Search for Physics beyond SM at the Precision Frontiers

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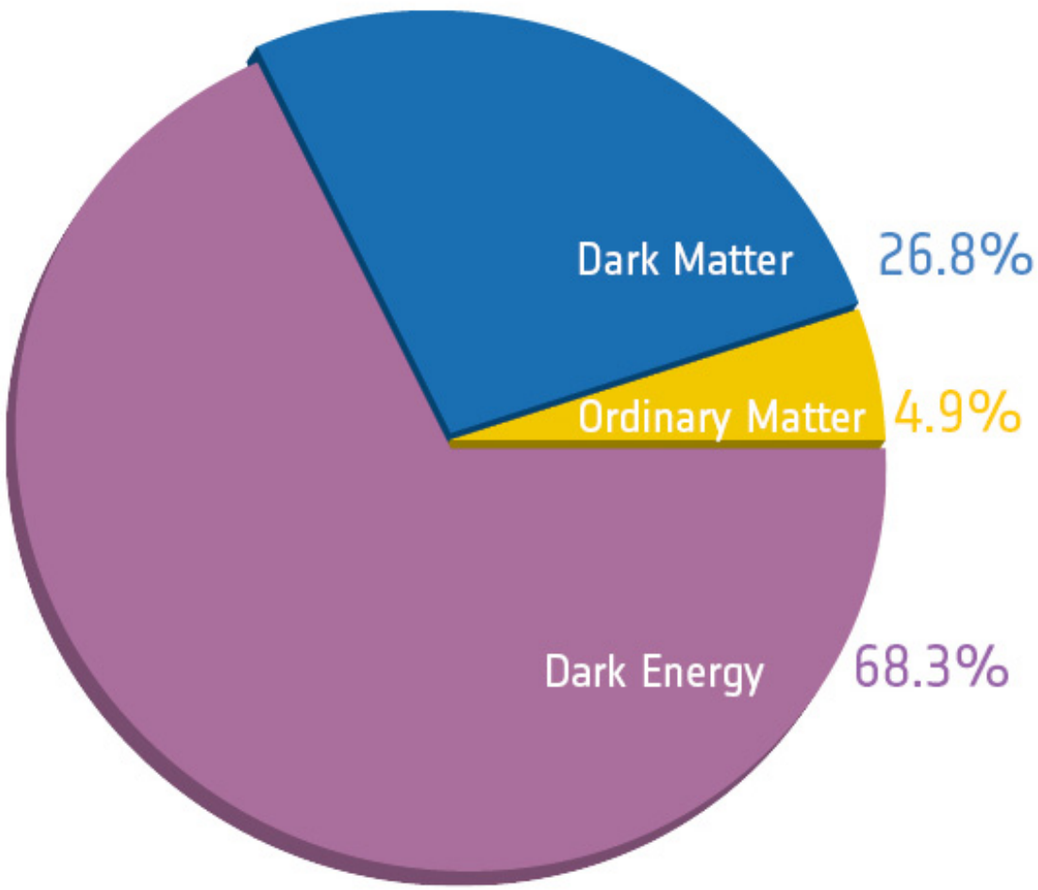
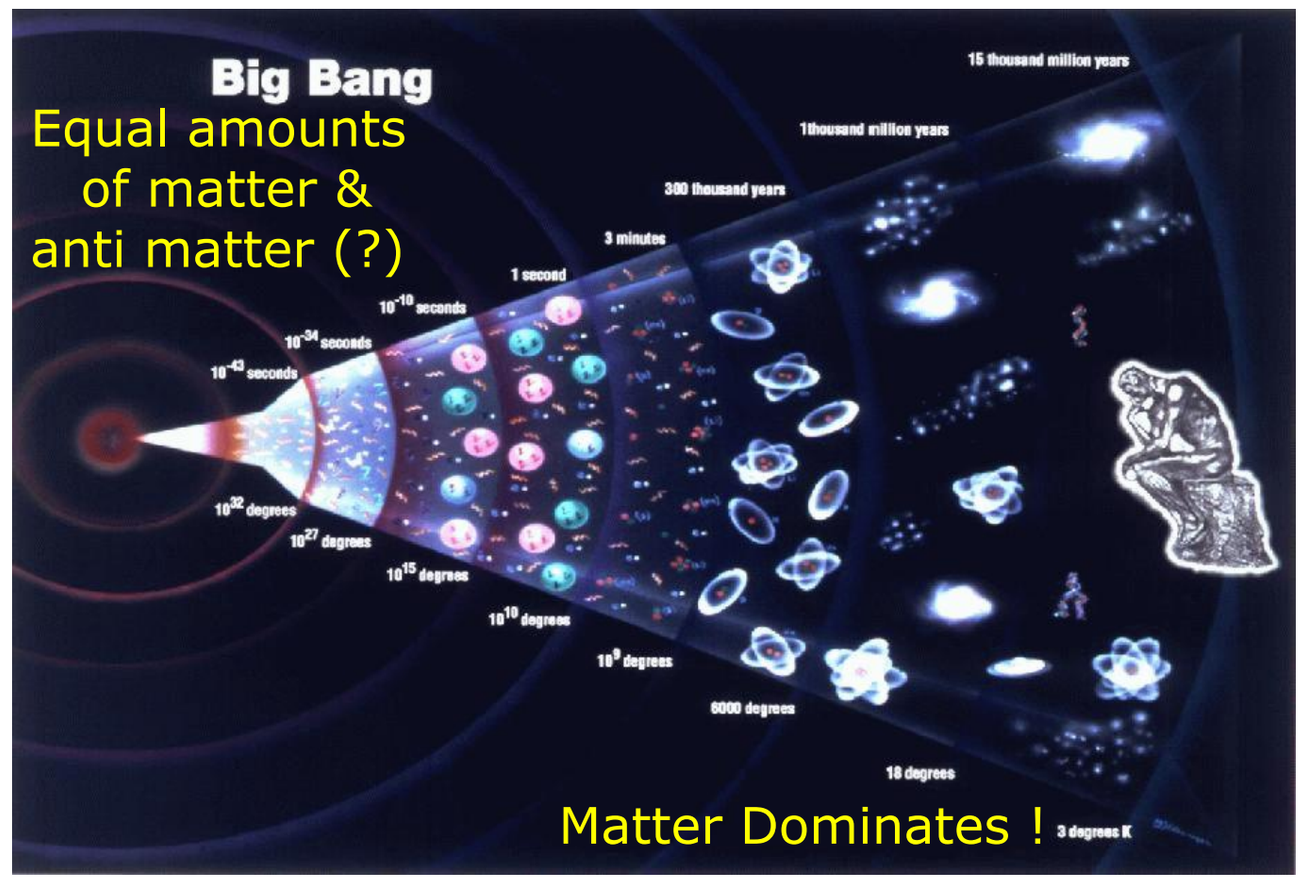
Problems with Standard Model

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

It does not explain Dark Matter and Dark Energy:



It does not explain matter and anti-matter asymmetry:



SM expectation: vs. Observed:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18} \qquad \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

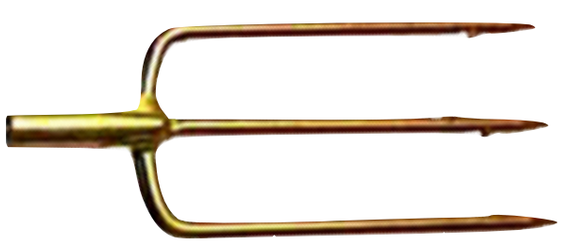
Frontiers of BSM Physics Search

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

The Energy Frontier (high-energy colliders)

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

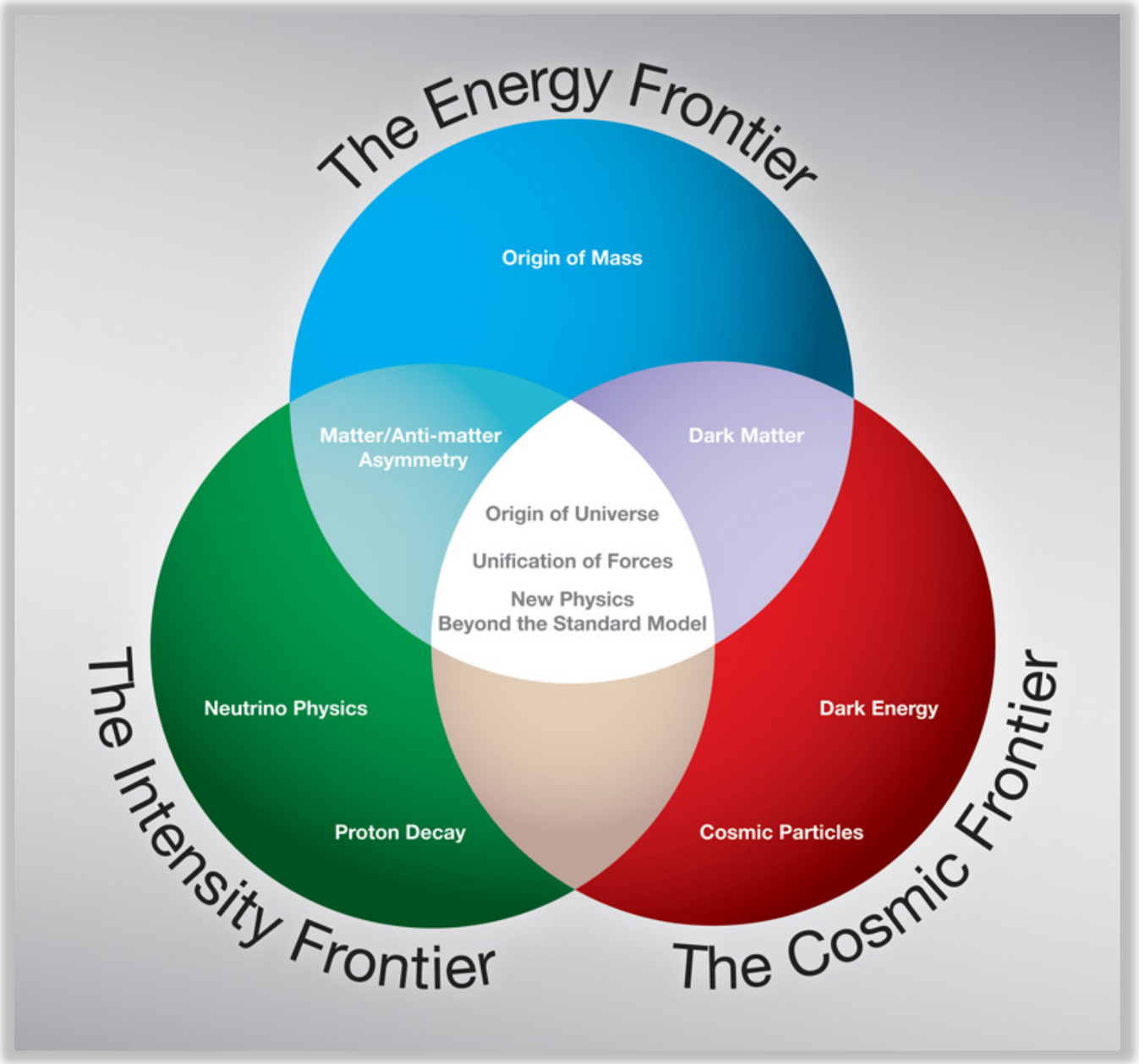
The Intensity/Precision Frontier (intense particle beams)



Energy

Intensity/Precision

Cosmic



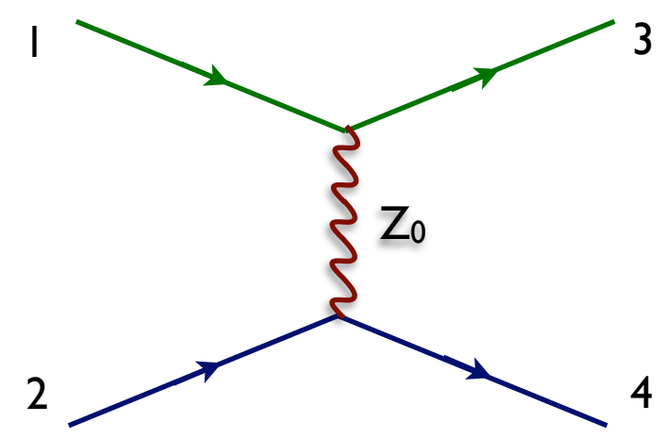
Precision Scattering

• 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 multi-TeV level, we need to push one or more experimental parameters to the extreme precision.

- *$\delta(\sin^2\theta_W) \leq 0.002$*



•Precision Neutrino Scattering
•New Physics/Weak-Electromagnetic Interference

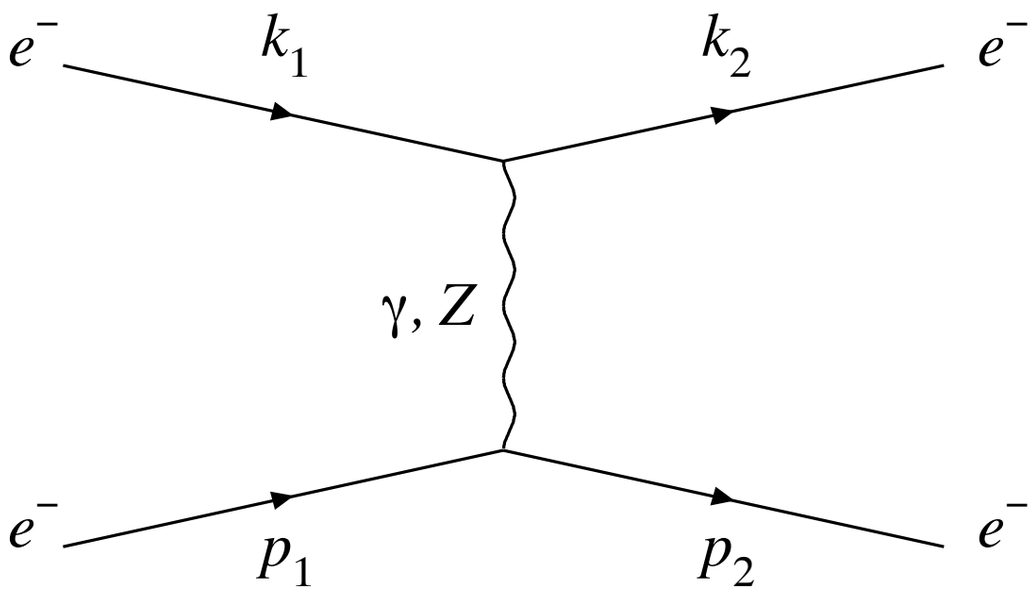
- *opposite parity transitions in heavy atoms*
- *parity-violating electron scattering*

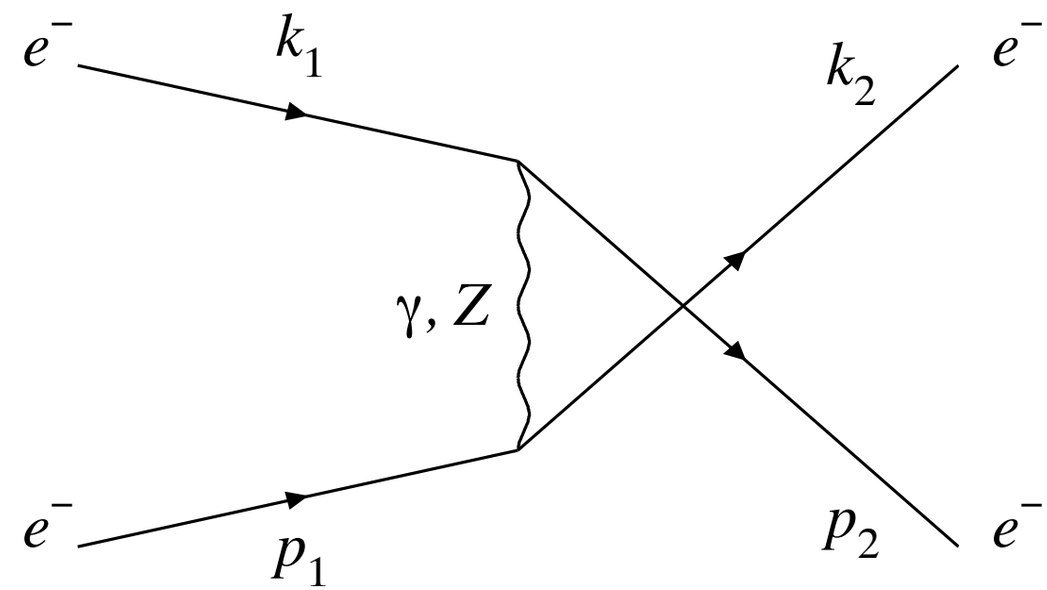
Weak interaction provides indirect access to the new physics via interference terms between neutral weak and new physics amplitudes.

Møller scattering at the tree level

The process of electron–electron scattering (Møller process)

C. Møller, Annalen der Physik 406, 531 (1932)





- Straightforward process!

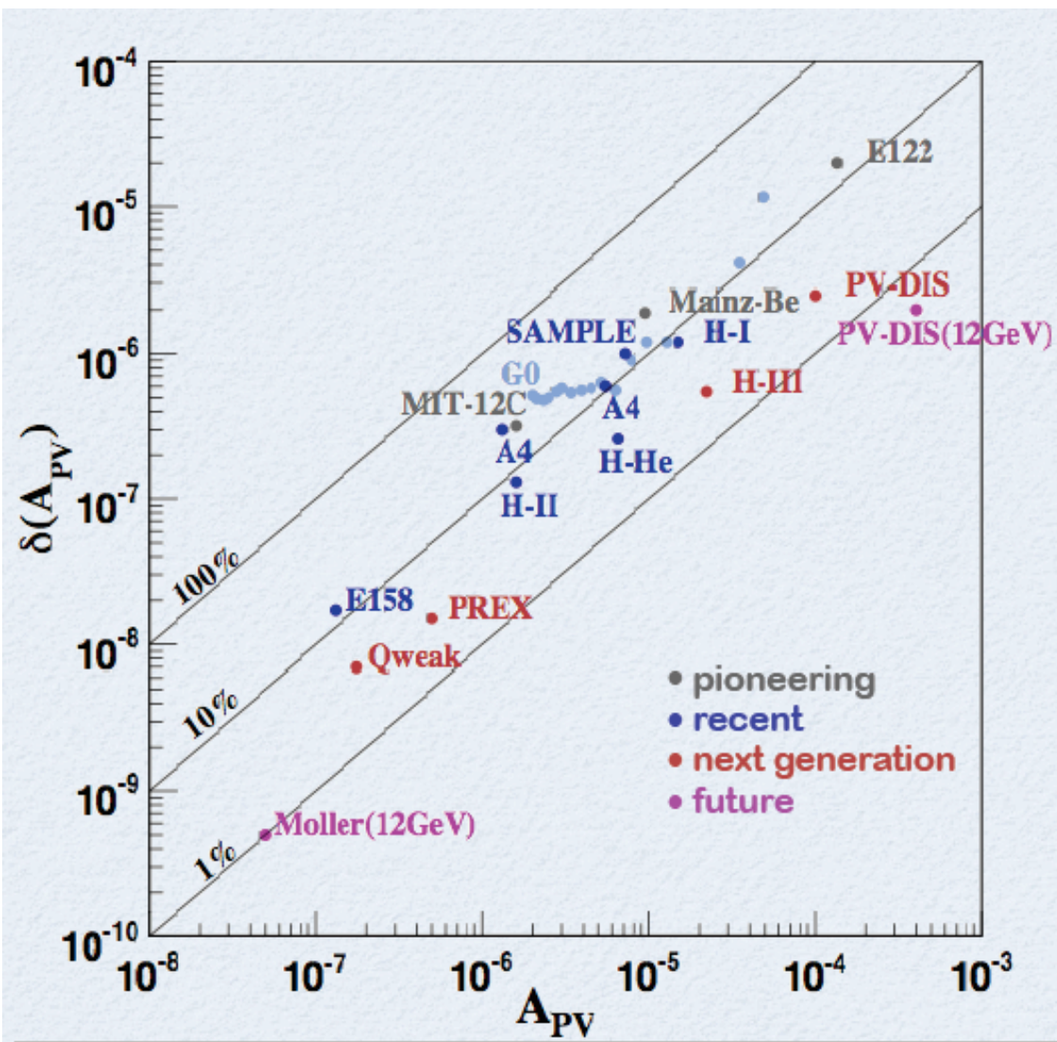
$$A_{LR} = \frac{\sigma_{LL} + \sigma_{LR} - \sigma_{RL} - \sigma_{RR}}{\sigma_{LL} + \sigma_{LR} + \sigma_{RL} + \sigma_{RR}} = \frac{\sigma_{LL} - \sigma_{RR}}{\sigma_{LL} + 2\sigma_{LR} + \sigma_{RR}}$$

$$A^0_{LR} = \frac{s}{2m_W^2} \frac{y(1-y)}{1 + y^4 + (1-y)^4} \frac{1 - 4s_W^2}{s_W^2}, \quad y = -t/s$$

Precision Scattering: MOLLER

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

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



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

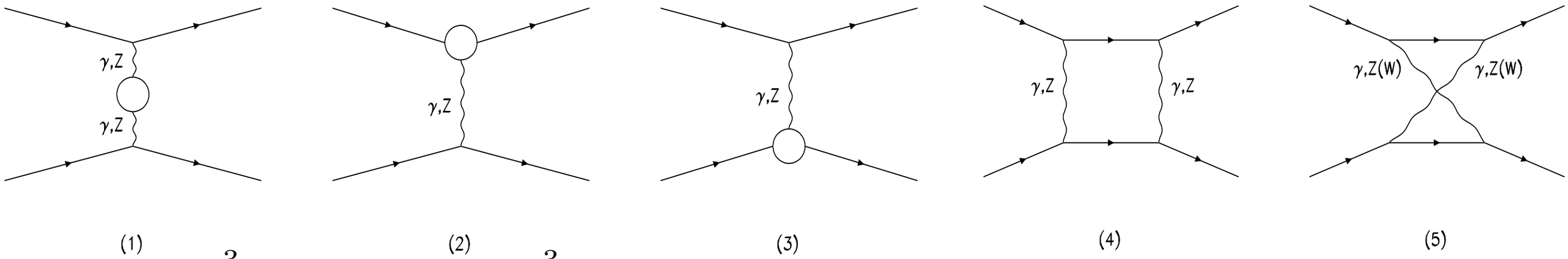
Motivation

Although PV asymmetry ($A_{LR} \sim 10^{-7}$) is very small, the accuracy of modern experiments exceeds the accuracy of the theoretical result in Born approximation. One–loop contribution was found to be rather big in the previous works:

A. Czarnecki, W. J. Marciano, Phys. Rev. D53, 1066 (1996);
A. Denner, S. Pozzorini, Eur. Phys. J. C7, 185 (1999);
A. Aleksejevs, S. Barkanova, A. Ilyichev, V. Zykunov, Phys. Rev. D82, 093013 (2010).

- Approach to improve theoretical precision:
  - Make sure that everything is correct for the given level of perturbation (start with one loop)
    - For that, we choose and compare two approaches: “on paper” and computer-based using on-shell renormalization and using two different renormalization conditions (RC).
  - Since the precision of experimental measurements is below 1%, higher order effects (beyond one-loop) are important:
    - Using the same approach, determine effects of quadratic corrections.
    - Calculate all reducible two-loop contributions.
    - Calculate all irreducible two-loop contributions (in progress).

One-loop



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

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

- Calculated in on-shell renormalization using:
  - Feynarts, FormCalc, LoopTools, Form and FeynCalc.

  T. Hahn, Comput. Phys. Commun., 140 418 (2001);
  T. Hahn, M. Perez-Victoria, Comput. Phys. Commun., 118, 153 (1999);
  J. Vermaseren, arXiv:math-ph/0010025, (2000);
  V. Shtabovenko, R. Mertig and F. Orellana, arXiv:1601.01167 (2016);
  R. Mertig, M. Böhm, and A. Denner, Comput. Phys. Commun., 64, 345-359 (1991).

  - "On paper" using 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 $\sqrt{s} \gg 500\ GeV$

One-loop: Gauge Invariance

- For a gauge invariant set, physical results should be invariant under different renormalization conditions.
- Renormalization constants are fixed by the renormalization conditions.
- Consider two classes:

  1. The first determines the renormalization of the parameters and is related to physical observables at a given order of perturbation theory. These conditions are identical in both Hollik RC (HRC) and Denner RC (DRC).

$$\mathrm{Re}\hat{\Sigma}_T^W(m_W^2) = \mathrm{Re}\hat{\Sigma}_T^Z(m_Z^2) = \mathrm{Re}\hat{\Sigma}^f(m_f^2) = 0,$$
$$\hat{\Gamma}_\mu^{ee\gamma}\left(k^2 = 0,\, p^2 = m^2\right) = ie\gamma_\mu.$$

  2. The second class fixes the renormalization of fields and is related to the Green's functions and has no effect on calculations of S-matrix elements.

$$\hat{\Sigma}_T^{\gamma Z}(0) = 0, \quad \frac{\partial}{\partial k^2}\hat{\Sigma}_T^{\gamma}(0) = 0$$

W. Hollik, Fortschr. Phys. 38, 165 (1990).

$$\hat{\Sigma}_T^{\gamma Z}(0) = 0, \quad \frac{\partial}{\partial k^2}\hat{\Sigma}_T^{\gamma}(0) = 0$$

$$\mathrm{Re}\hat{\Sigma}_T^{\gamma Z}(m_Z^2) = 0, \ \mathrm{Re}\frac{\partial}{\partial k^2}\hat{\Sigma}_T^{Z}(m_Z^2) = 0, \quad \mathrm{Re}\frac{\partial}{\partial k^2}\hat{\Sigma}_T^{W}(m_W^2) = 0.$$

A. Denner, Fortsch. Phys. 41, 307 (1993).

One-loop: Results

The relative correction to the Born asymmetry A^0_{LR} is defined as follows:

$$\delta_A = \frac{A^C_{LR} - A^0_{LR}}{A^0_{LR}}$$

where index C means a specific contribution (C = BSE, Ver, Box, ...), A^0_{LR} is the Born asymmetry, and A^C_{LR} is the total asymmetry including electroweak radiative corrections.

Input parameters: α=1/137.035999,
m_W = 80.398 GeV,
m_Z = 91.1876 GeV.

$\sqrt{s}$, GeV	Result of Denner and Pozzorini	Our result
100	−0.2787	−0.2790
500	−0.3407	−0.3406
2000	−0.9056	−0.9066

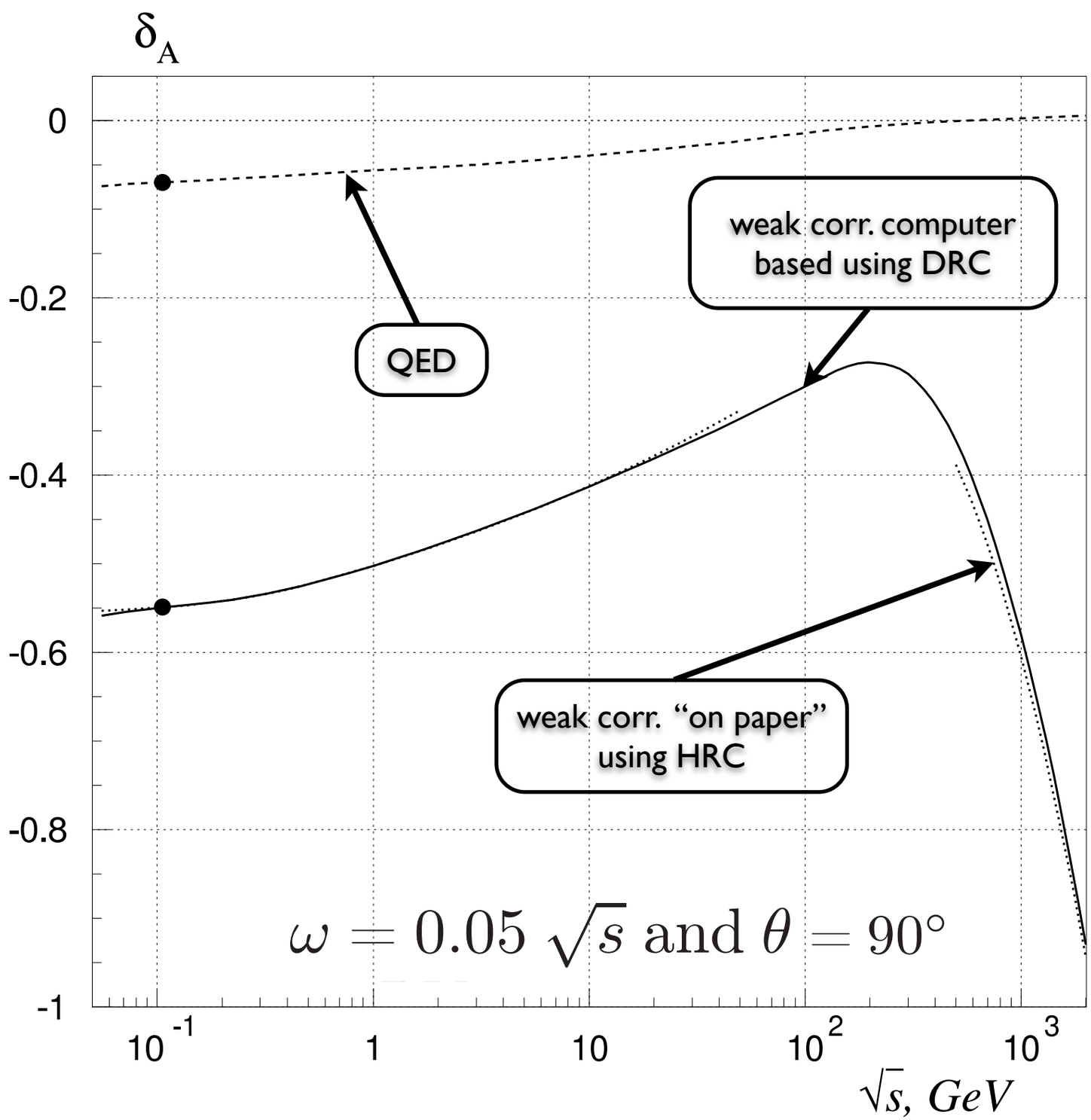
Comparison of our result for the weak correction to asymmetry with the result of arXiv:hep-ph/9807446.

One-loop: Results

The Born asymmetry A^0_{LR} and the structure of relative *weak* corrections to it for $E_{\rm lab} = 11$ GeV at different θ.

$\theta,^\circ$	20	30	40	50	60	70	80	90
A^0_{LR}, ppb	6.63	15.19	27.45	43.05	60.69	77.68	90.28	94.97
$\gamma\gamma$-SE, DRC	−0.0043	−0.0049	−0.0054	−0.0058	−0.0062	−0.0064	−0.0066	−0.0067
$\gamma\gamma$-SE, HRC	−0.0043	−0.0049	−0.0054	−0.0058	−0.0062	−0.0064	−0.0066	−0.0067
γZ-SE, DRC	−0.2919	−0.2916	−0.2914	−0.2912	−0.2911	−0.2910	−0.2909	−0.2909
γZ-SE, HRC	−0.6051	−0.6043	−0.6042	−0.6038	−0.6034	−0.6031	−0.6028	−0.6028
ZZ-SE, DRC	−0.0105	−0.0105	−0.0105	−0.0105	−0.0105	−0.0105	−0.0105	−0.0105
ZZ-SE, HRC	0.0309	0.0309	0.0309	0.0309	0.0309	0.0309	0.0309	0.0309
HV, DRC	−0.2946	−0.2633	−0.2727	−0.2703	−0.2714	−0.2712	−0.2711	−0.2710
HV, HRC	−0.0015	−0.0012	−0.0010	−0.0009	−0.0008	−0.0007	−0.0007	−0.0007
ZZ-box, exact	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013
ZZ-box, approx.	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013	−0.0013
WW-box, exact	0.0239	0.0238	0.0238	0.0239	0.0239	0.0238	0.0238	0.0238
WW-box, approx.	0.0238	0.0238	0.0238	0.0238	0.0238	0.0238	0.0238	0.0238
total *weak*, DRC, exact	−0.5643	−0.5430	−0.5508	−0.5489	−0.5500	−0.5495	−0.5493	−0.5493
total *weak*, HRC, approx.	−0.5526	−0.5514	−0.5511	−0.5505	−0.5500	−0.5496	−0.5493	−0.5493

One-loop: Results and Comparison



$$\delta_A = \frac{A^C_{LR} - A^0_{LR}}{A^0_{LR}}$$

The relative weak (solid line in DRC (semi-automated) and dotted line in HRC ("on paper") and QED (dashed line) corrections to the Born asymmetry A^0_{LR} versus $\sqrt{s}$ at $\theta = 90°$.

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

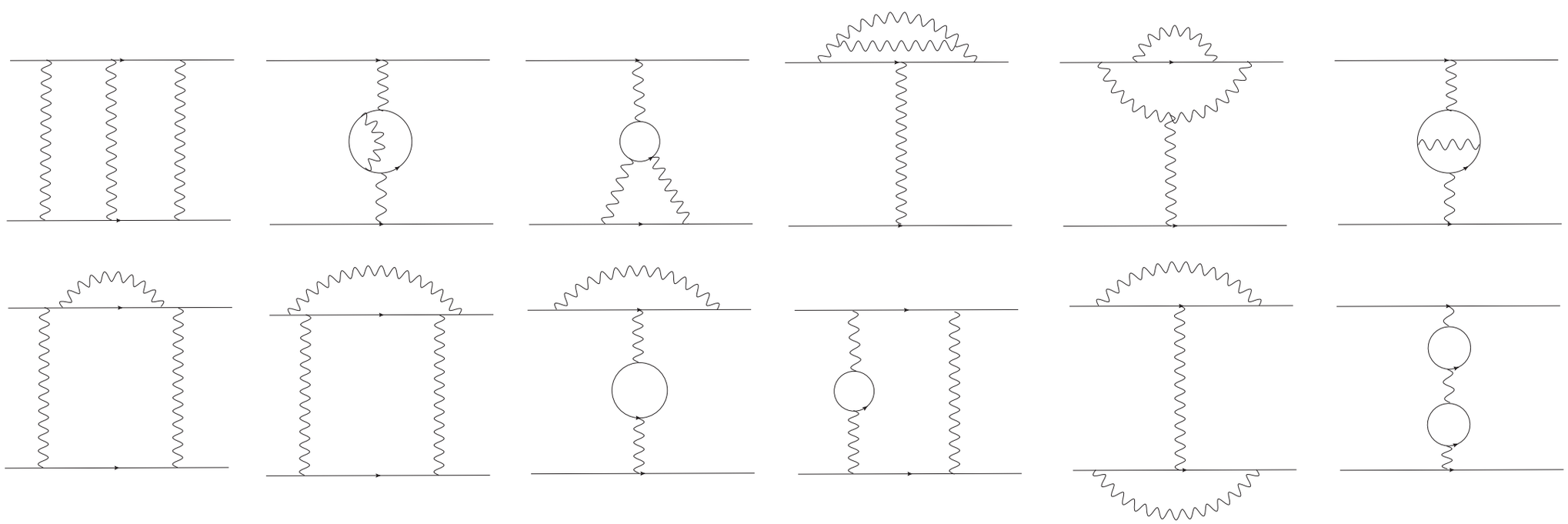
Higher-order Corrections

The Next-to-Next-to-Leading Order (NNLP) 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 ~ $2\mathrm{Re}M_0M_{2\text{-loop}}^+$.

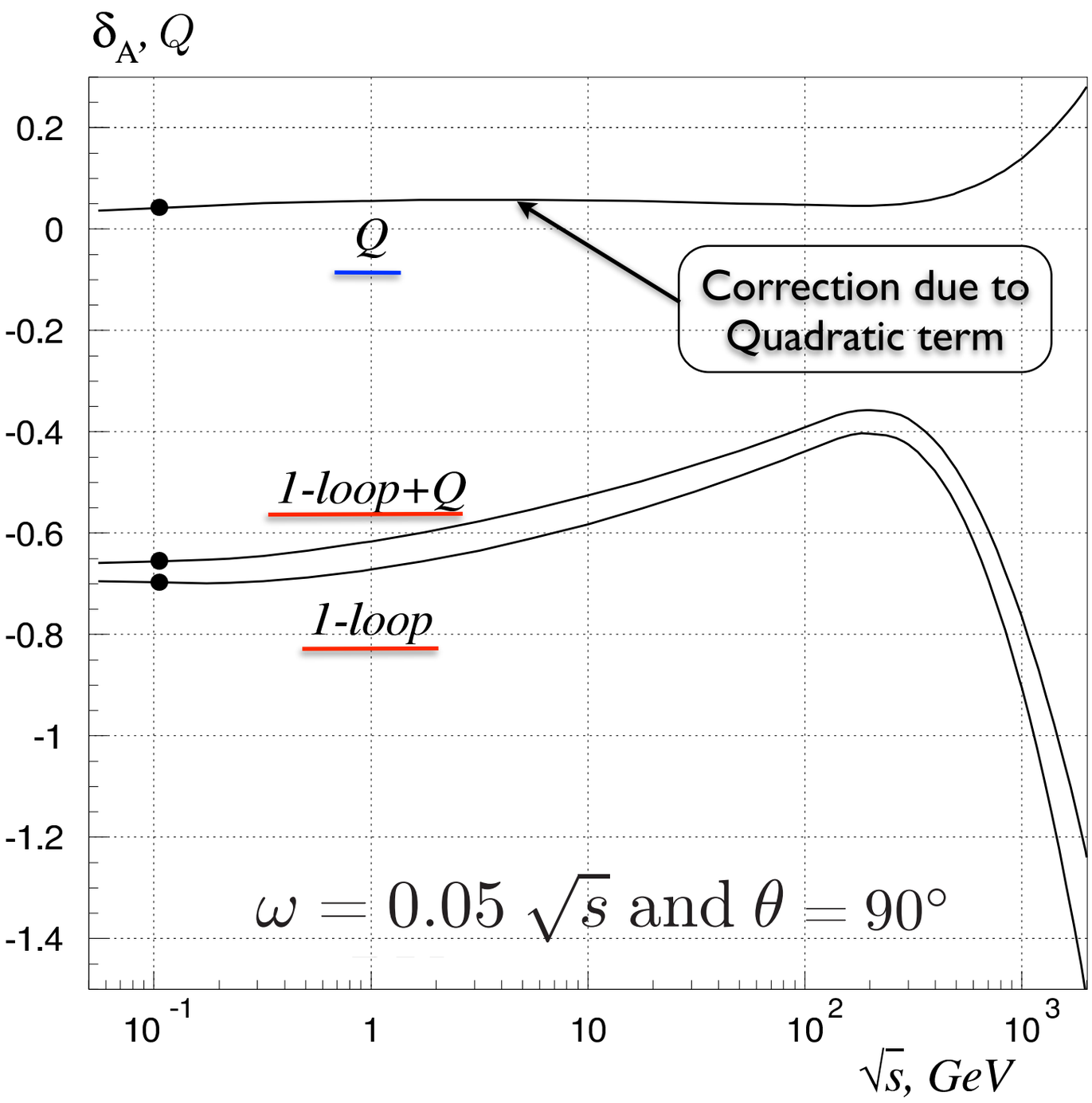
$$\sigma = \frac{\pi^3}{2s}|M_0 + M_1|^2 = \frac{\pi^3}{2s}(\underbrace{M_0M_0^+}_{\propto\,\alpha^2} + \underbrace{2\mathrm{Re}M_1M_0^+}_{\propto\,\alpha^3} + \underbrace{M_1M_1^+}_{\propto\,\alpha^4}) = \sigma_0 + \sigma_1 + \sigma_Q$$

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



+ …

Quadratic correction: Results



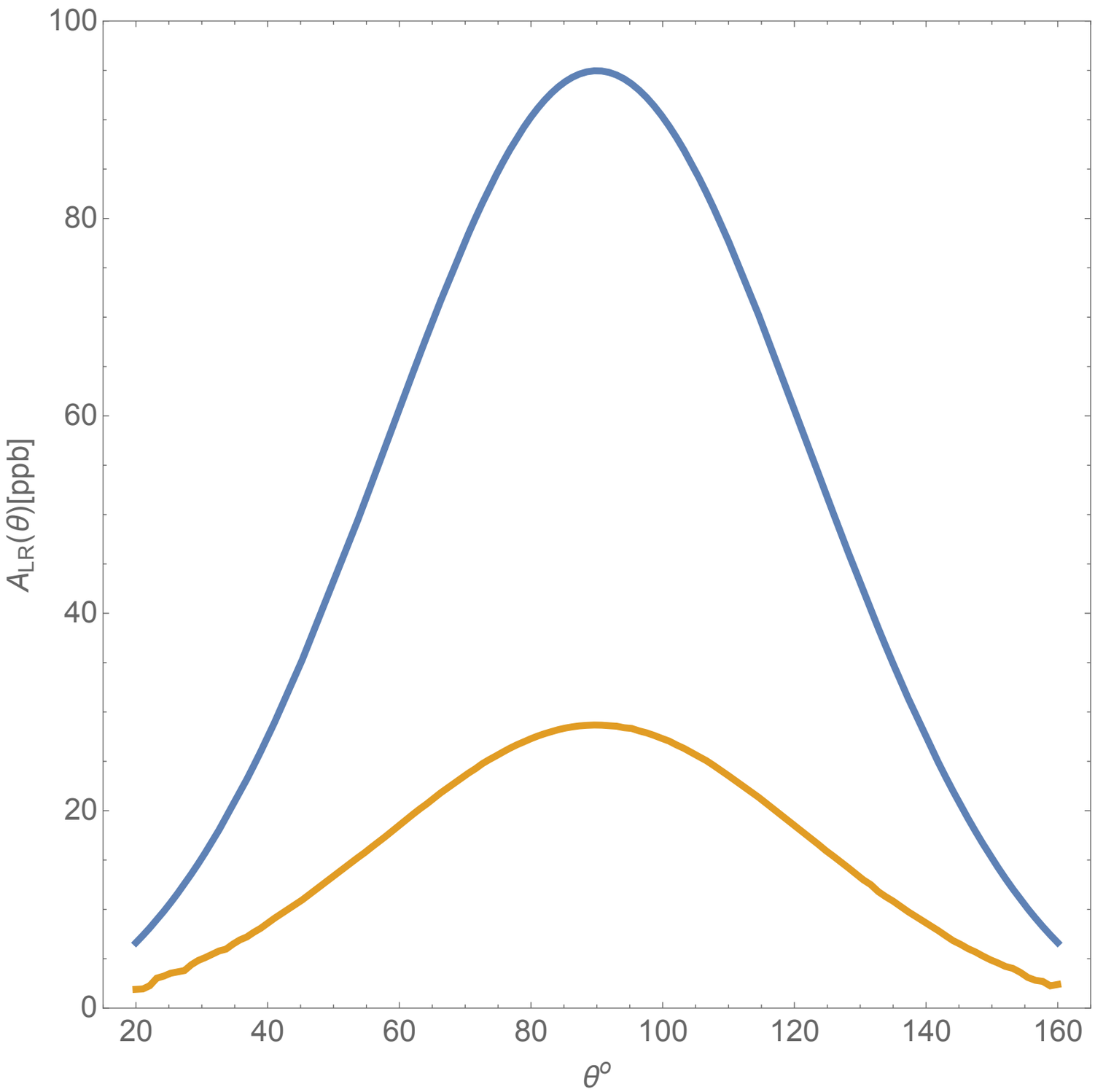
$$\delta_A = (A^C_{LR} - A^0_{LR})/A^0_{LR}$$

$$Q = (A^{1-\mathrm{loop+Q}}_{LR} - A^{1-\mathrm{loop}}_{LR})/A^0_{LR}$$

The scale of the Q-part contribution in the low-energy region is approximately constant, but starting from $\sqrt{s} \geq m_Z$, where the weak contribution becomes comparable with electromagnetic, the effect of Q-part grows sharply.

This effect of increasing importance of higher order contribution at higher energies may have a significant effect on the asymmetry measured at the future $e^- e^-$ -colliders.

PV Asymmetry



Predicted PV asymmetry (E_{lab} = 11GeV):

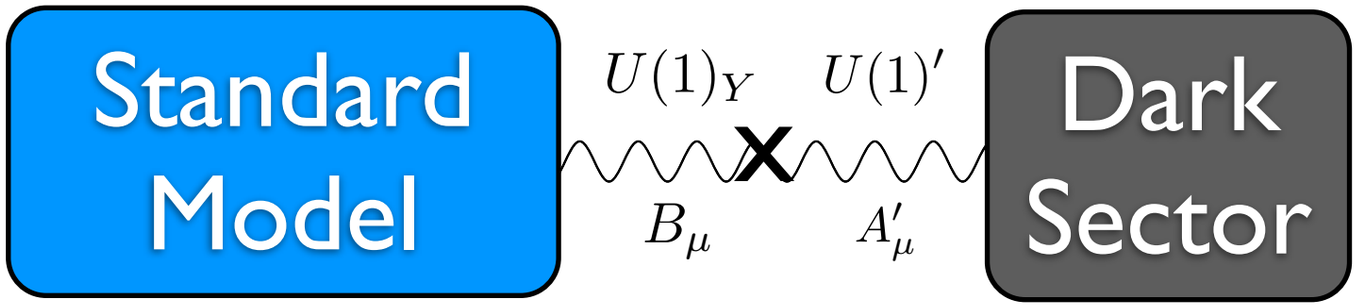
$A_{PV}^{(LO)}$ (90°)= 94.96 (ppb)

$A_{PV}^{(LO+NLO+Qpart)}$ (90°)≃ 32.7 (ppb)

Although suppression of Born asymmetry due to loops correction is quite large, overall uncertainty of theoretical results is below 1%.

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):

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

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: $\varepsilon \sim (g_Y g_{A'})/(16\pi^2) \lesssim 10^{-3}$

BSM Physics with Dark Vector

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

Dark Photon

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

- 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)

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

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

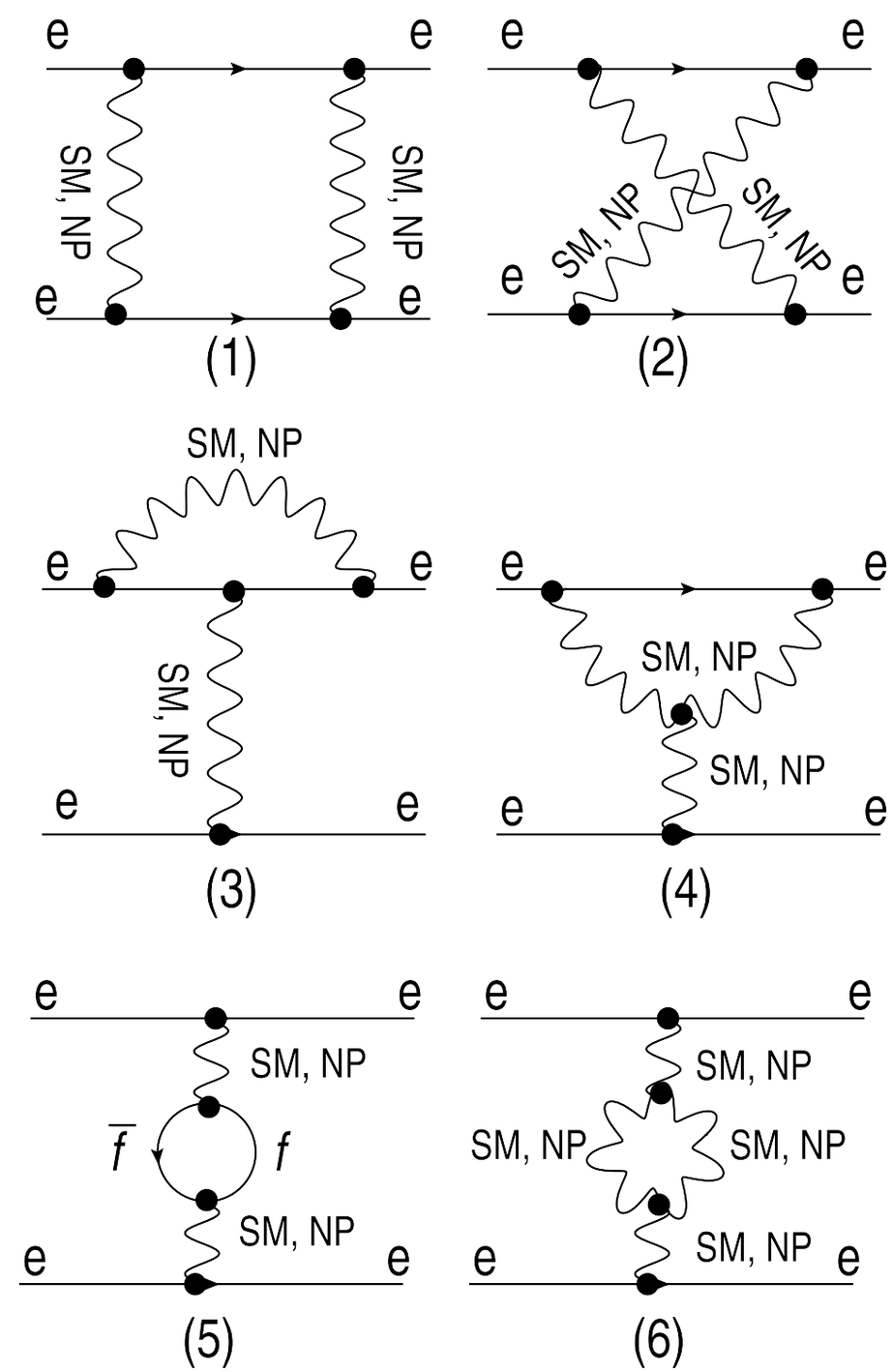
Dark-Vector in Moller Scattering

Calculation Strategy

- Using FeynArts, FormCalc, LoopTools and FORM complete the calculations of PV MOLLER asymmetries including one-loop (NLO) for the SM particles. This will define SM central value.

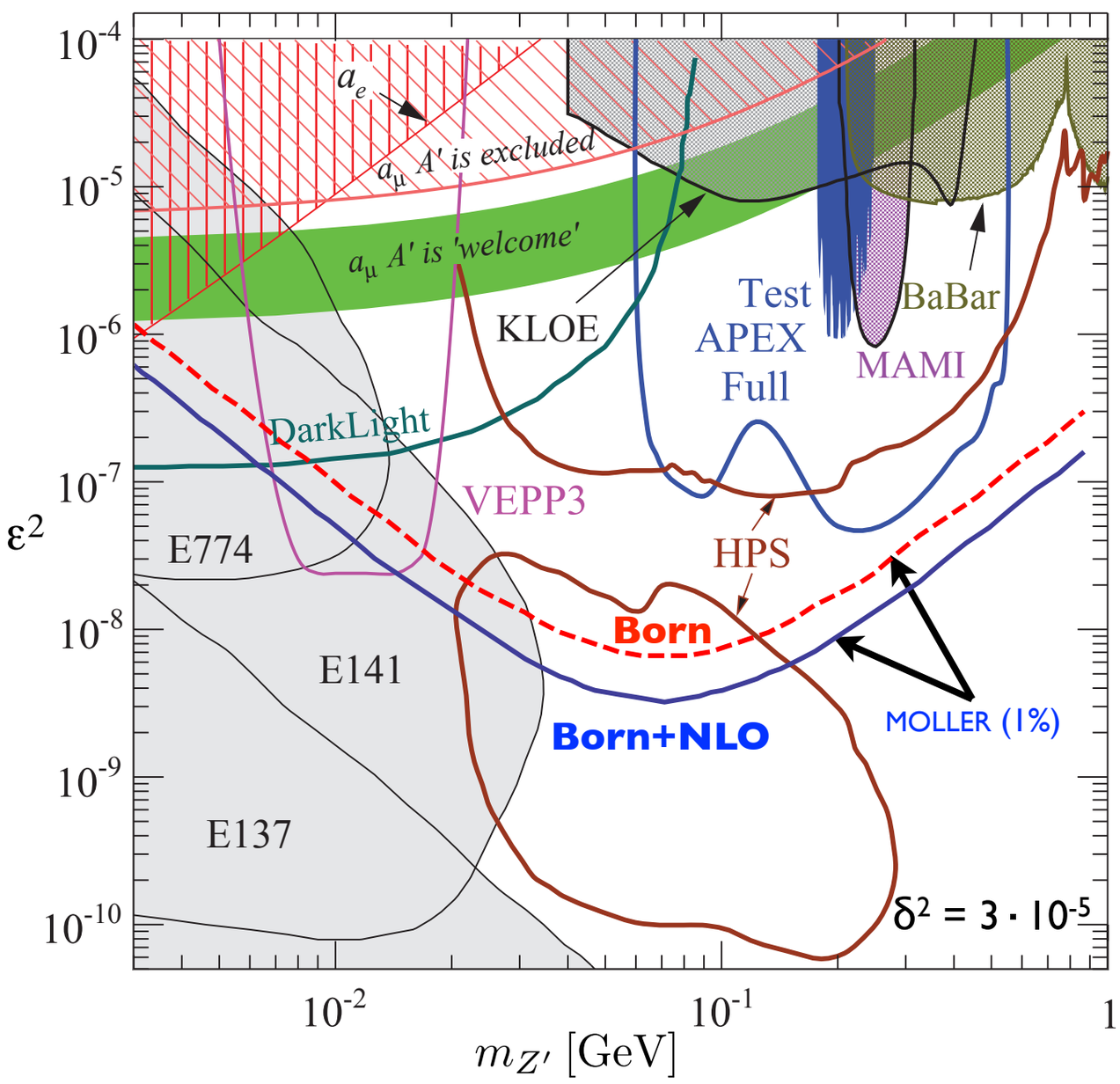
- Proceed with calculations of PV asymmetries with **BSM physics particles including one-loop** and construct exclusion plots for 1% deviations from the SM central values.

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

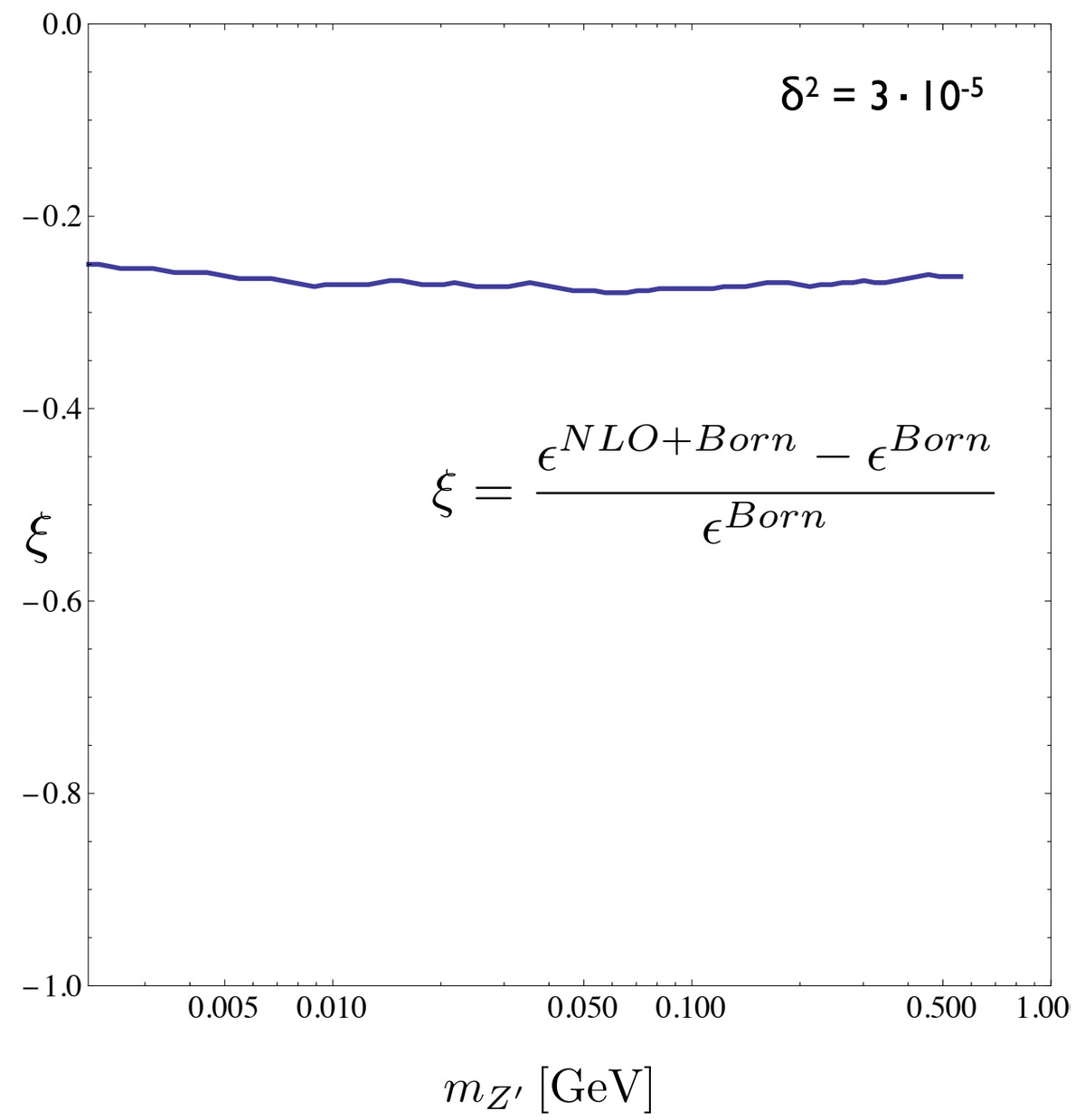


Dark-Vector in Moller Scattering

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



Relative correction to ϵ mixing parameter due to loops

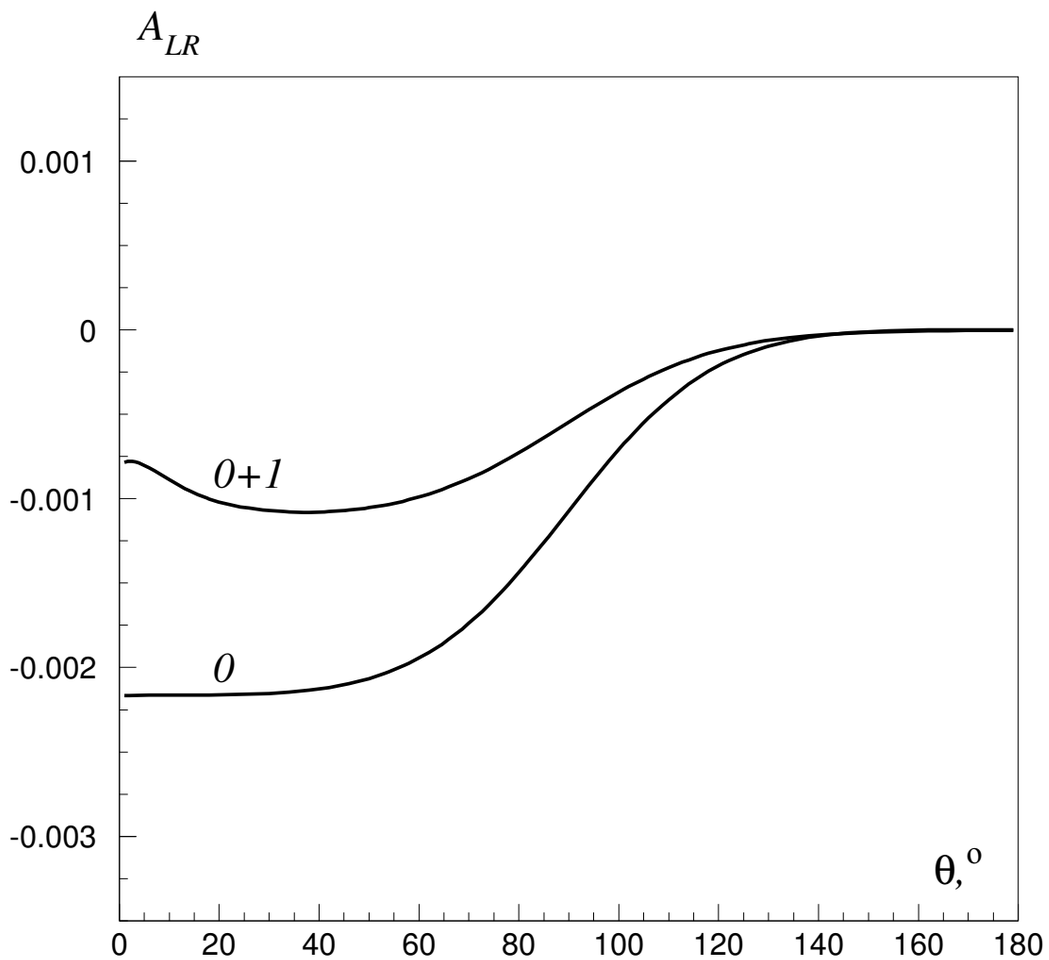


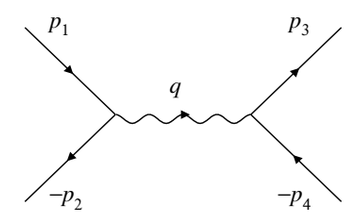
AA, S. Barkanova, V. Zykunov, S. Wu, arXiv:1410.6970

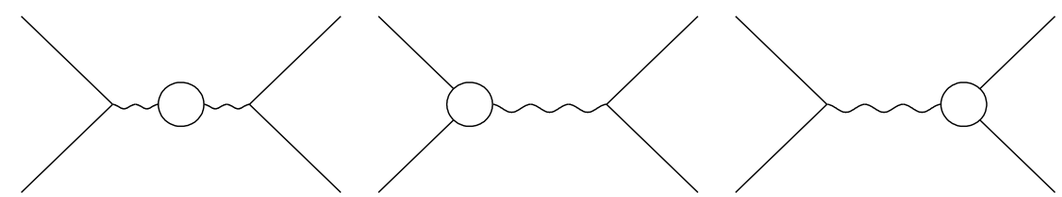
Polarization Asymmetry in Electron-Positron Collisions: $e^+ + e^- \rightarrow \mu^+ + \mu^-$

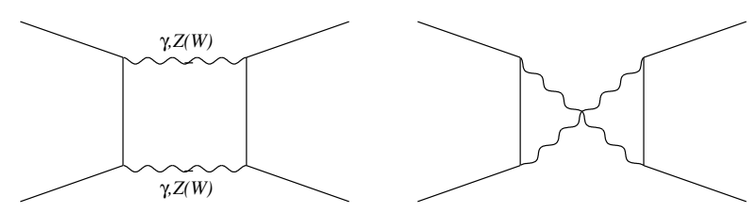
$$A_{LR}^C = \frac{\sigma_L^C - \sigma_R^C}{\sigma_L^C + \sigma_R^C}.$$

M. Bohm, H. Spiesberger and W. Hollik, Fortschr. Phys., 34 (1986) 11, 687 -751









$\theta,^\circ$	10	30	50	70	90	110	130	150	170
approx acc. (1)	0.0180	−0.0456	−0.0738	−0.0935	−0.1099	−0.1264	−0.1460	−0.1743	−0.2378
SAA	0.0179	−0.0455	−0.0738	−0.0934	−0.1099	−0.1263	−0.1459	−0.1742	−0.2372

Table shows correction to unpolarized cross section calculated using "on-paper" and computer based approaches.

Sensitivity of Polarization Asymmetry to effective mixing angle

Pinch Technique representation of effective Born amplitude:

D. Binosi, J. Papavassiliou, arXiv:0909.2536
D. Kennedy, B. Lynn, Nucl. Phys. B322 (1989) 1
W. Hollik, DESY Report, DESY 88-188 (1988)

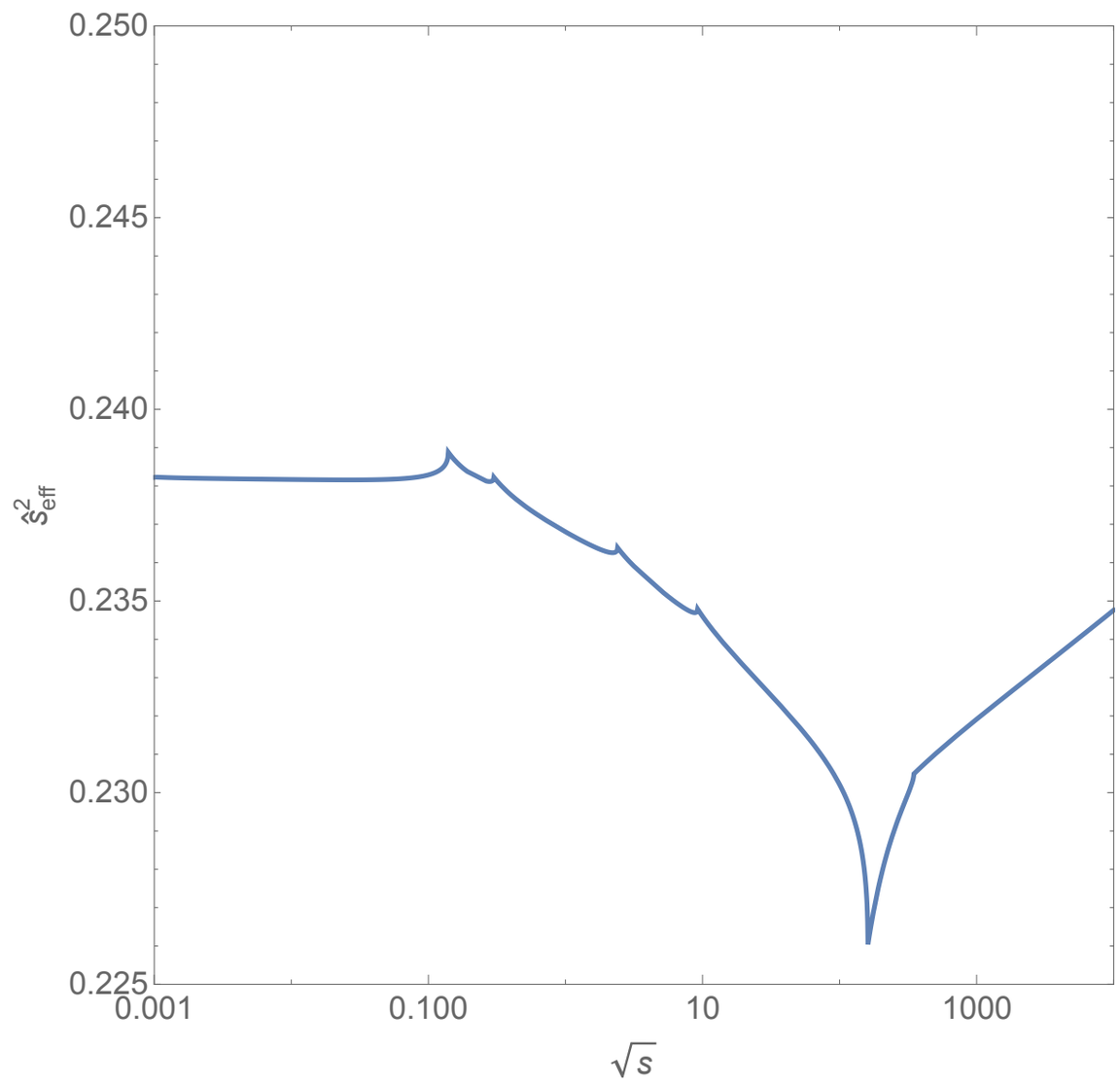
$$\mathfrak{M}_\gamma = \frac{\alpha(s) Q_e Q_\mu}{s} \left(\bar{v}_e \gamma_\mu u_e\right) \left(\bar{u}_\mu \gamma^\mu v_\mu\right)$$

$$\mathfrak{M}_Z = \frac{G_\mu}{\sqrt{2}} \kappa \frac{m_Z^2}{s - m_Z^2 + i \frac{s}{m_Z} \Gamma_Z} \left(\bar{v}_e \gamma_\mu \left[I_3^e - 2\bar{s}_W^2(s) Q_e - I_3^e \gamma_5\right] u_e\right) \left(\bar{u}_\mu \gamma^\mu \left[I_3^\mu - 2\bar{s}_W^2(s) Q_\mu - I_3^\mu \gamma_5\right] v_\mu\right)$$

Effective Weinberg mixing angle up to one-loop correction:

$$\bar{s}_W^2(s) = s_W^2 - s_W c_W \frac{\mathrm{Re}\left[\hat{\Sigma}_{\gamma Z}(s)\right]}{s + \mathrm{Re}\left[\hat{\Sigma}_{\gamma\gamma}(s)\right]}.$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}.$$



Sensitivity of Polarization Asymmetry to effective mixing angle

$$\bar{s}_W^2(s) = s_W^2 - s_W c_W \frac{\mathrm{Re}\left[\hat{\Sigma}_{\gamma Z}(s)\right]}{s + \mathrm{Re}\left[\hat{\Sigma}_{\gamma\gamma}(s)\right]}.$$

s (GeV^2)	$\bar{s}^2_{W(on-shell)}$	$\bar{s}^2_{W(\bar{MS})}$[1]	$\bar{s}^2_{W(\bar{MS})}$PDG(2014)
0	0.2382	0.2387	0.2386
m_z	0.2313	0.2320	0.2313

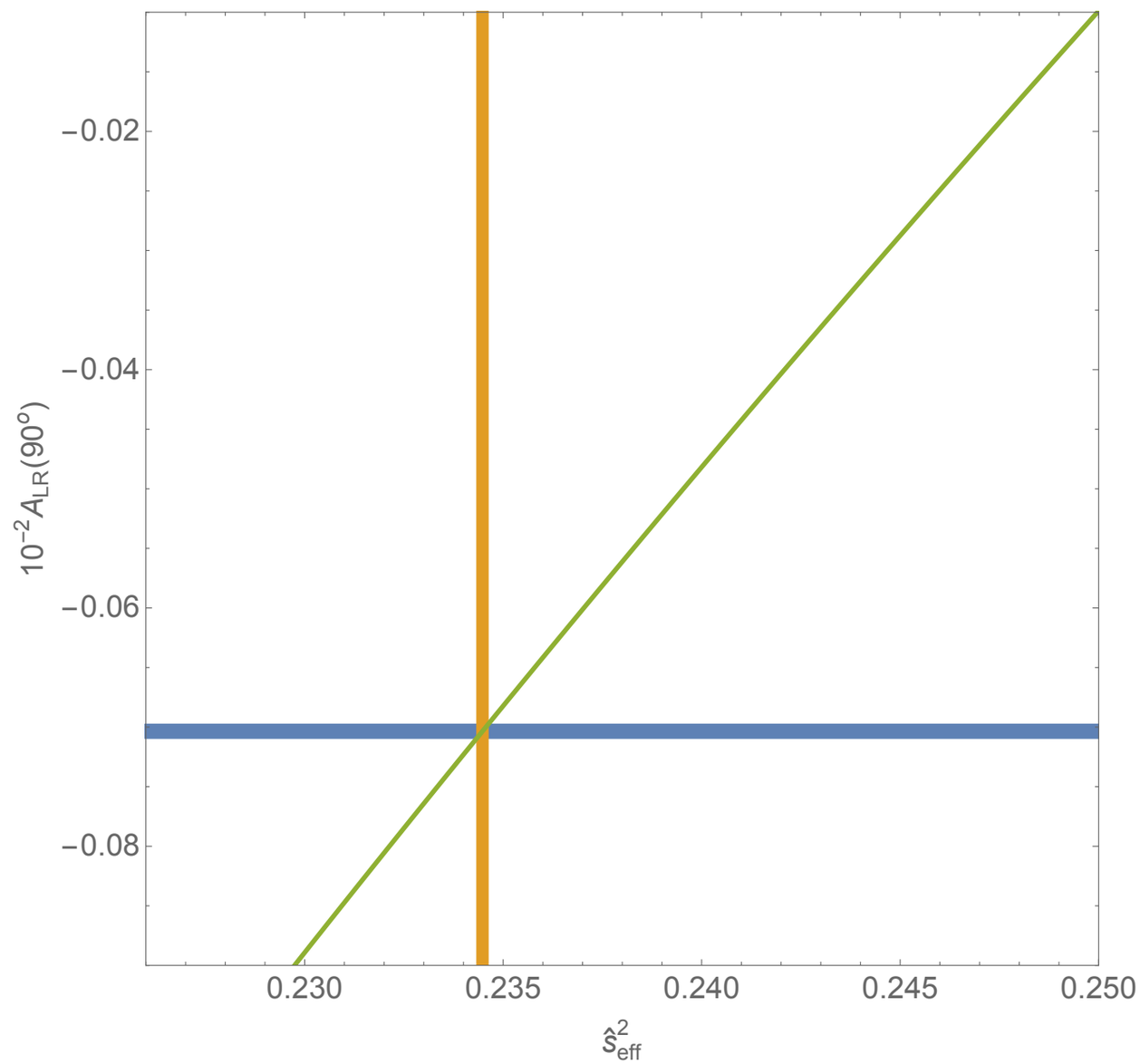
Mass of W boson is fixed from muon decay data:

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu \sin^2\theta_W(1-\Delta r)}.$$

m_W = 80.46 GeV

Value of the effective s_W^2 for Belle II kinematics:

$$\bar{s}_W^2(s = 10.58^2\ GeV^2) = 0.2345.$$



Conclusion

- For PV processes, electroweak radiative corrections could be large, so it is essential to include higher order (one, two-loop) corrections.

- Application of the computer algebraic packages proved to be an excellent way to improve precision in the calculations of radiative corrections.

- MOLLER experiment can 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 $(g\text{-}2)_\mu$, where deviation with SM predictions reach 3.6σ.

- If MOLLER does not find Z' boson, it will exclude entire region where Z' is welcome in $(g\text{-}2)_\mu$ experiment.

- Proposed Belle II experiment, with 1% uncertainty on polarization asymmetry, would put 0.3% constrain on the measured value of effective Weinberg mixing angle.