Standard model extensions for PV electron scattering, g–2, EDM: *Overview*

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Outline

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- The SM and Beyond

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- Illustrative example: supersymmetric extentions

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- Electric Dipole Moments

The SM and Beyond

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  - discovery of weak neutral currents
  - PVeDIS (consistent with ν scattering) ***SLAC-E-122 (1978)***
  - discovery of W and Z bosons

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  - discovery of W and Z bosons
- SM as spontaneously broken, renormalizable QFT established — before Higgs discovery — through
  - high precision Z factories LEP & SLC (also Tevatron)

Status

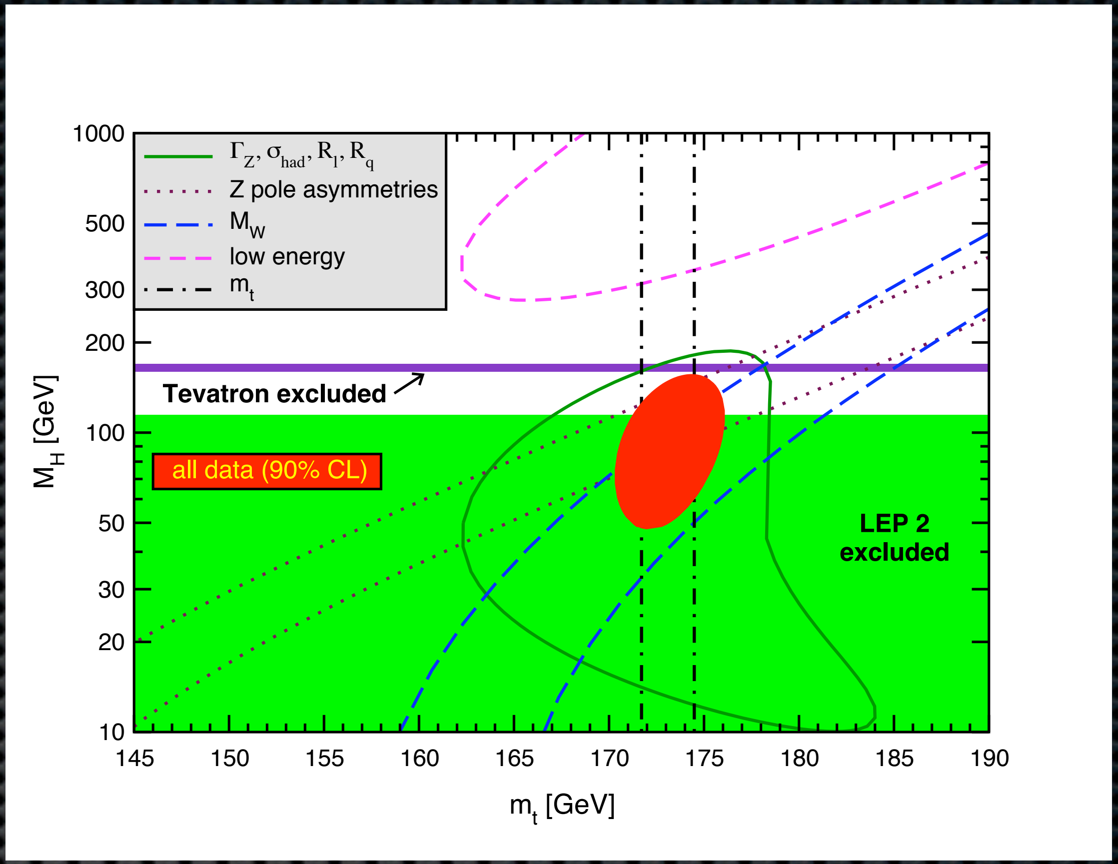
- closing in on the Higgs

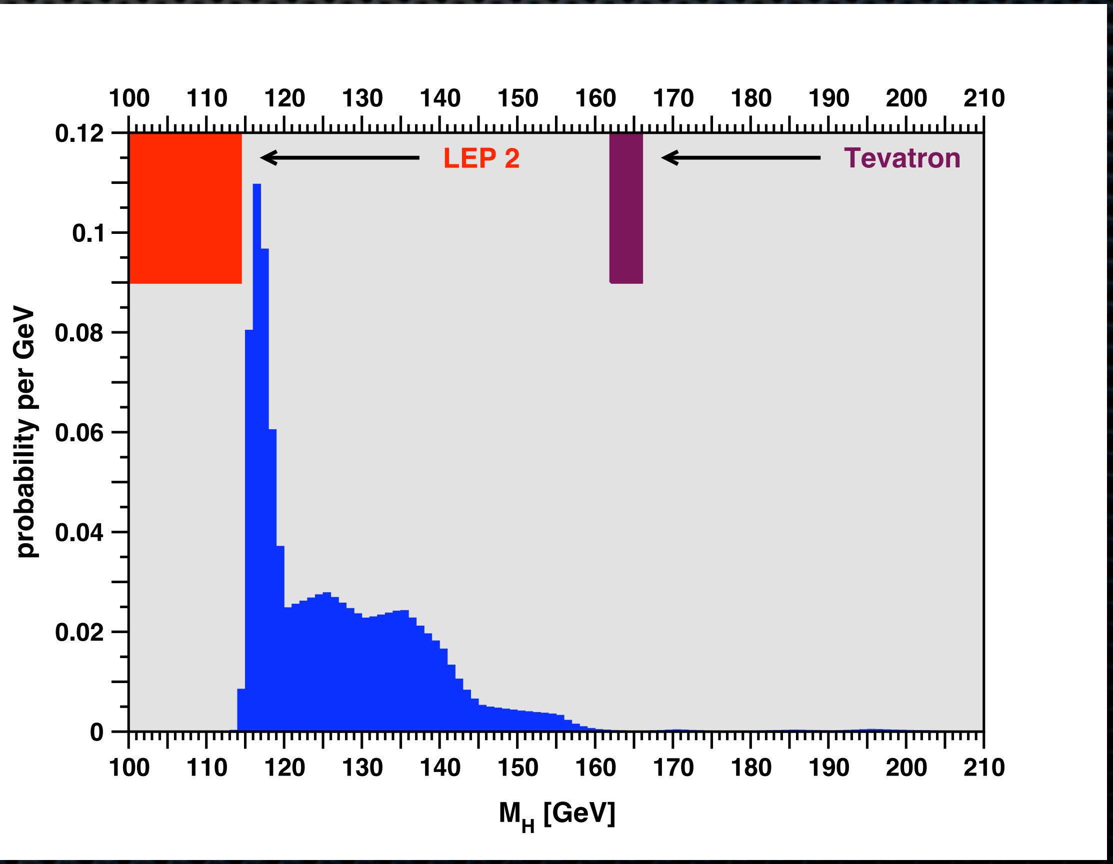
  ☞ ***talk by Daniele del Re***

  consistent (sadly) with precision constraints

- small deviations occur, but nothing conclusive

- m_ν just dimension 5 $HH\bar{L}L$-operator?





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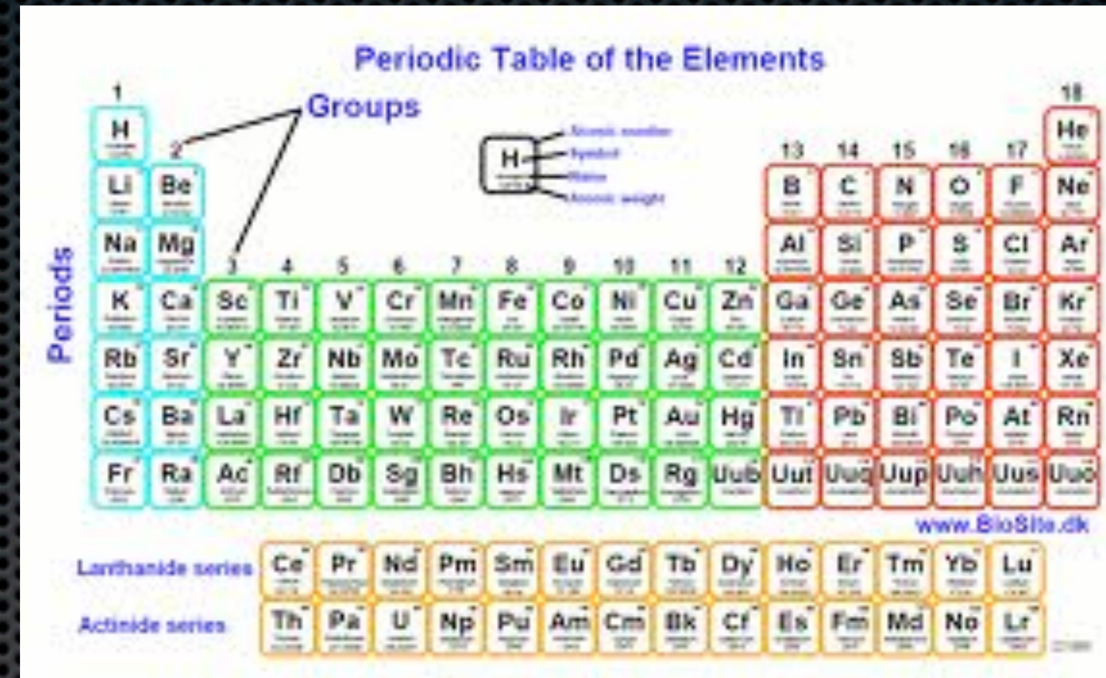
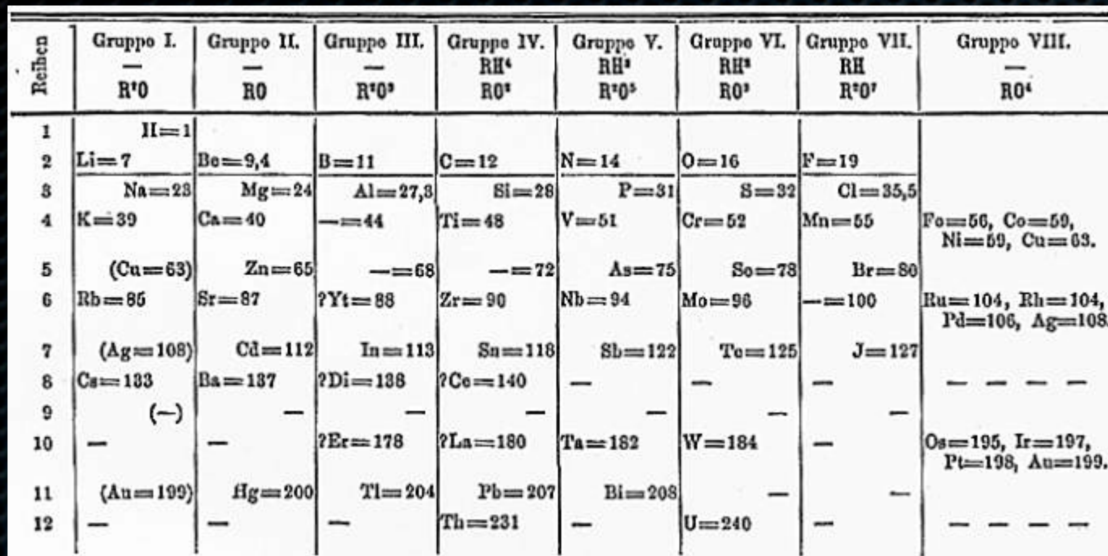
- theory: hierarchy and cosmological constant problems (also strong CP problem, but less severe)
- arbitrariness of gauge group, multiplets & parameters, but tantalizing hints at unification structure (E_6 & subgroups) and gauge coupling unification (in MSSM)
- overriding goal: finding principles underlying the SM

Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Mendeleev (1871)





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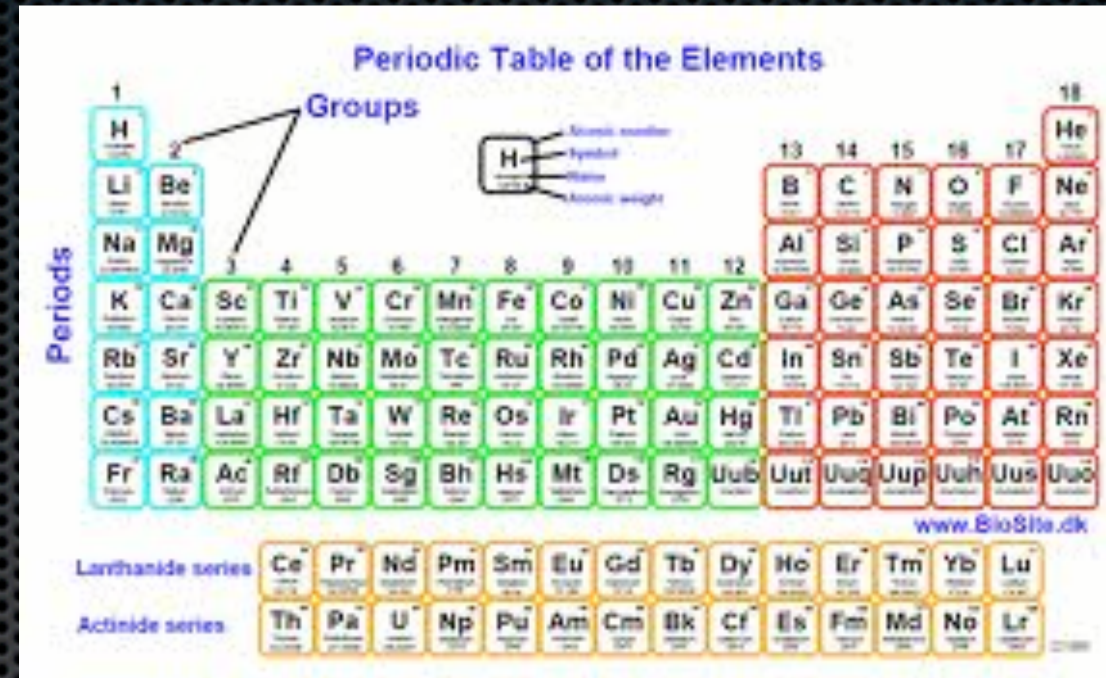

ν_τ s=½	τ^- s=½	τ^+ s=½	t s=½	t s=½	t s=½	$\bar{t}$ s=½	$\bar{t}$ s=½	$\bar{t}$ s=½	b s=½	b s=½	b s=½	$\bar{b}$ s=½	$\bar{b}$ s=½	$\bar{b}$ s=½
ν_μ s=½	μ^- s=½	μ^+ s=½	c s=½	c s=½	c s=½	$\bar{c}$ s=½	$\bar{c}$ s=½	$\bar{c}$ s=½	s s=½	s s=½	s s=½	$\bar{s}$ s=½	$\bar{s}$ s=½	$\bar{s}$ s=½
ν_e s=½	e^- s=½	e^+ s=½	u s=½	u s=½	u s=½	$\bar{u}$ s=½	$\bar{u}$ s=½	$\bar{u}$ s=½	d s=½	d s=½	d s=½	$\bar{d}$ s=½	$\bar{d}$ s=½	$\bar{d}$ s=½
H s=0	$H^\pm$ s=0	Z s=1	W^- s=1	W^+ s=1	g s=1	g s=1	g s=1	g s=1	g s=1	g s=1	g s=1	g s=1	γ s=1	G s=2

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  - $\Lambda_{new} \simeq 3.4$ TeV (E158)
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- EM dipole moments: $L = \frac{1}{2} [D\, \bar{\psi}\, \sigma_{\mu\nu}\, P_R\, \psi + \text{H.c.}]\, F^{\mu\nu}$
  - $\Re e\, D = e\, a/(2\, m) \Rightarrow\ \Lambda_{new} \simeq m_\mu/\sqrt{\Delta a_\mu} = 3.8$ TeV (MDM)
  - $\Im m\, D = d \Rightarrow\ \Lambda_{new} \simeq \sqrt{(e\, m_e/2\, \Delta d_e)} = 83$ TeV (EDM)
  - $\mu \to e$ conversion: $\Lambda_{new} \gtrsim 130$ TeV (transition moment)

Illustrative example:
supersymmetric extentions

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  - elegant solution to hierarchy problem (makes sense also in combination with other ideas like LEDs)
- observation: gauge coupling unification (one-loop)
  - solid prediction for a light Higgs ($M_H \lesssim 150$ GeV)
  - natural radiative EW symmetry breaking for large m_t
  - dark matter candidate

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- SUSY breaking (hidden sector) and mediation
- (non)-observation of sparticles and extra Higgs particles
- little hierarchy problem (fine tuning)

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- but even with an LHC discovery unlikely the full TeV scale theory
- expect extra ingredients to solve its problems (such as extra gauge symmetries)
- SUSY may itself be merely one ingredient to stabilize other types of possible TeV scale physics (like LEDs)

$g_\mu - 2$

$g_\mu - 2$ in the SM

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  - $\Delta a_\mu(\tau) - \Delta a_\mu(e^+ e^-) = (0.91 \pm 0.50)\times 10^{-9}$ (1.8 σ)
    Davier, Höcker, Malaescu, Zhang (2010)

g_μ–2 in the SM

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- Δa_μ(average) = $(69.61 \pm 0.36) \times 10^{-9}$
  - ➡ $a_\mu^{exp} - a_\mu^{th} = (2.50 \pm 0.77) \times 10^{-9}$ (3.2 σ)

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- $\Delta a_\mu(\gamma \times \gamma) = (1.05 \pm 0.26) \times 10^{-9}$ (included above)
  Prades, de Rafael, Vainshtein (2009)

  - $\Delta a_\mu(\gamma \times \gamma) < 1.59 \times 10^{-9}$ (95% CL) ***JE, Toledo (2006)***

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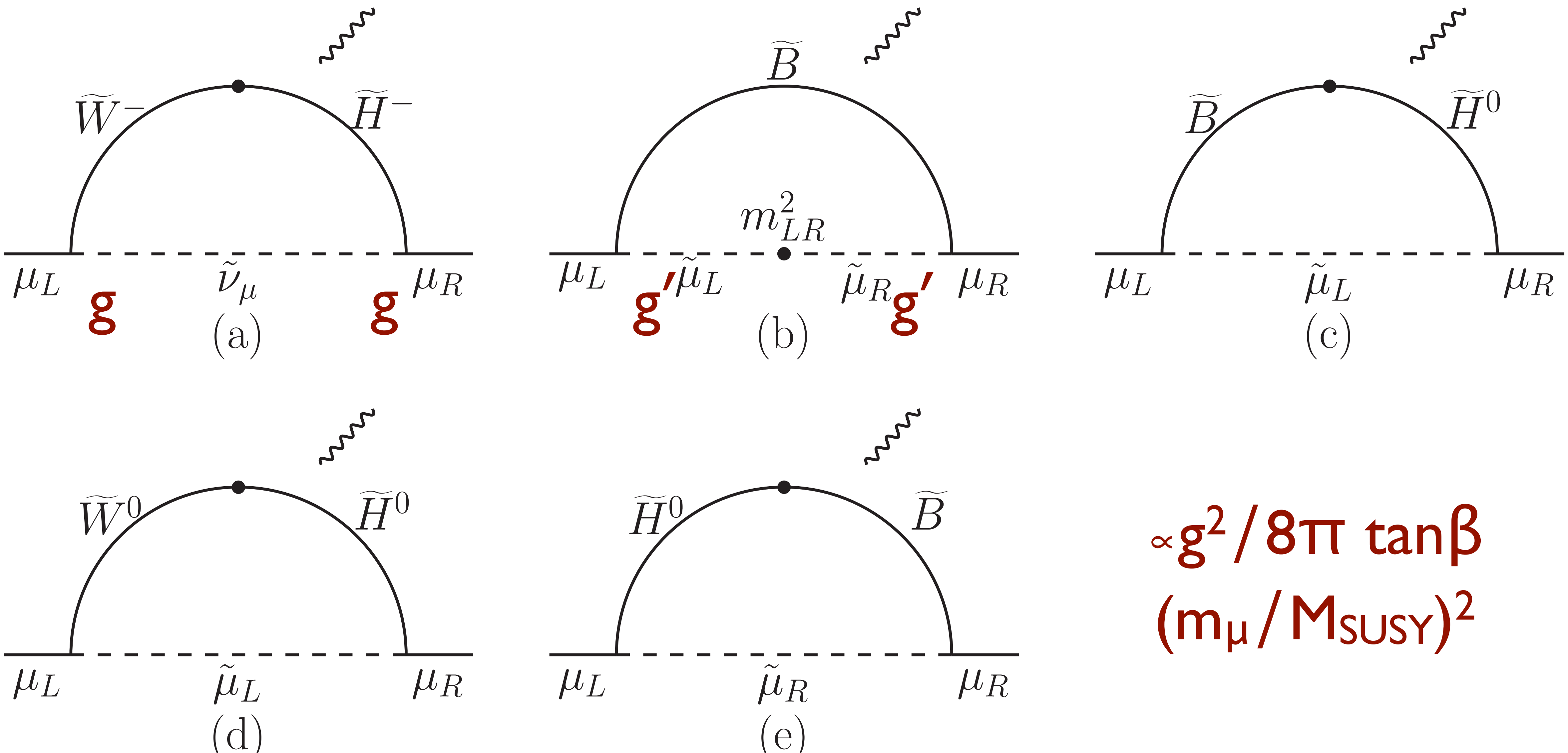
can be pushed below 3×10^{-10} then 5 σ discovery would be established (if central value does not change)

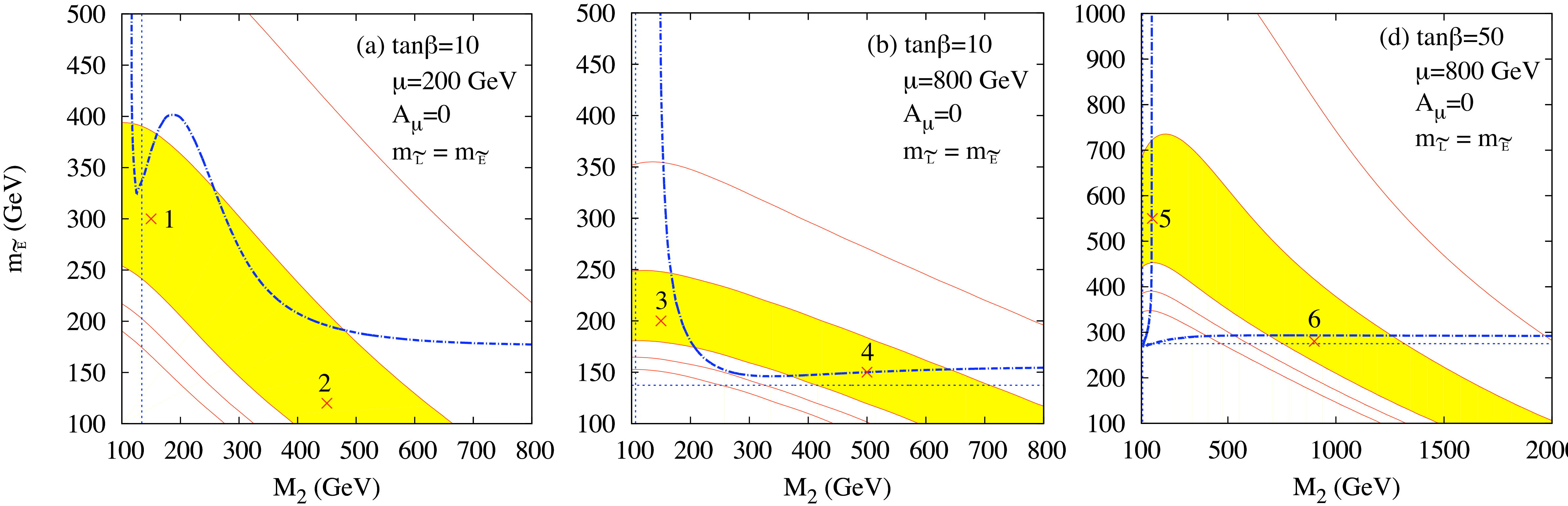
($\gamma\times\gamma$ already there but hardest to defend)

$g_\mu - 2$ in the MSSM



$\propto g^2/8\pi \tan\beta$
$(m_\mu/M_{SUSY})^2$

Cho, Hagiwara, Matsumoto, Nomura (2011)



No.	$\tan\beta$	μ	M_2	$m_{\tilde{E}}$	(a)	(b)	(c)	(d)	(e)	(a)-(e)	total	pull
1	10	200	150	300	29.6	1.1	0.7	−2.9	−1.3	27.2	25.0	−0.1
2	10	200	450	120	27.5	8.8	3.3	−7.1	−6.7	25.9	25.9	0.0
3	10	800	150	200	14.3	16.2	0.6	−2.7	−1.3	27.1	27.1	0.1
4	10	800	500	150	6.9	21.3	1.0	−2.5	−2.1	24.7	24.3	−0.2
5	50	800	150	550	26.9	2.4	0.5	−2.6	−1.0	26.3	26.0	0.0
6	50	800	900	280	18.0	18.0	2.5	−5.9	−5.1	27.7	27.6	0.2

$(\delta a_\mu \times 10^{-10})$

Cho, Hagiwara, Matsumoto, Nomura (2011)

Practical example:

gauge extensions

Z′ bosons

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- diagnostics: charges can hint at underlying principles

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  - the U(1)′ forbids dimension 4 proton decay ***JE (2000)***

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Z′ bosons from E_6

- $E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi\times U(1)_\psi$
- $Z' = \cos\alpha \cos\beta\, Z_\chi + \sin\alpha \cos\beta\, Z_Y + \sin\beta\, Z_\psi$

  $\sim c_1\, Z_R + \sqrt{3}\,(c_2\, Z_{R1} + c_3\, Z_{L1})$
- kinetic mixing: $\alpha \neq 0 \sim F^{\mu\nu} F'_{\mu\nu}$
- trinification: $E_6 \to SU(3)^3 \to SU(3)_C\times SU(2)_L\times U(1)_{L1}\times SU(2)_R\times U(1)_{R1}$
- classification in progress ***JE, Rojas (2011)***

Z' charges in E_6 models

l	ν, e^-		$-2c_2$	$-c_3$	$\bar{\nu}$	$-c_1$	$+c_2$	$+2c_3$
					e^+	$+c_1$	$+c_2$	$+2c_3$
q	u, d			$+c_3$	$\bar{u}$	$-c_1$	$-c_2$	
					$\bar{d}$	$+c_1$	$-c_2$	
L	N, E^-	$-c_1$	$+c_2$	$-c_3$	D			$-2c_3$
					$\bar{D}$		$+2c_2$	
$\bar{L}$	E^+, $\bar{N}$	$+c_1$	$+c_2$	$-c_3$	S		$-2c_2$	$+2c_3$

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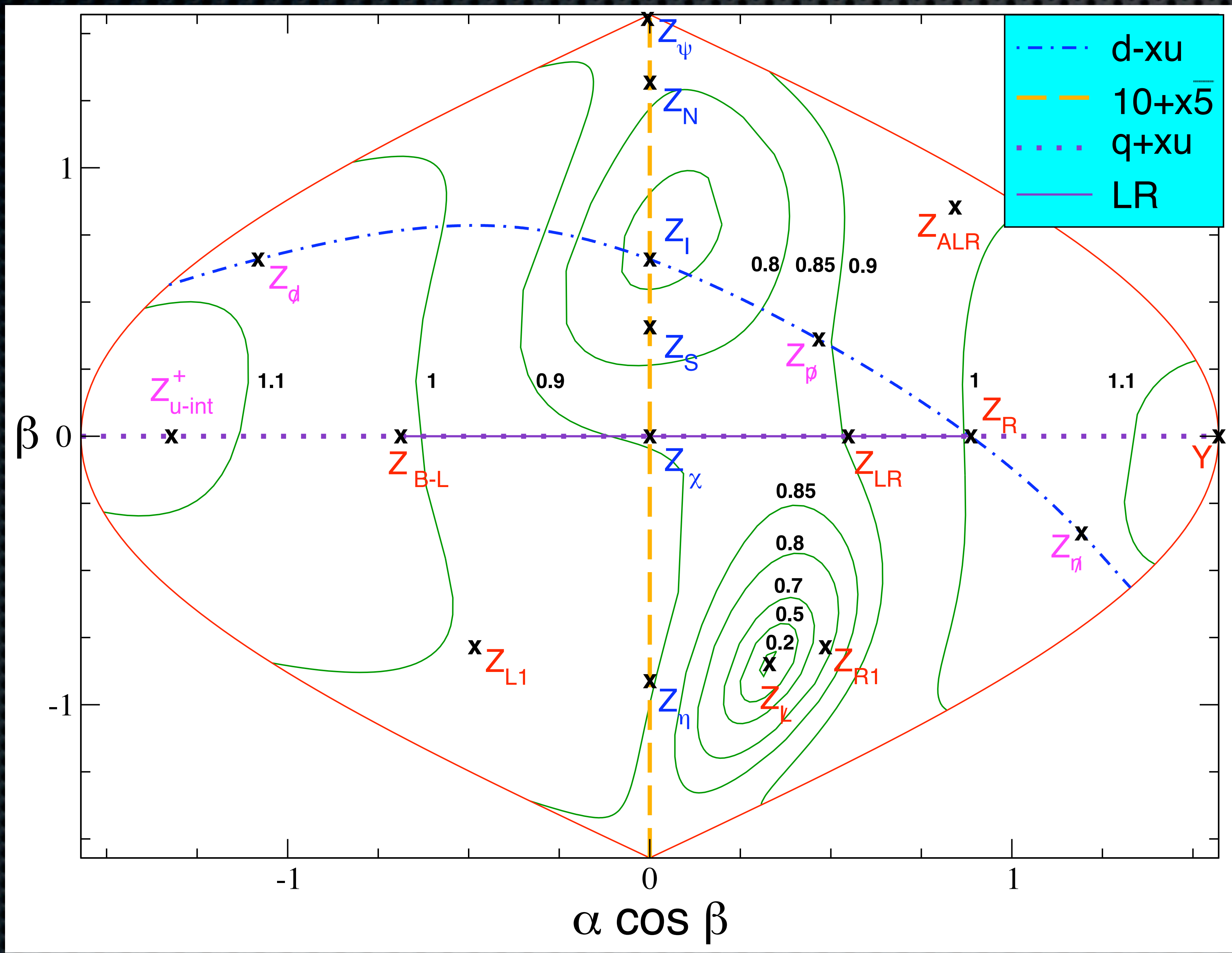
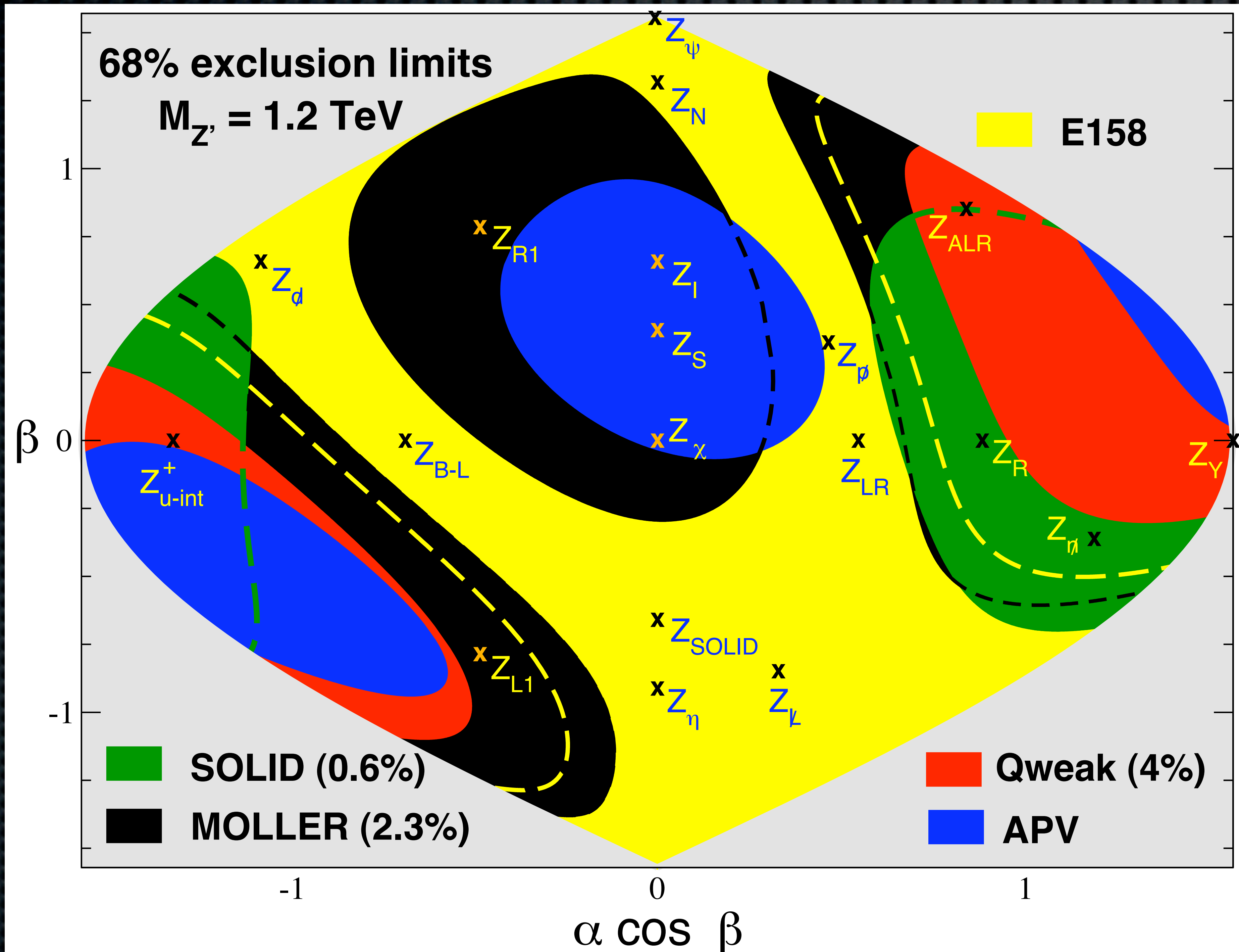
E_6 inspired models



- horizontal line: SO(10) (including left-right) models
- vertical line: no kinetic mixing
- blue line: $U(1)_{d-xu}$

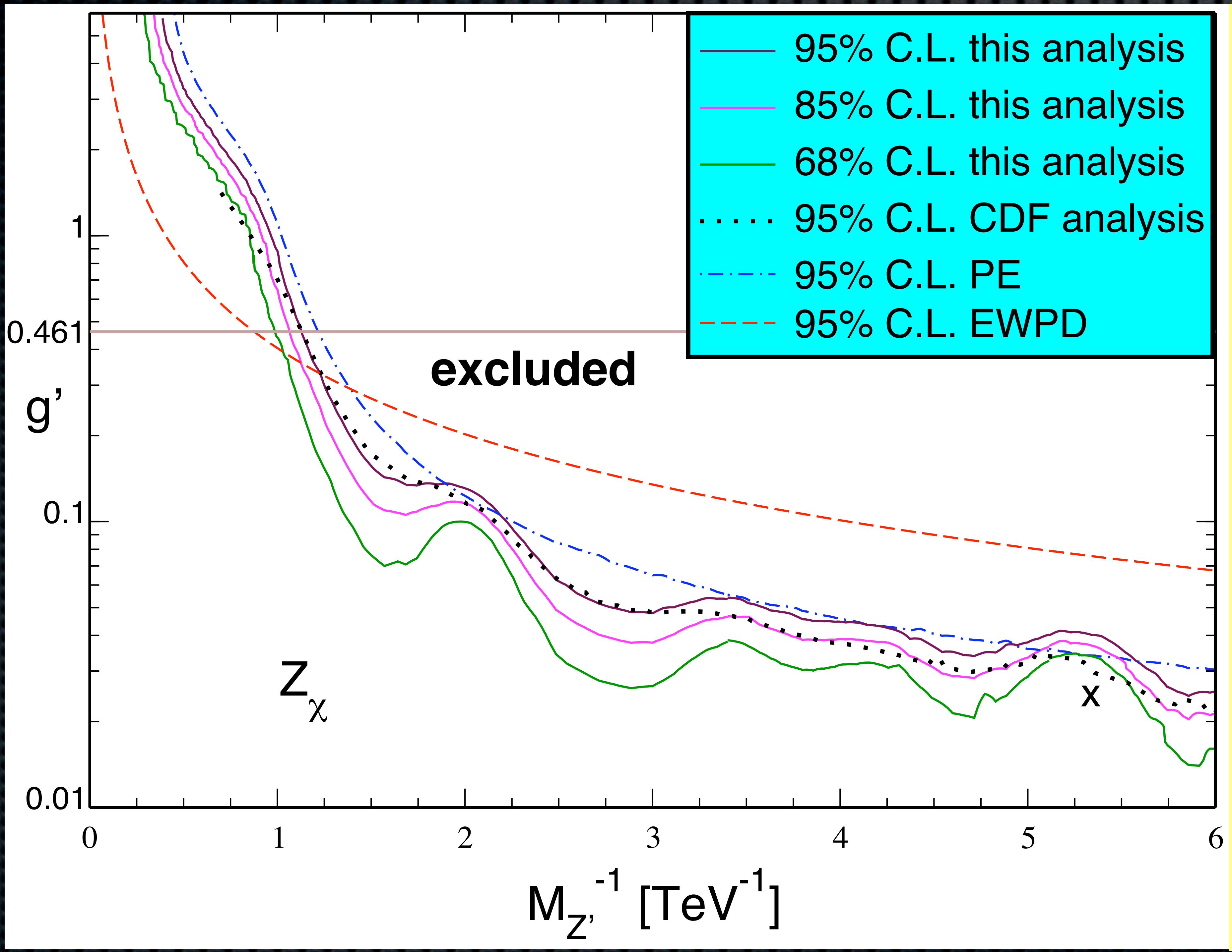
Parity violation in electron scattering atoms and ions

E_6 models & parity violation



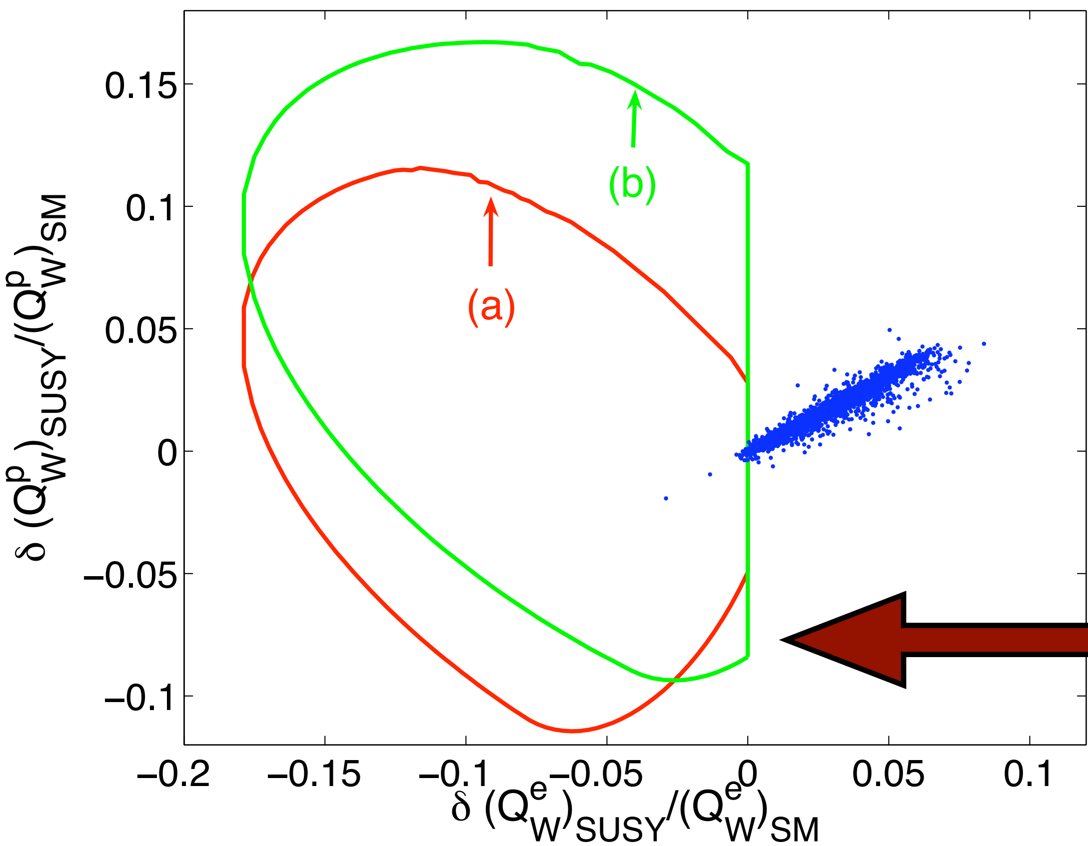
- APV (Boulder)
- E158 (SLAC)
- MOLLER
- Qweak
- SOLID

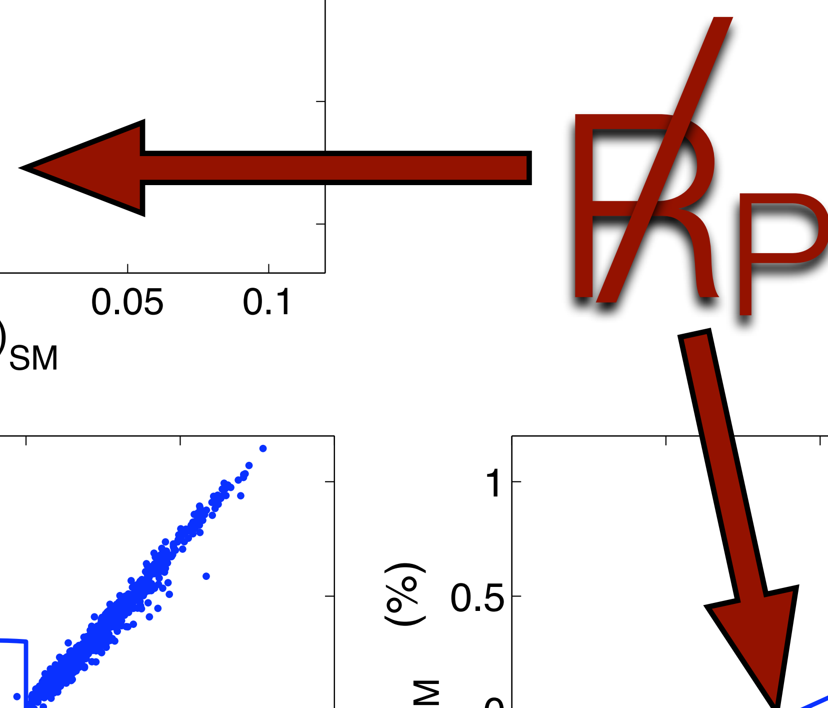
Comparative analysis of the Z_χ



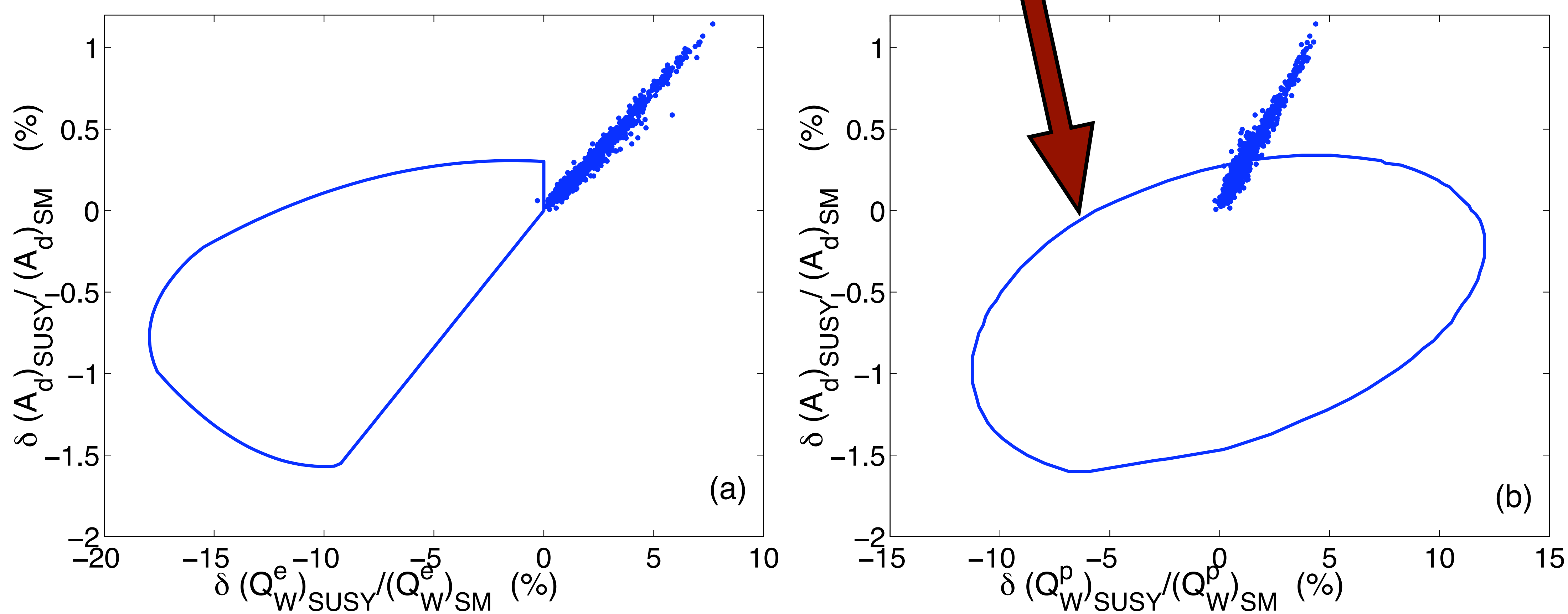
electroweak precision data complement di-lepton channel analyses

e^- scattering and SUSY

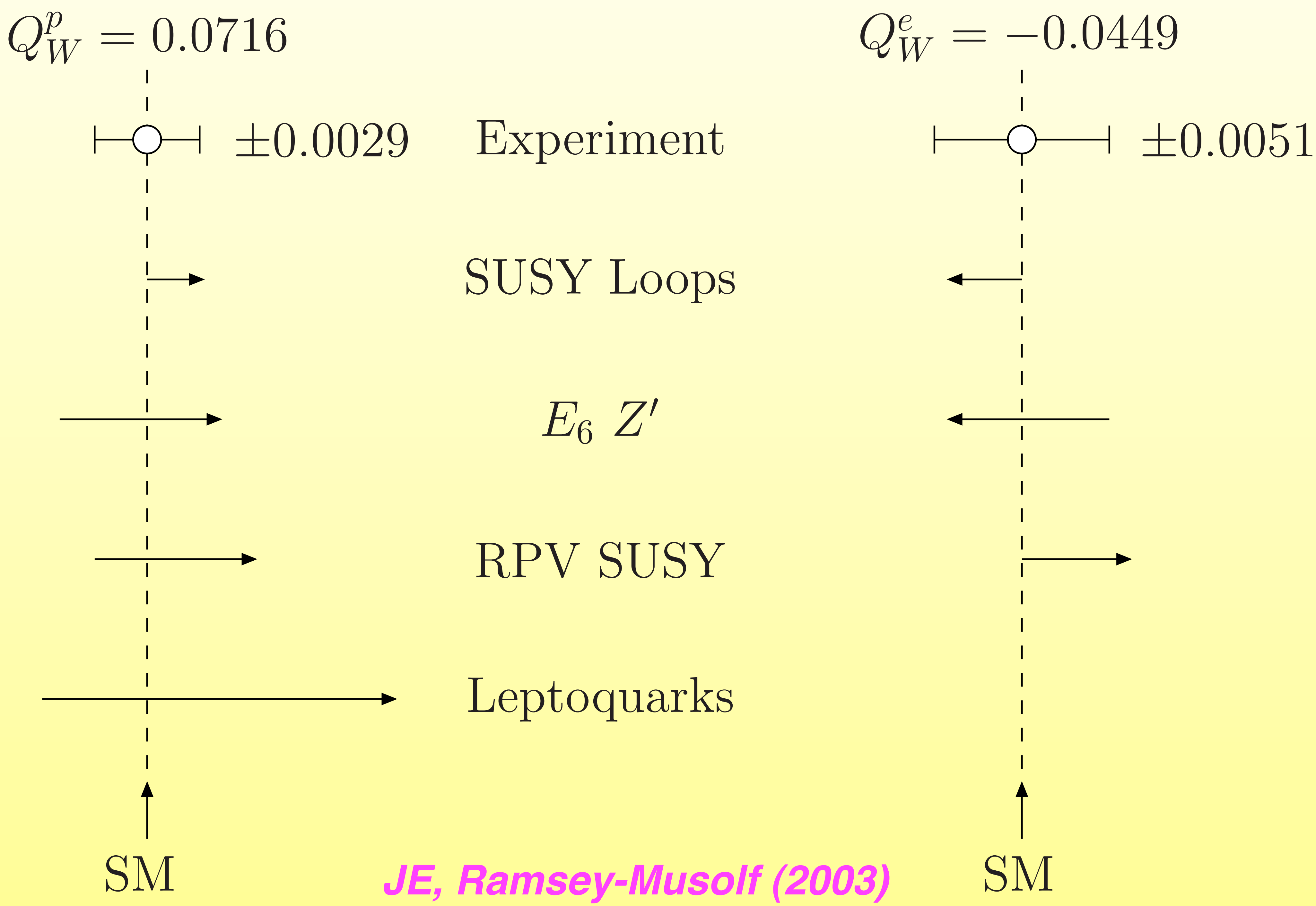




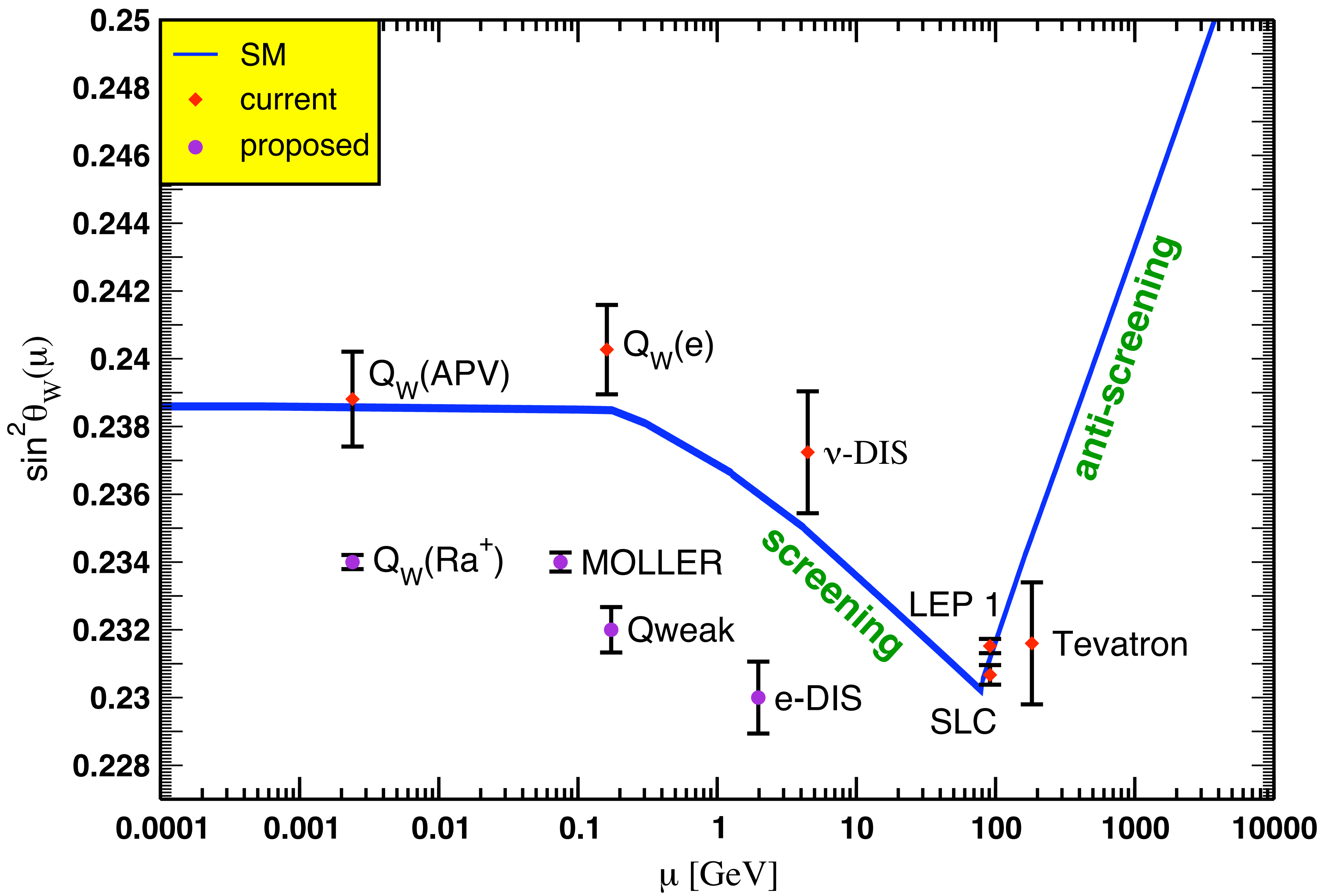
Ramsey-Musolf, Su (2006)



Weak Charges & New Physics



Running weak mixing angle



uncertainty in prediction is small except possibly in the hadronic transition region ***JE, Ramsey-Musolf (2005)***

Electric Dipole Moments

EDMs and CP violation

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- $(-1)^{2j}\,\Psi = T^2\,\Psi = T\,\xi\Psi = \xi^*\,T\Psi = |\xi|^2\,\Psi = \Psi$
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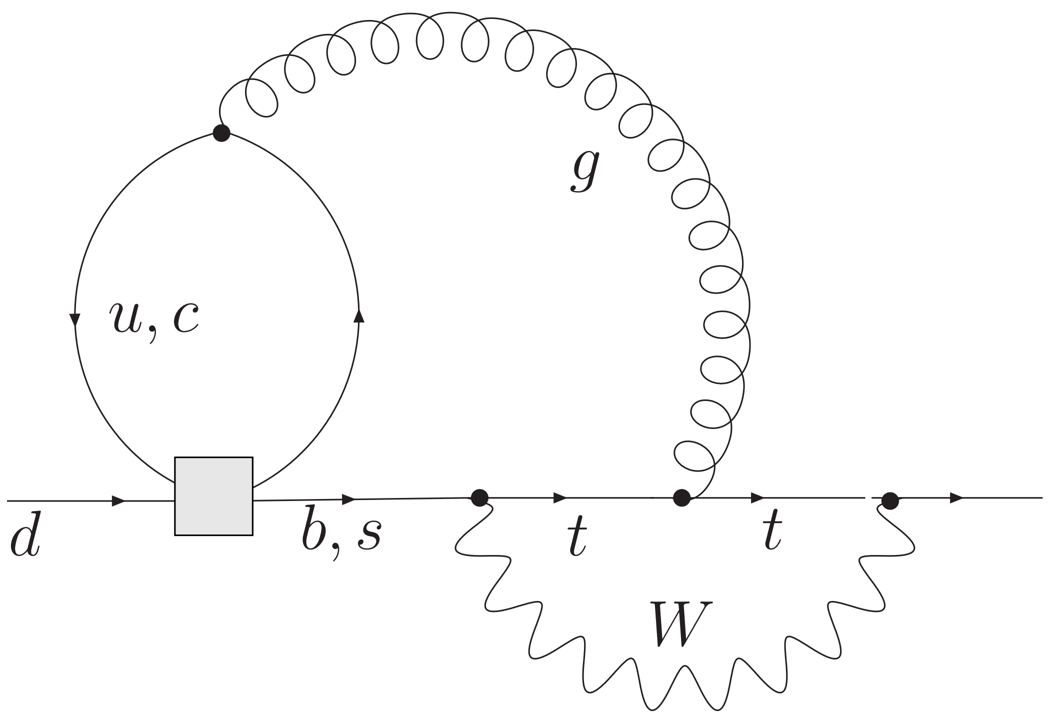
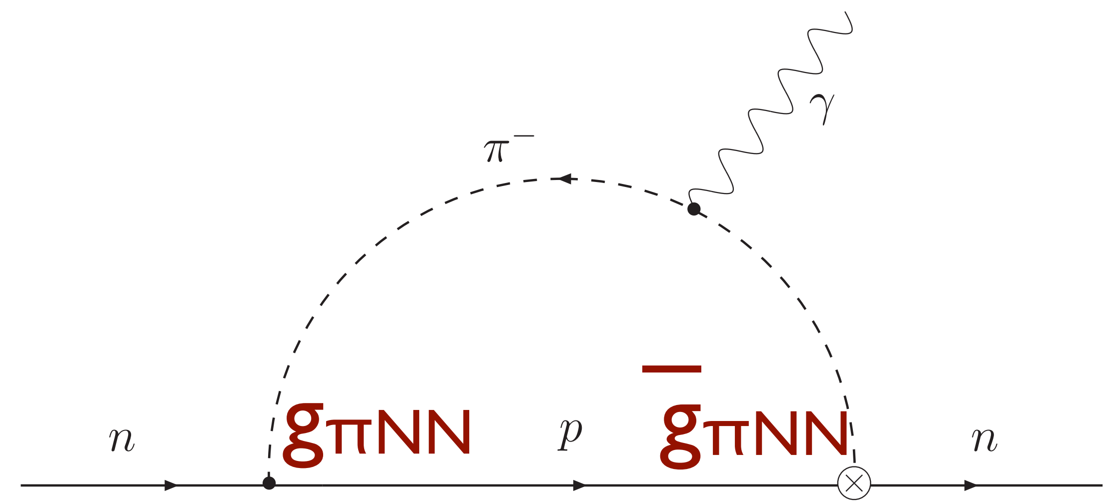
- SM: $|d_n| \simeq 10^{-19}$ e fm ***McKellar, Choudhury, He, Pakvasa (1987)***

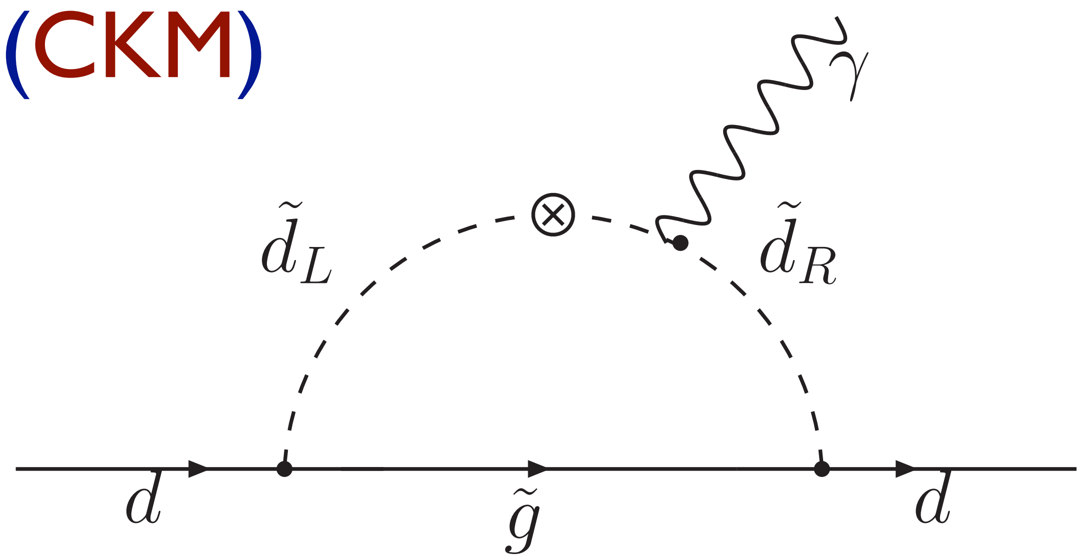
Sources for EDMs



Electroweak (CKM)



QCD (θ-term)



New Physics (SUSY)

Pospelov, Ritz (2010)

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- analogous logs enter chromo-electric ***de Vries, Timmermans, Mereghetti, van Kolck (2010)*** and gravitational dipole moments

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- consider simple toy model

Grojean, Servant, Wells (2004); Huber, Pospelov, Ritz (2005)

$$L = (H^\dagger H)^3/\Lambda^2 + Z_t\,(H^\dagger H)\,\bar{Q}_3\,H\,t$$

$\Rightarrow$ $\eta_B \sim 10^{-10}$ if $\Lambda_{CP} \sim 400 \ldots 800$ GeV, while next generation of EDM experiments will probe $\Lambda_{CP} \sim 3$ TeV!

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  ➡ $\Lambda > 56$ TeV (if tree level induced; loop induced $/2\pi$)
- SUSY thresholds: $\Lambda \gtrsim 10^5$ TeV ***Pospelov, Ritz, Santoso (2005)***

Summary and Outlook

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  - PV e^- scattering and $g_\mu-2$ will help to discriminate between scenarios and models, and fix parameters
- scenario 2: nothing or little beyond the Higgs at LHC
  - use ultra-high precision Møller, APV & EDM efforts to see if new physics is pushed up by merely a little hierarchy – such as in little and littlest Higgs theories
    Arkani-Hamed, Cohen, Georgi (2001);
    Arkani-Hamed, Cohen, Katz, Nelson (2002)

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Summary and outlook

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- scenario 2+: beyond that, need SM rare and forbidden processes from CP (EDMs) and flavor sectors
  ☞ ***talk by Toshio Numao*** to study PeV region
  - these observables have fantastic reach
  - but single number measurements (no cross checks)
  - on the other hand, no “look elsewhere effect”
  - nEDM by itself — while a breakthrough in its own right (θ_{QCD}) — not enough to establish new physics