Parity Violation and the Standard Model

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Parity Violation experiments have recently featured quite prominently in the Jefferson Lab program and there are a number of such experiments planned for the future. The technique is versatile, but often the intention is to measure Standard Model parameters. This talk will start with an introduction into the relationship between measurements of parity violation in electron scattering and Standard Model parameters and the promise of "new physics". Particular present and future experiments will be discussed.

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Arts & Sciences

Outline

Standard Model

Parity Violation

Electroweak Fits

Parity Violation Experiments

Conclusions

- The Standard Model has 3 electroweak parameters that appear in a multitude of different reactions.

- Experiments are ultimately sensitive to combinations of all parameters. Multi-loop calculations are necessary to compare experiment to theory.

- The theory should be able to describe experimental data to arbitrary precision. (It does so far!)

- Precision experiments test the theory. These can be done at Jefferson lab.

Standard Model

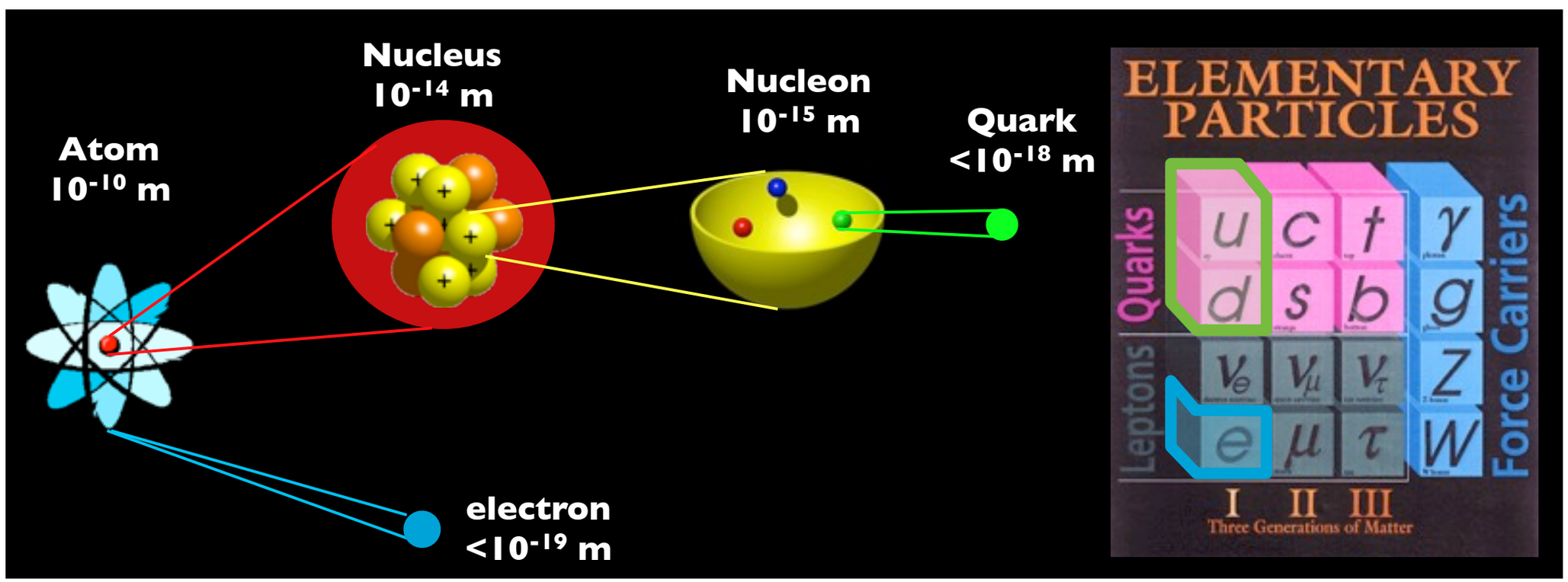
The Standard Model

of particle physics

Forces ...

	Gravity	Weak	Electromagnetic	Strong
mediator	(not found)	W^+, W^-, Z^0	γ	gluons
acts on	all	quarks and leptons	Electrically charged	quarks and gluons
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

and particles



Electroweak Model

see pdg review

Glashow, Weinberg and Salam proposed a unified theory of weak and electro-magnetic interactions. Predicted Z boson and introduced the mixing angle.

$$SU(2) \times U(1)$$

start with a symmetry with bosons (force carriers) and couplings

$$W^{i=0,1,2} \qquad B$$

$$g \qquad g'$$

mixes neutral bosons

Electroweak symmetry spontaneously broken

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Higgs allows a gauge theory with massive bosons

$$W^{\pm} \equiv (W^1 \mp iW^2)/\sqrt{2}$$

left–handed fermions transform as weak isodoublets

$$\begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix} \quad \begin{pmatrix} u_i \\ d_i' \end{pmatrix}$$

right–handed components transform as weak isosinglets

θ_W in more detail

$$M_H = \lambda\nu$$

$$M_W = \frac{e\nu}{2\sin\theta_W}$$

$$M_Z = \frac{M_W}{\cos\theta_W}$$

relates the masses of bosons at lowest order

$$\sin^2\theta_W = 1 - (M_W/M_Z)^2$$

"beautiful relation" - Marciano

$$m_W = 80.384(17)\ \mathrm{GeV/c^2}$$

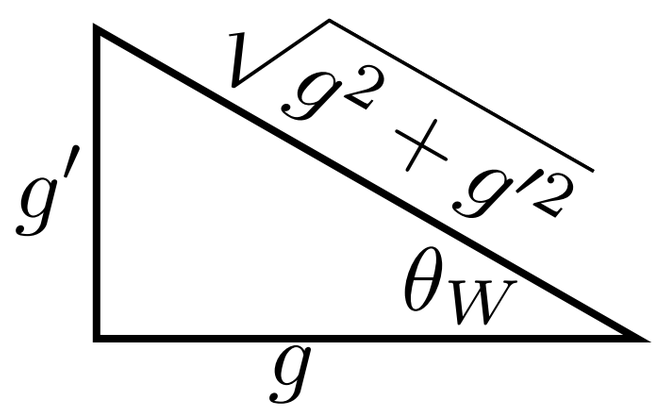
$$m_Z = 91.1876(21)\ \mathrm{GeV/c^2}$$

$$\sin^2\theta_W(m_Z)_{\mathrm{MS}} = 0.23125(16)$$

$$e = g\sin\theta_W$$

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}$$

$$\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$



relationship between coupling constants for electromagnetic and weak interactions

Consequences

weak interaction via boson exchange
weak coupling ~ electro-magnetic coupling
weak bosons very heavy (this is why the force is weak)

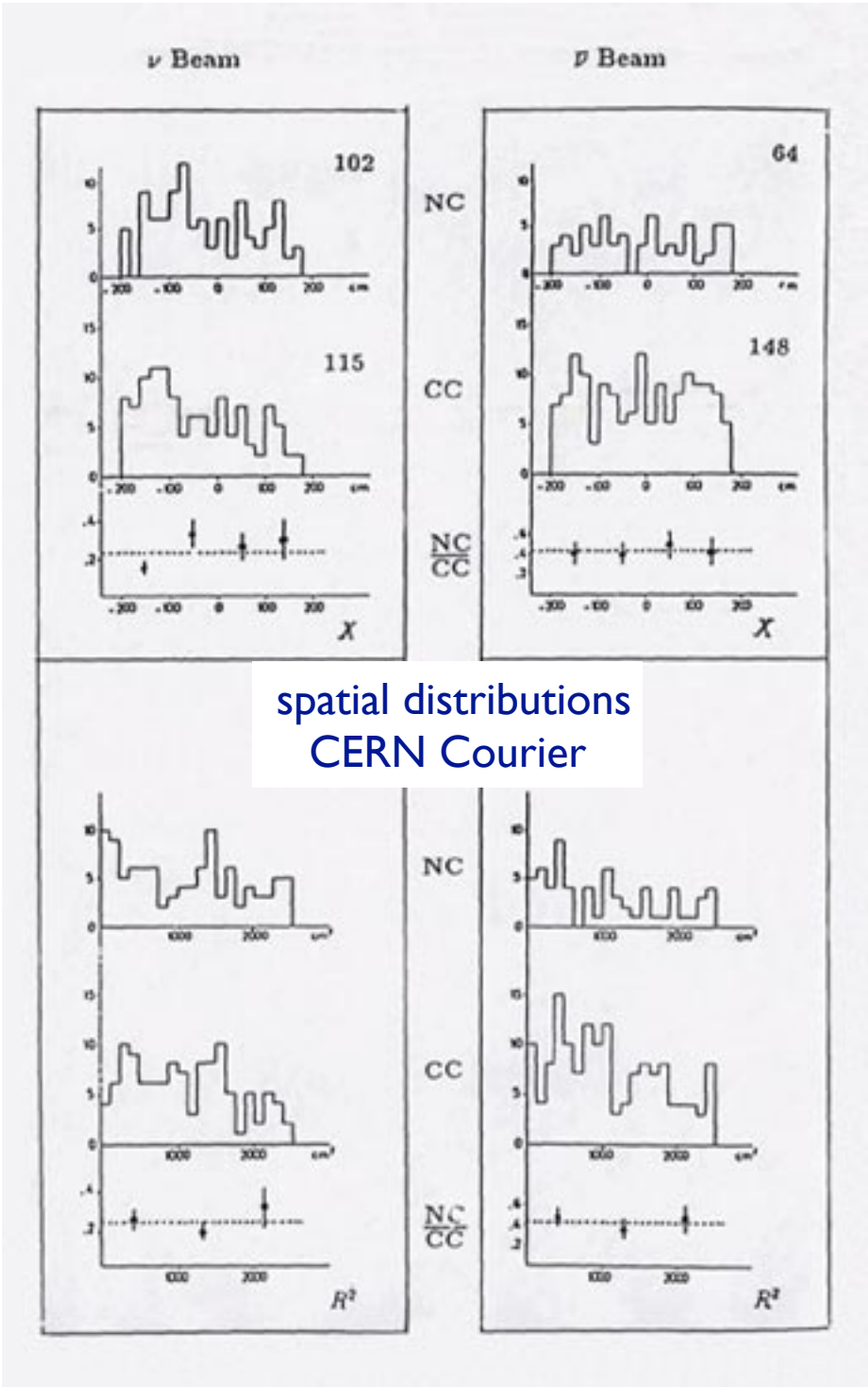
$\sin^2\theta_W$ is as fundamental as the boson masses.

The Higgs gives mass to W and Z. All of their properties are intertwined.

The Standard Model does not predict the mass or coupling of any particle. What is does is relate the masses and couplings to one another.

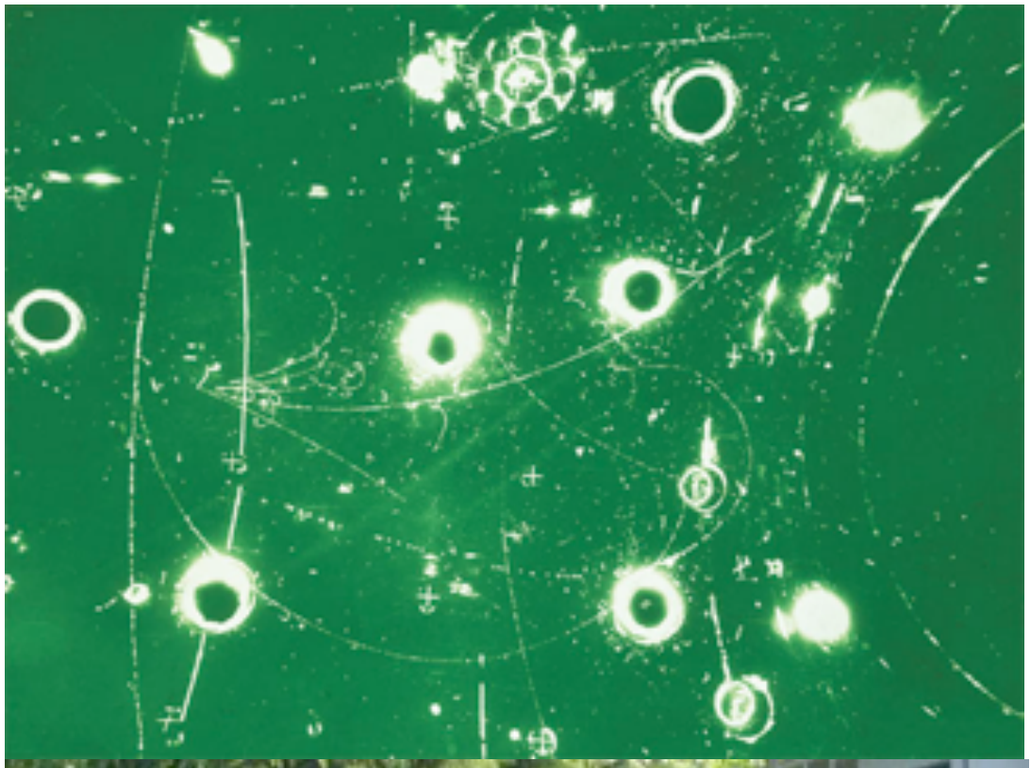
Neutral Weak Current Observed

Observed at CERN and Fermi Lab early 70s.



spatial distributions
CERN Courier

measured the ratio of neutral–current to charged–current events giving $\sin^2\theta_W \sim 0.3$ to 0.4

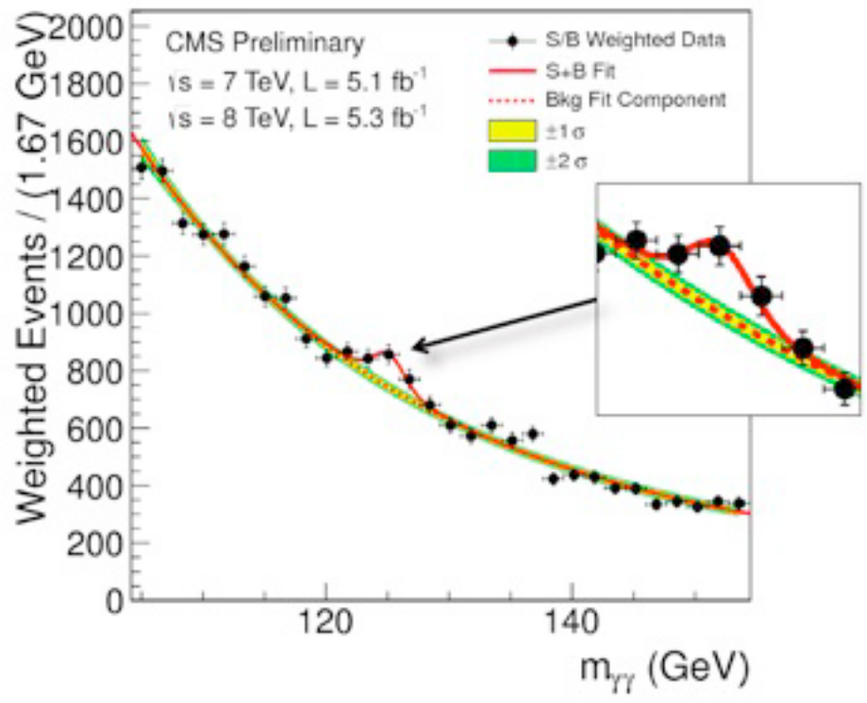


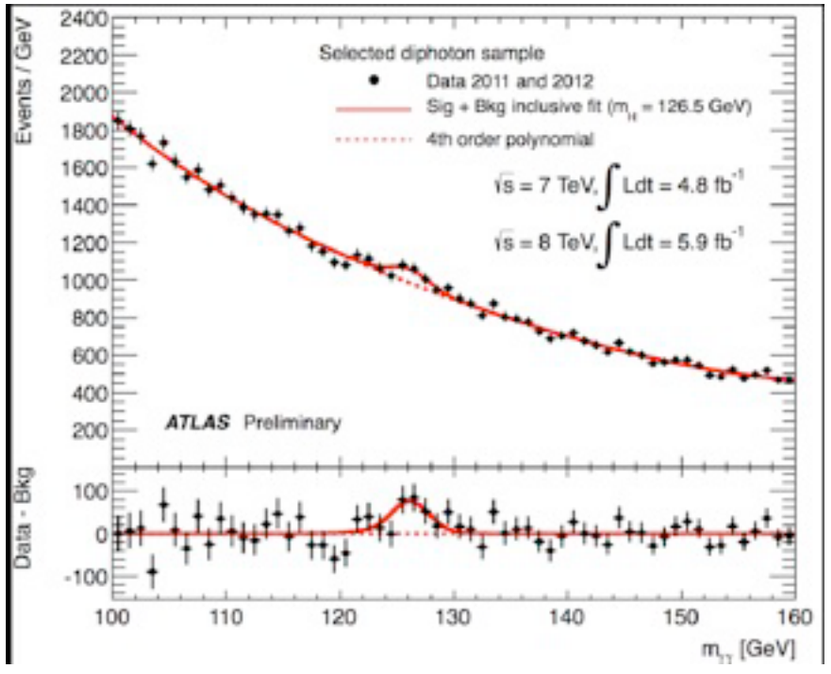
Gargamelle bubble chamber

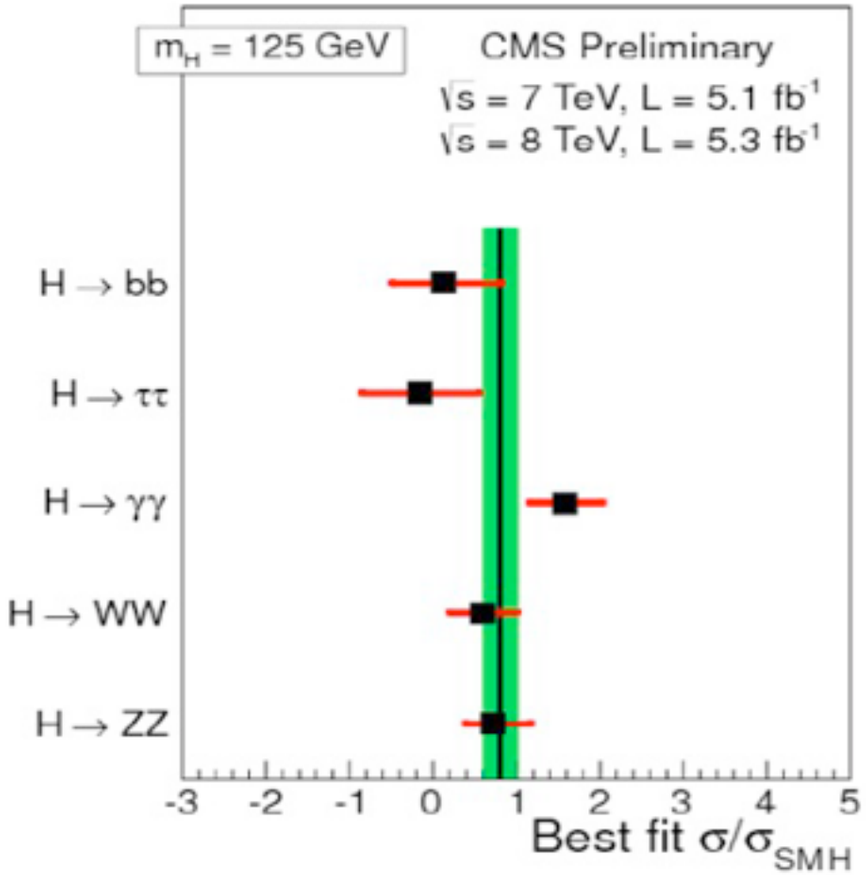
Latest from the LHC

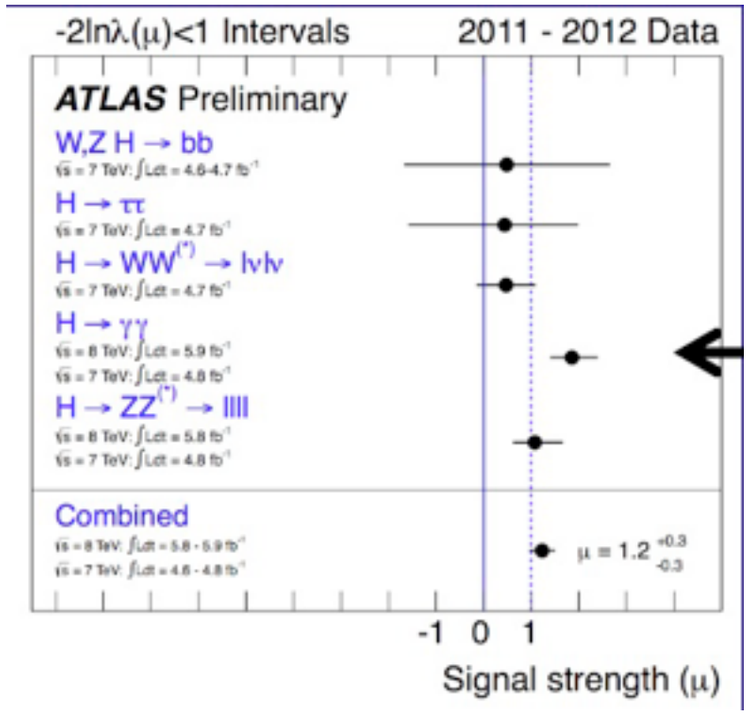
Vincenzo Cirigliano

"New bosonic particle discovered (≥5.0σ) by CMS and ATLAS with the same mass ~125-126 GeV."









BR(H→γγ) High by 1.5-2.0

No fancy new stuff, SUSY etc. Yet!

Why should there be new physics?

Open SM Questions (Ramsey-Mulsolf's list)

What is the origin of matter (both visible and dark) ?
What is the dark energy and what is the nature of the dark sector ?
What is the origin of the dimensionful parameters of the SM ($m_{q,\nu}$, G_F, Λ_{QCD},...) and why are they stable against quantum corrections ?
What are the discrete symmetries of the early universe (P, **CP**, T, B, L,...) ?
When and how were they broken ? i.e. where is the anti-matter ?

Physics beyond the SM

Two lines of attack

Energy frontier

Tevatron and Large Hadron Collider

examples: See SUSY particles
see additional neutral Z'

Precision frontier

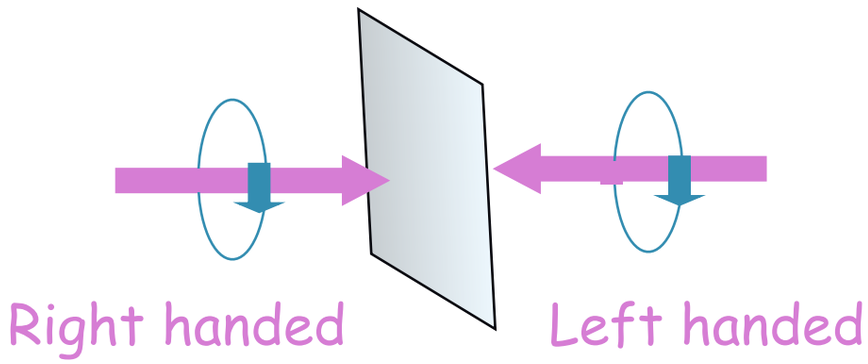
looking for tiny deviations from SM predictions or at phenomena that are highly-suppressed or forbidden by SM symmetries

Pattern of deviations:
guidance into nature of new physics

examples: Electric Dipole Moments
neutrino-less double beta decay ($0\nu\beta\beta$)
Baryon number or lepton flavor violation
Parity-Violating Electron Scattering

Parity Violation

Parity Transformation



The parity transformation is like looking in a mirror.

Reverses momentum but preserves angular momentum.

Reverses helicity: spin in direction of motion.

Helicity

$$h = \vec{S} \cdot \vec{p} = \pm 1$$

Parity Transformation

$$x, y, z \rightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}$$

$$\vec{L} \rightarrow \vec{L}$$

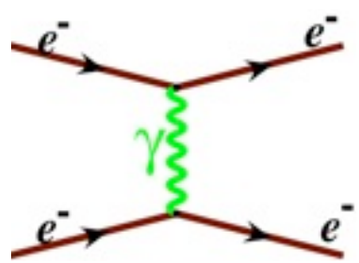
$$\vec{S} \rightarrow \vec{S}$$

Parity Symmetry: interaction unchanged by parity transformation.

Parity Symmetry Violation

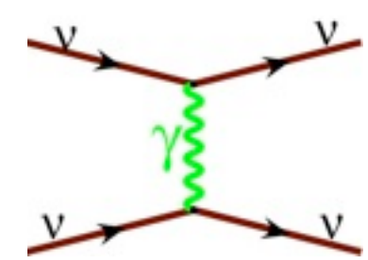
Electric charge determines strength of electric force

Observed in the charged weak current in 1957.



observed

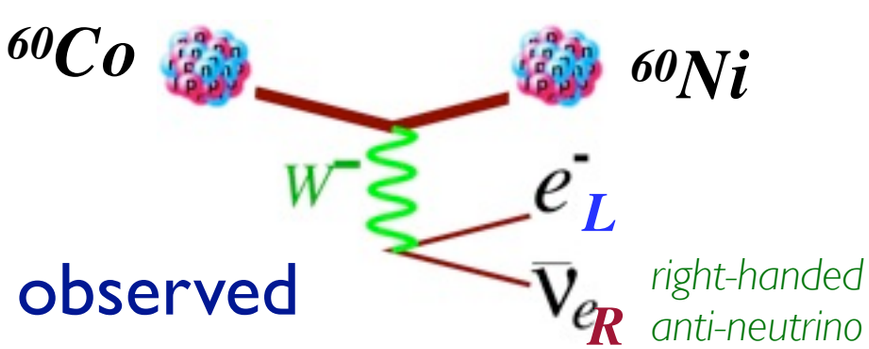
Neutrinos are "charge neutral": do not feel the electric force



not observed

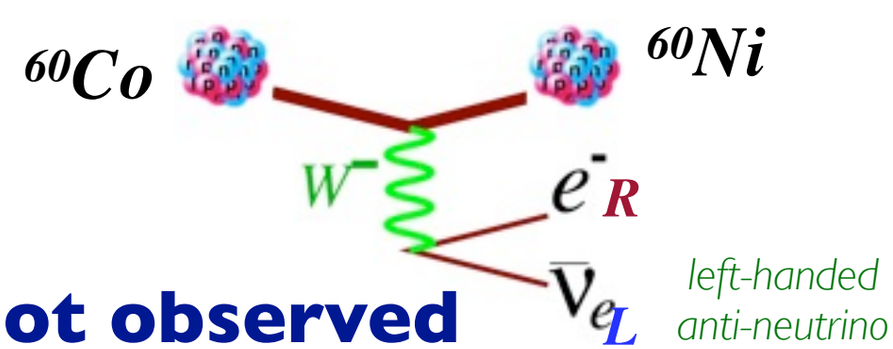
Weak charge determines strength of weak force

Left-handed particles
(Right-handed antiparticles)
have weak charge



observed

Right-handed particles
(left-handed antiparticles)
are "weak charge neutral"



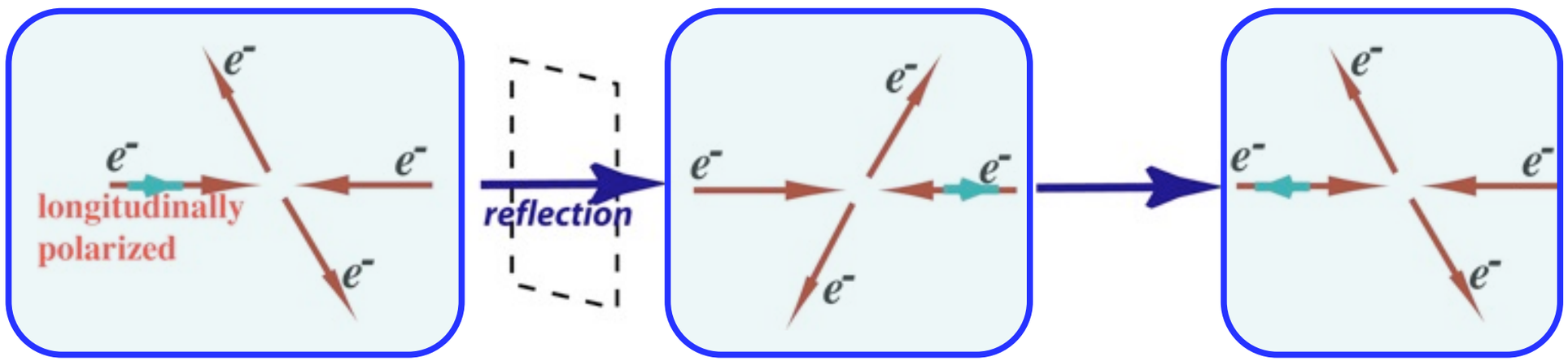
not observed

Measuring a Parity Violation

Measure asymmetry → avoid systematic errors that arise in cross-section measurements: thickness of the target, acceptance of detector etc. cancel in the ratio

$$\sigma \propto |A_\gamma + A_{\text{weak}}|^2$$
$$\sim |A_\gamma|^2 + 2A_\gamma A^*_{\text{weak}}$$

Change helicity of beam - equivalent to changing parity



interference between neutral weak and electromagnetic amplitudes

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\left|\gamma \quad Z^0\right|}{\left|\gamma\right|^2} \approx \frac{|M_Z|}{|M_\gamma|}$$

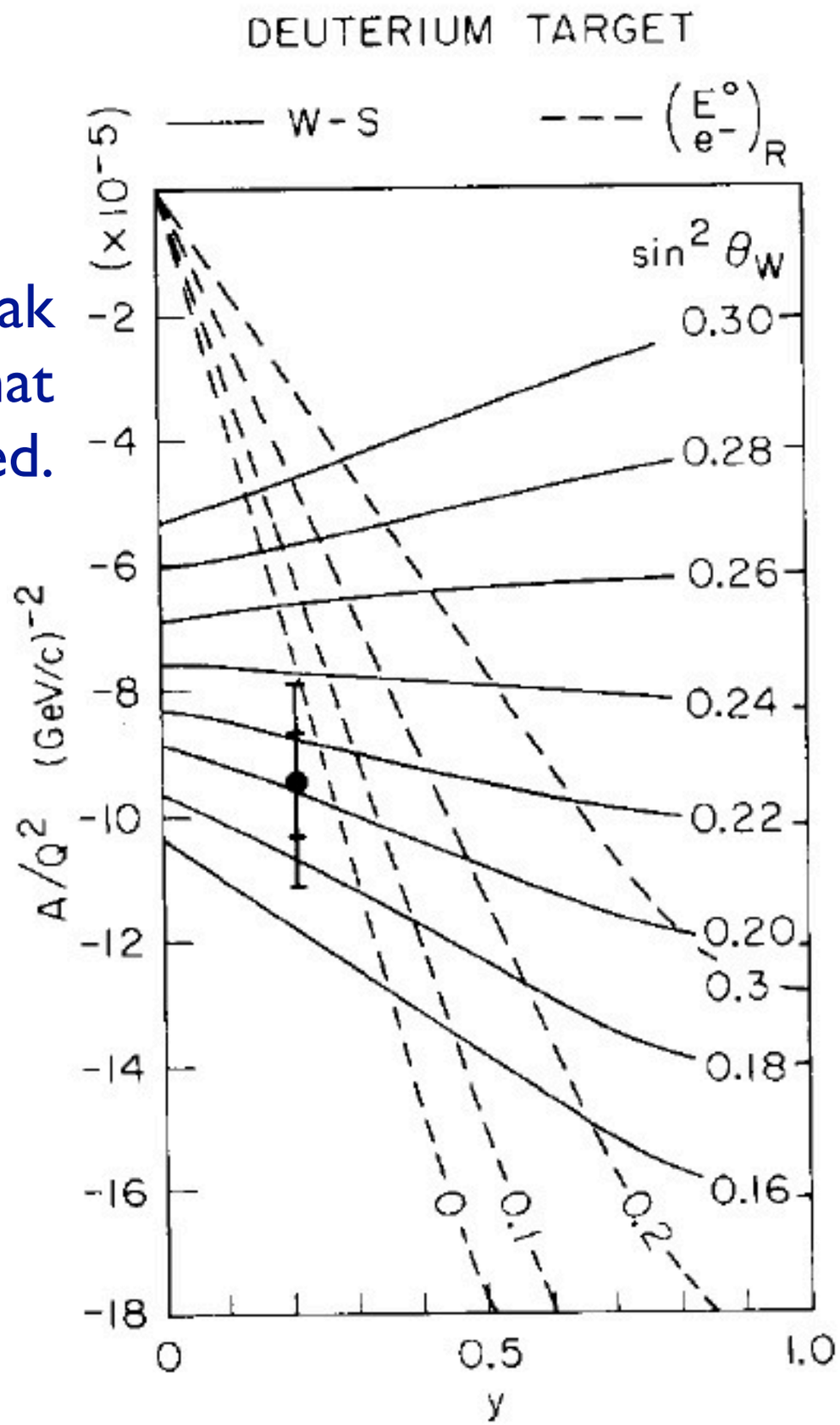
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L}$$

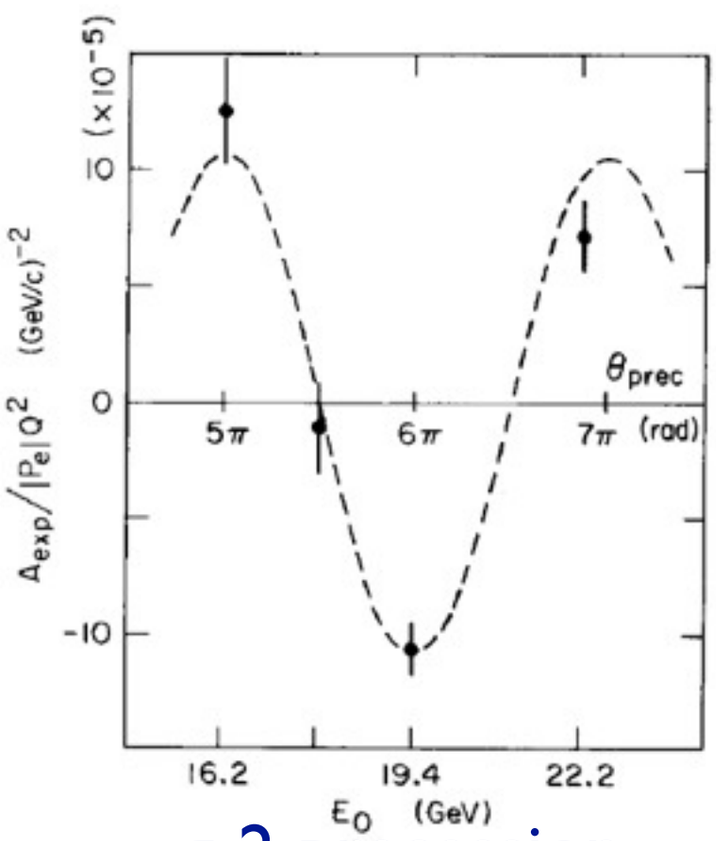
Prescott Experiment

Parity violation in DIS off Deuterium

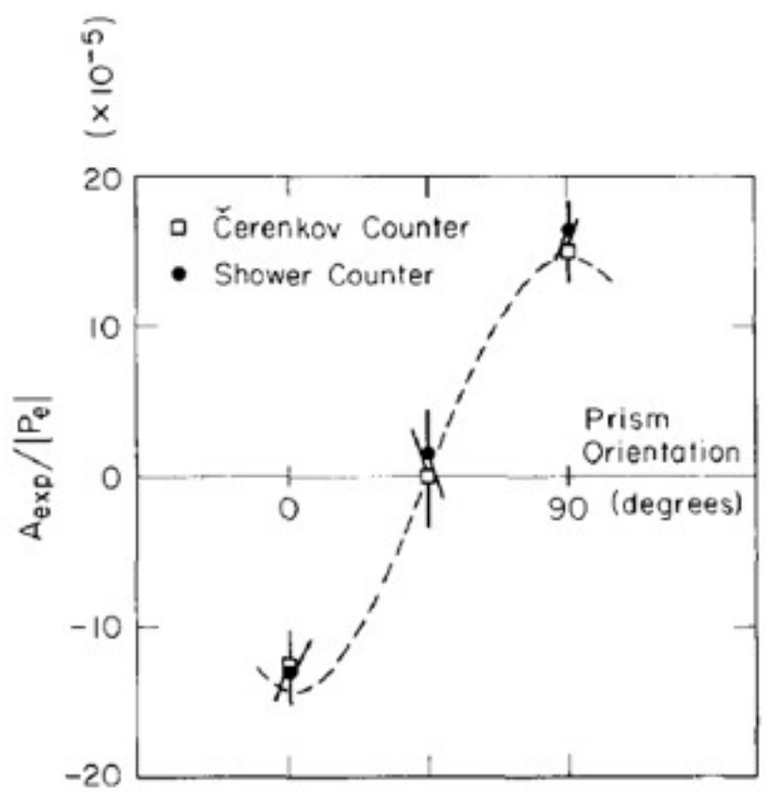
To prove that EM and weak do interfere in the way that W-S predicted.

Prove that asymmetry actually from helicity reversal





g-2 precession



laser polarization

Electroweak Fits

Electroweak parameters

To describe electroweak interactions, there are three parameters needed: (after Higgs boson mass, M_H, the fermion masses and mixings, and the strong coupling constant, αs)

1. Scale of electromagnetism i.e. the fine structure constant
2. Scale of the weak interaction i.e. the W boson mass
3. Weak mixing angle i.e. the ratio of W and Z boson masses

The actual parameters are chosen from the three most precise EW experimental measurements:

1. electron g-2 → fine structure $\sigma \sim 3.2\times10^{-10}$
2. muon lifetime → Fermi constant $\sigma \sim 5.1\times10^{-7}$
3. Z line shape → Z mass $\sigma \sim 2.3\times10^{-5}$

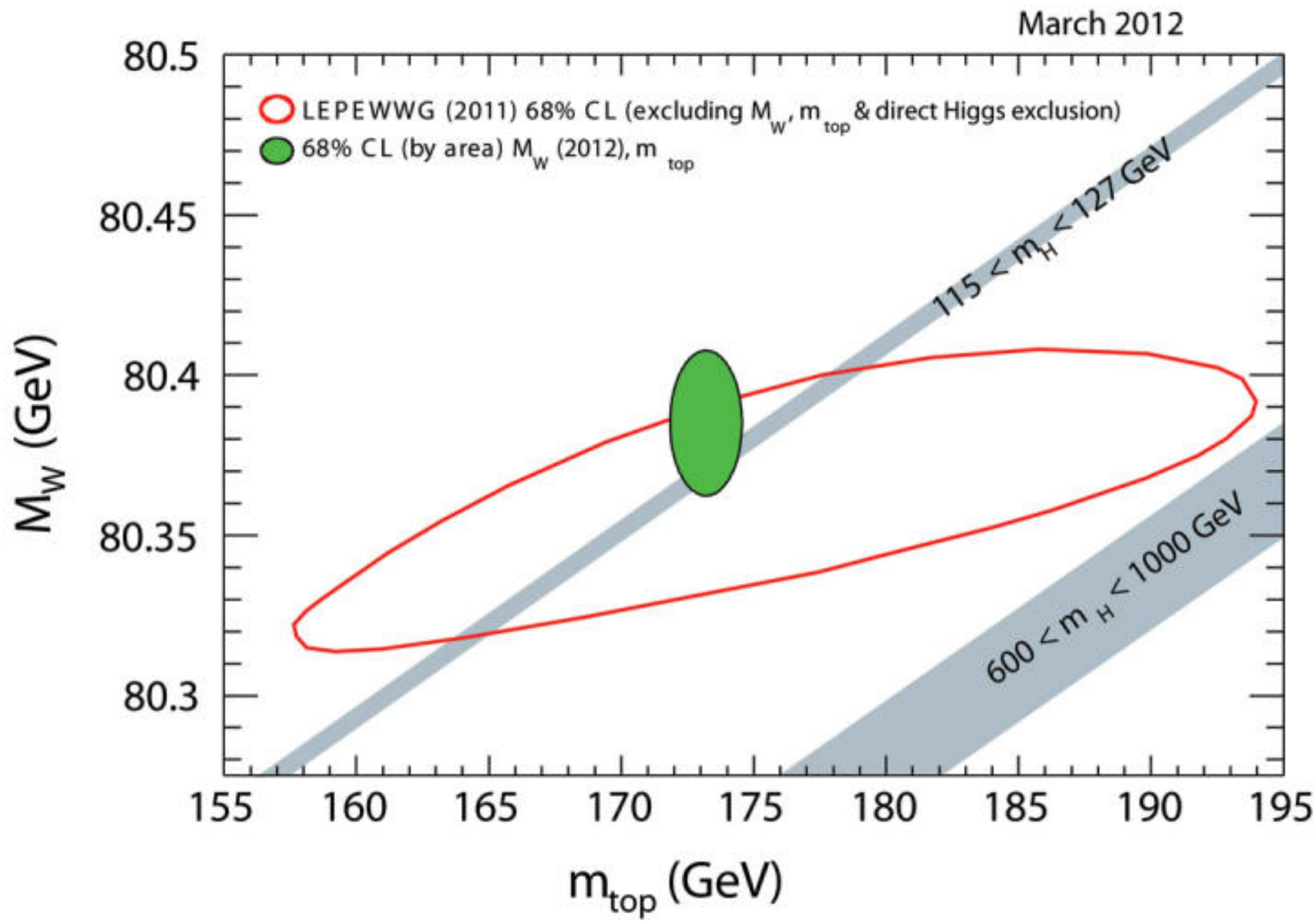
4th, 5th etc. measurements: M_W, $\sin^2\theta_W$ … can then act as tests of the structure.

If measured values differ from predictions: indirect access to "heavy" physics

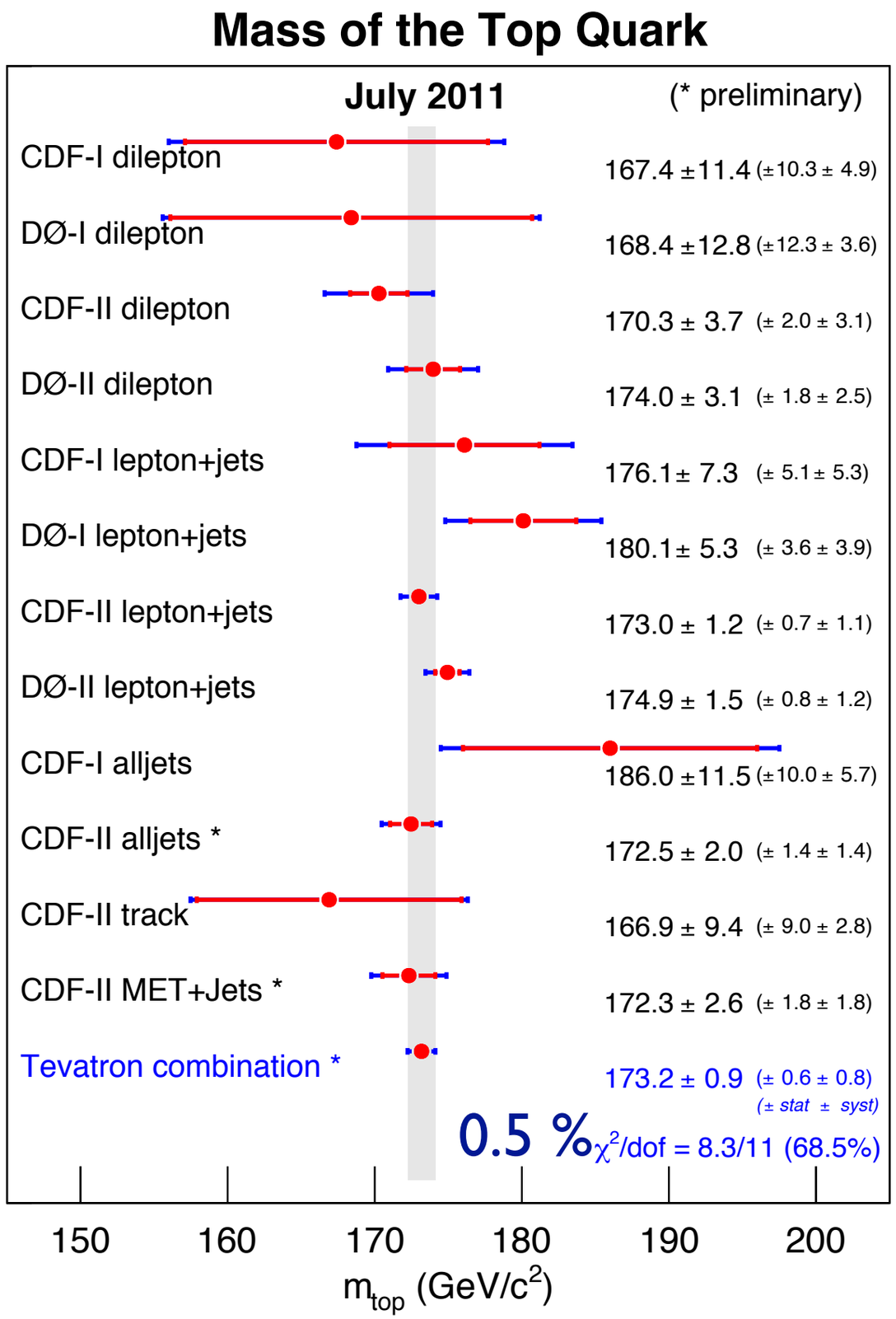
W mass, top mass and Higgs mass

The Higgs couples to particles according to their mass. Thus the W boson and top quark masses are most sensitive to the Higgs mass.

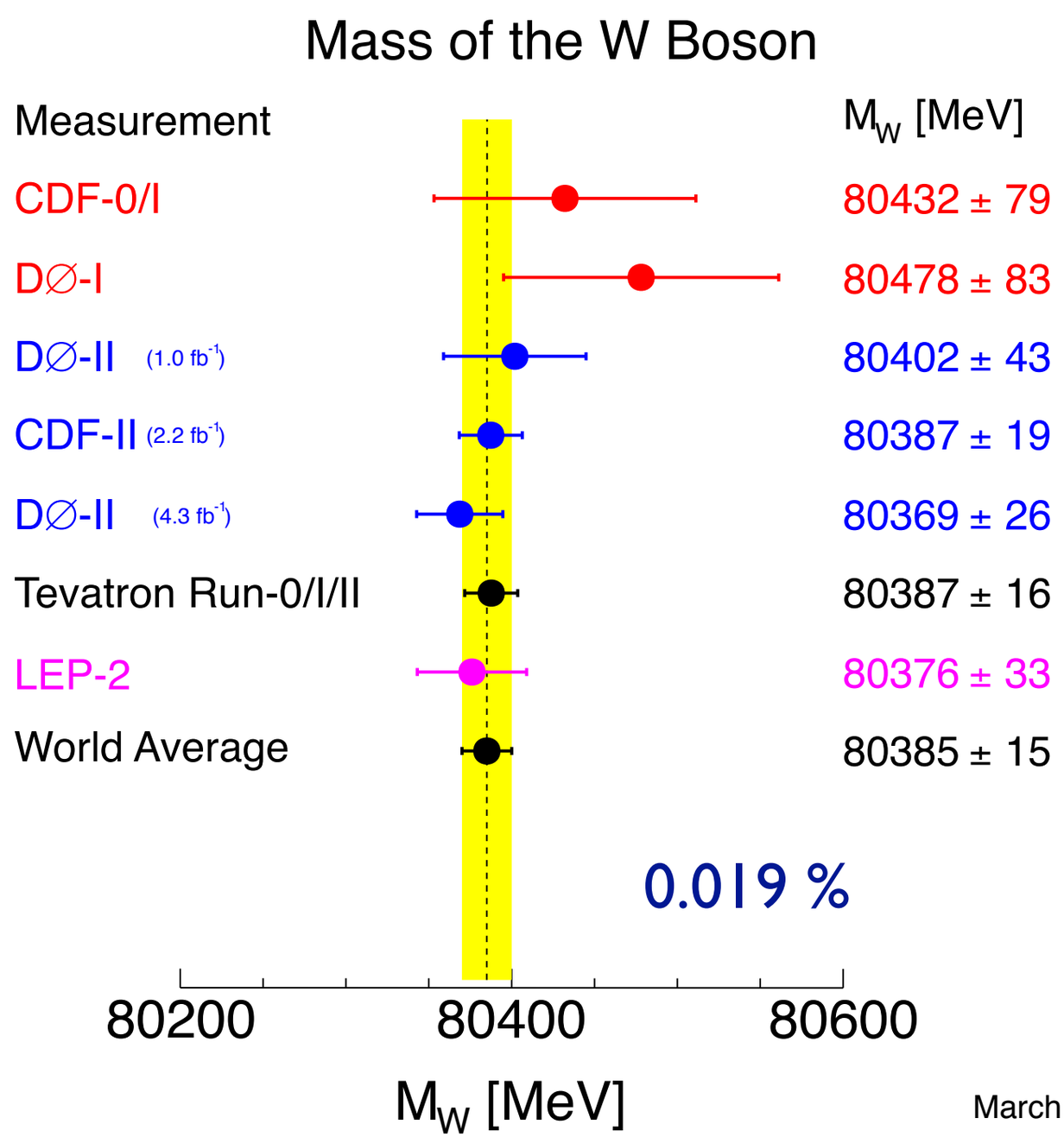
CDF and DØ combined result for the W mass



Precision measurements of mass



Masses of rare particles are hard to measure extremely precisely.



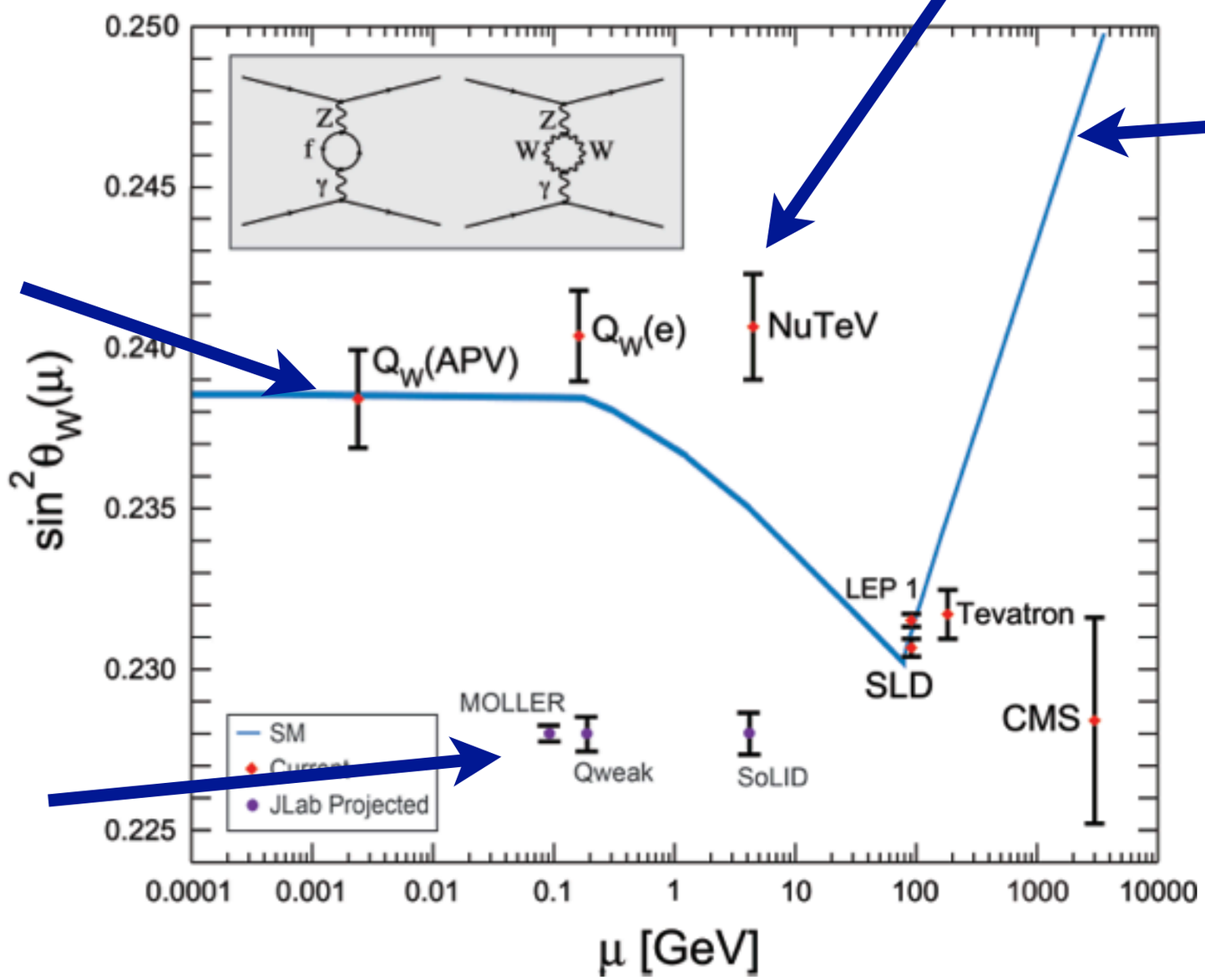
Running of weak mixing angle

This is complicated "scheme dependent" many orders in loops of all particles

neutrino deep-inelastic scattering cross-sections

electroweak fit with uncertainty

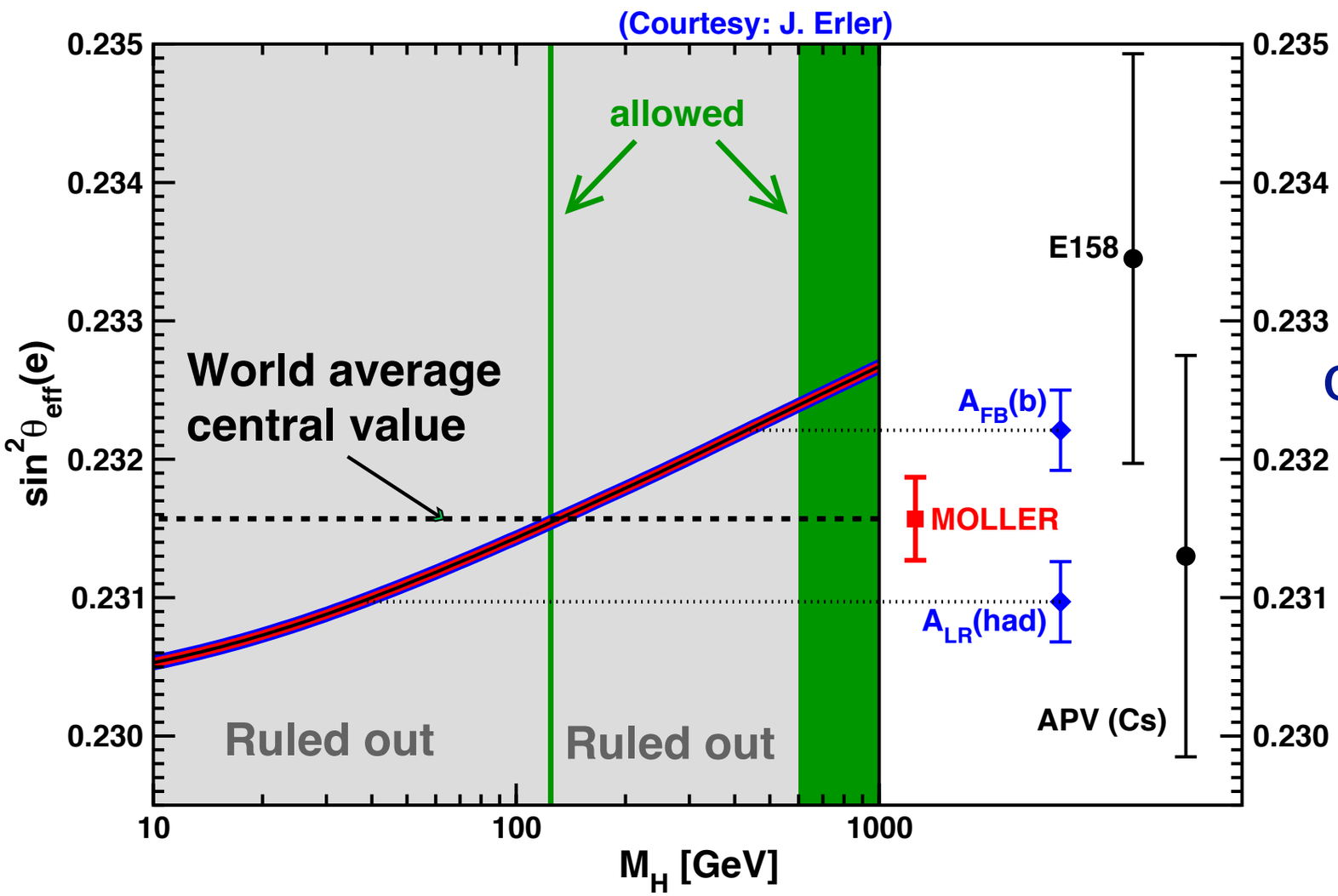
6S → 7S ^{133}Cs atomic transition



Major improvements planned for the near future

Do we really know $\sin^2\theta_W$?

average value works very well with measured Higgs mass



$\sigma \sim 1.2\times10^{-3}$

most precise measurements, by collider experiments, differ by ~ 3σ

Parity Violation Experiments

Illustrative Thought Experiment

Lets measure a 1 ppm asymmetry to 5 % statistical uncertainty.

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx 10^{-6} \rightarrow \frac{\sigma_A}{A} = \frac{1}{A}\frac{1}{\sqrt{2N}} = 5\%$$

$$\rightarrow N \sim 10^{14} \text{ !!!}$$

Need huge statistics to get reasonable uncertainties.

$$\rightarrow \frac{10^{14}}{100 \text{ KHz}} = 10^9 \text{ seconds} \sim 30 \text{ years} \equiv \infty$$

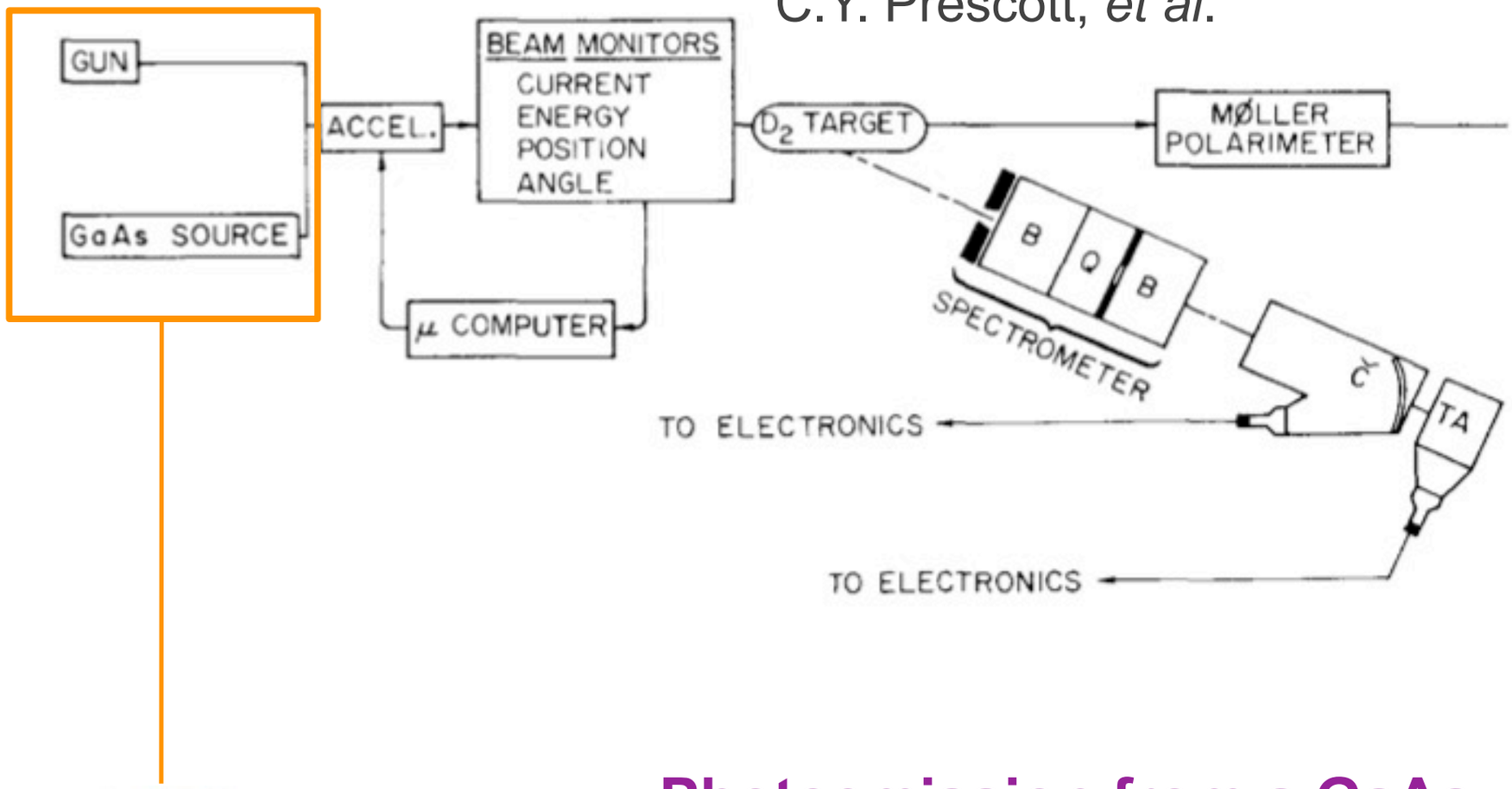
Integrate charge instead of counting particles.

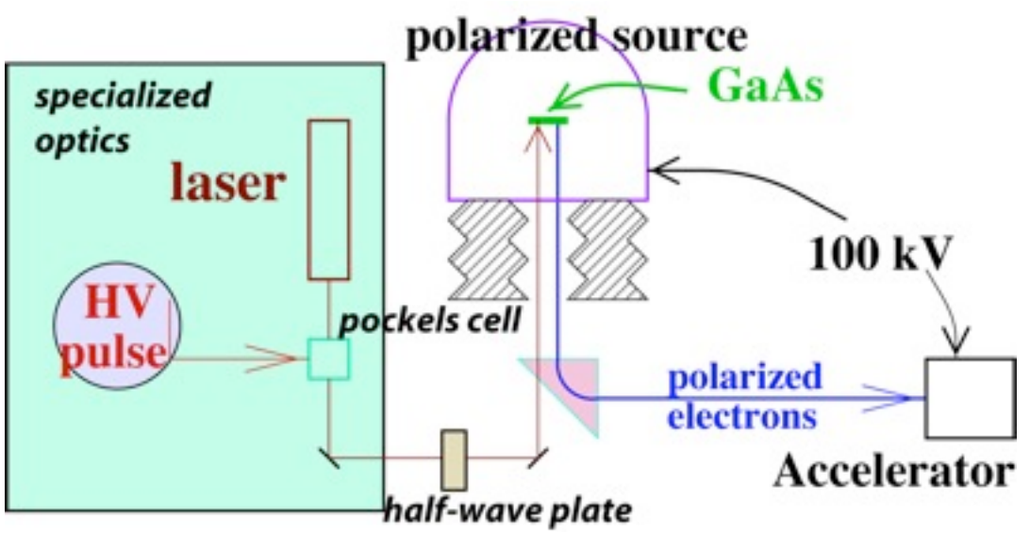
Requires a high degree of **linearity** in photomultiplier tubes and ADCs.

Post analysis difficult or impossible.

Anatomy of a Parity Experiment

C.Y. Prescott, *et al*.





- **Photoemission from a GaAs wafer: "black magic" chemical treatment creates a Negative Electron Affinity cathode**
- **Rapid helicity reversal: polarization sign flips ~100 Hz to minimize the impact of drifts**
- **Helicity-correlated beam motion: under sign flip, beam stability at the micron level**

Anatomy of a Parity Experiment

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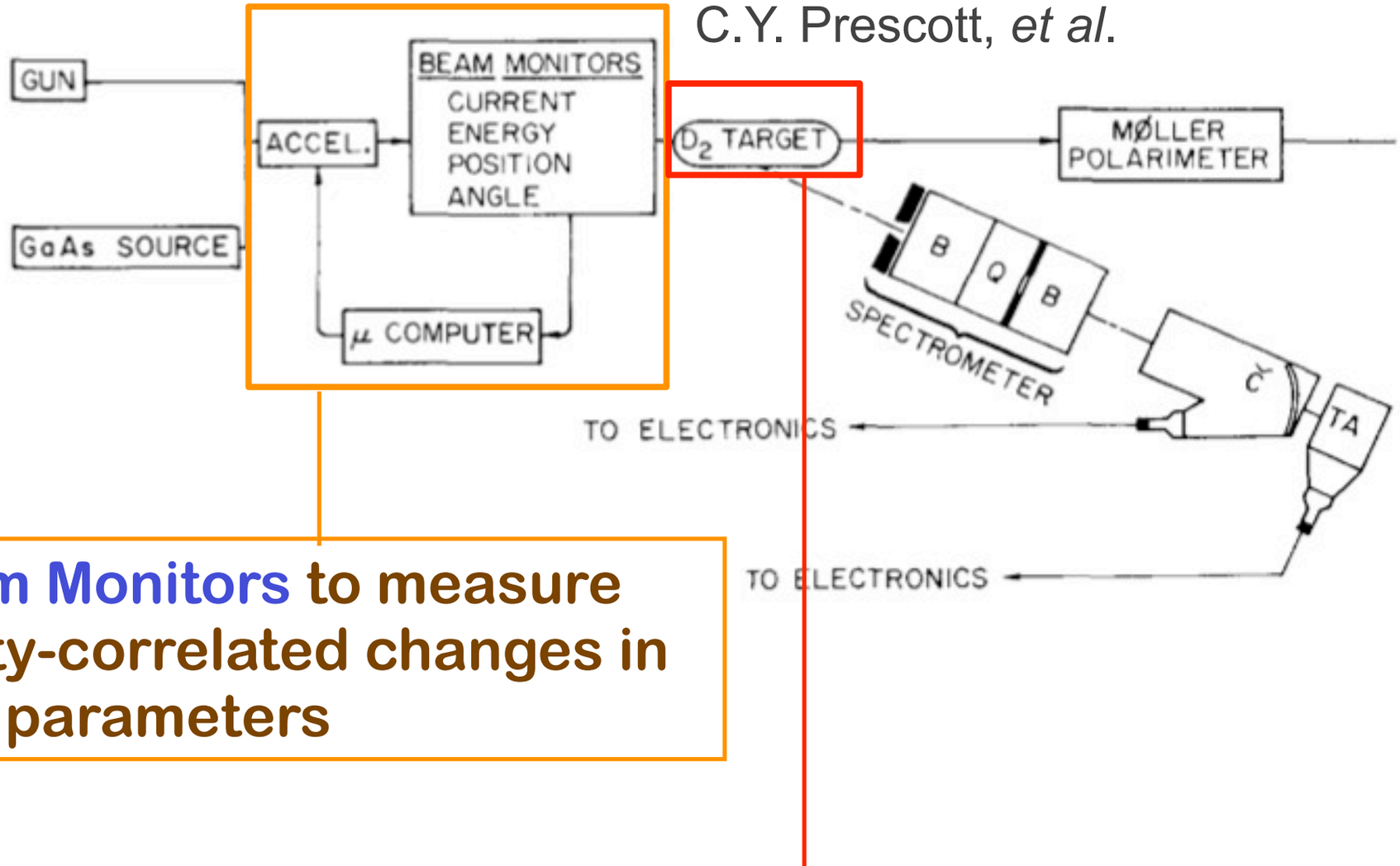

- **Beam Monitors to measure helicity-correlated changes in beam parameters**

- **High-power cryotarget 30 cm long for high luminosity**

Anatomy of a Parity Experiment

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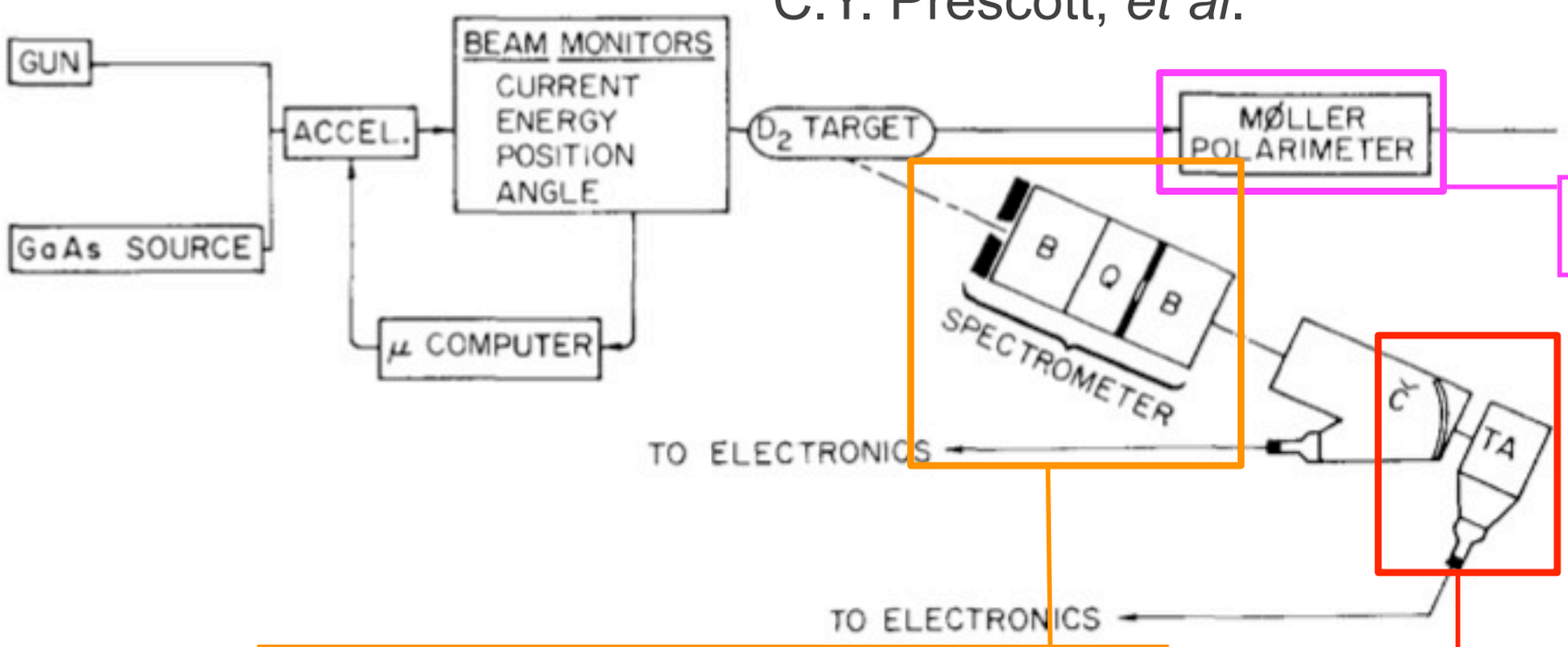
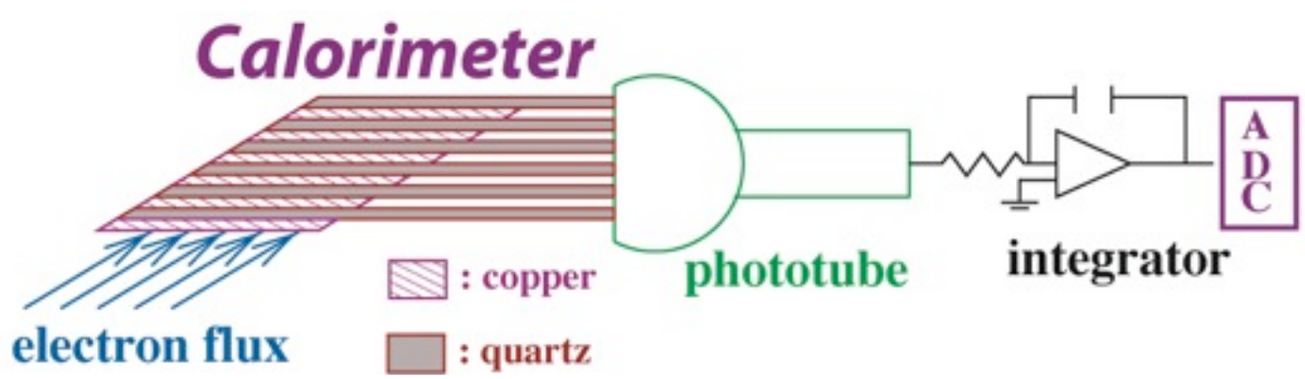


- Polarimetry

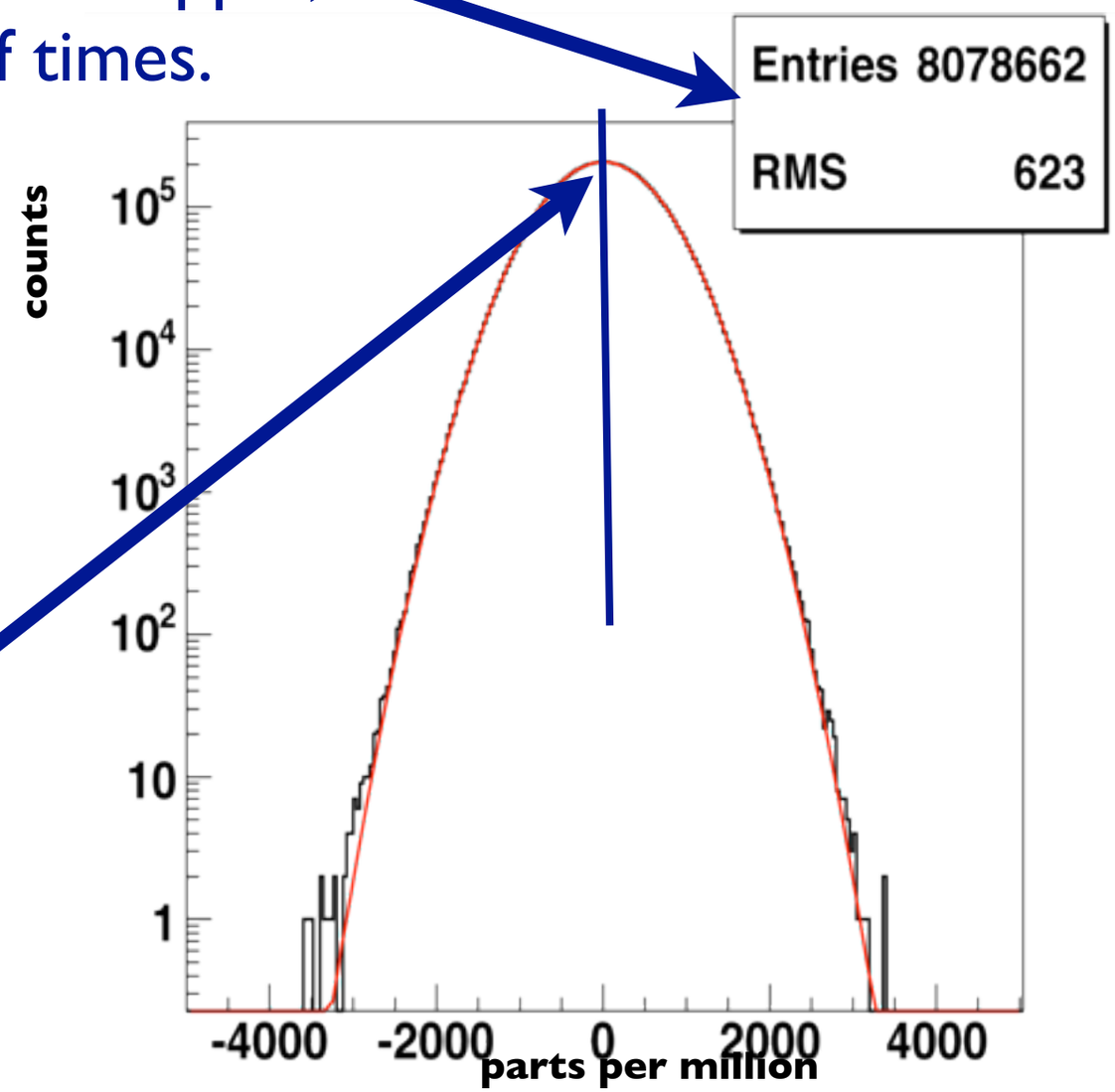
- Magnetic spectrometer directs flux to background-free region

- Flux Integration measures high rate without deadtime



Real Numbers, HAPPEx II

H-II measured a ~ -1.5 ppm asymmetry to 600 ppm, millions of times.



Mean is result: A_{PV}

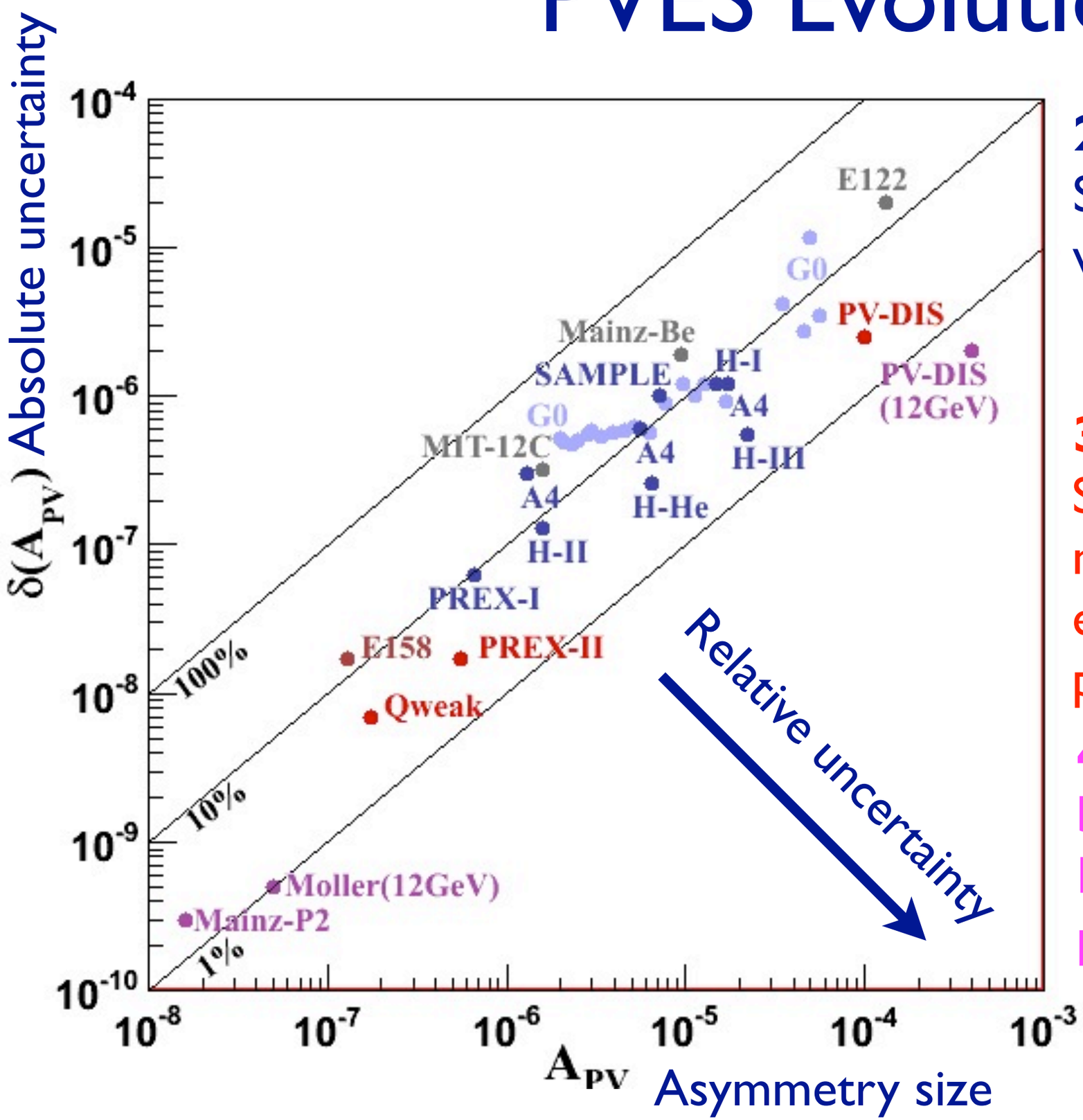
Gaussian to 5 orders of magnitude

Final Uncertainty

$$\delta(A_{PV}) = \frac{600\text{ppm}}{\sqrt{8 \times 10^6}} = 0.2\text{ppm}$$

Random fluctuations **broaden** this peak
Helicity correlated differences **shift** it

PVES Evolution



2nd generation: complete
Strange quarks in the nucleon, weak charge on electron.

3rd generation: in progress
Strange quarks swansong, neutron self interaction energy, weak charge on proton.

4th generation:
beginning 2016?
Fundamental Standard Model parameters.

QWeak Experiment

$$A_{PV} \approx -230 \pm 5 \pm 4 \text{ ppb}$$

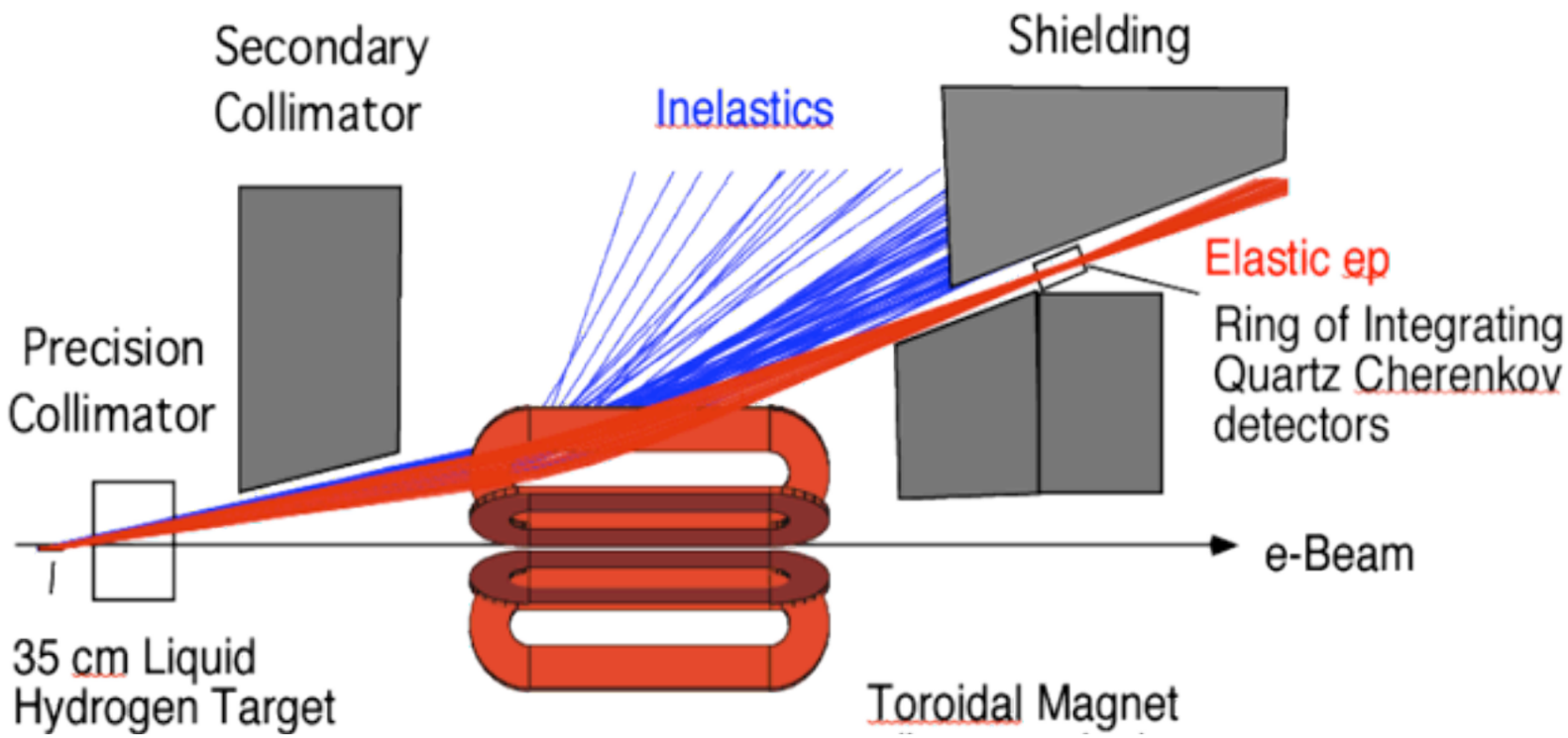
Small angle, low $Q^2 \sim 0.03$ GeV^2 to suppress target structure

Small relative and absolute uncertainty. Gives great precision on SM parameter.

$$F \sim \frac{Q^2}{4M_p^2}(1+\mu_p)\mu_n + O(Q^2)\text{strange quarks}$$

$$\delta Q_W^p = \pm 4\%$$
$$\Longrightarrow \delta(\sin^2\theta_W) = \pm 0.3\%$$

Proton structure *F*, constrained by strange quark program, contributes ~30% to asymmetry, ~2% to $\delta(Q_W^P)/Q_W^P$



QWeak Apparatus

Spectrometer

for high rates…

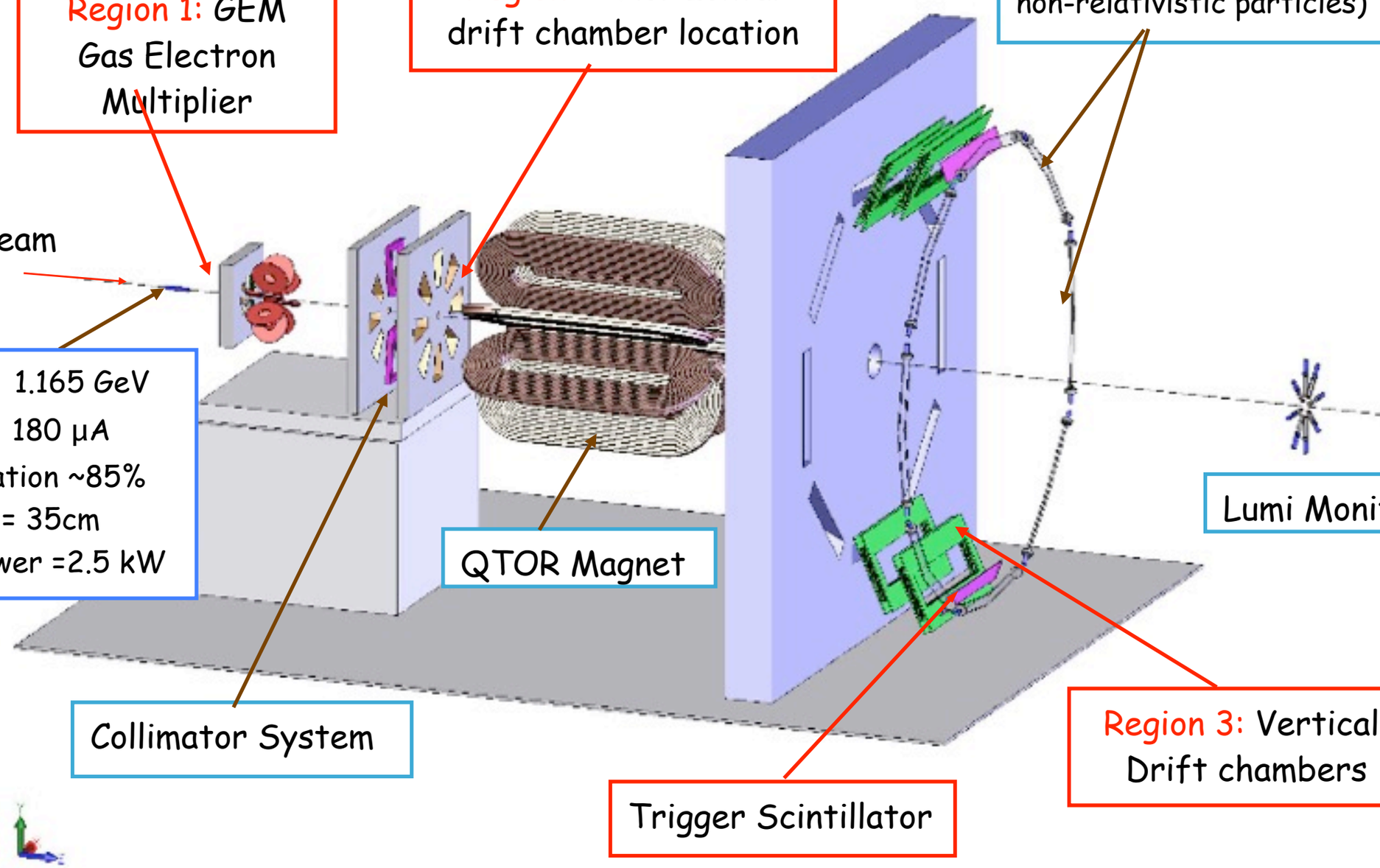
Tracking System

for calibration…

Region 1: GEM Gas Electron Multiplier

Region 2: Horizontal drift chamber location

Quartz Cerenkov Bars (insensitive to non-relativistic particles)



e^- beam

E_{beam} = 1.165 GeV
I_{beam} = 180 μA
Polarization ~85%
Target = 35cm
Cryopower =2.5 kW

QTOR Magnet

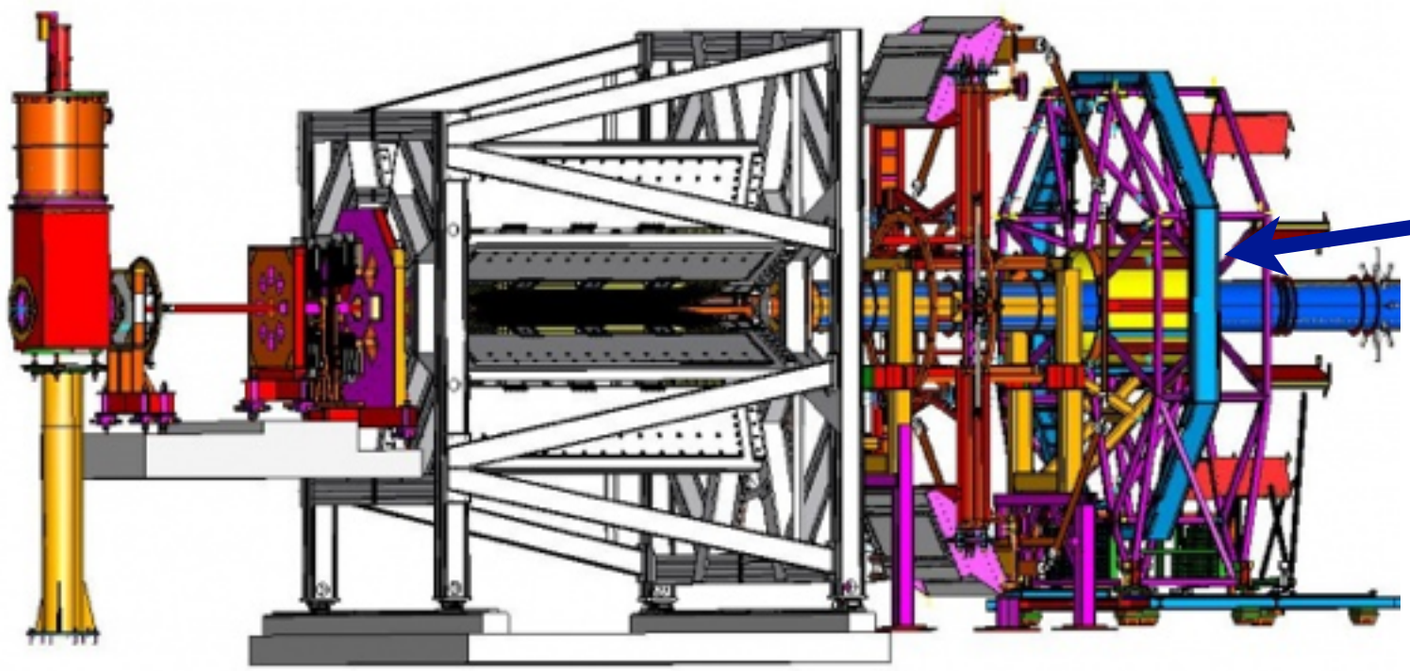
Lumi Monitors

Collimator System

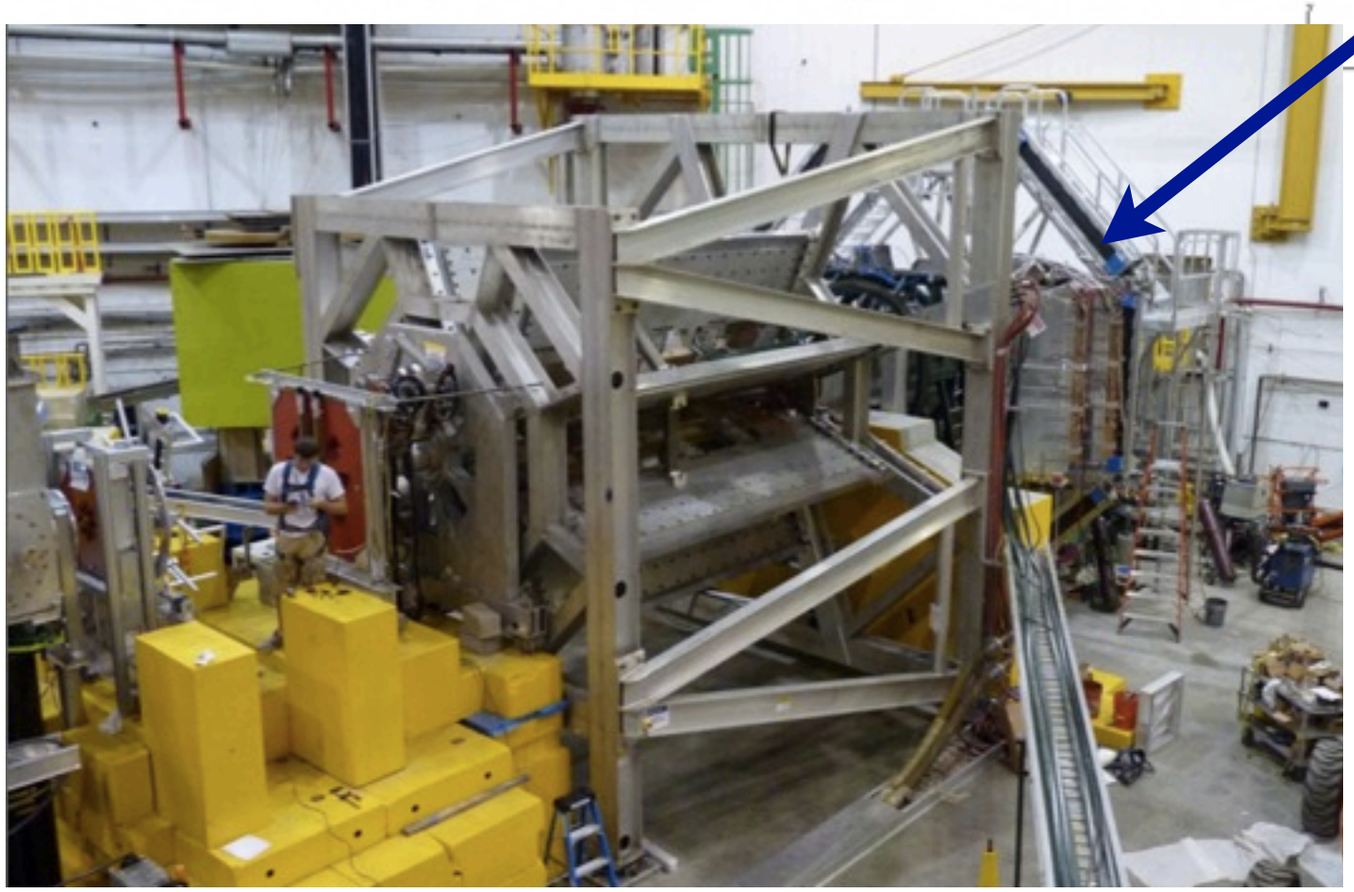
Region 3: Vertical Drift chambers

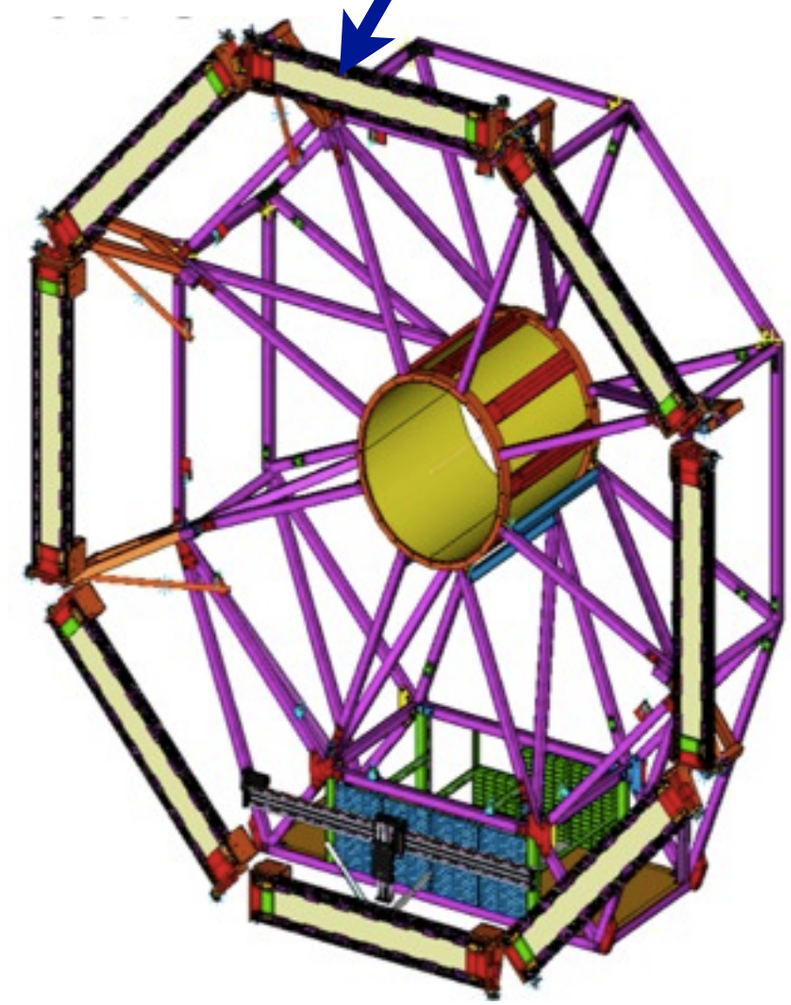
Trigger Scintillator

QWeak detector geometry



Azimuthally symmetric detectors decrease sensitivity to 1st moment HC beam motions.



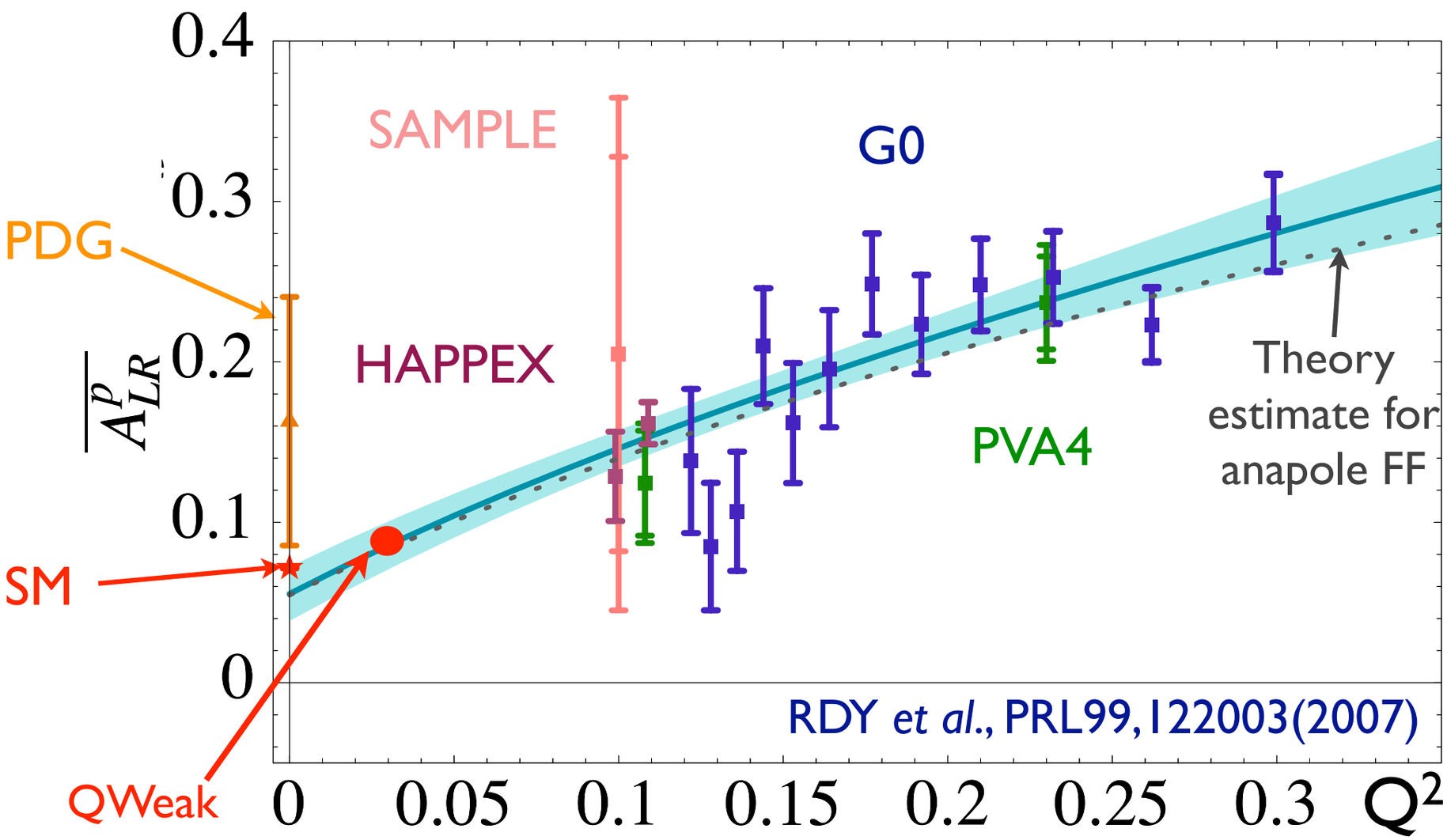


Proton Weak Charge

Proton weak charge precisely known from EW gauge theory and precision EW at the Z-pole

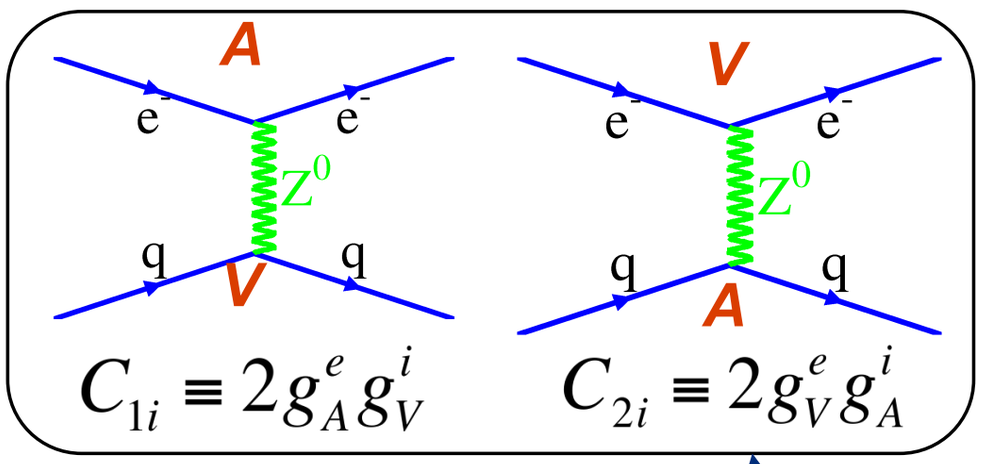
If measurement at low energy comes up different, indicates proton charged for some other (parity-violating) interaction

$$A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha}[Q_W^p + F(\theta, Q^2)]$$



Electron-Quark Scattering

QWeak will constrain vector coupling to quarks, complimentary to Atomic Parity Violation



Large scattering angles

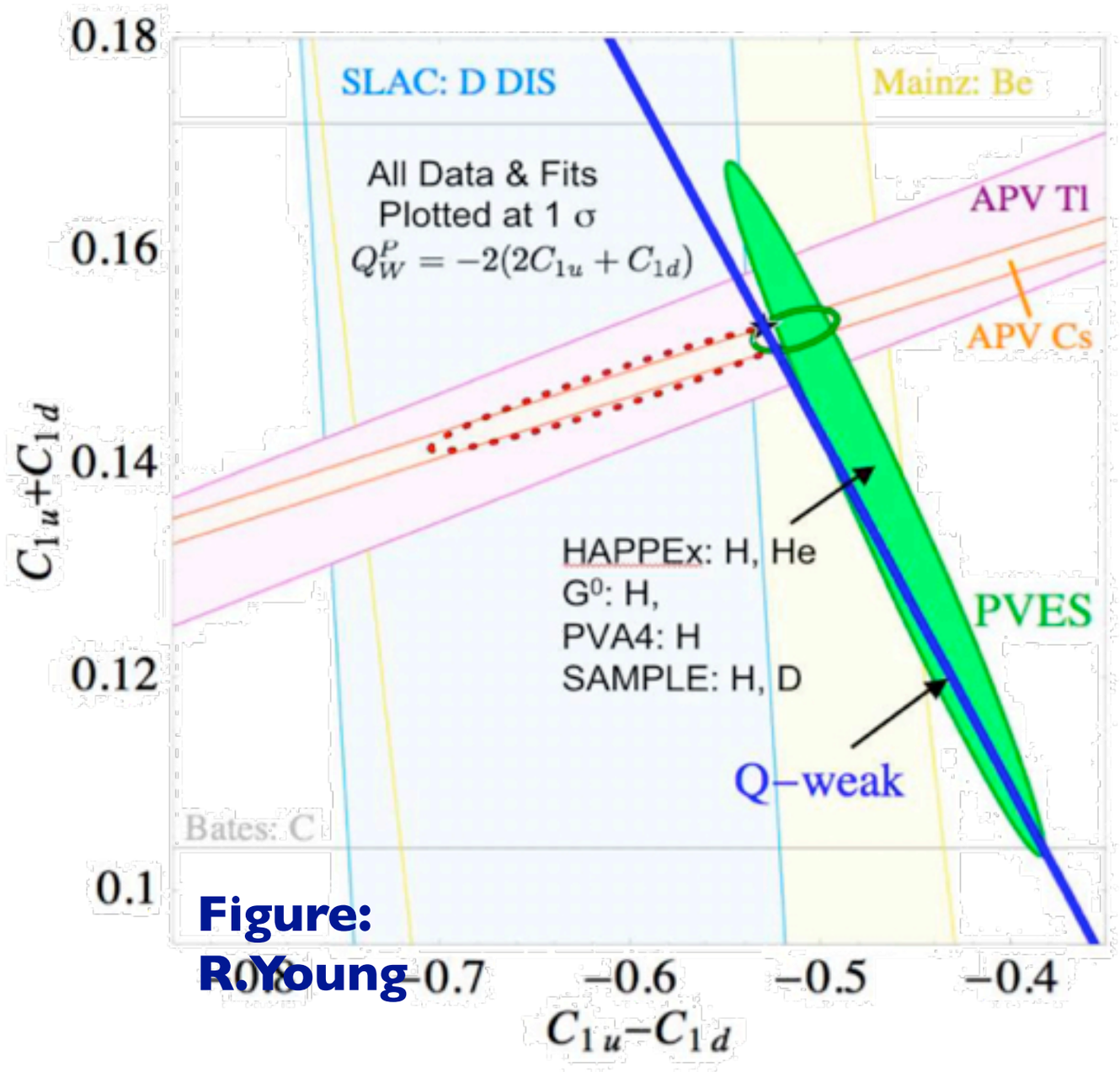


Figure: R. Young

QWeak Status

First results to be shown at DNP meeting in October.

25% Q_{weak} : Preliminary Results

Preliminary (blinded) results from 25% measurement (my thesis analysis)

Polarization $= (88.75 \pm 2.16)\%$

$Q^2 = (0.0252 \pm 0.0007)$ GeV^2

$$A_{ep} = -264.4 \pm 40.3_{stat} \pm 29.1_{sys} \pm 68_{blinding} \text{ ppb}$$

Summary of the relative uncertainties on A_{ep} for this measurement

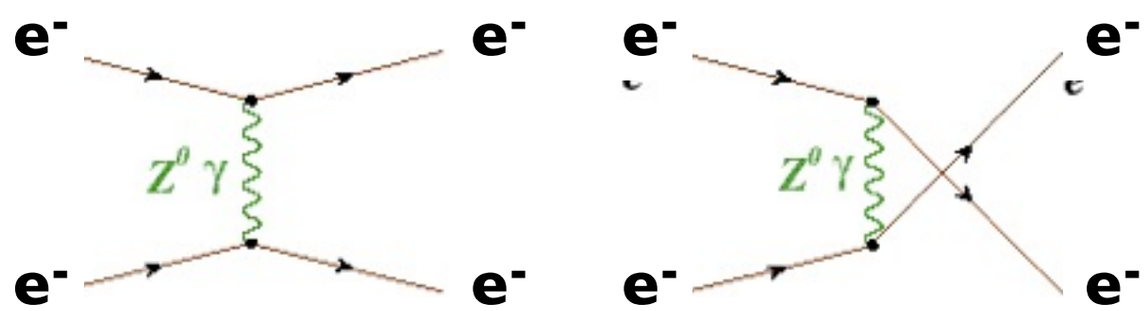
Source	Contribution to (dA_{ep}/A_{ep}) for this measurement	Estimated Requirement for final measurement
Statistics	15.2%	2.1%
Polarization:	2.4%	1.0%
Q^2 Determination:	2.6%	0.5%
Backgrounds:	9.4%	0.7%
Regression:	3.3%	0.4%
Nonlinearity	1.5%	0.4%
Cut Dependence:	1.8%	0.4%
Transverse	2.1%	0.2%
TPE Exchange:	0.1%	0.1%
Total:	**18.8%** $\Rightarrow$ 25% on dQ_W^p/Q_W^p	**2.6%**

Note: Numbers will change for final 25% result

Measurement
Of
Lepton-
Lepton
Electroweak
Reaction

MOLLER Experiment

Measuring weak charge on the electron to very high precision with "low" energy Moller scattering.



$\theta_{lab} \sim 0.3°\text{-}1.03°$
$I_{beam} = 75\ \mu A$
150 cm LH_2 target

~150 GHz !

Small angle

Huge rate

$$A_{PV} = -35\ \text{ppb}$$
$$\delta(A_{PV}) = 0.73\ \text{ppb}$$
$$\delta(Q_W^e) = \pm 2.1\% \pm 1.0\%$$

Tiny asymmetry

High precision

Matches best collider (Z-pole) measurement!

$$\delta(\sin^2\theta_W) = \pm 0.00029$$

Complementary to LHC

For the additional neutral Z' scenario:
LHC sensitive to ~5 TeV, properties to 1-2 TeV
MOLLER can help pin down couplings

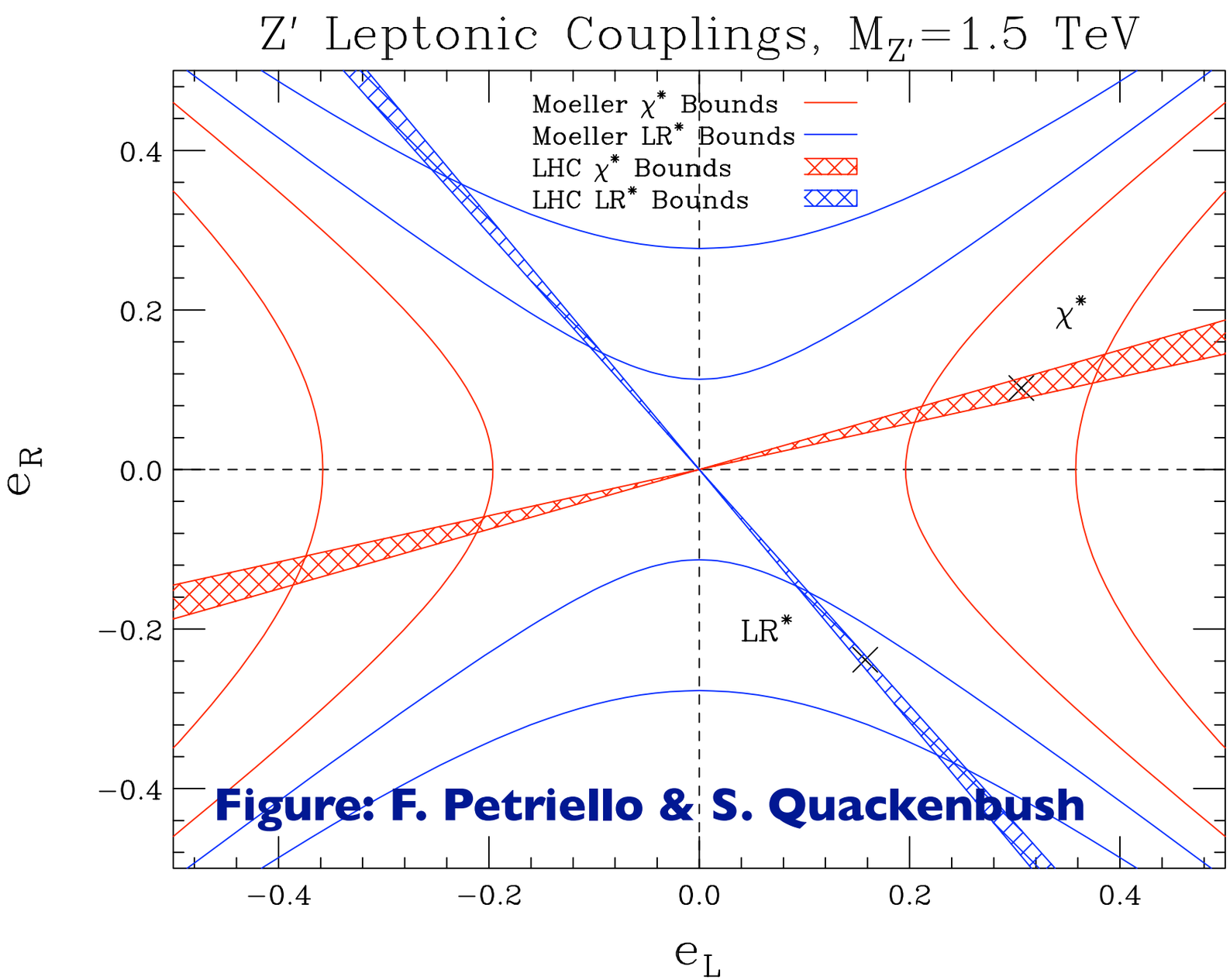


Figure: F. Petriello & S. Quackenbush

lepton coupling only: could break degeneracy between q and e couplings to Z'
QWeak can get sign of q×e

MOLLER sensitivity:

$$\frac{g_{RR}^2 - g_{LL}^2}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2} \sim \frac{1}{(7.5\mathrm{TeV})^2}$$

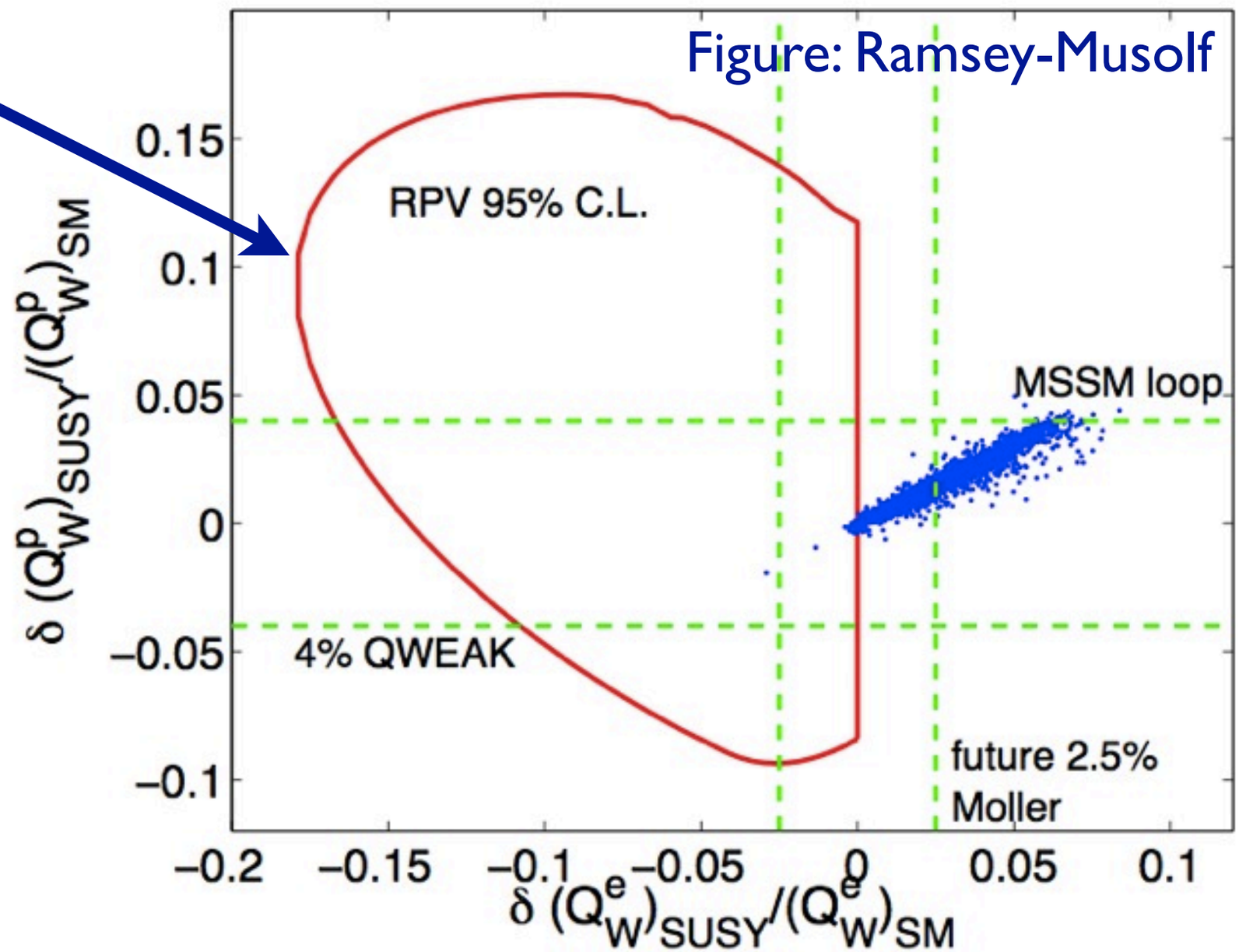
With mass, width, and A_{FB}, LHC can get constraint on e_R/e_L

PVES access to New Physics

Including global fit constraints

⇒ νs are Majorana

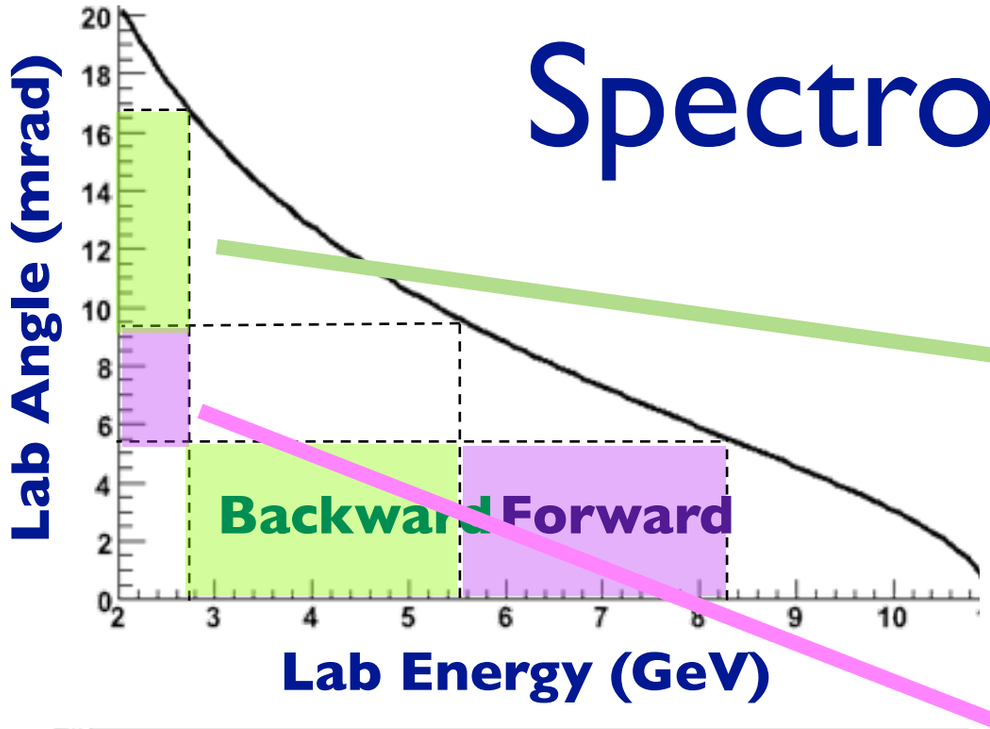
⇒ Lightest Supersymmetric Particle can't be Dark Matter

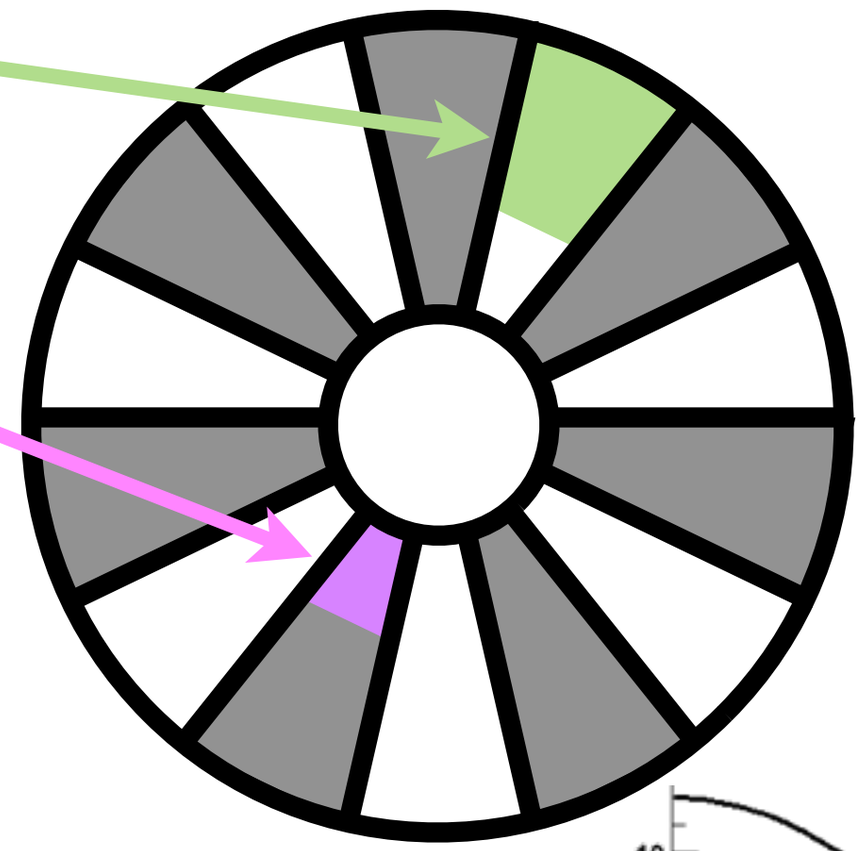


Tension between E158 and (g-2)μ

(if interpreted in SS, favors large loop effects)

Spectrometer Concept





Collimate opposing sectors.

Eliminates double counting.

Plenty of space for coils with **full** azimuthal acceptance.

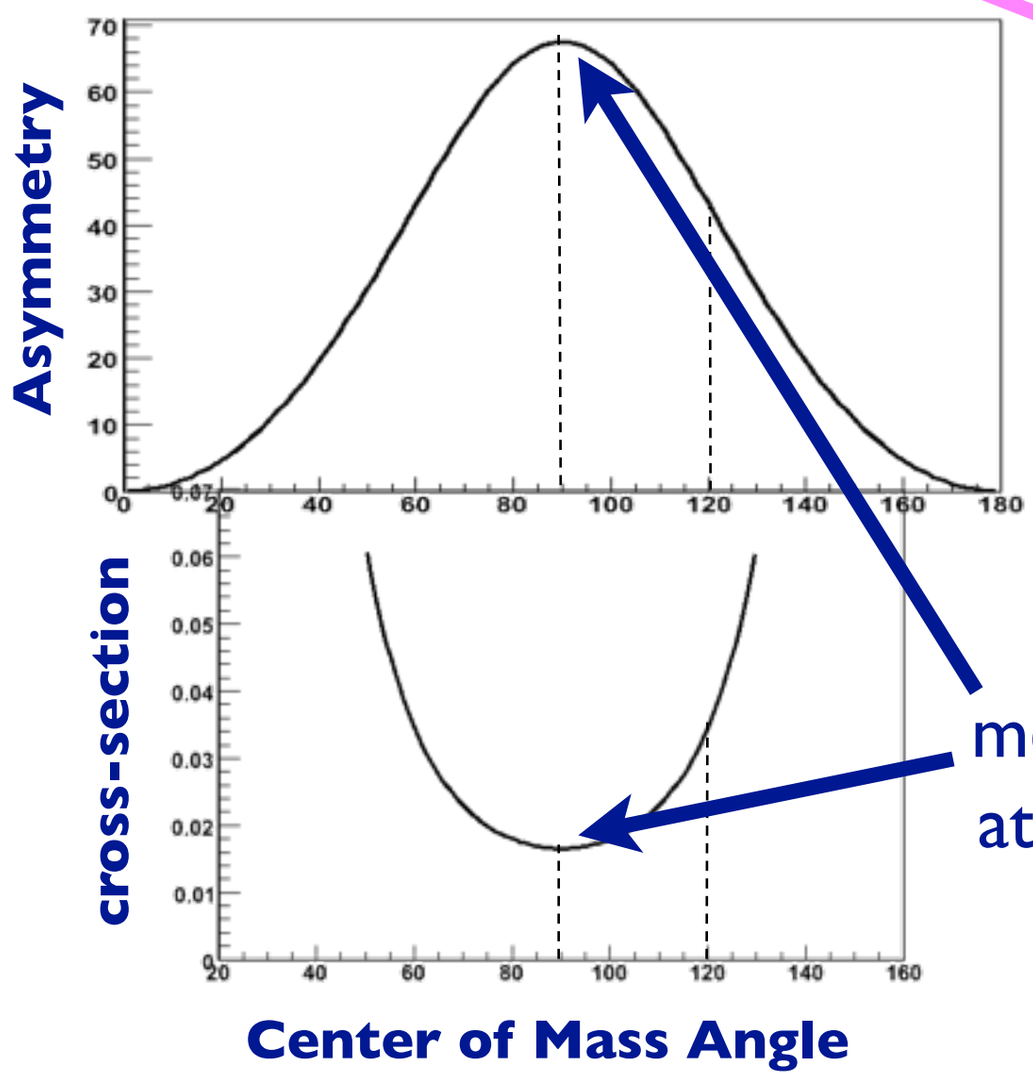
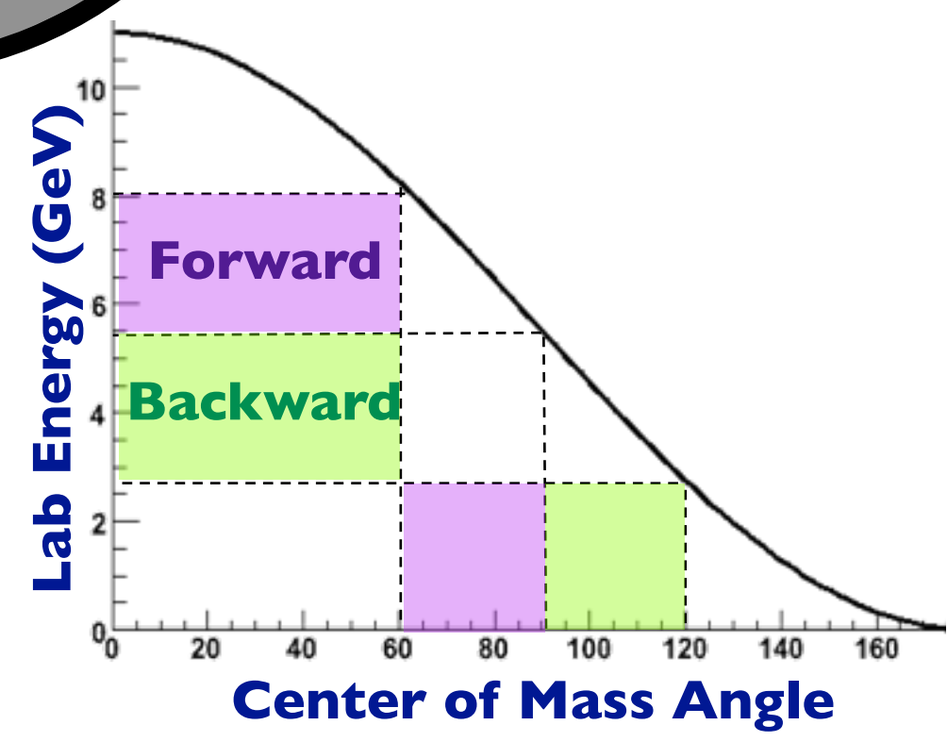
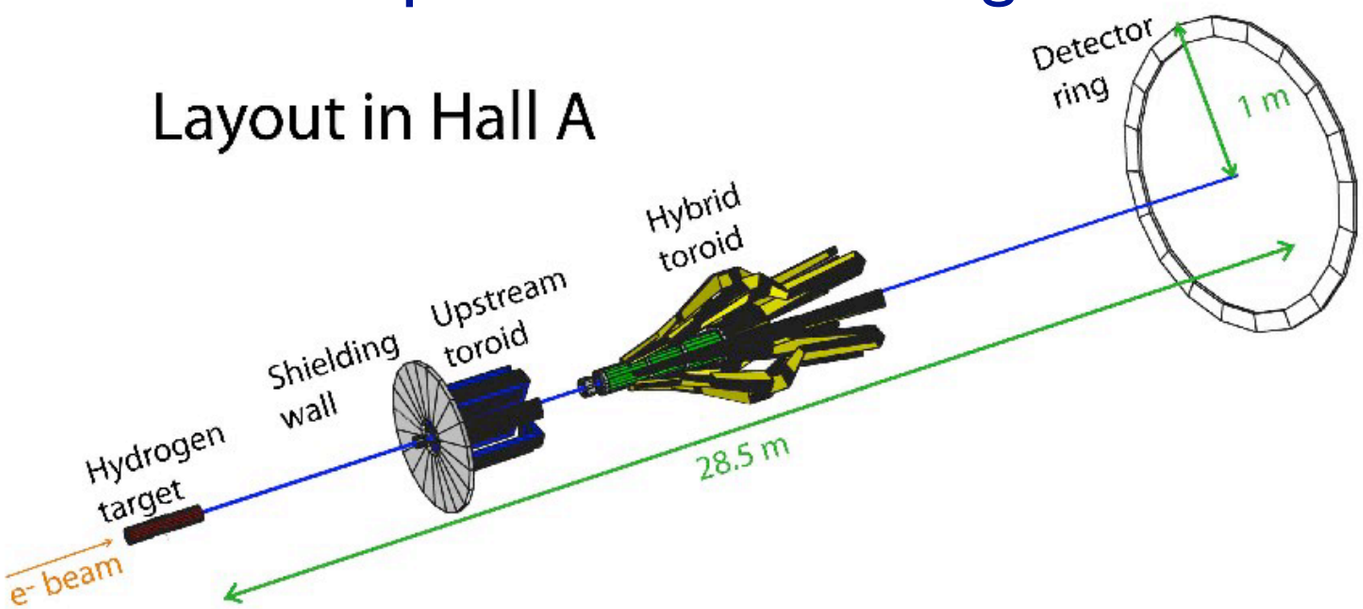


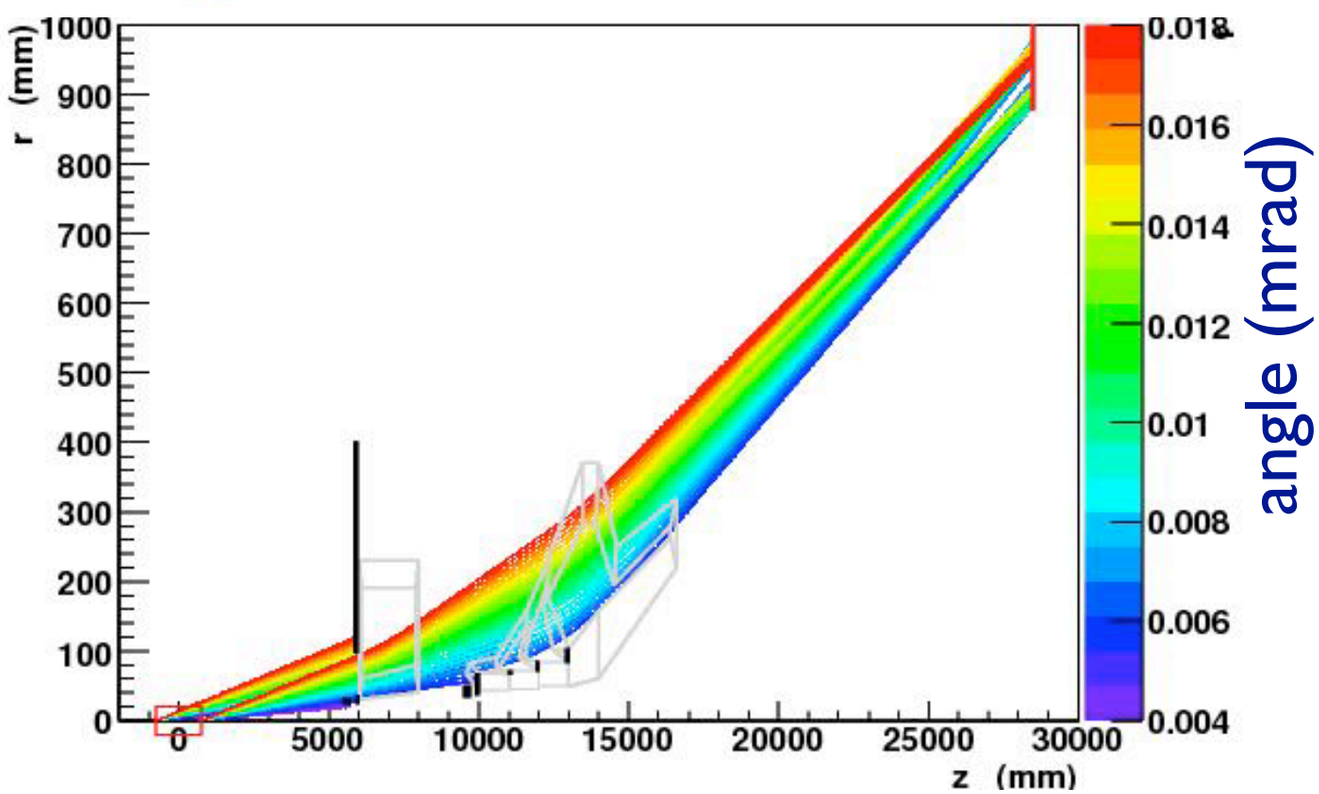
Figure of merit highest at $\theta_{CM} = 90°$

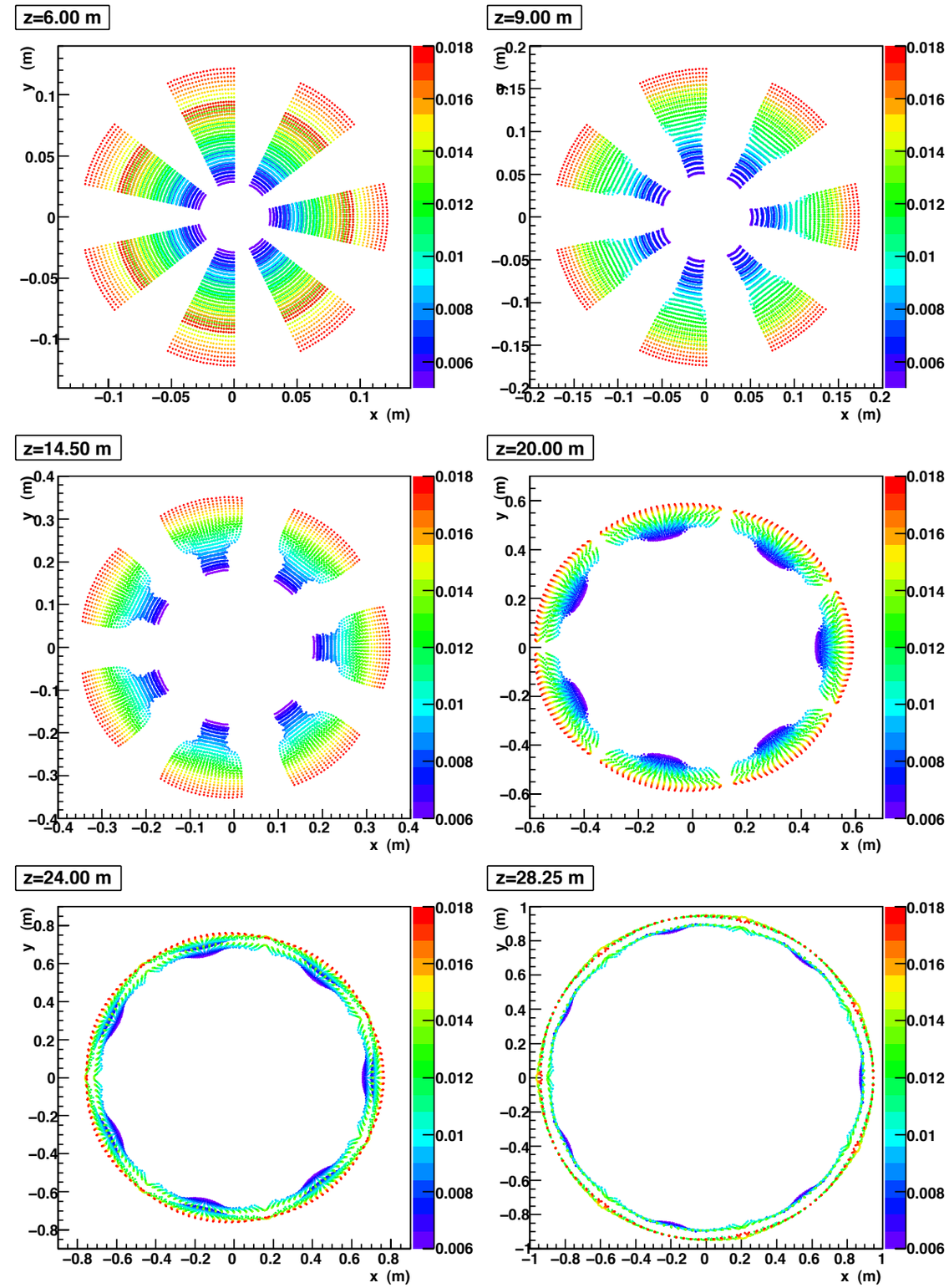


Two Toroid Configuration

1 meter radial focus, 30 meters from target
Clean separation from backgrounds





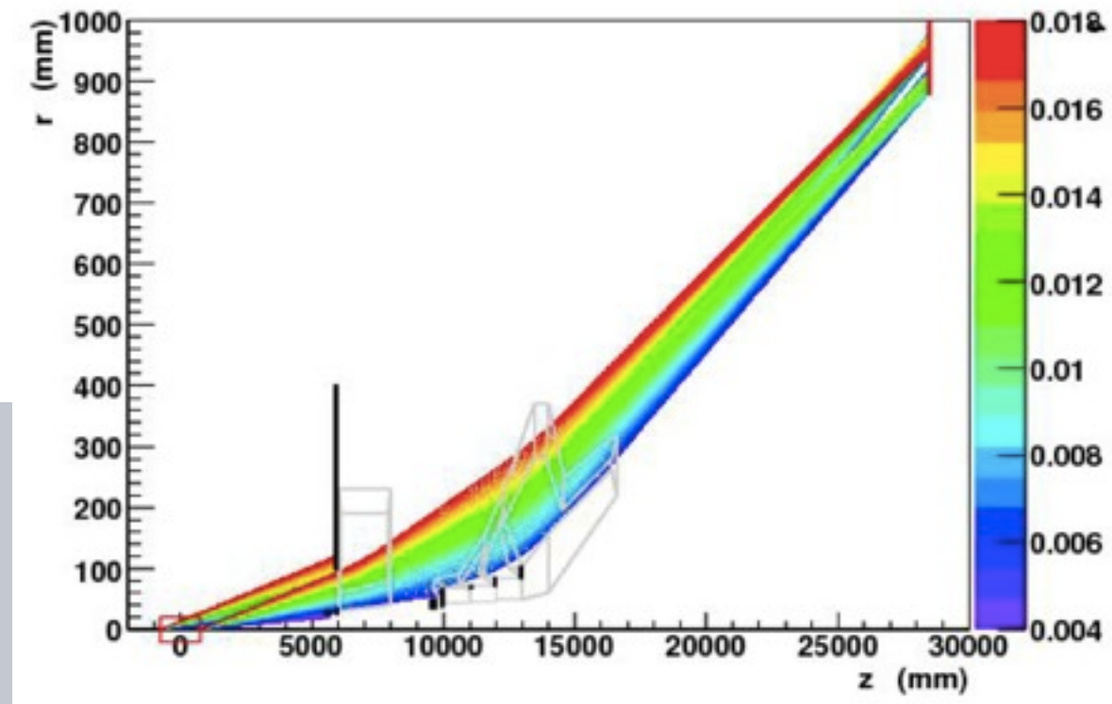


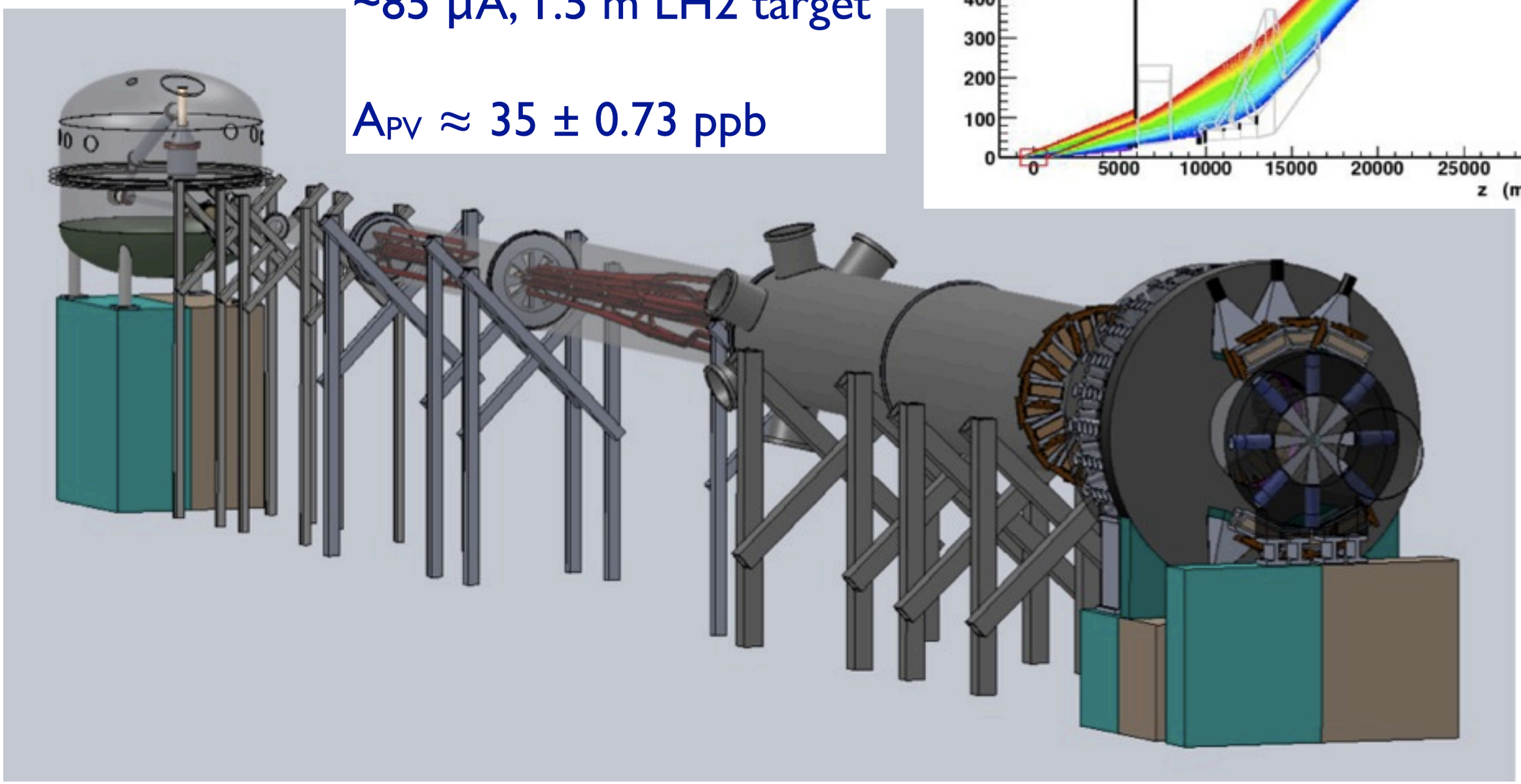
MOLLER Experiment

$Q^2 = 0.0056\ (\mathrm{GeV}/c)^2$
$E_{beam} = 11$ GeV
$0.29° < \theta_{lab} < 0.97°$

~85 μA, 1.5 m LH2 target

$A_{PV} \approx 35 \pm 0.73$ ppb





Statistics and Systematics Comparison

Accuracy goals for MOLLER are factors of 2 to 10 beyond those of E158 & Qweak

parameter	E158	Qweak	MOLLER
Rate	3 GHz	6 GHz	135 GHz
reversal rate	120 Hz	960 Hz	1920 Hz
pair stat. width	200 ppm	400 ppm	82.9 ppm
δ(Araw)	11 ppb	4 ppb	0.544 ppb
δ(Astat)/A	10%	3%	2.1%
$\delta(\sin^2\theta_W)$stat	0.001	0.0007	0.00026

Extremely narrow width increases sensitivity to noise sources e.g. electronics noise

MOLLER apparatus

Enormous technical challenges: MOLLER is a IV Generation Expt at JLab

Polarized Beam
- unprecedented polarized luminosity
- unprecedented beam stability

Liquid Hydrogen Target
- 5 kW dissipated power (2 X QWeak)
- computational fluid dynamics

Toroidal Spectrometer
- Novel 7 "hybrid coil" design
- warm magnets, aggressive cooling

Integrating Detectors
- build on QWeak and PREX
- intricate support & shielding
- radiation hardness and low noise

MOLLER error budget

source of error	% error
absolute value of Q2	0.5
beam second order	0.4
longitudinal beam polarization	0.4
inelastic e-p scattering	0.4
elastic e-p scattering	0.3
beam first order	0.3
pions and muons	0.3
transverse polarization	0.2
photons and neutrons	0.1
Total	**1.0**

Very little room for uncertainties from HC beam properties

Technical Challenges

~150 GHz Scattered Rate

Must flip Pockels cell ~ **2 kHz**

- **80 ppm** pair statistical fluctuations
  - electronic noise and density fluctuations $<10^{-5}$
  - beam jitter ~10 microns or less
  - beam monitoring resolution ~ few micron
  - ~**1 nm / 0.1 nrad** beam position change with helicity
  - >10 gm/cm^2 target, 1.5 meter LH2, ~**5kW**

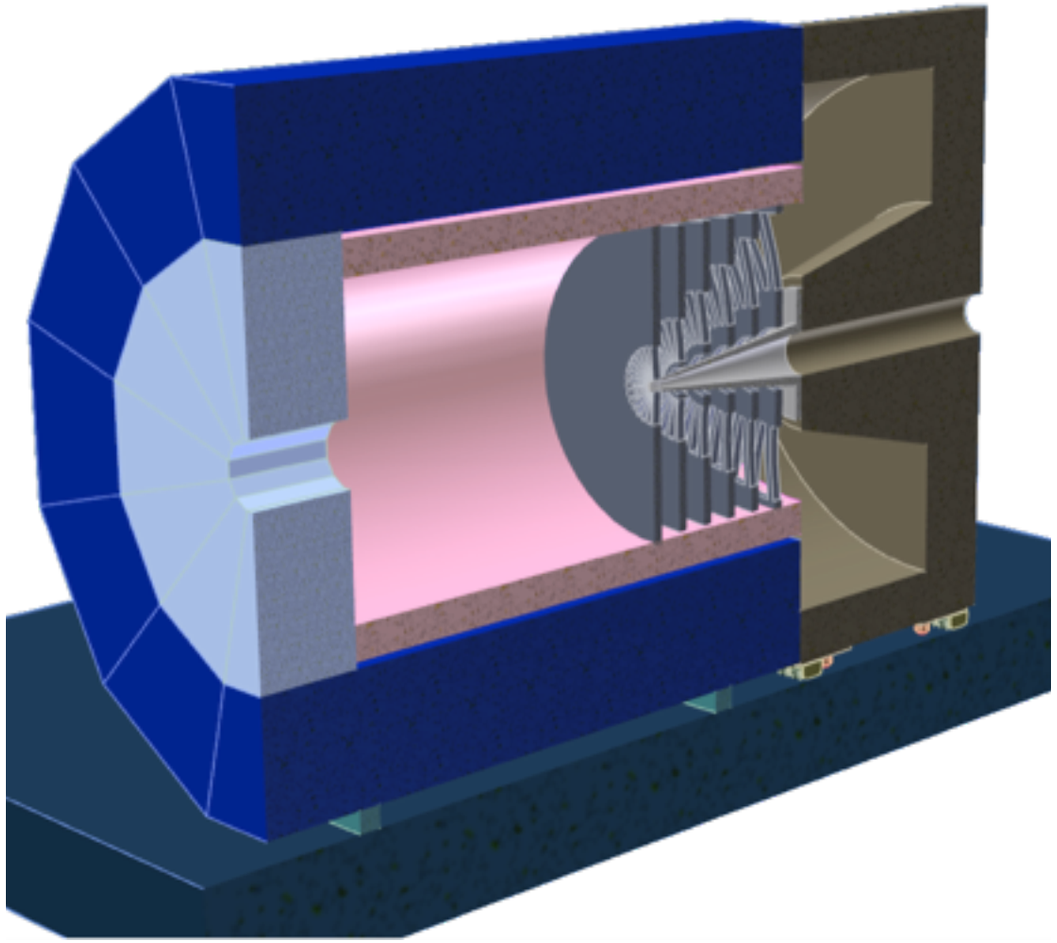
Full azimuthal acceptance for 0.3° scattering

- **novel** two-toroid spectrometer
- radiation hard integrating detectors

Robust and redundant **0.4% beam polarimetry**

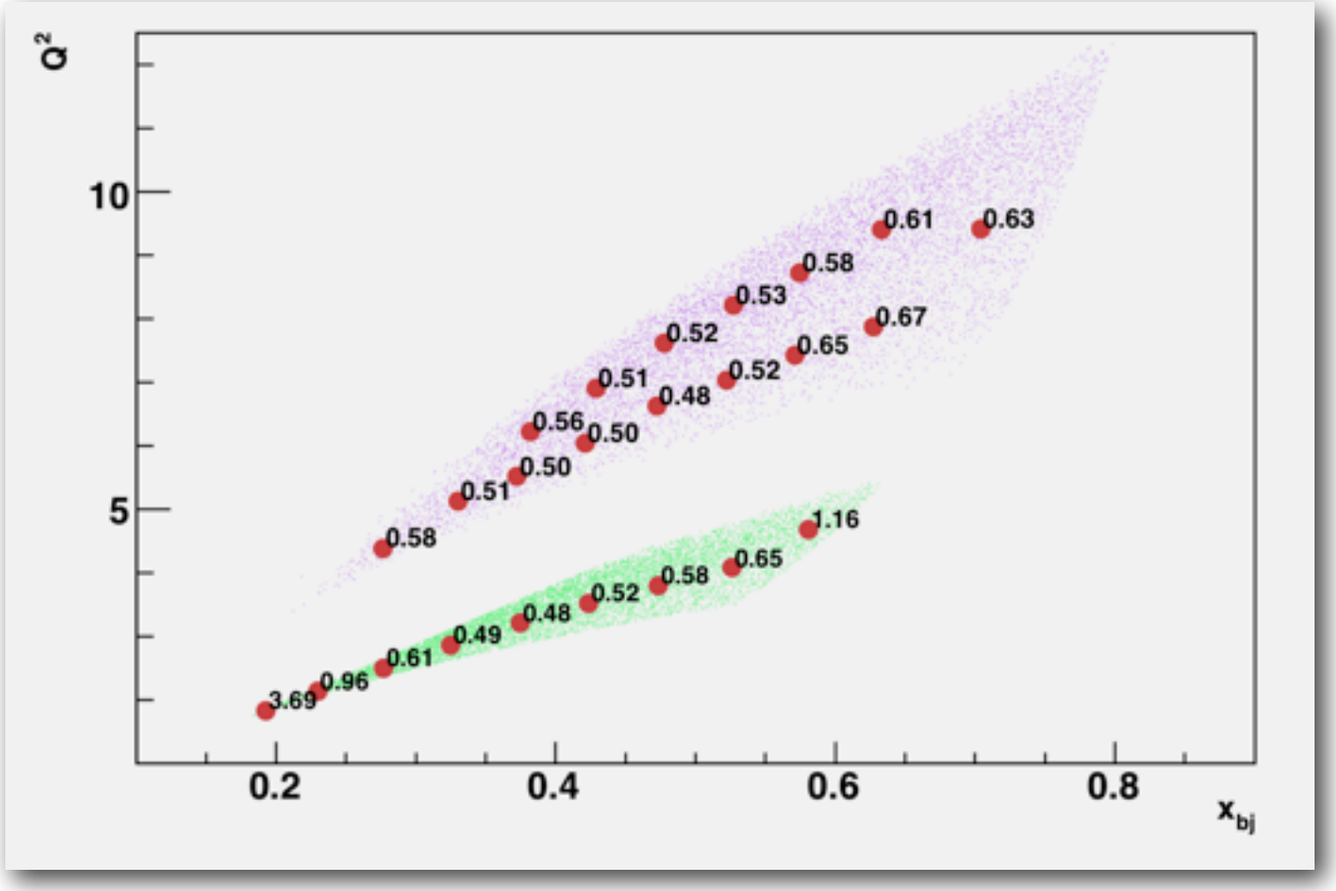
- Both atomic hydrogen Moller and improved Compton

SOLID



Unique access to axial weak hadronic coupling tests un-illuminated corner of BSM parameter space

Broad program of hadronic studies: high-x partonic structure, transverse spin structure, nuclear modification, QCD studies



Conclusions

- The Standard Model has 3 electroweak parameters that appear in a multitude of different reactions.

- Experiments are ultimately sensitive to combinations of all parameters. Multi-loop calculations are necessary to compare experiment to theory.

- The theory should be able to describe experimental data to arbitrary precision. (It does so far!)

- Precision experiments test the theory. These can be done at Jefferson lab.