Parity Violation at Jefferson Lab

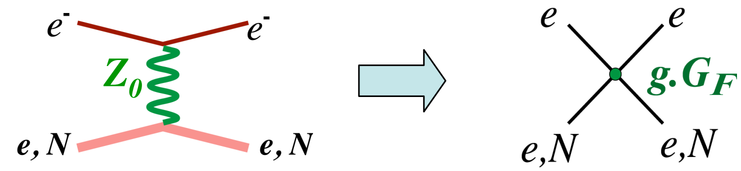
Fundamental Symmetries and Neutrinos Workshop
Chicago

August 11, 2012

Kent Paschke
University of Virginia

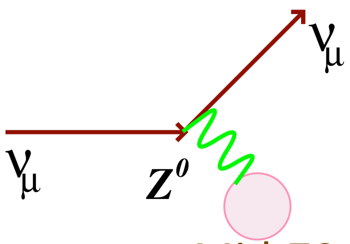
Weak Neutral Current Interactions

Low energy WNC interactions ($Q^2 \ll M_Z^2$)

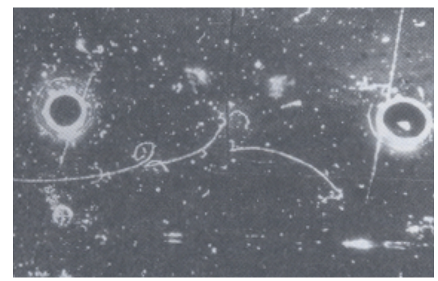


Historical Context:

- 1960s: An Electroweak Model of Leptons (and quarks)
  - **$SU(2)_L$ X $U(1)_Y$ theory predicted the Z boson, introduced $\sin^2\vartheta_W$**
- 1973: antineutrino-electron scattering
  - **First weak neutral current observation**



- **Gargamelle observes one ν_μ e^- event**
- **First measurement of weak mixing angle**



- Mid-70s: Does the Weak Neutral Current interfere with the Electromagnetic Current?
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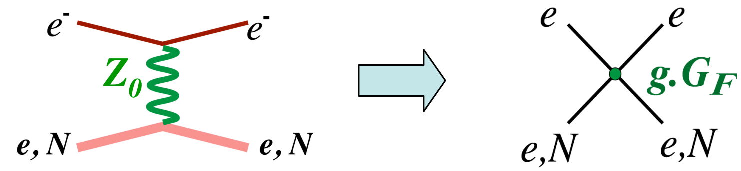

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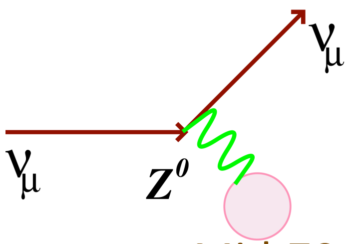

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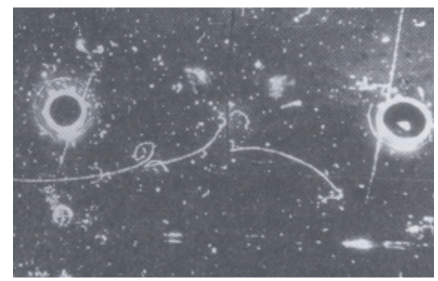

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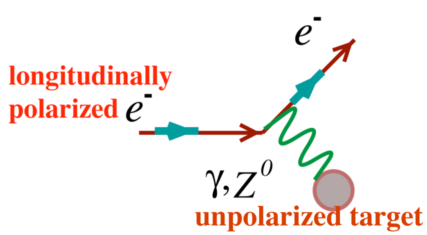


$$\sigma \;\alpha\; | A_\gamma + A_{weak} |^2$$

$$\sim |A_{EM}|^2 + 2 A_{EM} A^*_{weak} + \ldots$$

$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$\sim 10^{-4}$$

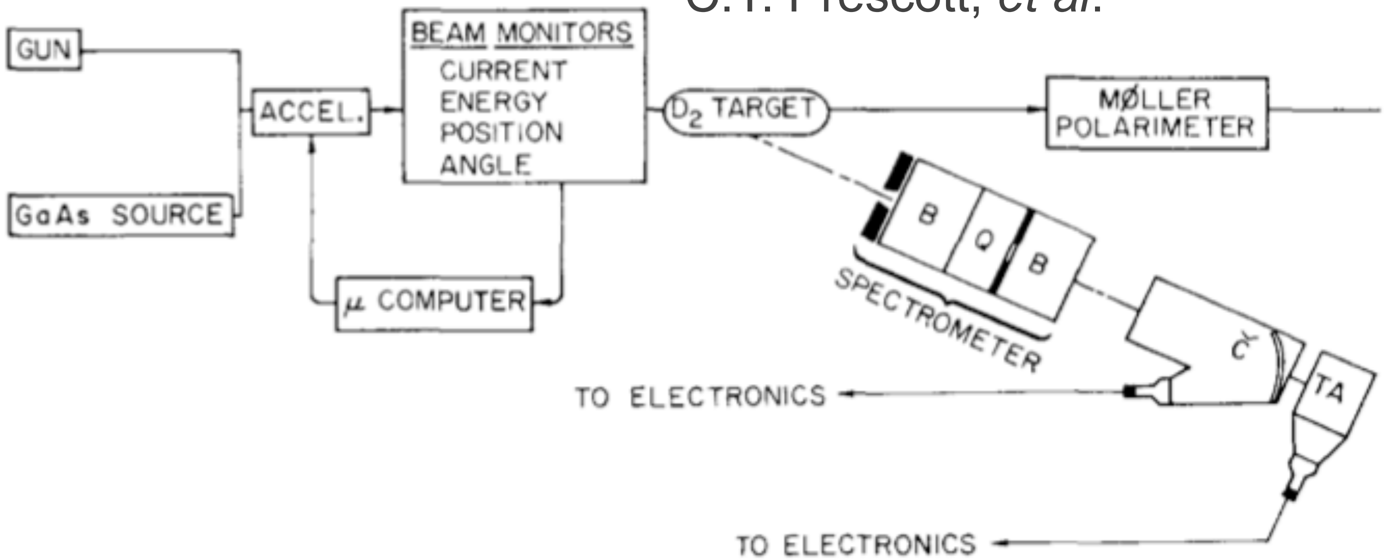
Need few x 10^{11} events

⇨ ***Count at ~ 100 kHz***

⇨ ***$\delta(A_{PV})$ ~ few ppm***

Anatomy of a Parity Experiment

C.Y. Prescott, *et al.*



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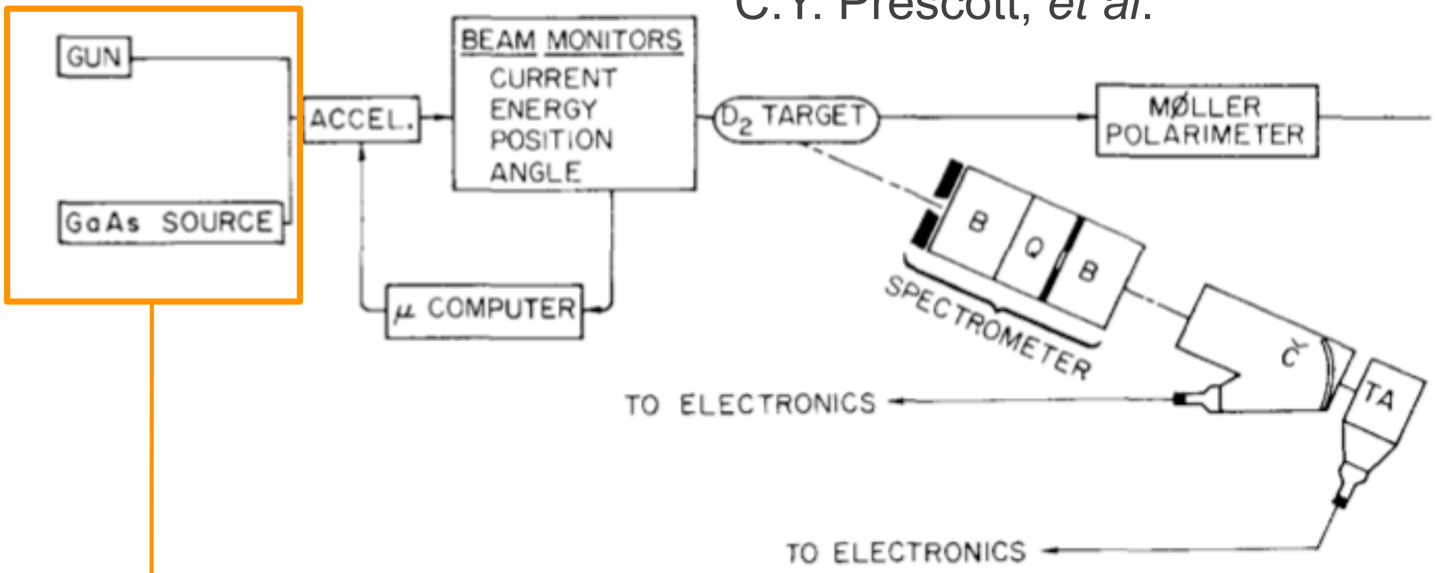

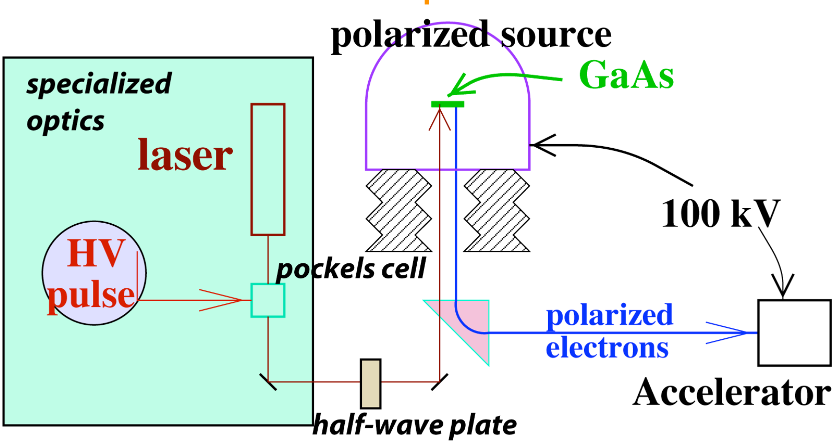

- **Photoemission from a GaAs wafer: "black magic" chemical treatment creates a Negative Electron Affinity cathode**
- **Rapid helicity reversal: polarization sign flips ~ 100 Hz to minimize the impact of drifts**
- **Helicity-correlated beam motion: under sign flip, beam stability at the micron level**

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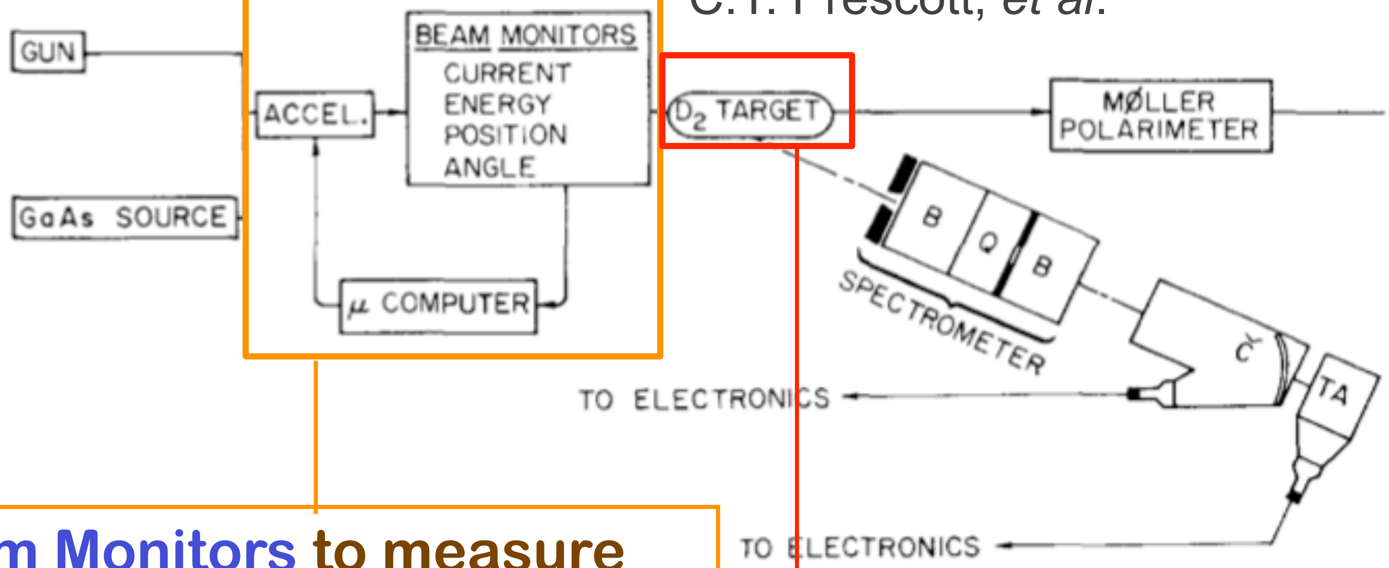

- **Beam Monitors to measure helicity-correlated changes in beam parameters**

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

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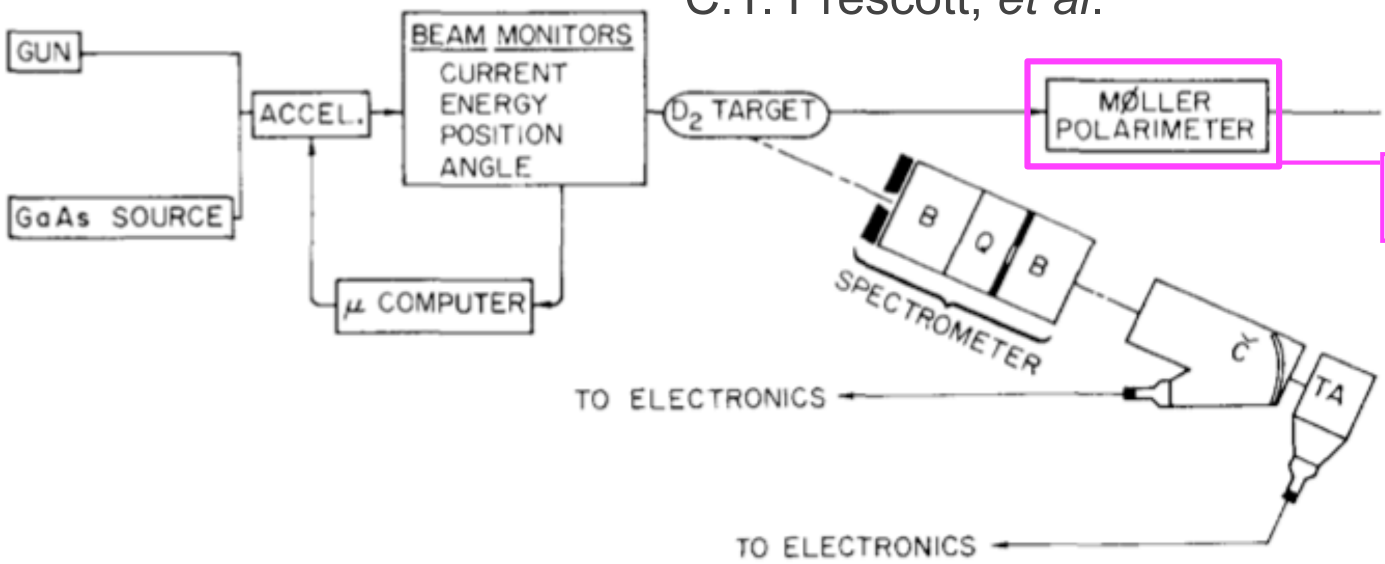

- Polarimetry

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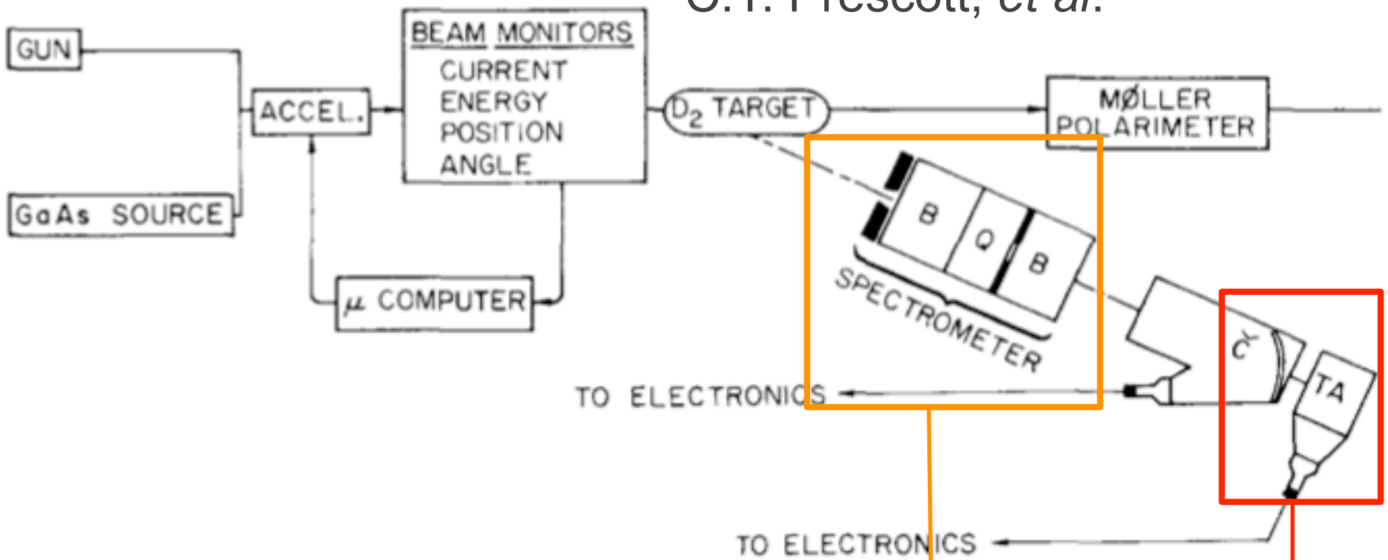
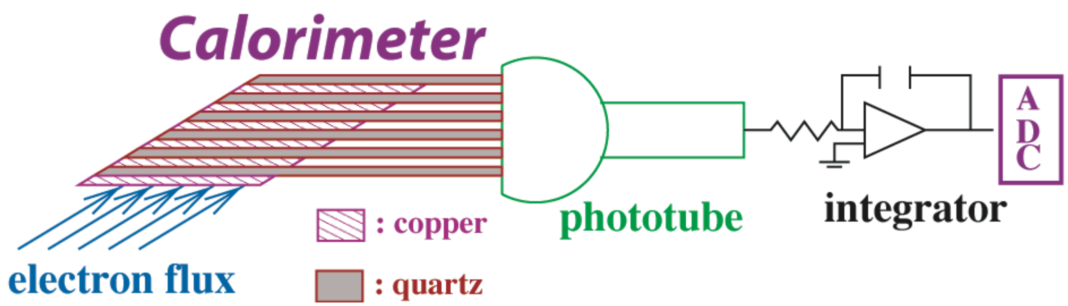


- **Magnetic spectrometer directs flux to background-free region**

- **Flux Integration measures high rate without deadtime**



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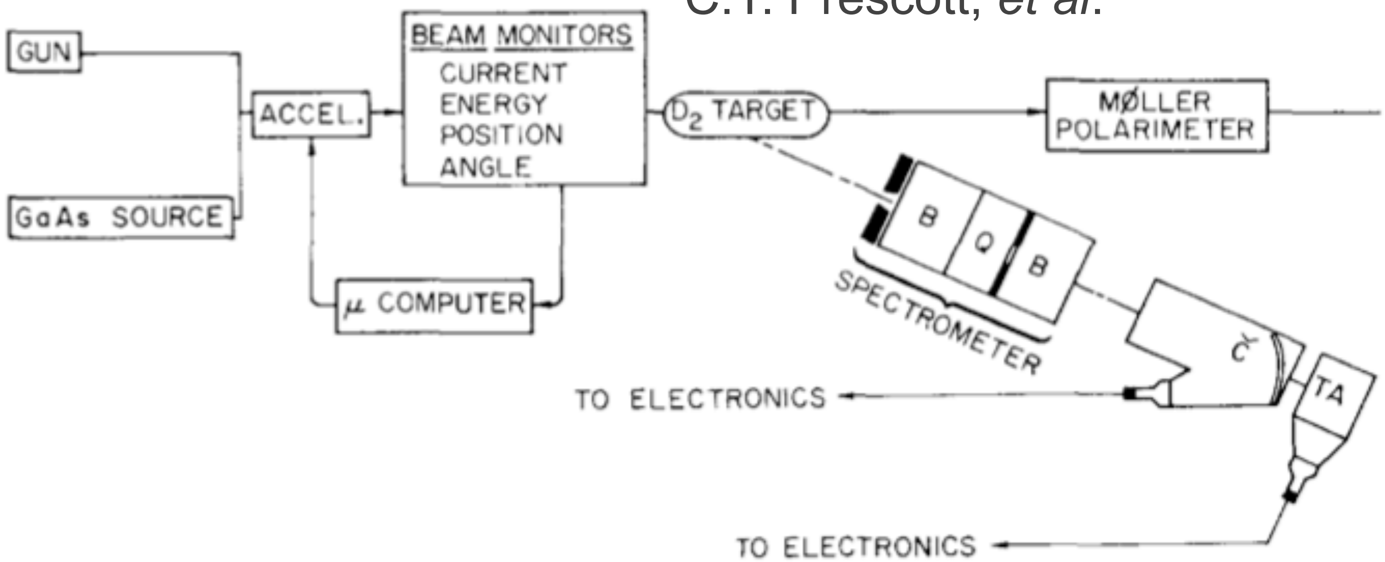

A_{PV} ~ 100 ± 10 ppm

- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

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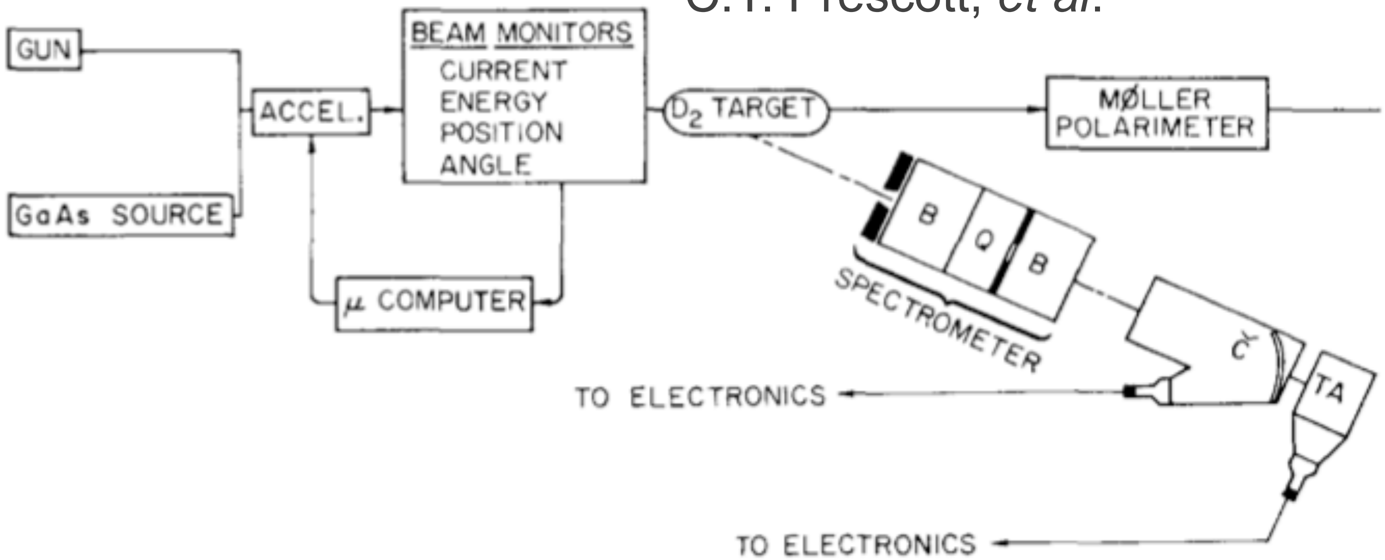

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Glashow, Weinberg, Salam
Nobel Prize awarded in 1979

Search for, or study, new neutral currents

Many new physics models give rise to new heavy neutral current interactions

$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{new}}$$

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

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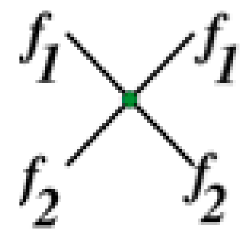
Consider $f_1 f_1 \rightarrow f_2 f_2$ **or** $f_1 f_2 \rightarrow f_1 f_2$



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{i\,j}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Eichten, Lane and Peskin, PRL50 (1983)

mass scale Λ, coupling g **for each fermion and handedness combination**

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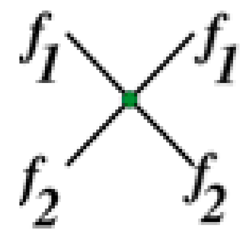

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Sensitivity to TeV-scale contact interactions if:

- $\delta(\sin^2\theta_W) \leq 0.5\%$
- away from the Z resonance

- Precision neutrino scattering
- PV couplings through interference with EM
  - opposite-parity transitions in heavy atoms
  - parity-violating electron scattering

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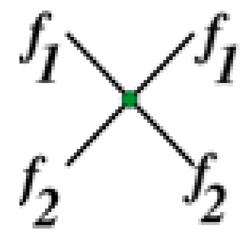

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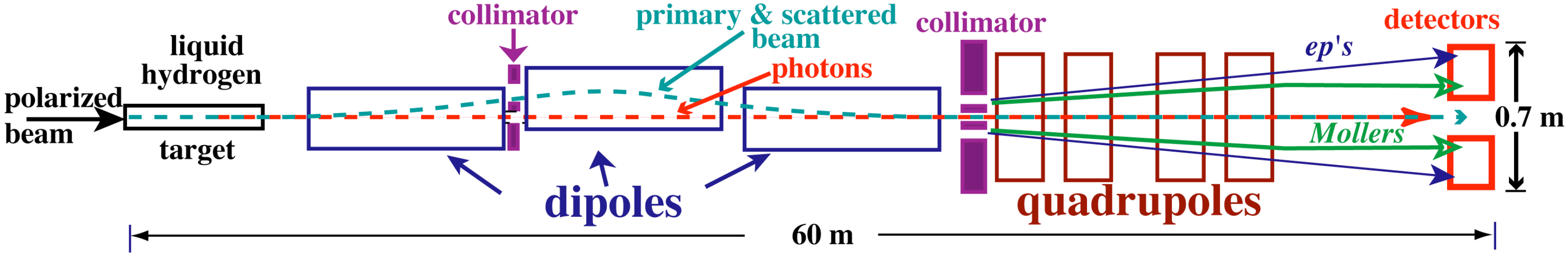
Electromagnetic amplitude interferes with Z-exchange as well as any new physics

$$\left|\mathbf{A}_\gamma + \mathbf{A}_\mathbf{Z} + \mathbf{A}_{\mathrm{new}}\right|^2 \rightarrow \mathbf{A}^2_\gamma \left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A}_\mathbf{Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\mathrm{new}}}{\mathbf{A}_\gamma}\right)\right]$$

SLAC E158

1997-2004

48 GeV Møller Scattering



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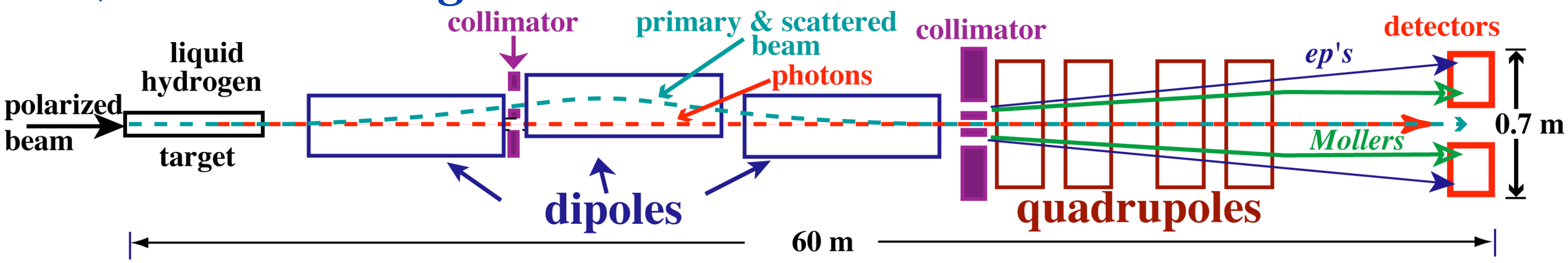

A large number of technical challenges

- 10 nm control of beam centroid on target
  - R&D on polarized source laser transport elements
- 12 microamp beam current maximum
  - 1.5 meter Liquid Hydrogen target
- 20 Million electrons per pulse @ 120 Hz
  - 200 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-4}*
    - *Pulse-to-pulse monitoring resolution ~ 1 micron*
    - *Pulse-to-pulse beam fluctuations < 100 microns*
  - 100 Mrad radiation dose from scattered flux
    - *State-of-the-art radiation-hard integrating calorimeter*
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - Quadrupole spectrometer
  - Complex collimation and radiation shielding issues

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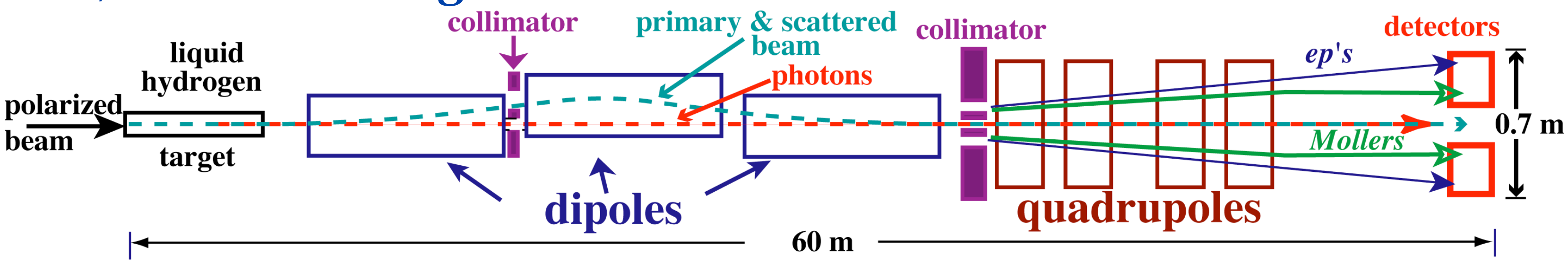

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Phys. Rev. Lett. **95** 081601 (2005)

A_{PV} = (-131 ± 14 ± 10) ppb

EW Quantum Corrections

Precision Measurements of Electroweak (EW) Couplings

For electroweak interactions, 3 input parameters needed:

1. **electron g-2 anomaly**
2. **The muon lifetime**
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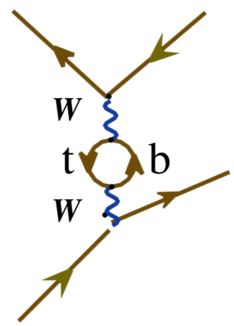
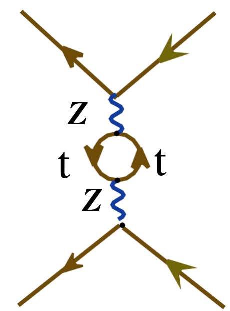
4th and 5th best measured parameters: M_W and $\sin^2\theta_W$

Values differ from tree level predictions:
indirect access to "heavy" physics

Known "heavy" physics: the top quark
Assumed "heavy physics": the Higgs boson



Muon decay



Z production

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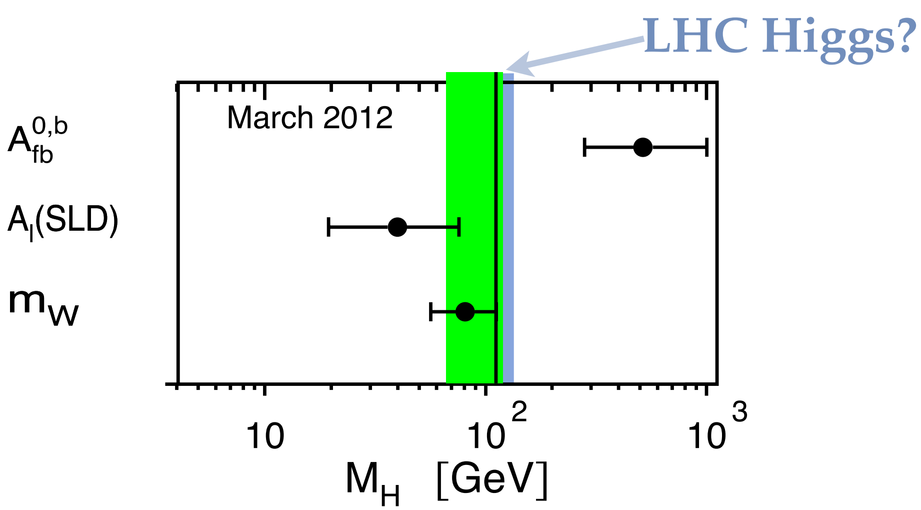
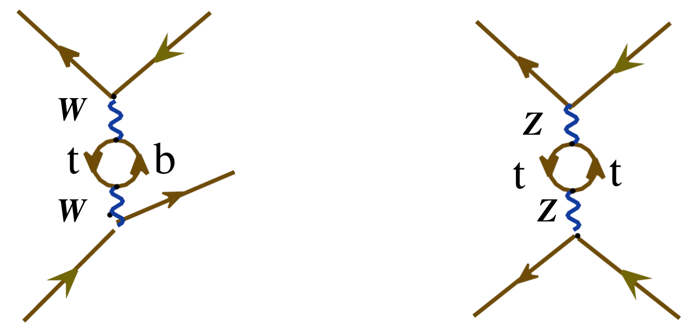
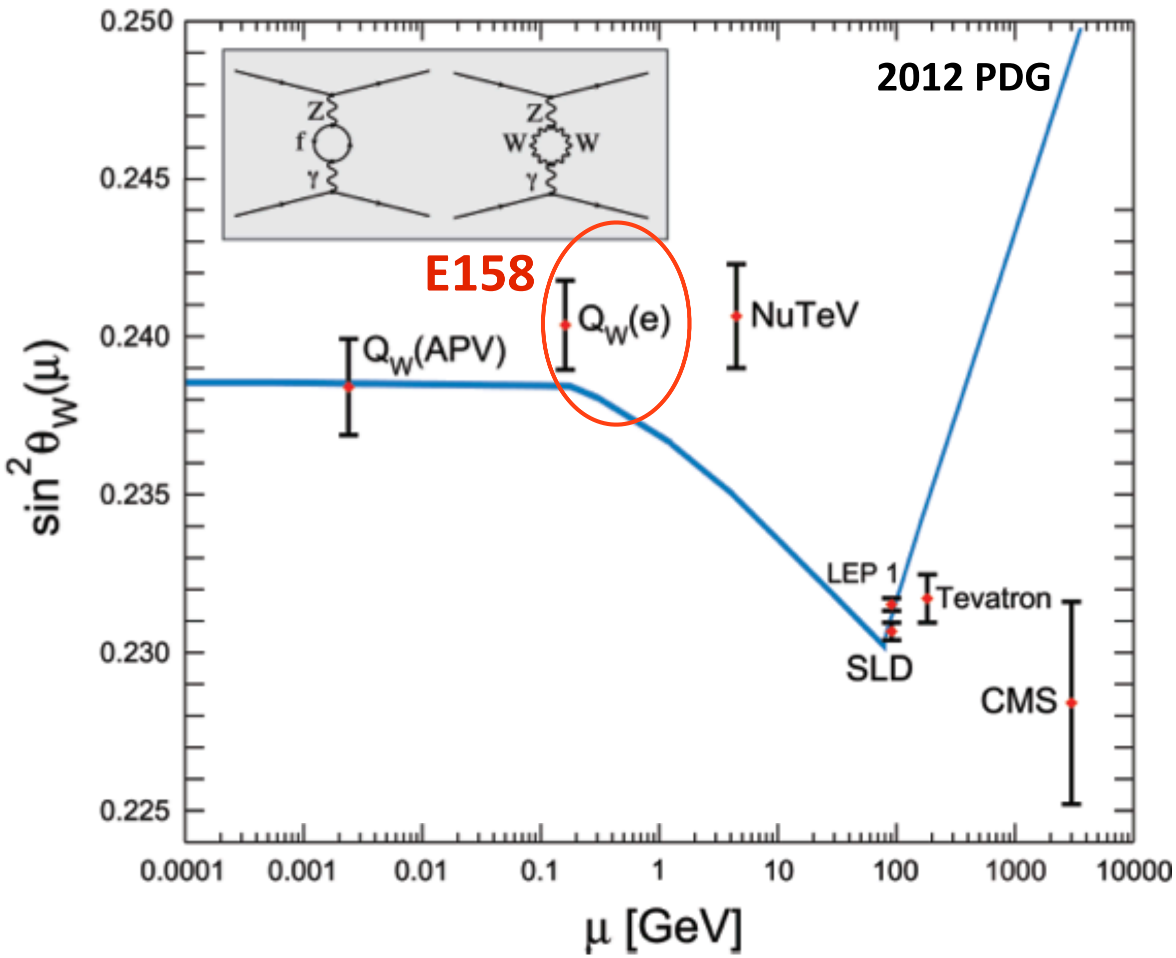




Muon decay *Z production*

Running Weak Charge



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Improvement in SM prediction

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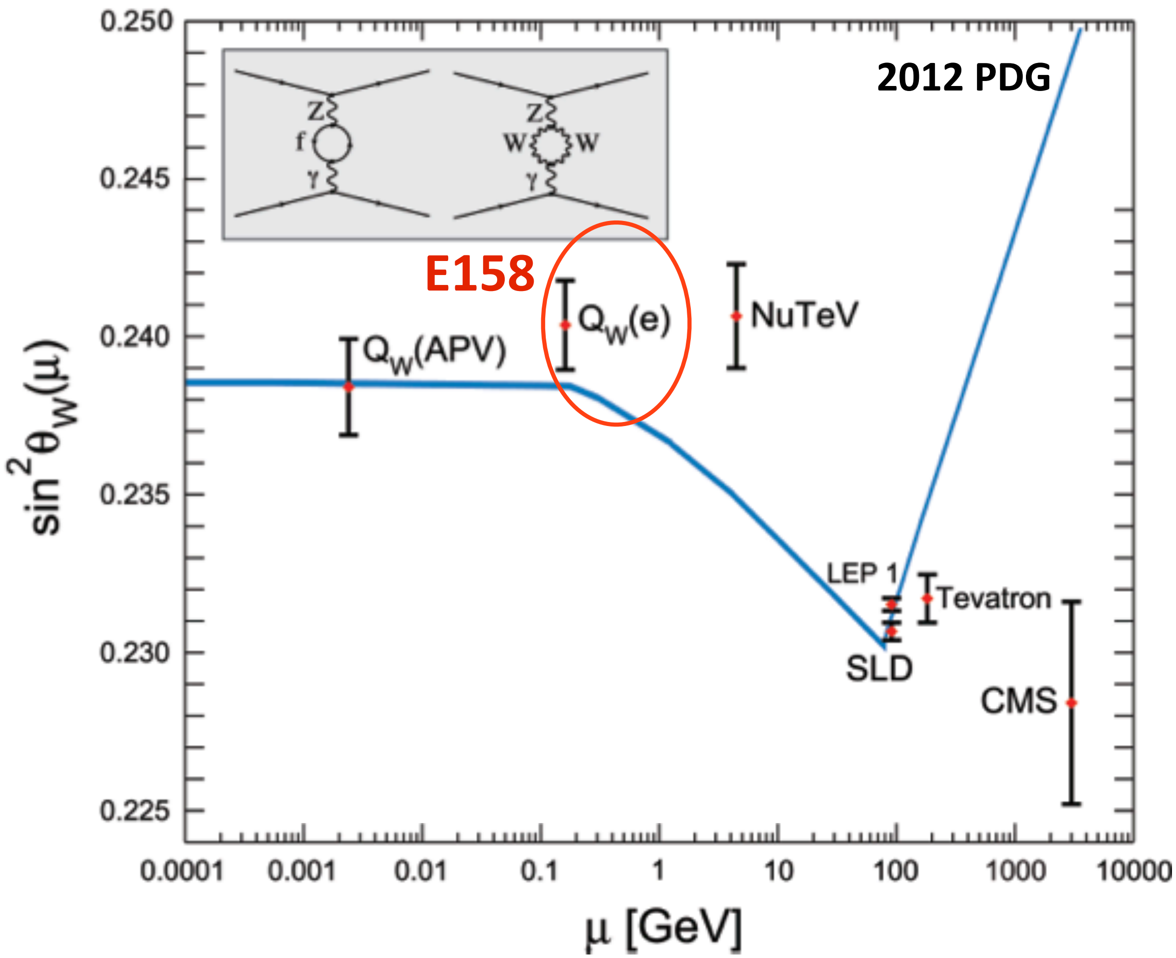

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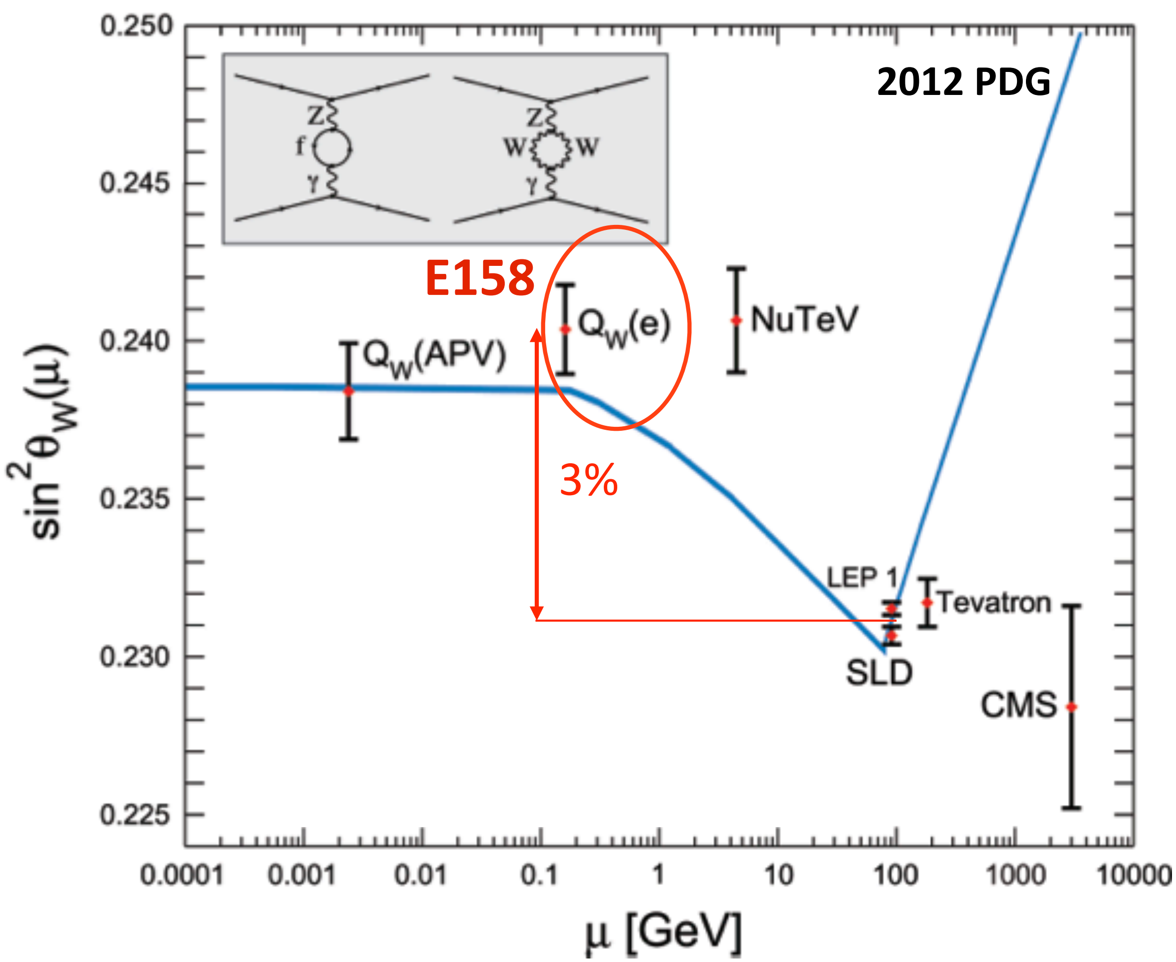

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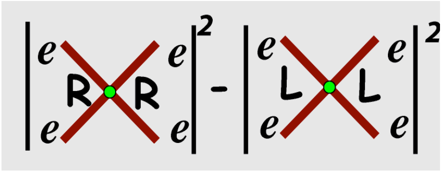
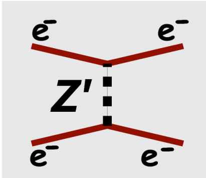
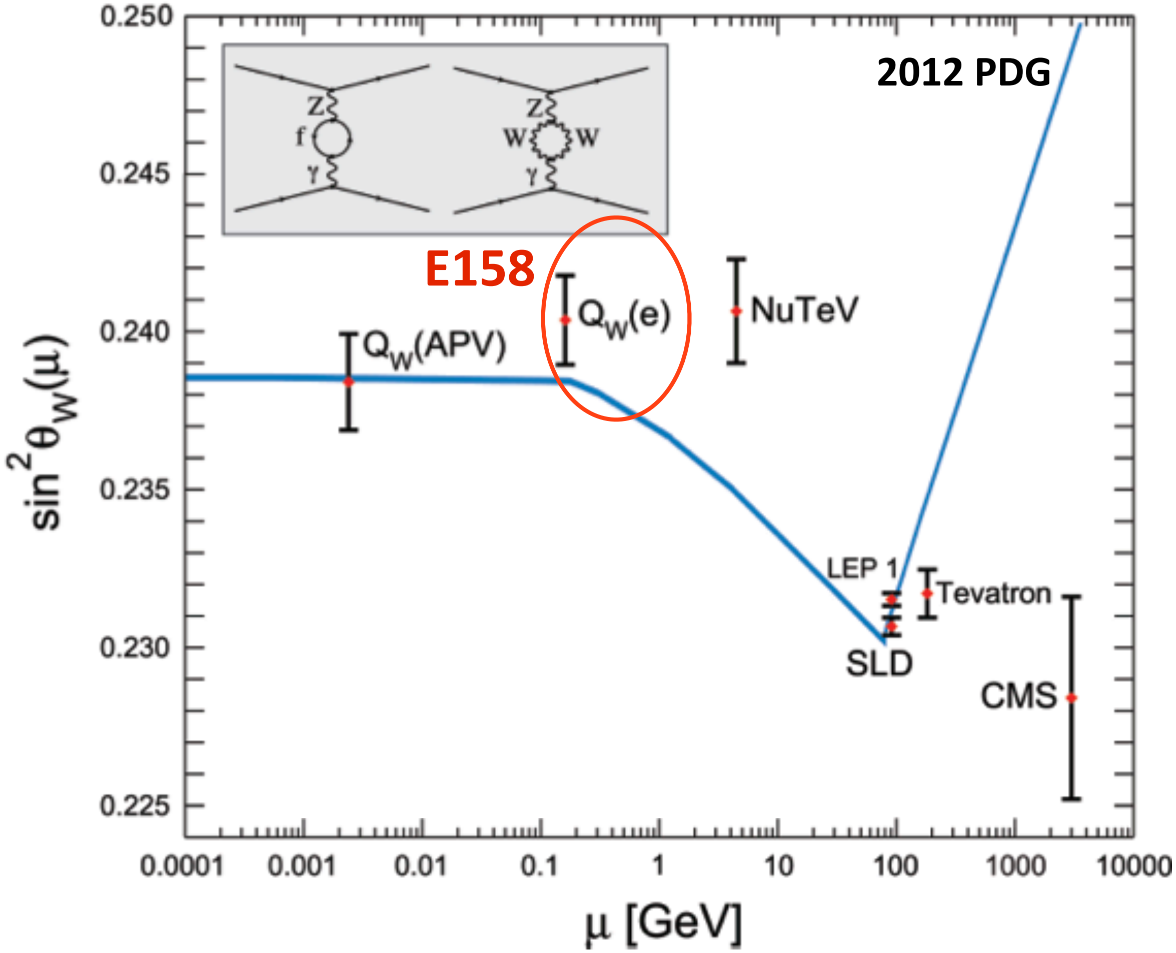


Constraints on new physics into
15 TeV (lepton compositeness)
0.5-2 TeV (Z', extra dimensions)





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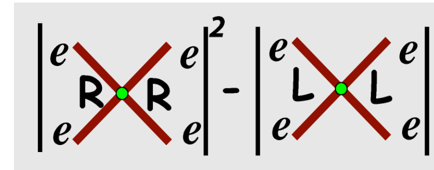

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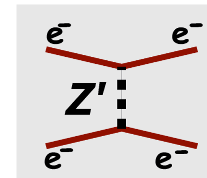
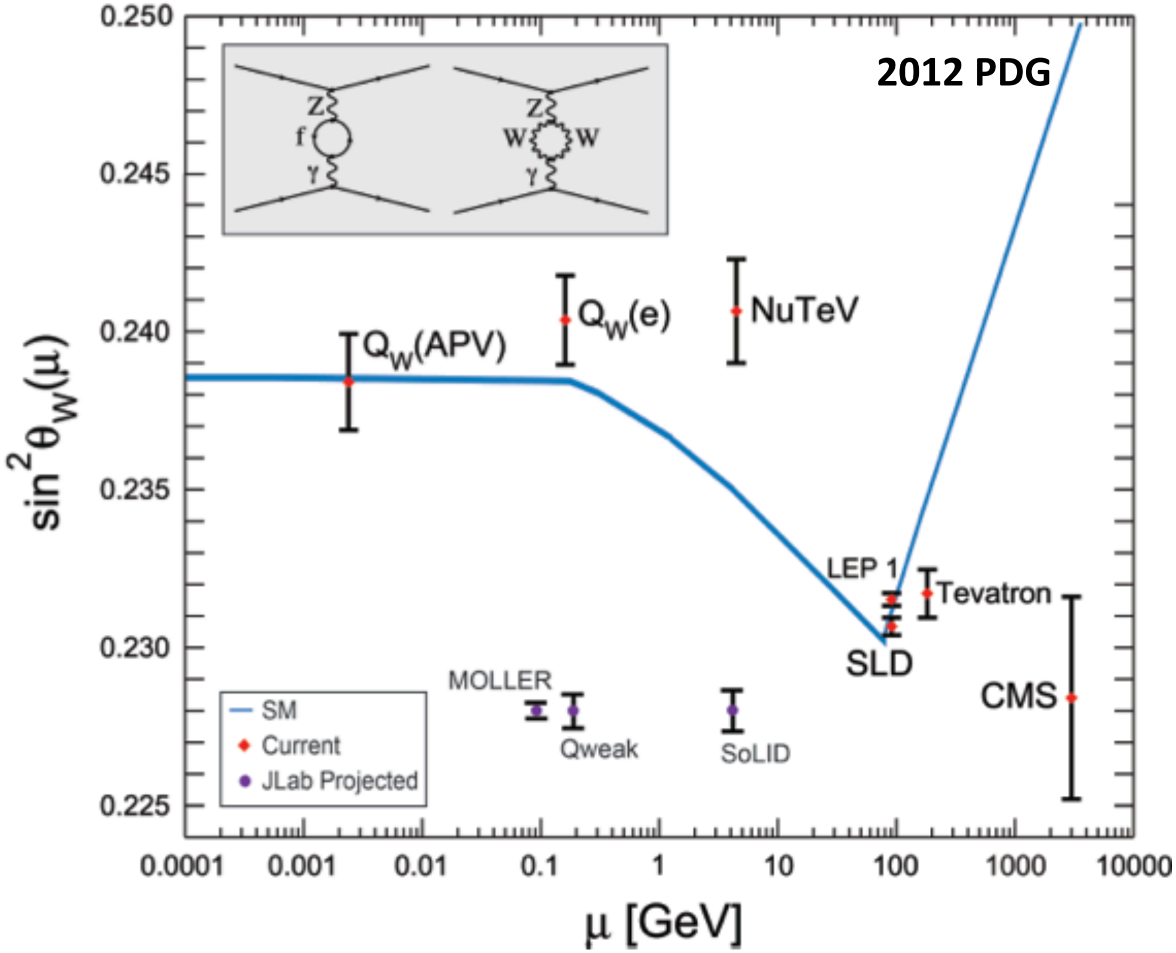
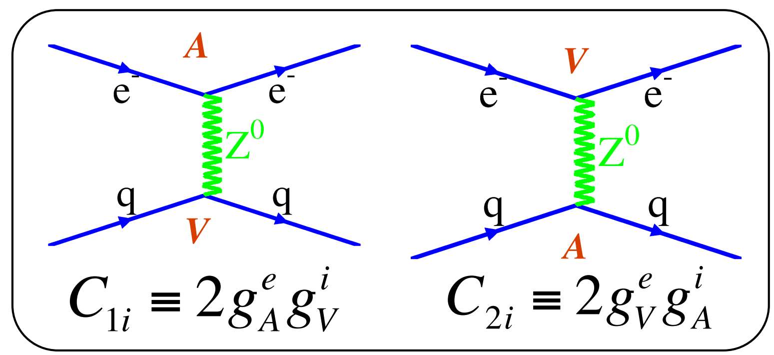




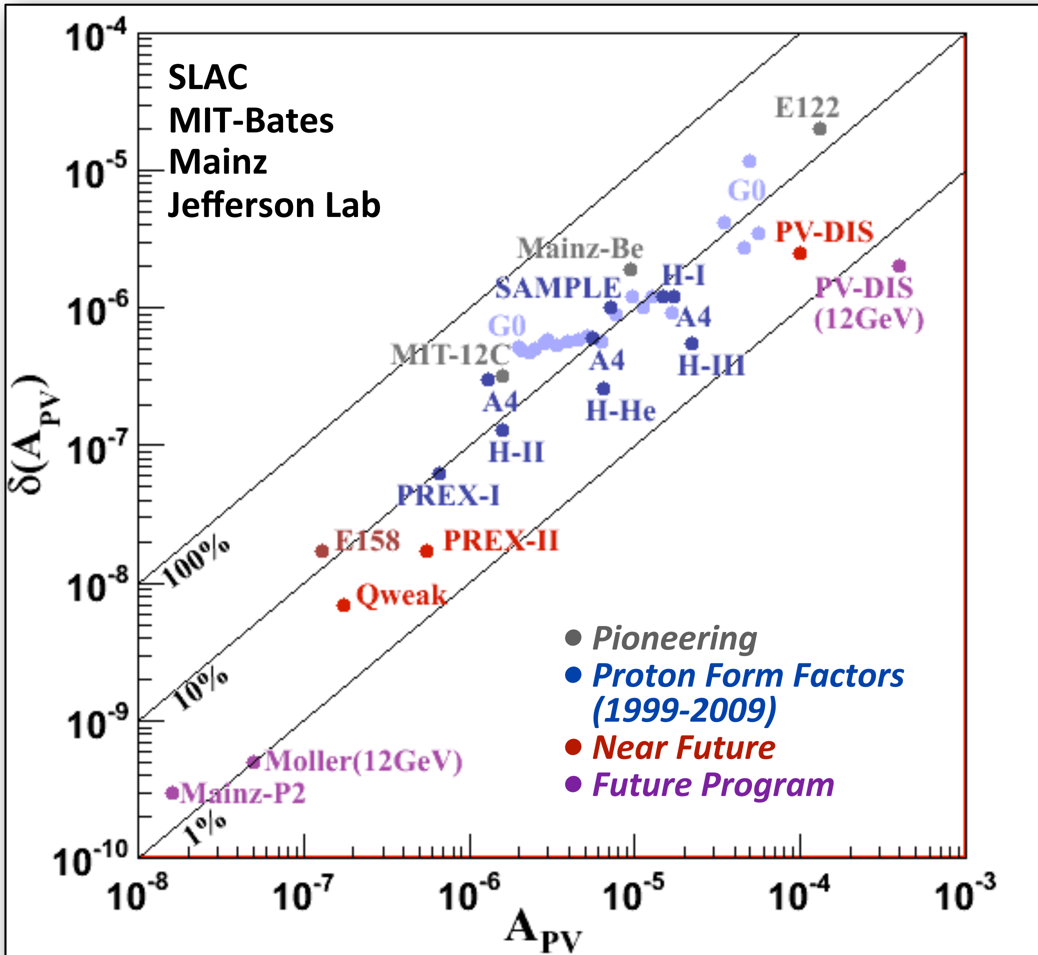
Future Program of Precision Weak Charge Measurements



- **Elastic Electron-Proton Scattering**
- **Deep Inelastics Scattering off Deuterium**
- **Moller Scattering**

3 Decades of Technical Progress

Parity-violating electron scattering has become a precision tool



Interplay between probing hadron structure and electroweak physics

- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

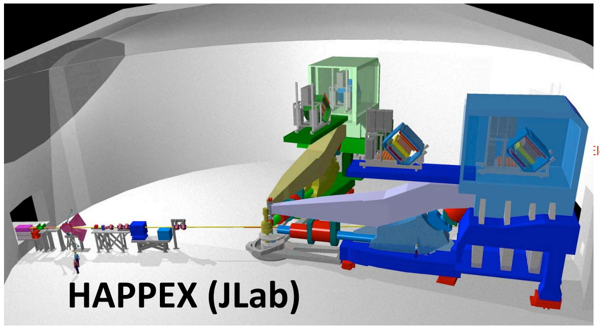
For future program:

- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

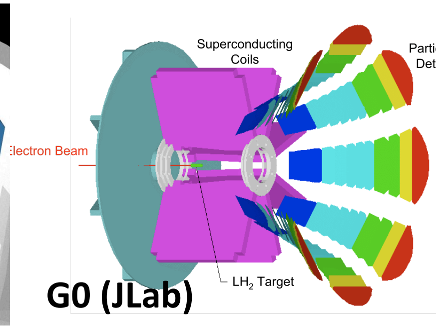
photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

Proton Weak Charge

Strange Vector Form Factors Are Small



HAPPEX (JLab)



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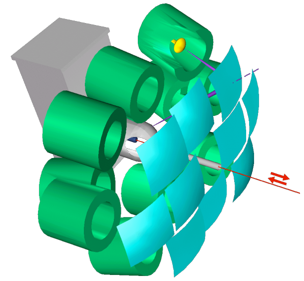
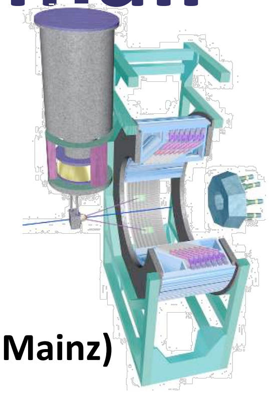


SAMPLE (Bates)



A4 (Mainz)

Form factors for elastic scattering

$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

$$G_M^p = \frac{2}{3}G_M^{u,p} - \frac{1}{3}G_M^{d,p} - \frac{1}{3}G_M^s$$

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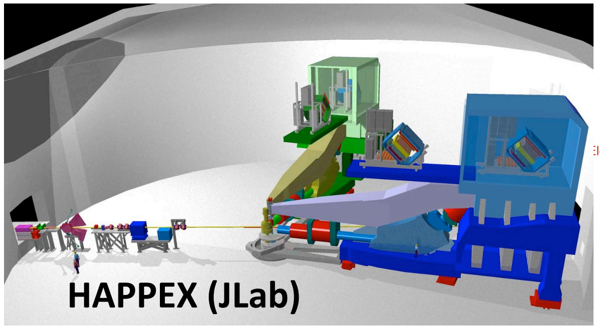

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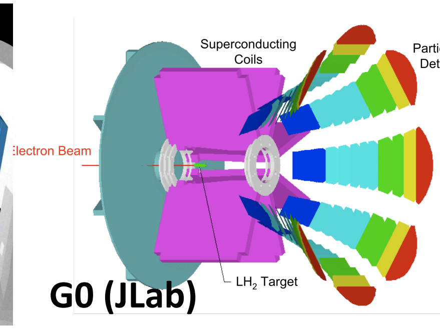

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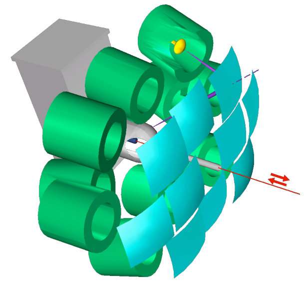
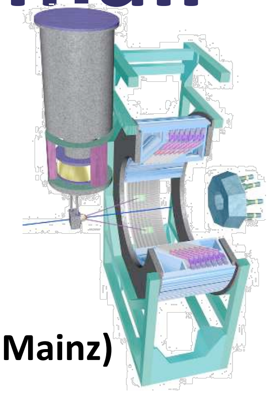


SAMPLE (Bates)



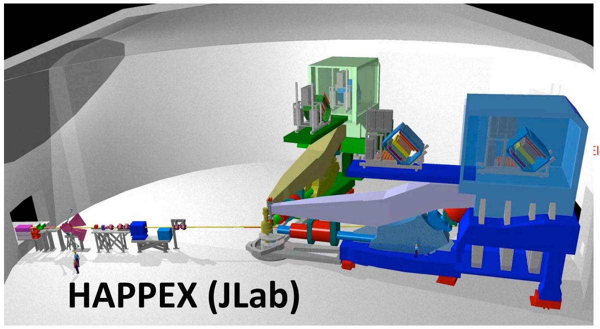
A4 (Mainz)

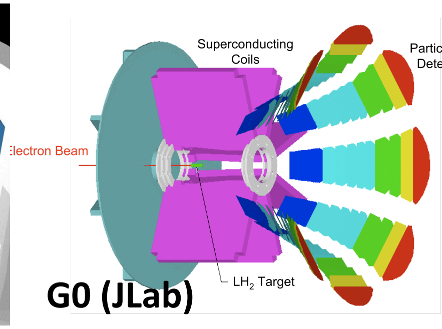
Form factors for elastic scattering

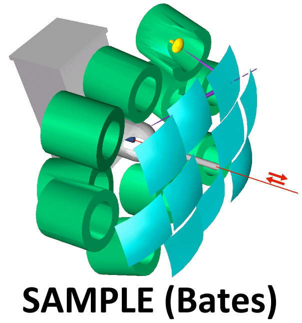
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

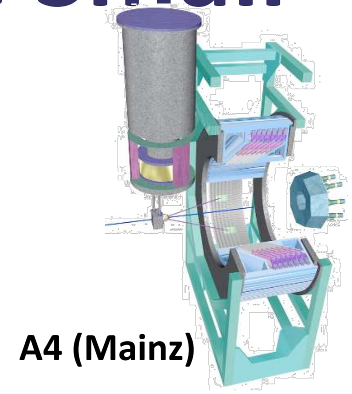
$$G_M^p = \frac{2}{3}G_M^{u,p} - \frac{1}{3}G_M^{d,p} - \frac{1}{3}G_M^s$$

Strange Vector Form Factors Are Small









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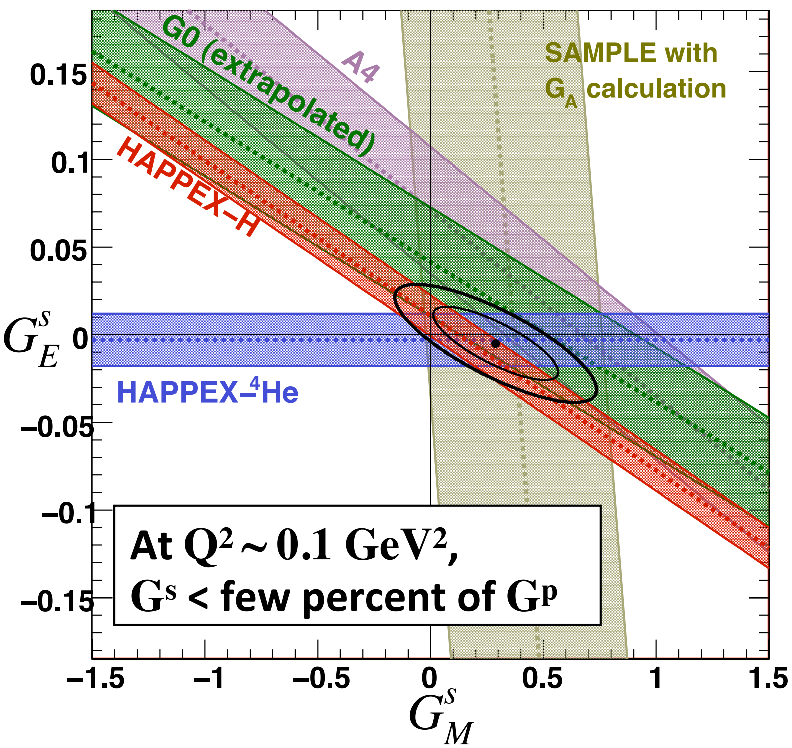
Probing over a range of low-Q², effects are small (<3%) and consistent with zero.



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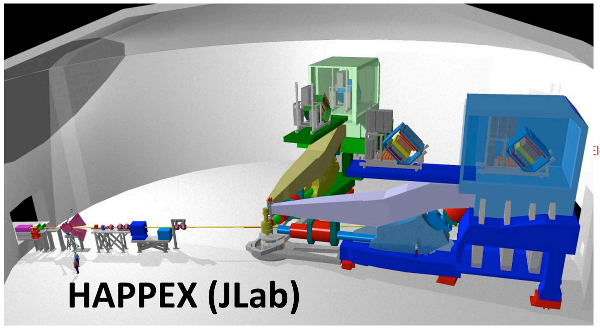

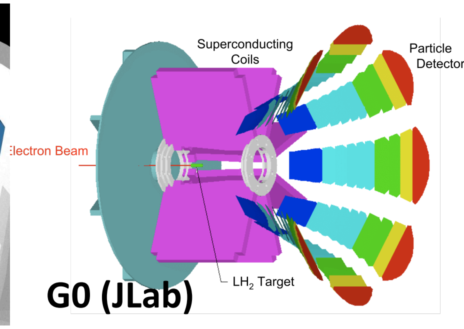

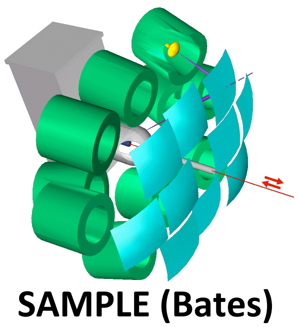

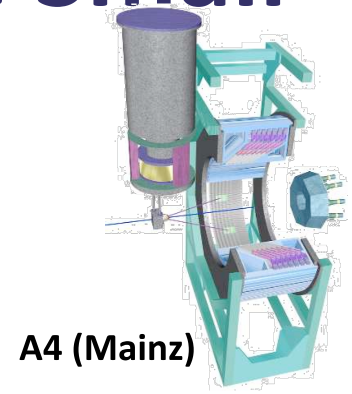

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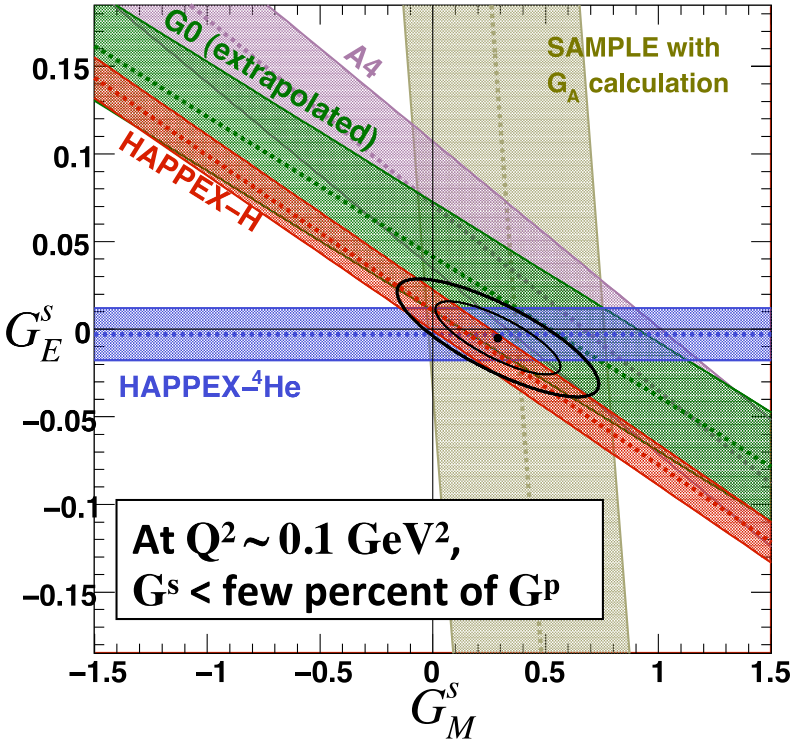

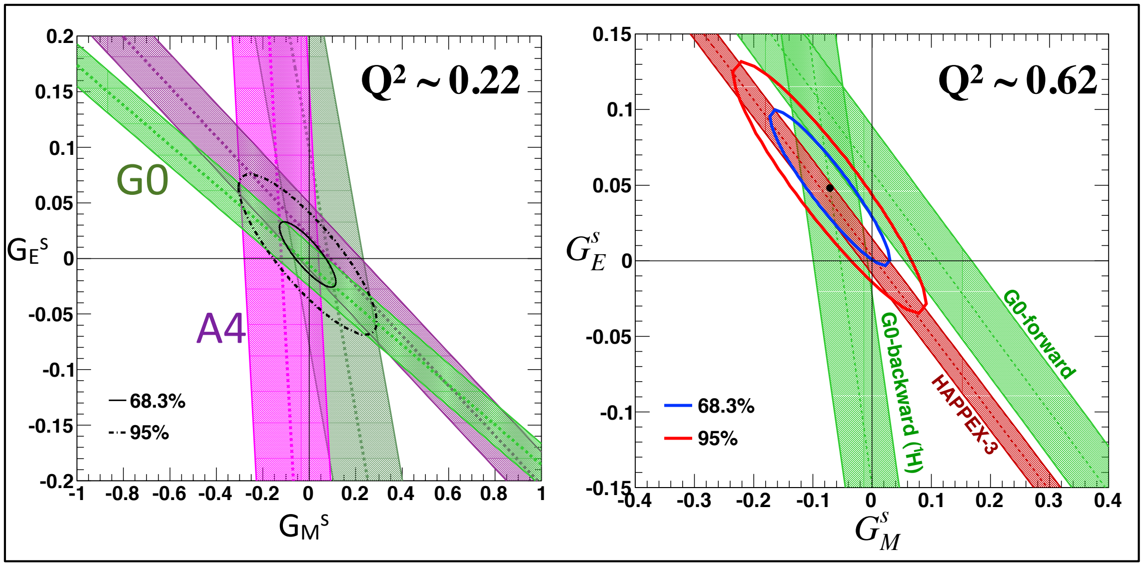

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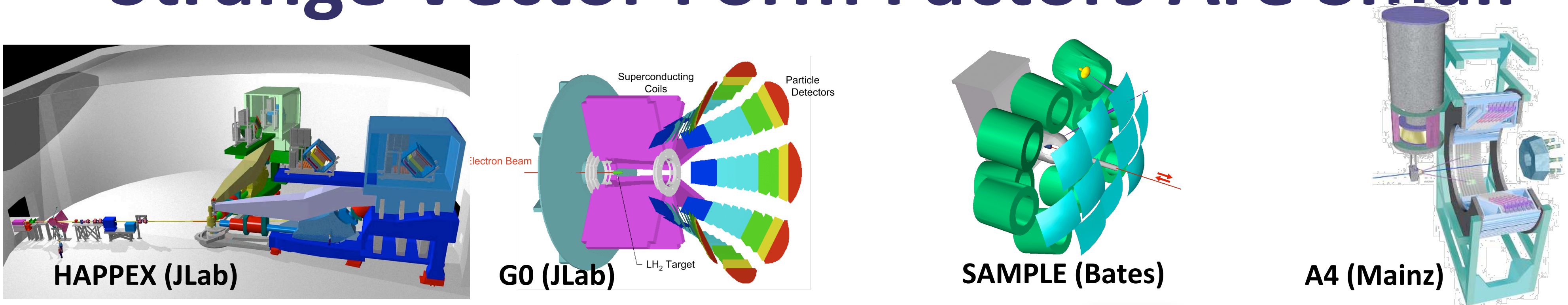

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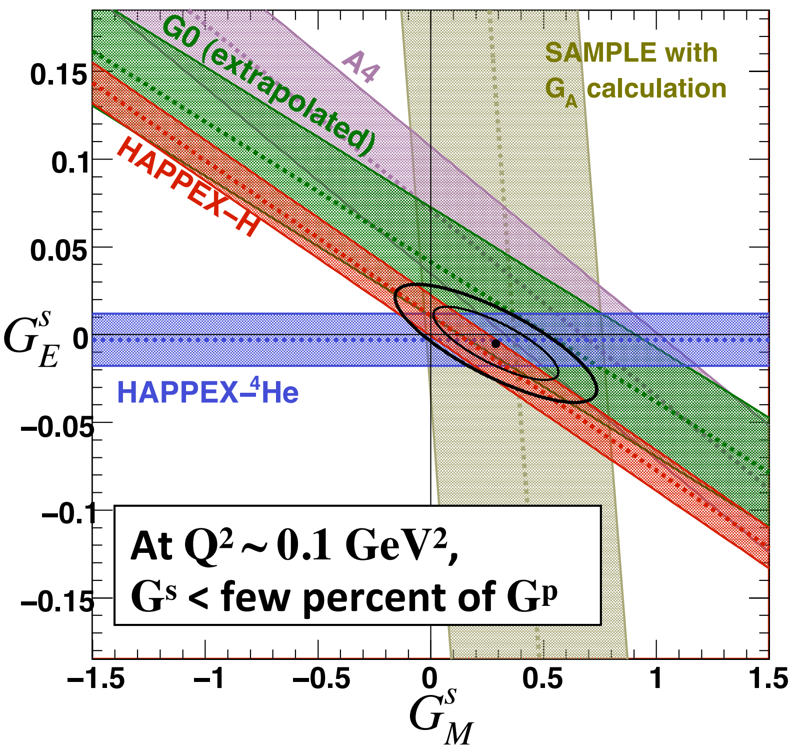
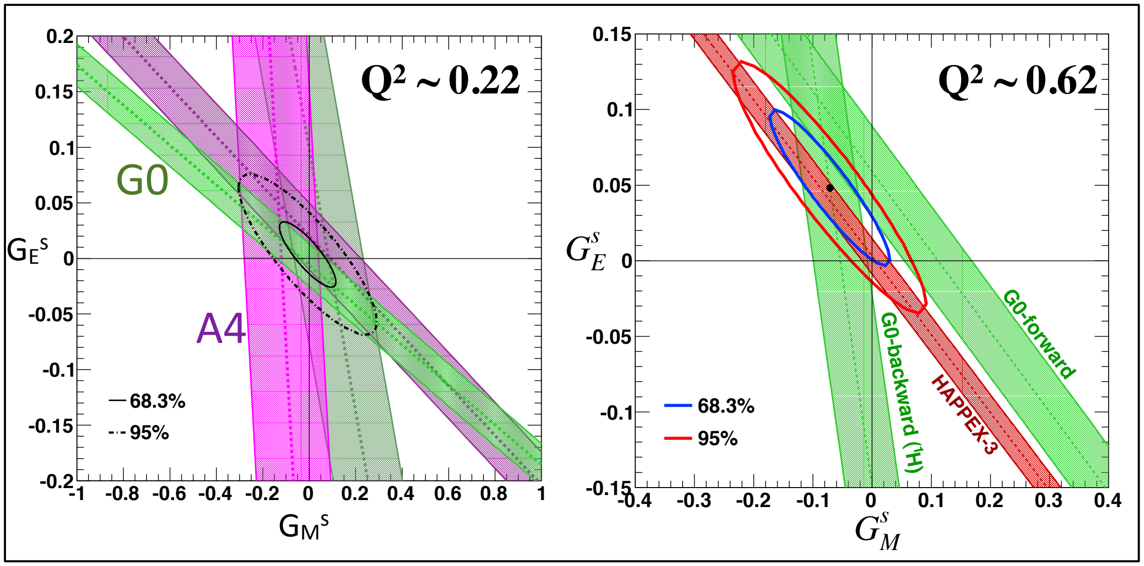
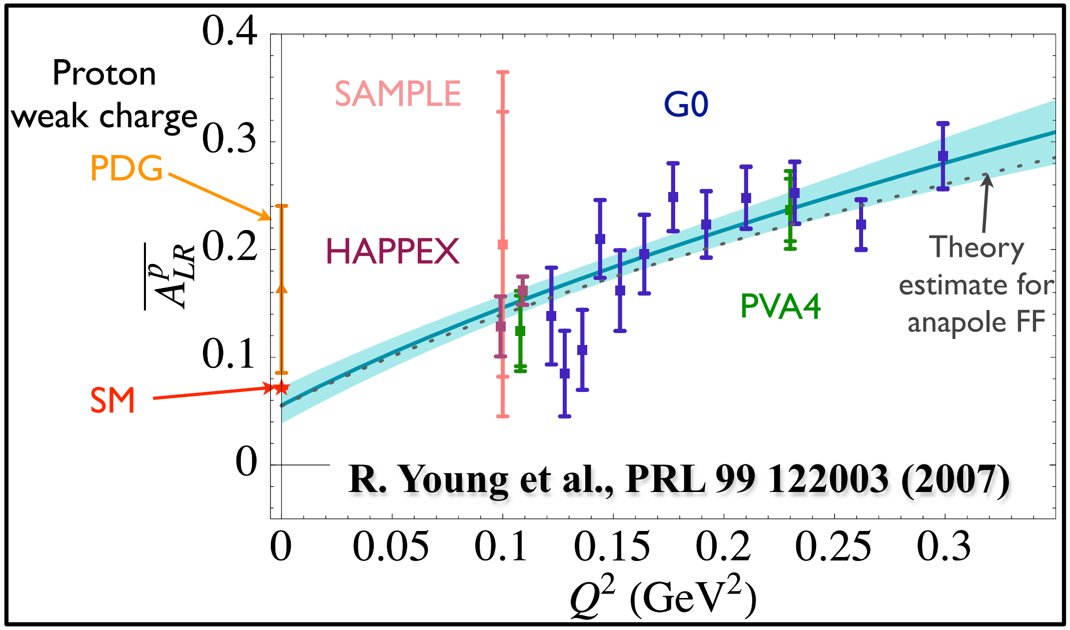




Whether strange quarks, charge symmetry breaking, axial contributions - proton structure effects in A_{PV} must go to zero at $Q^2 = 0$

Proton Weak Charge, Q_W^p



At small angle and low Q^2, form-factor and other contributions are small

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

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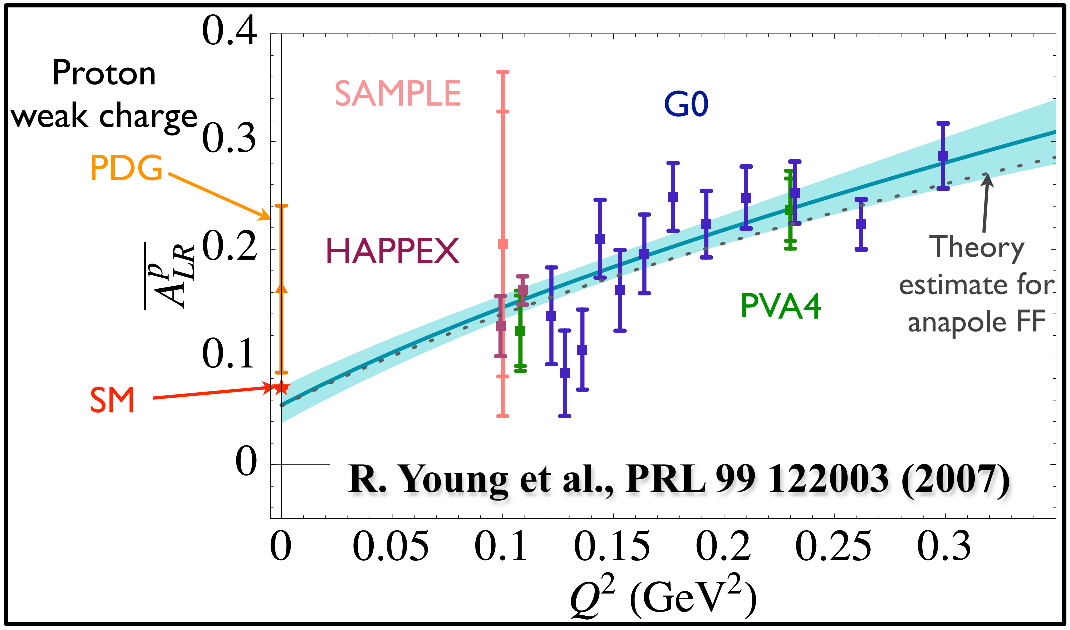

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Global fit of existing strange-quark program data provides an important constraint on Standard Model $\mathbf{C_{1u}}$ and $\mathbf{C_{1d}}$

$$Q^p_W = 2\, C_{1u} + C_{1d}$$

$$C_{1q} = g_V^q g_A^e$$

$$C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

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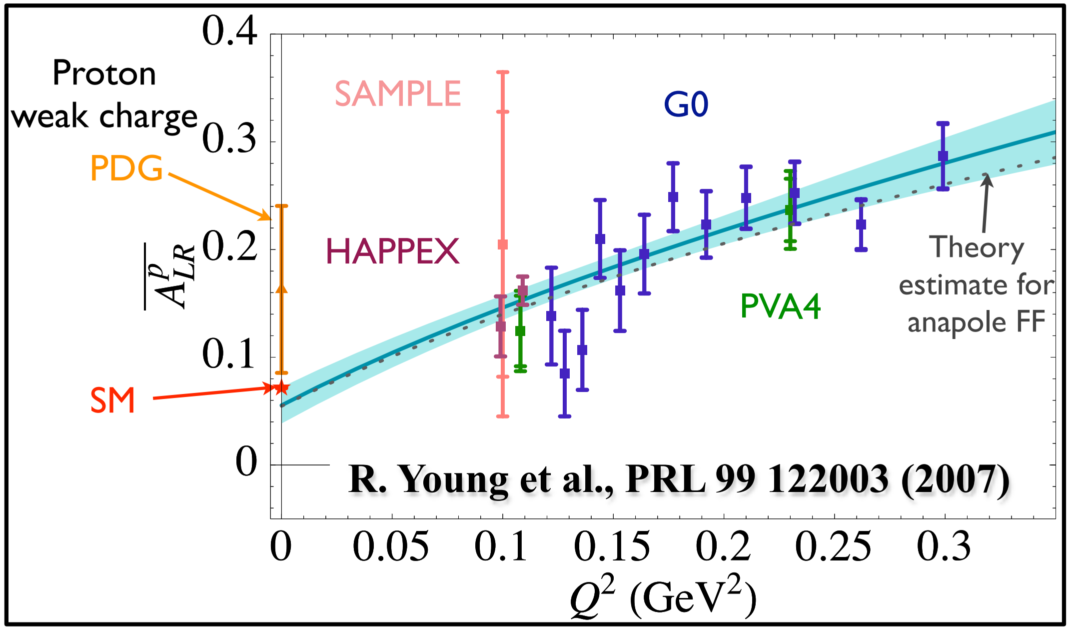

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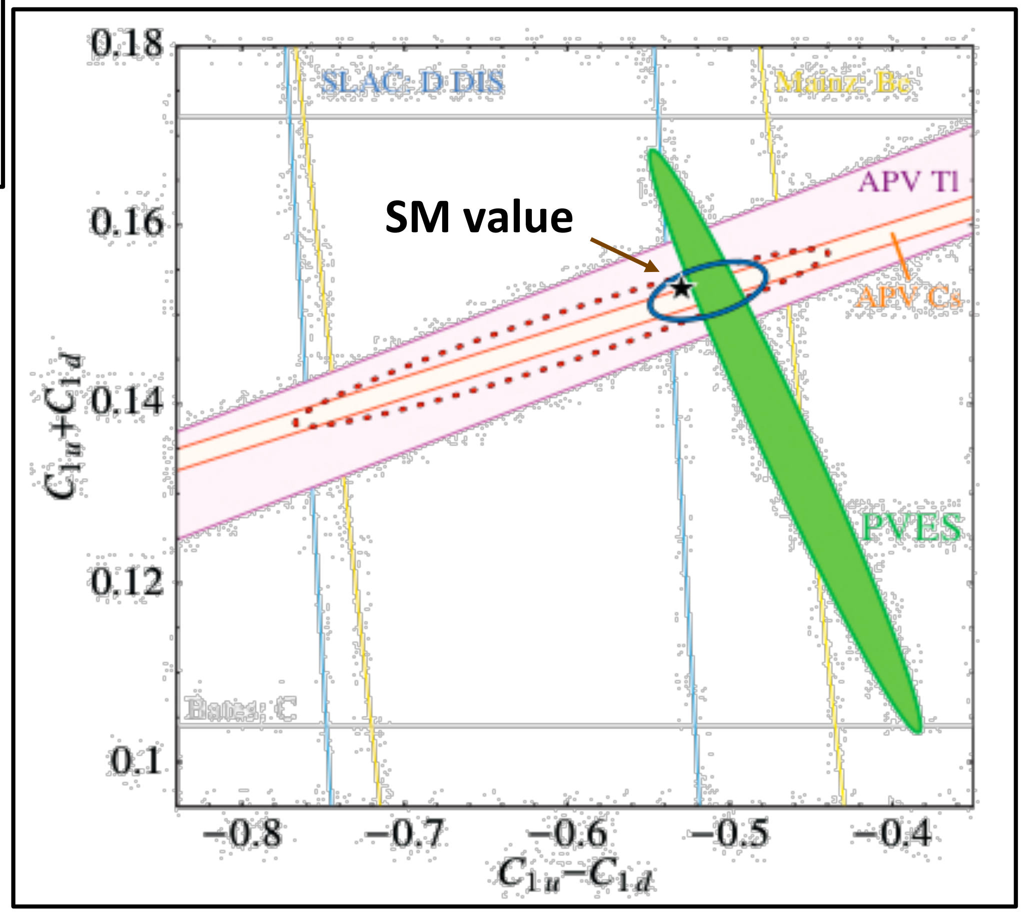

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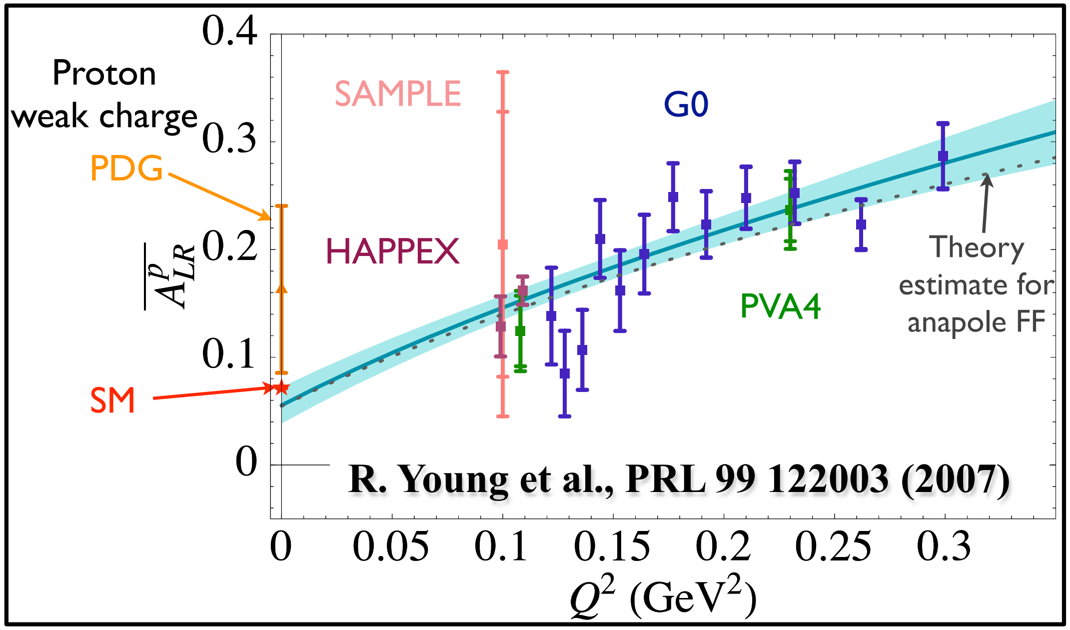

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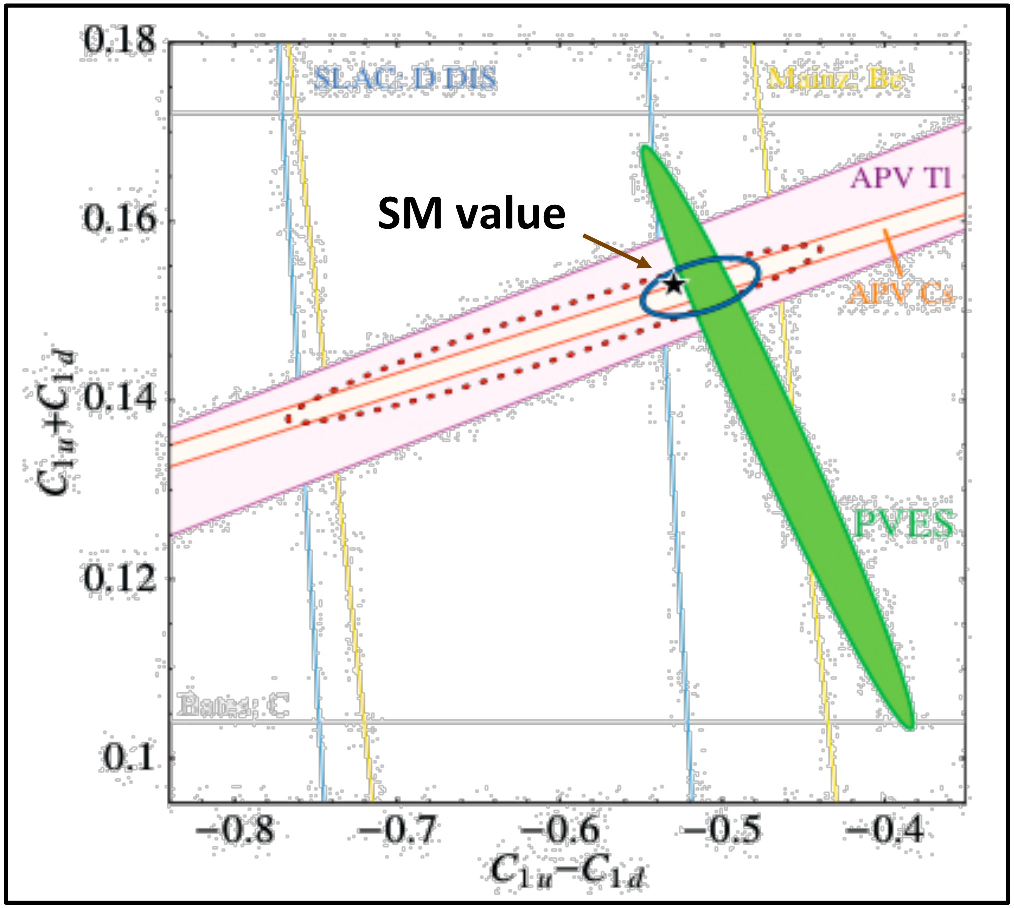
Conclusion of the strange quark program has led to significant improvement in constraints on non-SM couplings



QWeak: precision measurement of Q_W^p

Dedicated measurement at small angle, low $Q^2 \sim 0.03$ GeV^2

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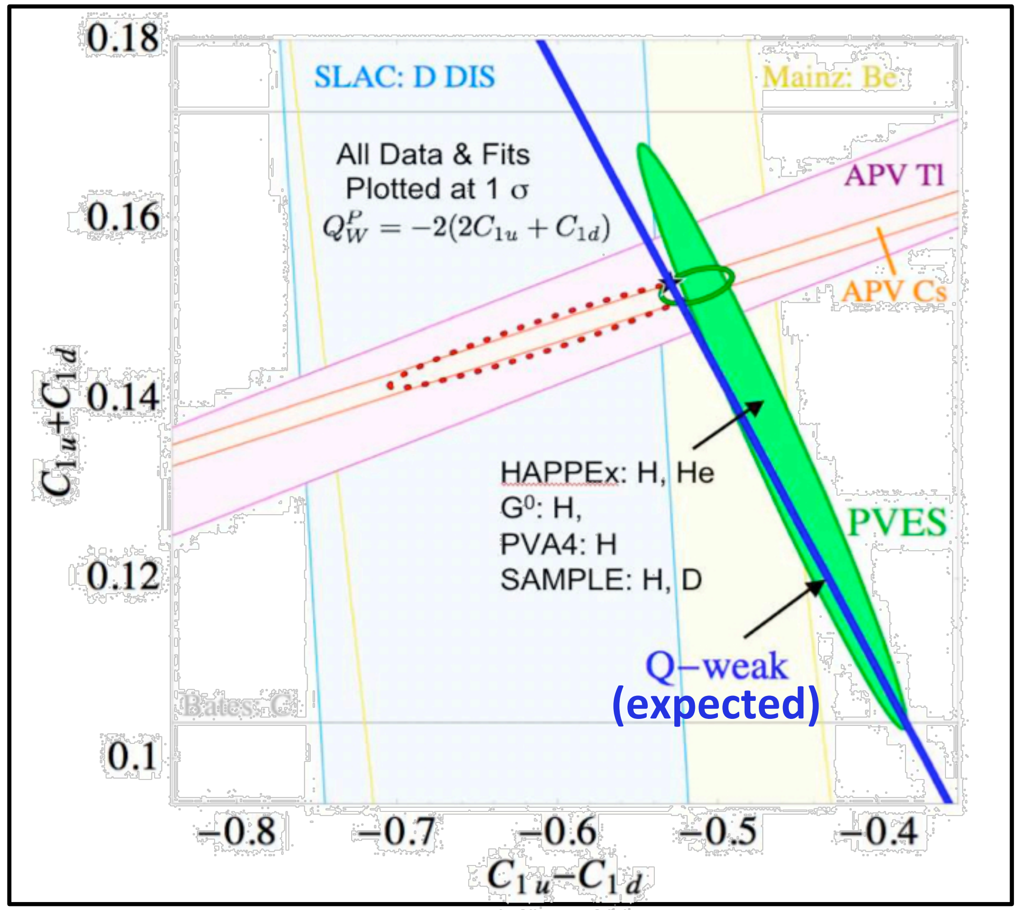
Proton structure F, contributes ~30% to asymmetry, **~2% to $\delta(Q_W^p)/Q_W^p$**

$$\delta Q_W^p = \pm 4\%$$

$$\Rightarrow \delta(\sin^2\theta_W) = \pm\ 0.3\%$$



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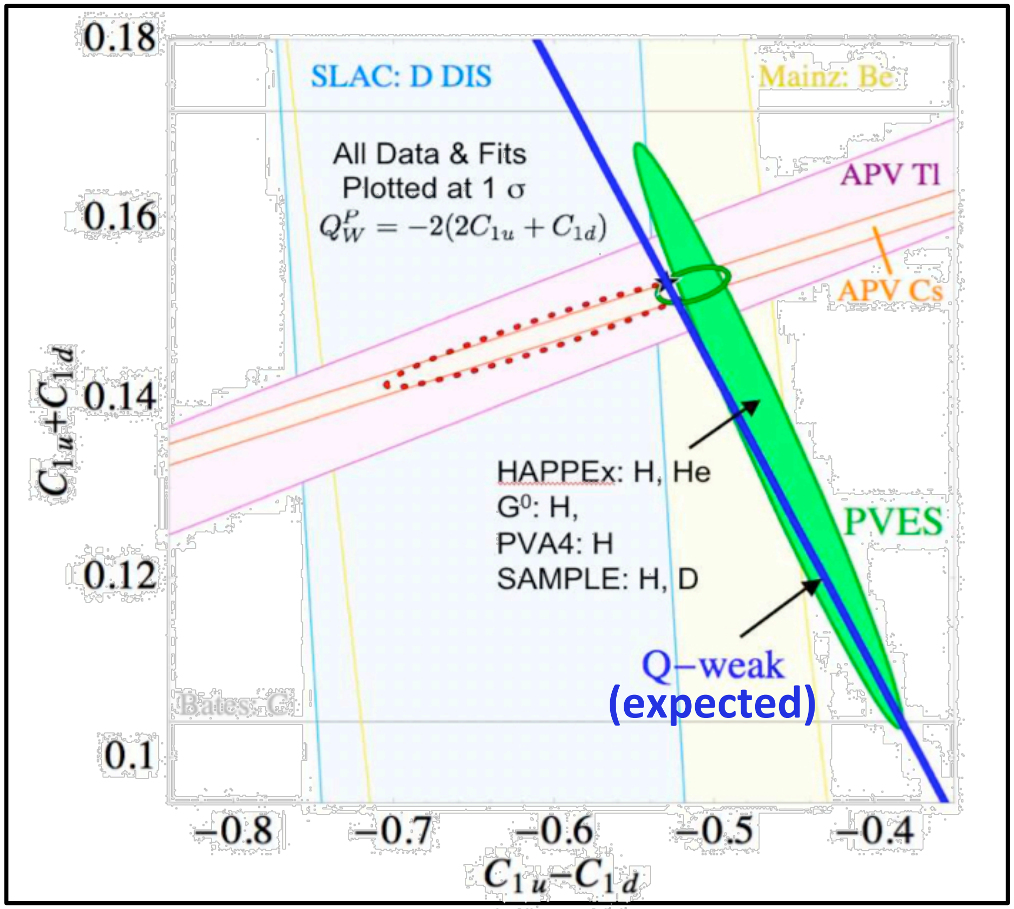
$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_\mu |\Delta Q_W^p|}} \sim 4.6\text{TeV}$$



Non-perturbative theory

g ~ 2π　　Λ ~ 29 TeV

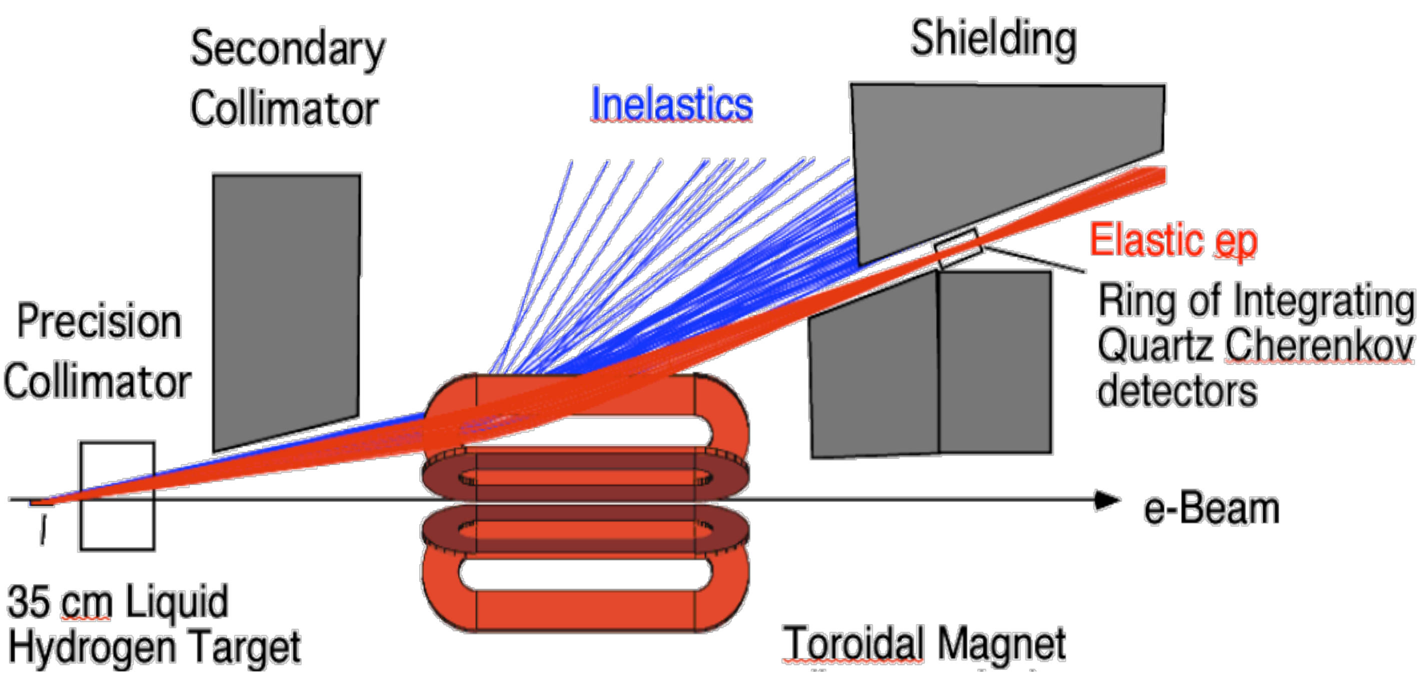
Extra Z'

g ~ 0.45　　$m_{Z'}$ ~ 2.1 TeV

QWeak

A new standard in precision

- High power, low noise target
- Low system noise - 5 GHz rate!
- High rate, radiation hard readout
- Control and correction for beam systematics
- Polarimetry approaching 1% (new)
- Background and calibration precision



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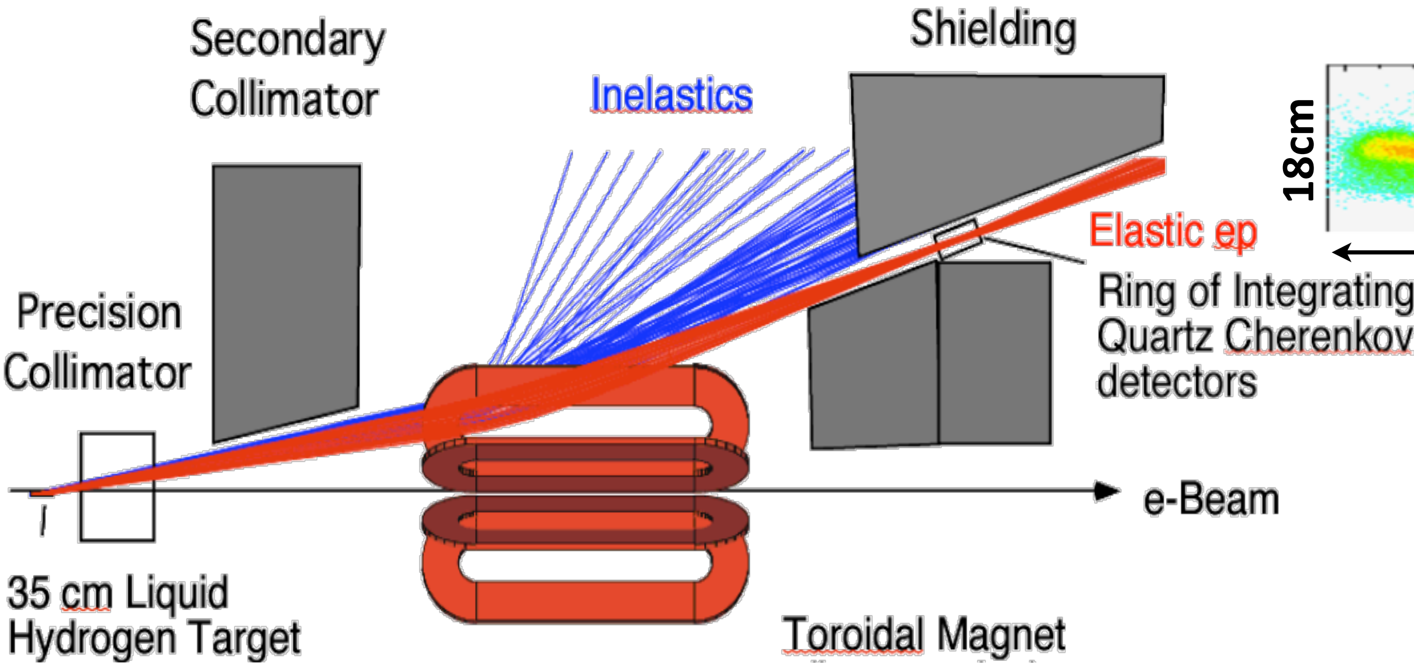

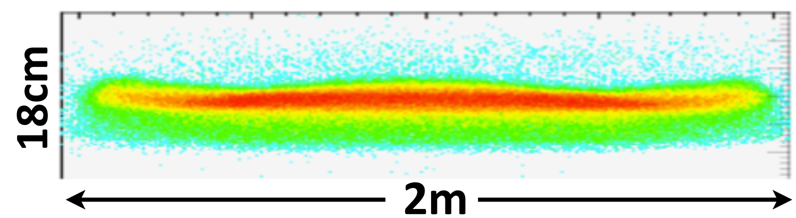

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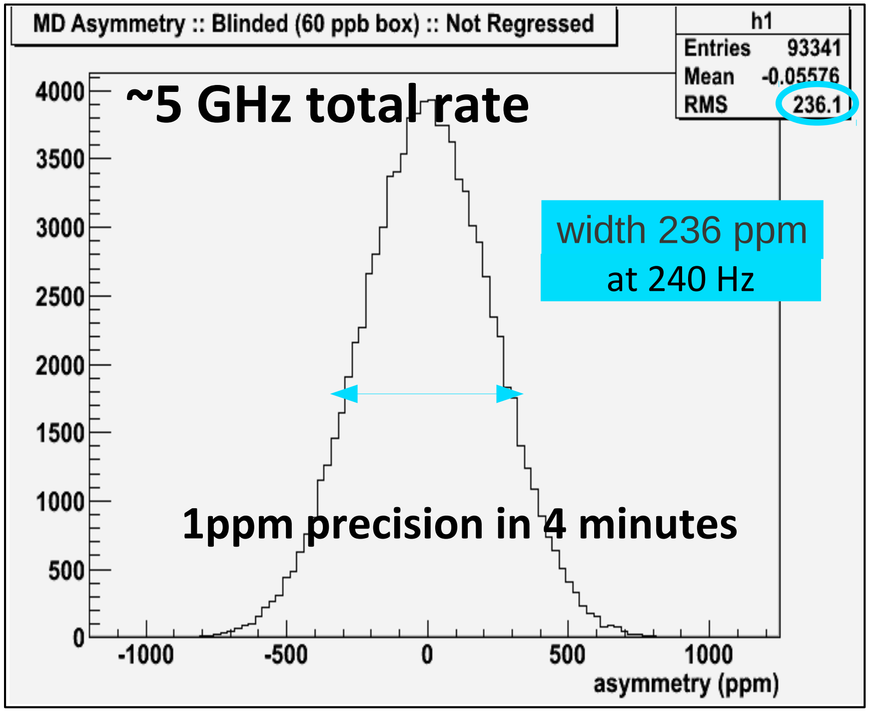
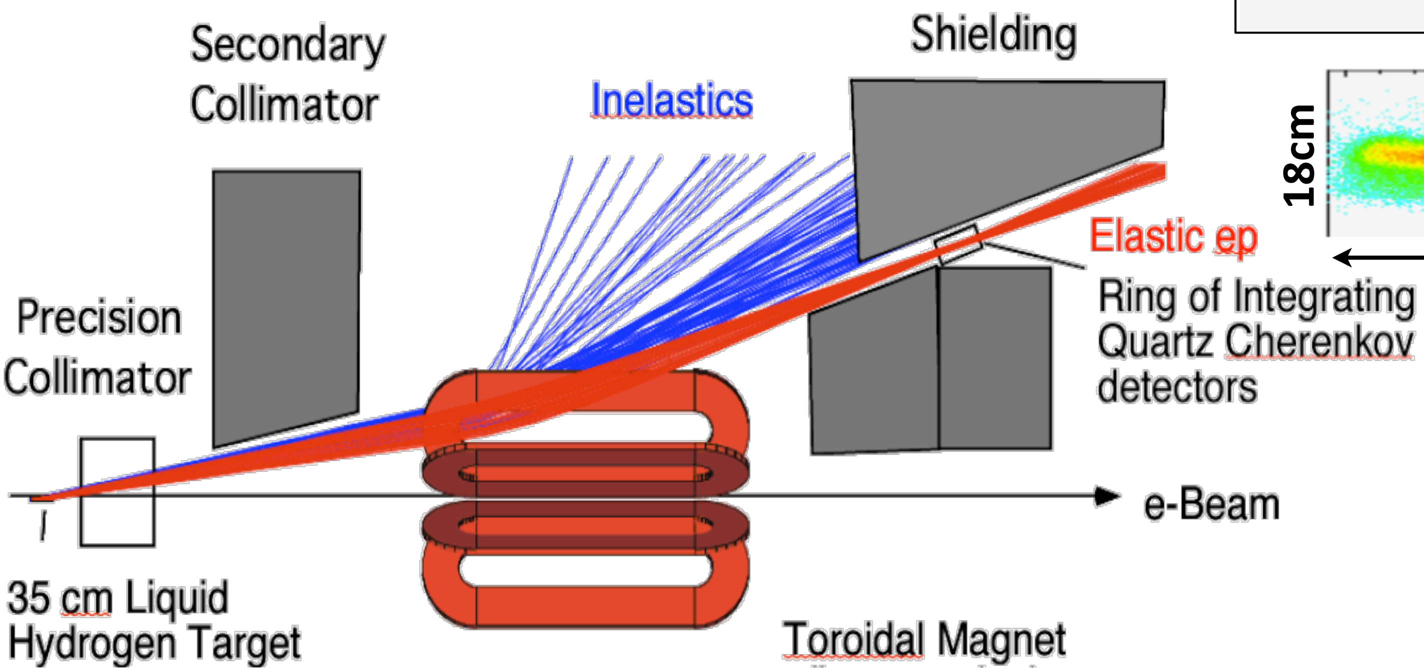
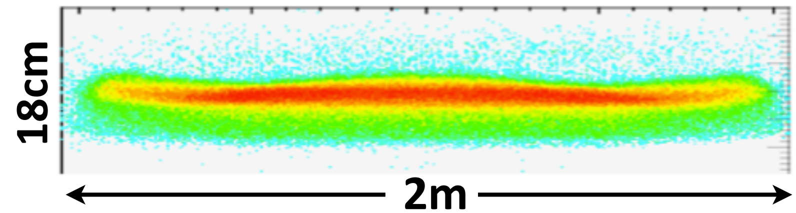




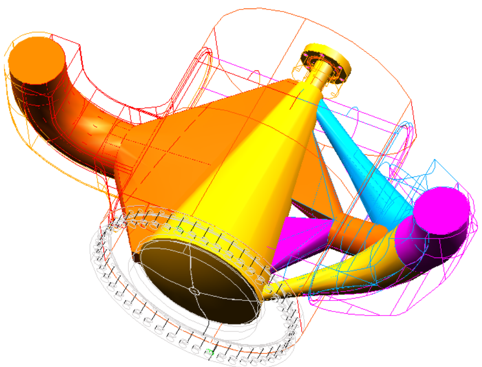


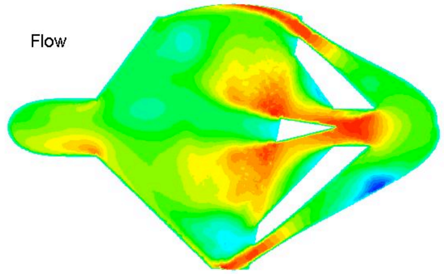
QWeak

Liquid Hydrogen:
35cm cell, 180 μA

World's highest power cryotarget
2300 Watts

Designed with CFD simulation





Boiling <40ppm at 180 μA (about 3% excess noise)

preliminary "internal consumption only"

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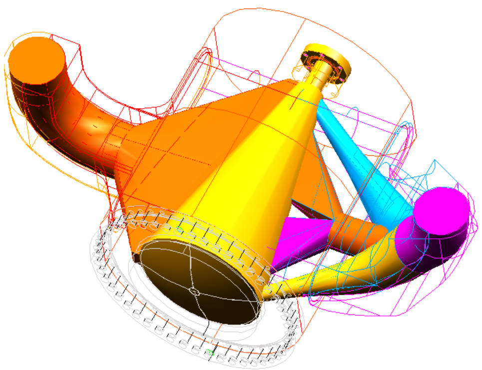

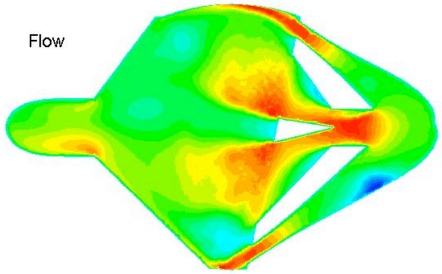

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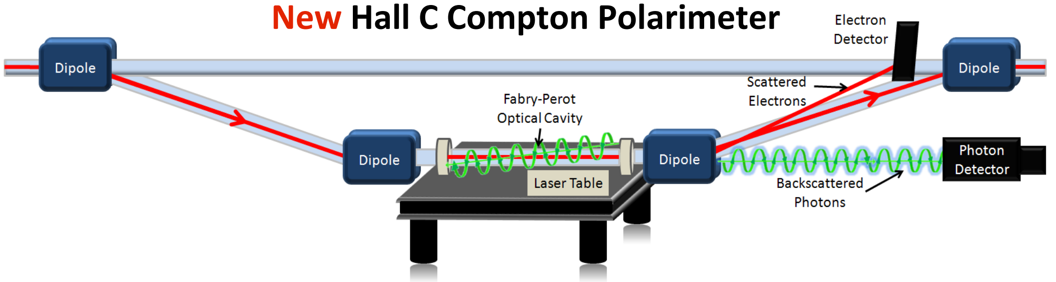
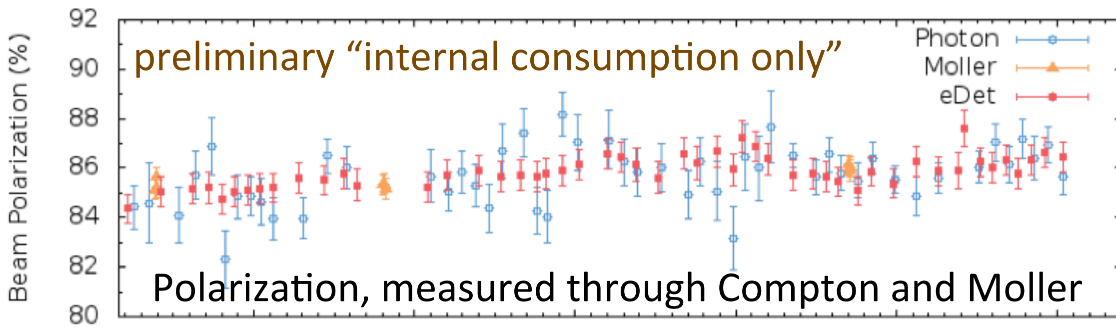
New Hall C Compton Polarimeter





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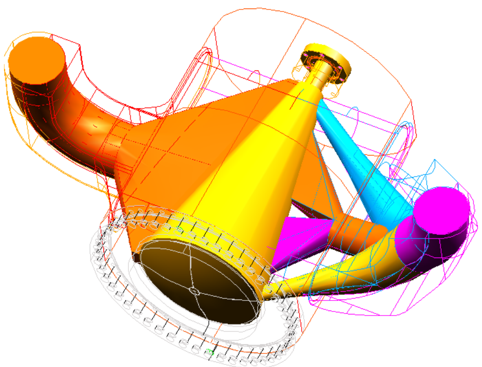

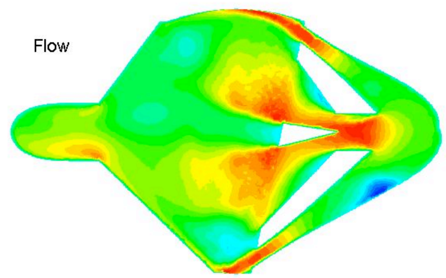

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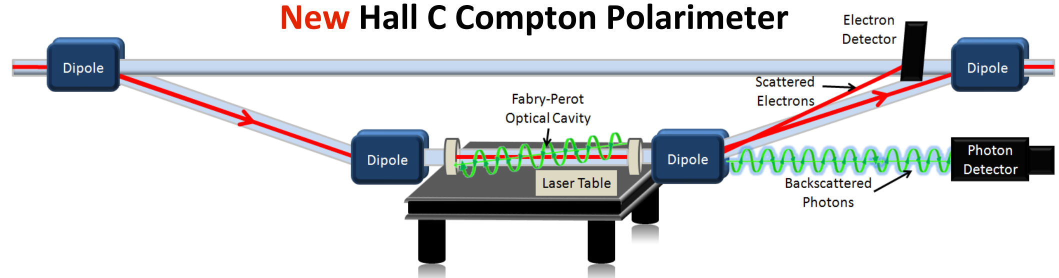

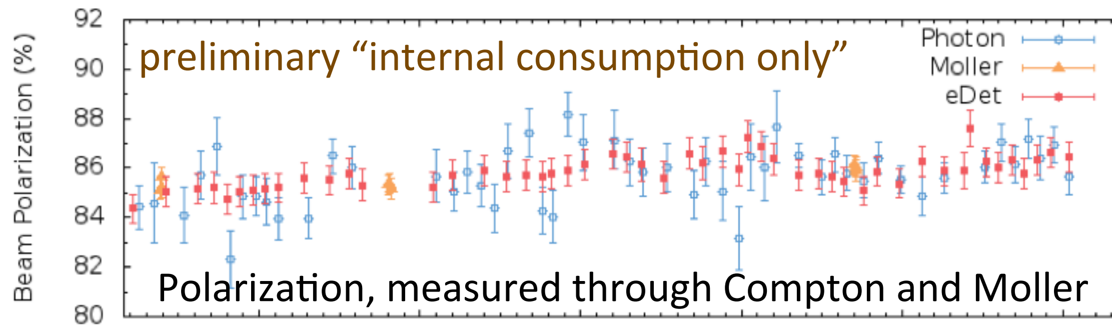

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Run II Beam Properties	
Δx	-0.95 nm
Δy	-0.24 nm
Δx'	-0.07 nrad
Δy'	-0.06 nrad
A_{Energy}	0.23 ppb

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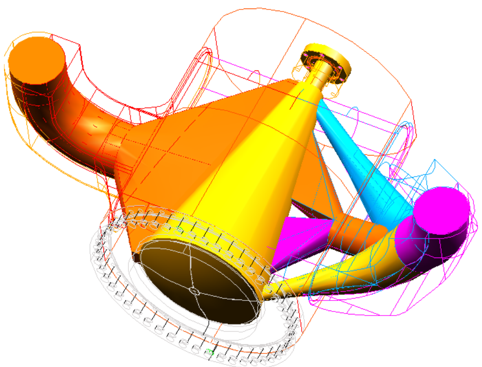

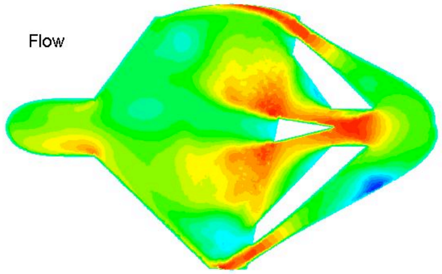

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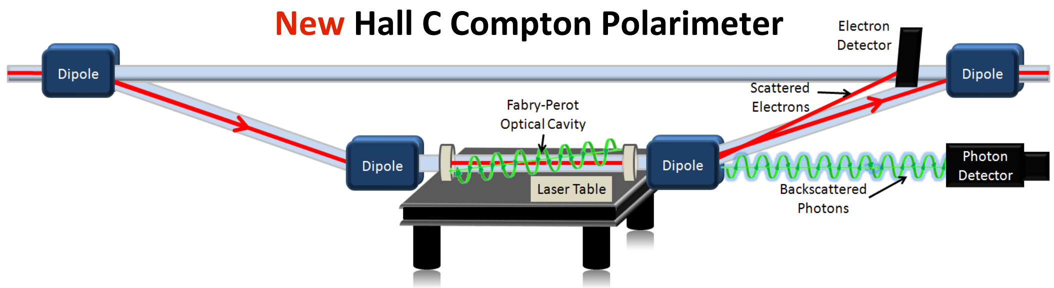
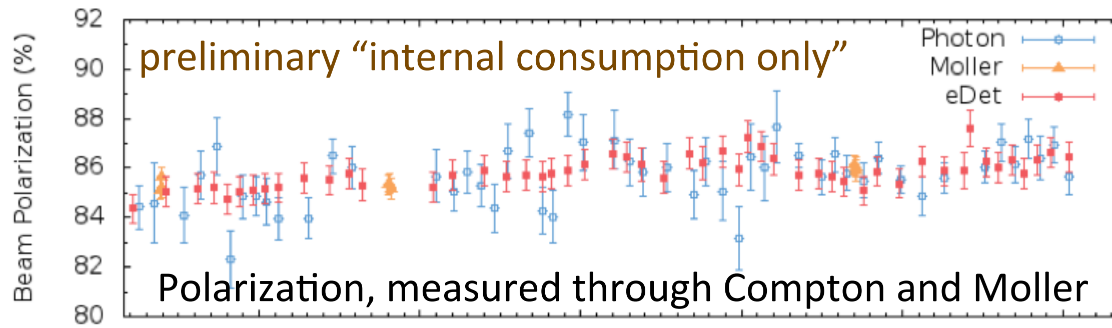
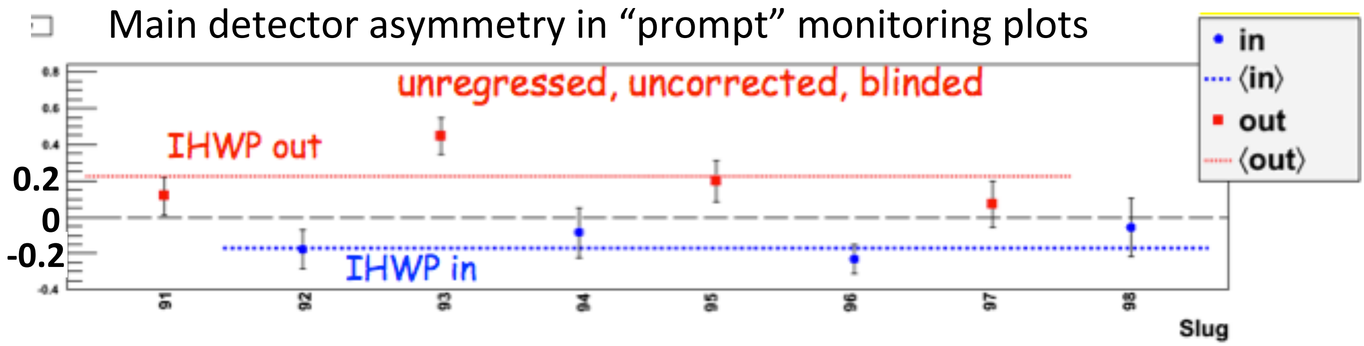




Main detector asymmetry in "prompt" monitoring plots



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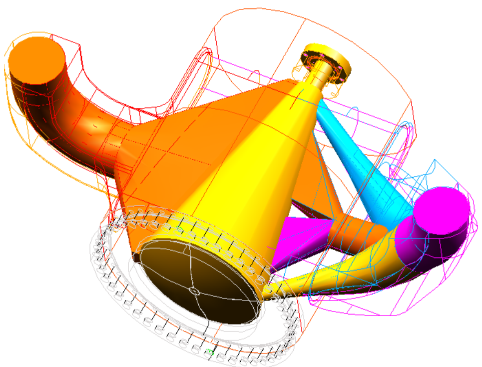

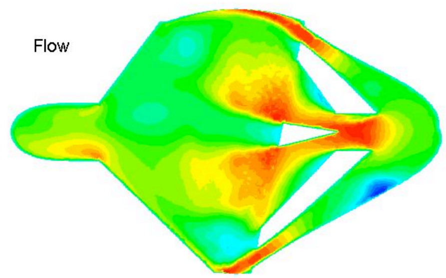

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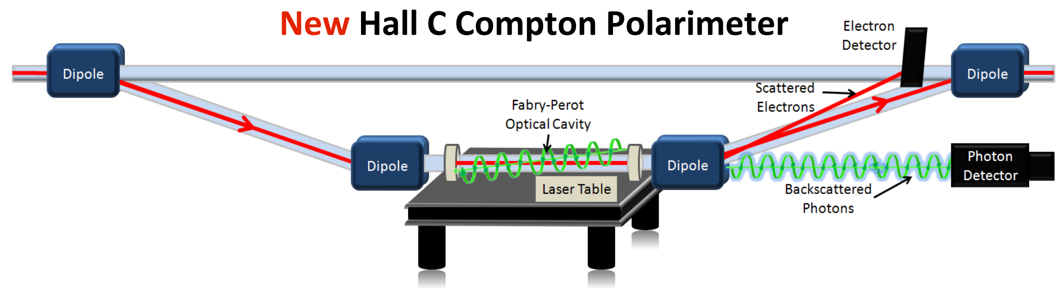

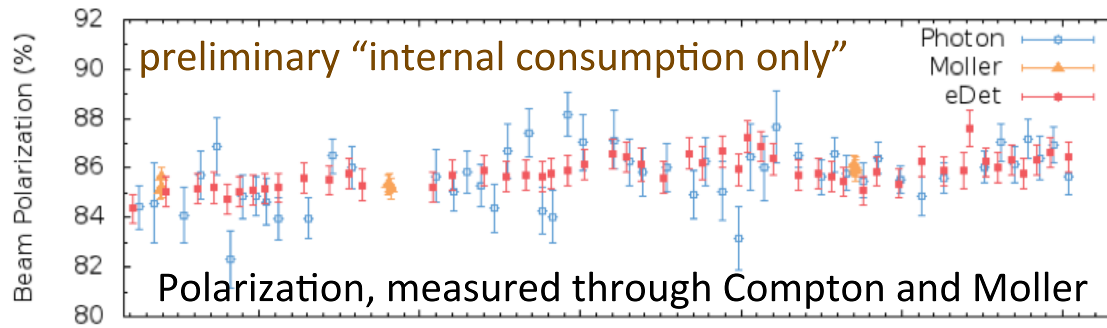

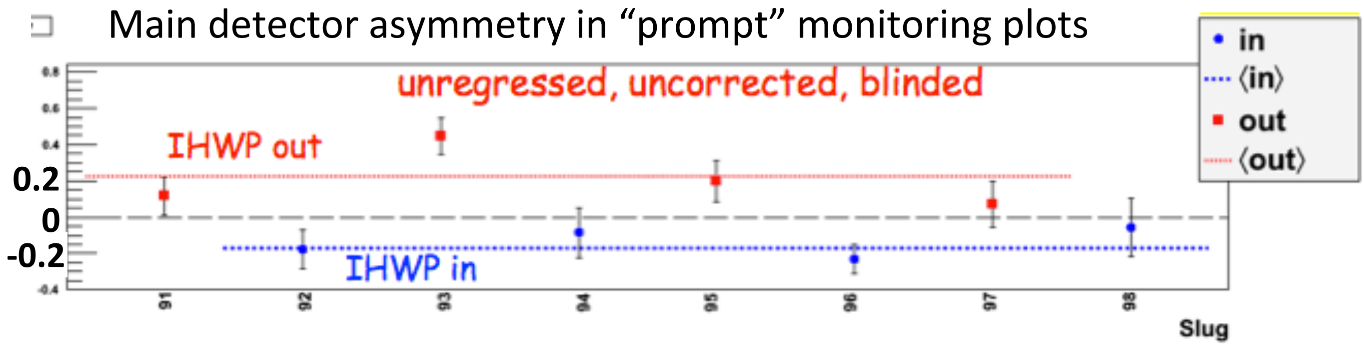

Completed run (2010-2012)

First results (~5% of data) to be released at DNP

MESA/P2 at Mainz

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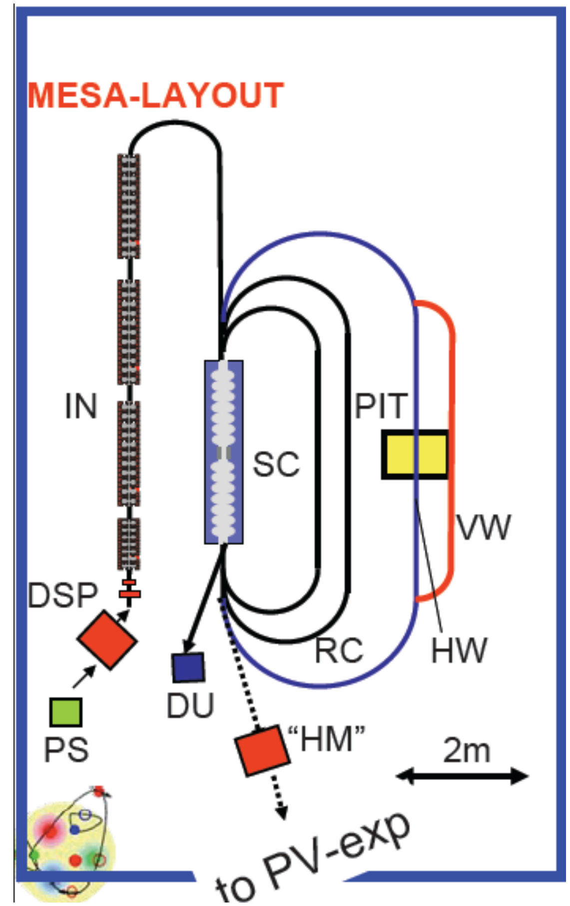
Qweak: proton structure F contributes ~30% to asymmetry, ~2% to $\delta(Q_W^p)/Q_W^p$

Negligible for significantly lower Q^2

- rate up 100x, Q2 down 10x: same FOM of Apv and 2x FOM on Q2
- reduced sensitivity to radiative corrections and proton structure

New research machine based on ERL will also support a high-current extracted beam at 100-200 MeV suitable for a PV experiment



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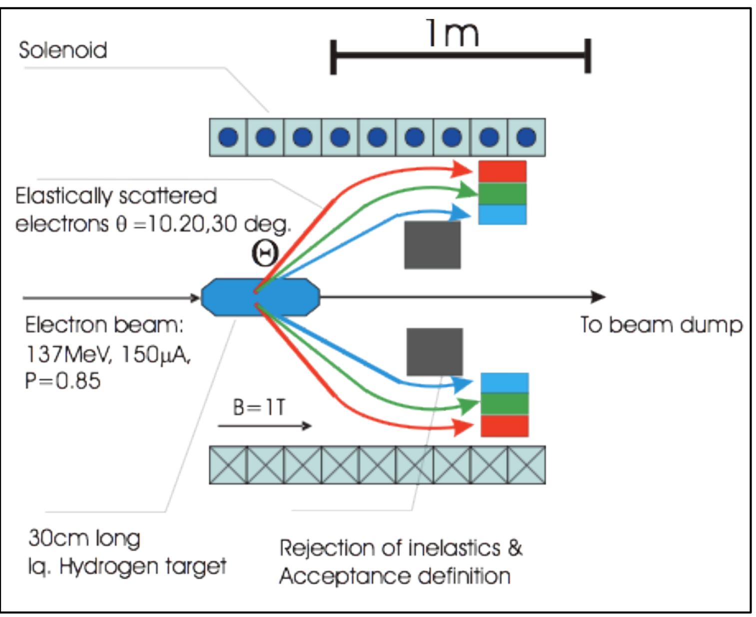
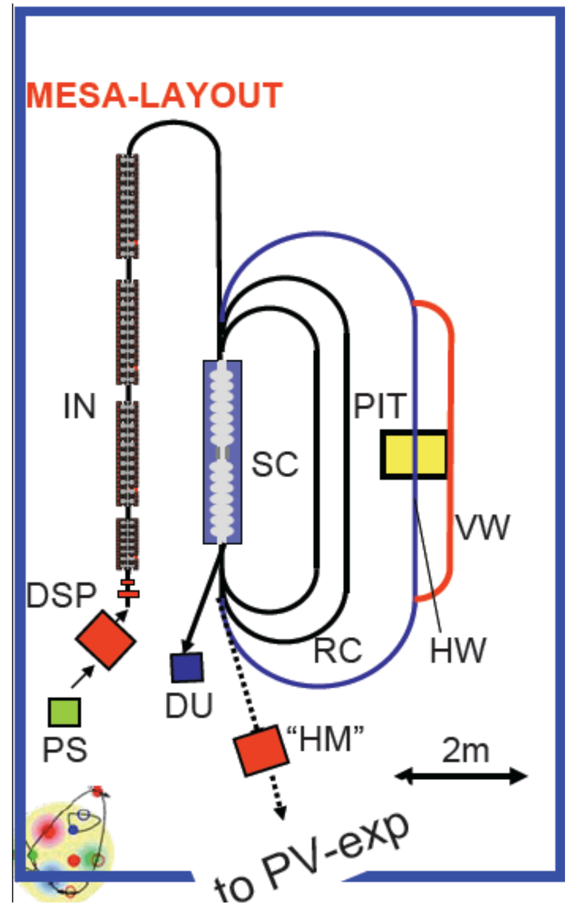


- E_{beam} = 200 MeV, 10-30°
- Q^2 = 0.0048 GeV^2
- 30 cm target, 150 uA, 10^4 hours, 85% polarization
- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%



MESA/P2 at Mainz

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

Qweak: proton structure F contributes ~30% to asymmetry, ~2% to $\delta(Q_W^p)/Q_W^p$

Negligible for significantly lower Q^2

- rate up 100x, Q2 down 10x: same FOM of Apv and 2x FOM on Q2
- reduced sensitivity to radiative corrections and proton structure

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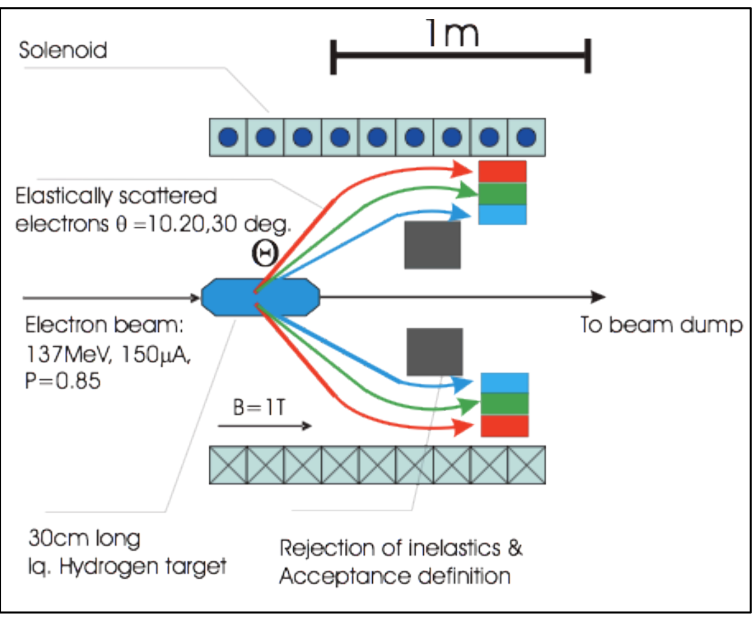

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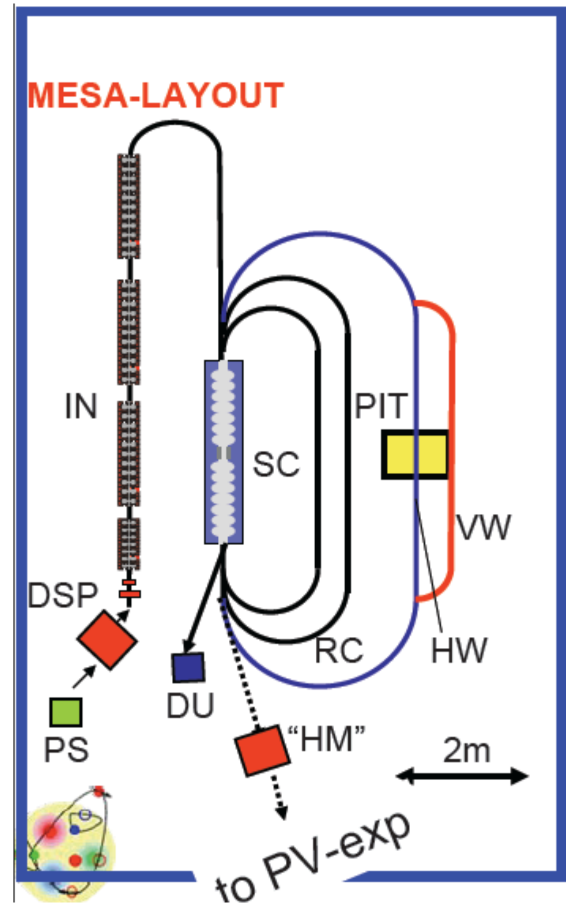


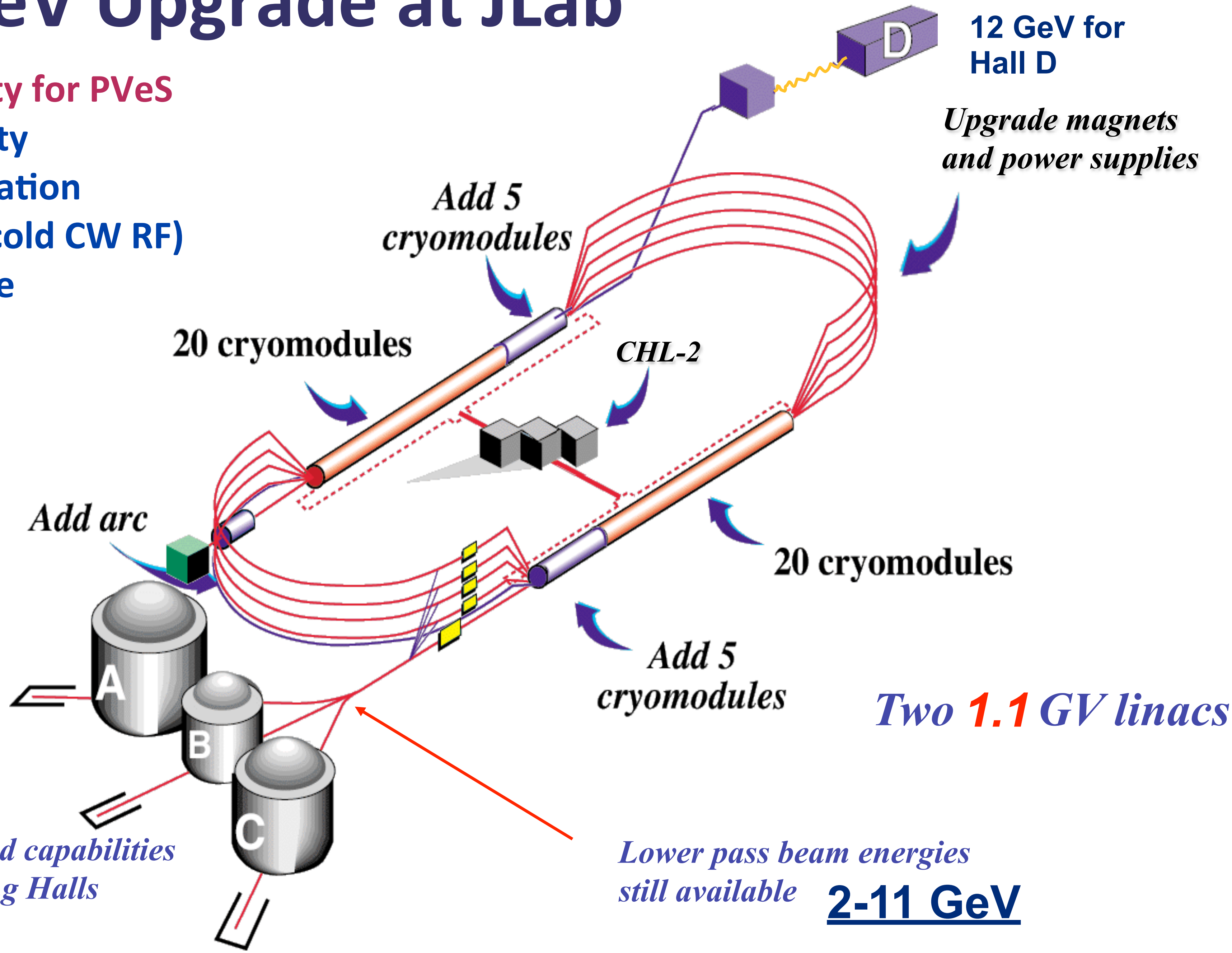
- **Development starting now**
- **P2 on the floor and commissioning in 2015**
- **MESA complete and in operations in 2016**
- **P2 production 2017-2019, to full precision**

MOLLER at 11 GeV

12 GeV Upgrade at JLab

Unique Facility for PVeS

- High intensity
- High polarization
- Low noise (cold CW RF)
- Energy range



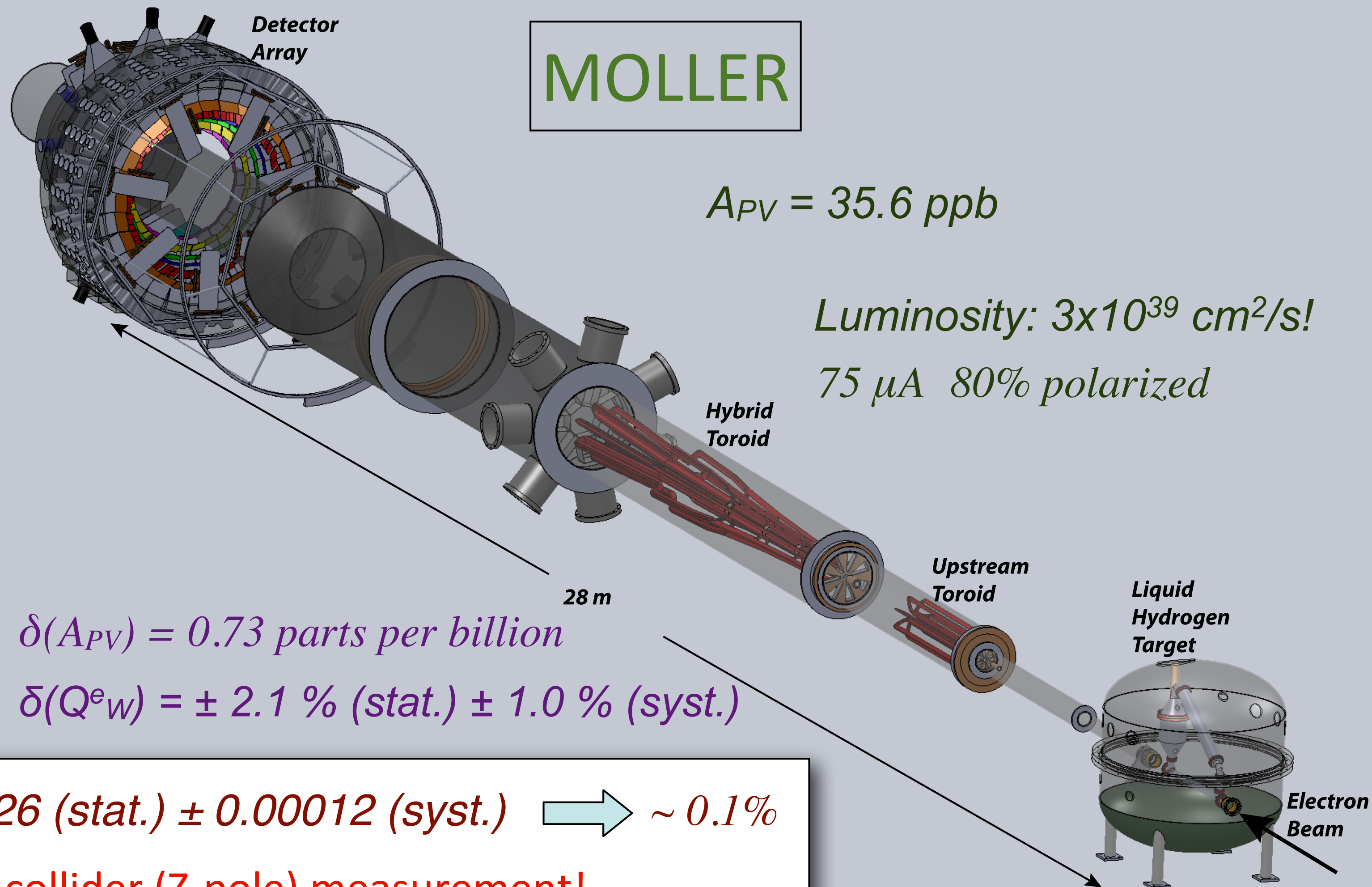
Back to Møller Scattering: MOLLER at 11GeV JLab

An ultra-precise measurement of the weak mixing angle using Møller scattering

$$A_{PV} \propto E_{\text{lab}}\, Q_W^e\,, \quad \sigma \propto \frac{1}{E_{\text{lab}}}$$

Figure of Merit proportional to beam power

At 11 GeV, JLab luminosity and stability makes large improvement possible



A_{PV} = 35.6 ppb

Luminosity: 3×10^{39} cm²/s!

75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm\, 2.1\,\%$ (stat.) $\pm\, 1.0\,\%$ (syst.)

$\delta(\sin^2\theta_W) = \pm\, 0.00026$ (stat.) $\pm\, 0.00012$ (syst.) ⇨ ~ 0.1%

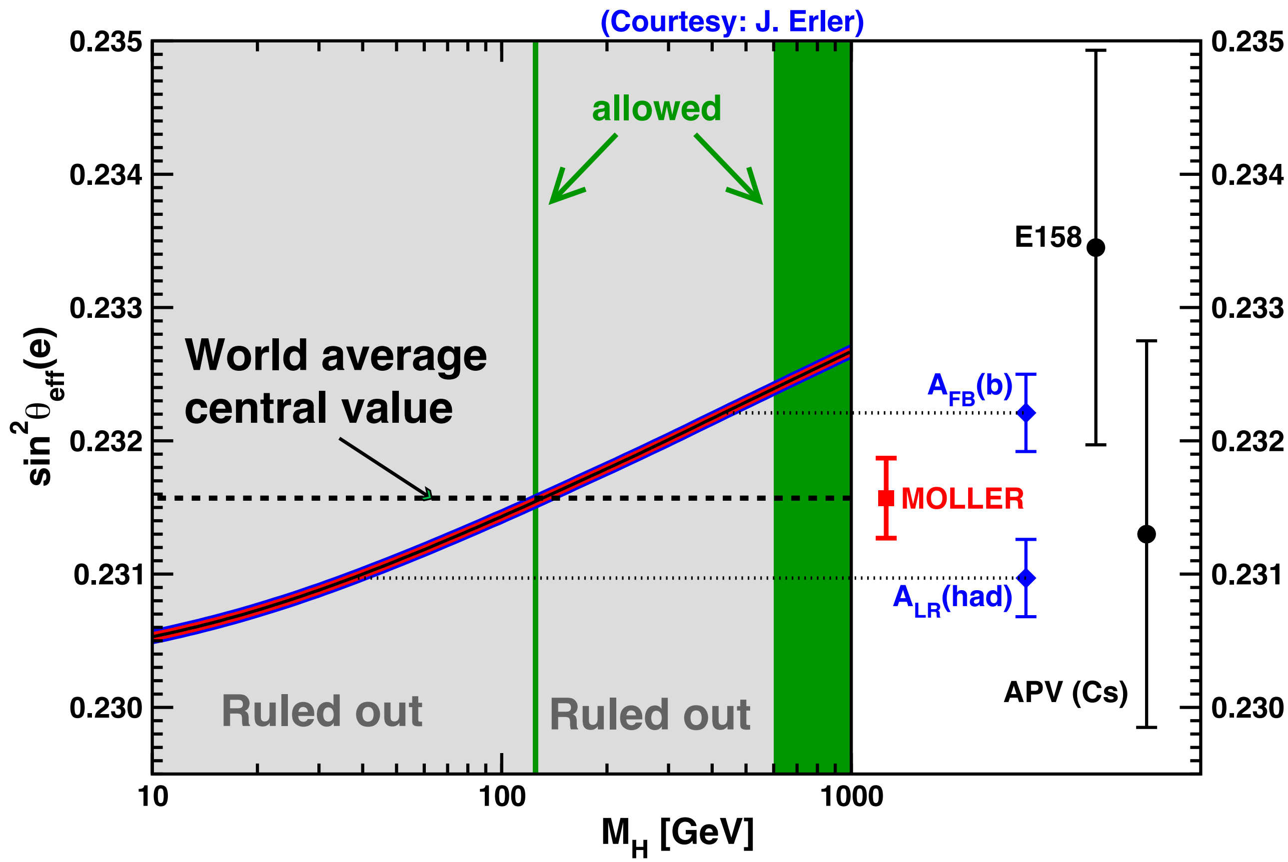
Matches best collider (Z-pole) measurement!

Precision Measurement of $\sin^2\theta_W$

Direct measurement of SM weak mixing angle is average of two measurements that disagree by 3σ...

...yet the naive statistical average agrees to a very high level with the LHC Higgs candidate

We failed to nail $\sin^2\theta_W$ when we had the colliders! -B.Marciano



The consistency of the SM prediction, between directly measured m_H, m_W, m_t, $\sin^2\theta_W$ bears testing

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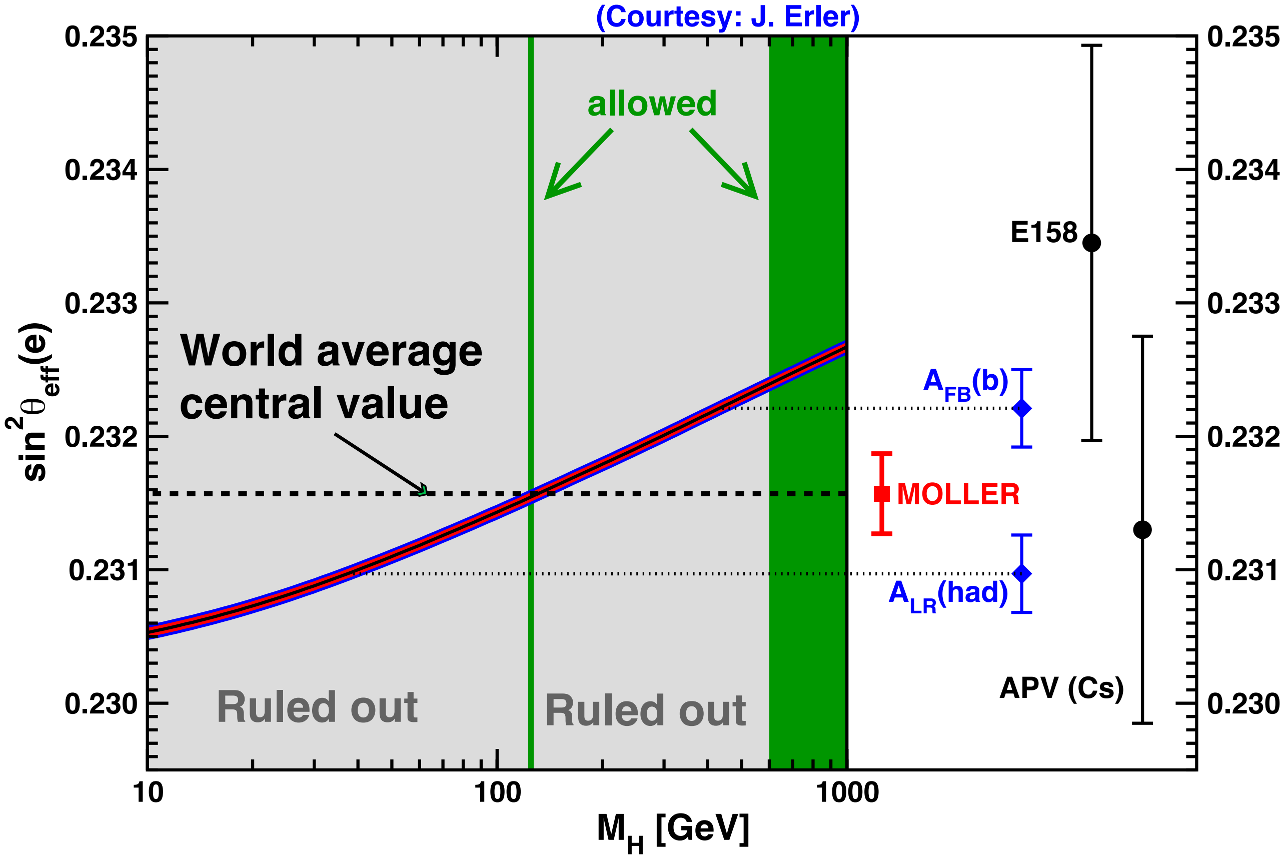

The consistency of the SM prediction, between directly measured m_H, m_W, m_t, $\sin^2\theta_W$ bears testing

- **$\sin^2\theta_W$ improvements at hadron colliders very challenging**
- **"Giga-Z" option of ILC or neutrino factory: powerful but far future**

MOLLER Sensitivity to BSM Physics

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

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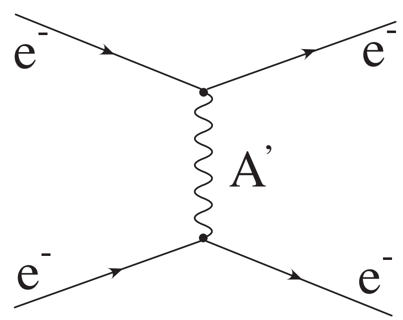
Heavy Photons: The Dark Sector



Hypothesis could explain $(g\text{-}2)_\mu$ discrepancy as well as several intriguing astrophysical anomalies related to dark matter

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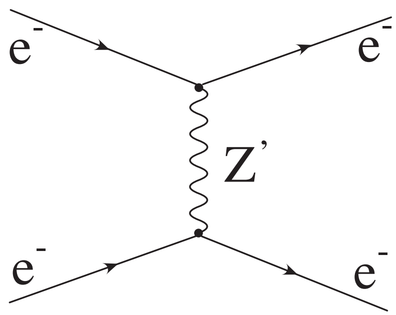

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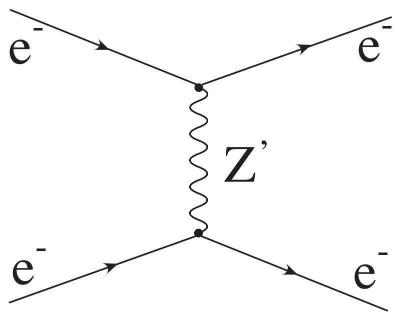

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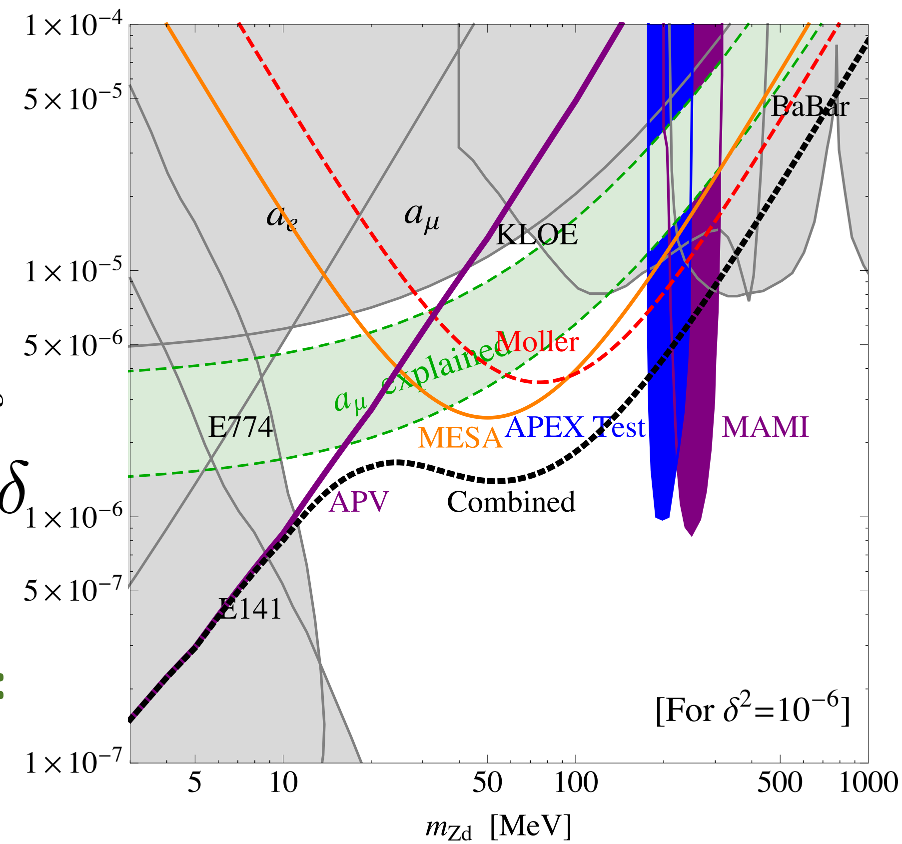
Beyond kinetic mixing: introduce mass mixing with Z

$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

Davoudiasl, Lee, Marciano arXiv:1203.2947v2

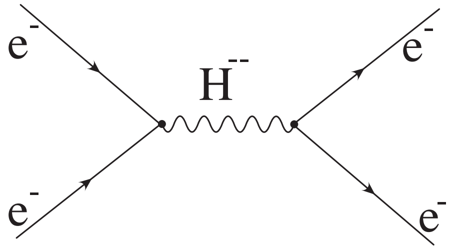
Complementary to direct heavy photon searches: Lifetime/branching ratio model dependence vs mass mixing assumption

MOLLER reach: red dashed lines



Complementarity to LHC Direct Searches

Doubly-charged Scalars



$$\mathcal{M}^{\rm PV} \sim \frac{|h^{ee}_{L,R}|^2}{2M^2_{\delta_L}} \bar{e_L}\gamma_\mu e_L \bar{e_L}\gamma^\mu e_L$$

$$\frac{M_{\delta_L}}{|h^{ee}_L|} \sim 5.3 \text{ TeV}$$

improves reach significantly beyond LEP-200

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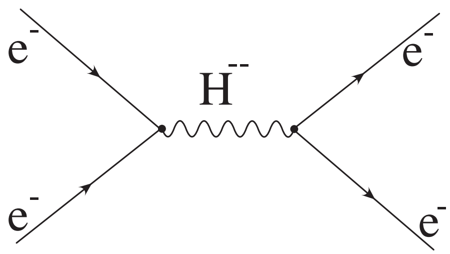

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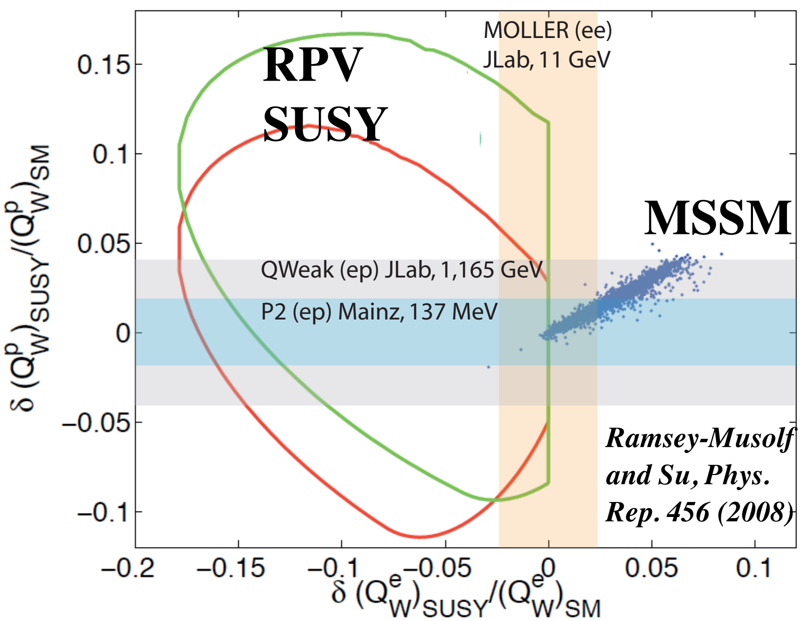
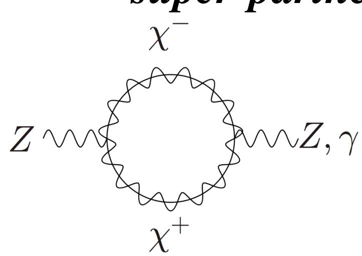
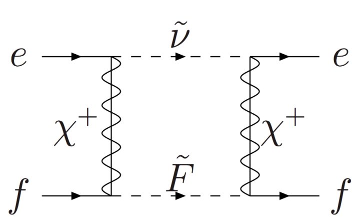


MSSM sensitivity if light super-partners, large tanβ





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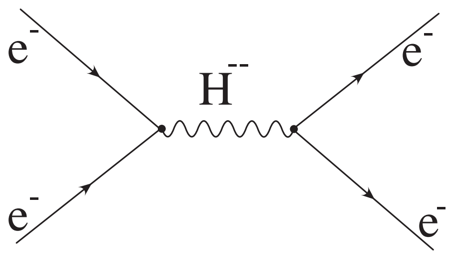

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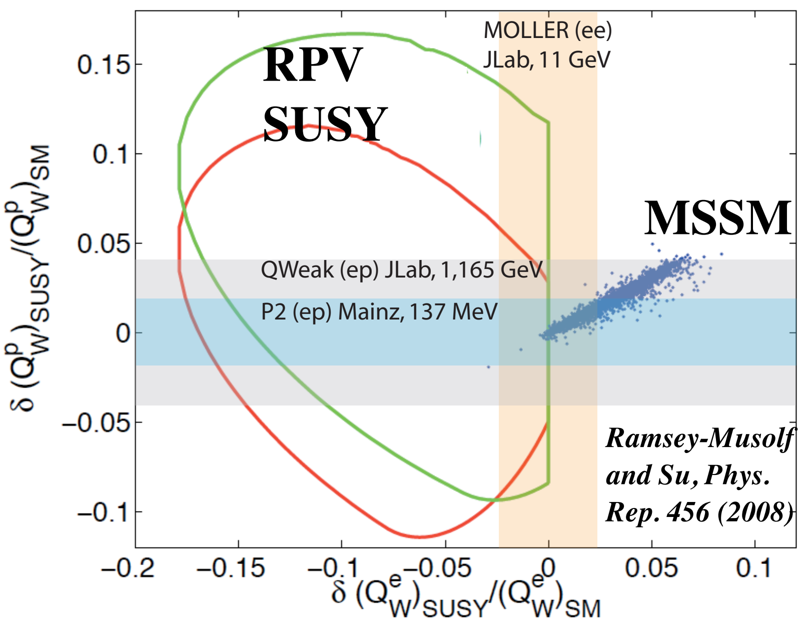

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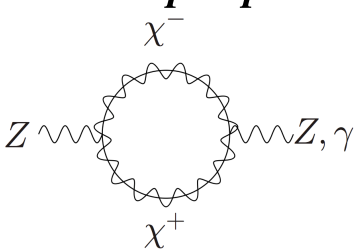
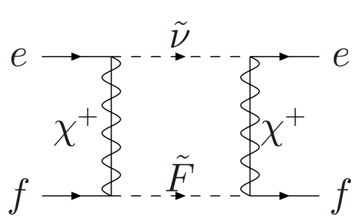
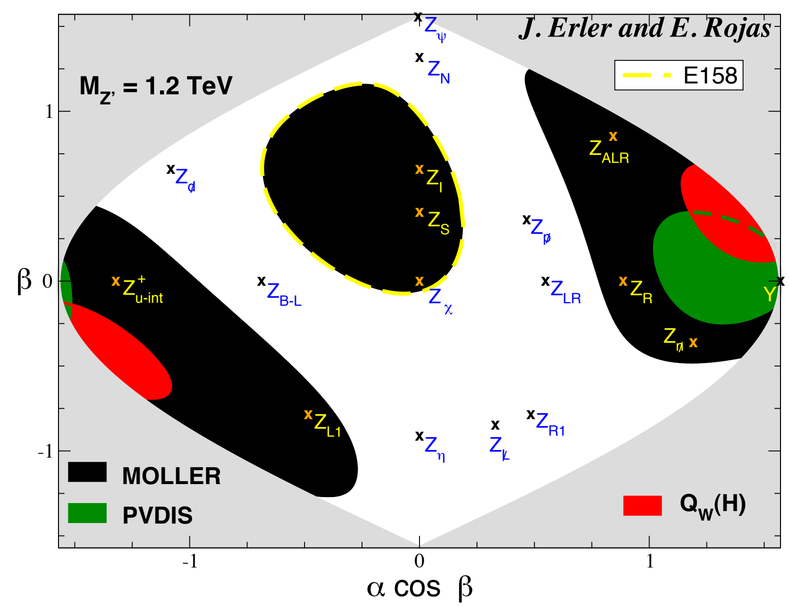




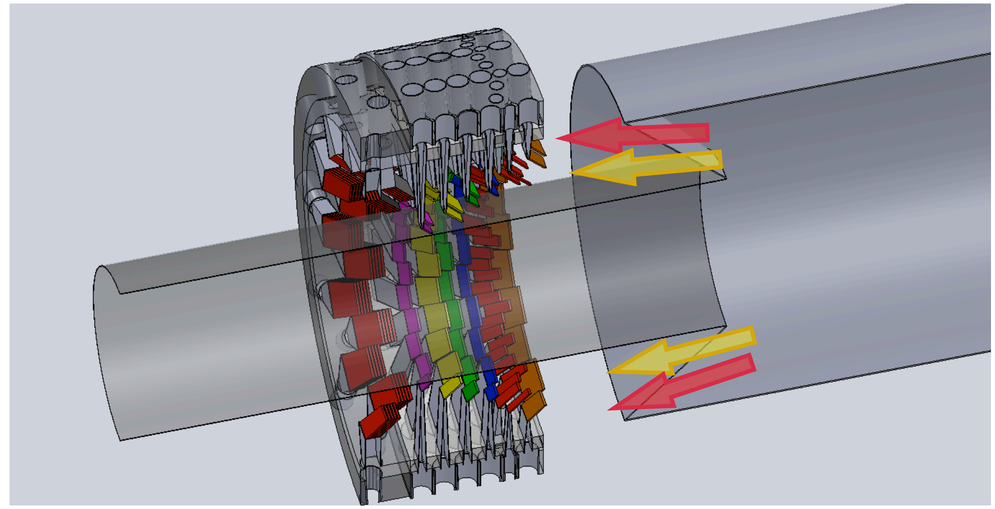
- *Virtually all GUT models predict new Z's*
- *For 'light' 1-2 TeV, Z' properties can be extracted*

Suppose a 1 to 2 TeV heavy Z'
is discovered at the LHC

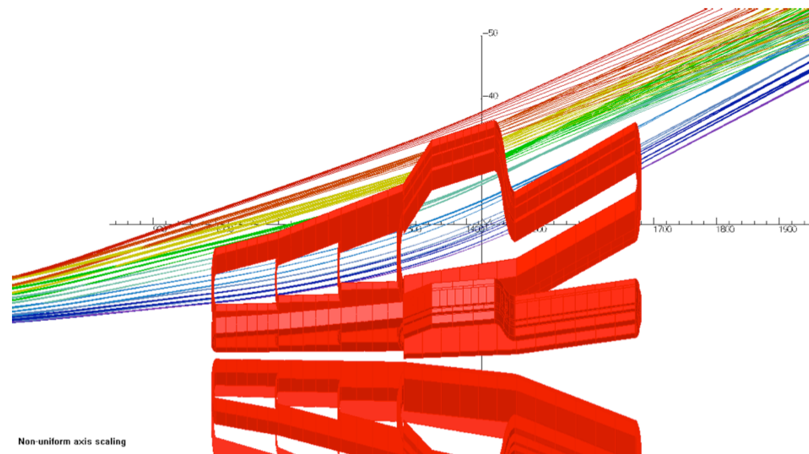
Can we point to an underlying GUT model?



Unprecedented Precision



- ~ 150 GHz scattered electron rate
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
  - Beam monitor precision
- 1 nm control of beam centroid on target
  - Modest improvement in polarized source laser controls
  - Improved methods of "slow helicity reversal"
- > 10 gm/cm^2 target needed
  - 1.5 m Liquid Hydrogen target: ~ 5 kW @ 85 µA
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry
  - Plan to pursue both Compton and Atomic Hydrogen techniques



MOLLER Status

Funding Proposal submitted to Nuclear Physics Division of the Department of Energy

sub-system	Institutions
polarized source	*UVa, JLab, Miss. St.*
Target	*JLab, VaTech, Miss. St.*
Spectrometer	*Canada, ANL, MIT, UVa*
Integrating Detectors	*Syracuse, Canada, JLab*
Luminosity Monitors	*VaTech, Ohio U.*
Pion Detectors	*UMass/Smith, LATech*
Tracking Detectors	*William & Mary, Canada, INFN Roma*
Electronics	*Canada, JLab*
Beam Monitoring	*UMass, JLab*
Polarimetry	*UVa, Syracuse, JLab, CMU, ANL, Miss. St., Claremont-Ferrand, Mainz*
Data Acquisition	*Ohio U., Rutgers U.*
Simulations	*LATech, UMass/Smith, UC Berkeley*

- Strong Collaboration being formed
  - ~ 100 authors, ~ 30 institutions
  - Expertise: A4, HAPPEX, PREX, Qweak, E158
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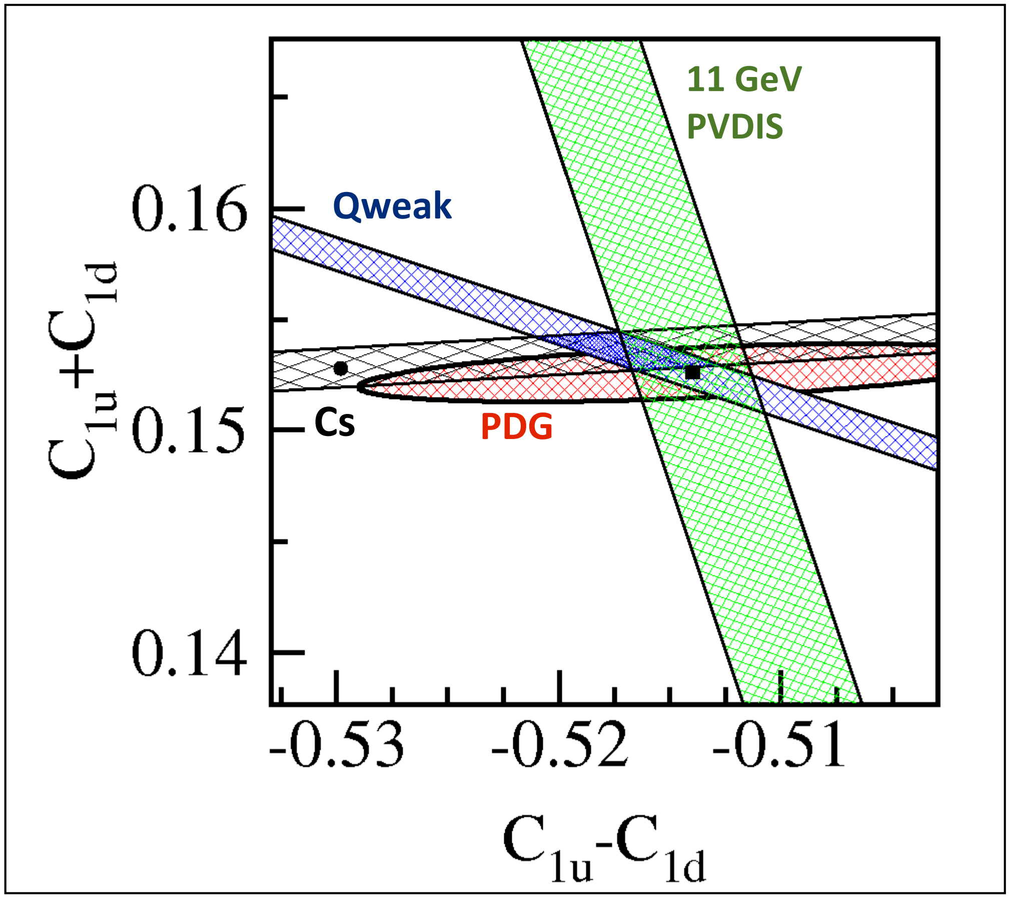
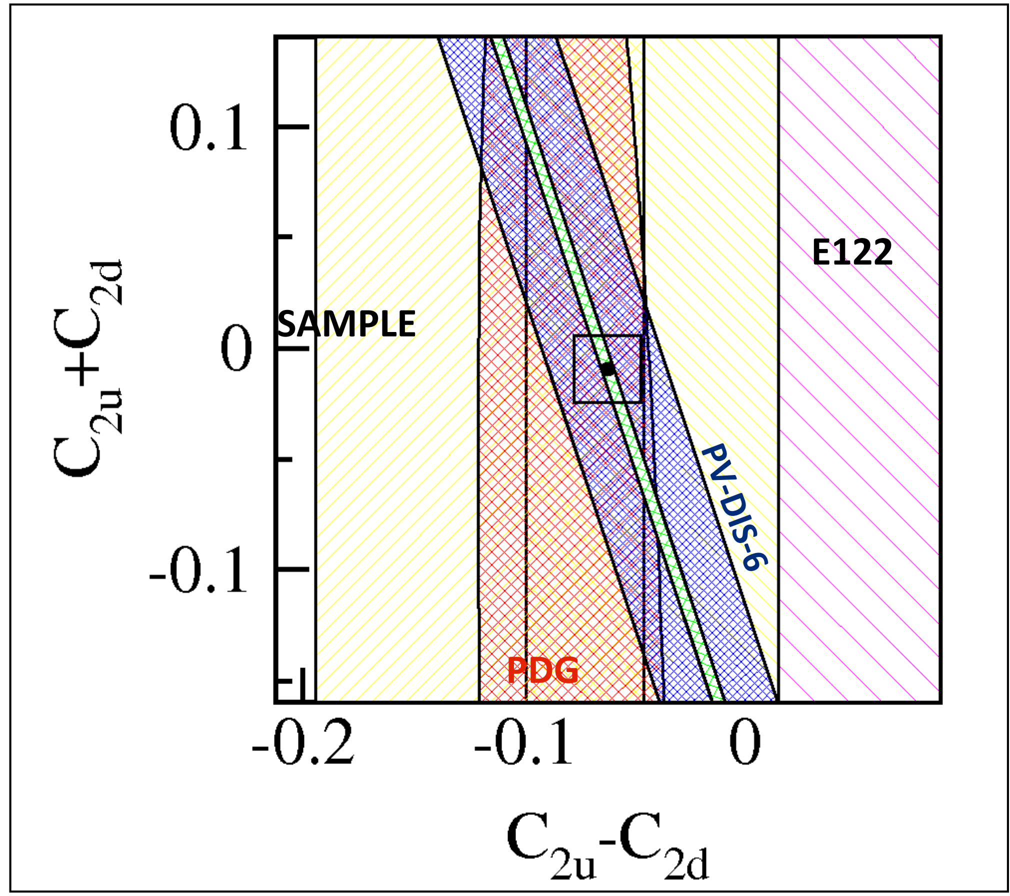
- Recent Progress
  - Director's review chaired by C. Prescott: strong endorsement and encouragement to proceed
  - Developed a conceptual design of spectrometer, and a cost range (~ 20M$)
- Funding
  - Recently submitted a funding proposal to DoE Nuclear Physics
- Potential Schedule
  - goal is for funding to begin 2014/2015
  - goal is for installation in 2016/2017
- Possible Beam Time Allocation
  - Run I: 3 months (6 wks setup + 6 wks data): E158 error
  - Run II: 6 months: 25% statistics; already world's best measurement
  - Run III: 2 years: full statistics with 60% efficiency

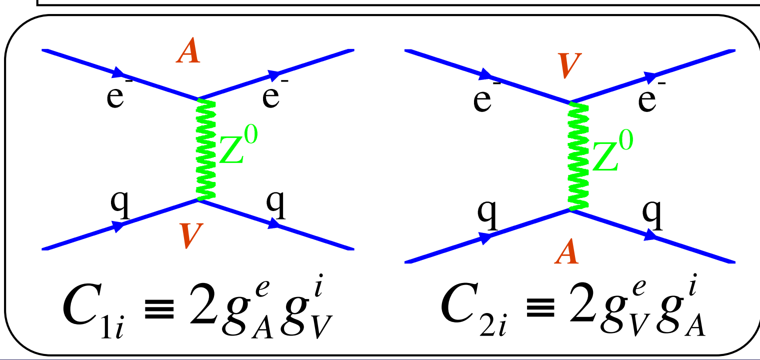
Goal - collecting final statistics by 2020

SOLID for PV-DIS at 11 GeV

How well measured are the C_{1q}, C_{2q}?







$$C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$C_{2q} = (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

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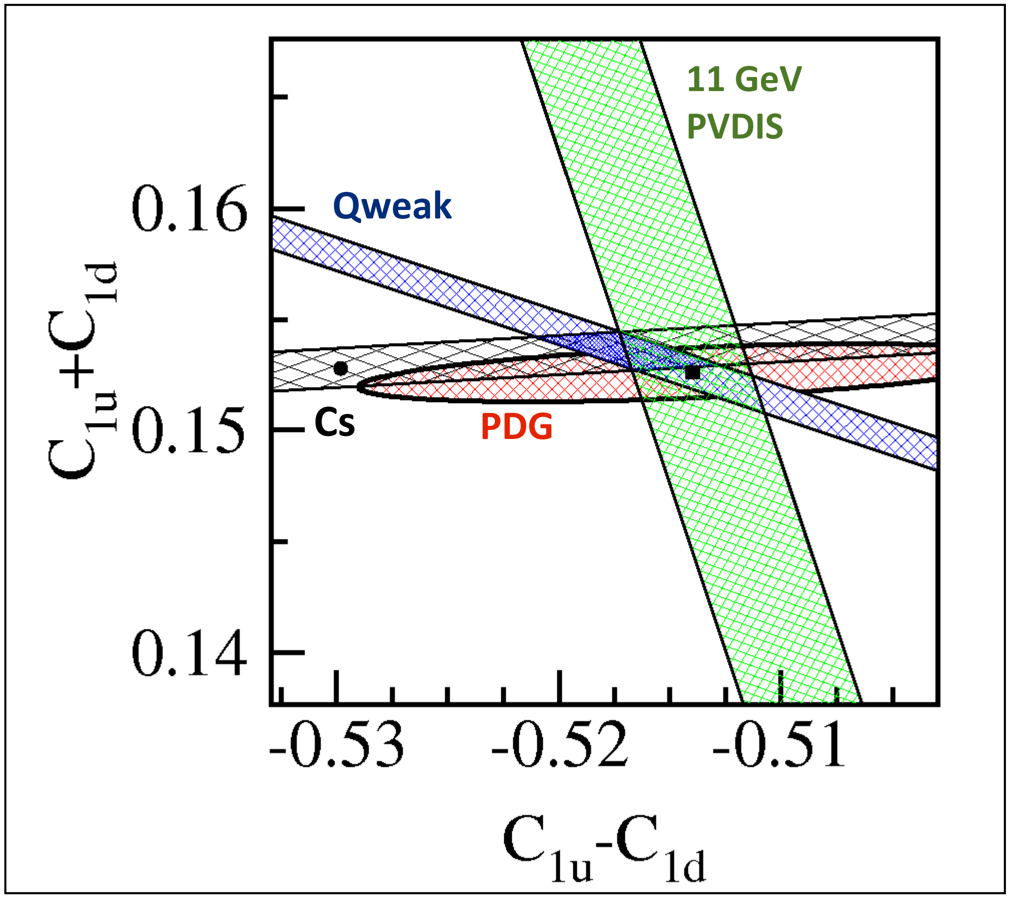
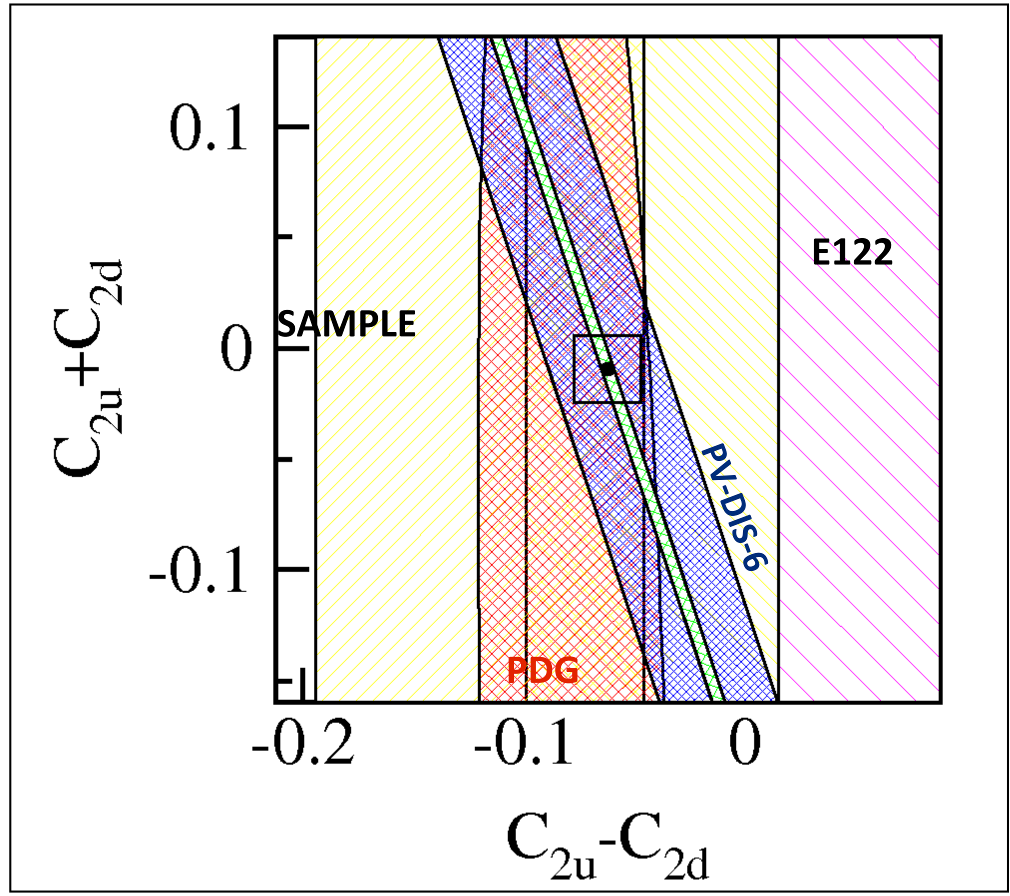
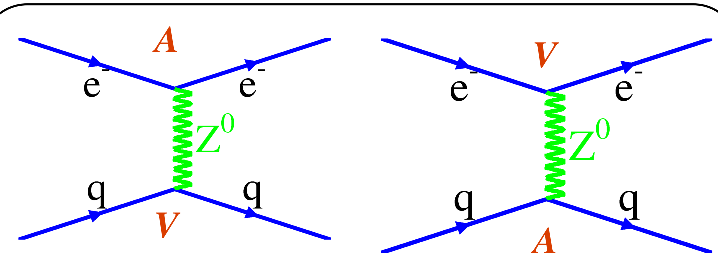


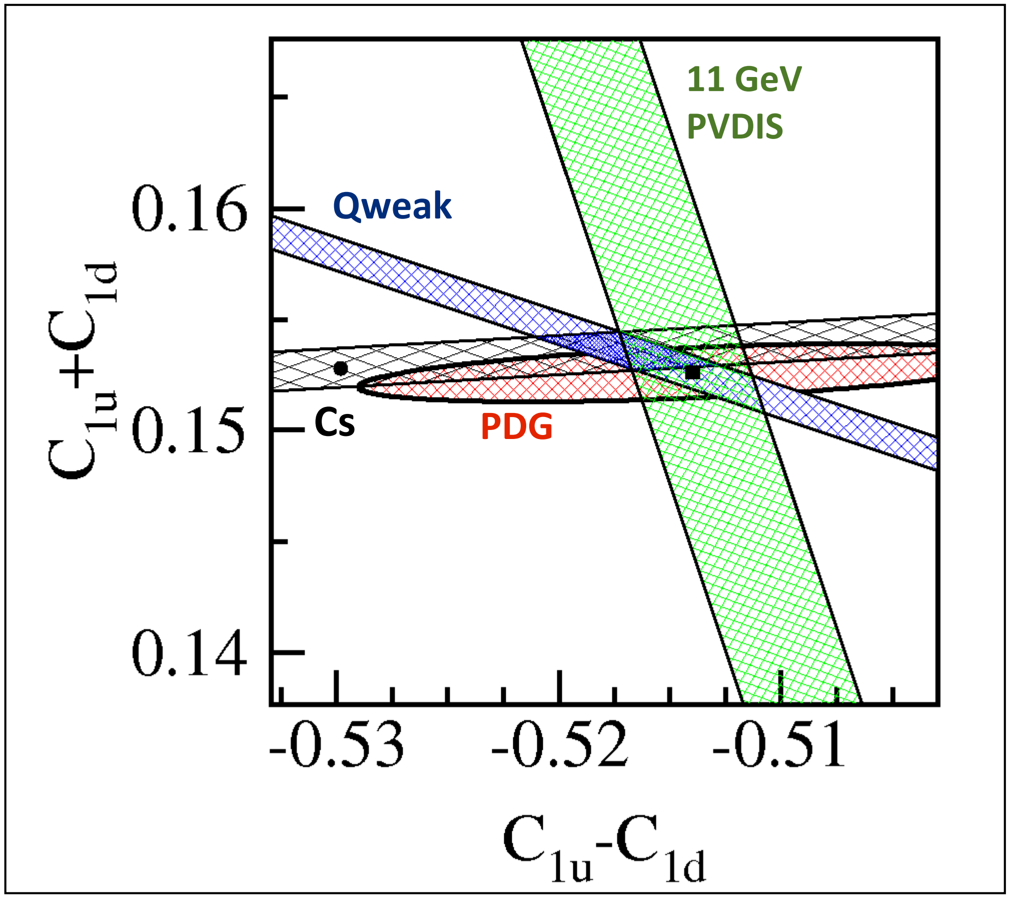


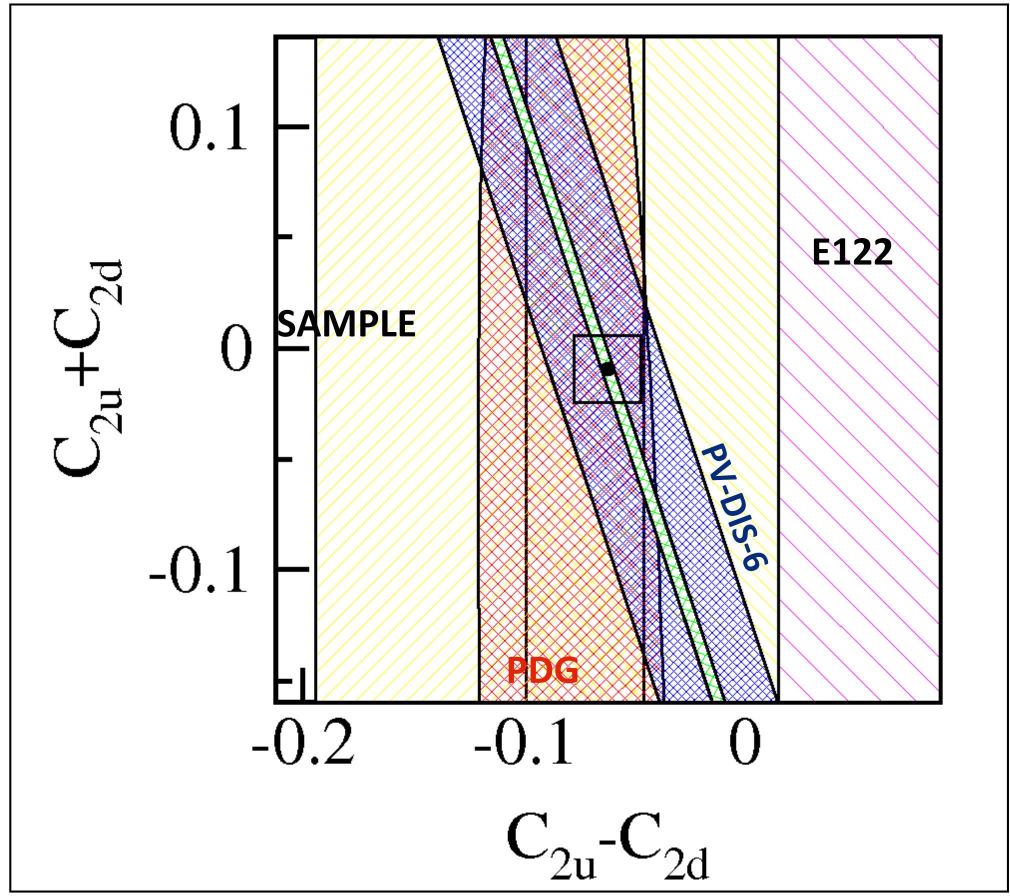


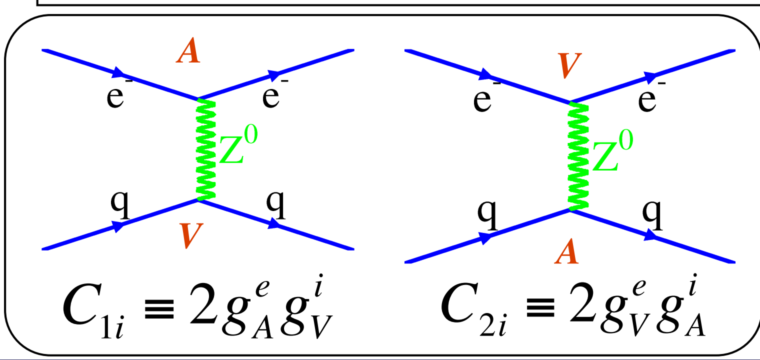
$C_{1i} \equiv 2g_A^e g_V^i$ $\qquad$ $C_{2i} \equiv 2g_V^e g_A^i$

$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx -0.19\\
C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx 0.35\\
C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx -0.04\\
C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx 0.04
\end{aligned}$$

How well measured are the C_{1q}, C_{2q}?







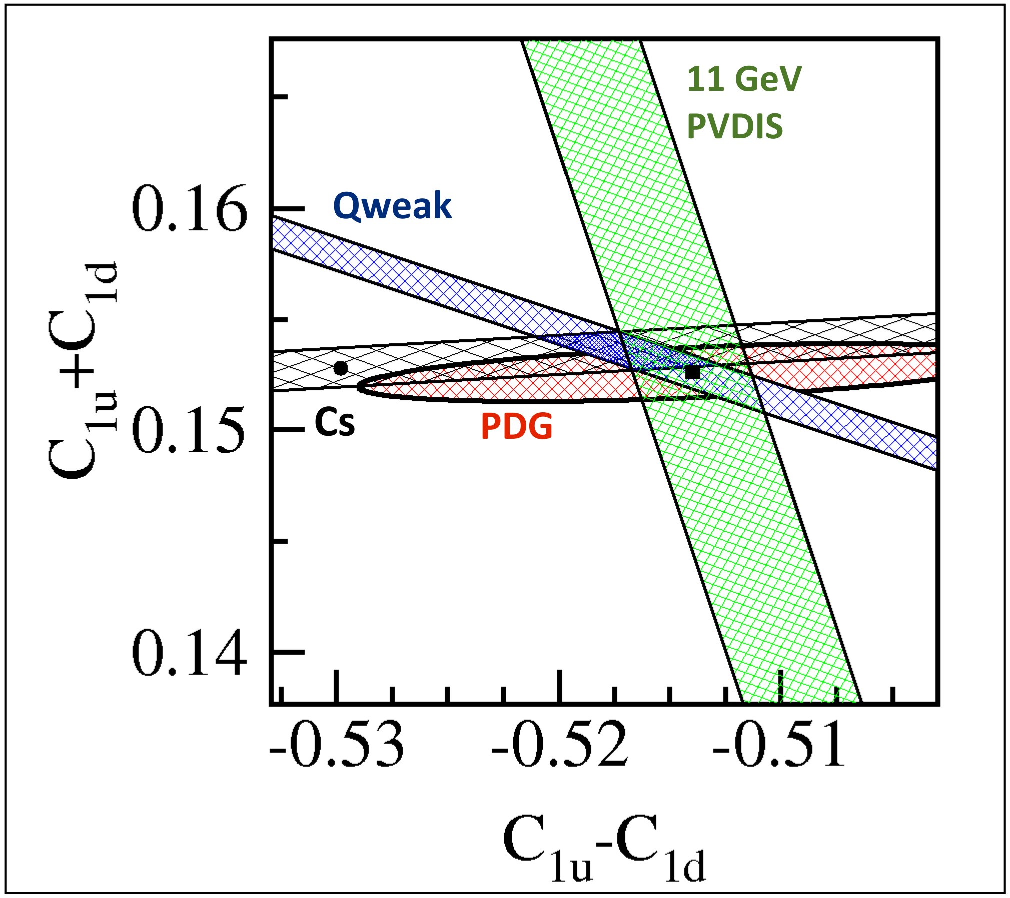
Red ellipses are PDG fits

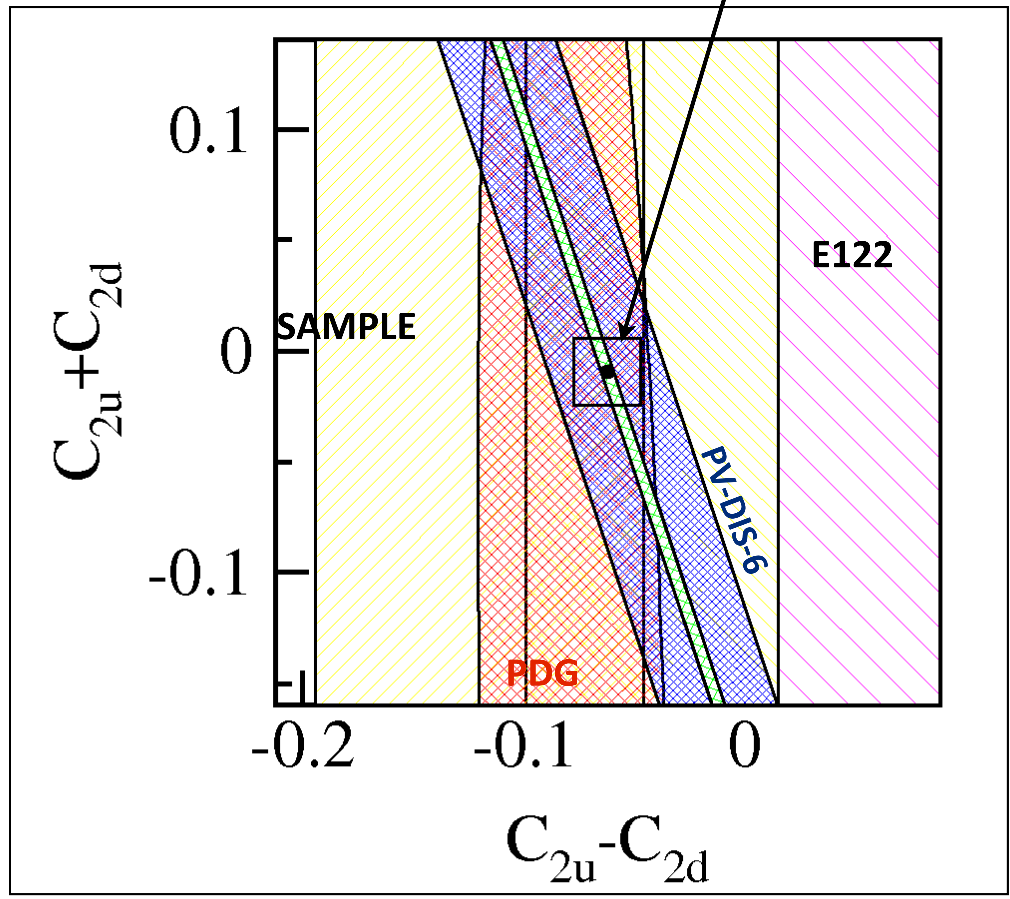
Blue bands represent **expected** data: Qweak (left) and PV-DIS-6GeV (right)

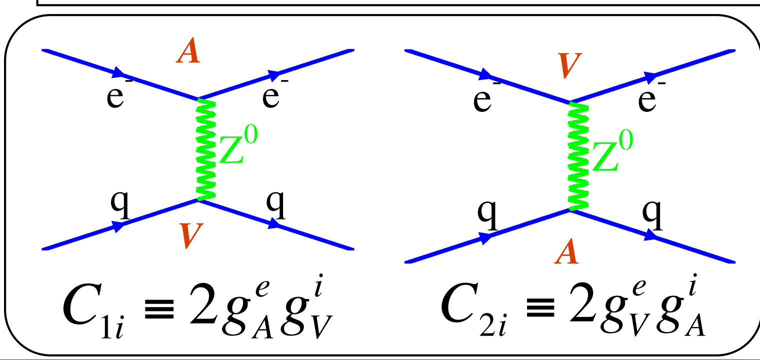
Green bands are the proposed measurement of PV-DIS

How well measured are the C_{1q}, C_{2q}?

This box matches the scale of the C_{1q} plot







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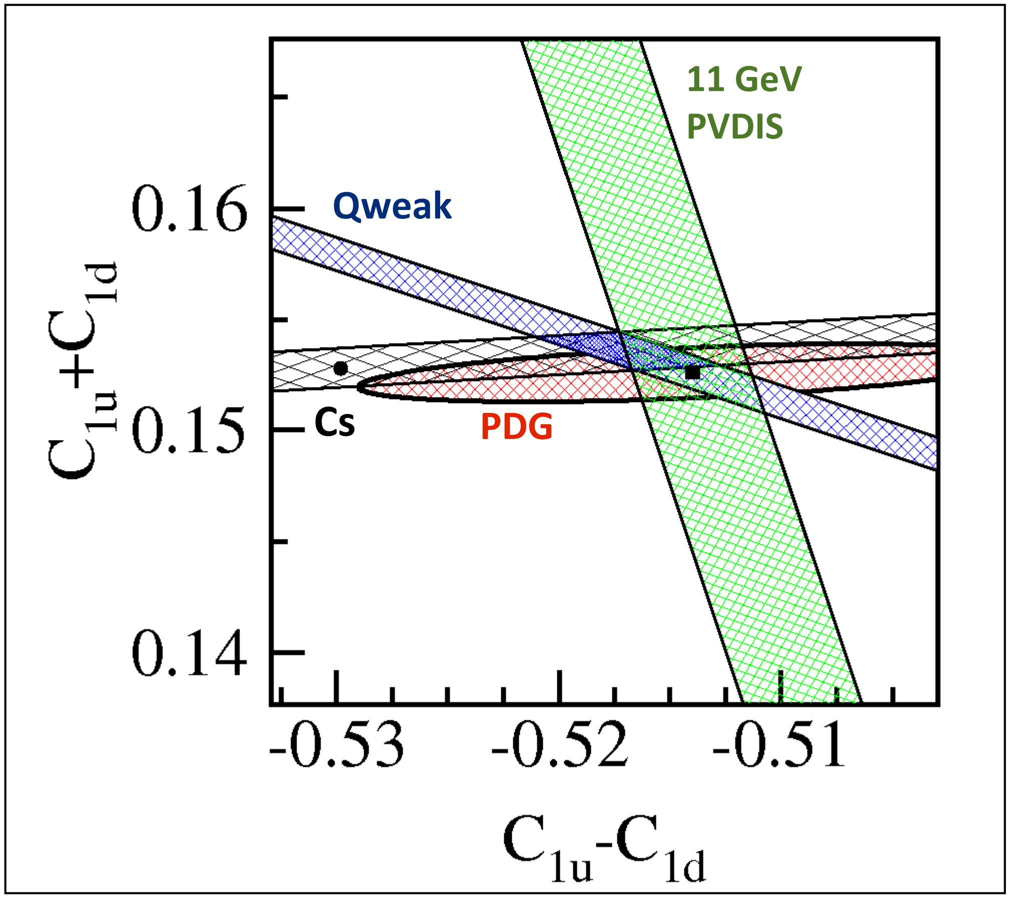

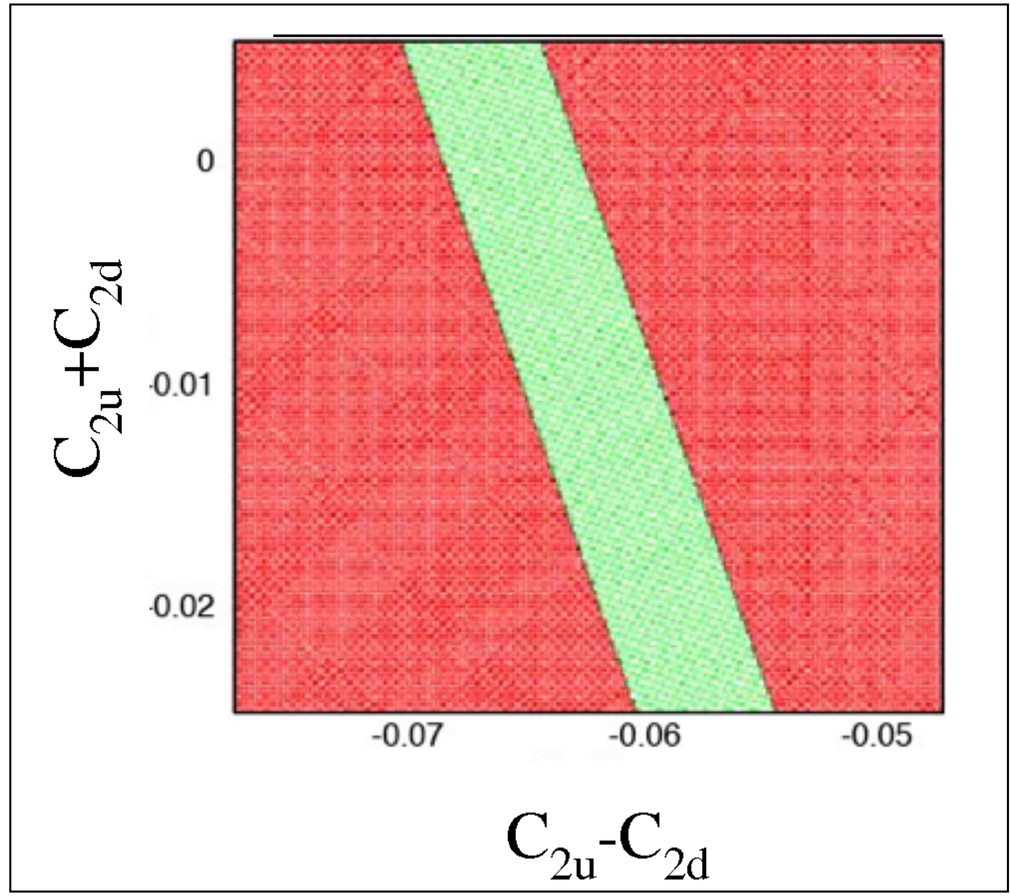

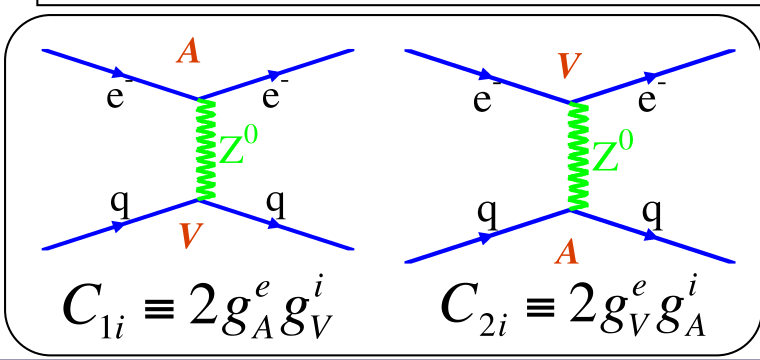

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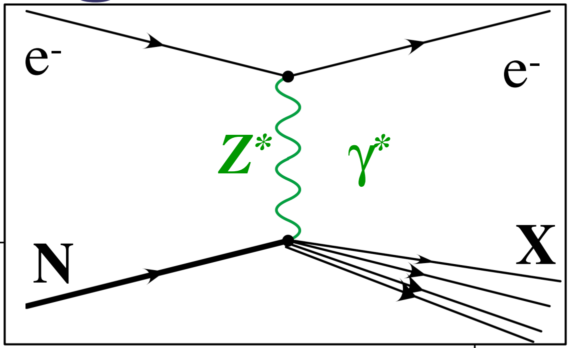
Deep Inelastic Scattering

For an isoscalar target like ^{2}H, the poorly-measured axial quark couplings are accessible



$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

$$x \equiv x_{Bjorken}$$

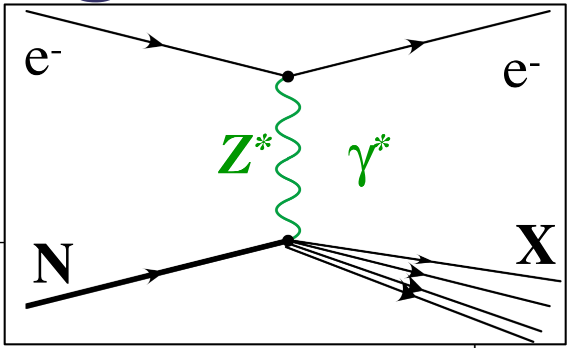
$$y \equiv 1 - E'/E$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x, Q^2) = \sigma^l/\sigma^r \approx 0.2$$

Deep Inelastic Scattering

For an isoscalar target like ^{2}H, the poorly-measured axial quark couplings are accessible



$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right) \frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}$$

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

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At high x, A_D becomes independent of x & W, with well-defined SM prediction for Q^2 and y

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

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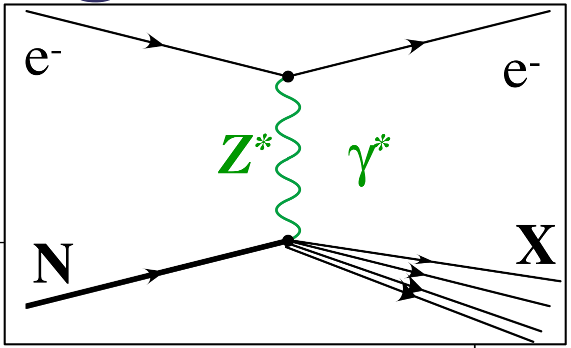

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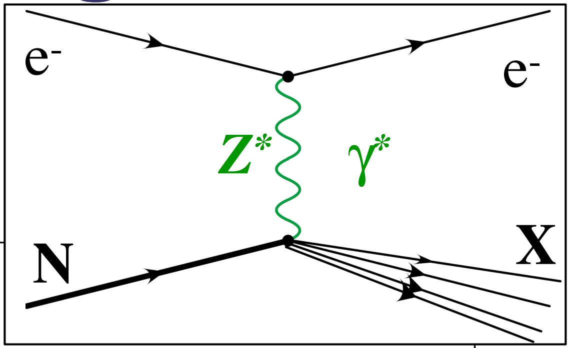

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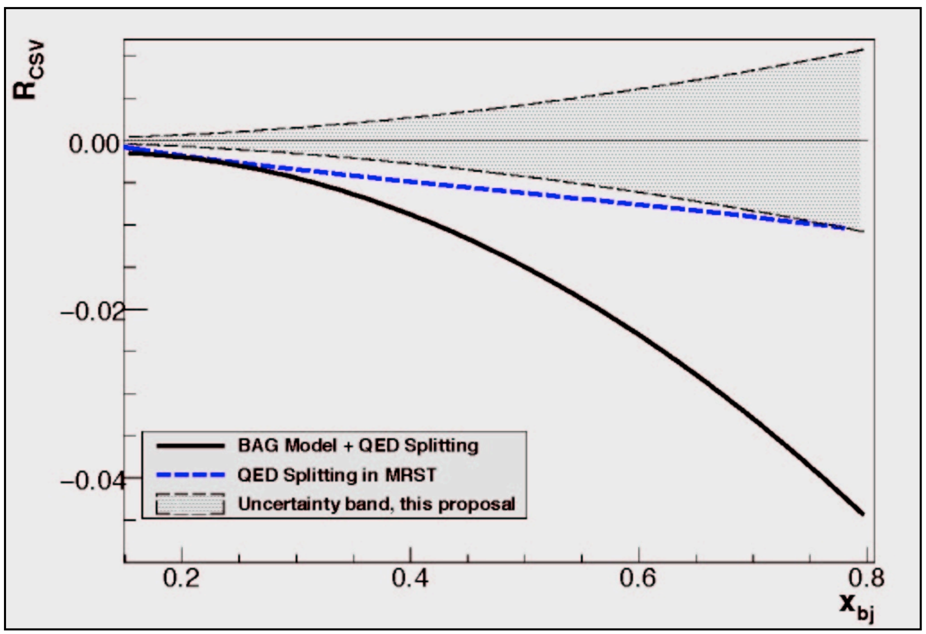
QCD
- Parton distributions (s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)

QCD and Hadronic Structure in PV-DIS

Charge Symmetry Violation:

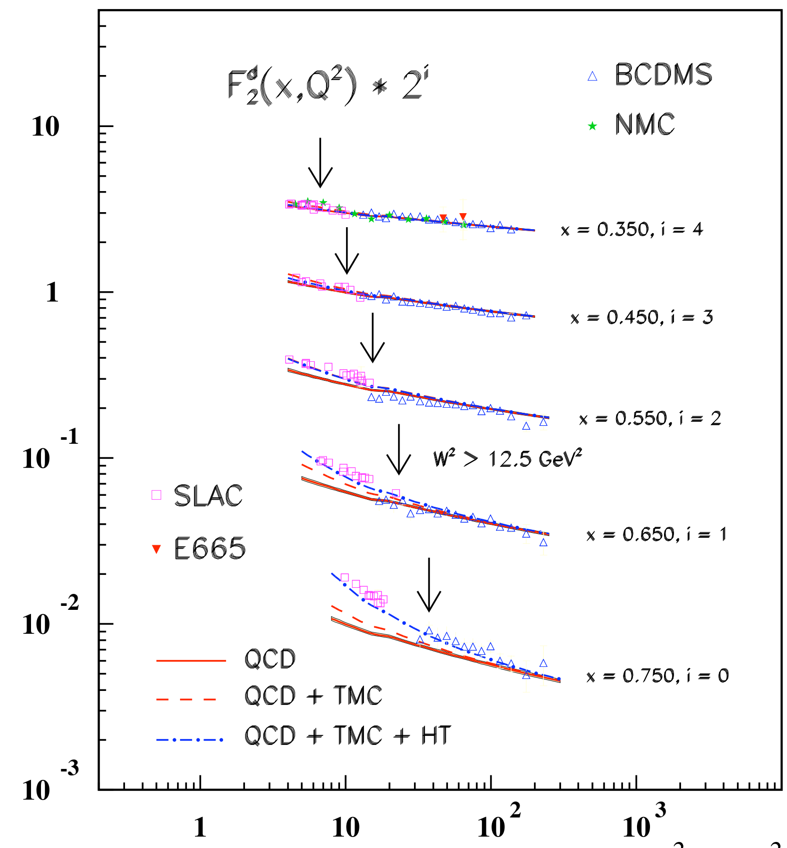
- u-d mass difference
- electromagnetic effects
- proton structure

- **Direct sensitivity of parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explaination of the NuTeV anomaly**



Higher Twist

- **cancellations isolate effects to coherent operator: Diquarks!**
- **HT thumbprint (increase with x, Q^2) should be clear if it is significant**



Bluemlein and Bottcher

Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

Measure A_d in **narrow** bins of x, Q^2 with 0.5% precision

A_d / Q^2 should be FLAT in x, Q^2 above x=0.3-0.4

Variations in x, Q^2 would indicate identifiable QCD effects

higher twist: Q^4 dependence, larger at higher x

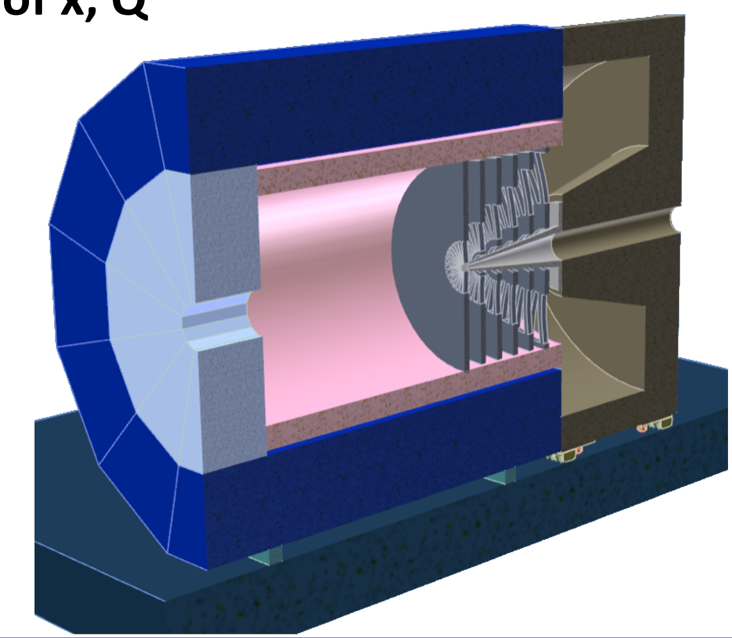
CSV: expected to have less Q^2 dependence, grow rapidly at high x

A_d around x~0.4, high Q^2, will determine a combination of C_{1q}'s, C_{2q}'s to 0.6%

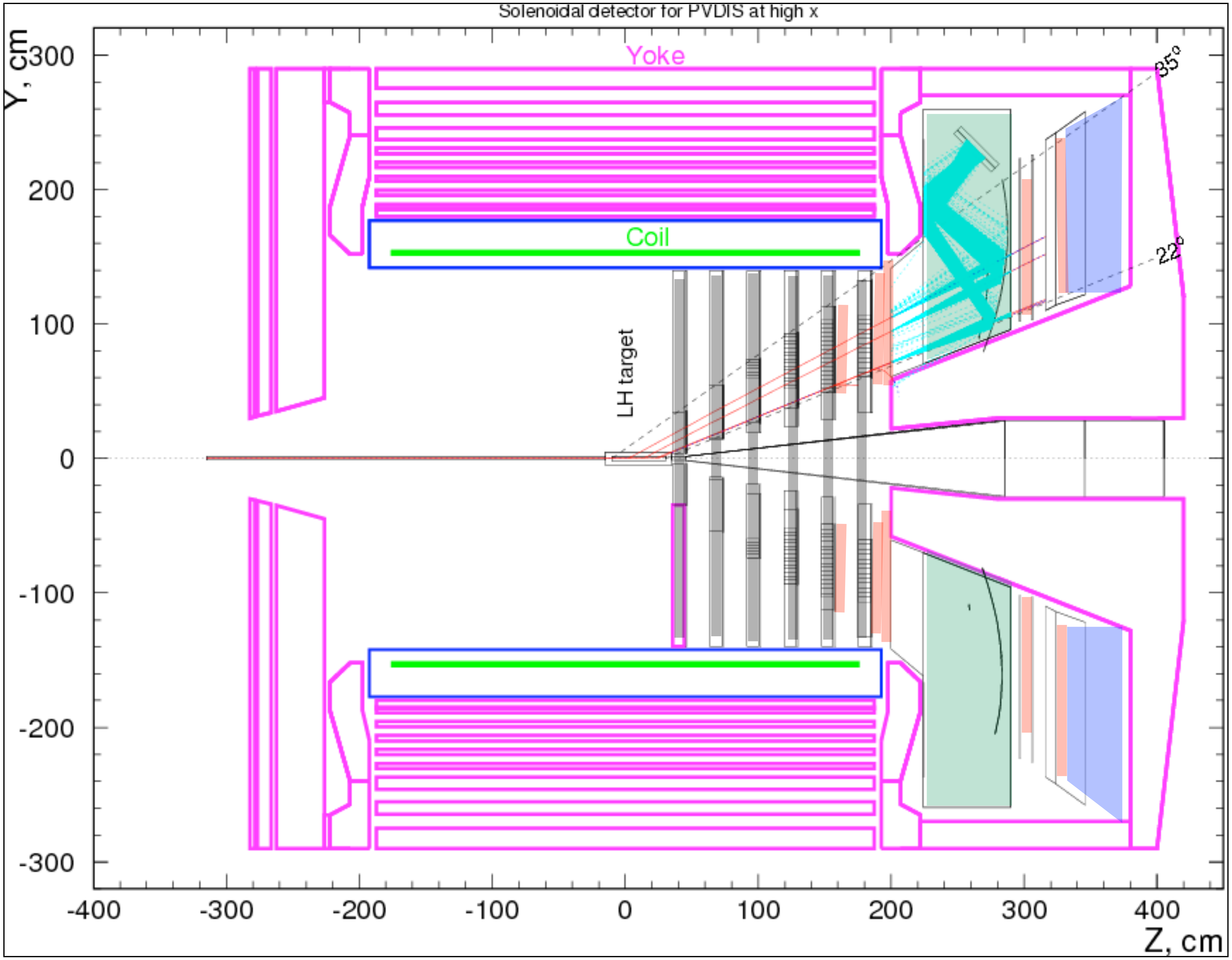
Possible at 11 GeV JLab - requires a spectrometer optimized to precise measurements at high luminosity over a broad range of x, Q^2

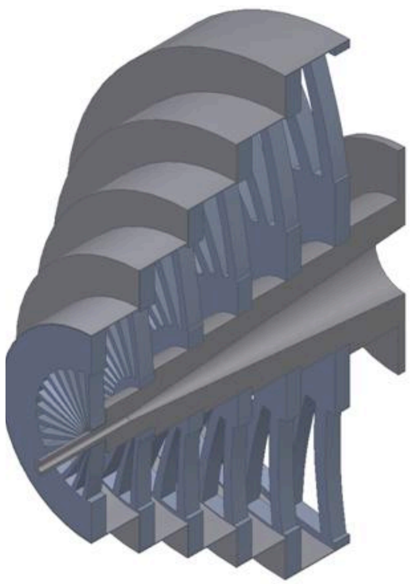
SOLID:

- High luminosity from H and D, <1% precision in fine bins
- x_B range 0.25-0.75, W^2 > 4 GeV^2, large Q^2 range
- Baffling to cut backgrounds
- Fast tracking—GEM, particle ID, calorimetry, and pipeline electronics
- Precision polarimetry (0.4%) Compton and atomic hydrogen Moller



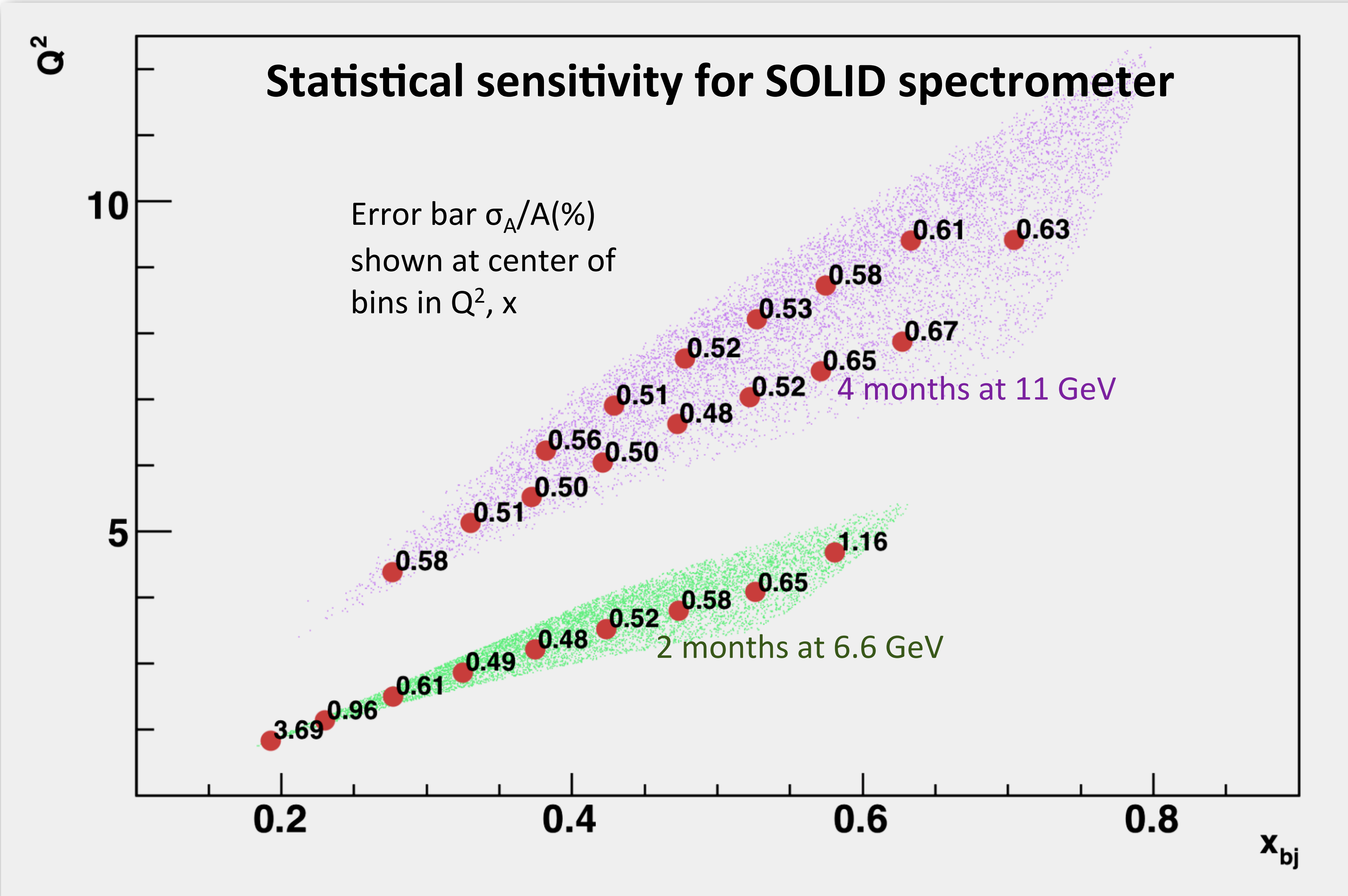
SoLID Design for PVDIS Physics





- 20° - 35°, E'~ 1.5 - 5 GeV, δp/p ~ 2%
- some regions 10's of kHz/mm², Pion rejection with Cerenkov + segmented calorimeter
- Several large solenoids would work (Zeus, Babar): present design focuses on CLEO

Statistical Errors (%) vs. Kinematics



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No other technique can provide comparable precision on axial hadronic weak neutral currents

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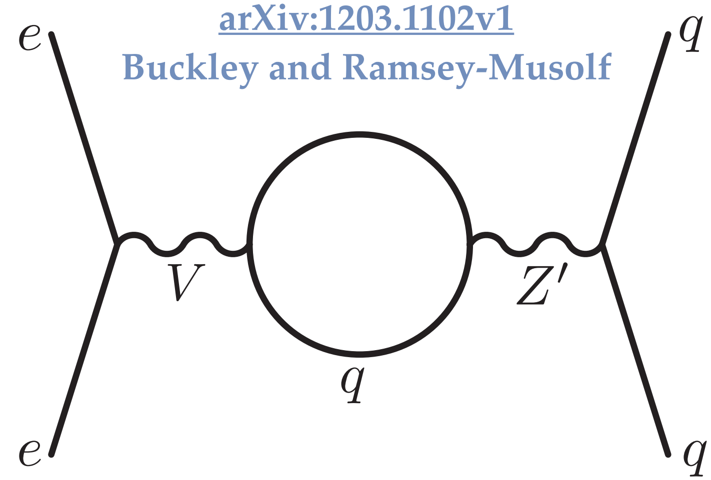
Leptophobic Z'

arXiv:1203.1102v1

Buckley and Ramsey-Musolf



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- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV could have escaped detection*

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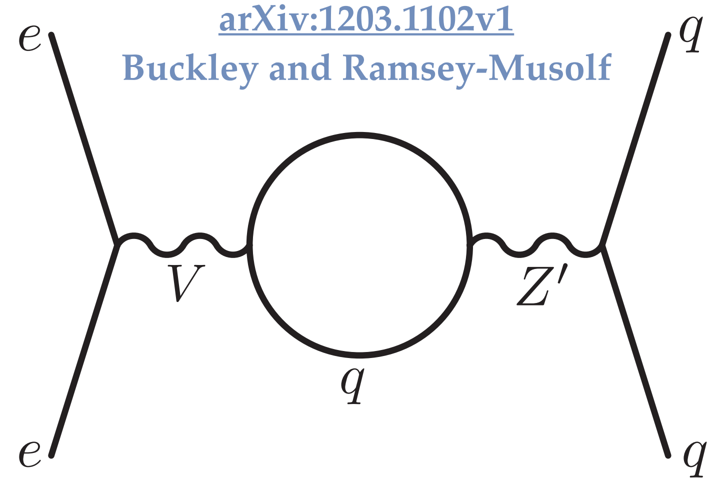

SOLID can improve sensitivity: 100-200 GeV range

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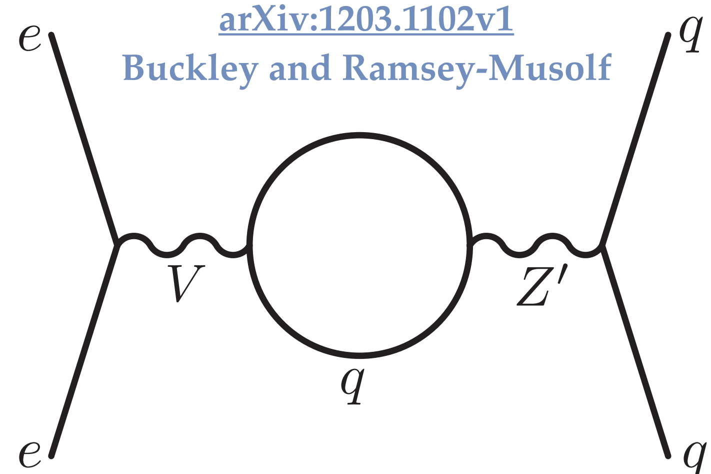

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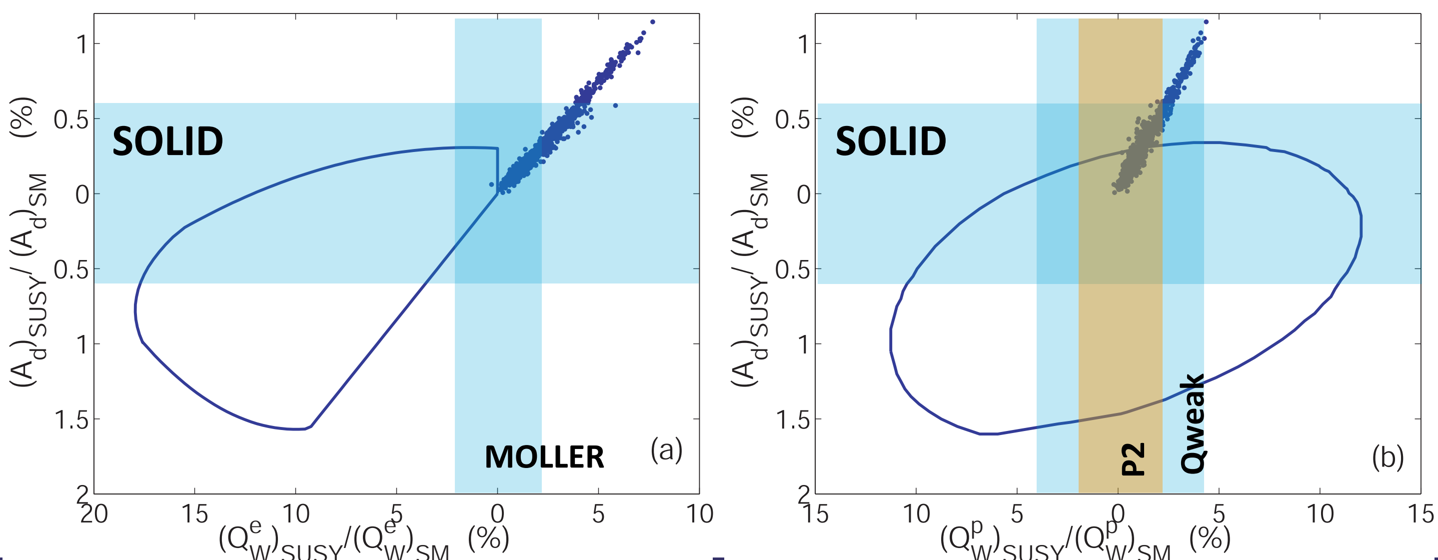
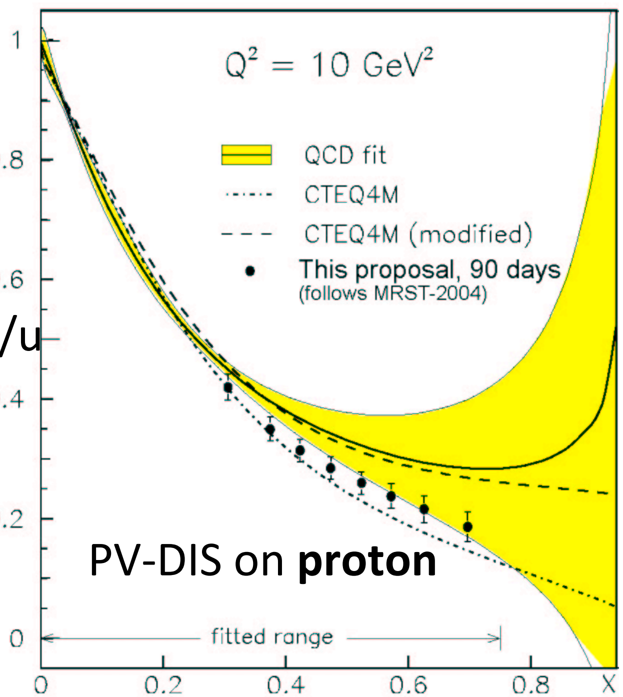


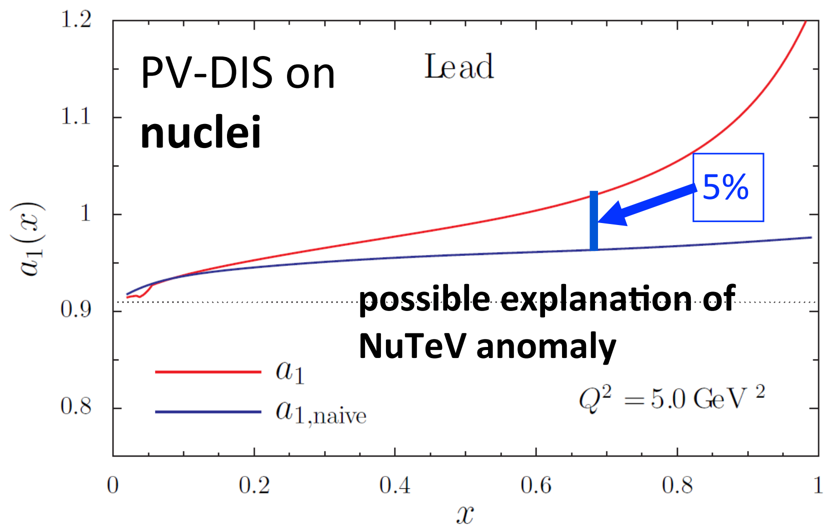
Complementary sensitivity to SUSY

Ramsey-Musolf and Su, Phys. Rep. 456 (2008)

Broad SoLID Program

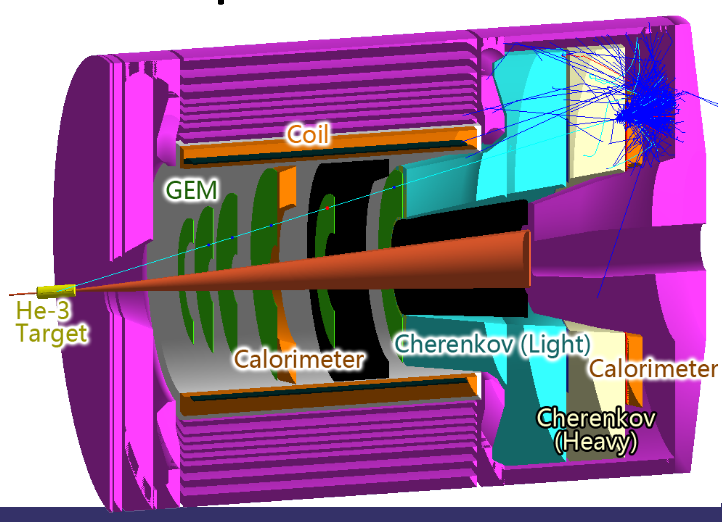


Deuterium PV-DIS drives the need for SoLID, but a broad program of hadronic studies will also make use of it



Transverse Spin Structure

semi-inclusive DIS from polarized targets



E12-10-006: *Transverse Single Spin Asymmetry ^{3}He*

E12-11-007: *Single and Double Spin Asymmetry ^{3}He*

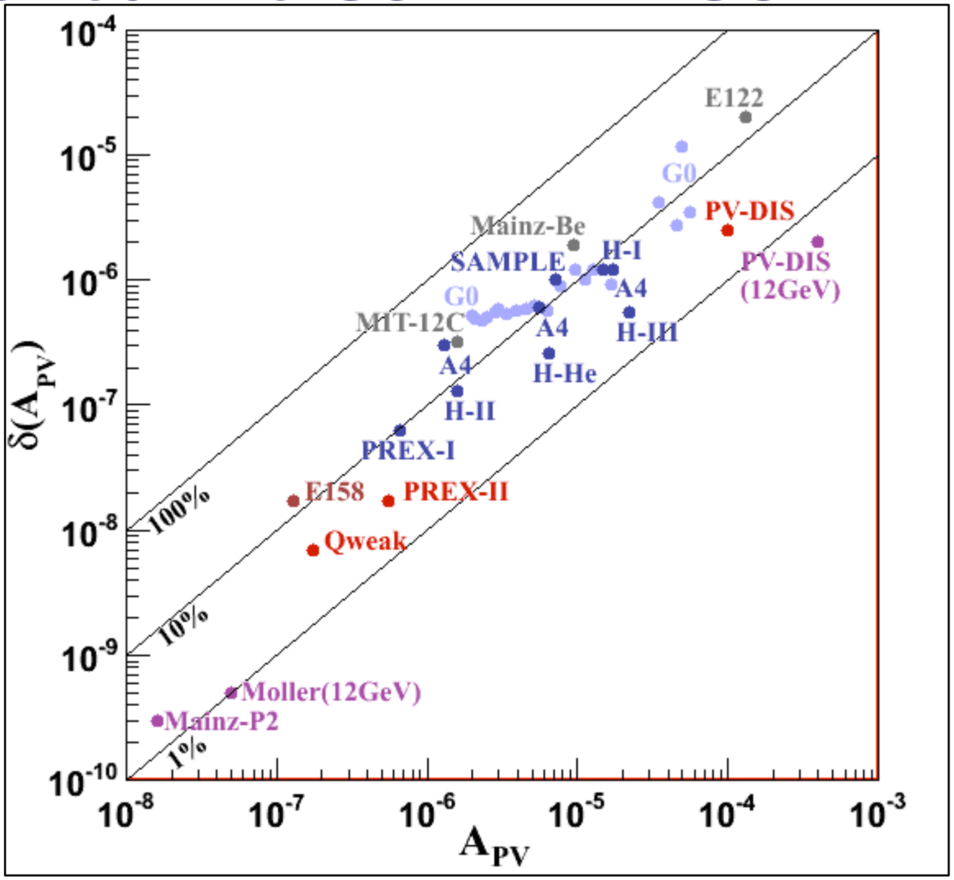
PR12-11-108: *Single and Double Spin Asymmetries on Transverse Proton*

PR12-12-006: *Near Threshold Electroproduction of Jpsi at 11 GeV*

Compelling new opportunities in PVeS

Since 2007:

- New constraint on quark vector weak charges
- (Completion of Strange quark program)
- (First electroweak observation of neutron skin in a heavy nucleus)
- Successfully completed PV-DIS-6 running (results soon!)
- Successfully completed QWeak running



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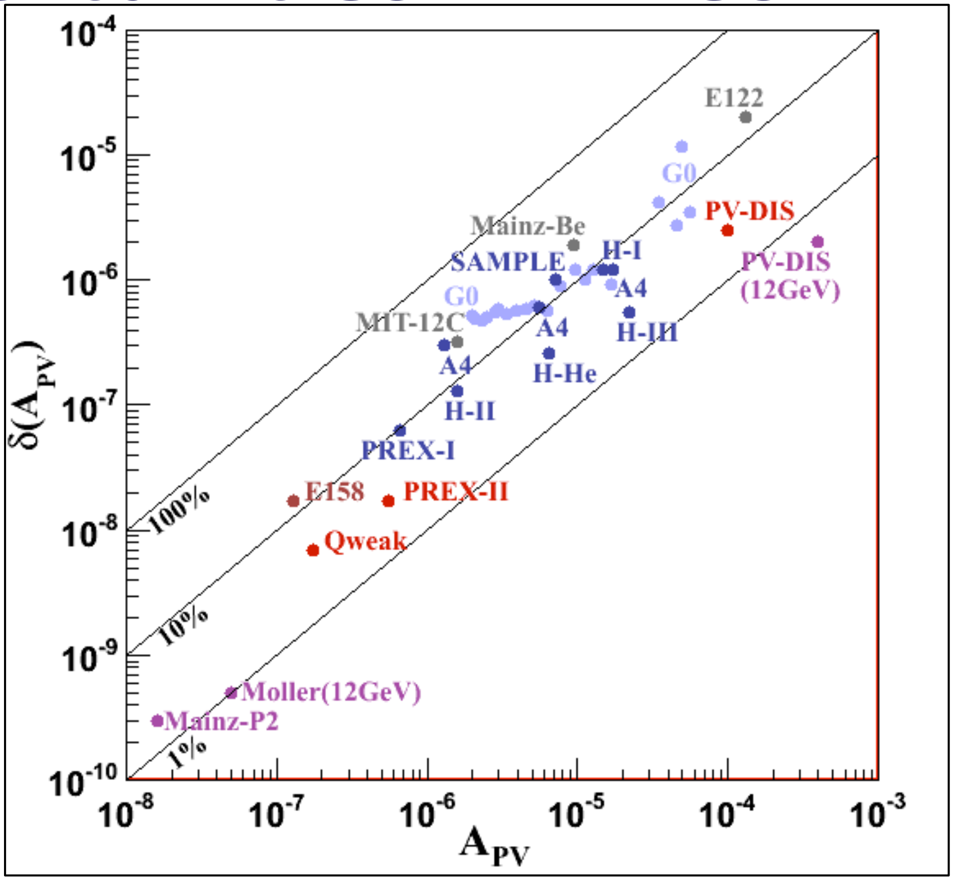

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- Ultra-precise weak-mixing angle comparable to the best collider measurements, needed and unavailable anywhere else!
- TeV-scale BSM sensitivity to complement LHC

SOLID at JLab

- 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 studes

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- Extend precision and improved interpretation

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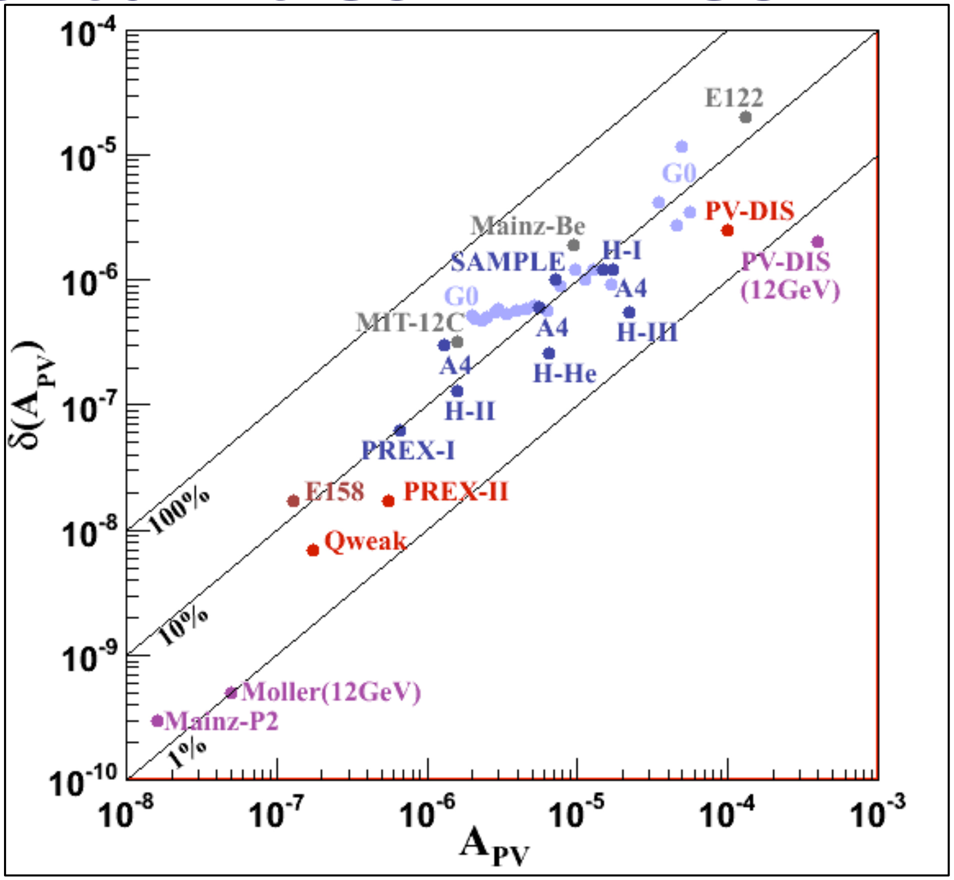


International Context

- JLab is a unique facility, attracting foreign collaborators to this effort

Vision for 2020:

- Conclusion of MOLLER production running
- Final results of P2 under preparation
- Opening a broad program of study of inclusive and semi-inclusive DIS with SOLID

Charge Symmetry Violation

We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

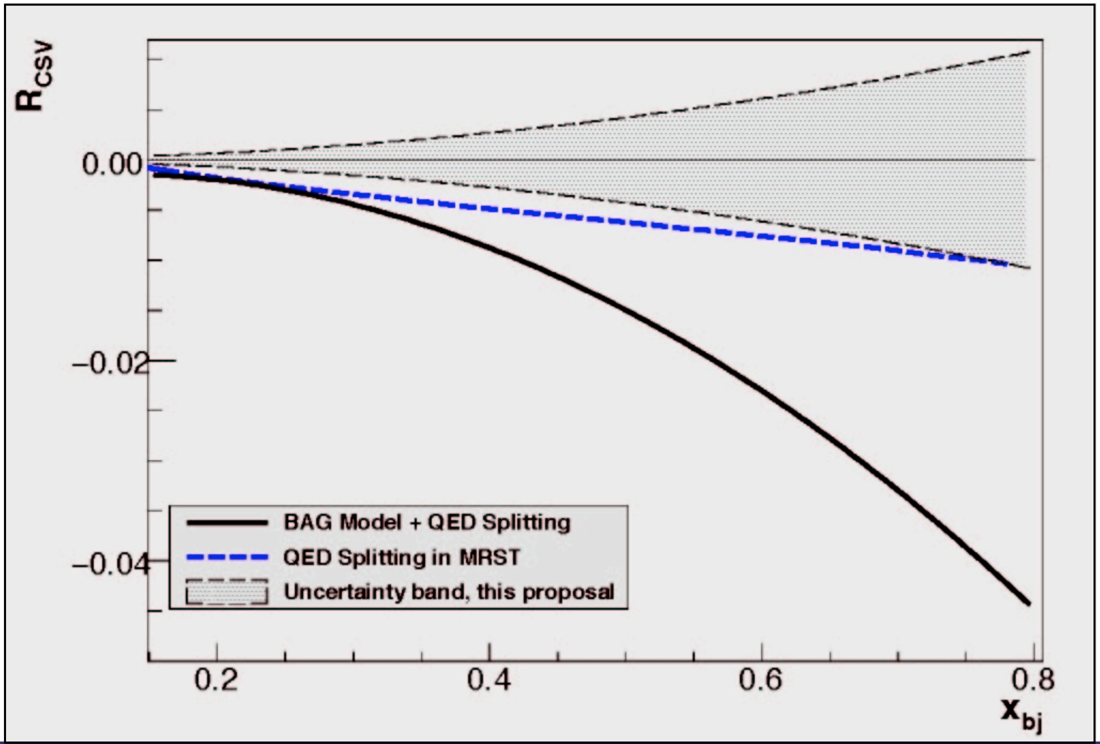
  - **Direct sensitivity of parton-level CSV**
  - **Important implications for PDF's**
  - ***Could be* partial explaination of the NuTeV anomaly**

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$

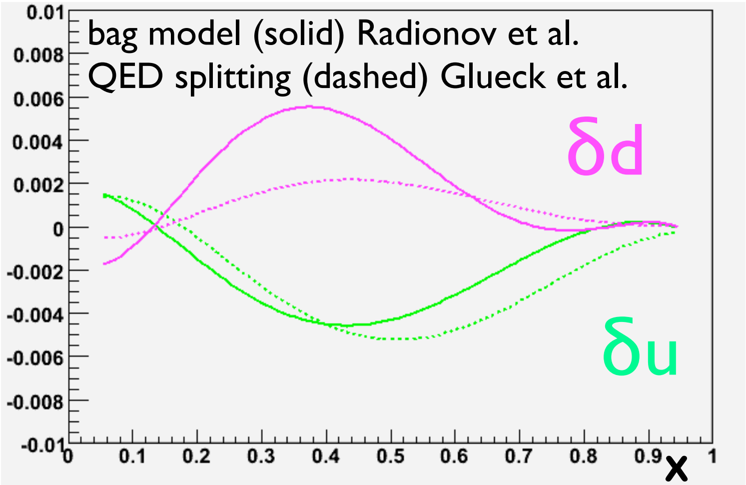
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

For A_{PV} in electron-^{2}H DIS



Sensitivity will be enhanced if *u+d* falls off more rapidly than *δu-δd* as *x* → 1



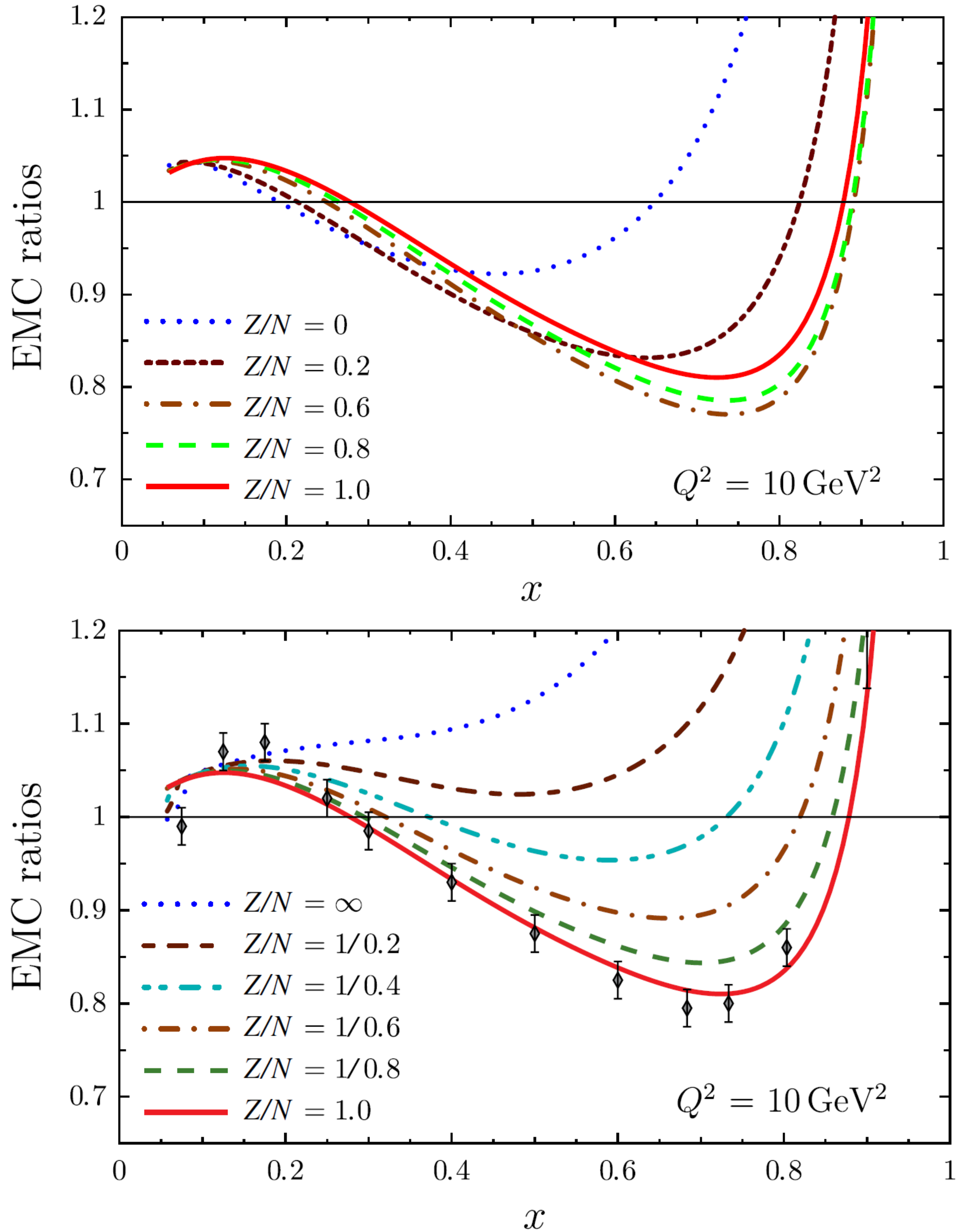
Significant effects are predicted at high *x*

CSV in Heavy Nuclei: EMC Effect

Isovector EMC Effect and the NuTeV Anomaly

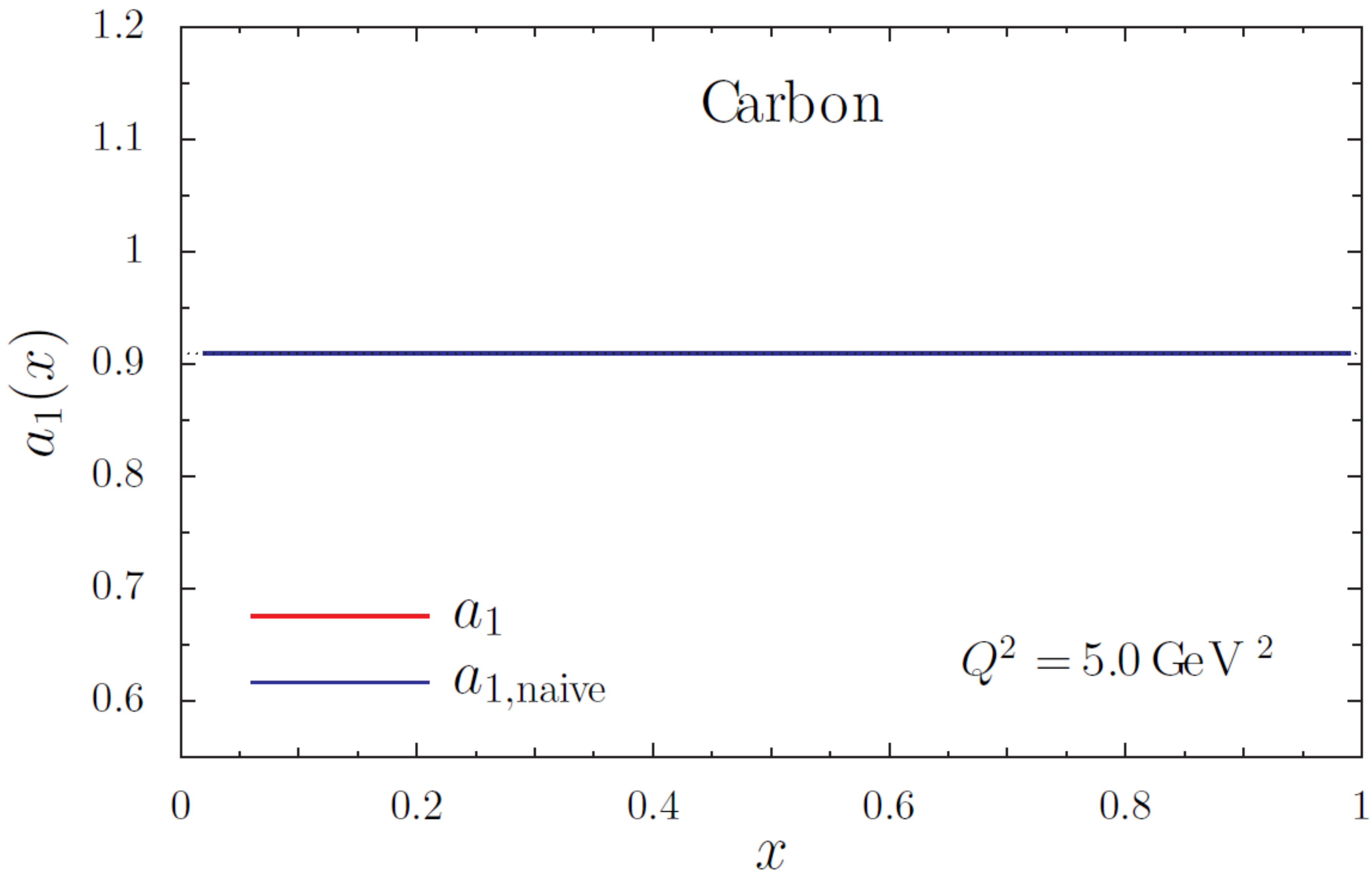
I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[3]

PRL **102,** 252301 (2009)



- Mean Field approach to estimate an EMC-like effect for N ≠ Z nuclei
- Possible explanation for NuTeV anomaly which used iron target.

CSV in Heavy Nuclei: EMC Effect



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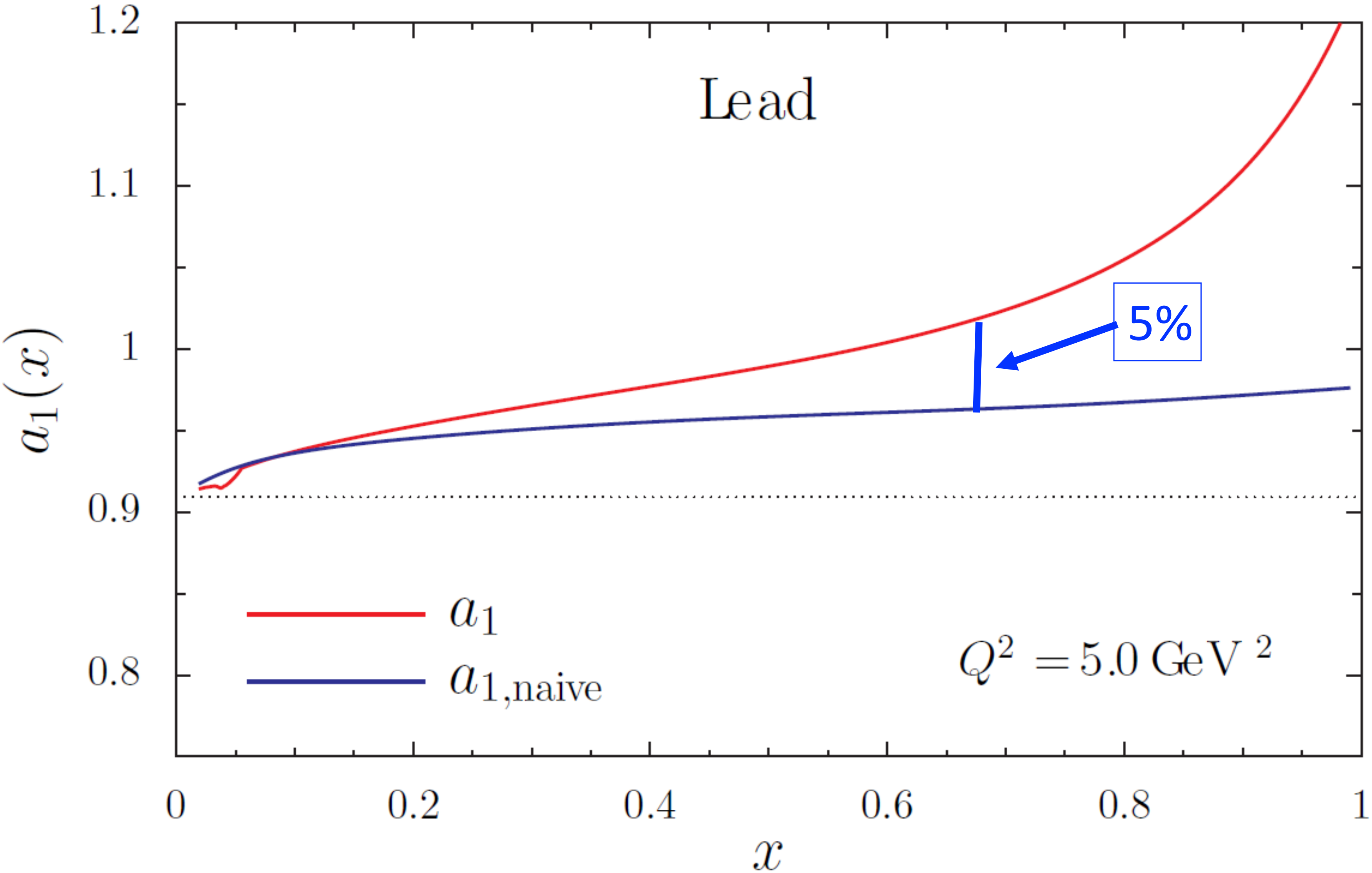


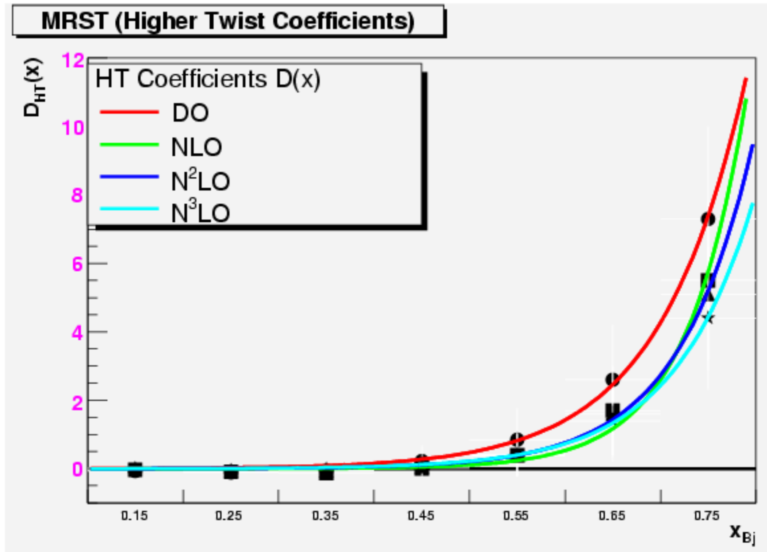
Higher Twist -- MRST Fits

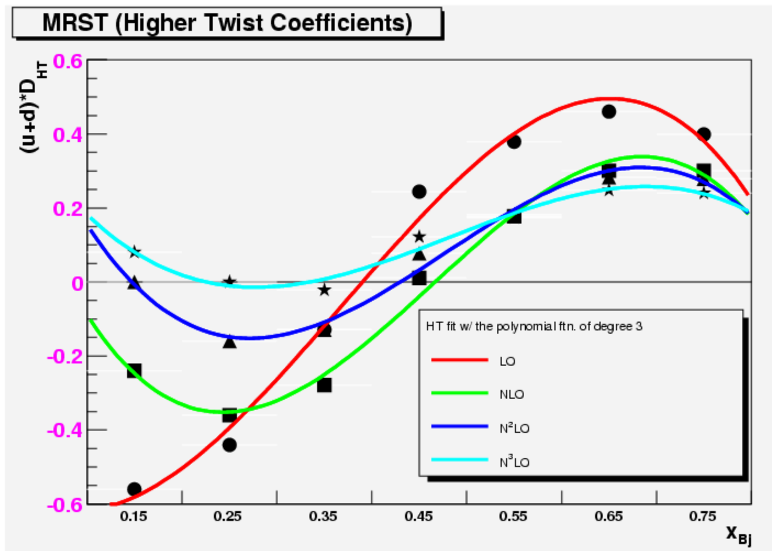
$F_2(x,Q^2)=F_2(x)(1+D(x)/Q^2)$ $Q^2=(W^2-M^2)/(1/x-1)$ $Q^2_{min}=Q^2(W=2)$

Order of DGLAP influences size of HT

MRST, PLB582, 222 (04)

x	Q^2_{min}	D(x)		D/Q^2_{min} (%)	
		LO	N^3LO	LO	N^3LO
0.1-0.2	0.5	-.007	0.001	-14	2
0.2-0.3	1.0	-.11	0.003	-11	0.0
0.3-0.4	1.7	-.06	-0.001	-3.5	-0.5
0.4-0.5	2.6	.22	0.11	8	4
0.5-0.6	3.8	.85	0.39	22	10
0.6-0.7	5.8	2.6	1.4	45	24
0.7-0.8	9.4	7.3	4.4	78	47





$$A_{\text{meas.}} = A_{\text{PV}}\left[1+\frac{C(x)}{Q^2}\right]$$

If C(x)~D(x), there is large sensitivity al large x.

Higher twist falls slowly compared to PDF's at large x.

HT may be most visible at the highest x

Higher Twist and q-q coherence

The observation of Higher twist in PV-DIS would be exciting direct evidence for diquarks

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

$$A \propto \frac{l_{\mu\nu}\int\langle D\,|\,j^{\mu}(x)J^{\nu}(0)+J^{\mu}(x)j^{\nu}(0)\,|\,D\rangle e^{iq\cdot x}d^4x}{l_{\mu\nu}\int\langle D\,|\,j^{\mu}(x)j^{\nu}(0)\,|\,D\rangle e^{iq\cdot x}d^4x}$$

$$V_{\mu}=\left(\bar{u}\gamma_{\mu}u-\bar{d}\gamma_{\mu}d\right)\Leftrightarrow S_{\mu}=\left(\bar{u}\gamma_{\mu}u+\bar{d}\gamma_{\mu}d\right) \qquad \langle VV\rangle = l_{\mu\nu}\int\langle D\,|\,V^{\mu}(x)V^{\nu}(0)\,|\,D\rangle e^{iq\cdot x}d^4x$$

Isospin decomposition before using PDF's

$$A=\frac{(C_{1u}-C_{1d})\langle VV\rangle+\frac{1}{3}(C_{1u}+C_{1d})\langle SS\rangle}{\langle VV\rangle+\frac{1}{3}\langle SS\rangle}$$

Zero in QPM

$$\langle VV\rangle-\langle SS\rangle=\langle (V-S)(V+S)\rangle \propto l_{\mu\nu}\int\langle D\,|\,\bar{u}(x)\gamma^{\mu}u(x)\bar{d}(0)\gamma^{\nu}d(0)\rangle e^{iq\cdot x}d^4x$$

Higher-Twist valance quark-quark correlations

HT in F_2 may be dominated by quark-quark correlations

Vector-hadronic piece only
Use ν data for small b(x) term.

HT in the a3 term

$$\frac{1-(1-y)^2}{1-y-y^2/2(1+R)}\,a_3(Q^2,\nu) \propto \frac{\sigma^{\nu}-\sigma^{\bar{\nu}}}{\sigma^{\nu}+\sigma^{\bar{\nu}}}$$

These hadronic corrections can be obtained from charged-current neutrino scattering data

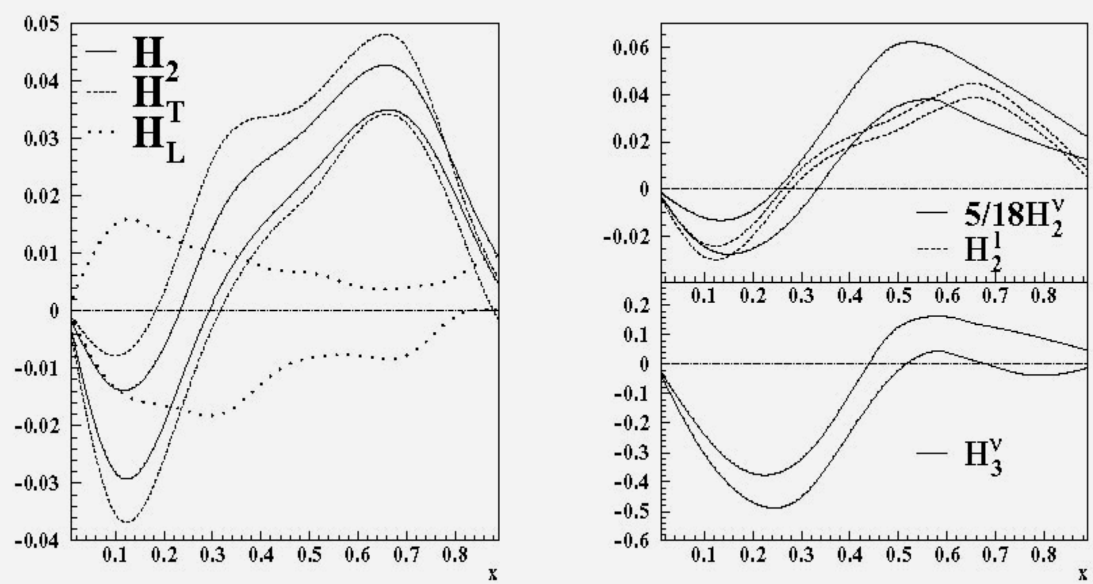


FIGURE 2. Left figure: the 1σ error bands for the high-twist terms in the isospin-symmetric combinations of different structure functions (solid lines: F_2, dashes: F_T, dots: F_L) for charged leptons. Right figure: corresponding 1σ bands for neutrino scattering off an isoscalar target (upper panel: F_2, lower panel: xF_3). The predictions for F_2 from charged leptons rescaled by the corresponding leading twist terms are also shown for comparison.

High Sensitivity, Complementary to LHC

Moller sensitivity: $$\frac{\mathbf{\Lambda}}{\sqrt{|\mathbf{g^2_{RR}} - \mathbf{g^2_{LL}}|}} = \mathbf{7.5}\ \mathrm{TeV}$$

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Best current limits on 4-electron contact interactions: LEPII at 200 GeV (Average of all 4 LEP experiments)

$$\frac{\mathbf{\Lambda}}{\sqrt{|\mathbf{g_{RR}^2 + g_{LL}^2}|}} = \mathbf{4.4}\ \mathrm{TeV}$$ OR $$\frac{\mathbf{\Lambda}}{\mathbf{g_{RL}}} = \mathbf{5.2}\ \mathrm{TeV}$$

insensitive to $|\mathbf{g_{RR}^2 - g_{LL}^2}|$

To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider, neutrino factory or muon collider

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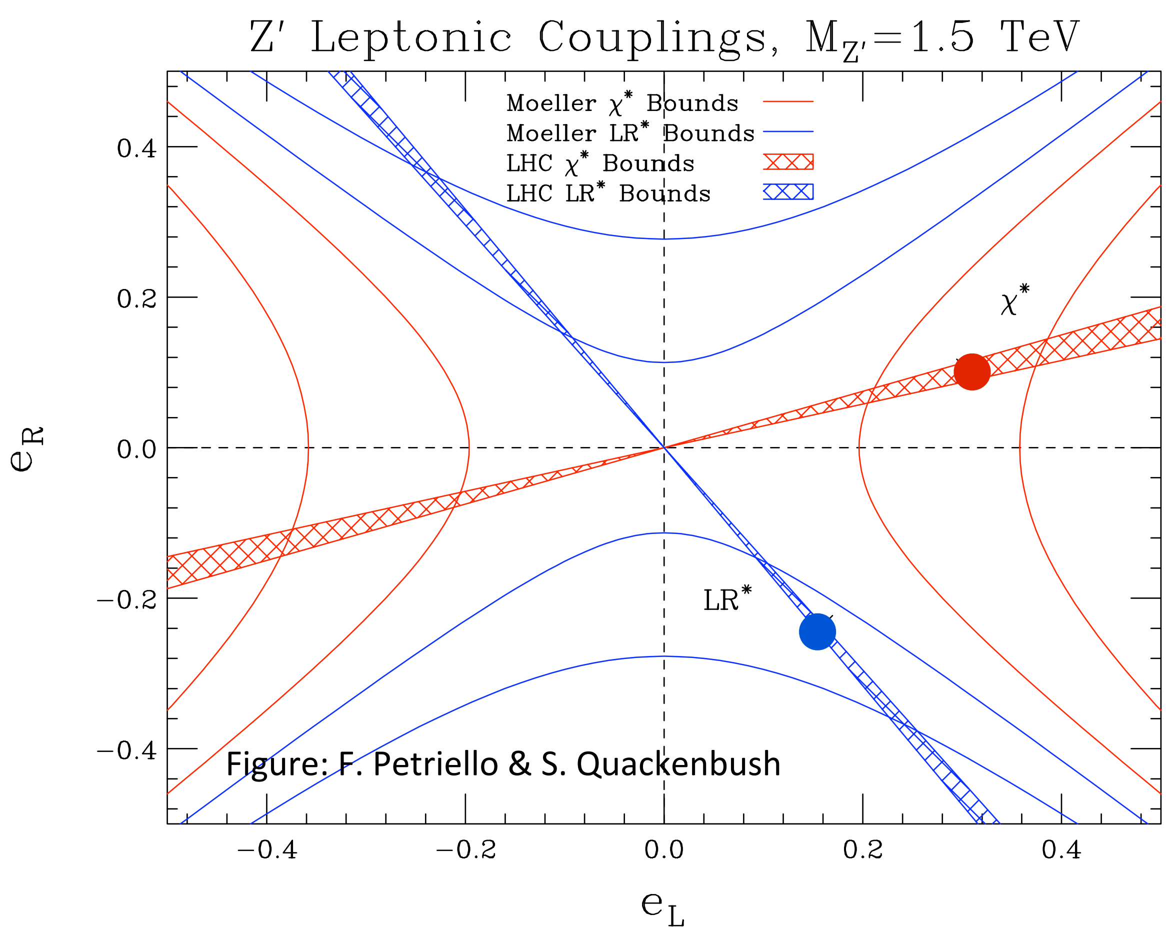

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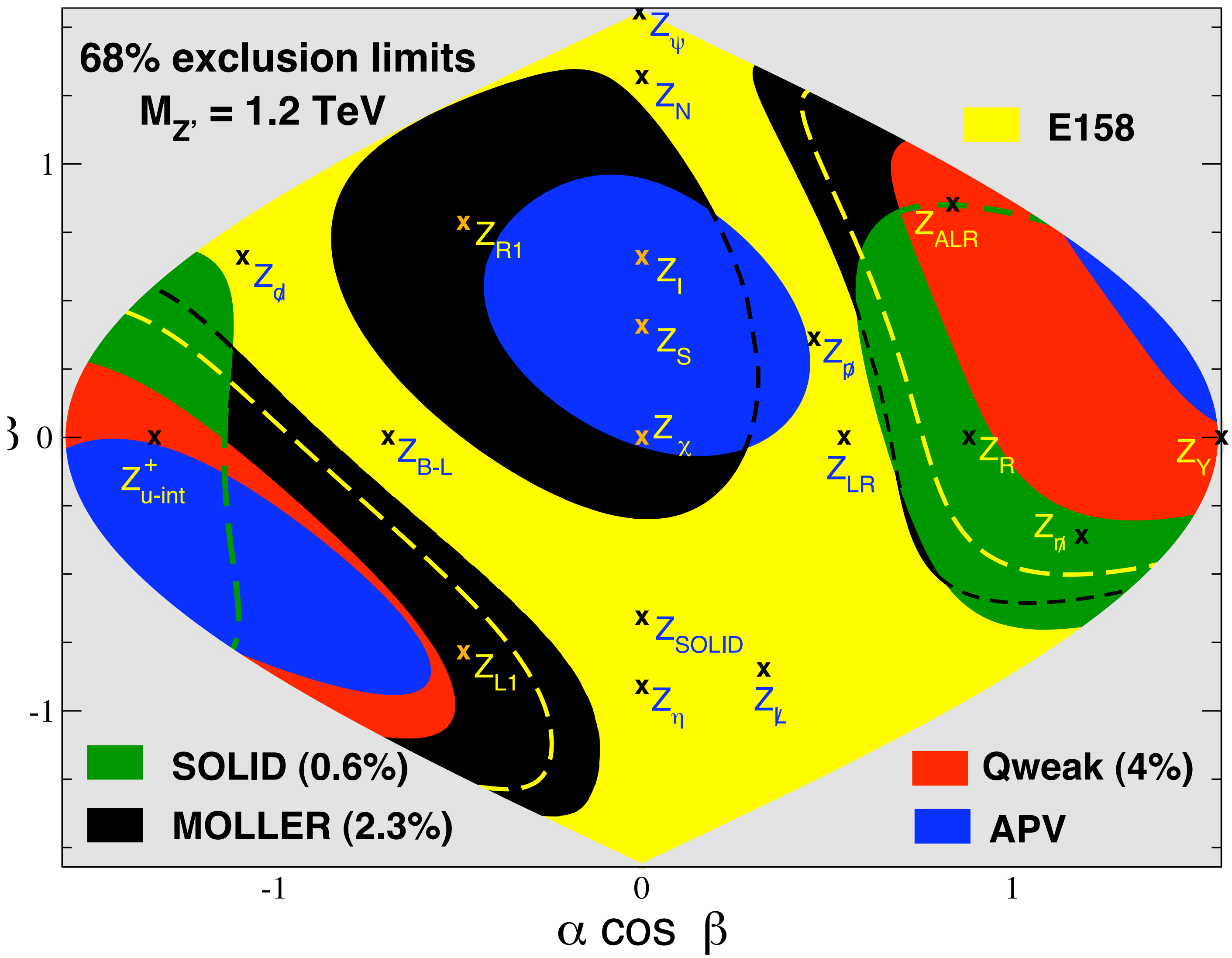
Moller:

$$\frac{g_{RR}^2 - g_{LL}^2}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2}$$

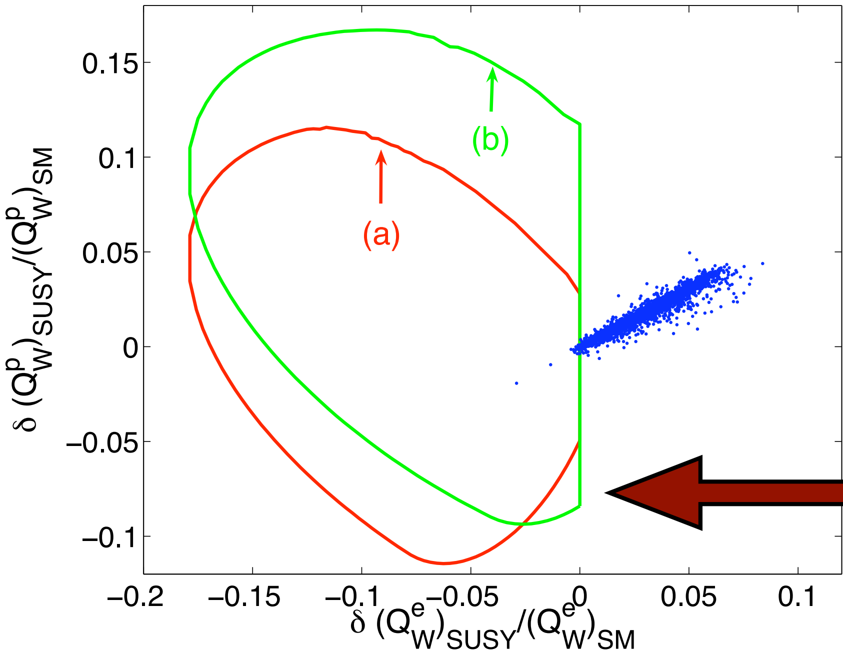
LHC:

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



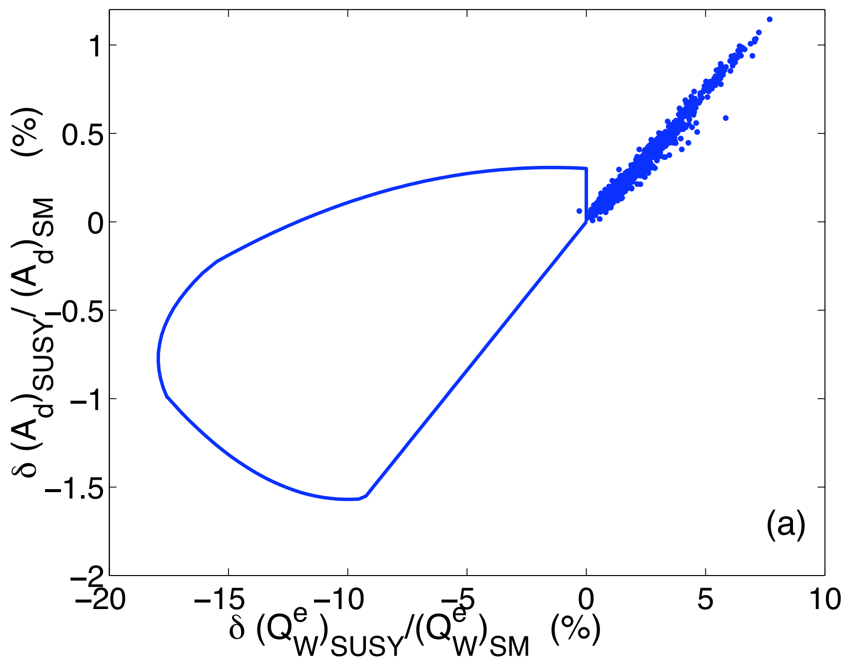
- APV (Boulder)
- E158 (SLAC)
- MOLLER
- Qweak
- SOLID

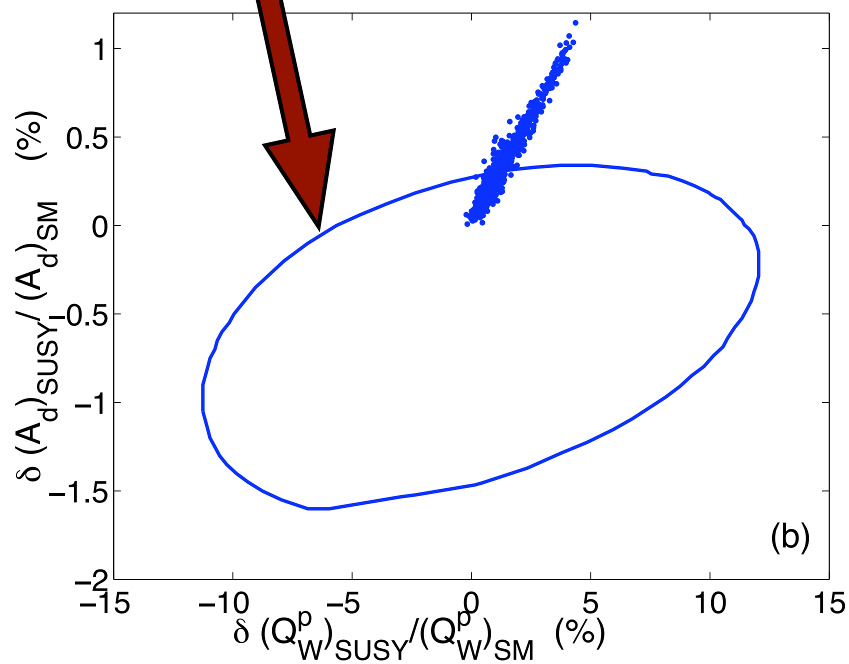
e^- scattering and SUSY



$\not{R}_P$

Ramsey-Musolf, Su (2006)





Measuring Strange Vector Form Factors

More recently: an international program of measurements of elastic electron-nucleon scattering, with an eye to extracting strange quark contributions to the proton form factors

Proton:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

~ few parts per million

$$A_E = \epsilon G_E^p G_E^Z \qquad A_M = \tau G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$

Forward angle — Backward angle

"Anapole" radiative corrections are problematic

$$G_{E,M}^Z = (1 - 4\sin^2\theta_W)G_{E,M}^p - G_{E,M}^n - G_{E,M}^s$$

from assumption of charge symmetry

Spin=0,T=0 ^{4}He: **G^s_E only!**

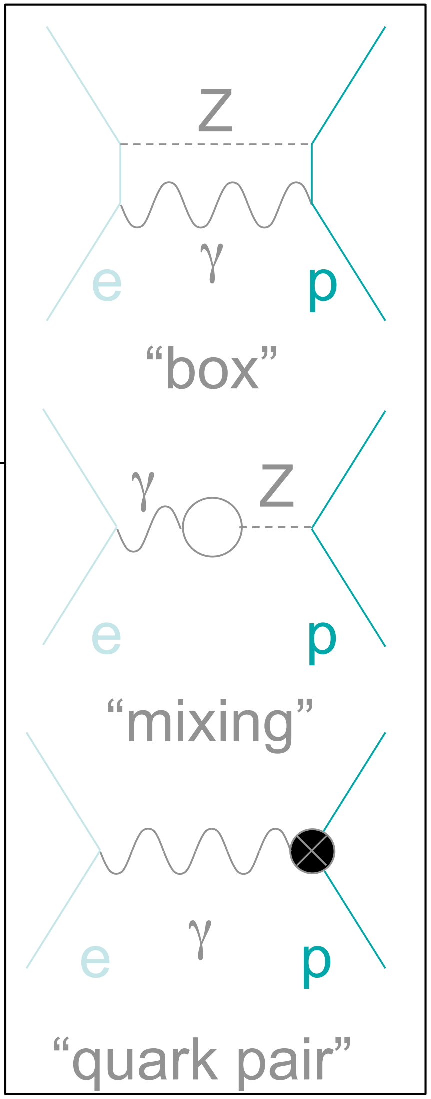
Deuterium: **Enhanced G_A**

The Axial Term and the Anapole Moment

Axial form-factors G_A^p, G_A^n

$$\tilde{G}_A^{p,n} = -\tau_3\left(1 + R_A^{T=1}\right)G_A^{(3)} + \sqrt{3}R_A^{T=0}G_A^{(8)} + \Delta s$$

- **Determined at Q^2=0 from neutron and hyperon decay parameters (isospin and SU(3) symmetries)**
- **Q^2 dependence often assumed to be dipole form, fit to ν DIS and π electroproduction**
- **Includes also Δs, fit from ν-DIS data**



Anapole Moment Correction:

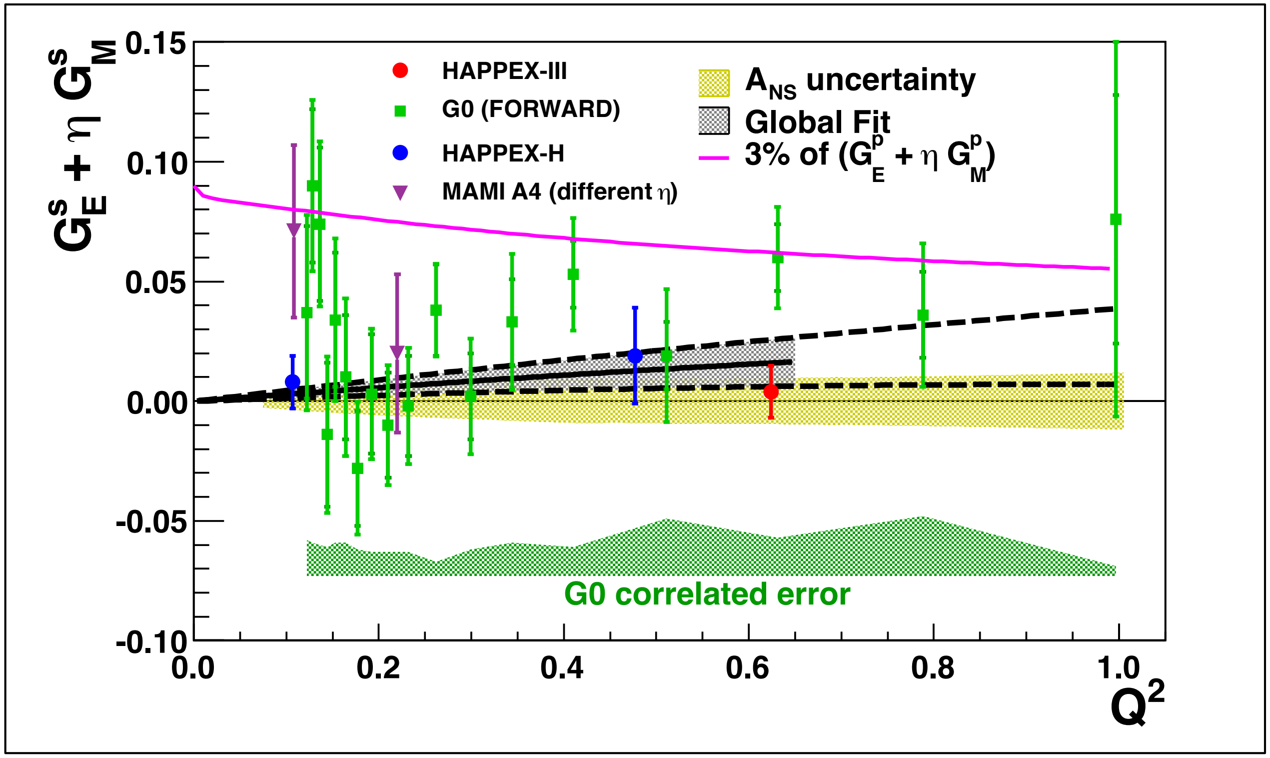
Multiquark weak interaction in $R_A^{(T=1)}$, $R_A^{(T=0)}$

Zhu, Puglia, Holstein, Ramsey-Musolf, Phys. Rev. D **62**, 033008

- **Model dependent calculation with large uncertainty**
- **Uncertainty dominates axial term**

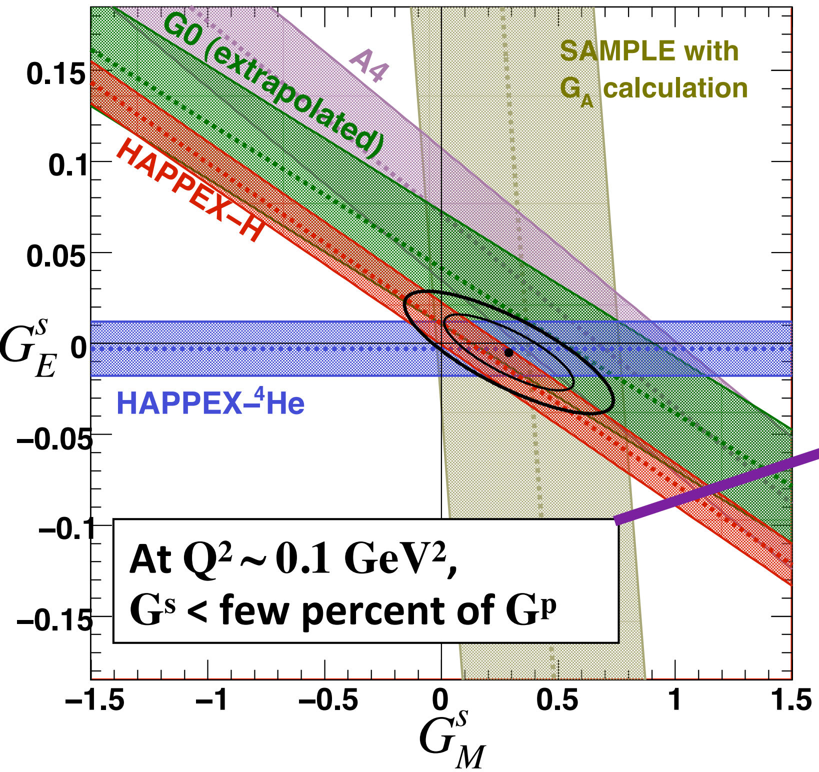
Difficult to achieve tight experimental constraint

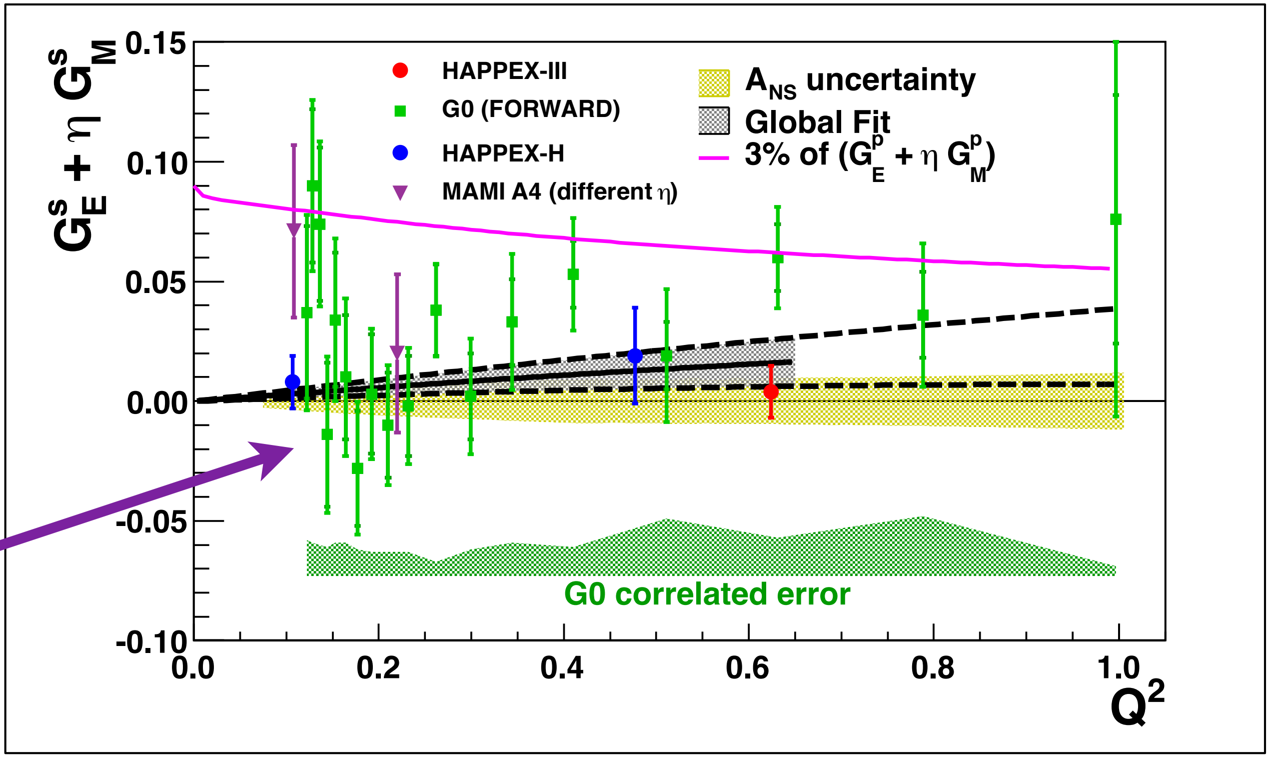
Strange Vector Form Factors Are Small



Probing over a range of low-Q^2, effects are small (<3%) and consistent with zero.

Strange Vector Form Factors Are Small





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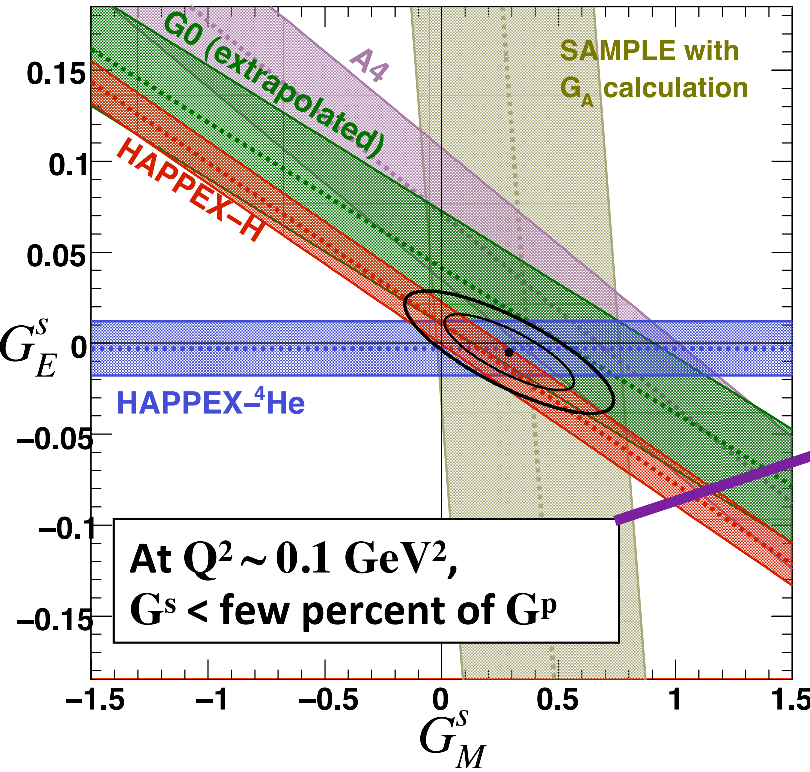
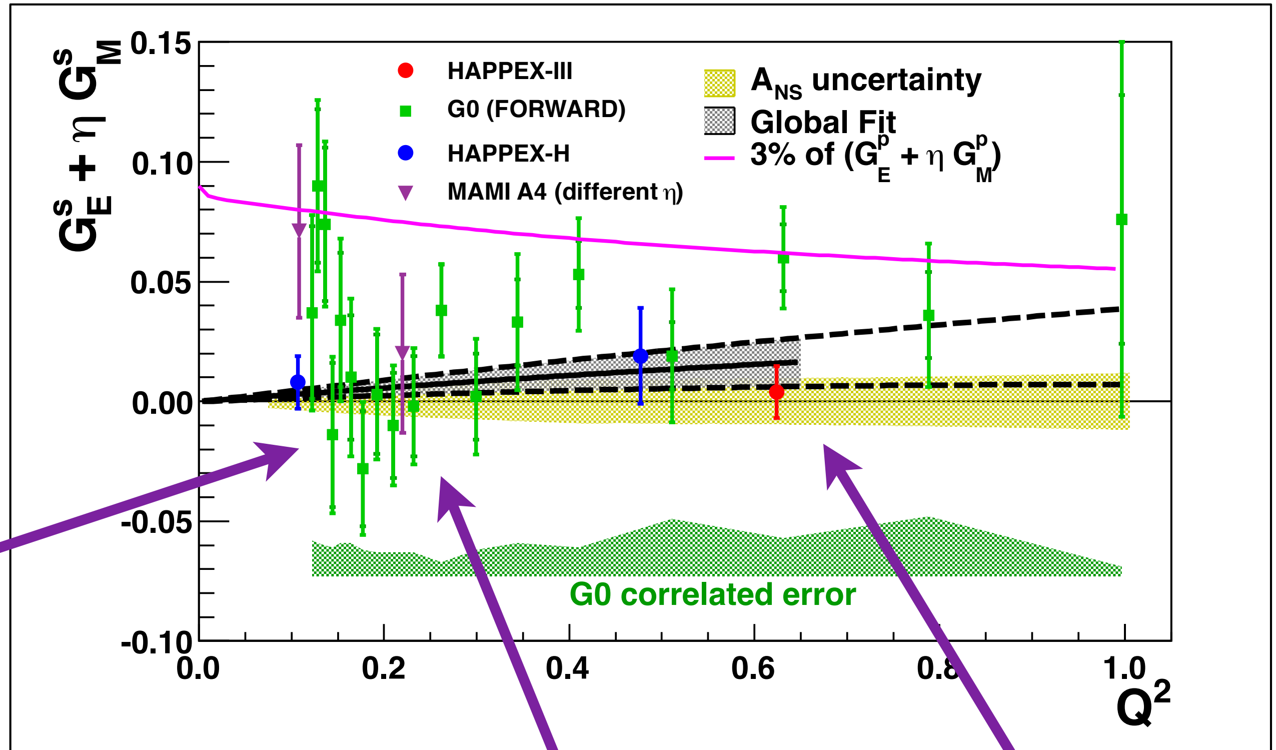
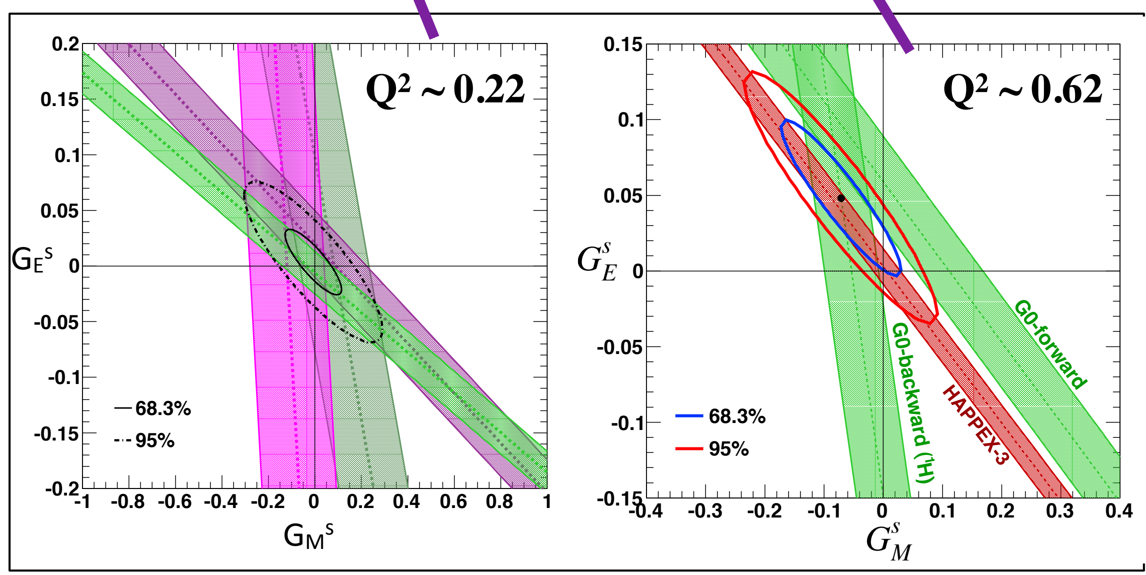


At $Q^2 \sim 0.1$ GeV^2,
G^s < few percent of G^p





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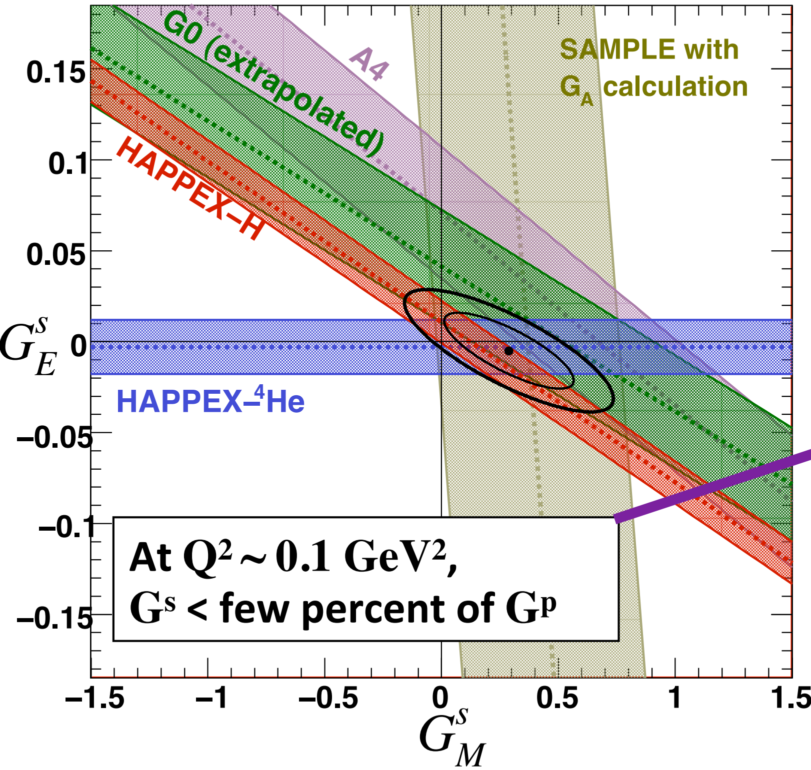
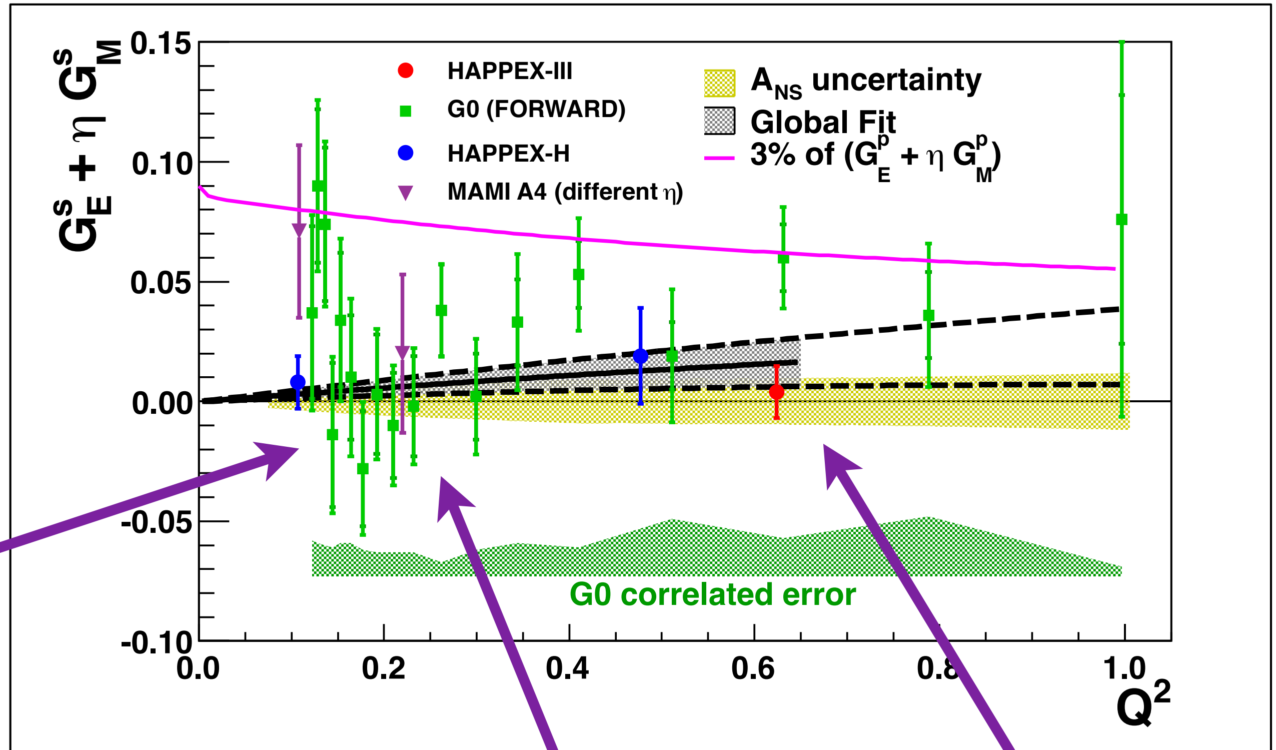
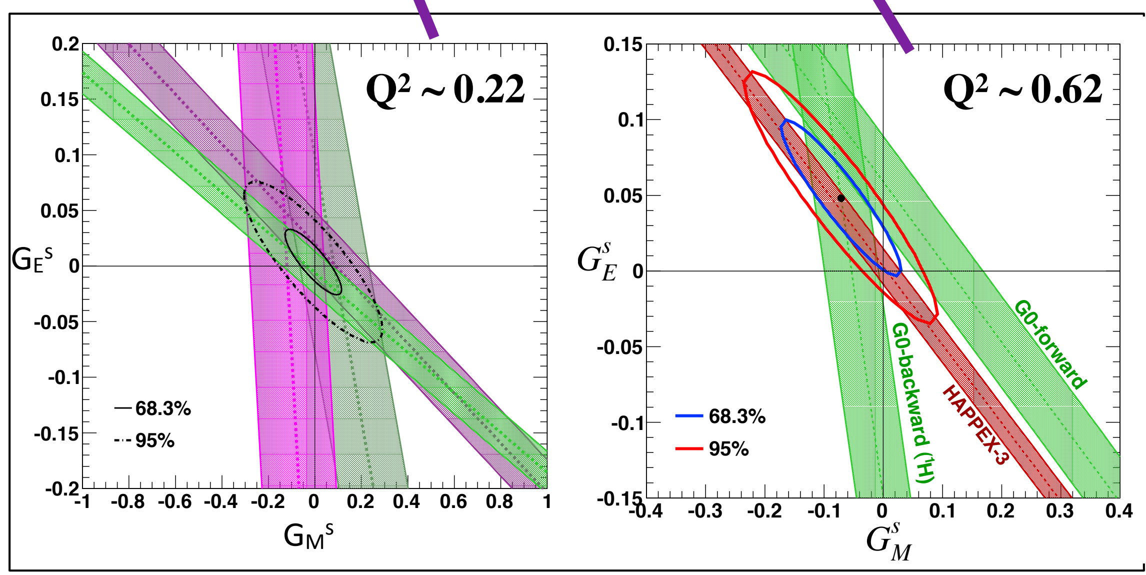






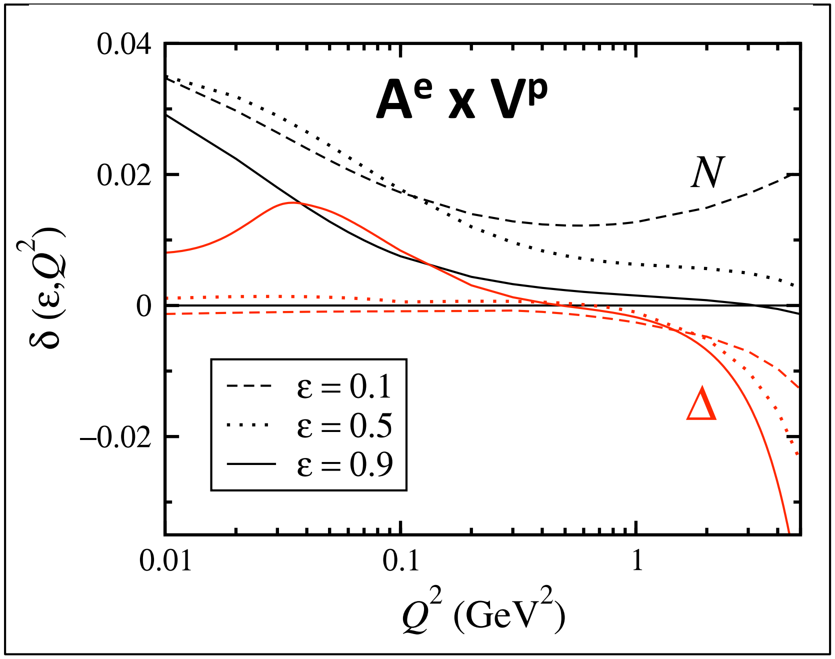
Probing over a range of low-Q^2, effects are small (<3%) and consistent with zero.

Whether strange quarks, charge symmetry breaking, axial contributions - all effects must go to zero at zero Q^2

γZ box contributions

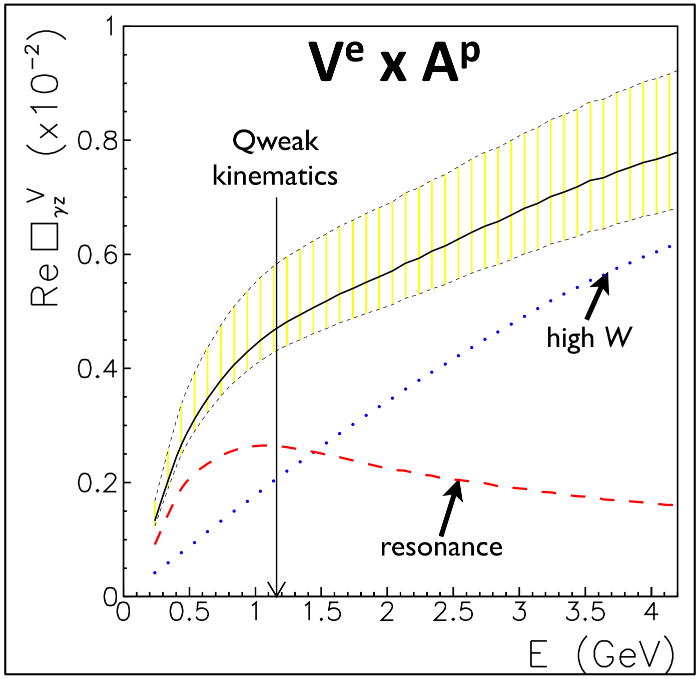
$$A_{PV} = (1+\delta)A^0_{PV} \equiv \left(\frac{1+\delta_{Z(\gamma\gamma)}+\delta_{\gamma(Z\gamma)}}{1+\delta_{\gamma(\gamma\gamma)}}\right) A^0_{PV}$$

$$Q^p_W = (1+\Delta\rho+\Delta_e)(1-4\sin^2\theta_W(0)+\Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)\ ,$$



Tjon, Blunden, Melnitchouk (2009)

Also results from Zhou, Kao, Yang, Nagata (2010)



Sibirtsev, Blunden, Melnitchouk, Thomas (2010)

Also results from: Rislow, Carlson (2010), Gorchtein, Horowitz, M. Ramsey-Musolf(2011)

Electron and neutrino DIS and resonance measurements are necessary input

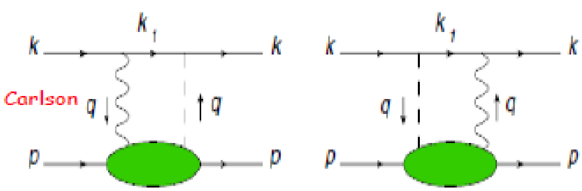
Look to be under control, but work is not yet complete

Radiative Corrections

Several corrections: $\Delta sin^2\theta_W(M_Z)$, WW and ZZ box – but these have small uncertainties

Focus on: **γZ Box Corrections near 1.16 GeV**

Rislow and Carlson



* In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

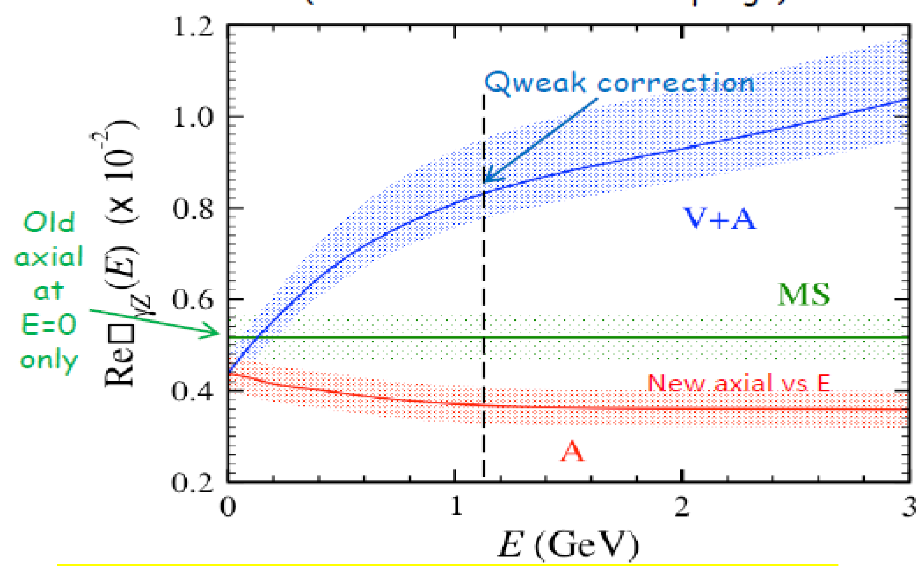
* This soon led to more refined calculations with corrections of ~8% and error bars ranging from ±1.1% to ±2.8%.

* It will probably also spark a refit of the global PVES database used to constrain G_E^s, G_M^s, G_A.

PV Amplitude	Authors	Correction* @ E=1.165 (GeV)
$A^e \times V^p$ (vanishes as E→0)	GH	0.0026+-0.0026**
	SBMT	$0.0047\ ^{+0.0011}_{-0.0004}$
	RC	0.0057±0.0009
	GHR-M	0.0054±0.0020
$V^e \times A^p$ (finite as E→0)	MS (as updated by EKR-M)	0.0052±0.0005***
	BMT	0.0037±0.0004

*Does not include a small contribution from the elastic.
** 5.7%×Q_w^p(LO) = 0.0026. Q_w^p(LO) = 0.04532.
***Included in Q_w^p. For reference, Q_w^p =0.0713(8).

Blunden, Melnitchouk, Thomas (2011)
(V and A are hadronic couplings)



Forthcoming axial results for Q_w^n have the potential to impact the interpretation of Cs APV.

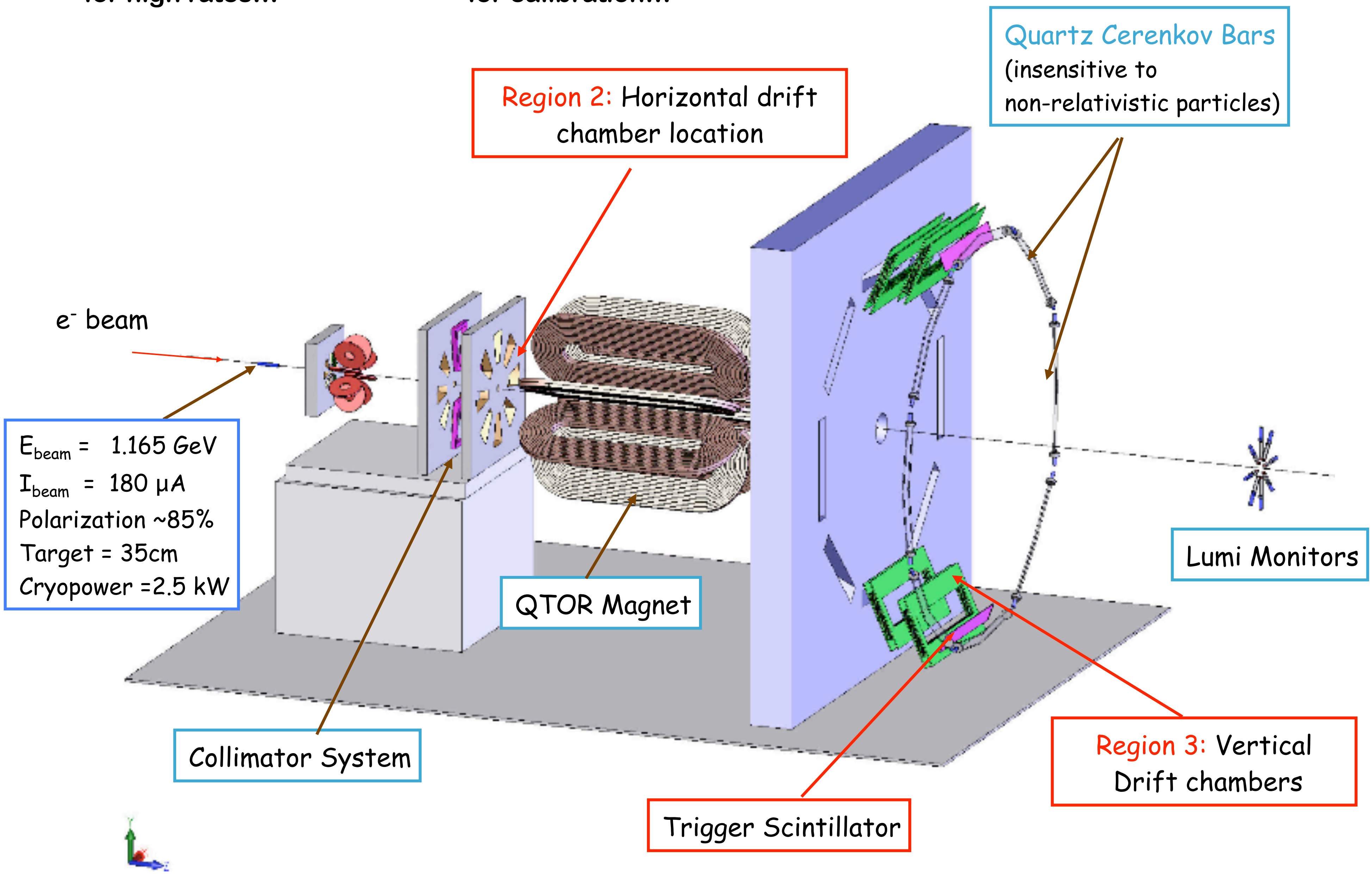
1

Spectrometer

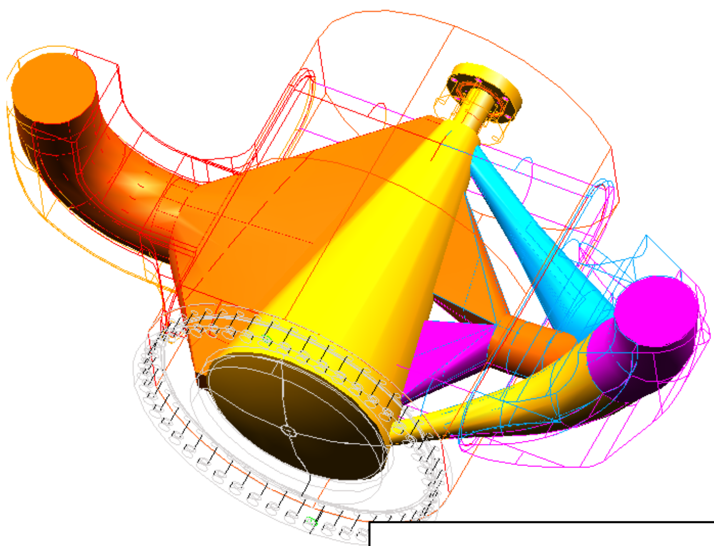
for high rates...

Tracking System

for calibration...



Cryotarget

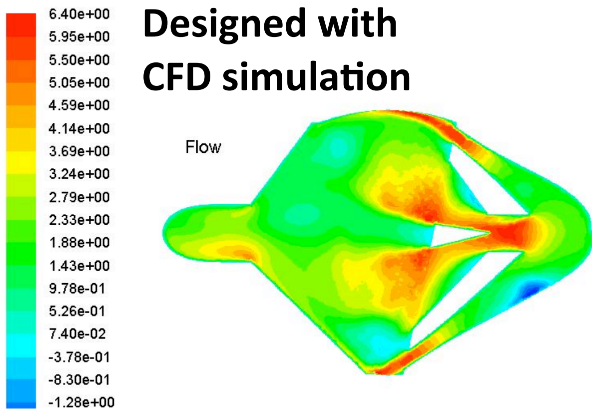


Liquid Hydrogen:

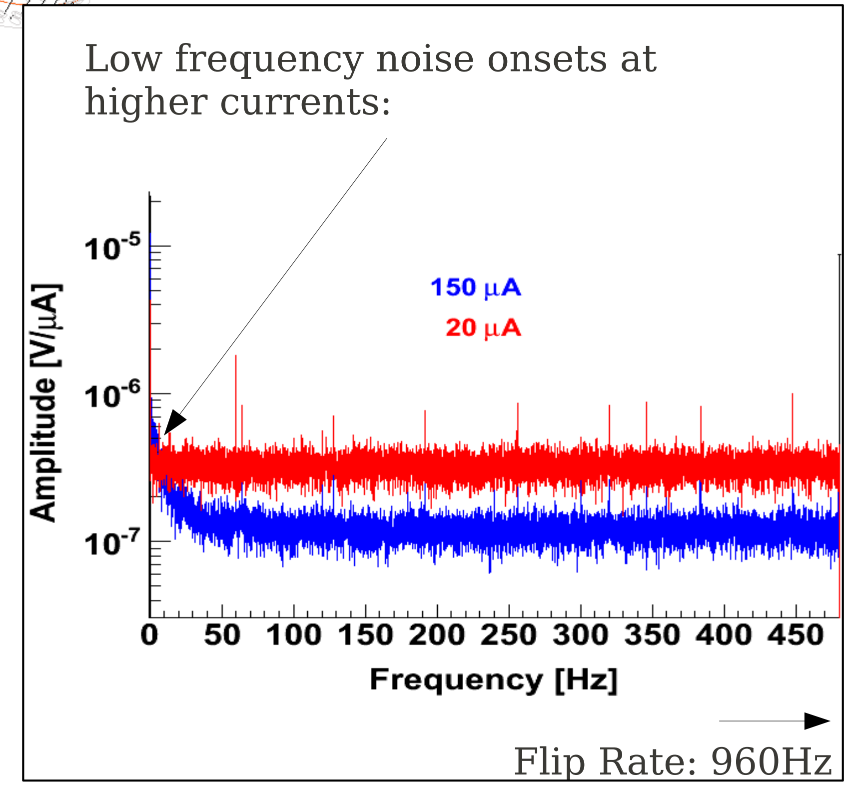
35cm cell, 180 μA

2300 Watts

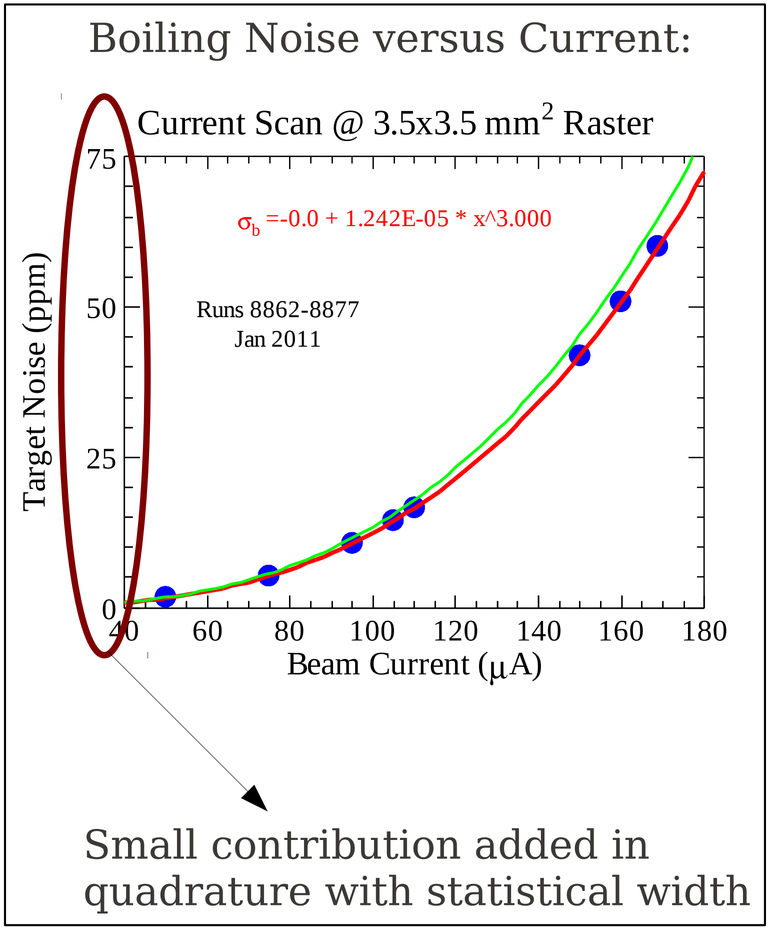
World's highest power cryotarget



Designed with CFD simulation



"fast" reversal makes asymmetry measurement faster than the bubbles move!

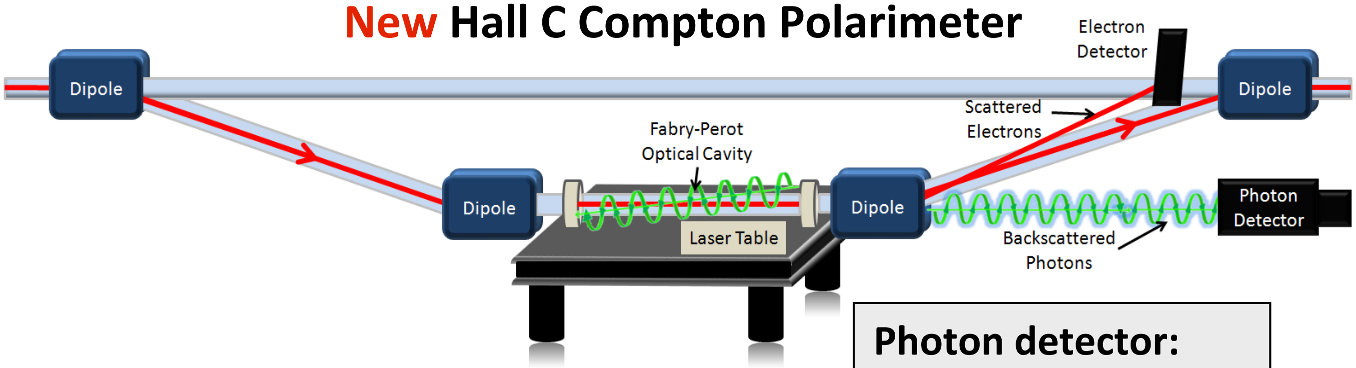


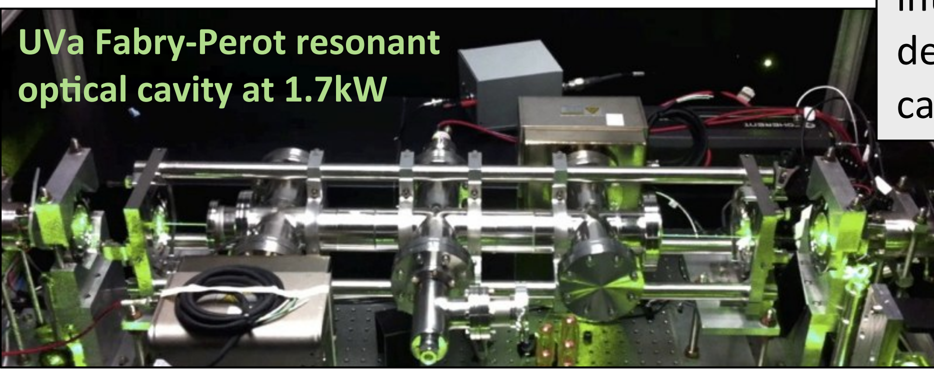
Boiling <60ppm = about 4% excess noise

Polarimetry

Redundant 1% electron beam polarimetry

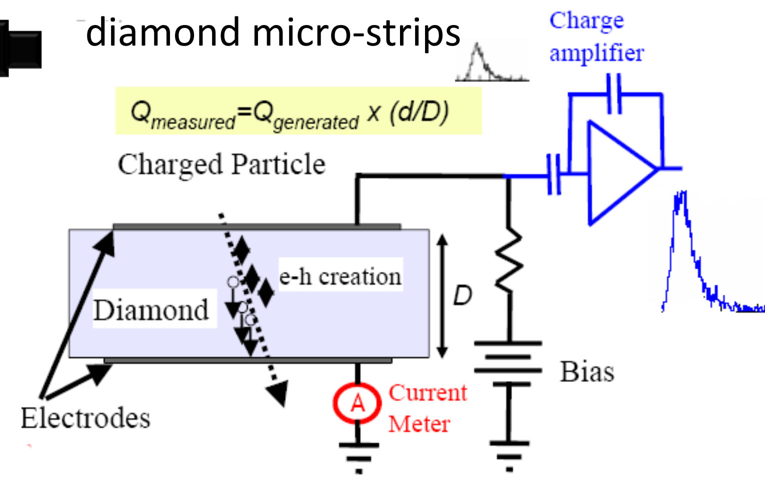
New Hall C Compton Polarimeter





Photon detector: integrating photon detection improves calibration precision

Electron detector: radiation-hard diamond micro-strips



High-Field Moller Polarimeter

- Saturated iron foil; well-known target polarization
- Precision scannable collimation, to control Levchuk effect

Each point represents ~1hr of data