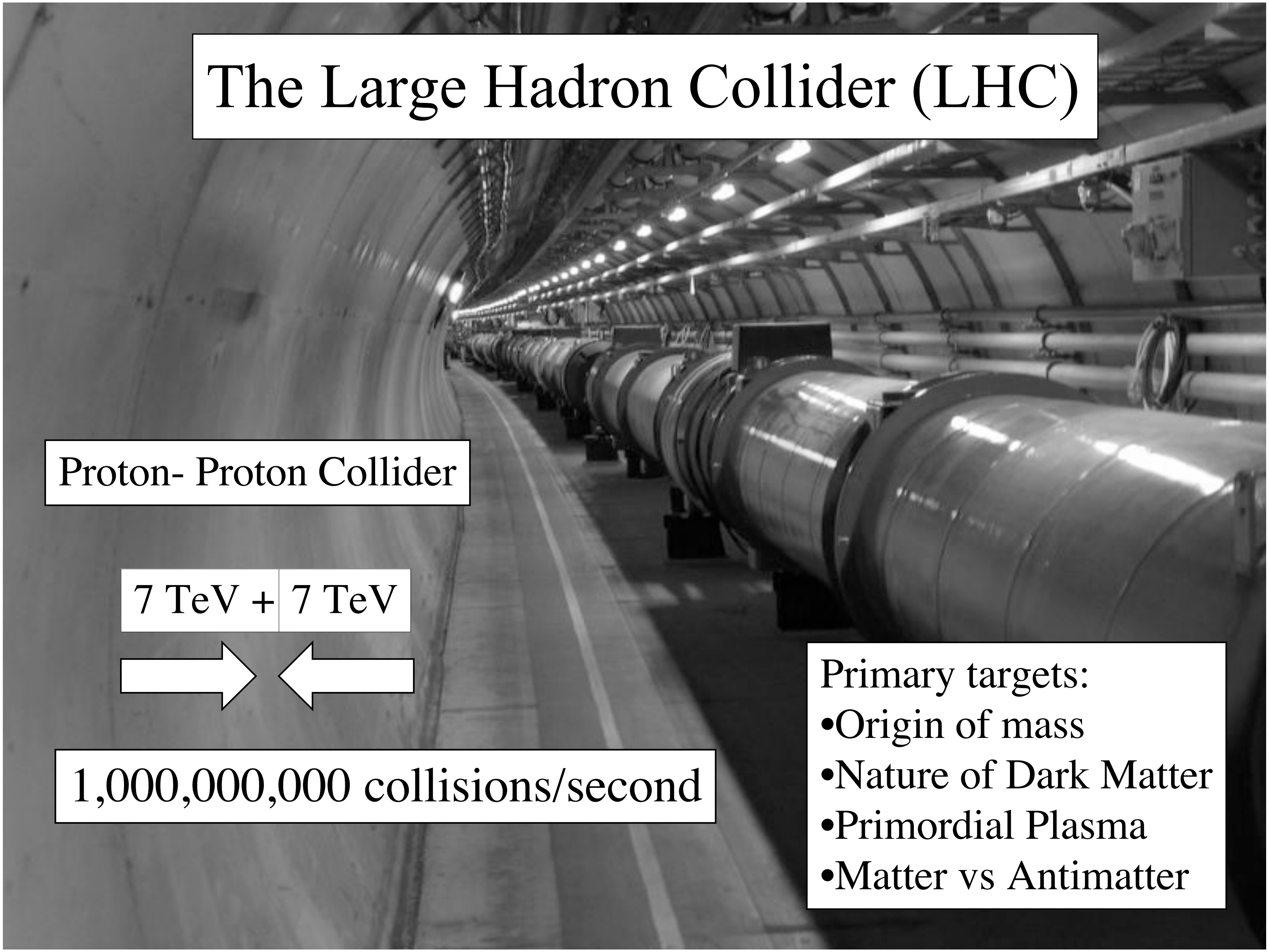

The Large Hadron Collider (LHC)
Proton- Proton Collider
7 TeV + 7 TeV
1,000,000,000 collisions/second
Primary targets:
•Origin of mass
•Nature of Dark Matter
•Primordial Plasma
•Matter vs Antimatter

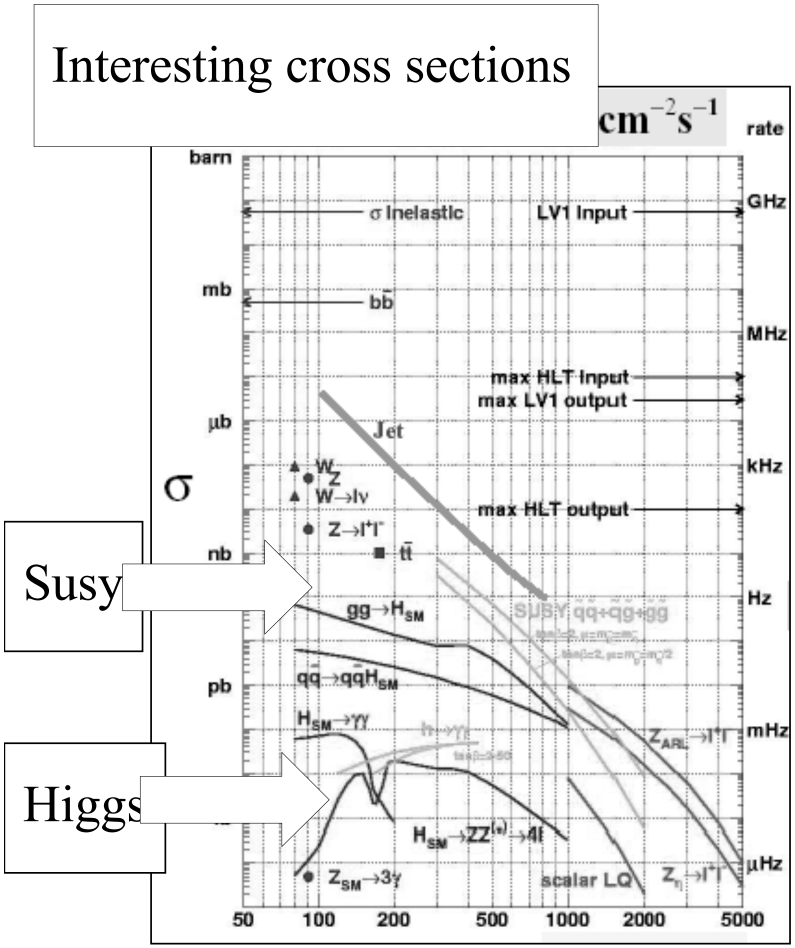
Huge Statistics thanks to High Energy and Luminosity

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
[illegible]	1	10^7	10^4 Tevatron
[illegible]	10^6	10^{12} – 10^{13}	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
[illegible] 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)



- Cross sections for heavy particles

  $\sim 1/(1\ \text{TeV})^2$
- Most have small couplings $\sim \alpha^2$
- Compare with total cross section

  $\sim 1/(100\ \text{MeV})^2$
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle

  $\sim 1/100{,}000{,}000\ \text{m}^3$
- Haystack $\sim 100\ \text{m}^3$
- Must look in ~ 100,000 haystacks

The LHC's Most Anticipated Discovery

6 December 2008

Evidence for a Higgs boson production in pp collisions at $\sqrt{s}$ = 14 TeV

CMS collaboration

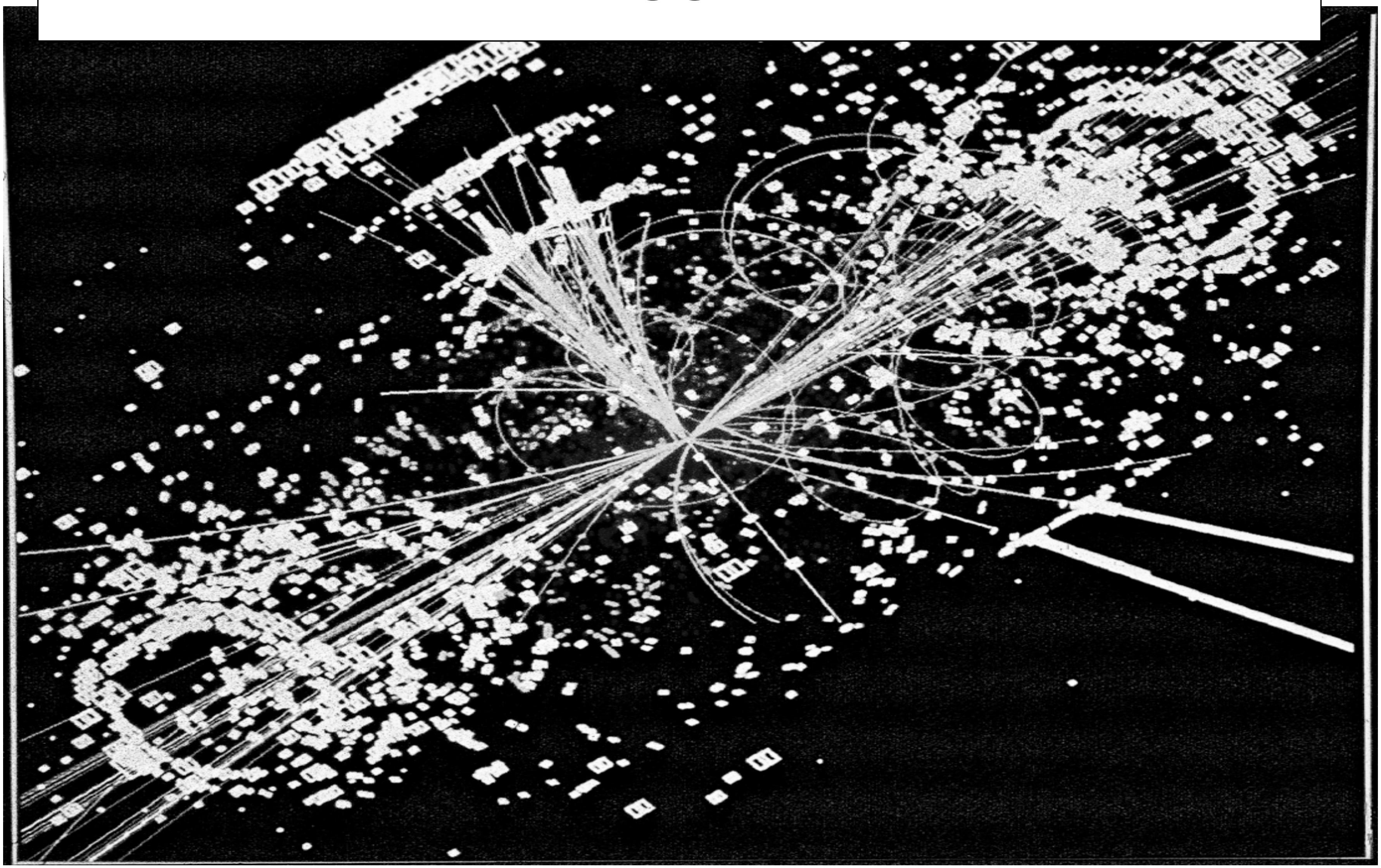
Abstract

Experimental evidence for a Higgs boson production in pp collisions $\sqrt{s}$ = 14 TeV with an integrated luminosity 1 fb^{-1} at the Large Hadron Collider at CERN is reported. The CMS experiment

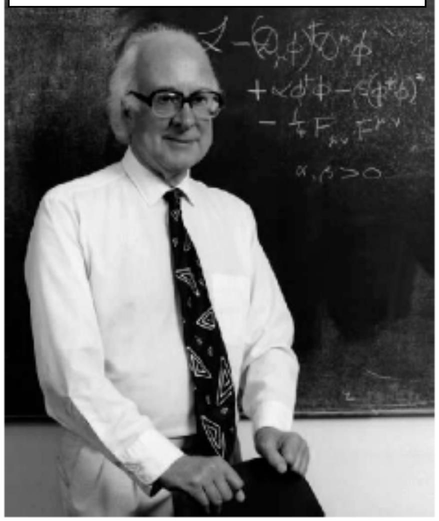
…

Submitted to *European Journal of Physics*

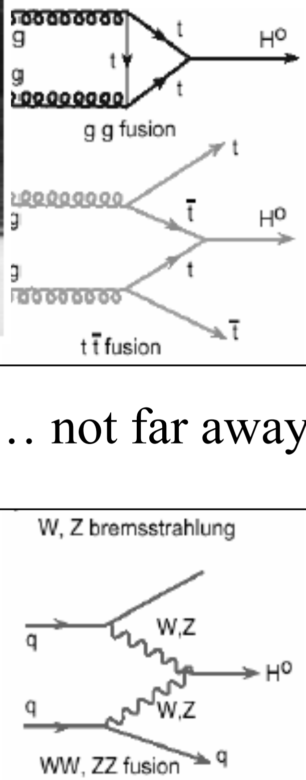
A Simulated Higgs Event in CMS

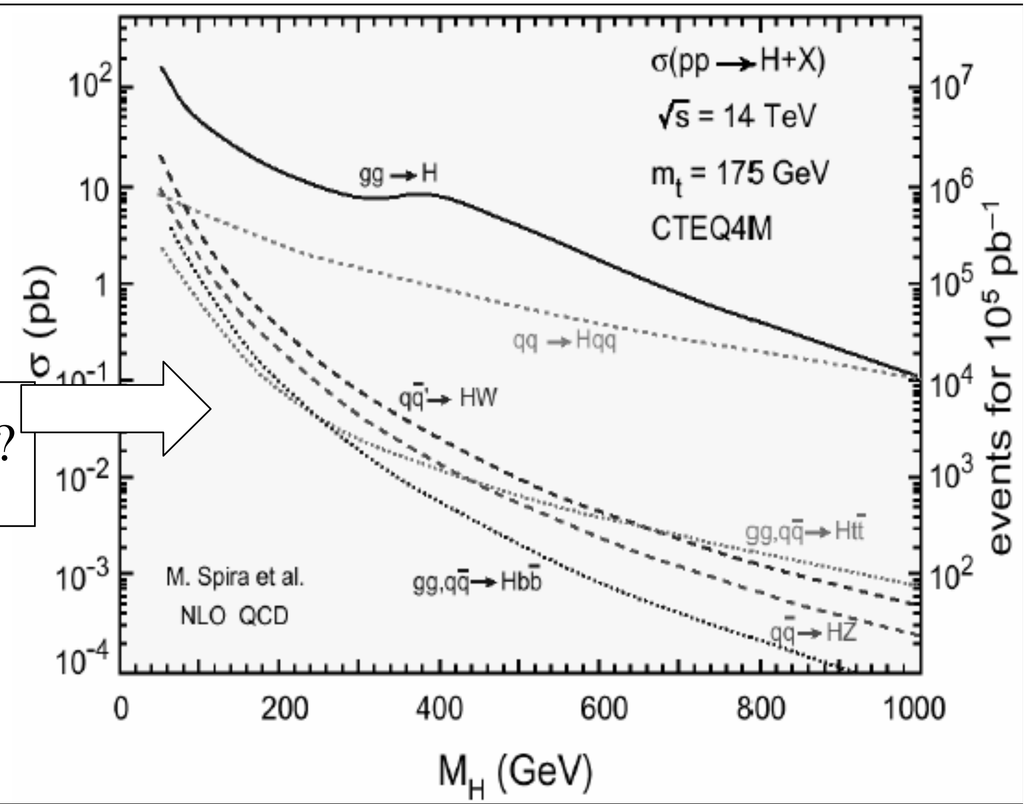


A la recherche du Higgs perdu …

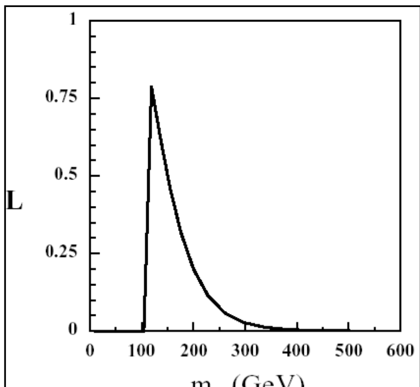


Higgs Production at the LHC





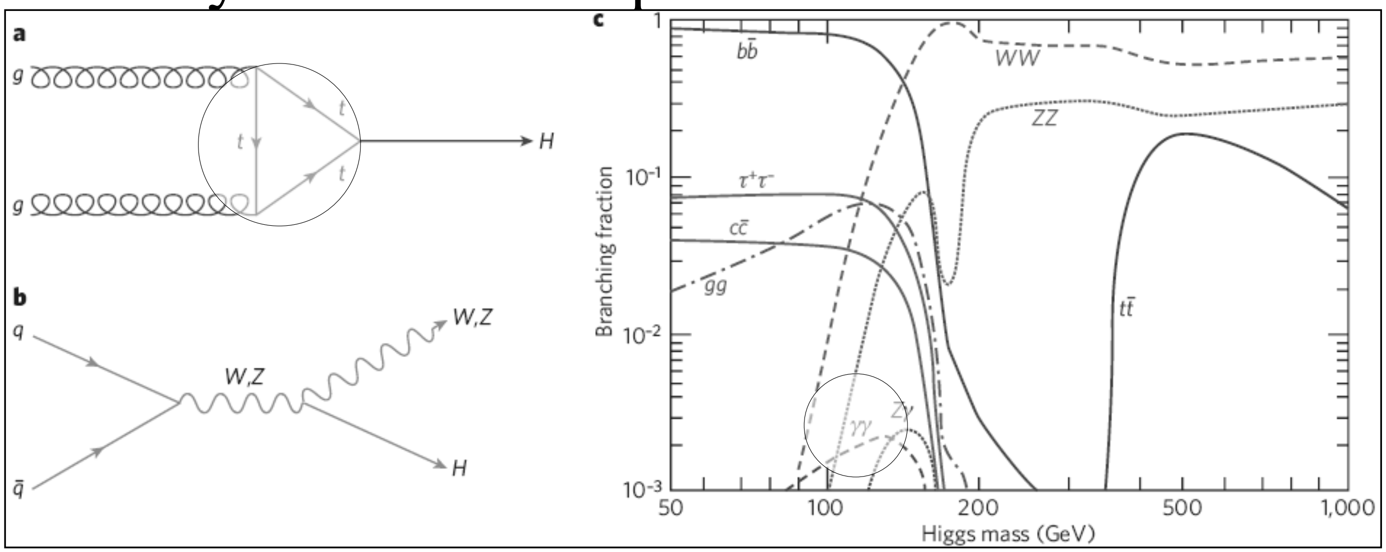
… not far away?



Combining direct, Indirect information

Higgs Decay Branching Ratios

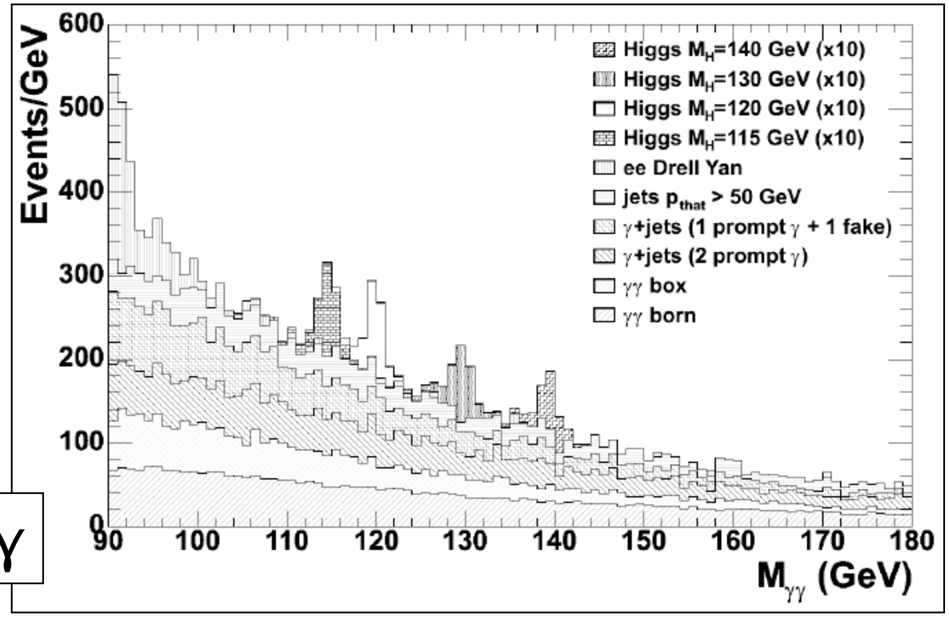
- Couplings proportional to mass:
  – Decays into heavier particles favoured



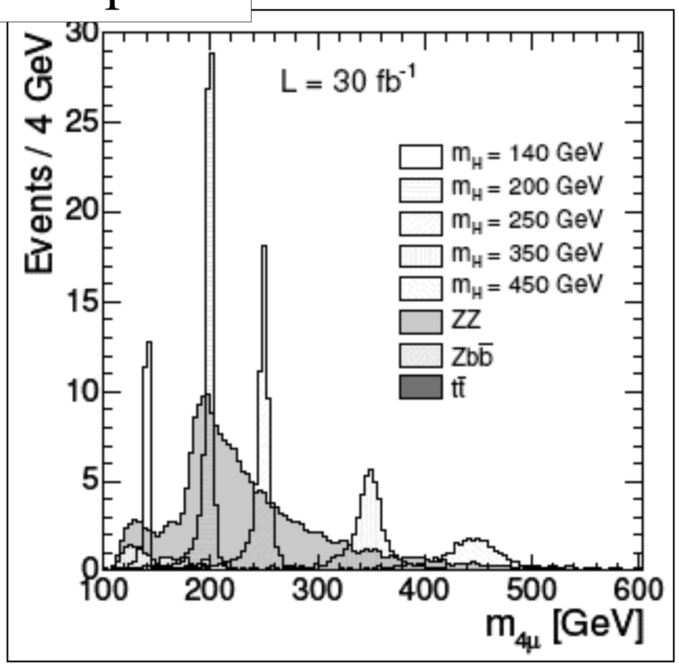
- But: important couplings through loops:
  – gluon + gluon → Higgs → γγ

Some Sample Higgs Signals

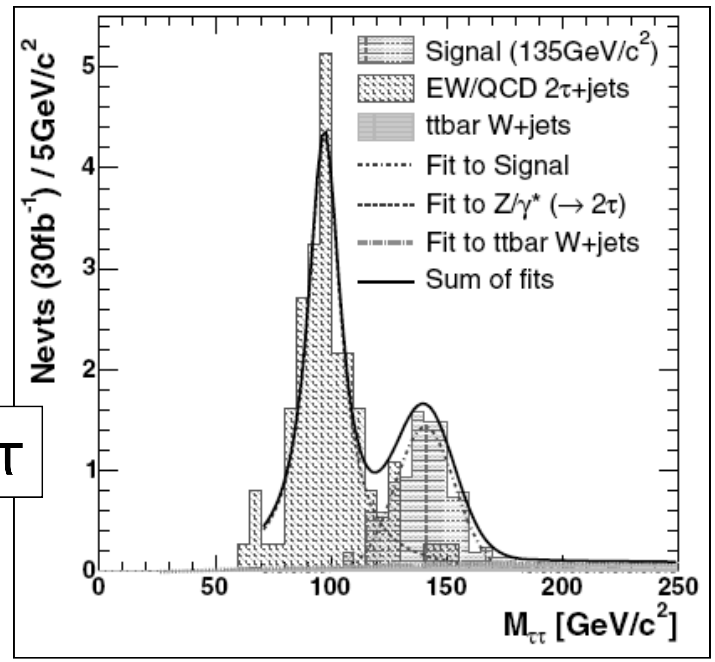
γγ



ZZ* -> 4 leptons

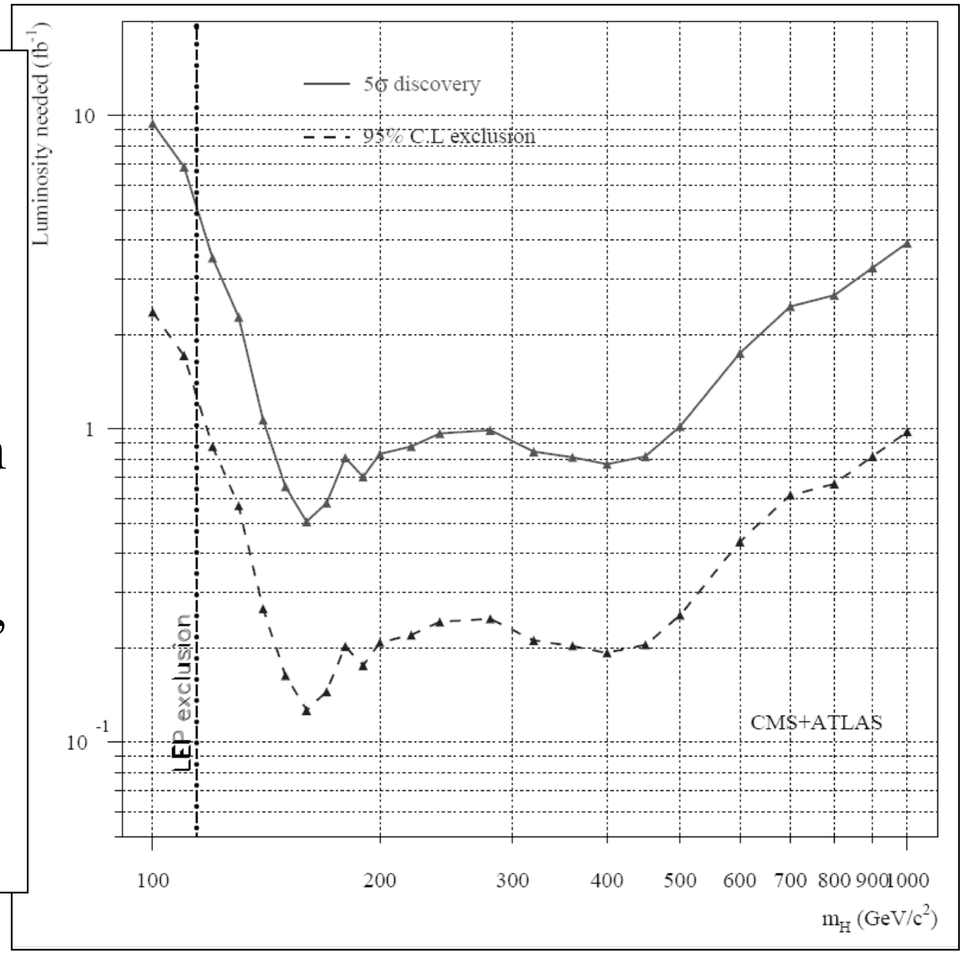


ττ



Potential of Initial LHC running

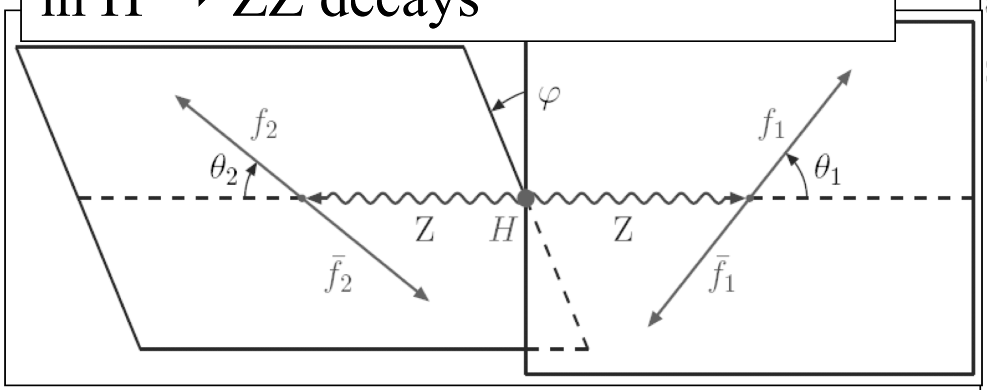
- A Standard Model Higgs boson could be discovered with 5-σ significance with $5fb^{-1}$, $1fb^{-1}$ would be sufficient to exclude a Standard Model Higgs boson at the 95% confidence level
- Signal would include $\tau\tau$, $\gamma\gamma$, bb, WW and ZZ
- Will need to understand detectors very well

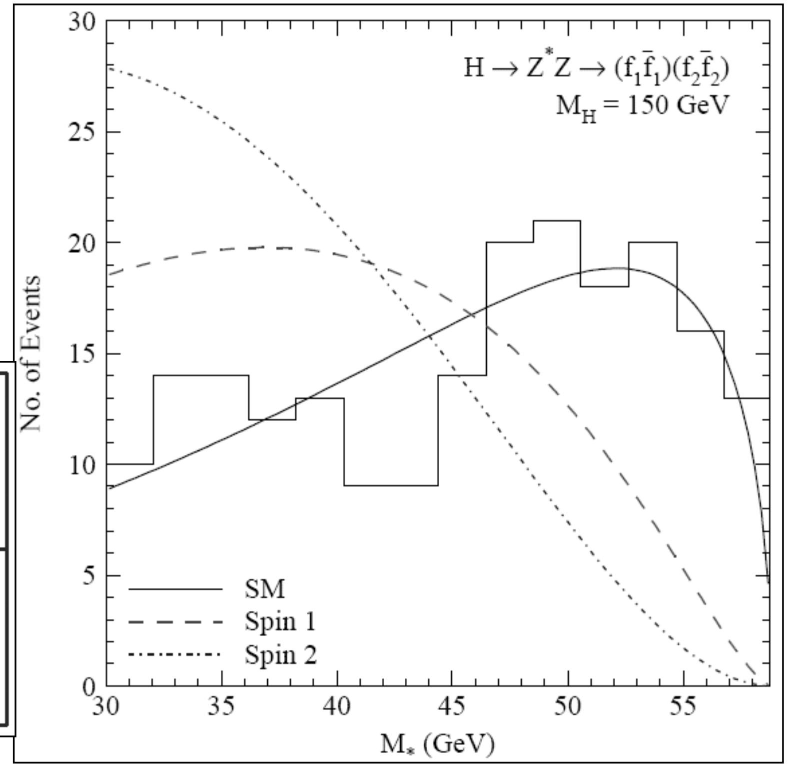


The Spin of the Higgs Boson @ LHC

Low mass: if H →γγ, It cannot have spin 1

Higher mass: angular correlations in H → ZZ decays





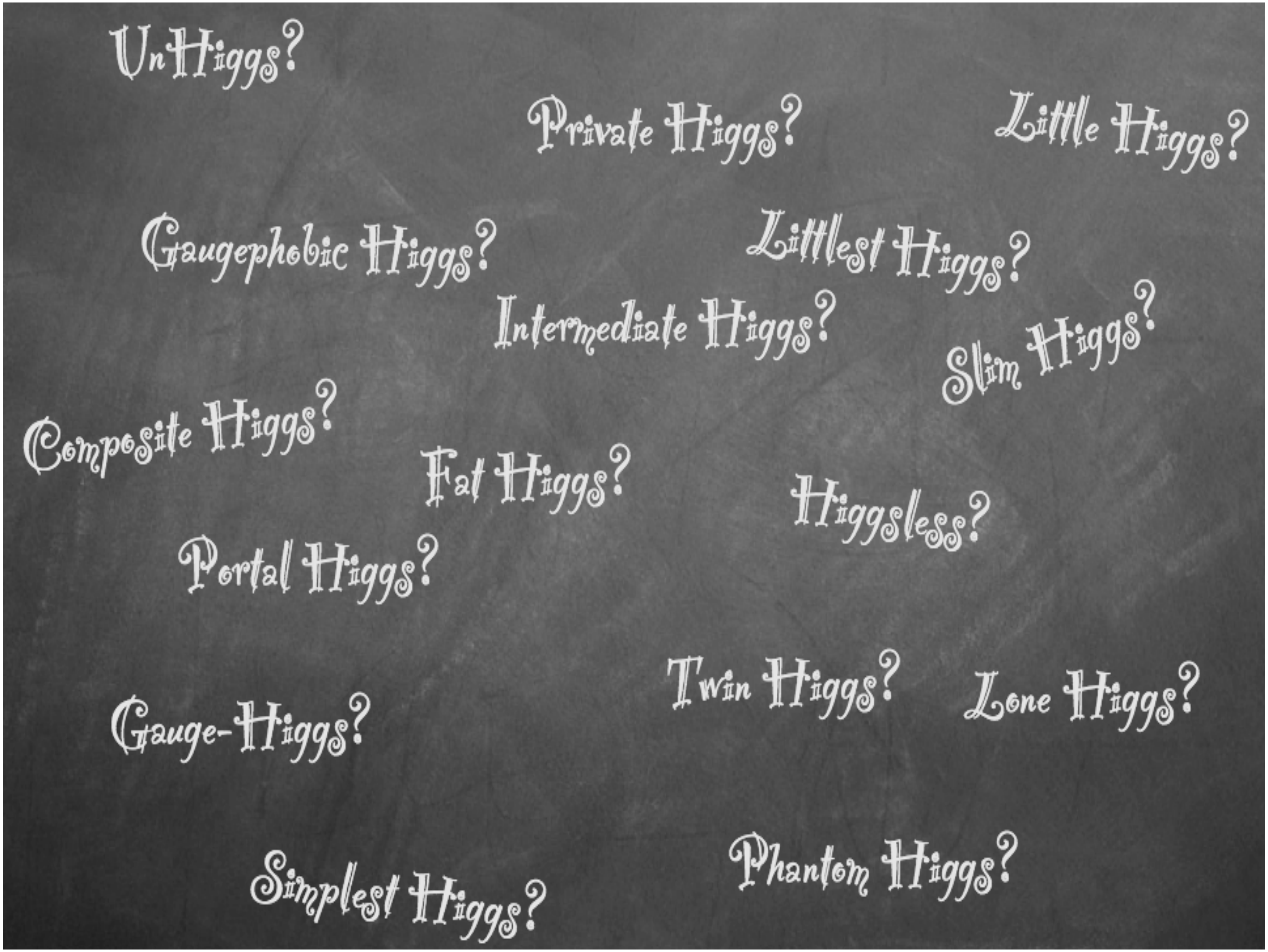
Significance for exclusion of other J^{CP} states than 0^+

ATLAS + CMS, 2 x 300 fb^{-1}

m_H (GeV)	$J^{CP} = 1^+$	$J^{CP} = 1^-$	$J^{CP} = 0^-$
200	6.5 σ	4.8 σ	40 σ
250	20 σ	19 σ	80 σ
300	23 σ	22 σ	70 σ

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!


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?
Phantom Higgs?
Simplest Higgs?

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)

Theorists getting Cold Feet

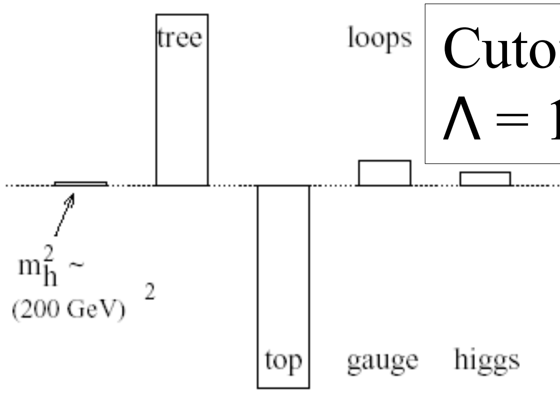
- Composite Higgs model?
  conflicts with precision electroweak data
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra `Top', gauge bosons, `Higgses'
- Higgsless models?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

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff
Λ = 10 TeV

- Cut-off Λ ~ 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

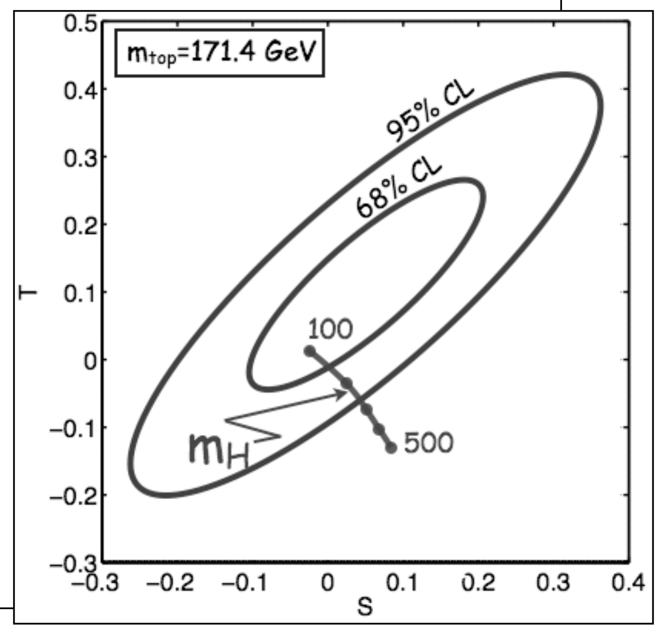
$$\rho \equiv 1 + \alpha_{em} T \qquad \rho \equiv \frac{M_W^2}{M_Z^2 c^2}$$

- Contributions from Standard Model Higgs

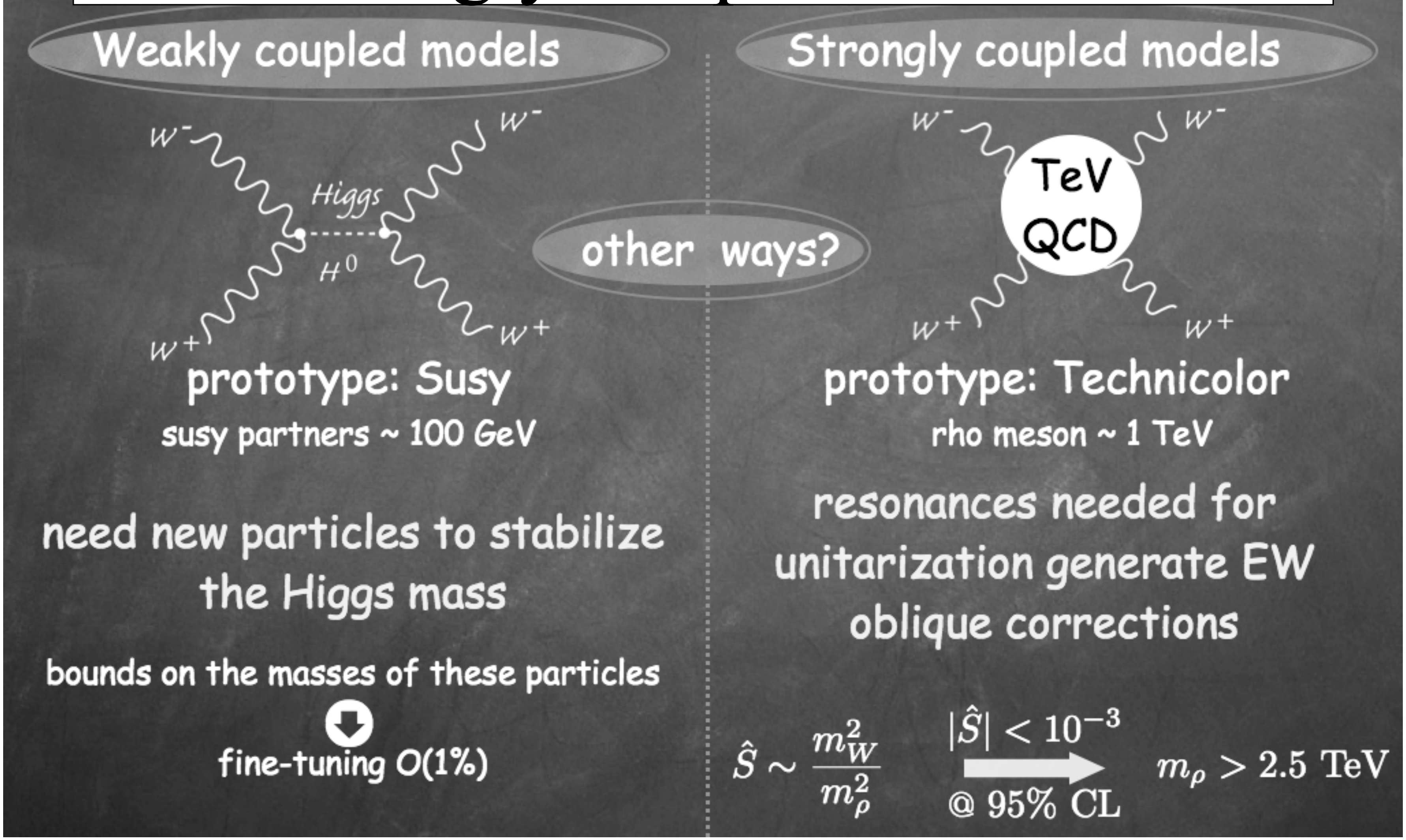
$$\delta S = \frac{1}{12\pi} \log \frac{m_h^2}{m_{h_0}^2}$$

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

- Low m_H compatible with data

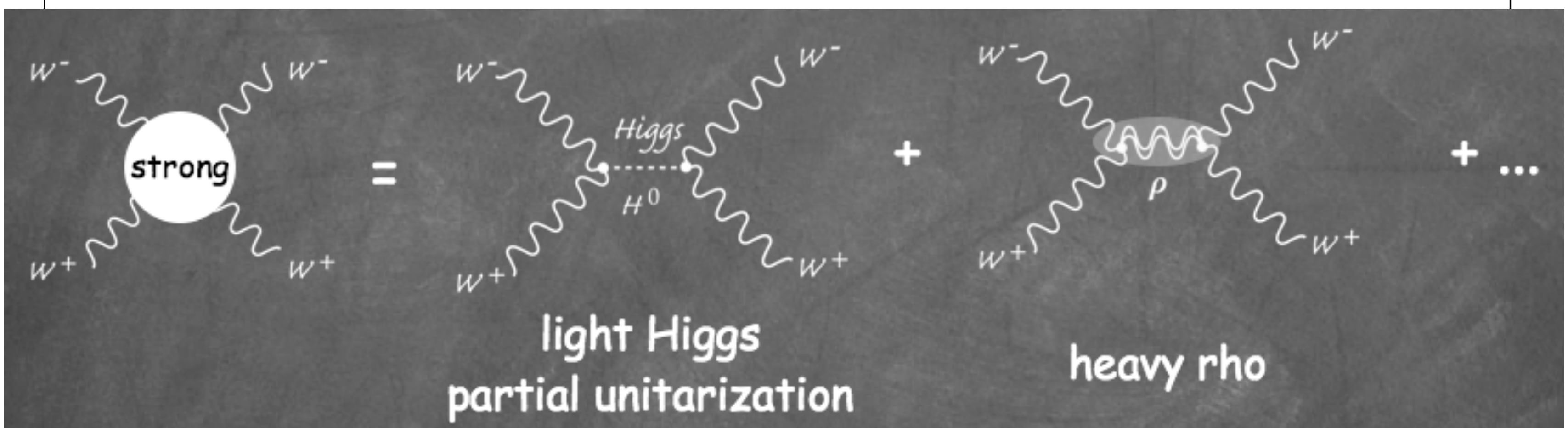


Comparison between Weakly- and Strongly-coupled Models



Interpolating Models

- Combination of Higgs boson and vector ρ

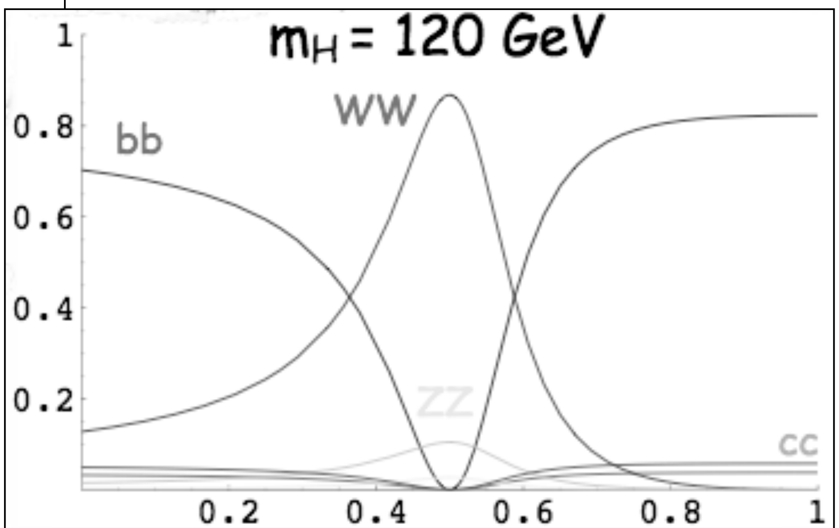


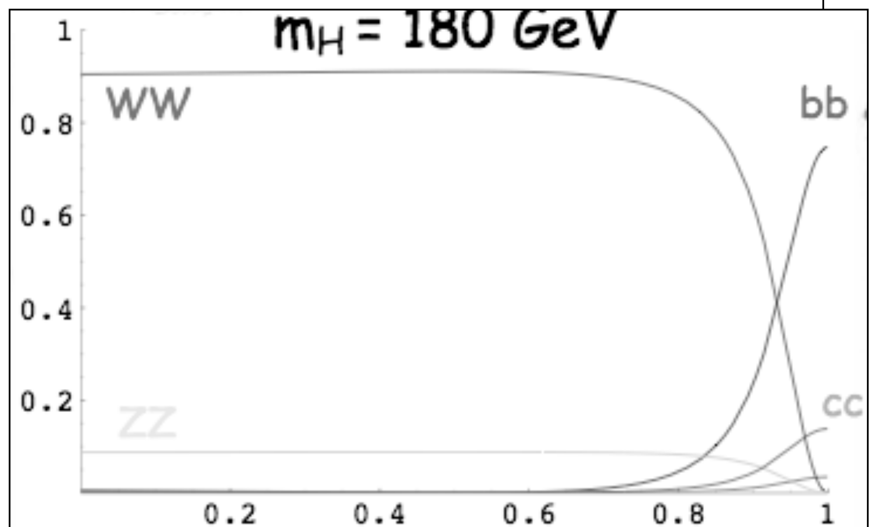
- Two main parameters: m_ρ and coupling g_ρ
- Equivalently ratio weak/strong scale:

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

Effects on Higgs Decays

- Dependences on ξ of Higgs branching ratios

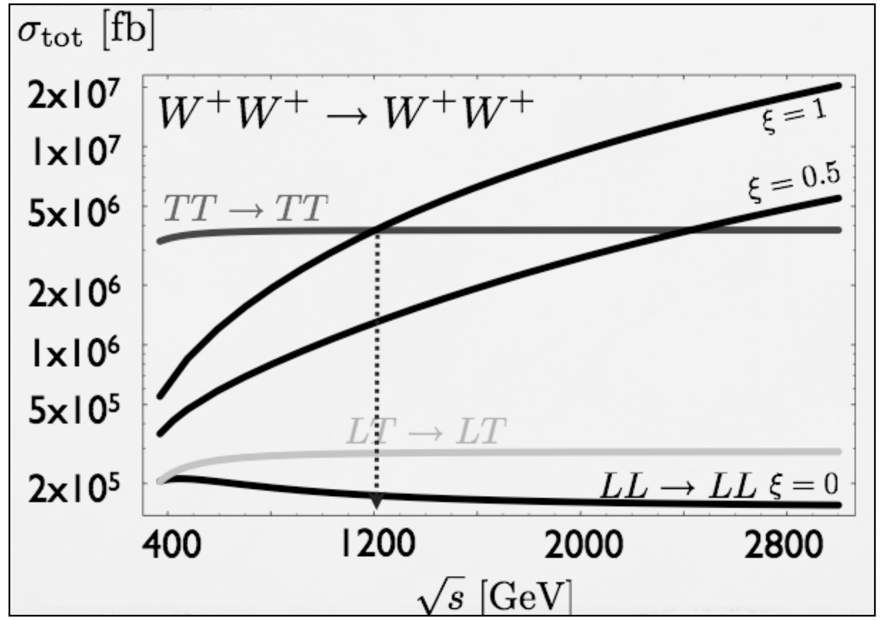


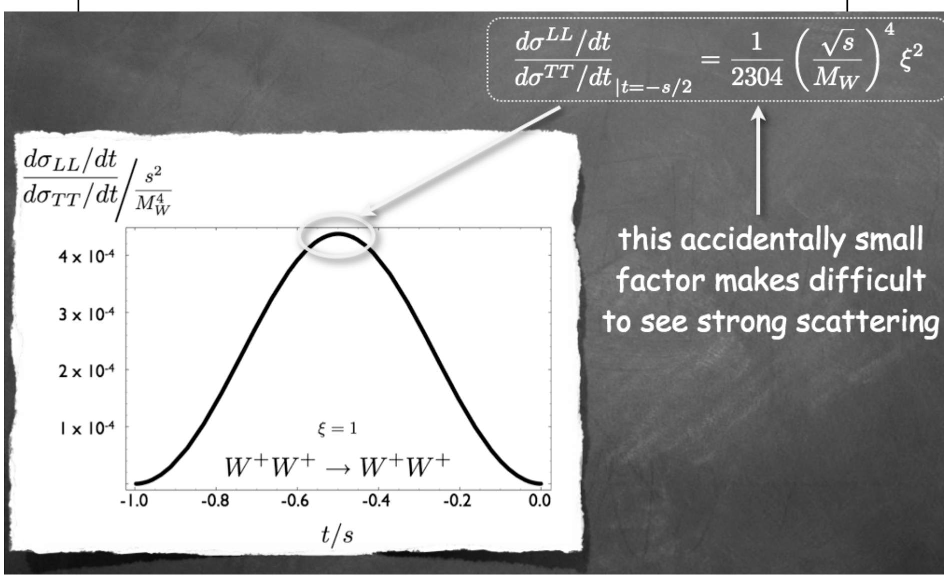


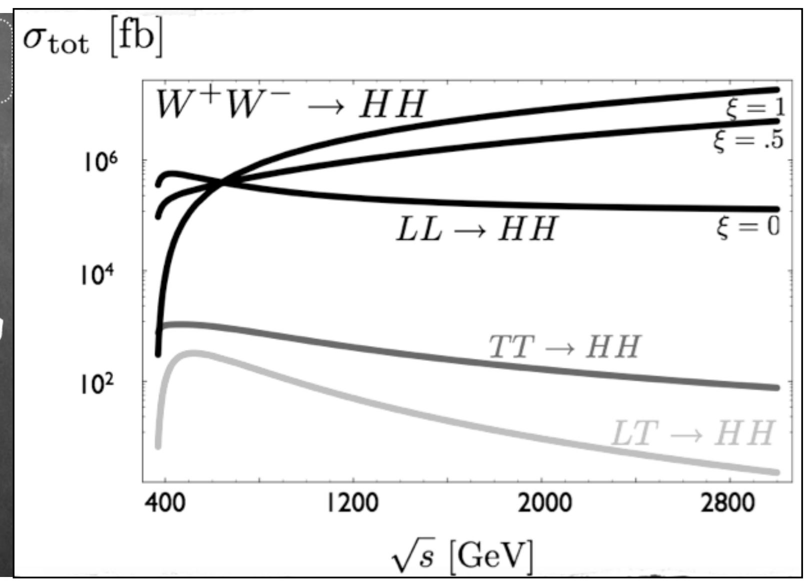
- Standard Model recovered in limit ξ → 0

Effects in WW Scattering?

- Look for effects in $W_L W_L$ scattering
- Drowned by $W_T W_T$
- Some hope for double Higgs production?

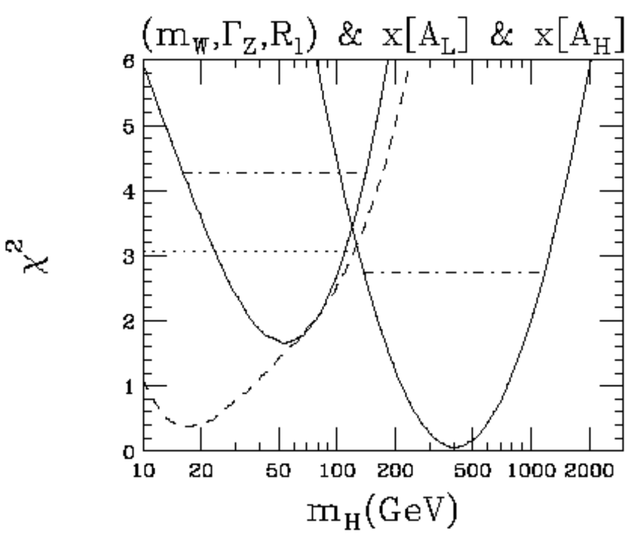




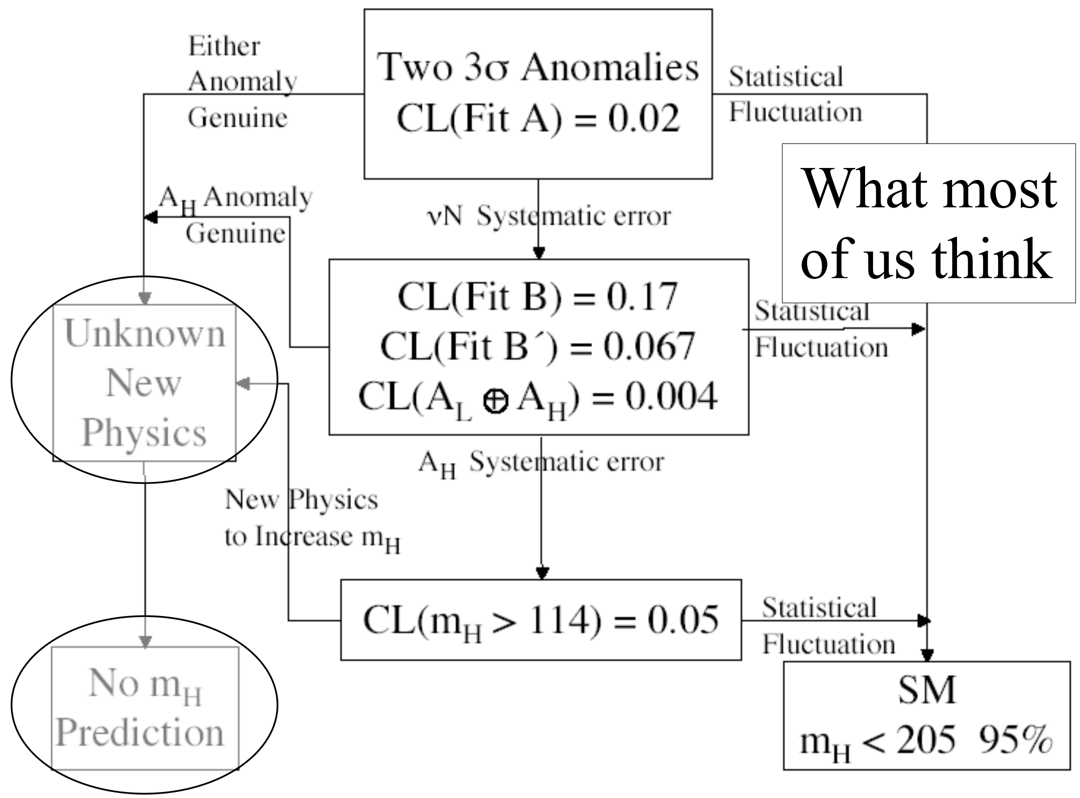


Heretical Interpretation of EW Data

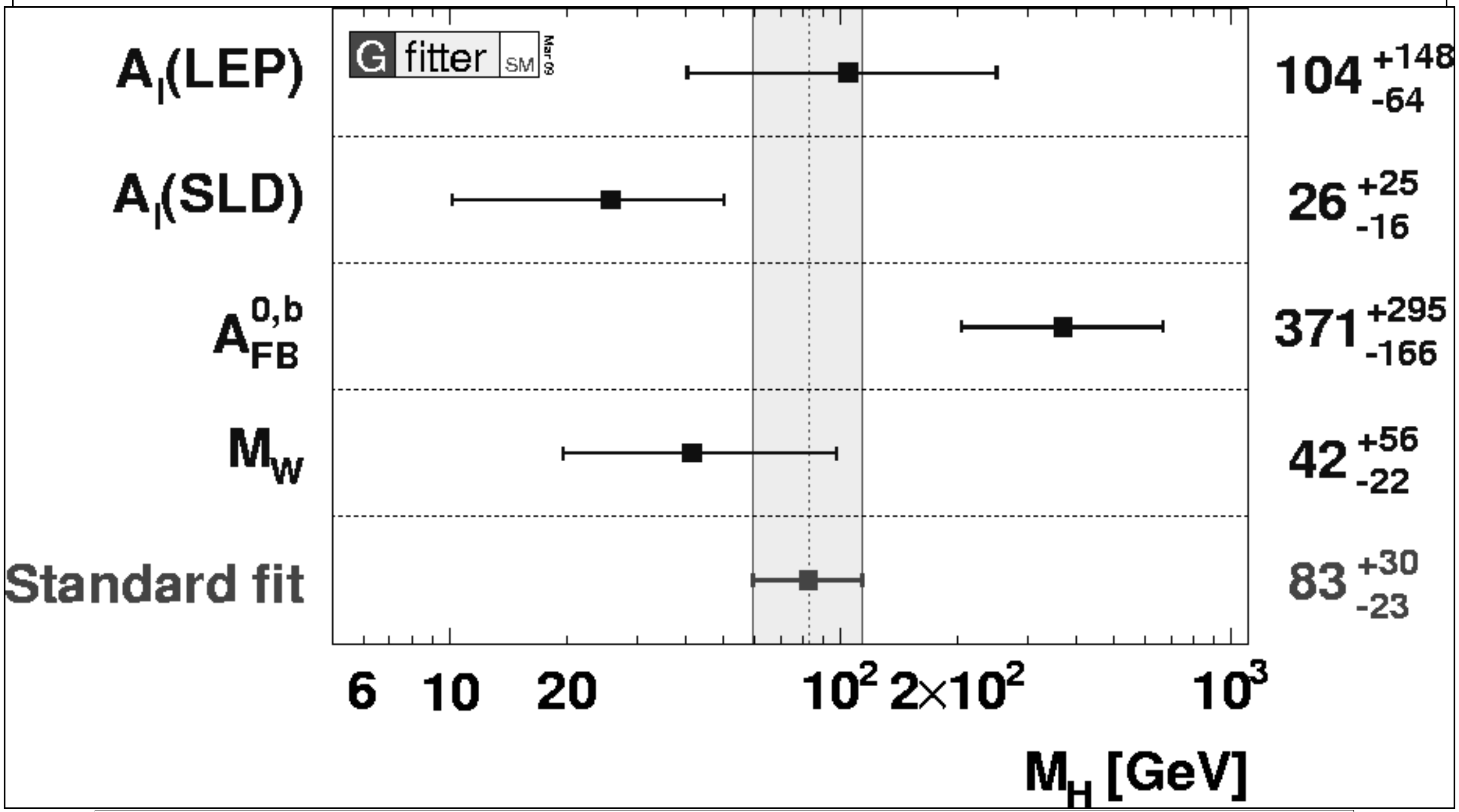
Do all the data tell the same story? e.g., A_L vs A_H



What attitude towards LEP, NuTeV?



Estimates of m_H from different Measurements



Spread looks natural: no significant disagreement

Higgs + Higher-Order Operators

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

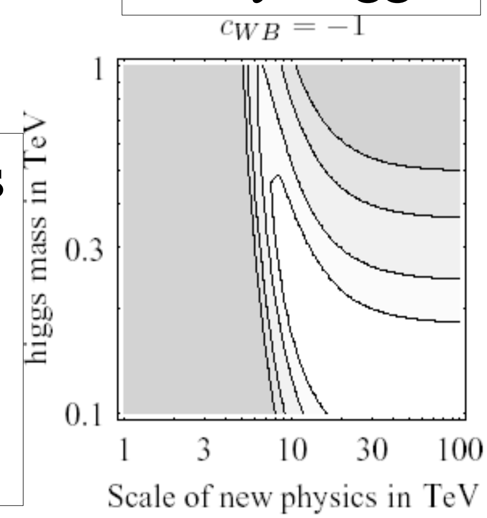
Precision EW data suggest they are small: why?

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
$\mathcal{O}_H = \|H^+ D_\mu H)\|^2$	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 …?



Do not discard possibility of heavy Higgs

Little Higgs Models

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

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

with new heavy T quark $m_T > 2\lambda_t f \sim 2f \quad f > 1 \text{ TeV}$

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

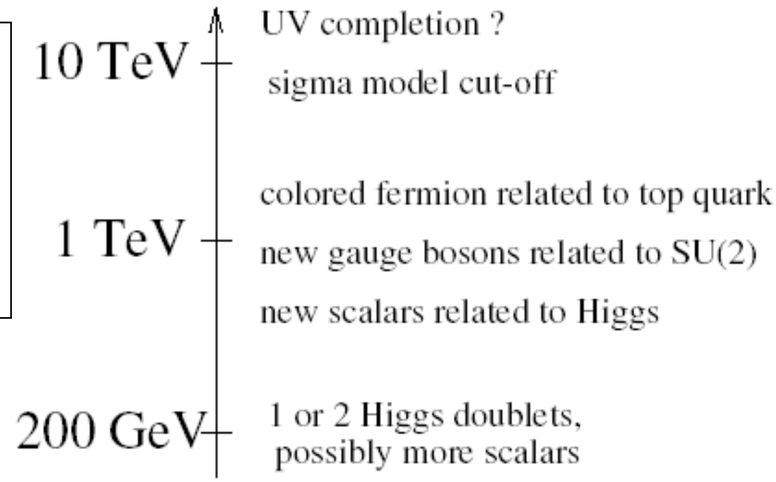
- New gauge bosons, Higgses
- Higgs light, other new physics heavy

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

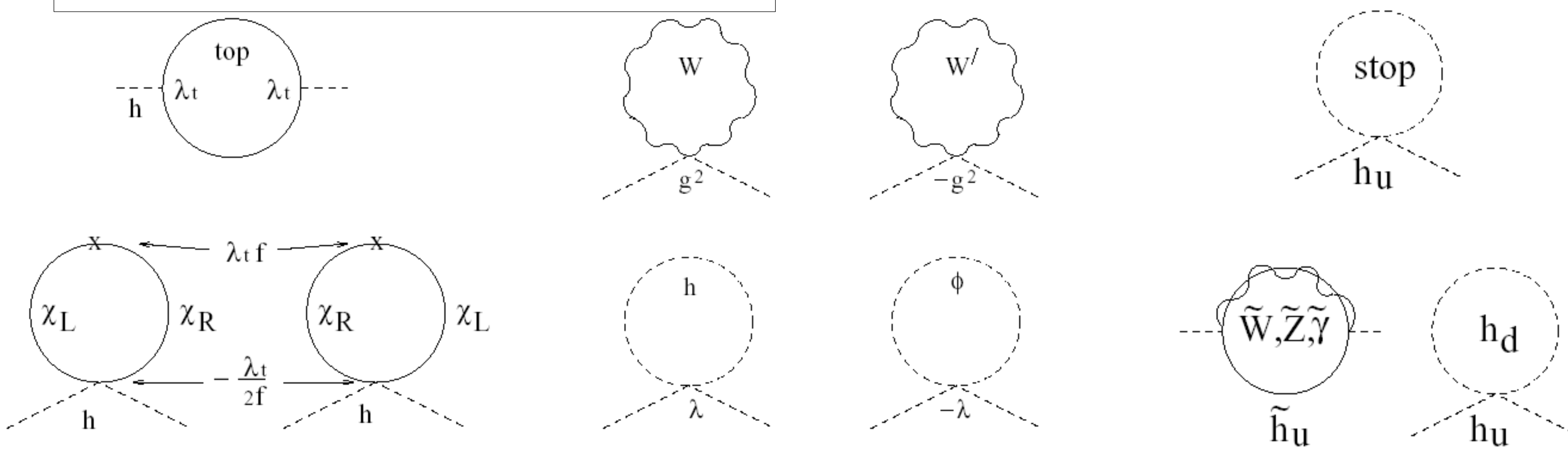
Not as complete as susy: more physics > 10 TeV

Generic Little Higgs Models

(Higgs as pseudo-Goldstone boson of larger symmetry)



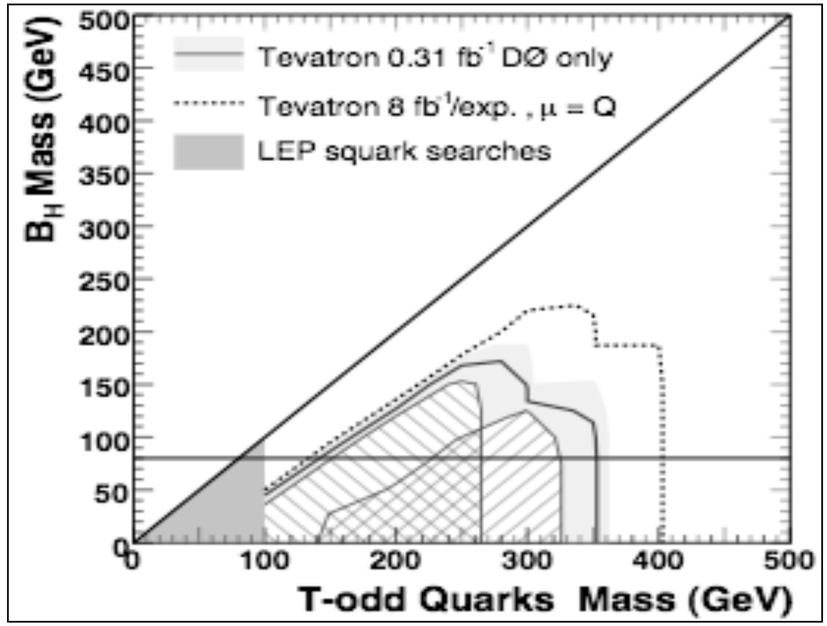
Loop cancellation mechanism

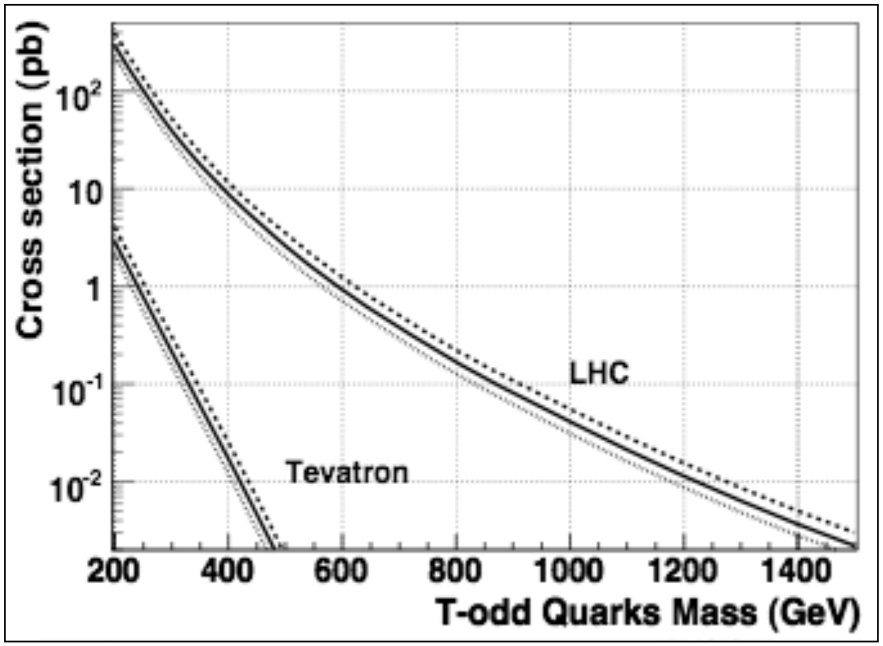


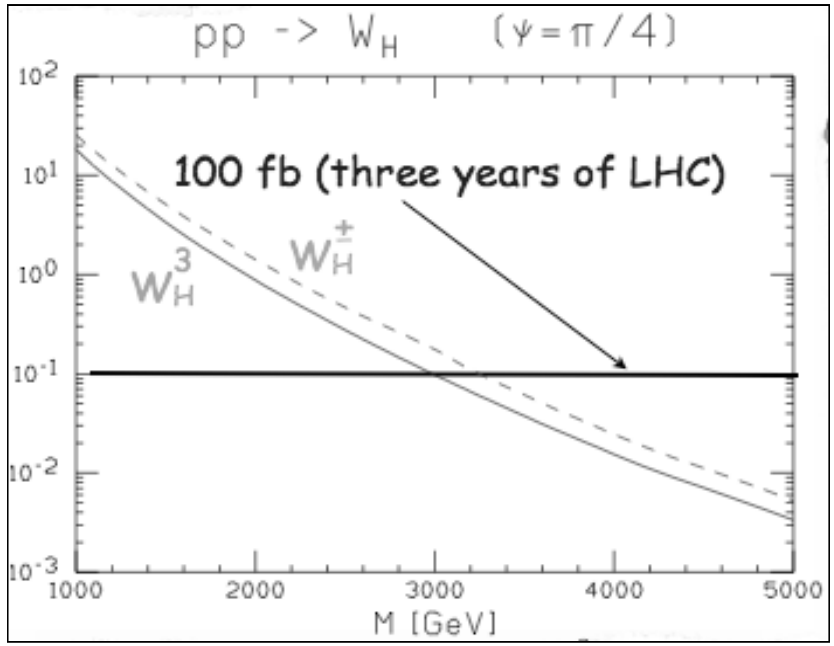
Little Higgs

Supersymmetry

Searches for Extra Particles in Little Higgs Models







Higgsless Models?

- Four-dimensional versions:

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

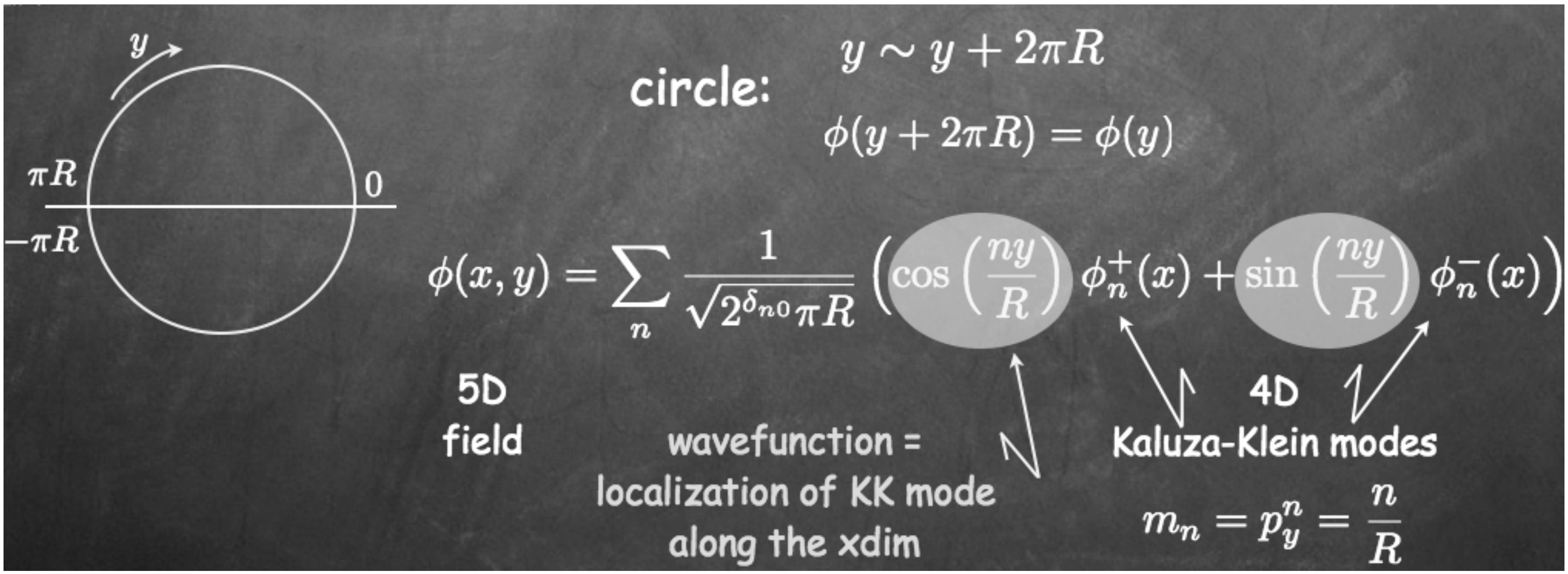
  delay strong WW scattering to ~ 10 TeV?

  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

Particle Spectrum in Simplest Model with Extra Dimensions



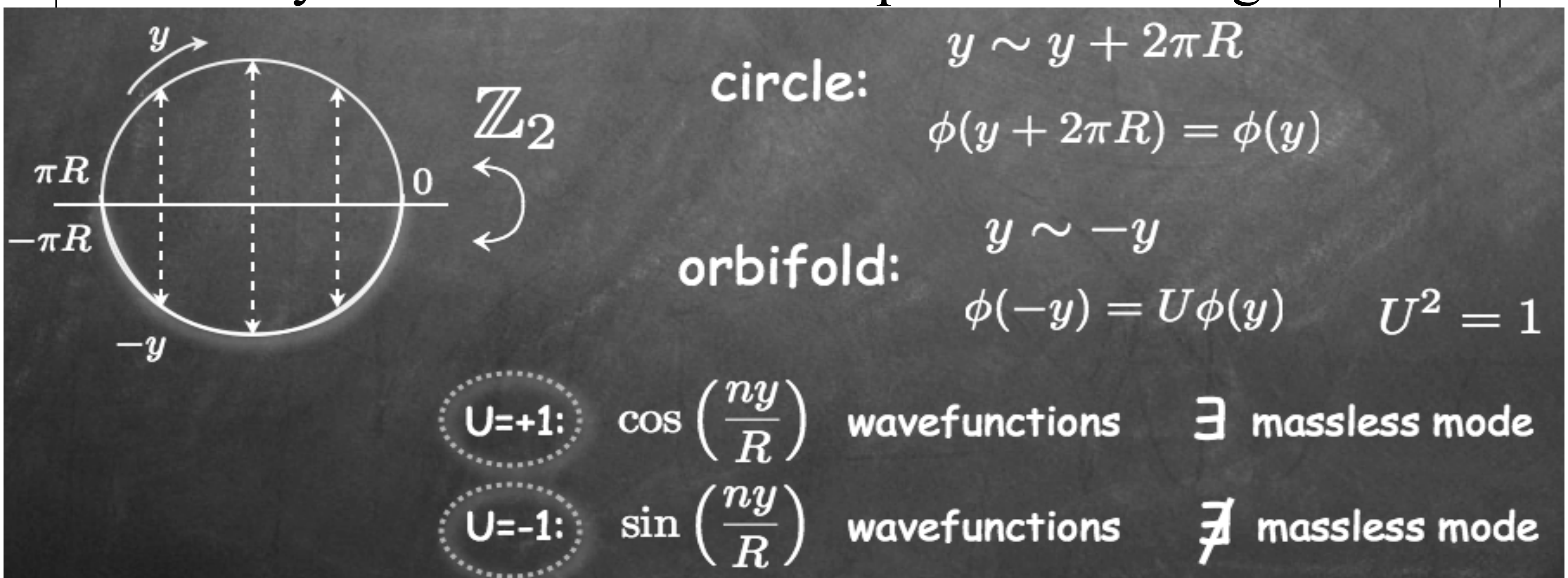
Lowest-lying states have flat wave functions (n = 0)

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

Mass ∝ n/R (R = radius of circle)

‘Fold’ Circle: Orbifold

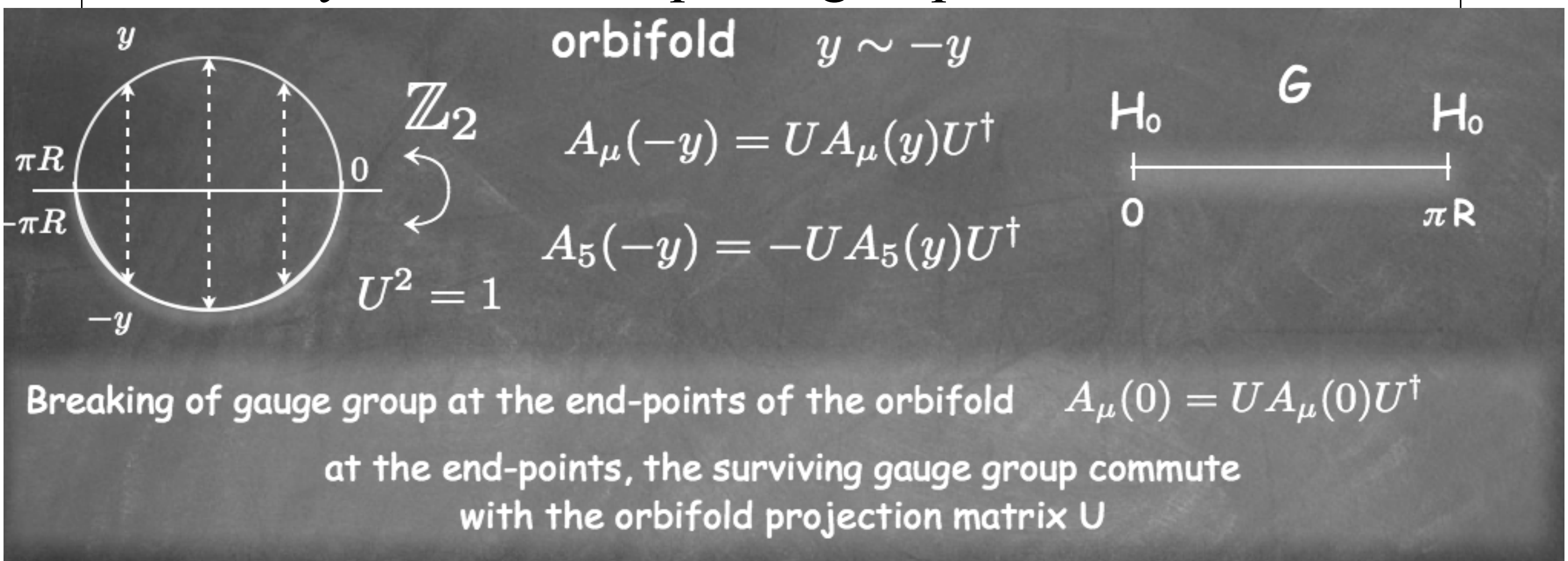
- Identify two halves of circle: up to a minus sign



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

Mechanism to break Gauge Symmetry

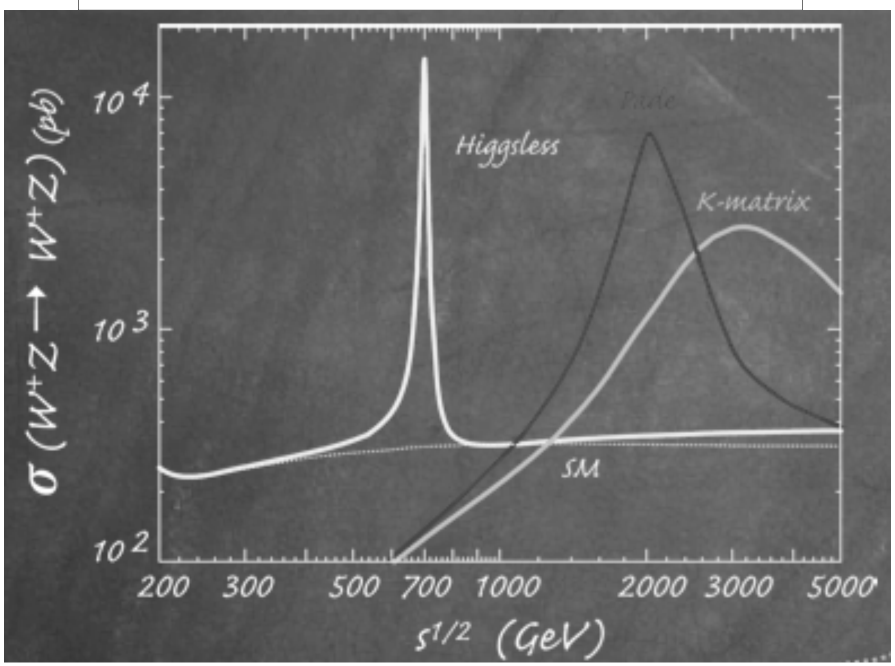
- Identify two halves up to a group transformation U



- 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