Parity Violation Parallel Sessions

Intense Electron Beam Workshop
Ithaca, NY
June 17-19, 2015
Convenors: M. Perelstein, K. Paschke

Krishna Kumar	**Parity-Violating Electron Scattering: Status and Prospects**
Charles Horowitz	**Nuclear Weak Form-Factors**
Hooman Davoudiasl	**Dark Z and Parity Violation**
Carl Carlson	**Calculations of Gamma-Z Box Diagrams**
Oscar Moreno	**Nuclear and nucleon structure effects in low-energy parity-violating electron scattering**
Roger Carlini	**Qweak + Torroidal Spectrometer Options**
Dominik Becker	**Monte Carlo simulations of a solenoid spectrometer for Project P2**
Paul Souder	**Carbon with Solenoidal Spectrometer**

3 Topics

- Neutron distribution in heavy nuclei
- Strange form factors
- Standard Model tests and beyond Standard Model reach

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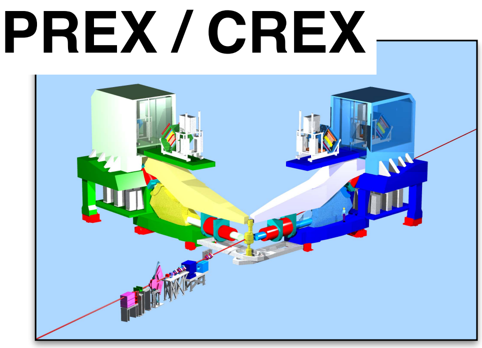

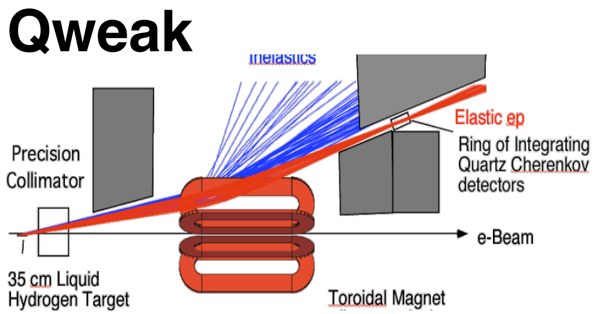

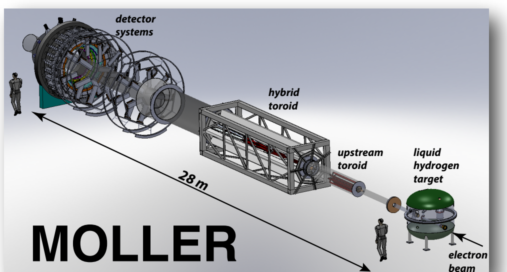

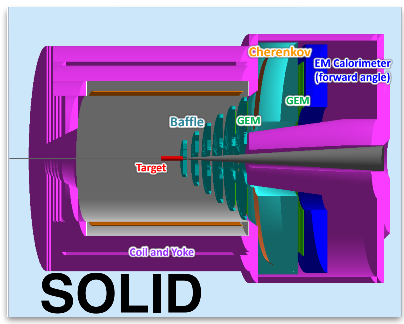

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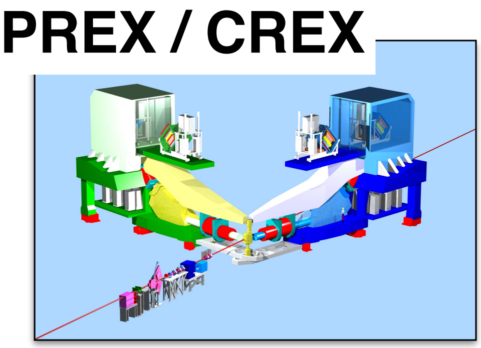

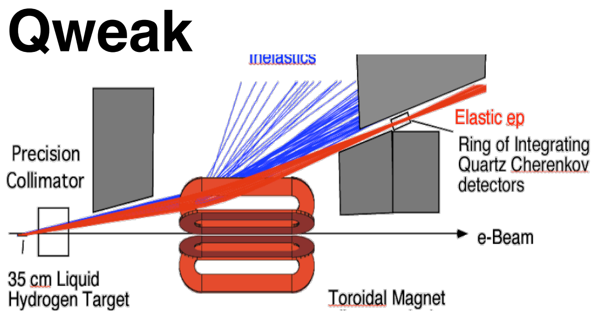

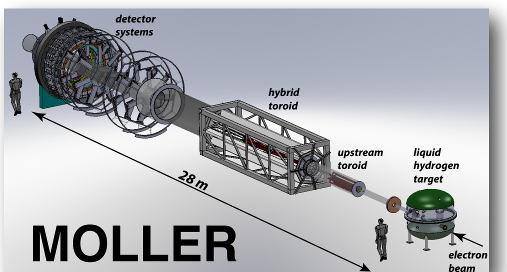

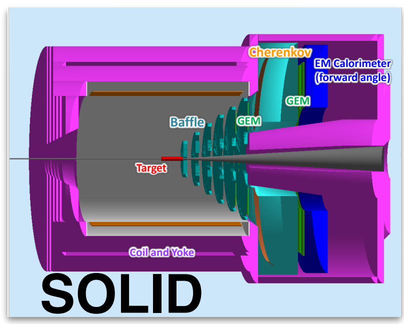

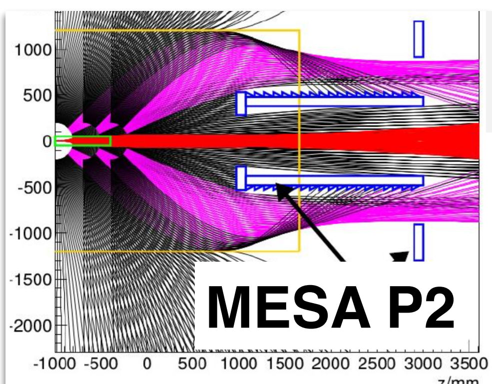

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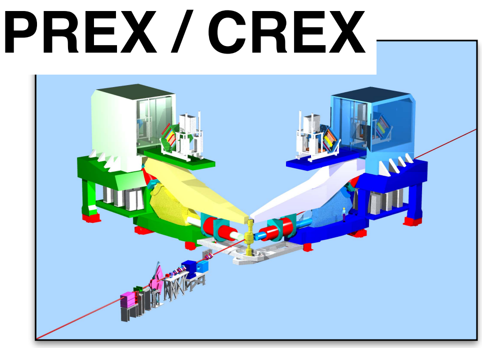

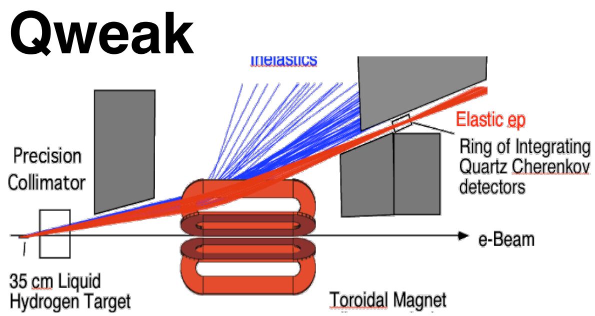

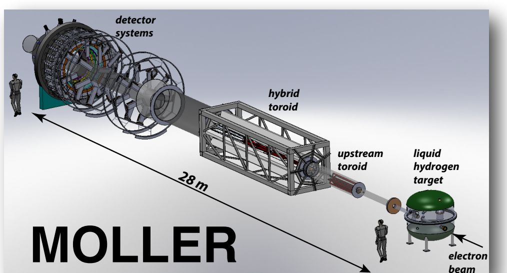

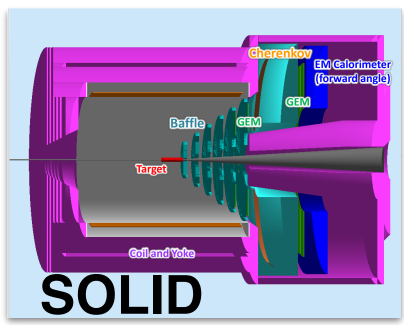

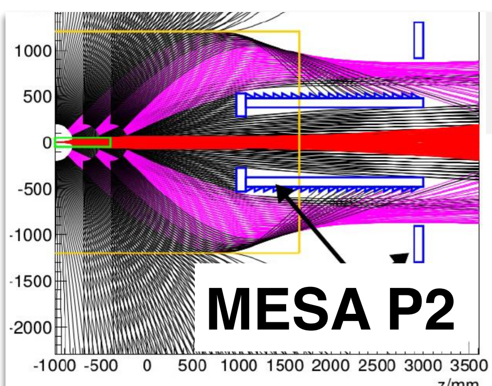

$\mathcal{L} \sim 10^{39}$ / (s-cm^2)

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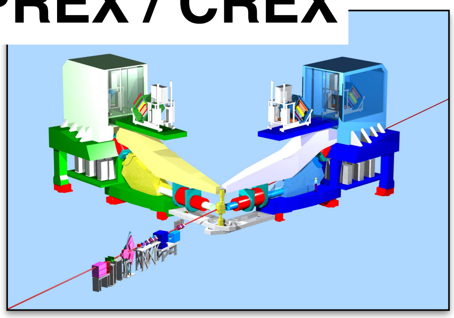
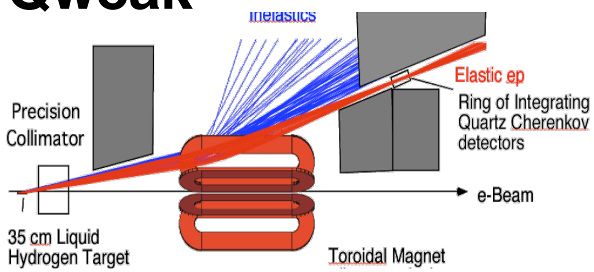
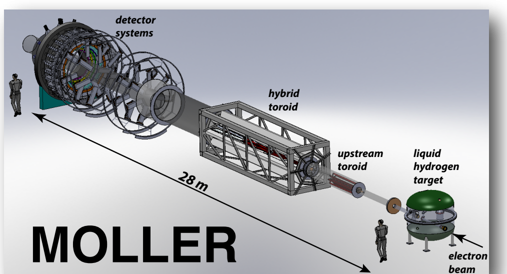
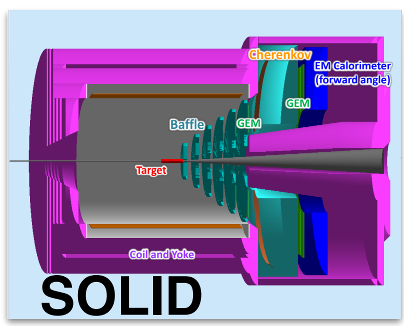
PREX / CREX

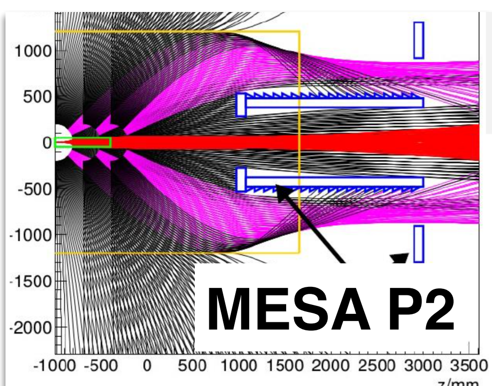


Qweak









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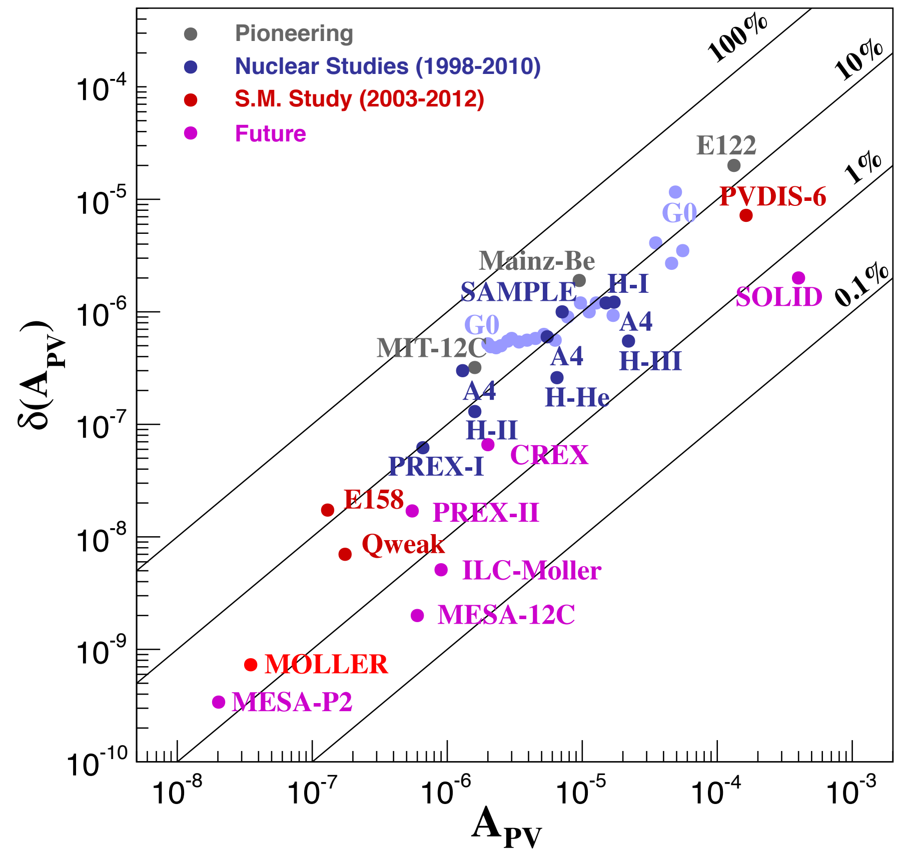

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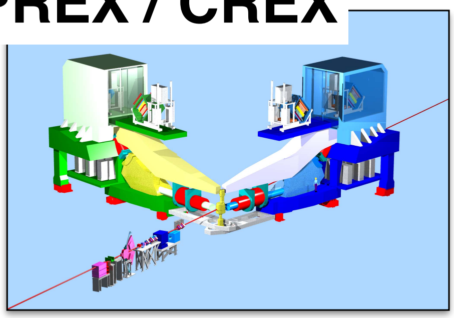

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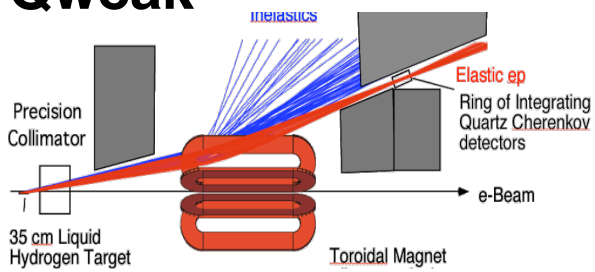

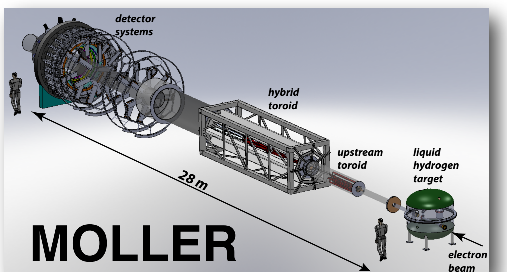

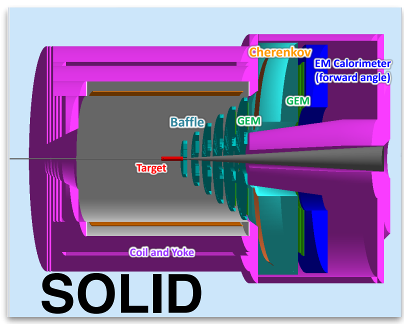

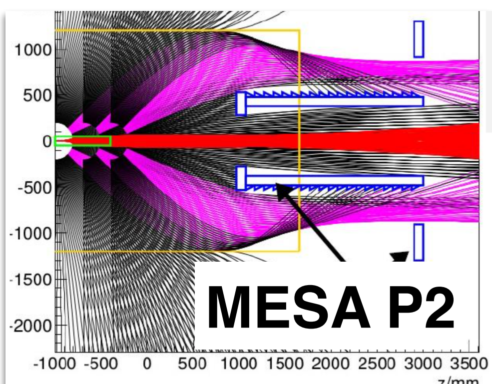

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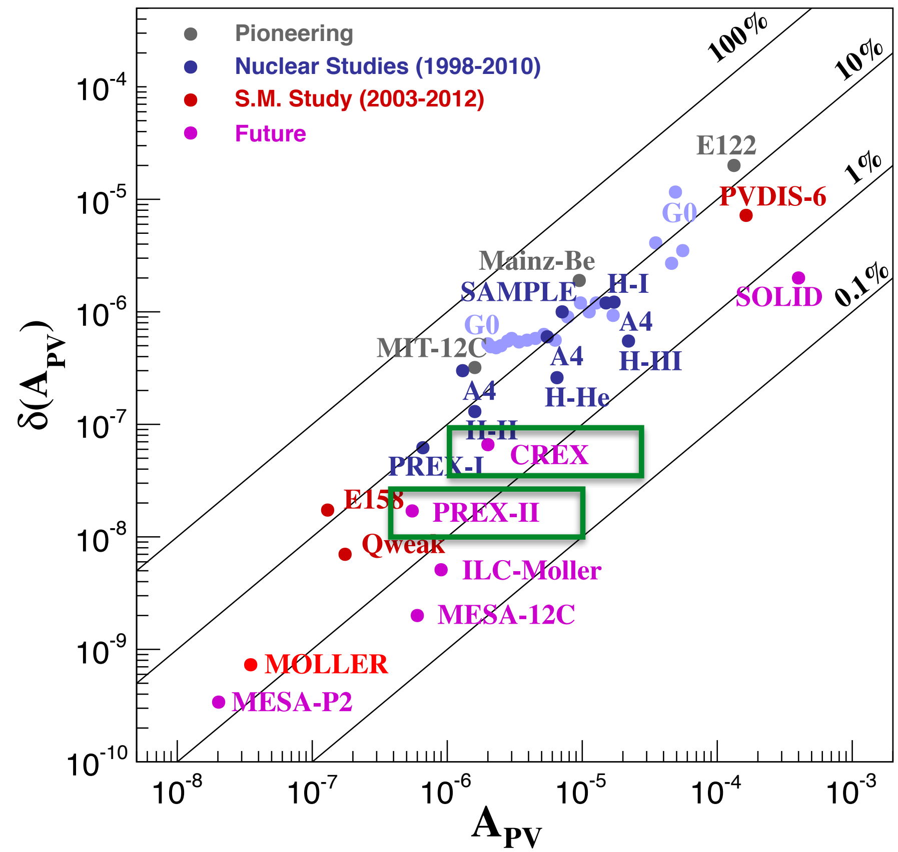

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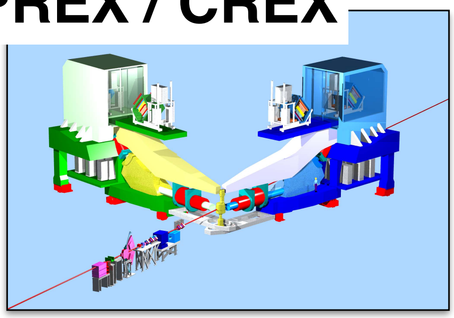

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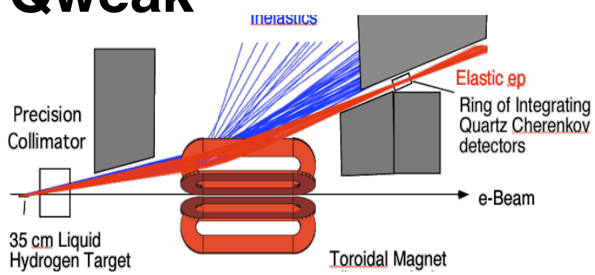

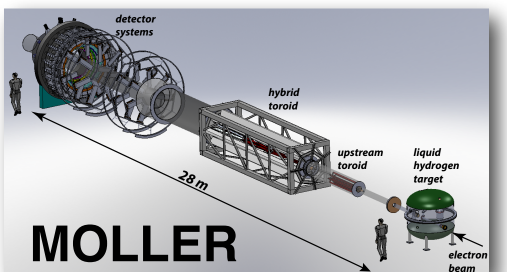

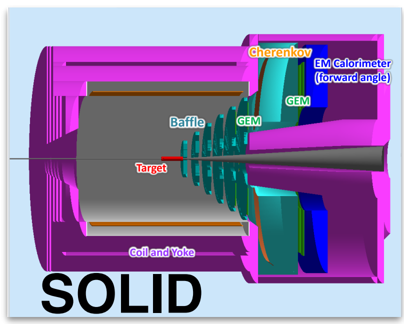

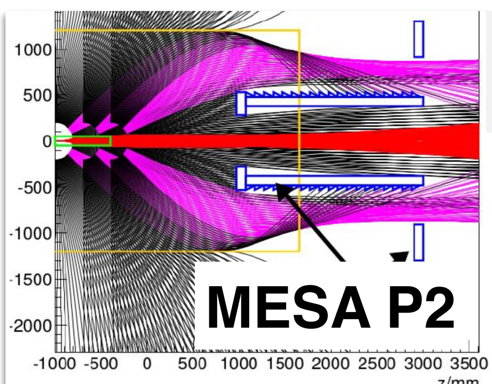

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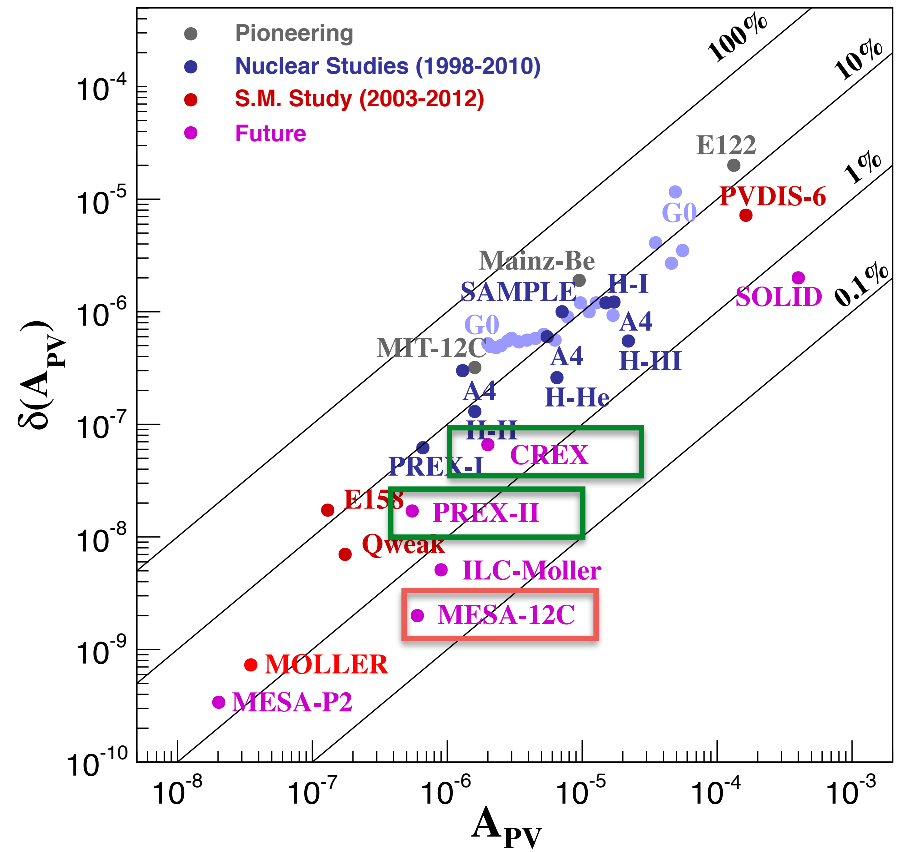

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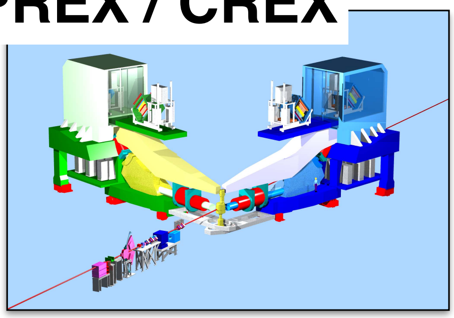

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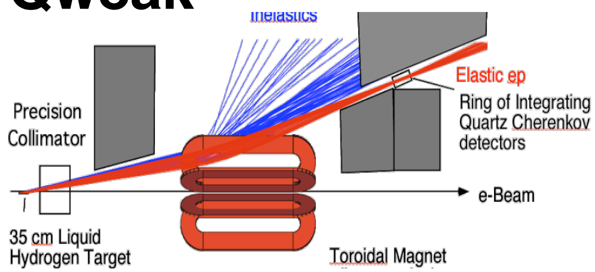

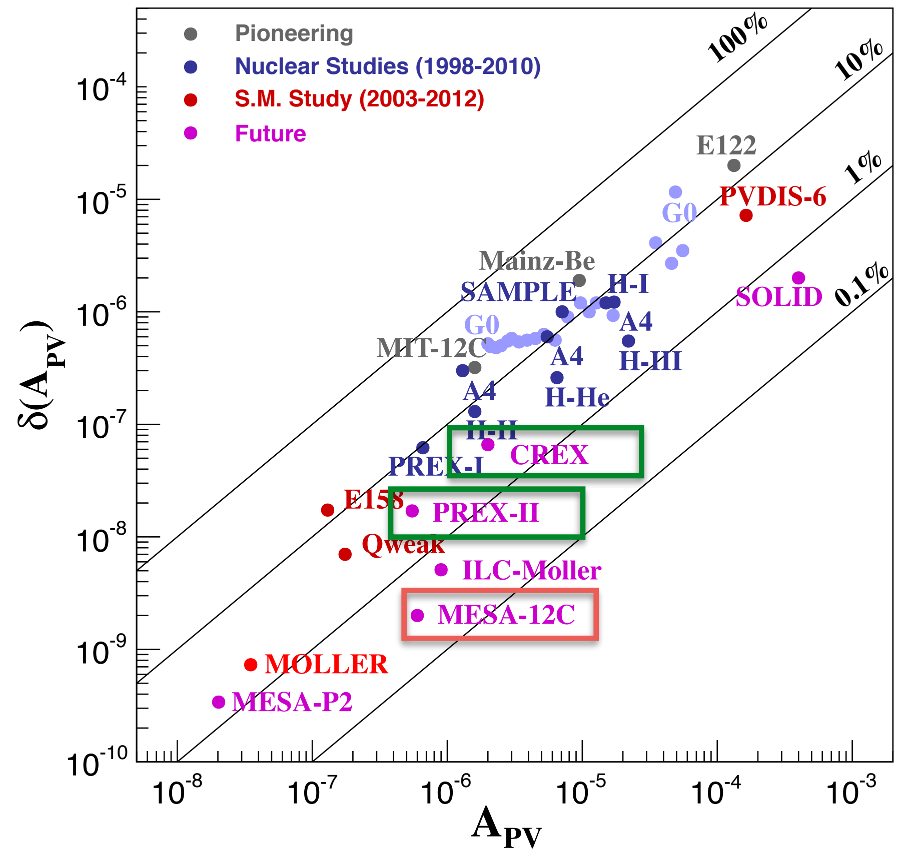

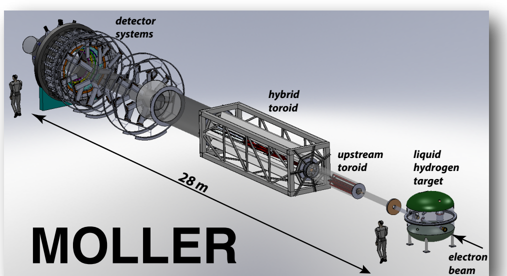

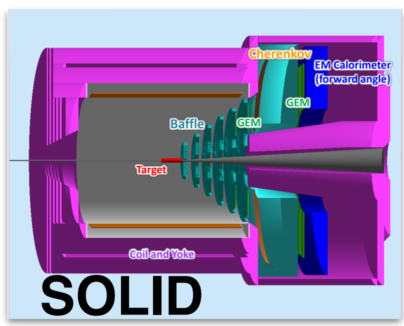

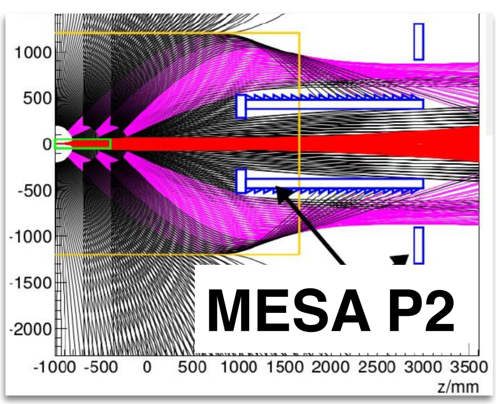

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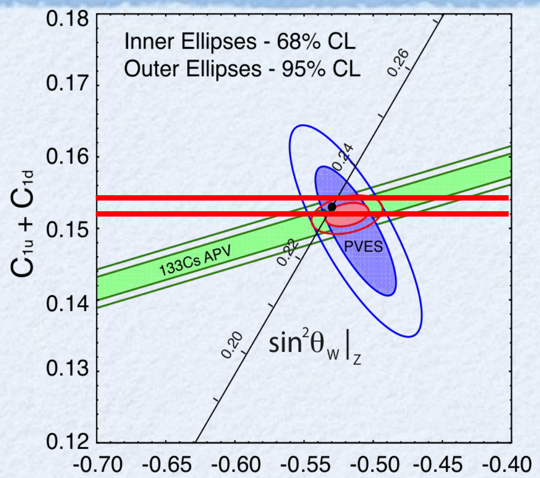
MESA: E_b = 150 MeV

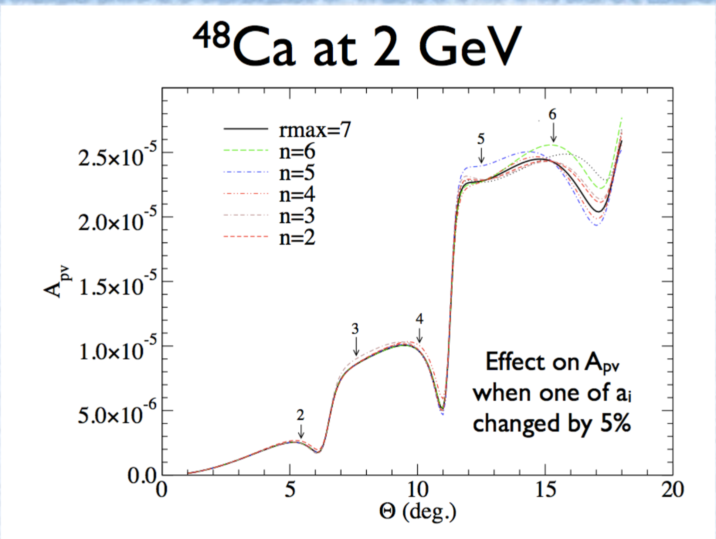
I = 150 μA

Potential of New Machine



$$A_{PV} = \frac{G_F Q^2}{\sqrt{2\pi\alpha}} \sin^2\theta_W$$

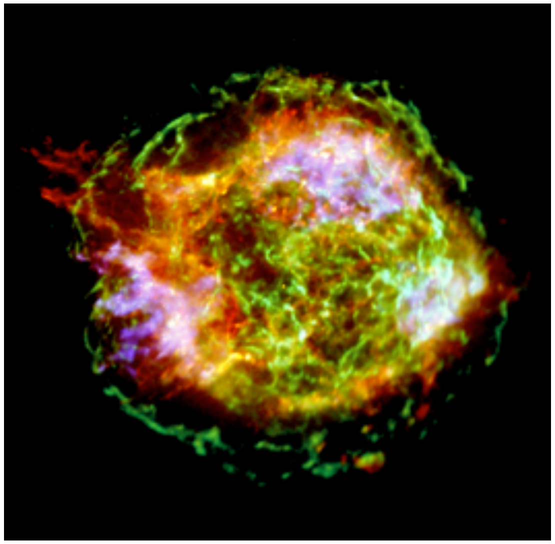
for spinless, isoscalar nucleus



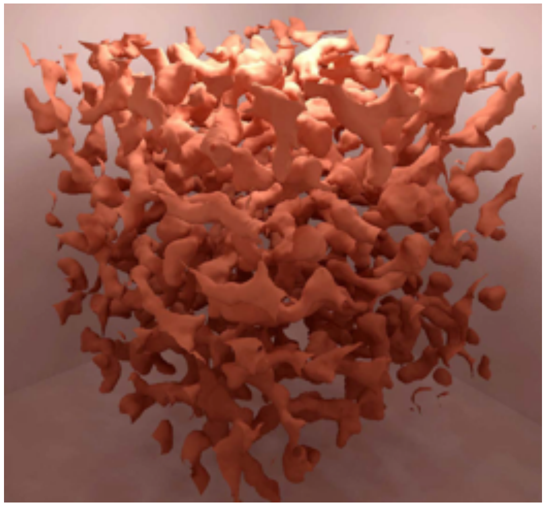
- **New measurements on Carbon-12**
  - ***A Standard Model test extremely interesting if 0.3% can be reached***
  - ***Must be coupled with higher Q^2 measurements to constrain strange quark radius (strange quark contribution to charge radius)***
- **New measurements on Calcium-48**
  - ***CREX will make a very precise low Q^2 measurement***
  - ***Higher Q^2 measurements will provide a complete and model-independent distribution of neutrons in the ground state***
- **Ideal requirements:**
  - ***several hundred microamps (polarized) with up to 500 MeV***
    - could do quite a bit with 286 MeV and 100 microamps

Neutron Rich Matter

- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?
- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor (T_c=10^{10} K!), superfluid, color superconductor...*

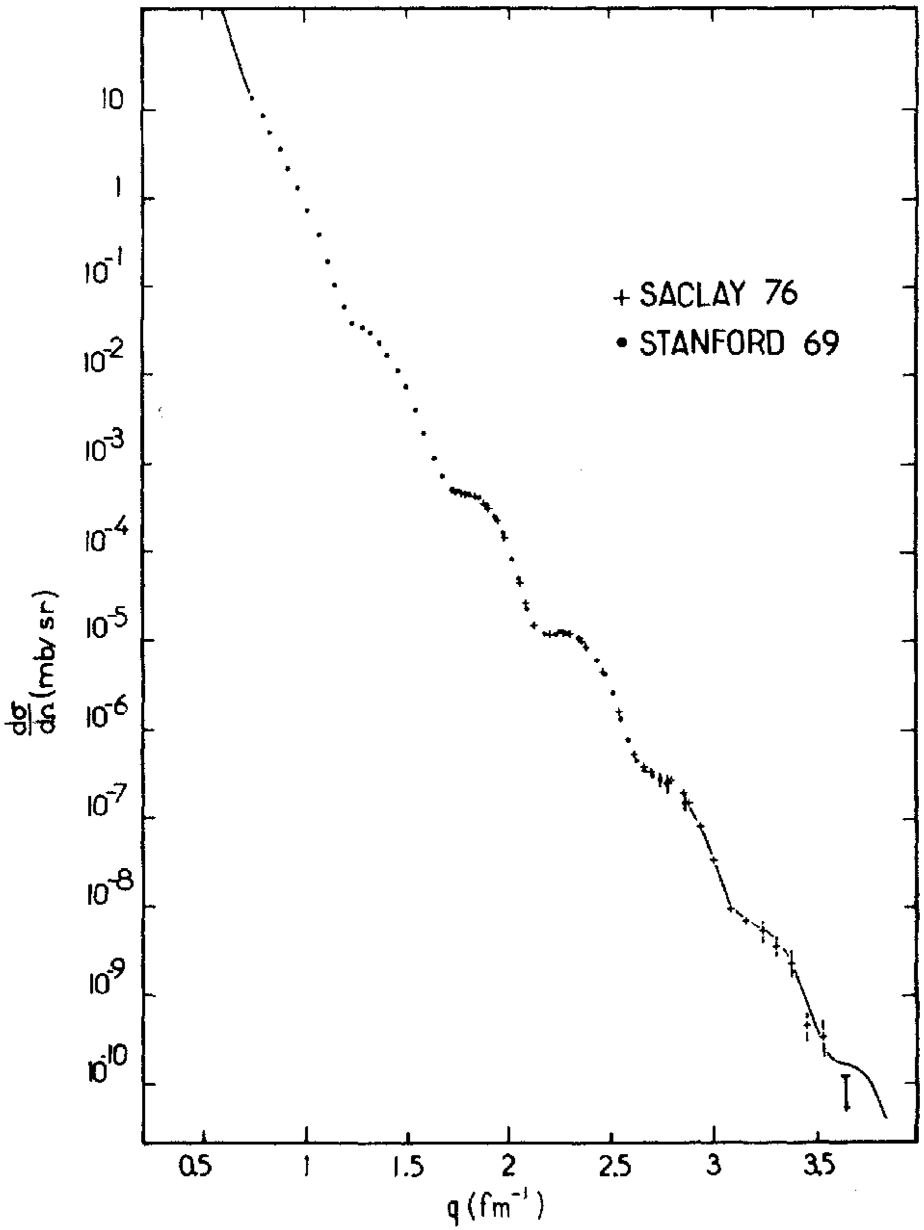


Supernova remanent Cassiopea A in X-rays

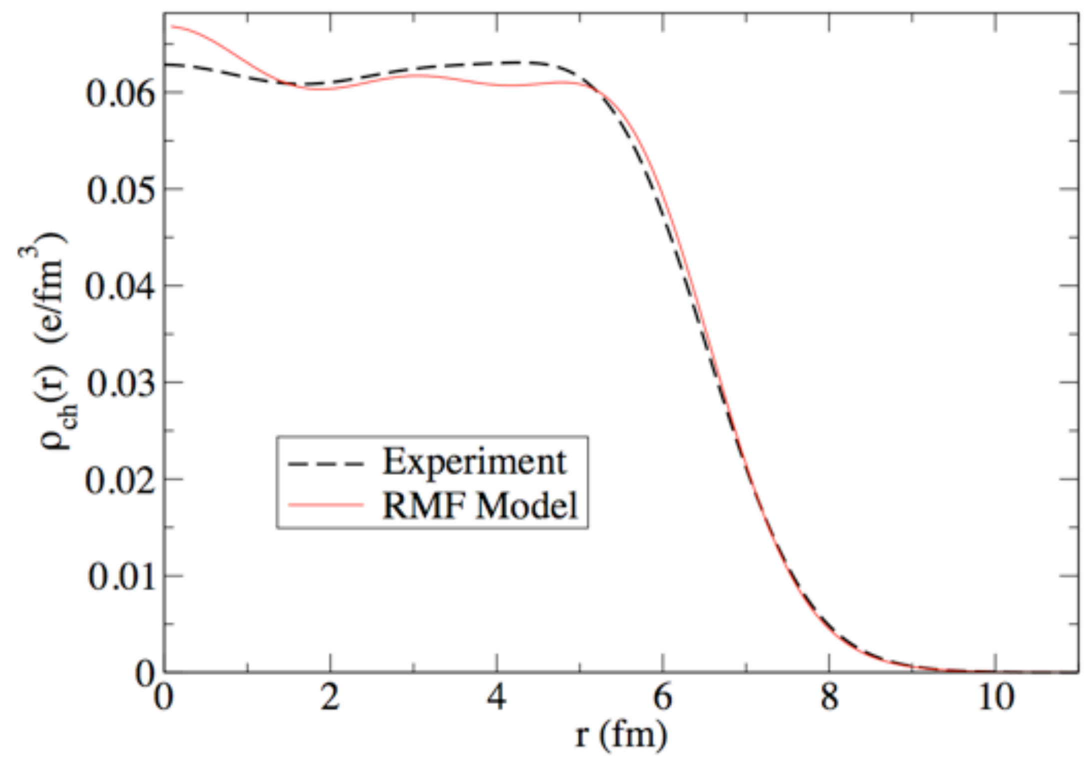


MD simulation of Nuclear Pasta with 100,000 nucleons

C. Horowitz



Charge Density of ^{208}Pb, accurately measured in elastic electron scattering.

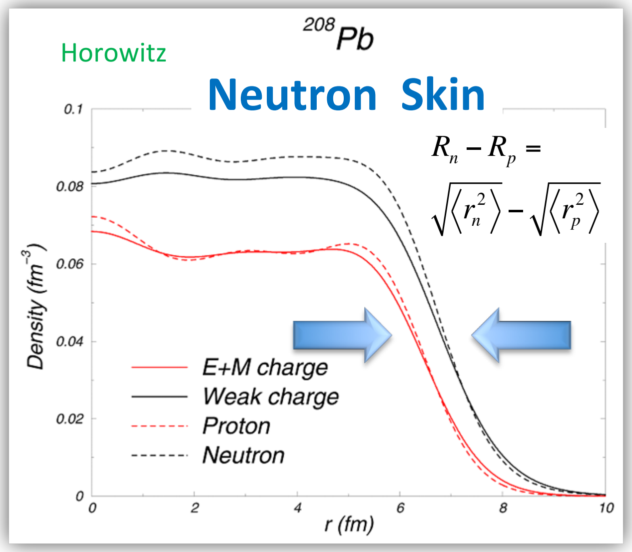


Cross section measured over 12 orders of magnitude.

These elastic charge densities ***are*** our picture of the atomic nucleus!

C. Horowitz

Neutron Skin of Heavy Nuclei

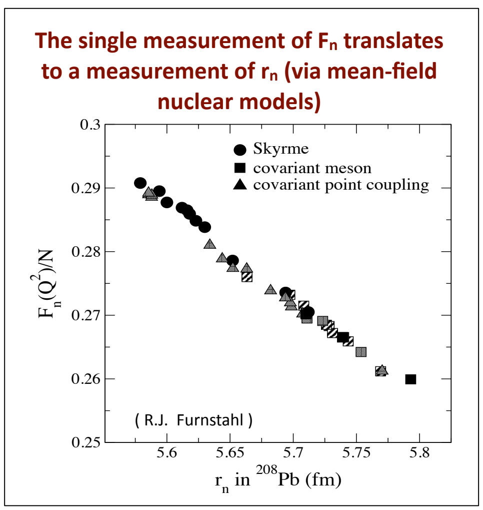


Nuclear theory predicts a neutron "skin" in heavy nuclei

Neutron distribution is not sensitive to the charge-sensitive photon

➔ access through weak charge distribution

	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**



For spin 0 nucleus:

$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\frac{F_n(Q^2)}{F_p(Q^2)} \right] \quad F_{n,p}(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_{n,p}(r)$$

- Measurement of R_n in ^{208}Pb calibrates the equation of state in neutron rich nuclear matter (determines density dependence of symmetry energy)
- Applications to neutron stars, heavy ion physics, atomic parity violation

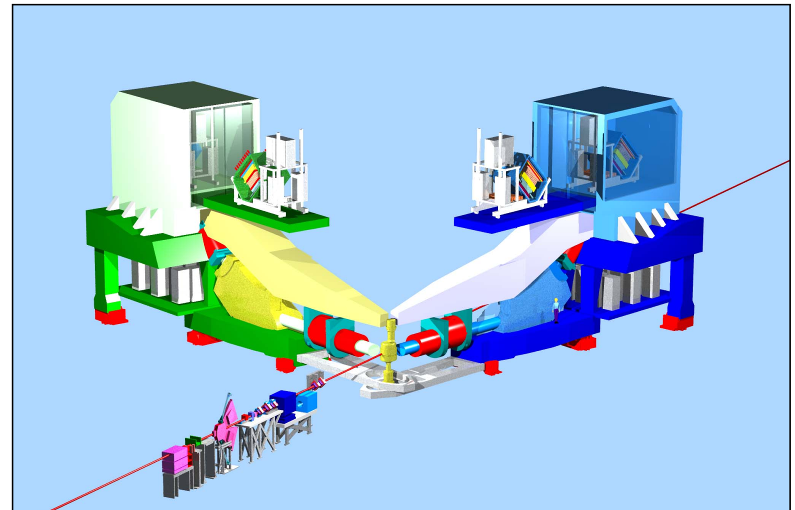
M. Pitt

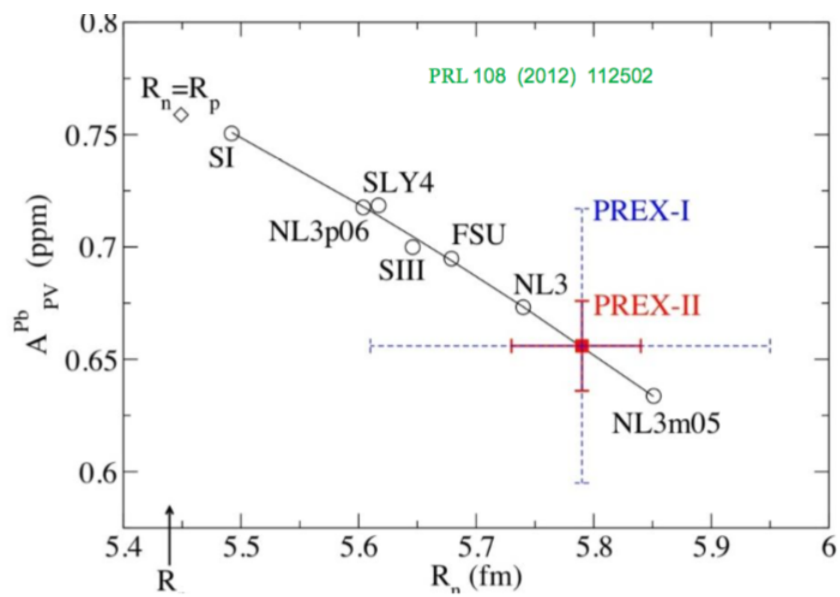
PREX/CREX

Q^2 ~ 0.01 GeV^2
5º scattering angle
⇨
A_{PV} ~ 0.6 ppm
Rate ~1.5 GHz

PREX-I (2012):
A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sys) ppm
$r_n - r_p$ = $0.33^{+0.16}_{-0.18}$ fm

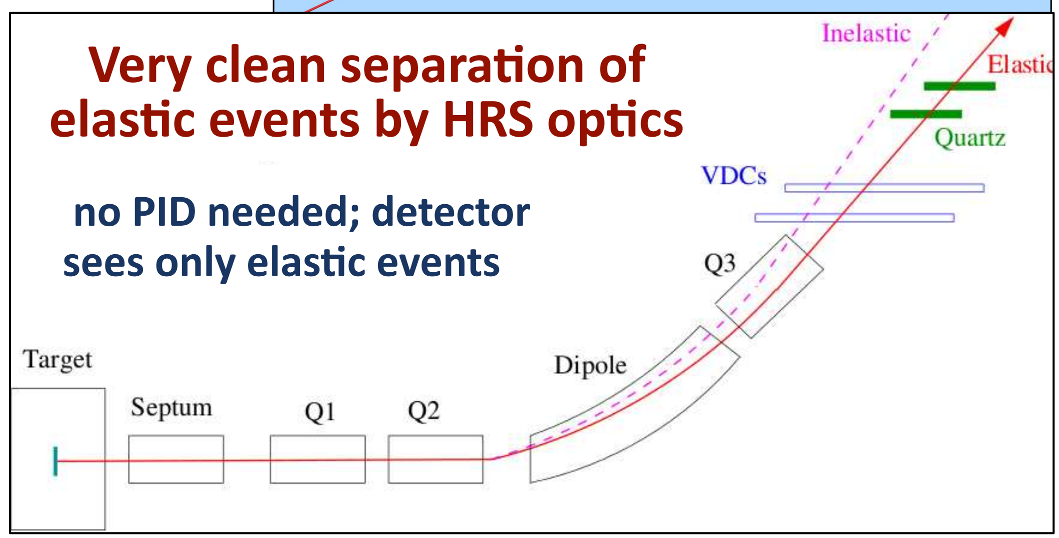
- **0.5 mm ^{208}Pb foil, 70 µA**
- **5º scattering**
- **P_b~ 90% +/- 1%**





Very clean separation of elastic events by HRS optics

no PID needed; detector sees only elastic events

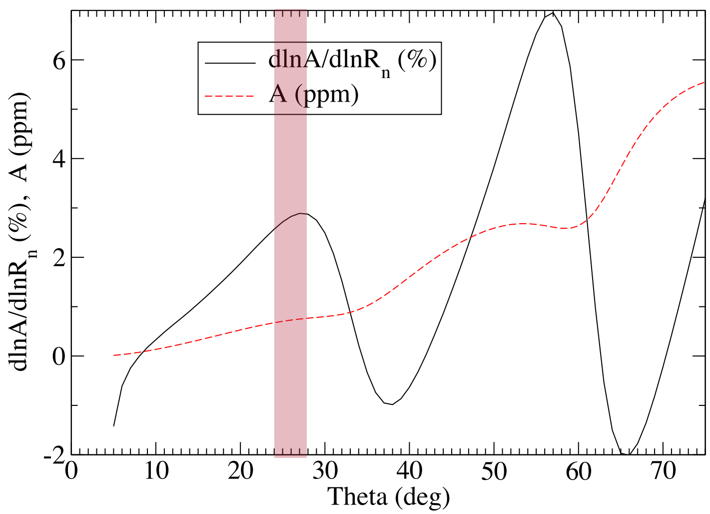


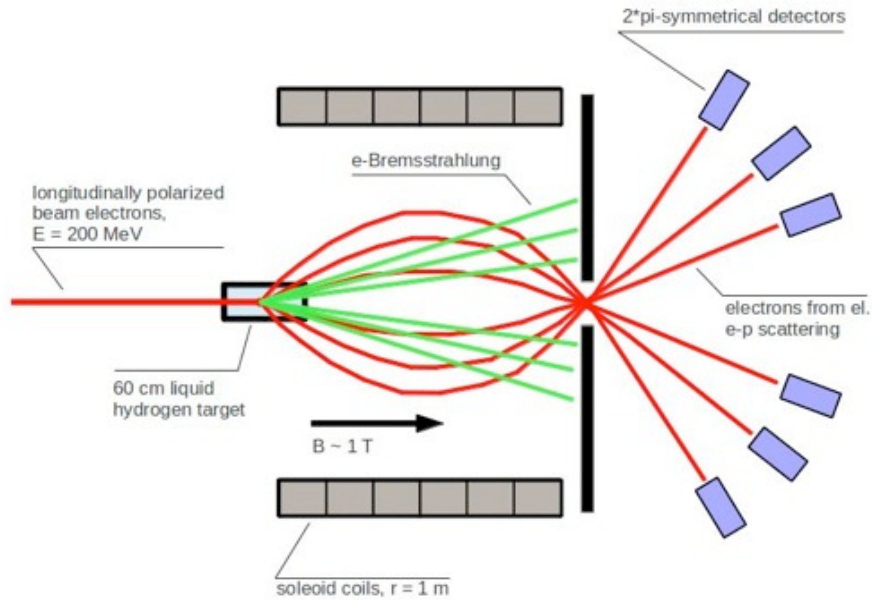
Summer 2017: PREX (3% A_{PV}, r_n to 0.06 fm), CREX (2.5% A_{PV}, r_n to 0.02 fm)

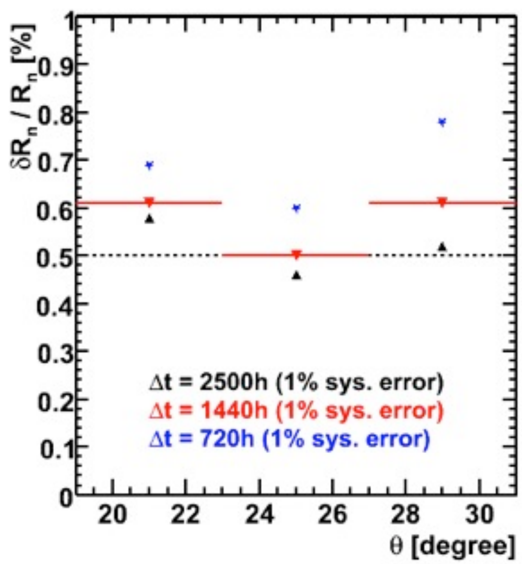
Opportunities: “Super PREX”

N_{Skin} measurement@MESA

Sensitivity *(C. Horowitz)*







Same PREX Luminosity (0.25mm ^{208}Pb)

$\Delta\theta=4^o$: Rate=9.75 GHz, $A_{PV}=0.68\times10^{-6}$

1440h ➜ $\delta A_{PV}/A_{PV}$ = 6.52 $\times10^{-3}$

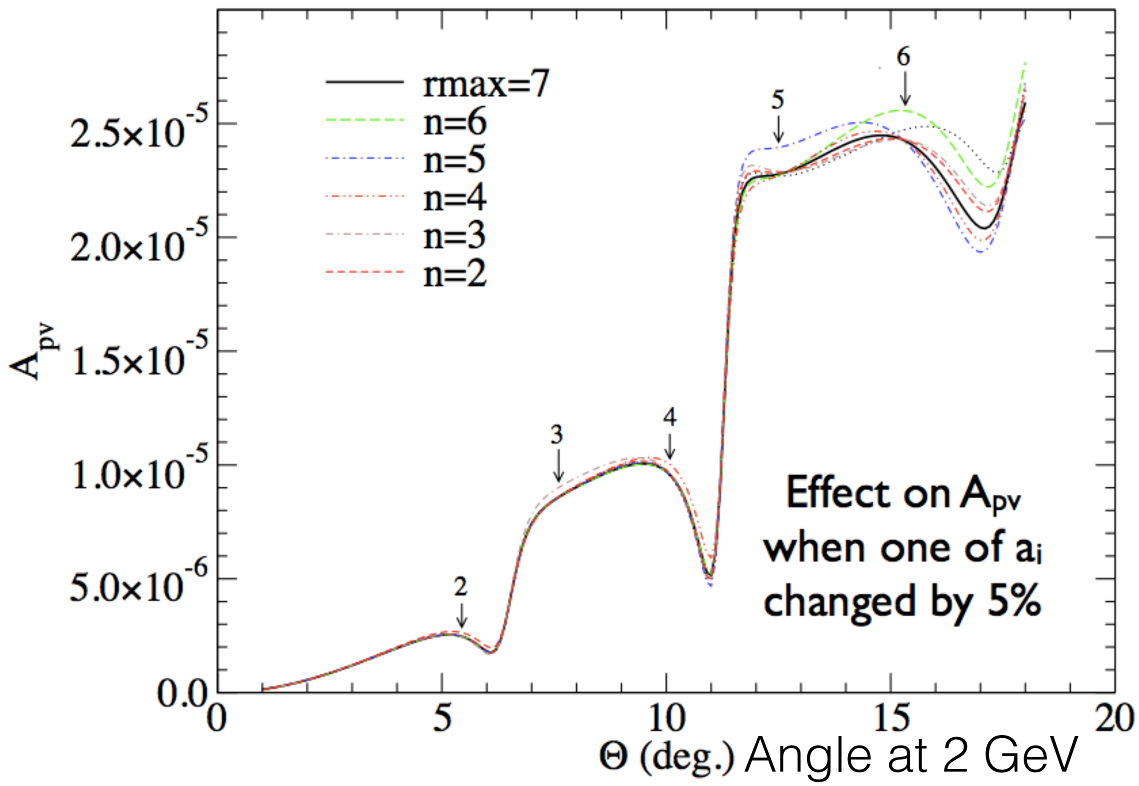
➜ $\delta R_n/R_n$ = 5.04 $\times10^{-3}$

(stat + syst 1%)

C. Sfienti, PAVI-14

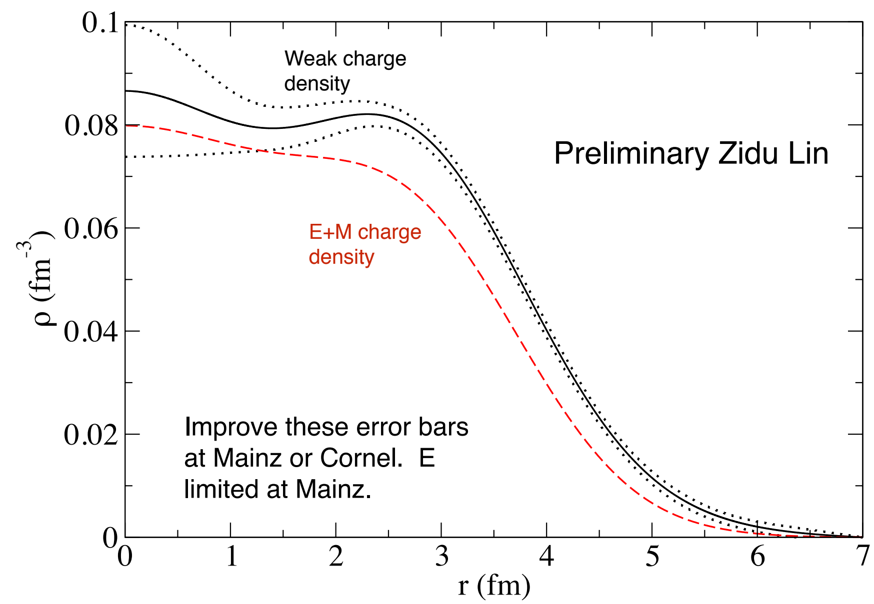
Opportunities

Map neutron distribution of ^{48}Ca



Angle at 2 GeV

Example statistical error at JLAB: 60 days for all five q^2



C. Horowitz

arXiv: 1505.06358

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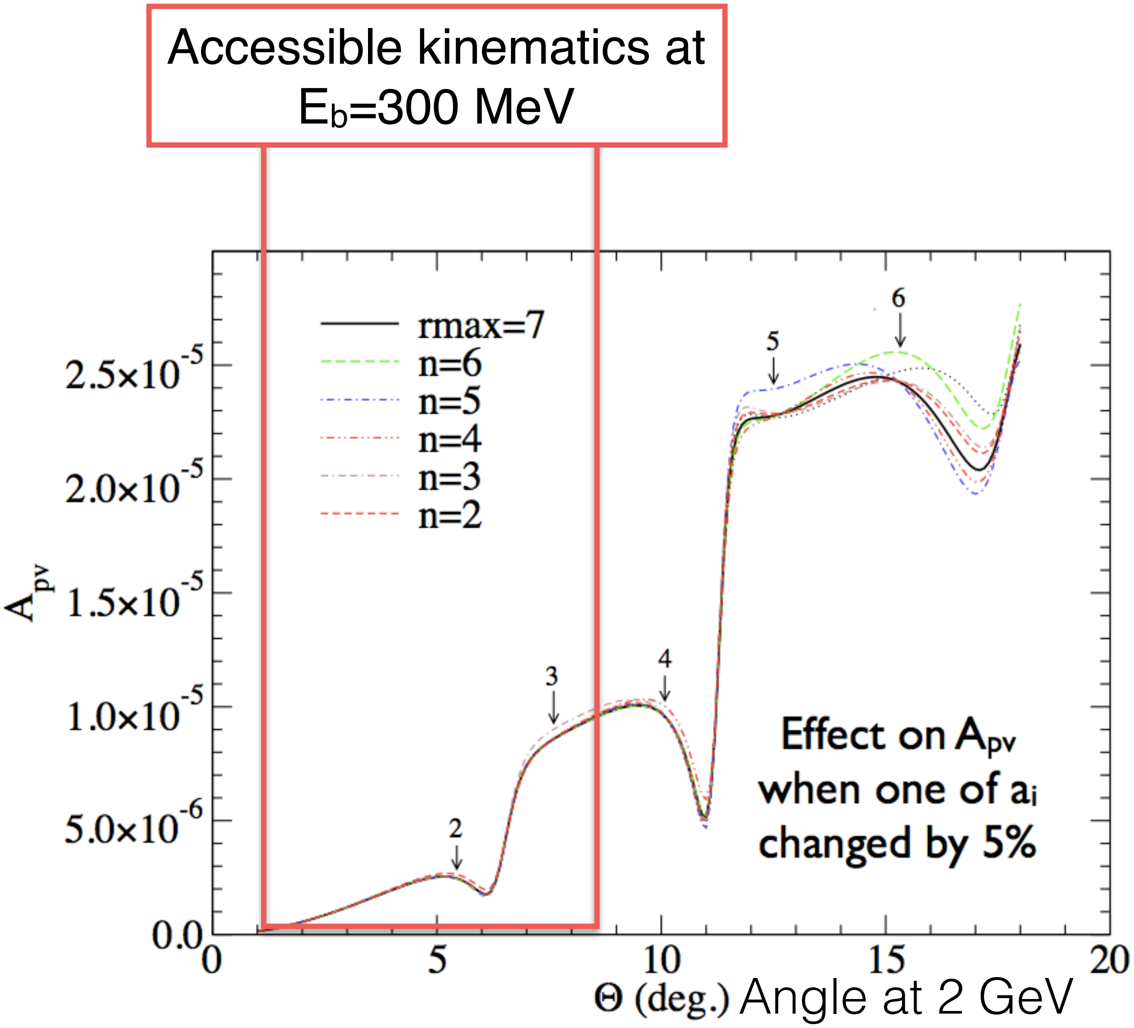

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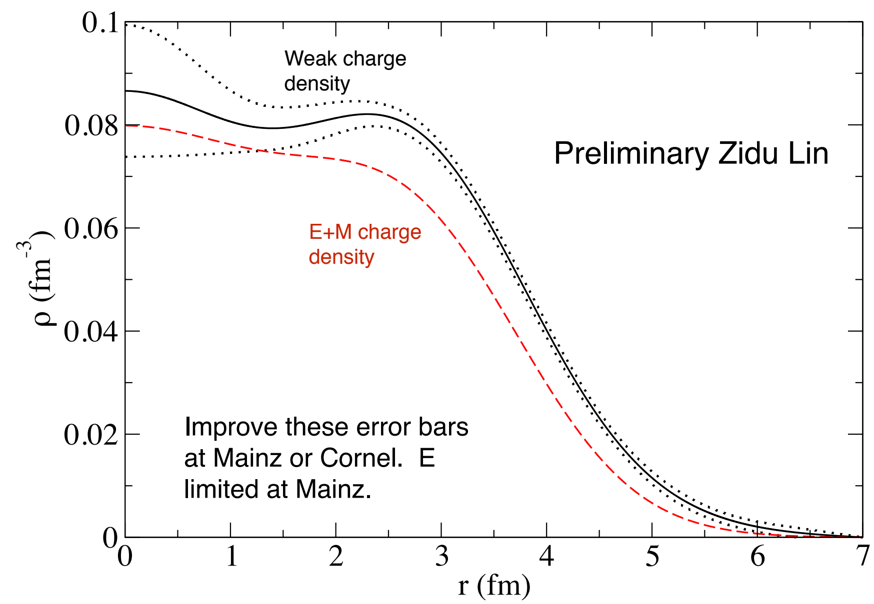

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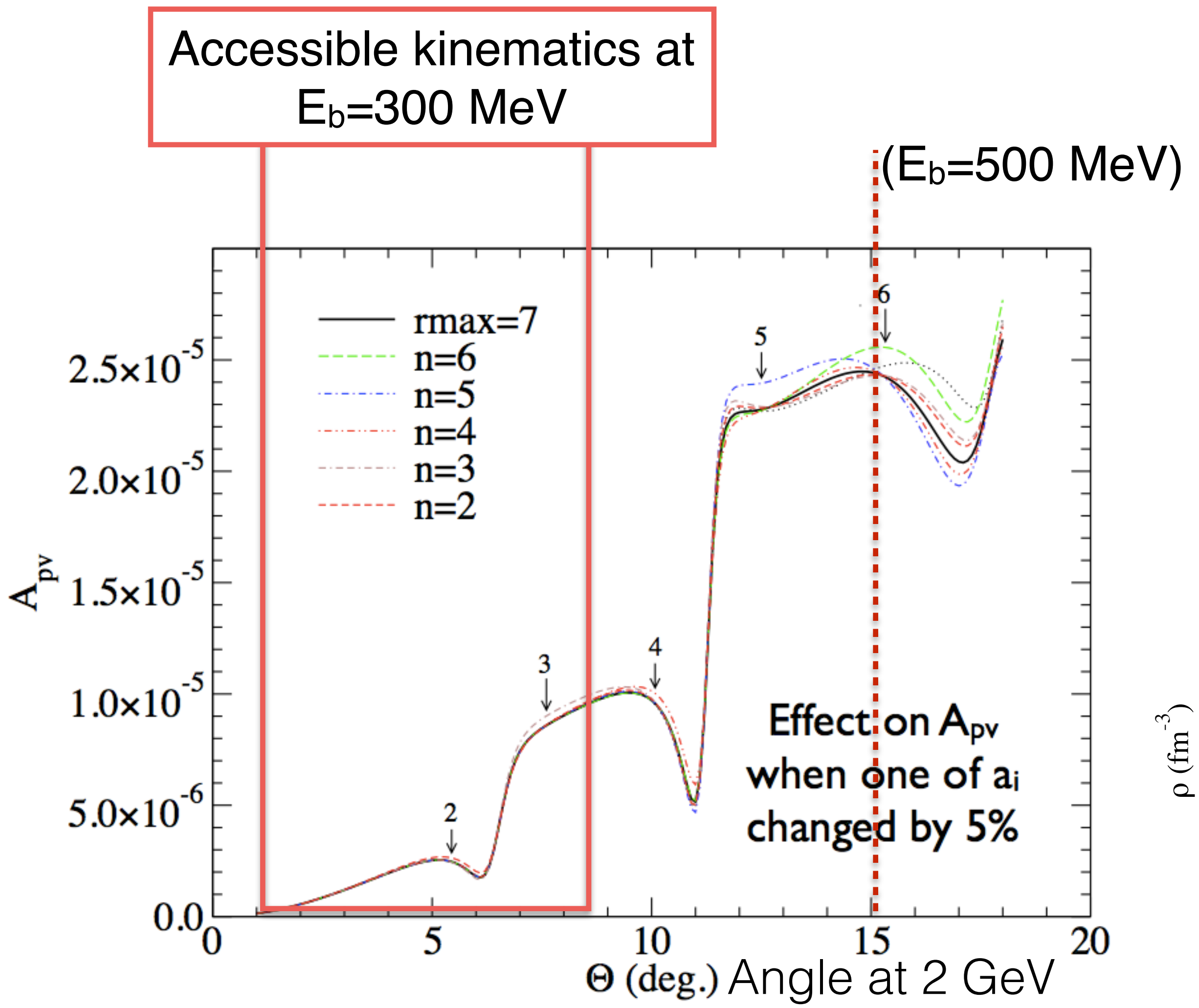

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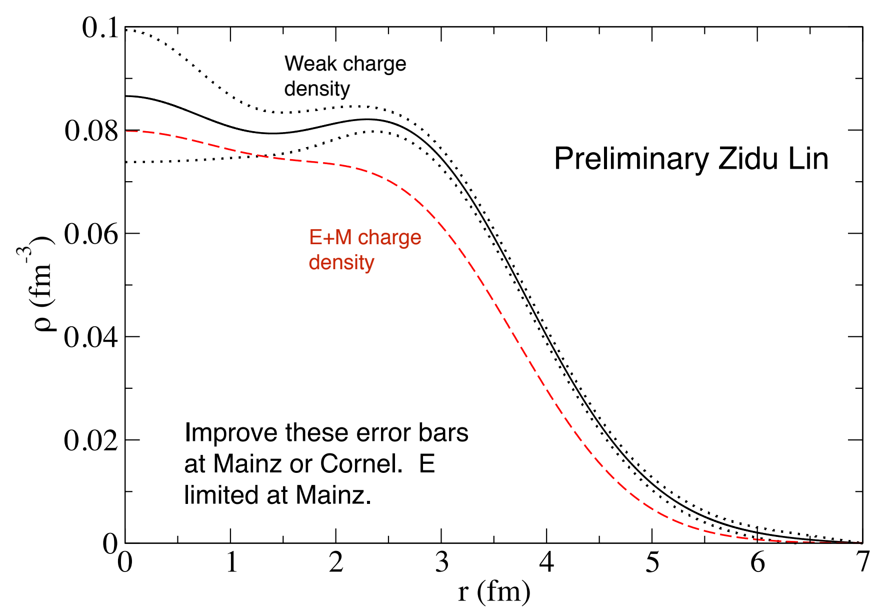

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Full ^{48}Ca weak charge density

- Would provide **text book picture of where neutrons and protons are in a nucleus**.
- Learn about shell oscillations of neutrons, saturation density of nuclear matter, neutron skin thickness, surface thickness of the neutrons…
- We expect central baryon density in ^{208}Pb to be approximately constant but we only know what the proton density is.
- Compare to new microscopic calculations of the neutron density in ^{48}Ca based on chiral effective field theory two and three nucleon interactions.

Summary: Neutron distributions

- Crucial calibration on nuclear structure models
- "Super PREX" (also ^{48}Ca, ^{128}Sn? ~1000 hr each)
- Optimize program of neutron distribution measurements (this is sometime MESA cannot do)

Precision Measurements To Date

- **Atomic Parity Violation**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering**
  - future measurements and theory challenging
- **PV Møller Scattering**
  - E158 at SLAC (total uncertainty 17 ppb)
    - *statistics limited, theory robust*

Technology developed to improve uncertainty by factor ~ 25

Precision Measurements To Date

- **Atomic Parity Violation**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering**
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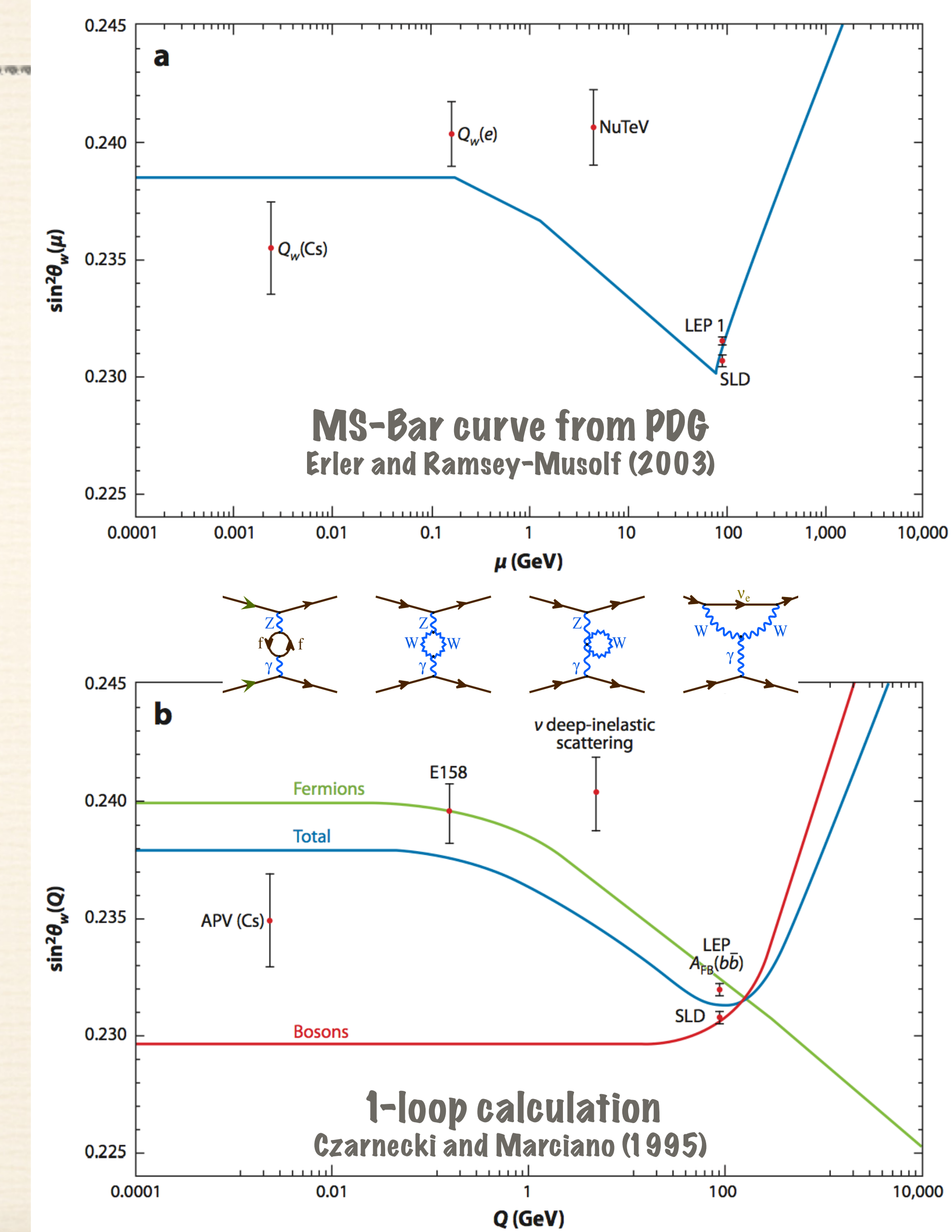
- **PV Møller Scattering**
  - E158 at SLAC (total uncertainty 17 ppb)
    - *statistics limited, theory robust*

Technology developed to improve uncertainty by factor ~ 25



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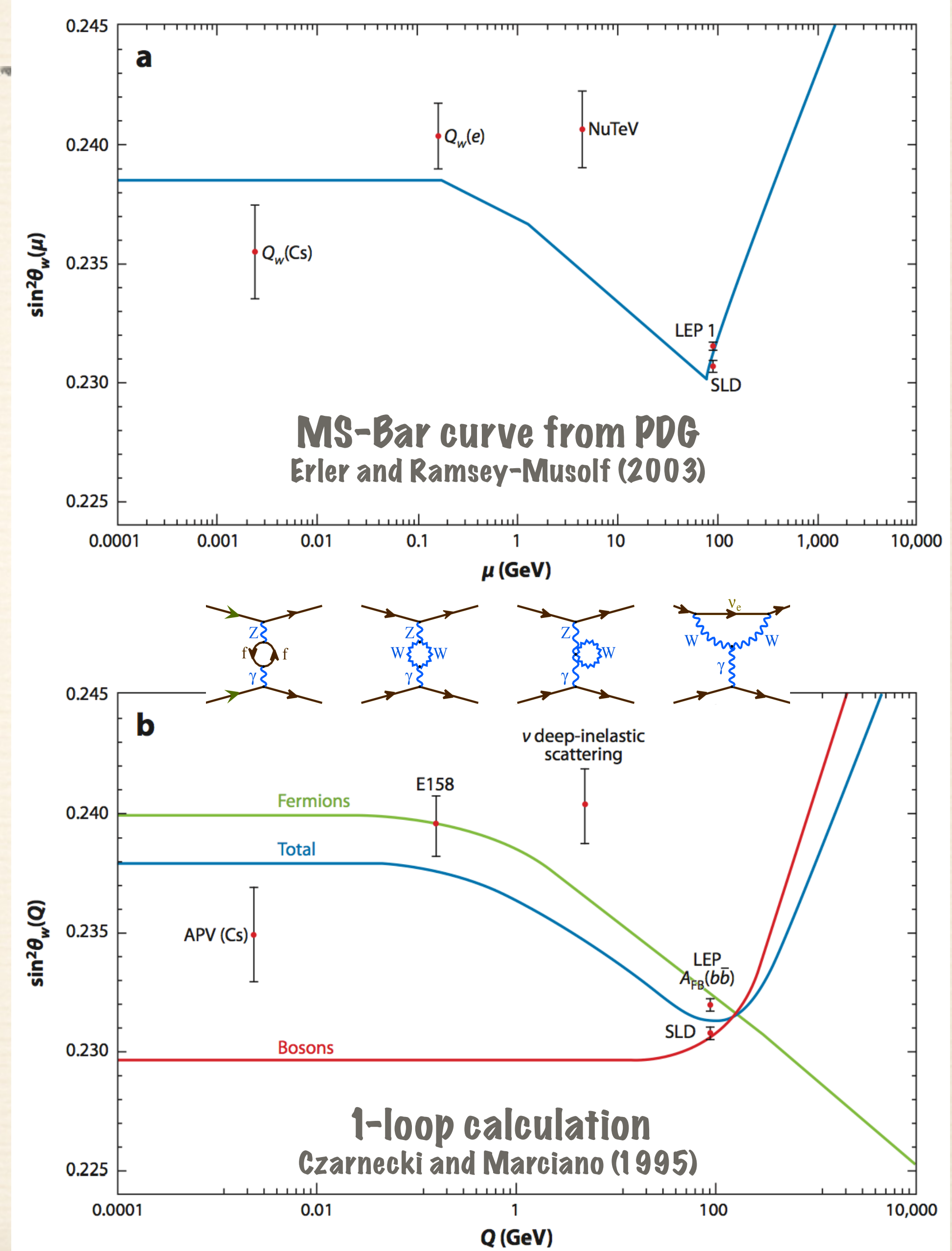
Recent Progress

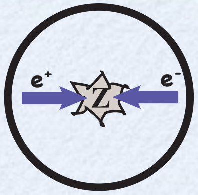
6 GeV PVDIS at JLab: first non-zero determination of axial-vector quark couplings

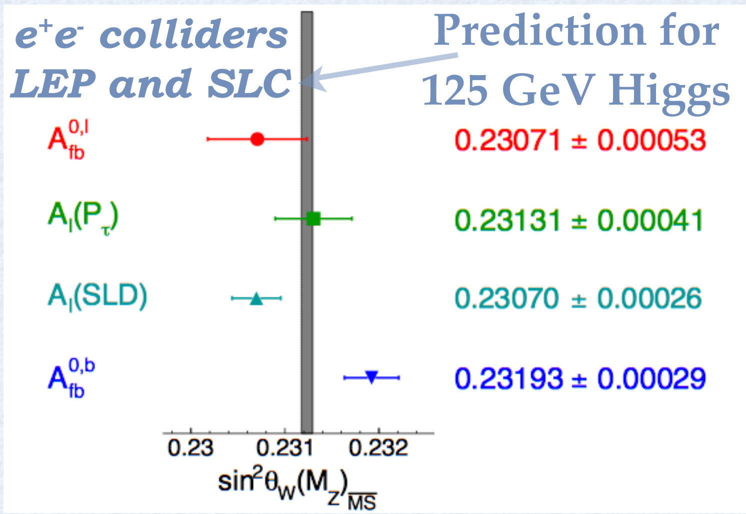
Qweak at JLab: should produce precision measurement soon

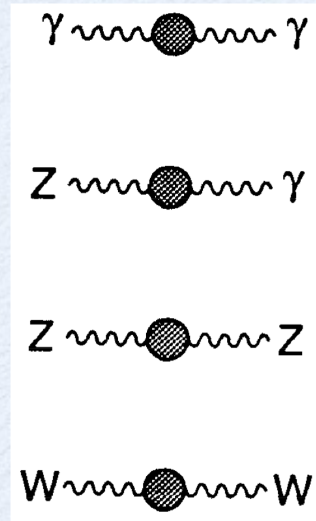


Measurements of $\sin^2\theta_W$

The most precise measurements are from LEP/SLC







S, T, U parameters

Stringent constraints on large classes of new physics models

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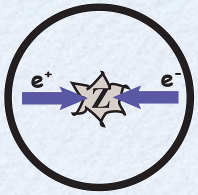

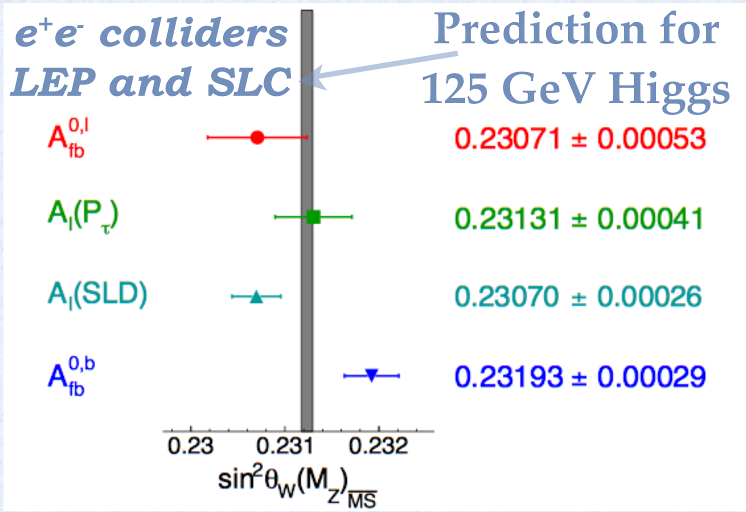

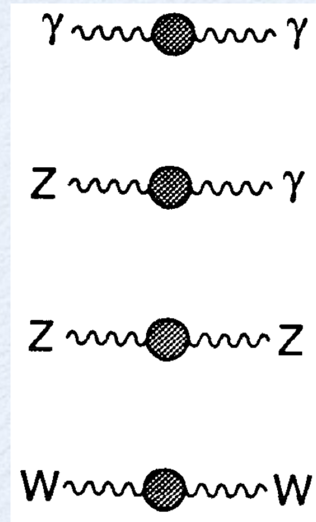

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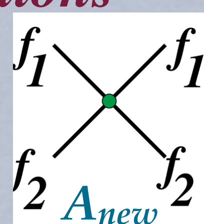
Stringent constraints on large classes of new physics models

Flavor Diagonal Contact Interactions

Consider $f_1\bar{f}_1 \rightarrow f_2\bar{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$



New heavy physics that does not couple directly to SM gauge bosons

Measurements of $\sin^2\theta_W$

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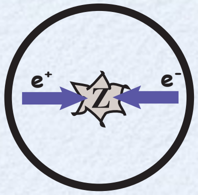

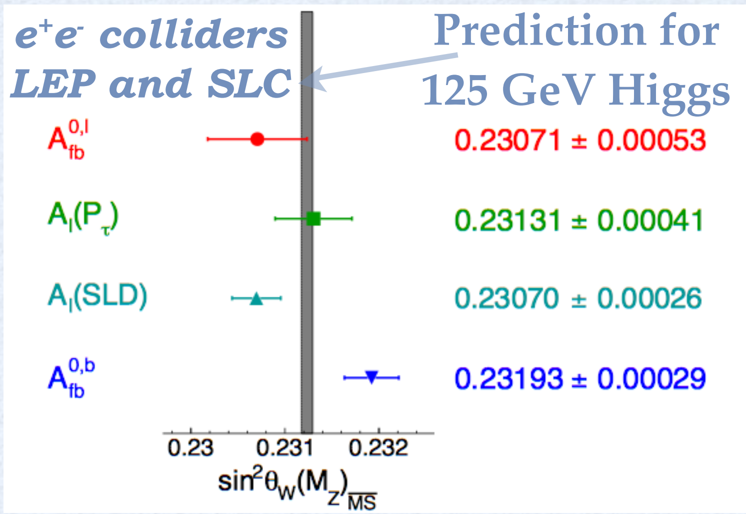

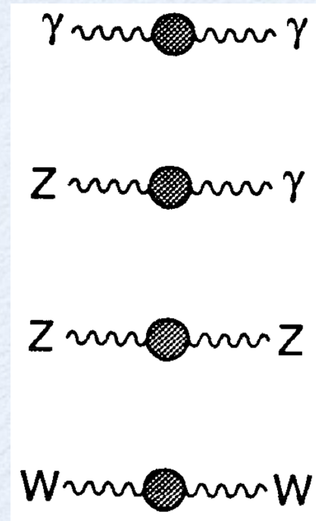

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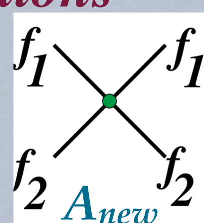

New heavy physics that does not couple directly to SM gauge bosons

on resonance: A_Z is imaginary

$$\left|A_Z + A_{new}\right|^2 \to A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

no interference!

Unique role for Low Energy Weak Neutral Current Measurements

Measurements of $\sin^2\theta_W$

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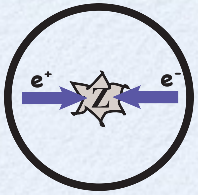

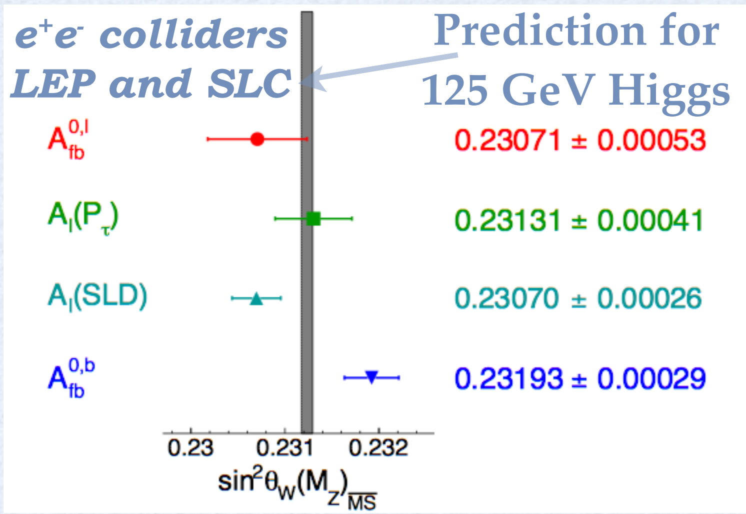

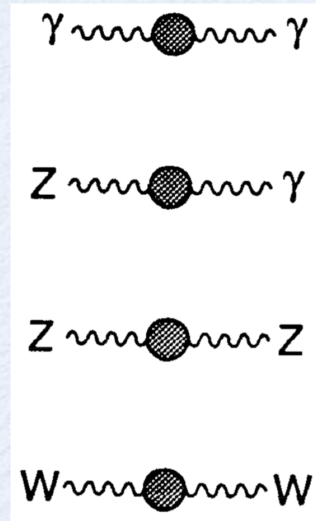

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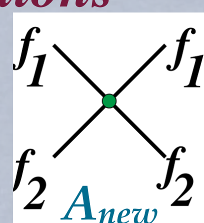

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on resonance: A_Z is imaginary

$$\left|A_Z + A_{new}\right|^2 \to A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

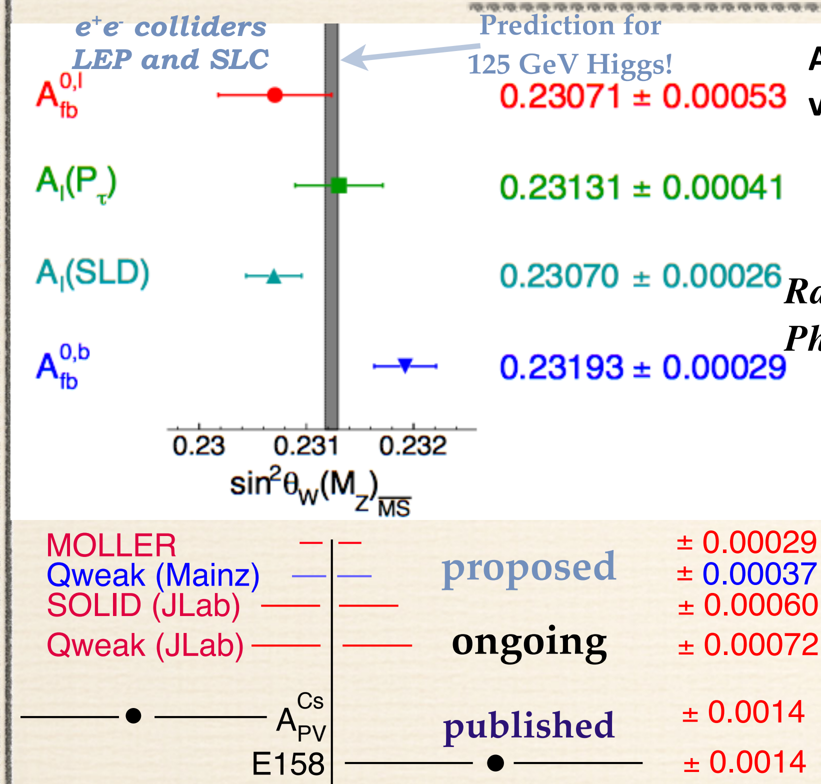
no interference!

New flavor diagonal interactions mediated by a new light boson such as the "dark Z"

$$Q^2 \ll M_Z{}^2$$

New Physics Complementarity

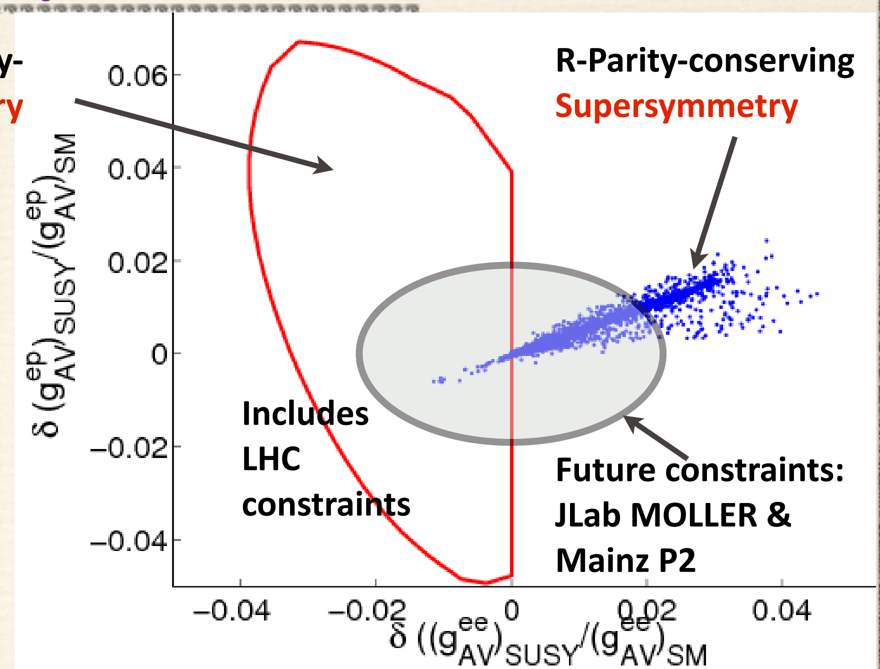
Z resonance measurements: little sensitivity to new contact interactions



Allowed region: R-Parity-violating Supersymmetry

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

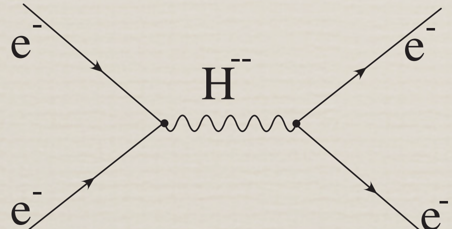
Erler and Su, arXiv:1303.5522



Lepton Number Violation

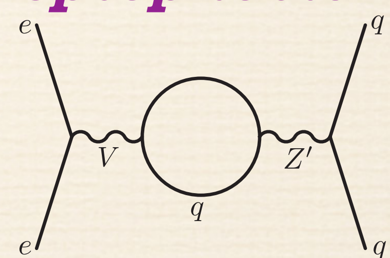
Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

Leptophobic Z'



SOLID can improve sensitivity: 100-200 GeV range

Dark Z and Parity Violation

- Low Q^2 ($< m_{Z_d}^2$) parity violation from $Z - Z_d$ mixing

- Z_d effects can be parameterized by HD, Lee, Marciano, 2012

$$G_F \to \rho_d G_F \quad \text{and} \quad \sin^2\theta_W \to \kappa_d \sin^2\theta_W$$

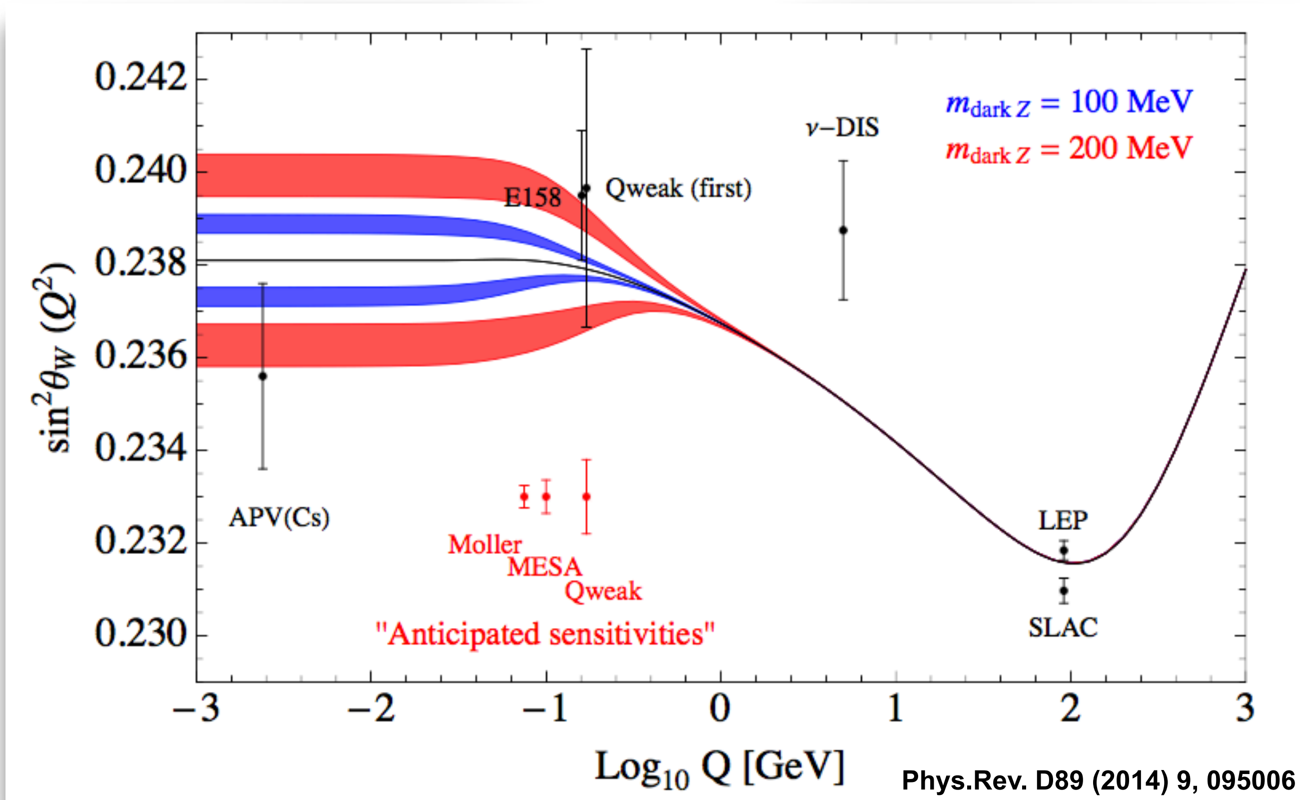
with $\rho_d = 1 + \delta^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$ and $\kappa_d = 1 - \varepsilon \frac{m_Z}{m_{Z_d}} \delta \frac{\cos\theta_W}{\sin\theta_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$

- Leads to variation of $\sin^2\theta_W$ with Q^2:

$$\boxed{\Delta \sin^2\theta_W(Q^2) = -\varepsilon\delta \frac{m_Z}{m_{Z_d}} \sin\theta_W \cos\theta_W f\left(Q^2/m_{Z_d}^2\right)}$$

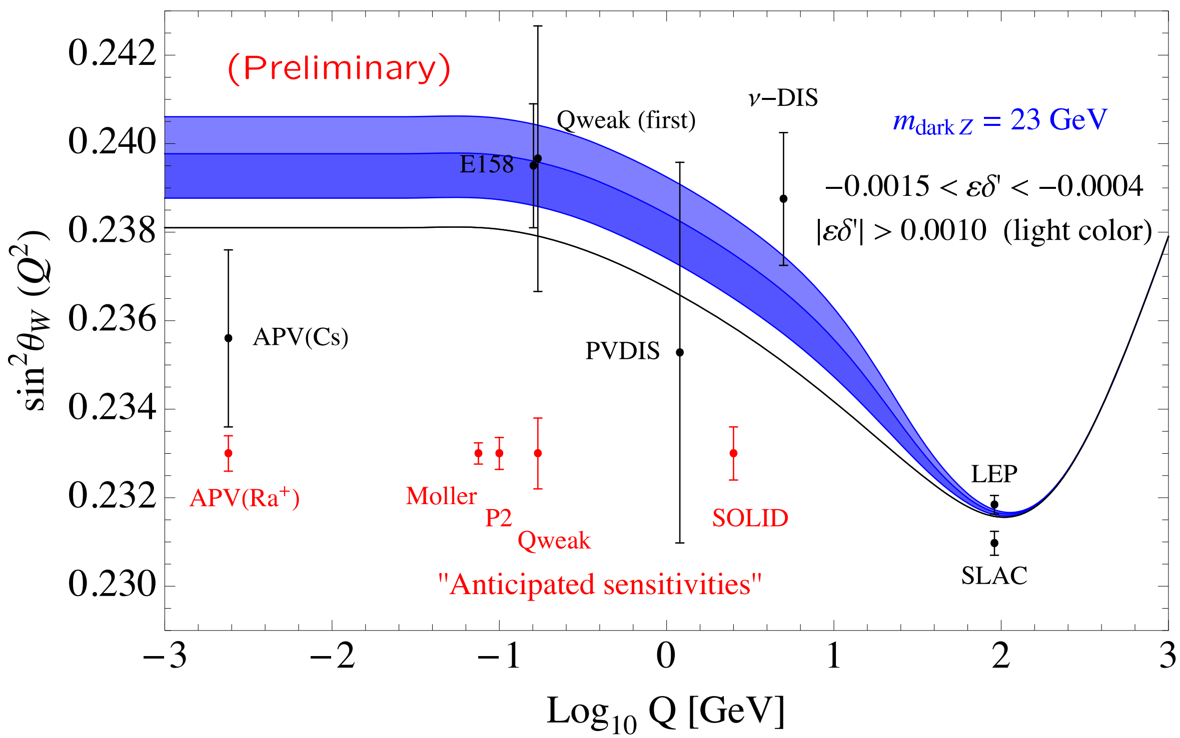
$f\left(Q^2/m_{Z_d}^2\right) = 1/(1 + Q^2/m_{Z_d}^2)$

Complementary “dark” U(1) search, not dependent on decay or production modes



light Z_d Q^2 dependent shift

HD, Lee, Marciano, work in progress



- $\varepsilon\delta' < 0$ range corresponds to 1 σ band for $\sin^2\theta_W$ deviation
- The upper region of the band: tension with constraints
- Interesting implications for planned experiments at different Q^2
- Near future: Q_{weak} results can shed further light on this scenario

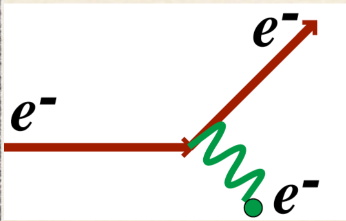
H. Davoudiasl

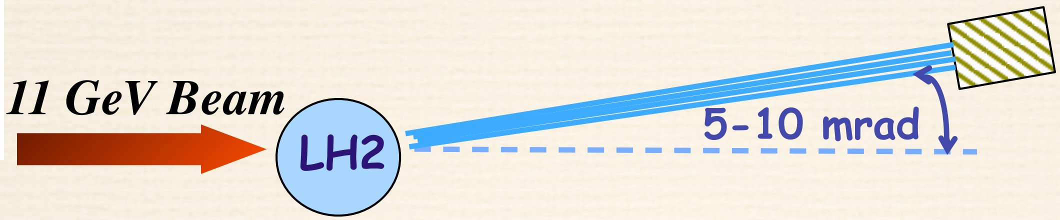
An ultra-precise measurement of the weak mixing angle using Møller scattering

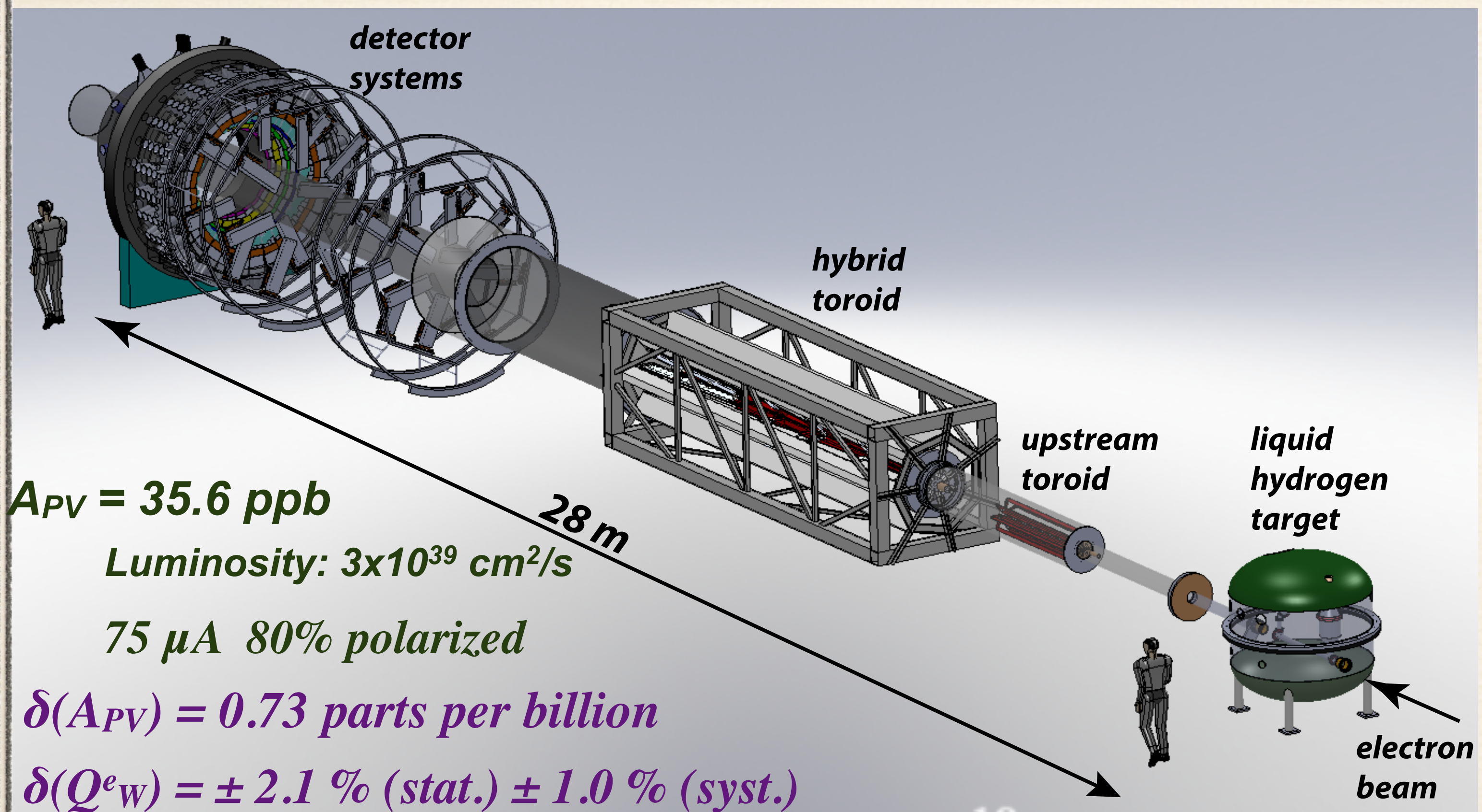
11 GeV Møller scattering

MOLLER at JLab

Measurement Of Lepton Lepton Electroweak Reaction







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.) ± 1.0 % (syst.)

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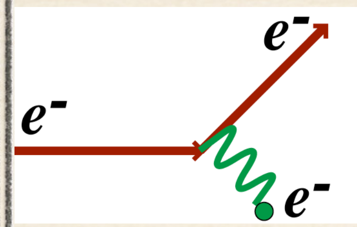
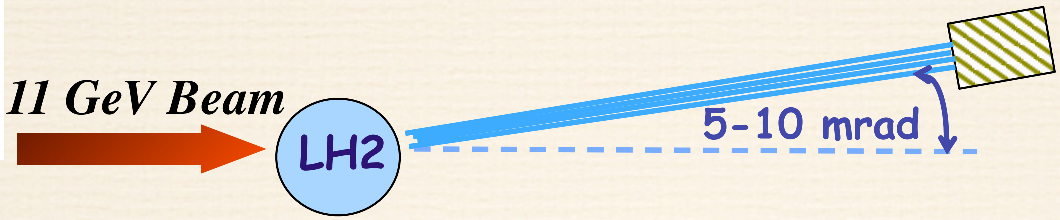
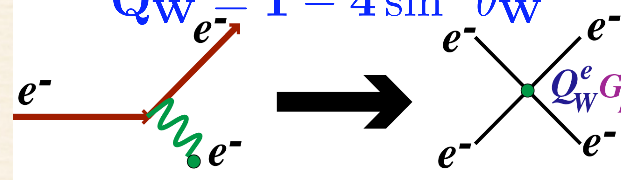
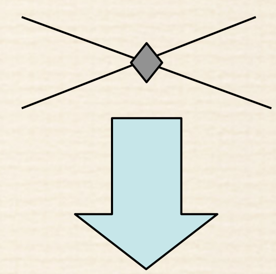




$Q_W^e = 1 - 4\sin^2\theta_W$

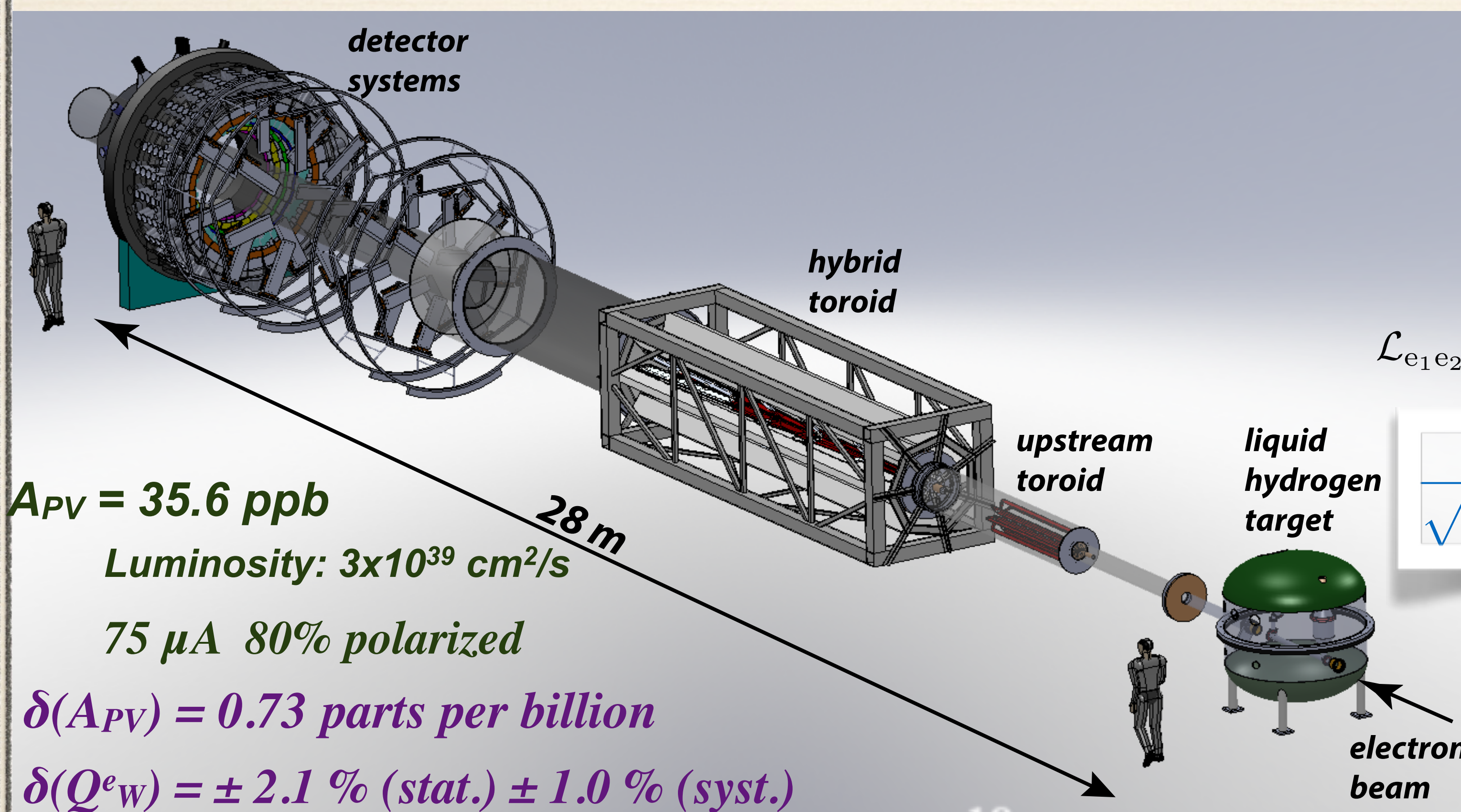




$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \mathrm{TeV}$$



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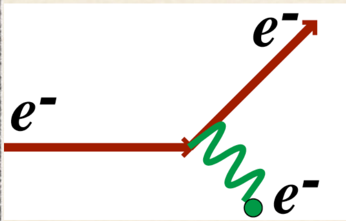


11 GeV Beam

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

Matches best collider (Z-pole) measurements!

best contact interaction reach for leptons at low OR high energy

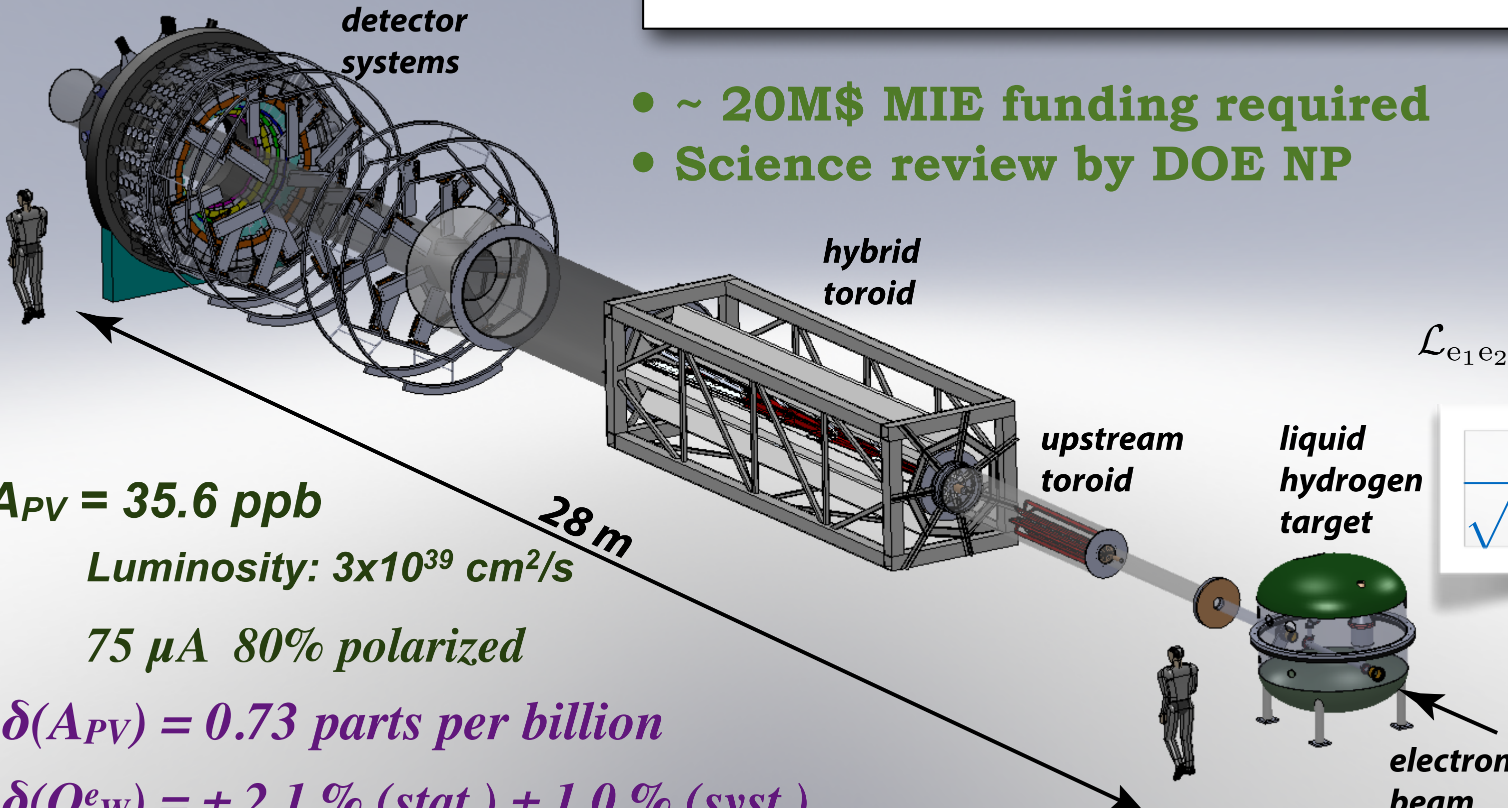
To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider, neutrino factory or muon collider

$$+ \; \frac{1}{\Lambda^2}\mathcal{L}_6$$

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \text{TeV}$$

- **~ 20M$ MIE funding required**
- **Science review by DOE NP**



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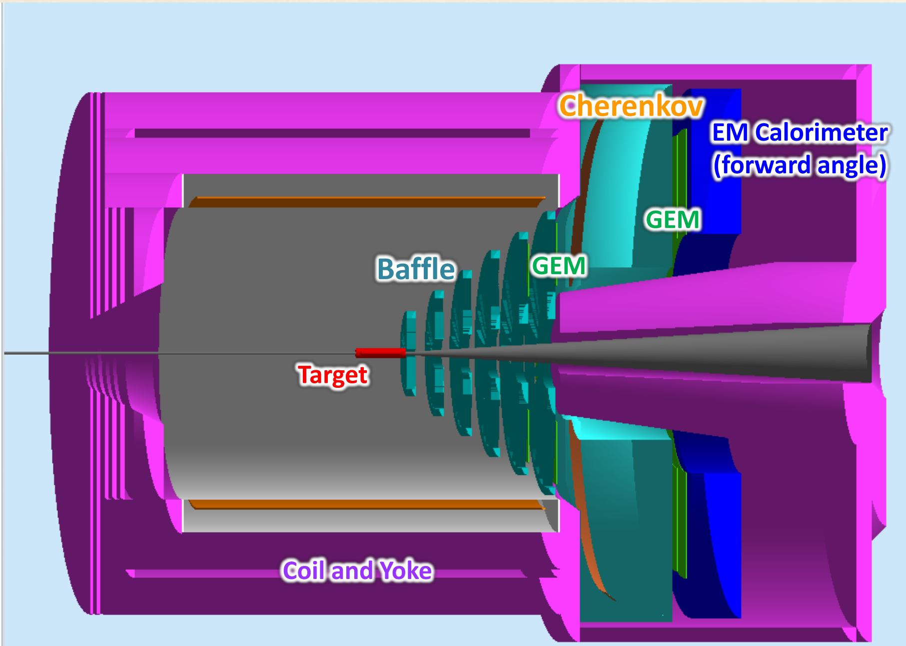
SOLID with the 12 GeV Upgrade



Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

Requirements

- *High Luminosity with E > 10 GeV*
- *Large scattering angles (for high x & y)*
- *Better than 1% errors for small bins*
- *x-range 0.25-0.75*
- *W^2 > 4 GeV^2*
- *Q^2 range a factor of 2 for each x*
  - (Except at very high x)
- *Moderate running times*

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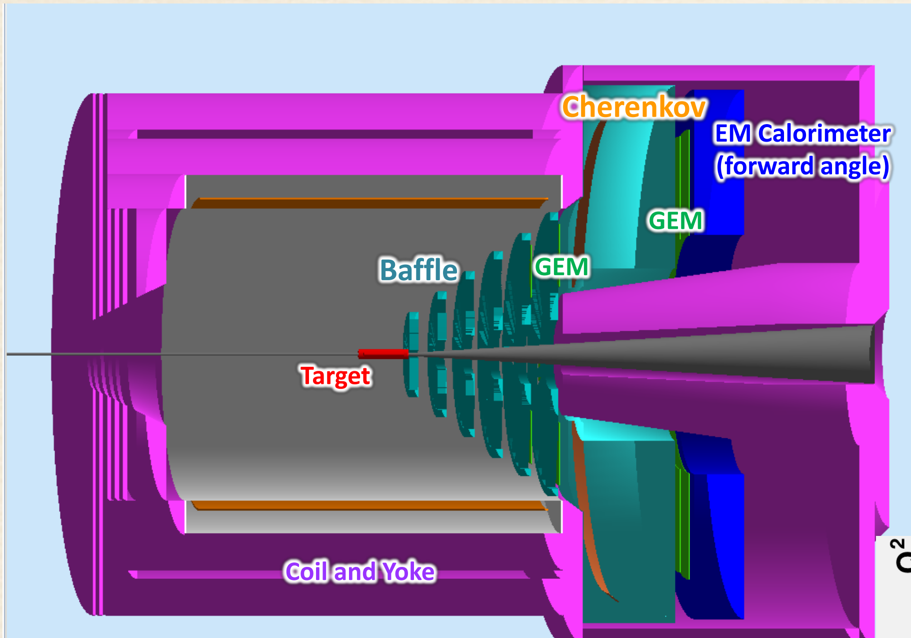

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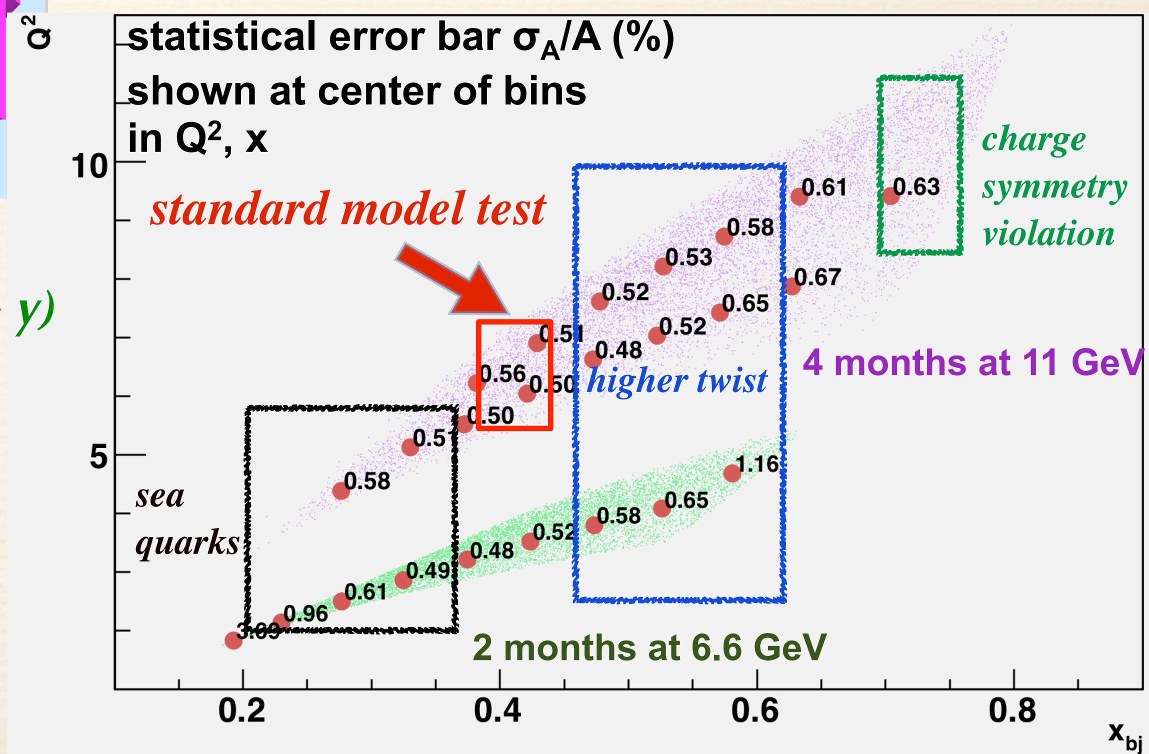


Krishna S. Kumar

JLab Qweak: First Measurement of Proton's Weak Charge

$$Q_W^p \equiv -2[2C_{1u} + C_{1d}] = (1 - 4\sin^2\theta_W)$$

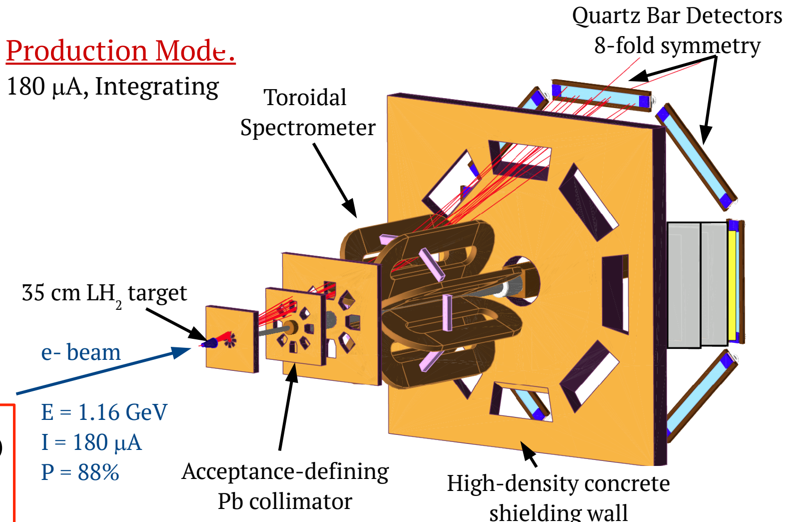
$$A \sim \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q_{weak}^p + Q^4 B(Q^2)\right]$$

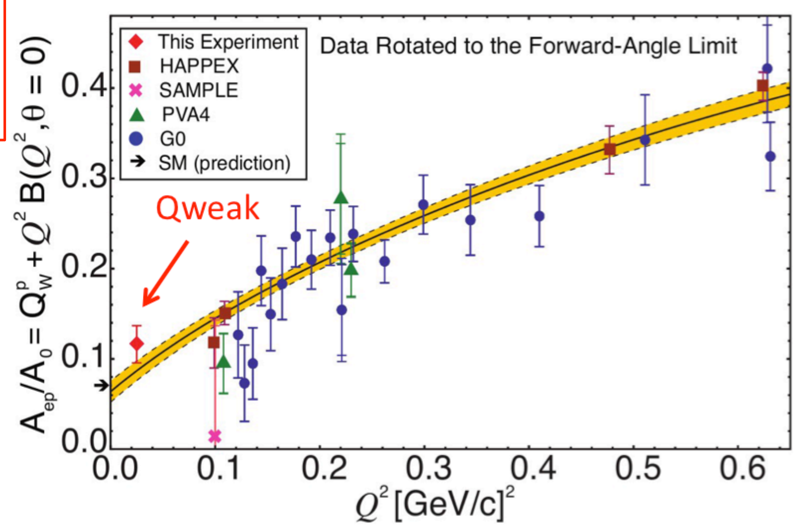
(1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb}$$

$$\langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$$

$$Q_W^p(\text{PVES}) = 0.064 \pm 0.012$$

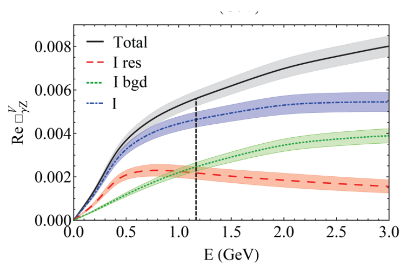


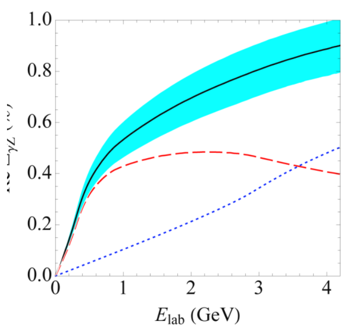


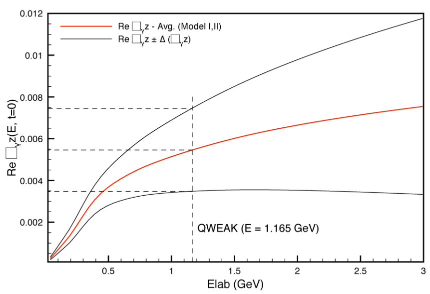
M.Pitt

Vector box plots today

Hall *et al.*	Carlson and Rislow	Gorchtein *et al.*
PRD 88, 013011 (2013)	PRD 83, 113007 (2011)	PRC 84, 015502 (2011)







$$\mathrm{Re}\Box^V_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$$(5.6 \pm 0.36) \times 10^{-3} \quad (5.7 \pm 0.9) \times 10^{-3} \quad (5.4 \pm 2.0) \times 10^{-3}$$

- Central values close
- Differences come from the treatment of the structure functions
- BTW, we combined errors directly, Hall et al. in quadrature. Could repeat:

$$\mathrm{Re}\,\Box^V_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$$(5.6 \pm 0.36) \times 10^{-3} \quad (5.7 \pm 0.52) \times 10^{-3} \quad (5.4 \pm 2.0) \times 10^{-3}$$

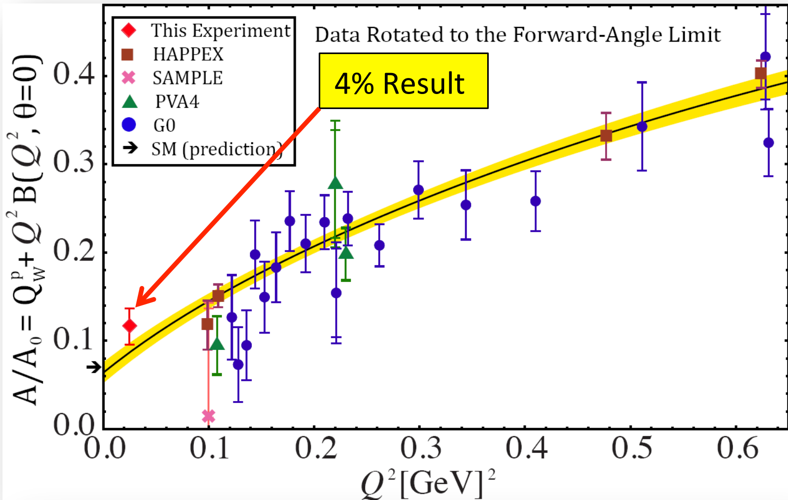
C. Carlson

Summary

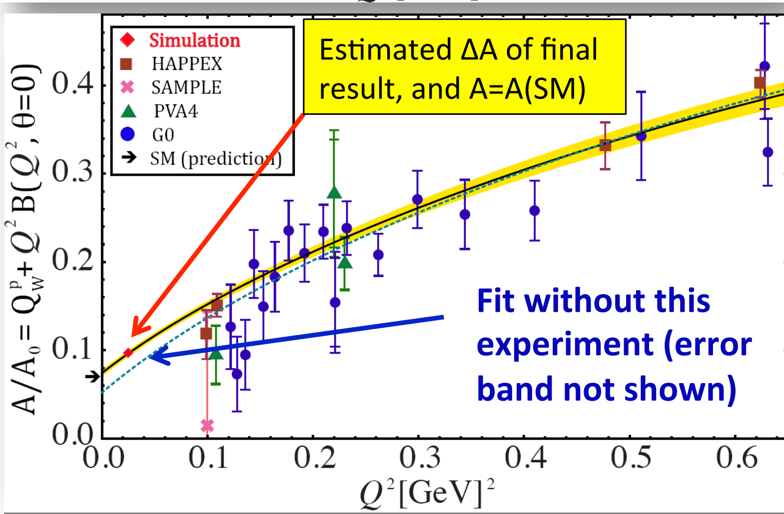
- The world is saved—maybe—regarding the γZ corr. to Q_{Weak}.
- I.e., $\Box_{\gamma Z}^{V}$ now calculated.
- About (8.1±1.4)% of Q_W^p at E_{elec}=1.165 GeV. Proportional to E_{elec}.
- Not discussed here: $\Box_{\gamma Z}^{A}$ also now calculated w/o guesswork certain log terms
- About (6.3±0.6%) of Q_W^p at E_{elec} threshold. Small dependence on E_{elec}. Might still like to improve.
- For goal of 1% or better measurement of QWeak (Mesa), energy is about 1/6 of JLab experiment, and corrections and error in $\Box_{\gamma Z}^{V}$ scale with energy.
- PVDIS can help shrink uncertainty limits.

C. Carlson

Global fit of $Q^2 < 0.63$ (GeV/c)^2 PVES Data



A = -279 ± 35 ± 31 ppb
$Q_W(p)$ = 0.064 ± 0.012
(only 1/25th of all data collected)
SM value = 0.0710(7)



Estimated Fit Uncertainties with Final Result (Assuming SM Value)

R. Carlini

P2 at Mainz MESA – Proton Weak Charge

$\vec{e} + p \rightarrow e' + p \quad Q_W^p \equiv -2\left[2C_{1u} + C_{1d}\right] = \left(1 - 4\sin^2\theta_W\right)$

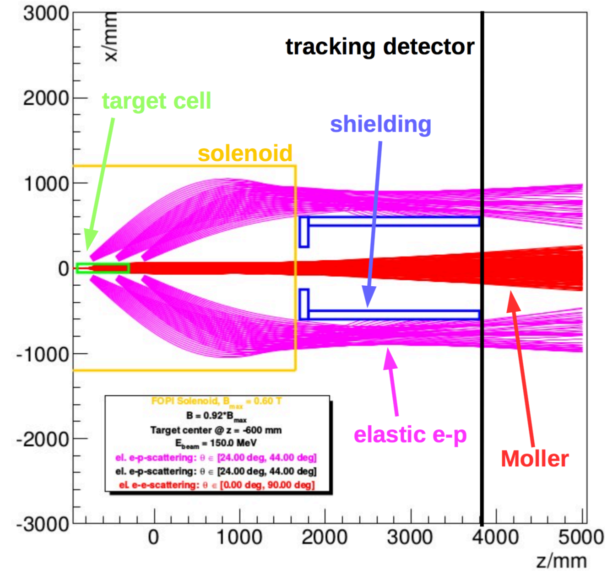
$$A \sim \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

Run at low energy; reduce hadronic contributions and gamma-Z box radiative

- E_{beam}= 155 MeV, 25-45°
- Q^2 = 0.0049 GeV^2
- 60 cm LH_2 target, 150 µA, 10,000 hours
- Total rate ~ 0.5 THz
- A = - 28 ppb to 1.5%

- **Improve Jlab Qweak's determination of proton weak charge by factor of 2.5**
- **0.13% precision on $\sin^2\theta_W$**

spectrometer concept

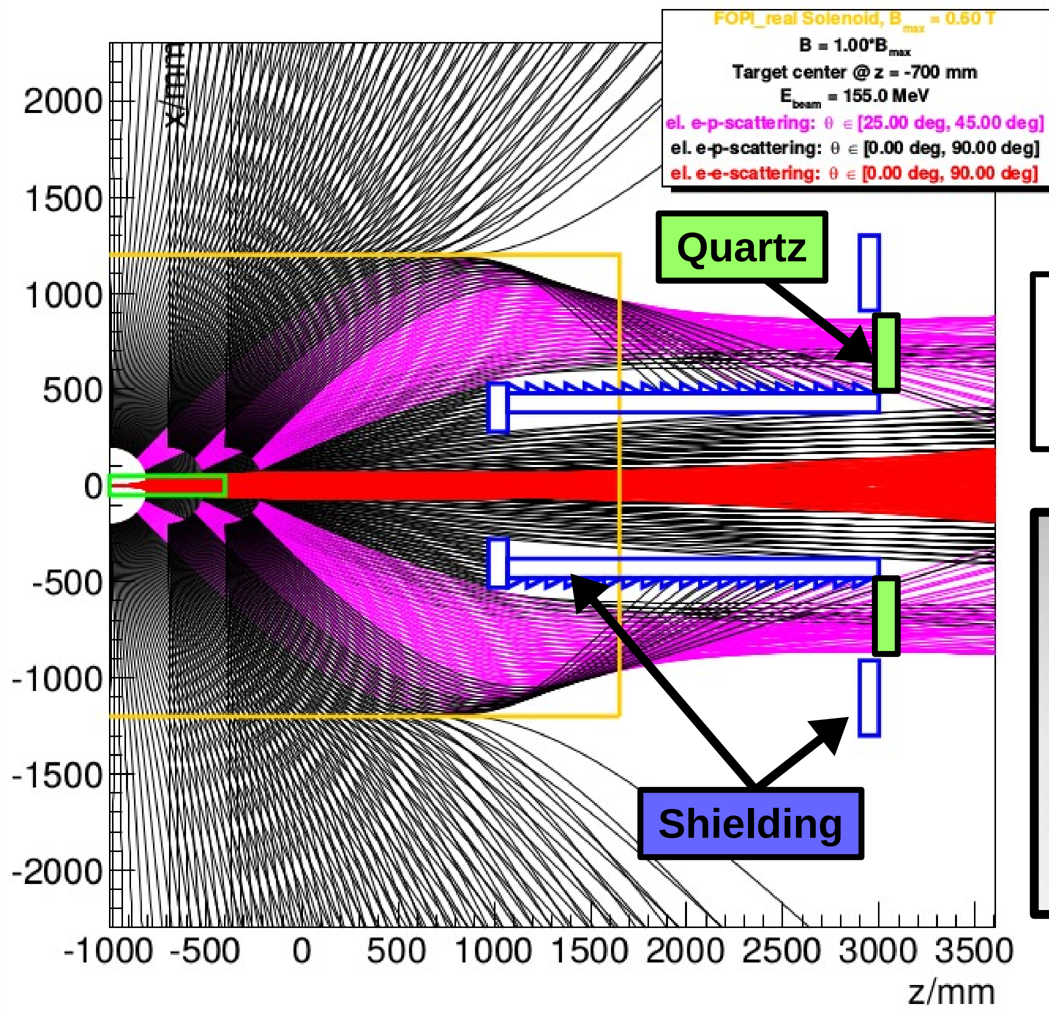


Status:
- Collaborators from Germany and US
- Funding approval by DFG
- R&D in progress
- Aim to run from 2017-2020

See D. Becker talk

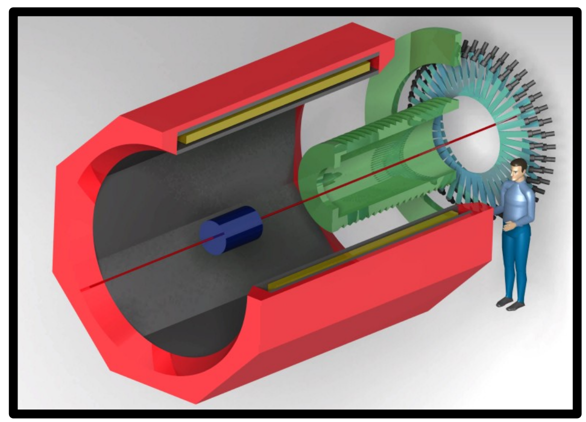
M.Pitt

Raytrace simulations in the magnetic field



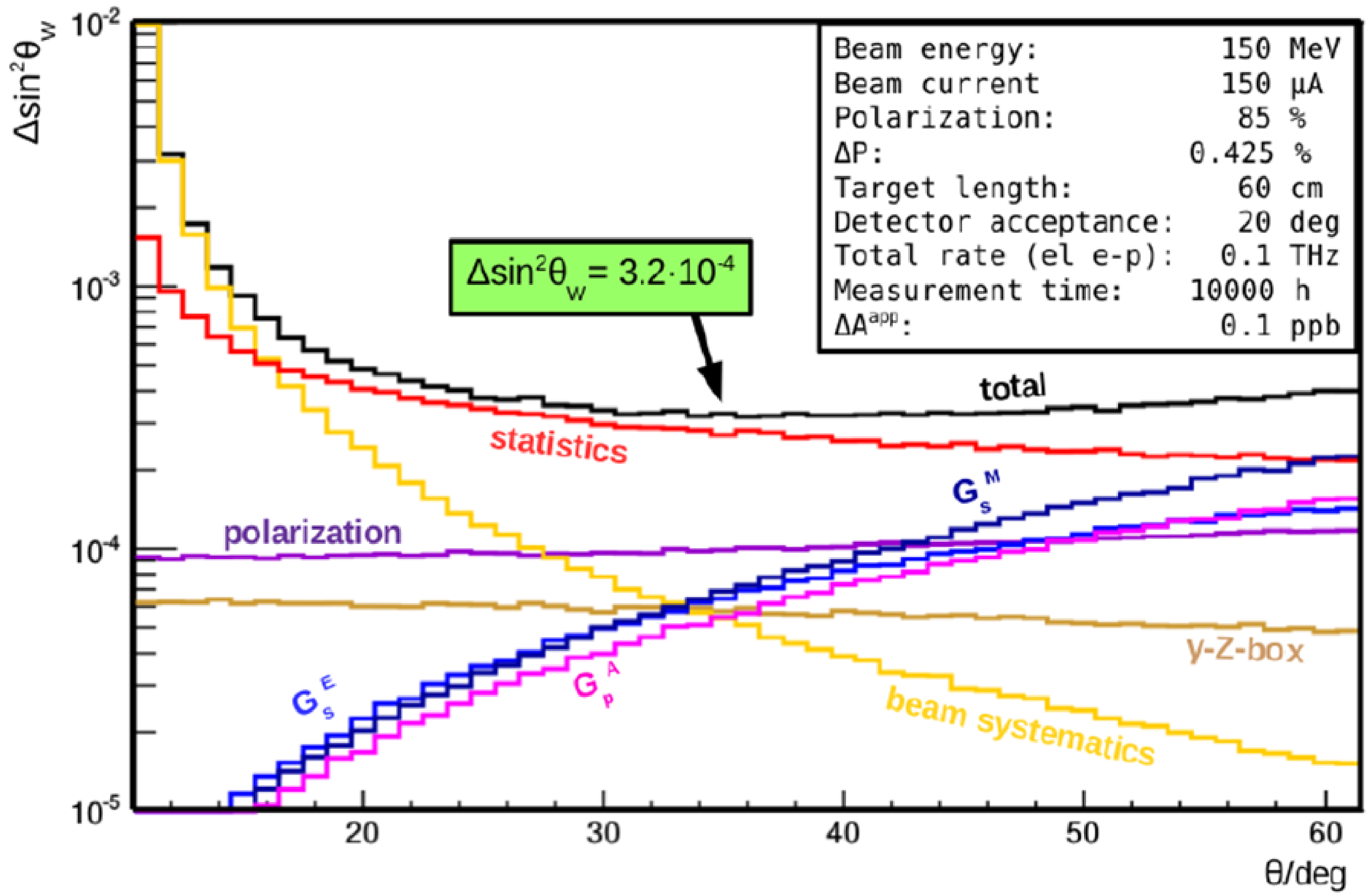
Magnetic field:
0.6 T

Beam energy = 155 MeV
Moller, θ ∈ [0°, 90°]
Elastic e-p, θ ∈ [25°, 45°]
Elastic e-p, θ ∈ [0°, 90°]



D. Becker

Choice of kinematics for the P2 experiment



D. Becker

Facts and Figures

The following results are based on error propagation calculations **including** the results of the Geant4 simulation of the experimental setup:

Beam energy	155 MeV	
Beam current	150 µA	
Polarization	85 %	± 0.425 %
Target	60 cm	liquid hydrogen
Detector acceptance	2π·20°	θ ϵ [25°, 45°]
Detector rate	0.5 THz	
Measurement time	1e4 h	
$\langle Q^2 \rangle$	4.49e-3 GeV^2/c^2	
A^{exp}	-28.35 ppb	

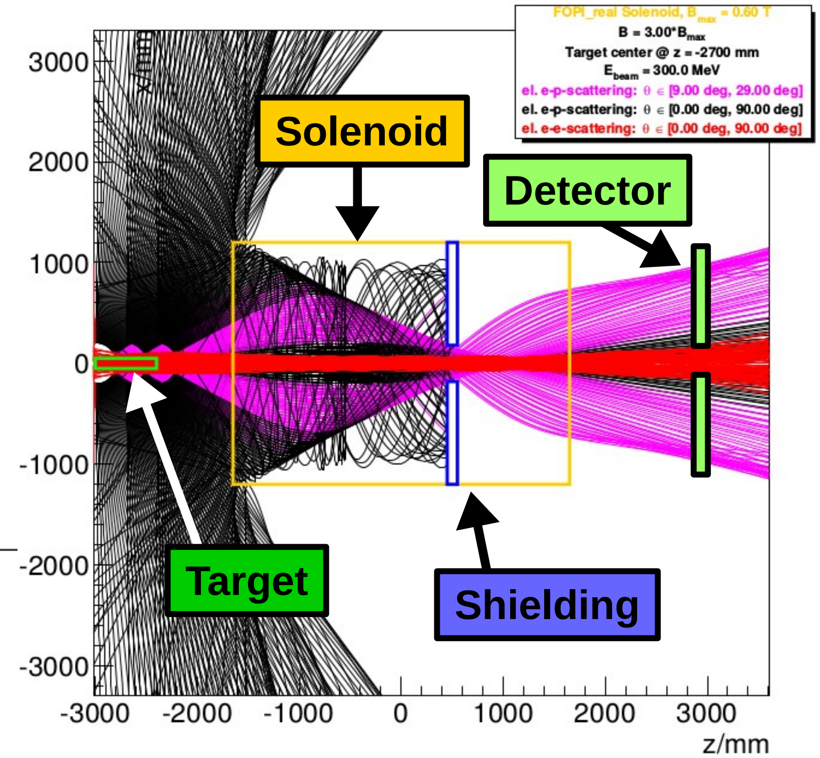
	Total	Statistics	Polarization	Apparative	Form factors	Re($\square_{\gamma ZA}$)
$\Delta sin^2(\theta_W)$	**3.1e-4 (0.13 %)**	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	**0.44 (1.5 %)**	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

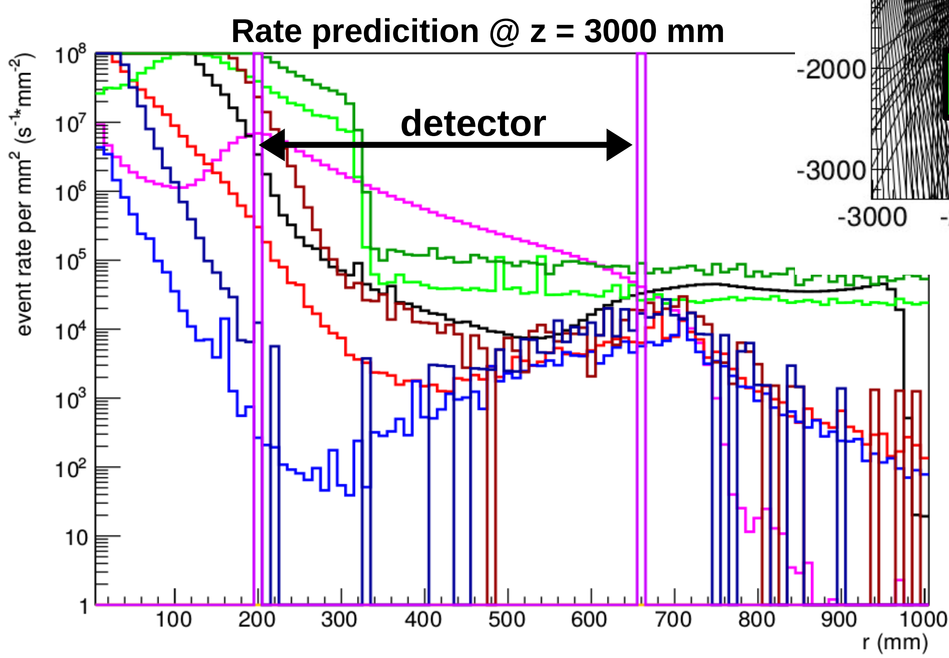
D. Becker

A very first idea for 300 MeV

Beam energy: 300 MeV
Beam current : 150 μA
Central magnetic field: 1.8 Tesla

Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [9°, 29°]
Elastic e-p, θ ϵ [0°, 90°]





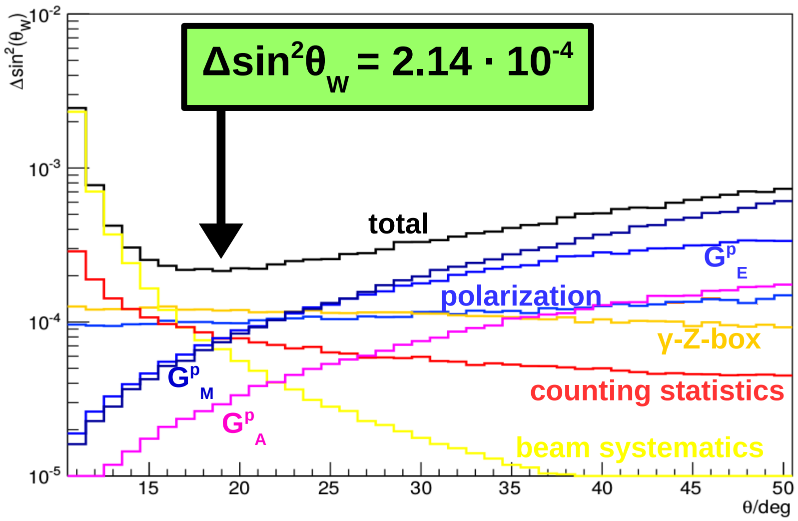
Elastic e-p, θ in [9°, 29°]
Elastic e-p, θ not in [9°, 29°]
Moller, e-p
Moller, background
Positrons, e-p
Positrons, background
Photons, e-p
Photons, background

D. Becker

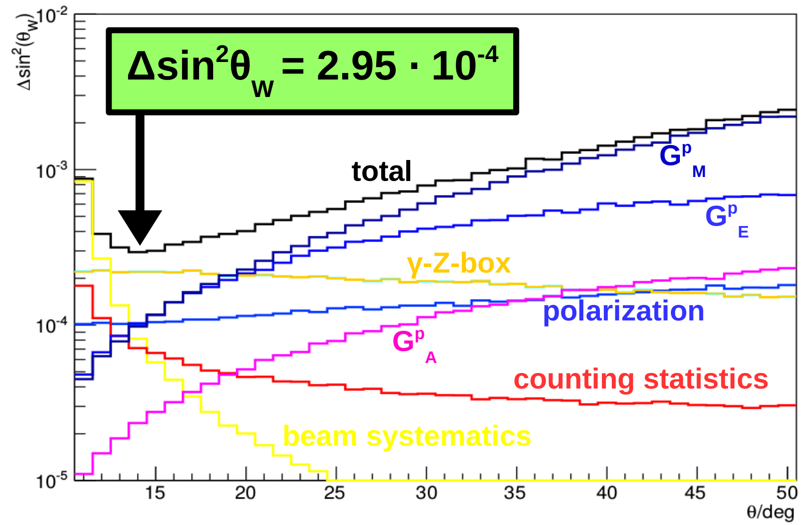
Achievable precision @ higher energies/beam current

Beam current:	**1 mA**
Polarization:	85 % ± 0.425 %
Target material:	liquid hydrogen
Target:	60 cm
Measurement time:	10000 h
Detector acceptance:	2π·20°
ΔA^{app}:	0.1 ppb

Beam energy: 300 MeV
Central scattering angle: 19°
A^{PV} = (-30.8 ± 0.34) ppb
$\langle Q^2 \rangle$ = 4.84e-3 GeV²/c²
Rate elastic e-p: 1.8 THz



Beam energy: 500 MeV
Central scattering angle: 14°
A^{PV} = (-24.8 ± 0.36) ppb
$\langle Q^2 \rangle$ = 3.82e-3 GeV²/c²
Rate elastic e-p: 3.6 THz



For 0.1mA, statistics dominated: $\Delta(\sin^2\theta_W) \sim 0.00032$

Matches P2, requires 10k hours

D. Becker

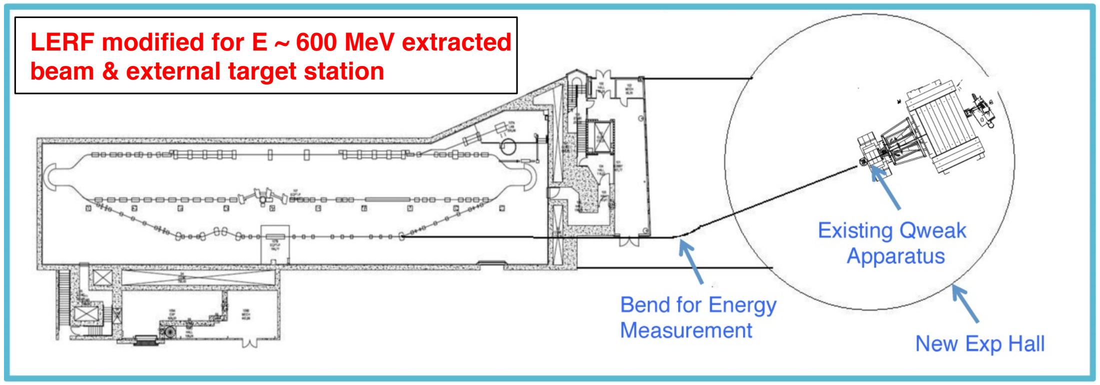
Qweak Apparatus Reused at Lower Energy

What might be achievable by re-using the Qweak apparatus at lower beam energy for a much lower Q^2 measurement of the proton's weak charge?

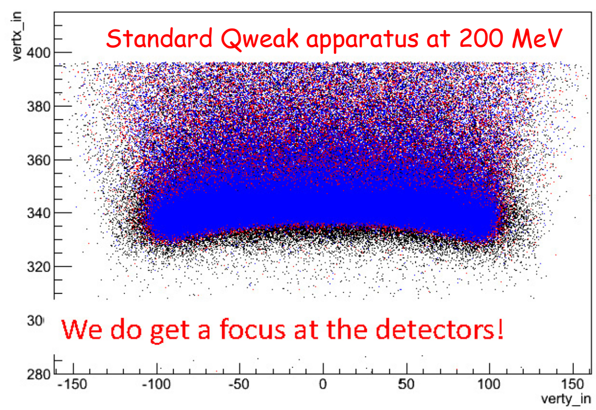
How Qweak Exp might look at an upgraded LERF

OR

other equivalent facility



Monte Carlo studies by Juliette Mammei and Kurtis Bartlett (using Qweak apparatus with same relative target/collimators/spectrometer postions, etc.) indicates there is a focus at lower energies (200 MeV to 600 MeV).



R. Carlini

Projections for Using Qweak Apparatus at 600 MeV

Projected rates/asymmetries for standard Qweak apparatus at 600 Mev:
Case A: standard 2.5 kW LH_2 target; Case B: 3.8 kW LH_2 target

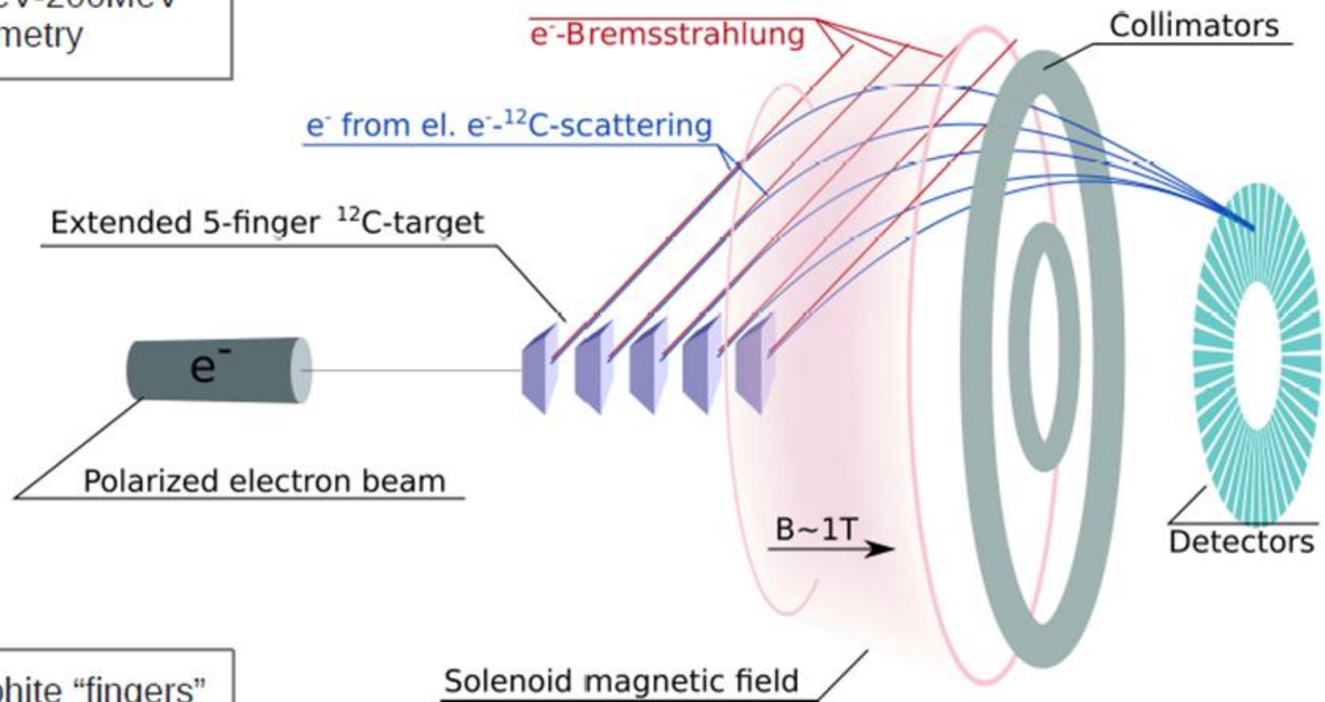
Parameter	MESA P2*	Q-weak 600, case A	Q-weak 600, case B
E_{beam}	200 MeV	600 MeV	600 MeV
Time	10000 hours	10000 hours	10000 hours
Current	150 μA	200 μA	300 μA
LH_2 Target Length	60 cm	35 cm	35 cm
Polarization	85%	85%	85%
Central θ	20^o	8^o	8^o
$<Q^2>$	.0029 GeV^2	.0065 GeV^2	.0065 GeV^2
Total rate	440 GHz	30 GHz	44 GHz
Asym. Width @240 Hz	23 ppm	89 ppm	74 ppm
A_{phys} (ppb)	-20 ppb	-46 ppb	-46 ppb
Hadronic "B" term	9%	10%	10%
ΔA (stat)	0.25 ppb (1.2%)	0.96 ppb (2.1%)	0.79 ppb (1.7%)
ΔA (syst)	0.19 ppb (0.9%)	0.41 ppb (0.9%)	0.41 ppb (0.9%)
ΔA (tot)	0.34 ppb (1.7%)	1.20 ppb (2.6%)	1.01 ppb (2.2%)
ΔQ^p_W	0.0014 (2.0%)	0.0021(3.0%)	0.0019 (2.6%)
$\Delta\sin^2\theta_W$	3.6×10^{-4} (0.15%)	5.4×10^{-4} (0.23%)	4.7×10^{-4} (0.20%)

* MESA P2 parameters come from F. Maas talk at "Dark Forces at Accelerators" Frascati, Oct. 2012

R. Carlini

Measurements with other targets at P2

MESA:
- 150µA
- 150MeV-200MeV
- Polarimetry



Target:
- 5 graphite “fingers”
- 5 g/cm² total
- 36mm spacing

S. Baunack

C12 @ P2 MESA – Weak Charge of the ^{12}C Nucleus

PV Elastic Electron Scattering
on J=0, T= 0 Nucleus:

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \sin^2\theta_W$$

^{12}C measurement at P2

@ Beam energy E = 150MeV
Scattering angle Θ = 40° +- 9°
Target density d = 5g/cm²

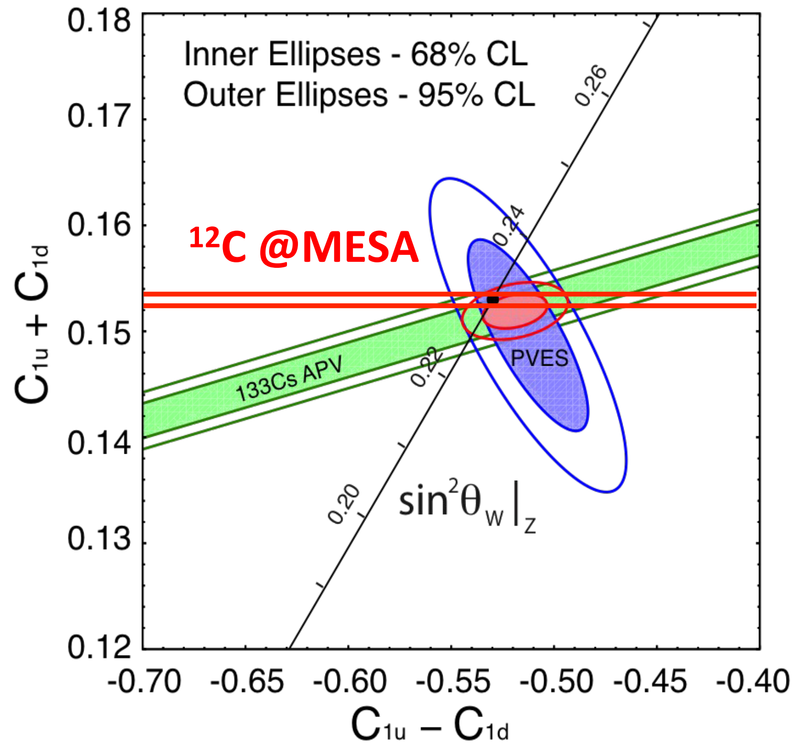
Measuring time t = 2500h
Beam current I = 150μA

We can achieve $\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$

$A_{PV} = \frac{G_F \cdot Q^2}{\sqrt{2}\pi\alpha}\sin^2\Theta_W$ →

$Q_W^C = -24\sin^2\Theta_W$ →

$$\frac{\delta A_{PV}}{A_{PV}} = \frac{\delta Q_W^C}{Q_W^C} = \frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$$



S. Baunack

3x better than APV, nearly same coupling combination

Moderate runtime

Inelastic Levels: Experiment

Q = 240 MeV
=1.2 fm-1

566 1961 R. HOFSTADTER

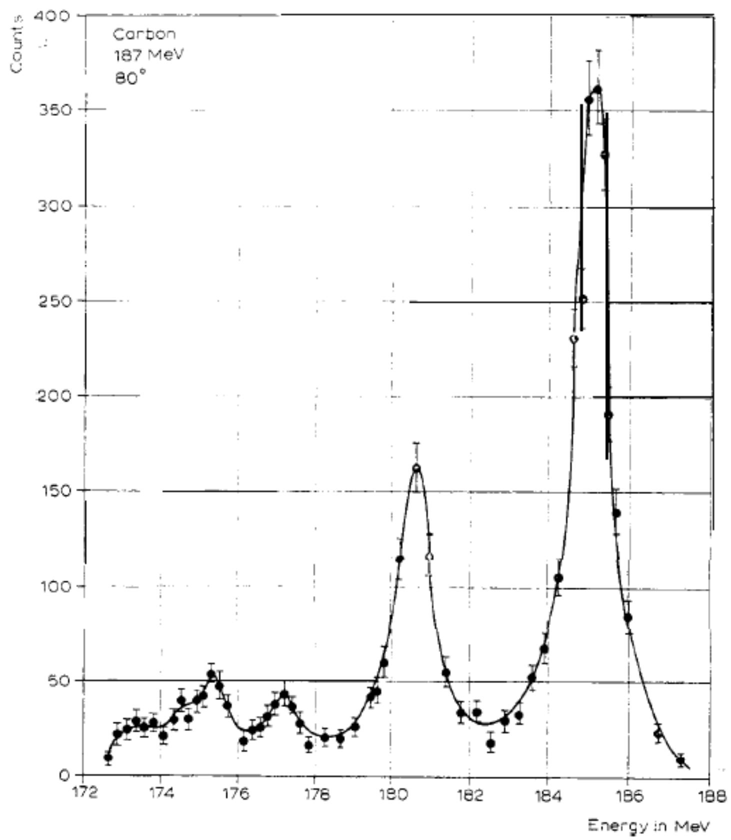
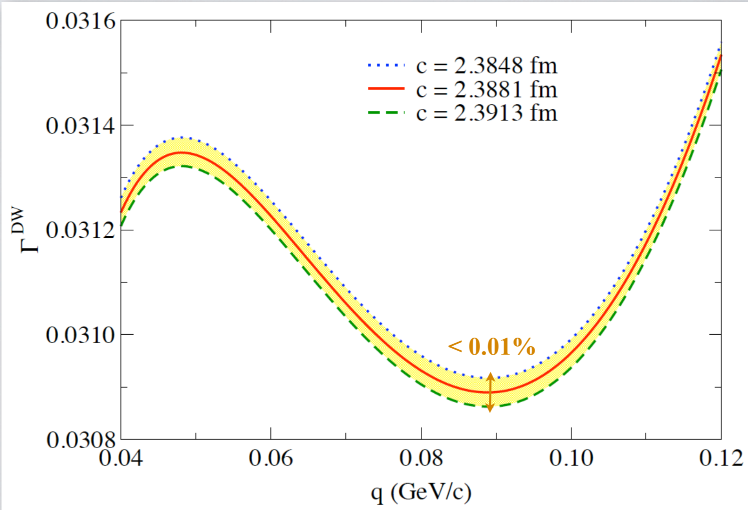


Fig. 4. This figure[8] shows the elastic-scattering peak from carbon at an abscissa near 185 MeV, and the inelastic-scattering peaks from the excited states of ^{12}C. The peak near 180.7 MeV is associated with the 4.43-MeV level.

P. Souder

COULOMB DISTORTION EFFECT

Theoretical uncertainties in the PV asymmetry due to a reasonable variability in the nuclear charge distributions



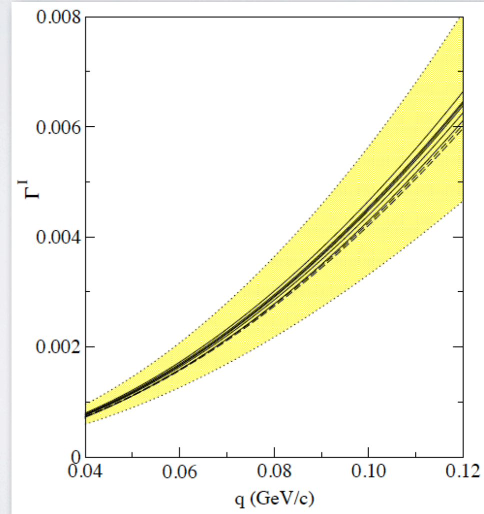
PRC 89 (2014) 015501

INTENSE ELECTRON BEAMS WORKSHOP
CORNELL UNIVERSITY, JUNE 17-19, 2015
Nuclear effects in PV e⁻ scattering (^{12}C)
O. Moreno

NUCLEAR ISOSPIN MIXING EFFECT

Theoretical uncertainties in the PV asymmetry from a reasonable variability in the neutron vs. the proton distributions

DIFFERENT NUCLEON-NUCLEON FORCES: HF MEAN FIELD



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O. Moreno

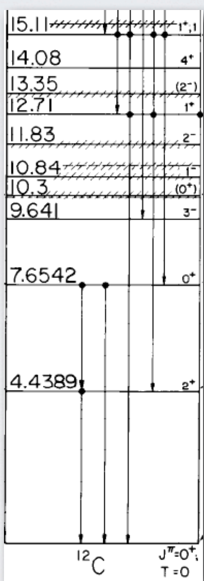
INELASTIC TRANSITIONS EFFECT

Theoretical uncertainties in the PV asymmetry due to possible transitions to excited states in the target

Total asymmetry:

$$A = \sum_{i=0}^{n} f_i A_i$$

$$f_i = \frac{\sigma_i^{EM}}{\sum_{k=0}^{n} \sigma_k^{EM}}$$



T = 1 levels:
Different asymmetry
(isovector contribution)

T = 0 levels:
Same asymmetry
as for ground state
($\Gamma^{inel.} = 0$)
(in absence of strangeness and at tree-level)

O. Moreno

PRC 89 (2014) 015501

INTENSE ELECTRON BEAMS WORKSHOP
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O. Moreno

CONCLUSIONS

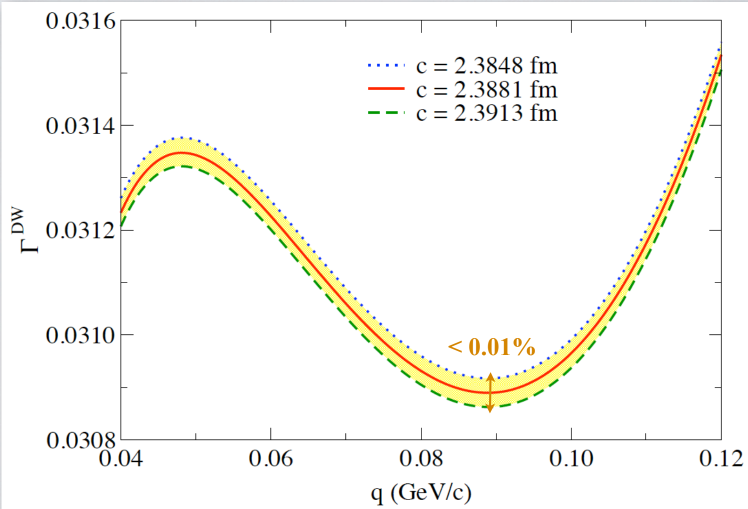
SUMMARY OF SIZES AND UNCERTAINTIES

150 MeV incident energy, 25º-45º scattering angular range

Contribution to PV asymmetry	Relative size	Relative uncertainty
Coulomb distortion of projectile wave function	3%	0.01%
Nuclear isospin mixing (electromagnetic origin)	0.4%	0.05%
Nucleon strangeness content (mainly electric)	0 - 1 %	1%
Meson exchange currents	< 0.1 %	< 0.1 %
Inelastic contributions	< 0.1 %	--

COULOMB DISTORTION EFFECT

Theoretical uncertainties in the PV asymmetry due to a reasonable variability in the nuclear charge distributions



PRC 89 (2014) 015501

NUCLEAR ISOSPIN MIXING EFFECT

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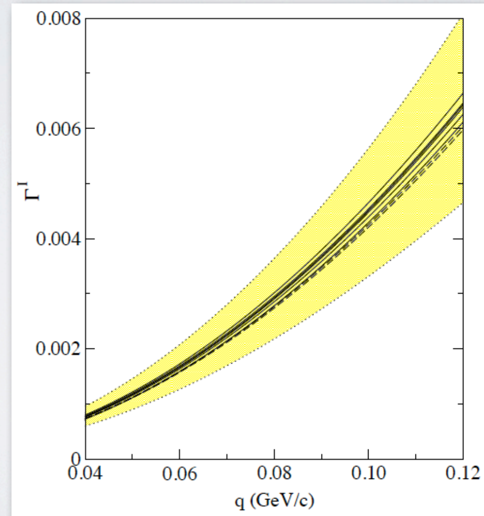

PRC 89 (2014) 015501

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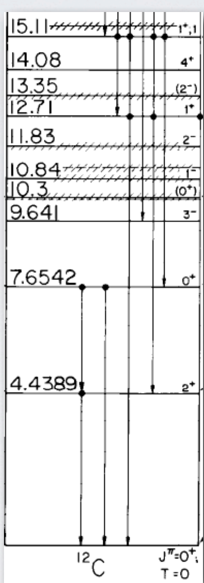

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O. Moreno

PRC 89 (2014) 015501

CONCLUSIONS

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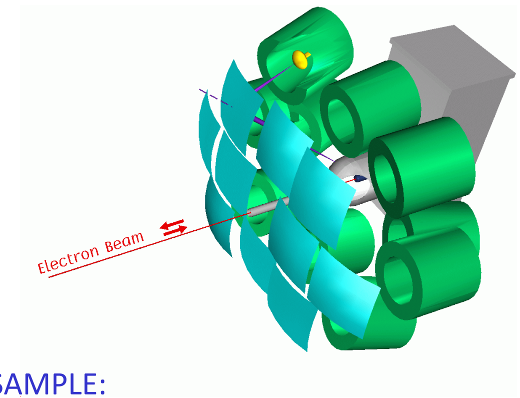
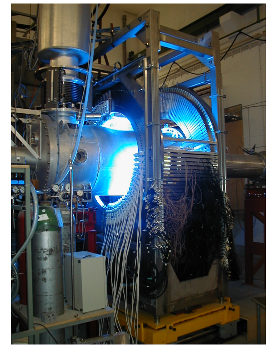
Nucleon strangeness content (mainly electric)	0 - 1 %	1%
Meson exchange currents	< 0.1 %	< 0.1 %
Inelastic contributions	< 0.1 %	--

Strange Form Factors – Worldwide Program

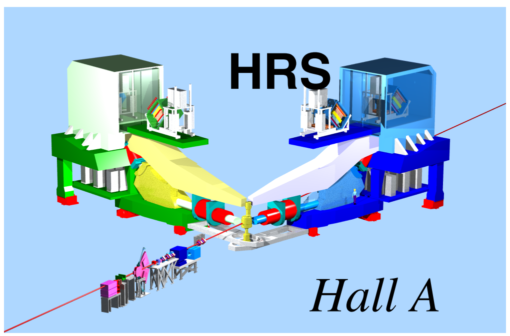
1992 – 2011: Worldwide program on strange form factors measured with PVES



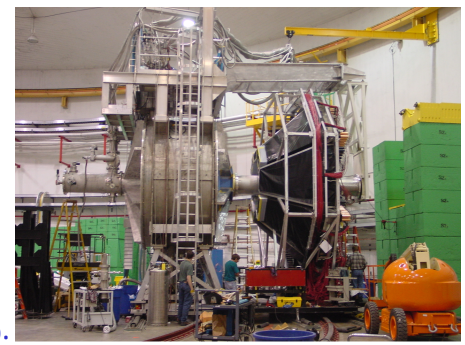
SAMPLE:
Location: MIT-Bates
Targets: p,d
Kinematics: backward angle, Q^2 = .038,.10 GeV^2



Mainz PV-A4:
Location: Mainz MAMI microtron
Targets: p,d
Kinematics: forward & backward angles
Q^2 = .11, .23, .62 GeV^2



HAPPEx I, II, III:
Location: Jefferson Lab Hall A
Targets: p, ^{4}He
Kinematics: forward angle, Q^2 = .10,.48, .62 GeV^2



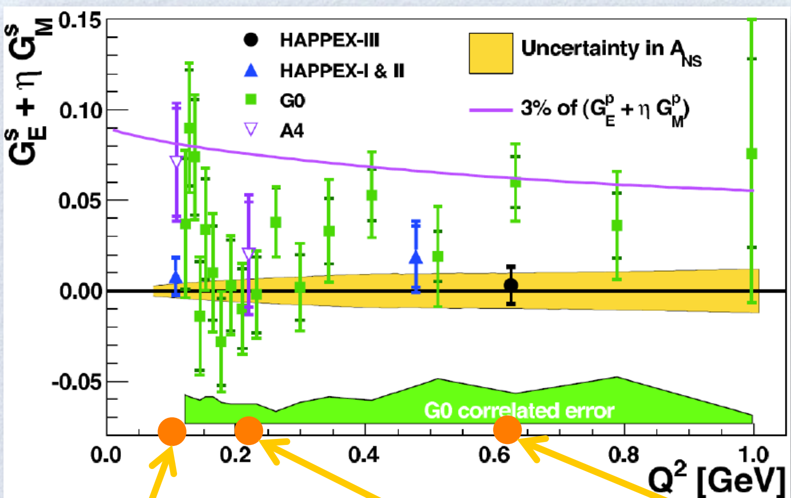
G^0:
Location: Jefferson Lab Hall C
Targets: p, d
Kinematics: forward & backward angles
Q^2 = .1 – 1 GeV^2

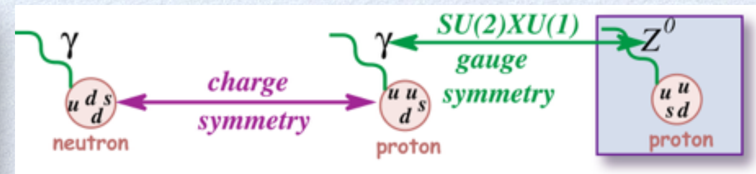
M. Pitt

2011: Completion of a 2-decade program

Strange Form Factor Summary

Strange quarks carry nucleon momentum: Other external properties affected?

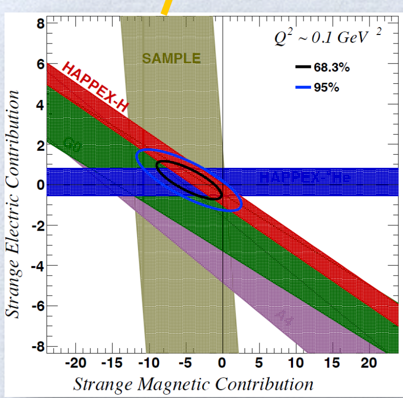


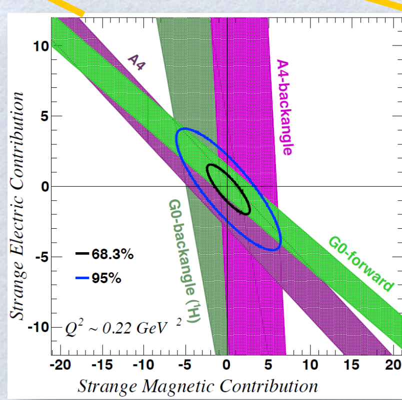


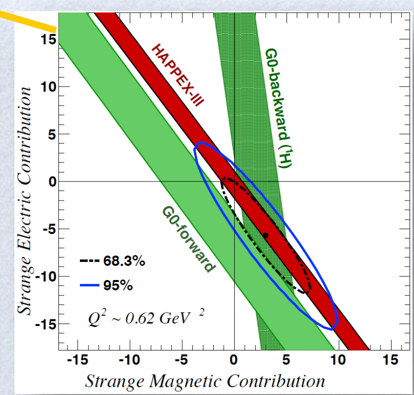
$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

- Sensitive Flavor separation at 3 Q^2 values
- No more than few % of EM structure
- Recent lattice results in agreement







Strange Form Factors – Measurements at Low Energy?

Are further strange form factor measurements warranted?

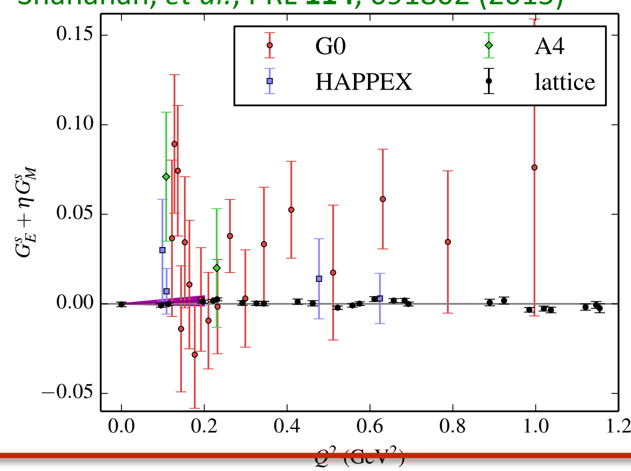
State-of-the-art lattice QCD calculations set the scale of what is interesting.

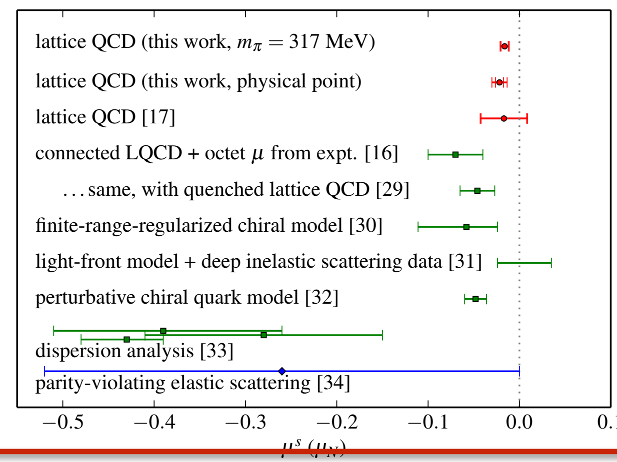
Recent lattice predictions for the strange magnetic moment:

$G_M^s\ (Q^2 = 0) \equiv \mu_s = -0.07 \pm 0.03\ \mu_N$ Green, *et al.*, arXiv:1505.01803

$G_M^s\ (Q^2 = 0) \equiv \mu_s = -0.022 \pm 0.004 \pm 0.004 \pm 0.006\ \mu_N$ Shanahan, *et al.*, PRL **114**, 091802 (2015)

Shanahan, *et al.*, PRL **114**, 091802 (2015)





Possible backangle measurements at low energies?

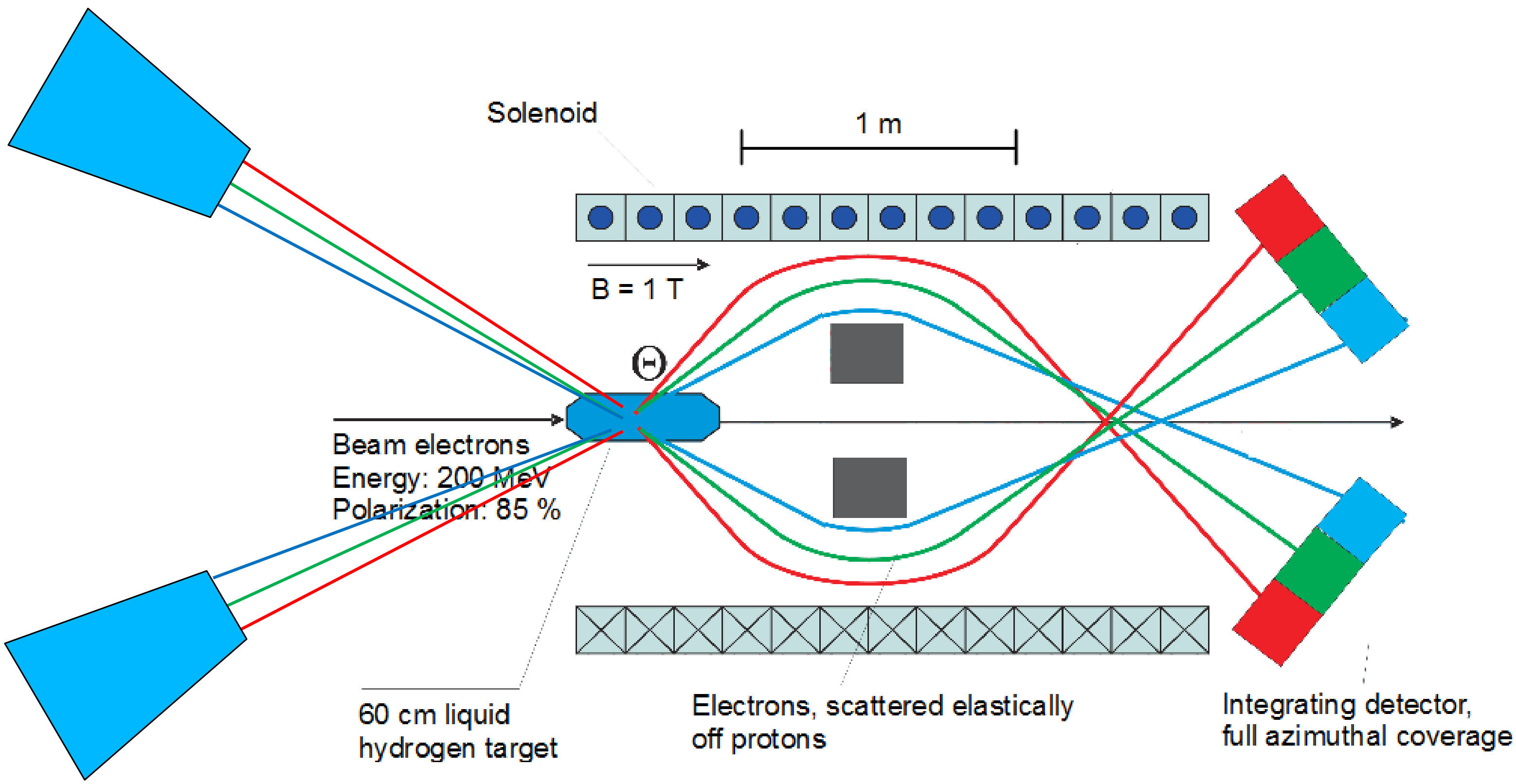
- ”A4 style” fast calorimeter during P2, θ ~ 140 – 150°, 150 MeV, 150 μA, 60 cm LH/D_2 targets, 1000 hours each ➔ $\delta G^s_M \sim \pm 0.05\ \mu_N$ (Baunack, PEB2013)
- “SAMPLE” style air Cerenkov, θ ~ 130 – 170°, not yet estimated

See K. Kumar talk for possibilities for strange radius at low energies

M. Pitt

P2 back angle measurement!

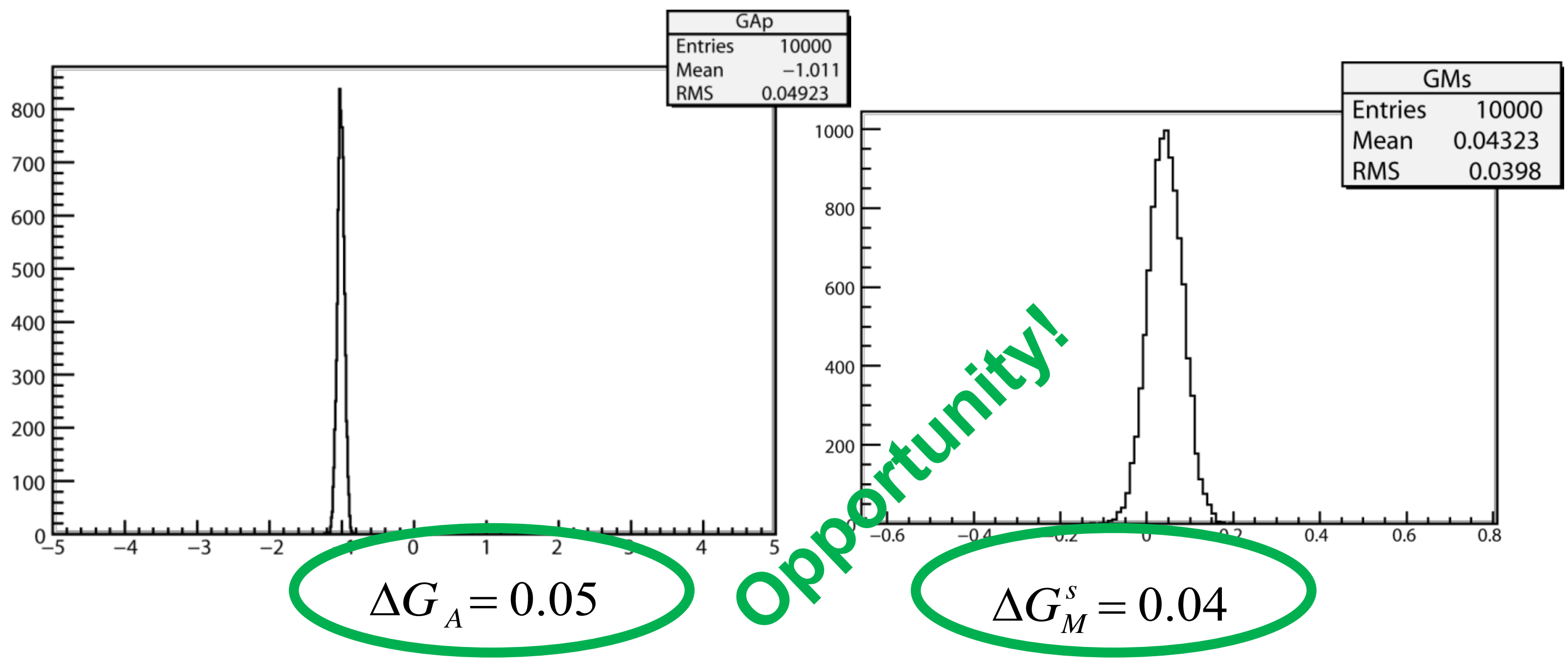
Back angle measurements: Determination of G_M^s and G_A



S. Baunack

Possible uncertainties of G_A and G_M^s with P2 back angle measurement

- Q^2=0.06 GeV^2
- Numerical determination of precision
- Choose randomly EM form factors and asymmetries according to their uncertainties and calculate G_A and G_M^s
- Correlation of electromagnetic form factors input taken into account



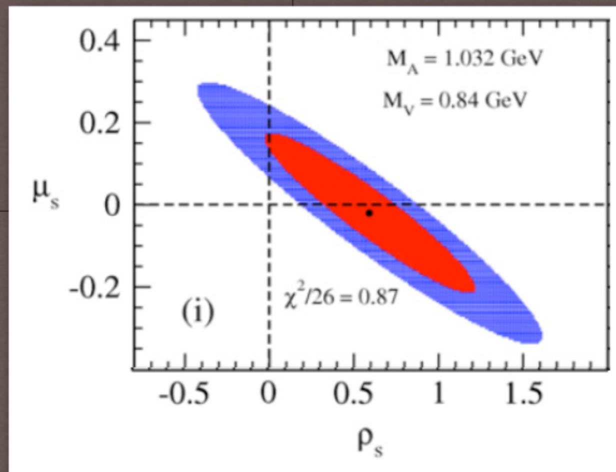
S. Baunack

Strangeness using isoscaler nucleus: ^{12}C

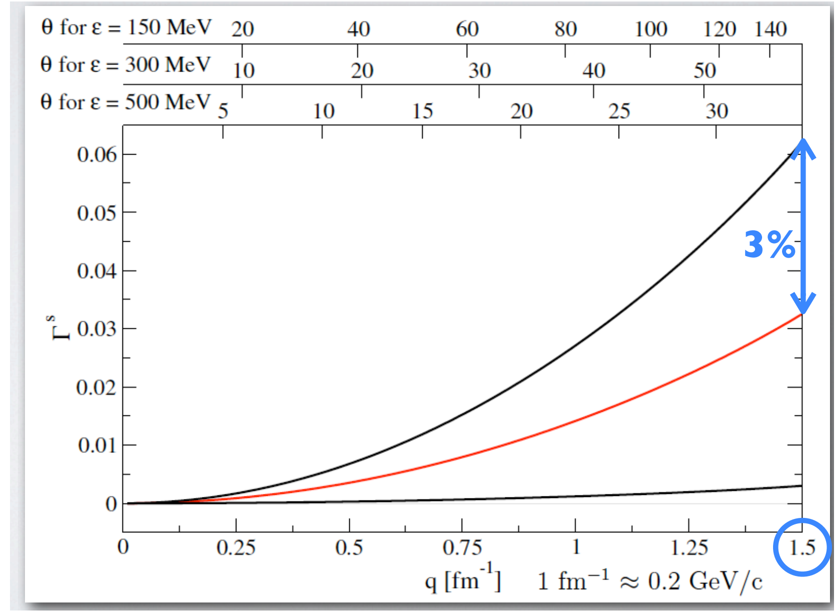
$$G_E^{(s)} = \frac{|Q^2|}{4m_N^2}\,\frac{\rho_s}{(1+|Q^2|/M_V^2)^P}$$

$$G_M^{(s)} = \frac{\mu_s}{(1+|Q^2|/\widetilde{M}_V^2)^P}$$

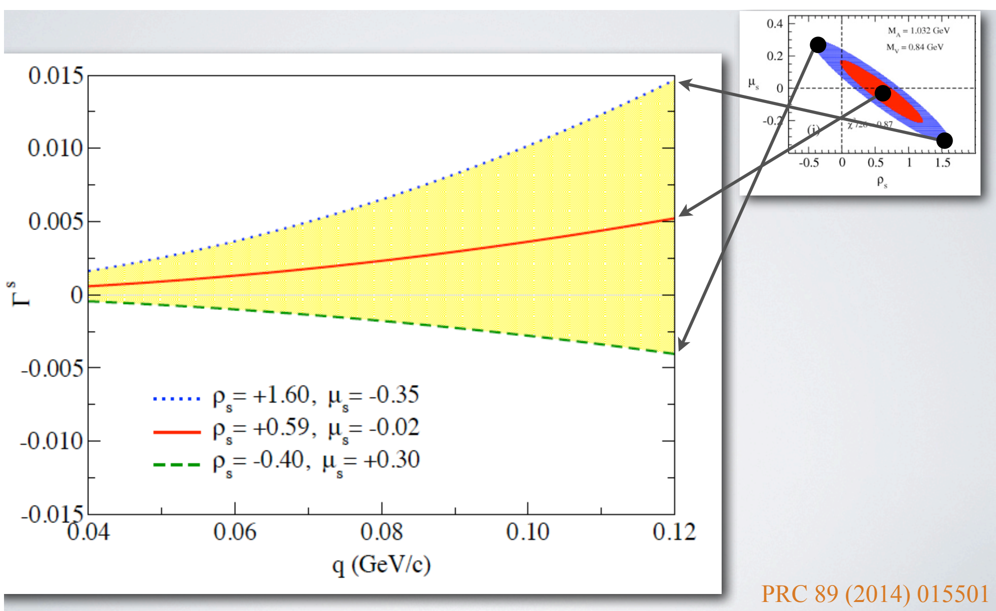
$$\chi^2 = \sum_{j=1}^{28}\left(\frac{\mathcal{A}_j^{exp}-\mathcal{A}_j^{th}}{\Delta\mathcal{A}_j^{exp}}\right)^2$$



R. González-Jiménez, J. A. Caballero, T. W. Donnelly, Phys. Rep. 524 (2013) 1



Strangeness uncertainty for 12C measurement



Measurement of ^{12}C at higher q pins strangeness radius (G_E^s), calibrates low-q Standard Model study

Moderate running time, needs 300 MeV or more

O. Moreno

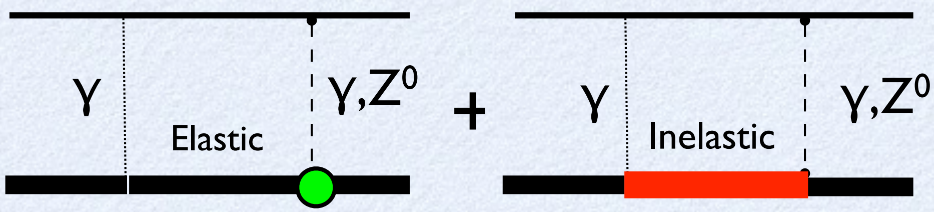
Summary: Weak Charge

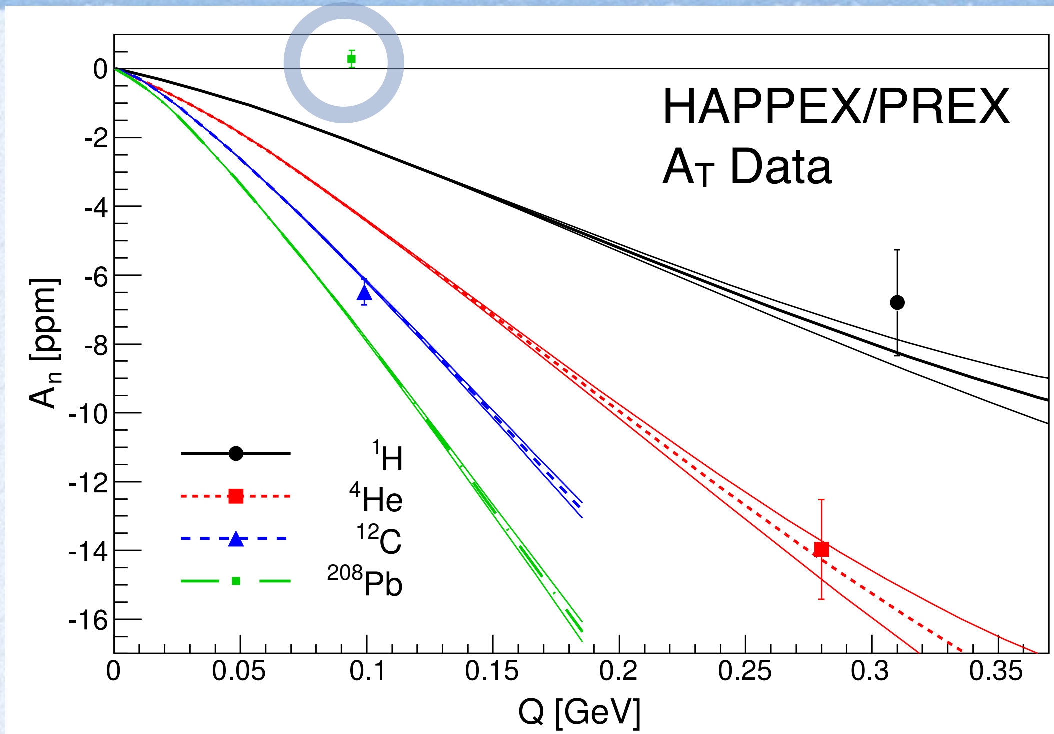
- Proton weak charge - hard to beat P2
- ^{12}C can provide powerful SM test (2500 hrs)
- ^{12}C requires additional precision on GEs.
  - Hard to do at MESA, needs 300 MeV

Vector Analyzing Power

$$A_T \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$

We measured this, in part, because it is a possible systematic error for the PV measurements.





- **What does the Pb-208 A_T result imply?**
  - ***dispersion corrections on top of Coulomb distortions?***
  - ***What if it is a very sensitive cancellation?***
    - What happens when we run again at slightly different kinematics?
    - What if Ca-48 doesn't have this accidental cancellation?
  - ***should other electroweak corrections be revisited?***
  - ***Motivates more A_T measurements at different energies***

Experimental Requirements

$\mathcal{L} \sim 10^{39}$ / (s-cm^2)

Charge-normalized yield : $Y = \frac{S}{I}$

S: Integrated detector signal
I: Integrated charge measurement

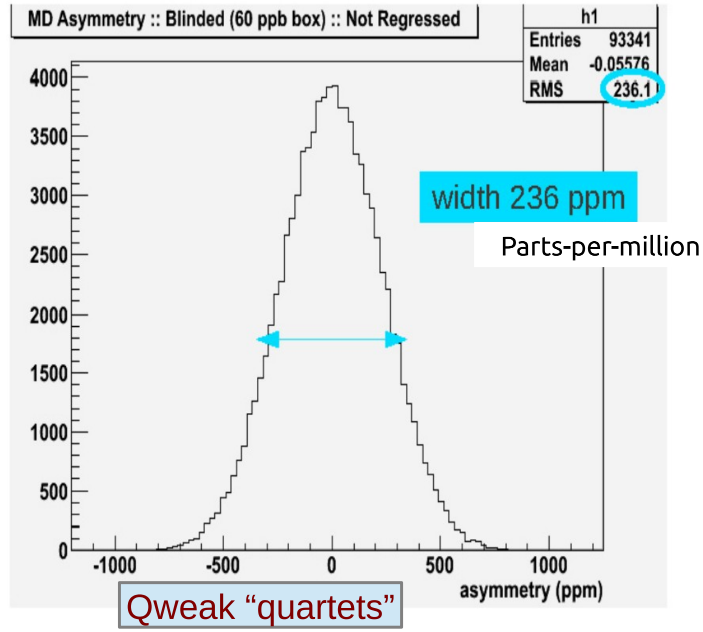
Requires precise (relative) charge measurement

Raw measured asymmetry :

$$A_{raw} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

High precision (part-per-billion level) achieved through repeated measurements.

RMS of distribution important figure-of-merit.
Noise contributions must be suppressed, precision monitoring required



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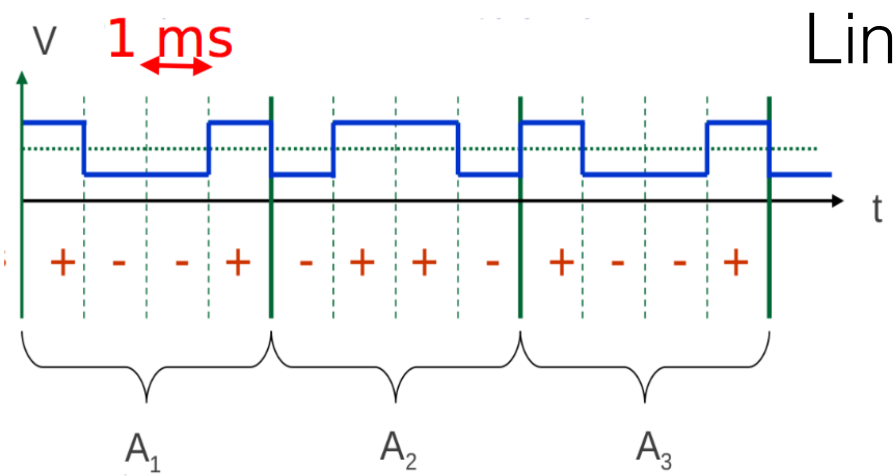


Linear integration over helicity "window"

RF beam monitors - well known technology, but linear integration requirement is sometimes different

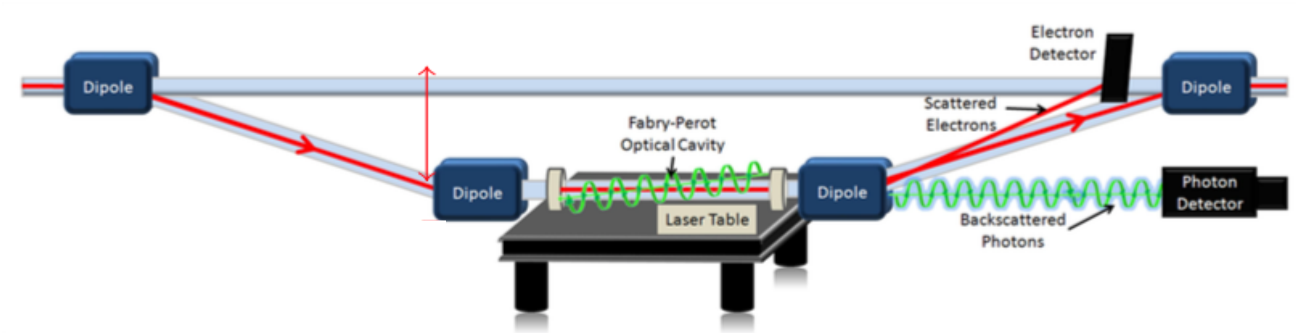
modest resolution ~ 1 micron over 1 ms

Polarimetry

Compton

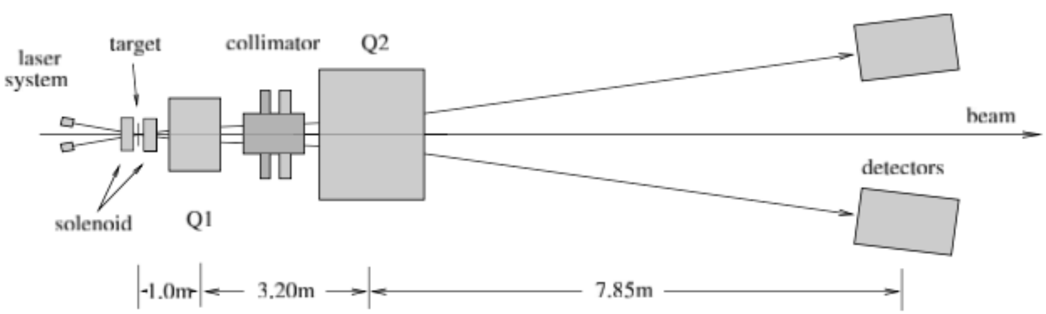
532 nm laser, 300 MeV:
Compton edge ~3 MeV

Require 2+ meter dispersion for electron measurement

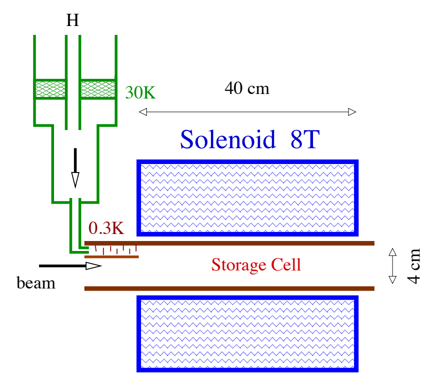


Possible for 0.5% or better… but very hard

Atomic hydrogen Moller



Storage Cell



First: 1980 (I.Silvera,J.Walraven)
$\vec{p}$ jet (Michigan)
Never put in high power beam

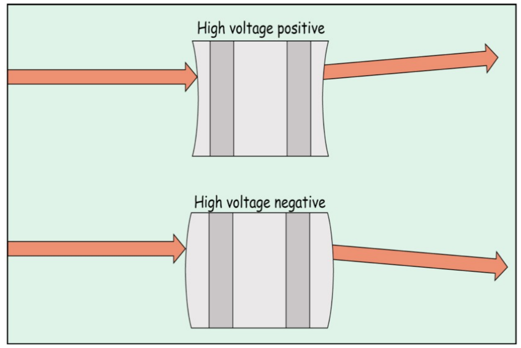
- $-\vec{\nabla}(\vec{\mu_H}\vec{B})$ force in the field gradient
  - pulls $|a\rangle$, $|b\rangle$ into the strong field
  - repels $|c\rangle$, $|d\rangle$ out of the field
- $H+H \rightarrow H_2$ recombination (+4.5 eV) high rate at low T
  - parallel electron spins: suppressed
  - gas: 2-body kinematic suppression
  - gas: 3-body density suppression
  - surface: strong unless coated $\sim$50 nm of superfluid ^4He
- Density $3 \cdot 10^{15} - 3 \cdot 10^{17}$ cm^{-3}.
- Gas lifetime $>$ 1 h.

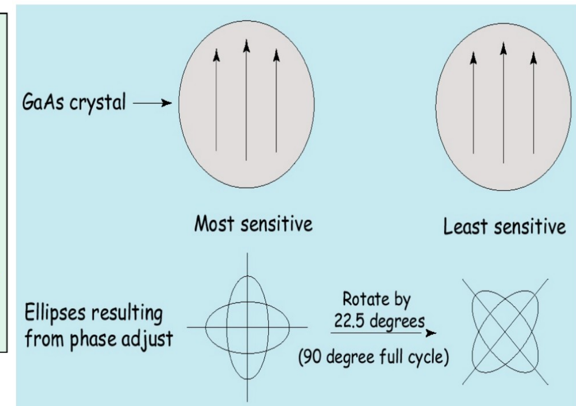
from E. Chudakov

Generation of Helicity-Correlated differences in the source

Mechanical PC steering

Polarization effects:
PC birefringence gradients coupled with cathode analyzing power

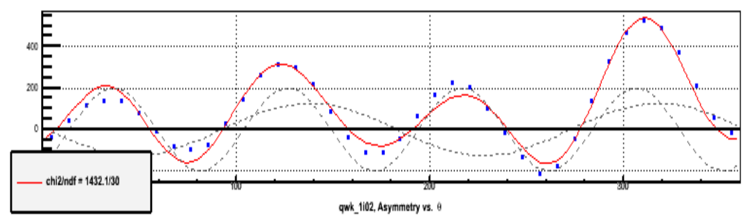




Optimization strategies:

- Careful alignment on laser table
- Balance residual linear polarization from PC with vacuum window birefringence and cathode analyzing power

Δx on injector BPM



RHWP angle

M. Kargiantoulakis

Apparatus

- Assumption: 100 microAmp at 300 MeV

- Solenoid, not toroid (resolution to isolate elastic signal)

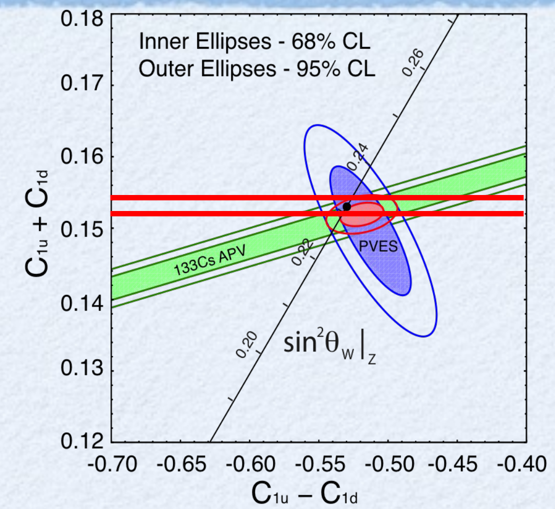
- Extracted beamline
  - Space for apparatus, diagnostic beamline, fast raster
  - beam height ~ 3m
  - Space for polarimeters - atomic hydroMoller
  - Beam dump (with acceptance for disrupted beam)

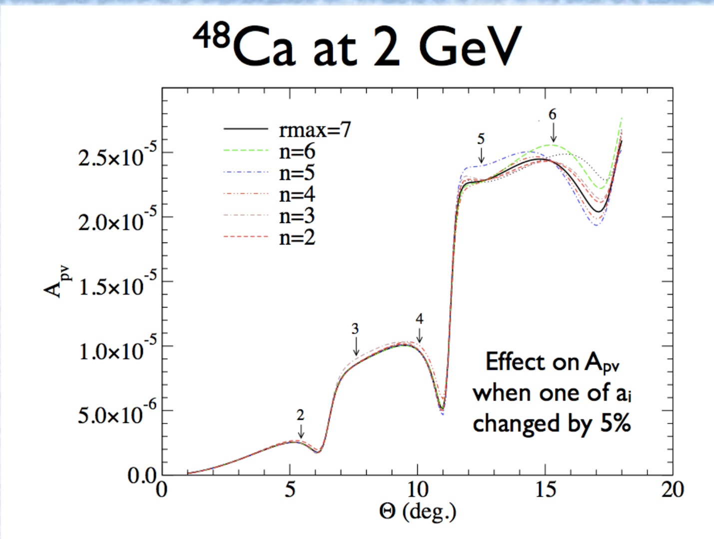
- High dispersion point (few meters?) for E measurement
  - (and another?) for Compton Polarimetry (2+ meters)

- Linear integrating beam monitors, spanning phase space

- Special considerations in polarized source

Potential of New Machine





- **Program with 300 MeV, 100 microamps**
    - ***Higher current, higher E would help***
- **New measurements on Carbon-12**
    - ***A Standard Model test extremely interesting if 0.3% can be reached***
    - ***Must be coupled with higher Q^2 measurements to constrain strange quark radius (strange quark contribution to charge radius)***
- **New measurements on neutron-rich nuclei**
    - ***"Super" PREX/ CREX / Sn-REX***
    - ***Higher Q^2 measurements will provide a complete and model-independent distribution of neutrons in the ground state***