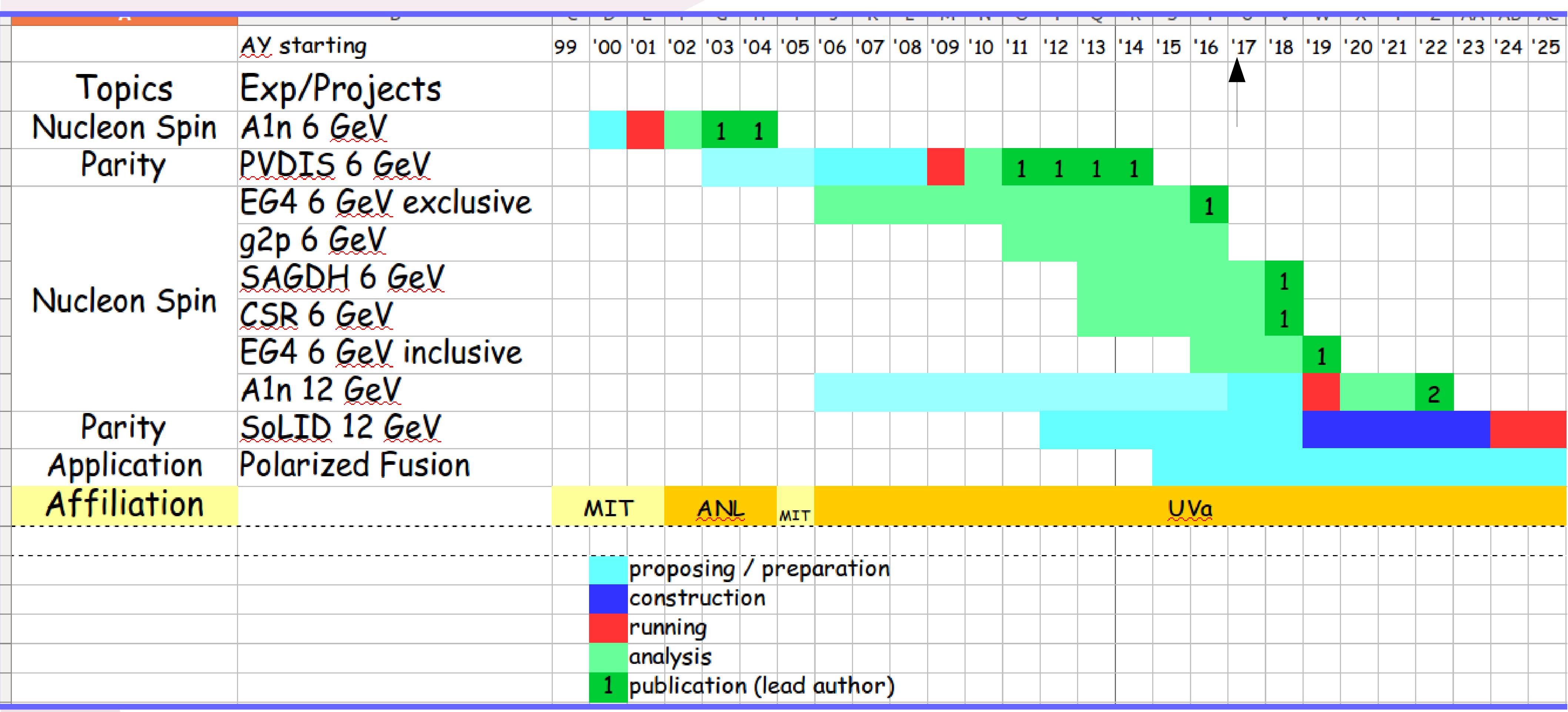



**The Jefferson Lab PVDIS Collaboration**

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

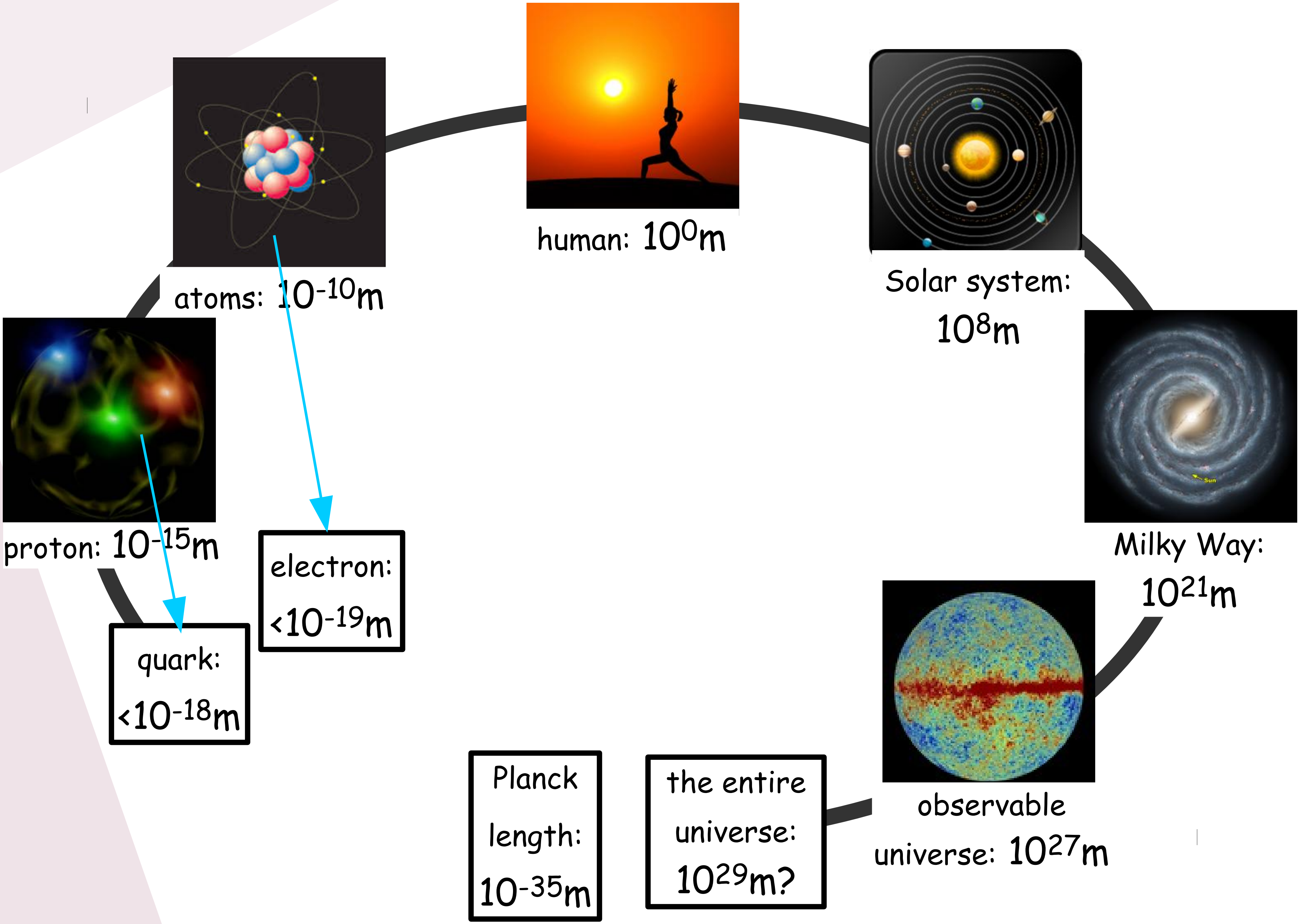
# Peeling the Atomic Onion

Xiaochao Zheng

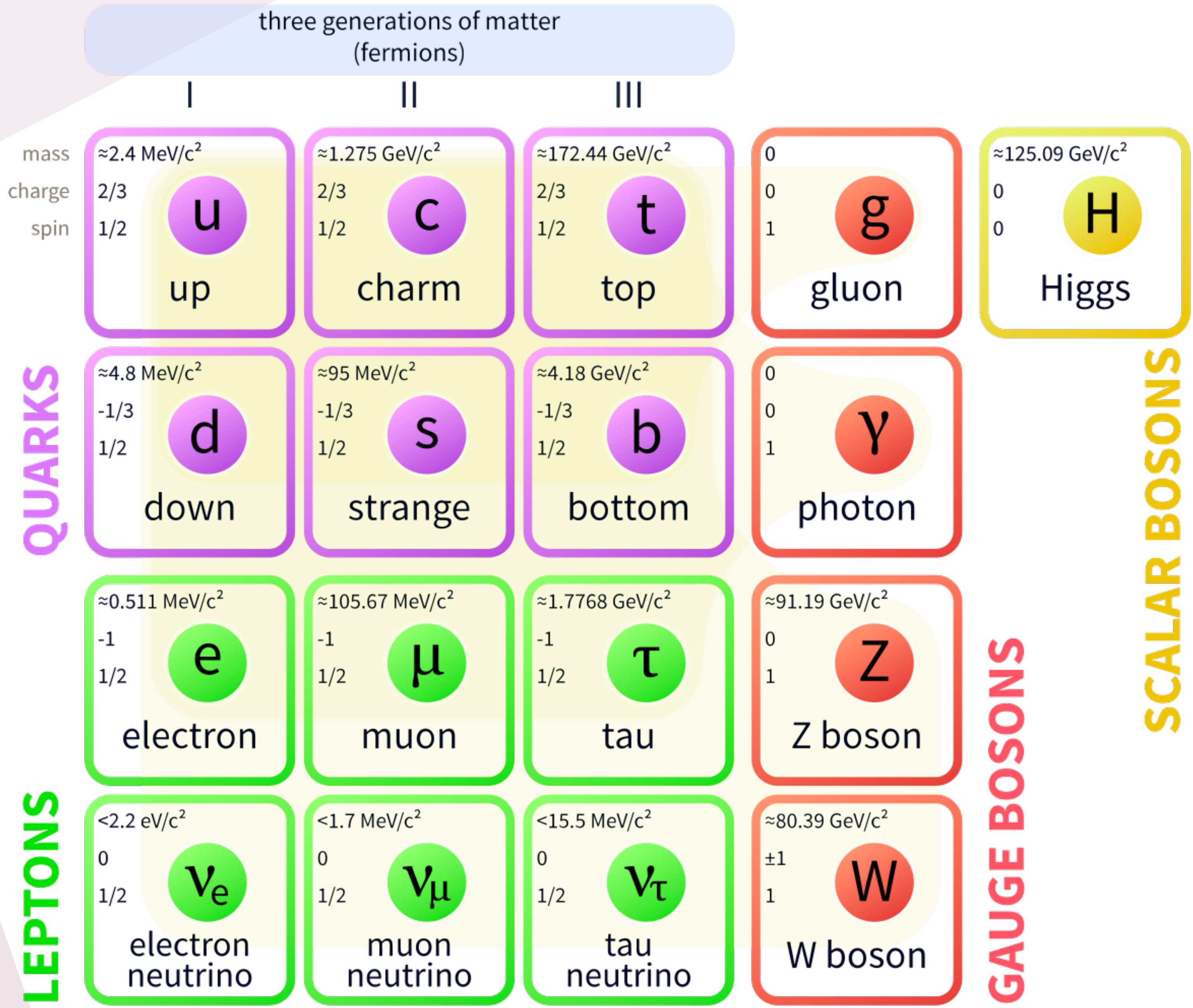
September 29th, 2017

- The Scale of Everything and the Standard Model of Particle Physics
- Questions to be asked
- Electron scattering, deep inelastic scattering (DIS), and quarks
- Parity-violation in DIS, electron-quark effective couplings and “new” contact interactions
- Summary and outlook

# The Beauty of Physics – From Leptons and Quarks to the Cosmos



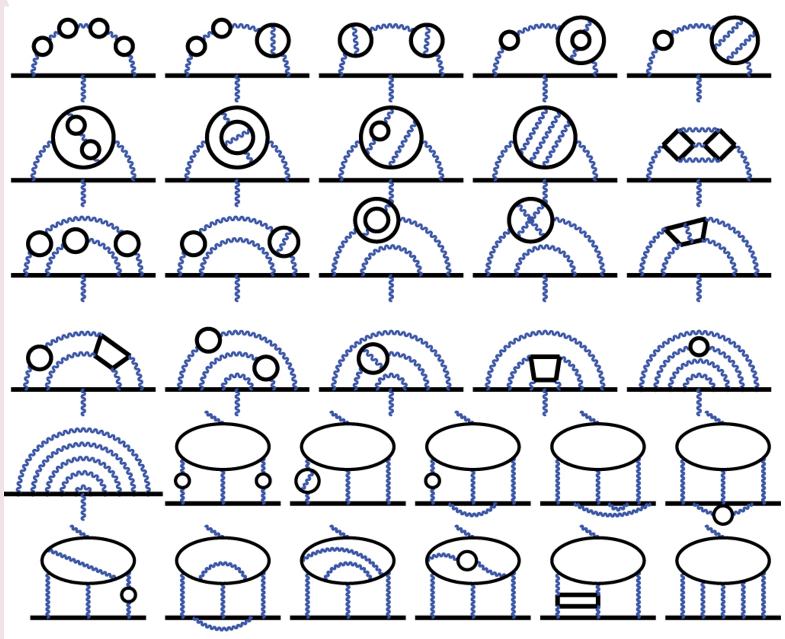
# Standard Model of Elementary Particles



# The Four Interactions of Nature

| | | |
|---|---|---|
| Electromagnetic | $10^{-2}$ | SU(2)xU(1) |
| Weak | $10^{-5}$ at low E | |
| Strong | $10^{-1}\sim10^{0}$ | SU(3) QCD |
| Gravitational | $10^{-38}$ | General relativity |

QED: tested to $10^{-9}$ accuracy



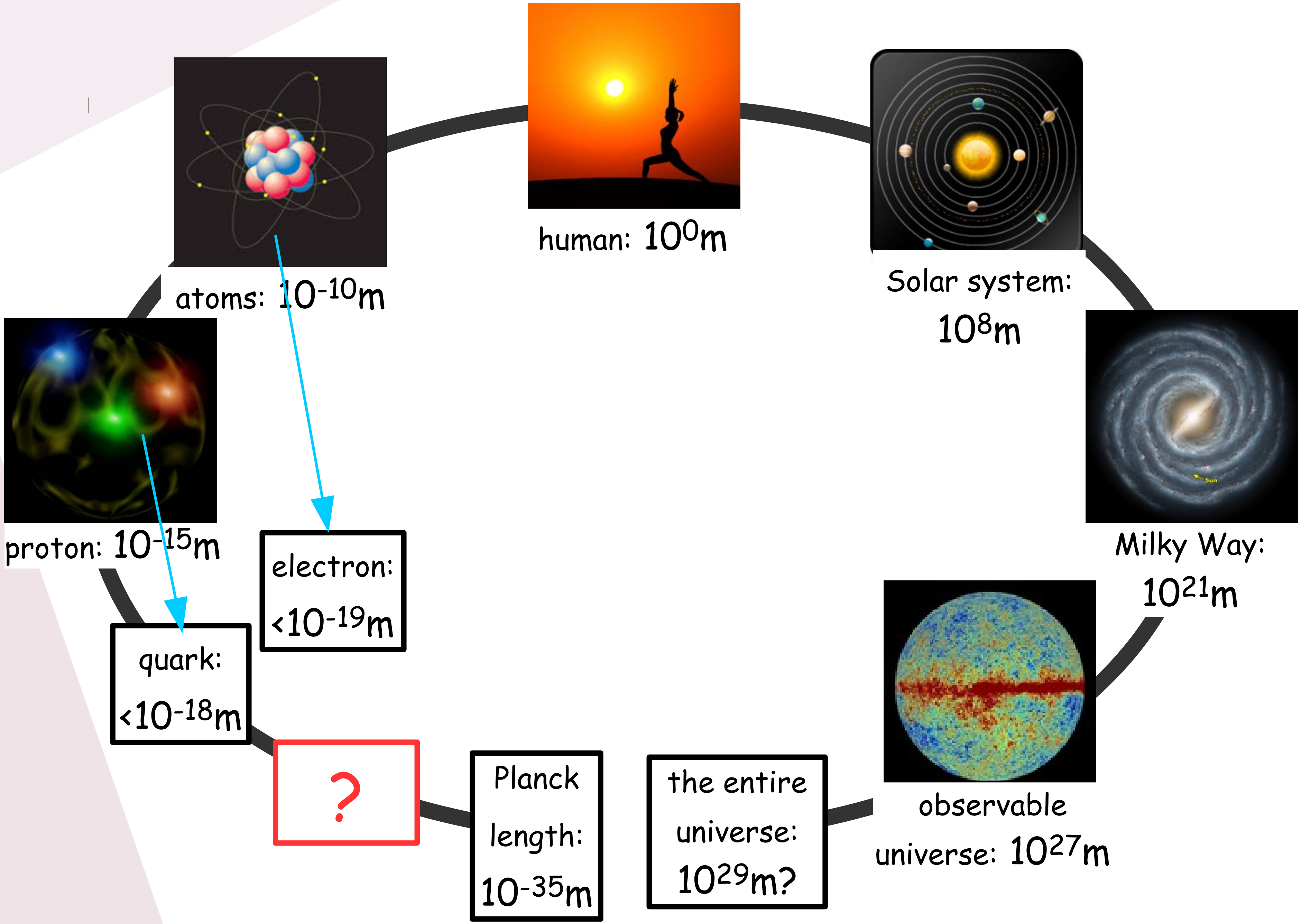
Weak

- Tested to good precision, but there are uncharted areas

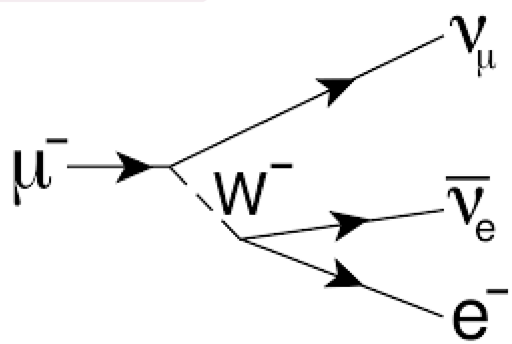
Strong

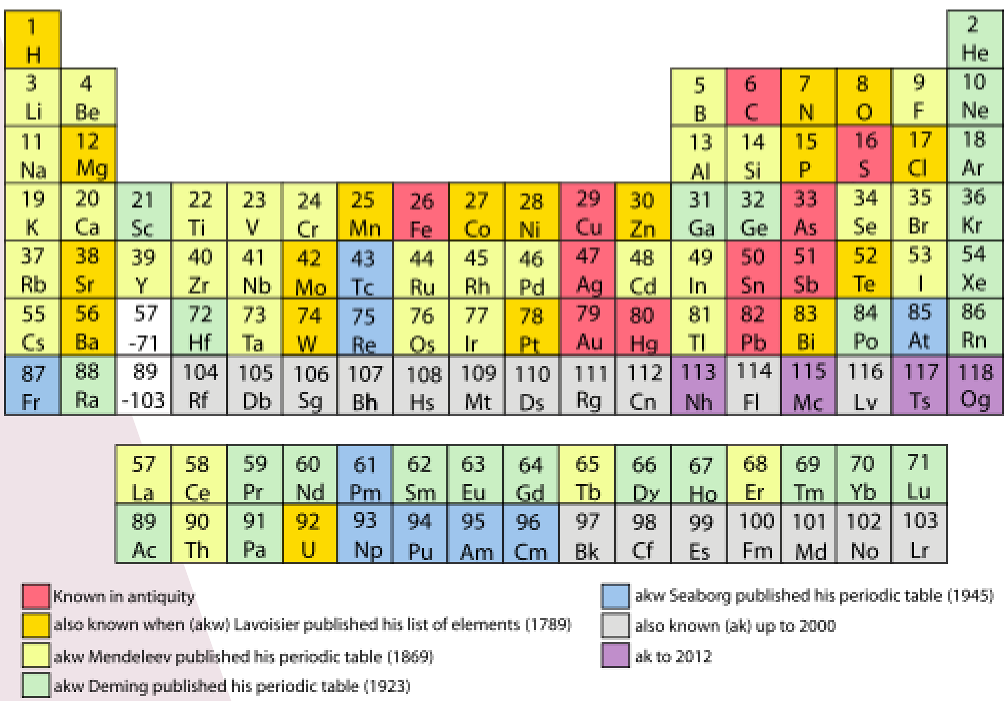
- Gluons carry colors!
- quasi-free at small scales, color confinement at large scales

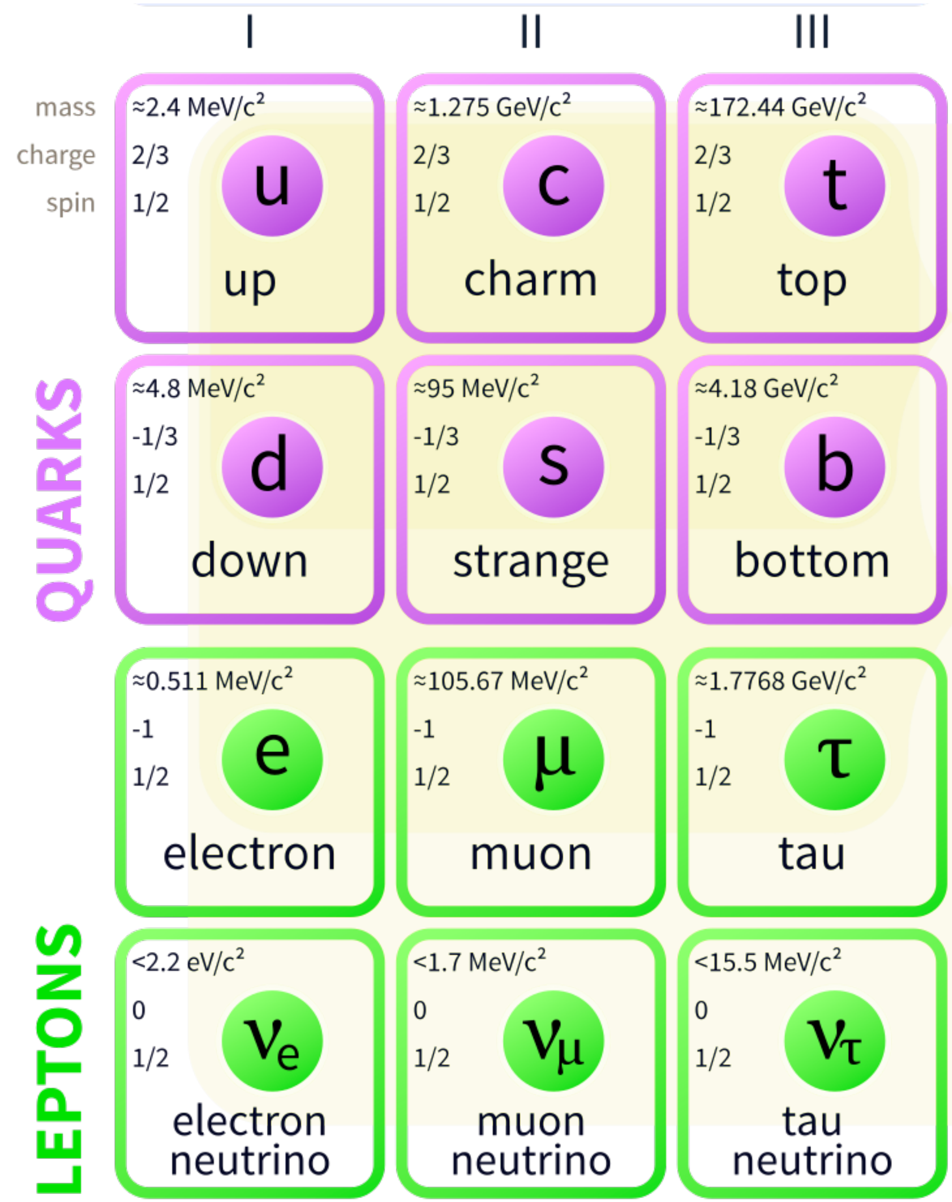
# The Beauty of Physics – From Leptons and Quarks to the Cosmos



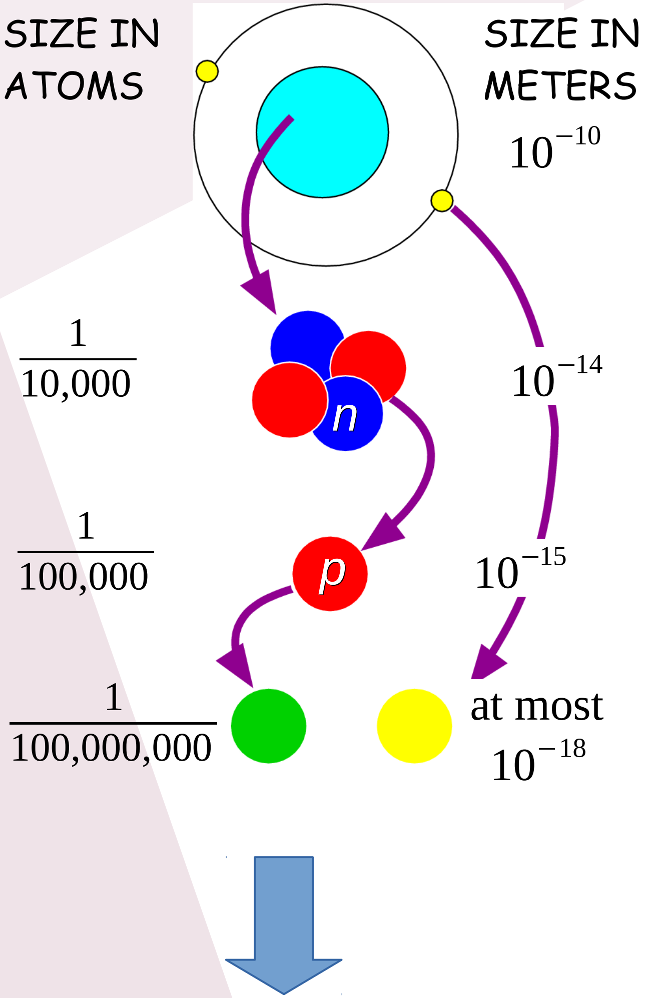
# Caught in the Act !



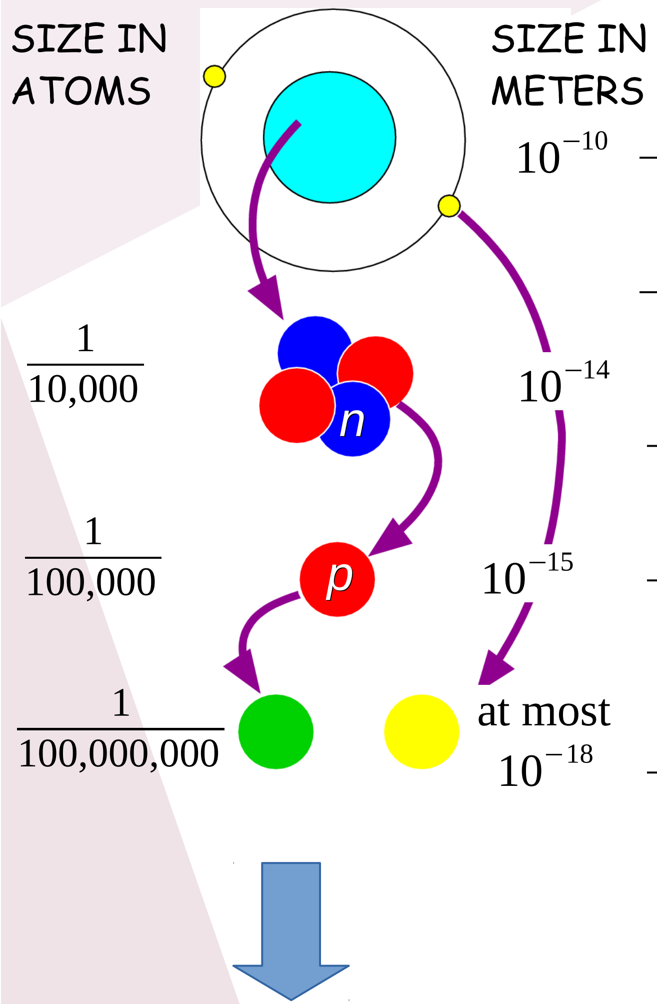
# More Layers?




"preons"?
（初子？）

Just as nuclear power was inconceivable before the discovery of atomic structure, unveiling a new layer of matter would reveal phenomena we cannot imagine.

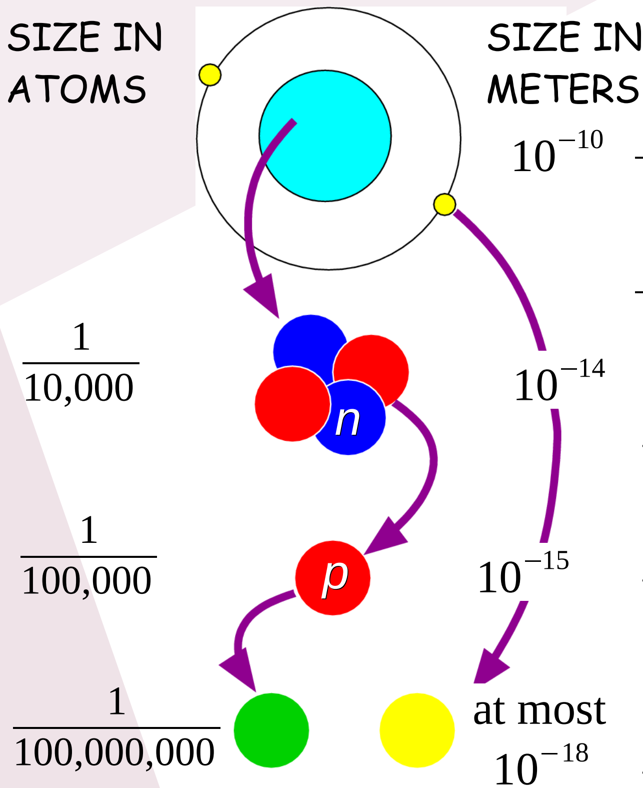
# Modern Physics Homework




“preons”?
（初子？）

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

# Modern Physics Homework

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|---|---|---|---|
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| nucleons in the nucleus | $10^{(-14\sim-15)}$m | $\approx 10^2$MeV | $\approx 10^1$MeV |
| quarks in nucleons | $10^{-15}$m | $\approx 10^2$MeV | ($\approx 10^2$MeV) |
| preons in quarks and leptons: | $10^{-19\sim-18}$ m | $\approx 10^2$GeV -TeV | ≈TeV |

"preons"?
（初子？）

- If preons exist, they may (must?) interact through a new interaction, with an energy scale at the TeV level; The effect would be extremely small at low energies

# The Four Interactions of Nature

| | | |
|---|---|---|
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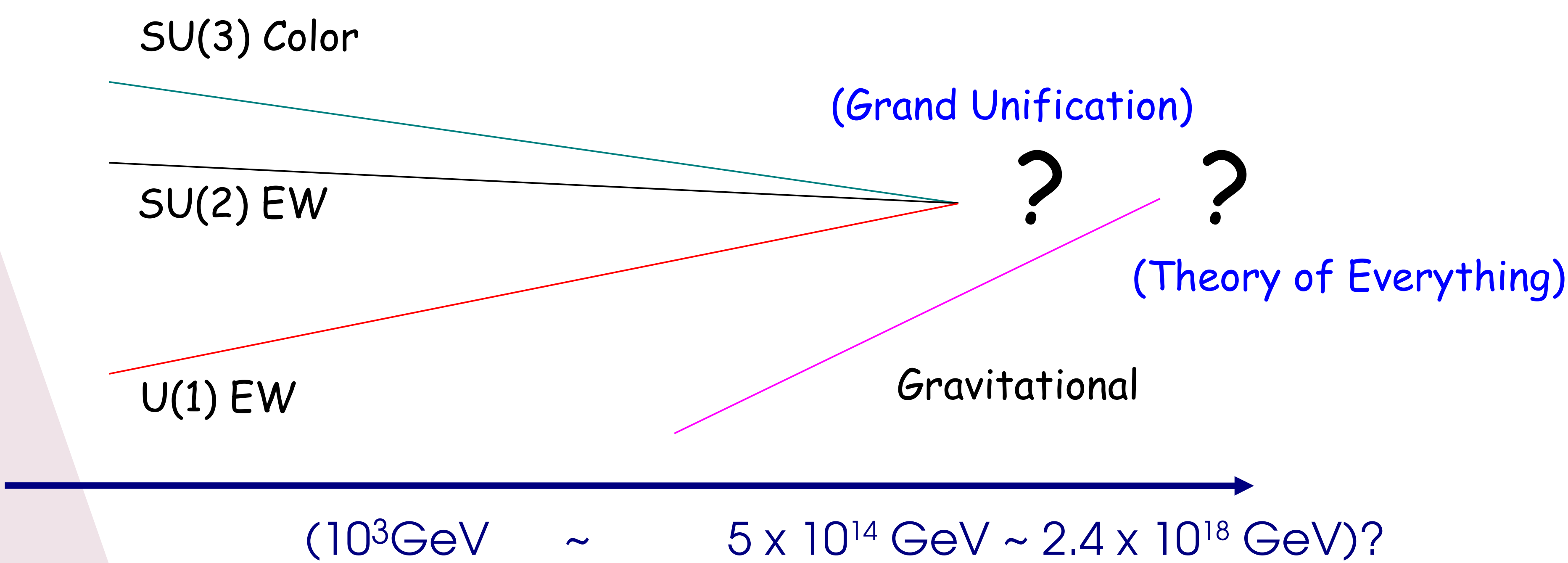


# Questions to be asked

- Are quarks and leptons the end of the story? Is there an end to our study of the subatomic structure?
- Are there new interactions (new physics) beyond the four known interactions?
- Do our answers to the above two questions automatically answer some of the existing questions about the Standard Model?

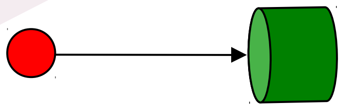
# The Role of Electron-Nucleon Scattering

Electron beam = a source of photons and $Z^0$'s

- photons: probe structure of the nucleon – how do quarks form the nucleon energy, mass, spin … … via strong interactions?
- $Z^0$s: parity violation electron scattering – high precision test of the electroweak interaction and to search for new physics beyond the Standard Model

# Electron Scattering on Fixed Nuclear or Nucleon Targets

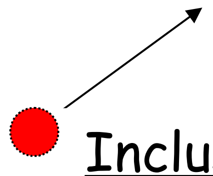
electron beam (GeV)



target (at rest)

**Before**

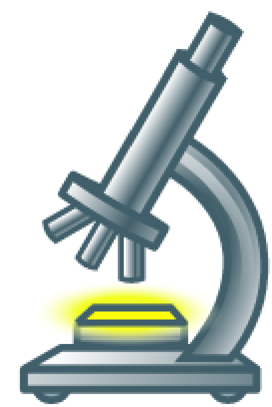
to detector



Inclusive: only the scattered electron is detected

**After**

$$\lambda_{DB} = \frac{197\ MeV \cdot fm}{1\,GeV} = 0.2\ fm$$



# Electron Scattering on Fixed Nuclear or Nucleon Targets

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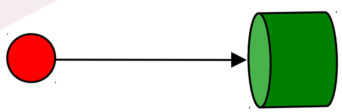
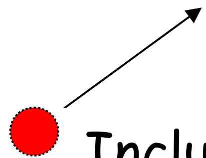


target (at rest)

**Before**

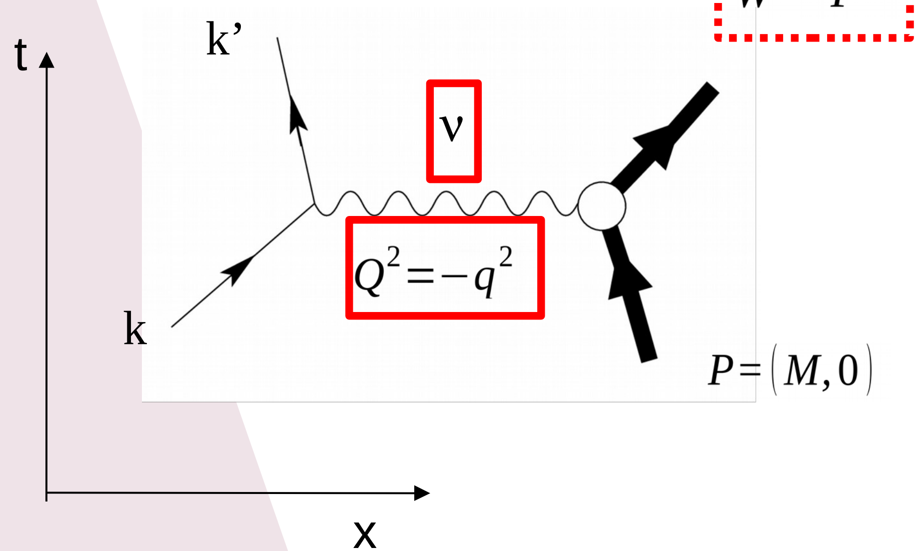
to detector

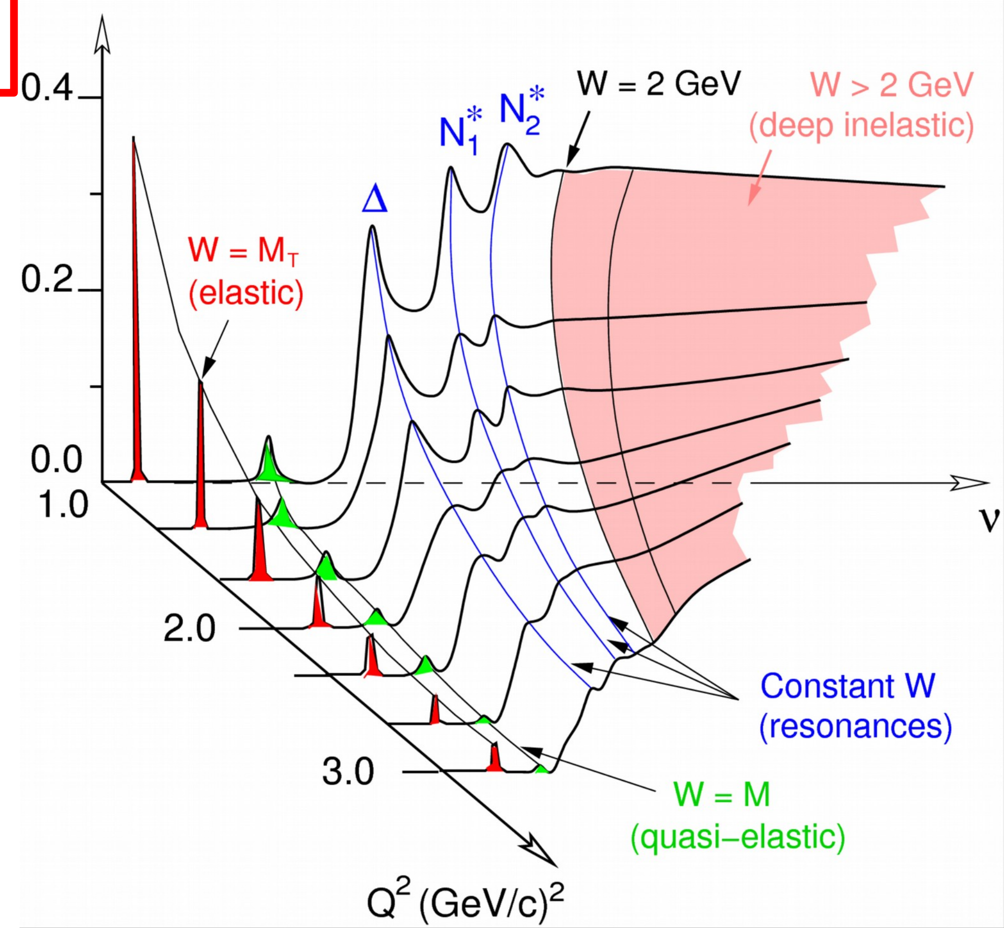


<u>Inclusive</u>: only the scattered electron is detected

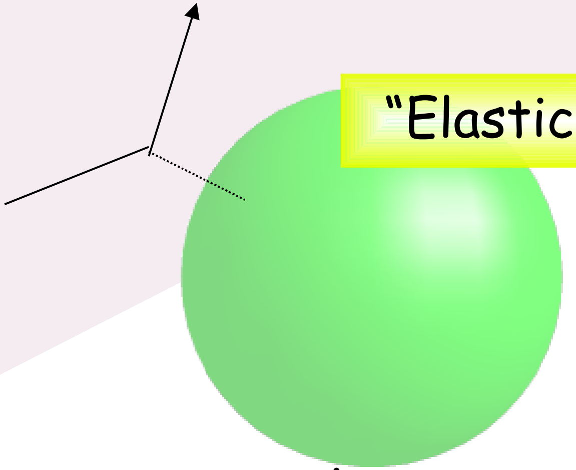
**After**

$$\lambda_{DB} = \frac{197\, MeV \cdot fm}{1\, GeV} = 0.2\, fm$$



# Three kinematic regions

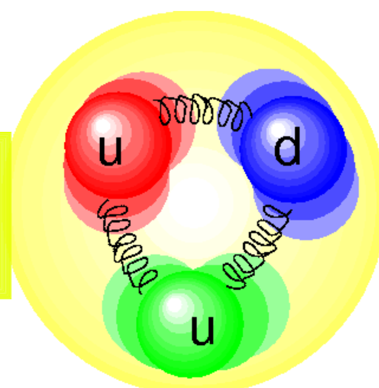


"Elastic": $W=M_t$ or $M_p$

1961

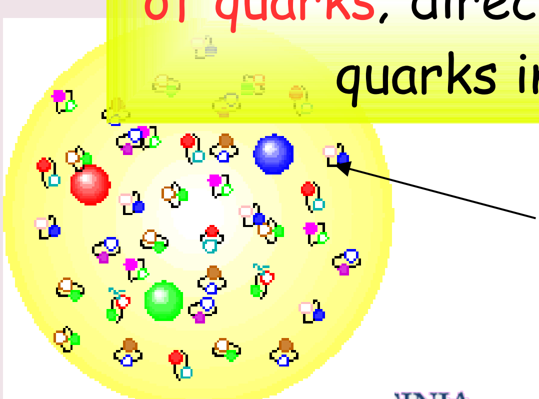
From cross section we extract "elastic form factors"

"Resonance": 1<W<2GeV



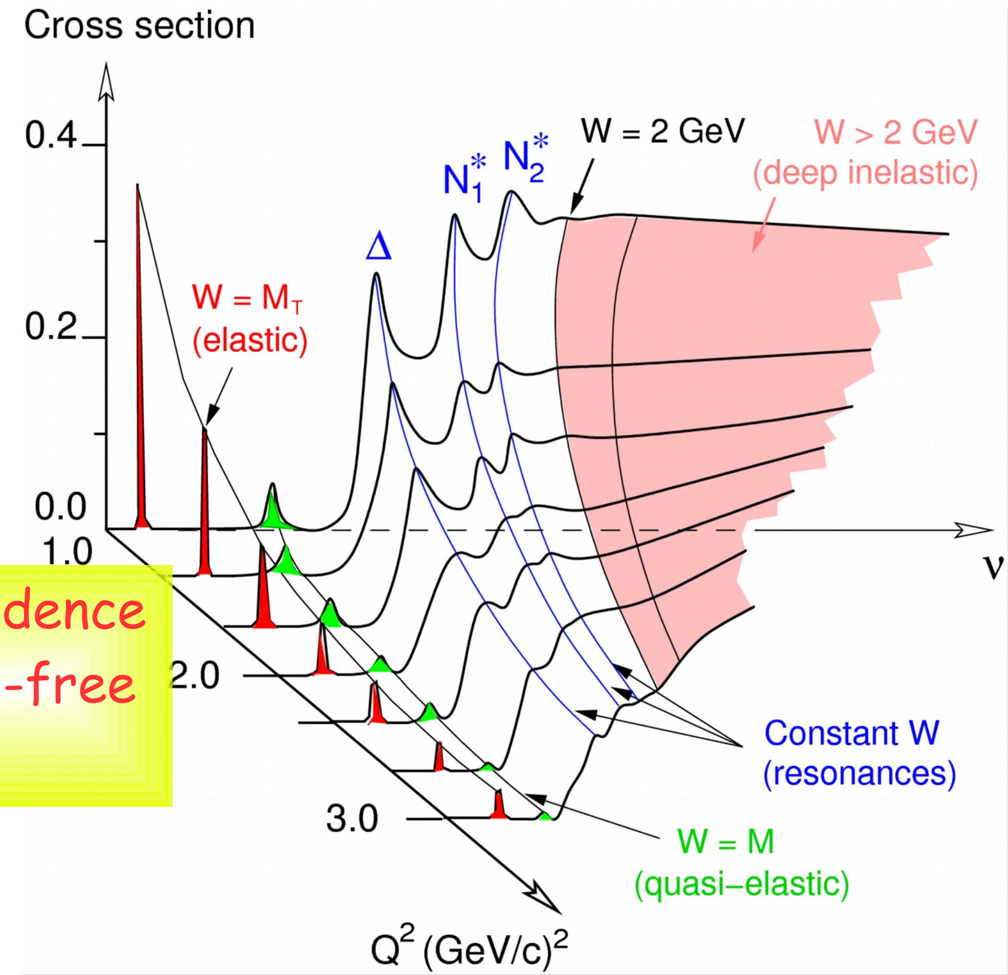

1999
2004

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



$10^{-18}$m or smaller

We can select the physics by choosing carefully the angle and the momentum of scattered electrons



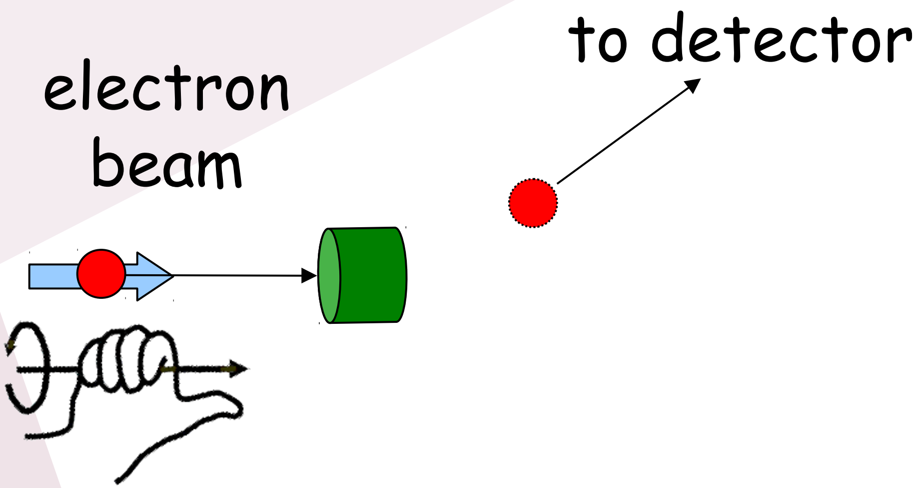
# Symmetry permeates Nature, and Our Lives

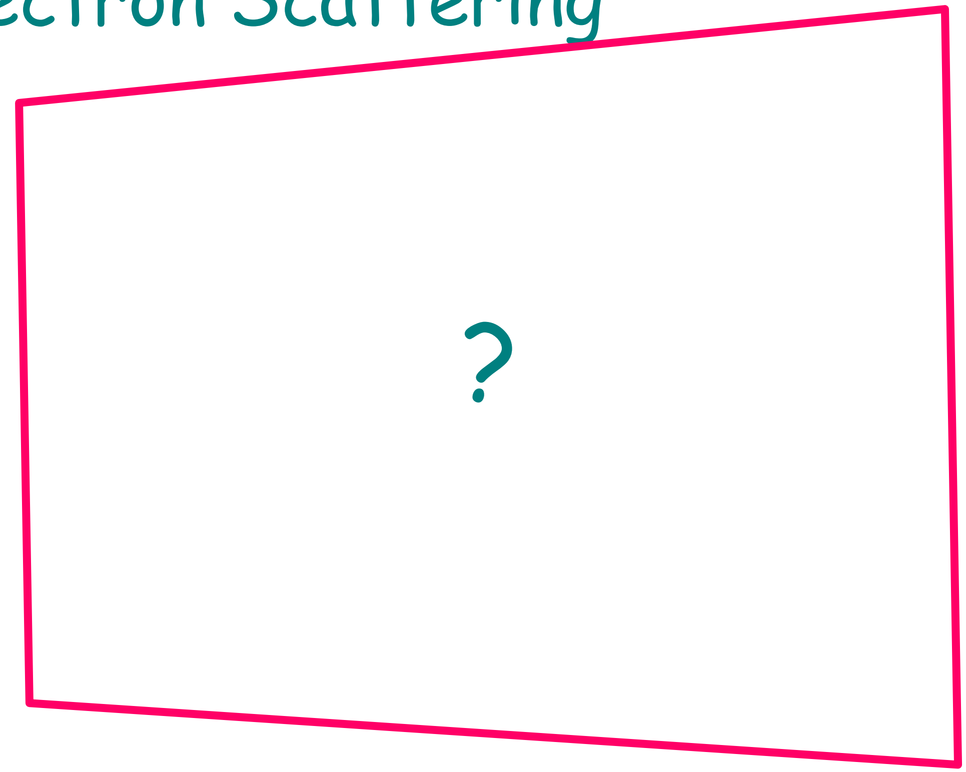

SEEN AROUND BOSTON

**“MIT Stata Center aka The Ugly Building”**

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

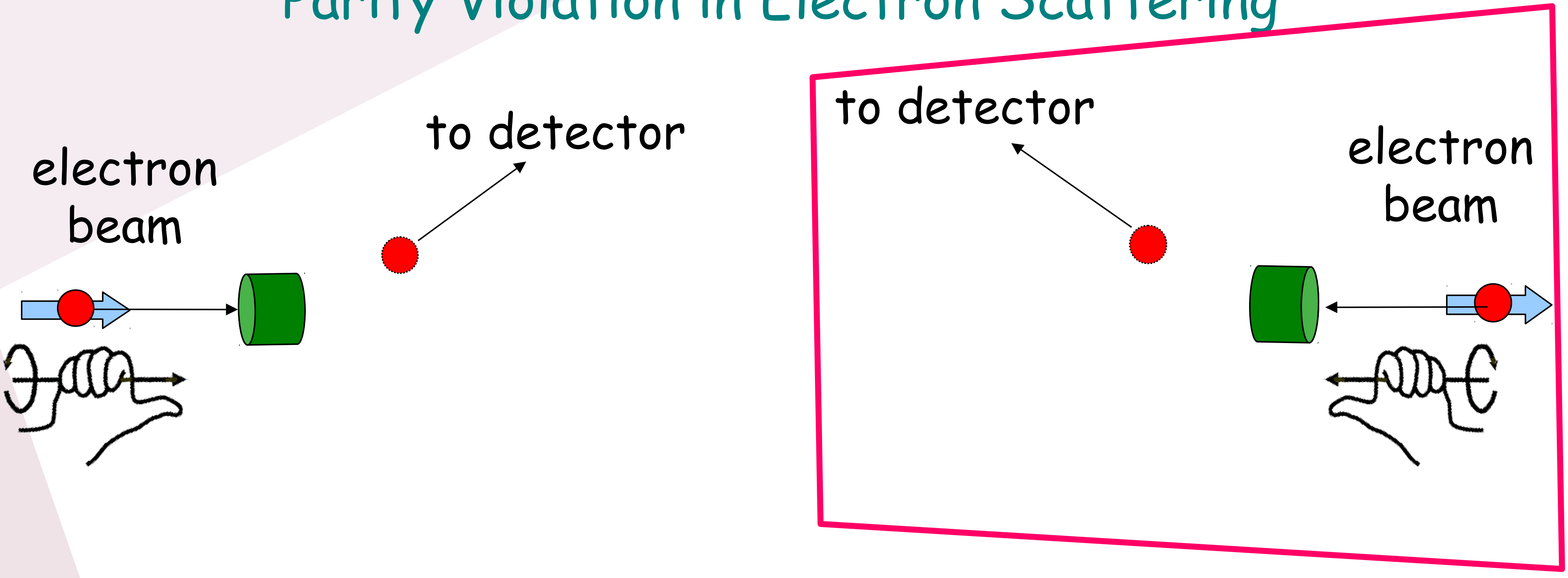
# Parity Violation in Electron Scattering



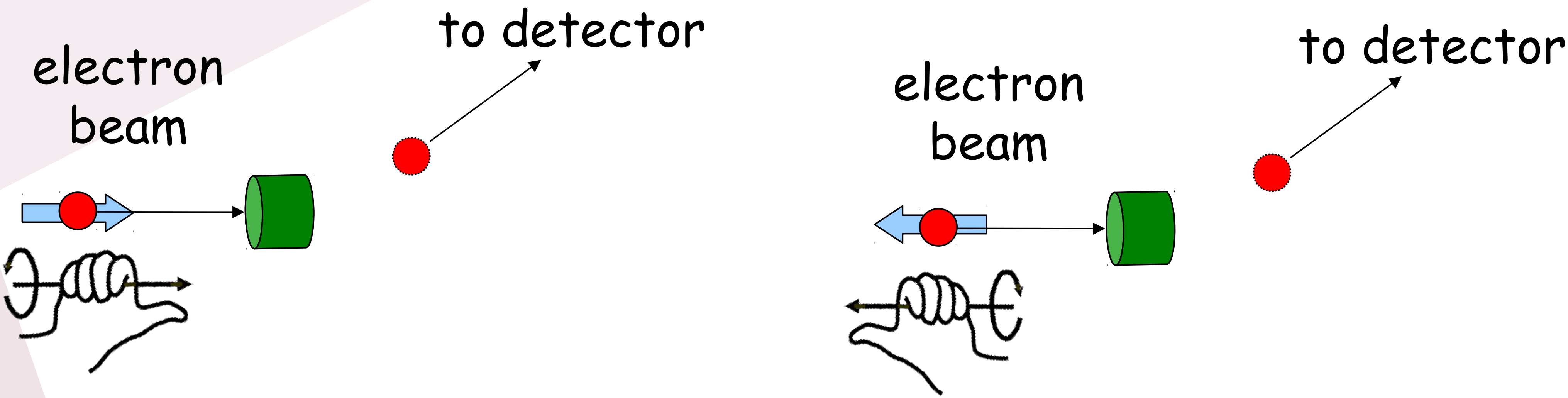




- If parity symmetry were exact, then the physical law behind a process is the same as the law behind its mirror process.

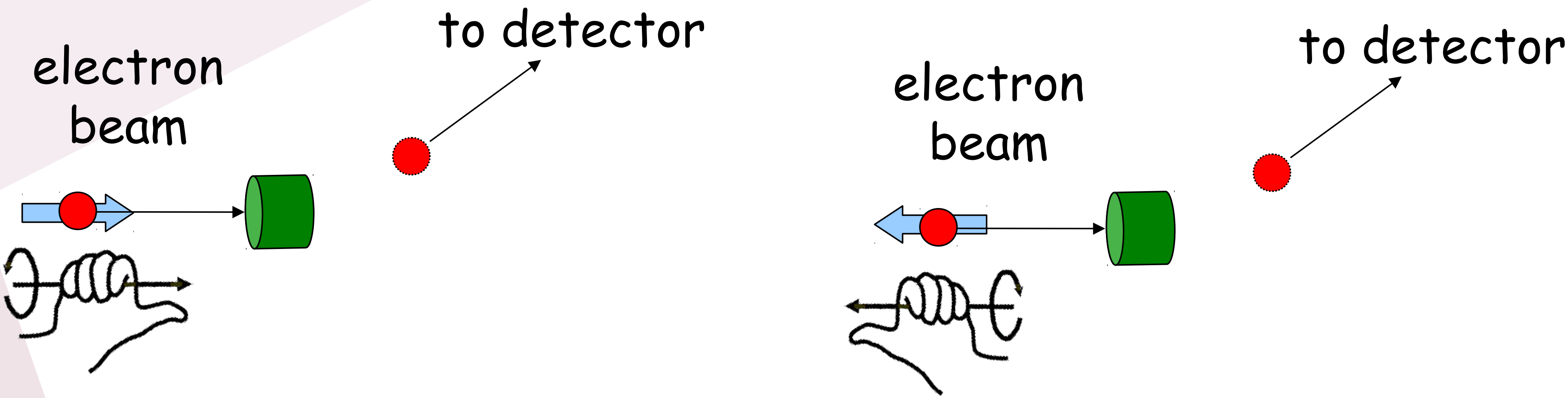
# Parity Violation in Electron Scattering



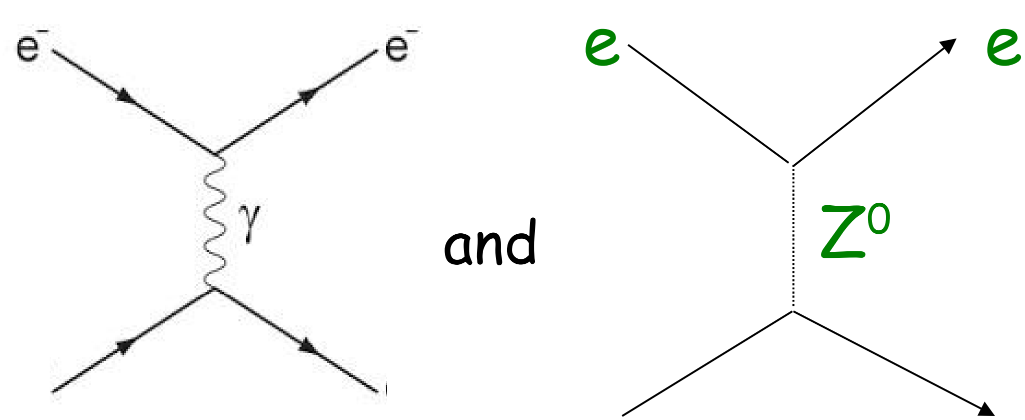
# Parity Violation in Electron Scattering



# 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:



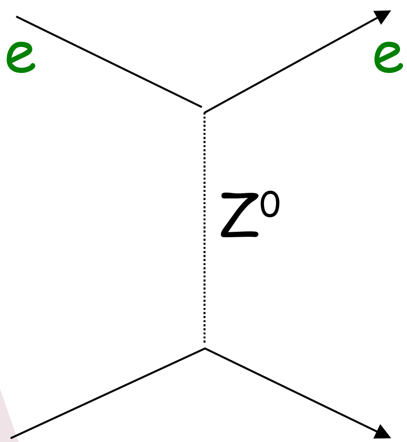

$$A_{LR} \equiv \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} \approx \frac{Q^2}{M_Z^2} \approx 120\,ppm \quad at \quad Q^2 = 1\left(GeV/c\right)^2$$

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

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

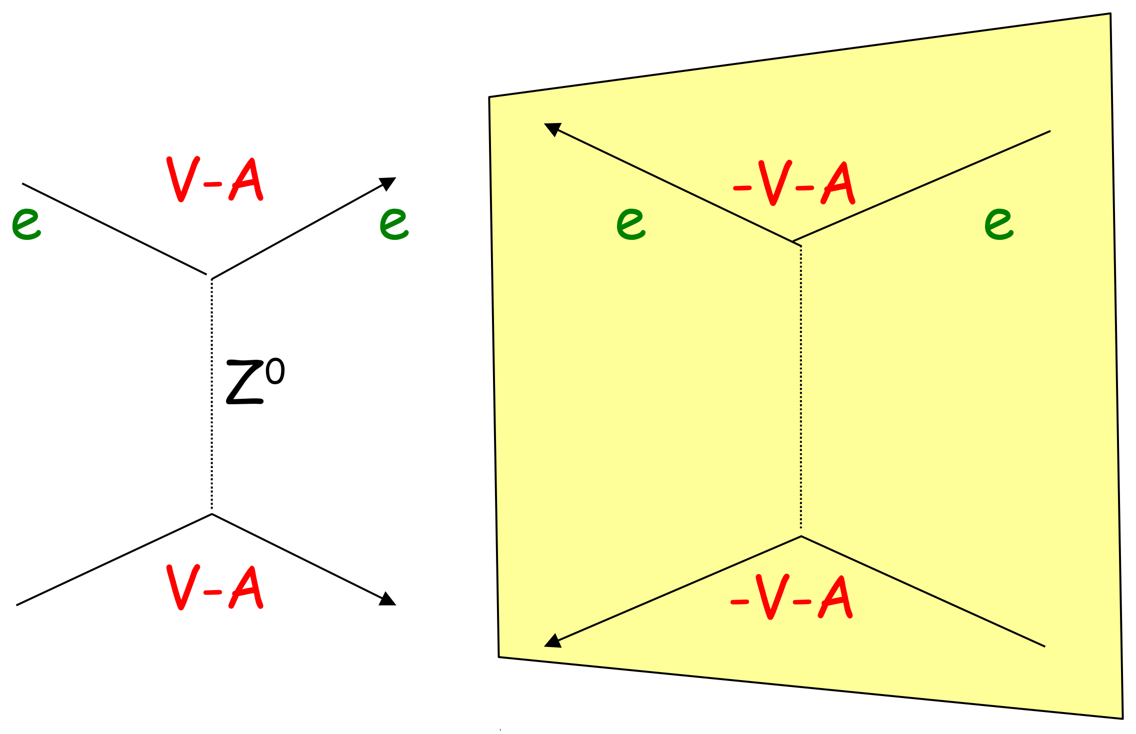



| fermions | $g_A^f = I_3$ | $g_V^f = I_3 - 2Q\sin^2\theta_W$ |
| --- | --- | --- |
| $\nu_e, \nu_\mu$ | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $e$-, $\mu$- | $-\frac{1}{2}$ | $-\frac{1}{2}+2\sin^2\theta_W$ |
| $u$, $c$ | $\frac{1}{2}$ | $\frac{1}{2}-\frac{4}{3}\sin^2\theta_W$ |
| $d$, $s$ | $-\frac{1}{2}$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

# 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: $g_V \sim (g_L + g_R)$ $g_A \sim (g_L - g_R)$
- PVES asymmetry comes from V(e)xA(targ) and A(e)xV(targ)

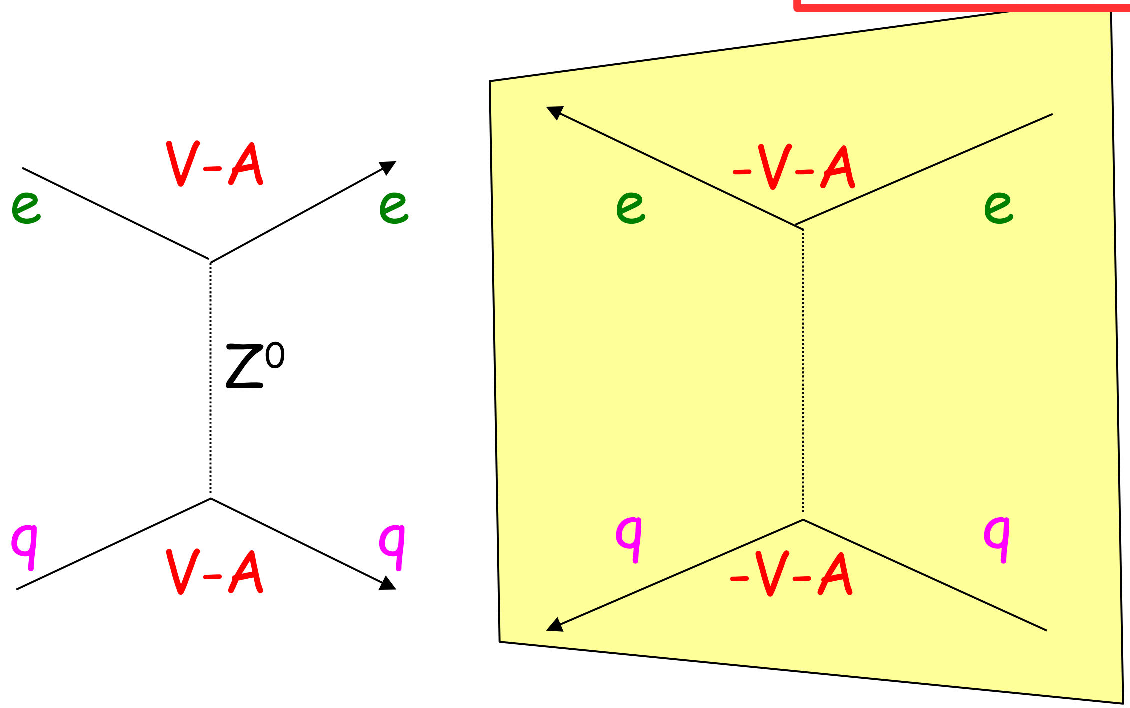


# Standard Model Predictions for PVES

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

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

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

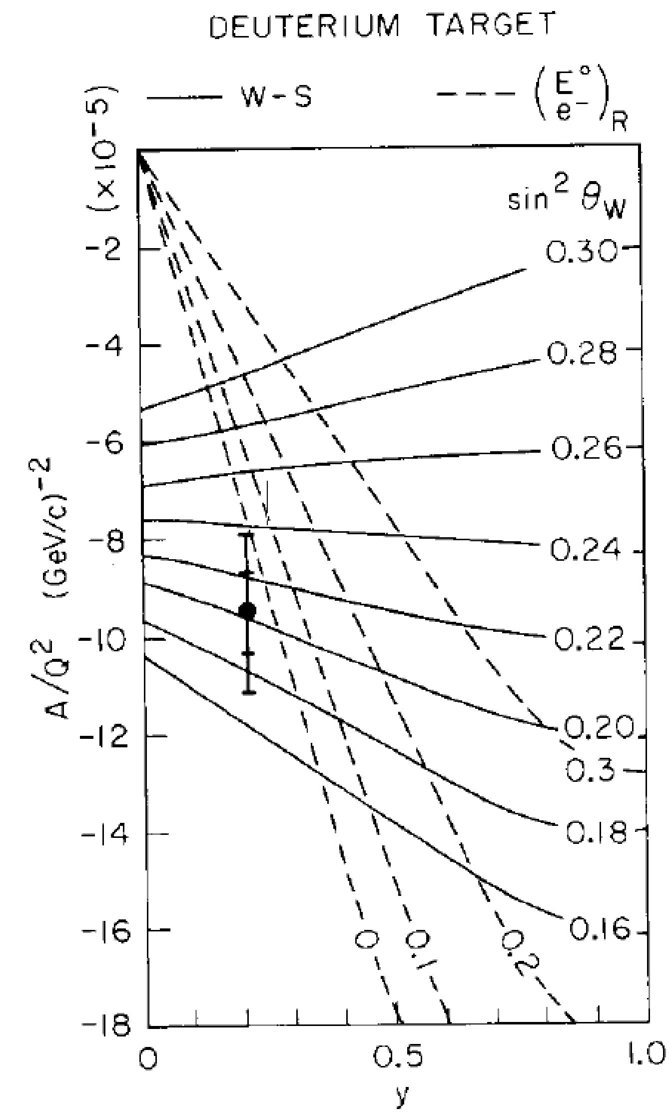



"electron-quark effective couplings"

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.

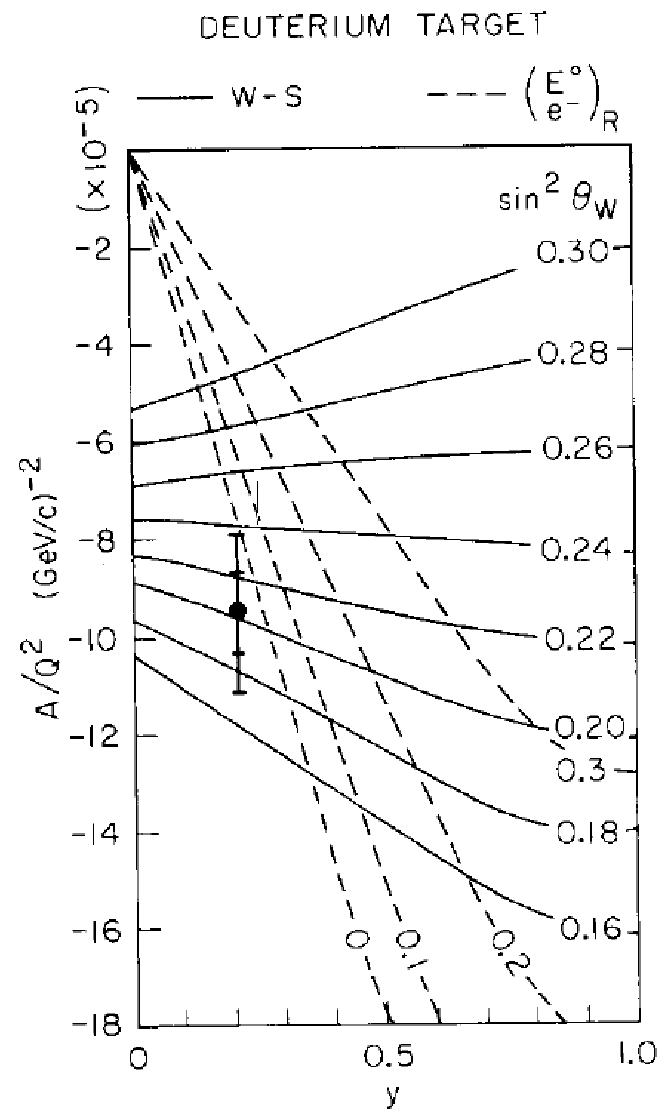



Prescott et al, Phys. Lett. 77B, 347 (1978)

# 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.

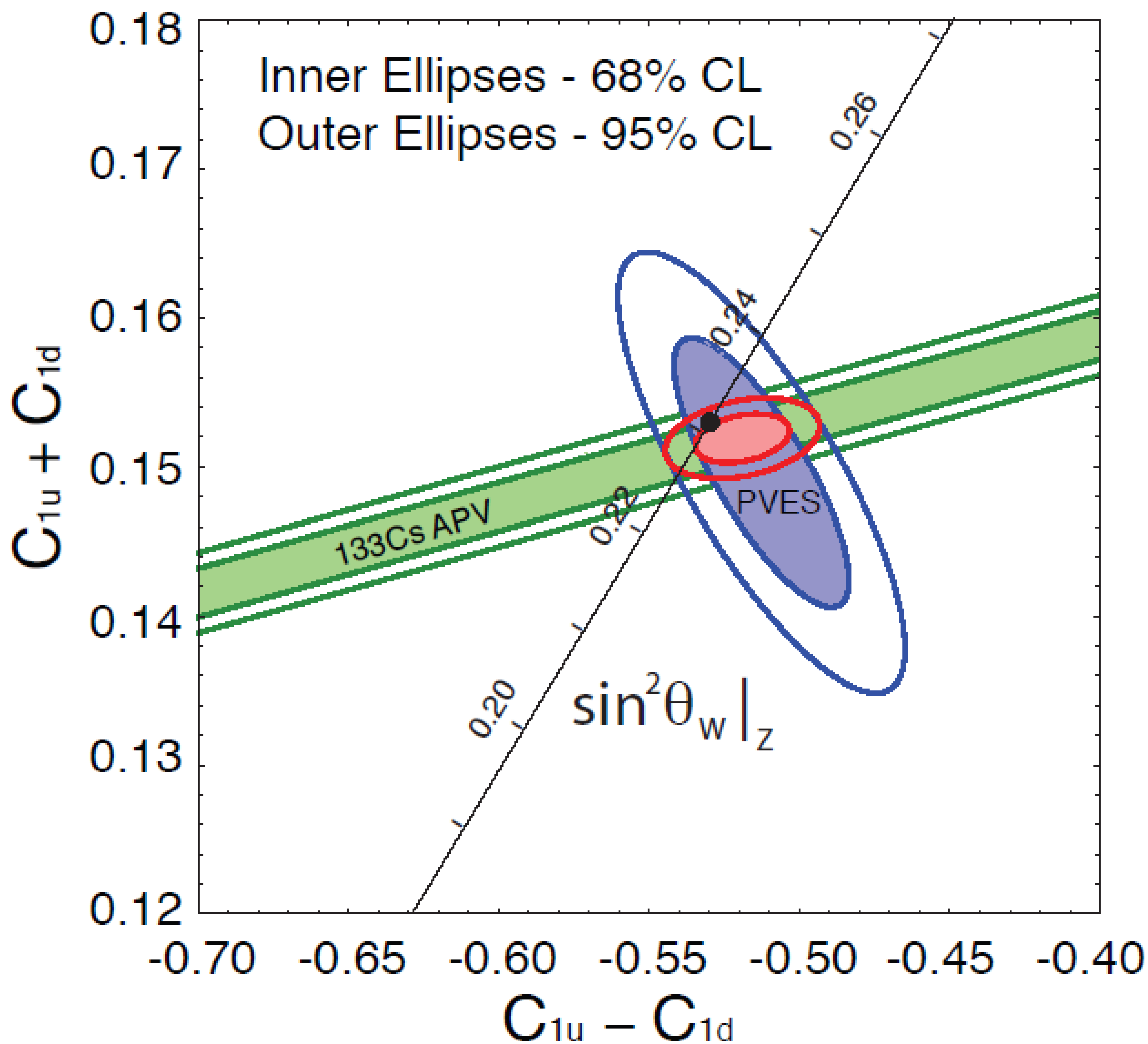
- Nowadays, PVES is being used to test the Standard Model, and to set limits on new physics.
- PVES in elastic scattering can access $C_{1q}$, while PVDIS can access both $C_{1q}$ and $C_{2q}$.




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

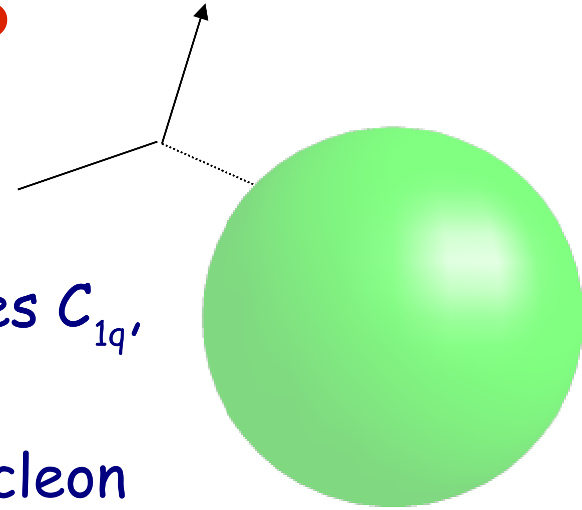
# Best Data on $C_{1q}$ (eq AV couplings) from elastic PVES+APV

Qweak has already released their final results. Maybe the colloquium next week will reveal new exciting plots!



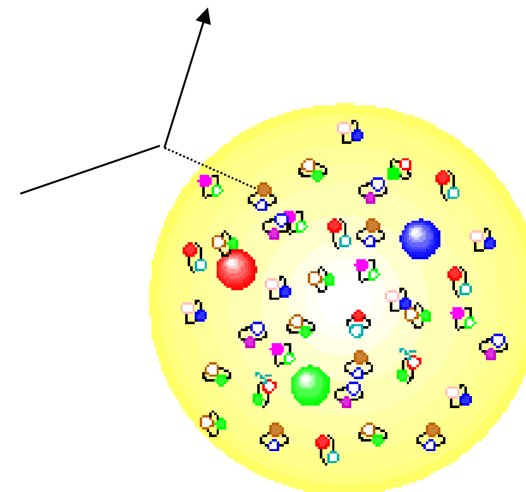

Androic et al., PRL 111, 141803 (2013);

# 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.

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

# Formalism for PVDIS

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

**For an isoscalar target ($^2H$):**

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

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**"static limit": 0** **1**

# Formalism for PVDIS

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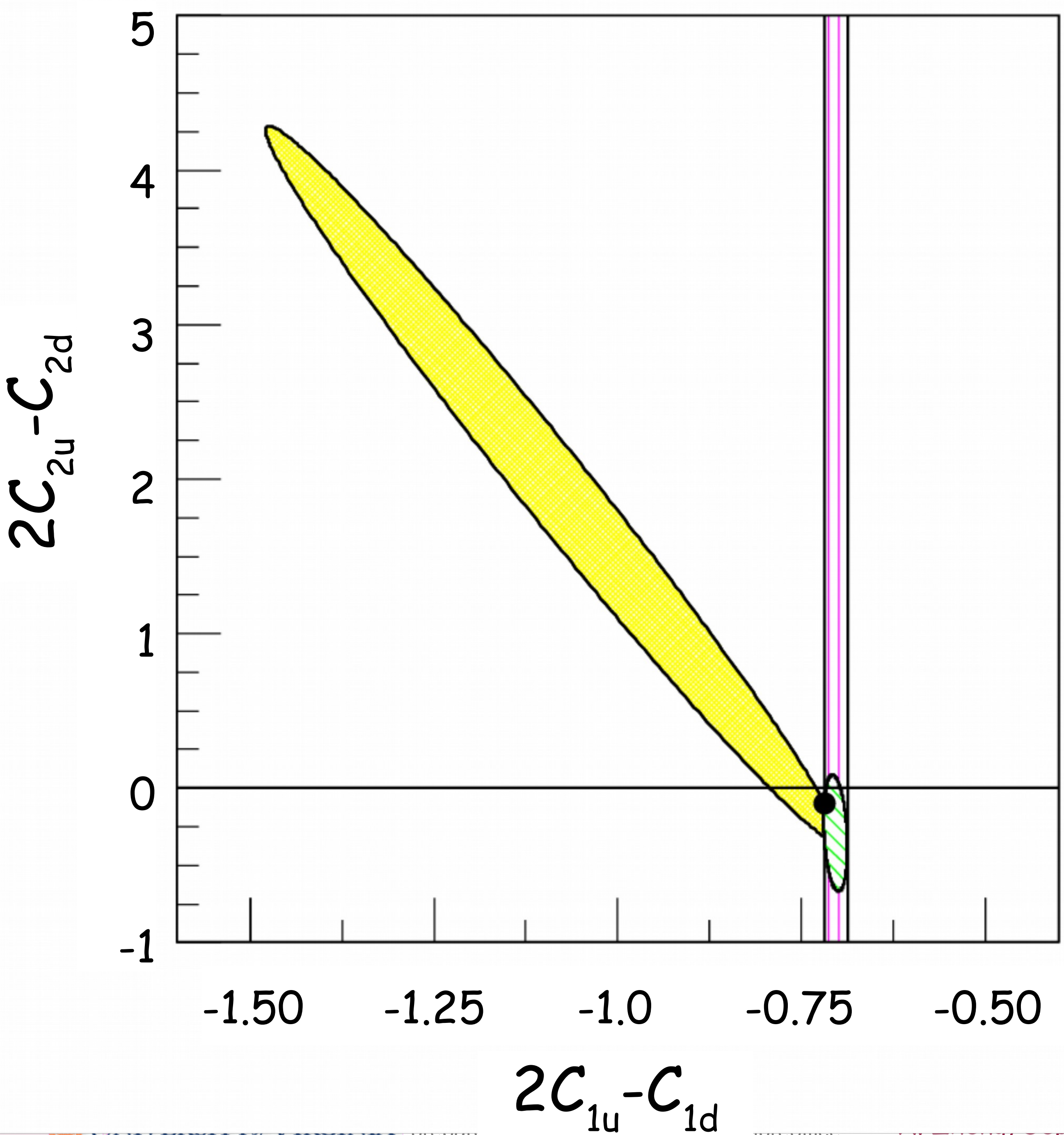
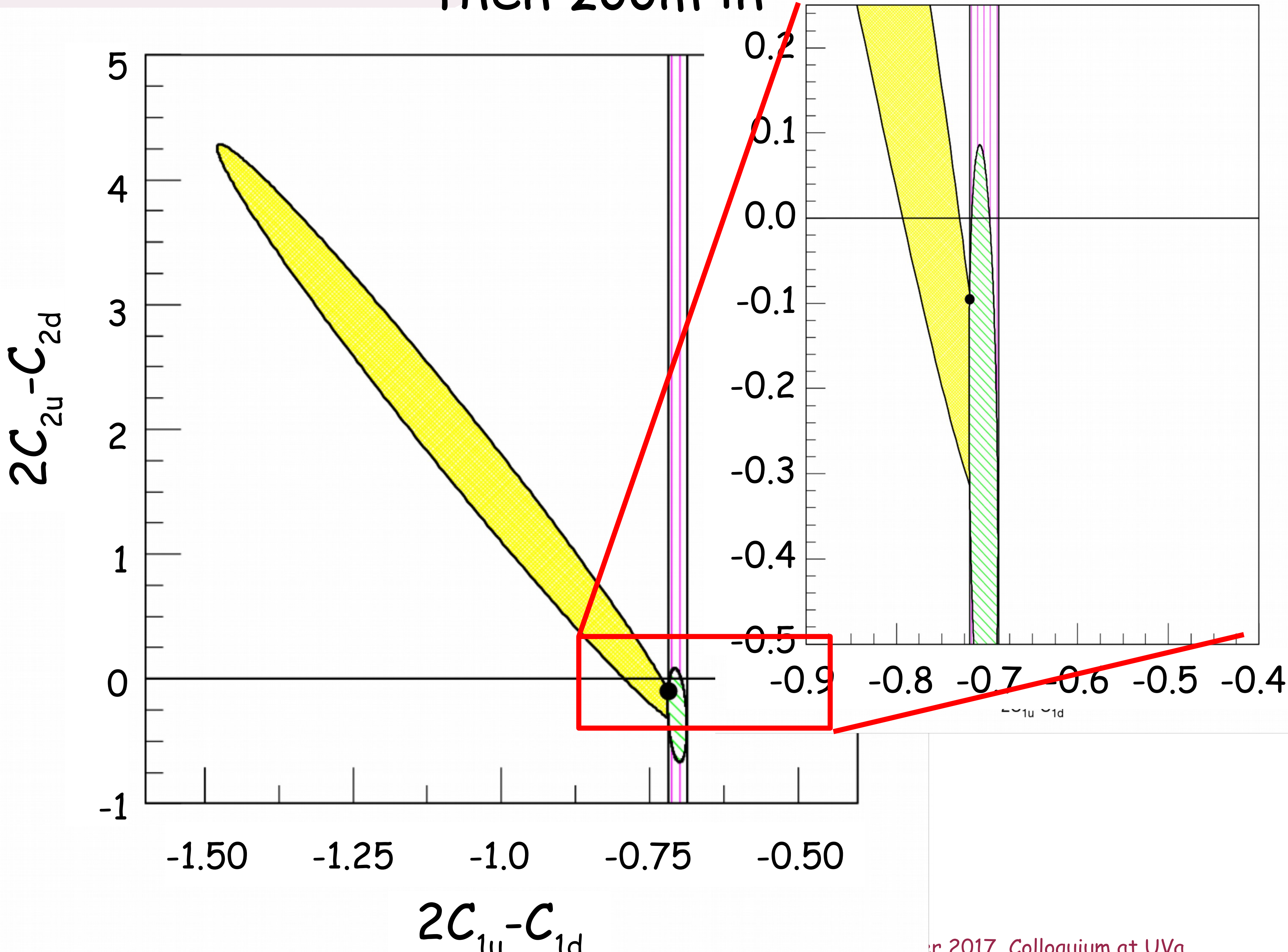
"static limit": 0     1

$$-\frac{3}{2}+\frac{10}{3}\sin^2\theta_W \qquad -\frac{3}{2}\left(1-4\sin^2\theta_W\right)$$

# $C_{2q}$ from E122 (before JLab)

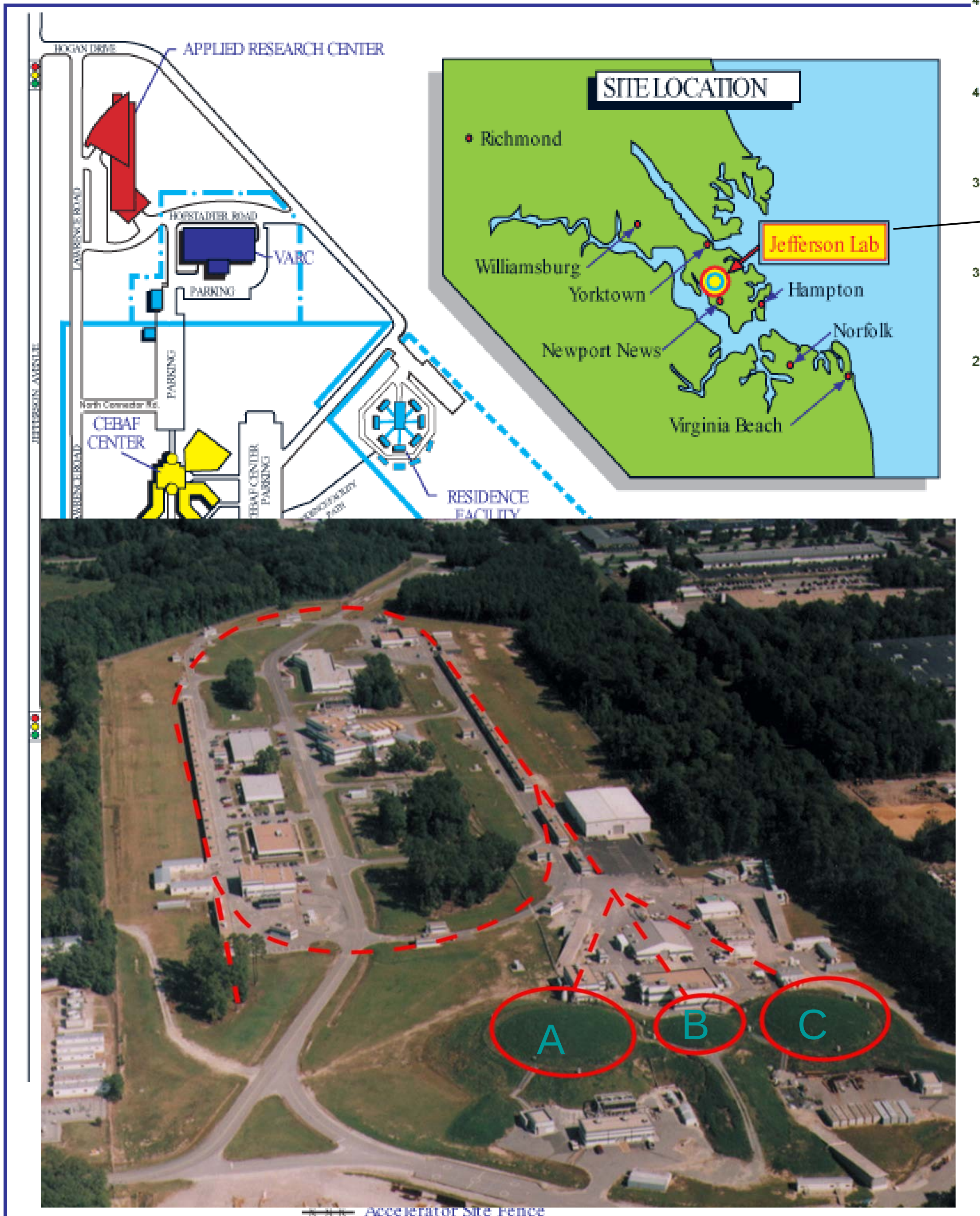


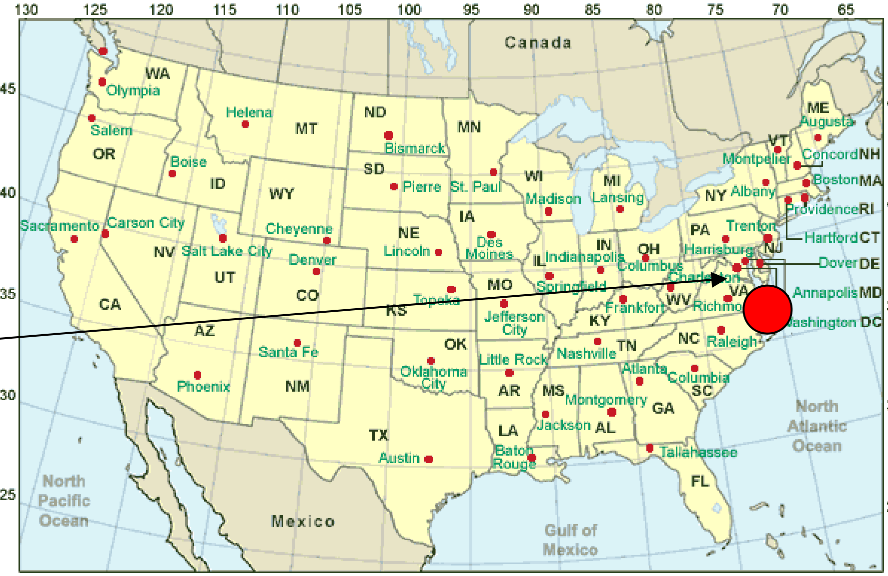
# then zoom in



5
4
3
2
1
0
-1
-1.50
-1.25
-1.0
-0.75
-0.50
$2C_{2u}-C_{2d}$
$2C_{1u}-C_{1d}$
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 $GeV^2$
- LOI 2003, proposal approved 2005 and re-approved in 2008; ran in Nov-Dec. 2009, four publications in 2012-2015.

# 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

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

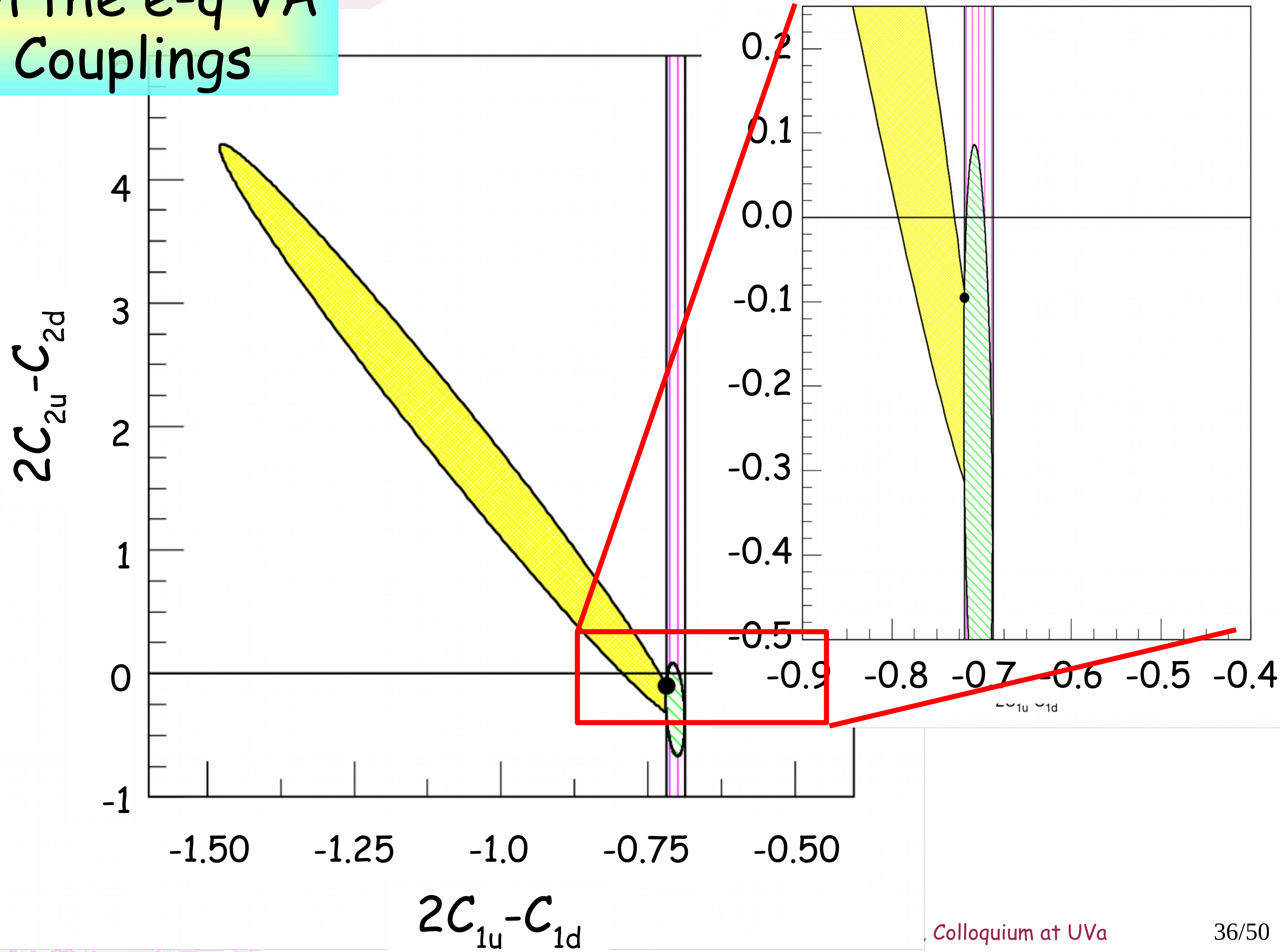
$$A^{phys}_{Q^2=1.901, x=0.295} = -160.80 \pm 6.39 \pm 3.12\ ppm$$

compare to

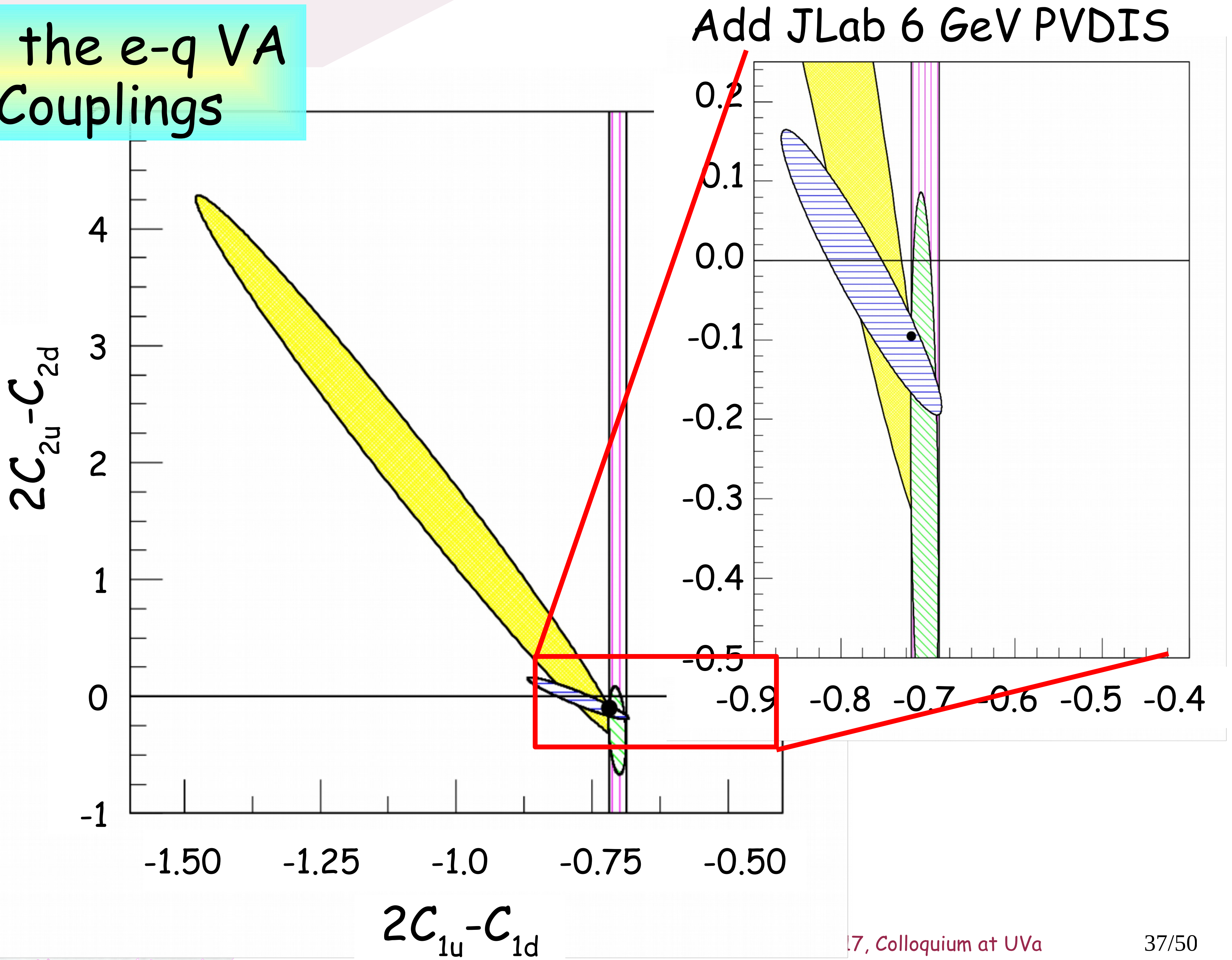
$$A^{SM} = (2.022\times 10^{-4})\left[(2C_{1u} - C_{1d}) + 0.594(2C_{2u} - C_{2d})\right]$$

# On the e-q VA Couplings

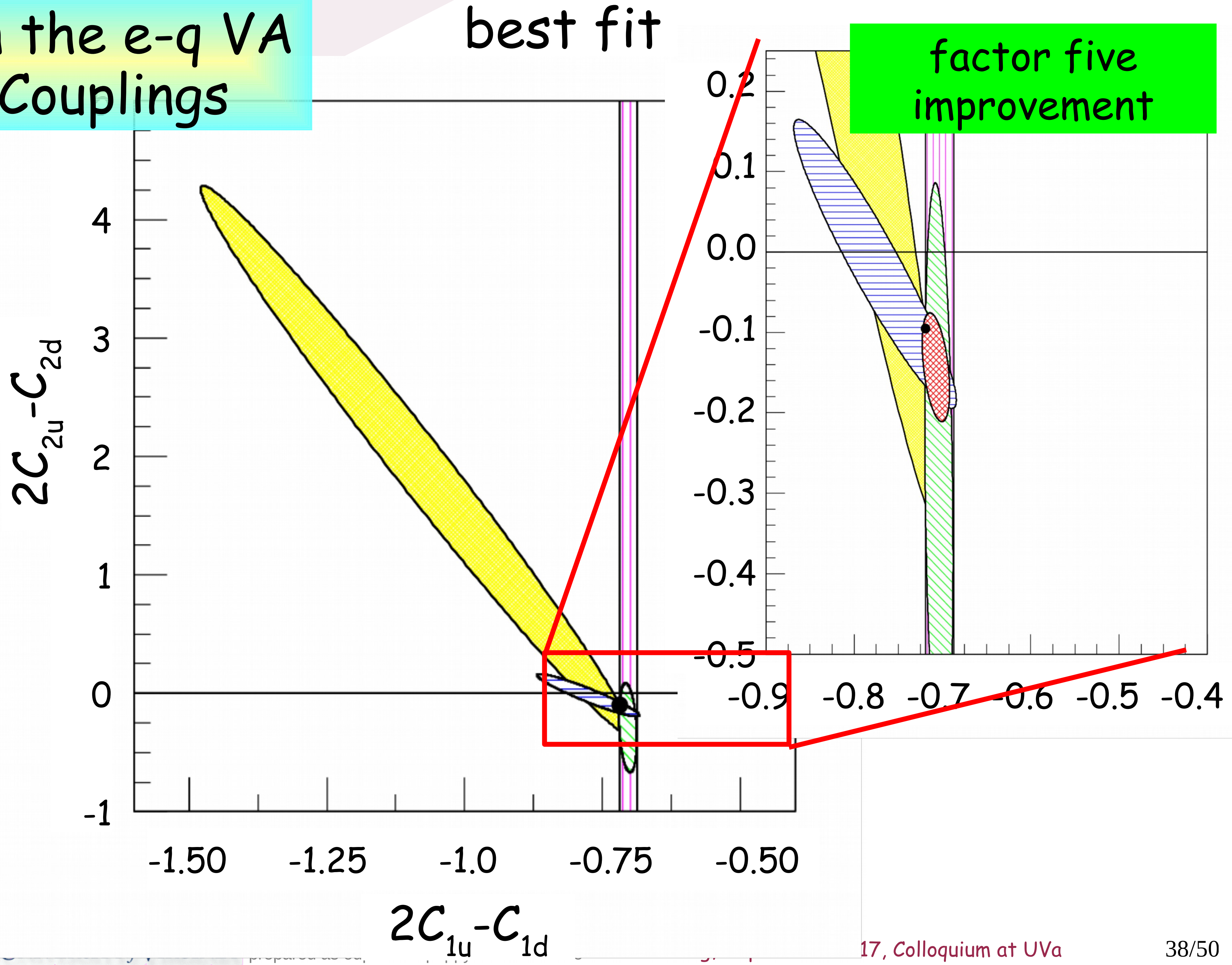
Previous data: E122, Elastic PVES + APV



# On the e-q VA Couplings



# On the e-q VA Couplings



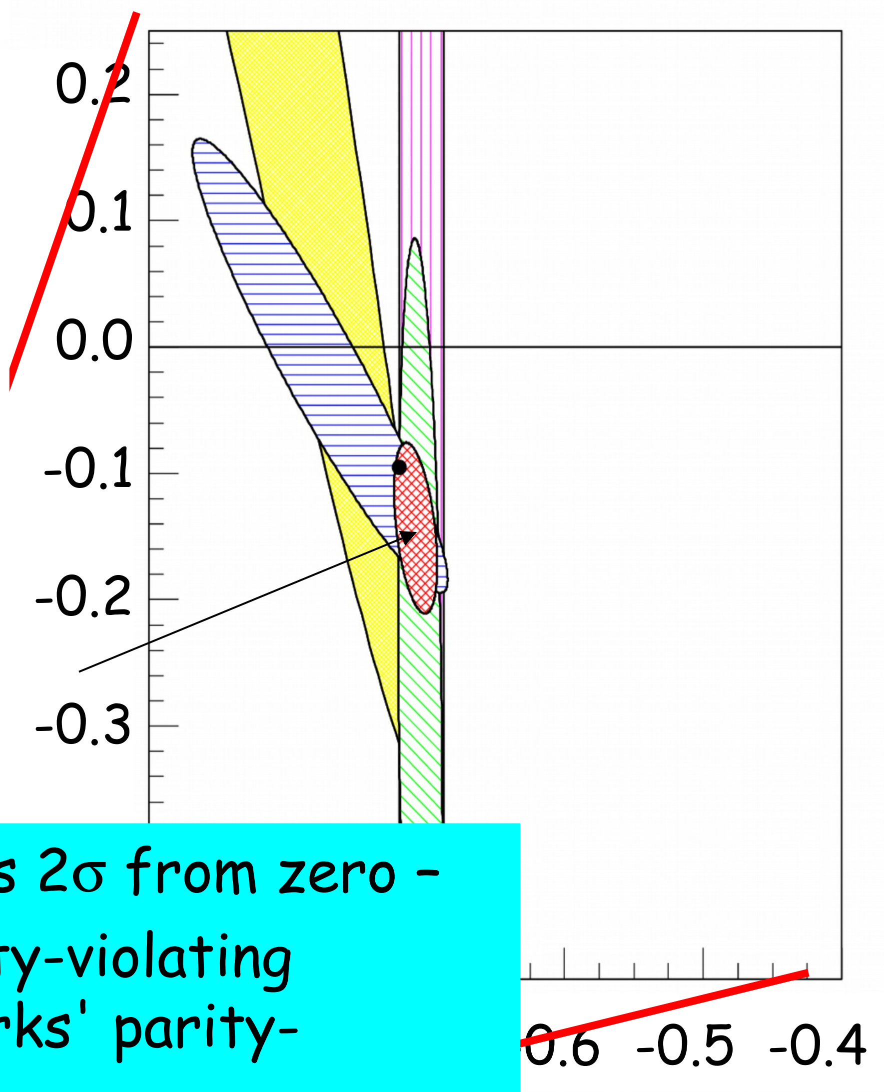
PARTICLE PHYSICS

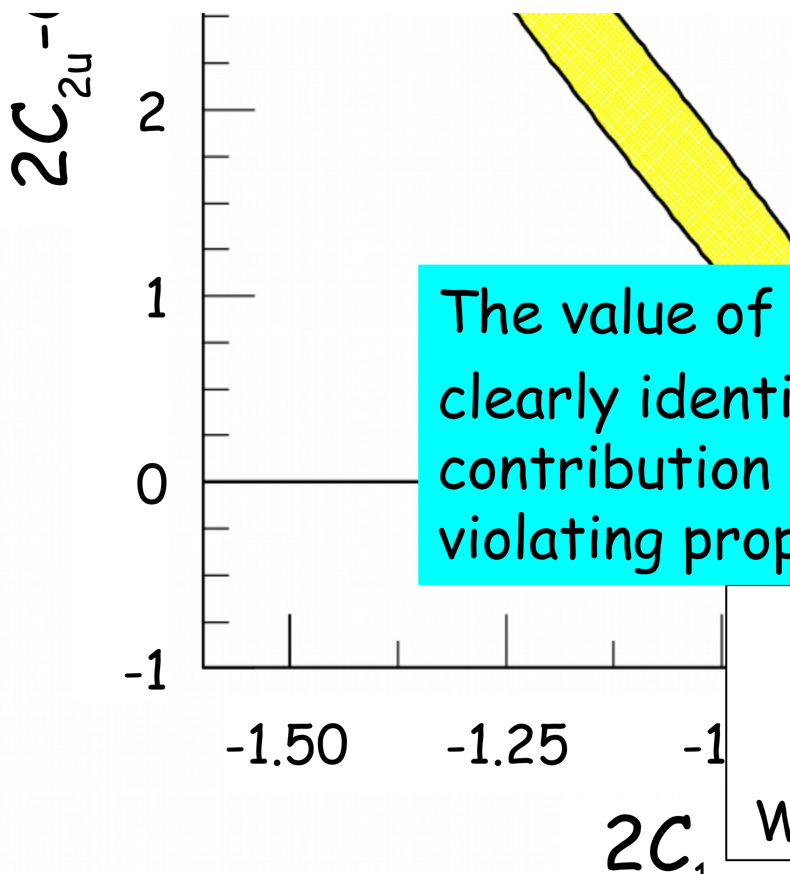
# Quarks are not ambidextrous

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);
( Quarks are like people, most prefer to use their right hands, but some prefer left... )

fit



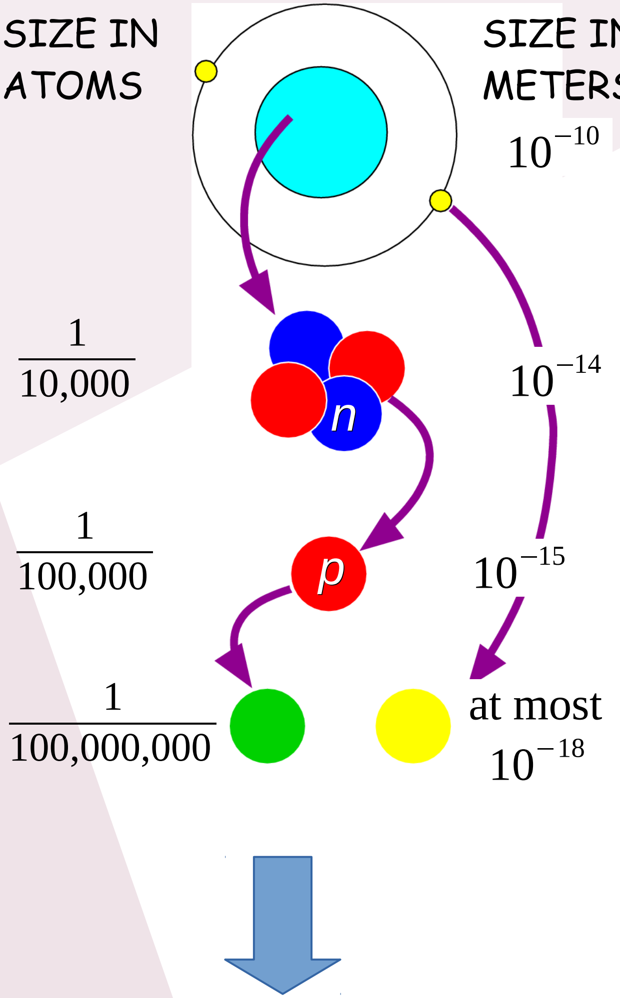




The value of $2C_{2u}$-$C_{2d}$ is $2\sigma$ from zero – clearly identified parity-violating contribution from quarks' parity-violating property

"Measurement of parity violation in electron-quark scattering"

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

# Description of New Physics




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

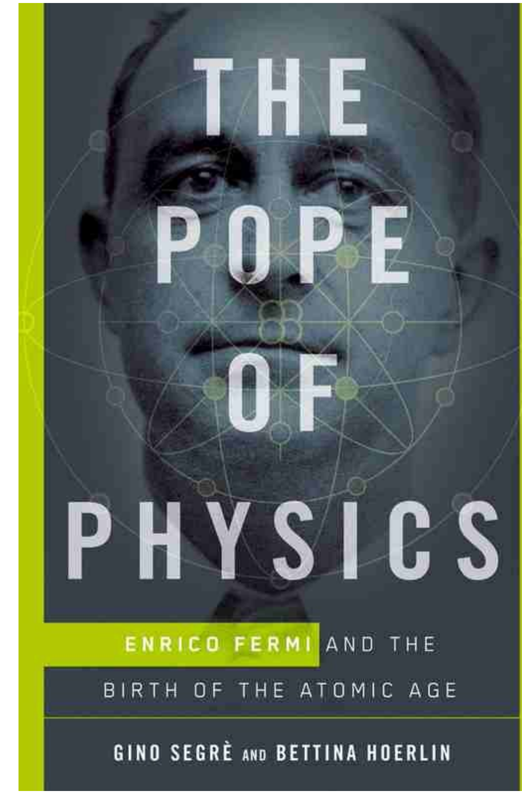
"preons"?
（初子？）

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

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

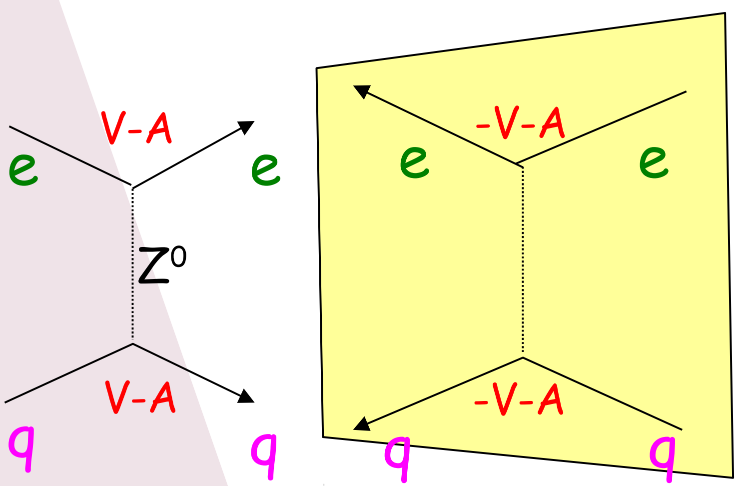
mass scale $\Lambda$

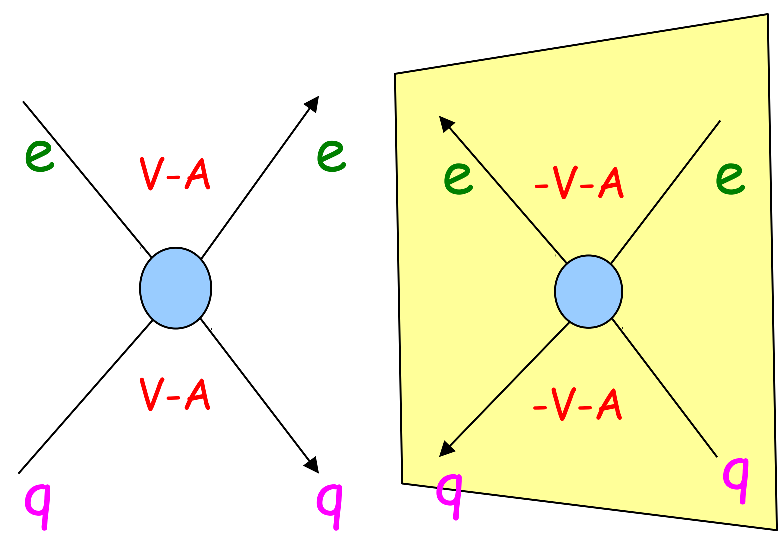
# Searching for "New Contact Interactions"




Below the mass scale $\Lambda$: 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.

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

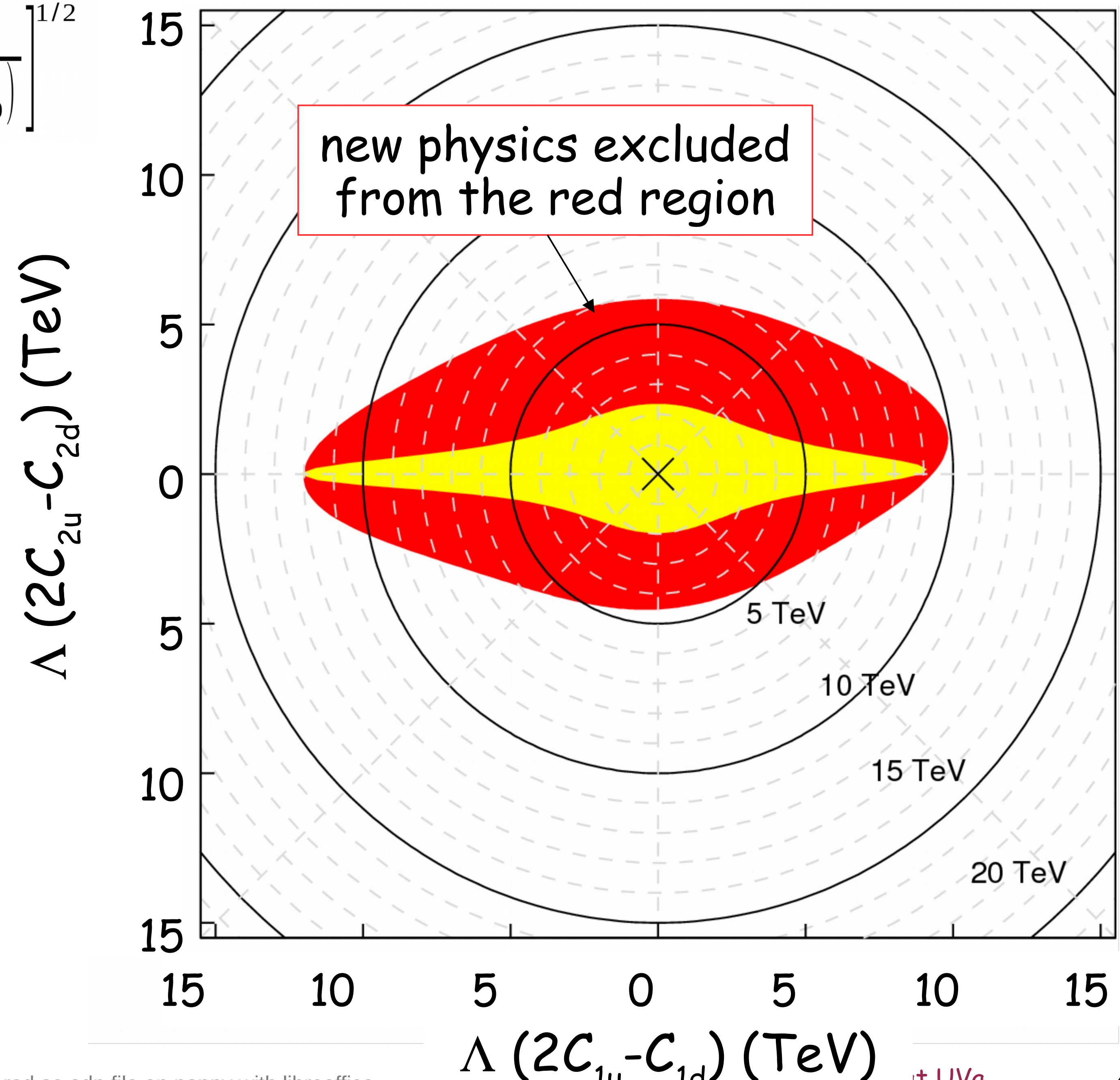



Erler&Su, Prog. Part. Nucl. Phys. 71, 119 (2013)

# Limit on new eq VA contact interactions

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

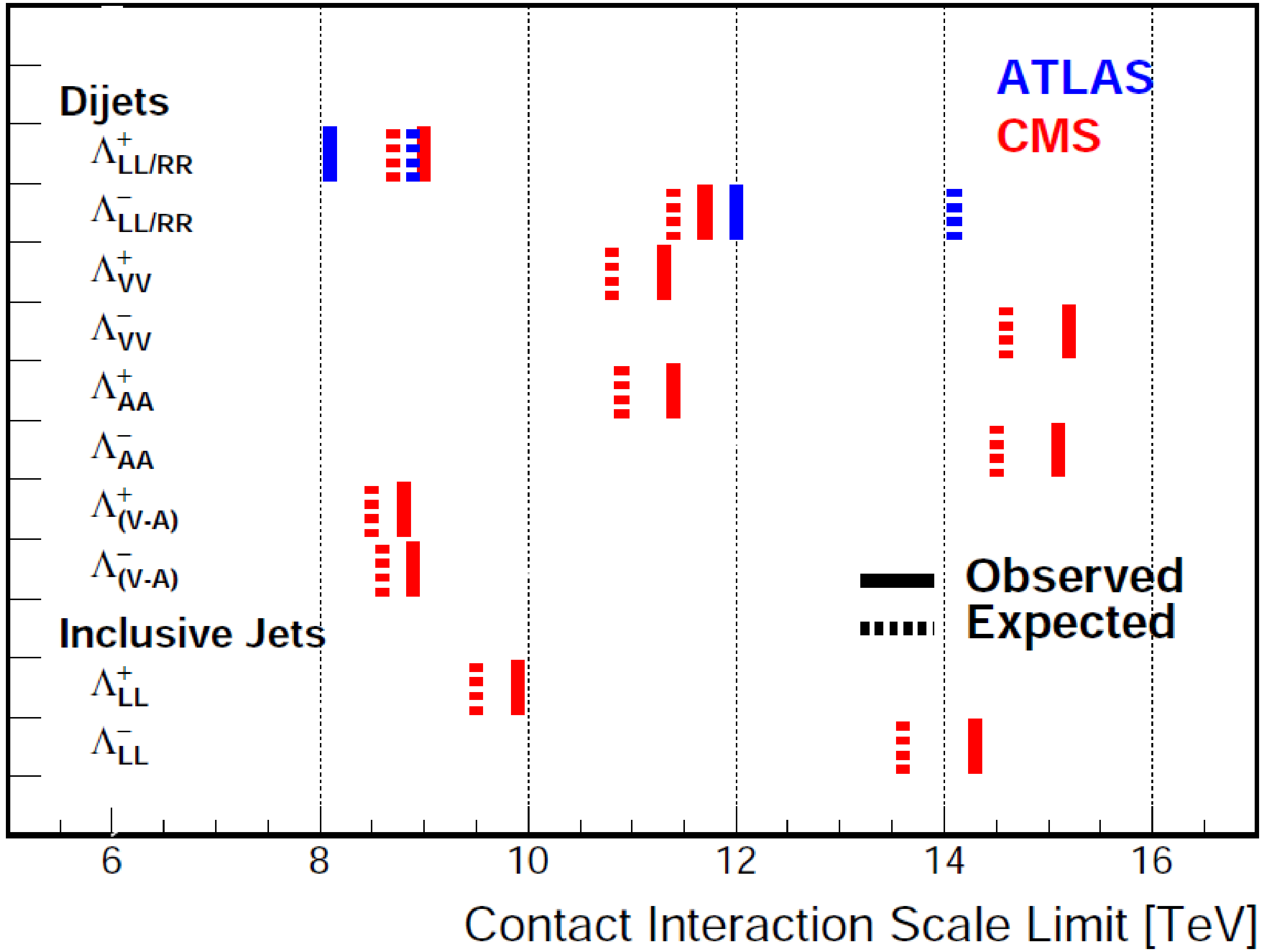



(PS it was an awkward timing that our Nature paper was released on Feb. 14th, 2014)

# Contact Interaction Limits from LHC (PDG)

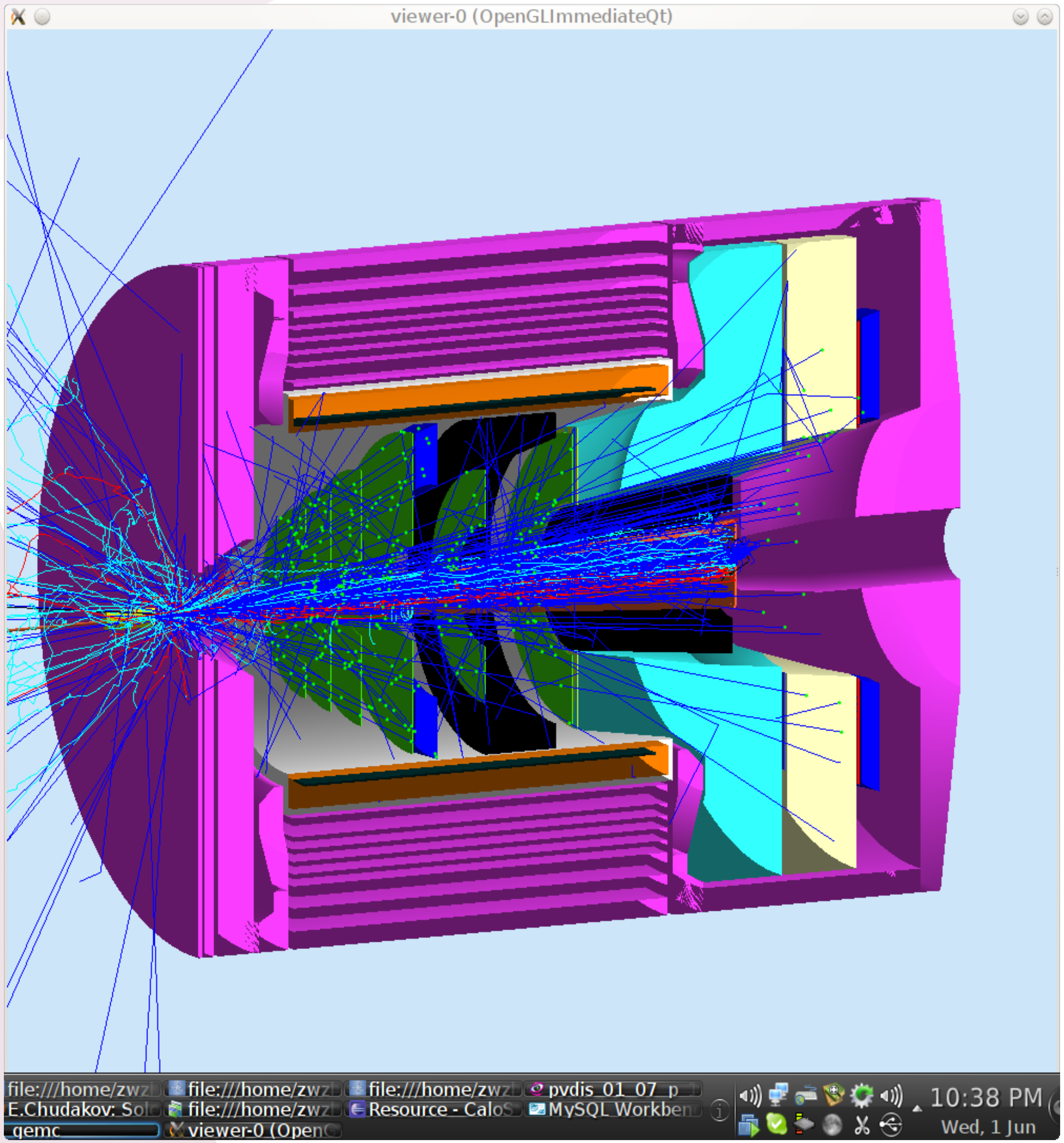
No access to AV or VA terms

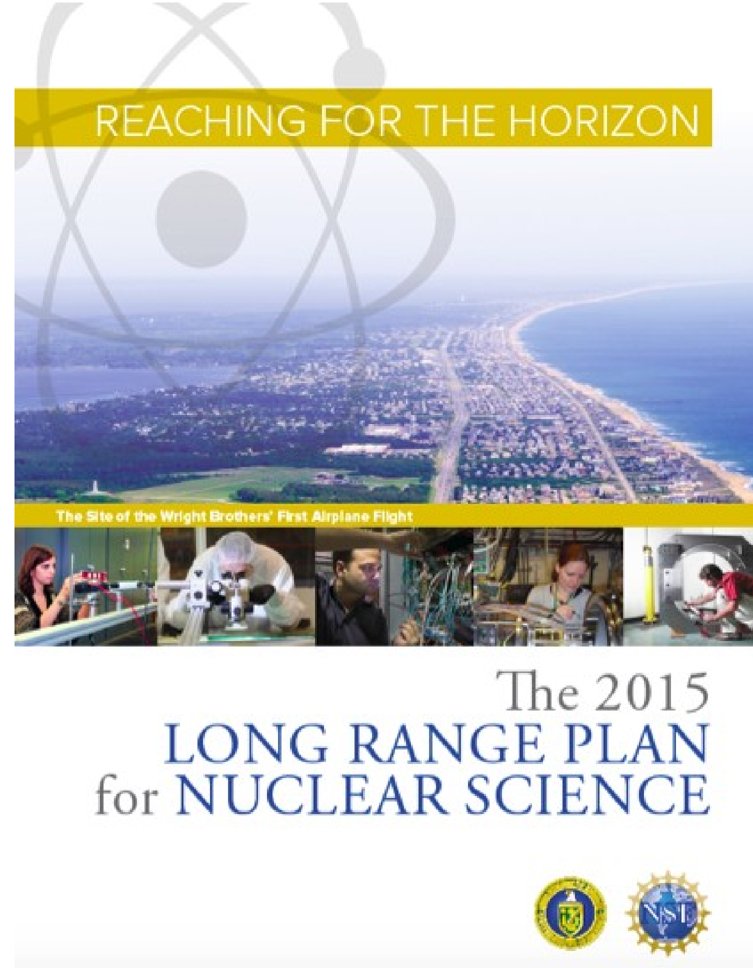
PVES is complementary to collider searches



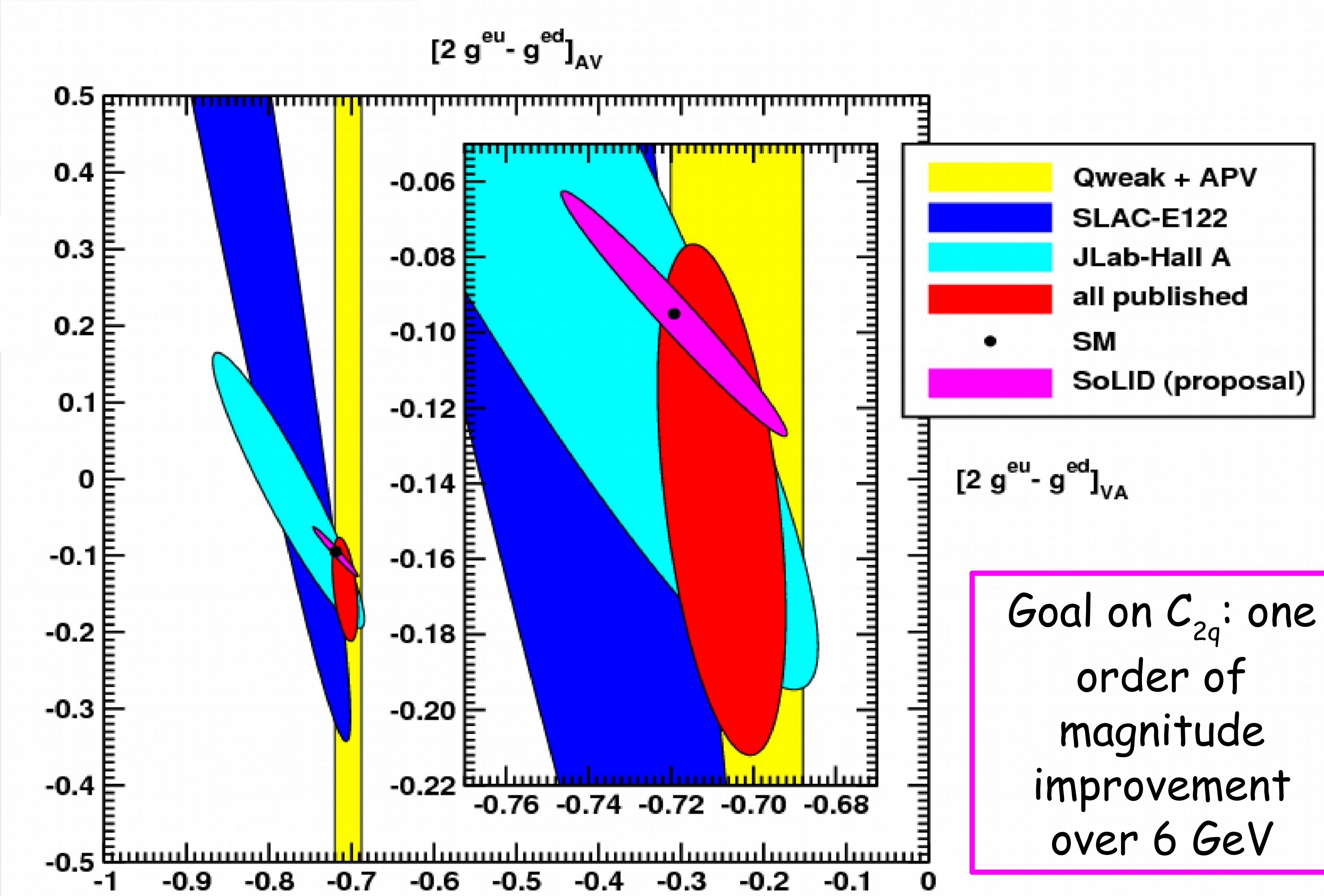
# Coherent PVDIS Program with SoLID @ 12 GeV

## "Solenoid Large Intensity Device"



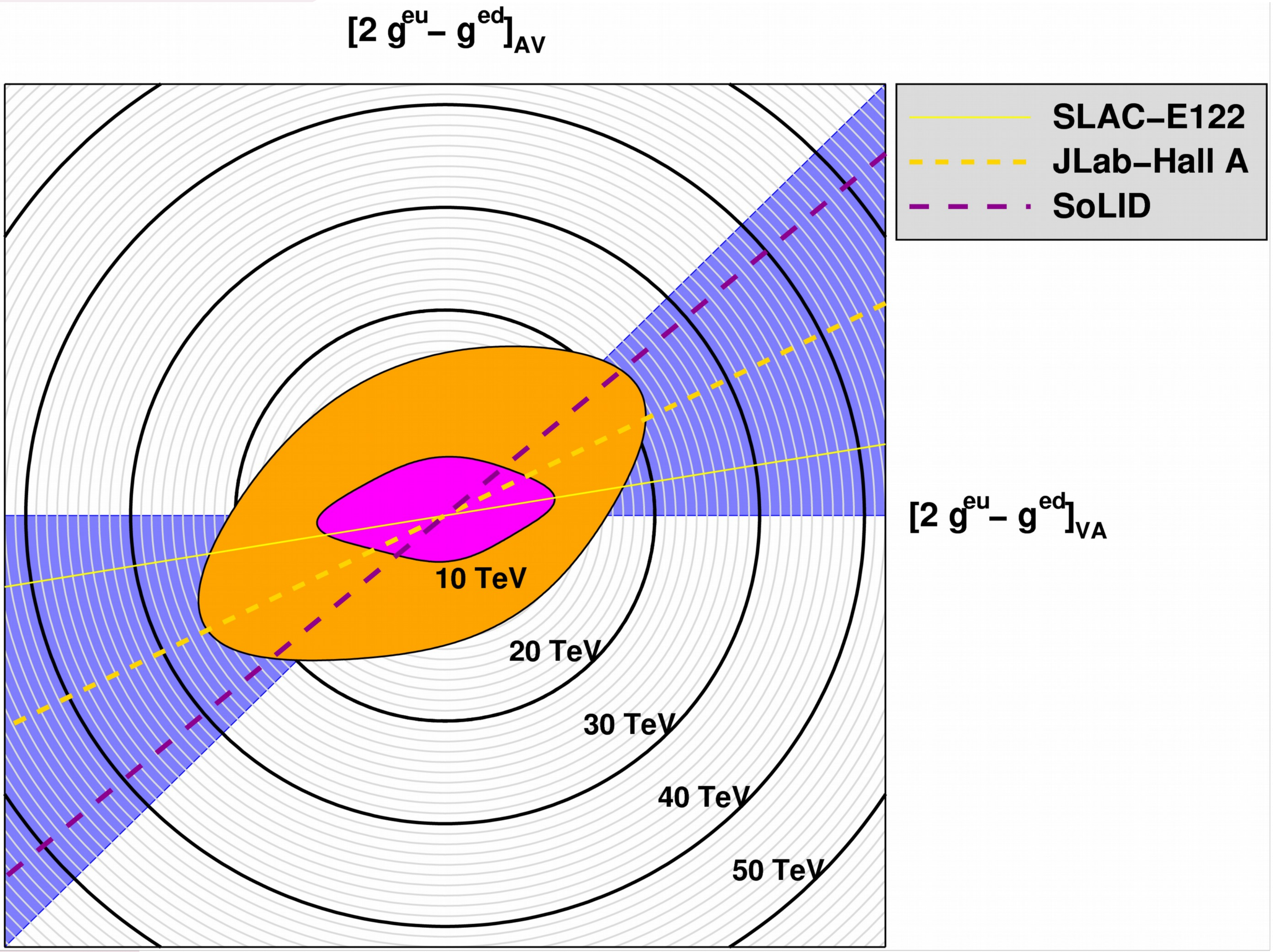



# Coherent PVDIS Program with SoLID @ JLab 12 GeV




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

# Coherent PVDIS Program with SoLID @ 11 GeV



to be updated

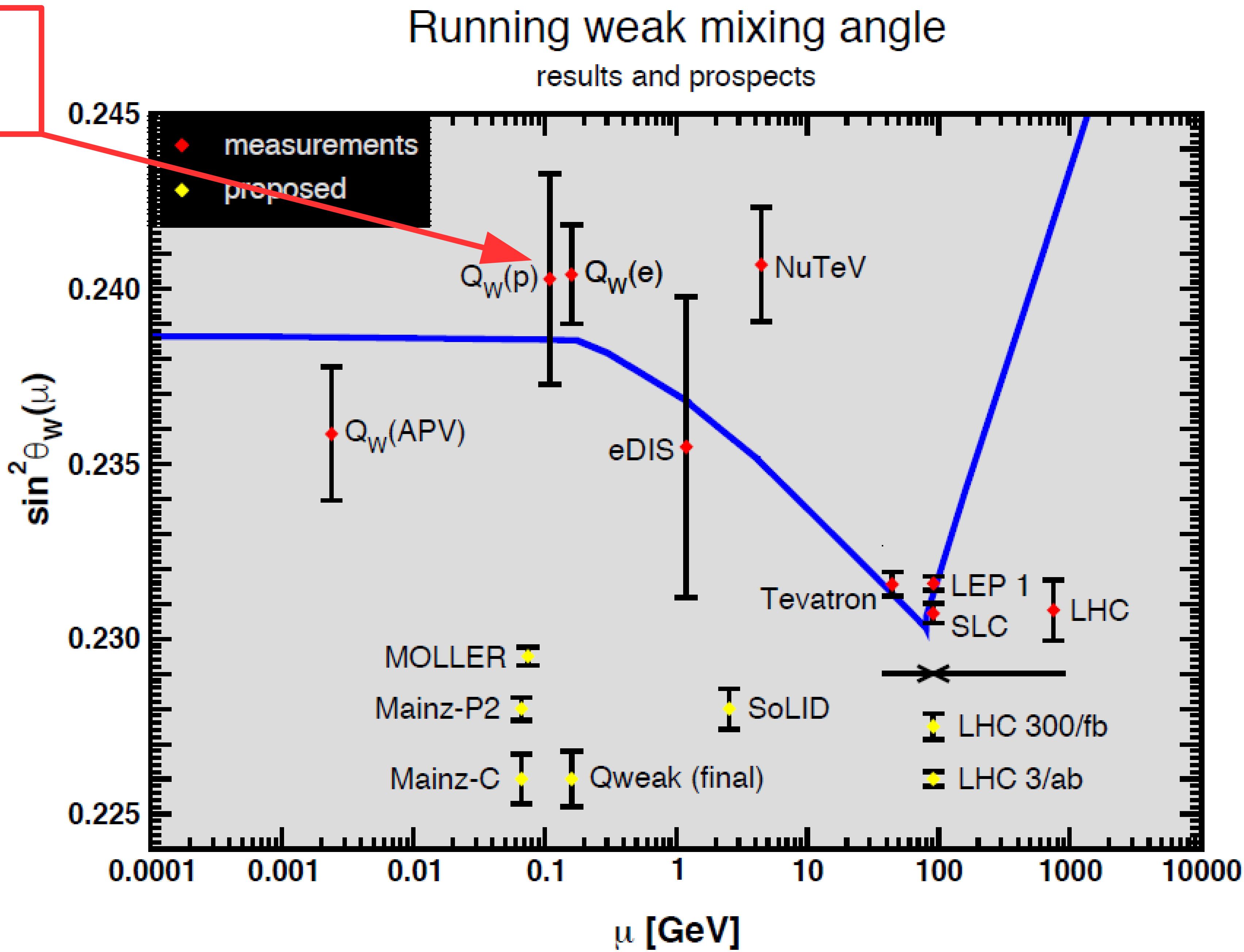
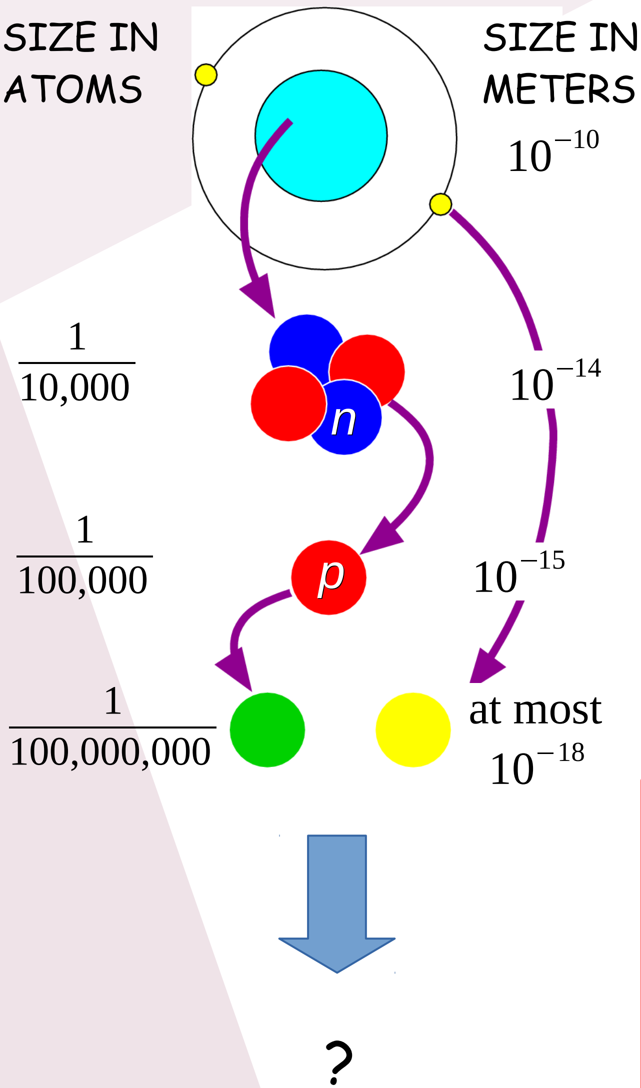



Figure from Jens Erler, WIN2017

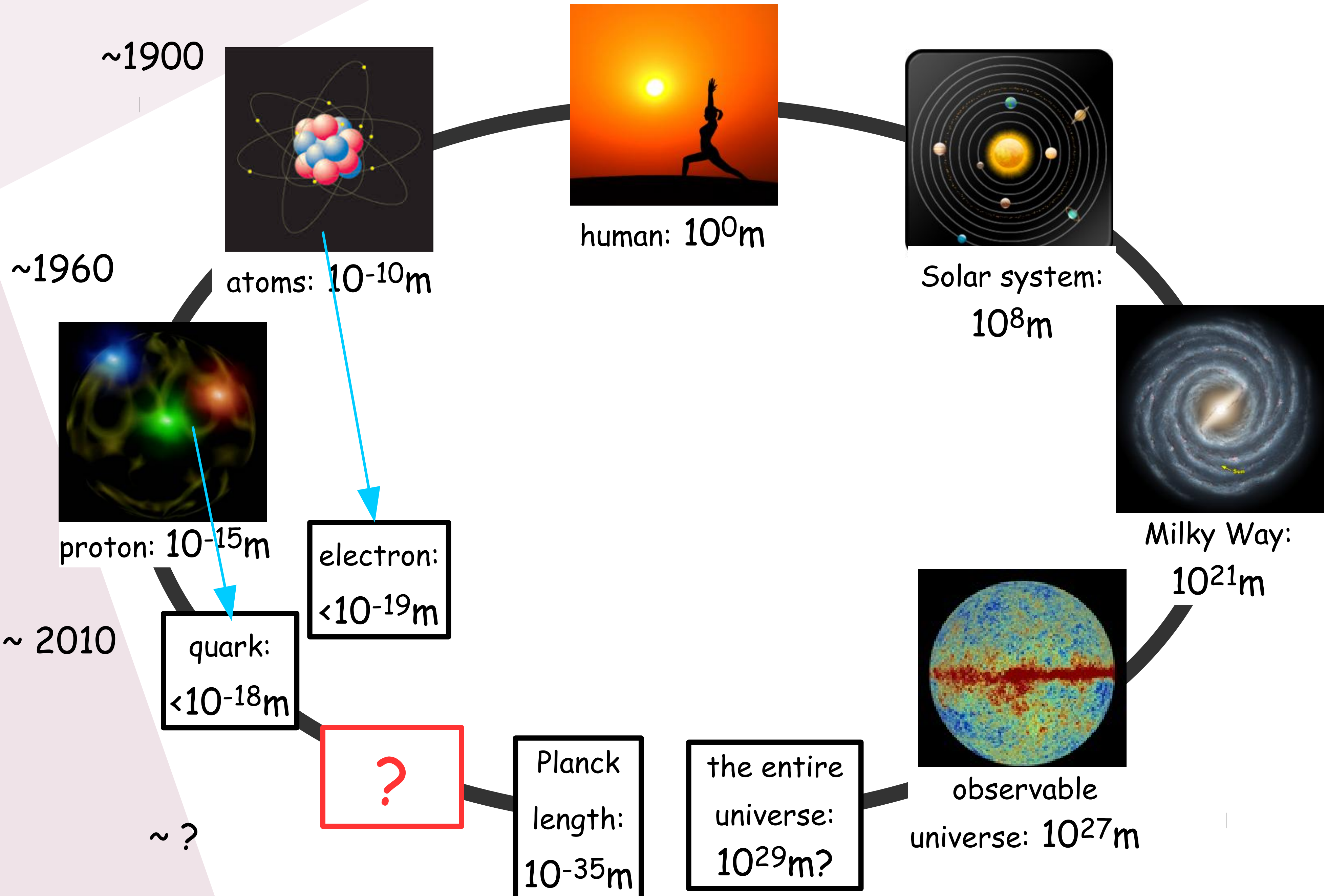
# Summary (1 of 3)




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

By conducting high precision measurements with high intensity electron beams, we are now venturing into a new era of studies of the Standard Model and the subatomic structure of matter, in a way that is complementary to the direct search of new physics (at colliders).

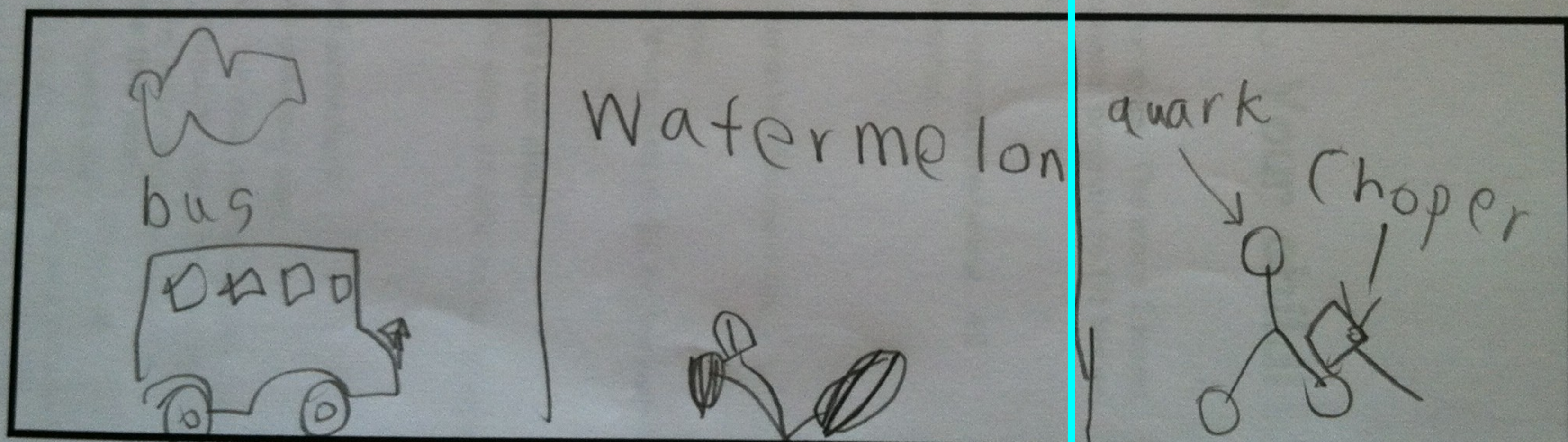
# Summary (2 of 3)



# Our "***Hopes and Dreams***" For

# Louis.Deuf in First Grade Are:

- Ihave a Water-melon plant.
- Isee inside a quark
- Istay in a bus for a log time.



festations of life. "The universe," he said, "is a dissymmetric whole. I am led to believe that life, as it is revealed to us, must be a function of the dissymmetry of the universe, or of the consequences that it involves."

As his organization of his work in the School progressed, Pierre

# Compare to Standard Model?

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

$$A^{SM} = (1.156\times10^{-4})\left[\left(2C_{1u}-C_{1d}\right)+0.348\left(2C_{2u}-C_{2d}\right)\right] = -87.7\ ppm$$

uncertainty due to PDF: 0.5% 5%

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

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

$$A^{SM} = (2.022\times10^{-4})\left[\left(2C_{1u}-C_{1d}\right)+0.594\left(2C_{2u}-C_{2d}\right)\right] = -158.9\ ppm$$

uncertainty due to PDF: 0.5% 5%

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