Huge Statistics thanks to High Energy and Luminosity

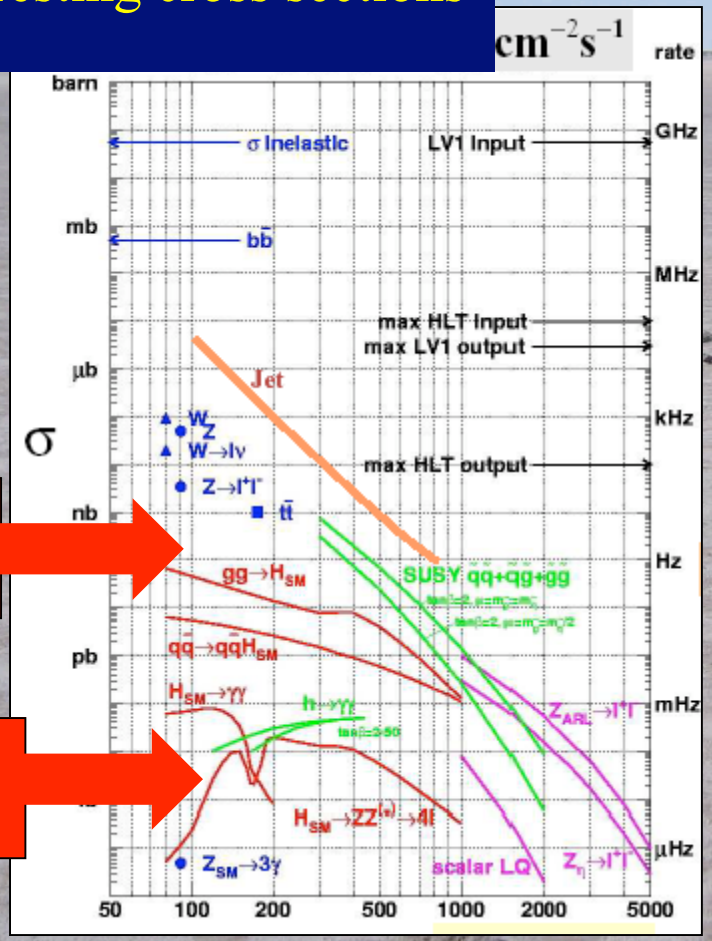
Event rates in ATLAS or CMS at $L = 10^{33}$ cm^{-2} s^{-1}

Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12} - 10^{13}	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

LHC is a factory for anything: top, W/Z, Higgs, SUSY, etc….
mass reach for discovery of new particles up to m ~ 5 TeV

The LHC Physics Haystack(s)

Interesting cross sections



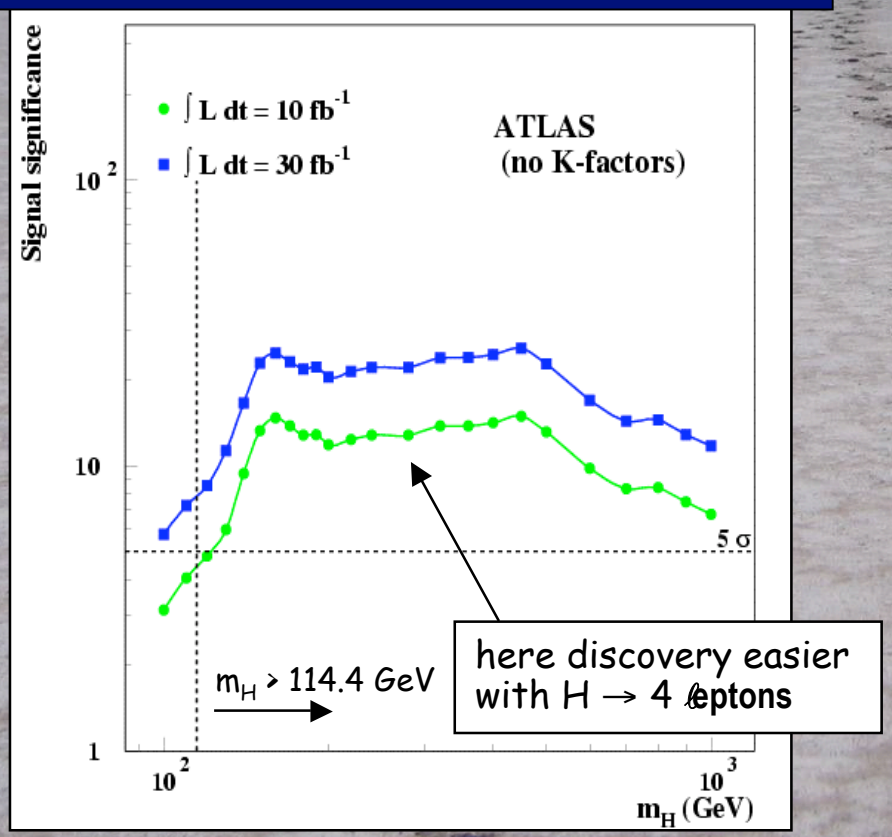
Susy

Higgs

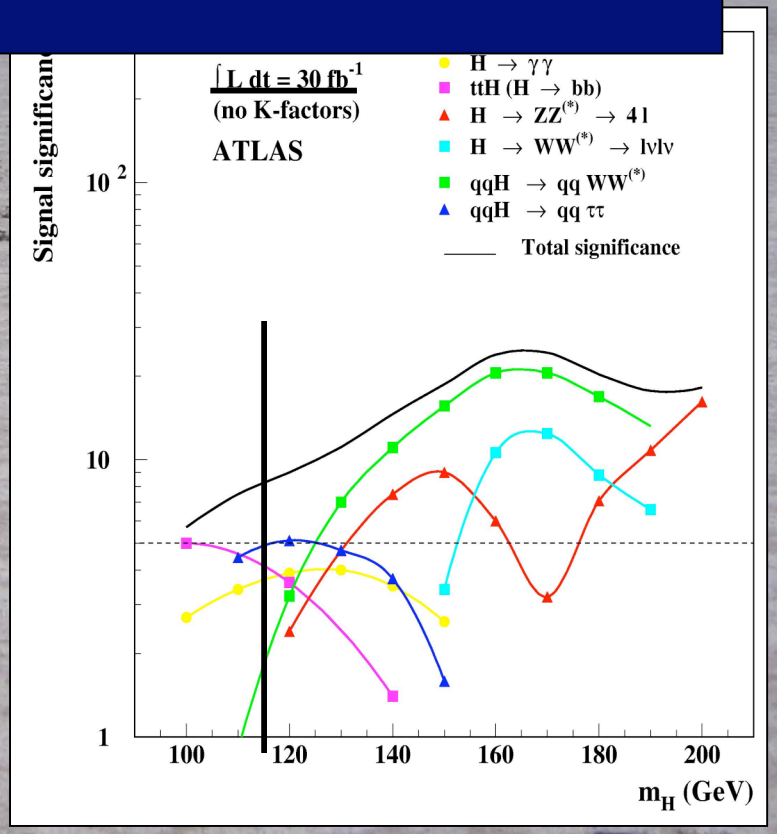
- Cross sections for heavy particles
  ~ 1 /(1 TeV)^2
- Most have small couplings ~ α^2
- Compare with total cross section
  ~ 1/(100 MeV)^2
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle
  ~ 1/100,000,000 m^3
- Haystack ~ 100 m^3
- Must look in ~ 100,000 haystacks

Higgs Detection at the LHC

The Higgs may be found quite quickly …

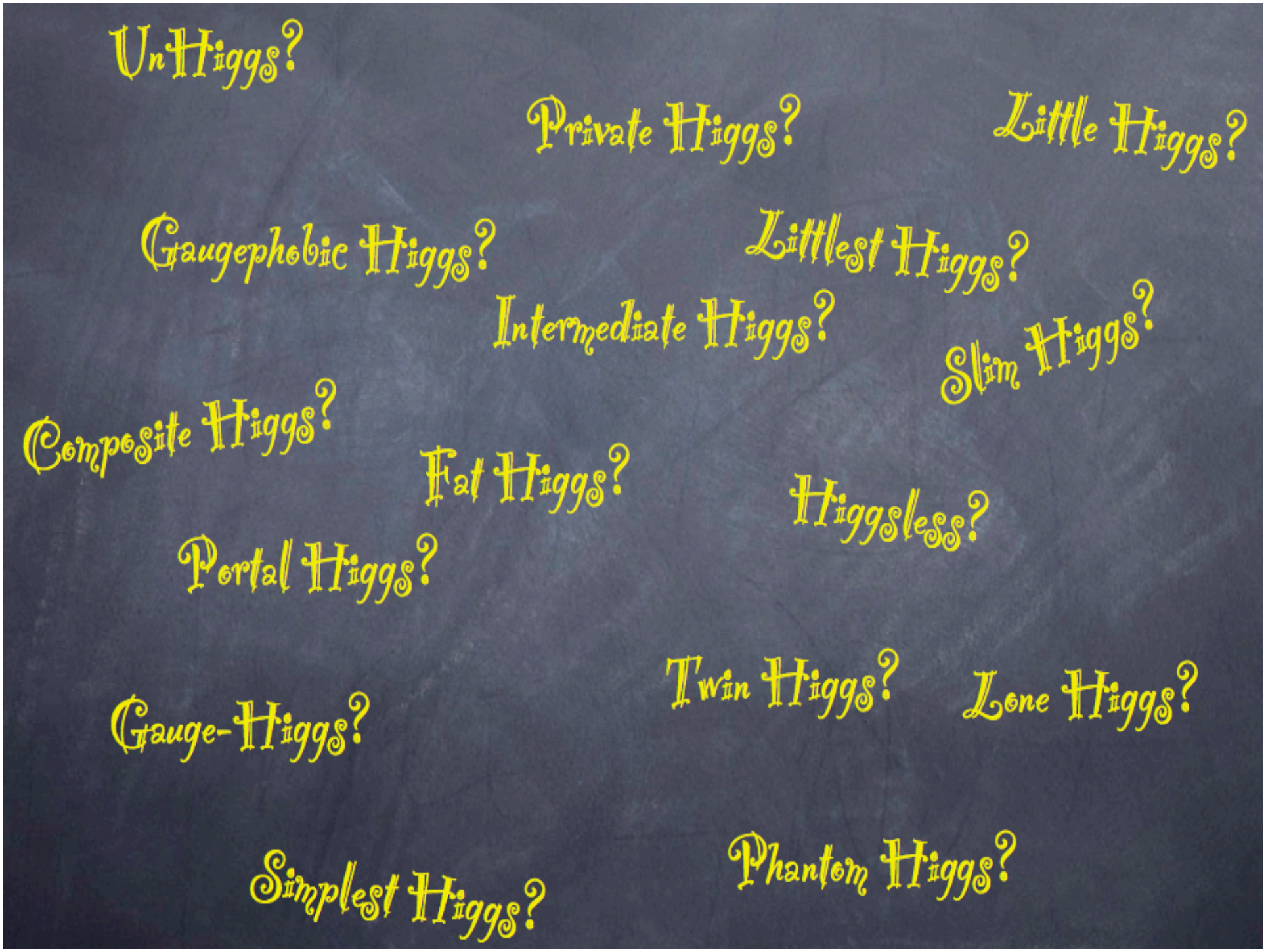


… in several different channels



Theorists getting Cold Feet

- Composite Higgs model?
  conflicts with precision electroweak data
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra `Top', gauge bosons, `Higgses'
- Higgsless models?
  strong WW scattering, extra D?


UnHiggs?
Private Higgs?
Little Higgs?
Gaugephobic Higgs?
Littlest Higgs?
Intermediate Higgs?
Slim Higgs?
Composite Higgs?
Fat Higgs?
Higgsless?
Portal Higgs?
Twin Higgs?
Lone Higgs?
Gauge-Higgs?
Simplest Higgs?
Phantom Higgs?

The LHC Roulette Wheel

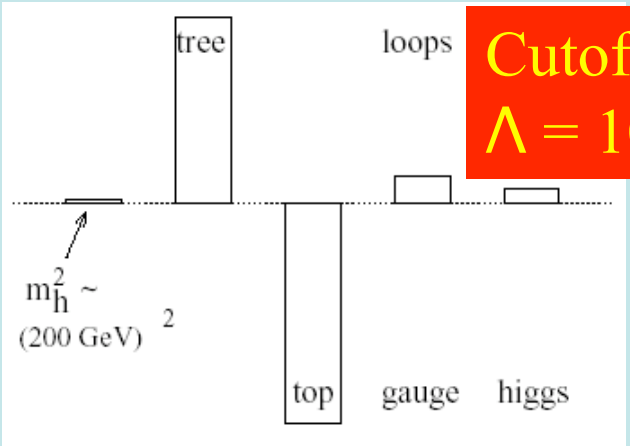
Techni colour

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff
$\Lambda = 10$ TeV

- Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

- New technicolour force? inconsistent with precision electroweak data?

General Parametrization of Radiative Corrections

- 'Oblique' corrections S, T

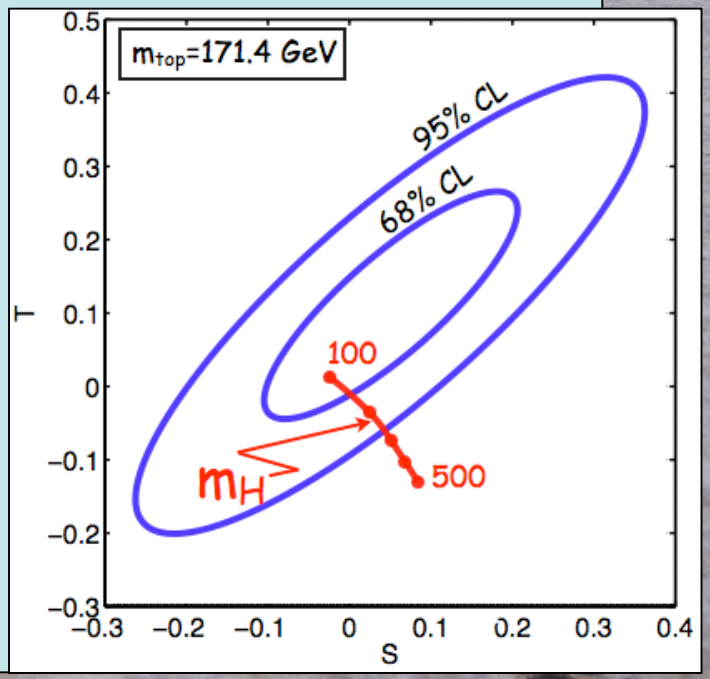
$$\rho \equiv 1 + \alpha_{em} T \qquad \rho \equiv \frac{M_W^2}{M_Z^2 c^2}$$

- Contributions from Standard Model Higgs

$$\delta S = \frac{1}{12\pi} \log \frac{m_h^2}{m_{h_0}^2}$$

$$\delta T = -\frac{3}{16\pi c^2} \log \frac{m_h^2}{m_{h_0}^2}$$

- Low m_H compatible with data
- Technicolour ↔high m_H



Comparison between Weakly- and Strongly-coupled Models

Weakly coupled models

prototype: Susy

susy partners ~ 100 GeV

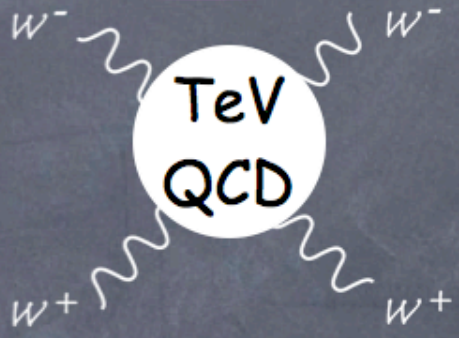
need new particles to stabilize the Higgs mass

bounds on the masses of these particles

fine-tuning O(1%)

other ways?

Strongly coupled models



prototype: Technicolor

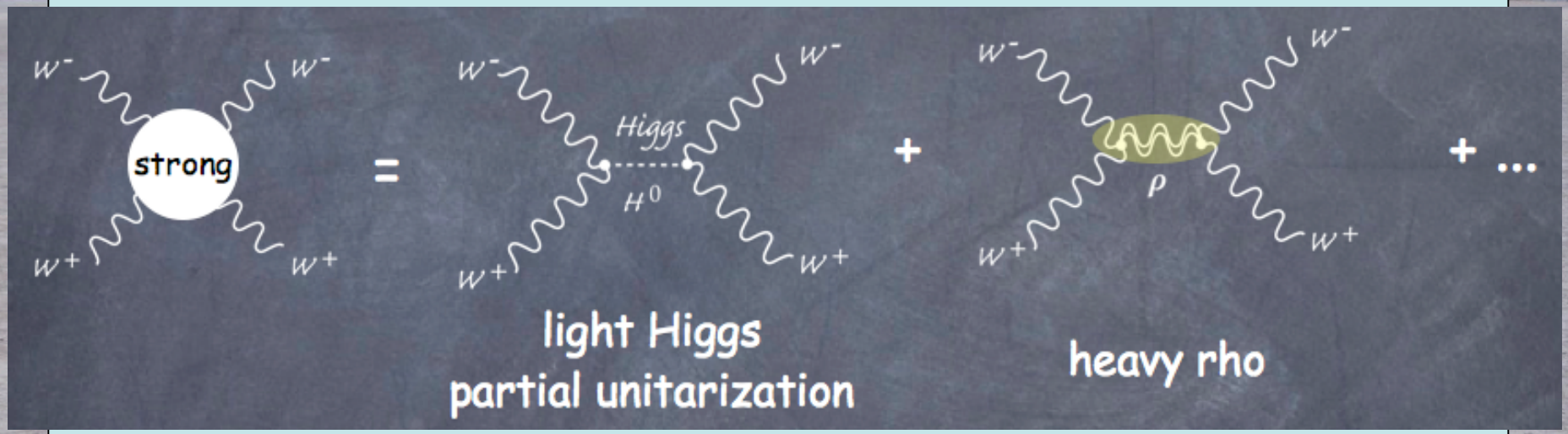
rho meson ~ 1 TeV

resonances needed for unitarization generate EW oblique corrections

$\hat{S} \sim \frac{m_W^2}{m_\rho^2}$ $\quad |\hat{S}| < 10^{-3}$ @ 95% CL $\quad m_\rho > 2.5$ TeV

Interpolating Models

- Combination of Higgs boson and vector ρ



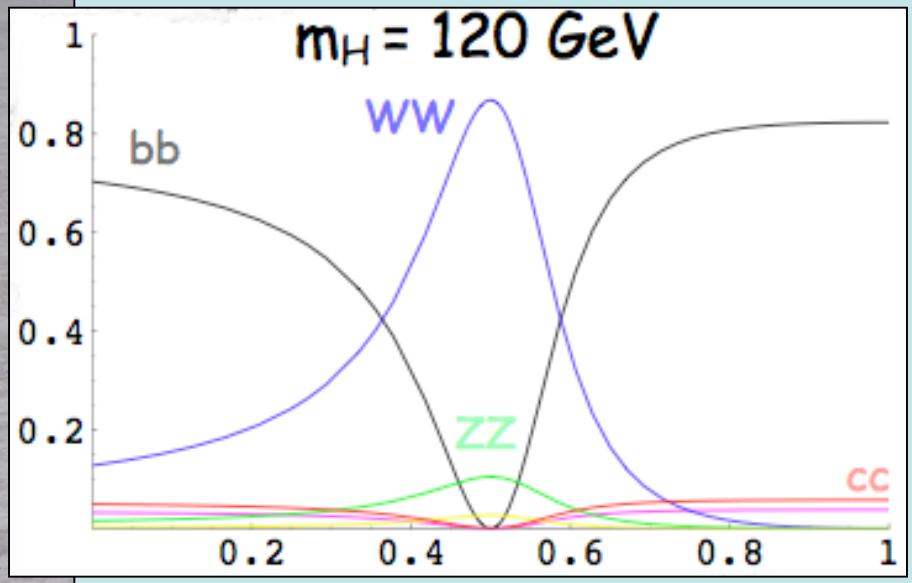
- Two main parameters: m_ρ and coupling g_ρ
- Equivalently ratio weak/strong scale:

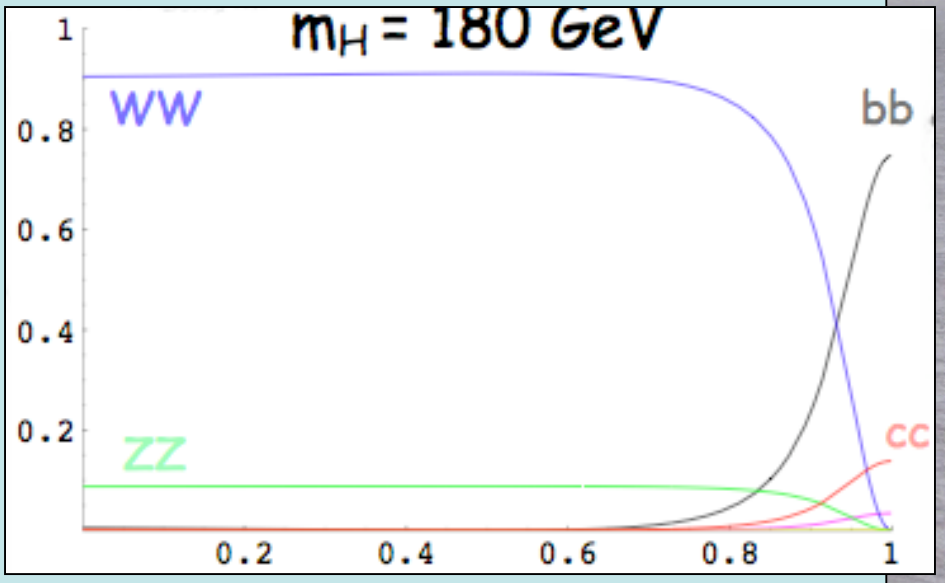
$$\xi \equiv v\, g_\rho / m_\rho$$

Grojean, Giudice, Pomarol, Rattazzi

Effects on Higgs Decays

- Dependences on ξ of Higgs branching ratios



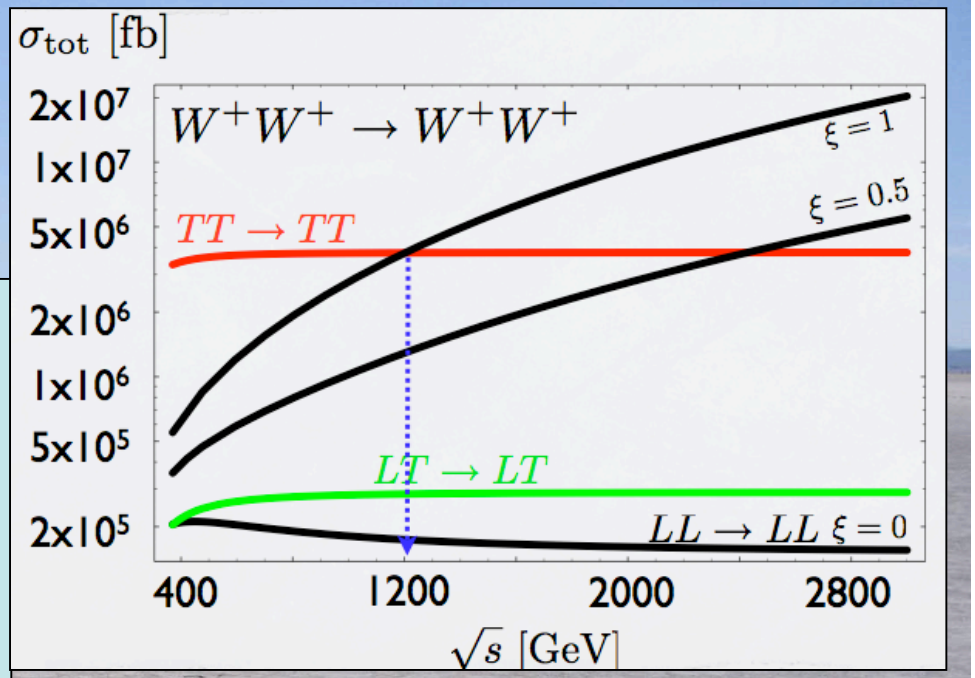


- Standard Model recovered in limit ξ → 0

Grojean, Giudice, Pomarol, Rattazzi

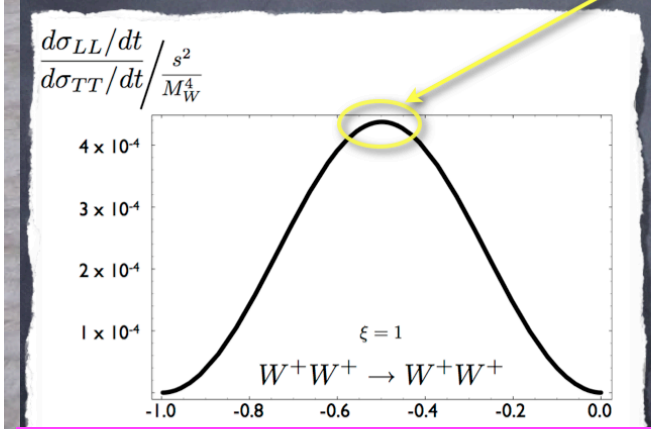
Effects in WW Scattering?

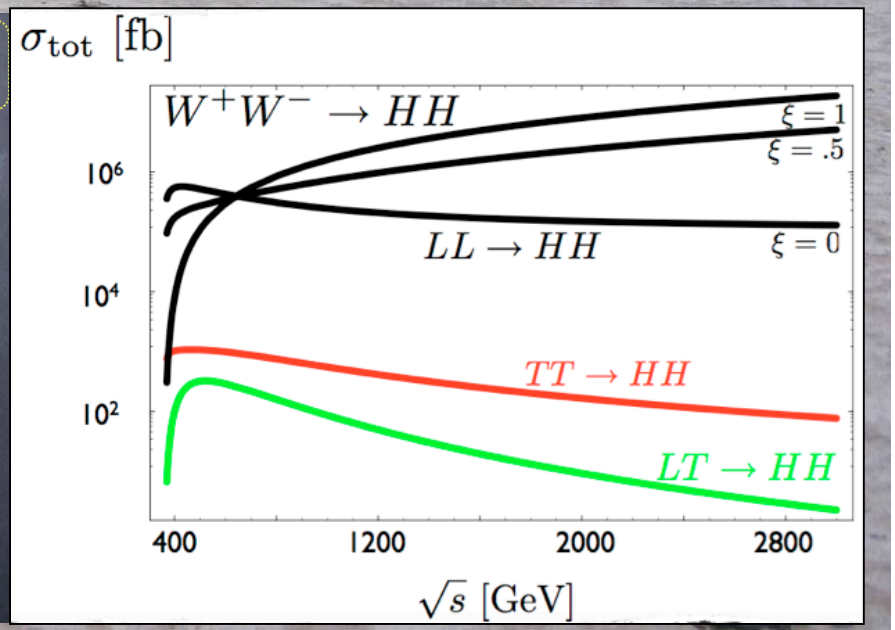
- Look for effects in $W_L W_L$ scattering ($W_L \leftrightarrow H$)
- Drowned by $W_T W_T$ ($W_L \leftrightarrow V$)
- Some hope for double Higgs production?



$$\frac{d\sigma^{LL}/dt}{d\sigma^{TT}/dt}_{|t=-s/2} = \frac{1}{2304}\left(\frac{\sqrt{s}}{M_W}\right)^4 \xi^2$$

this accidentally small factor makes difficult to see strong scattering



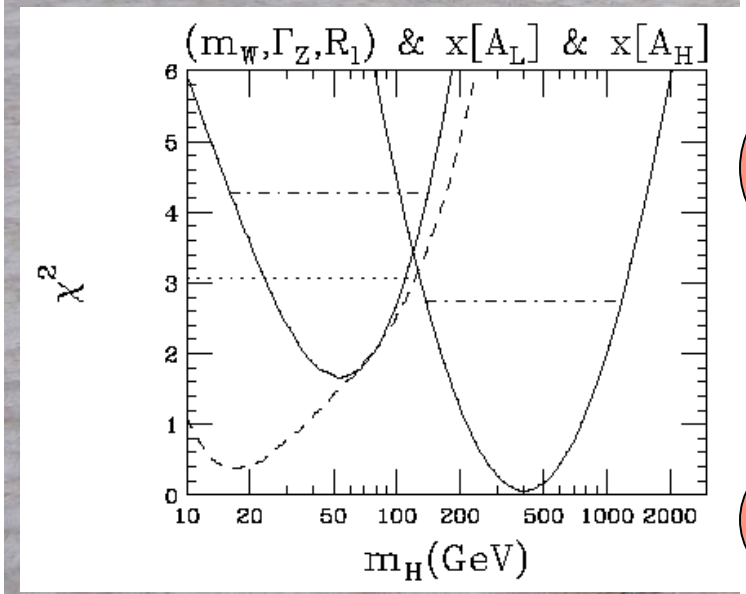


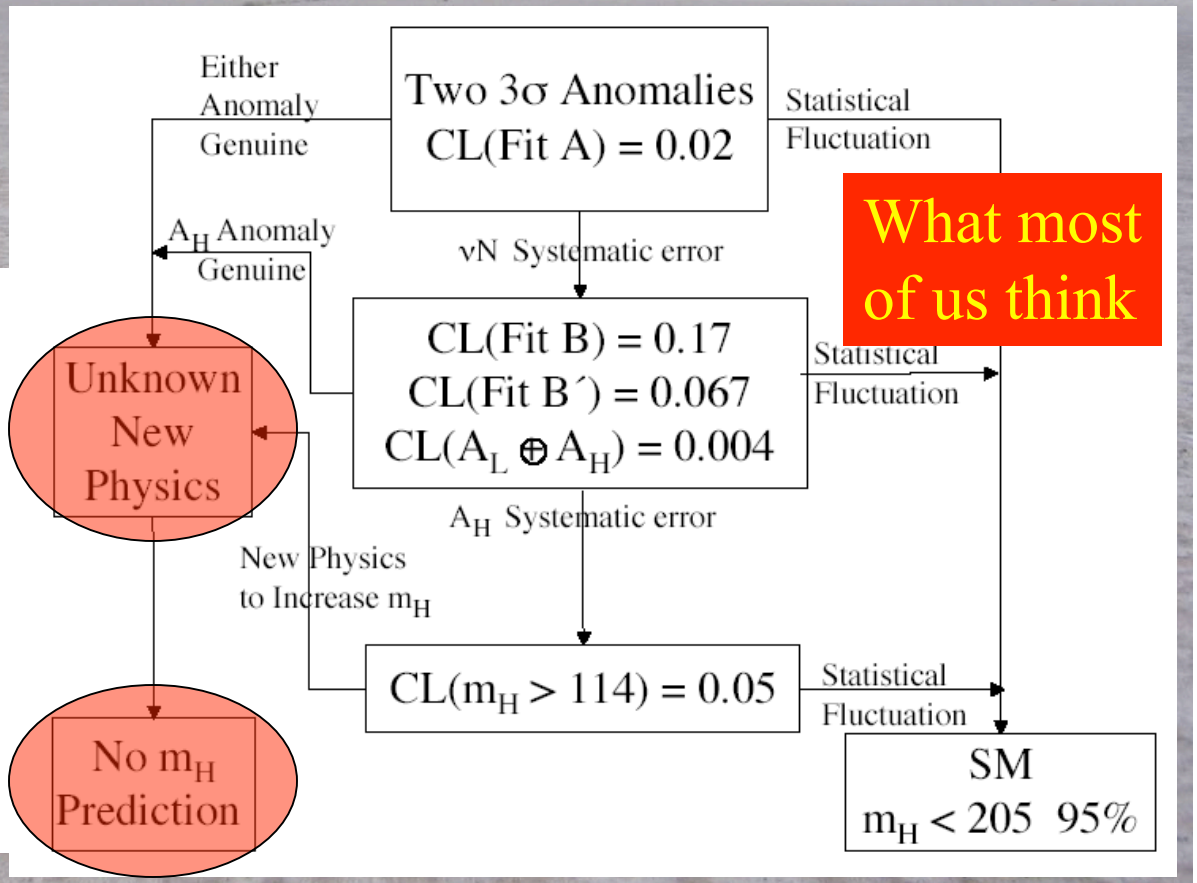
Grojean, Giudice, Pomarol, Rattazzi

Heretical Interpretation of EW Data

What attitude towards LEP, NuTeV?

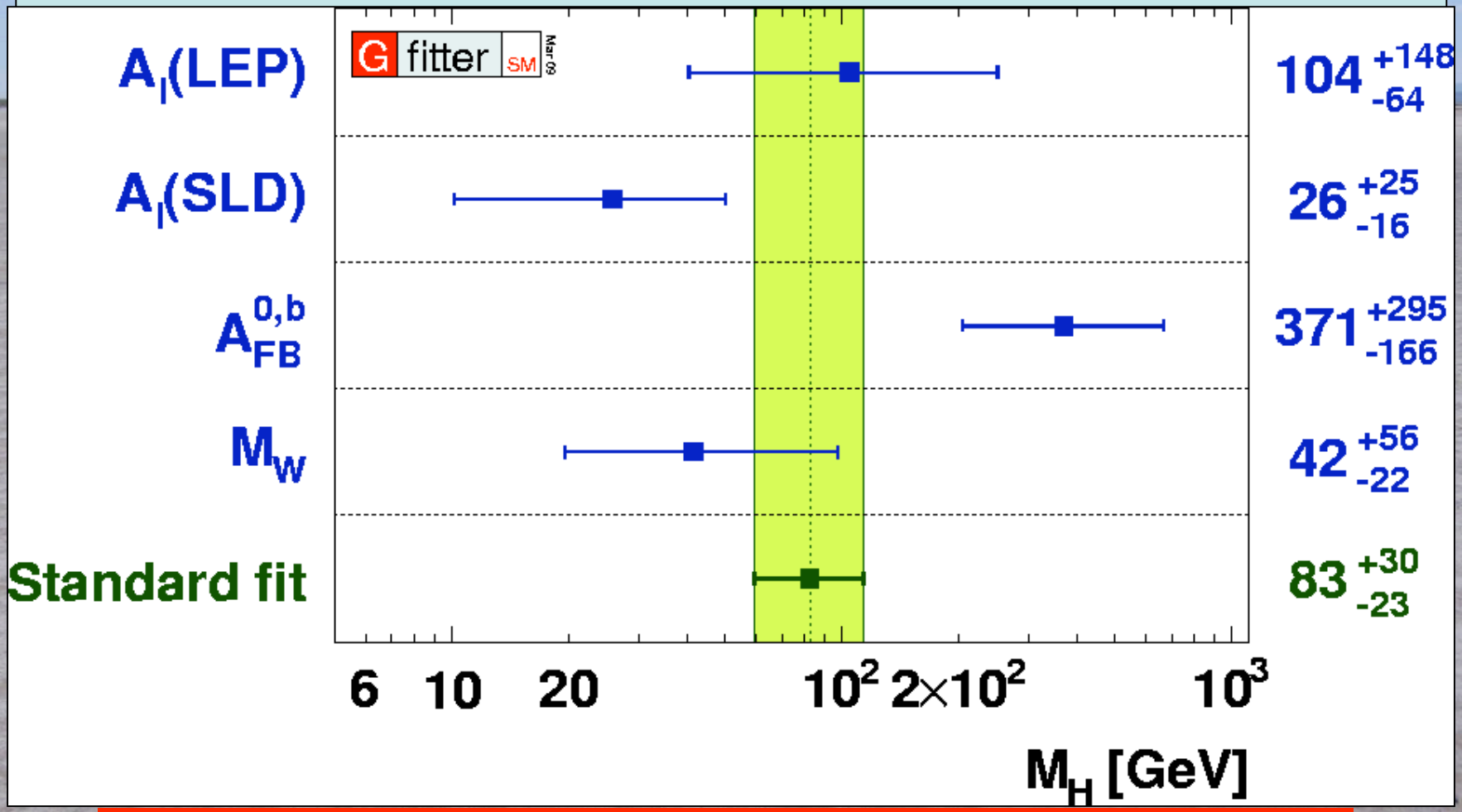
Do all the data tell the same story?
e.g., A_L vs A_H





Chanowitz

Estimates of m_H from different Measurements



Spread looks natural: no significant disagreement

Higgs + Higher-Order Operators

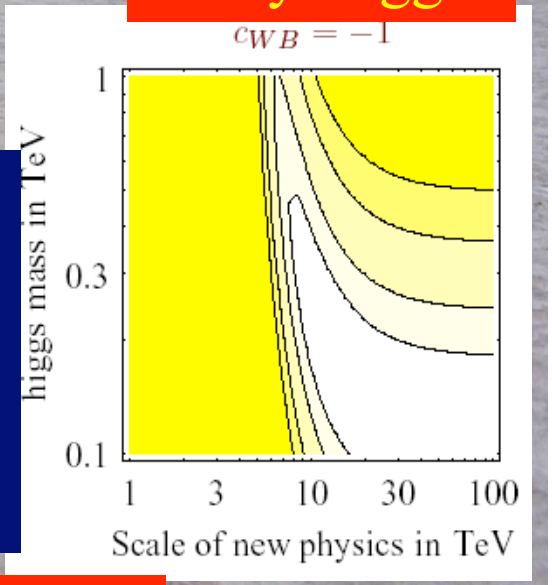
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^p}\mathcal{O}_i^{(4+p)}$$

Precision EW data suggest they are small: why?

Corridor to heavy Higgs?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+\sigma^a H)W^a_{\mu\nu}B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H)\rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu\sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

95% lower bounds on Λ/TeV

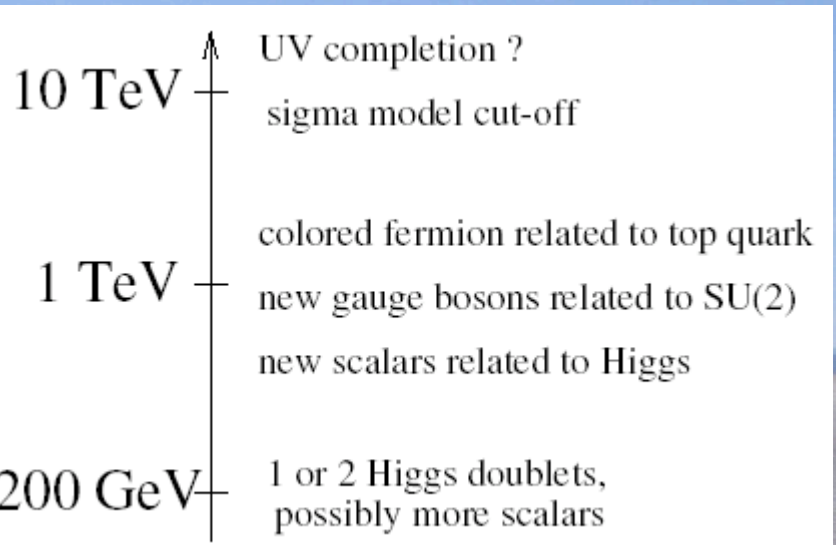


But conspiracies are possible: m_H could be large, even if believe EW data …?

Barbieri, Strumia

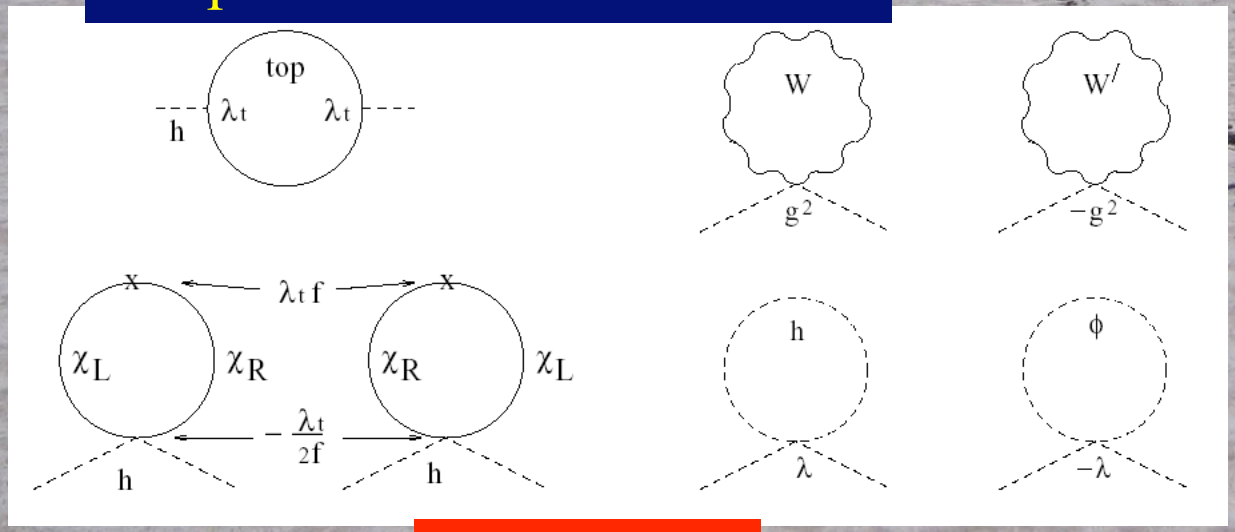
Do not discard possibility of heavy Higgs

Generic Little Higgs Models

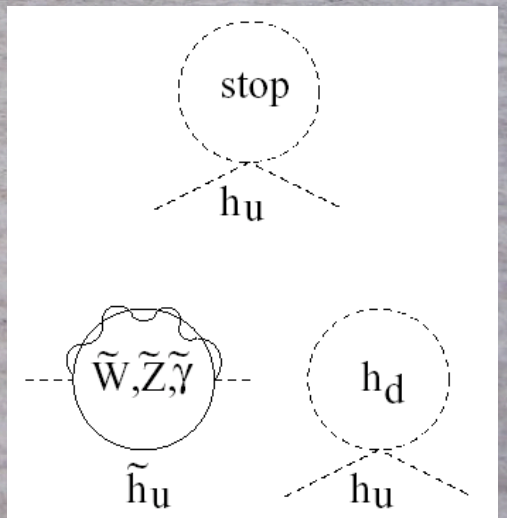


(Higgs as pseudo-Goldstone boson of larger symmetry)

Loop cancellation mechanism



Little Higgs



Supersymmetry

Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2(\frac{\Lambda}{400GeV})^2$$

with new heavy T quark

$$m_T > 2\lambda_t f \sim 2f \quad f > 1 \text{ TeV}$$

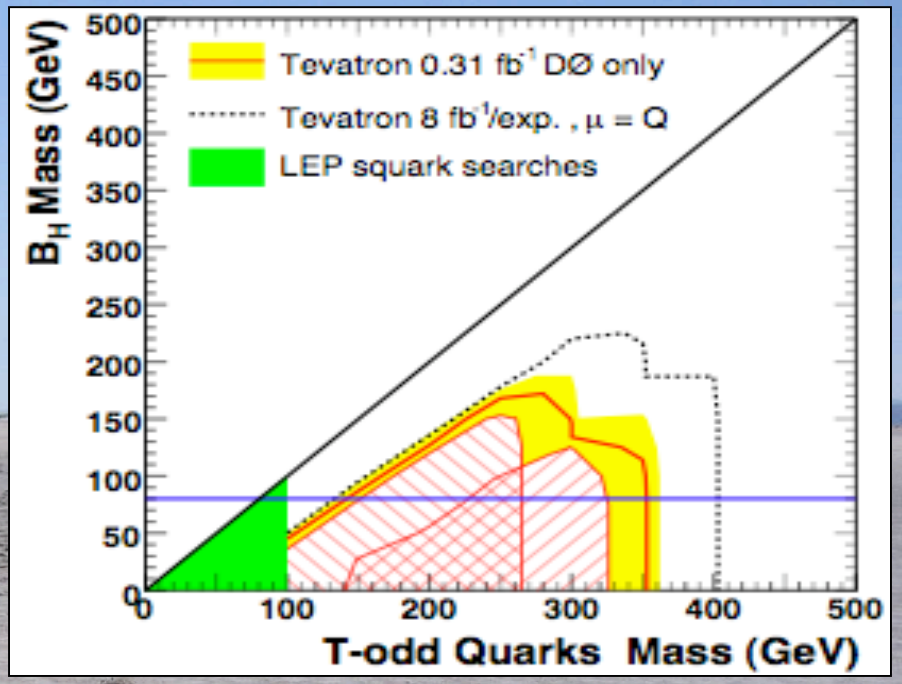
$$\delta m^2_{H,top}(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log\frac{\Lambda}{m_T} \gtrsim 1.2f^2$$

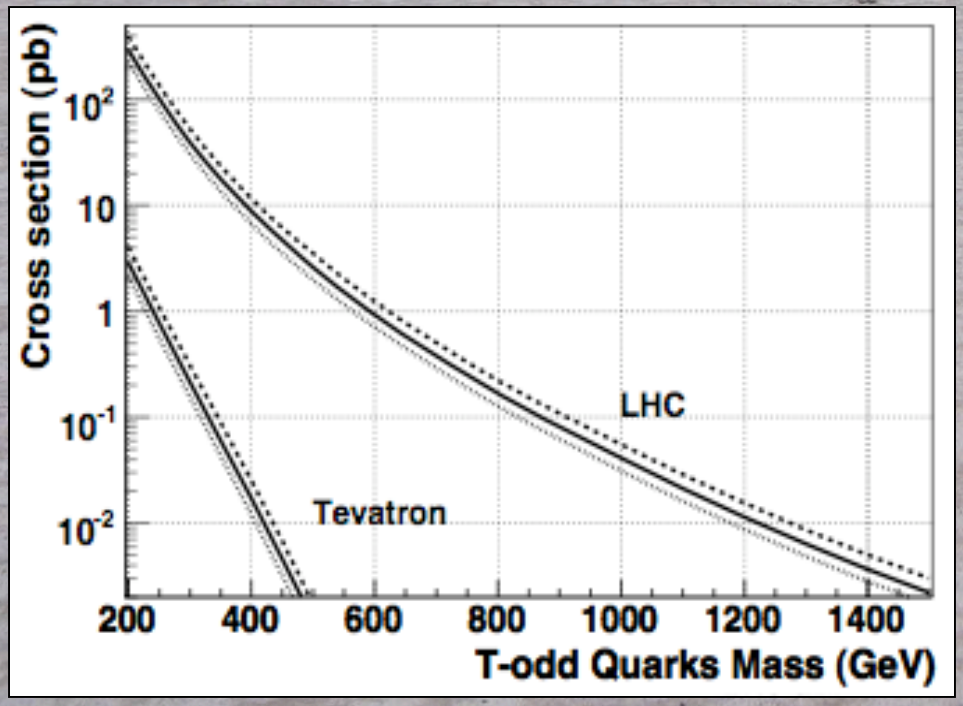
- New gauge bosons, Higgses
- Higgs light, other new physics heavy

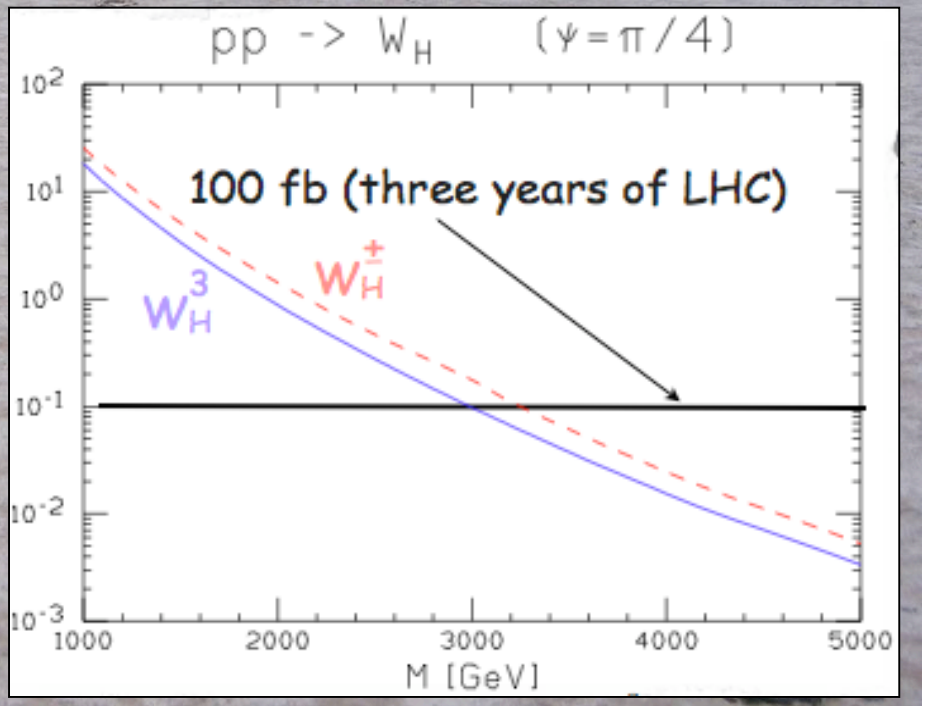
$M_T < 2$ TeV $(m_h / 200$ GeV$)^2$
$M_{W'} < 6$ TeV $(m_h / 200$ GeV$)^2$
$M_{H++} < 10$ TeV

Not as complete as susy: more physics > 10 TeV

Searches for Extra Particles in Little Higgs Models







To Higgs or not to Higgs?

- Higgs must discriminate between different types of particles:
  - Some have masses, some do not
  - Masses of different particles are different
- In mathematical jargon, symmetry must be broken: how?
  - Break symmetry in equations?
  - **Or in solutions to symmetric equations?**
- This is the route proposed by Higgs
  - **Is there another way?**

Where to Break the Symmetry?

- Throughout all space?
  - Route proposed by Higgs
  - Universal Higgs (snow)field breaks symmetry
  - **If so, what type of field?**
- Or at the edge of space?
  - **Break symmetry at the boundary?**
- Not possible in 3-dimensional space
  - No boundaries
  - **Postulate extra dimensions of space**
- Different particles behave differently in the extra dimension(s)

The LHC Roulette Wheel

Higgsless model

Higgsless Models?

- Four-dimensional versions:

  Strong WW scattering @ TeV, incompatible with precision data?
- Break EW symmetry by boundary conditions in extra dimension:

  delay strong WW scattering to ~ 10 TeV?

  Kaluza-Klein modes: $m_{KK} > 300$ GeV?

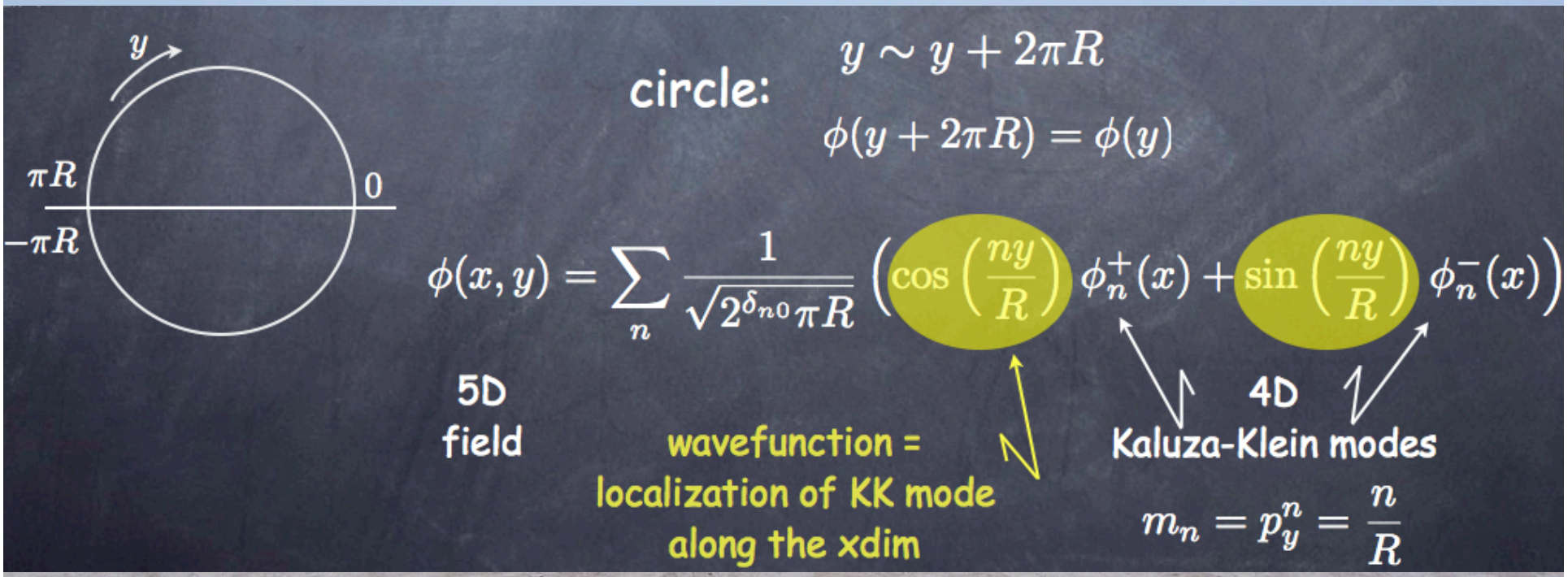
  compatibility with precision data?
- Warped extra dimension + brane kinetic terms?

Lightest KK mode @ few 00 GeV, strong WW @ 6-7 TeV

The LHC Roulette Wheel

Extra dimensions

Particle Spectrum in Simplest Model with Extra Dimensions



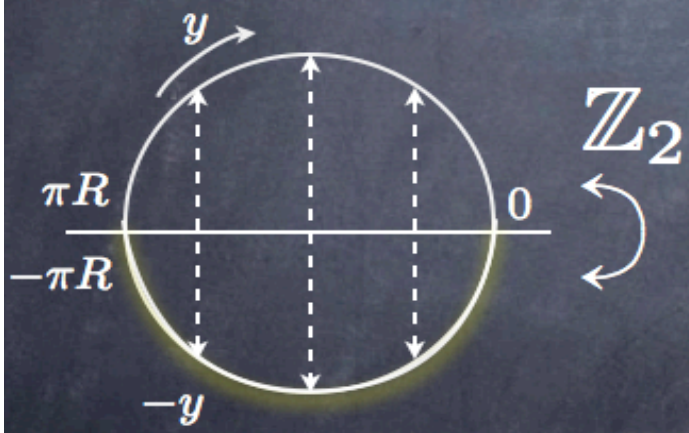
Lowest-lying states have flat wave functions (n = 0)

Excitations (Kaluza-Klein) have nodes (n > 0):

Mass ∝ n/R (R = radius of circle)

‘Fold’ Circle: Orbifold

- Identify two halves of circle: up to a minus sign



$\mathbb{Z}_2$

circle: $y \sim y + 2\pi R$

$\phi(y + 2\pi R) = \phi(y)$

orbifold: $y \sim -y$

$\phi(-y) = U\phi(y)$ $\quad U^2 = 1$

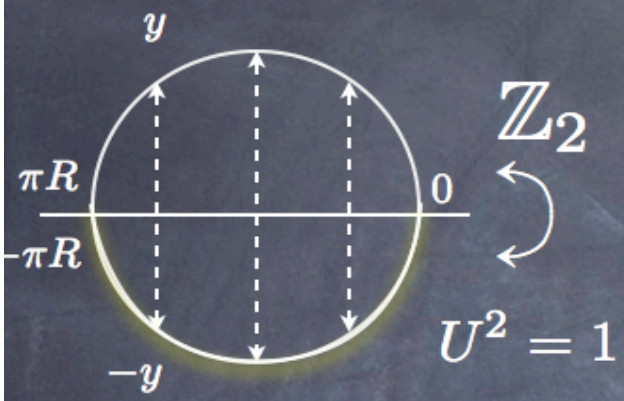
U=+1: $\cos\left(\frac{ny}{R}\right)$ wavefunctions $\quad \exists$ massless mode

U=-1: $\sin\left(\frac{ny}{R}\right)$ wavefunctions $\quad \nexists$ massless mode

- ‘Even’ particles include massless: odd ones all massive
- A way to give masses to particles that are asymmetric

Mechanism to break Gauge Symmetry

- Identify two halves up to a group transformation U



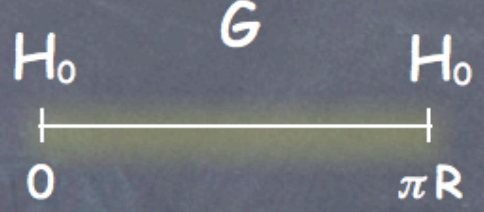
$\mathbb{Z}_2$

$U^2 = 1$

orbifold $y \sim -y$

$A_\mu(-y) = U A_\mu(y) U^\dagger$

$A_5(-y) = -U A_5(y) U^\dagger$



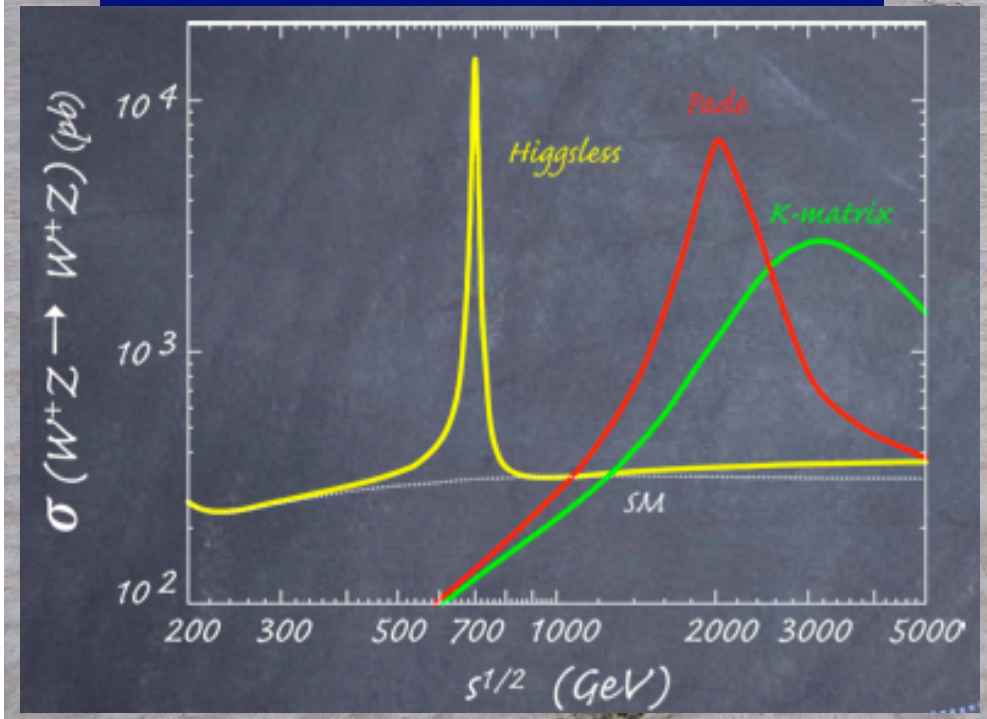
Breaking of gauge group at the end-points of the orbifold $A_\mu(0) = U A_\mu(0) U^\dagger$

at the end-points, the surviving gauge group commute with the orbifold projection matrix U

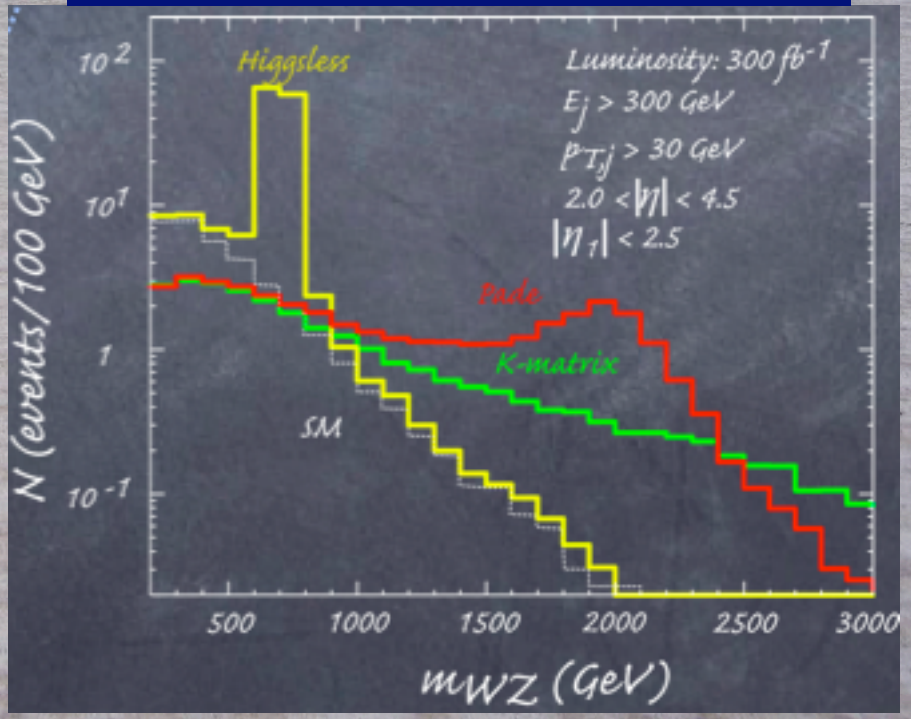
- Unbroken part of gauge group commutes with U
- Masses for asymmetric particles:
  - e.g., SU(2) × U(1) → U(1)

Search for Vector Resonance in Higgsless Model

Vector resonance structure in WZ scattering

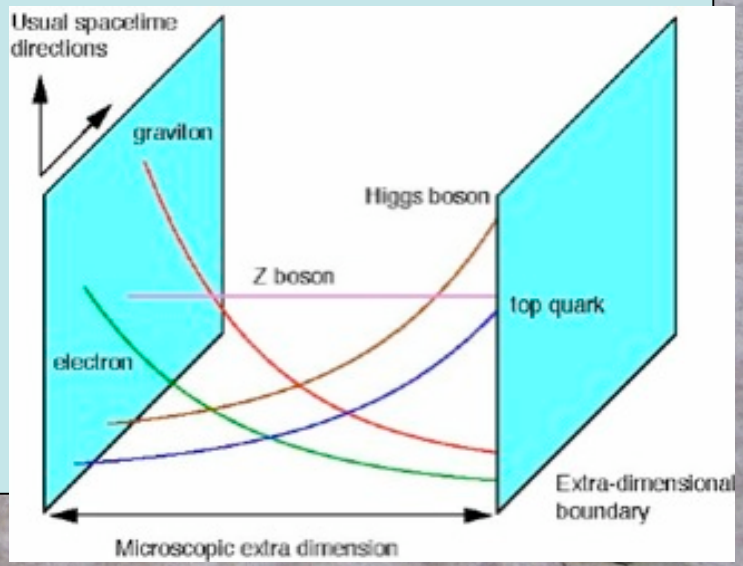


Simulation of resonance structure in m_{WZ} @ LHC



Holographic Technicolour

- Holography: physics of one theory in a volume V is equivalent to a dual theory on its surface A
  - weak coupling ↔ strong coupling
  - gauge theory ↔ gravity theory
- Weak coupling description of technicolour using a (warped) extra dimension



The Stakes in the Higgs Search

- How is gauge symmetry broken?
- Is there any elementary scalar field?
- Would have caused phase transition in the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe: electroweak baryogenesis
- A related inflaton might have expanded the Universe when it was about 10^{-35} seconds old
- Contributes to today's dark energy: 10^{60} too much!