# Precision Electroweak Experiments at GeV Energies

*Parity Violating Electron Scattering at Jefferson Lab*

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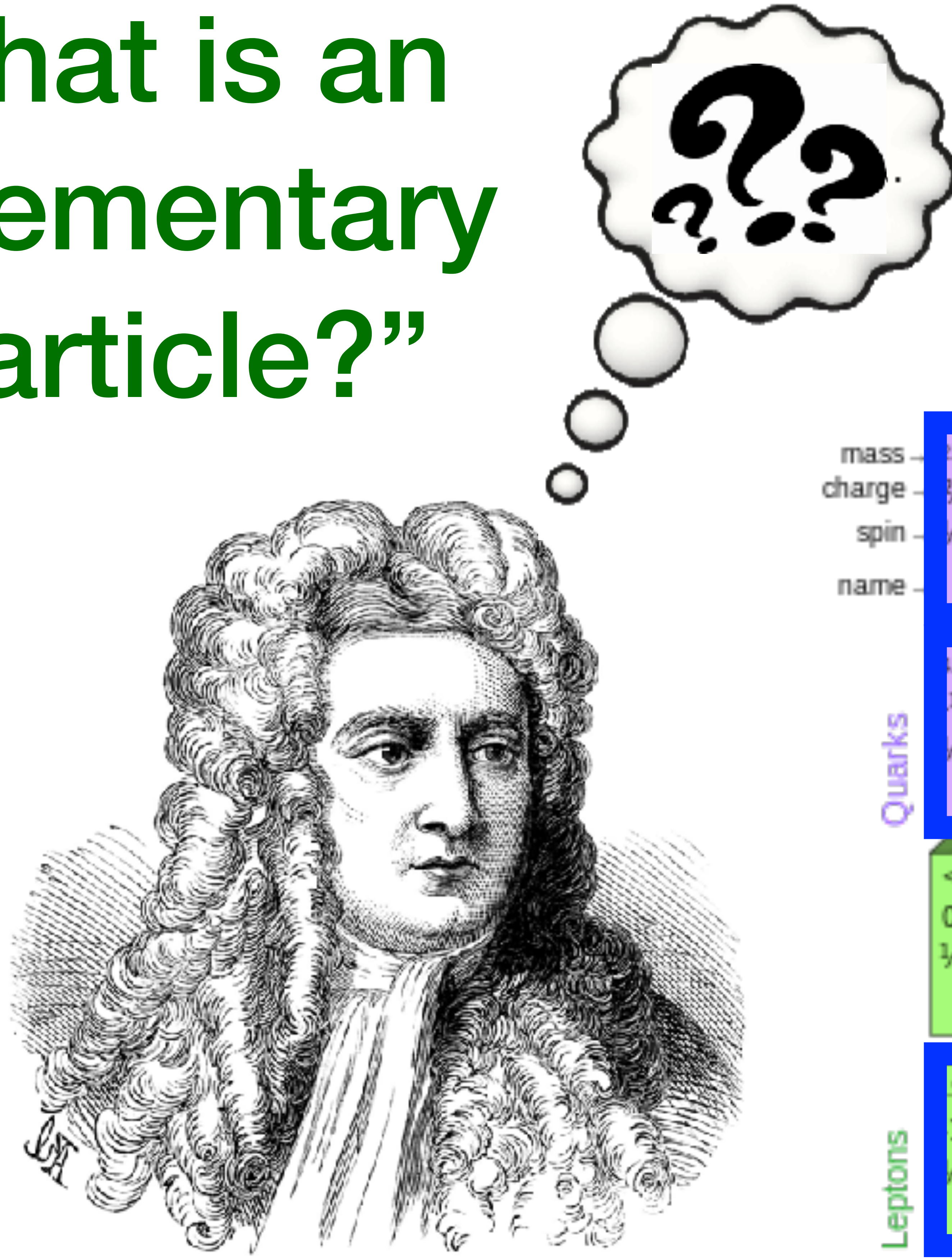
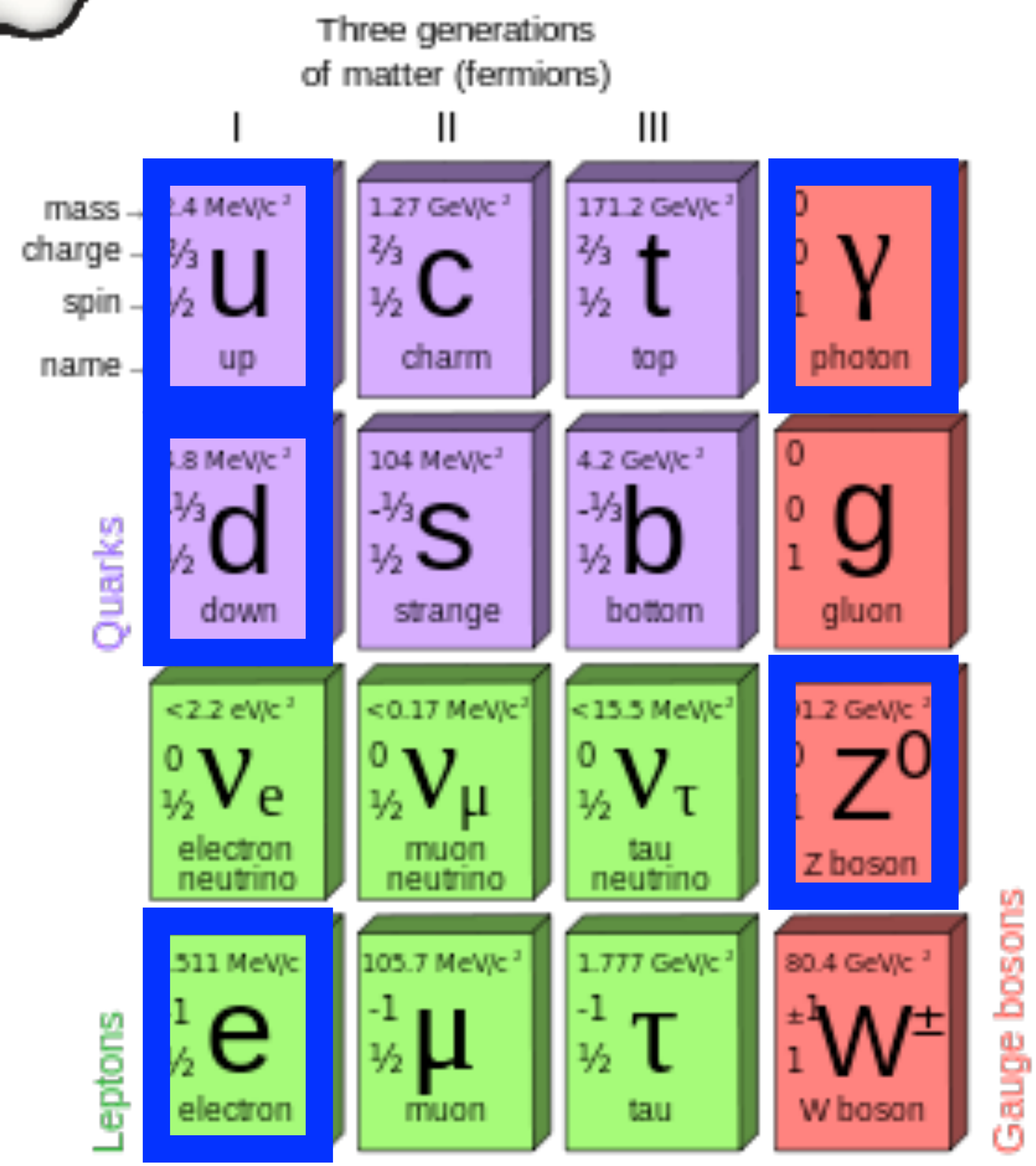
1 Nov 2021

# What is an “Elementary Particle?”

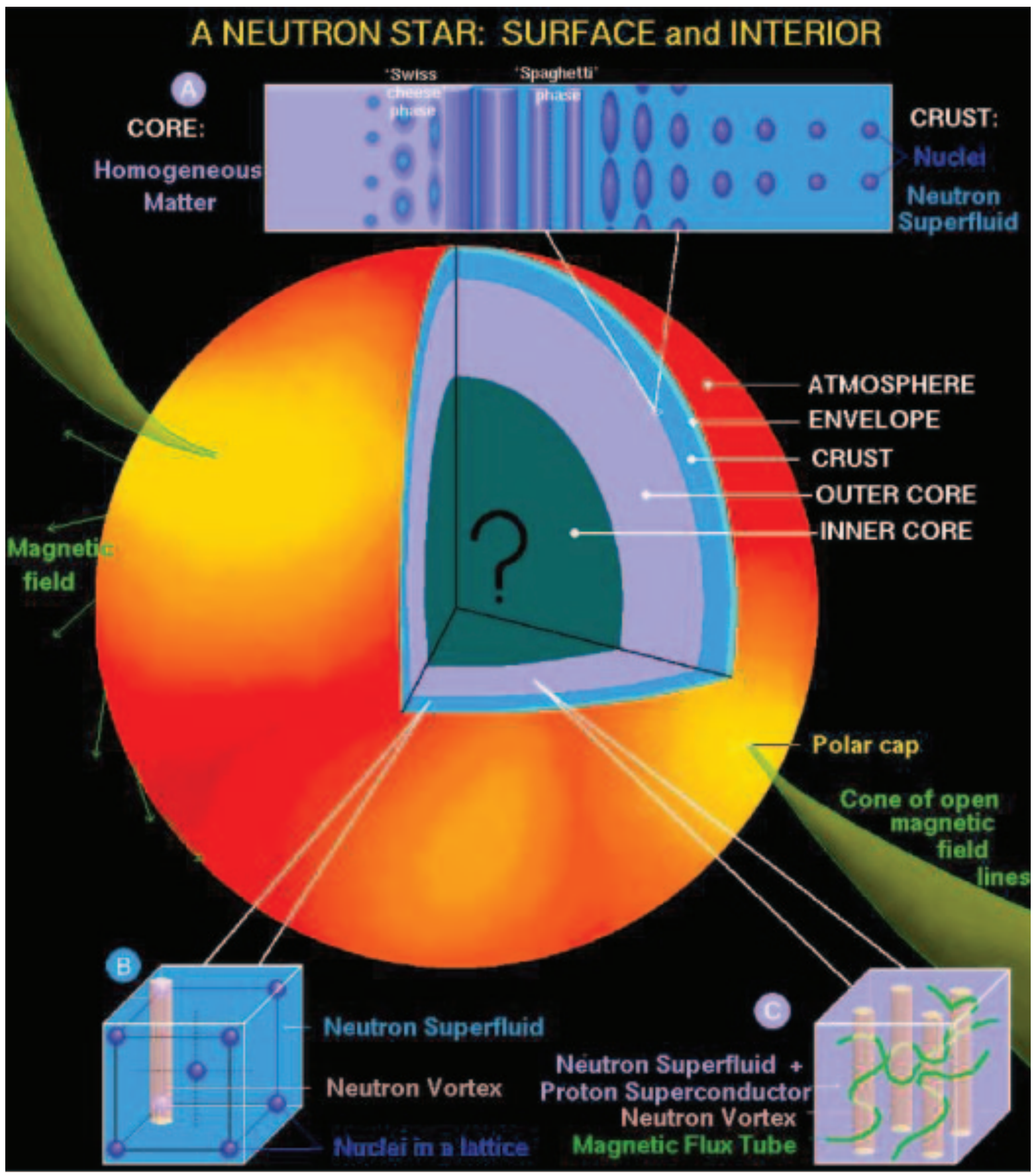


## Today’s Players



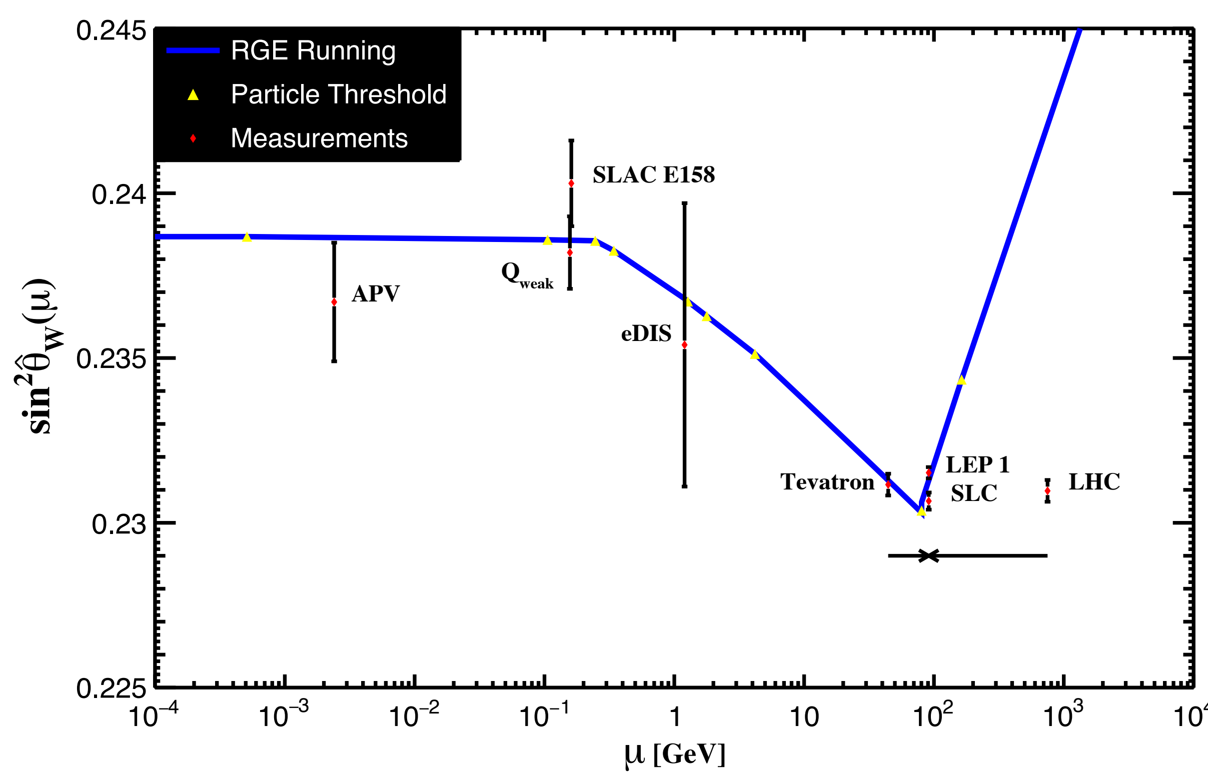
# Today’s Physics Topics

## (1) Neutron Stars



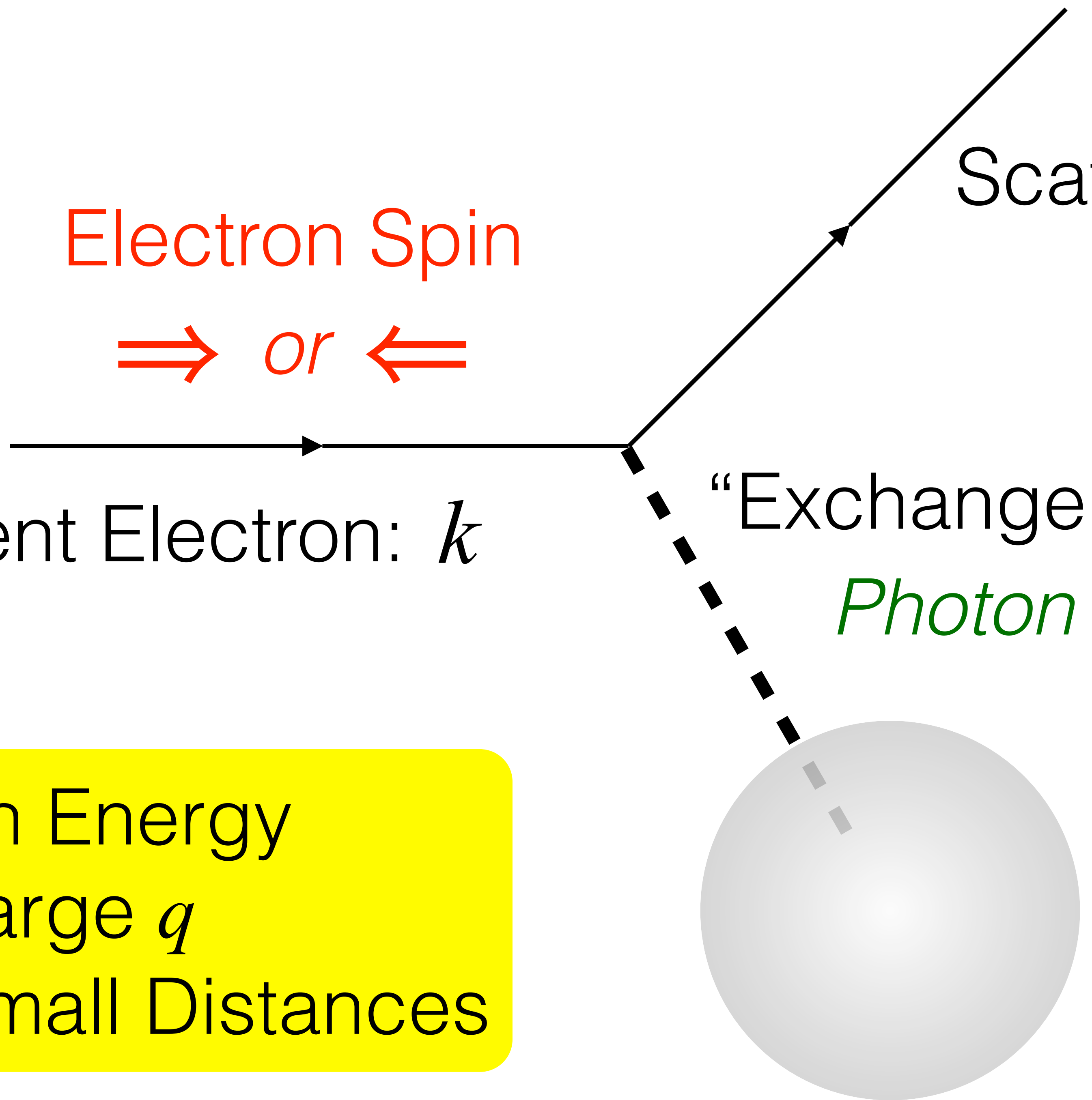

Science 304(2004)536

## (2) Beyond the Standard Model




PDG 2020

# The Tool: Electron Scattering

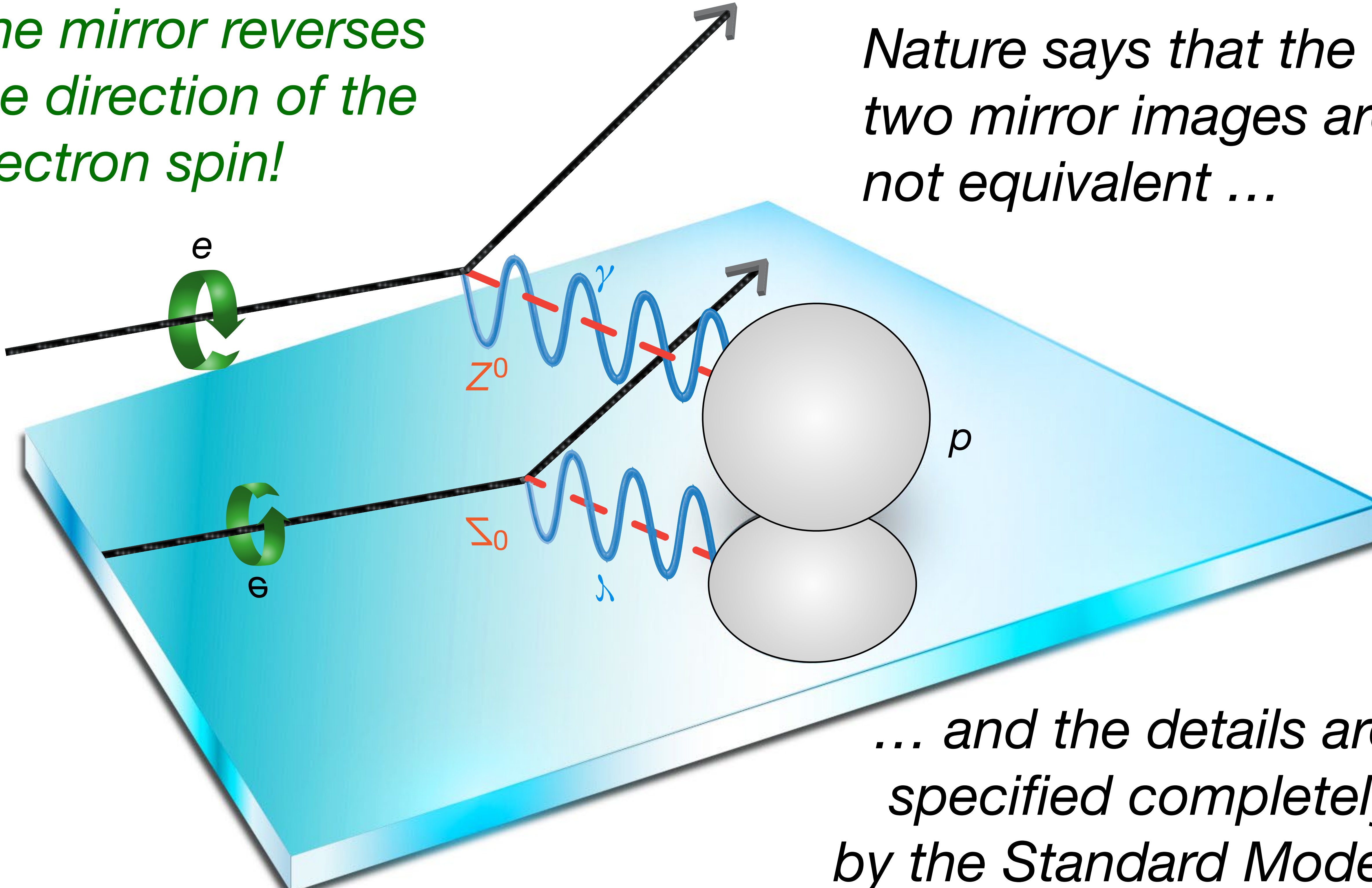



High Energy
➥Large $q$
➥Small Distances

# Parity Violating Electron Scattering

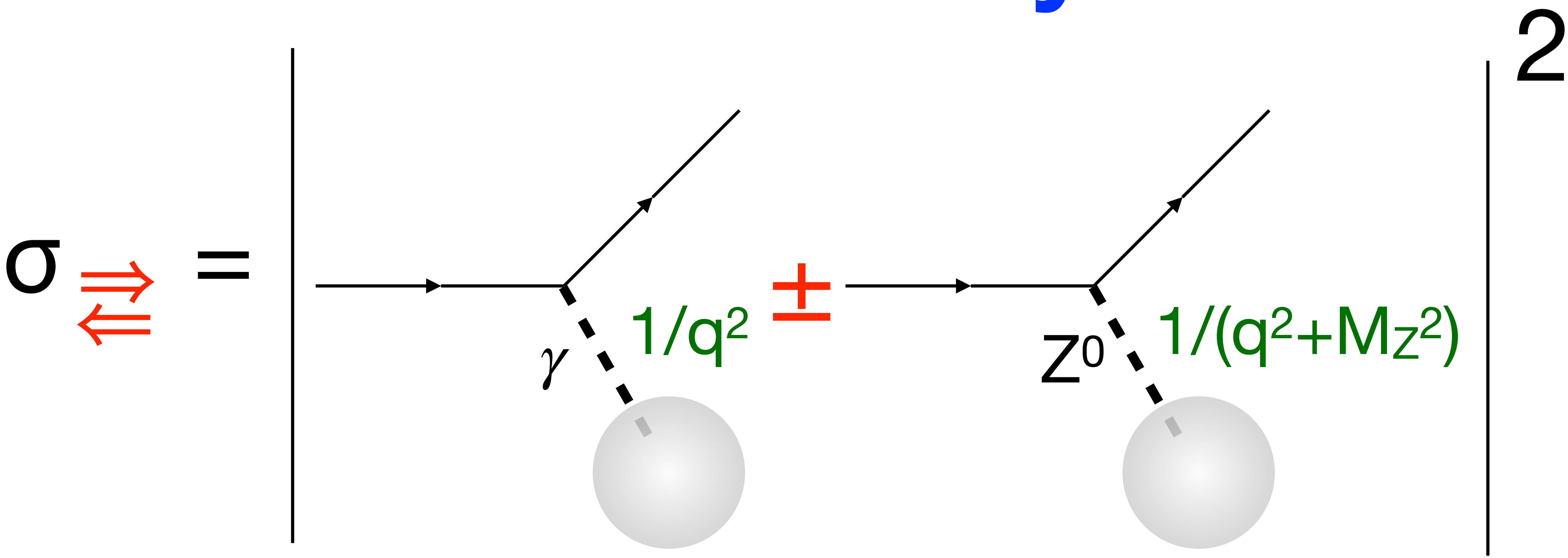
*The mirror reverses the direction of the electron spin!*

*Nature says that the two mirror images are not equivalent …*




*… and the details are specified completely by the Standard Model*

# The Effect is Very Small!




$$A_{PV} = \frac{\sigma_{\Rightarrow} - \sigma_{\Leftarrow}}{\sigma_{\Rightarrow} + \sigma_{\Leftarrow}} \approx \frac{q^2}{M_Z^2} \approx \text{“ppb”}$$

… where details depend on the interaction with the target!

# Axial Vector Couplings of $Z^0$

*Getting at the "Physics"*

Axial Vector/Vector Interference is the key!

➥ What are the different $Z^0$ axial couplings?

| | |
|---|---|
| Electron | $+1-4\sin^2\theta_W$ |
| Up quark (u) | $-1+(8/3)\sin^2\theta_W$ |
| Down quark (d) | $+1-(4/3)\sin^2\theta_W$ |
| Proton = 2u+d | $-1+4\sin^2\theta_W$ |
| Neutron = u+2d | $+1$ |

Note: $\sin^2\theta_W$ is close to 1/4

➥ Electron and proton couplings <u>are small</u> !

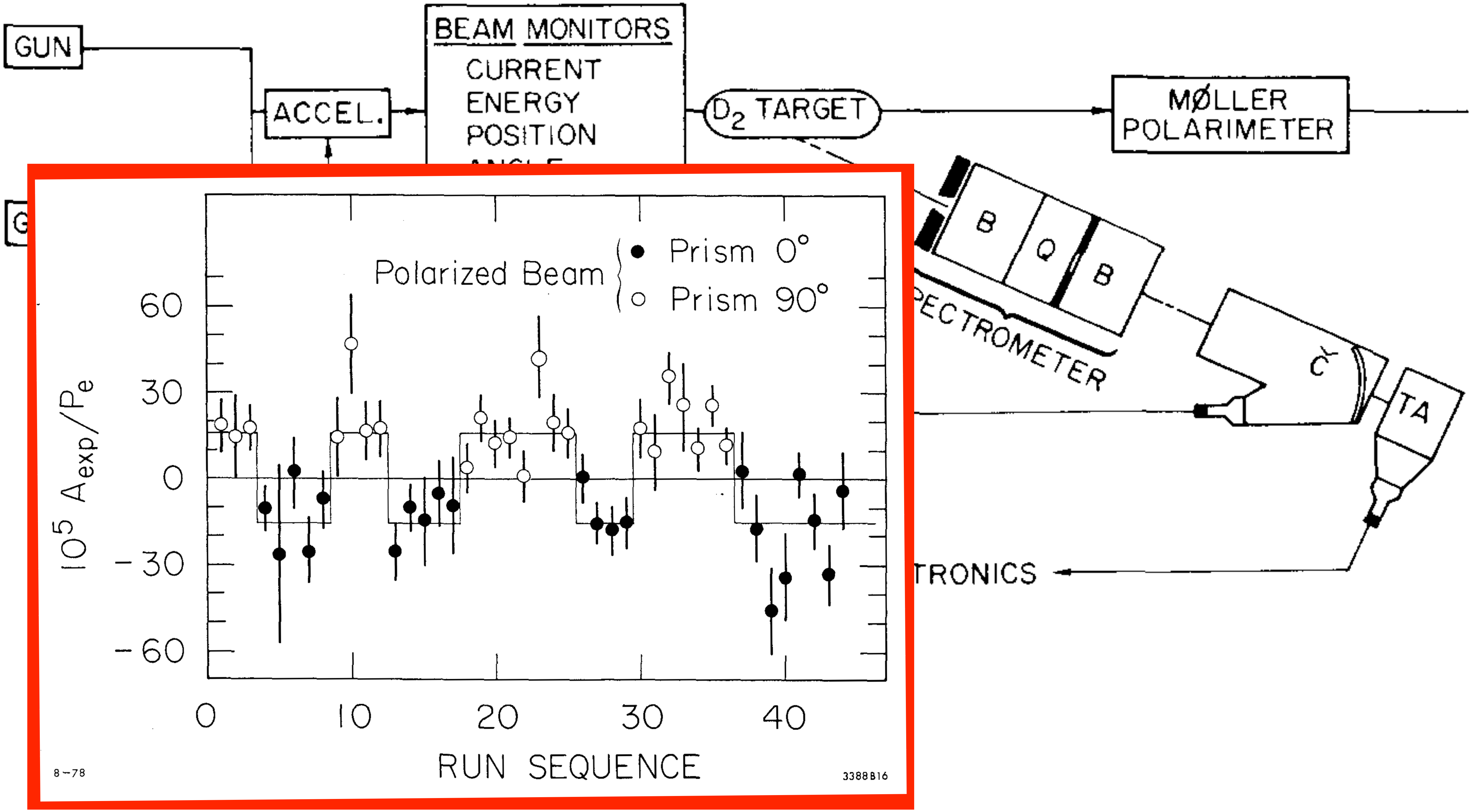
# Some Previous ePV Experiments

*All asymmetries given in parts per billion (ppb)*

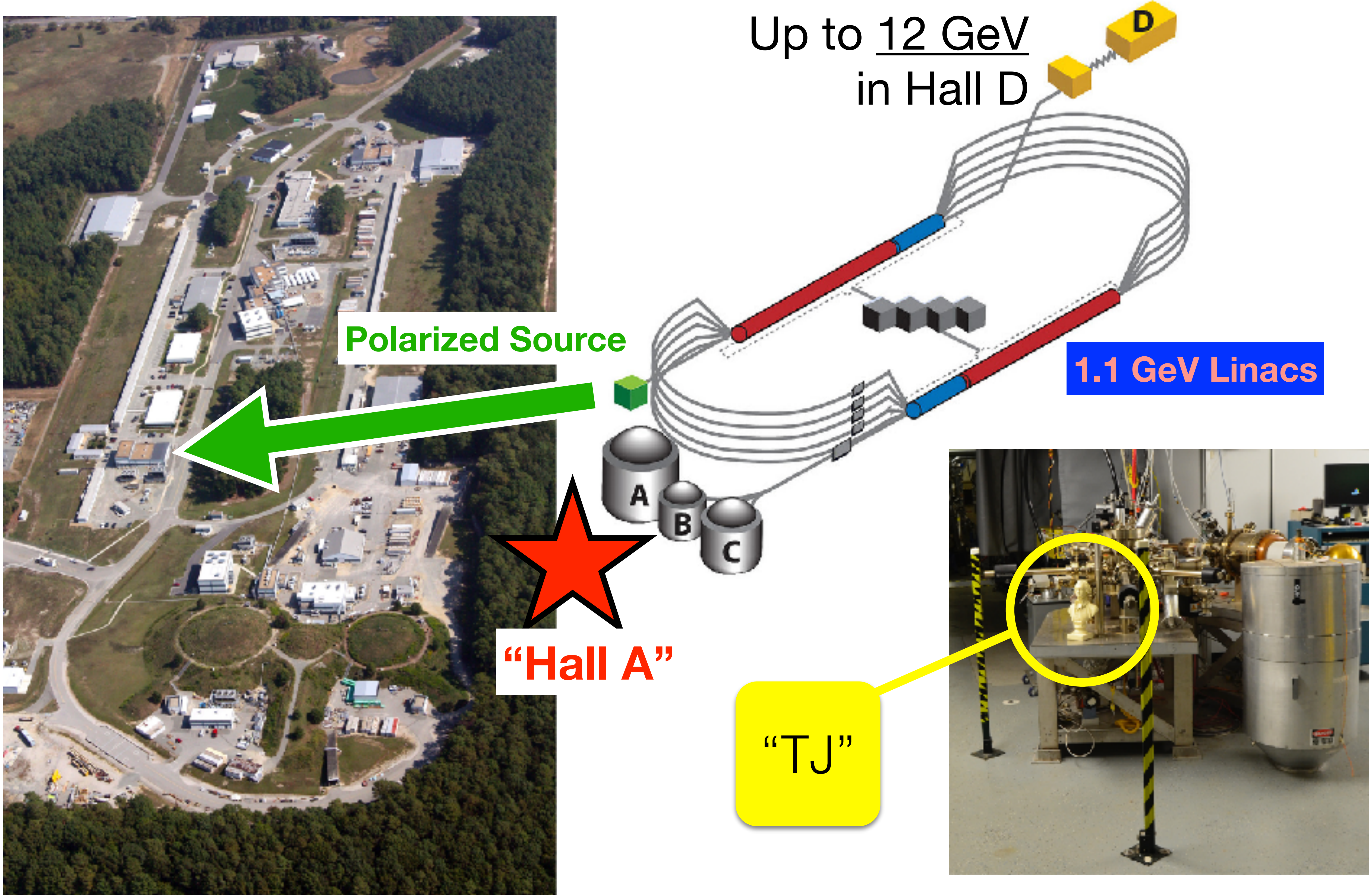
| Year | Lab | Target | $A_{PV}$ | $\delta A_{PV}$ | Comments |
|---|---|---|---|---|---|
| 1978 | SLAC | $H_2$ (DIS) | 49,000 | 8000 | Confirmation of the Standard Model |
| 1990 | Bates | $^{12}C$ (Elastic) | 600 | 140 | Isolation of one term in the current |
| 1997 | Bates | p (Elastic) | 6340 | 160 | SAMPLE: Strangeness in the nucleon |
| 2005 | SLAC | $e^-$ (Møller) | 117 | 16 | E158: Test of running value of $\sin^2\theta_W$ |
| 2006 | JLab | $^4He$ (Elastic) | 5981 | 810 | HAPPEX-$^4$He: Strange nucleon form factor |
| 2007 | JLab | p (Elastic) | 1500 | 110 | HAPPEX-II: Strange form factor of proton |
| 2012 | JLab | $^{208}Pb$ (Elastic) | 584 | 53 | PREX-I: Neutron skin thickness |
| 2014 | JLab | $H_2$ (DIS) | 80,000 | 3000 | PVDIS: Precision & wide kinematic range |
| 2018 | JLab | p (Elastic) | 227 | 9 | QWeak: Precision at very low $q^2$ |

# Example: SLAC (1978)

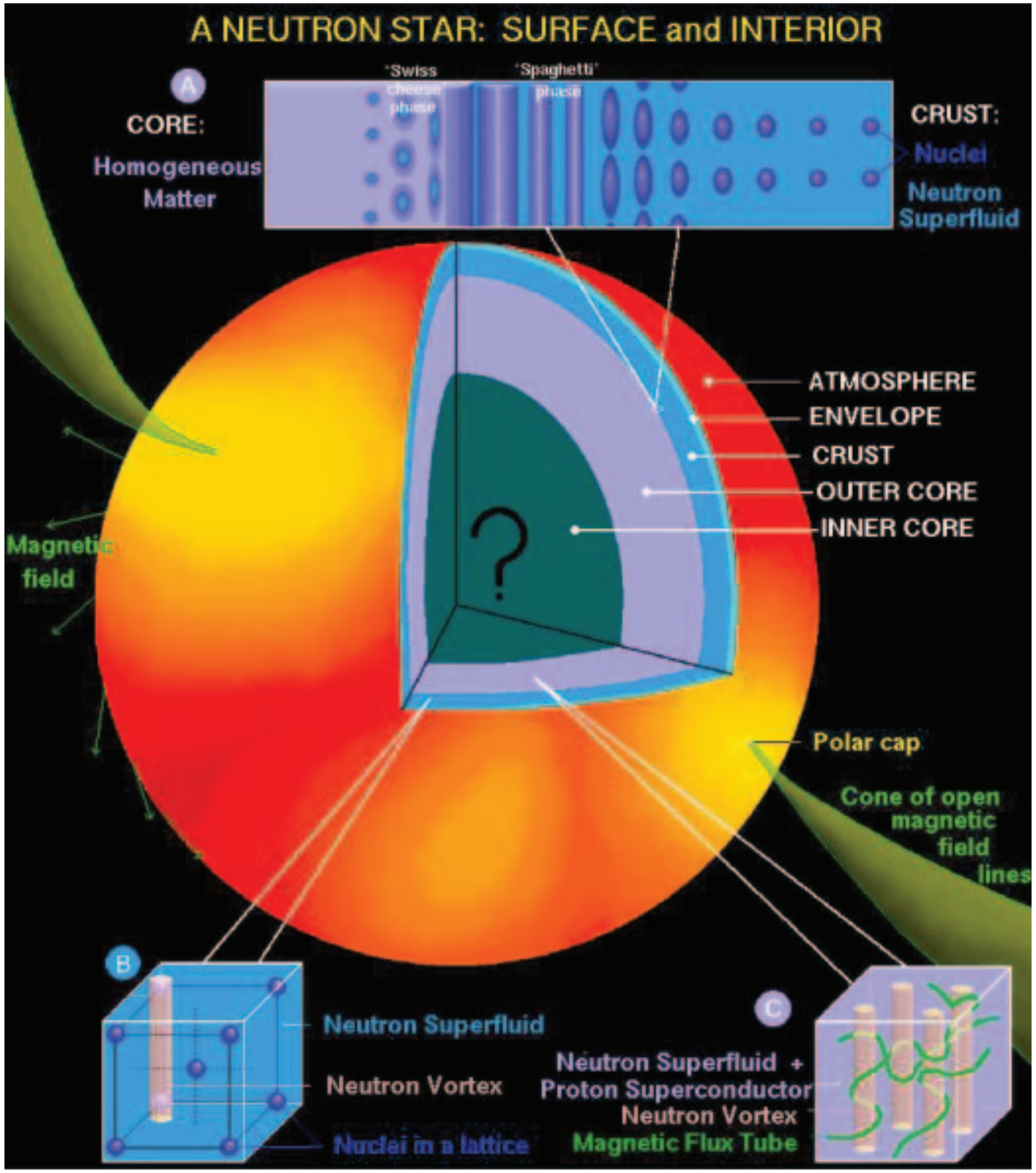
C. Prescott, et al, Phys. Lett. 77B (1978) 347



# CEBAF @ Jefferson Lab



# (1) Neutron Stars



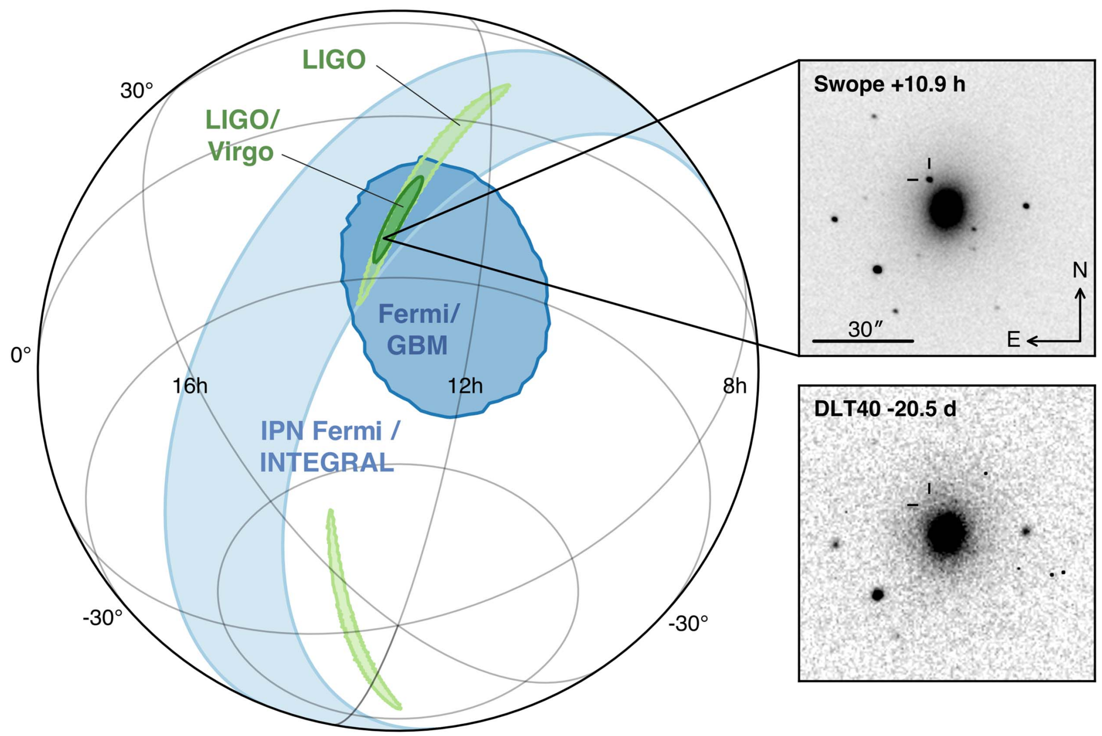

Using neutron-rich nuclei to learn about neutron matter.

Can this help us to understand some of the mysteries about neutron stars?

# Neutron Stars in the News

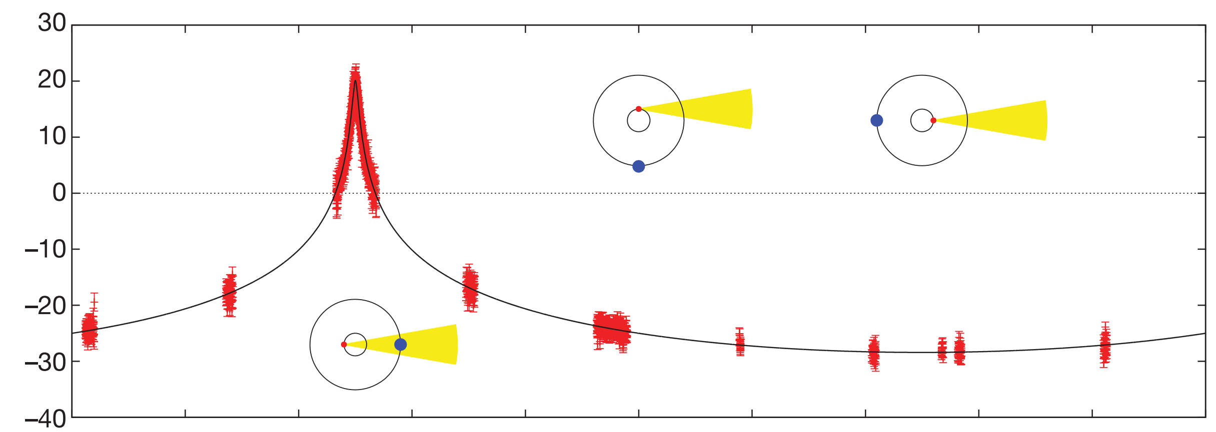
## Neutron Star Binary Mergers in the Multi-Messenger Age

GW170817:
PRX 9 (2019)011001
ApJ 848 2017 L12




## Discovery of Neutron Stars with Mass >2 Solar Masses

PSR J1614-2230:
Nature 467(2010)1081




Also
PSR J0348+0432:
Science 340(2013)448

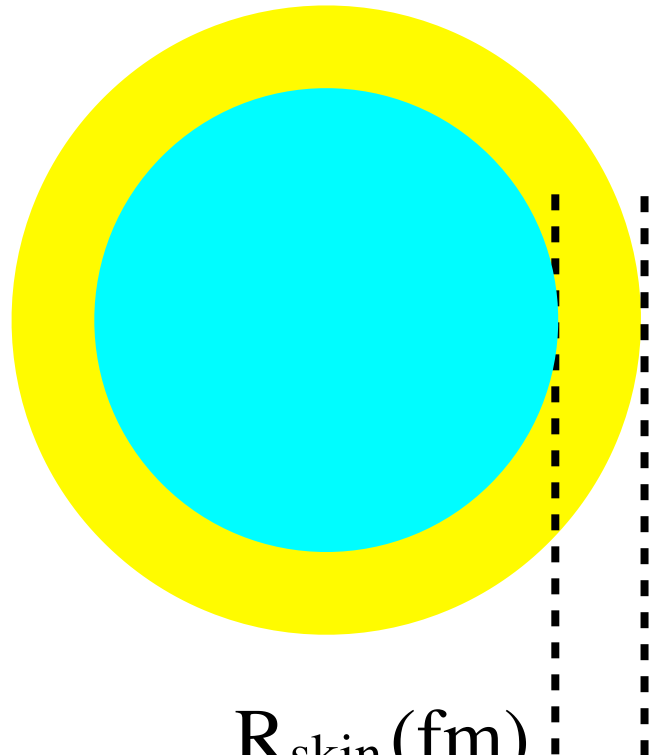
➥ *It is imperative to learn about neutron matter*

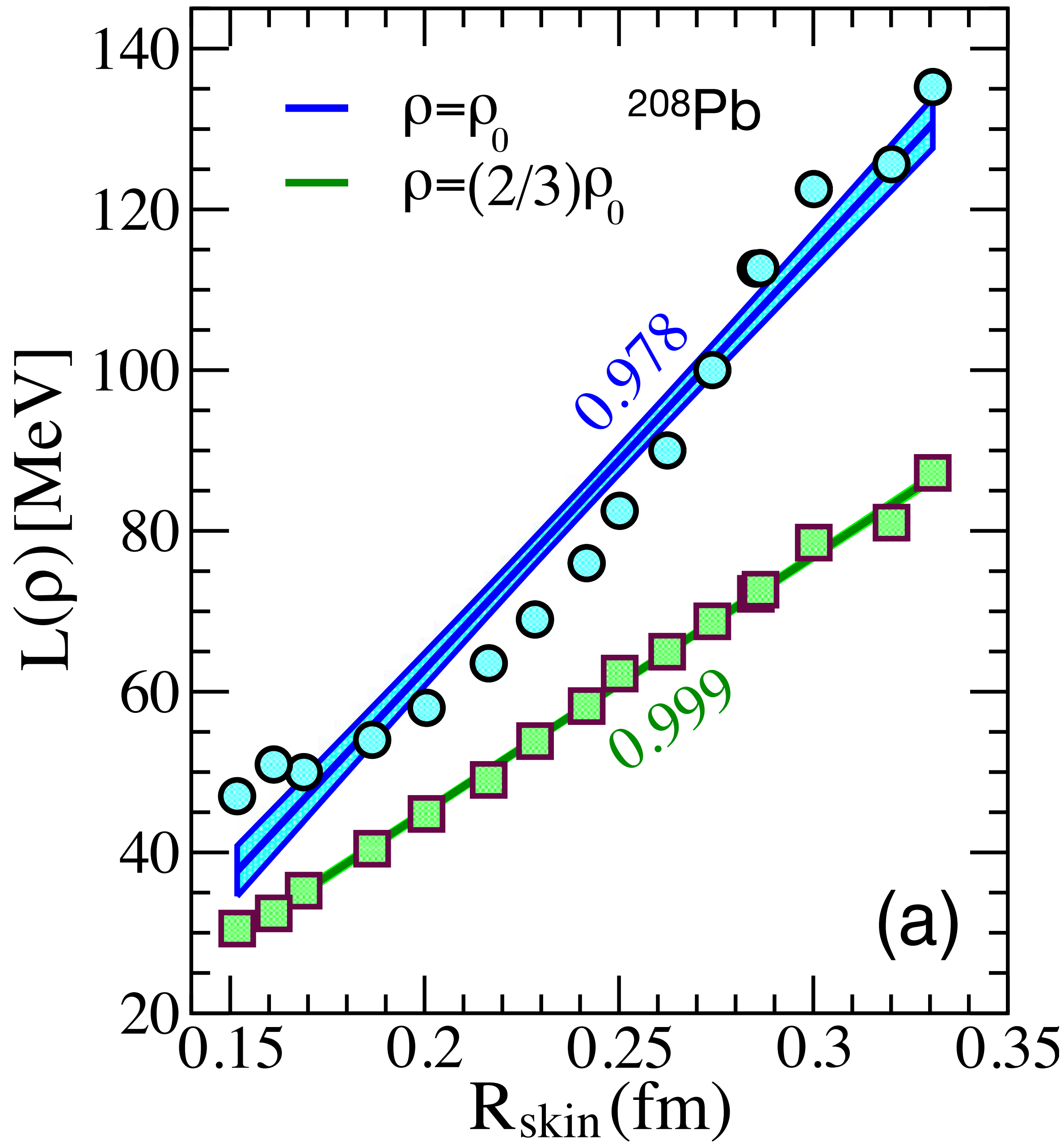
# Neutron Stars & Neutron Skins

*See Reed, et al, Phys.Rev.Lett 126(2021)172503*

~~Spherical ball of neutrons~~

Spherical neutron rich nucleus (eg $^{208}$Pb or $^{48}$Ca)




"Liquid Drop"

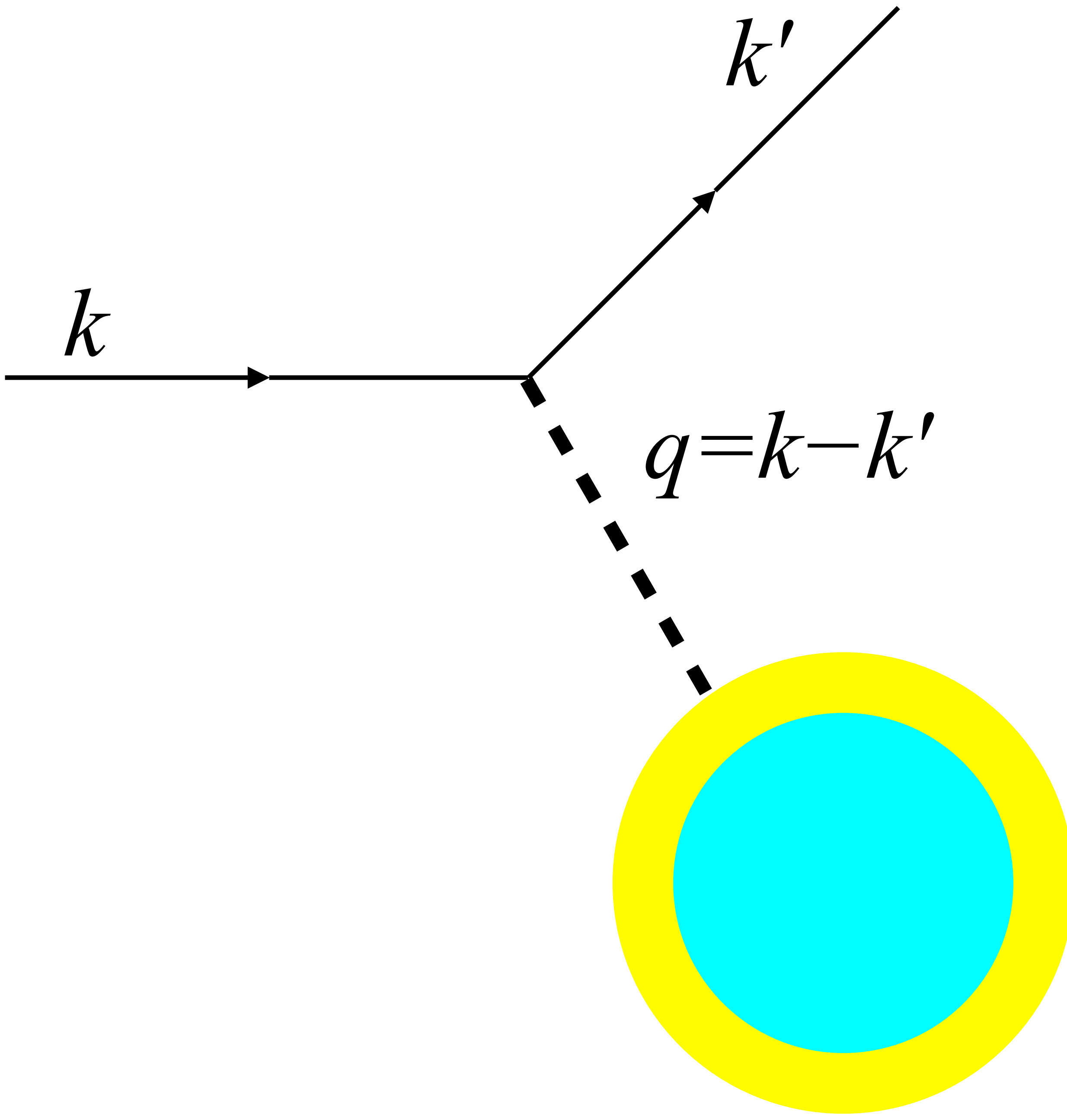
$$\frac{E}{A} - M \approx \mathcal{E}_{\mathrm{SNM}} + \left(\frac{\rho_n - \rho_p}{\rho}\right)^2 S(\rho)$$

"Symmetry Energy"

$$S(\rho) = J + L(\rho)\frac{\rho - \rho_0}{3\rho_0}$$

The "Physics" is in L(ρ)

# Elastic Scattering Form Factors



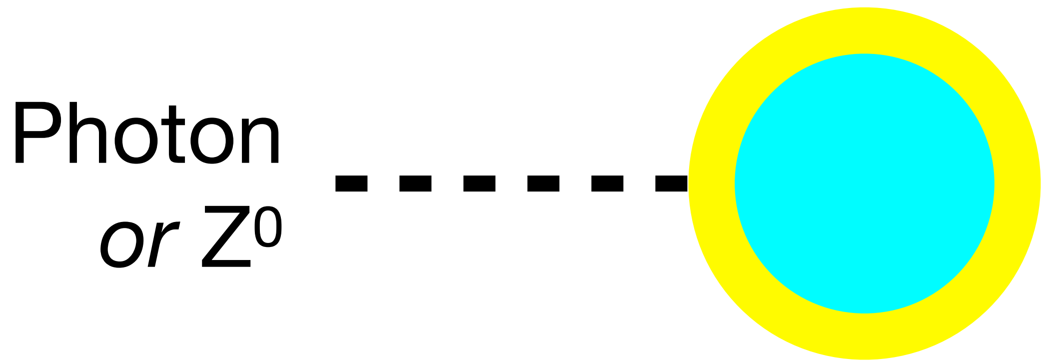

Scattering amplitude is proportional to

$$F(q) = \int \rho(r) e^{i\mathbf{q}\cdot\mathbf{r}}\, dV$$
$$= 1 - \frac{q^2}{6}\int r^2 \rho(r)\, dV + \cdots$$
$$= 1 - \frac{q^2}{6}\langle r^2\rangle + \cdots$$

Note!

The mean square radius $\langle r^2 \rangle$ gives the "radius" of the distribution $\rho(r)$.

# Measuring the Neutron Skin




| **Recall:** | Photon | $Z^0$ |
|---|---|---|
| Proton | 1 | Small |
| Neutron | ≈0 | 1 |

$$A_{\rm PV} = \frac{d\sigma(\Rightarrow) - d\sigma(\Leftarrow)}{d\sigma(\Rightarrow) + d\sigma(\Leftarrow)}$$

$$= \frac{G_F q^2}{4\pi\alpha}\frac{F_Z(q)}{F_\gamma(q)}$$

$$= \frac{G_F q^2}{4\pi\alpha}\left\{1 - \frac{q^2}{6}\left[\langle r_n^2\rangle - \langle r_p^2\rangle\right] + \cdots\right\}$$

*Parity Violating elastic scattering directly measures the neutron skin…*

*… but this term is small.*

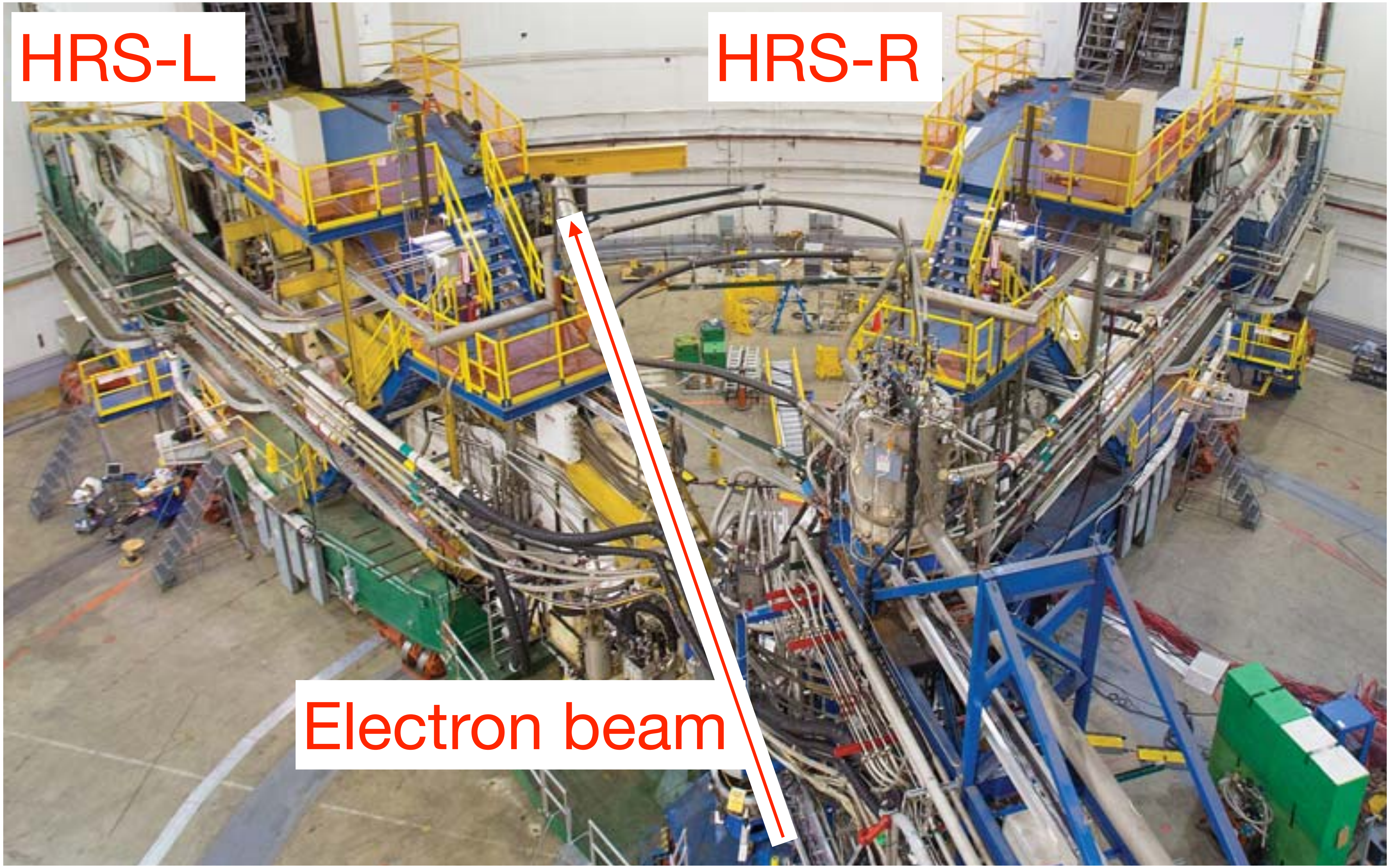
# PREX and CREX

| | $^{208}$Pb | $^{48}$Ca |
|---|---|---|
| Energy | 1.0 GeV | 2.2 GeV |
| Angle | 5 degrees | 4 degrees |
| $A_{PV}$ | 0.6 ppm | 2 ppm |
| $1^{\text{st}}$ Ex. State | 2.60 MeV | 3.84 MeV |
| beam current | 70 $\mu$A | 150 $\mu$A |
| rate | 1 GHz | 100 MHz |
| run time | 35 days | 45 days |
| $A_{PV}$ precision | 9% (PREX-I) 3% (PREX-II) | 2.4% |
| Error in $R_N$ | 0.06 fm (PREX-II) | 0.02 fm |

$^{208}$Pb: Large nucleus ⇒ nuclear matter

$^{48}$Ca: Microscopic calculation tractable

# Hall A at Jefferson Lab



# Put in Numbers for $^{208}$Pb

*Precision is the key!*

$$A_{\mathrm{PV}} = \frac{G_F q^2}{4\pi\alpha}\left\{1 - \frac{q^2}{6}\left[\langle r_n^2\rangle - \langle r_p^2\rangle\right] + \cdots\right\}$$

$$\begin{aligned}\langle r_n^2\rangle - \langle r_p^2\rangle &= \left(\langle r_n^2\rangle^{1/2} + \langle r_p^2\rangle^{1/2}\right)\left(\langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{1/2}\right)\\ &\approx \qquad\qquad 2R_{\mathrm{Pb}} \qquad\qquad\qquad \Delta_{\mathrm{Skin}}\end{aligned}$$

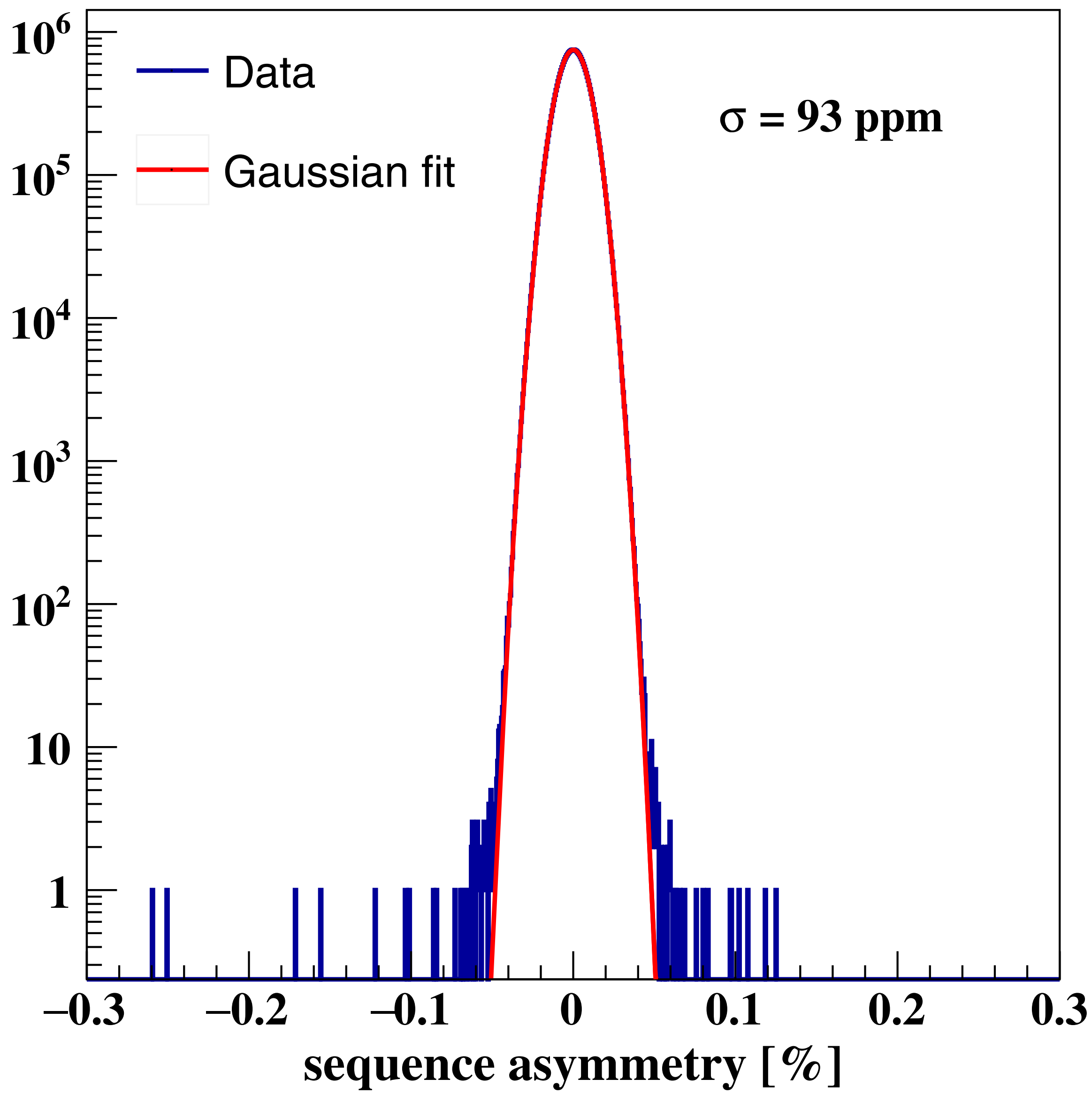
| | |
|---|---|
| $q^2$ | $0.076\ \mathrm{GeV}^2$ |
| $R_{\mathrm{Pb}}$ | $6\ \mathrm{fm}$ |
| $\Delta_{\mathrm{Skin}}$ | $\sim 0.2\ \mathrm{fm}$ |
| $q^2\left[\langle r_n^2\rangle - \langle r_p^2\rangle\right]/6$ | $0.076$ |
| $\delta A_{\mathrm{PV}}$ | $3\%$ |
| $\delta\Delta_{\mathrm{Skin}}$ | $0.07\ \mathrm{fm}$ |

If we can measure the (small!) parity violating asymmetry itself to about 3%, then we should be able to determine the skin thickness with an uncertainty near 0.07 fm.

# The PREX Result

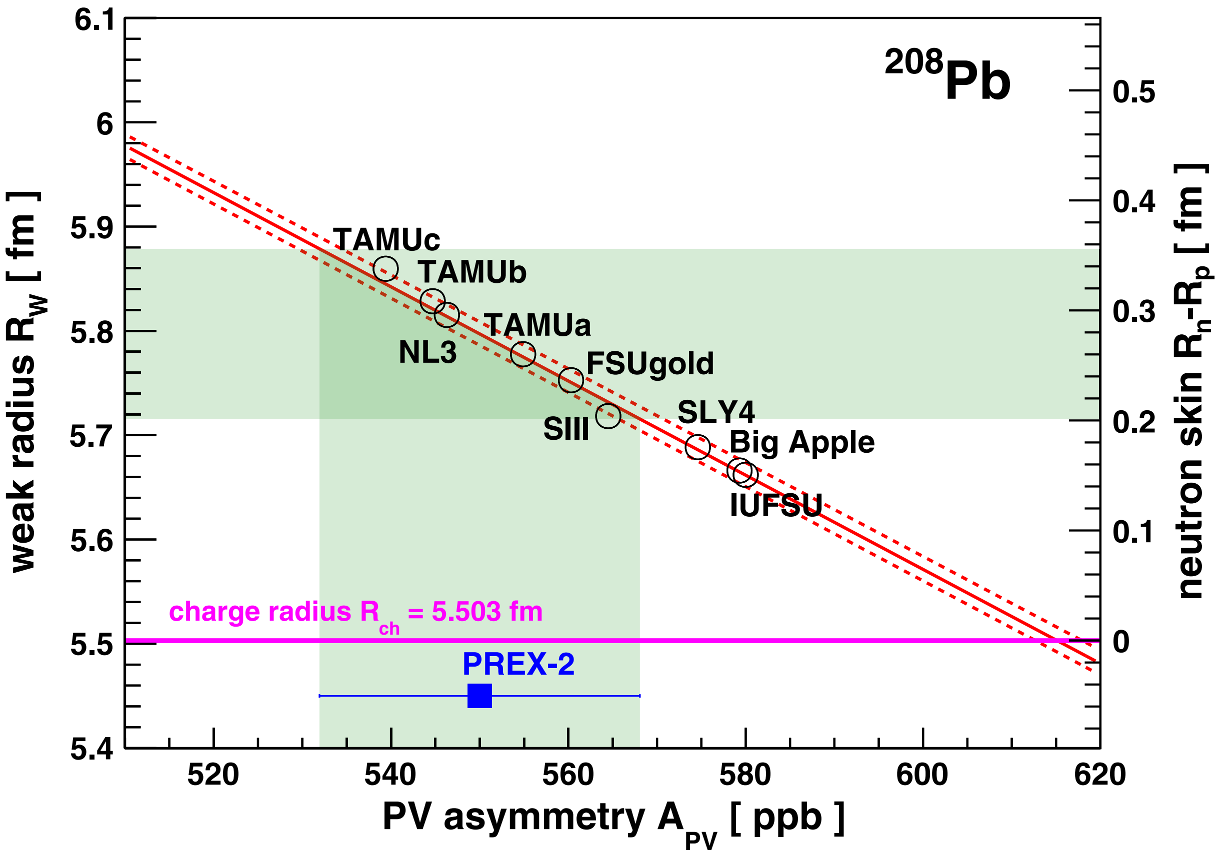
*Adhikari, et al, Phys.Rev.Lett 126(2021)172502*

3×10⁶ 1/30 sec @ 240 Hz




$$A_{PV}^{meas} = 550 \pm 16\,(\mathrm{stat}) \pm 8\,(\mathrm{syst})\ \mathrm{ppb}$$

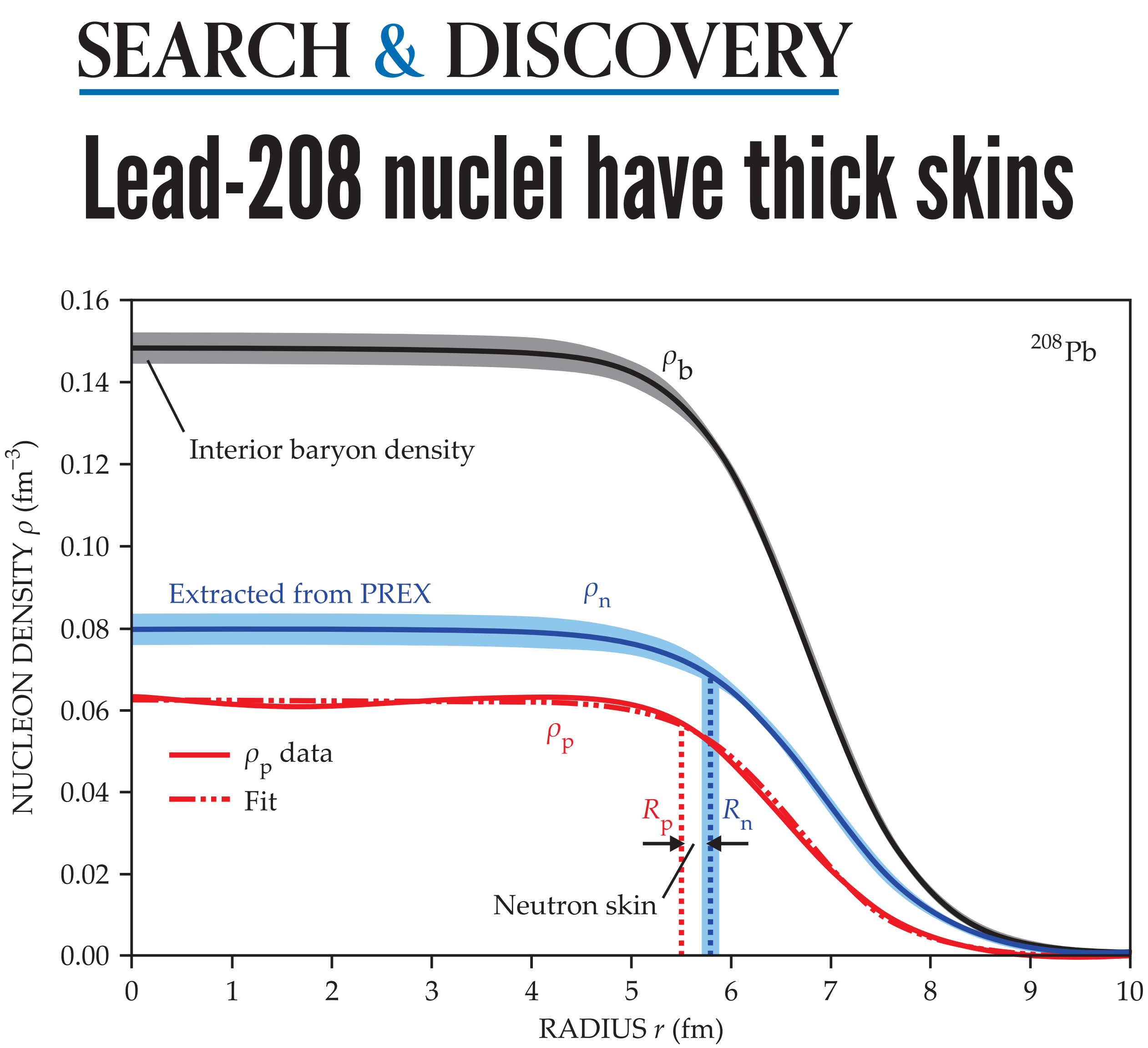
$$F_W(\langle Q^2 \rangle) = 0.368 \pm 0.013\,(\mathrm{exp}) \pm 0.001\,(\mathrm{theo})$$



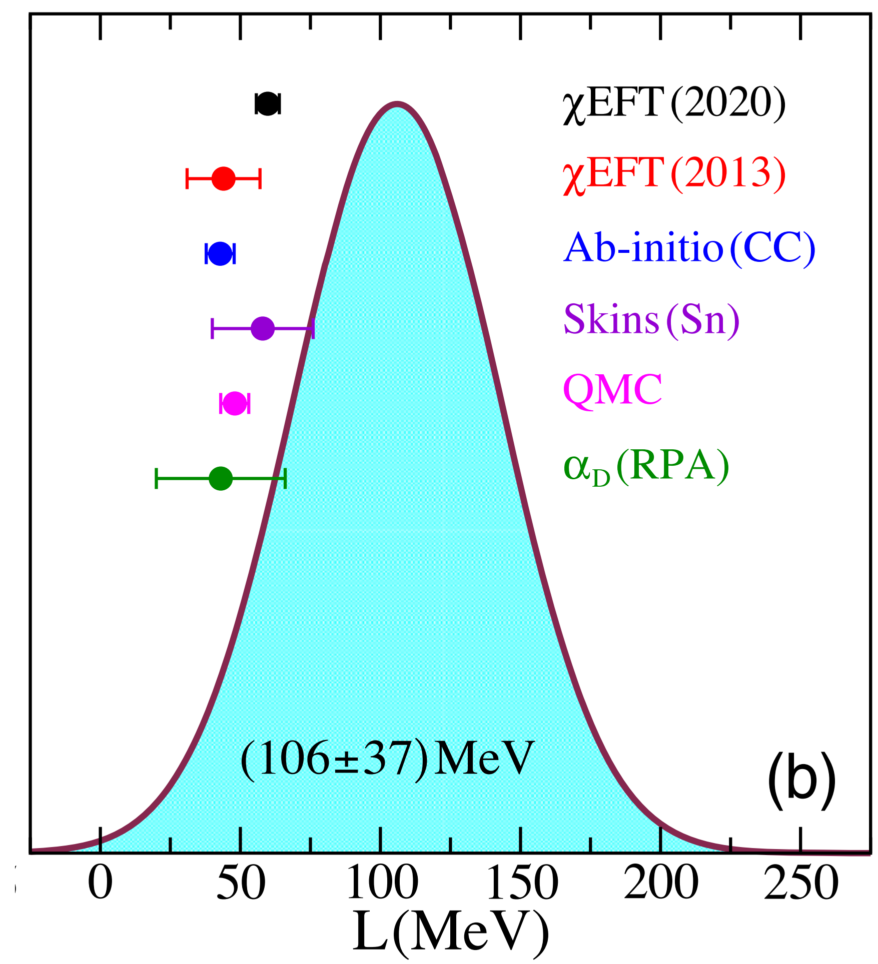

| $^{208}$Pb Parameter | Value |
|---|---|
| Weak radius ($R_W$) | $5.800 \pm 0.075$ fm |
| Interior weak density ($\rho_W^0$) | $-0.0796 \pm 0.0038$ fm$^{-3}$ |
| Interior baryon density ($\rho_b^0$) | $0.1480 \pm 0.0038$ fm$^{-3}$ |
| Neutron skin ($R_n - R_p$) | $0.283 \pm 0.071$ fm |

# PREX Media Attention

*Physics Today 74(2021)12 & K Scholberg https://physics.aps.org/articles/v14/58*

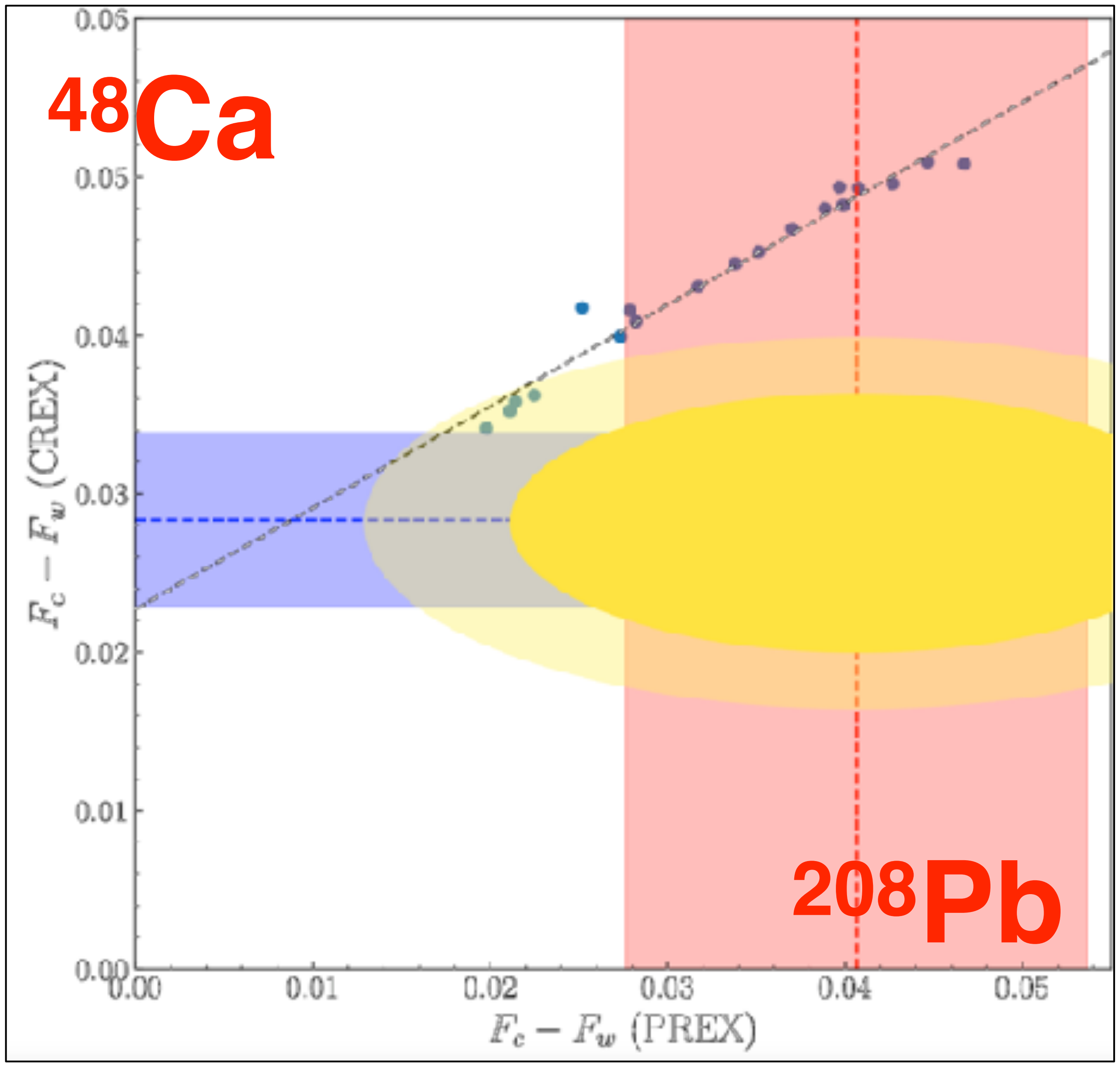



Nuclear matter calculations generally predicted a smaller value for the “pressure” $L$.



# CREX Just Released

$A_{PV} = 2658.6 \pm 113.2 \text{ ppb } (4.3\%)$




*Points are a collection of Relativistic and Non-Relativistic DFT calculations*

Compare to predictions of microscopic calculations?

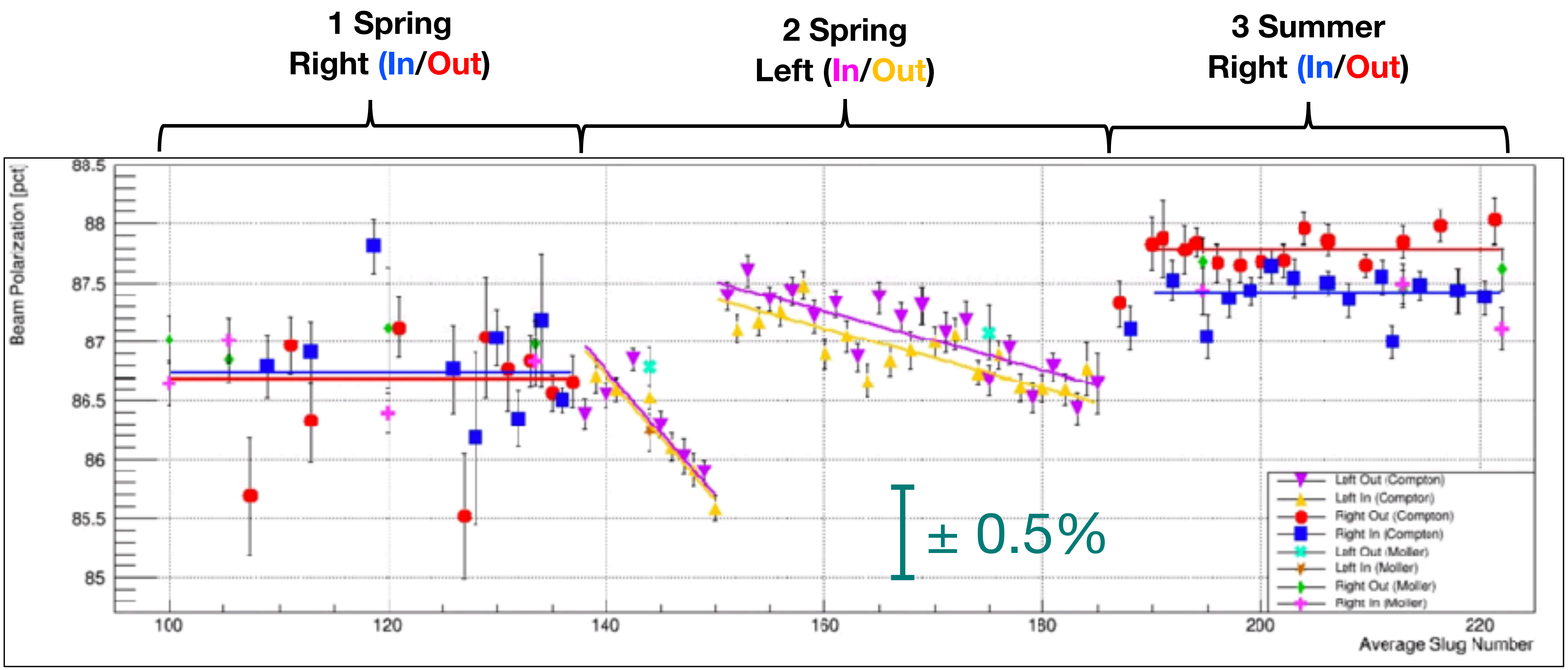
eg G. Hagen et al, Nature Physics 12 (2016) 186

First need to sort out some issues, including a strong "weak spin orbit" effect that mainly effects $^{48}Ca$

eg Horowitz and Piekarewicz, Phys Rev C86(2012)045503

# Electron Beam Polarization

*High Precision Necessary*



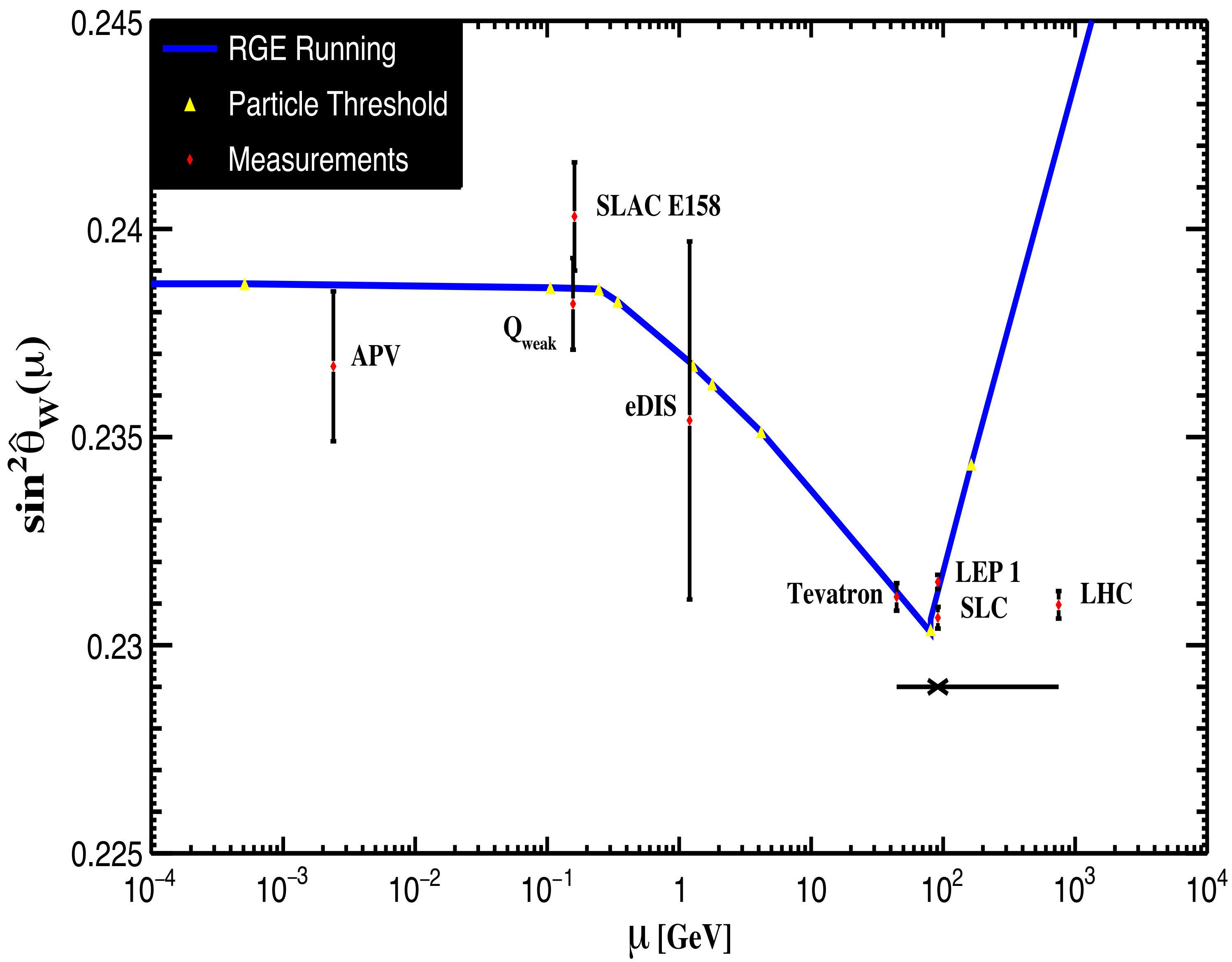

Two Approaches: Møller and Compton

$P_e = 87.09 \pm 0.44\%$

# (2) Beyond the Standard Model

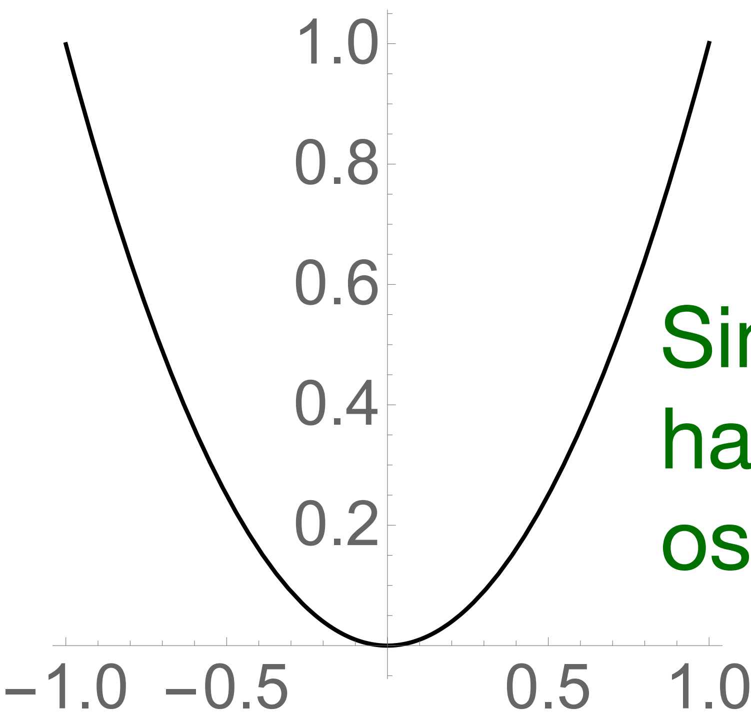
Standard Model gives the weak neutral couplings to high precision.

But is there a hint of "new physics" in the LEP1/SLC discrepancy?



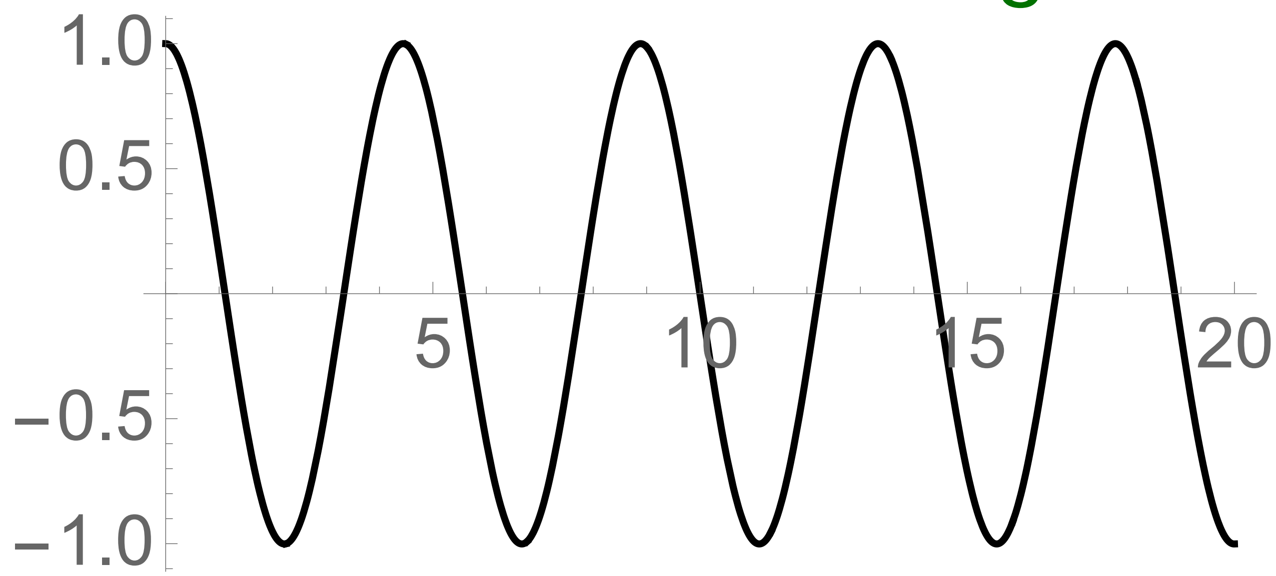

➥ Want to look for new bosons at high masses!

# “High Energy Physics” at Low Energies

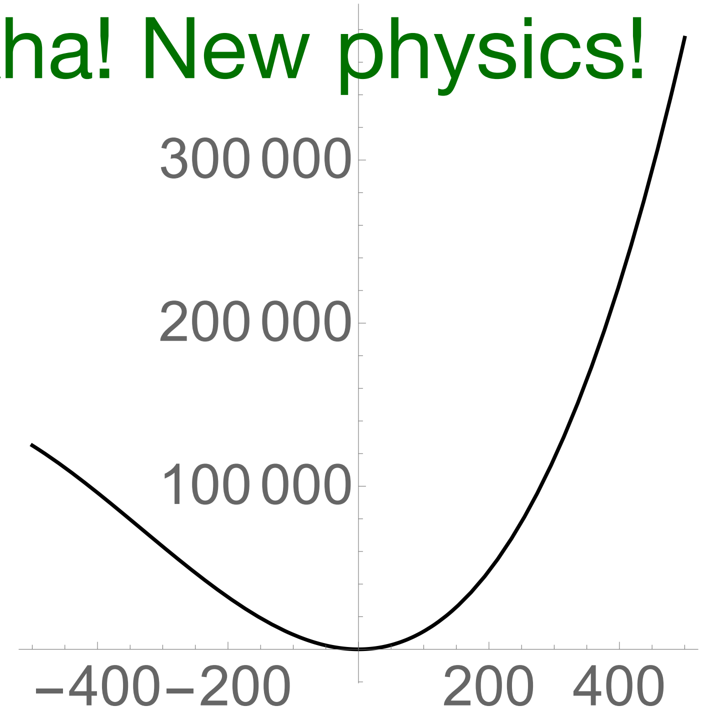



Simple harmonic oscillator?

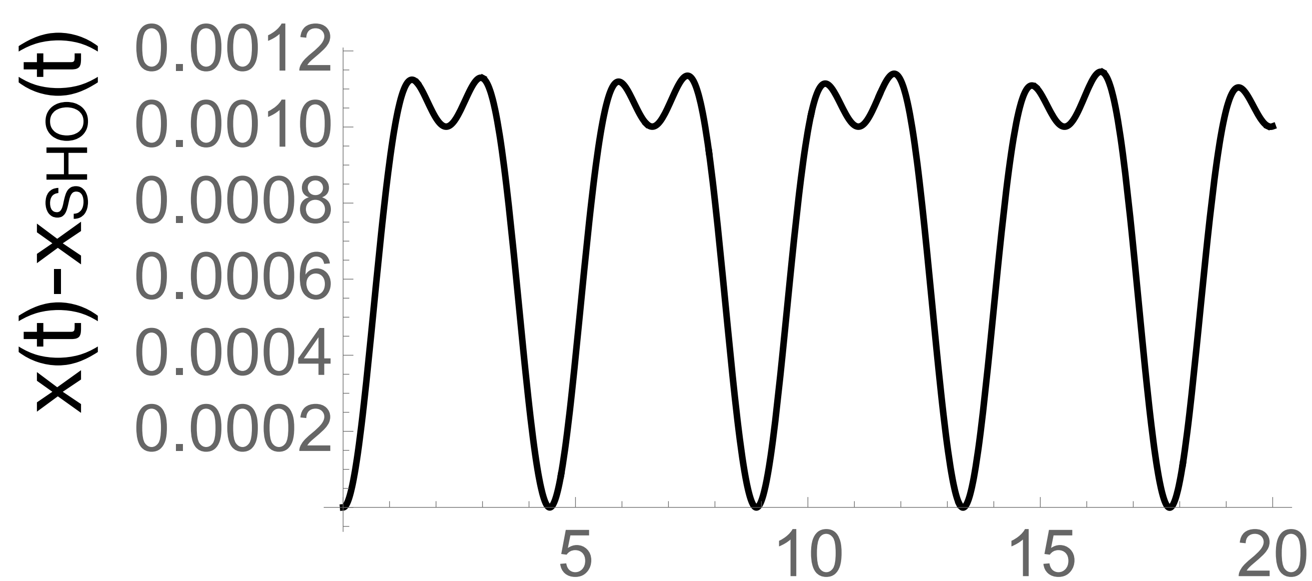
The motion looks right!




Aha! New physics!



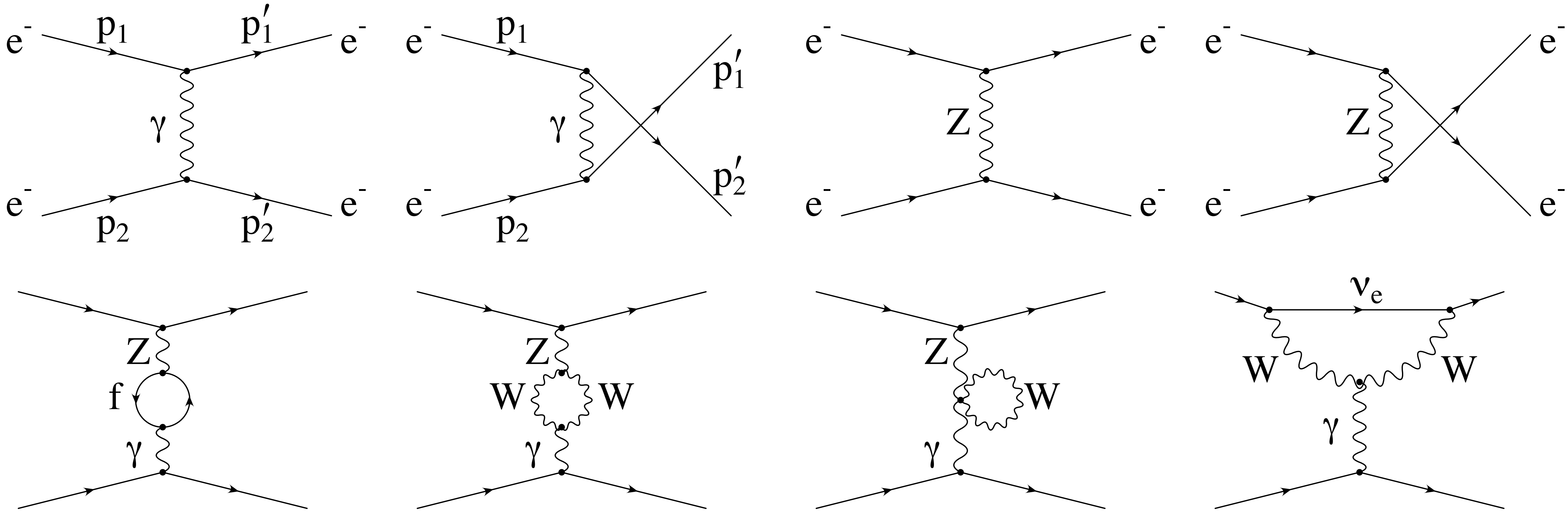

Unless you take a closer look!



# MOLLER @ JLab

## **M**easurement **O**f **L**epton-**L**epton **E**lastic **R**eaction

*Parity Violation in Electron-Electron Elastic Scattering*




➥ *Look for deviations from the calculated result!*

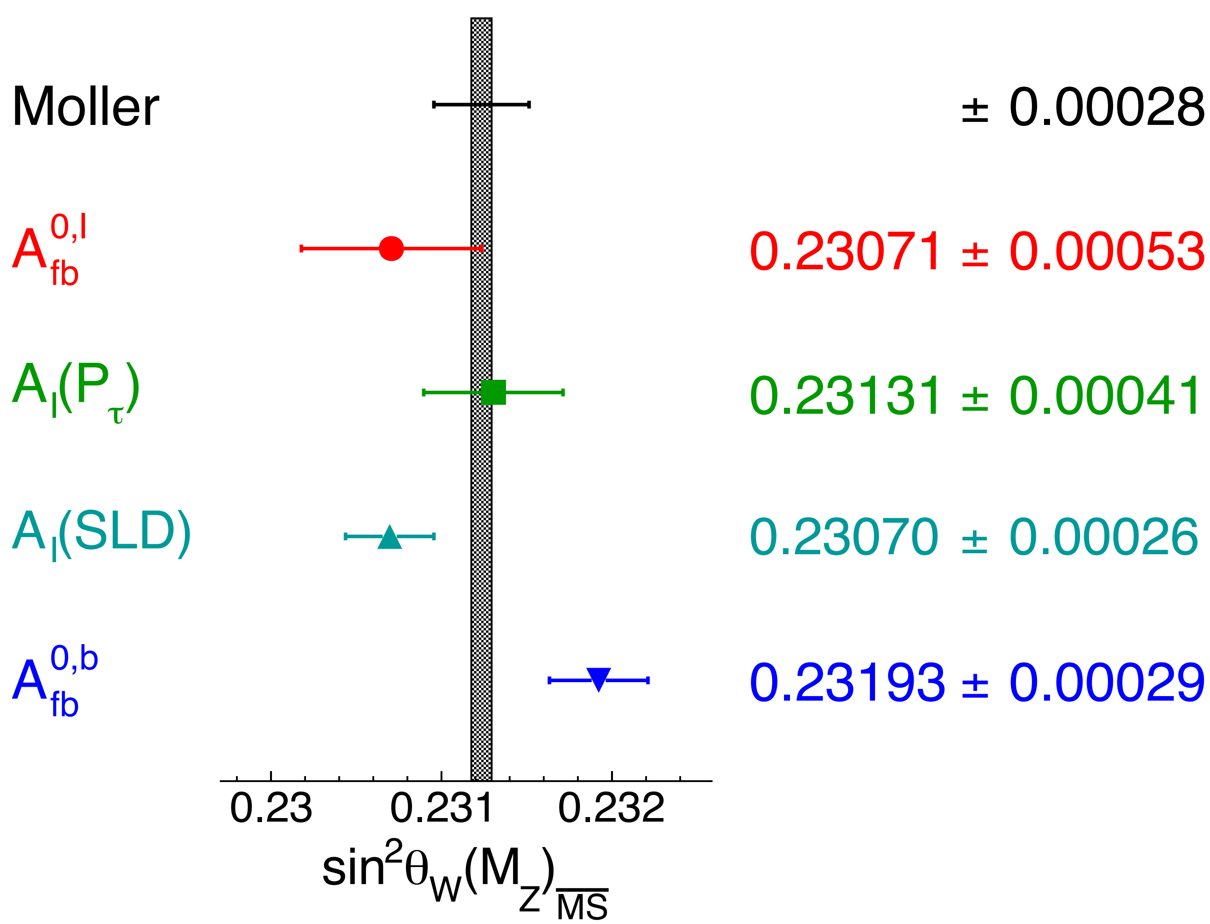
Asymmetry is 33 ppb. Precision goal is 2.4% (0.7 ppb)

# Sensitivity to New Physics

*Standard Model → New Physics Added*

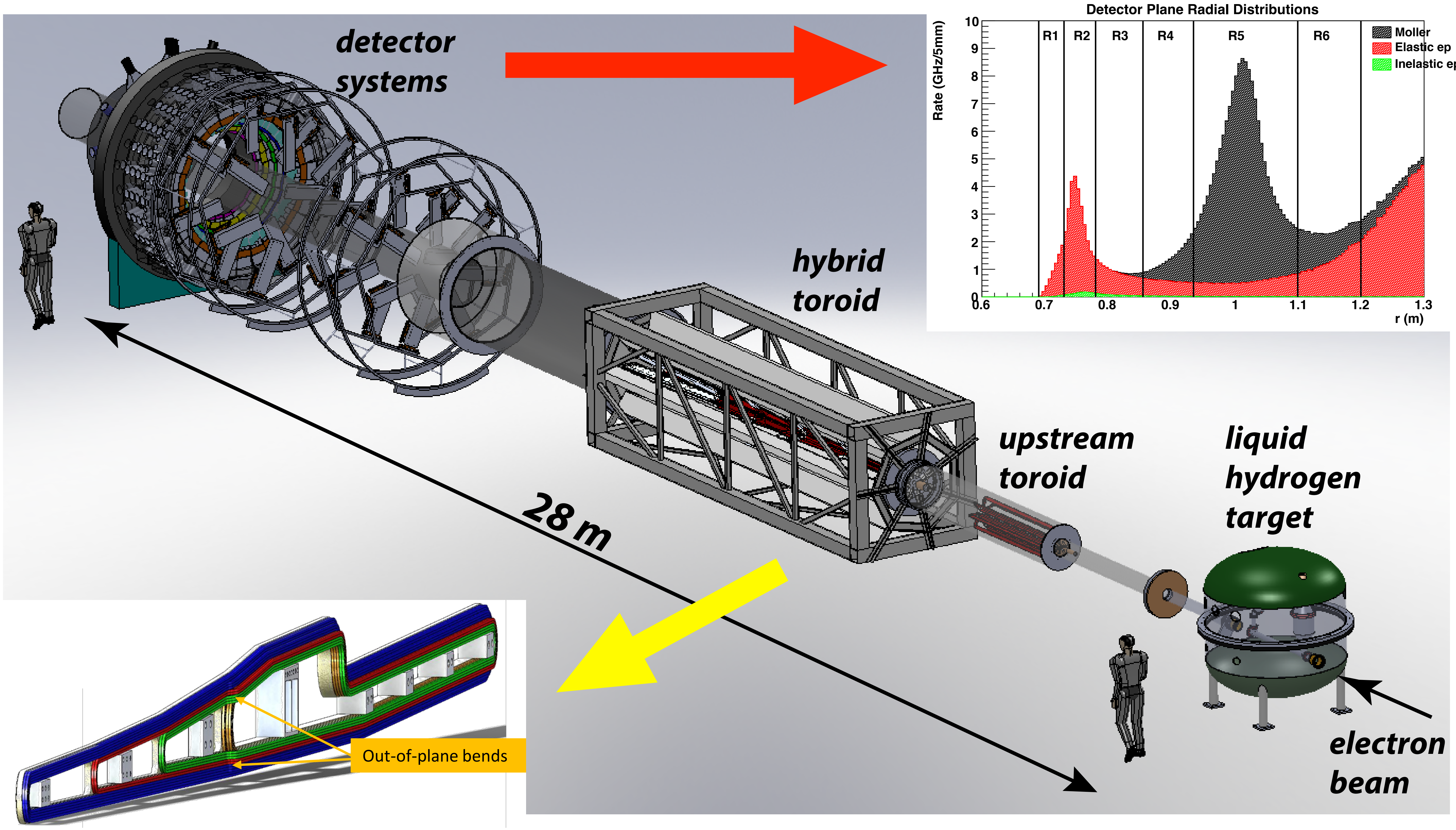
$$\frac{g_{AV}^{eq}}{2v^2}\bar{e}\gamma^\mu\gamma^5 e\bar{q}\,\gamma_\mu q \rightarrow \left[\frac{g_{AV}^{eq}}{2v^2} + \frac{4\pi}{(\Lambda_{AV}^{eq})^2}\right]\bar{e}\gamma^\mu\gamma^5 e\bar{q}\,\gamma_\mu q$$

*Higgs* *A New Scale!*

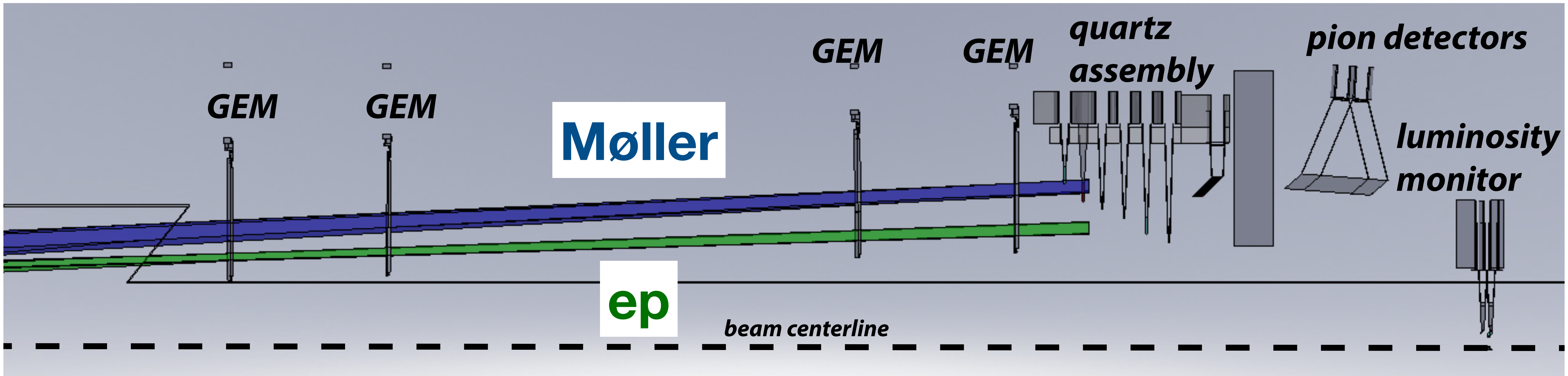


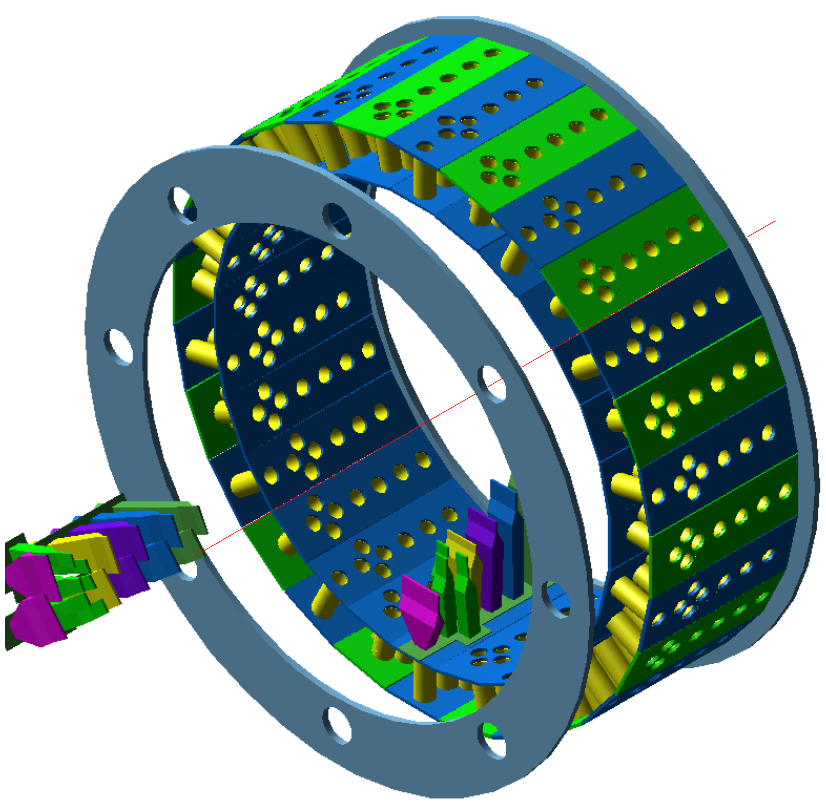

*Depending on the new couplings, the MOLLER result will test for Higgs-like particles with mass up to ≈10 TeV (roughly 100×Higgs)*

# Experimental Setup



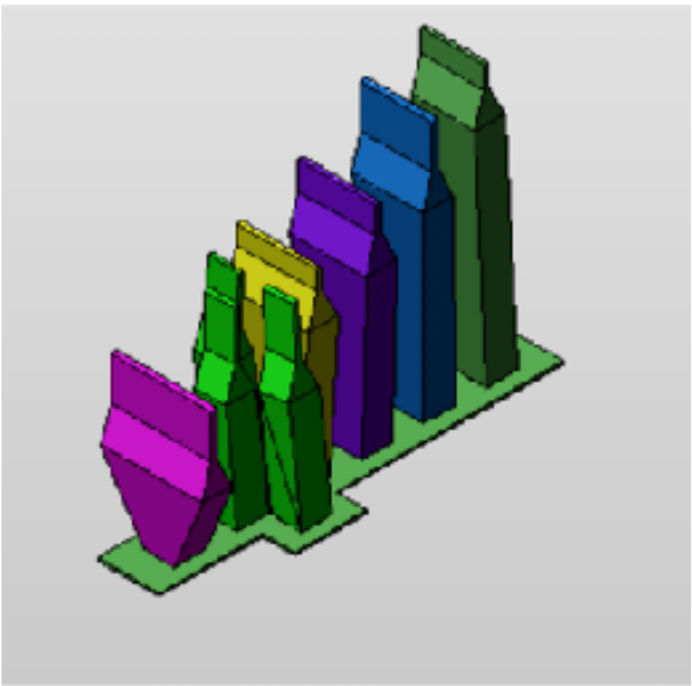
# Detector Arrangement



Quartz Cherenkov detectors to gather light from scattered electrons.

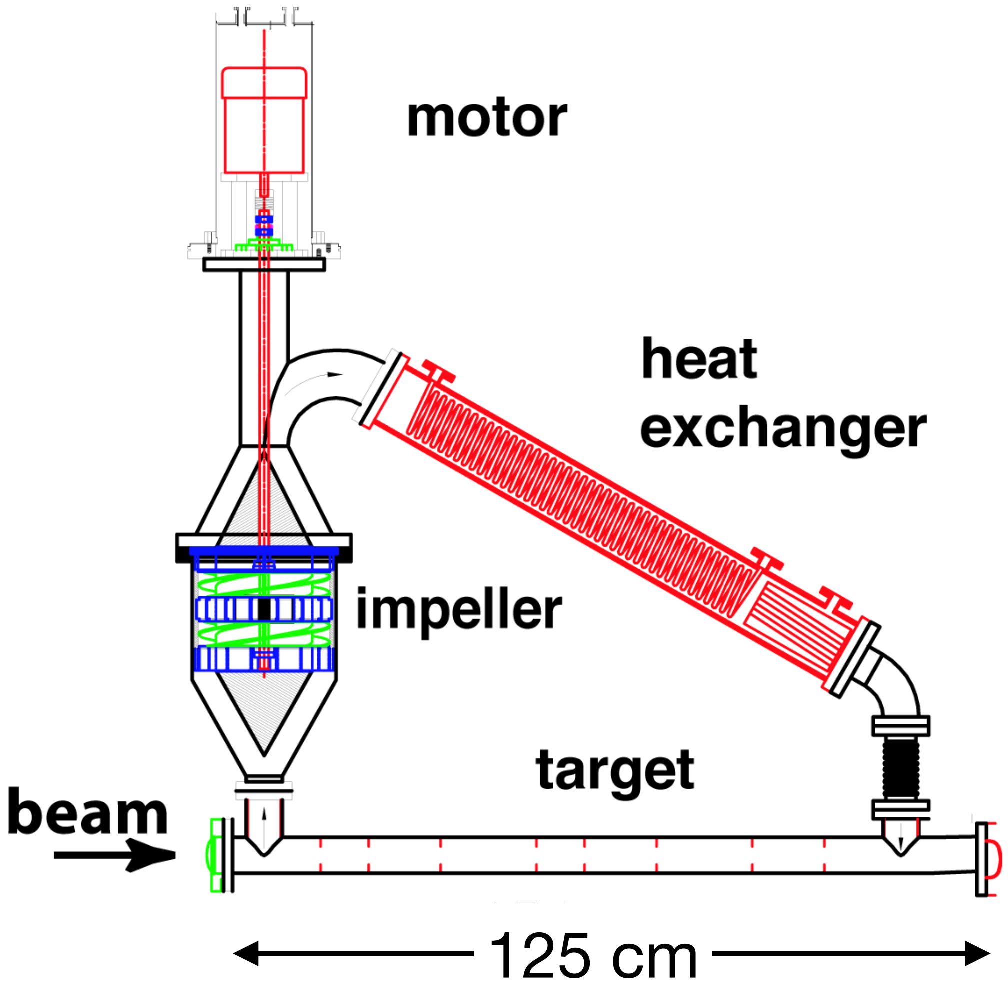
PMT signals are integrated for each polarization state.



# Some Parameters

| | |
|---|---|
| Beam E | 11 GeV |
| Møller E′ | 1.7 - 8.5 GeV |
| $\theta_{CM}$ | 46° - 127° |
| $\theta_{Lab}$ | 0.23° - 1.1° |
| $\langle Q^2 \rangle$ | 0.0058 $GeV^2$ |
| Current | 70 μA |
| Møller rate | 123 GHz |
| Flip rate | 1920 Hz |

Liquid Hydrogen Target




Deposited power = 4kW

# Uncertainty Budget

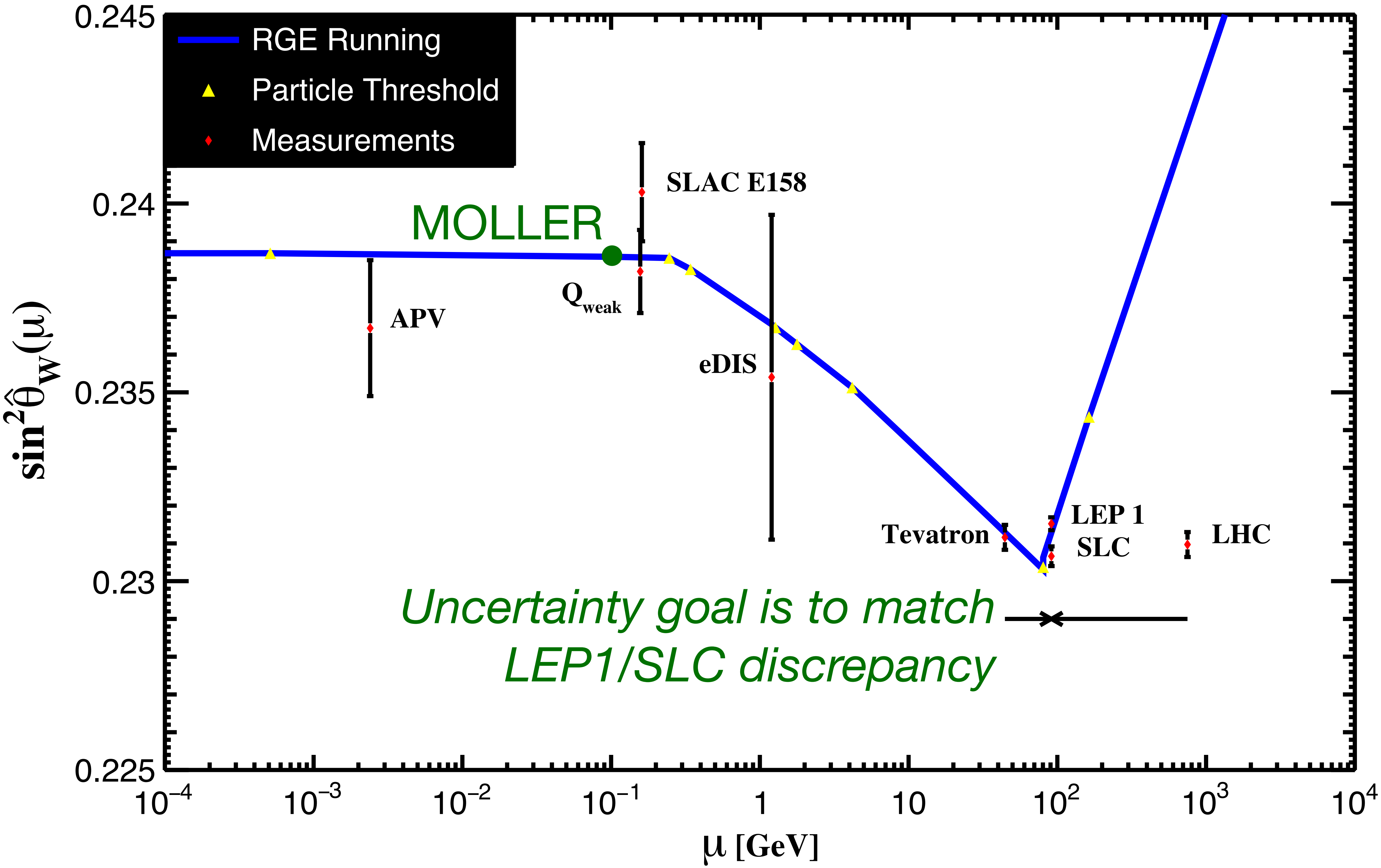
Challenging Experiment!

But the scientific case is solid, CD1 is granted, R&D to finalize design is underway, and we are on a path for installation some time in 2025.

| Error Source | Fractional Error (%) |
|---|---|
| Statistical | **2.1** |
| Absolute value of $Q^2$ | 0.5 |
| beam (second order) | 0.4 |
| beam polarization | 0.4 |
| $e + p(+\gamma) \rightarrow e + X(+\gamma)$ | 0.4 |
| beam (position, angle, energy) | 0.4 |
| beam (intensity) | 0.3 |
| $e + p(+\gamma) \rightarrow e + p(+\gamma)$ | 0.3 |
| $\gamma^{(*)} + p \rightarrow \pi + X$ | 0.3 |
| Transverse polarization | 0.2 |
| neutrals (soft photons, neutrons) | 0.1 |
| Total systematic | **1.1** |

| Beam Property | Assumed Sensitivity | Accuracy of Correction | Required 1 kHz random fluctuations | Required cumulative helicity-correlation | Systematic contribution |
|---|---|---|---|---|---|
| Intensity | 1 ppb / ppb | $\sim$1% | $<$ 1000 ppm | $<$ 10 ppb | $\sim$ 0.1 ppb |
| Energy | -1.4 ppb / ppb | $\sim$10% | $<$ 286 ppm | $<$ 0.7 ppb | $\sim$ 0.05 ppb |
| Position | 0.85 ppb / nm | $\sim$10% | $<$ 47 $\mu$m | $<$ 1.2 nm | $\sim$ 0.05 ppb |
| Angle | 8.5 ppb / nrad | $\sim$10% | $<$ 4.7 $\mu$rad | $<$ 0.12 nrad | $\sim$ 0.05 ppb |

# Comparison with Other Results



# Conclusions

Parity Violating electron scattering with GeV beams is a useful tool for studying nature.

We now have new information that will help us understand the structure of neutron stars!

Next: MOLLER will search for New Physics at multi-TeV energies through Precision ePV.

**Thank You!**