Parity-Violation and New Physics

Theory, Motivation, Landscape

Town Meeting for the next **NSAC Long Range Plan** on

Fundamental Symmetries, Neutrinos, Neutrons and related Nuclear Astrophysics

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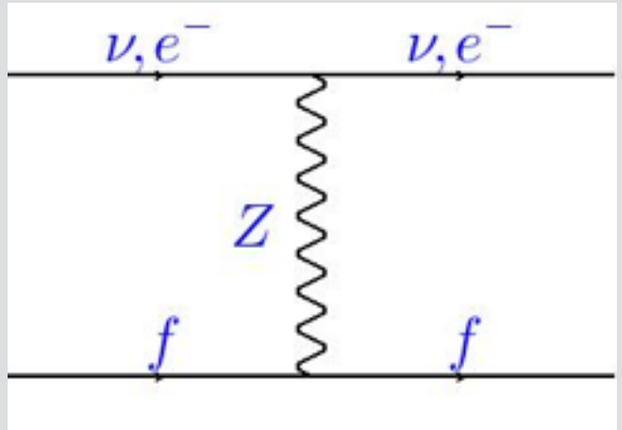
Chicago, IL

September 28, 2014
Crowne Plaza O'Hare



Global context

- energy frontier (LHC): Higgs boson found ➡ Standard Model (SM) complete
- cosmic frontier: dark matter ➡ physics beyond the SM already discovered
- What is it? Use intensity and precision frontiers:
  - "super-allowed" but ultra-high precision: g_μ–2
  - SM suppressed: parity violation (PV) and ν-scattering (**this Session**)
  - rare processes: weak decays and oscillations
  - (effectively) SM forbidden: EDMs, CLFV, proton decay, n-n̄-oscillations
  - SM @ dimension 5: ν-oscillations and ~~ν~~ββ-decay

➡ probes of **very different scales and types** of new physics (need all)

Low energy Lagrangian (v)

$$\mathcal{L}_{\rm NC}^{\nu_\mu e} = -\frac{2}{v^2}\overline{\nu_{\mu L}}\gamma^\rho \nu_{\mu L}\left[g_{LL}^{\nu e}\overline{e_L}\gamma_\rho e_L + g_{LR}^{\nu e}\overline{e_R}\gamma_\rho e_R\right]$$

$$g_{LV}^{\nu_\mu e} = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_{LA}^{\nu_\mu e} = -\frac{1}{2}$$

SM tree level

$$\mathbf{v = [\sqrt{2}G_F]^{-1/2}} \qquad \mathbf{\sin^2\theta_W = 1 - M_W^2/M_Z^2}$$

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$$\mathcal{L}_{\rm NC}^{\nu q} = -\frac{2}{v^2}\overline{\nu_L}\gamma^\mu \nu_L\left[g_{LL}^{\nu u}\overline{u_L}\gamma_\mu u_L + g_{LR}^{\nu u}\overline{u_R}\gamma_\mu u_R + (u\to d)\right]$$

$$g_{LL}^{\nu u} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \qquad g_{LR}^{\nu u} = -\frac{2}{3}\sin^2\theta_W$$

$$g_{LL}^{\nu d} = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W \qquad g_{LR}^{\nu d} = \frac{1}{3}\sin^2\theta_W$$

SM tree level

$$g_L^2 \equiv (g_{LL}^{\nu u})^2 + (g_{LL}^{\nu d})^2 \qquad g_R^2 \equiv (g_{LR}^{\nu u})^2 + (g_{LR}^{\nu d})^2$$

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isoscalar combinations

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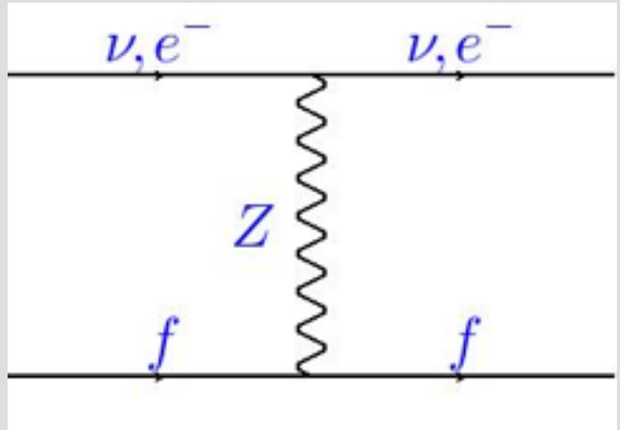
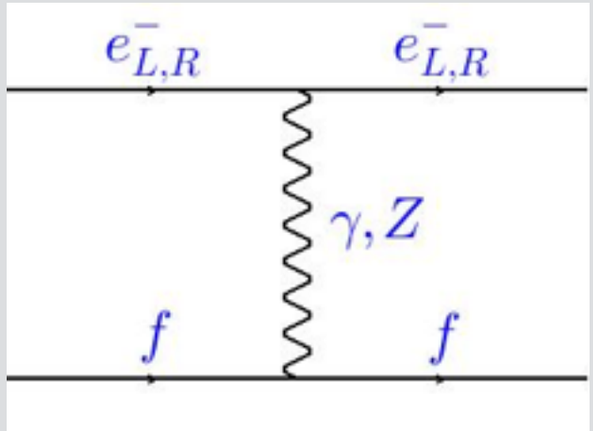


ν scattering

- ν(ν̄)-e scattering (discovery of weak NC 1973): $g_{LV,LA}^{\nu e}$ (**CHARM II**: ± 0.017)
  - clean but low statistics; improve to ± 0.003 at FNAL? ***Mishra et al., 0812.4527***
- ν(ν̄)-N DIS: rather clean for **isoscalar** targets; g_L^2 and g_R^2 (**NuTeV**: ± 0.0011)
  - but CSV & N > Z can modify PDFs; many other corrections (uncertainty?)
- ν(ν̄)-p: difficult to interpret both elastic (s quarks) & DIS (model dependence)
- ν-induced coherent π^0 production from nuclei: $g_{LA}^{\nu u} - g_{LA}^{\nu d}$ (± 0.06)
- coherent elastic ν-N scattering (CENNS): $Q_W(N)$ mostly $g_{LV}^{\nu u} + g_{LV}^{\nu d}$ (± 0.01)
- **CENNS** & **COHERENT** position papers ➡ ν-scattering talks in this session



Parity violation

- Use **parity symmetry** of strong and EM interactions to isolate **weak** interaction and **new physics** effects ➡ SM allowed but suppressed
  - atomic parity violation (**APV**):
    - Boulder, Paris, TRIUMF, Groningen, Berkeley/Mainz, Yale
    - needs atomic structure theory and neutron distributions
  - parity-violating electron scattering (**PVES**): SLAC, JLab, Mainz (**P2**)
    - often extra suppression by $1 - 4 \sin^2\theta_W \approx 0.045$
    - ➡ O(10%) measurements probes **TeV scale** (LHC territory)
    - ➡ few % precision ➡ ‰ determination of $\sin^2\theta_W$ (LEP/SLC precision)

Low energy Lagrangian (e)

$$\mathcal{L}_{\rm NC}^{ef} = \frac{\overline{e}\gamma^\mu\gamma^5 e}{2v^2}\left(g_{AV}^{ee}\frac{\overline{e}\gamma_\mu e}{2} + \sum_{q=u,d} g_{AV}^{eq}\overline{q}\gamma_\mu q\right)$$

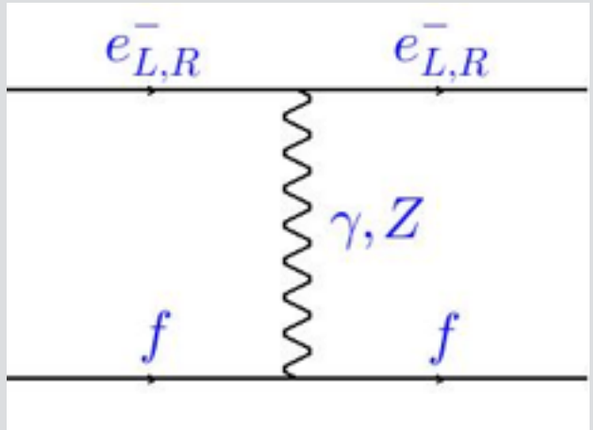
$$+ \frac{\overline{e}\gamma^\mu e}{2v^2}\sum_{q=u,d} g_{VA}^{eq}\overline{q}\gamma_\mu\gamma^5 q$$

$$g_{AV}^{ee} = -\frac{2g_{VA}^{eu} - g_{VA}^{ed}}{3} = \frac{1}{2} - 2\sin^2\theta_W$$

$$g_{AV}^{ep} \equiv 2g_{VA}^{eu} + g_{VA}^{ed} = -\frac{1}{2} + 2\sin^2\theta_W$$

$$g_{AV}^{en} \equiv g_{VA}^{eu} + 2g_{VA}^{ed} = \frac{1}{2}$$

SM tree level



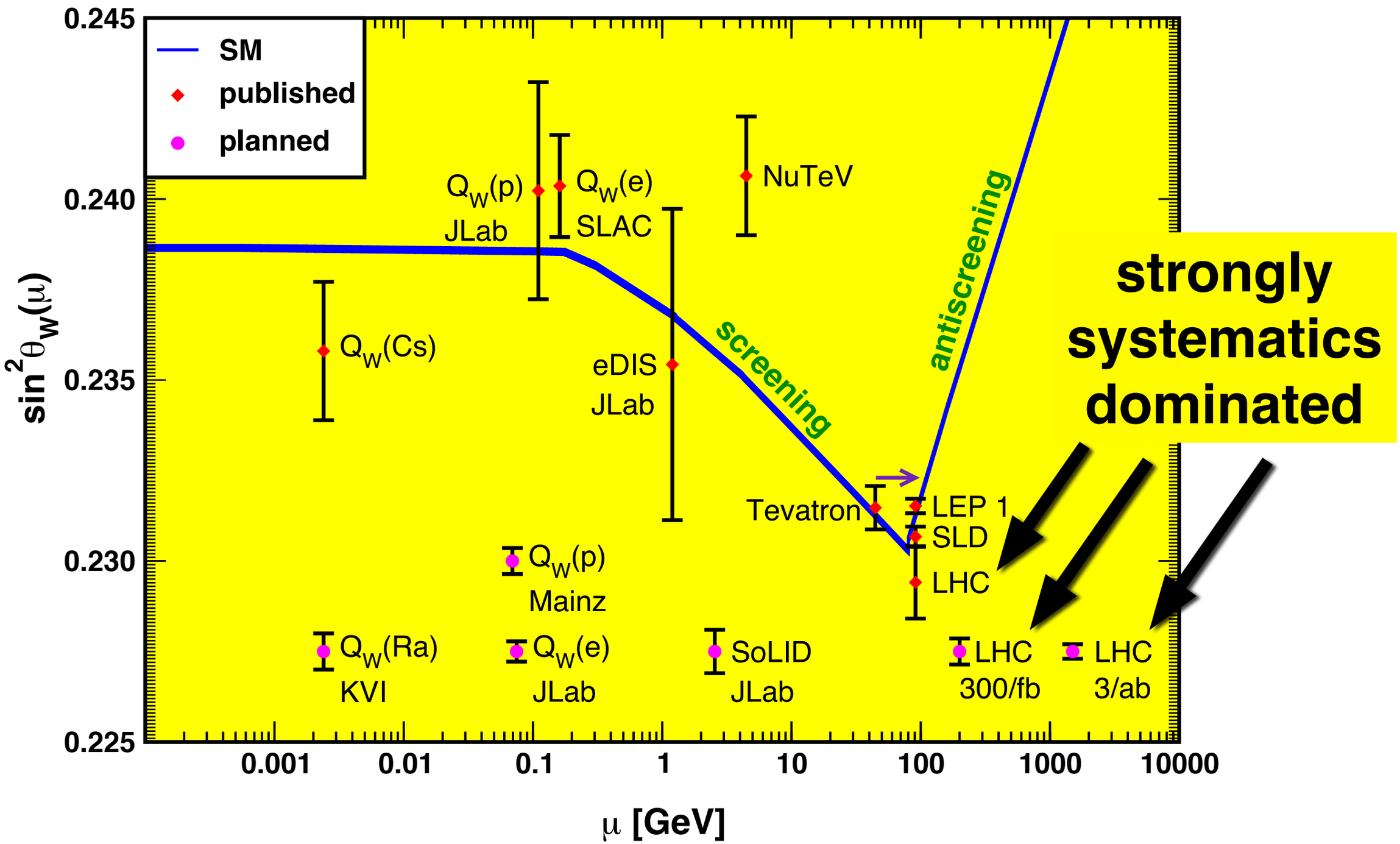
APV and PVES

- APV in single heavy isotopes: ~ 1.5 g_{AV}^{en} + g_{AV}^{ep}; most precise in ^{133}Cs

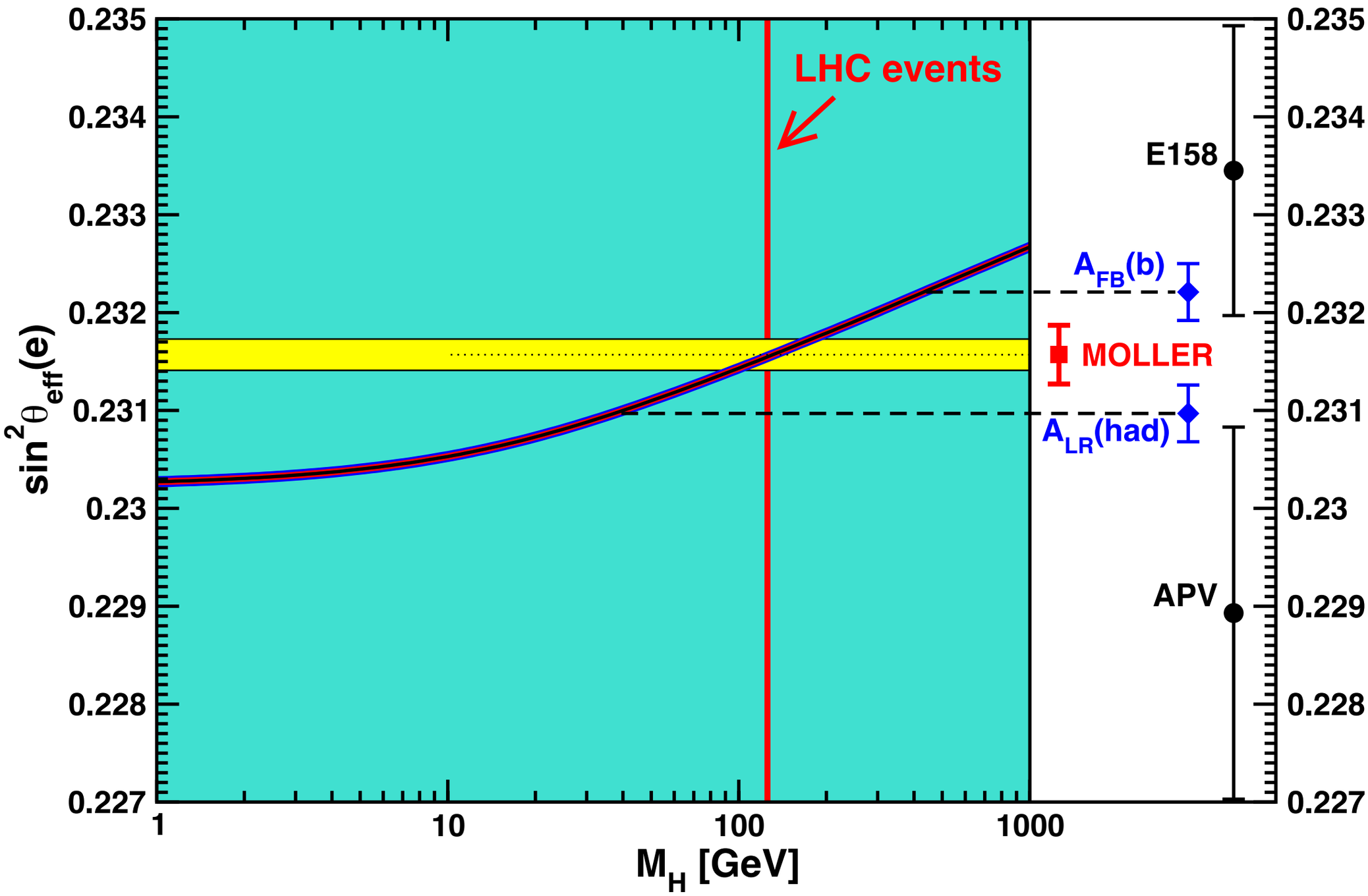
  (± 0.4% experiment ± 0.4% theory) ***Wood et al Science 275 (1997); Dzuba et al 1207.5864***

- APV isotope ratios: mostly g_{AV}^{ep} but needs ± 0.2‰ to match **Qweak**
- e-e: very clean g_{VA}^{ee} (**E158**: ± 0.005) ➡ **MOLLER**: ± 0.0011
- e-d DIS: 2 g^{eu} – g^{ed} (**PVDIS**: ± 4%) ➡ **SoLID**: ± 0.6% (isolate CSV & HT)
- e-p elastic: g_{AV}^{ep} (**Qweak** run I: ± 0.006) ➡ final: ± 0.0016, **P2**: ± 0.0008
- e-C elastic: g_{AV}^{en} + g_{AV}^{ep} ➡ **P2**: ± 0.0014 (requires ≤ 0.25% polarimetry)
- **FrPNC**, **MOLLER** & **SoLID** position papers

Weak mixing angle (scale dependence)



Weak mixing angle and Higgs mass



Radiative corrections

- very clean in **MOLLER** and ν-e
  - for **MOLLER** theory community should target full 2-loop calculation
    - major effort, but techniques in place
- hadronic γ-Z box diagrams
  - need further experimental input to constrain dispersively
  - more than factor 3 (2) smaller effect (uncertainty) in **P2** than **Qweak**
  - $(1 - 4 \sin^2\theta_W)$ suppressed in APV
  - calculable perturbatively in eDIS
    - both necessary and possible for **SoLID** precision

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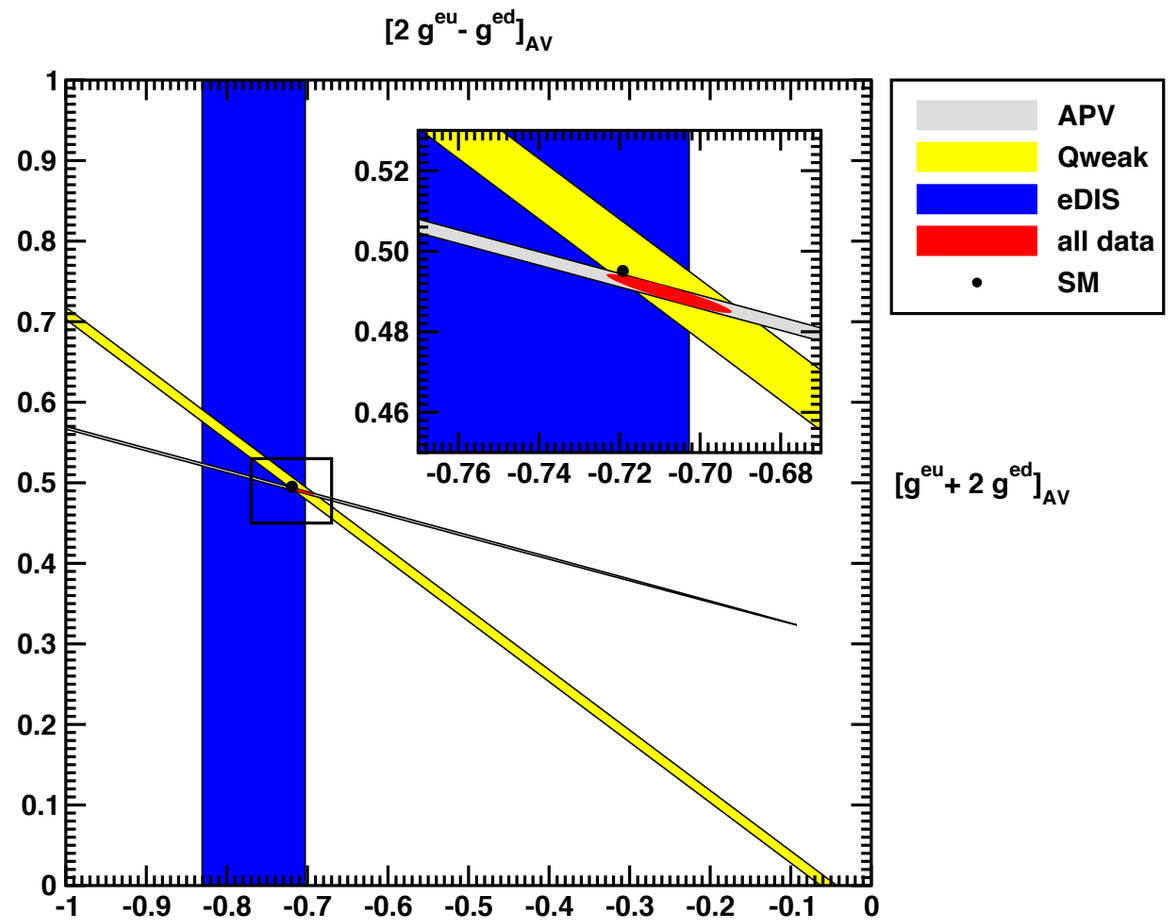
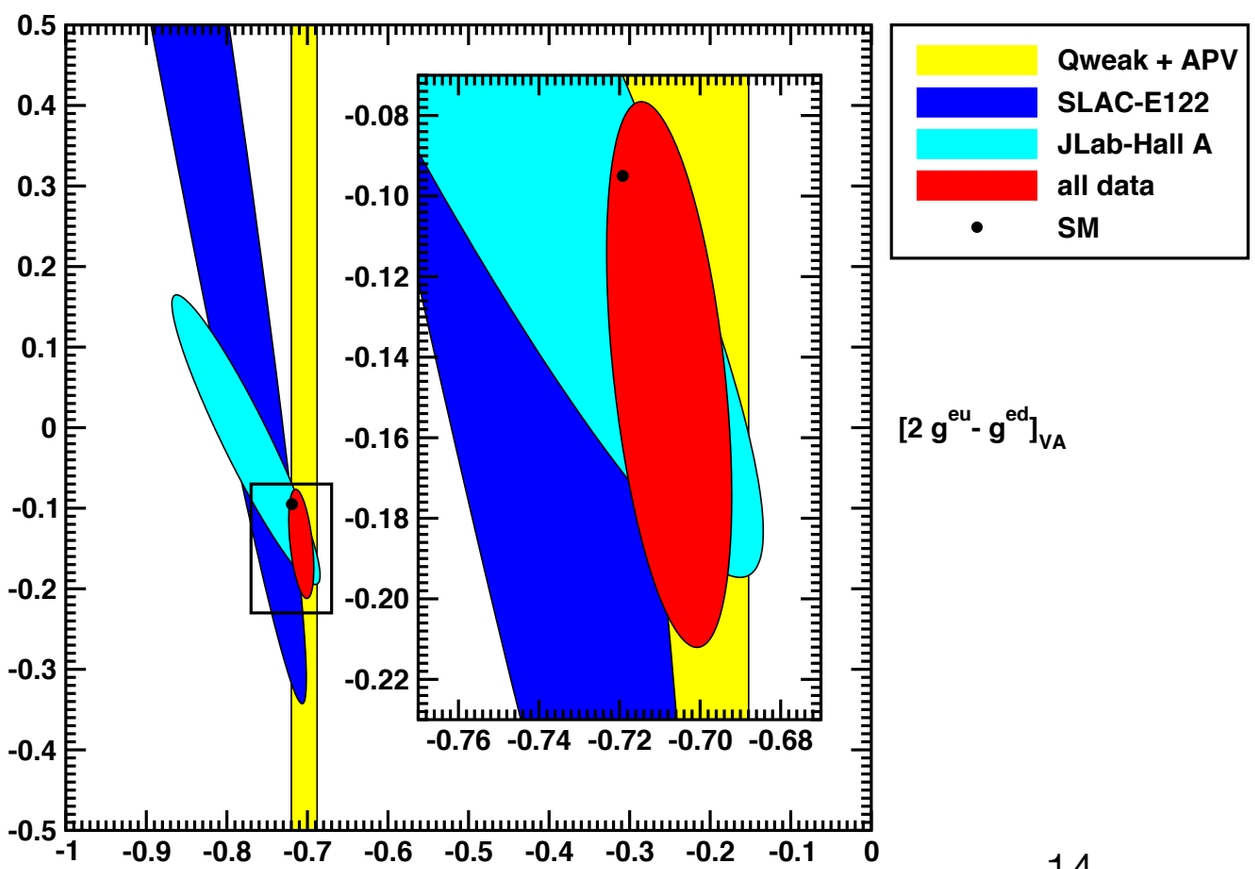
Effective couplings





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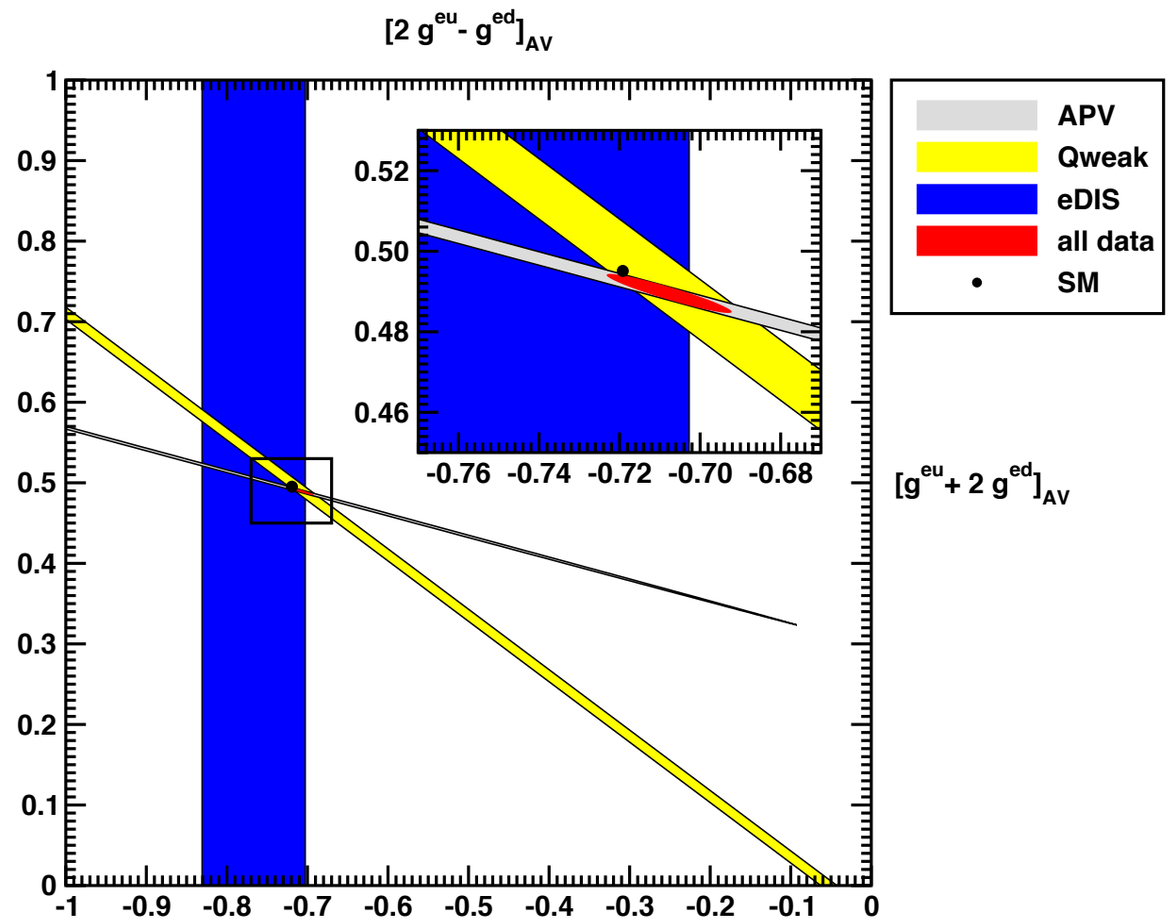
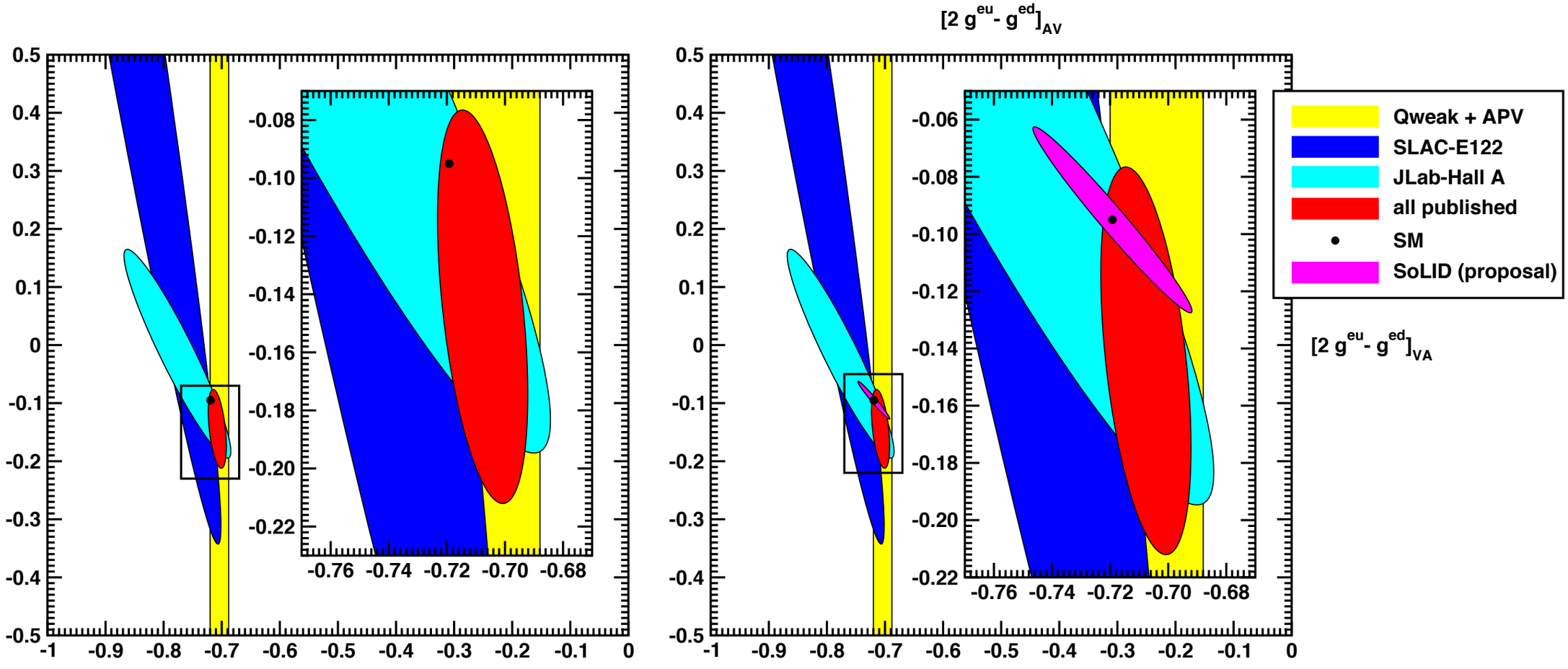
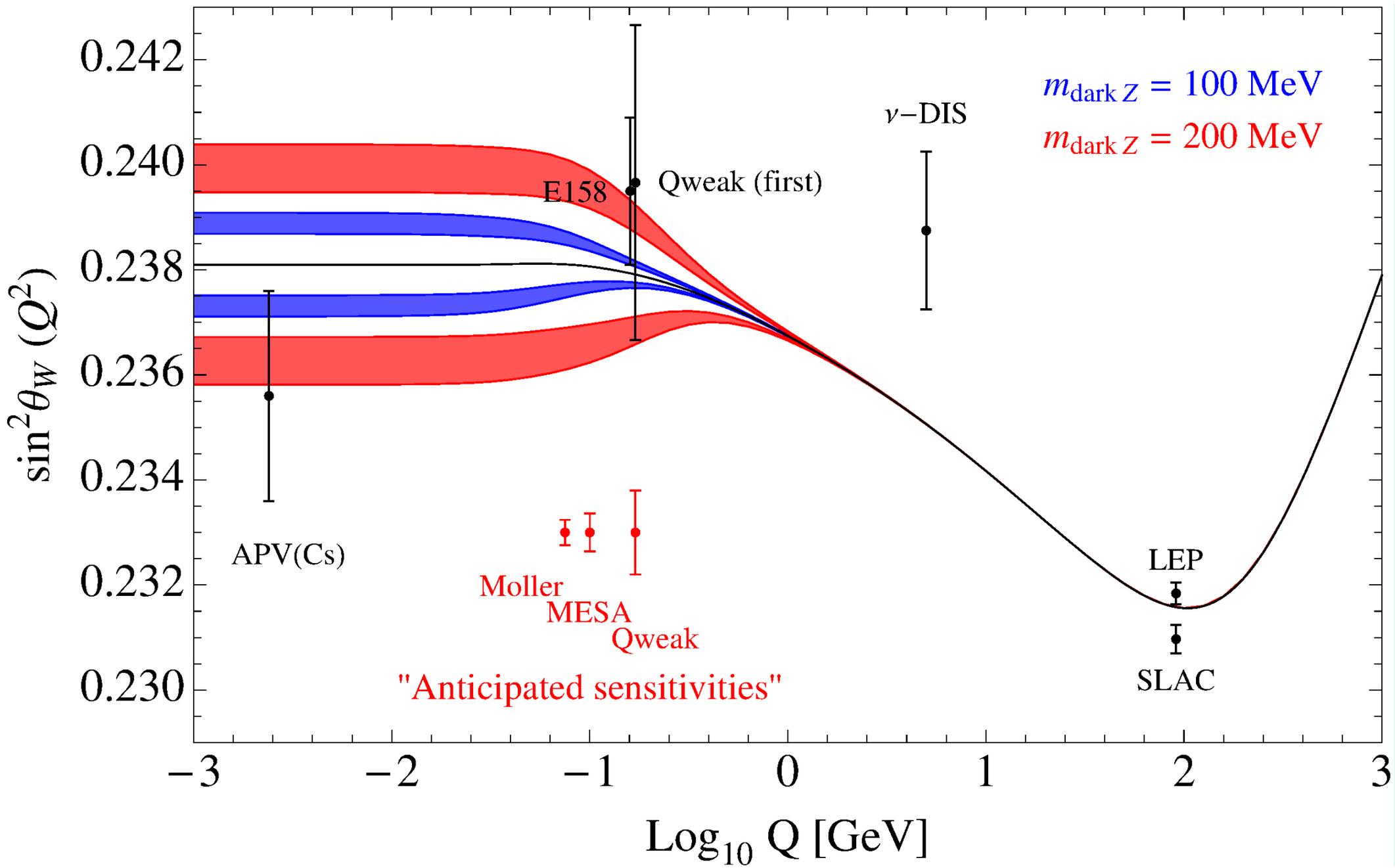




Complementarity

- new amplitudes (low energy) ↔ modification of $Z f\bar{f}$ couplings (Z pole)
- $\sqrt{Q^2} >$ O(100 MeV) (**Qweak**) ↔ $\sqrt{Q^2} <$ O(5 MeV) (APV isotope ratios)
- $\sqrt{Q^2} >$ O(100 MeV) (**P2**-C) ↔ $\sqrt{Q^2} <$ O(5 MeV) (APV single isotope)
- ν-q ↔ ν-e ↔ e-e ↔ e-q
- VV and AA (Z pole) ↔ AV (APV and elastic PVES) ↔ VA (eDIS)
- new physics in loops (M_W-M_Z-G_F-$\sin^2\theta_W$ interdependence) ↔ new tree amplitudes (Z', doubly charged scalars, leptoquarks, KK modes)
- γ-Z box ↔ atomic theory complications

Dark Z boson (kinetic + mass mixing)



Davoudiasl, Lee, Marciano

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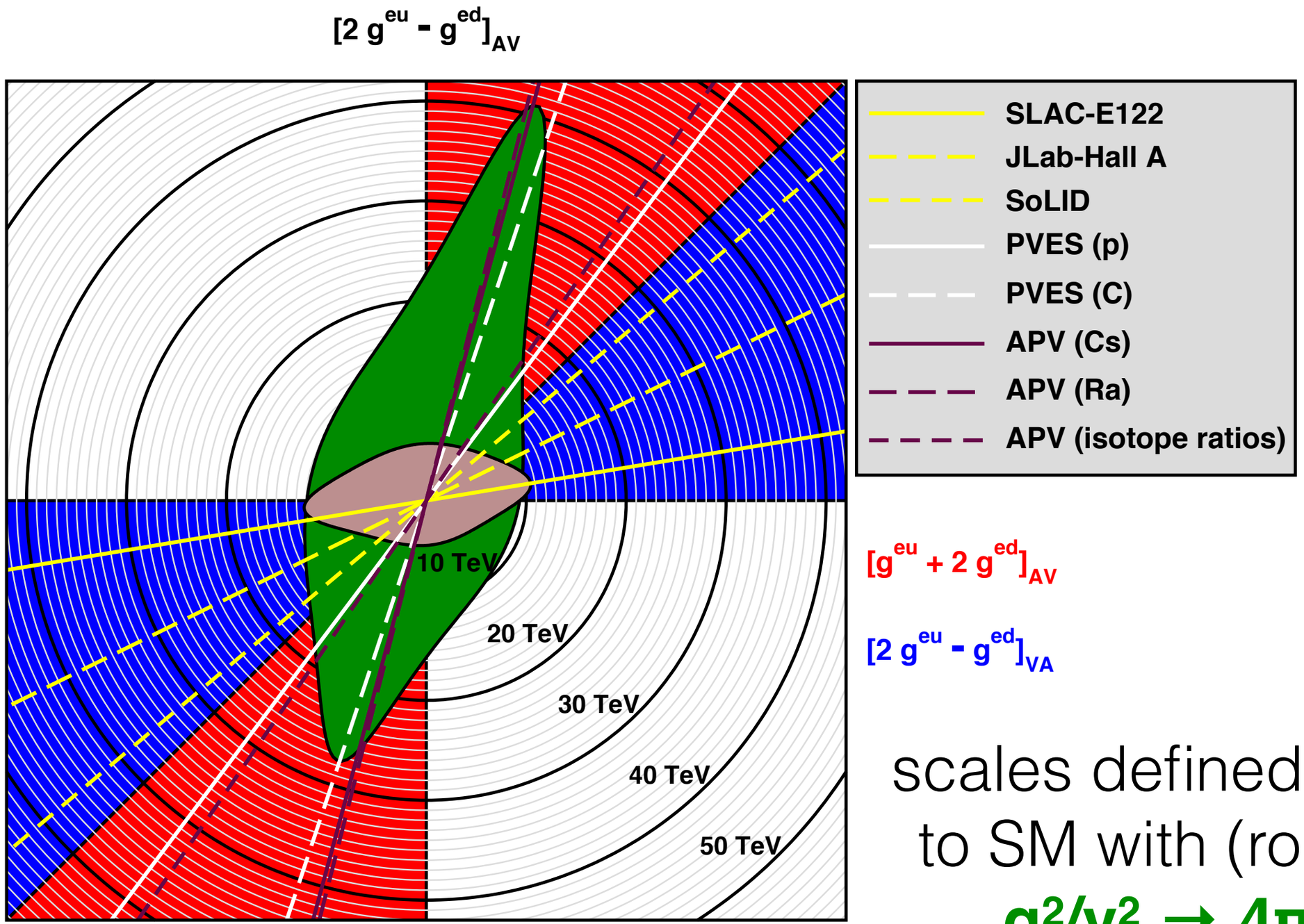
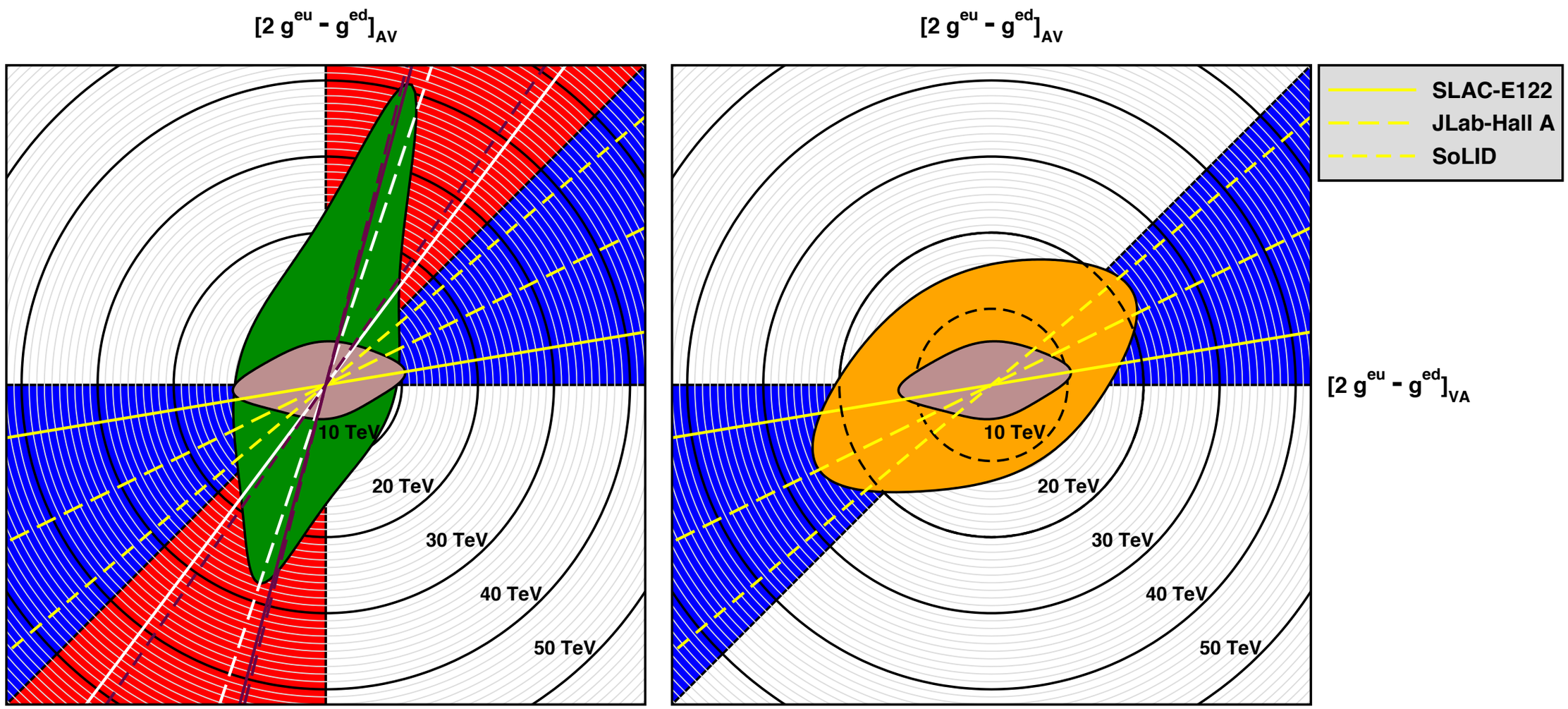
Compositeness scales from PV (*current*)



scales defined similar to SM with (roughly)

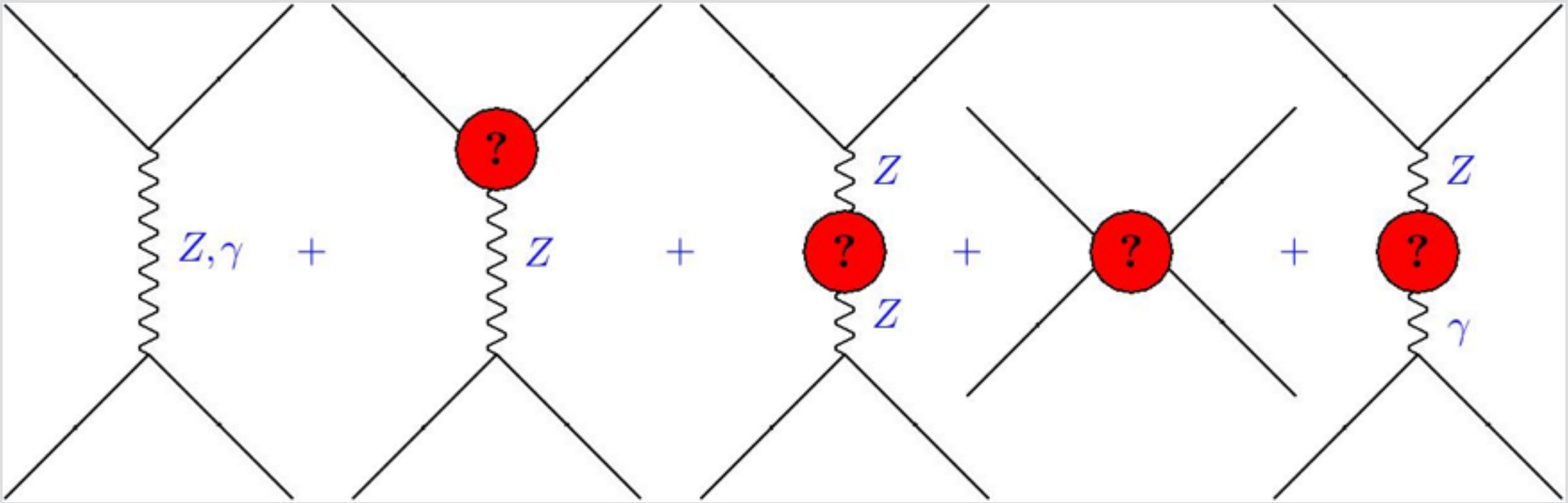
$g^2/v^2 \rightarrow 4\pi/\Lambda^2$

Compositeness scales from PV (*future*)



Conclusions

- **MOLLER** first (before LHC) to measure $\sin^2\theta_W$ matching Z-factories in precision
- **SoLID**: axial-quark coupling (first measurement by **PVDIS** published in *Nature*)
- also need elastic e-C and APV in isotope ratios and push ν-scattering, single isotope APV, and elastic e-p
- complementary efforts crucial as new physics may enter in many different ways



Position papers for Session E:
Lepton Properties and Interactions II

- **CENNS** Collaboration:
  Measuring Coherent Elastic Neutrino Nucleus Scattering at an Off-Axis High-Energy Neutrino Beam Target

- **COHERENT** Collaboration:
  COHERENT at the Spallation Neutron Source

- **FrPNC** Collaboration:
  Weak interaction studies in Fr

- **MOLLER** Collaboration:
  Measurement of Lepton-Lepton Electroweak Reaction

- **SoLID** Collaboration:
  Parity Violation in DIS at JLab with SoLID