Synergies with Nuclear Physics

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Wisconsin-Madison
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Lepton Photon, June 2013

Outline

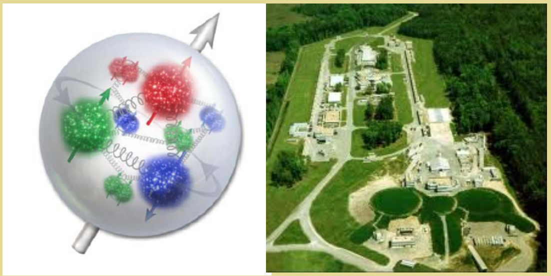
I. The Nuclear Physics Context

II. EDMs & the Origin of Matter

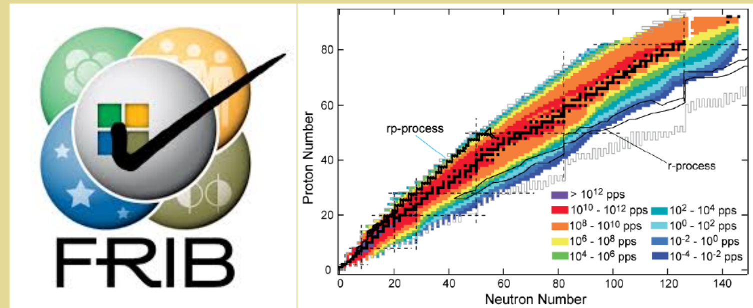
III. PV: BSM “diagnostic”

IV. Summary

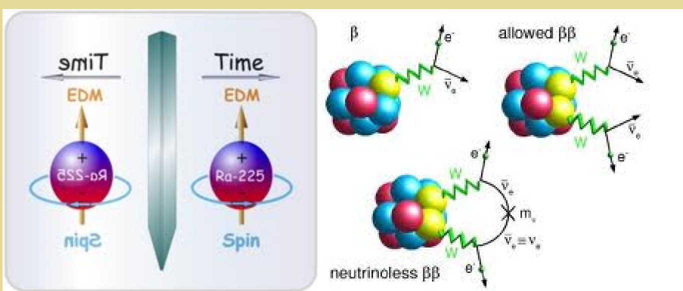
Nuclear Physics Today



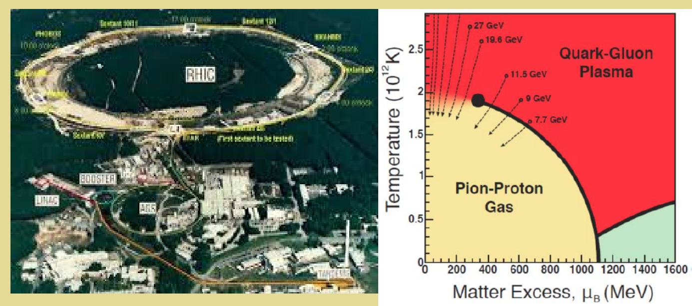
Hadron structure & dynamics: “cold QCD”



Rare isotopes: nuclear structure & astrophysics

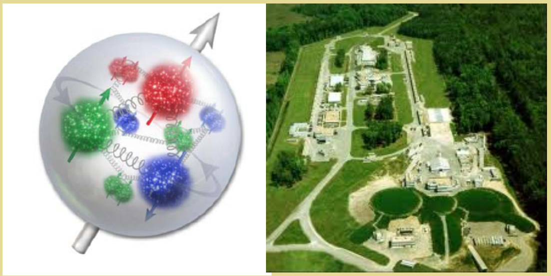


Fundamental symmetries & neutrinos: “Intensity Frontier”



Relativistic heavy ions: “hot & dense QCD”

Nuclear Physics Today



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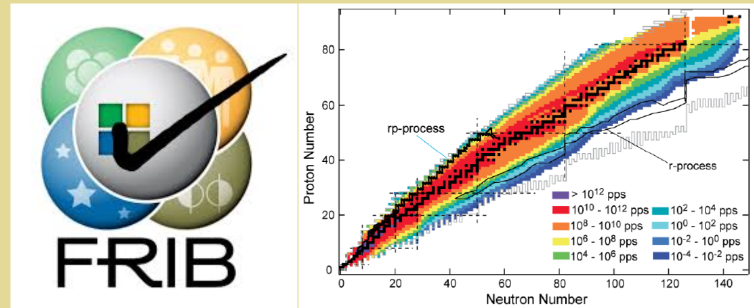

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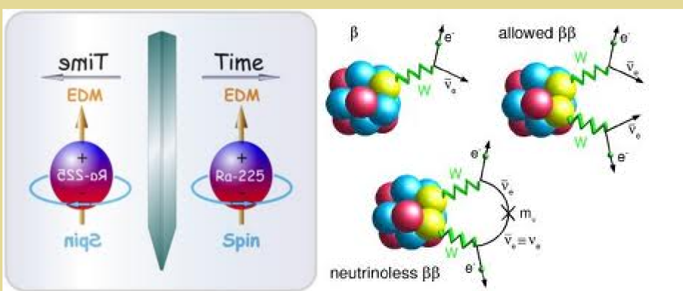

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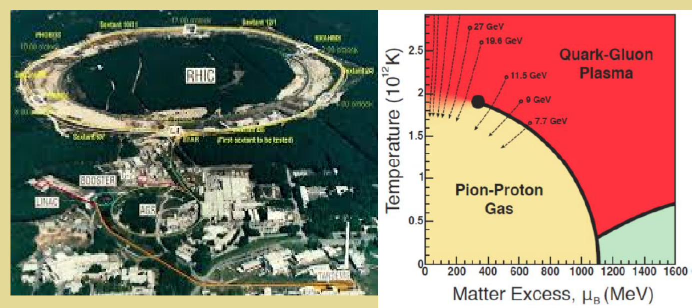

Relativistic heavy ions: “hot & dense QCD”

Scientific Questions

2007 NSAC LRP:

- *What are the masses of neutrinos and how have they shaped the evolution of the universe?*
- *Why is there more matter than antimatter in the present universe?*
- *What are the unseen forces that disappeared from view as the universe cooled?*

Four Components **

EDM searches: *BSM CPV, Origin of Matter*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

*** 2012 NSAC Subcommittee Report*

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EDMs & PV Electron Scattering

BSM Signal $\sim (v / \Lambda)^2$

EDMs & PV Electron Scattering

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BSM Probe :	θ_{QCD} *& BSM CPV*	*EDM*
	BSM "diagnostic"	*PV*

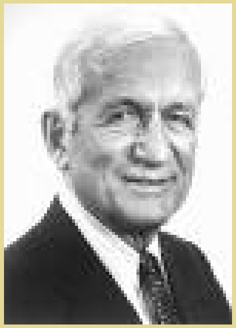
EDMs & the Origin of Matter

I. The experimental situation

II. Theoretical interpretation: multiple scales & multiple systems

III. Implications for baryogenesis

EDM Experiments



PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. SMITH,* E. M. PURCELL, AND N. F. RAMSEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts

(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

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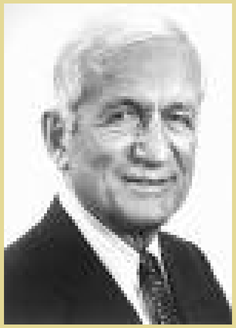

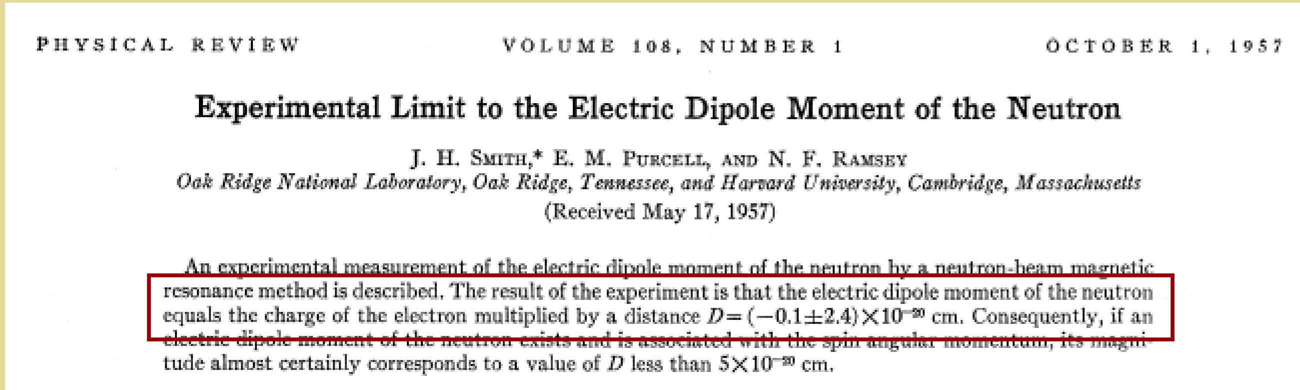

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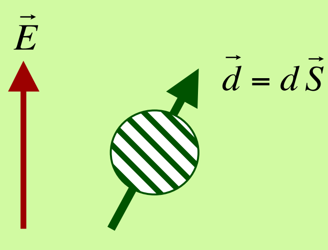
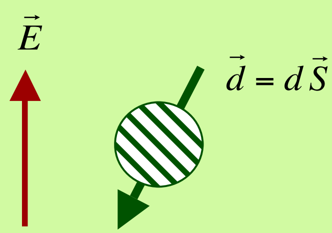
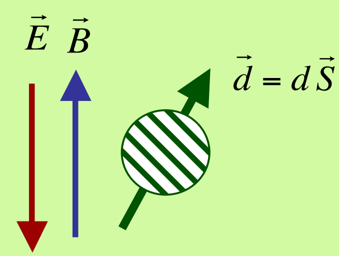


$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$



$$\nu_{EDM} = -\frac{d(-\vec{S})\cdot\vec{E}}{h}$$

T-odd $\rightarrow$ CP-odd by CPT theorem



$$\nu_{EDM} = -\frac{d\vec{S}\cdot(-\vec{E})}{h}$$

P-odd: used to find signal

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
YbF	1.8×10^{-21} **	10^{-32}	10^{-22}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent: 10.5×10^{-28} (thanks: T. Chupp)

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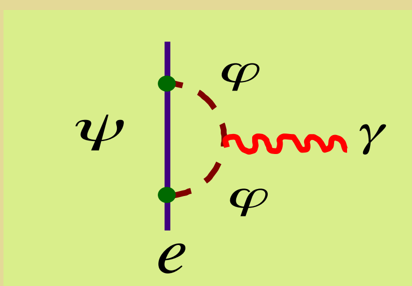
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow M > 5000$ GeV

$M < 500$ GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

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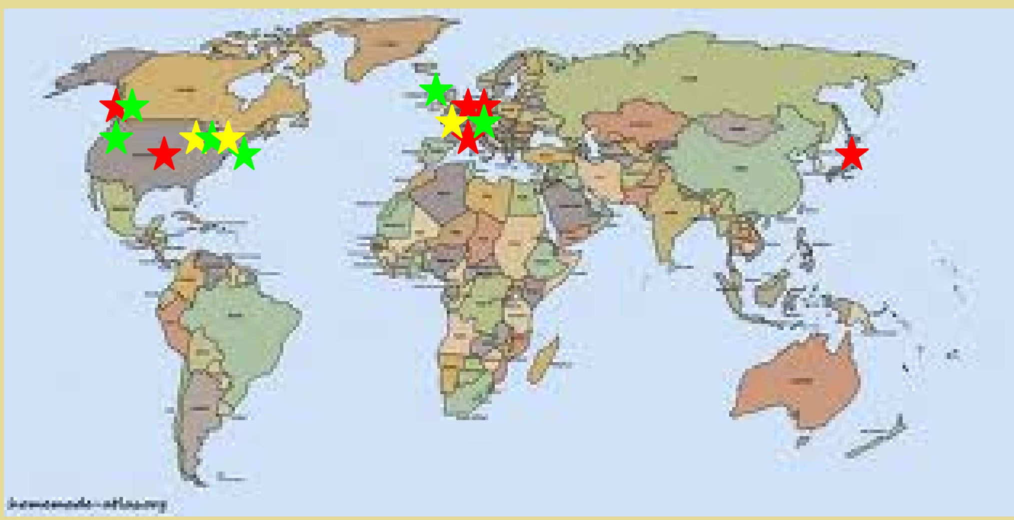


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

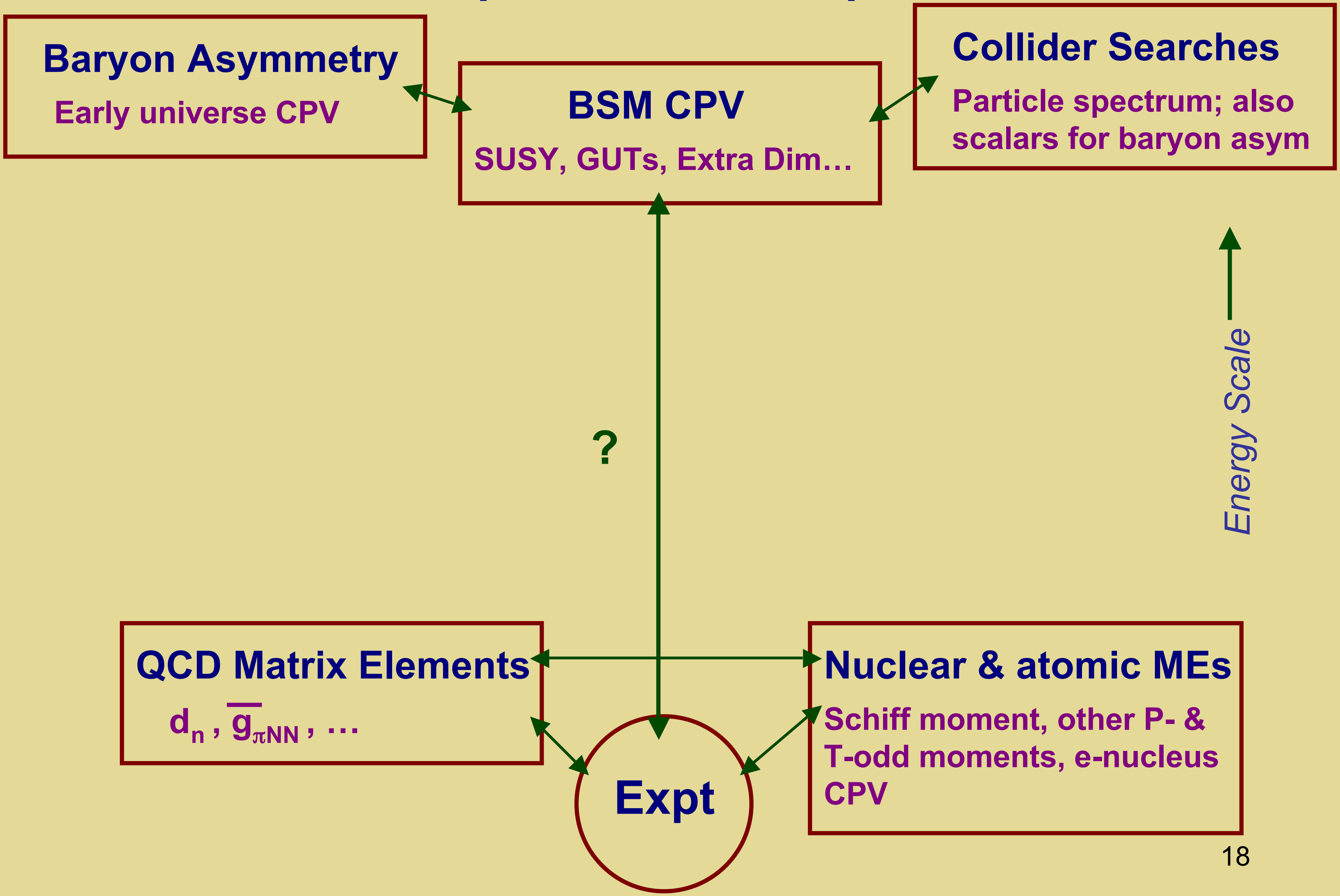
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales



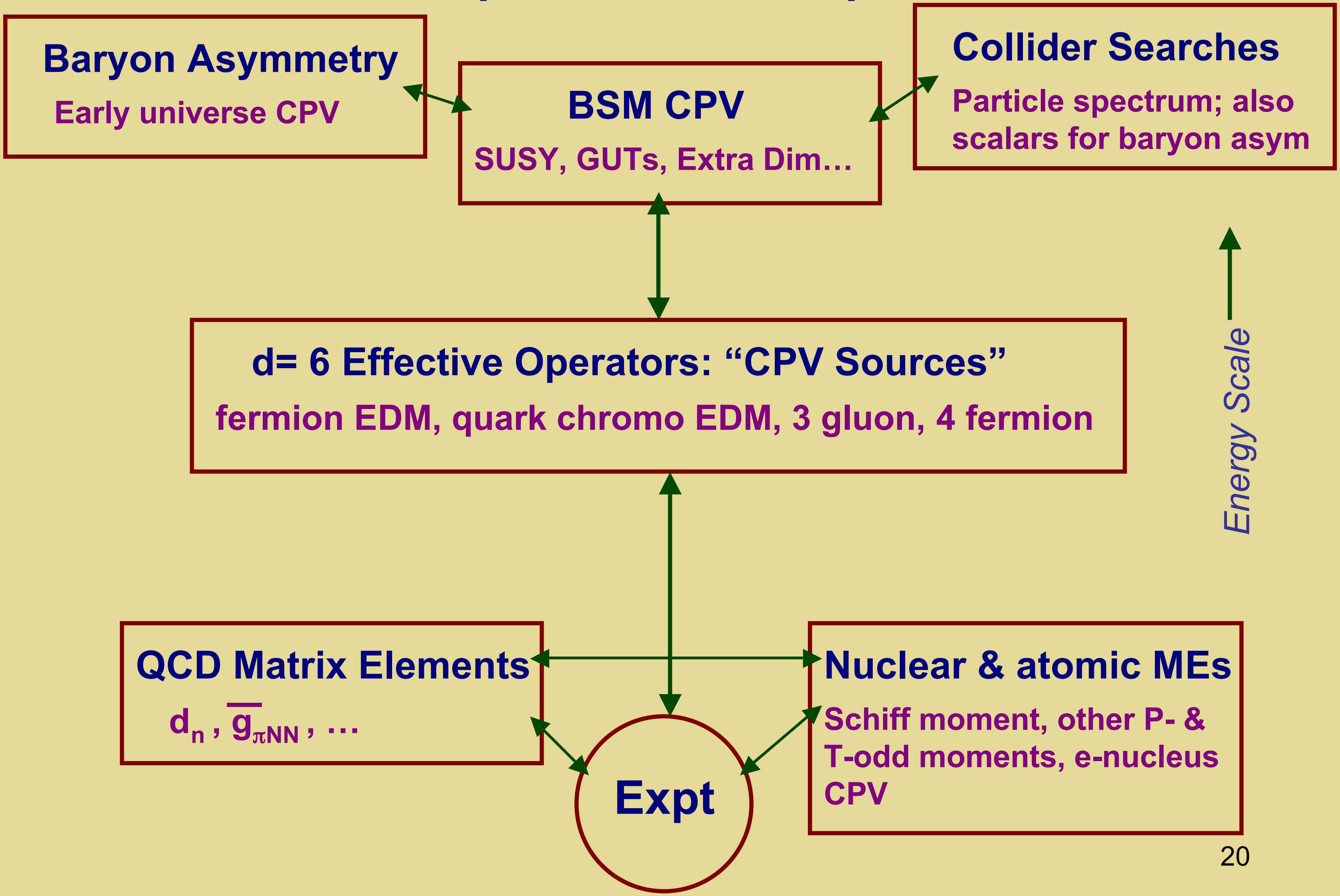
Effective Operators

$$\mathcal{L}_{\mathrm{CPV}} = \mathcal{L}_{\mathrm{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}}$$

$$\mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)}$$

$+ \ldots$

EDM Interpretation & Multiple Scales



BSM Origins

EDM: γff
CEDM: gff

Weinberg ggg:

Four fermion

udHH

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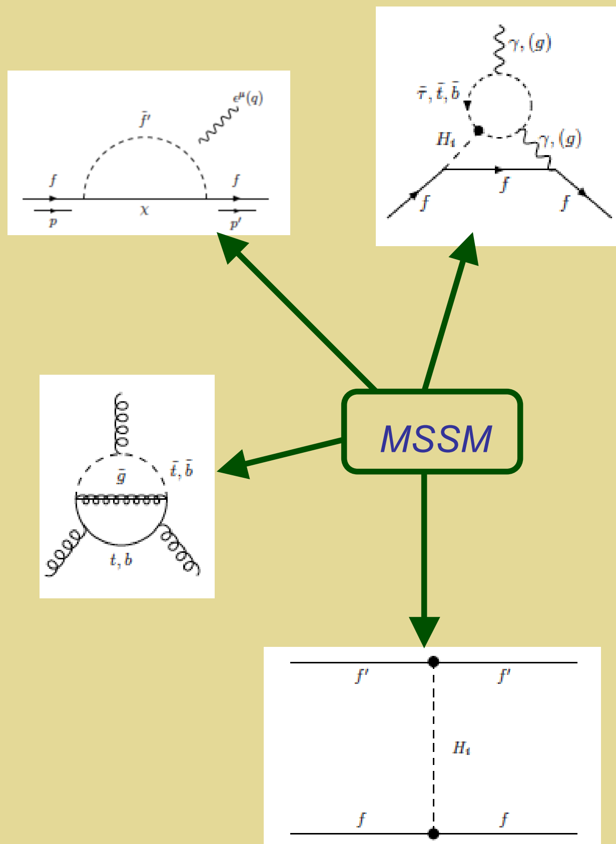

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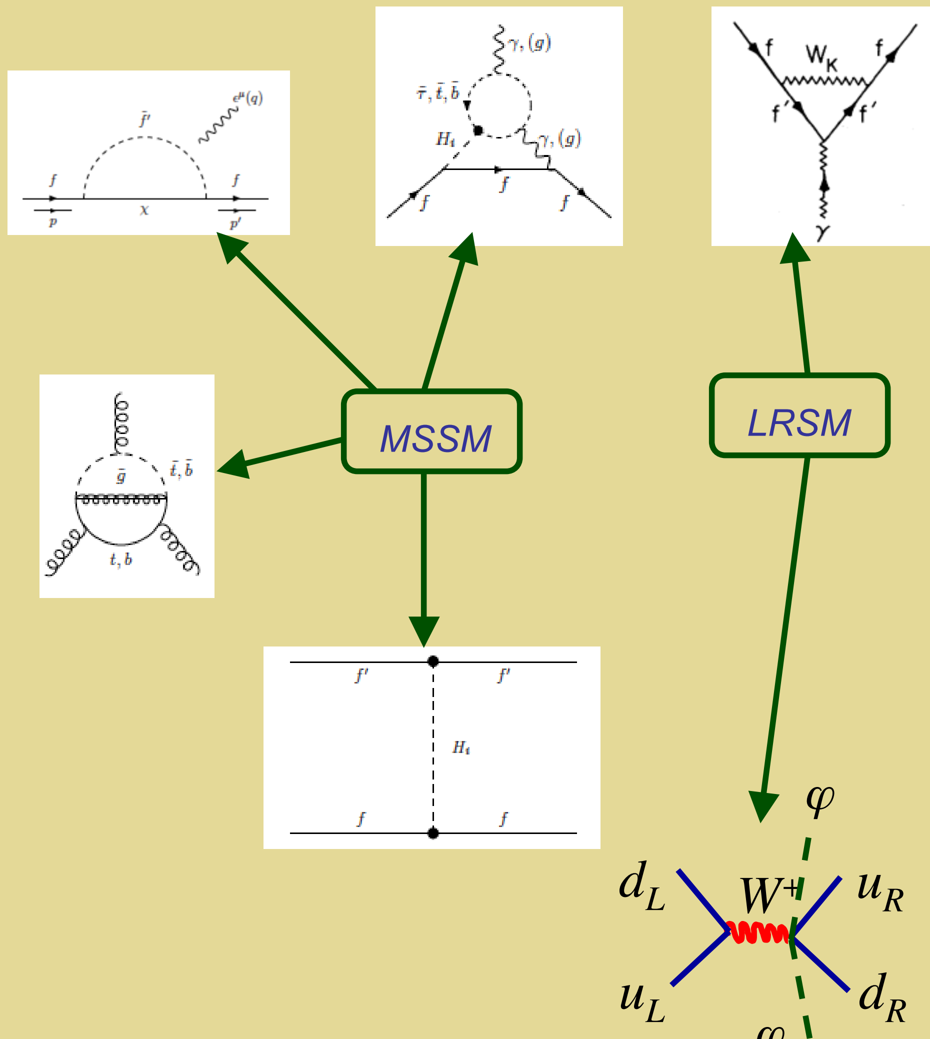

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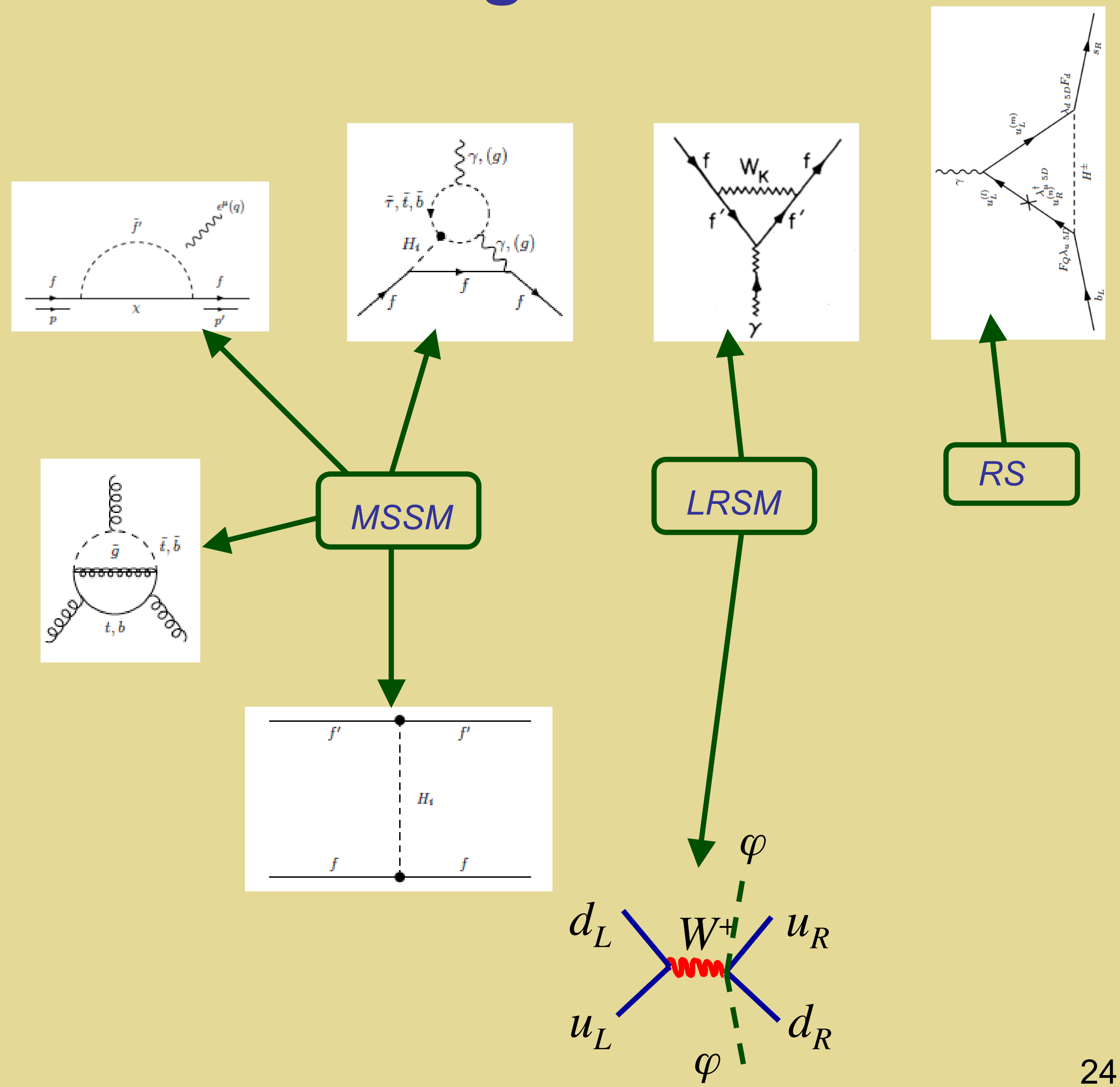
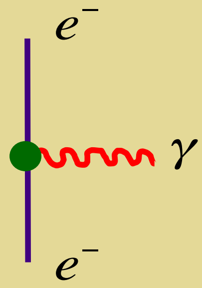


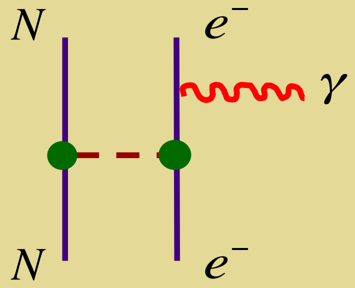
Why Multiple Systems ?

Multiple sources & multiple scales

Exploit complementary sensitivity to search for & identify CPV

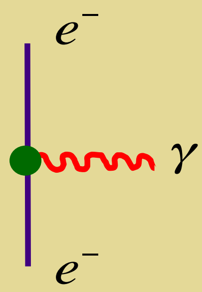
Paramagnetic Systems: Two Sources



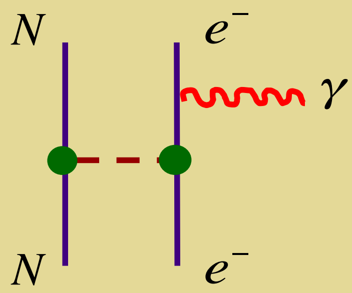


Tl, YbF, ThO…

Paramagnetic Systems: Two Sources



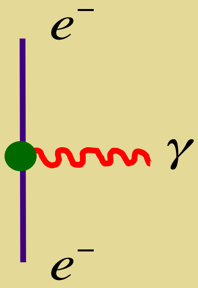
$$d_f = -(1.13 \times 10^{-3}\, e\,\text{fm}) \left(\frac{v}{\Lambda}\right)^2 \; Y_f \; \delta_f$$



$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \text{Im}\, C_{eq}^{(-)}$$

Tl, YbF, ThO…

Paramagnetic Systems: Two Sources



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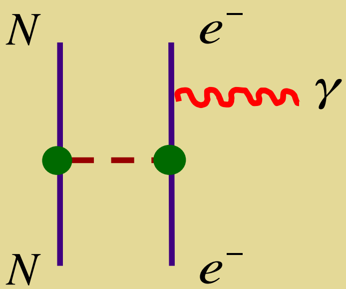

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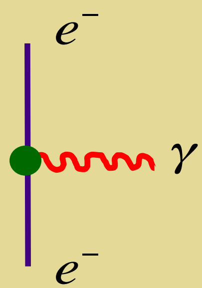

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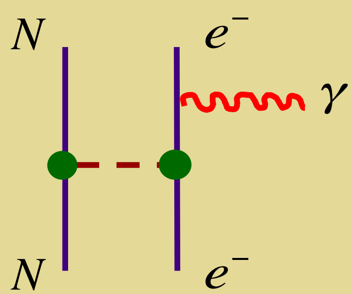
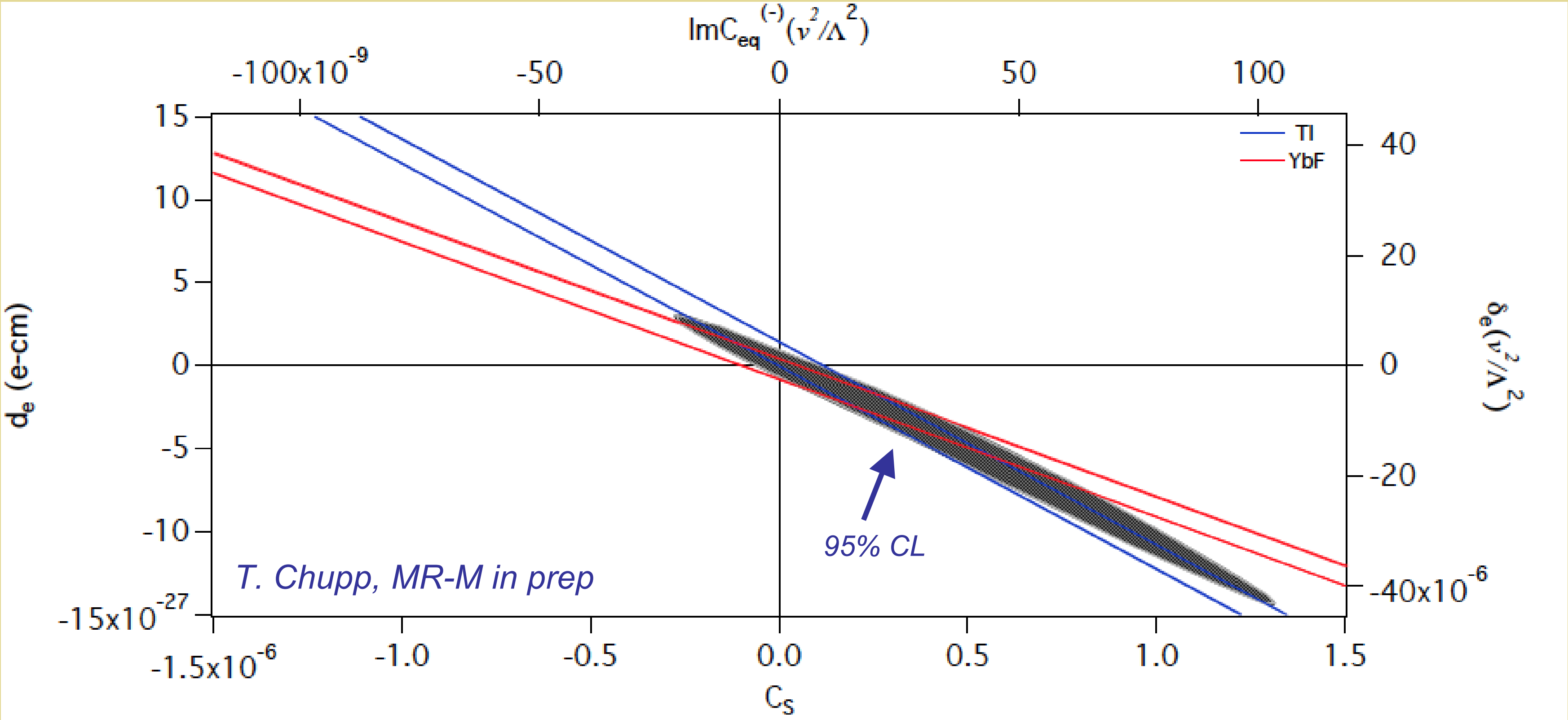


$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\, C_{eq}^{(-)}$$

~ 100 x greater sensitivity to C_{eq} than to δ_e

Tl, YbF, ThO…

Paramagnetic Global Fit

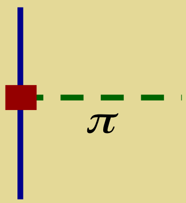


- $Im\ C_{eq}\ (v/\Lambda)^2 < 5.6 \times 10^{-8}$
- $\delta_e\ (v/\Lambda)^2 < 2.2 \times 10^{-5} \leftrightarrow d_e < 7.3 \times 10^{-27}$ e cm

See also Jung '13

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction



Neutron, proton & light nuclei (future), diamagnetic atoms

Hadronic CPV: Nucleons, Nuclei, Atoms

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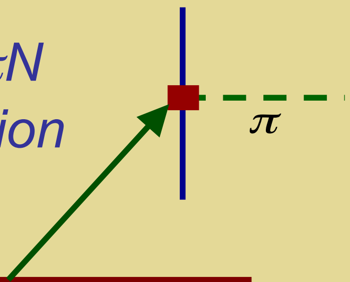

- chromo EDM
- 3 gluon
- 4 quark
- θ_{QCD}

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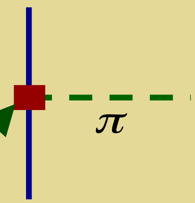

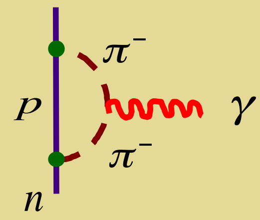

- *chromo EDM*
- *3 gluon*
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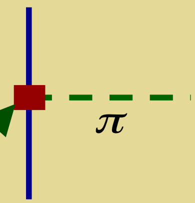
Nucleon EDM

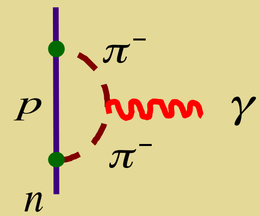
+ quark EDM

Neutron, proton & light nuclei (future), diamagnetic atoms

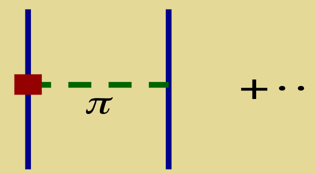
Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction





Nucleon EDM



Nuclear EDM & Schiff moment

- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

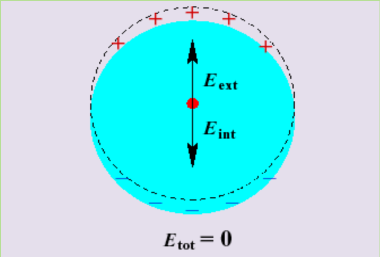
+ *quark EDM*

+ ~~*quark EDM*~~

Neutron, proton & light nuclei (future), diamagnetic atoms

Diamagnetic Systems: Schiff Moments

Schiff Screening



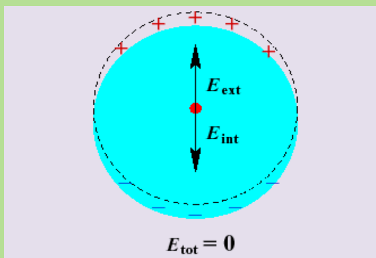
Atomic effect from nuclear finite size: Schiff moment

Neutral atoms: nuclear EDM invisible to external probe

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems: Schiff Moments

Schiff Screening



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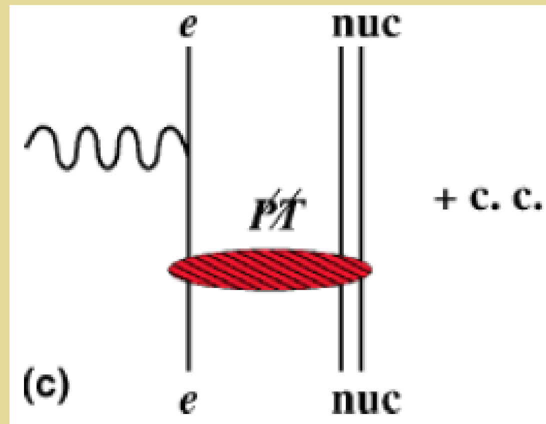
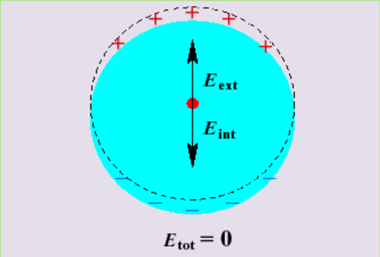


Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems: Schiff Moments

Schiff Screening



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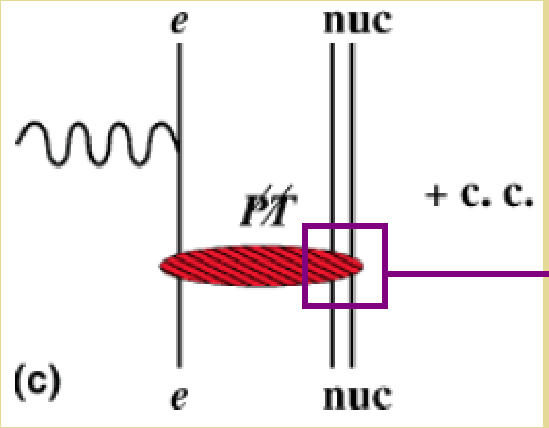


Schiff moment, MQM,…

Nuclear Schiff Moment

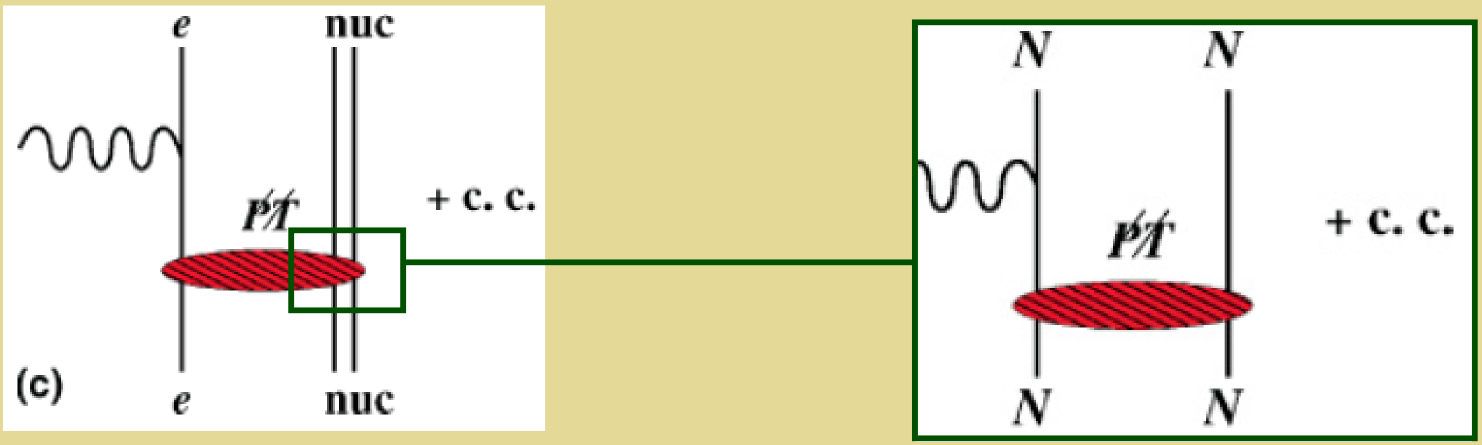
$$S \sim \int d^3x \, x^2 \, \vec{x} \, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



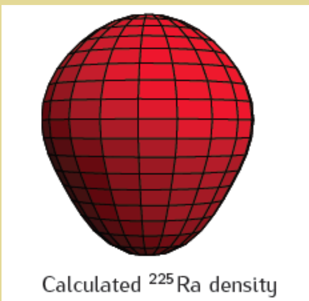
Schiff moment, MQM,…

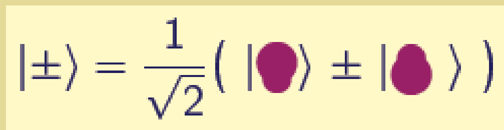
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

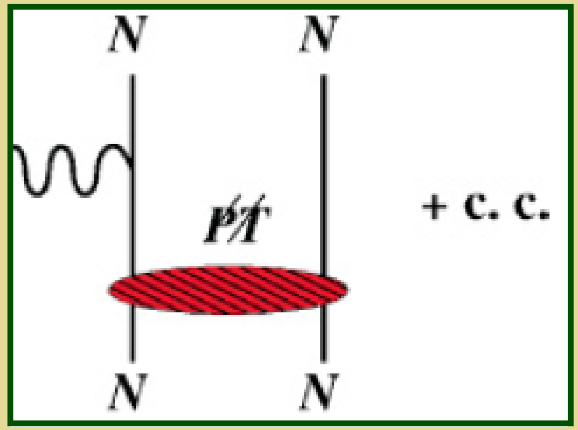
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation





Opposite parity states mixed by H^{TVPV}



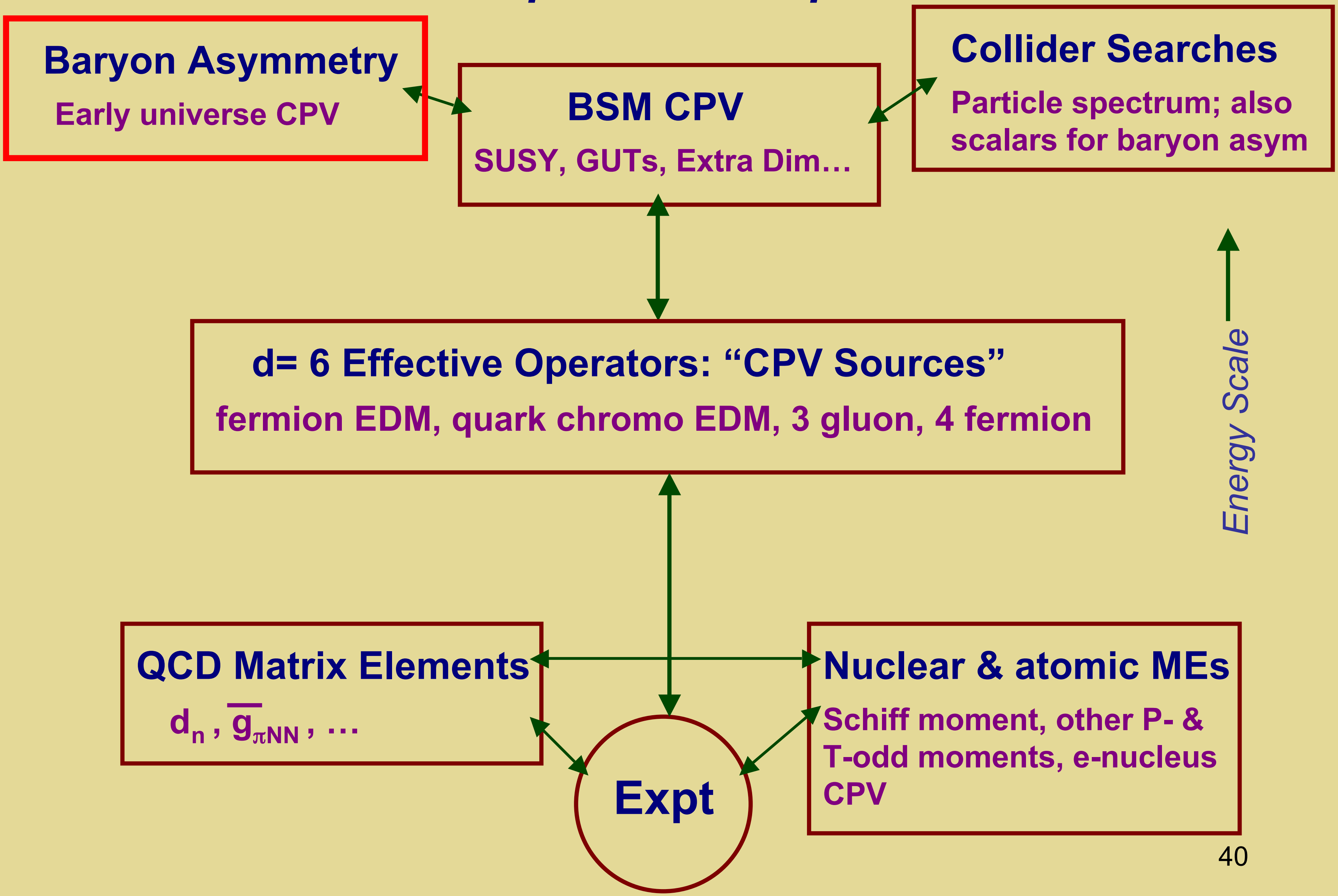
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

"Nuclear amplifier"

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel

EDM Interpretation: Implications



EDMs & Baryogenesis

	Standard Model	BSM
• *B violation (sphalerons)*	✔	✔
• *C & CP violation (BSM)*	✖	✔
• *Out-of-equilibrium or CPT violation (BSM)*	✖	✔

EDMs & Baryogenesis

Electroweak baryogenesis

- *Testable*
- *Was BAU produced ~ 10ps after Big Bang or earlier ?*

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation (BSM)*	✖	✔
• *Out-of-equilibrium or CPT violation (BSM)*	✖	✔

EDMs & Baryogenesis

Electroweak baryogenesis

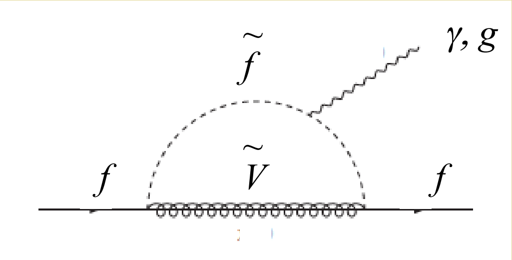
- *Testable*
- *Was BAU produced ~ 10ps after Big Bang or earlier ?*

Illustrative case: MSSM

	Standard Model	BSM
• B violation (sphalerons)	✔	✔
• C & CP violation (BSM)	✖	✔
• Out-of-equilibrium or CPT violation (BSM)	✖	✔

EDMs & EW Baryogenesis: MSSM

One-loop EDMs preclude MSSM baryogenesis



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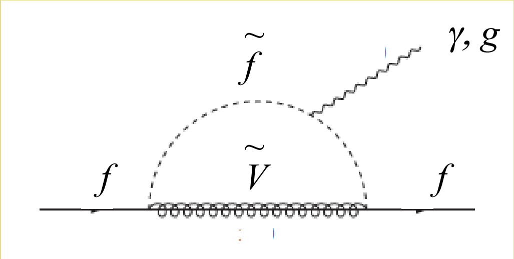
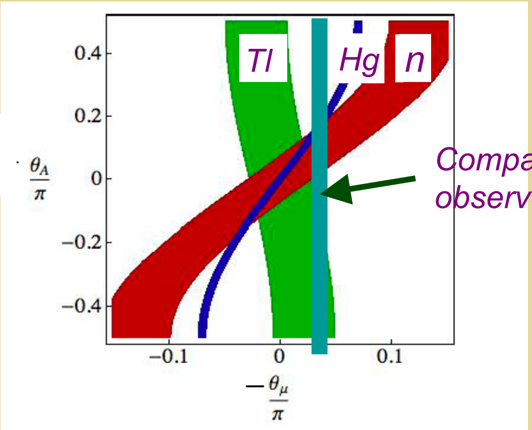


Universal gaugino phases

$Arg(\mu M_i b^*) =$

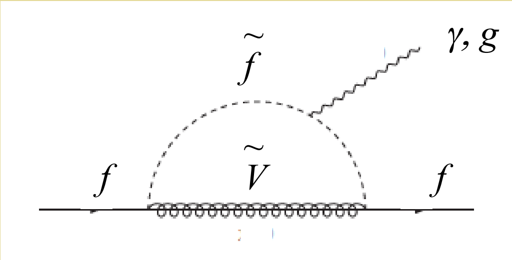
$Arg(\mu M_j b^*)$



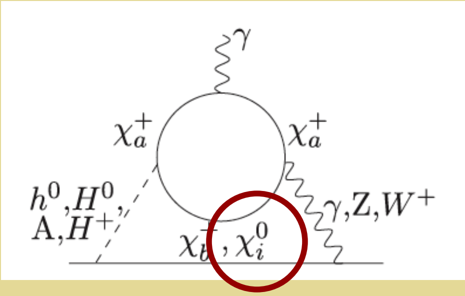
Ritz CIPANP 09 +

Cirigliano, R-M, Tulin, Lee '06

EDMs & EW Baryogenesis: MSSM

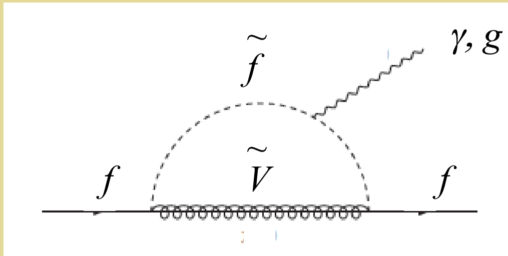


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

EDMs & EW Baryogenesis: MSSM



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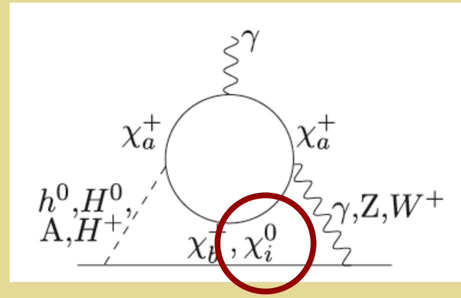
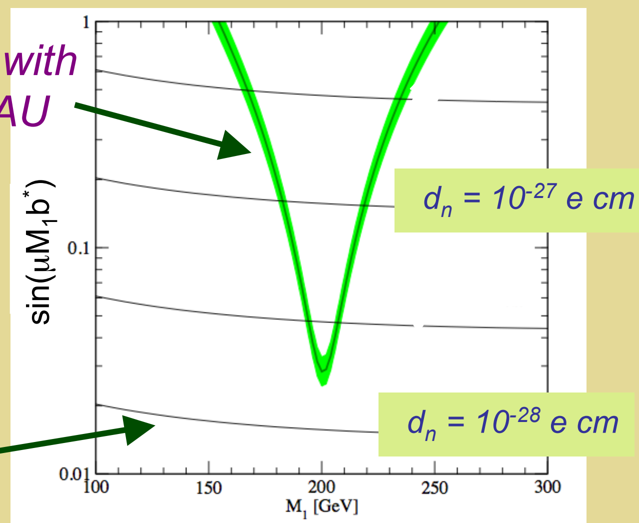


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



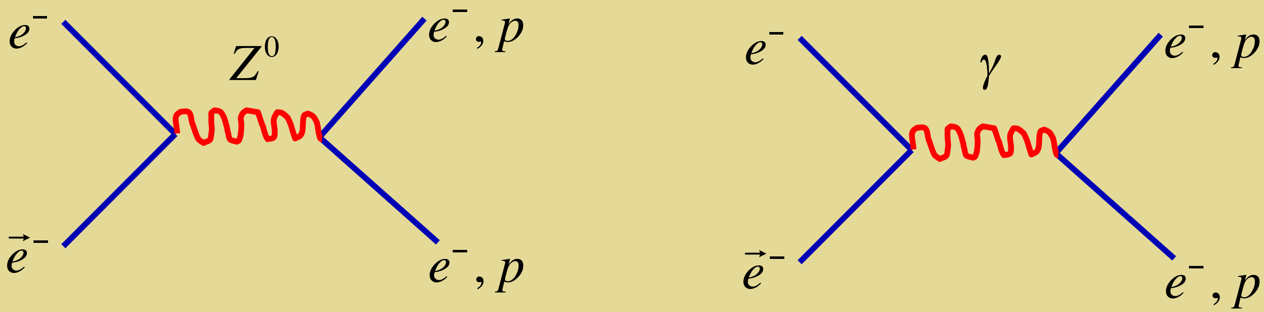
Next generation d_n

Li, Profumo, RM '09-'10

PV Electron Scattering: BSM Diagnostic

I. *The experimental situation*
II. *The Standard Model: $\sin^2\theta_W$*
III. *BSM*

Parity-Violation & Weak Charges



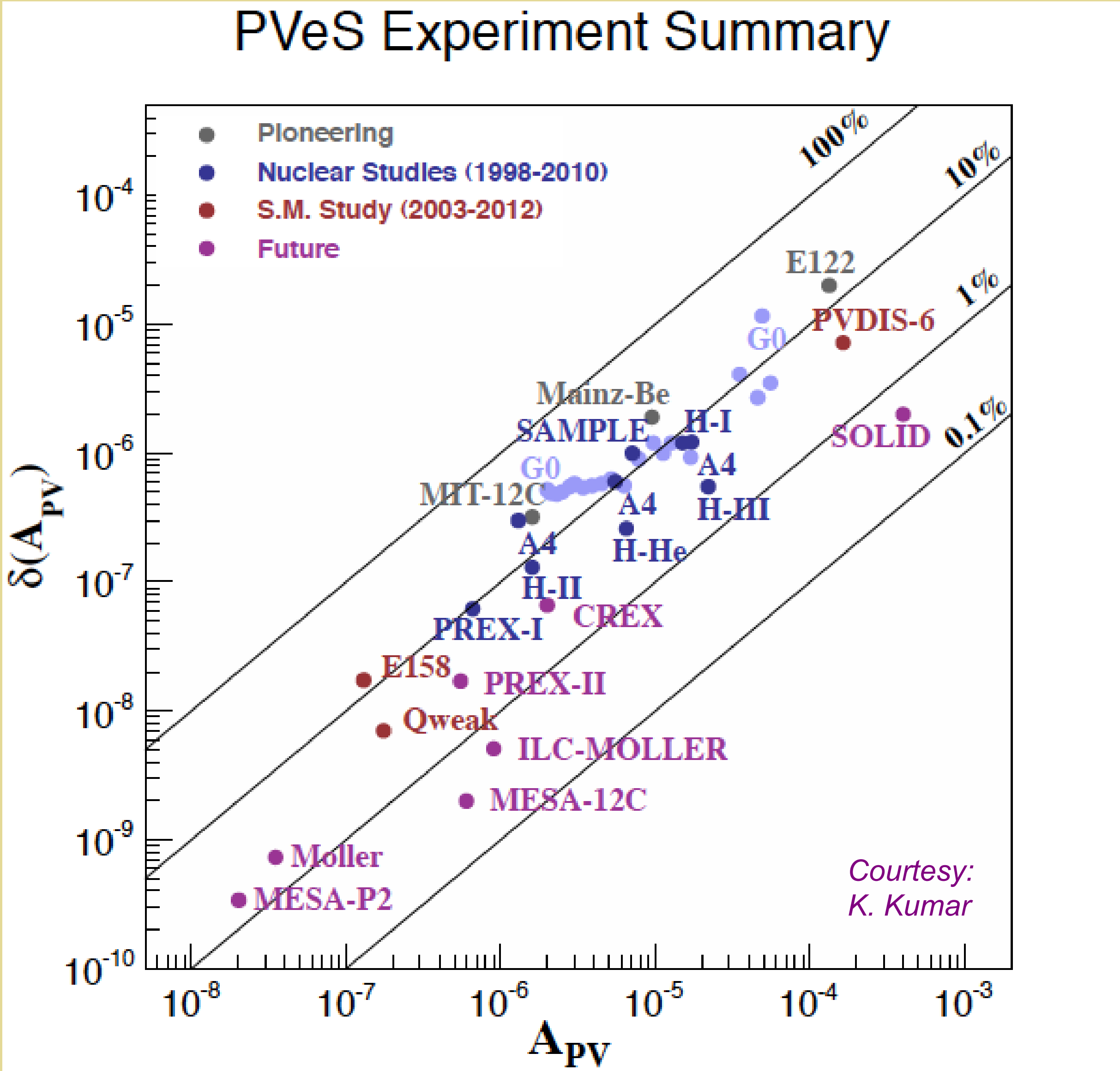
Parity-Violating electron scattering

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

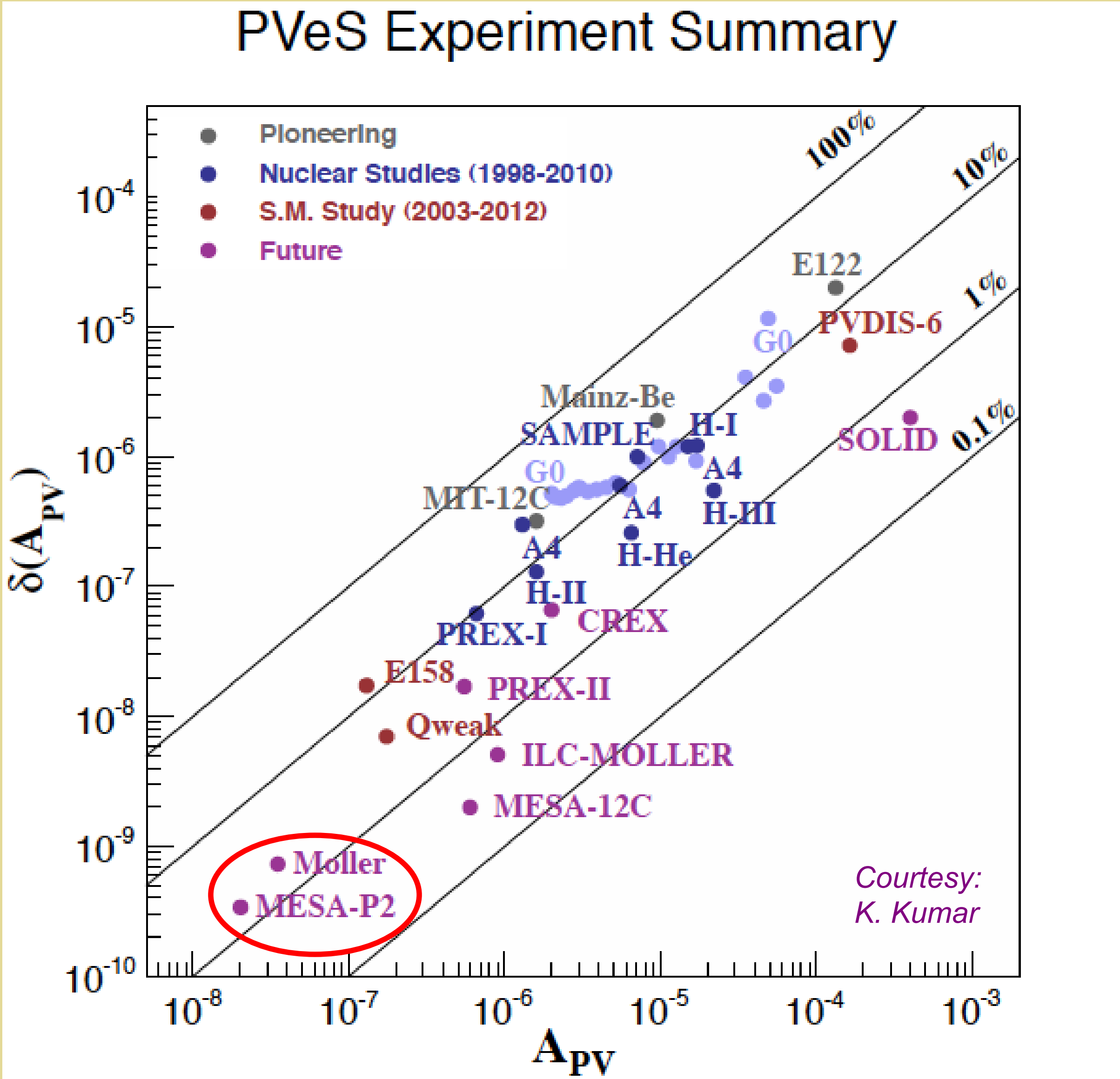
Atomic parity-violation

$$E_1^{PV} / \beta = i\ e\ \mathcal{M} \times 10^{-11}\ a_0\ (Q_W / N) / \beta$$

Parity-Violation Electron Scattering



Parity-Violation Electron Scattering



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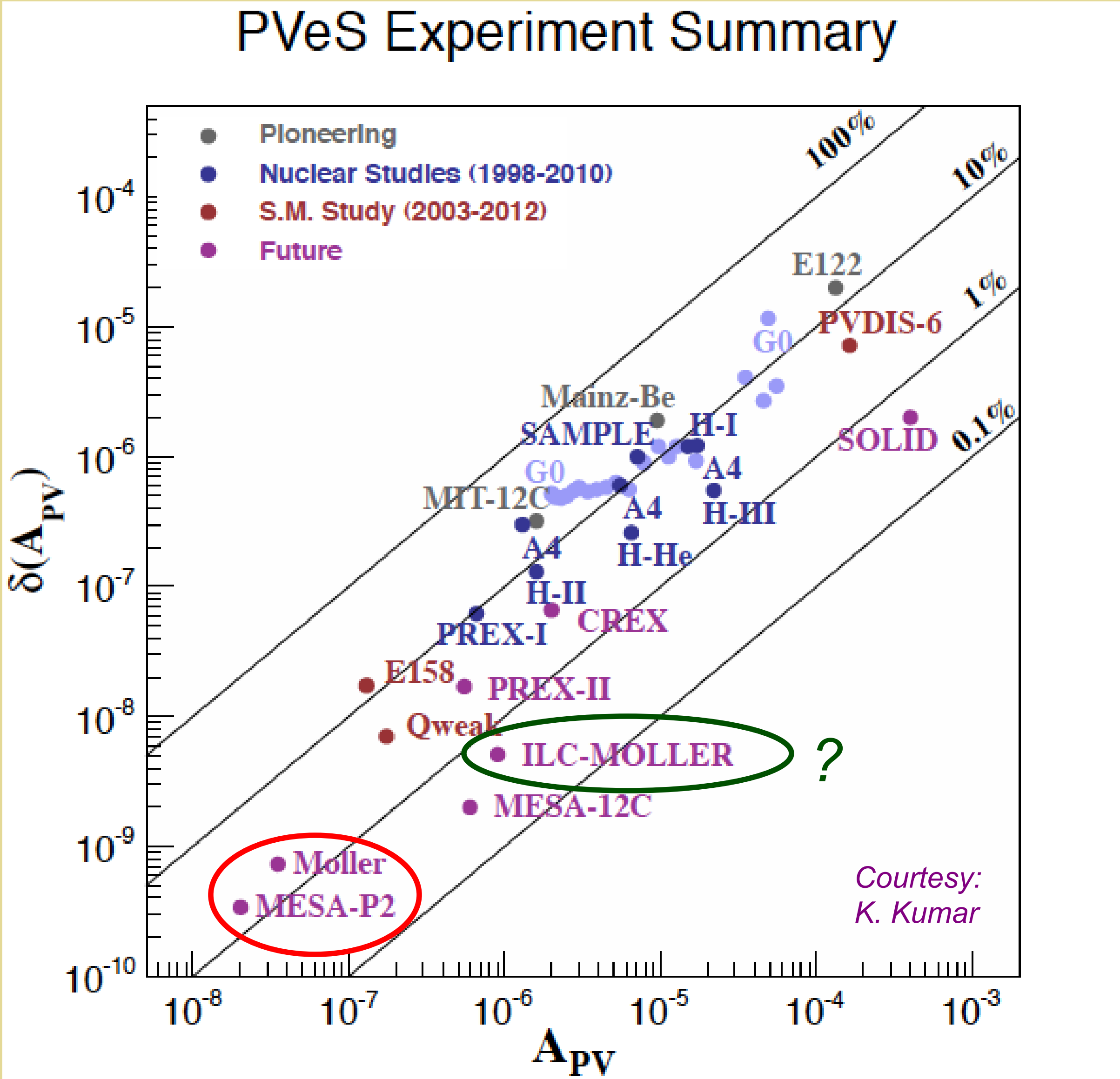
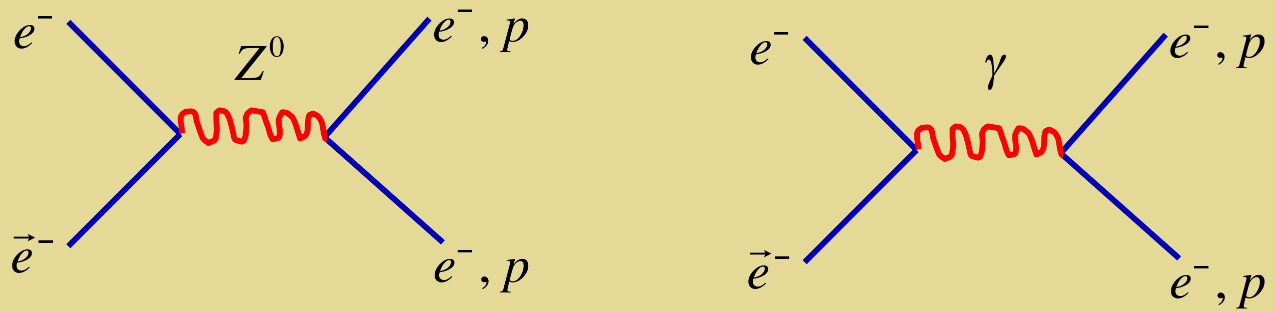


Parity-Violation & Weak Charges



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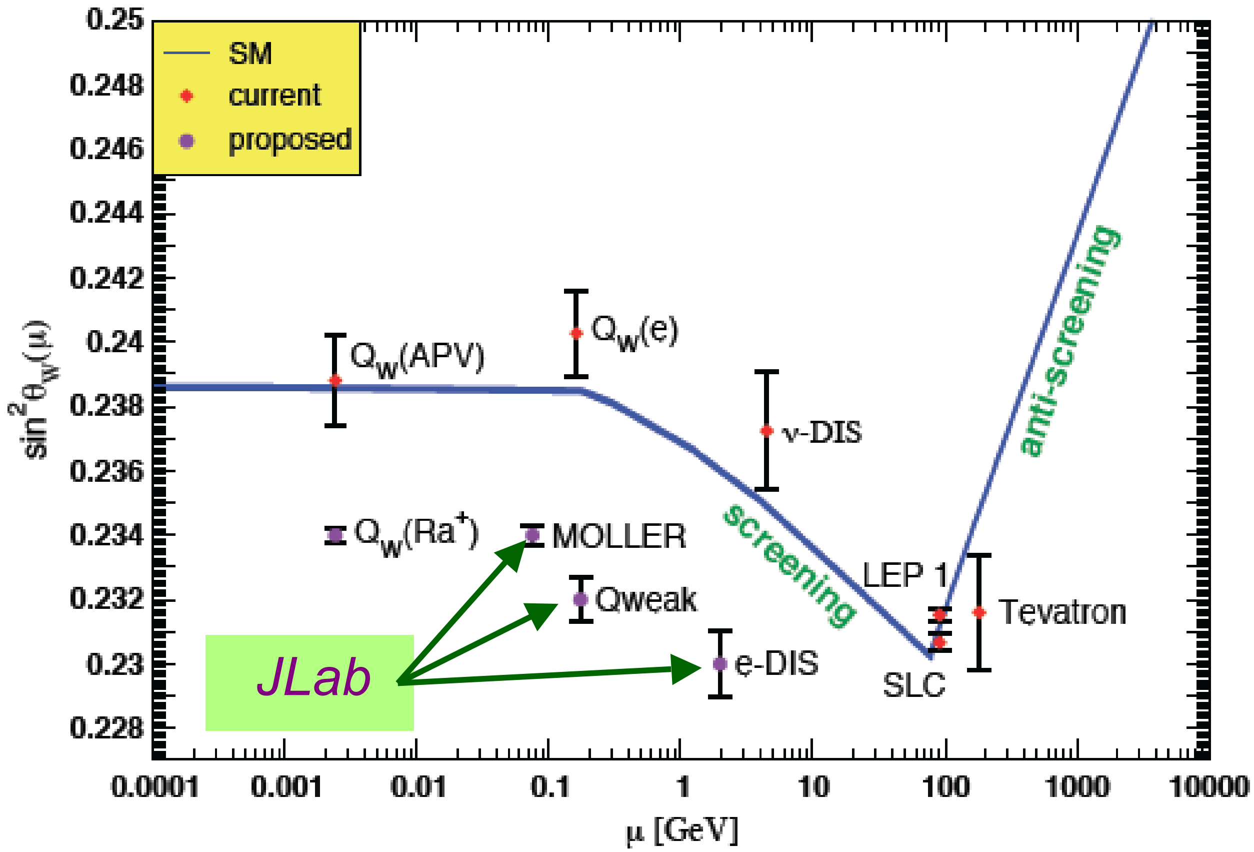
Weak Mixing in the Standard Model

$Q_W = 2\, I_3 - 4\, Q \sin^2\theta_W$

Courtesy
J. Erler

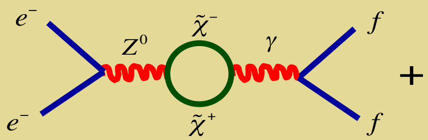


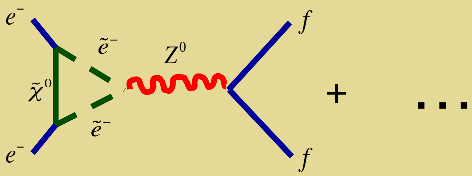
Scale-dependence of Weak Mixing

Marciano & Czarnecki;
Erler & R-M

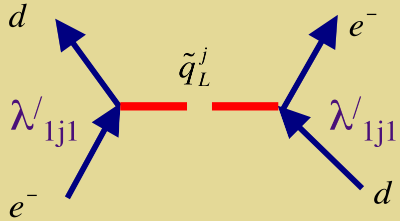
Deviations: BSM "Diagnostic"

SUSY



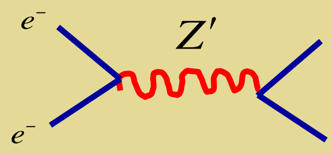


Radiative Corrections



RPV

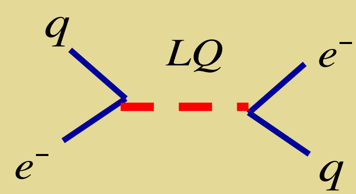
Z' Bosons



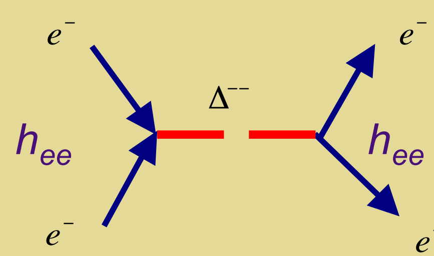
Semi-leptonic only

Moller only

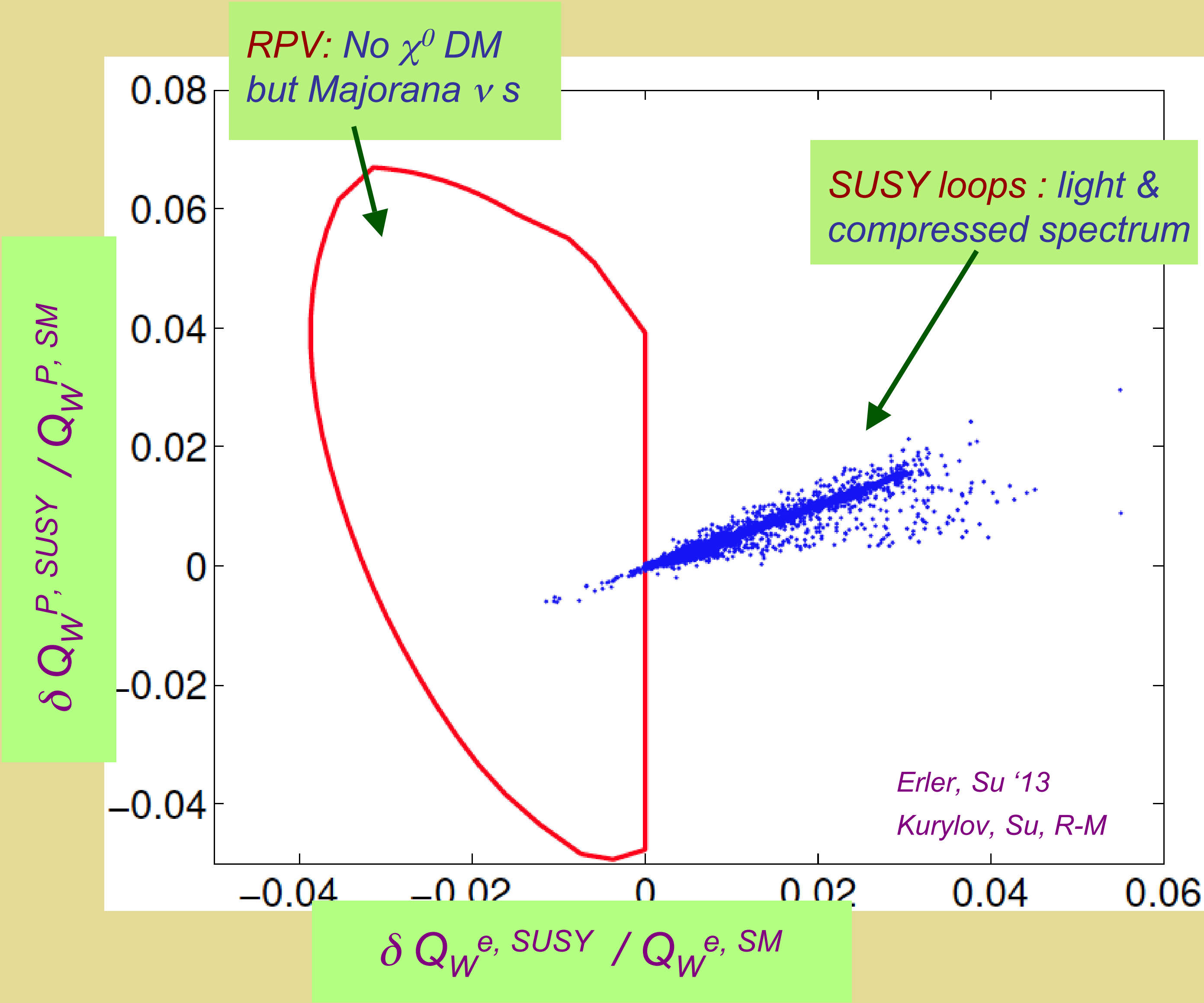
Leptoquarks



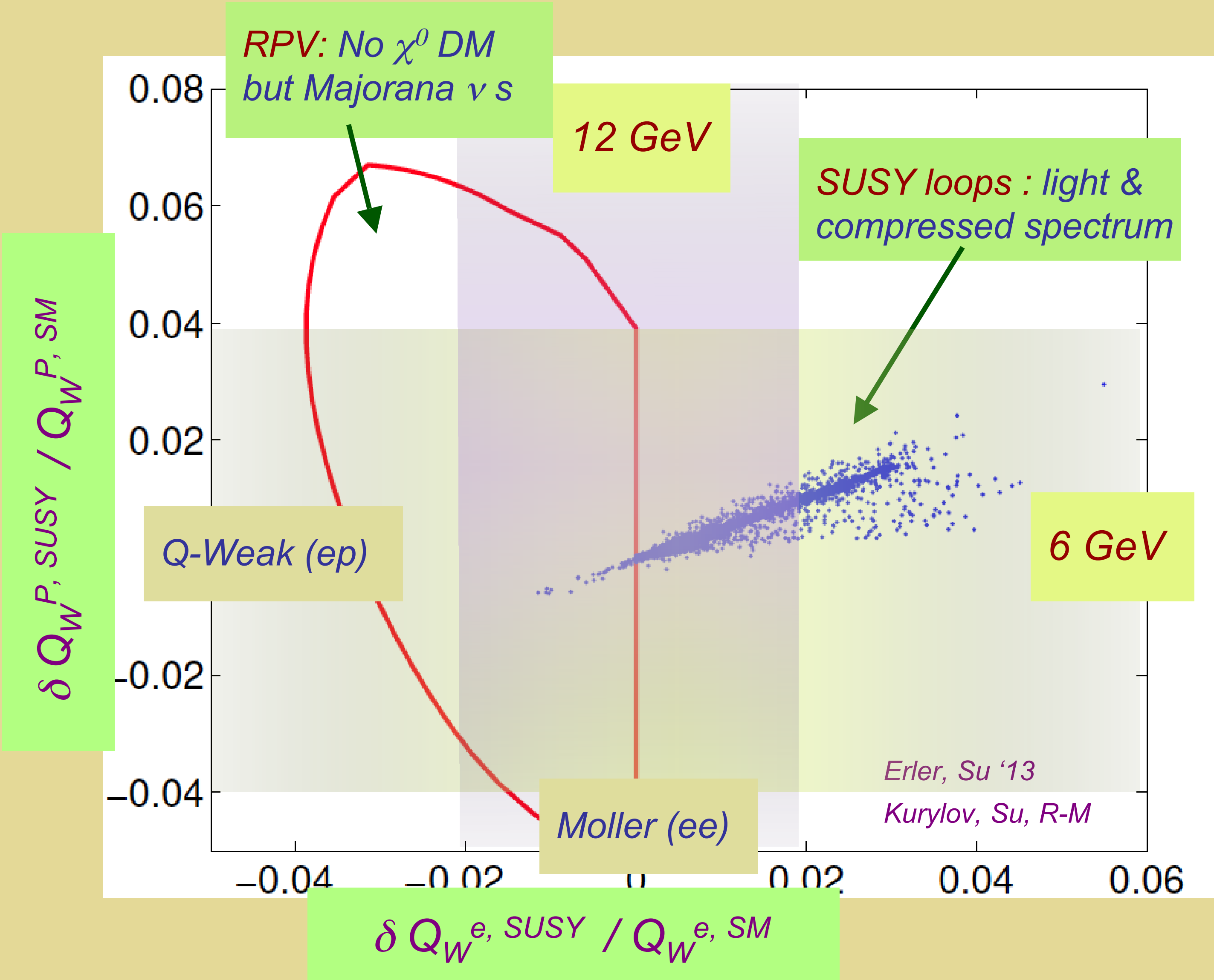
Doubly Charged Scalars



PV Electron Scattering: Diagnostic Tool



PV Electron Scattering: Diagnostic Tool



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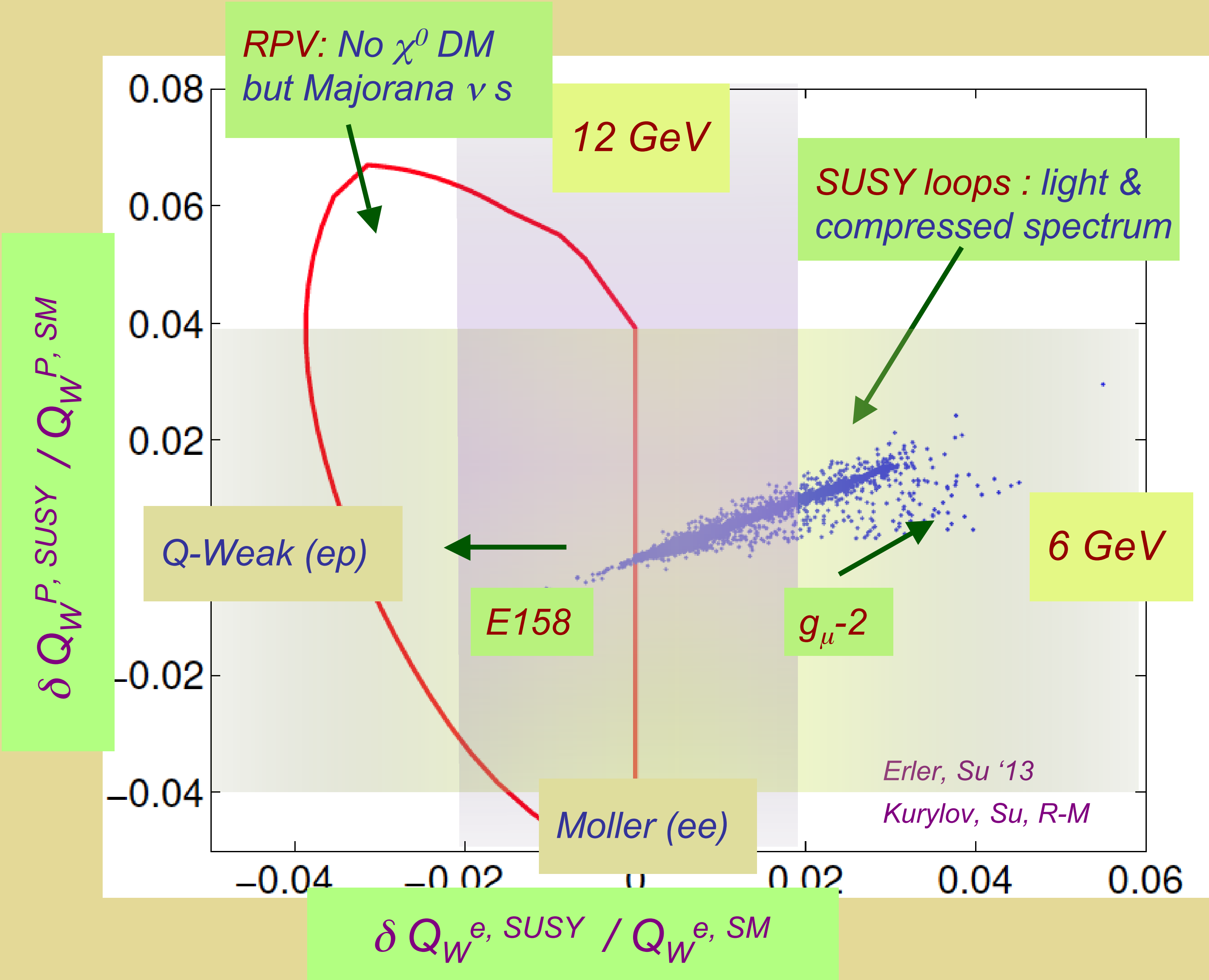

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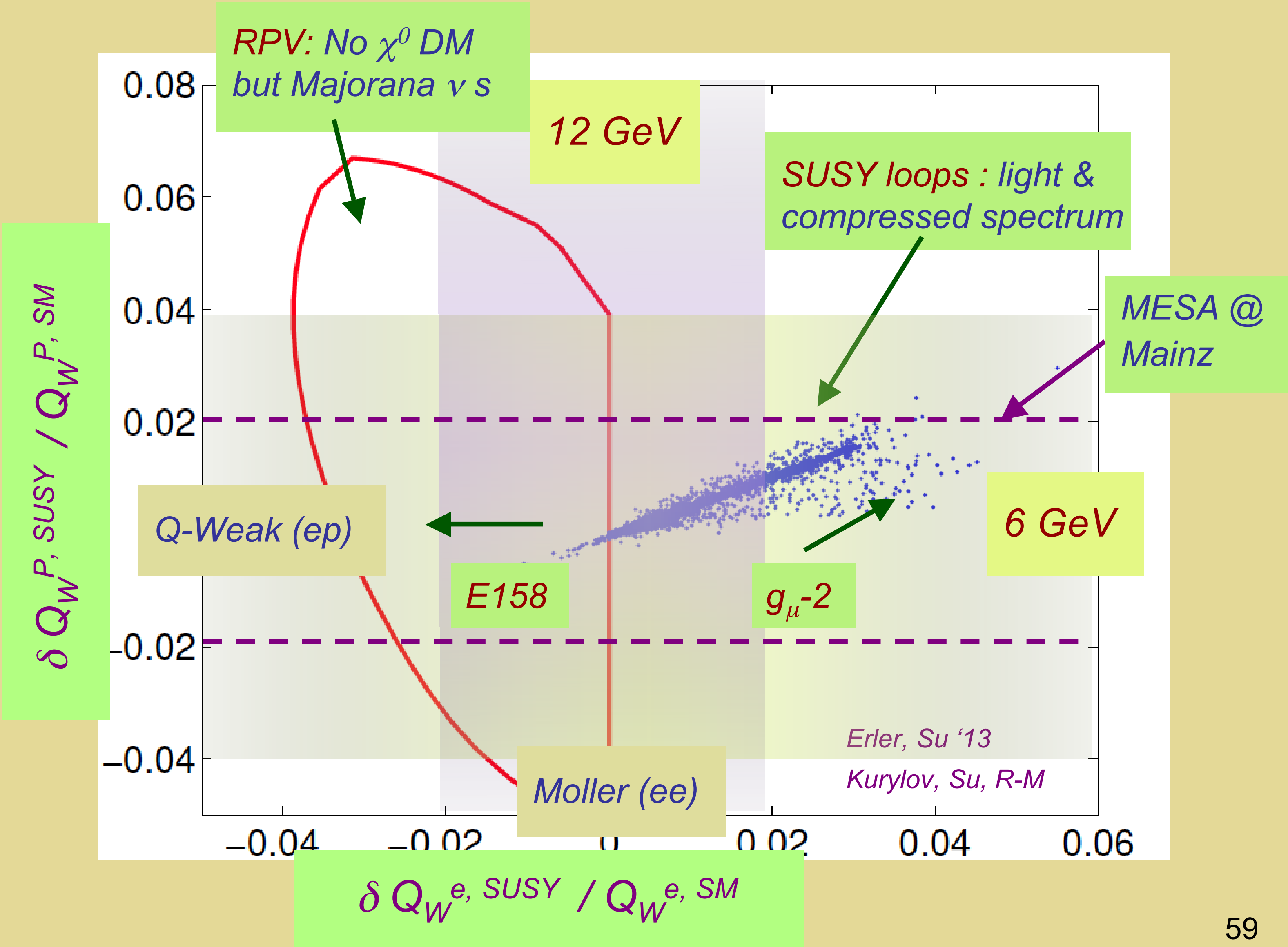
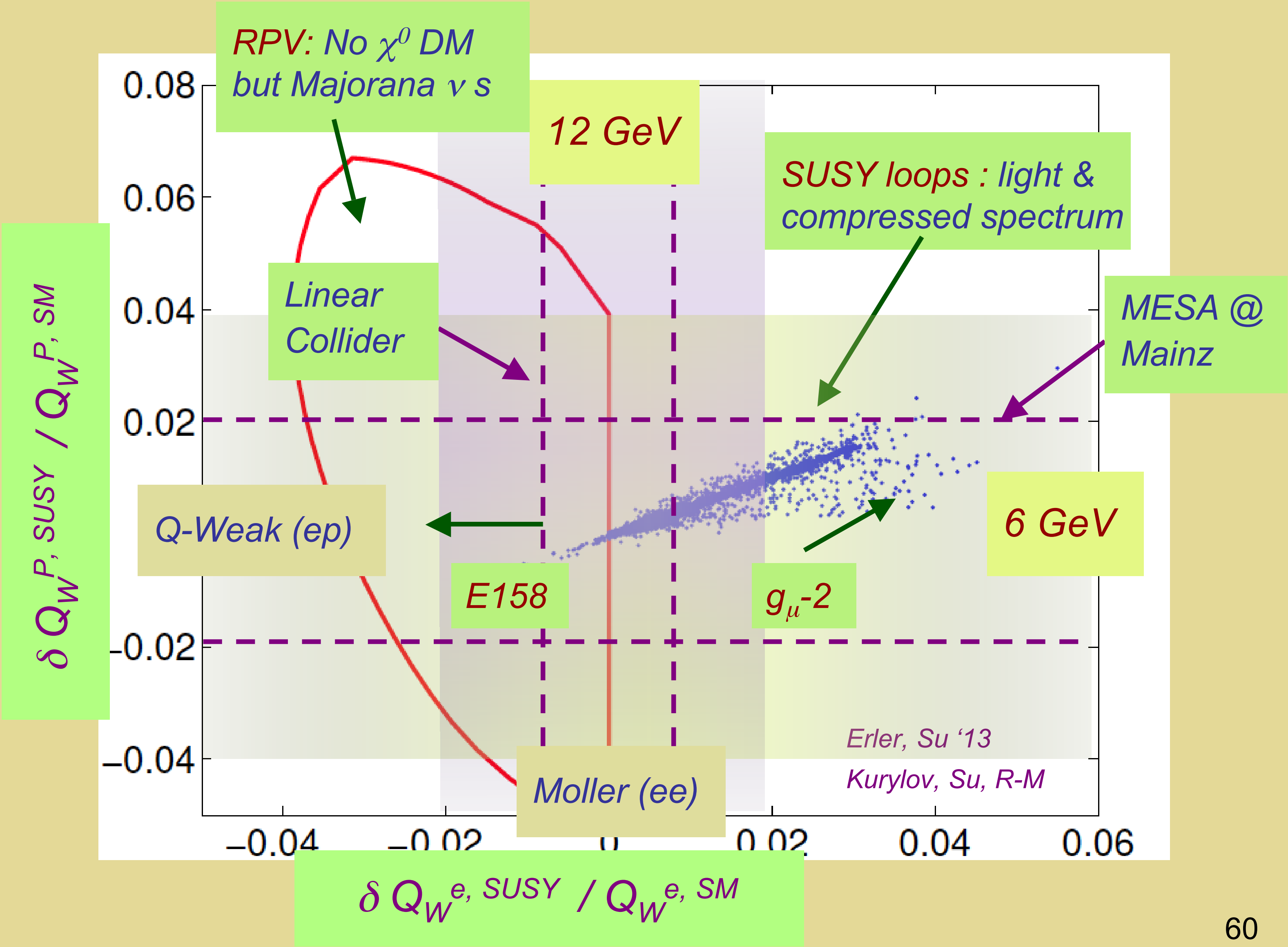


PV Electron Scattering: Diagnostic Tool



Summary

NP studies of fundamental symmetries & neutrinos:

- *A growing pillar of the global NP program*
- *Highly synergistic with HEP & a cornerstone of the Intensity Frontier*
- *Significant potential for discovery and insight (origin of matter, BSM diagnostic)*
- *Rich opportunities for future interplay between NP and HEP communities*

Thanks !

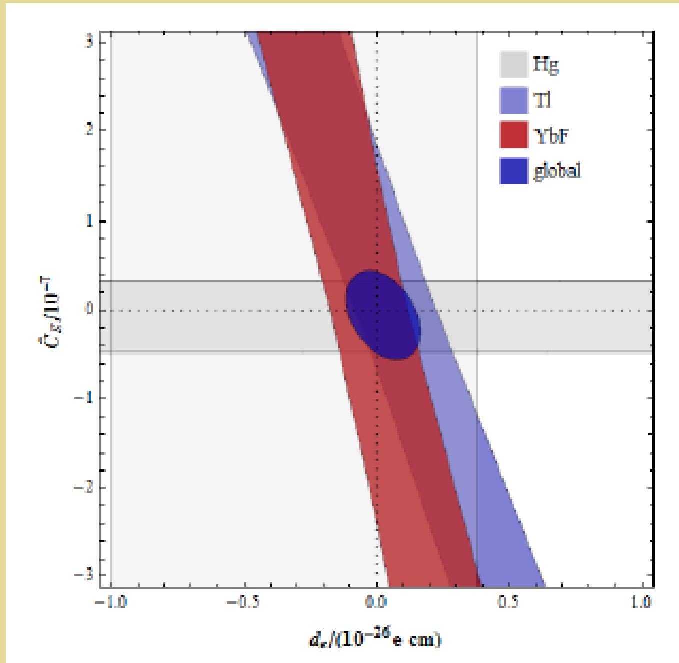
- *Lepton Photon organizers*
- *T. Chupp, K. Kumar*

Further reading:

- *EDM: 1303.2371, hep-ph/0504231*
- *PV: 1302.6263, 1303.5522*
- *Project X: 1306.5009*

Back Up Slides

AMO Global Analysis



Jung '13

$$\frac{k_S^{(0)}}{e\zeta_A^e} \approx -37$$

- *Dominant operators: e EDM, $C_S^{(0)} \sim \mathrm{Im}\, C_{eq}^{(-)}$*
- *Includes ^{199}Hg w/ $C_S^{(0)}$ no Schiff moment !*
- *Tl & YbF only: $|d_e| < 0.89 \times 10^{-26}$ e cm*

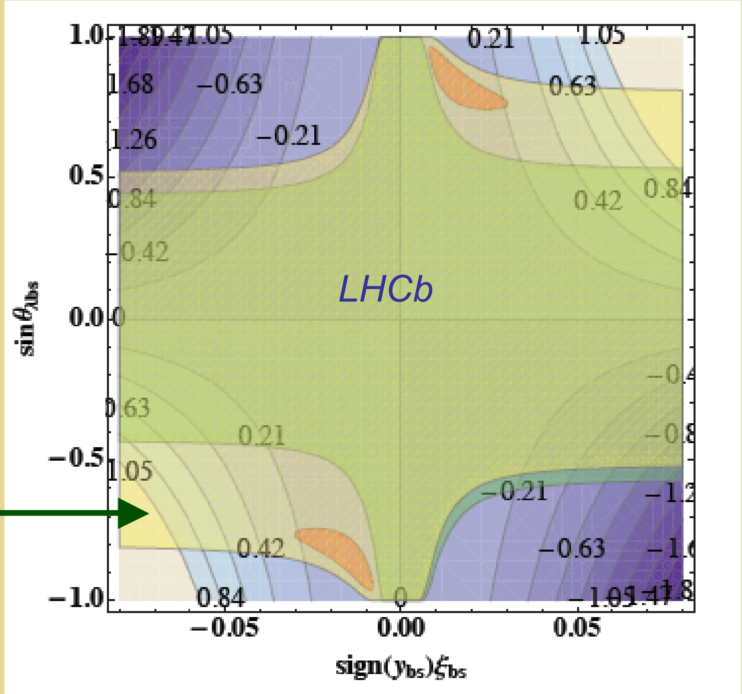
Flavored CPV & EWB

CPV & 2HDM

$$\mathcal{L} = -y^u_{ij}\bar{Q}^i(\epsilon H_u^\dagger)u^j_R - y^d_{ij}\bar{Q}^i H_u d^j_R$$
$$-\lambda^u_{ij}\bar{Q}^i H_d u^j_R - \lambda^d_{ij}\bar{Q}^i(\epsilon H_d^\dagger)d^j_R + h.c..$$

Liu, R-M, Shu '11; see also Tulin & Winslow '11; Cline et al '11

constant n_B / s



Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

Largely unexplored: flavored EWB

Flavored CPV & EWB

CPV & 2HDM

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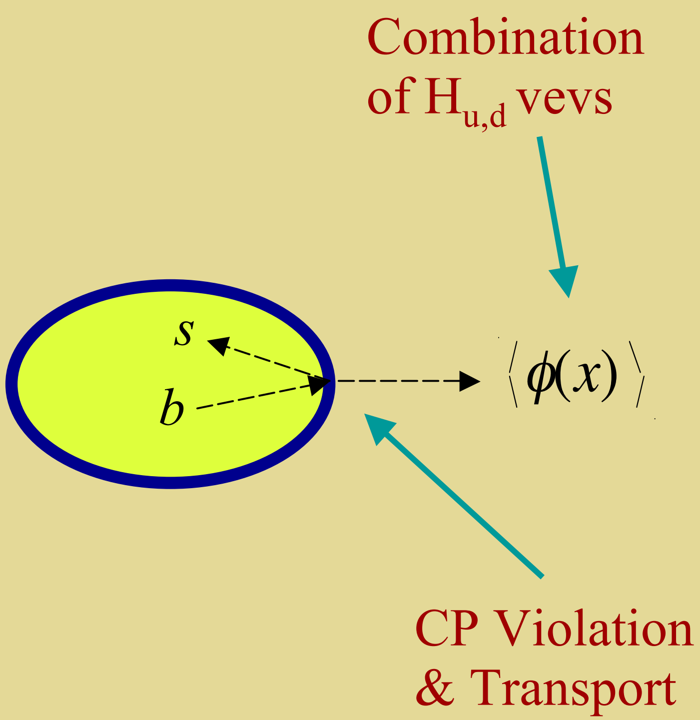

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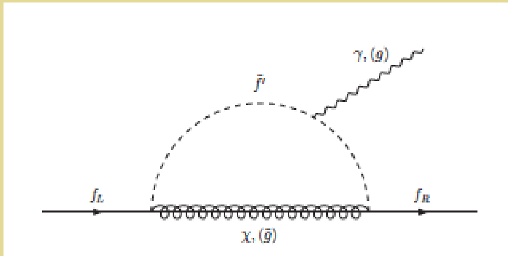
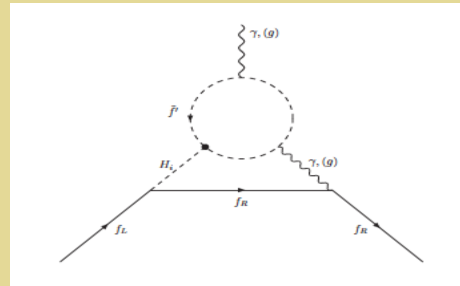
EDM Probes: EWB Implications



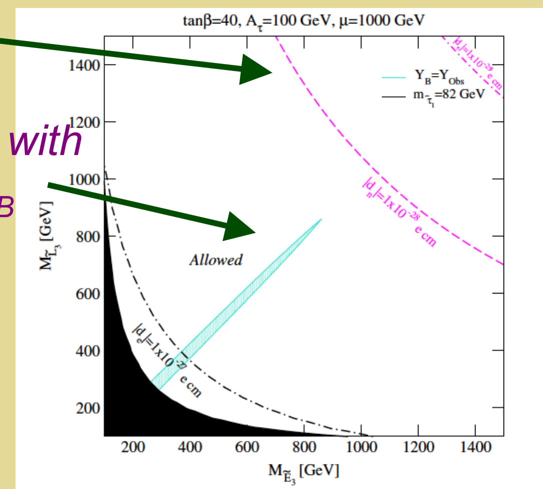
Light staus: LHC consistent & suppress 1-loop EDMs



No CEDM (^{199} Hg): EWB-viable but $m_H \rightarrow$ New scalars for EWPT

Next gen d_n

Compatible with observed Y_B



Kozaczuk, Wainwright, Profumo, RM

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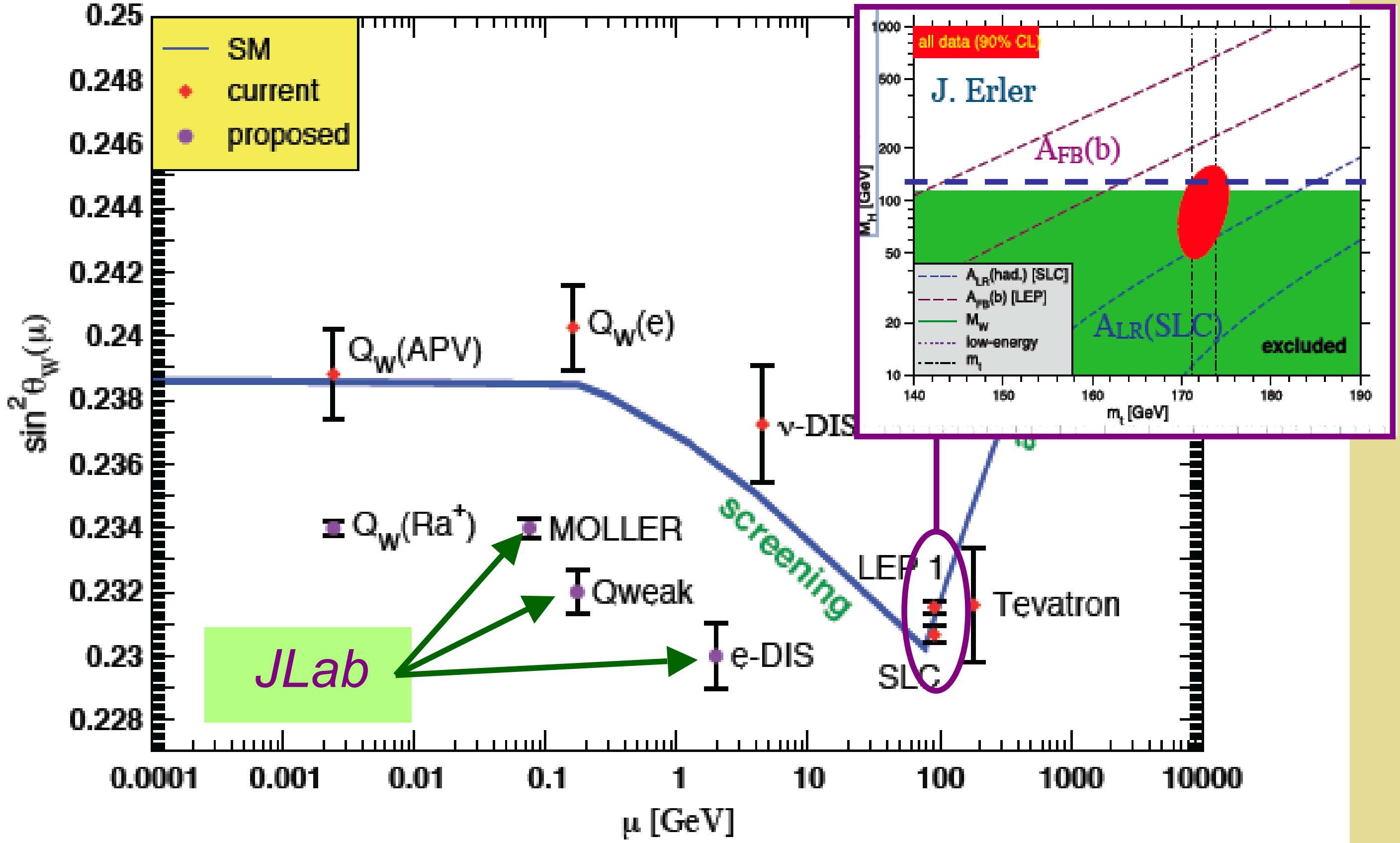
Courtesy J. Erler



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