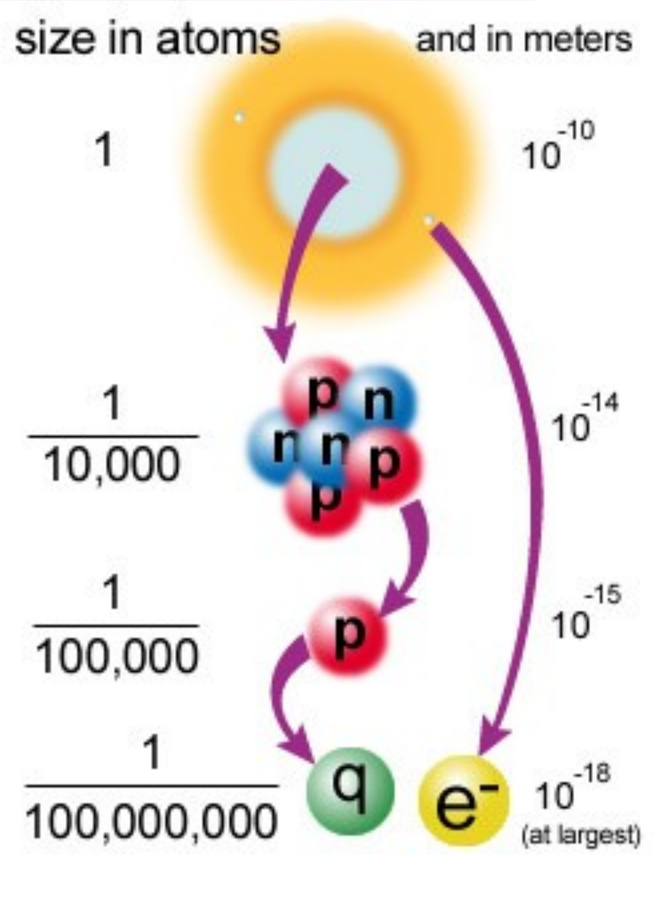
Parity-Violating Deep Inelastic Scattering at Jefferson Lab and Limits on New Contact Interactions

Xiaochao Zheng (郑晓超， Univ. of Virginia)

July 27, 2017

- "Opening quiz"
- Parity Violation in Deep Inelastic Scattering (PVDIS) and the Electroweak Standard Model
- JLab 6 GeV PVDIS results and mass limits on new contact interactions
- JLab 12 GeV PVDIS with SoLID

"Opening Quiz" – A typical Modern Physics homework



	δx	$\delta p = \frac{\hbar}{2\,\delta x}$	δE (binding energy)
electrons in an atom	10^{-10} m	≈ keV	≈ eV
nucleons in the nucleus	$10^{(-14\sim-15)}$m	≈10^2MeV	≈10^1MeV
quarks in nucleons	10^{-15}m	≈10^2MeV	(≈10^2MeV)
preons in quarks and leptons:	$10^{-19\sim-18}$ m	?	?

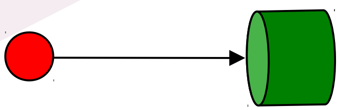
（此题属本科大二现代物理课内容）

"preons"?

（初子？）

Electron Scattering on Fixed Nuclear or Nucleon Targets

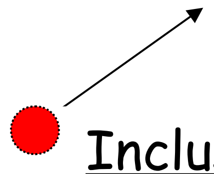
electron beam (GeV)



target (at rest)

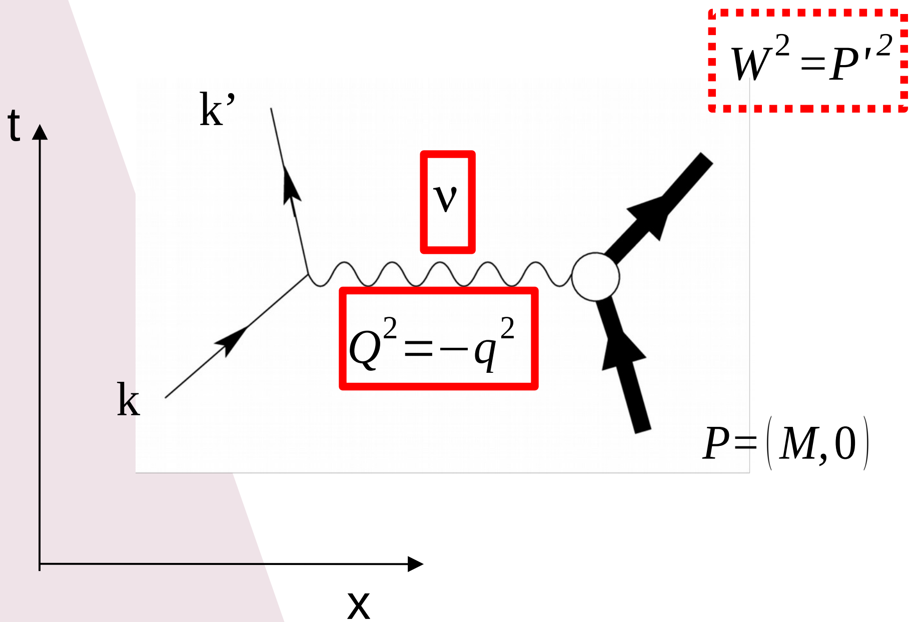
Before

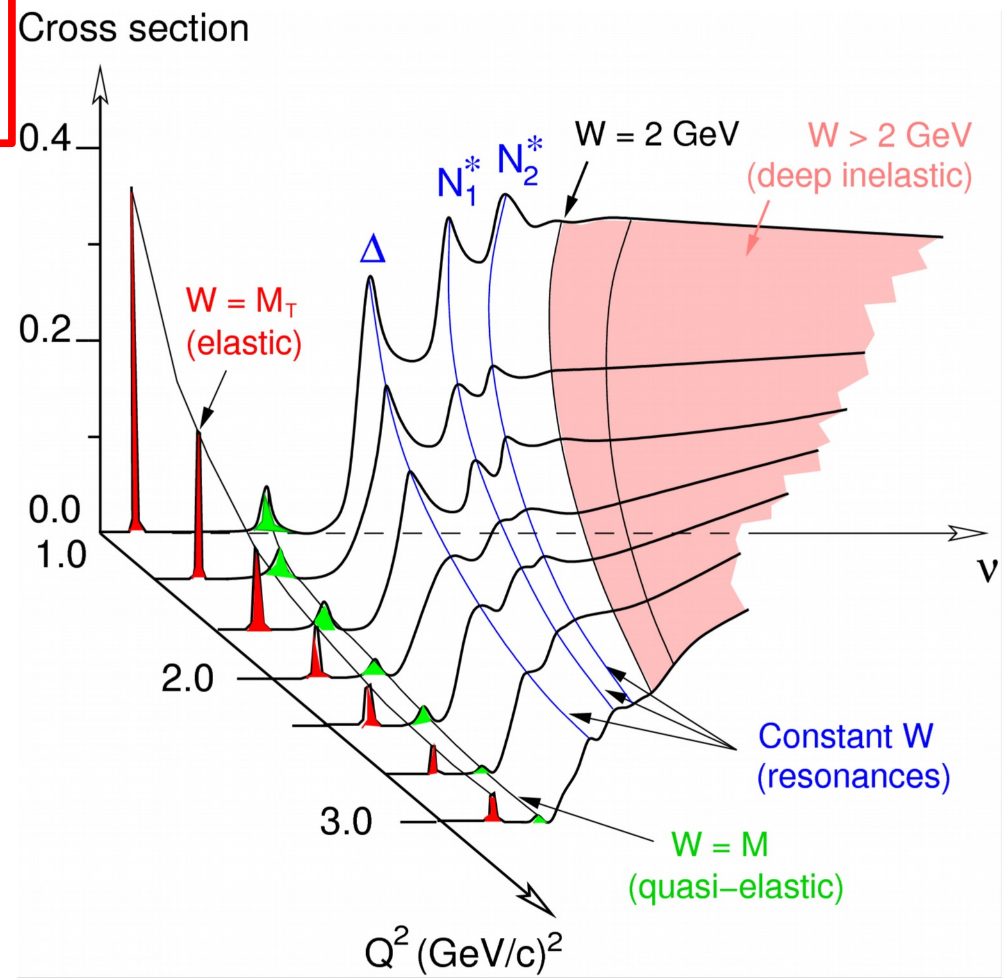
to detector



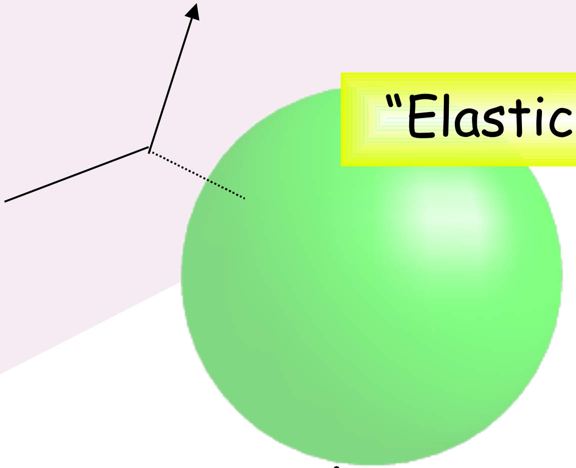
<u>Inclusive</u>: only the scattered electron is detected

After





Three kinematic regions

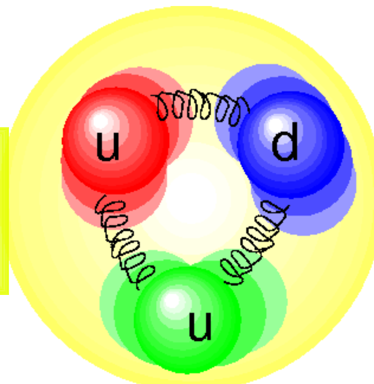


"Elastic": $W=M_t$ or M_p

1961

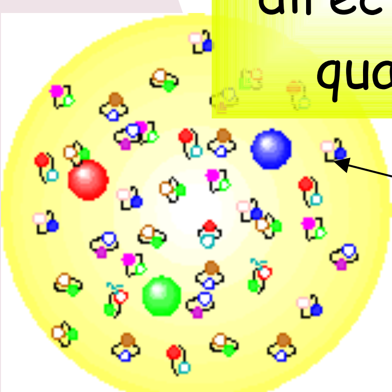
From cross section we extract "elastic form factors"

"Resonance": 1<W<2GeV

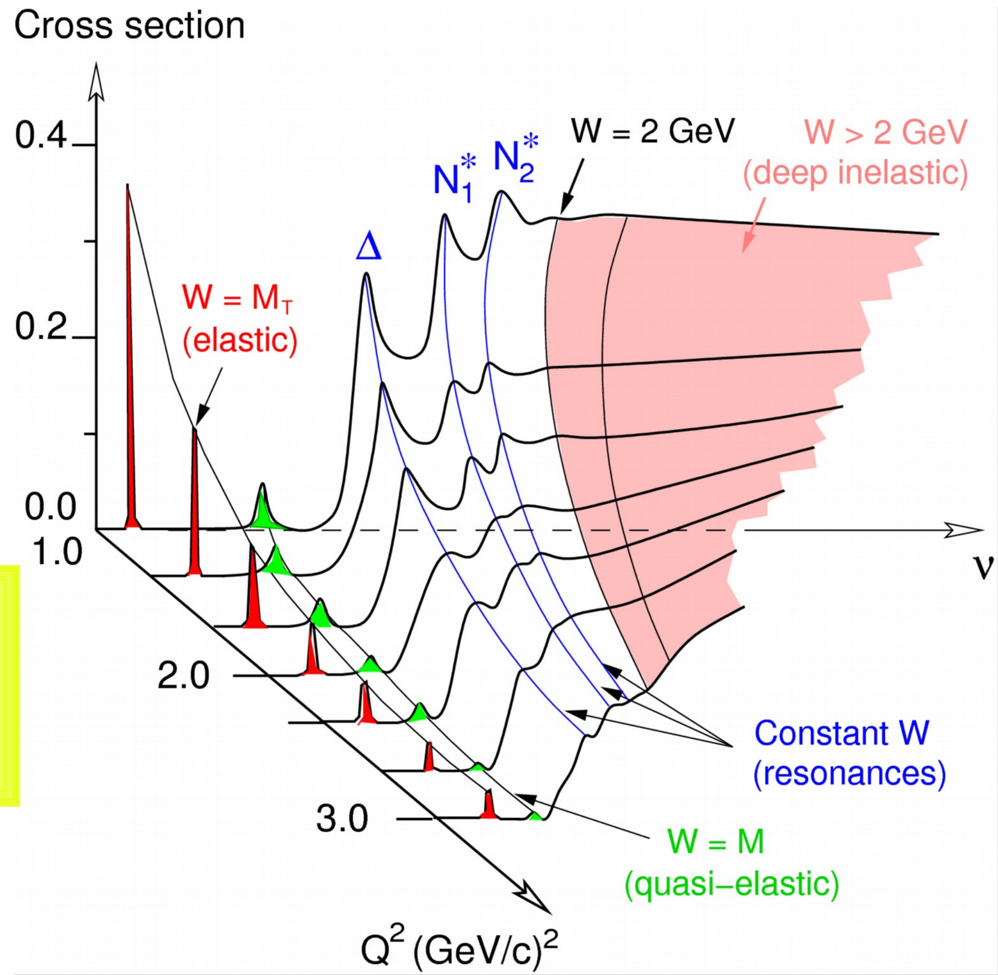


1999
2004

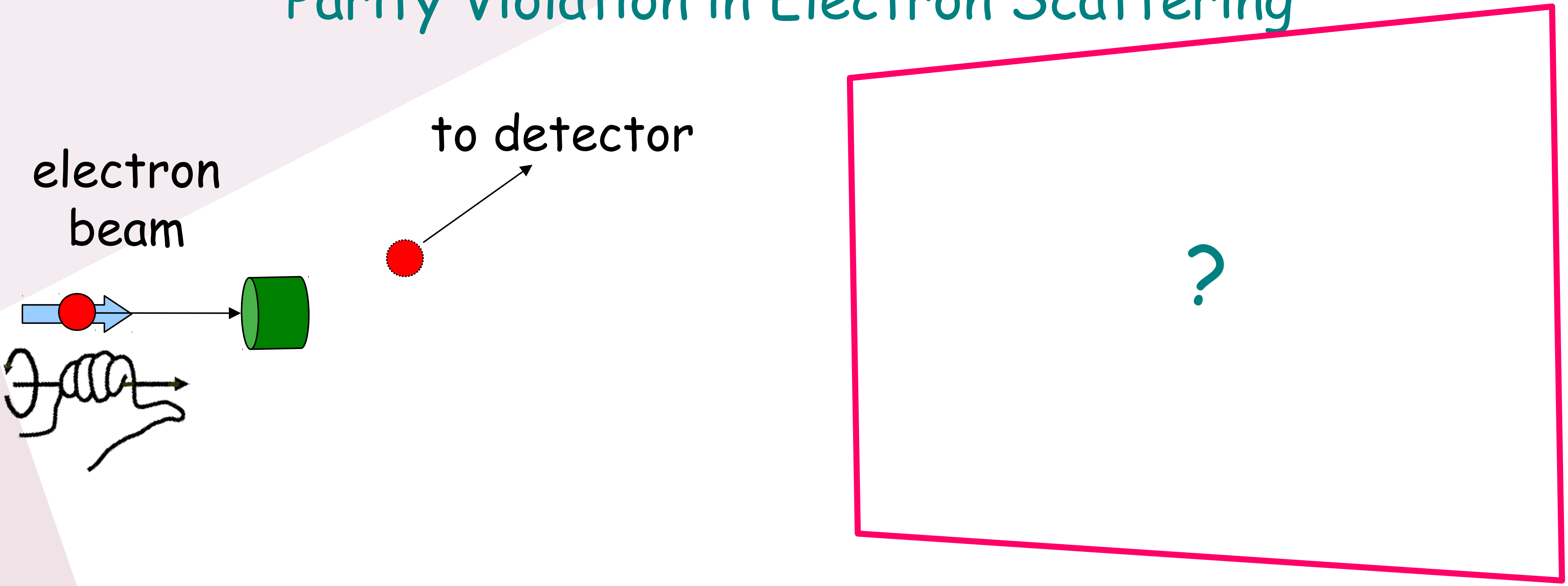
"Deep Inelastic": W>2 GeV, directly probes the quasi-free quarks inside the nucleon.



10^{-18}m or smaller

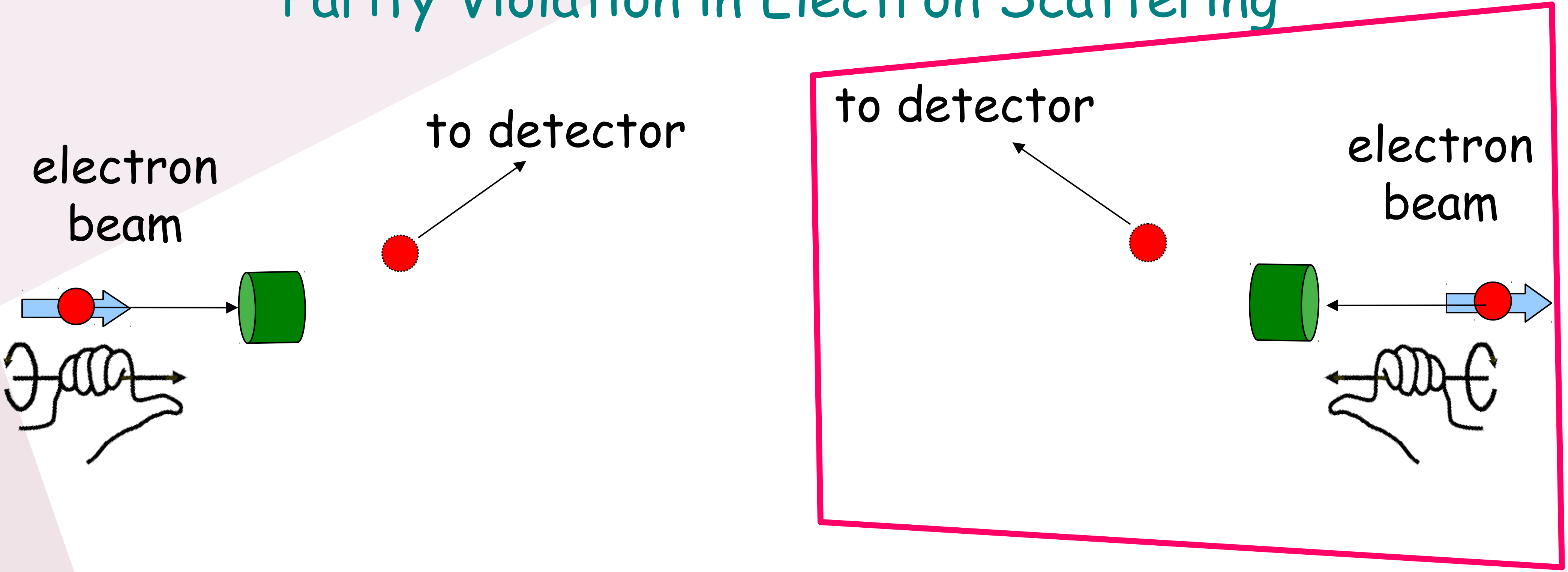


Parity Violation in Electron Scattering

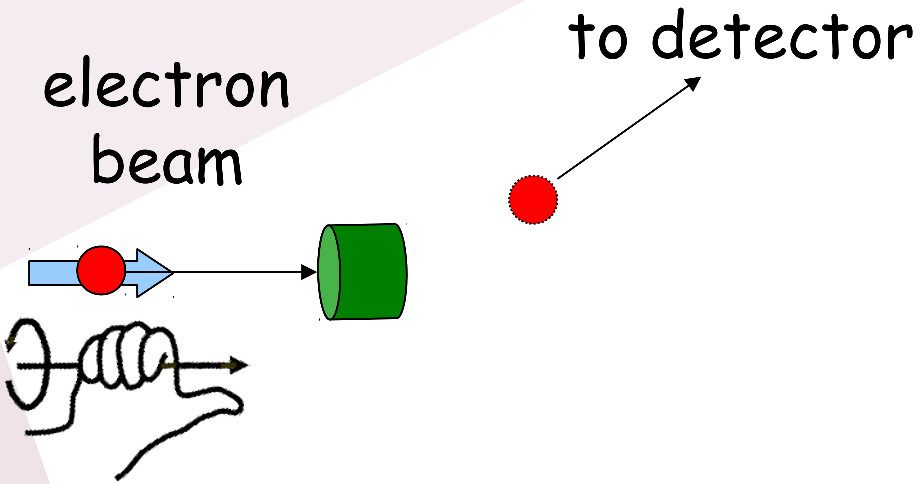


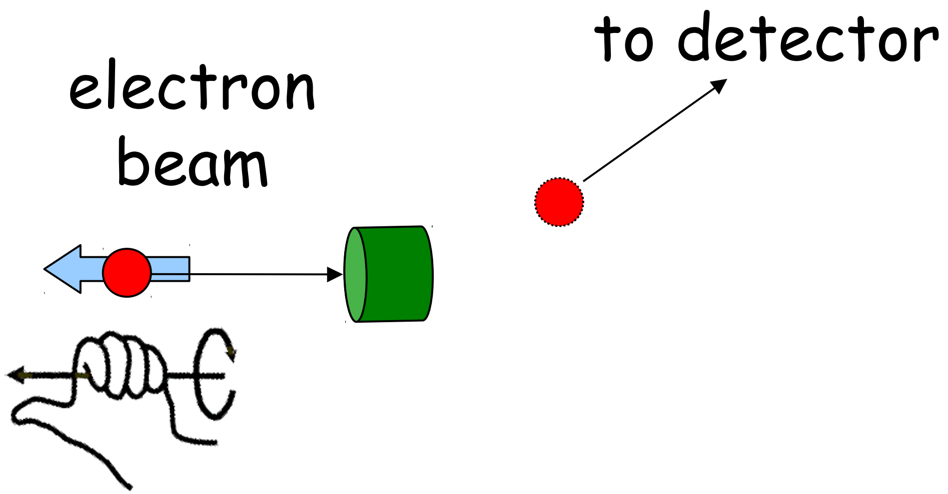
- If parity symmetry were exact, then the physical law behind a process is the same as the law behind its mirror process.

Parity Violation in Electron Scattering

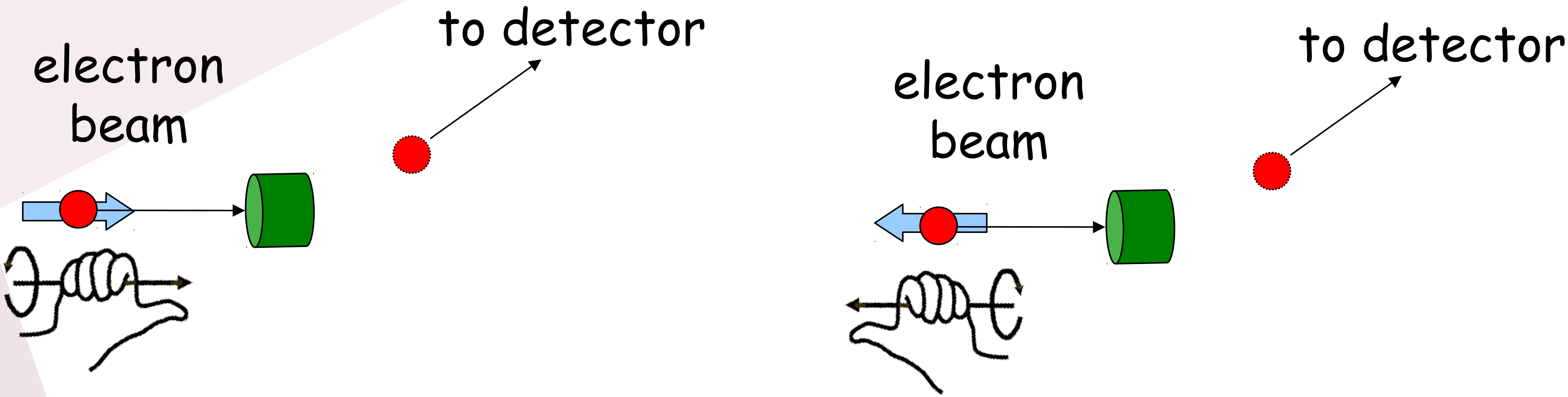


Parity Violation in Electron Scattering

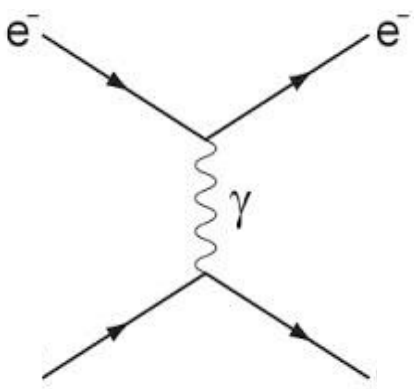




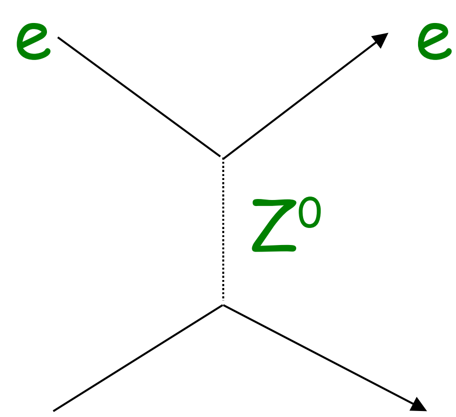
Parity Violation in Electron Scattering



- 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 the interference term between:



and

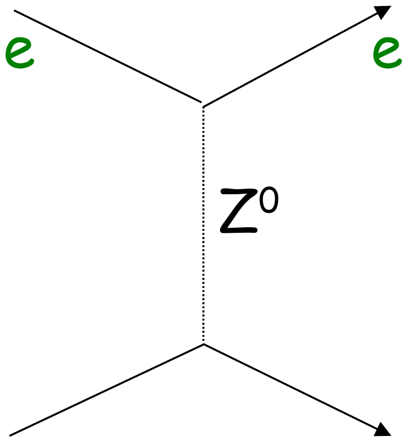


Standard Model Predictions for PVES

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

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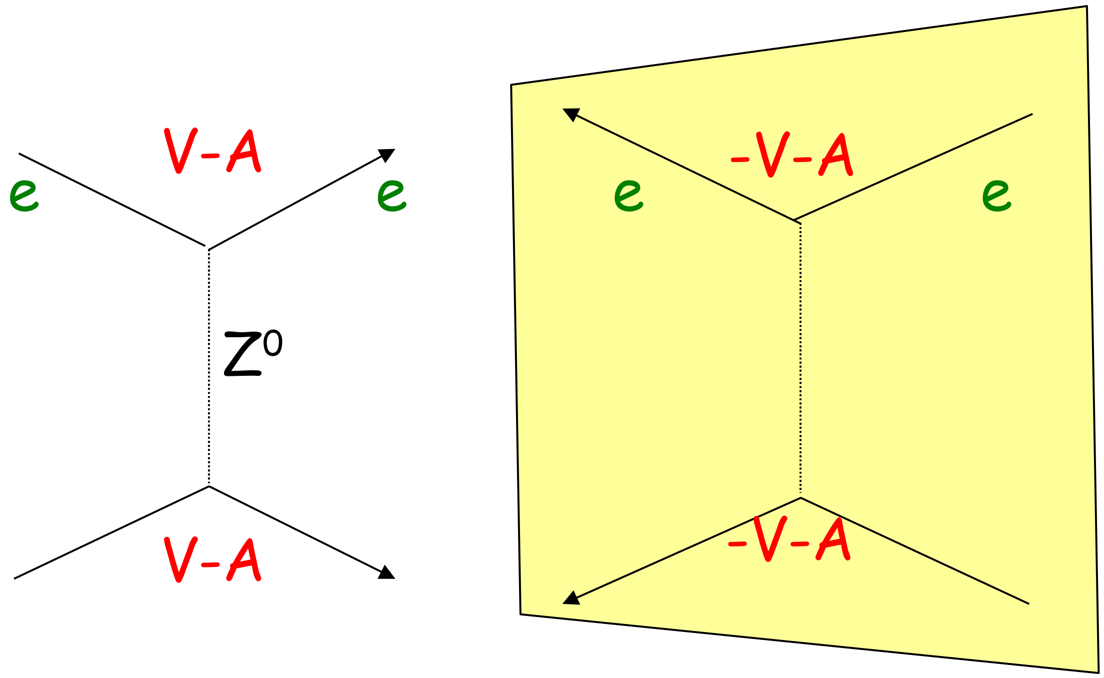
- PVES asymmetry comes from V(e)xA(targ) and A(e)xV(targ)



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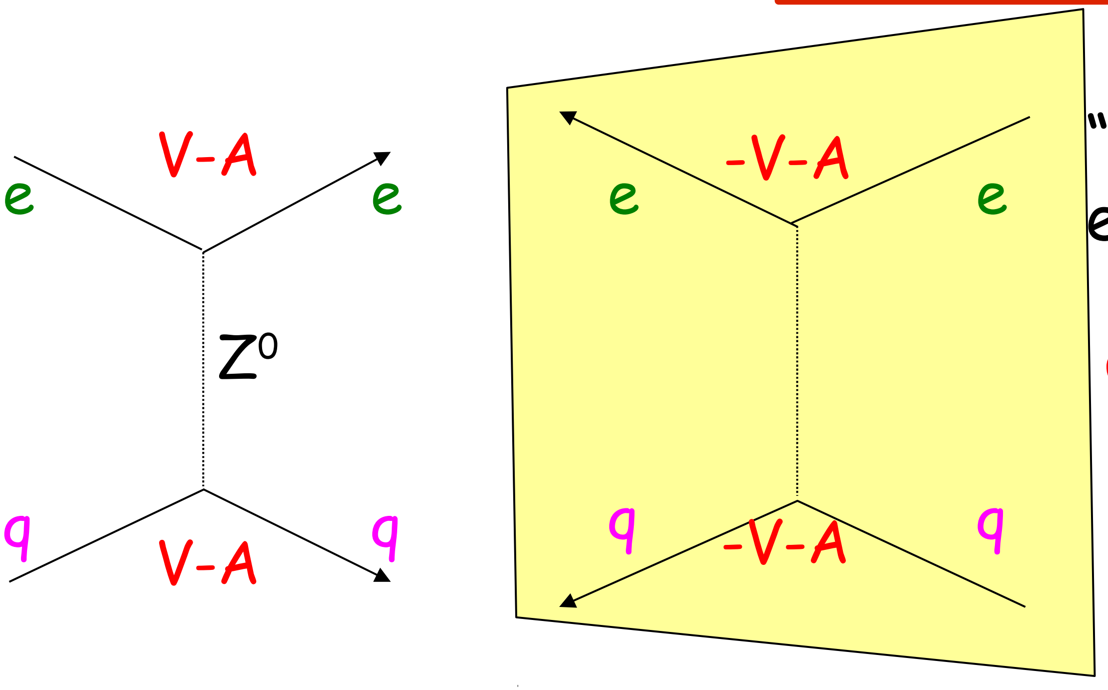
  or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$

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

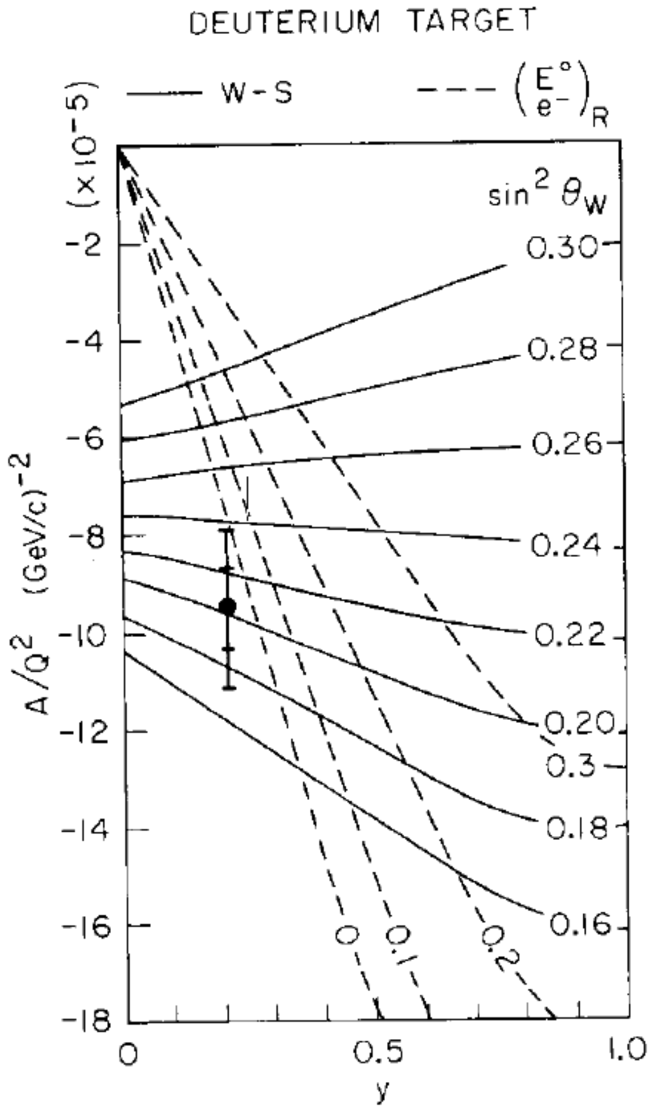


"electron-quark effective couplings"

and can be directly related to $\sin^2\theta_W$

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.



Prescott et al, Phys. Lett. 77B, 347 (1978)

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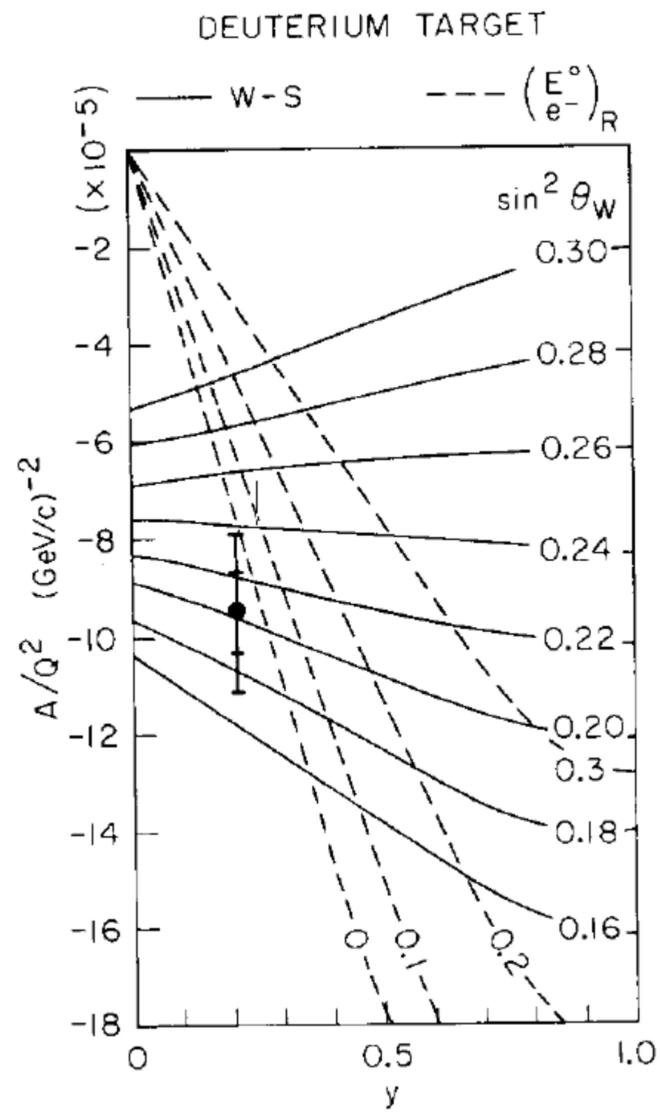
- Nowadays, PVES is being used to test the Standard Model, and to set limits on new physics.



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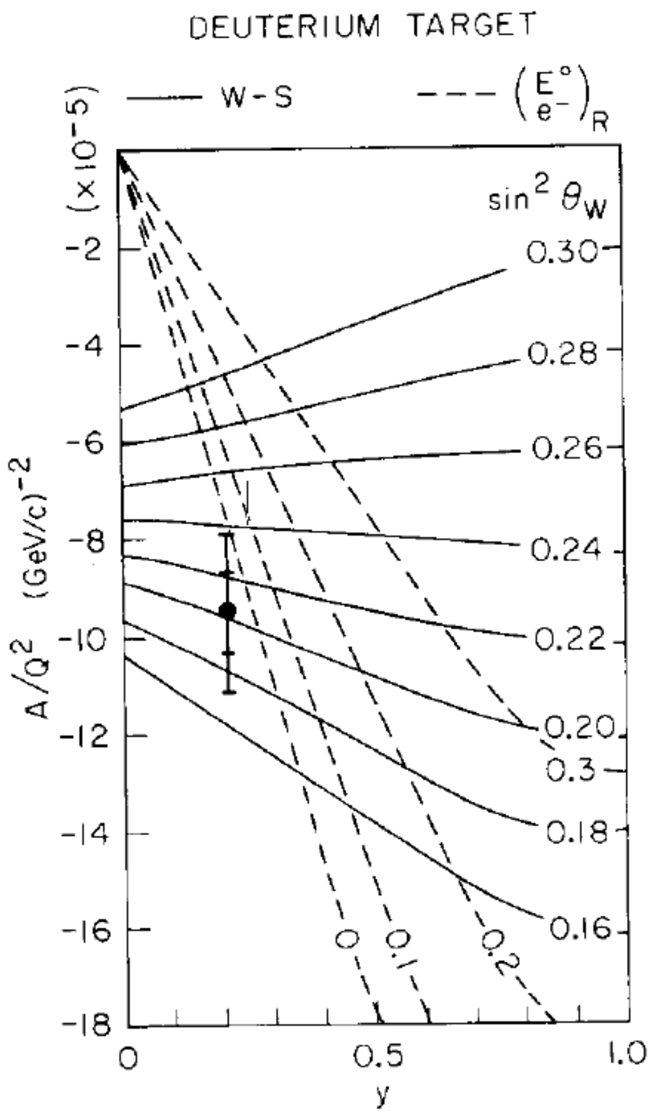
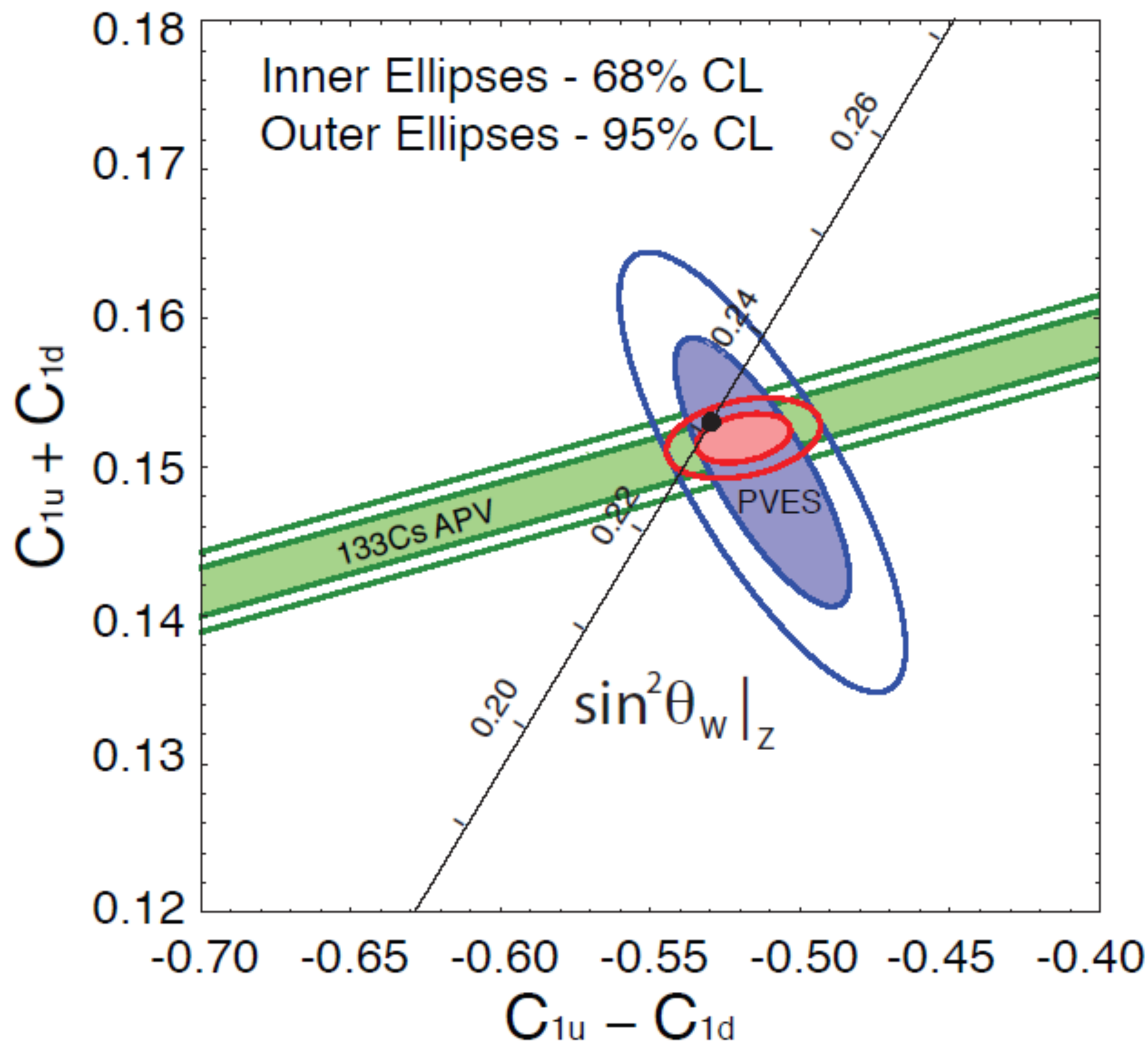
- PVES in elastic scattering can access C_{1q}, while PVDIS can access both C_{1q} and C_{2q}.



Prescott et al, Phys. Lett. 77B, 347 (1978)

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

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



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

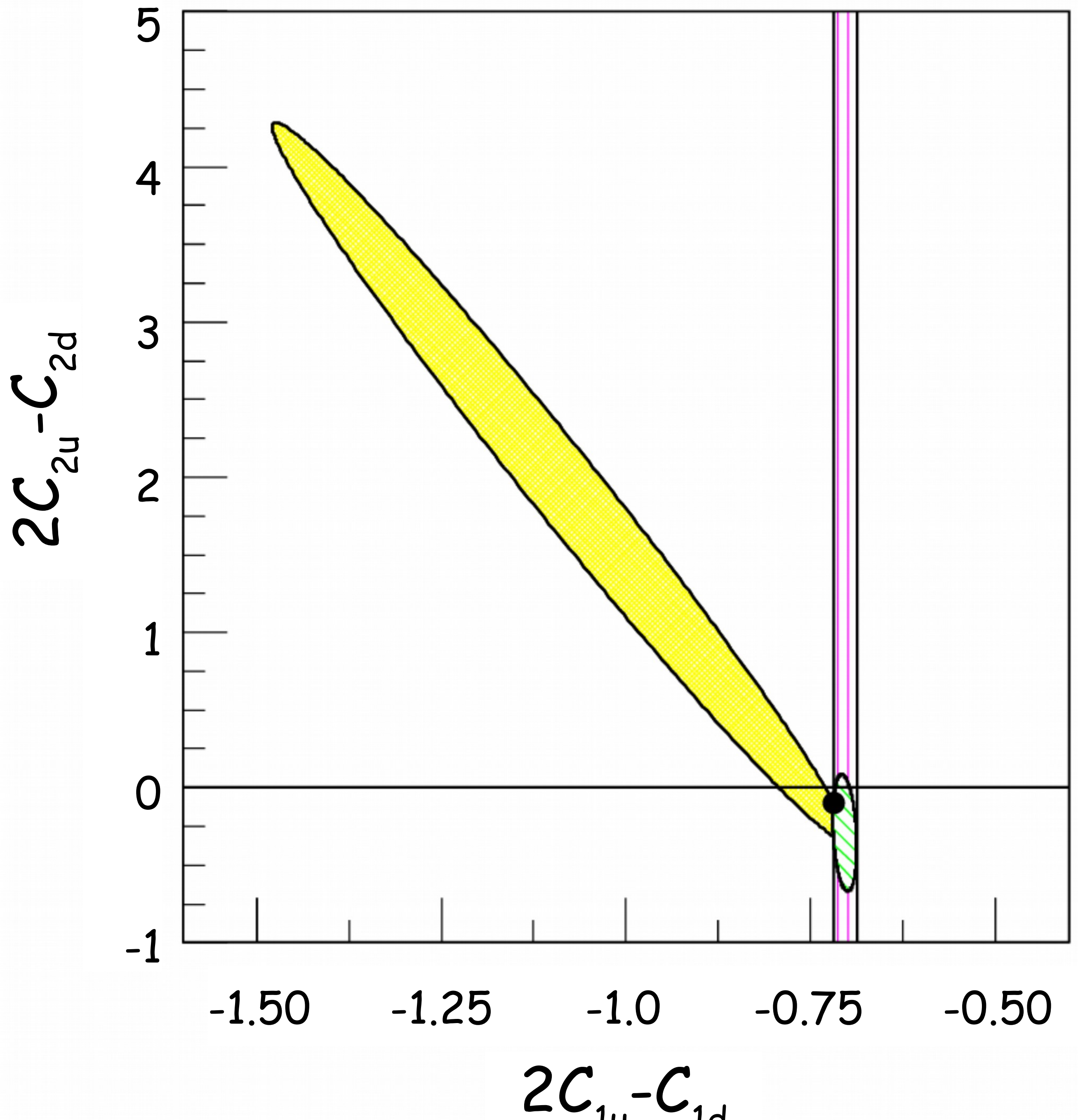
Formalism for PVDIS

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

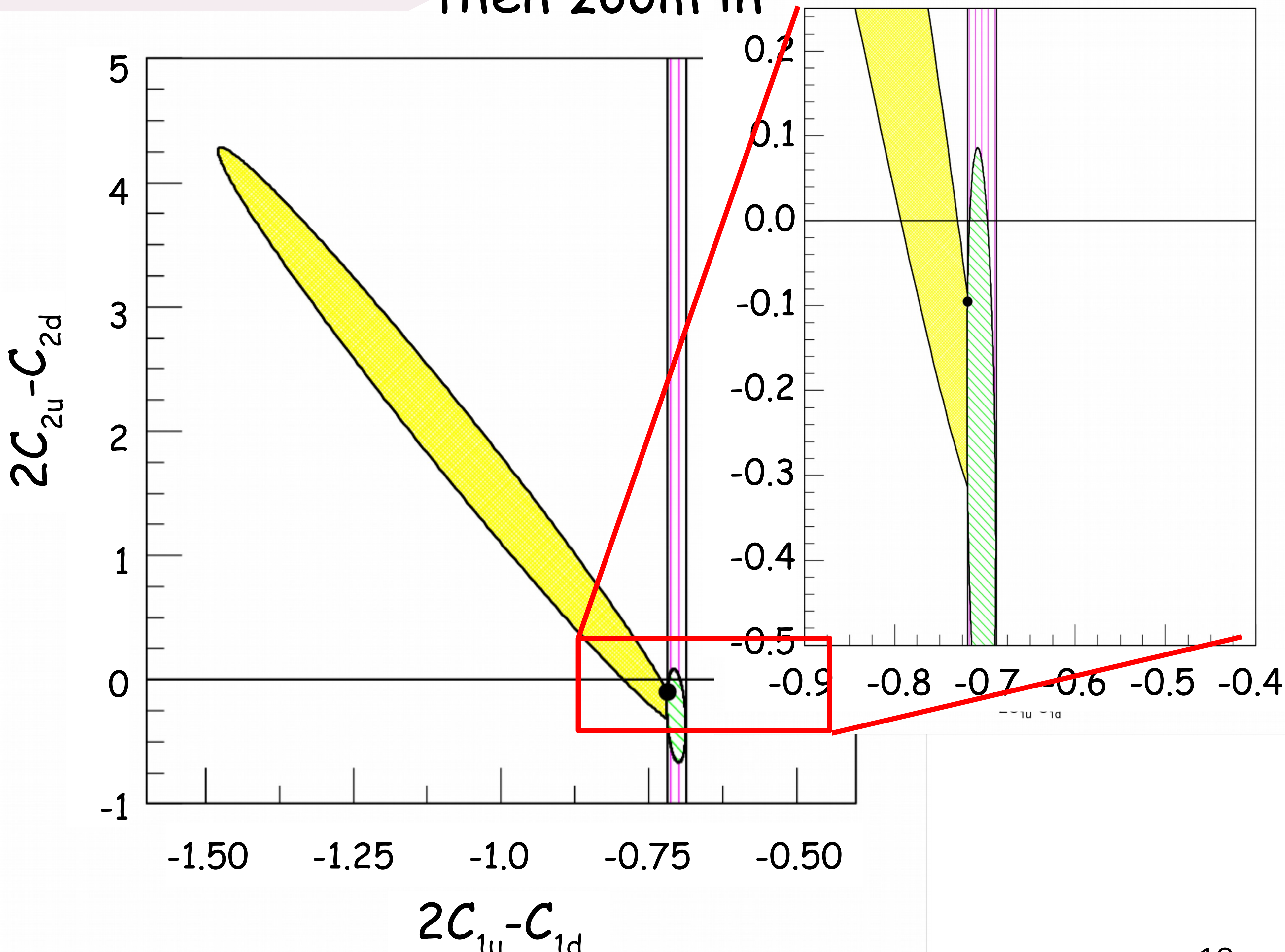
For an isoscalar target (^{2}H):

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

C_{2q} from E122 (before JLab)

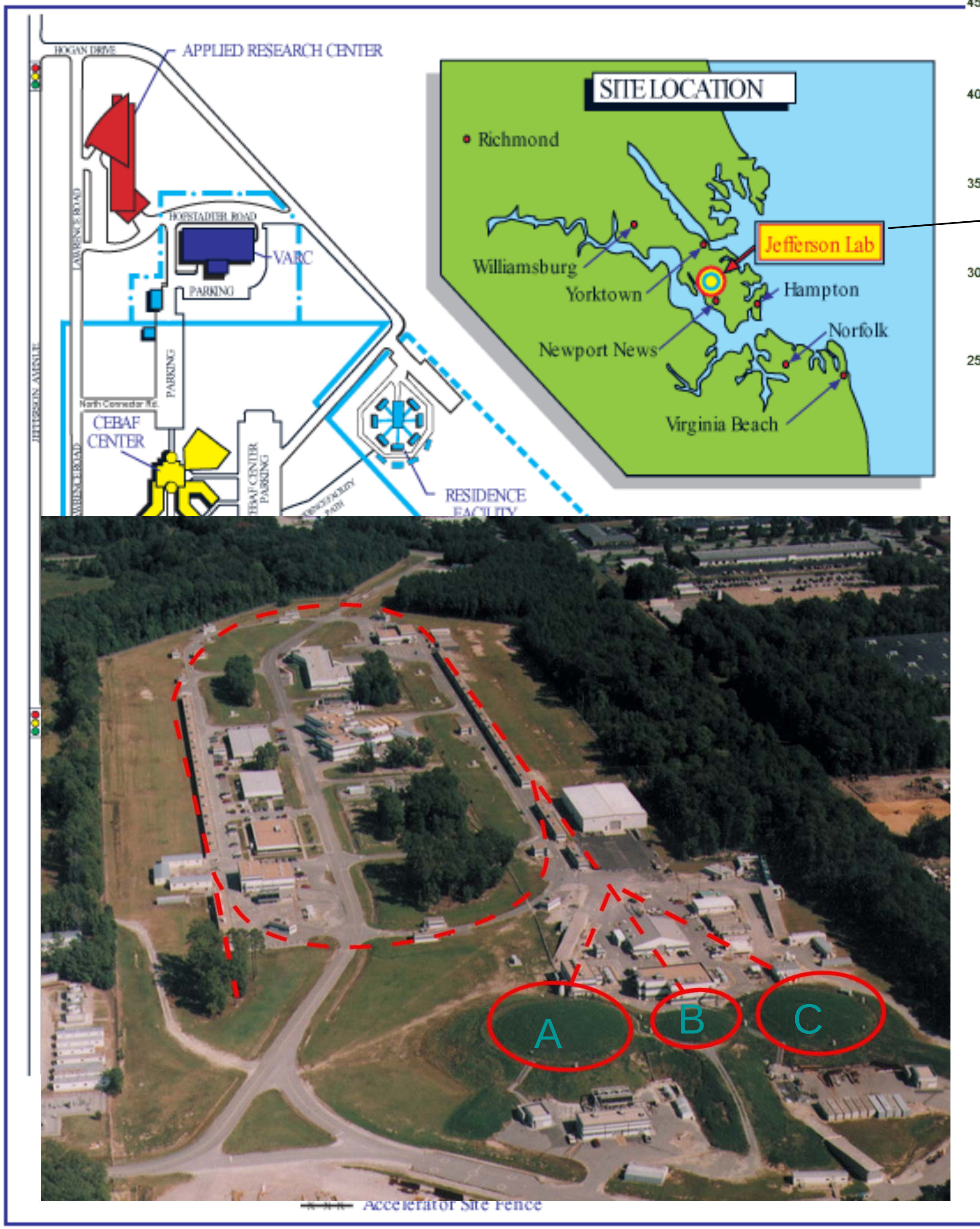


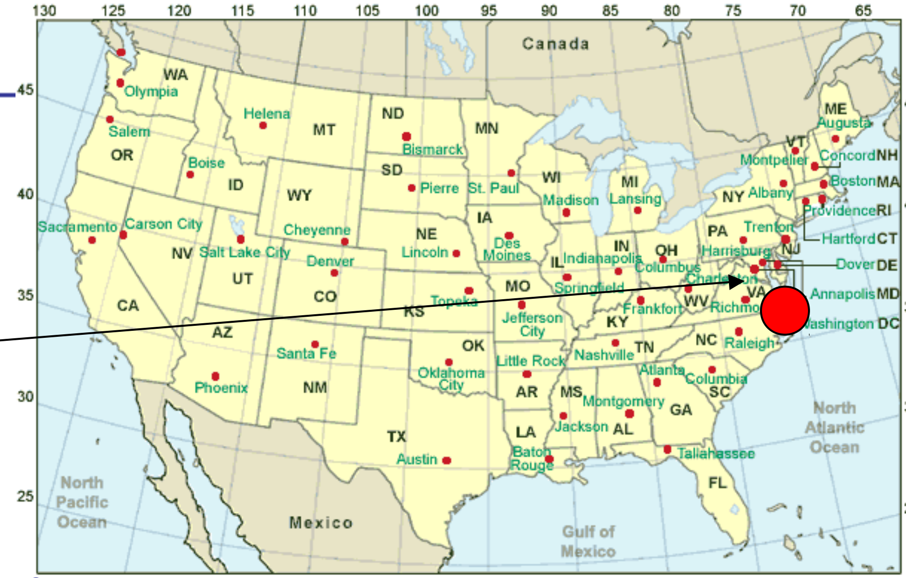
then zoom in



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

PVDIS at 6 GeV (Jefferson Lab)





- 100uA, 90% polarized beam on a 20cm liquid deuterium target
- Measured two DIS points: Q^2=1.085 and 1.901 $(GeV/c)^2$
- Ran in Hall A in Nov-Dec.2009, results published in 2013-2015.

PVDIS at 6 GeV (JLab Hall A)

- Results:

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

compare to

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

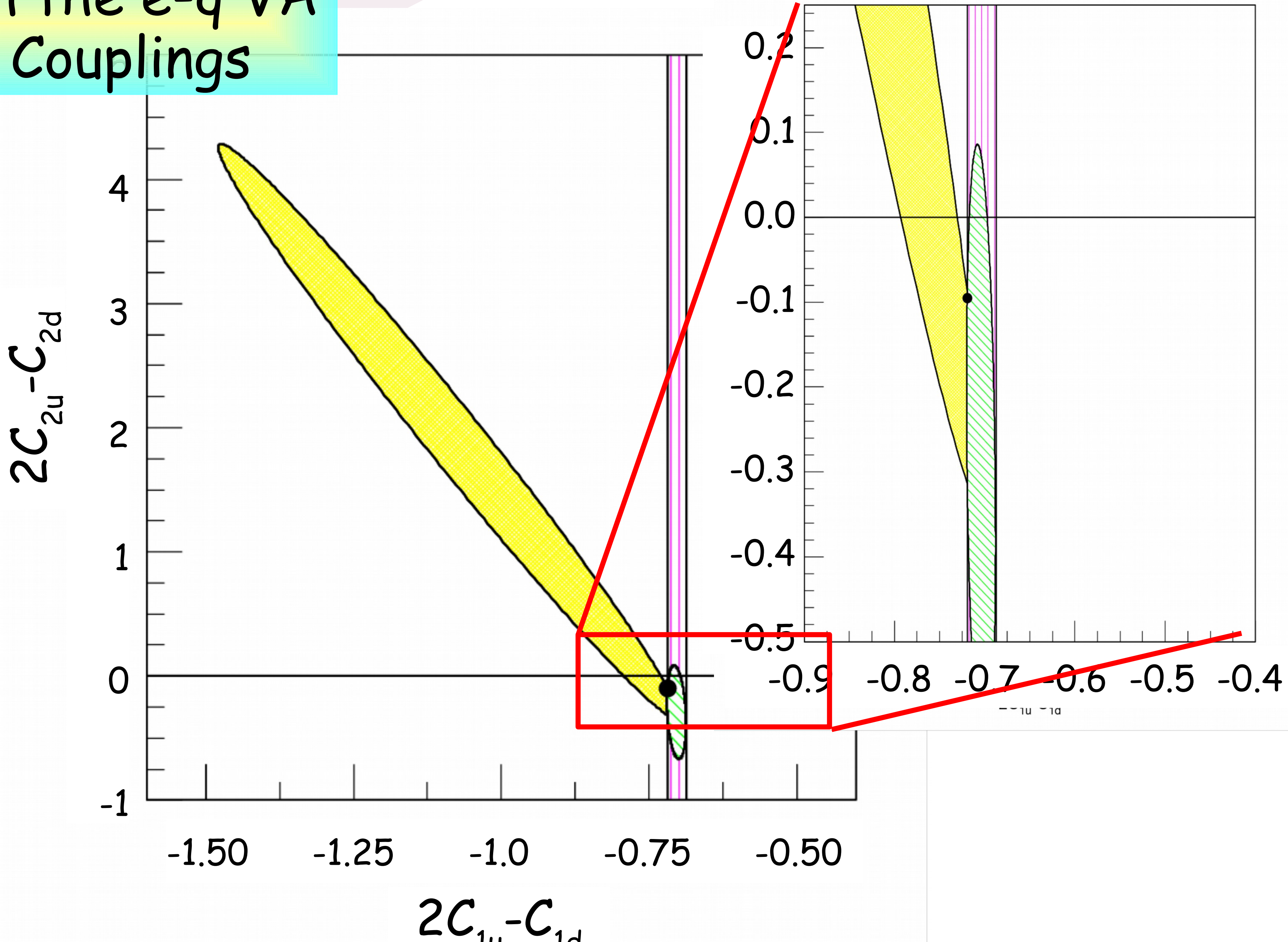
$$\boxed{A^{phys}_{Q^2=1.901,x=0.295} = -160.80 \pm 6.39 \pm 3.12\ ppm}$$

compare to

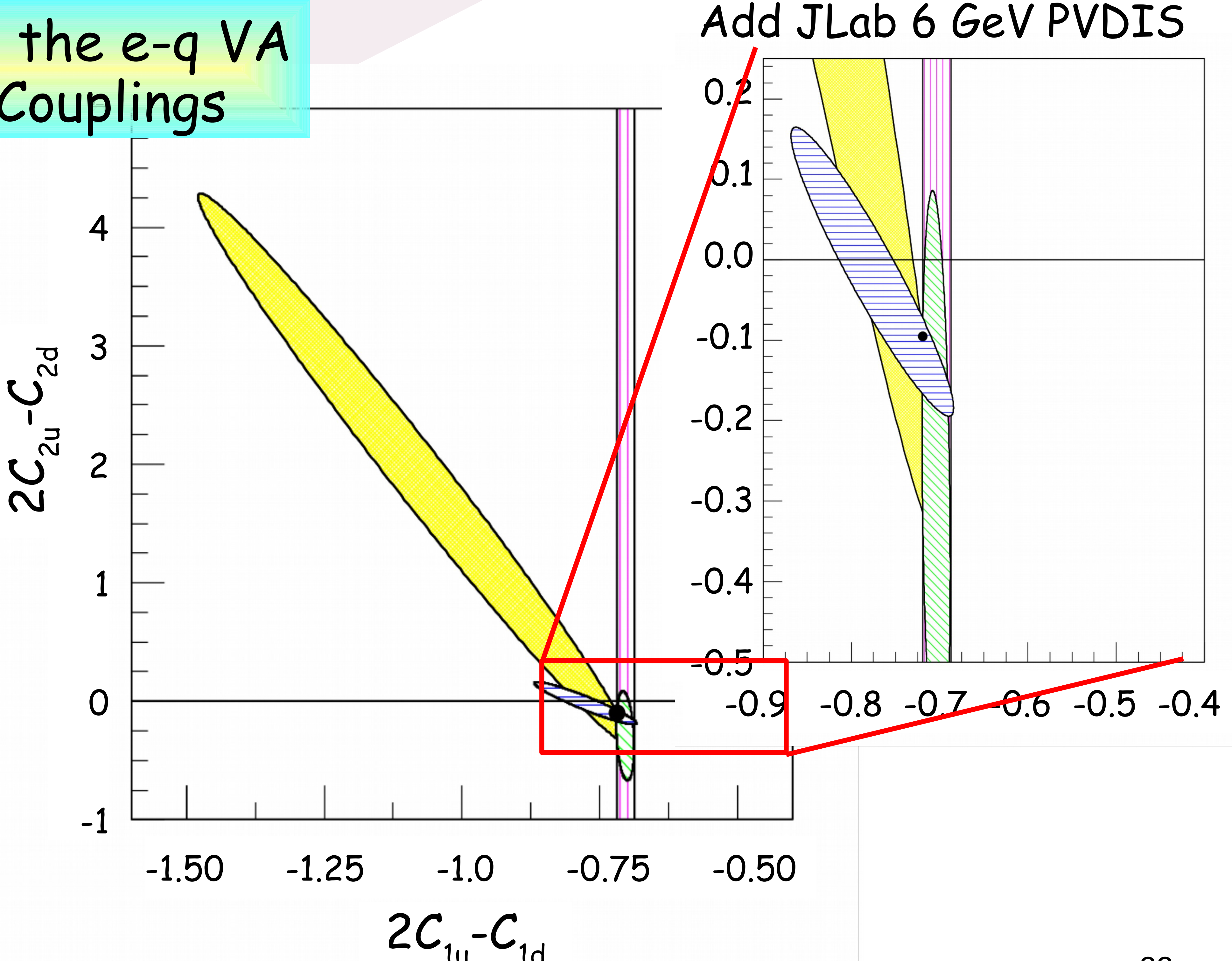
$$A^{SM} = \left(2.022\times 10^{-4}\right)\left[\left(2C_{1u}-C_{1d}\right)+0.594\left(2C_{2u}-C_{2d}\right)\right]$$

On the e-q VA Couplings

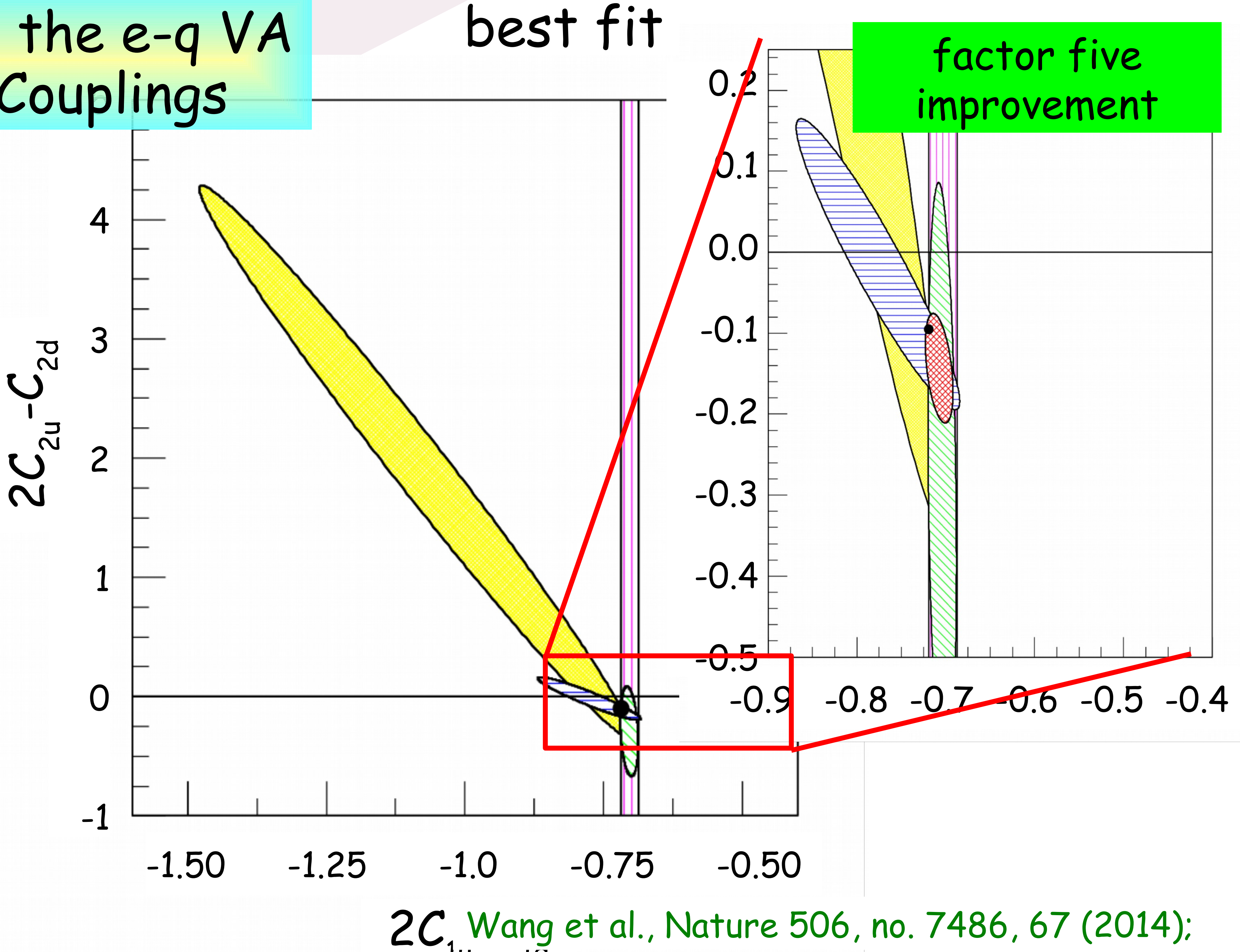
Previous data: E122, Elastic PVES + APV



On the e-q VA Couplings



On the e-q VA Couplings



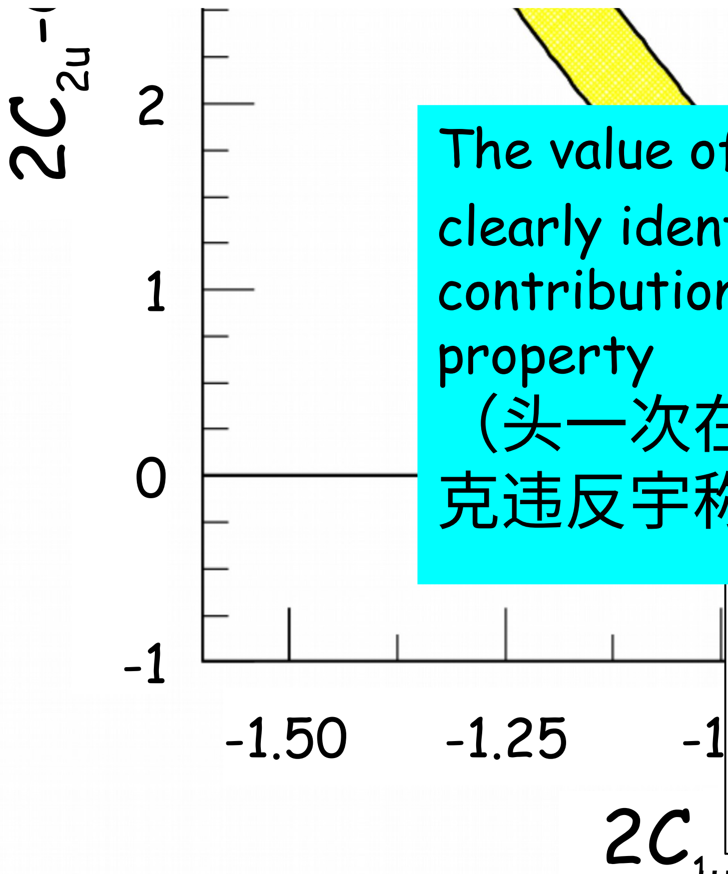
Wang et al., Nature 506, no. 7486, 67 (2014);

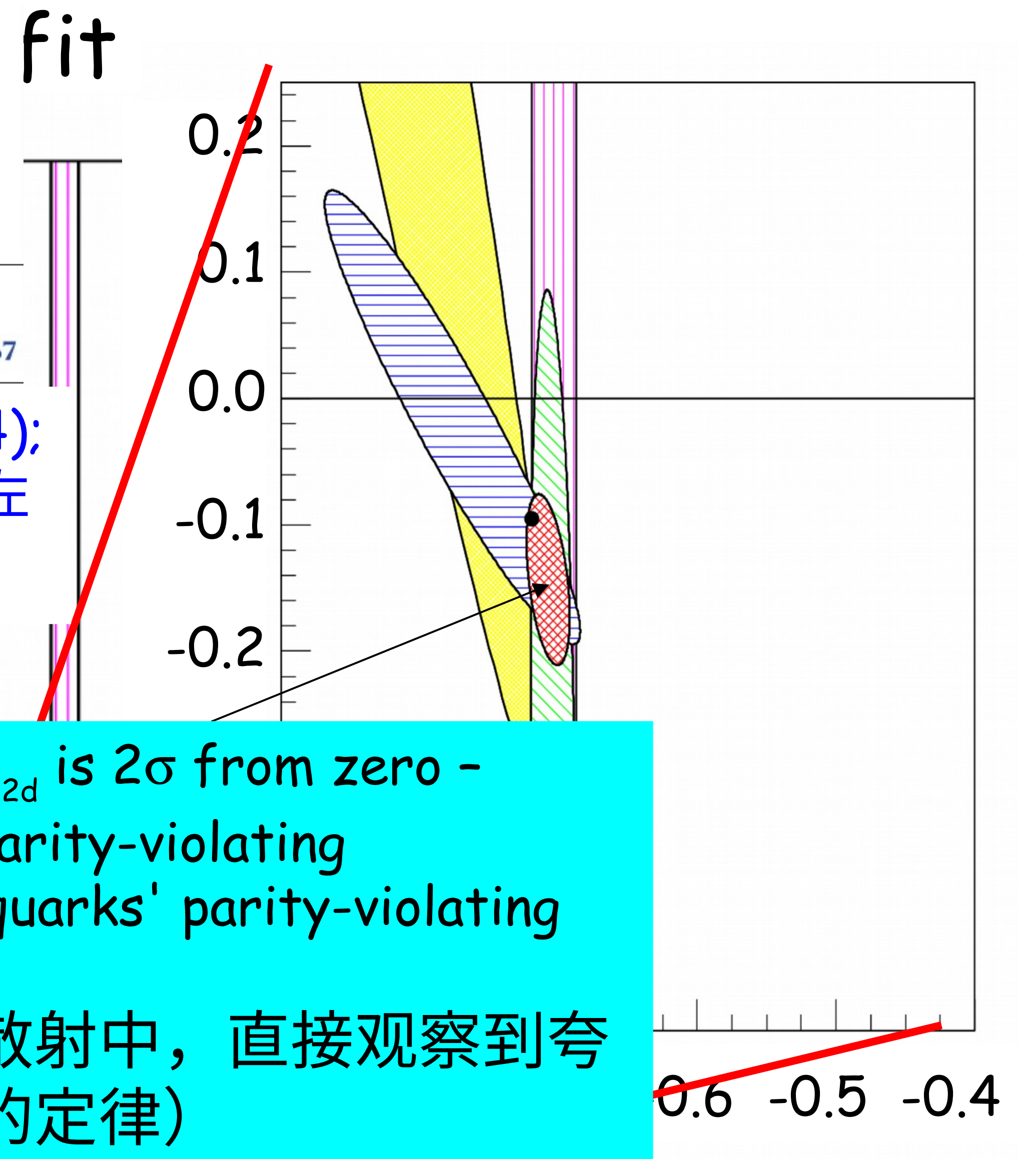
PARTICLE PHYSICS

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);
（夸克和人一样，有的喜用右手，有的则是左撇子）



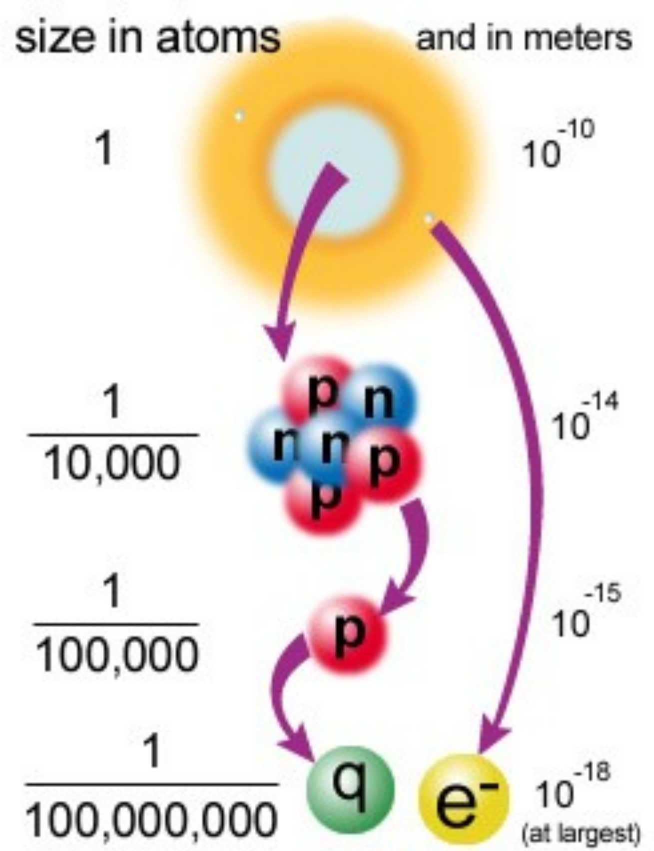


The value of $2C_{2u}$-C_{2d} is 2σ from zero – clearly identified parity-violating contribution from quarks' parity-violating property
（头一次在电子散射中，直接观察到夸克违反宇称守恒的定律）

"Measurement of parity violation in electron-quark scattering"

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

Answer to the Opening Quiz



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preons in quarks and leptons:	$10^{-19\sim-18}$ m	≈ 10^2GeV -TeV	≈TeV

"preons"?

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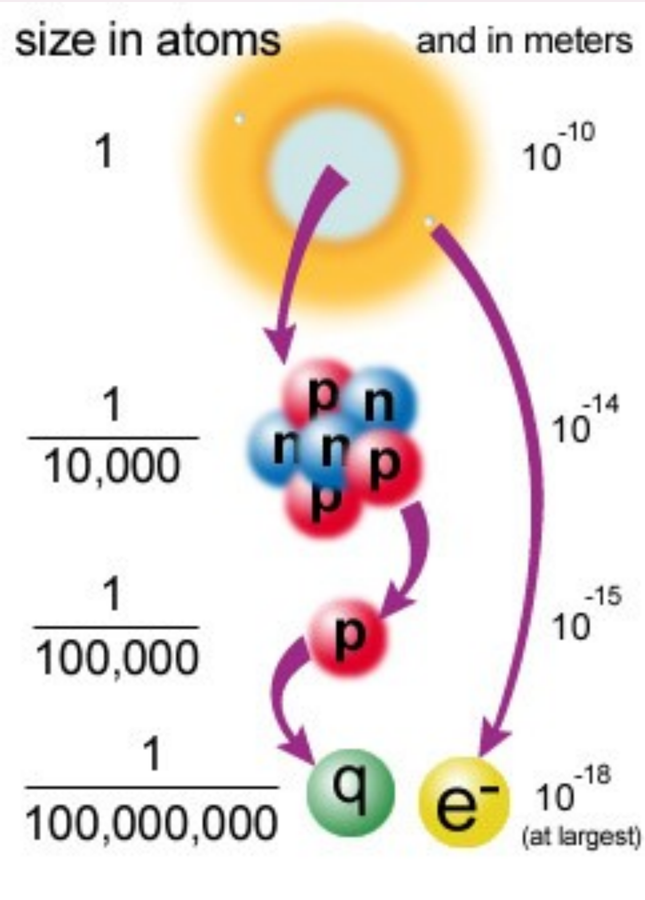

"preons"?

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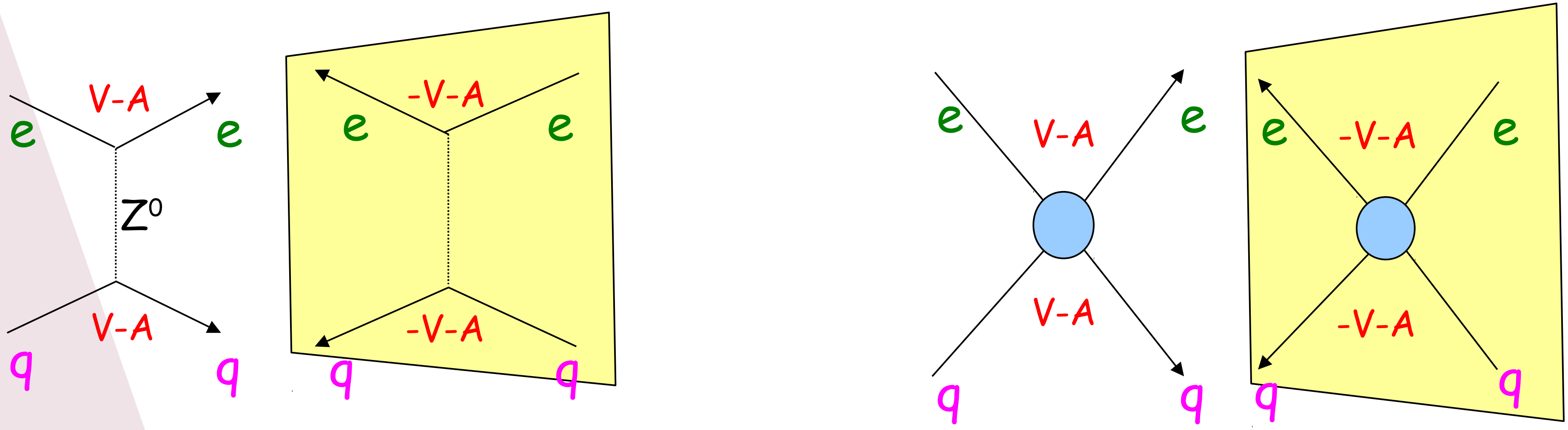
preons in quarks and leptons:	$10^{-19\sim-18}$ m	≈ 10^2GeV -TeV	≈TeV

If preons exist, they must interact through a new interaction, with an energy scale at the TeV level.

$$\boxed{\mathcal{L}_{\psi\psi} = (g^2/2\Lambda^2)[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L].}$$

Effective Couplings and New Contact Interactions

Below the energy scale Λ: such new physics will manifest itself as new llqq-type 4-fermion contact interactions, that modify the values of C_{1q} and C_{2q} from their Standard Model predictions.



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

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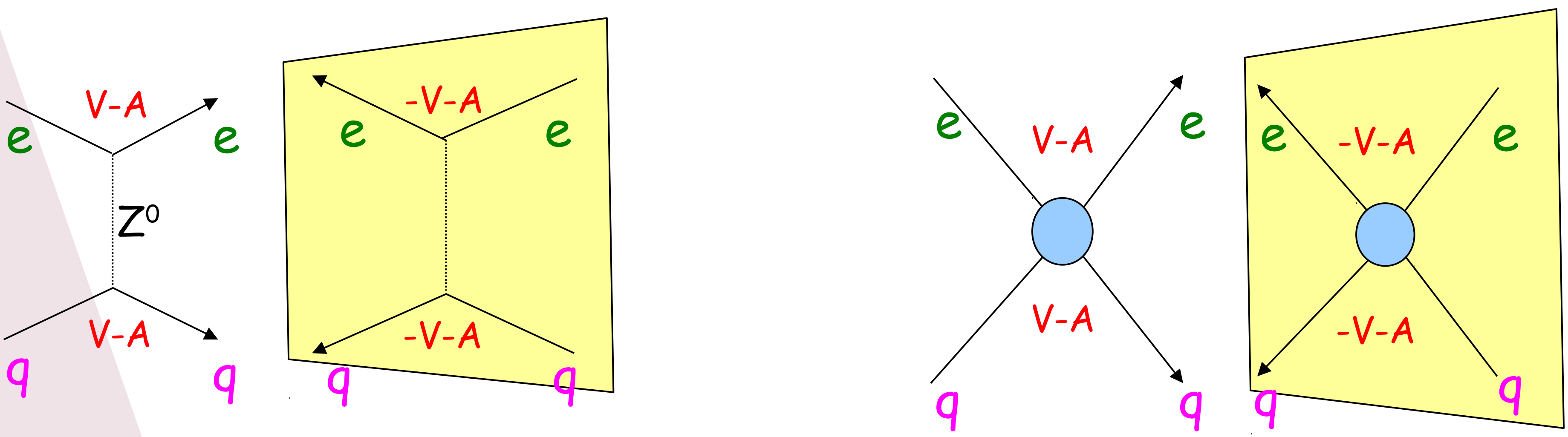
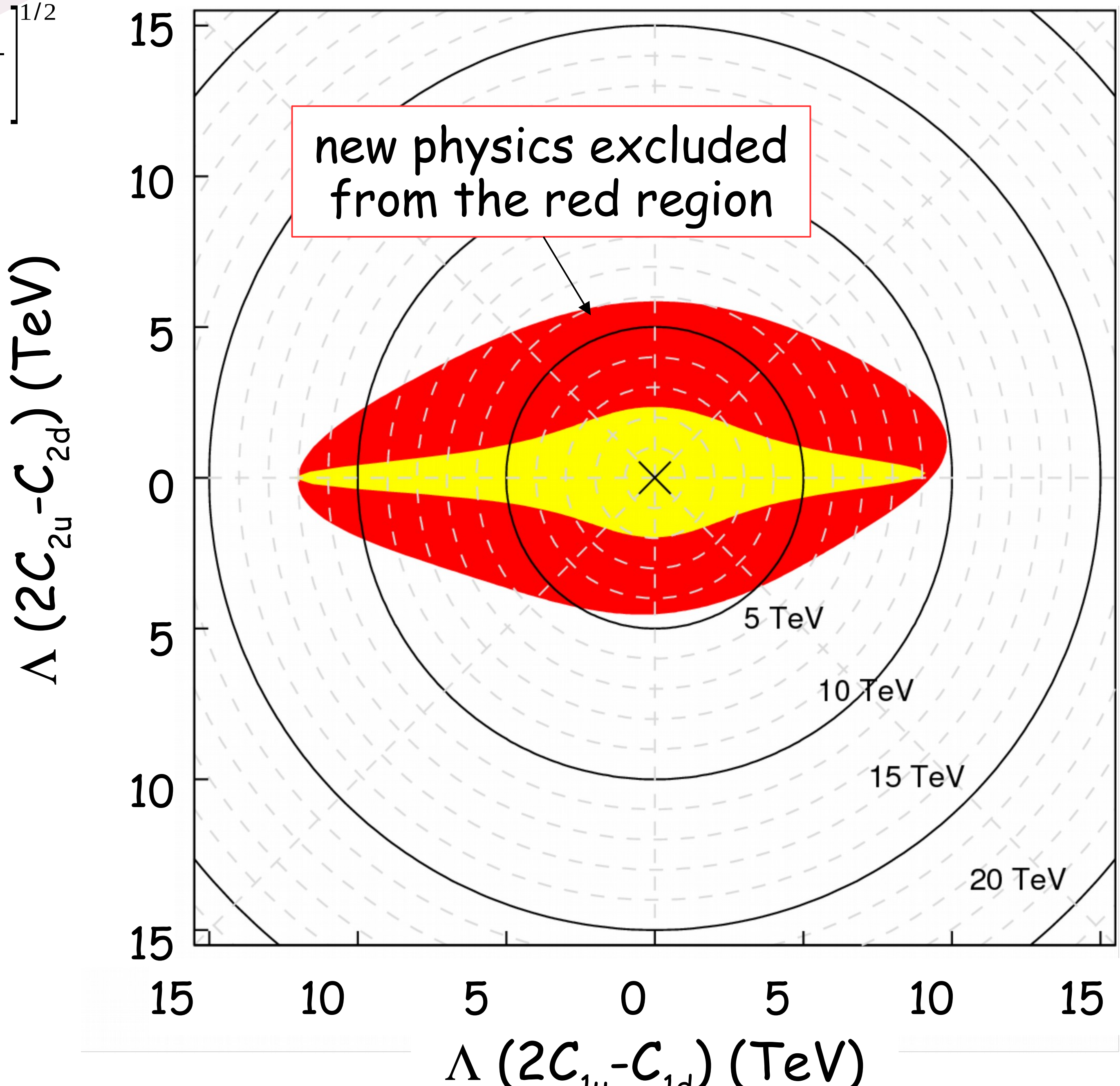
$$\Lambda = v\left[\frac{8\sqrt{5}\pi}{\left(\delta\left(2C_{2u}-C_{2d}\right)_{Q^2=0}\right)}\right]^{1/2}$$



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

Limit on new eq VA contact interactions

$$\Lambda = v\left[\frac{8\sqrt{5}\pi}{\left|\delta\left(2C_{2u}-C_{2d}\right)_{Q^2=0}\right|}\right]^{1/2}$$



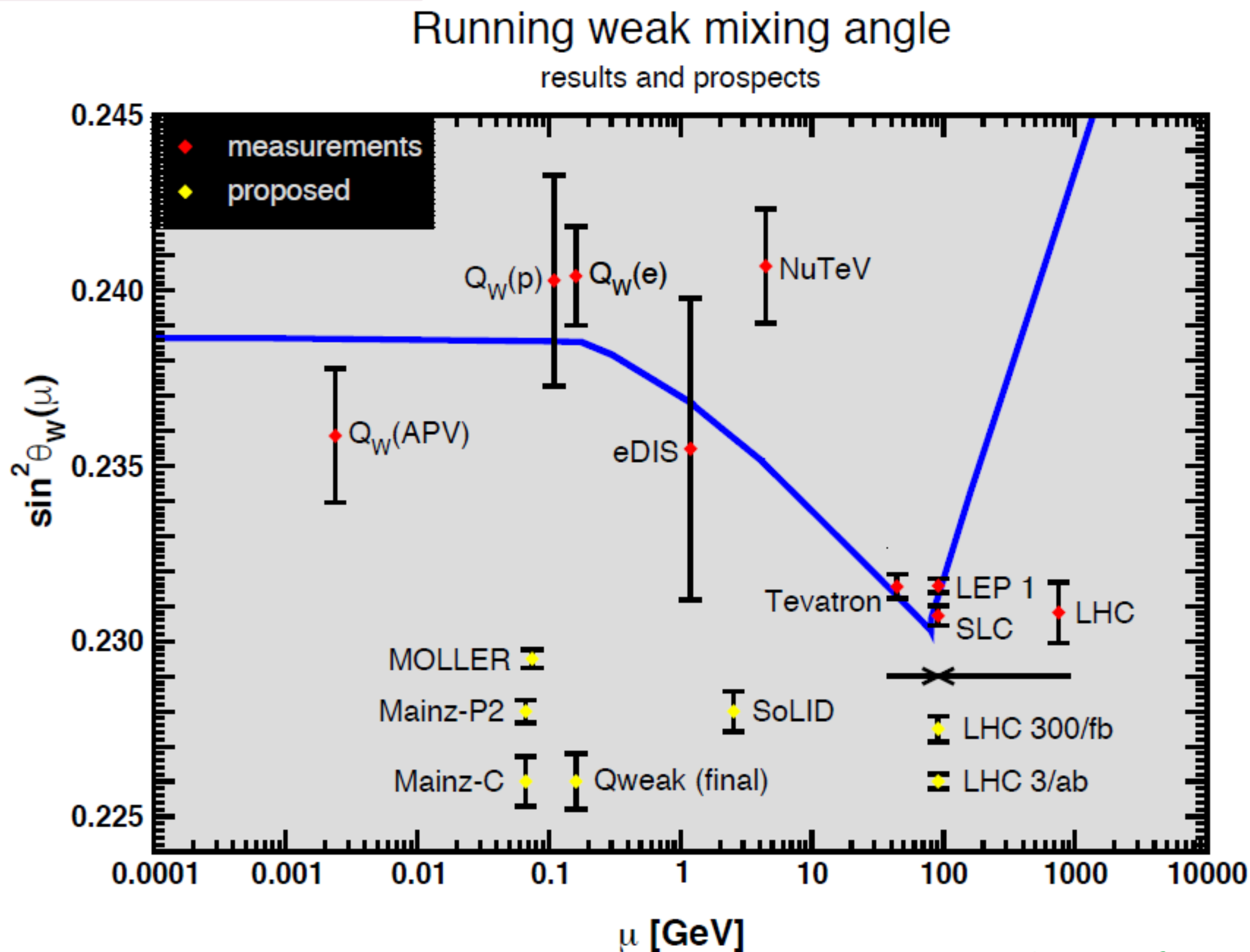
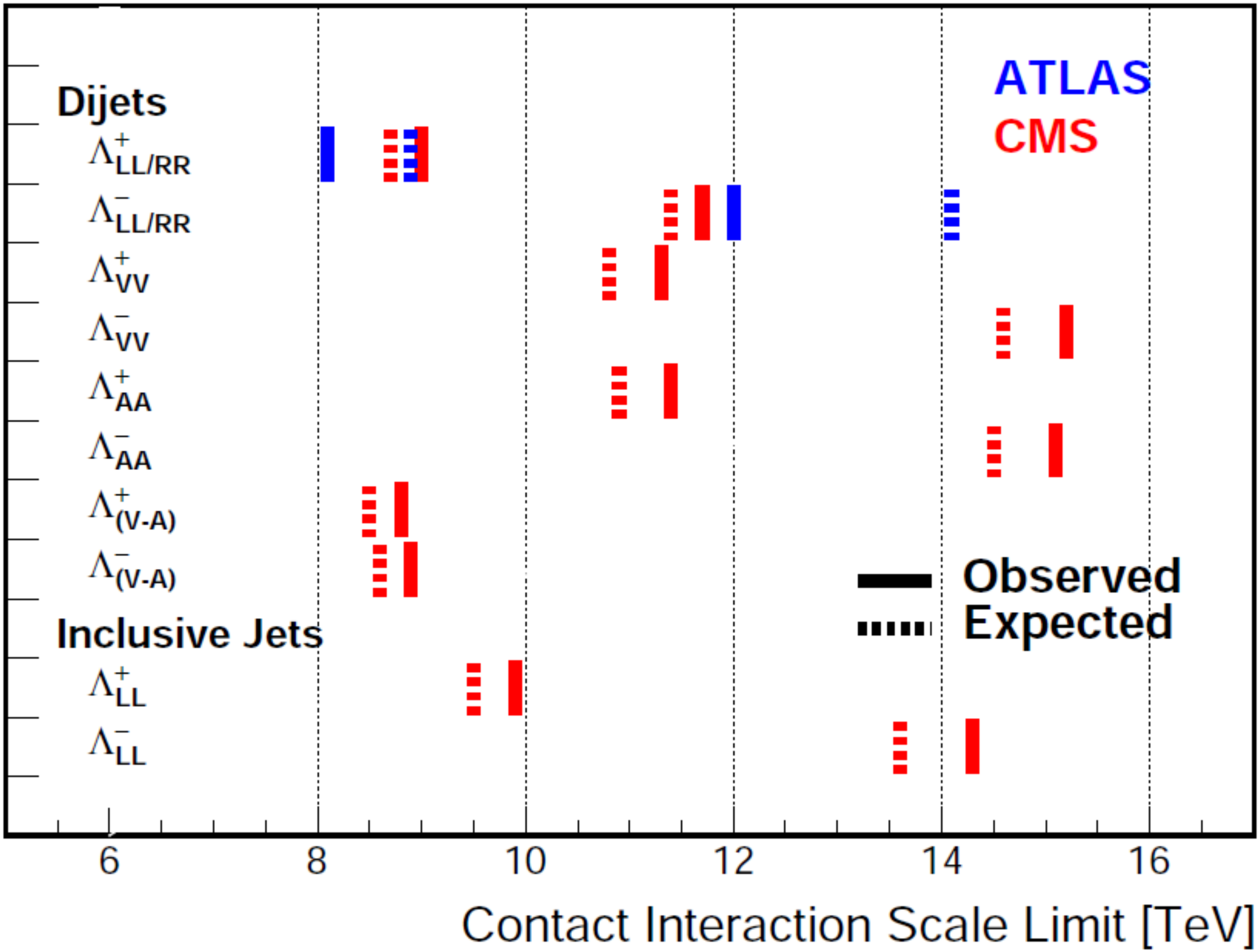


Figure from Jens Erler, WIN2017

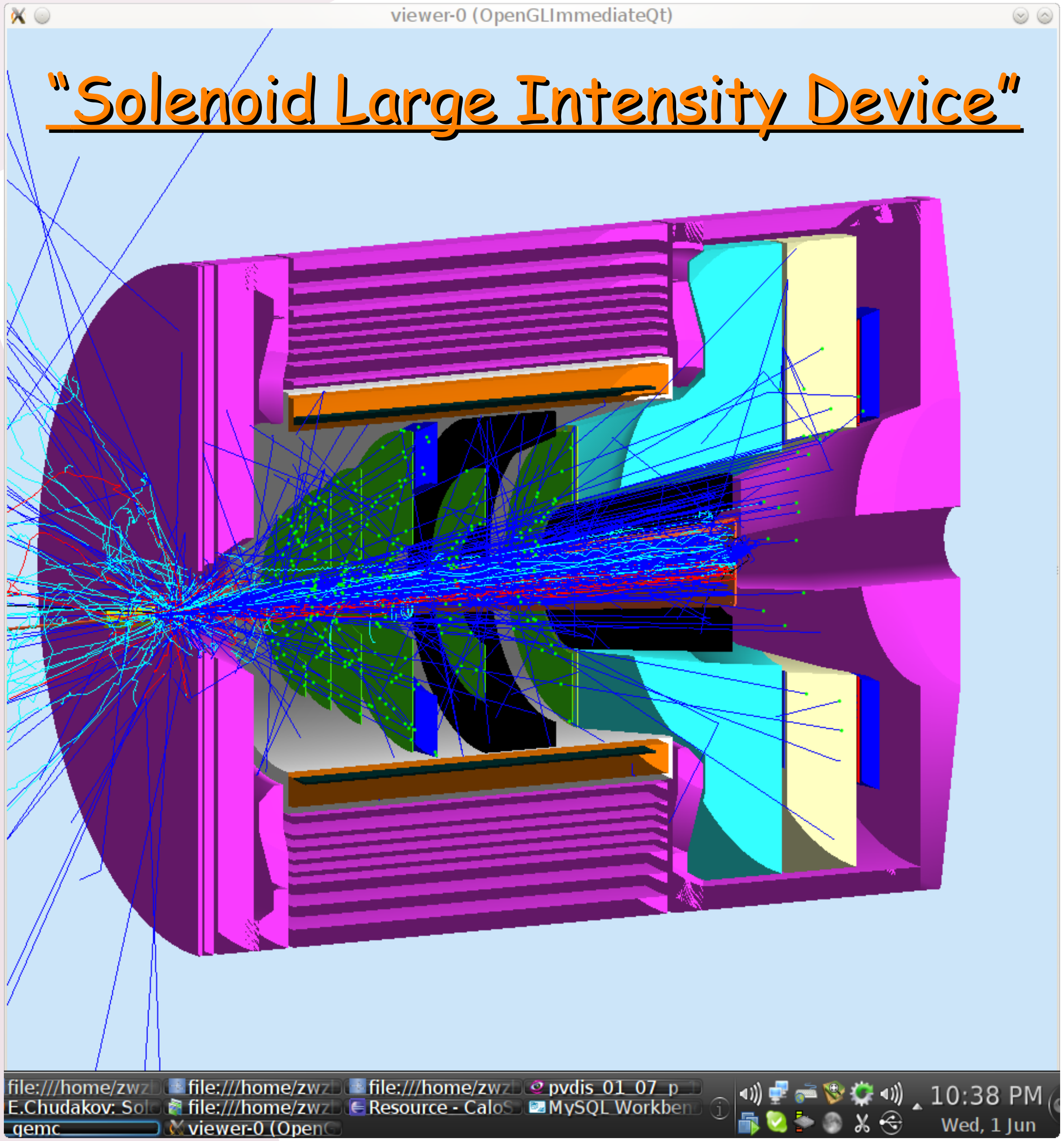
Contact Interaction Limits from LHC (PDG)



We have made the Olympic qualifier, but the semi-final is still a distance away

(我们已经入选奥运，但离前四强还有一定距离）

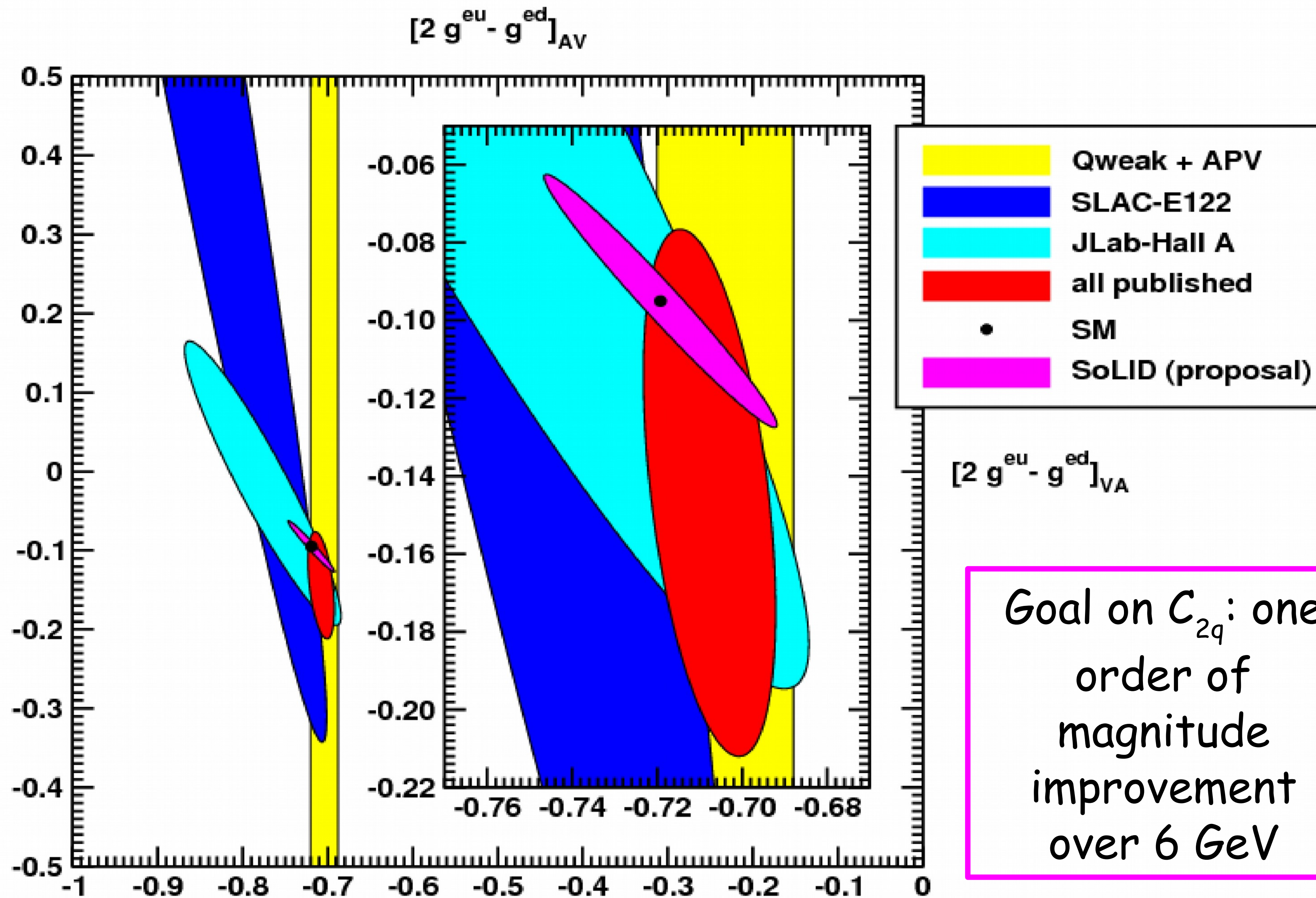
Coherent PVDIS Program with SoLID @ 12 GeV



Planned for Hall A, SoLID Physics topics include:

- PVDIS
- SIDIS
- DVCS
- J/ψ
- … …

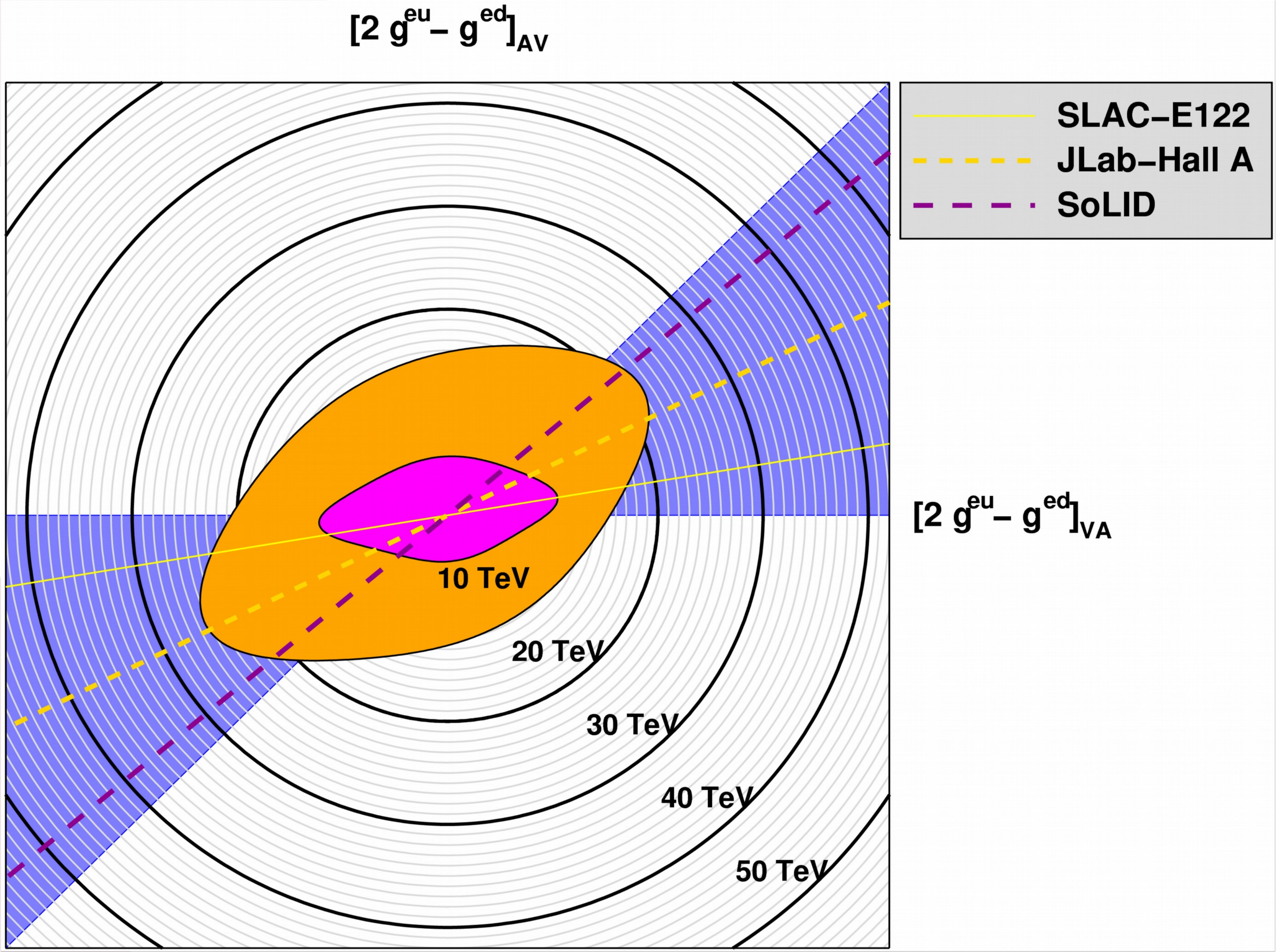
Coherent PVDIS Program with SoLID @ JLab 12 GeV



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

X.

Coherent PVDIS Program with SoLID @ 11 GeV



X. Zheng, University of Virginia, talk at Hadron2017, July 27, 2017, Nanjing, China

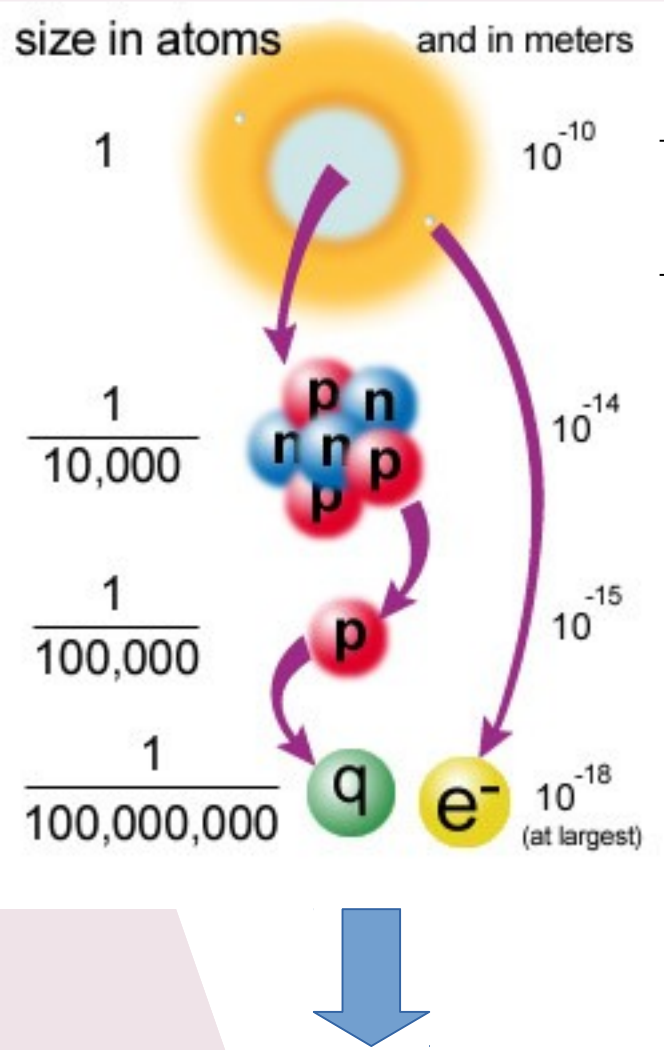
SoLID in the 2015 US Nuclear Science Long Range Plan

… ... Finally, the proposed multipurpose SoLID detector (see Figure 2.6) would realize the full potential of the upgraded CEBAF.

SoLID boasts large acceptance detection with operability at extremely high luminosities and offers unprecedented opportunities to provide precision 3D imaging of the motion of valence quarks in the nucleon and to probe the Standard Model.

Because of quantum corrections, θW varies with the energy scale of the reaction and could be influenced sensitively by non-Standard-Model physics. New projects, SoLID at JLab and P2 at Mainz, Germany, are planned to limit or discover such contributions in a manner complementary to MOLLER and collider experiments. SoLID, whose design also enables a multi-faceted hadron physics program, will measure the variation of θW in a regime where a previous experiment, NuTeV, found an unexpected discrepancy. SoLID has unique sensitivity to new quark-quark neutral weak forces in an energy regime that is challenging to isolate in other PVES and collider experiments. Indeed, model independent considerations show that the projected sensitivity of all three PVES proposals match, and in some cases exceed, the direct reach of the next phase of the LHC, besides being mutually complementary.

Summary

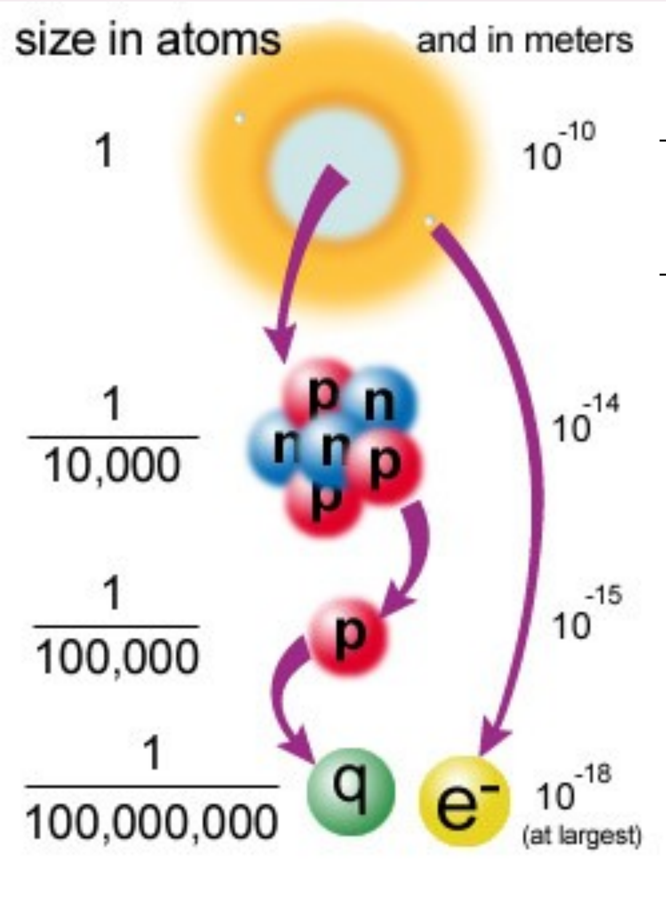


“preons”?

	δx	$\delta p = \frac{\hbar}{2\,\delta x}$	binding energy
electrons in an atom	10^{-10} m	≈ keV	≈ eV
nucleons in the nucleus	$10^{(-14\sim-15)}$m	≈10^2MeV	≈10^1MeV
quarks in nucleons	10^{-15}m	≈10^2MeV	(≈10^2MeV)
preons in quarks and leptons:	$10^{-19\sim-18}$ m	≈ 10^2GeV -TeV	≈TeV

Precision PVES study and SoLID as one of the mid-scale new construction projects, have become central to the US 2015 Nuclear Science Long Range Plan. We are now venturing into a new era of Standard Model study using tools from nuclear physics.

Summary



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"Physicists from China are driving a science program around the foreseen SoLID apparatus." (2015 LRP) – Let's keep it this way, or better, play more leading roles in more SoLID science programs.

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

The Jefferson Lab PVDIS Collaboration

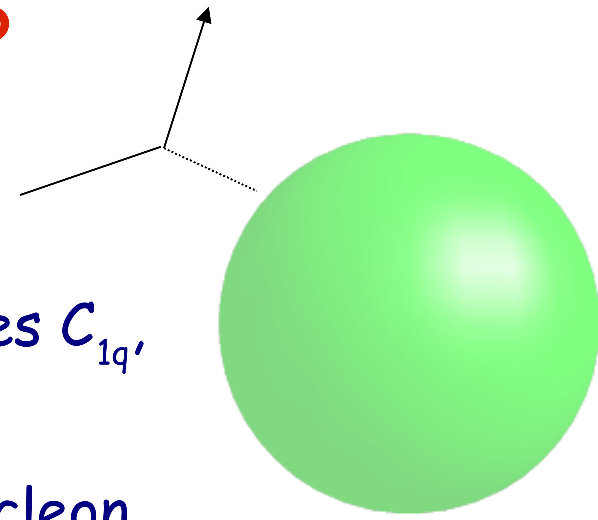
D. Wang, K. Pan, R. Subedi, X. Deng, Z. Ahmed, K. Allada, K. A. Aniol, D. S. Armstrong, J. Arrington, V. Bellini, R. Beminiwattha, J. Benesch, F. Benmokhtar, W. Bertozzi, A. Camsonne, M. Canan, G. D. Cates, J.-P. Chen, E. Chudakov, E. Cisbani, M. M. Dalton, C. W. de Jager, R. De Leo, W. Deconinck, A. 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

Backup

$$\mathfrak{L}_{\psi\psi} = (g^2/2\Lambda^2)[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L].$$

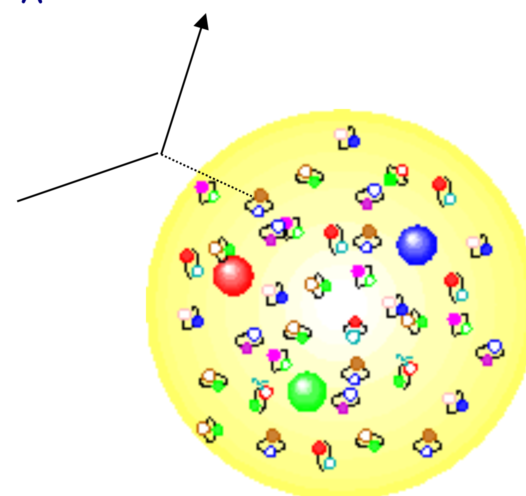
$$VV = +LL + LR + RL + RR$$
$$VA = -LL + LR - RL + RR$$
$$AV = -LL - LR + RL + RR$$
$$AA = +LL - LR - RL + RR$$

Accessing C_{2q} in PVES



- **Elastic PVES:**
  - Hadronic effects suppressed, 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

PV in Deep Inelastic Scattering (PVDIS):



measure both C_{1q} and C_{2q} explicitly.

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

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

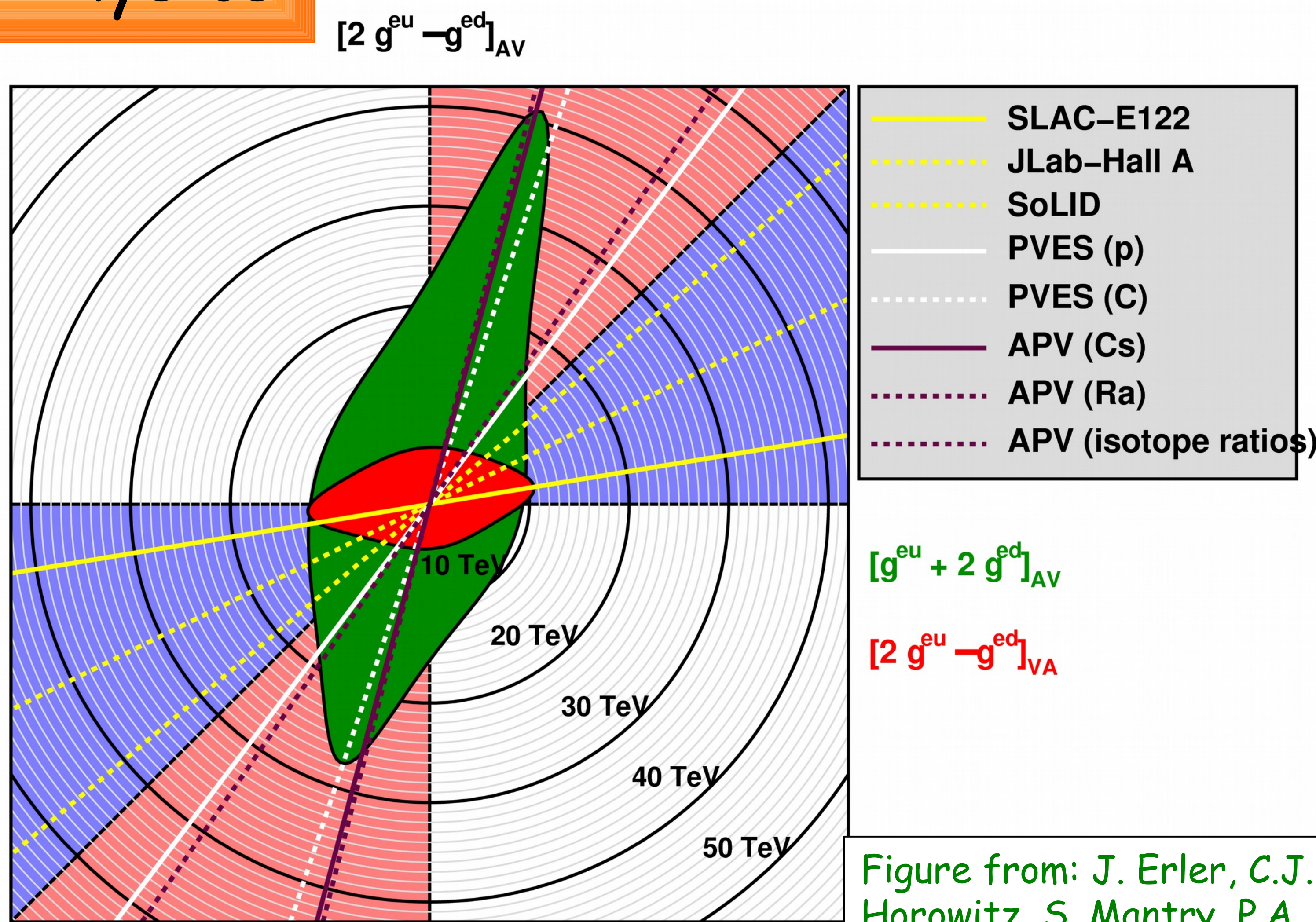
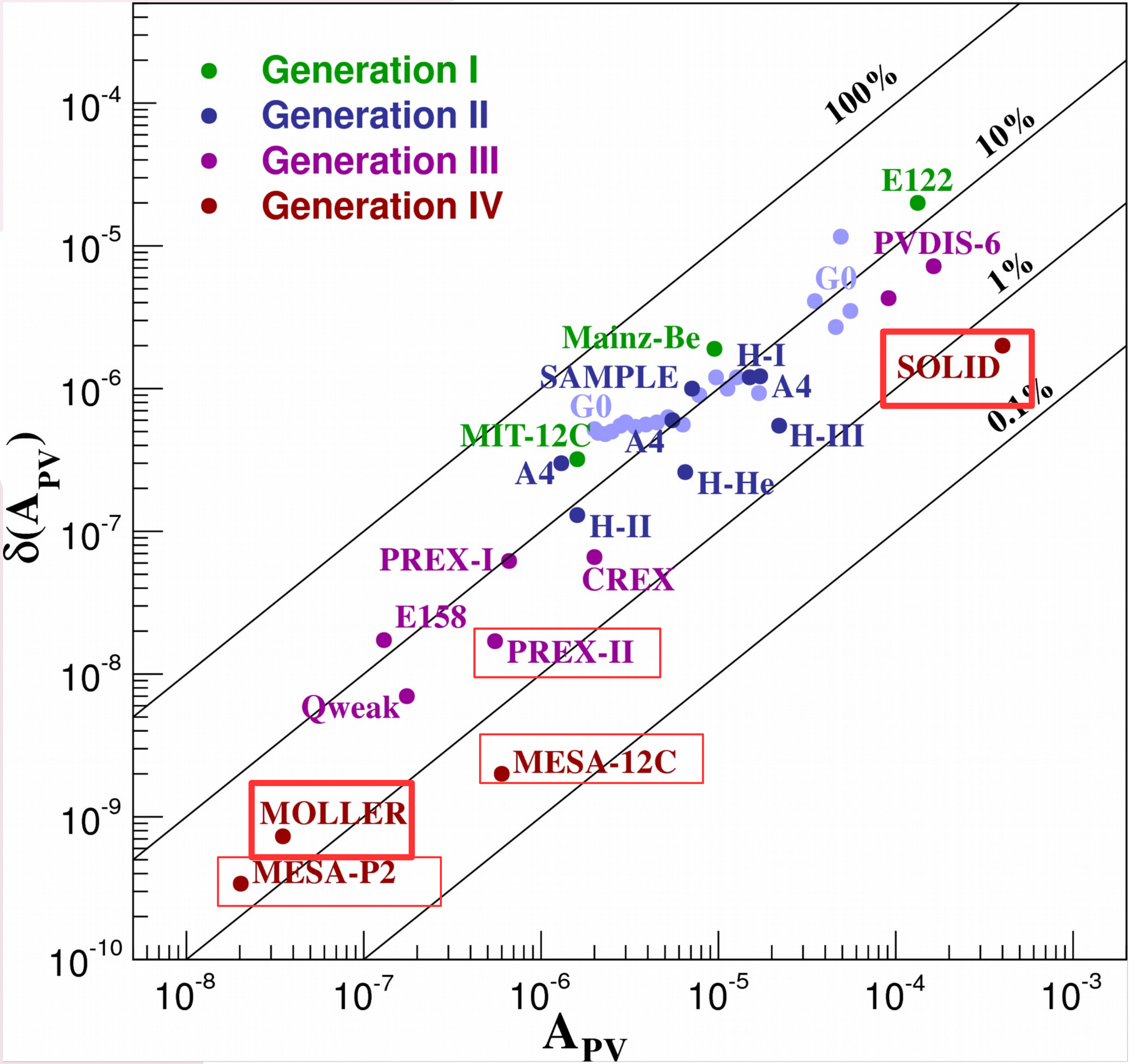


Figure from: J. Erler, C.J. Horowitz, S. Mantry, P.A. Souder, arxiv/1401.6199, Annual Review of Nucl and Part. Science, 64 (2014)

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