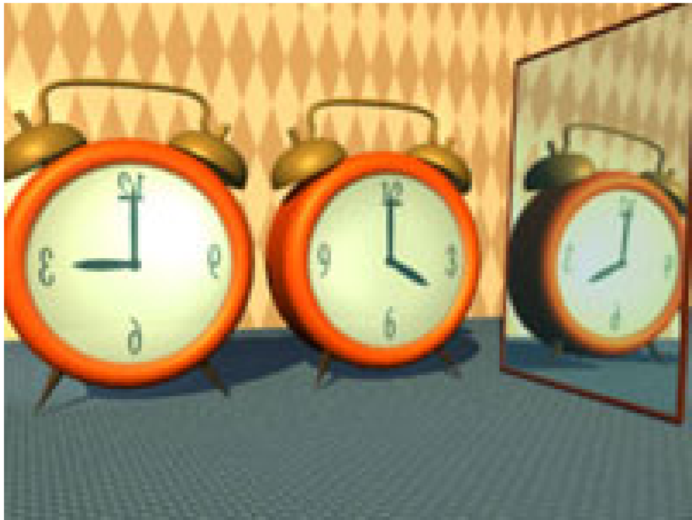
Parity Violation in Electron Scattering

Yury Kolomensky

UC Berkeley

03/14/2013

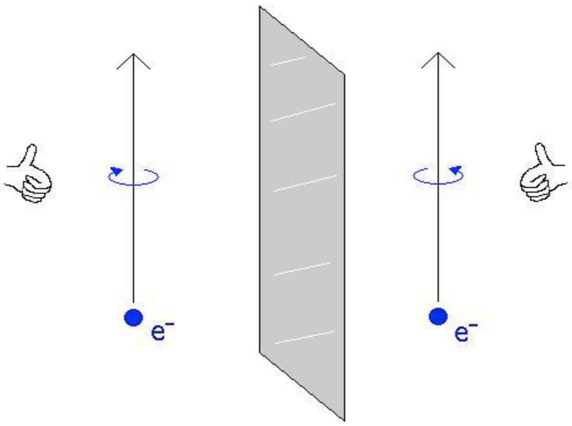


Outline

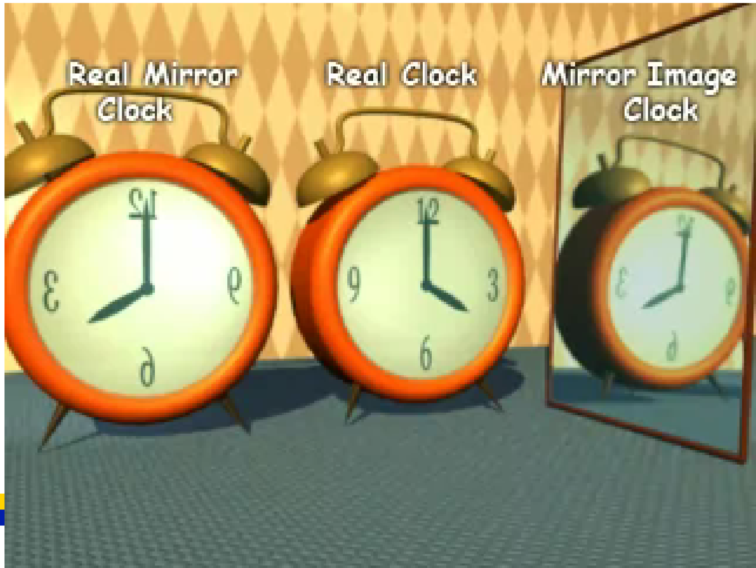
- Parity violation (PV) as a probe of short-range physics
- Historical interlude
- TeV physics: Electroweak measurements
- MeV/GeV physics: hadronic physics
- Outlook

Parity Non-Conservation

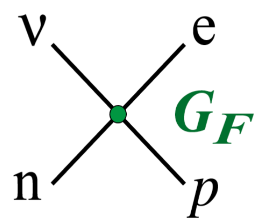
Parity Reversal: $\boldsymbol{r} \rightarrow -\boldsymbol{r}$ (mirror image)



- Vectors change sign
  - ☞ $\boldsymbol{p} \rightarrow -\boldsymbol{p}$, $\boldsymbol{E} \rightarrow -\boldsymbol{E}$
- Axial vectors keep sign
  - ☞ $\sigma \rightarrow \sigma$, $\boldsymbol{B} \rightarrow \boldsymbol{B}$
- Parity-conserving interactions: EM, strong
  - ❑ Only PC observables
    - ☞ $A = \boldsymbol{p} \bullet \boldsymbol{p}'$, $U \sim E^2+B^2$
- Weak interactions violate parity
  - ❑ PV observables
    - ☞ $A = \sigma \bullet \boldsymbol{p}$, $U \sim \boldsymbol{E} \bullet \boldsymbol{B}$

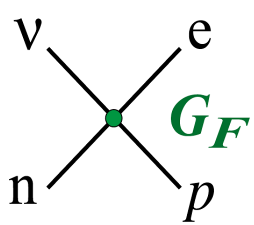


Weak Interactions

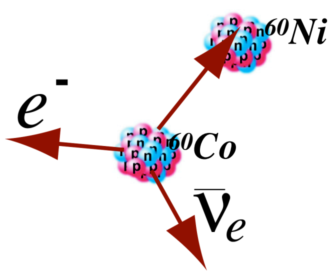


Nuclear (neutron) β Decay: Effective Fermi Theory for weak interactions: with universal coupling G_F

Weak Interactions

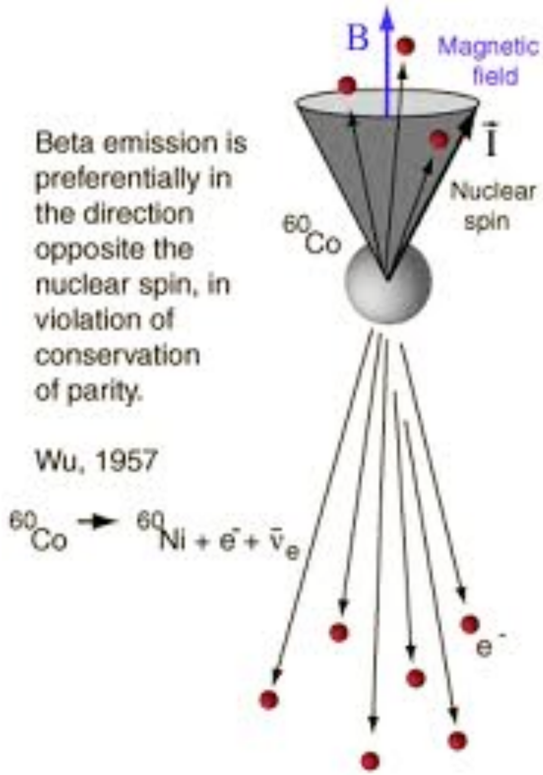


Nuclear (neutron) β Decay: Effective Fermi Theory for weak interactions: with universal coupling G_F

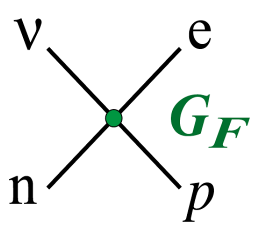


Weak decay of ^{60}Co Nucleus

1957: observed anisotropy in β-emission when nuclear spin is aligned with the magnetic field: signature of parity violation



Weak Interactions



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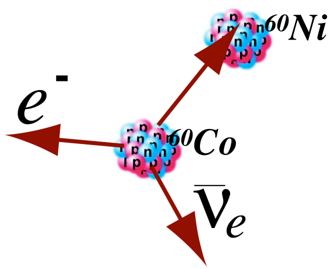

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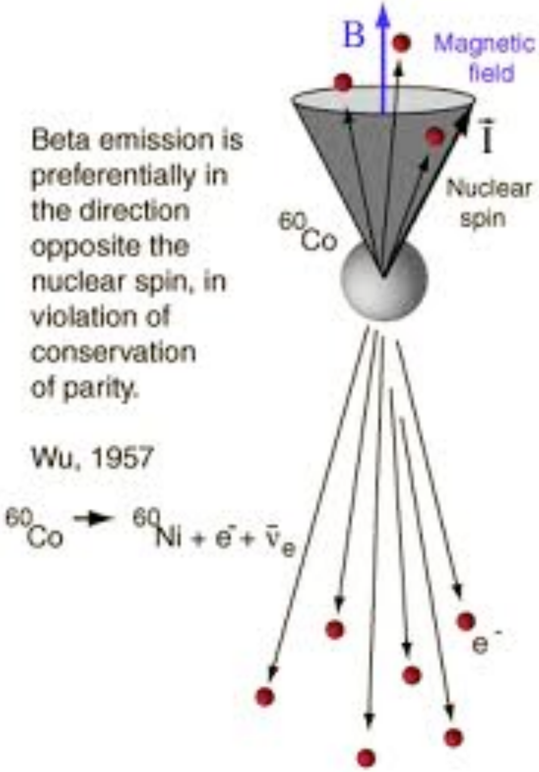
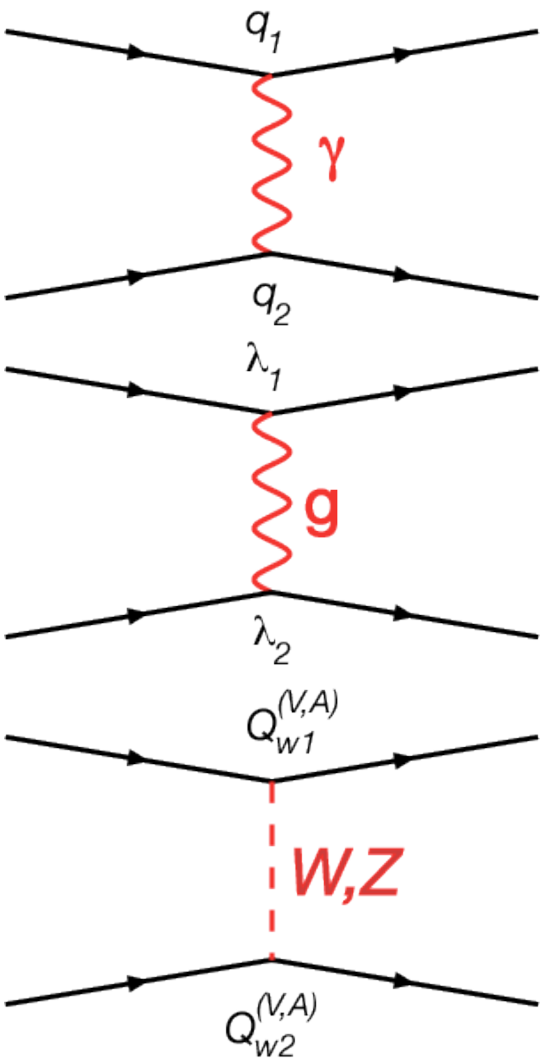


(Charged) weak interactions violate parity maximally

Parity Violation Measurements enable sensitive probes of (electro)weak interaction

Standard Model Primer

3 fundamental interactions



Electromagnetic: $U=q_1q_2/r$

Vector couplings

Strong: $U=\lambda_1\lambda_2/r$

Vector couplings

Weak: $U=Q_{w1}Q_{w2}\exp(-M_{W(Z)}r)/r$

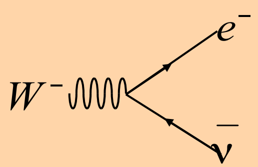
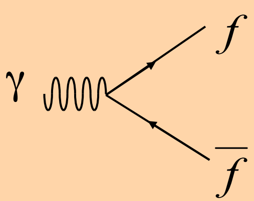
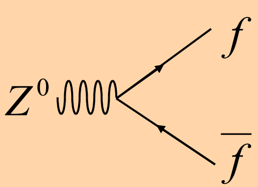
Axial ($W^{\pm}$,Z^0) and vector (Z^0) couplings

Electroweak Theory

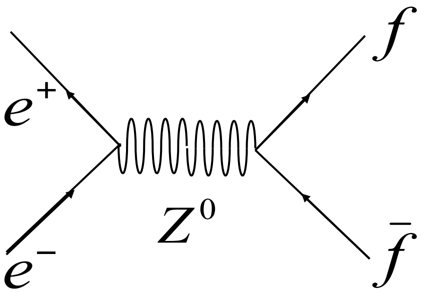
$SU(2)_L$ x U(1), with isotriplet field W_i^μ and isosinglet field B^μ

$SU(2)_L$ coupling constant is g
U(1) coupling constant is g'

W_1^μ, W_2^μ are charged fields and correspond to W^+, W^- particles
W_3^μ, B^μ are neutral and can mix, giving the Z^0 and γ particles
Weak mixing angle: $g' = g \tan\theta_W$

	LH coupling	RH coupling
	$g/\sqrt{2}$	0
	$Q^f g \sin\theta_W$	$Q^f g \sin\theta_W$
	$(g^2+g'^2)^{1/2}(I_3^f - Q^f \sin^2\theta_W)$	$(g^2+g'^2)^{1/2}(-Q^f \sin^2\theta_W)$

Parity Violation at Z-pole



$$\frac{d\sigma}{d\cos\theta} \propto \left(v_f^2 + a_f^2\right) \times \left[(1 - P_e A_e)(1 + \cos^2\theta) + 2A_f(A_e - P_e)\cos\theta\right]$$

$$A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{2v_f a_f}{v_f^2 + a_f^2}$$

$$A_{e,\mu,\tau} = 0.1513 \pm 0.0021$$

$$A_b = 0.922 \pm 0.020$$

$$A_s = 0.895 \pm 0.091$$

$$A_c = 0.670 \pm 0.026$$

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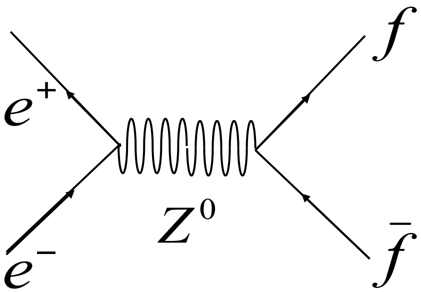

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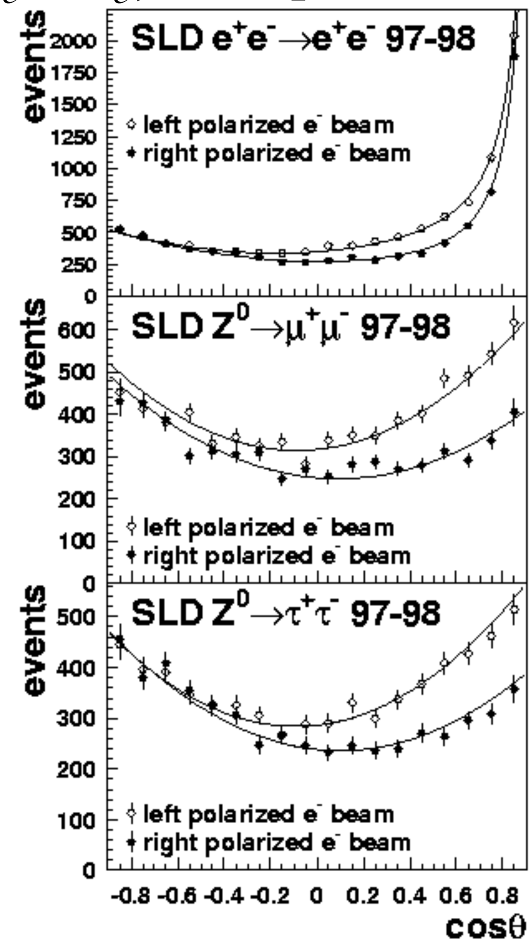
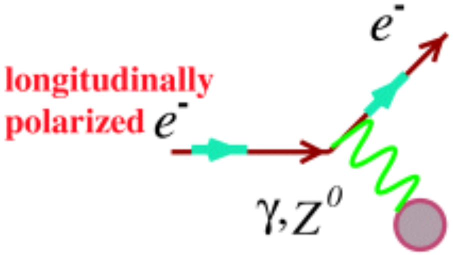


Parity Violation at Low Q^2: Electron Scattering



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

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

$$Q^2 \sim 0.01 - 1\ \mathrm{GeV}^2 \longrightarrow A_{PV} \lesssim 10^{-7} - 10^{-4}$$

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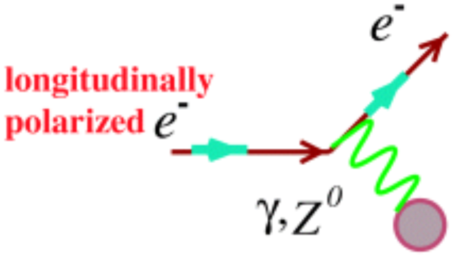

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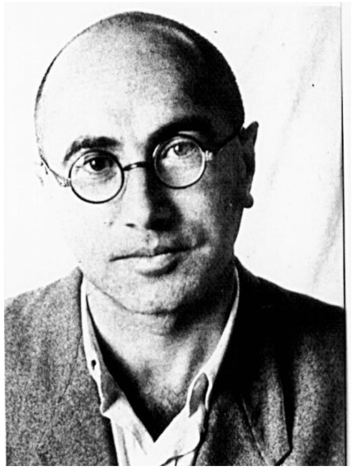
Idea: Yakov Zel'dovich
(JETP Letters 36, 954 (1959))



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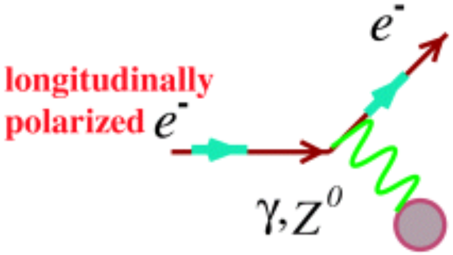

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First measurement: SLAC E-122 (lepton-nucleon DIS):

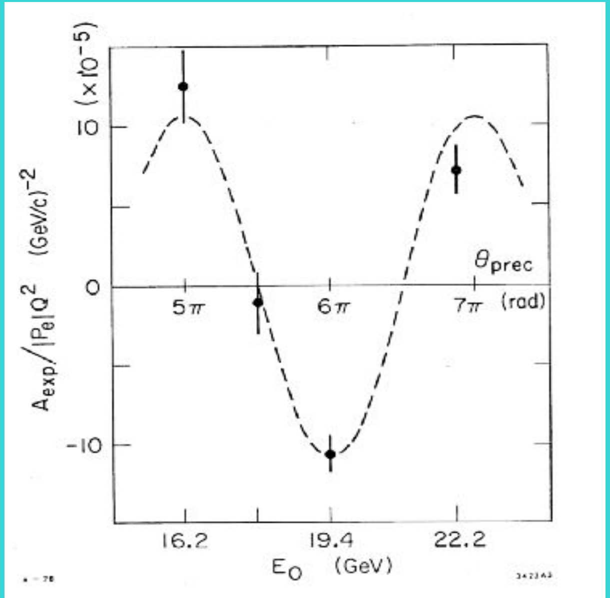
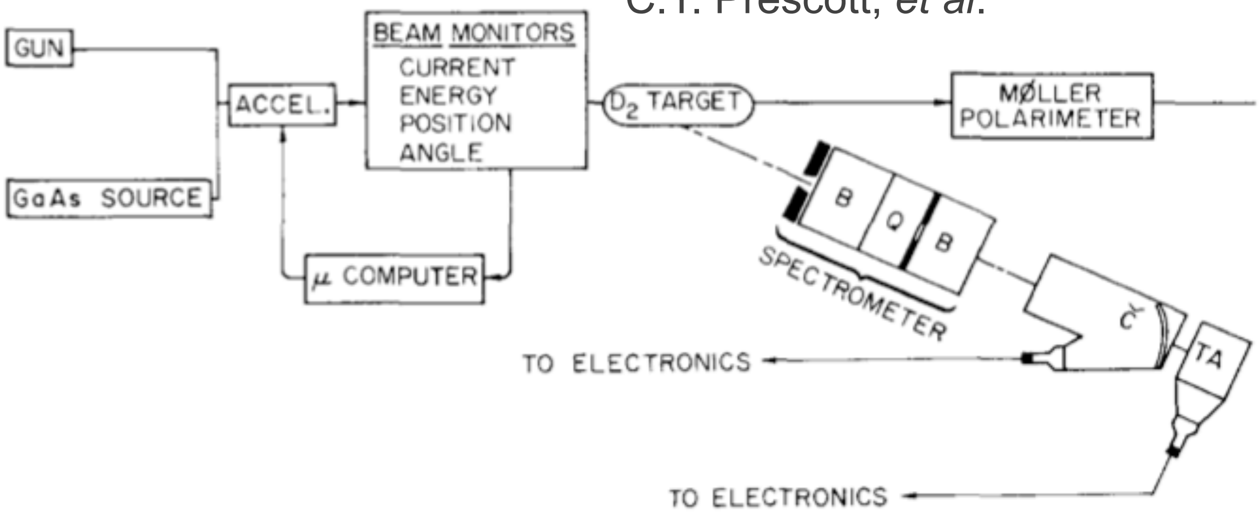


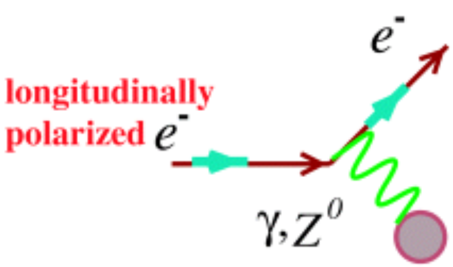
Fig. 3

$$\sin^2\theta_W = 0.224 \pm 0.020$$

Parity Experiment: Main Ingredients

C.Y. Prescott, *et al.*





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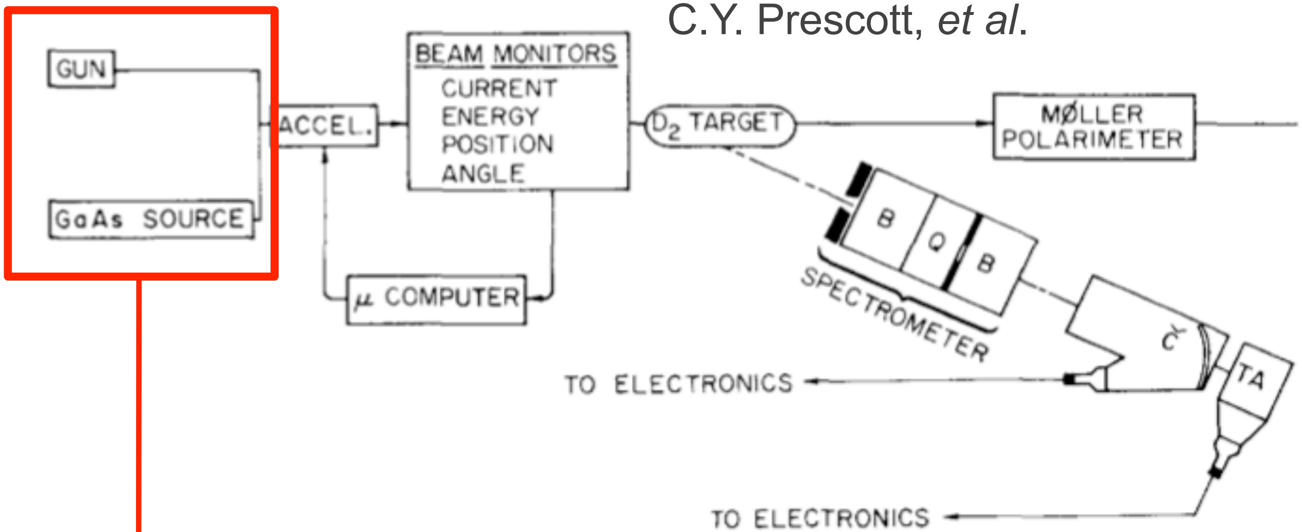
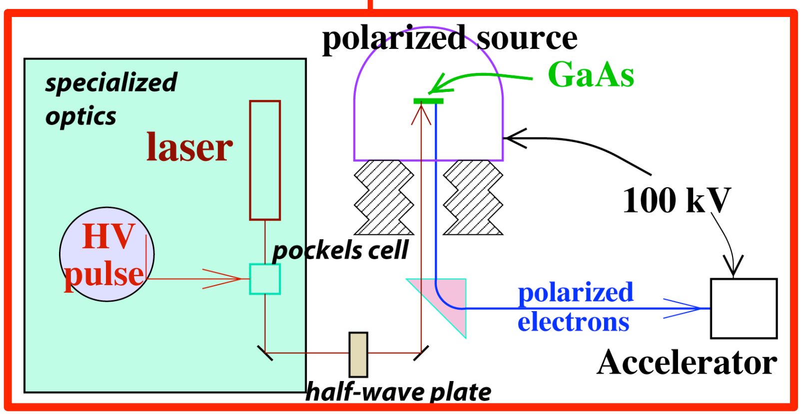
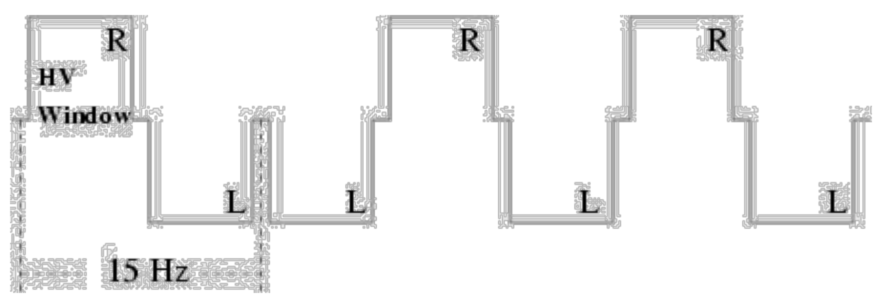




- ✧High statistics: 10^{12} electrons → ppm uncertainty
- ✧Rapid helicity reversal: minimize effect of slow drifts
- ✧ Pseudo-random helicity sequence
  - Helicity state, followed by its complement
  - Data analyzed as "pulse-pairs"



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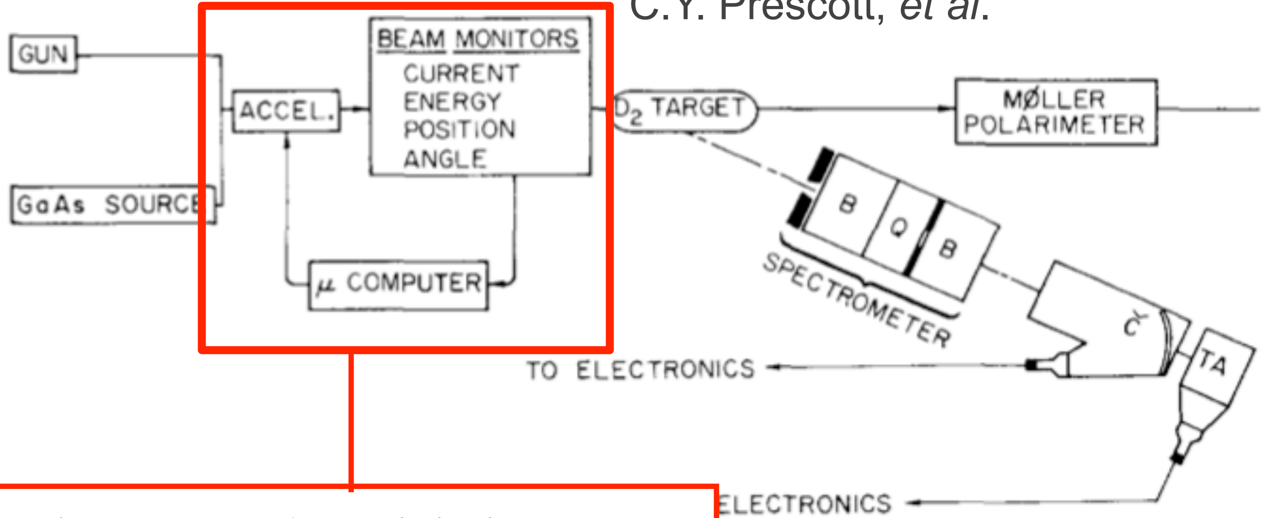
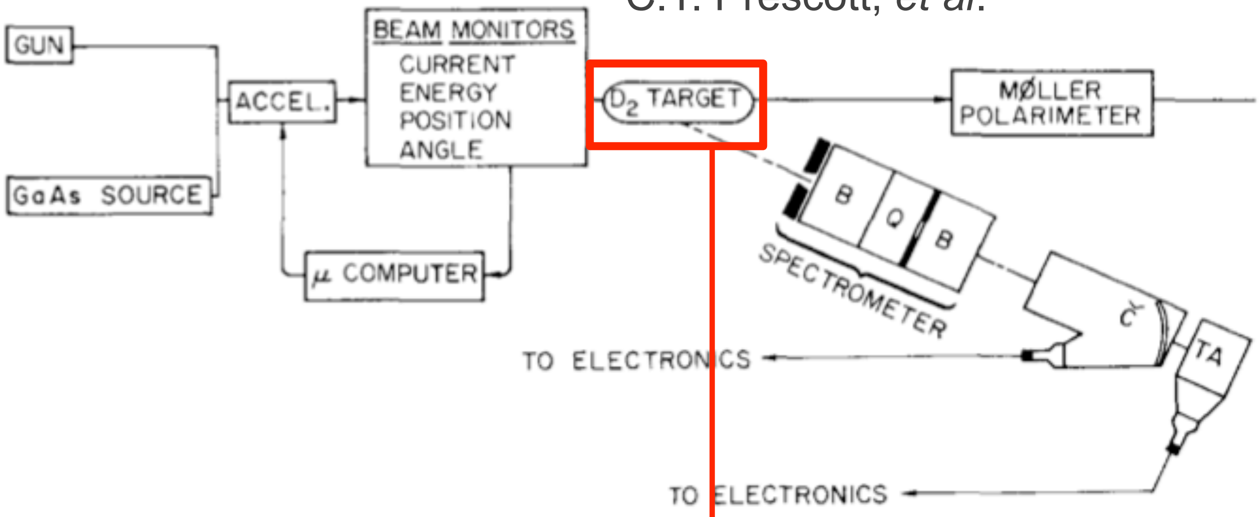


- Accelerator tuned to minimize helicity-dependent differences in beam properties
- Beam Monitors to measure helicity-correlated changes in beam parameters

Parity Experiment:Main Ingredients

C.Y. Prescott, *et al.*



- High-power cryotarget for high luminosity

Parity Experiment: Main Ingredients

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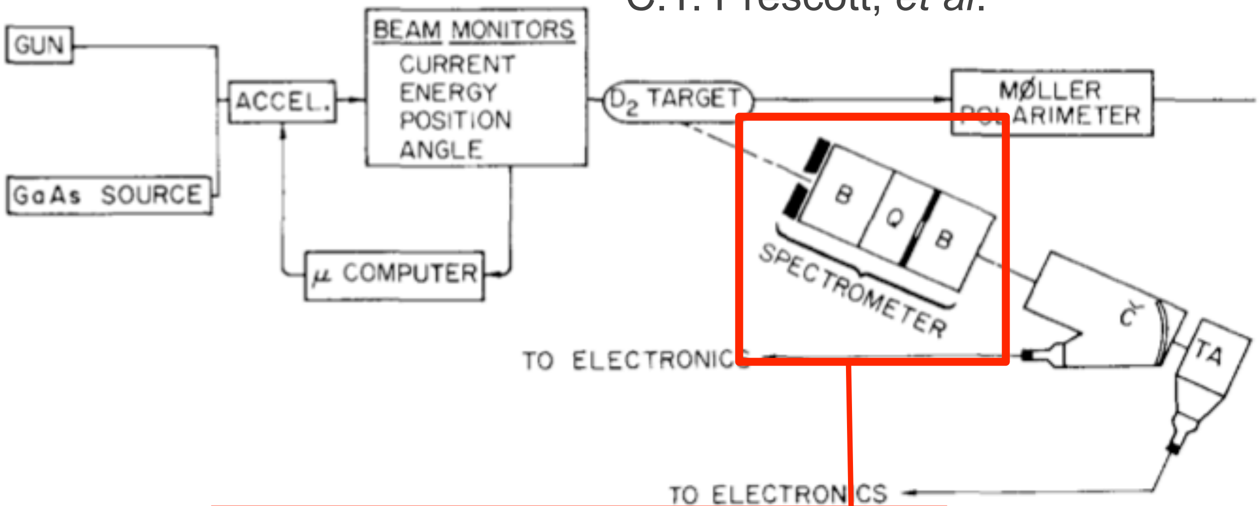

• Magnetic spectrometer directs flux to background-free region

Parity Experiment:Main Ingredients

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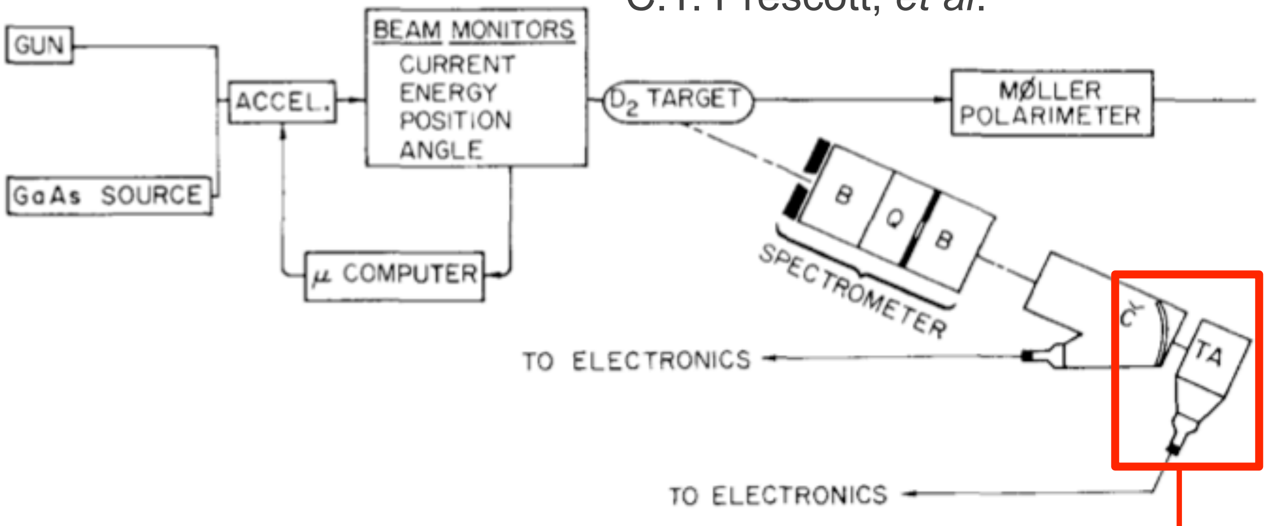
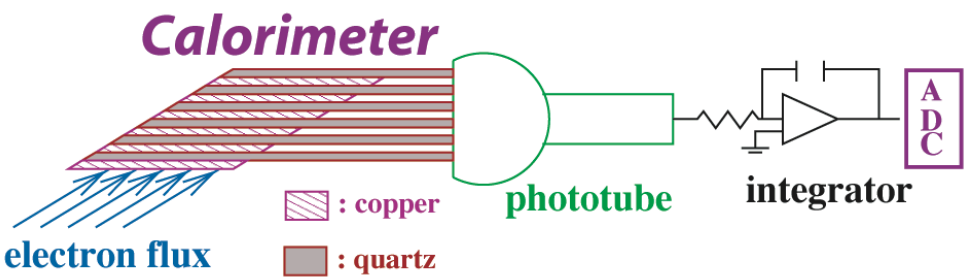


- Flux Integration measures high rate without deadtime



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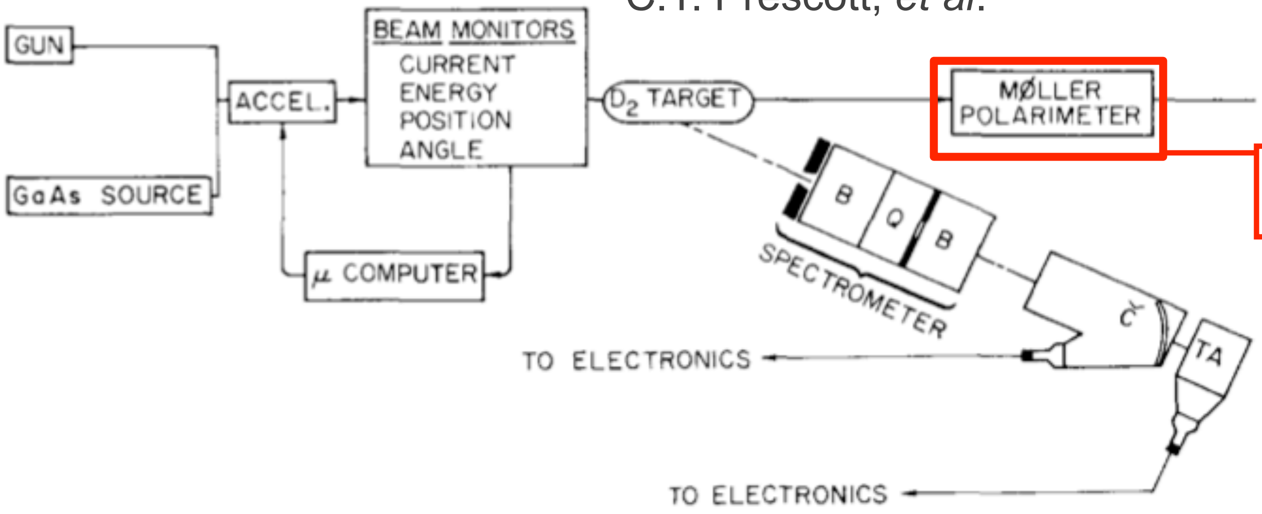
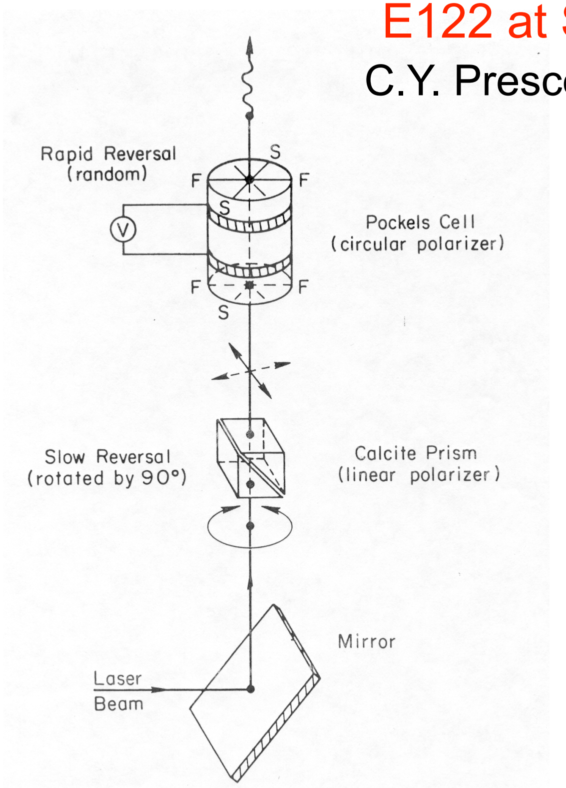


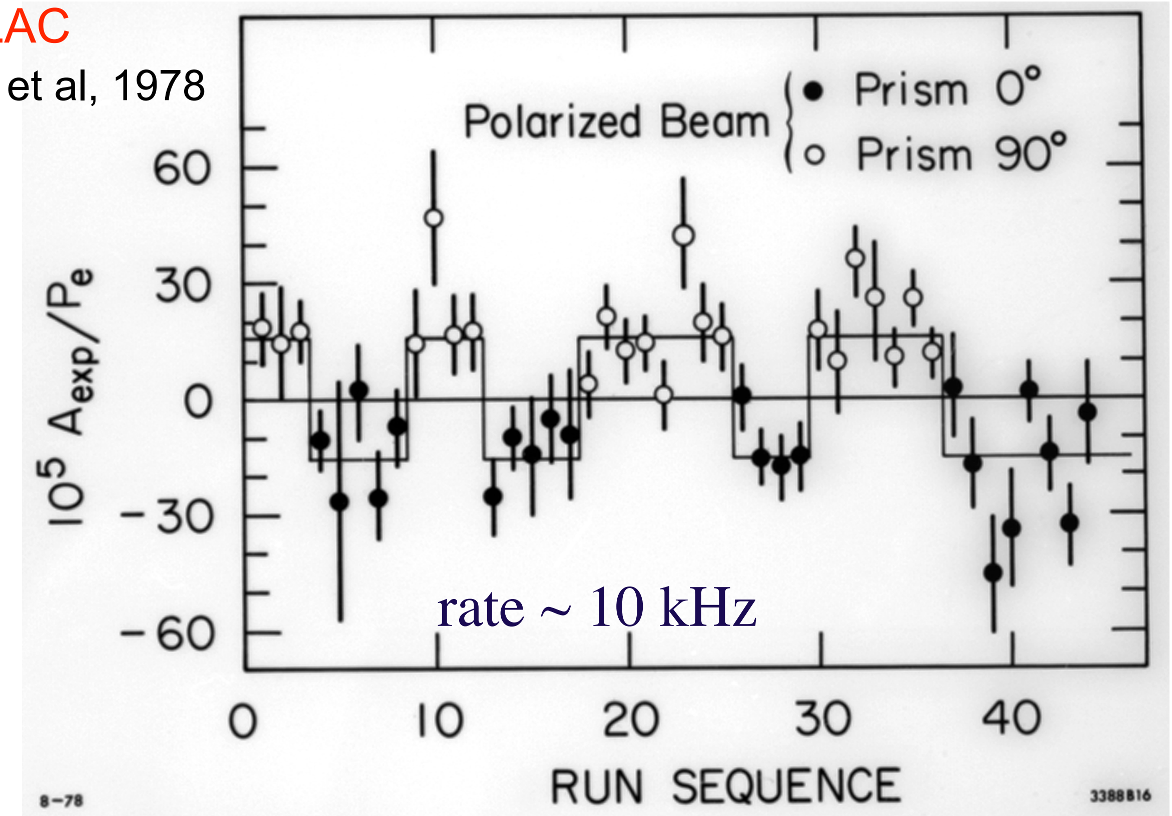
- Polarimetry

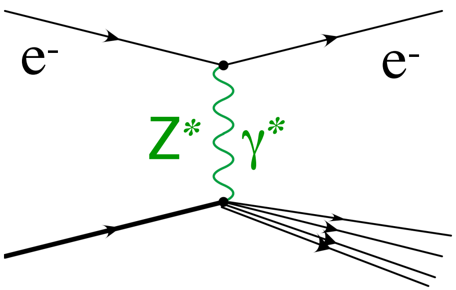
A Landmark Experiment

E122 at SLAC

C.Y. Prescott et al, 1978







$$A_{PV} \sim 10^{-4}$$
$$\delta(A_{PV}) \sim 10^{-5}$$

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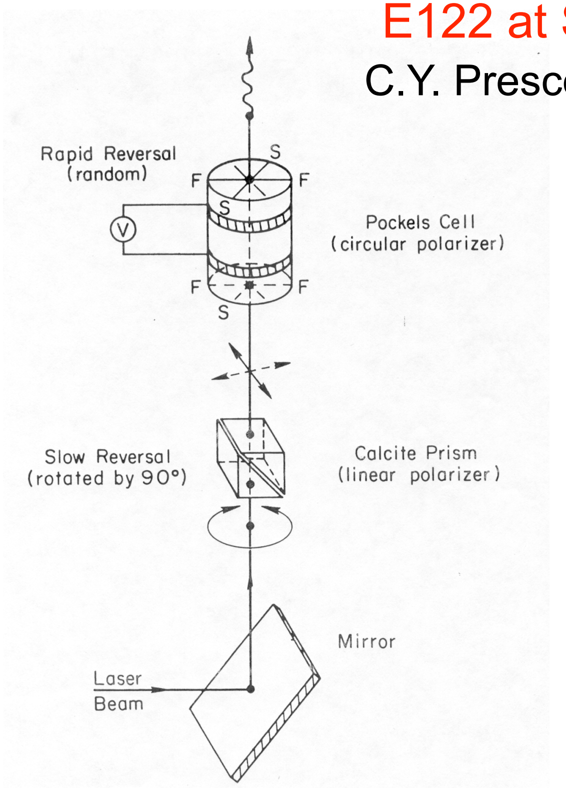
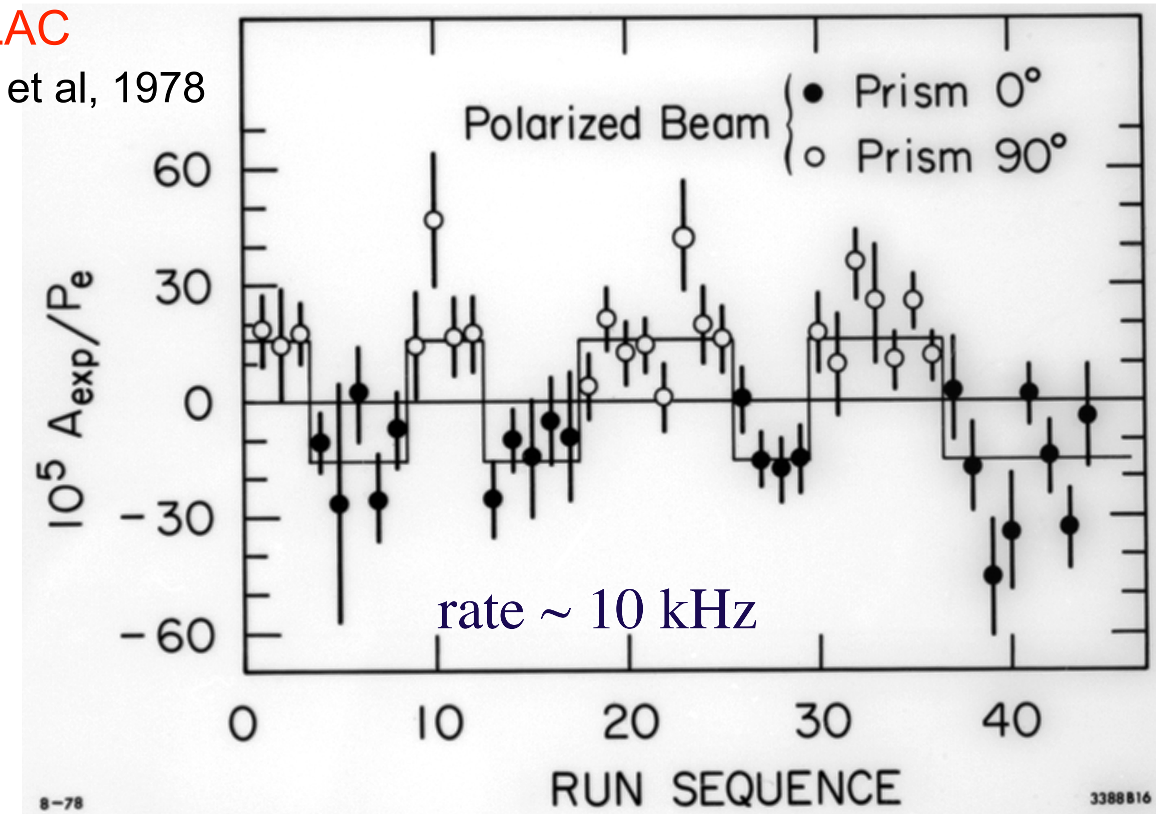
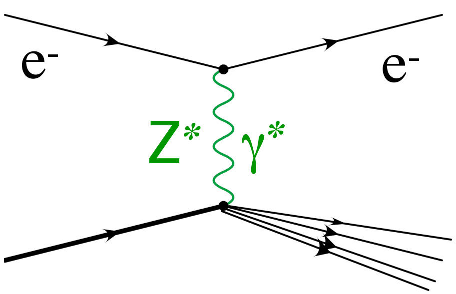


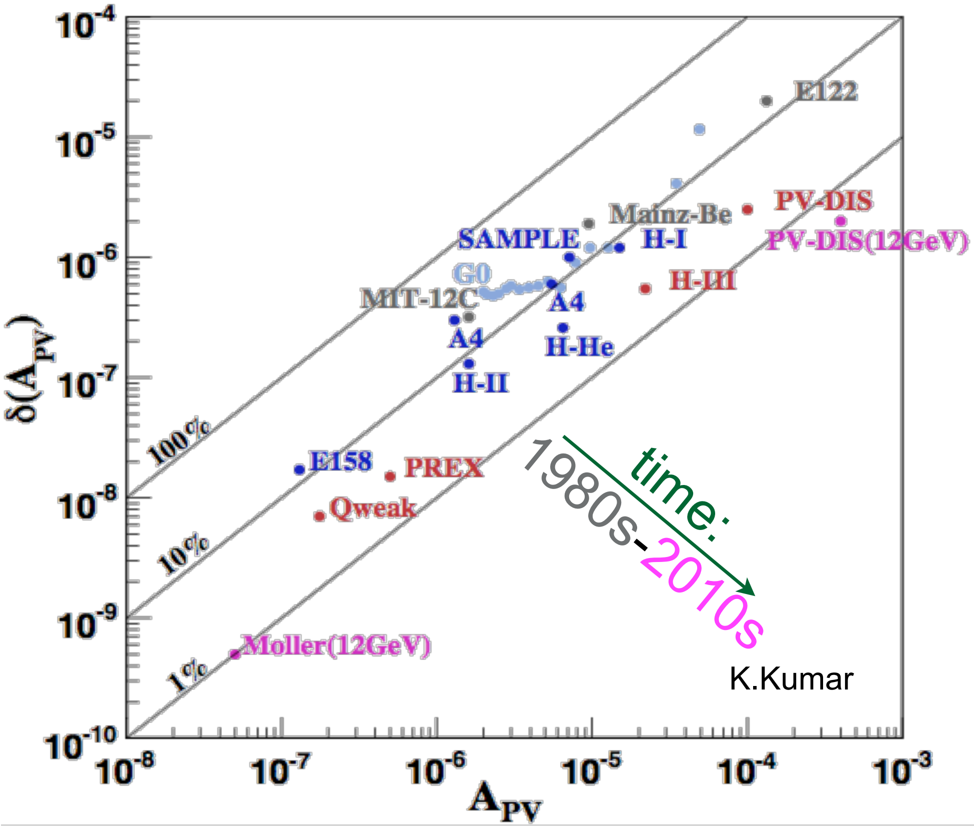




- Unambiguously established PV in Weak Neutral Current Interactions
- $\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering

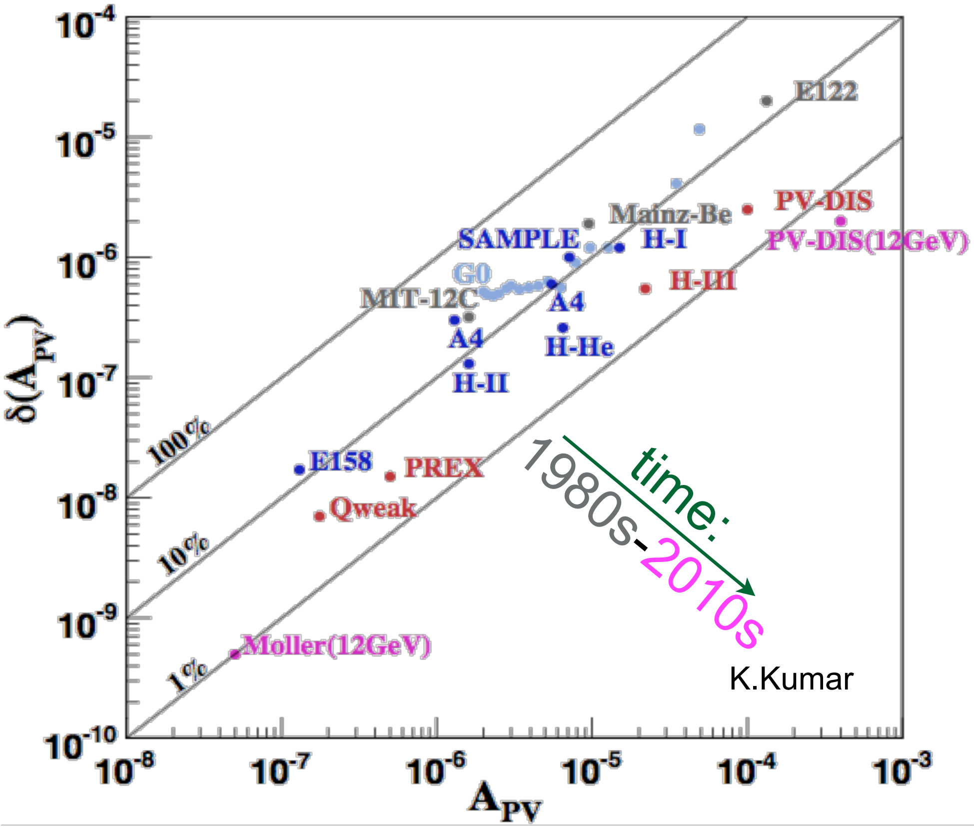
$$A_{PV} \sim 10^{-4}$$
$$\delta(A_{PV}) \sim 10^{-5}$$

"Moore's Law" for PV Experiments



- Foundation of Standard Model
  - E122 @ SLAC
- Perturbative and non-perturbative QCD structure of the nucleon
  - Bates-^{12}C, SAMPLE (MIT-Bates), Mainz-Be, A4 @ Mainz, G0, HAPPEX, PV-DIS @ JLab
- Neutron skin of a heavy nucleus
  - PREX @ JLab
- Beyond Standard Model Searches
  - E158 @ SLAC, QWeak, MOLLER, SOLID @ JLab

"Moore's Law" for PV Experiments



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Parity-violating electron scattering has become a precision tool

→ Sub-ppb statistical and systematic uncertainties, sub-1% normalization

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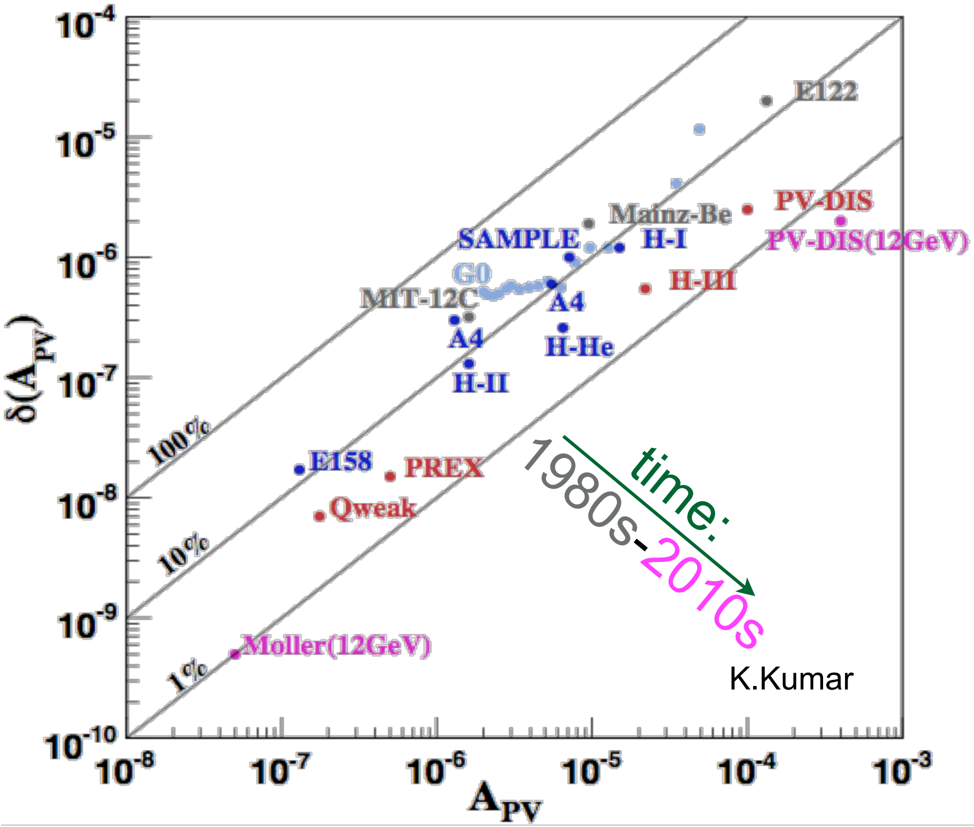

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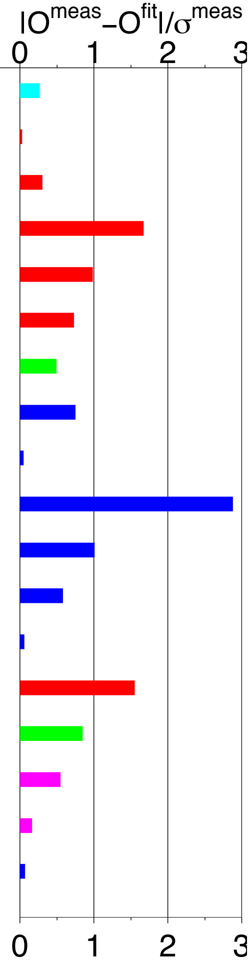
Technical progress: photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

Electroweak Measurements

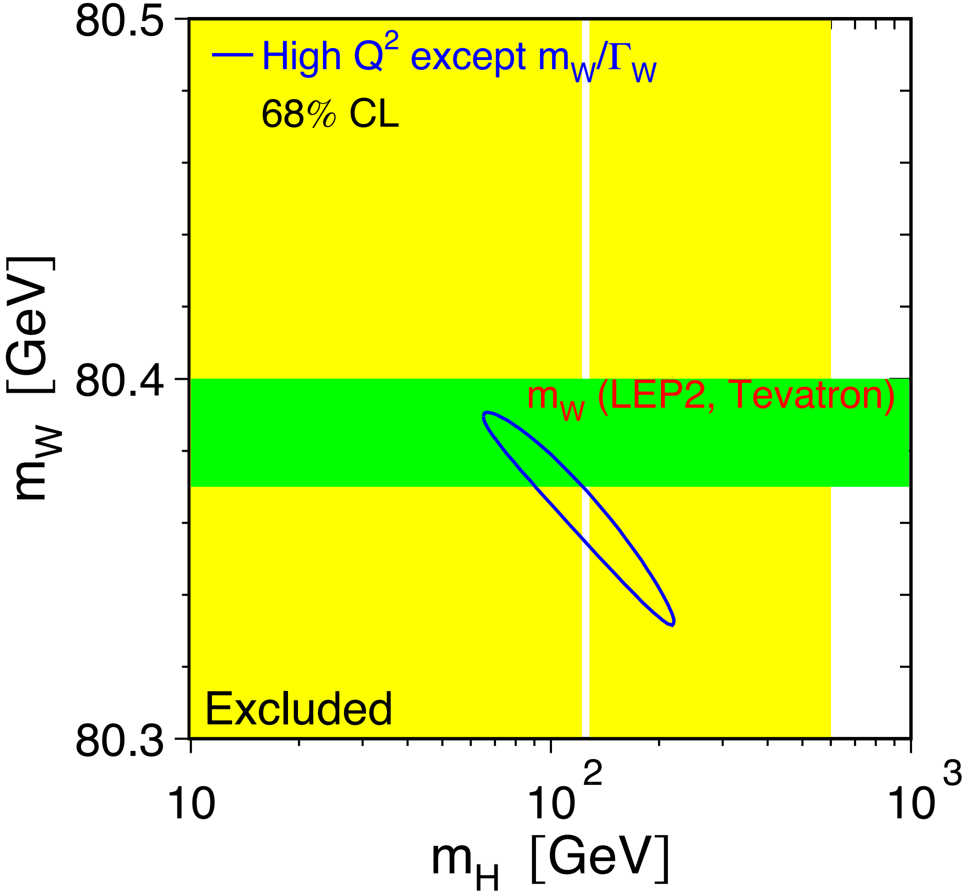
Precision Electroweak Physics

(LEP EWWG, Mar 2012/Feb 2013)

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012



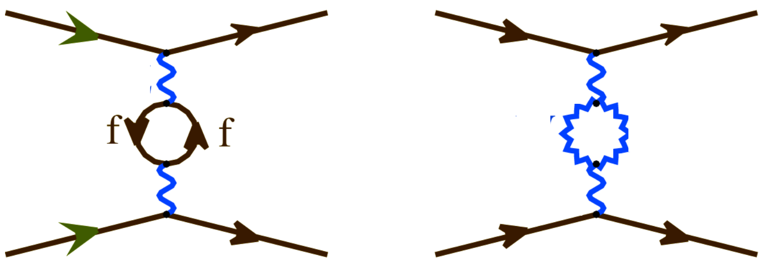
"High Energy" EW Data

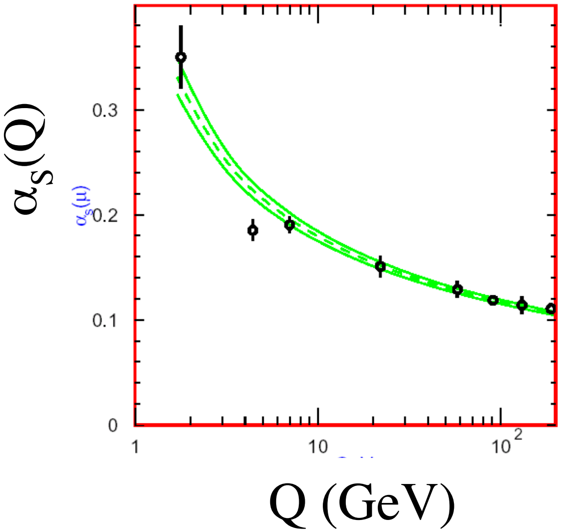
- Spectacular precision
  - Quantum loop level (LO to NNLO)
  - Precise indirect constraints on top and Higgs masses
    - ☞ Before confirmation by direct observation !
  - General consistency with the Standard Model
    - ☞ Few smoking guns
    - ☞ Leptonic and hadronic Z couplings seem inconsistent ?
- Direct searches have not yielded new physics phenomena (so far)

➔ Complementary sensitivity at low energies
  - Rare or forbidden processes
  - Symmetry violations
  - ➔ Precision measurements

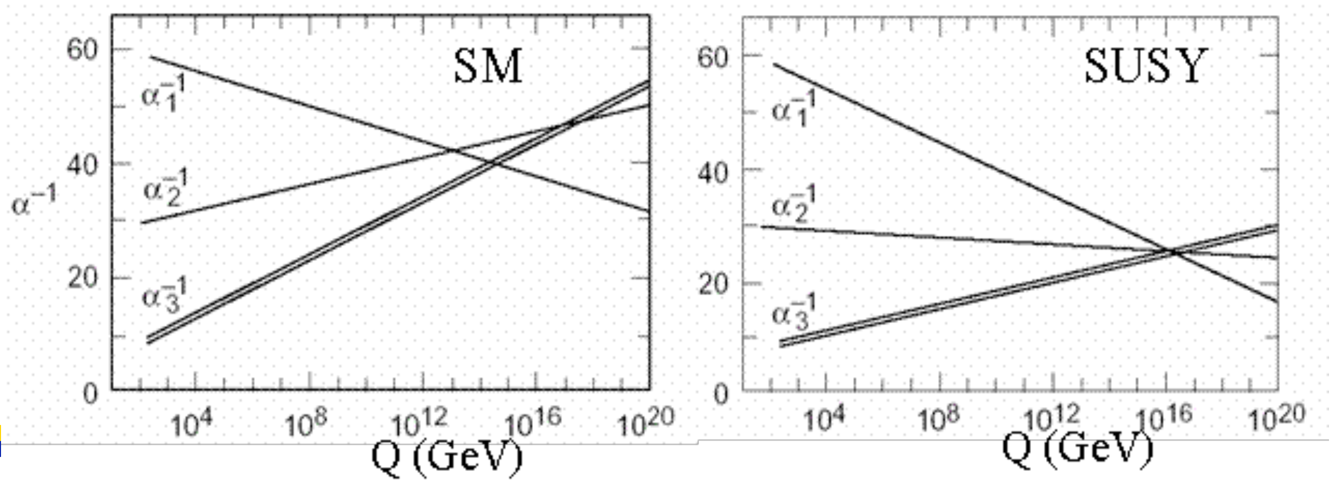
Running of Coupling Constants

Generic property of any field theory: higher order corrections (loops) induce momentum (distance) dependence of coupling constants



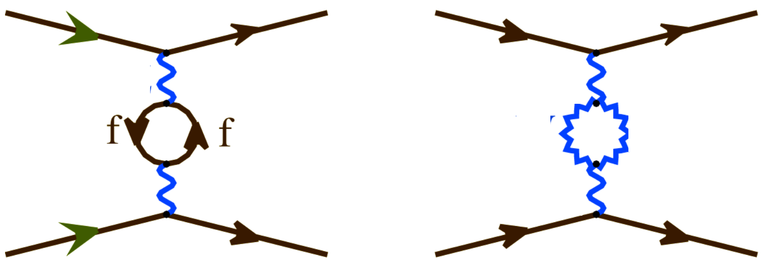


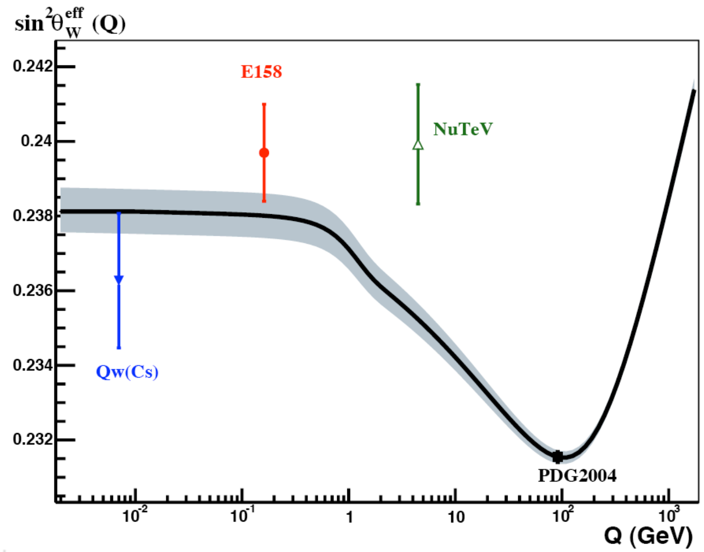
Grand Unification ?



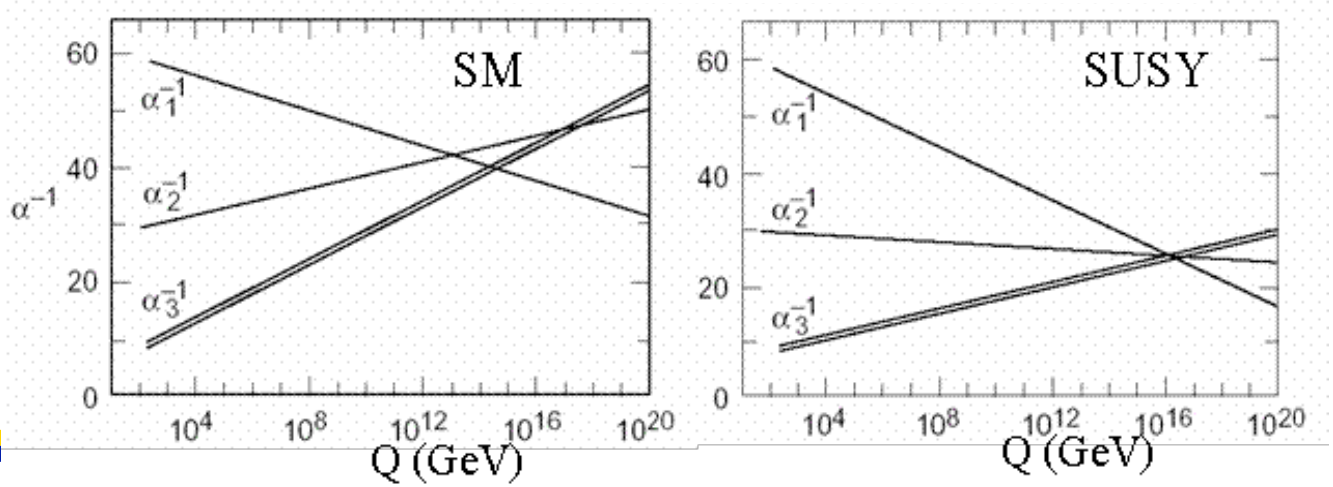
Running of Coupling Constants

Generic property of any field theory: higher order corrections (loops) induce momentum (distance) dependence of coupling constants





Grand Unification ?



Direct vs Indirect Searches

(according to Grimm Brothers)

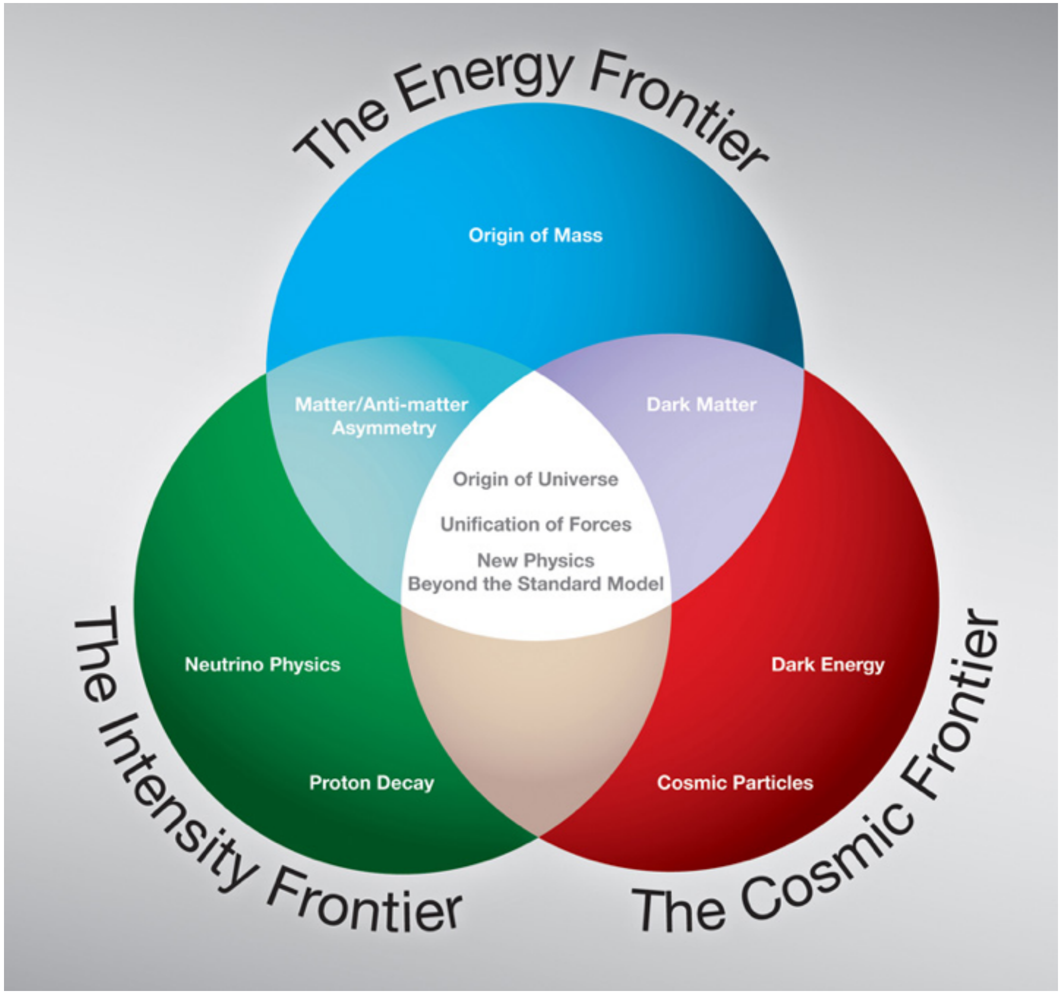
Direct vs Indirect Searches

(according to Grimm Brothers)

Direct vs Indirect Searches

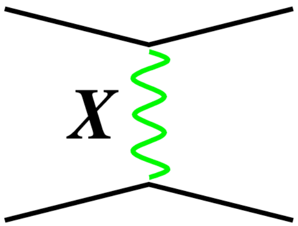
(according to Grimm Brothers)

Direct vs Indirect Searches
(according to DOE)

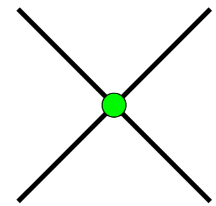


Electroweak Physics Away from Z pole

consider



$$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2} \longrightarrow$$



Contact interaction

$Q^2 \sim M_Z^2$ **on resonance:** A_Z ***imaginary*** $\longrightarrow A_Z^2 \left[1 + \frac{A_X^2}{A_Z^2} \right]$

no interference!

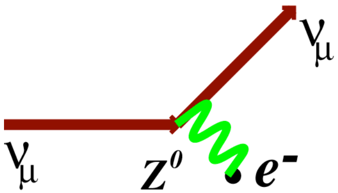
➔ Precision Z observables establish anchor points for SM

➔ Low energy observables sensitive to interference between SM and NP

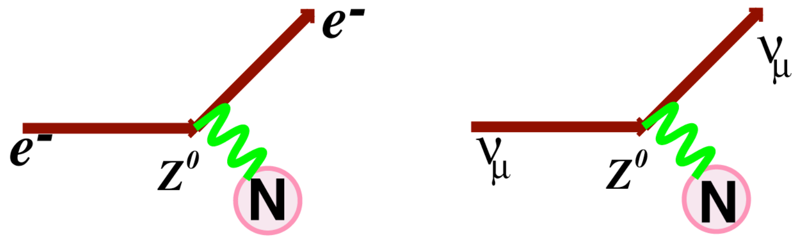
➔ Current “low energy” experiments are accessing scales of beyond 10 TeV

➔ Alternatively (ignoring NP effects), can use EW probes to understand non-perturbative dynamics in hadronic systems

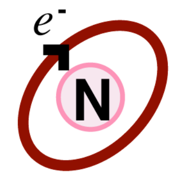
Low Energy Electroweak Measurements



statistics

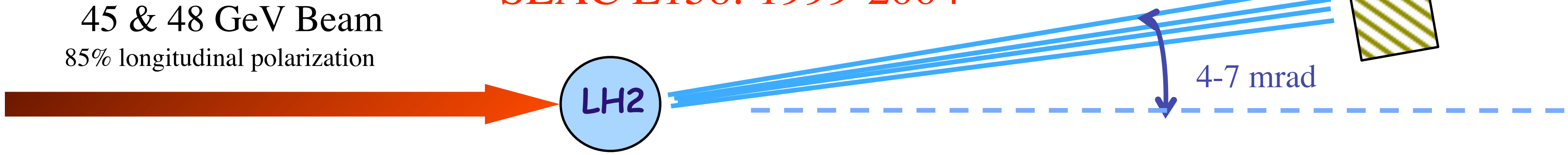


hadronic physics

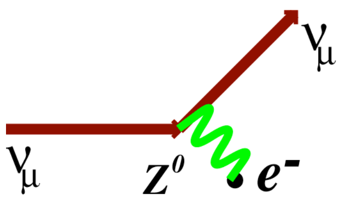


atomic wave function

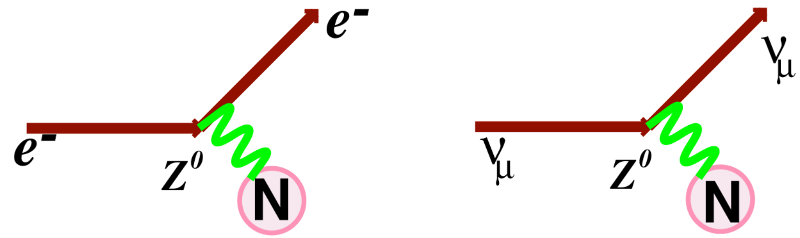
SLAC E158: 1999-2004



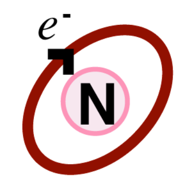
Low Energy Electroweak Measurements



statistics

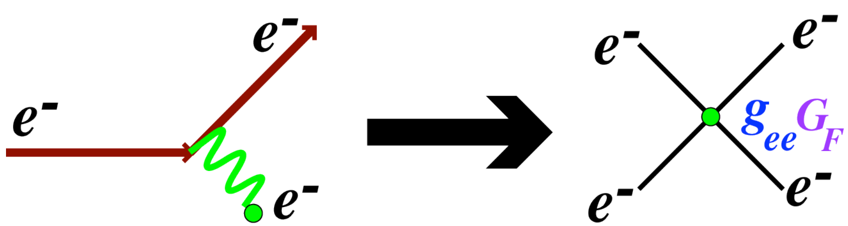


hadronic physics



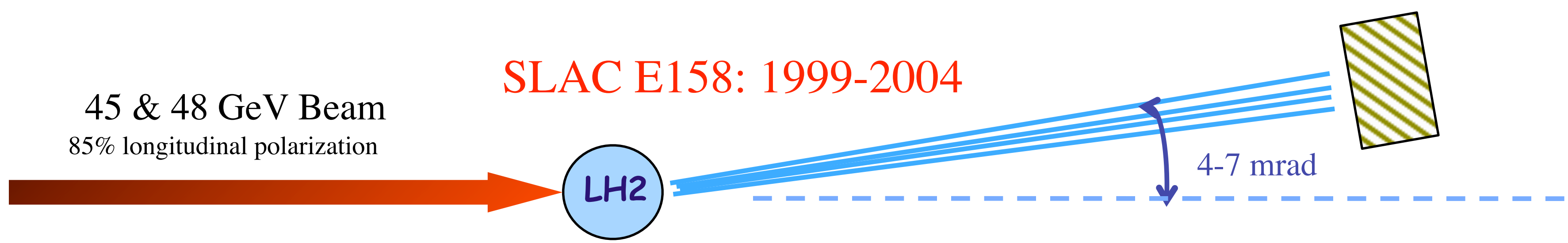
atomic wave function

Polarized Møller Scattering:

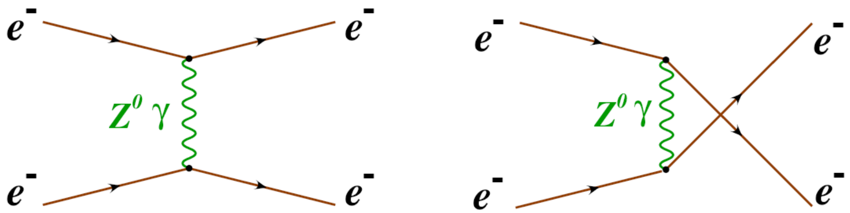


Purely leptonic reaction

$g_{ee} \sim 1 - 4\sin^2\theta_W$



Parity Violation in Møller Scattering



- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_{LR}$$
- Small tree-level asymmetry

$$A_{PV} = -mE\frac{G_F}{\sqrt{2\pi\alpha}}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}\left(\frac{1}{4} - \sin^2\theta_W\right)$$

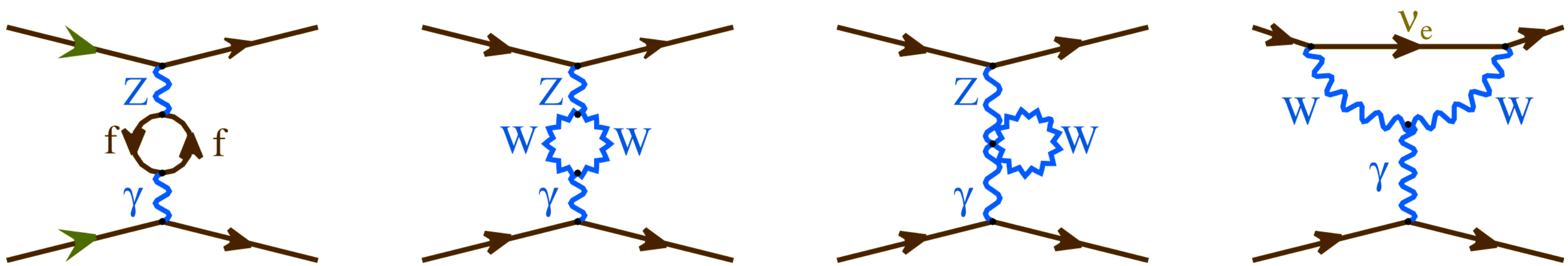
- At tree level, $A_{PV} \approx$ 280 parts per billion
- Raw asymmetry about 130 ppb
  - E158: precision of ~10%

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

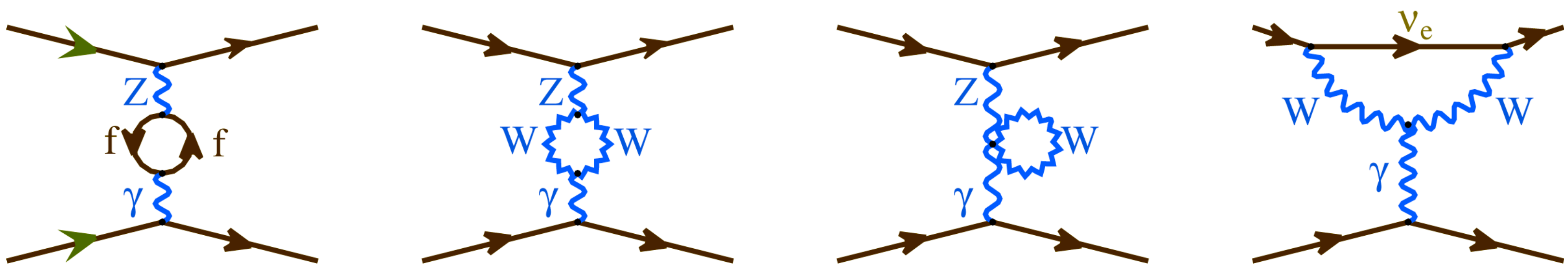
A_{PV} (e^-e^- at Q^2=0.026 GeV^2) = –131 ± 14 (stat) ± 10 (syst) ppb

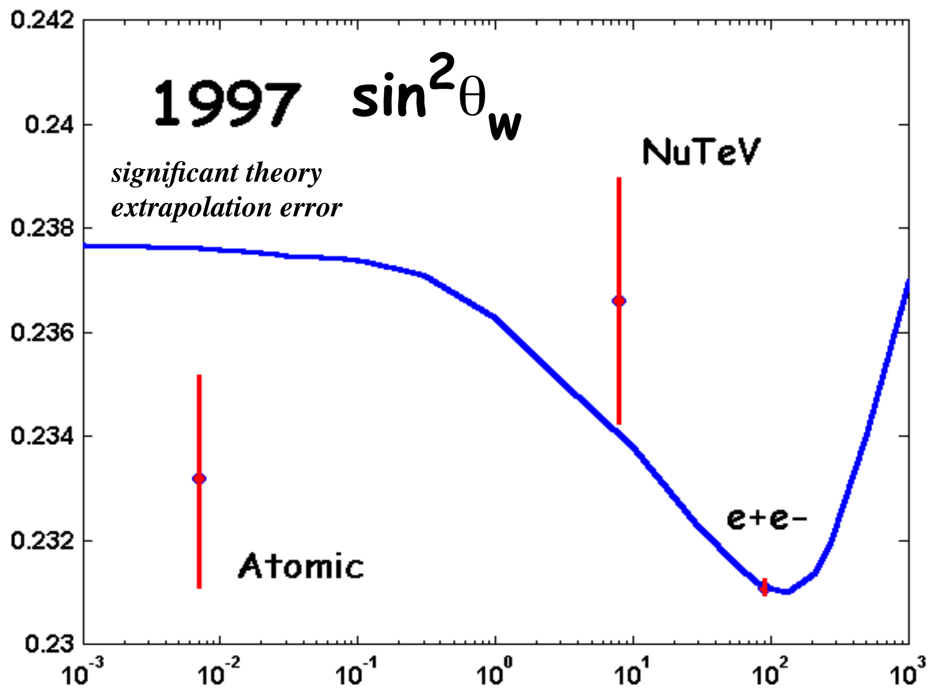
E158 Impact

E158 Impact

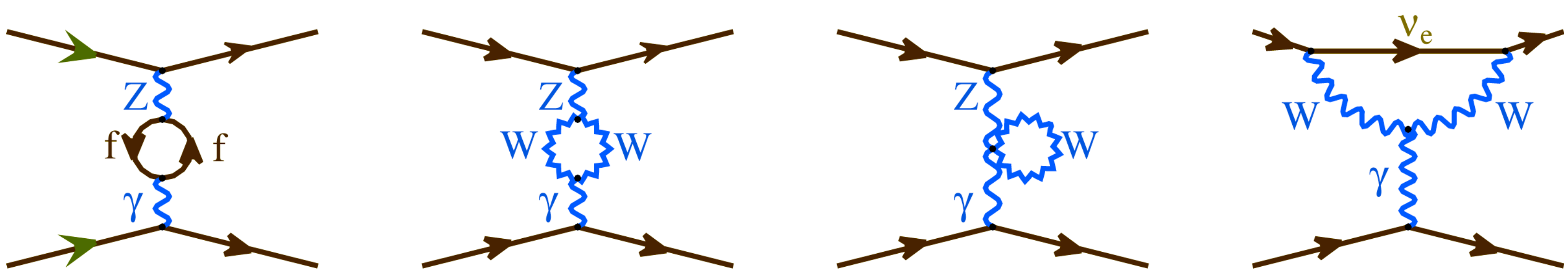


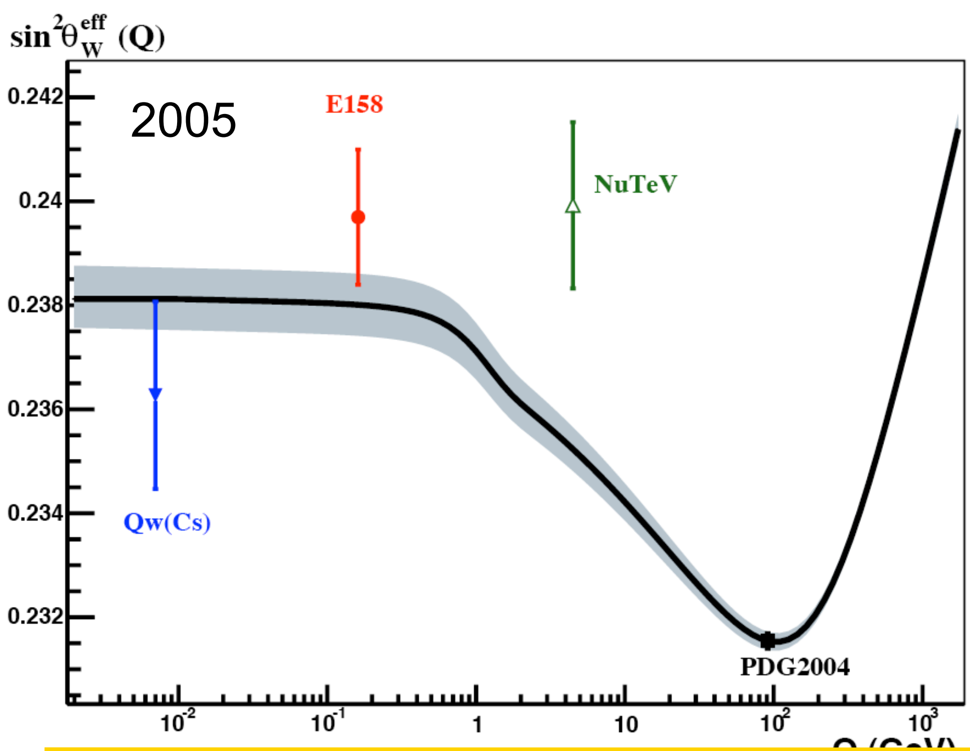
E158 Impact


Z
f
f
γ
Z
W
W
γ
Z
W
γ
ν_e
W
W
γ

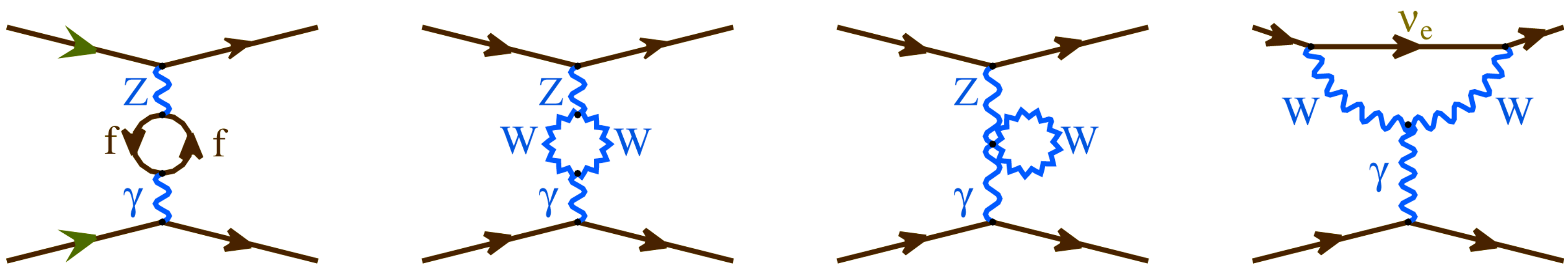

1997 $\sin^2\theta_W$
significant theory
extrapolation error
NuTeV
e+e-
Atomic
0.242
0.24
0.238
0.236
0.234
0.232
0.23
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

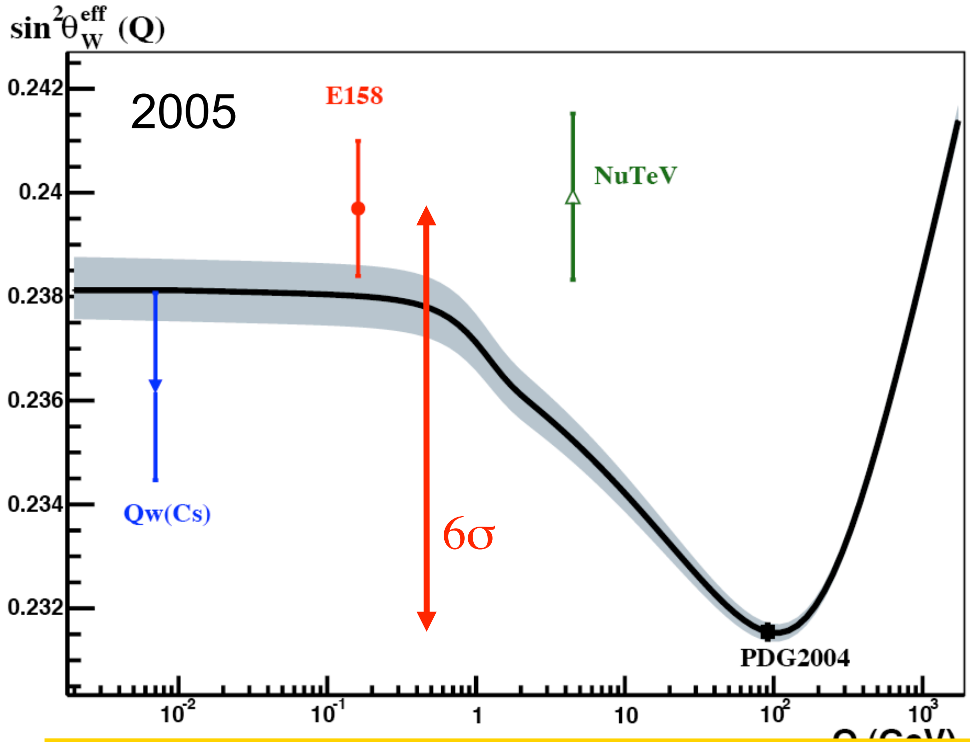
E158 Impact


Z
f
f
γ
Z
W
W
γ
Z
W
γ
ν_e
W
W
γ


$\sin^2\theta_W^{eff}$ (Q)
0.242
0.24
0.238
0.236
0.234
0.232
2005
E158
NuTeV
Qw(Cs)
PDG2004
10^{-2}
10^{-1}
1
10
10^2
10^3

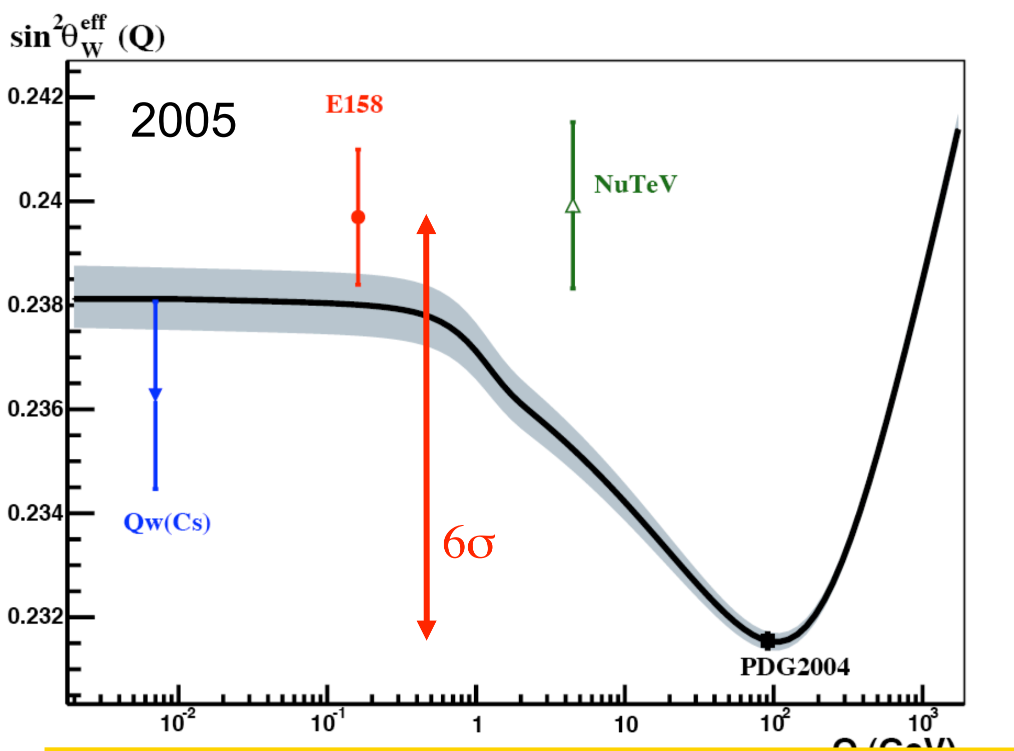
E158 Impact

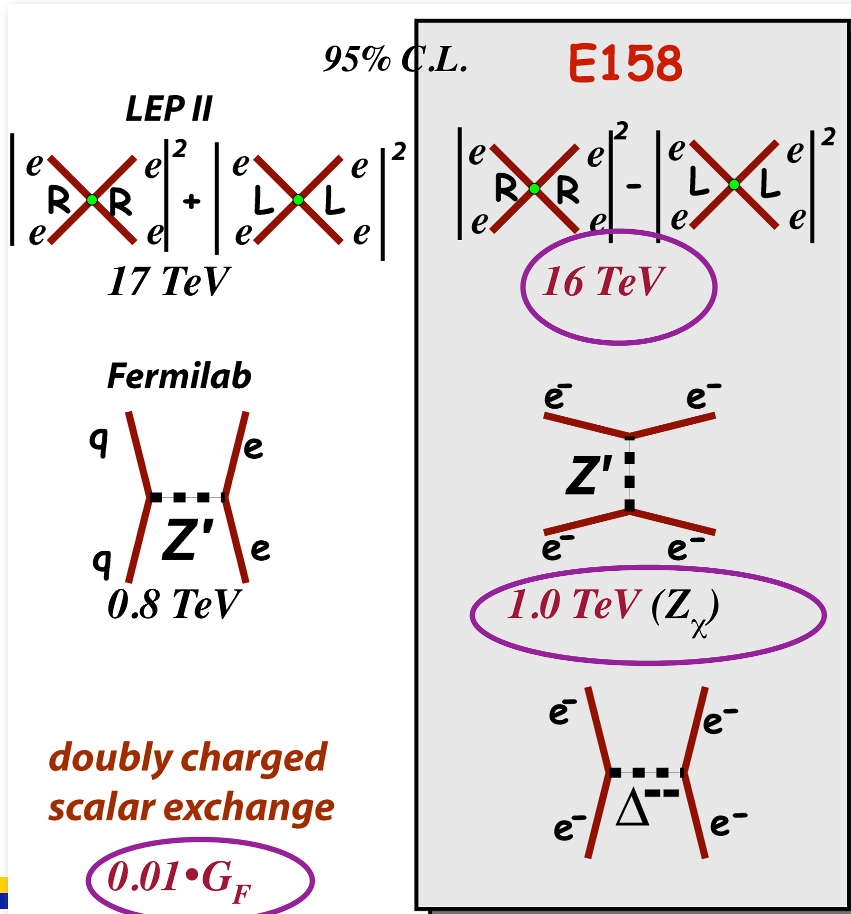

Z
f
f
γ
Z
W
W
γ
Z
W
γ
ν_e
W
W
γ


$\sin^2\theta_W^{eff}$ (Q)
2005
E158
NuTeV
Qw(Cs)
6σ
PDG2004
0.242
0.24
0.238
0.236
0.234
0.232
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}

E158 Impact

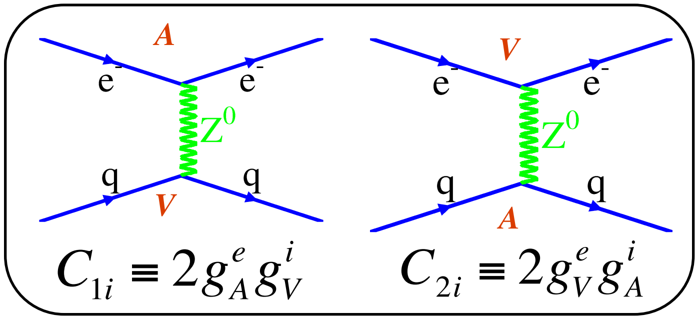
Limits on "New" Physics



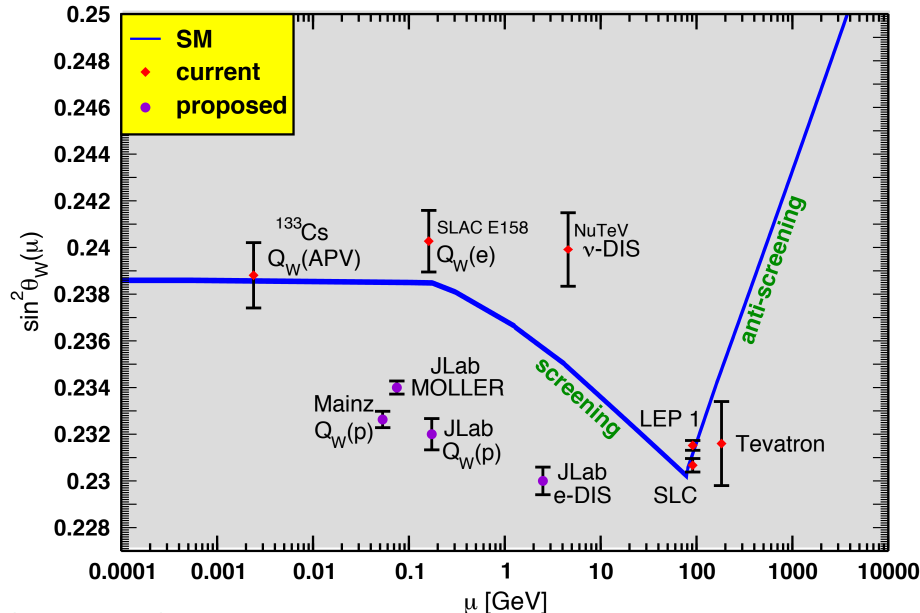


Precision Weak Charges

Current and future measurements of parity-violating asymmetries



e-q and e-e couplings



Elastic Electron-Proton Scattering

- ★ QWeak at JLab has accumulated full dataset
- ★ New proposal to improve QWeak by a further factor of 2 at Mainz

Elastic Electron-12C Scattering ?

- ★ B. Marciano, K. Gerz in PS1C

R&D beginning; physics 2015-20

Deep Inelastic Scattering off Deuterium

- ★ 6 GeV JLab experiment completed: analysis ongoing
- ★ SoLID: New Apparatus with a large solenoid using 11 GeV beam

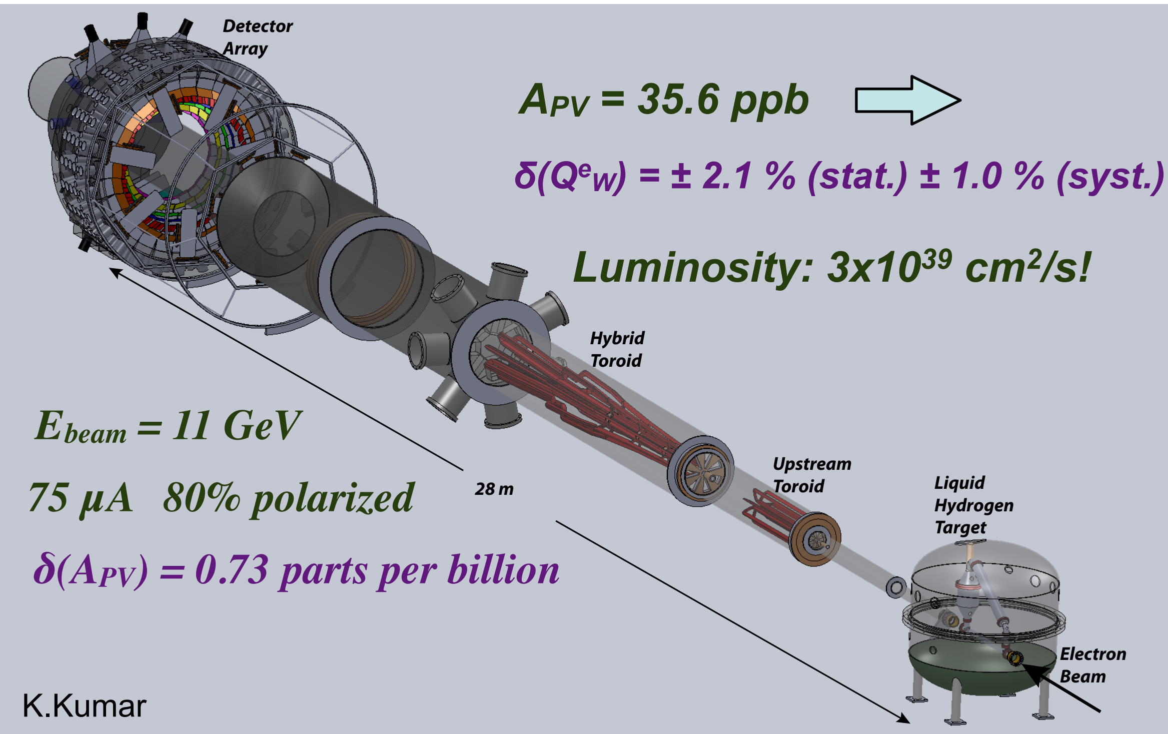
Møller Scattering

- ★ MOLLER: New project to improve E158 by a factor of 5

After JLab energy upgrade in 2013; physics 2017-20

MOLLER at JLab

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



A_{PV} = 35.6 ppb ⇨

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

Luminosity: 3×10^{39} cm^2/s!

E_{beam} = 11 GeV

75 μA 80% polarized

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

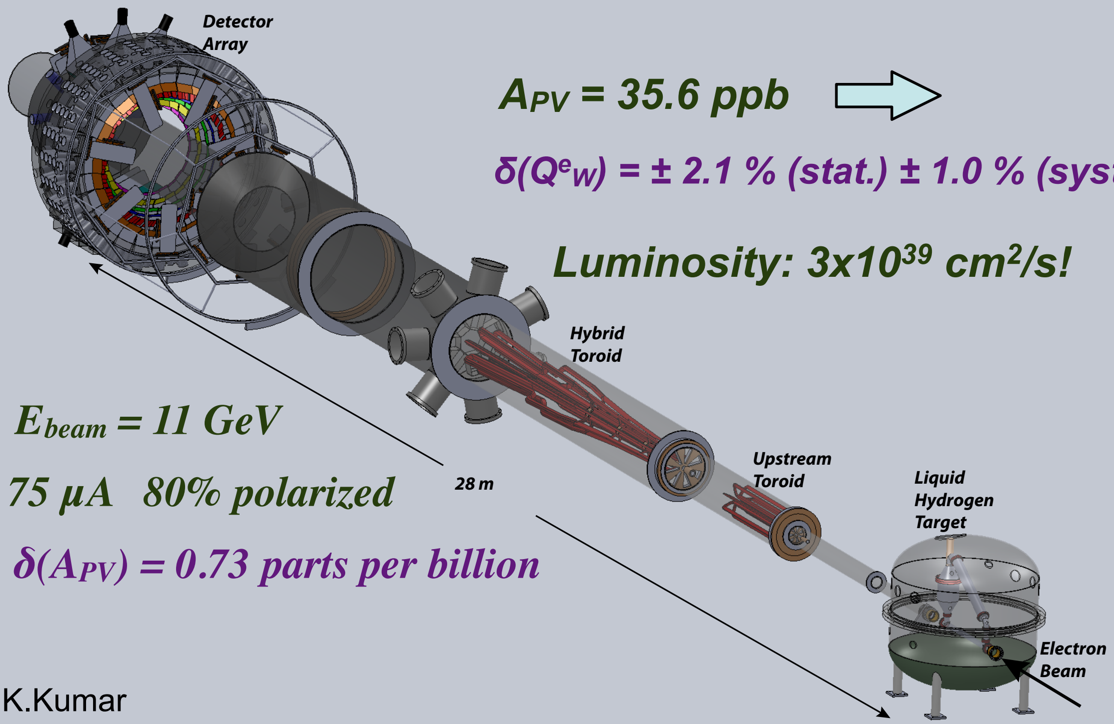
$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \Rightarrow \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

best contact interaction reach for leptons at low OR high energy

MOLLER at JLab

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

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



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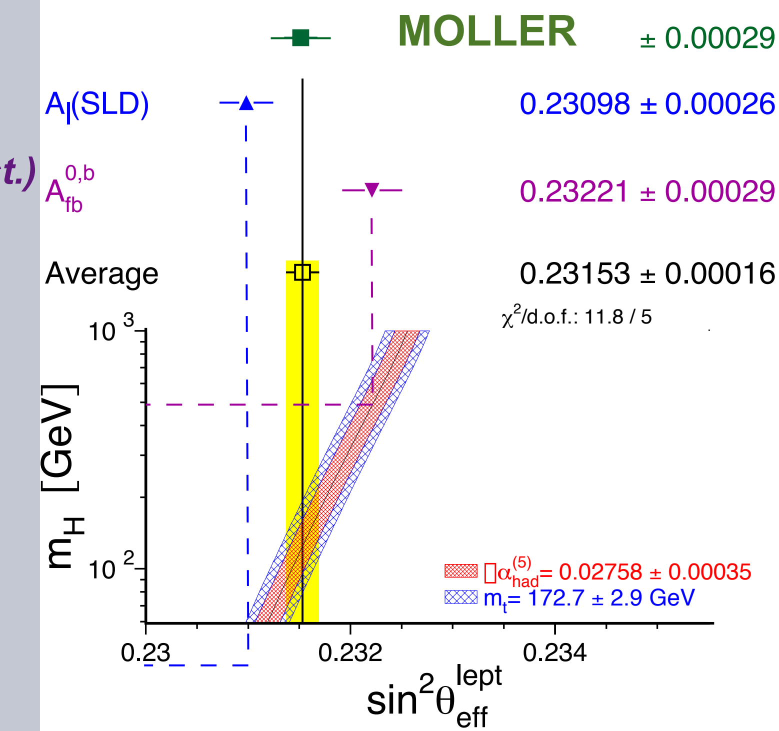
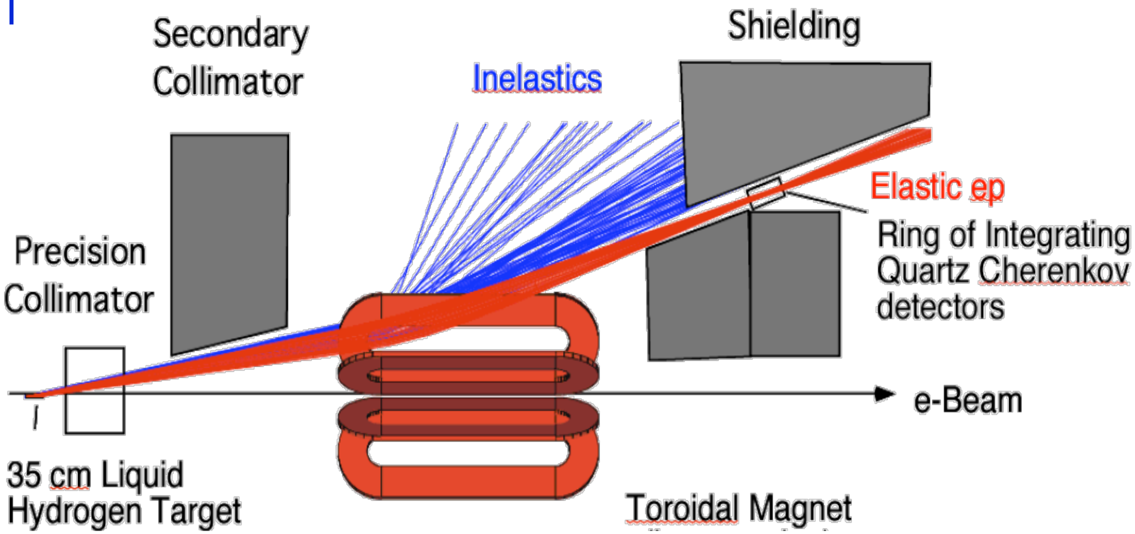


$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \text{TeV}$$

best contact interaction reach for leptons at low OR high energy

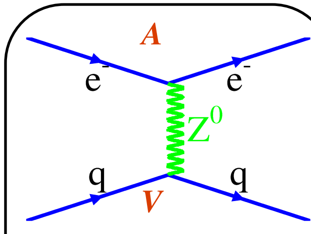
QWeak at JLab



$$\delta(A_{PV}) = 7\ ppb$$

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

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

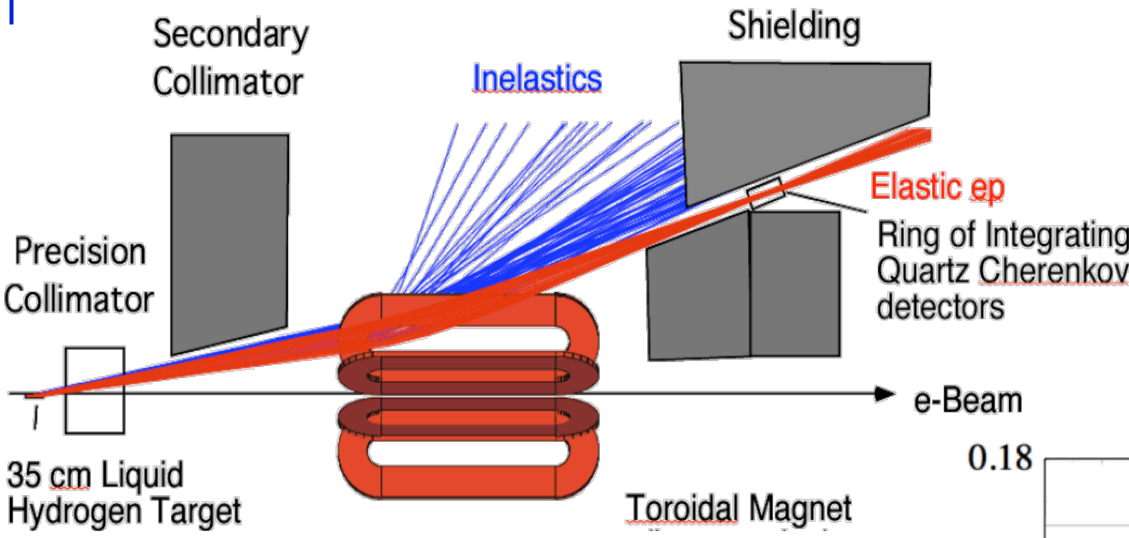


$$C_{1i} \equiv 2 g_A^e g_V^i$$

See M.Pitt in PS1A

K.Paschke, M. Dalton

QWeak at JLab



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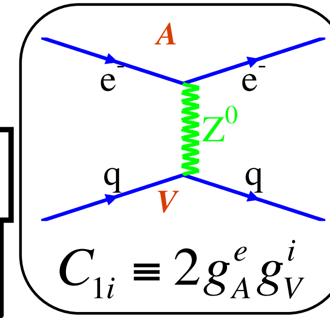


$C_{1i} \equiv 2 g_A^e g_V^i$

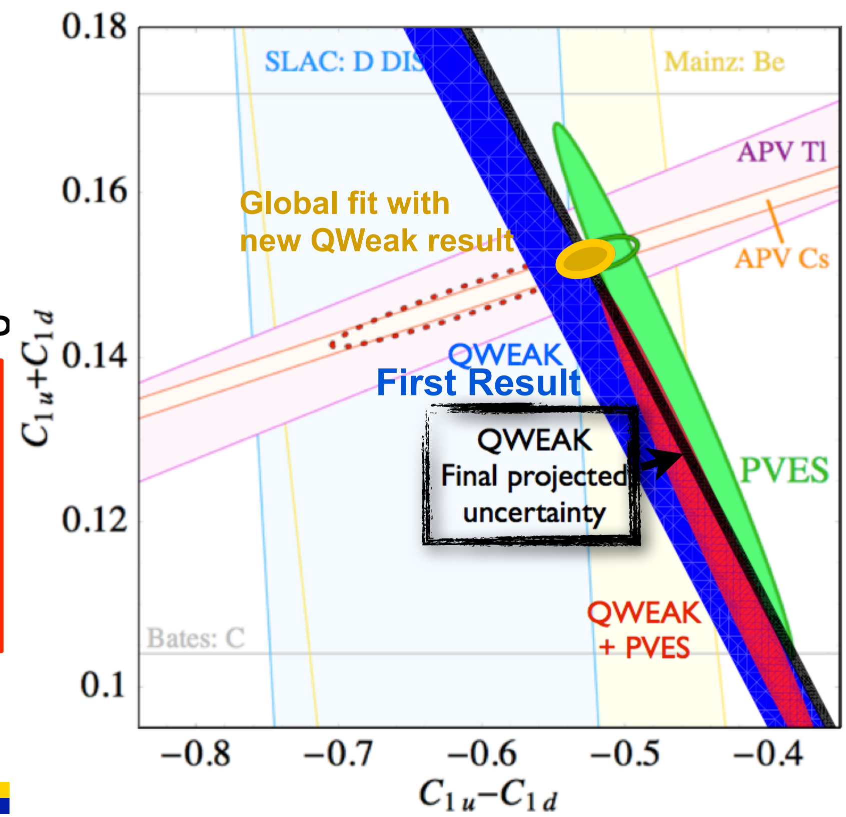
Significant Accomplishment:

- full data set in hand (run completed 2012).
- First result (4% of data set) released at DNP

$$A_{\rm PV} = -281.2 \pm 35.1({\rm stat}) \pm 29.6({\rm syst})\ {\rm ppb}$$

$$Q_W^p = 0.0945 \pm 0.0156({\rm stat}) \pm 0.0132({\rm syst}) \pm 0.001({\rm th})$$

(Consistent with SM prediction)



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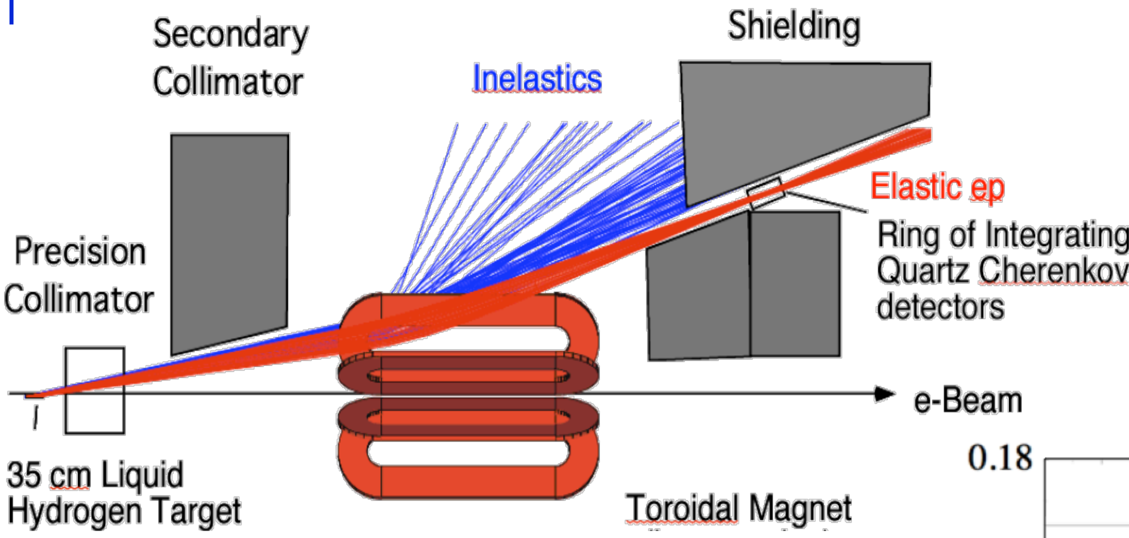

$\delta(A_{PV}) = 7\ ppb$

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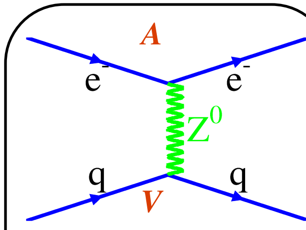
$\Rightarrow\ \delta(\sin^2\theta_W) = \pm\ 0.3\%$



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

Significant Accomplishment:

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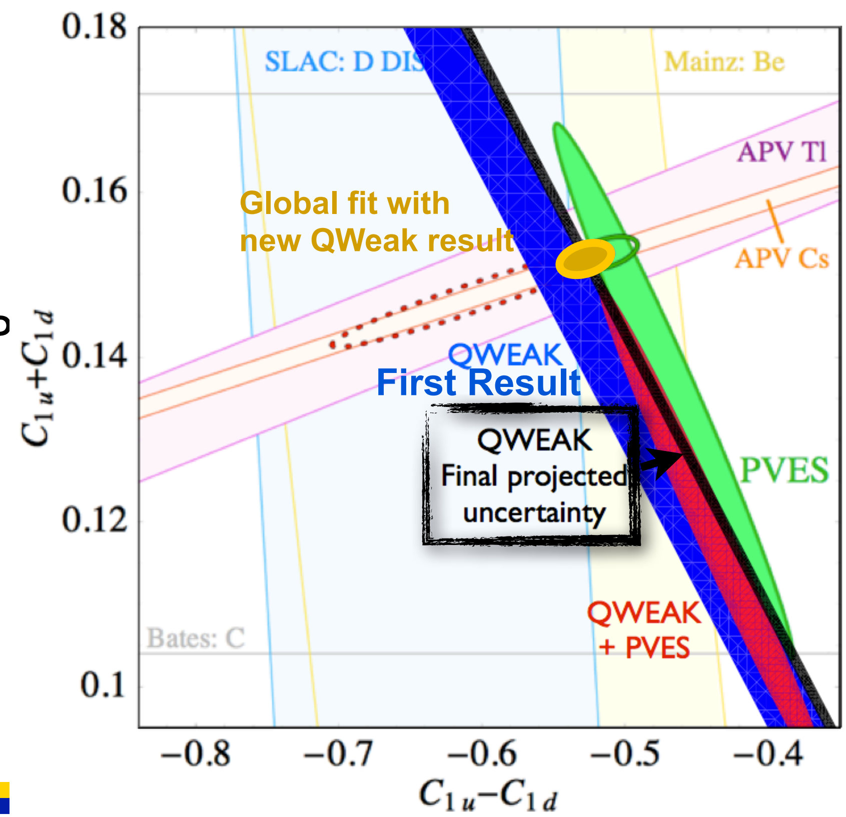
- First result (4% of data set) released at DNP
- Important technologies for future program



Non-perturbative theory	$g \sim 2\pi$	$\Lambda \sim 29$ TeV
Extra Z'	$g \sim 0.45$	$m_{Z'} \sim 2.1$ TeV

See M.Pitt in PS1A

K.Paschke, M. Dalton

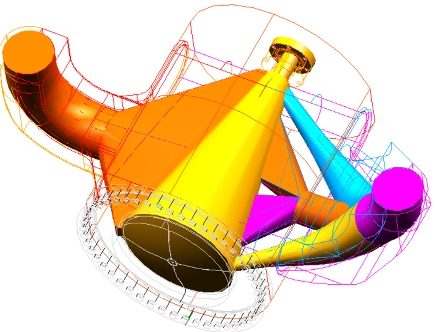
QWeak: Current State of the Art

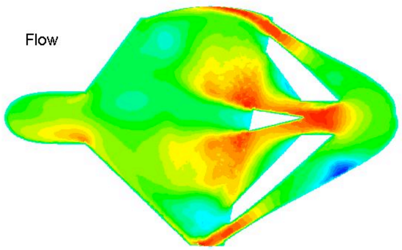
Liquid Hydrogen:
35cm cell, 180 μA

World's highest power cryotarget

2300 Watts

Designed with CFD simulation





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

K.Paschke

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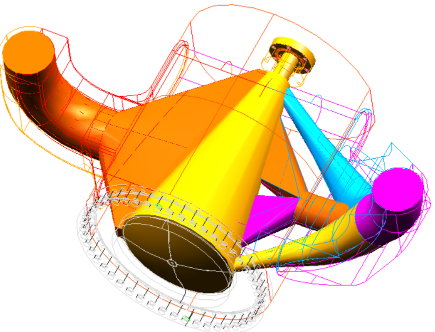

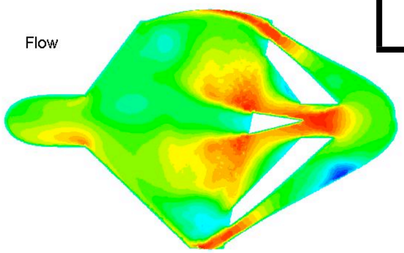

Run II Beam Properties	
Δx	-0.95 nm
Δy	-0.24 nm
$\Delta x'$	-0.07 nrad
$\Delta y'$	-0.06 nrad
A_{Energy}	0.23 ppb

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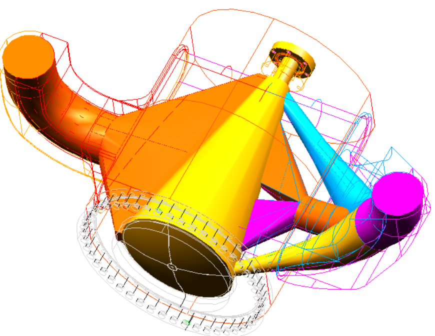

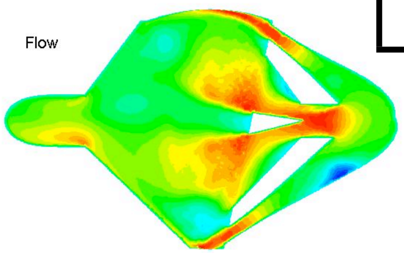

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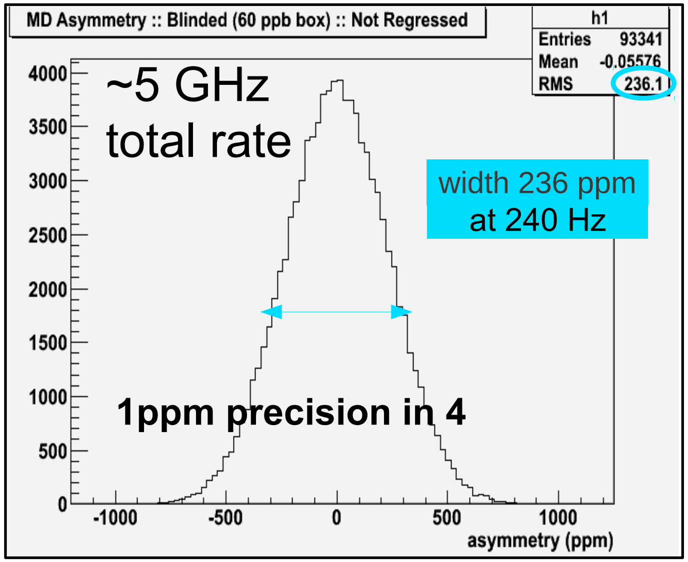

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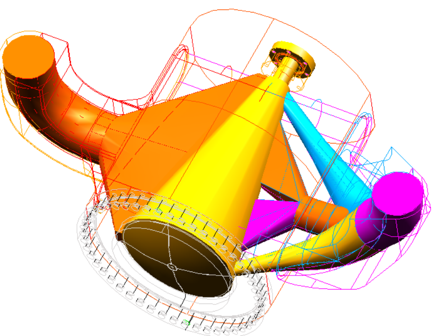

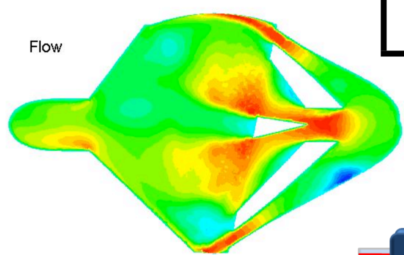

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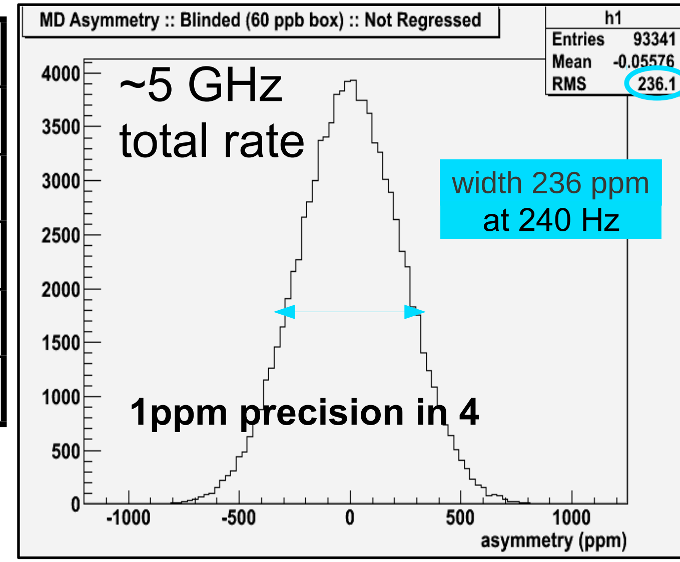
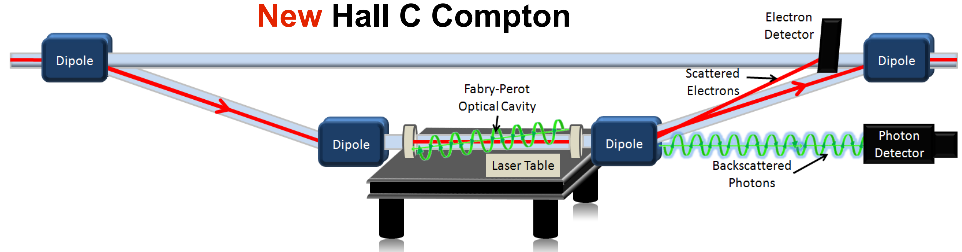
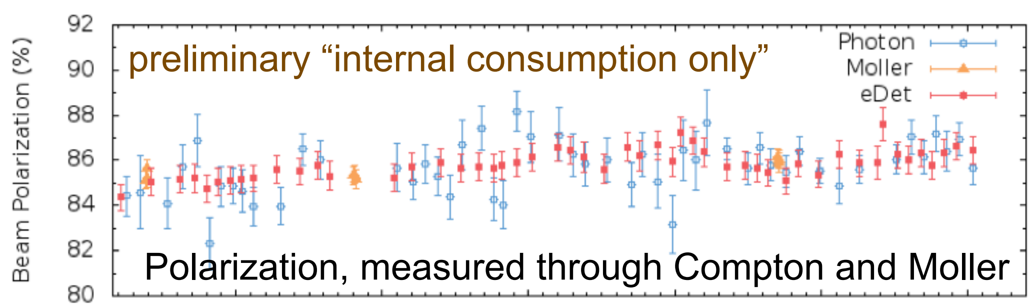


New Hall C Compton





K.Paschke

MESA/P2 at Mainz

K.Paschke

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

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

Negligible for significantly lower Q^2

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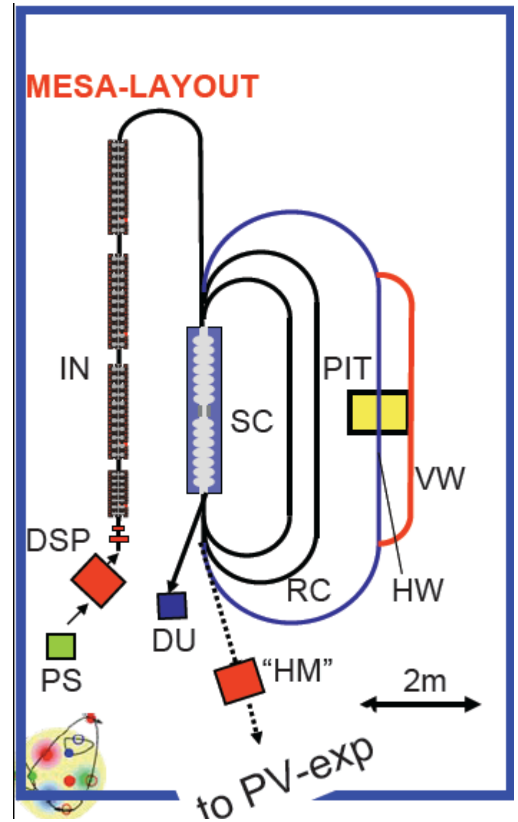
New research machine based on ERL will also support a high-current extracted beam at 100-200 MeV suitable for a PV experiment



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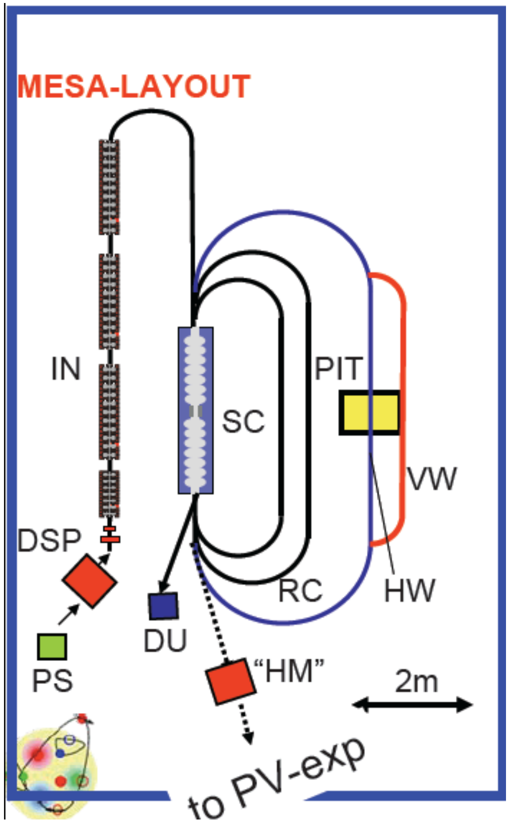
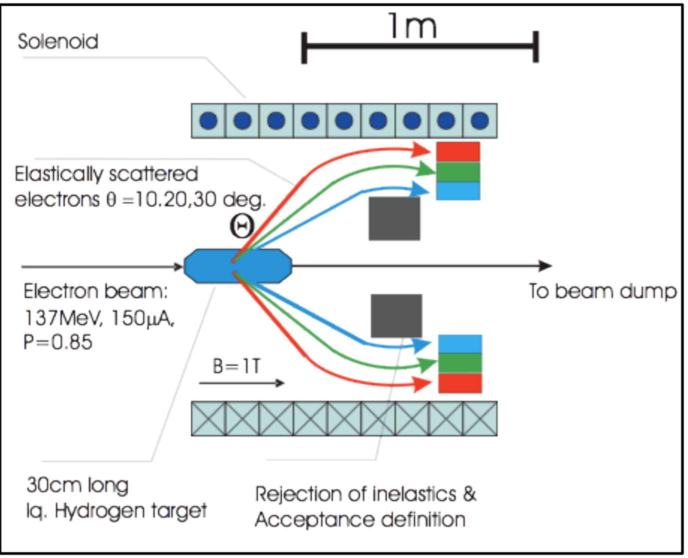


- E_{beam} = 200 MeV, 10-30°
- Q^2 = 0.0048 GeV^2
- 30 cm target, 150 uA, 10^4 hours, 85% polarization
- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%



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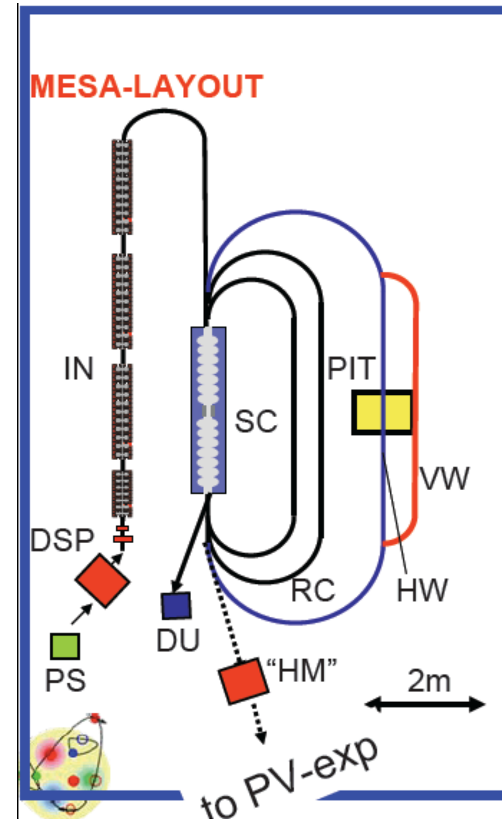

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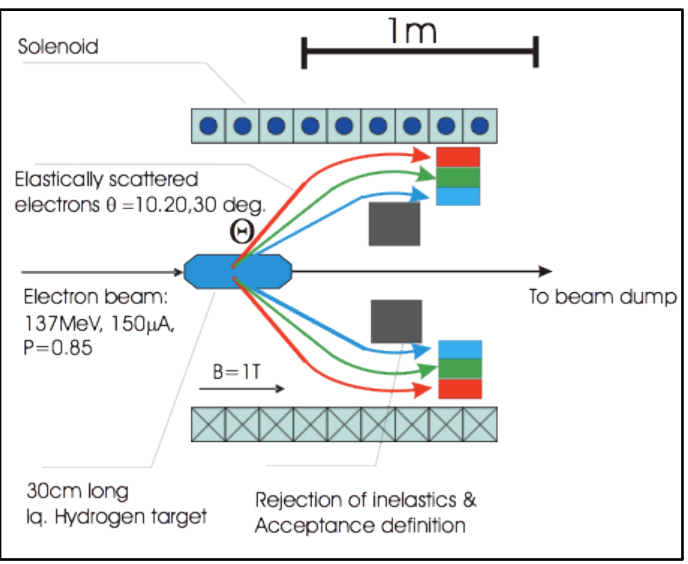
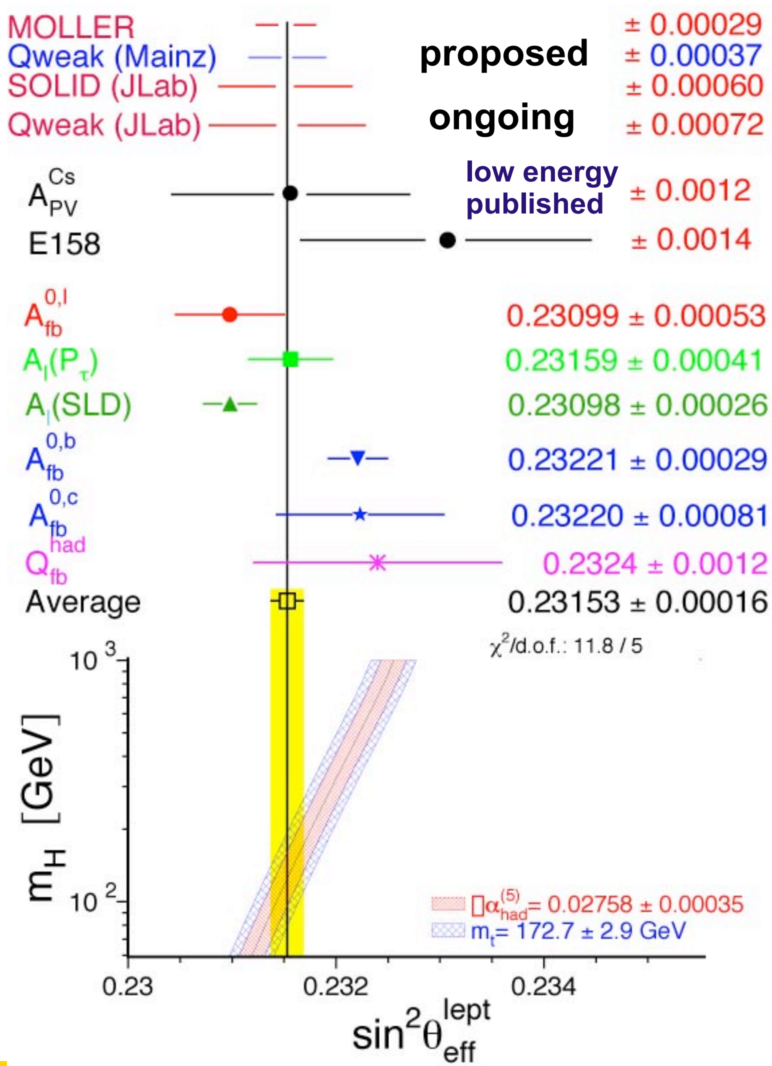


- Development starting now
- P2 on the floor and commissioning in 2015
- MESA complete and in operations in 2016
- P2 production 2017-2019, to full precision
- D.Becker in PS1B

Future Weak Charge Measurements



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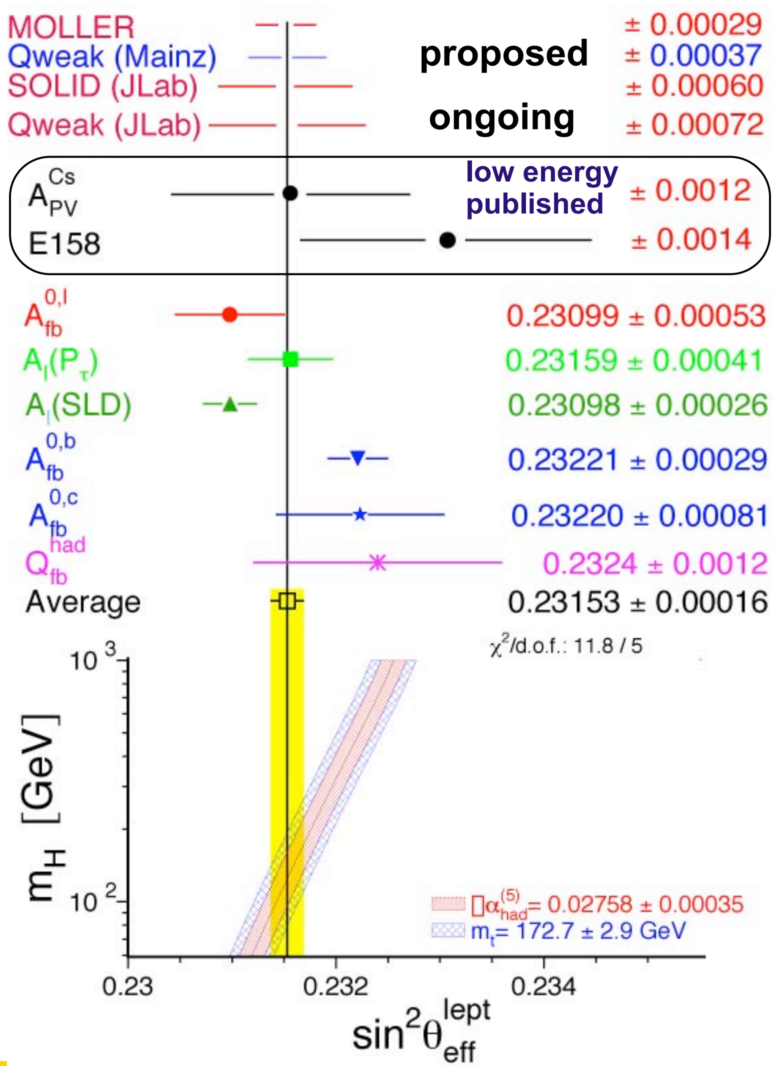

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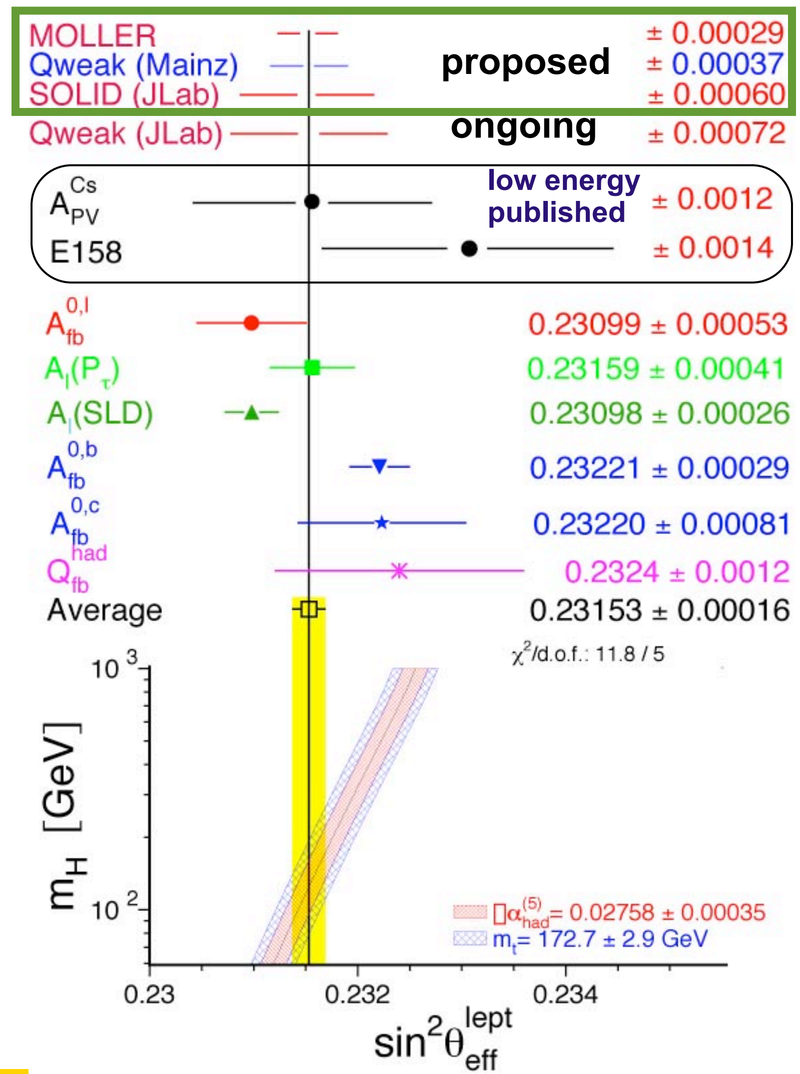
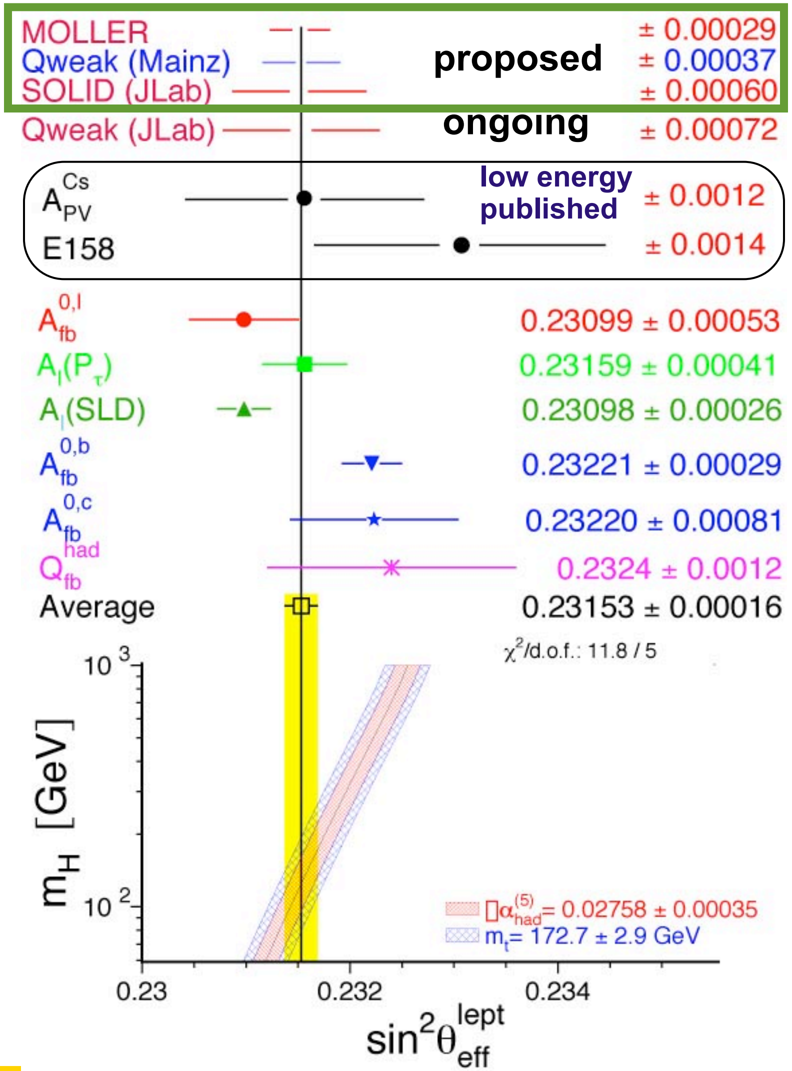


Future Weak Charge Measurements

LHC new physics signals could have multiple interpretations: weak charge measurements can discriminate among scenarios



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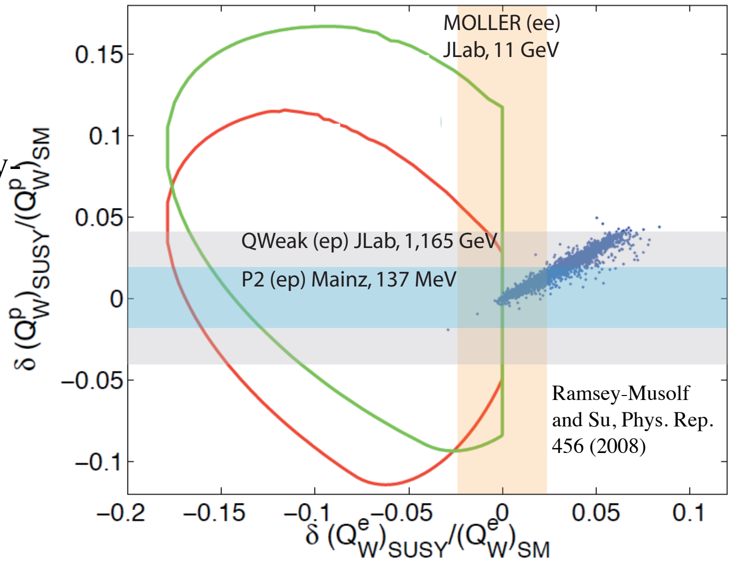
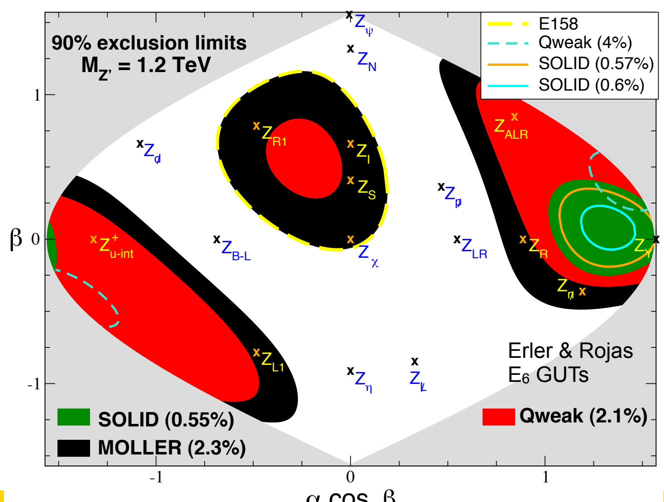
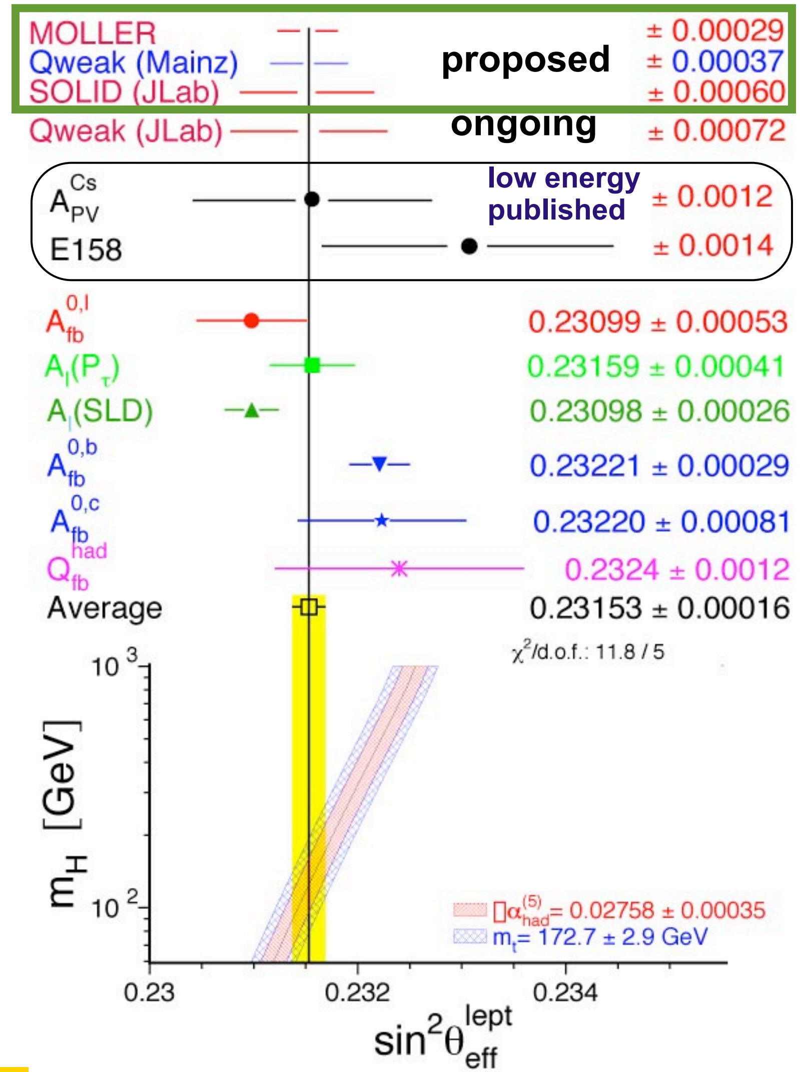
Sensitivity to R-Parity-violating Supersymmetry

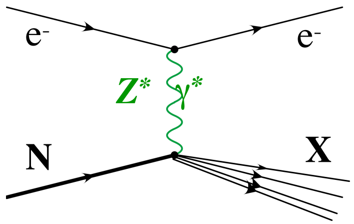


Assume a 1.2 TeV resonance observed at LHC which is consistent with being a Z' boson





PV in Deep Inelastic Scattering



A_{PV} in Electron-Nucleon DIS:

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

$Q^2 >> 1\ GeV^2$, $W^2 >> 4\ GeV^2$

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

For ^2H, assuming charge symmetry, structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots \qquad b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

Unique sensitivity to couplings C_2

Target: measure A_{PV} to 0.5% fractional accuracy!

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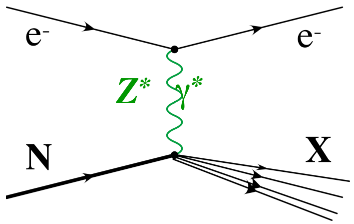

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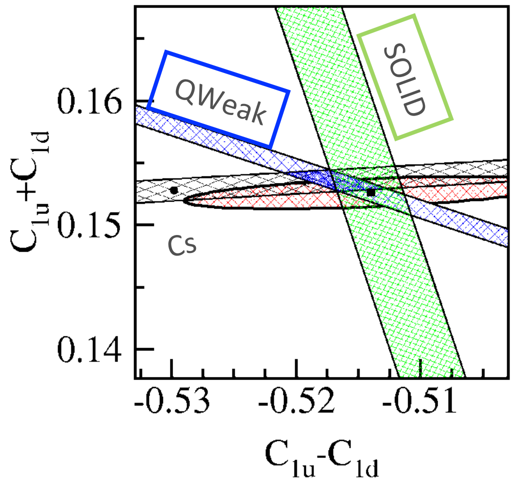
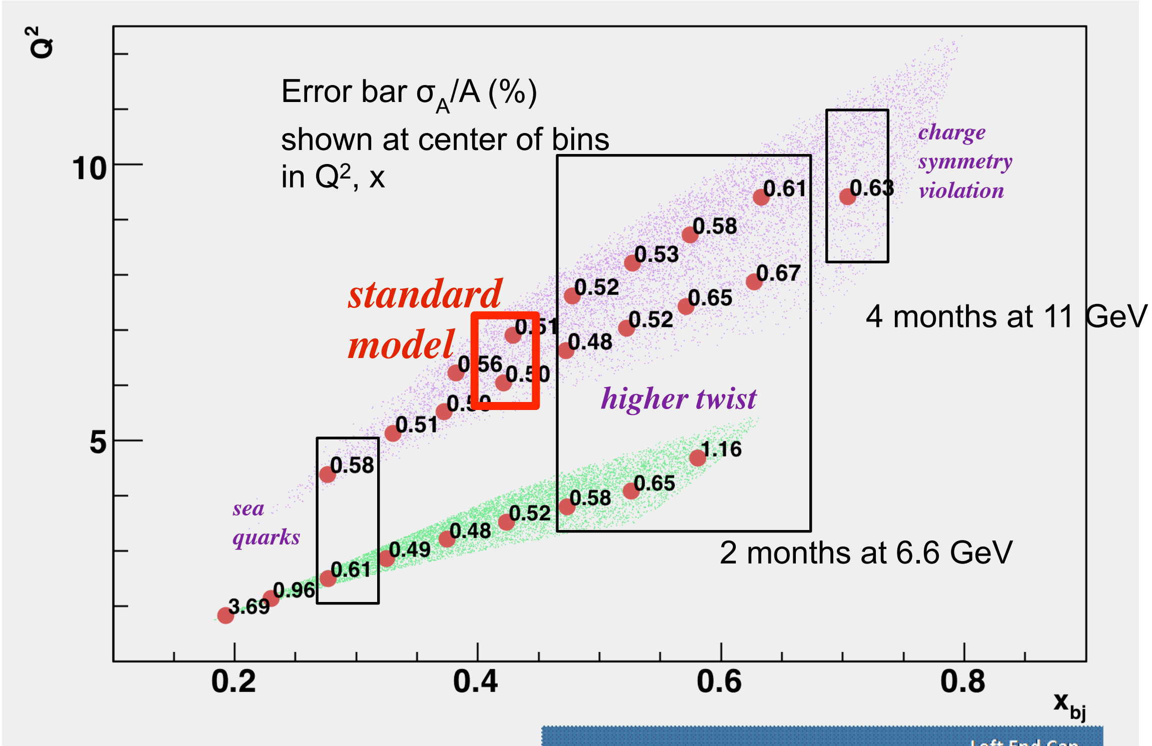
Target: measure A_{PV} to 0.5% fractional accuracy!

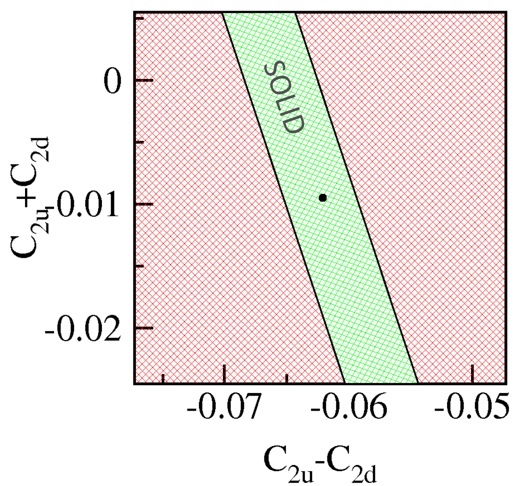
- First experiment at 6 GeV: ran Oct-Dec '09; ~4% accuracy @ Q^2 ~ 1-2 GeV^2
- Approved Hall C proposal at 11 GeV using planned upgrade for spectrometers
- SOLID: New large acceptance solenoidal spectrometer approved for Hall A

SOLID at JLab

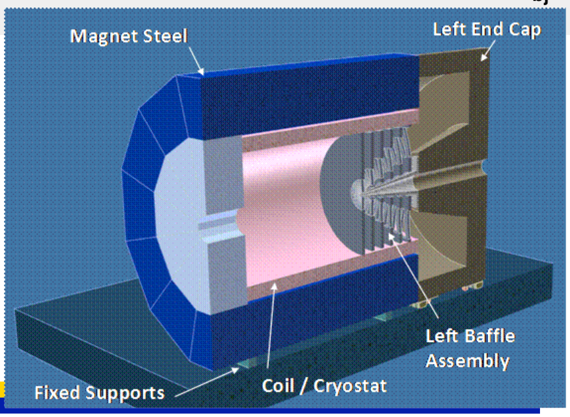
Simultaneous measurements of ~ 20 “NuTeV” points





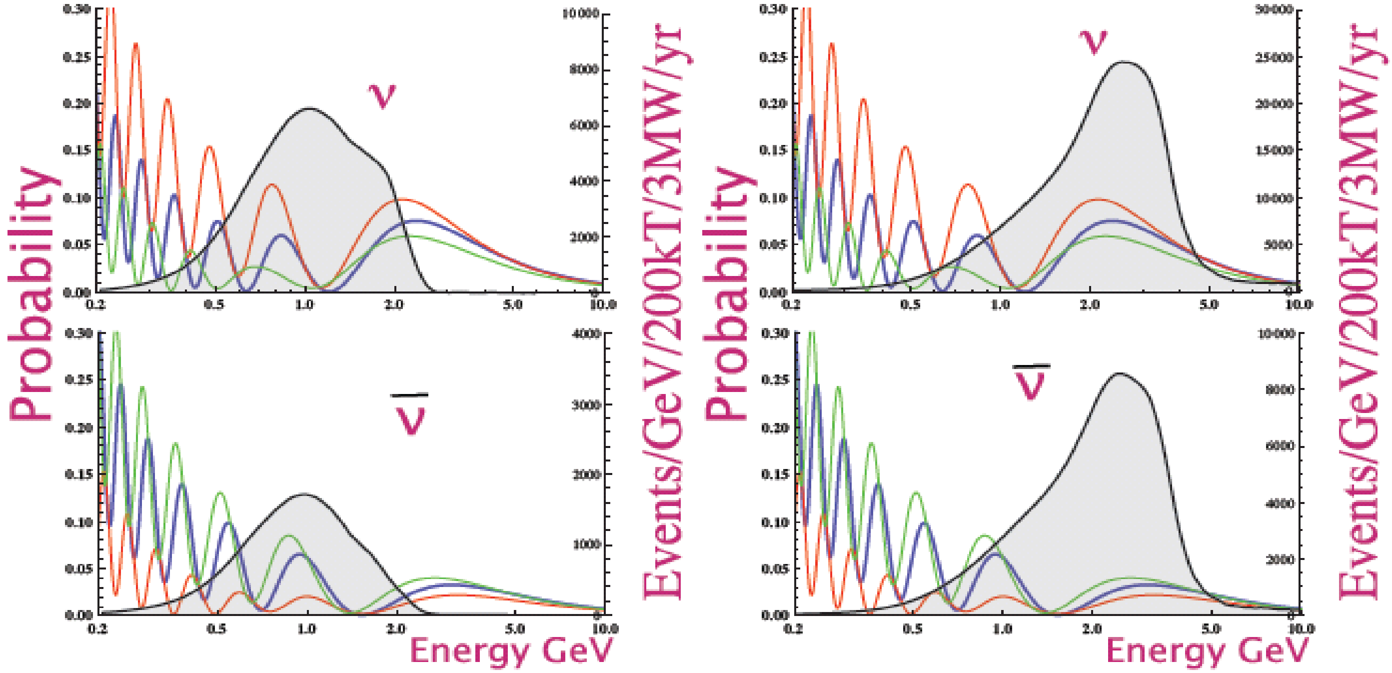


<u>Strategy:</u> sub-1% precision over broad kinematic range for **sensitive Standard Model test** *and* **detailed study of hadronic structure effects**



Additional Physics @ SoLID ?

- US-HEP is planning to build a ~$1B facility to measure neutrino mass hierarchy and CP violation in neutrino sector: LBNE
  - Far detectors based on LAr
  - Interpretation of measurements depends critically on measurements of neutrino energy in CC processes



From: Bishai et al arXiv:1203.409

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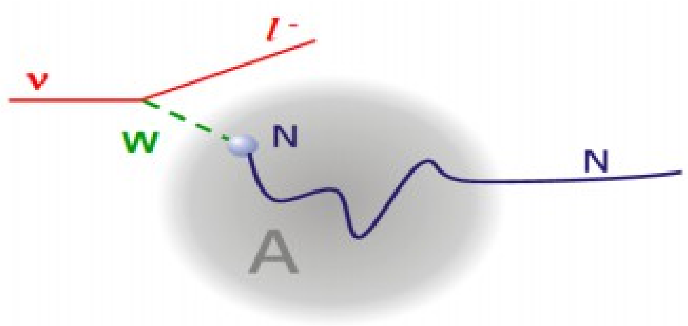

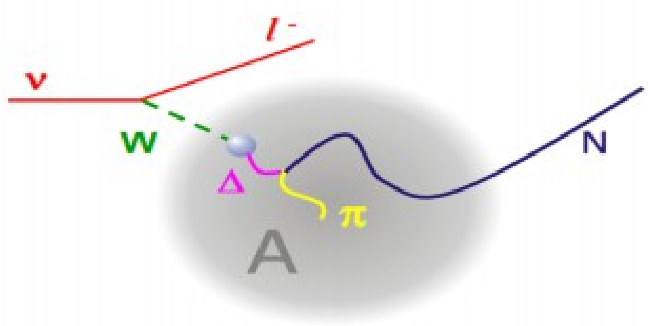

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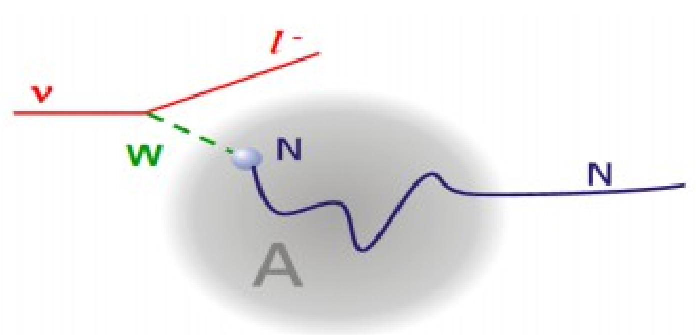

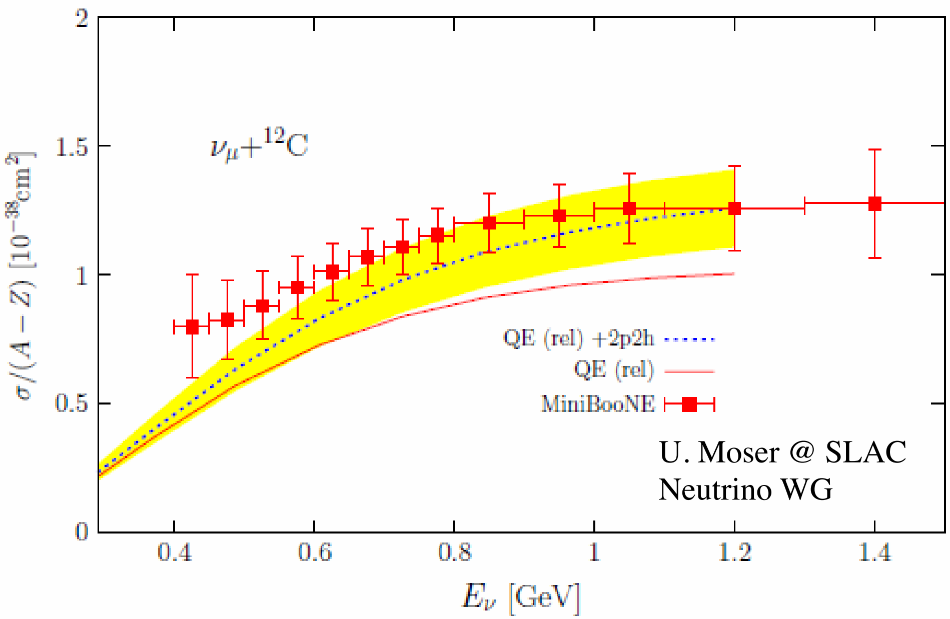

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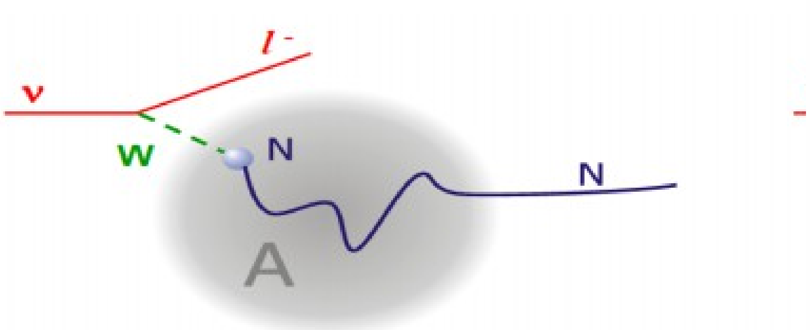

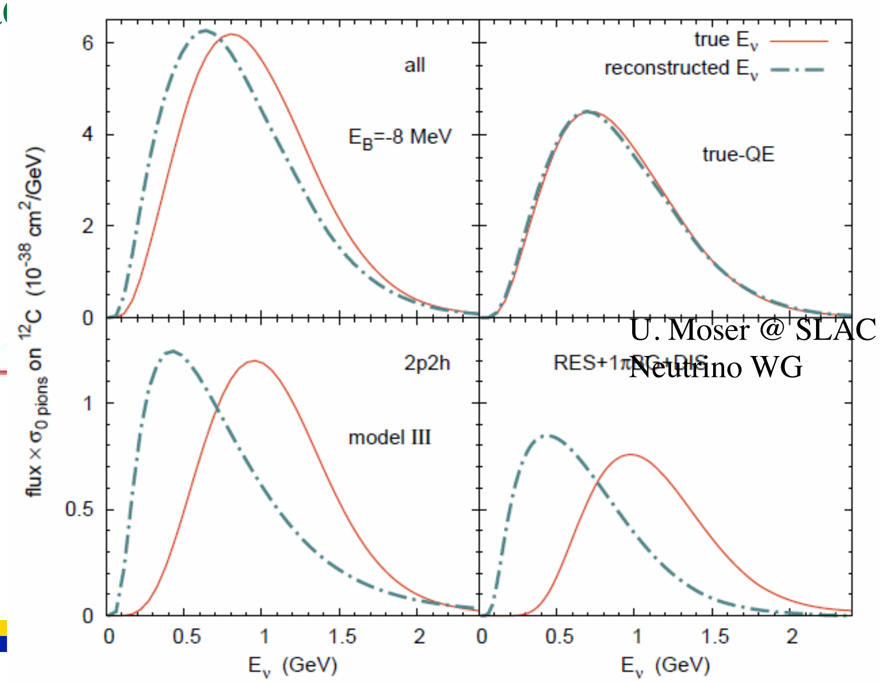

U. Moser @ SLAC Neutrino WG

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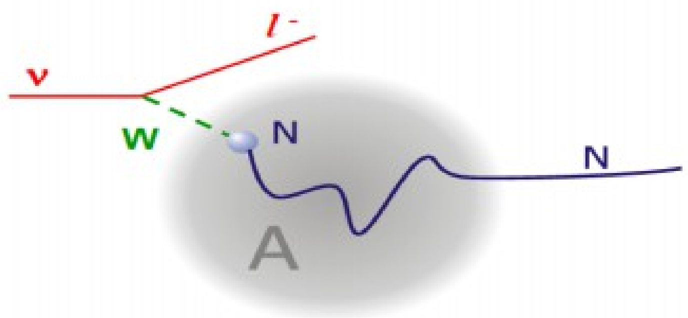
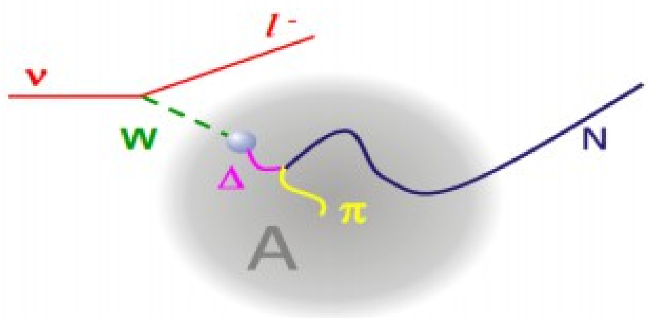
    - SoLID run on LAr target may provide a clean measurement





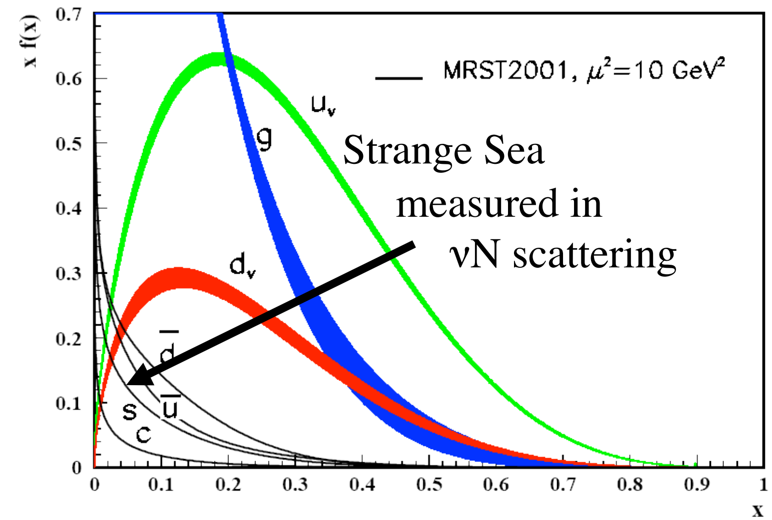
Hadronic Structure through PV Electron Scattering

Strangeness in Nucleons

Quark Model ⟺ ? QCD *1980's*

K. Kumar

Strange quarks carry nucleon momentum: Other external properties affected?



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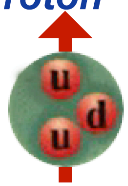
spin dependent deep inelastic scattering

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L$$

Proton Spin



Experiments:
$\Delta\Sigma \sim 0.25$

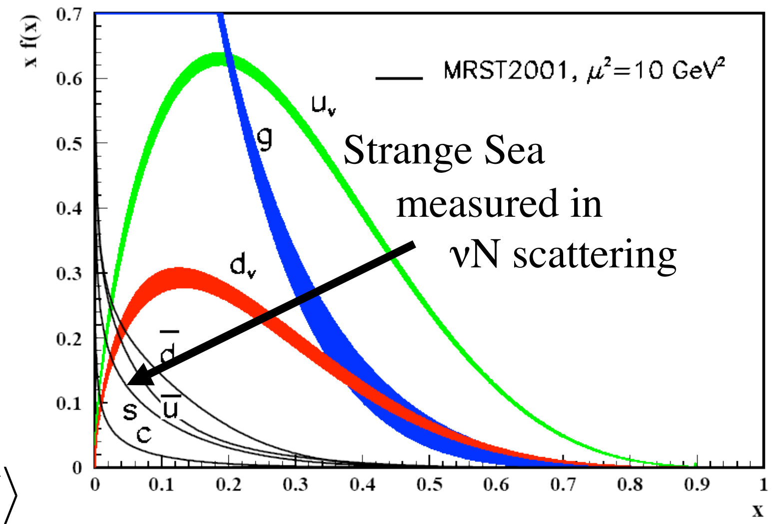
$$A_{\parallel} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}}$$

+ *Hyperon decay*
+ *$SU(3)_f$ Symmetry:*

$\Delta s \sim -0.1$?

$$\Delta s \sim \langle N|\bar{s}\gamma_\mu\gamma_5 s|N\rangle$$

Breaking of SU(3) flavor symmetry introduces uncertainties



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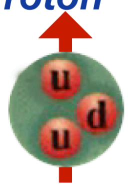

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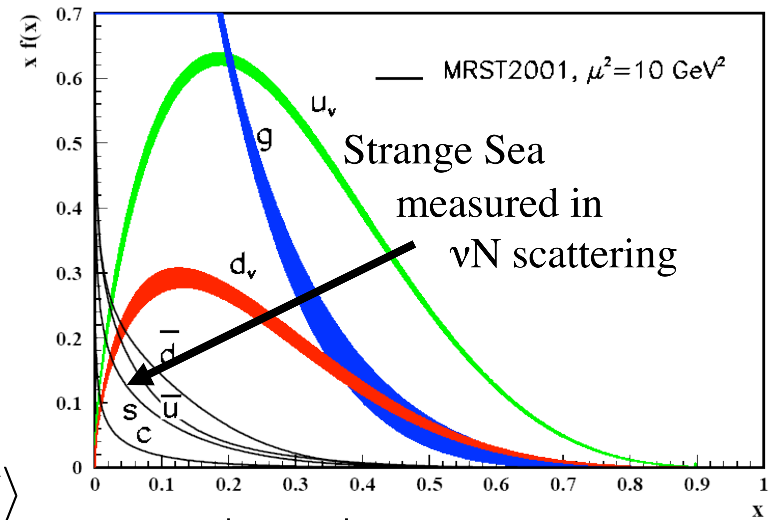
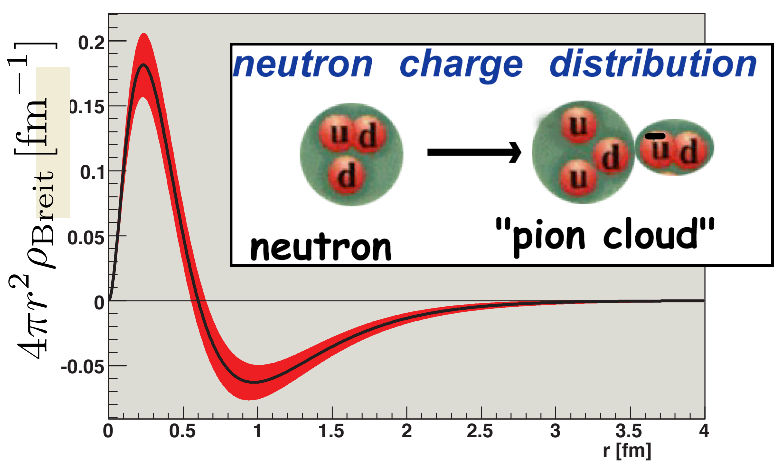
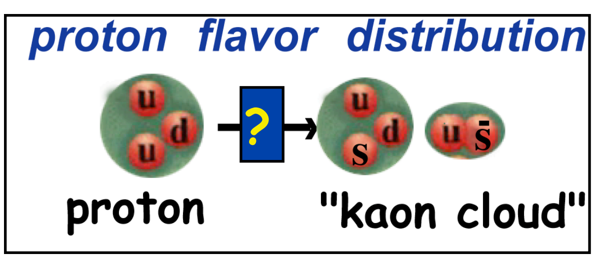


Breaking of SU(3) flavor symmetry introduces uncertainties

$$\Delta s \sim \langle N | \bar{s}\gamma_{\mu}\gamma_5 s | N \rangle$$

$$\langle N | \bar{s}\gamma_{\mu} s | N \rangle \neq 0\,?$$

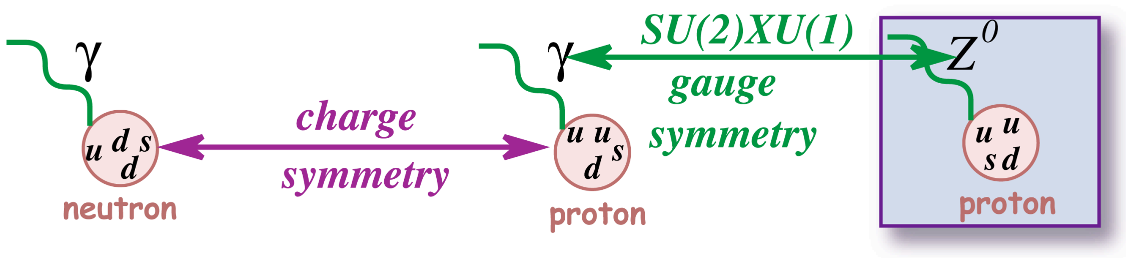




Early calculations predicted substantial effects

Elastic Electroweak Scattering

K. Kumar

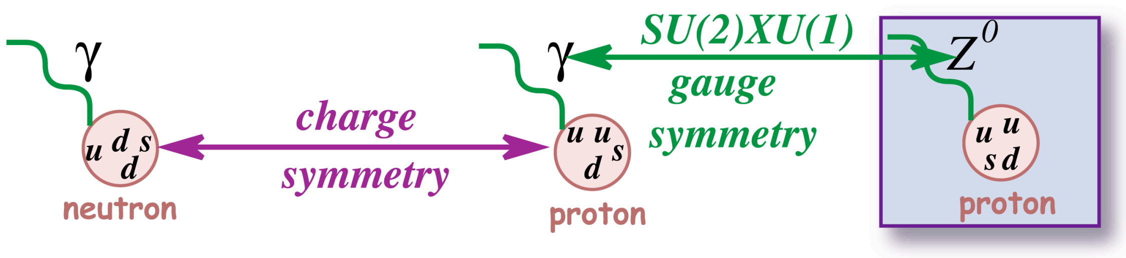


Kaplan & Manohar (1988)
McKeown (1990)

$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s \quad \Rightarrow \quad G_E^s(Q^2),\, G_M^s(Q^2)$$

Elastic Electroweak Scattering

K. Kumar



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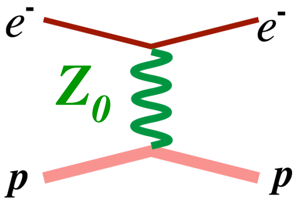

A_{PV} **for elastic e-p scattering:**

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

Elastic Electroweak Scattering

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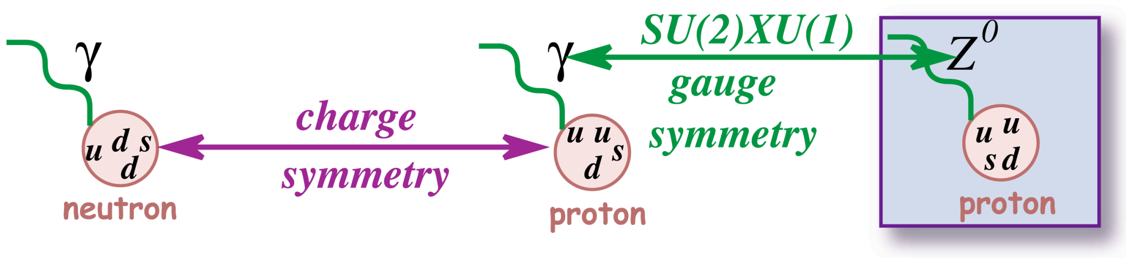

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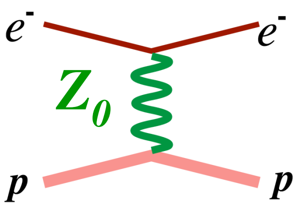

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$$A_E = \epsilon G_E^p G_E^Z \qquad A_M = \tau G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$

Forward angle — Backward angle

"Anapole" radiative corrections are problematic

$$\mathbf{G^Z_{E,M} = (1 - 4\sin^2\theta_W)G^p_{E,M} - G^n_{E,M} - G^s_{E,M}}$$

Elastic Electroweak Scattering

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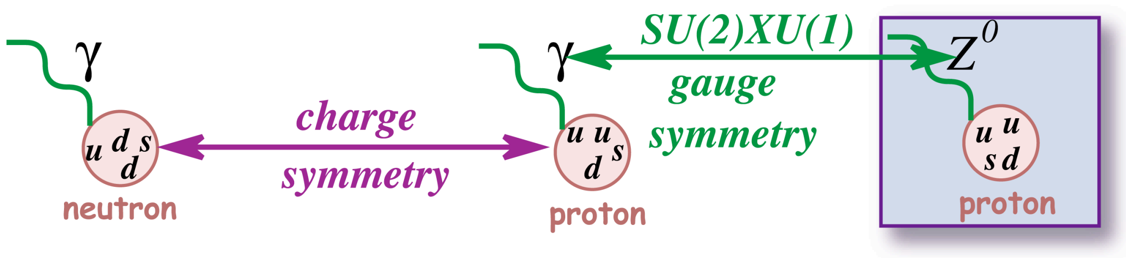

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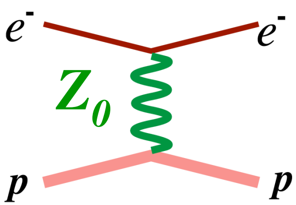


A_{PV} for elastic e-p scattering:

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

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

Forward angle — Backward angle

"Anapole" radiative corrections are problematic

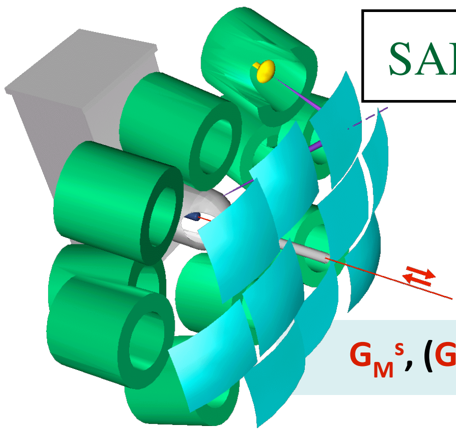
$$\mathbf{G^Z_{E,M} = (1 - 4\sin^2\theta_W)G^p_{E,M} - G^n_{E,M} - G^s_{E,M}}$$

For a spin=0,T=0 ^{4}He: G^s_E only!

For deuterium: Enhanced G_A

World Program

1990-2011

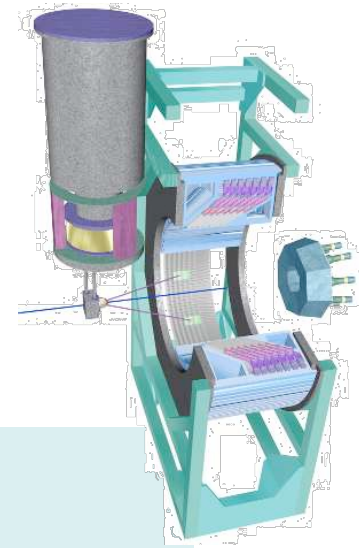


SAMPLE @ Bates

open geometry, integrating detector

G_M^s, (G_A) at $Q^2 = 0.1$ GeV^2

A4 @ Mainz



Open geometry

Fast counting calorimeter for background rejection

$G_E^s + 0.23\, G_M^s$ at $Q^2 = 0.23$ GeV^2

$G_E^s + 0.10\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23$ GeV^2

HAPPEX @ JLab

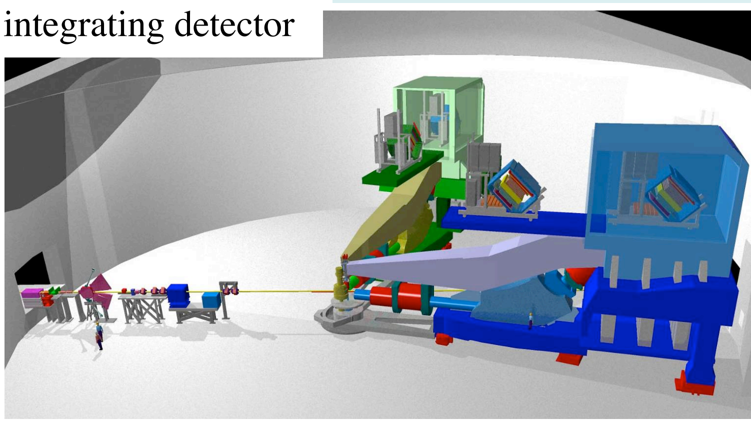
Precision spectrometer, integrating detector

$G_E^s + 0.39\, G_M^s$ at $Q^2 = 0.48$ GeV^2

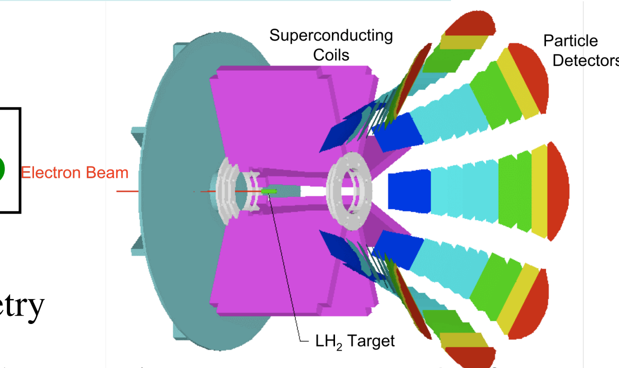
$G_E^s + 0.08\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_E^s at $Q^2 = 0.1$ GeV^2 (^{4}He)

$G_E^s + 0.48\, G_M^s$ at $Q^2 = 0.62$ GeV^2



G0 @ JLab



Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

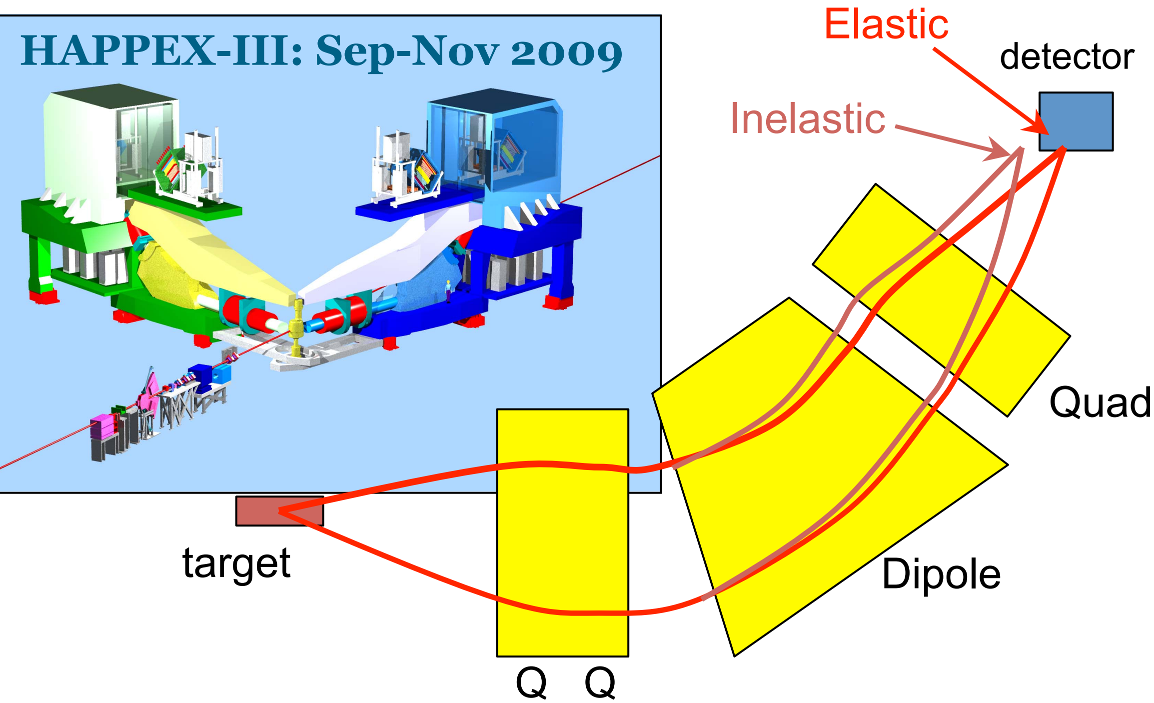
$G_E^s + \eta\, G_M^s$ over $Q^2 = [0.12, 1.0]$ GeV^2

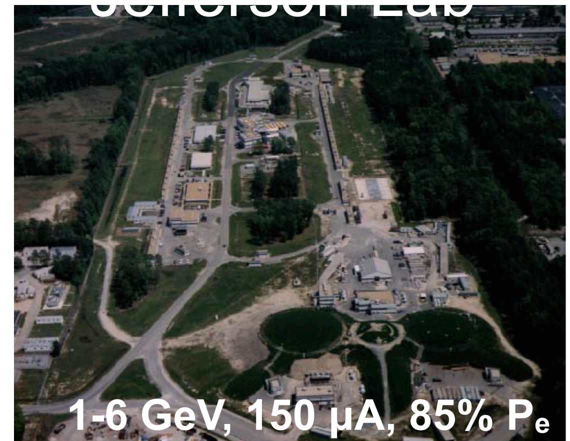
G_M^s, G_A^e at $Q^2 = 0.23, 0.62$ GeV^2

State of the Art: HAPPEX

$E = 3.3$ GeV, $\theta_{lab} = 14^{o}$, 100 μA with 85% P_e

K. Kumar



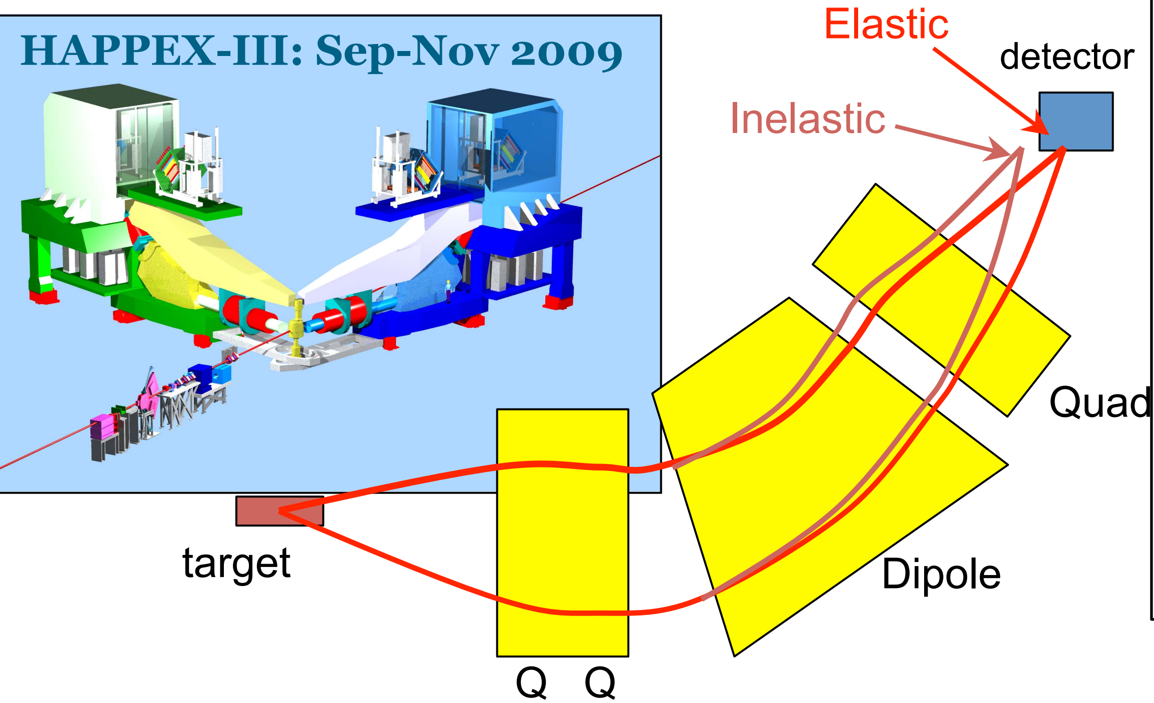


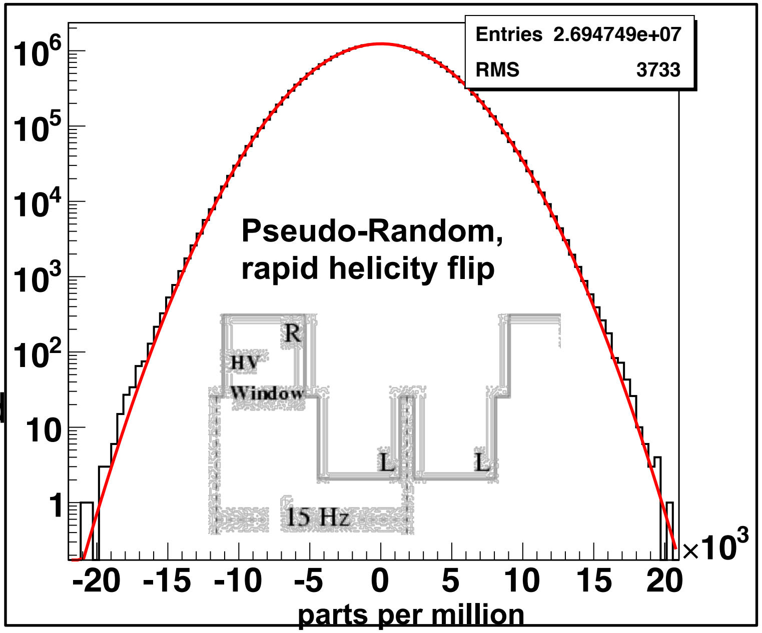
2013: Energy Upgrade to 12 GeV

State of the Art: HAPPEX

$E = 3.3$ GeV, $\theta_{lab} = 14^o$, 100 μA with 85% P_e

K. Kumar





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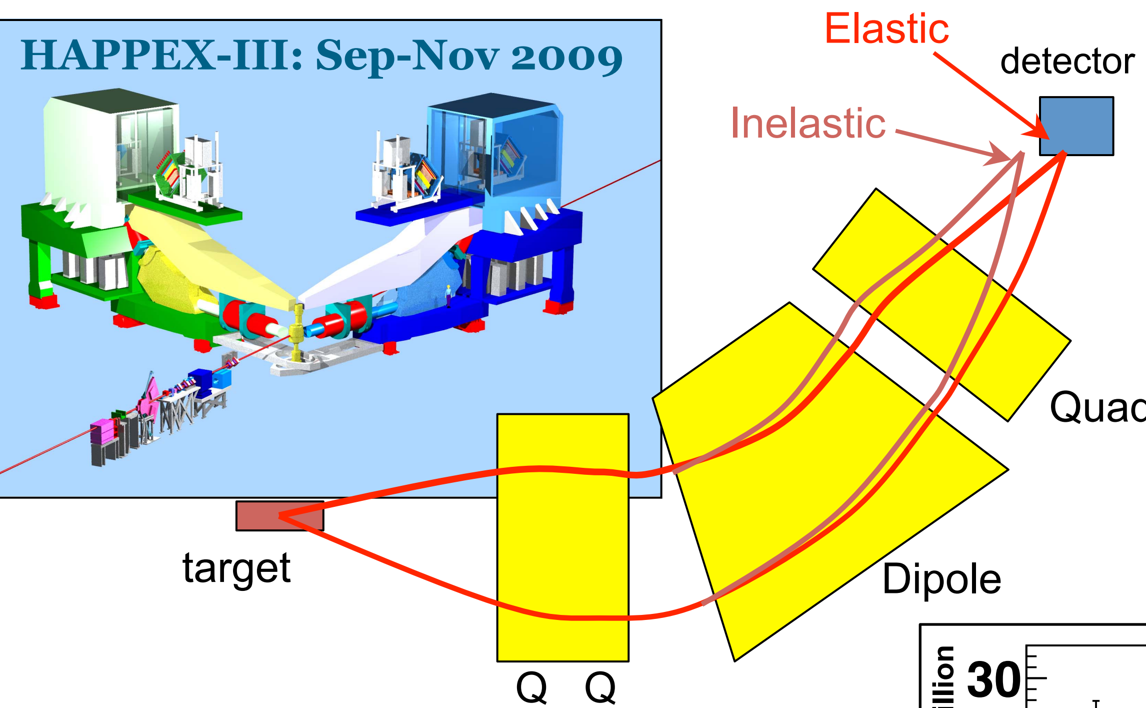
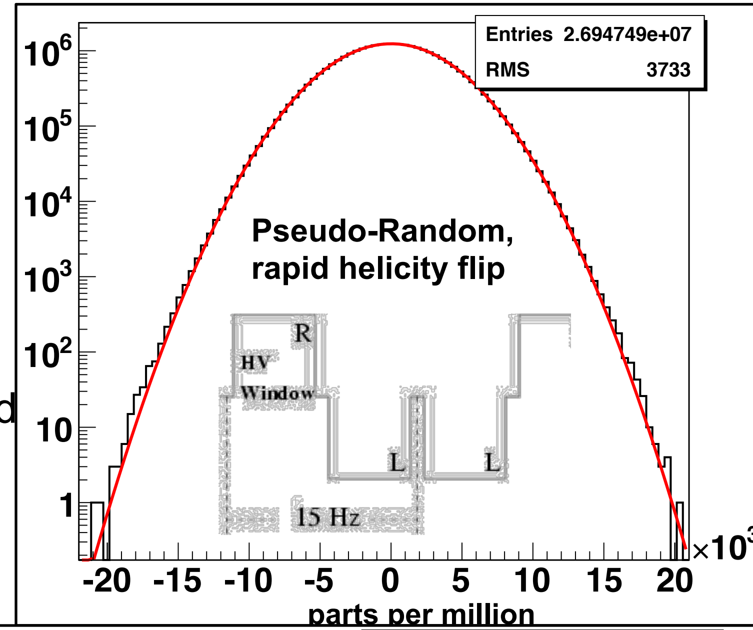
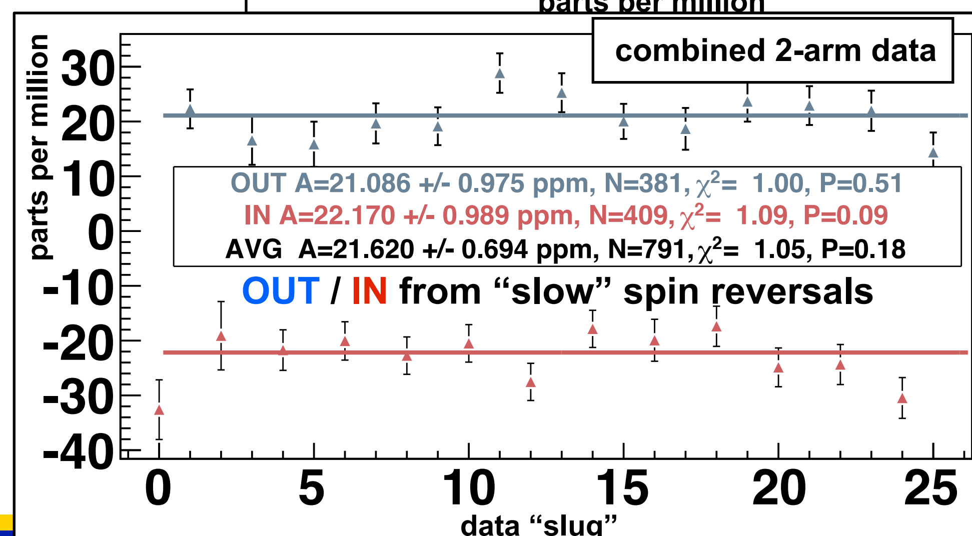






A_{RAW} = -21.591 ± 0.688 (stat) ppm

This includes

- beam asymmetry correction (-0.01 ppm)
- charge normalization (0.20 ppm)

3.26% (stat)± 1.49% (syst)

total correction ~2.5% + polarization

HAPPEX Result & Perspective

K. Kumar

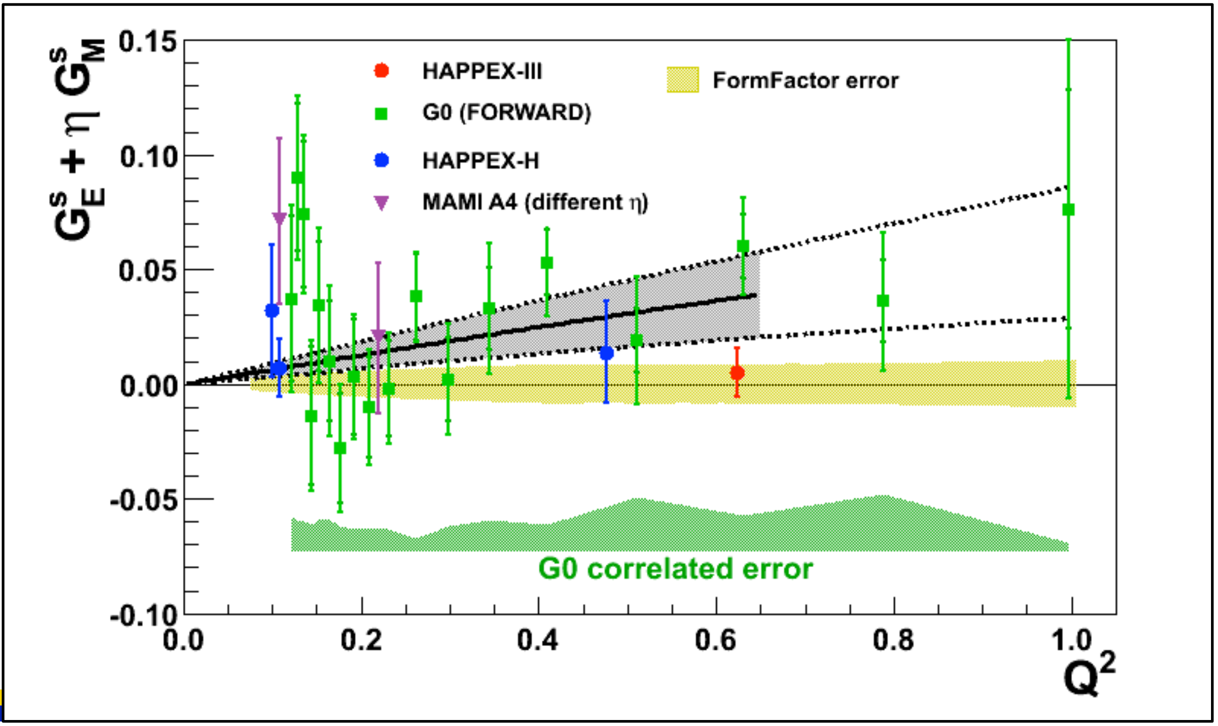
Phys.Rev.Lett. **108,** 102001 (2012)

$$A_{PV} = -23.742 \pm 0.776\ (stat) \pm 0.353\ (syst)\ ppm$$

$$Q^2 = 0.6241 \pm 0.0028\ (GeV/c)^2$$

$A(G^s=0) = -24.158$ ppm $\pm$ 0.663 ppm

$$G^s_E + 0.52\ G^s_M = 0.005 \pm 0.010_{(stat)} \pm 0.004_{(syst)} \pm 0.008_{(FF)}$$



HAPPEX Result & Perspective

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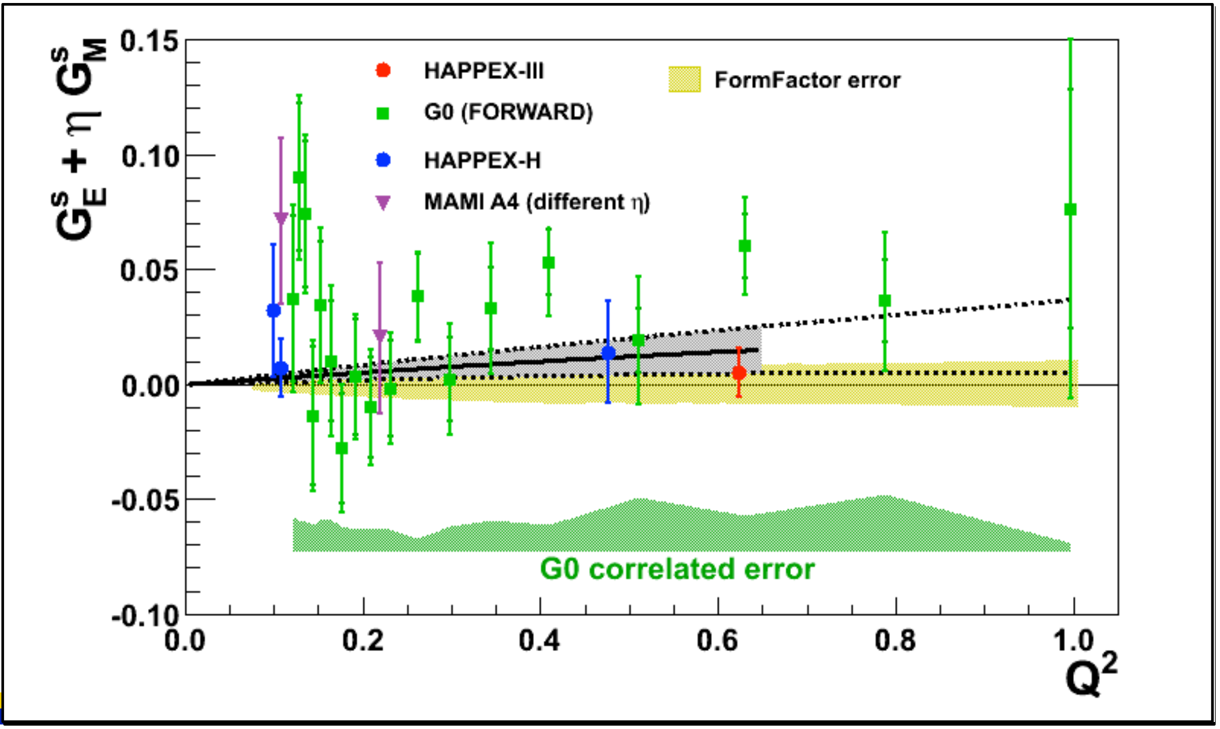
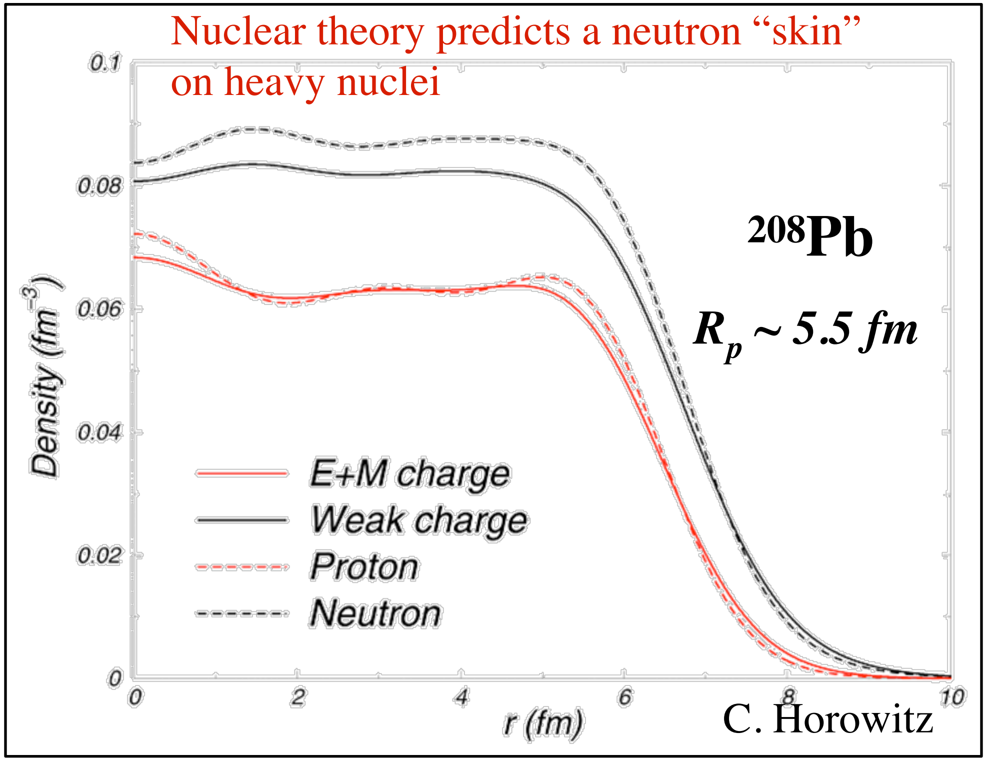
The small size of strange vector matrix elements are in line with modern calculations, especially with input from lattice QCD

New measurements with a ~200 MeV linac ? (parallel sessions)



Nuclear Weak Density

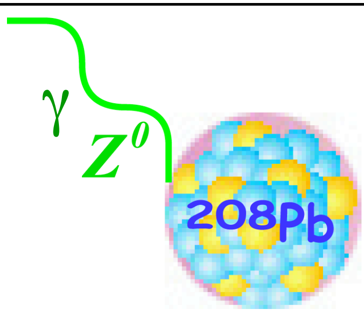
K. Kumar



Neutron distribution is not readily accessible to the charge-sensitive photon probe.

Weak neutral current, however, is most sensitive to neutron distribution

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	1



$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

Nuclear Weak Density

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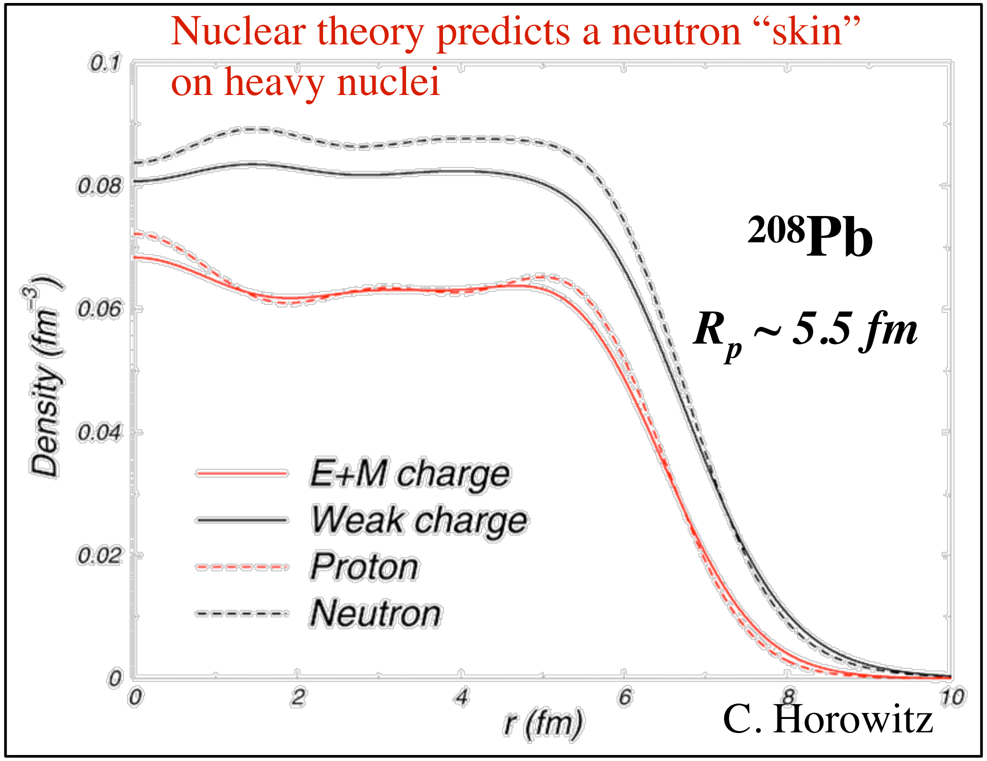

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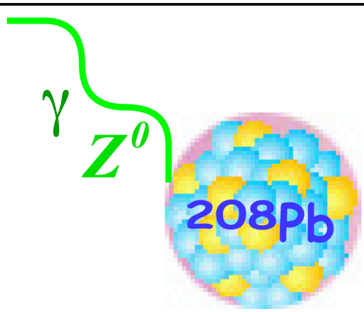
PREX (Pb-Radius EXperiment)

$Q^2 \sim 0.01$ GeV^2 ⟹ $A_{PV} \sim 0.6$ ppm

5° scattering angle — Rate ~1.5 GHz



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$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

PREX Results and Future

$$A_{PV} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst}) \text{ ppm}$$

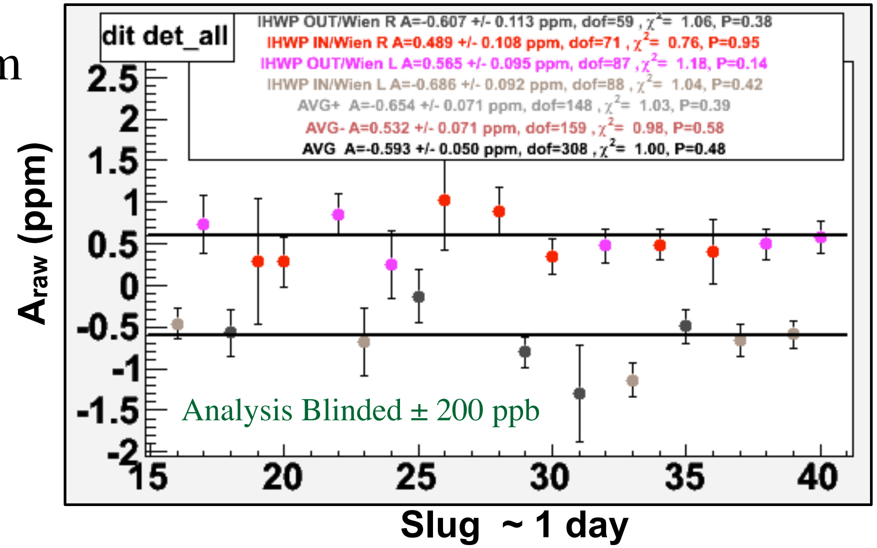
9.1 % 2.1 %

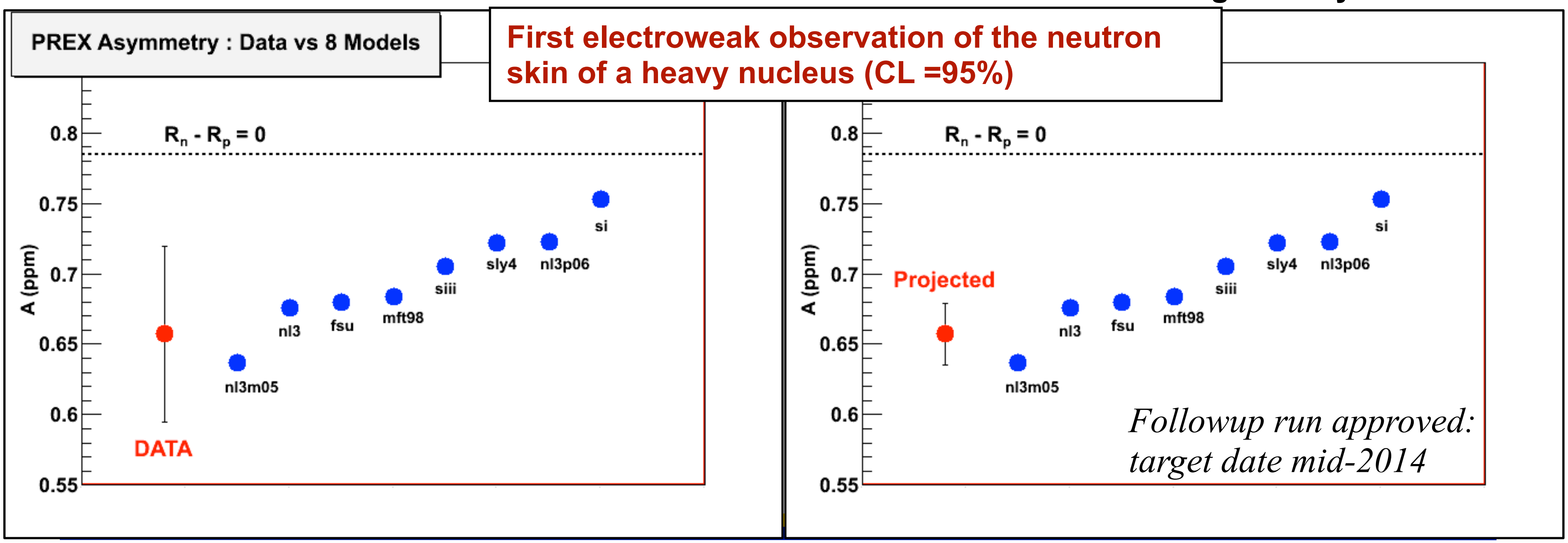
J. Mammei, arXiv:1209.3179 (preliminary)

Neutron Skin:

$$R_n - R_p = 0.33 \, {}^{+0.16}_{-0.18} \text{ fm}$$

Preliminary estimate from C.J. Horowitz





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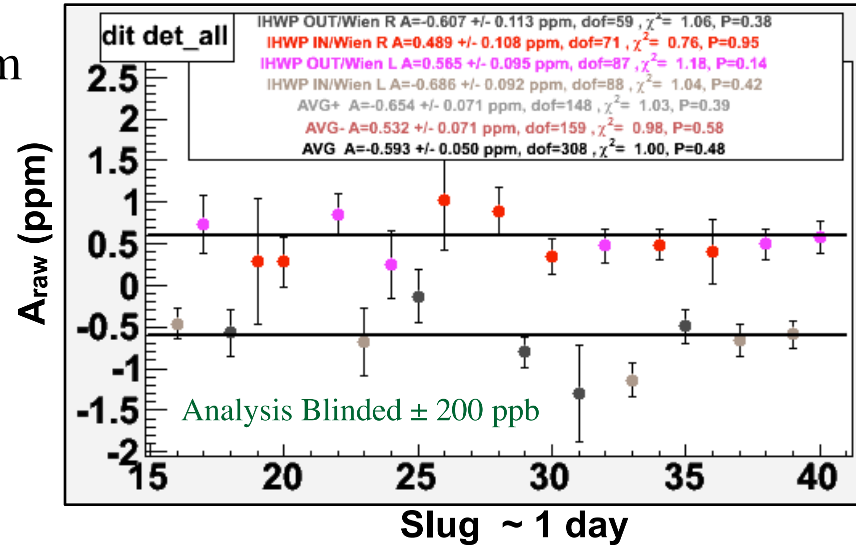

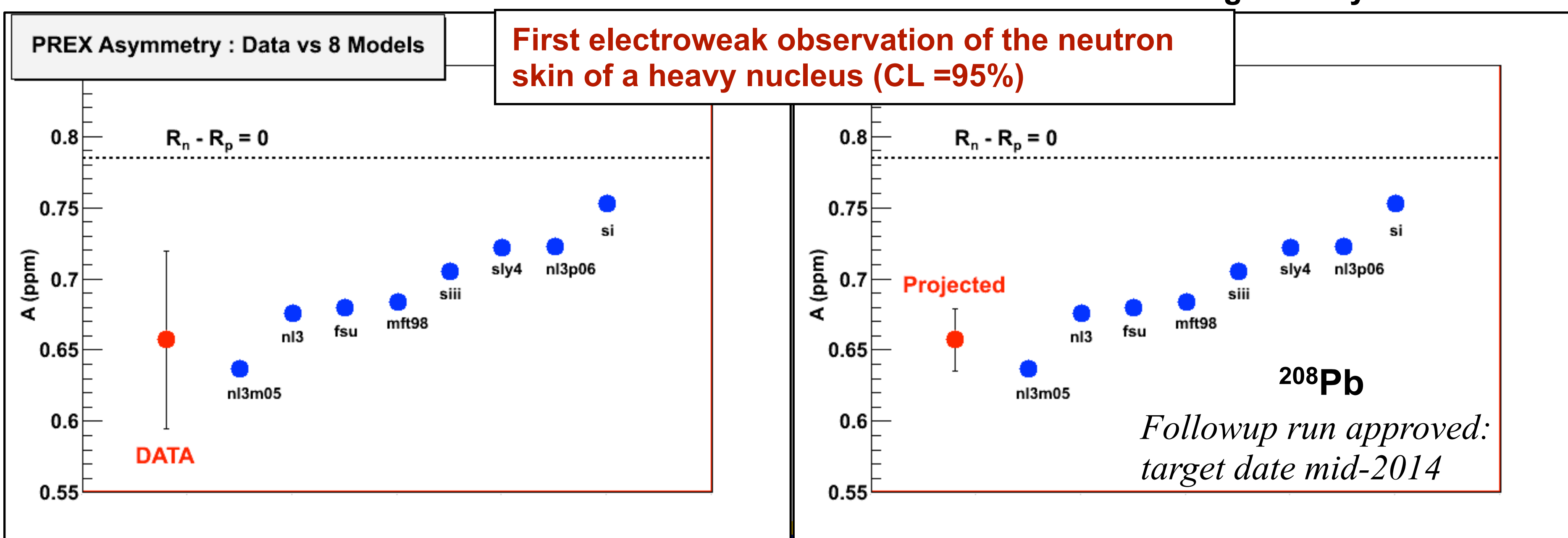

Summary and Conclusions

- Precision Era in Parity-Violating Electron Scattering
  - Percent-level precision (statistics *and* systematics)
    - High currents, high polarization, novel instrumentation
- These tools open new windows for studies of fundamental interactions
  - New Physics at TeV scales
  - Hadronic (nucleon, nuclear) physics at MeV-GeV scales with exquisite precision
- Opportunities for new initiatives !