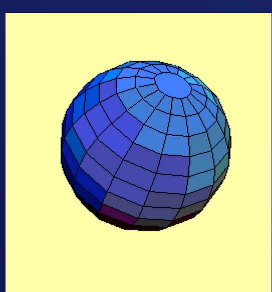
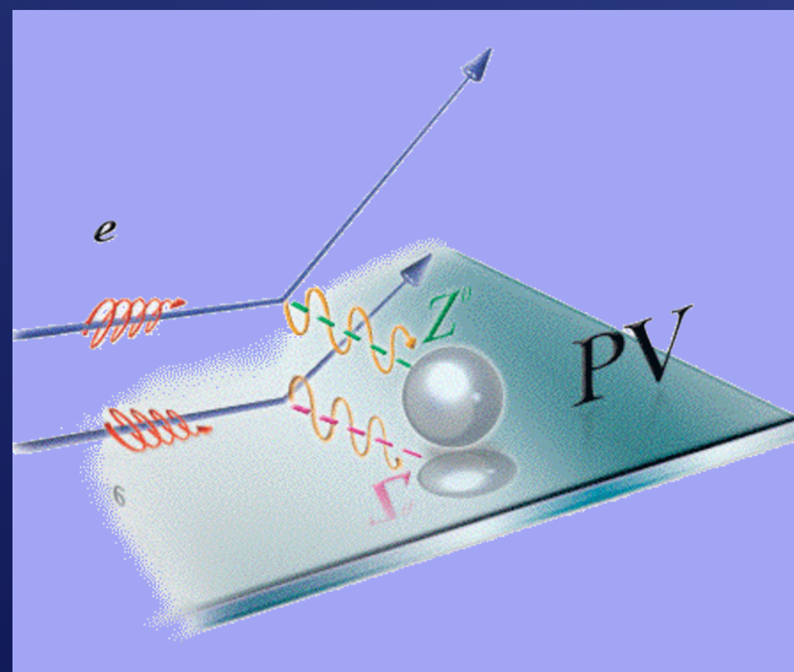
Weak form factors and standard model tests



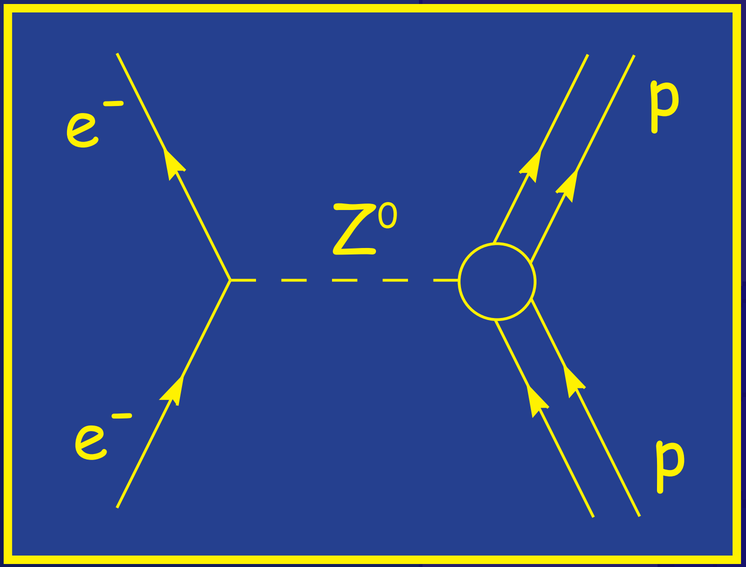


Gordon D. Cates

University of Virginia

QCD and Hadron Physics Town Meeting - Rutgers- January 12, 2007

The Z^0 has shown itself to be an increasingly versatile probe over the past 2+ decades

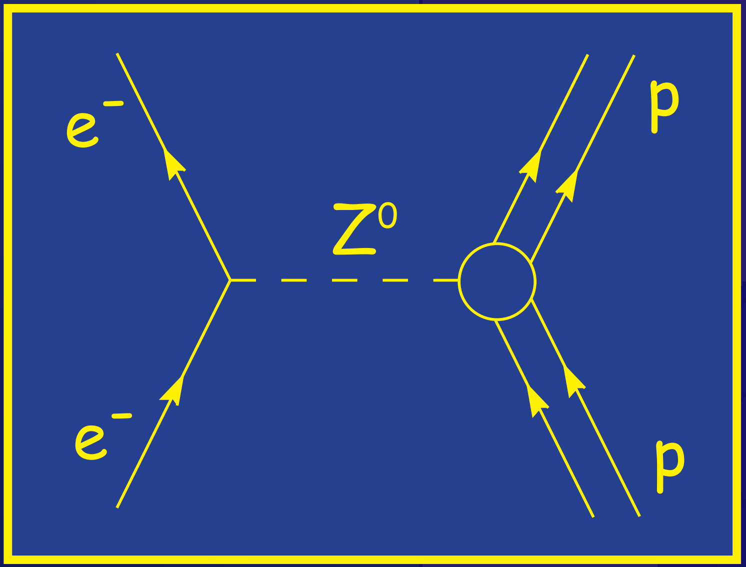


- Establishing the standard model.
- Exploring the role of strange quarks in hadronic structure.
- Searching for physics beyond the standard model.

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F\, Q^2}{4\pi\,\alpha}$$

Weak amplitudes can be readily studied by measuring parity violating asymmetries that result from their interference with electromagnetic amplitudes.

The Z^0 has shown itself to be an increasingly versatile probe over the past 2+ decades



- Establishing the standard model.
- Exploring the role of strange quarks in hadronic structure.
- Searching for physics beyond the standard model.

Exciting and diverse new applications are coming. For example:

- PREx: Mapping out the neutron distribution in lead.
- Studying charge symmetry violation (CSV) in the parton distribution functions.

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F\, Q^2}{4\pi\, \alpha}$$

Weak amplitudes can be readily studied by measuring parity violating asymmetries that result from their interference with electromagnetic amplitudes.

Parity violating spin-asymmetry in elastic scattering from the proton

The parity violating spin-asymmetry that results from elastic scattering off the proton is rich with diverse types of physics !

$$A^{PV} = \left[\frac{-G_F\, M_p^2\, Q^2}{\pi\alpha\sqrt{2}}\right]\left[(1 - 4\sin^2\theta_W) - \frac{\epsilon\, G_E^{p\gamma}(G_E^{n\gamma} + G_E^s) + \tau\, G_E^{p\gamma}(G_M^{n\gamma} + G_M^s)}{\epsilon(G_E^{p\gamma})^2 + \tau(G_M^{p\gamma})^2}\right] - A_A$$

Parity violating spin-asymmetry in elastic scattering from the proton

The parity violating spin-asymmetry that results from elastic scattering off the proton is rich with diverse types of physics !

$$A^{PV} = \left[\frac{-G_F\, M_p^2\, Q^2}{\pi\alpha\sqrt{2}}\right]\left[(1 - 4\sin^2\theta_W) - \frac{\epsilon\, G_E^{p\gamma}(G_E^{n\gamma} + G_E^s) + \tau\, G_E^{p\gamma}(G_M^{n\gamma} + G_M^s)}{\epsilon(G_E^{p\gamma})^2 + \tau(G_M^{p\gamma})^2}\right] - A_A$$

This term is proportional to the weak charge.

Parity violating spin-asymmetry in elastic scattering from the proton

The parity violating spin-asymmetry that results from elastic scattering off the proton is rich with diverse types of physics !

$$A^{PV} = \left[\frac{-G_F\, M_p^2\, Q^2}{\pi\alpha\sqrt{2}}\right]\left[(1-4\sin^2\theta_W) - \frac{\epsilon\, G_E^{p\gamma}(G_E^{n\gamma}+G_E^s) + \tau\, G_E^{p\gamma}(G_M^{n\gamma}+G_M^s)}{\epsilon(G_E^{p\gamma})^2 + \tau(G_M^{p\gamma})^2}\right] - A_A$$

This term is proportional to the weak charge.

This term is proportional to hadronic structure, including the strange-quark form factors.

Parity violating spin-asymmetry in elastic scattering from the proton

The parity violating spin-asymmetry that results from elastic scattering off the proton is rich with diverse types of physics !

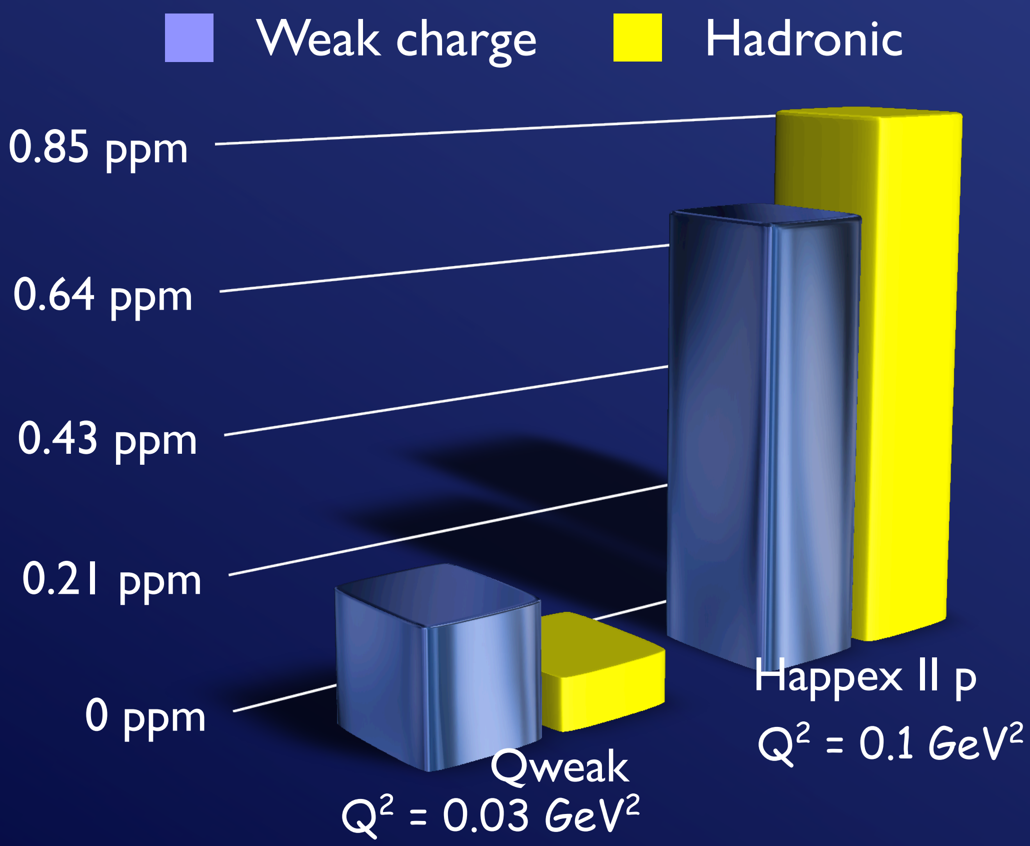
$$A^{PV} = \left[\frac{-G_F\, M_p^2\, Q^2}{\pi\alpha\sqrt{2}}\right]\left[(1-4\sin^2\theta_W) - \frac{\epsilon\, G_E^{p\gamma}(G_E^{n\gamma}+G_E^s) + \tau\, G_E^{p\gamma}(G_M^{n\gamma}+G_M^s)}{\epsilon(G_E^{p\gamma})^2+\tau(G_M^{p\gamma})^2}\right] + A_A$$

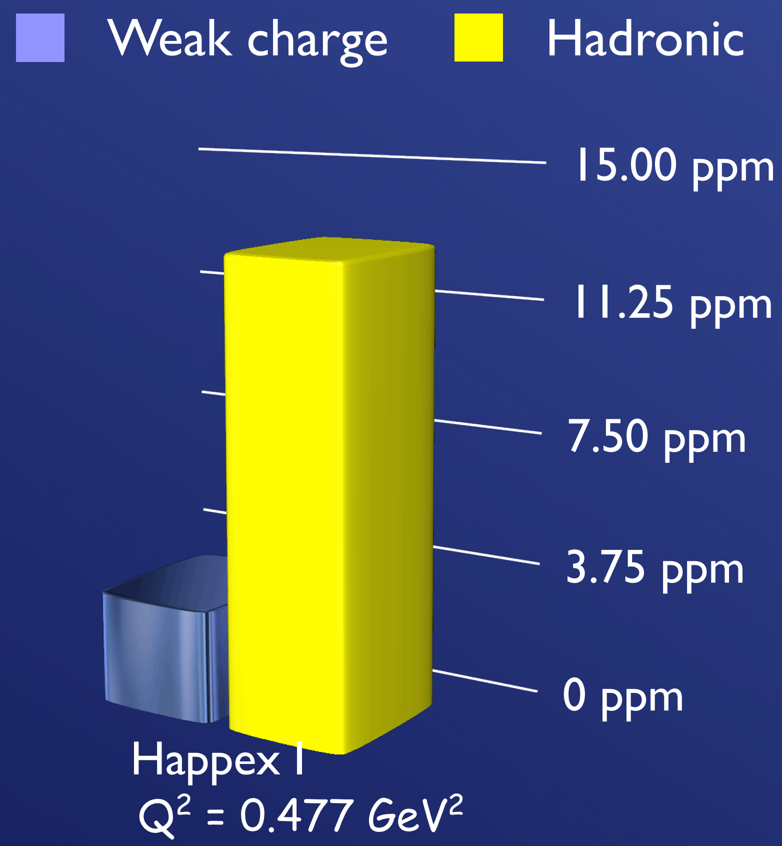
This term is proportional to the weak charge.

This term is proportional to hadronic structure, including the strange-quark form factors.

This term is proportional to the neutral weak axial form factor, and contains contributions from things such as the anapole moment.

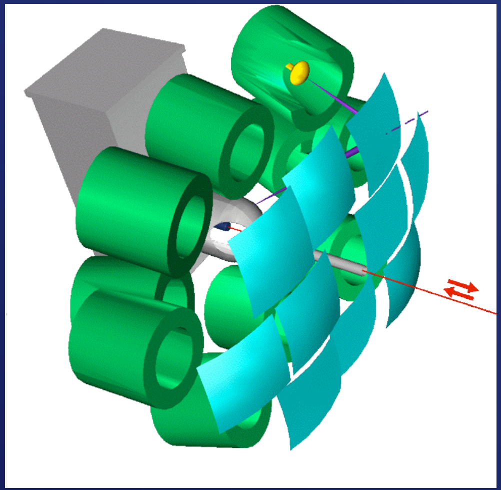
In PV elastic $\vec{e}$-p scattering, different kinematics emphasizes different physics





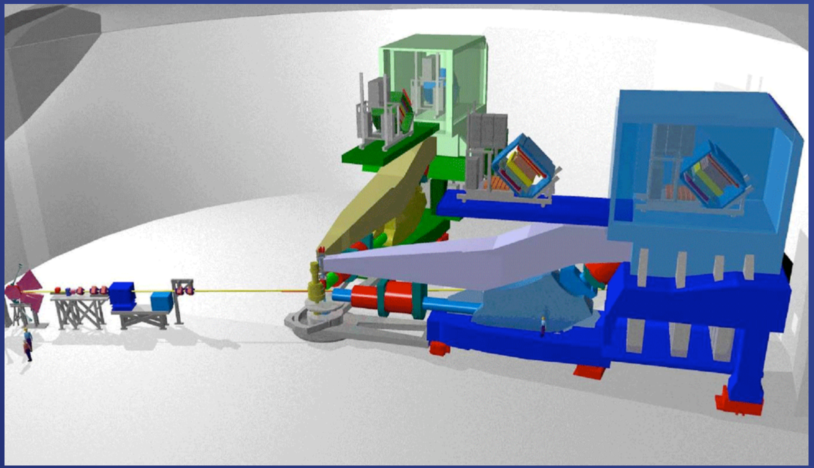
The relative contributions from the weak charge and hadronic structure change dramatically depending on the Q^2

experiments to measure strange form factors

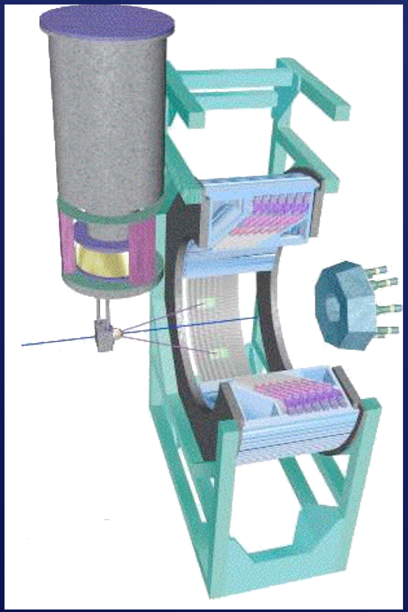


SAMPLE
Open geometry, backward angle, integrating,
G_M^s and G_A at Q^2=0.1 GeV^2

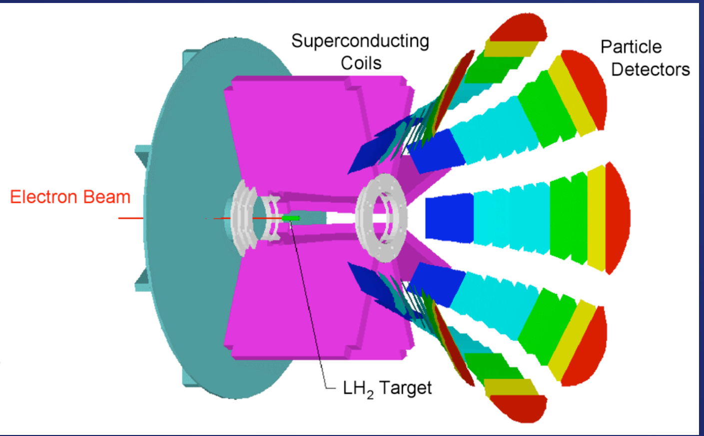
HAPPEX
forward angle, integrating,
G_E^s + 0.39 G_M^s at Q^2=0.48 GeV^2
G_E^s + 0.08 G_M^s at Q^2=0.1 GeV^2
G_E^s at Q^2=0.1 GeV^2 (^{4}He)



A4 (Mainz)
fast-counting calorimeter for background rejection
G_E^s + 0.23 G_M^s at Q^2=0.23 GeV^2
G_E^s + 0.1 G_M^s at Q^2=0.1 GeV^2
G_M^s, G_A at Q^2=0.1, 0.23, 0.5 GeV^2

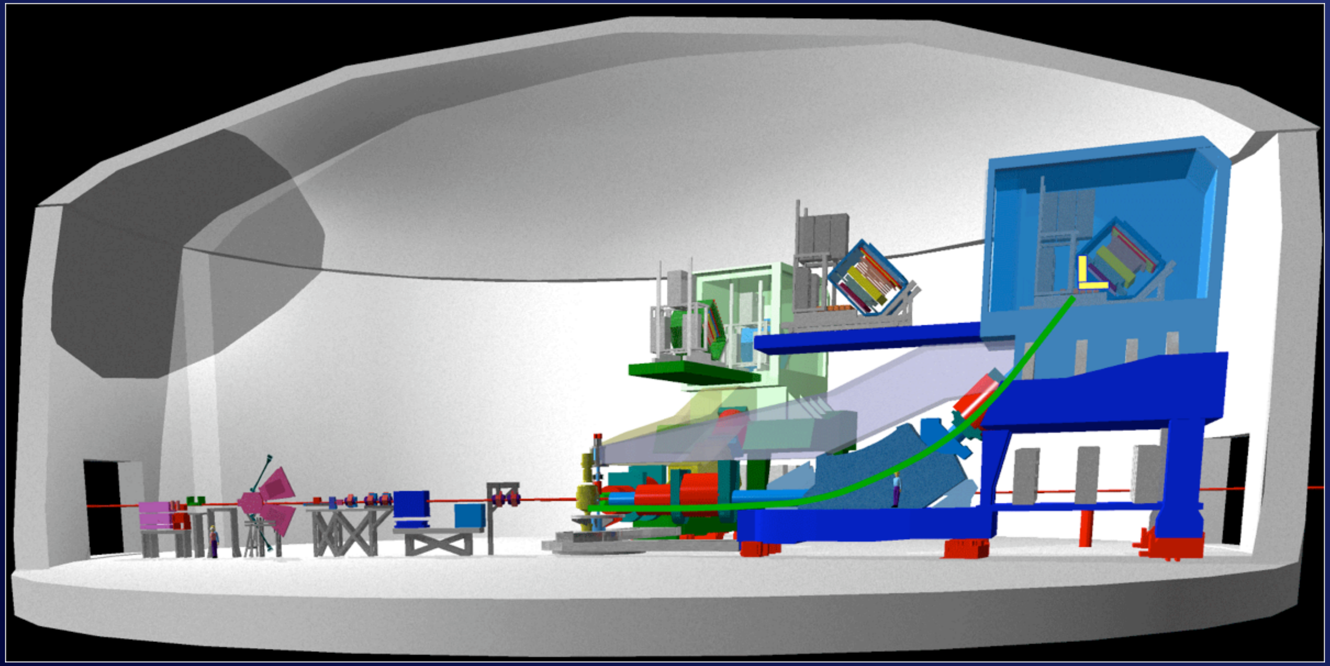


G0
fast counting, open geometry with ToF for background rejection
G_E^s + η G_M^s over Q^2=[0.12,1.0] GeV^2
G_M^s, G_A at Q^2= 0.23, 0.63 GeV^2



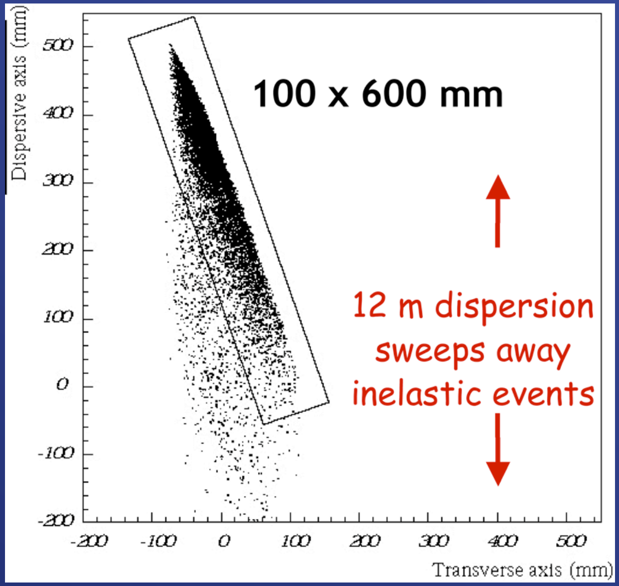
Experimental approach for Happex

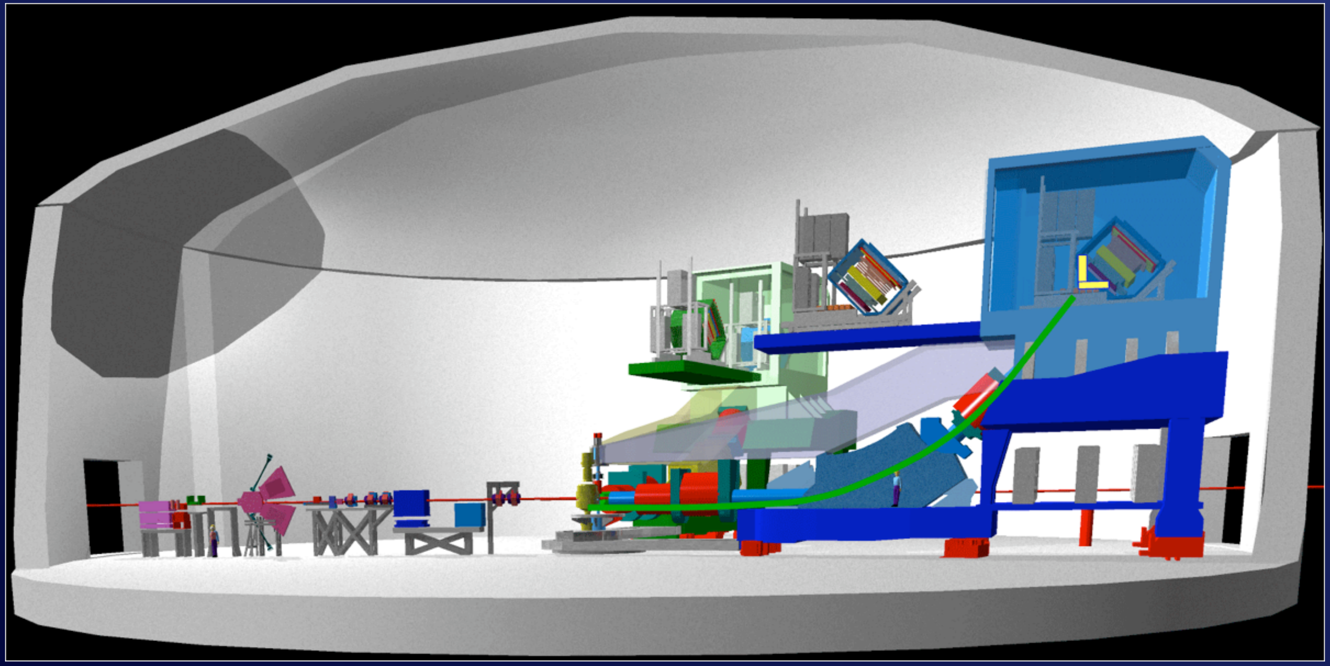
- Polarized electrons are scattered off protons or ^{4}He nuclei in a 20 cm 400W transverse-flow LH_2 or high-pressure ^{4}He target.



Experimental approach for Happex

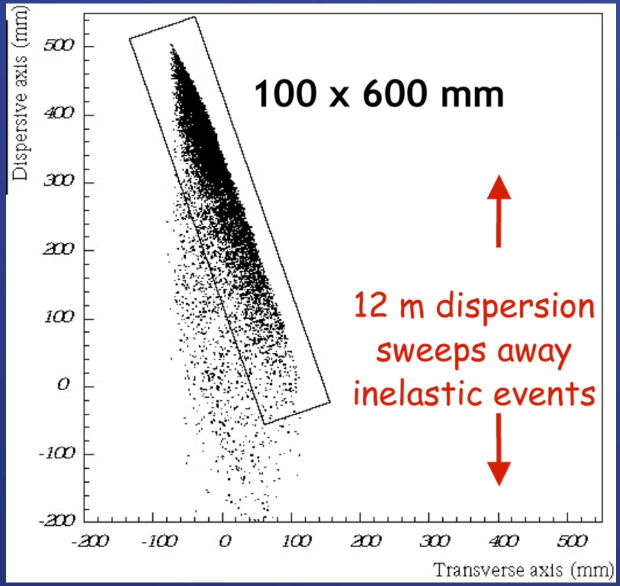
- Polarized electrons are scattered off protons or ^{4}He nuclei in a 20 cm 400W transverse-flow LH_2 or high-pressure ^{4}He target.
- Elastically scattered electrons are detected using a high-resolution spectrometer (septum + QQDQ) at 4°-8° and 5 mstr/spectrometer arm.

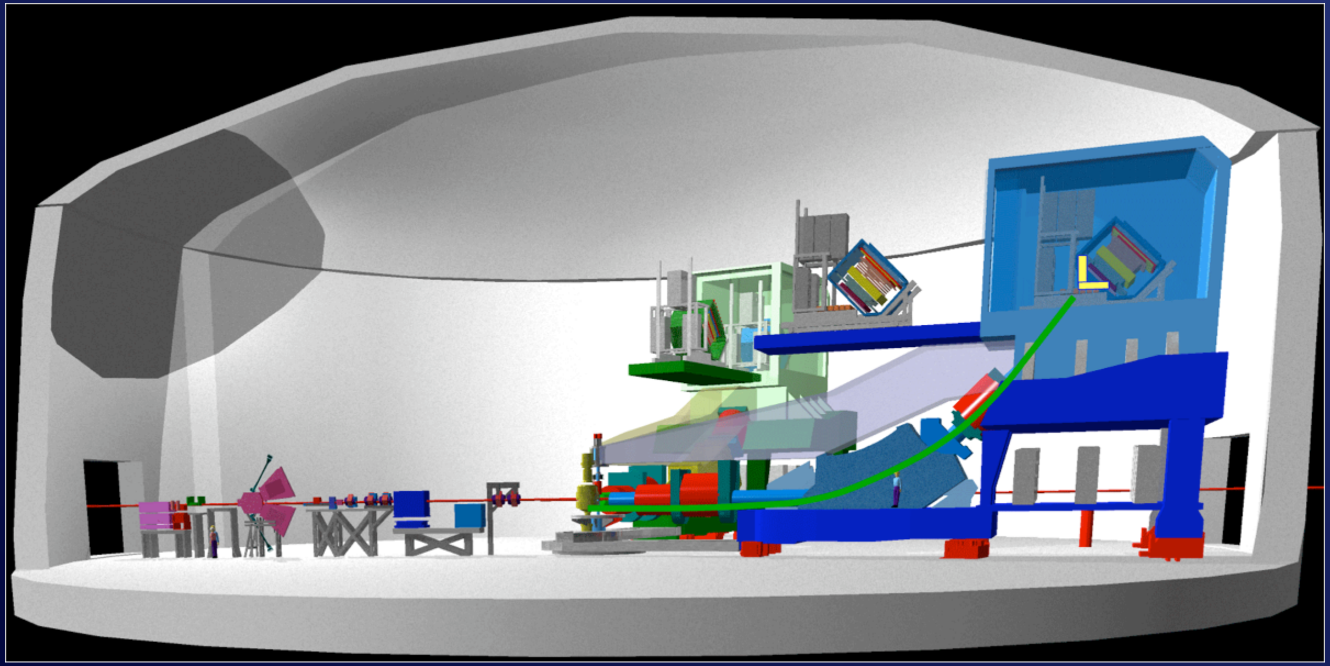


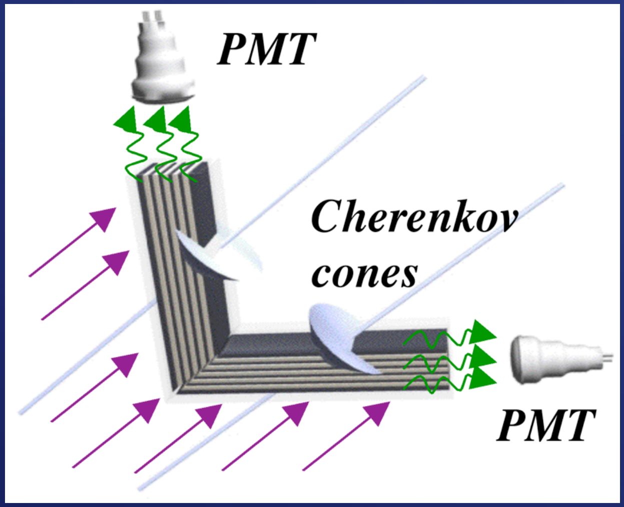


Experimental approach for Happex

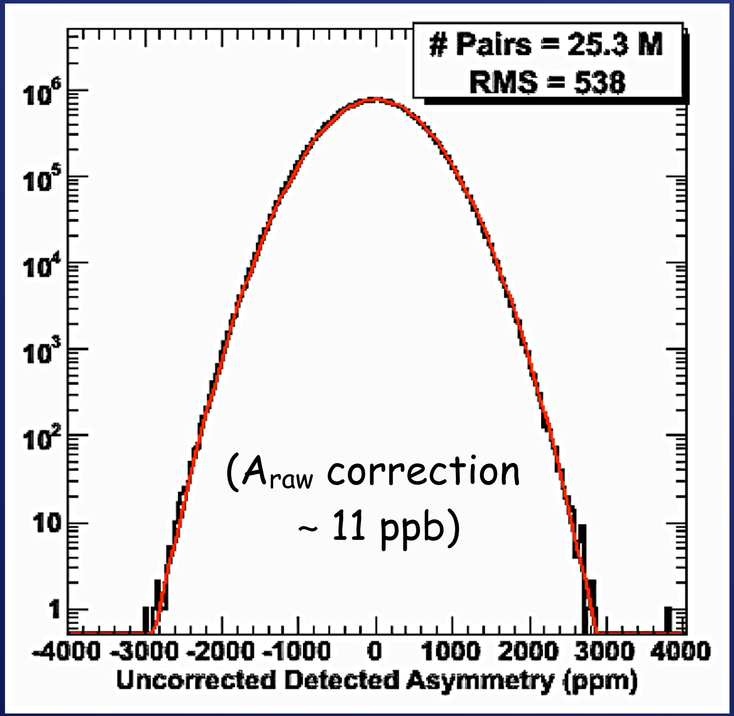
- Polarized electrons are scattered off protons or ^{4}He nuclei in a 20 cm 400W transverse-flow LH_2 or high-pressure ^{4}He target.
- Elastically scattered electrons are detected using a high-resolution spectrometer (septum + QQDQ) at 4°-8° and 5 mstr/spectrometer arm.
- High rates (120 MHz for H and 12 MHz for ^{4}He) are handled using integrating Cherenkov detectors.



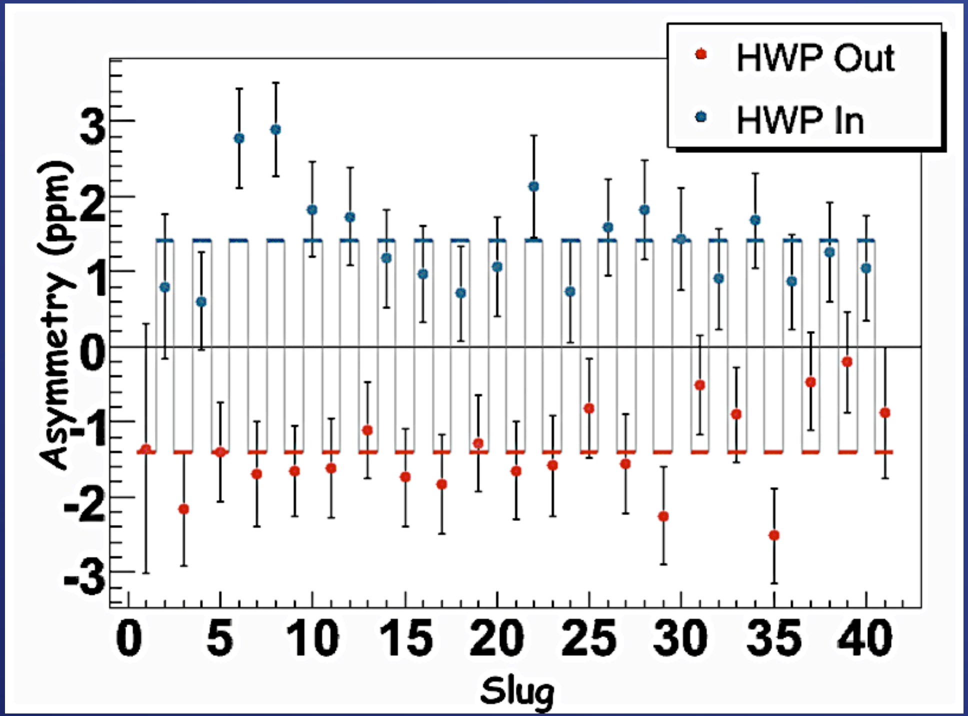




Data from Happex II proton run



Histogram of asymmetries associated with individual pulse pairs shows Gaussian behavior over six decades

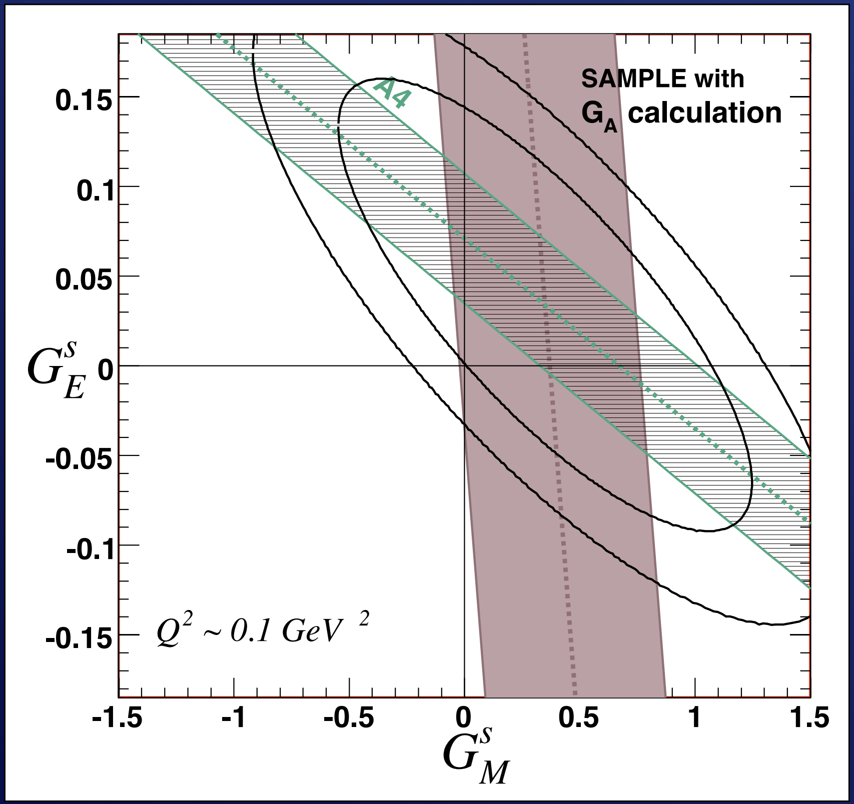


Asymmetries associated with each slug - a group of runs taken for a given half-wave plate setting.

Q^2 = 0.1089 +/- 0.0011 GeV^2

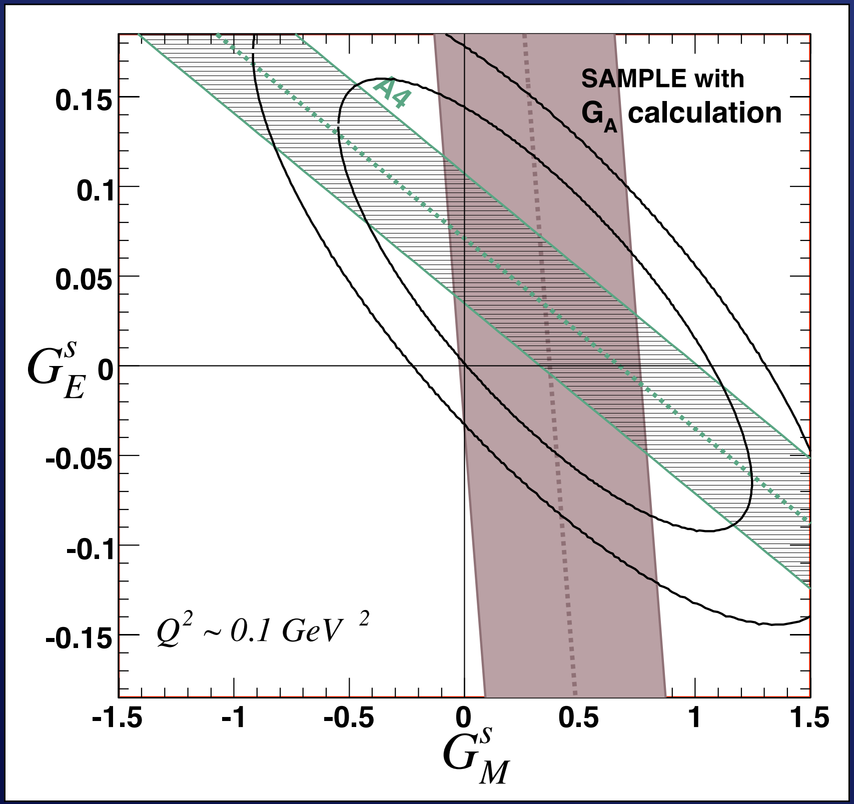
A_{raw} = -1.418 +/- 0.105 ppm (stat)

Overall, there has been tremendous progress on our understanding of G_E^s and G_M^s. At $Q^2 = 0.1\ GeV^2$:

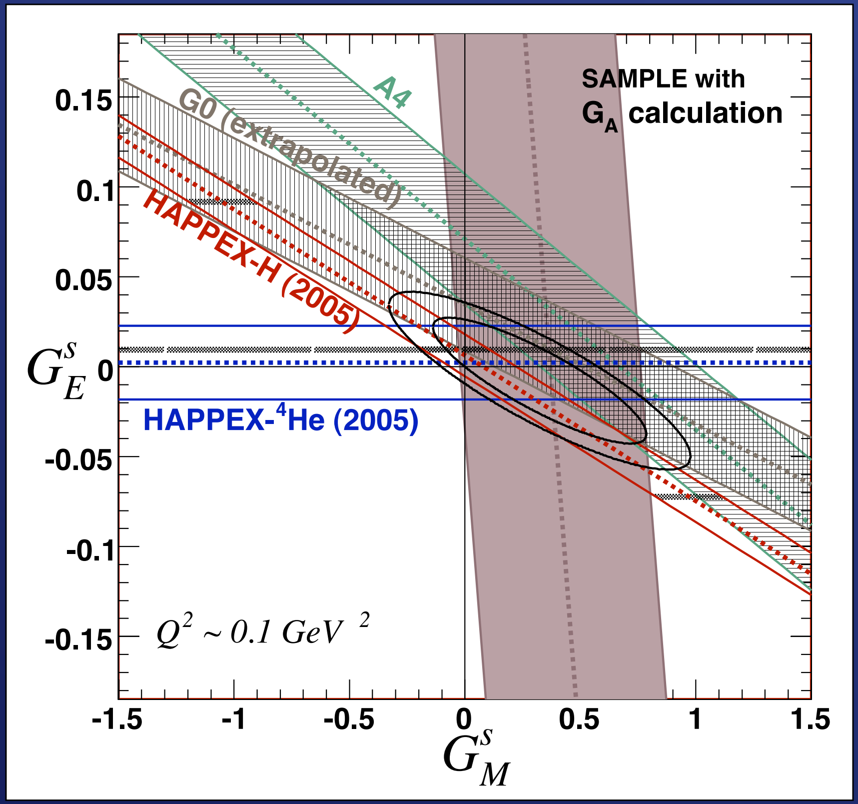


Pre-Happex II pre-G0 time period with only A4 (Mainz) and SAMPLE

Overall, there has been tremendous progress on our understanding of G_E^s and G_M^s. At Q^2 = 0.1 GeV^2:

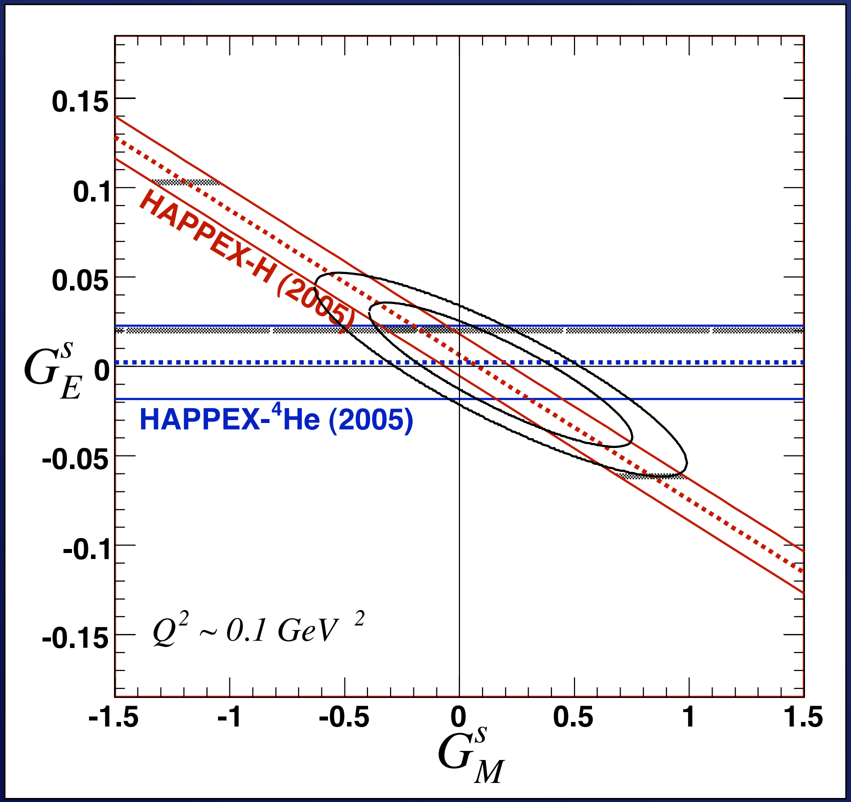


Pre-Happex II pre-G0 time period with only A4 (Mainz) and SAMPLE

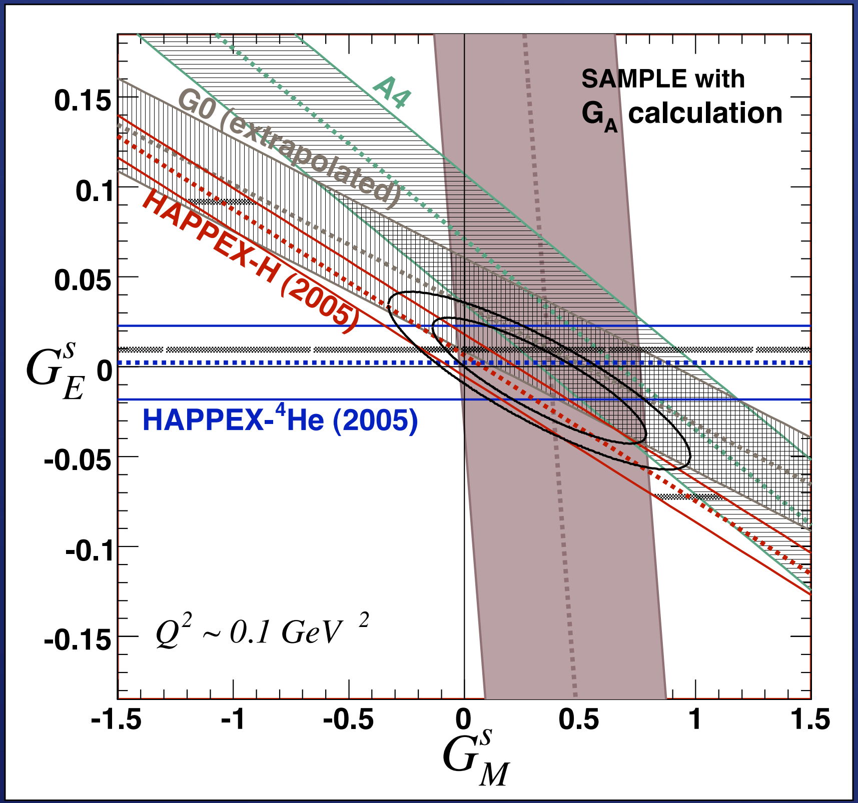


All results, including SAMPLE, A4, Happex II, and G0 extrapolated to 0.1 GeV^2

Overall, there has been tremendous progress on our understanding of G_E^s and G_M^s. At $Q^2 = 0.1$ GeV^2:

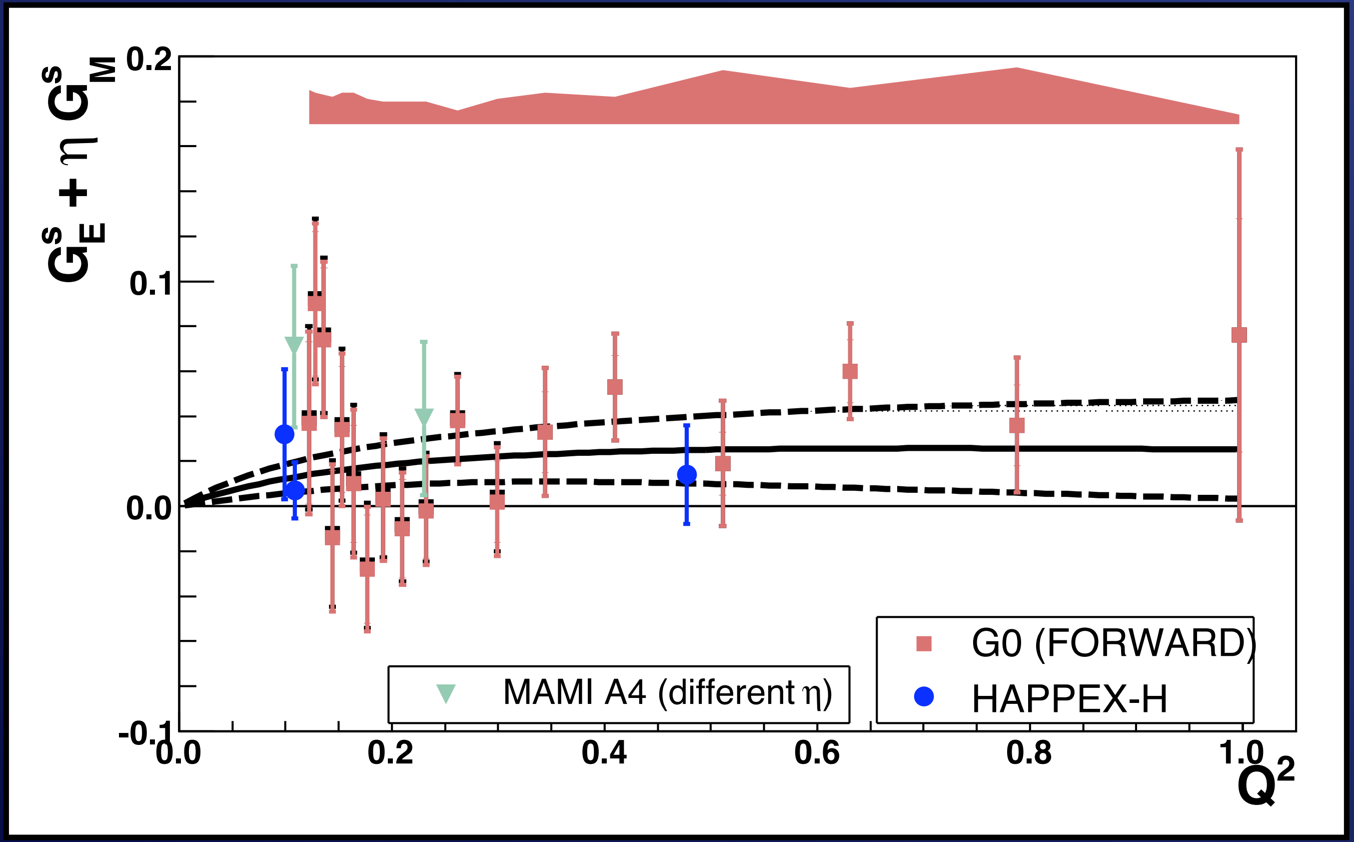


Happex II only



All results, including SAMPLE, A4, Happex II, and G0 extrapolated to 0.1 GeV^2

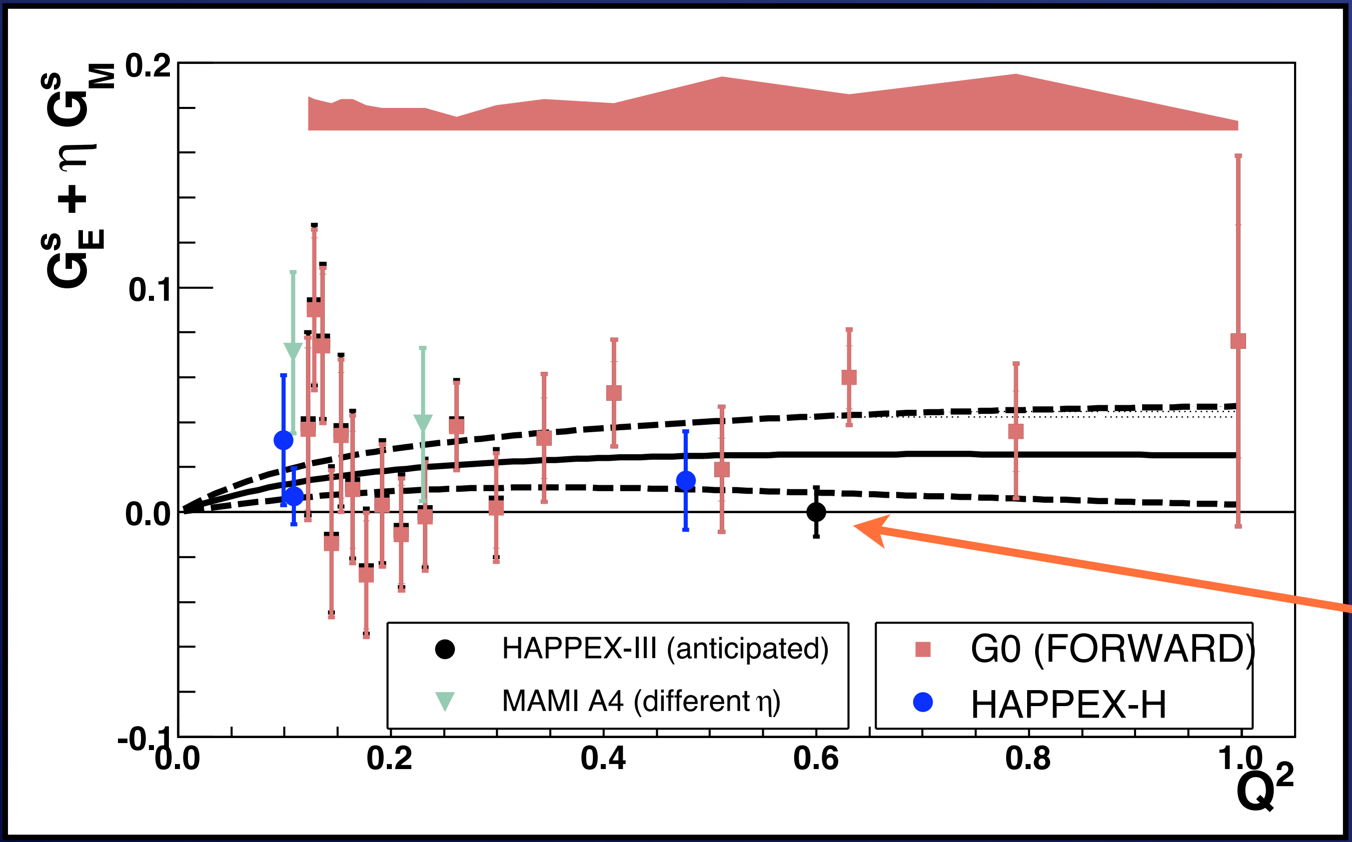
Current and future data on $G_E^s + \eta G_M^s$ at forward angles at all Q^2



Black line shows very simple naive fit.

Data are suggestive of positive values, but would be unlikely to convince a skeptic.

Current and future data on $G_E^s + \eta G_M^s$ at forward angles at all Q^2

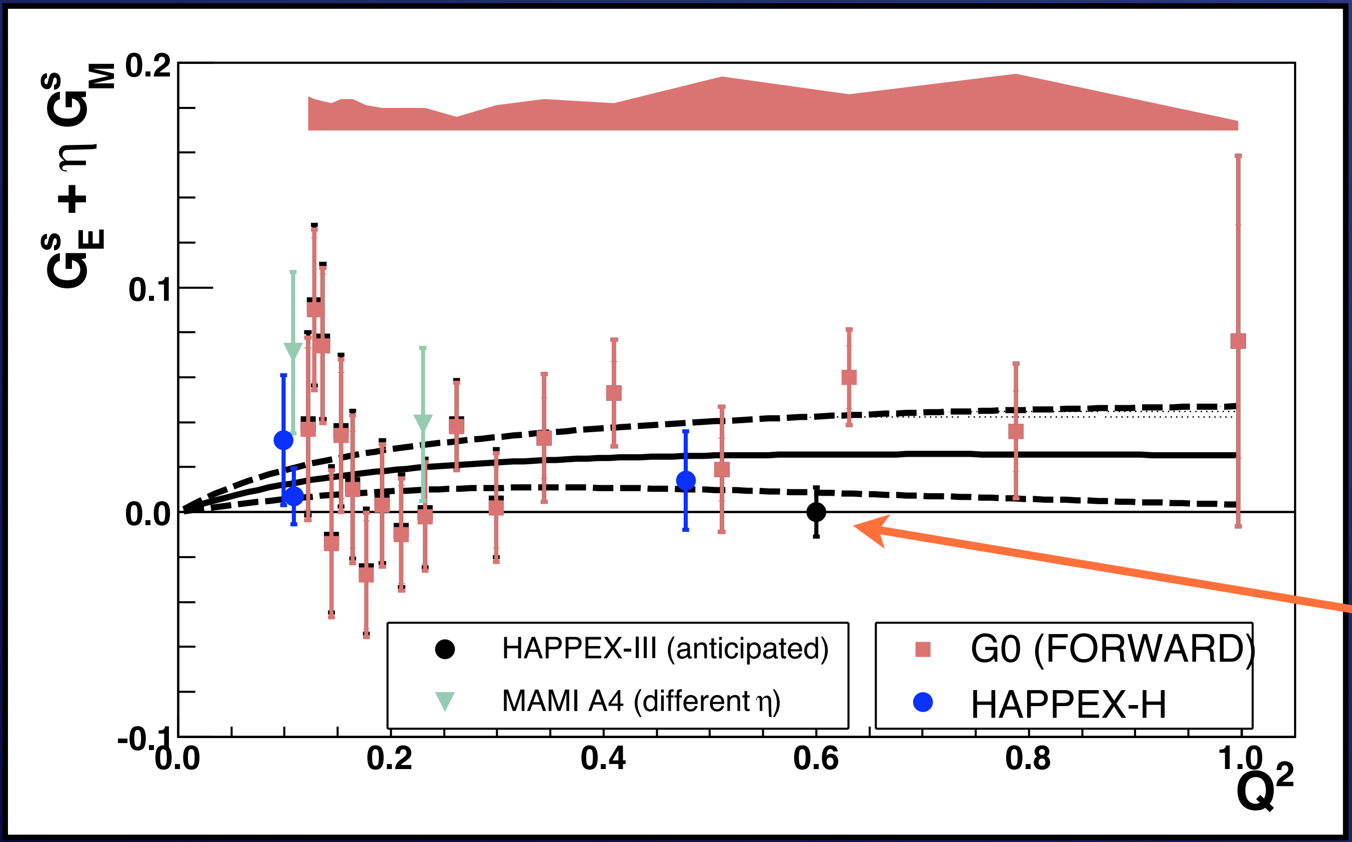


Black line shows very simple naive fit.

Data are suggestive of positive values, but would be unlikely to convince a skeptic.

More Happex data are forthcoming at Q^2 = 0.6 GeV^2, (centered at zero). Not shown are upcoming back-angle data from both G0 and A4

Current and future data on $G_E^s + \eta G_M^s$ at forward angles at all Q^2



Black line shows very simple naive fit.

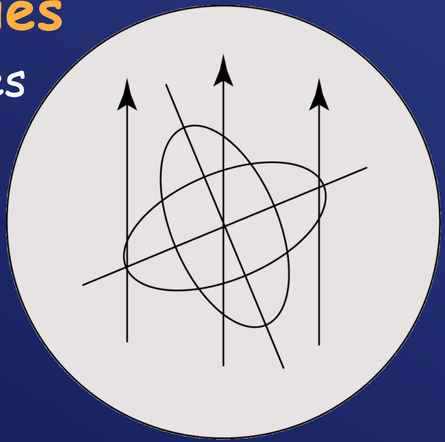
Data are suggestive of positive values, but would be unlikely to convince a skeptic.

More Happex data are forthcoming at Q^2 = 0.6 GeV^2, (centered at zero). Not shown are upcoming back-angle data from both G0 and A4

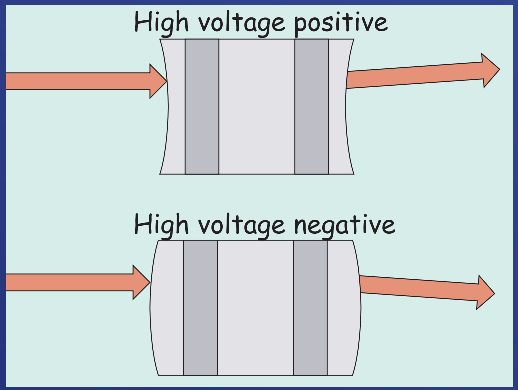
New data at Q^2 = 0.6 GeV^2 should strongly constrain the higher Q^2 region.

Two decades of effort has resulted in atomic-scale control over helicity-correlated beam parameter differences

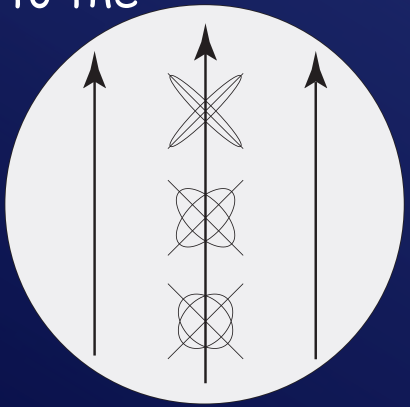
Charge asymmetries or "PITA" effect: Bates carbon experiment.

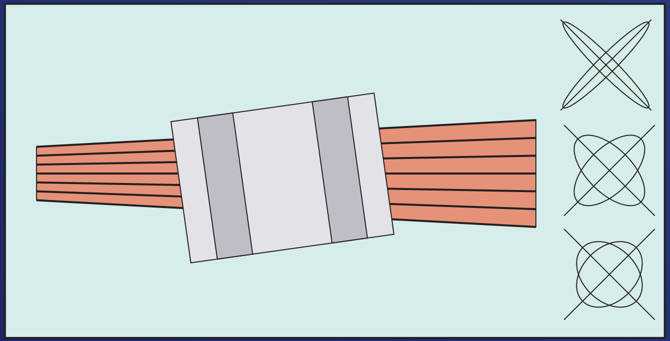


Position differences from lensing: steering from lensing-type phenomena: Bates carbon experiment.



Position differences from intrinsic phase gradients: due to phase gradients intrinsic to the Pockels cell or other optical components, SLAC E158.





Position differences from induced phase gradients: due to coupling of divergence to the Pockels cell tilt: Happex II.

Helicity-correlated beam parameters averaged over the Happex II runs

		Helium	Hydrogen
Charge asymmetry →	A_Q	-0.377 ppm	0.406 ppm
Energy difference →	A_{Energy}	3 ppb	0.2 ppb
x-position difference →	Δx	-0.2 nm	0.5 nm
x-angle difference →	$\Delta x'$	4.4 nrad	-0.2 nrad
y-position difference →	Δy	-26 nm	1.7 nm
y-angle difference →	$\Delta y'$	-4.4 nrad	0.2 nrad

The control achieved during the hydrogen run was unprecedented. Control during the helium run, while more than sufficient, was limited due to electronic cross-talk problems .

Steady progress has made it possible to consider increasingly challenging parity experiments

Selected parity experiments and their measured or projected demands on suppression of helicity-correltated beam-parameter differences

Experiment (*) actual (†) projected	physics asymmetry	stat. error	sys. error due to beam	limits on position differences	limits on angle differences
*HAPPEX I	-15,050 ppb	980 ppb	±20 ppb	< 12 nm	
*SLAC E158	-131 ppb	14 ppb	±3 ppb	< 12 nm	0.4 nrad
*HAPPEX II-p	-1,580 ppb	120 ppb	±17 ppb	< 1.7 nm	0.2 nrad

Steady progress has made it possible to consider increasingly challenging parity experiments

Selected parity experiments and their measured or projected demands on suppression of helicity-correltated beam-parameter differences					
Experiment (*) actual (†) projected	physics asymmetry	stat. error	sys. error due to beam	limits on position differences	limits on angle differences
*HAPPEX I	-15,050 ppb	980 ppb	±20 ppb	< 12 nm	
*SLAC E158	-131 ppb	14 ppb	±3 ppb	< 12 nm	0.4 nrad
*HAPPEX II-p	-1,580 ppb	120 ppb	±17 ppb	< 1.7 nm	0.2 nrad
†PREX	510 ppb	15 ppb	±1.0 ppb	< 1.0 nm	
†HAPPEX III	-22,100 ppb	550	±66 ppb	< 40 nm	
†Qweak	-288 ppb	5 ppb	14 ± 1.4 ppb	< 40 nm	100 nrad
† 12 GeV Møller	40 ppb	0.6 ppb	±0.2 ppb	∼ 1 nm	0.03 nrad

The long legacy of parity experiments positions our community to perform sensitive searches for physics beyond the SM

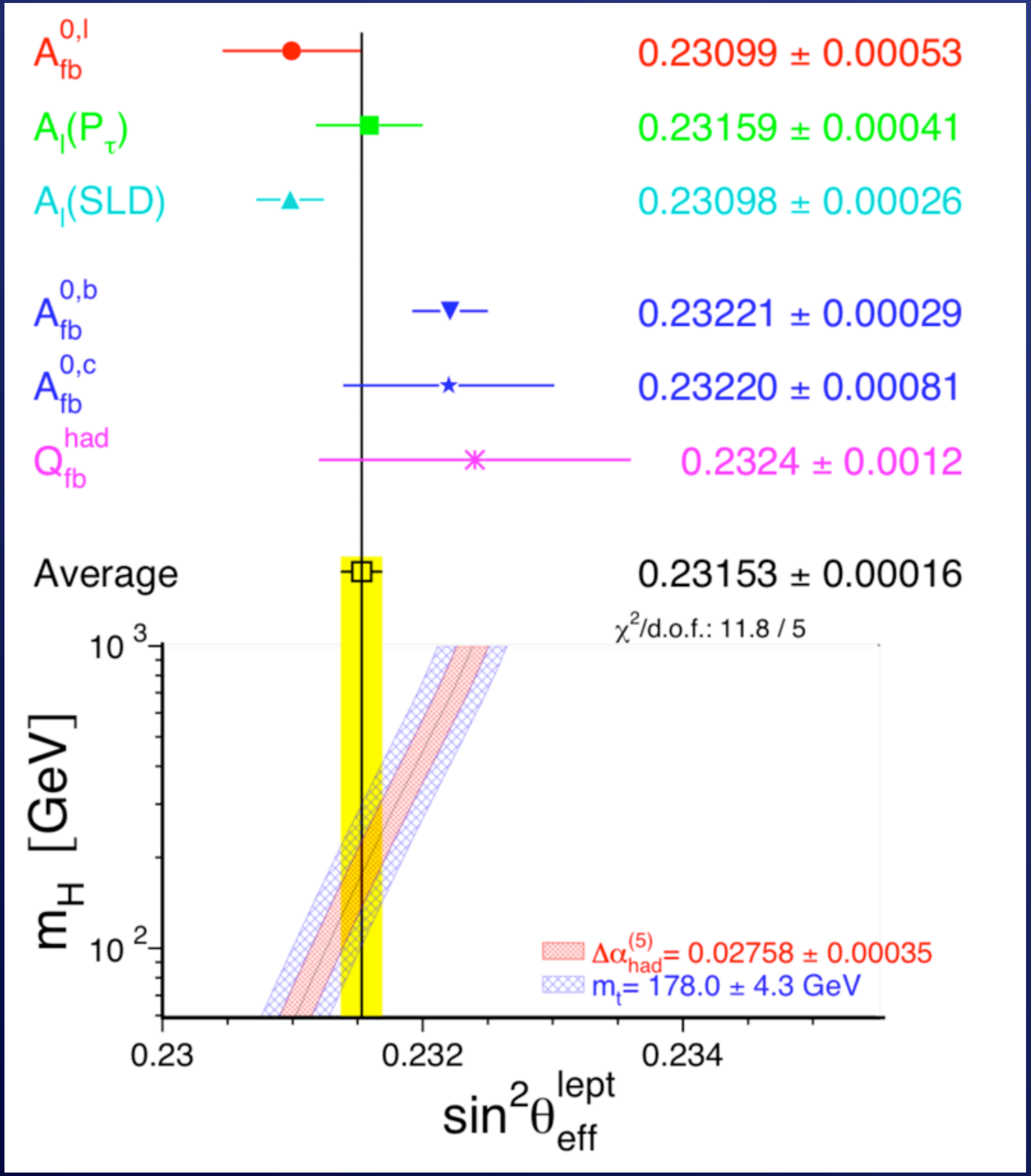
Control of helicity-correlated effects at ppb levels.

Strong constraints on hadronic effects such as non-zero strange-quark matrix elements

Un-precedented figures of merit in terms of polarization^2 x luminosity

→ Sensitive searches for physics beyond the SM such as Qweak (scheduled), and perhaps an 11 GeV Møller experiment

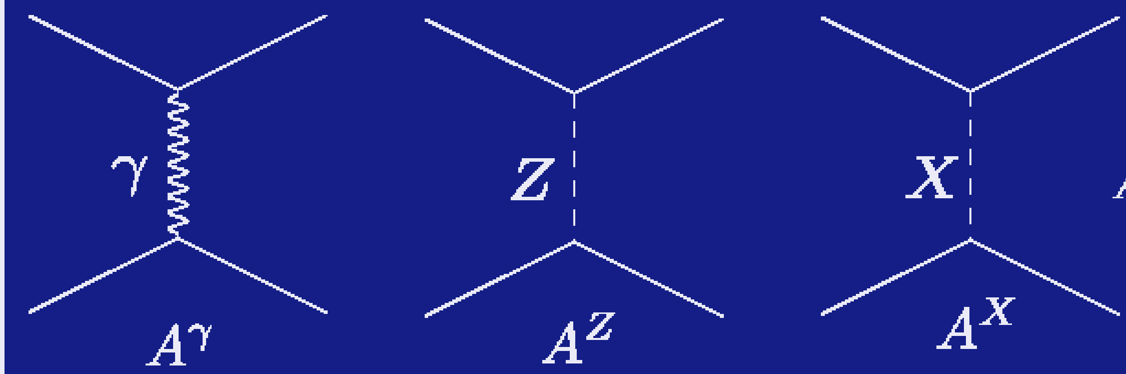
There are exciting hints indicating physics beyond Standard Model



- Measurements of $\sin^2\theta_W$ agree fairly poorly.
- g-2 of the muon is 2-3 σ off the SM.
- Dark matter is unexplained.
- There are good reasons to expect additional physics !

Electron scattering compliments collider measurements

Consider an amplitude A^X due to new physics at a mass scale $M_X{}^2 \gg Q^2$.



$$A^X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{1}{M_X^2}$$

On the Z pole, A_Z will be purely imaginary while A_X will likely be real. Accordingly:

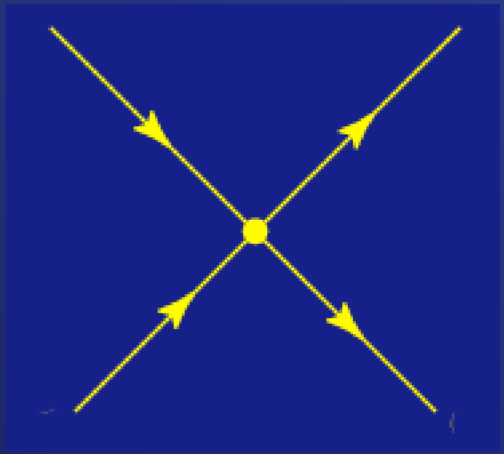
$$\sigma \sim |A^Z|^2 + |A^X|^2 \qquad \text{and} \qquad A_{RL} \sim \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim A_{RL}^Z \left(1 + \frac{|A^X|^2}{|A^Z|^2}\right)$$

Away from the Z pole, at higher and lower energies, both amplitudes are real and interferences can occur.

$$\sigma \sim |A^\gamma + A^Z + A^X|^2 \qquad \text{and} \qquad A_{RL} \sim \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A^Z + A^X}{A^\gamma}$$

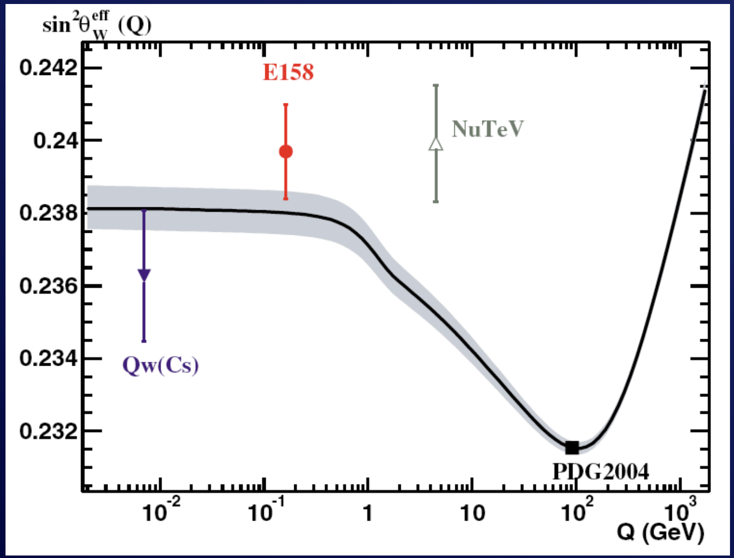
Electron scattering provides access to very high energy scales

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\,G_f}$$



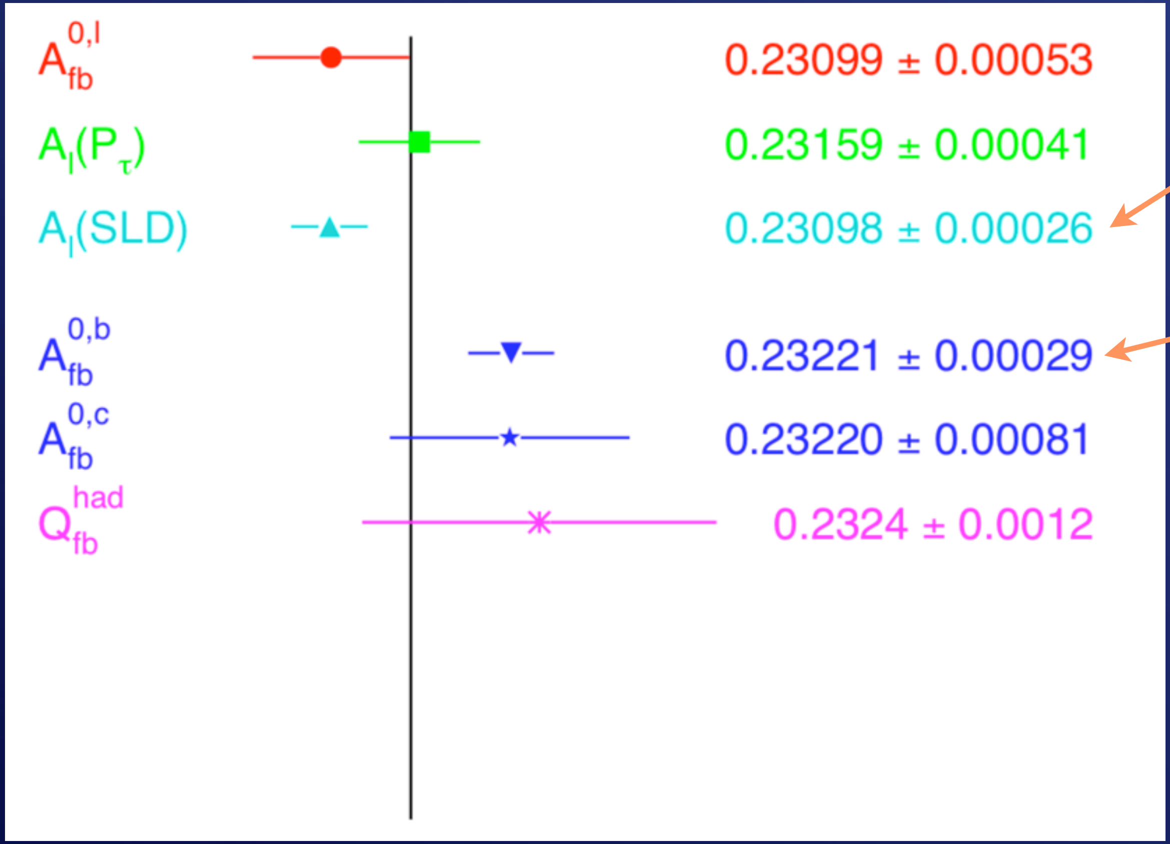
Sensitivity to new contact interactions will extend to energy scales Λ on the order of roughly 10 TeV

Already E158 provides the most accurate measurement of $\sin^2\theta_W$ at low Q^2



Qweak and a possible Møller experiment at 11 GeV provide sensitivity that would be tremendously valuable in the upcoming era of LHC

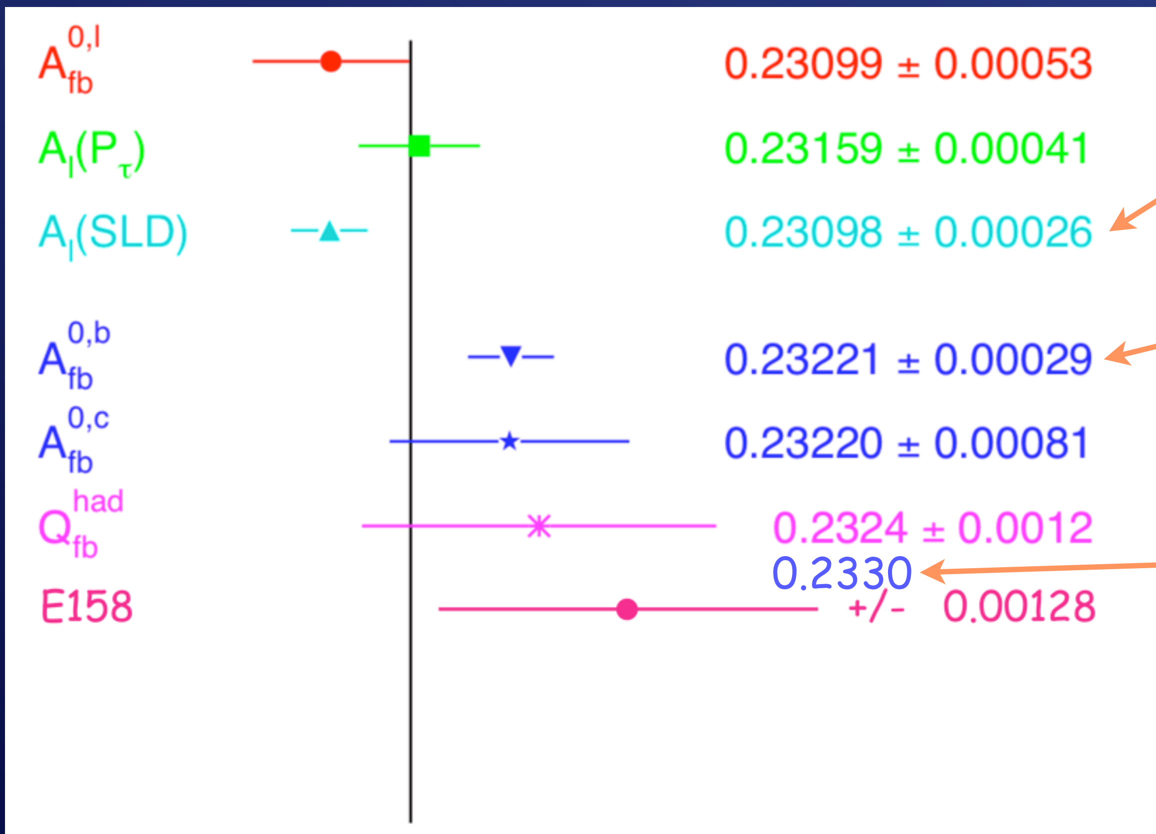
Marciano likes to point out that if either the SLD or the best CERN numbers were not there, we would have a very different picture right now



SLD number, if correct, would tend to favor SUSY

CERN number, if correct, would tend to favor "modern" technicolor

Marciano likes to point out that if either the SLD or the best CERN numbers were not there, we would have a very different picture right now

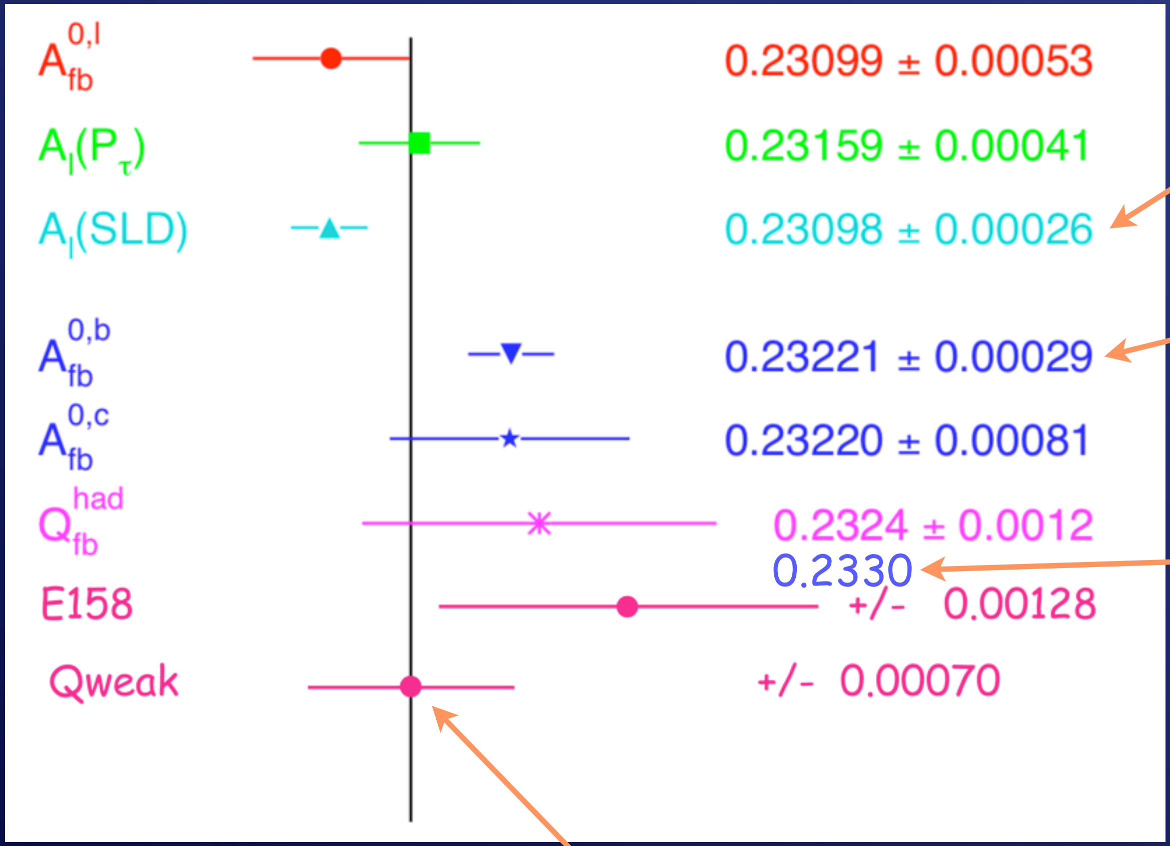


SLD number, if correct, would tend to favor SUSY

CERN number, if correct, would tend to favor "modern" technicolor

E158 number, if correct, would tend (ever so slightly) to support support the technicolor scenario! Amusing, but should not be taken seriously

Marciano likes to point out that if either the SLD or the best CERN numbers were not there, we would have a very different picture right now



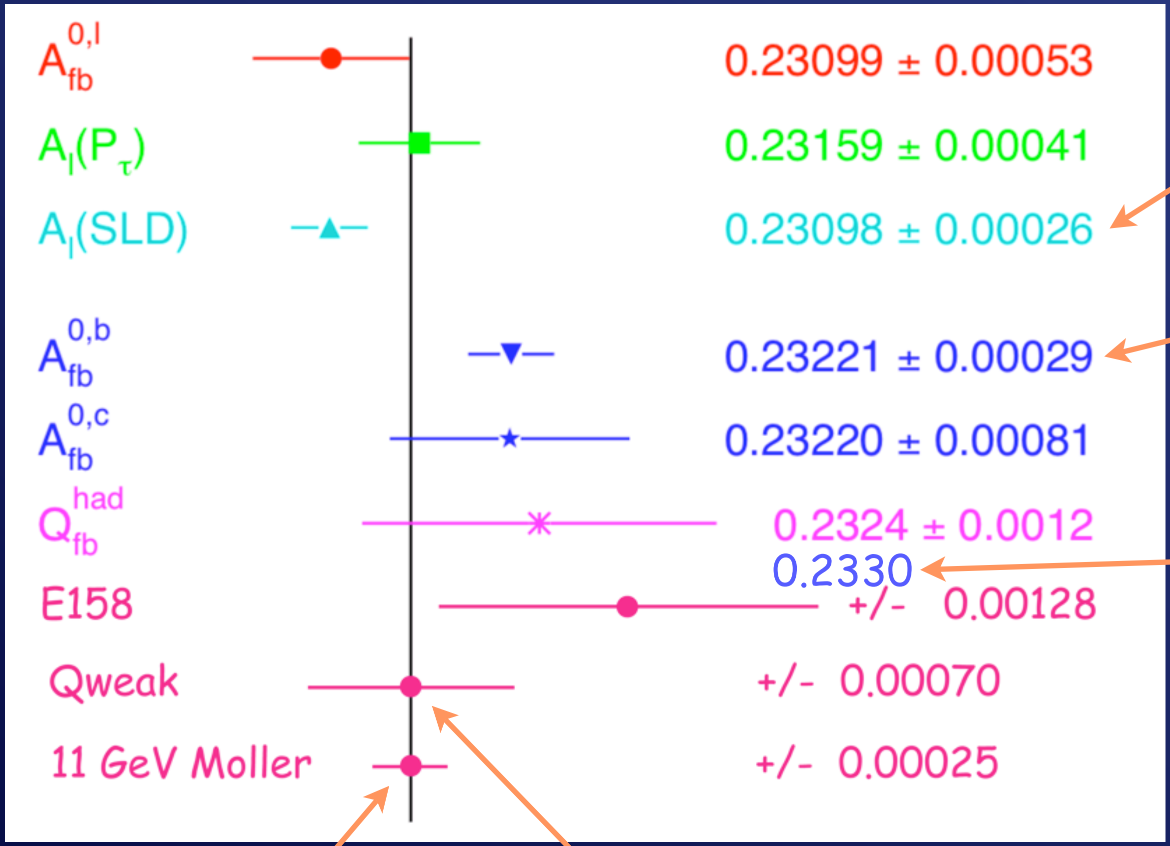
SLD number, if correct, would tend to favor SUSY

CERN number, if correct, would tend to favor “modern” technicolor

E158 number, if correct, would tend (ever so slightly) to support support the technicolor scenario! Amusing, but should not be taken seriously

Qweak would have greatly improved sensitivity to complimentary physics

Marciano likes to point out that if either the SLD or the best CERN numbers were not there, we would have a very different picture right now



SLD number, if correct, would tend to favor SUSY

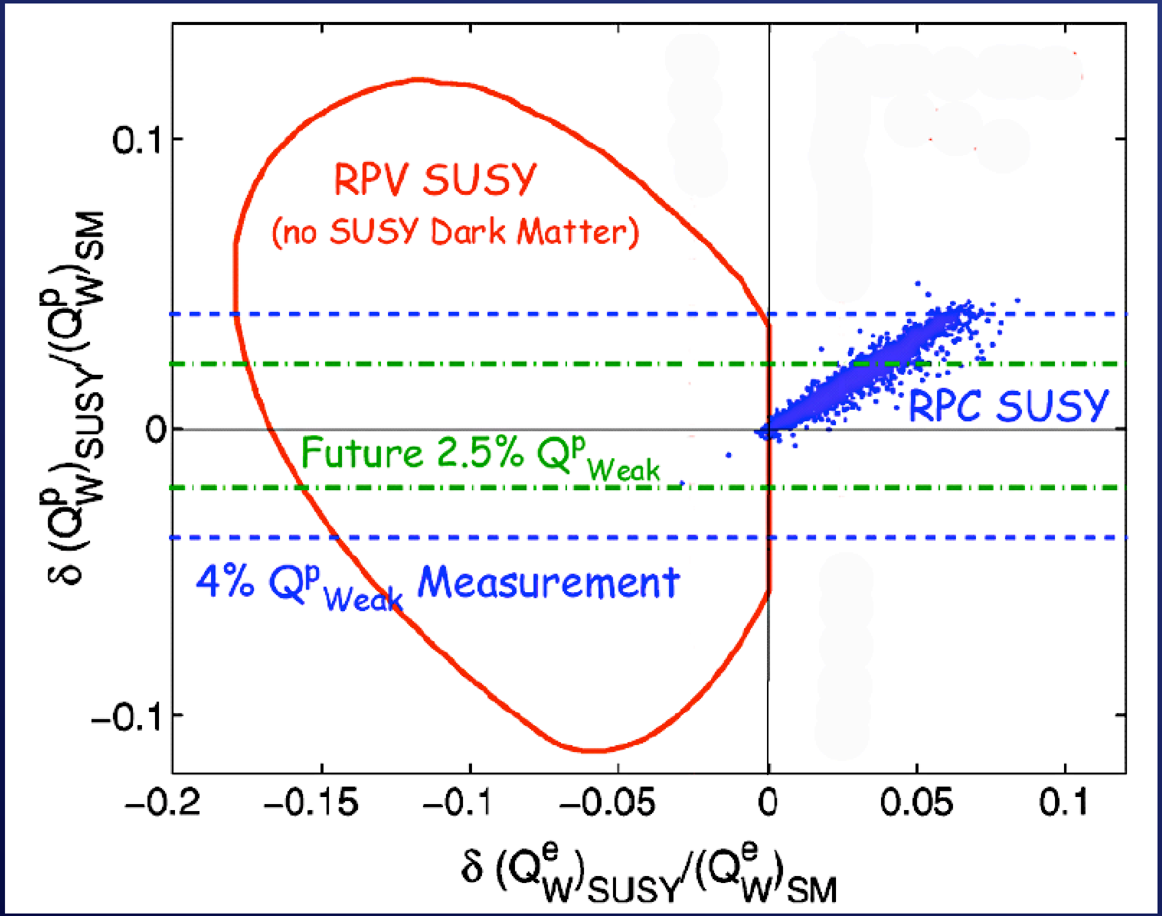
CERN number, if correct, would tend to favor "modern" technicolor

E158 number, if correct, would tend (ever so slightly) to support support the technicolor scenario! Amusing, but should not be taken seriously

Qweak would have greatly improved sensitivity to complimentary physics

An 11 GeV Møller experiment, the ONLY possibility of resolving outstanding issues here, could be equal to or better than the best single measurement existing.

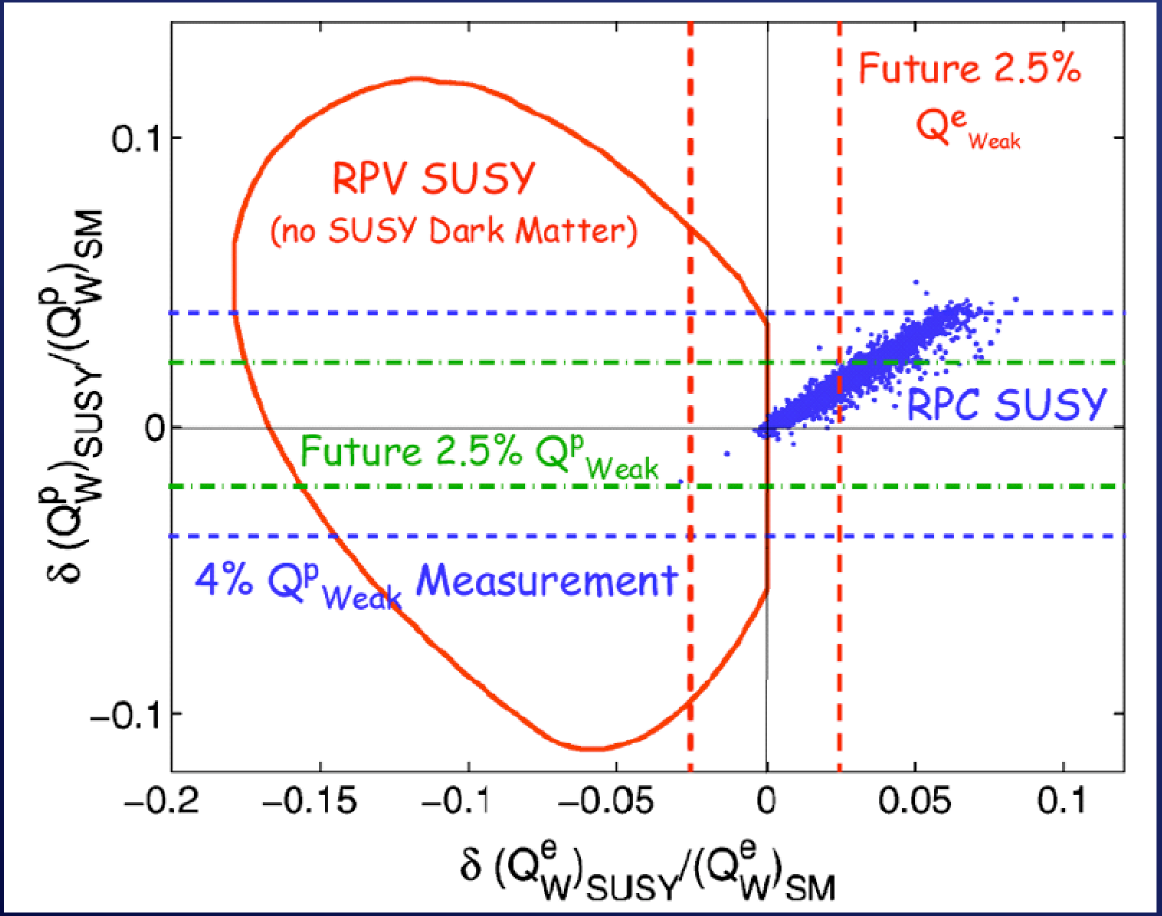
Qweak will (and an 11 GeV Møller experiment could) provide powerful probes of SUSY theories



Qweak, by itself, provides considerable sensitivity to RPV SUSY theories.

Kurylov, Ramsey-Mulsolf, Su

Qweak will (and an 11 GeV Møller experiment could) provide powerful probes of SUSY theories

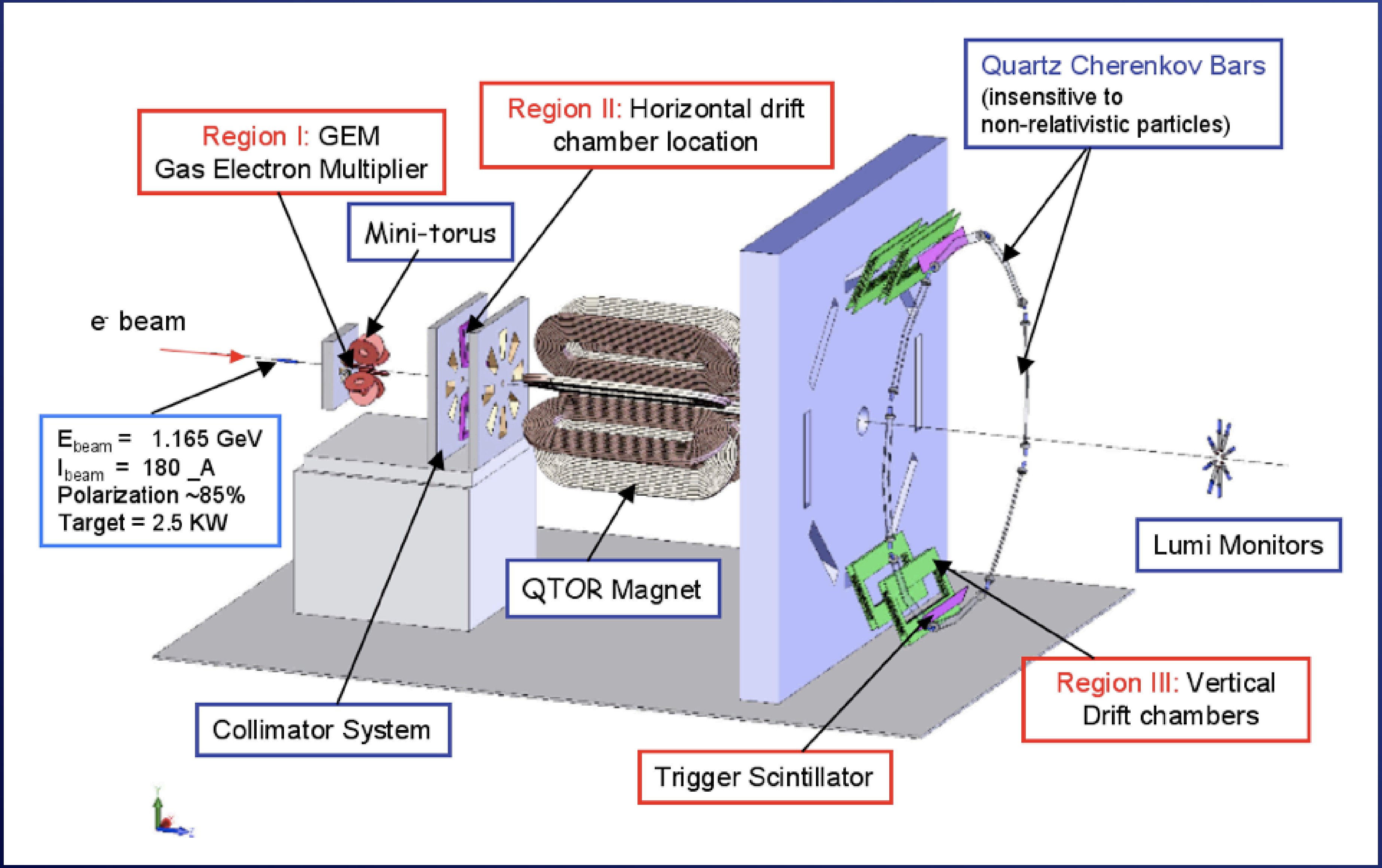


Qweak, by itself, provides considerable sensitivity to RPV SUSY theories.

An 11 GeV Møller experiment could provide important sensitivity to RPC SUSY theories that include stable particles that could contribute to dark matter.

Kurylov, Ramsey-Mulsolf, Su

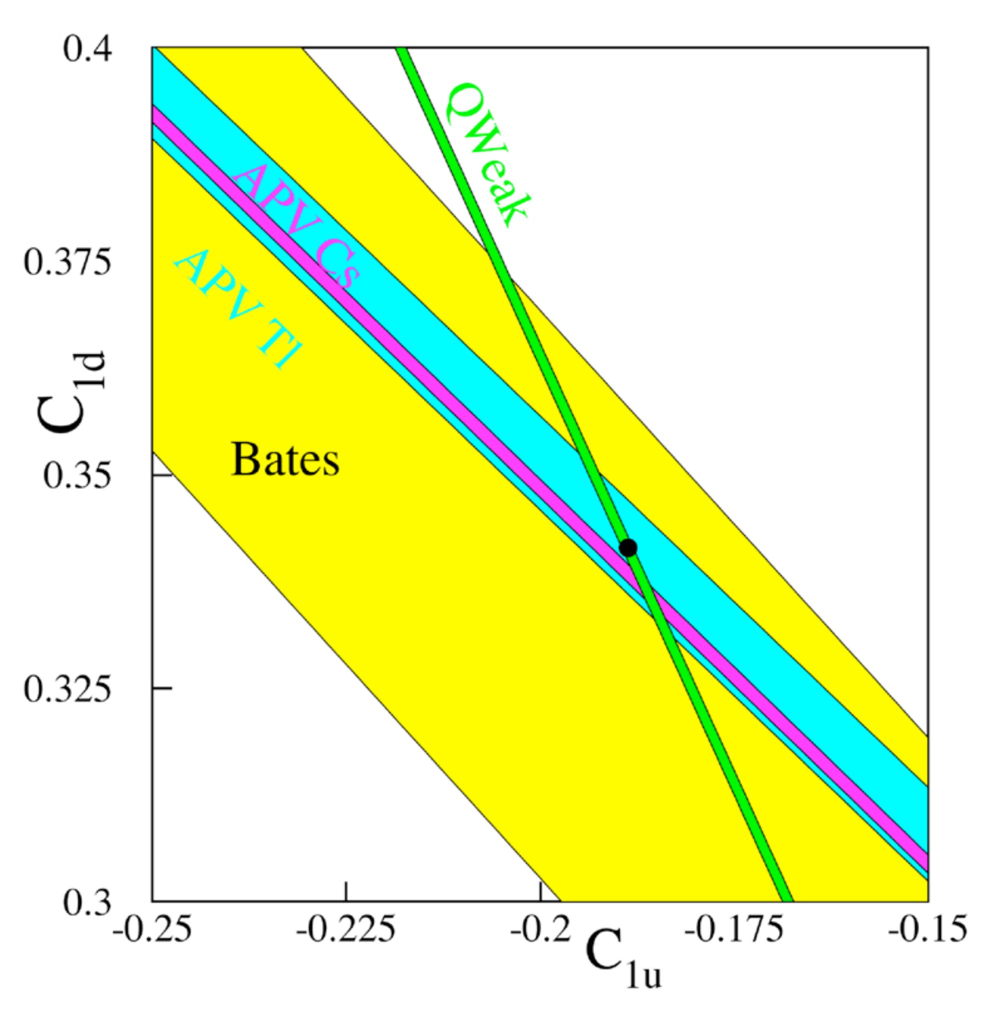
Qweak apparatus



An important perspective on SM tests is to consider a model independent effective Lagrangian

$C_{1i} \equiv 2 g_A^e g_V^i$ $\qquad$ $C_{2i} \equiv 2 g_V^e g_A^i$

Each parity violating asymmetry can then be interpreted to constrain the coefficients C_{1u}, C_{1d}, C_{2u}, and C_{2d}



Qweak is seen to put excellent constraints on a linear combination of C_{1u} and C_{1d}

To learn about ALL the coefficients C_{1u}, C_{1d}, C_{2u}, and C_{2d}, we need additional types of parity violating semi-leptonic measurements:

PV deep inelastic scattering (PVDIS)

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

$$x \equiv x_{Bjorken}$$

$$y \equiv 1 - E'/E$$

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i^+(x)}{\sum_i Q_i^2 f_i^+(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i^-(x)}{\sum_i Q_i^2 f_i^+(x)}$$

$$f_i^{\pm} \equiv f_i \pm \overline{f}_i$$

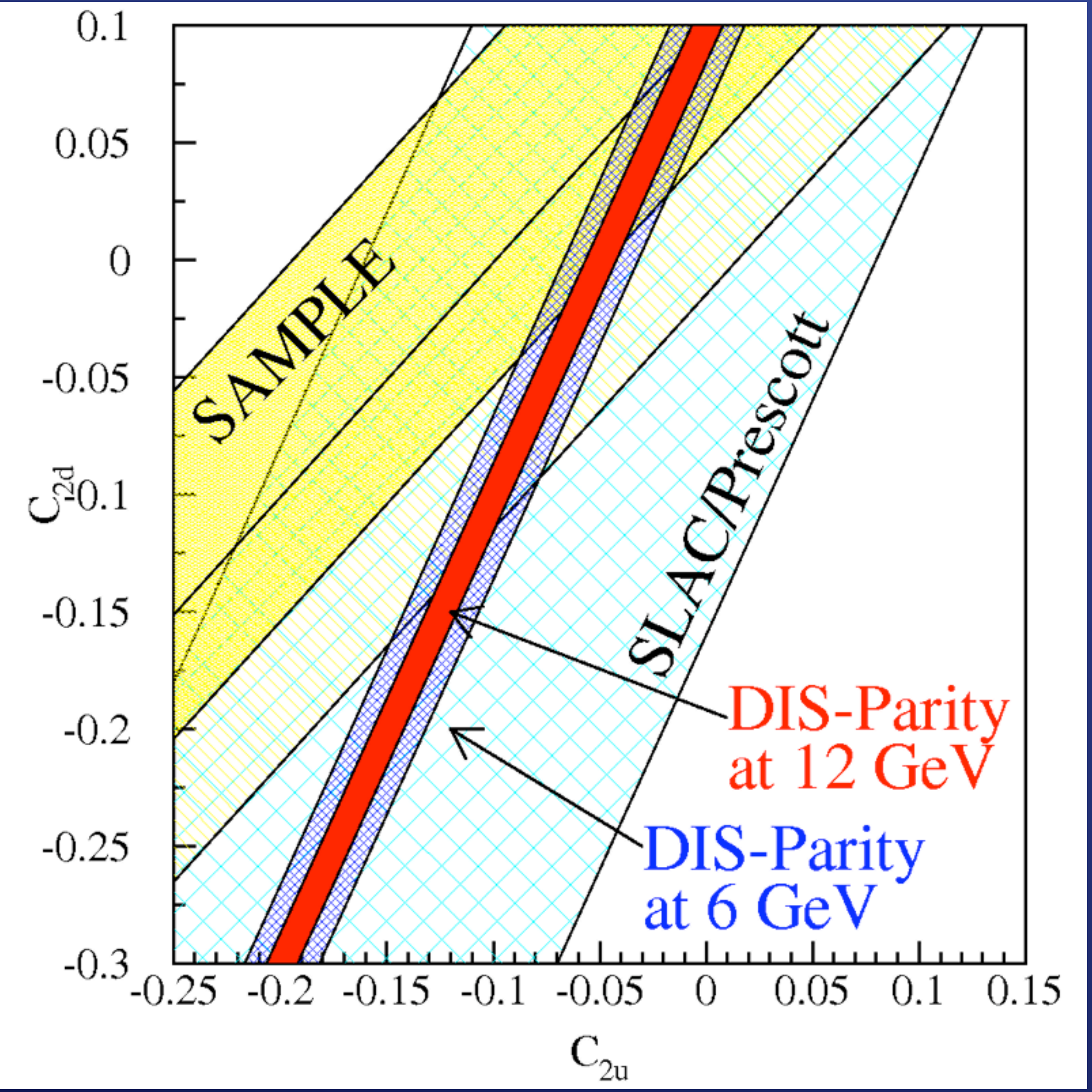
Just as with parity violation in elastic scattering, PVDIS can be used to study of host of physics phenomena, from standard model tests, to charge symmetry violation, to higher twist effects, and even d/u.

Sensitivity of PV DIS experiments approved or being considered at JLab

The coefficients C_{2u}, and C_{2d} are relatively small in the standard model.

This in fact makes them more sensitive to certain types of new physics.

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \approx -0.19$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \approx 0.35$$
$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) \approx -0.04$$
$$C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$



Looking toward the future

Looking toward the future

- The role of strange quarks is far better understood today and more information is coming.

Looking toward the future

- The role of strange quarks is far better understood today and more information is coming.
- Parity violation in electron scattering will provide the ONLY means for accessing certain important questions in electroweak physics until the ILC is built.

Looking toward the future

- The role of strange quarks is far better understood today and more information is coming.
- Parity violation in electron scattering will provide the ONLY means for accessing certain important questions in electroweak physics until the ILC is built.
- Both Møller and PVDIS are critical if we are to understand semi-leptonic interactions.