Why Higgs?

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LBL, September 24, 2004

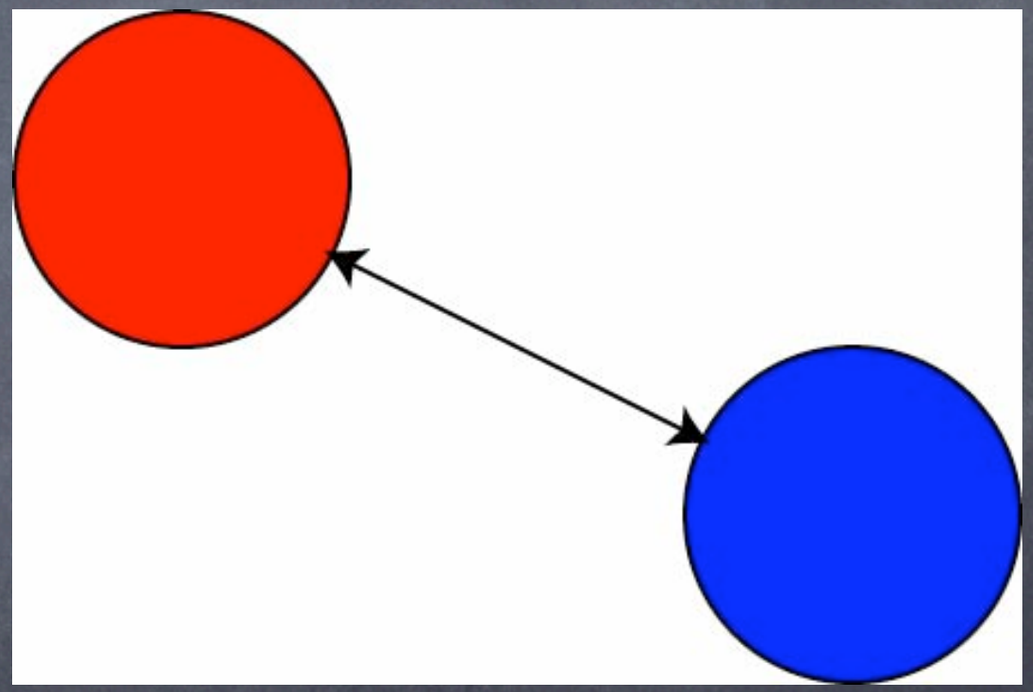
Outline

- Why We Need Higgs
- Any Way Out?

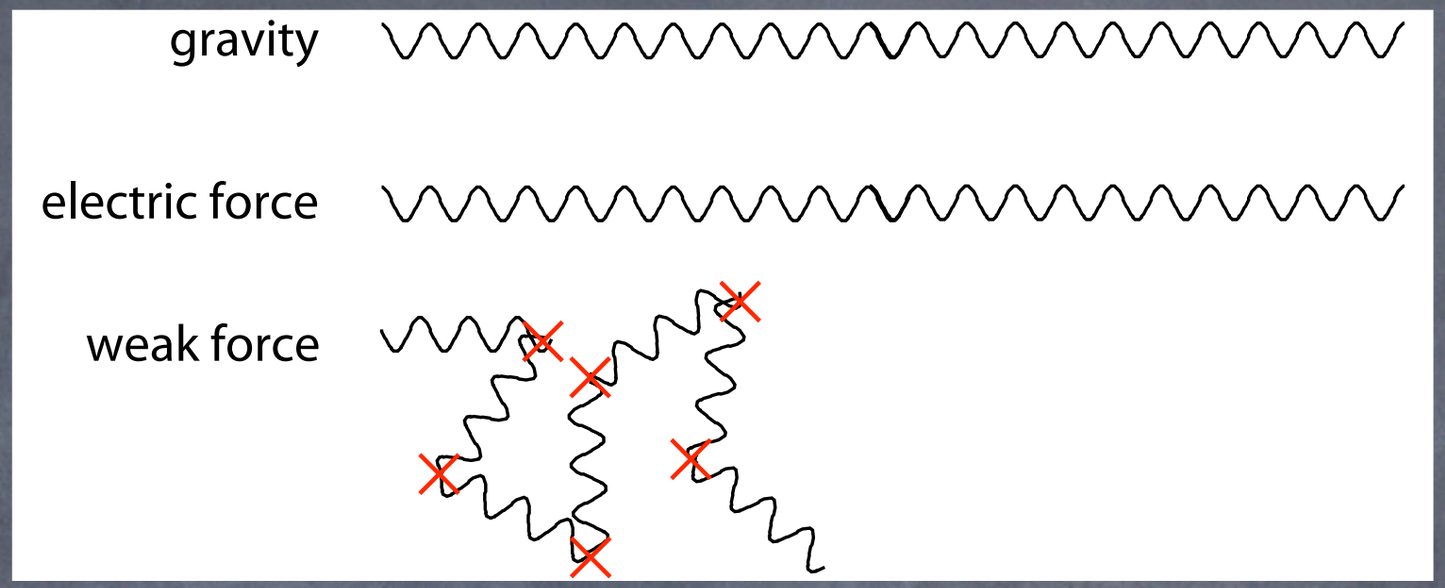
Why We Need Higgs

Mystery of the weak force

- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 10^{-16} cm



"Dark Field"

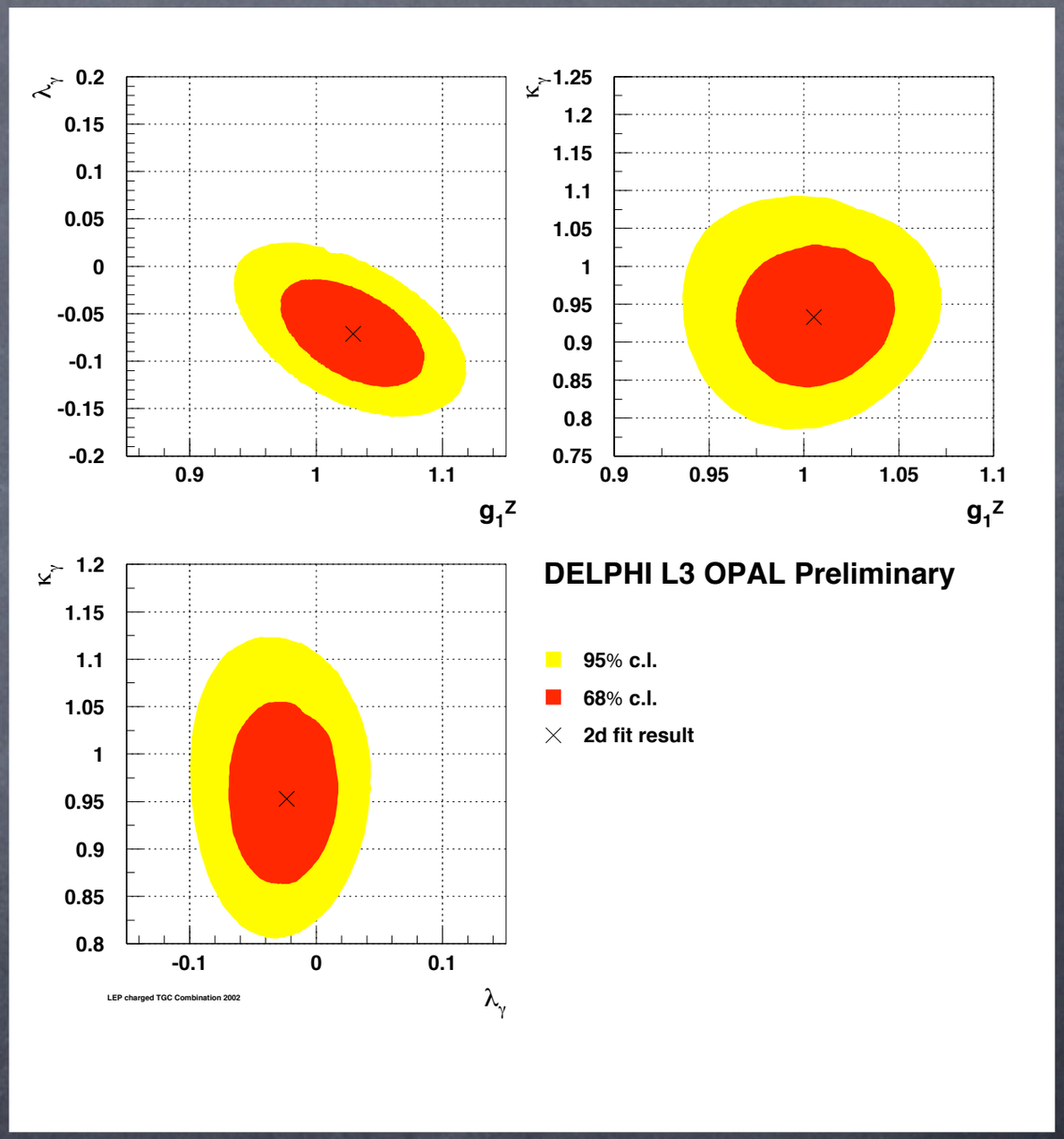


- There is something filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- In fact, it is the "mother of mass" for all elementary particles
- What is it??

Textbook

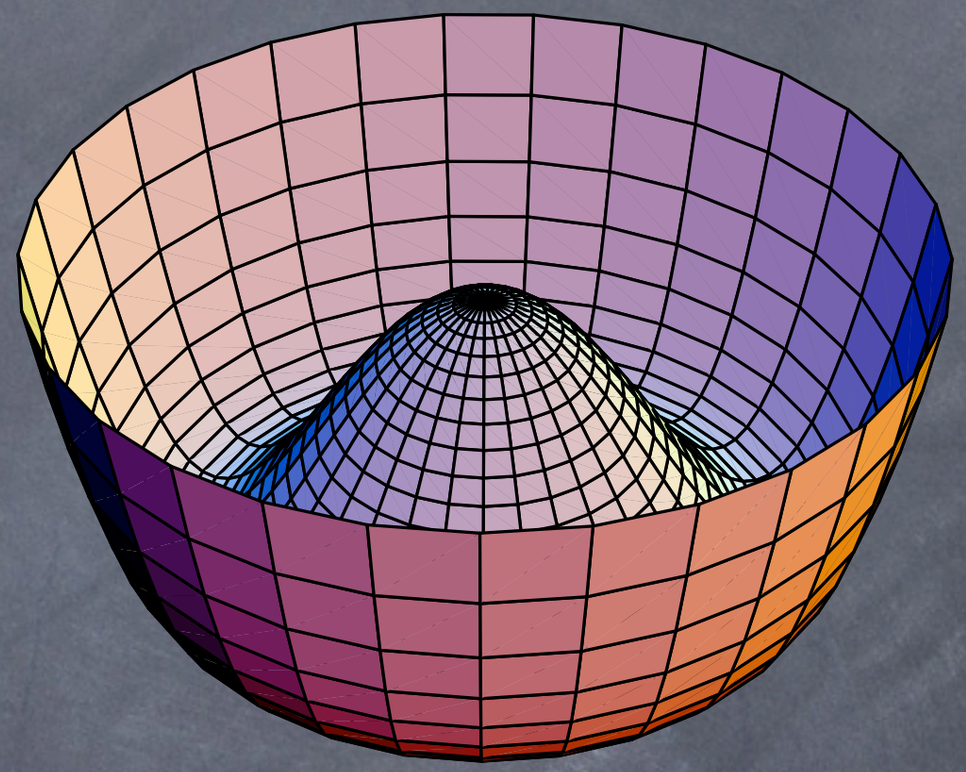
- W and Z are massive vector bosons
- Only known consistent (renormalizable) quantum field theory of massive vectors is gauge theory with Higgs mechanism
- Therefore, W and Z bosons must be gauge bosons, broken by a Higgs

S. Weinberg

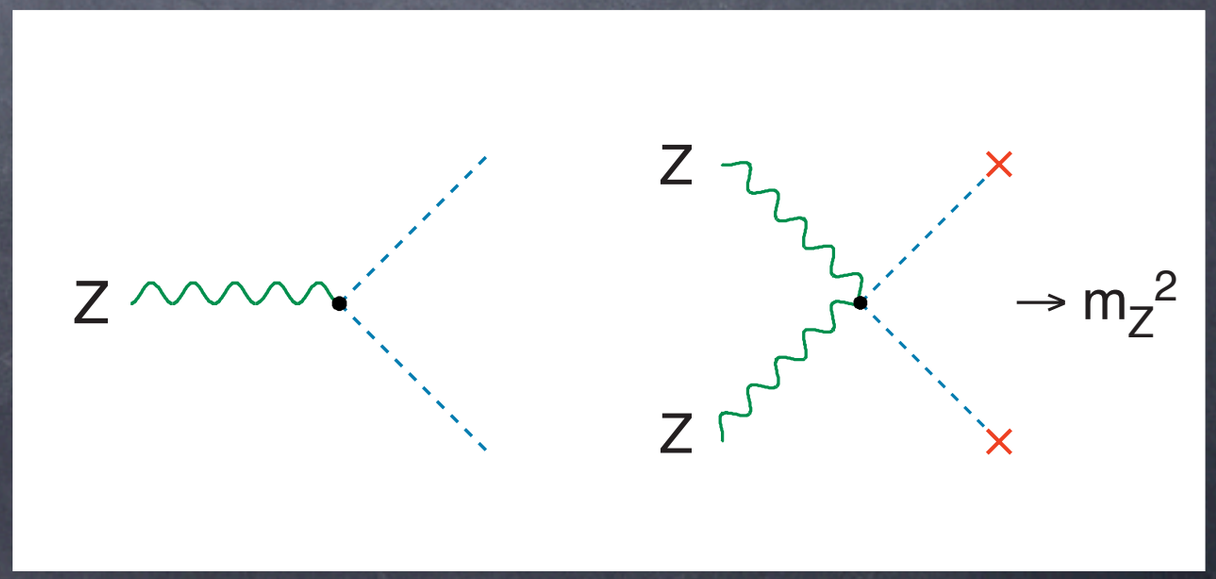


Now added evidence of vector boson self-couplings

Standard Model

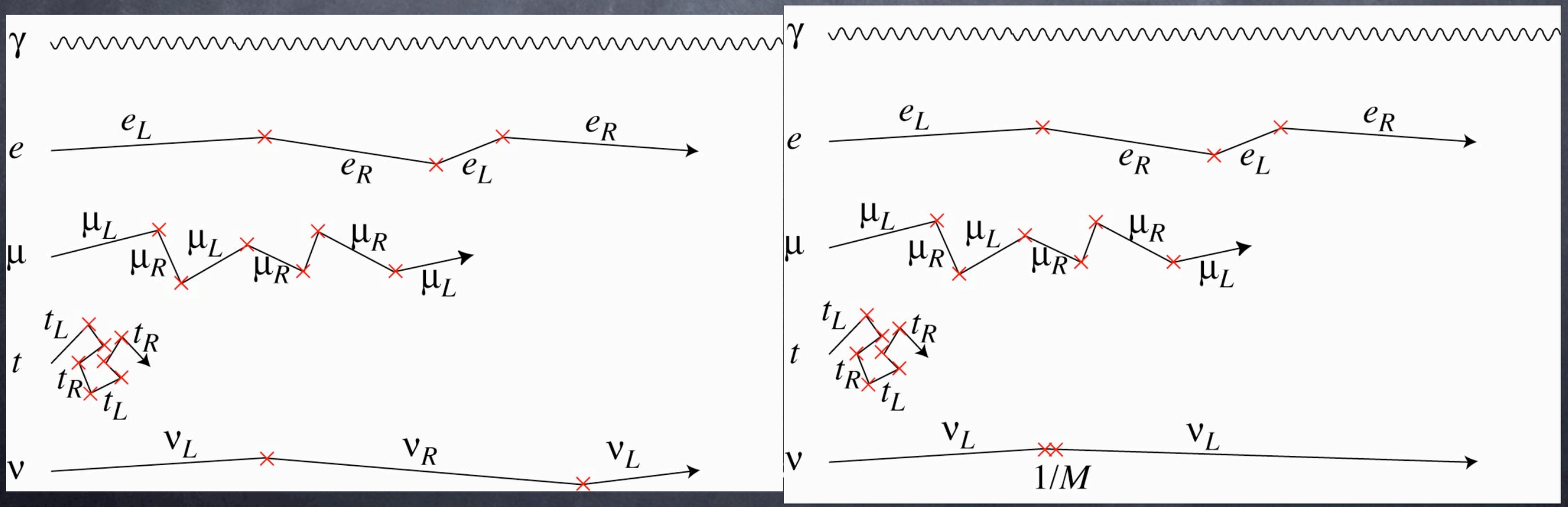


- $V=\lambda|H|^4-\mu^2|H|^2$
- The minimum of the potential has $\langle H\rangle^2=\mu/2\lambda$
- The scalar Higgs boson has two kinds of interactions with Z, W
- Once Higgs is replaced by the expectation value, there is mass for Z, W!



Mother of Masses

- It is not only W and Z bosons
- All elementary matter particles we know (quarks, leptons) get masses from the "Dark Field" from the Yukawa coupling $y\bar{f}_L f_R H + c.c.$
- How exactly neutrinos do that is still a big question!



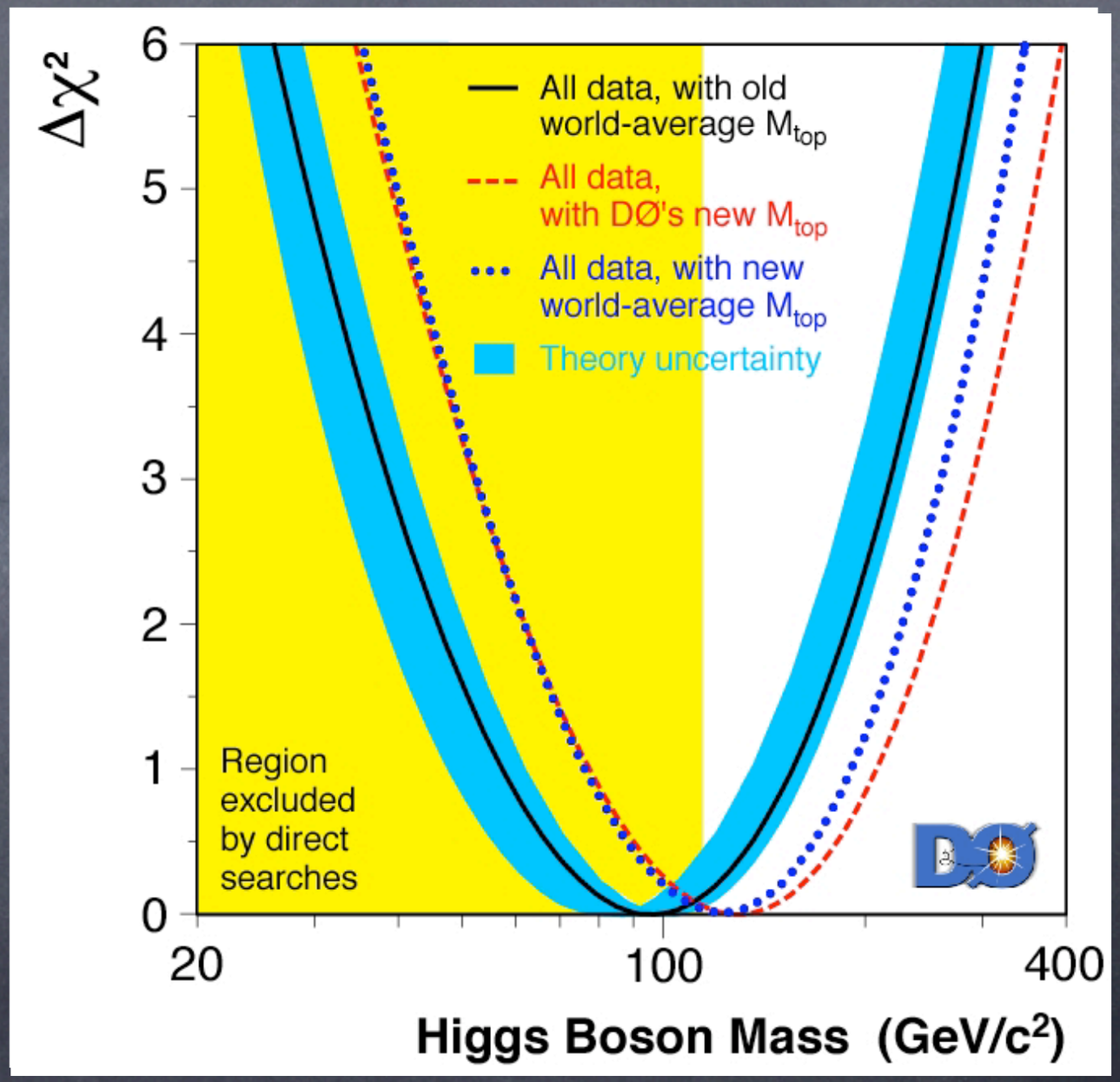
Like a superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"
  - ⇒ Magnetic field is short-ranged!
- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Doesn't have enough energy (gap) to break up Cooper pairs

That's the stage where we are!

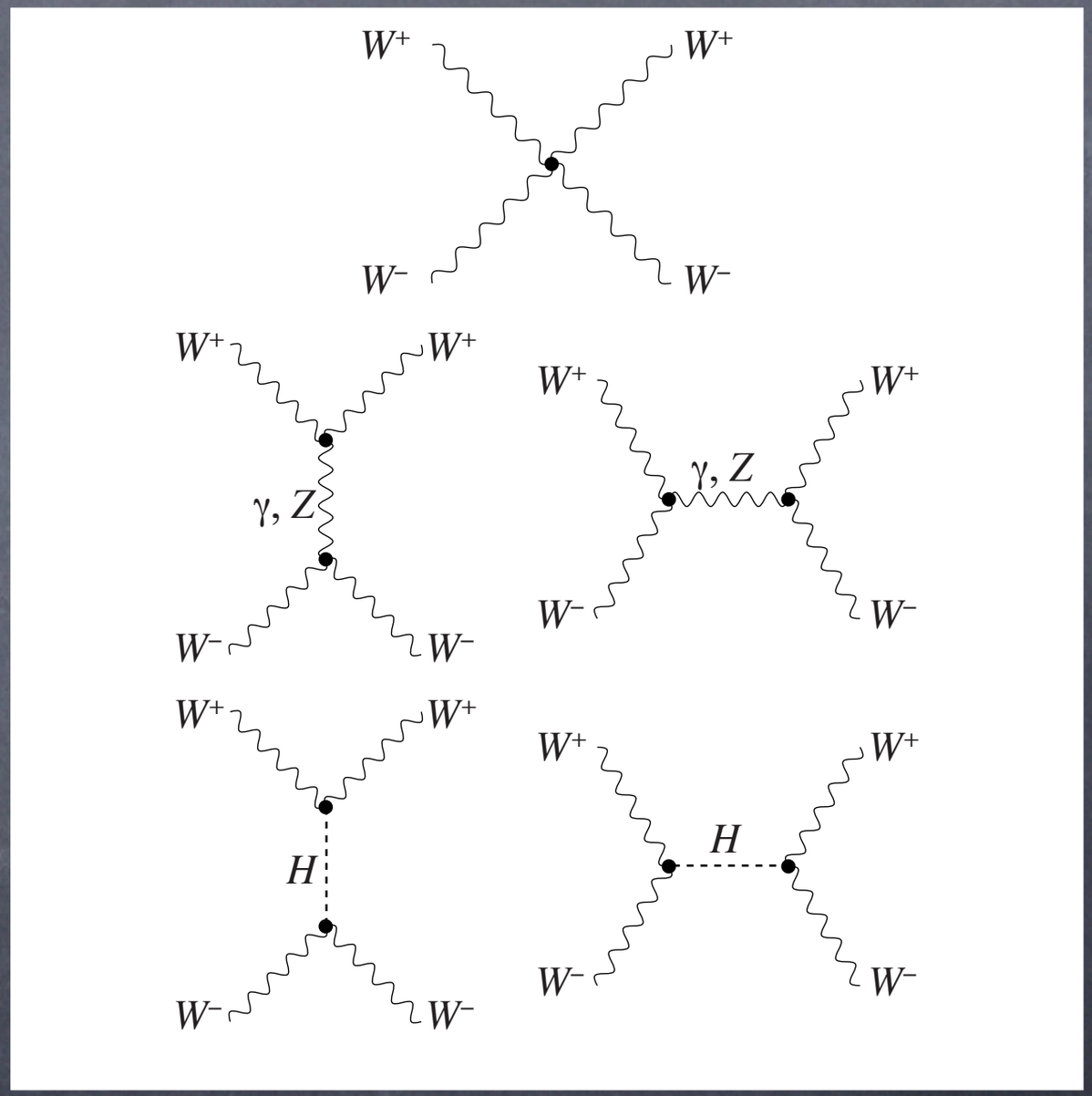
Higgs Boson is Most Likely "Just Around the Corner"

- Higgs boson
  = gap excitation
- Current data combined with the Standard Model theory predict
  m_H ~~<196~~ 237 GeV (95%CL)
- Tevatron at Fermilab has a chance to discover or exclude the SM Higgs boson by 2008



unitarity

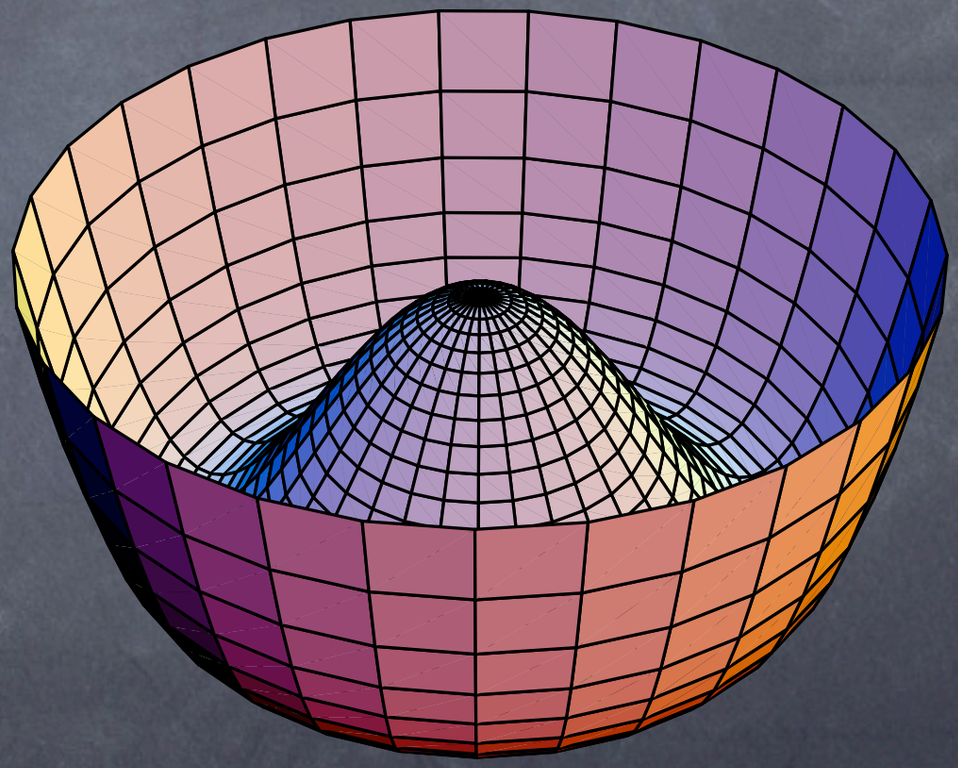
- W-boson scattering grows with energy $A \sim G_F E^2$ and violates unitarity at 1.8TeV
- If you allow only one extra particle beyond what we know to restore unitarity, the only possibility is to add a spin zero particle whose couplings are precisely those of the SM Higgs



C. H. Llewellyn Smith; D. A. Dicus and V. S. Mathur;
J. M. Cornwall, D. N. Levin and G. Tiktopoulos

ugly

- $V=\lambda|H|^4-\mu^2|H|^2$
- Why negative mass-squred?
- Why only one scalar in the SM?
- Hierarchy problem because of its quadratic divergence
- does not appear fundamental, i.e. Ginzburg-Landau vs BCS



Once upon a time, there was a hierarchy problem...

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{\alpha}{r_e} \sim \mathrm{GeV}\,\frac{10^{-17}\,\mathrm{cm}}{r_e}$$

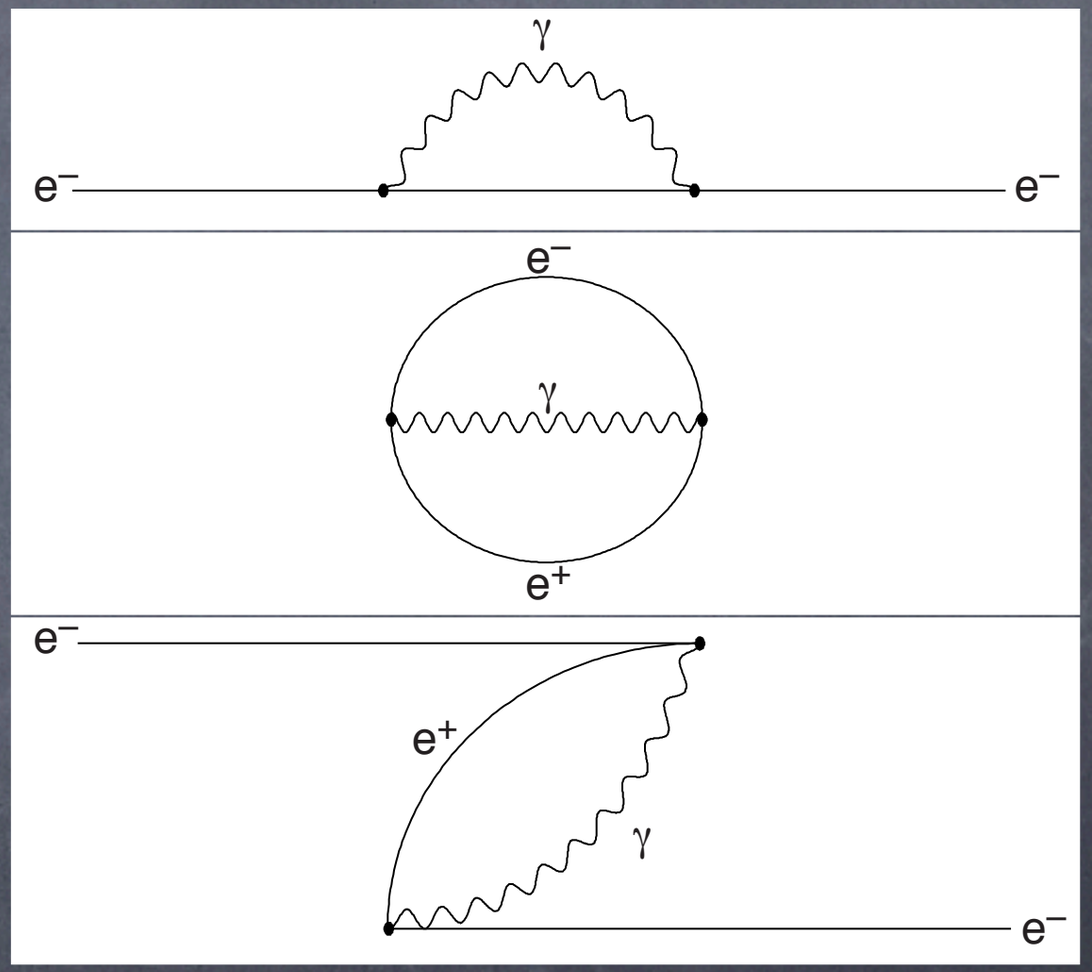
- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism

  $\Rightarrow$ Can't discuss physics below 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

⇒ only 10% of mass even for Planck-size



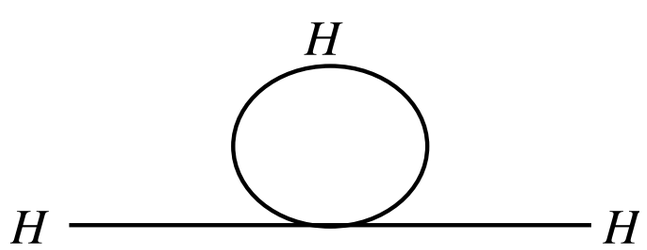
$$\frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \log(m_e r_e)$$

History repeats itself?

- Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force

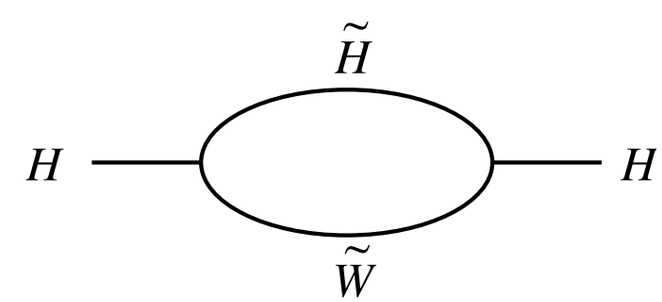
double #particles again
⇒ superpartners

"Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself



$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$

$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$



Good

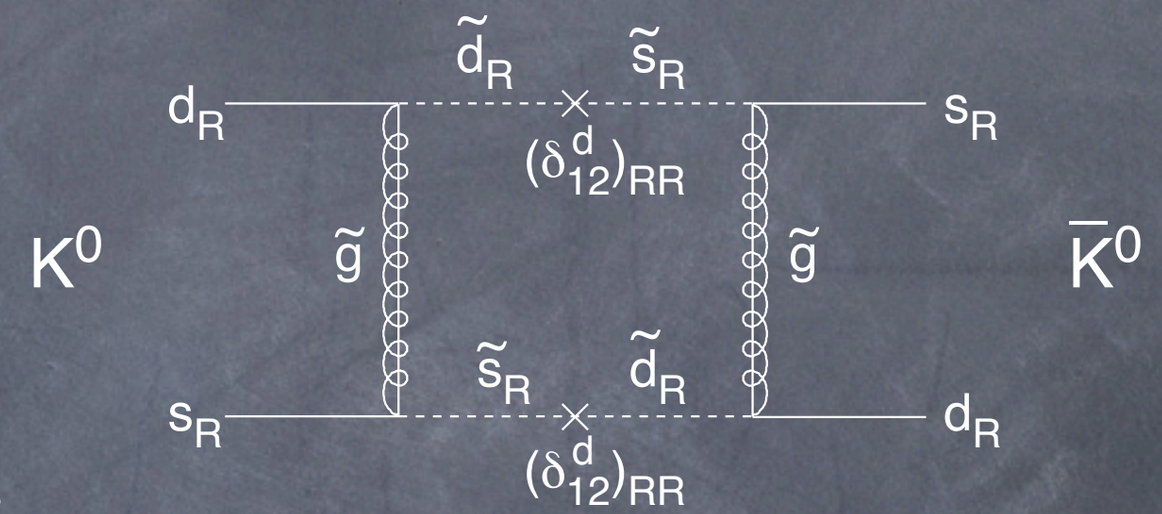
- Even with Planck-scale cutoff, supersymmetry protects the hierarchy
- SUSY
  - Higgs only one of many scalars that happen to acquire negative mass-squared
  - SUSY stabilizes the hierarchy
- Dark Matter is quite natural in supersymmetry, once "R-parity" is imposed to avoid too rapid proton decay
  Typically neutralino=photino+zino+higgsino
  but could be gravitino etc
- makes gauge coupling constants unify ⇒ GUT
- string theorists like it

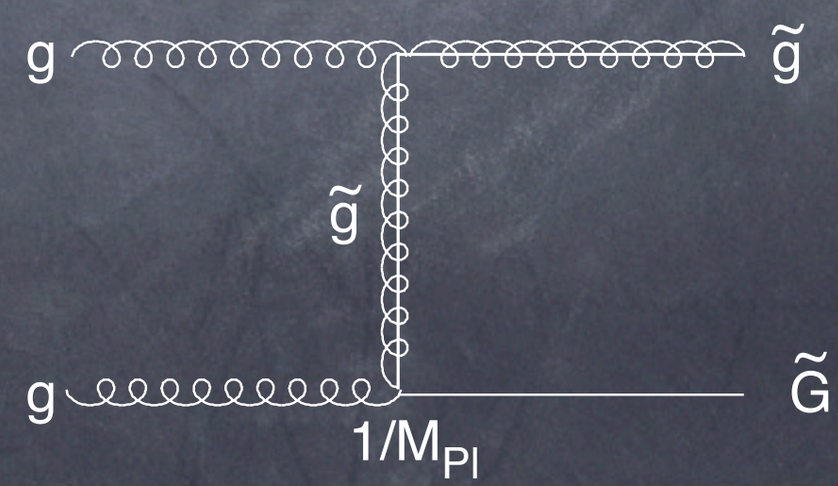
Bad

- Tends to give excessive flavor-changing and/or CP-violating effects
- gravitino decays late and screw up Big-Bang Nucleosynthesis

$\sigma \sim 1/M_{Pl}^2$,

$Y_{3/2} \sim \sigma T^3/(T^2/M_{Pl}) \sim T/M_{Pl}$





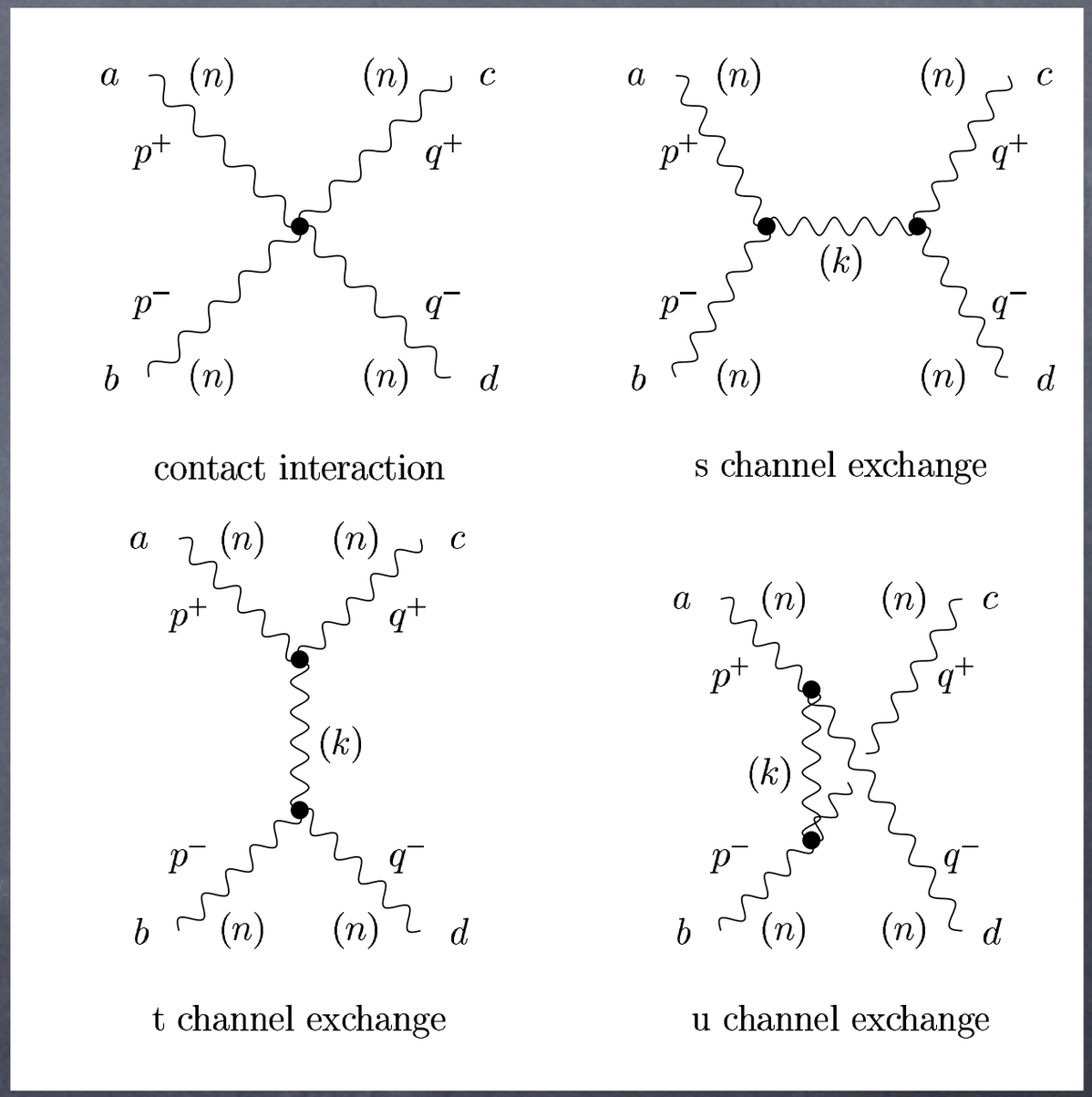
Any Way Out?

C. Csáki, C. Grojean, HM, J. Terning, L. Pilo

hep-ph/0305237

unitarity again

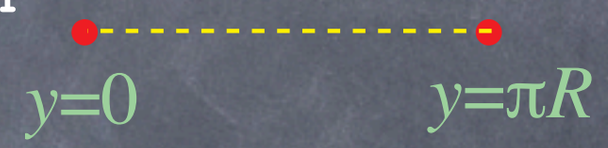
- The only way to restore unitarity in WW scattering is to add Higgs boson
- True, if only one (or finite) particle
- What about an infinite tower of particles?
- extra dimensions give an infinite tower of Kaluza-Klein states
- Maybe another way to restore unitarity?
- need cancellations both in E^4 and E^2 terms



$$g^2_{nnnn} = \sum_k g^2_{nnk}$$

$$4 g^2_{nnnn} M_n^2 = 3 \sum_k g^2_{nnk} M_k^2$$

boundary conditions



- put theory on an interval $[0, \pi R]\times R^{3,1}$
- impose boundary conditions at each boundary, i.e., Dirichlet or Neumann
- only Neumann[2] leads to zero modes
- regard W and Z boson as the lightest KK state
- No Higgs mechanism, no physical scalar bosons ⇒ "Higgsless model"

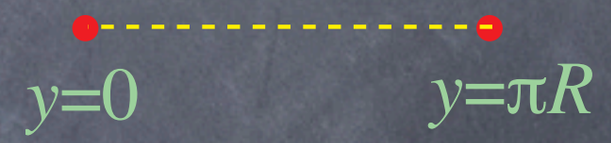
(all non-zero mode A_5 can be "gauged away")

Toy model

- SU(2) in the bulk
- boundary conditions break SU(2)→U(1)

  $A_\mu^{1,2}(0)=0,\ \partial_5 A_\mu^{1,2}(0)=0$

  $\partial_5 A_\mu^{1,2,3}(\pi R)=0$



- $m_\gamma=0,\ 2/R,\ 4/R,\ \ldots$
- $m_W=1/R,\ 3/R,\ 5/R,\ \ldots$
- scattering of the lowest W unitarized by the exchange of KK photons

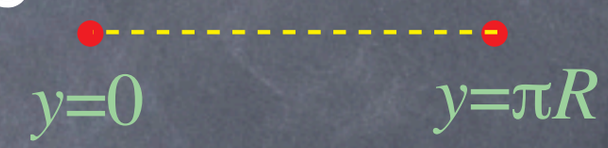
$$g^2_{nnnn} = \sum_k g^2_{nnk} \qquad 4g^2_{nnnn}M_n^2 = 3\sum_k g^2_{nnk}M_k^2$$

Can it be made realistic?

- Toy model does not reduce the rank e.g., $SU(2)\times U(1)\rightarrow U(1)$
- Unrealistic mass spectrum. How can we make m_W and m_Z different? How do they depend on gauge couplings?
- can one incorporate fermion masses?

More complicated boundary conditions

- can reduce the rank by imposing, e.g., $W_\mu^3(0)+B_\mu(0)=0$



- with gauge kinetic terms $\propto g^{-2}$, such boundary conditions actually depend on gauge couplings
- semi-realistic example $SU(2)_L \times SU(2)_R \times U(1)_X$
  - at y=0, break $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
  - at y=πR, break $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$

$$M_k^W = \frac{2k-1}{4R} \qquad M_k^Z = M_0 + \frac{k-1}{R} \qquad M_k^{Z'} = -M_0 + \frac{k}{R} \qquad M_0 = \frac{1}{\pi R}\arctan\sqrt{1+\frac{2g'^2}{g^2}} \sim \frac{0.29}{R}$$

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \sim 1.10$$

Anti-deSitter

- Later, Csáki, Grojean, Pilo, and Terning, hep-ph/0308038, proposed to use AdS instead, akin to Randall-Sundrum I setup
- on Plank brane, break $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
- on TeV brane, break $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$
- Main advantages
  - the lowest W, Z more or less flat except for the vicinity of the TeV brane
  - higher KK states much heavier than W, Z
  - rho parameter = 1 to 1% level

Further improvements

- Y. Nomura, hep-ph/0309189
- C. Csáki, C. Grojean, J. Hubisz, Y. Shirman, and J. Terning, hep-ph/0310355
- 1st, 2nd generations localized close to the Plank brane
- 3rd generation, esp right-handed top close to the TeV brane
- FCNC looks OK
- precision EW marginal
- more studies needed

Higgsless phenomenology

- Whole tower of KK vector bosons=technirho's
  - mass: ~300-2100 GeV
  - Can be produced at LHC, on-resonance e^+e^-
  - If on high-end, WW scattering becomes quite strong before the first resonance comes in
- interesting FCNC effects in the third generation
- may or may not have SUSY

Conclusions

- We need a Dark Field filling up our universe
- We are approaching the correct energy scale to probe it
- Alternatives marginal
- Yet they predict something within reach
- We will know the answer!