# Parity Violation from Low-Energy Experiments

**Yong Du（杜勇）**

第二届惠州大装置高精度物理研讨, 中山大学, **2024年8月25号**

Based on

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2405.09625, in collaboration with Xin-Yu Du, Xiao-Gang He, Jian-Ping Ma

Ongoing projects with
Ayres Freitas, Justin Fagnoni, Leon Friedrich, Michael Ramsey-Musolf, Jia Zhou

李政道研究所
TSUNG-DAO LEE INSTITUTE

# A short history

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

**Question of Parity Conservation in Weak Interactions***

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in $\beta$ decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

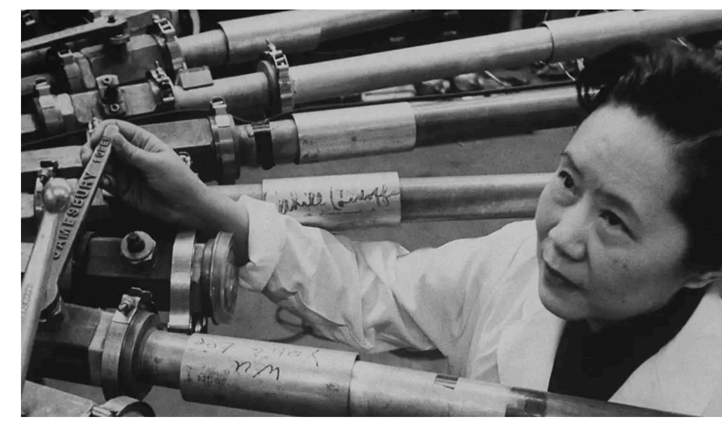
**Experimental Test of Parity Conservation in Beta Decay***

C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON, *National Bureau of Standards, Washington, D. C.*

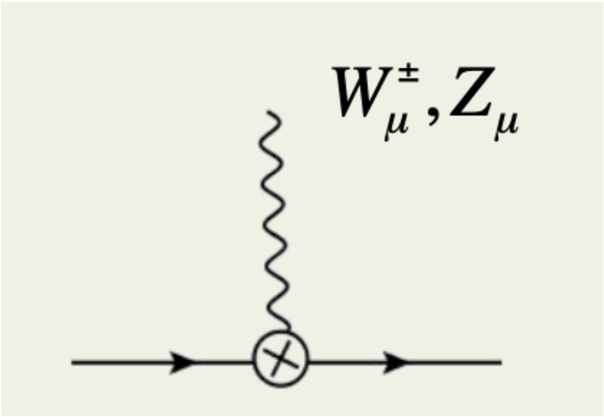
(Received January 15, 1957)

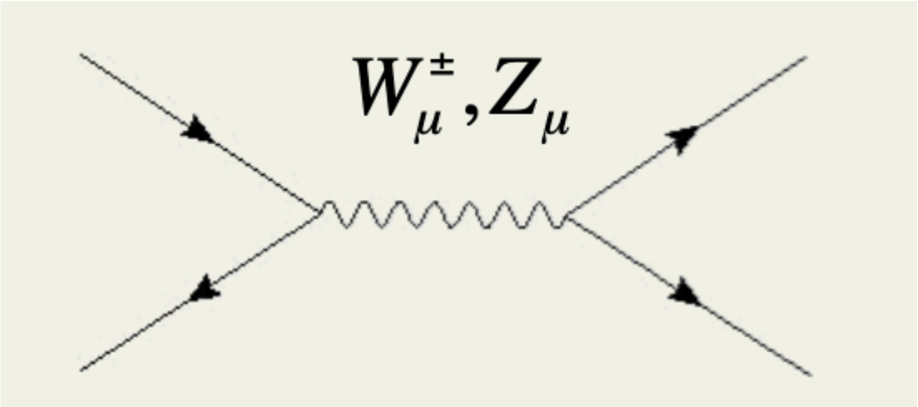


The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee "for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

# A short history

In the SM, parity violation arises from the gauge structure of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$, where $W^{\pm}/Z$ interacts differently with left- and right-handed particles.




$$g_{W^{\pm}ff'} = \frac{g_2}{2}\gamma^{\mu}(1-\gamma_5)$$

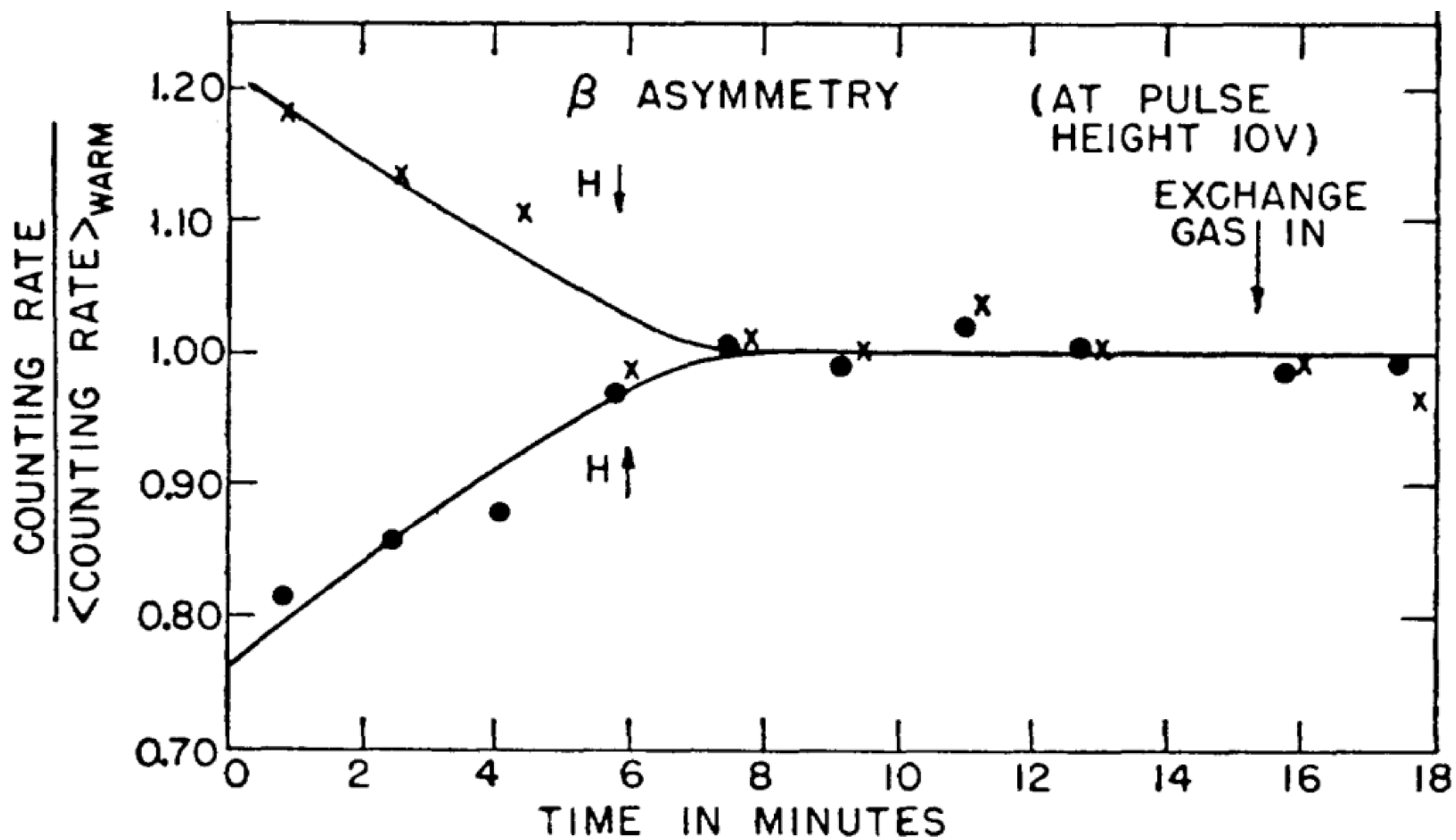
Maximally violated (no $\nu_R$ in the SM)

$$g_{Z^{\pm}ff} = \frac{g_2}{\cos\theta_W}\gamma^{\mu}(g_V - g_A\gamma_5)$$

NOT maximally violated

# A short history

The parity-violating nature thus permits a direct observation of an asymmetry similar to the Wu experiment:




C.S. Wu et al, 1957

# A short history

A question I have heard in the past:

*Parity violation has been observed and well understood in the SM. Why this focus?*

My answer:

Parity violation has helped the construction of the SM (first evidence of a neutral current in 1973; the exclusion of alternatives models at that time), and we are now also in need of new physics.

Parity violation has reached the precision era at *different scales*, which provides an ideal testbed for both the SM and new physics beyond it. Chances are that new particles/theories could emerge from this kind of study.

*(Disclaimer: In terms of the precision, I will only focus on selected neutral-current cases in the following.)*

# Schematics

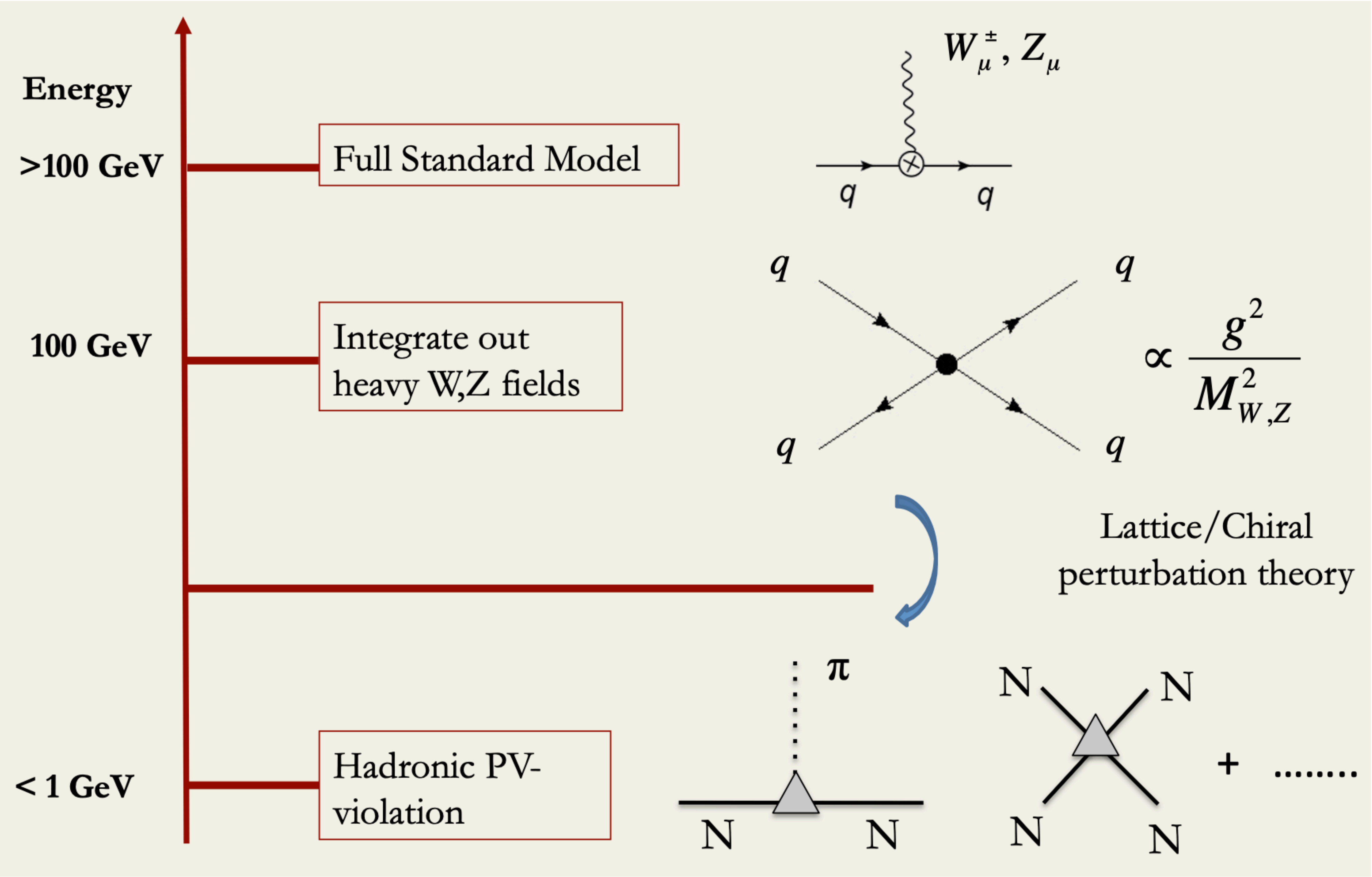
In the neutral current case, the process that violates parity is mediated by the $Z$. When $s \ll m_Z^2$, Fermi's theory is ideal to start with

$$\mathscr{L} = \frac{g^2}{c_W^2} \frac{1}{s - m_Z^2} \left(\bar{f}\gamma^\mu P_{L,R} f\right) \left(\bar{f}'\gamma^\mu P_{L,R} f'\right)$$

$$\hookrightarrow G_F\, g_{\text{eff}} \left(\bar{f}\gamma^\mu P_{L,R} f\right) \left(\bar{f}'\gamma^\mu P_{L,R} f'\right)$$

The theory is totally predictive and more importantly, there is only one free parameter if $\mathscr{L}$ has a UV realization being the SM at the weak scale, *i.e.*, $\sin\theta_W$. (again, this is how we select the weak theory as the correct one in the early 1980s)

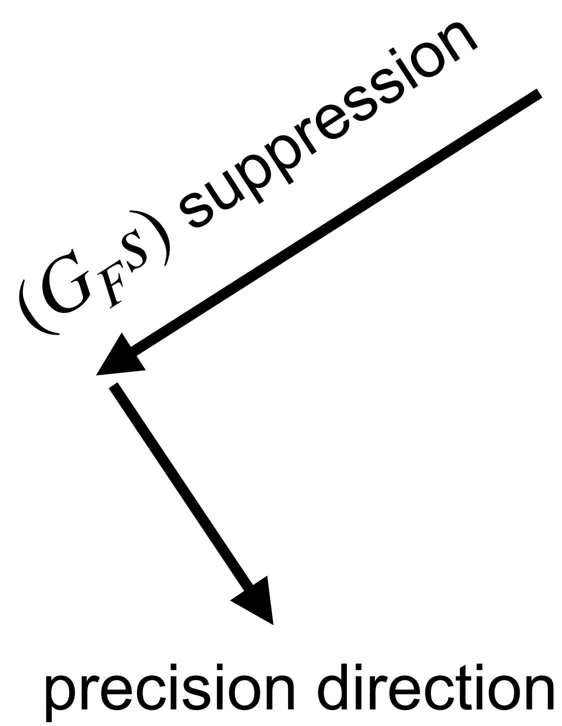
# Schematics

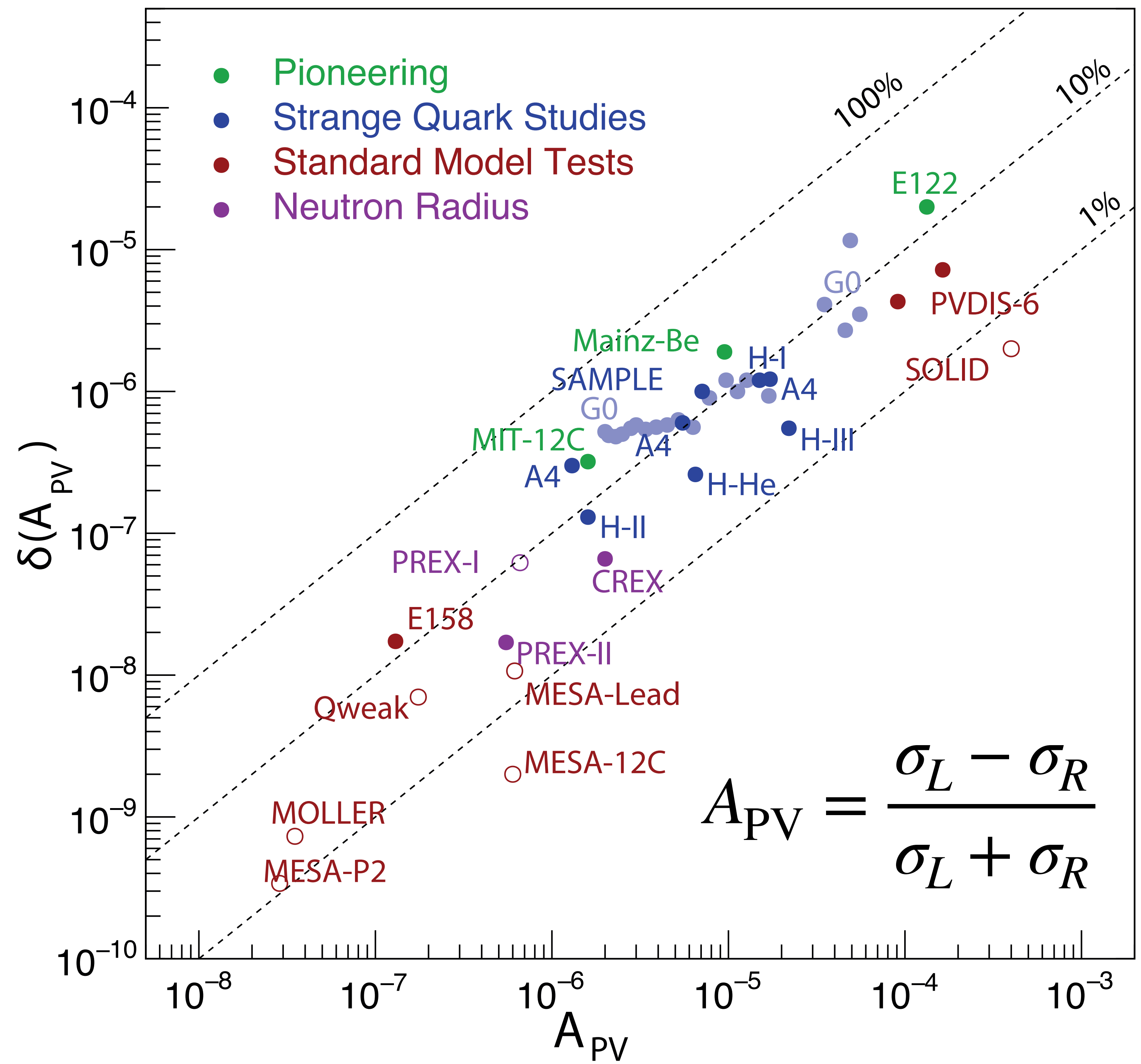



* Credit to Jordy de Vries

# Parity violation status

The state of the art



# Parity violation status

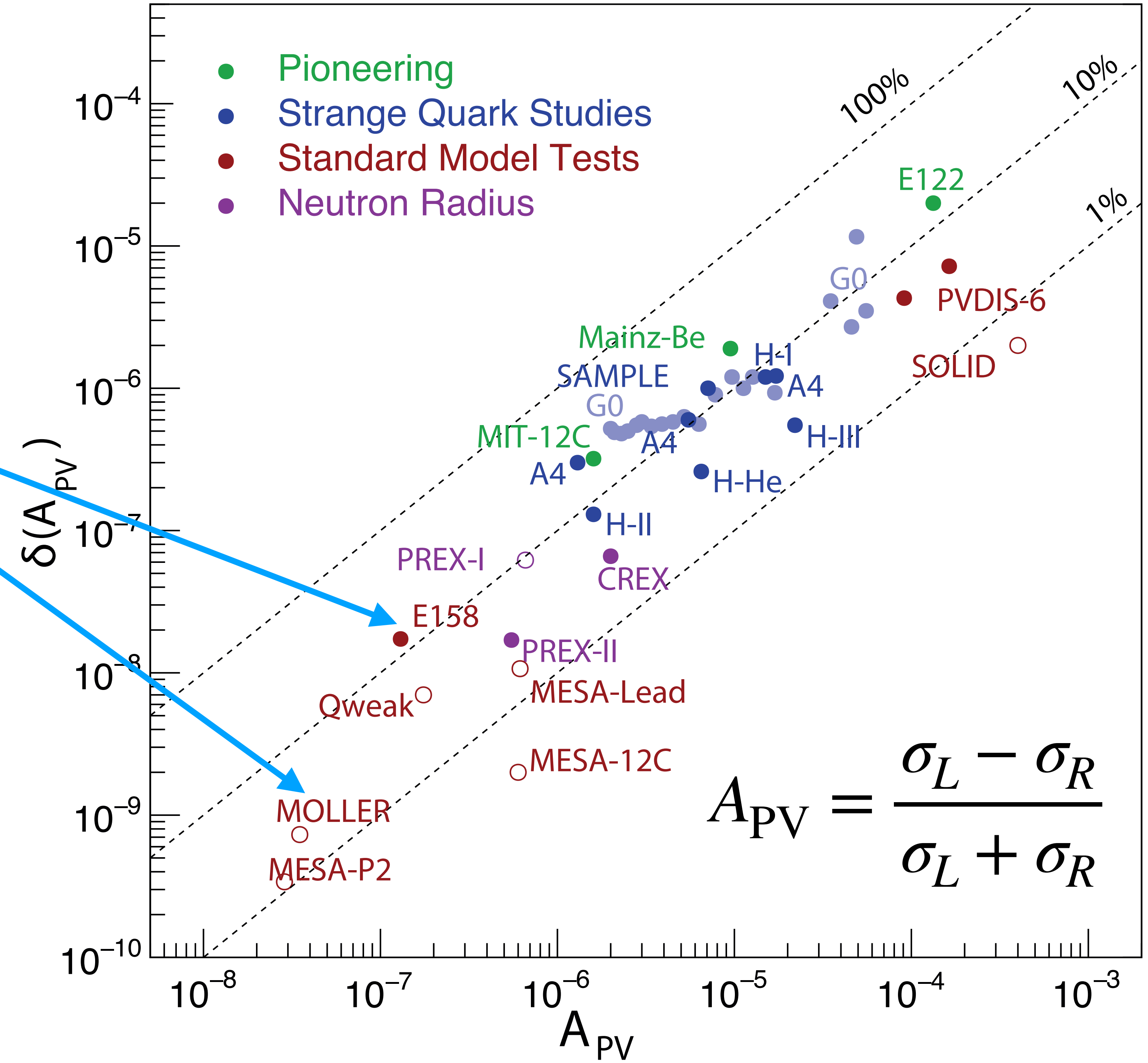
The state of the art

Different types of tests:

*e*-*e* scattering

*e*-*p* scattering

*e*-${}^A_ZN$ scattering




$$A_{\mathrm{PV}} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

# Parity violation status

The state of the art

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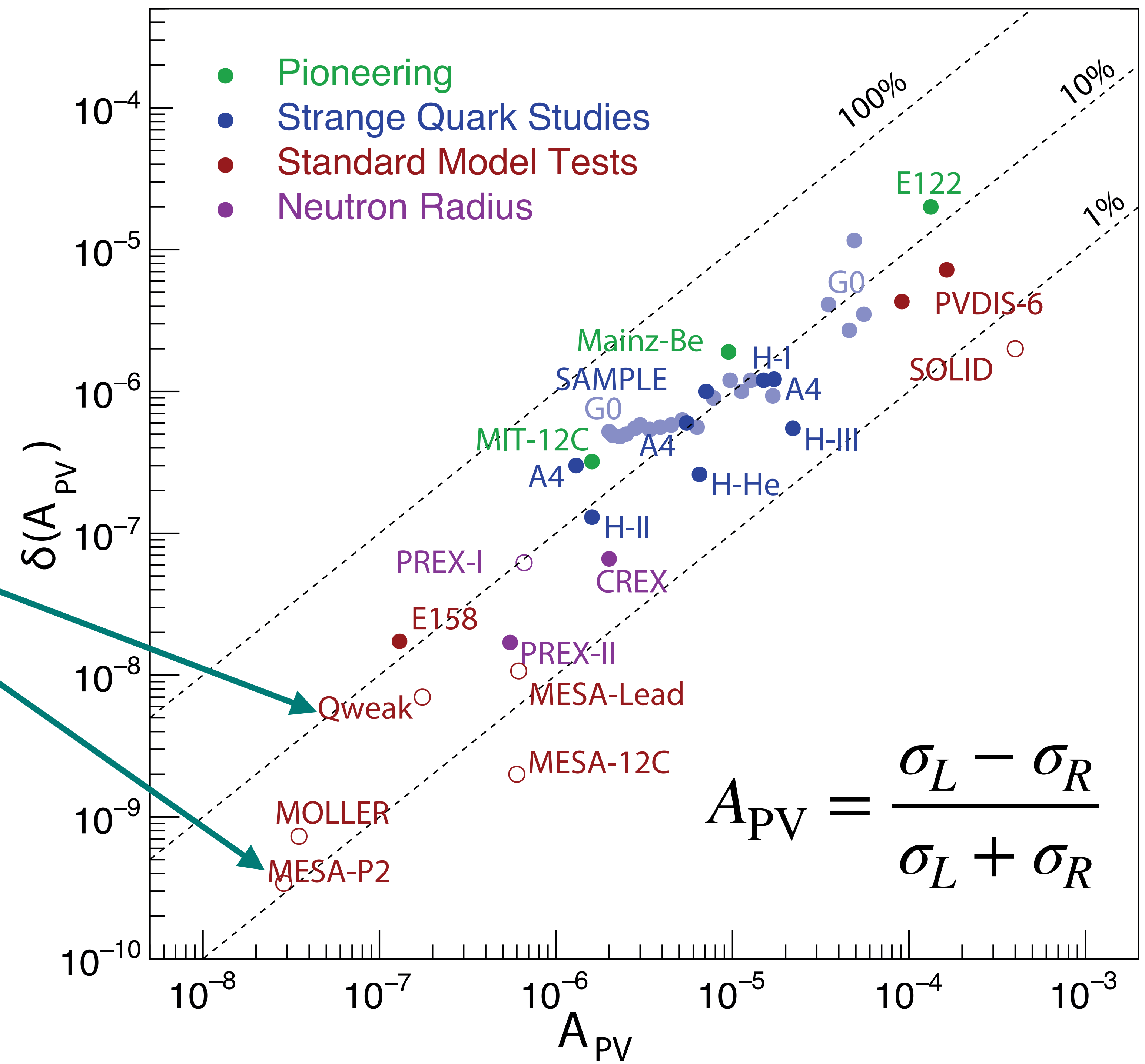

# Parity violation status

The state of the art

Different types of tests:

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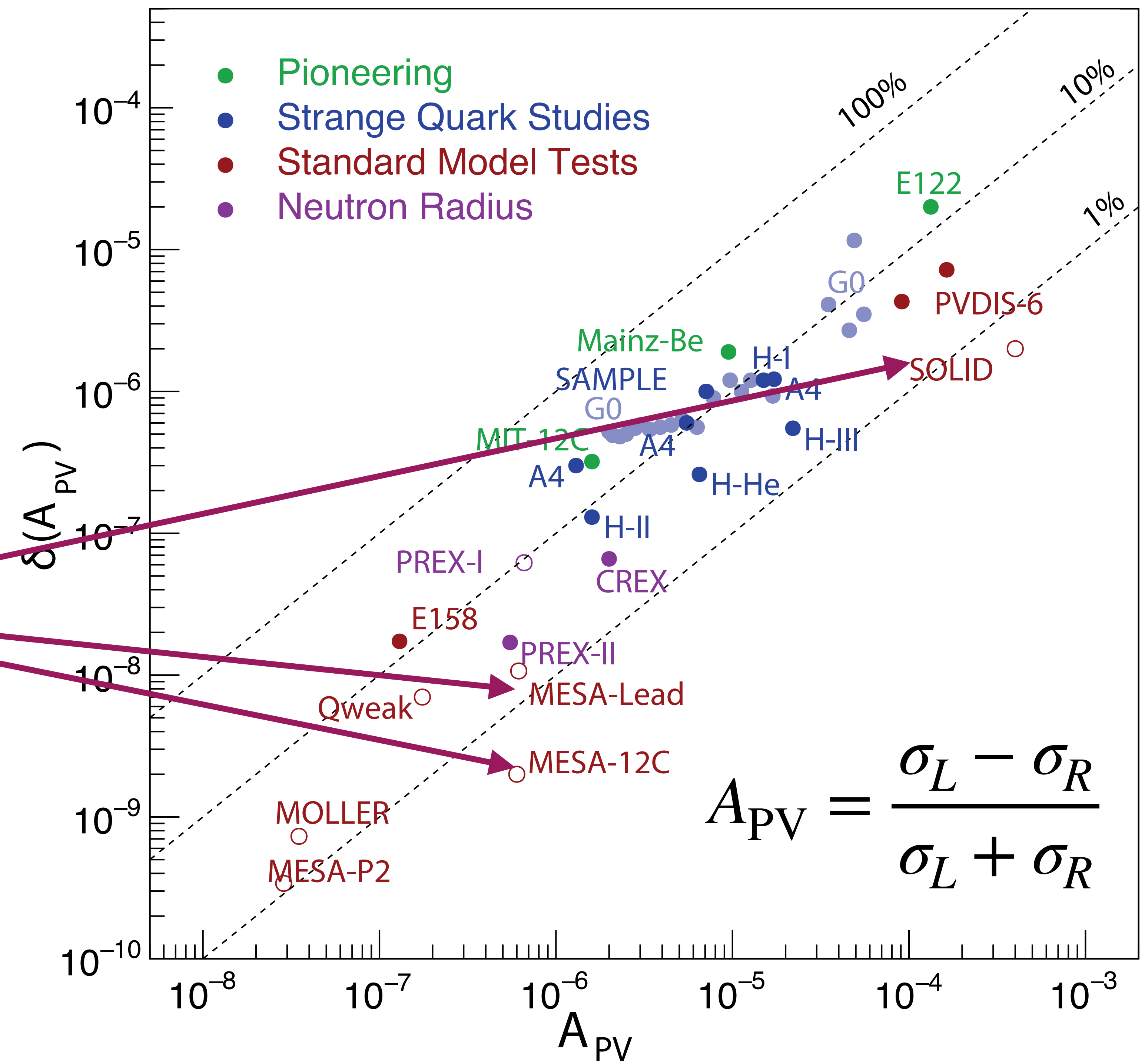
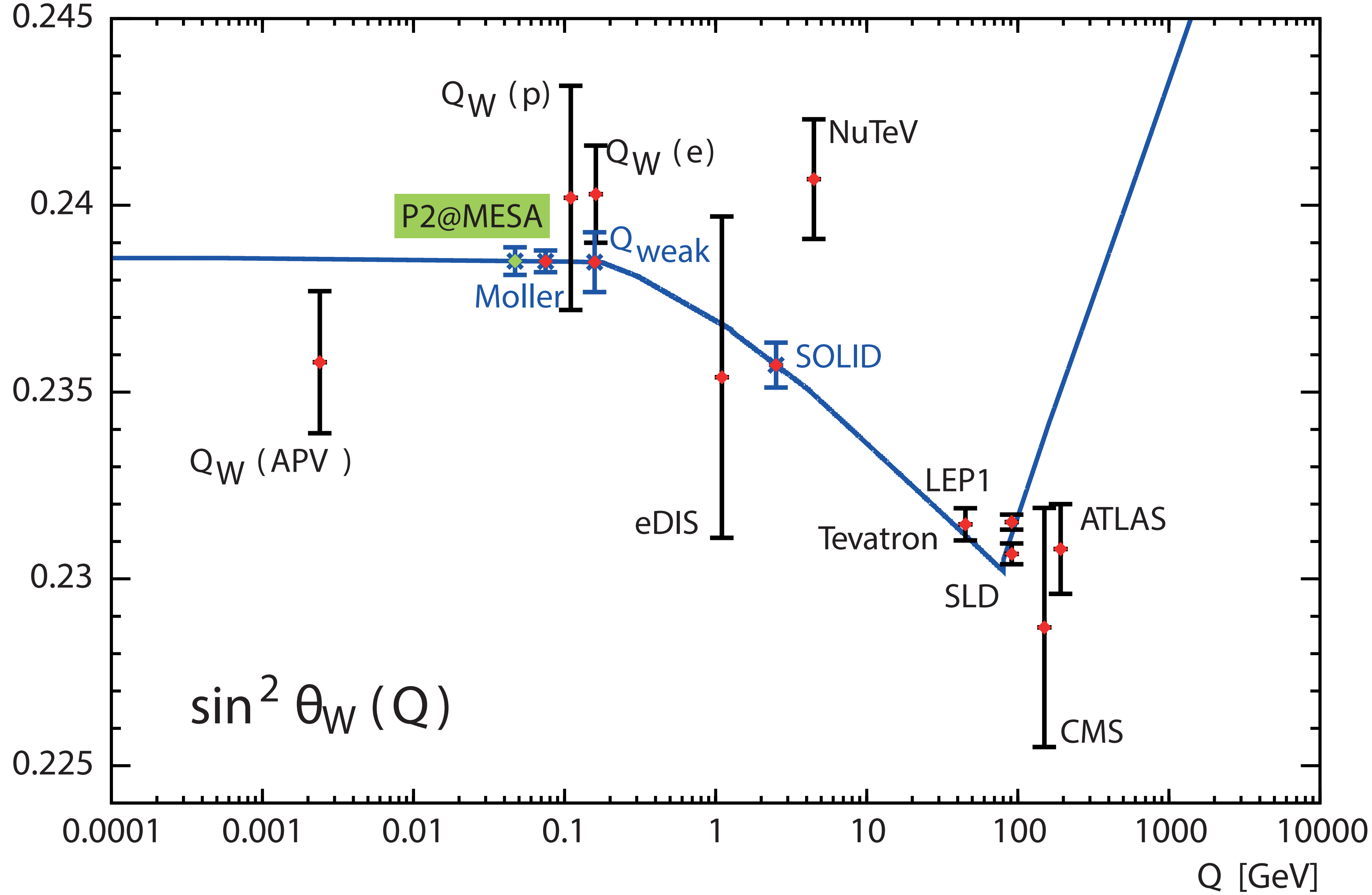



$$A_{\rm PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

# Parity violation status

Extraction of $\sin\theta_W$




Berger et al, 2016

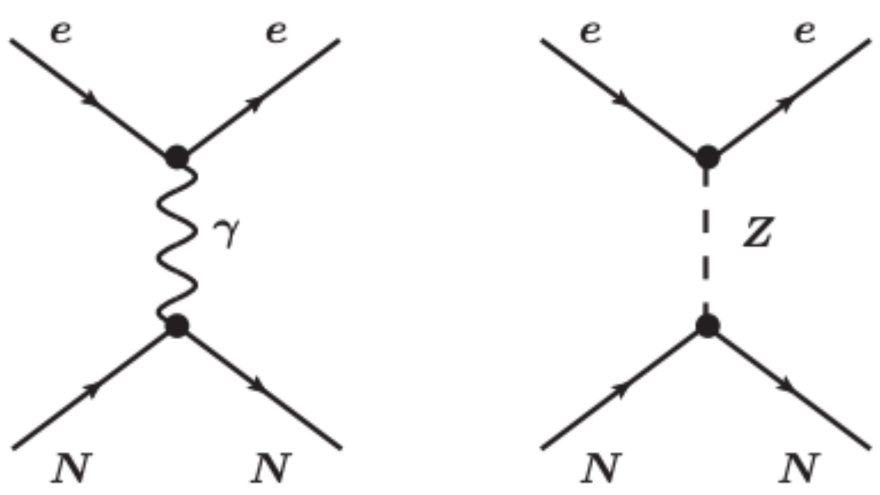
So we are literally performing a precision test of the SM (at one point from a single experiment, and the running of $\sin\theta_W$ globally speaking)

# Atomic PV

In the *atomic* cases, $A_{\rm PV}$ can be characterized by the so-called weak charge of the target:

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

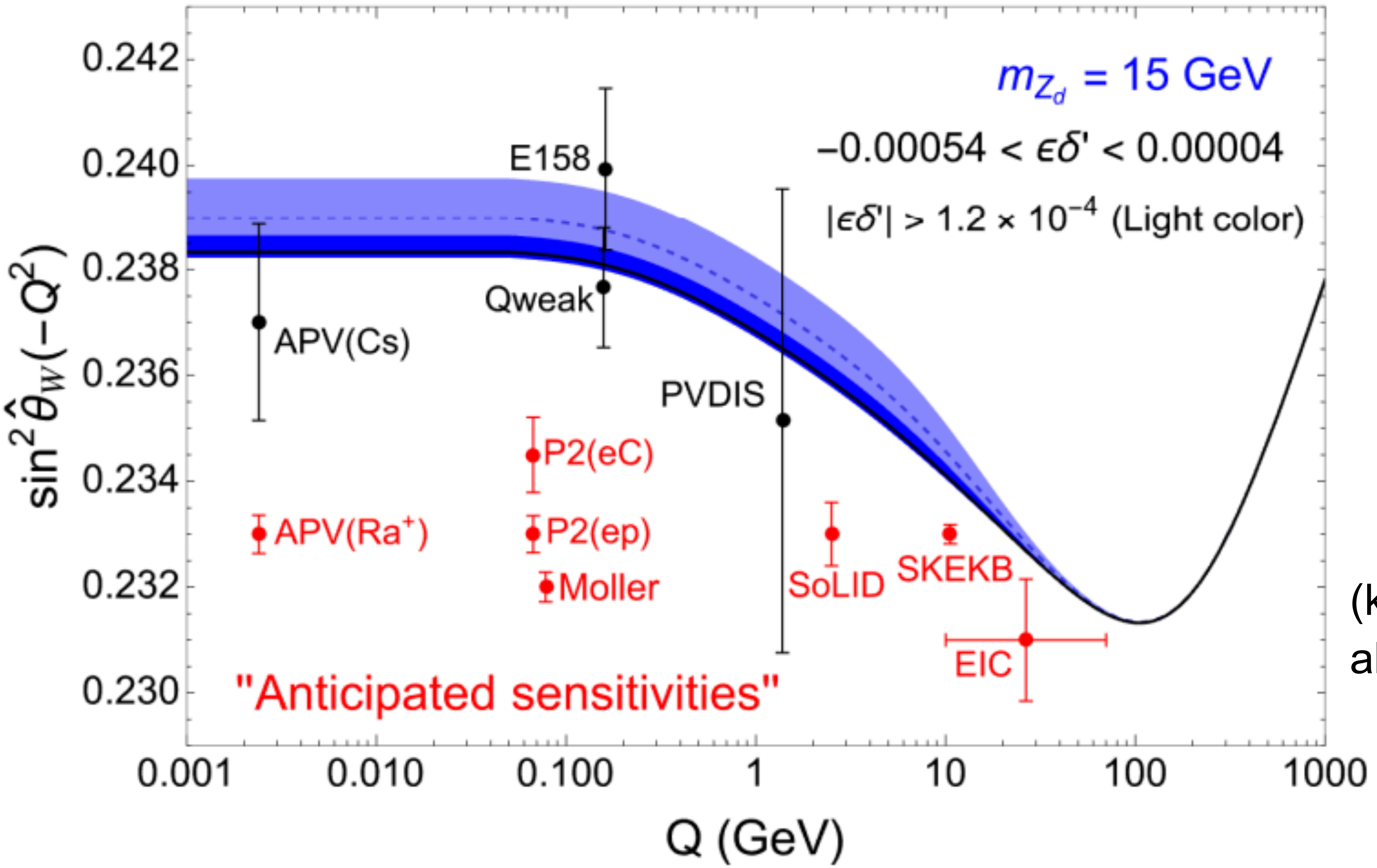
as a consequence of coherence due to the small momentum transfer in these experiments, where $p$ and $n$ form an iso-spin doublet. This is subject to radiative corrections as well as chiral symmetry breaking effects etc, whose impact depends on the process under study.

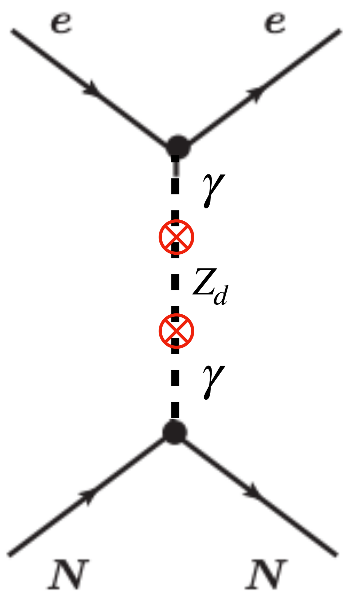



$$A_{\rm PV}(Z,N) = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{Q_W(Z,N)}{Z}(1+\Delta_{\rm RC})$$

# Atomic PV: Light New Physics

The precision in atomic $A_{\rm PV}$ also makes it a sharp probe of new physics.




(kinetic mixing via loops, also solves $a_\mu$)

Marciano et al, 2309.04060

# Atomic PV: Heavy New Physics

How about the heavy case? In this case, it is better to interpret the results *model independently*

$$\mathscr{L} = \frac{G_F}{\sqrt{2}} \sum_q \left( C_q^{(1)} \bar{e}\gamma_\mu\gamma_5 e \bar{q}\gamma^\mu q + C_q^{(2)} \bar{e}\gamma_\mu e \bar{q}\gamma^\mu\gamma_5 q \right)$$

polarized beam

polarized target

Another equivalent language is used by PDG

$$g_{AV}^{eu} = -0.1887, \quad g_{AV}^{ed} = +0.3419$$
$$g_{VA}^{eu} = -0.0351, \quad g_{VA}^{ed} = +0.0247$$

# Atomic PV: Heavy New Physics

This model-independent interpretation is convenient given the lack of new physics evidence at the LHC, rendering an EFT interpretation of the coefficients $C_q^{(1,2)}$ or $g_{VA,AV}^{eu,ed}$.

# Atomic PV: Heavy New Physics

This model-independent interpretation is convenient given the lack of new physics evidence at the LHC, rendering an EFT interpretation of the coefficients $C_q^{(1,2)}$ or $g_{VA,AV}^{eu,ed}$.

Buchmuller and Wyler, Nucl.Phys.B 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 10 (2010) 085

The SMEFT is a minimal extension at the weak scale

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$ |

| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$ |

| $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$ | | B-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar l_p^j e_r)(\bar d_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$ | | |

examples of new physics types (operator unfolding can be done systematically)

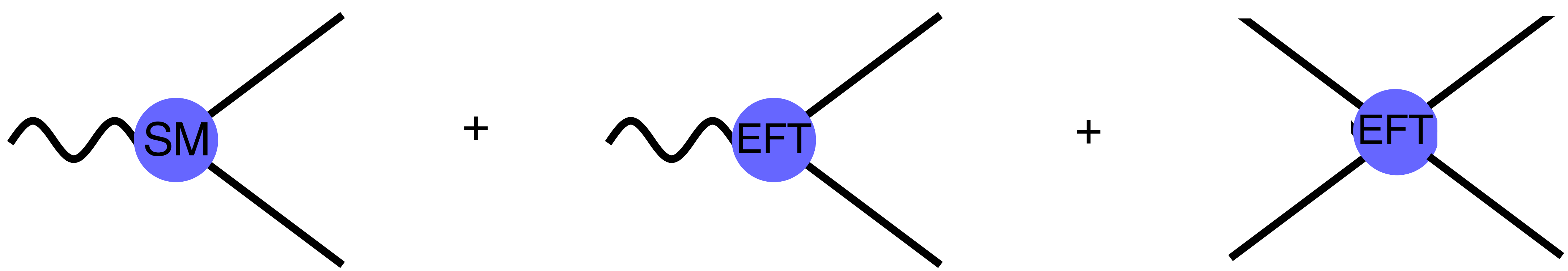
# Atomic PV: Heavy New Physics

Our electroweak input parameters are $[\alpha_{\rm EM}, m_Z, G_F]$ given their precision. These parameters are obviously modified by new physics like the SMEFT operators.

Take $G_F$ as an example, which is determined from $\mu \to e2\nu$. In the SM,

$$G_F = \frac{1}{\sqrt{2}v^2}$$

In the SMEFT, the rate $\mu \to e2\nu$ is modified by 3- and 4-point interactions:

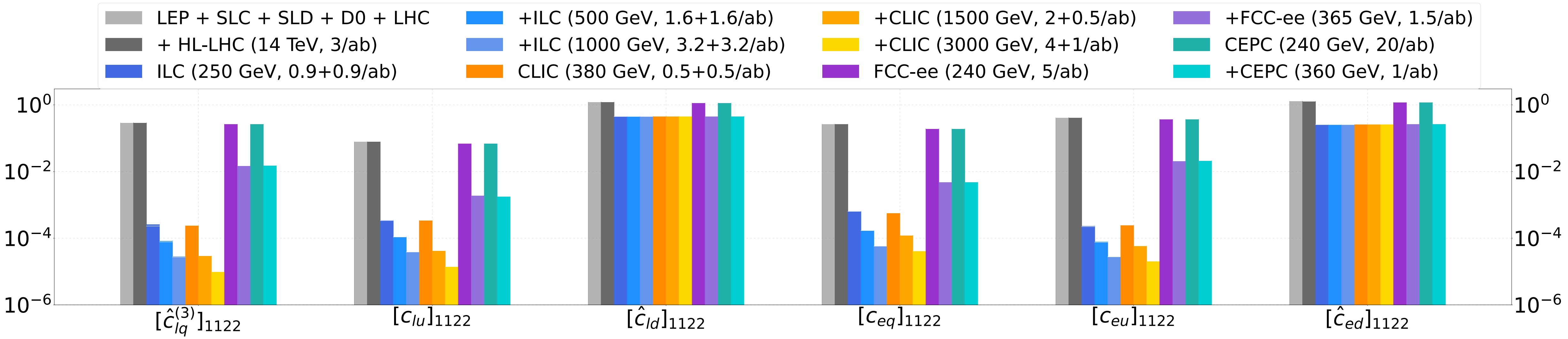



$$\frac{\delta G_F}{G_F} = v^2\left(\left[C^{(3)}_{H\ell}\right]_{\mu\mu} + \left[C^{(3)}_{H\ell}\right]_{ee} - \frac{1}{2}\left[C_{\ell\ell}\right]_{\mu ee\mu} - \frac{1}{2}\left[C^{(3)}_{\ell\ell}\right]_{e\mu\mu e}\right)$$

Taking $G_F$ as out input means this correction is taken as a boundary condition onto the new physics parameter space, which is absorbed into the redefinition of $v$ such that its value ( $\simeq 246$ GeV) is given by the muon lifetime.

# Atomic PV: Heavy New Physics

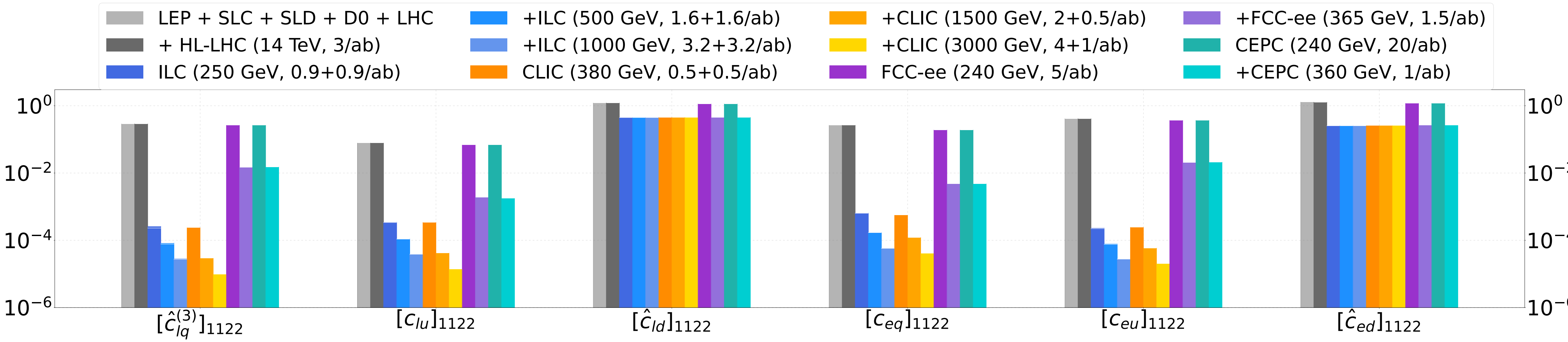
de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326




Its interaction with the other experiments is interesting, and $A_{\rm PV}$ is also indispensable in eliminating flat direction.

# Atomic PV: Heavy New Physics

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

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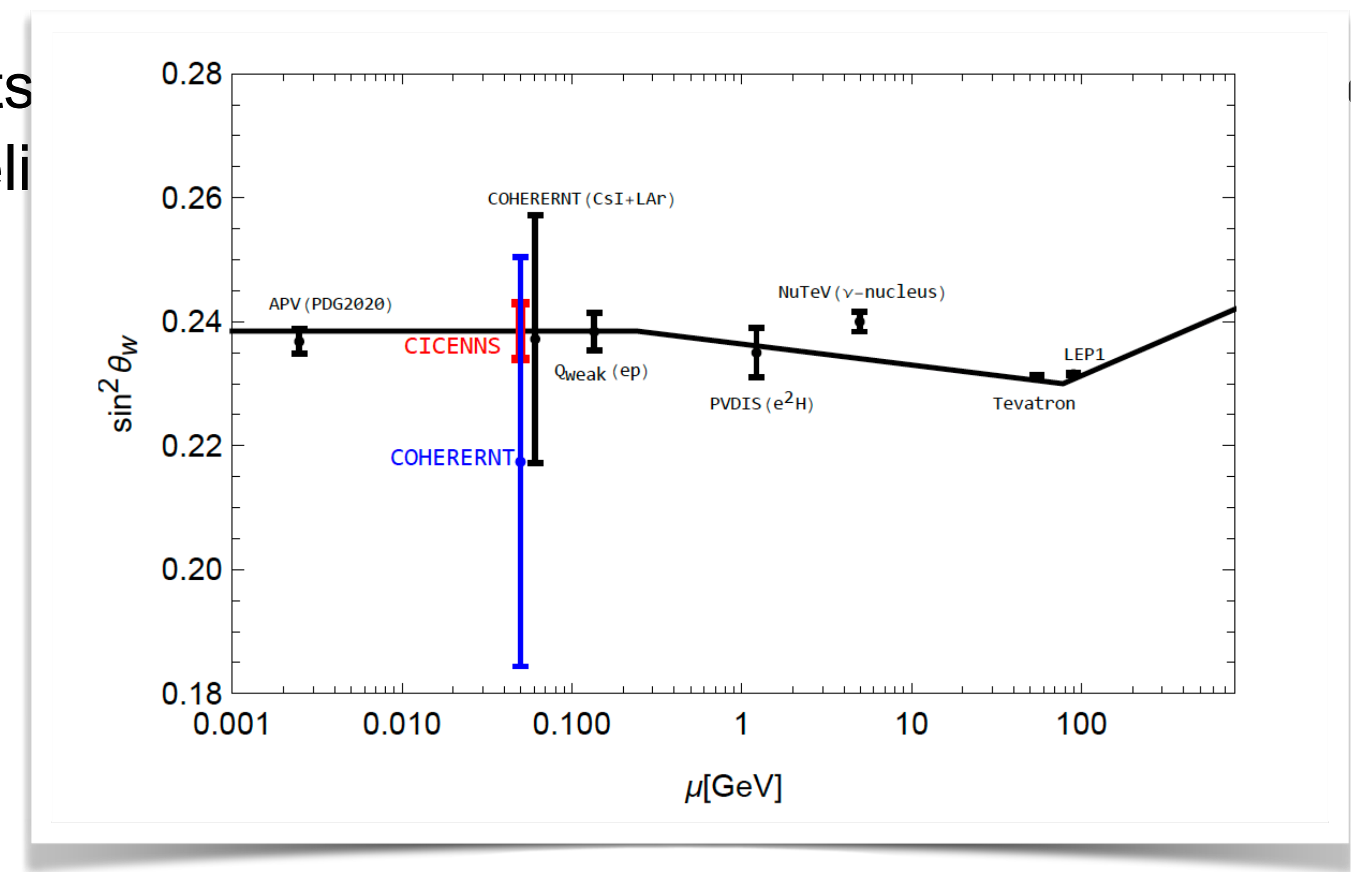


This is certainly true for CICENNS at CiADS!

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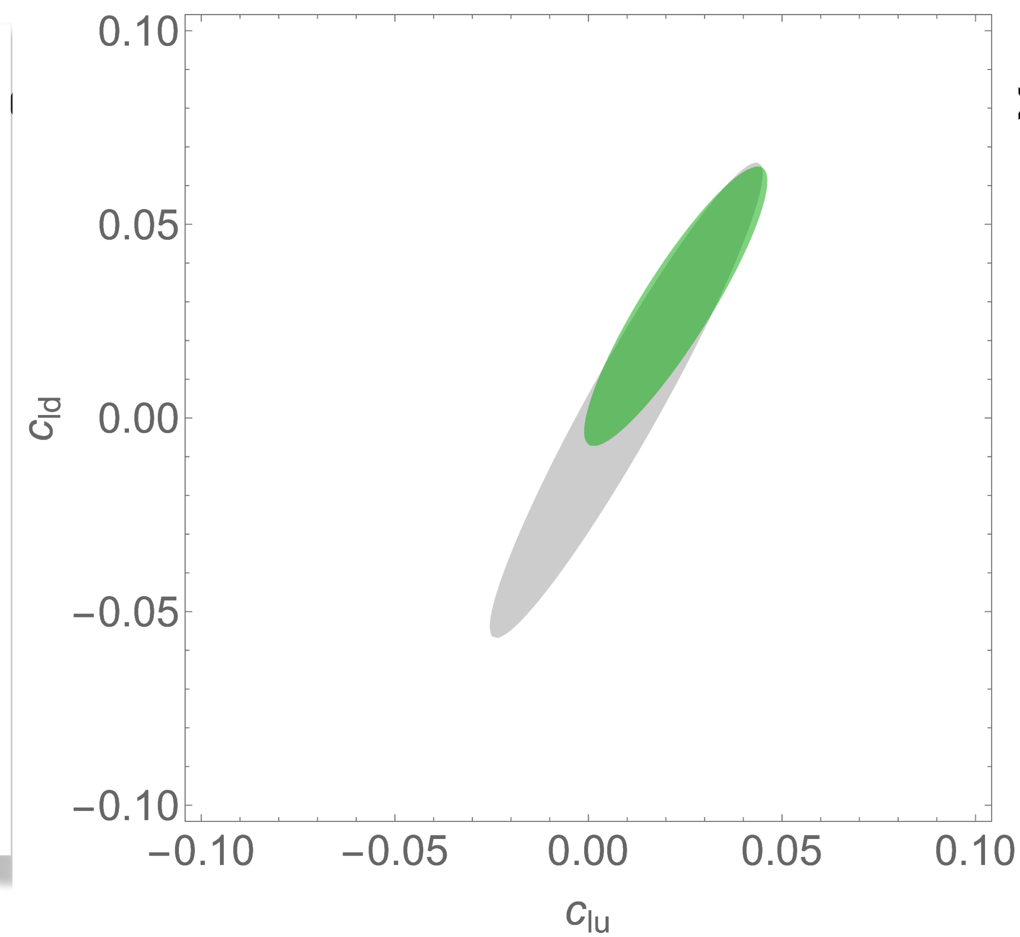
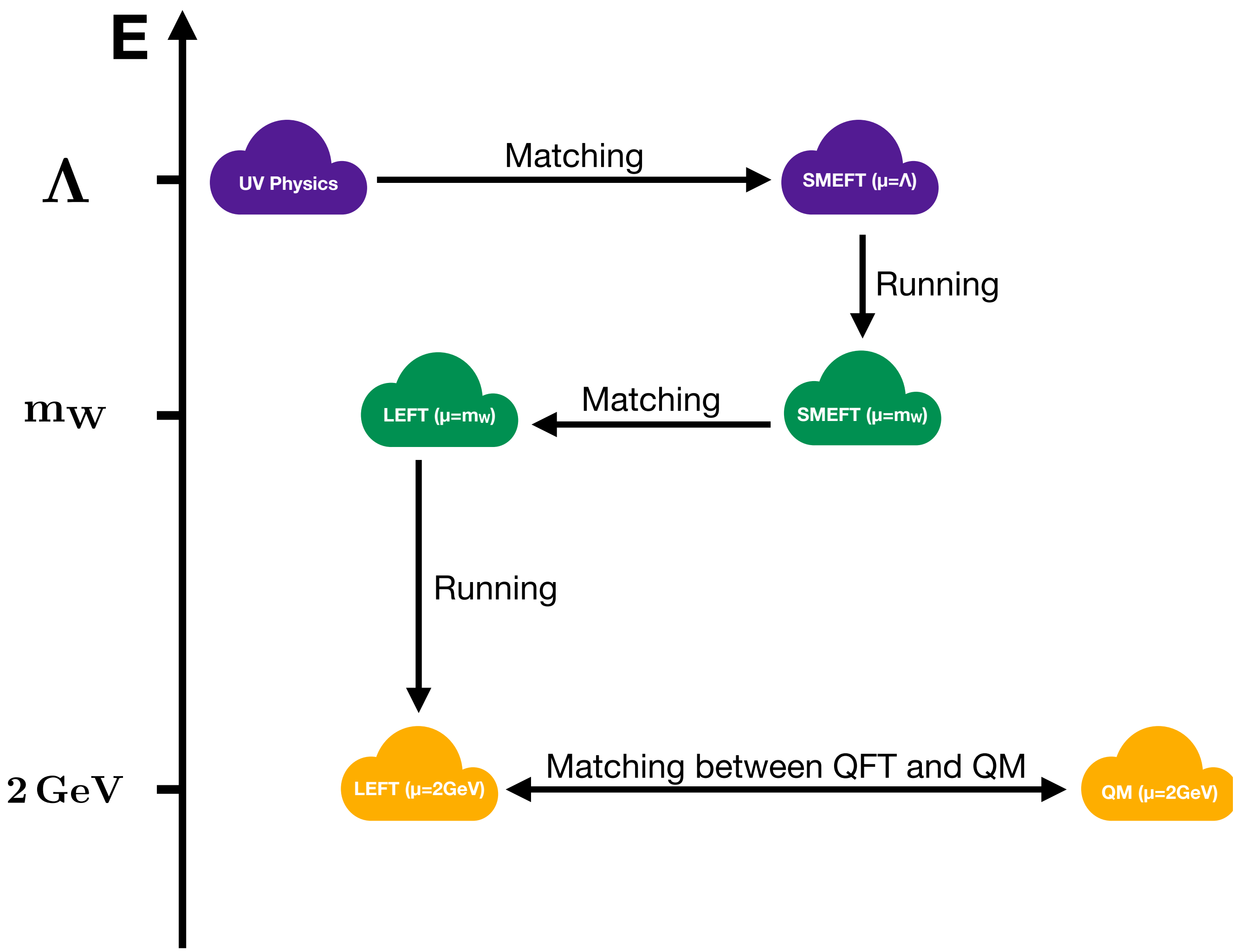
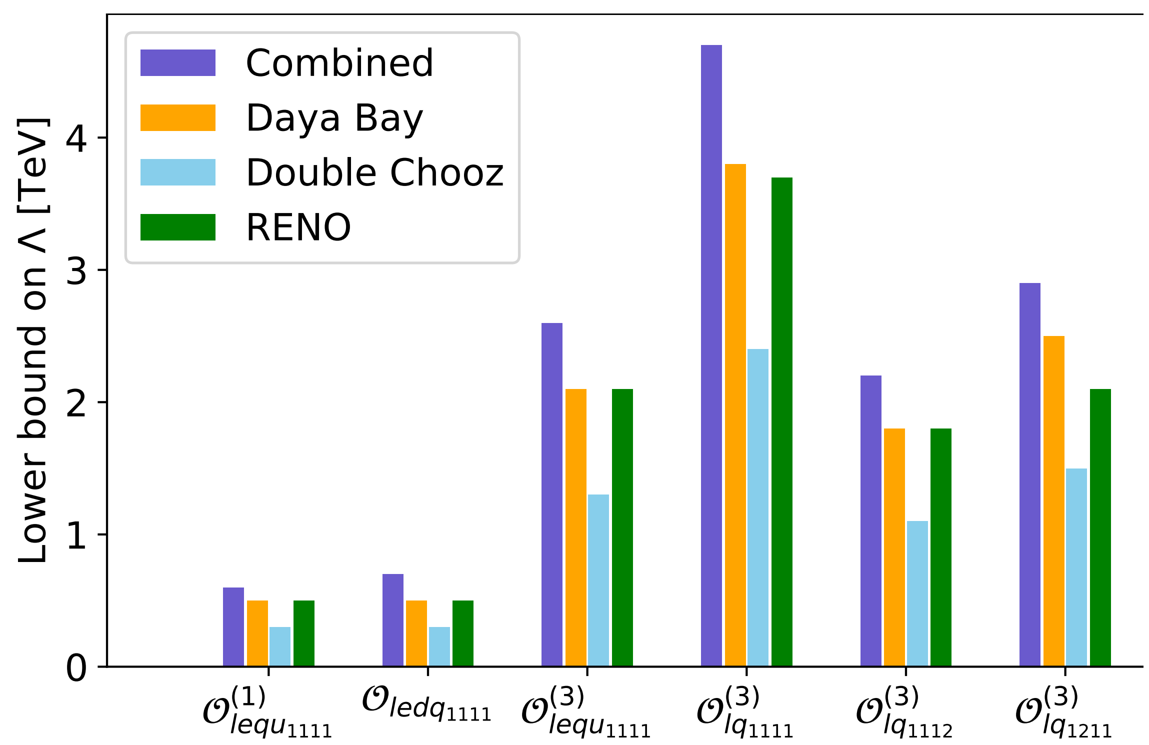



Breso-Pla, et al, 2301.07036

# Atomic PV: $\nu$ oscillations

The atomic $A_{\rm PV}$ has an even broader impact. These same interaction (including those in the SMEFT) also induce neutrino non-standard interaction and modified matter effects, thus relevant for neutrino oscillation experiments for instance.

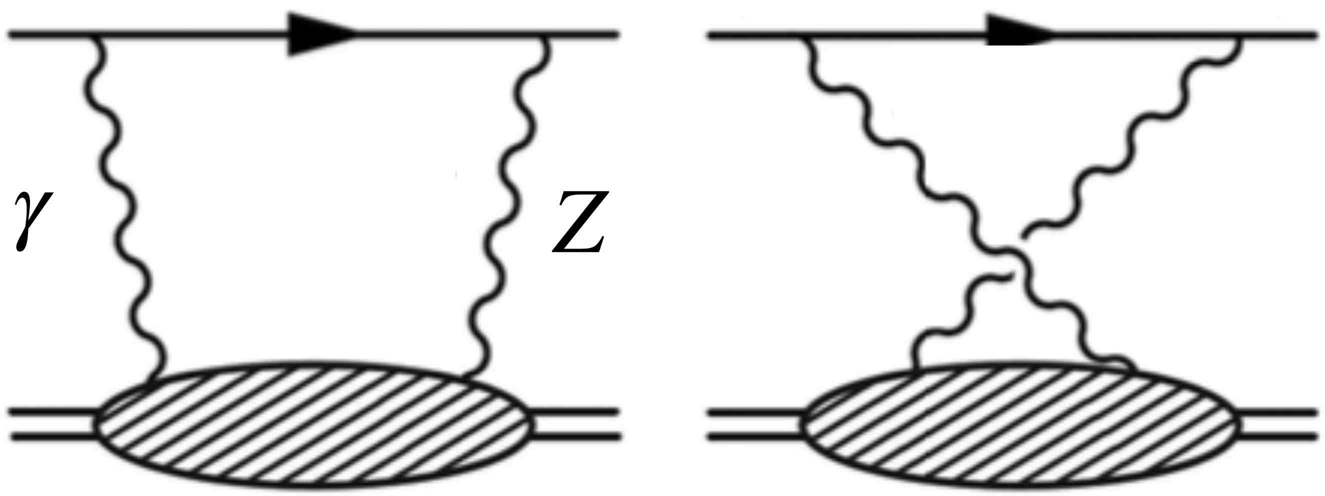



YD, Li, Tang, Vihonen, Yu, arXiv: 2011.14292
YD, Li, Tang, Vihonen, Yu, arXiv: 2106.15800

# Atomic *vs* nucleon PV

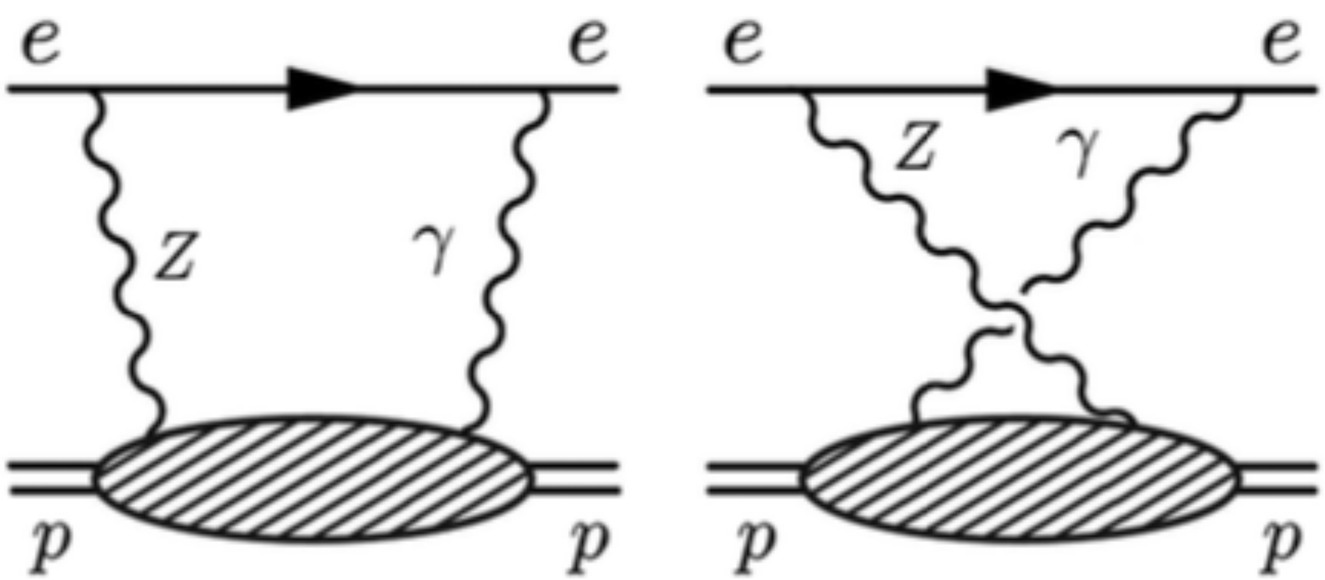
We shall keep in mind that: There is one theoretical challenge for precision atomic $A_{\mathrm{PV}}$




the soft photon induces large QCD uncertainties due to non-perturbativity (input from lattice calculation would be desirable) in $\gamma Z$ box diagrams (other topologies can be computed perturbatively based on the CVC assumption). This is an urgent task for precision party-violating experiments including a proton target like MESA@P2 (a similar challenge exists in the charged-current case for beta decay.)

# Proton PV: $Q_p(1,0)$

Radiative corrections to the proton weak-charge $Q_p$ is relatively simpler due to the absence of a complicate nuclear structure




$$\delta(x^0 - y^0)\left[J_1(x), J_2(y)\right] = \delta^{(n)}(x-y)\psi^\dagger(x)\left[\gamma^0\mathcal{O}_1, \gamma^0\mathcal{O}_2\right]\psi(x)$$

A direct computation of the $S$-matrix element with the help of current algebra directly relates radiative corrections to the third structure function:

Has to be further reduced for P2 from a 2-loop calculation!

$$Q_p \supset \cdots + \Box^A_{\gamma Z}(E) = \frac{2}{\pi}\int_0^\infty dQ^2 \frac{v_e\left(Q^2\right)\alpha\left(Q^2\right)}{Q^2\left(1+Q^2/M_Z^2\right)} \times \int_0^1 dx F_3^{\gamma Z}\left(x, Q^2\right) f(r, t') \sim (4\cdot 10^{-3})$$

Erler et al, 1907.07928

# Atomic *vs* electron PV

The cleanest example is SLAC E158 and Moller, corresponding to $e$-$e$ scattering with polarized beams

$$A_{LR} = \frac{G_\mu Q^2}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4}(1-4\sin^2\theta_W + \delta Q_W^e)$$

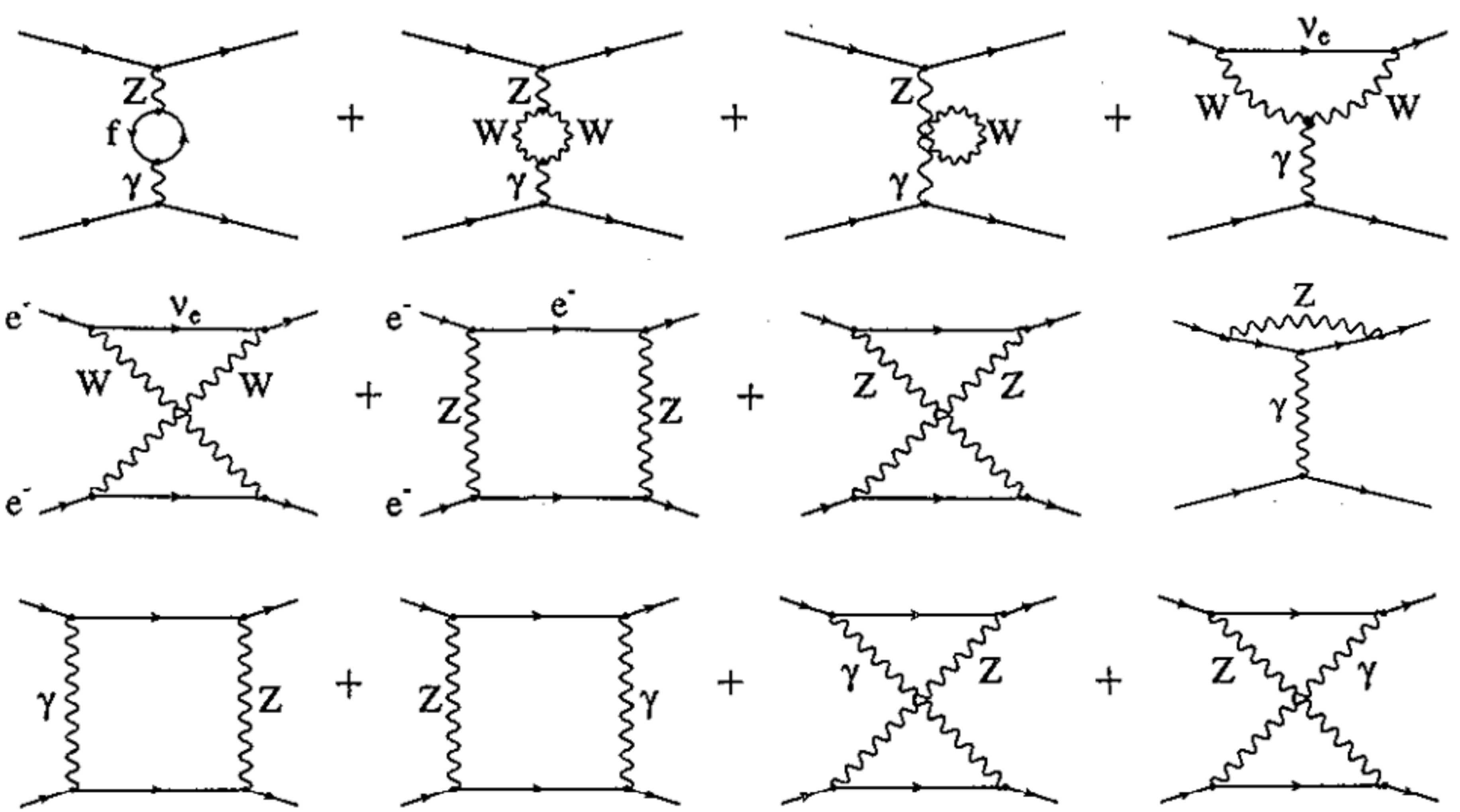
*vs*

$$A^{\rm PV}(Z,N) = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{Q_W(Z,N)}{Z}(1+\Delta_{\rm RC})$$

Small asymmetry in the pure leptonic case due to accidentally small electron weak charge since $\sin^2\theta_W \approx 1/4$.

# $A_{LR}$ in MOLLER: SLAC E158

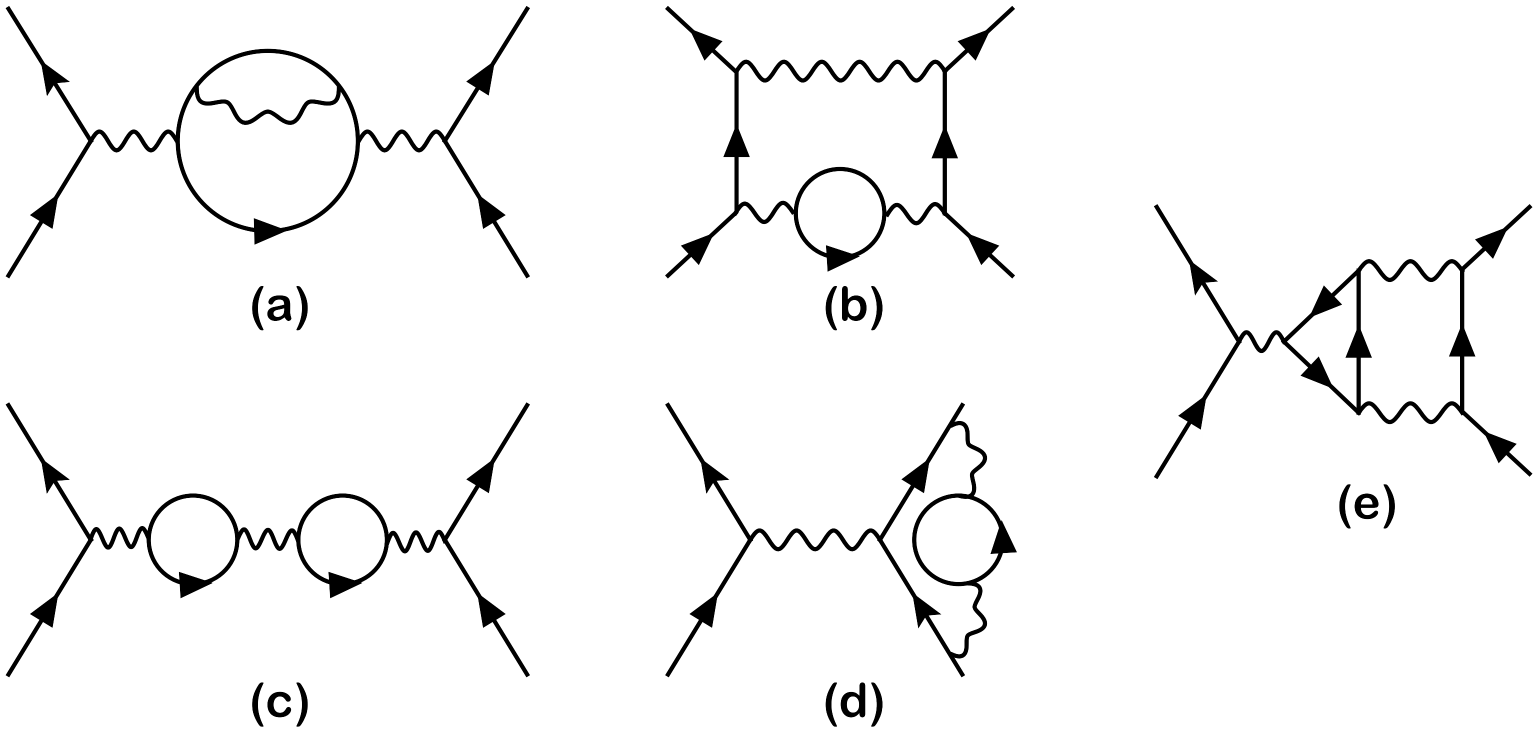
Tree $A_{LR}$ further reduced from one-loop radiative corrections by 40%




Czarnecki, Marciano, 1996

# $A_{LR}$ in MOLLER: MOLLER

MOLLER is the next-generation leading experiment. Its precision goal requires a full two-loop computation:




| Quantity | Contribution ($\times 10^{-3}$) |
|---|---|
| $1\text{–}4\,\sin^2\theta_W$ | $+74.4$ |
| $\Delta Q^e_{W(1,1)}$ | $-29.0$ |
| $\Delta Q^e_{W(1,0)}$ | $+3.1$ |
| $\Delta Q^e_{W(2,2)}$ | $-0.18^{+0.0024}_{-0.0040}$ |
| $\Delta Q^e_{W(2,1)}$ | $+1.18^{+0.015}_{-0.010}$ |
| $\Delta Q^e_{W(2,0)}$ | $\pm 0.13$ (estimate) |

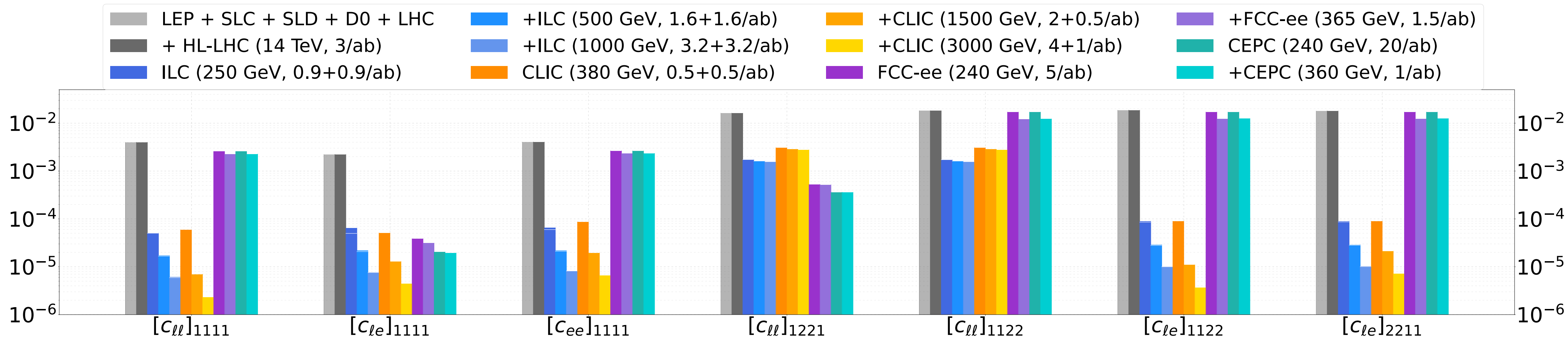
YD, Freitas, Patel, Ramsey-Musolf, PRL 2021

# $A_{LR}$ in MOLLER: Heavy New Physics

Not necessarily respected by new physics, thus stringent constraints on BSM extensions

$$A_{LR} = \frac{G_\mu Q^2}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4}(1 - 4\sin^2\theta_W + \delta Q_W^e)$$

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326




Complementary to atomic $A_{\rm PV}$, $A_{\rm LR}$ is sensitive to 4-lepton operators

| | | |
|---|---|---|
| 1. | −0.538 | 0.141 |
| −0.538 | 1. | −0.535 |
| 0.141 | −0.535 | 1. |

# $A_{LR}$ in MOLLER: Heavy New Physics

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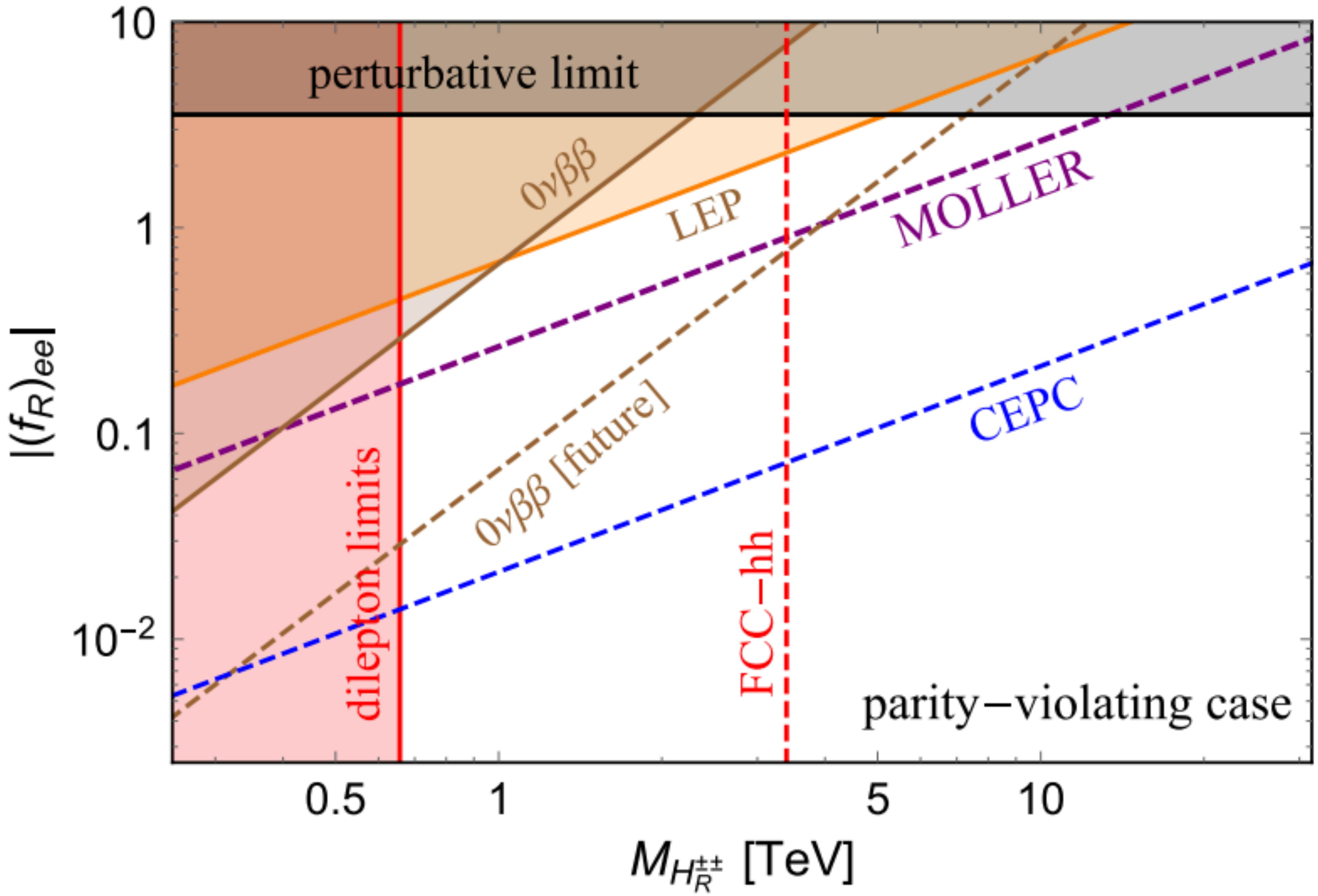
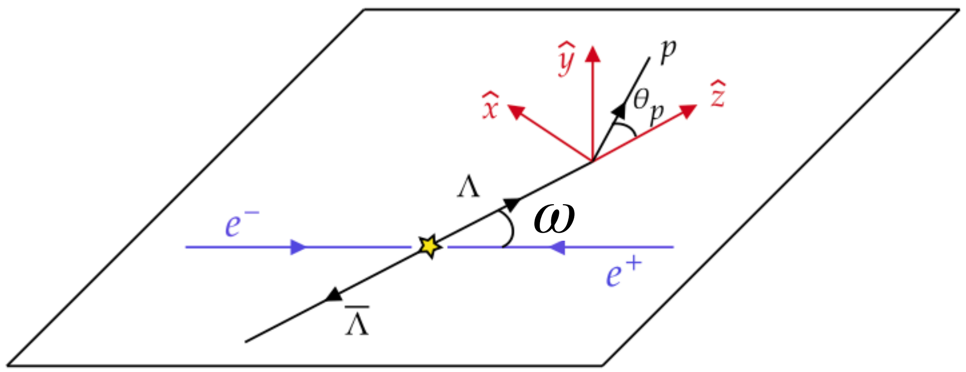
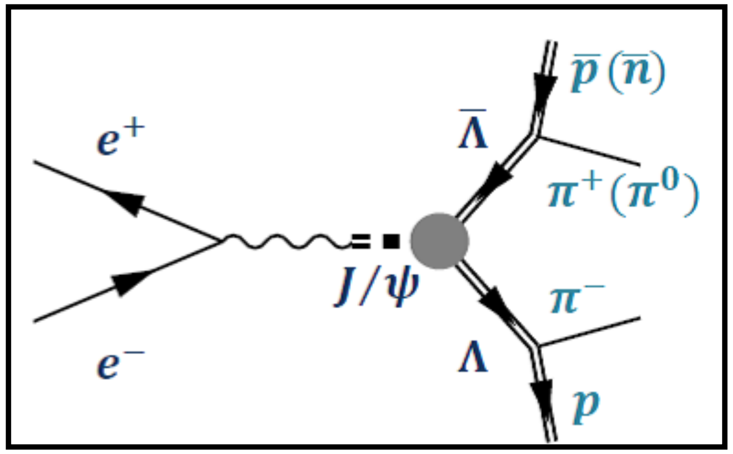



Bhupal Dev et al, 2018

# $A_{PV}$ in Baryons

The 10 billion $J/\psi$ collected at BESIII provides another possibility at the $J/\psi$ threshold, and the parity-violating asymmetry can be measured from the final state angular distribution




$$A_{\rm PV}^{(1)} \simeq \frac{4\alpha}{3\mathcal{N}} E_c^2 d_J \left( 2y_m {\rm Re}\left( G_1 G_2^* \right) + \left| G_1 \right|^2 \right)$$

production $(\boldsymbol{l}_p \cdot \boldsymbol{p}_e)$

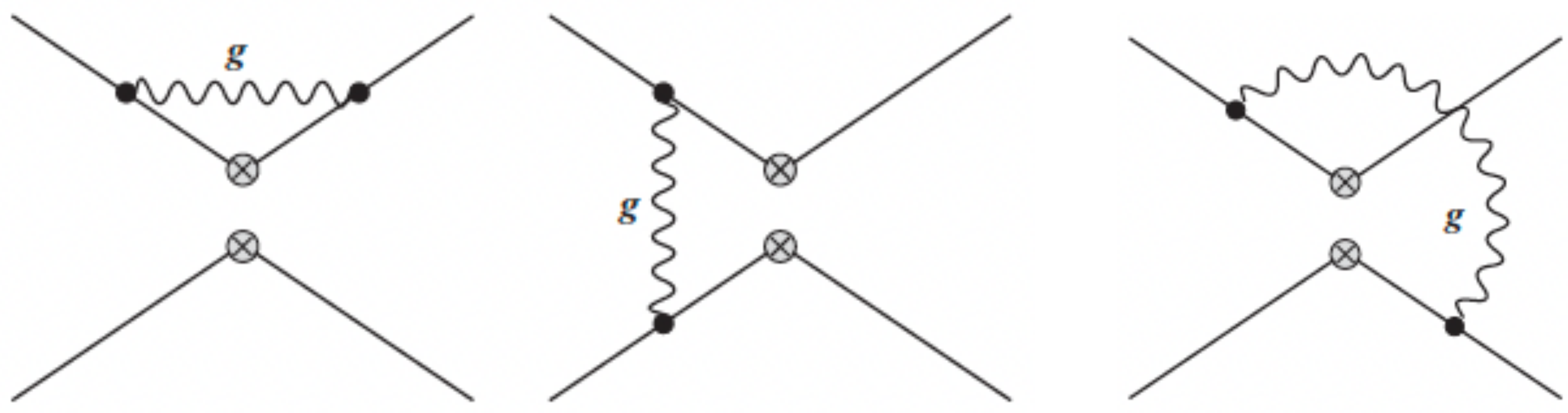
$$A_{\rm PV}^{(2)} \simeq \frac{8\alpha\beta}{3\mathcal{N}} E_c^2 \, {\rm Re}\left( F_A G_1^* \right)$$

decay $(\boldsymbol{l}_p \cdot \boldsymbol{p}_B)$

$$\mathcal{M} = \epsilon_\mu^{J/\psi}(q)\bar{u}(k_1)\left[\gamma^\mu F_V + \gamma^\mu\gamma_5 F_A + \frac{i}{2m_B}\sigma^{\mu\nu}q_\nu H_\sigma + \sigma^{\mu\nu}q_\nu\gamma_5 H_T\right] v(k_2)$$

# $A_{PV}$ in Baryons: RG running

Large QCD running effects on parity from the weak scale down to the $J/\psi$ decay scale




$$\mathcal{O}^{LR}_{ud+} = \frac{1}{N_c}\left(\bar{d}_R\gamma_\mu d_R\right)\left(\bar{c}_L\gamma_\mu c_L\right) + 2\left(\bar{d}_R\gamma_\mu T^A d_R\right)\left(\bar{c}_L\gamma_\mu T^A c_L\right) \qquad \mathcal{O}^{LR}_{ud-} = -\frac{4C_F}{N_c}\left(\bar{d}_R\gamma_\mu d_R\right)\left(\bar{c}_L\gamma_\mu c_L\right) + \frac{4}{N_c}\left(\bar{d}_R\gamma_\mu T^A d_R\right)\left(\bar{c}_L\gamma_\mu T^A c_L\right)$$

$$\mathscr{L}_Z \supset -4\sqrt{2}G_F \cdot \sum_{q=d,s}\left[\frac{g^q_{V-A}g^c_{V+A}}{N_c}C^{LR}_{ud+}\mathcal{O}^{LR}_{ud+} - \frac{g^q_{V-A}g^c_{V+A}}{2}C^{LR}_{ud-}\mathcal{O}^{LR}_{ud-}\right]$$

$$C^{LR}_{ud+} = 1 \to 2.76$$

$$C^{LR}_{ud-} = 1 \to 0.88$$

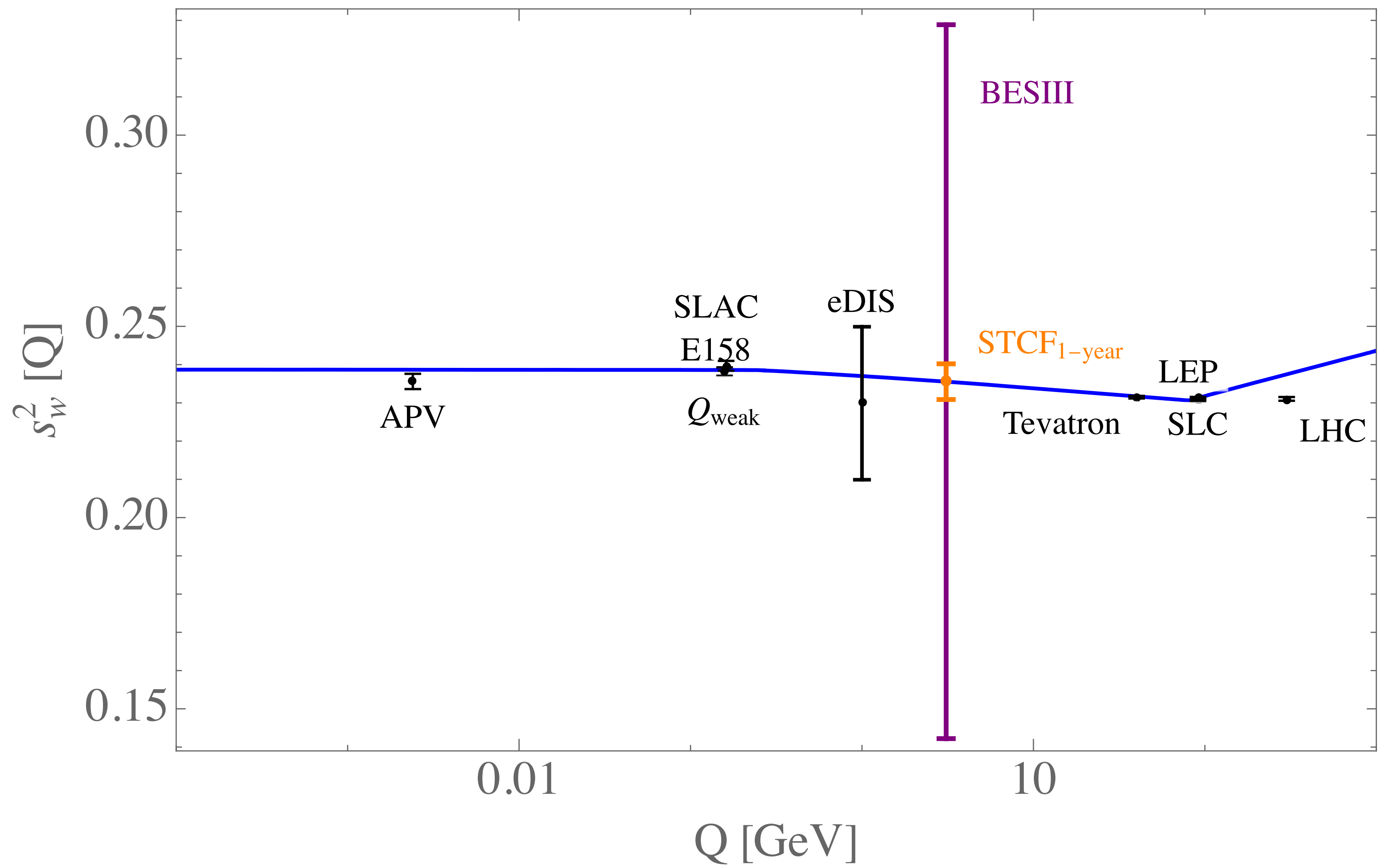
$$16\pi^2\frac{d}{d\ln\mu}\begin{pmatrix} C^{LR}_{ud+} \\ C^{LR}_{ud-}\end{pmatrix} = 16\pi^2\frac{d}{d\ln\mu}\begin{pmatrix} \frac{6C_F}{b}\alpha_s & 0 \\ 0 & -\frac{3}{bN_c}\alpha_s\end{pmatrix}$$

YD, X-G He, J-P Ma, X. Du, 2405.09625

# $A_{\rm PV}$ in Baryons: $\sin^2\theta_W$ det

First determination of $\sin\theta_W$ at the $J/\psi$ threshold

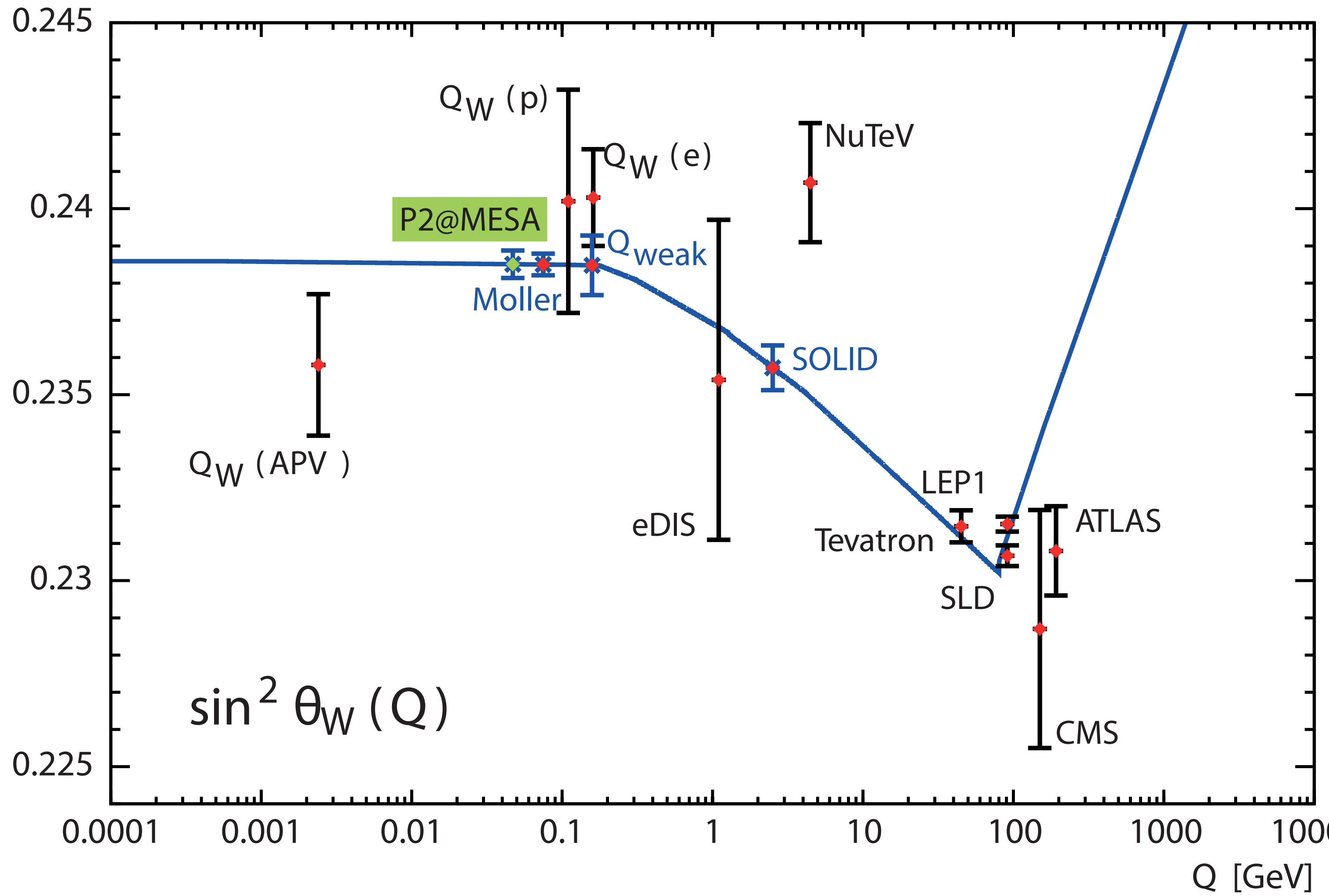
$$\frac{\delta s_w^2}{s_w^2} = a_0\frac{\delta m_B}{m_B} \oplus a_1\frac{\delta m_{J/\psi}}{m_{J/\psi}} \oplus a_2\frac{\delta R}{R} \oplus a_3\frac{\delta\alpha}{\alpha} \oplus a_4\frac{\delta\Delta\Phi}{\Delta\Phi} \oplus a_5\frac{\delta A_{\rm PV}^{(1)}}{A_{\rm PV}^{(1)}}$$




YD, X-G He, J-P Ma, X. Du, 2405.09625

# Summary

From non-perturbative to perturbative regions, we are precisely testing our models. Theoretical computations are urgently needed, and imprint of new physics might be seen in the coming years, otherwise stringent constraint on potential models can be obtained.




DDH, $\chi$PT

$SU(N)_L \otimes SU(N)_R$

Pert. QCD

+ ***All-range*** Precision EW test in the leptonic sector