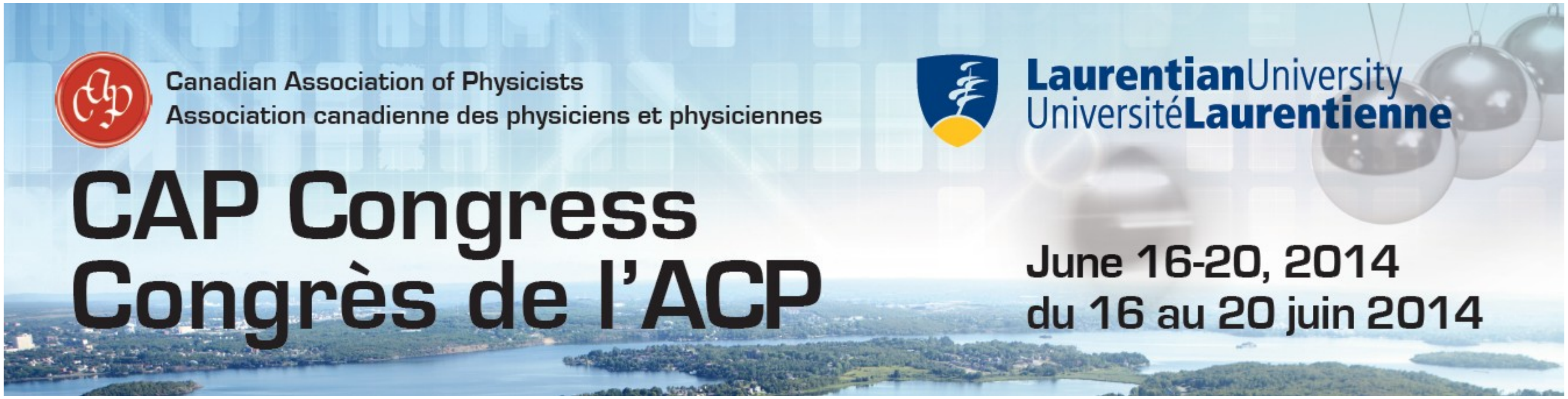
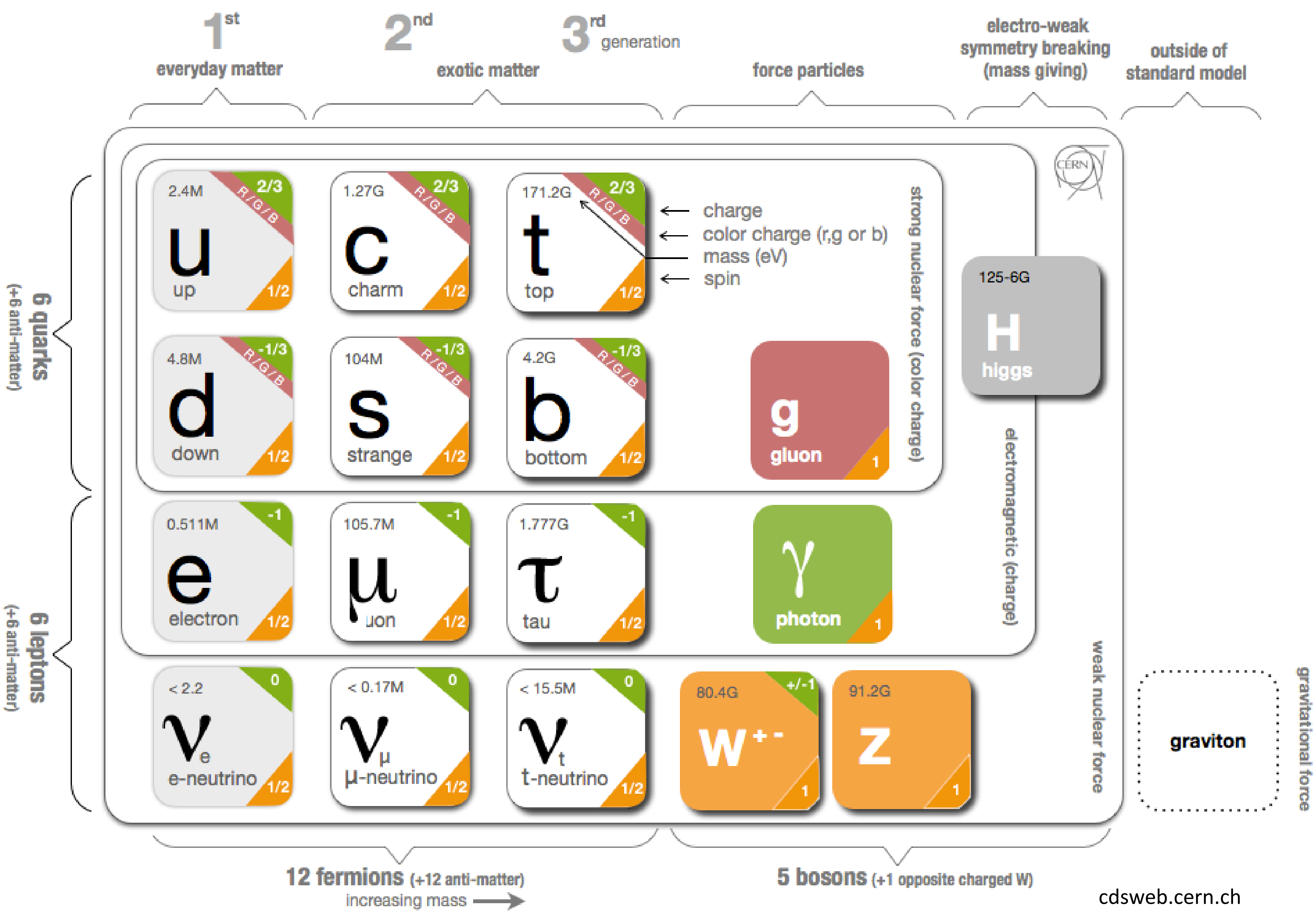
Testing Fundamental Symmetries with Precision Parity-Violating Experiments: Past, Present and Future

A. Aleksejevs, Memorial University, Newfoundland, Canada
S. Barkanova, Acadia University, Nova Scotia, Canada



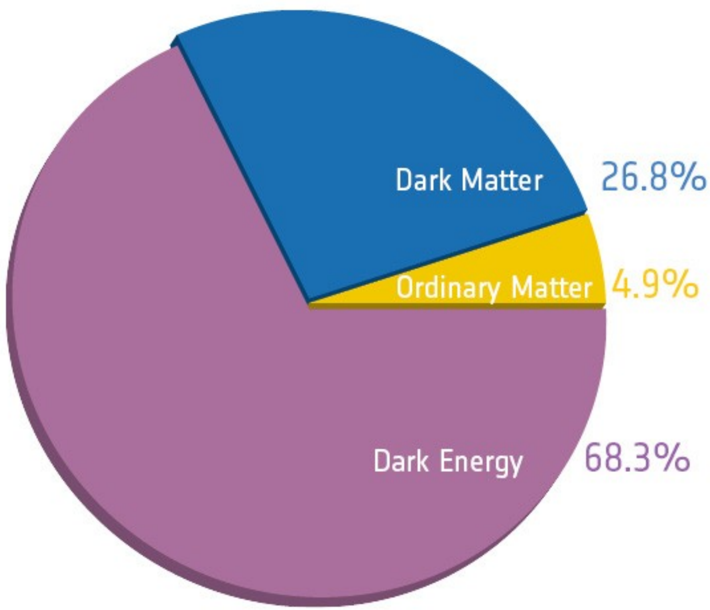
Standard Model (SM) of Particle Physics:



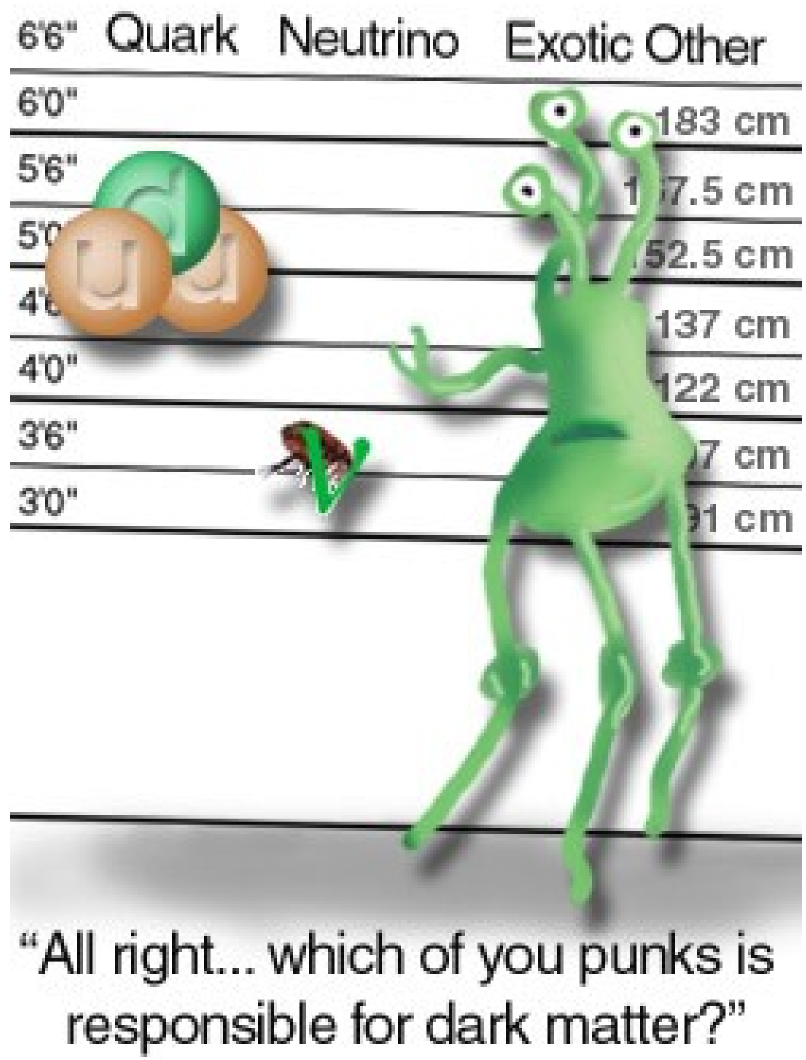
cdsweb.cern.ch

Although the Standard Model has been enormously successful to date, we known it is incomplete.

For example, it does not explain Dark Matter and Dark Energy:



planck.cf.ac.uk



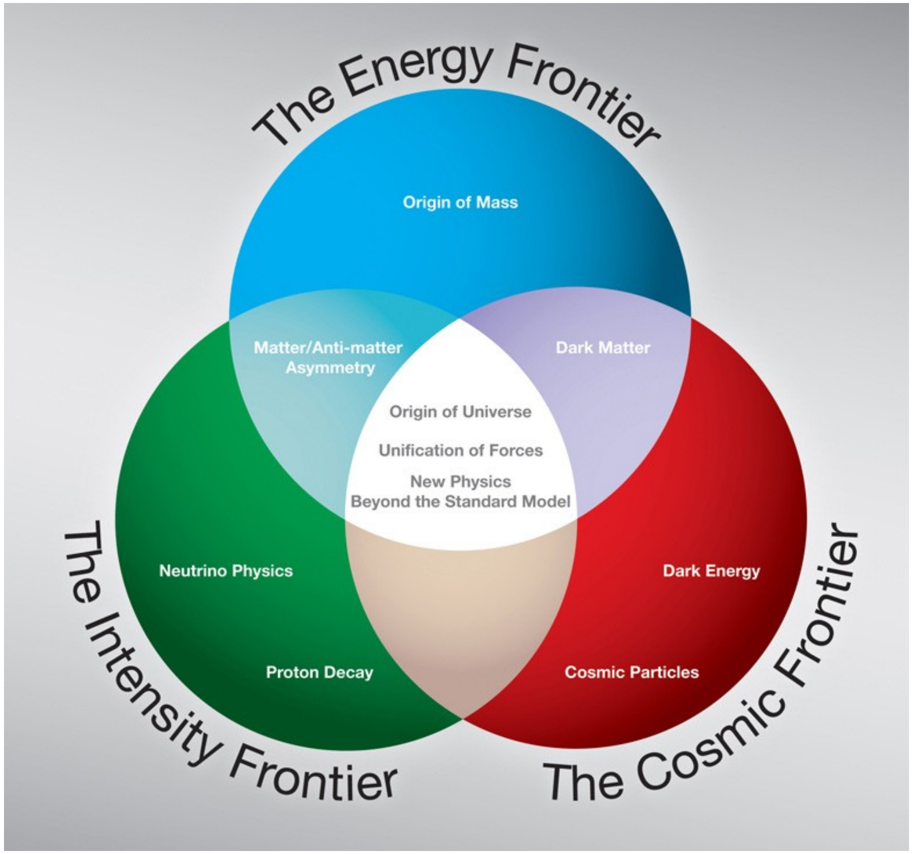
particleadventure.org

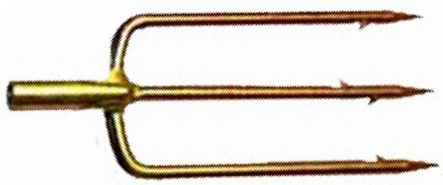
To look for New Physics beyond the Standard Model, we use the **three-prong approach:**

The Energy Frontier (high-energy colliders)

The Intensity/Precision Frontier (intense particle beams)

The Cosmic Frontier (underground experiments, ground and space-based telescopes)





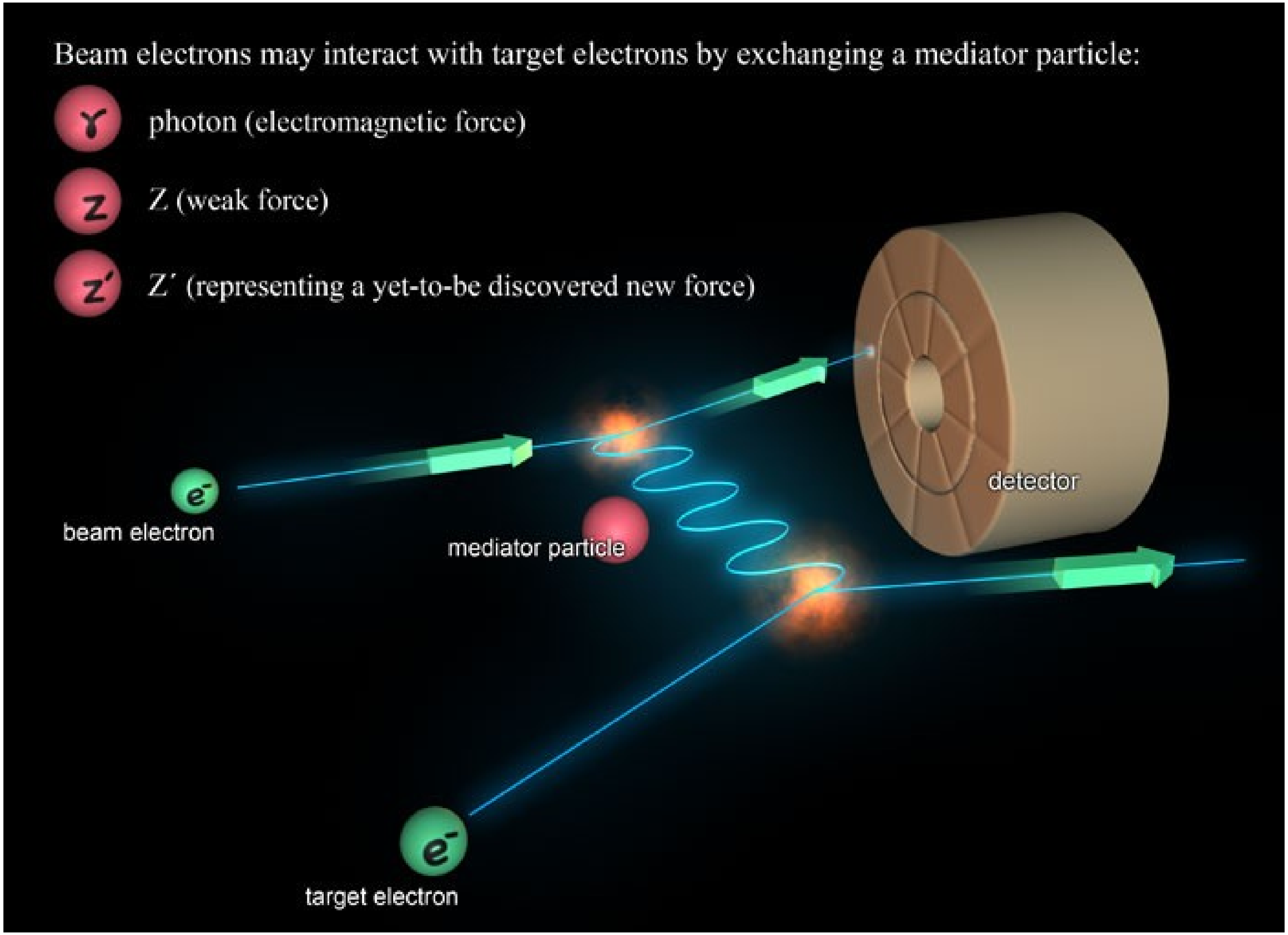
Energy

Intensity/Precision

Cosmic

"US Particle Physics: Scientific Opportunities
A Strategic Plan for the Next Ten Years"

$$d\sigma \sim |M^\gamma + M^Z|^2 = |M^\gamma|^2 + 2Re\{(M^\gamma)^* M^Z\} + |M^Z|^2$$



SLAC E158

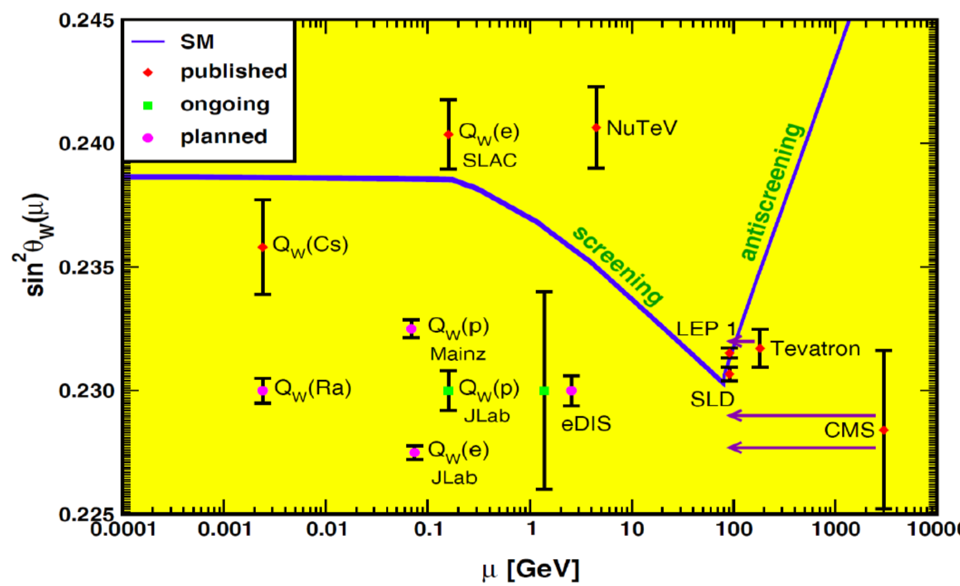
To test the at the level of quantum corrections, the electroweak parameters m_W, m_Z, G_F , α and $\sin^2 \theta_W$ have to be determined with *O(0.1%)* or better.

G_F *and* α are well-known, and m_W and m_Z has been recently much improved.

Original on-shell definition:

$$\sin^2 \theta_W \equiv 1 - m_W^2 / m_Z^2$$

$\overline{\text{MS}}$ (modified minimal subtraction) prescription, with an arbitrary sliding mass scale μ:



$$\sin^2 \theta_W(\mu)_{\overline{\text{MS}}} = e^2(\mu)_{\overline{\text{MS}}} / g^2(\mu)_{\overline{\text{MS}}}$$

Plot: Michael Gericke for MOLLER Collaboration, IPP General Meeting, 16/06/2014

In SM at three level (Born):

$$Q_W(p) = 1 - 4\sin^2\theta_W$$

Since the value of the weak mixing angle is very close to 0.25, weak charge of proton (and electron) is suppressed in the SM, so $Q_W(p)$ and $Q_W(e) = - Q_W(p)$ offer a unique place to extract $sin^2\theta_W$.

For proton (current Qweak at JLab, planned P2 at MESA in Mainz):

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

Parity-violation effects are enhanced in atoms with a large number of protons (Z) and neutrons (N) (parity-violation experiments with ^{209}Bi, ^{205}Tl and ^{133}Cs):

$$Q_W(Z, N) = Z(1 - 4\sin^2\theta_W) - N$$

The low-energy effective electron-quark *A(e) × V (q)* Lagrangian:

$$\mathcal{L} = \mathcal{L}^{\rm PV}_{\rm SM} + \mathcal{L}^{\rm PV}_{\rm NEW}$$

$$\mathcal{L}^{\rm PV}_{\rm SM} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\ \bar{q}\gamma^\mu q$$

$$\mathcal{L}^{\rm PV}_{NEW} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_f h^q_V\ \bar{q}\gamma^\mu q$$

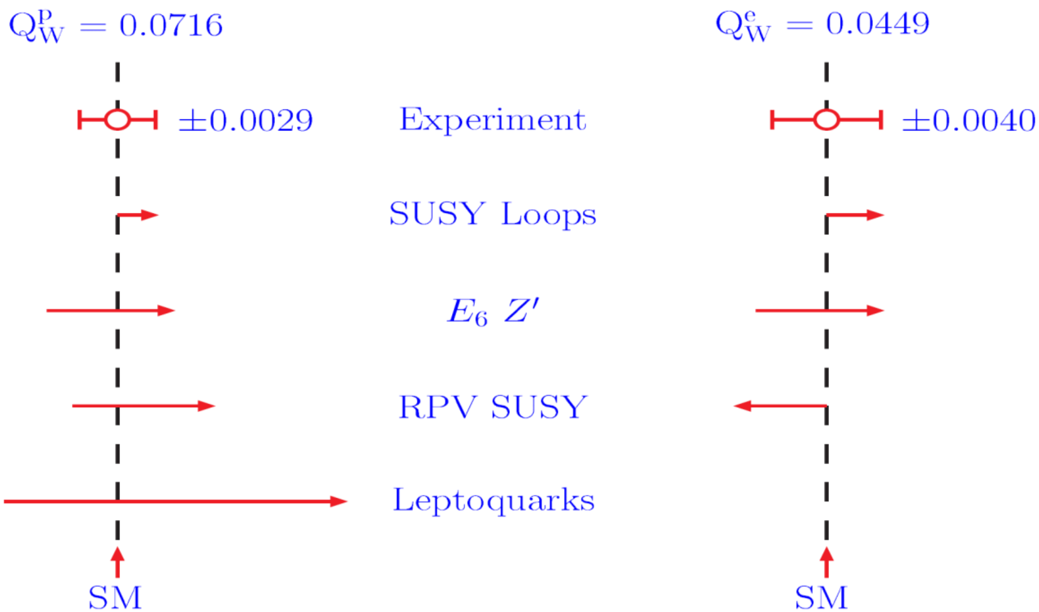
where *g is* the coupling constant, Λ is the mass scale, and the $h^q{}_V$ are the effective coefficients of the new physics.

In SM at three level:

$$Q^p_W(\rm SM) = -2(2C_{1u} + C_{1d})$$

A precise measurement of $Q_W(p)$ would thus test new physics scales up to TeV scales:

$$\frac{\Lambda}{g} \approx \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q^p_W|}}$$



Experiment	Λ	Coupling
Cesium APV	9.9 TeV	$C_{1u} + C_{1d}$
E-158	8.5 TeV	C_{ee}
Qweak	11 TeV	$2C_{1u} + C_{1d}$
SoLID	8.9 TeV	$2C_{2u} - C_{2d}$
MOLLER	19 TeV	C_{ee}
P2	16 TeV	$2C_{1u} + C_{1d}$

Comparison of anticipated errors for $Q_W(p)$ and $Q_W(e)$ expected from various extensions and allowed (at 95% C.L.) by fits to existing data (2003).

95% C.L. reach of experiments to the new physics mass scale Λ.

J. Erler et al., Phys.Rev. D68 (2003) 016006, arXiv:hep-ph/0302149

K.S. Kumar et al., Ann.Rev.Nucl.Part.Sci. 63 (2013) 237-267, arXiv:1302.6263

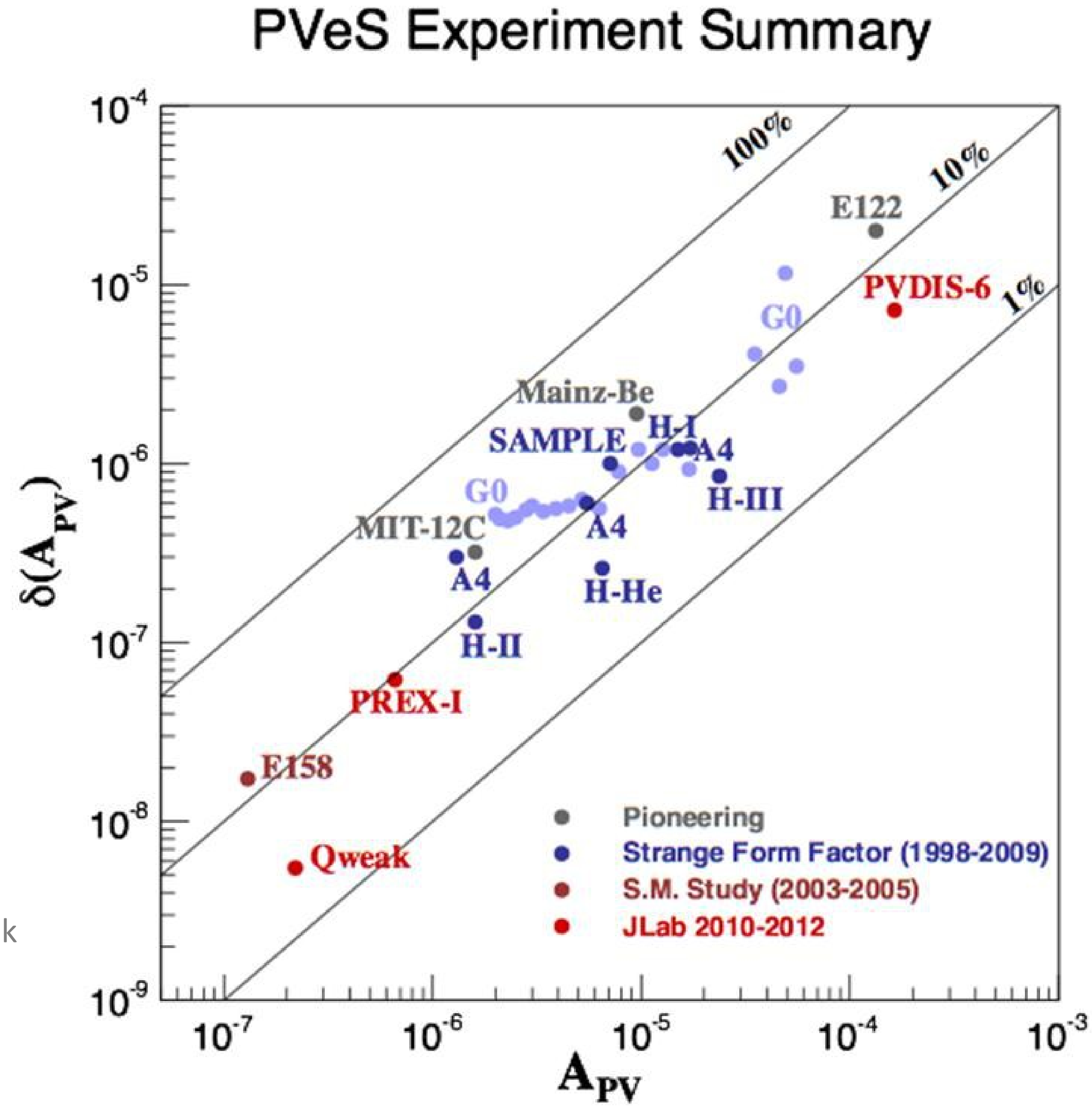
SLAC E122, 1978:

Helicity dependence in the inclusive cross-section for deep-inelastic scattering of longitudinal polarized electrons on unpolarized ^{2}H.

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{PV} \simeq 1.5 \times 10^{-4}$$

Plot: Rakitha Beminiwattha for Qweak Collaboration, JLab Users Group Meeting, 03/06/2014



The first Q_{weak} result! (4% of the total data acquired during the experiment)

PRL **111,** 141803 (2013) PHYSICAL REVIEW LETTERS week ending 4 OCTOBER 2013

First Determination of the Weak Charge of the Proton

D. Androic,[1] D. S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] J. Beaufait,[5] R. S. Beminiwattha,[6] J. Benesch,[5] F. Benmokhtar,[7] J. Birchall,[8] R. D. Carlini,[5,2,†] G. D. Cates,[9] J. C. Cornejo,[2] S. Covrig,[5] M. M. Dalton,[9] C. A. Davis,[10] W. Deconinck,[2] J. Diefenbach,[11] J. F. Dowd,[2] J. A. Dunne,[12] D. Dutta,[12] W. S. Duvall,[13] M. Elaasar,[14] W. R. Falk,[8] J. M. Finn,[2,*] T. Forest,[15,16] D. Gaskell,[5] M. T. W. Gericke,[8] J. Grames,[5] V. M. Gray,[2] K. Grimm,[16,2] F. Guo,[4] J. R. Hoskins,[2] K. Johnston,[16] D. Jones,[9] M. Jones,[5] R. Jones,[17] M. Kargiantoulakis,[9] P. M. King,[6] E. Korkmaz,[18] S. Kowalski,[4] J. Leacock,[13] J. Leckey,[2,‡] A. R. Lee,[13] J. H. Lee,[6,2,§] L. Lee,[10,8] S. MacEwan,[8] D. Mack,[5] J. A. Magee,[2] R. Mahurin,[8] J. Mammei,[13,‖] J. W. Martin,[19] M. J. McHugh,[20] D. Meekins,[5] J. Mei,[5] R. Michaels,[5] A. Micherdzinska,[20] A. Mkrtchyan,[3] H. Mkrtchyan,[3] N. Morgan,[13] K. E. Myers,[20,¶] A. Narayan,[12] L. Z. Ndukum,[12] V. Nelyubin,[9] Nuruzzaman,[11,12] W. T. H. van Oers,[10,8] A. K. Opper,[20] S. A. Page,[8] J. Pan,[8] K. D. Paschke,[9] S. K. Phillips,[21] M. L. Pitt,[13] M. Poelker,[5] J. F. Rajotte,[4] W. D. Ramsay,[10,8] J. Roche,[6] B. Sawatzky,[5] T. Seva,[1] M. H. Shabestari,[12] R. Silwal,[9] N. Simicevic,[16] G. R. Smith,[5] P. Solvignon,[5] D. T. Spayde,[22] A. Subedi,[12] R. Subedi,[20] R. Suleiman,[5] V. Tadevosyan,[3] W. A. Tobias,[9] V. Tvaskis,[19,8] B. Waidyawansa,[6] P. Wang,[8] S. P. Wells,[16] S. A. Wood,[5] S. Yang,[2] R. D. Young,[23] and S. Zhamkochyan[3]

(Q_{weak} Collaboration)

Qweak Collaboration, Phys. Rev. Lett. 111, 141803 (2013), arXiv:1307.5275

See Shelley Page invited talk, CAP Congress, 16/06/2014

The Qweak Collaboration

97 collaborators 23 grad students
10 post docs 23 institutions

Institutions:
[1] University of Zagreb
[2] College of William and Mary
[3] A. I. Alikhanyan National Science Laboratory
[4] Massachusetts Institute of Technology
[5] Thomas Jefferson National Accelerator Facility
[6] Ohio University
[7] Christopher Newport University
[8] University of Manitoba,
[9] University of Virginia
[10] TRIUMF
[11] Hampton University
[12] Mississippi State University
[13] Virginia Polytechnic Institute & State Univ
[14] Southern University at New Orleans
[15] Idaho State University
[16] Louisiana Tech University
[17] University of Connecticut
[18] University of Northern British Columbia
[19] University of Winnipeg
[20] George Washington University
[21] University of New Hampshire
[22] Hendrix College, Conway
[23] University of Adelaide

D. Androic,[1] D.S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] J. Beaufait,[5] R.S. Beminiwattha,[6] J. Benesch,[5] F. Benmokhtar,[7] J. Birchall,[8] R.D. Carlini,[5, 2] G.D. Cates,[9] J.C. Cornejo,[2] S. Covrig,[5] M.M. Dalton,[9] C.A. Davis,[10] W. Deconinck,[2] J. Diefenbach,[11] J.F. Dowd,[2] J.A. Dunne,[12] D. Dutta,[12] W.S. Duvall,[13] M. Elaasar,[14] W.R. Falk,[8] J.M. Finn,[2,] T. Forest,[15, 16] D. Gaskell,[5] M.T.W. Gericke,[8] J. Grames,[5] V.M. Gray,[2] K. Grimm,[16, 2] F. Guo,[4] J.R. Hoskins,[2] K. Johnston,[16] D. Jones,[9] M. Jones,[5] R. Jones,[17] M. Kargiantoulakis,[9] P.M. King,[6] E. Korkmaz,[18] S. Kowalski,[4] J. Leacock,[13] J. Leckey,[2,] A.R. Lee,[13] J.H. Lee,[6, 2,] L. Lee,[10] S. MacEwan,[8] D. Mack,[5] J.A. Magee,[2] R. Mahurin,[8] J. Mammei,[13,] J.W. Martin,[19] M.J. McHugh,[20] D. Meekins,[5] J. Mei,[5] R. Michaels,[5] A. Micherdzinska,[20] A. Mkrtchyan,[3] H. Mkrtchyan,[3] N. Morgan,[13] K.E. Myers,[20] A. Narayan,[12] L.Z. Ndukum,[12] V. Nelyubin,[9] Nuruzzaman,[11, 12] W.T.H van Oers,[10, 8] A.K. Opper,[20] S.A. Page,[8] J. Pan,[8] K.D. Paschke,[9] S.K. Phillips,[21] M.L. Pitt,[13] M. Poelker,[5] J.F. Rajotte,[4] W.D. Ramsay,[10, 8] J. Roche,[6] B. Sawatzky,[5] T. Seva,[1] M.H. Shabestari,[12] R. Silwal,[9] N. Simicevic,[16] G.R. Smith,[5] P. Solvignon,[5] D.T. Spayde,[22] A. Subedi,[12] R. Subedi,[20] R. Suleiman,[5] V. Tadevosyan,[3] W.A. Tobias,[9] V. Tvaskis,[19, 8] B. Waidyawansa,[6] P. Wang,[8] S.P. Wells,[16]S.A. Wood,[5] S. Yang,[2] R.D. Young,[23] and S. Zhamkochyan [3]

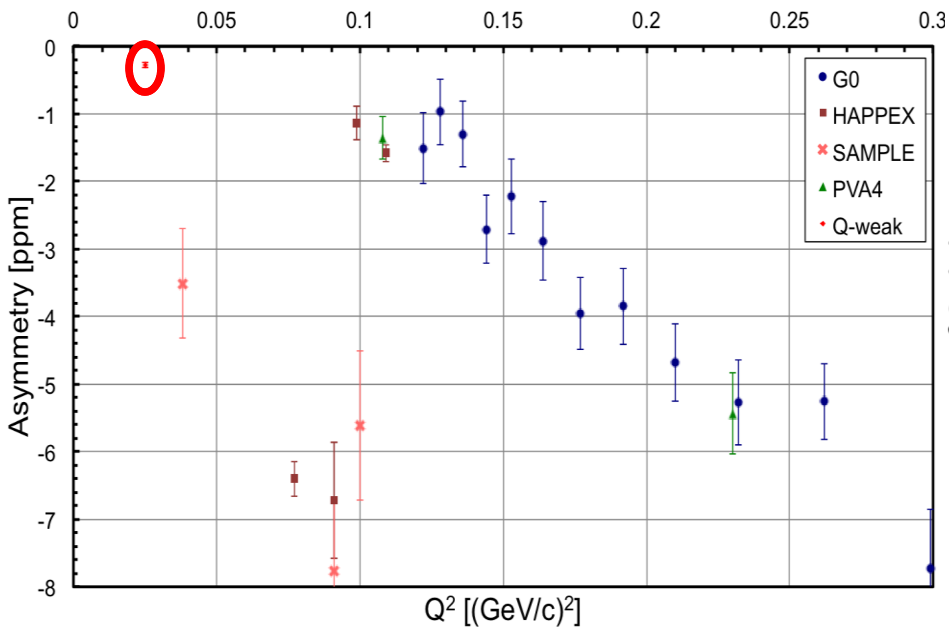
Spokespersons Project Manager Grad Students

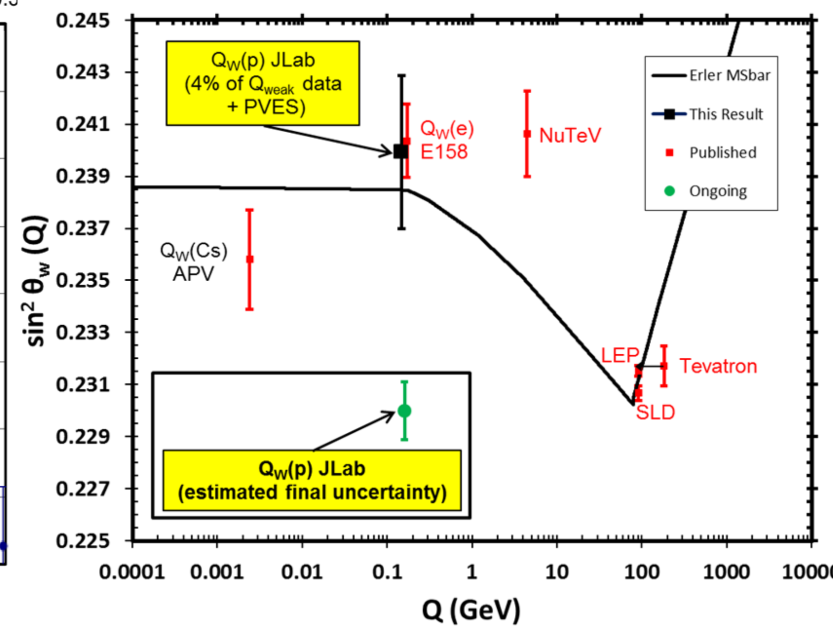
Run 0 Asymmetry Results (4% of full data):

Beam energy at vertex , $< E_{eff} >$	1.155 ± 0.003 GeV
Momentum transfer $< Q^2_{eff} >$	0.0250 ± 0.0006 $(GeV)^2$
Effective scattering angle, $< \theta_{eff} >$	7.90 ± 0.30^o

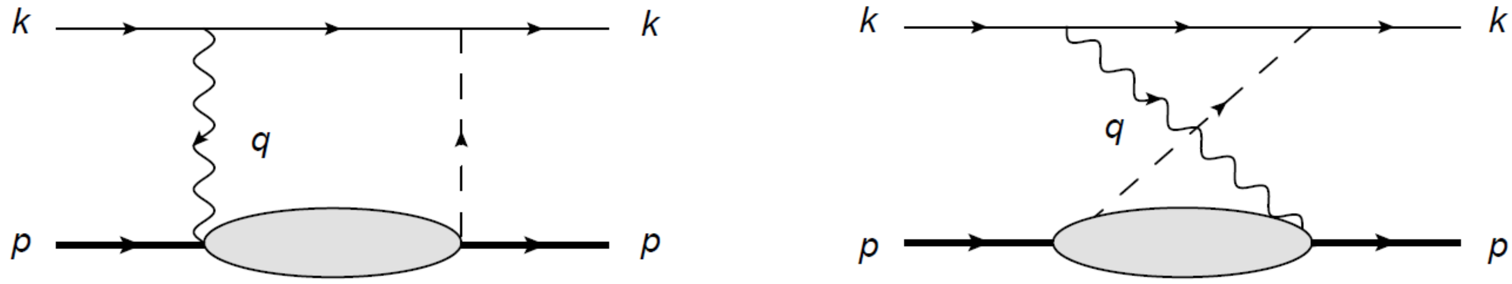
$$A_{\vec{e}p}(< Q^2 >_{eff}) = -0.279 \pm 0.035 \text{ (stat.) } \pm 0.031 \text{ (syst.) ppm}$$

Qweak Collaboration





Q_{weak} Theory Input:



One way to do it: Parameterization approach by Hall, Blunden, Melnitchouk, Thomas, Young

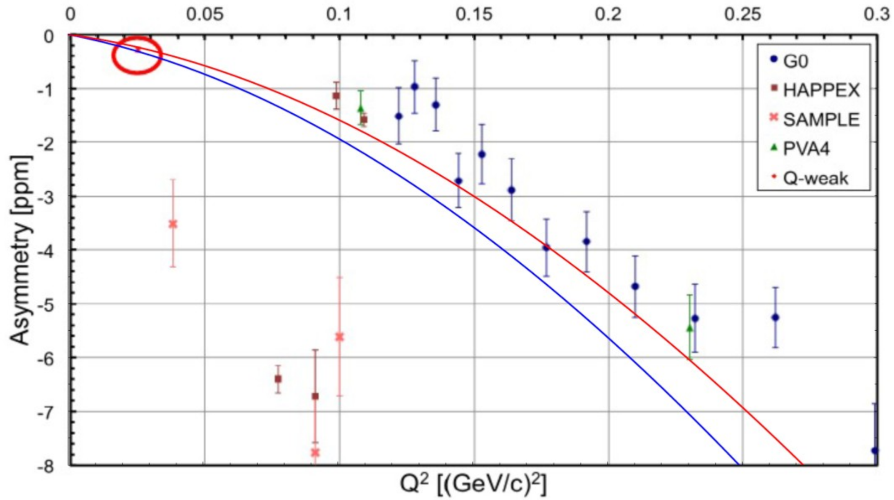
$$A_{\rm PV} = \frac{G_F}{4\pi\alpha\sqrt{2}}\, t\, Q_W^p$$

$$Q_W^p = (1+\Delta\rho+\Delta_e)\left(1-4\sin^2\theta_W(0)+\Delta_e'\right)+\Box_{WW}+\Box_{ZZ}+\Box_{\gamma Z}(0)$$

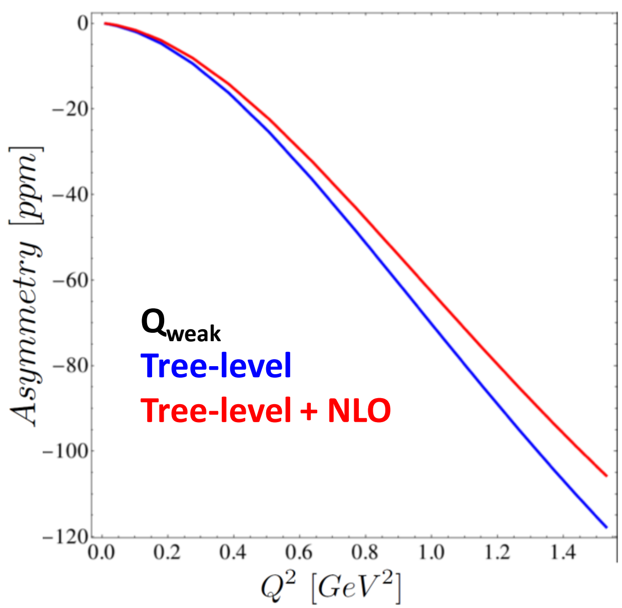
$$\Re e\, \Box_{\gamma Z}^V = (5.57 \pm 0.36)\times 10^{-3}$$

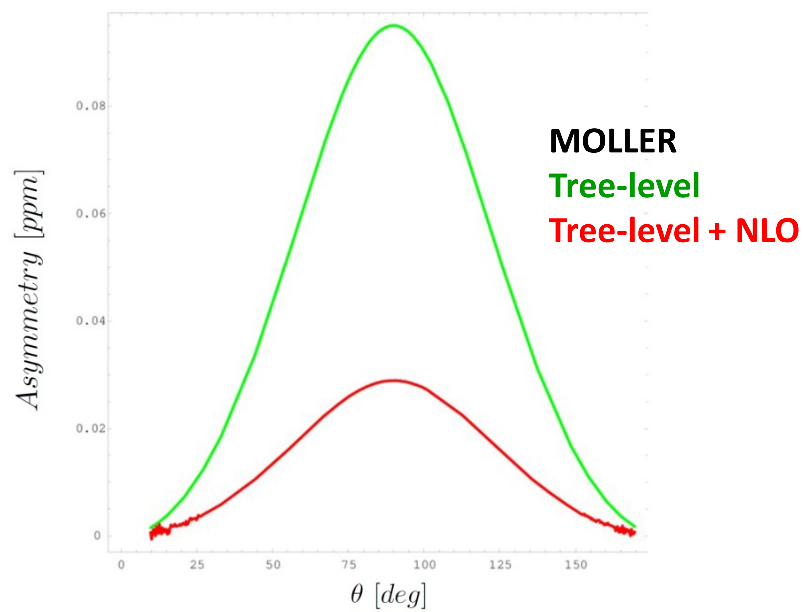
Hall et al, PhysRevD.88, 013011 (2013), arXiv:1304.7877

Alternative way – calculate A_{PV}, including all NLO EWC (and maybe some NNLO), then compare with the measured A_{PV} to extract the new physics parameters.

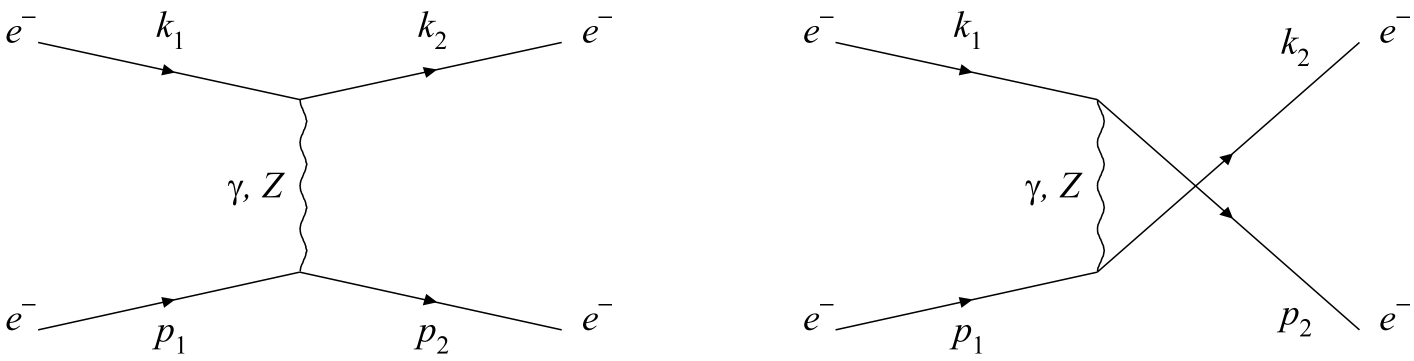


A_{PV} (Q_{weak}, predicted) ≈ - 228 ppb
(with dE = m_π)
A_{PV} (MOLLER, predicted) ≈ 29 ppb
(with dE = $0.05 \cdot E_{CM}$)





C. Møller, Annalen der Physik 406, 531 (1932): electron–electron scattering (Møller process)



Neutral current t-channel and u-channel amplitudes leading to the asymmetry A_{LR} at tree level.

The first observation of Parity Violation in Møller scattering by E-158 at SLAC, with 45 or 48 GeV polarized electrons scattered from a 1.5 m long hydrogen target.

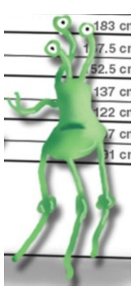
$$Q^2 = 0.026GeV^2, A_{LR} = (1.31 \pm 0.14(stat.) \pm 0.10(syst.)) \times 10^{-7}$$

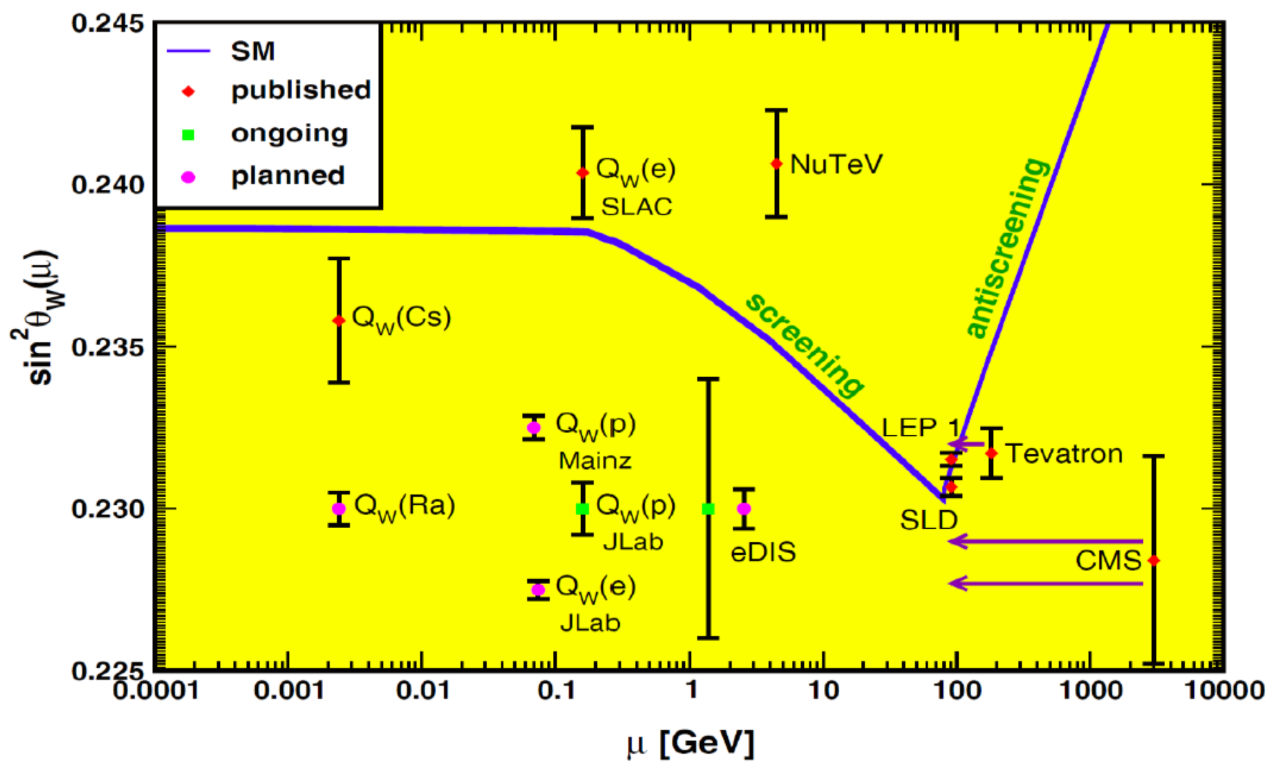
$$\sin^2(\hat{\theta}_W) = 0.2403 \pm 0.0013 \text{ in } \overline{MS}$$

The MOLLER experiment, planned at JLab following the 11 GeV upgrade, aims to measure the parity-violating asymmetry in the scattering of longitudinally polarized electrons off an unpolarized hydrogen target.

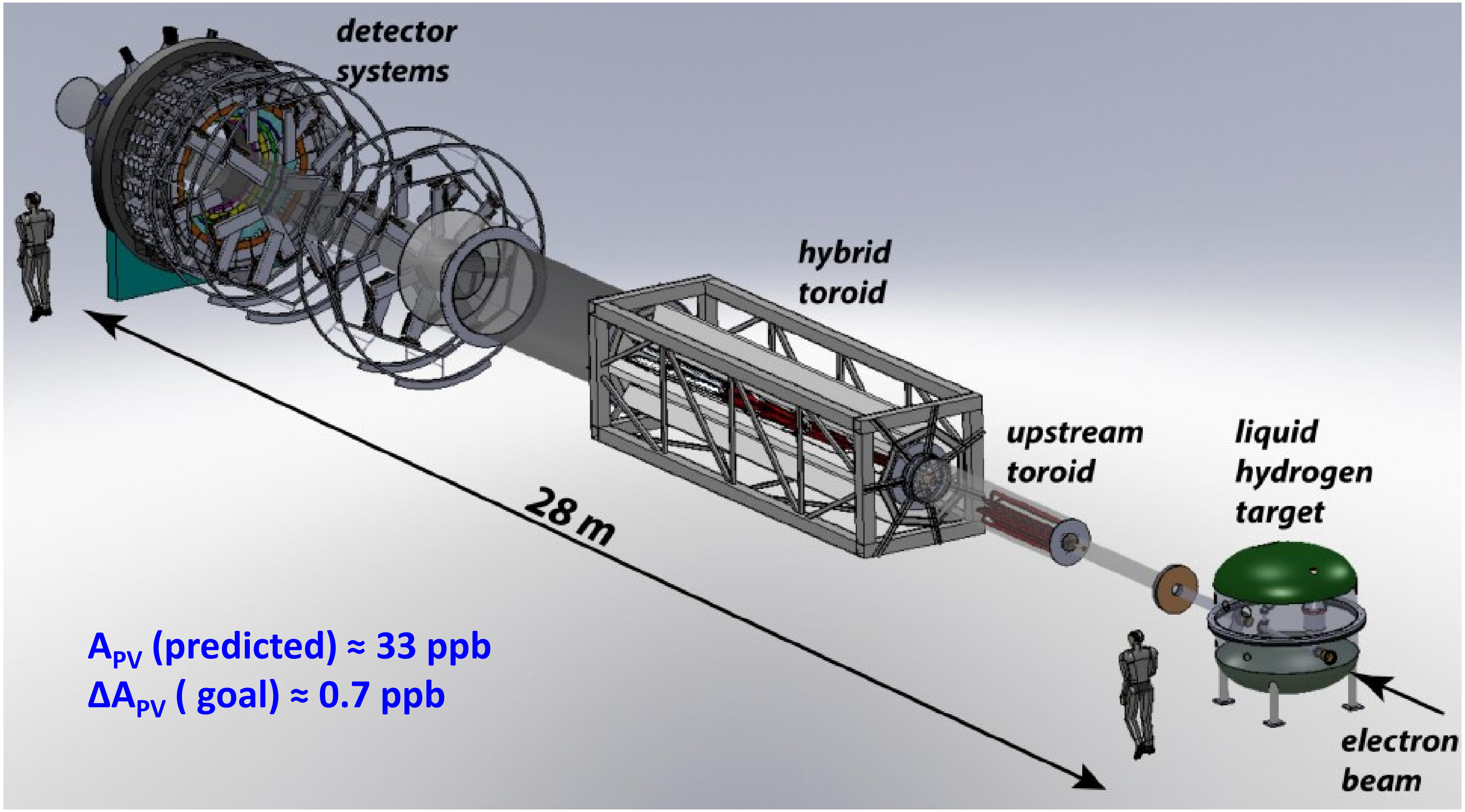
The MOLLER will allow a determination of the weak mixing angle with an uncertainty of about 0.1%, **a factor of five improvement** in fractional precision over the measurement by E-158.

At such precision, any inconsistency with the Standard Model predictions will clearly signal **new physics**.





The MOLLER Experiment (Measurement Of a Lepton Lepton Electroweak Reaction)



A_{PV} (predicted) ≈ 33 ppb
ΔA_{PV} (goal) ≈ 0.7 ppb

DOE MOLLER Proposal, March 2014. See Michael Gericke talk at IPP General Meeting, 16/06/2014

The MOLLER group needs more people!

The Current Canadian Group

University of Manitoba: Jim Birchall, Michael Gericke, Juliette Mammei, Shelley Page, Willem van Oers

University of Winnipeg: Jeff Martin, Russel Mammei

University of Northern British Columbia: Elie Korkmaz

Acadia University: Svetlana Barkanova

Memorial University: Aleksandrs Aleksejevs

We would welcome more collaborators !

Contributions could be made in:

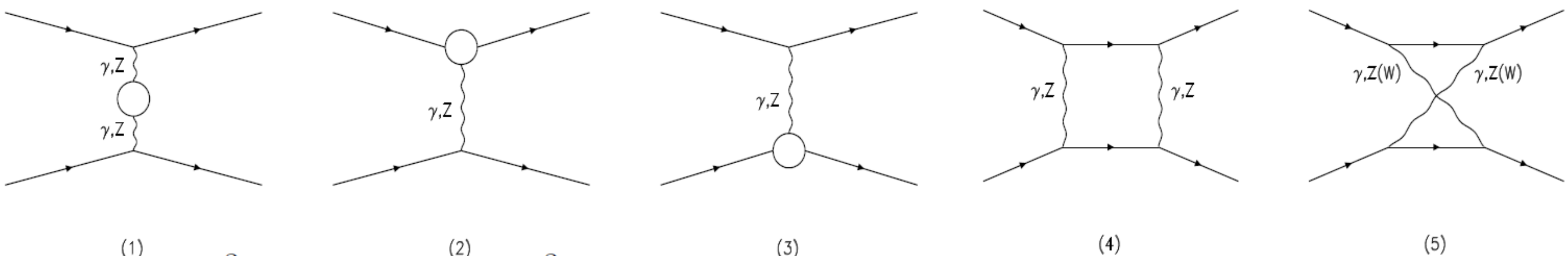
- **Detector Design / contruction**
- **Tracking**
- **Simulations**

Michael Gericke, IPP General Meeting, 16/06/2014

MOLLER Theory Input:

At certain kinematic conditions, NLO EWC can reduce the asymmetry up to 70%, and they strongly depend on the experimental cuts.

Obviously, before we can interpret the high-precision scattering experiments in terms of possible new physics, it is crucial to have the SM electroweak radiative corrections under a very firm control.

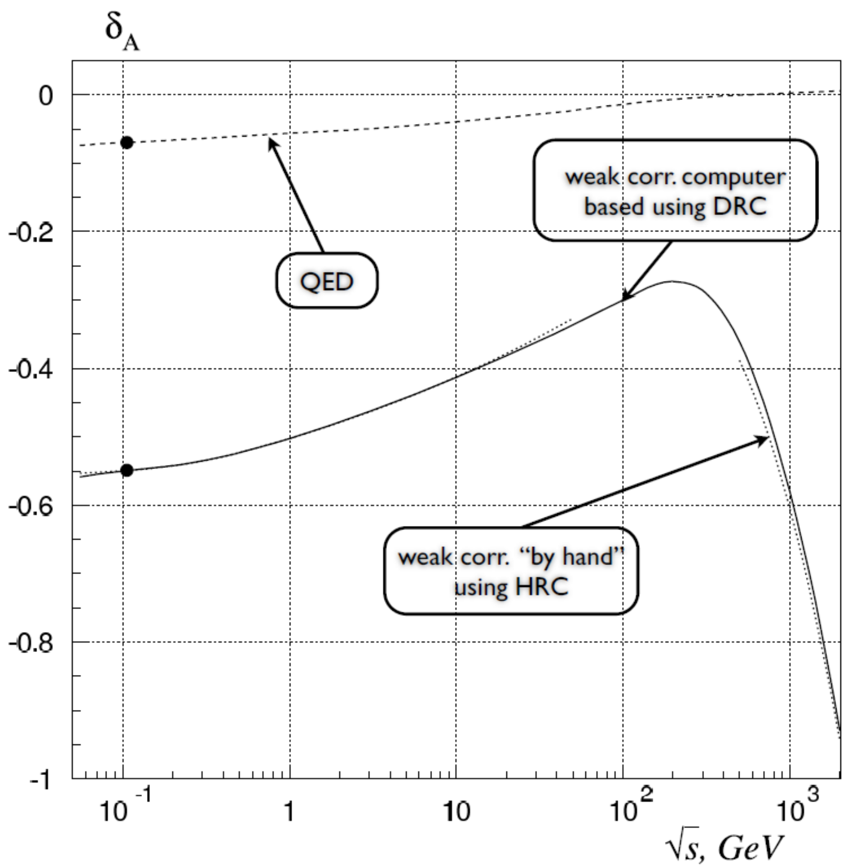


$$\sigma = \frac{\pi^3}{2s}|M_0 + M_1|^2 = \frac{\pi^3}{2s}(\underbrace{M_0 M_0^+}_{\propto\,\alpha^2} + \underbrace{2\mathrm{Re}M_1 M_0^+}_{\propto\,\alpha^3} + \underbrace{M_1 M_1^+}_{\propto\,\alpha^4}) = \sigma_0 + \sigma_1 + \sigma_Q$$

$$\sigma_1 = \sigma_1^{BSE} + \sigma_1^{Ver} + \sigma_1^{Box}$$

To make sure that everything is correct for one loop (NLO), we compare two approaches:

"by hand" and computer-based; with on-shell renormalization and using two different renormalization conditions (RC), by Denner and Hollik.



We define the relative corrections to the Born asymmetry as

$$\delta_A^C = \frac{A_{LR}^C - A_{LR}^0}{A_{LR}^0}$$

The relative weak (solid line in DRC (semi-automated) and dotted line in HRC ("by hand")) and QED (dashed line) corrections to the Born asymmetry A^0_{LR} versus √s at θ = 90°. The filled circle corresponds to our predictions for the MOLLER experiment.

DRC and HRC stand for Denner and Hollik renormalization conditions, respectively.

The Next-to-Next-to-Leading Order (NNLO) EWC to the Born ($\sim M_0 M_0^+$) cross section can be divided into two classes:

- Q-part induced by quadratic one-loop amplitudes $\sim M_1 M_1^+$, and
- T-part – the interference of Born and two-loop diagrams $\sim 2ReM_0M_{2\text{-}loop}^+$.

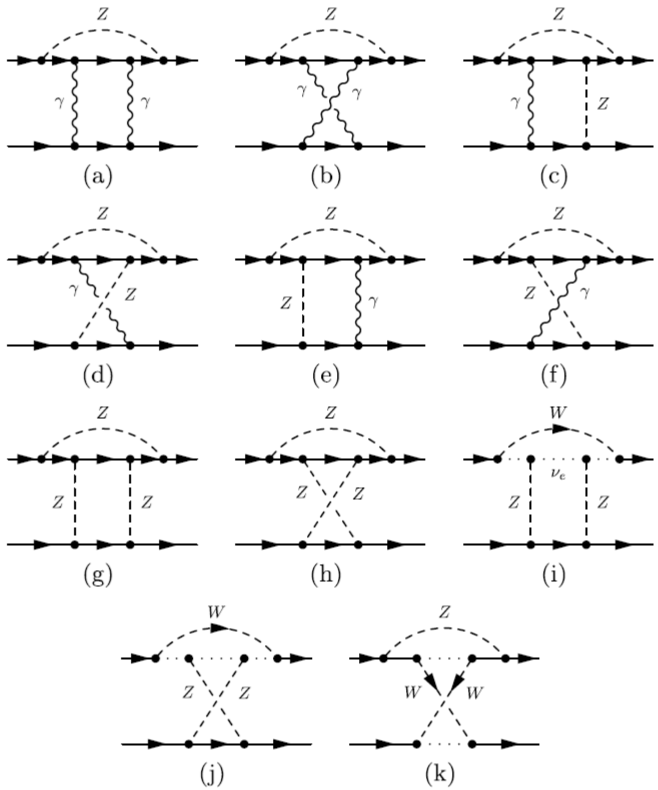
$$\sigma = \frac{\pi^3}{2s}|M_0 + M_1|^2 = \frac{\pi^3}{2s}(\underbrace{M_0 M_0^+}_{\propto\,\alpha^2} + \underbrace{2\mathrm{Re} M_1 M_0^+}_{\propto\,\alpha^3} + \underbrace{M_1 M_1^+}_{\propto\,\alpha^4}) = \sigma_0 + \sigma_1 + \sigma_Q$$

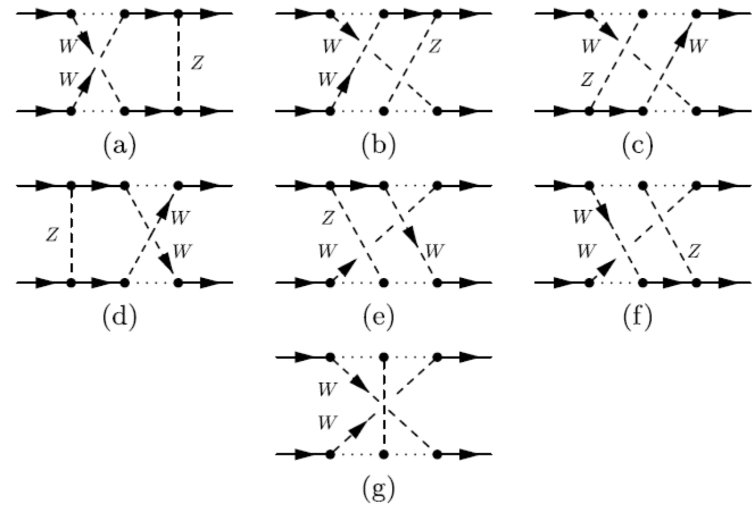
$$\sigma_T = \frac{\pi^3}{s}\ \mathrm{Re} M_2 M_0^+ \propto \alpha^4$$

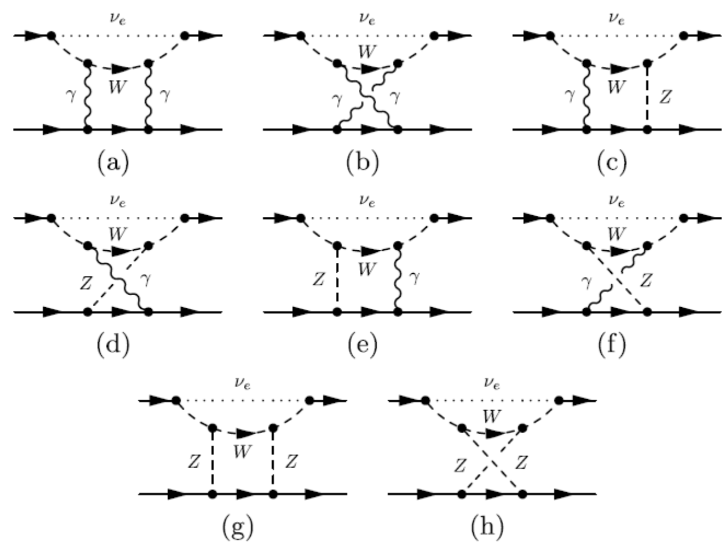
At the MOLLER kinematic conditions, quadratic one-loop term can increase the asymmetry up to ~ 4%. Work on the two-loop corrections is ongoing.

A. Aleksejevs et al., Phys. Rev. D 85, 013007, arXiv:1110.1750

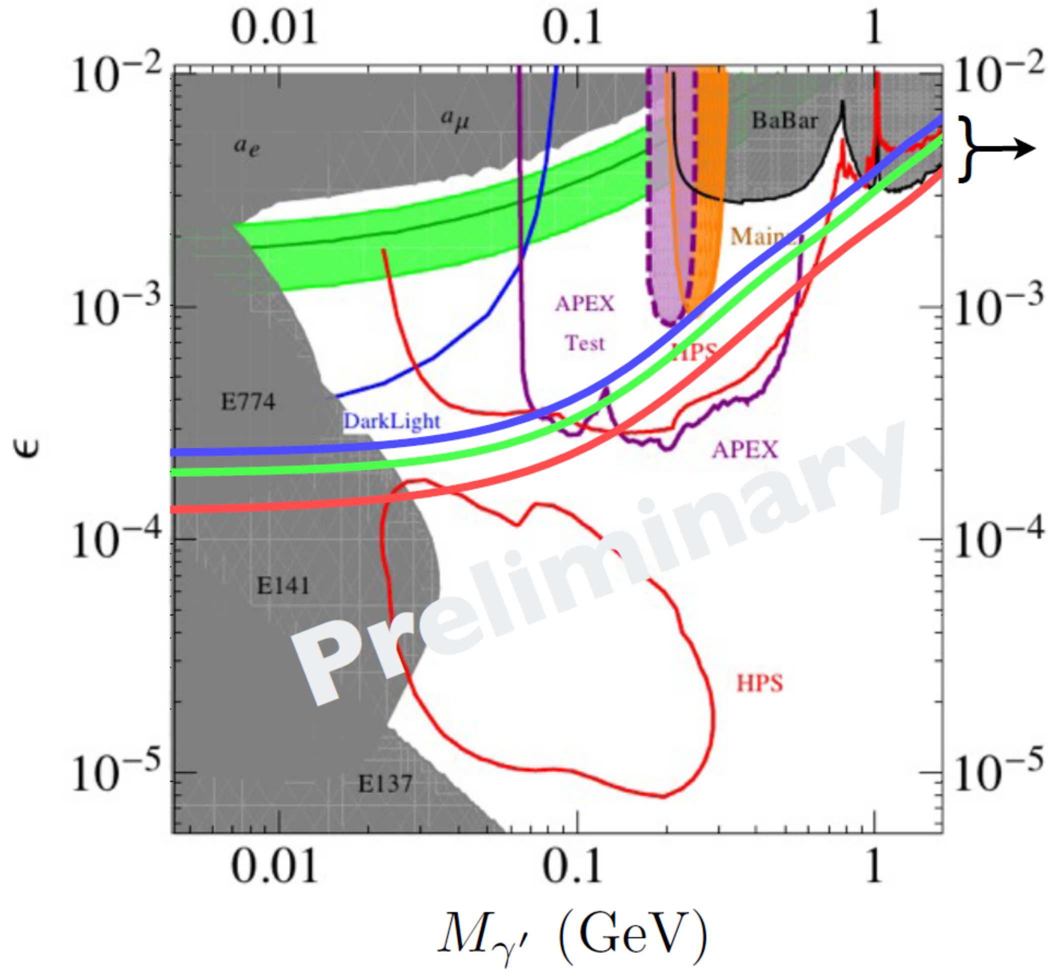
Example of the two-loop contributions – double boxes:







A. Aleksejevs et al., Eur. Phys. J. C (2012) 72:2249



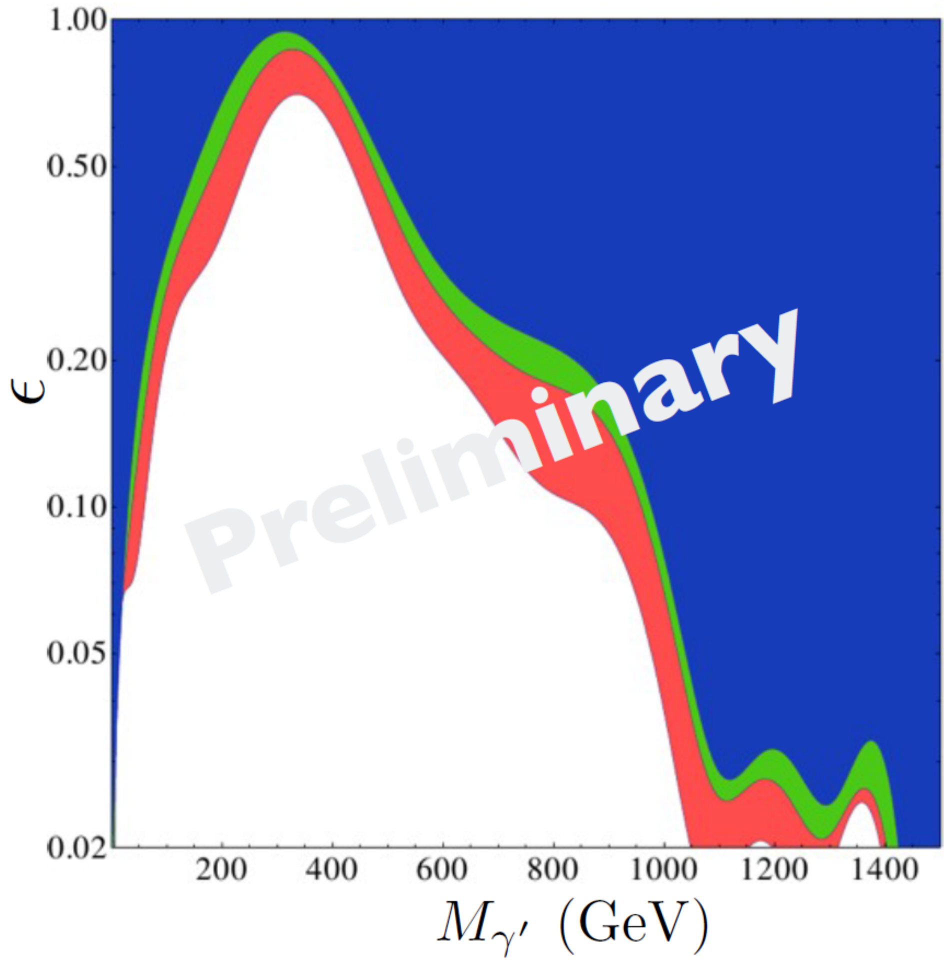
MOLLER (1%, 2%, 3%)
A. Aleksejevs, S. Barkanova and W. Shihao

The mixing of the new U(1) and $U(1)_Y$ of the Standard Model is induced by loops of heavy particles coupling to both fields.

We assume minimal coupling for $X\mu$ to all charged Standard Model fermions ψ, with effective charge $e_\psi \equiv e$, and e_ψ being the fermionic charge under $U(1)_{QED}$.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\epsilon}{2}X_{\mu\nu}F^{\mu\nu} + \underline{e_\psi \epsilon \bar{\psi}\gamma_\mu \psi X^\mu} + \frac{m^2_{\gamma'}}{2}X_\mu X^\mu$$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$



MOLLER (1%, 2%, 3%)
A. Aleksejevs, S. Barkanova and W. Shihao

The mixing of the new U(1) and $U(1)_Y$ of the Standard Model is induced by loops of heavy particles coupling to both fields.

We assume minimal coupling for $X\mu$ to all charged Standard Model fermions ψ, with effective charge $e_\psi \equiv e$, and e_ψ being the fermionic charge under $U(1)_{QED}$.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\epsilon}{2}X_{\mu\nu}F^{\mu\nu} + \underline{e_\psi \epsilon \bar{\psi}\gamma_\mu \psi X^\mu} + \frac{m^2_{\gamma'}}{2}X_\mu X^\mu$$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$

Conclusions:

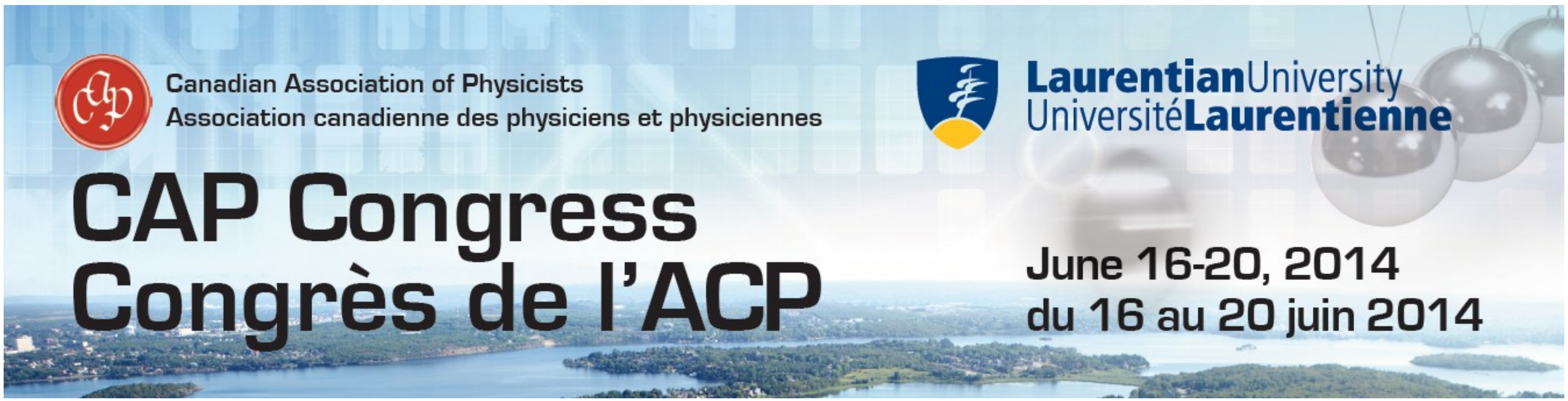
Although the Standard Model (SM) of Particle Physics has been enormously successful to date, we known it is incomplete. We look for new physics beyond SM at the energy frontier, the cosmic frontier, and the precision/intensity frontier.

High-precision parity-violating electroweak experiments can provide access to new physics at a wide range of energy scales, and many are currently running or planned.

The first subset of results from Qweak recently completed at JLab provides the smallest e-p asymmetry ever measured, making possible the first determination of the weak charge of the proton.

For PV processes, electroweak radiative corrections can be very large, so the SM prediction must be carried out with full treatment of one-loop corrections and at least leading two-loop corrections. Incorporating new physics particles into NLO predictions for the asymmetry is in progress.

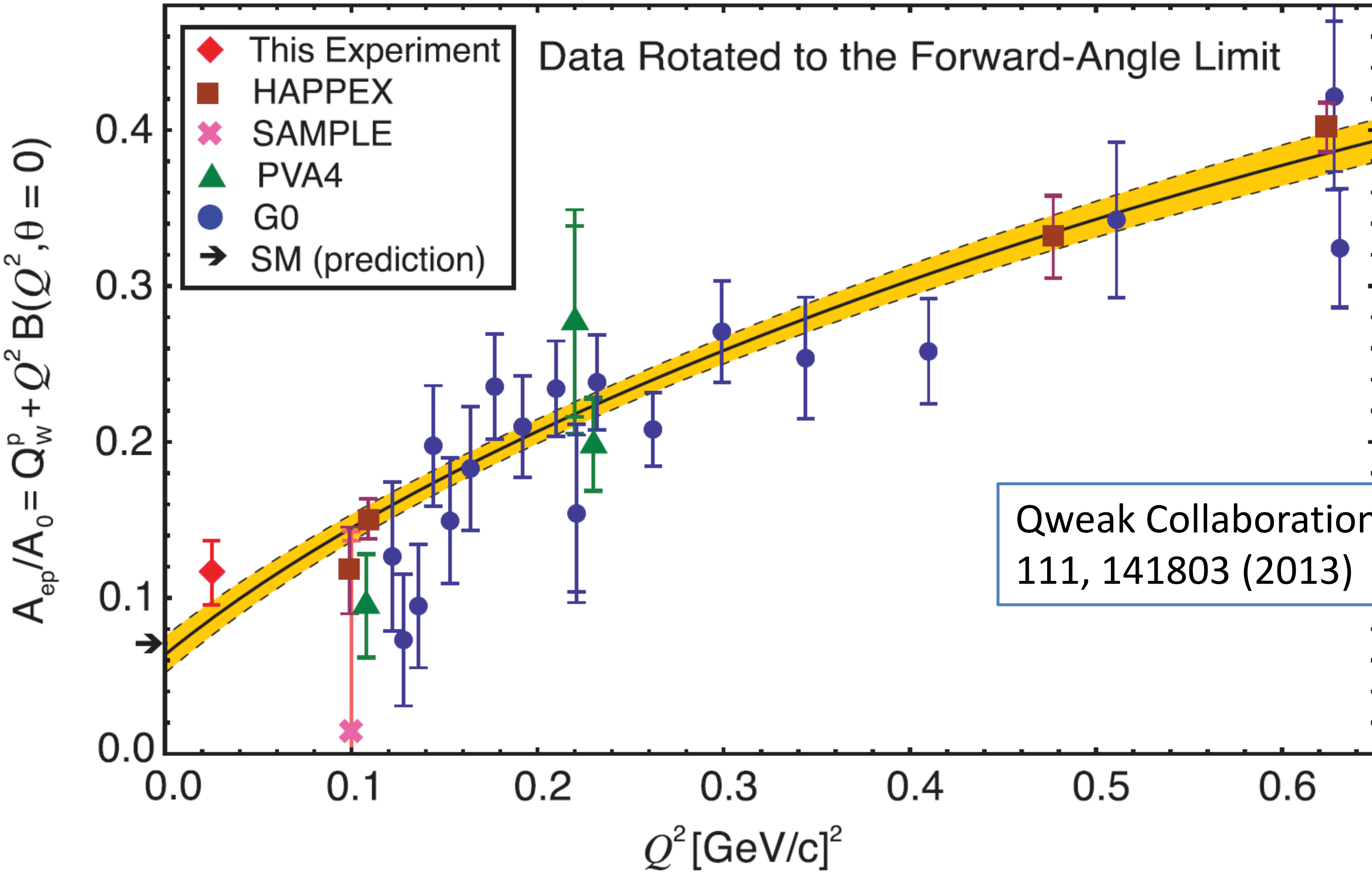
THANK YOU!



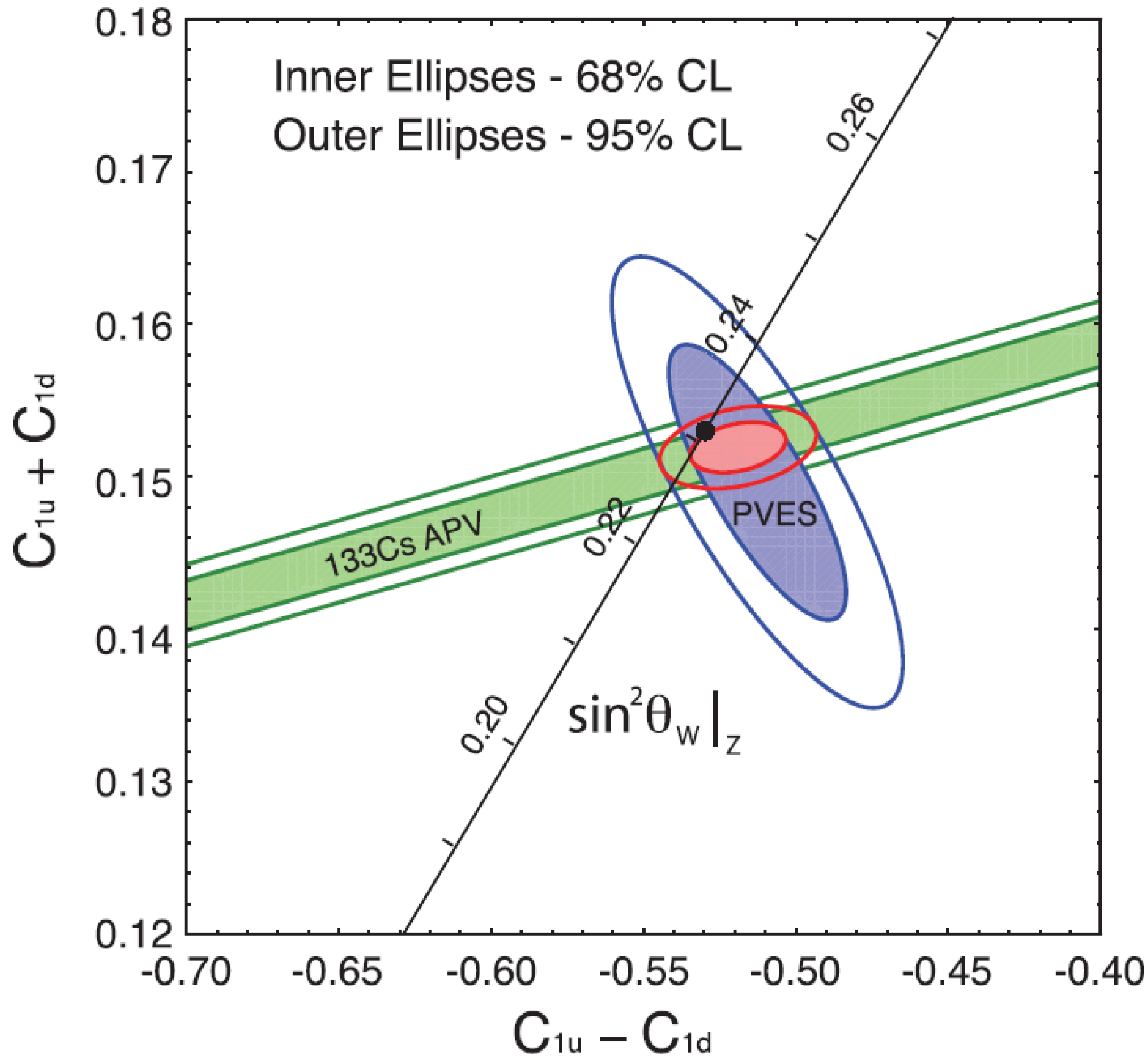
Many thanks to JLab for hospitality, and to the members of Qweak and MOLLER collaborations for explaining their experiments.

This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

Extra Slides



Qweak Collaboration, PRL 111, 141803 (2013)



Qweak Collaboration, PRL 111, 141803 (2013)