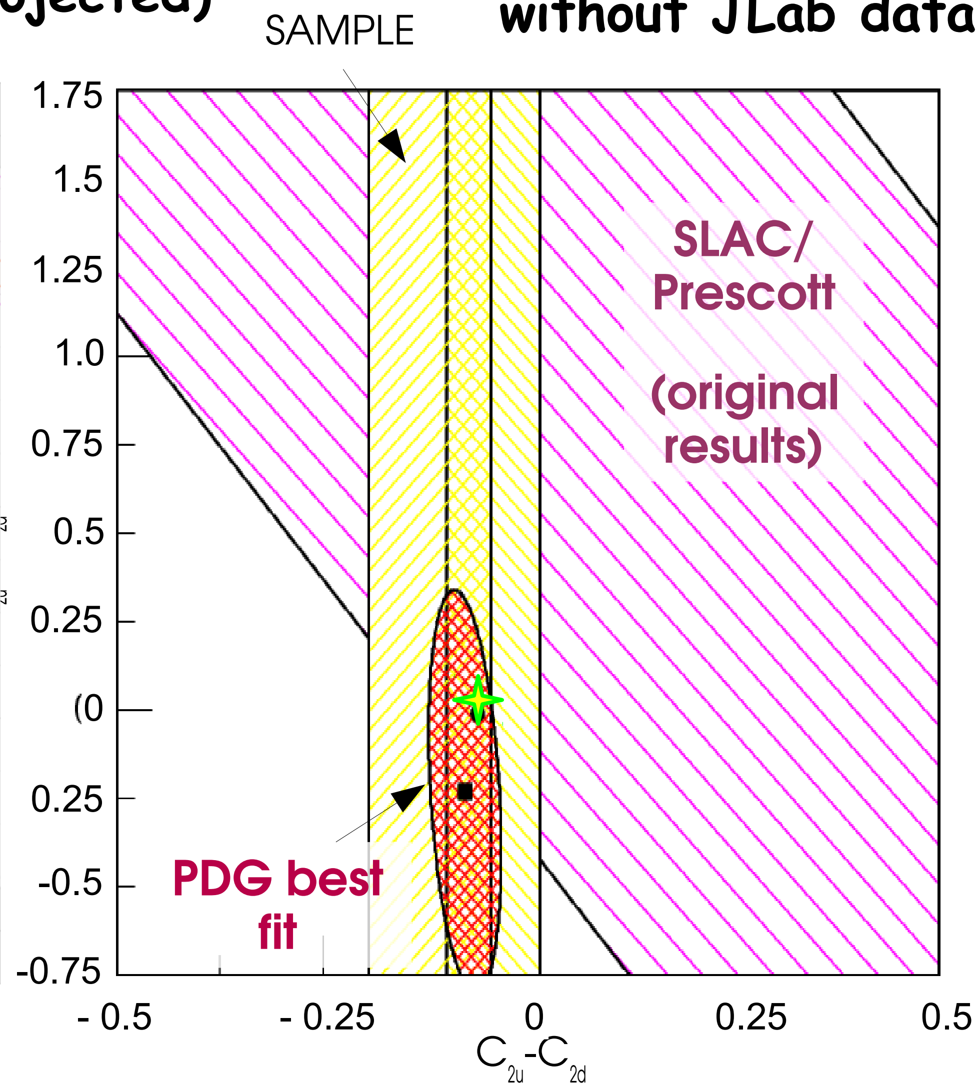
Some Older Plots

all are 1 σ limit

with recent PVES data and Qweak (projected)



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 $Q^p_W=-2(2C_{1u}+C_{1d})$

Electron Scattering Basics