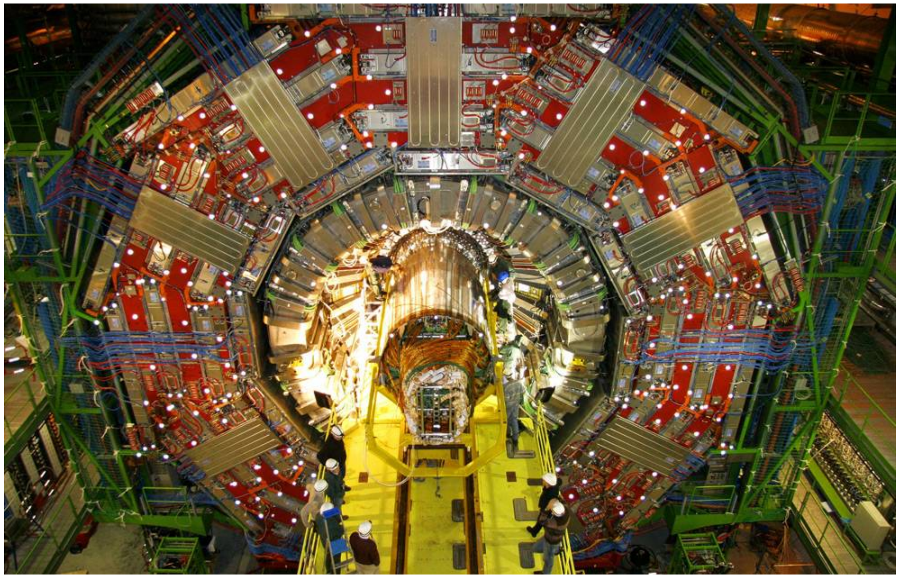
The hunt for new physics at the LHC

- The standard model
- Testing the standard model
- Problems
- Beyond the standard model/paradigm
- New physics at the LHC



The Standard Model

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

- Mathematically consistent, renormalizable theory

- Correct to 10^{-16} cm:
  - QCD: short distance, long distance symmetries
  - QED, WCC, WNC, W, Z
  - Gauge self-interactions

- Missing: Higgs (or alternative), dark matter, dark energy

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

The Fundamental Forces

<table>
<tr><th>Strong</th><th>Electromagnetic</th><th>Weak</th><th>Gravity</th></tr>
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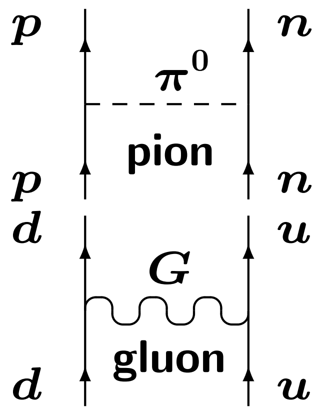
<td>
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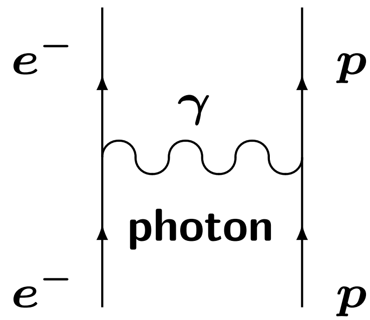
<td>
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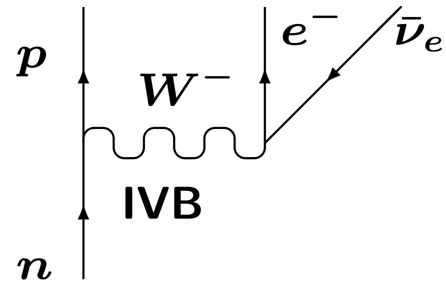
<td>
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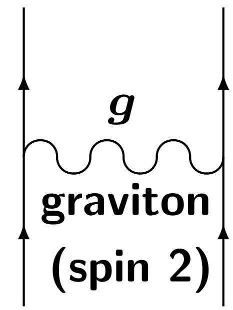
<td>
</td>
</tr>
<tr><td>$V = g_\pi^2 \frac{e^{-m_\pi r}}{r}$</td><td>$\frac{e^2}{r}$</td><td>$g^2 \frac{e^{-M_W r}}{r}$</td><td>$G_N \frac{m_1 m_2}{r}$</td></tr>
<tr><td>strength: $\frac{g_\pi^2}{4\pi} \sim 14$</td><td>$\alpha = \frac{e^2}{4\pi} \sim \frac{1}{137}$</td><td>$\frac{g^2 E^2}{M_W^2} \sim 10^{-11}$
$(E = 1$ MeV$)$</td><td>$G_N m_1 m_2 \sim 10^{-38}$
$(m_1 = m_2 = 1$ GeV$)$</td></tr>
<tr><td>range: $\frac{\hbar}{m_\pi c} \sim 10^{-13}$ cm $\equiv 1$ fm</td><td>∞</td><td>$\frac{\hbar}{M_W c} \sim 10^{-16}$ cm</td><td>∞</td></tr>
</table>

Unification of Forces

<table>
<tr><th>Strong</th><th>Electromagnetic</th><th>Weak</th><th>Gravity</th></tr>
<tr><td>hadrons: p, n; pions: $\pi^{\pm}, \pi^{0}$; (QCD: quarks, gluons)</td><td>charged particles: e^{-}, μ^{-}, τ^{-}; p; $\pi^{\pm}$</td><td>p, n, π; e, μ, τ;, neutrinos: ν_e, ν_μ, ν_τ</td><td>all particles (always attractive)</td></tr>
<tr><td>nuclear binding; energy in stars</td><td>atoms, crystals, molecules; light; chemical energy</td><td>decays: $n \to pe^{-}\bar{\nu}_e$; element synthesis</td><td>weight; binding of solar system, stars, galaxies</td></tr>
<tr><td></td><td>$\leftarrow$ $E + B$ $\rightarrow$ (Maxwell)</td><td></td><td></td></tr>
<tr><td>$\leftarrow$ QCD $\rightarrow$</td><td colspan="2">$\leftarrow$ Electroweak $(SU(2) \times U(1))$ $\rightarrow$</td><td></td></tr>
<tr><td colspan="3">$\leftarrow$ Grand Unification (GUT)? $\rightarrow$</td><td></td></tr>
<tr><td colspan="4">$\leftarrow$ Theory of Everything (superstring)? $\rightarrow$</td></tr>
</table>

The Standard Model

- Gauge group $SU(3) \times SU(2) \times U(1)$; gauge couplings g_s, g, g'

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

$$\begin{array}{cccc} u_R & u_R & u_R & \nu_{eR}(?) \\ d_R & d_R & d_R & e^-_R \end{array}$$

(L = left-handed, R = right-handed)

- $SU(3)$: $u \leftrightarrow u \leftrightarrow u$, $d \leftrightarrow d \leftrightarrow d$ (8 gluons)

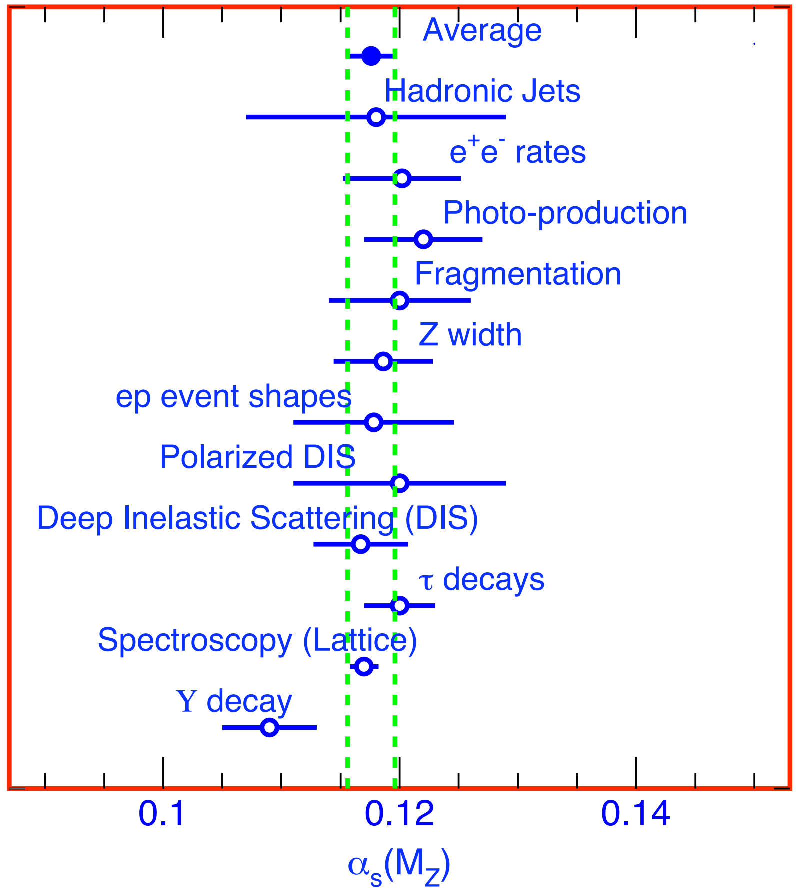
- $SU(2)$: $u_L \leftrightarrow d_L$, $\nu_{eL} \leftrightarrow e^-_L$ $(W^\pm)$; phases (W^0)

- $U(1)$: phases (B)

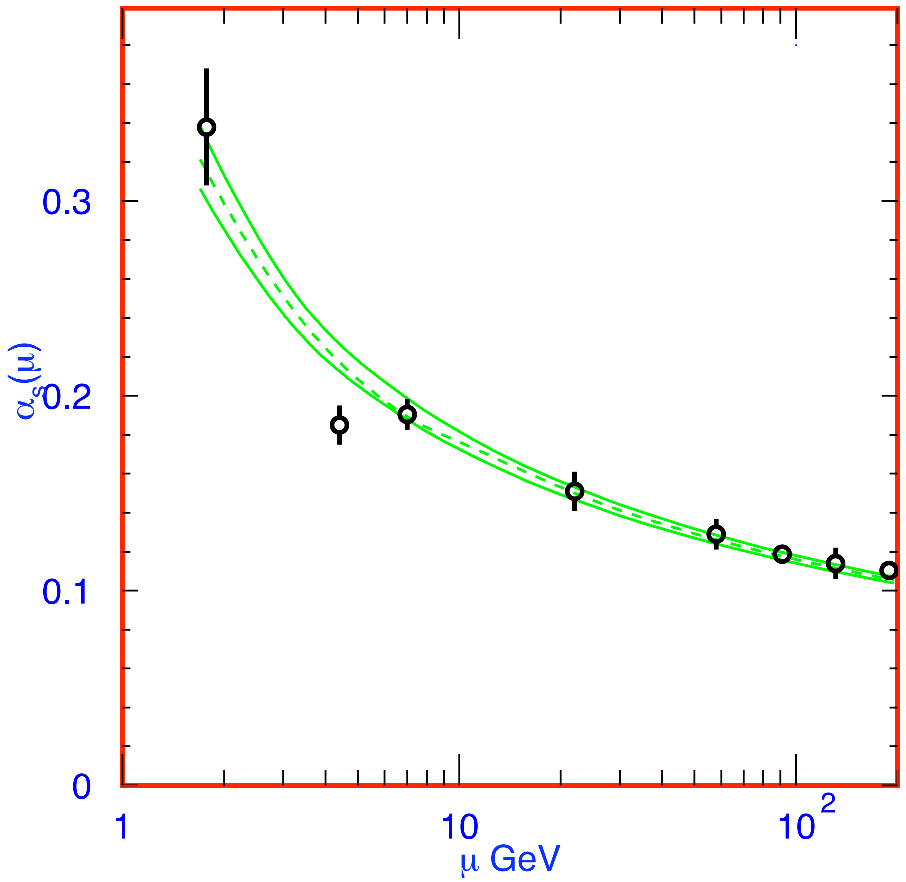
- Heavy families (c, s, ν_μ, μ^-), (t, b, ν_τ, τ^-)

Quantum Chromodynamics (QCD)

- QCD now very well established
- Short distance behavior (asymptotic freedom)
- Confinement, light hadron spectrum (lattice)
  - $g_s = O(1)$ ($\alpha_s(M_Z) = g_s^2/4\pi \sim 0.12$)
  - Strength $+$ gluon self-interactions $\Rightarrow$ confinement
  - Yukawa model $\Rightarrow$ dipole-dipole
- Approximate global $SU(3)_L \times SU(3)_R$ symmetry and breaking (π, K, η are pseudo-goldstone bosons)
- Unique field theory of strong interactions



Average
Hadronic Jets
e+e- rates
Photo-production
Fragmentation
Z width
ep event shapes
Polarized DIS
Deep Inelastic Scattering (DIS)
τ decays
Spectroscopy (Lattice)
Υ decay
0.1
0.12
0.14
$\alpha_s(M_Z)$



$\alpha_s(\mu)$
0.3
0.2
0.1
0
1
10
10^2
μ GeV

Quantum Electrodynamics (QED)

Experiment	Value of α^{-1}	Precision	Δ_e
$a_e = (g_e - 2)/2$	$137.035\ 999\ 683\ (94)$	$[6.9 \times 10^{-10}]$	–
h/m (Rb, Cs)	$137.035\ 999\ 35\ (69)$	$[5.0 \times 10^{-9}]$	0.33 ± 0.69
Quantum Hall	$137.036\ 003\ 0\ (25)$	$[1.8 \times 10^{-8}]$	-3.3 ± 2.5
h/m (neutron)	$137.036\ 007\ 7\ (28)$	$[2.1 \times 10^{-8}]$	-8.0 ± 2.8
$\gamma_{p,{}^3He}$ (J. J.)	$137.035\ 987\ 5\ (43)$	$[3.1 \times 10^{-8}]$	12.2 ± 4.3
$\mu^+ e^-$ hyperfine	$137.036\ 001\ 7\ (80)$	$[5.8 \times 10^{-8}]$	-2.0 ± 8.0

Spectacularly successful:

- Most precise: e anomalous magnetic moment $\rightarrow \alpha$
- Many low energy tests to few $\times 10^{-8}$
- $m_\gamma < 6 \times 10^{-17}$ eV, $\quad q_\gamma < 5 \times 10^{-30}|e|$
- Running $\alpha(Q^2)$ observed
- Muon $g - 2$ sensitive to new physics. Anomaly?

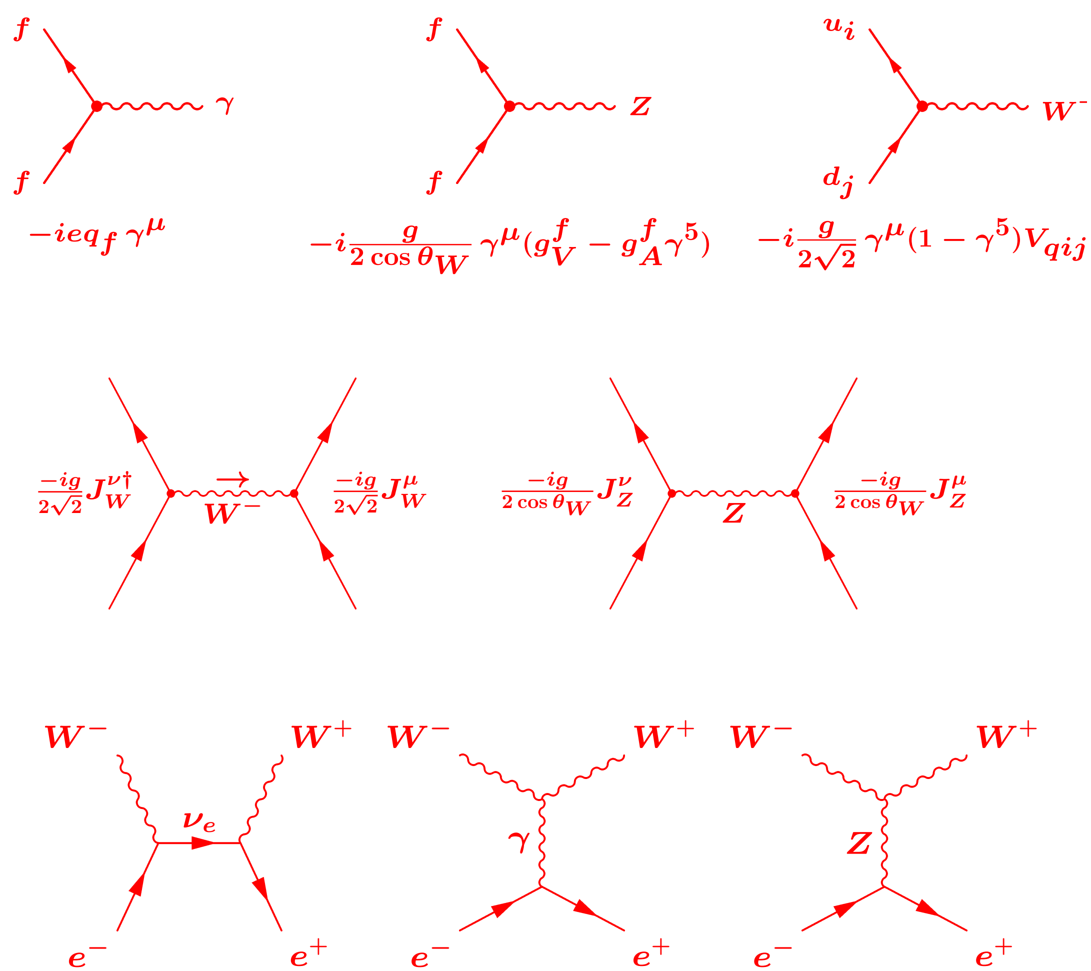
The Electroweak Theory

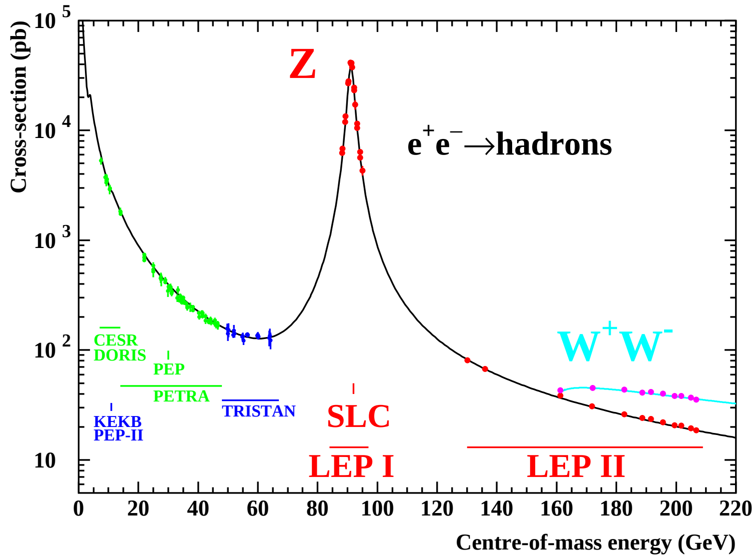
- **QED and weak charged current unified**

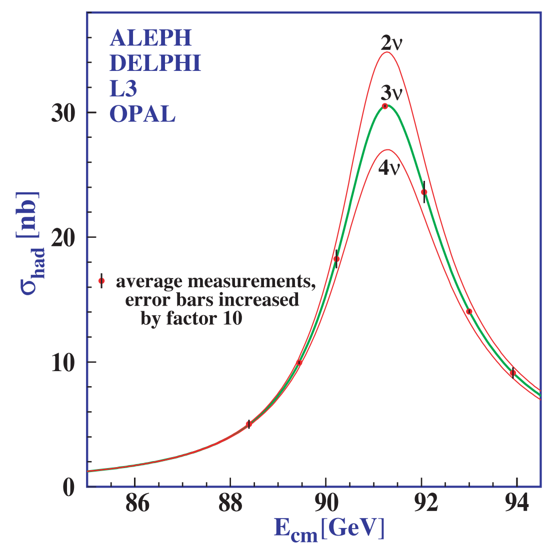
- **Weak neutral current (Z) predicted**
  ($\nu N \to \nu X$, atomic parity violation)

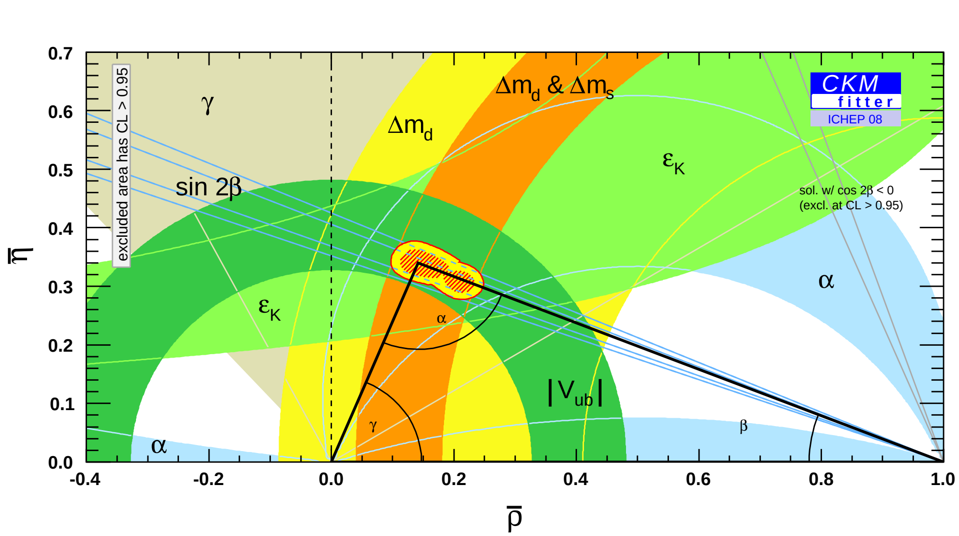
- **Stringent tests of WCC, CP-violation, WNC, Z-pole, beyond**

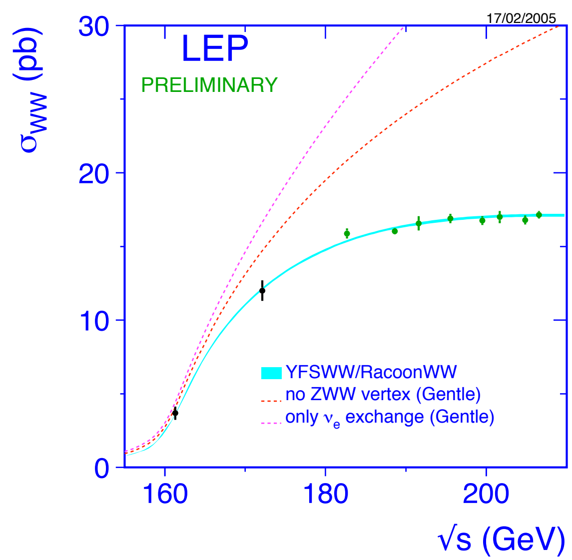
- **Fermion gauge and gauge self-interactions**




Z
$e^+e^- \to$hadrons
Cross-section (pb)
Centre-of-mass energy (GeV)
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
W^+W^-


ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10
σ_{had} [nb]
E_{cm}[GeV]


excluded area has CL > 0.95
γ
Δm_d
Δm_d & Δm_s
ε_K
sin 2β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
$|V_{ub}|$
β
CKM
fitter
ICHEP 08
$\bar{\eta}$
$\bar{\rho}$


17/02/2005
LEP
PRELIMINARY
σ_{WW} (pb)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)
√s (GeV)

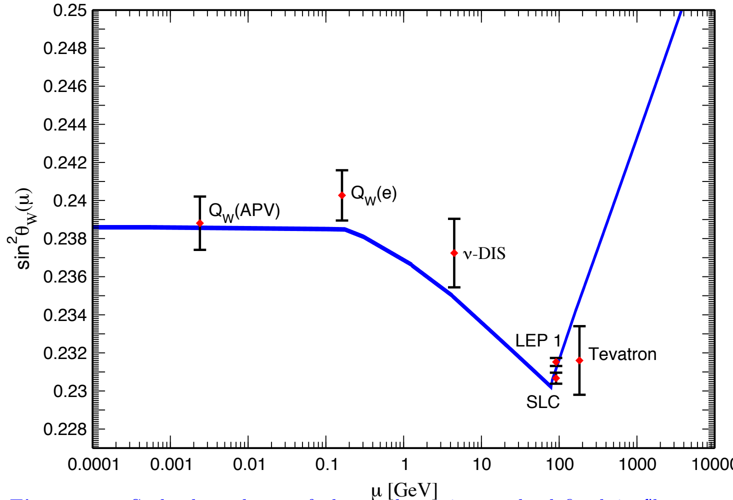
- **SM correct and unique to zeroth approx. (gauge principle, group, representations)**

- **SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)**

- **TeV physics severely constrained (unification versus compositeness)**

- **Consistent with light elementary Higgs**

- **Precise gauge couplings (SUSY gauge unification)**

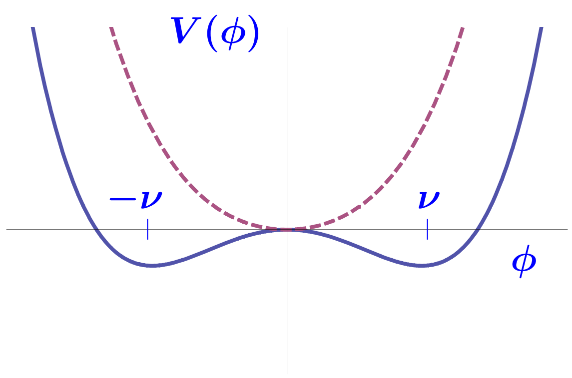


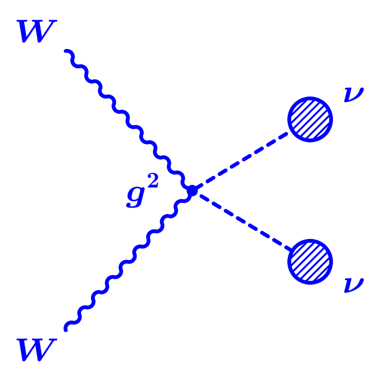
The Higgs Mechanism

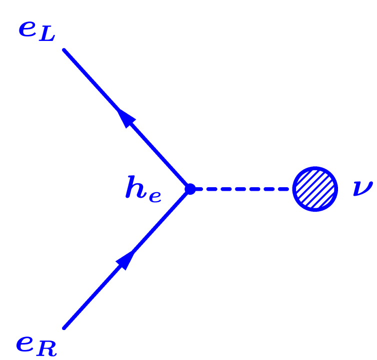
- **Gauge symmetry forbids elementary masses for W, Z, fermions**

- **Introduce Higgs field H, with classical value ν and potential energy $V(\nu) = \frac{1}{2}\mu^2\nu^2 + \frac{1}{4}\lambda\nu^4$**

- **W, Z, fermions acquire effective masses by coupling to H (transparent to photon)**







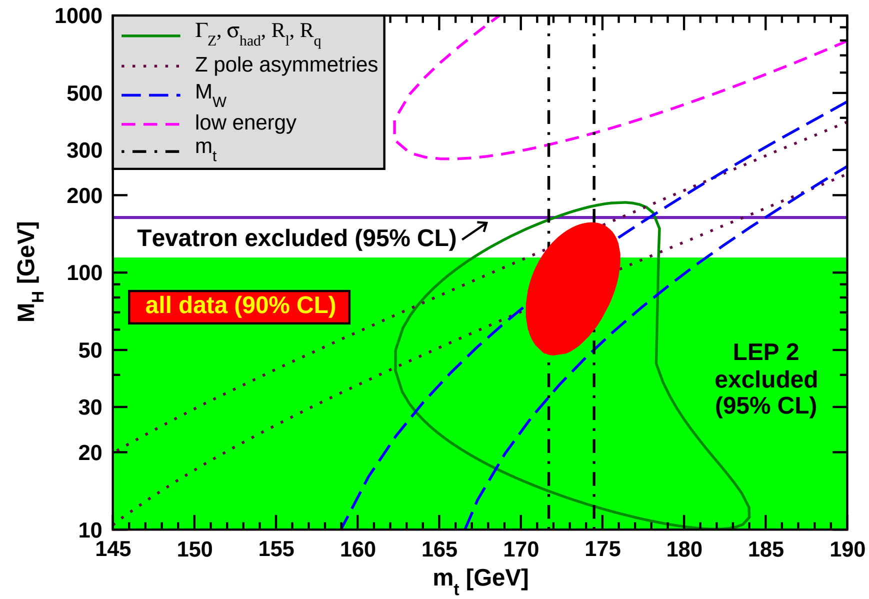
- Higgs mass $M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}\nu$ ($\nu \sim 246$ GeV, λ unknown)

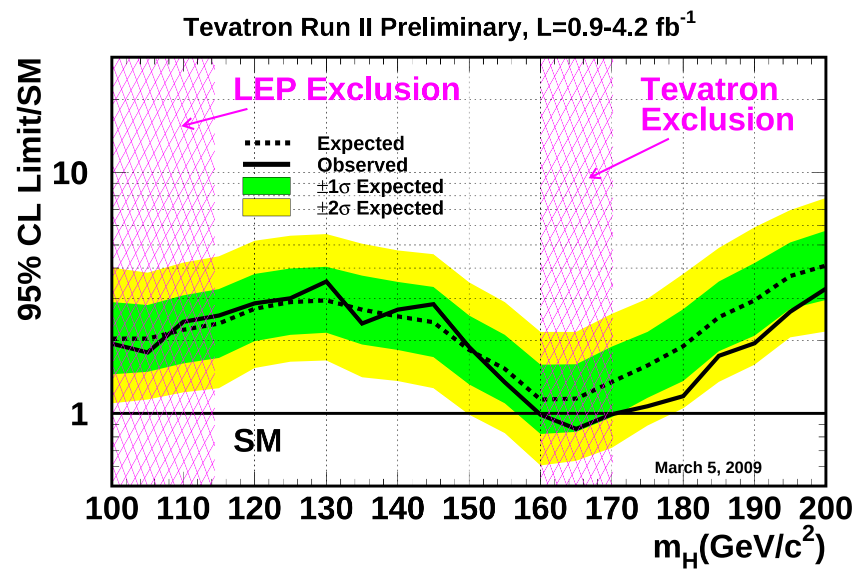
- LEP search $e^+e^- \to Z^* \to ZH$: $M_H > 114.4$ GeV

- Indirect (electroweak radiative corrections)) + direct: $M_H < 149$ GeV (95%)

- Tevatron searches now sensitive enough for higher masses

- LHC will cover full range for standard model Higgs





Problems with the Standard Model

Lagrangian after symmetry breaking:

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

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

Mathematically consistent, renormalizable theory

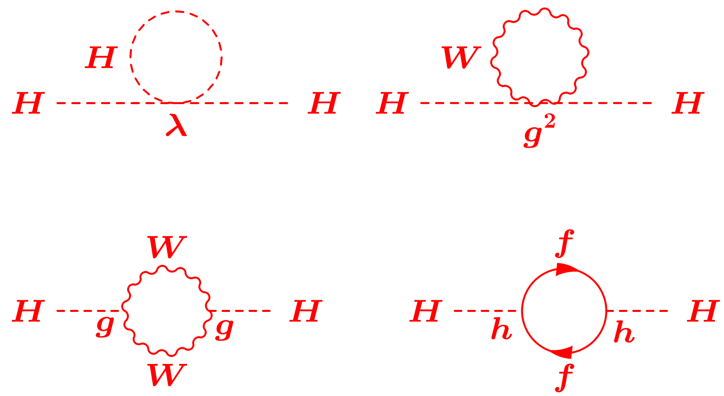
Correct to 10^{-16} **cm**

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 (only EW chiral)
  - 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? Probe of Planck/GUT scale?
  - 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 and/or warped extra dimensions; Little Higgs; anthropically motivated fine-tuning (split supersymmetry) (landscape)

- **Strong CP problem**
  - Can add $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ to QCD (breaks, P, T, CP)
  - $d_N \Rightarrow \theta < 10^{-11}$, 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**
- $\Lambda_{cosm} = \Lambda_{bare} + \Lambda_{SSB}$. **Anthropically motivated fine-tuning** (landscape)?

Necessary new ingredients

- Mechanism for small neutrino masses
  - Planck/GUT scale? Small Dirac (intermediate scale)?
- Mechanism for baryon asymmetry?
  - Electroweak transition (Z' or extended Higgs?)
  - Heavy Majorana neutrino decay (seesaw)?
  - Decay of coherent field? CPT violation?
- What is the dark energy?
  - Cosmological Constant? Quintessence?
  - Related to inflation? Time variation of couplings?

- **What is the dark matter?** **(Recent anomalies in e^+/e^-, DAMA, etc?)**
  - **Lightest supersymmetric particle (LSP)? Axion? Gravitino? Primordial black hole? SuperWIMP?**
  - **"Ad hoc" weakly coupled dark sector?**

- **Suppression of flavor changing neutral currents? Proton decay? Electric dipole moments?**
  - *Automatic* **in standard model, but not in extensions**
    ("particle Fermi paradox" a.k.a. little hierarchy problem)

New Physics

- A new layer at the TeV scale
  - Compositeness, Little Higgs, twin Higgs, Higgless, dynamical symmetry breaking, strong dynamics
  - Precision electroweak constraints, FCNC, UV completions?

- Large and/or warped extra dimensions; possible low fundamental or string scale

- Unification at the Planck scale, $M_P = G_N^{-1/2} \sim 10^{19}$ GeV
  - Supersymmetry (between fermions and bosons), grand unification, strings?
  - Top-down remnants: Z', W', extended Higgs, exotic fermions, $\ldots$

Compositeness, Strong Dynamics

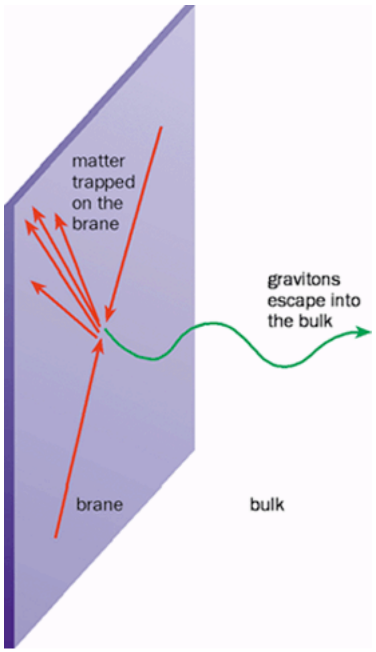
- Composite fermions, scalars (onion-like layers)
  - *Not* like to atom $\rightarrow$ nucleus $+e^- \rightarrow p + n \rightarrow$ quark
- Alternative electroweak breaking: Little Higgs, dynamical symmetry breaking, topcolor, $\cdots$
- At most one more layer accessible (Tevatron, LHC, ILC)
- Rare decays (e.g., $K \rightarrow \mu e$)
- Usually few % effects at LEP/SLC, LEP2, WNC (challenge for models)
- LHC: anomalous VVV, new particles, strong $WW \rightarrow WW$
- Also: FCNC, EDM

Extra dimensions (deconstruction, brane worlds)

- Motivated by strings

- Can be large, warped, stringy

- Matter can be trapped on branes, at boundaries, or in bulk



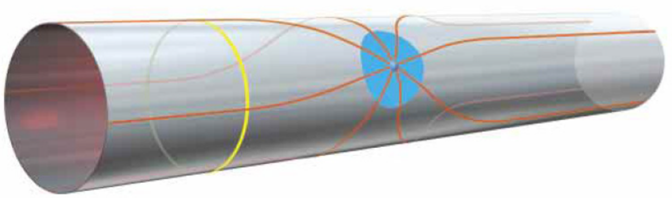
- E.g., new dimensions much larger than $M_P^{-1} \sim 10^{-33}$ cm

- Fundamental scale: $M_F \sim (1 - 100)$ TeV $\ll \bar{M}_{Pl} = 1/\sqrt{8\pi G_N} \sim 2.4 \times 10^{18}$ GeV

  – Assume δ extra dimensions with volume $V_\delta \gg M_F^{-\delta}$

$$\bar{M}_{Pl}^2 = M_F^{2+\delta} V_\delta \gg M_F^2$$

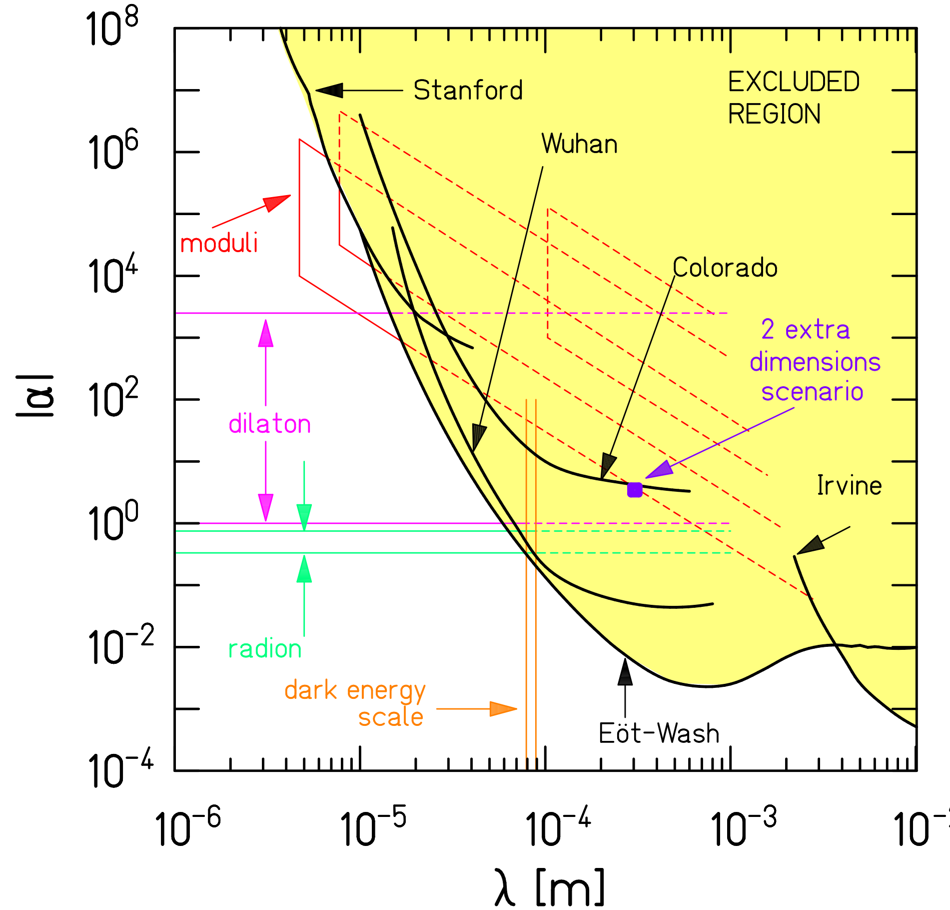
(but new hierarchy problem)



- **LHC: Kaluza-Klein excitations, string excitations, graviton emission, black holes**

- **Astrophysics**

- **Macroscopic gravity effects**

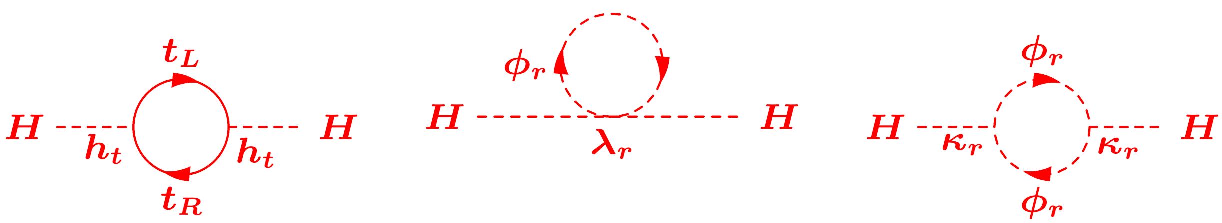


Unification

- **Unification of interactions**
- **Grand desert to unification (GUT) or Planck scale**
- **Elementary Higgs, supersymmetry (SUSY), GUTs, strings**
- **Possibility of probing to M_P and very early universe**

Supersymmetry

- Fermion $\leftrightarrow$ boson symmetry
- Motivations
  - Incorporation of gravity (*but* M_{SUSY} could be very large)
  - Stabilization of electroweak scale



But landscape ideas (anthropically-motivated fine tuning); variants (e.g., split supersymmetry); alternative EWSB

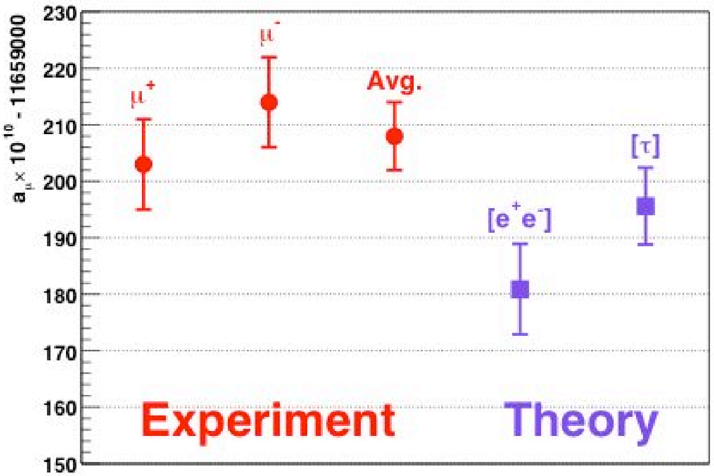
– **Gauge unification**

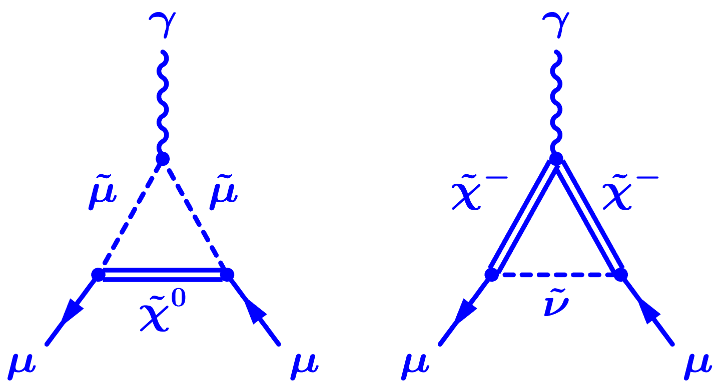
– **Cold dark matter (LSP) if R-parity (R_P) conserved**

– **Z-pole: any new physics decouples**

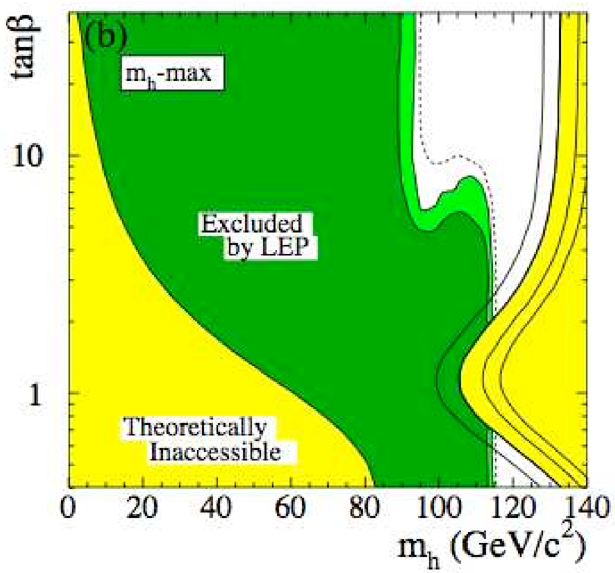
– **Radiative electroweak breaking** (large $m_t \rightarrow m_{Hu}^2 < 0$)

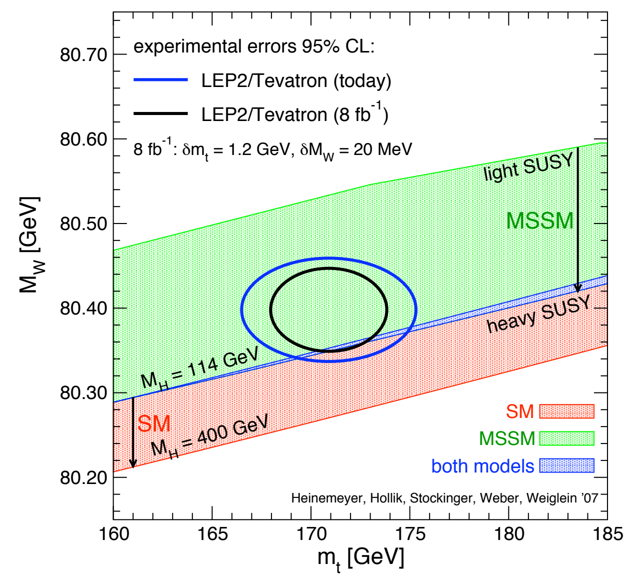
– **Anomalous magnetic moment of muon** ($g_\mu - 2$)**?**





- **Additional charged and neutral Higgs particles**
  - $M^2_{H^0} < \cos^2 2\beta M^2_Z +$ H.O.T. $(O(m_t^4)) < (130\ \text{GeV})^2$, consistent with LEP (standard model: $M_{H^0} < 1000$ GeV)
  - CDF/D0 searches for heavier states
  - LHC ultimately sensitive to entire range



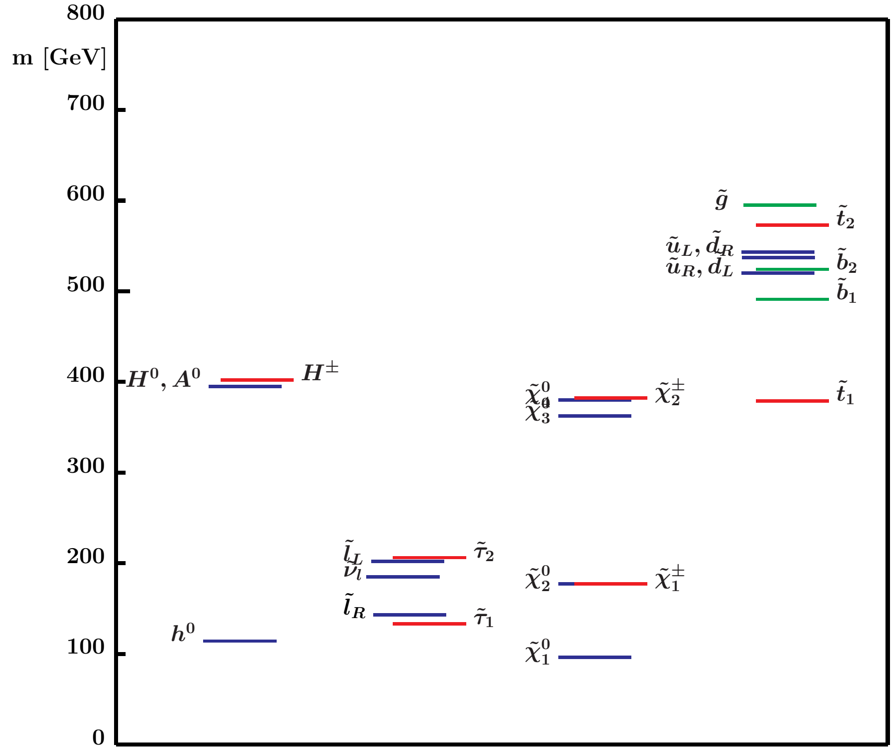


- **Simplest version: supersymmetric contribution to Higgs mass must be of $O(100)$ GeV (not 10^{19})** (μ problem)

- Superpartners

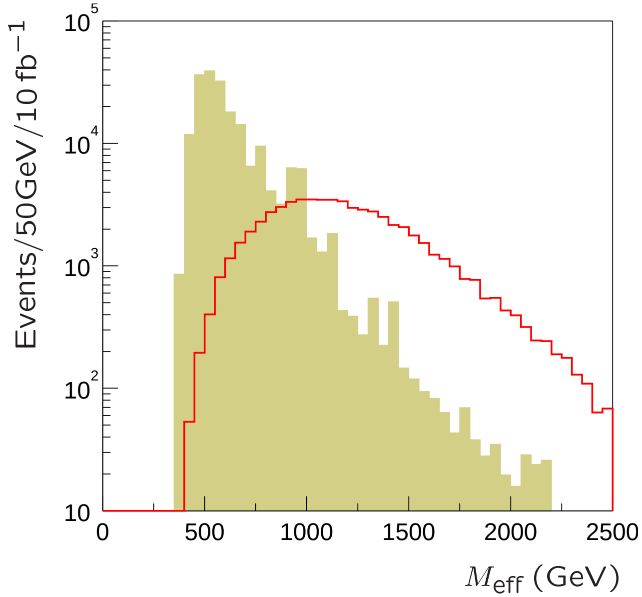
  - $q \Rightarrow \tilde{q}$ (scalar quark)
  - $\ell \Rightarrow \tilde{\ell}$ (scalar lepton)
  - $H \Rightarrow \tilde{H}$ (Higgsino)
  - $G, W, B \Rightarrow \tilde{G}, \tilde{W}, \tilde{B}$ (gauginos)

  - typical scale: several hundred GeV
  - LSP: dark matter candidate
  - SUSY breaking $\Leftrightarrow$ large m_t
  - May be large FCNC, EDM, $\Delta(g_\mu - 2)$

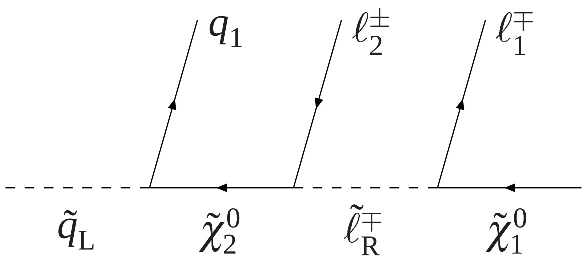


Tevatron, LHC Signatures

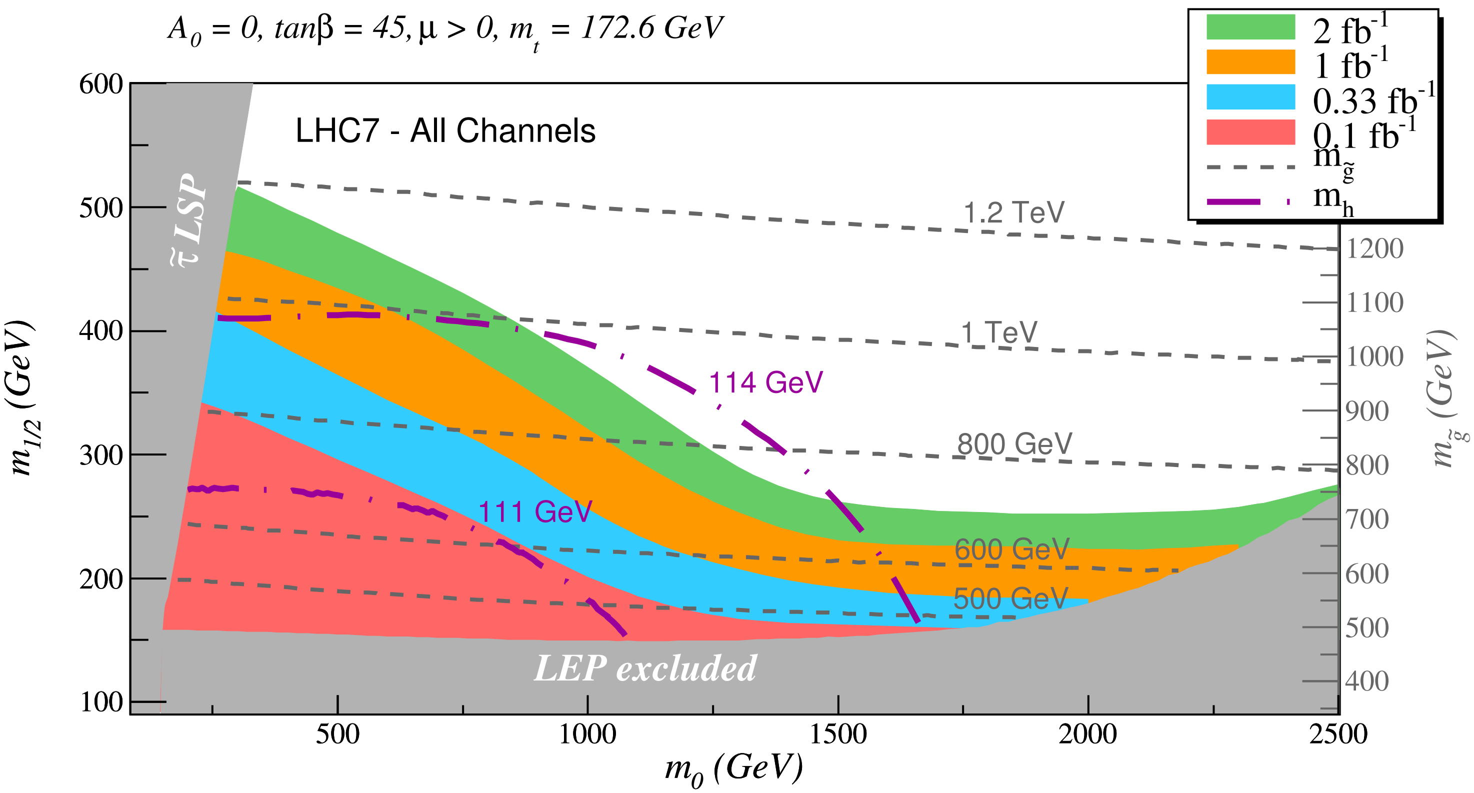
- Squarks, gluinos pair-produced at large rate by QCD
- Sleptons, charginos, neutralinos: smaller direct rate (Drell-Yan and t-channel squark), but occur in squark decay chains
- Missing transverse energy: decay chains end in LSP (e.g., $\tilde{\chi}^0_1$ in supergravity)
- Cascade decays $\rightarrow$ multiple jets and leptons (same/opposite sign dileptons, trileptons); kinematic edges (mass eigenstates); some spin information
- Same sign leptons $\leftrightarrow$ Majorana fermions



$$M_{\rm eff} = \not{E}_T + \Sigma_{i=1}^4 p_T^i$$



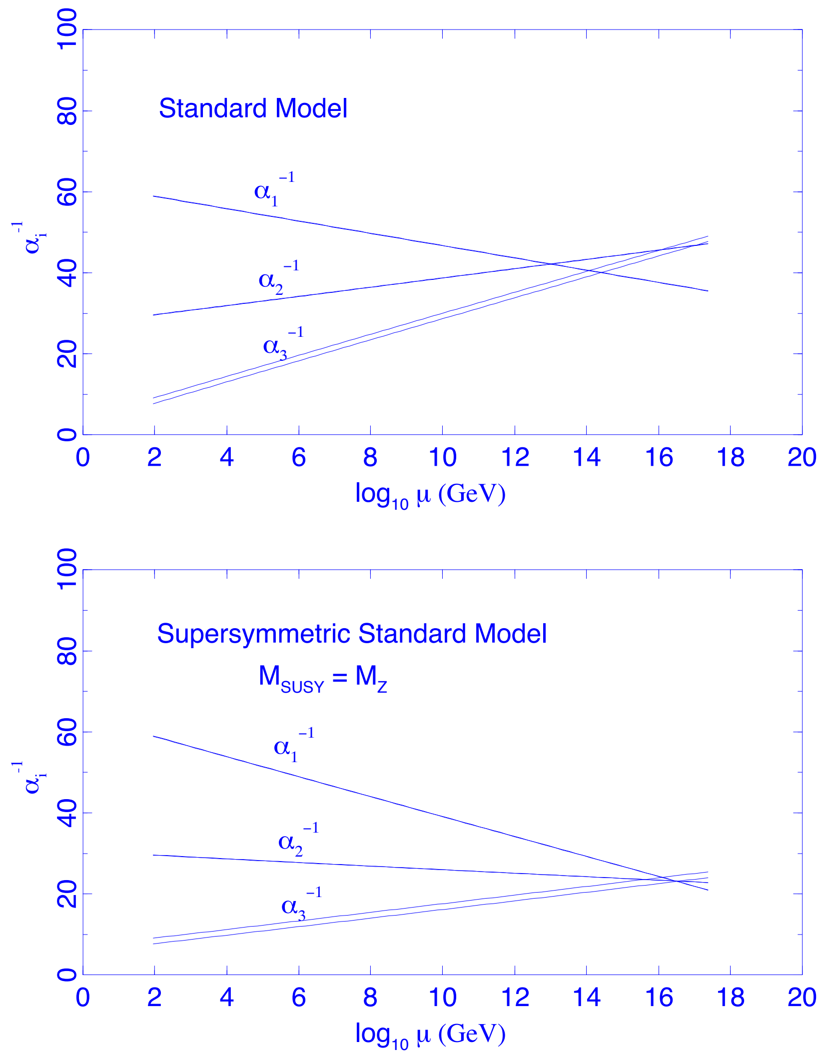
- **LHC reach at 7 TeV (Baer, Barger, Lessa, Tata, 1004.3594)**



Grand Unification

- **Unify strong $SU(3)$ and electroweak $SU(2)\times U(1)$ in simple group (e.g., $SU(5)$, $SO(10), E_6$), broken at $\sim 10^{16}$ GeV**

- **Gauge unification (only in supersymmetric version)**



- **Seesaw model for small m_ν** (but why are mixings large?)

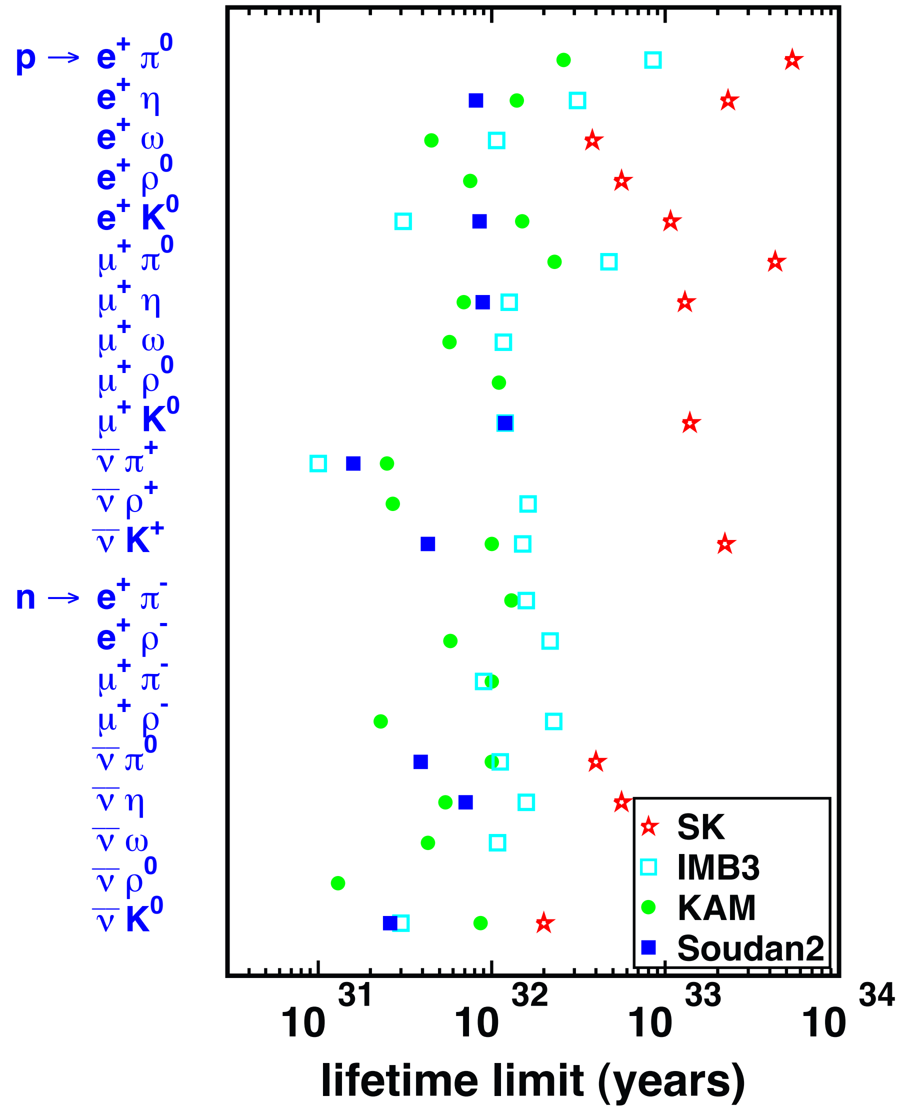
- **Quark-lepton $(q-l)$ unification** ($\Rightarrow$ charge quantization)

- **$q-l$ mass relations** (work only for third family in simplest versions)

- **Proton decay?** (simplest versions excluded)

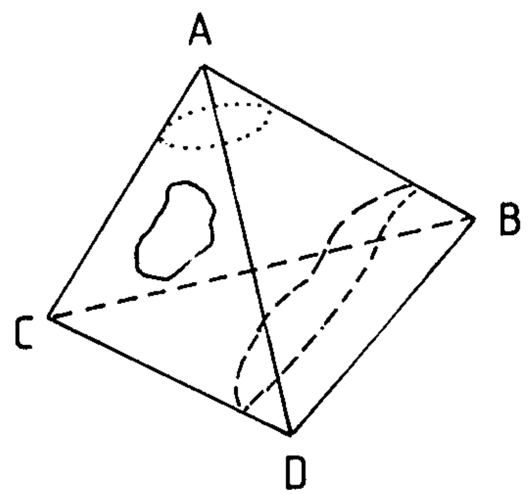
- **Doublet-triplet problem?**

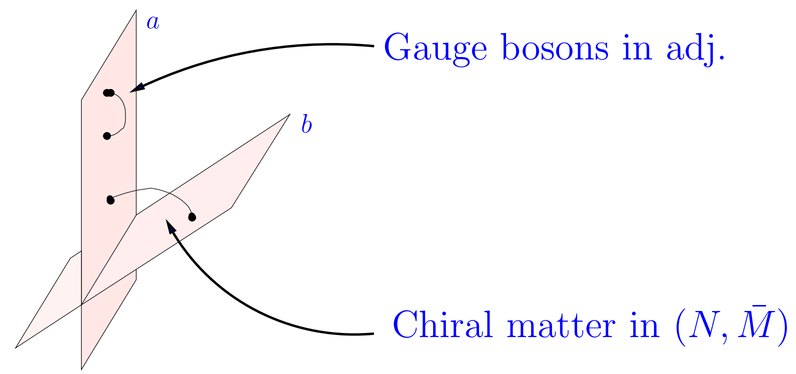
- **String embedding?** (breaking, families may be entangled in extra dimensions)



Superstrings

- Finite, "parameter-free" "theory of everything" (TOE), including quantum gravity
  - 1-d string-like object
  - Appears pointlike for resolution $> M_s^{-1} \sim M_P^{-1} \sim 10^{-33}$ cm
  - Vibrational modes $\rightarrow$ particles
  - 10 space-time dimensions $\rightarrow$ 6 must compactify to scale M_s^{-1}
  - 4-dim supersymmetric gauge theory below M_s
  - May also be solitons (branes), terminating open strings





- Problems
  - Which type? Dualities
  - Which compactification manifold?
  - Relation to supersymmetric standard model, GUT?
  - Supersymmetry breaking/mediation? Scale? Cosmological constant?
  - Many moduli/vacua. Landscape ideas - any predictability left? (TOE $\Rightarrow$TOA?)

- The great debate: is our physics environmental or selected?
  - Small cosmological constant, weak scale appear needed for life
  - Physics depends on location in multiverse? i.e., $O(10^{500})$ vacua of landscape continually sampled by pockets of eternally inflating multiverse!

Remnant Physics from the Top-Down

- Z' **or other gauge** (μ problem, electroweak baryogenesis, $\cdots$)
- **Extended Higgs/neutralino** (doublet, singlet)(cascades, dark matter,$\cdots$)
- **Quasi-Chiral Exotics** (may be quasi-stable)
- **Quasi-hidden** (SUSY breaking? Dark sector? Composite family?)
- **Non-seesaw** m_ν
- **LED/low** M_s (Kaluza Klein/string excitations, TeV black holes)
- **Charge** $1/2$ (Confinement?, Stable relic?)
- **Time varying couplings**
- **LIV, VEP** (e.g., $v_{\rm max}$, decays (oscillations) of HE γ, e, gravity waves (ν's))

Conclusions

- The standard model is approximately correct description of fermions/gauge bosons down to $\sim 10^{-16}$ cm $\sim \frac{1}{1 \text{ TeV}}$ (but EWSB?)

- Standard model is complicated/fine-tuned $\rightarrow$ must be new physics

- Precision tests severely constrain new TeV-scale physics

- Promising theoretical ideas at Planck scale

- Promising experimental program at LHC (also flavor, ν, cosmology)

- Challenge to make contact between theory and experiment

- Many semi-realistic string constructions suggest extended gauge, Higgs, neutralino, fermion sectors, alternative m_ν