Electroweak Physics

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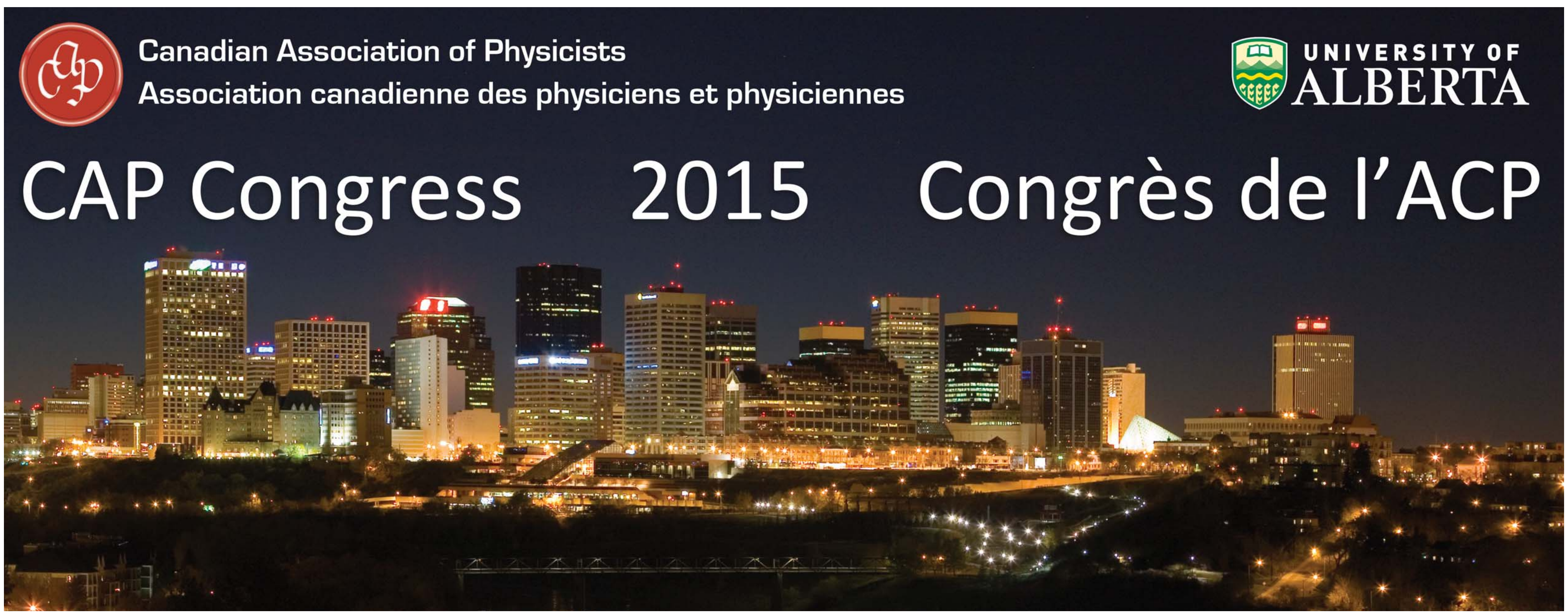

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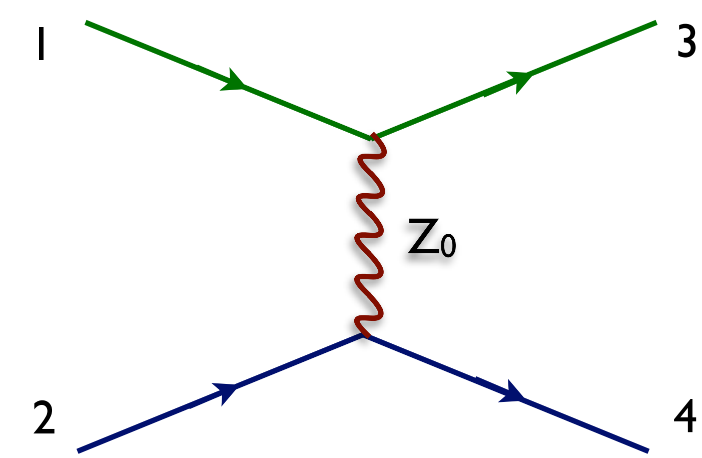
Precision Scattering

- Many theories predict new particles, which disappeared at the time when the universe cooled.
- New physics particles are now present indirectly as interaction carriers and can be probed through precision measurements at low momentum transfer.
- To access the scale of the new physics at TeV level, we need to push one or more experimental parameters to the extreme precision.
- Low-Q^2 neutral-current interaction becomes sensitive to the TeV scale if:
    - *$\delta(\sin^2\theta_W) \leq 0.5\%$*
    - *away from the Z resonance*



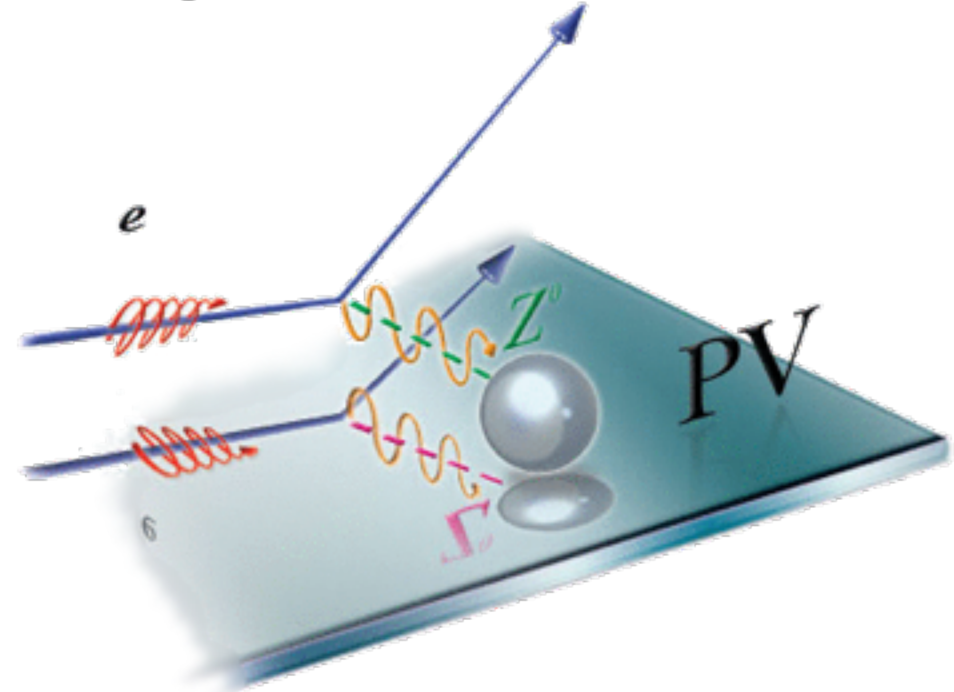
- Precision Neutrino Scattering
- New Physics/Weak-Electromagnetic Interference
    - *opposite parity transitions in heavy atoms*
    - *parity-violating electron scattering*

Weak interaction provides indirect access to the new physics via interference terms between neutral weak and new physics amplitudes.

Precision Scattering: Qweak

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):

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

Precision Scattering: Qweak

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 tree level:

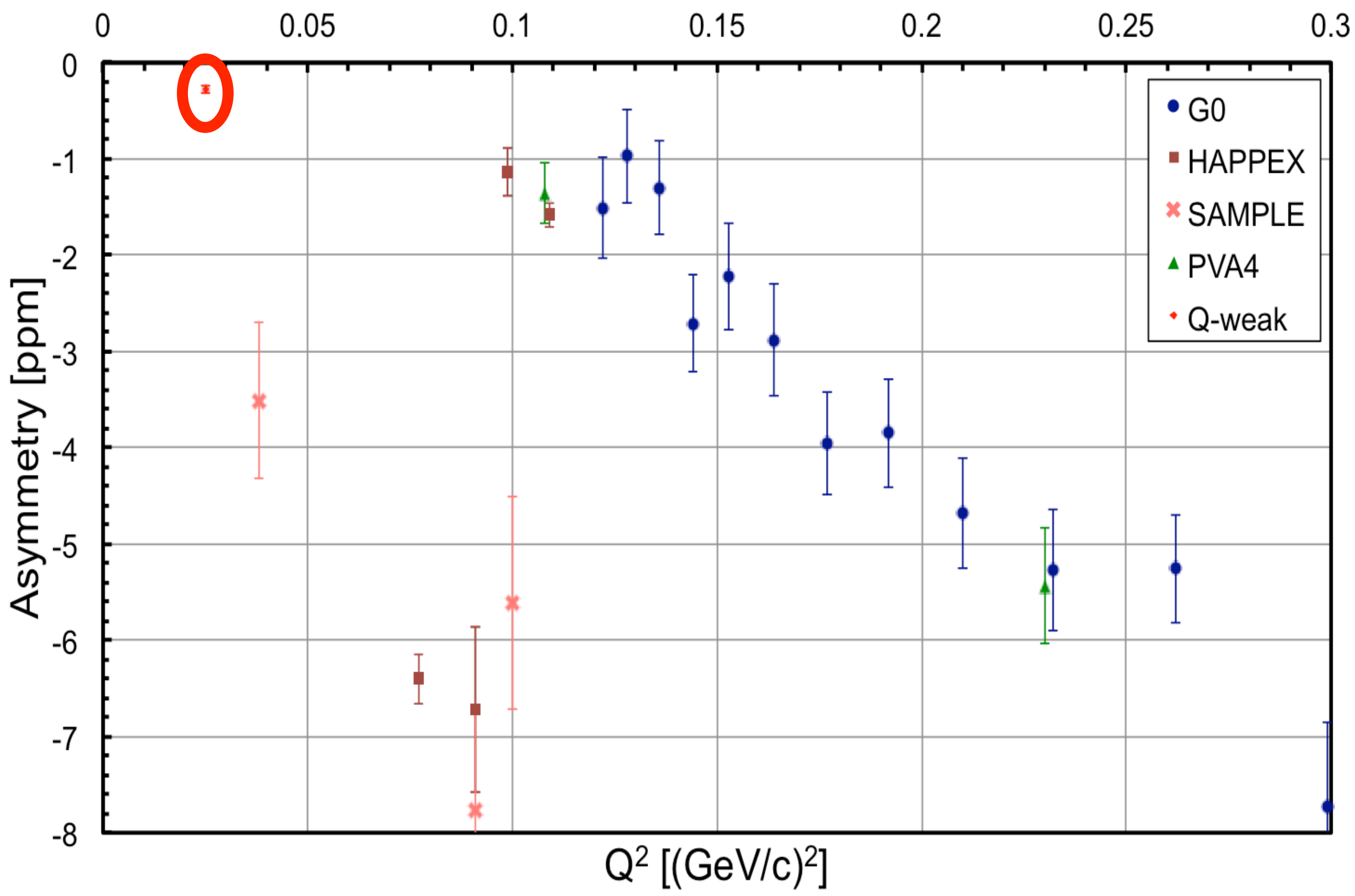
$$Q^p_W(\mathrm{SM}) = -2(2C_{1u} + C_{1d})$$

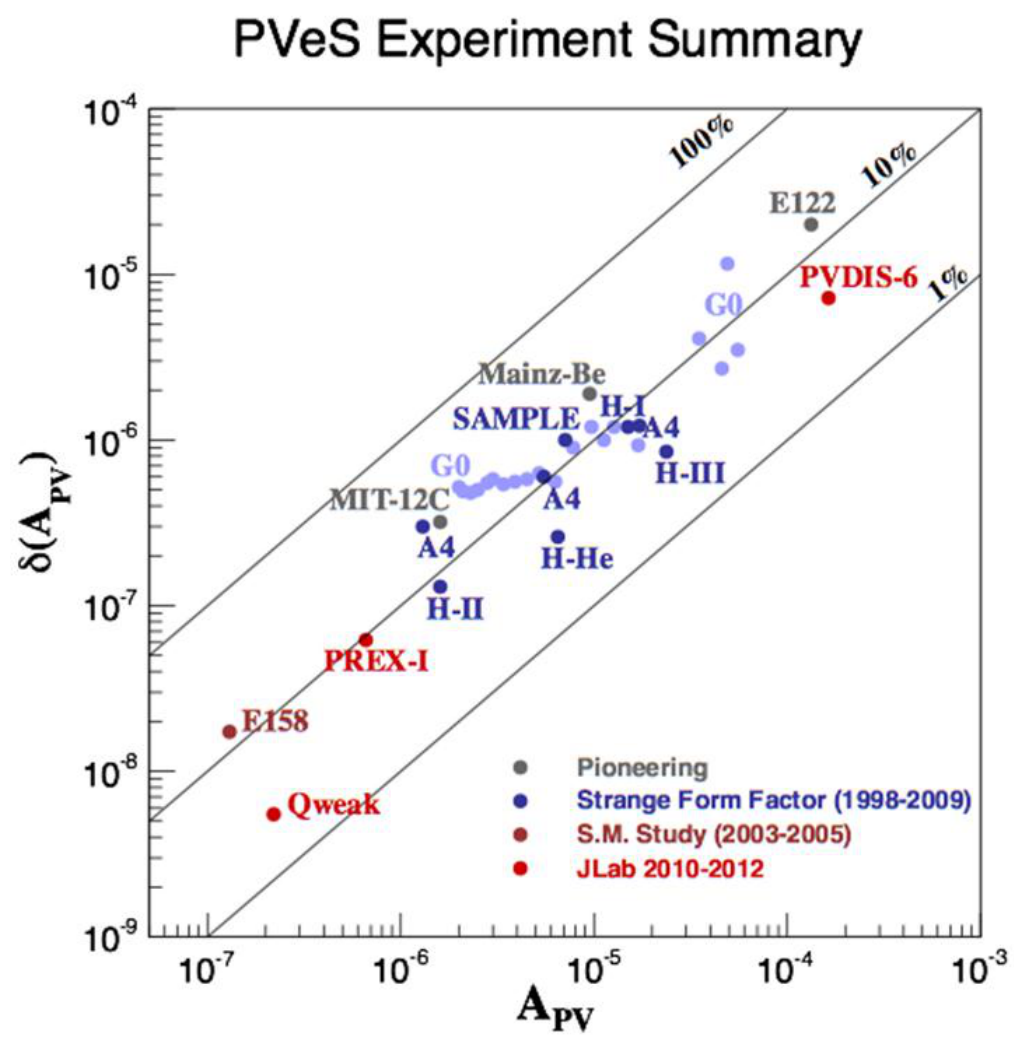
A precise measurement of $Q_W(p)$ would thus test new physics scales up to TeV scales:

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

Precision Scattering: Qweak

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





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

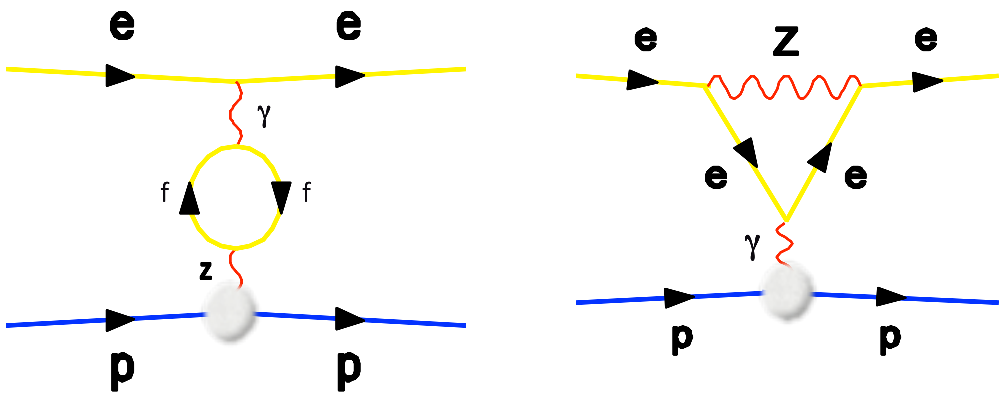
$$A_{\vec{e}p}(< Q^2 >_{\rm eff}) = -0.279 \pm 0.035\ ({\rm stat.})\ \pm 0.031\ ({\rm syst.})\ {\rm ppm}$$

Qweak Collaboration: PRL 111, 141803 (2013)

Precision Scattering: Qweak

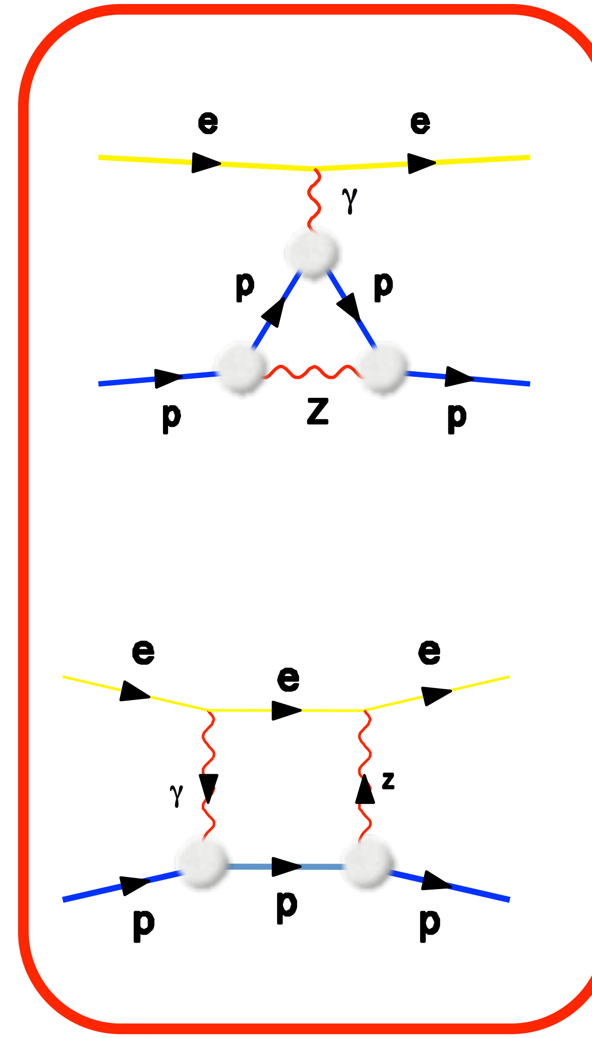
Theory Input: Hadronic Corrections and Total Asymmetry

Model Independent



$$A \propto \frac{\mathrm{Re}\left(M'^{0}_{\gamma}\,(M'^{0*}_{Z} + M'^{(1)*}_{Z})\right)_{\pm}\cancel{\left(\frac{\Lambda^2}{\Lambda^2-q^2}\right)^2}}{\left|M'^{0}_{\gamma}\right|^2\cancel{\left(\frac{\Lambda^2}{\Lambda^2-q^2}\right)^2}}$$

Model Dependent

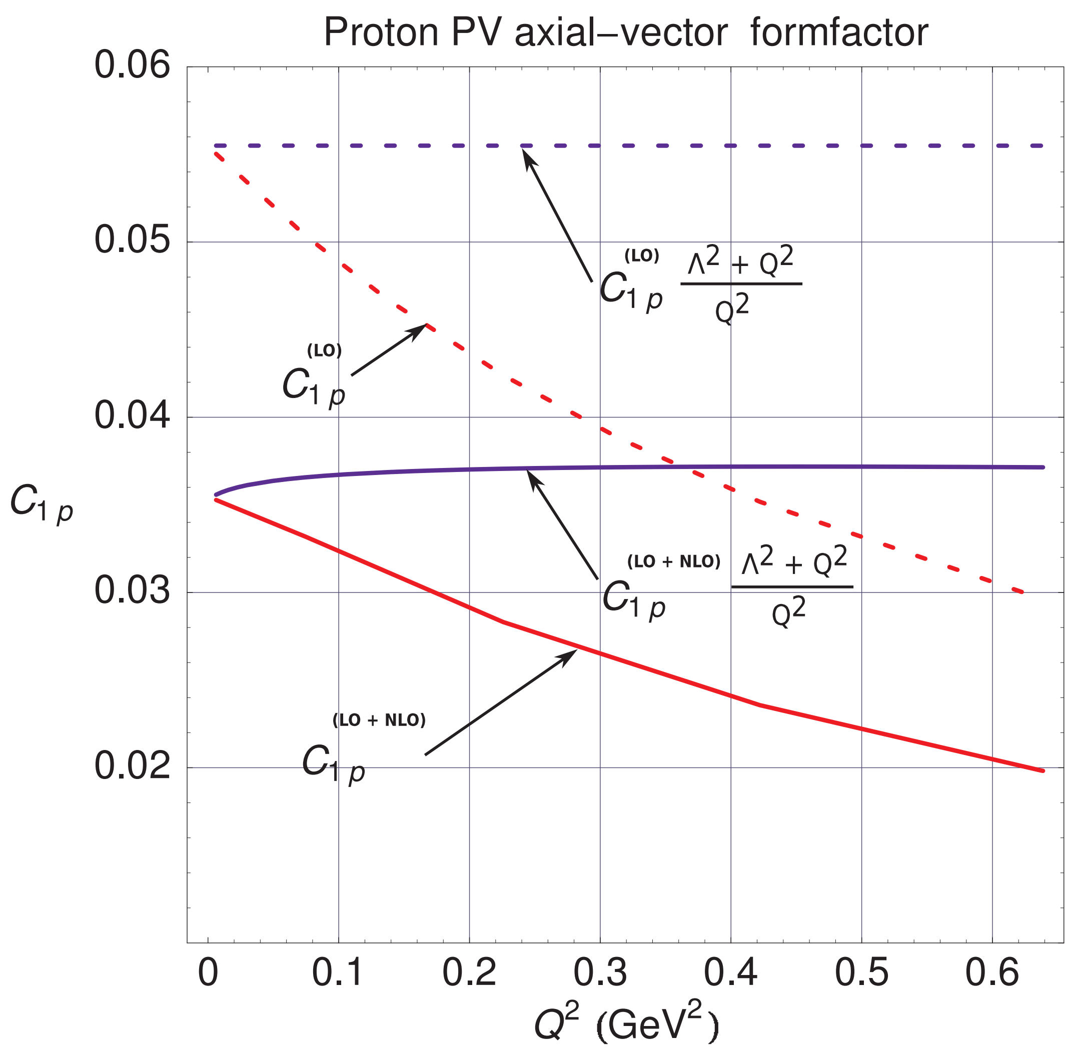


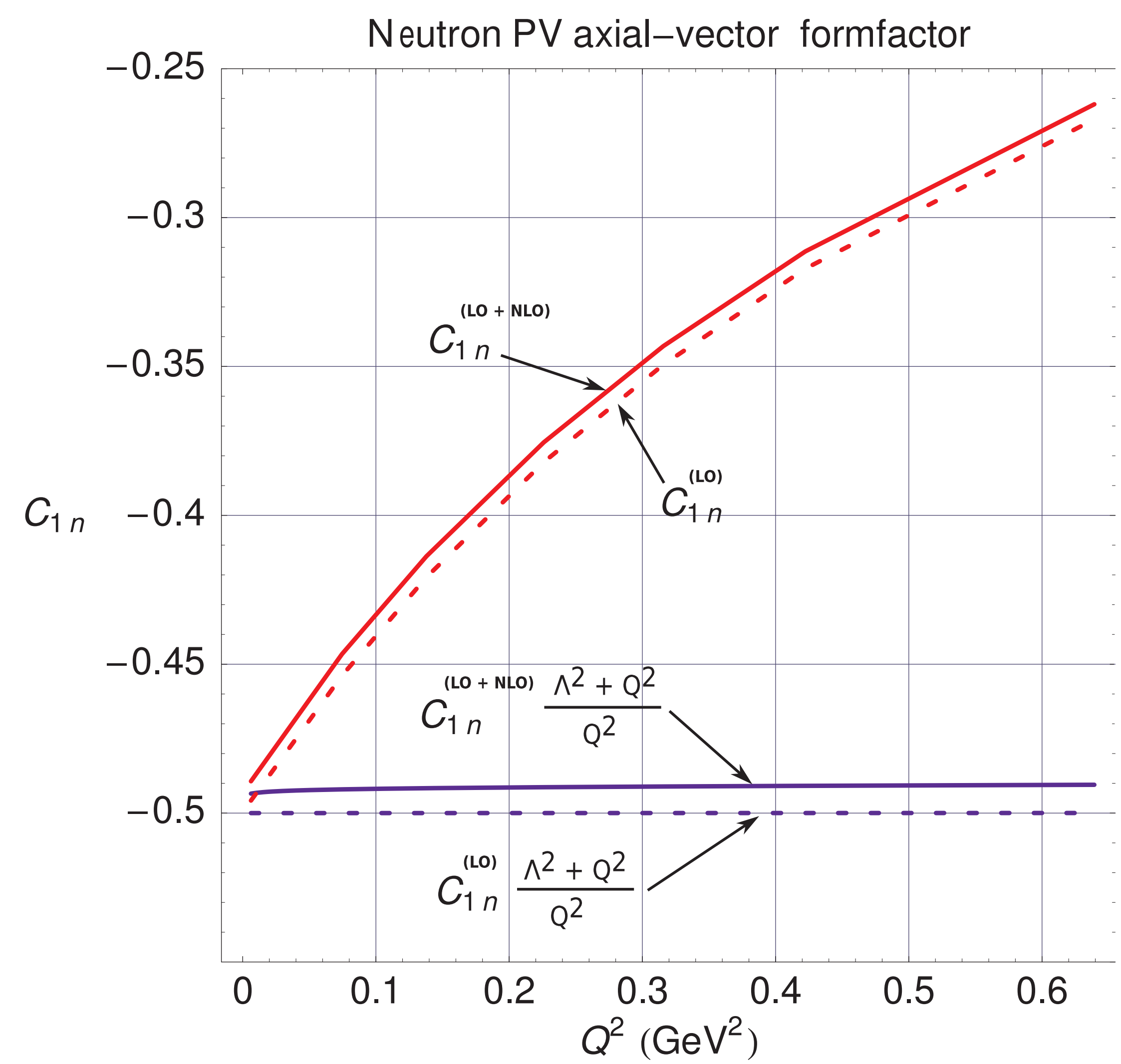
Using hadronic uncertainty analyzes for γZ box from M. Gorchtein, Phys. Rev. Lett. 102, 091806 (2009) and A. Sibirtsev et. al., arXiv:1002.0740 [hep-ph], and applying full set of on-shell NLO contributions, we get following PV electron-proton asymmetry:

$A_{PV}^{(Th)}$ = - 0.233 ± 0.007 (ppm)
$A_{PV}^{(Exp)}$ = - 0.279 ± 0.035 (stat.) ± 0.031 (syst.) (ppm)

Precision Scattering: Qweak

$$H^{PV} = \frac{G_F}{\sqrt{2}}[C_{1N}(\bar{u}_e\gamma_\mu\gamma_5 u_e)(\bar{u}_N\gamma^\mu u_N) + C_{2N}(\bar{u}_e\gamma_\mu u_e)(\bar{u}_N\gamma^\mu\gamma_5 u_N)]$$





$$Q^p_{weak} = 2C_{1p}\left(Q^2 \to 0\, GeV^2\right)$$

$$Q^n_{weak} = 2C_{1n}\left(Q^2 \to 0\, GeV^2\right)$$

$$Q^{p(Th)}_{weak} = 2C_{1p} = 0.0720 \pm 0.0010$$

$$Q^{n(Th)}_{weak} = 2C_{1n} = -0.990 \pm 0.005$$

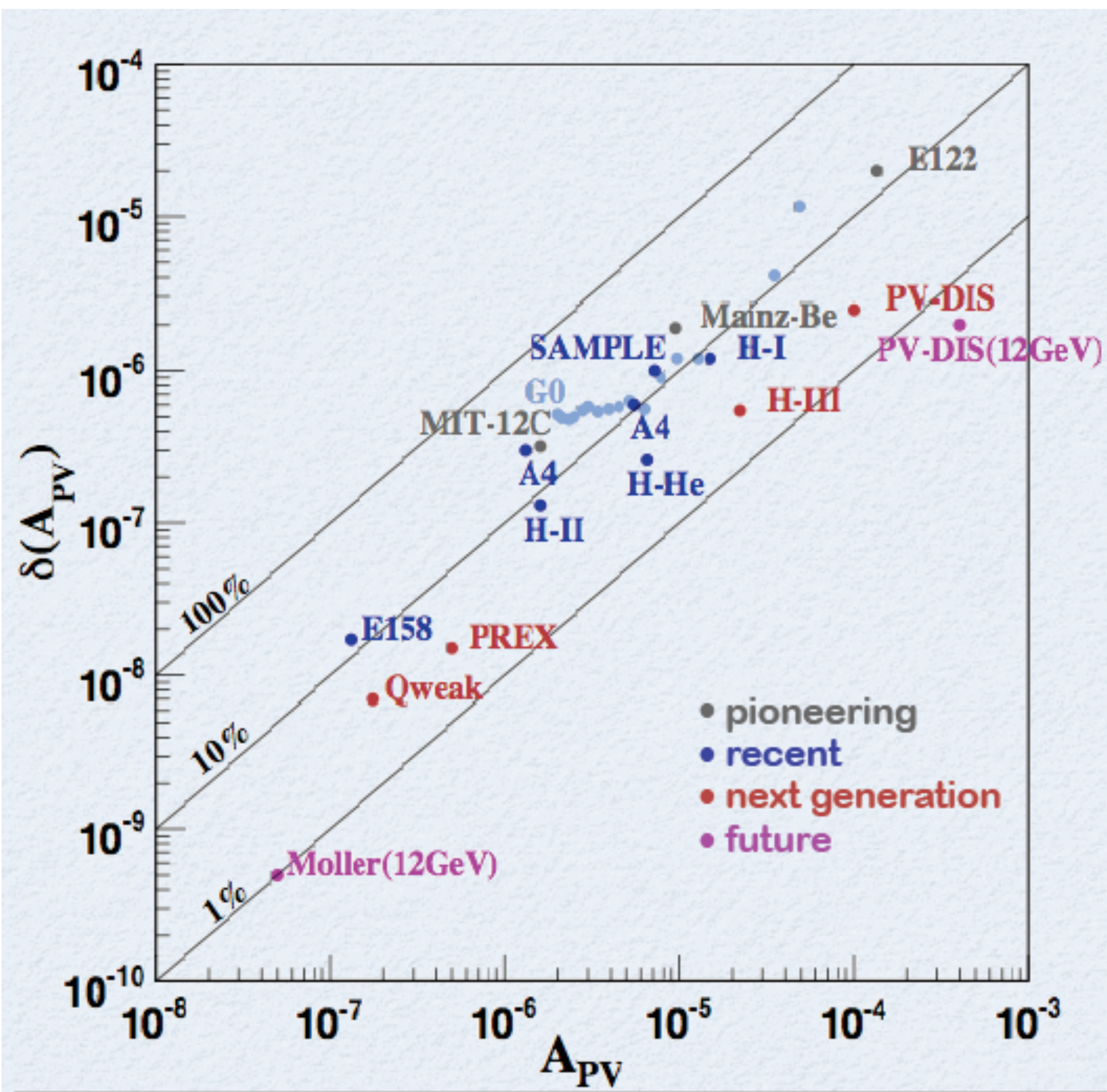
$$Q^{p(Exp)}_{weak} = 2C_{1p} = 0.064 \pm 0.012$$

$$Q^{n(Exp)}_{weak} = 2C_{1n} = -0.975 \pm 0.010$$

Precision Scattering: MOLLER

Asymmetry is an observable which is directly related to the interference term:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \simeq \frac{2Re(M_\gamma M_Z^+ + M_\gamma M_{NP}^+ + M_Z M_{NP}^+)_{LR}}{\sigma_L + \sigma_R} \sim (10^{-5}\ to\ 10^{-4}) \cdot Q^2$$



To access multi-TeV electron scale it is required to measure:

$$\delta(\sin^2\theta_W) < 0.002$$

MOLLER experiment offers an unique opportunity to reach multi-TeV scale and will become complimentary to the LHC direct searches of the new physics.

Precision Scattering: MOLLER

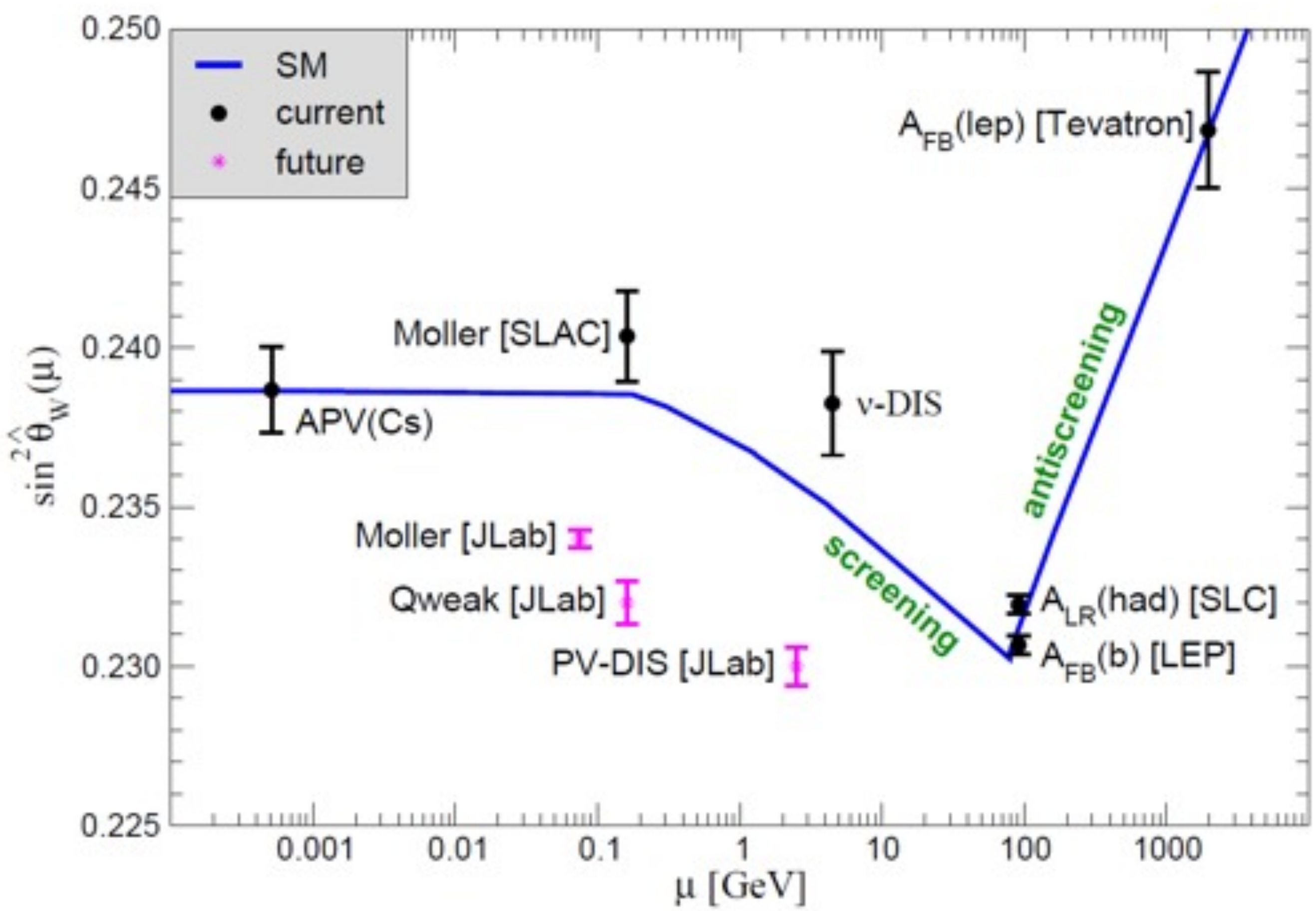
The first observation of Parity Violation in Møller scattering was made by E-158 experiment at SLAC:

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

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

MOLLER, planned at JLab following the 11 GeV upgrade, will offer a new level of sensitivity and measure the parity-violating asymmetry in the scattering of longitudinally polarized electrons off unpolarized target to a precision of 0.73 ppb.

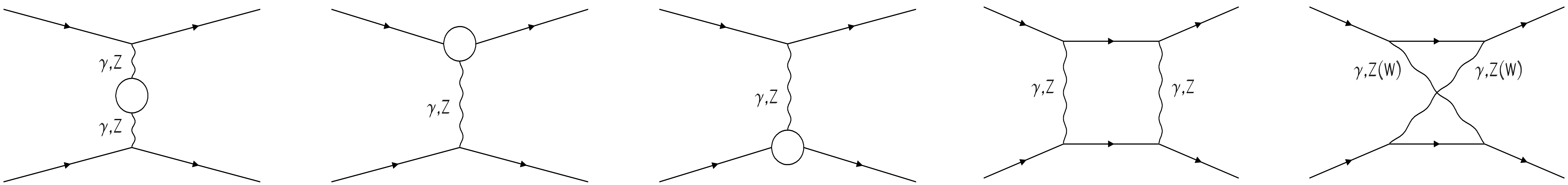
That would allow a determination of the weak mixing angle with an uncertainty of about 0.1%, a factor of five improvement in fractional precision over the measurement by E-158.



J. Benesch et al., MOLLER Proposal to PAC34, 2008

Precision Scattering: MOLLER

Theory Input: NLO and NNLO corrections



(1) (2) (3) (4) (5)

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

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

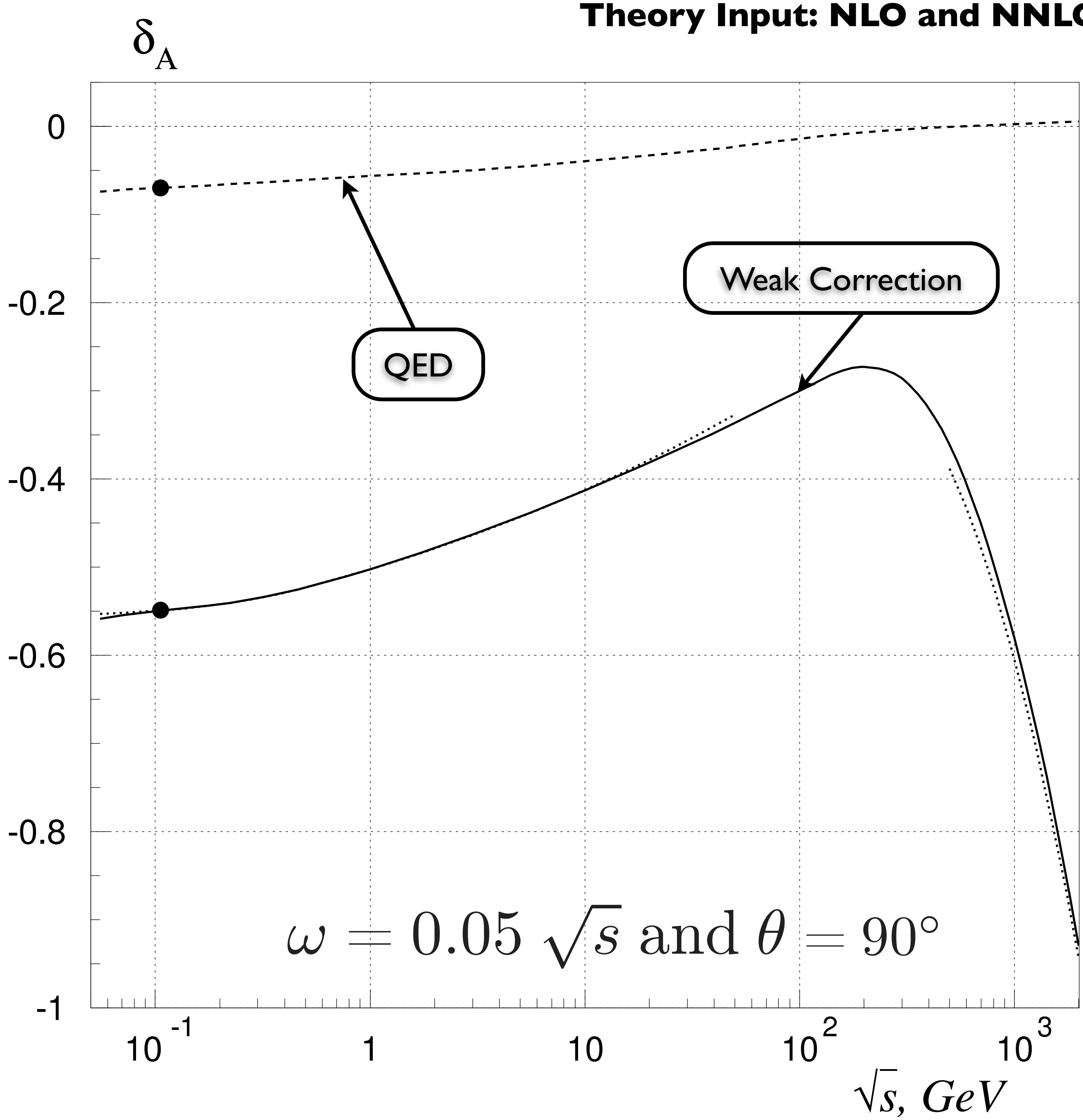
- Calculated in the on-shell renormalization, using both:
  - Computer-based approach, with Feynarts, FormCalc, LoopTools and Form

  T. Hahn, Comput. Phys. Commun. 140 418 (2001);
  T. Hahn, M. Perez-Victoria, Comput. Phys. Commun. 118, 153 (1999);
  J. Vermaseren, (2000) [arXiv:math-ph/0010025]

  - "By hand", with approximations in small energy region $\frac{\{t,u\}}{m_{Z,W}^2} \ll 1$, for $\sqrt{s} \ll 30\ GeV$ and high energy approximation for $\sqrt{s} \gg 500\ GeV$

Precision Scattering: MOLLER

Theory Input: NLO and NNLO corrections



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

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 $\sqrt{s}$ at $\theta = 90^\circ$.

The filled circle corresponds to our predictions for the MOLLER experiment.

Precision Scattering: MOLLER

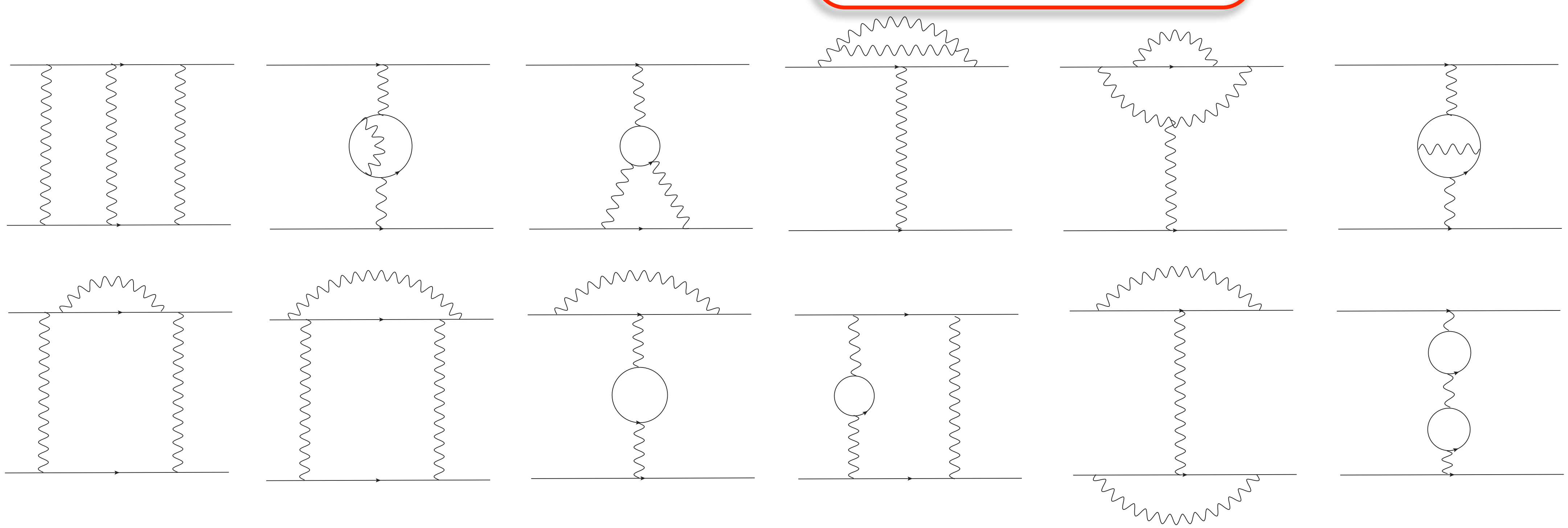
Theory Input: NLO and NNLO corrections

The Next-to-Next-to-Leading Order (NNLO) EWC to the Born (~ $M_0M_0^+$) cross section can be divided into two classes:

- Q-part induced by quadratic one-loop amplitudes ~ $M_1M_1^+$, and
- T-part – the interference of Born and two-loop diagrams ~ $2\mathrm{Re}M_0M_{2\text{-loop}}^+$.

$$\sigma = \frac{\pi^3}{2s}|M_0 + M_1|^2 = \frac{\pi^3}{2s}(\underbrace{M_0M_0^+}_{\propto\,\alpha^2} + \underbrace{2\mathrm{Re}M_1M_0^+}_{\propto\,\alpha^3} + \underbrace{M_1M_1^+}_{\propto\,\alpha^4}) = \sigma_0 + \sigma_1 + \sigma_Q$$

$$\sigma_T = \frac{\pi^3}{s}\ \mathrm{Re}M_2M_0^+ \propto \alpha^4$$



\+ ...

Precision Scattering: MOLLER

Theory Input: NLO and NNLO corrections

For the orthogonal kinematics: $\theta = 90^\circ$

Type of contribution	δ_A^C	Published
NLO	-0.6953	PRD'10, YaF'12
...+Q+ BBSE +VVer+ VerBSE	-0.6420	PRD'12, YaF'13
...+ double boxes	-0.6534	EPJ'12
...+NNLO QED	-0.6500	
...+SE and Ver in boxes	-0.6504	YaF' 15
...+NNLO EW Ver	under way	

Correction to PV asymmetry:

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

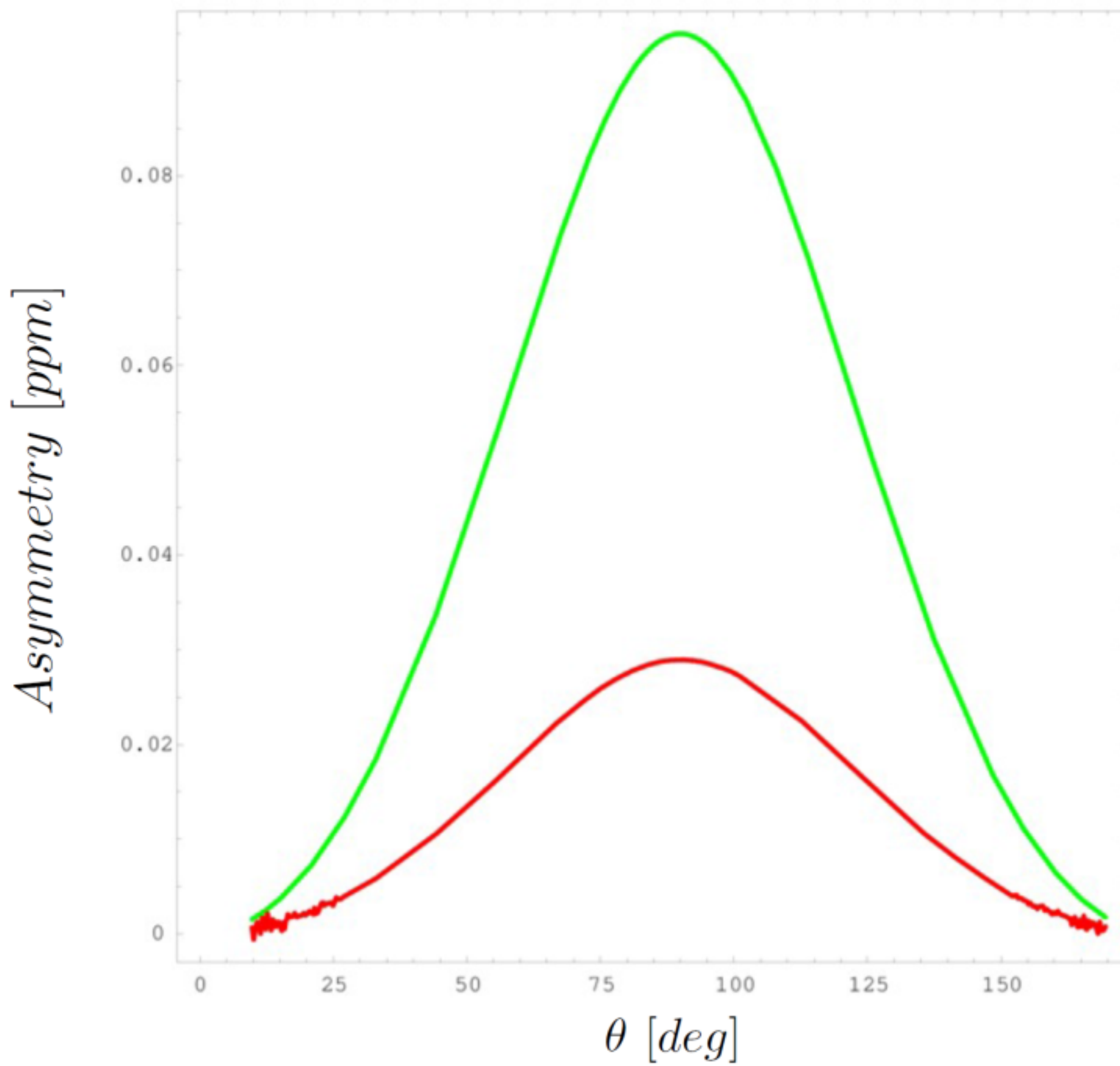
Soft-photon bremsstrahlung cut:

$$\omega = 0.05\sqrt{s}$$

"..." means all contributions from the lines above

Precision Scattering: MOLLER

Theory Input: NLO and NNLO corrections



Predicted PV asymmetry up to NNLO:

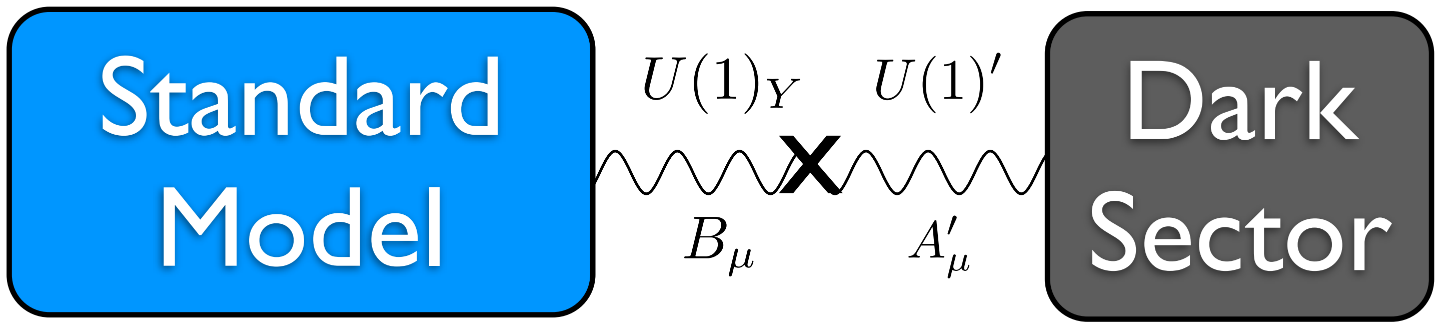
$A_{PV}^{(LO)} = 94.96$ (ppb)

$A_{PV}^{(LO+NLO+NNLO)} \simeq 33.2$ (ppb)

Precision Scattering: MOLLER

Theory Input: BSM Physics with Dark Vector

Consider a U(1)’ gauge symmetry which may interact with hidden sector particles:



The gauge boson kinetic term (QED example):

$$L^{QED}_{kin} = -\frac{1}{4} A_{\mu\nu} A^{\mu\nu} \qquad \text{(with } A_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu\text{)}$$

The A’ couples to SM particles through kinetic mixing of $U(1)_Y$ & U(1)’ [Holdom (1986)]:

$$L_{kin} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} \frac{\epsilon}{\cos\theta_W} B_{\mu\nu} A'^{\mu\nu} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu}$$

In general case A’ represents dark photon (parity-conserving) or Z’ (parity-violating) interaction carrier.

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$

Expected size of kinetic mixing from loops of heavy fermions: $\varepsilon \sim (g_Y\, g_{A'})/(16\pi^2) \lesssim 10^{-3}$

Precision Scattering: MOLLER

Theory Input: BSM Physics with Dark Vector

- Parity-conserving, dark vector boson (kinetic) mixing with photon produces:

Dark Photon

$$L_{int} = -eQ_f \epsilon \underline{\bar{f}\gamma_\mu f} \cdot (A^\mu + \underline{\epsilon A'^\mu}) - \frac{e}{\sin\theta_W \cos\theta_W} \bar{f}(c_V^f \gamma_\mu + c_A^f \gamma_\mu \gamma_5) f \cdot Z^\mu$$

- Parity violating, dark vector boson (mass) mixing with photon and Z boson produces:

Dark Z' Boson

H. Davoudiasl, et. al., arXiv:1203.2947v2, Phys. Rev. D 85, 115019 (2012).

$$L_{int} = -eQ_f \epsilon \underline{\bar{f}\gamma_\mu f} \cdot (A^\mu + \underline{\epsilon A'^\mu}) - \frac{e}{\sin\theta_W \cos\theta_W} \underline{\bar{f}(c_V^f \gamma_\mu + c_A^f \gamma_\mu \gamma_5) f} \cdot (Z^\mu + \underline{\epsilon_{Z'} A'_\mu})$$

$\epsilon_{Z'} = \delta \frac{m_{Z'}}{m_Z}$, where $\delta = 3 \cdot 10^{-5}$ is an arbitrary model-dependent parameter

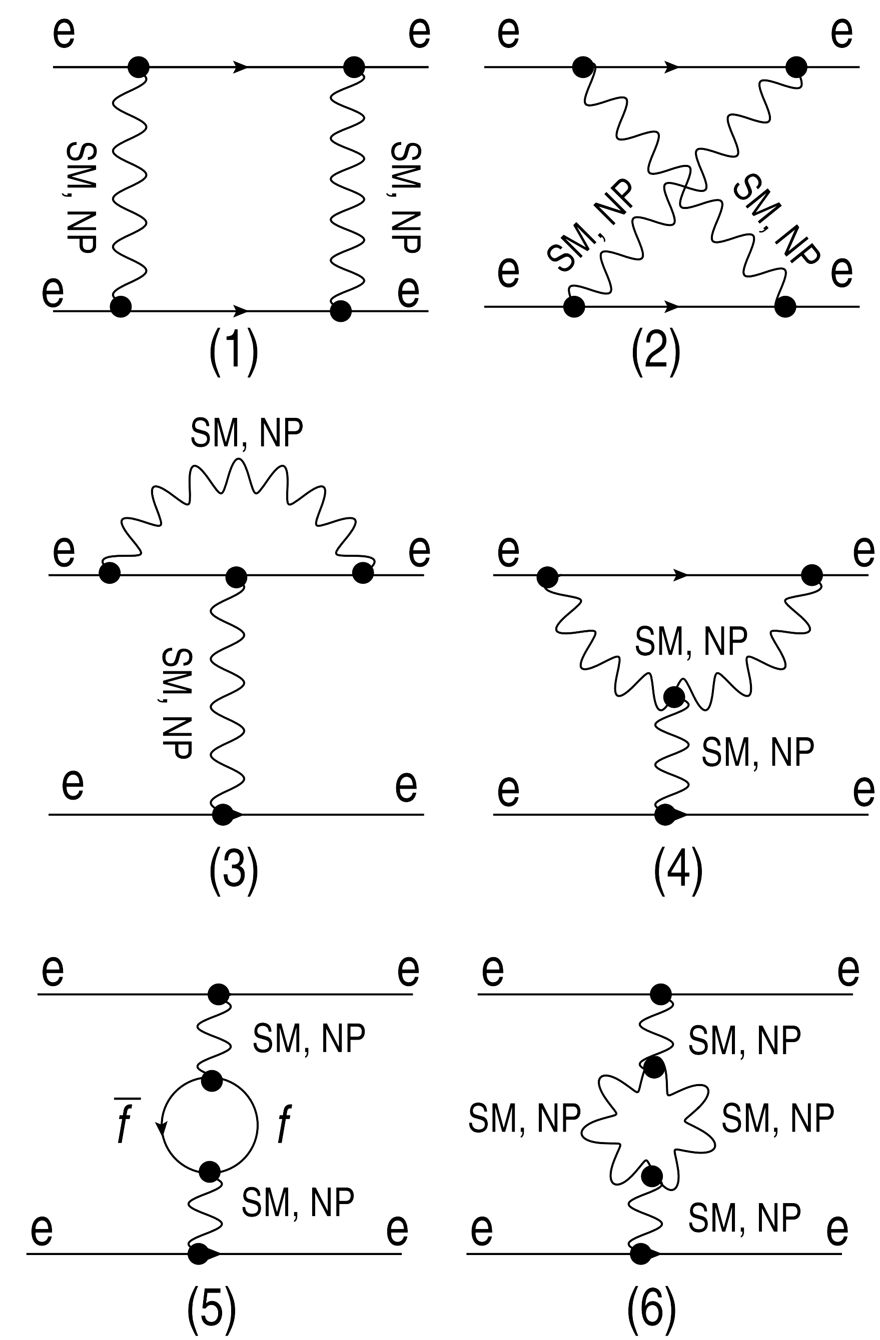
Precision Scattering: MOLLER

Theory Input: BSM Physics with Dark Vector

Calculation Strategy

- Complete the calculations of PV MOLLER asymmetries including one-loop (NLO) for the SM particles. This will define SM central value.
- Proceed with calculations of PV asymmetries with **new physics particles including one-loop** and construct exclusion plots for 1% deviations from the SM central values.

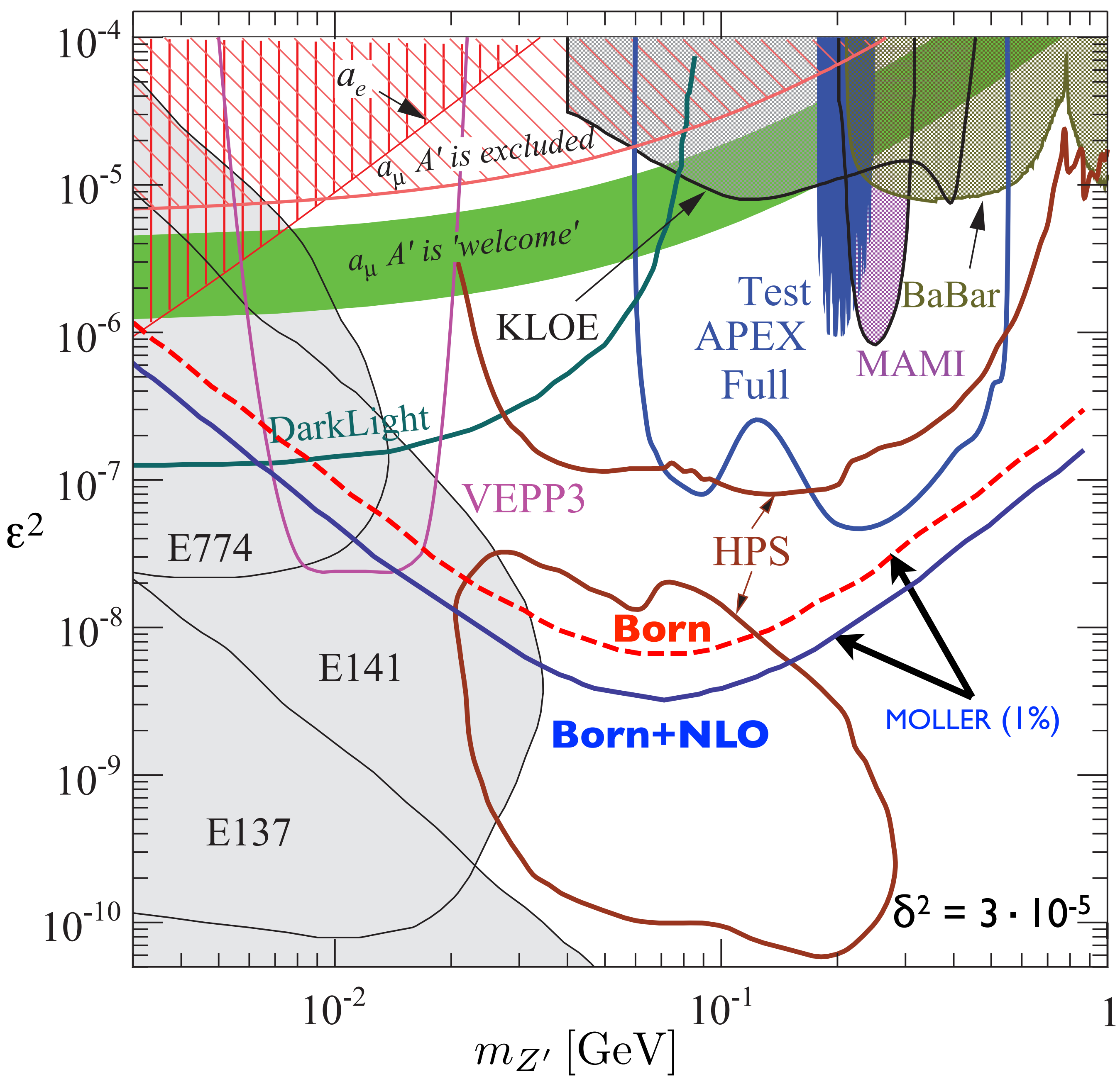
New-Physics particles (Dark Photon or Z') in the loops



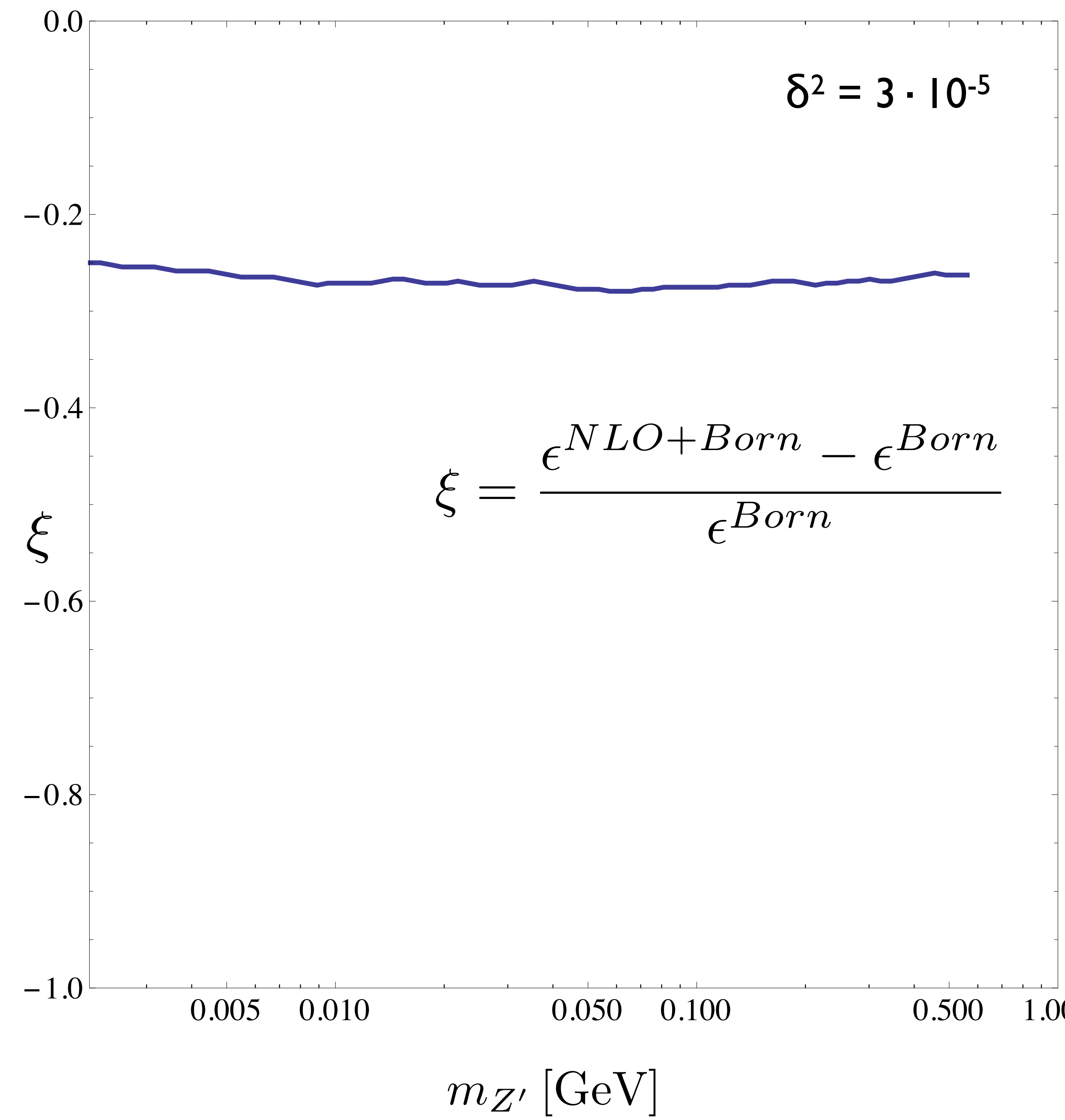
Precision Scattering: MOLLER

Theory Input: BSM Physics with Dark Vector

Exclusion plot for MOLLER using Z' as a candidate for BSM physics



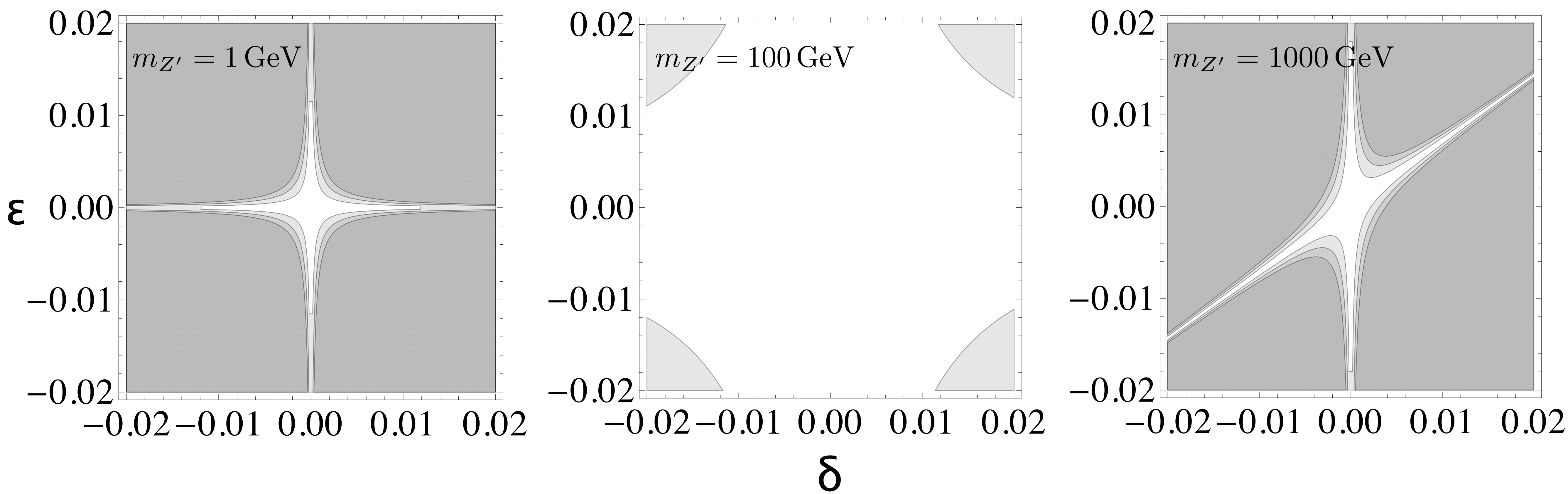
Relative correction to ϵ mixing parameter due to loops



Precision Scattering: MOLLER

Theory Input: BSM Physics with Dark Vector

Sensitivity of the kinetic (ε) and mass (δ) mixing parameters to different masses of Z' within 1% deviation from SM central value



Conclusions

- Two electroweak PV experiments: Qweak (completed) and MOLLER (planned) are complimentary to LHC search for BSM physics.

- With relatively large uncertainty arising from Υ-Z boxes, Qweak results are in agreement with SM predictions for weak charge of proton and neutron .

- MOLLER experiment is highly needed to put new constrains on weak charge of the electron.

- Dark Vector BSM physics scenarios for Moller process have best sensitivity for Z'.

- The Z' search in MOLLER is complimentary to $(g-2)_\mu$, where deviation with SM predictions reach 3.6σ