Status and Phenomenology of the Standard Model

- **The new standard model**
- **Experimental tests, unique features, anomalies, hints of new physics**
  - **Precision tests**
  - **Higgs**
  - **Heavy quarks**
  - **Neutrinos**
  - **FCNC and EDMs**
  - **Astrophysics and cosmology**
- **Theoretical problems**
- **Perspective**

The *New* Standard Model

- Standard model, supplemented with neutrino mass (Dirac or Majorana):

$$SU(3) \times \underbrace{SU(2) \times U(1)}_{\text{focus of talk}} \times \text{classical relativity}$$

- Mathematically consistent field theory of strong, weak, electromagnetic interactions

- Correct to first approximation down to 10^{-16} cm

- Complicated, free parameters, fine tunings $\Rightarrow$must be new physics

- Many special features *usually not* maintained in BSM
  - $m_\nu = 0$ in *old* standard model (need to add singlet fermion and/or triplet Higgs and/or higher dimensional operator (HDO))
  - Yukawa coupling $h \propto gm/M_W \Rightarrow$ flavor conserving and small for light fermions (partially maintained in MSSM and simple 2HDM)
  - No FCNC at tree level (Z or h); suppressed at loop level (SUSY loops; Z' from strings, DSB)
  - Suppressed off-diagonal $\not{C}\not{P}$; highly suppressed diagonal (EDMs) (SUSY loops, soft parameters, exotics)
  - B, L conserved perturbatively ($B - L$ non-perturbatively) (GUT (string) interactions, $\not{R}_p$)
  - New TeV scale interactions suggested by top-down (Z', exotics, extended Higgs)

The Weak Charged Current

Fermi Theory incorporated in SM and made renormalizable

CKM matrix for $F = 3$ involves 3 angles and 1 CP-violating phase (after removing unobservable q_L phases) (new interations involving q_R could make observable)

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

Extensive studies, especially in B decays, to test unitarity of V as probe of new physics and test origin of CP violation

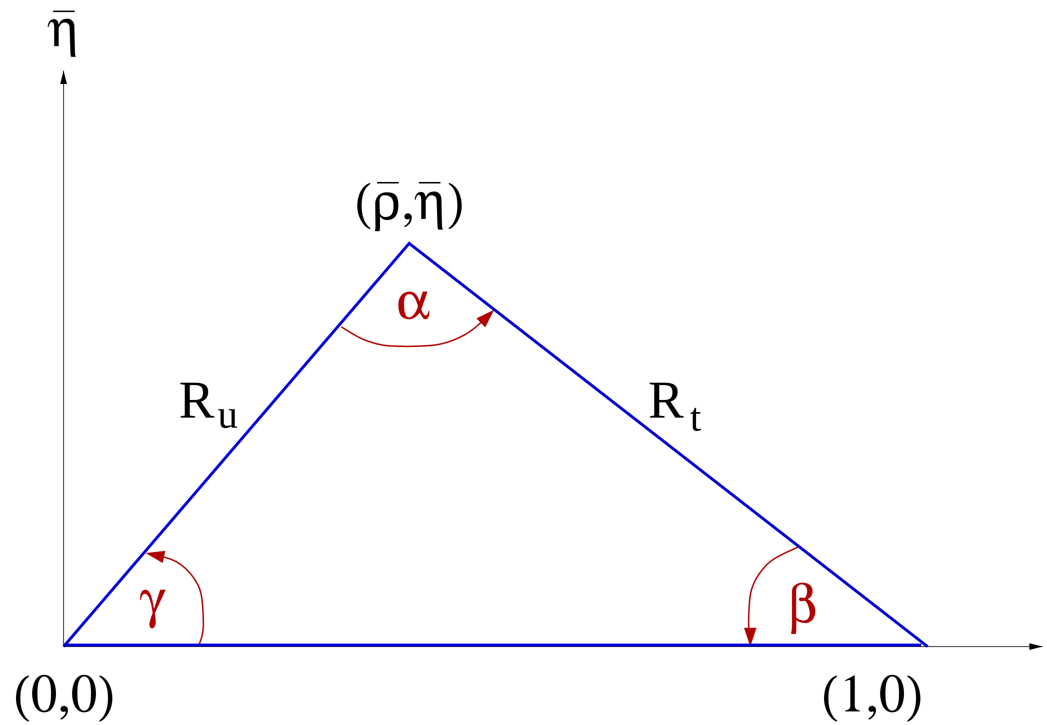
Need additional source of CP breaking for baryogenesis

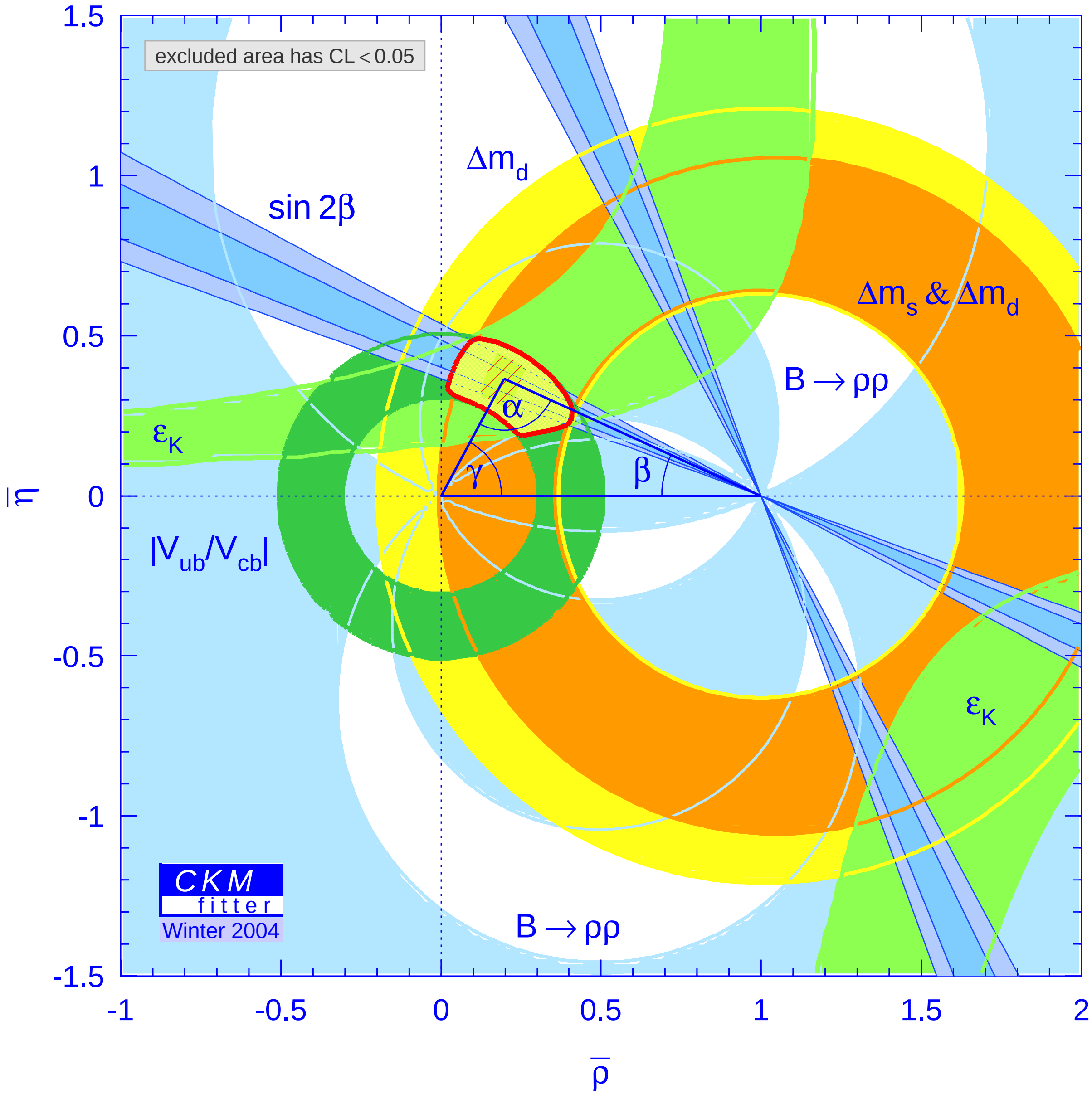
- Overconstrain unitarity triangle as test of SM

- Babar, Belle: $\sin 2\beta = 0.736 \pm 0.049$ from $B_d^0(t) \to J/\psi K_S$ (little theory error)

- α, γ harder

- Anomalies in electroweak penguins?





excluded area has CL < 0.05
Δm_d
sin 2β
Δm_s & Δm_d
B → ρρ
α
ε_K
γ
β
|V_ub/V_cb|
ε_K
CKM
fitter
Winter 2004
B → ρρ
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2
η̄
ρ̄

The Weak Neutral Current

Prediction of $SU(2) \times U(1)$

WNC discovered 1973: Gargamelle at CERN, HPW at FNAL

Tested in many processes: $\nu e \rightarrow \nu e$, $\nu N \rightarrow \nu N$, $\nu N \rightarrow \nu X$; $e^{\uparrow\downarrow} D \rightarrow e X$; atomic parity violation; $e^+ e^-$, Z-pole reactions

WNC, W, and Z are primary test/prediction of electroweak model

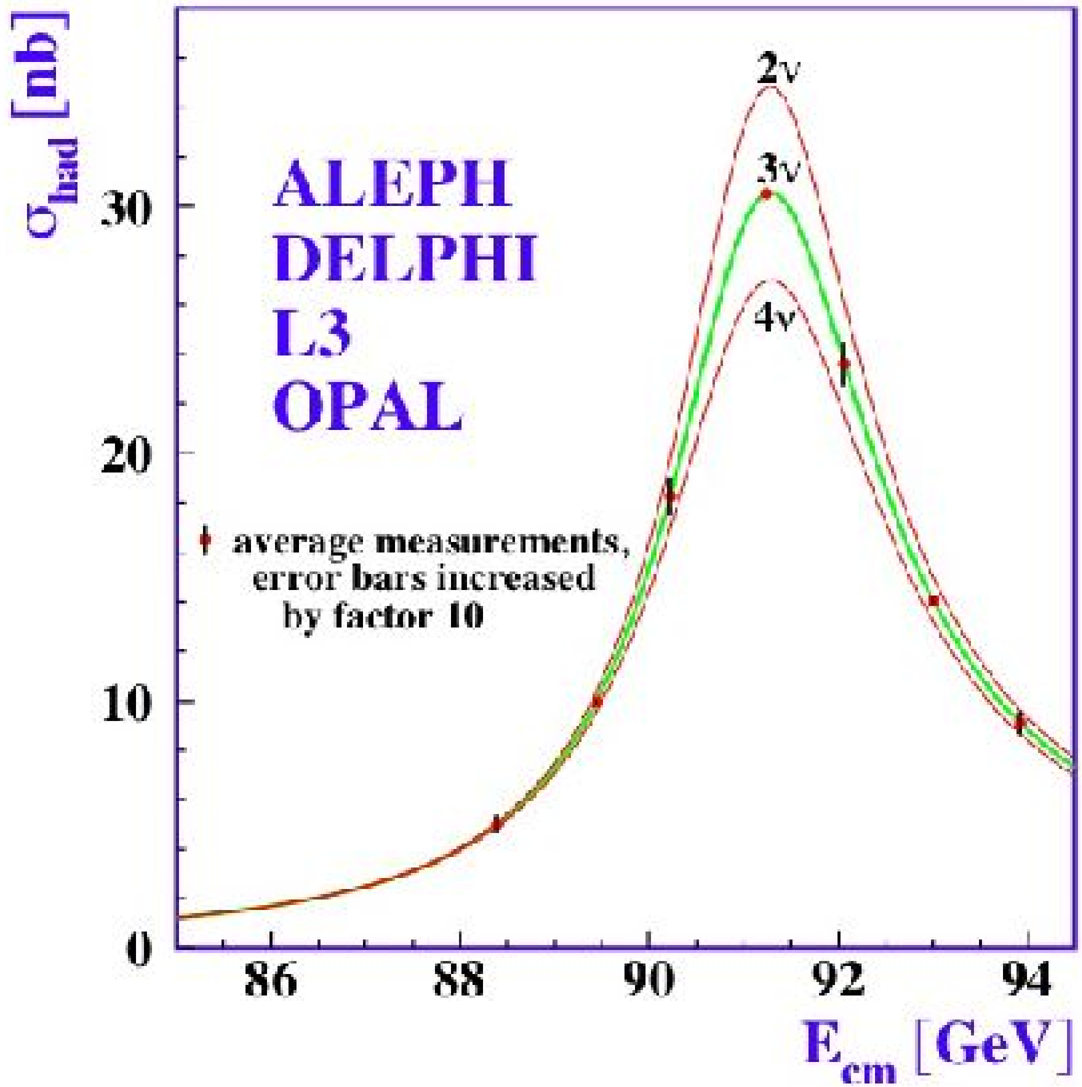
The LEP/SLC Era

- Z **Pole:** $e^+e^- \to Z \to \ell^+\ell^-, \quad q\bar{q}, \quad \nu\bar{\nu}$
  - **LEP (CERN),** $2 \times 10^7 Z's$, **unpolarized** (ALEPH, DELPHI, L3, OPAL); **SLC (SLAC),** 5×10^5, $P_{e^-} \sim$ **75 %** (SLD)

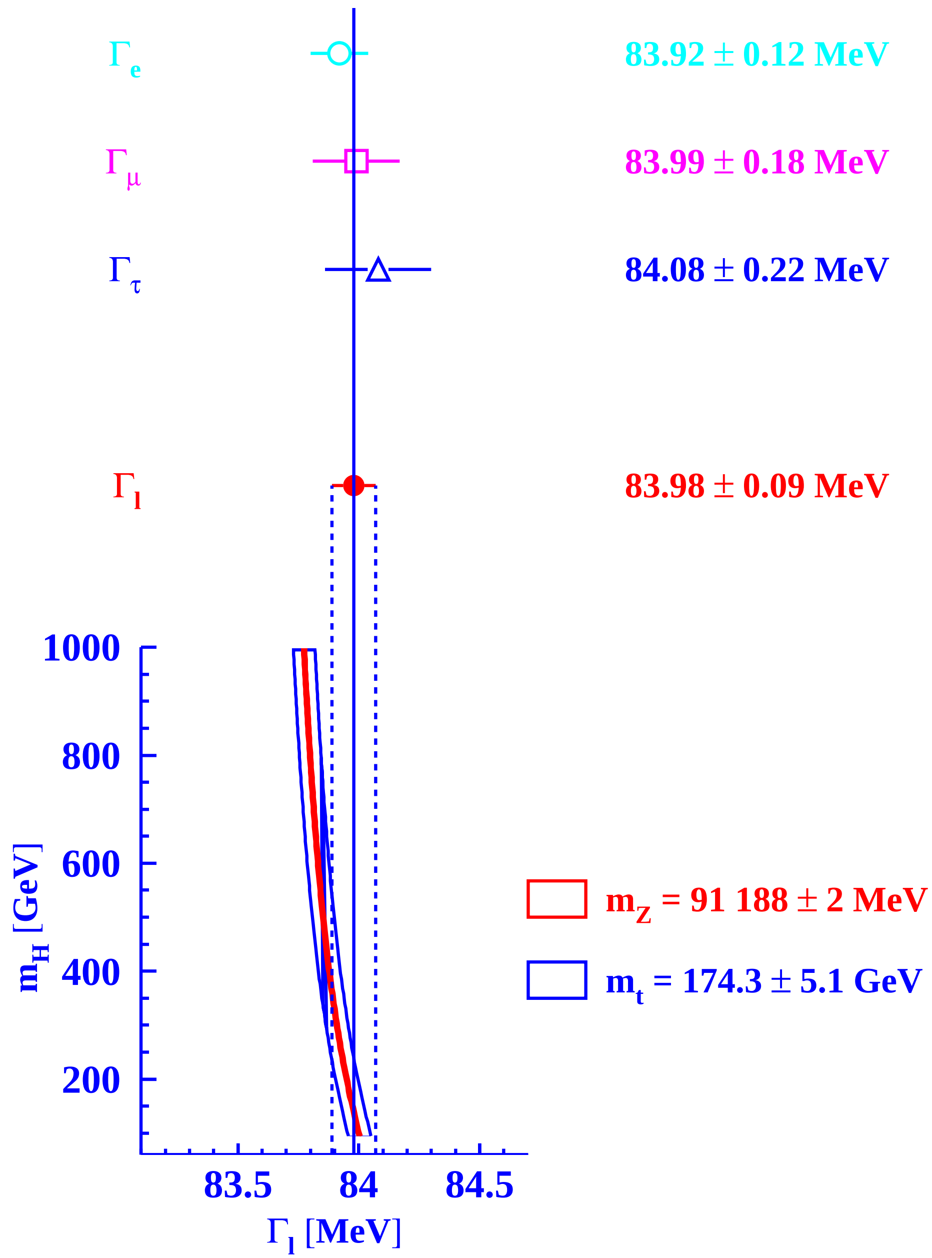
- Z **pole observables**
  - **lineshape:** M_Z, Γ_Z, σ
  - **branching ratios**
    - $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    - $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    - $\nu\bar{\nu} \Rightarrow N_\nu = 2.9841 \pm 0.0083$ **if** $m_\nu < M_Z/2$
  - **asymmetries: FB, polarization,** P_τ, **mixed**
  - **lepton family universality**

$N_\nu = 2.9841(83)$

($2\,\sigma$, cf σ_{had})

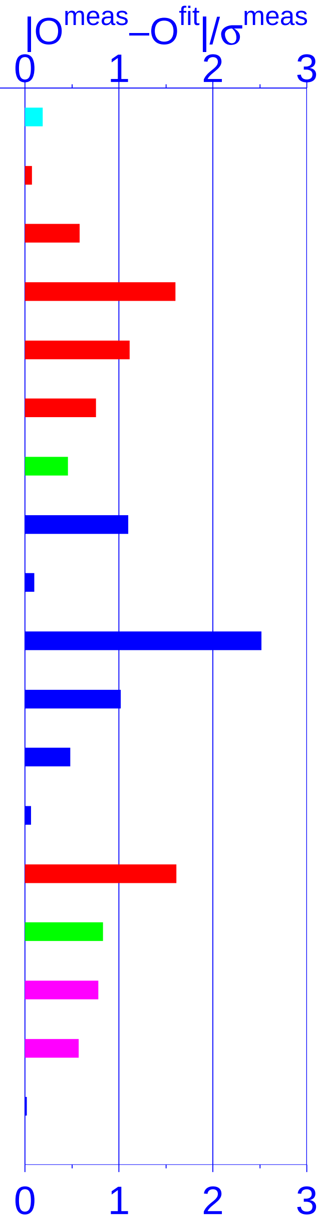


LEP averages of leptonic widths



Winter 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1

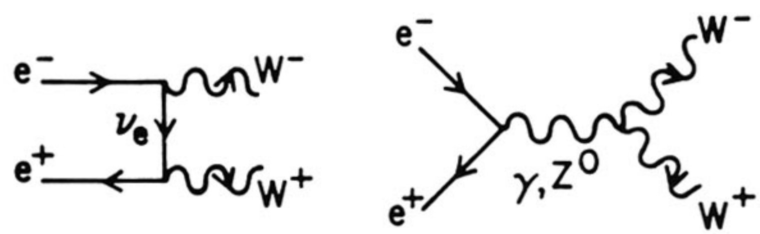


Gauge Self-Interactions

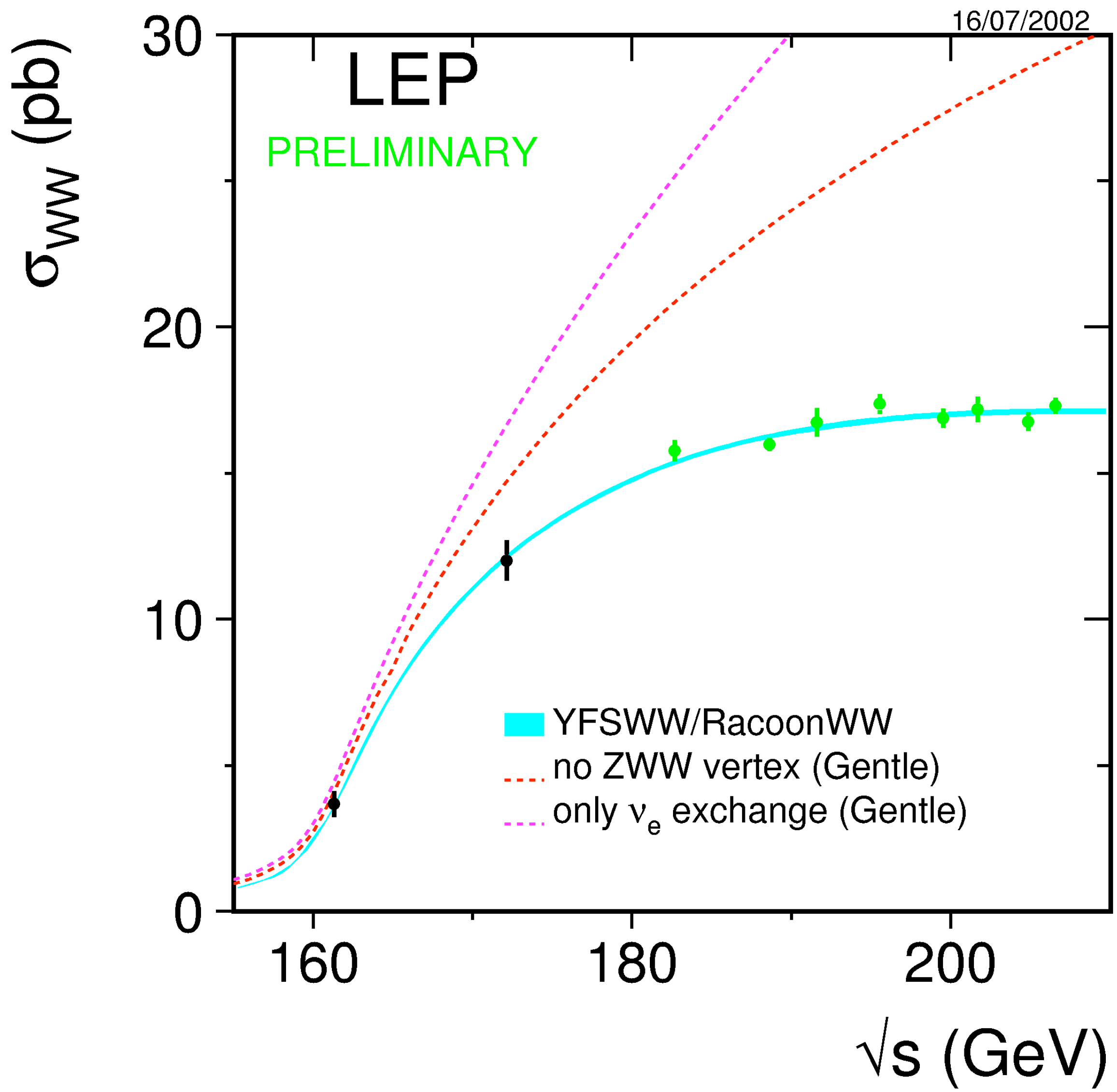
Three and four-point interactions predicted by gauge invariance

Indirectly verified by radiative corrections, α_s running in QCD, etc.

Strong cancellations in high energy amplitudes would be upset by anomalous couplings



Tree-level diagrams contributing to $e^+e^-\rightarrow W^+W^-$


16/07/2002
LEP
PRELIMINARY
30
20
10
0
160
180
200
σ_{WW} (pb)
$\sqrt{s}$ (GeV)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)

The Precision Program

- **WNC, Z, Z-pole, W, m_t**
- **Implications**
  - **SM correct and unique to zeroth approx. (gauge principle, group, representations)**
  - **SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)**
  - **TeV physics severely constrained (unification vs compositeness)**
  - **Precise gauge couplings (gauge unification)**

Problems with the Standard Model

Lagrangian after symmetry breaking:

$$\begin{aligned}\mathcal{L} &= L_{\text{gauge}} + L_{\text{Higgs}} + \sum_i \bar{\psi}_i \left(i \not{\partial} - m_i - \frac{m_i H}{\nu} \right) \psi_i \\ &\quad - \frac{g}{2\sqrt{2}} \left(J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+ \right) - e J_Q^\mu A_\mu - \frac{g}{2\cos\theta_W} J_Z^\mu Z_\mu\end{aligned}$$

Standard model: $SU(2) \times U(1)$ (extended to include ν masses) + QCD + general relativity

Mathematically consistent, renormalizable theory

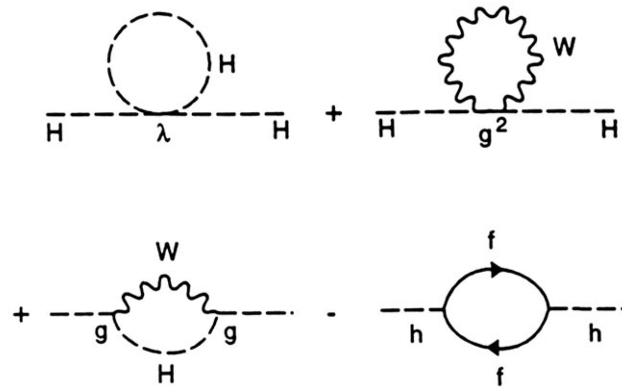
Correct to 10^{-16} cm

However, too much arbitrariness and fine-tuning: $O(27)$ parameters (+ 2 for Majorana ν), and electric charges

- Gauge Problem
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
  - Possible solutions: strings; grand unification; magnetic monopoles (partial); anomaly constraints (partial)

- Fermion problem
  - Fermion masses, mixings, families unexplained
  - Neutrino masses, nature?
  - CP violation inadequate to explain baryon asymmetry
  - Possible solutions: strings; brane worlds; family symmetries; compositeness; radiative hierarchies. New sources of CP violation.

- **Higgs/hierarchy problem**
  - **Expect** $M_H^2 = O(M_W^2)$
  - **higher order corrections:** $\delta M_H^2/M_W^2 \sim 10^{34}$



Possible solutions: supersymmetry; dynamical symmetry breaking; large extra dimensions; Little Higgs

- **Strong CP problem**
  - **Can add** $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ **to QCD (breaks, P, T, CP)**
  - $d_N \Rightarrow \theta < 10^{-9}$
  - **but** $\delta\theta|_{\rm weak} \sim 10^{-3}$
  - **Possible solutions: spontaneously broken global** $U(1)$ **(Peccei-Quinn)** $\Rightarrow$ **axion; unbroken global** $U(1)$ **(massless** u **quark); spontaneously broken CP + other symmetries**

- **Graviton problem**
  - gravity not unified
  - quantum gravity not renormalizable
  - cosmological constant: $\Lambda_{\rm SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\rm obs}$ (10^{124} for GUTs, strings)
  - Possible solutions:
    * supergravity and Kaluza Klein unify
    * strings yield finite gravity.
    * Λ?

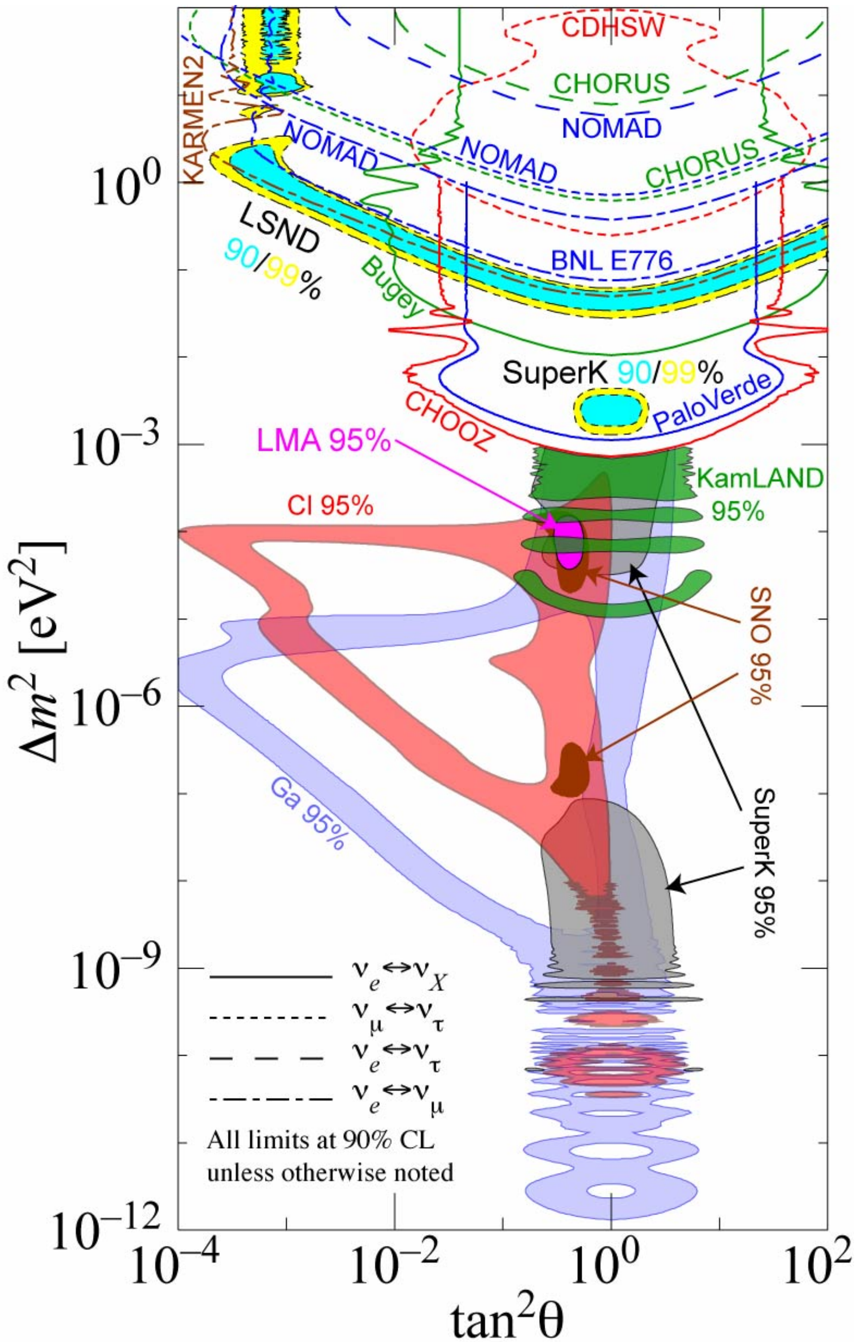
(Nearly) Unique Features of the *old* Standard Model

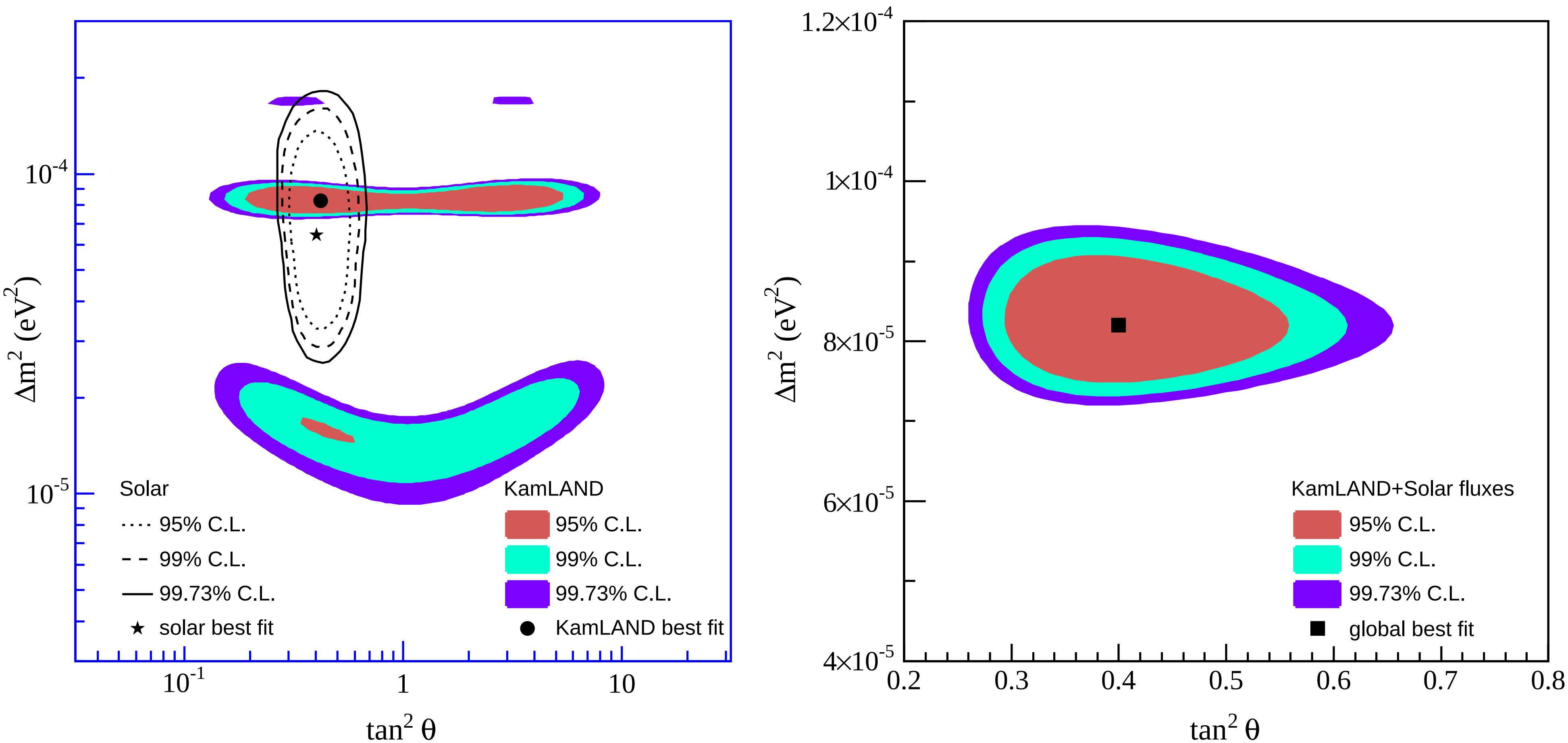
$m_\nu = 0$ **in** *old* **standard model** (need to add singlet fermion and/or triplet Higgs and/or higher dimensional operator (HDO))

- **Oscillation experiments confirm non-zero masses, LMA, SSM (also helioseismology)**
  - **Excluded sterile, RSPF, new interactions as** *dominant*
  - **Oscillation dip observed (further constrains/excludes alternatives)**

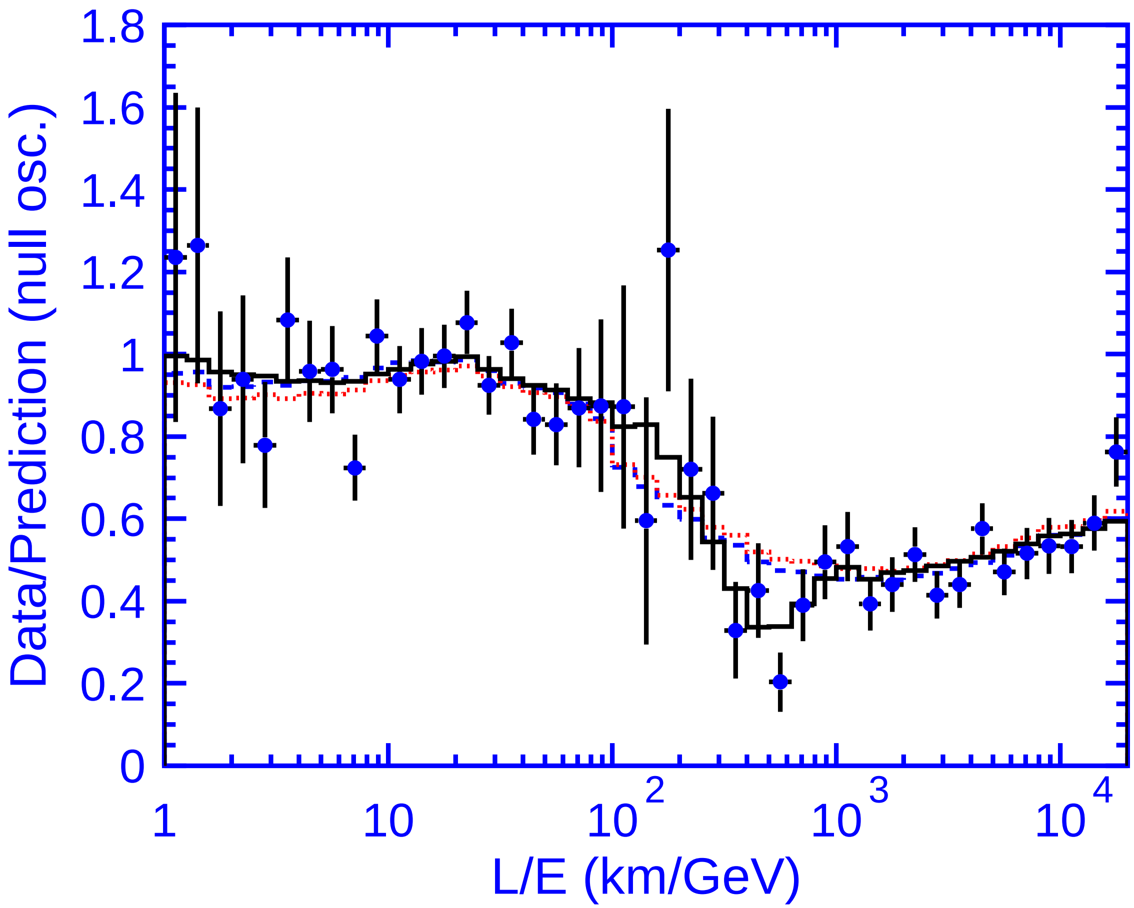
3 ν Patterns

- **Solar: LMA (SNO, Kamland)**
- **$\Delta m^2_\odot \sim 8\times10^{-5}$ eV^2 for LMA**
- **Atmospheric: $\Delta m^2_{\rm Atm} \sim 3\times10^{-3}$ eV^2, near-maximal mixing**
- **Reactor: U_{e3} small**





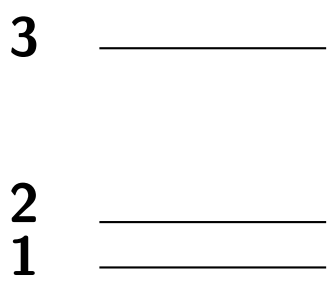
10^{-4}
10^{-5}
Δm^2 (eV^2)
Solar
95% C.L.
99% C.L.
99.73% C.L.
solar best fit
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
KamLAND best fit
10^{-1}
1
10
$\tan^2\theta$
1.2×10^{-4}
1×10^{-4}
8×10^{-5}
6×10^{-5}
4×10^{-5}
KamLAND+Solar fluxes
95% C.L.
99% C.L.
99.73% C.L.
global best fit
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$\tan^2\theta$

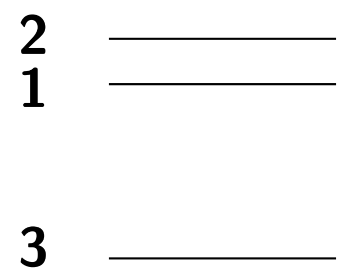


Data/Prediction (null osc.)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10 2
10 3
10 4
L/E (km/GeV)

Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:

$$
\begin{aligned}
\nu_3 &\sim \nu_+ \\
\nu_2 &\sim \cos\theta_\odot\ \nu_- - \sin\theta_\odot\ \nu_e \\
\nu_1 &\sim \sin\theta_\odot\ \nu_- + \cos\theta_\odot\ \nu_e
\end{aligned}
$$





Hierarchical pattern

- Analogous to quarks, charged leptons
- $\beta\beta_{0\nu}$ rate very small

Inverted quasi-degenerate pattern

- $\beta\beta_{0\nu}$ if Majorana
- May be radiative unstable

Outstanding issues

- Dirac or Majorana

- Distinguish by $\beta\beta_{0\nu}$, at least for inverted, degenerate. Observation?

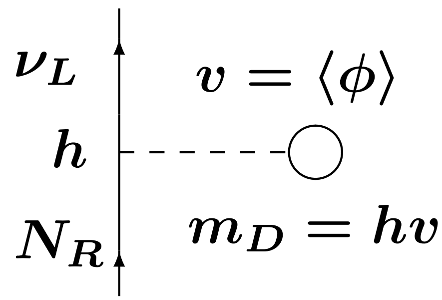
Dirac Mass

- Connects distinct Weyl spinors (usually active to sterile): $(m_D \bar{\nu}_L N_R + h.c.)$

- 4 components, $\Delta L = 0$

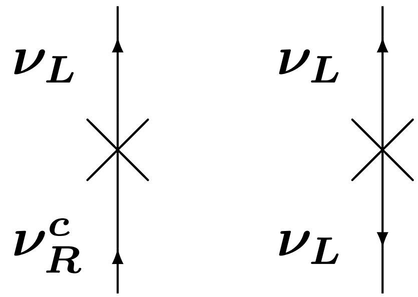
- $\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet

- Why small? LED? HDO?



Majorana Mass

- **Connects Weyl spinor with itself:** $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ **(active);** $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ **(sterile)**
- **2 components,** $\Delta L = \pm 2$
- **Active:** $\Delta I = 1 \rightarrow$ **triplet or seesaw**
- **Sterile:** $\Delta I = 0 \rightarrow$ **singlet or bare mass**



- **Scale of neutrino masses: 0.05 eV $< m_\nu <$ O(0.3 eV). Probe by β decay (KATRIN), cosmology, $\beta\beta_{0\nu}$**

- **Type of hierarchy: $\beta\beta_{0\nu}$**

- **U_{e3}, leptonic $\not{C}P$**

- **LSND? $\Rightarrow$Additional (sterile) neutrino(s) which mix with ordinary. MiniBooNE.**

- **Leptogenesis?**

Flavor Changing Neutral Currents

- In SM: Yukawa coupling $h \propto gm/M_W \Rightarrow$ flavor conserving and small for light fermions (partially maintained in MSSM and simple 2HDM)

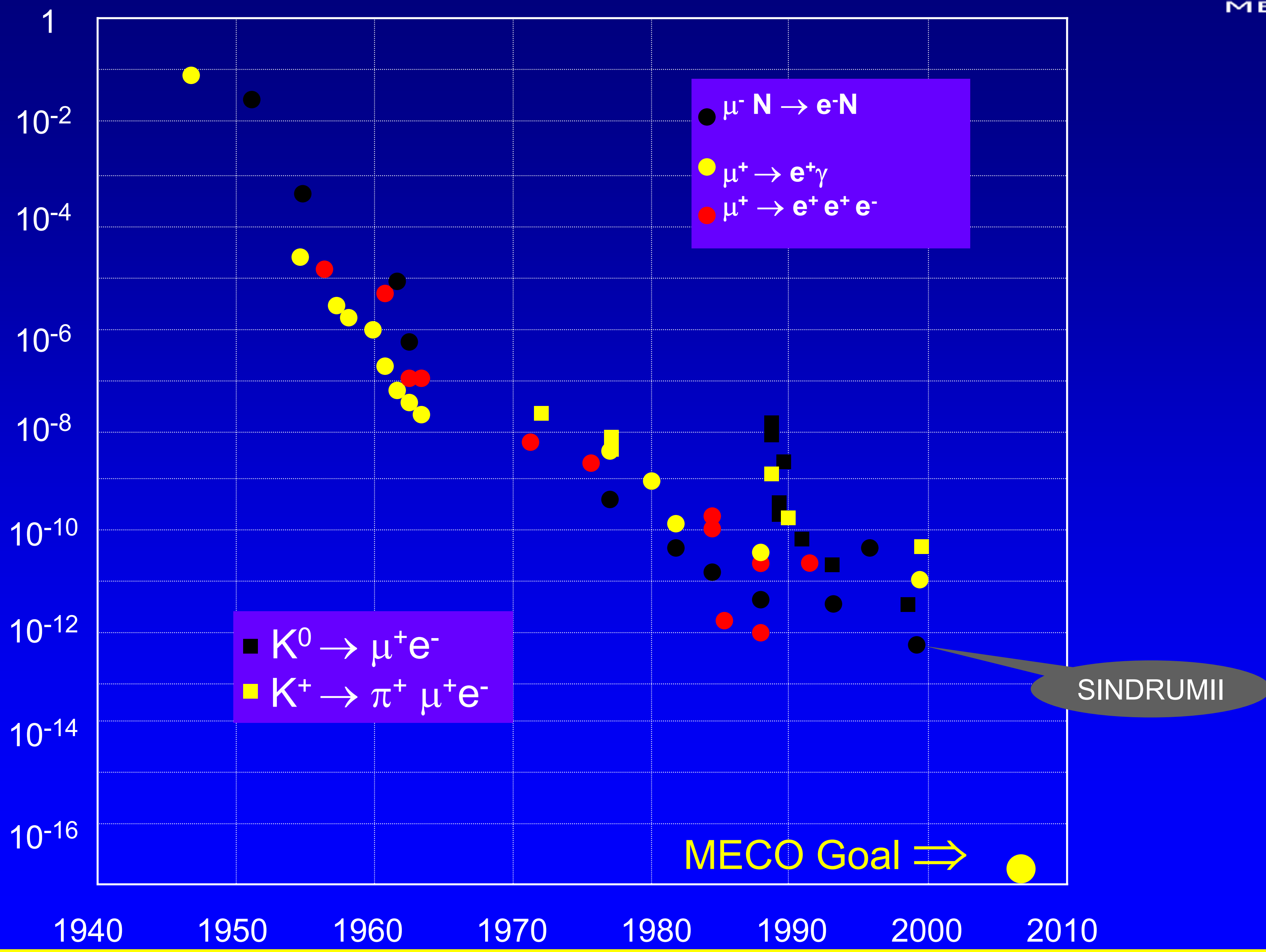
- In SM: no FCNC at tree level (Z or h); suppressed at loop level

- Violated in almost all extensions, including SUSY loops; Z' from strings, DSB

- Hard to give precise expectations, but critical to search

- Third family transitions (rare B, τ) often largest, but small induced effects in first two families (μ, K decays) may be more sensitive (MEG at PSI, MECO at BNL, PRIME at JHF)

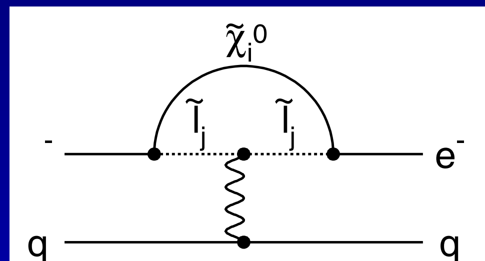
History of Lepton Flavor Violation Searches

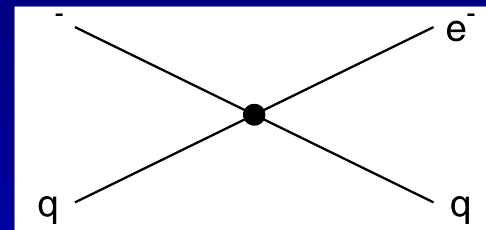


What might we expect?

Supersymmetry

Predictions at 10^{-15}



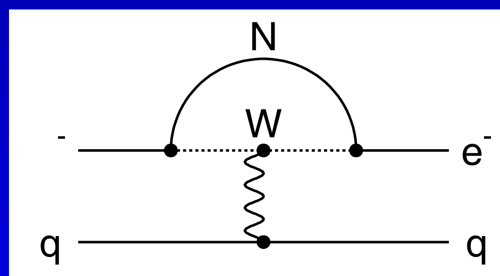


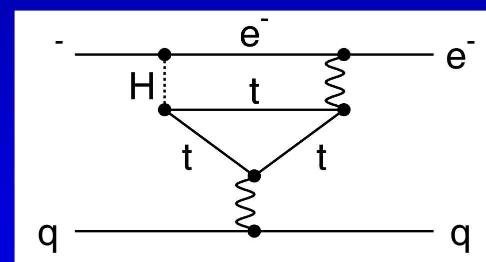
Compositeness

$\Lambda_C = 3000\ \text{TeV}$

Heavy Neutrinos

$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$



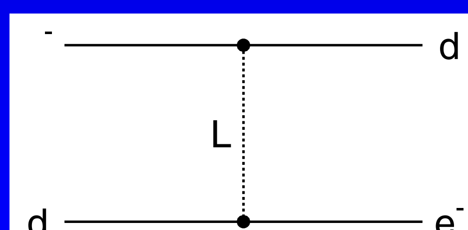


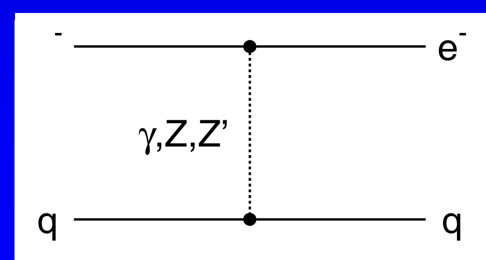
Second Higgs

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}\ \text{TeV}/c^2$





Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000\ \text{TeV}/c^2$

$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

CP Violation

- SM: suppressed off-diagonal $\not{C}P$; highly suppressed diagonal (EDMs)

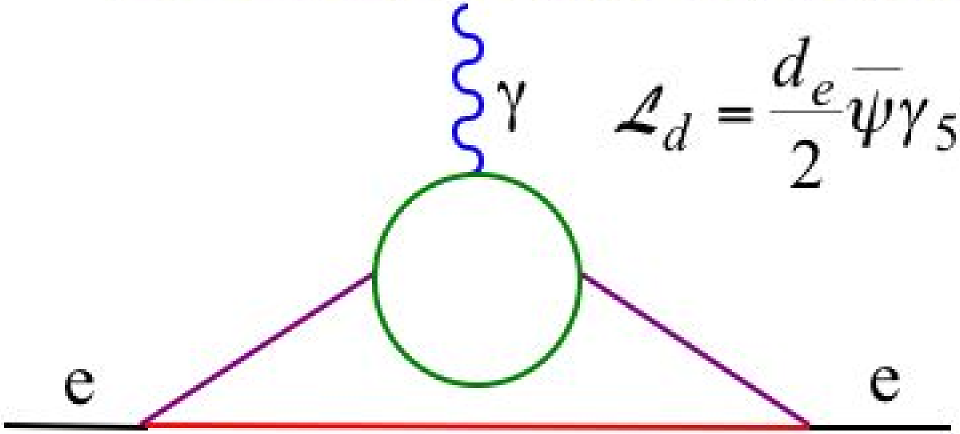
- Larger in SUSY (loops, soft parameters) unless tuning or cancellations

- Larger in other extensions, e.g., singlet scalars in Z' models (but may be hidden)

- B decays, leptonic $\not{C}P$, EDMs

- Need additional $\not{C}P$ for baryogenesis

Electron EDM in various SM extensions



$$\mathcal{L}_d = \frac{d_e}{2}\bar{\psi}\gamma_5\sigma_{\mu\nu}\psi F_{\mu\nu}$$

not renormalizable
⇒ loop diagrams

Physics model	$\lvert d_e \rvert$
Standard Model	**$\sim 10^{-41}$ e·cm**
Left-right symmetric	**10^{-26}-10^{-28} e·cm**
Lepton flavor-changing	**10^{-26}-10^{-29} e·cm**
Multi-Higgs	**10^{-27}-10^{-28} e·cm**
Technicolor	**10^{-27}-10^{-29} e·cm**
Supersymmetry	**$< 10^{-25}$ e·cm**

Experimental limit:
$\lvert d_e \rvert < 1.6\times10^{-27}$ e·cm

B. Regan, E. Commins, C. Schmidt, D. DeMille, PRL **88**, 071805 (2002)

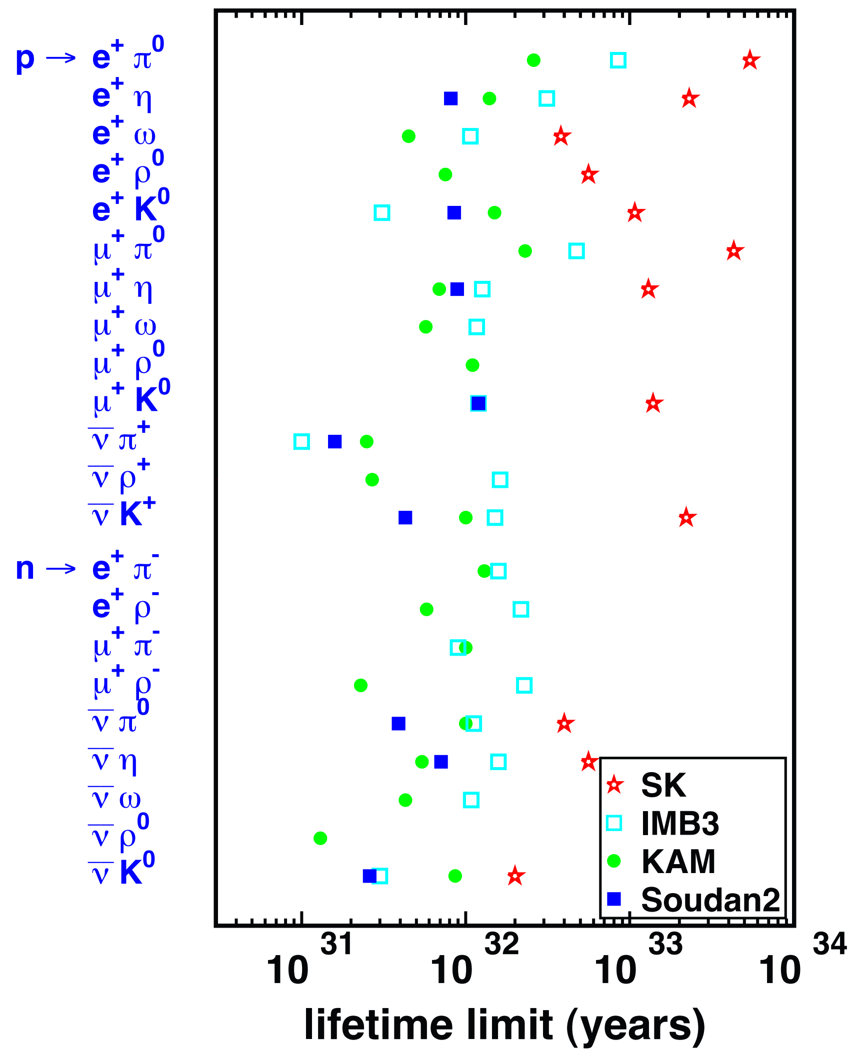
Models assume new physics at ~100 GeV & CP-violating phases ~1

(D. DeMille)

Baryon and Lepton Number Violation

- **SM: B, L conserved perturbatively ($B - L$ non-perturbatively)**
- **Violated in BSM, e.g., by GUT (string) interactions or $\not{R}_p$**
- **Proton decay expected at some level in many extensions, especially Planck scale**
- **$\not{L}$ needed for Majorana neutrino masses $\Rightarrow \beta\beta_{0\nu}$**
- **New B and/or L invoked in $some$ baryogenesis schemes**

mode	exposure (ktï yr)		εB_m (%)	observed event	B.G.
$p \to e^+ + \pi^0$	92	40	0	0.2	54
$p \to \mu^+ + \pi^0$	92	32	0	0.2	43
$p \to e^+ + \eta$	92	17	0	0.2	23
$p \to \mu^+ + \eta$	92	9	0	0.2	13
$n \to \bar{\nu} + \eta$	45	21	5	9	5.6
$p \to e^+ + \rho$	92	4.2	0	0.4	5.6
$p \to e^+ + \omega$	92	2.9	0	0.5	3.8
$p \to e^+ + \gamma$	92	73	0	0.1	98
$p \to \mu^+ + \gamma$	92	61	0	0.2	82
$p \to \bar{\nu} + K^+$	92				22
$K^+ \to \nu\mu^+$ (spectrum)		34	--	--	4.2
prompt $\gamma + \mu^+$		8.6	0	0.7	11
$K^+ \to \pi^+\pi^0$		6.0	0	0.6	7.9
$n \to \bar{\nu} + K^0$	92				2.0
$K^0 \to \pi^0\pi^0$		6.9	14	19.2	3.0
$K^0 \to \pi^+\pi^-$		5.5	20	11.2	0.8
$p \to e^+ + K^0$	92				10.7
$K^0 \to \pi^0\pi^0$		9.2	1	1.1	8.7
$K^0 \to \pi^+\pi^-$					
2-ring		7.9	5	3.6	4.0
3-ring		1.3	0	0.1	1.7
$p \to \mu^+ + K^0$	92				13.9
$K^0 \to \pi^0\pi^0$		5.4	0	0.4	7.1
$K^0 \to \pi^+\pi^-$					
2-ring		7.0	3	3.2	4.9
3-ring		2.8	0	0.3	3.7



TeV Physics

- New TeV scale interactions suggested by top-down

- Z' or other new interactions
  - Implications for highly non-standard Higgs, FCNC, CDM, baryogenesis

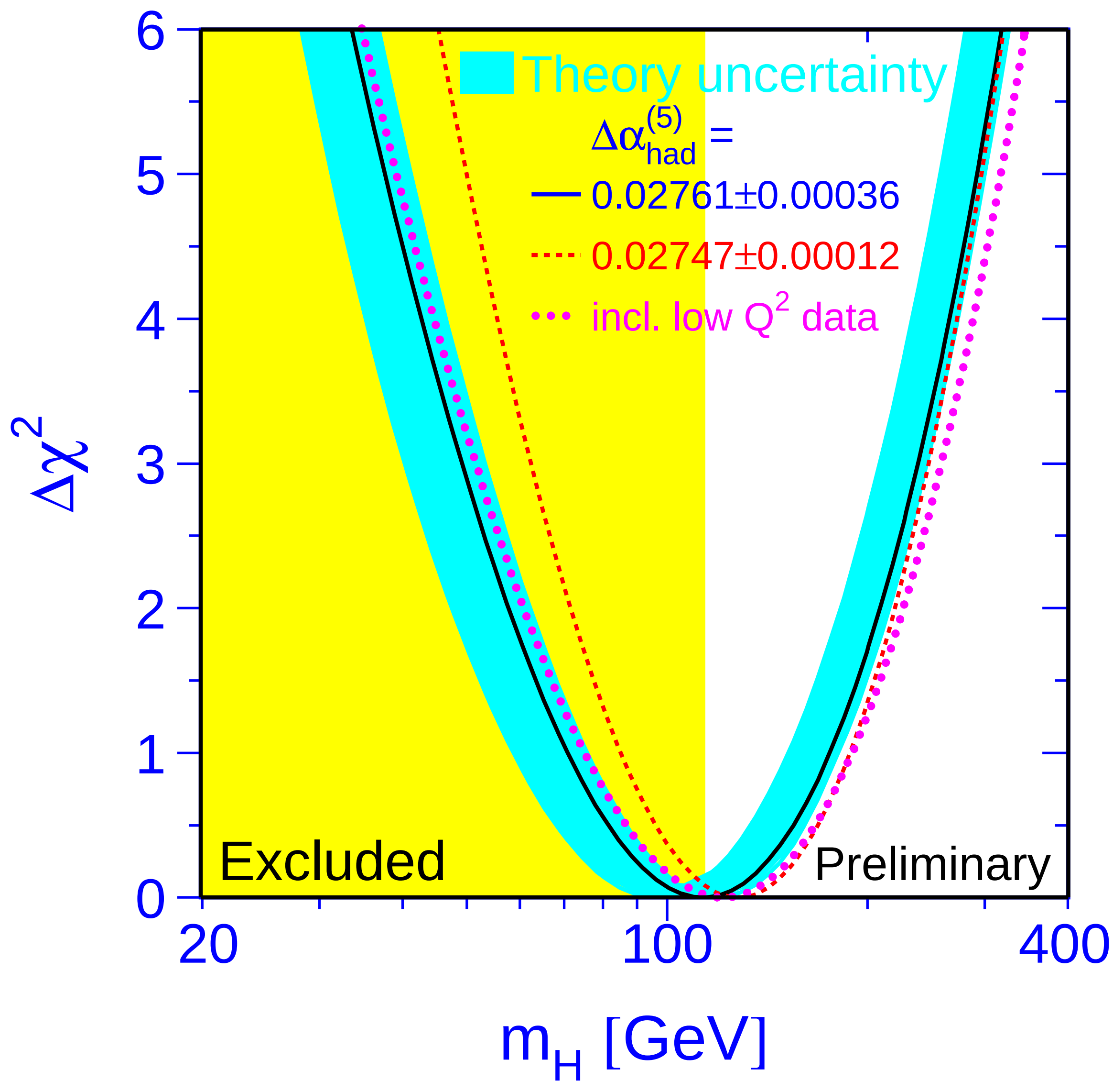
- Exotics
  - Extra Higgs doublets and singlets
  - Exotic quarks and leptons
  - Fractional charges

- Quasi-hidden sectors

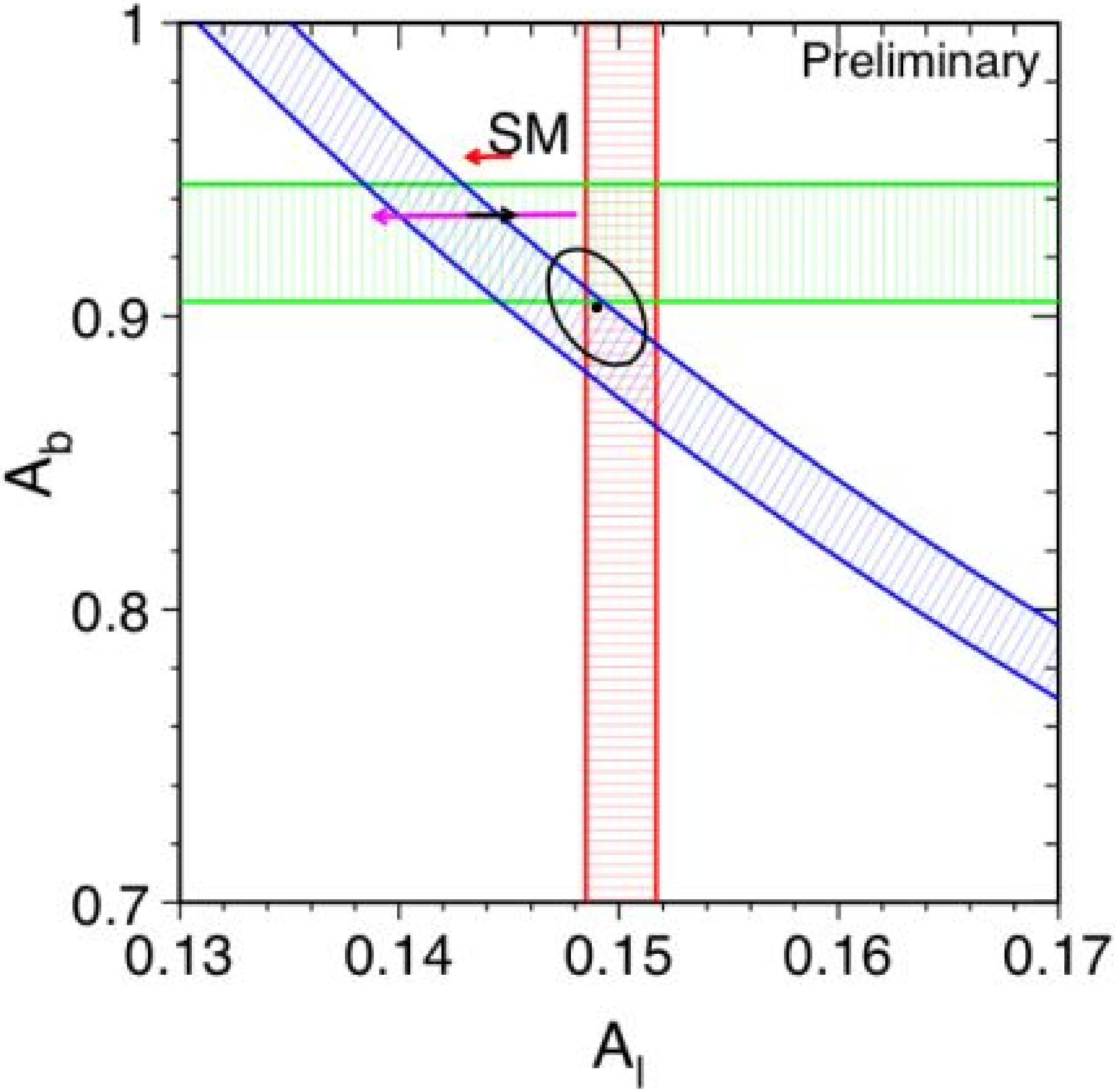
Hints and Anomalies

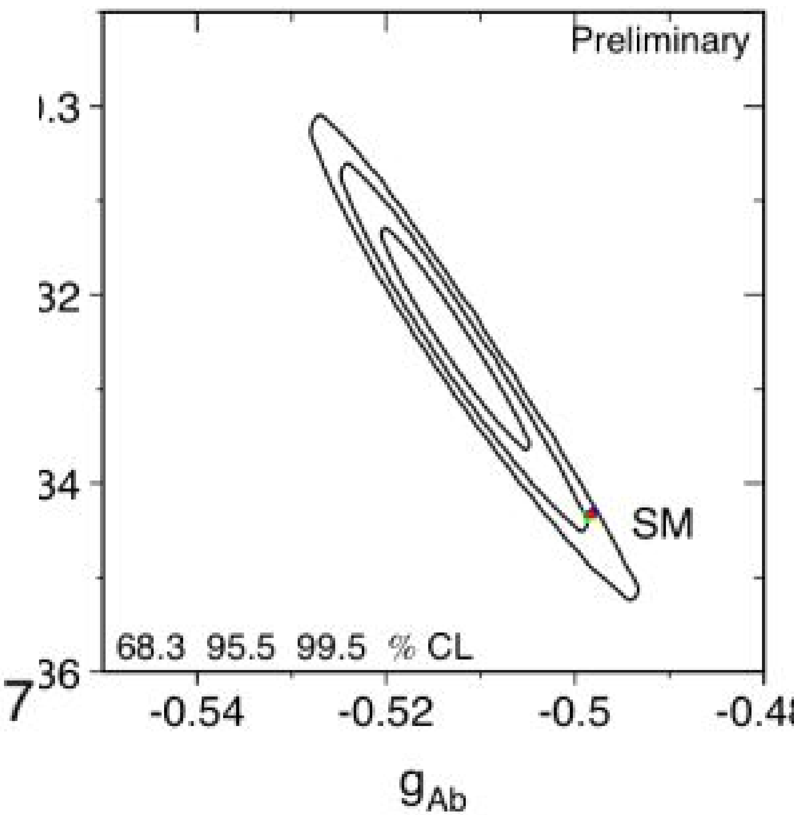
- Gauge unification in supersymmetric extension
  - If not accident or compensation, severely limits new TeV scale physics
- Precision data suggests light Higgs

- **Precision data suggests light Higgs**
- $M_H = 113^{+56}_{-40}$ **GeV ($<$ 246 GeV at 95% including indirect)**
- **Consistent with SUSY (but does not prove)**
- **Has increased due to new D0 m_t value and lower M_W**
- A^b_{FB} **pulls up,** A_l **down**



- **Tension between lepton and quark asymmetries**
- **$A_{FB}(b)$ and A_l**
- **New physics in 3rd family?**

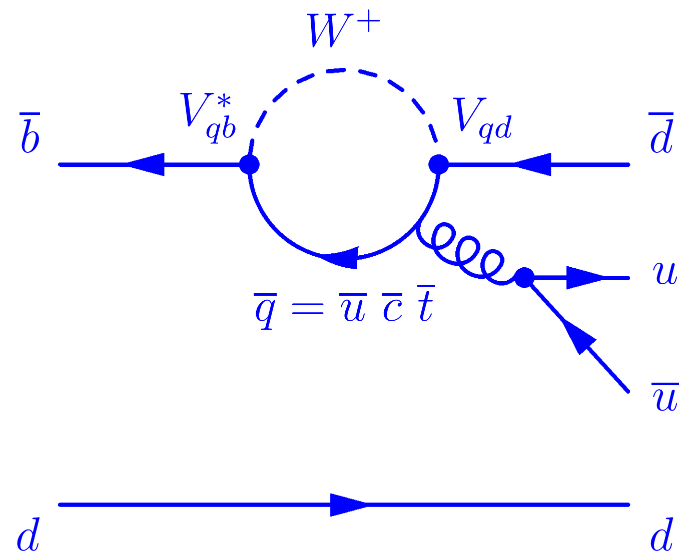




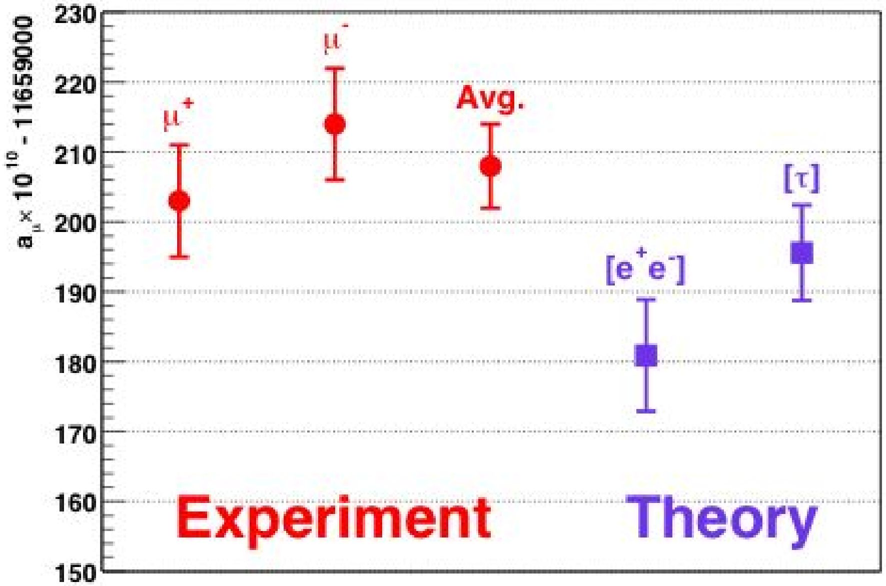
- **Atomic parity violation? Now in agreement after complete radiative corrections.**

- **NuTeV? Unresolved. Likely QCD or structure function issue.**

- **Electroweak penguins in $B \to \phi K_S, K\pi$?**
  - **Experimental situation uncertain**
  - **SUSY loops for large $\tan\beta$ or tree effects, e.g. FCNC Z'**



- **Anomalous magnetic moment of muon**
  - **Hadronic vacuum polarization (e^+e^- vs τ decay); light by light**
  - **If real, then SUSY with large $\tan\beta$ and low masses is possibility**

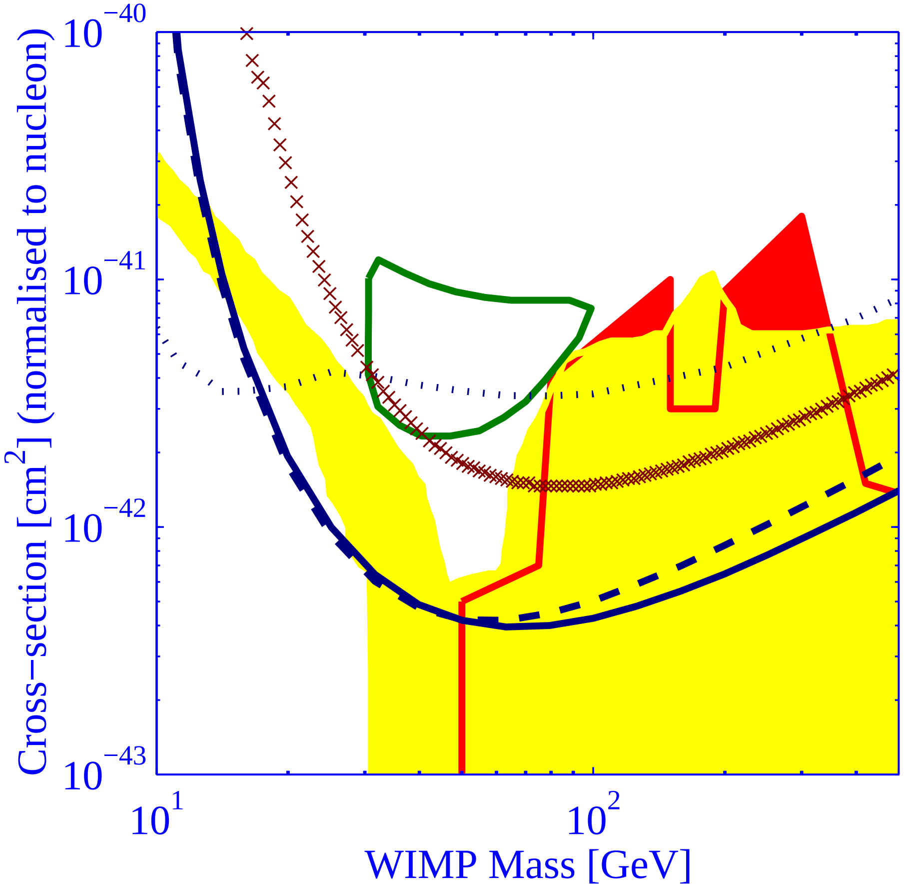


$$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10} \quad 2.4 \text{ s.d.}$$

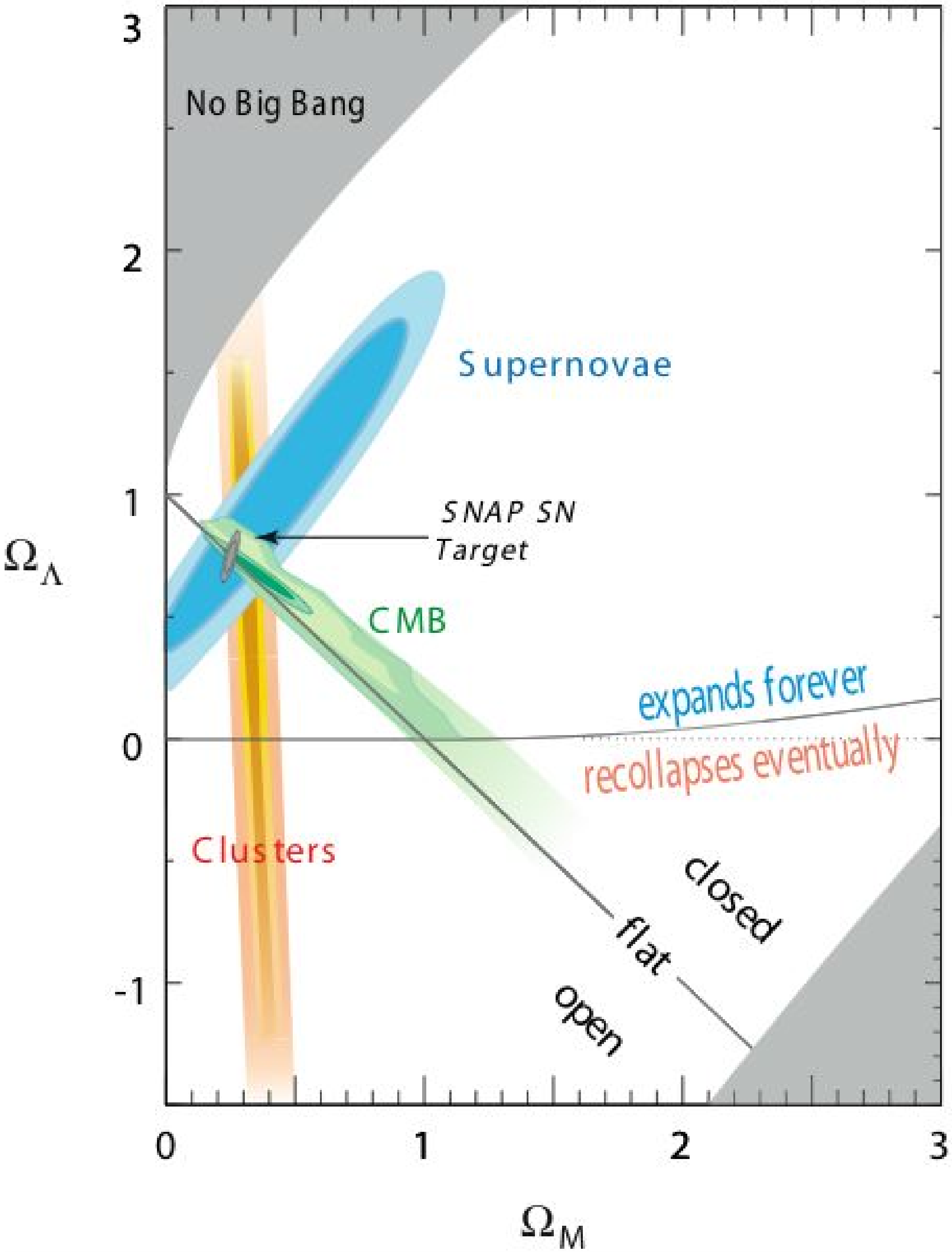
$$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10} \quad 0.9 \text{ s.d.}$$

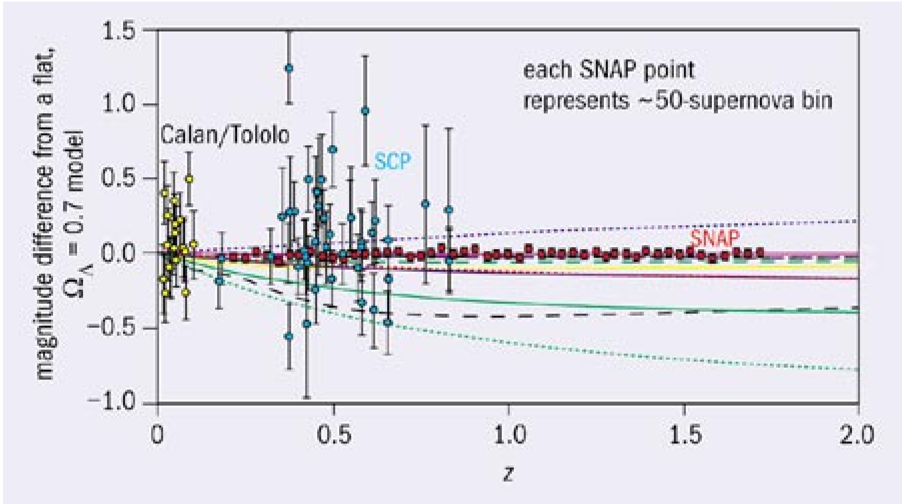
CKM Universality

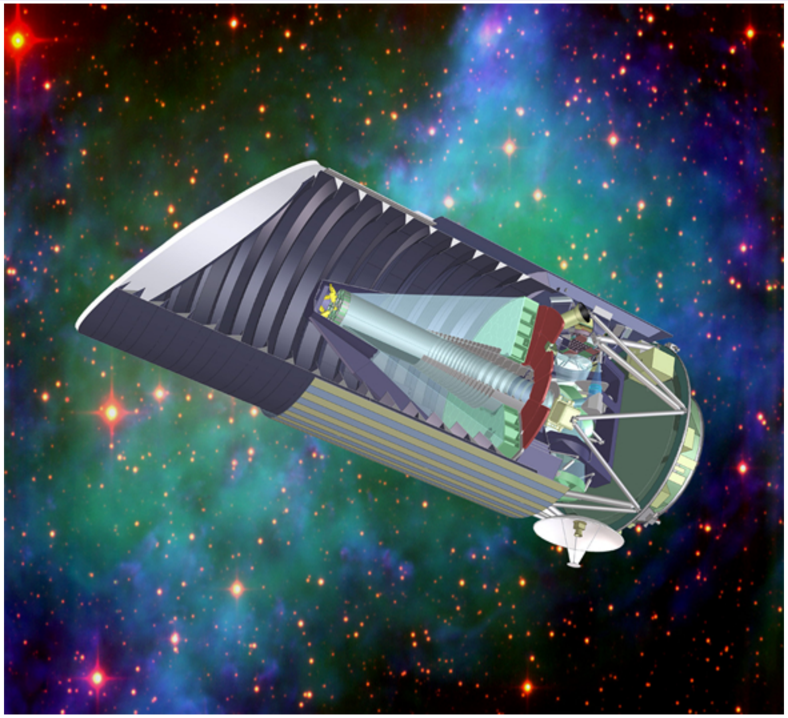
- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta$
  - PDG 2002: $\Delta = 0.0042 \pm 0.0019$
  - New physics? Constrains $\nu - \nu_{heavy}$ explanations of NuTeV
  - Problem in V_{ud}?
    - Superallowed: $|V_{ud}|$=0.9740(5), many checks
    - Neutron: 0.9745 (16) (common structure-independent rad corr)
    - Pion beta decay: 0.9716(39) (new)
  - Problem in V_{us}?
    - BNL E685, KTEV, KLOE but not CERN NA 48



- **Dark Matter**
  - **$\sim$ 30% matter, mainly dark**
  - **No SM candidates; SUSY LSP if R_P conserved (MSSM tightly constrained); axions**
- **$\sim$ 70% dark energy**
  - **Higgs VeV, QCD vacuum energy in SM, but too large by $\sim$ 10^{50}; new fields? quintessence?**
  - **JDEM (SNAP)**


No Big Bang
Supernovae
SNAP SN
Target
CMB
expands forever
recollapses eventually
Clusters
closed
flat
open
Ω_Λ
Ω_M


each SNAP point
represents ~50-supernova bin
Calan/Tololo
SCP
SNAP
magnitude difference from a flat, Ω_Λ = 0.7 model
z



Baryogenesis

- Baryon asymmetry $n_B/n_\gamma \sim 6 \times 10^{-10}$

- Possible mechanisms

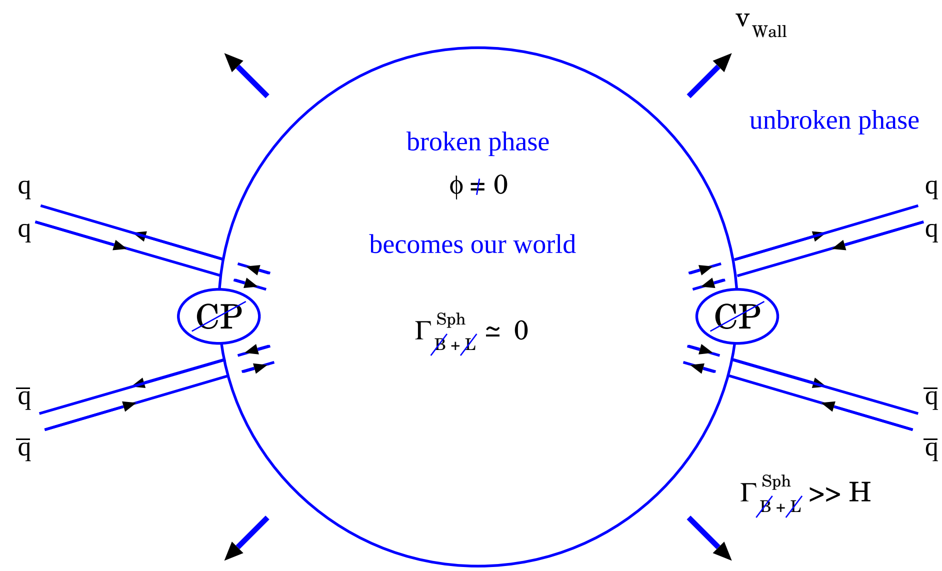
  - GUT baryogenesis (wiped out by sphalerons for $B - L$=0)
  - Leptogenesis (for heavy right-handed Majorana neutrino in seesaw)
  - Electroweak baryogenesis

- **EB requires strong first order transition, $v(T_c)/T_c \gtrsim 1-1.3$ and adequate CP violation in expanding bubble wall**

- **Absent in SM**

- **Narrow parameter range in MSSM**

- **Possible in Z'**



(W. Bernreuther, hep-ph/0205279)

Conclusions

- Standard Model is spectacularly successful, but has many parameters, tunings, and unexplained features
- Must be new physics
- Theoretical ideas
  - Strings
  - Grand Unification (canonical or modified)
  - Supersymmetry
  - Top-down remnants (Z', exotics)
  - Large extra dimensions, deconstruction
  - Dynamical symmetry breaking, compositeness, Little Higgs

- **Experimental probes**
  - Hadron colliders: Tevatron, LHC
  - Linear collider/CLIC
  - FCNC, EDM, heavy quark, precision, neutrino, p decay
  - Cosmology/astrophysics

- **Tremendous opportunities in particle physics, to develop standard theory valid to the Planck scale**