PVDIS at JLab – Results from 6 GeV and the SoLID program

Xiaochao Zheng (Univ. of Virginia)

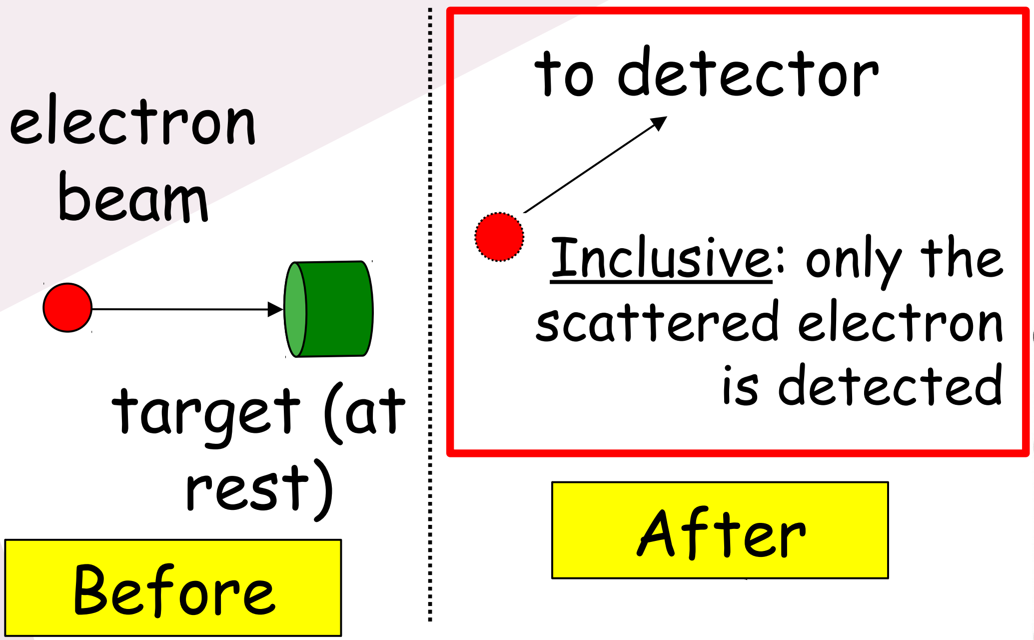
Feb. 3rd, 2017

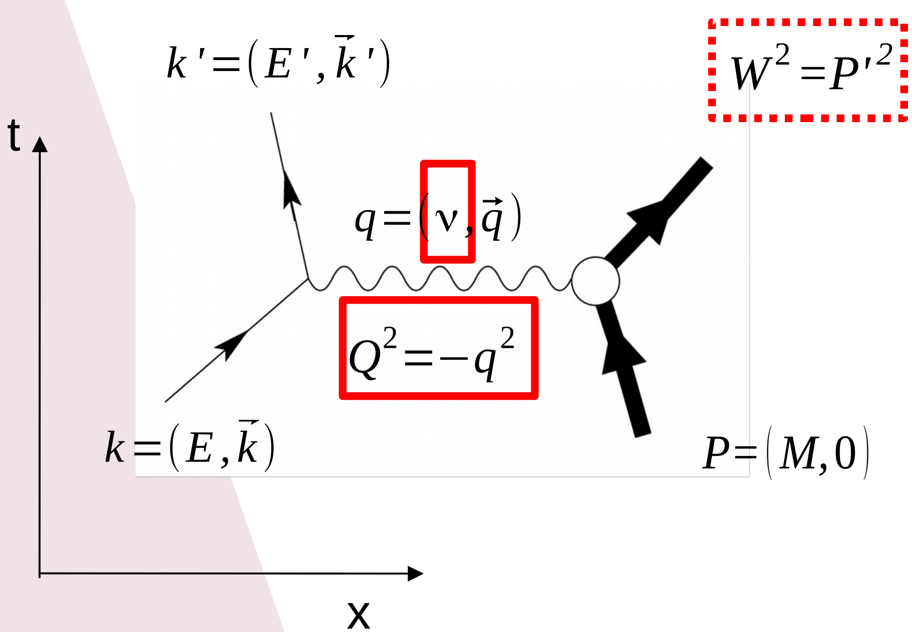
- Parity Violation in Electron Scattering (PVES) and the Standard Model
- PV Deep Inelastic Scattering results from Jefferson Lab 6 GeV
- Outlook – PVDIS at 12 GeV with SoLID

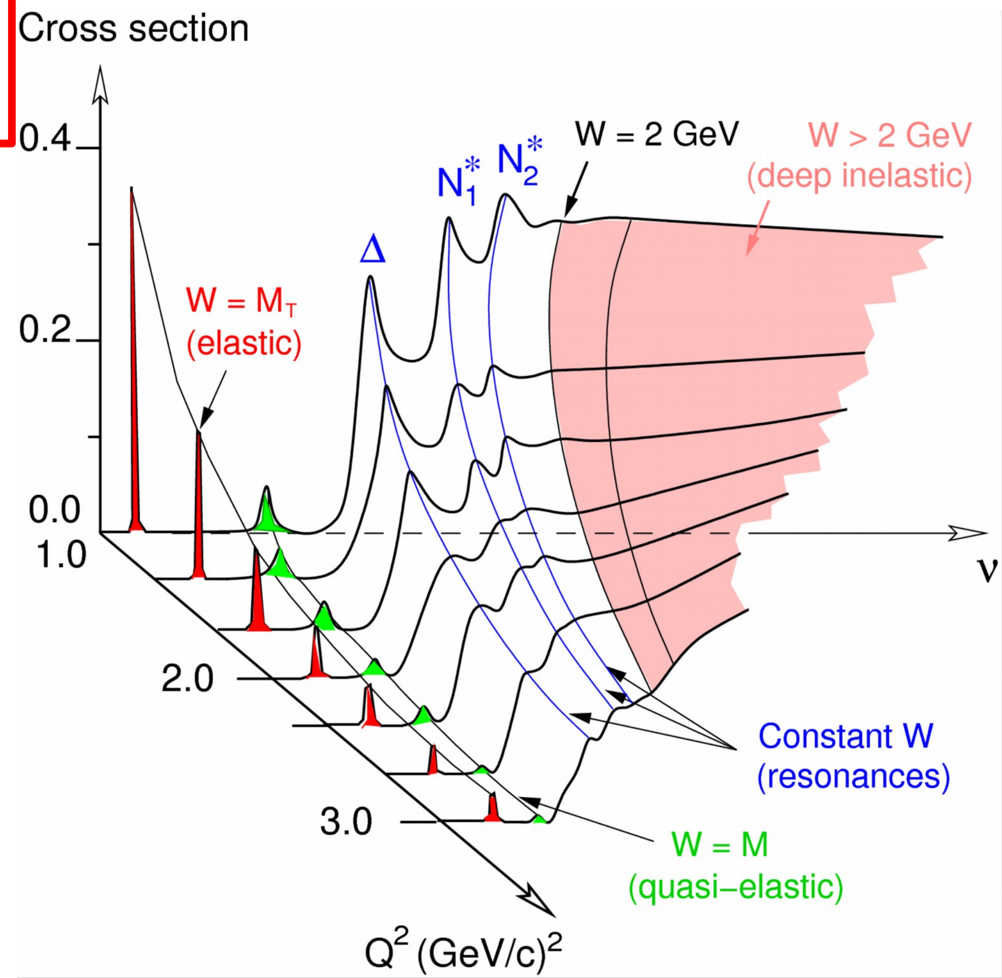
Jefferson Lab

UNIVERSITY OF VIRGINIA 1819

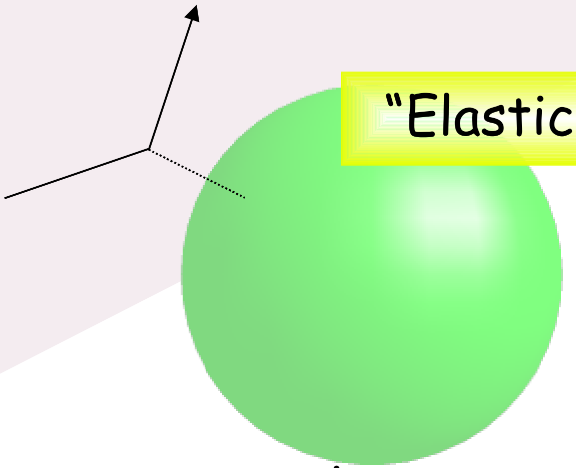
Electron Scattering on Fixed Nuclear Targets







Three Types of Kinematics

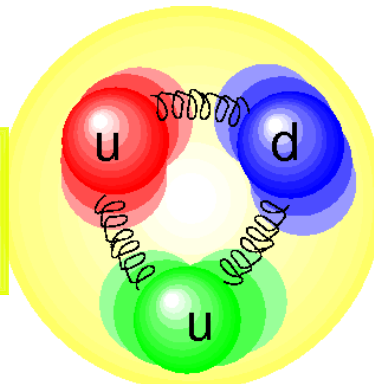


"Elastic": $W=M_t$ or M_p

1961

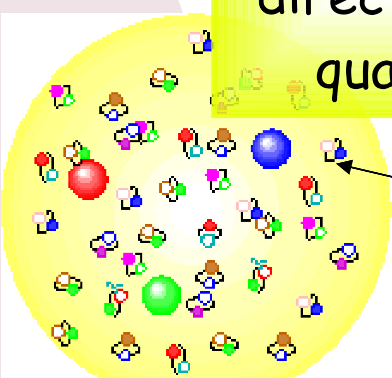
From cross section we extract "elastic form factors"

"Resonance": $1<W<2$GeV

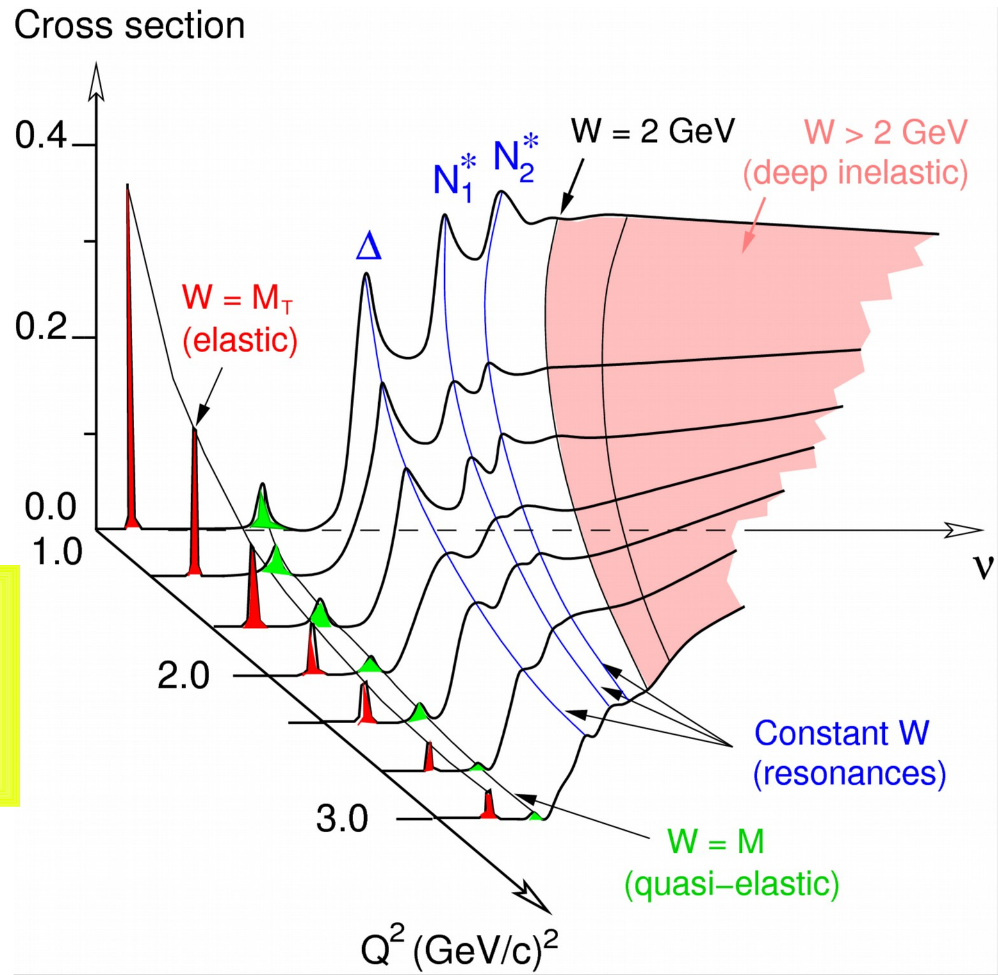


1999
2004

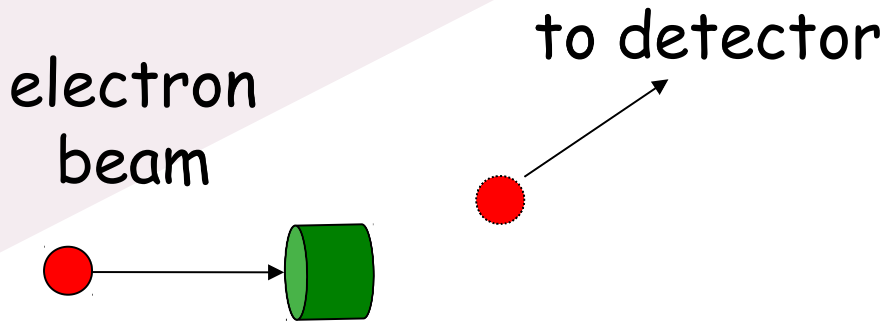
"Deep Inelastic": W>2 GeV, directly probes the quasi-free quarks inside the nucleon.

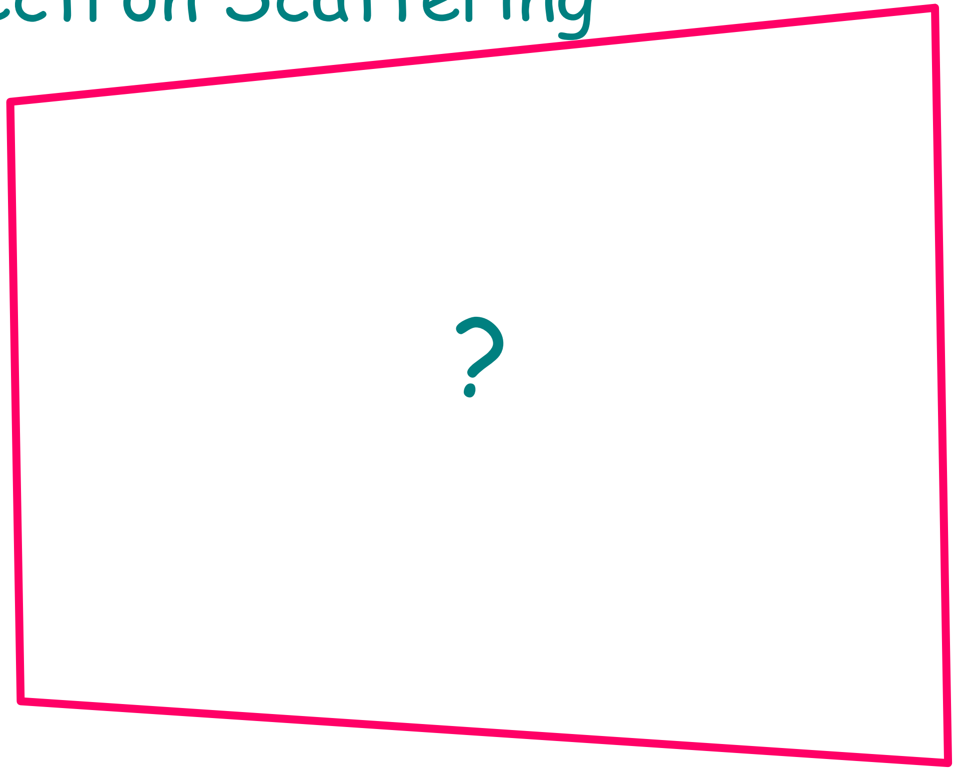


10^{-18}m or smaller



Parity Violation in Electron Scattering





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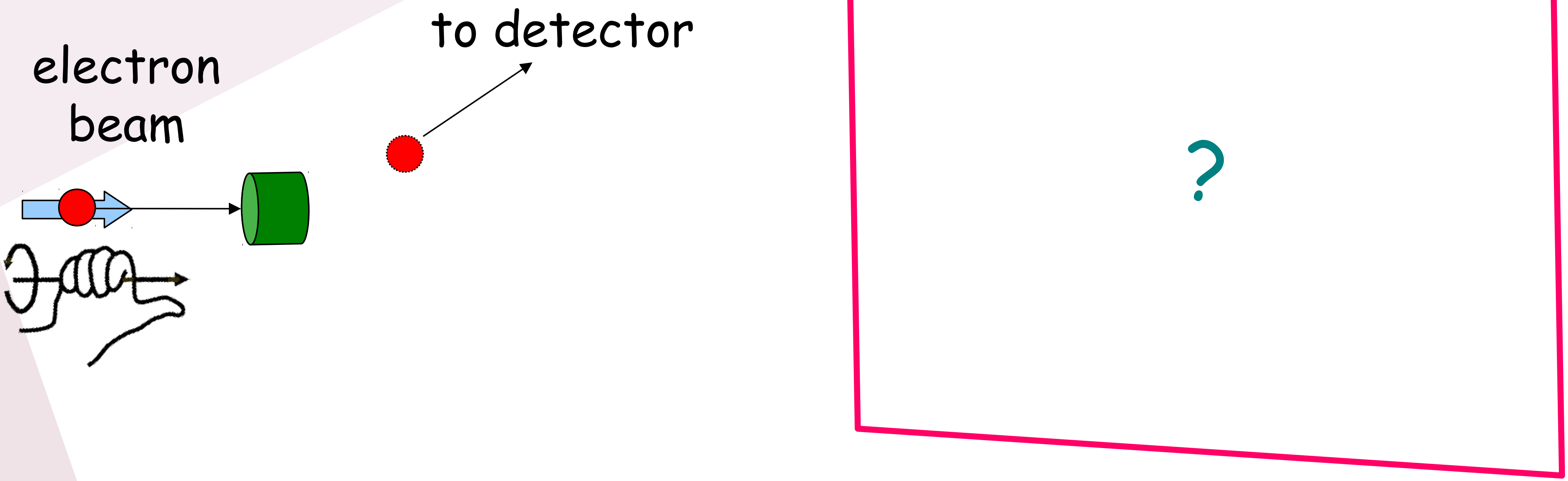
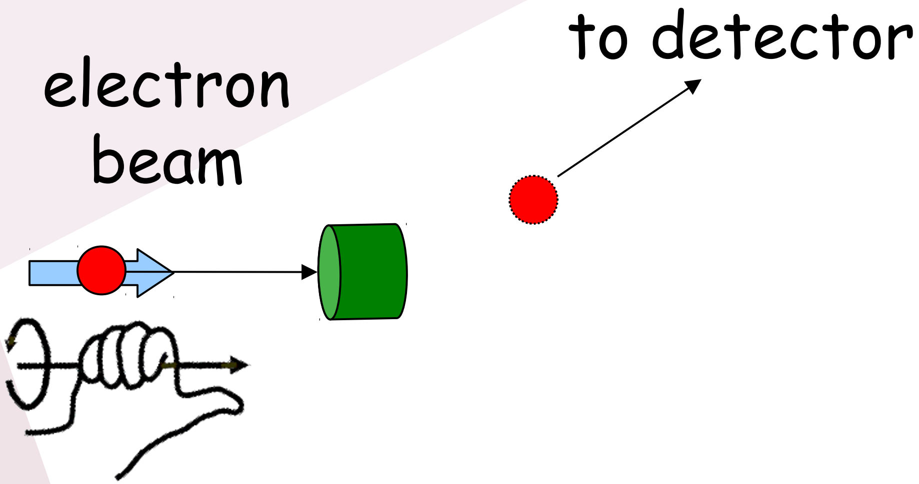
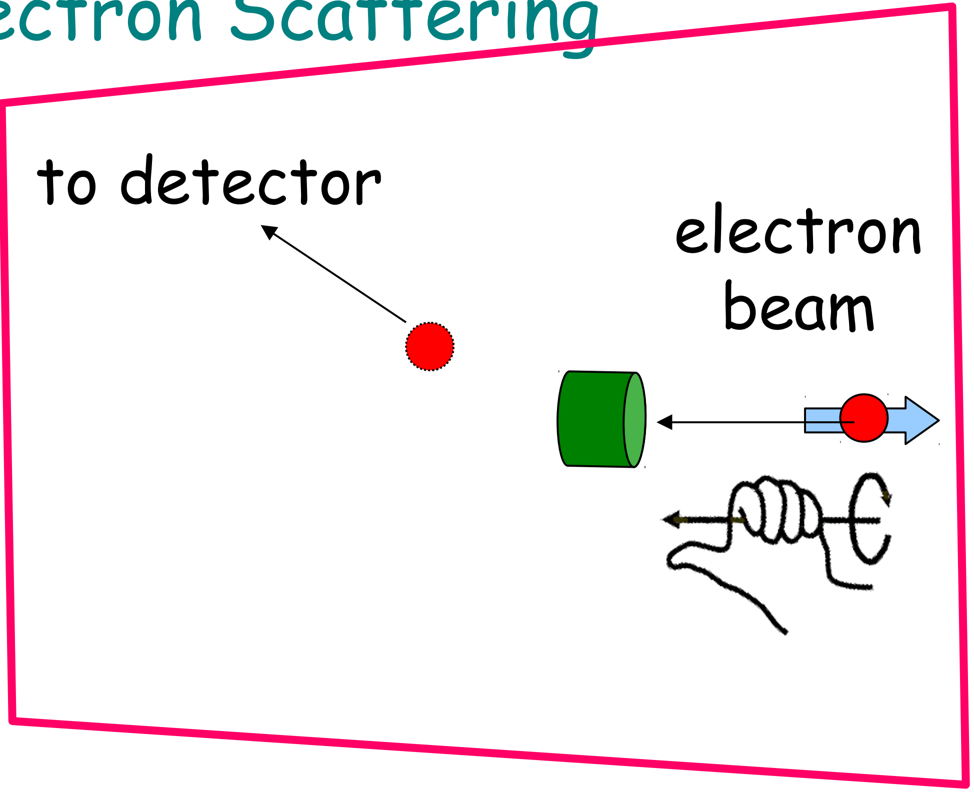
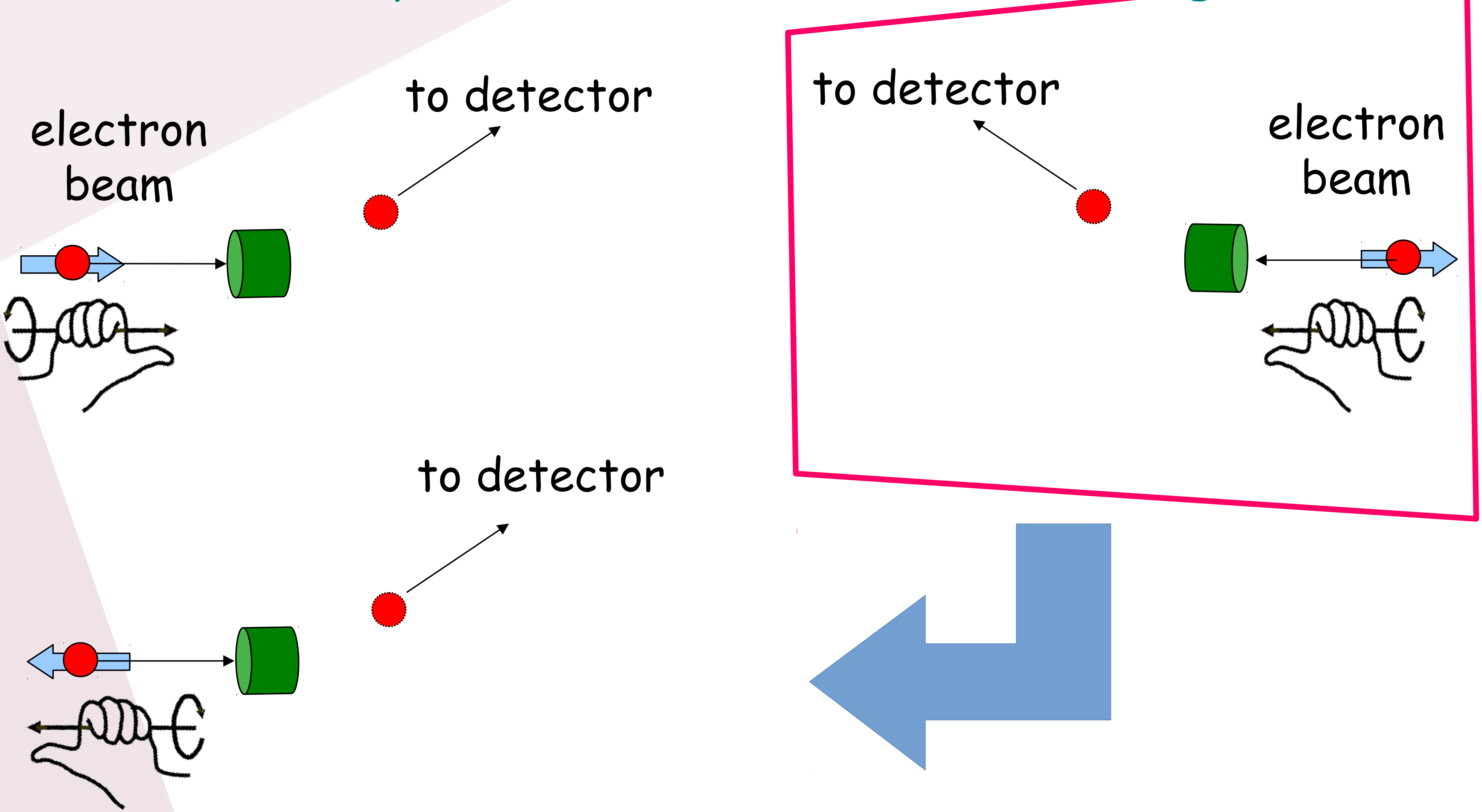


Parity Violation in Electron Scattering



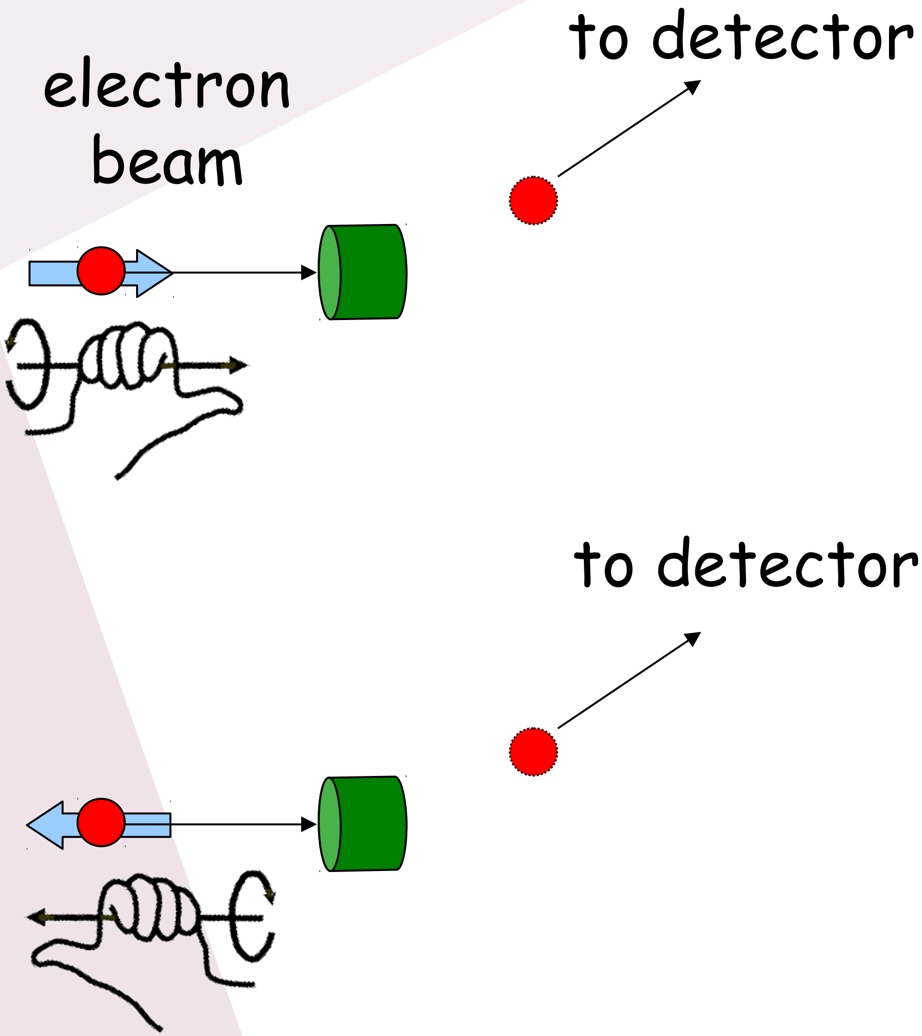


Parity Violation in Electron Scattering

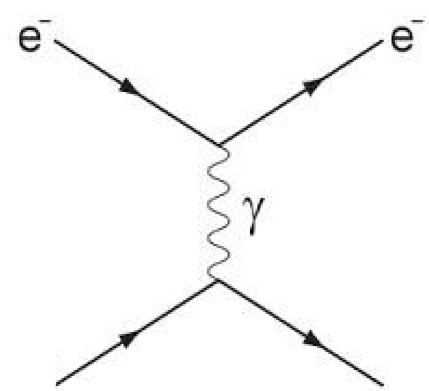


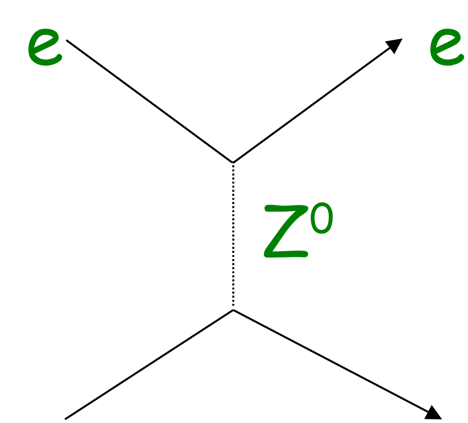
Parity, or mirror symmetry, is often referred to as left-right symmetry

Parity Violation in Electron Scattering



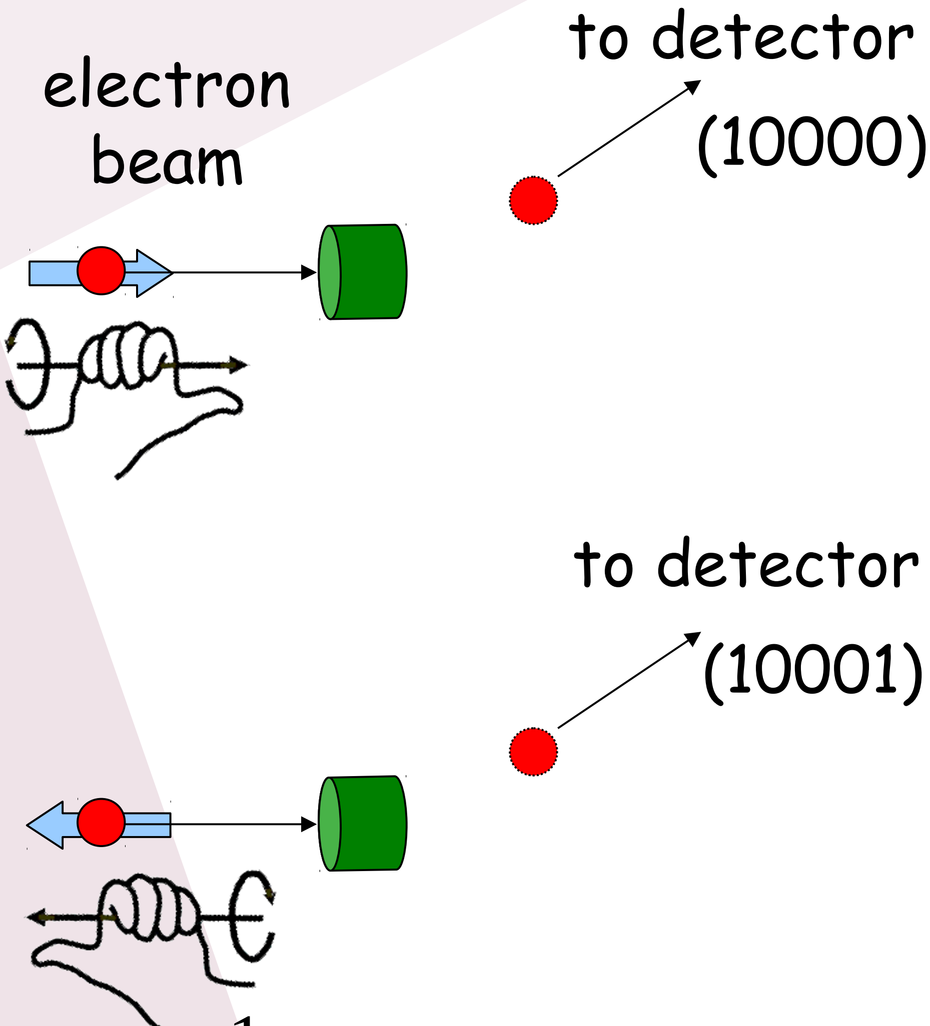
- We can access parity violation by the count difference between left- and right-handed beam electrons.
- In the electroweak Standard Model, this is given by



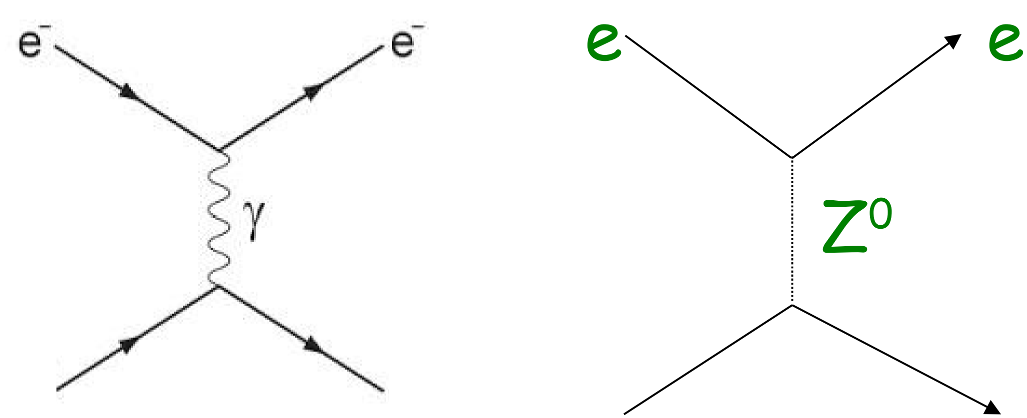


$$A_{PV} \approx \frac{Q^2}{Q^2 + M_Z^2} \approx 10^{-4} Q^2 \approx 100\, ppm \times Q^2$$

Parity Violation in Electron Scattering



- We can access parity violation by the count difference in the detected electrons between left- and right-handed beam electrons.
- In the electroweak Standard Model, this is given by



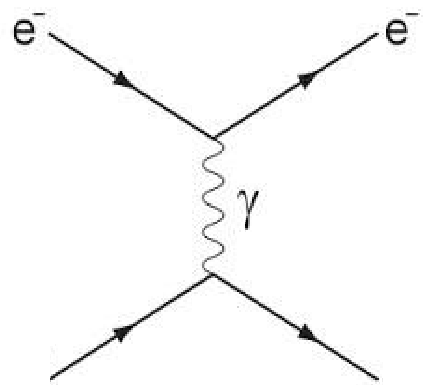
$$\Delta A = \frac{1}{\sqrt{N}} \rightarrow N = 100{,}000{,}000{,}000$$

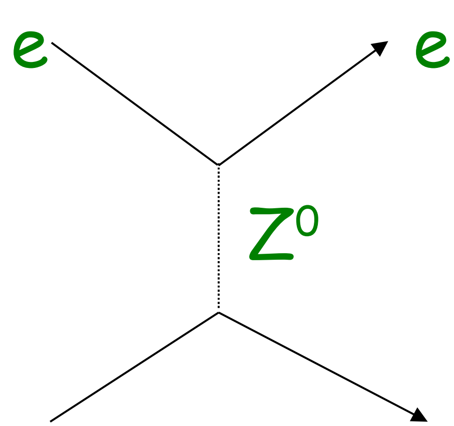
is needed to reach ΔA/A=3%
if A=100ppm

$$A_{PV} \approx \frac{Q^2}{Q^2 + M_Z^2} \approx 10^{-4} Q^2 \approx 100\, ppm \times Q^2$$

Physics Accessed in PVES

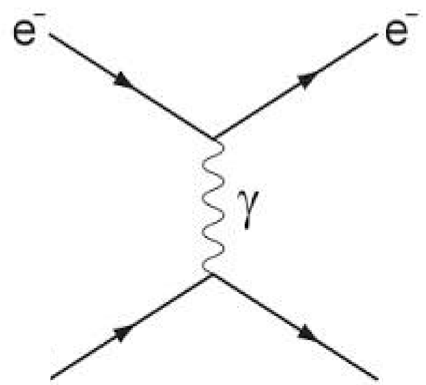
- The first PVES (SLAC E122, 1978) measured $\sin^2\theta_W$ for the first time, established parity violation in neutral weak current and the Weinberg-Salam-Glashow model.

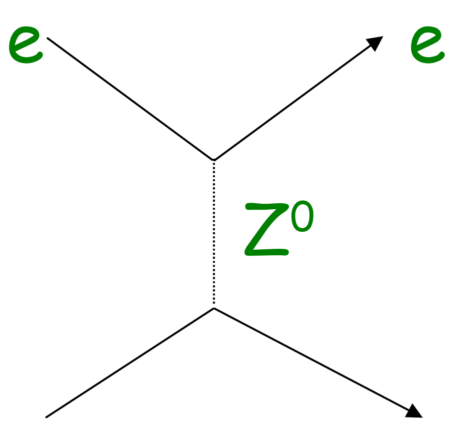




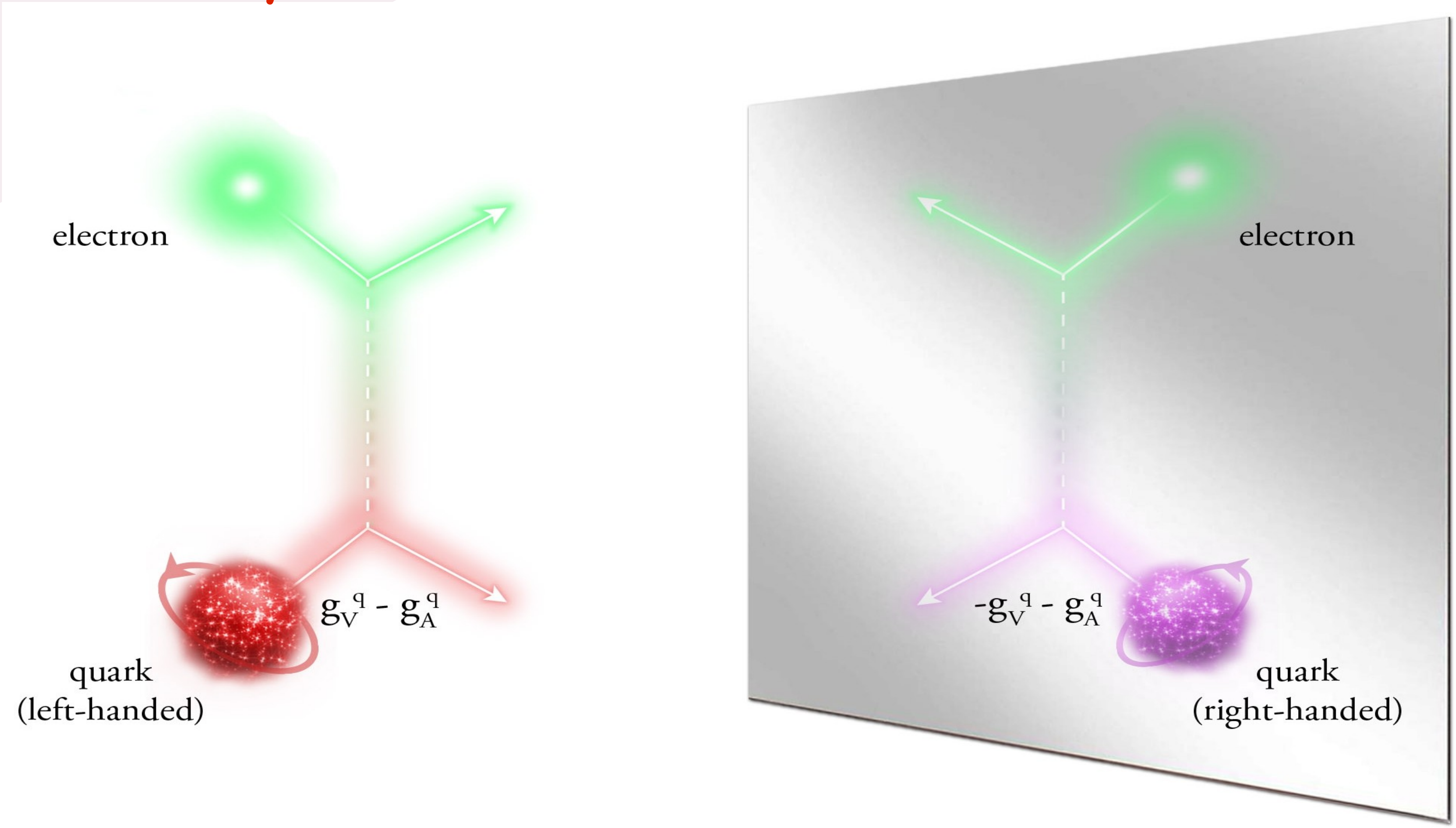
Physics Accessed in PVES

- The first PVES (SLAC E122, 1978) measured $\sin^2\theta_W$ for the first time, established parity violation in neutral weak current and the Weinbery-Salam-Glashow model.
- To study nucleon structure not accessible in electromagnetic interaction:
  - elastic PVES: nucleon strange form factors (MIT Bates, Mainz, JLab); "neutron skin" in heavy nucleus (JLab)
- To test the electroweak Standard Model (effective couplings):
  - e-e (E158/SLAC, future Moller)
  - elastic PVES near Q^2=0 (Qweak)
  - PVDIS (6 GeV, future 12 GeV)

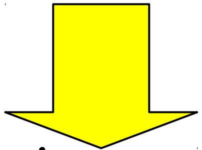




Parity Violation in the Standard Model



- In weak interaction, all elementary fermions behave differently under parity (mirror) transformation



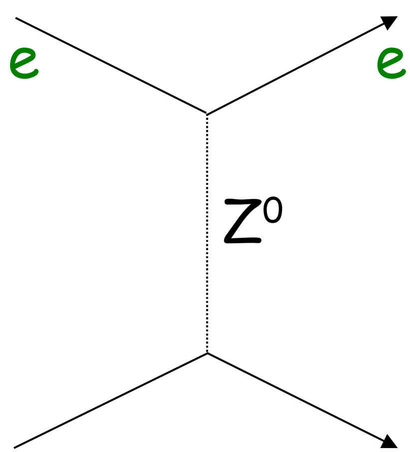
- They couple more to the Z^0 when in a specific (left or right) chirality state.

Effective Couplings $C_{1,2}$ in the Standard Model

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

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

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



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	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$

Effective Couplings $C_{1,2}$ in the Standard Model

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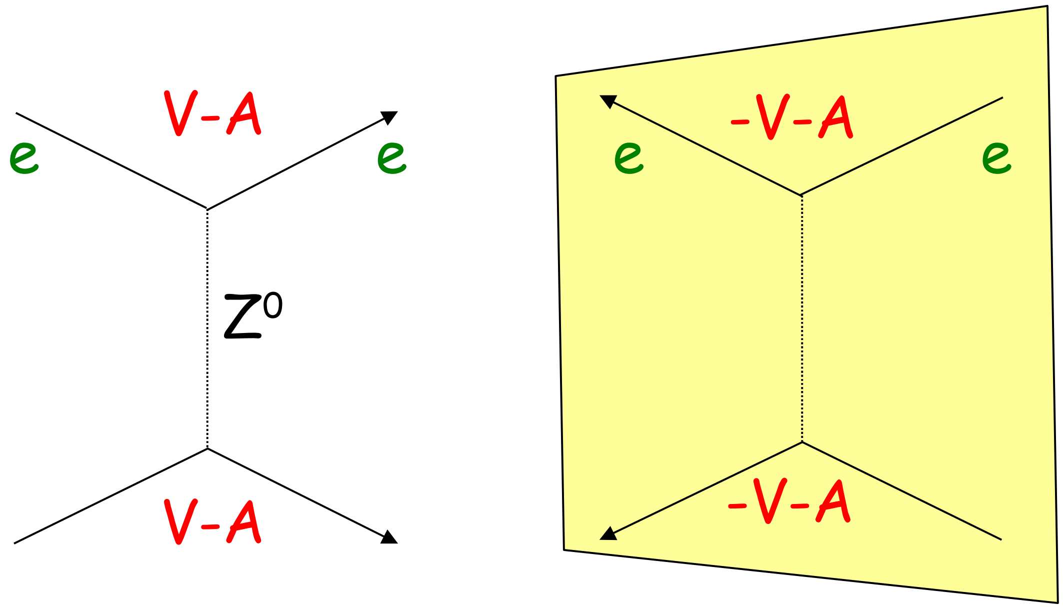
  or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$
- PVES asymmetry comes from V(e)xA(targ) and A(e)xV(targ)



Effective Couplings $C_{1,2}$ in the Standard Model

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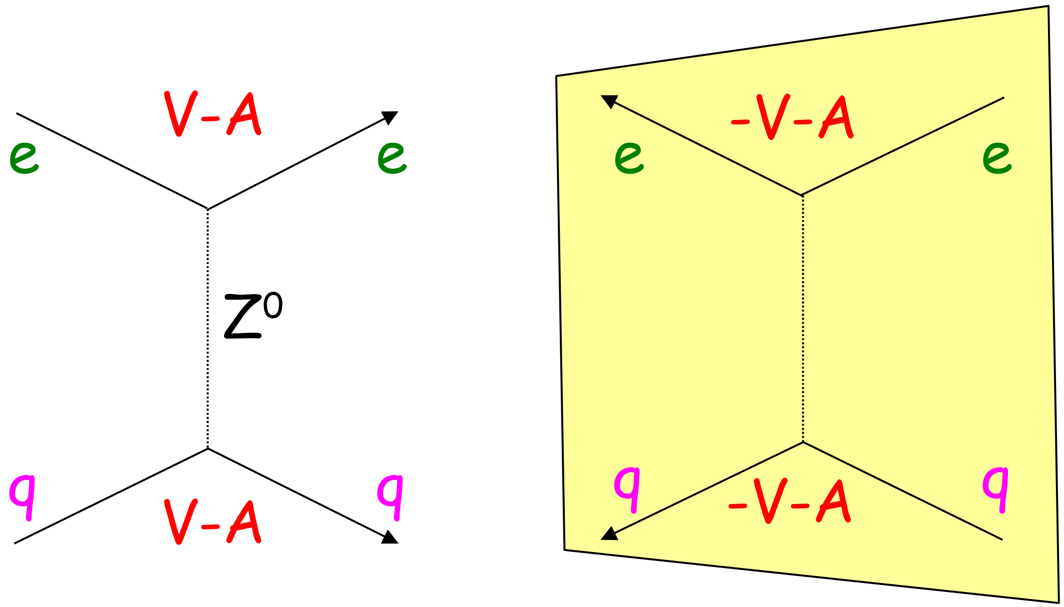
- PVES asymmetry comes from:

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



"electron-quark effective couplings"

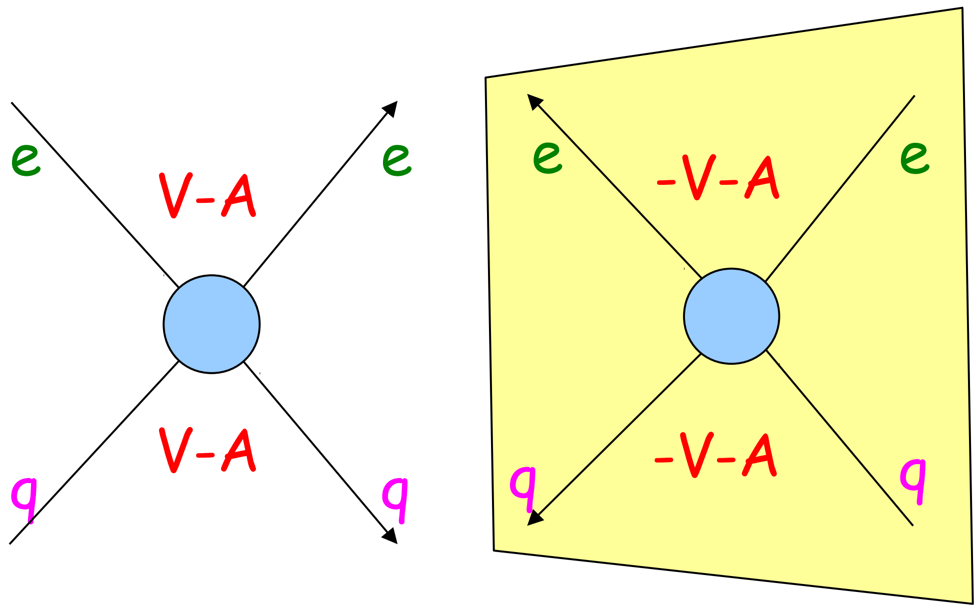
Effective Couplings and New Contact Interactions

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

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

- PVES asymmetry comes from:

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

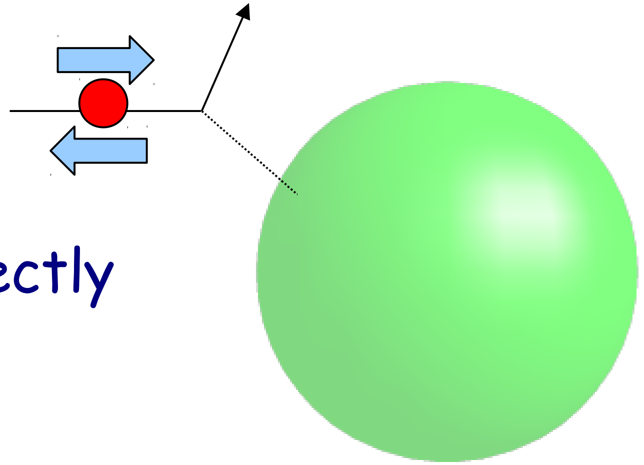


"electron-quark effective couplings"

"new contact interactions"

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

Accessing C_{1q} in Elastic PVES



- Elastic PVES:
  - Hadronic effects suppressed at $Q^2=0$, directly probes C_{1q} as the proton weak charge

$$A_{PV}^{elastic} \propto -Q^2\left[Q_W^p + F\left(\theta, Q^2\right)\right]$$

$$Q_W^p = -2\left(2C_{1u} + C_{1d}\right)$$

$$\text{or} = -2\left(2g_{AV}^{eu} + g_{AV}^{ed}\right) = 1 - 4\sin^2\theta_W$$

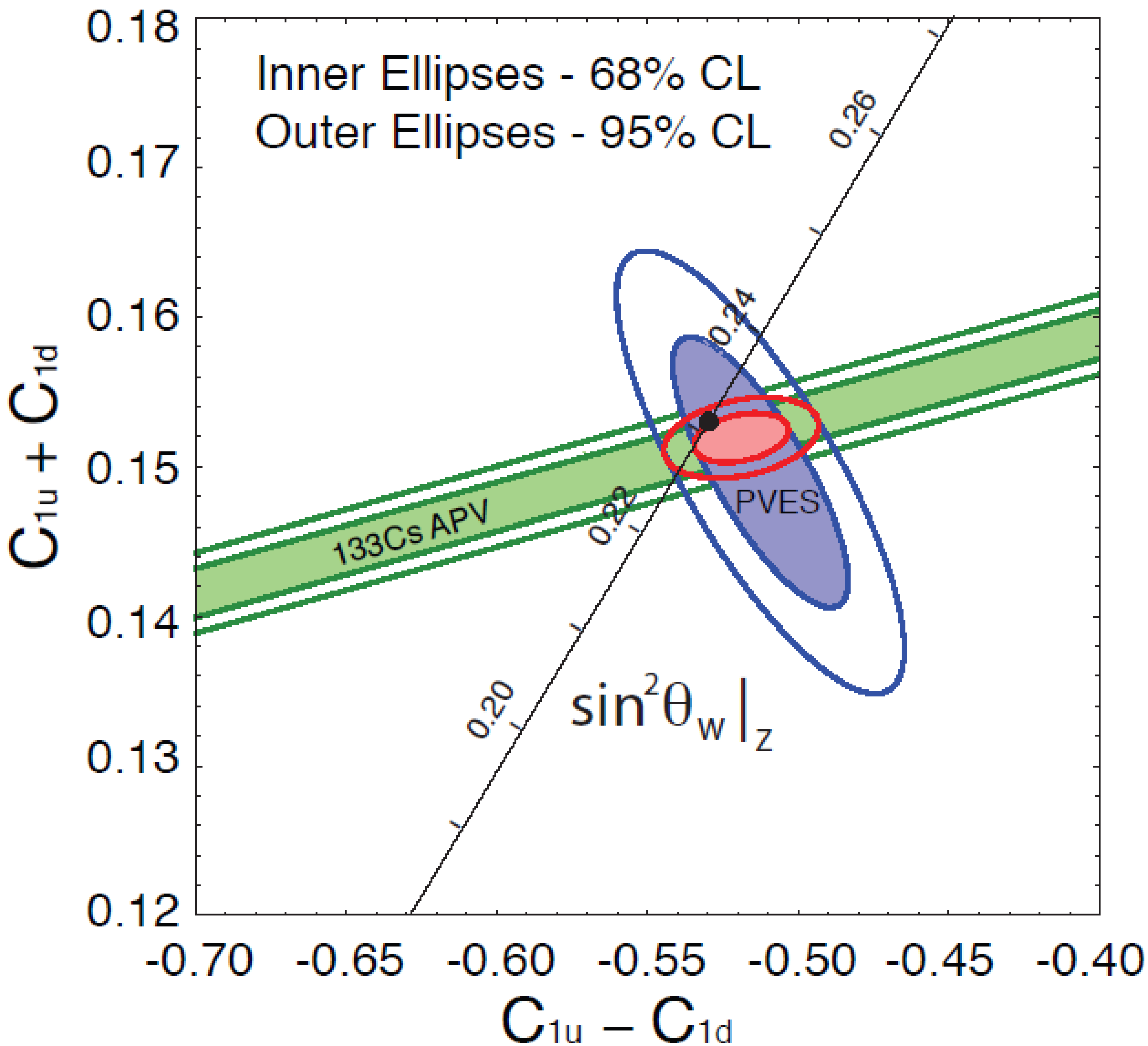
Electron axial weak charge (L-R)

* by

$$G_E^p\left(Q^2=0\right) = 1 = 2\left(Q_u\right) + 1\left(Q_d\right)$$

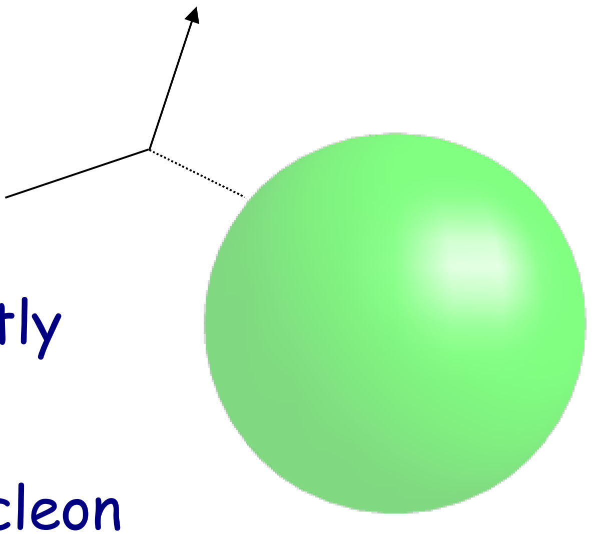
Quark vector weak charge (L+R)

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



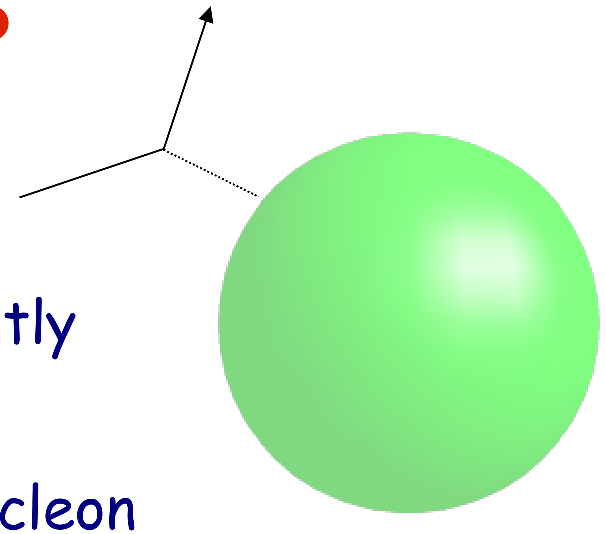
Androic et al., PRL 111, 141803 (2013);

Accessing C_{2q} in PVES



- Elastic PVES:
  - Hadronic effects suppressed at Q^2=0, directly probes C_{1q}, as the proton weak charge;
  - Hadronic parity violation shows up as the nucleon axial form factor G_A, and extracting C_{2q} from G_A is model dependent (almost like extracting the nucleon magnetic moment from Gm)

Accessing C_{2q} in PVES



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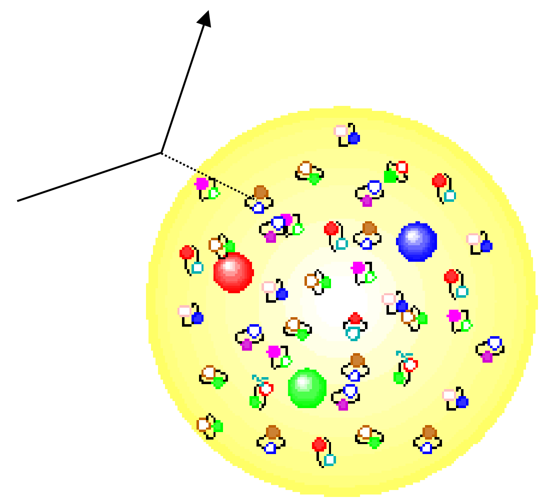

- **PV in Deep Inelastic Scattering (PVDIS):**
  - measure both C_{1q} and C_{2q} explicitly.

Formalism for Parity Violation in DIS

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

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

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

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

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

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

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

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

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

Formalism for Parity Violation in DIS

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

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

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

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

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

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

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

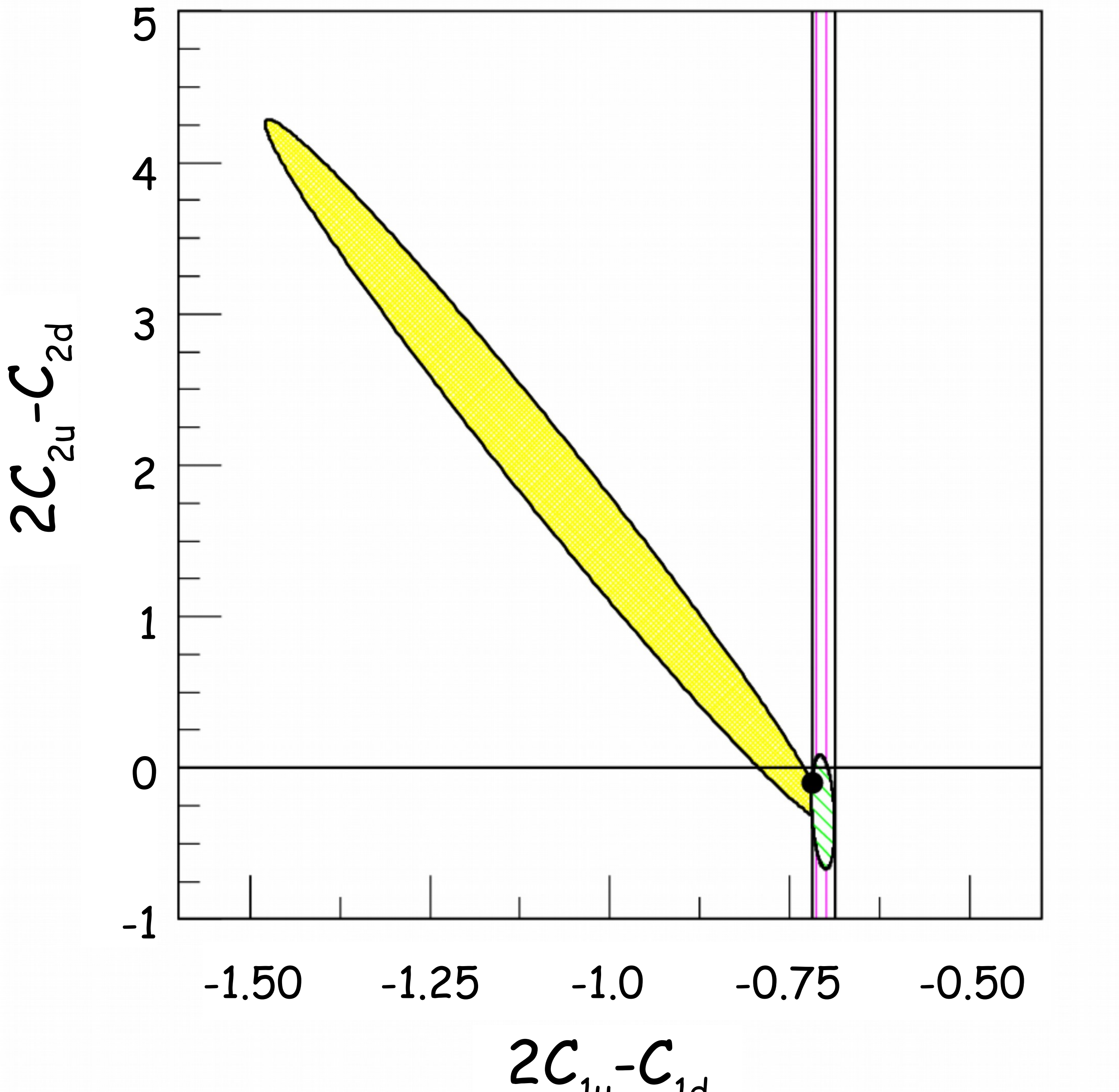
0

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

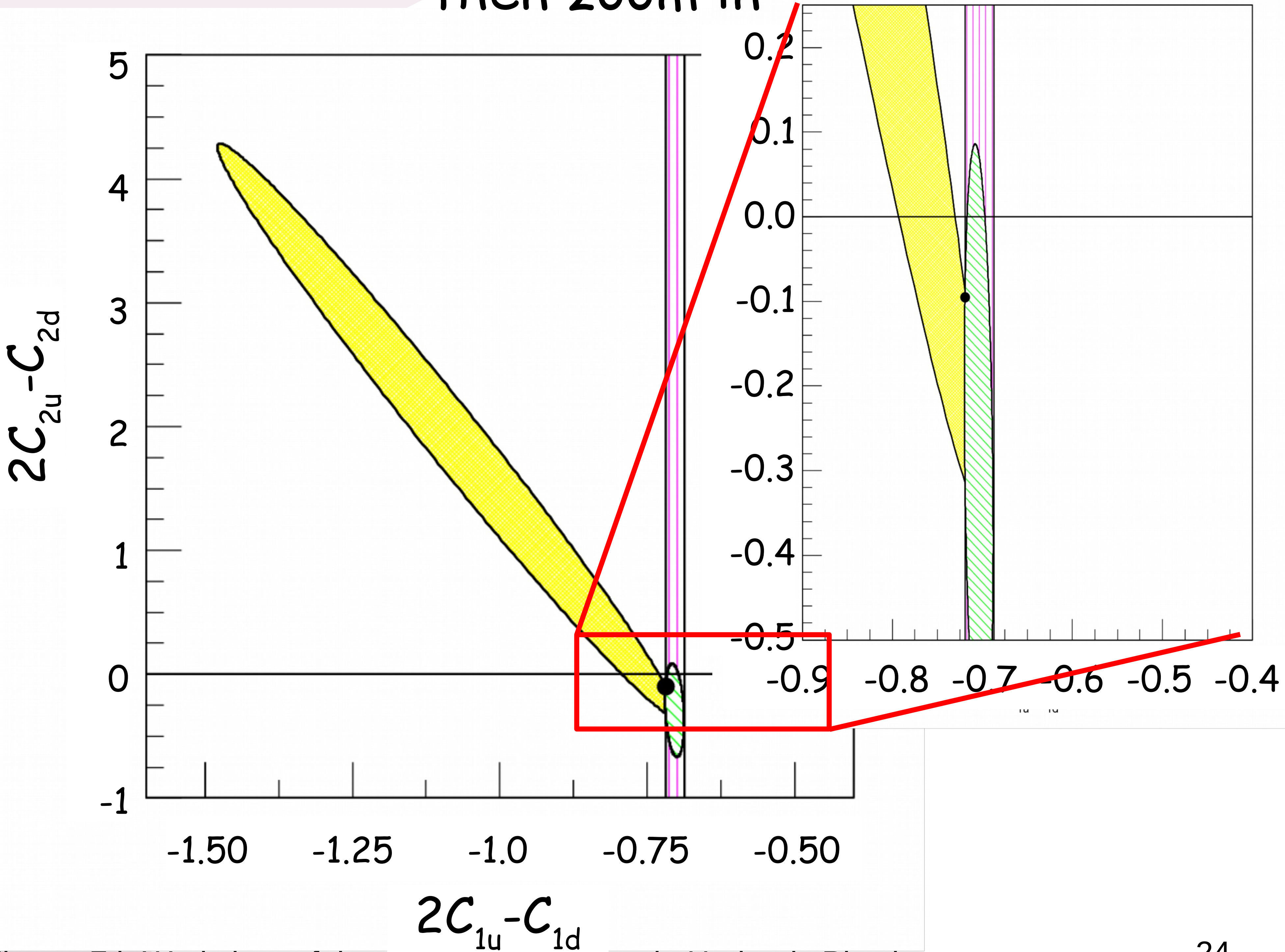
1

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

C_{2q} from Elastic PVES and E122



then 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

It is difficult to determine C2q's

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

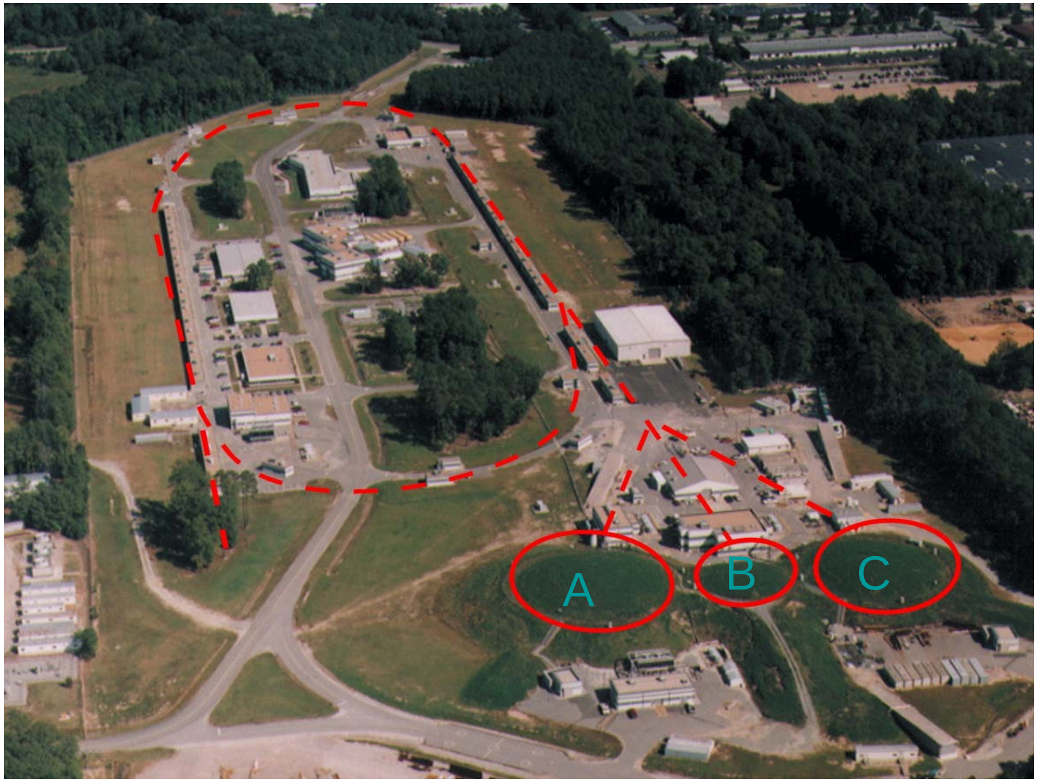
$$a(x) = \frac{3}{10}\left(2C_{1u} - C_{1d}\right)\left(1 + \frac{0.6\,s^{+\cdot}}{u^{+\cdot} + d^{+\cdot}}\right)$$

$$-\frac{3}{2} + \frac{10}{3}\sin^2\theta_W$$

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

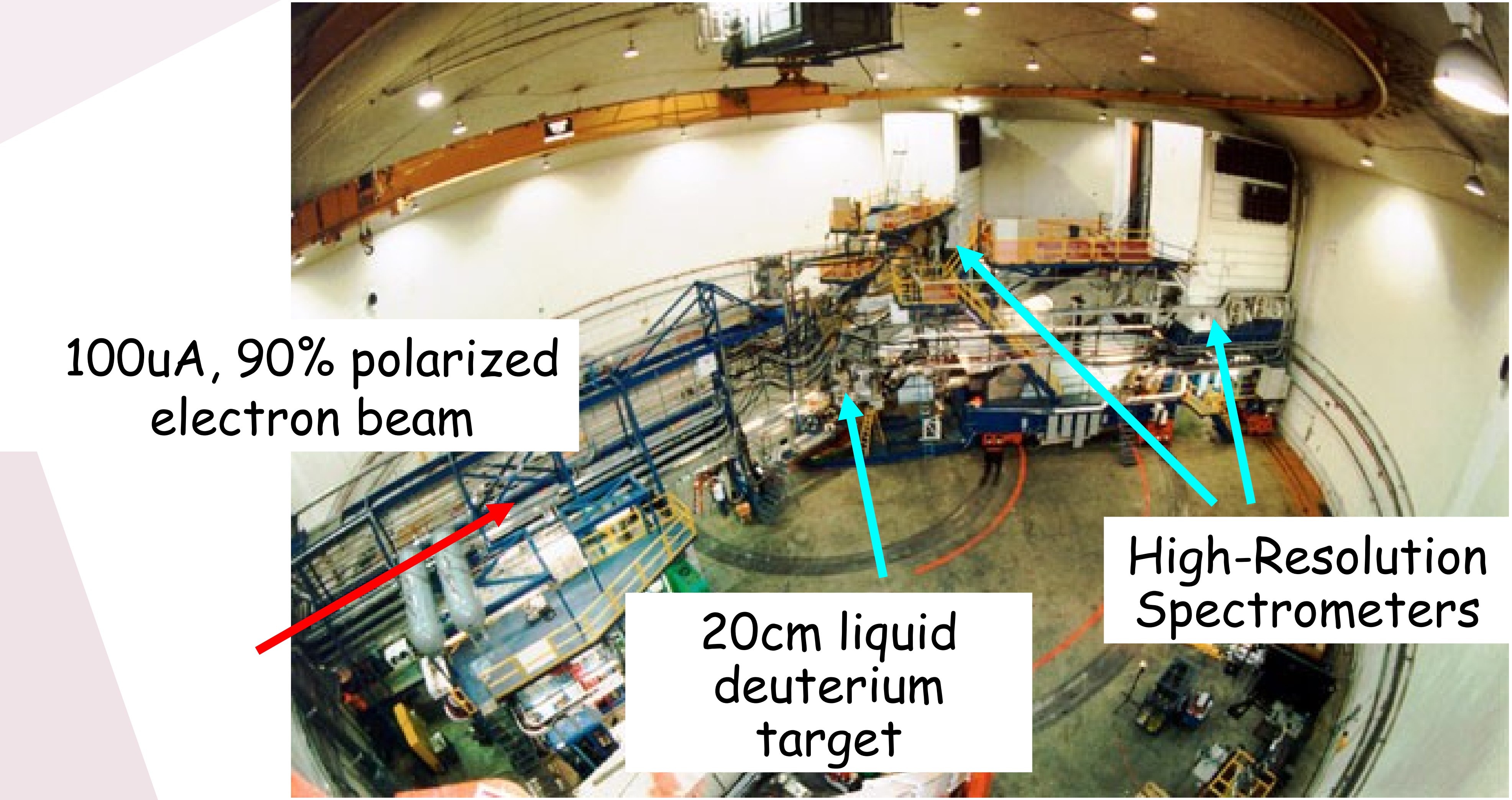
$$-\frac{3}{2}\left(1 - 4\sin^2\theta_W\right)$$

PVDIS at 6 GeV (JLab E08-011)



PVDIS at 6 GeV (JLab Hall A)

- Measured two DIS points: Q^2=1.085 and 1.901 $(GeV/c)^2$



- Ran from Oct-Dec 2009
- Dedicated DAQ system counted 170 billion (E9) electrons in total

PVDIS at 6 GeV (JLab Hall A)

- Results:

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

compare to

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

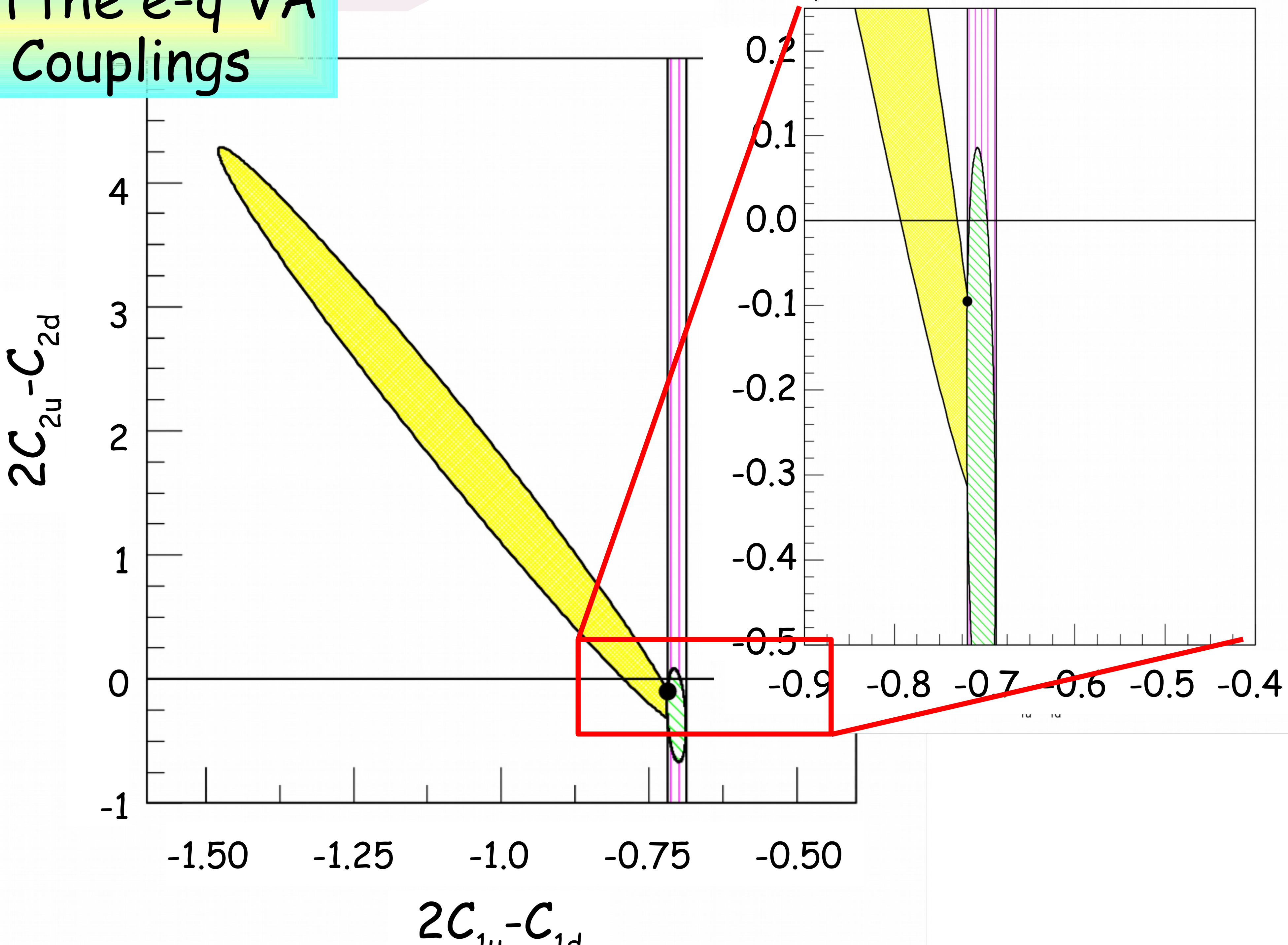
$$A^{phys}_{Q^2=1.901,\, x=0.295} = -160.80 \pm 6.39 \pm 3.12\ ppm$$

compare to

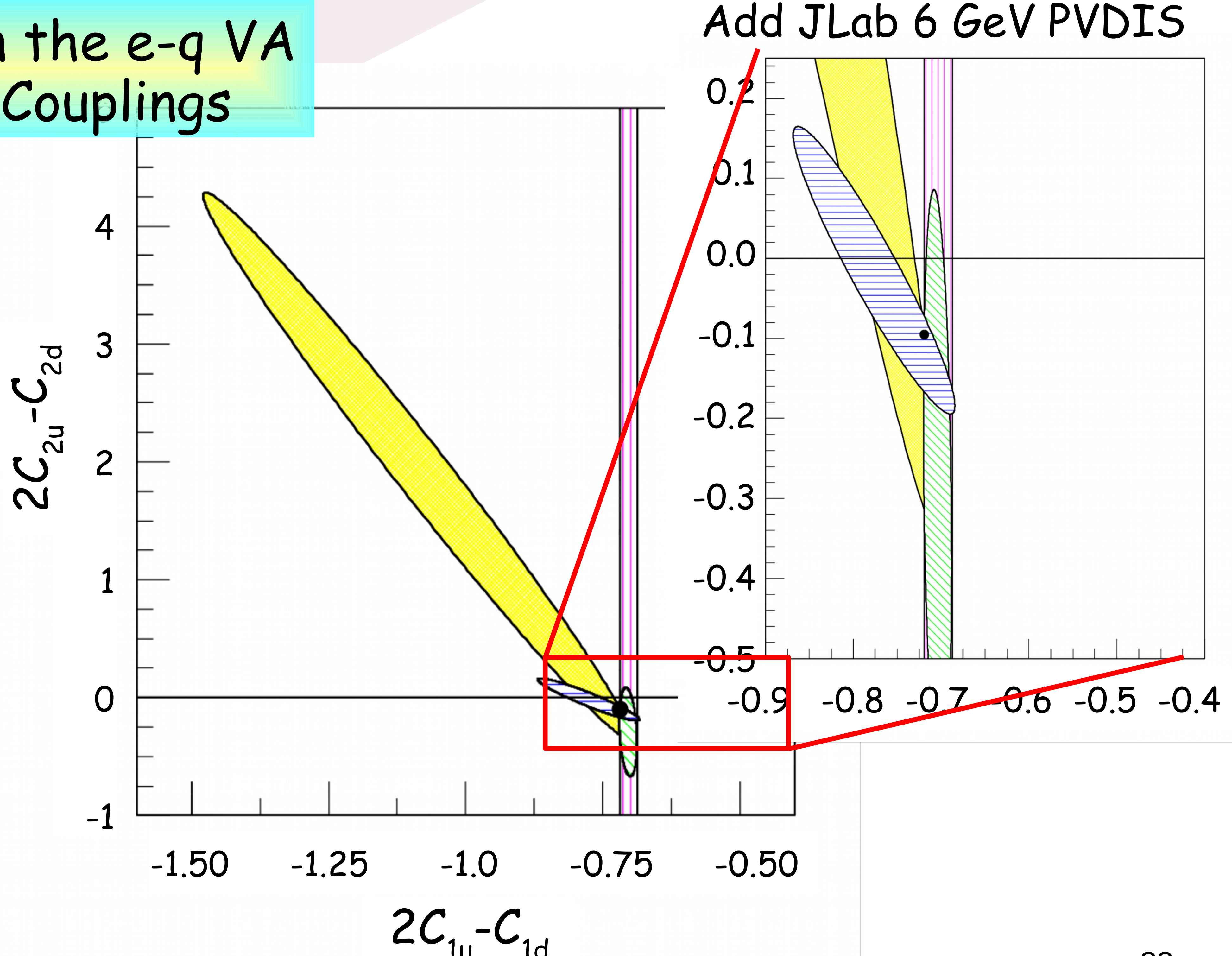
$$A^{SM} = (2.022\times 10^{-4})\left[\left(2C_{1u}-C_{1d}\right)+0.594\left(2C_{2u}-C_{2d}\right)\right]$$

On the e-q VA Couplings

Previous data: E122, Elastic PVES + APV



On the e-q VA Couplings



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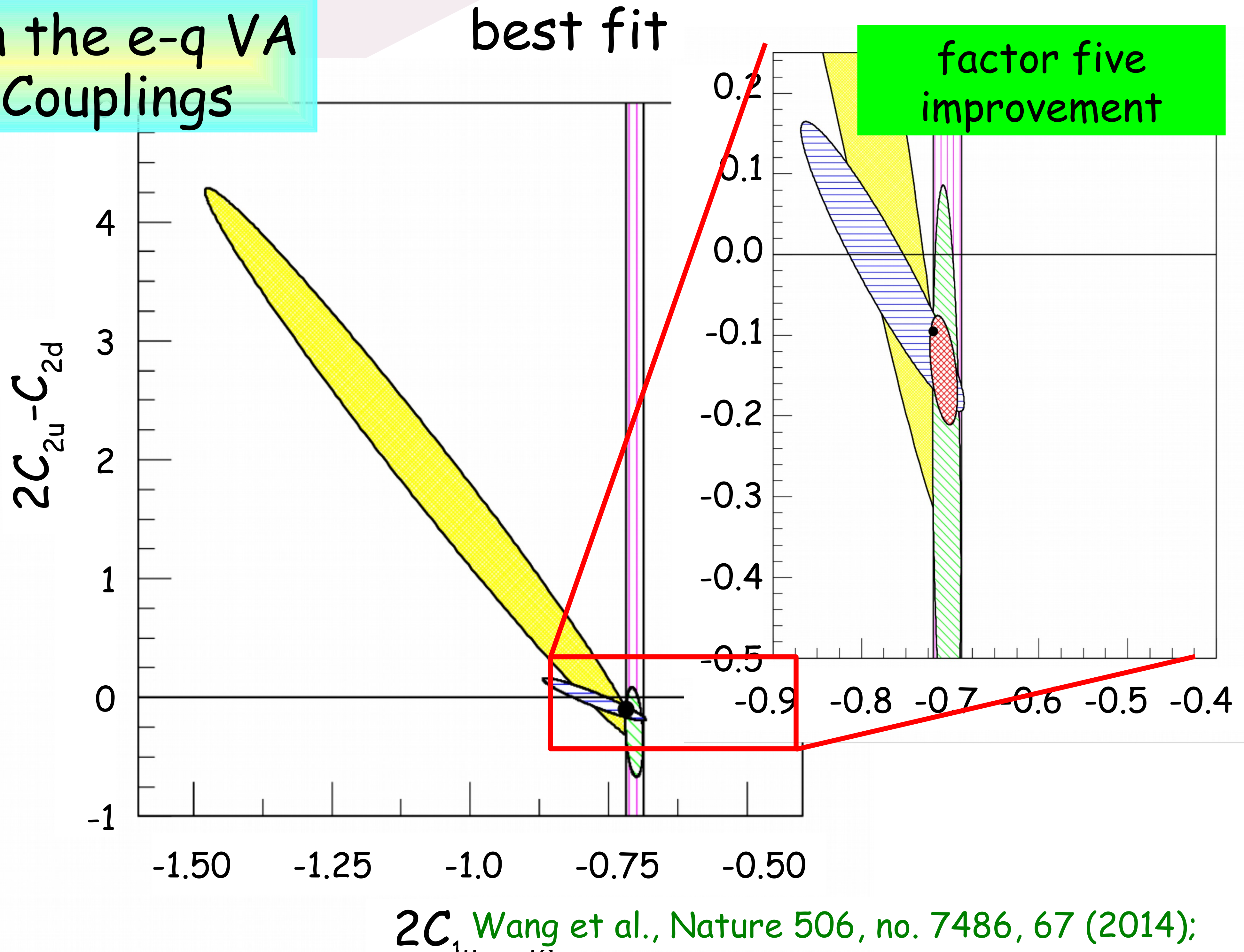


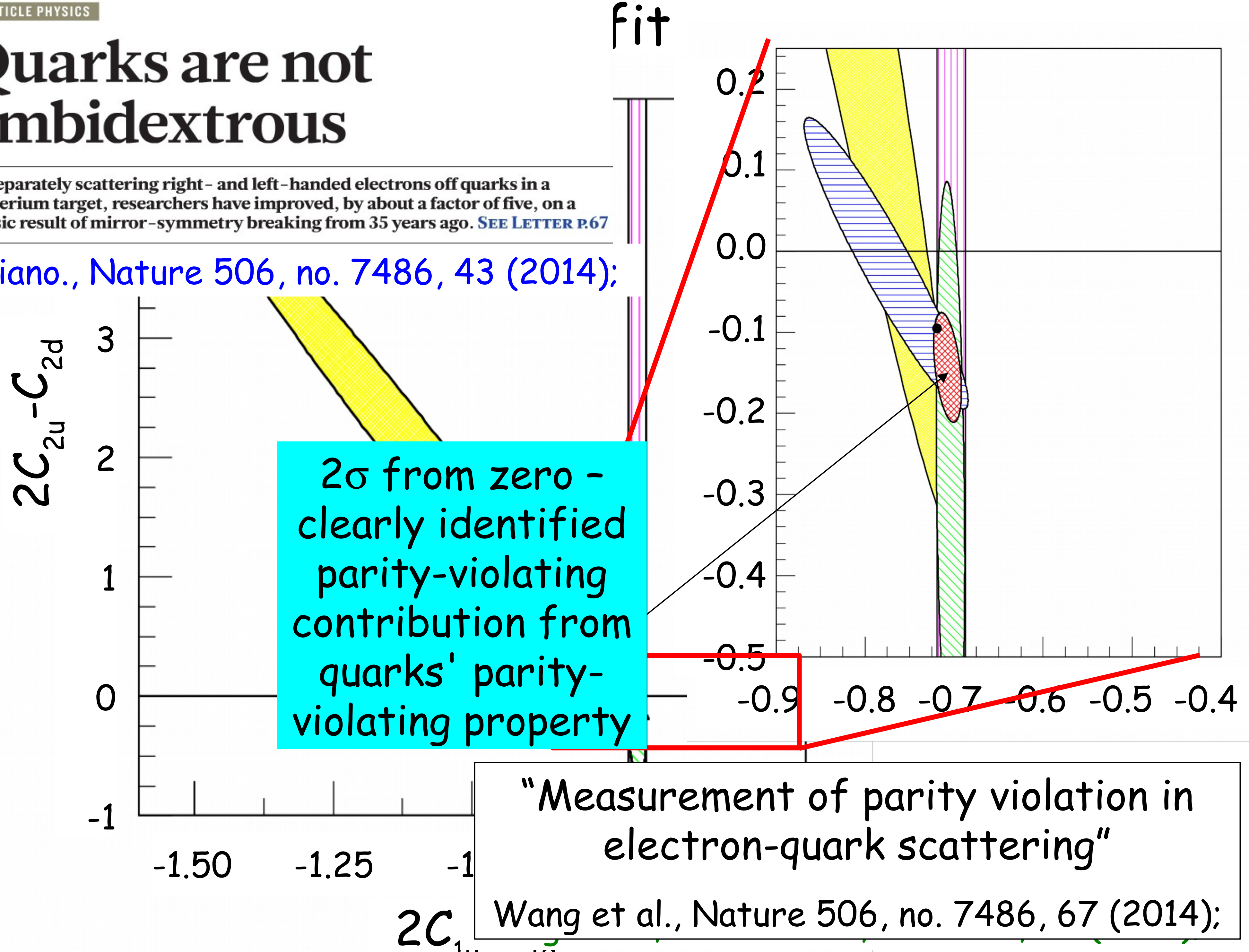
Wang et al., Nature 506, no. 7486, 67 (2014);

PARTICLE PHYSICS

Quarks are not ambidextrous

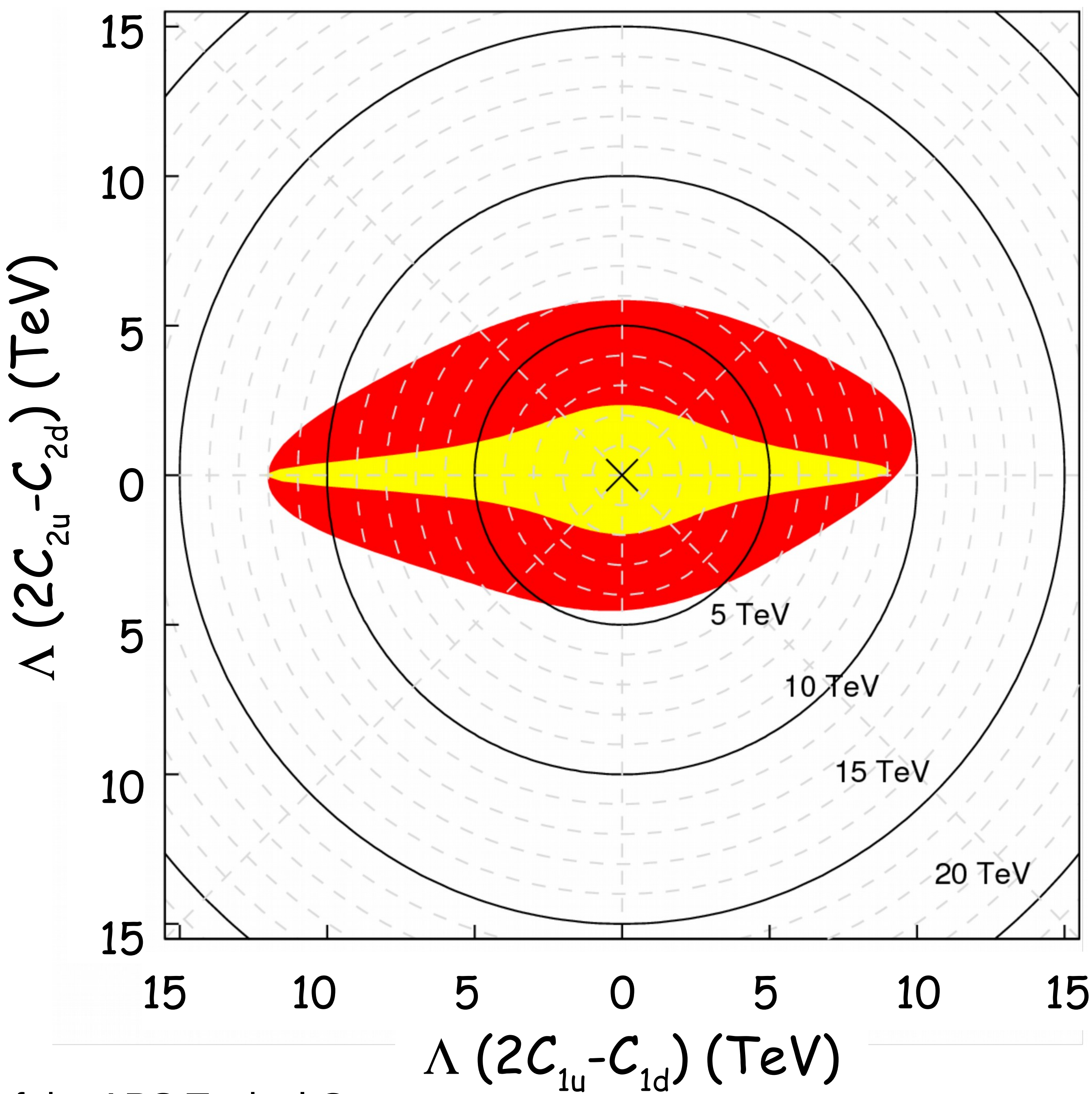
By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. SEE LETTER P.67

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



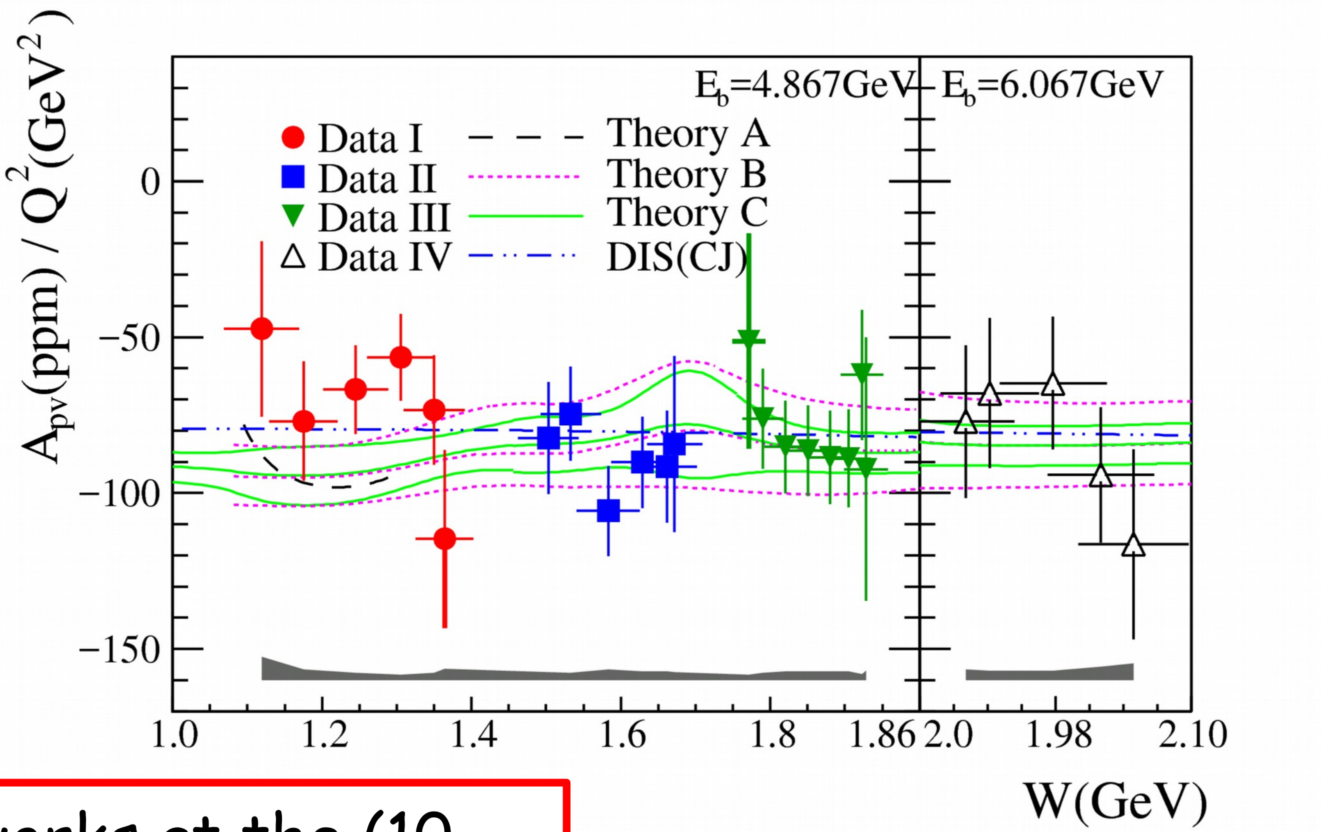
BSM Mass Limit on eq VA contact interaction

Complementary to LHC results on the mass limit of electron-quark contact interactions



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)

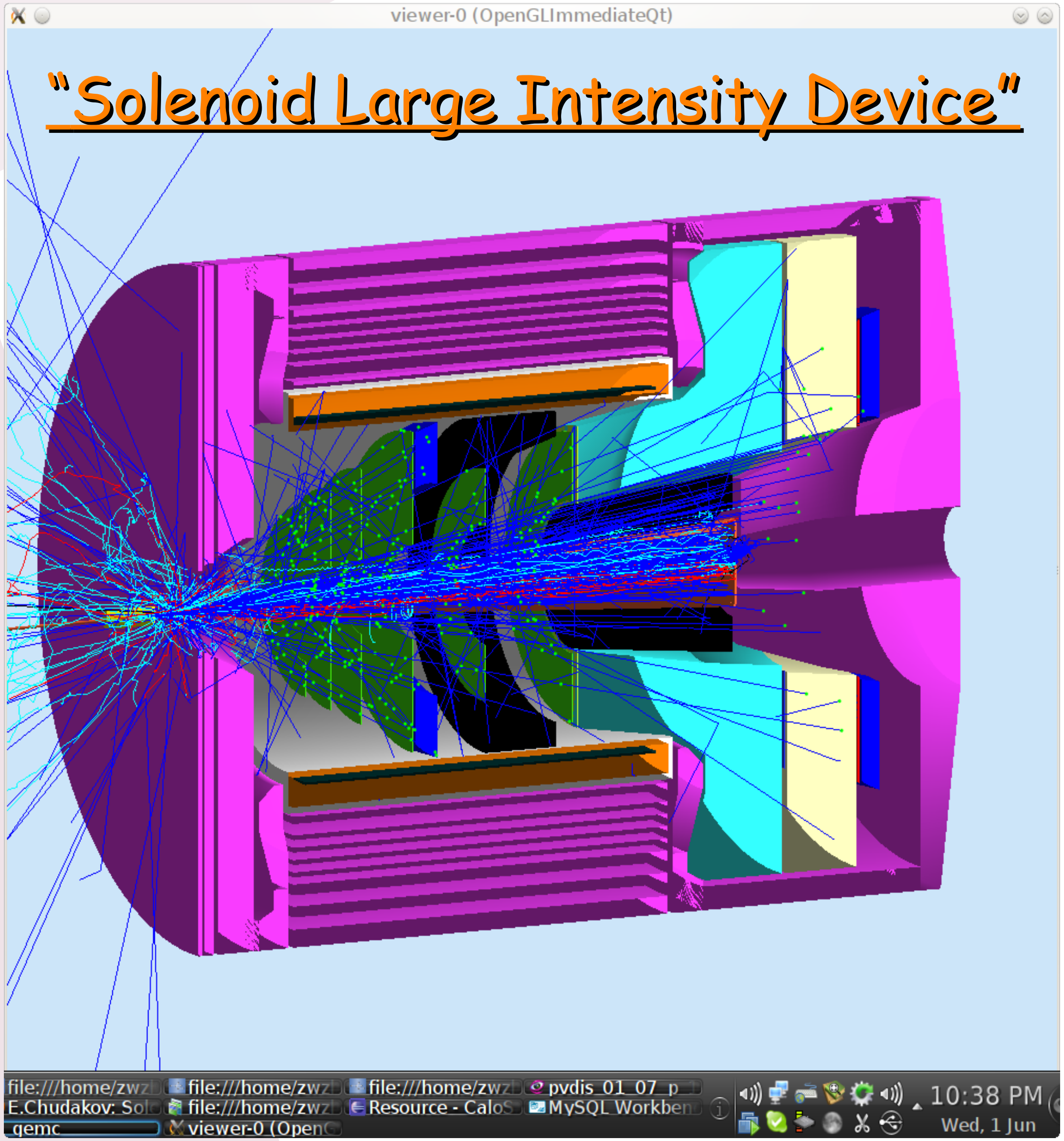


- "duality works at the (10-15)% level"
- helps to constraint γ-Z box diagram correction for PVES experiments

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

Will a better measurement of res-parity help to constrain γ-Z models?

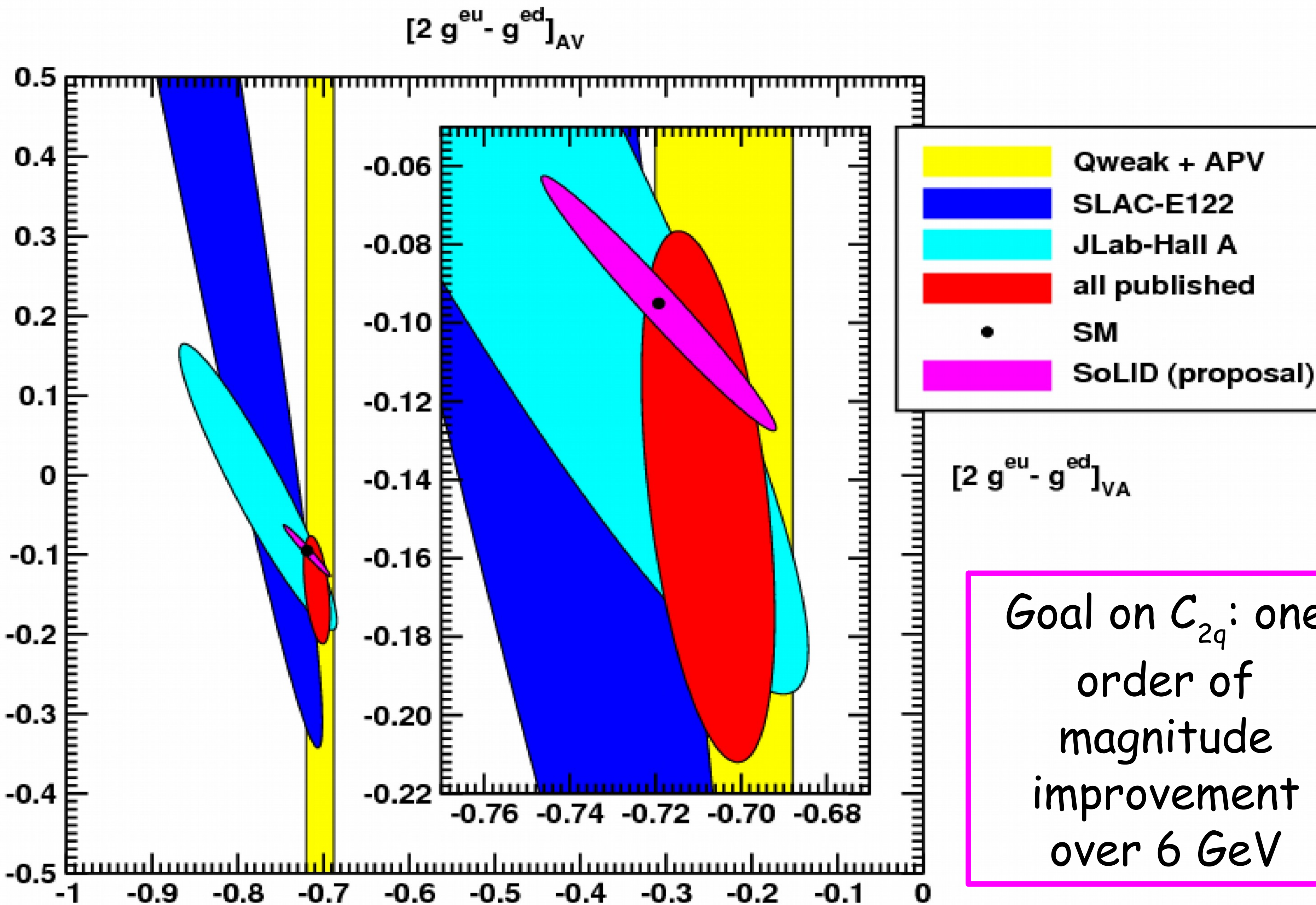
Coherent PVDIS Program with SoLID @ 12 GeV



Planned for Hall A, SoLID Physics topics include:

- PVDIS
- SIDIS
- J/ψ

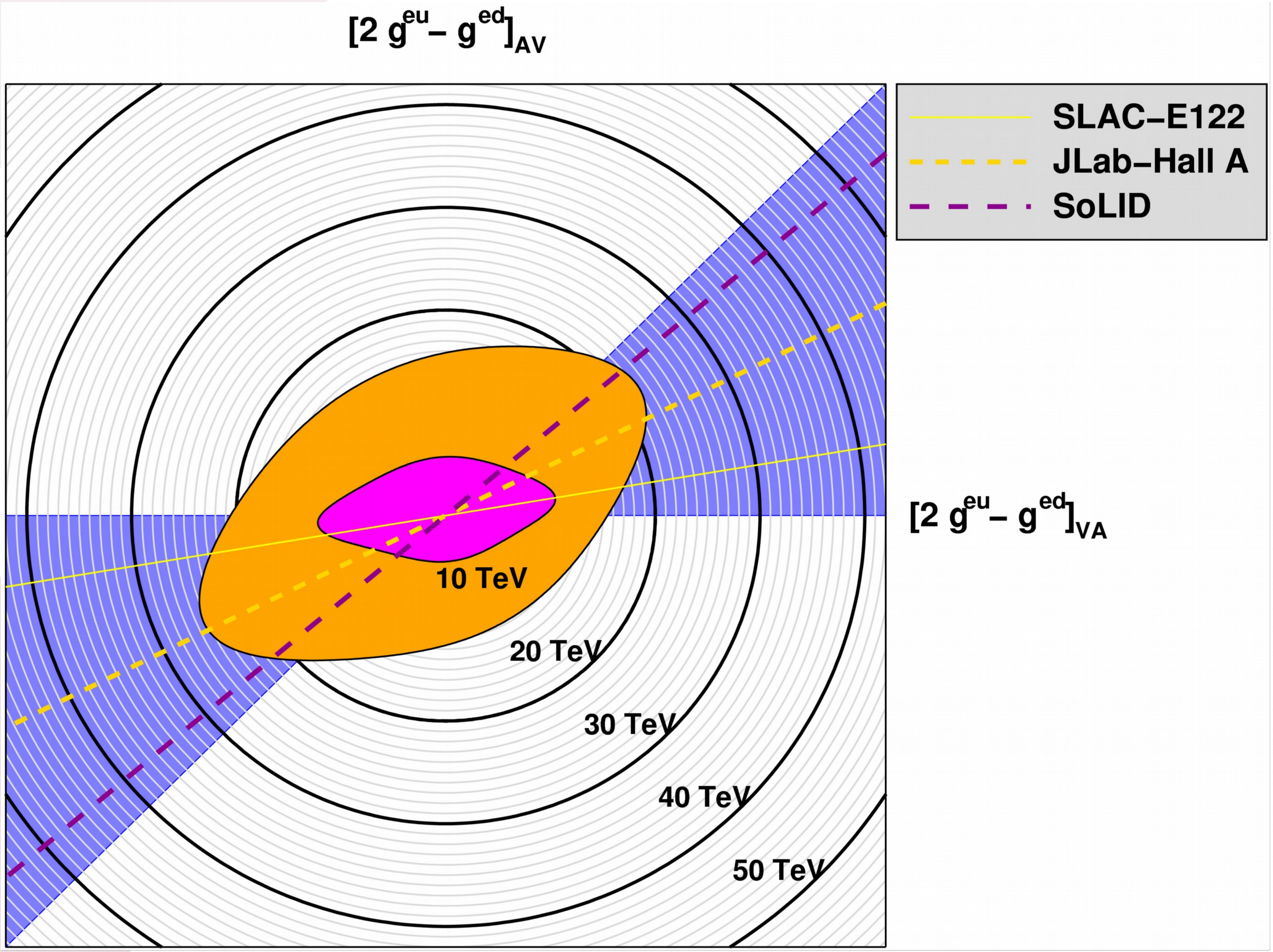
Coherent PVDIS Program with SoLID @ JLab 12 GeV



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

X.

Coherent PVDIS Program with SoLID @ 11 GeV



Acknowledgement: JLab Hall A and PVDIS collaborations; and CJ PDF group.

The Jefferson Lab PVDIS Collaboration

D. Wang, K. Pan, R. Subedi, X. Deng, Z. Ahmed, K. Allada, K. A. Aniol, D. S. Armstrong, J. Arrington, V. Bellini, R. Beminiwattha, J. Benesch, F. Benmokhtar, W. Bertozzi, A. Camsonne, M. Canan, G. D. Cates, J.-P. Chen, E. Chudakov, E. Cisbani, M. M. Dalton, C. W. de Jager, R. De Leo, W. Deconinck, A. Deur, C. Dutta, L. El Fassi, J. Erler, D. Flay, G. B. Franklin, M. Friend, S. Frullani, F. Garibaldi, S. Gilad, A. Giusa, A. Glamazdin, S. Golge, K. Grimm, K. Hafidi, J.-O. Hansen, D. W. Higinbotham, R. Holmes, T. Holmstrom, R. J. Holt, J. Huang, C. E. Hyde, C. M. Jen, D. Jones, Hoyoung Kang, P. M. King, S. Kowalski, K. S. Kumar, J. H. Lee, J. J. LeRose, N. Liyanage, E. Long, D. McNulty, D. J. Margaziotis, F. Meddi, D. G. Meekins, L. Mercado, Z.-E. Meziani, R. Michaels, M. Mihovilovic, N. Muangma, K. E. Myers, S. Nanda, A. Narayan, V. Nelyubin, Nuruzzaman, Y. Oh, D. Parno, K. D. Paschke, S. K. Phillips, X. Qian, Y. Qiang, B. Quinn, A. Rakhman, P. E. Reimer, K. Rider, S. Riordan, J. Roche, J. Rubin, G. Russo, K. Saenboonruang, A. Saha, B. Sawatzky, A. Shahinyan, R. Silwal, S. Sirca, P. A. Souder, R. Suleiman, V. Sulkosky, C. M. Sutera, W. A. Tobias, G. M. Urciuoli, B. Waidyawansa, B. Wojtsekhowski, L. Ye, B. Zhao & X. Zheng

Thank you!

The combination of parity violation, Standard Model electroweak physics, electron DIS, and studies of the quark property has been an "inter-subfield" topic.

I am glad this topic has now found a home – GHP!

Backup

Our everyday life is so complicated that we keep searching for simplicity. Symmetry fulfills this strong desire.

Mass Limits on eq AV and VA BSM Physics

Complementary to LHC results on the mass limit of eq contact interactions

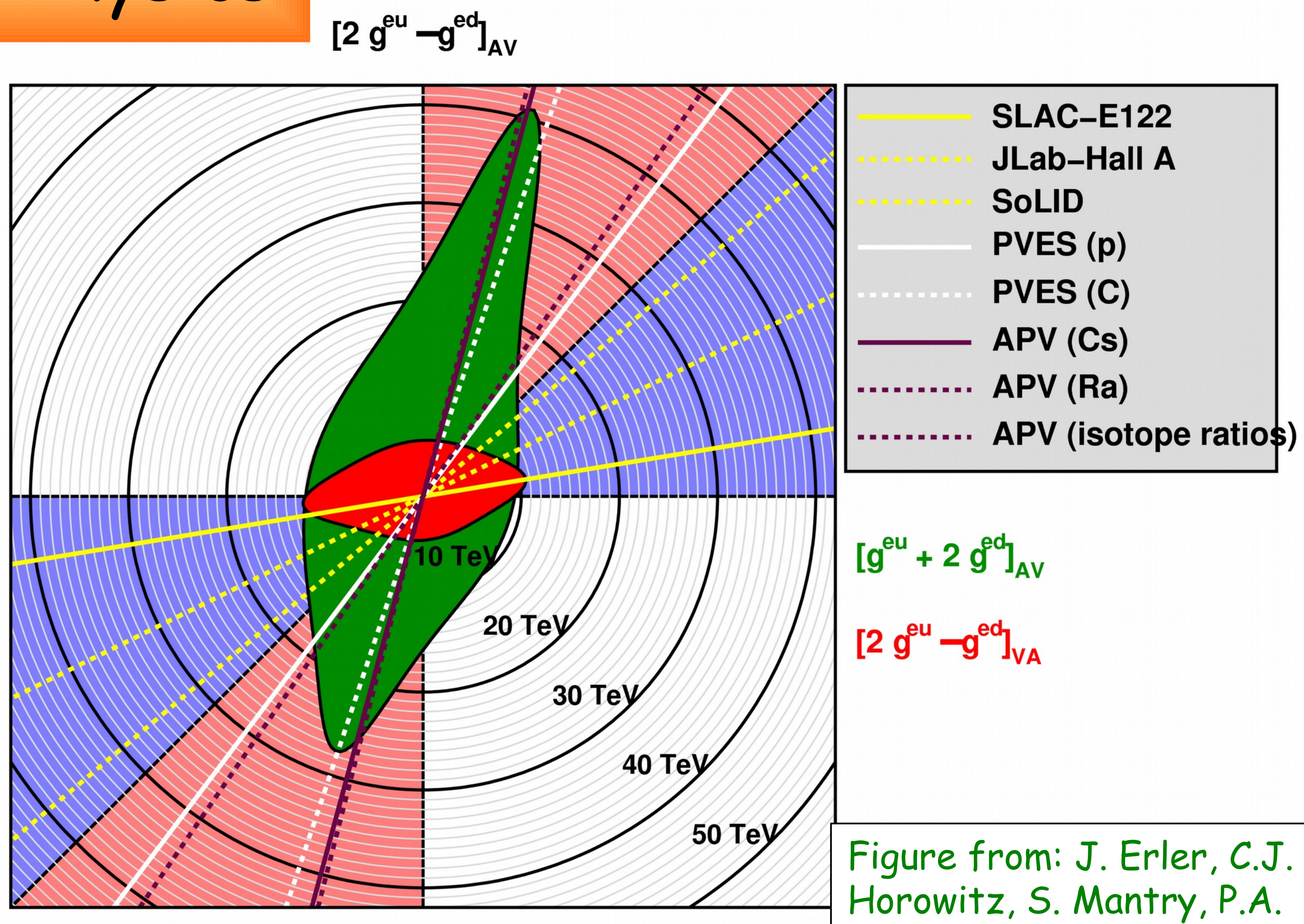
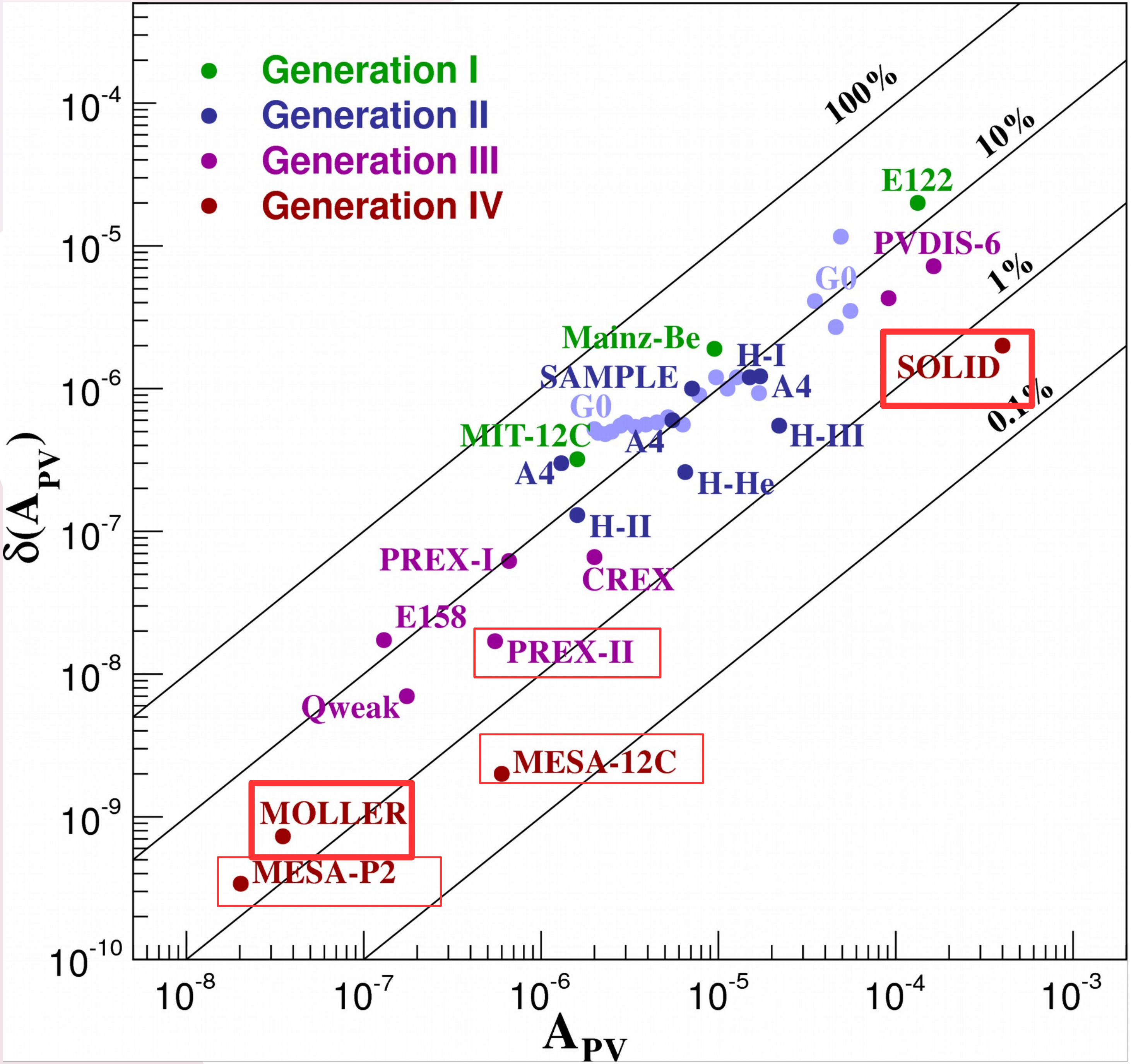


Figure from: J. Erler, C.J. Horowitz, S. Mantry, P.A. Souder, arxiv/1401.6199, Annual Review of Nucl and Part. Science, 64 (2014)

Parity-Violating Electron Scattering - Past, Present, and Future



Coming Next:

- SoLID (PVDIS) and Moller have both been recommended by the 2015 NSAC Long Range Plan