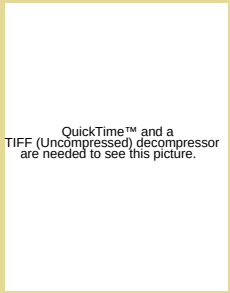
PV & New Physics: An Overview



M.J. Ramsey-Musolf

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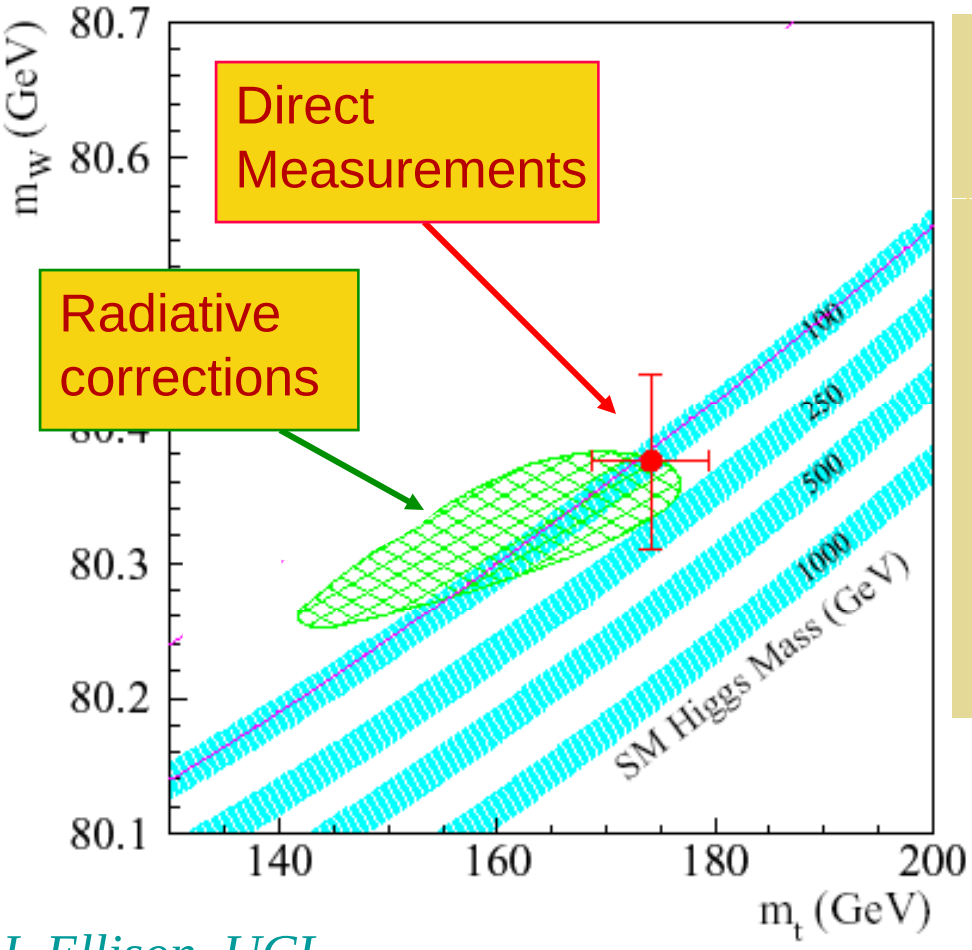
Theoretical Nuclear, Particle, Astrophysics & Cosmology

http://www.physics.wisc.edu/groups/particle-theory/

PAVI09 Bar Harbor, June 2009

Precision & Energy Frontiers



Precision Frontier:

- *Precision ~ Mass scale*
- *Look for pattern from a variety of measurements*
- *Identify complementarity with collider searches*
- *Special role: SM suppressed processes*

Stunning SM Success

J. Ellison, UCI

Outline

- *PVES: New Physics (SUSY, Z', LQ) & Hadron Structure (HT)*

SUSY

- *MSSM*
- *Radiative Corrections*
- *RPV & $0\nu\beta\beta$ Decay*
- *PVES Probes*

R-M & Su, Phys. Rep. ***456*** *(2008) 1*

mmetric Standard
MSSM)

No new coupling constants

Two Higgs vevs

$$\tan\beta = v_u/v_d$$

Supersymmetric Higgs mass, μ

mmetry

Fermions	Bosons
$e_{L,R}$, $q_{L,R}$	W, Z, γ, g
	H

king

One solution: $a_f \sim Y_f$

$$\mathbf{a_u} = A_t \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix}, \quad \mathbf{a_d} = A_d \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix}, \quad \mathbf{a_e} = A_e \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix}.$$

retical models
SY breaking

$$\mathcal{L}_{\rm soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B}) + c.c.$$

Gaugino mass

$$-(\tilde{u}\mathbf{a_u}\tilde{Q}H_u - \tilde{d}\mathbf{a_d}\tilde{Q}H_d - \tilde{e}\mathbf{a_e}\tilde{L}H_d) + c.c.$$

Triscalar interactions

$$-\tilde{Q}^\dagger\mathbf{m_Q^2}\tilde{Q} - \tilde{L}^\dagger\mathbf{m_L^2}\tilde{L} - \tilde{u}\mathbf{m_{\bar{u}}^2}\tilde{u}^\dagger - \tilde{d}\mathbf{m_{\bar{d}}^2}\tilde{d}^\dagger - \tilde{e}\mathbf{m_{\bar{e}}^2}\tilde{e}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d$$

$$-(bH_uH_d - c.c.)$$

Sfermion mass

~ 100 new parameters
40 new CPV phases
Flavor mixing parameters

O(1) CPV phases & flavor mixing ruled out by expt: "SUSY CP" & "SUSY flavor" problems

How is SUSY broken?

SUSY and R Parity

$$P_R = (-1)^{3(B-L)} (-1)^{2S}$$

If nature conserves P_R $\Longrightarrow$ vertices have even number of superpartners

Consequences

- Lightest SUSY particle $(\tilde{\chi}^0)$ is stable $\Longrightarrow$ viable dark matter candidate
- Proton is stable
- Superpartners appear only in loops

PVES & SUSY Radiative Corrections

Tree Level

$$Q_W^f = g_V^f \, g_A^e$$

Radiative Corrections

Flavor-dependent

$$Q_W^f = \rho_{PV} \left(2 I_3^f - 4 Q_f \kappa_{PV} \sin^2 \theta_W \right) + \lambda_f$$

Constrained by Z-pole precision observables

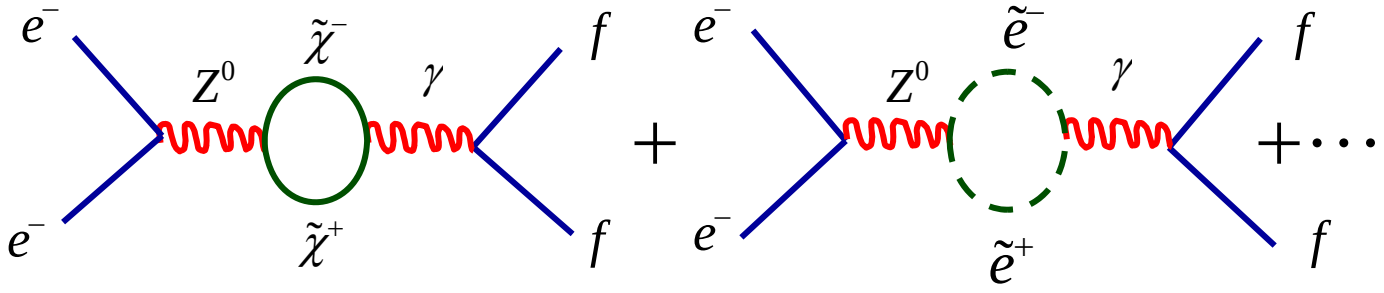
Large logs in κ :

Sum to all orders with running $\sin^2 \theta_W$ & RGE

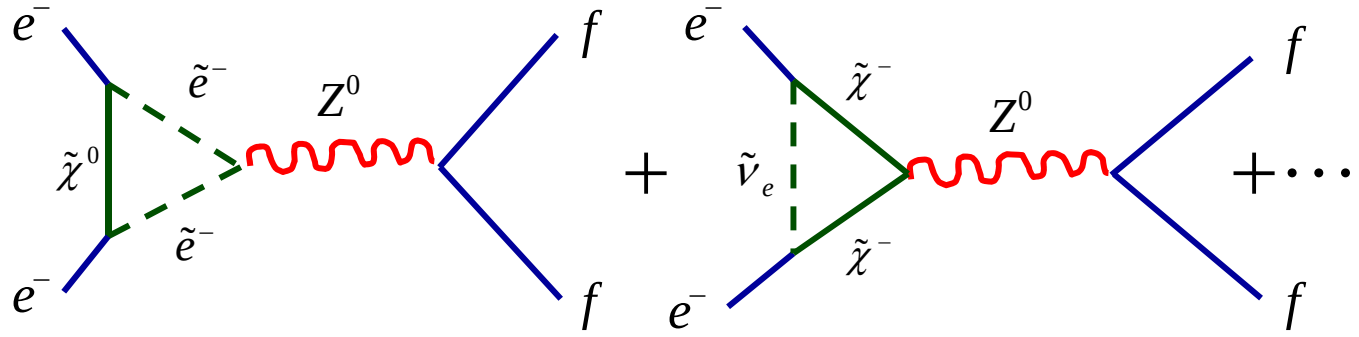
Flavor-indeper

SUSY Radiative Corrections

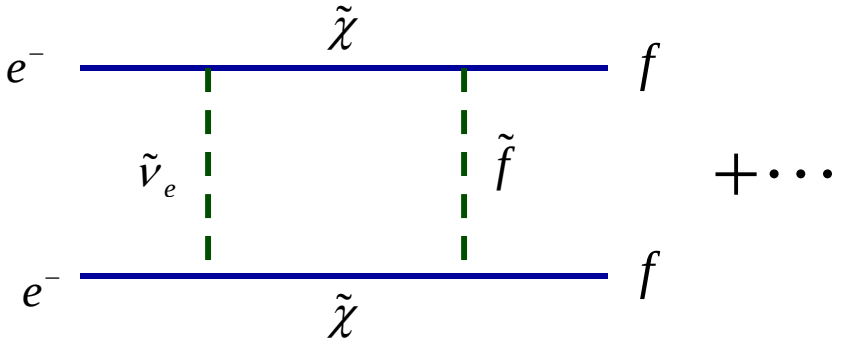
Propagator



Vertex & External leg



Box



Kurylov, RM, Su

Universal Corrections

The ρ parameter:

muon decay

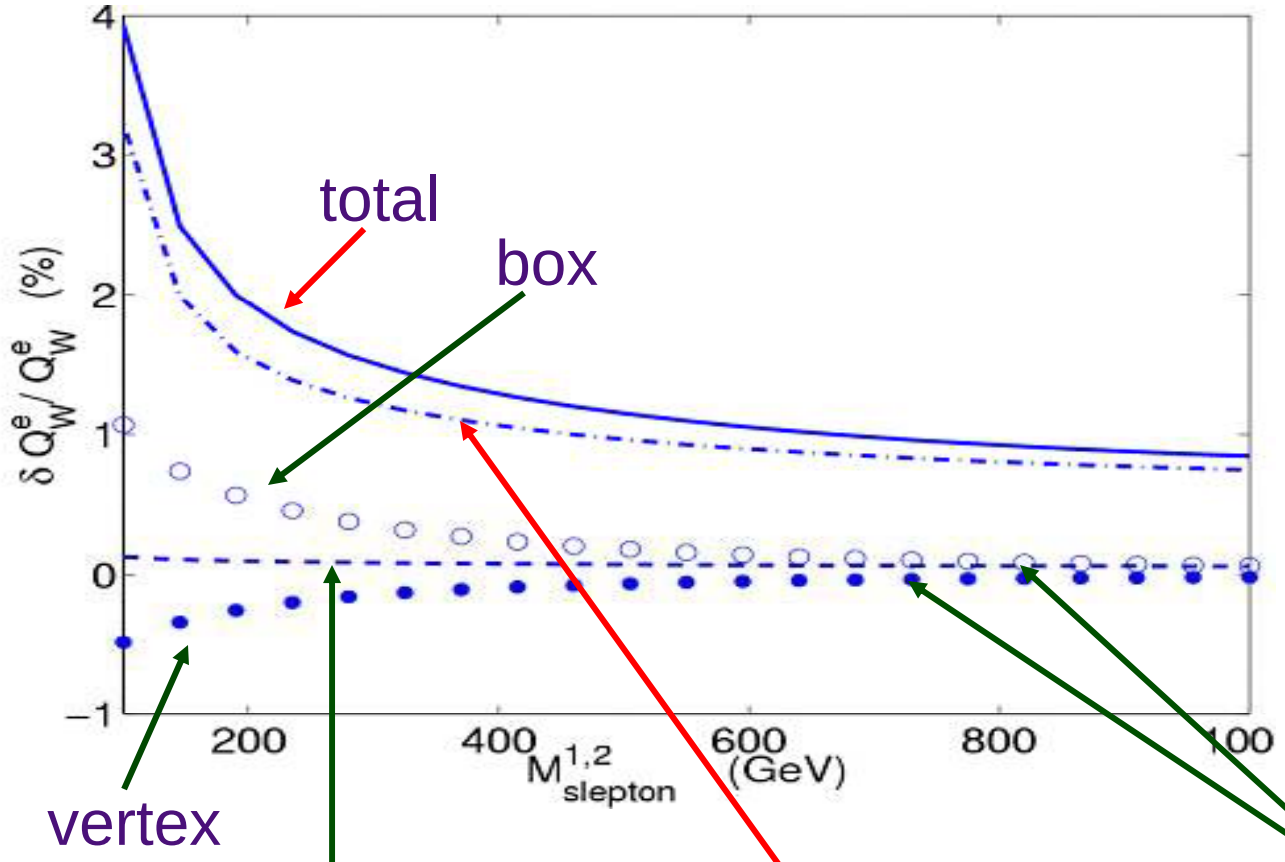
$$\delta\hat{\rho}^{\mathrm{SUSY}} = \hat{\alpha}T - \hat{\delta}^{\mu}_{VB}$$

Weak mixing:

$$\left(\frac{\delta \sin^2\hat{\theta}^{\mathrm{eff}}_{W}}{\sin^2\hat{\theta}^{\mathrm{eff}}_{W}}\right)^{\mathrm{SUSY}} = \left(\frac{\hat{c}^2}{\hat{c}^2-\hat{s}^2}\right)\left(\frac{\hat{\alpha}}{4\hat{s}^2\hat{c}^2}S - \hat{\alpha}T + \hat{\delta}^{\mu}_{VB}\right) + \frac{\hat{c}}{\hat{s}}\left[\frac{\hat{\Pi}_{Z\gamma}(k^2)}{k^2} - \frac{\hat{\Pi}_{Z\gamma}(M_Z^2)}{M_Z^2}\right]$$
$$+\left(\frac{\hat{c}^2}{\hat{c}^2-\hat{s}^2}\right)\left[-\frac{\hat{\Pi}_{\gamma\gamma}(M_Z^2)}{M_Z^2} - \frac{\Delta\hat{\alpha}}{\alpha}\right]$$

Can impose constraints from global fits to EWPO via S,T,U-dependence of these quantities

Correlated Radiative Corrections



$$Q_W^f = \rho_{PV}\left(2I_3^f - 4Q_f\kappa_{PV}\sin^2\theta_W\right) + \lambda_f$$

"Superpotential" : a convenient way to derive supersymmetric interactions by taking derivatives w.r.t. scalar fields

(RPV)

$\Delta L=1$

$$W_{RPV} = \lambda_{ijk}\, L^i L^j E^k + \lambda'_{ijk}\, L^i Q^j D^k + \mu'_i\, L^i H_u$$

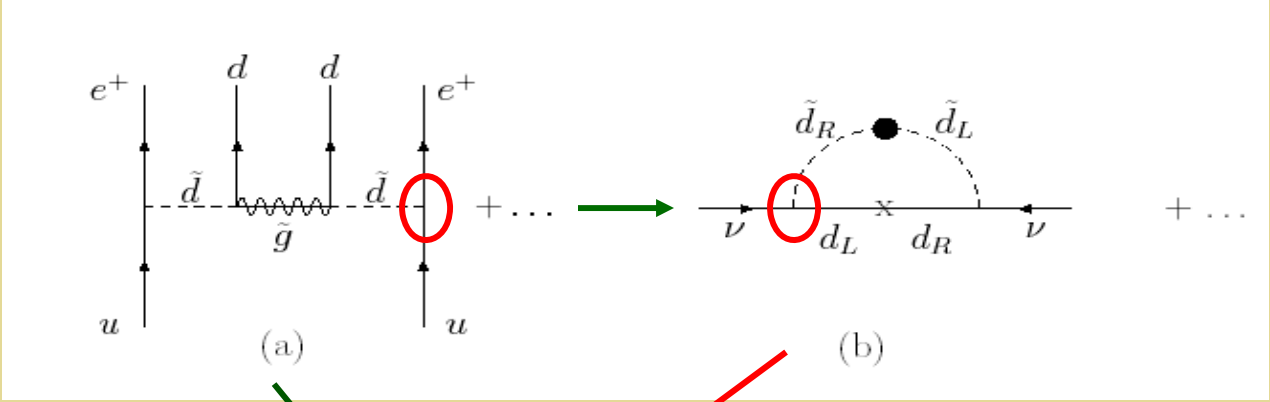
$$+ \lambda''_{ijk} U^i D^j D^k$$

$\Delta B=1$ proton decay:
Set $\lambda''_{ijk} = 0$

L^i, Q^i $SU(2)_L$ doublets

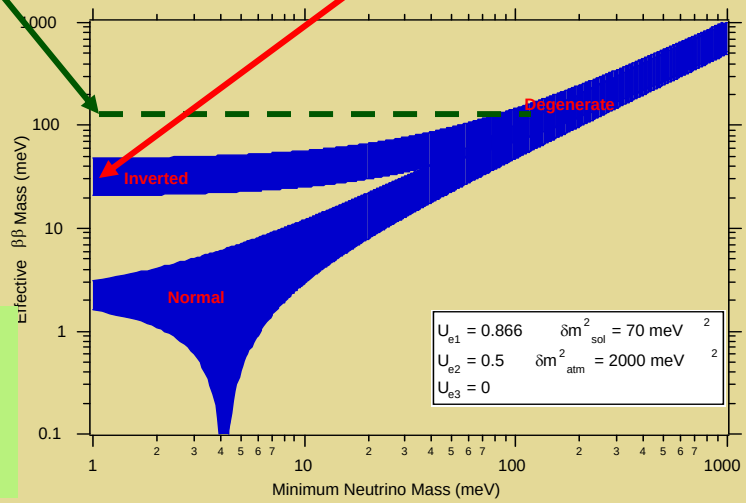
E^i, U^i, D^i $SU(2)_L$ singlets

RPV & $0\nu\beta\beta$-Decay

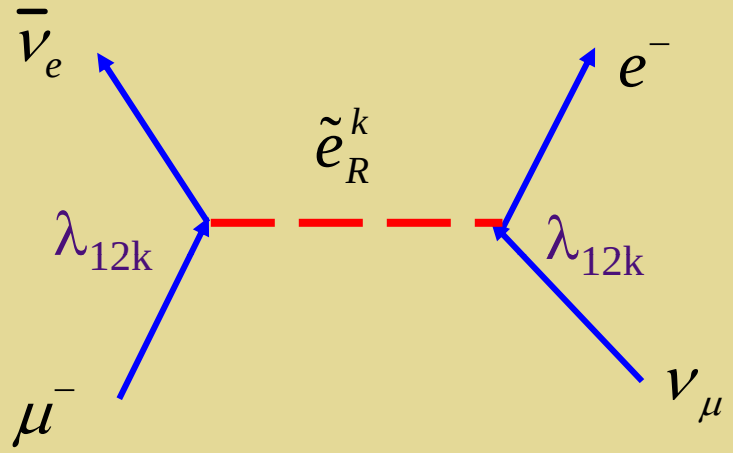


$0\nu\beta\beta$ signal equivalent to degenerate hierarchy

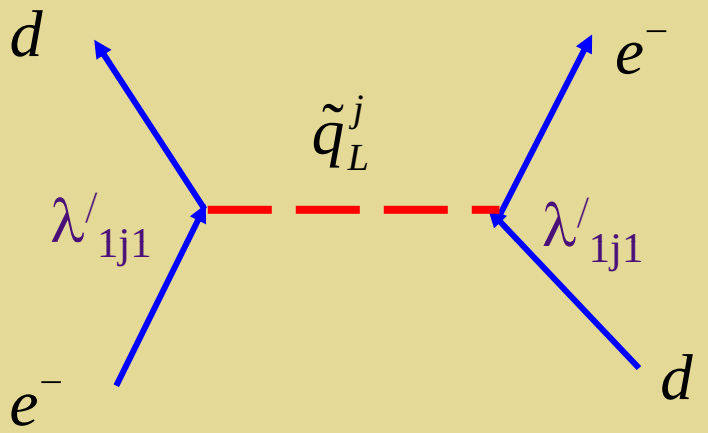
Loop contribution to m_ν of inverted hierarchy scale



Four-fermion Operators



$\Delta L=1$



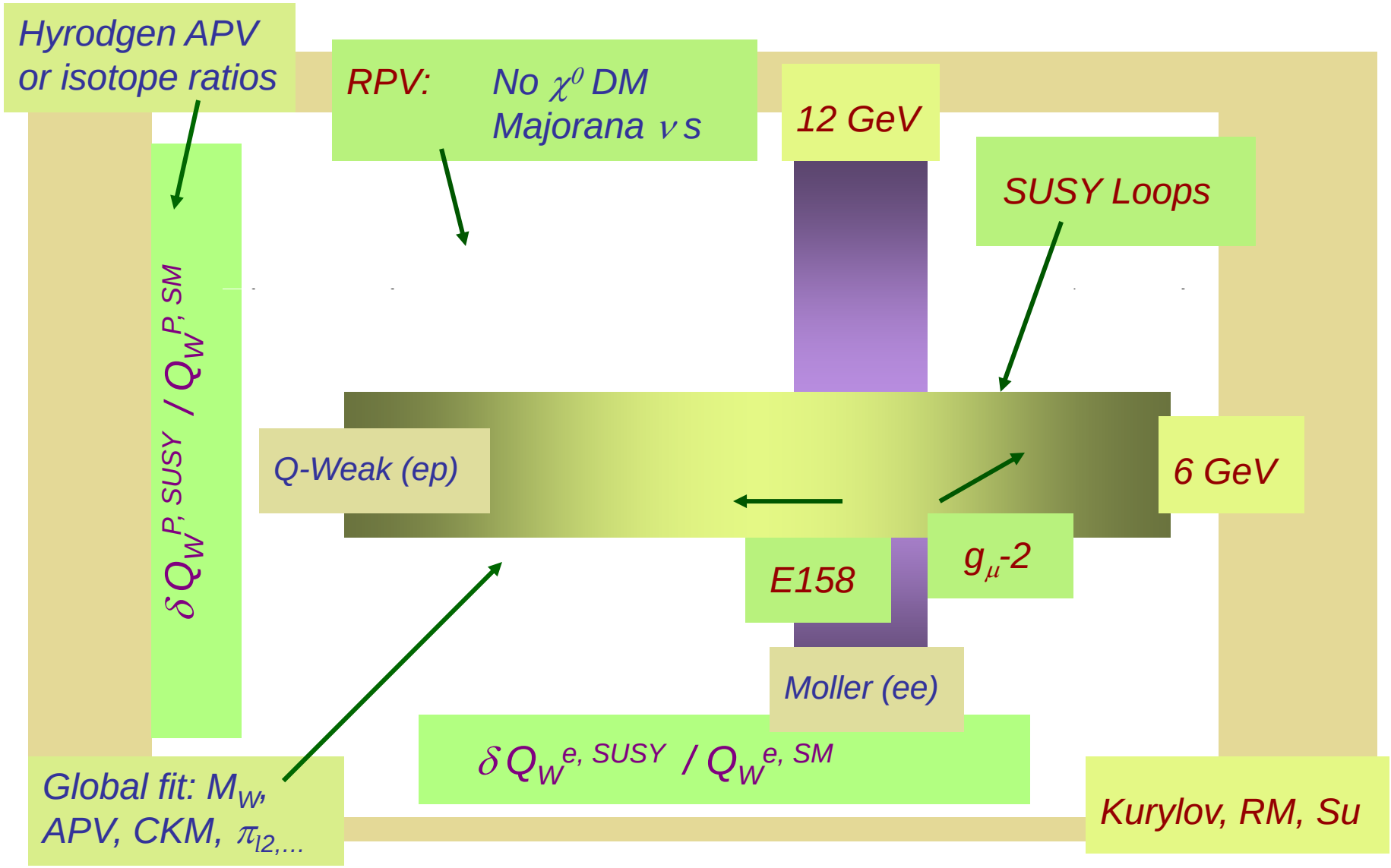
$\Delta L=1$

- *No χ^0 DM: unstable*
- *Neutrinos are Majorana*

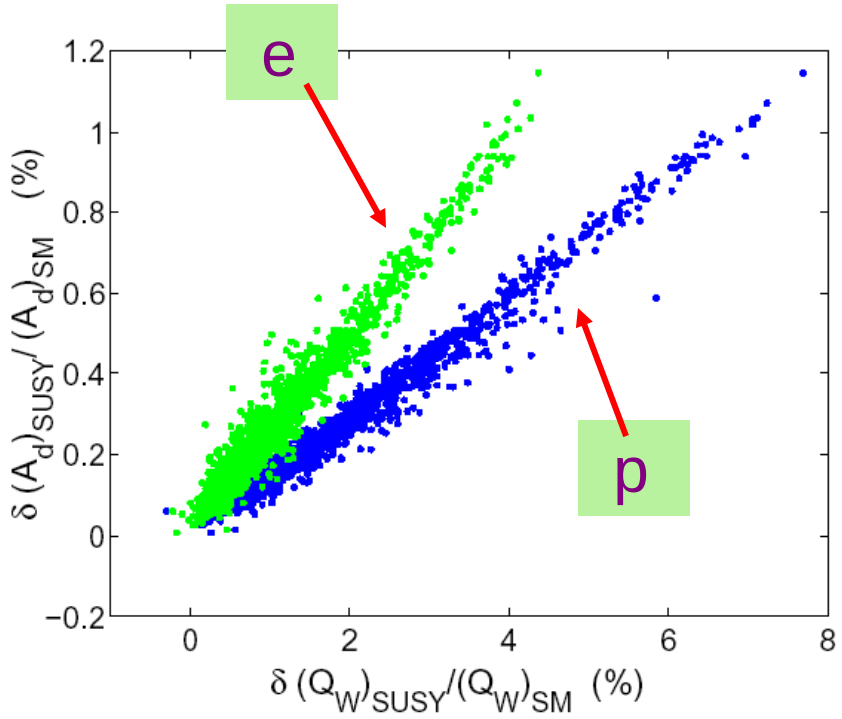
QuickTime™ and a decompressor are needed to see this picture.

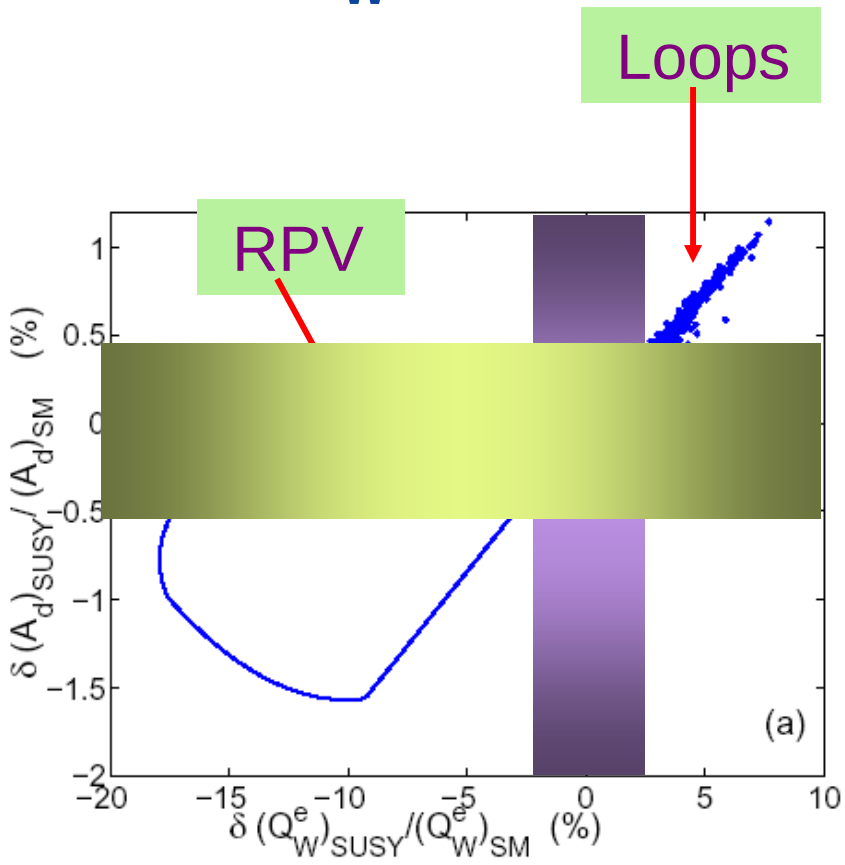
$$\Delta'_{1j1} = \frac{\left|\lambda'_{iji}\right|^2}{4\sqrt{2}G_F M^2_{\tilde{q}_L^j}}$$

PVES & APV Probes of SUSY



Comparing A_d^{DIS} and $Q_w^{p,e}$





New Z Bosons

- *E_6 Paradigm*
- *PVES Sensitivity*
- *LHC & PV Complementarity*

- *Erler & R-M, Prog. Nuc. Part. Phys. **54** (2005) 351*
- *R-M, Phys. Rev. **C60** (1999) 015501*
- *Li, Petriello & Quackenbush (in prog)*

Probing Z' with PVES

Heterotic string motivated Z'

$$E_8 \times E_8'$$

$$\begin{aligned} E_8 &\rightarrow E_6 \\ E_6 &\rightarrow SO(10) \times U(1)_\psi \\ &\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \end{aligned}$$

$$Z' = \cos\phi\, Z_\psi + \sin\phi\, Z_\chi$$

$$\Delta Q_W^f = \zeta\, h_V^f \qquad \zeta = \frac{8\sqrt{2}\pi\alpha'}{M_{Z'}^2 G_F}$$

$$h_v^d = -h_V^e = [\sin^2\phi - \sqrt{15}\sin\phi\cos\phi/3]/20 \qquad h_v^u = 0$$

See also: J. Erler PAVI 09
Erler et al, arXiv:0906.2435

Kinetic mixing: additional models

Probing Z' with PVES

PV Sensitivities $Z' = \cos\phi\, Z_\psi + \sin\phi\, Z_\chi$

$$\Delta Q_W^f = \zeta\, h_V^f \qquad \zeta = \frac{8\sqrt{2}\pi\alpha'}{M_{Z'}^2 G_F}$$

$$h_v^d = -h_V^e = [\sin^2\phi - \sqrt{15}\sin\phi\cos\phi/3]/20 \qquad h_v^u = 0$$

QuickTime™ and a
decompressor
are needed to see this picture.

Z_χ Limits:

LEP: 673

CDF: 892 (2.3 fb^{-1})

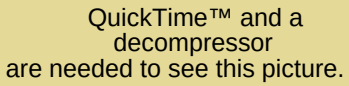
Cs APV: 890

E158: 670

See also: J. Erler Loop Fest 09
Erler & Langacker PRL 84:212 (2000)

Probing Z' : LHC Discovery

Petriello (CIPANP 09)



Probing Z' : PVES & LHC

Petriello (CIPANP 09)

PV Couplings: $q_R e_L$

QuickTime™ and a
decompressor
are needed to see this picture.

Leptonic PV Couplings: $e_{L,R}$

QuickTime™ and a
decompressor
are needed to see this picture.

Qweak: Break LHC Sign Degeneracy

LHC: Cone in e_L - e_R plane
Moller: Hyperbola

See also Chang, Ng, & Wu: 0901.0163

Leptoquarks:

- *General Classification*
- *PVES Sensitivity*
- *GUT Example: LQ's & m_ν*
- *LHC & Low Energy Probes*

- *R-M, Phys. Rev. **C60** (1999) 015501*
- *Erler, Kurylov, R-M, Phys Rev. **D68** (2003) 034016*
- *Fileviez Perez, Han, Li, R-M, 0810.4238*

Probing Leptoquarks with PVES

General classification: $SU(3)_C \times SU(2)_L \times U(1)_Y$

QuickTime™ and a
decompressor
are needed to see this picture.

SU(5) GUT:

m_ν , τ_{prot}

LQ 2 15_H

Dorsner & Fileviez Perez,
*NPB **723** (2005) 53*

Fileviez Perez, Han, Li, R-M
*NPB **819** (2009) 139*

Q-Weak sensitivities:

QuickTime™ and a
decompressor
are needed to see this picture.

Leptoquarks: PVES, m_ν & LHC

PV Sensitivities

$$\lambda_S \leq \gamma_q \left(M_{\rm LQ}/100\,{\rm GeV} \right)$$

LHC Search

QuickTime™ and a
decompressor
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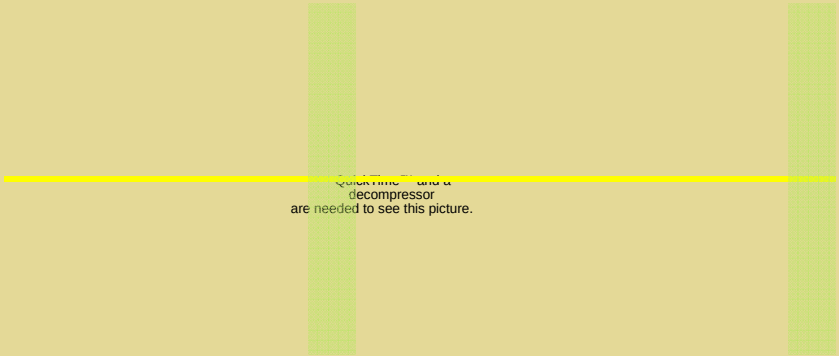
QuickTime™ and a
decompressor
are needed to see this picture.

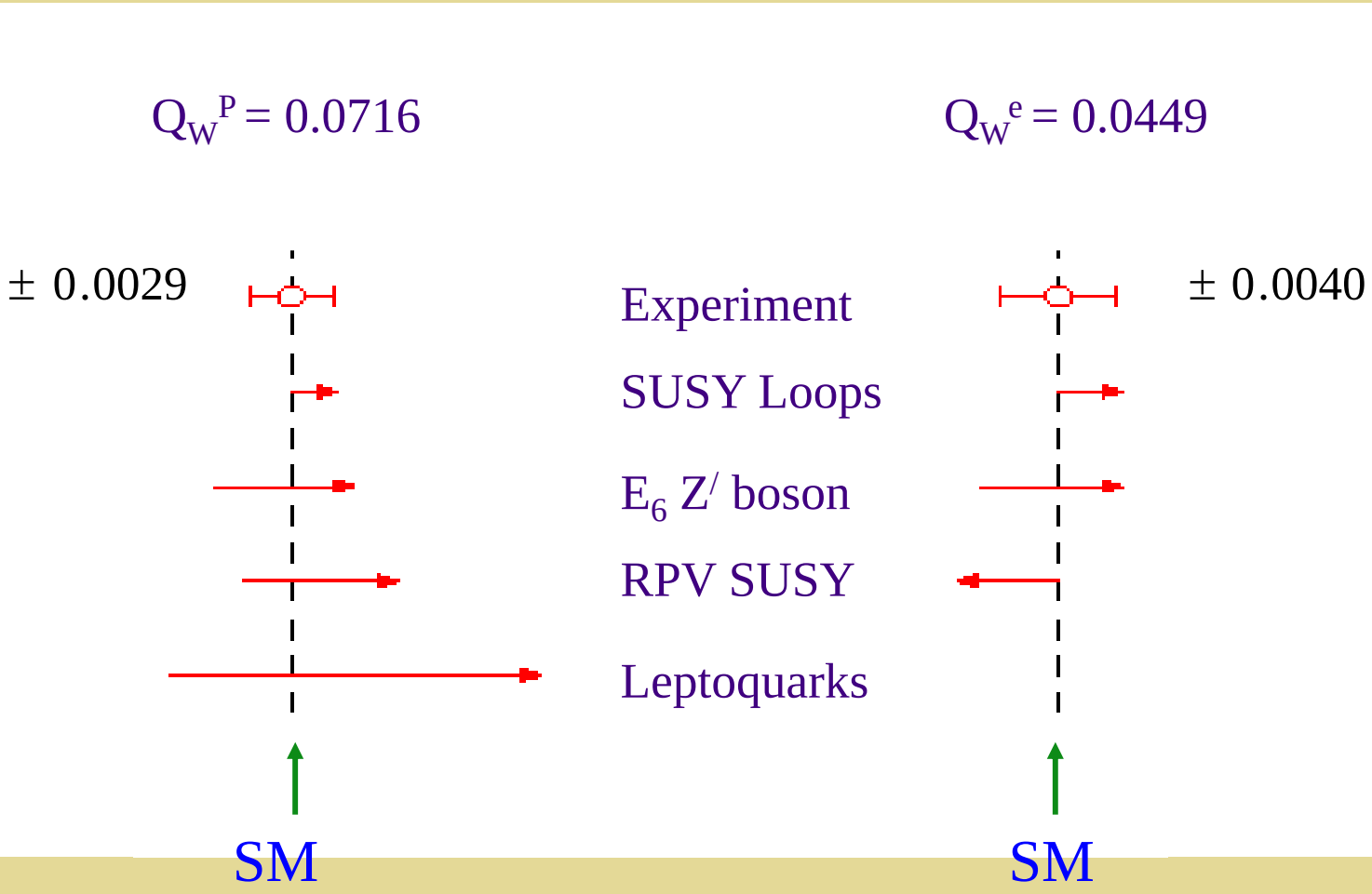


$$\lambda_S = \sqrt{2} Y_\nu^{11} / \mathrm{V}_\Delta$$

4% Q_W^p
(*M_{LQ}=100 GeV*)

Fileviez Perez, Han, Li, R-M
*NPB **819** (2009) 139*

PVES: Diagnostic Tool for NP



PVDIS & QCD

Low energy effective PV eq interaction

$$L_{PV}^{eq} = \frac{G_\mu}{\sqrt{2}} \sum_q \left[C_{1q} \bar{e}\gamma^\mu\gamma_5 e \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu\gamma_5 q \right]$$

PV DIS eD asymmetry: leading twist

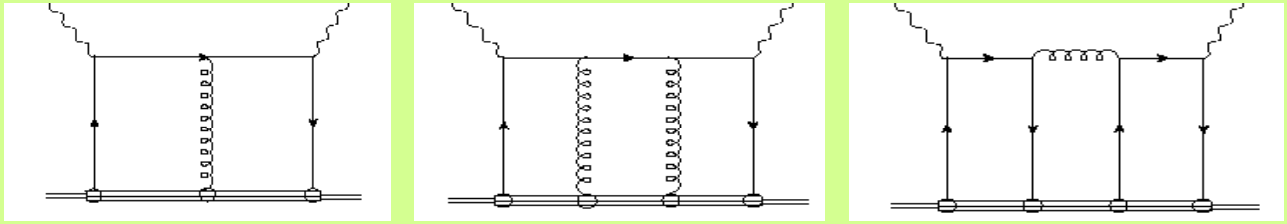
$$A_{PV}^{eD} = \frac{3G_\mu Q^2}{2\sqrt{2}\pi\alpha} \left[\frac{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})}{5} \right]$$

+

Higher Twist (J Lab)

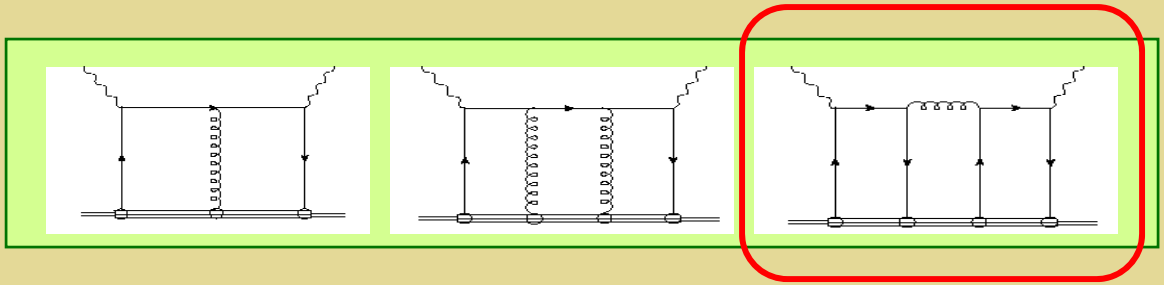
CSV (J Lab, EIC)

d/u (J Lab, EIC)



Bjorken & Wolfenstein ‘78

Isolates 4q HT operator: PVDIS a unique probe



y-independent term: C_{1q}

QuickTime™ and a
decompressor
are needed to see this picture.

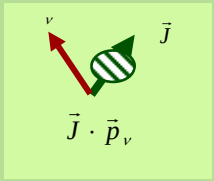
Differences in VV and SS:

QuickTime™ and a
decompressor
are needed to see this picture.

C_{1q} terms are “contaminated” only by 4q, double handbag $\tau = 4$ effects

ecays & SUSY

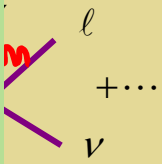
PV Neutrino correlation



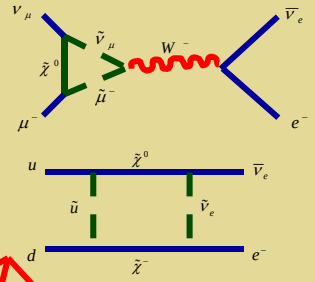
QuickTime™ and a decompressor are needed to see this picture.

SUSY: Observable E-dependence implies super heavy non-SM Higgs

Profumo, RM, Tulin



QCD
gliano



SUSY effects in weak decays

$$dW \propto 1 + B(m_e/E_e)\vec{\sigma}_n \cdot \frac{\vec{p}_\nu}{E_\nu} + \cdots$$

- *n decay correlations*
- *nuclear β decay*
- *pion decays*

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$$R_{e/\mu} = \frac{\Gamma[\pi^- \to e^- \bar{\nu}_e(\gamma)]}{\Gamma[\pi^- \to \mu^- \bar{\nu}_\mu(\gamma)]} = \frac{m_e^2}{m_\mu^2}\left[\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right]^2 \left\{1 + \frac{\alpha}{\pi}\left[F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + C_{QCD}^{e-\mu}(\mu)\right] + \Delta_{NEW}^{e-\mu}\right\}$$

V_{ud} & CKM Unitarity

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r^{\mathrm{SM}} + \Delta^{\mathrm{new}}\right)$$

EDMs: New CPV?

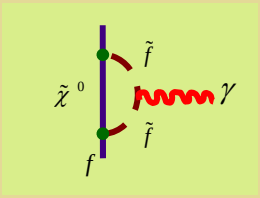
A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	*n* (UCN)	SNS
Cs (trapped)	Texas	*n* (UCN)	ILL
Cs (fountain)	LBNL	*n* (UCN)	PSI
YbF (beam)	Imperial	*n* (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	deuteron (ring)	BNL?

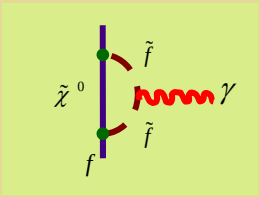
EDMs: Complementary Searches

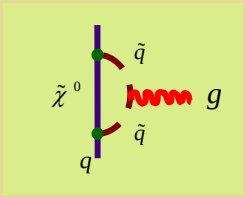
Improvements of 10^2 to 10^3

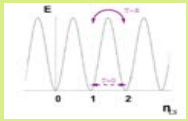
Electron



Neutron

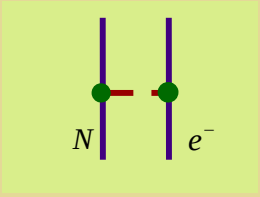


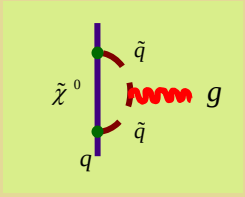


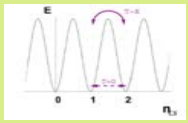


QCD

Neutral Atoms

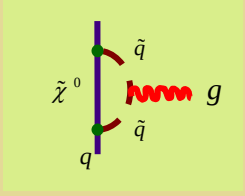


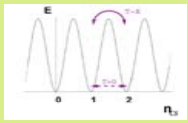




QCD

Deuteron





QCD

Baryogenesis & EDMs

Sakharov Criteria

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

QuickTime™ and a decompressor are needed to see this picture.

Sakharov, 1967

Anomalous B-violating processes

SM Sphalerons:

$$\Gamma(A+B \to C) \neq \Gamma(\bar{A}+\bar{B} \to \bar{C})$$

EDMs

SM CKM CPV:

Prevent washout by inverse processes

LHC: Scalars

SM EWPT:

Electroweak Baryogenesis

Supersymmetry

Leptogenesis

Baryogenesis: New Electroweak Physics

Weak Scale Baryogenesis

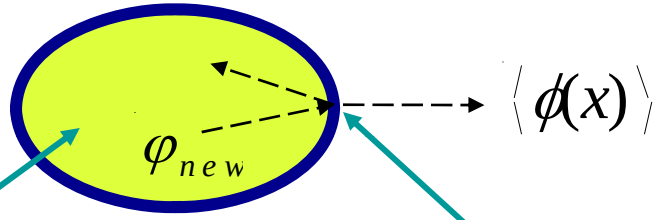
- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

QuickTime™ and a decompressor are needed to see this picture.

Sakharov, 1967

Unbroken phase

Topological transitions

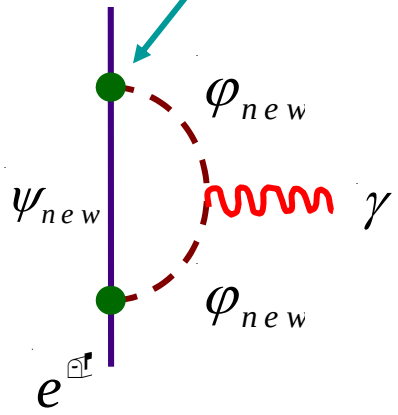


Broken phase

CP Violation

1st order phase transition

- *Is it viable?*
- *Can experiment constrain it?*
- *How reliably can we compute it?*



SUSY: EWB & EDMs

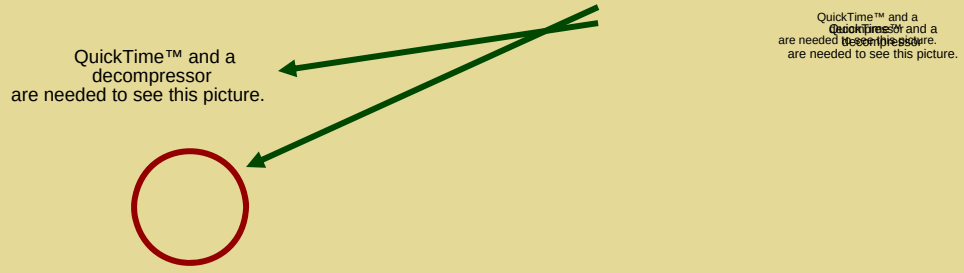
For EWB, we live in a two-loop world:

1st generation sfermions are heavy

Cirigliano, R-M, Tulin, Lee '06

Ritz CIPANP 09

Compatible with observed Y_B



$Arg(\mu M_1 b^*) \neq Arg(\mu M_2 b^*)$

Li, Profumo, RM

SUSY: EWB & EDMs cont'd

For EWB, LHC & EWPO matter:

Small tanβ

Large tanβ

QuickTime™ and a
decompressor
are needed to see this picture.

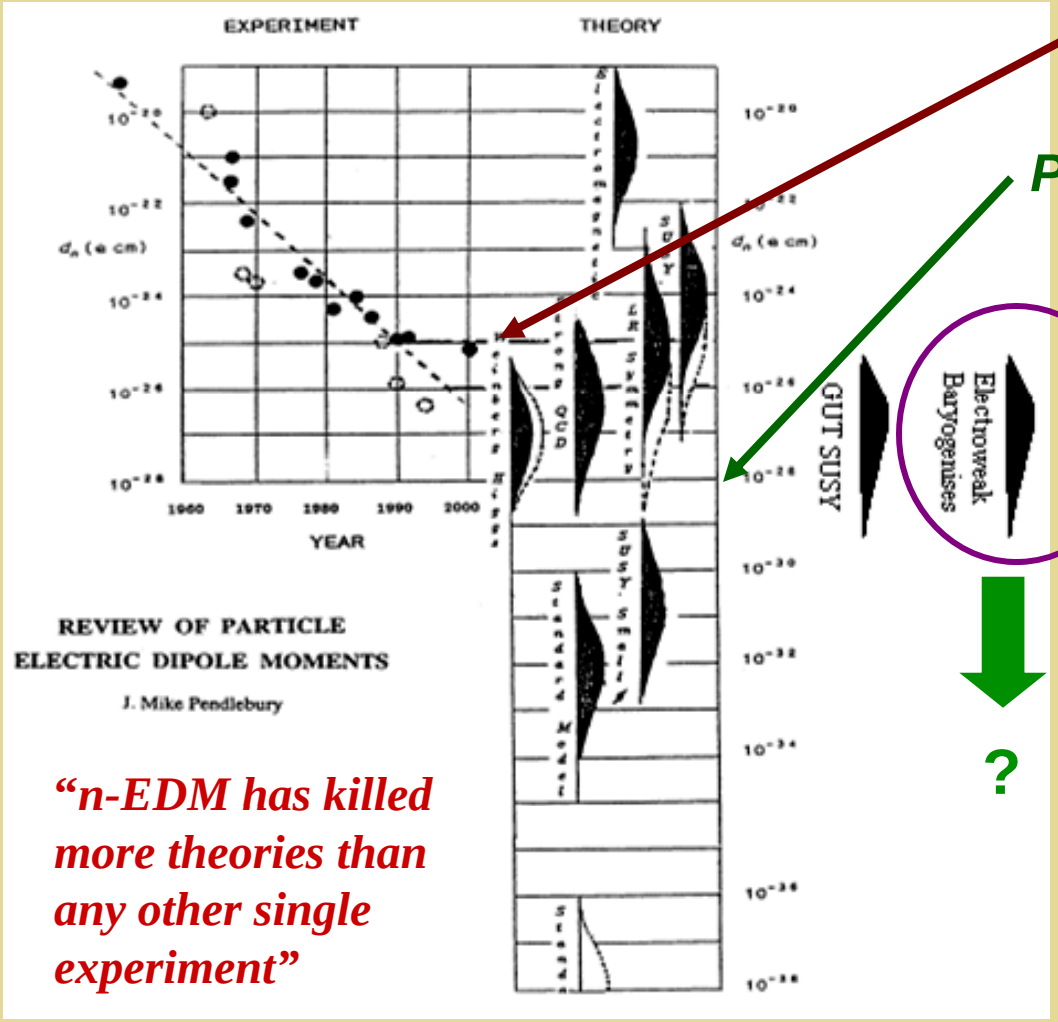
g_μ-2

Magnitude & sign of Y_B can be sensitive to third generation sfermion spectrum for given CPV phase

Chung, Garbrecht, RM, Tulin

Info from LHC & EWPO essential

EDMs: What We May Learn



"n-EDM has killed more theories than any other single experiment"

Present n-EDM limit

Proposed n-EDM limit

GUT SUSY

Electroweak Baryogeneses

?

Matter-Antimatter Asymmetry in the Universe

Refined theory ?
New theory ?
Leptogenesis ?

Conclusions

- *Low energy PV will provide a powerful probe of new physics during the LHC era, providing a unique sensitivity to detailed nature of new particles and their interactions*
- *Measurements using a variety of systems with complementary NP sensitivity needed (Q-Weak & Moller, eEDM & nEDM, PVES & weak decays)*
- *It is a rich and growing field with many exciting experimental and theoretical challenges ahead*