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Introduction to Physics beyond the Standard Model

Part 3: Precision Tests of the Standard Model

Osaka University, 20/21 May 2014

Plan

- Precision measurements:
  - LEP
  - Hadron Colliders
  - Polarized Low Energy Electron Scattering
  - Atomic Parity Violation
  - Anomalous Magnetic Moments
- Flavor Physics and CP violation
- Null tests:
  - Proton Stability
  - Lepton Flavor Violation
  - Electric Dipole Moments

Precision Observables

Precision Physics

- Standard Model has 18 free parameters:
  - (3+3+3=9) Masses of quarks and leptons
  - (3) Gauge couplings of SU(3)xSU(2)xU(1)
  - (2) Higgs mass and vacuum expectation value
  - (4) Angles + physical phase of CKM matrix

- But number of observables is infinite!

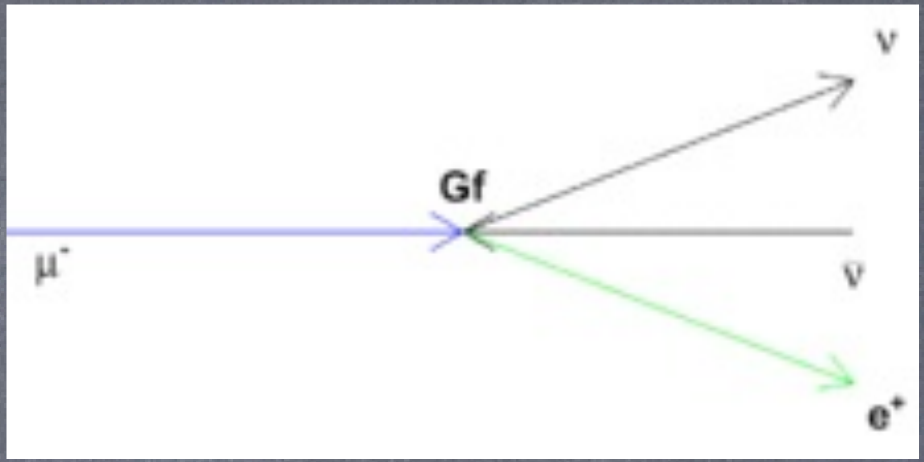
- We can measure all these 18 parameters in various processes, and then predict the outcome of all other processes. This is what we call <u>precision tests of the Standard Model.</u>

EWPT

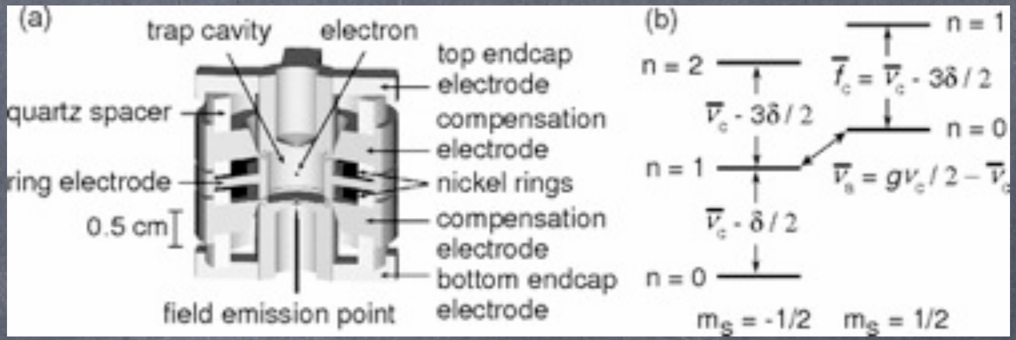
- In high-energy colliders fermion masses (except for the top quark) and CKM angles are typically too small to give observable effects
- In particular at LEP, 4 of the free parameters are most relevant: 3 gauge couplings of SU(3)xSU(2)xU(1) (which set the interaction strength of the electroweak gauge bosons with fermions) the vacuum expectation value of the Higgs field (which set the W and Z boson masses)
- Also, indirect sensitivity to top quark and Higgs boson masses

EWPT - SM input parameters

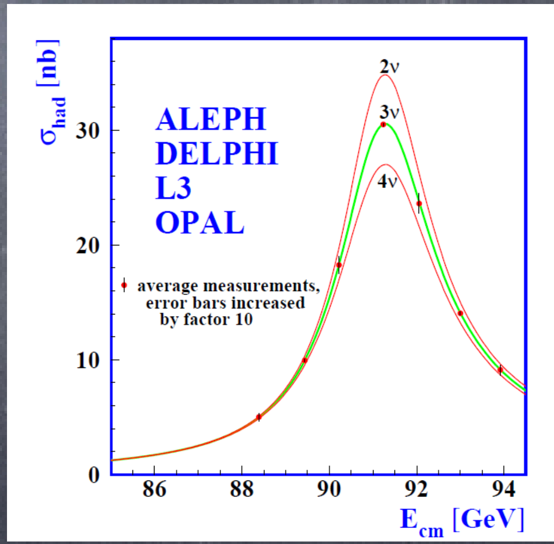
- Muon decay lifetime gives precise determination of Higgs expectation value v



- Anomalous magnetic moment of electron gives a very precise measurement of electromagnetic coupling constant α



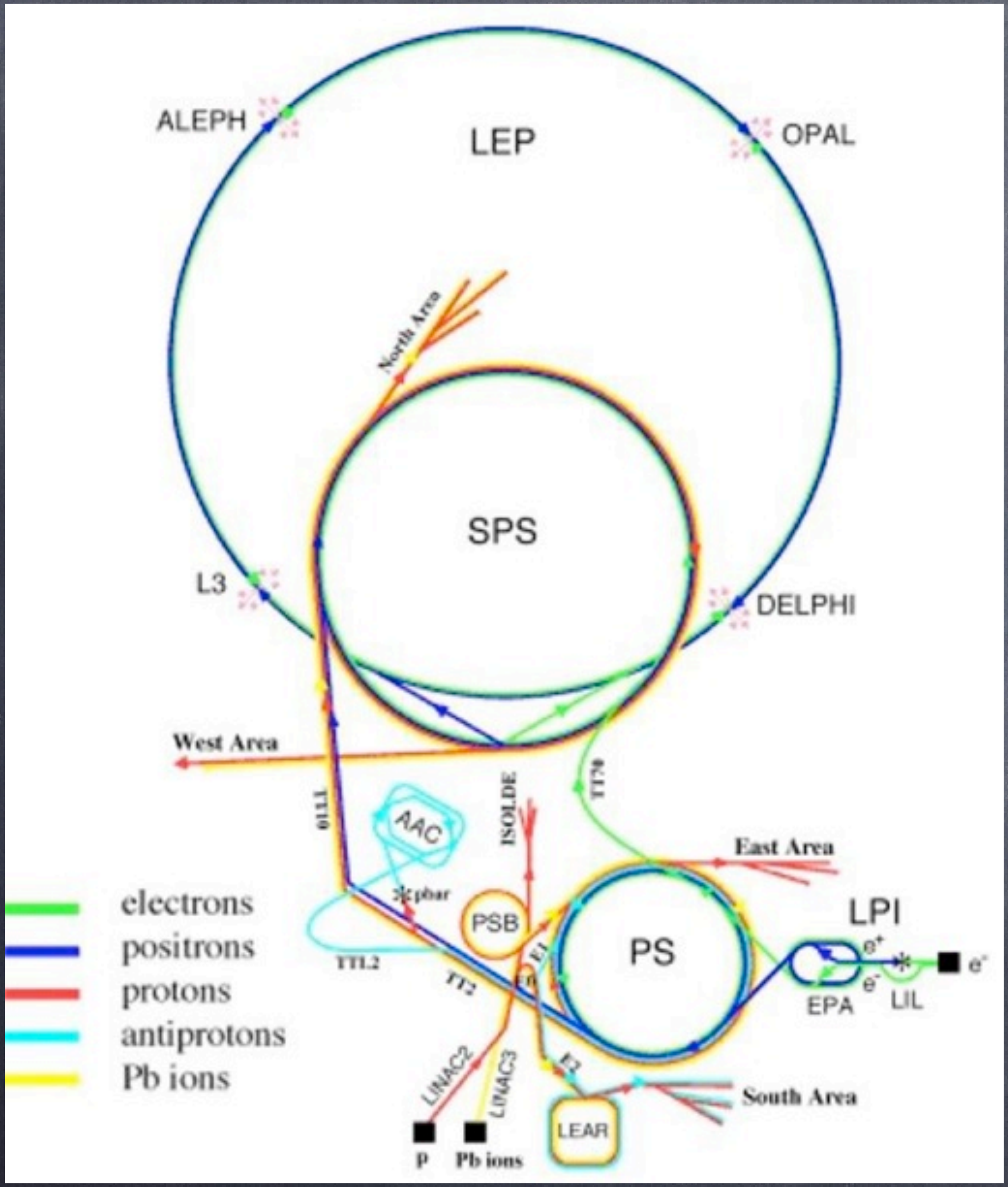
- From LEP-1 collider we know very precisely mass of Z boson mZ and strong coupling constant αs



$$\alpha = \frac{g_L^2 g_Y^2}{4\pi(g_L^2 + g_Y^2)}, \qquad m_Z = \frac{\sqrt{g_L^2 + g_Y^2}\, v}{2} \qquad \alpha_s = \frac{g_s^2}{4\pi}$$

LEP

Large Electron-Positron Collider



- Electron-Positron collider back in the 90s
- First at energy 91.2 GeV at resonance with Z
- then going in steps up to 209 GeV energy

LEP constraints

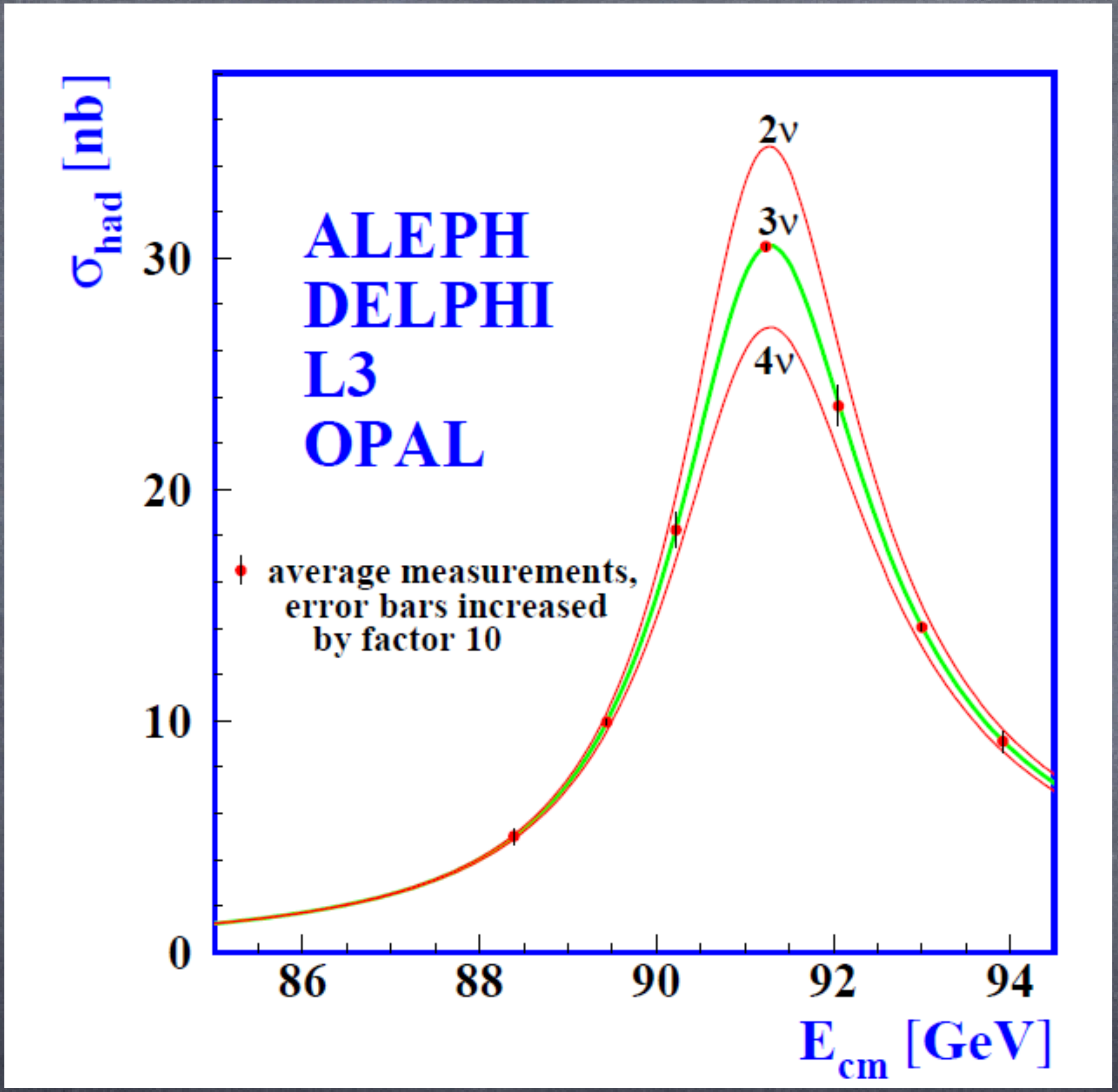
- LEP-1 sensitive to Z boson couplings. Relative precision of order 0.1% for lepton couplings, and of order 1% for quark couplings.
- Direct Z width measurement hence constraints on number of neutrinos
- Also, indirect sensitivity to propagation of all electroweak gauge bosons
- The latter further constrained in LEP-2
- Cubic interactions of gauge bosons constrained in LEP-2 with precision 10%

LEP Legacy

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ $^{(\triangle\triangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\mathrm{th}} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4	4	–
$\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-1.4	4.7	–

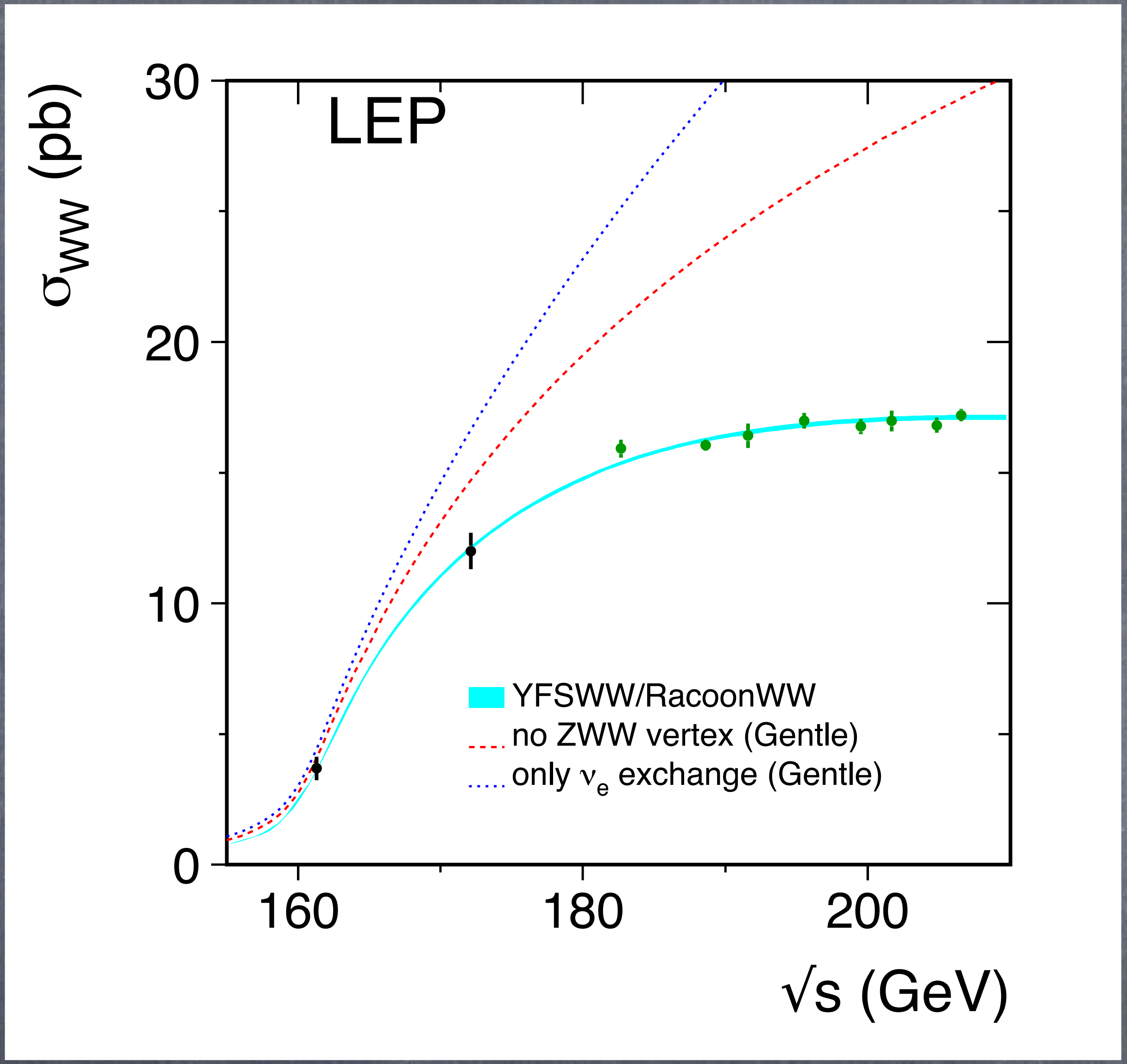
From Gfitter 1209.2716

LEP - number of neutrinos



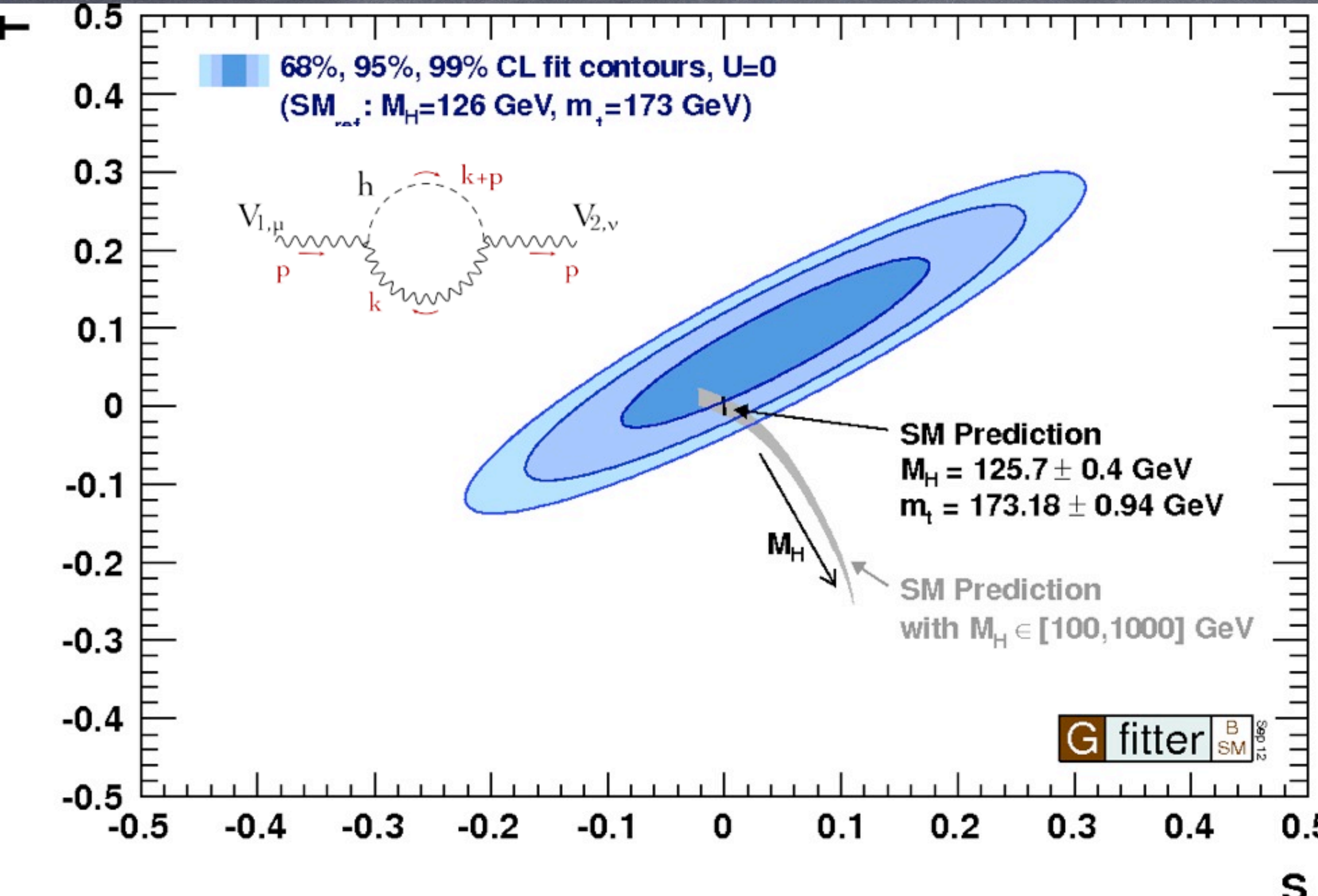
$$N_\nu = 2.984 \pm 0.008$$

LEP - gauge boson self-interactions



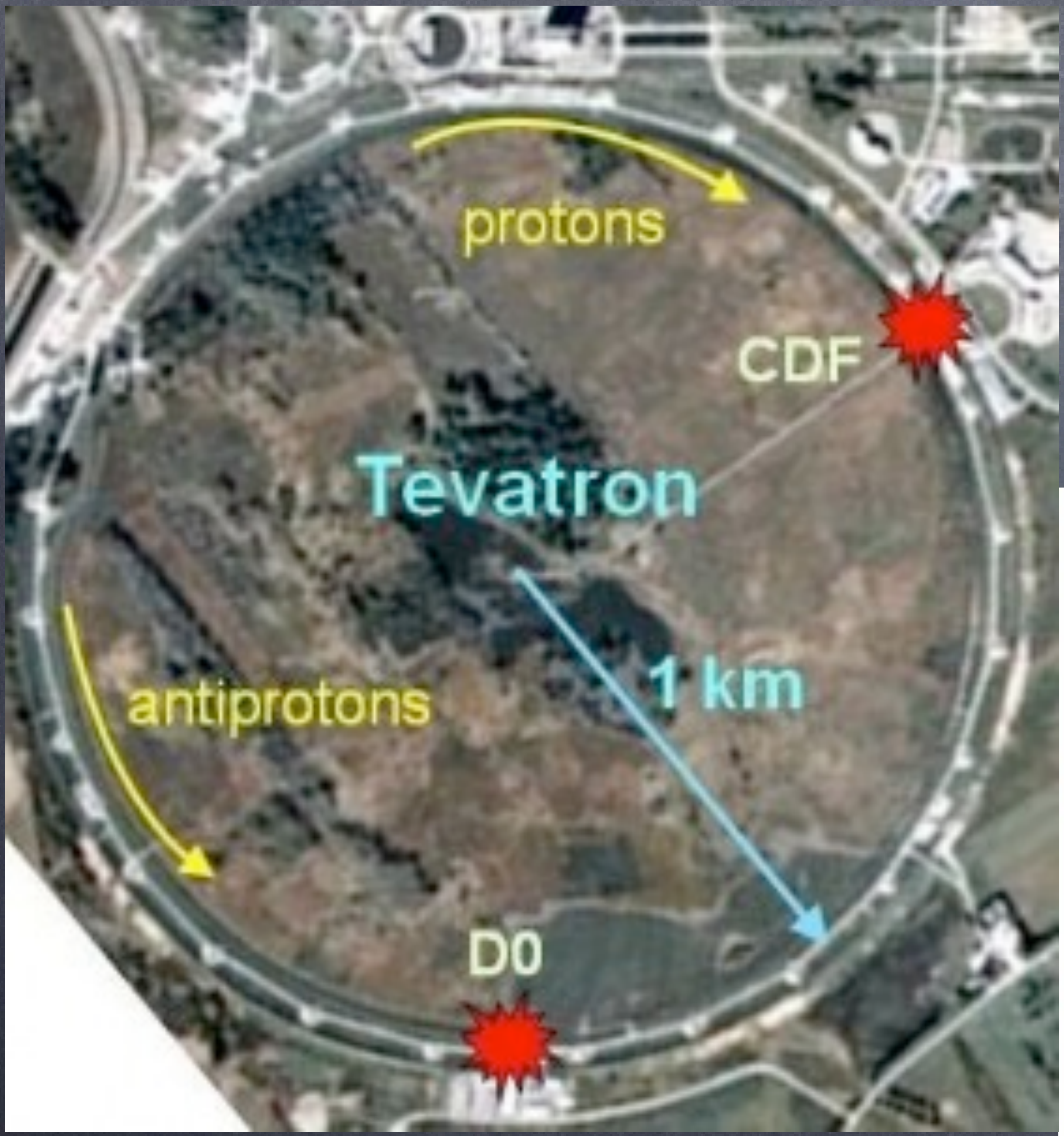
Evidence for WWZ interactions ==
direct confirmation of non-abelian structure of SM

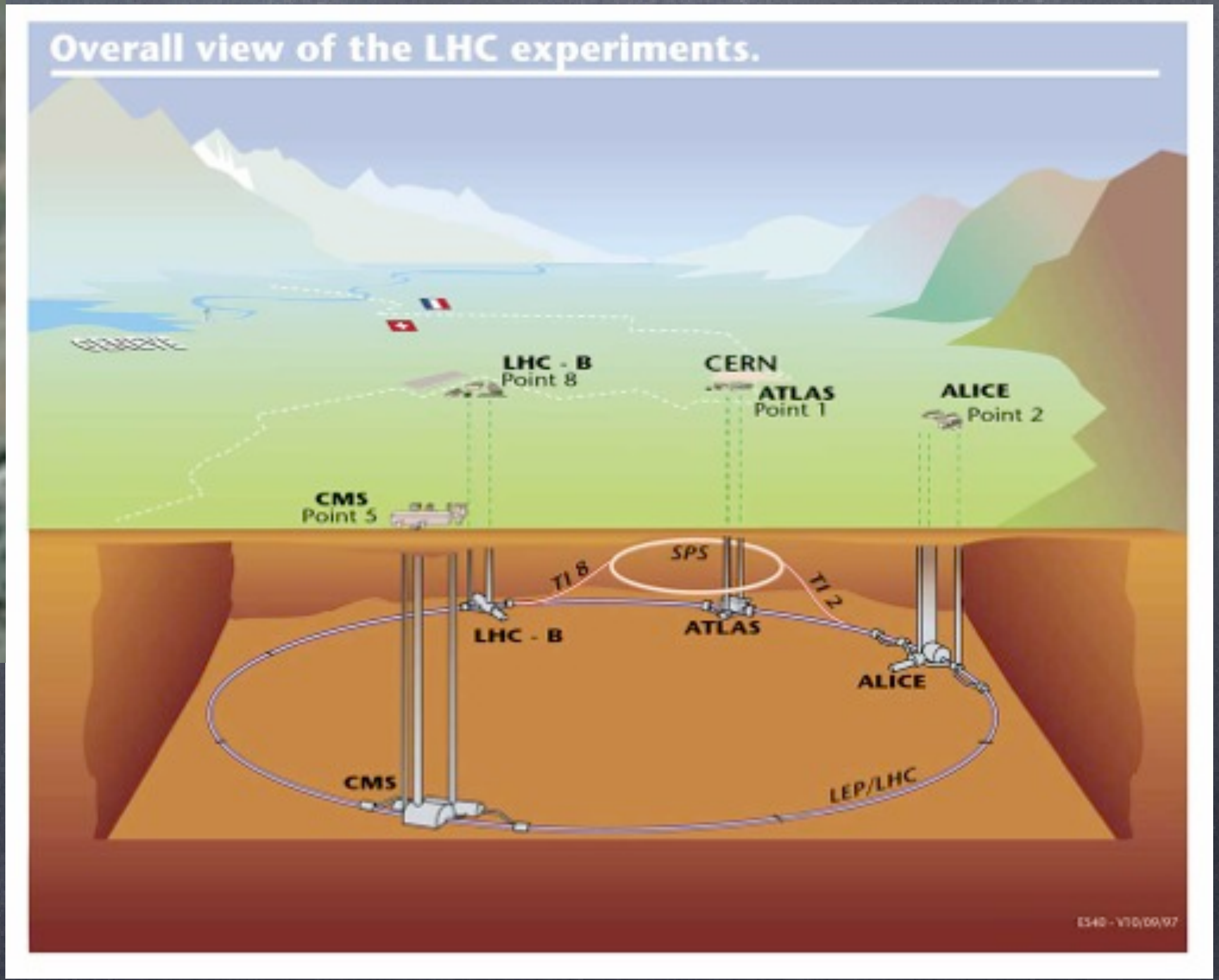
LEP constraints - oblique parameters



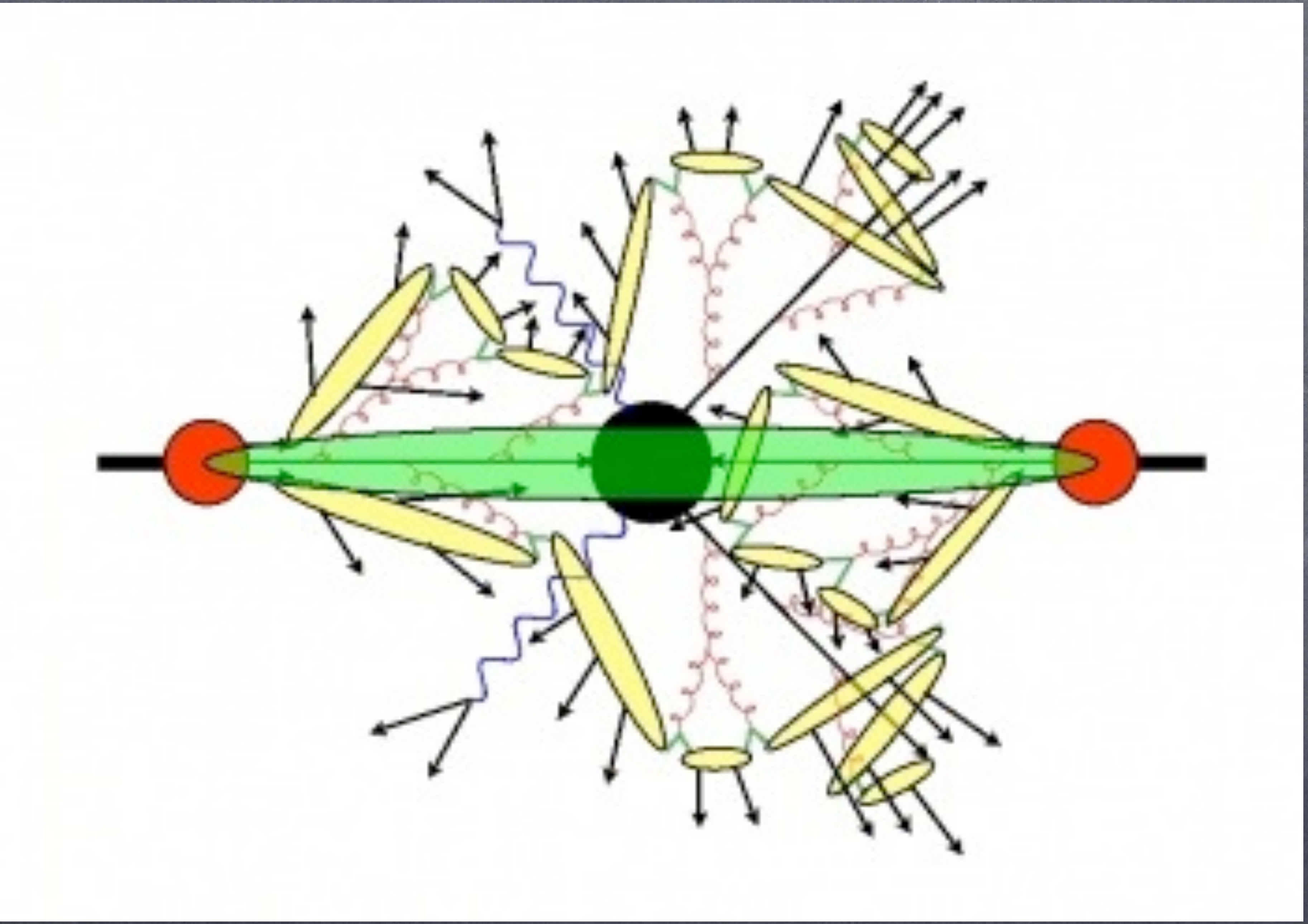
Hadron Colliders

Precision tests in hadron colliders



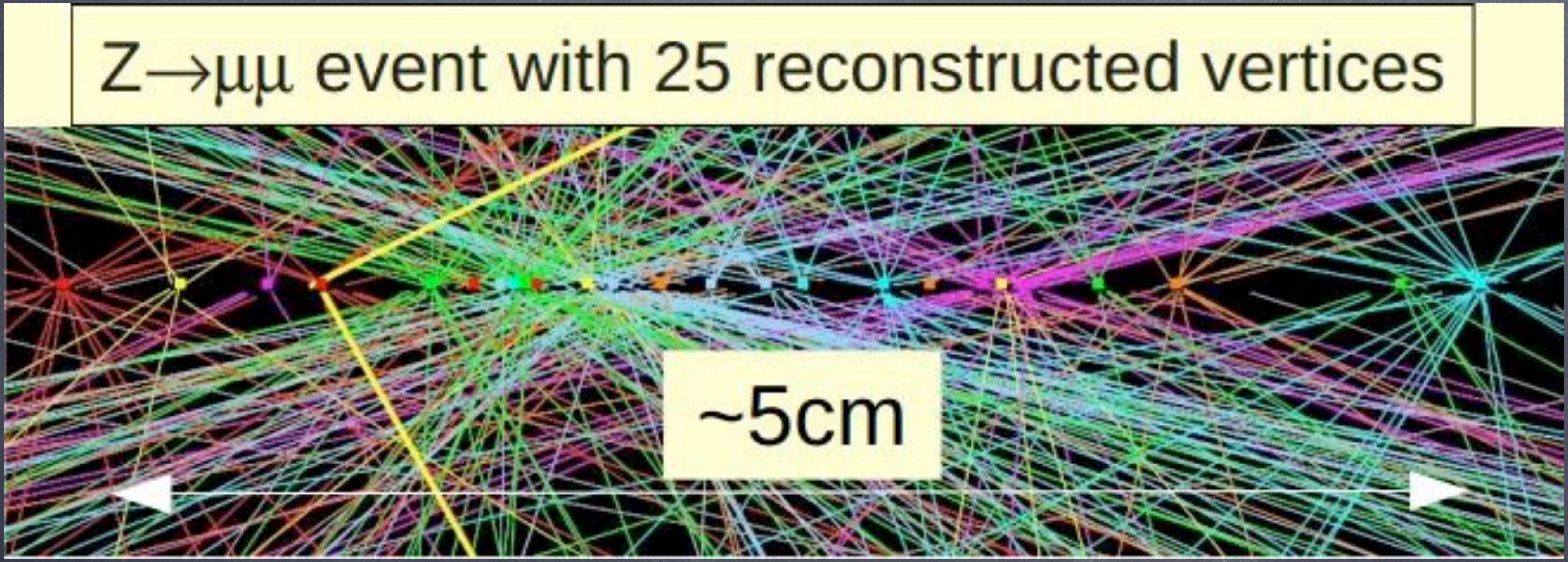


Precision tests in hadron colliders



Naively, not the best place for precision physics

Precision tests in hadron colliders



Naively, not the best place for precision physics

Precision tests in hadron colliders

- Testing QCD, but in most case it rather tests our ability to calculate in QCD
- So far only way to measure top quark mass, and best measurement of W boson mass
- Precision tests of cubic and quartic self-interactions of electroweak gauge bosons
- Higgs couplings measurements

Higgs Couplings Measurements

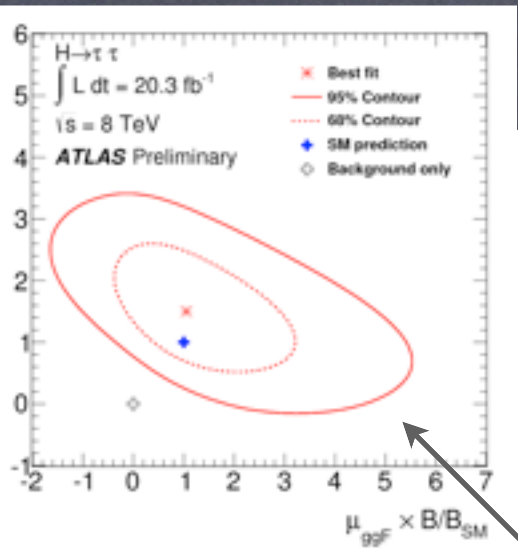
Simplified Effective Higgs Lagrangian

$$\begin{aligned}\mathcal{L}_{h,\mathrm{sim}} = \frac{h}{v}\Big(\quad & 2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu \\ -c_u \sum_{q=u,c,t} m_q \bar{q}q - c_d & \sum_{q=d,s,b} m_q \bar{q}q - c_l \sum_{l=e,\mu\tau} m_l \bar{l}l \\ & + \frac{1}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu}\gamma_{\mu\nu} \\ -\frac{1}{2} c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{4} & c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z_{\mu\nu} \Big)\end{aligned}$$

$$c_{WW} = c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} \qquad c_{ZZ} = c_{\gamma\gamma} + \frac{c_w^2 - s_w^2}{c_w s_w} c_{Z\gamma}$$

- Simpler effective theory with 7 free parameters
- <ALL> these parameters are meaningfully constrained by current Higgs data
- Limit of SM+SILH with constraints $\bar{c}_T = \bar{c}_6 = 0 \qquad \bar{c}_{HW} + \bar{c}_{HB} = 0 \qquad \bar{c}_B + \bar{c}_{HB} = 0$
- Standard Model limit: $c_V = c_f = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$

Higgs: the story so far



ATLAS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$1.55^{+0.33}_{-0.29}$	[5, 6]
	ZZ	$1.41^{+0.42}_{-0.33}$	[5, 7]
	WW	$0.98^{+0.33}_{-0.26}$	[5, 8]
	$\tau\tau$	$1.4^{+0.4}_{-0.5}$	[9]
VH	bb	$0.2^{+0.7}_{-0.6}$	[10]
ttH	bb	2.69 ± 5.53	[11]
	$\gamma\gamma$	-1.39 ± 3.18	[12]
inclusive	$Z\gamma$	2.96 ± 6.69	[13]
	$\mu\mu$	1.75 ± 4.26	[14]

CMS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$0.77^{+0.29}_{-0.26}$	[15]
	ZZ	$0.92^{+0.29}_{-0.24}$	[16]
	WW	$0.68^{+0.21}_{-0.19}$	[16]
	$\tau\tau$	0.87 ± 0.29	[17]
VH	bb	1.00 ± 0.49	[18]
VBF	bb	0.7 ± 1.4	[19]
ttH	bb	$1.0^{+1.9}_{-2.0}$	[20]
	$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$	[20]
	$\tau\tau$	$-1.4^{+6.3}_{-5.5}$	[20]
	multi-ℓ	$3.7^{+1.6}_{-1.4}$	[21]
inclusive	$Z\gamma$	-0.21 ± 4.86	[22]
	$\mu\mu$	$2.9^{+2.8}_{-2.7}$	[23]

7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.03}$$

$$c_u = 1.30^{+0.23}_{-0.27}$$

$$c_d = 1.03^{+0.27}_{-0.17}$$

$$c_l = 1.10^{+0.18}_{-0.15}$$

$$c_{gg} = \frac{g_s^2}{16\pi^2}\left(-0.48^{+0.44}_{-0.17}\right)$$

$$c_{\gamma\gamma} = \frac{e^2}{16\pi^2}\left(0.2^{+2.8}_{-3.3}\right)$$

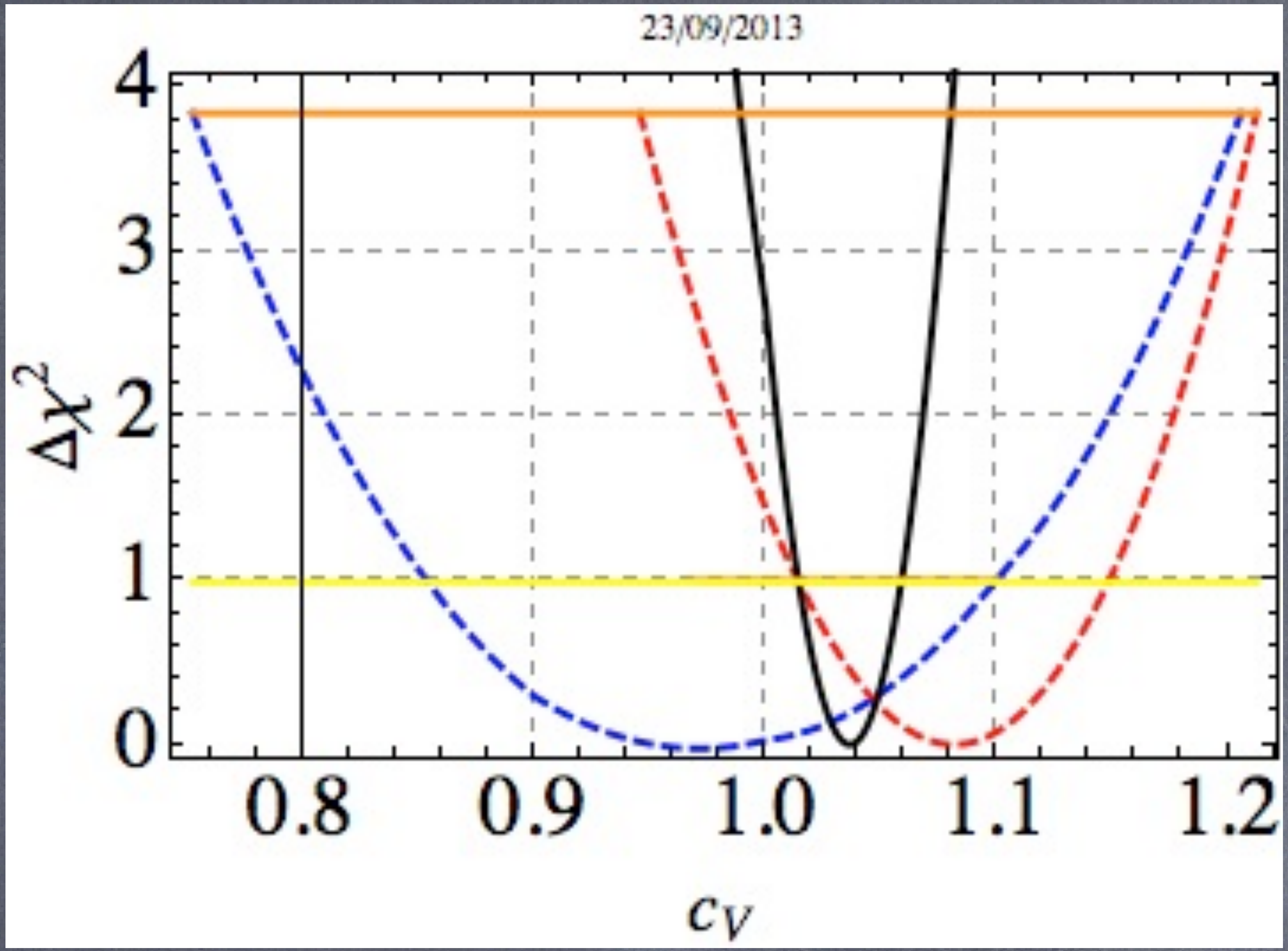
$$c_{Z\gamma} = \frac{e g_L}{\cos\theta_W 16\pi^2}\left(4^{+10}_{-19}\right)$$

using only Higgs data:

$$c_V = 1.03^{+0.08}_{-0.08}$$

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} \approx 5.5$,
with 7 d.o.f.
SM hypothesis is
a perfect fit

7 parameter fit



- Overwhelming evidence it is *a* Higgs boson (particle coupled to mass of W and Z)
- Statement independent of possible higher order couplings to W and Z
- Smells like *the* Higgs boson

Anomalous Magnetic Moments

Magnetic Dipole Moments

- Magnetic dipole moments arise in the Standard Model
- For elementary Dirac fermions (electrons, muons, taus) renormalizability implies g=2
- Small corrections to g-2 from quantum effects, so that g= 2(1 +a)
- One of best measured quantities in physics!

$$\begin{aligned}\vec{\mu} &= g\frac{e}{2mc}\vec{s} \\ g &= \underline{2 \quad (\text{not } 1!)}\end{aligned}$$

$$H_{MDM} = -\mu\vec{S}\cdot\vec{B}$$

Magnetic Dipole Moments

For electron MDM, very precise predictions

- The SM prediction is:

$$a_e^{SM}(\alpha) = a_e^{QED}(\alpha) + a_e^{EW} + a_e^{HAD}$$

- The EW (1&2 loop) term is: Czarnecki, Krause, Marciar

$$a_e^{EW} = 0.2973\,(52) \times 10^{-13}$$

- The Hadronic contribution is: Nomura & Teubner '12,

$$a_e^{HAD} = 16.82\,(16) \times 10^{-13}$$

$$a_e^{QED} = +\,(1/2)(\alpha/\pi) - 0.328\,478\,444\,002\,55(33)\,(\alpha/\pi)^2$$

Schwinger 1948   Sommerfield; Petermann; Suura&Wichmann '57; Elend '66; CODATA Mar '12

$$A_1^{(4)} = -0.328\,478\,965\,579\,193\,78\ldots$$
$$A_2^{(4)}(m_e/m_\mu) = 5.197\,386\,68\,(26) \times 10^{-7}$$
$$A_2^{(4)}(m_e/m_\tau) = 1.837\,98\,(33) \times 10^{-9}$$

$$+\,1.181\,234\,016\,816\,(11)\,(\alpha/\pi)^3$$

Kinoshita; Barbieri; Laporta, Remiddi; … , Li, Samuel; MP '06; Giudice, Paradisi, MP 2012

$$A_1^{(6)} = 1.181\,241\,456\,587\ldots$$
$$A_2^{(6)}(m_e/m_\mu) = -7.373\,941\,62\,(27) \times 10^{-6}$$
$$A_2^{(6)}(m_e/m_\tau) = -6.5830\,(11) \times 10^{-8}$$
$$A_3^{(6)}(m_e/m_\mu, m_e/m_\tau) = 1.909\,82\,(34) \times 10^{-13}$$

$$-\,1.9097\,(20)\,(\alpha/\pi)^4$$

Kinoshita & Lindquist '81, … , Kinoshita & Nio '05; Aoyama, Hayakawa, Kinoshita & Nio 2012

$$+\,9.16\,(58)\,(\alpha/\pi)^5$$ **COMPLETED!** (12672 mass independent diagrams!)

Aoyama, Hayakawa, Kinoshita, Nio, PRL 109 (2012) 111807.

So precise,
it is used to measure
the electromagnetic
coupling constant α

- The 2008 measurement of the electron g-2 is:

$$a_e^{EXP} = 11596521807.3\,(2.8) \times 10^{-13}$$ Hanneke et al, PRL100 (2008) 120801

Slides borrowed from M. Passera

Magnetic Dipole Moments

Intriguing discrepancy for muon MDM

$$a_\mu^{EXP} = 116592089\ (63) \times 10^{-11}$$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda = \mu_\mu/\mu_p$ from CODATA'06

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
$116\,591\,793\ (66)$	$296\ (91) \times 10^{-11}$	3.2 [1]
$116\,591\,813\ (57)$	$276\ (85) \times 10^{-11}$	3.2 [2]
$116\,591\,839\ (58)$	$250\ (86) \times 10^{-11}$	2.9 [3]

with the "conservative" $a_\mu^{HHO}(lbl) = 116\ (39) \times 10^{-11}$ and the LO hadronic from:

[1] Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1

[2] Davier et al, EPJ C71 (2011) 1515 (includes BaBar & KLOE10 2π)

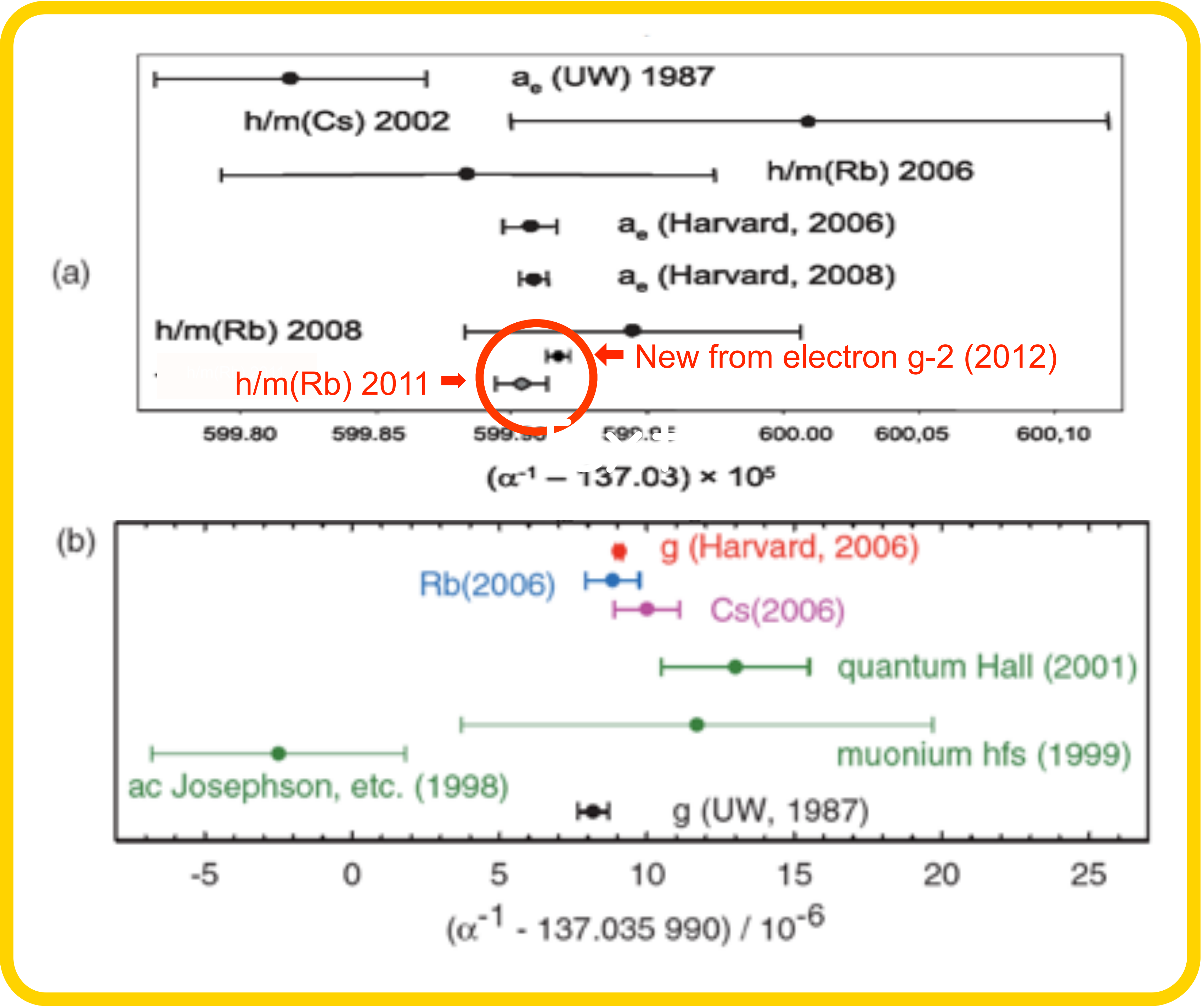
[3] Hagiwara et al, JPG38 (2011) 085003 (includes BaBar & KLOE10 2π)

Slide borrowed from M. Passera

Atomic Transitions

Atomic Transitions

Can be used measure α



Gabrielse, Hanneke, Kinoshita, Nio & Odom, PRL99 (2007) 039902
Hanneke, Fogwell & Gabrielse, PRL100 (2008) 120801
Bouchendira et al, PRL106 (2011) 080801

Atomic Parity Violation

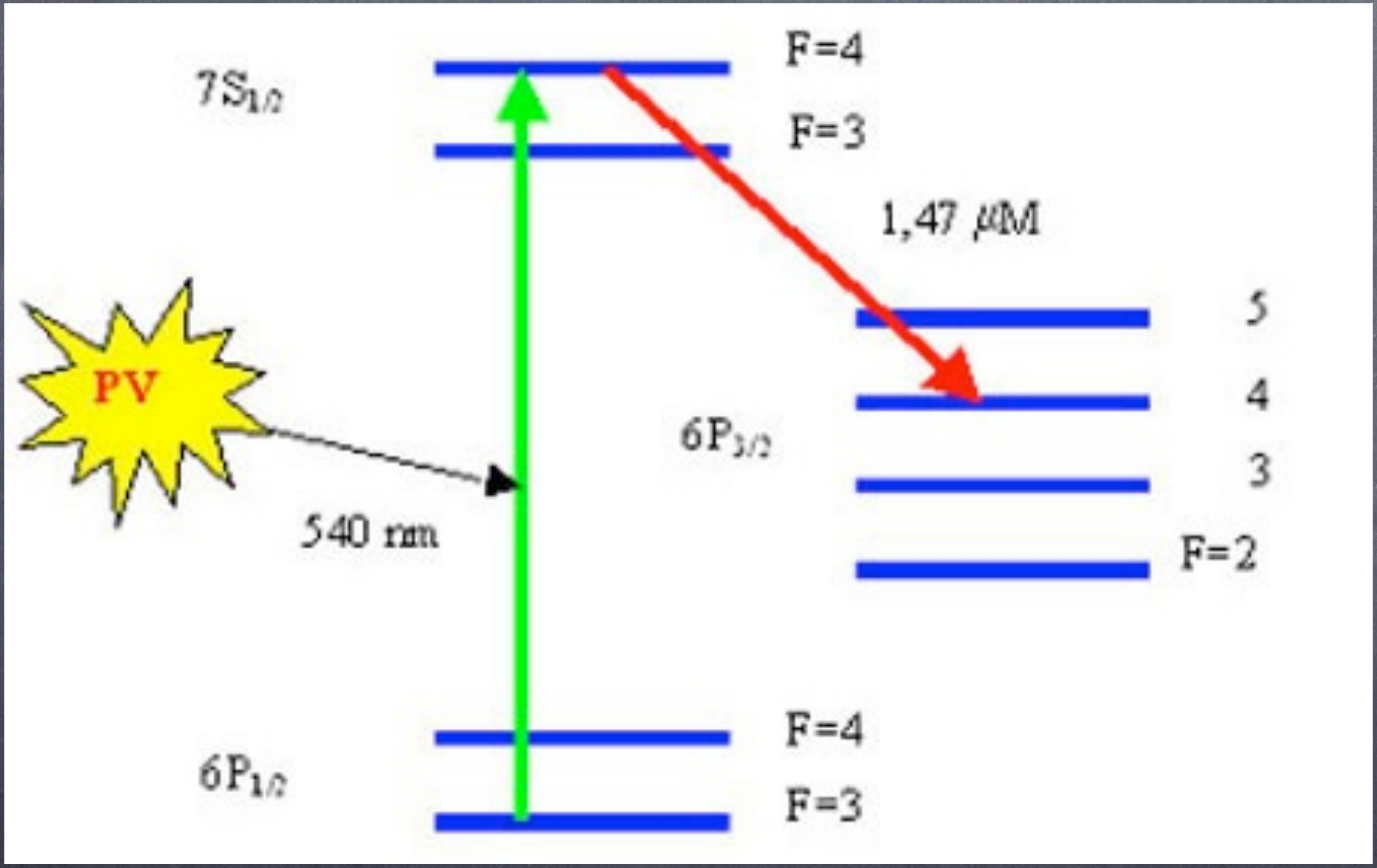
- In the SM, exchange of the Z boson leads to effective force between electrons and quarks
- At low energies, this becomes new effective force between electrons and protons/ neutrons
- Because couplings of Z boson violate parity, there will be a new parity violating spin-momentum interaction in the quantum mechanical Hamiltonian

Weak Charge

$$V_{pv} = \frac{Q_W G_F}{4\sqrt{2}} \delta^3(r_e) \frac{\sigma_e \cdot p_e}{m_e c} + H.C.$$

Atomic Parity Violation

"Forbidden" transitions in Cesium atoms



$$Q_W^{\text{Ce}} = -73.16 \pm 0.35 \qquad Q_W^{\text{Ce}}(SM) = -73.16 \pm 0.03$$

Low Energy Electron Scattering

Atomic Parity Violation

- In the SM, exchange of the Z boson leads to effective force between electrons and quarks that violates parity

- Therefore left-handed and right handed electrons interact differently with nuclei

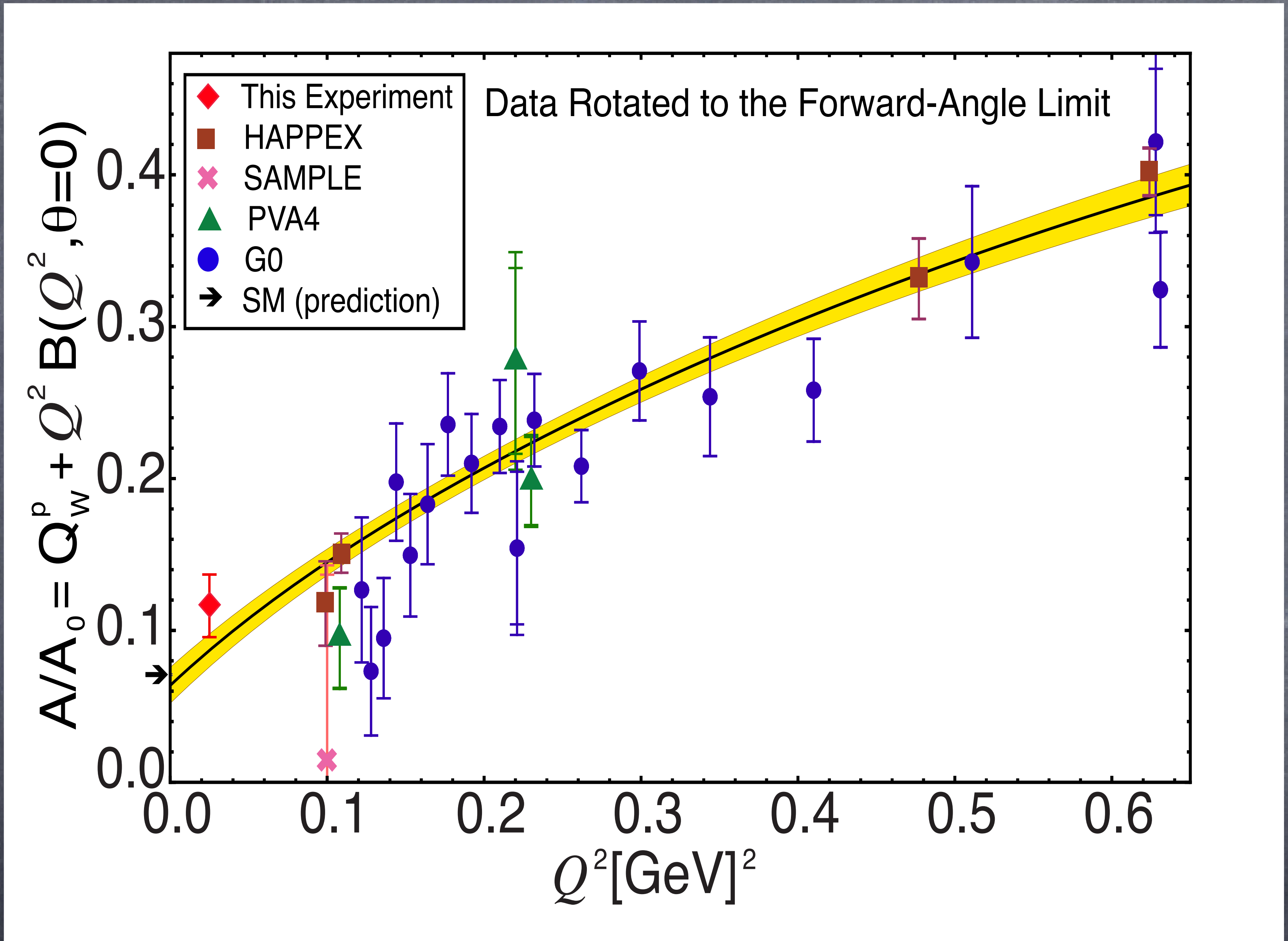
- One can precisely measure left-right asymmetry for another measurement of weak charge

Weak Charge

$$V_{pv} = \frac{Q_W G_F}{4\sqrt{2}} \delta^3(r_e) \frac{\sigma_e \cdot p_e}{m_e c} + H.C.$$

Atomic Parity Violation

Measuring the weak charge of the proton



QWEAK, 1311.6437

$$Q_W^p = 0.064 \pm 0.012 \qquad Q_W^p(SM) = 0.0710 \pm 0.0007$$

Measured Predicted

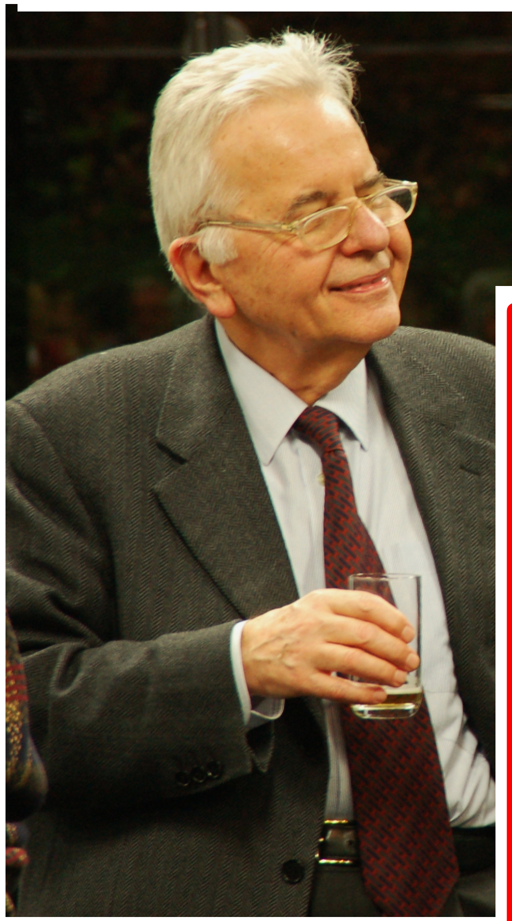
Flavor Physics
and
CP violation

Flavor Tests

- Flavor Physics = transition between different quarks (more precisely, between hadrons built of different quarks)
- In the Standard Model, all flavor transitions are described by 3x3 unitary matrix called the CKM matrix.
- 3 angles + 1 CP violating phase account for all flavor transitions observed so far!

CP violation and quark mixing

$$\mathcal{L}_{\mathrm{CC}} = -\frac{g}{\sqrt{2}} \left(\bar{\tilde{U}}_L \gamma^\mu W_\mu^+ V \tilde{D}_L + \bar{\tilde{D}}_L \gamma^\mu W_\mu^- V^\dagger \tilde{U}_L \right) .$$



CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Graphics borrowed from Marcela Bona's lectures

CP violation and quark mixing

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}}\left(\bar{\tilde{U}}_L\gamma^\mu W_\mu^+ V\tilde{D}_L + \bar{\tilde{D}}_L\gamma^\mu W_\mu^- V^\dagger \tilde{U}_L\right).$$

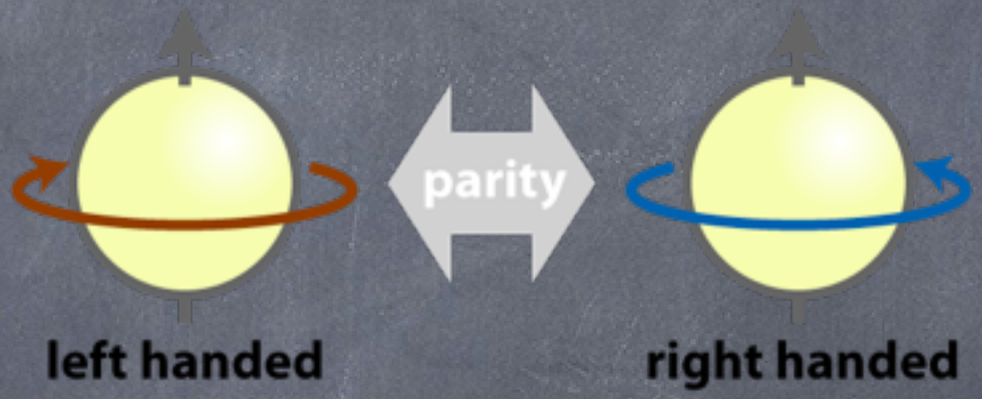
CKM matrix

$$V = \begin{pmatrix} 1-\lambda^2/2 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & +A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

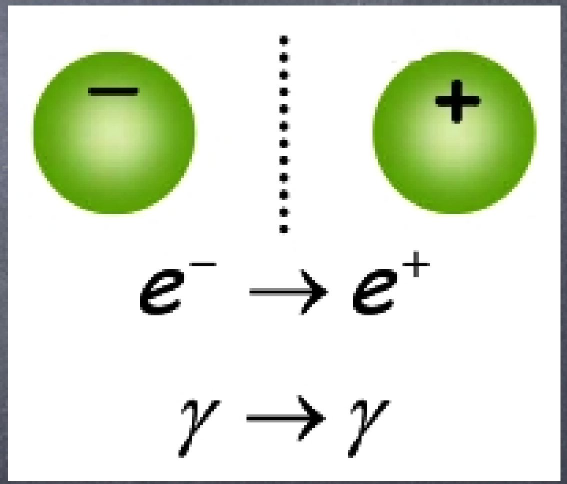
Graphics borrowed from Marcela Bona's lectures

C, P, and CP symmetries

- Parity changes sign of spatial coordinates, and all vectors (not pseudo-vectors). For spin 1 and 1/2 relates opposite helicities



- Charge conjugation changes particle into anti-particle with the same helicity



- What really makes difference between matter and anti-matter is the CP symmetry

Graphics borrowed from Quantum Diaries, and Marcela Bona's lectures

CP violation and quark mixing

$$\mathcal{L}_{\rm kin} = i\bar\psi_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\partial^\mu\psi_\beta + i\bar\psi^c_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\partial^\mu\psi^c_\beta$$
$$\mathcal{L}_{\rm mass} = -m\psi^\alpha\psi^c_\alpha - m\bar\psi^c_{\dot\alpha}\bar\psi^{\dot\alpha}$$
$$\mathcal{L}_{\rm int} = g_{V,L}V^\mu\bar\psi_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\psi_\beta - g_{V,R}V^\mu\bar\psi^c_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\psi^c_\beta$$

- For fermions P and C interchange spinor with its conjugate spinor
- P and C broken when couplings are axial, gVL ≠ gVR
- Breaking CP requires complex coupling constants

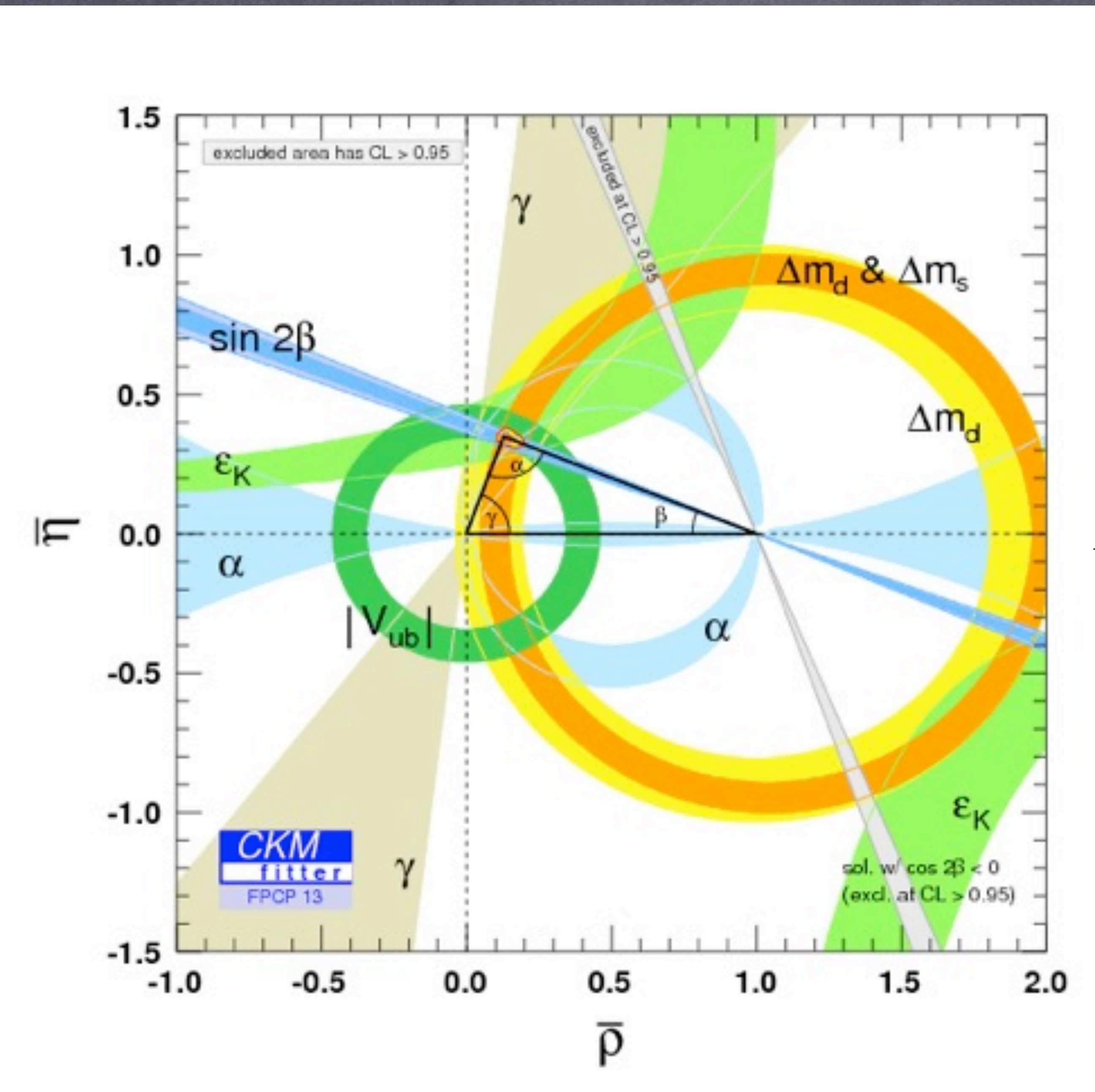
$$\mathbf{P}: \quad \psi_\alpha \to \delta^{\dot\alpha}_\alpha\bar\psi^c_{\dot\alpha} \quad V^0 \to +V^0 \quad V^i \to -V^i$$

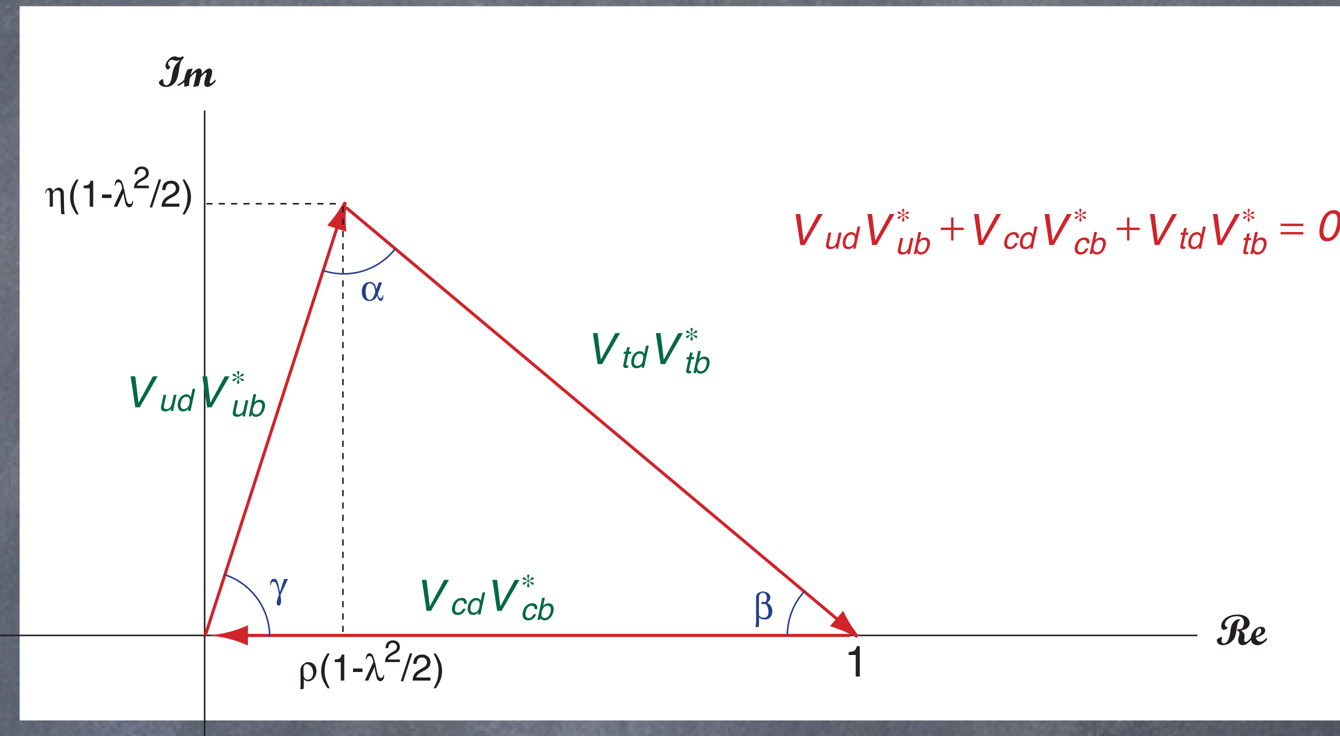
$$\mathbf{C}: \quad \psi_\alpha \to \psi^c_\alpha \quad V^\mu \to -V^\mu$$

$$\mathbf{CP}: \quad \psi_\alpha \to \delta^{\dot\alpha}_\alpha\bar\psi_{\dot\alpha} \quad V^0 \to -V^0 \quad V^i \to +V^i$$

$$gV^\mu\bar\psi_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\chi_\beta + g^*V^\mu\bar\chi_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\psi_\beta \to g^*V^\mu\bar\psi_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\chi_\beta + gV^\mu\bar\chi_{\dot\alpha}\bar\sigma_\mu^{\dot\alpha\beta}\psi_\beta$$

CP violation and quark mixing

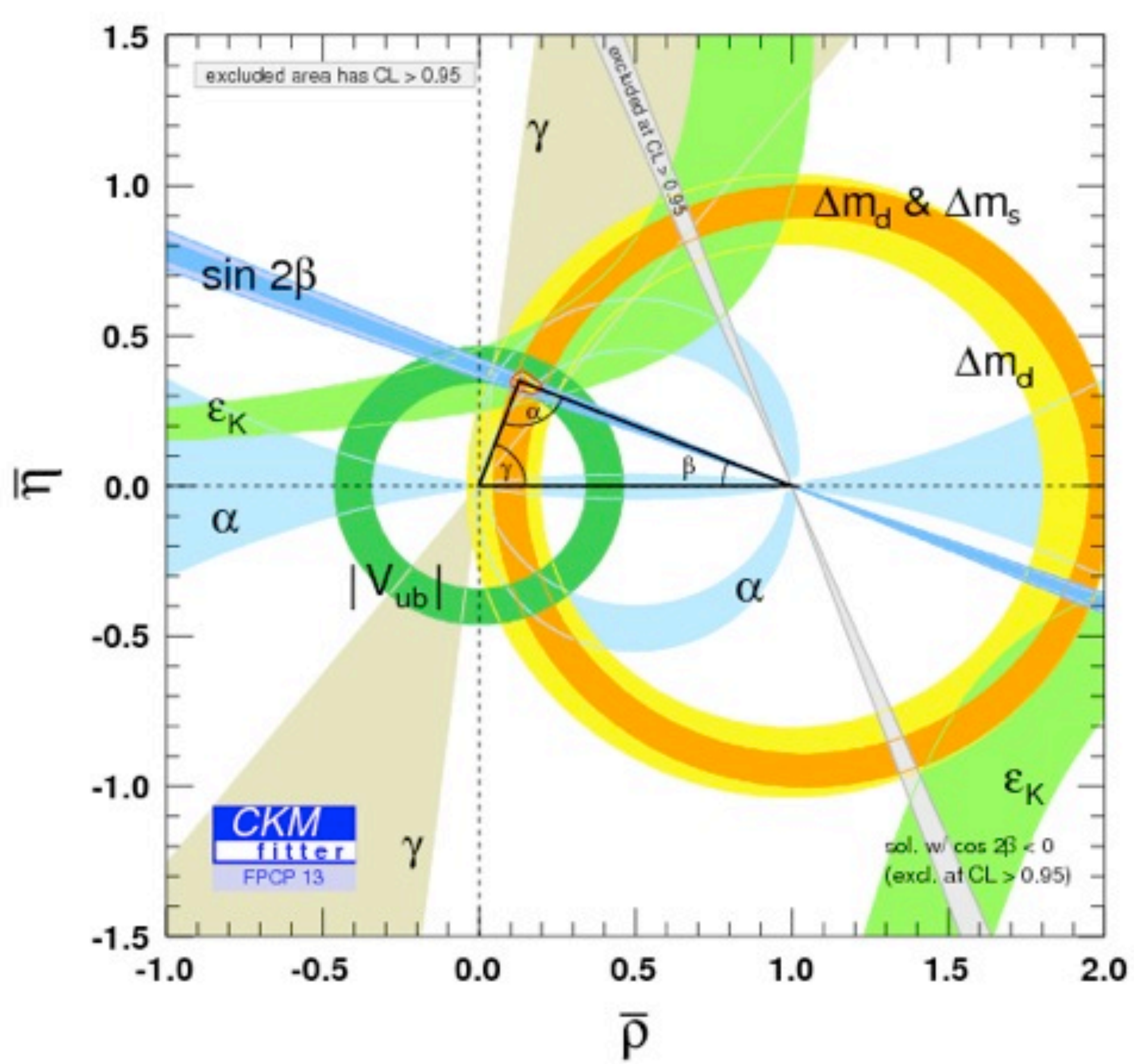




$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Triangle borrowed from Hans of Nikhef

CP violation and quark mixing



Sides:

V_{ud}	β-decay	$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$	$\cos\vartheta_C$
V_{us}	K-decay	$K^+ \to \pi^0 + \ell^+ + \nu_\ell$	$\sin\vartheta_C$
		$K^0 \to \pi^- + \ell^+ + \nu_\ell$	
V_{cd}	ν-production of c's	$\nu_\ell + d \to \ell^- + c$	$\cos\vartheta_C$
V_{cs}		$D^\pm \to K^0 + \ell^\pm + \nu_\ell$	$\sin\vartheta_C$
V_{ub}	B-decay	$b \to u + \ell^- + \bar{\nu}_\ell$	
V_{cb}		$b \to c + \ell^- + \bar{\nu}_\ell$	
V_{td}	Δm in B^0-$\bar{B}^0$		

$B^0_d \to J/\Psi\, K_S$	sin 2β
$B^0_d \to \pi^+\pi^-$	sin 2α
$B^0_s \to D_S^\pm K^\mp$	sin 2γ

Borrowed from Hans of Nikhef

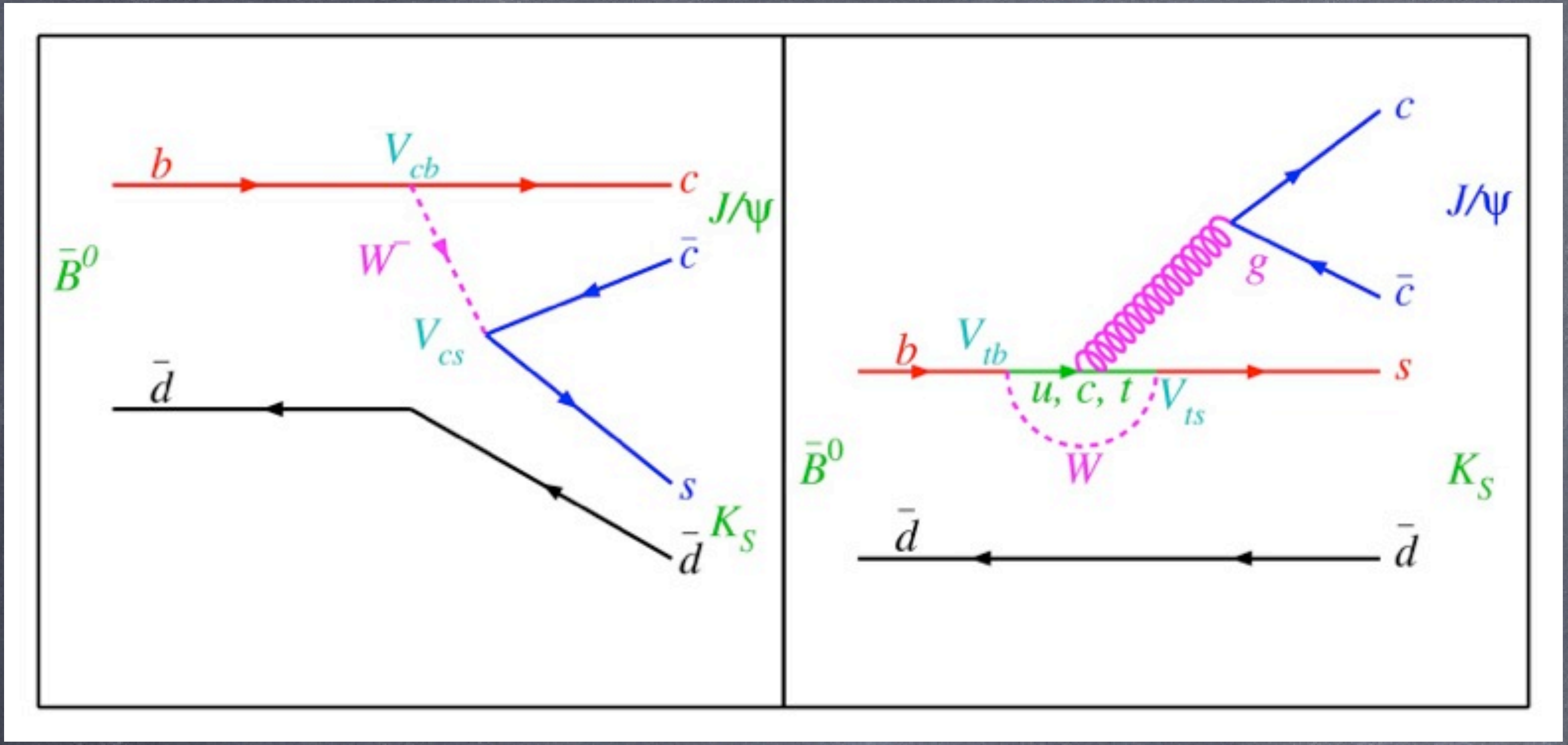
CP violation and quark mixing

Strong bounds on flavor violating higher-dimensional operators

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

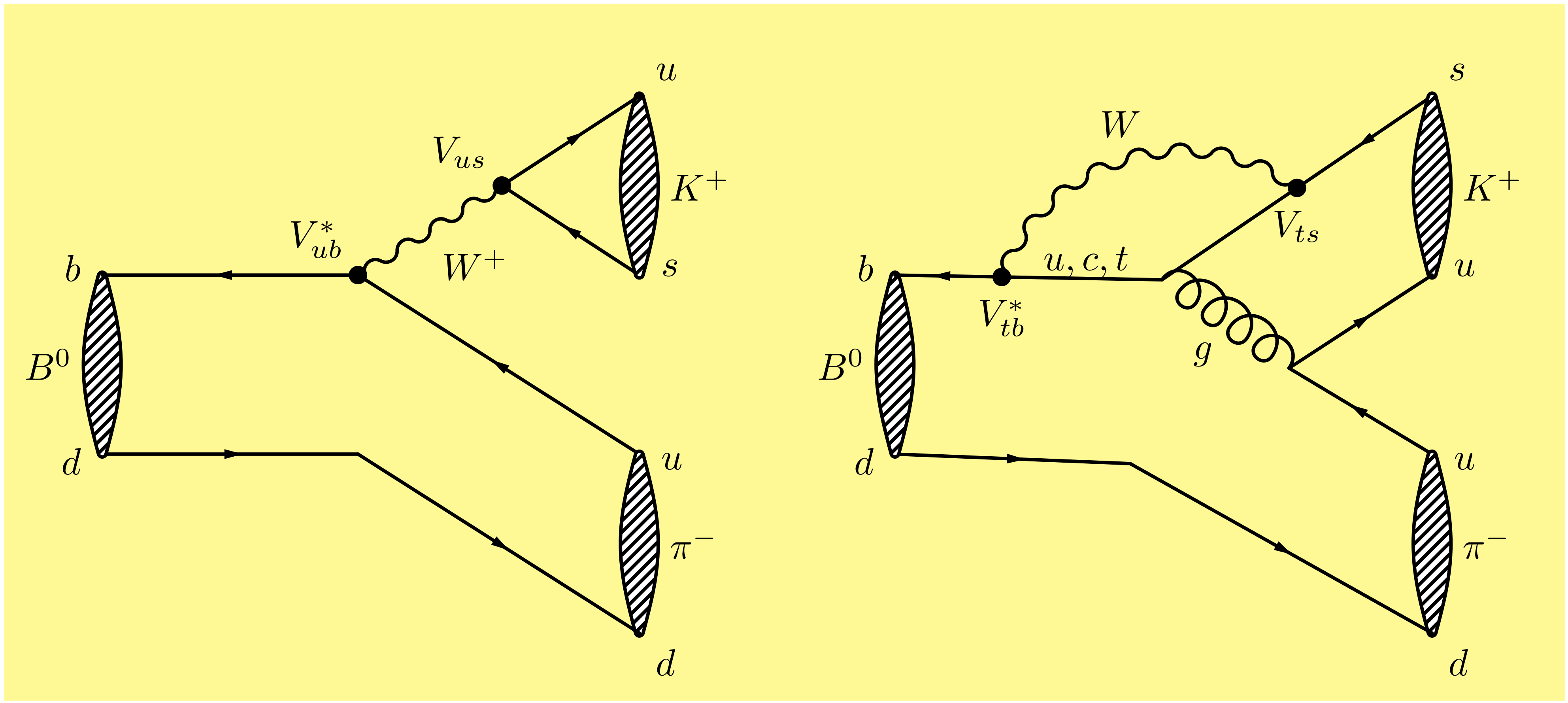
from Isidori et al. 1002.0900

Flavor Physics - CP violation



$$\boxed{A_{\mathrm{CP},\ B^0\to J/\psi K^0_S}(t) = -\sin 2\beta \sin(\Delta m t)}$$

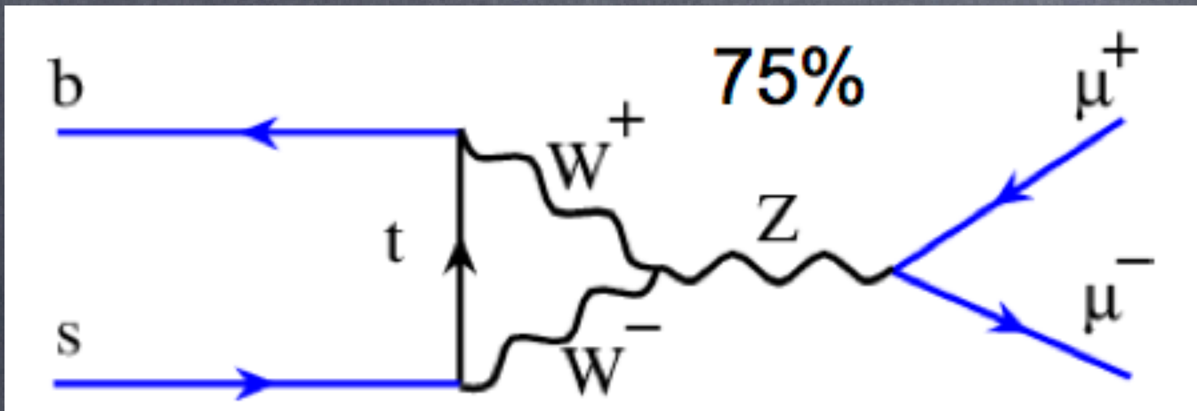
Flavor Physics - CP violation

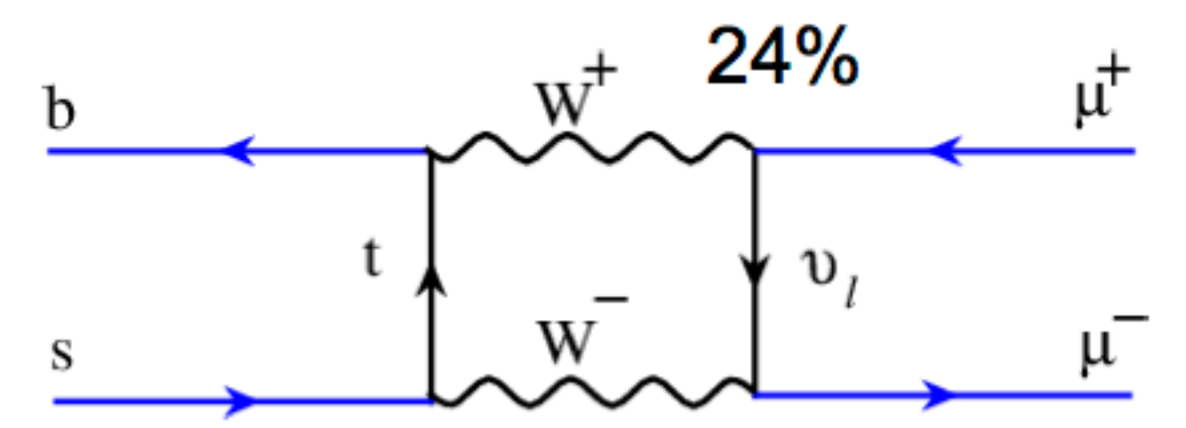


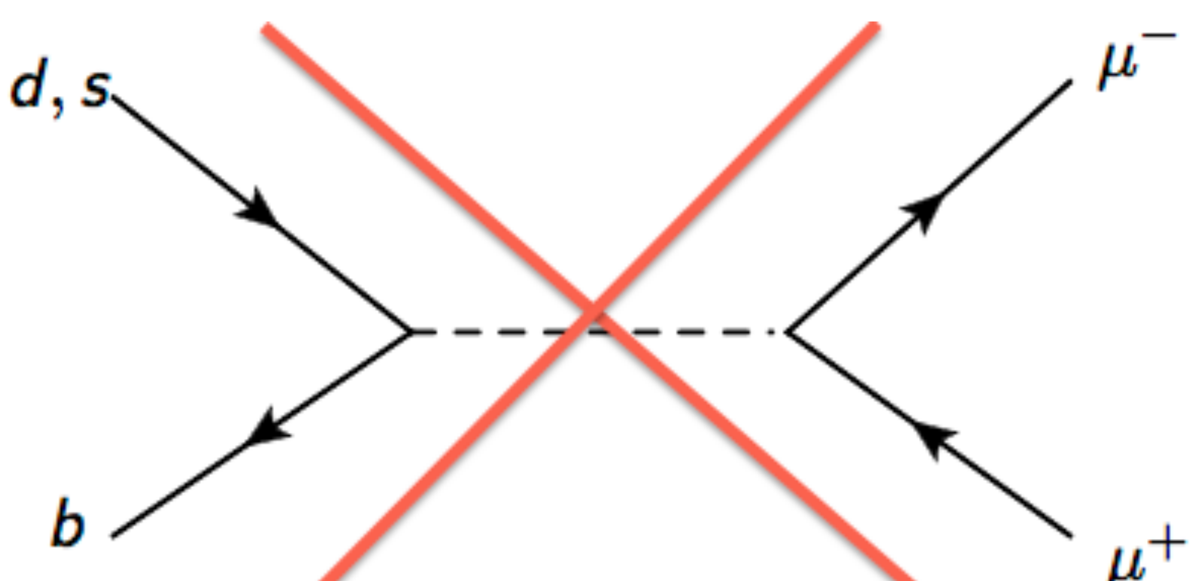
$$A_{CP} = \frac{\Gamma_{B^0 \to \pi^- K^+} - \Gamma_{\bar{B}^0(t) \to \pi^+ K^-}}{\Gamma_{B^0(t) \to \pi^- K^+} + \Gamma_{\bar{B}^0(t) \to \pi^+ K^-}} = -0.098 \pm 0.012$$

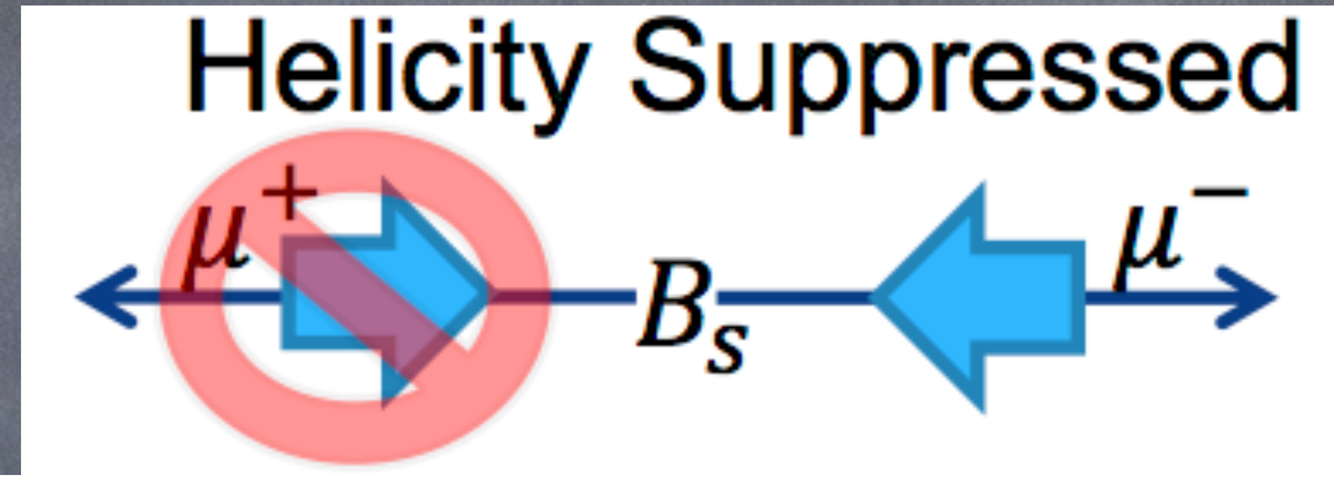
Borrowed from lectures of P. Kooijman & N. Tuning

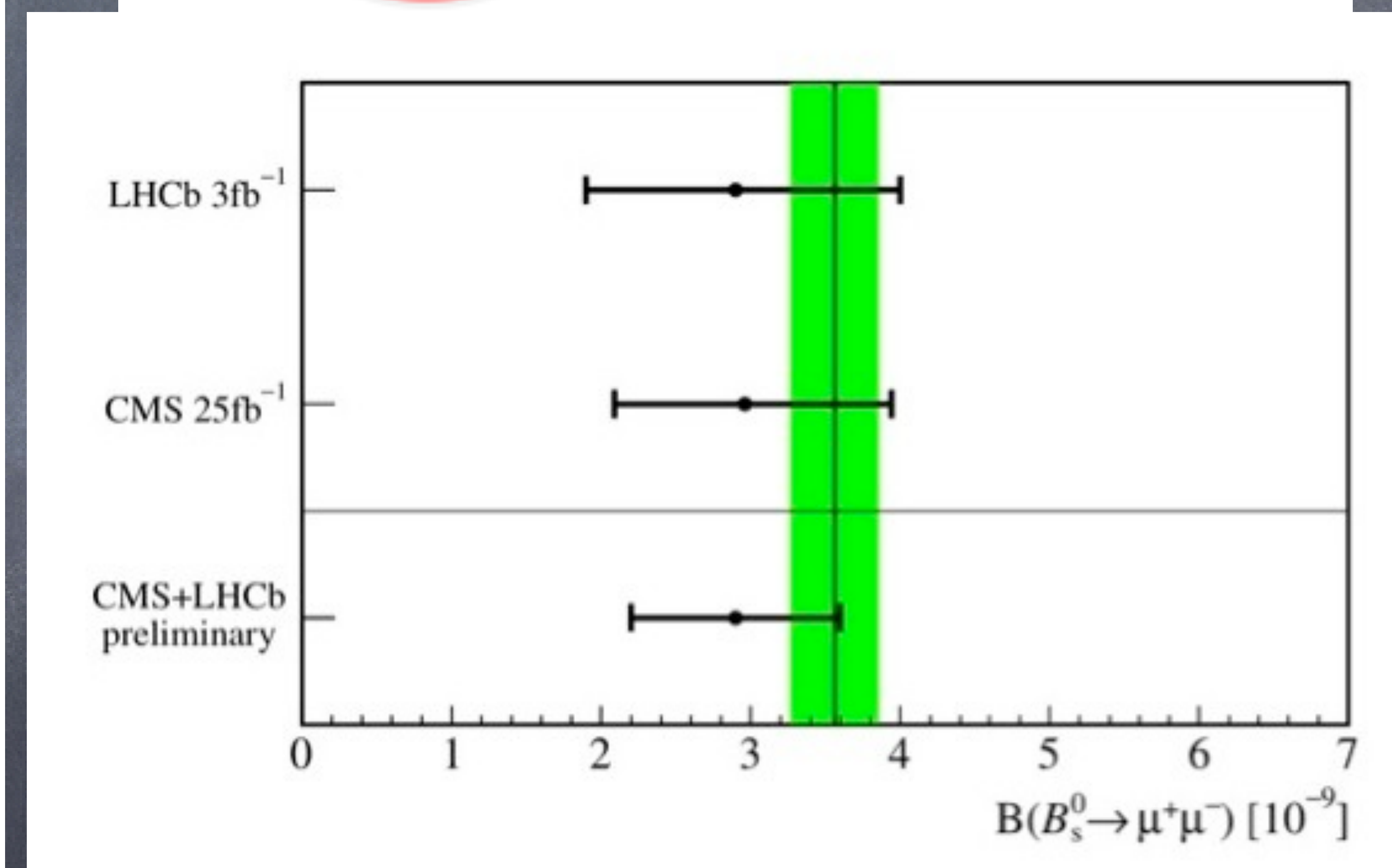
Flavor Physics - Rare Decays











FCNC suppressed in the SM

Null Tests

Null Tests

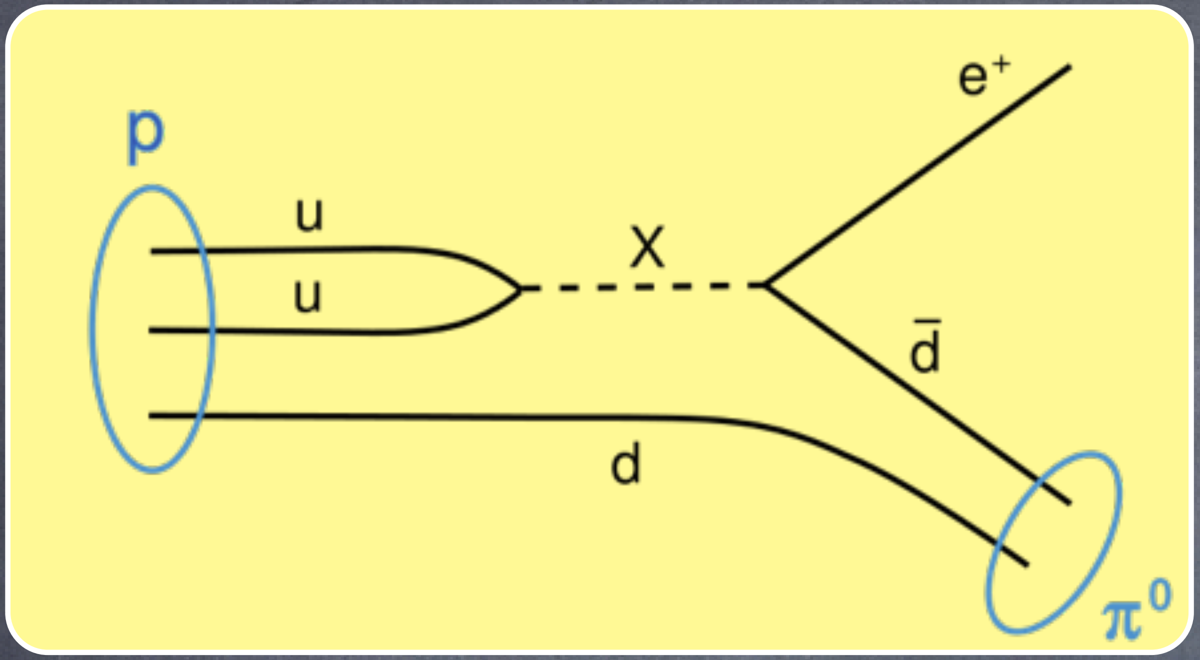
- SM has several accidental symmetries: baryon and 3 lepton number conservation
- Certain processes predicted not to occur at all, or occur with a negligible branching fraction
- Very clean tests of the Standard Model, and opportunity to pinpoint the nature of new physics

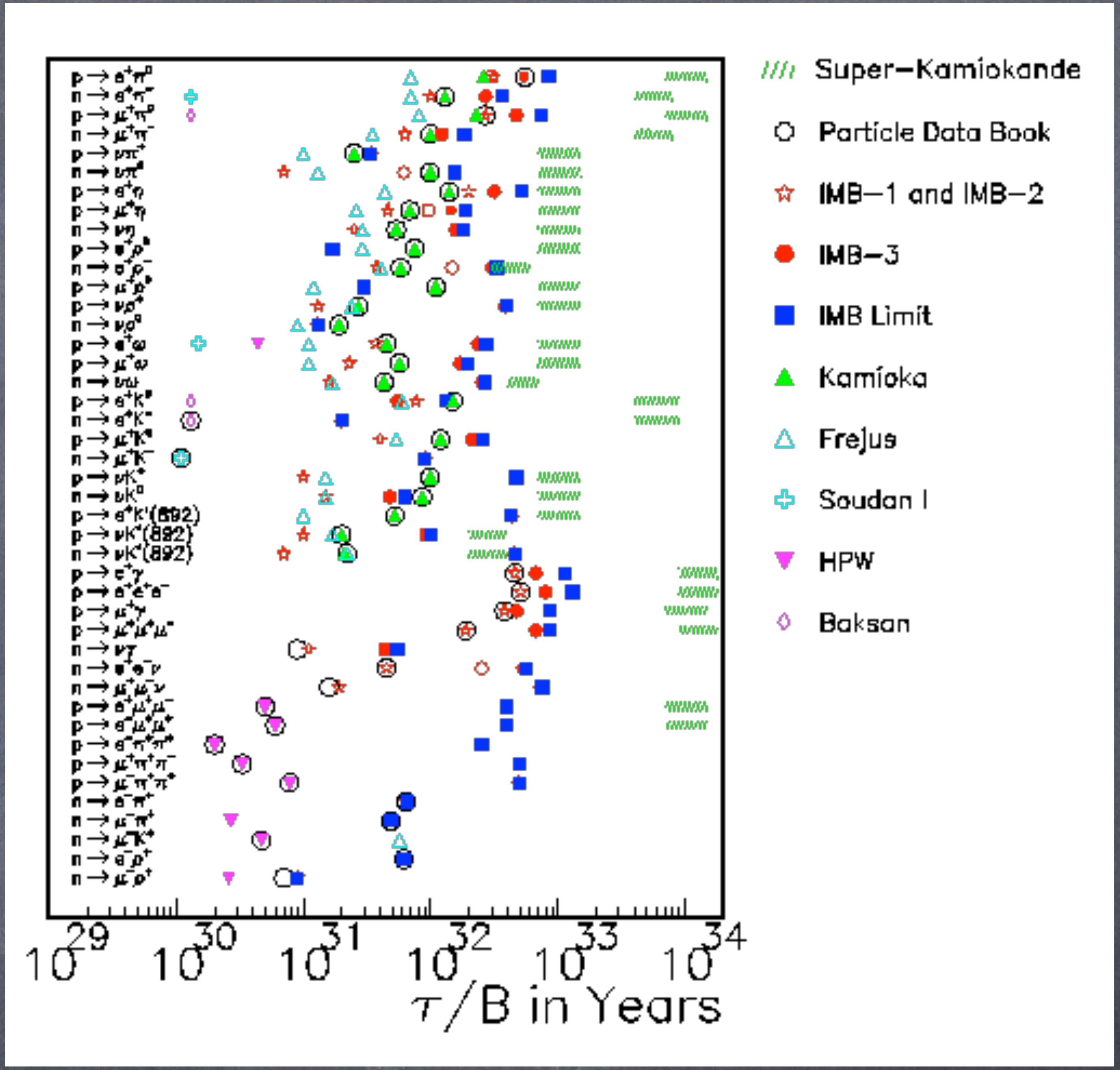
Proton Decay

Null Tests - Proton Decay

- In SM baryon number is perturbatively conserved (up to non-perturbative effects)
- This implies that the lightest particle carrying the baryon number = the proton, must be stable
- Observing proton decay would mean a discovery of new physics beyond the standard model

Null Tests - proton decay



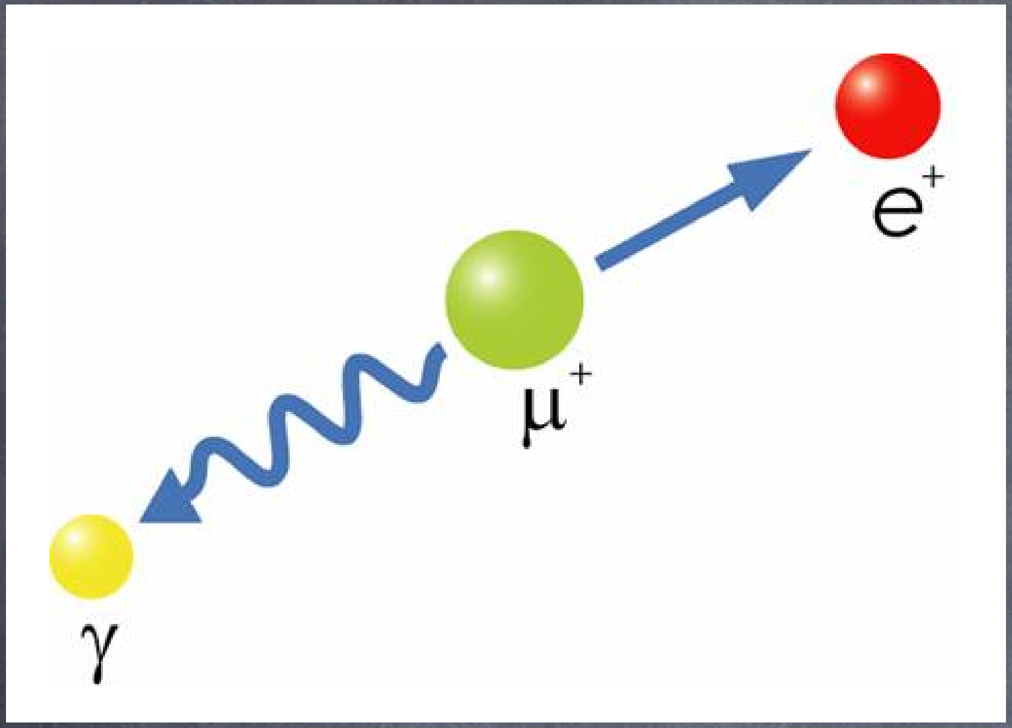


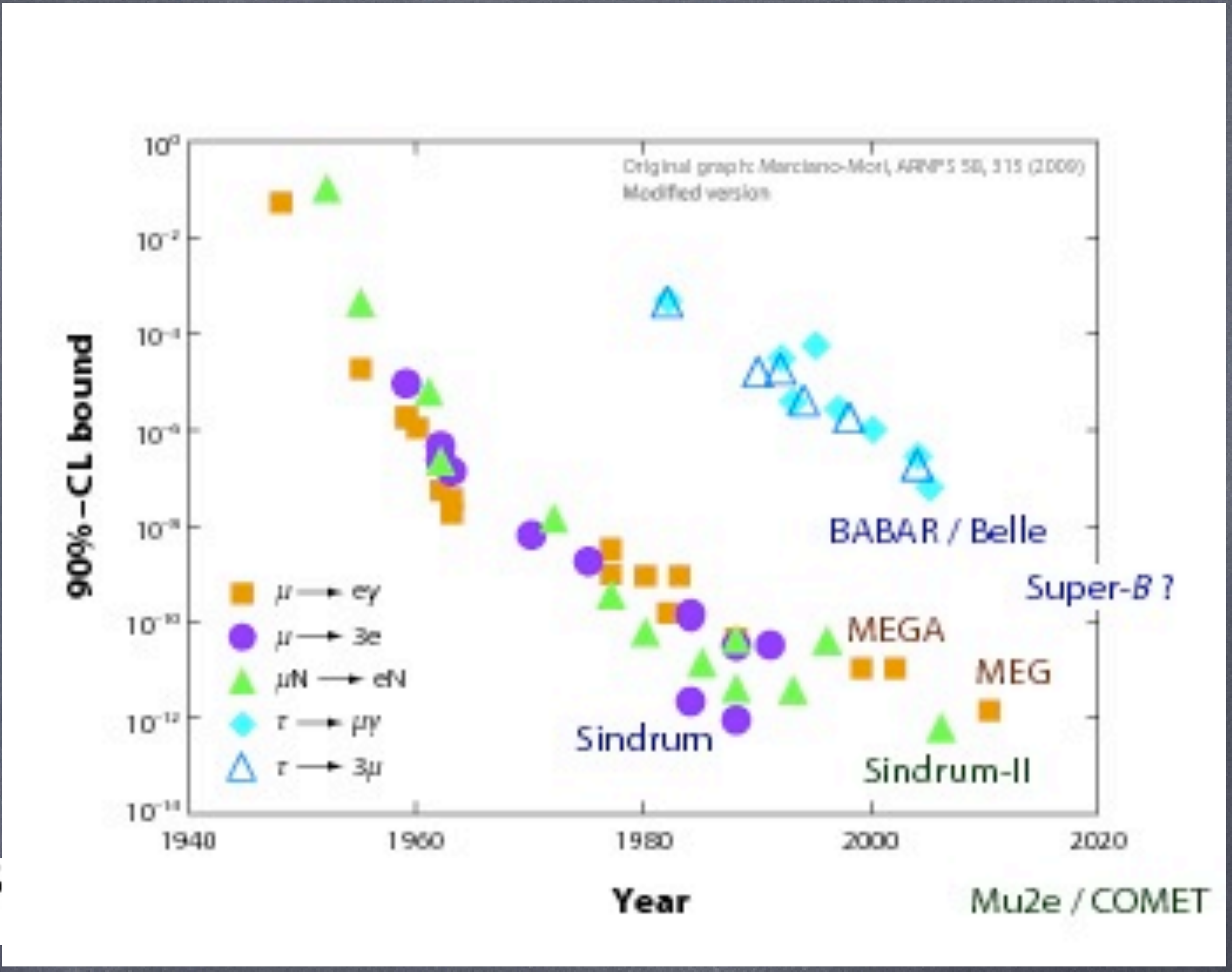
Lepton Flavor Violation

Null Tests - LFV

- In SM lepton number is conserved (up to small non-perturbative effects) for each generation separately
- This implies that muon cannot decay into electron without emitting two anti-neutrinos (muon and electron one)
- Observing neutrinoless decay of muon into electron would be a discovery of new physics beyond the Standard Model

Null Tests - LFV





MEG (2013):

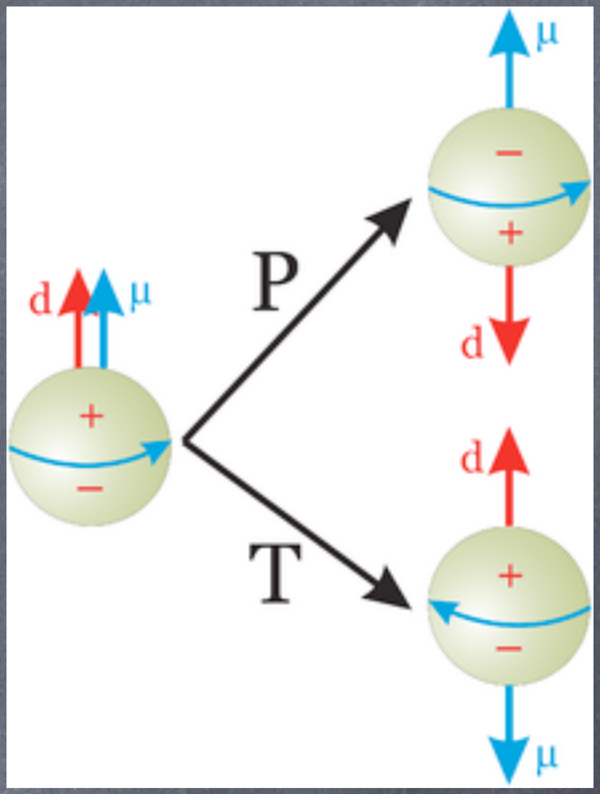
$$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

Hoecker, 1201.5093

Electric Dipole Moments

Null Tests -EDMs

- Electric Dipole Moments violate CP symmetry
- At zeroth order, EDMs of elementary particles in the Standard Model are forbidden by renormalizability
- They are generated by quantum effects but because CP violation is small, they are predicted to be unobservably small

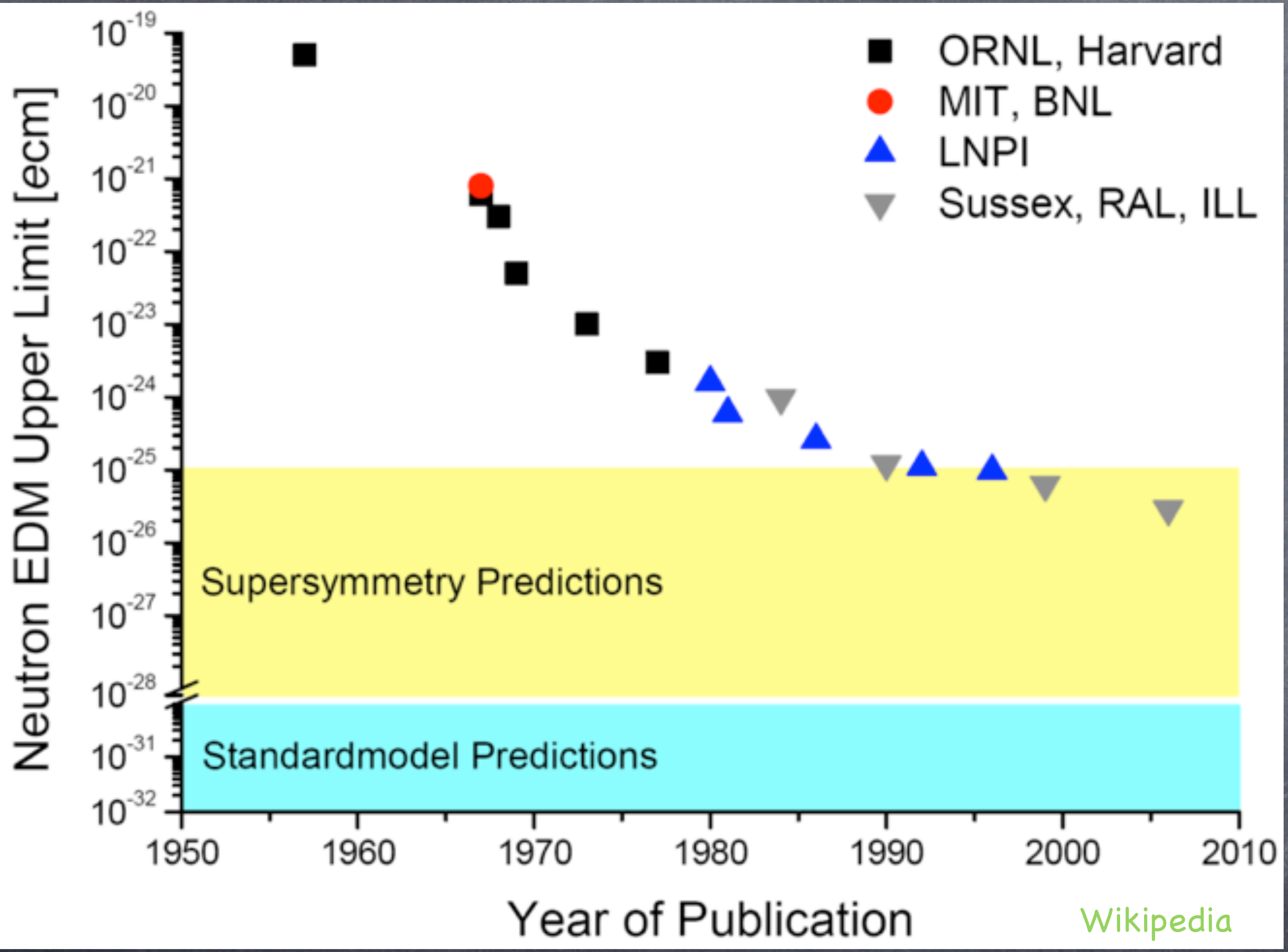


Wikipedia

$$H_{\rm EDM} \approx -d_e \vec{S}_e \cdot \vec{E}$$

Null Tests - EDMs

Neutron EDM



Electron EDM:

$$|d_e| \leq 8.7 \times 10^{-29} e \cdot \mathrm{cm} = \frac{e}{2 \times 10^{14} \mathrm{GeV}}$$

ACME, 1310.7534