Precision Standard Model Tests (at JLab)

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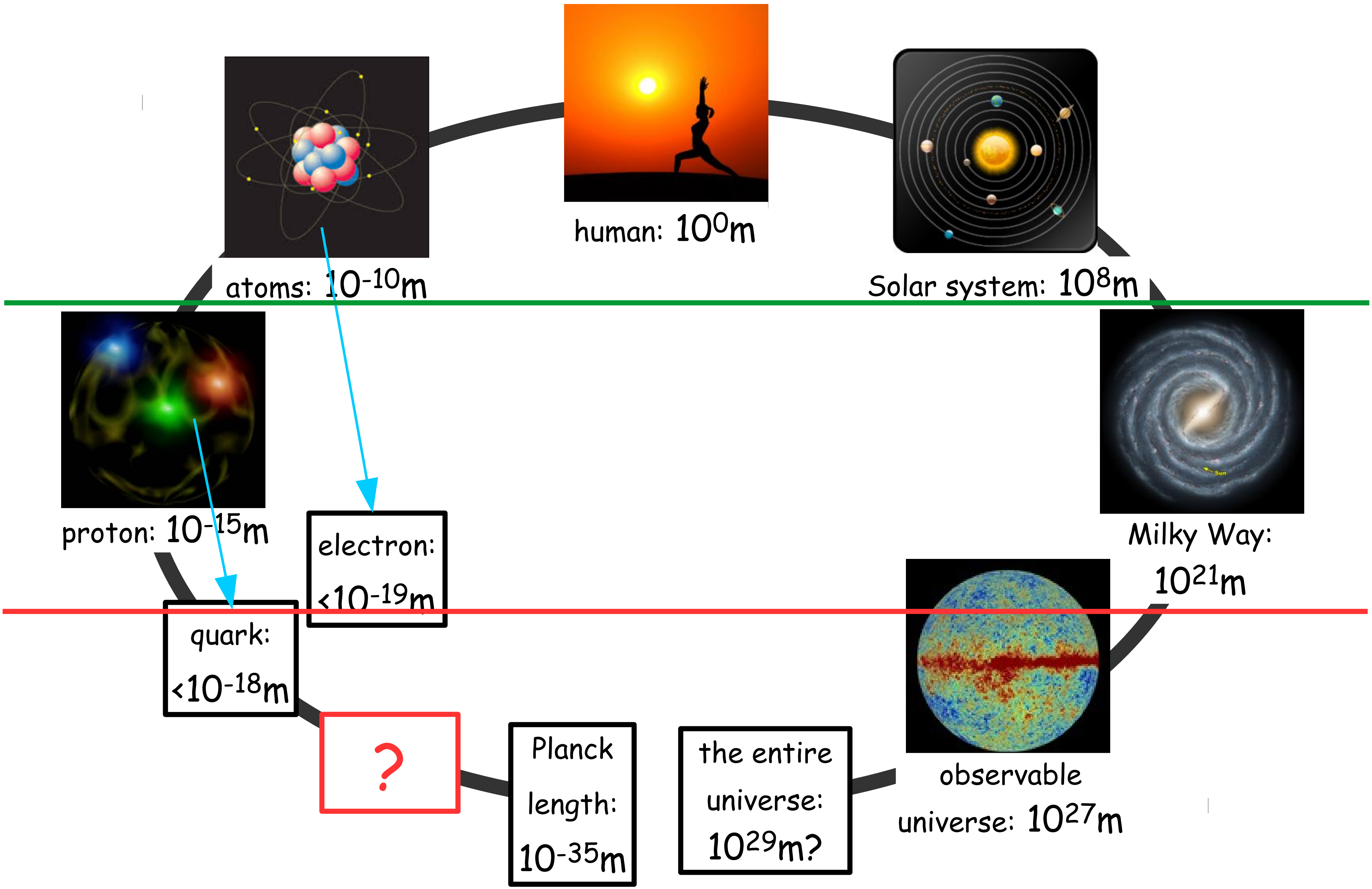
June 21st, 2018

- The Standard Model of Particle Physics
- How should we search for new physics?
- Precision SM tests at Jefferson Lab
  - Qweak, PVDIS
  - Moller, 12 GeV PVDIS

From Leptons and Quarks to the Cosmos

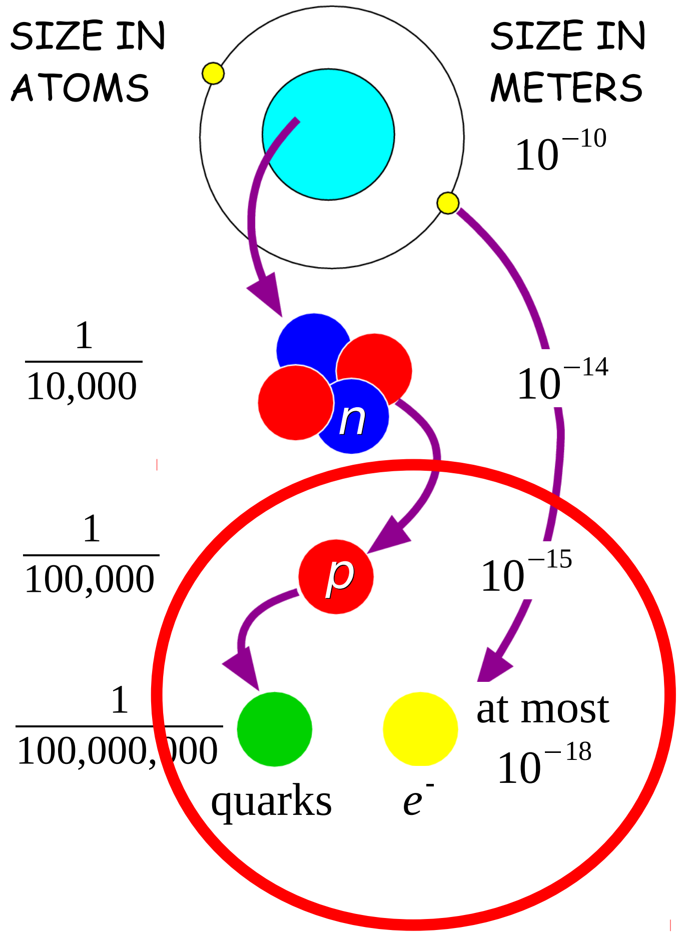


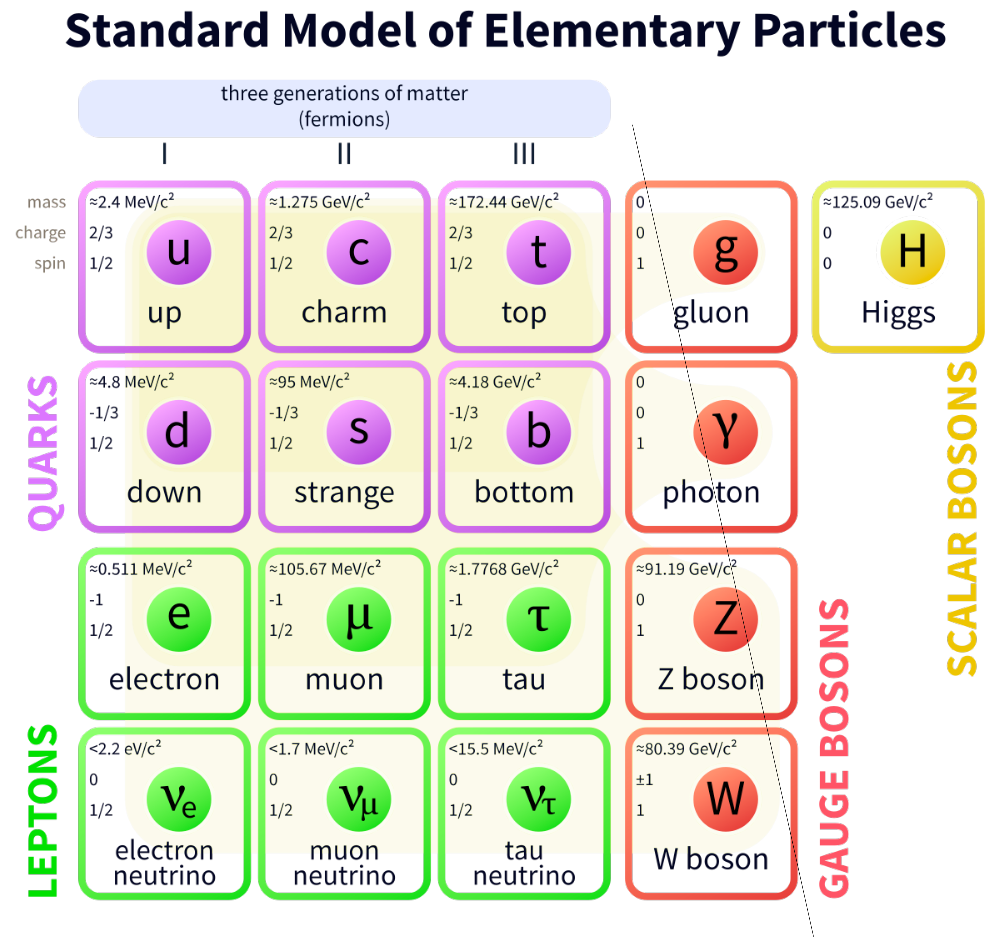
The Standard Model

(1) the elementary fermions – quarks and leptons

(2) the symmetries (of charges → interactions)

(3) the origin of masses





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

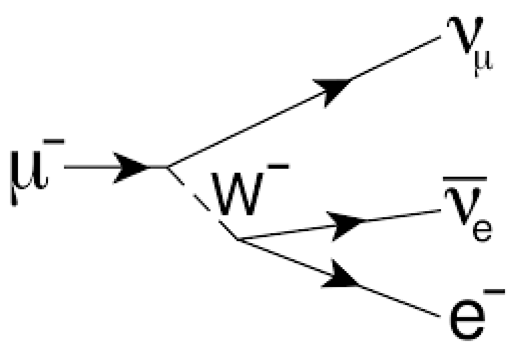
Limits of the Standard Model

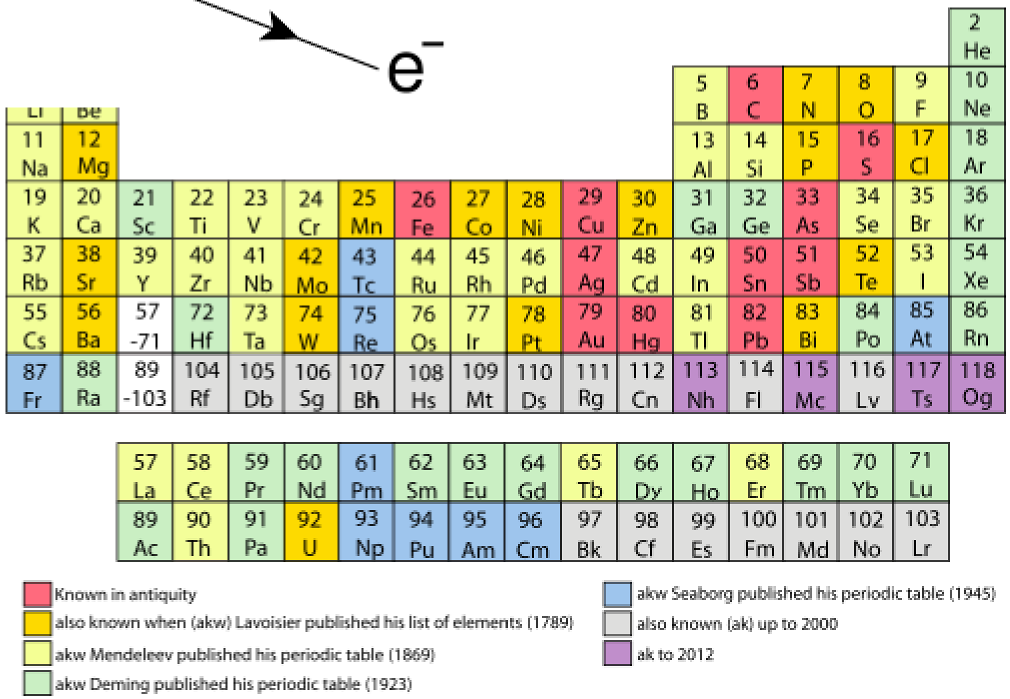
The Standard Model is "an effective theory at the electroweak scale"

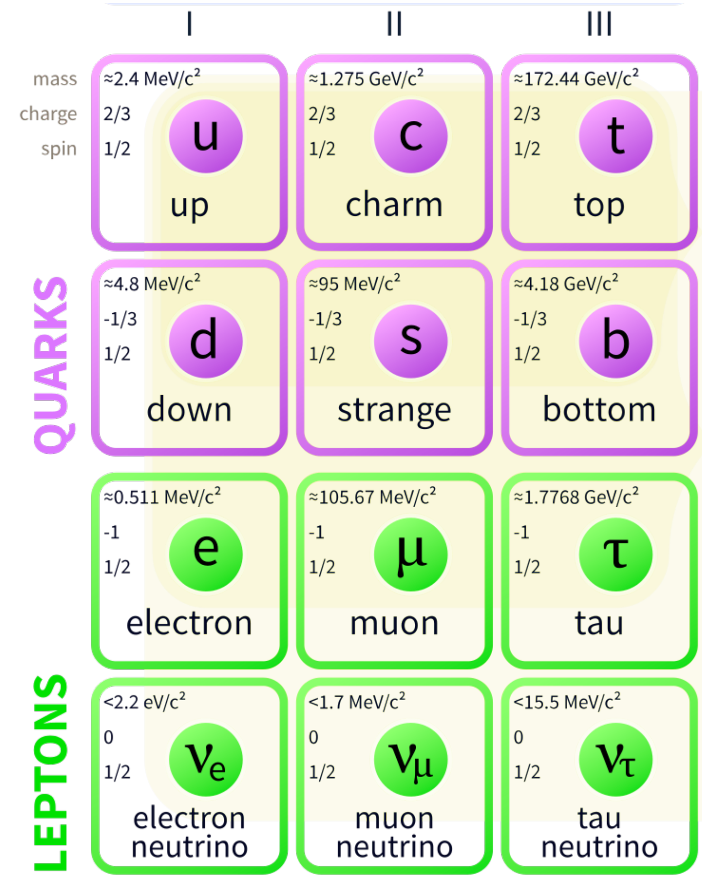
(choose your favorite:)

- Why are there three generations of quarks and leptons?
- 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? How do we explain dark matter?
- Why are neutrinos so light in mass?
- And many more!

Caught in the Act !







Could this be an indication that quarks and leptons are composite particles? And what if they are??

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 … … (the simplest extension to SM would be another U(1) group/symmetry, a leptophobic Z'…)

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

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

- SU(5) multiplet:

$$\begin{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix} \\ \begin{pmatrix} \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \end{pmatrix} \end{pmatrix}_L \quad \begin{matrix} \text{W's} \\ \\ \text{gluons} \end{matrix}$$

→ new gauge bosons 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 → e+ pi0, predicted lifetime 10^{31} years (or longer).

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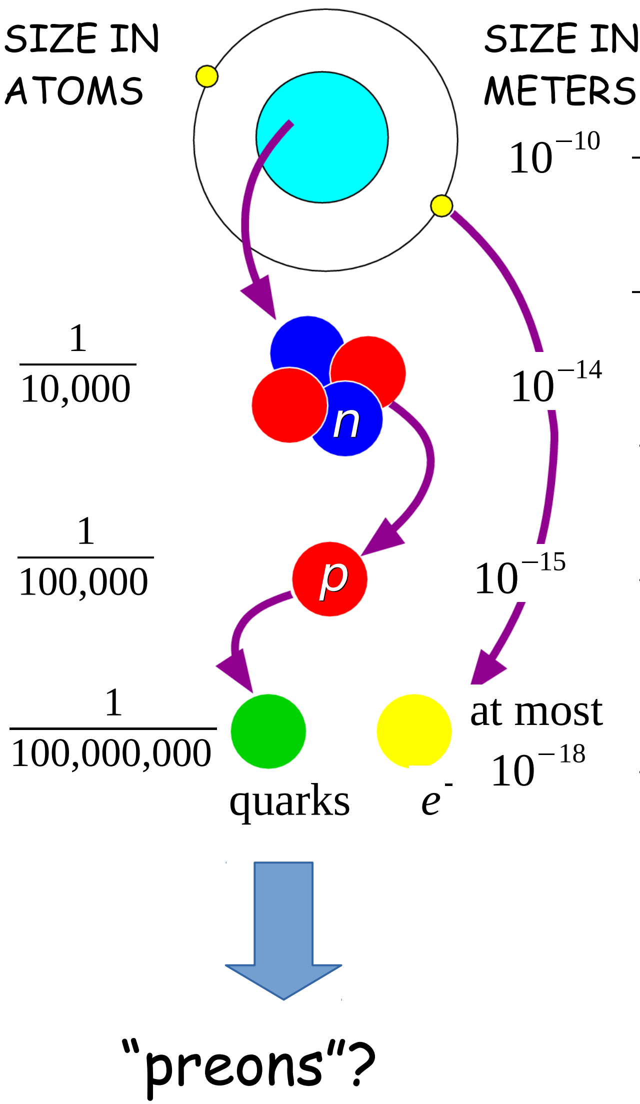
Recall your Modern Physics Homework ?



	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	$\approx 10^2$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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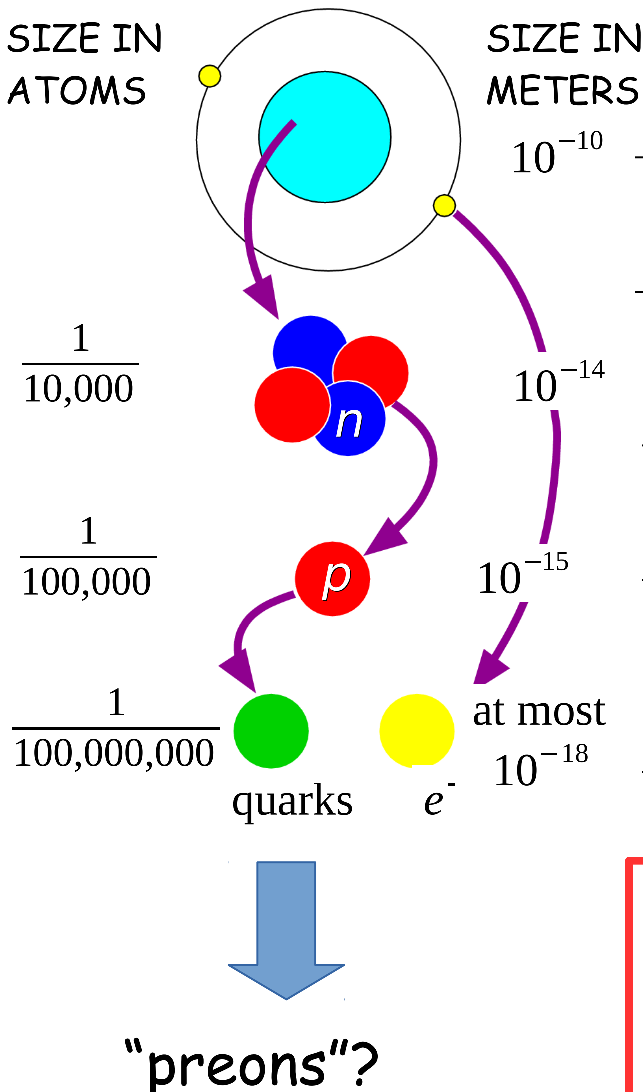

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preons in quarks and leptons:	$10^{-19\sim-18}$ m	~1TeV	~1TeV

- 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.
- However, this seems impossible, as then quarks and leptons must have rest mass (energy) at TeV level.

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!

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).

No, because the Standard Model is a relativistically correct quantum field theory. Therefore, nothing can happen until the Planck scale, where QFT itself breaks down along with the concept of continuous space.

- therefore: quarks and leptons must have an intrinsic size at the Planck scale.
- my answer: it has to be this way, otherwise we will find an infinite number of new interactions, at higher and higher energy scales!

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

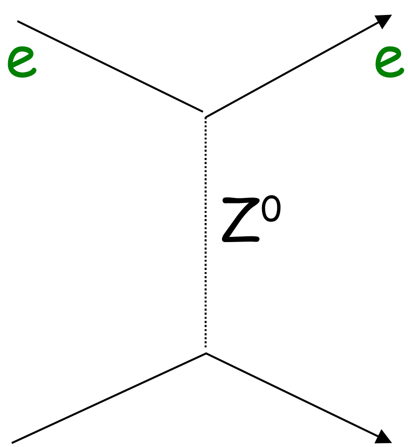
This is the role we play with PVES.

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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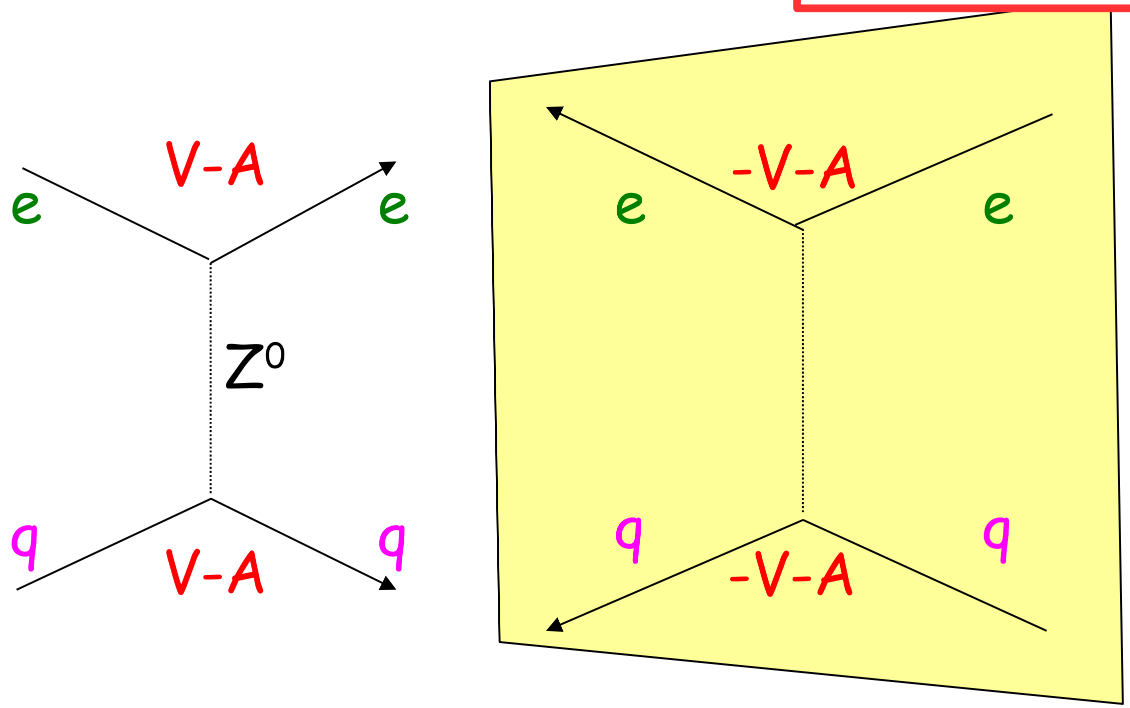
- PVES asymmetry comes from:

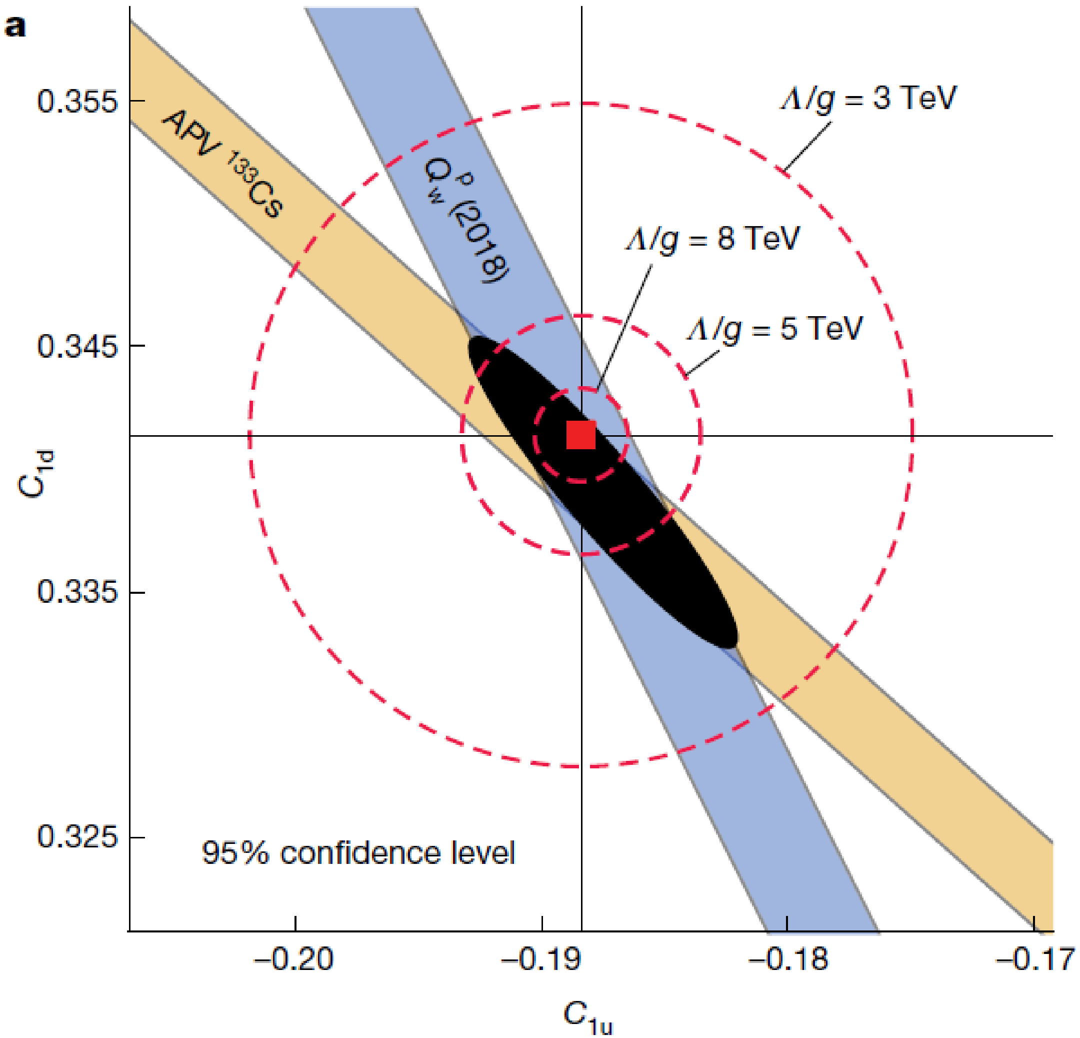
$$C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q$$

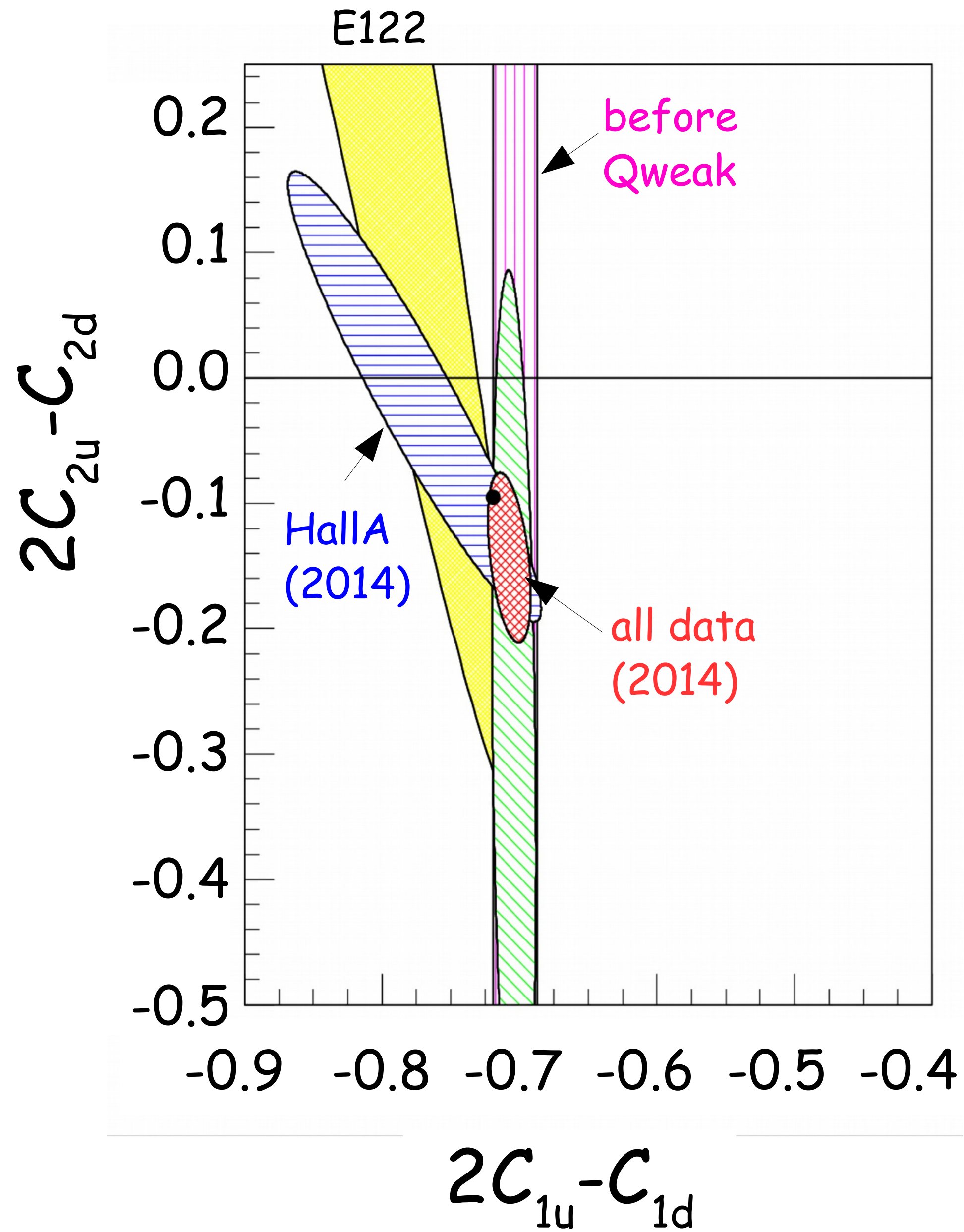


"electron-quark effective couplings"

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

Best Data on C_{1q} (AV) and C_{2q} (VA) couplings from PVES



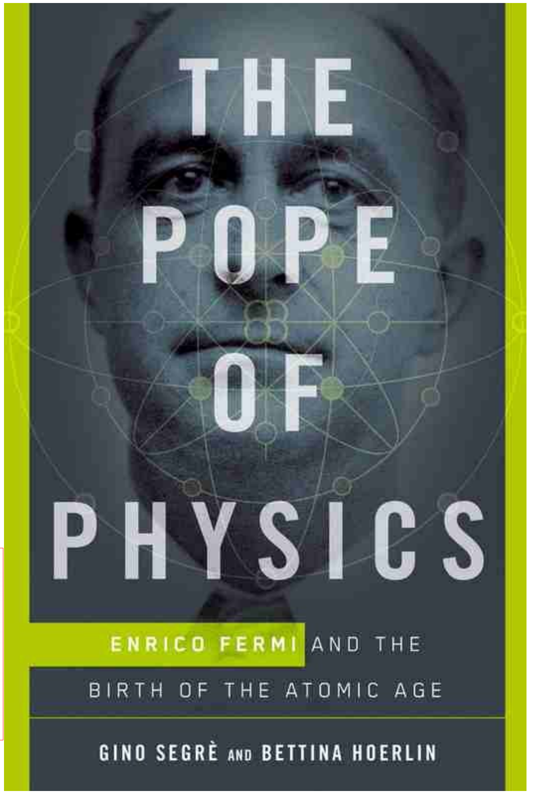


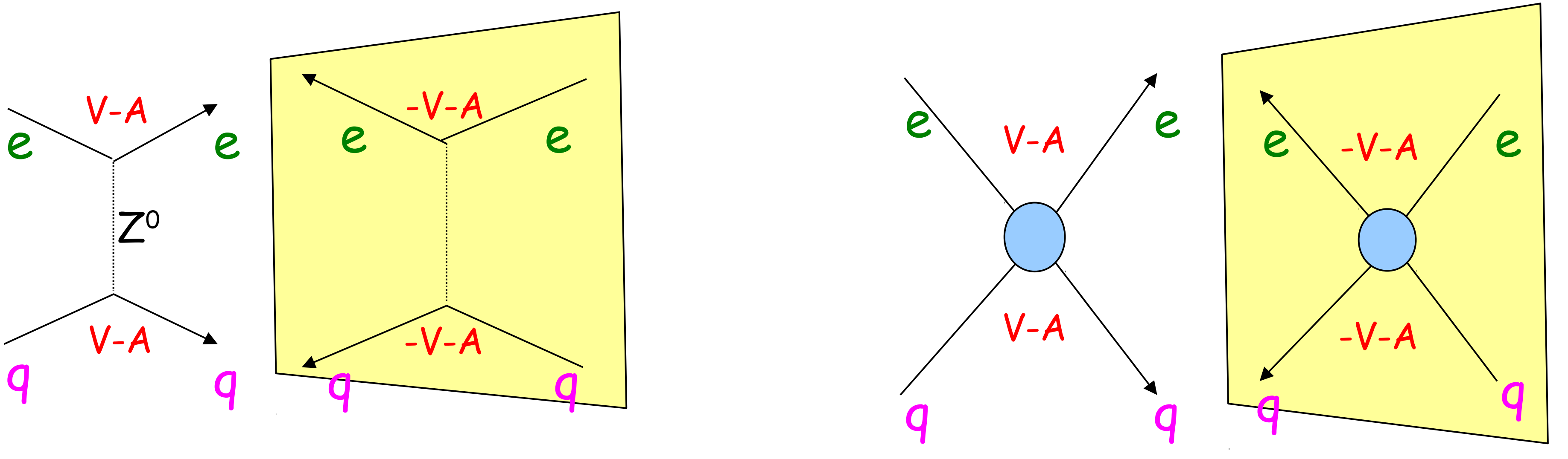
Searching for "New Contact Interactions"

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.

$$\frac{\Lambda_\pm}{g} = v\sqrt{\frac{4\sqrt{5}}{|Q^p_W \pm 1.96\Delta Q^p_W - Q^p_W(SM)|}}$$

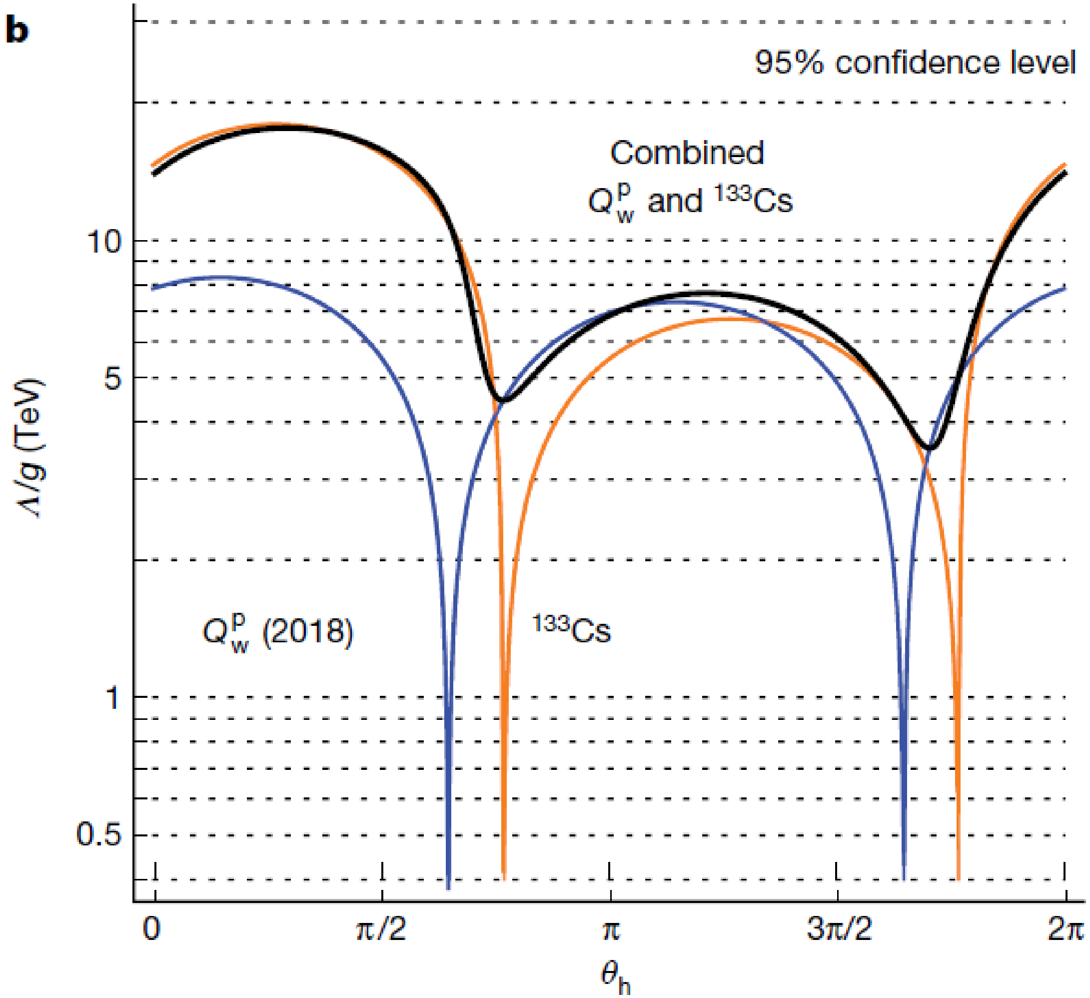
$$\Lambda = v\left[\frac{8\sqrt{5}\pi}{\left(\delta\left(2C_{2u} - C_{2d}\right)_{Q^2=0}\right)}\right]^{1/2}$$

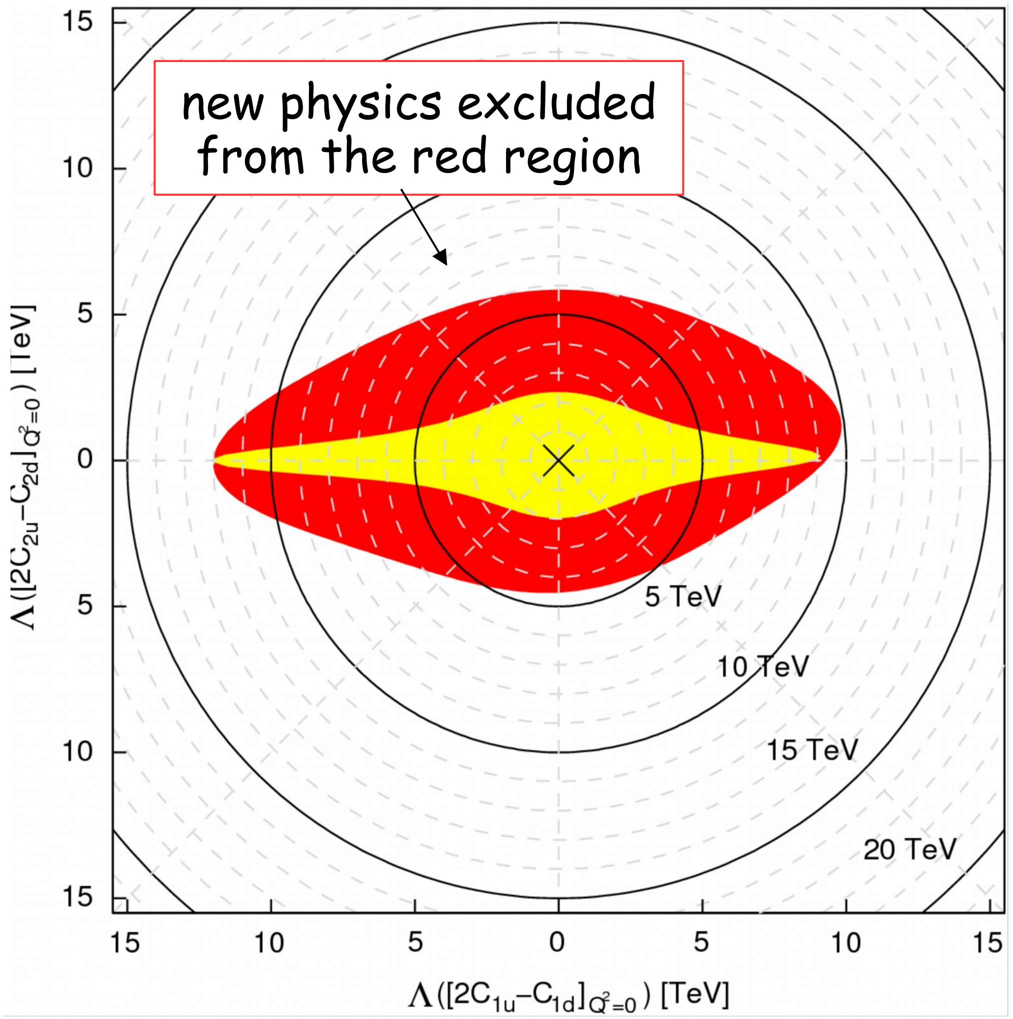




Erler&Su, Prog. Part. Nucl. Phys. 71, 119 (2013)

Limit on new electron-quark AV and VA contact interactions

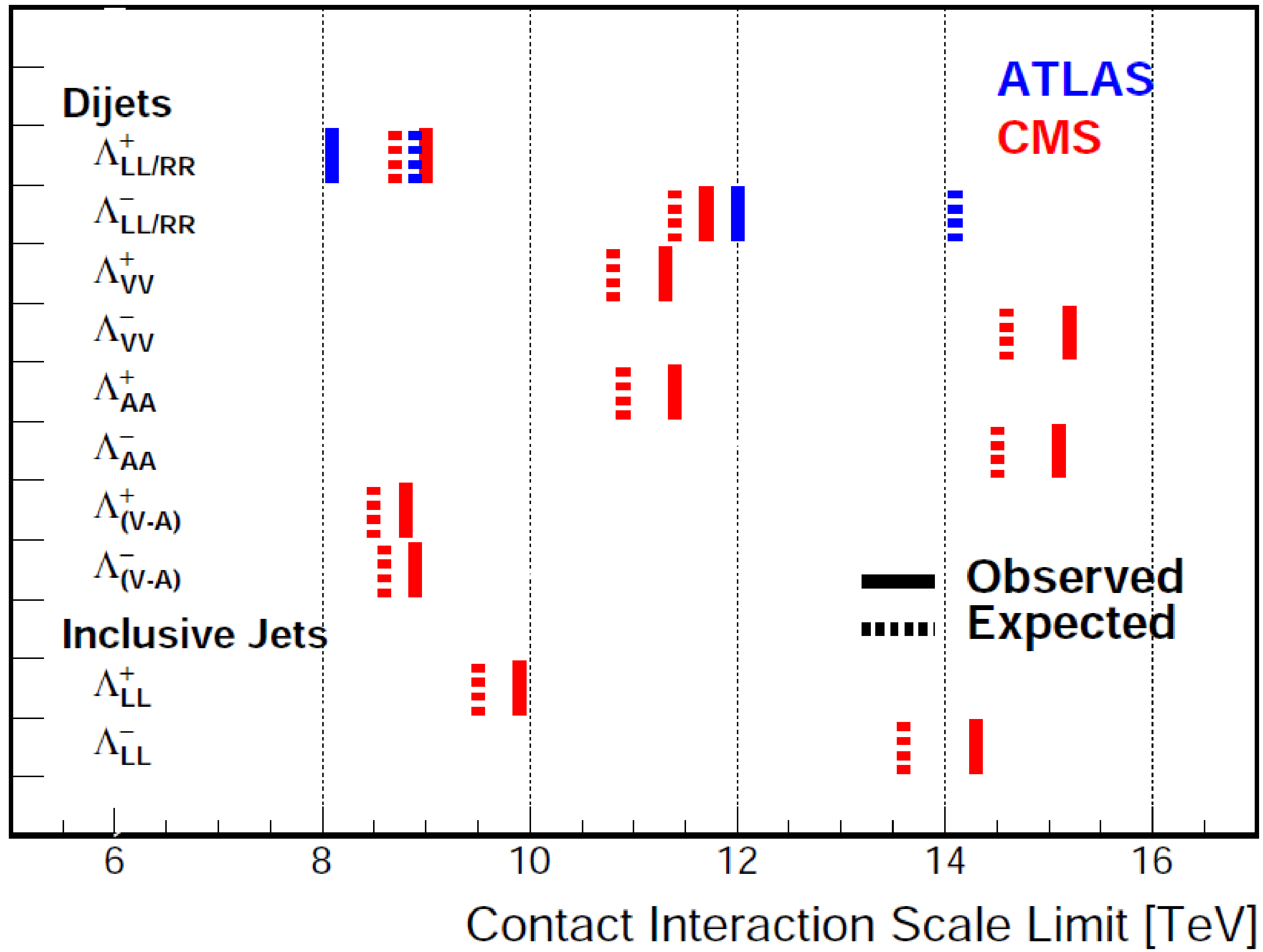




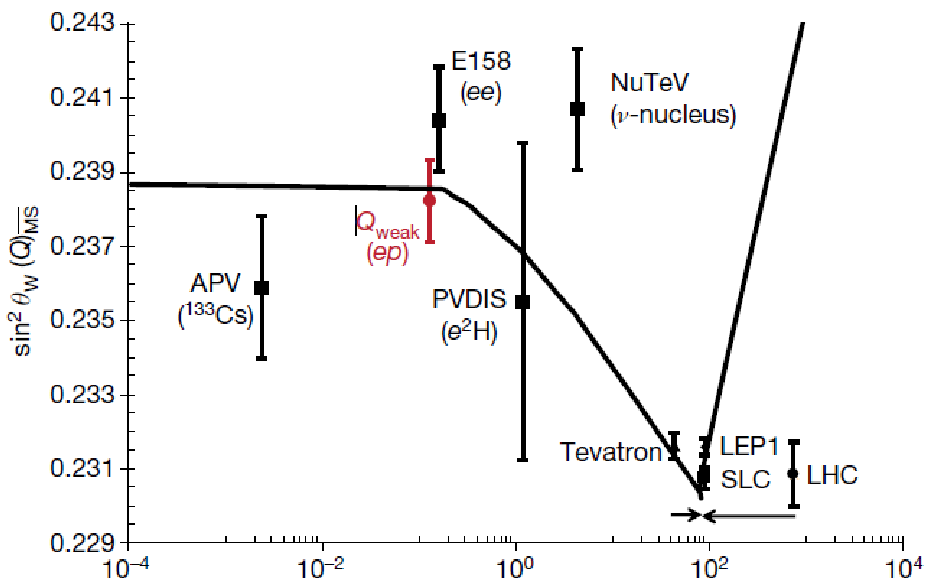
Contact Interaction Limits from LHC (PDG)

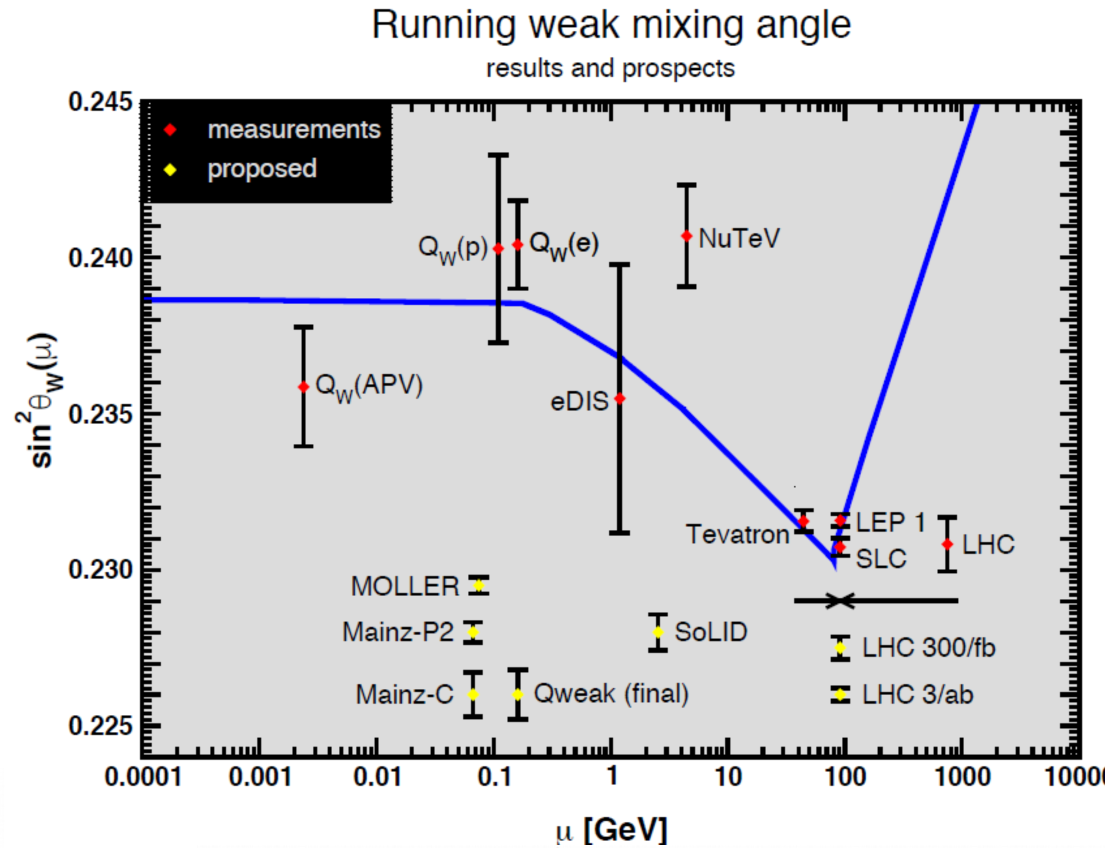
Colliders measure combinations of (VV+AA+AV+VA), no individual access to AV or VA terms !

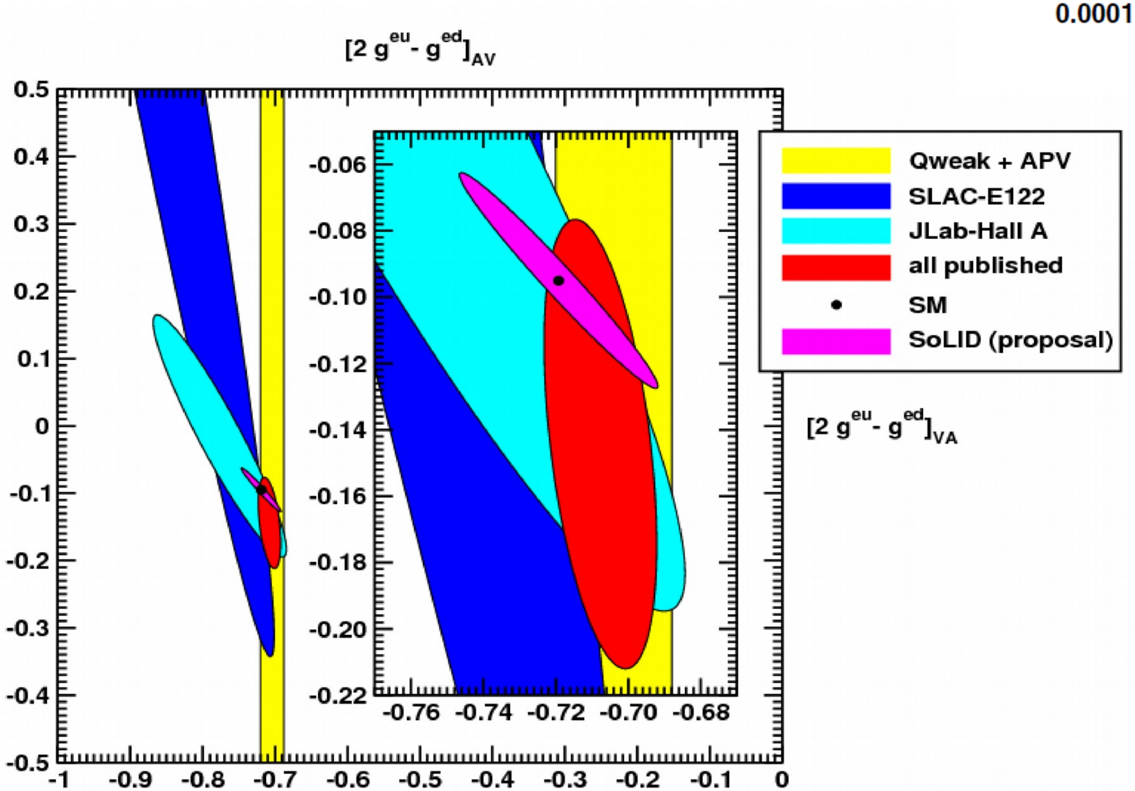
PVES is complementary to collider searches

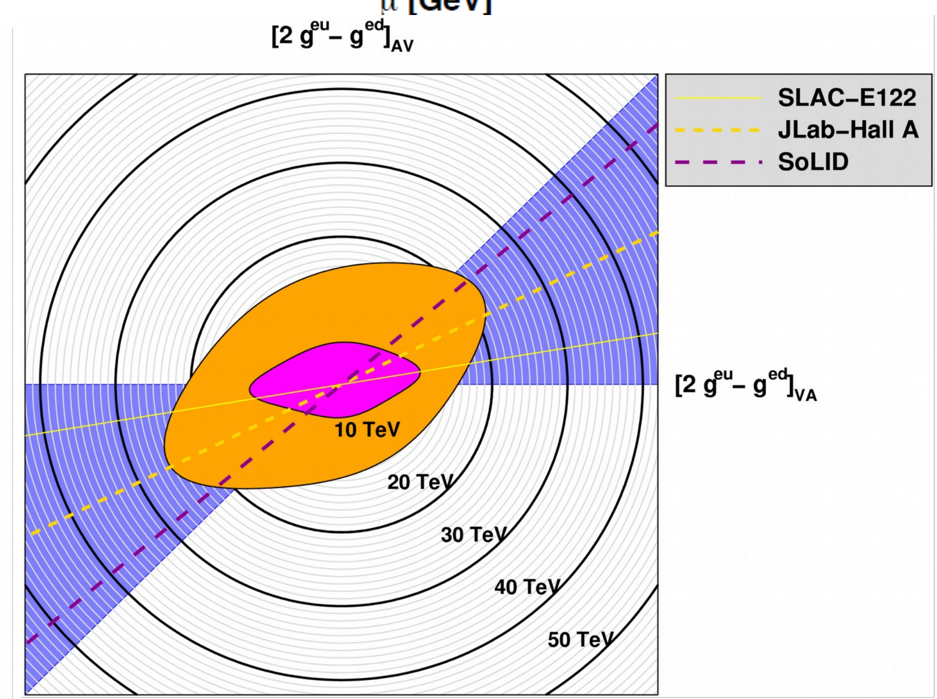


Moller and SoLID PVDIS









The Standard Model is a very successful theory up to the electroweak scale.

Evidence exists for theories beyond the Standard Model, but the arguments often are philosophical.

There are many ways to look for breakthrough. Among them, precision measurements of physical constants (coupling constants, for example) provide an effective way to search for possible directions where physics beyond the Standard Model may be found. Parity violating electron scattering provides a crucial tool to test the SM in the EW sector.

We at JLab have done a good job on this topic (carrying the torch over from SLAC), and we have a plan to continue in the 12 GeV era.

Are we going to see deviation from the SM? Probably not, but that's not why we do it. Stay tuned!