First Determination of the Weak Charge of the Proton

- *The Standard Model of Physics*
- The Qweak experiment
- First results
- Summary, outlook

Manolis
Kargiantoulakis

GPSA seminar 09/23/13

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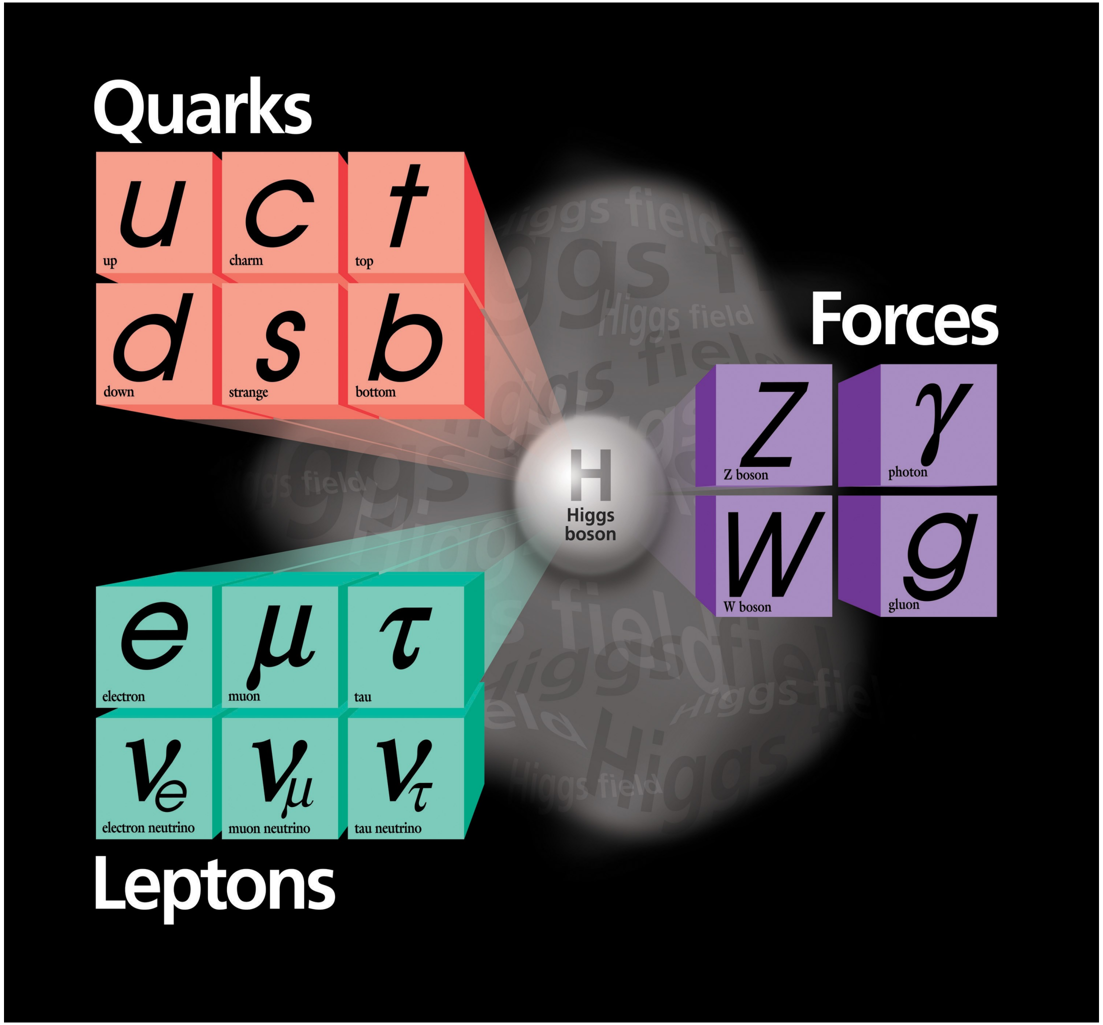
The Standard Model of Physics



An *extremely successful* theory, stood up to experimental tests for over 30 years.

"The theory of *almost* everything"

Includes all known fundamental particles, gives rise to every element in the periodic table.

A very economical model of 3 fundamental forces:

- Strong nuclear
- Electromagnetic
- Weak nuclear

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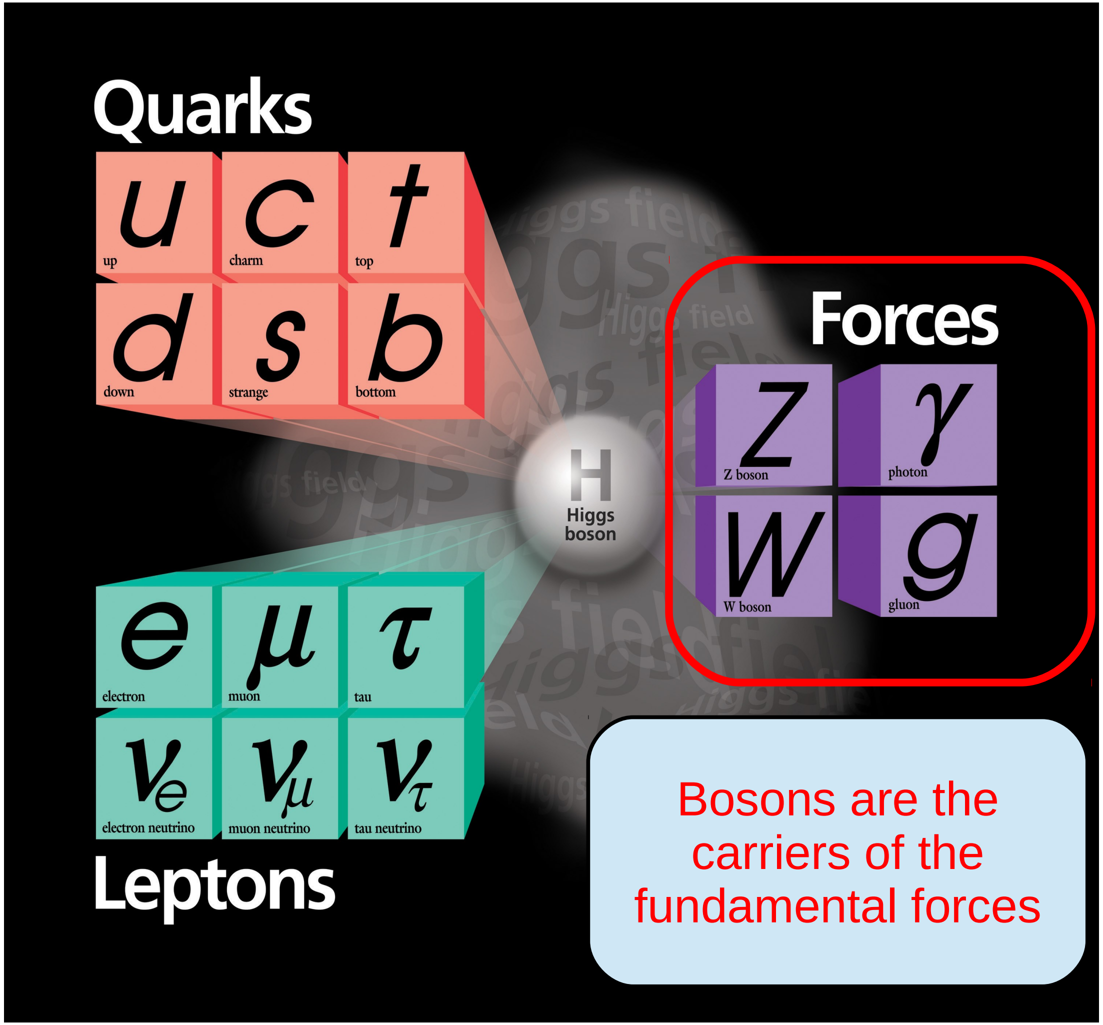

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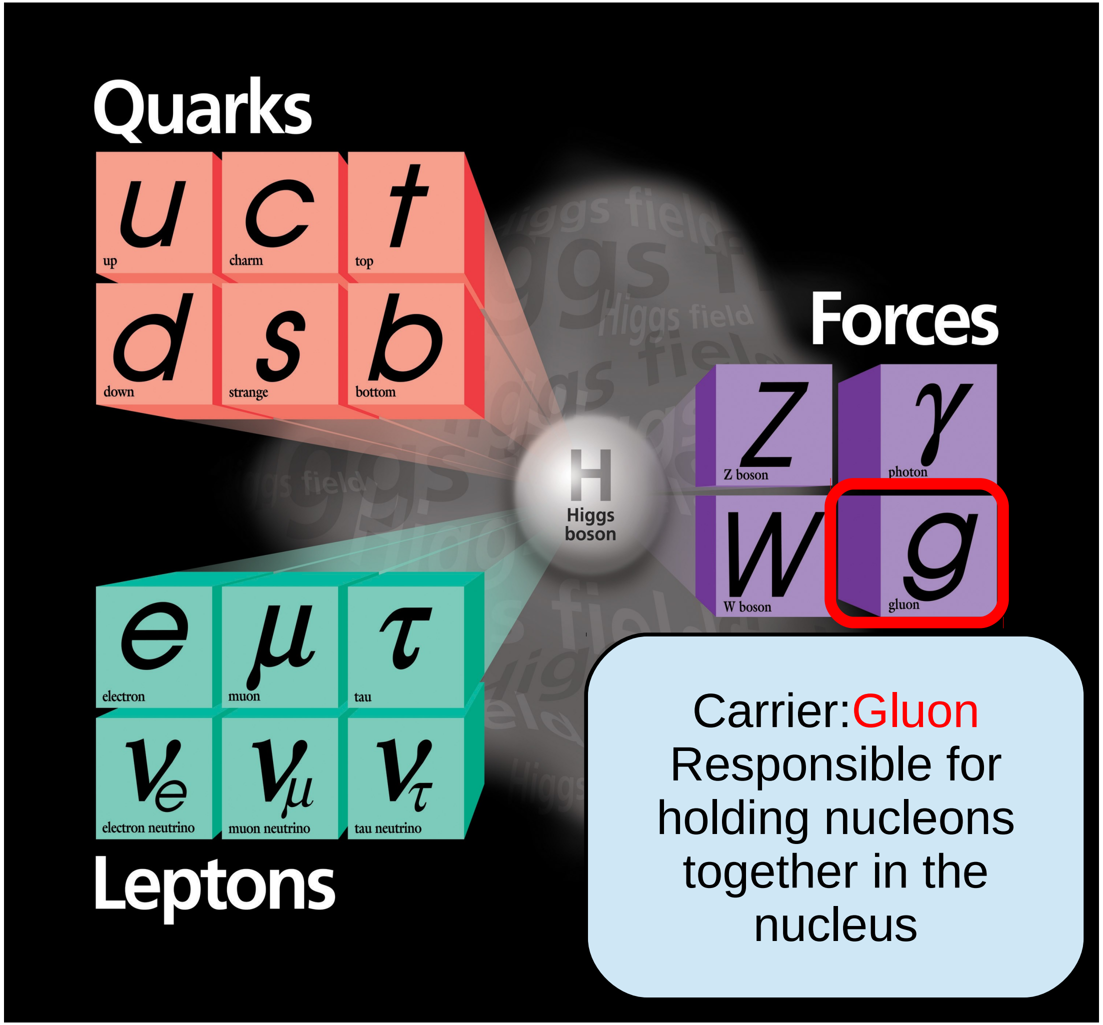

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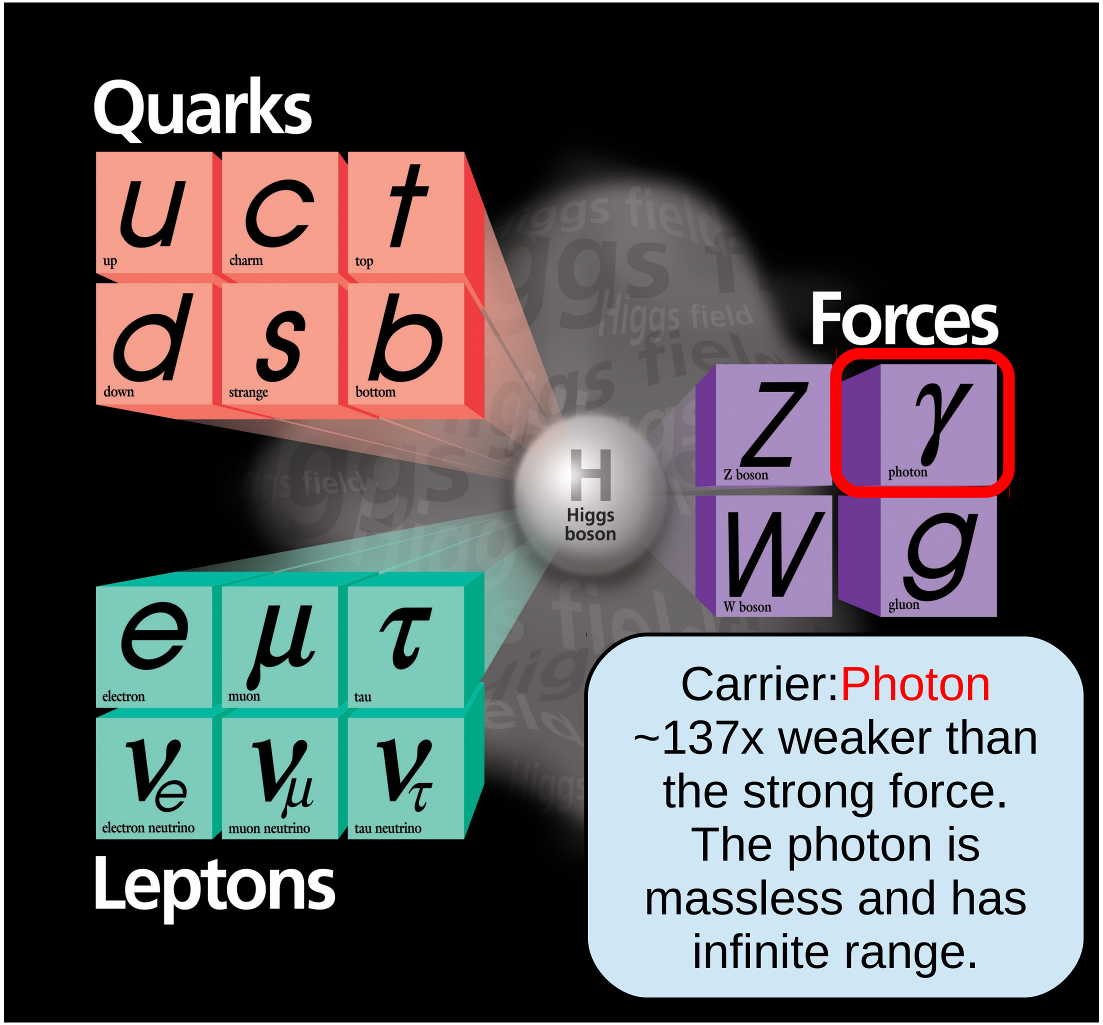

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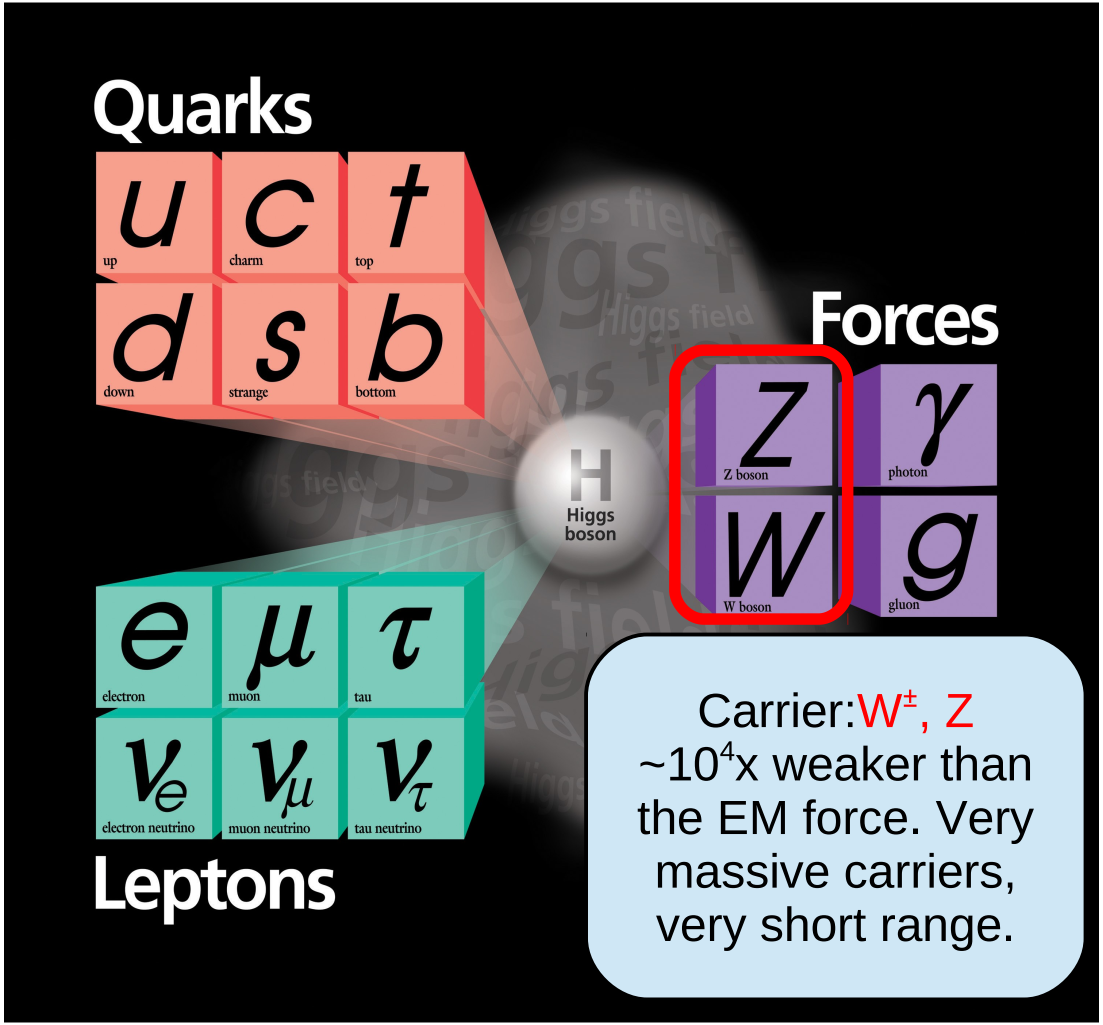

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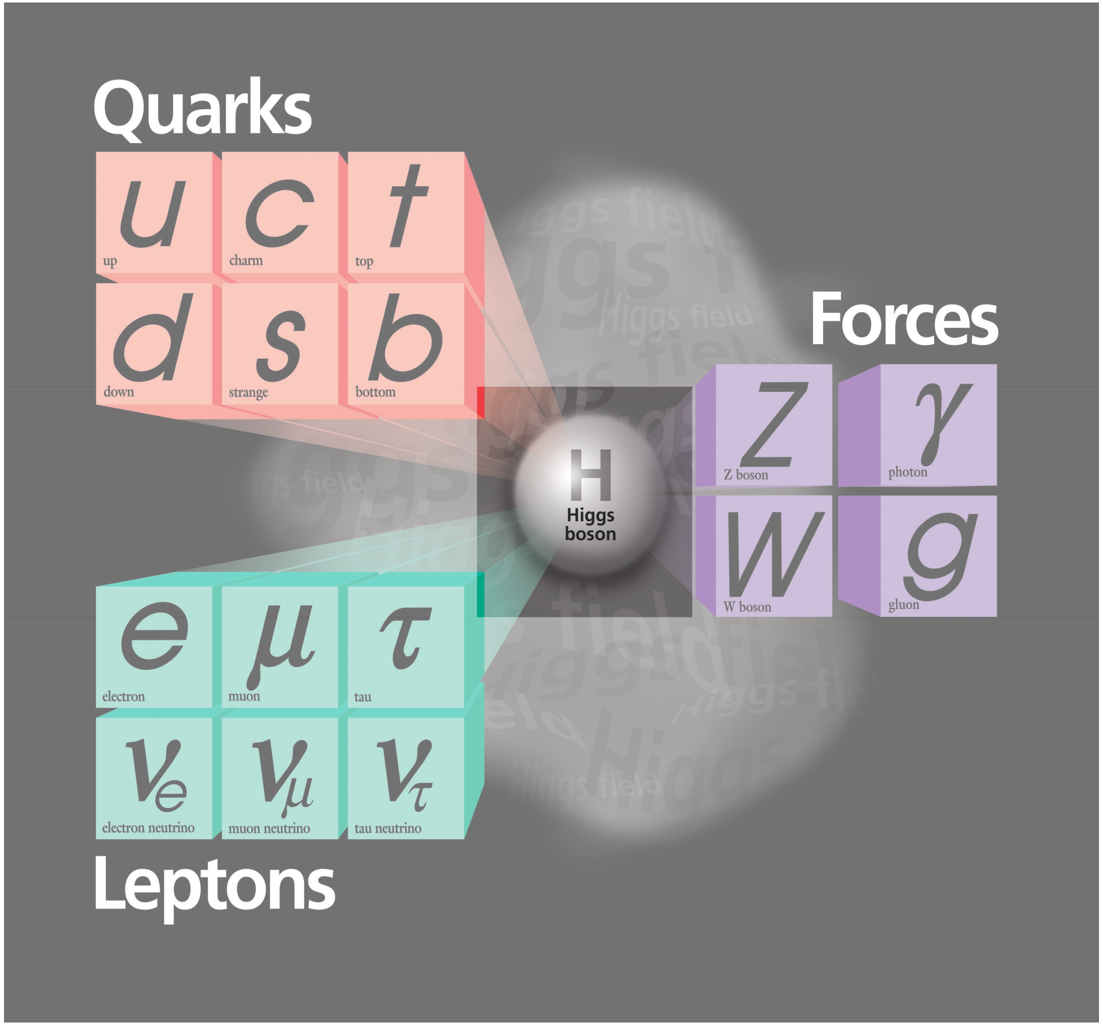


The Higgs boson: the last particle predicted by the SM. Something very close to it was observed at the LHC.

Yet another SM prediction verified by experiment (?)

So then why look for physics *beyond the Standard Model, since it's been so successful?*

The problems with the Standard Model

- ***Major omissions***

  What about gravity? Dark matter?

- ***Experimental tests***

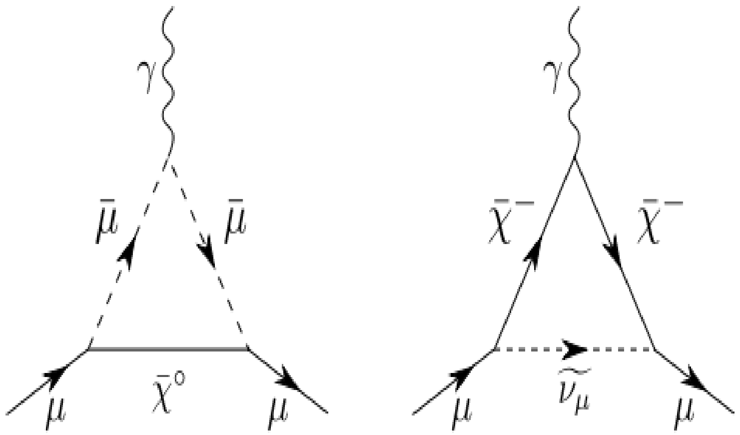
  Neutrino oscillations. Discrepancies with experimental **precision** tests (muon g-2)

- ***Naturalness, hierarchy***

  Gravity is ~10^{32}x weaker than the weak, fine-tuning required

- ***Too many free parameters***

  Up to 25 free parameters in the SM: how fundamental is *that*?



How can precision experiments at low energies probe for new physics? A SuperSymmetric example

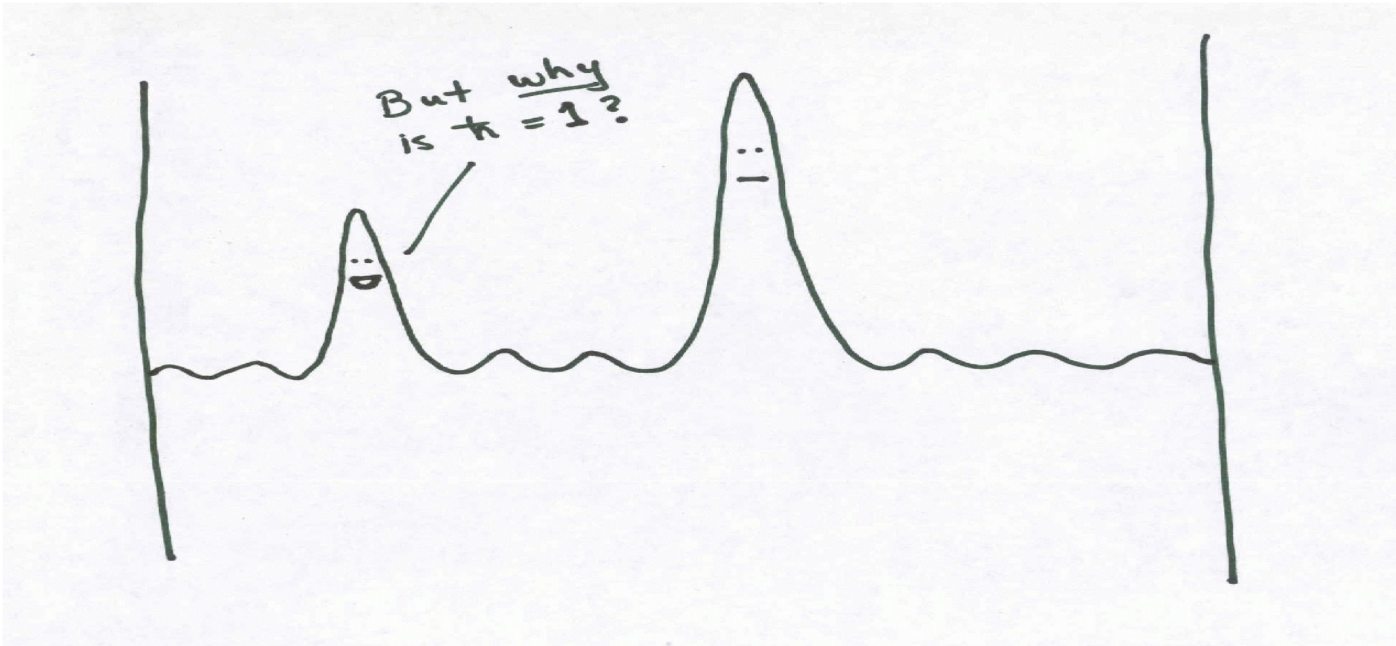
Is the SM just an effective theory at low energies, just like Newtonian gravity to General Relativity?

Is there an **underlying symmetry** at higher energies?

Of course, we could be wrong..

The parameters of the Standard Model *could* have been chosen randomly.

Only in a small subset of potential universes can living intelligence arise to ask annoying questions:



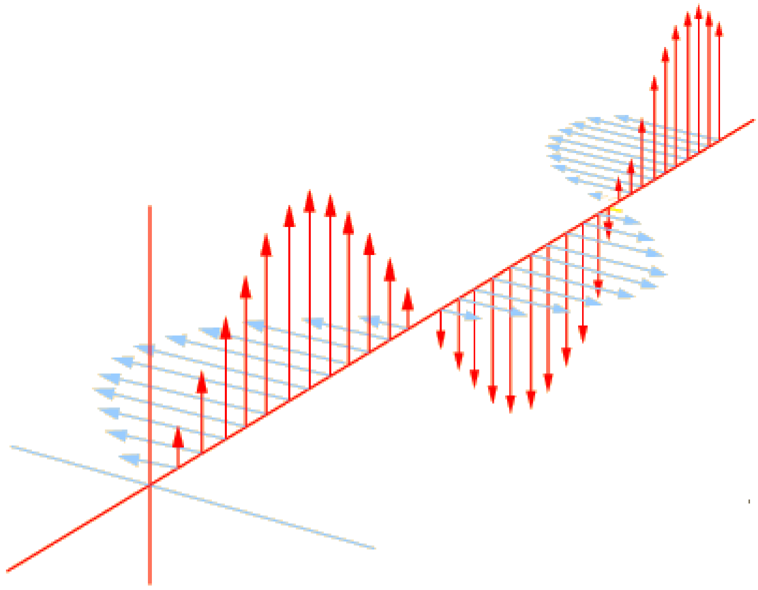
But the Anthropic Principle is a dead-end observation, not a strategy for learning.
We choose to learn.

Courtesy D.Mack

The concept of **symmetry** has guided our thought in understanding nature and searching for new physics

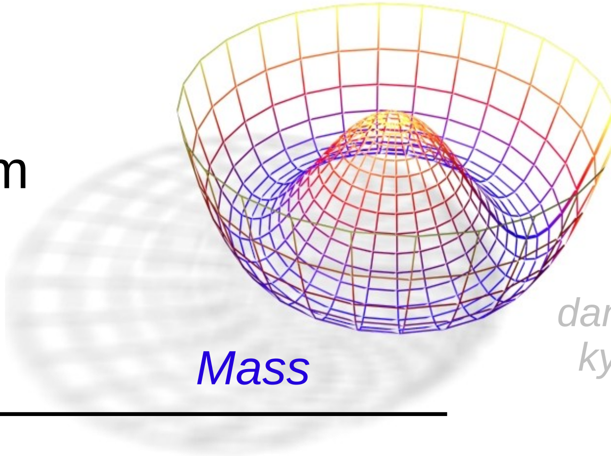
Example:
Electricity and Magnetism, once thought to be distinct phenomena.

Their symmetry was *hidden* from us until we found they are just "two sides of the same coin"



Another example of a hidden/broken symmetry:
Electro-Weak symmetry

Underlying symmetry: Electro-Weak unification
Broken at low energies through the *Higgs* mechanism



Interaction	*Carrier*	*Field*	*Mass*
EM	Photon	$A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$	Massless
(Neutral) Weak	Z boson	$Z_\mu = W^0_\mu \cos\theta_W - B^0_\mu \sin\theta_W$	91.2 GeV

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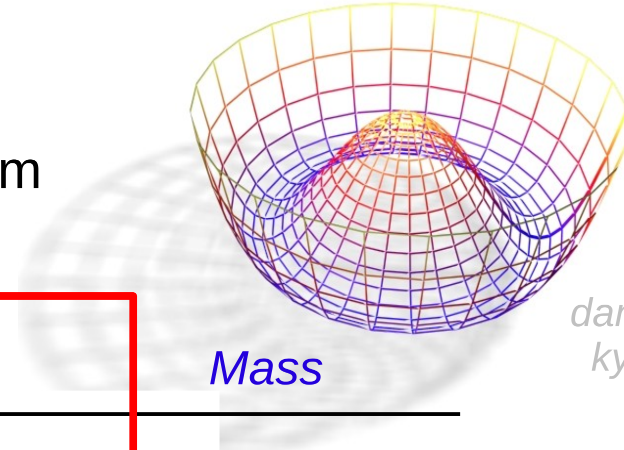

dani & kyle

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Combinations of the same fields!

The weak mixing angle, θ_w

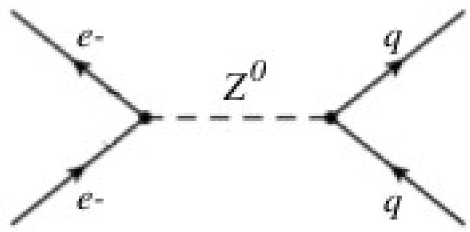
A fundamental parameter of the EW sector of the SM

Interlude:

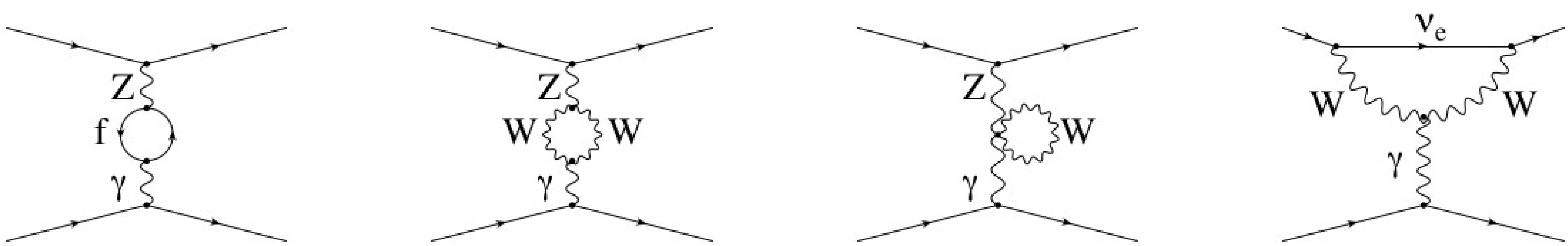
How do precision experiments at low energies access physics beyond the Standard Model?

Quantum fluctuations: "*Virtual*" particles may jump out of the "*vacuum*"

Simple exchange of Z between an e^- and a q

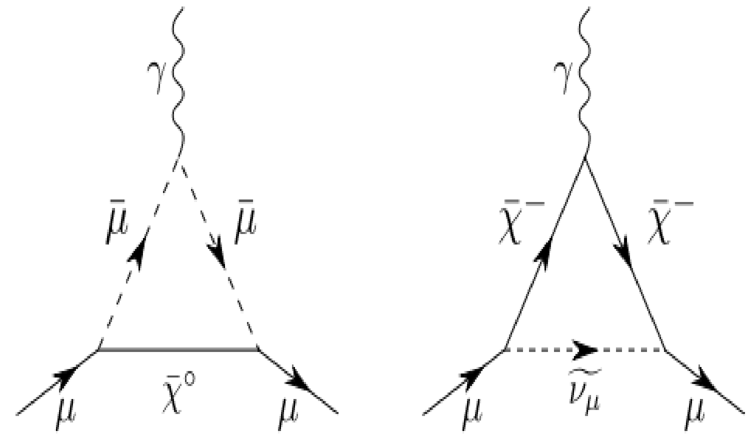


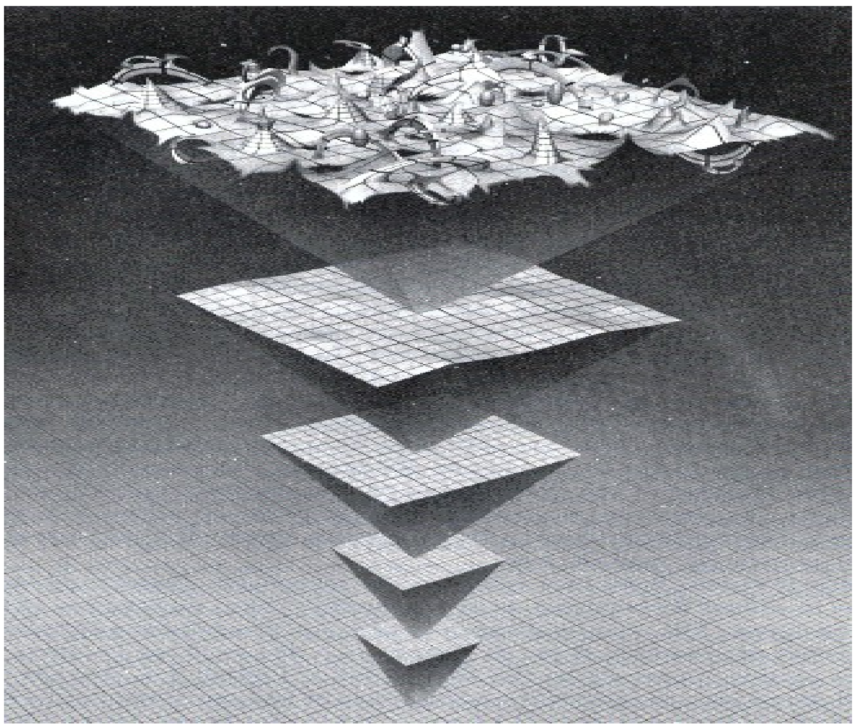
Must account for more complicated processes with "quantum loops", allowed from the uncertainty principle:



All these contributions should be calculable within the theory, if our theory is complete

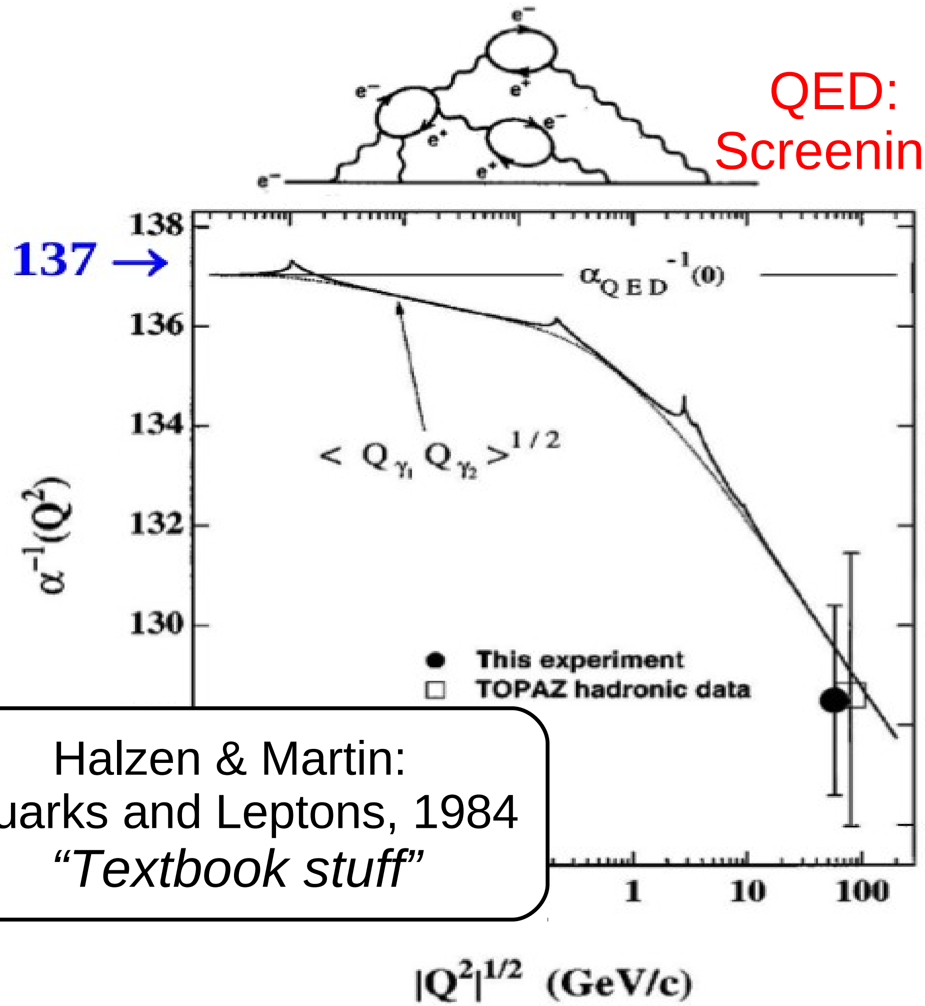
If a **precision** experiment finds discrepancy with theory, this may be a sign of new physics,
even well below the energy scale associated with the new physics.



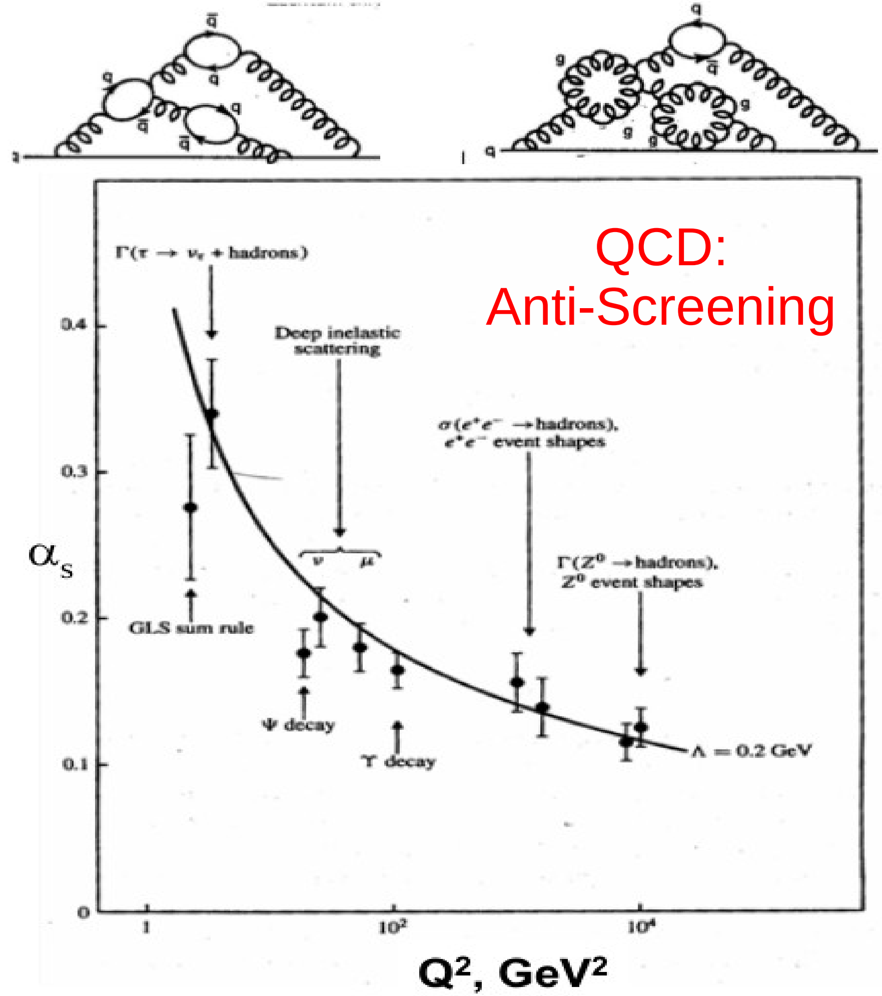


Higher energies
→ Smaller time and length scales
→ Contribution from quantum fluctuations depends on available energy

“Running” of fundamental constants: not constants at all!

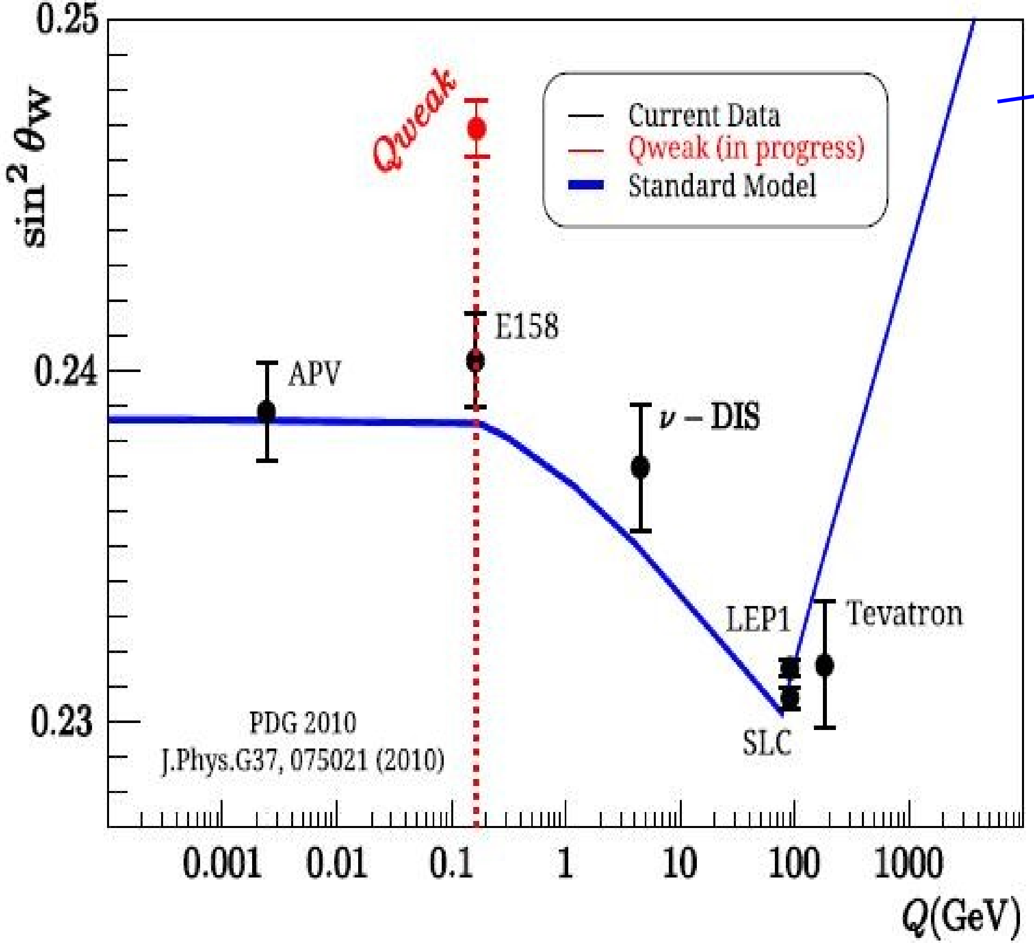


Halzen & Martin:
Quarks and Leptons, 1984
“Textbook stuff”



What about the Weak constant?

The Weak Mixing Angle



"Running" of $\sin^2\theta_w$ in the $\overline{MS}$ scheme

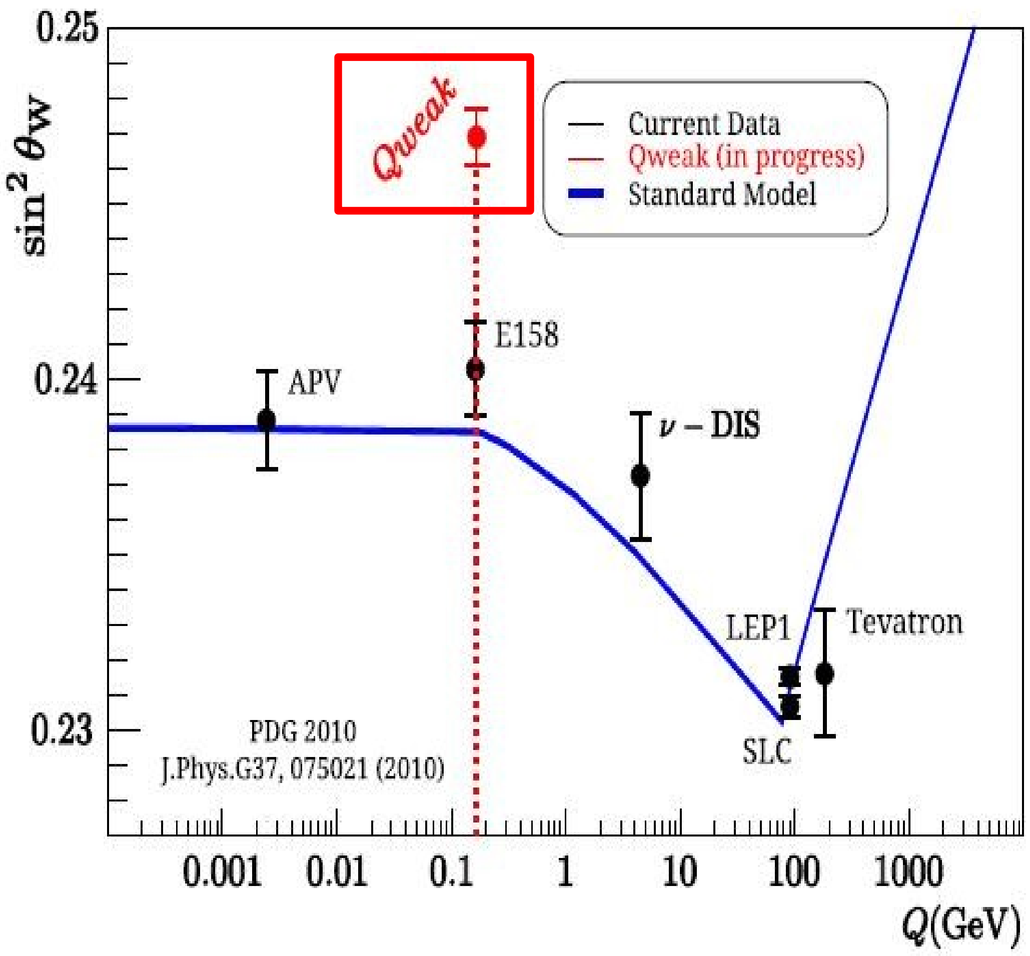
SM prediction

Current world data from:

- Z-pole measurements from colliders (LEP, SLD)
- ν-N scattering
- Moller scattering
- Atomic Cs transition

The Weak Mixing Angle

The Qweak experiment will measure $\sin^2\theta_w$ to 0.3% precision at low Q^2:



- Most precise determination off the Z-pole
- A 10-sigma confirmation of the predicted "running"
- *A unique testing ground for the SM*

Agreement with theory would impose <u>significant constraints</u> on possible SM extensions

A significant deviation could be <u>a signal of new physics</u> at the quantum loop level, with sensitivity up to the TeV scale (complimentary to LHC searches)

- *The Standard Model of Physics*
- ***The Qweak experiment***
- First results
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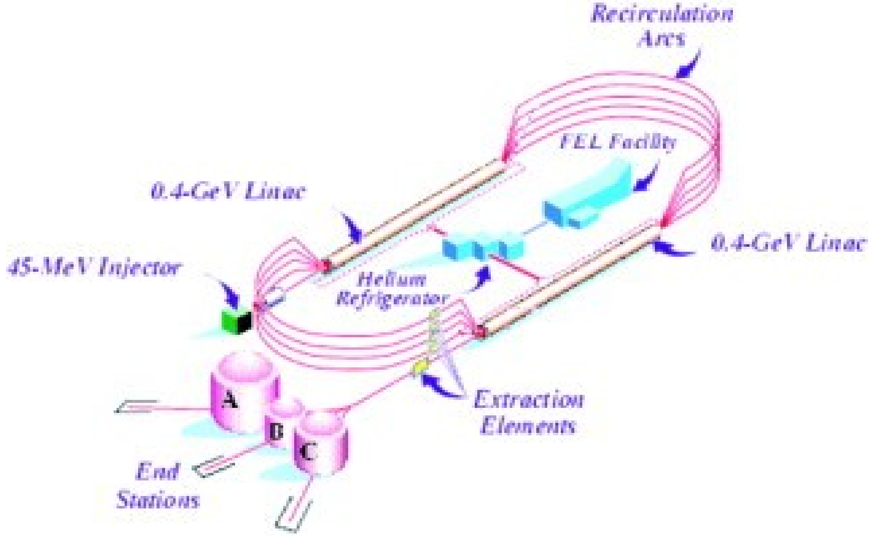
The Qweak experiment at Jefferson Lab

Qweak ran in Hall C
of Jefferson Lab
in Newport News, Va

Completed May 2012
after 2 years of data taking



The Thomas Jefferson
National Accelerator Facility
World-leading Parity Violation program

Qweak will make the first determination of the neutral weak charge of the proton, the weak analog to the electric charge:

Charge / Particle	Electric	Weak (vector)
u	+2/3	$-2\,C_{1u} = +1 - 8/3\,\sin^2\theta_W$
d	-1/3	$-2\,C_{1d} = -1 + 4/3\,\sin^2\theta_W$
Proton uud	+1	$Q_W^p = 1 - 4\,\sin^2\theta_W \approx 0.07$
Neutron udd	0	$Q_W^n = -1$

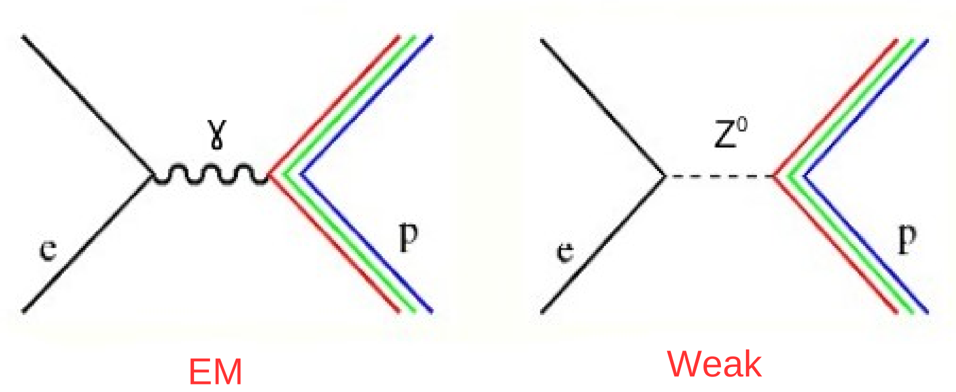
} Suppressed

Because of this suppression, a 4% determination of Q_w^p allows a 0.3% extraction of $\sin^2\theta_w$

→ *TeV-scale sensitivity to new physics*

Experimental probe:
electron-proton scattering

EM or weak interaction,
exchange of a photon or a Z boson



$$\sigma \propto \left| M_{EM} + M_{Weak} \right|^2 \approx M_{EM}^2 + 2 M_{EM} M_{Weak}$$

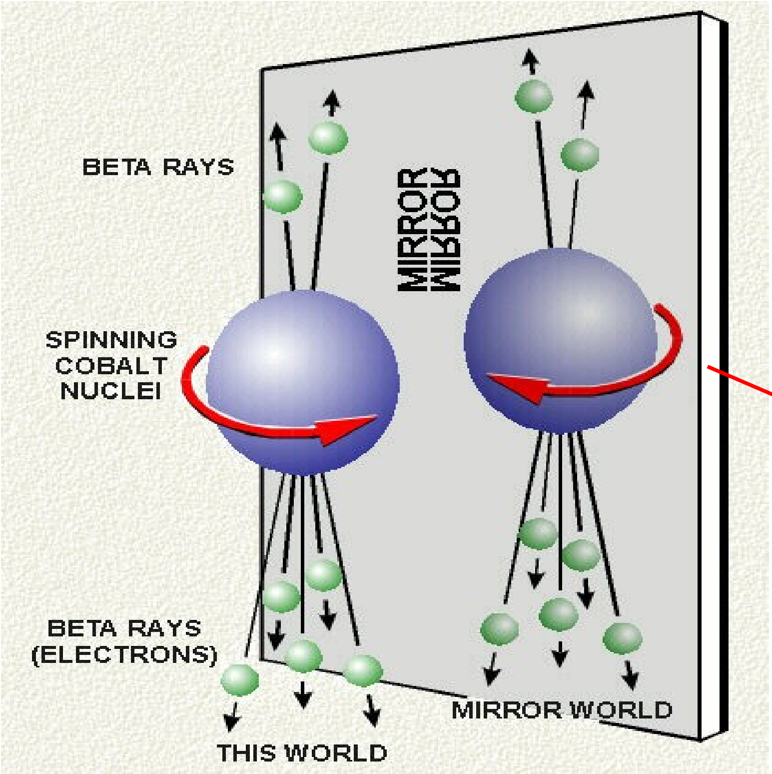
$$\left| M_{EM} \right| / \left| M_{weak} \right| \approx 10^4$$

But the weak amplitude is hopelessly swamped by the EM part!

→ Access the weak part of the interaction through *Parity Violation*

Parity is the symmetry under space inversion, equivalent to a mirror reflection

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \Rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} := \begin{pmatrix} x \\ y \\ -z \end{pmatrix}$$



All fundamental forces were thought to be symmetric under parity, until the 1956 Wu experiment: Beta emission from Co nuclei in magnetic field

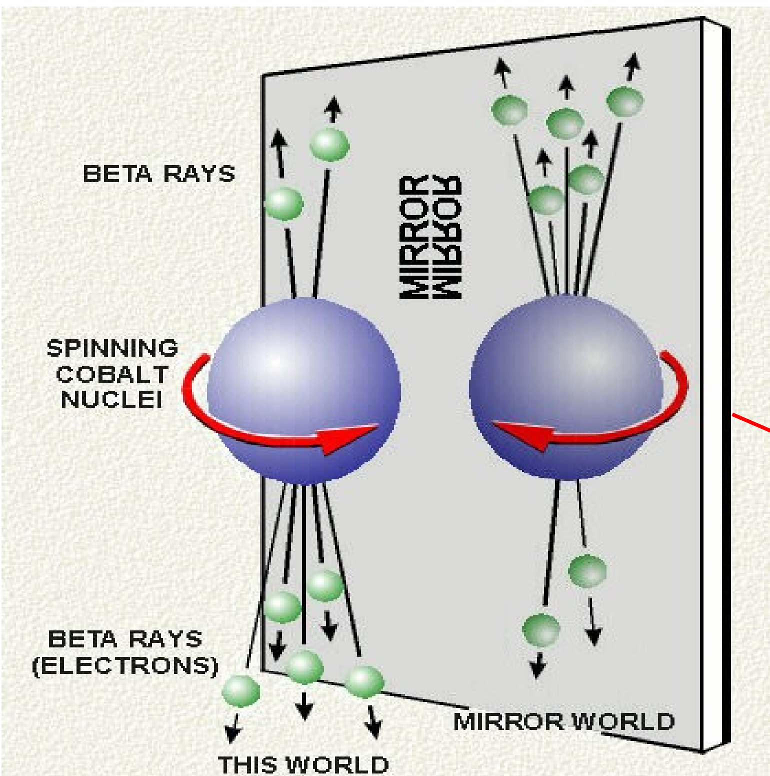
Expected (in 1956)

Parity is the symmetry under space inversion, equivalent to a mirror reflection

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \Rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} := \begin{pmatrix} x \\ y \\ -z \end{pmatrix}$$

Parity symmetry is violated in weak interactions!

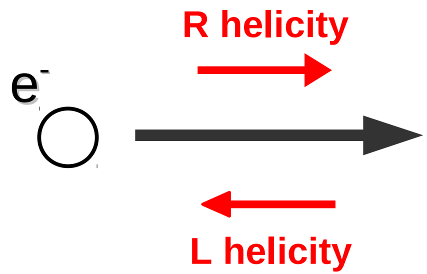
(1957 Nobel Prize Lee and Yang)

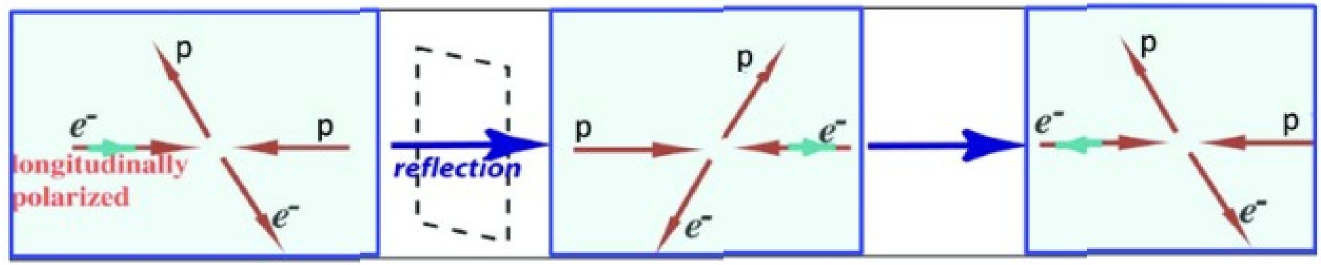


Observed

Parity violation is used to access the weak part of the e-p interaction.

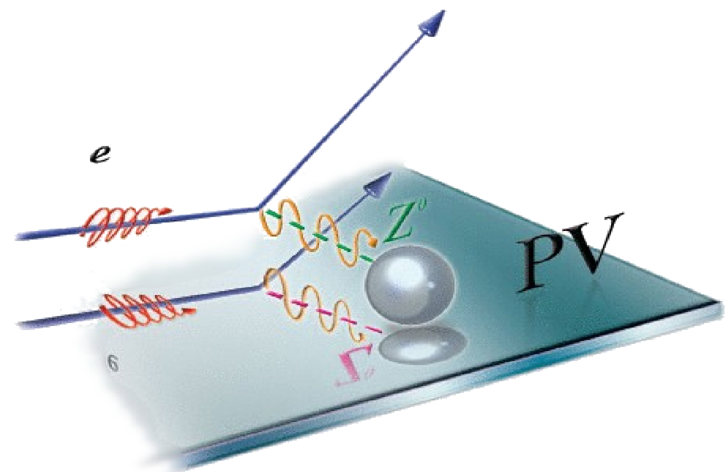
Electrons are prepared in two states of opposite helicity (**σ•p**), the two “mirror” states.





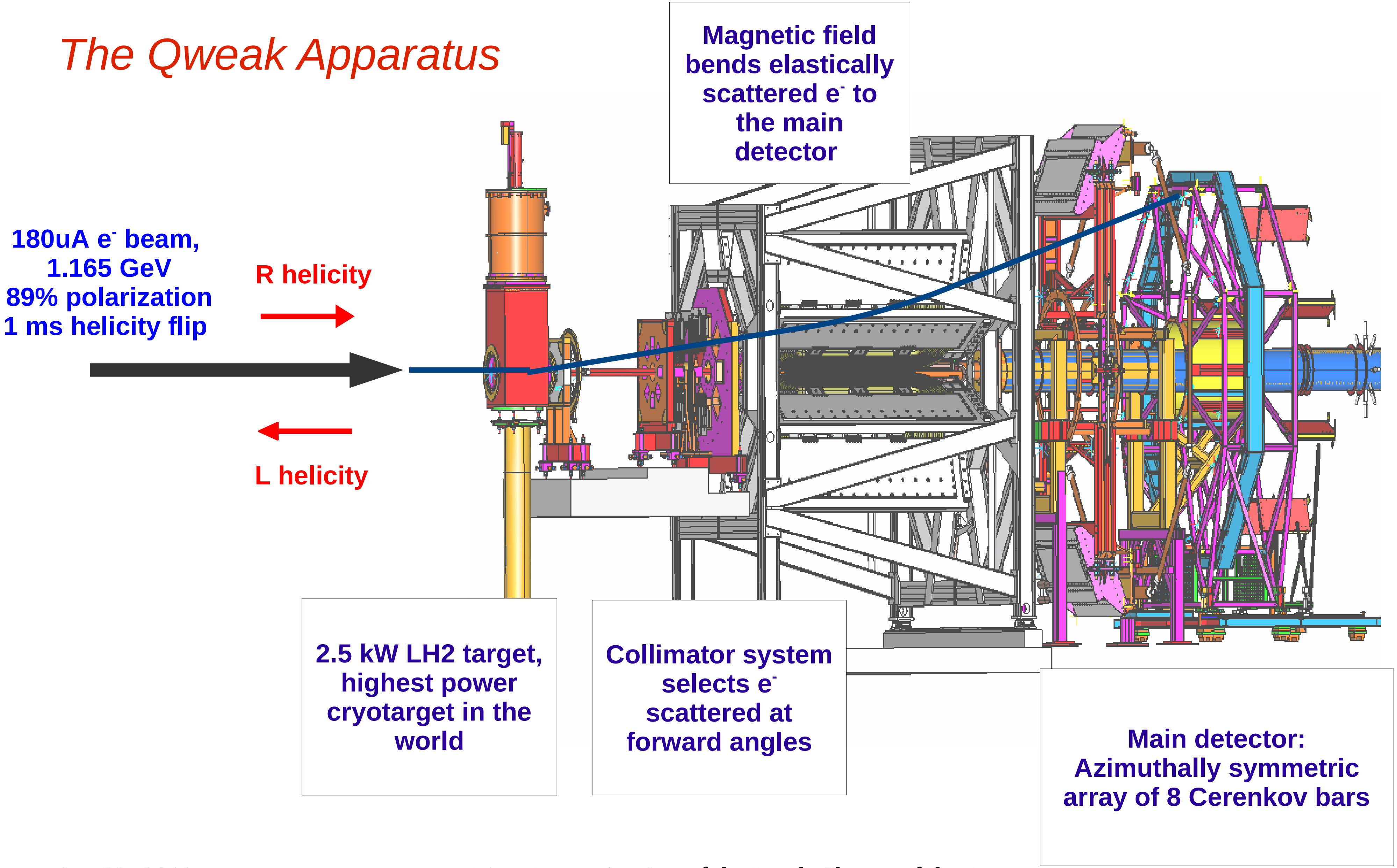
Then the *Parity-Violating Asymmetry* in the scattering rate is due to the weak interaction

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{2|M_{Weak}|}{|M_{EM}|}$$



Asymmetry still very small (~0.3 parts-per-million) and challenging to measure. Precision measurements using parity violation only possible with recent technological advances.

The Qweak Apparatus



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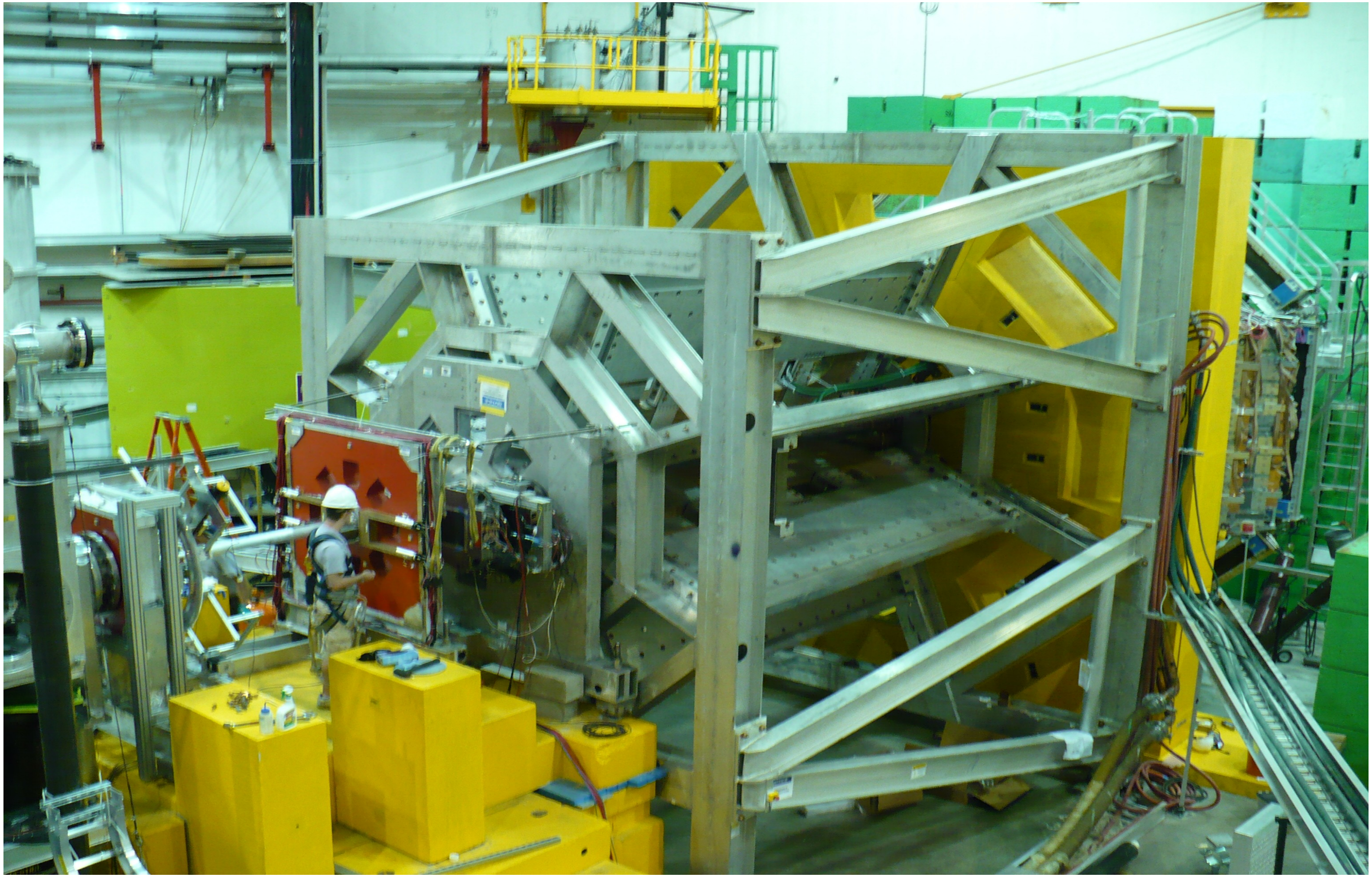

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- *First results*
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- First Qweak results released recently
  (now in print in PRL - arxiv.org/abs/1307.5275)
- Only 4% of full dataset, taken over a few days during commissioning
- Some subsystems were still in commission;
  Systematic uncertainties very conservative

$$A_{ep} = R_{tot} \frac{A_{msr}/P - \sum_{i=1}^{4} f_i A_i}{1 - \sum f_i}$$

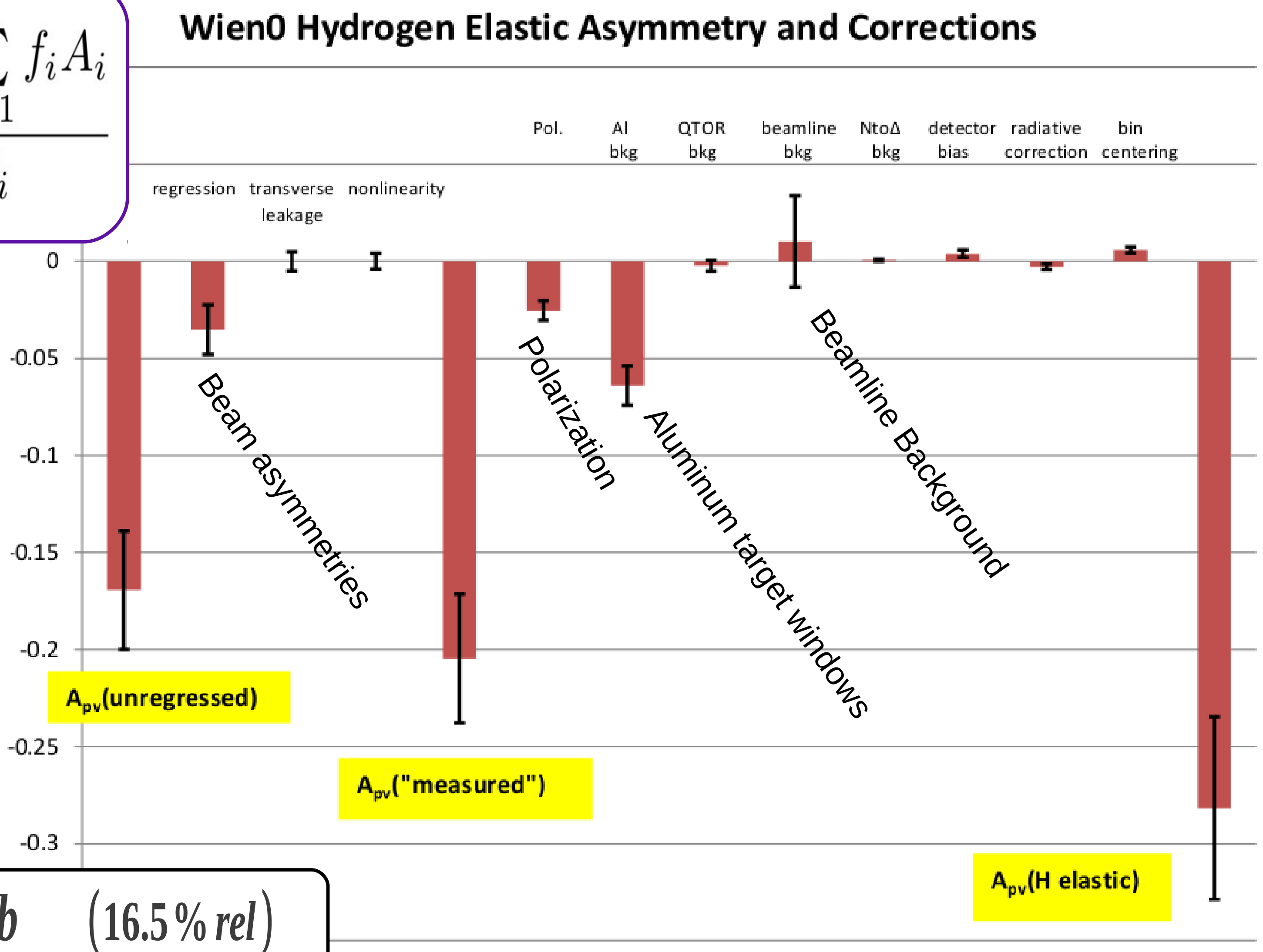
Measured asymmetry must be first corrected and normalized

R_{tot}: Radiative corrections, kinematics normalization

P : Polarization

f_i : Fraction of bkgd in signal (aka "dilution")

A_i : Asymmetry of bkgd



$$A_{msr} = -204 \pm 34 \;\; ppb \quad (16.5\,\%\,rel)$$

$$A_{ep} = -279 \pm 35\,(stat) \pm 31\,(syst) \;\; ppb \quad (16.8\,\%\,rel)$$

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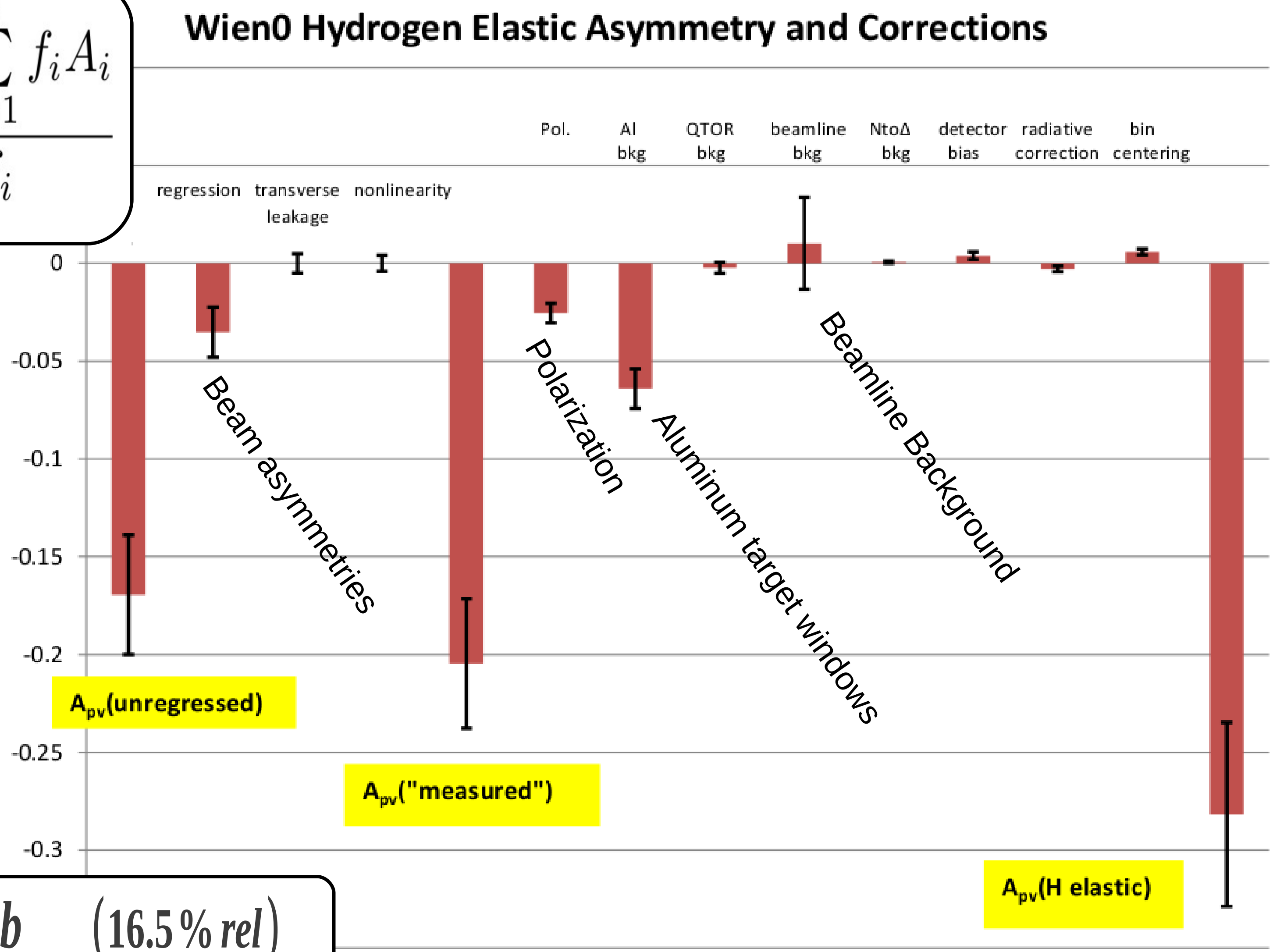


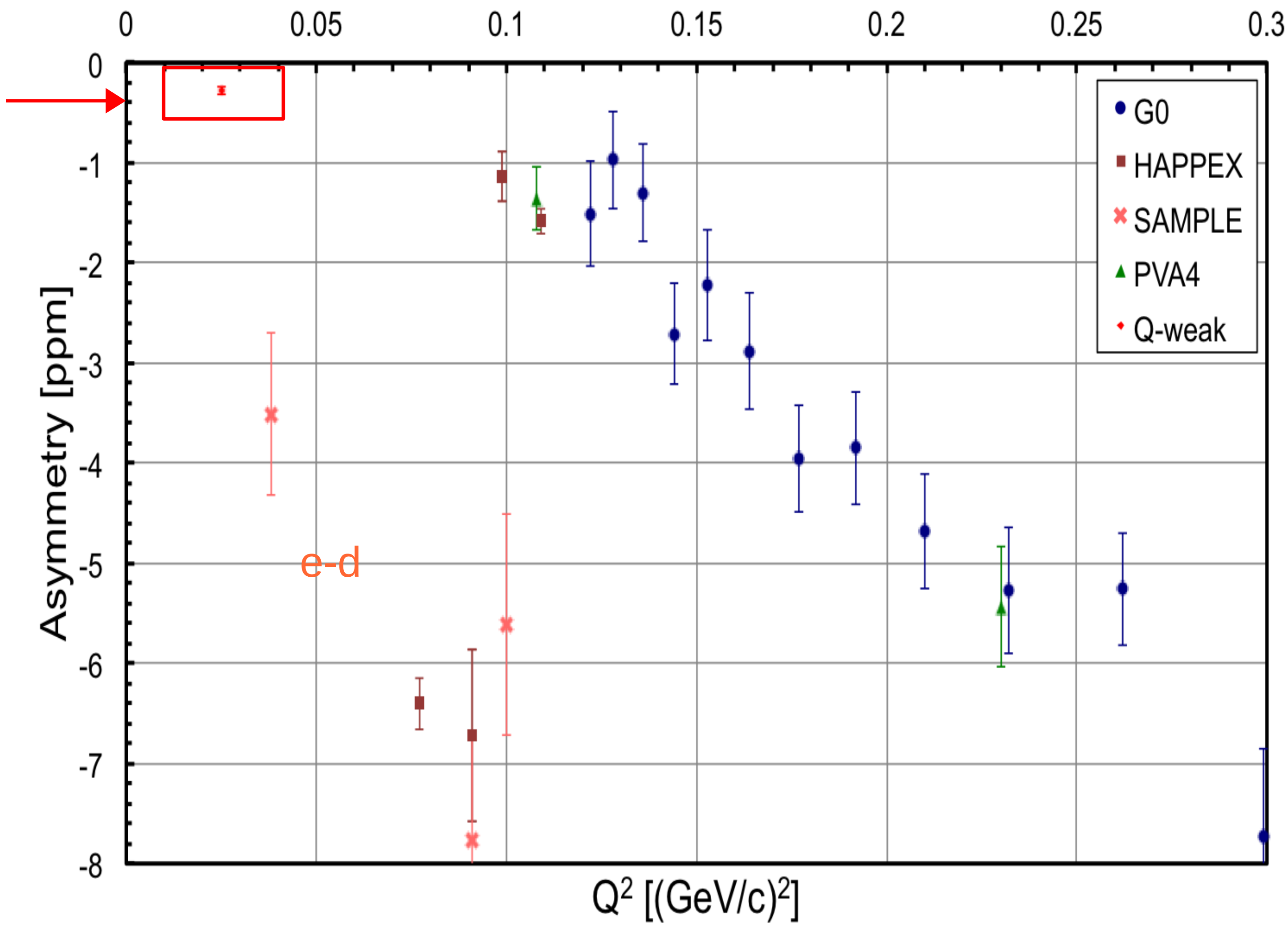
Smallest asymmetry and smallest absolute error bar ever measured in e-p scattering

$$A_{msr} = -204 \pm 34 \; ppb \qquad (16.5\,\%\,rel)$$

$$A_{ep} = -279 \pm 35\,(stat) \pm 31\,(syst) \; ppb \qquad (16.8\,\%\,rel)$$

Qweak measurement, error bars barely visible

A and ΔA are ~3x smaller than nearest competitor.



First determination of the neutral-weak charge of the proton, Q_w^p

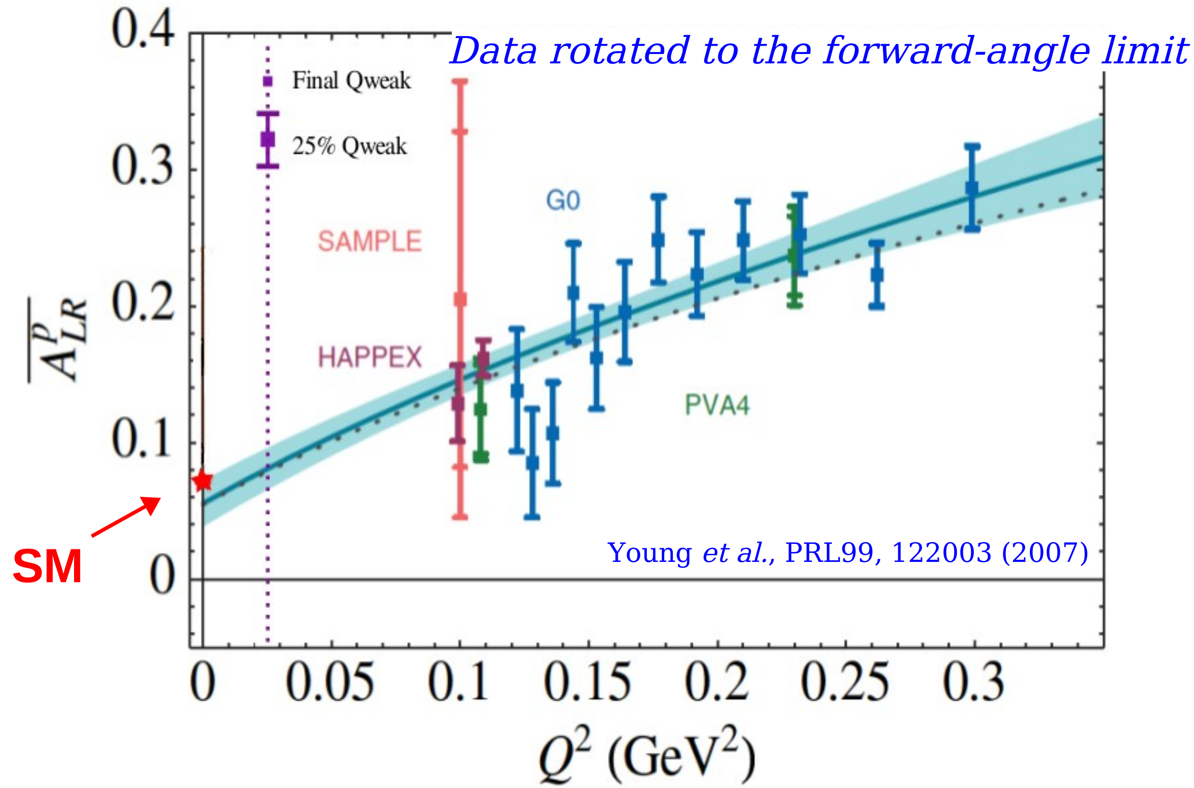
Q_w^p can be extracted from the PV asymmetry:

$$\overline{A_{LR}^p} = A_{LR}^p / A_0 = \underline{\underline{Q_w^p}} + Q^2 \boxed{B(Q^2)}, \quad A_0 = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}$$

(Forward angles, low Q^2)

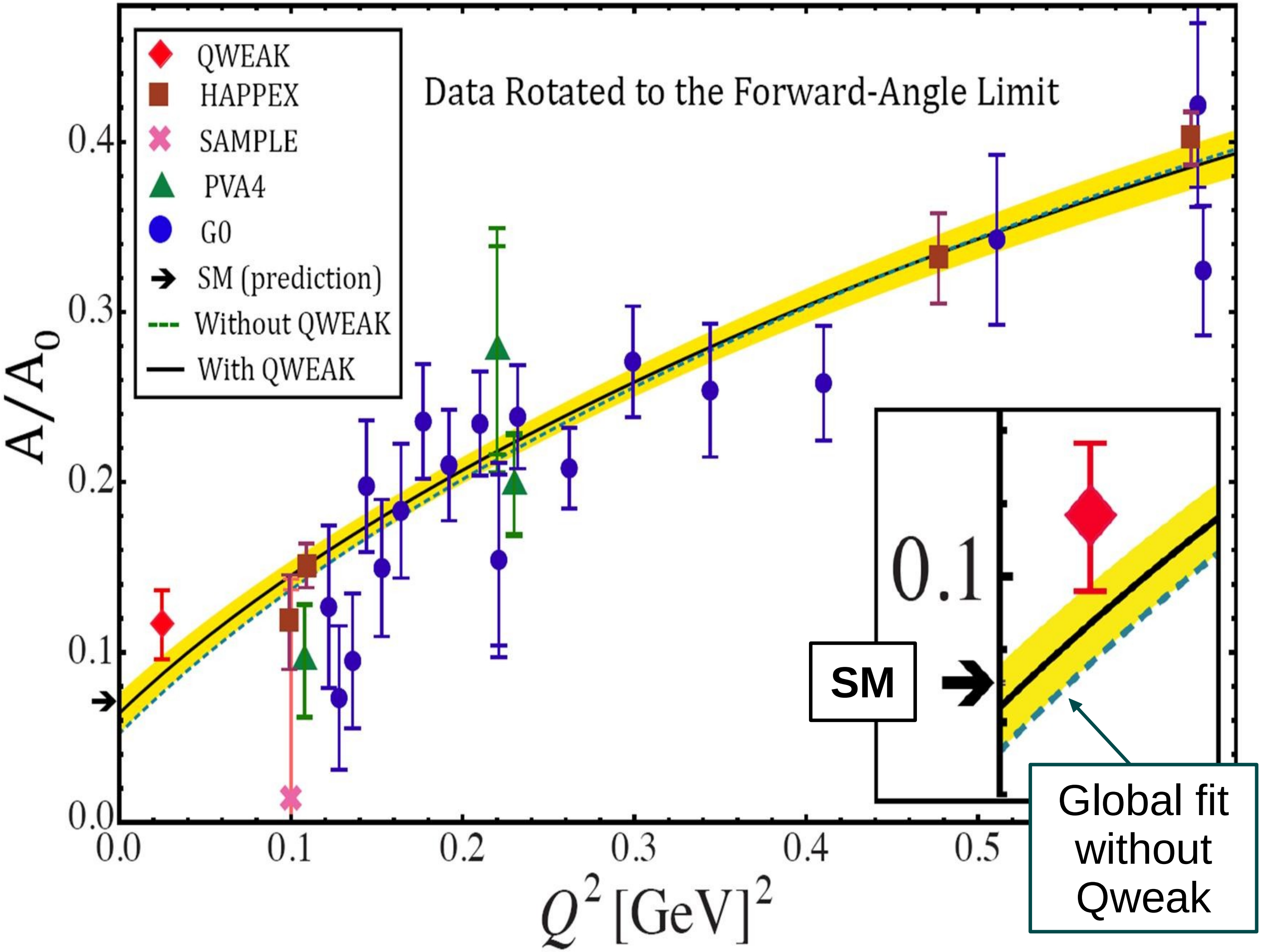
Hadronic structure enters here. Sufficiently constrained from world PVES data and suppressed at Qweak kinematics.

Low Q^2 means that Q_w^p can be extracted relatively cleanly.



First determination of the neutral-weak charge of the proton, Q_w^p

$$A/A_0 = Q_w^p + Q^2\, B(Q^2)$$



Global fit:

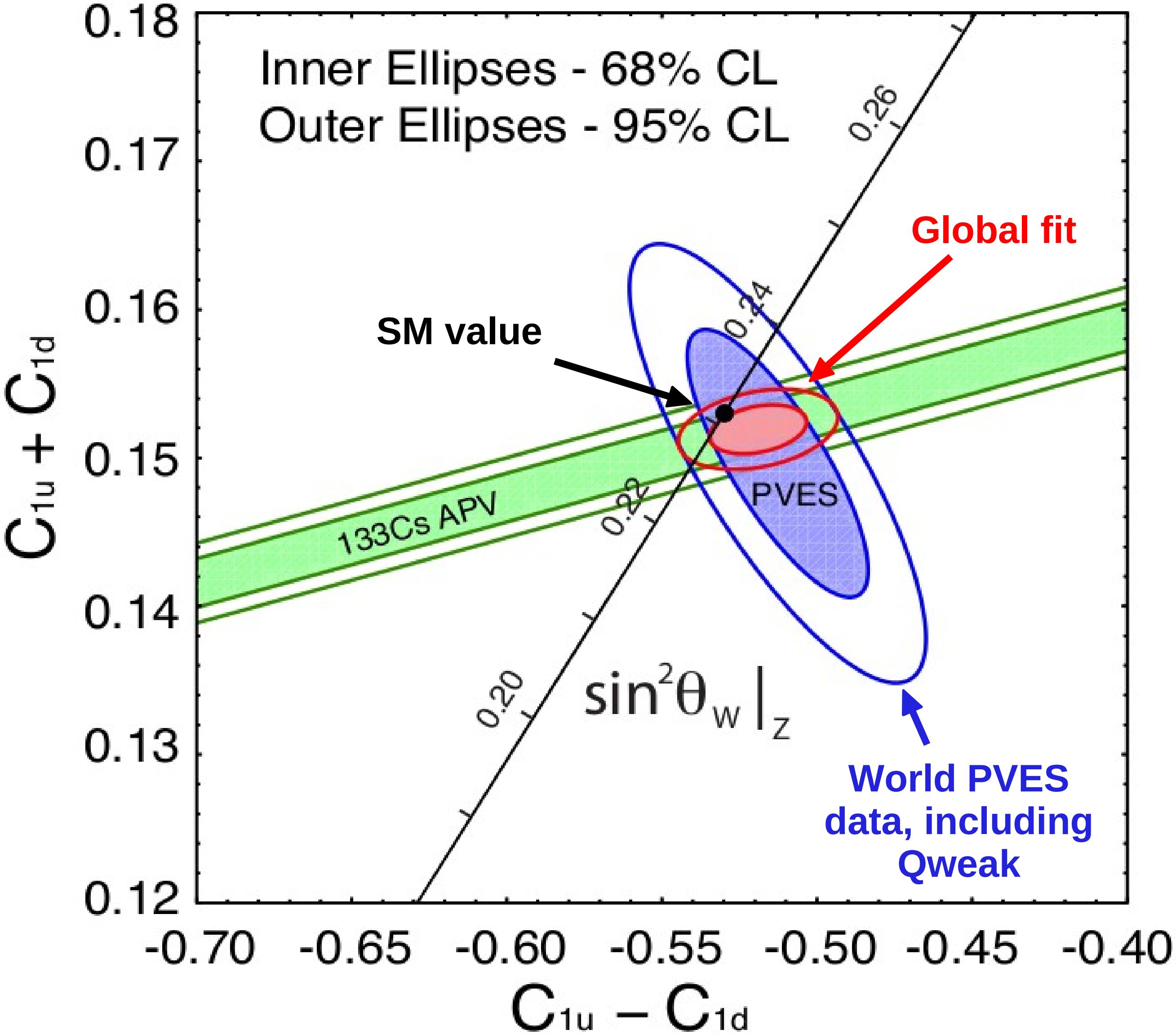
$$Q_w^p = 0.064 \pm 0.012$$

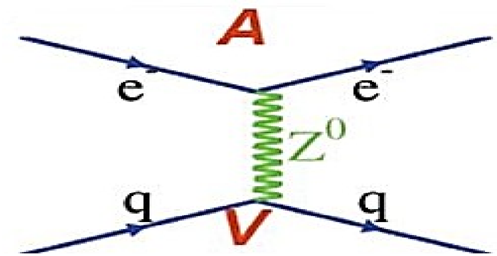
The Qweak point significantly shifts the result of the global fit and reduces the uncertainty

Increased consistency with SM value:

$$Q_w^p(SM) = 0.0710 \pm 0.0007$$

Constraints on C_{1q} couplings





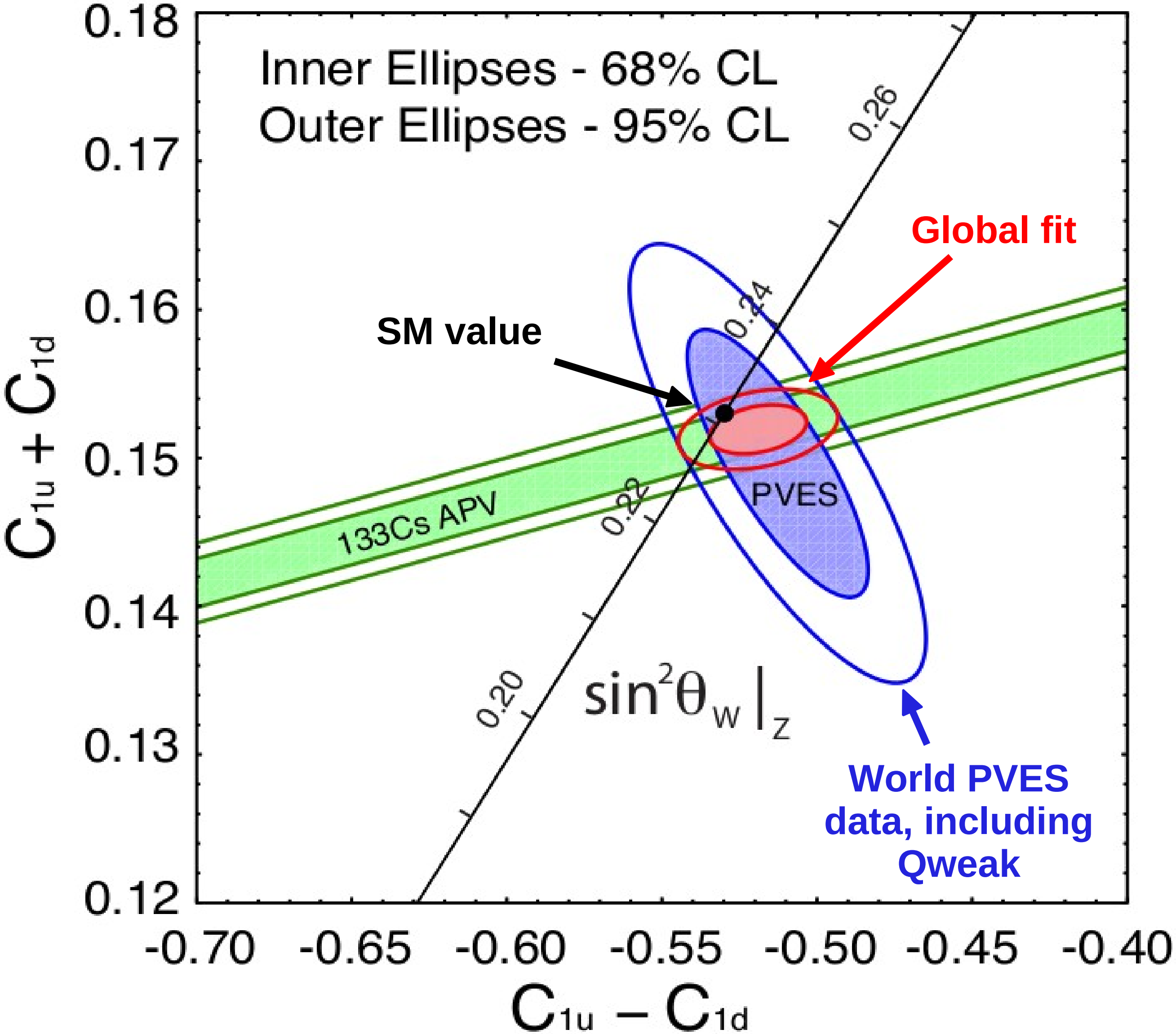
$$L^{PV}_{e\text{-}q} = \frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma^5 e \sum_q \underline{C_{1q}} \bar{q}\gamma^\mu q$$

C_{1q}: Vector quark couplings

$$Q^p_w = -2\left(2C_{1u} + C_{1d}\right)$$

PVES has sensitivity to a C_{1u},C_{1d} combination that is orthogonal to APV

Constraints on C_{1q} couplings



Combining APV + PVES, global constraints on C_{1q}:

$$C_{1u} = -0.184 \pm 0.005$$

$$C_{1d} = 0.335 \pm 0.005$$

From these the weak charge of the neutron is extracted for the first time:

$$Q_w^n = -2\left(2C_{1d} + C_{1u}\right)$$

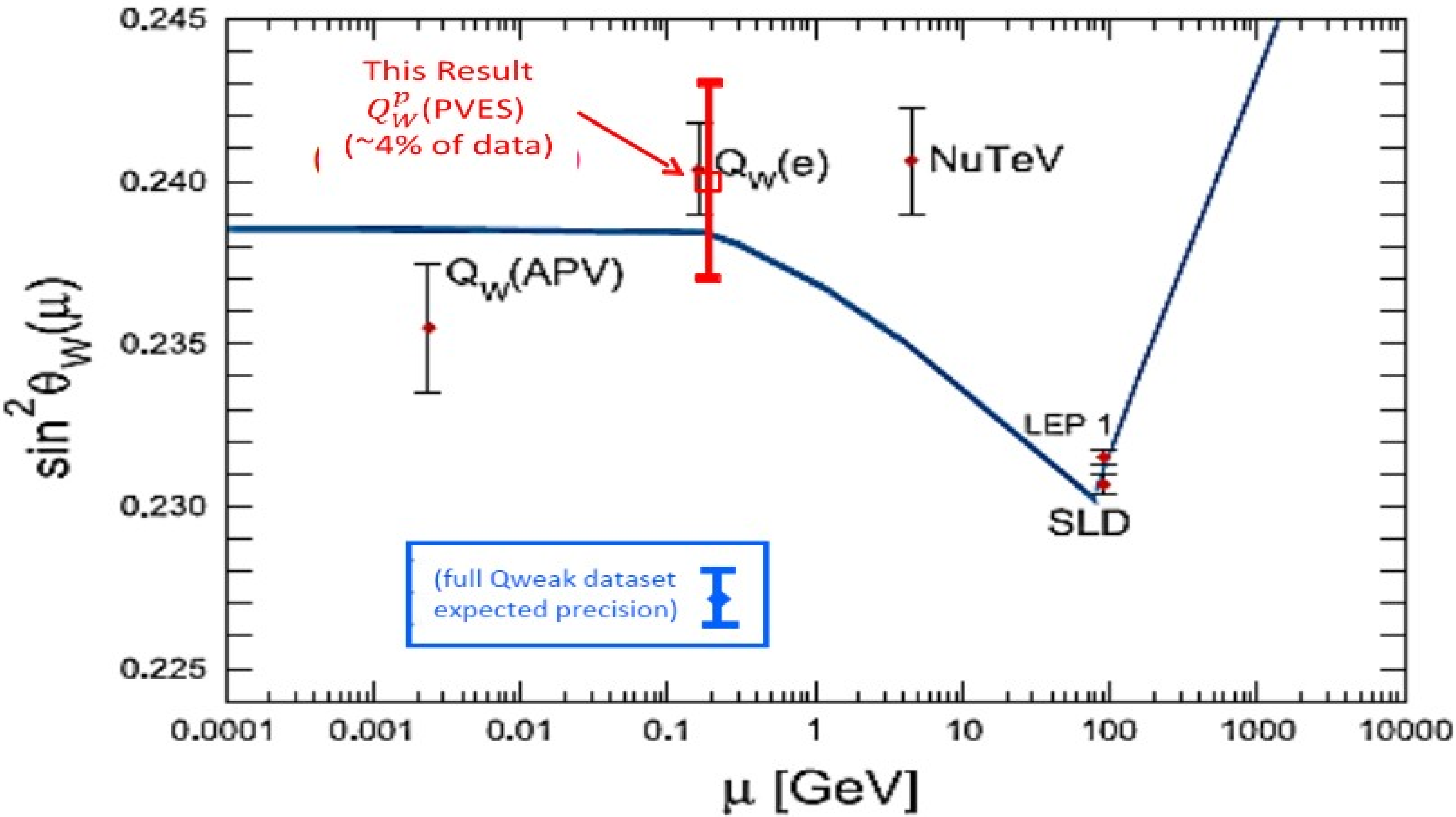
$$\Rightarrow Q_w^n = -0.975 \pm 0.010$$

In agreement with SM value:

$$Q_w^n(SM) = -0.9890 \pm 0.0007$$

Weak mixing angle

$$Q_W(p) = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta_e'] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



- Theoretical background,
  Motivation for the Qweak measurement

- An overview of the Qweak experiment

- First results:
  The 25% measurement

- Summary, Outlook

Summary

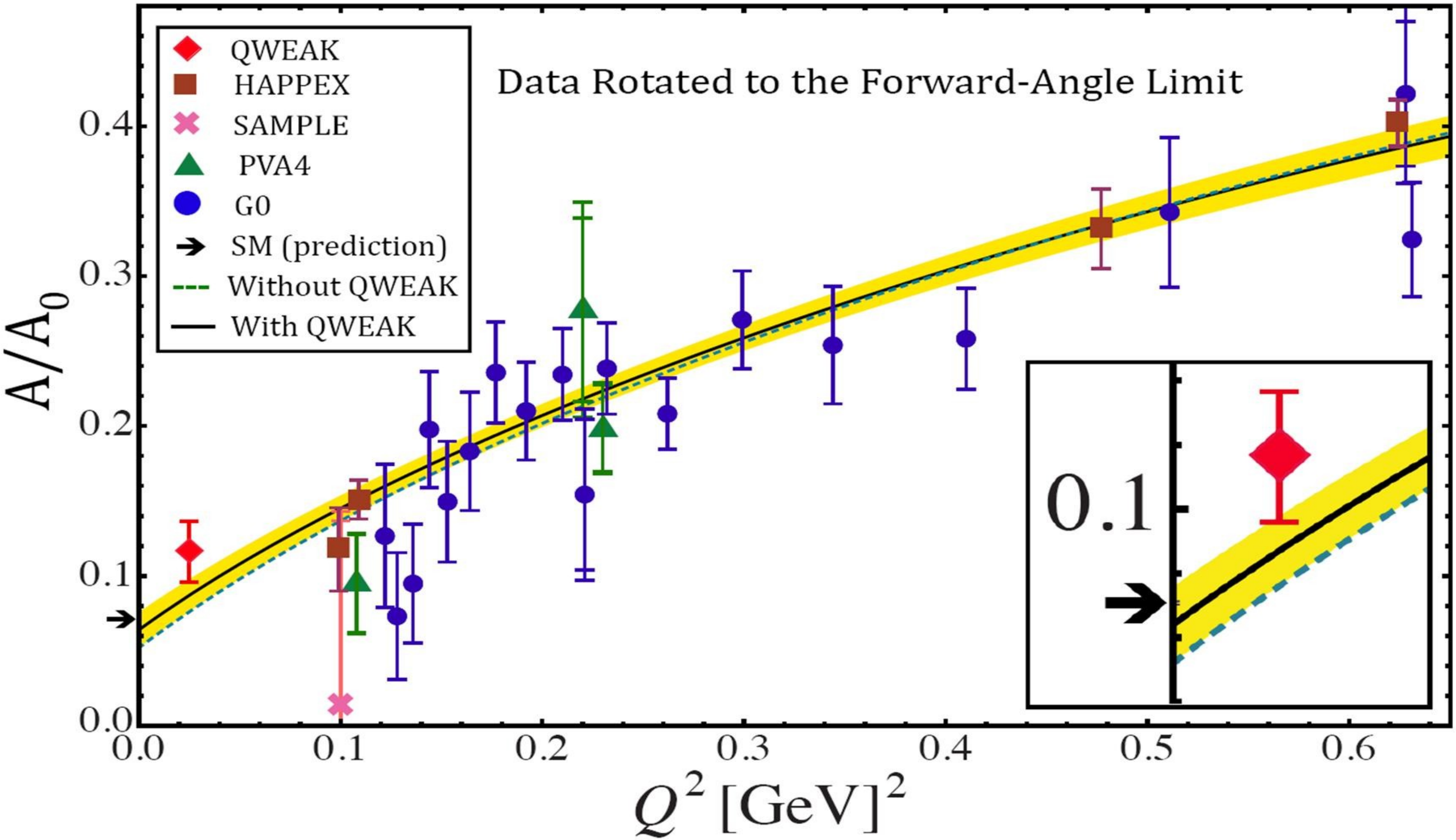
Qweak has achieved the first determination
of the weak charge of the proton, with 4% of the data set

~25 times more statistics and additional calibration data are in hand
for the full Qweak measurement; analysis ongoing

Full measurement will extend reach to the TeV-scale
and constrain scenarios for physics *beyond the Standard Model*

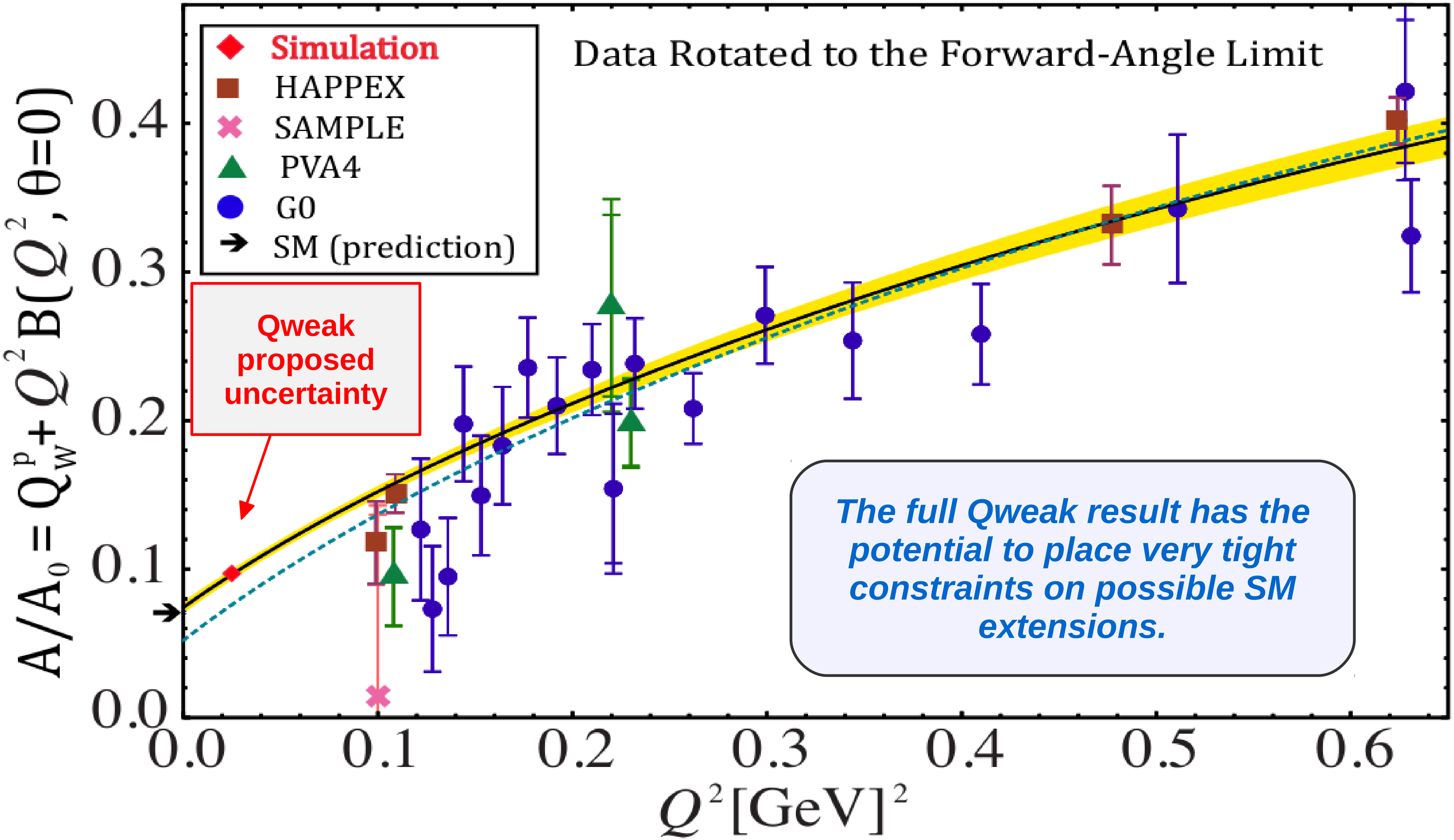
The experiment achieved and demonstrated the technological base for
future ultra-precision tests planned at the upgraded Jefferson Lab

Outlook



QWEAK
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Without QWEAK
With QWEAK
Data Rotated to the Forward-Angle Limit
0.0
0.1
0.2
0.3
0.4
0.5
0.6
A/A0
Q^2 [GeV]^2
0.1

Outlook

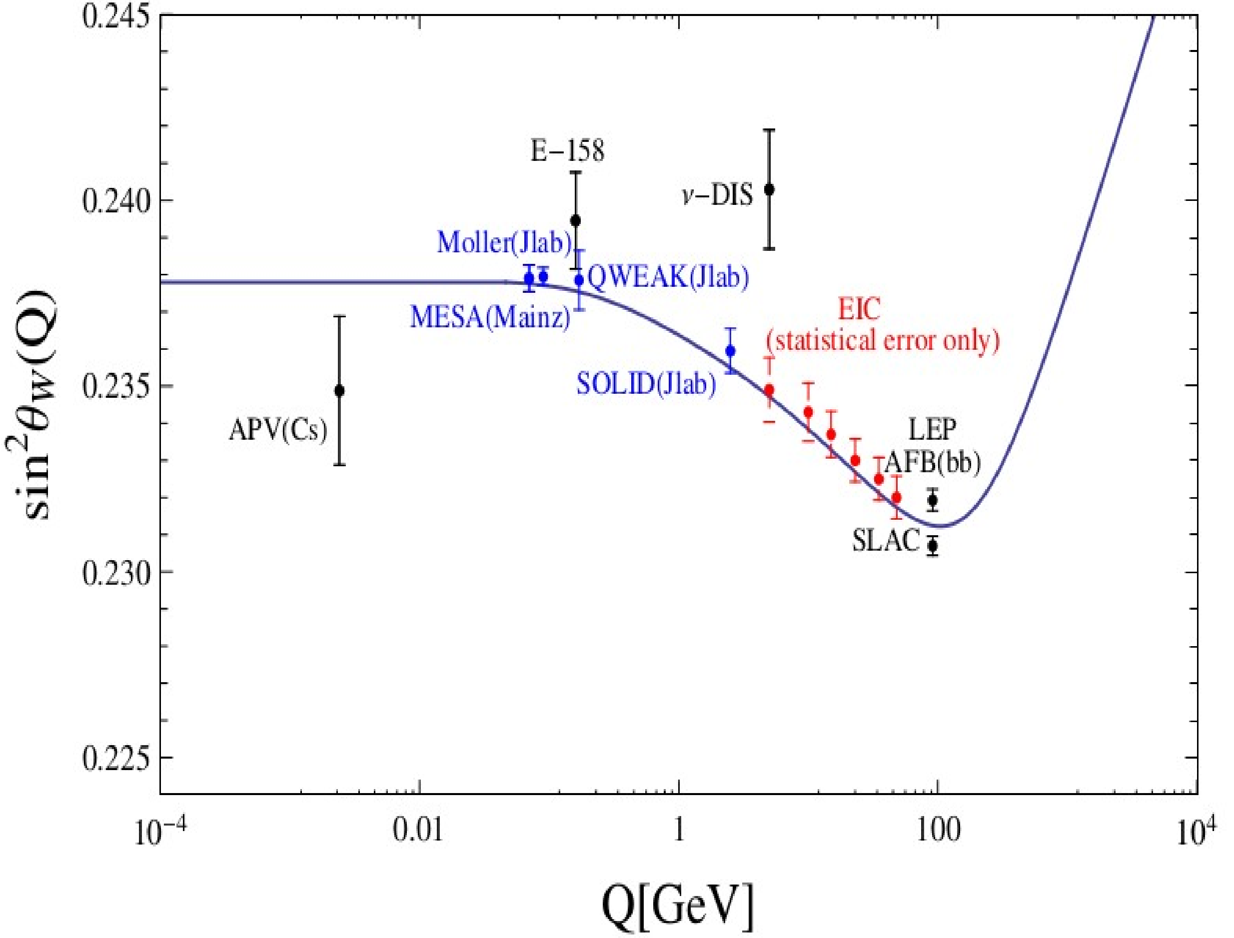


The full Qweak result has the potential to place very tight constraints on possible SM extensions.

Outlook

Next generation of experiments planned to test the EW sector of the SM.

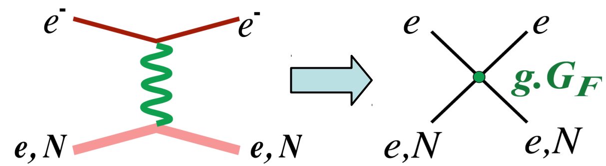
Moller, SOLID: Ultra-precision measurements planned in the upgraded 12GeV Jefferson Lab, after Qweak demonstrated sufficient control of systematics.



Backup Slides

$$\frac{1}{Q^2 - M^2} \xrightarrow{Q^2 \ll M^2} \frac{1}{M^2}$$

A "new physics" term in the Lagrangian
(approximating by a 4-fermion contact interaction) :



$$\mathcal{L}^{PV}_{e-q} = \mathcal{L}^{PV}_{SM} + \boxed{\mathcal{L}^{PV}_{New}}$$
$$= -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$\frac{\text{Mass}}{\text{Coupling}} \qquad \frac{\Lambda}{g} \approx \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q_W(p)\right|}} \approx 4.6\,TeV$$

Sensitivity to new physics up to the TeV scale
(thanks to suppression of $Q_W(p)$ in the SM)

Complementarity with searches at the intensity frontier:
In the event of a discovery at the LHC, precision experiments like Qweak will be very important to determine the characteristics of the new interaction.

First determination of the neutral-weak charge of the proton, Q_w^p

$$Q_w^p = 0.064 \pm 0.012$$

Even with only 4% of the full data set, Qweak significantly constrains new physics scenarios.

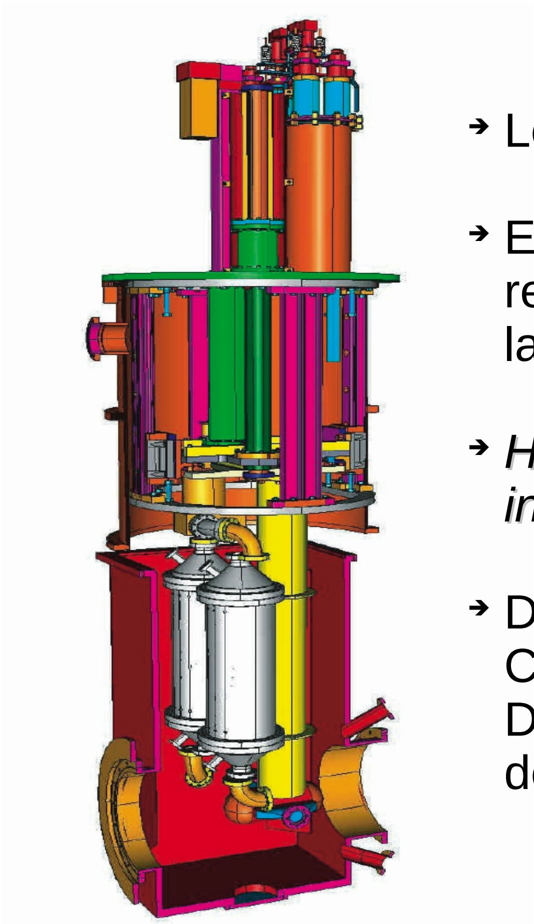
Model independent mass reach (95% CL) comparable to LHC limits:

Mass scale over coupling of new physics

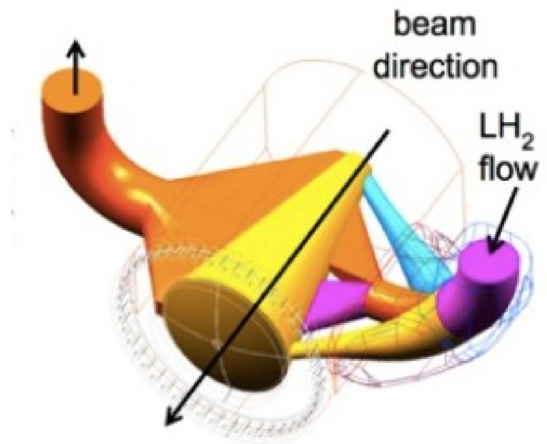
$$\frac{\Lambda}{g} \approx \frac{1}{\sqrt{\sqrt{2}\, G_F \left|\Delta Q_w^p\right|}} \sim 2.2\ TeV$$

Strongly coupled theories have $g^2 \sim 4\pi$.
Separate limits can be quoted for models that interfere constructively and destructively with the Standard Model.

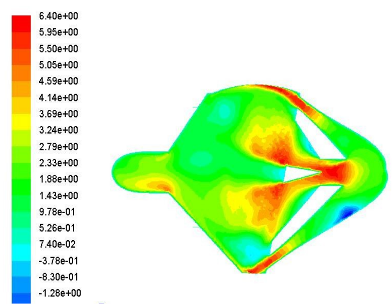
Liquid Hydrogen target



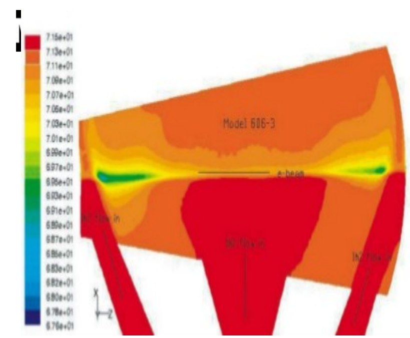
- Long (35cm) LH2 target
- Extreme cooling requirements due to large beam heat load
- *Highest power cryotarget in the world: 2.5kW*
- Design based on Computational Fluid Dynamics to reduce density fluctuations



Target Cell



Fluid velocity



Fluid density

Error Budget

Uncertainty	$\Delta A_{PV}/A_{PV}$	$\Delta Q_W/Q_W$
Statistical (~2,5k hours at 150 μA)	2.1%	3.2%
Systematic:		2.7%
Hadronic structure uncertainties	---	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity correlated beam properties	0.5%	0.8%
Total:	2.5%	4.2%

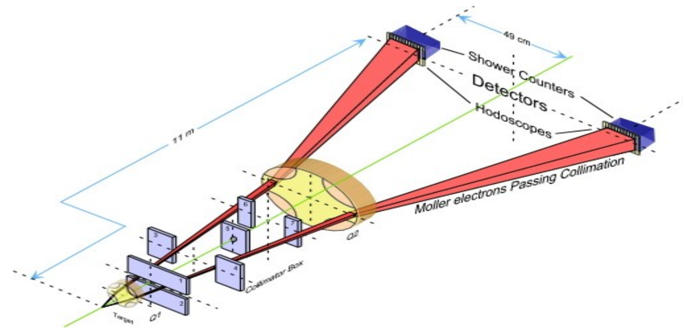
Error budget corresponds to a ~0.3% determination of $\sin^2\theta_W$, including uncertainties from higher order corrections:

$$Q_W(p) = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Polarimetry

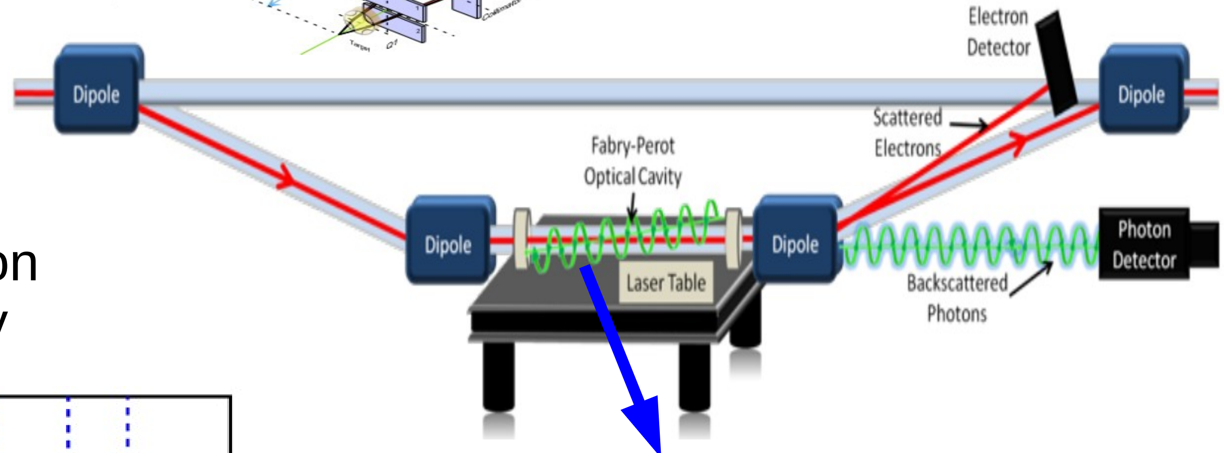
Qweak requirement: dP/P = 1%

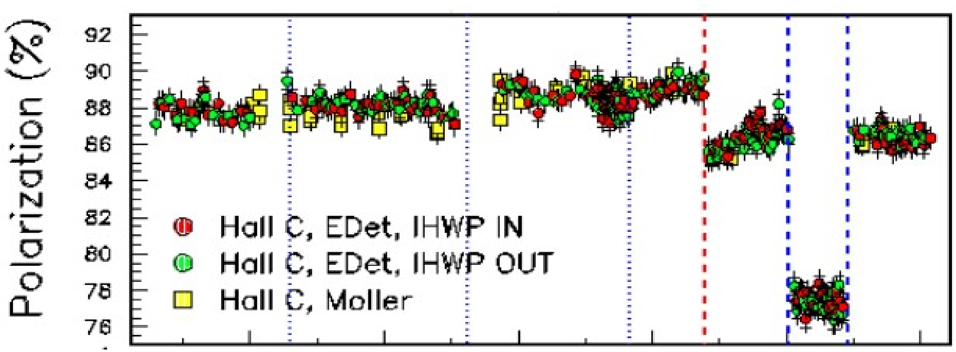
Two independent measurements:



Moller Polarimeter
Requires dedicated
low-current running

Compton Polarimeter
Installed by the collaboration
for continuous polarimetry



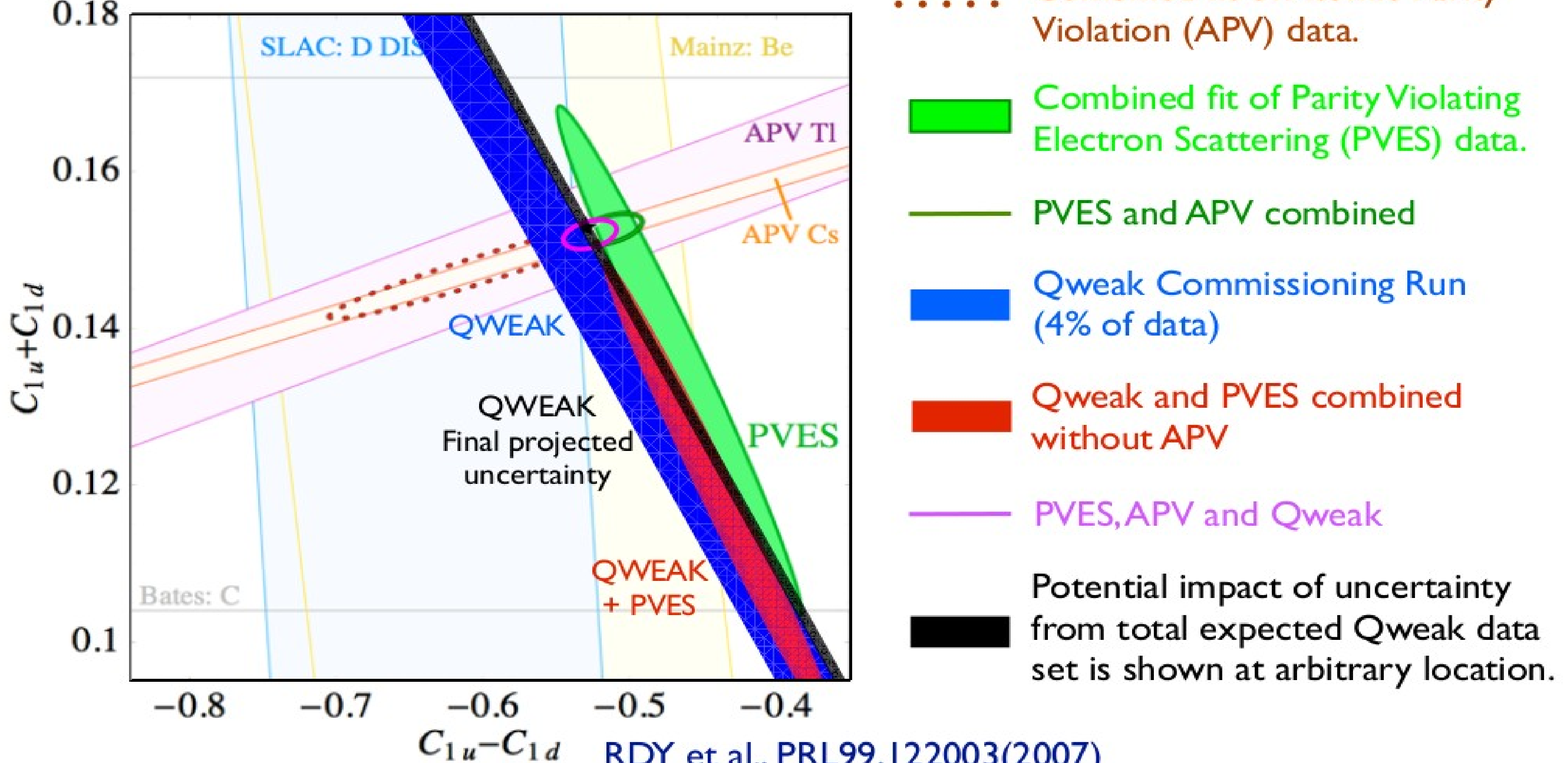


Consistency among independent measurements

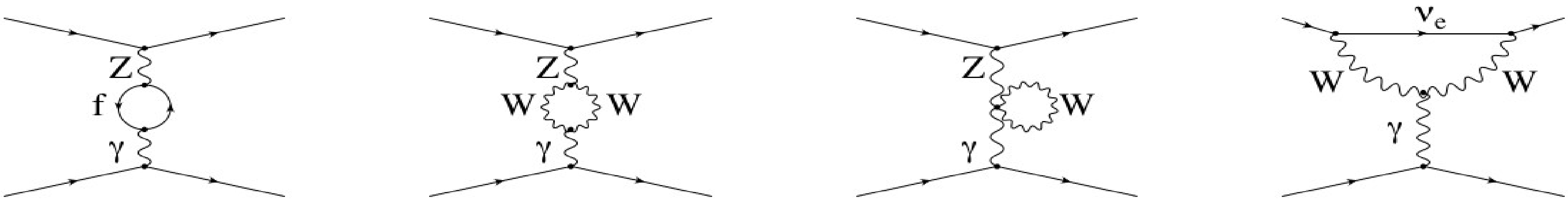
Fabry-Perot cavity
fabricated by UVA
UVA Polarimetry group
maintained the laser and
the photon detector

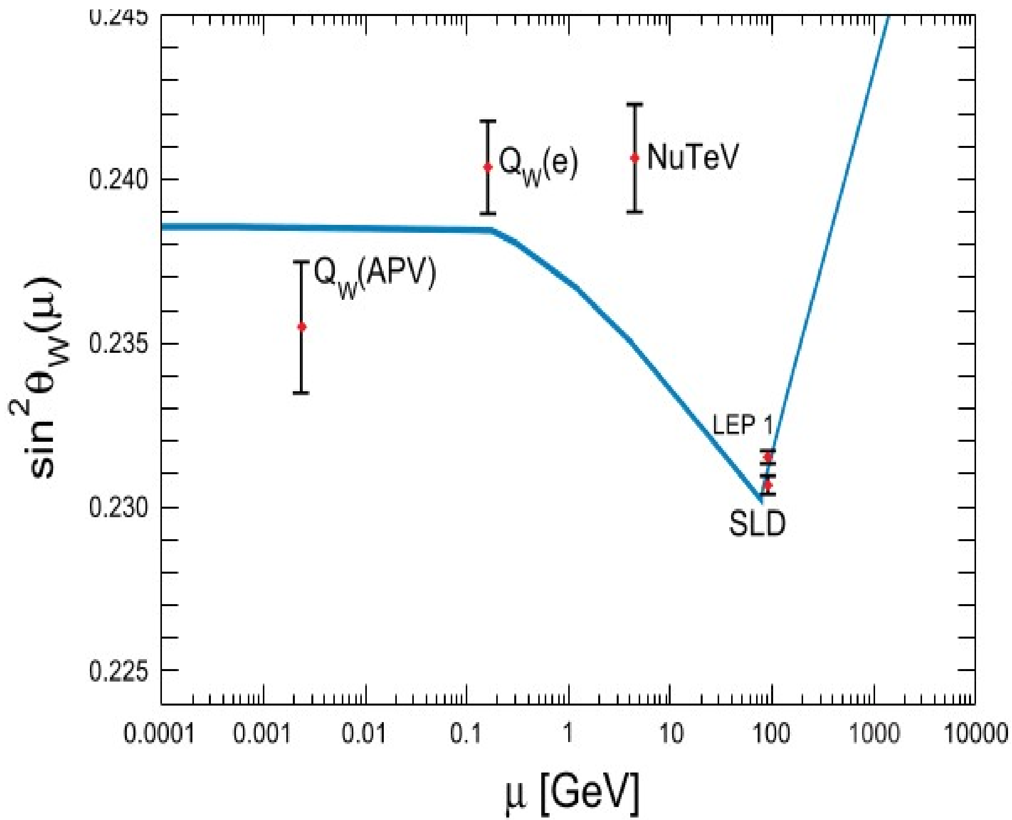
Impact on quark weak charges

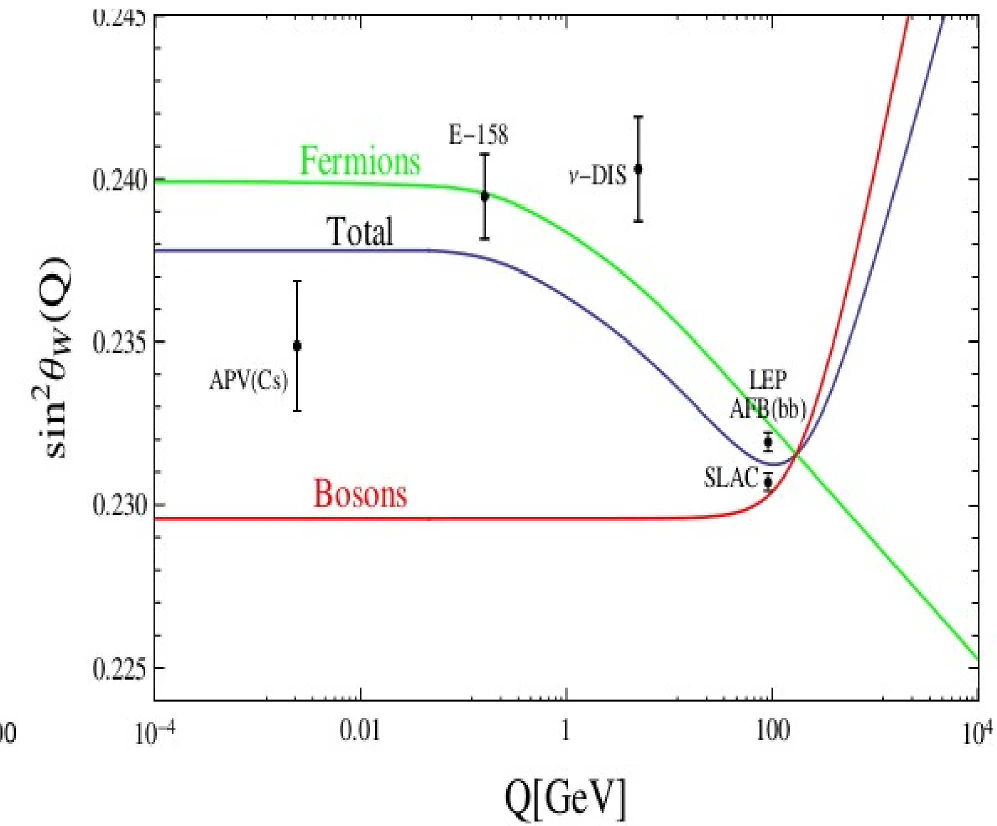
$Q_W(p) = -2(2C_{1u}+C_{1d})$



RDY et al., PRL99,122003(2007)

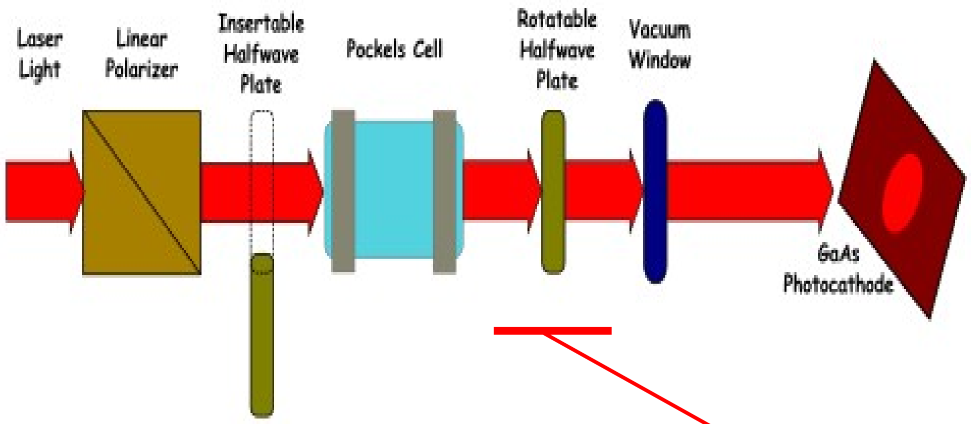


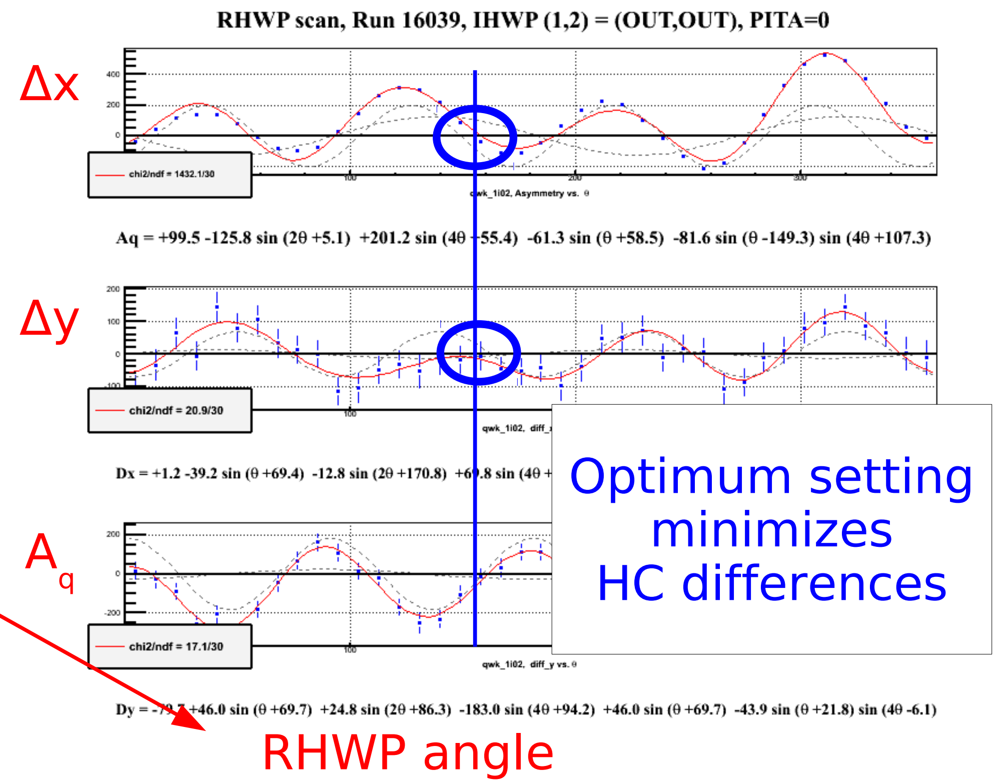




1302.6263v1 [hep-ex] (2013)

Polarized source at Jefferson Lab





Main source of
helicity correlated differences:
relative residual linear light
coupled with an asymmetric transport.

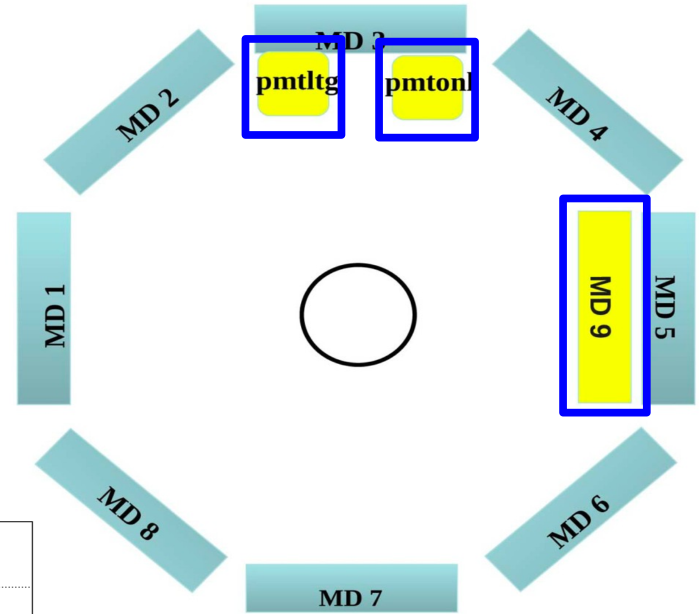
UVA Source group responsible for alignment and optimization,
achieved excellent suppression of HC differences in the injector
although optimum settings would drift.

Beamline Background Asymmetry

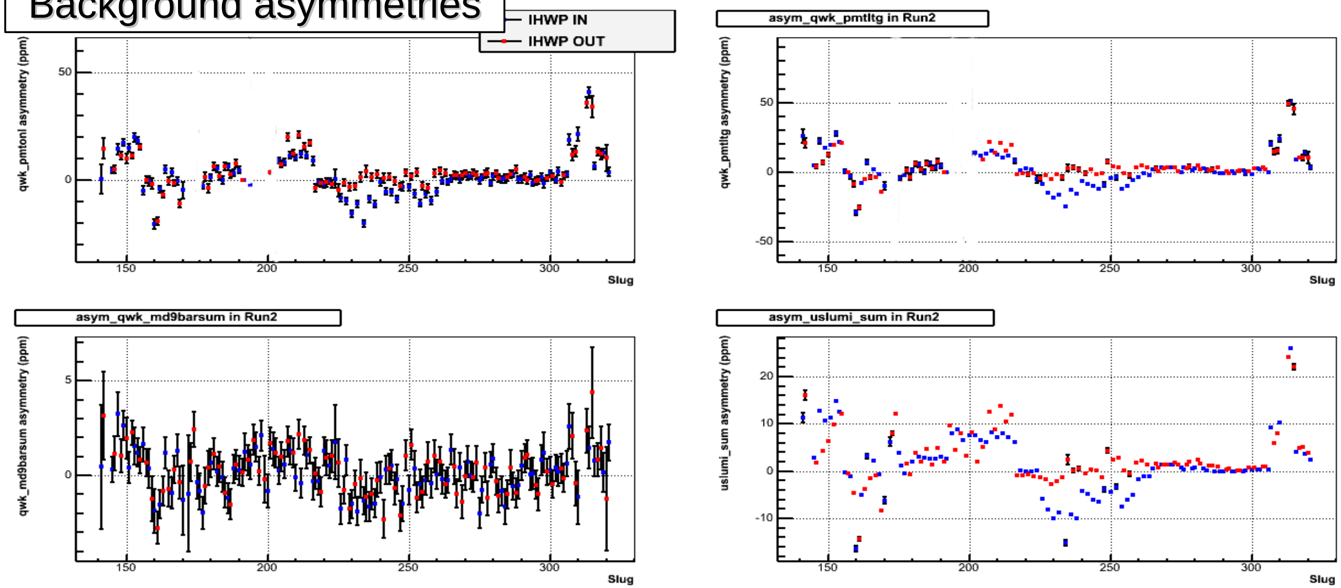
Hypothesis: Asymmetric “beam halo” interacts with the tungsten plug and the beamline

Different background detectors see asymmetries proportional to the background fraction in their signal

Quite large background asymmetries make this an important correction



Background asymmetries



Continuous monitoring from background detectors