Fundamental Symmetries & Neutrinos: The NP-HEP Interface

M.J. Ramsey-Musolf

Wisconsin-Madison

U Mass-Amherst

Amherst Center for Fundamental Interactions

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Outline

I. The Nuclear Physics Context

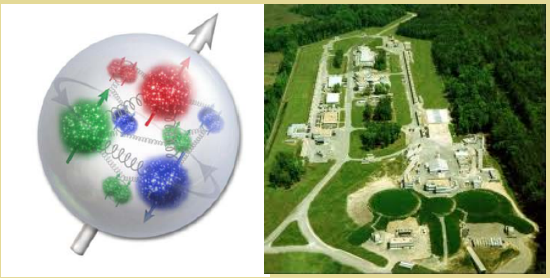
II. EDMs & the Origin of Matter

III. $0\nu\beta\beta$ Decay: LNV

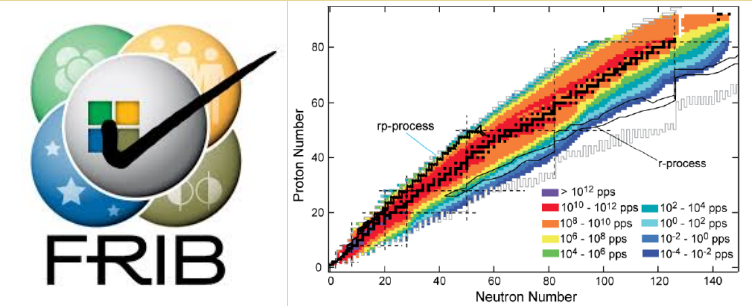
IV. Precision Tests: BSM Diagnostic

V. Summary

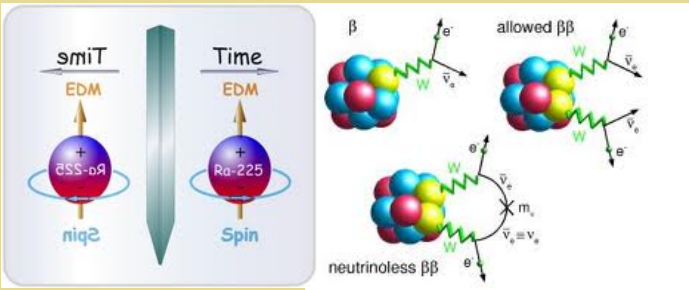
Nuclear Physics Today



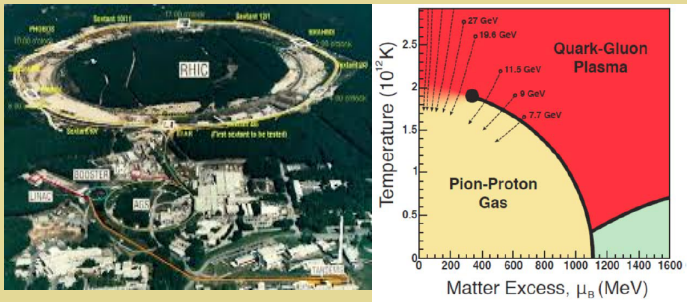
Hadron structure & dynamics: "cold QCD"



Rare isotopes: nuclear structure & astrophysics



Fundamental symmetries & neutrinos: "Intensity Frontier"



Relativistic heavy ions: "hot & dense QCD"

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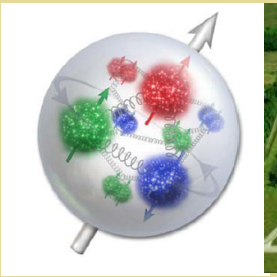

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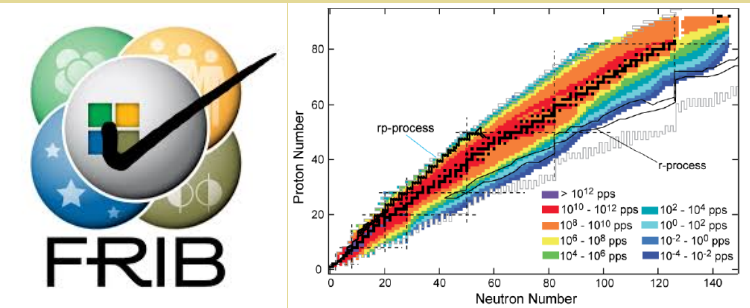

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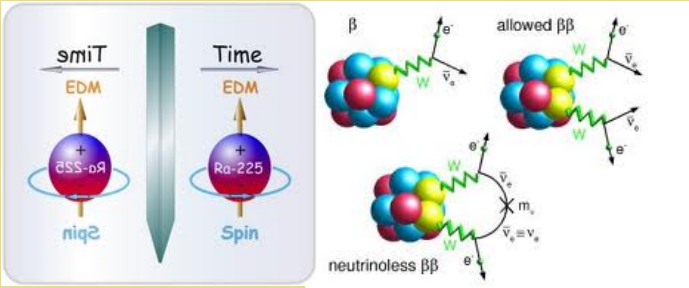

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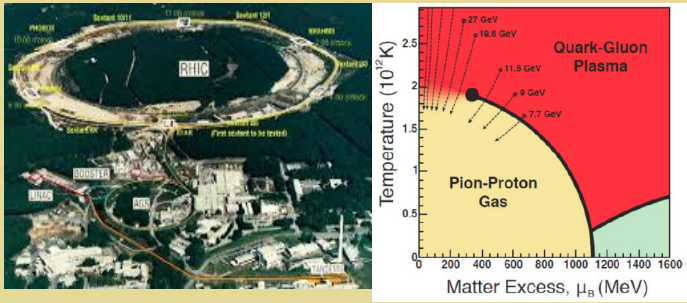

Relativistic heavy ions: "hot & dense QCD"

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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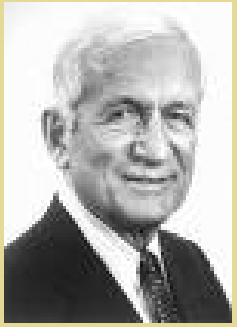

PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

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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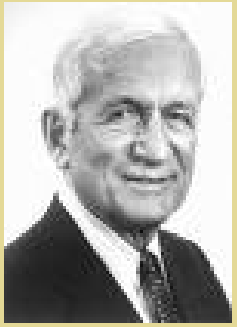

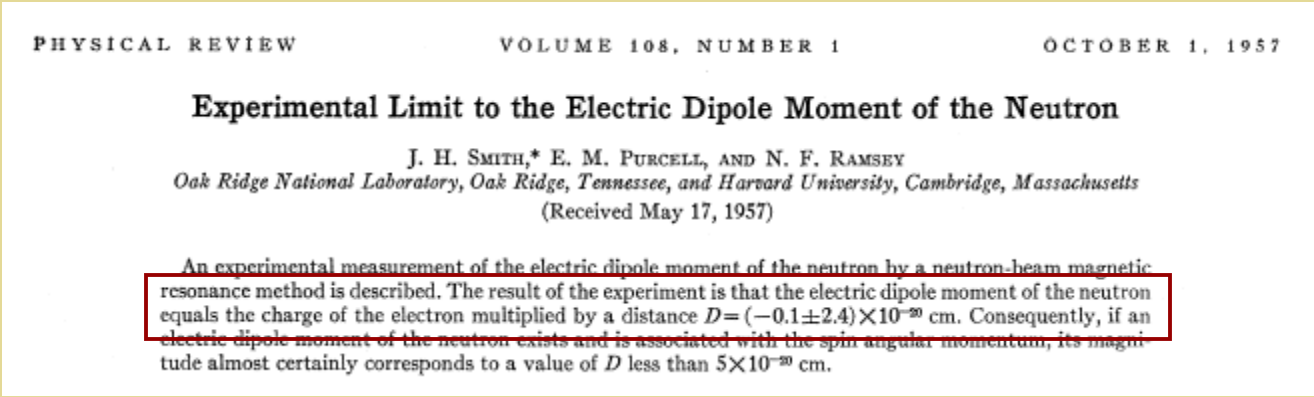

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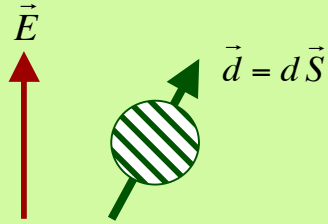
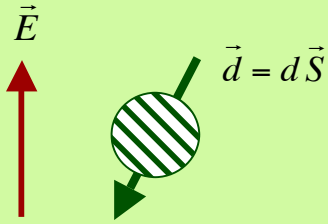
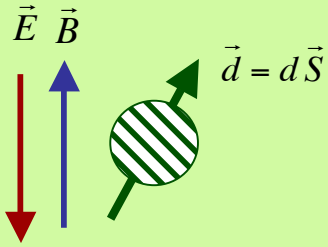


$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$



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

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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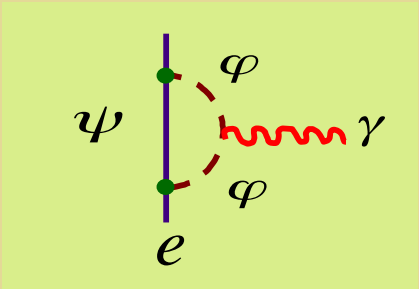
Mass Scale Sensitivity



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

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

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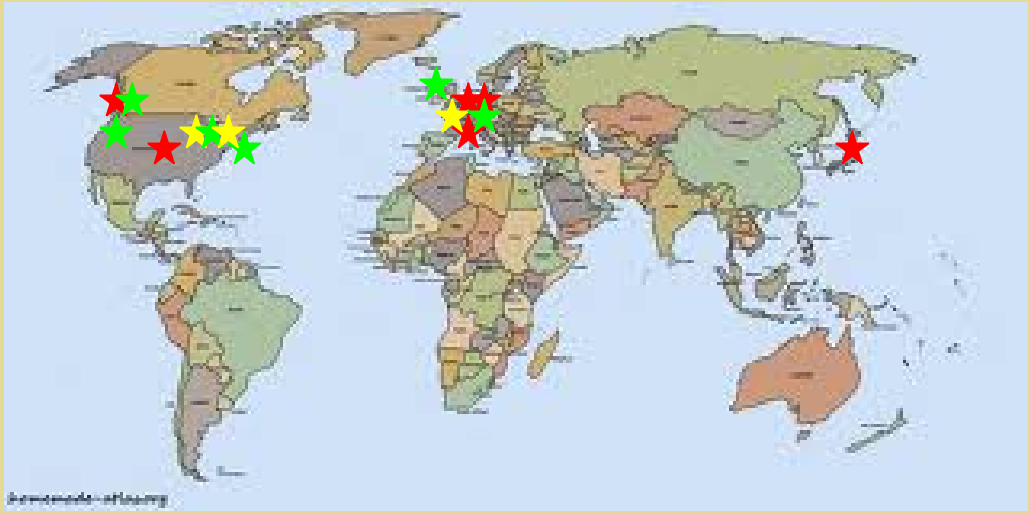


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

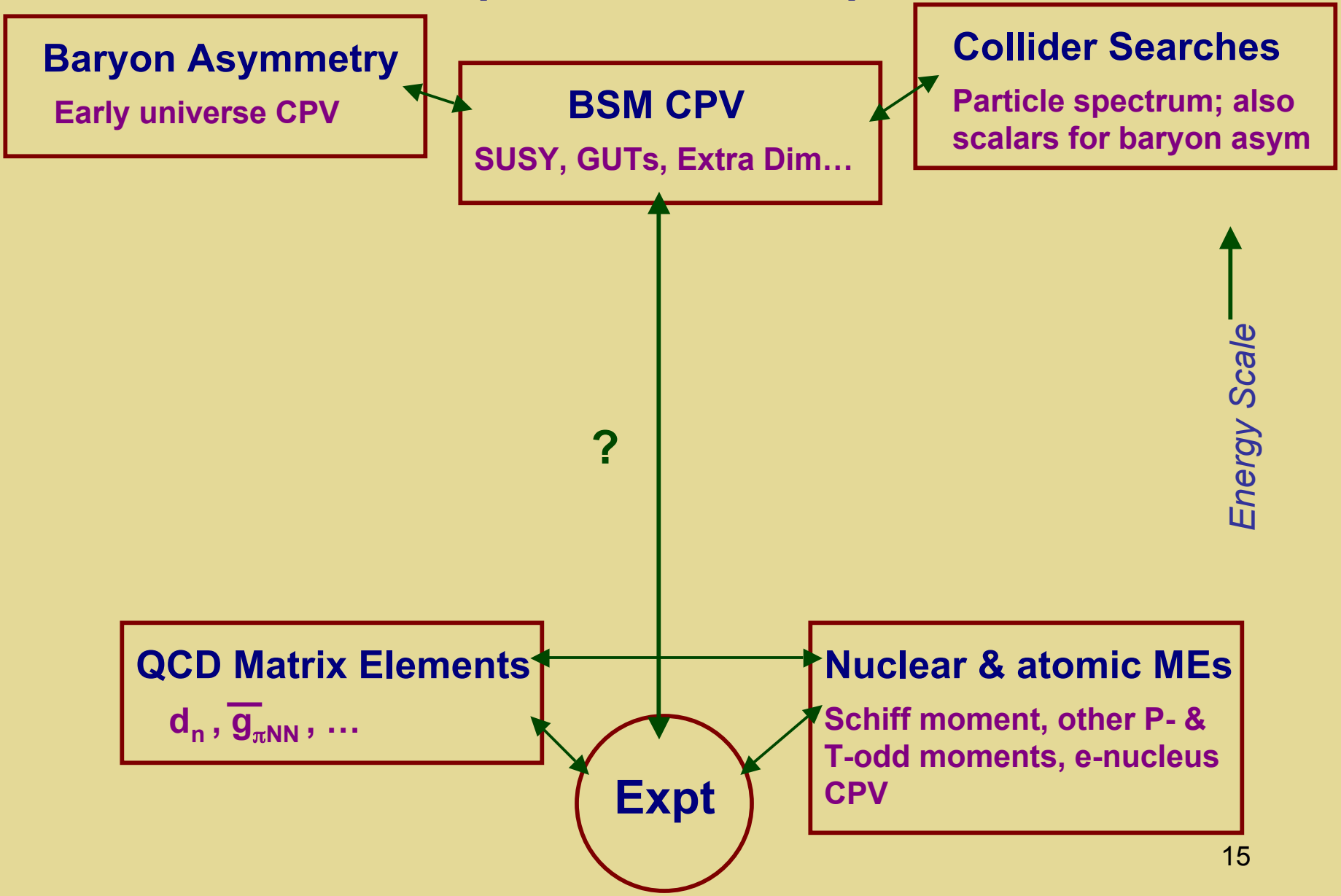
Not shown: muon

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales



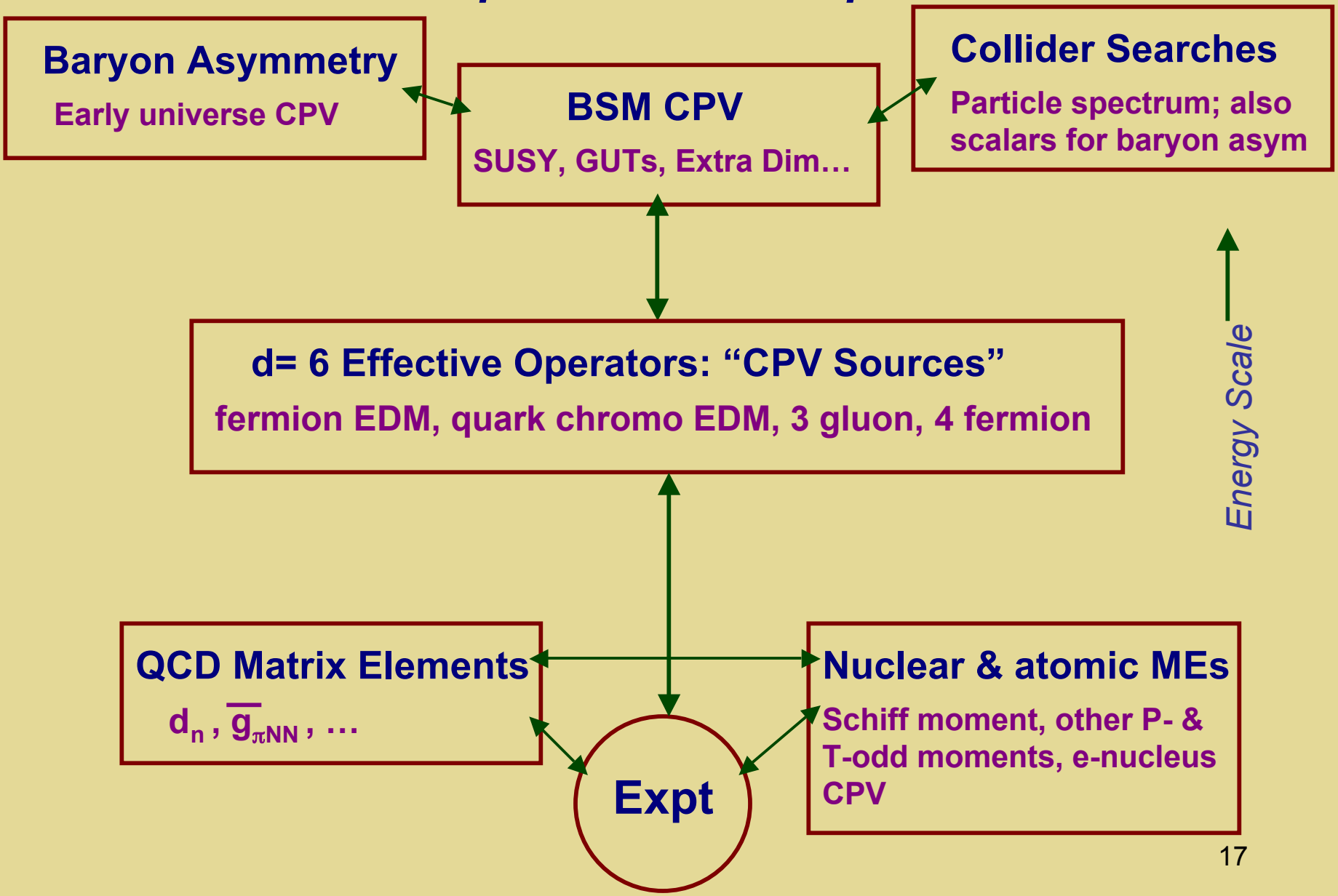
Effective Operators

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

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

+…

EDM Interpretation & Multiple Scales

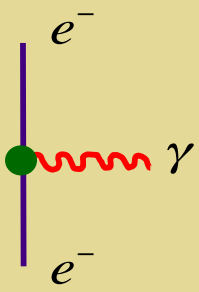


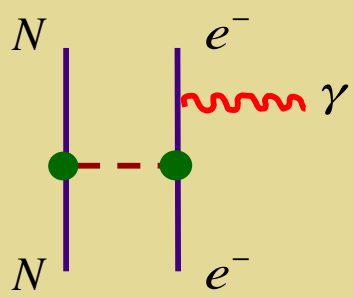
Why Multiple Systems ?

Multiple sources & multiple scales

Exploit complementary sensitivity to search for & identify CPV

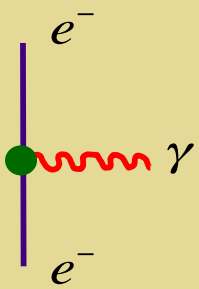
Paramagnetic Systems: Two Sources



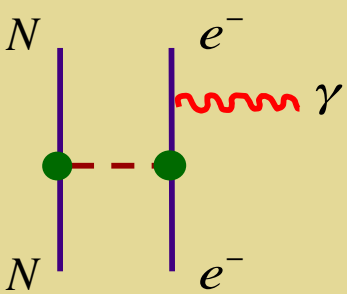


Tl, YbF, ThO…

Paramagnetic Systems: Two Sources



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



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

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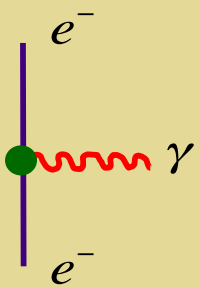

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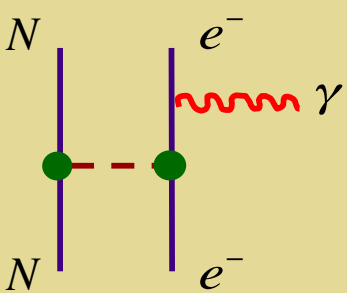

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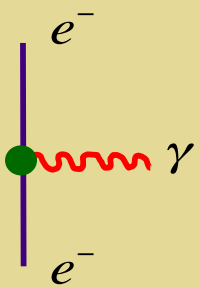

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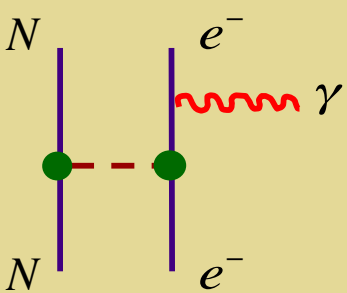

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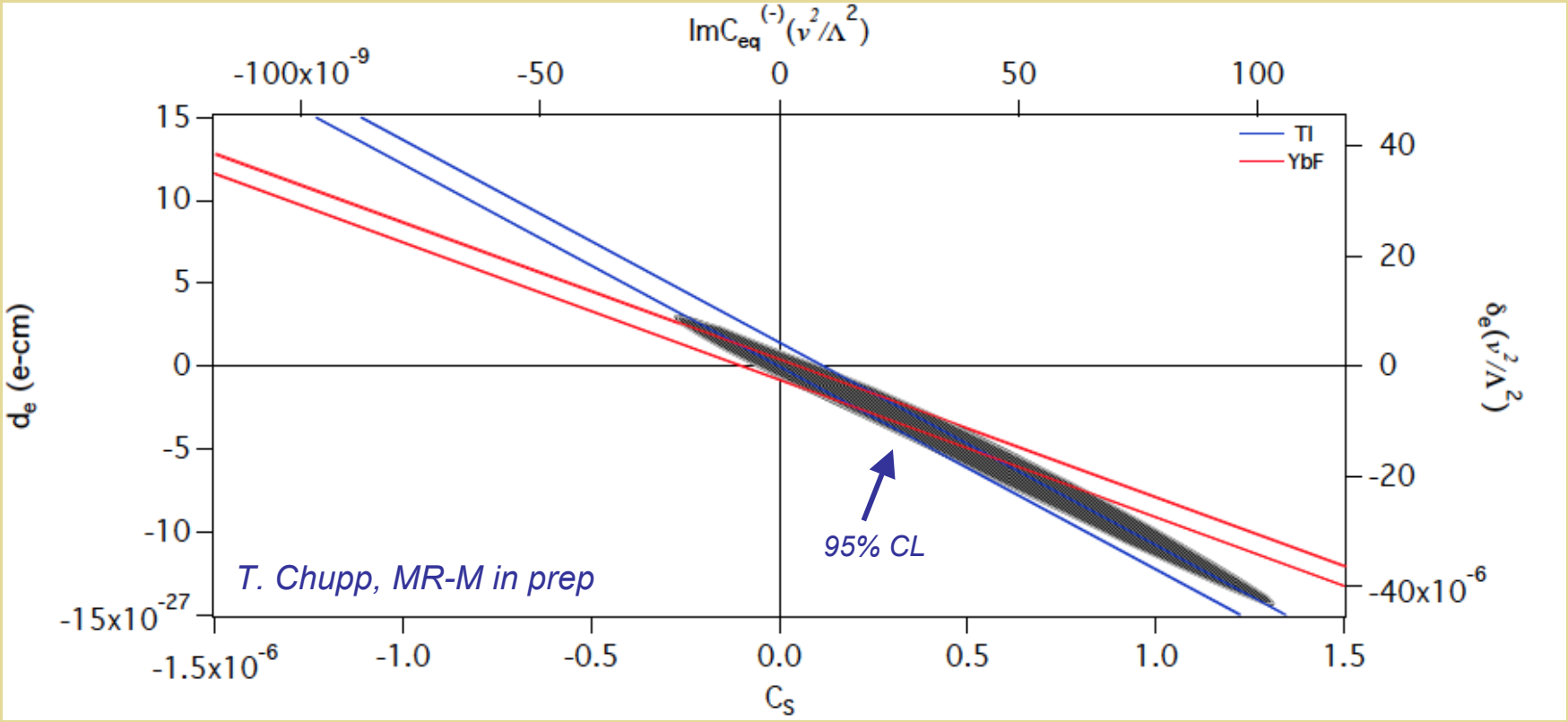
Tl, YbF, ThO…

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

Paramagnetic Global Fit



- *Im C_{eq} $(v/\Lambda)^2 < 5.6 \times 10^{-8}$*
- *δ_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

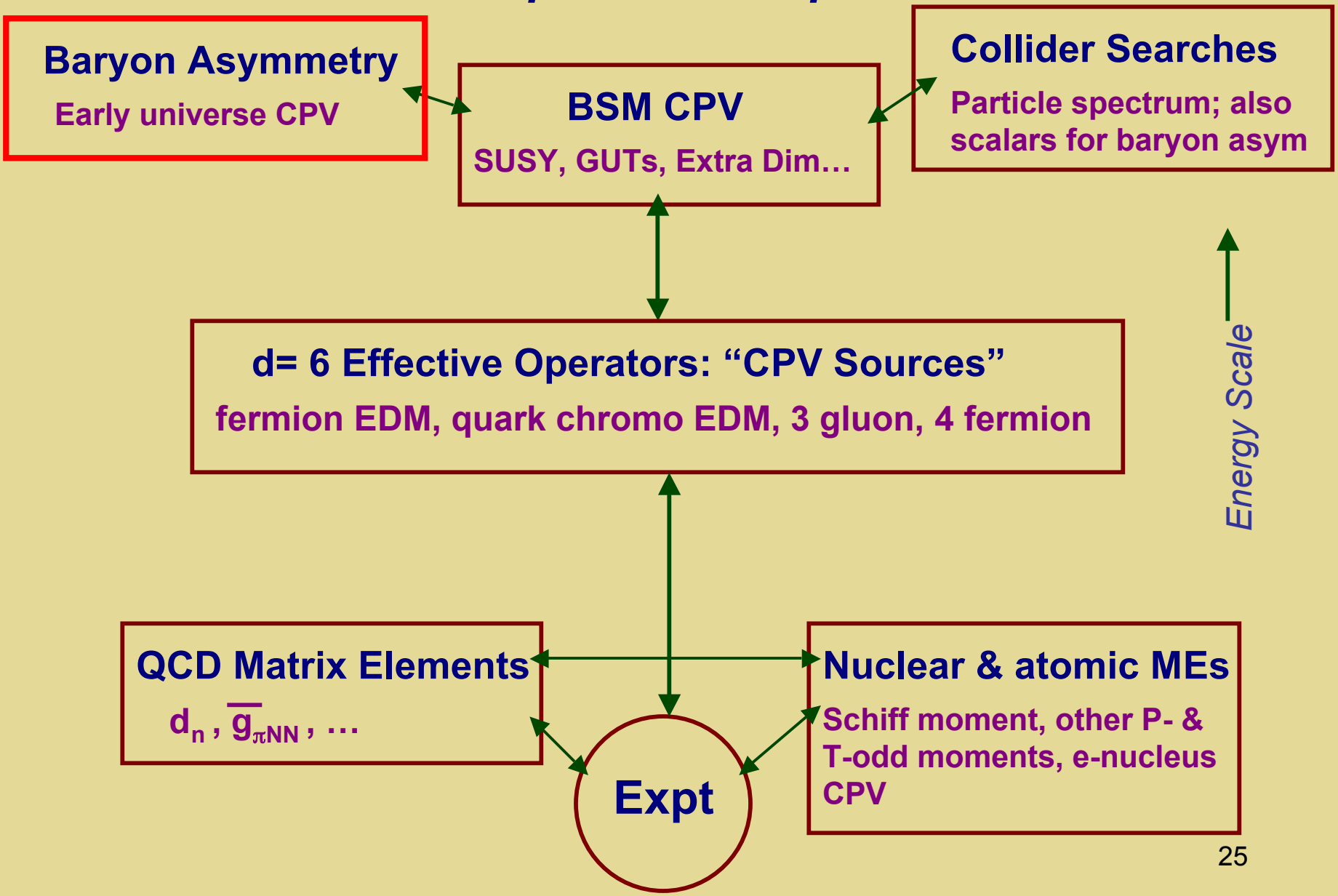
- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

→

- *Nucleons*
- *Diamagnetic atoms (Schiff moments)*
- *Light nuclei*

Details: discussion period & back-up slides

EDM Interpretation: Implications



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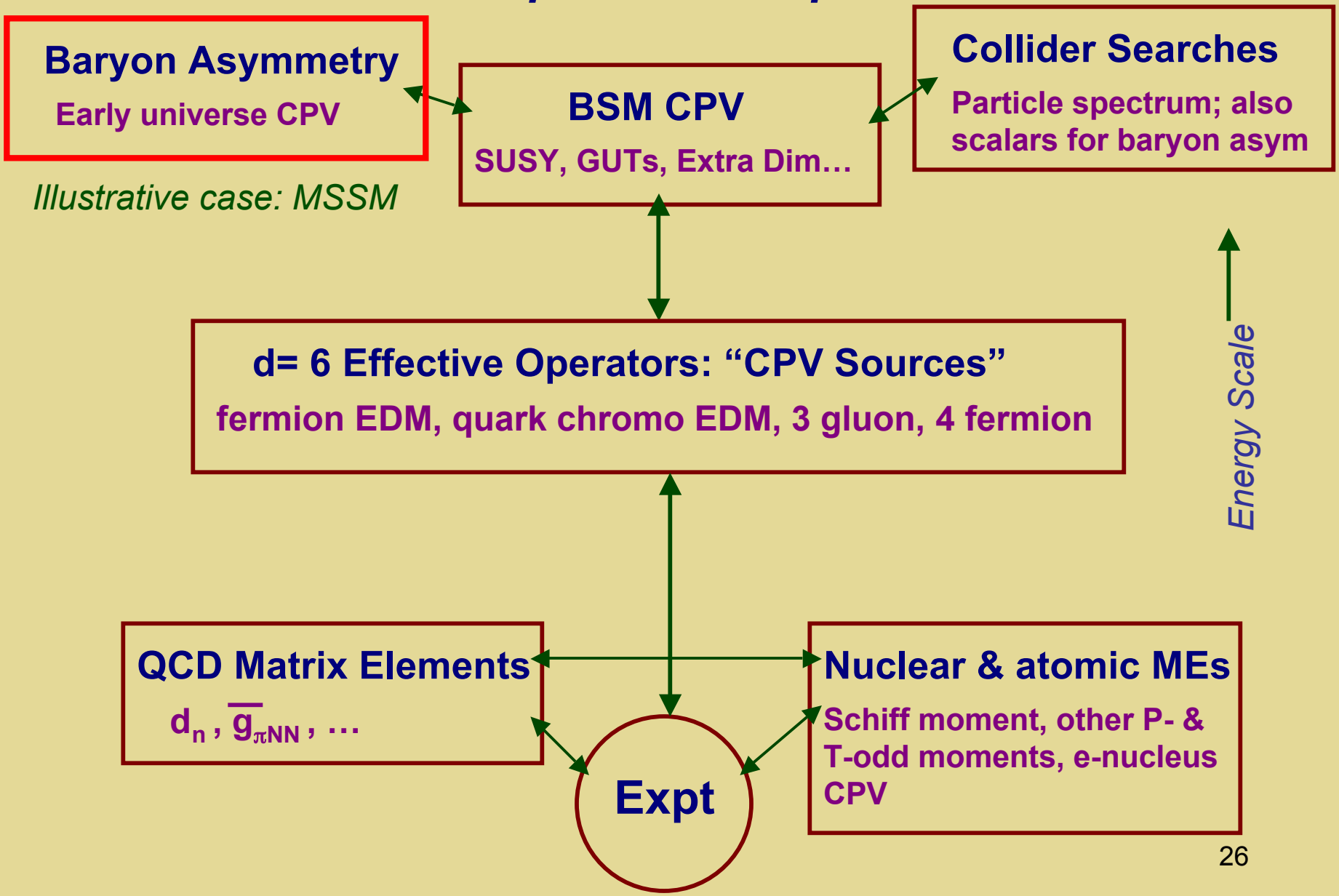
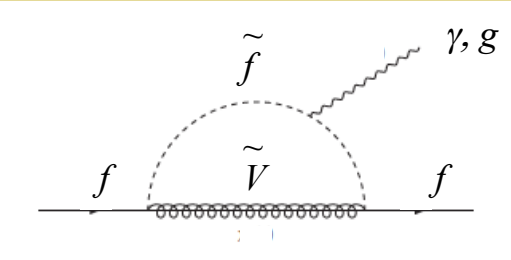


EDMs & EW Baryogenesis: MSSM

One-loop EDMs preclude MSSM baryogenesis



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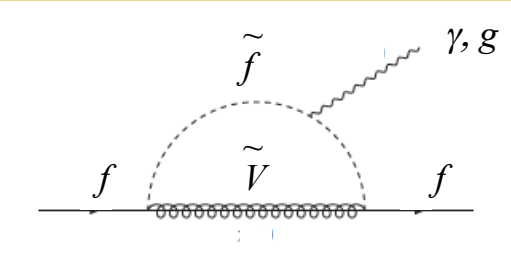
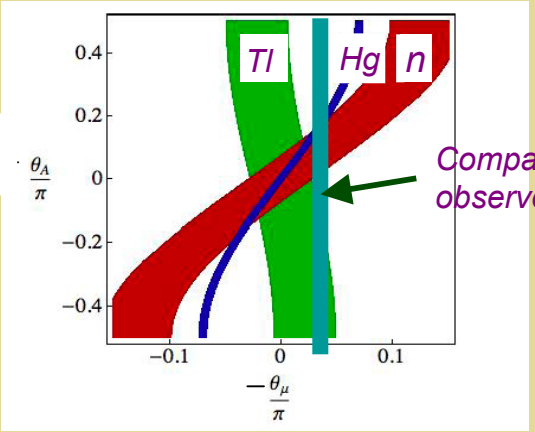


Universal gaugino phases

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



Compatible with observed BAU

Ritz CIPANP 09 +

Cirigliano, R-M, Tulin, Lee '06

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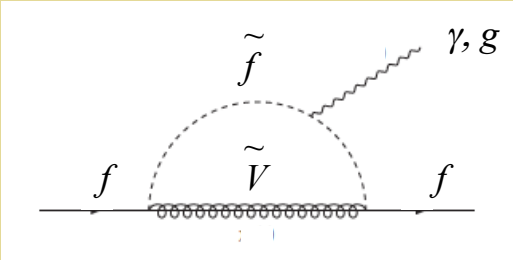
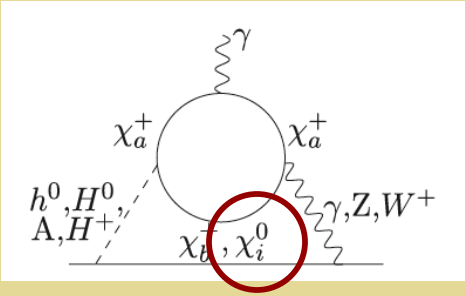


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

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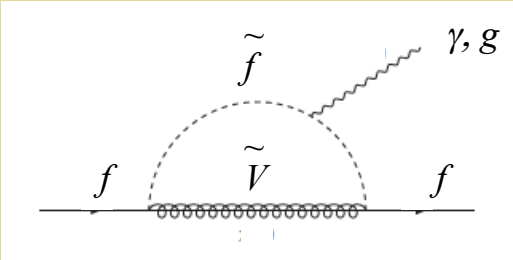

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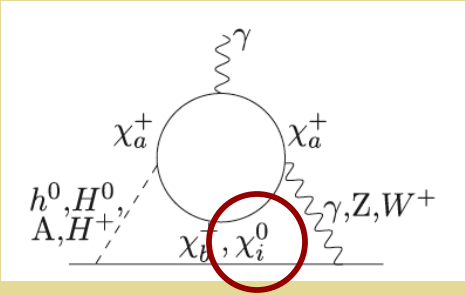

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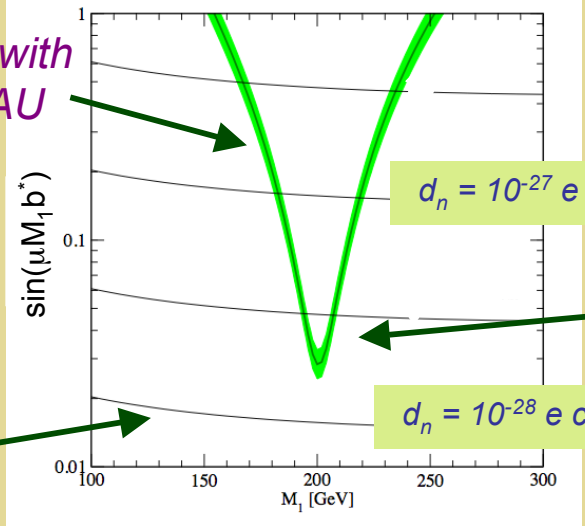

Compressed spectrum (stealthy SUSY)

Next generation d_n

Li, Profumo, RM '09-'10

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$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana

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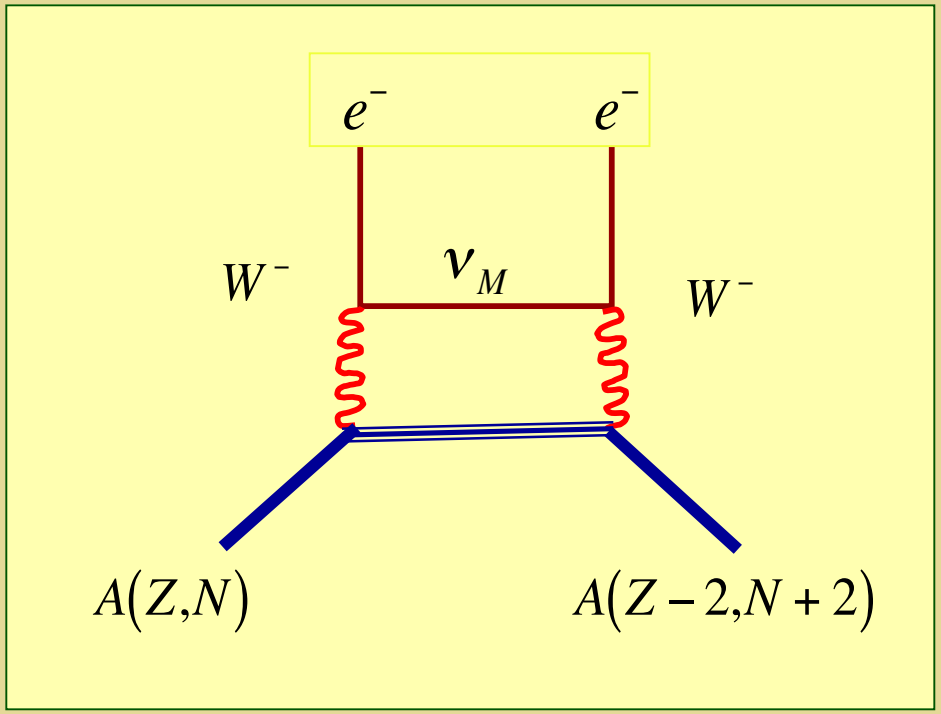

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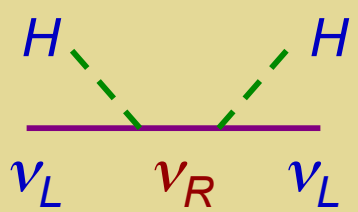
See-saw mechanism

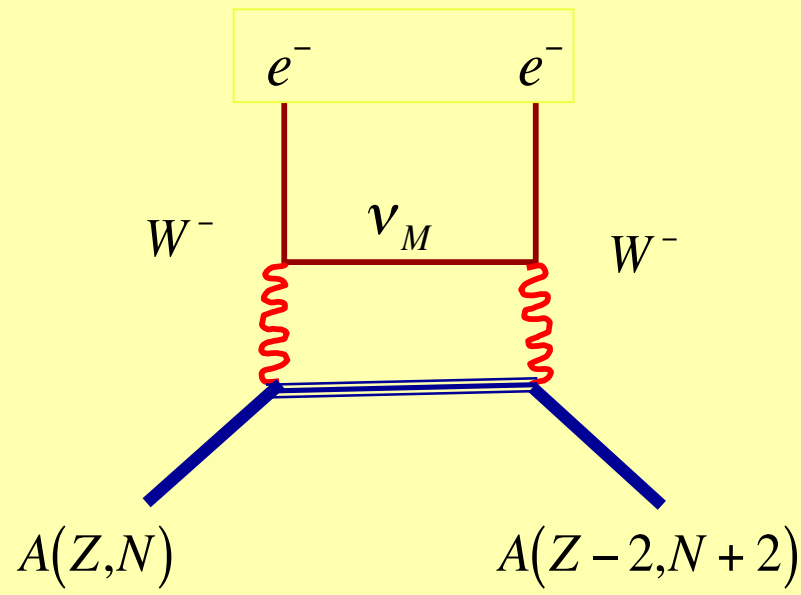


$$m_\nu = \frac{m_L^2}{M_R}$$

Leptogenesis

$$\Gamma(\nu_R \to X) \neq \Gamma(\nu_R \to \bar{X})$$

Lepton Asym -> Baryon Asym



$0\nu\beta\beta$-Decay: LNV? Mass Term?

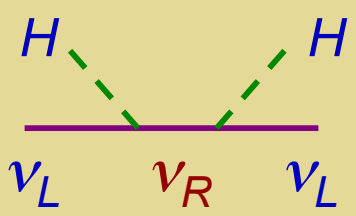
See-saw scale:

$M_R \sim 10^{12}$ GeV

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana

See-saw mechanism

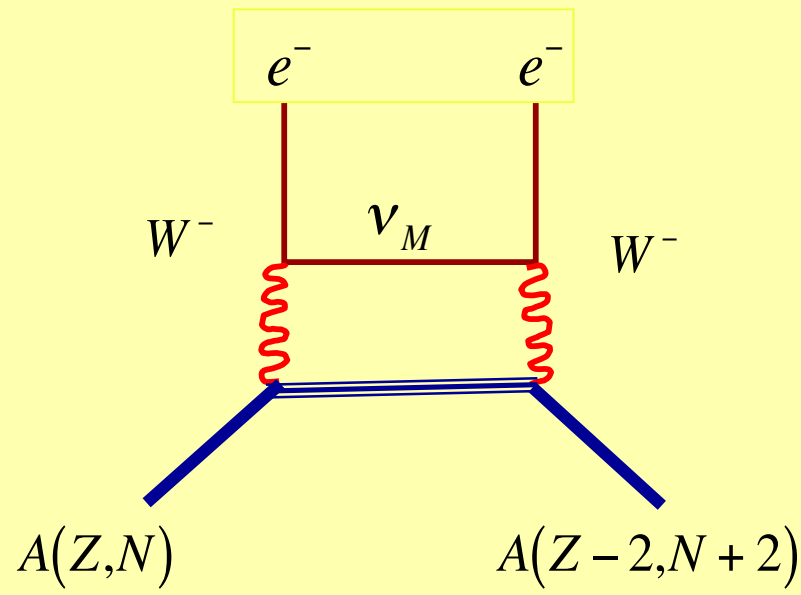


$$m_\nu = \frac{m_L^2}{M_R}$$

Leptogenesis

$$\Gamma(\nu_R \to X) \neq \Gamma(\nu_R \to \bar{X})$$

Lepton Asym -> Baryon Asym



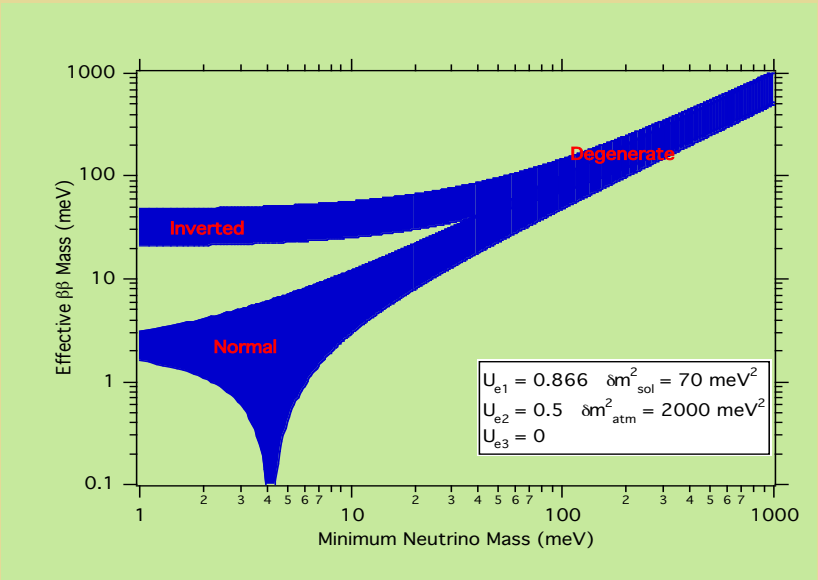
$0\nu\beta\beta$-Decay: LNV? Mass Term?

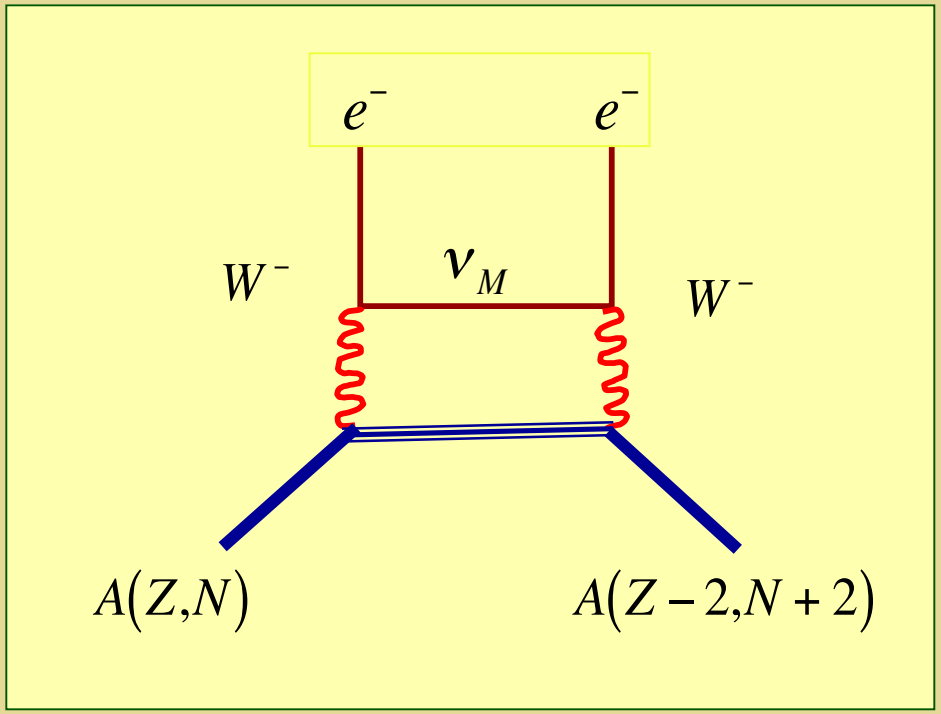
$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana





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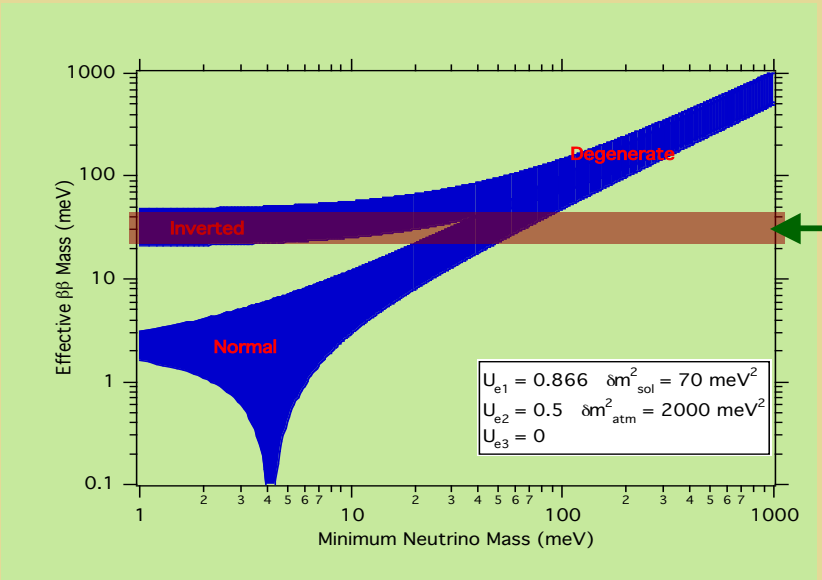

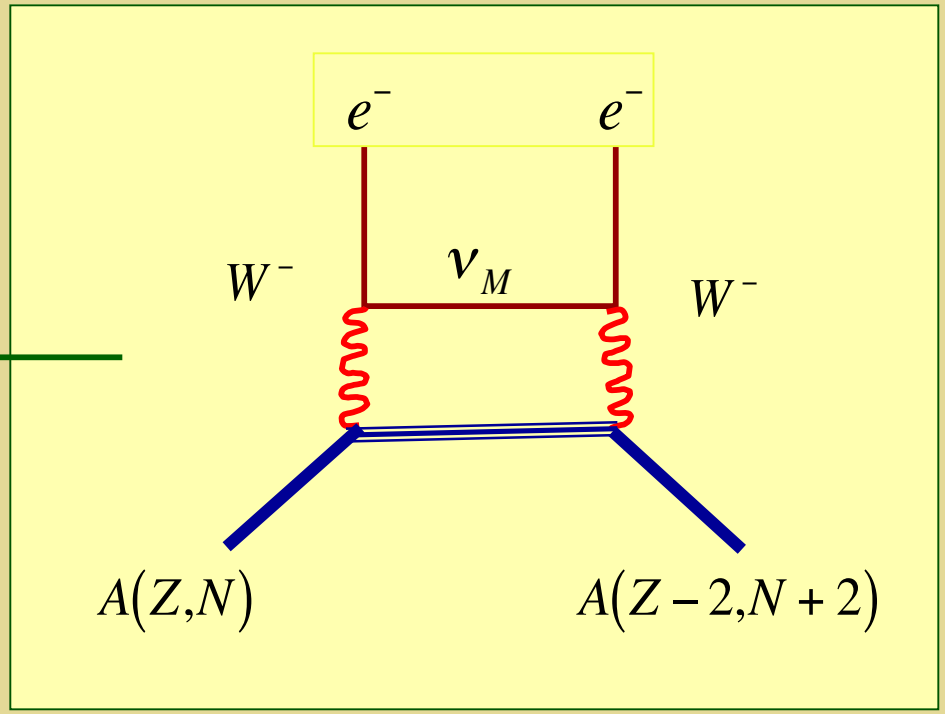

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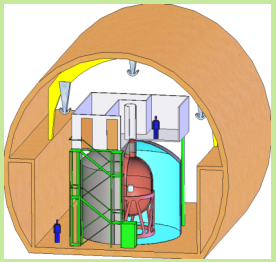
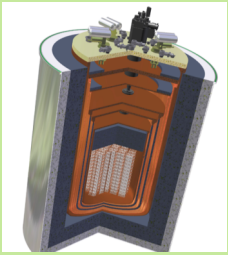
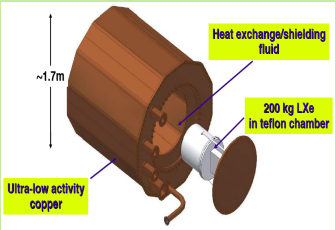


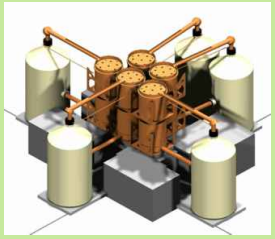
GERDA



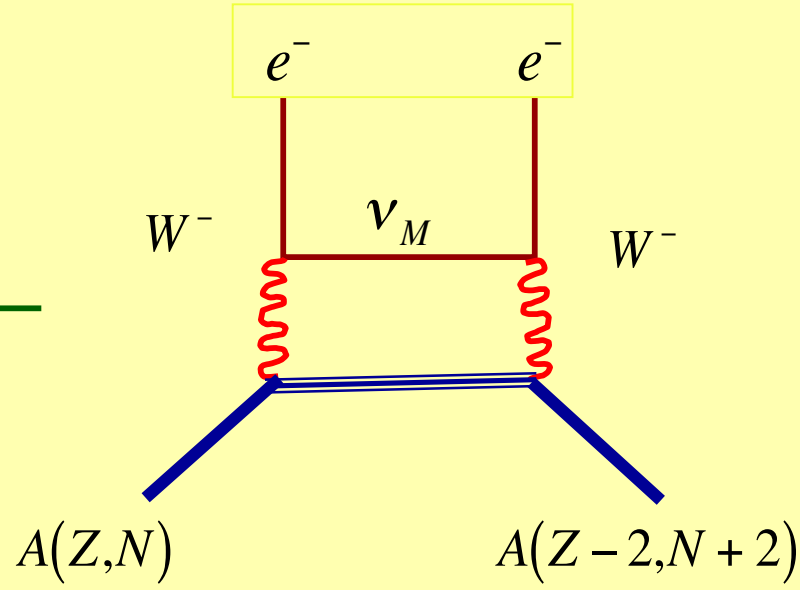
CUORE



EXO



Majorana



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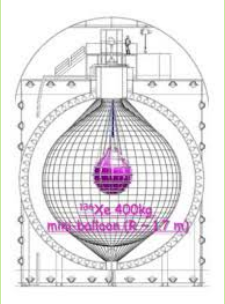
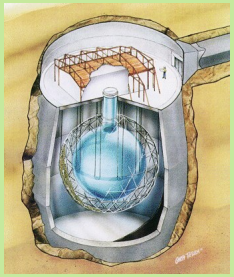


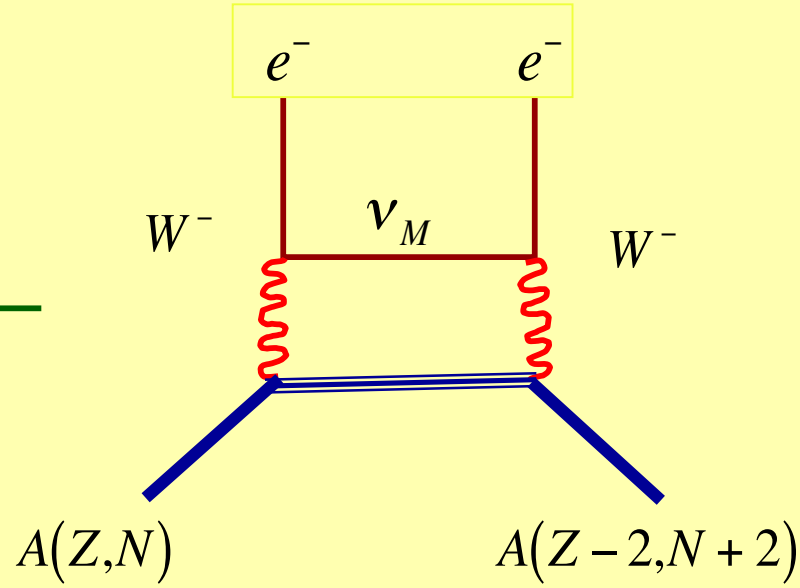
KamLAND -Zen



SNO+

supernemo collaboration

Super NEMO



Experimental Status

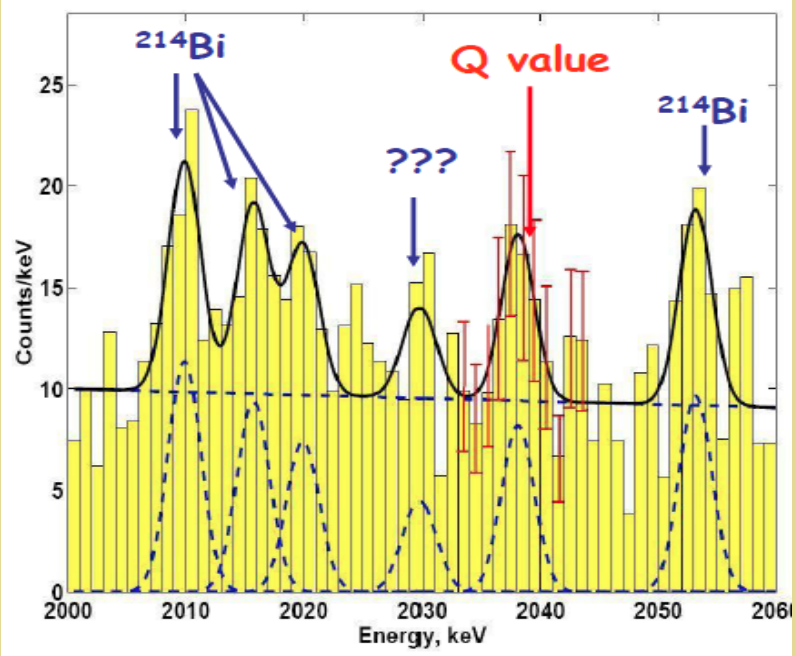
Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>5.8*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	47.7	$>1.9*10^{25}$ (90%	<0.35
^{82}Se			$>2.1*10^{22}$ CL)	
^{96}Zr			>9 (90%CL)	
^{100}Mo	Foil.Geiger tubes		10^{23} (90%CL)	
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te			$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO	12	$>3*10^{24}$ (90%CL)	<0.19-0.68
^{136}Xe		~4.5	$>1.2*10^{24}$ (90%CL)	<1.1-2.9
^{150}Nd			$>1.8*10^{22}$ (90%CL)	
160			$>1.3*10^{21}$ (90%CL)	

Simplified List of Limits for ββ0ν decay (pre-2012)

Courtesy: G. Gratta

Observation ?

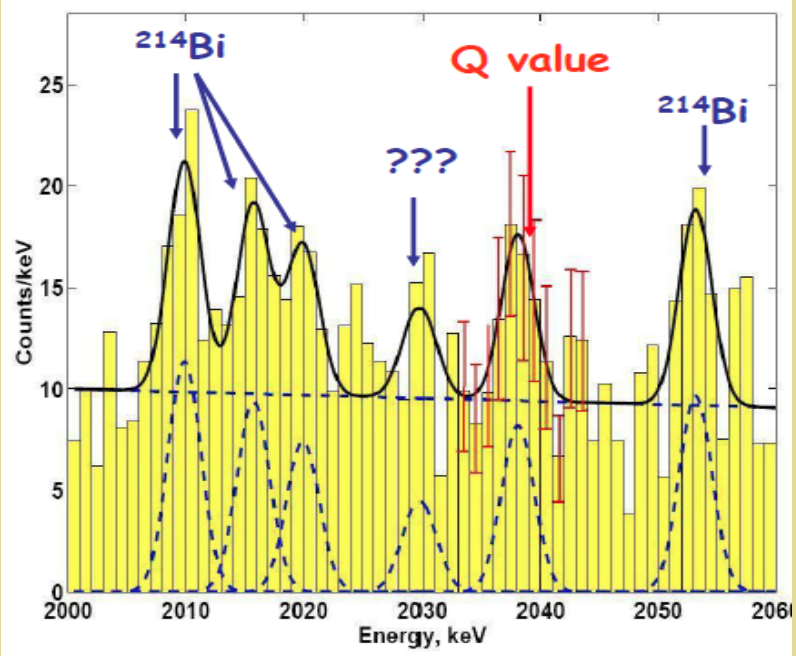
Courtesy: G. Gratta



H.V. Klapdor-Kleingrothaus et al, 2004, 2006: Observation of peak consistent with m_ν ~ eV (quasi-degenerate)

Observation ?

Courtesy: G. Gratta



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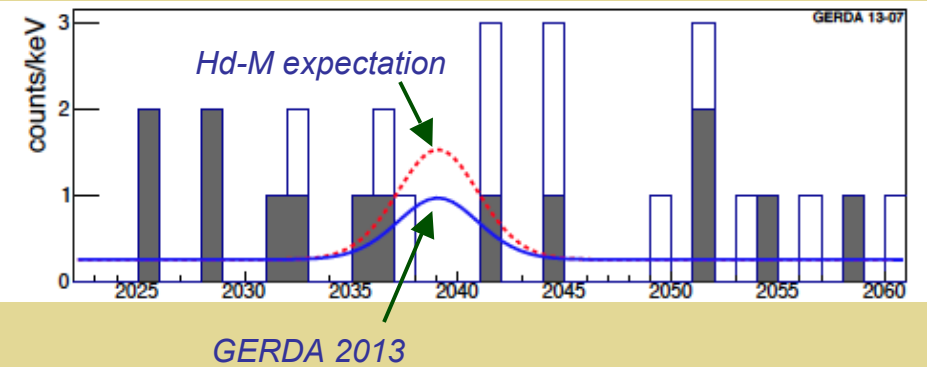
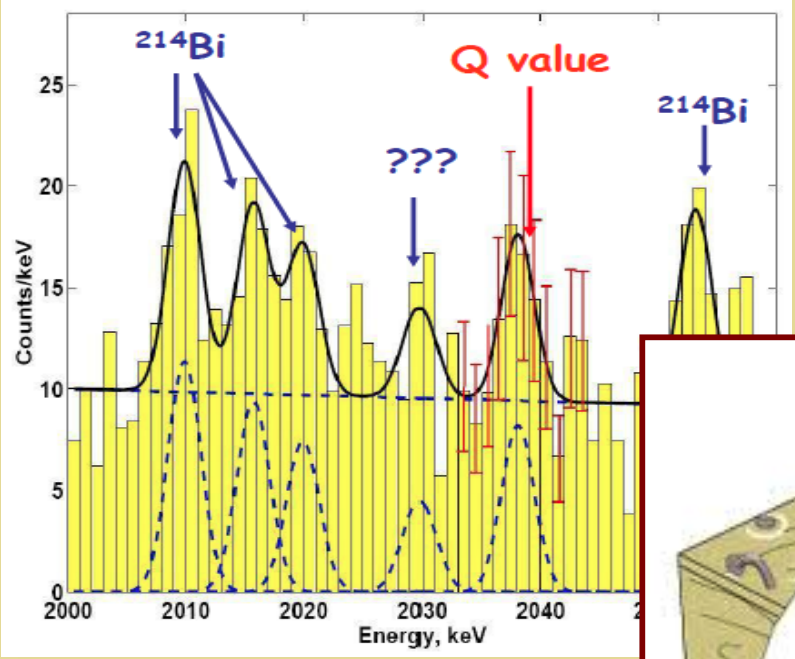


GERDA 2013 (Agostini et al): 90% CL exclusion

Observation ?

Courtesy: G. Gratta



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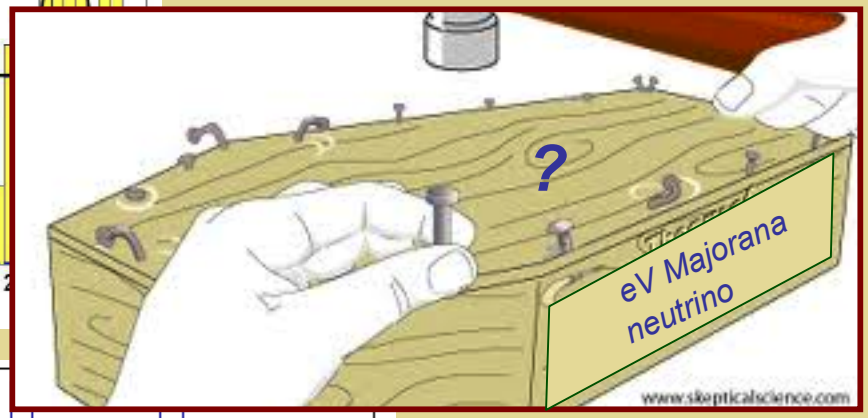

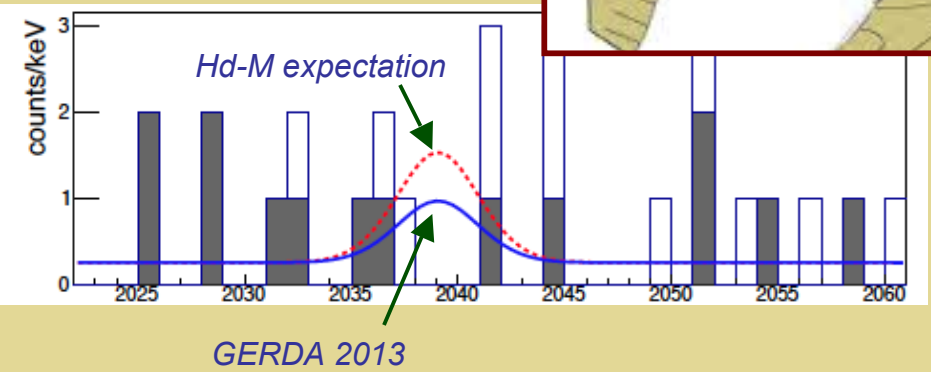

GERDA 2013 (Agostini et al): 90% CL exclusion

Experimental Plans

Isotope	Experiment	Main principle	Fid mass	Status	Lab
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30-60kg	Construction	SUSEL
	Gerda†	Eres,2site tag, LAr shield	34.3 kg	RESULTS '13	G Sasso
	MaGe/GeMa	See above	~1 ton	Planning	?
^{150}Nd	SNO+	Size/shielding	44 kg	Construction	SNOlab
^{82}Se	SuperNEMO‡	Tracking	100 kg	Planning	Canfranc Frejus
^{130}Te*	CUORE	E Res.	204 kg	Construction	G Sasso
^{136}Xe	KamLAND-Zen	Size/shielding	400 kg	RESULTS '13	Kamioka
^{136}Xe	EXO-200	Tracking/Eres	150 kg	RESULTS '12	WIPP
	nEXO	Track/Eres, Ba tag	5 ton	Planning	SNOlab?

Courtesy: G. Gratta

Experimental Plans

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	nEXO	Track/Eres, Ba tag	5 ton	Planning	SNOlab?

ONP: Next generation ("ton scale)" expt

Courtesy: G. Gratta

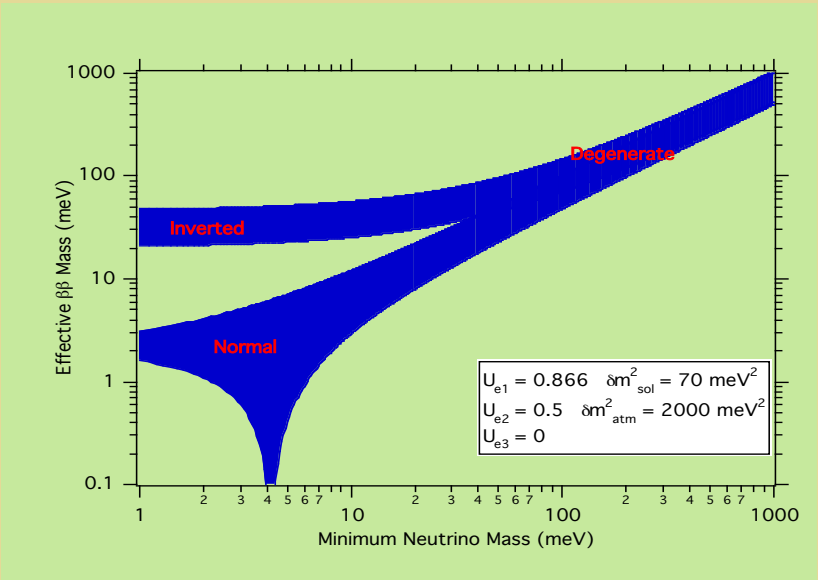
$0\nu\beta\beta$-Decay: Theoretical Interpretation

$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

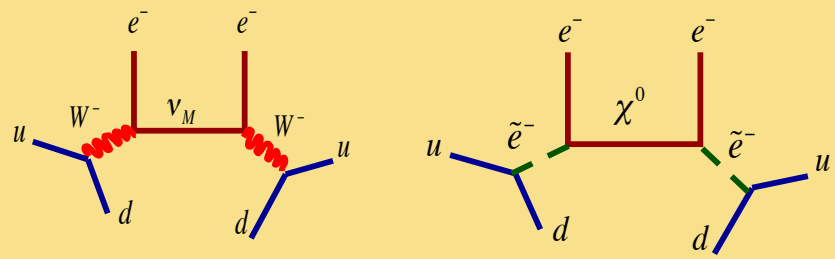
$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana



Theory Challenge: matrix elements+ mechanism

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k \, e^{2i\delta}$$



$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana

Mechanism: does light ν_M exchange dominate ?

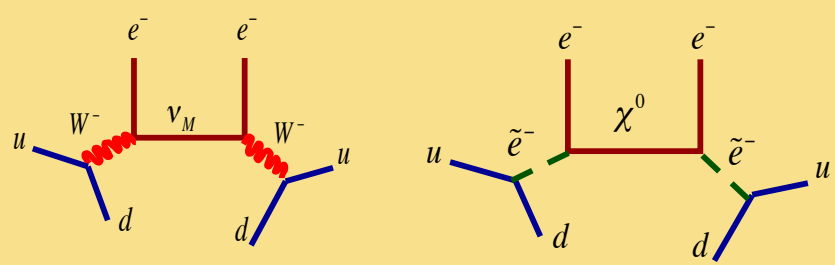
$$\frac{A_{\text{heavy}}}{A_{\text{light}}} \sim \frac{M_W^2\, k_{\text{eff}}^2}{\Lambda^5\, m_\nu^{\text{eff}}}$$

O(1) for Λ ~ TeV

How to calc effects reliably ?
How to disentangle H & L ?

Theory Challenge: matrix elements+ mechanism

$$\langle m_\nu \rangle^{EFF} = \sum_k |U_{ek}|^2 m_k\, e^{2i\delta}$$



$0\nu\beta\beta$-Decay: Nuclear Matrix Elements

$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana

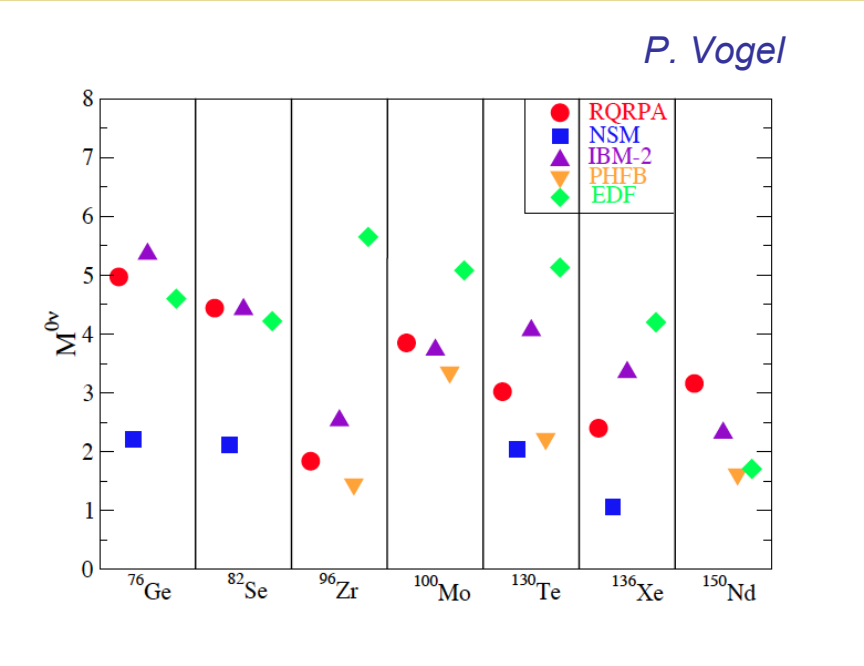
Light ν_M exchange: can we determine m_ν

$$\frac{1}{T_{1/2}} = G^{0\nu}(E,Z)\left|M_{0\nu}\right|^2 \langle m_\nu^{\mathrm{eff}}\rangle^2$$

Shell Model vs. QRPA

Configs near Fermi surface

Levels above Fermi surface



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*

Weak Decays: CKM Unitarity

$$d \rightarrow u\, e^- \bar{\nu}_e$$
$$s \rightarrow u\, e^- \bar{\nu}_e$$
$$b \rightarrow u\, e^- \bar{\nu}_e$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad \text{SM}$$

$$0.9999 \pm 0.0006 \quad \text{Expt}$$

0.9492 ± 0.0005

0.0507 ± 0.0004

0.00001 ± 0.000007

Includes theory error

CKM Unitarity & BSM Physics

$$d \to u\, e^- \bar{\nu}_e$$

$$s \to u\, e^- \bar{\nu}_e$$

$$b \to u\, e^- \bar{\nu}_e$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

β-decay

$$n \to p\, e^- \bar{\nu}_e$$

$$A(Z,N) \to A(Z-1,N+1)\, e^+ \nu_e$$

$$\pi^+ \to \pi^0\, e^+ \nu_e$$

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}| \left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

CKM Unitarity & BSM Physics

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$$s \rightarrow u\, e^- \bar{\nu}_e$$

$$b \rightarrow u\, e^- \bar{\nu}_e$$

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BSM physics

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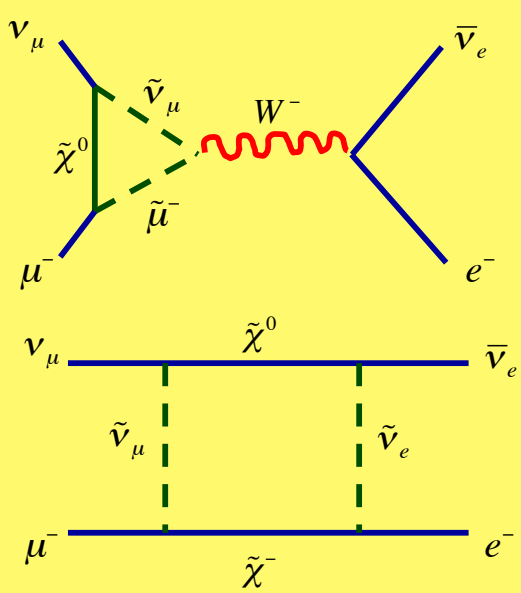

$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.001$$

$+ \cdots$

SUSY

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

BSM physics

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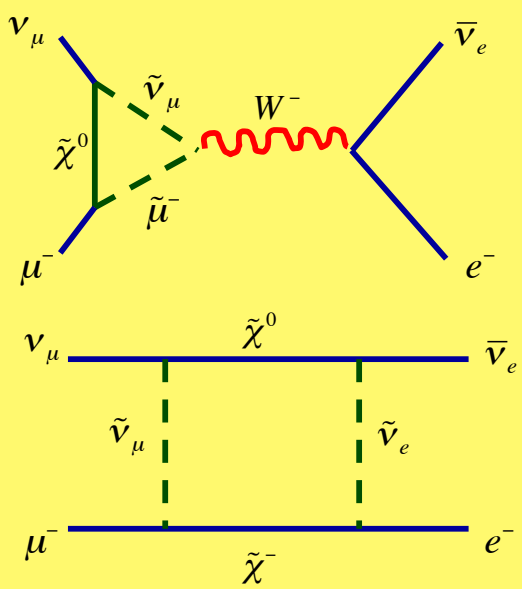

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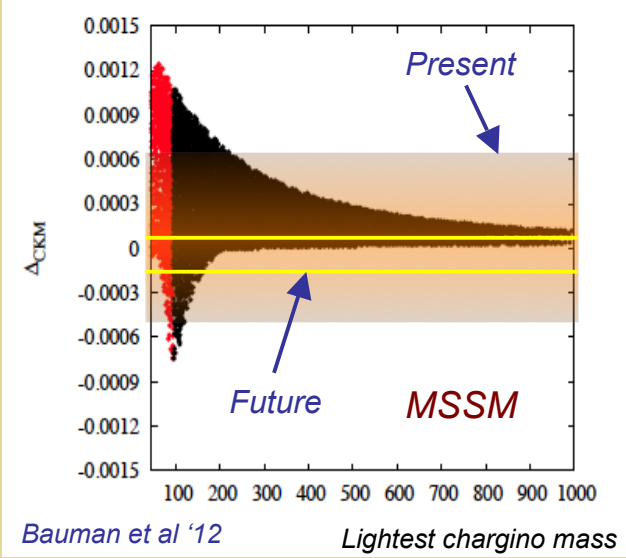
SUSY

CKM Unitarity



Next generation: ~ 10^{-4} precision

Worldwide Radioactivity

$$d \rightarrow u\, e^{-}\, \bar{\nu}_e$$

$$s \rightarrow u\, e^{-}\, \bar{\nu}_e$$

$$b \rightarrow u\, e^{-}\, \bar{\nu}_e$$

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★ *neutron*

★ *nuclei*

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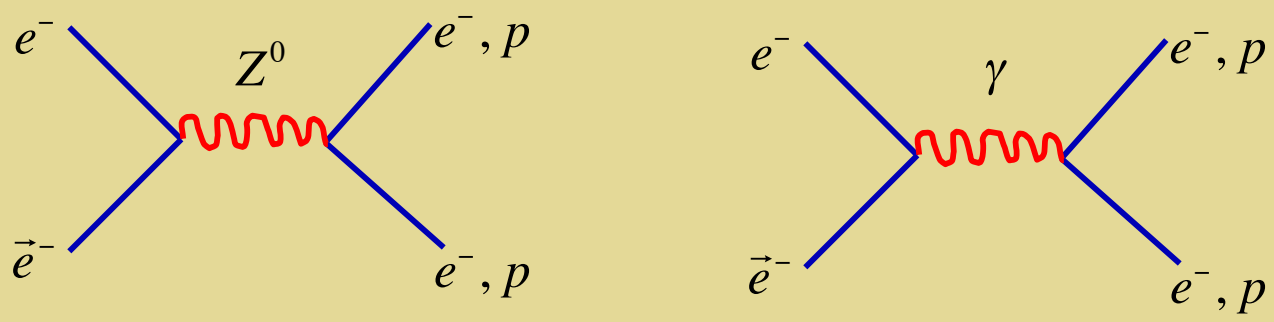
Parity-Violation & Weak Charges



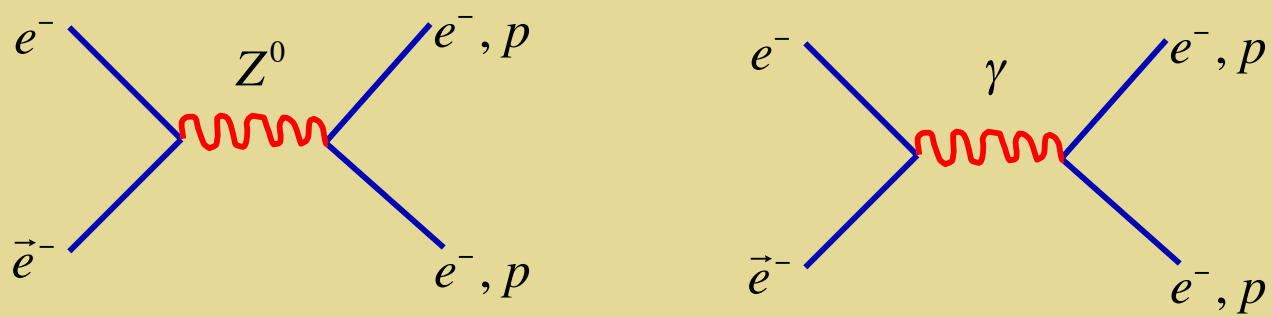
Parity-Violating electron scattering

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

Atomic parity-violation

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

Parity-Violation & Weak Charges



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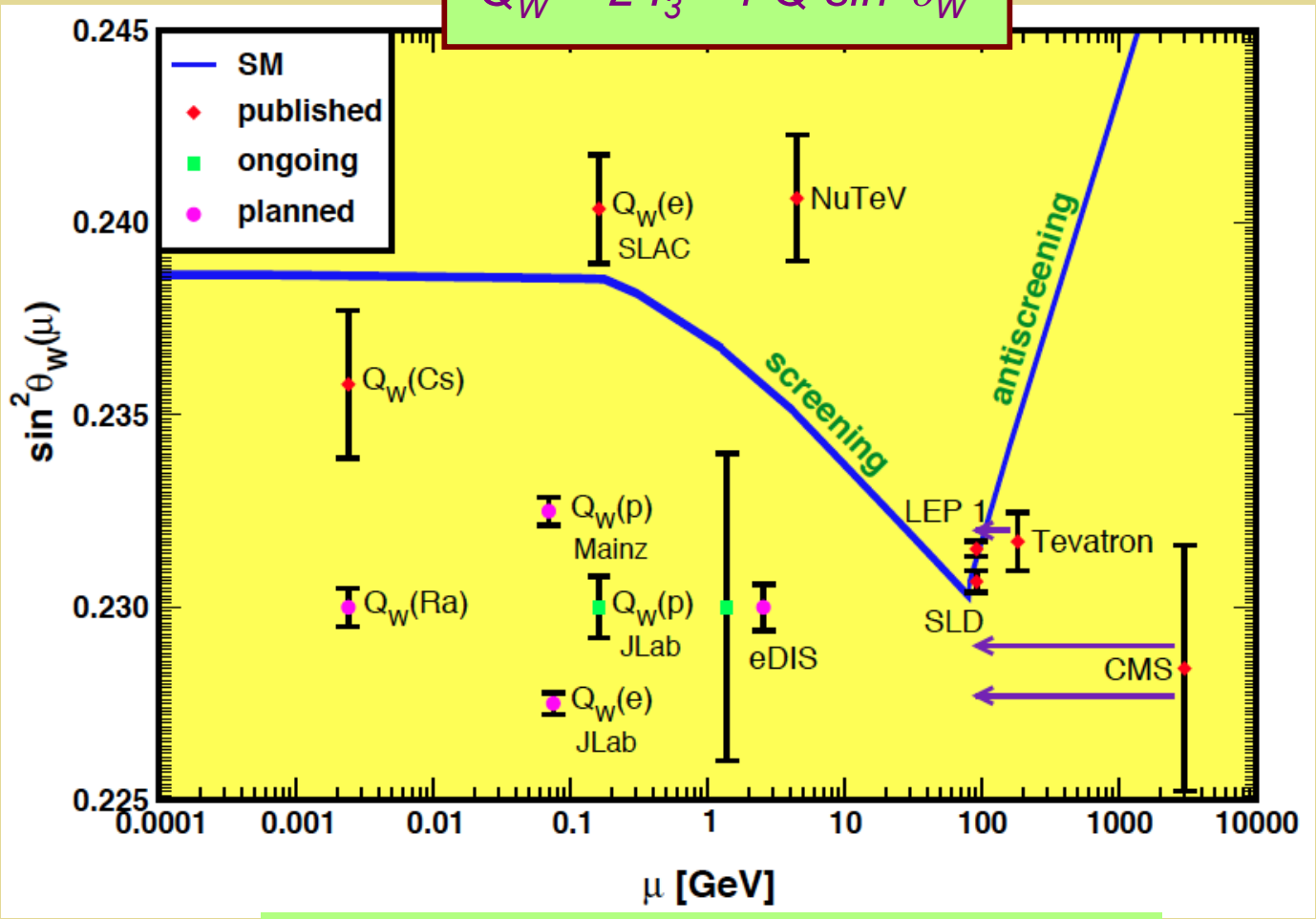
Atomic parity-violation

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

Weak Charges & Weak Mixing: SM

Courtesy J. Erler

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

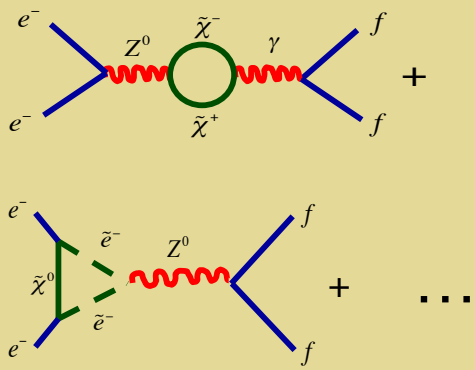


Scale-dependence of Weak Mixing

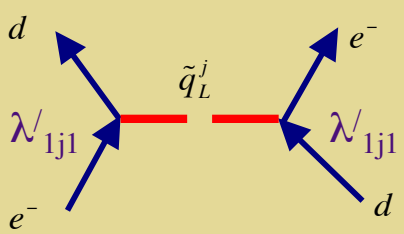
Marciano & Czarnecki; Erler & R-M

Deviations: BSM "Diagnostic"

SUSY

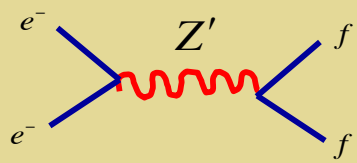


Radiative Corrections

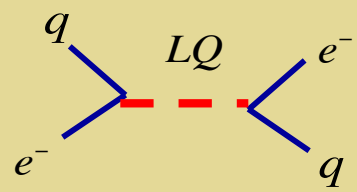


RPV

Z′ Bosons



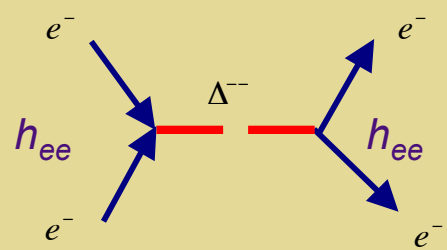
Leptoquarks



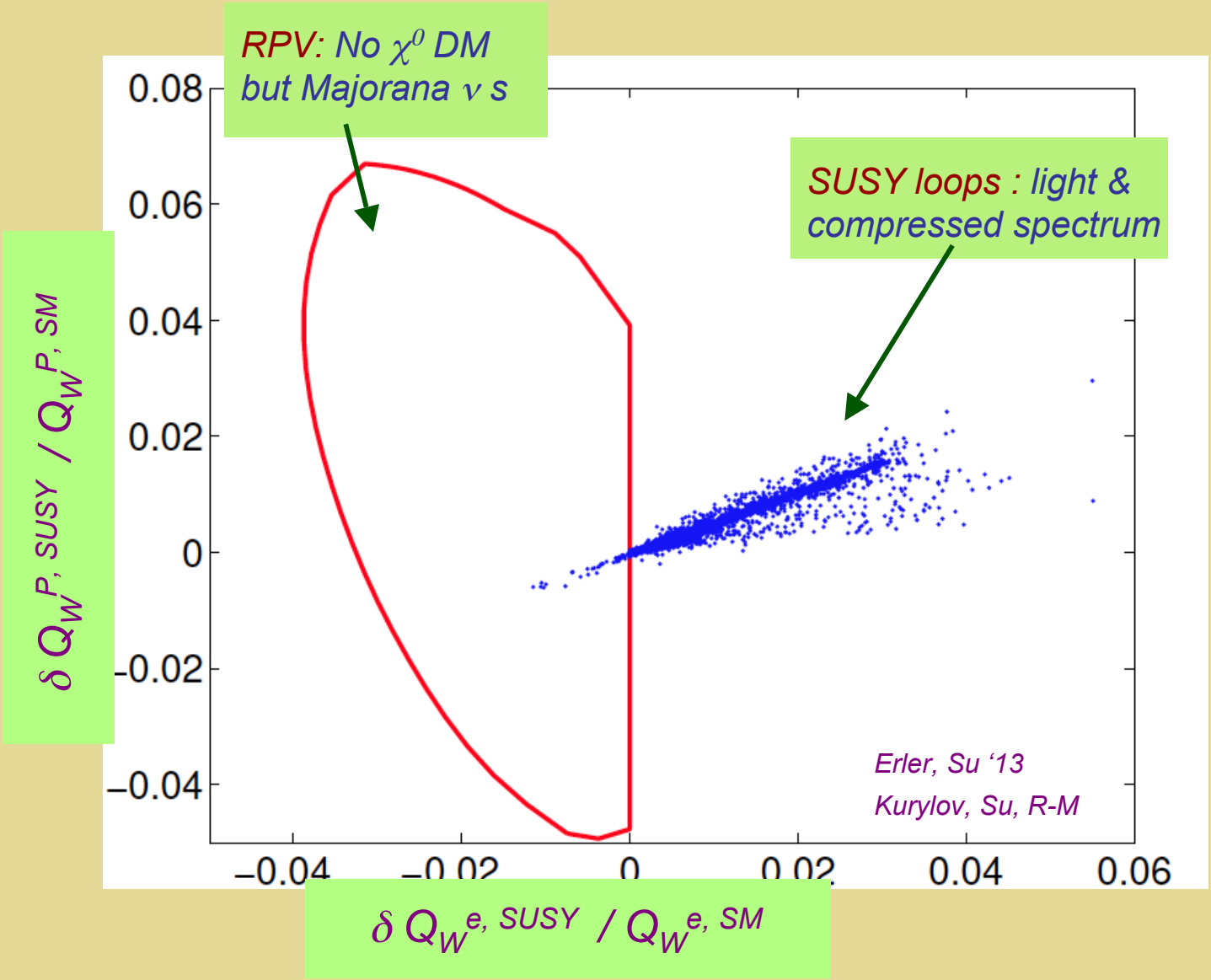
Semi-leptonic only

Doubly Charged Scalars

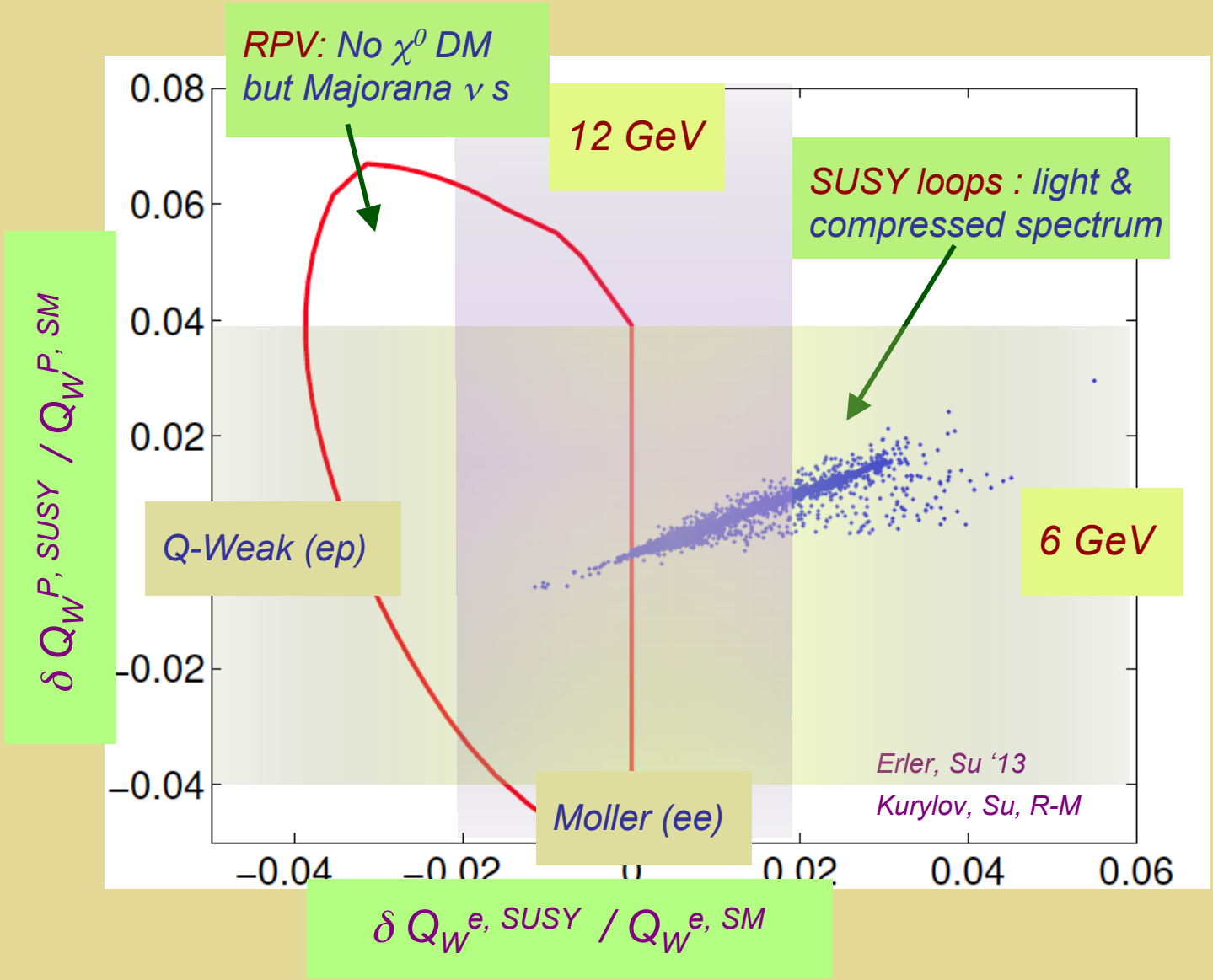
Moller only



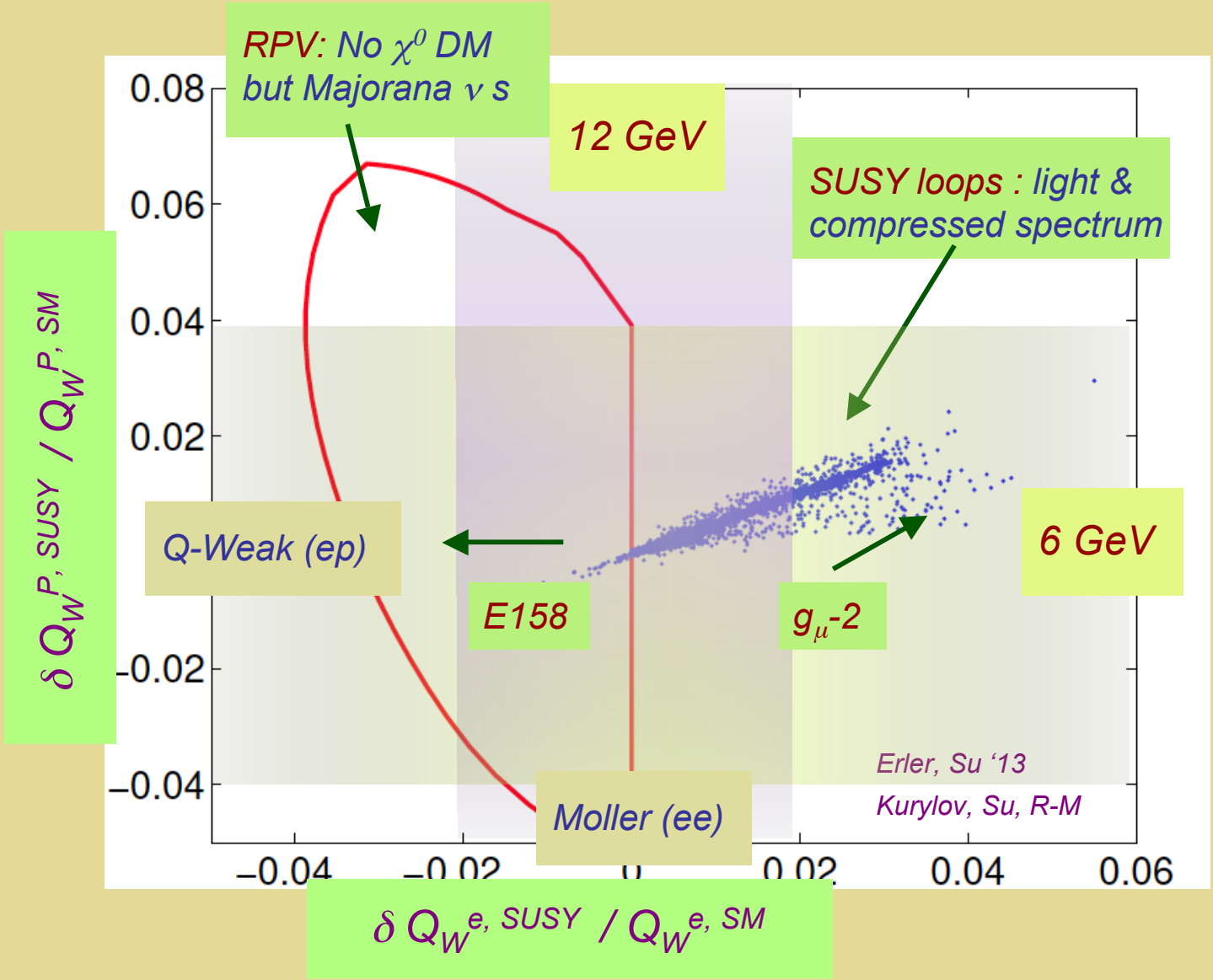
PV Electron Scattering: Diagnostic Tool



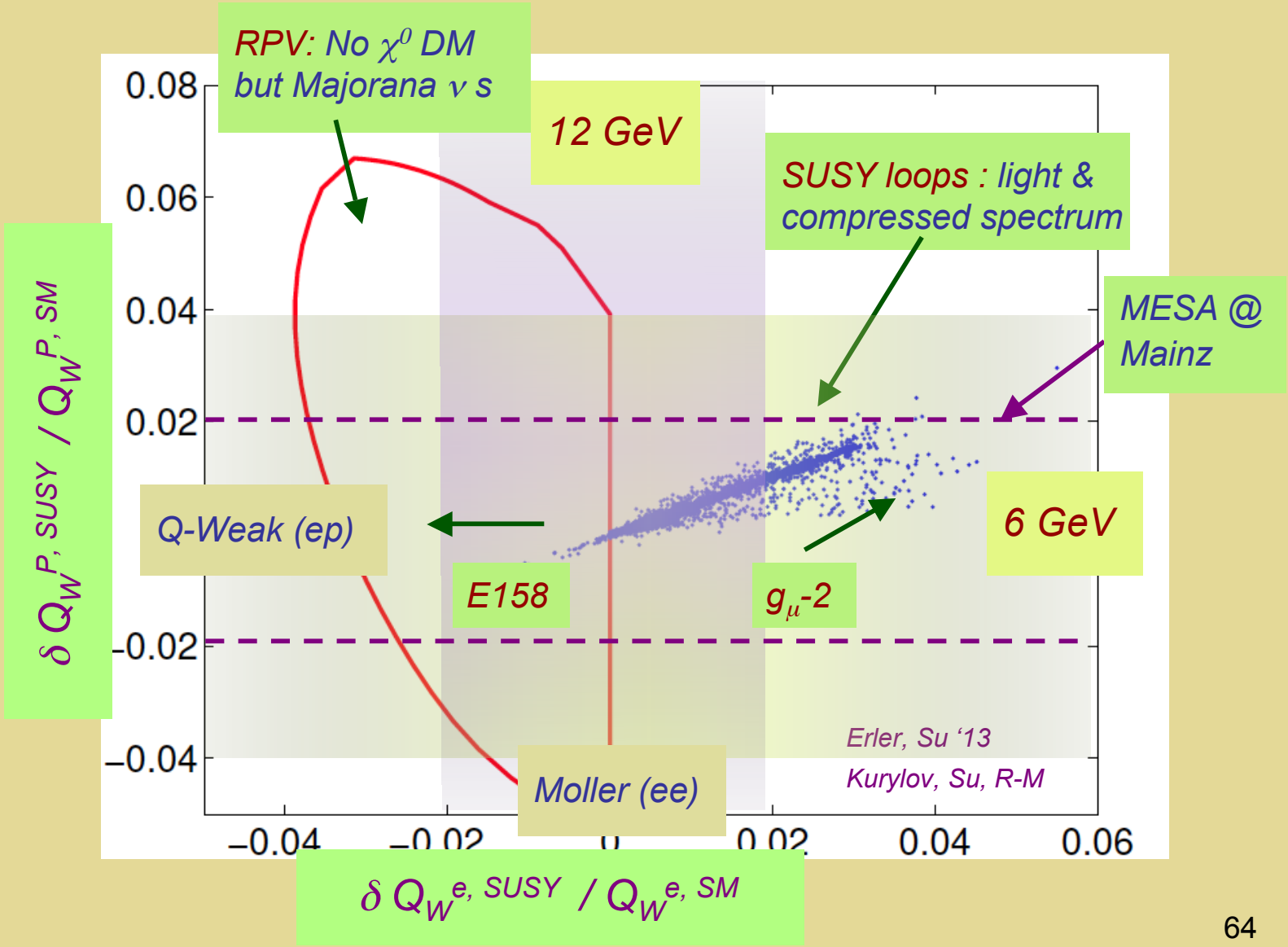
PV Electron Scattering: Diagnostic Tool



PV Electron Scattering: Diagnostic Tool



PV Electron Scattering: Diagnostic Tool



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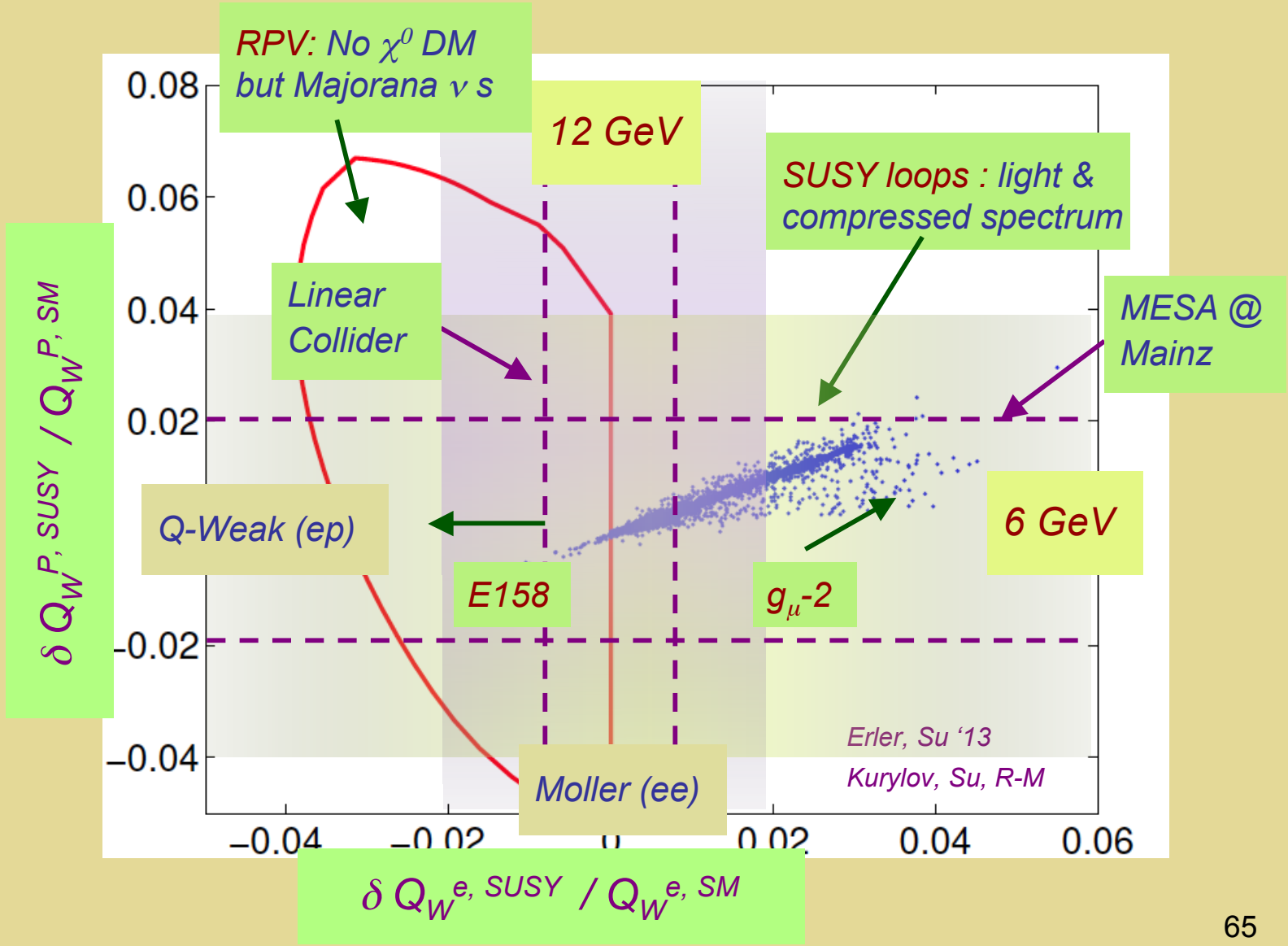


Other Important Efforts

Not covered due to time: see back up slides

- *Muon g-2*
- *Charged lepton flavor violation*
- *Pion leptonic decays*
- *….*

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, nature of ν, BSM diagnostic)*
- *Rich opportunities for future interplay between NP and HEP communities*

Thanks !

- *DPF, DNP, CSS Organizers*
- *T. Chupp, J. Erler, G. Gratta, K. Heeger, K. Kumar, P. Vogel, J. Wilkerson*

Further reading:

- *EDM: 1303.2371, hep-ph/0504231*
- *$0\nu\beta\beta$ decay: 1303.4907*
- *β decay: 1303.6953*
- *PV: 1302.6263, 1303.5522*
- *Project X: 1306.5009*

Talks @ CSS:

- *PVES: S Su*
- *EDM: B. Casey*
- *$0\nu\beta\beta$: K. Heeger*
- *…*

Back Up Slides

BSM Mass Scale Sensitivity

$$\text{BSM Signal} \sim (\upsilon / \Lambda)^2$$

EDM: $\Delta\nu$

$0\nu\beta\beta$: Γ light ν

EWPO: SM-BSM interference

$$\text{BSM Signal} \sim (\upsilon / \Lambda)^4$$

CLFV Γ

$$\text{BSM Signal} \sim (\upsilon / \Lambda)^{10}$$

$0\nu\beta\beta$: Γ TeV LNV

EDM

EDM Experimental Status & Plans

System	Present 90% C.L.	Sensitivity goal[b]	Group
	Limit (e fm)[a]		
Cs	1.2×10^{-10}		[169]
Tl	9.5×10^{-12}		[170]
YbF[d]	10.5×10^{-15}		[152]
ThO[d]	–	$10^{-15} \rightarrow 10^{-17}$	
n	2.7×10^{-13}		[171]
n		$(1-3) \times 10^{-14}$	CryoEDM
n		4×10^{-15}	nEDM/SNS
n		5×10^{-14}	nEDM/PSI
n		5×10^{-15}	n2EDM/PSI
n		2×10^{-15}	nedm/FRM-II Munich
n		$10^{-14} - 10^{-15}$	TRIUMF
p		10^{-16}	srEDM
^{199}Hg	2.6×10^{-16}	$(2.6-5) \times 10^{-17}$	[172]
^{225}Ra		$(10-100) \times 10^{-15}$	Argonne
$^{221/223}$Rn		1.3×10^{-14}	TRIUMF
$^{221/223}$Rn		2×10^{-15}	FRIB
^{129}Xe	5.5×10^{-14}		[173]

Engel, R-M, van Kolck, 1303.2371
*PPNP **71** (2013) 21*

BSM Origins

EDM: γff
CEDM: gff

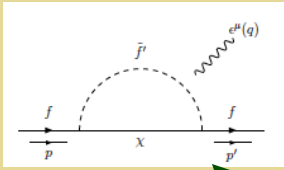
Weinberg ggg:

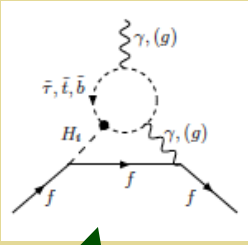
Four fermion

udHH

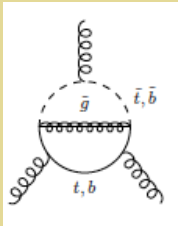
BSM Origins

EDM: γff
CEDM: gff



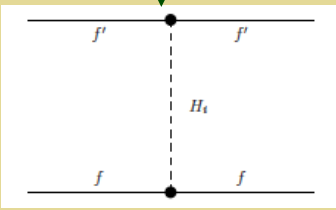


Weinberg ggg:



MSSM

Four fermion



udHH

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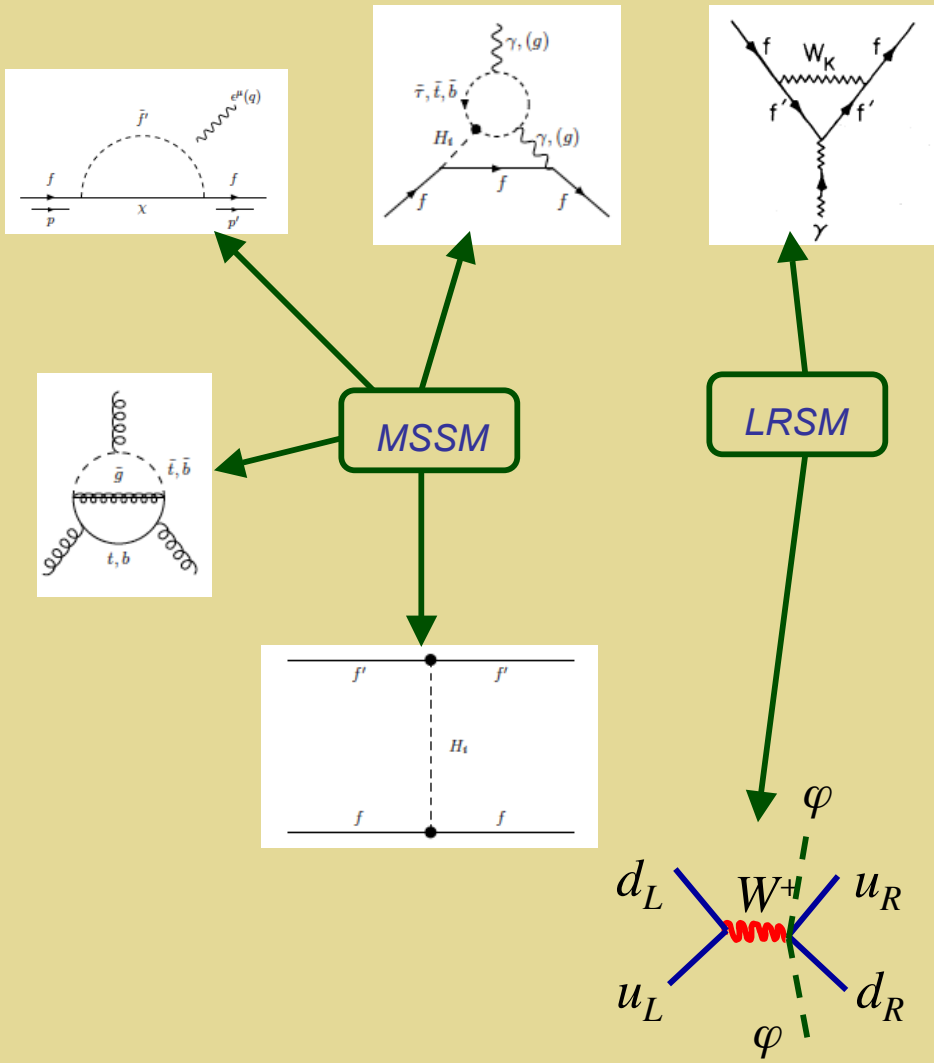

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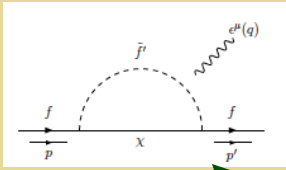
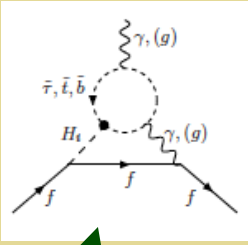
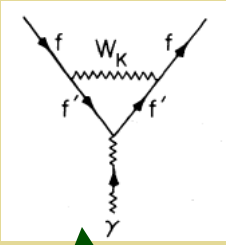
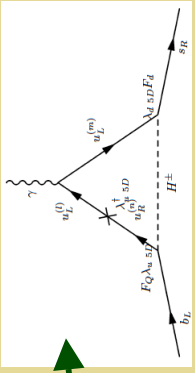
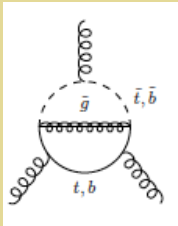






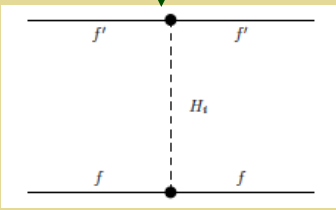


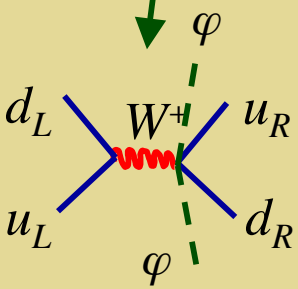


MSSM

LRSM

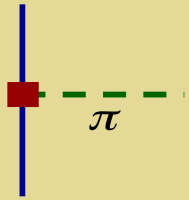
RS





Hadronic CPV: Nucleons, Nuclei, Atoms

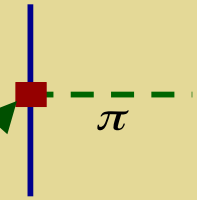
PVTV πN interaction



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

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction



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

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

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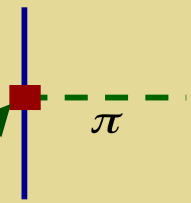

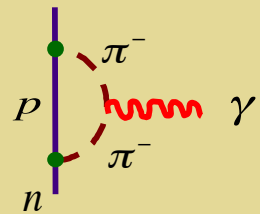

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Nucleon EDM

+ quark EDM

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

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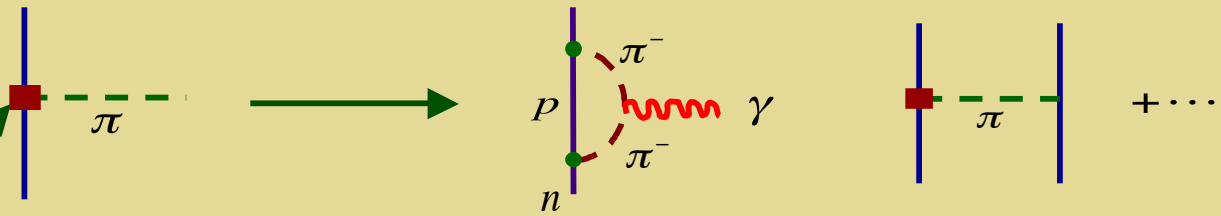


- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

Nucleon EDM

Nuclear EDM & Schiff moment

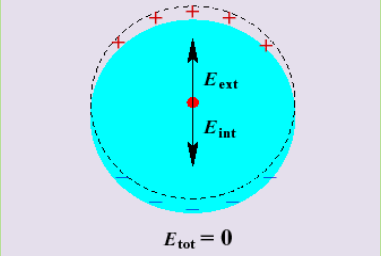
+ quark EDM

+ ~~quark EDM~~

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

Diamagnetic Systems: Schiff Moments

Schiff Screening



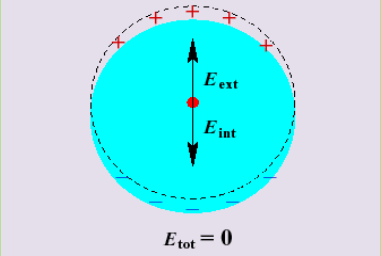
Atomic effect from nuclear finite size: Schiff moment

Neutral atoms: nuclear EDM invisible to external probe

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems: Schiff Moments

Schiff Screening



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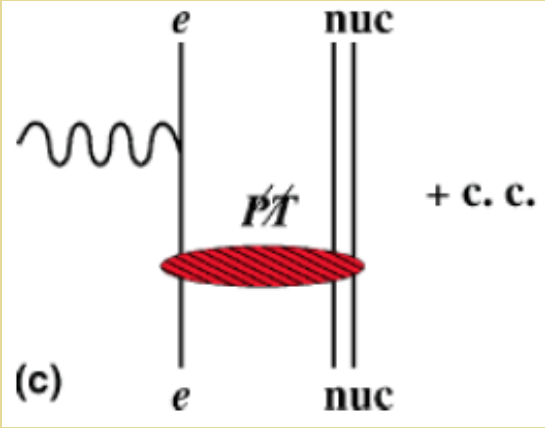
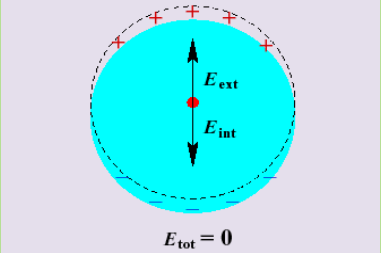


Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems: Schiff Moments

Schiff Screening



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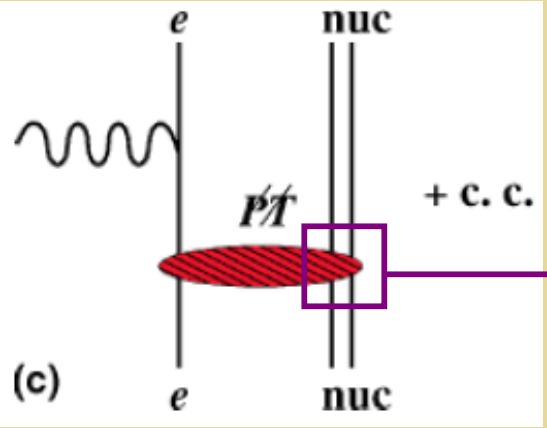


Schiff moment, MQM,…

Nuclear Schiff Moment

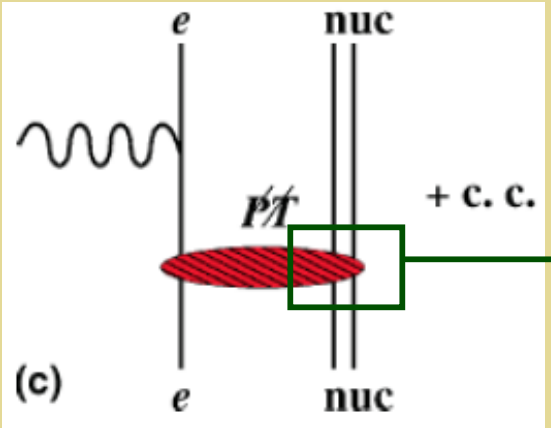
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

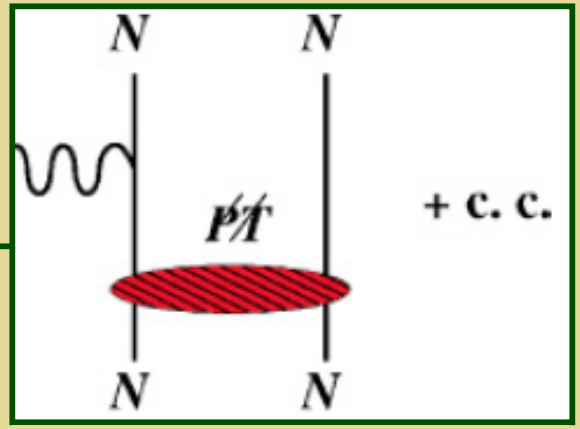
$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements





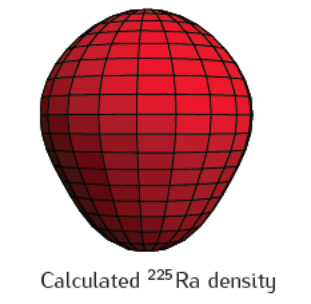
Schiff moment, MQM,…

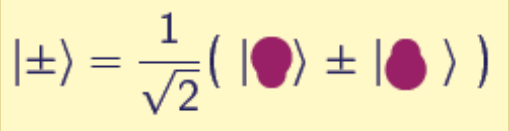
Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

EDMs of diamagnetic atoms (^{199}Hg)

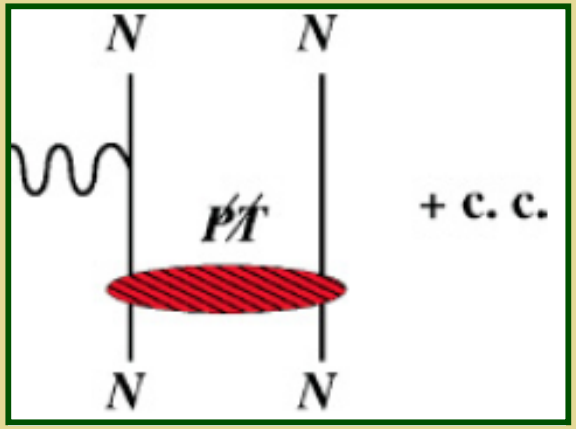
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation





Opposite parity states mixed by H^{TVPV}



Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

"Nuclear amplifier"

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel

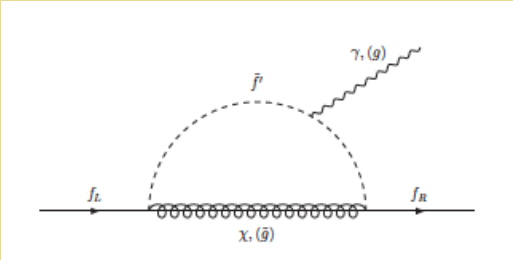
Hadronic Matrix Elements: QCD Theory

Param		Coeff	Best value[a]	Range
$\bar{\theta}$		α_n	0.002	(0.0005–0.004)
		α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	*(CEDM)*	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
		β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\mathrm{Im}\, C_{q\gamma}$	*(EDM)*	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2-0.6) \times 10^{-3}$
		$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8-2.4) \times 10^{-3}$
$C_{\tilde{G}}$	*(3 G)*	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2-40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	*(qqH)*	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1-10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	*(4q)*	β_n^{quqd}	40×10^{-7}	$(10-80) \times 10^{-7}$

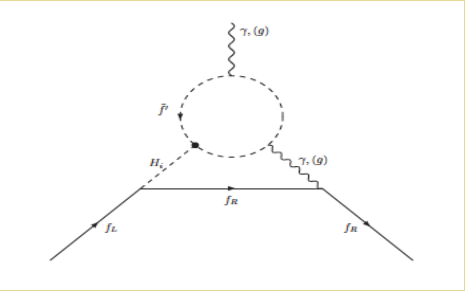
Neutron EDM sensitivity to CPV sources

Engel, R-M, van Kolck, 1303.2371
*PPNP **71** (2013) 21*

EDM Probes: EWB Implications



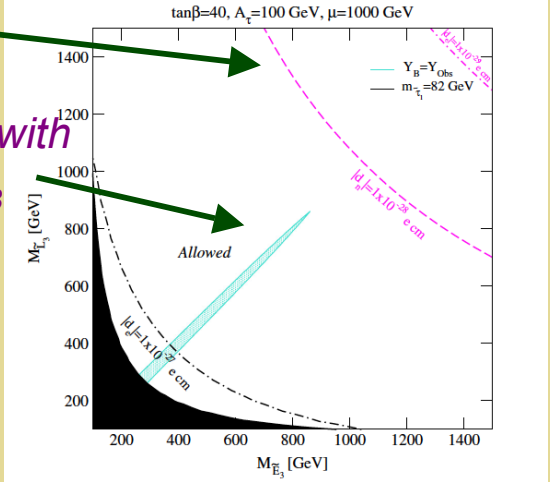
Light staus: LHC consistent & suppress 1-loop EDMs



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

Next gen d_n

Compatible with observed Y_B



Viable EWB & CPV:

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

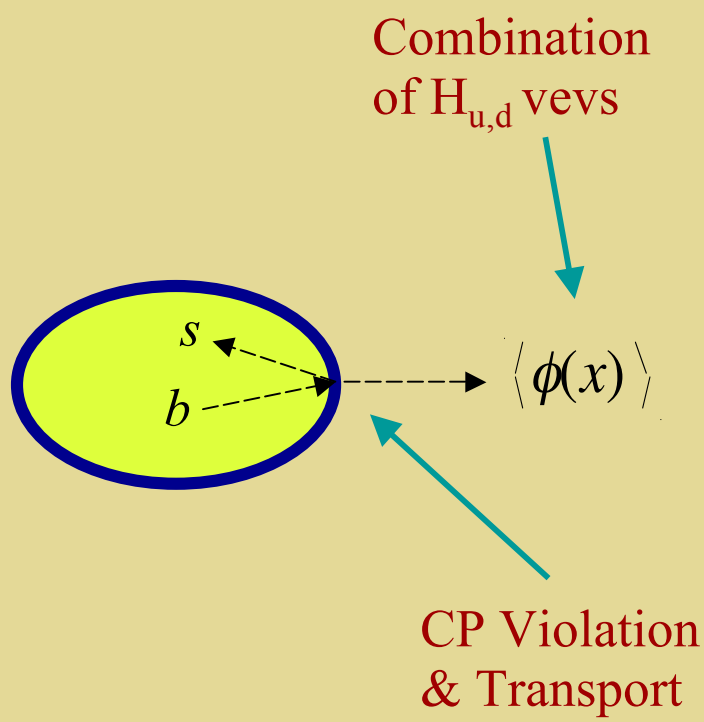
Kozaczuk, Wainwright, Profumo, RM

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



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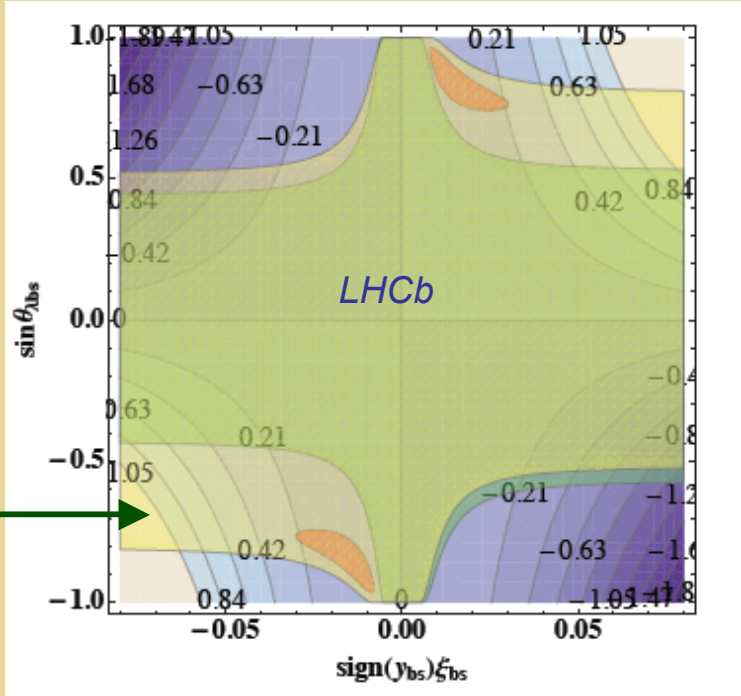
Flavored CPV & EWB

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



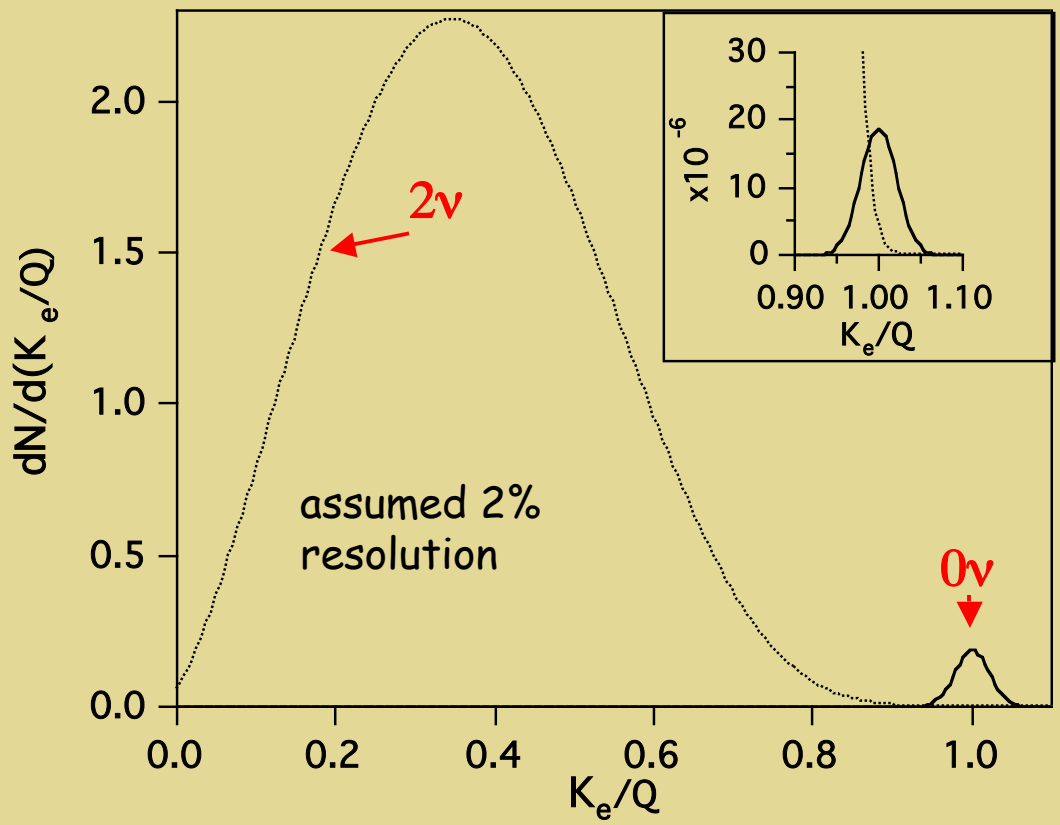
Viable EWB & CPV:

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

Largely unexplored: flavored EWB

DBD

$0\nu\beta\beta$ Decay vs. $2\nu\beta\beta$ Decay



ratio
$1:10^6$

ratio
1:100

Courtesy: P. Vogel

$0\nu\beta\beta$-Decay: Nuclear Matrix Elements

$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana

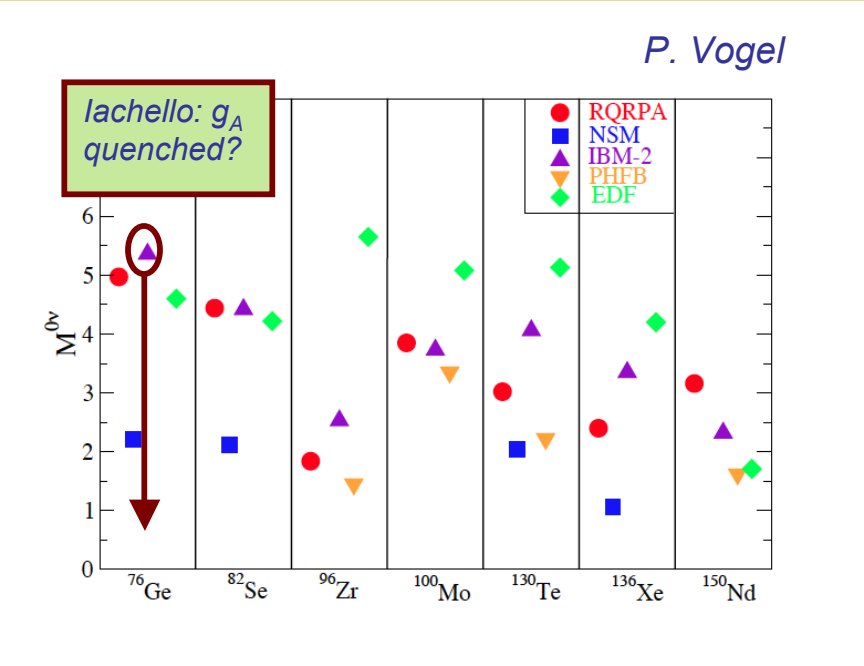
Light ν_M exchange: can we determine m_ν

$$\frac{1}{T_{1/2}} = G^{0\nu}(E,Z)\left|M_{0\nu}\right|^2 \langle m_\nu^{\mathrm{eff}}\rangle^2$$

Shell Model vs. QRPA

Configs near Fermi surface

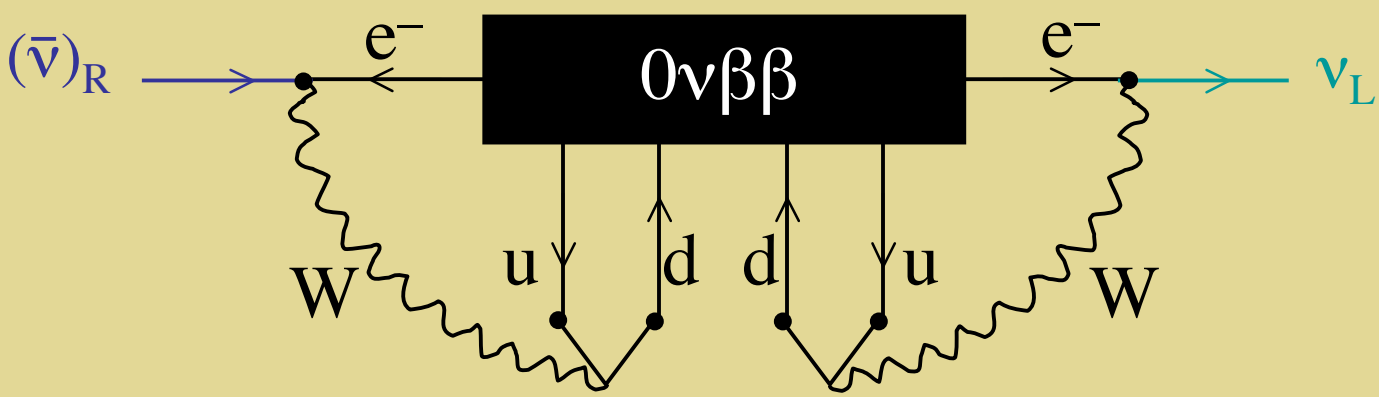
Levels above Fermi surface



$0\nu\beta\beta$ & Lepton Number Violation

Whatever processes cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

Schechter and Valle,82

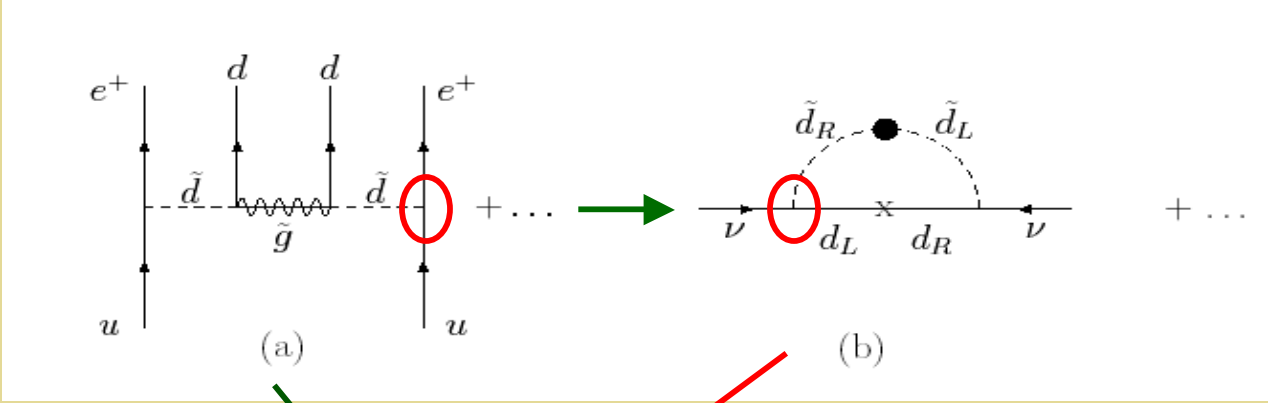


By adding only Standard model interactions we obtain

$(\bar{\nu})_R \rightarrow (\nu)_L$ ***Majorana mass term***

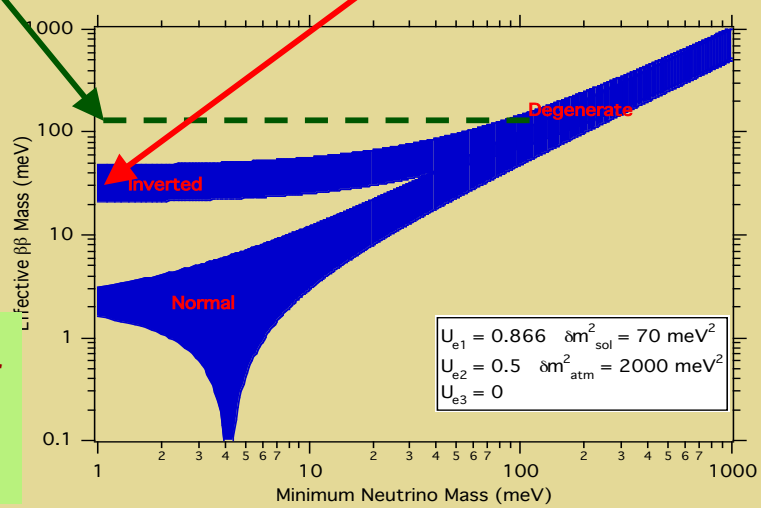
Courtesy: P. Vogel

$0\nu\beta\beta$-Decay: Interpretation



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

Loop contribution to m_ν of inverted hierarchy scale



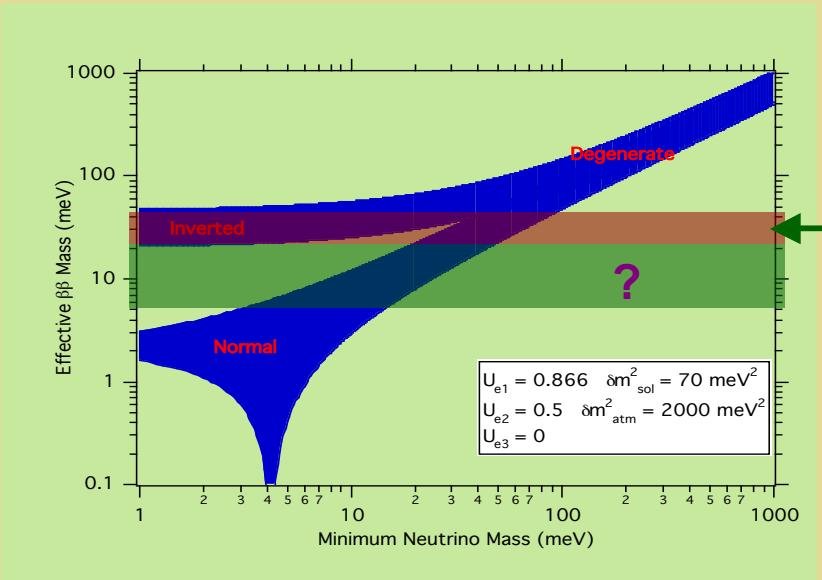
Next Generation Reach

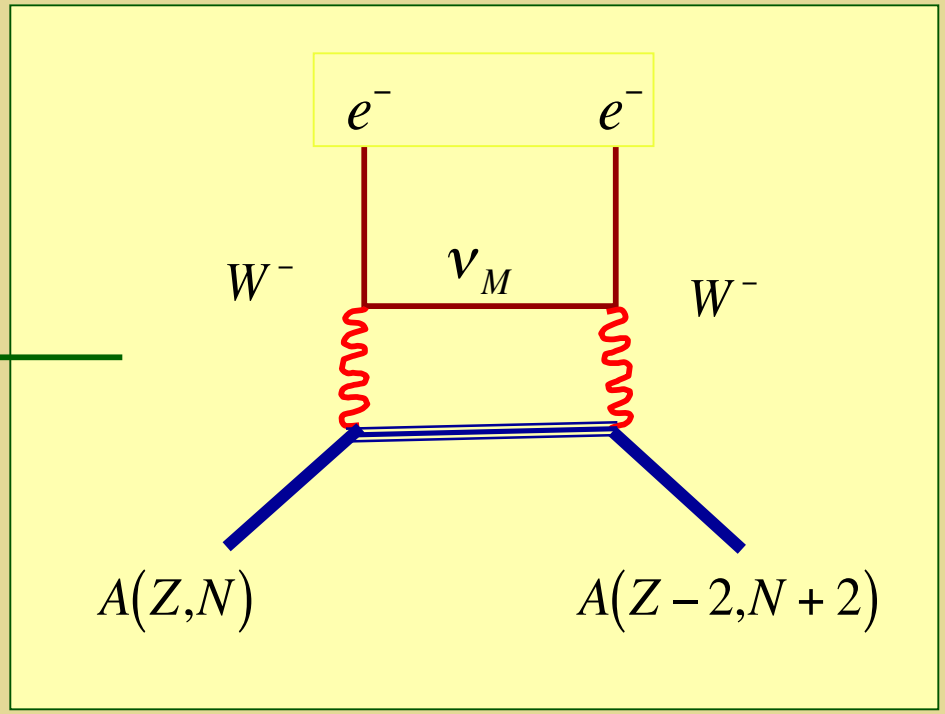
$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana





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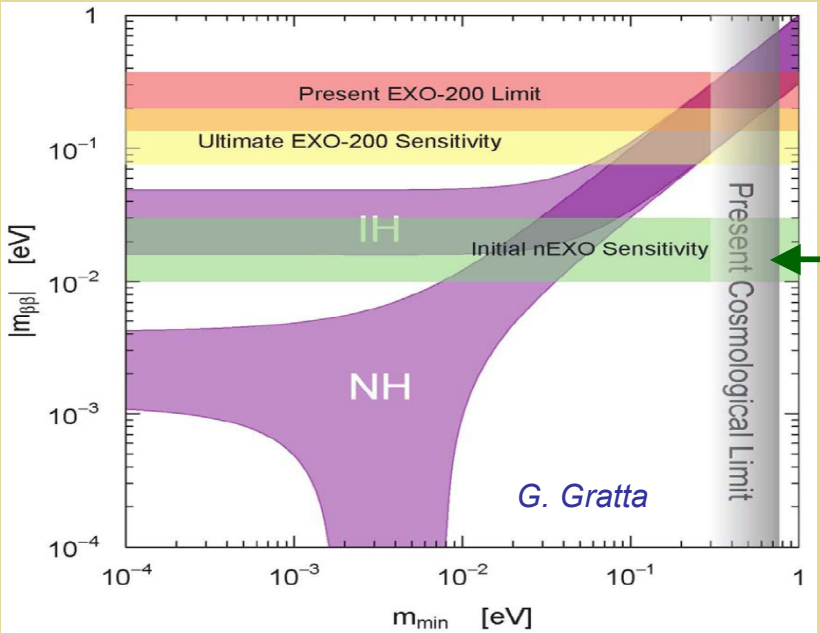

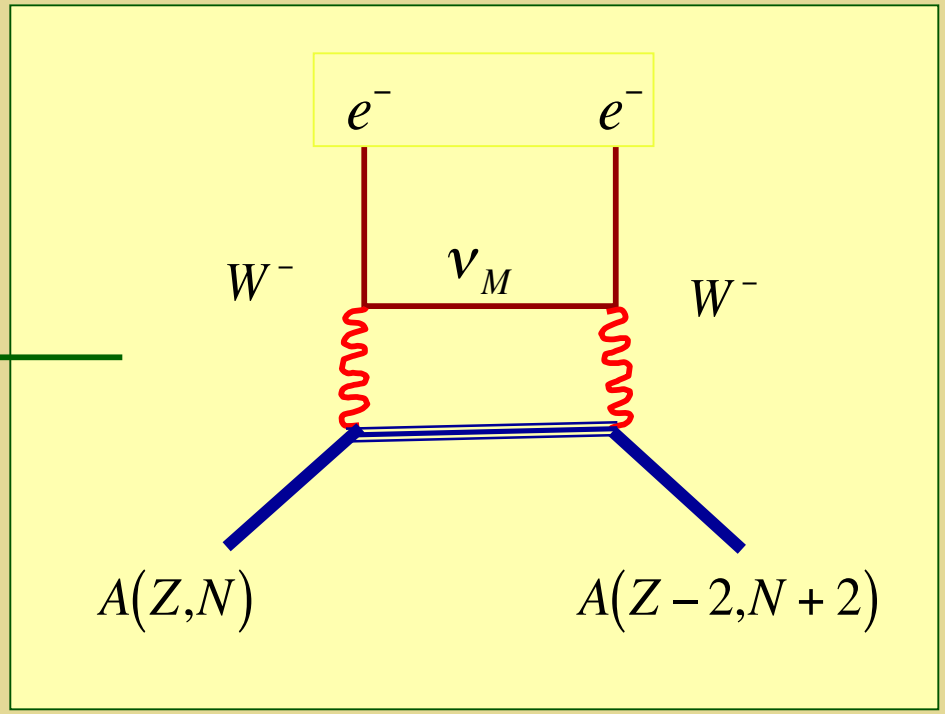

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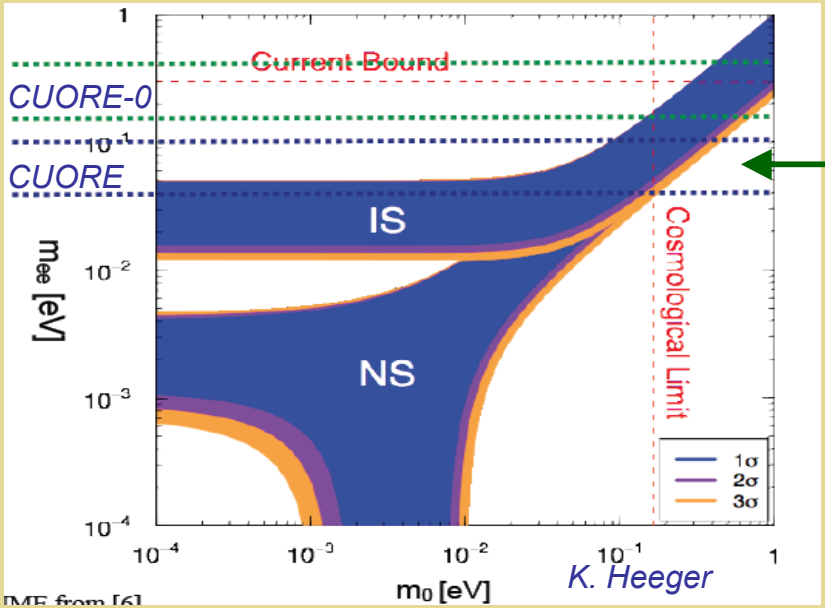
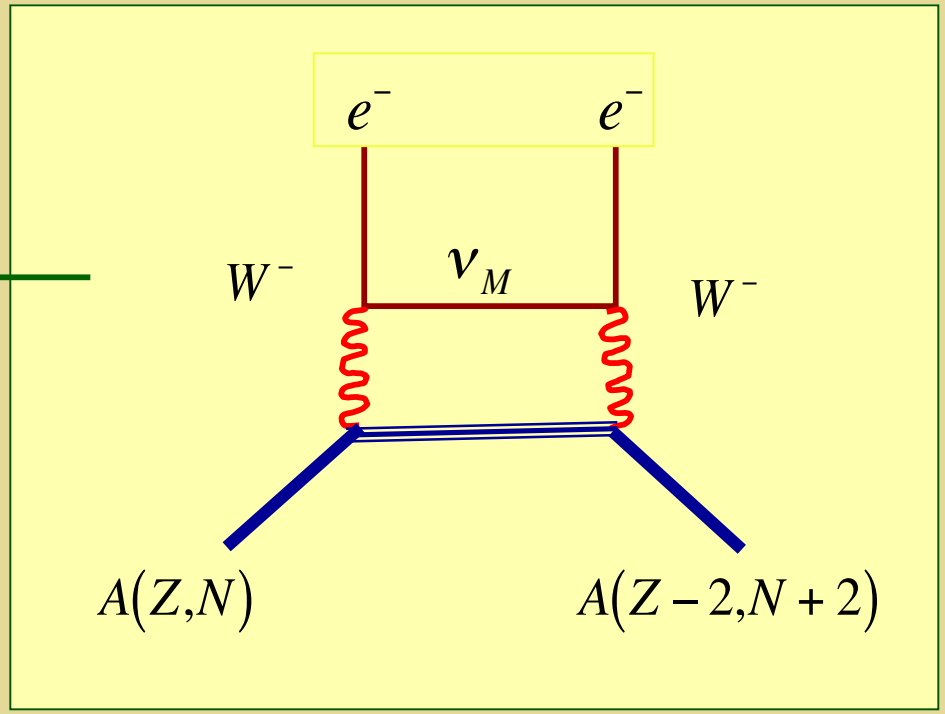




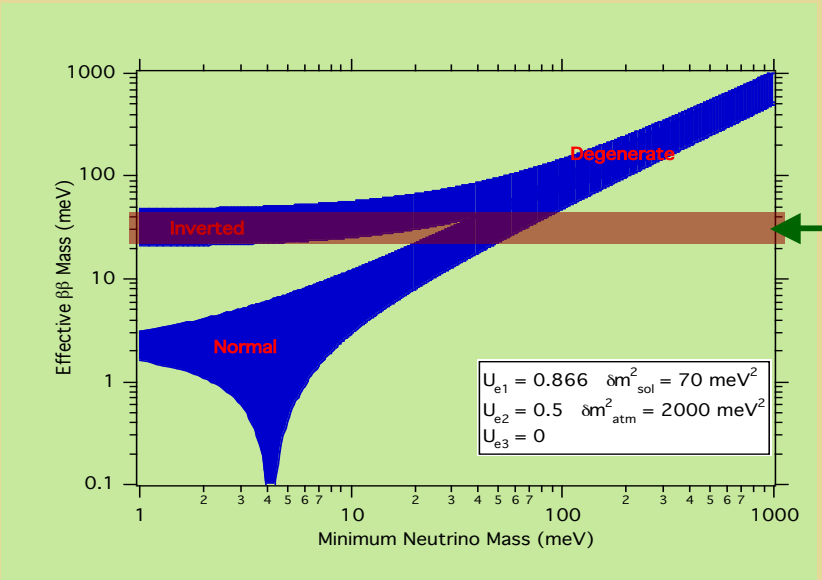
$0\nu\beta\beta$-Decay: LNV? Mass Term?

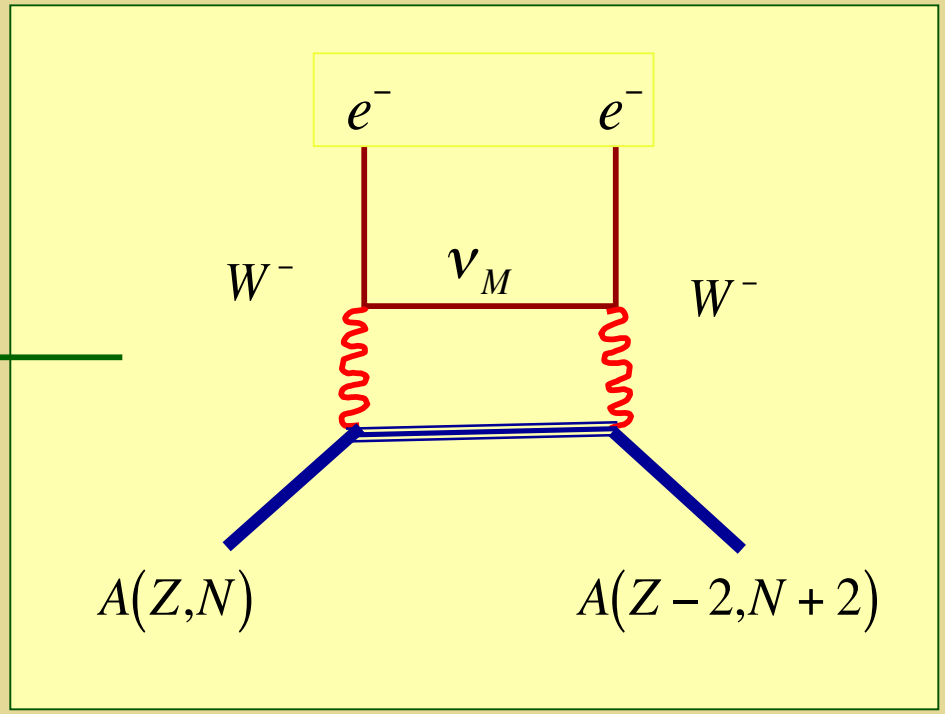
$$\mathcal{L}_{mass} = y\bar{L}\tilde{H}\nu_R + h.c.$$

Dirac Neutrinos ?

$$\mathcal{L}_{mass} = \frac{y}{\Lambda}\bar{L}^c\tilde{H}\tilde{H}^T L$$

Majorana





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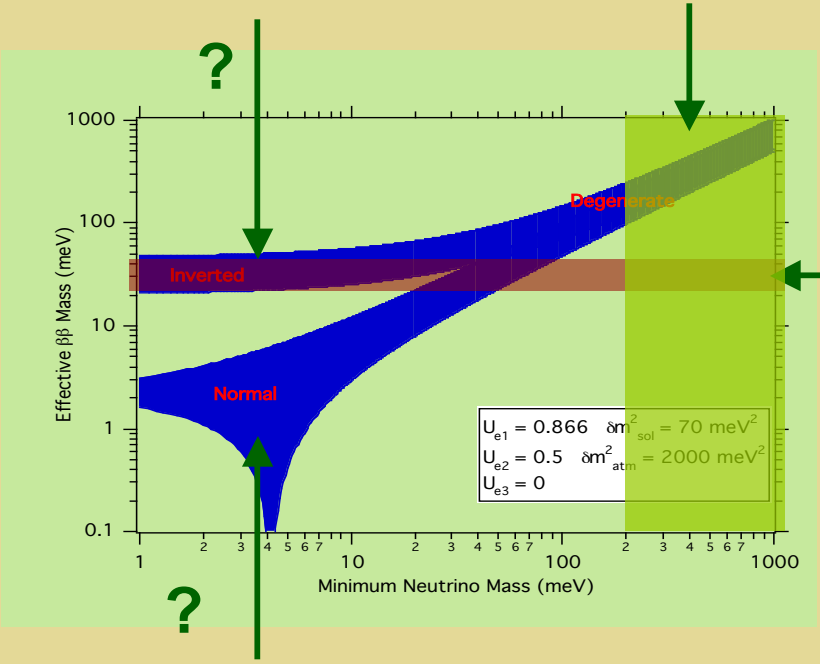
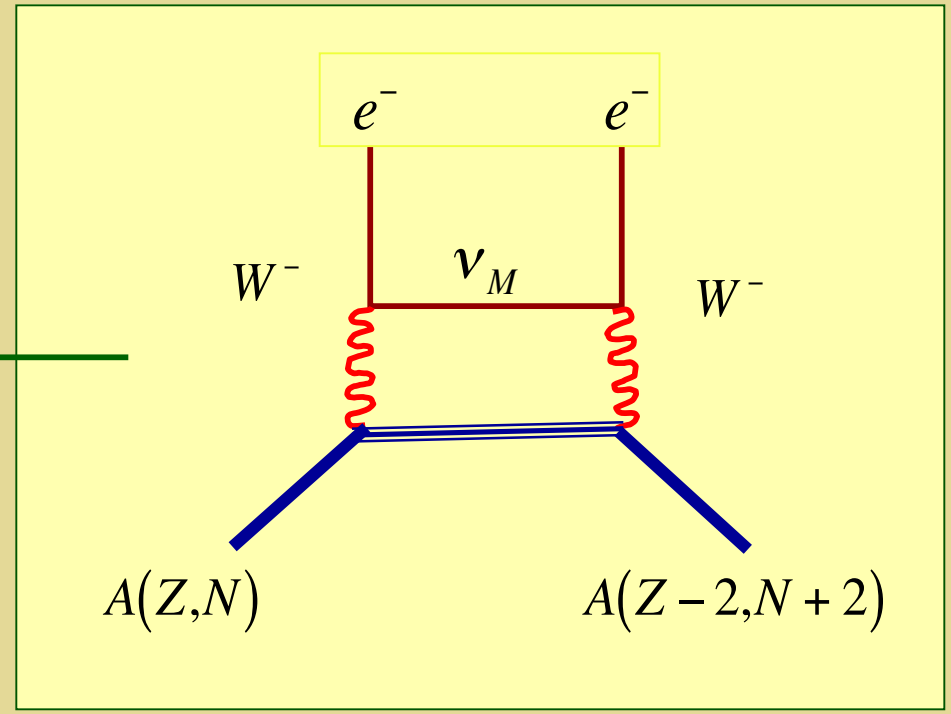
Majorana

Long baseline

β-decay





$0\nu\beta\beta$-Decay: LNV? Mass Term?

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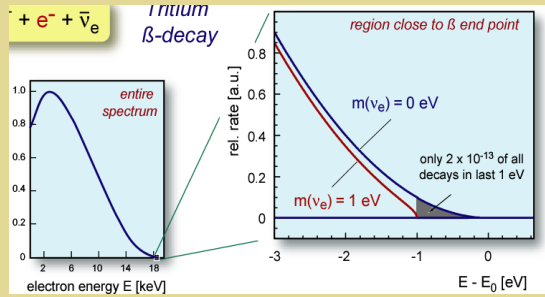
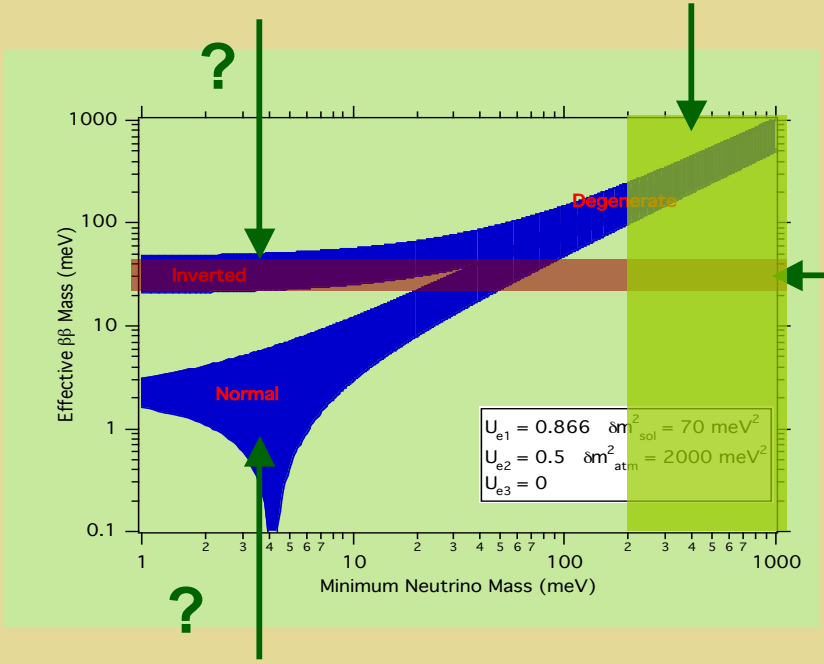
Dirac

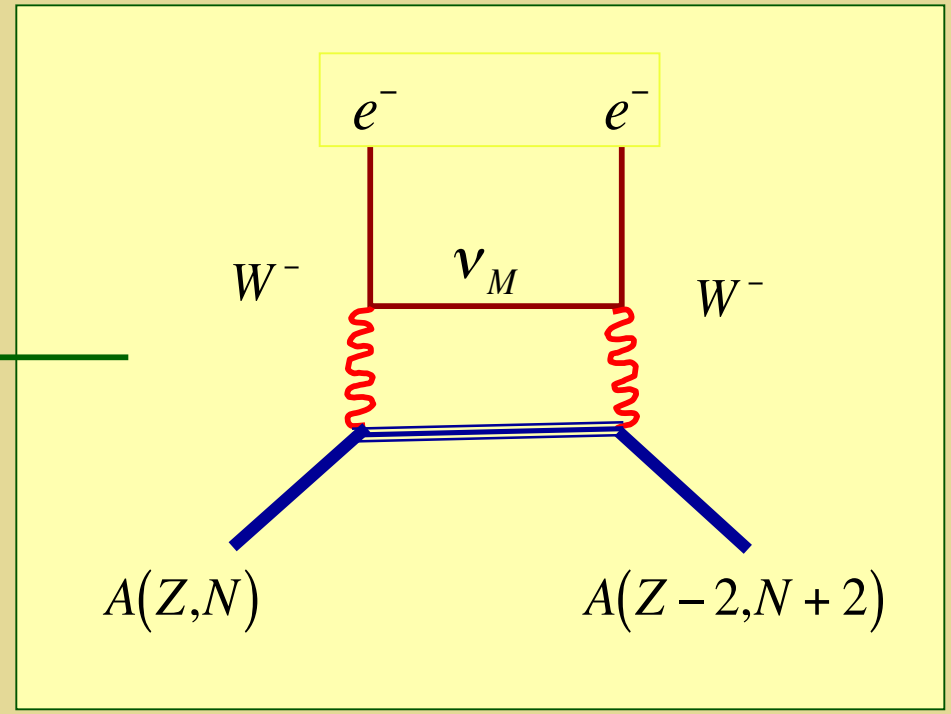


KATRIN

Long baseline

β-decay

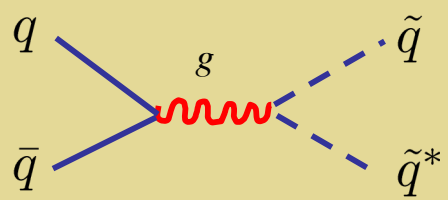




Precision Tests

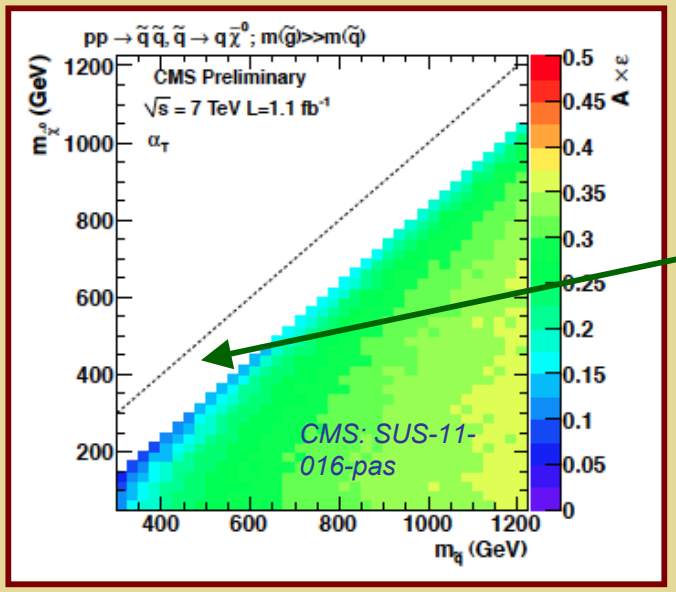
LHC BSM Challenge: Light but Compressed ?

Pair production of squarks



$$\tilde{q} \rightarrow q + \tilde{\chi}_1^0$$

Final state: 2j + $\not{E}_T$



No exclusion yet (jets analysis): is sub-TeV SUSY hiding here?

If so, will it show up in precision tests ?

LHC BSM Challenge: Light but Compressed ?

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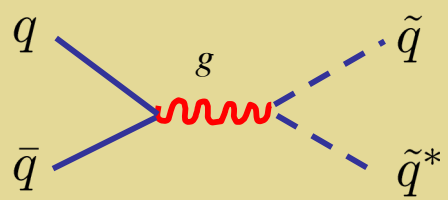

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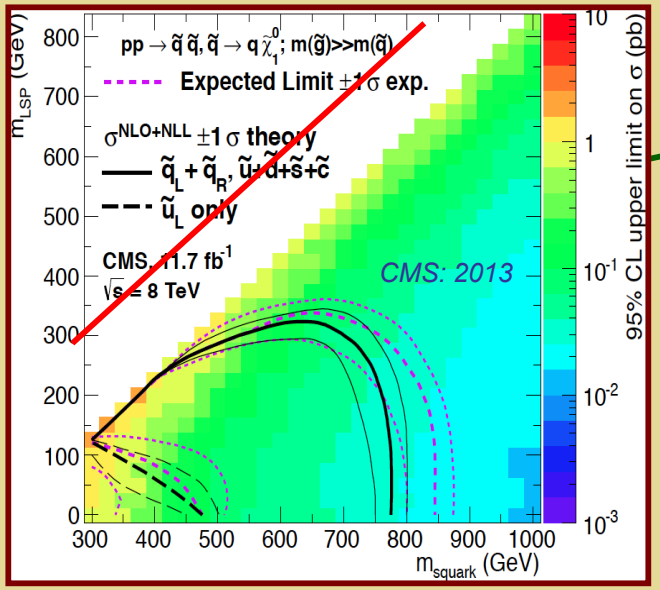

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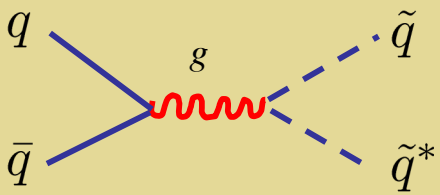
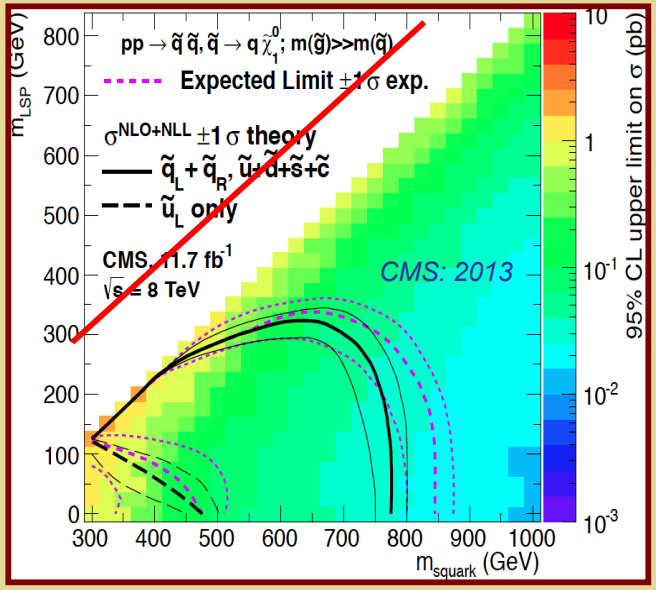
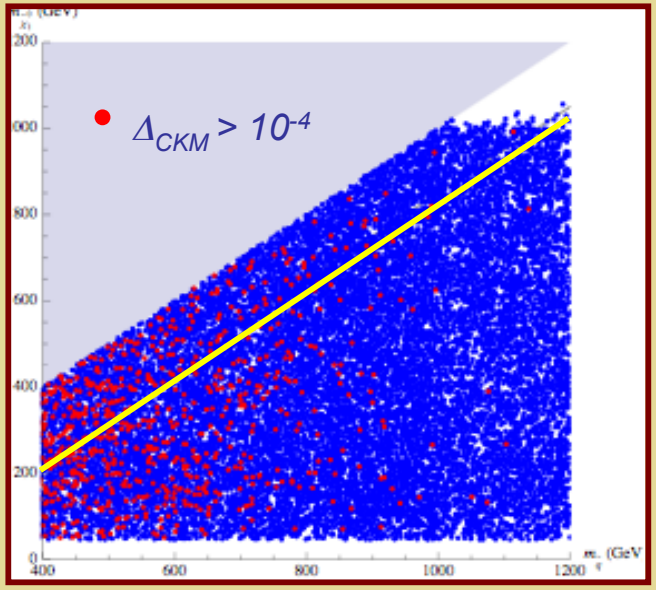




CKM Unitarity Tests

Bauman, Pitschmann, Erler, R-M preliminary



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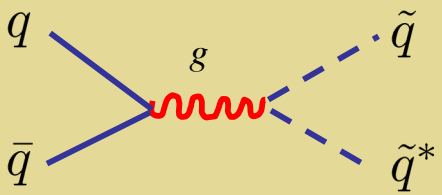

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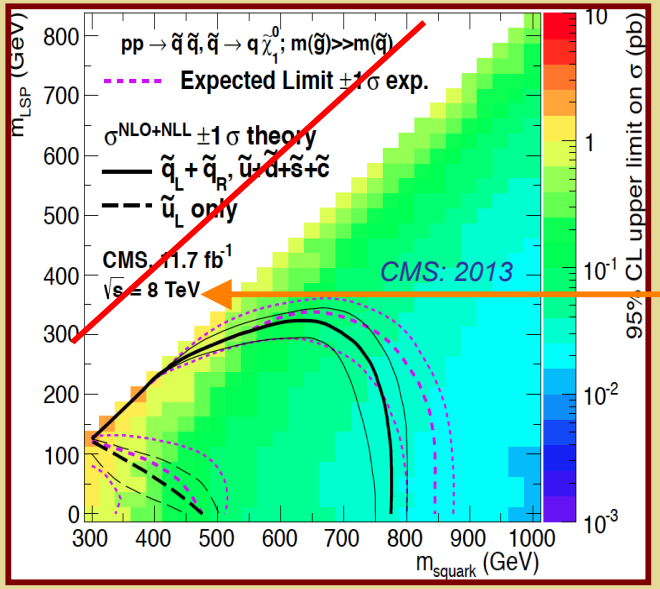
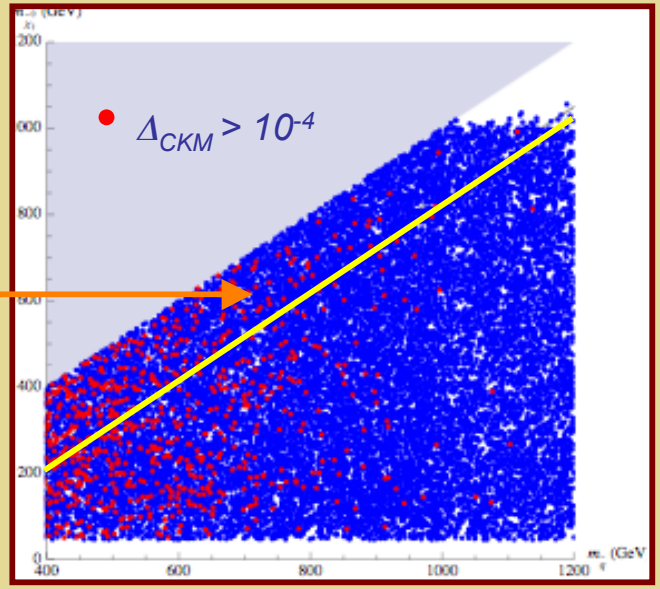
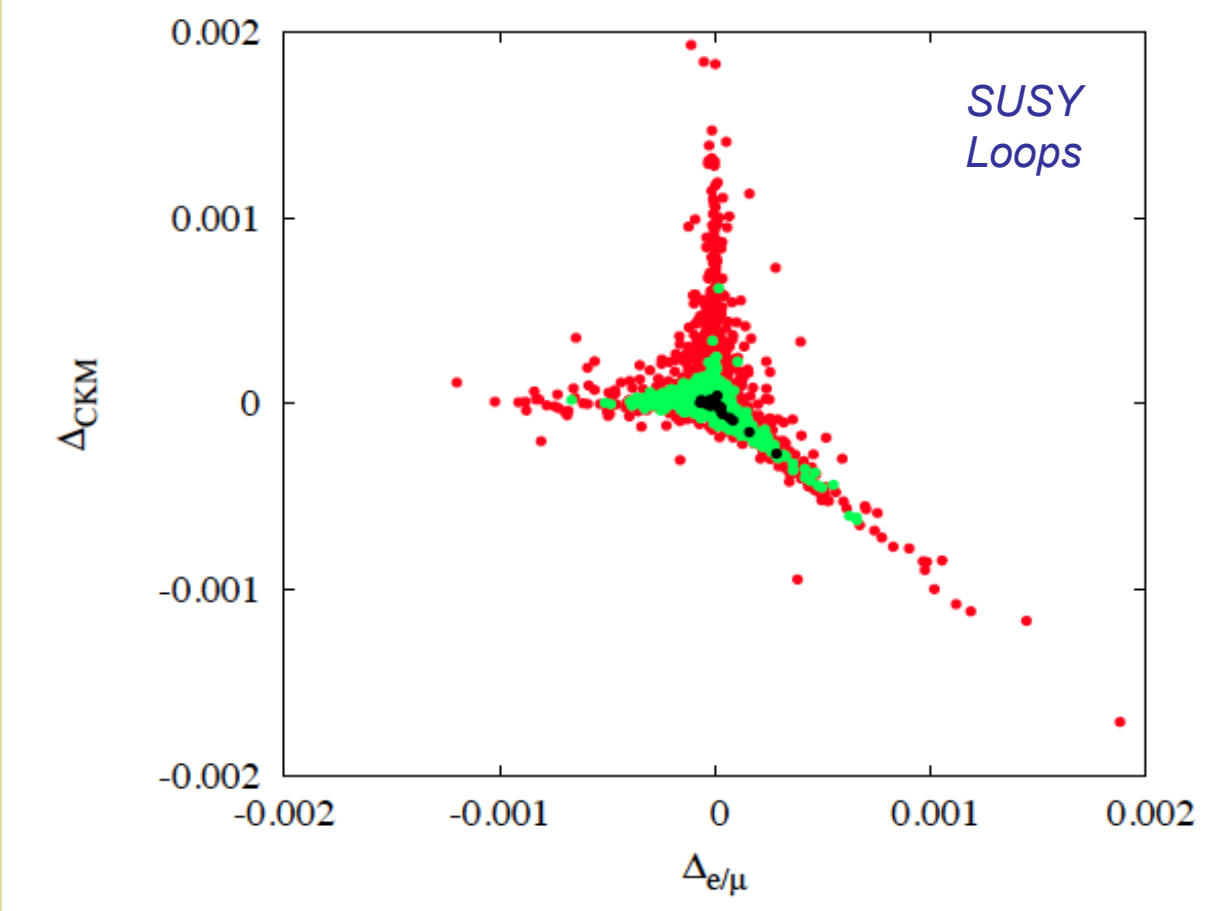




$\pi_{\ell 2}$ & β Decay: Diagnostic Tool

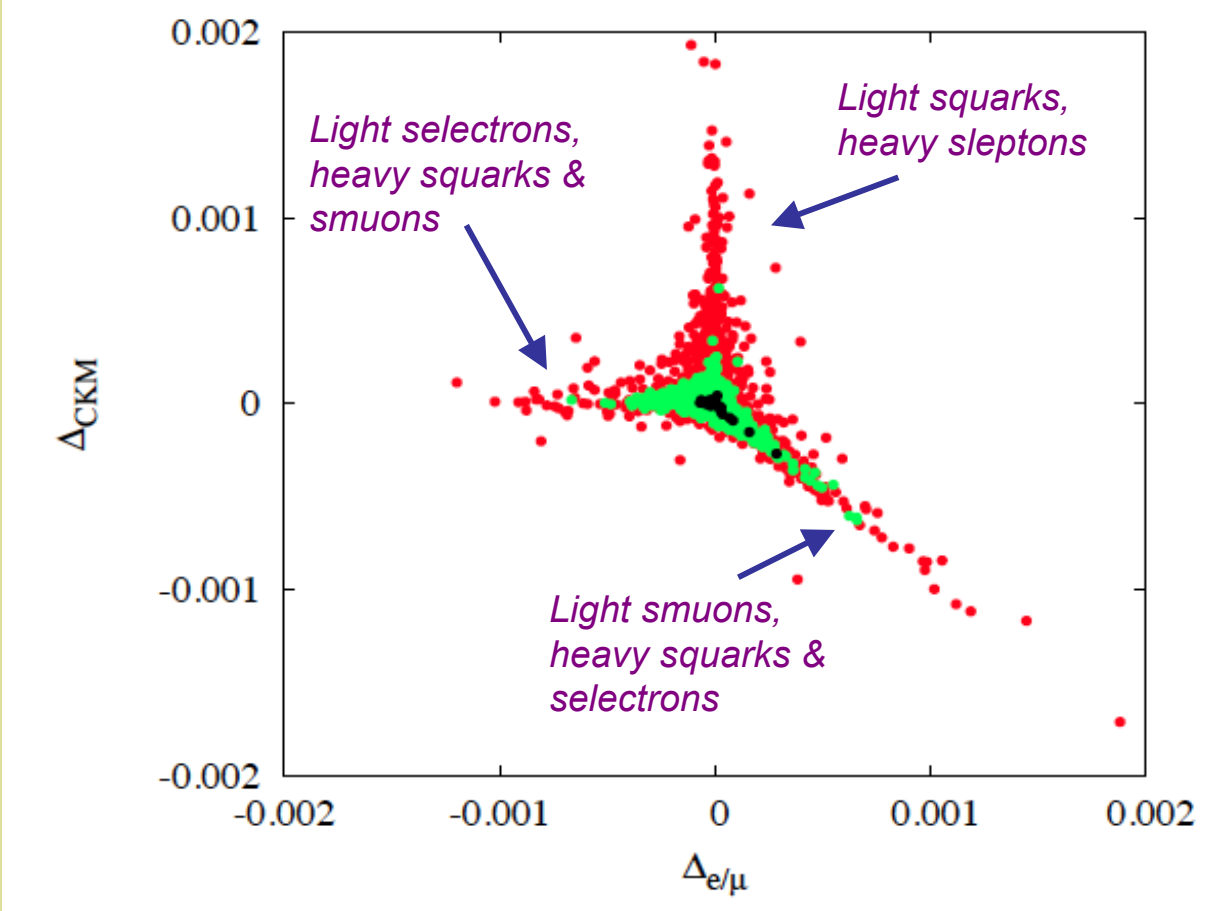
CKM Unitarity



Bauman, Erler, R-M

Lepton Universality

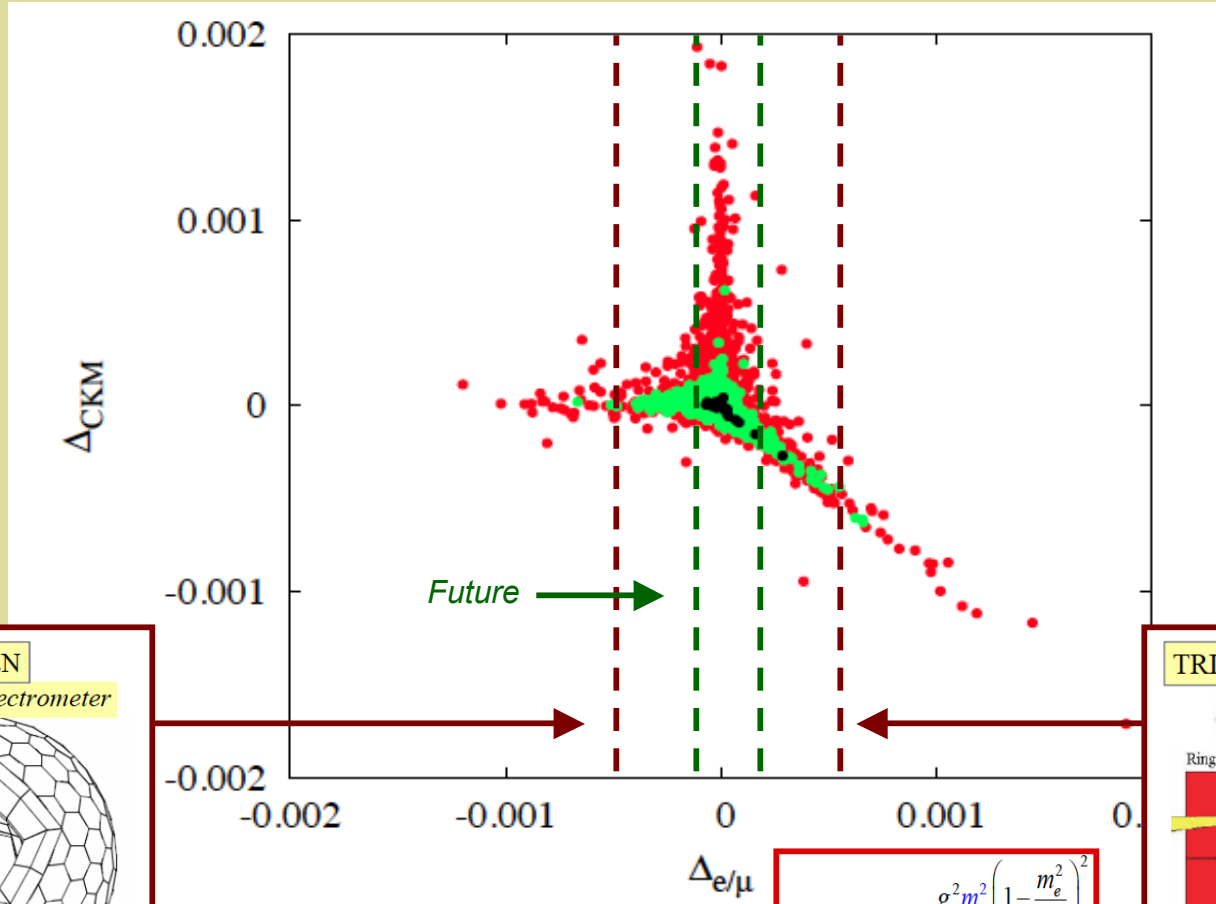
$\pi_{\ell 2}$ & β Decay: Diagnostic Tool

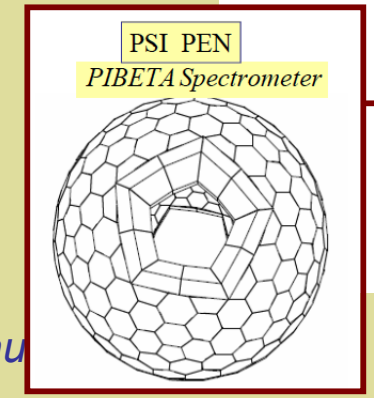


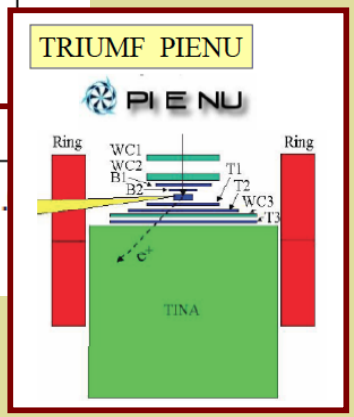
Bauman, Erler, R-M

$\pi_{\ell 2}$ & β Decay: Diagnostic

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2 m_e^2 \left(1 - \frac{m_e^2}{m_\pi^2}\right)^2}{g_\mu^2 m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2}$$







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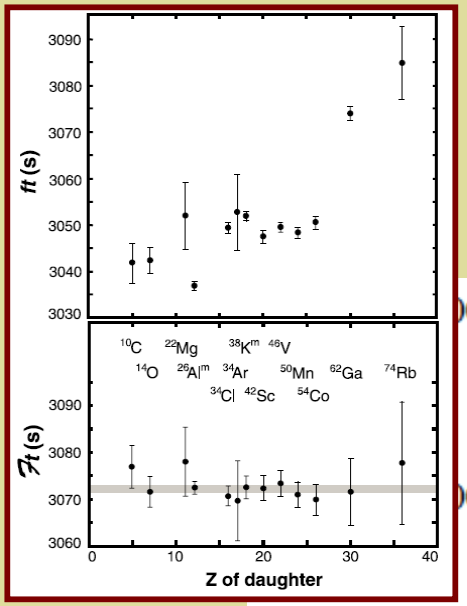
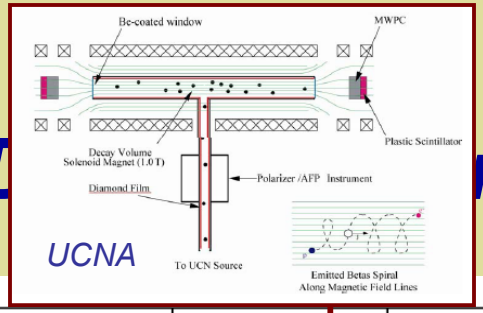
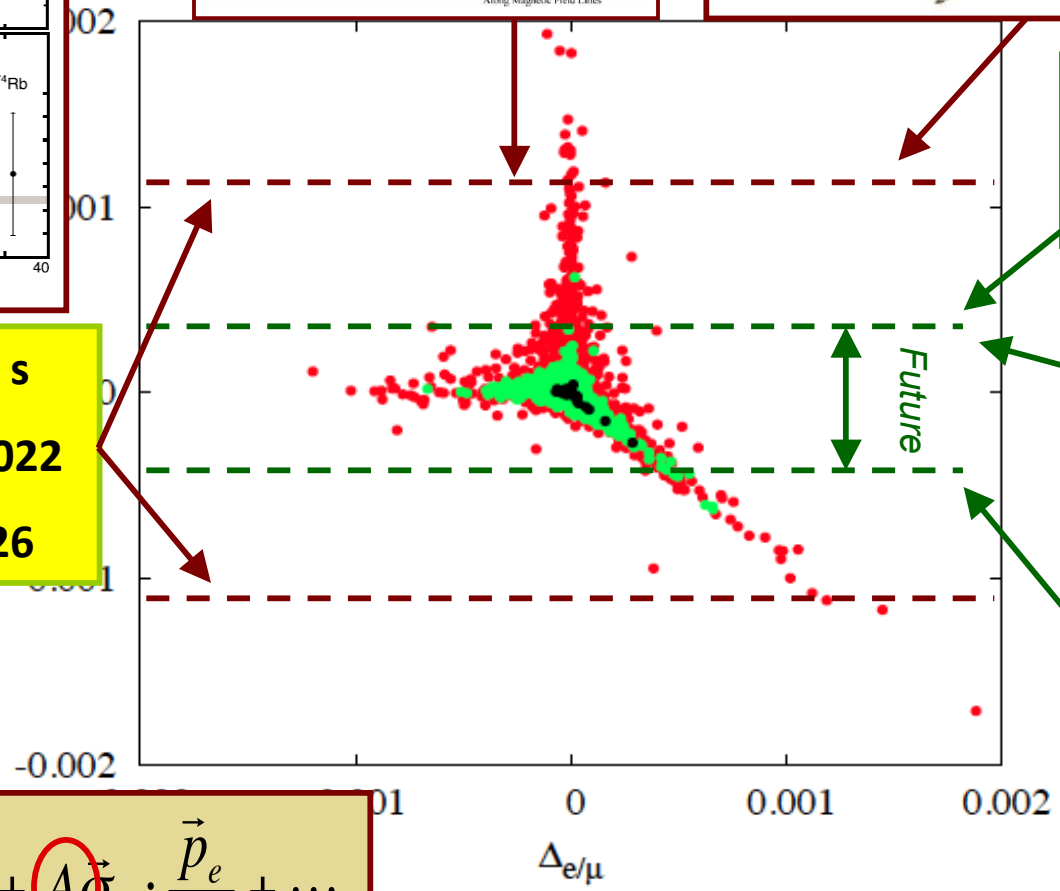
Bau

β D n







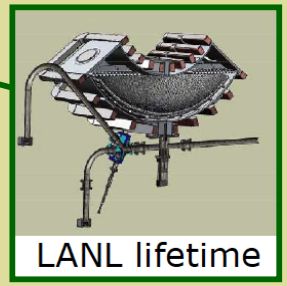
Ft **= 3072.08 ± 0.79 s**

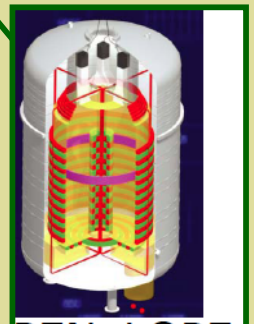
V_{ud} = 0.97425 ± 0.00022

b_F = -0.0022 ± 0.0026

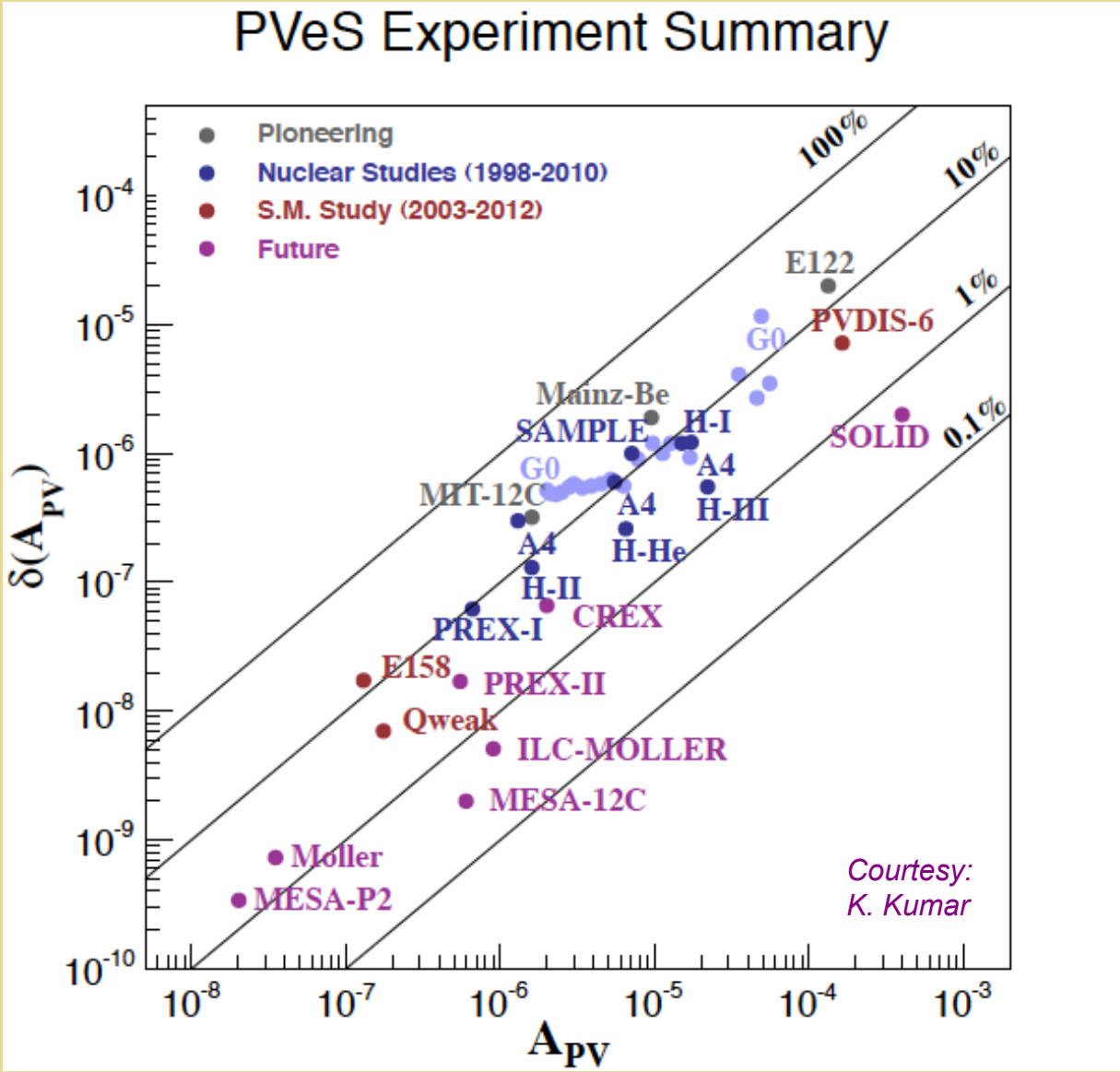
$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \cdots$$

PERC

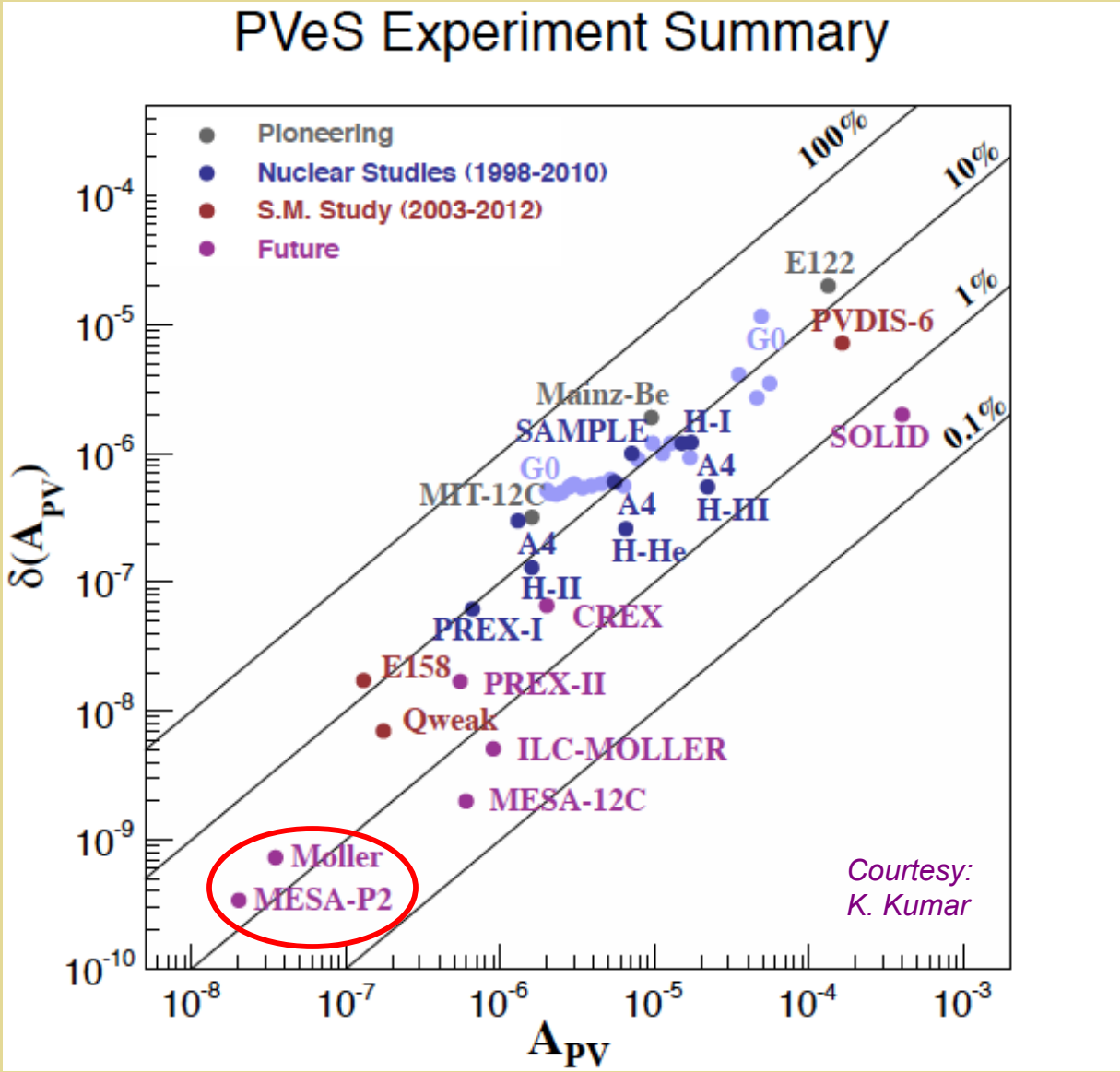

LANL lifetime


PENeLOPE
TUM

Parity-Violation Electron Scattering



Parity-Violation Electron Scattering



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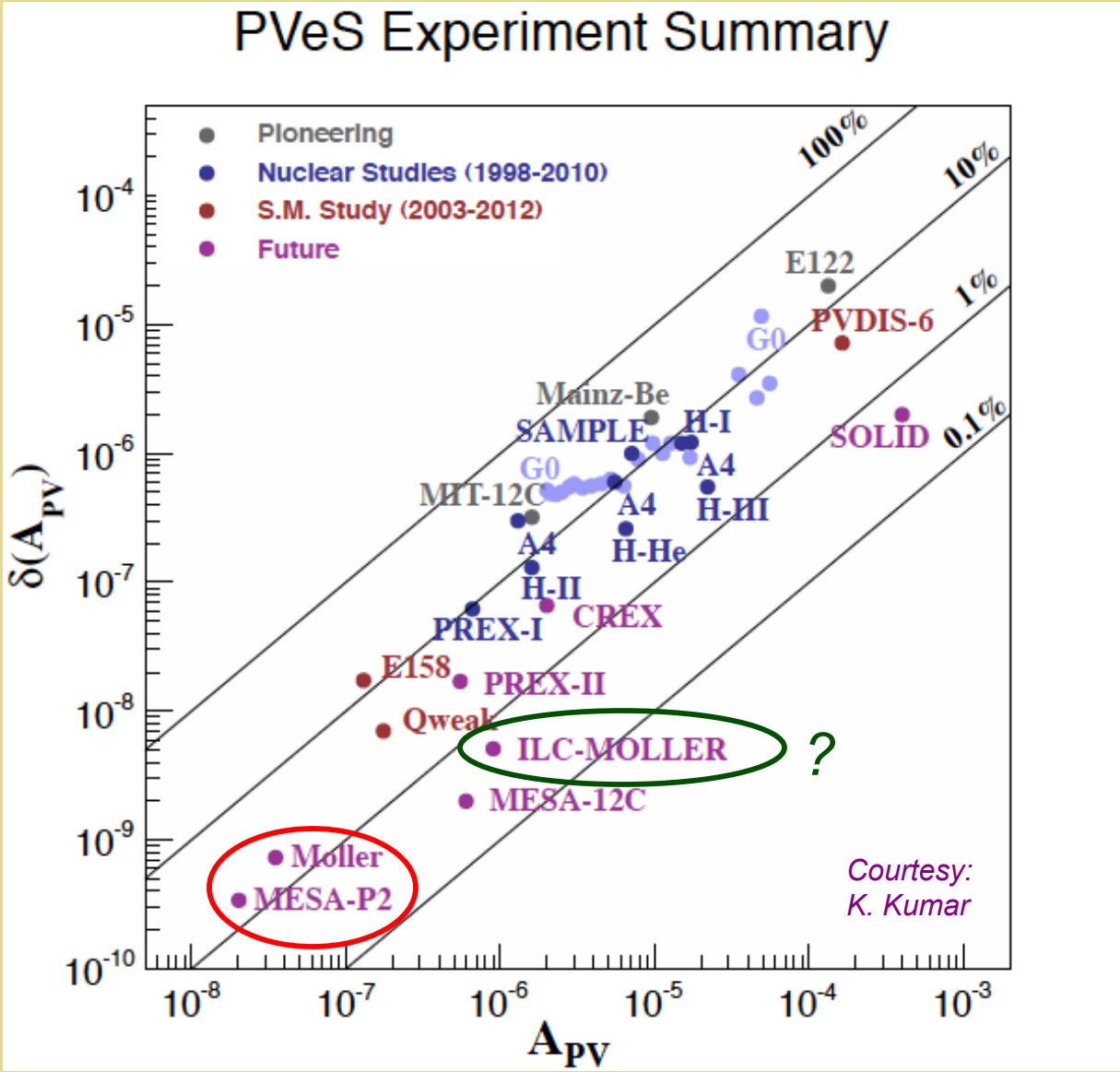
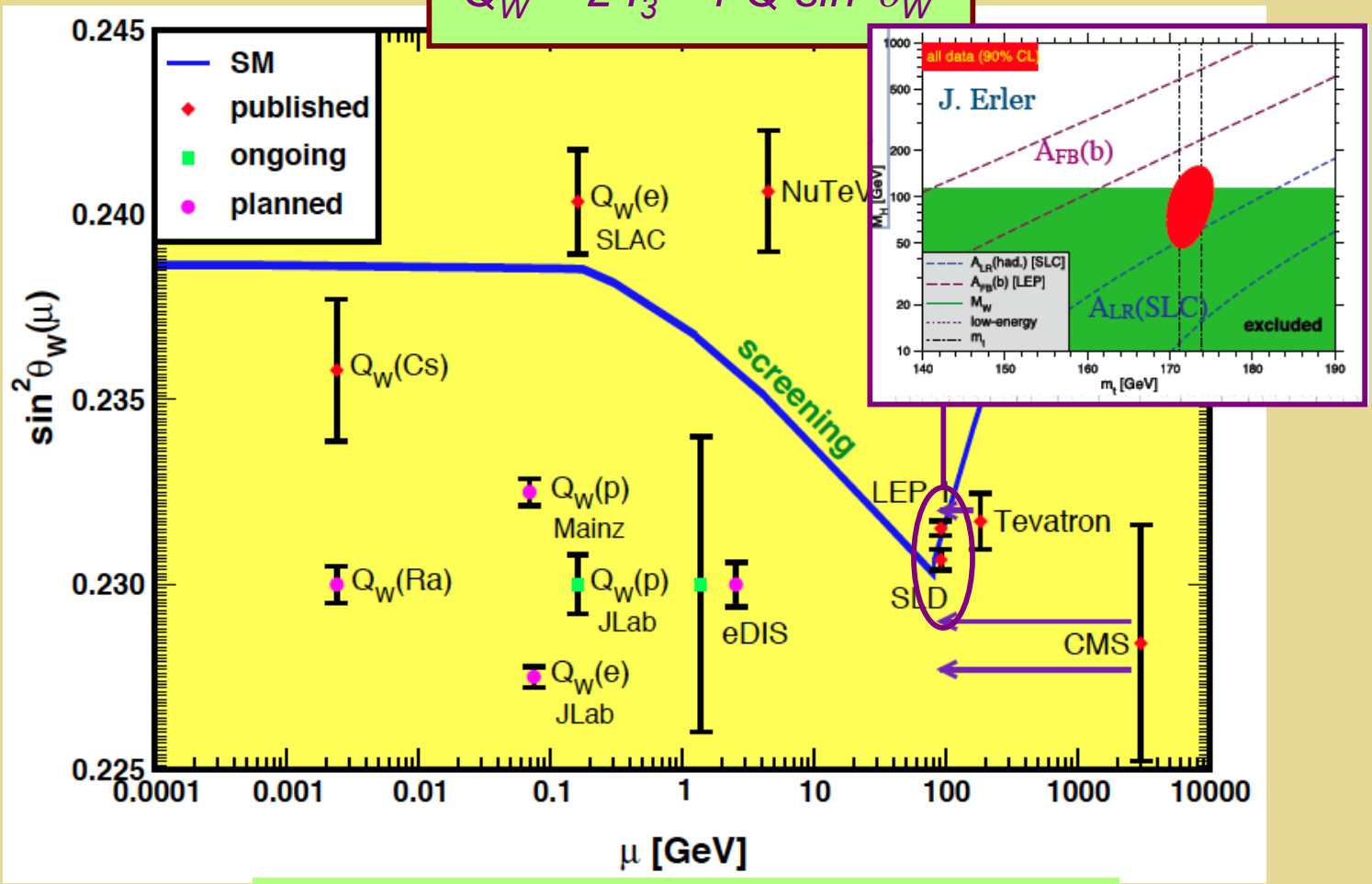


Weak Charges & Weak Mixing: SM

Courtesy J. Erler

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



Scale-dependence of Weak Mixing

Marciano & Czarnecki; Erler & R-M

Muon g-2: Theory Error Budget

$a_\mu(EW)$	=	$154\ (2) \times 10^{-11}$	
$a_\mu(HVP\text{-}LO)$	=	$6894\ (40) \times 10^{-11}$	
$a_\mu(HVP\text{-}NLO)$	=	$-98\ (1) \times 10^{-11}$	
$a_\mu(HLBL)$	=	$116\ (39) \times 10^{-11}$ $105\ (26) \times 10^{-11}$	Most challenging
δa_μ^{TH}	=	$\pm 48 \times 10^{-11}$	
δa_μ^{EXP}	=	$\pm 63 \times 10^{-11}$ $\pm 15 \times 10^{-11}$	BNL E821 FNAL New g-2

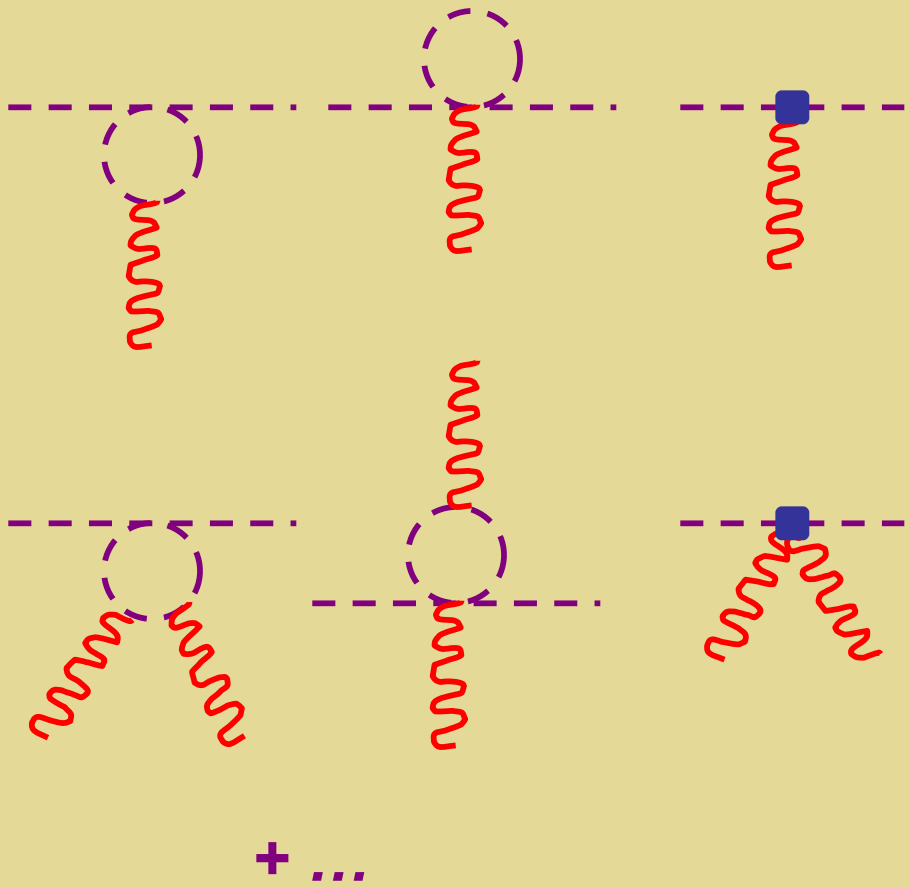
$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = 316\ (79) \times 10^{-11}$$

W. Marciano, arXiv: 1001.4528/hep-ph

Charged Pion Contribution: χPT

Kevin Engel (Caltech), Hiren Patel (Wisconsin), MRM

Beyond leading order: subgraphs



Pion charge radius: first non-trivial term in expansion of $F_\pi(q^2)$

$\mathcal{O}(p^4)$ LEC: α_9

Pion polarizability: distinct physics from ff

$\mathcal{O}(p^4)$ LEC: $\alpha_9 + \alpha_{10}$

Factor of two discrepancy: new J Lab experiment

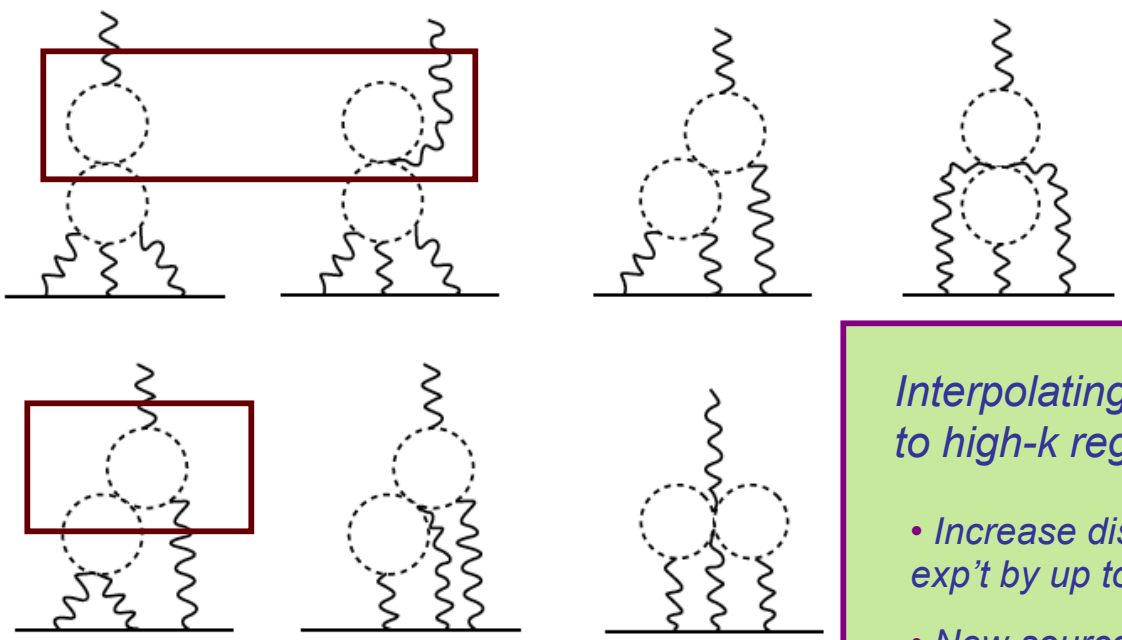
Charged Pion Contribution: χPT

Kevin Engel (Caltech), MRM

Beyond leading order: embedding subgraphs in full HLBL contribution

Charge radius

Pol'bility



Interpolating from chiral to high-k regimes:

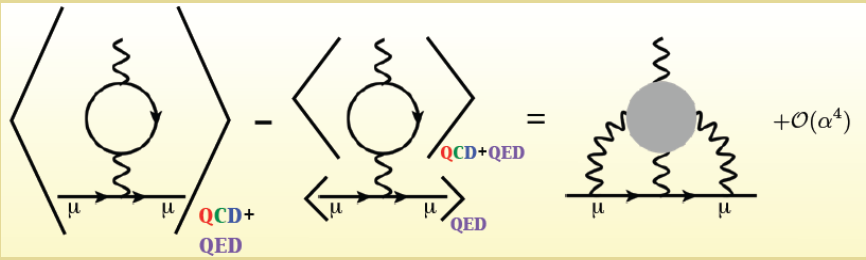
- *Increase discrepancy w/ exp't by up to 0.5σ*
- *New source of uncertainty (interpolation)*

Hadronic LBL: Lattice

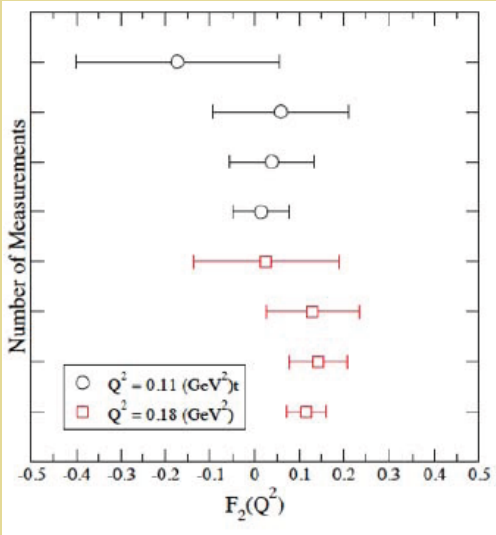
Lattice efforts

Collaboration	Method	N_f	Fermion action
RBC	QCD+QED	2+1	domain-wall
JLAB	$\pi^0 \to \gamma\gamma$ form factor	2+1	Clover
JLQCD	$\pi^0 \to \gamma\gamma$ form factor	2	overlap
QCDSF	direct $\langle JJJJ \rangle$	2	Clover

R. van de Water talk



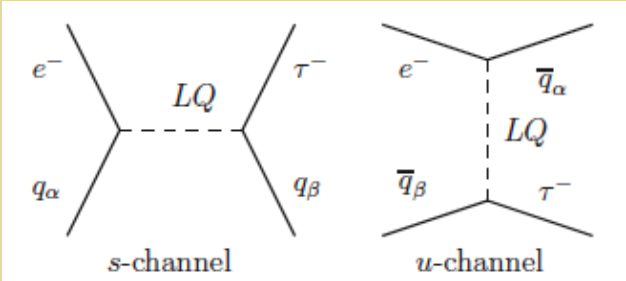
Blum et al



Blum et al '12

τ CLFV w/ Leptoquarks: EIC & HERA

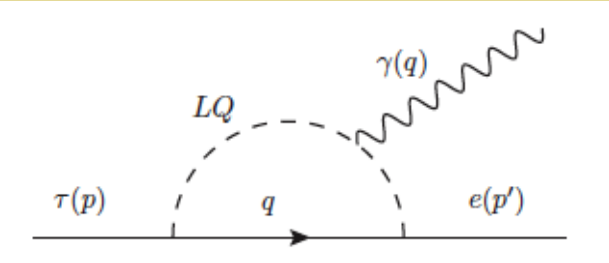
HERA & EIC

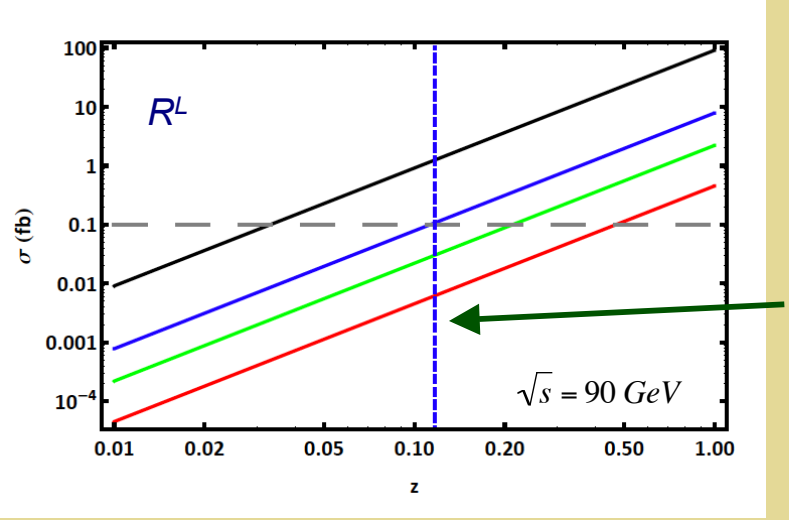


General Classification

$$\mathcal{L} = h_2^L \bar{u} \ell R_2^L + h_2^R \bar{q} i \tau_2 e R_2^R + \tilde{h}_2 \bar{d} \ell \tilde{R}_2^L + g_1^L \bar{q}^c i \tau_2 \ell S_1^L$$
$$+ g_1^R \bar{u}^c e S_1^R + \tilde{g}_1 \bar{d}^c e \tilde{S}_1^R + g_3 \bar{q}^c i \tau_2 \vec{\tau} \ell S_3 + h_1^L \bar{q} \gamma^\mu \ell U_{1\mu}^L$$
$$+ h_1^R \bar{d} \gamma^\mu e U_{1\mu}^R + \tilde{h}_1 \bar{u} \gamma^\mu e \tilde{U}_{1\mu}^R + h_3 \bar{q} \gamma^\mu \vec{\tau} \ell U_{3\mu}$$
$$+ g_2^L \bar{d}^c \gamma^\mu \ell V_{2\mu}^L + g_2^R \bar{q}^c \gamma^\mu e V_{2\mu}^R + \tilde{g}_2 \bar{u}^c \gamma^\mu \ell \tilde{V}_{2\mu}^L + \text{H.c.},$$

Rare Decays





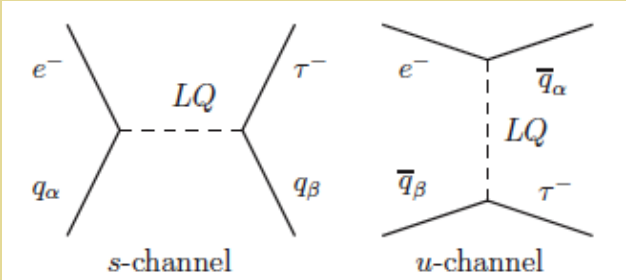
$\tau \to e\ \gamma$

Gonderinger, R-M JHEP 1006:045

$z = (\lambda^2 / M^2) / (\lambda^2 / M^2)_{HERA}$

τ CLFV w/ Leptoquarks: EIC & HERA

HERA & EIC

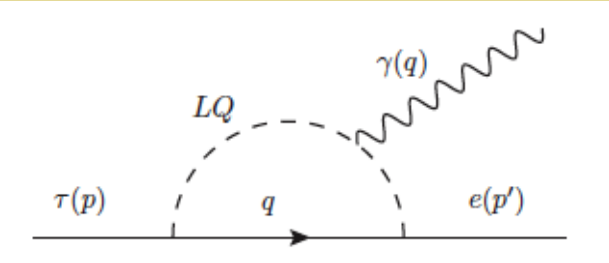


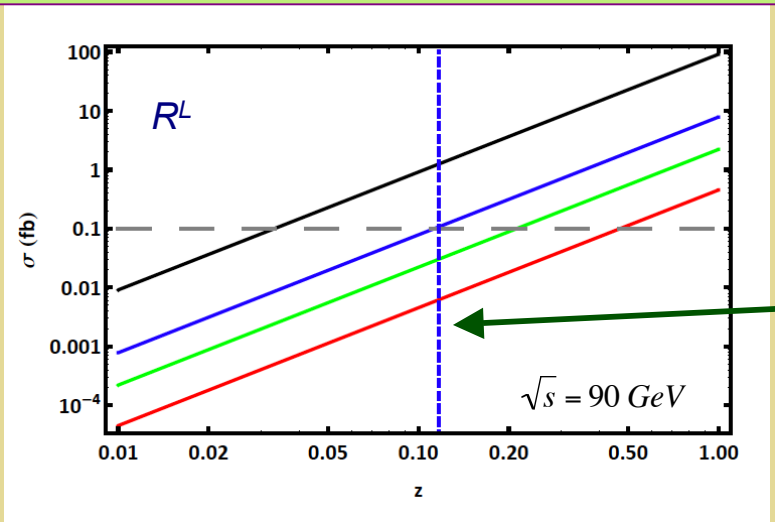
General Classification

$$\mathcal{L} = h_2^L \bar{u} \ell R_2^L + h_2^R \bar{q} i \tau_2 e R_2^R + \tilde{h}_2 \bar{d} \ell \tilde{R}_2^L + g_1^L \bar{q}^c i \tau_2 \ell S_1^L$$
$$+ g_1^R \bar{u}^c e S_1^R + \tilde{g}_1 \bar{d}^c e \tilde{S}_1^R + g_3 \bar{q}^c i \tau_2 \vec{\tau} \ell S_3 + h_1^L \bar{q} \gamma^\mu \ell U_{1\mu}^L$$

Extend HERA reach & compete with super B factories w/ 10 to 100 fb^{-1}

Rare Decays





$\tau \to e\ \gamma$

Gonderinger, R-M JHEP 1006:045

$z = (\lambda^2 / M^2) / (\lambda^2 / M^2)_{HERA}$