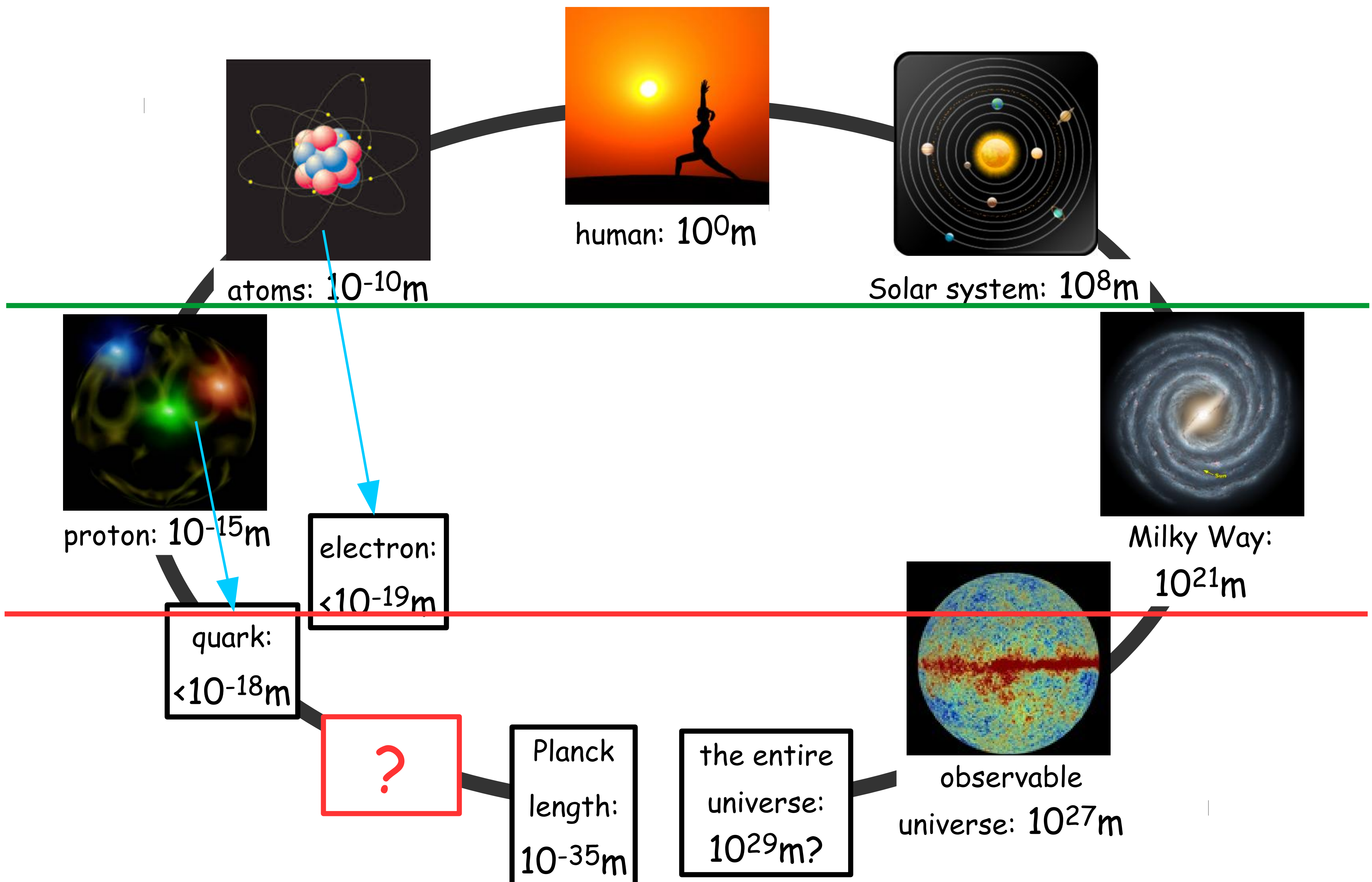
Precision Standard Model Tests Using Parity Violation in Electron Scattering

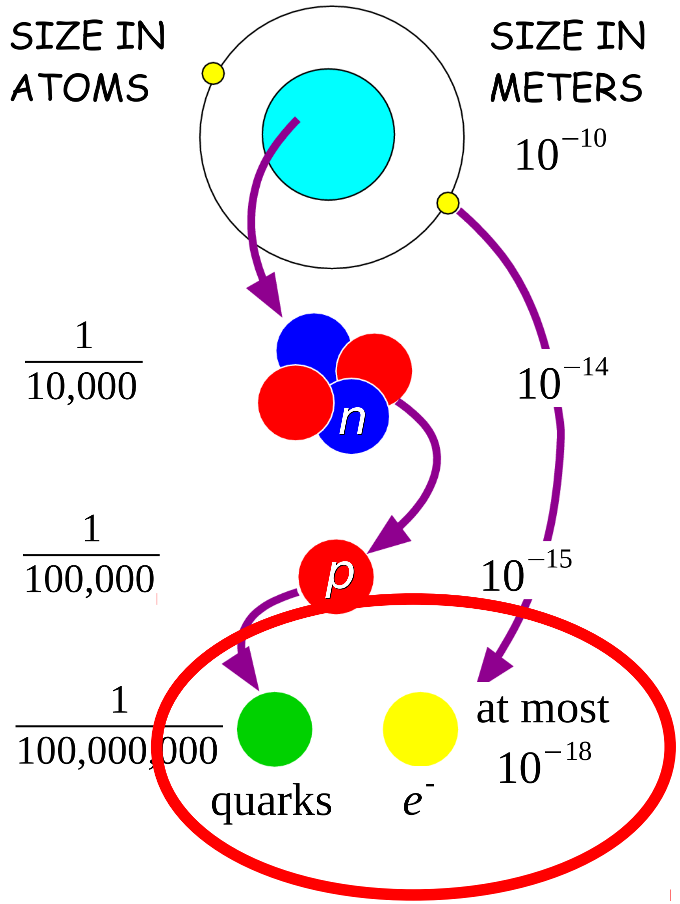
Xiaochao Zheng
University of Virginia,
Charlottesville, Virginia, USA

- The Standard Model of Particle Physics
- How should we search for new physics?
- Electron scattering, from elastic scattering to DIS
- Parity Violating Electron Scattering (PVES)
  - electron-quark effective coupling from PVDIS
- Summary

From Leptons and Quarks to the Cosmos



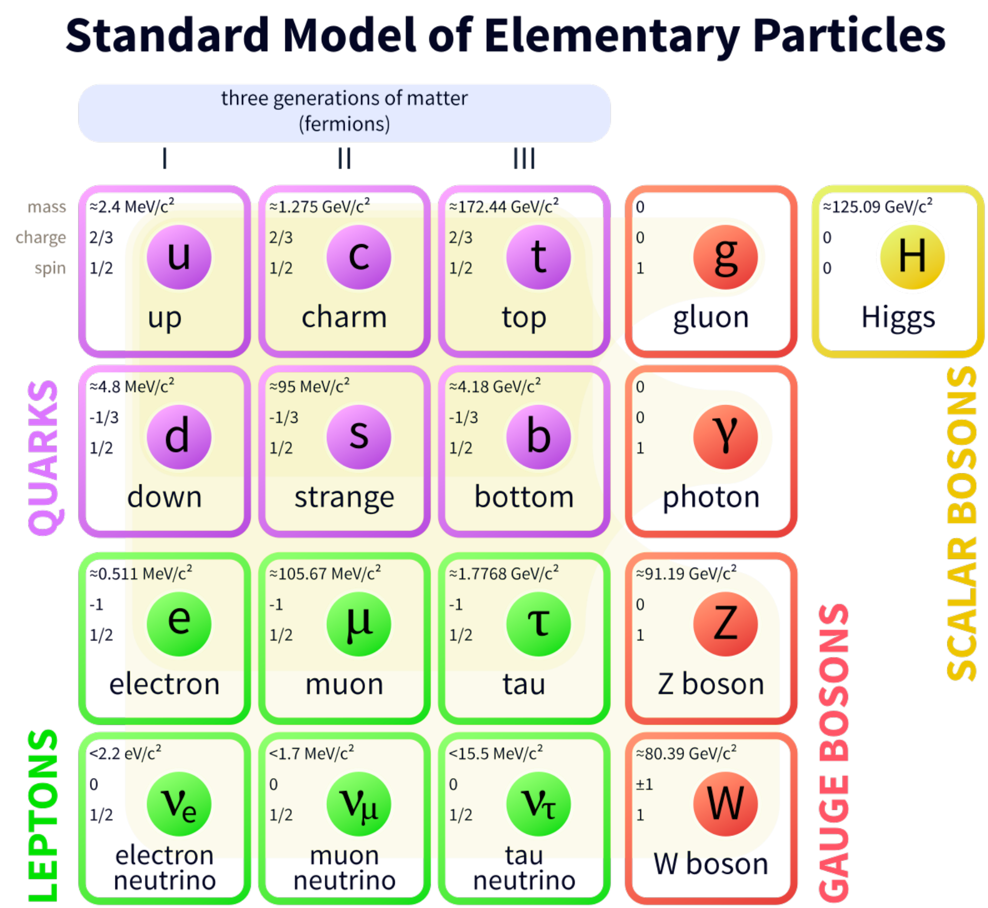
The Standard Model



(1) the elementary fermions – quarks and leptons

(2) the symmetries (gauge invariance → interactions)

(3) the origin of masses



$$D^\mu = \partial^\mu - i g_1 \frac{Y}{2} B^\mu - i g_2 \frac{\tau_i}{2} W_i^\mu - i g_3 \frac{\lambda_\alpha}{2} G_\alpha^\mu$$

The Four Interactions

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

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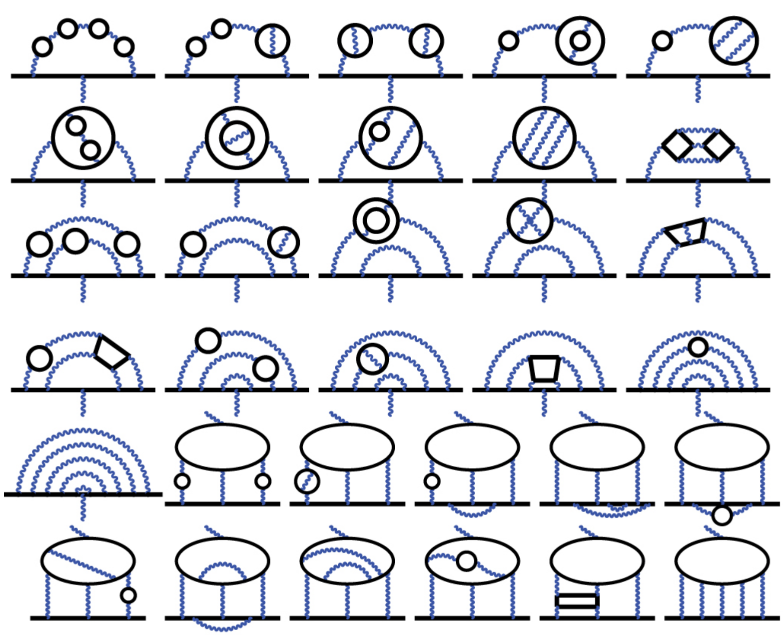
QED: tested to 10^{-9} accuracy

[(g-2) value of electrons]



Weak

- unified with electromagnetism
- By measuring the neutral weak process (APV, Qweak, Moller, PVDIS etc)

Strong

- quasi-free at small scales, color confinement at large scales
- By looking into processes involving the nucleon or quarks

Limits of the Standard Model

(choose your favorite question, from physical to philosophical:)

- Why are there three generations of quarks and leptons?
- Are quarks and leptons "the end of the matter compositeness"?
- Why do quarks have charges +2/3 or -1/3? Why do protons and electrons have opposite charges?
- How do we include gravity in quantum field theory? Should we attempt to explain gravity using quantum field theory method?
- How do we explain dark matter? (let alone dark energy)
- Why are neutrinos so light in mass?
- And many more!

The Standard Model is "an effective theory at the electroweak scale"

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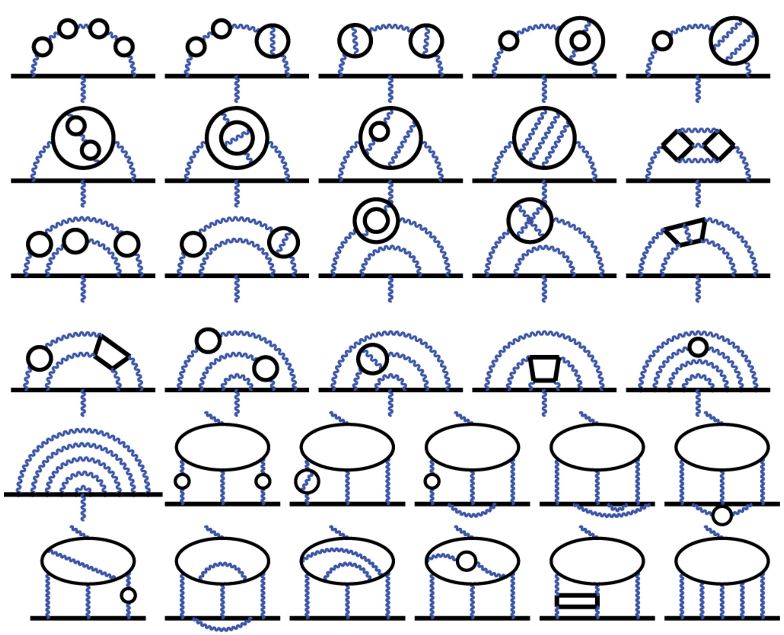

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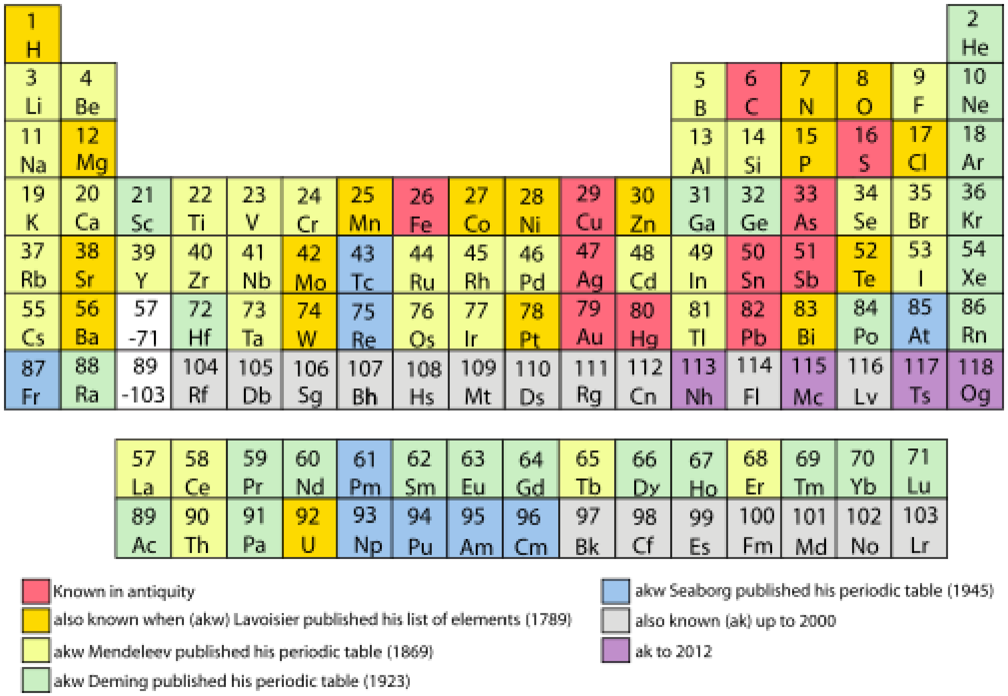
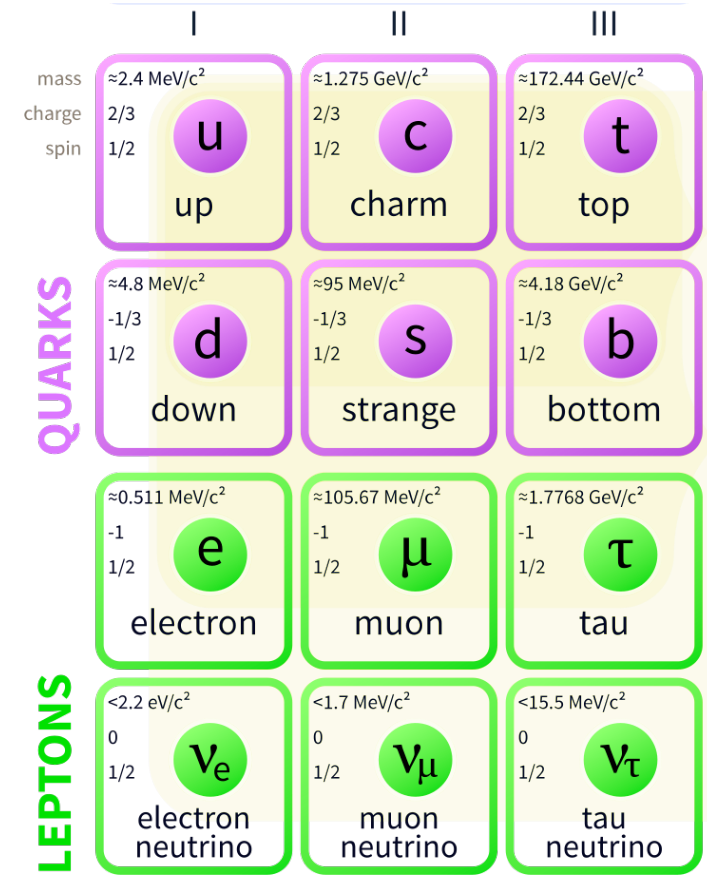
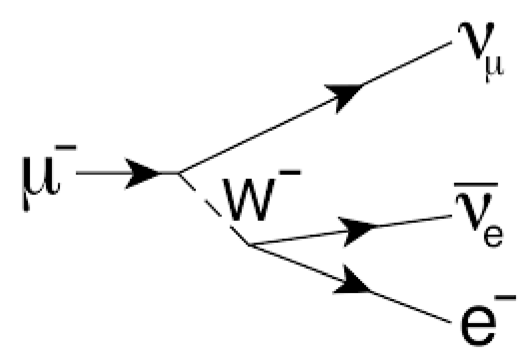
Caught in the Act !





Could the "repetivity" of the three generations be an indication that quarks and leptons are composite particles? And what if they are?

Could the decay of these particles an indication that they are composite particles??



How should we proceed?

Look more into math – Can the symmetries be unified? (Grand unification theory); Can there be higher levels of symmetries (supersymmetry)? – look for new phenomena predicted by GUT.

Look more into matter, are there more layers beyond quarks and leptons? – lepton and quark compositeness

Look more into existing discrepancies – muon g-2, proton radius, dark matter (searches) – measure them to higher precision! but can be clouded by experimental systematics, or the ability to experiment!

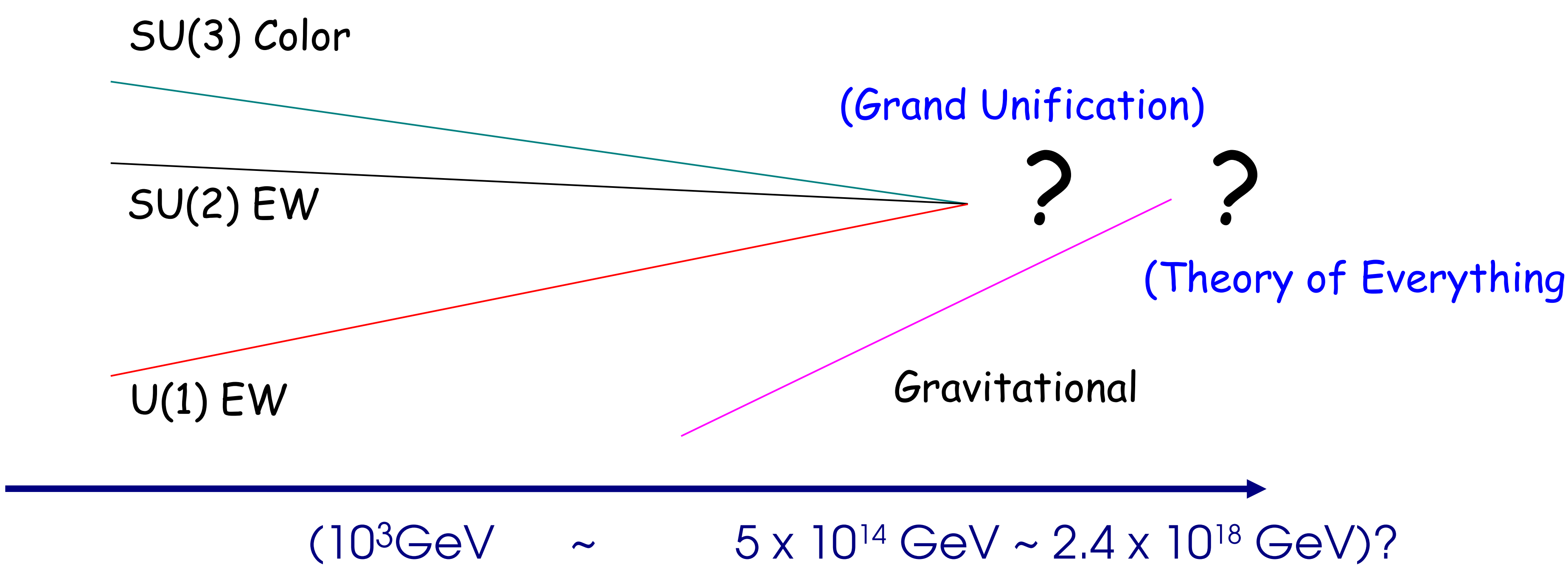
Try to find new discrepancies by measuring physical quantities to high precision – rare decays, universality, EDM, precision PVES… …

Look for new particles, new phenomenon, forbidden processes etc – a little harder, since it may not be clear where to look … … (Example: the simplest extension to SM would be another U(1) group/symmetry, a leptophobic Z'…)

More unification?

A popular idea is "Grand Unification Theory" (GUT) – the electroweak unification works so well that we think more should be unified

Pushing it one step further: quantum field theory works so well for 3 of the 4 interactions that we think it should also apply to gravity – quantum gravity, "Theory of Everything".



SU(5) as GUT ?

$$D^\mu = \partial^\mu - i g_1 \frac{Y}{2} B^\mu - i g_2 \frac{\tau_i}{2} W_i^\mu - i g_3 \frac{\lambda_\alpha}{2} G_\alpha^\mu$$

U(1)xSU(2)xSU(3)? That's too many groups! Let's make it one!

- SU(5) multiplet: $\begin{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix} \\ \begin{pmatrix} \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \end{pmatrix} \end{pmatrix}_L$ W's / gluons

→ there must exist new gauge bosons to "convert" from the upper doublet to the lower triplet – "X" and "Y"

It is certainly very attractive. It explains why quarks have charges +2/3 and -1/3 (of e). It unifies all three forces ($\alpha_{1,2,3}$) to one (α_5)!

One way to look for GUT is to measure proton decay $p \to e^+ \pi^0$, predicted lifetime 10^{31} years (or longer), but so far experimental limit has proven otherwise.

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Look more into matter, are there more layers beyond quarks and leptons?

Yes,

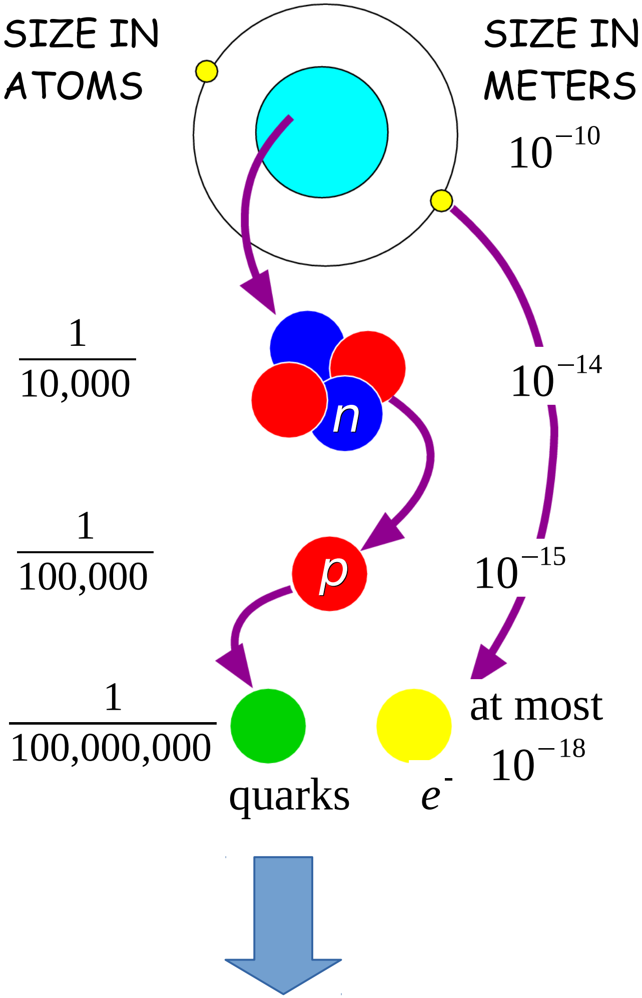
No,

Look more into matter, are there more layers beyond quarks and leptons?

Yes, The word "atom" (a-tomos) originates from ancient Greek philosophers, who argued that objects can be eventually divided into discrete, small particles, beyond which matter is no longer cuttable… … yet our research in the past century has proven just the opposite!

No, Or maybe the Greeks are correct?

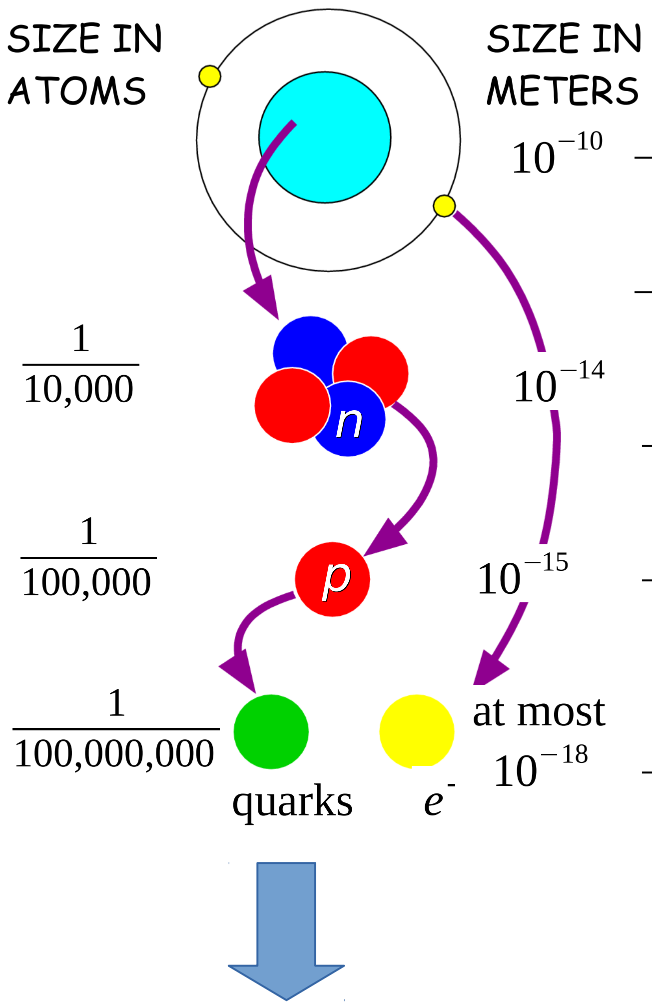
From Rutherford Scattering to Today's Electron Scattering



"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.

I assigned this as a Modern Physics Homework



“preons”?

（初子？）

	δx	$\delta p = \frac{\hbar}{2\,\delta x}$	binding energy needed
electrons in an atom	10^{-10} m	≈ keV	≈ eV
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	?	?

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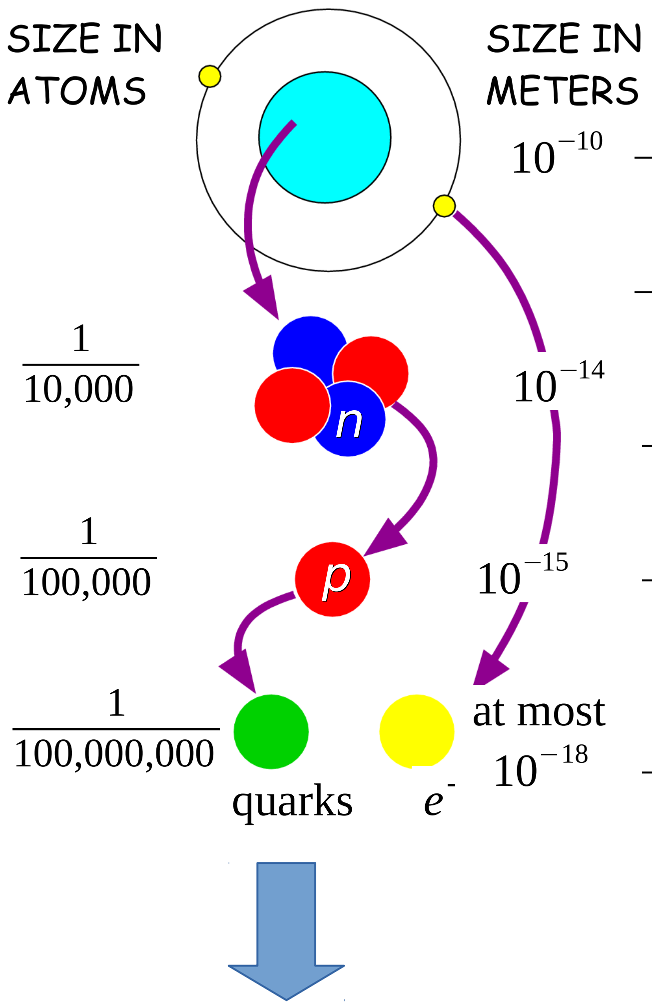

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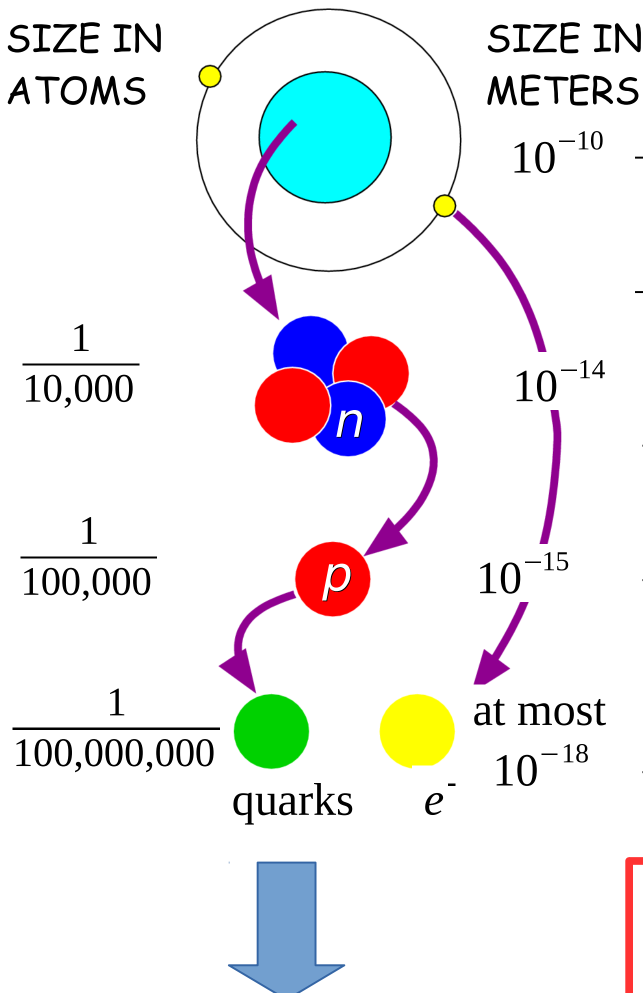

"preons"?
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	δx	$\delta p = \frac{\hbar}{2\,\delta x}$	binding energy needed
electrons in an atom	electromagnetic interaction		
nucleons in the nucleus	pion exchange (effective theory based on strong interaction)		
quarks in nucleons	strong interaction		
preons in quarks and leptons:	new interaction		

- If preons exist, they must interact through a new interaction, with an energy scale at the TeV level; The effect would be extremely small at low energies.
- This process could continue indefinitely… maybe until the Planck scale

Look more into matter, are there more layers beyond quarks and leptons?

Yes, since our quest for the structure of matter seems to continue indefinitely. It is hard to believe that nothing happens between 10^{-18}m and the Planck scale (10^{-35}m). And you have seen, each smaller layer will reveal one newer interaction at a higher energy.

No, because the Standard Model is a "relativistically correct quantum field theory". Therefore, if quarks and leptons have substructure, QFT must break down at that scale as well.

It is possible this will not happen until the Planck scale, where the concept of continuous space also ceases.

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The electroweak mixing happens in the neutral weak interactions. Therefore, neutral weak processes provide a rick playground for SM physicists!

This is the role we play with electron scattering.

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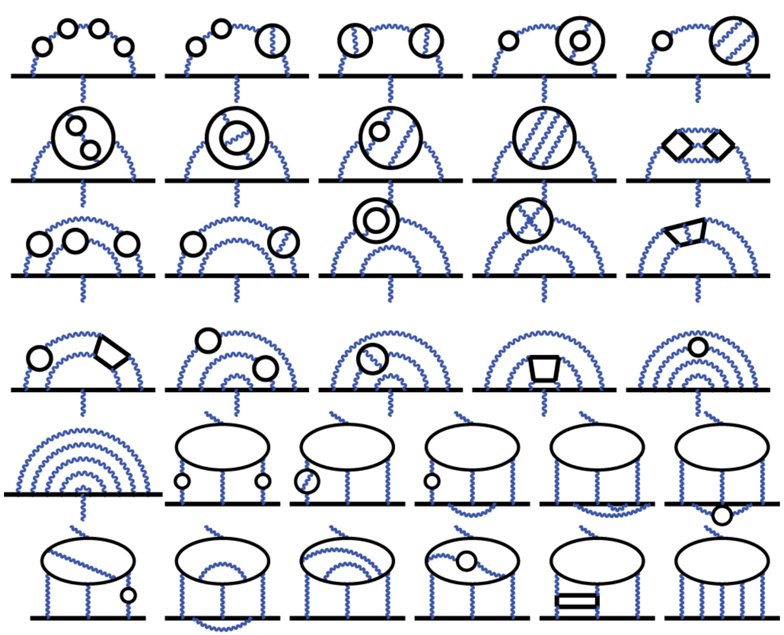

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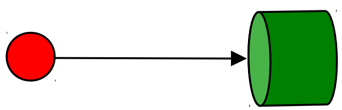
Brief Introduction to Electron Scattering

Electron Scattering on Fixed Nuclear or Nucleon Targets

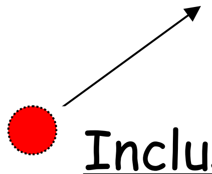
electron beam (GeV)



target (at rest)

Before

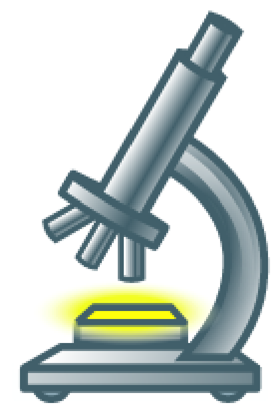
to detector



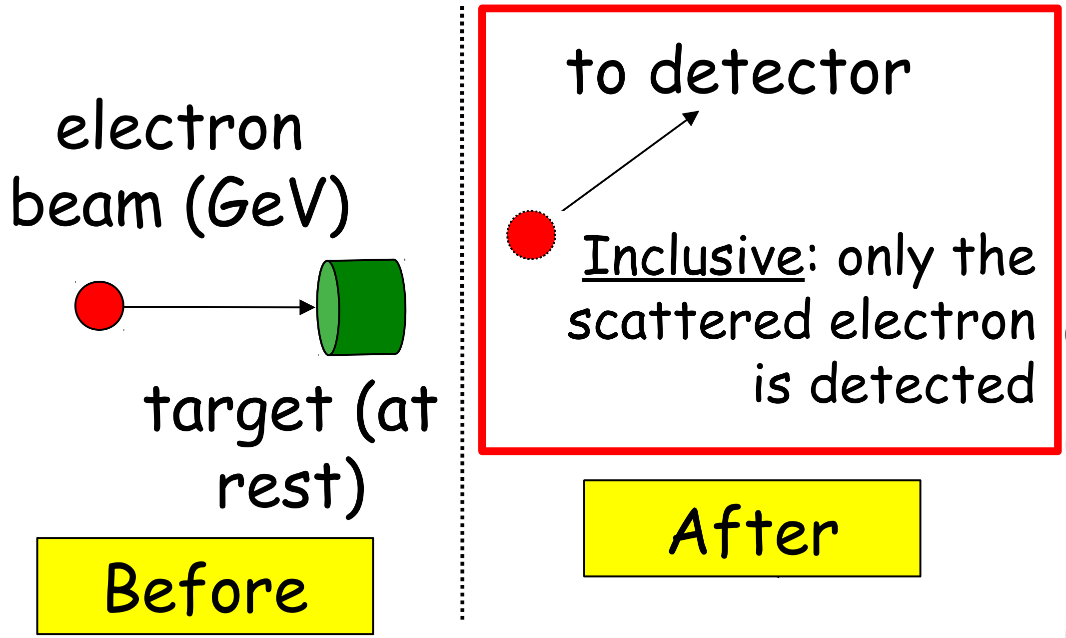
<u>Inclusive</u>: only the scattered electron is detected

After

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



Electron Scattering on Fixed Nuclear or Nucleon Targets



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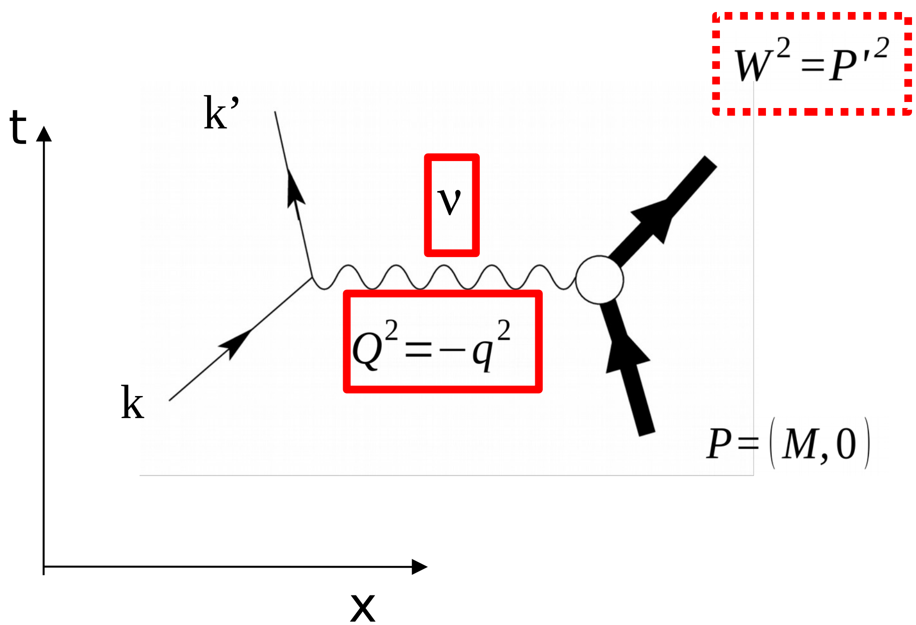
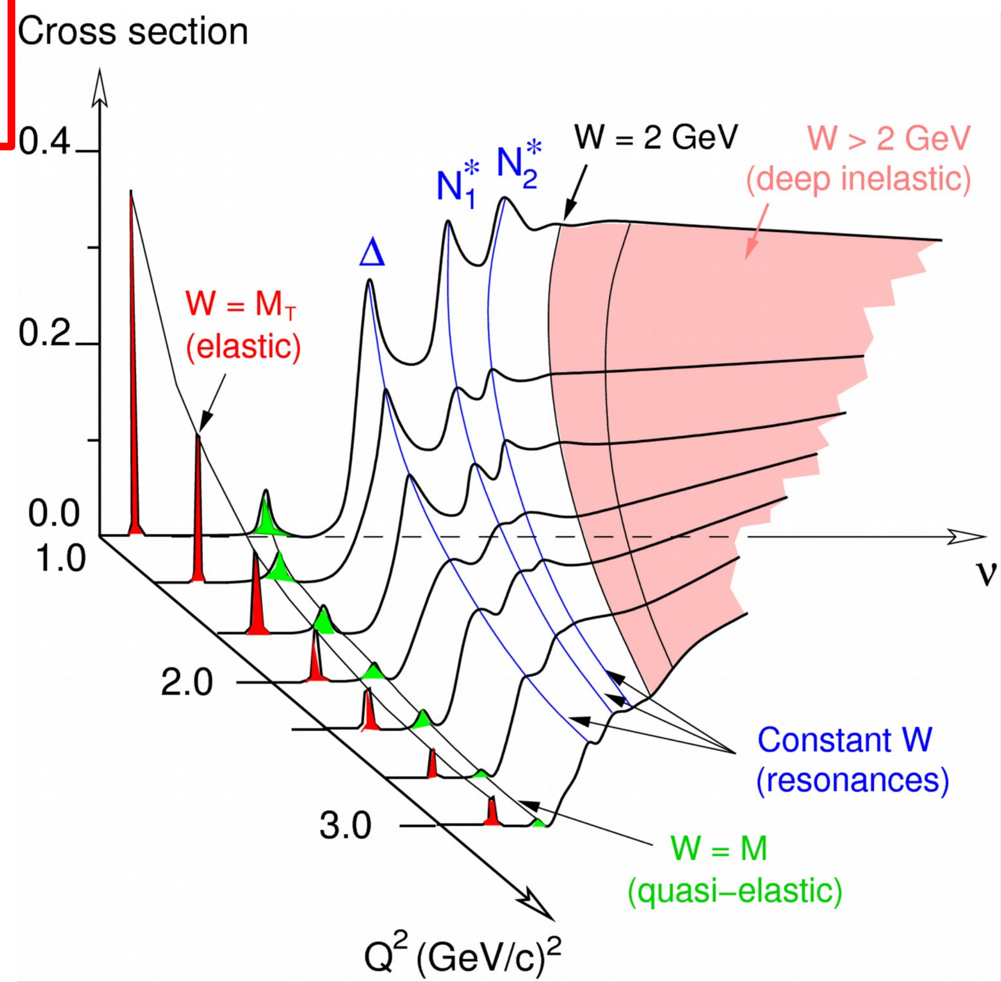
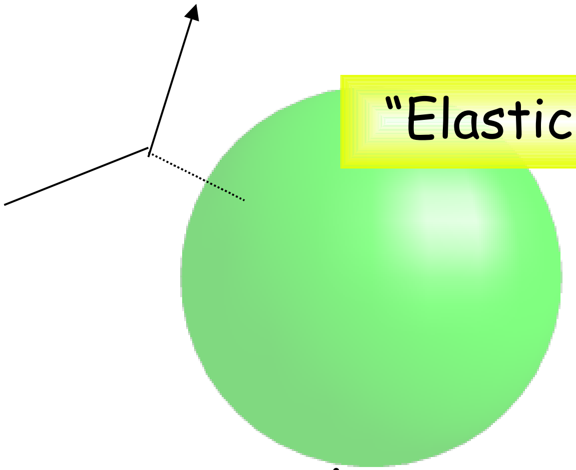




Three kinematic regions



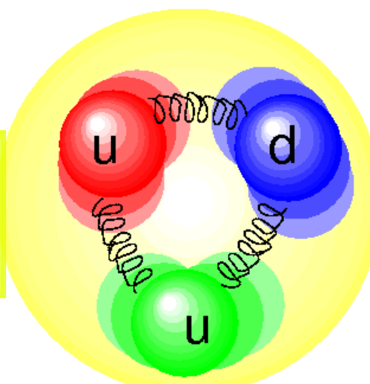
"Elastic": W=M_t or M_p

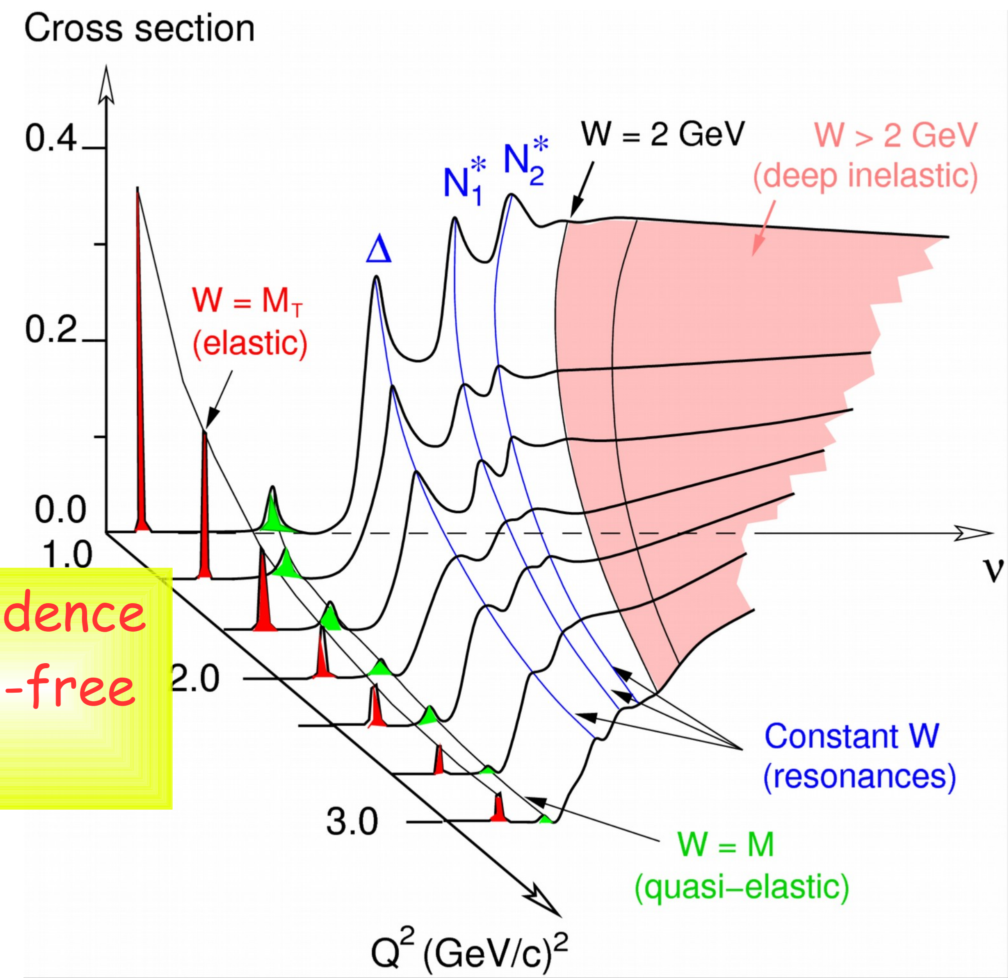
1961

From cross section we extract "elastic form factors"

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

"Resonance": 1<W<2GeV





1999

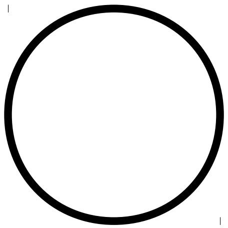
2004

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

10^{-18}m or smaller

Parity Violation in Electron Scattering

Symmetry – an object or process remains the same after a certain transformation



– Circular symmetry

Natural objects often exhibit certain symmetry, indicating such symmetry must be present in the physical/ chemical/ biological law behind it.

Symmetry fulfills our strong desire of simplifying our lives, and search for beauty.

We often design objects or architecture following certain symmetry rules.

Parity Symmetry

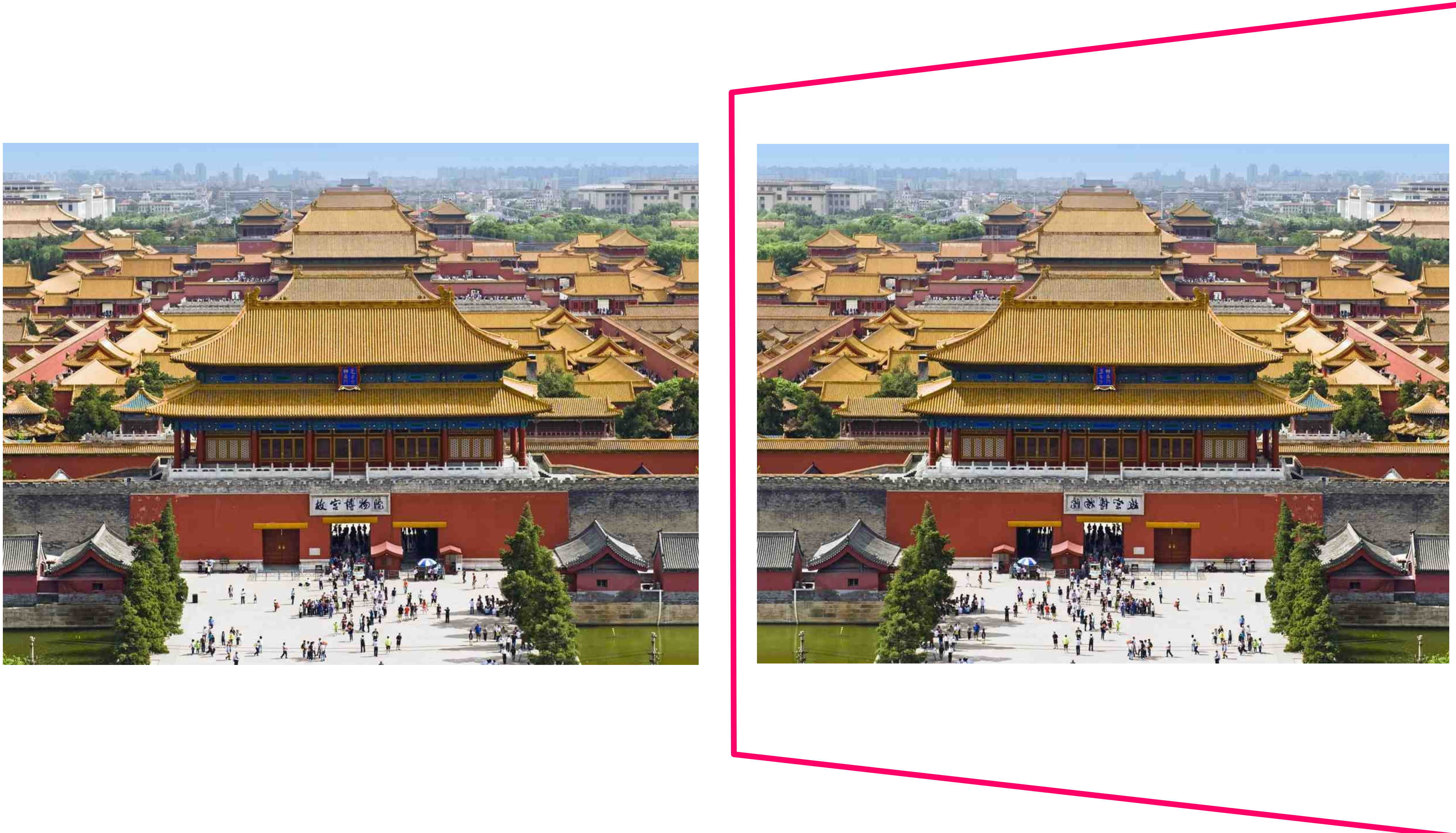
If a system is described by a function ϕ, and if it satisfies:

$$\phi(\vec{r}) = \phi(-\vec{r})$$

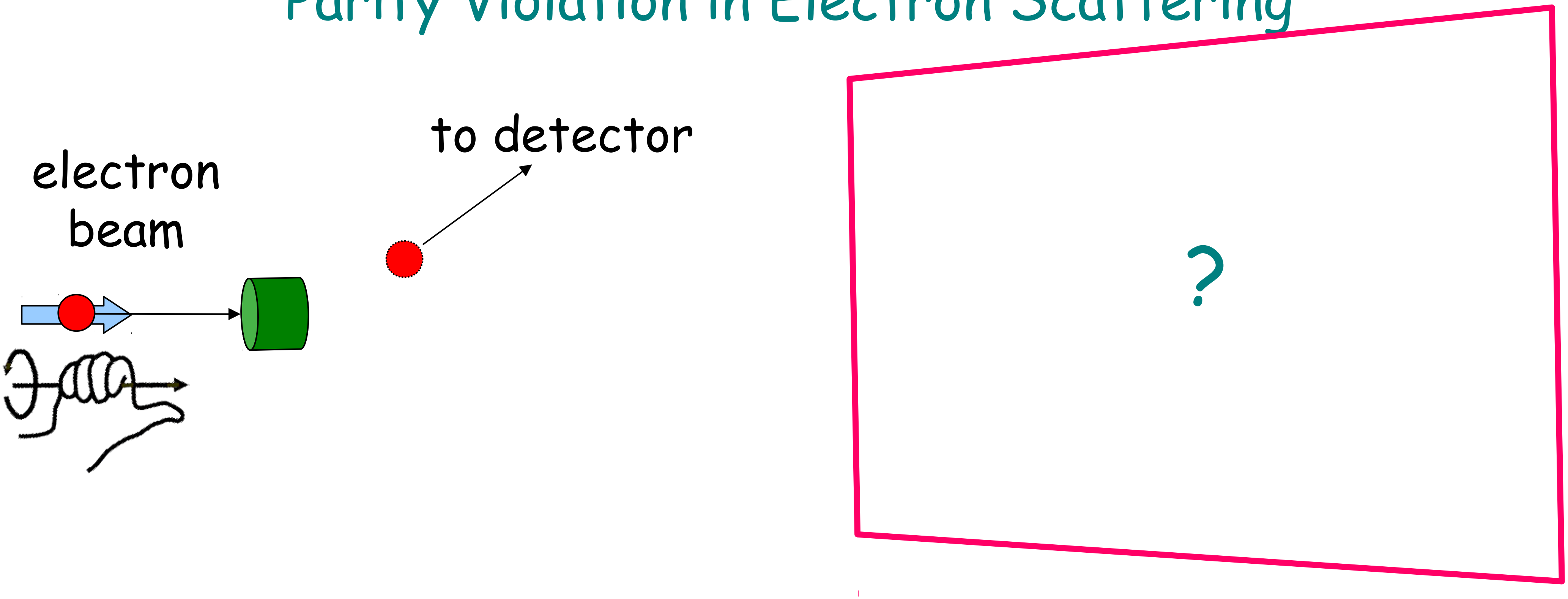
we say that the system remains unchanged (invariant) after the parity transformation $\vec{r} \rightarrow -\vec{r}$, and that the system exhibits the parity symmetry.

Very often, we care only the one- or two-dimensional description of a process. In this case, parity symmetry is equivalent to the mirror symmetry: If the process appears to be the same as its mirror image, we say it exhibits the mirror symmetry or "left/right symmetry".

Parity (Mirror) Symmetry



Parity Violation in Electron Scattering



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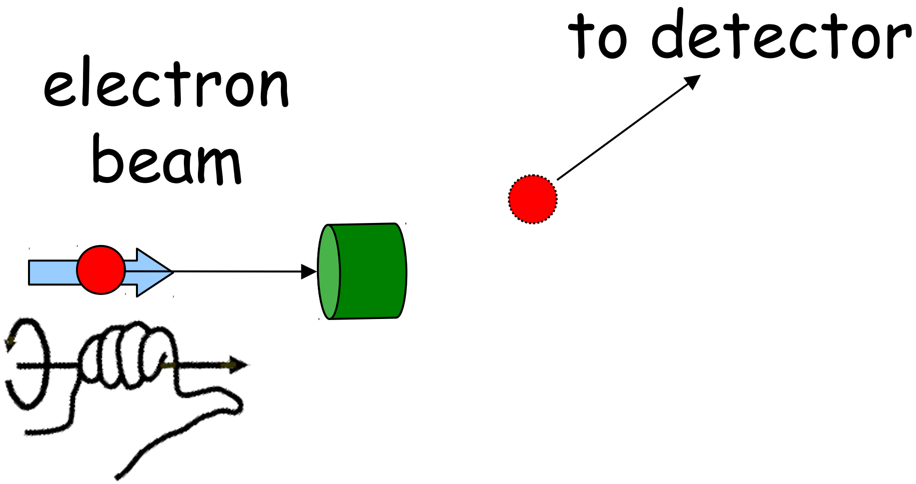

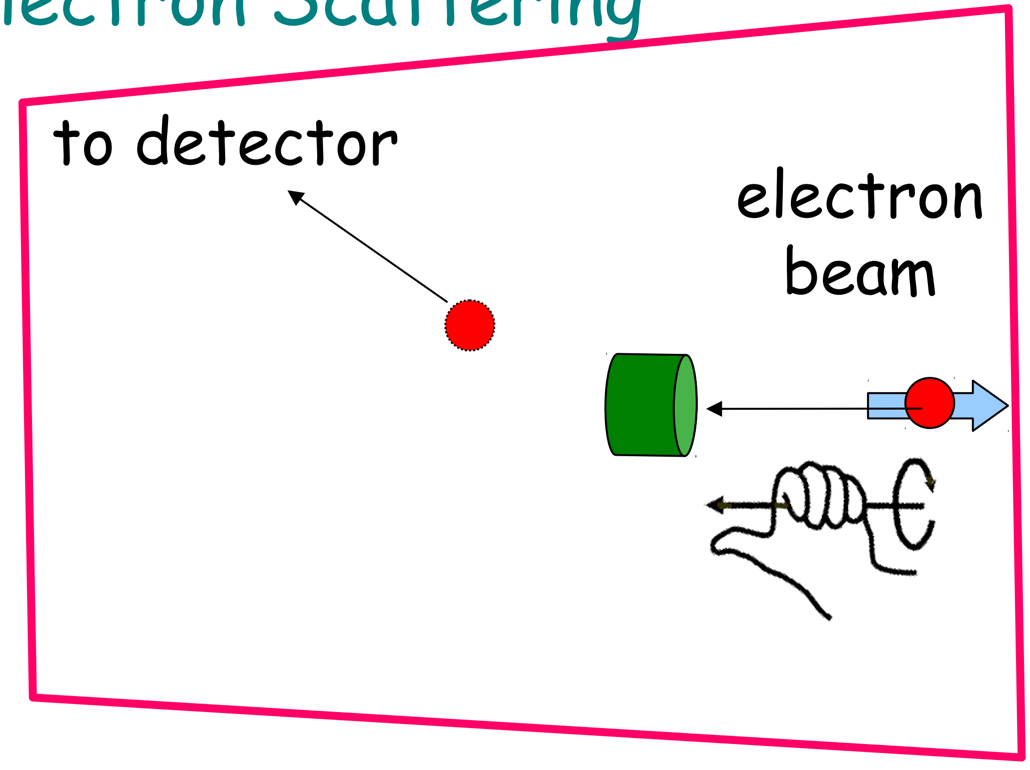

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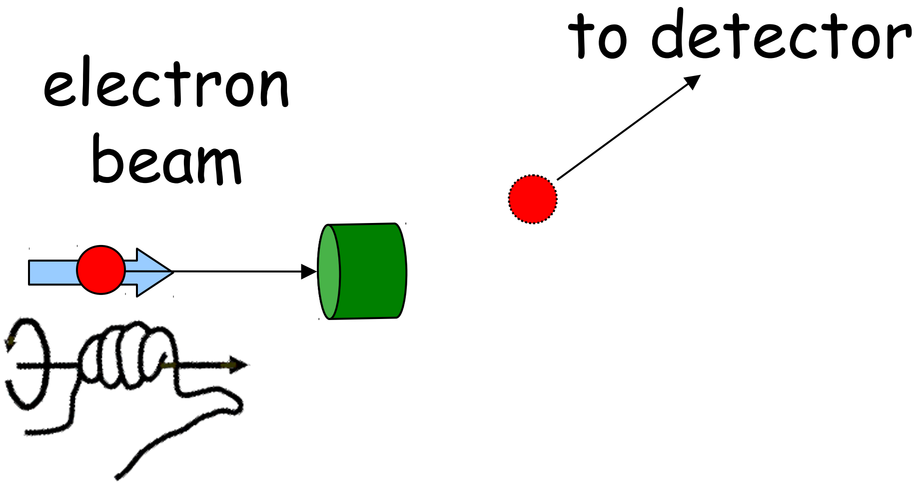
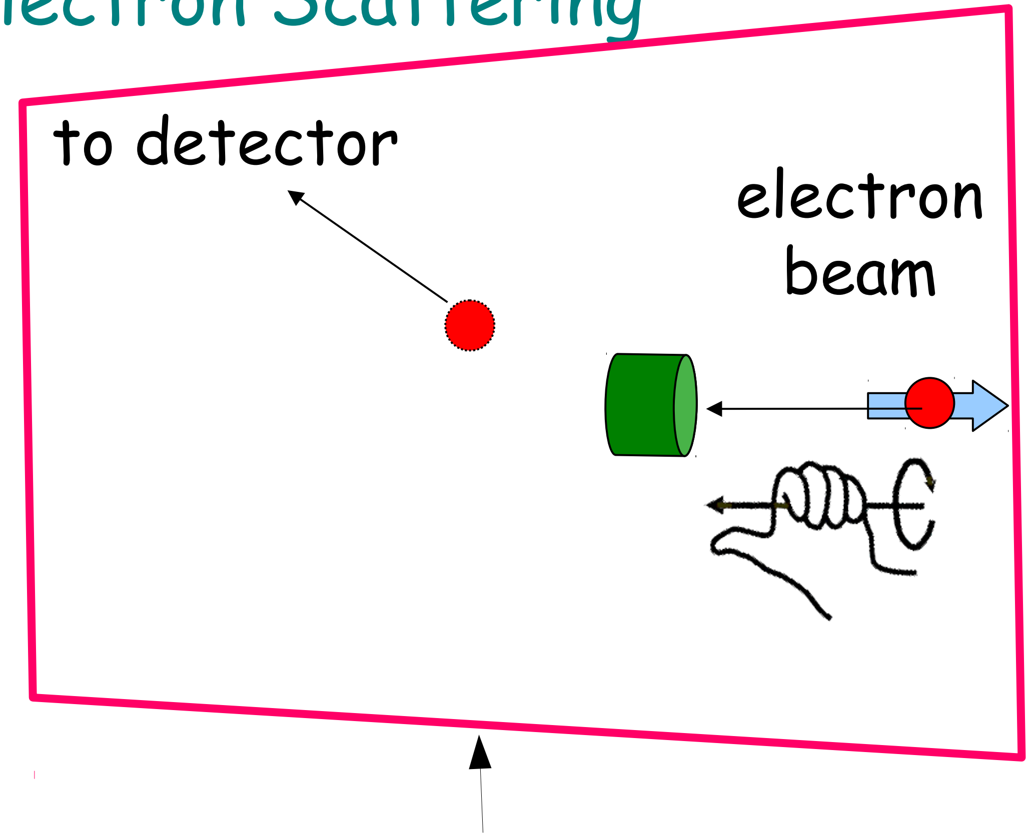
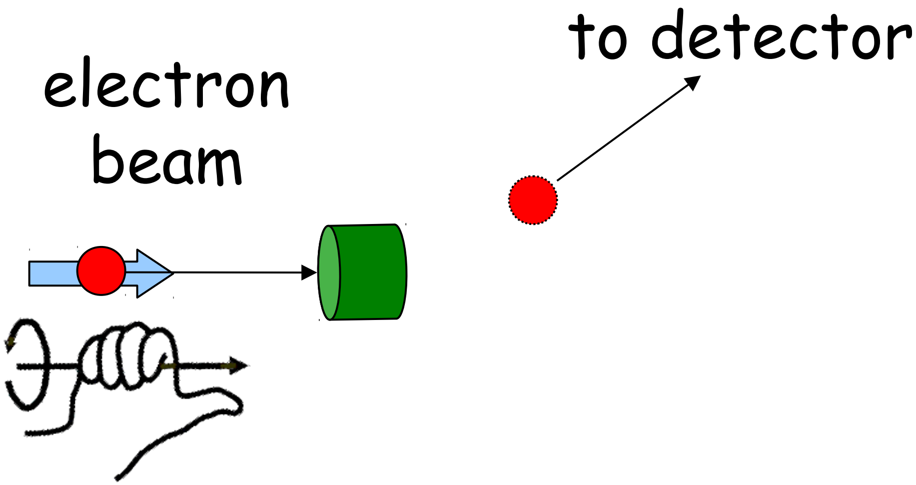
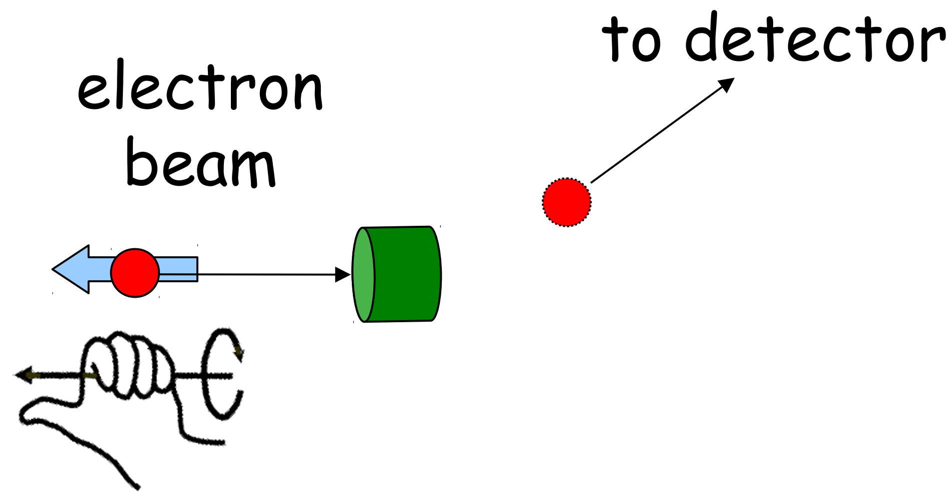




draw this on a piece of (transparent) paper, then flip it to the left

Parity Violation in Electron Scattering





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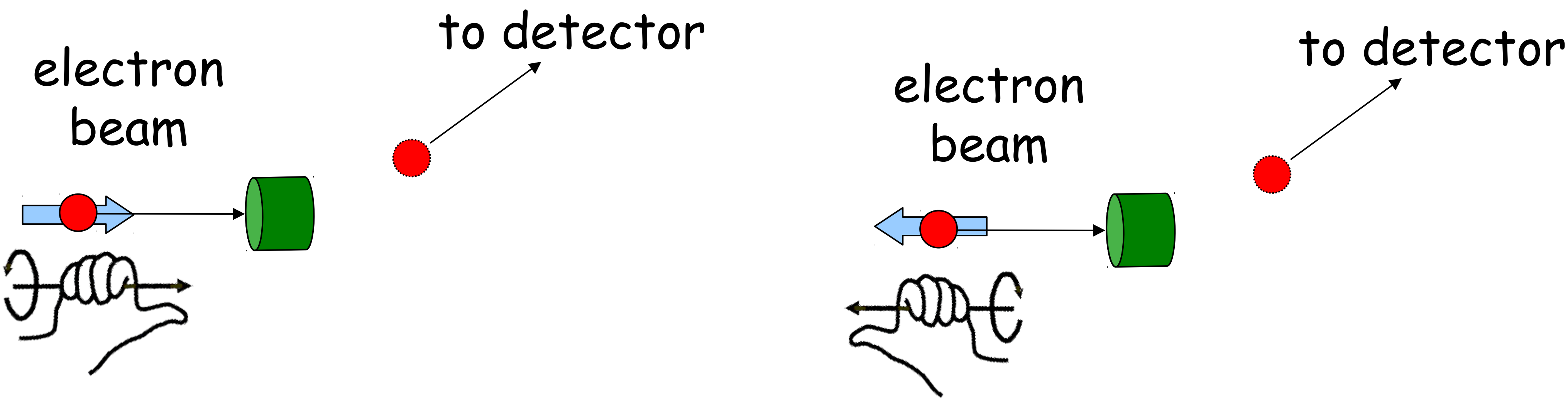
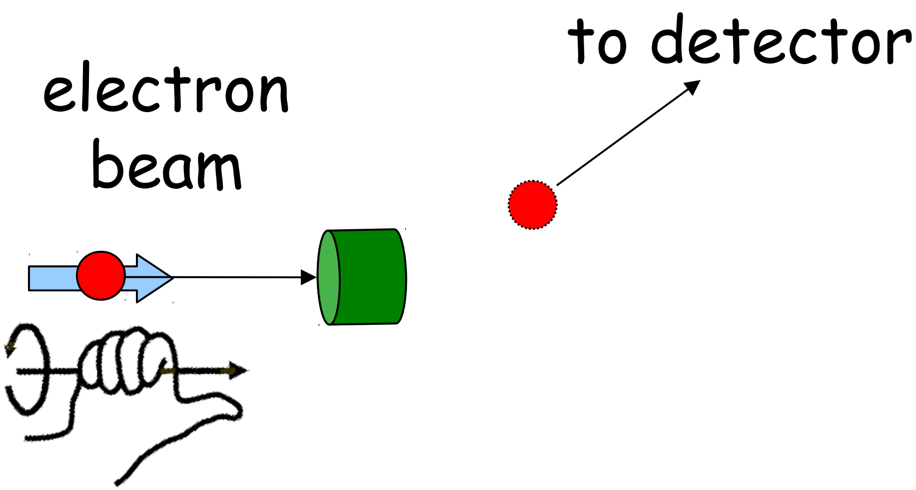
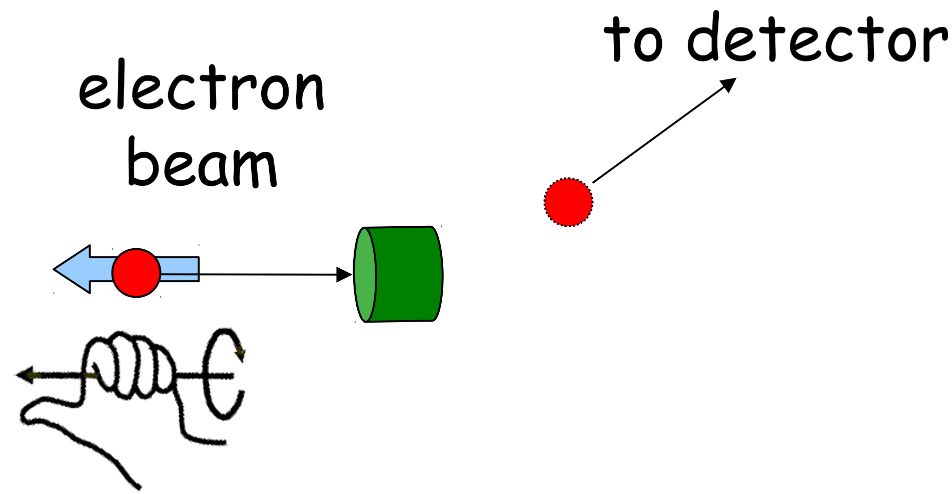


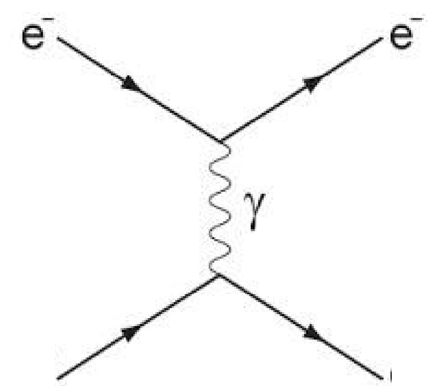
- If parity symmetry were exact, then the physical law behind a process is the same as the law behind its mirror process.
- In the above case, the scattering probability (cross-section) should be exactly the same for these two processes. That is, should be exactly the same between left- and right-handed beam electrons.

Parity Violation in Electron Scattering

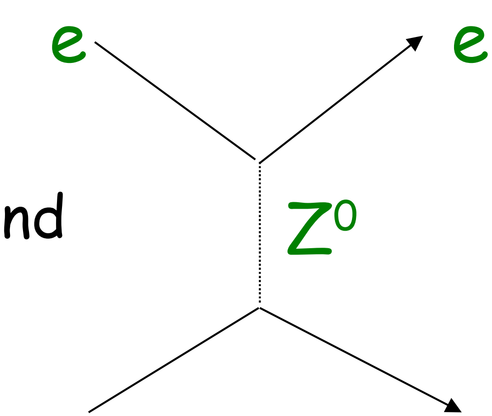




- We can access parity violation by the count difference between left- and right-handed beam electrons.
- In the Standard Model, only weak interaction violate parity symmetry. The "asymmetry" is given by the interference term between:



and



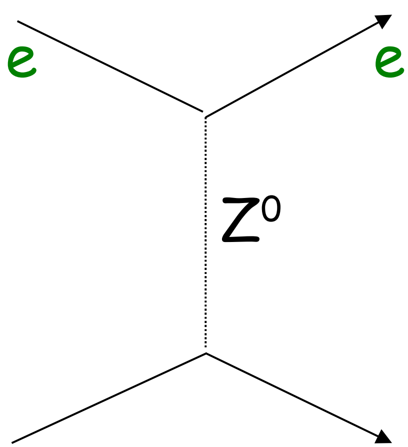
$$A_{LR} \equiv \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} \approx \frac{Q^2}{M_Z^2} \approx 120\, ppm \quad at \quad Q^2 = 1\left(GeV/c\right)^2$$

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

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



[for charged weak interaction, there is no mixing with electromagnetism and the vertex is simply ~ $\gamma^\mu(1-\gamma^5)$]

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

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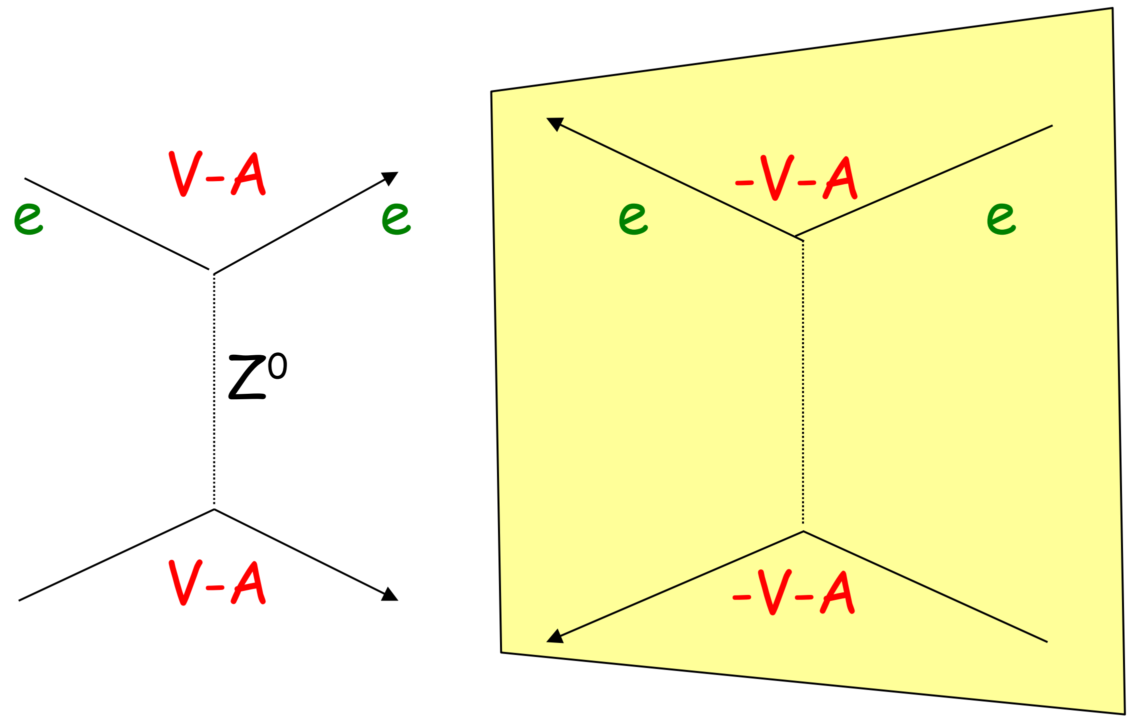
- PVES asymmetry comes from V(e)xA(targ) and A(e)xV(targ)



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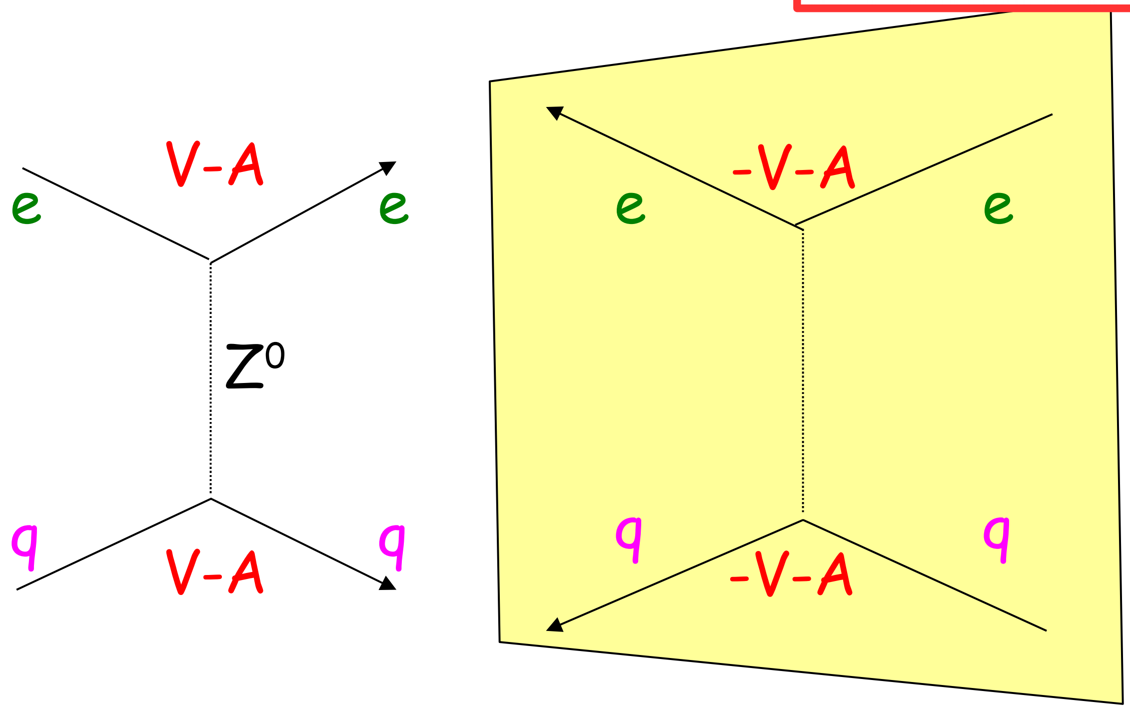
- PVES asymmetry comes from:

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



"electron-quark effective couplings"

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

Parity Violation in Deep Inelastic Scattering

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

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

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

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

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

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

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

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

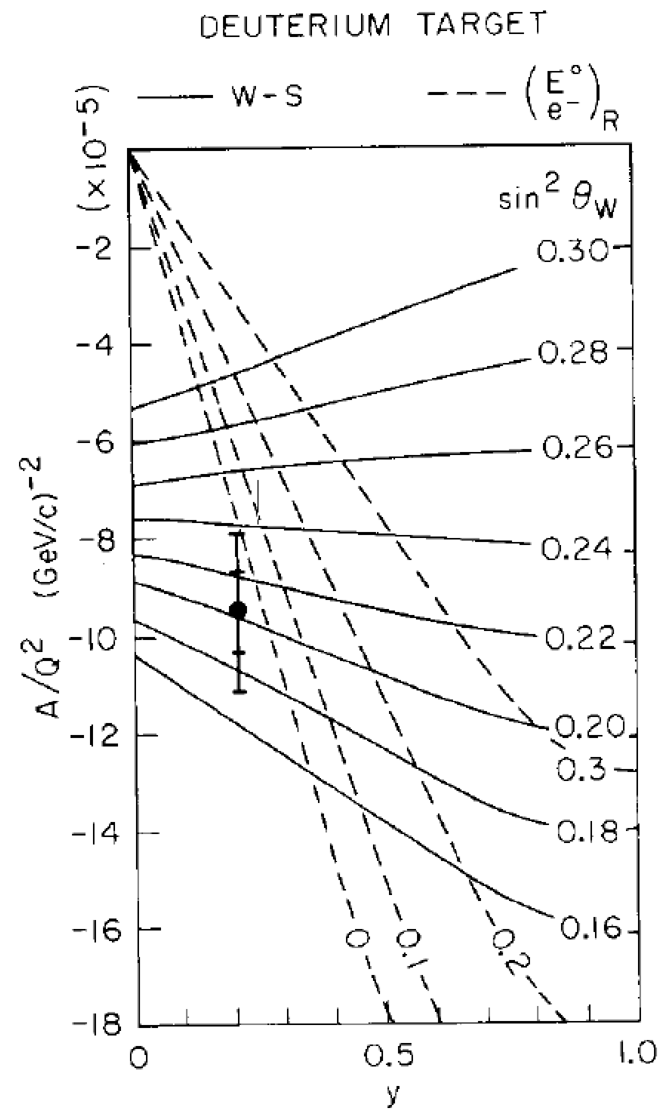
$$b(x) = \frac{3}{10}\left(2C_{2u} - C_{2d}\right)\left(\frac{u_V + d_V}{u^{+} + d^{+}}\right)$$

0

PVDIS: Only way to measure C_{2q} among current EW experiments

SLAC E122 (1978)

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



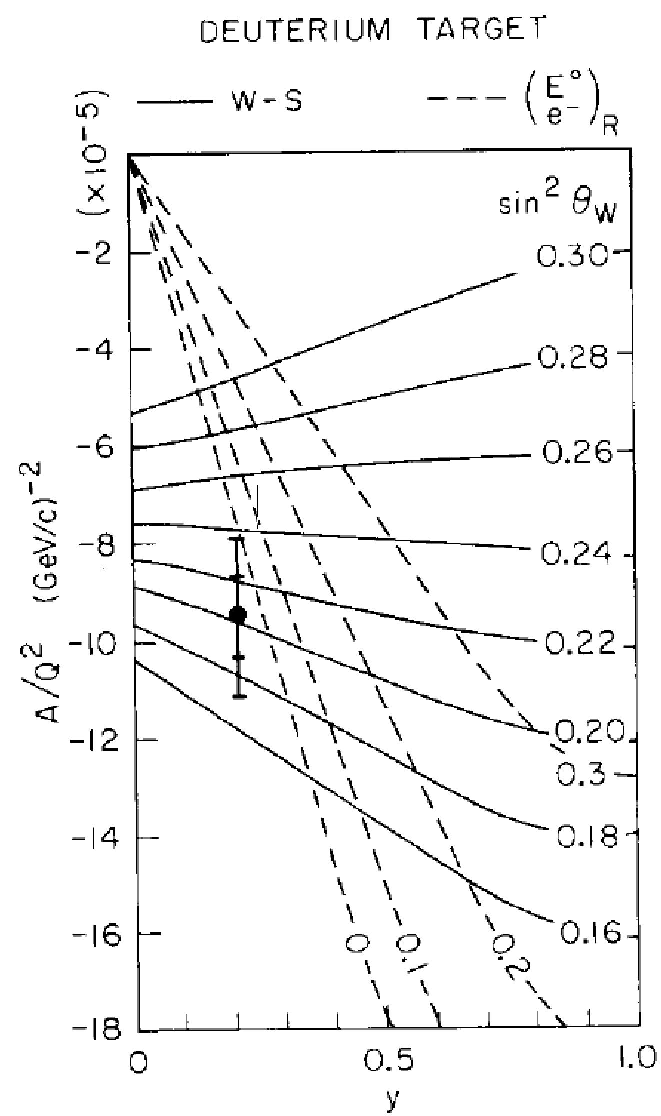
Prescott et al, Phys. Lett. 77B, 347 (1978)

Physics Accessed in PVES

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

- In the late 1990's – ~ 2006, PVES was used to measure the nucleon strange form factors in the elastic domain

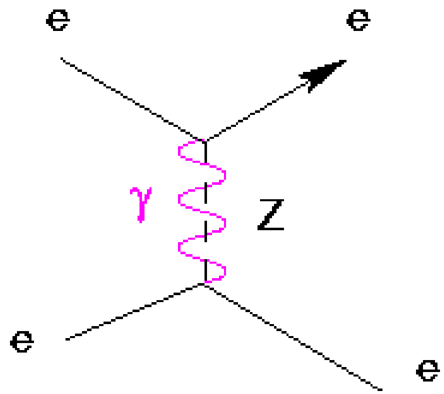
- Nowadays, PVES is being used to test the Standard Model, and to set limits on new physics: PVES in elastic scattering can access C_{1q}, while PVDIS can access both C_{1q} and C_{2q}.



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

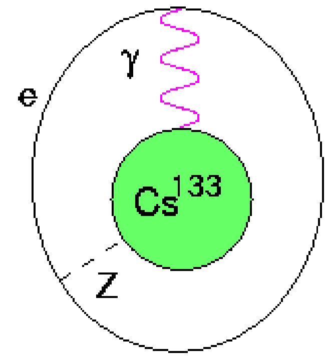
PV DIS and Other SM Test Experiments

E158/Moller (SLAC)



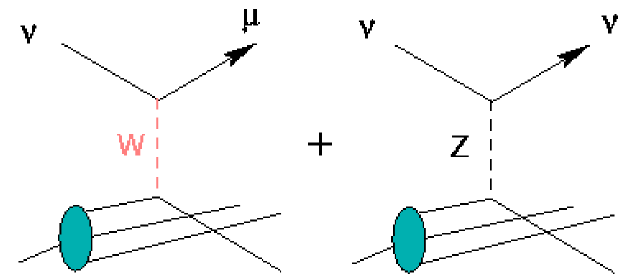
- Purely leptonic

Atomic PV



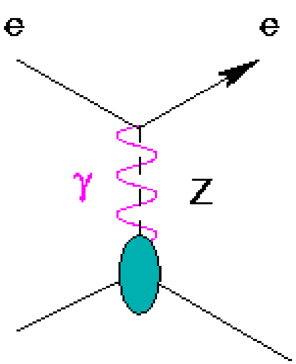
- Coherent Quarks in the Nucleus
- $-376C_{1u} - 422C_{1d}$
- Nuclear structure?

NuTeV (FNAL)



- Weak CC and NC difference
- Nuclear structure?
- Other hadronic effects?

Qweak (JLab)

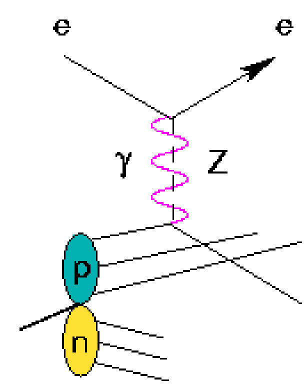


- $2(2C_{1u}+C_{1d})$ the "proton weak charge"

Different Experiments Probe Different Parts of Lagrangian,

PVDIS is the only one accessing C_{2q}

PVDIS (JLab)



- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Cartoons borrowed from R. Arnold (UMass)

Some Recent Results from JLab

(I will only present PVDIS. for Qweak results please come to the workshop)

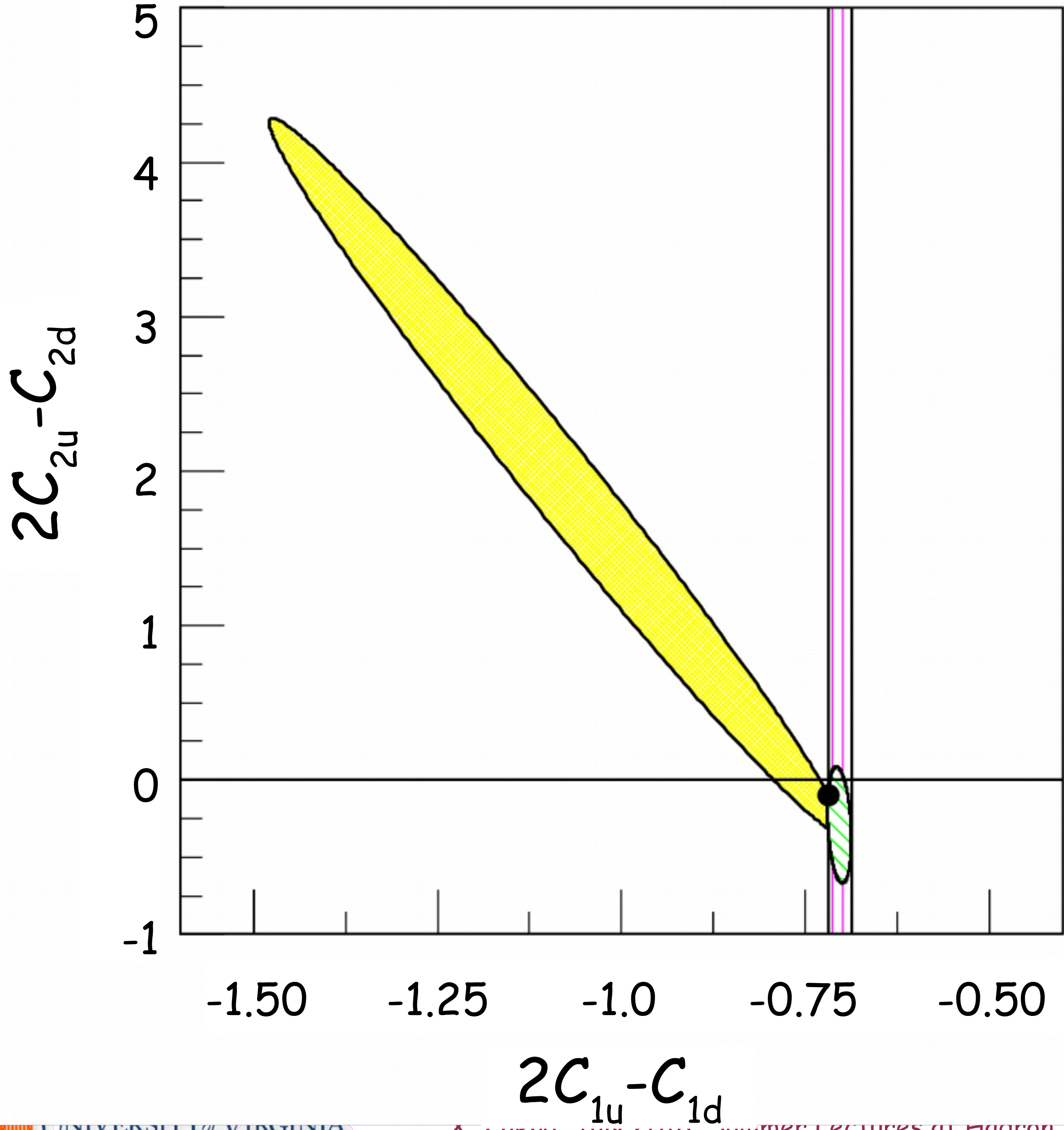
Formalism for PVDIS

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

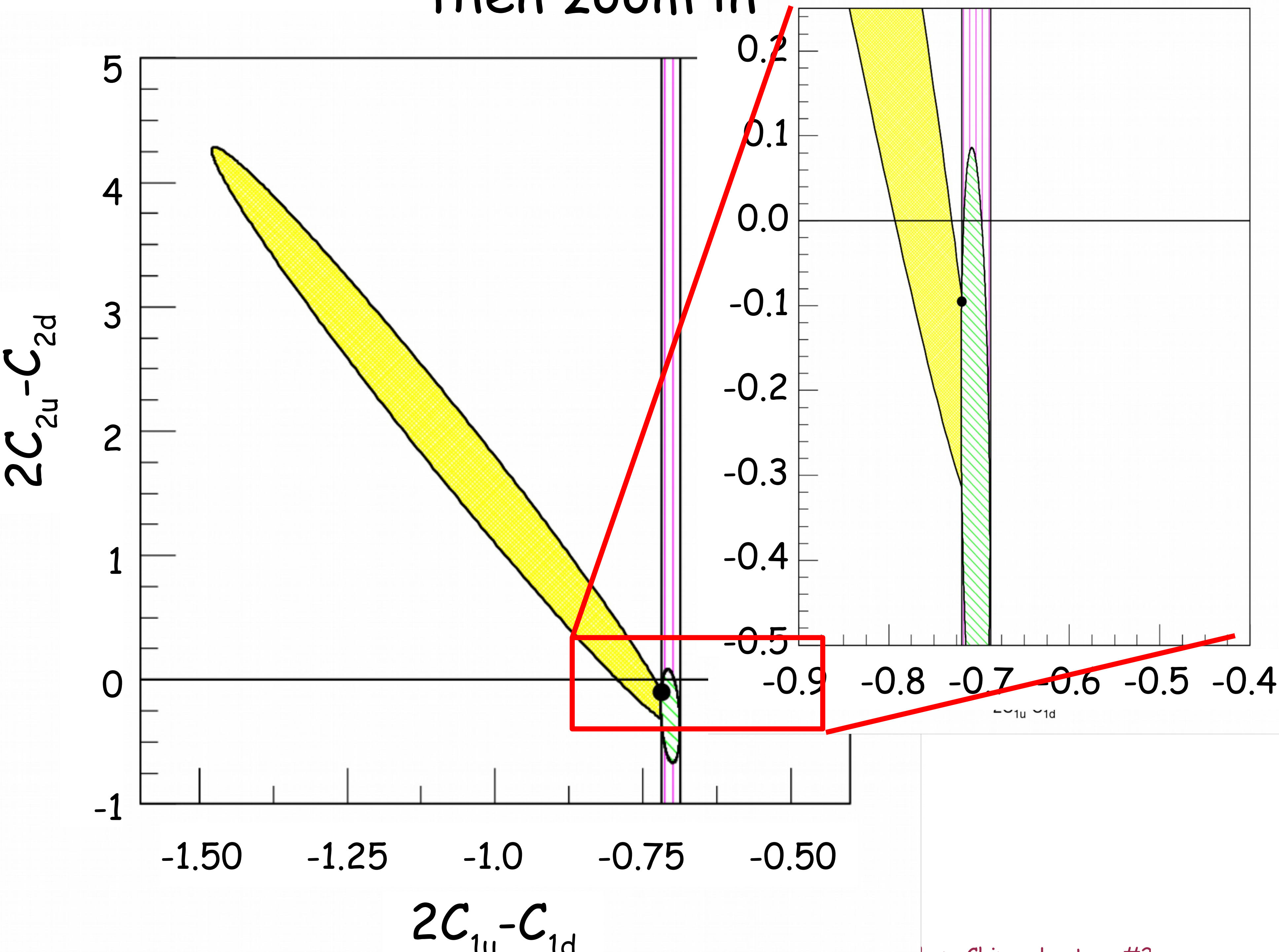
For an isoscalar target (^{2}H):

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

C_{2q} from E122 (before JLab)

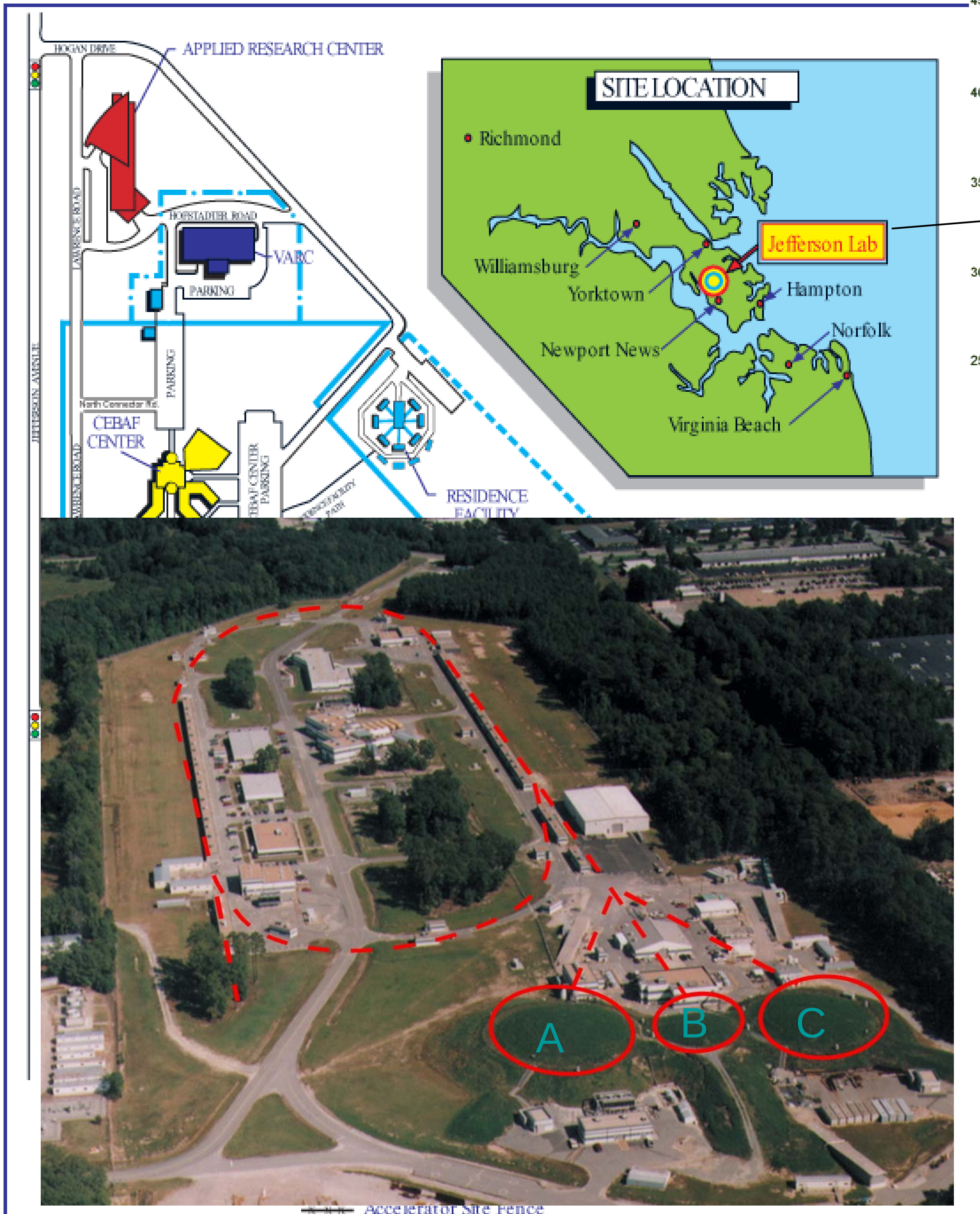


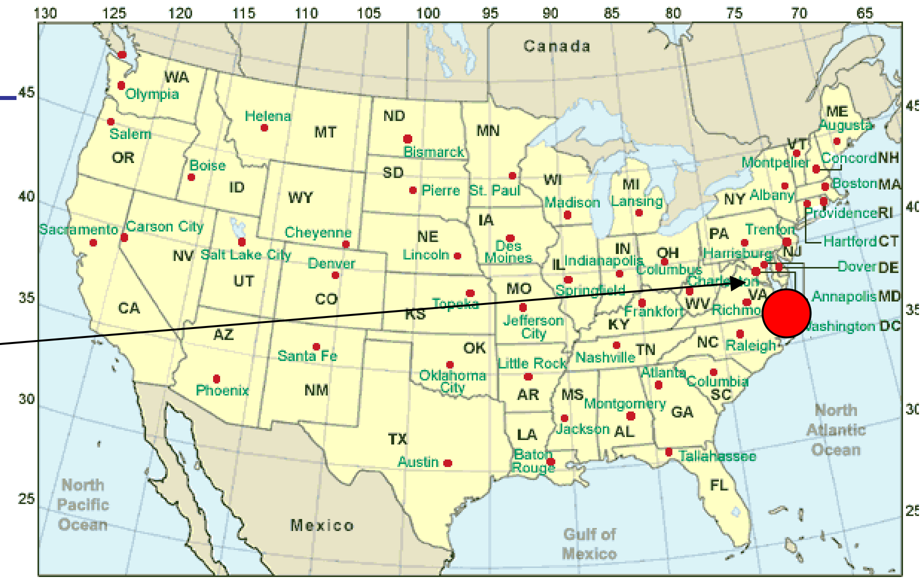
then zoom in



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^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

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

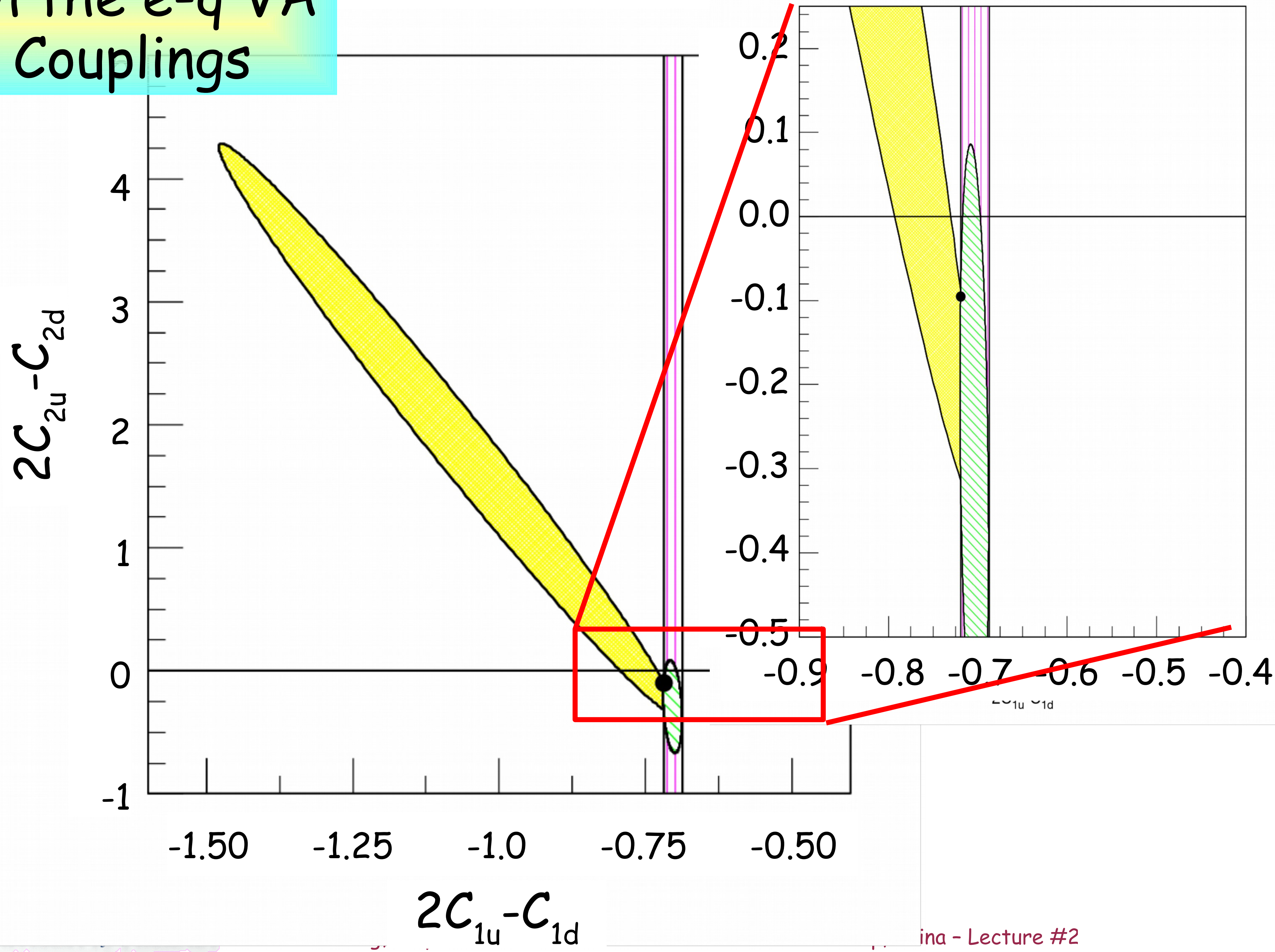
$$A^{phys}_{Q^2=1.901, x=0.295} = -160.80 \pm 6.39 \pm 3.12\ ppm$$

compare to

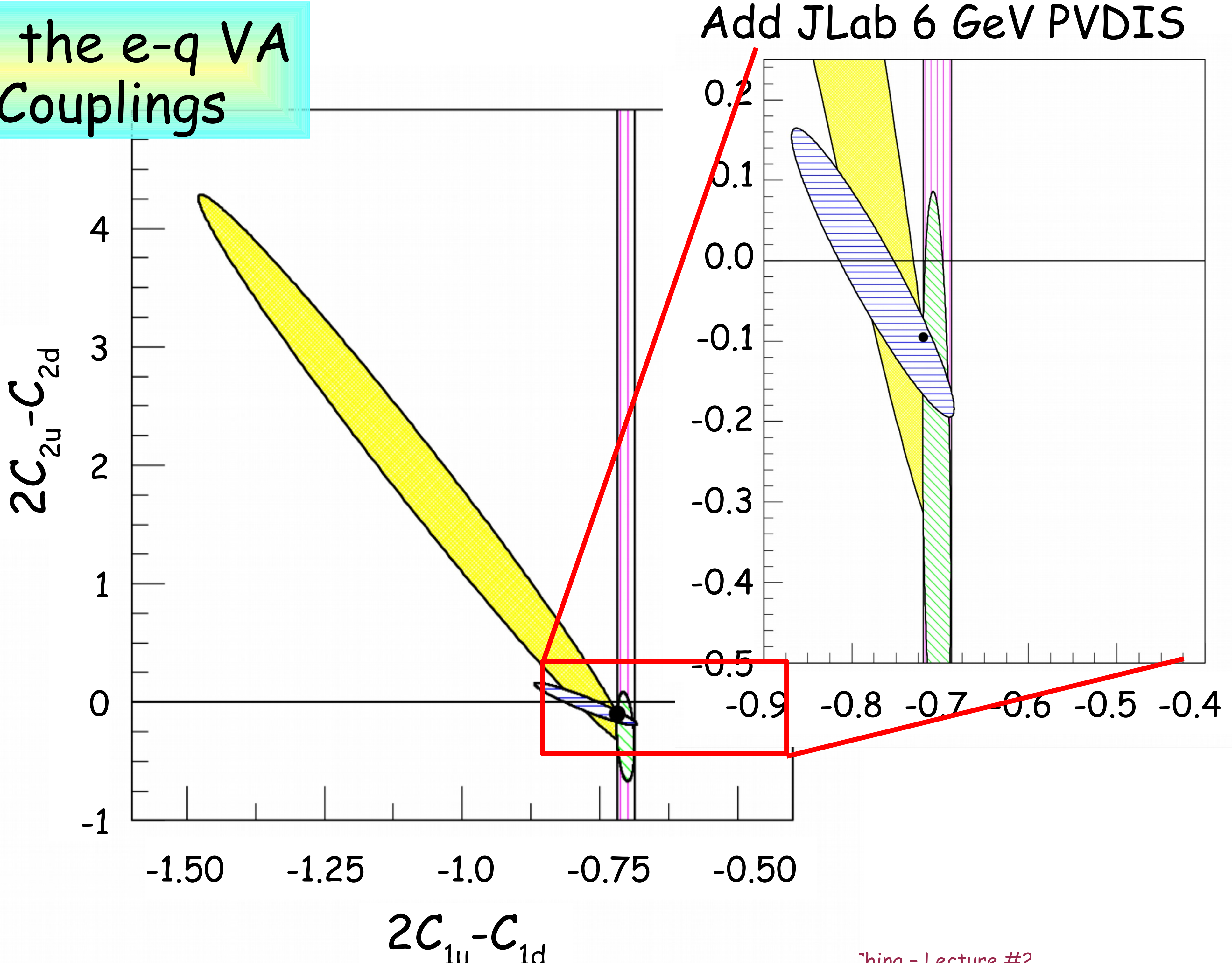
$$A^{SM} = \left(2.022\times10^{-4}\right)\left[\left(2C_{1u}-C_{1d}\right)+0.594\left(2C_{2u}-C_{2d}\right)\right]$$

On the e-q VA Couplings

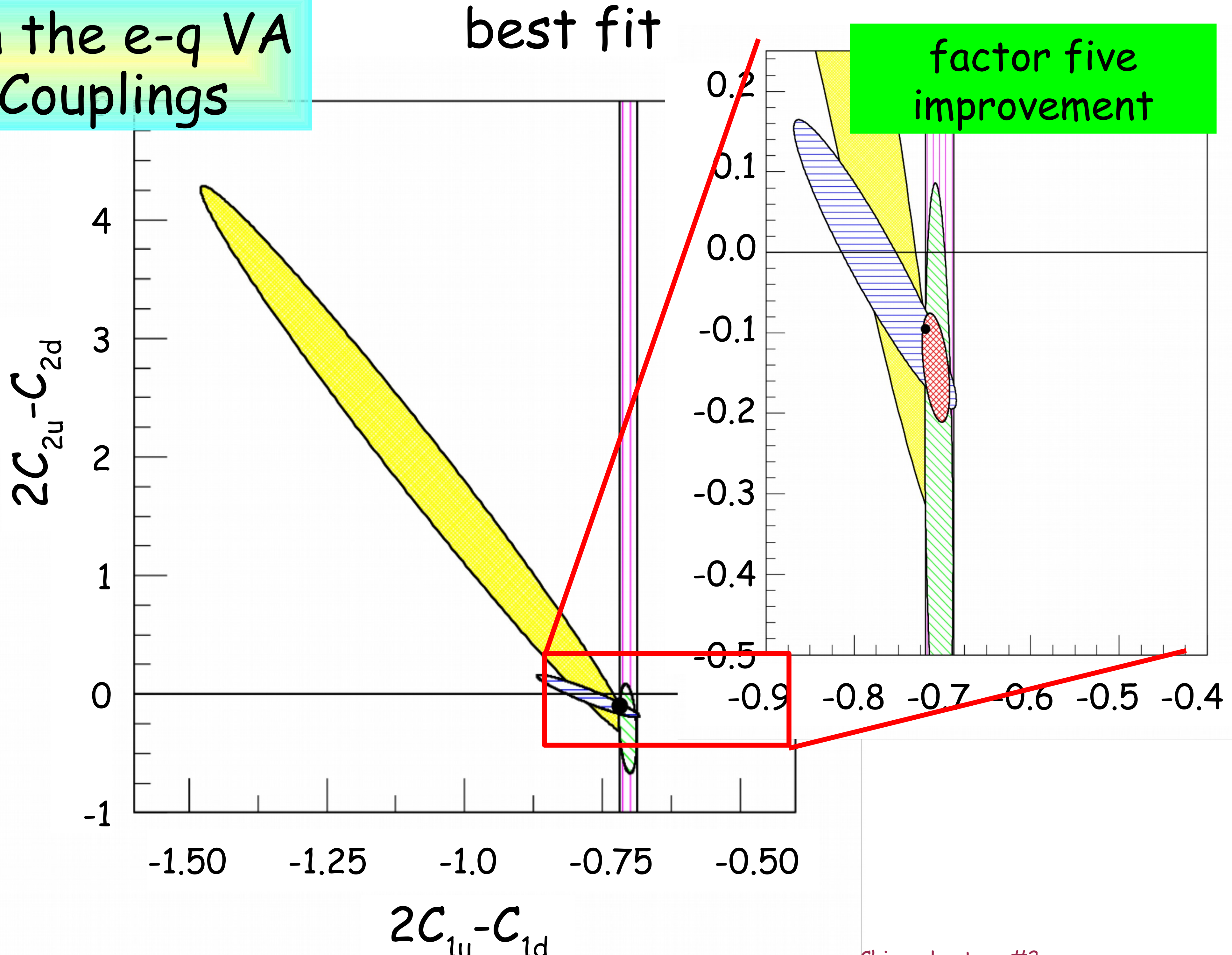
Previous data: E122, Elastic PVES + APV



On the e-q VA Couplings



On the e-q VA Couplings



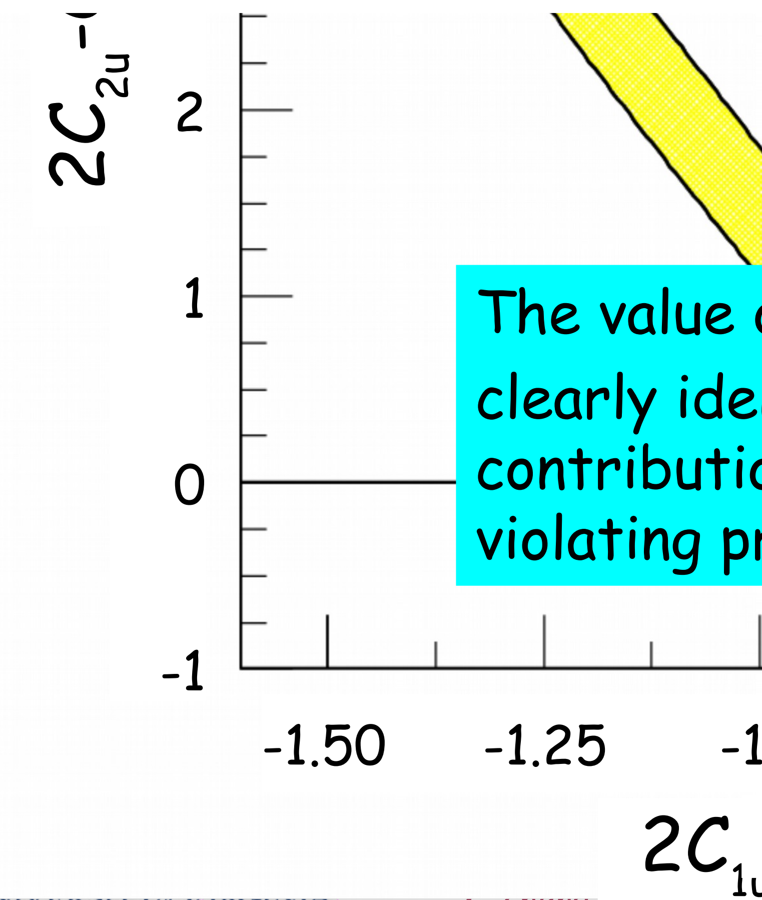
PARTICLE PHYSICS

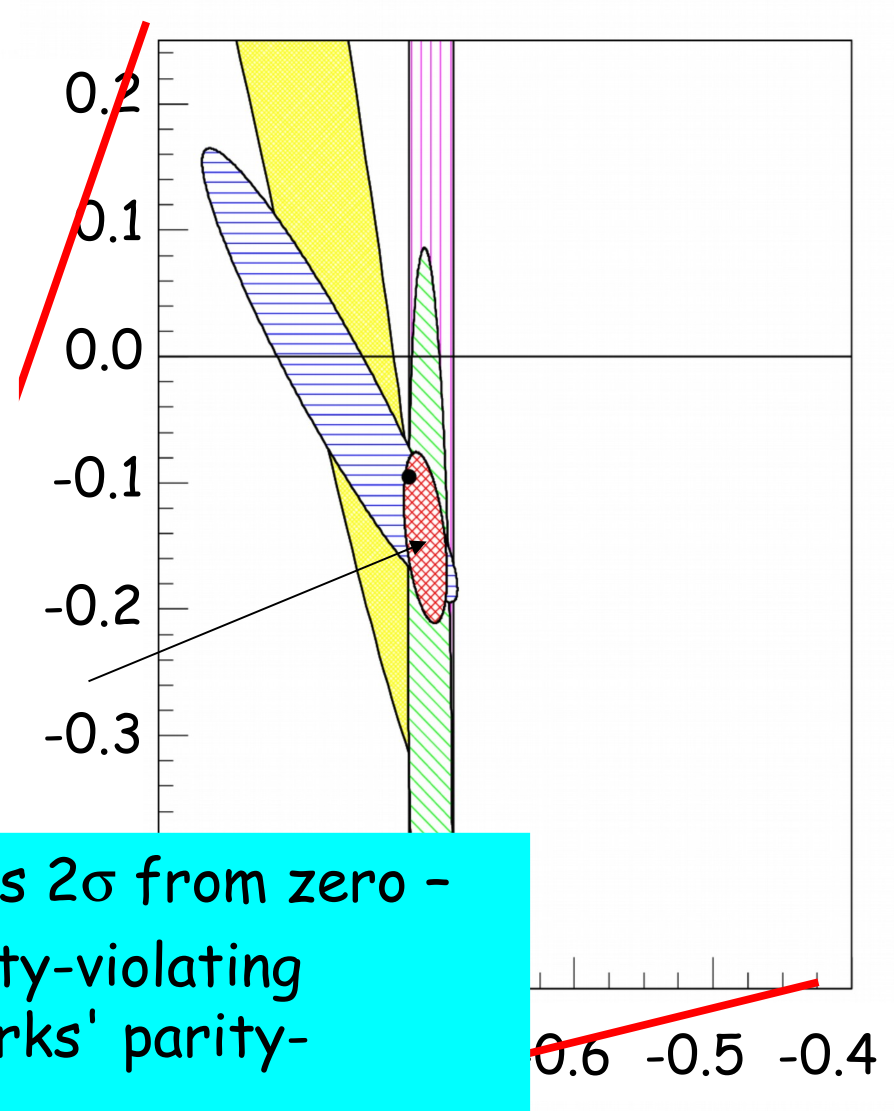
Quarks are not ambidextrous

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



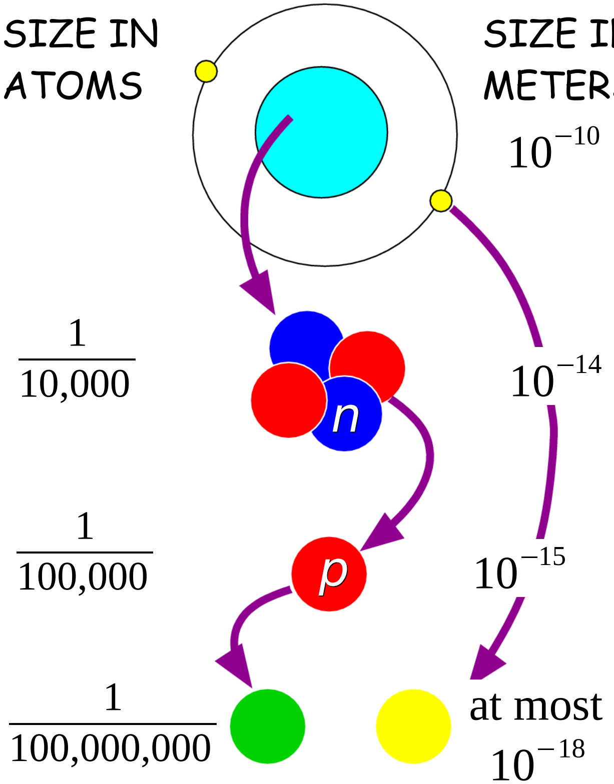


The value of $2C_{2u}-C_{2d}$ is 2σ from zero – clearly identified parity-violating contribution from quarks' parity-violating property

"Measurement of parity violation in electron-quark scattering"

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

Description of New Physics



"preons"?
（初子？）

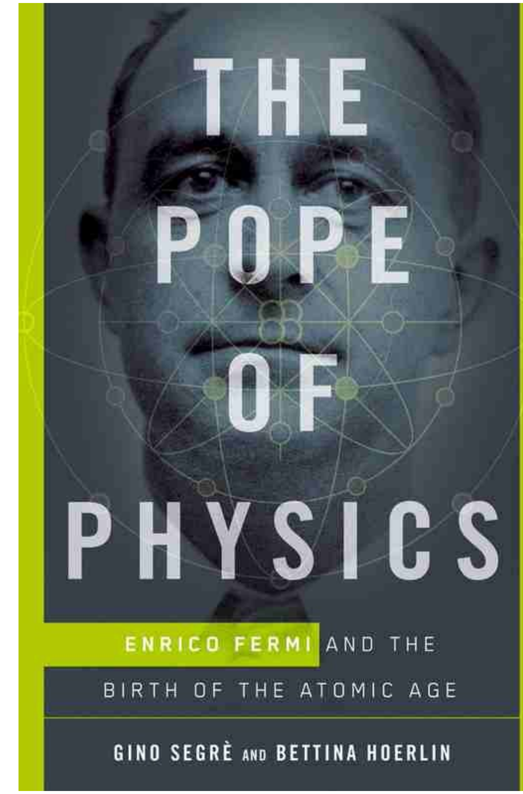
	δx	$\delta p = \frac{\hbar}{2\,\delta x}$	δE (binding energy)
electrons in an atom	10^{-10} m	≈ keV	≈ eV
nucleons in the nucleus	$10^{(-14\sim-15)}$m	≈10^2MeV	≈10^1MeV
quarks in nucleons	10^{-15}m	≈10^2MeV	(≈10^2MeV)
preons in quarks and leptons:	$10^{-19\sim-18}$ m	≈ 10^2GeV -TeV	≈TeV

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

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

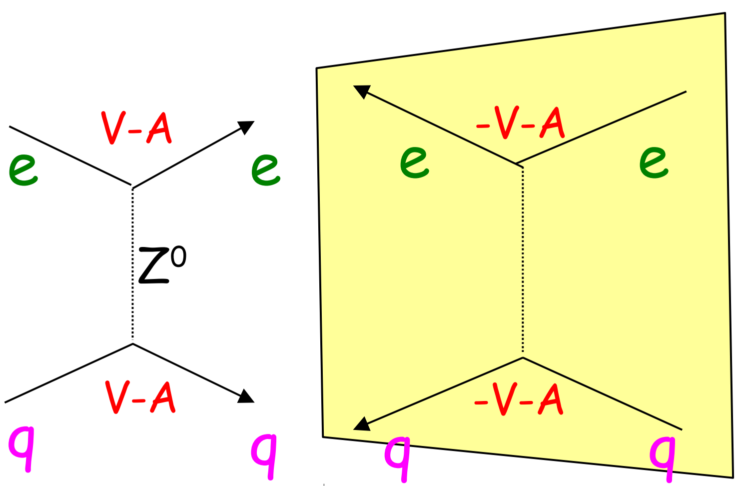
mass scale Λ

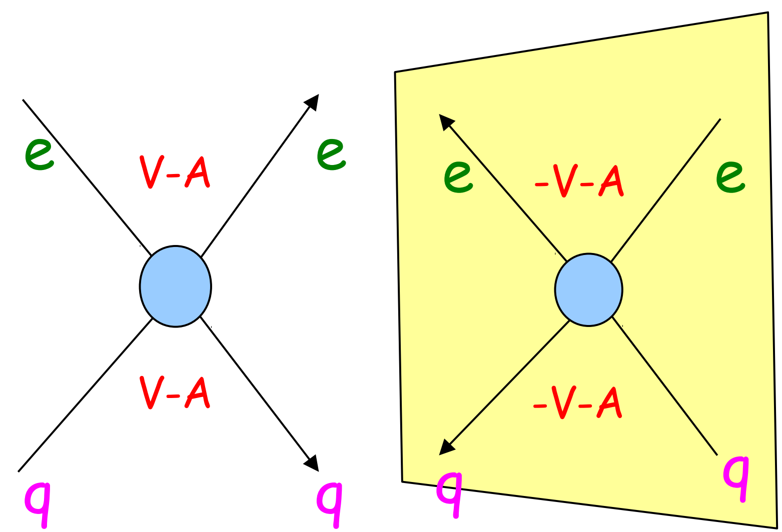
Searching for "New Contact Interactions"



Below the mass 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.

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

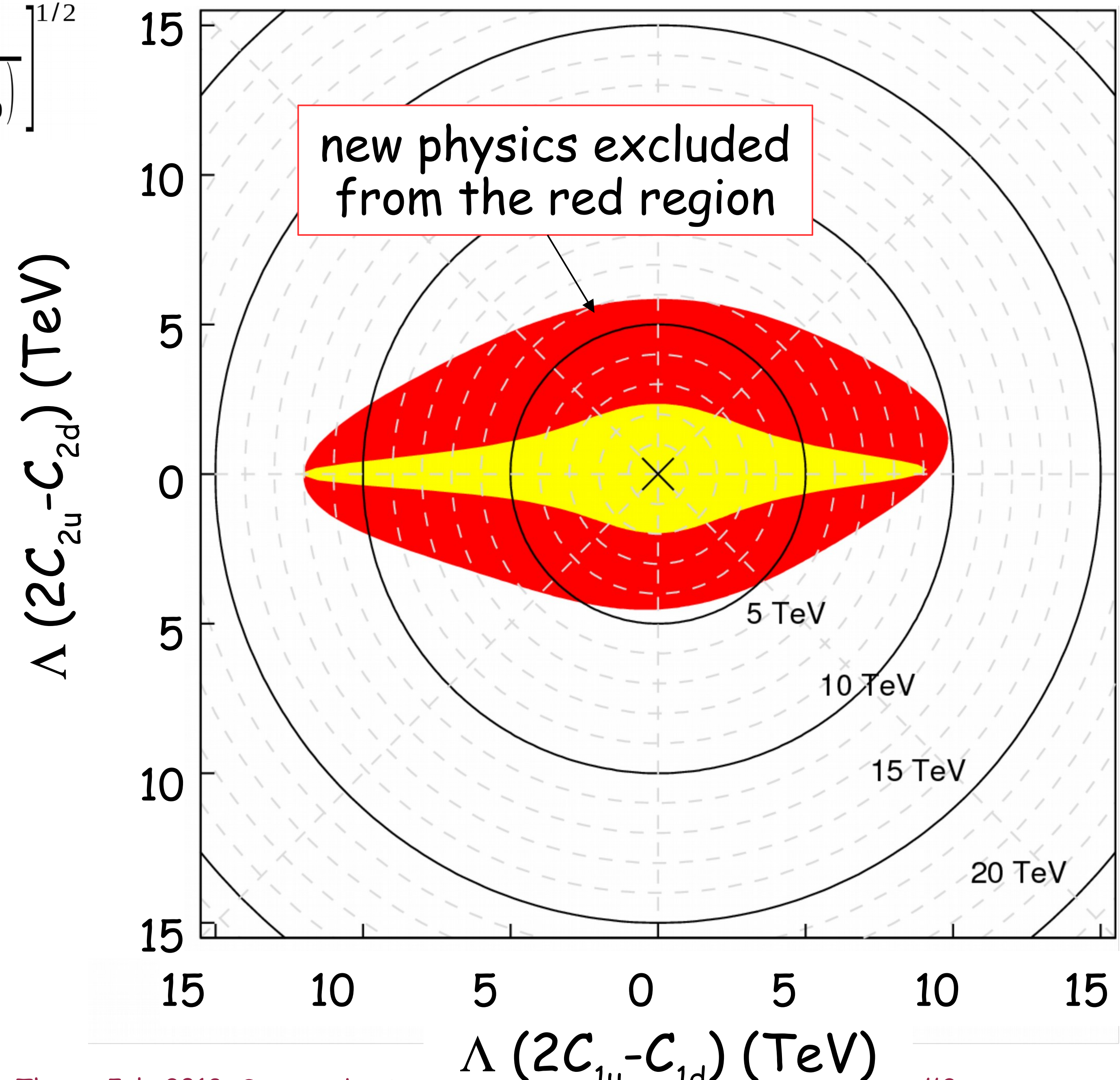




Erler&Su, Prog. Part. Nucl. Phys. 71, 119 (2013)

Limit on new eq VA contact interactions

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

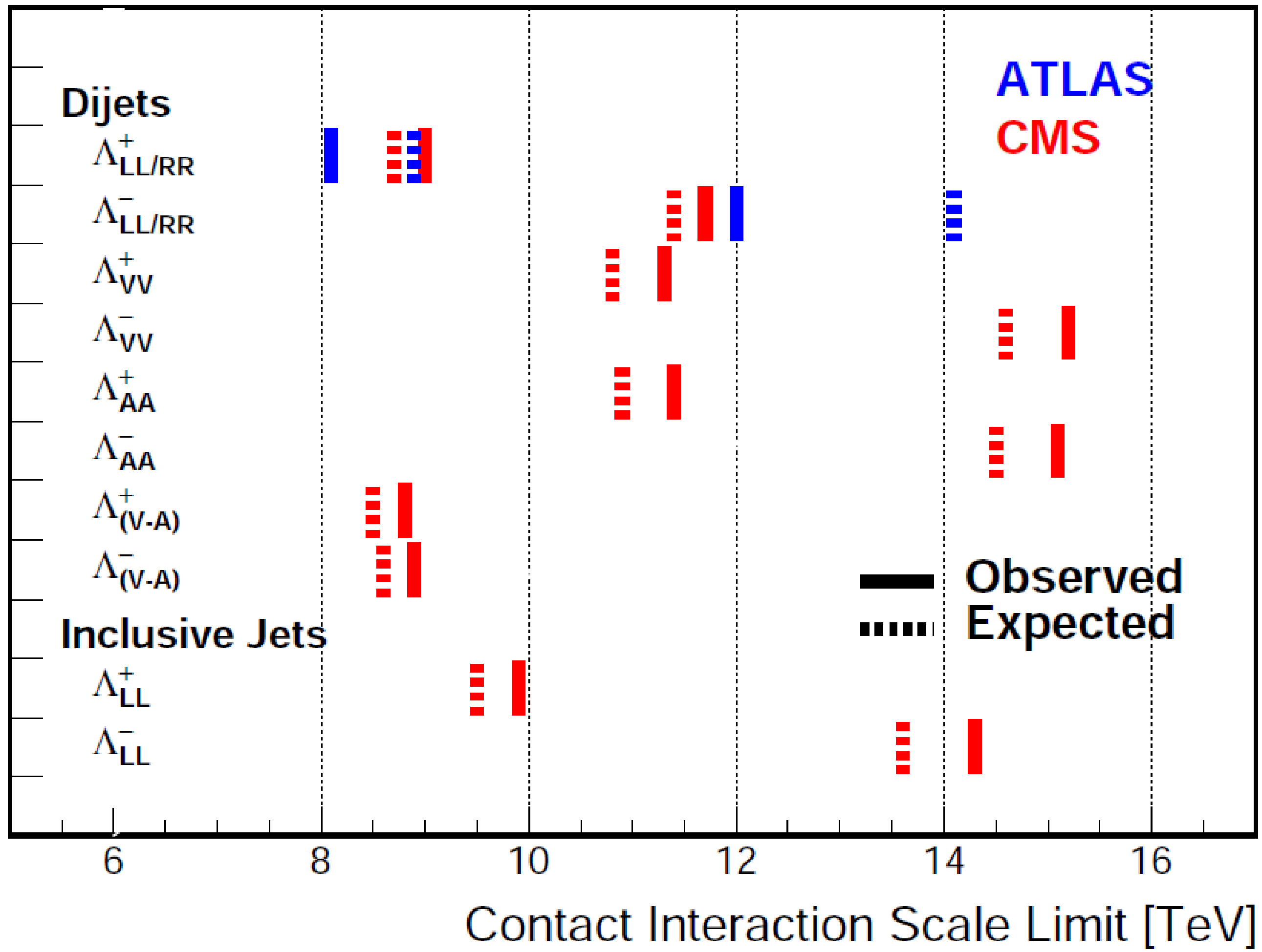


(PS it was an awkward timing that our Nature paper was released on Feb. 14th, 2014)

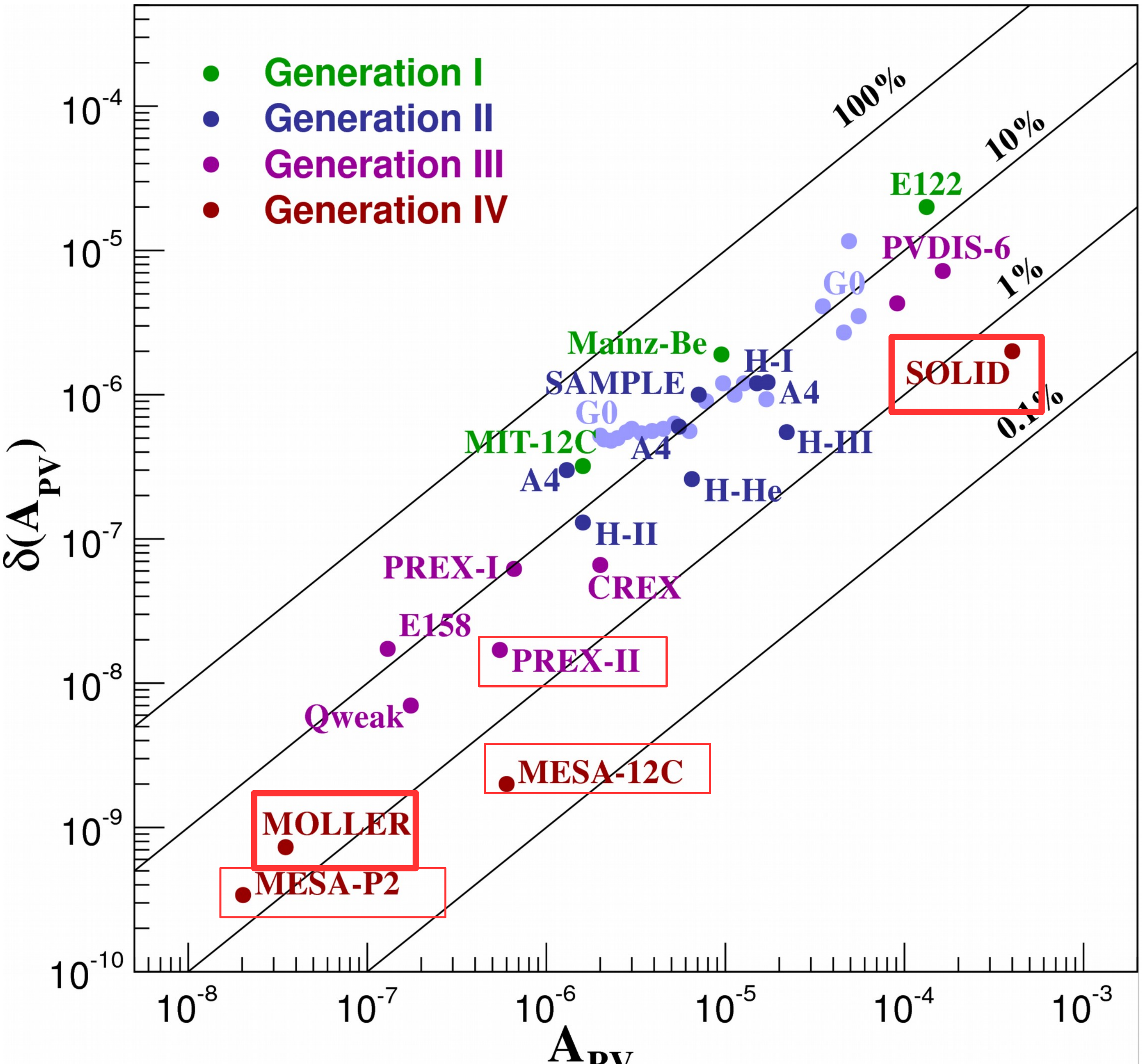
Contact Interaction Limits from LHC (PDG)

Colliders measure combinations of (VV+AA+AV+VA), no individual access to AV or VA terms !

PVES is complementary to collider searches



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

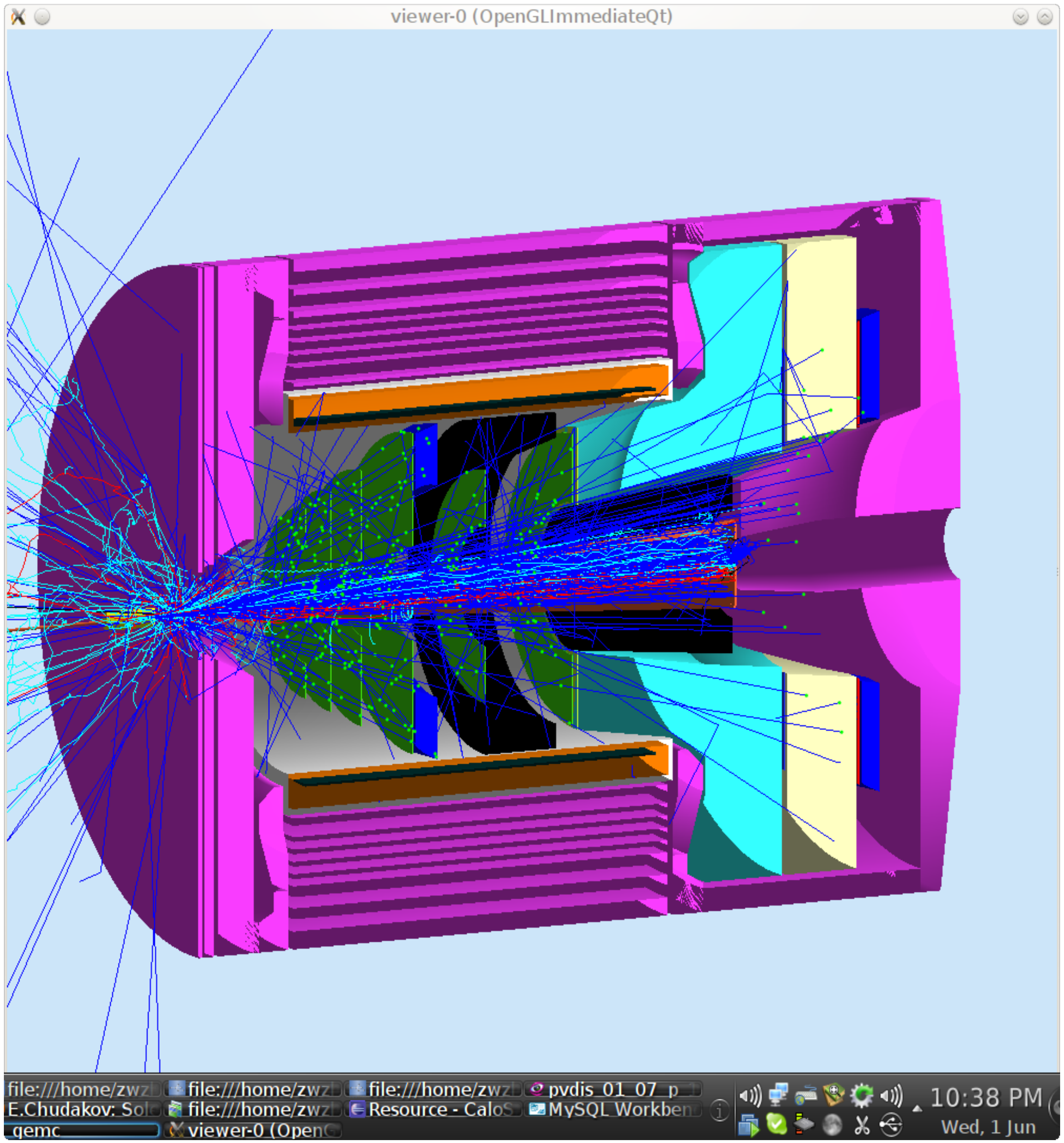


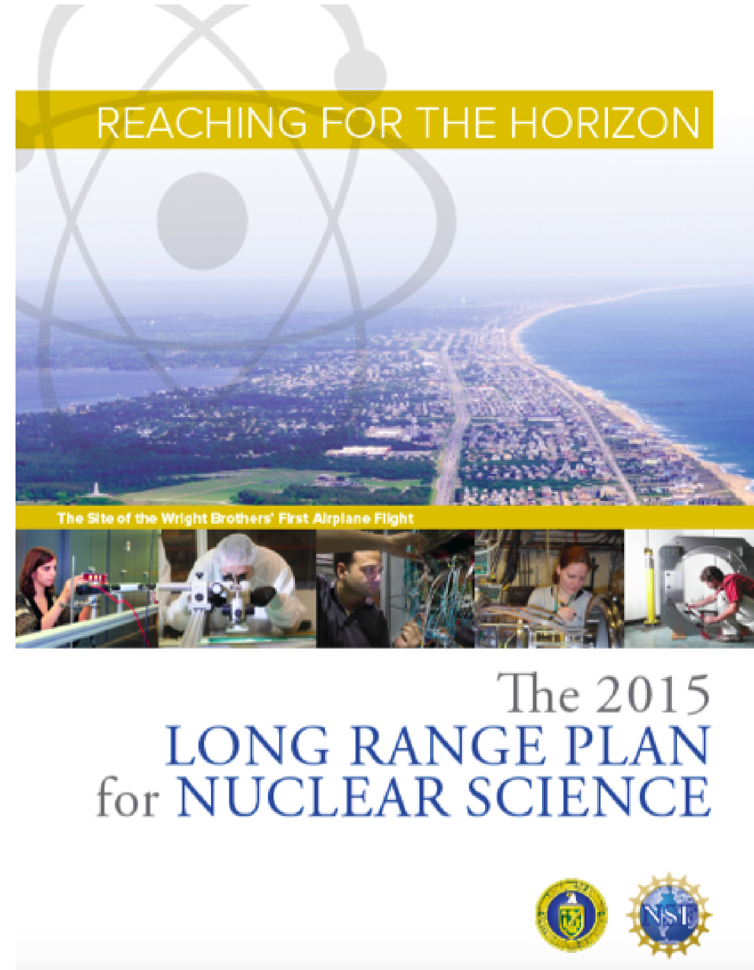
Coming up:

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

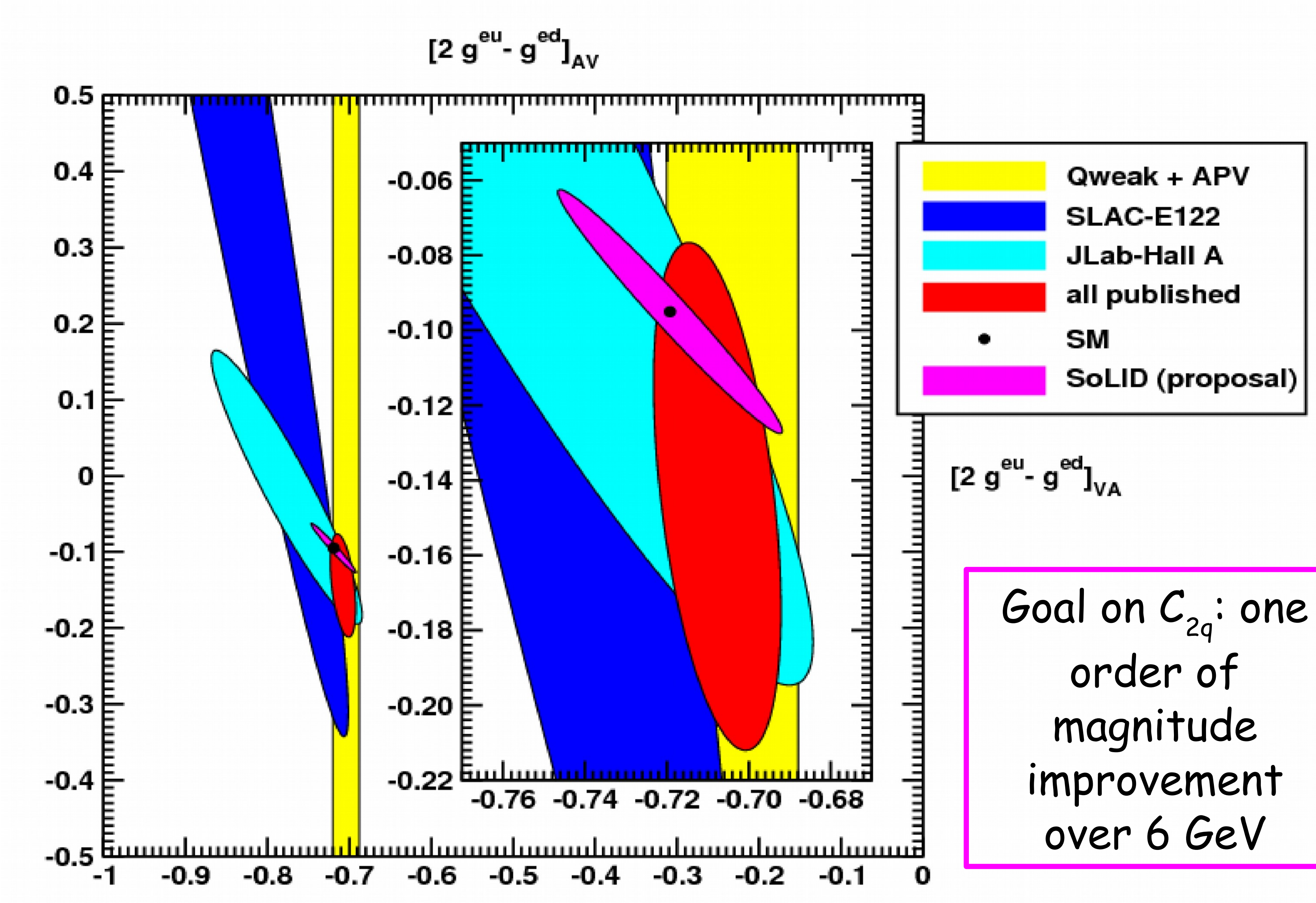
Coherent PVDIS Program with SoLID @ 12 GeV

"Solenoid Large Intensity Device"



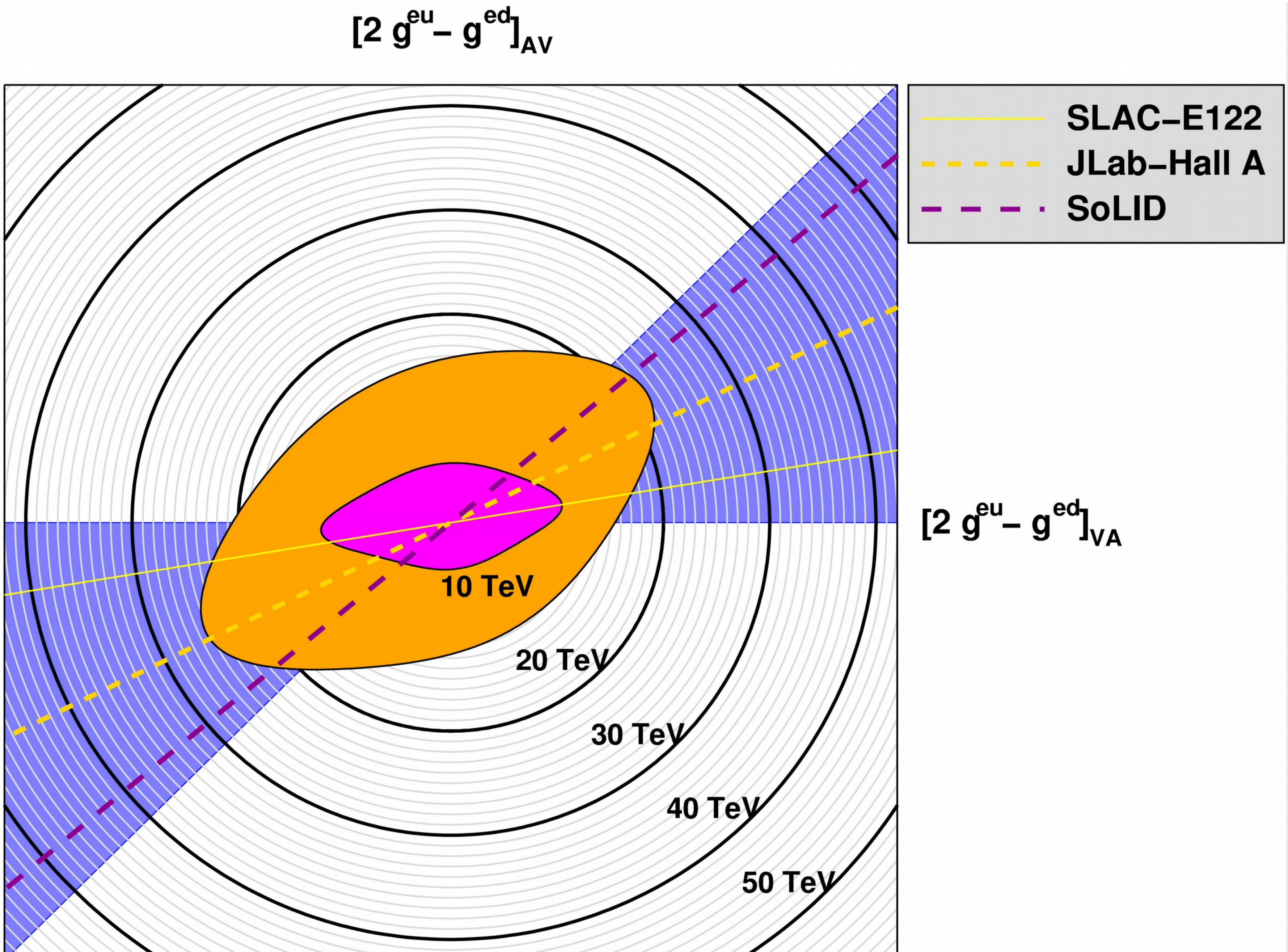


Coherent PVDIS Program with SoLID @ JLab 12 GeV



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

Coherent PVDIS Program with SoLID @ 11 GeV



to be updated

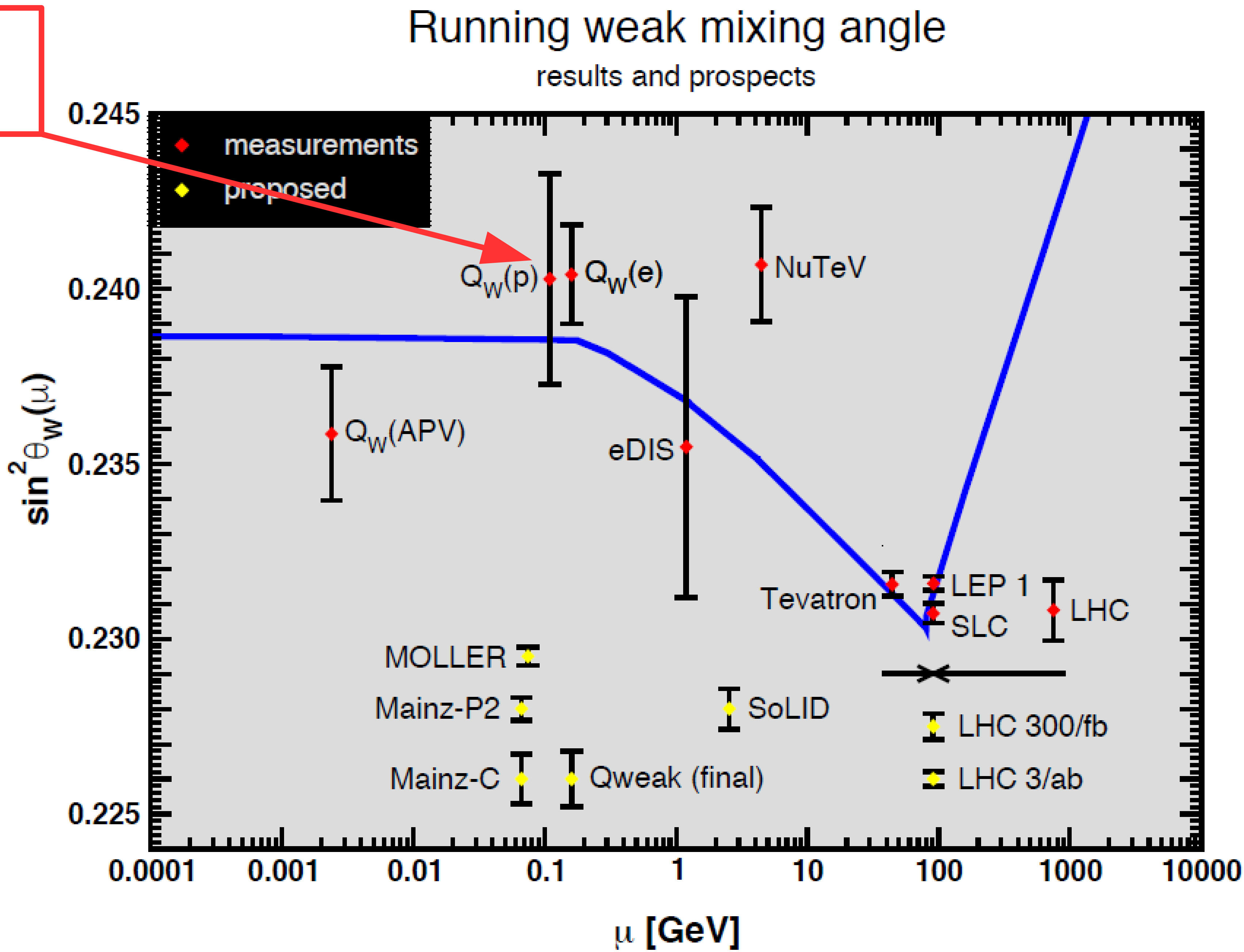
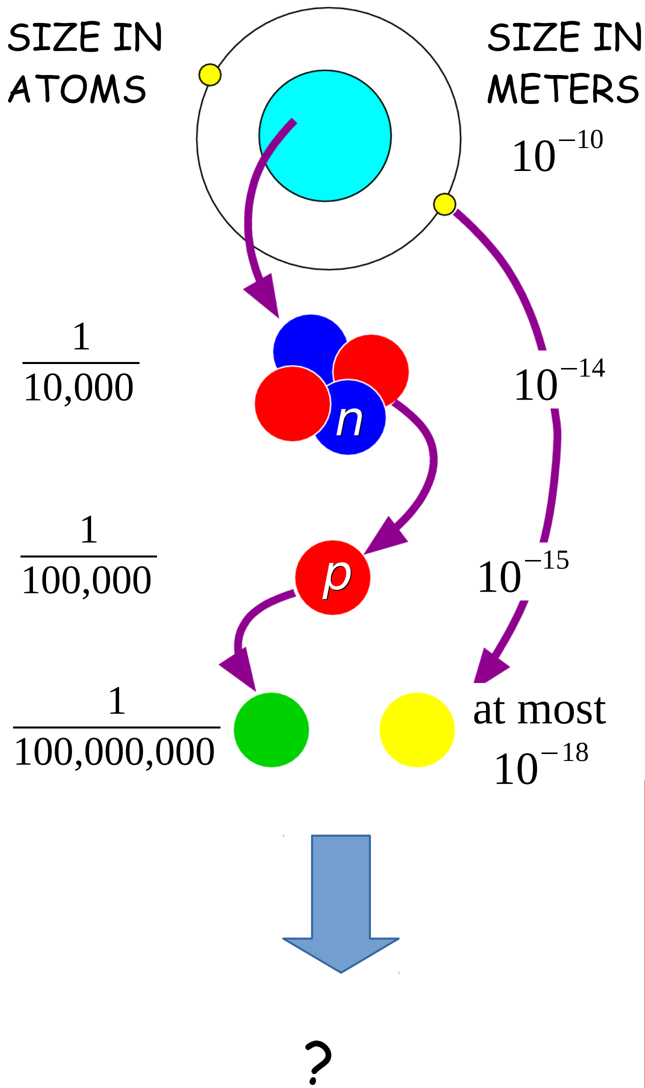


Figure from Jens Erler, WIN2017

Summary



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quarks in nucleons	10^{-15}m	≈10^2MeV	(≈10^2MeV)
within quarks and leptons:	$10^{-19\sim-18}$ m	≈ 10^2GeV -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).