Hunt for the New Physics at the Precision Frontiers

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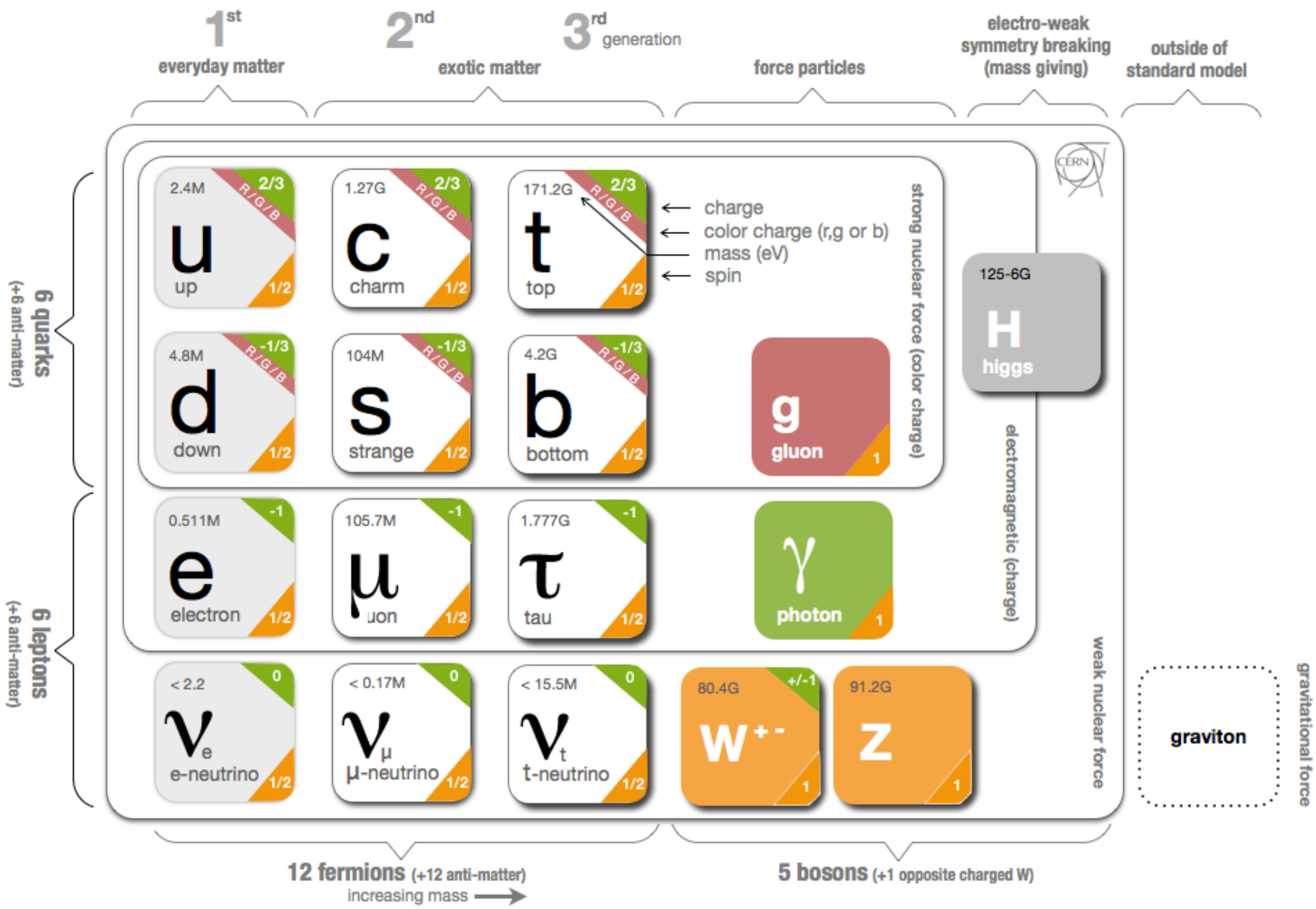
ACADIA UNIVERSITY

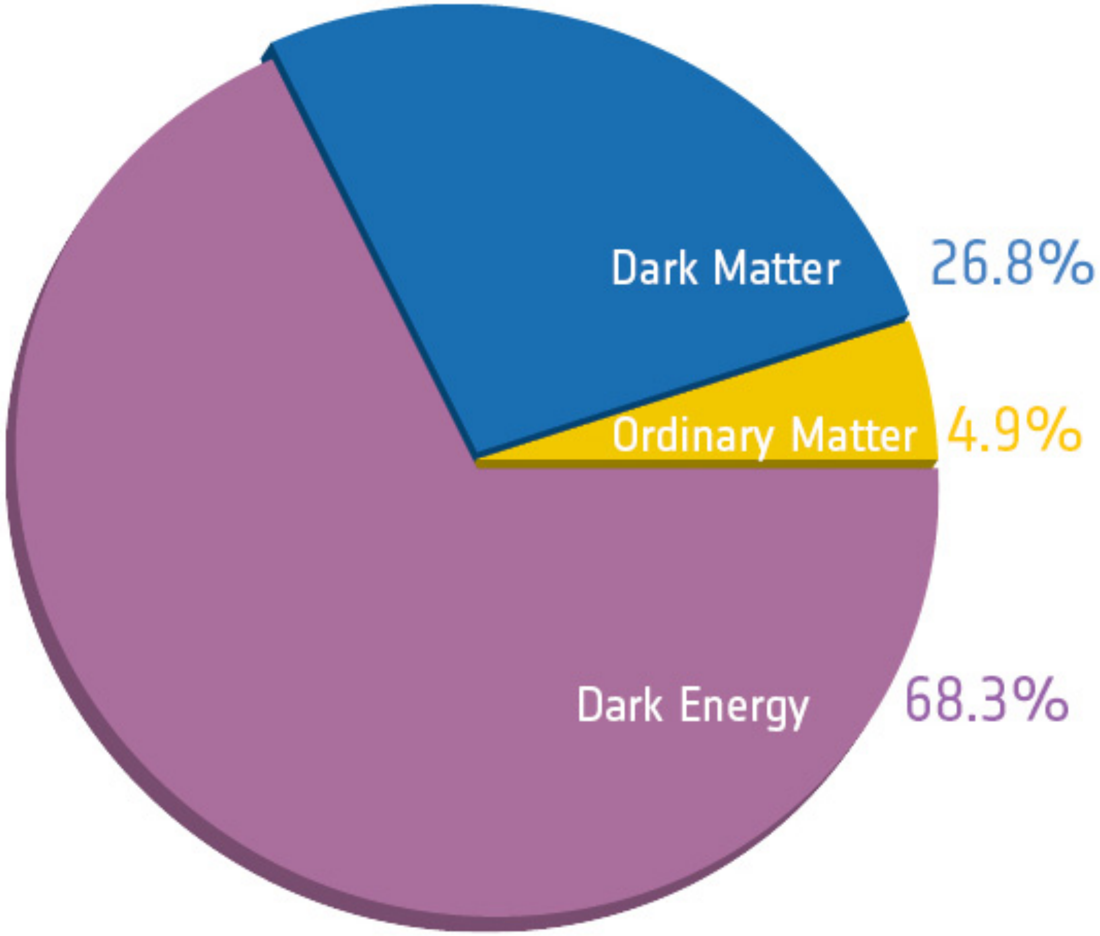
Standard Model



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:



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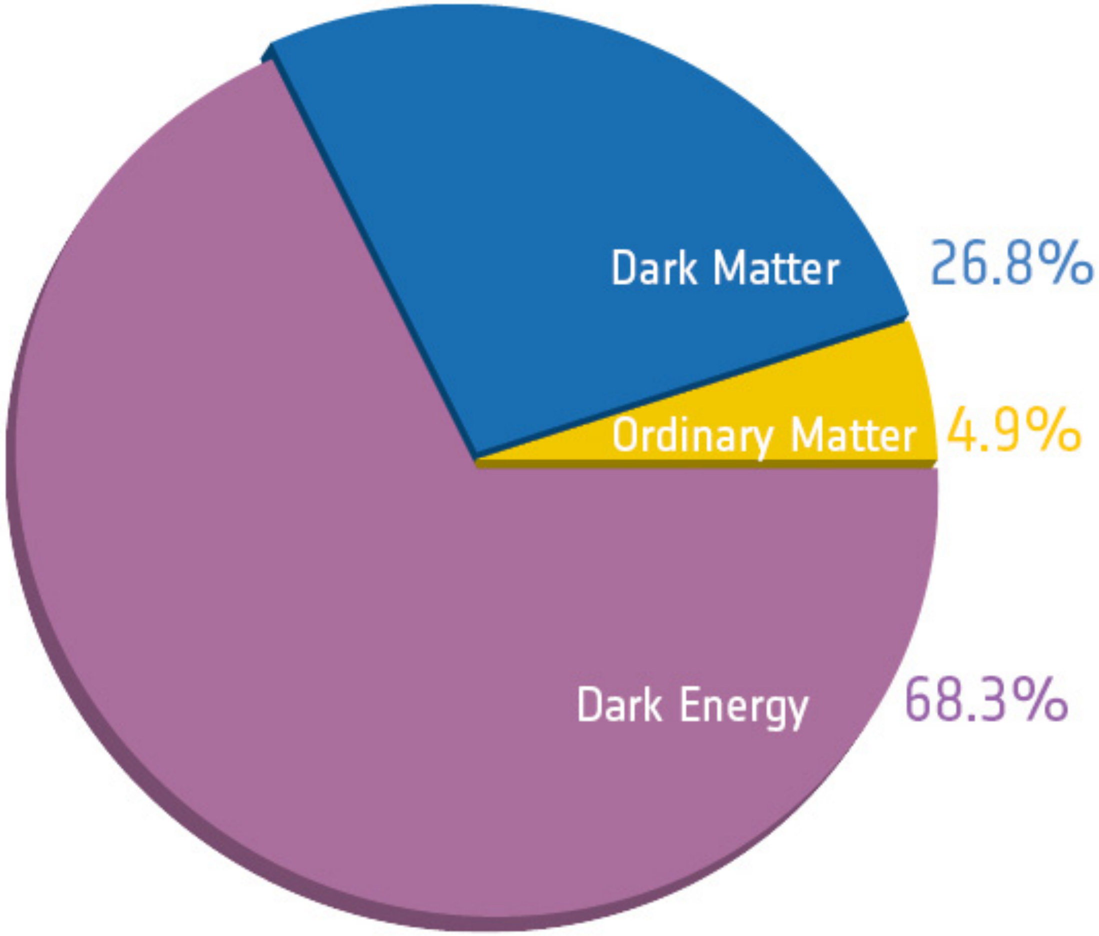
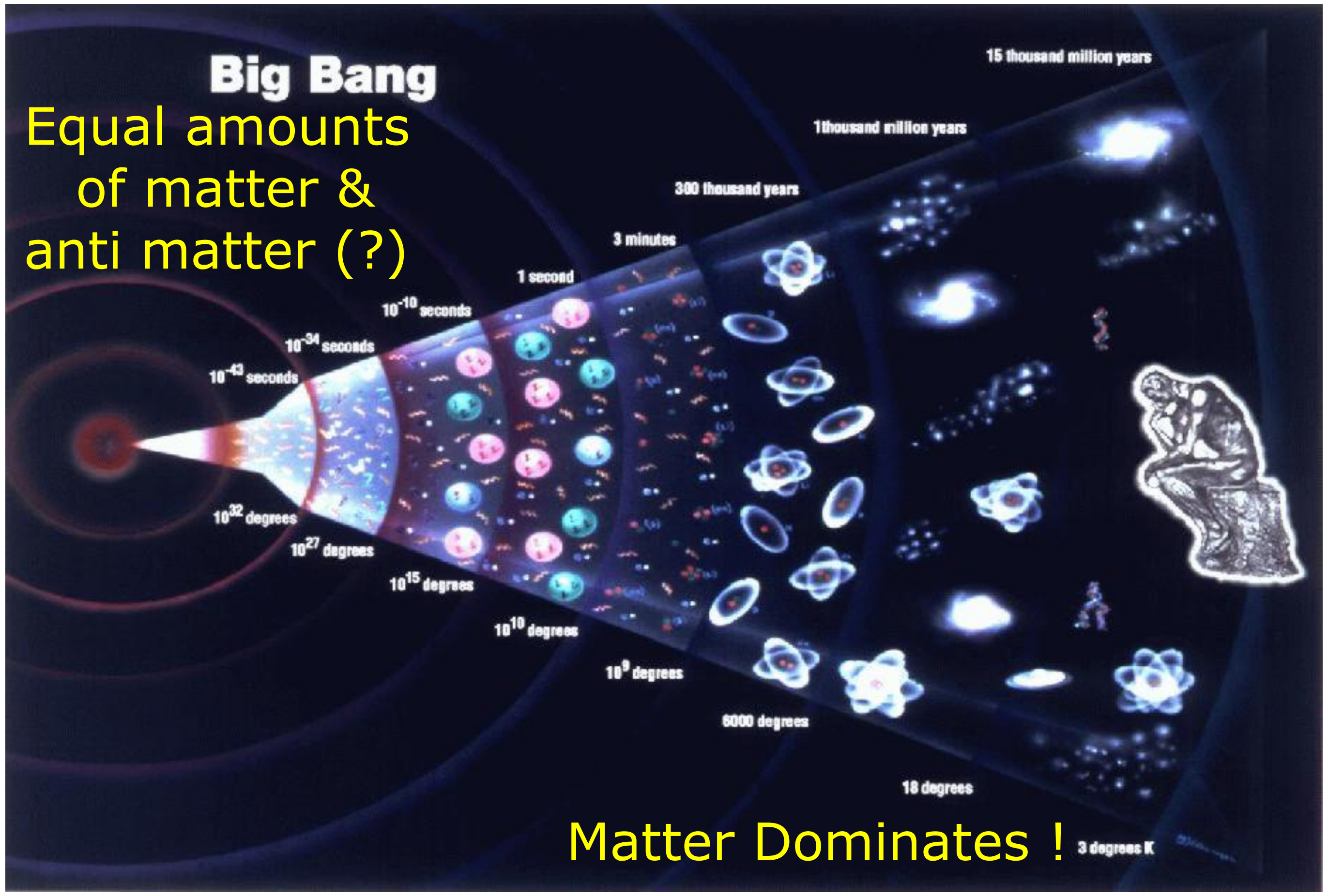


It does not explain matter and anti-matter asymmetry:



Equal amounts of matter & anti matter (?)

Matter Dominates !

SM expectation: vs. Observed:

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

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

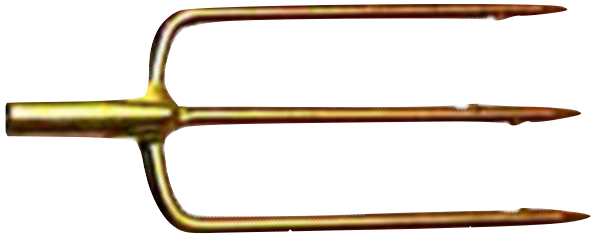
Frontiers of BSM Physics Search

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

The Energy Frontier (high-energy colliders)

The Intensity/Precision Frontier (intense particle beams)

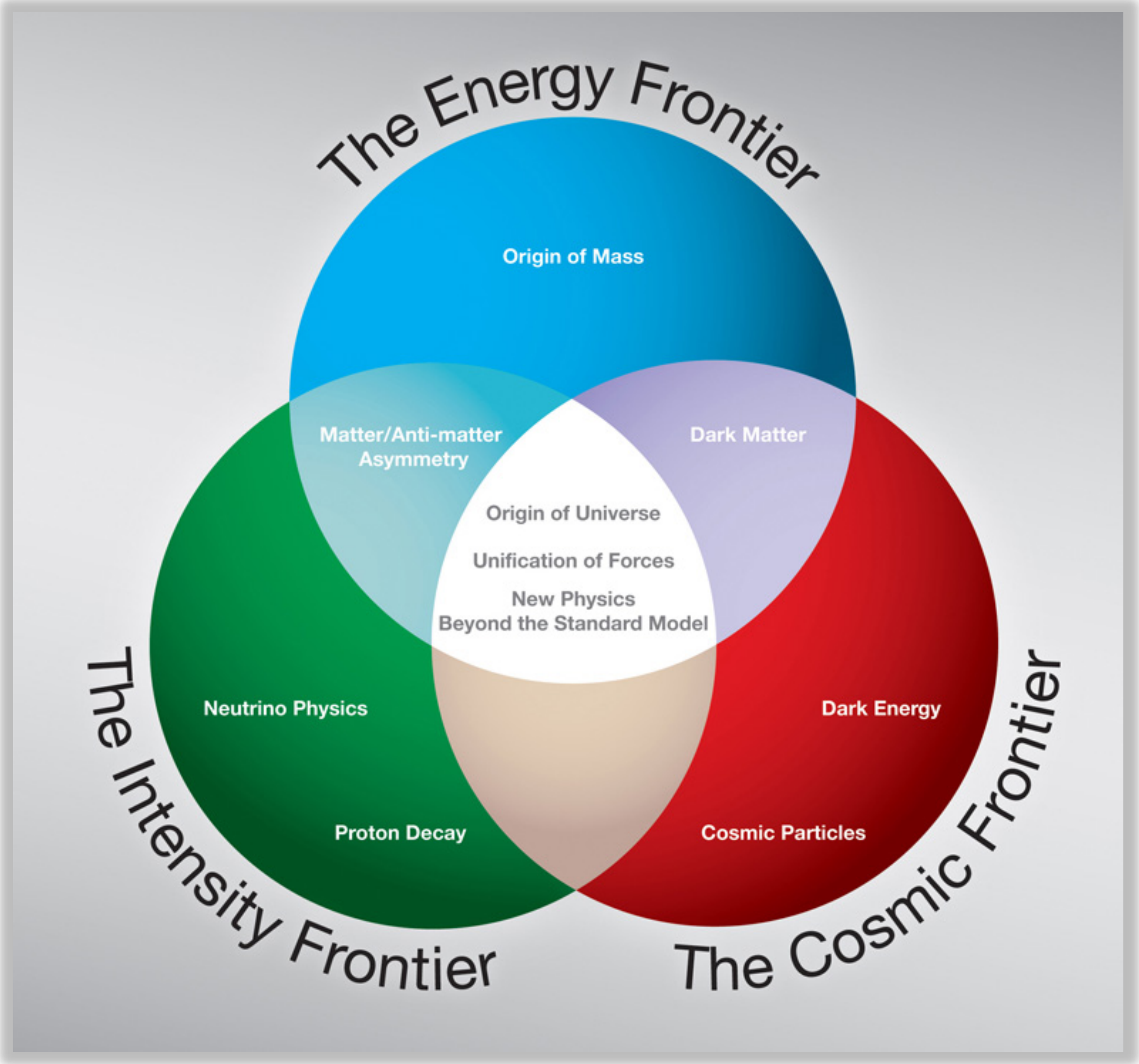
The Cosmic Frontier (underground experiments, ground and space-based telescopes)



Energy

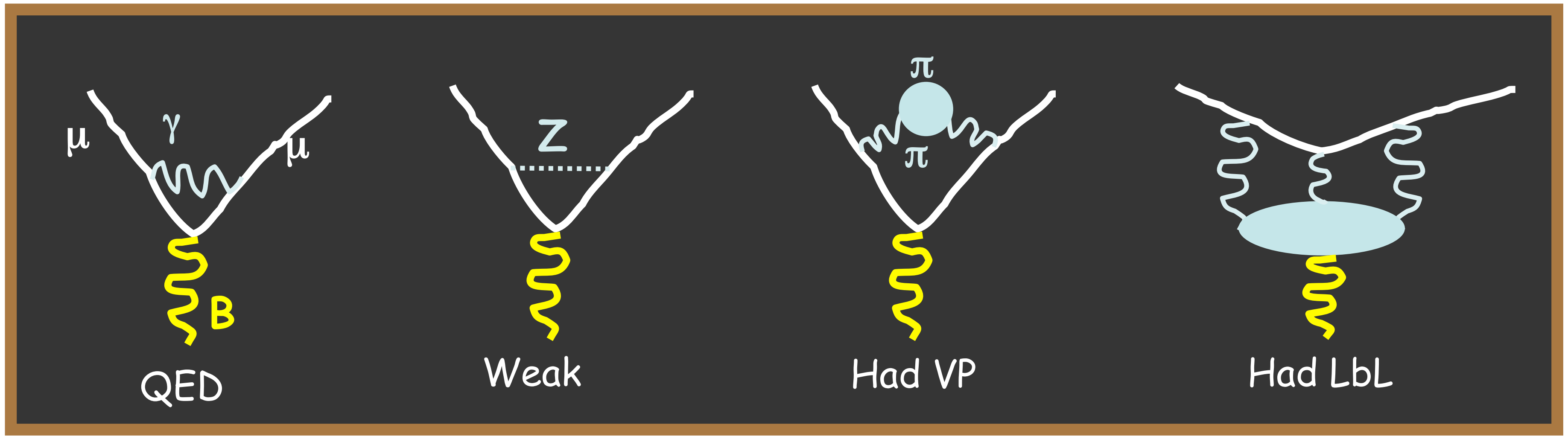
Intensity/Precision

Cosmic



Precision Frontier: $(g\text{-}2)_\mu$

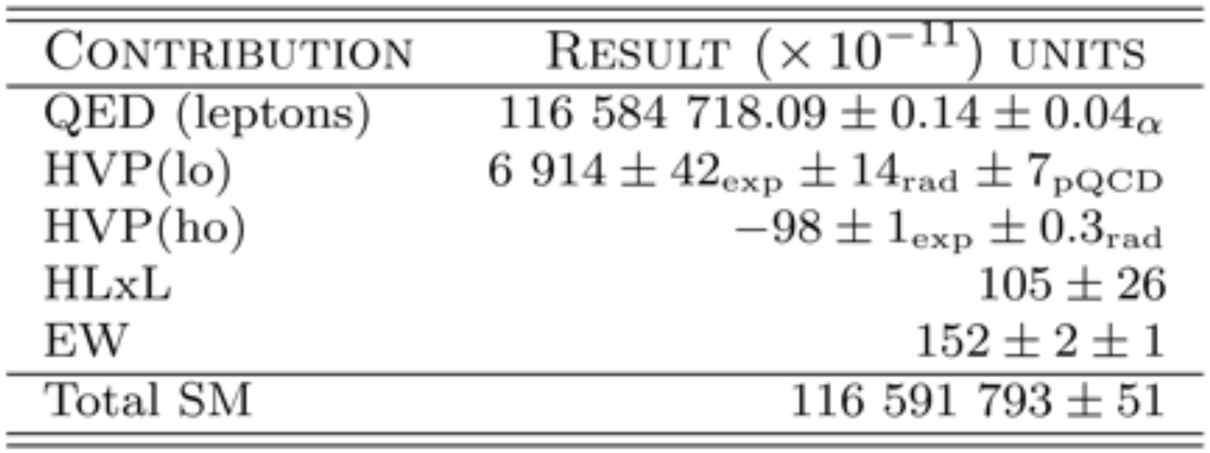
$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$



Known well

Theoretical work ongoing

$$a = \frac{g-2}{2}$$



CONTRIBUTION	RESULT ($\times 10^{-11}$) UNITS
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 914 \pm 42_{\rm exp} \pm 14_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-98 \pm 1_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 793 \pm 51$

The "g-2 test": Compare experiment to theory. Is SM complete?

$$\delta a_\mu^{NewPhysics} = a_\mu^{Expt.} - a_\mu^{Theory}$$

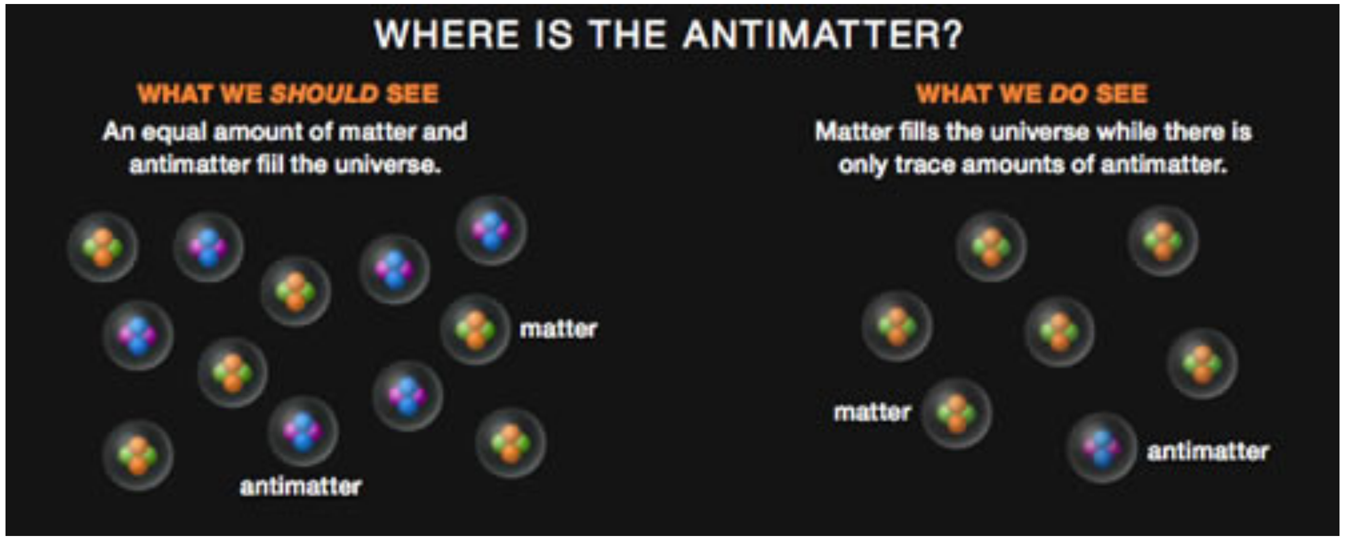
$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(80) \times 10^{-11}$ (*3.6σ discrepancy!*)

$\Delta a_e = a_e^{exp} - a_e^{SM} = -105(81) \times 10^{-14}$ (1000x more precise)

Matter/Antimatter Asymmetry

Sakharov criteria for matter/anti-matter asymmetry:

- *Baryon number violation*
- *C and* ***CP violation***
- *Thermal non-equilibrium*



WHERE IS THE ANTIMATTER?

WHAT WE *SHOULD* SEE

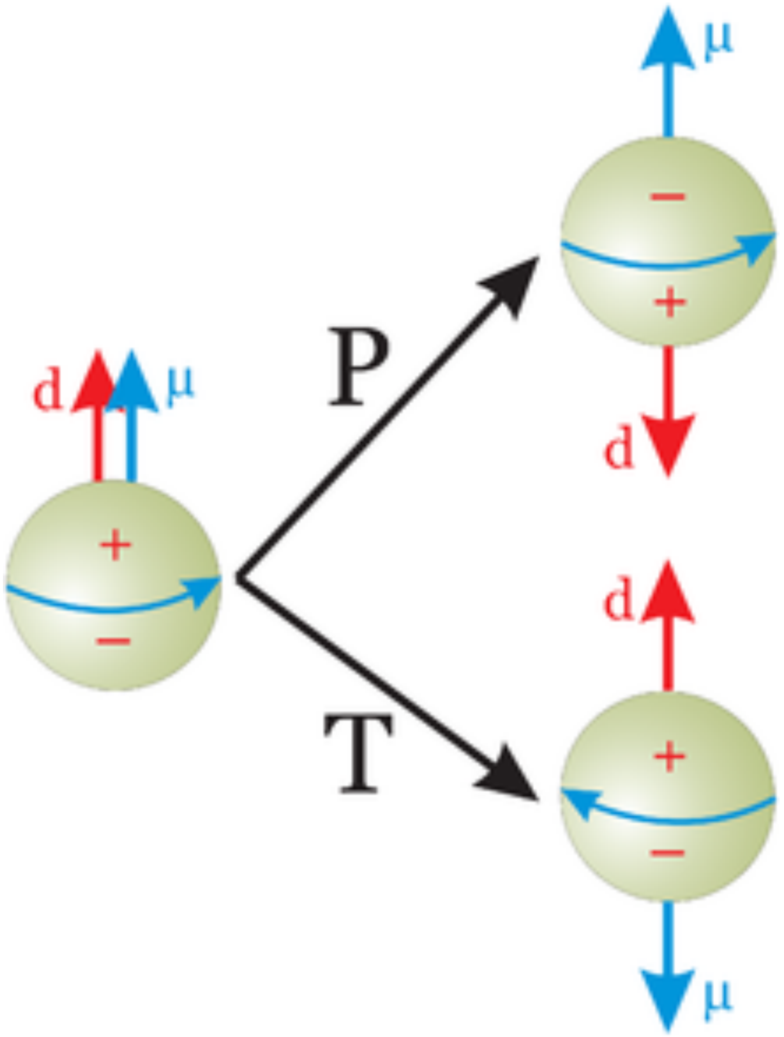
An equal amount of matter and antimatter fill the universe.

WHAT WE *DO* SEE

Matter fills the universe while there is only trace amounts of antimatter.

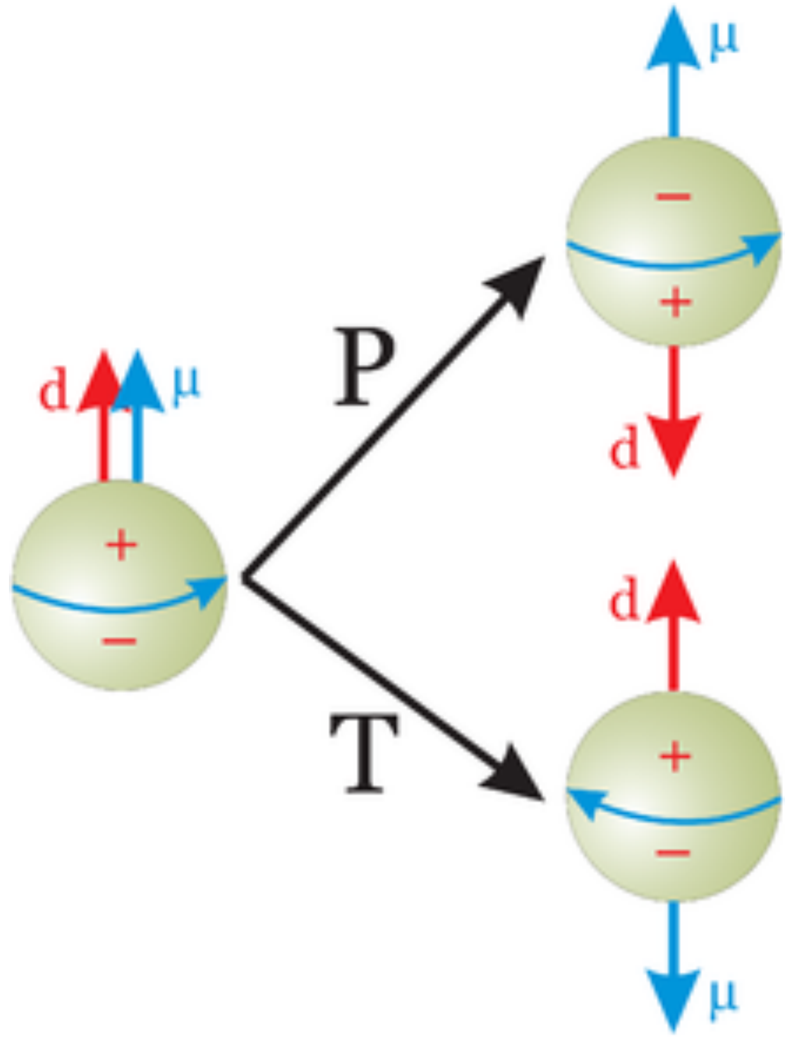
- CP violation so far only in weak decays.
- Might help explain BAU matter/anti-matter problem.
- Excellent probe for physics beyond the Standard Model (complementary to LHC)

Standard Model: CP Violation



A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP.

Standard Model: CP Violation



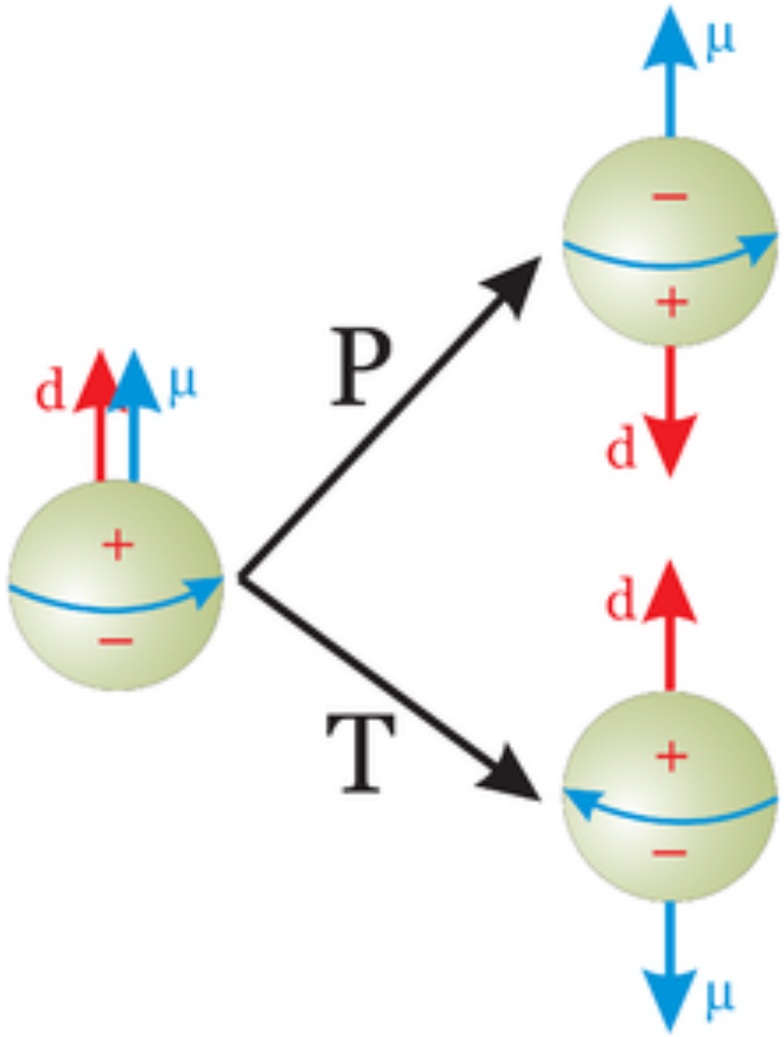
A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP.

QCD vacuum:

$$L_{eff} = L_{QCD} + \theta \frac{\alpha_s}{8\pi} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

$$d_n \approx \theta \times 10^{-15}\, e\cdot\text{cm} \rightarrow \theta \approx 10^{-10}$$

Standard Model: CP Violation



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Phase of CKM matrix:

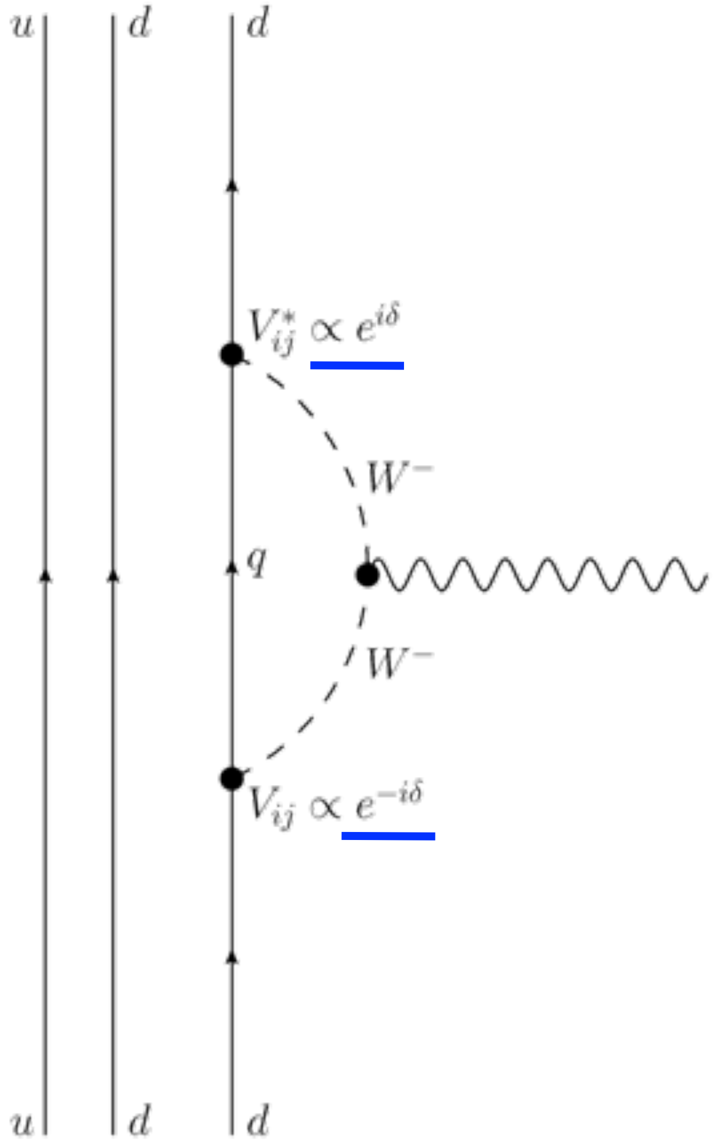
$$\begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{ub} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

Known from neutral K and B meson decays

nEDM from CKM Matrix

- No tree level contribution
- No first loop contribution
- No pure week interaction two loop contribution
- Only gluon two loop contribution
  → strongly suppressed

nEDM from CKM Matrix



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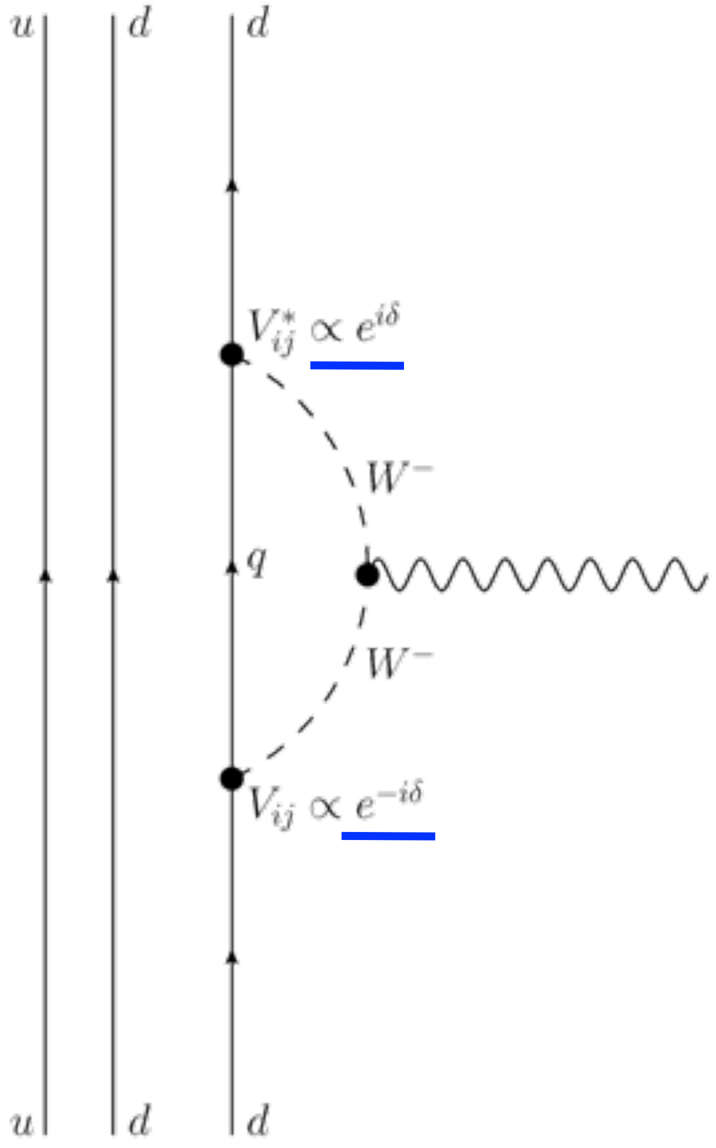

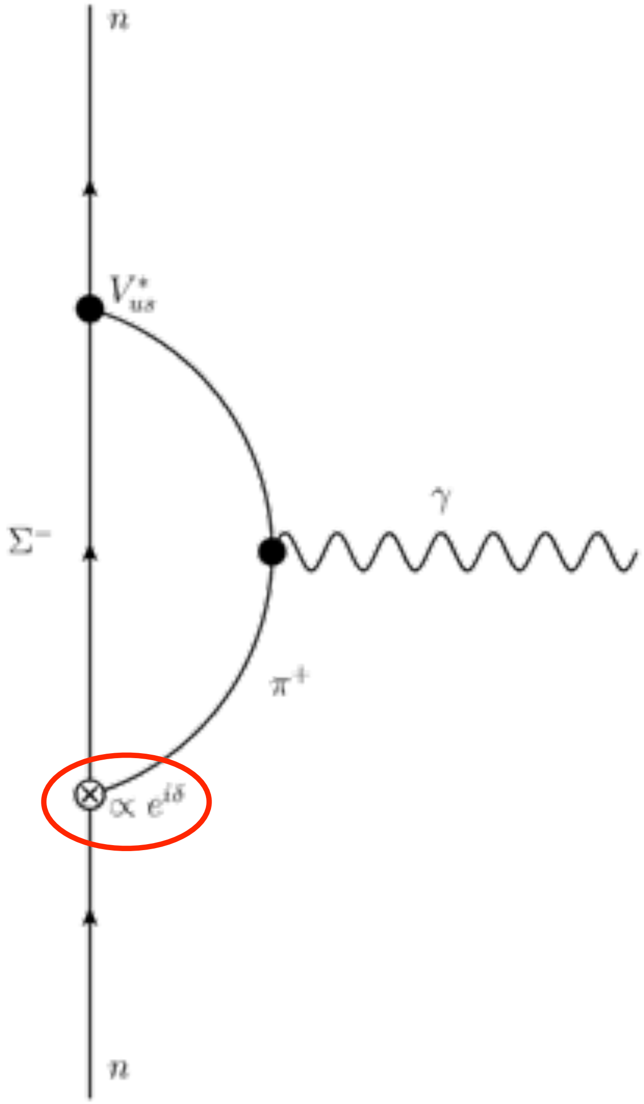

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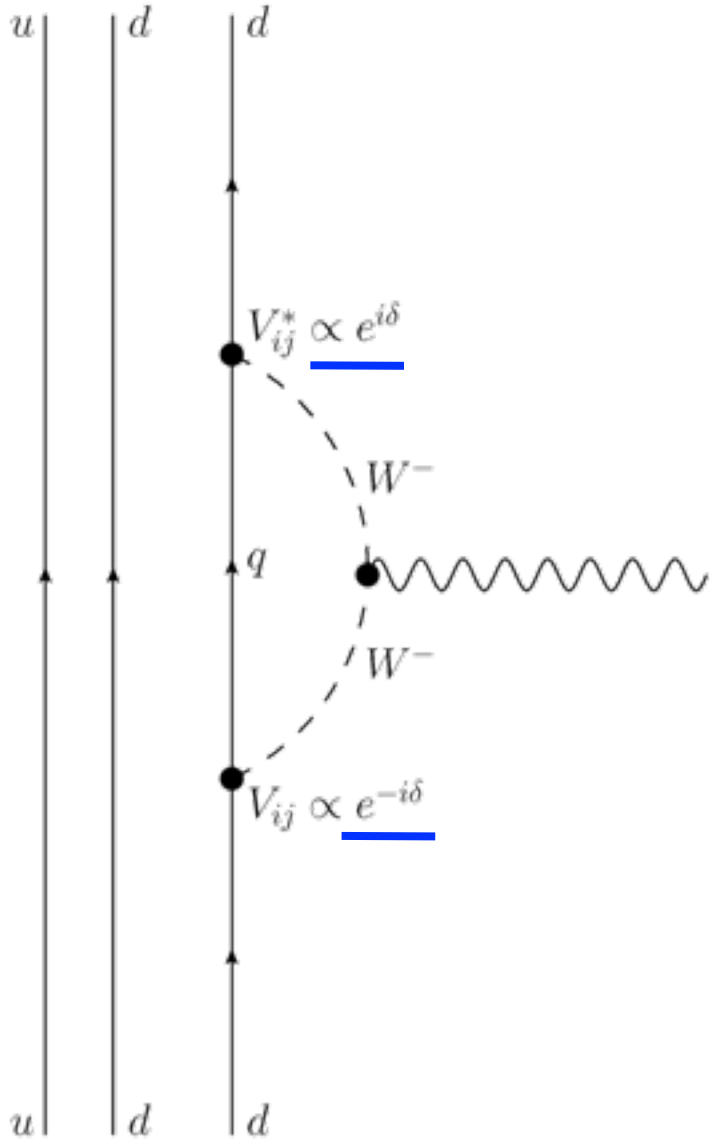
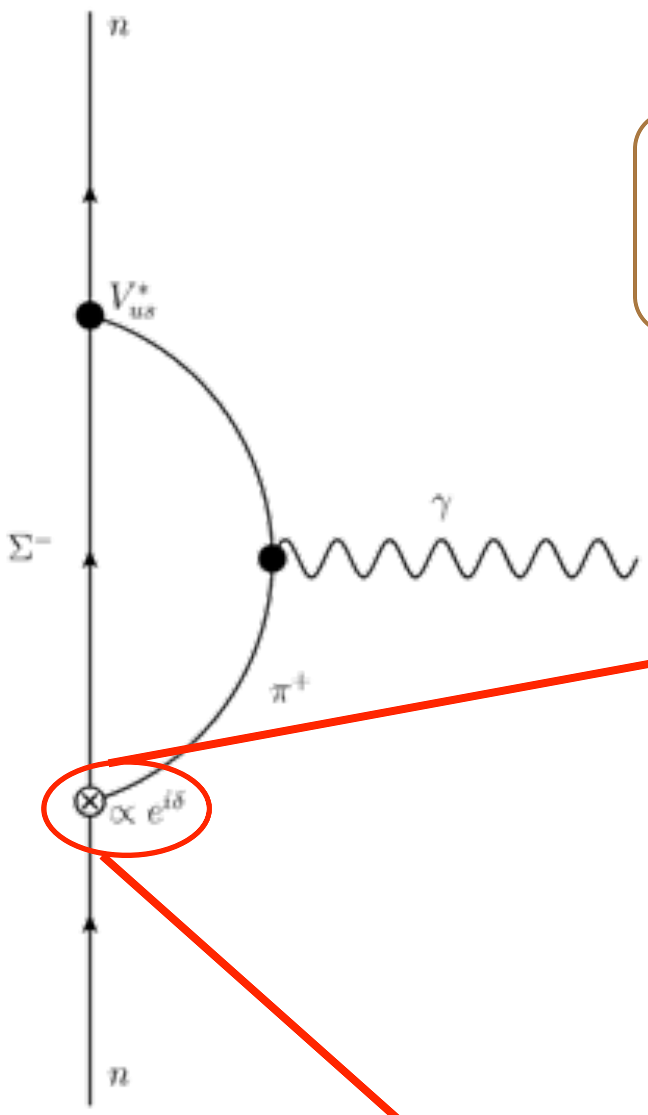
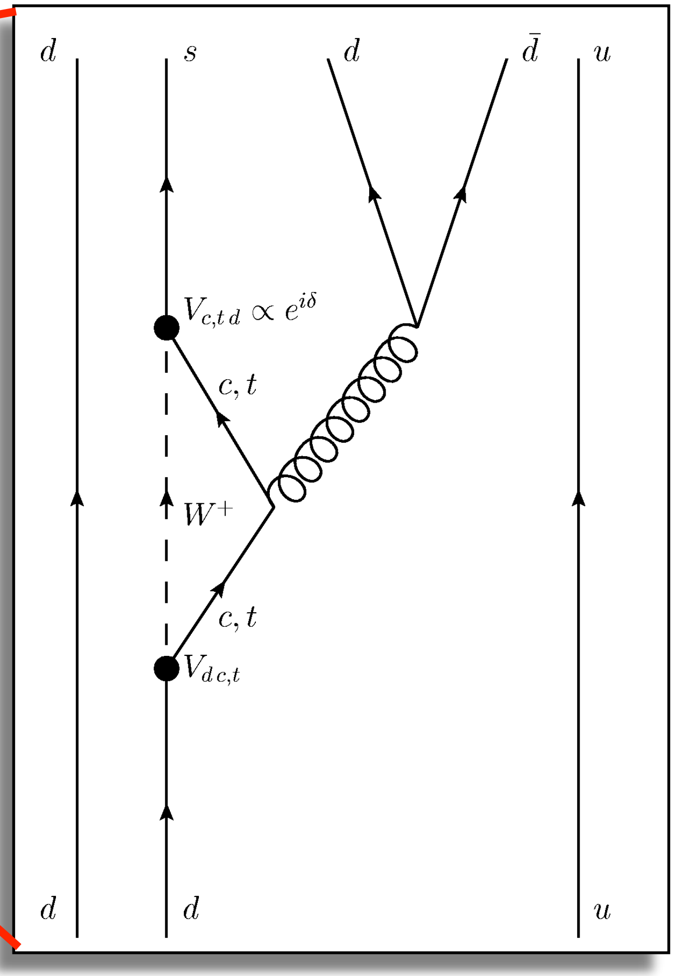






Standard Model nEDM:
10^{-30} e·cm > d_n >10^{-32} e·cm

- No tree level contribution
- No first loop contribution
- No pure week interaction two loop contribution
- Only gluon two loop contribution
  → strongly suppressed

Measurements of nEDM

First

Smith, Purcell, Ramsey

$d_n < 5 \times 10^{-20}$ **e cm**

PR 108 (1957) 120

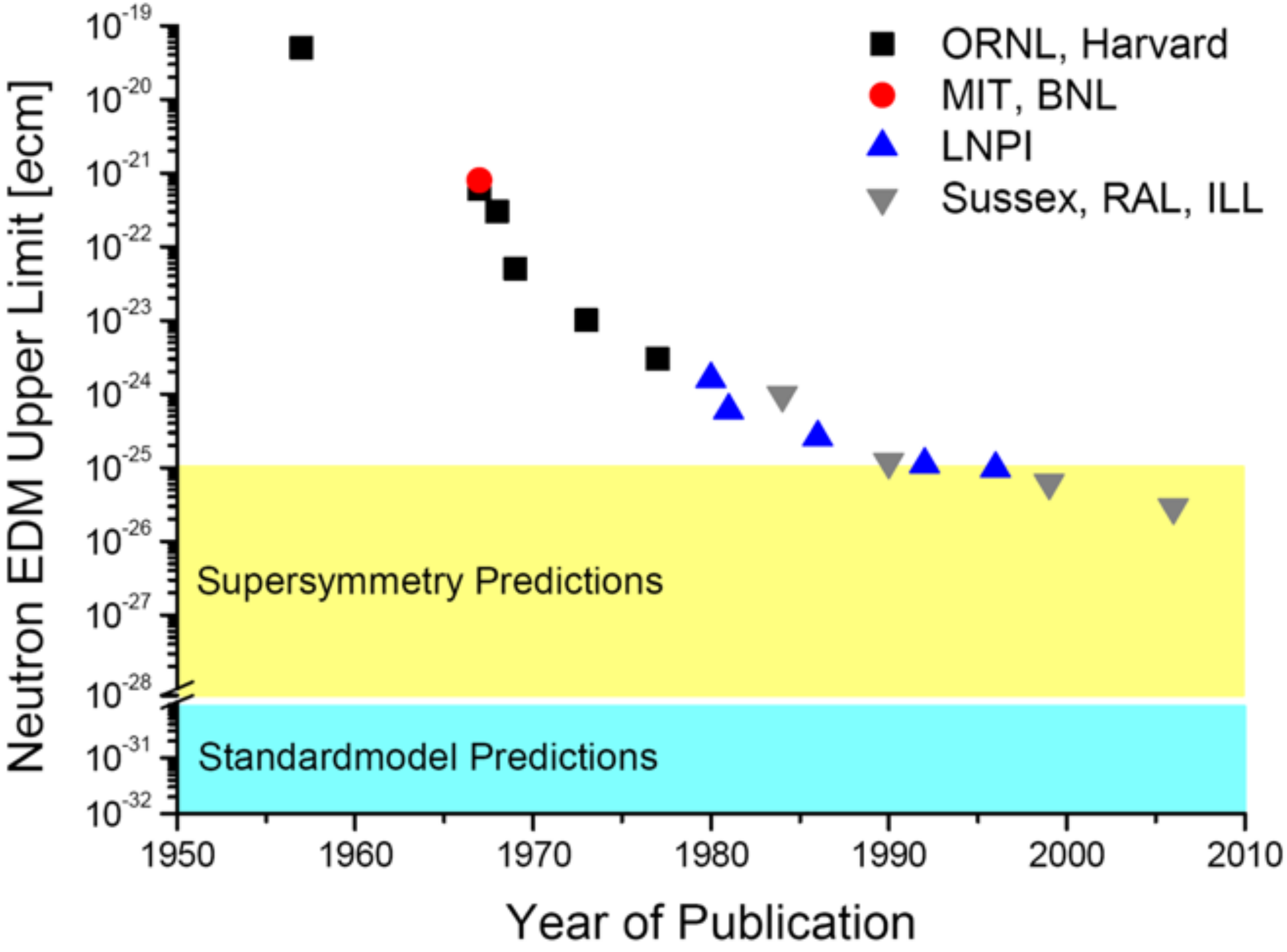
~ 50 years

Last

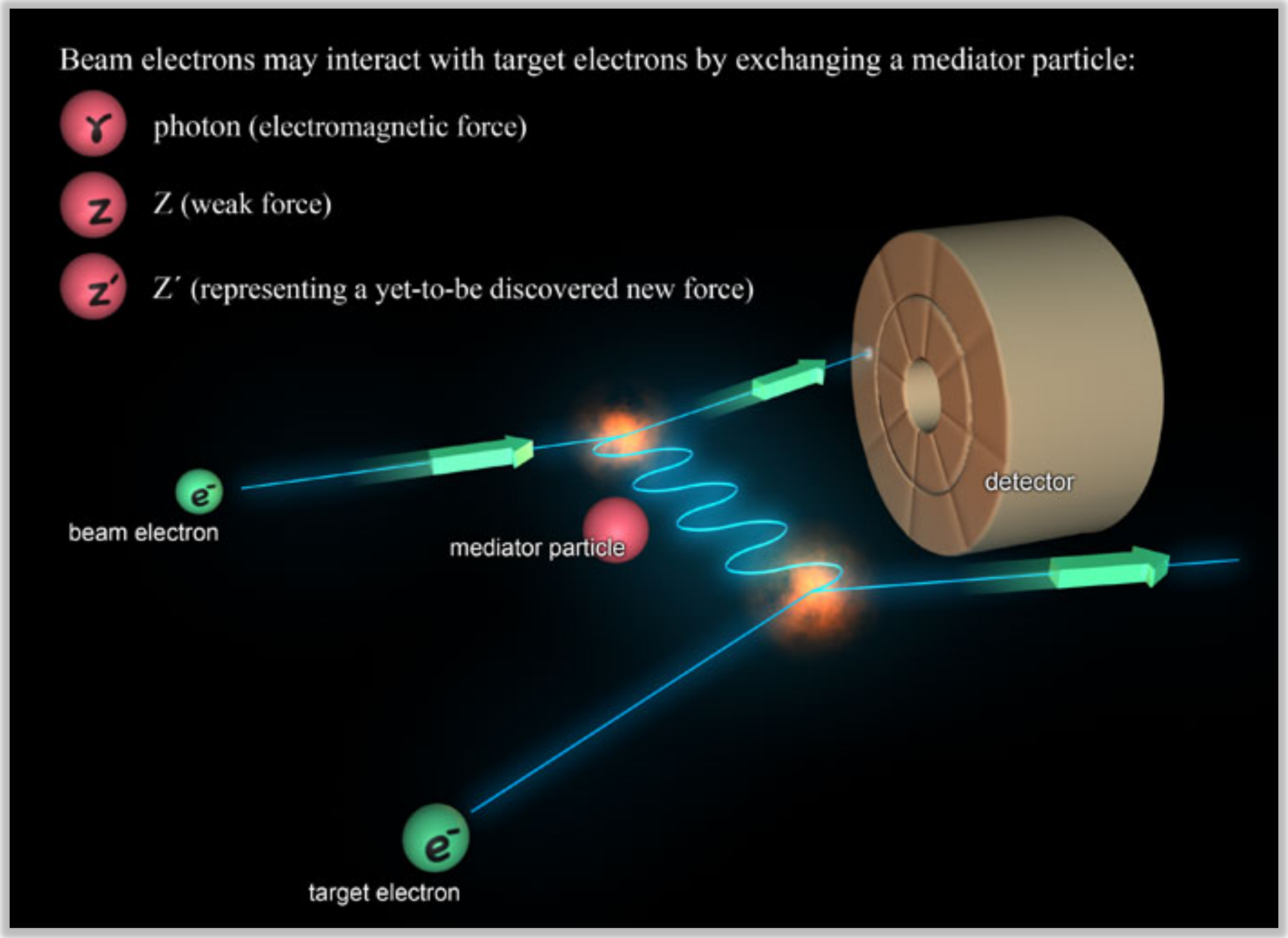
RAL-Sussex-ILL

$d_n < 2.9 \times 10^{-26}$ **e cm**

C.A.Baker et al., PRL 97 (2006) 131801



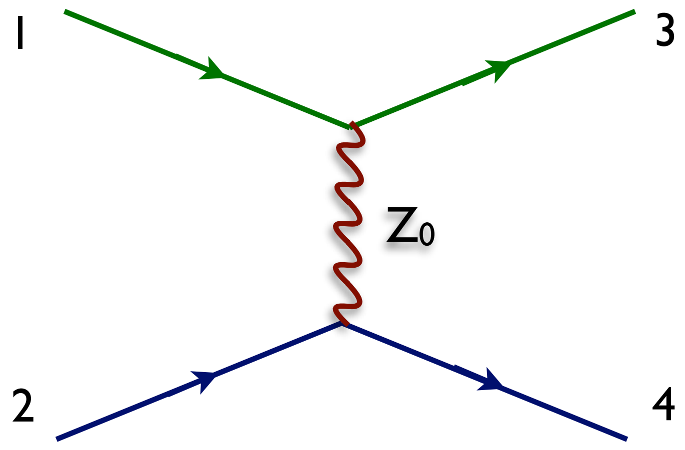
Precision scattering measurements



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

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*



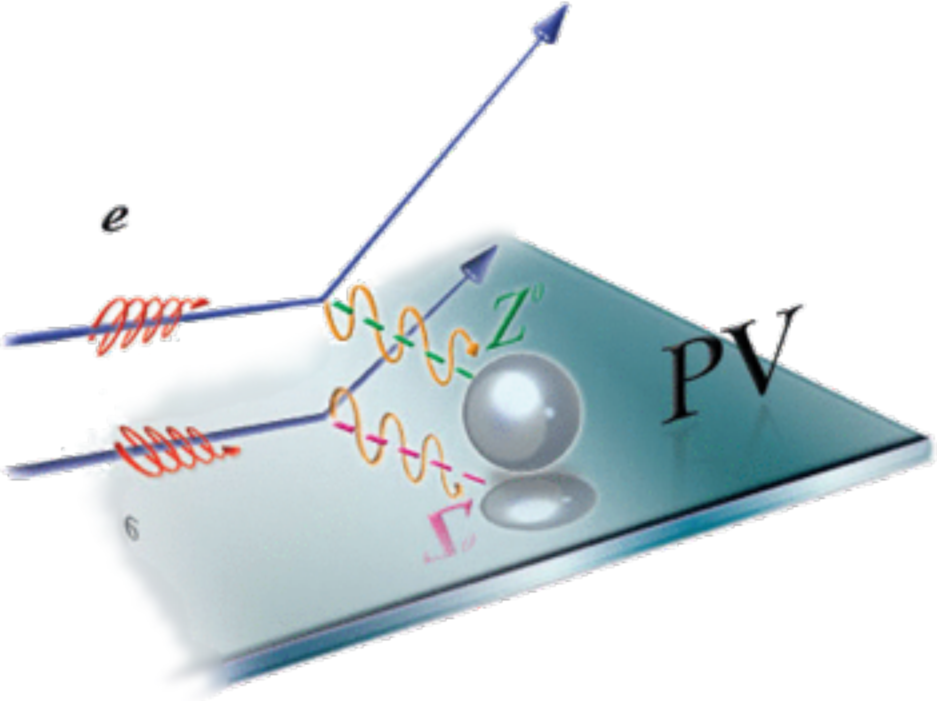
- Precision Neutrino Scattering
- New Physics/Weak-Electromagnetic Interference
  - *opposite parity transitions in heavy atoms*
  - *parity-violating electron scattering*

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

Weak Charge of Proton: 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):

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

Scale of BSM Physics in Weak Interactions

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

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

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

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

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:

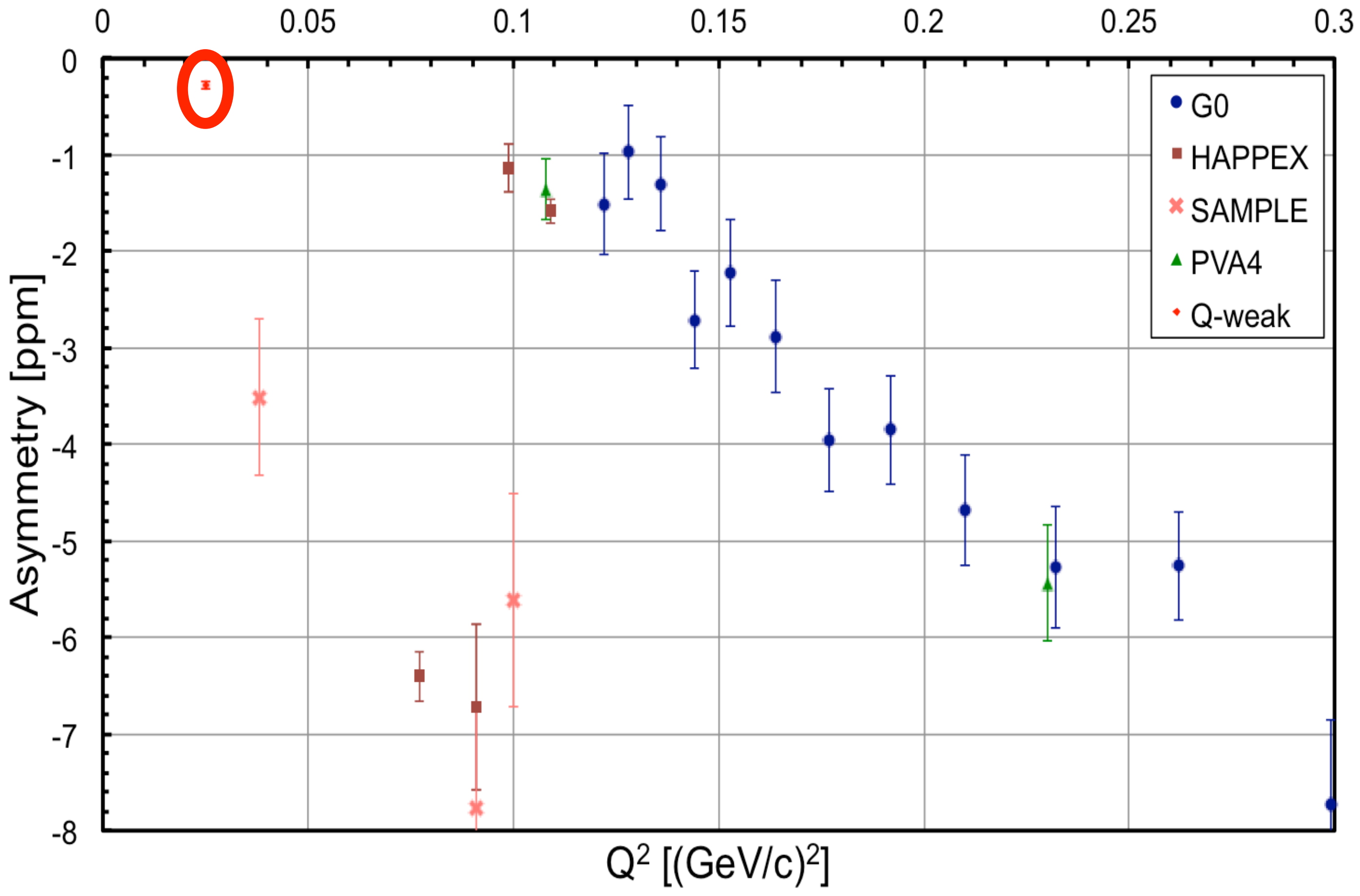
$$Q^p_W(\mathrm{SM}) = -2(2C_{1u} + C_{1d})$$

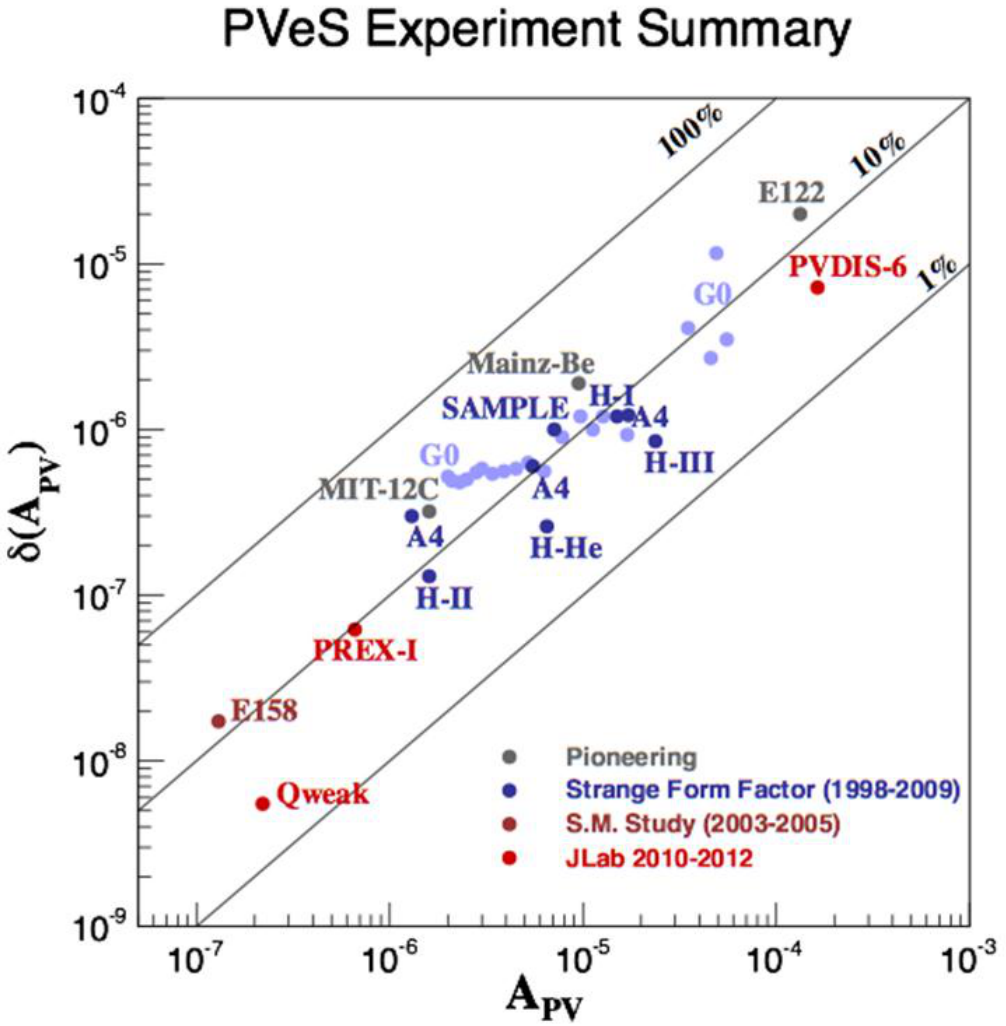
A precise measurement of $Q_W(p)$ would thus test new physics scales up to TeV scales:

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

Results from Qweak Experiment

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





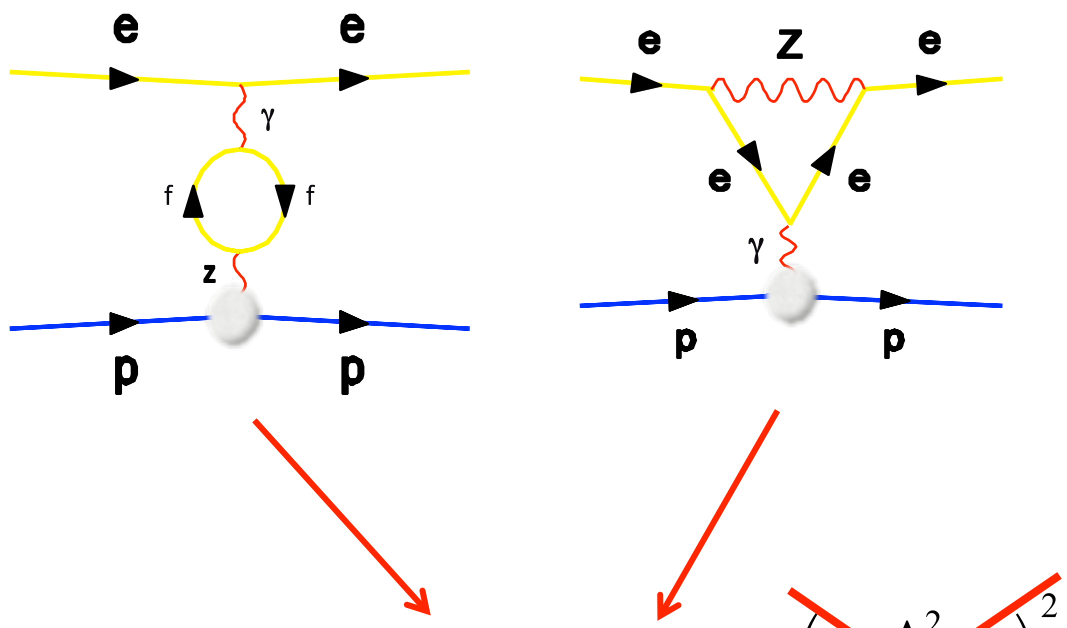
Beam energy at vertex , $< E_{\rm eff} >$	1.155 ± 0.003 GeV
Momentum transfer $< Q^2_{\rm eff} >$	0.0250 ± 0.0006 $({\rm GeV})^2$
Effective scattering angle, $< \theta_{\rm eff} >$	$7.90 \pm 0.30^{\circ}$

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

Qweak Collaboration: PRL 111, 141803 (2013)

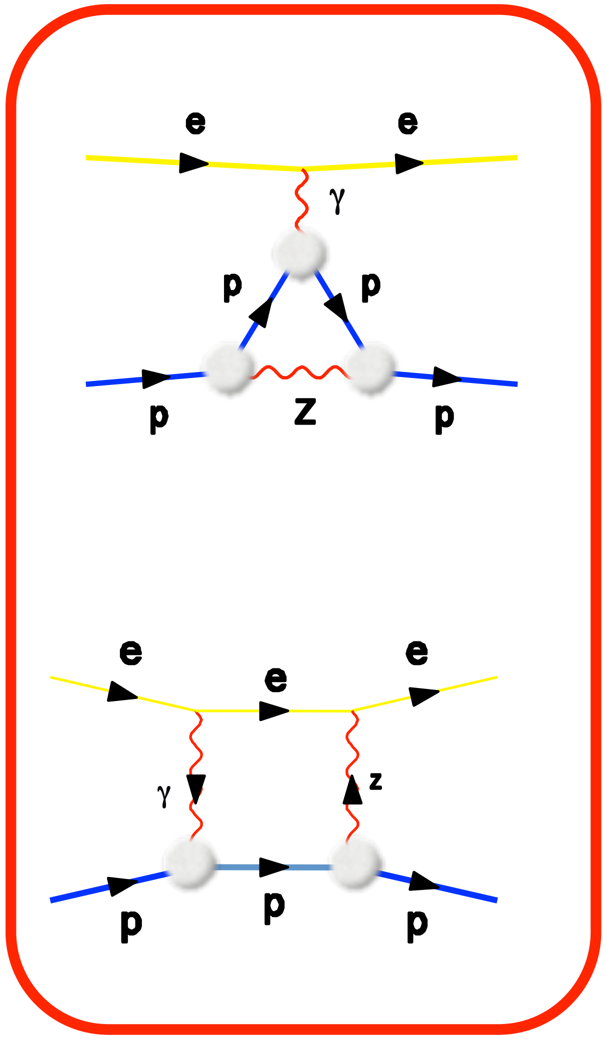
Hadronic Corrections and Total Asymmetry

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

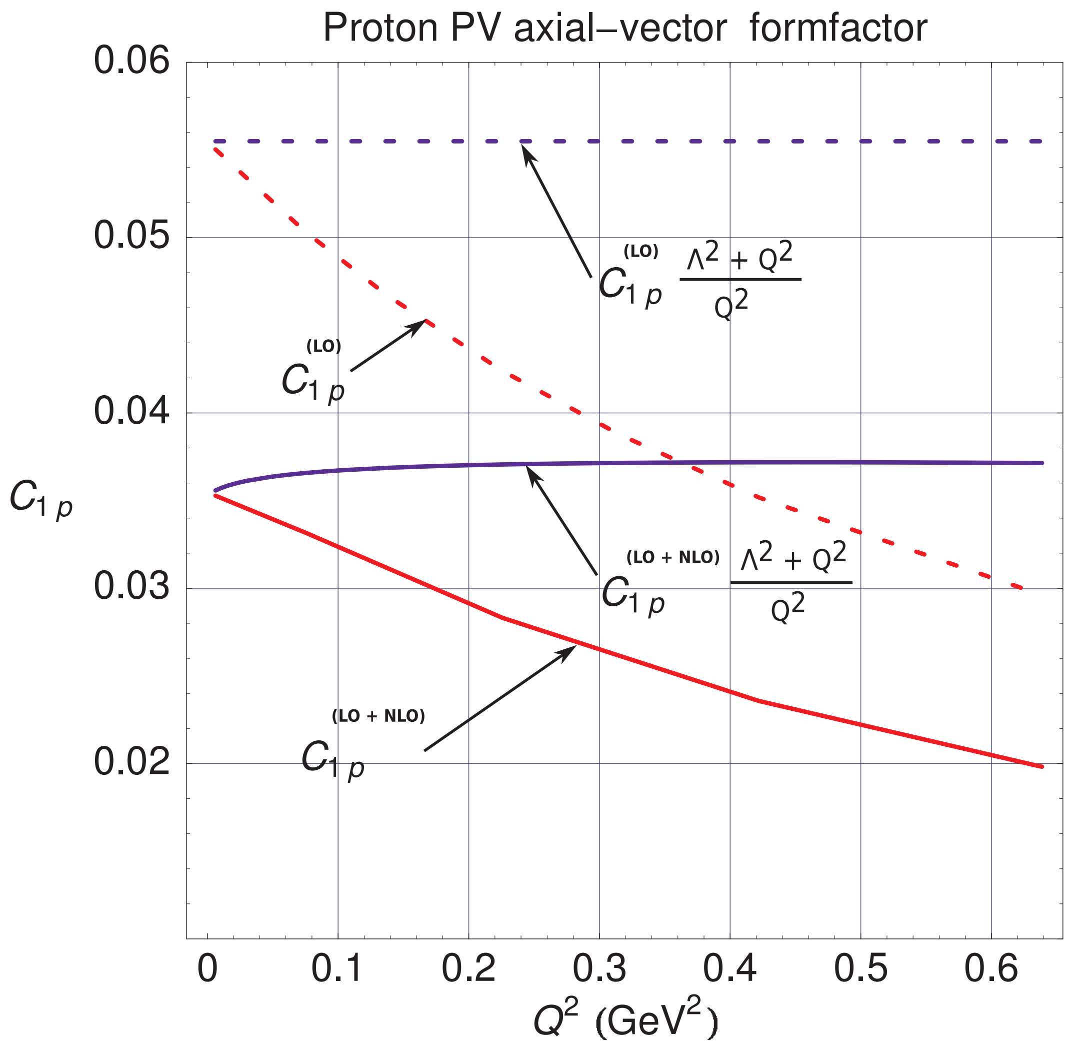


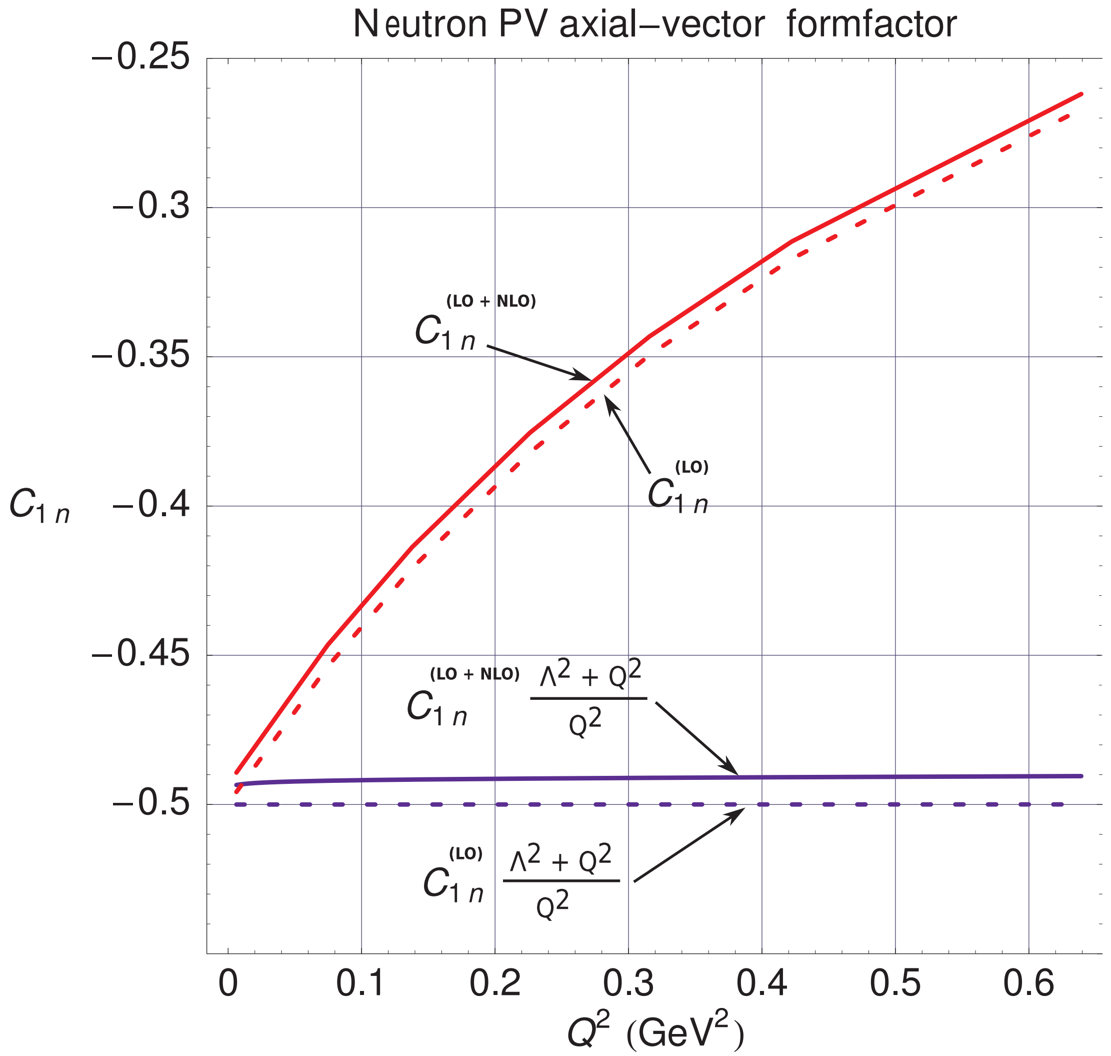
Using hadronic uncertainty analyzes for γZ box from M. Gorchtein, Phys. Rev. Lett. 102, 091806 (2009) and A. Sibirtsev et. al., arXiv:1002.0740 [hep-ph], and applying full set of on-shell NLO contributions, we get following PV electron-proton asymmetry:

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

Weak Formfactor and Weak Charge

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





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

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

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

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

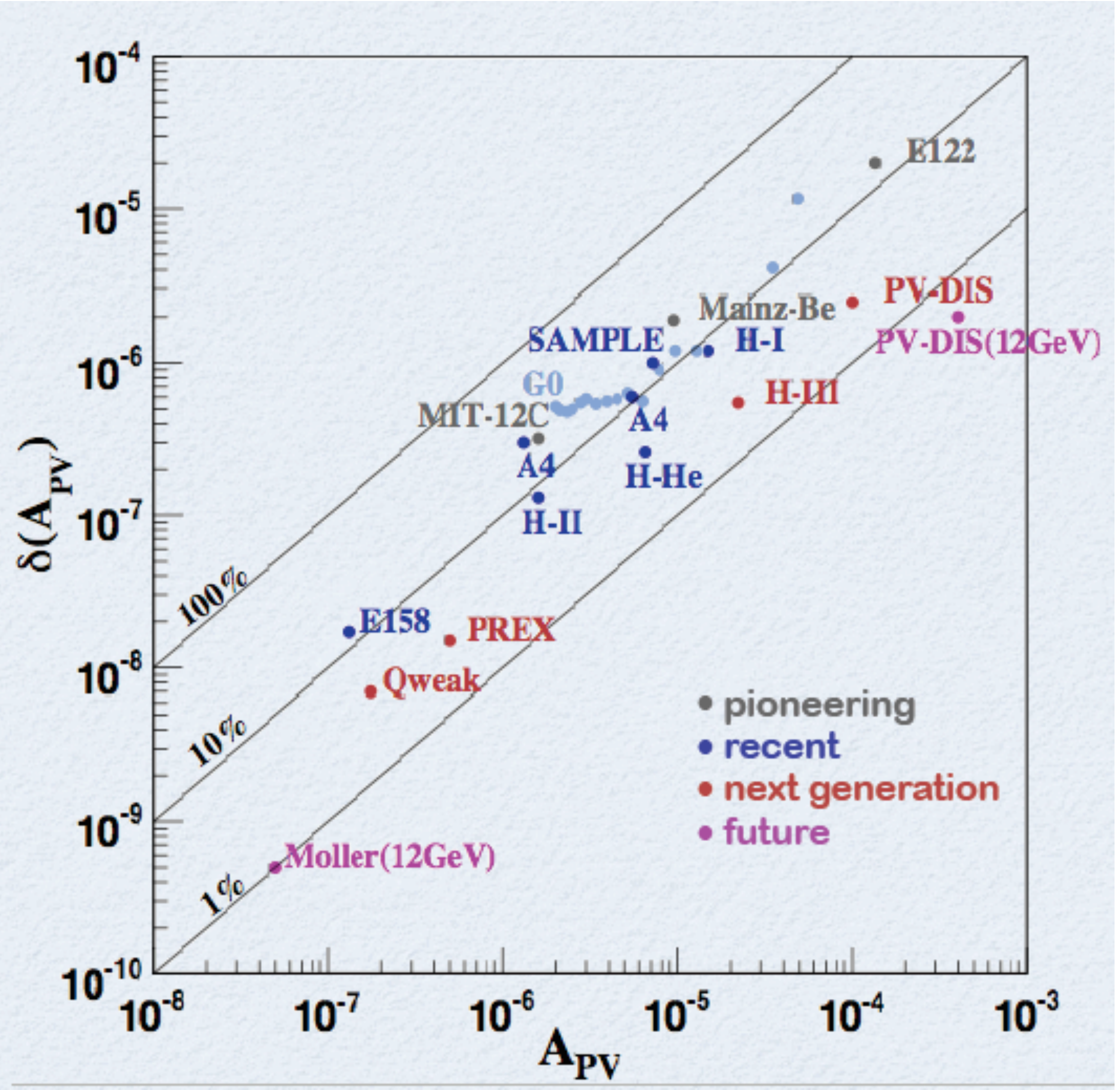
$$Q^{p(Exp)}_{weak} = 2C_{1p} = 0.064 \pm 0.012$$

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

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

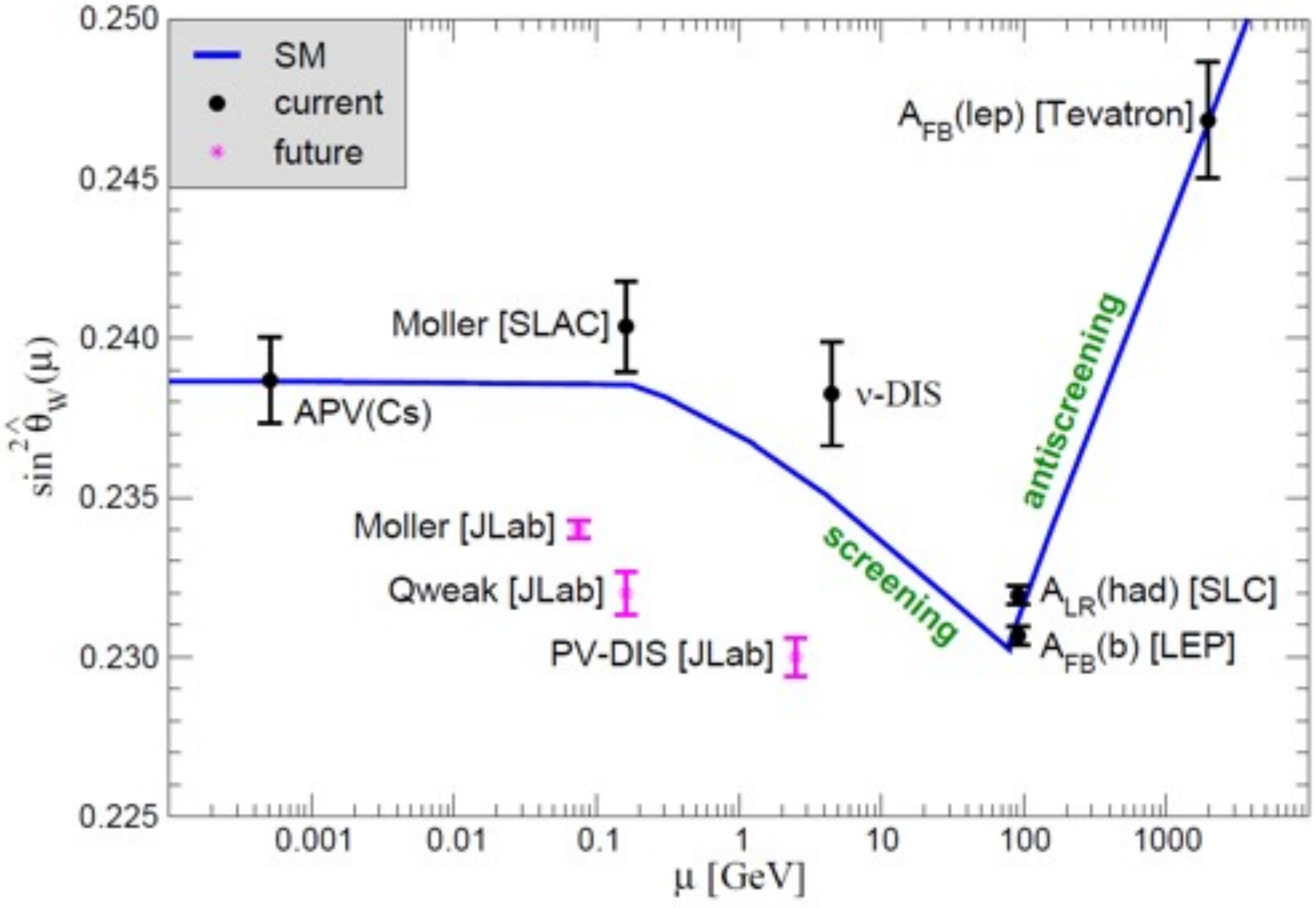
The first observation of Parity Violation in Møller scattering was made by E-158 experiment at SLAC:

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

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

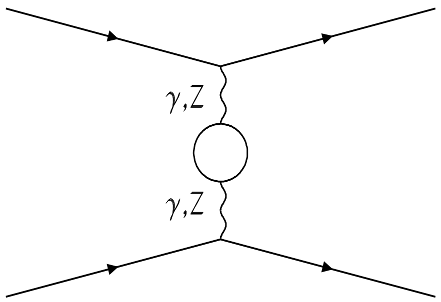
MOLLER, planned at JLab following the 11 GeV upgrade, will offer a new level of sensitivity and measure the parity-violating asymmetry in the scattering of longitudinally polarized electrons off unpolarized target to a precision of 0.73 ppb.

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.

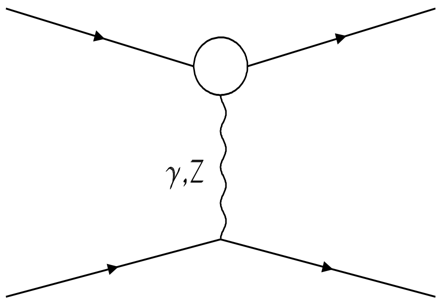


J. Benesch et al., MOLLER Proposal to PAC34, 2008

One-Loop Corrections for MOLLER



(1)



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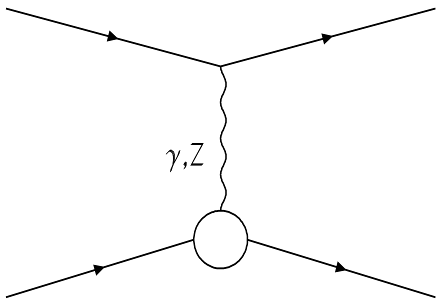

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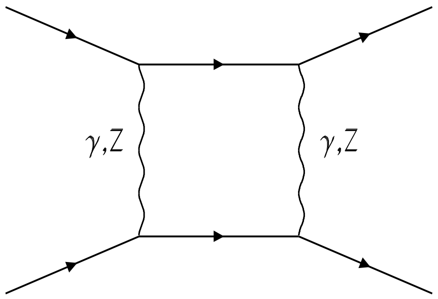

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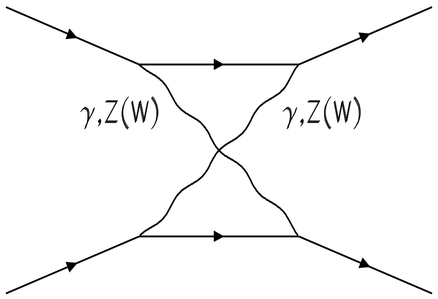


(5)

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

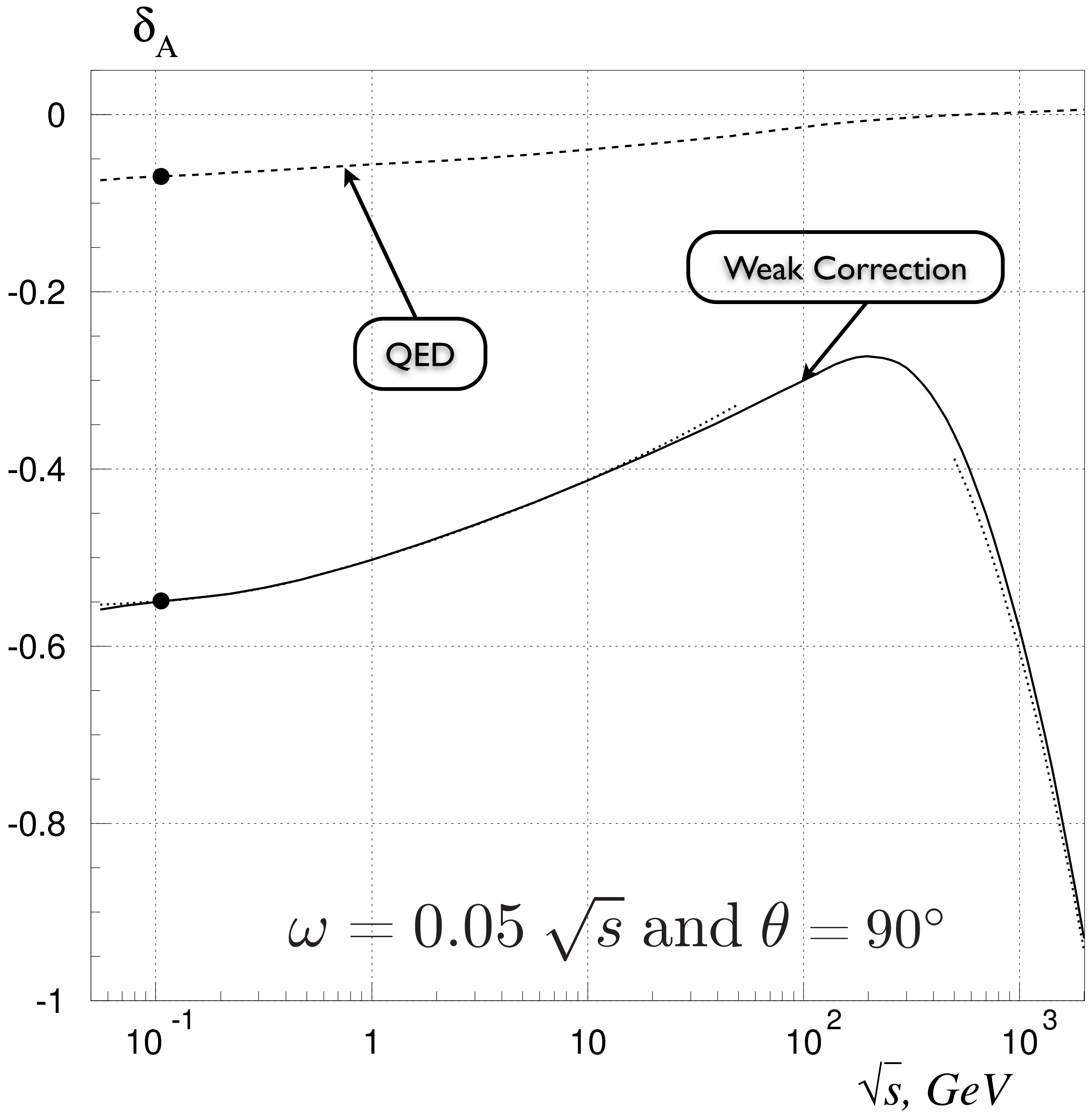
$$\sigma_1 = \sigma_1^{BSE} + \sigma_1^{Ver} + \sigma_1^{Box}$$

- 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 $\sqrt{s} \gg 500\ GeV$

One-Loop Corrections for MOLLER



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

The relative weak (solid line in DRC (semi-automated) and dotted line in HRC ("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.

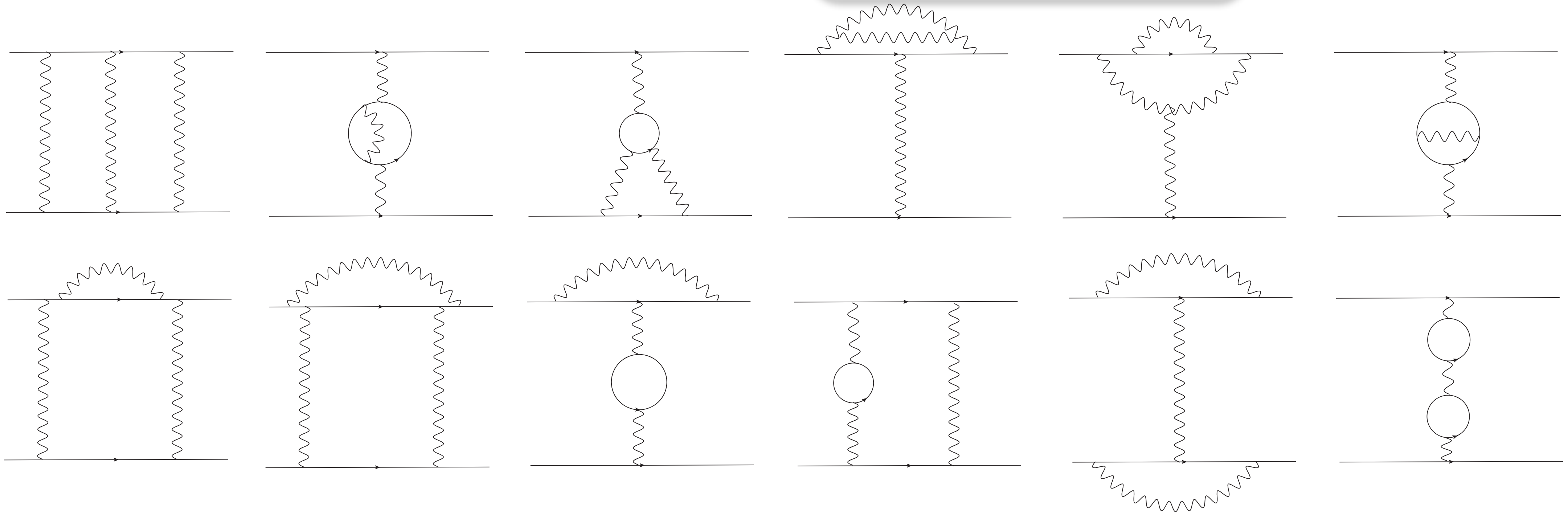
Two-Loop Corrections for MOLLER

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 ~ $2\text{Re}M_0M_{2\text{-loop}}^+$.

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

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



+ ...

Combination of 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:

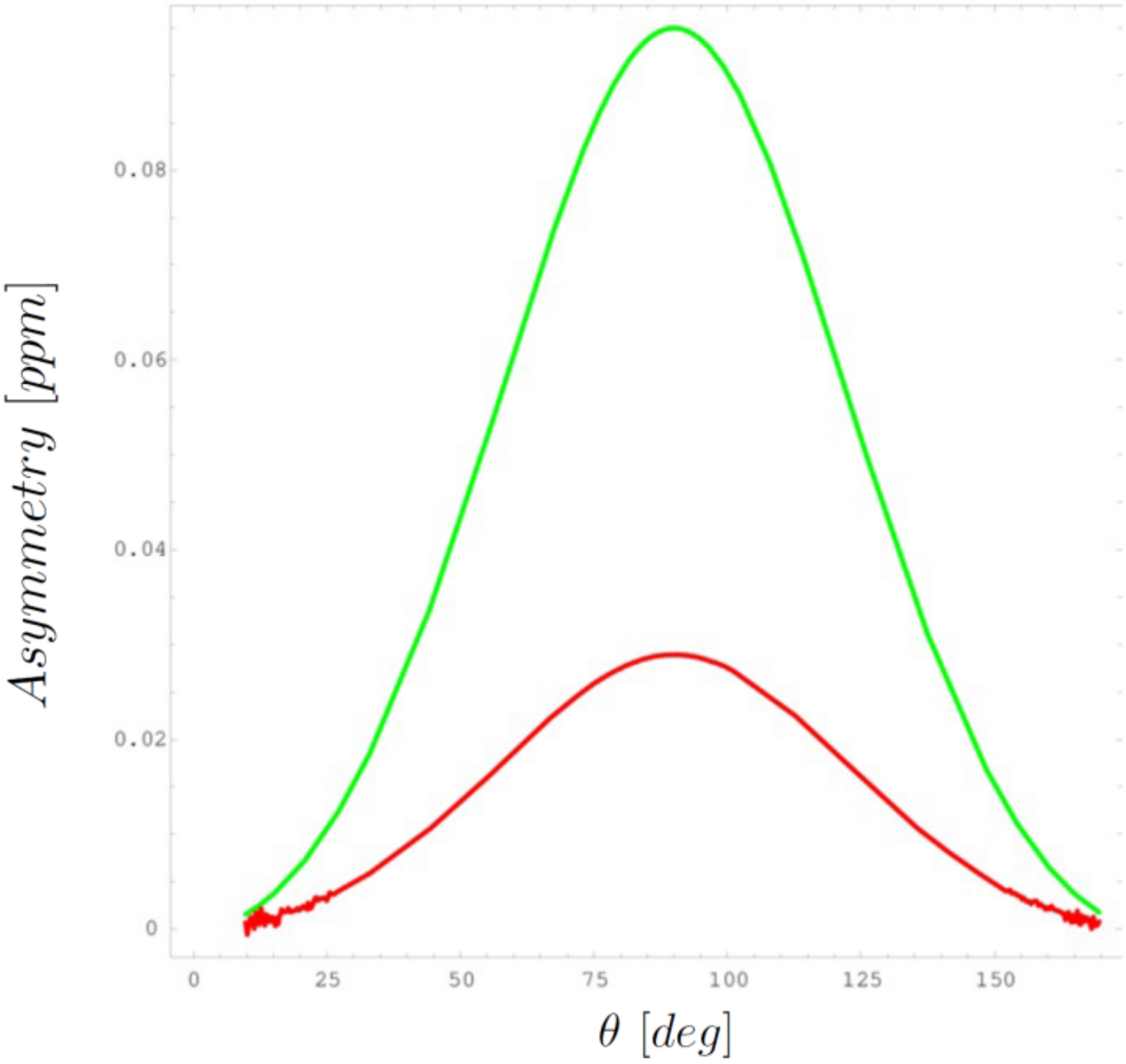
$$\delta_A^C = \frac{A_{LR}^C - A_{LR}^0}{A_{LR}^0}$$

Soft-photon bremsstrahlung cut:

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

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

PV Asymmetry



Predicted PV asymmetry up to NNLO:

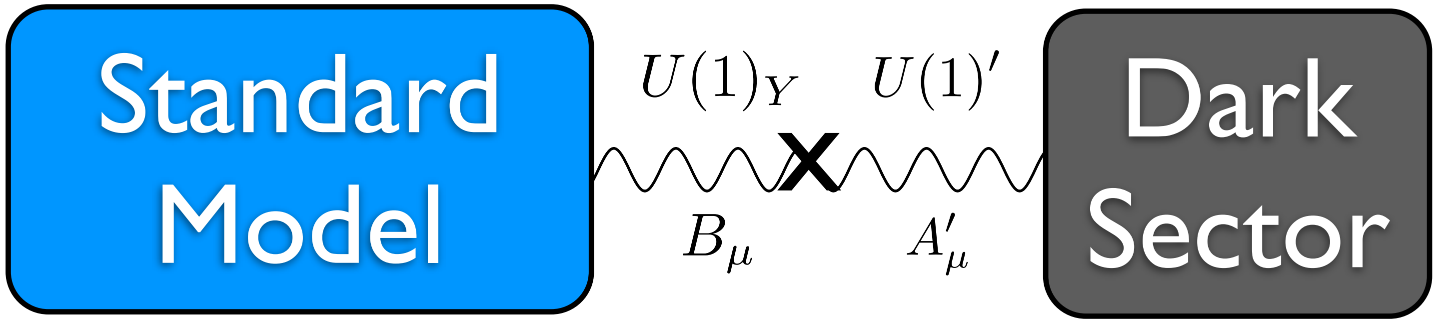
$A_{PV}^{(LO)}$ = 94.96 (ppb)

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

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

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

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

- 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)

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

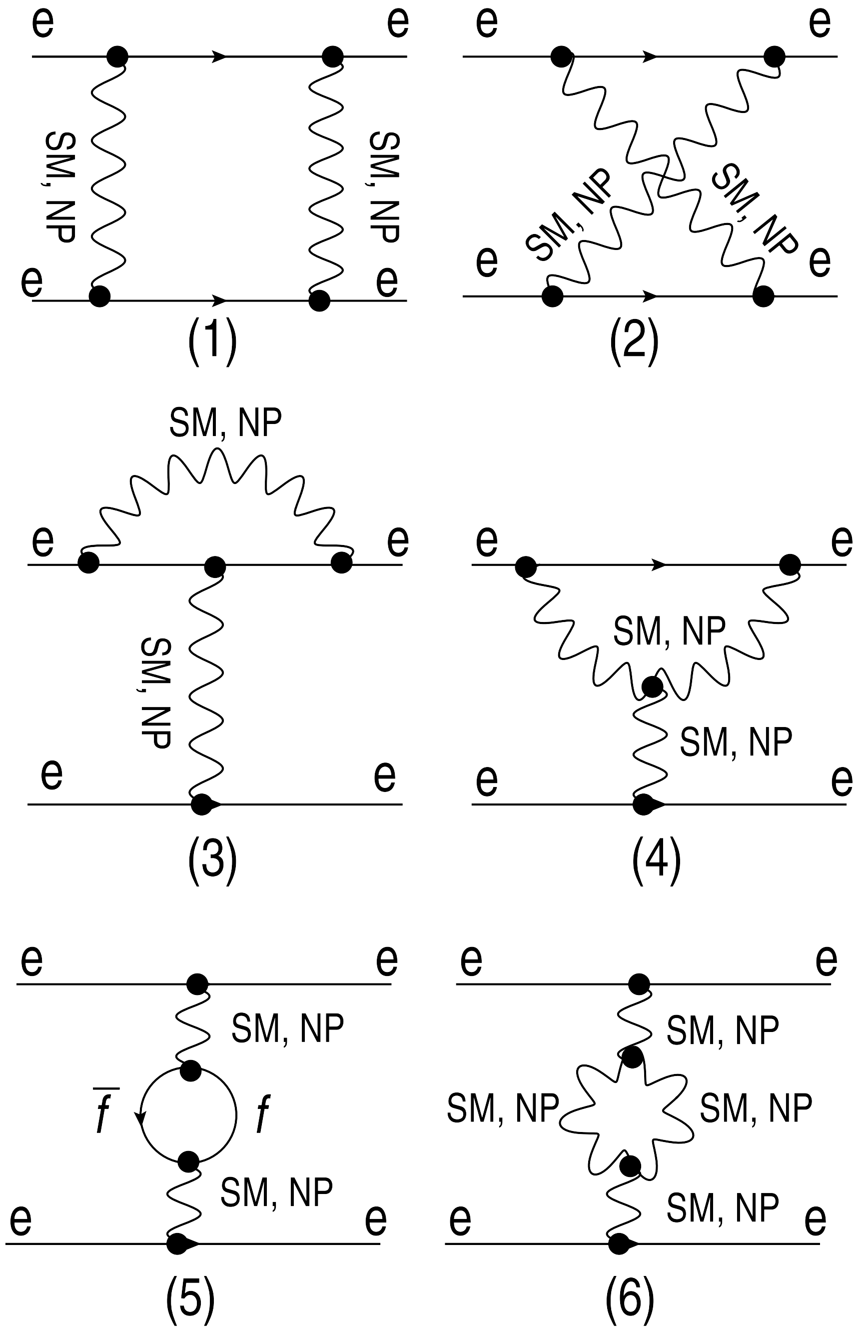
$\epsilon_{Z'} = \delta \frac{m_{Z'}}{m_Z}$, where $\delta = 3 \cdot 10^{-5}$ is an arbitrary model-dependent parameter

Dark-Vector in Moller Scattering

Calculation Strategy

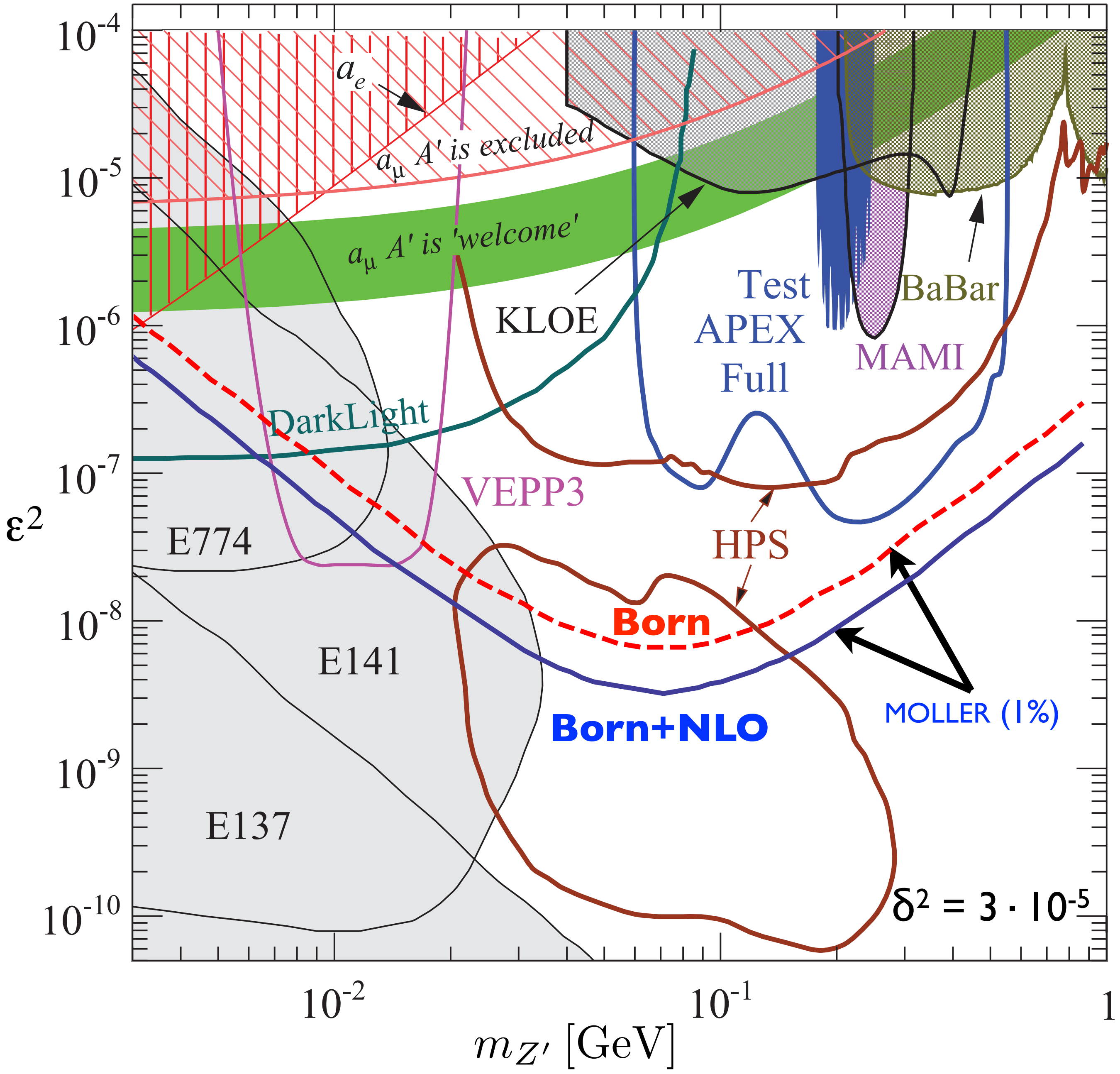
- Complete the calculations of PV MOLLER asymmetries including one-loop (NLO) for the SM particles. This will define SM central value.
- Proceed with calculations of PV asymmetries with **new physics particles including one-loop** and construct exclusion plots for 1% deviations from the SM central values.

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

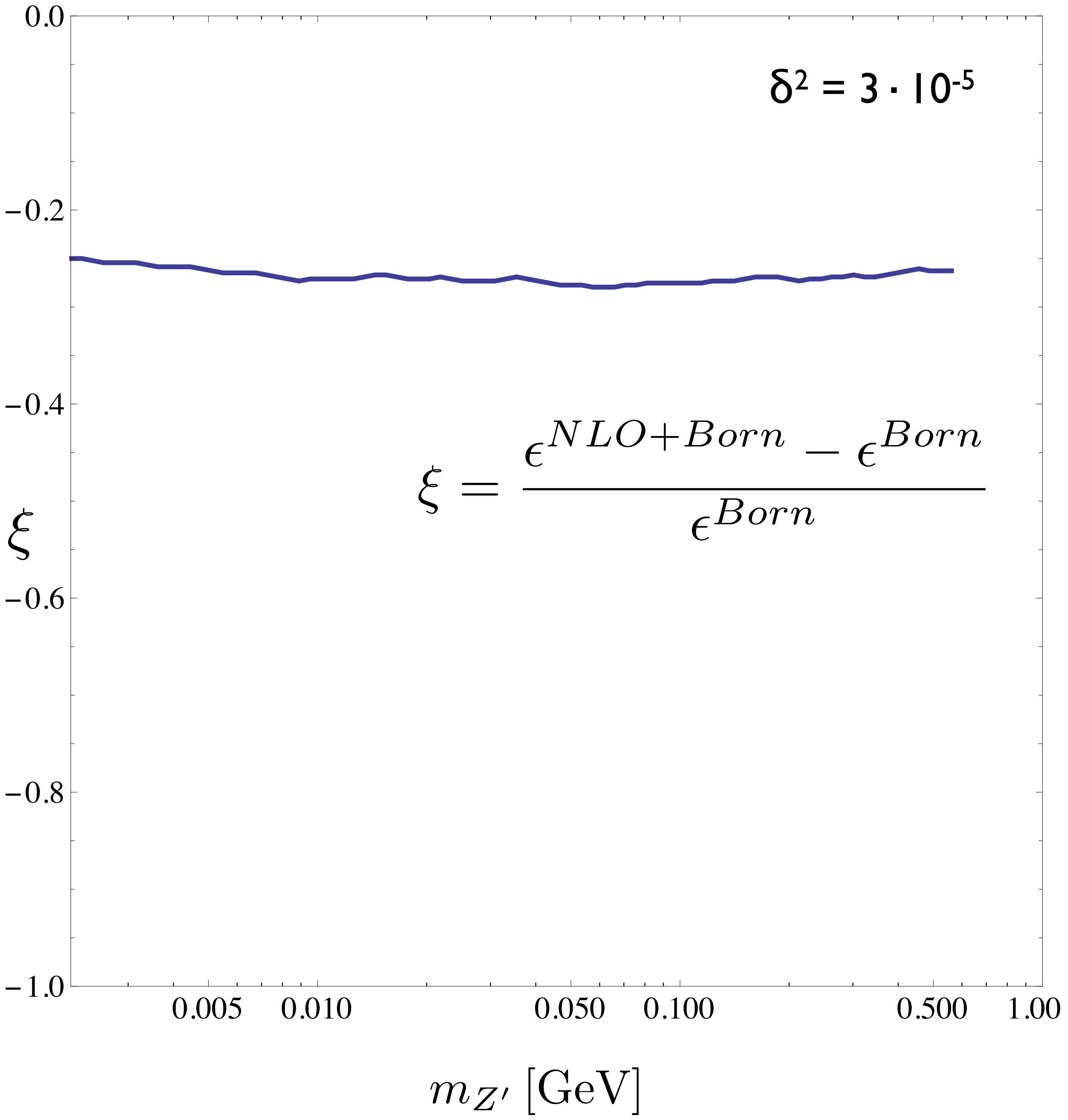


Dark-Vector in Moller Scattering

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



Relative correction to ϵ mixing parameter due to loops



Conclusions

- $(g\text{-}2)_\mu$ discrepancy could be explained by light dark photon. It is complementary to LHC program and so far is the strongest signal of BSM physics.

- nEDM measurements completed or planned (TRIUMF) will greatly improve our understanding of SUSY as a possible theory for BSM physics.

- 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 (4% of data) 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 $(g\text{-}2)_\mu$, where deviation with SM predictions reach 3.6σ