Parity-Violating Electron Scattering:
Physics Reach and Review of Experiments

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Stony Brook U

Intense Electron Beams Workshop, Cornell University,
June 18, 2015

Outline

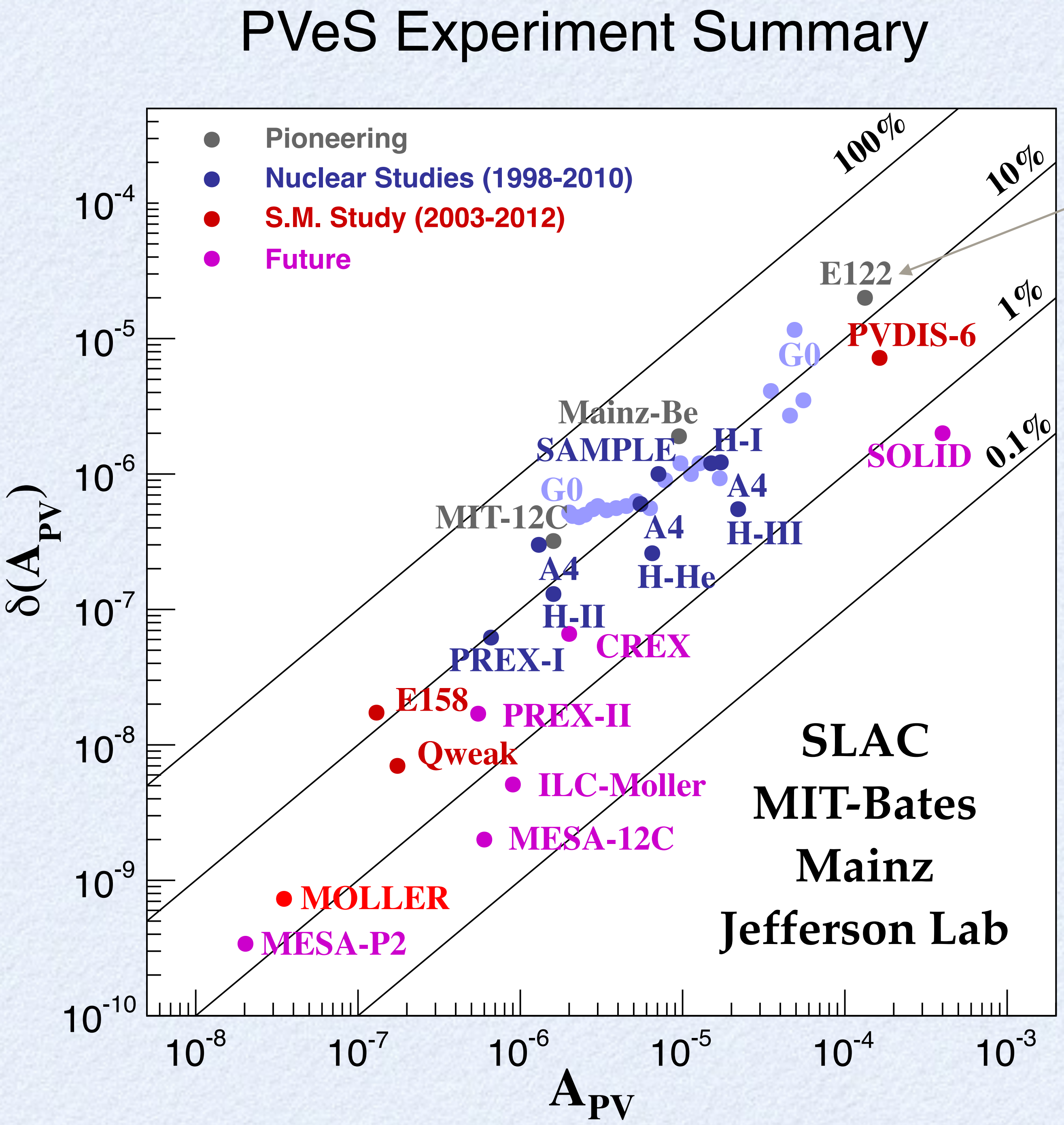
- **PVES and Beyond the Standard Model (BSM)**
  - ***Historical Motivation***
  - ***Modern Motivation***
- **PVES BSM Physics Reach**
  - ***Current Suite of Experiments***
  - ***Complementarity of Various Targets***
- **Outlook**
  - ***Possible New Opportunities***
  - ***Summary of Future Program***

Continuous interplay between probing hadron structure and electroweak physics

Decades of Progress

Parity-violating electron scattering (PVES) has become a precision tool

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



Pioneering electron-quark PV DIS experiment SLAC E122

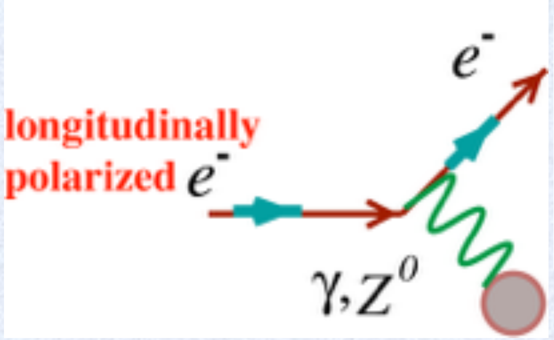
State-of-the-art:

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

Physics Topics

- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at the EIC*
- *Charge Lepton Flavor Violation at the EIC*

Status circa 1990



$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

g_V is a function of $\sin^2\theta_W$

Weak Charge Q_W

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ ***nuclei*** *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

But Q^2 had to be small (0.02 GeV^2!)

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

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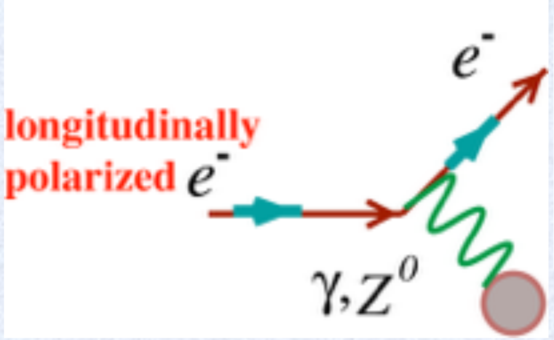

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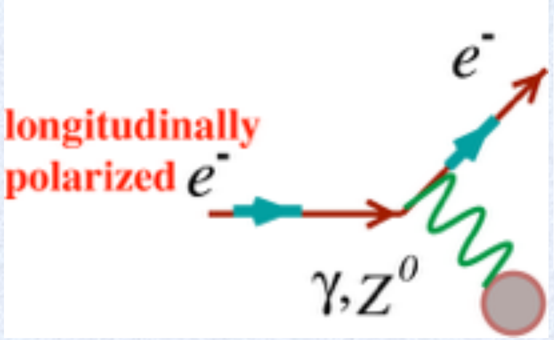

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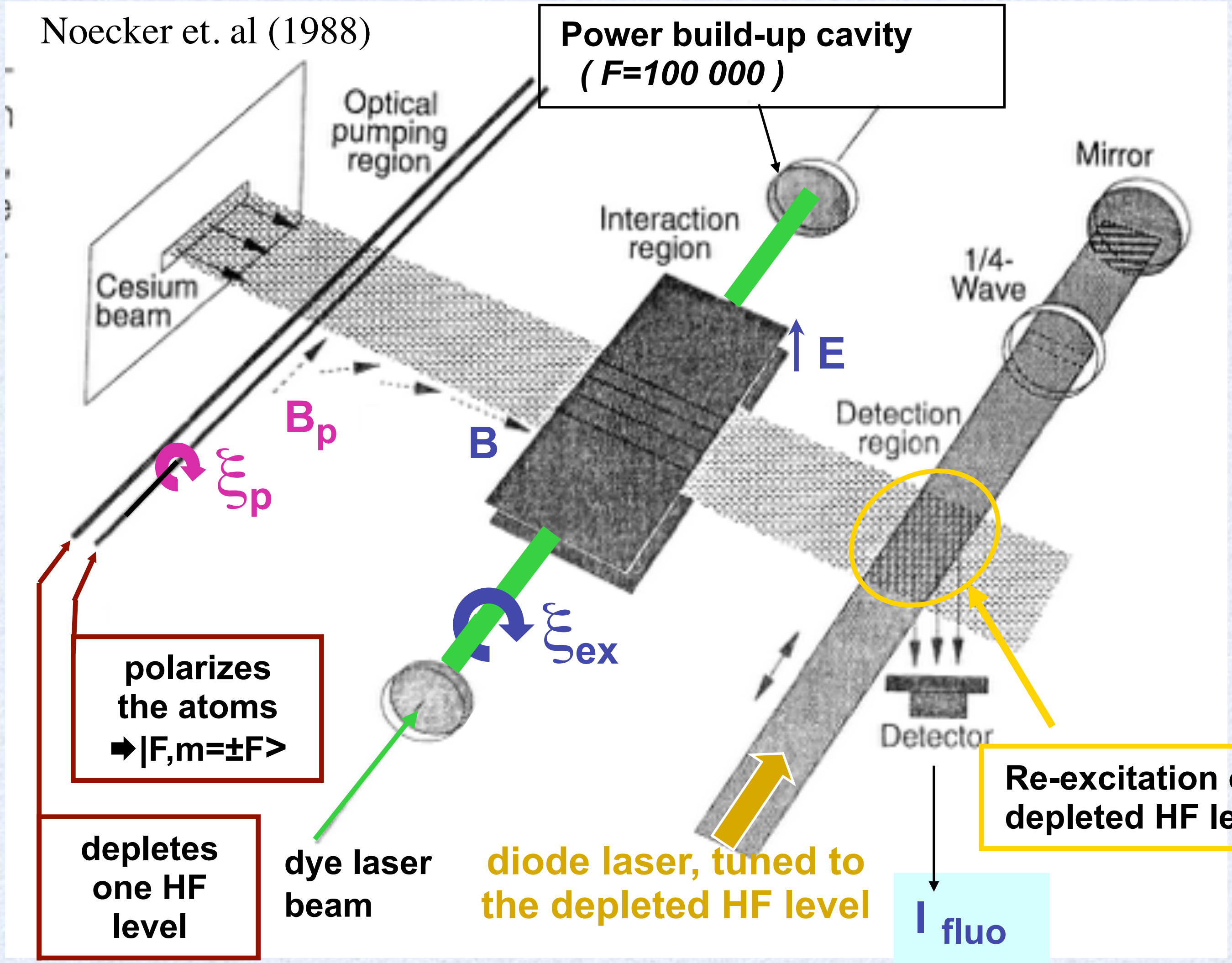
- ***First measurements of electron-nuclear neutral weak interactions***
- ***Pushed experimental technology***
- ***Low energy tests of electroweak theory***

Atomic Parity Violation

- *6S → 7S transition in ^{133}Cs is forbidden within QED*
- *Parity Violation introduces small opposite parity admixtures*
- *Induce an E1 Stark transition, measure E1-PV interference*
- *5 sign reversals to isolate APV signal and suppress systematics*
- *Signal is ~ 6 ppm, measured to 40 ppb*

Boulder Experiment



Noecker et. al (1988)

Power build-up cavity
(F=100 000)

polarizes the atoms
➡|F,m=±F>

depletes one HF level

dye laser beam

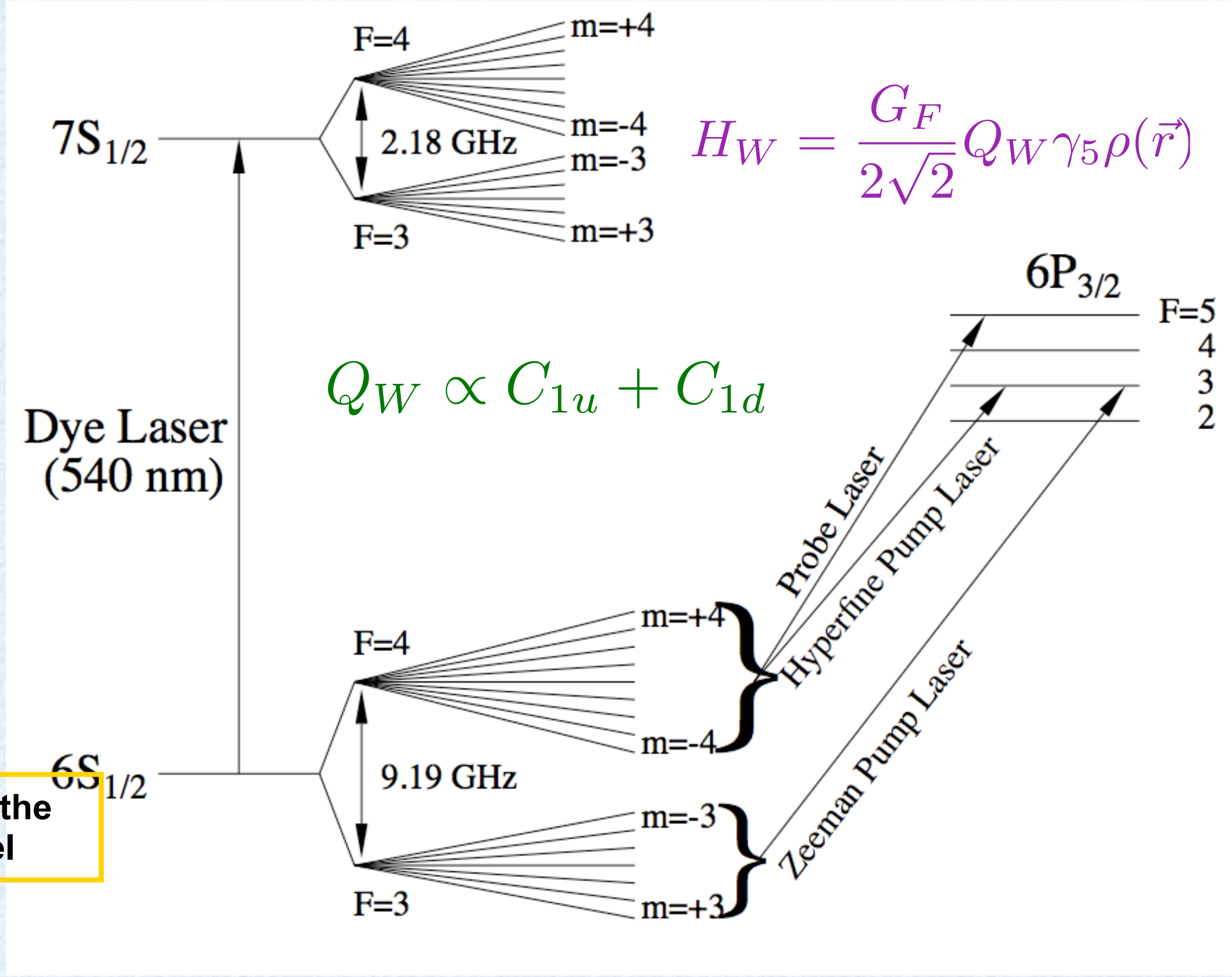
diode laser, tuned to the depleted HF level

Re-excitation of the depleted HF level

I_{fluo}

APV signal: odd in E, ξ_{ex}, B, B_p, ξ_p

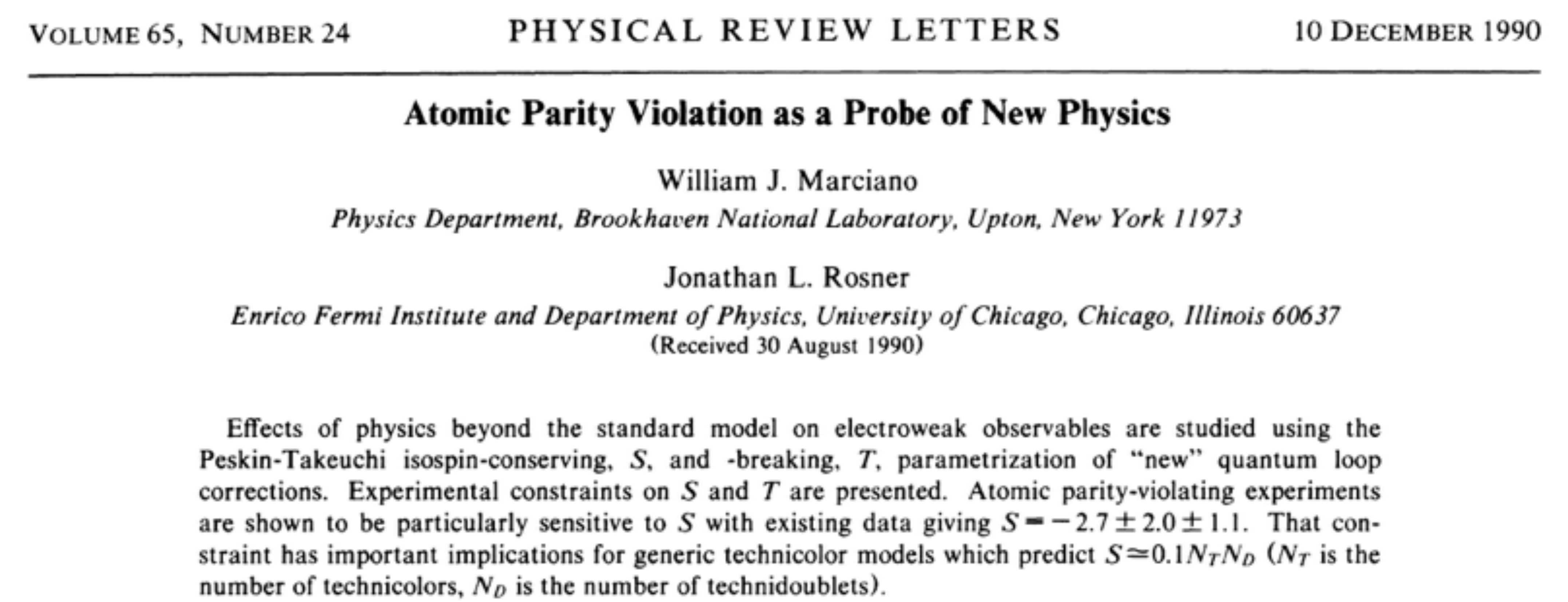
Partial Level Structure of Cesium



$$H_W = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

$$Q_W \propto C_{1u} + C_{1d}$$

New Physics at Low Q^2



VOLUME 65, NUMBER 24 PHYSICAL REVIEW LETTERS 10 DECEMBER 1990

Atomic Parity Violation as a Probe of New Physics

William J. Marciano
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Jonathan L. Rosner
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637

(Received 30 August 1990)

Effects of physics beyond the standard model on electroweak observables are studied using the Peskin-Takeuchi isospin-conserving, S, and -breaking, T, parametrization of "new" quantum loop corrections. Experimental constraints on S and T are presented. Atomic parity-violating experiments are shown to be particularly sensitive to S with existing data giving $S=-2.7\pm2.0\pm1.1$. That constraint has important implications for generic technicolor models which predict $S\simeq0.1N_TN_D$ (N_T is the number of technicolors, N_D is the number of technidoublets).

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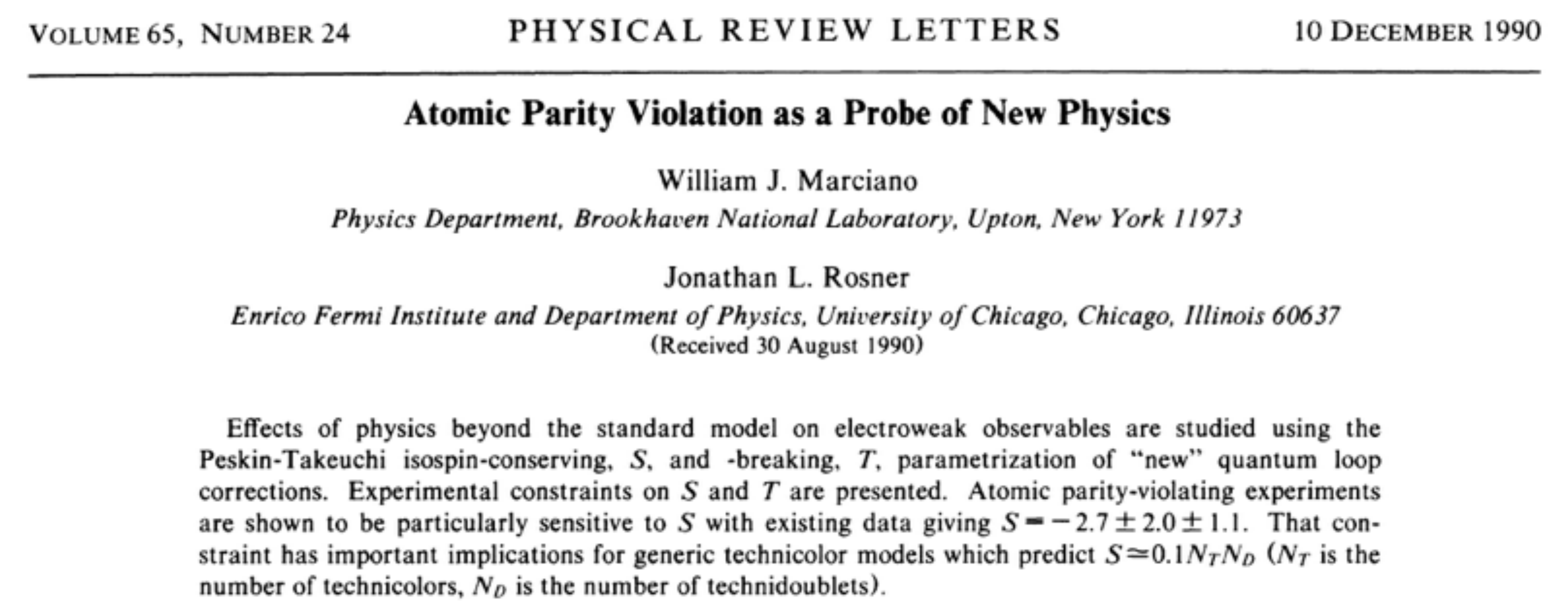

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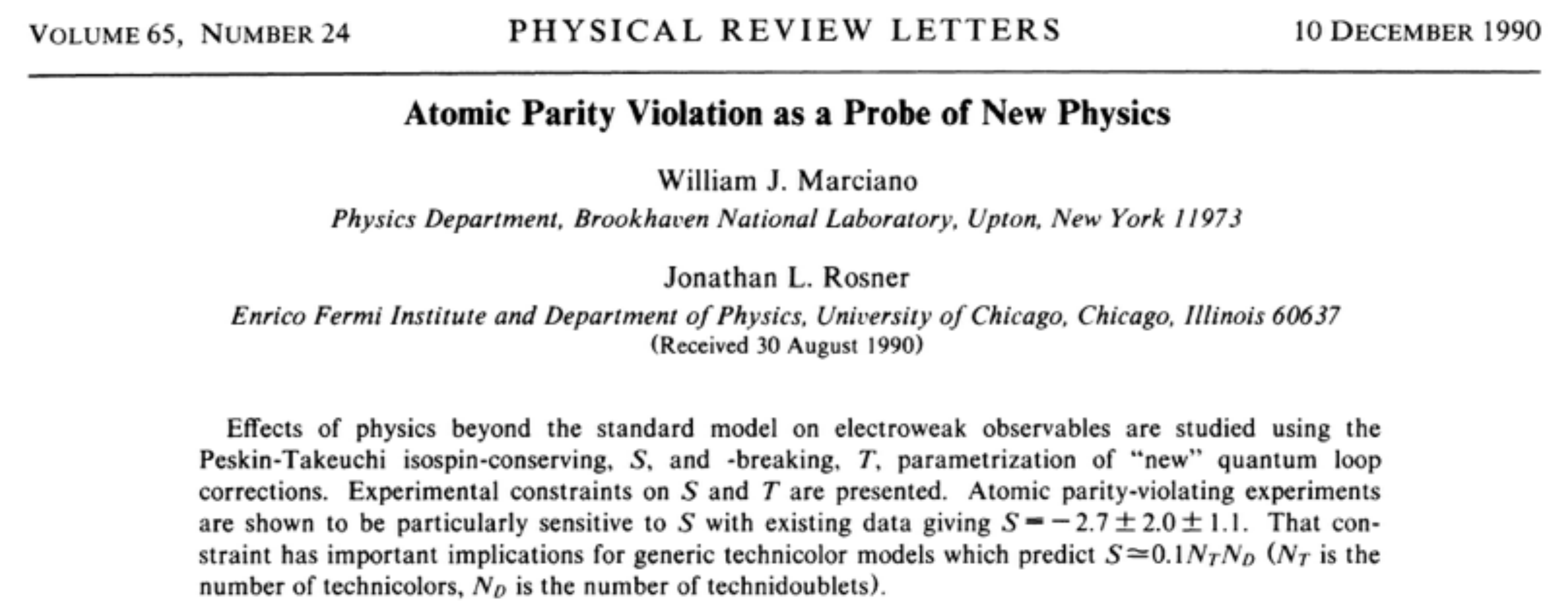

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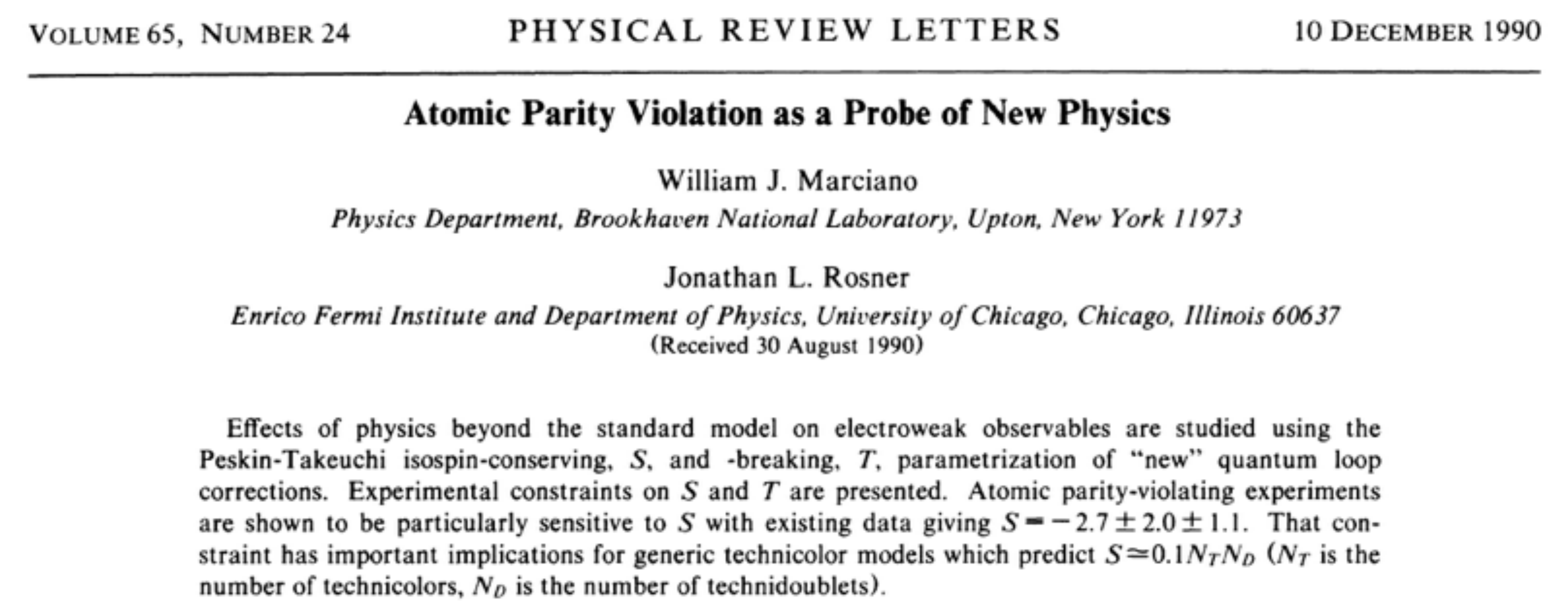

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small SM weak charge

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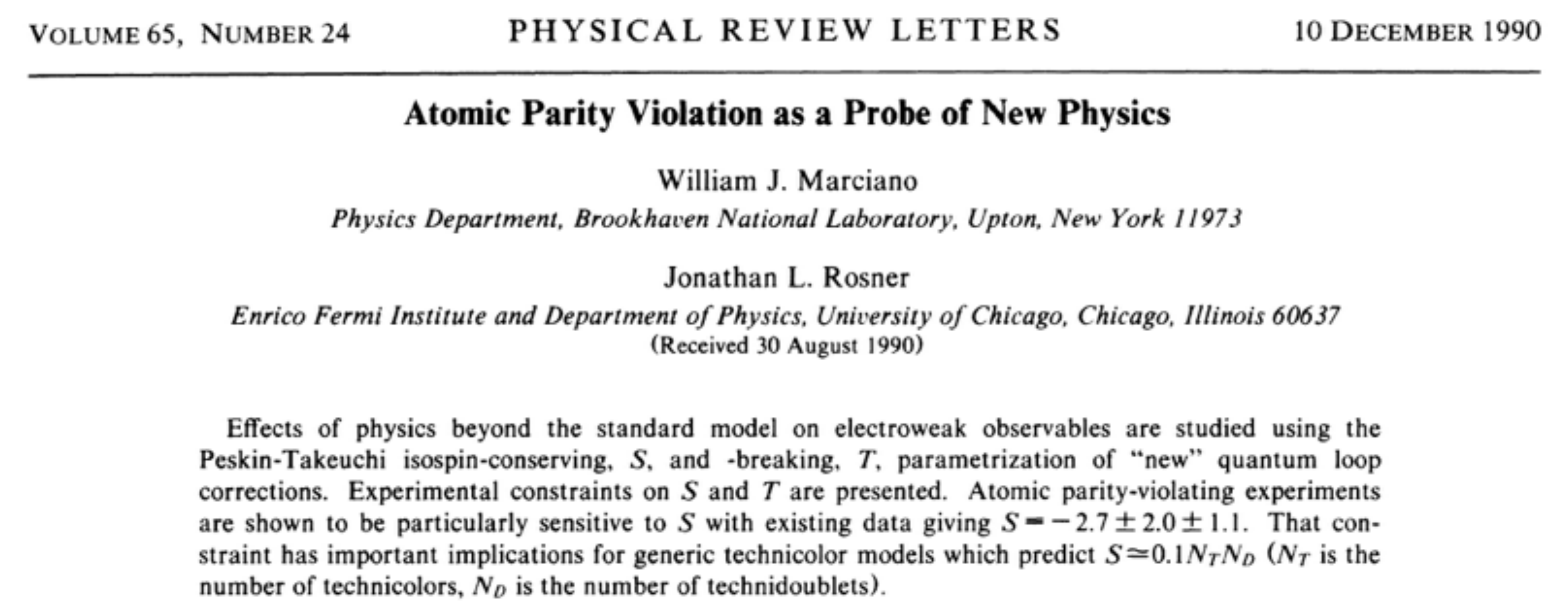

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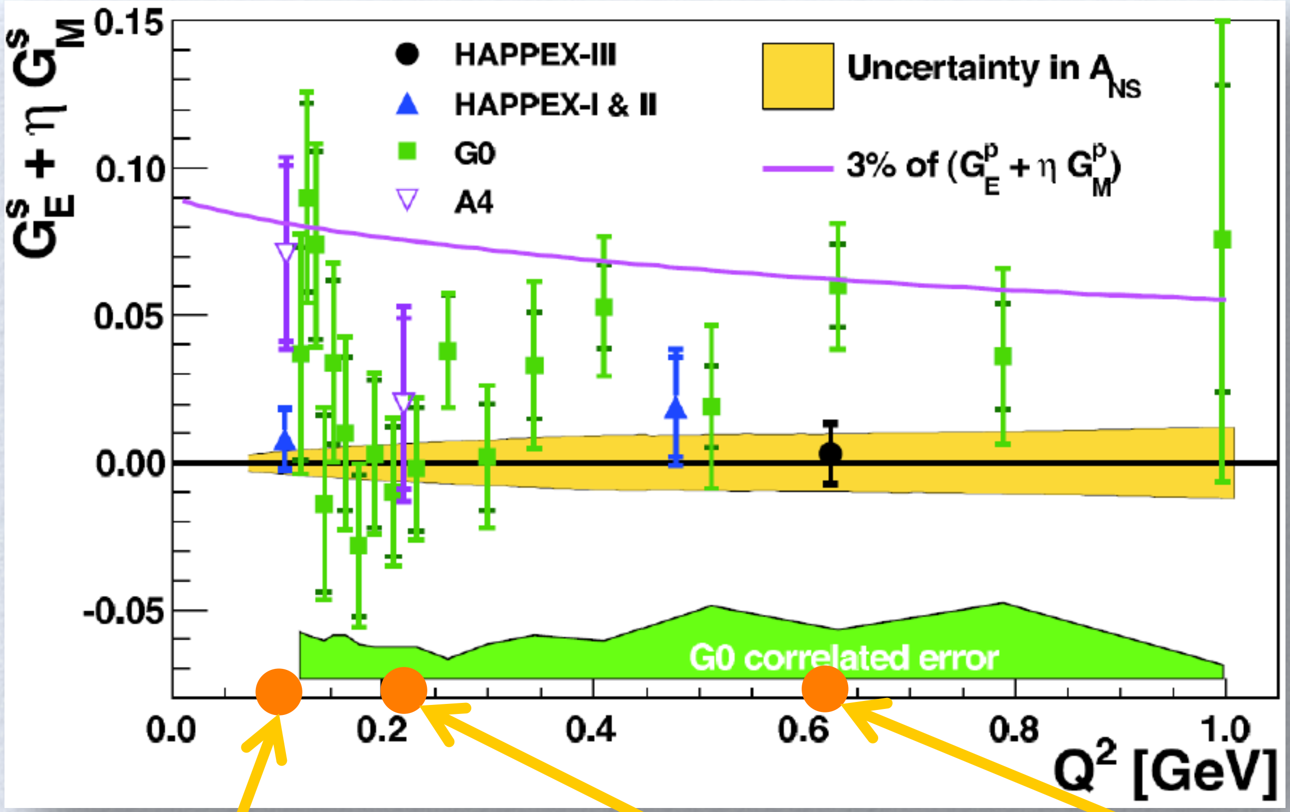
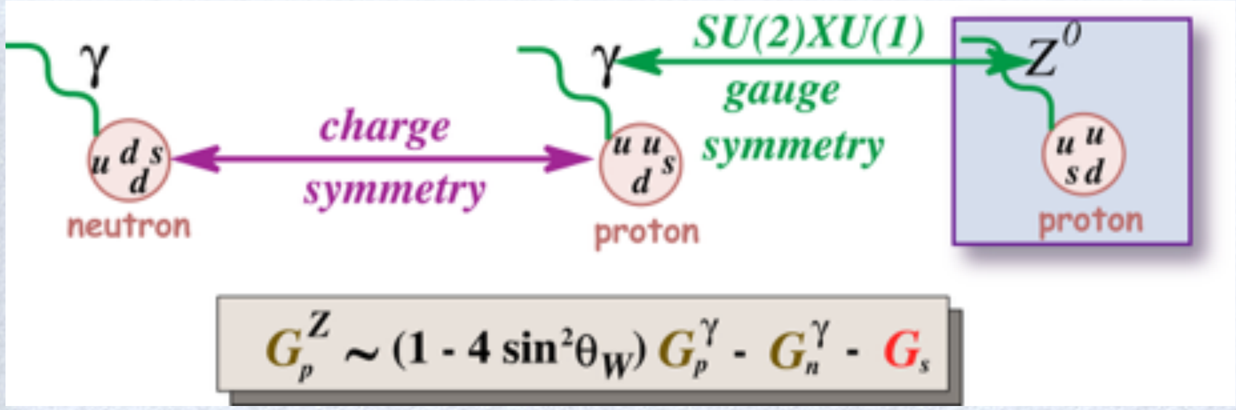
"Spin Crisis" raised questions about the interpretability of proton weak charge measurements

2011: Completion of a 2-decade program

Strange Form Factor Summary

Strange quarks carry nucleon momentum: Other external properties affected?

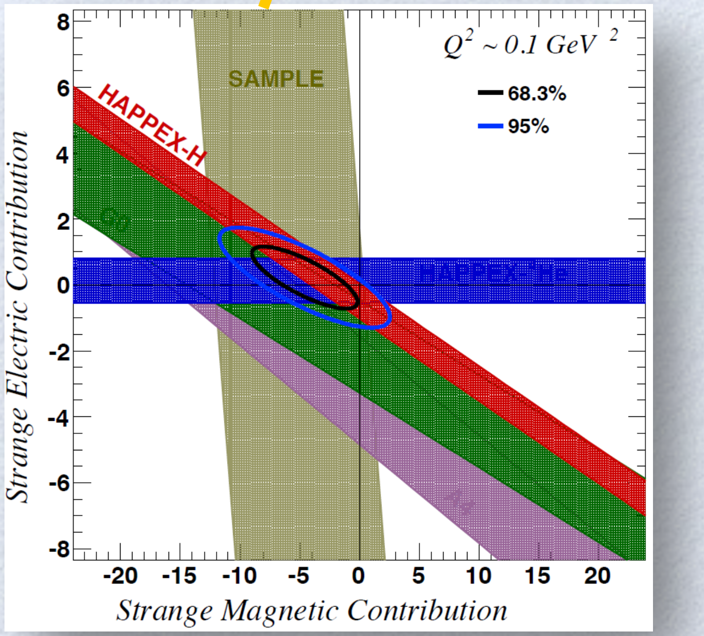


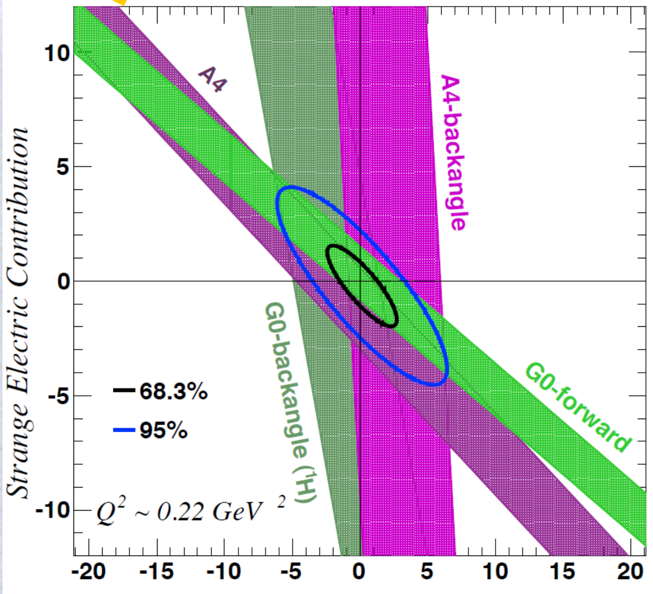


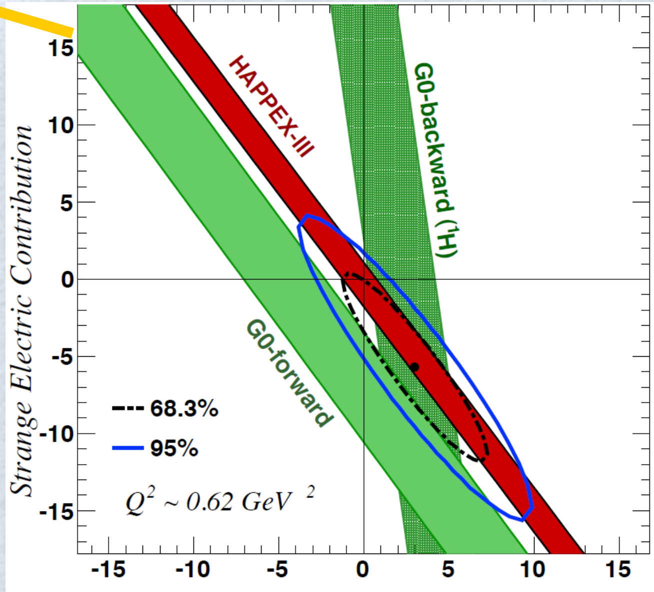
$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

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

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



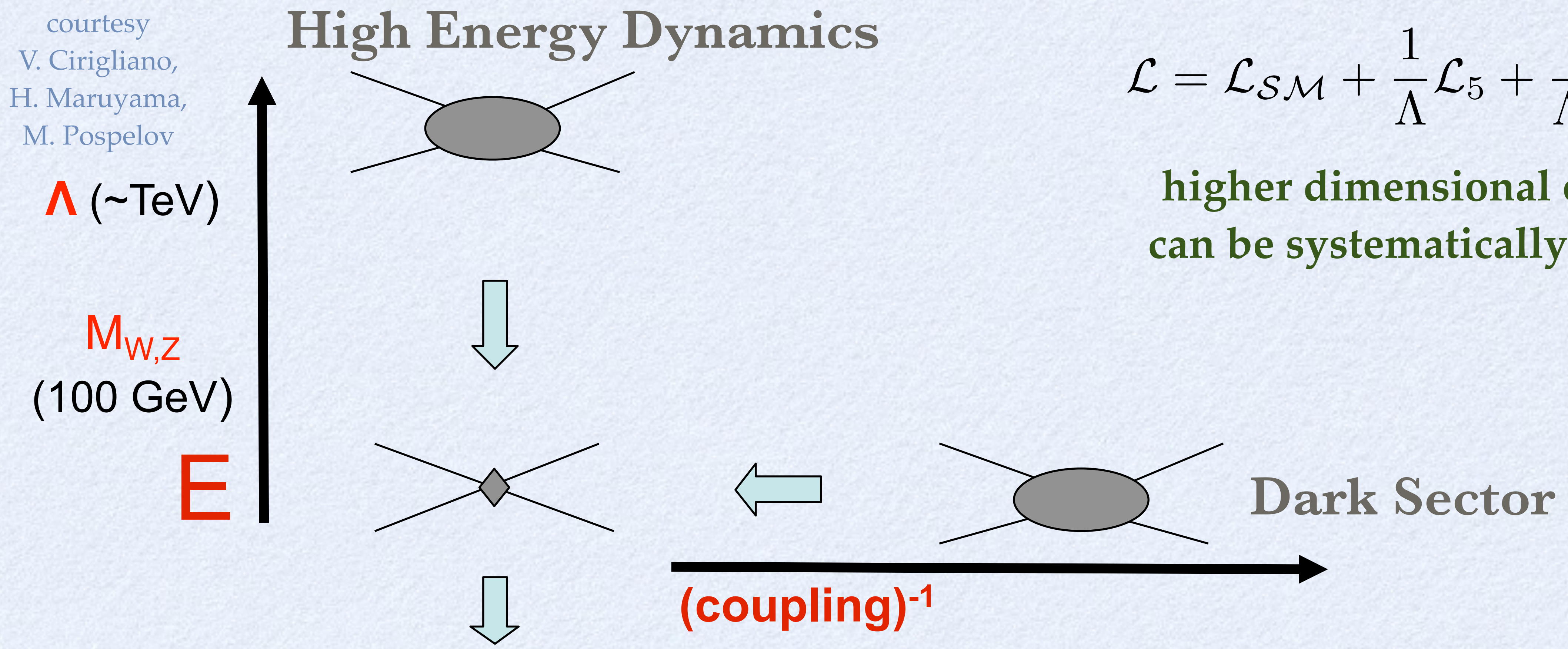




Comprehensive Strategy: Intensity Frontier (HEP) and Fundamental Symmetries and Neutrinos (NP)

PVES and New Physics

Electroweak Interactions at scales much lower than the W/Z mass



$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators
can be systematically classified

Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…

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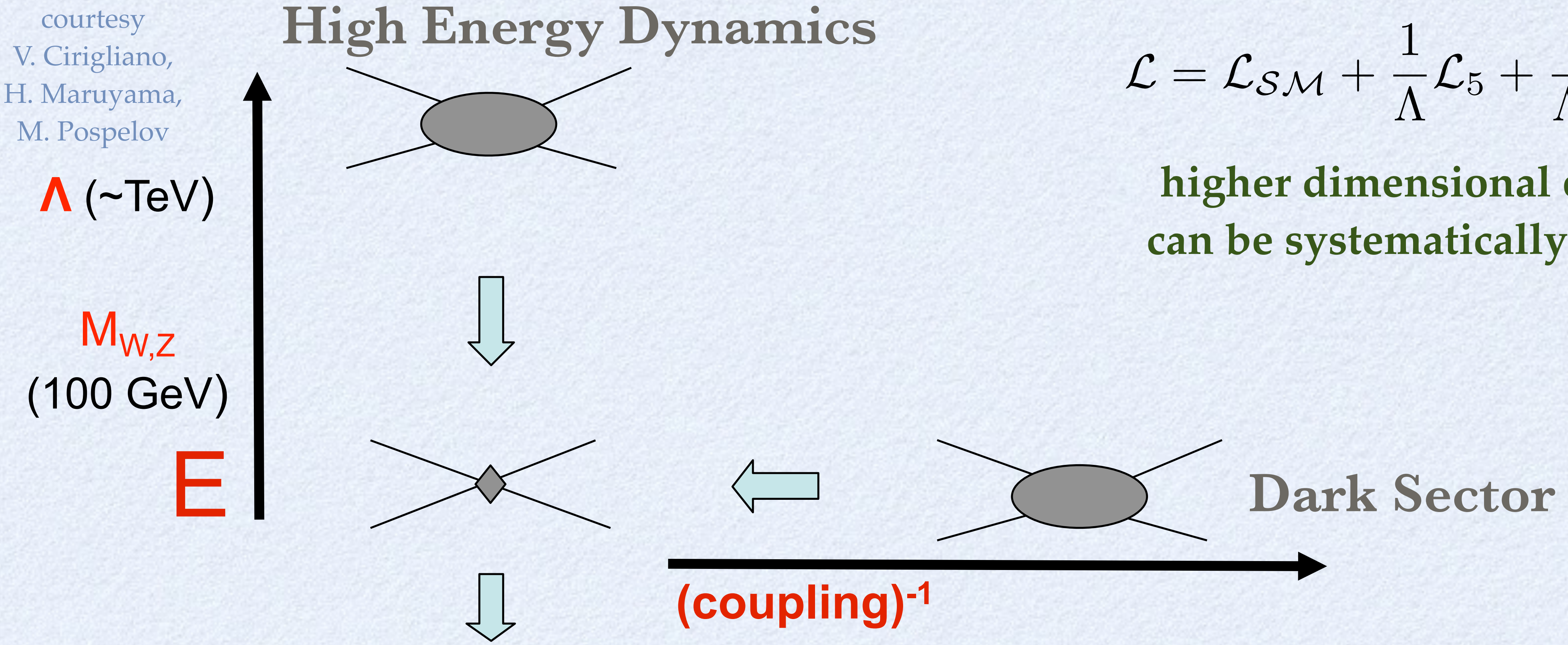
courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov



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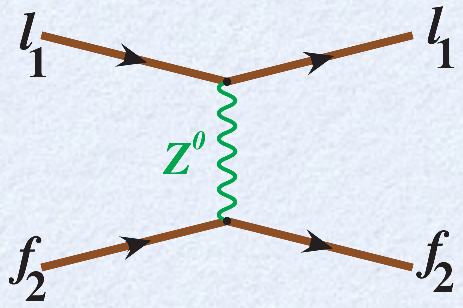
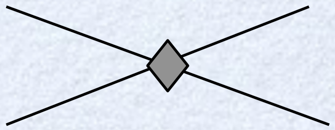


Search for new flavor diagonal neutral currents

Tiny yet measurable deviations from
SM processes with precise predictions

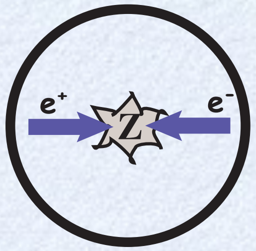
must reach Λ ~ 10 TeV

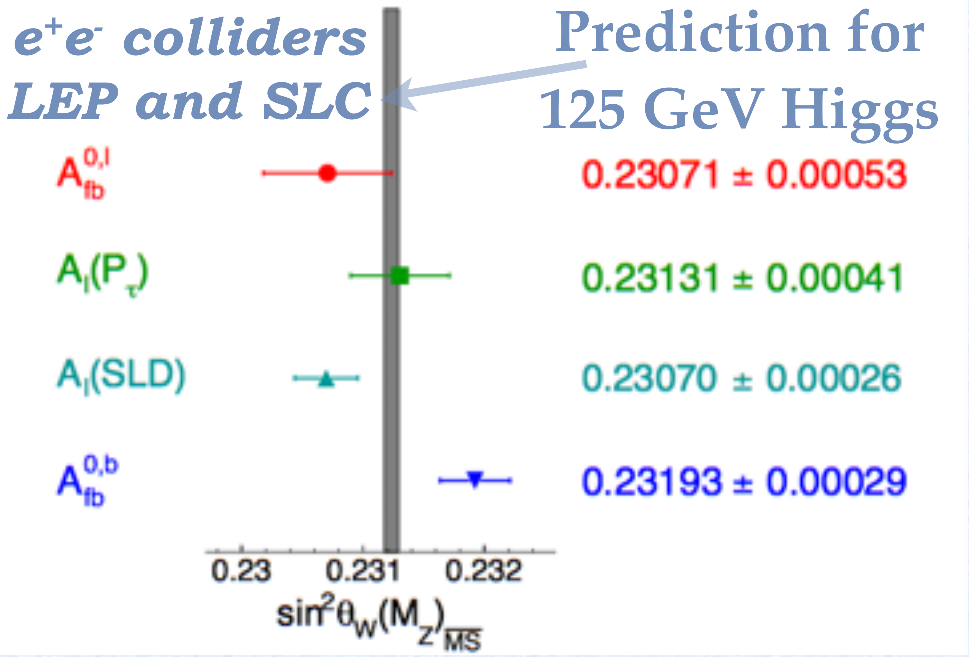


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

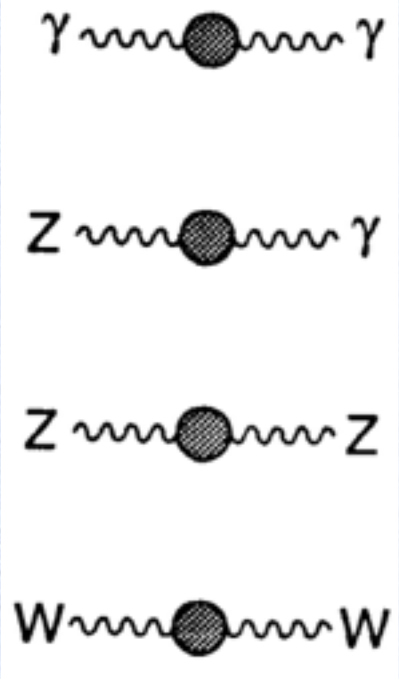
Measurements of $\sin^2\theta_W$

The most precise measurements are from LEP/SLC




e^+e^- colliders LEP and SLC

Prediction for 125 GeV Higgs



S,T, U parameters

Stringent constraints on large classes of new physics models

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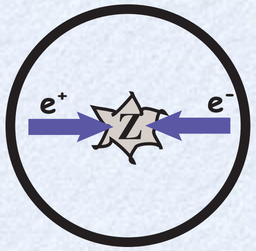

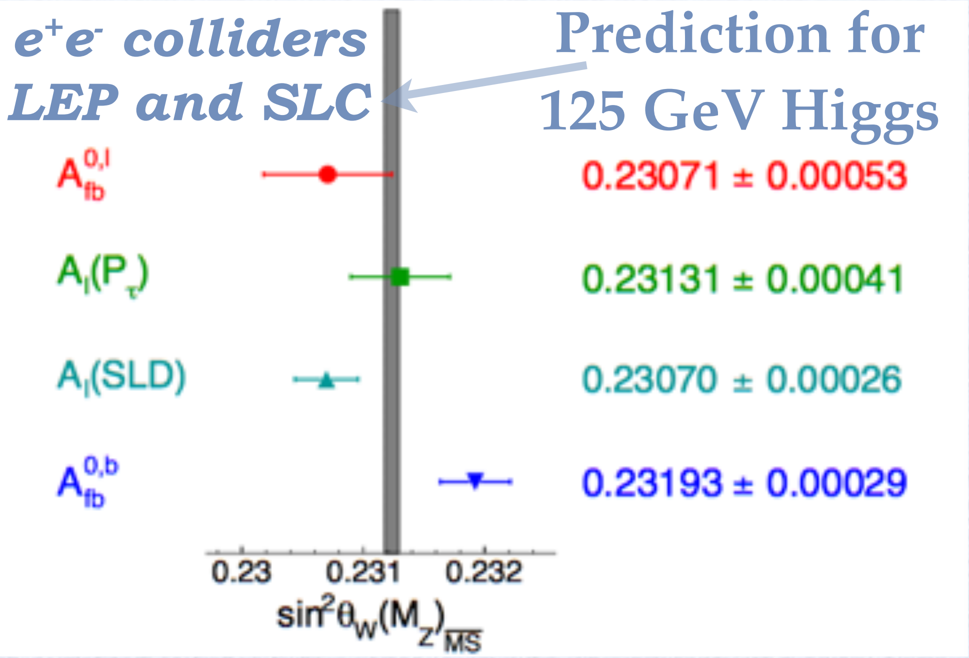
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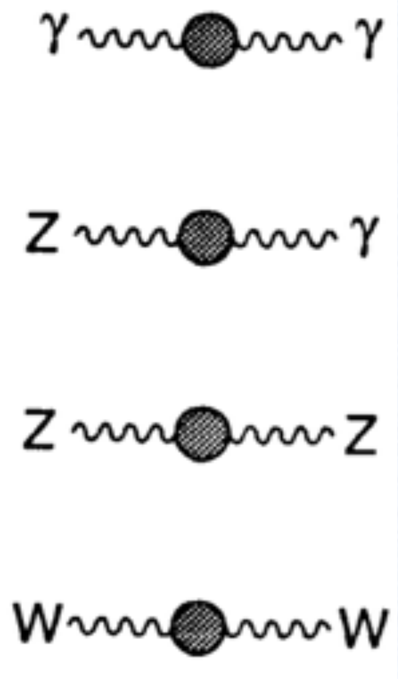

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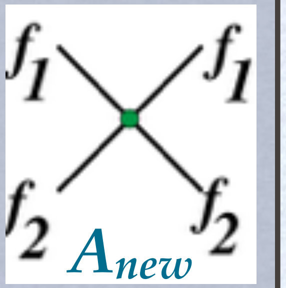
Flavor Diagonal Contact Interactions

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

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



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

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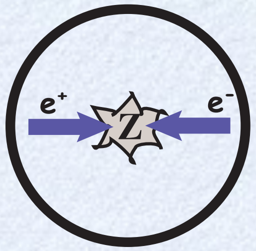

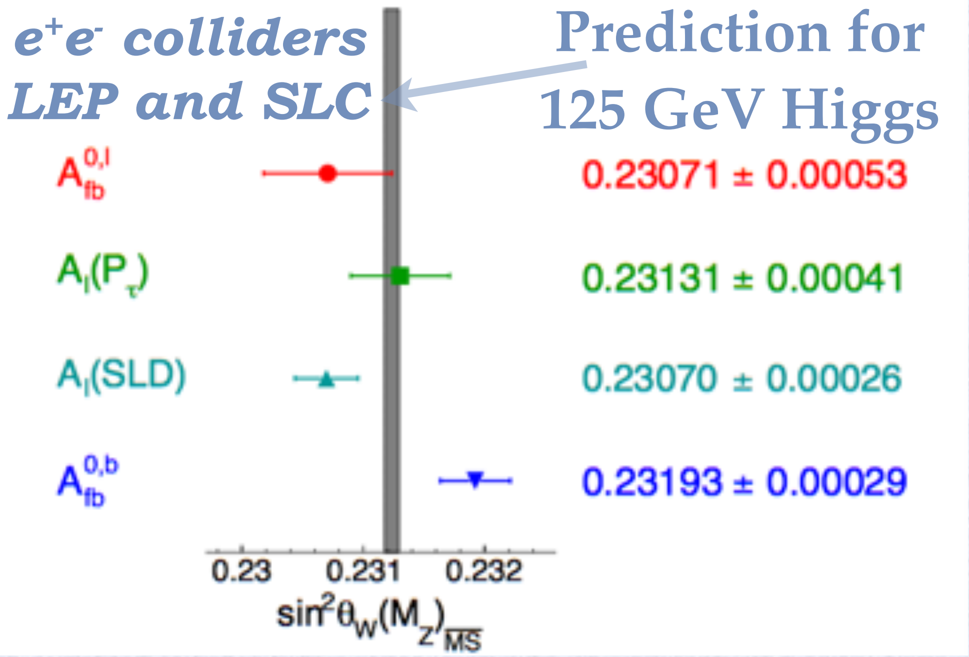

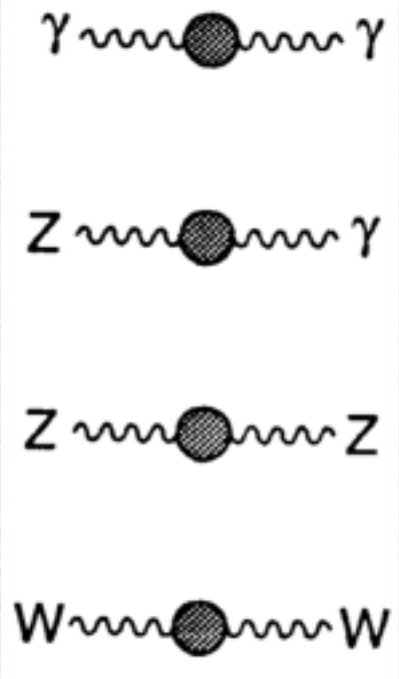

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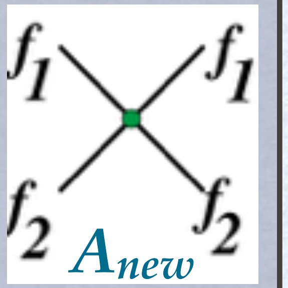

New heavy physics that does not couple directly to SM gauge bosons

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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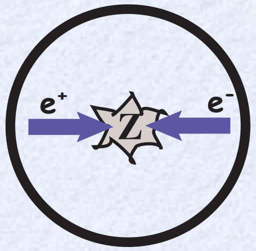

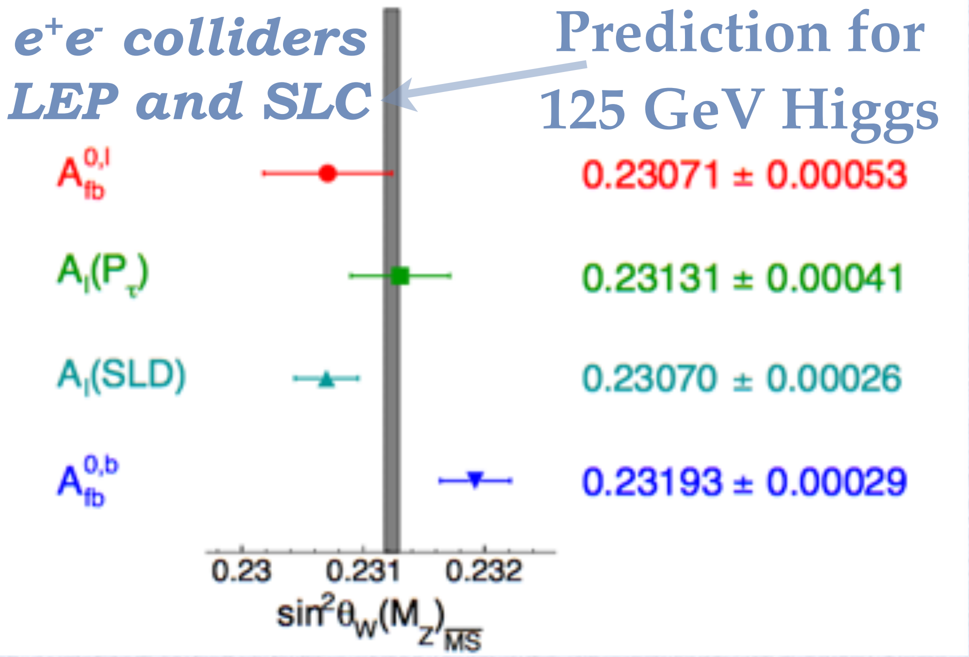

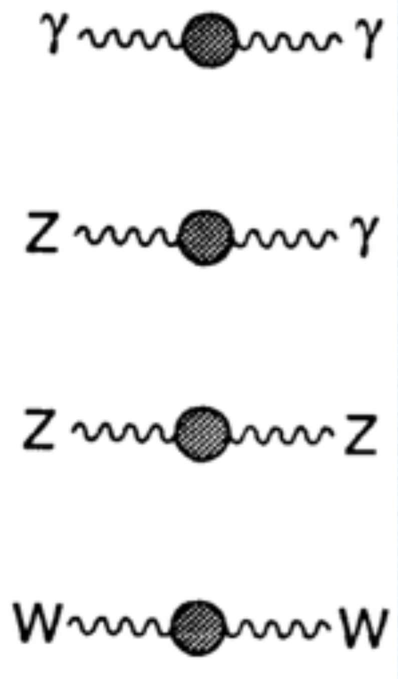

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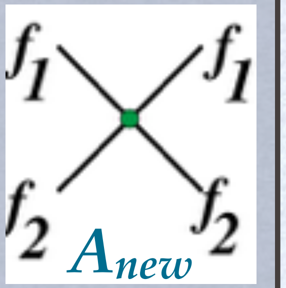

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New flavor diagonal interactions mediated by a new light boson such as the "dark Z"

$$Q^2 \ll M_Z^2$$

Precision Measurements To Date

- **Atomic Parity Violation**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering**
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Technology developed to improve uncertainty by factor ~ 25

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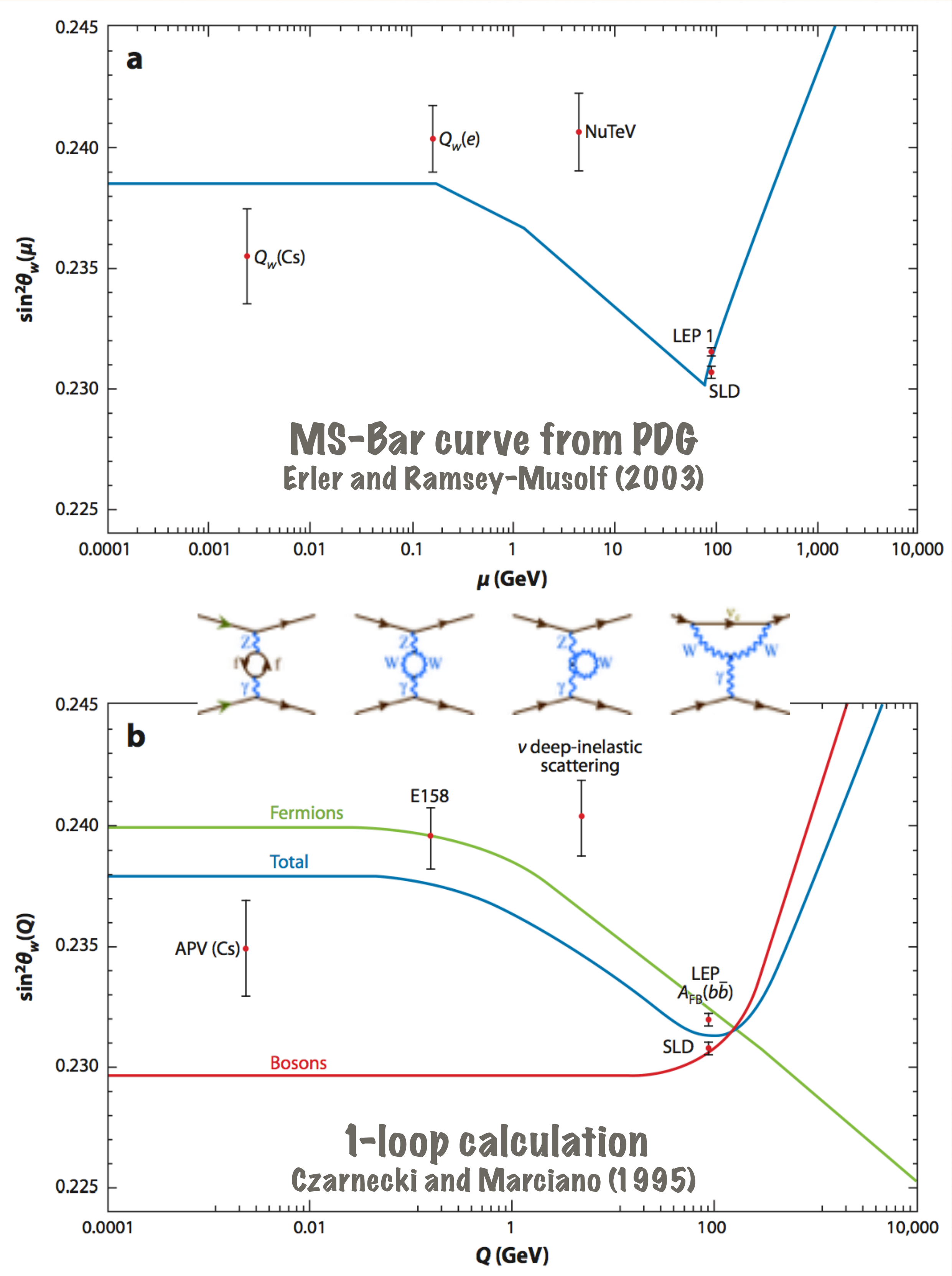

MS-Bar curve from PDG
Erler and Ramsey-Musolf (2003)

1-loop calculation
Czarnecki and Marciano (1995)

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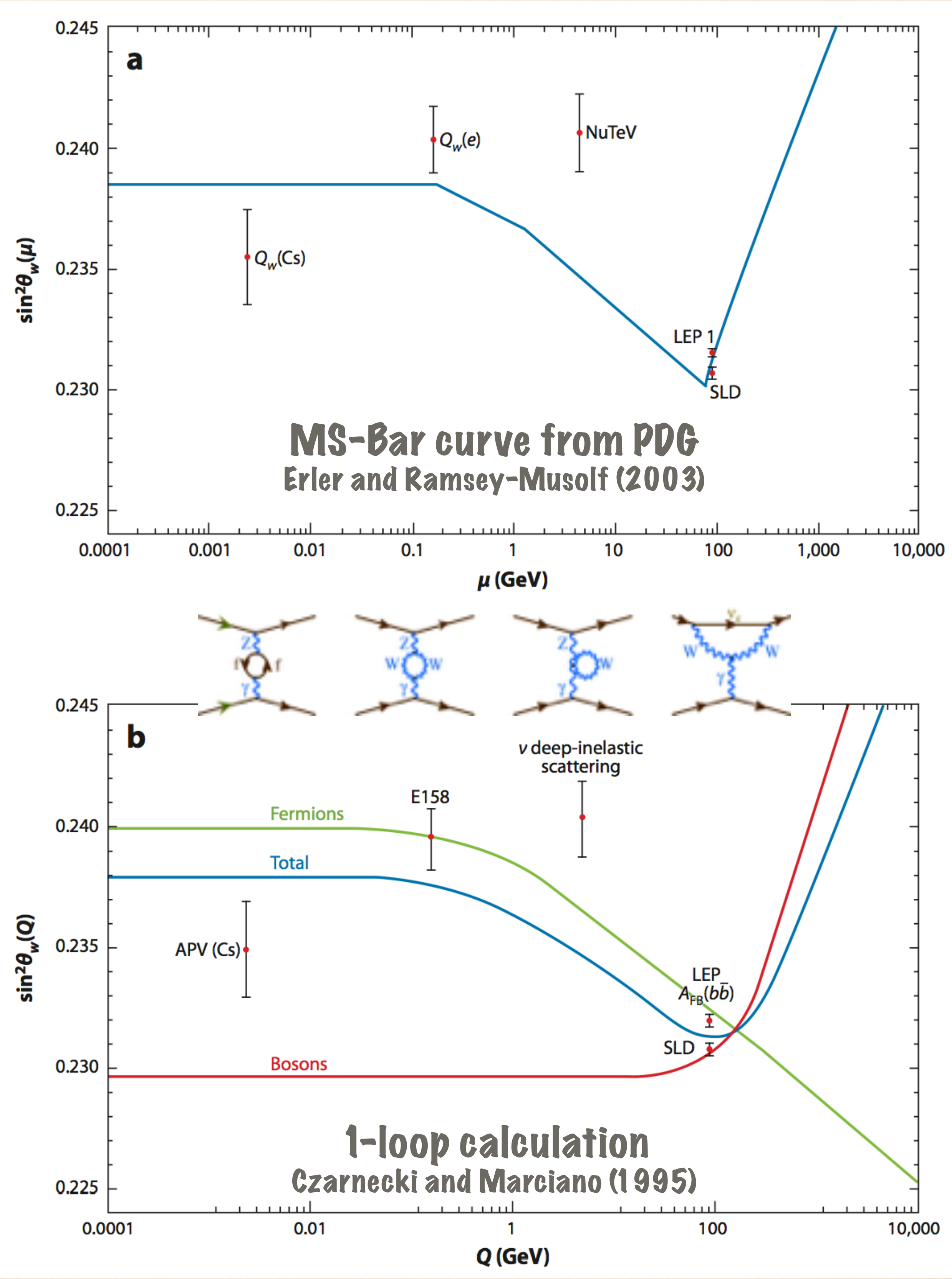
    - ✦ *statistics limited, theory robust*

Technology developed to improve uncertainty by factor ~ 25

Recent Progress

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

Qweak at JLab: should produce precision measurement soon



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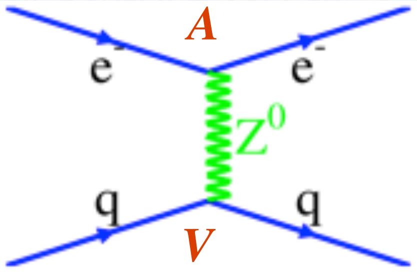
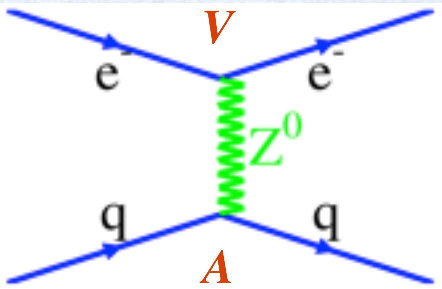
Weak Neutral Current Couplings



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



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

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$

$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

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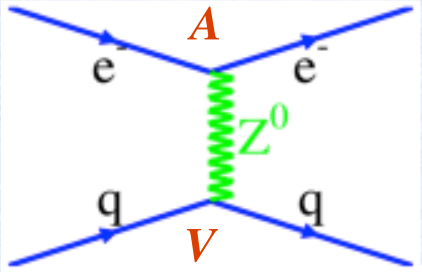

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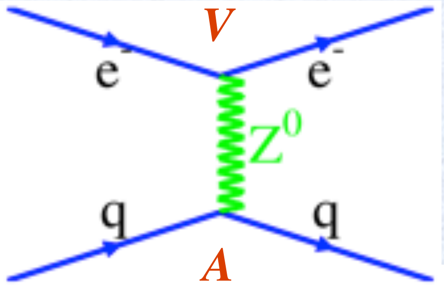

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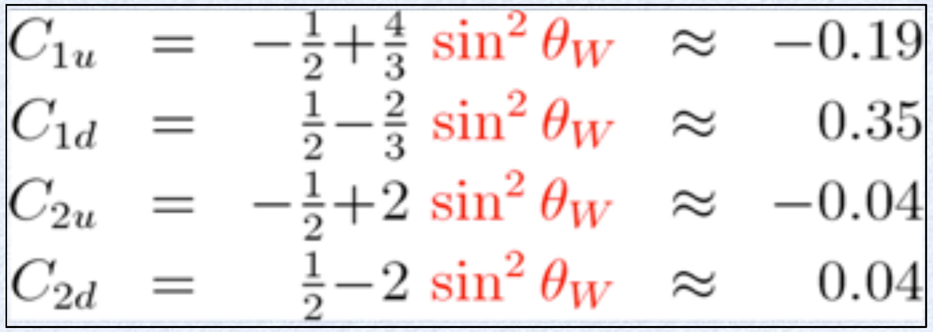

C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
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C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
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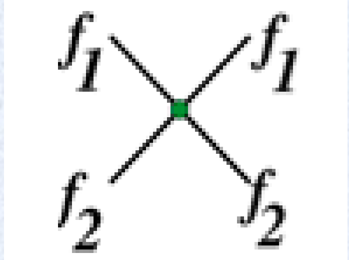
$+$

new physics



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

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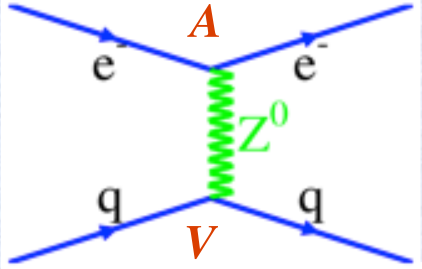

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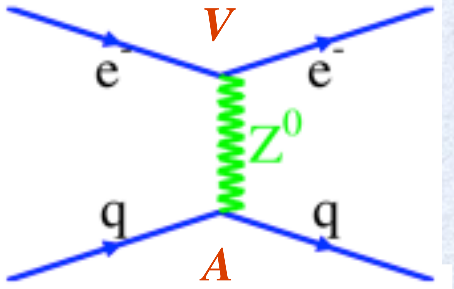

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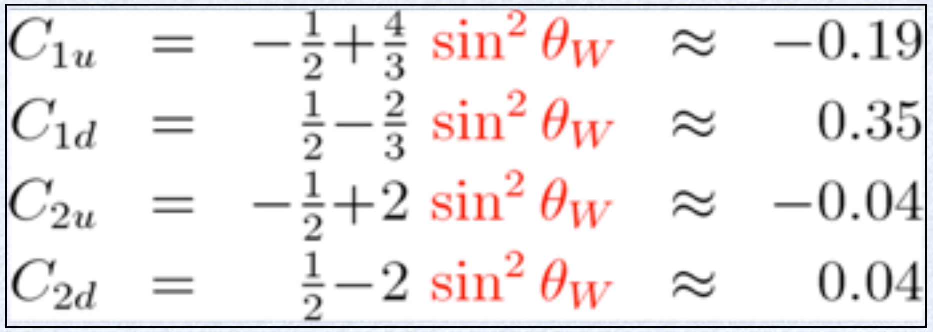

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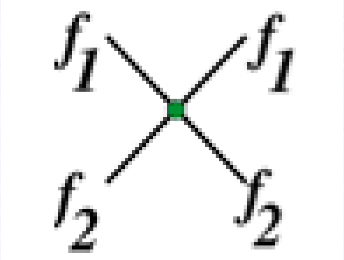

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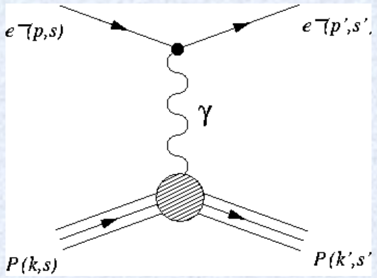
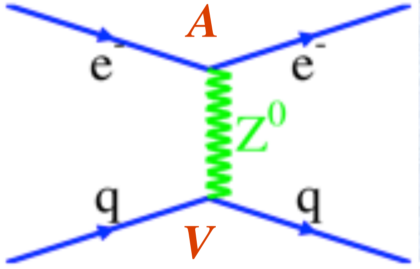
PV elastic e-N scattering,
Atomic parity violation



Weak Neutral Current Couplings



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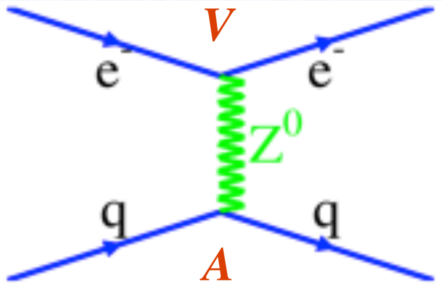

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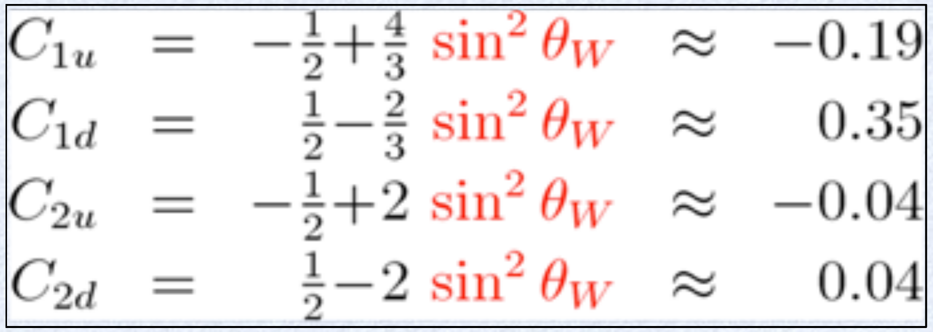

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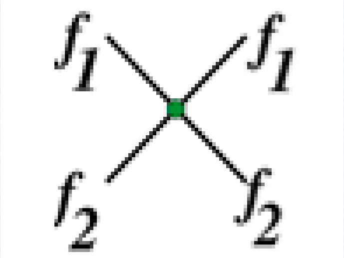

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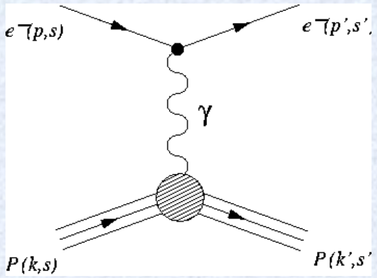

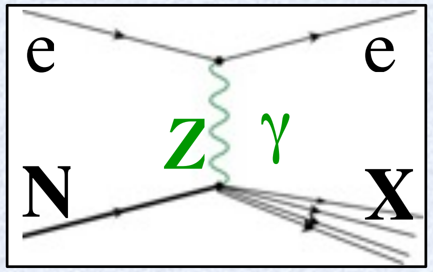

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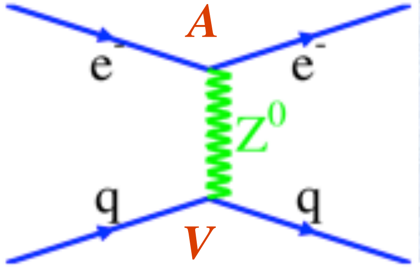

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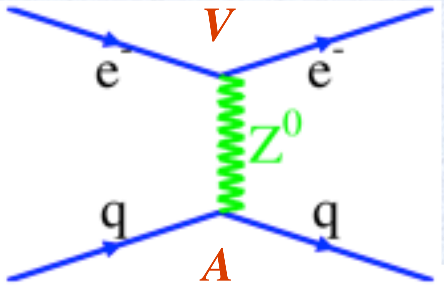

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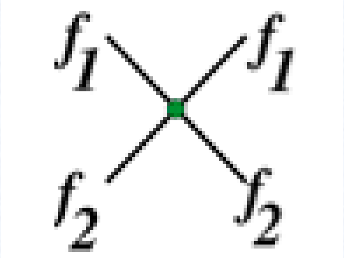
+

new physics



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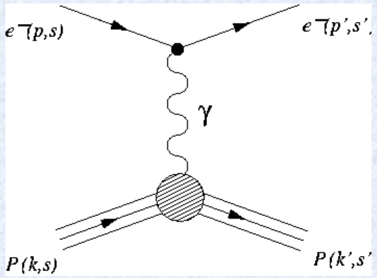
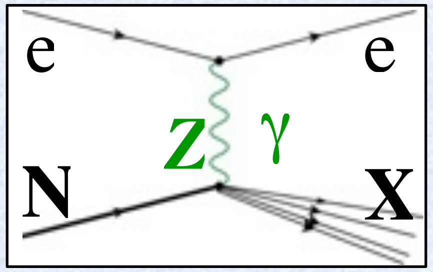
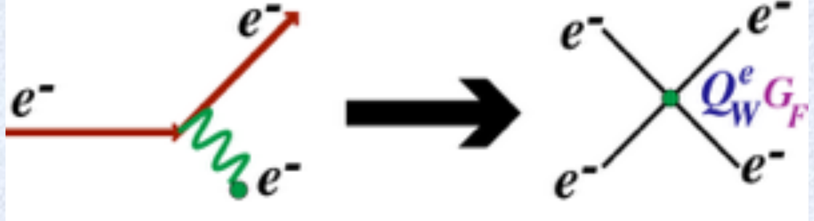
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇨ *PV Møller scattering*

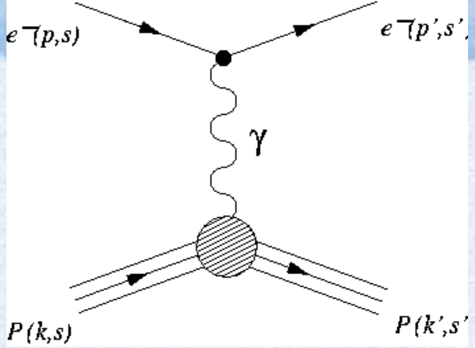




$Q_W = 1 - 4\sin^2\theta_W$



Weak Charge of the Proton



$$Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

For a ^{1}H target, nucleon structure contribution well-constrained from measurements

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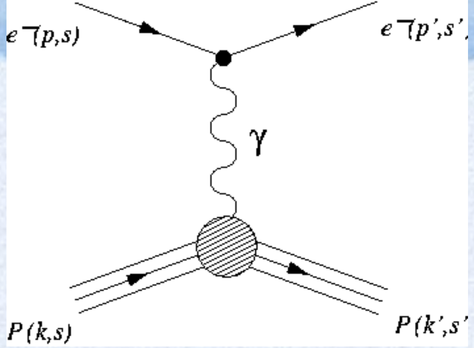

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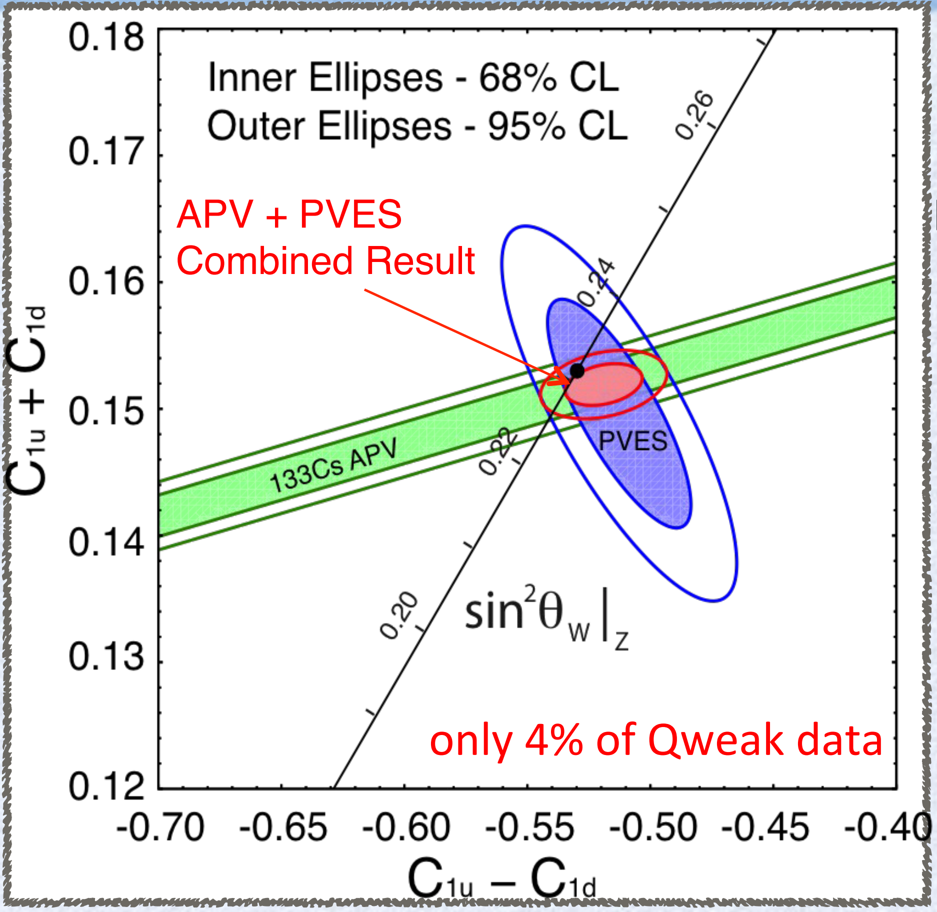
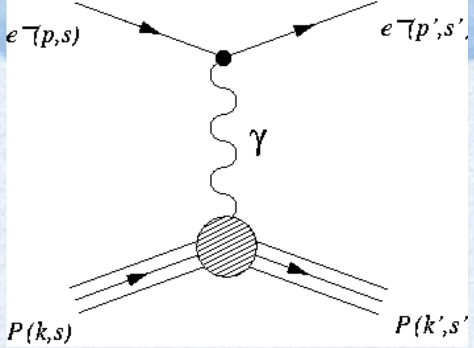


APV + PVES
Combined Result

only 4% of Qweak data

Weak Charge of the Proton



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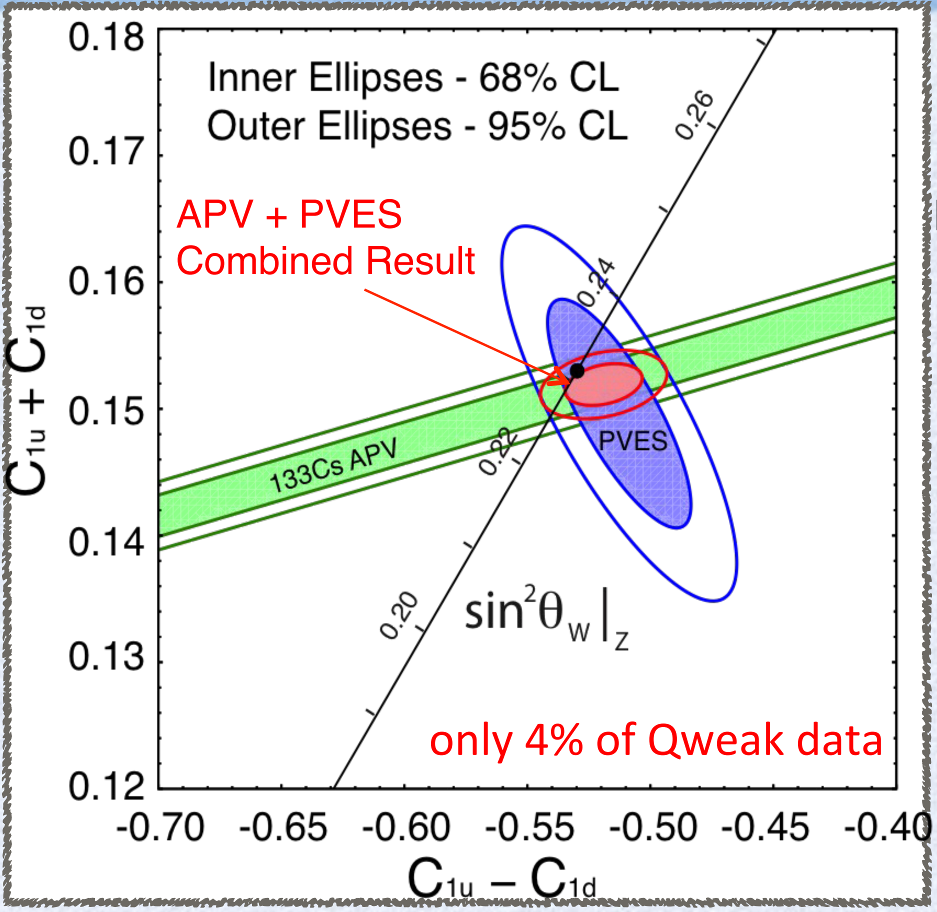
Final result with the full accumulated statistics is anticipated later this year



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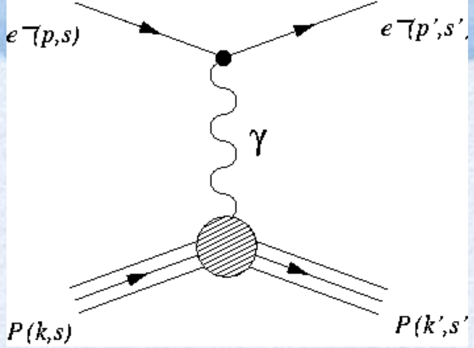

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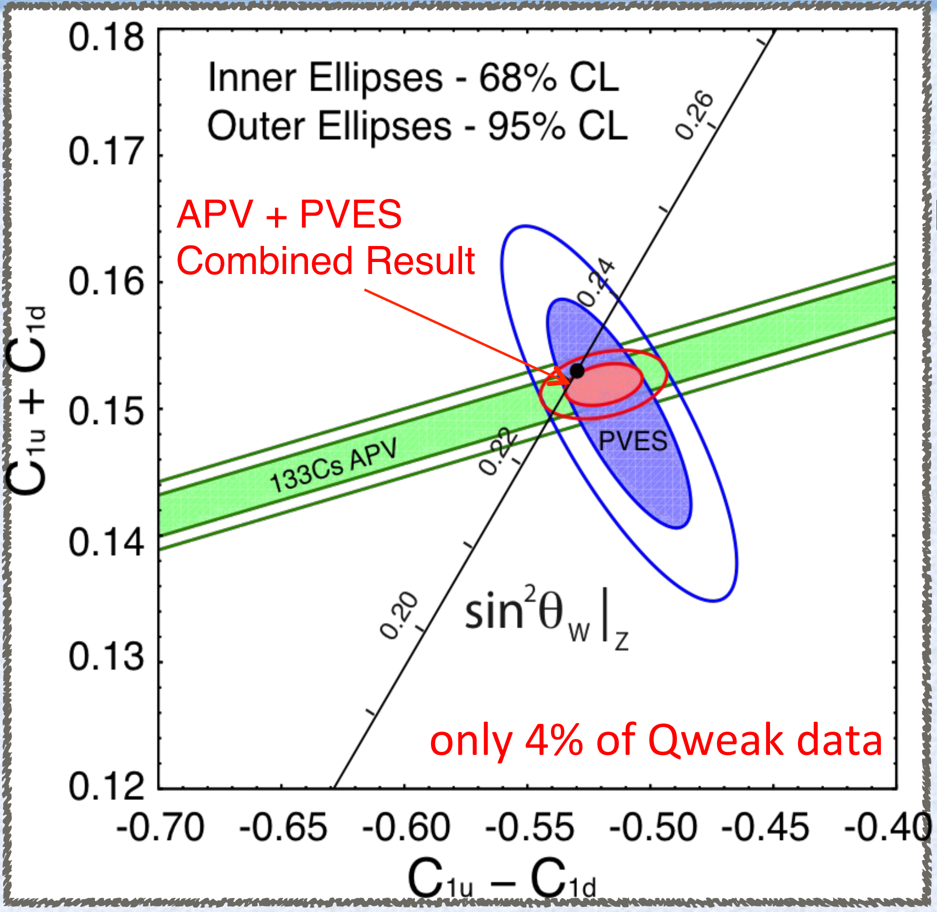
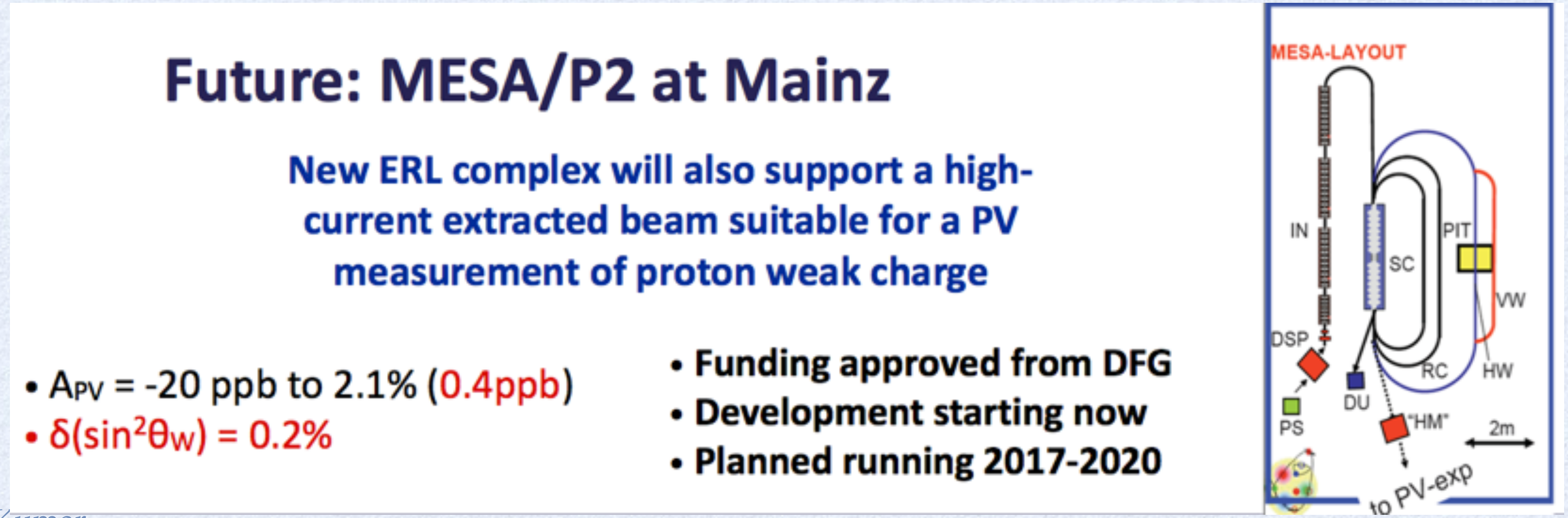




Future: MESA/P2 at Mainz

New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge

- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

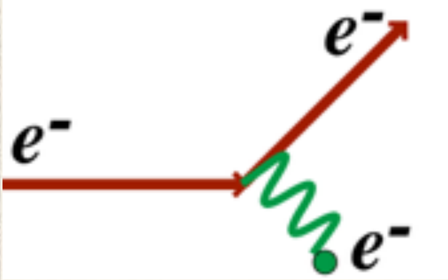
- Funding approved from DFG
- Development starting now
- Planned running 2017-2020

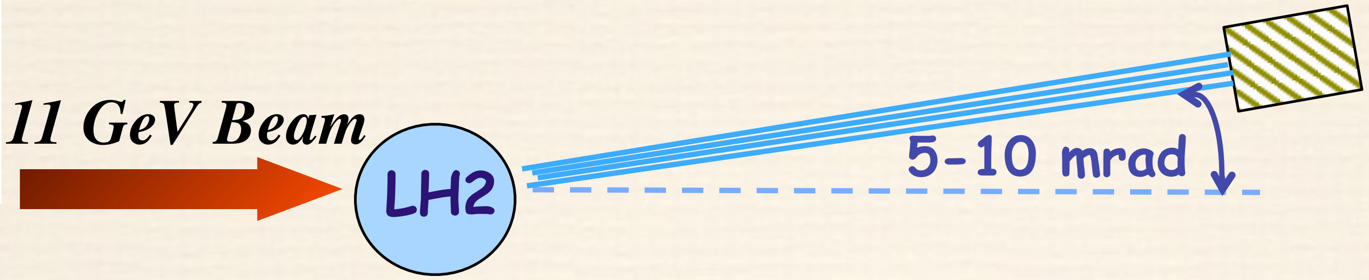
An ultra-precise measurement of the weak mixing angle using Møller scattering

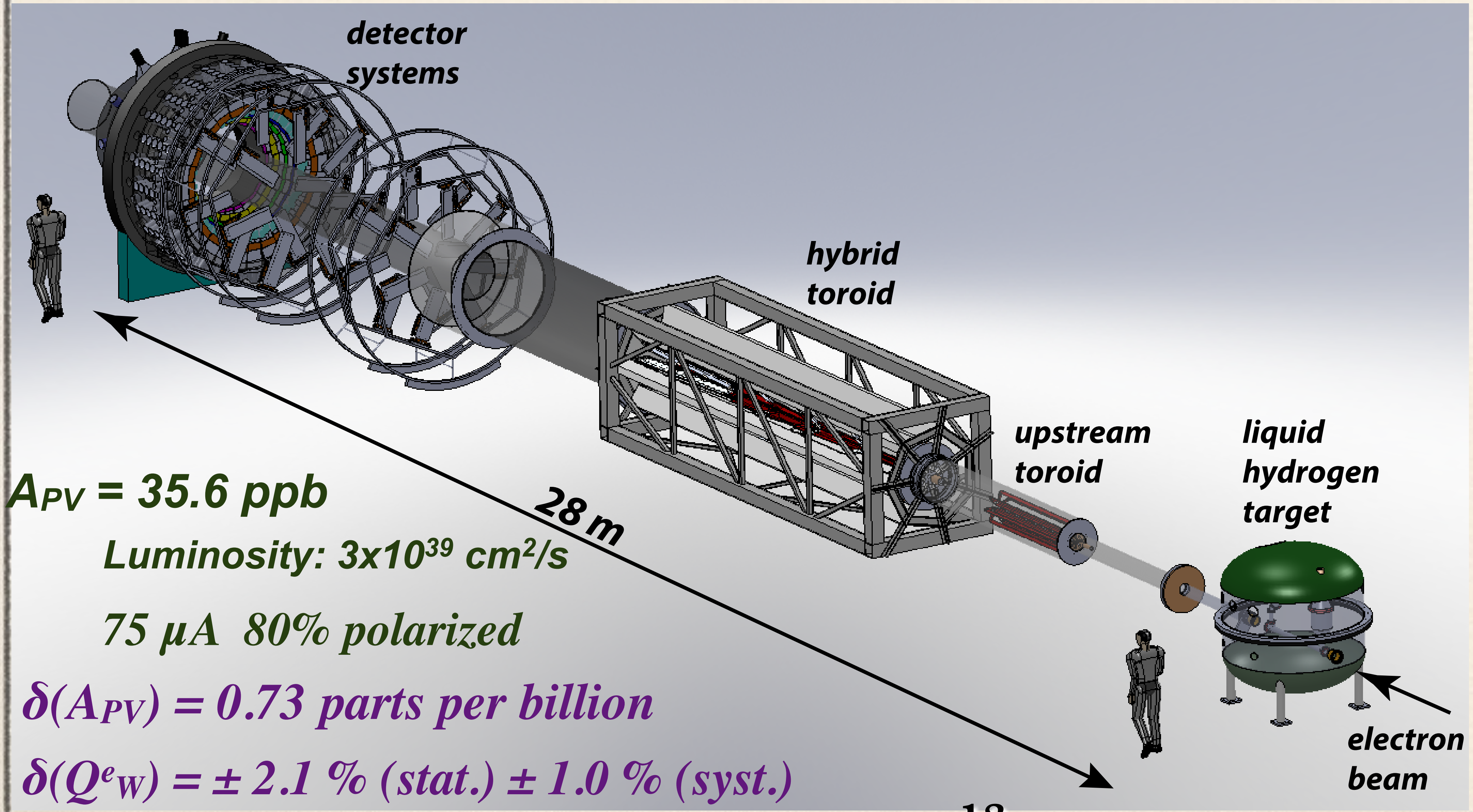
11 GeV Møller scattering

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

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

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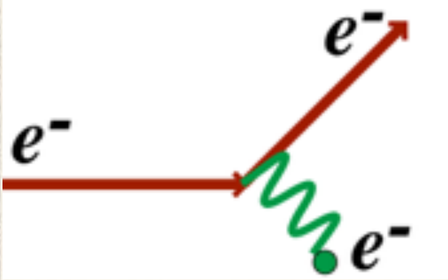
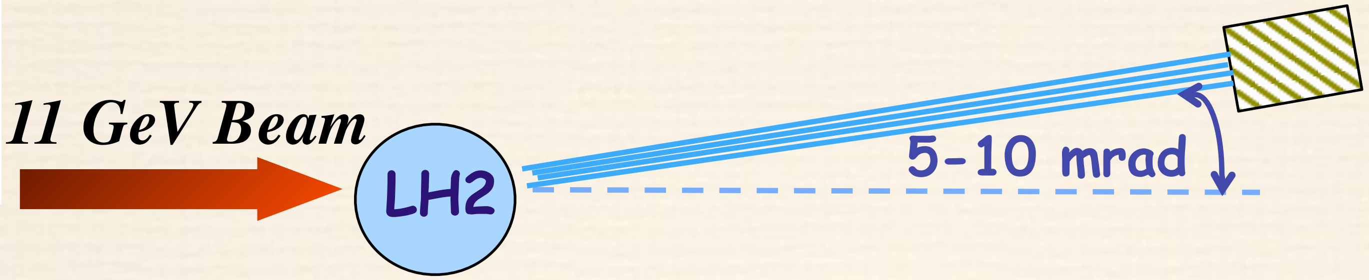
MOLLER at JLab

Measurement **O**f **L**epton **L**epton **E**lectroweak **R**eaction





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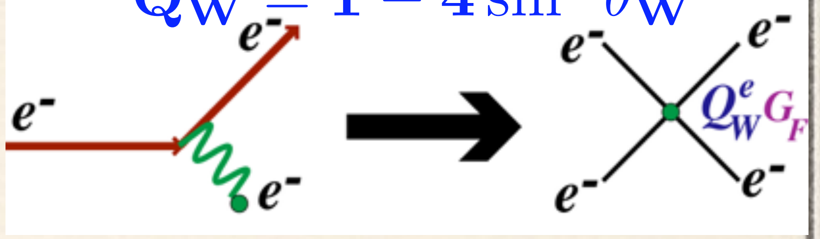
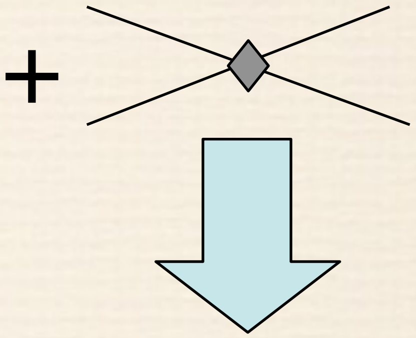
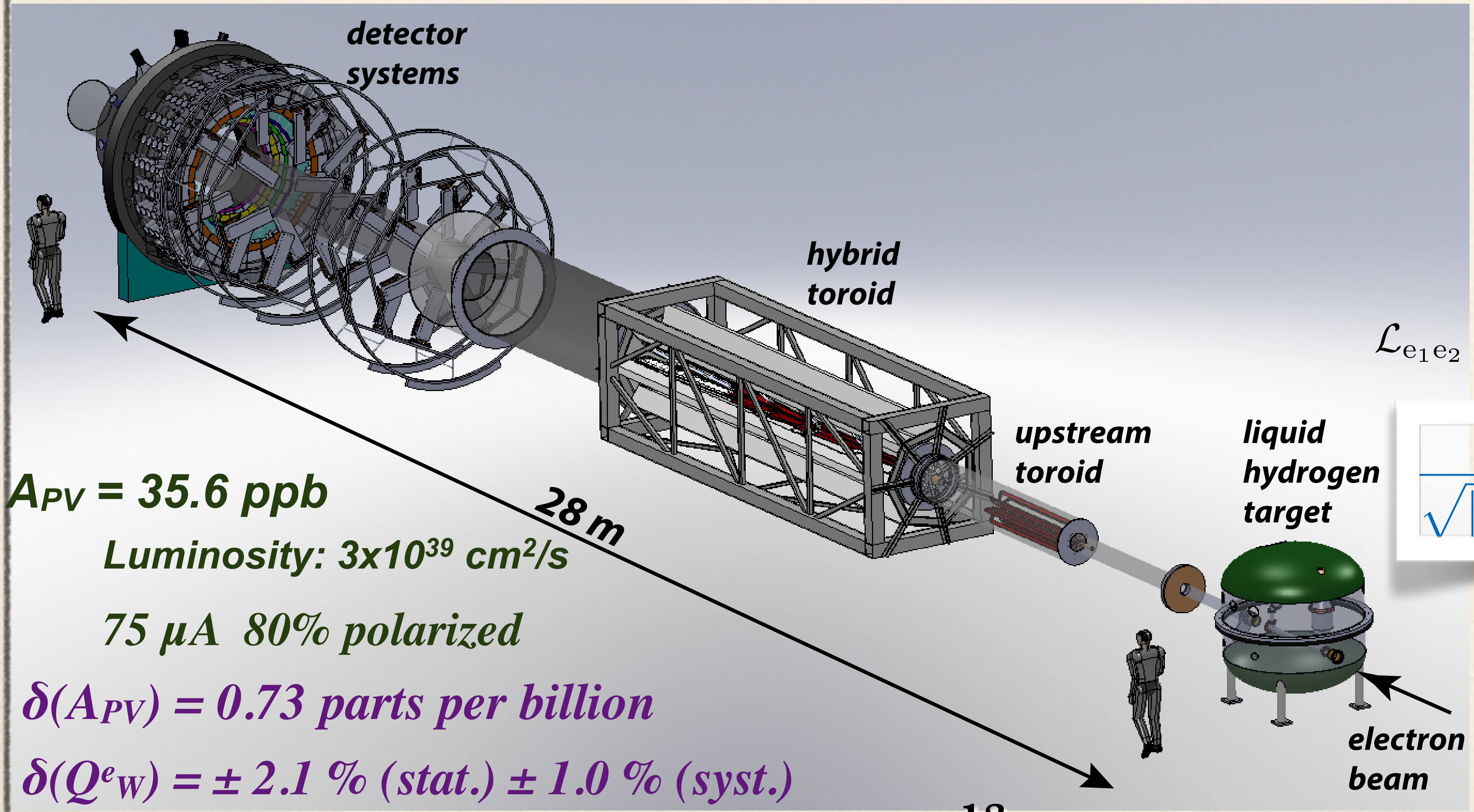




$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

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

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



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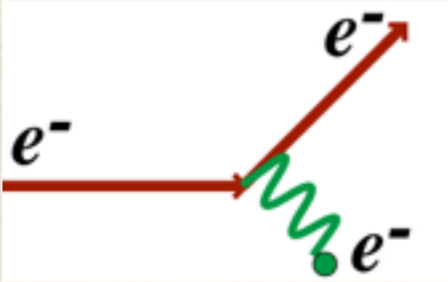
MOLLER at JLab

Measurement **O**f **L**epton **L**epton **E**lectroweak **R**eaction



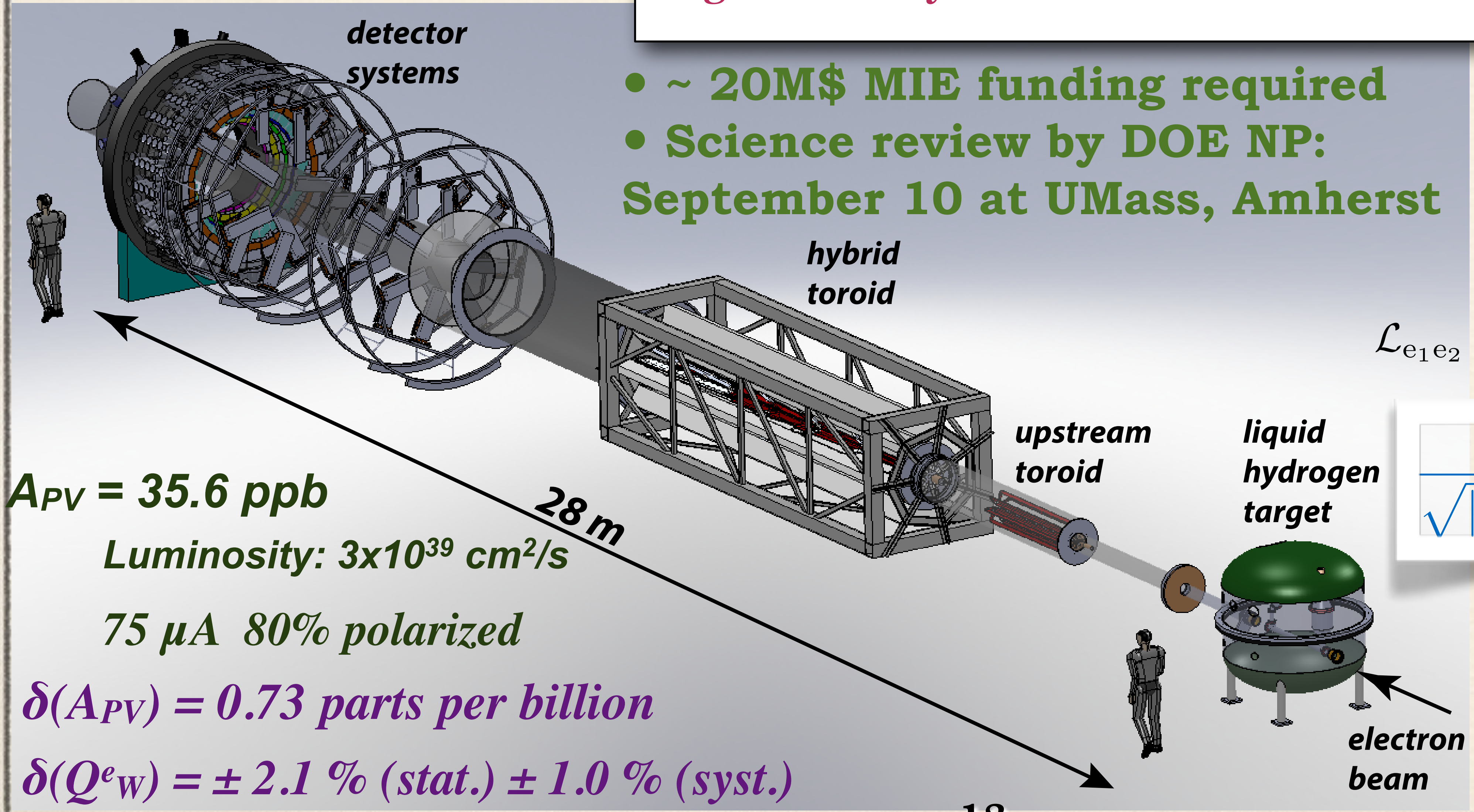
11 GeV Beam

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

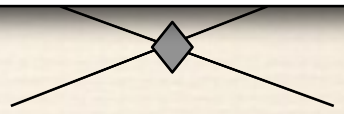
Matches best collider (Z-pole) measurements!

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



- **~ 20M$ MIE funding required**
- **Science review by DOE NP: September 10 at UMass, Amherst**

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

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

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

A_{PV} = 35.6 ppb

Luminosity: 3×10^{39} cm²/s

75 μA 80% polarized

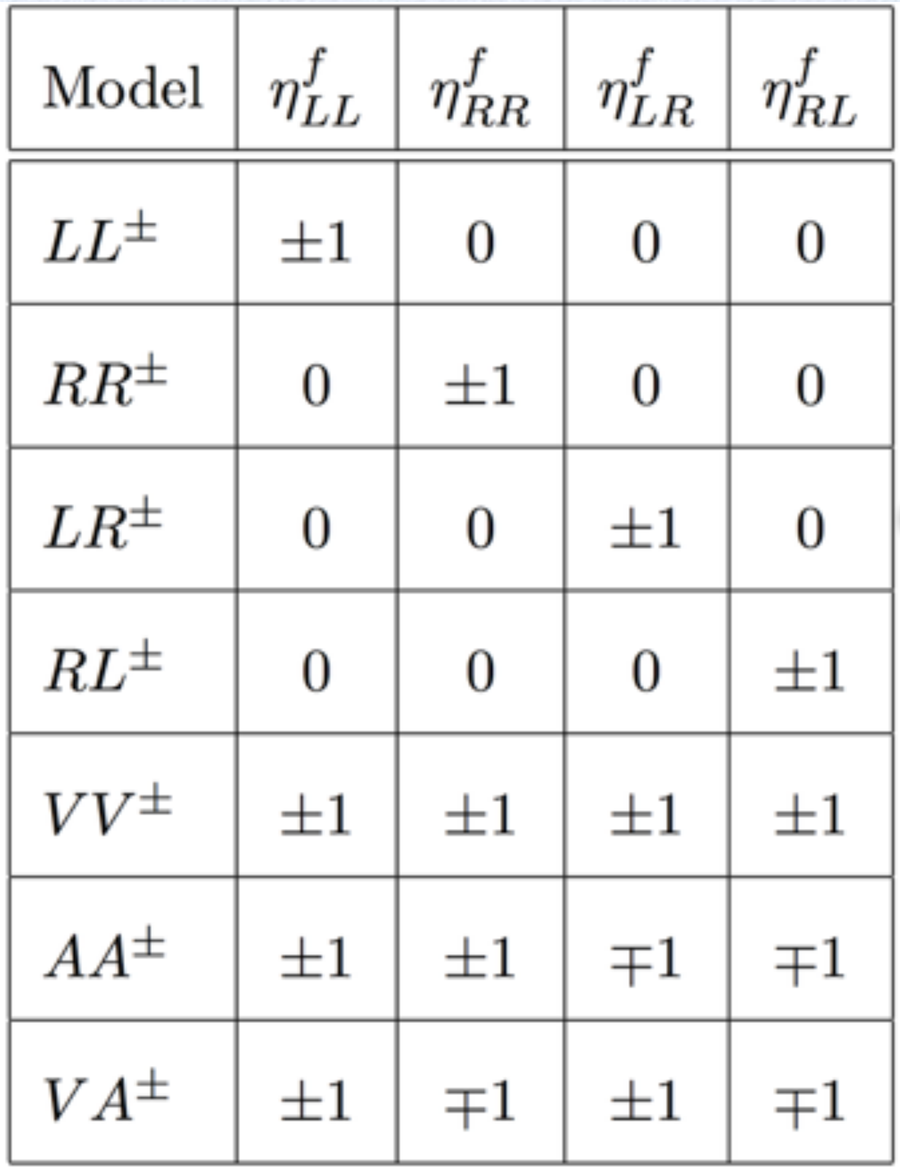
$\delta(A_{PV})$ *= 0.73 parts per billion*

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

95% C. L. Reach

Comparison with e^+e^- Collisions

Best reach on purely leptonic contact interaction amplitudes: LEP200



Model	η^f_{LL}	η^f_{RR}	η^f_{LR}	η^f_{RL}
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$LR^\pm$	0	0	±1	0
$RL^\pm$	0	0	0	±1
$VV^\pm$	±1	±1	±1	±1
$AA^\pm$	±1	±1	∓1	∓1
$VA^\pm$	±1	∓1	±1	∓1

Simultaneous fits to cross-sections and angular distributions

$\Lambda^{\rm ee}_{\rm LL} \sim 8.3$ TeV

$\Lambda^{\rm ee}_{\rm RR} \sim 8.2$ TeV

$\Lambda^{\rm ee}_{\rm VV} \sim 17.7$ TeV

$\Lambda^{\rm ll}_{\rm LL} \sim 12.8$ TeV

$\Lambda^{\rm ll}_{\rm RR} \sim 12.2$ TeV

$\Lambda^{\rm ll}_{\rm VV} \sim 22.2$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda^{\rm ee}_{\rm LL} \sim 12$ TeV

$\Lambda^{\rm ee}_{\rm RR-LL} \sim 17$ TeV

MOLLER Reach

$\Lambda^{\rm ee}_{\rm LL} \sim 27$ TeV

$\Lambda^{\rm ee}_{\rm RR-LL} \sim 38$ TeV

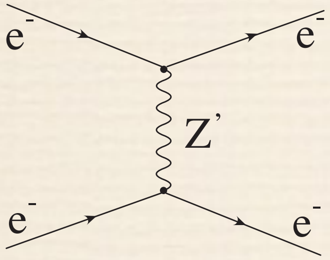
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

Unique Opportunity:* *Purely Leptonic* *Reaction at $Q^2 << M_Z^2$

New Physics Models

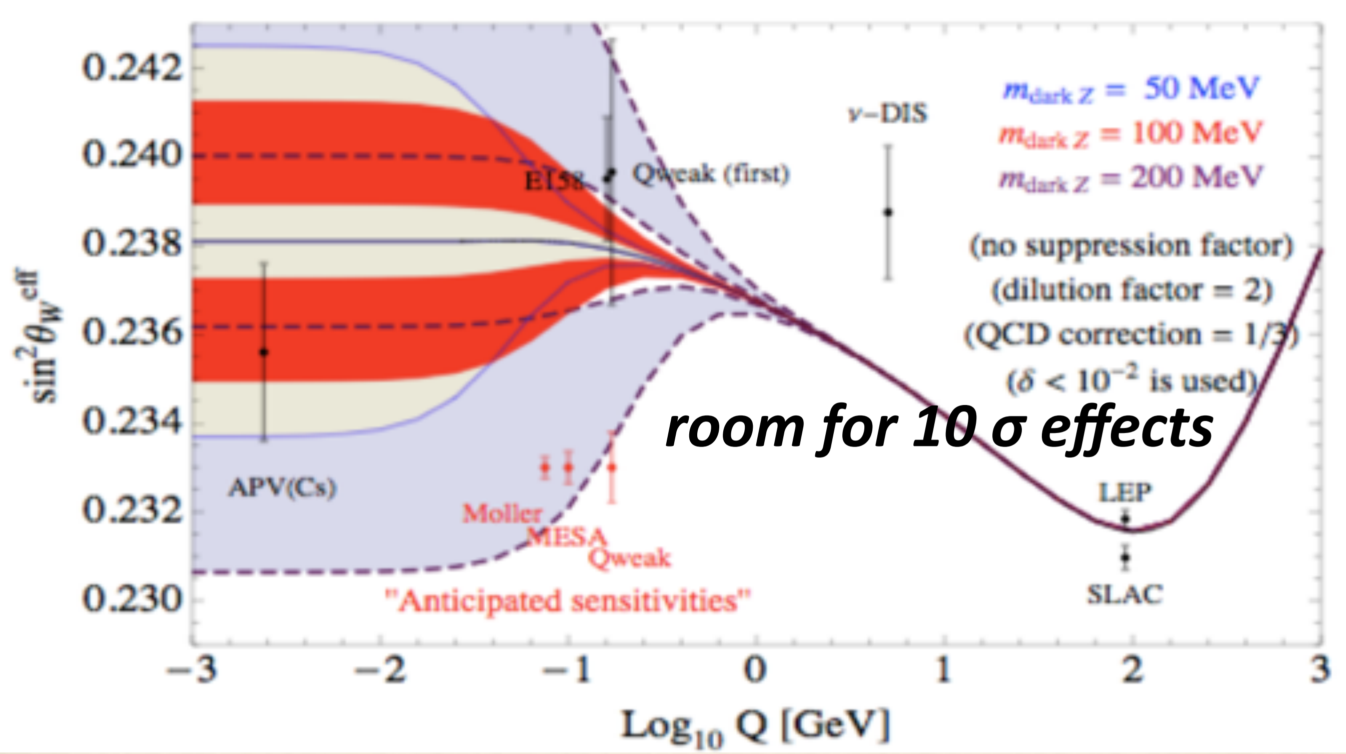
Deviations From Theory Prediction Interpretable as New Physics

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



room for 10 σ effects

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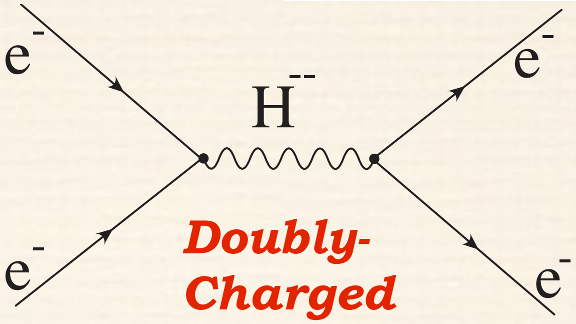
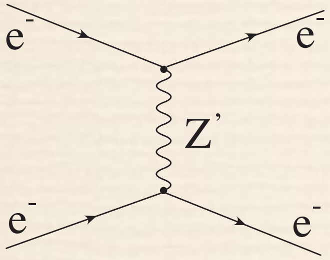
Lepton Number Violation



Doubly-Charged Scalar

$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV



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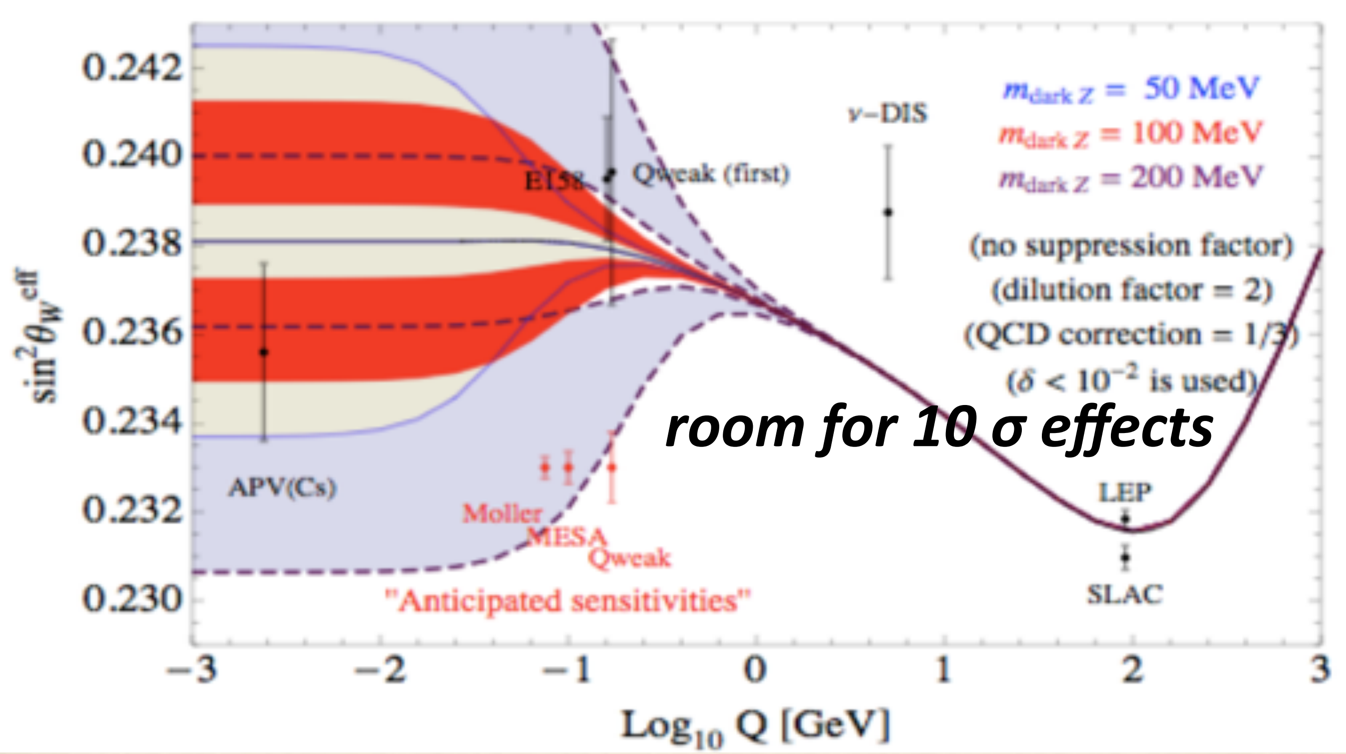

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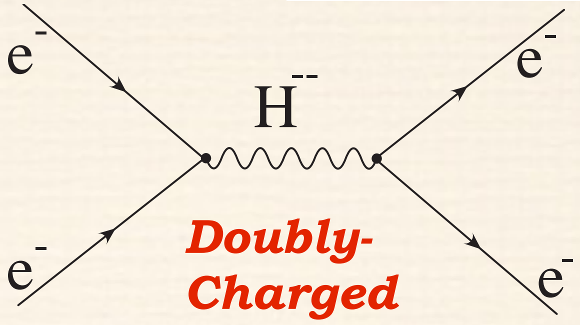

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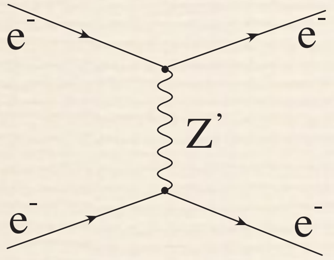

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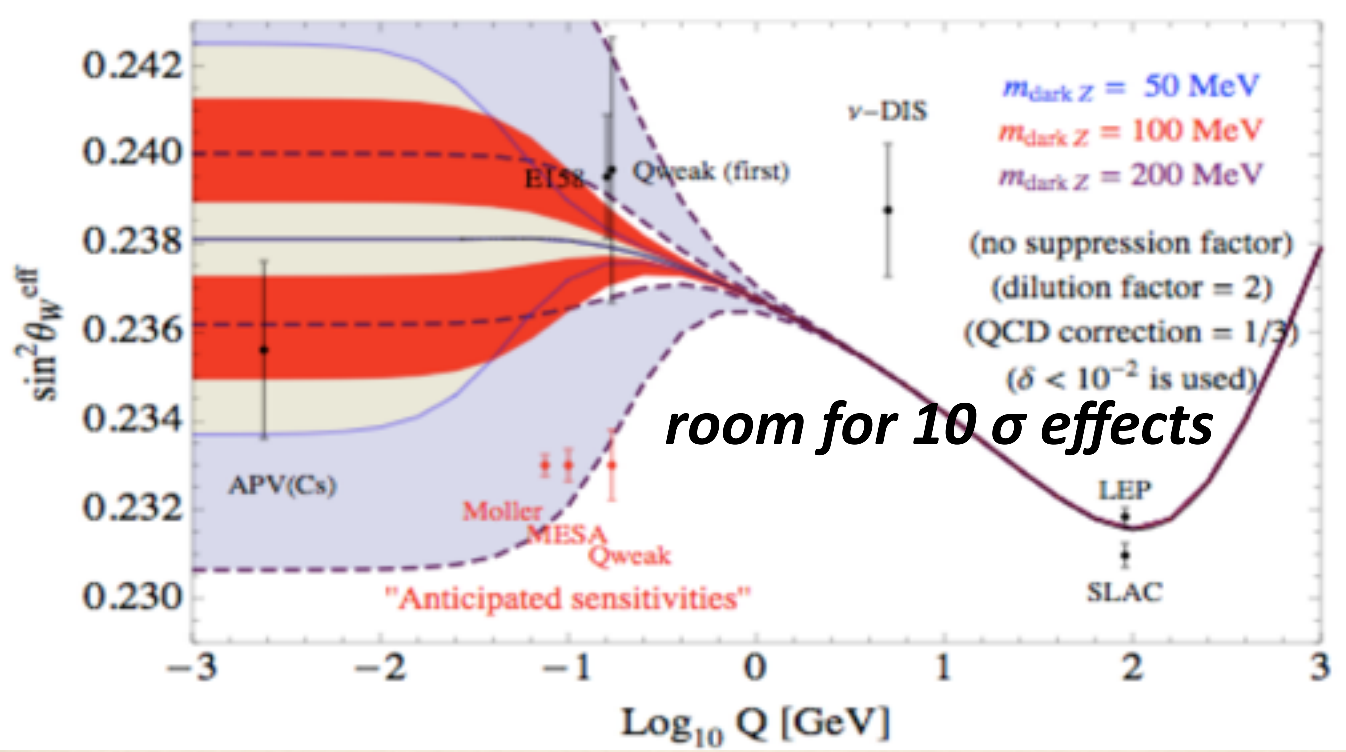
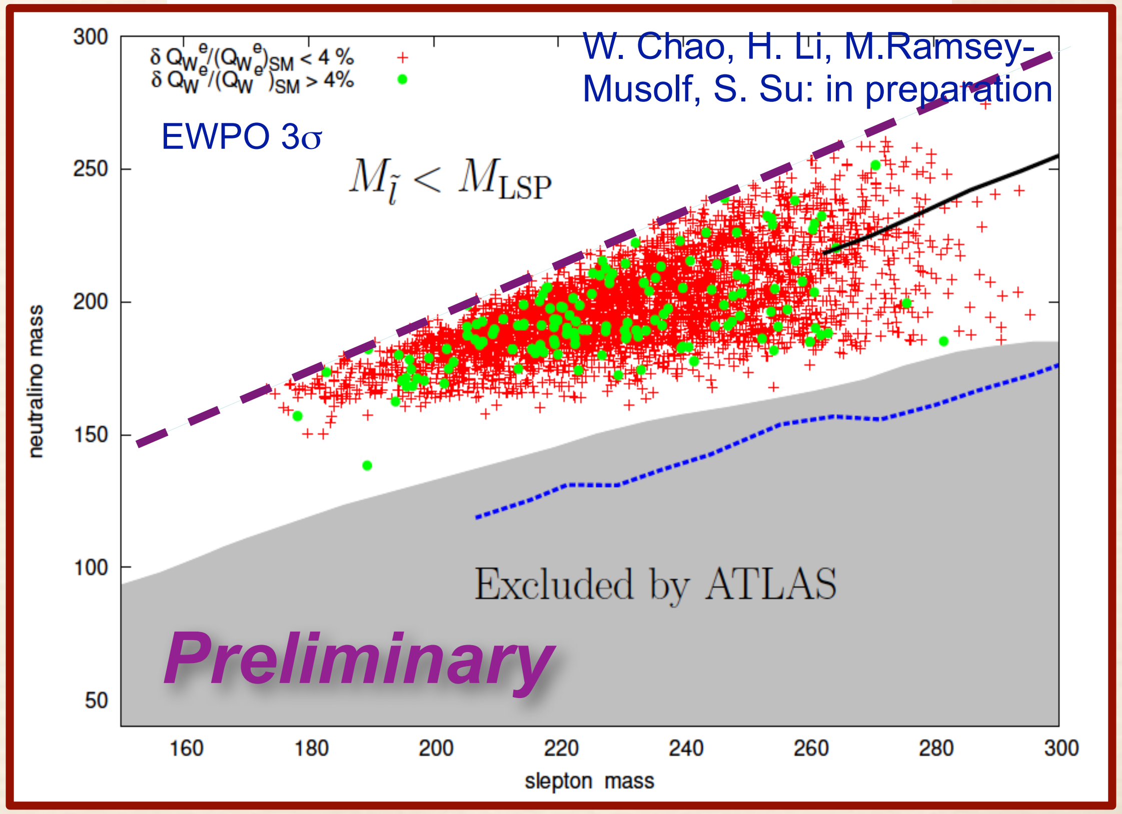


room for 10 σ effects

Light but Compressed Supersymmetry



W. Chao, H. Li, M.Ramsey-Musolf, S. Su: in preparation

Preliminary

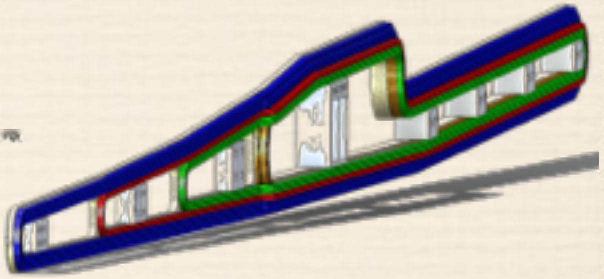
MOLLER Apparatus

Technical Challenges

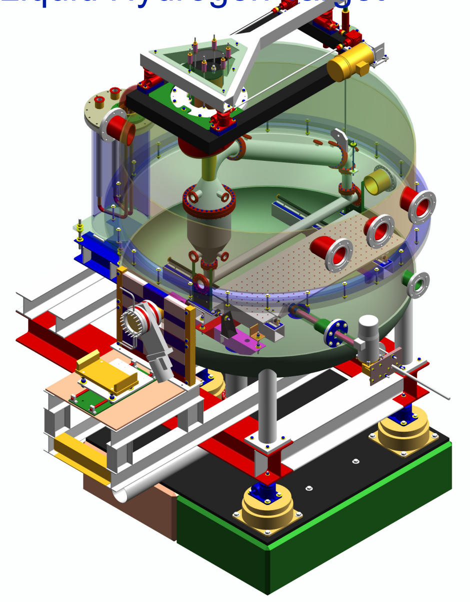
Evolutionary Improvements from Technology of Third Generation Experiments

- ~ 150 GHz scattered electron rate
- 1 nm control of beam centroid on target
- > 10 gm/cm^2 liquid hydrogen target
  - 1.5 m: ~ 5 kW @ 85 µA
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - novel toroidal spectrometer pair
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry

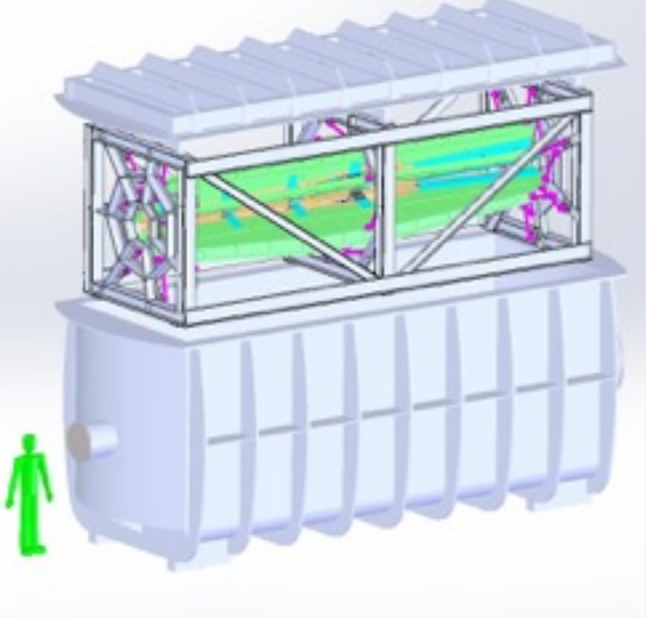
hybrid spectrometer coil

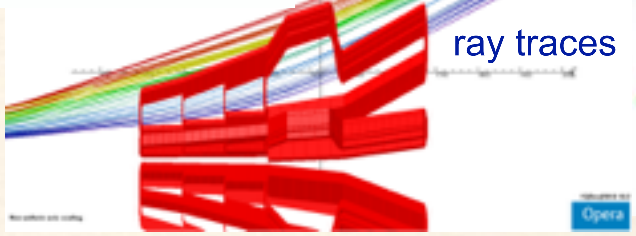


Liquid Hydrogen Target

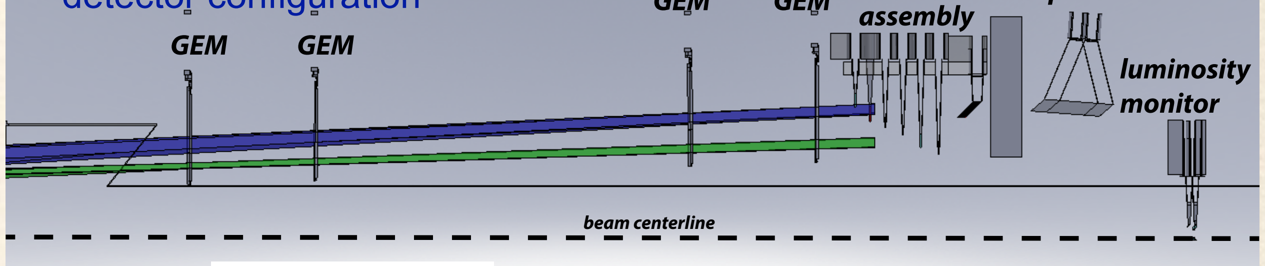


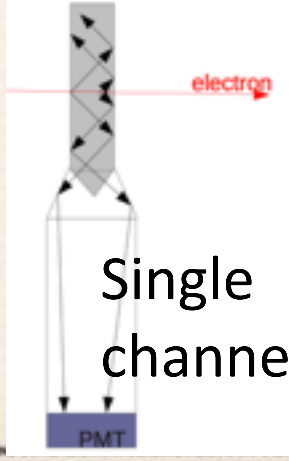
spectrometer housing




ray traces

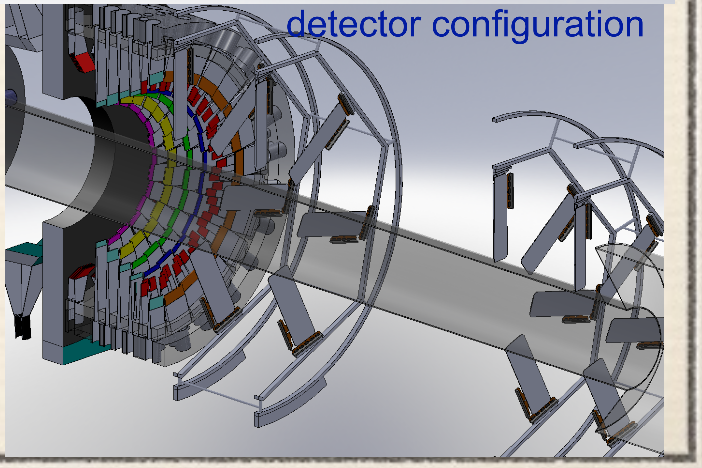
detector configuration





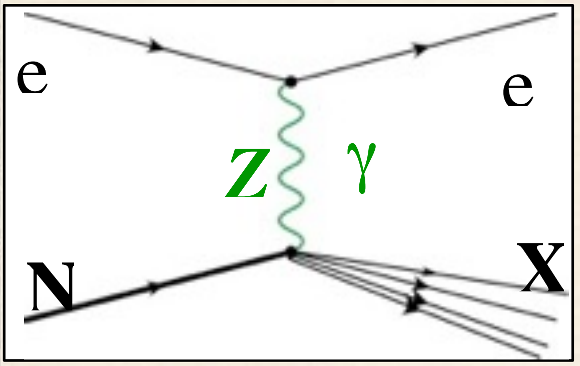
Single channel

detector configuration



Deep Inelastic Scattering on LD_2

A_{PV} in deep inelastic e-D scattering:



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

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

a(x): function of C_{1i}'s

b(x): function of C_{2i}'s

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

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

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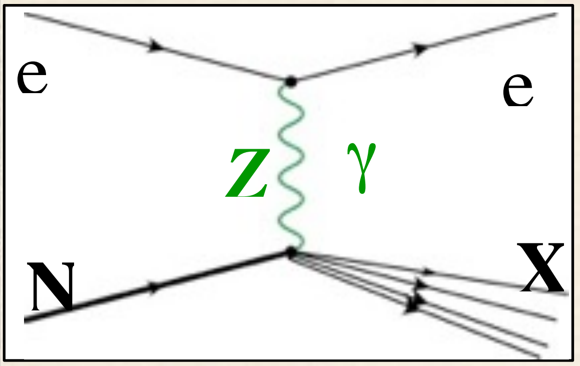

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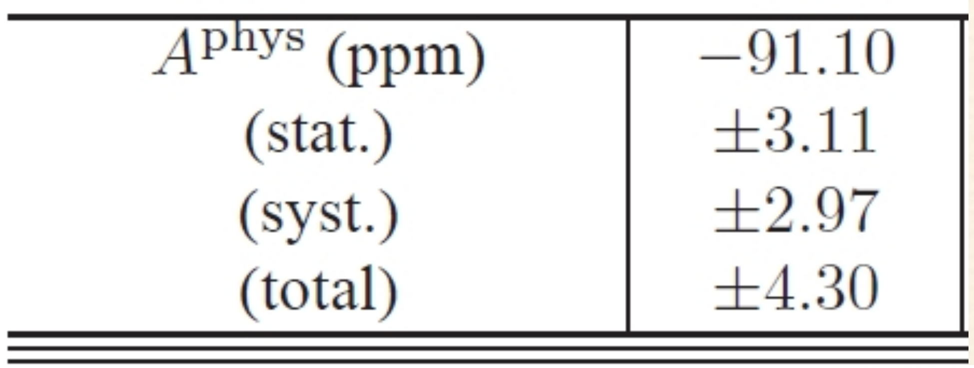
Wang et al., Nature 506, no. 7486, 67 (2014);

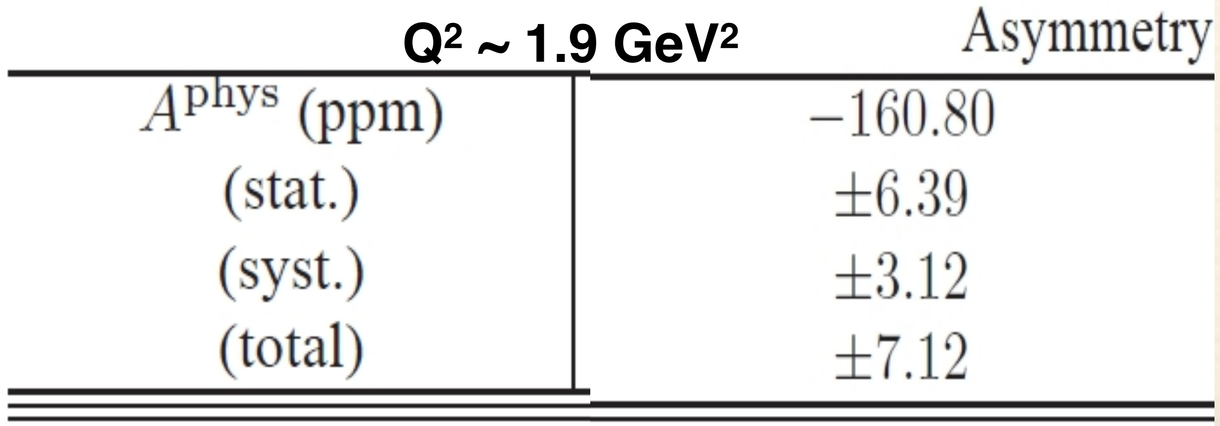
6 GeV run results

$Q^2 \sim 1.1$ GeV^2



A^{phys} (ppm)	-91.10
(stat.)	± 3.11
(syst.)	± 2.97
(total)	± 4.30

$Q^2 \sim 1.9$ GeV^2



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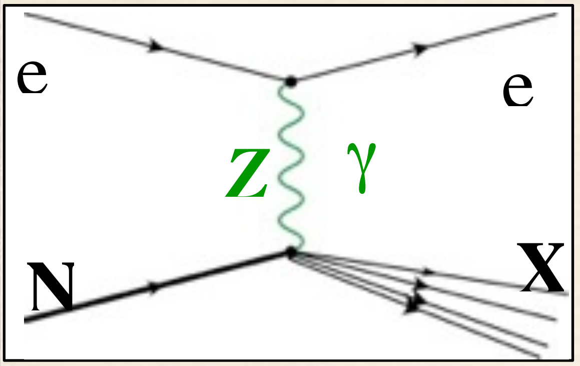

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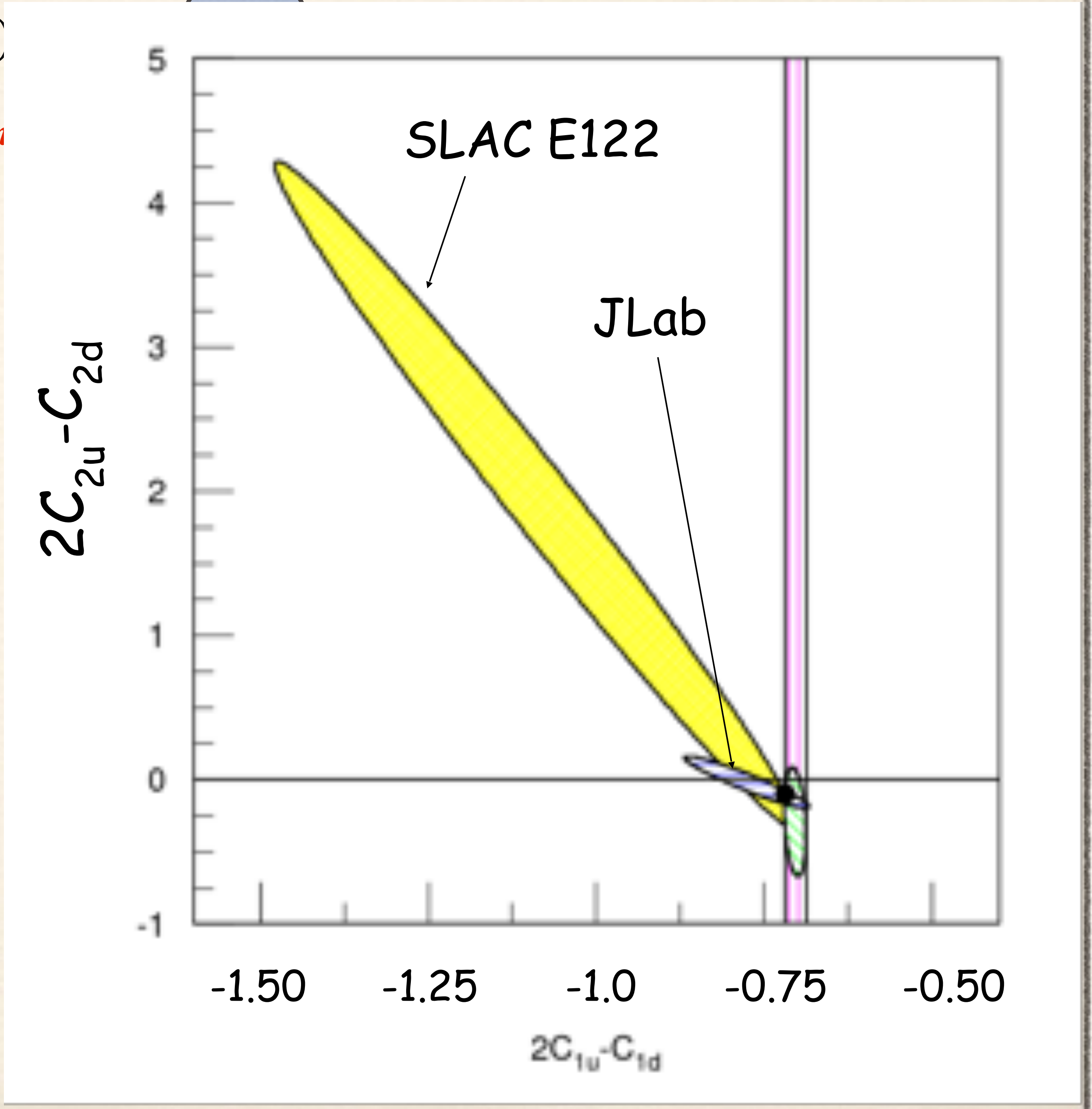

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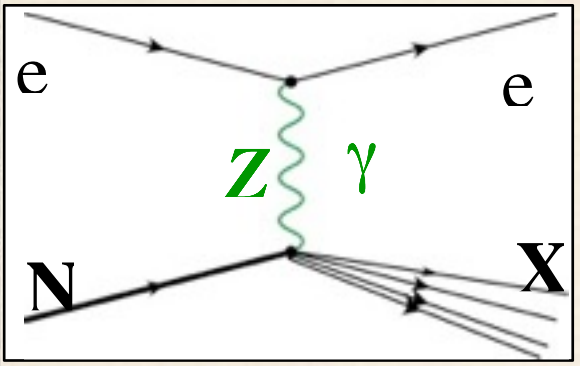

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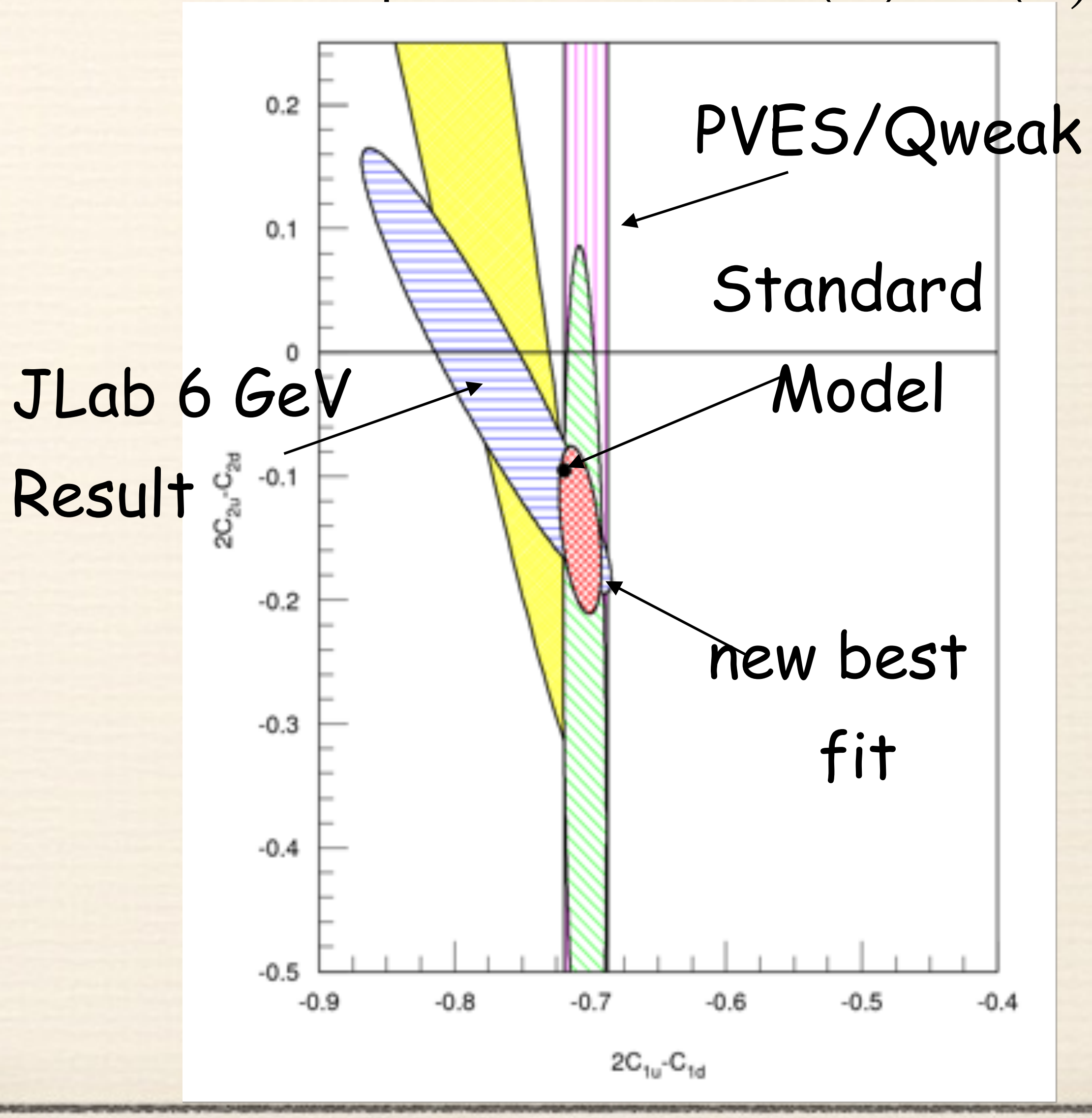

PVES/Qweak

Standard Model

JLab 6 GeV Result

new best fit

Deep Inelastic Scattering on LD_2

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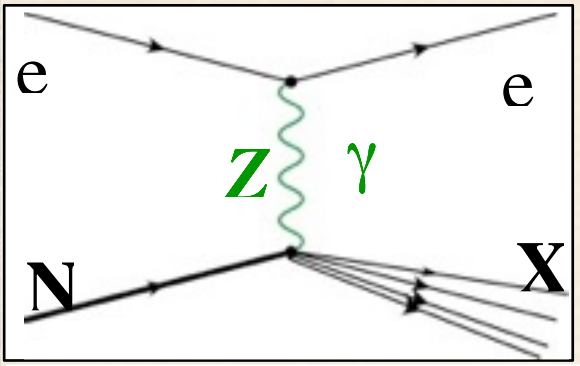

$Q^2 >> 1\ GeV^2\ ,\ W^2 >> 4$

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For ²H, assuming charge symmetry,

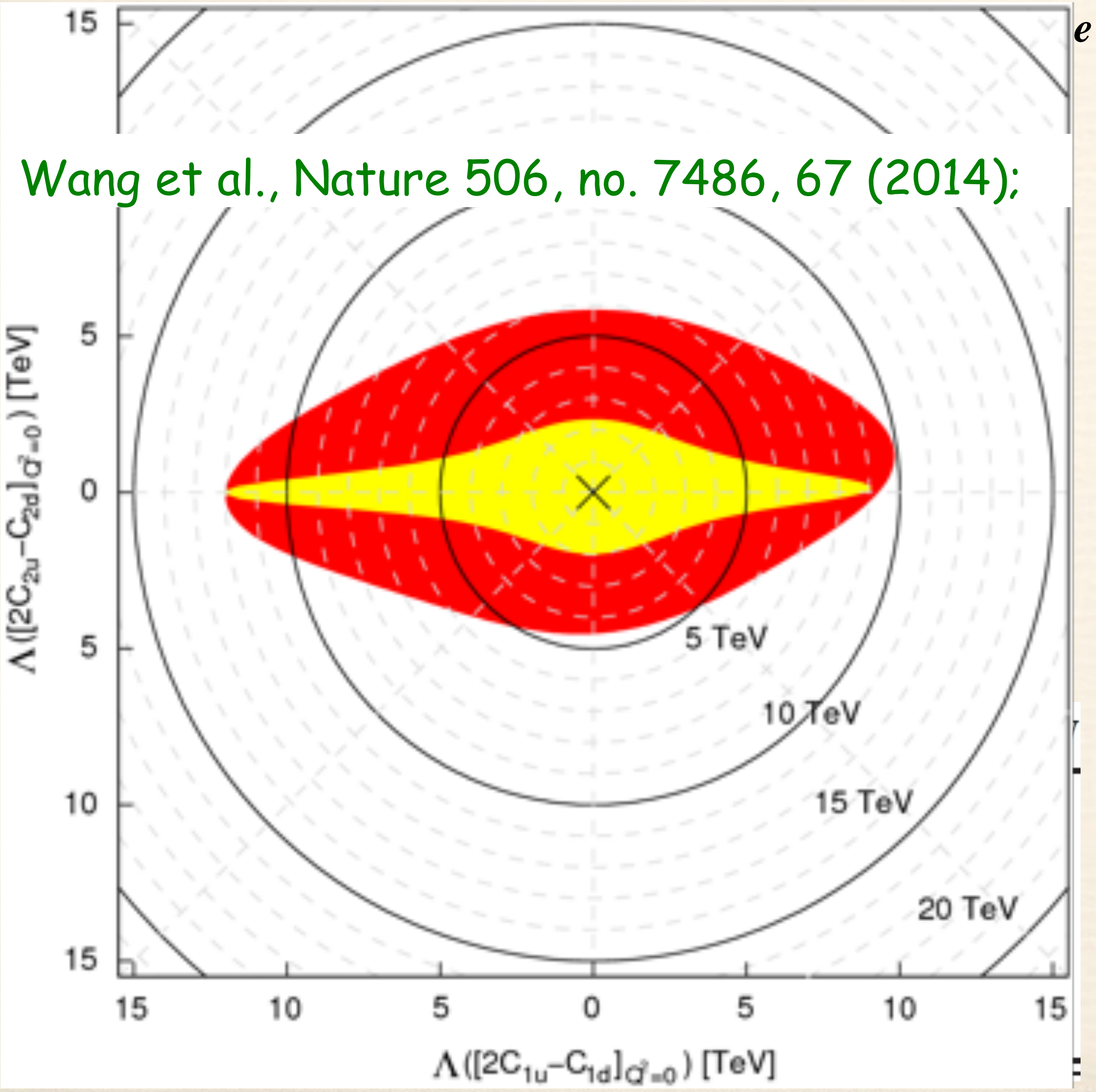
e ratio

PARTICLE PHYSICS

Quarks are not ambidextrous

W. Marciano
article in Nature

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. SEE LETTER P.67



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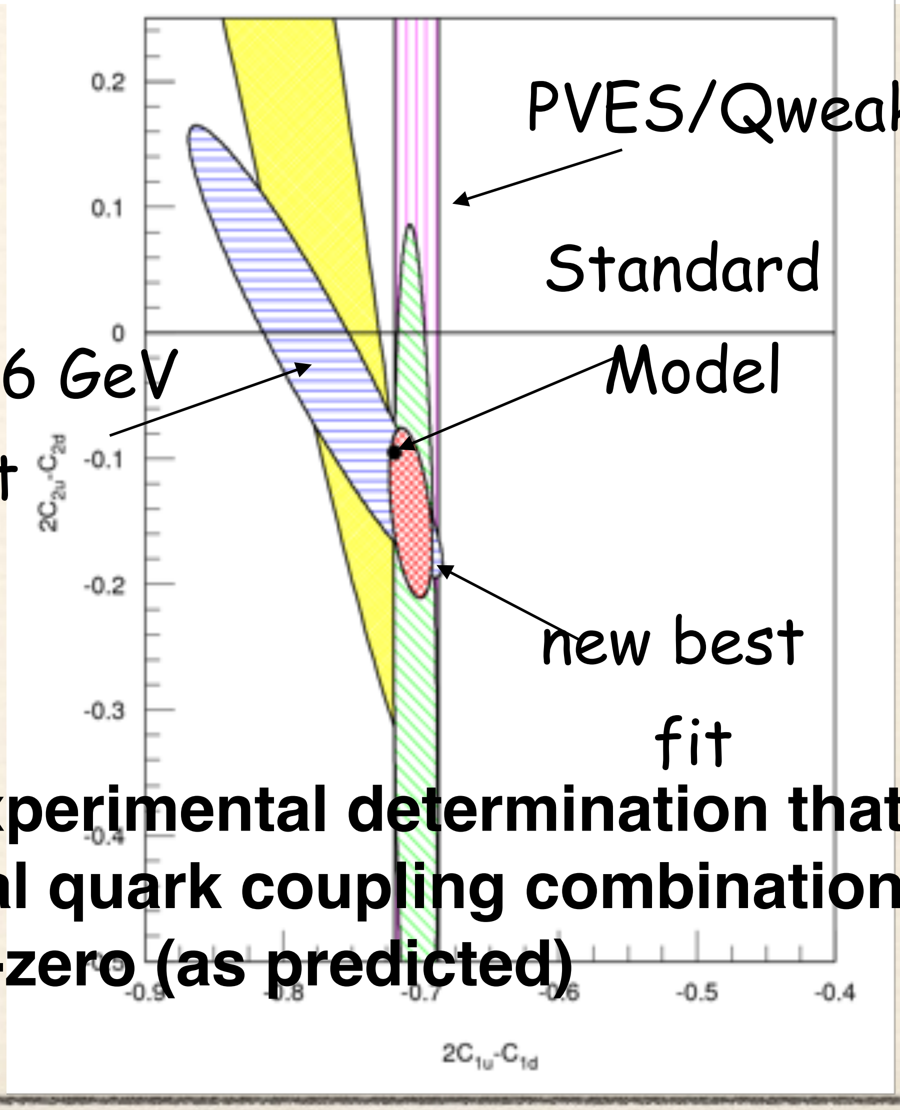
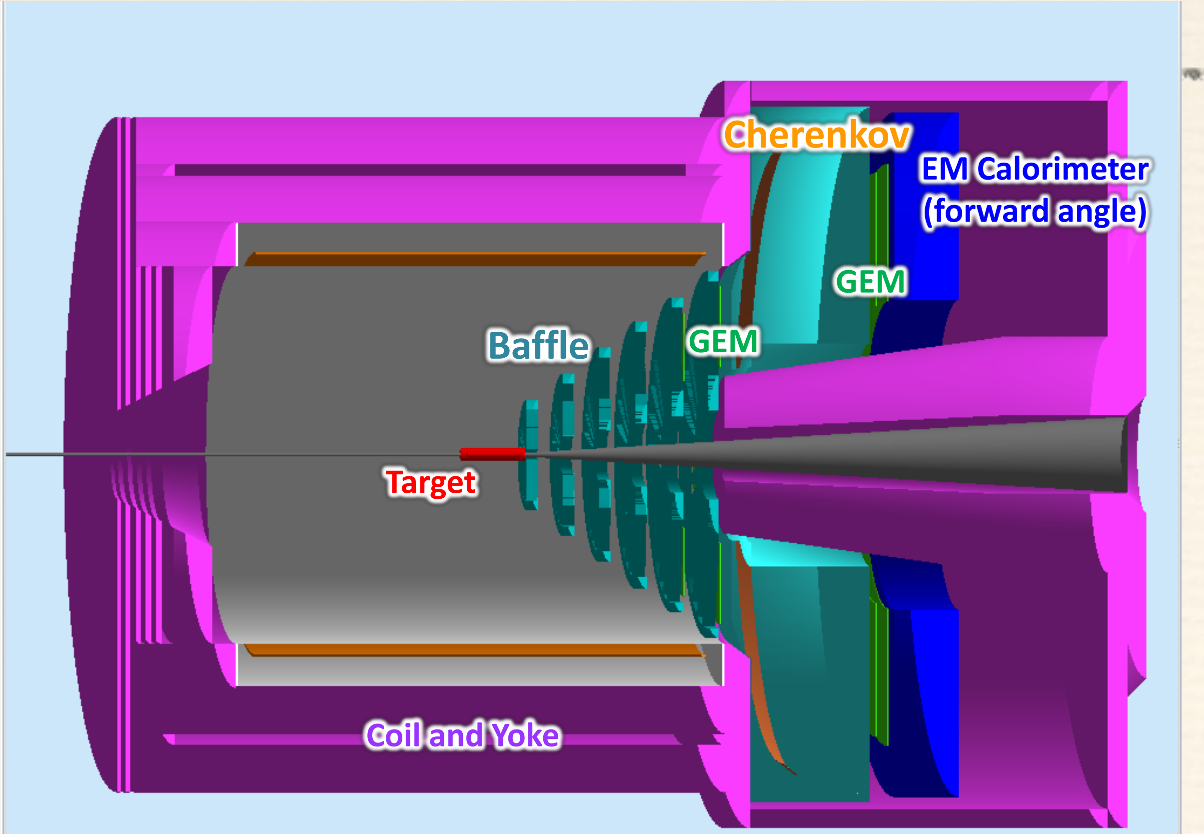


first experimental determination that an axial quark coupling combination is non-zero (as predicted)

SOLID with the 12 GeV Upgrade



<u>Strategy:</u> 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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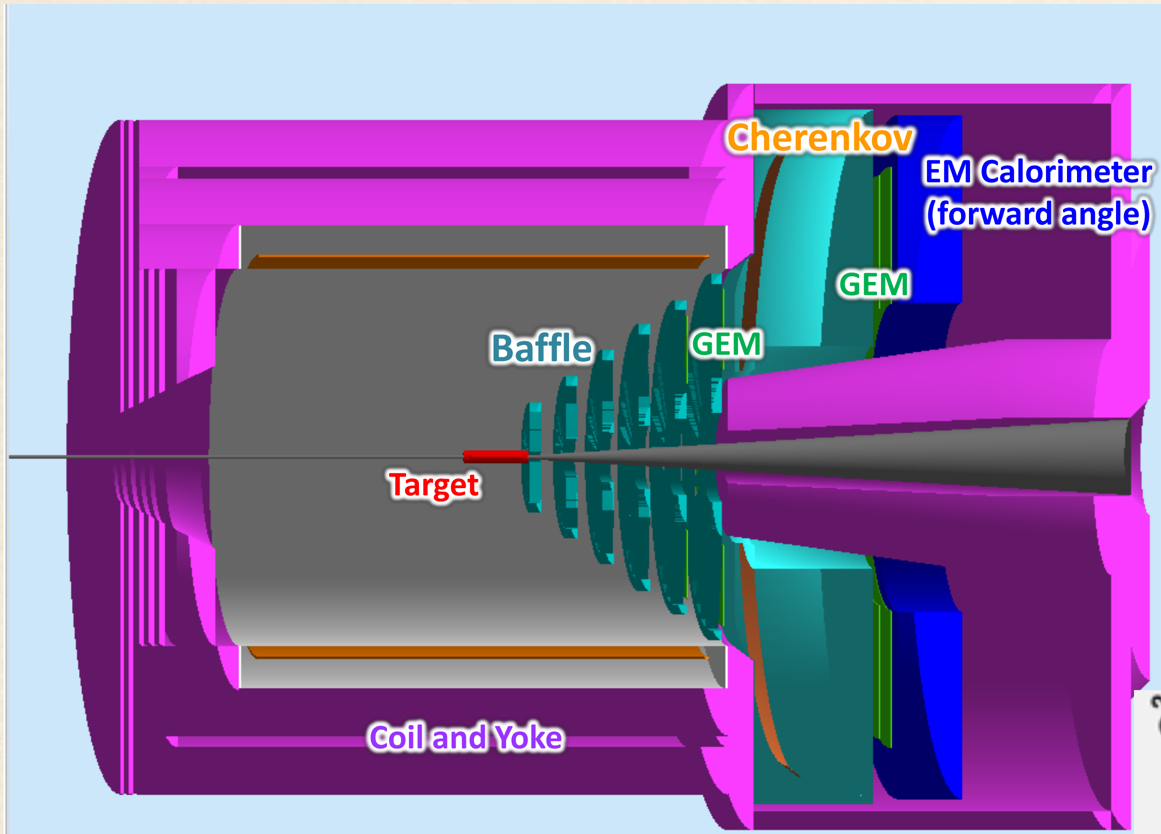

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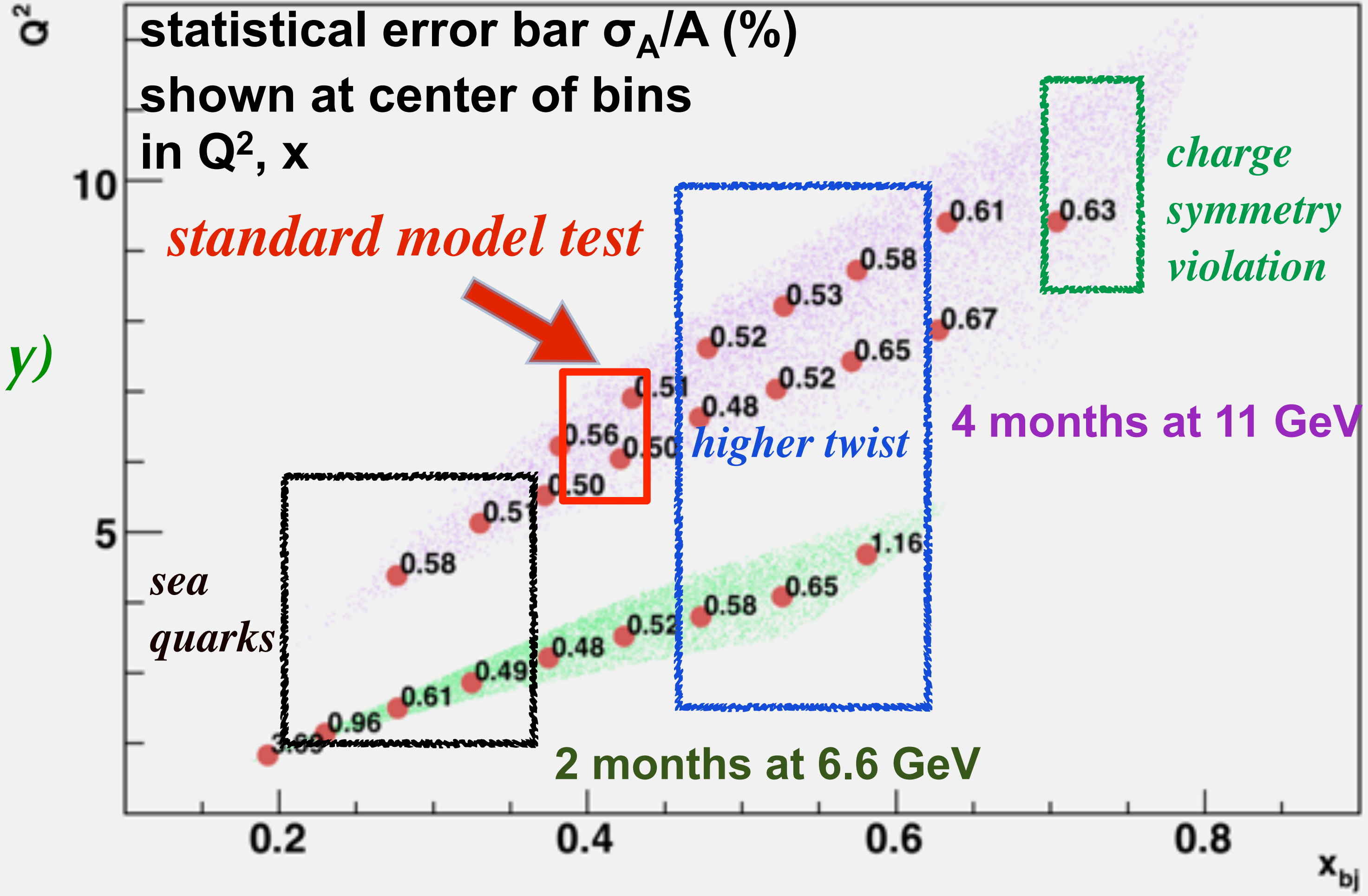
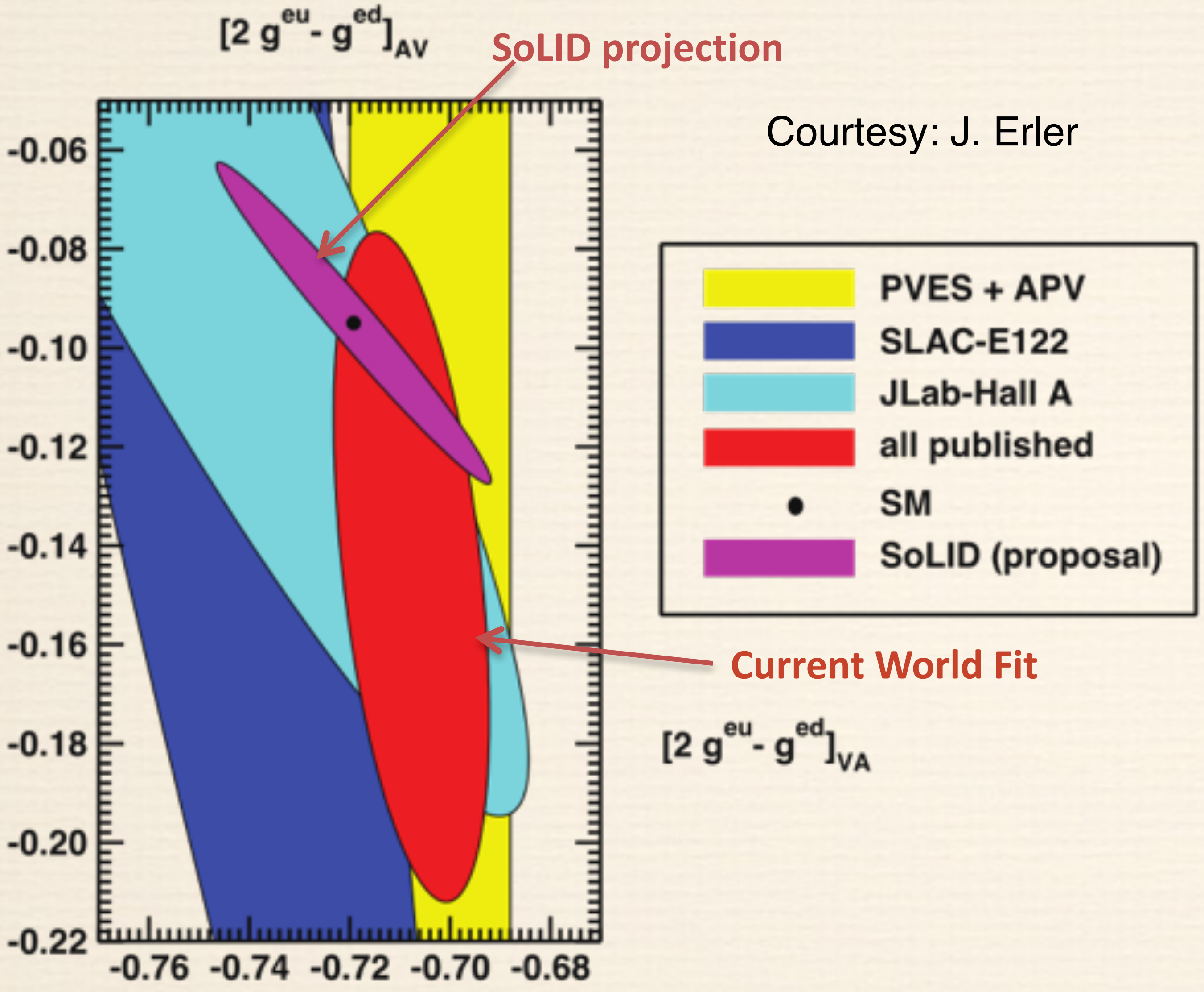
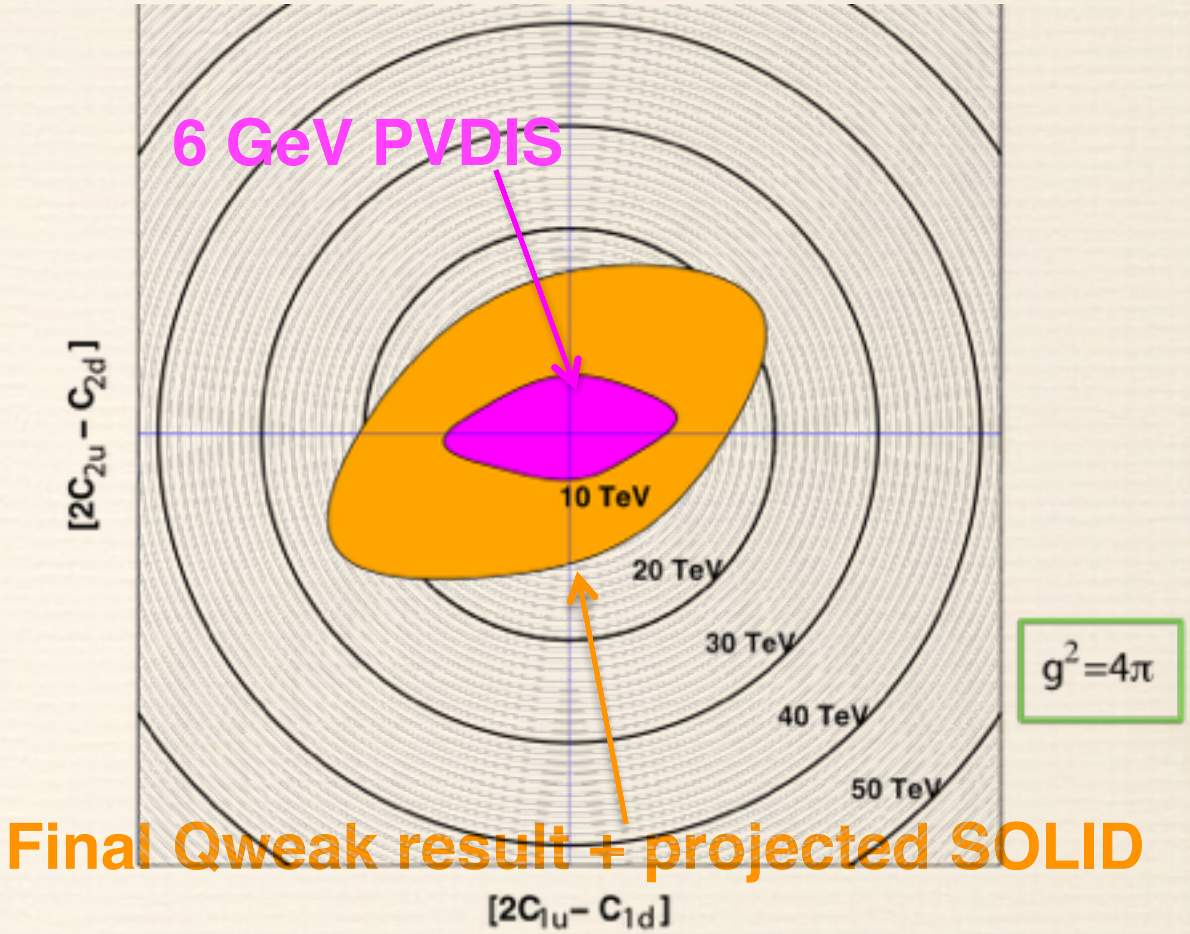


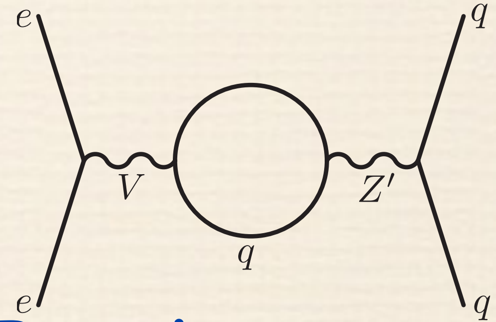
SOLID New Physics Sensitivity



Courtesy: J. Erler



Leptophobic Z'



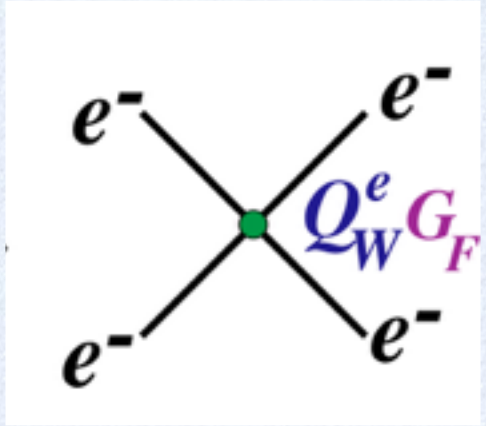
Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

SOLID can improve sensitivity: 100-200 GeV range

(ultra)-weak-electromagnetic interference

Weak Charge Measurements

leptonic and semi-leptonic weak neutral current amplitudes



$$\mathbf{Q^e_W \sim 0.045}$$

$$\frac{\delta \mathbf{Q^e_W}}{\mathbf{Q^e_W}} = \mathbf{2.4\%}$$

$$\mathbf{A_{new} \sim 0.001 \cdot G_F}$$

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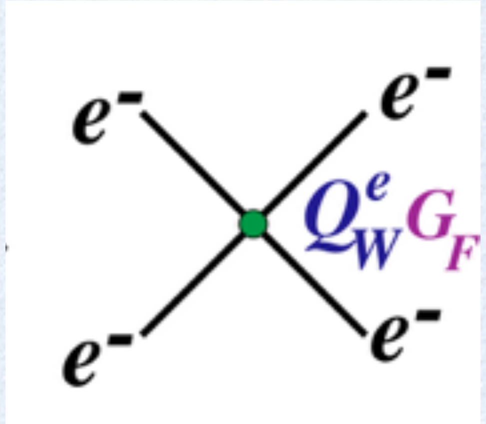

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Other complementary semi-leptonic measurements:

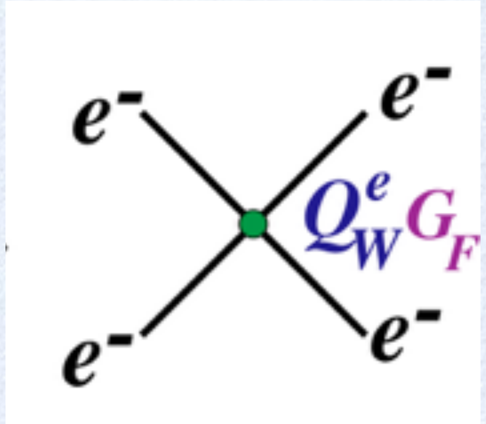
$$\delta[\mathbf{Q_W}(^{\mathbf{133}}\mathrm{Cs})/\mathbf{A}] \sim \mathbf{0.6\%} \Longrightarrow \mathbf{0.0033 \cdot G_F}$$

Atomic Parity Violation
PVES on C-12

(ultra)-weak-electromagnetic interference

Weak Charge Measurements

leptonic and semi-leptonic weak neutral current amplitudes



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Atomic Parity Violation
PVES on C-12

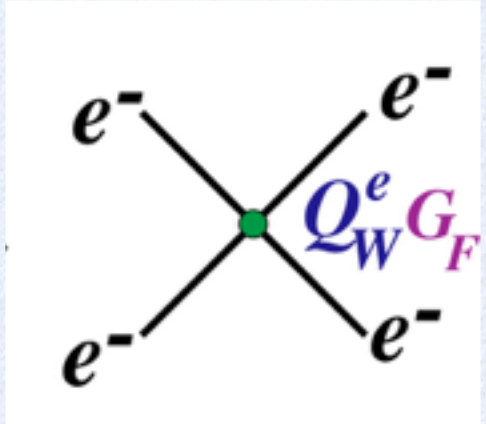
JLab Qweak $\delta[\mathbf{Q^p_W}] \sim 4\% \Longrightarrow \mathbf{0.003 \cdot G_F}$

Future Mainz P2:
improve by factor 2

(ultra)-weak-electromagnetic interference

Weak Charge Measurements

leptonic and semi-leptonic weak neutral current amplitudes



$$Q_W^e \sim 0.045$$

$$\frac{\delta Q_W^e}{Q_W^e} = 2.4\%$$

$$\boxed{A_{new} \sim 0.001 \cdot G_F}$$

Other complementary semi-leptonic measurements:

$$\delta[Q_W(^{133}Cs)/A] \sim 0.6\% \Longrightarrow 0.0033 \cdot G_F$$

Atomic Parity Violation
PVES on C-12

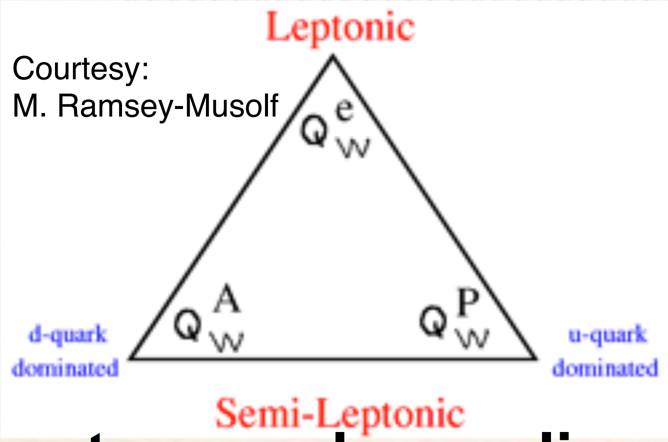
JLab Qweak $\delta[Q_W^p] \sim 4\% \Longrightarrow 0.003 \cdot G_F$

Future Mainz P2:
improve by factor 2

$$\delta[2C_{2u} - C_{2d}] \sim 5\% \Longrightarrow 0.004 \cdot G_F$$

SOLID: Unique sensitivity
to axial-quark couplings

PVES Initiatives: Complementarity



Courtesy:
M. Ramsey-Musolf

vector-quark couplings

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings

- **SUSY Loops** → **Q_W^e and Q_W^p:same absolute shift, smaller for others**
- **GUT Z'** → **High for Q_W(Cs), Q_W^e(relative), smaller for others**
- **Leptophobic Z'** → **axial-quark couplings (C_2's) only**
- **RPV SUSY** → **Different for all four in sign and magnitude**
- **Leptoquarks** → **semi-leptonic only; different sensitivities**
- **Lepton Number Violation** → **Q_W^e only**
- **Dark Z** → **Different Q^2 values carry different sensitivities**

Generic Model Reach

$$X(Q^2) \equiv \alpha^{-1}(\sin^2\theta_W(Q^2) - \sin^2\theta_W(M_Z^2))$$

$$Q_W^e = -0.0435[1 + 0.7\,X(Q^2) + 7m_Z^2/m_{Z_x}^2]$$

$$Q_W^p = 0.0707[1 + 0.43\,X(Q^2) + 4.3m_Z^2/m_{Z_x}^2]$$

$$Q_W(^{12}C) = -5.510[1 - 0.033\,X(Q^2) - m_Z^2/m_{Z_x}^2]$$

$$Q_W(^{133}Cs) = -73.24[1 - 0.023\,X(Q^2) - 0.9m_Z^2/m_{Z_x}^2]$$

$$\mathbf{2.4\%\ Q_W^e \implies 1.4\%\ Q_W^p,\ 0.34\%\ Q_W(^{12}C),\ 0.3\%\ Q_W(^{133}Cs)}$$

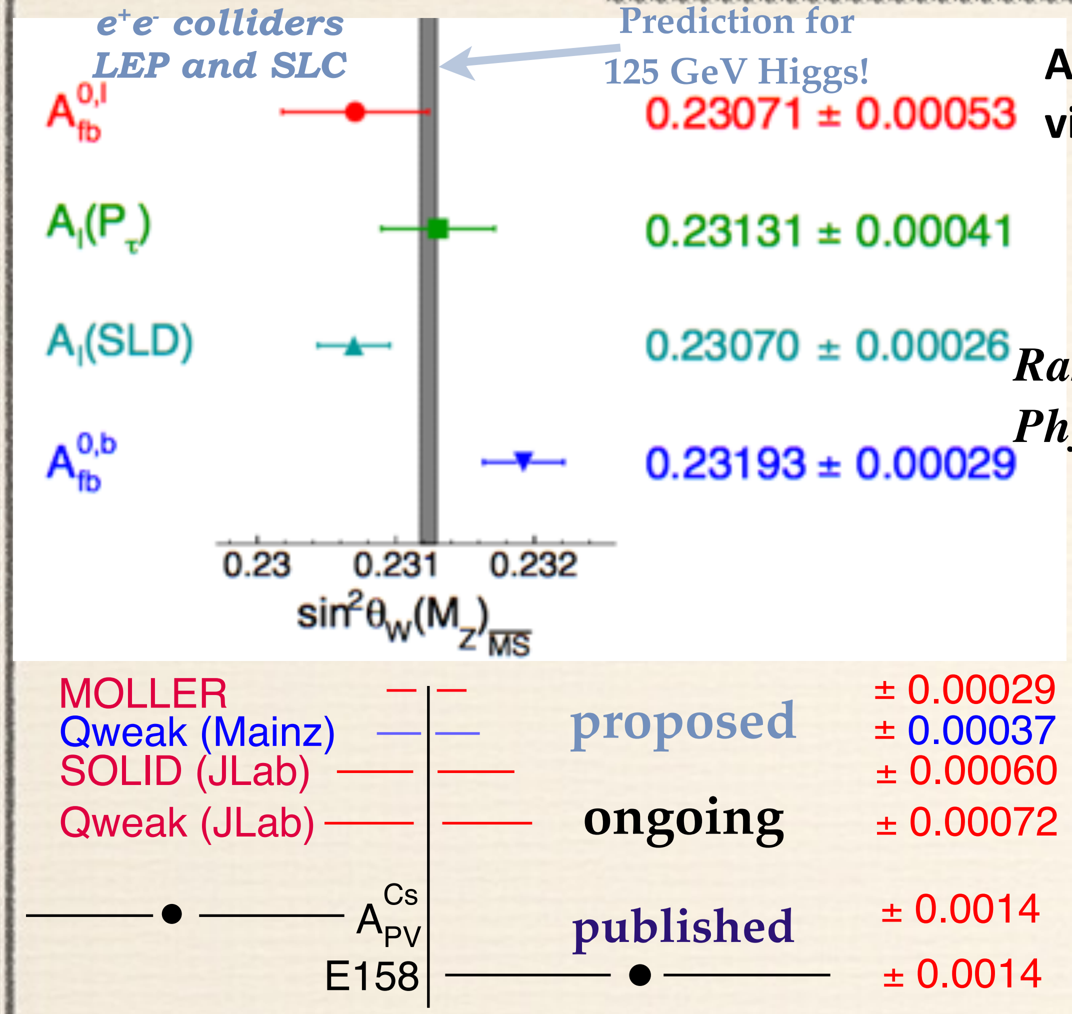
12% **17%** **25%** **0.6%**

published uncertainties

These numbers serve as uncertainty goals for the various targets

New Physics Complementarity

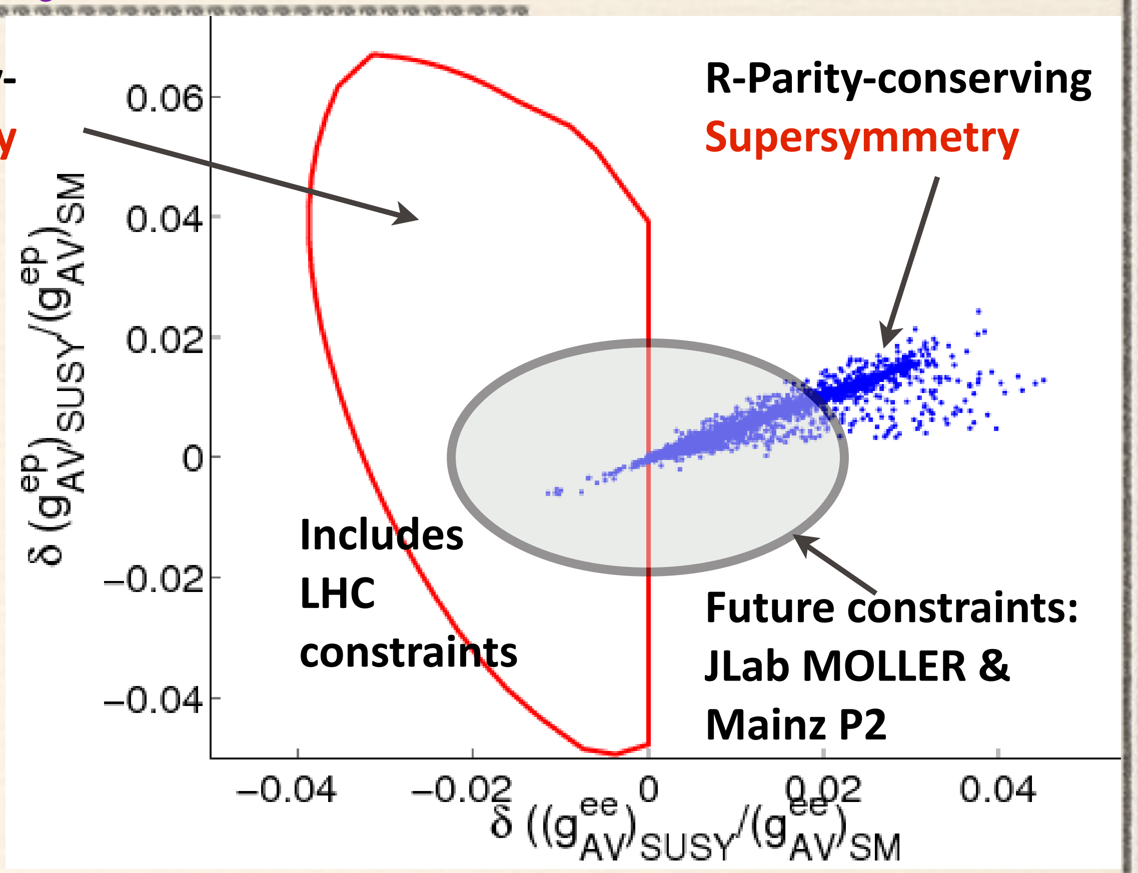
Z resonance measurements: little sensitivity to new contact interactions



Allowed region: R-Parity-violating Supersymmetry

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

Erler and Su, arXiv:1303.5522



R-Parity-conserving Supersymmetry

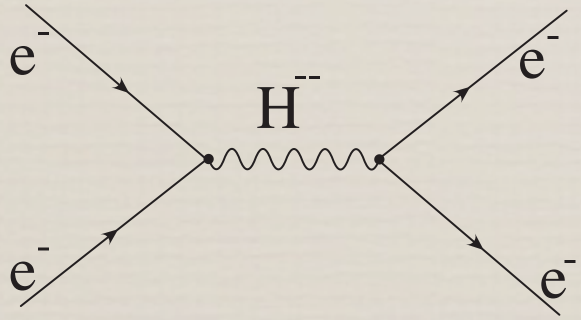
Includes LHC constraints

Future constraints: JLab MOLLER & Mainz P2

Lepton Number Violation

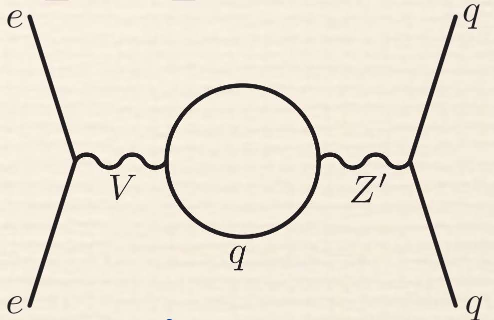
Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

Leptophobic Z'



SOLID can improve sensitivity:
100-200 GeV range

The LHC Context

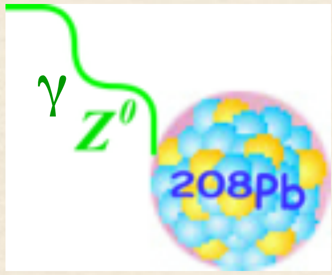
- **If LHC sees ANY anomaly in Runs 2 or 3 (~2022)**
  - The unique discovery space of low energy PVES will become a pressing need, like other sensitive probes (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Hidden weak scale scenarios
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - ...

PVES Evolution

- Development of the Electroweak Theory
  - *SLAC E122 played a pivotal role*
    - would not have been possible without the discovery of partons in Deep Inelastic Scattering!
  - *Key pioneering experiment in the development of spin physics*
- Neutral Weak Currents of Nucleons and Nuclei
  - *PVES Experiments in the 1980's made first measurements*
  - *Strange quarks vector currents became an important topic*
  - *Experimental techniques steadily improved*
- Search for new TeV-scale Physics
  - *Lack of new physics at colliders leads to comprehensive strategy*
  - *New low Q^2 experiments developed*
    - These measurements require critical knowledge of hadronic vector and axial-vector currents
- Novel Probes of Hadron Physics
  - *Neutron Skins of Ca-48 and Pb-208*
  - *Vector Analyzing Powers for a range of nuclei*
  - *Charge Symmetry Violation*
  - *Non-perturbative QCD dynamics e.g. Higher Twist*

PREX and CREX

EW Probe of Neutron Densities



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

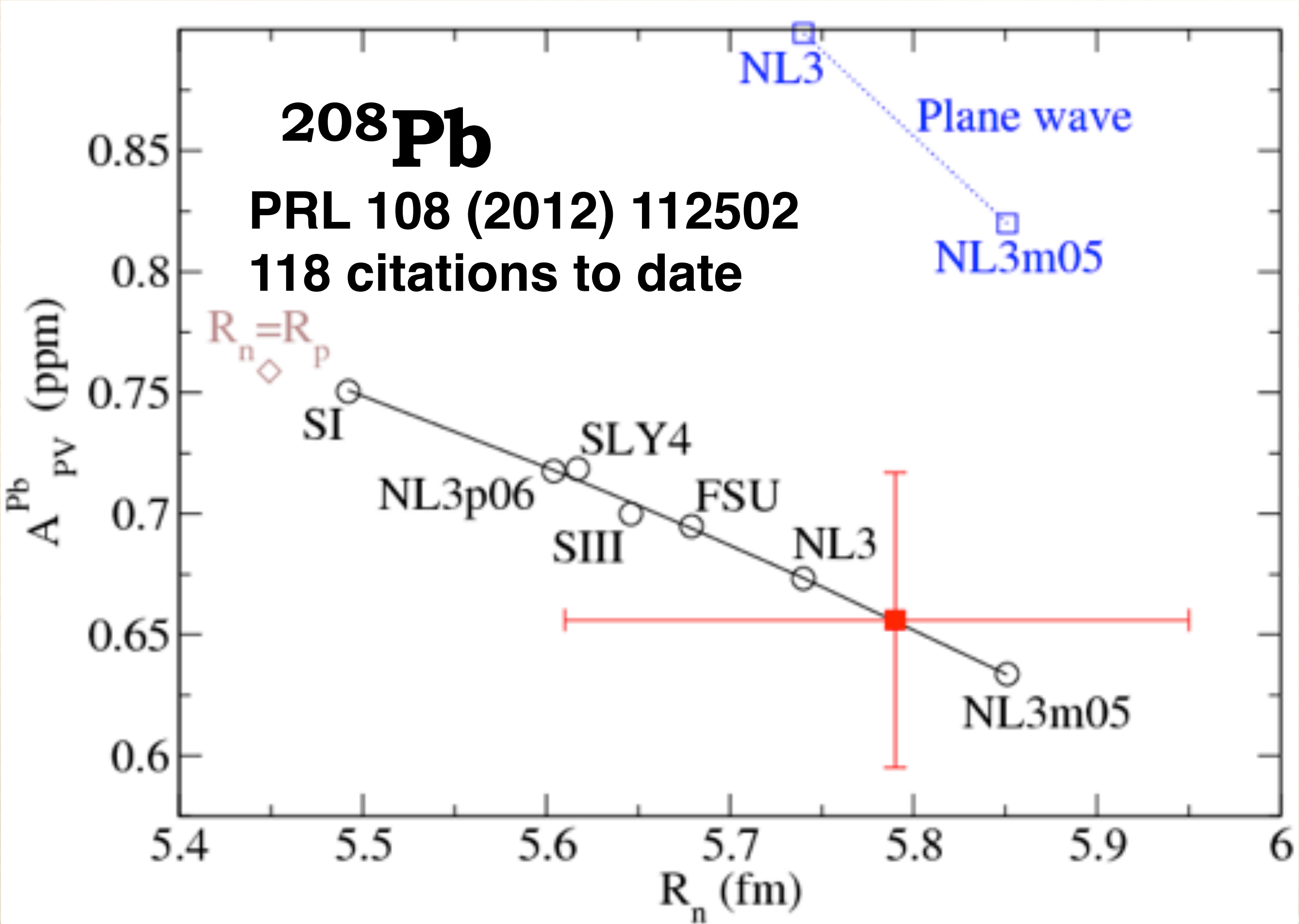
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

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

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n) \sim \pm 0.06\ fm$



^{208}Pb

PRL 108 (2012) 112502

118 citations to date

PREX and CREX

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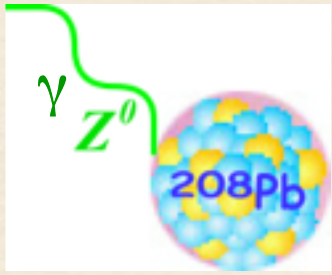

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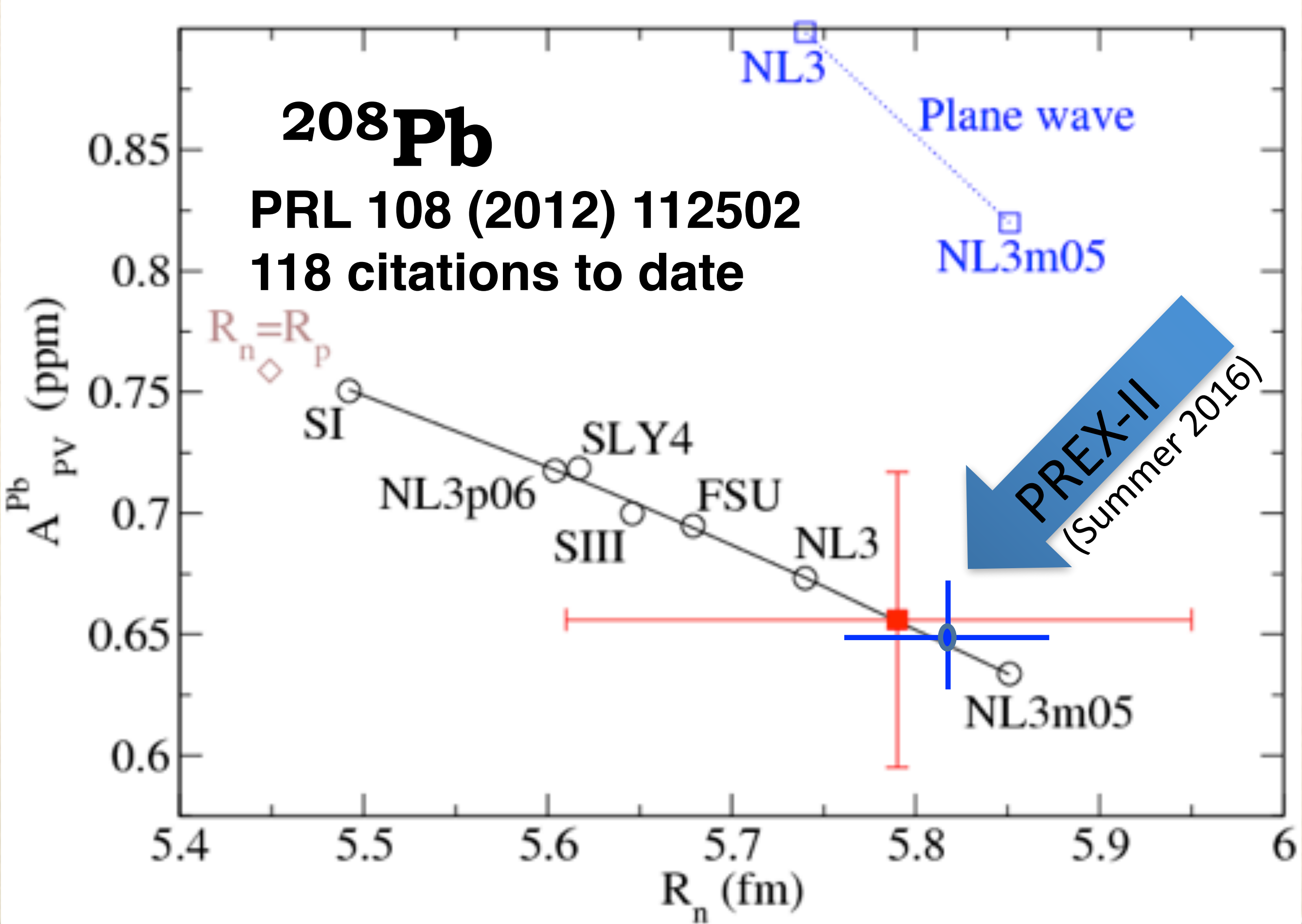
$$\boxed{\begin{array}{c} \delta(A_{PV})/A_{PV} \sim 3\% \\ \delta(R_n)/R_n \sim 1\% \end{array}}$$

⇒ $\delta(R_n) \sim \pm 0.06$ fm



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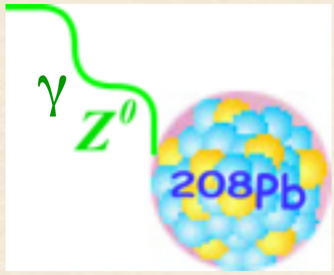

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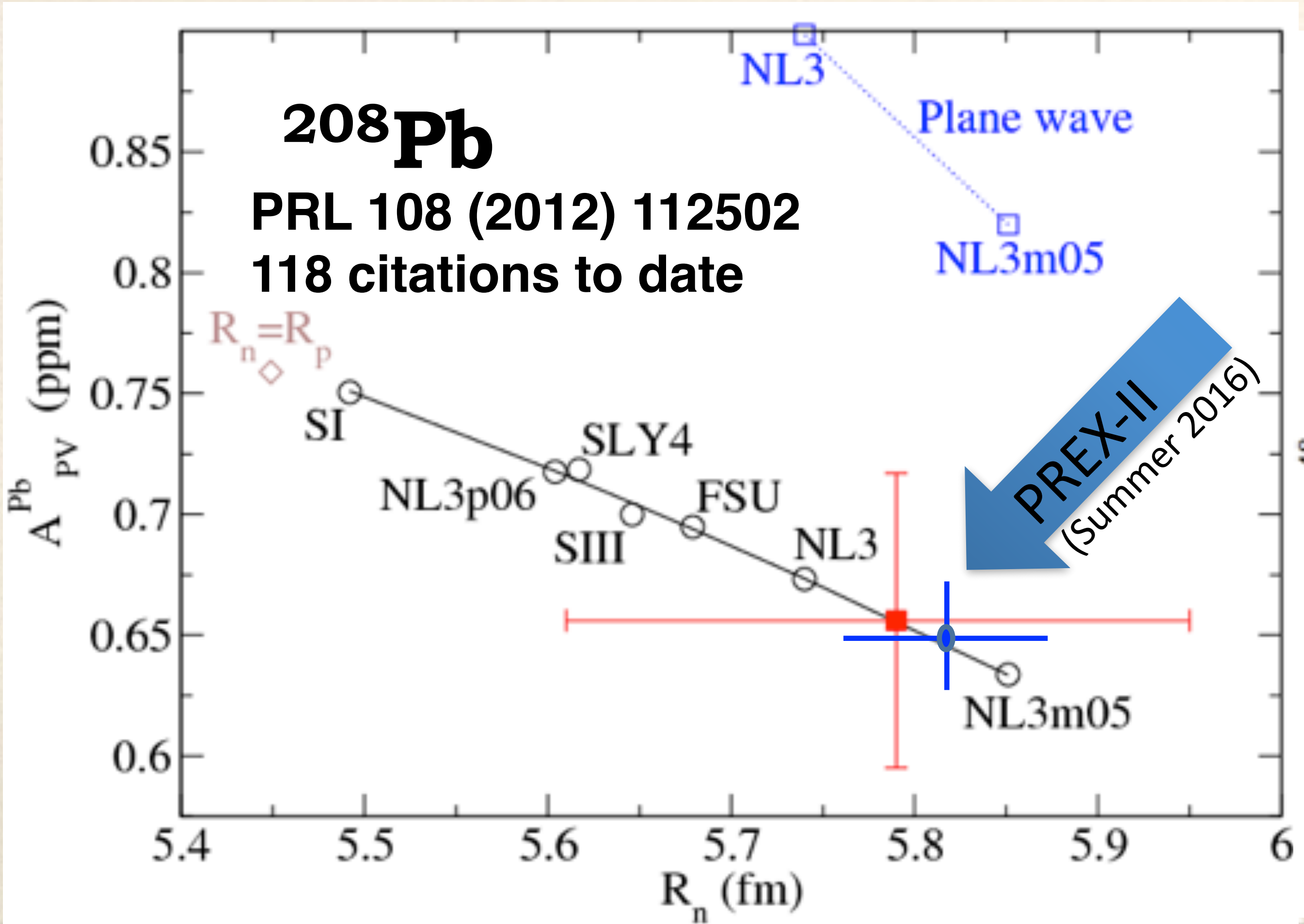
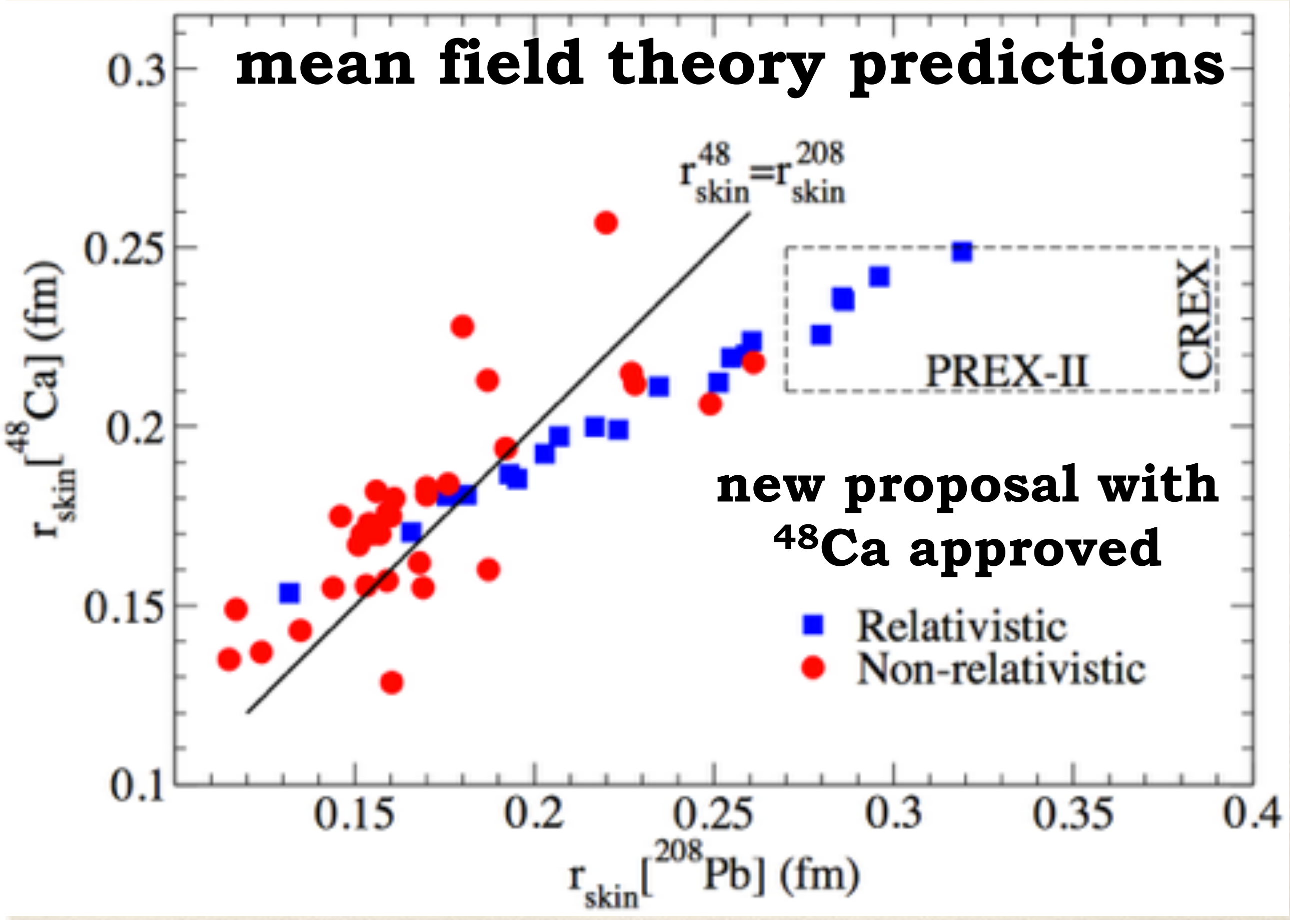


^{208}Pb

PRL 108 (2012) 112502
118 citations to date

PREX-II (Summer 2016)



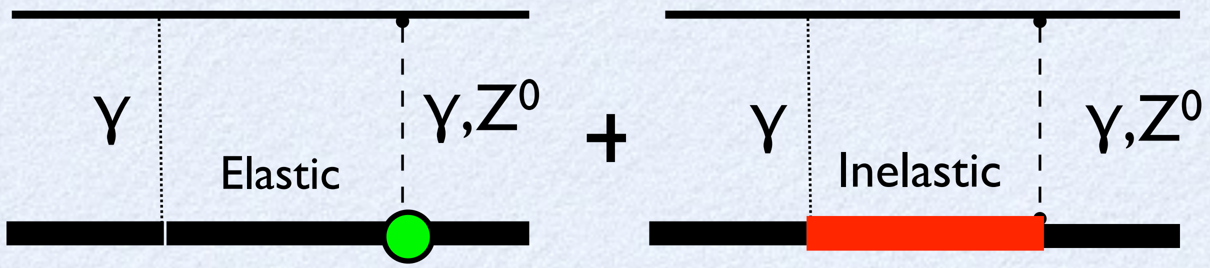
mean field theory predictions

new proposal with ^{48}Ca approved

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.



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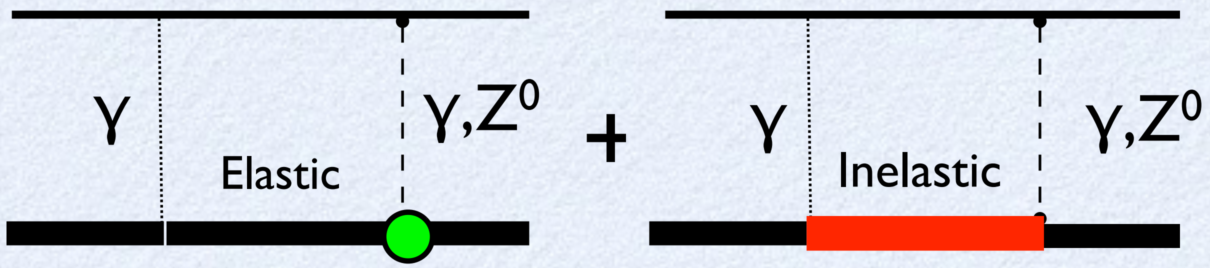

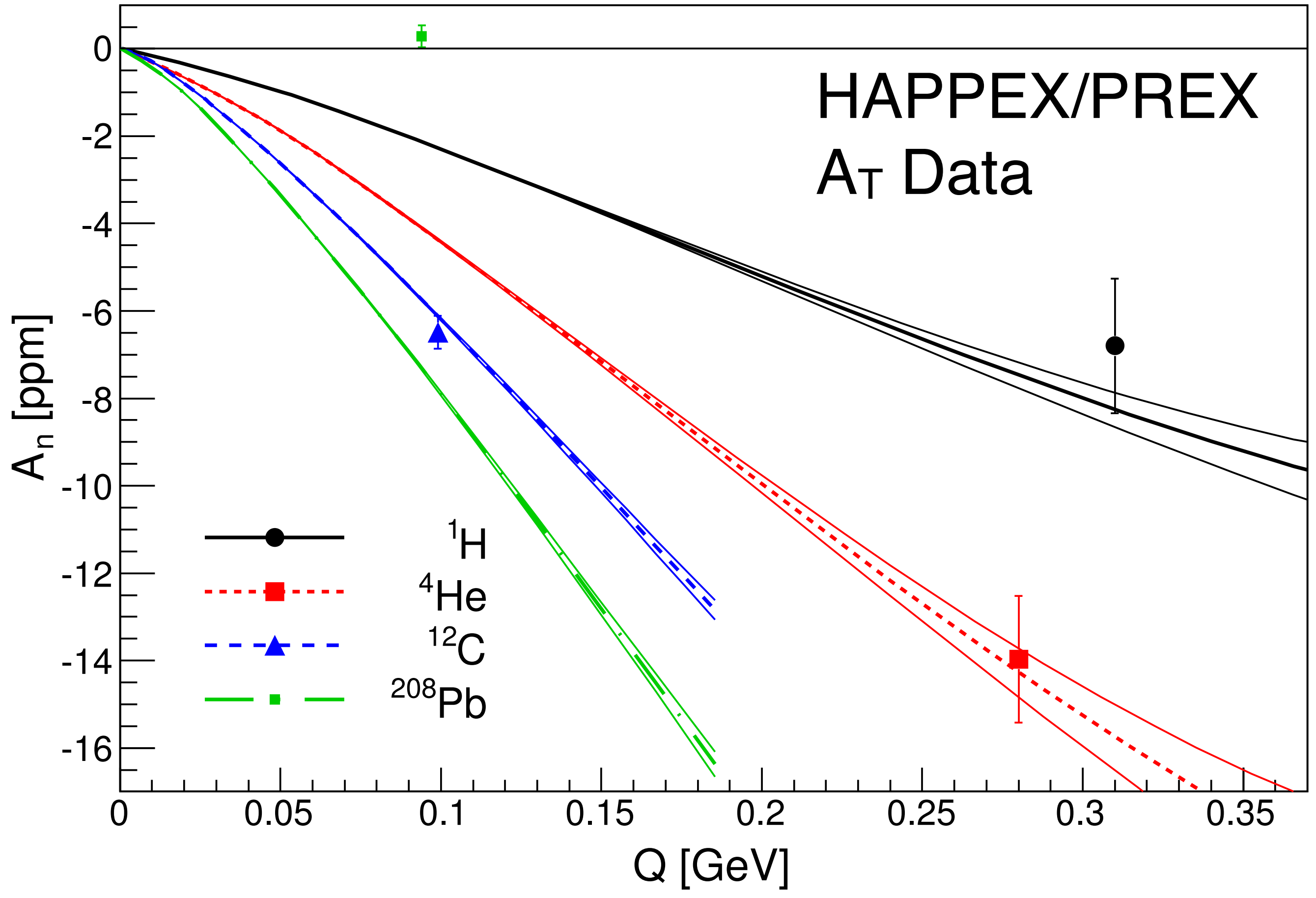

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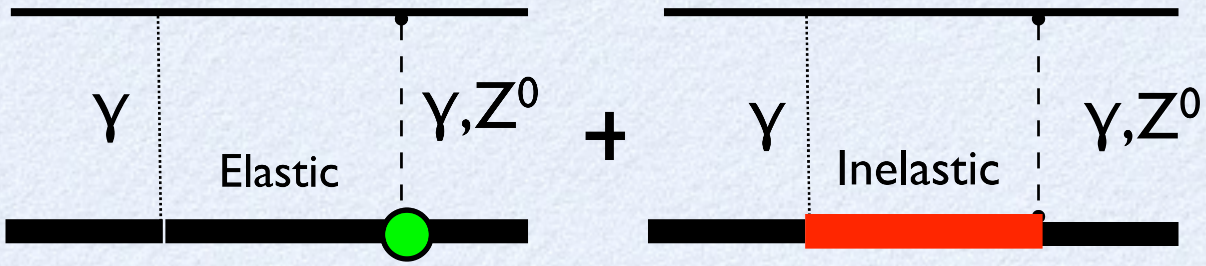

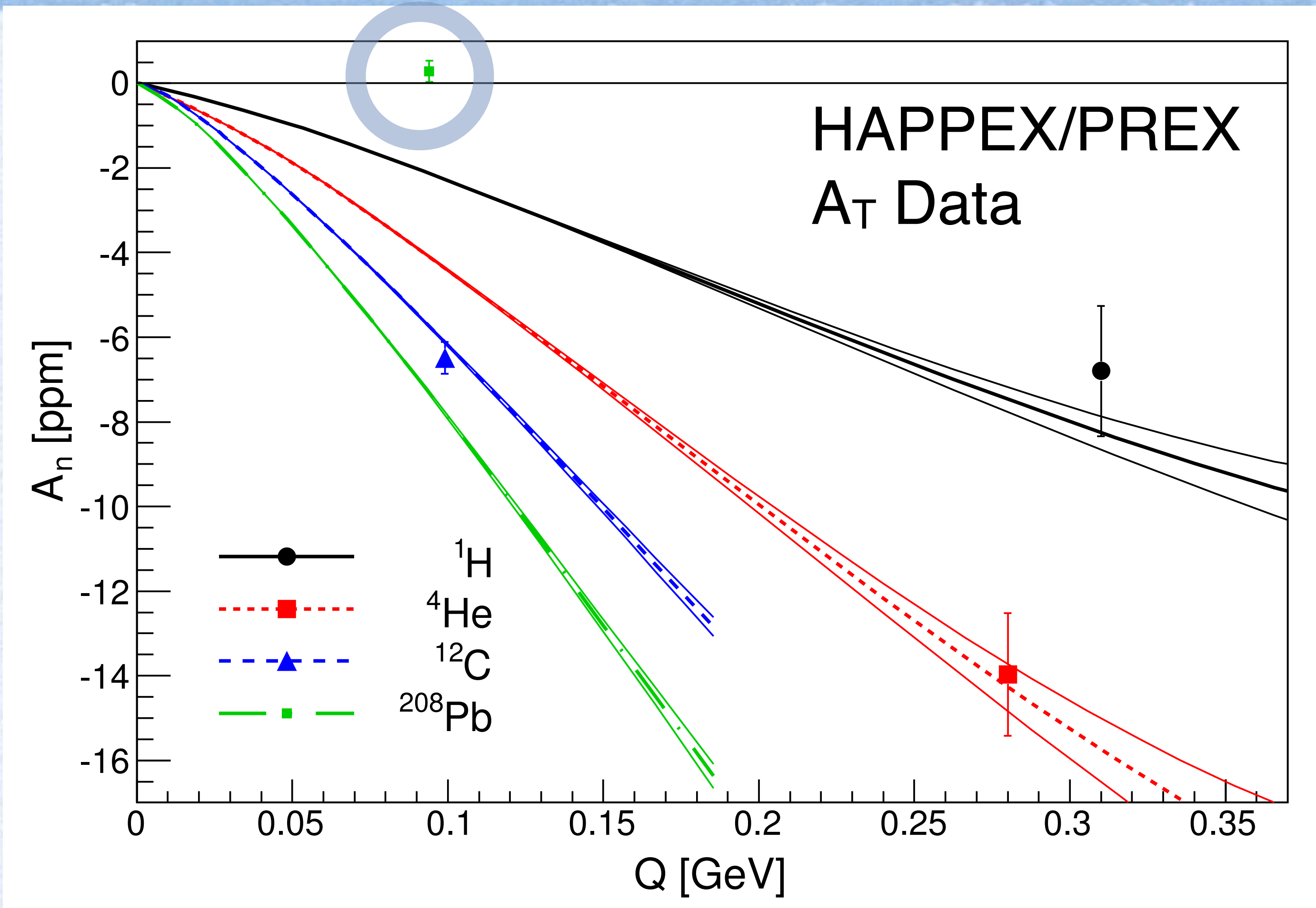

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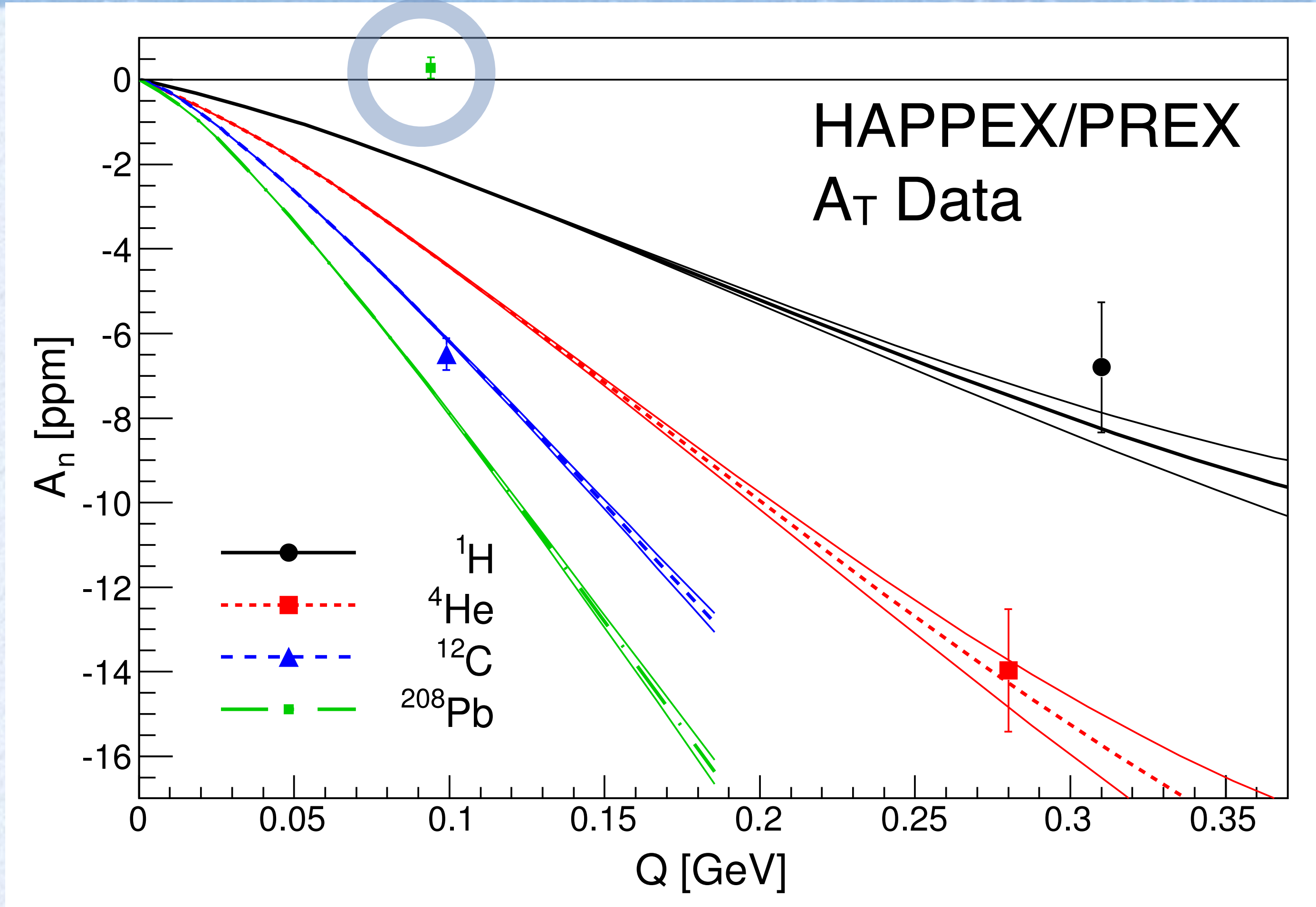

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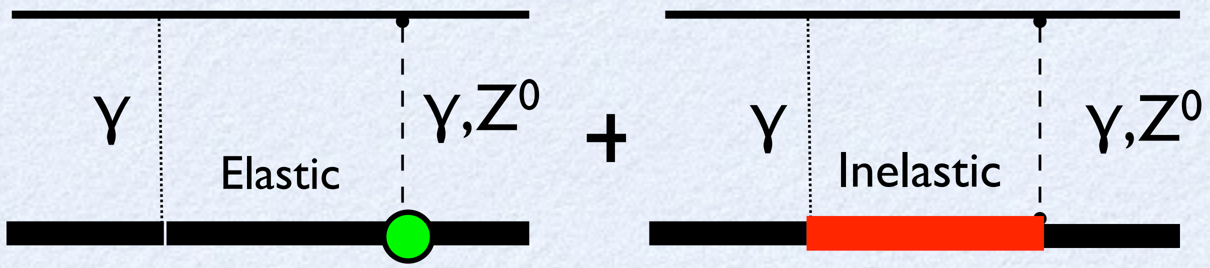

- **What does the Pb-208 A_T result imply?**

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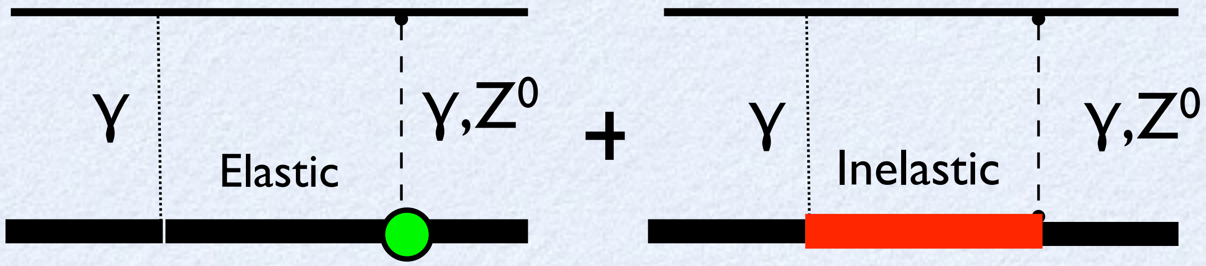

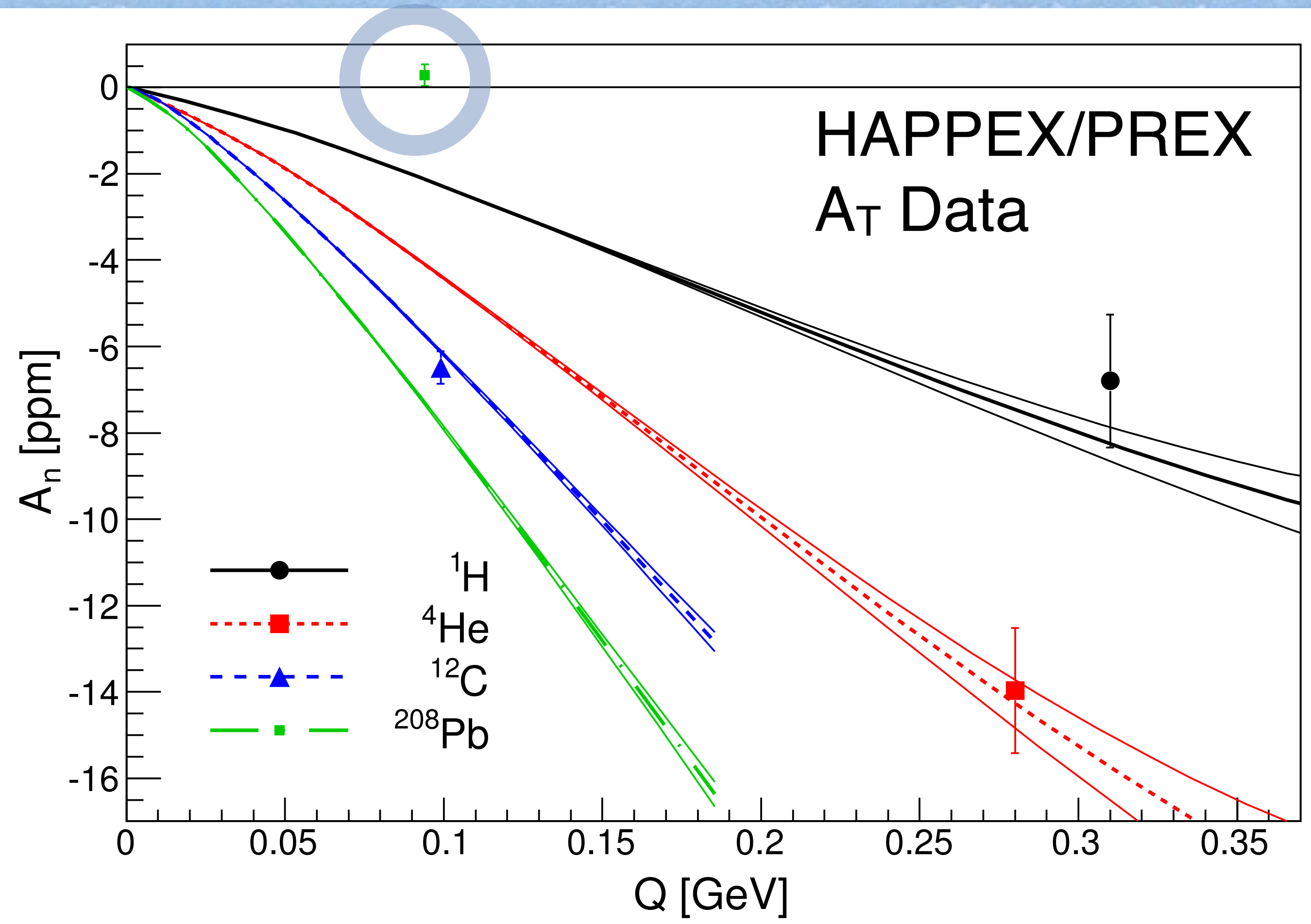

- **What does the Pb-208 A_T result imply?**
  - ***dispersion corrections on top of Coulomb distortions?***

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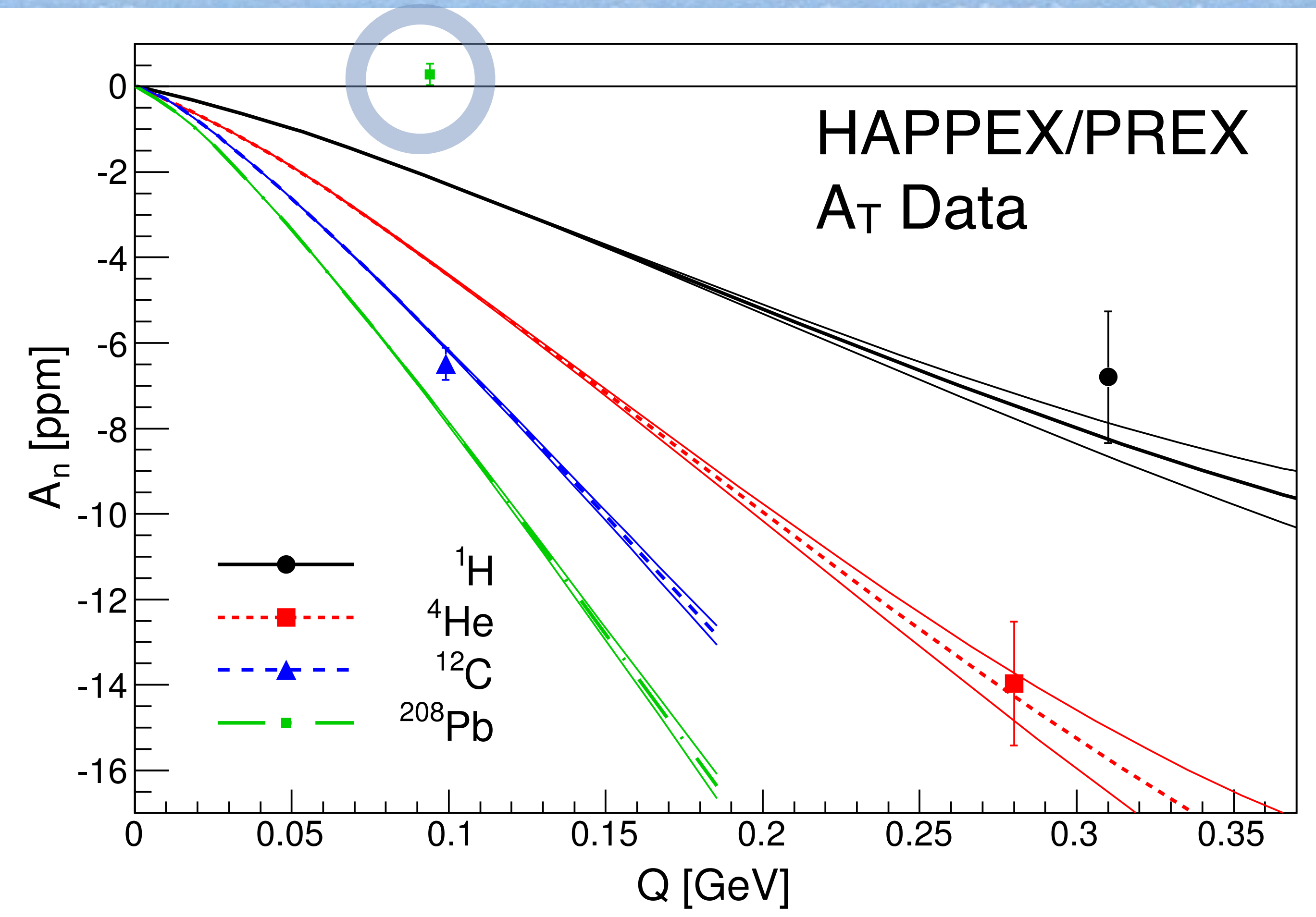

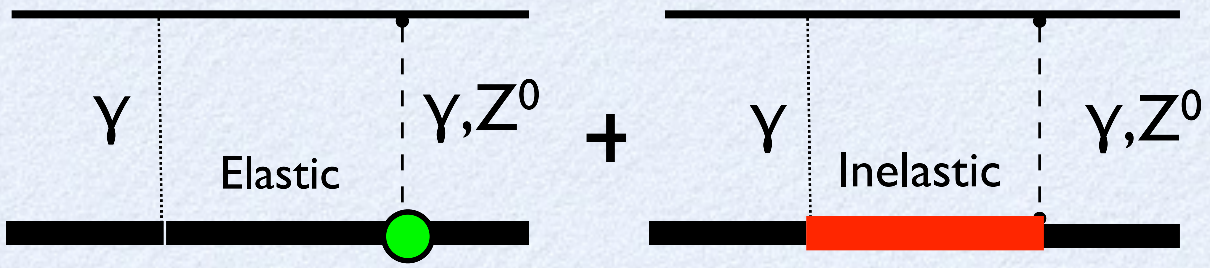

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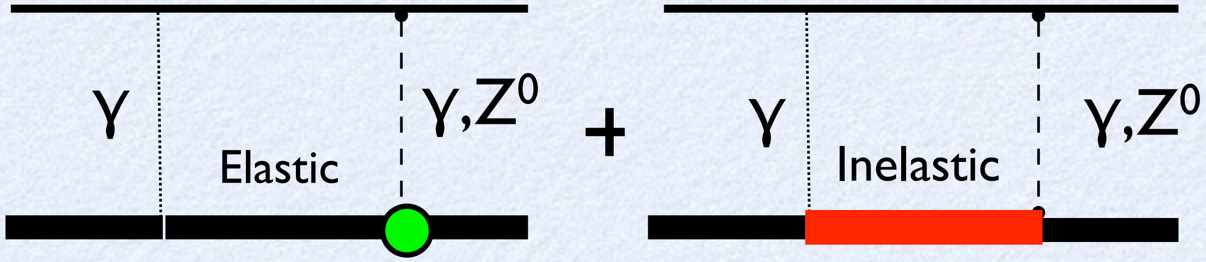

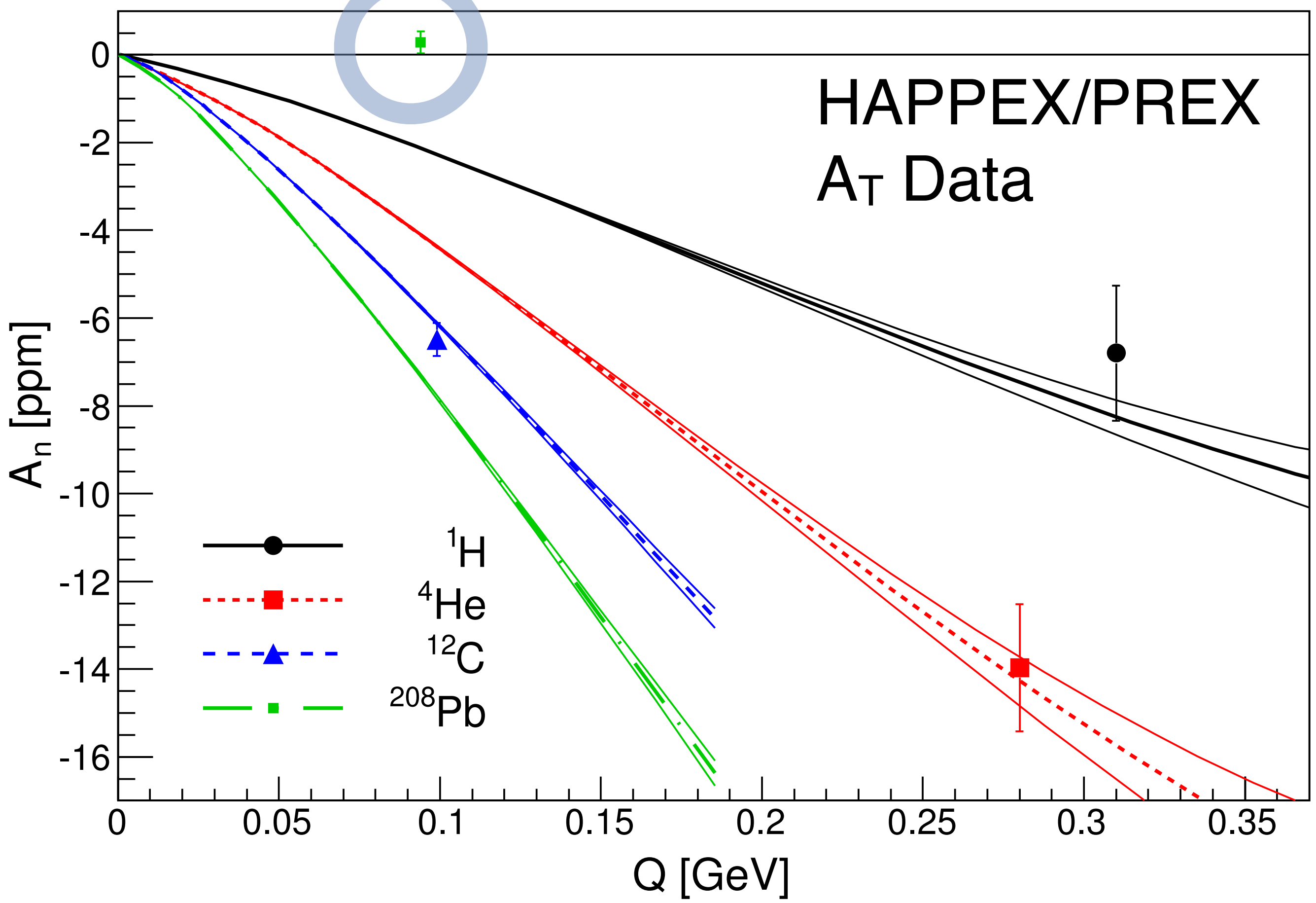

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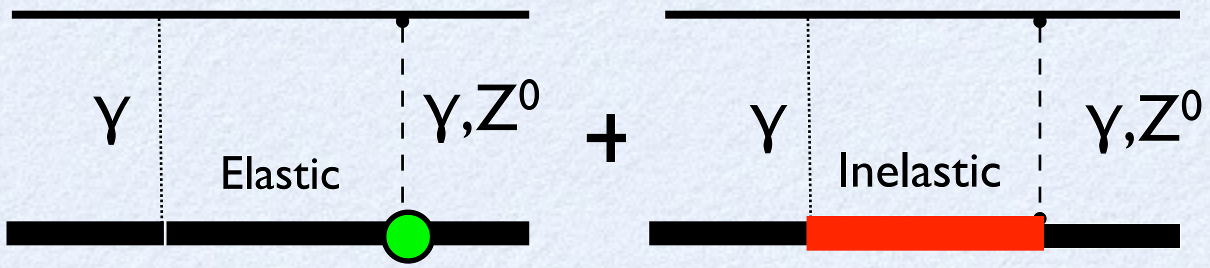

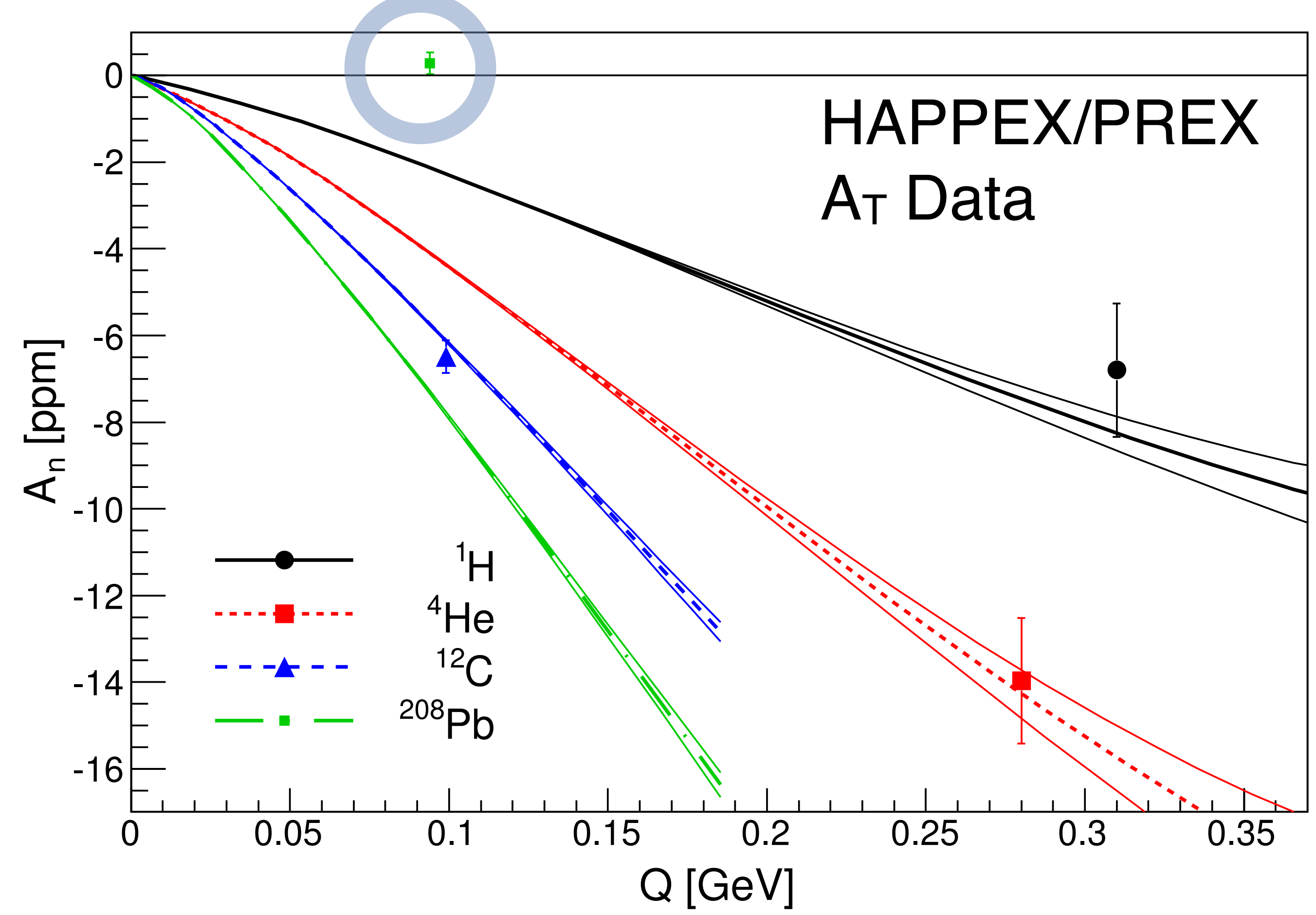

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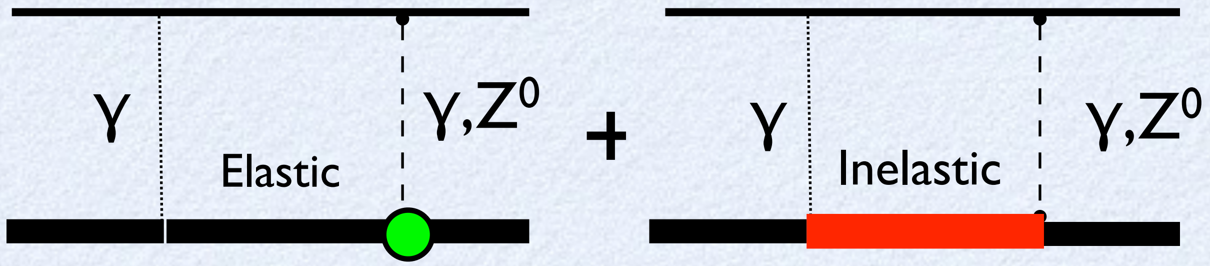

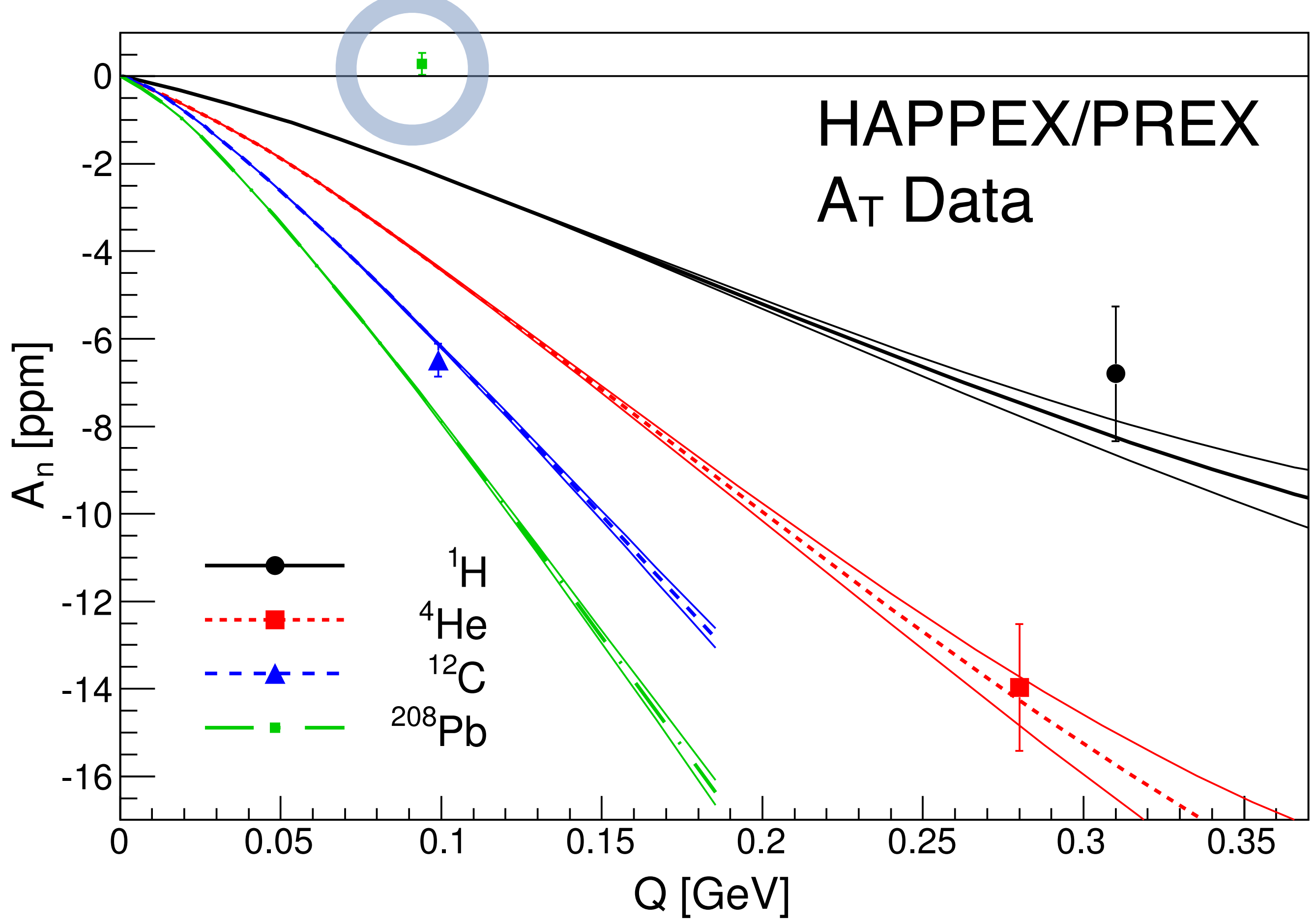

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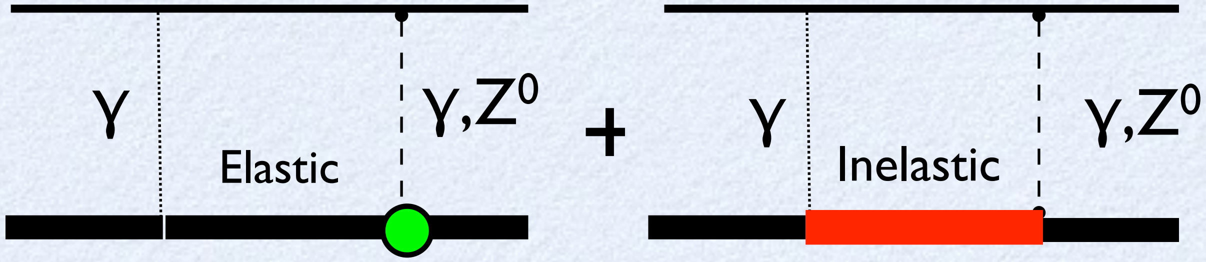

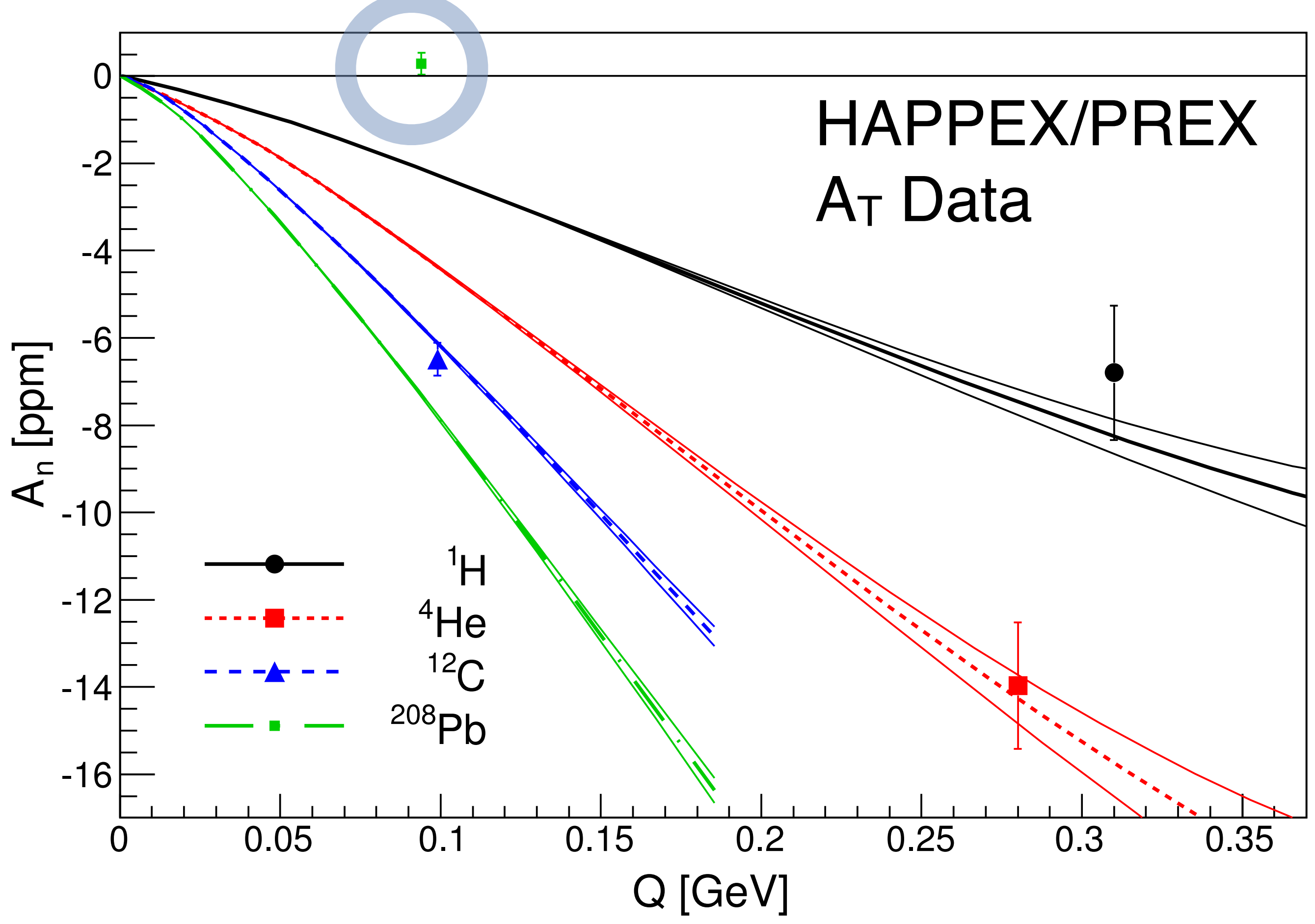

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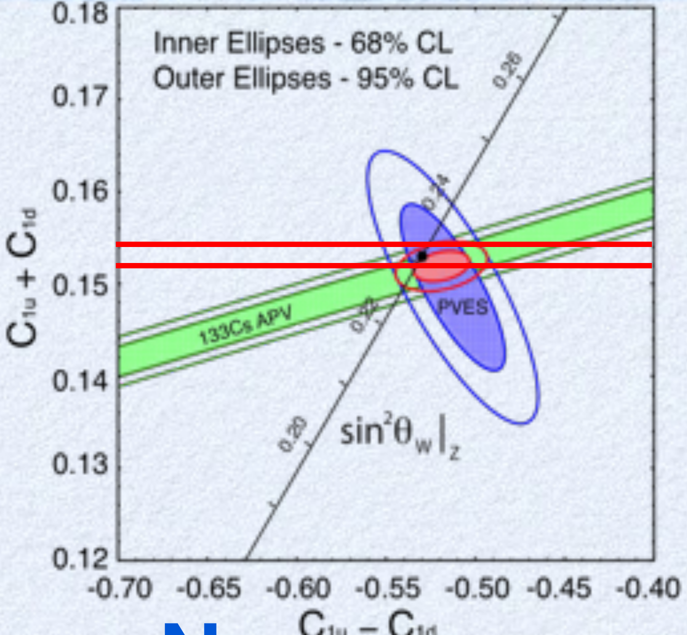
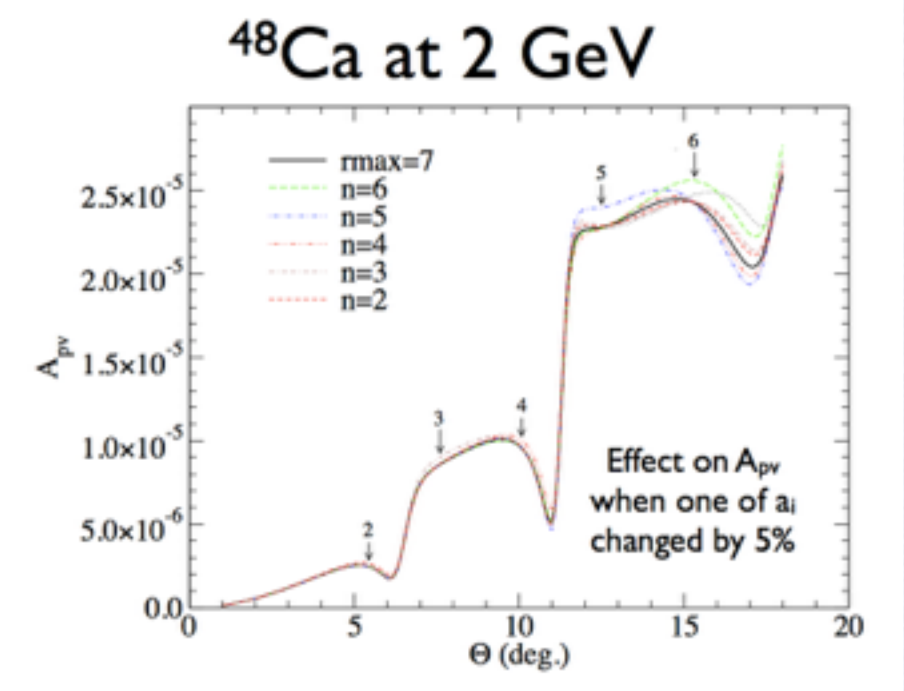
  - ***should other electroweak corrections be revisited?***
  - ***Motivates more A_T measurements at different energies***

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

Outlook

- **Jefferson Lab Program**
  - *PREX and CREX*
  - *MOLLER and SOLID*
- **Mainz Program**
  - *A_T measurements using the A1 spectrometer*
  - *MESA P2*
  - *MESA “Super-PREX”?*
  - *MESA “Super-Carbon”?*
  - *MESA A_T Measurements?*
- **New Machine**
  - *Multiple Carbon-12 measurements*
    - required to constrain strange radius
  - *A_T measurements at higher beam energy than MESA*
    - complementary information
    - easier spectrometer with higher beam energy
  - *Comprehensive Calcium-48 ground state neutron distribution*
    - requires at least 300 MeV beam energy

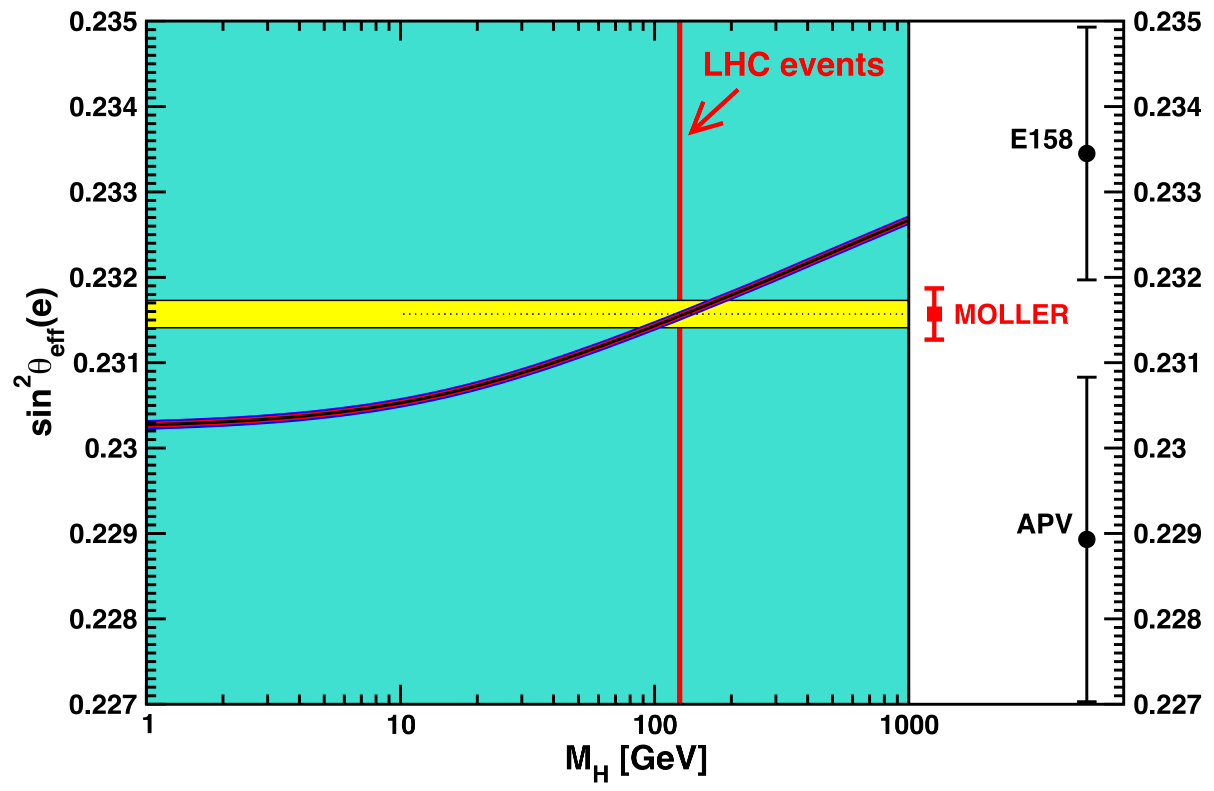
Backups

A Fundamental Parameter of the Electroweak Theory

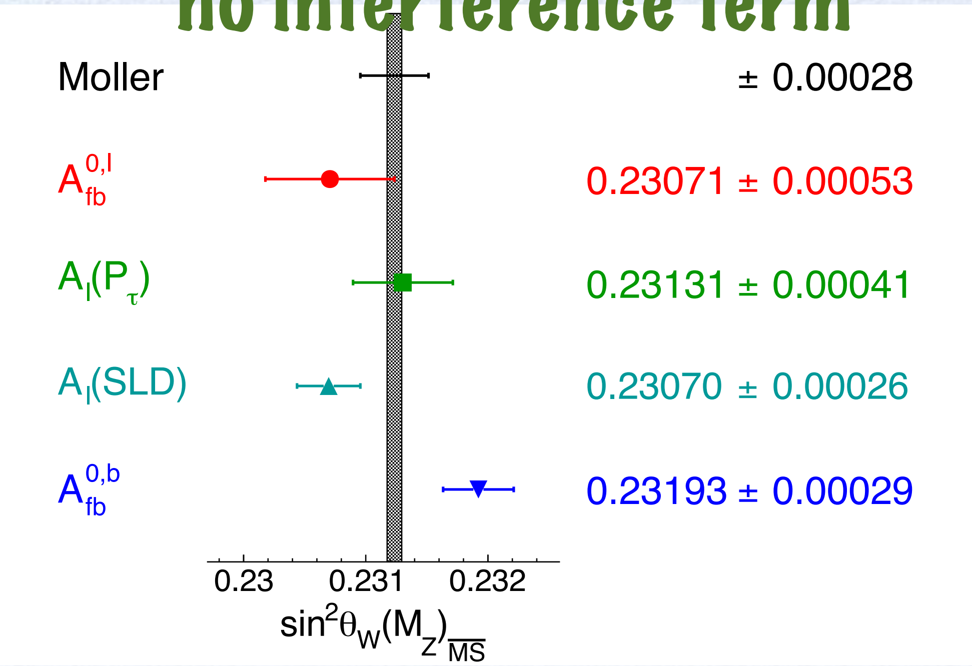
$\sin^2\theta_W$

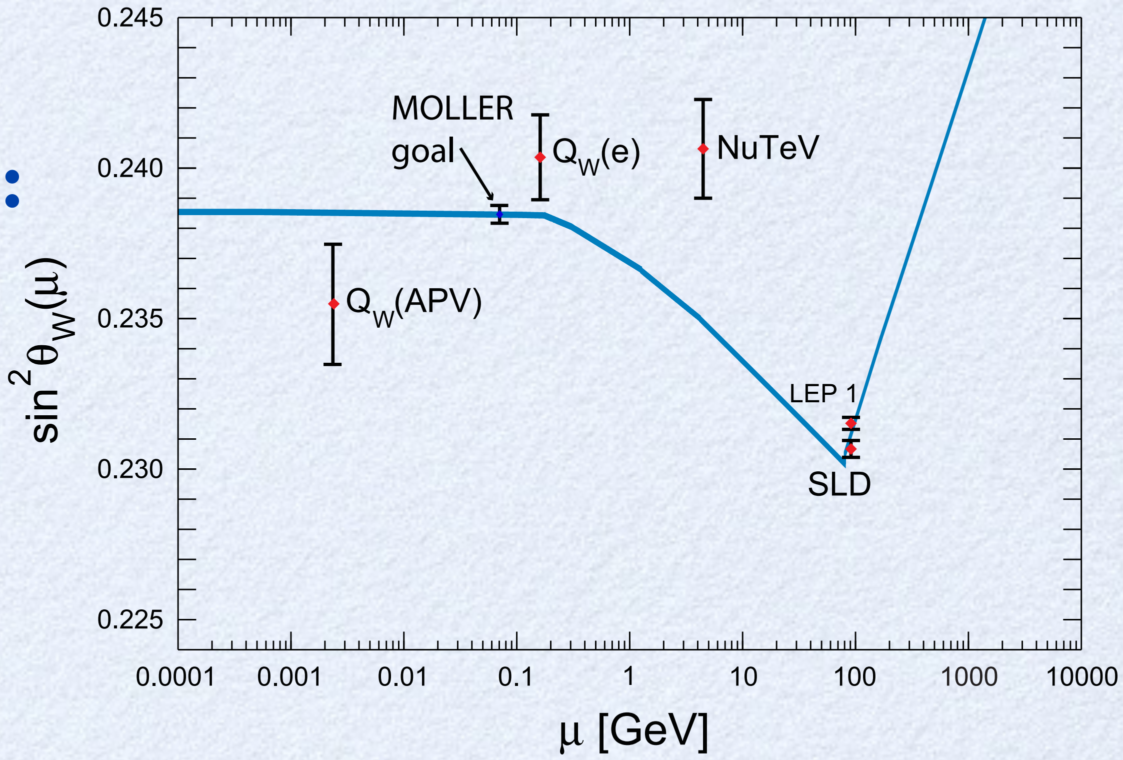
MOLLER Projection: $\delta(\sin^2\theta_W) = \pm\, 0.00024$ (stat.) $\pm\, 0.00013$ (syst.)

± 10σ discovery potential at $Q^2 \ll M_Z^2$



Z resonance measurements: no interference term





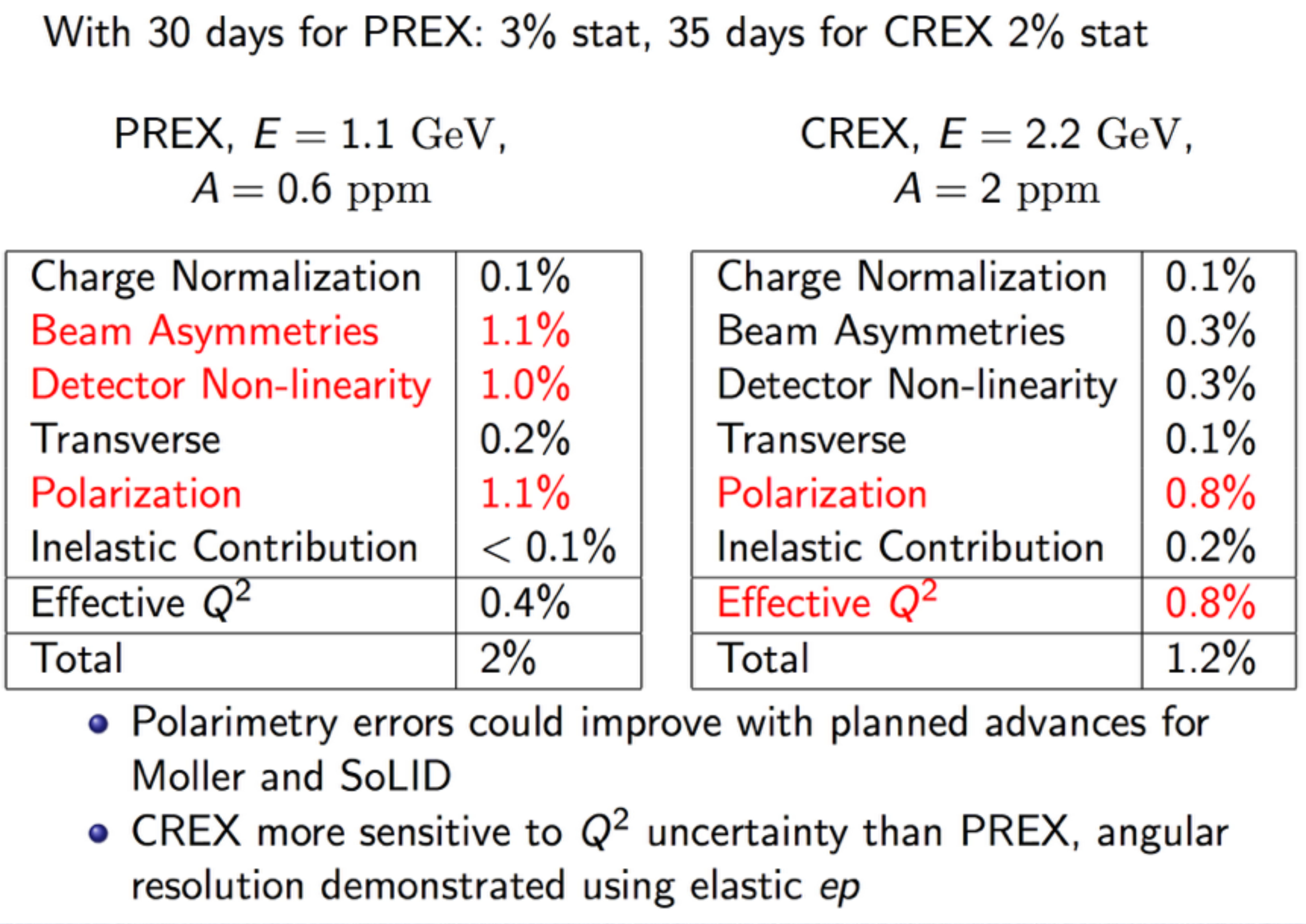
Future projections, similar time scale:

Mainz P2: ~ 0.00031

Final Tevatron: ~ 0.00041

LHC 14 TeV, 300 fb^{-1} : ~ 0.00036
Note: systematics-dominated (pdf uncertainties)

PREX/CREX Summary



With 30 days for PREX: 3% stat, 35 days for CREX 2% stat

PREX, $E = 1.1$ GeV,
$A = 0.6$ ppm

Charge Normalization	0.1%
Beam Asymmetries	1.1%
Detector Non-linearity	1.0%
Transverse	0.2%
Polarization	1.1%
Inelastic Contribution	$< 0.1\%$
Effective Q^2	0.4%
Total	2%

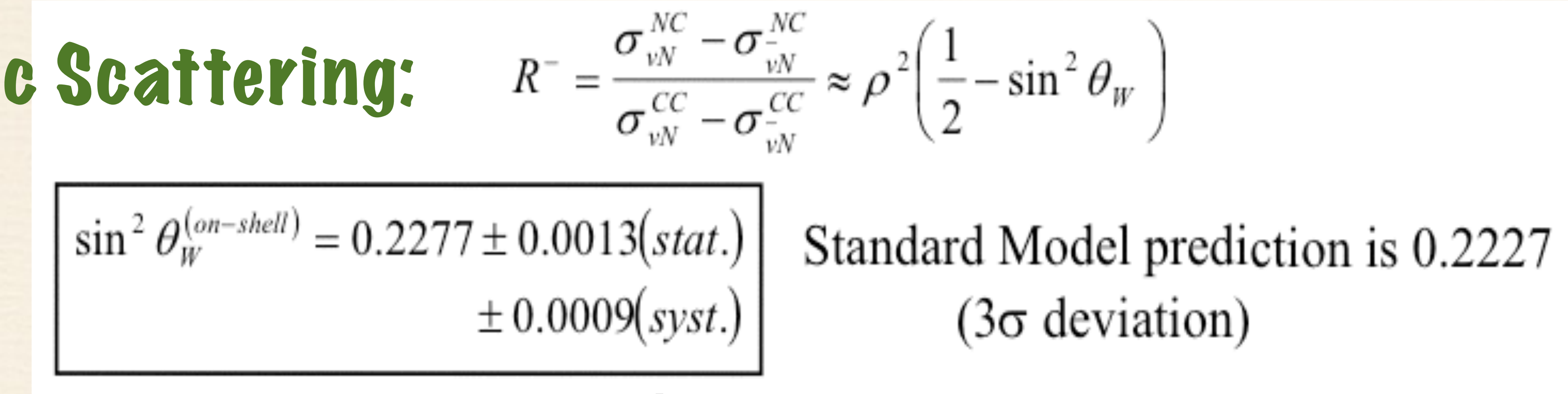
CREX, $E = 2.2$ GeV,
$A = 2$ ppm

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse	0.1%
Polarization	0.8%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total	1.2%

- Polarimetry errors could improve with planned advances for Moller and SoLID
- CREX more sensitive to Q^2 uncertainty than PREX, angular resolution demonstrated using elastic *ep*

(Anti-)Neutrino Scattering

Deep Inelastic Scattering:



$$R^{-} = \frac{\sigma_{\nu N}^{NC} - \sigma_{\bar{\nu} N}^{NC}}{\sigma_{\nu N}^{CC} - \sigma_{\bar{\nu} N}^{CC}} \approx \rho^{2}\left(\frac{1}{2} - \sin^{2}\theta_{W}\right)$$

NuTeV

$$\boxed{\begin{aligned}\sin^{2}\theta_{W}^{(on-shell)} &= 0.2277 \pm 0.0013(stat.)\\ &\pm 0.0009(syst.)\end{aligned}}$$

Standard Model prediction is 0.2227
(3σ deviation)

NuTeV measured a neutrino W/Z amplitude ratio to ~0.1%

Future improvements remain challenging to design: e.g. NuSONG proposal at Fermilab; fine-grained near detector at LBNE: they still do not achieve the sensitivity of PVES proposals being considered.

Elastic $\bar{\nu}$-electron Scattering: best direct comparison to MOLLER as a purely leptonic low Q^2 measurement

The most aggressive reactor experiment projections have fallen significantly short of the proposed MOLLER goal

Matching MOLLER precision and accuracy likely requires beta-beams and neutrino factories

Expertise from several generations of successful parity experiments

MOLLER Status

- **MOLLER Collaboration**
  - – 120 authors, 30 institutions, 5 countries
  - – Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - – 4th generation PVES experiment at JLab

- 20-25M$ project
- 3-4 years construction
- 3 years running

- **Science Review: Sep 10, 2014**
  - – Conducted by DOE NP: Tim Hallman, Chair
  - – theory talks: W.Marciano & M.Ramsey-Musolf
  - – 6 panelists: T.W.Donnelly, D.Hertzog, C.Horowitz, Z-T.Lu, M.Perelstein, T.Rizzo

Rigorous review by a panel of two nuclear theorists, two HEP theorists and two fundamental symmetries experimentalists

We passed!

★ Very positive outcome of Science Review

- *Highlighted unique opportunity: strong endorsement for the measurement*
- *Textbook measurement within SM*
- *must achieve proposed error bar*
- *theoretical cleanliness (purely leptonic!)*
- *No homework, concerns or followup: collaboration now ready and waiting to be reviewed for technical feasibility; build on the positive momentum*