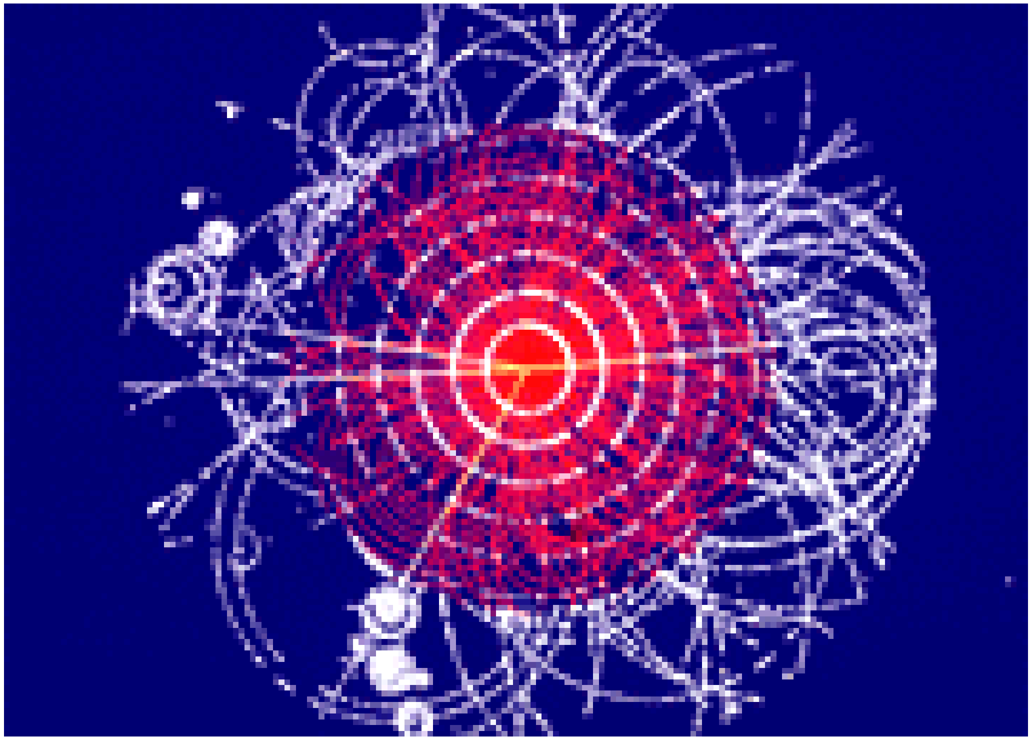
Physics at the LHC



Steve Godfrey
Carleton University

ATLAS Canada Physics Workshop, McGill, Dec 7 2005

Many physics topics to study at the LHC:

1. SM electroweak studies
2. QCD studies
3. t-quark studies
4. b-quark studies
5. EWSB
   - SM Higgs search and studies
   - Extended Higgs sector
   - Strongly interacting weak sector
6. BSM
   - supersymmetry
   - Topcolour
   - Little higgs models
   - Extra dimensions
   - String inspired models

Precision Electroweak Measurements

- How do we discover the new physics?
- How do we identify the new physics?

- Likely that discoveries at the LHC will get us started
- But will need the ILC to discriminate between models

Possible Routes:

- Direct Discovery
- Indirect discovery assuming specific models
- Indirect tests of New Physics via $\mathcal{L}_{eff}$

Tools:

- Di-fermion channel
- Anomalous gauge boson couplings
- Anomalous fermion couplings
- Higgs couplings

What is the source of mass?

What breaks $SU(2)_L \times U(1)_Y$?

- Higgs mechanism?
- Dynamical Symmetry Breaking?
- Extra Dimensions?
- .....?

Higgs Mechanism

Simplest possibility for Origin of Mass is Higgs Mechanism

- Gives gauge invariant masses to Wand Z
- Requires physical, scalar particle, H, with unknown mass

$$\mathcal{L}_{\rm scalar} = (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

Φ acquires degenerate non-zero minimum if: $\mu^2 < 0 \qquad \lambda > 0$

$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

Breaks the symmetry

$$v = 2M_W/g \simeq 246 \text{ GeV} \qquad M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}\, v$$

Also have: $m_f = \lambda_f \frac{v}{\sqrt{2}}$

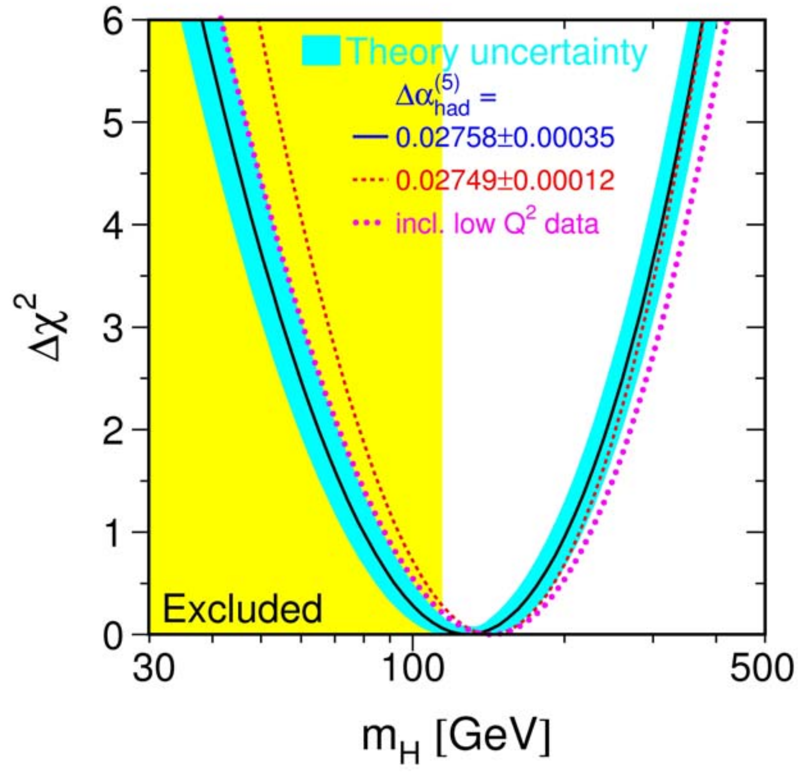
SM with light Higgs works pretty well

2005

2005

M_H < 285 GeV

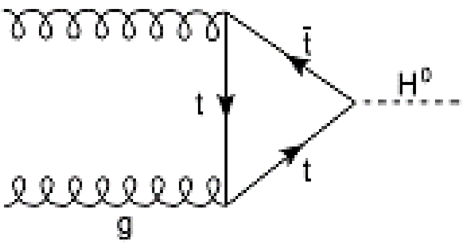
1 sided 95% cl



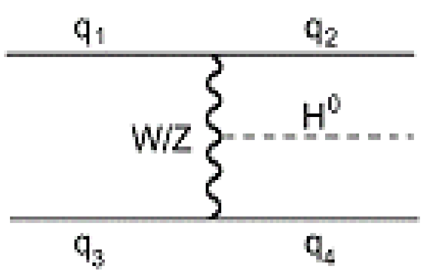
LEPEWWG, 2005

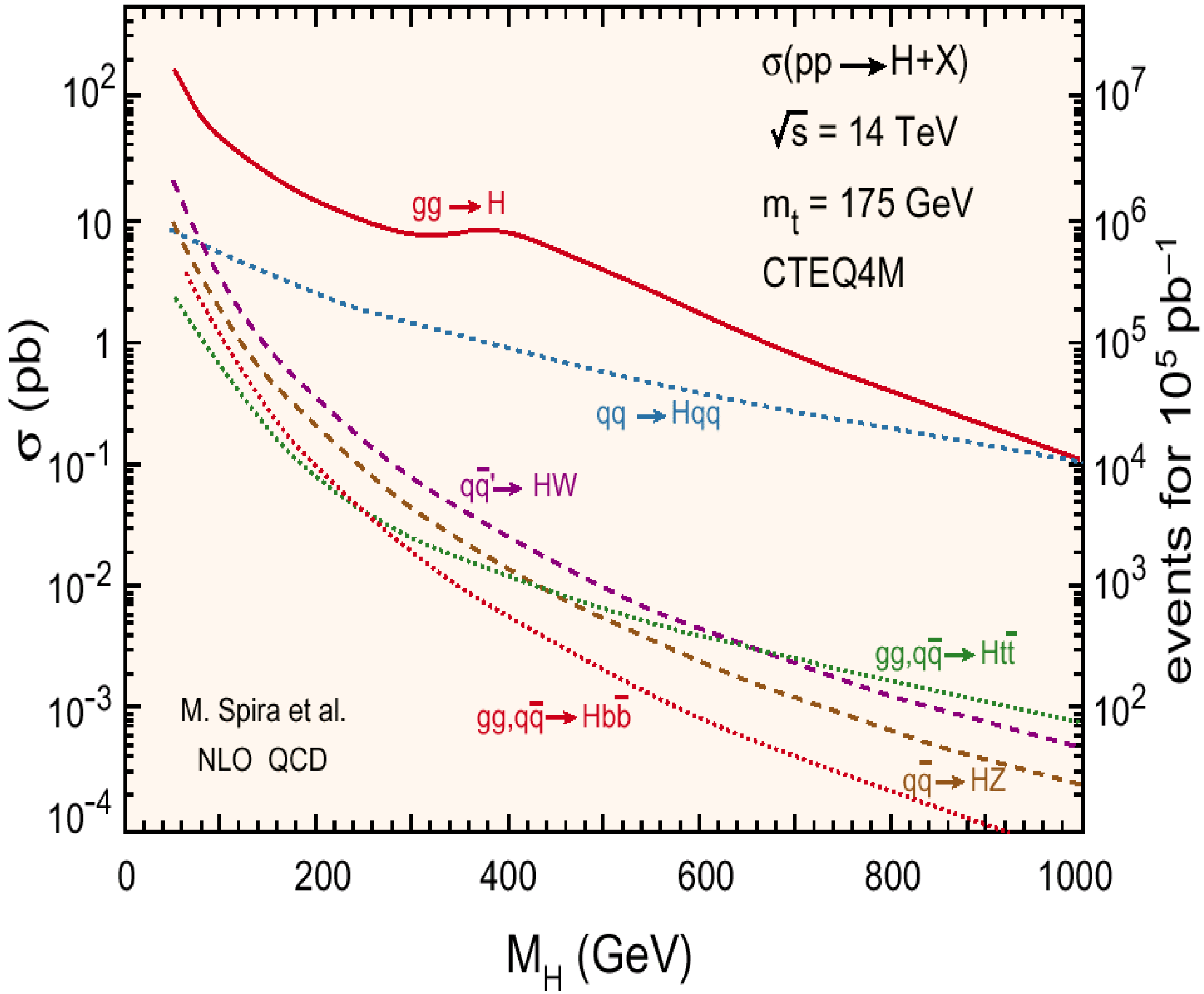
Higgs Production at LHC

Leading Process (gg fusion)



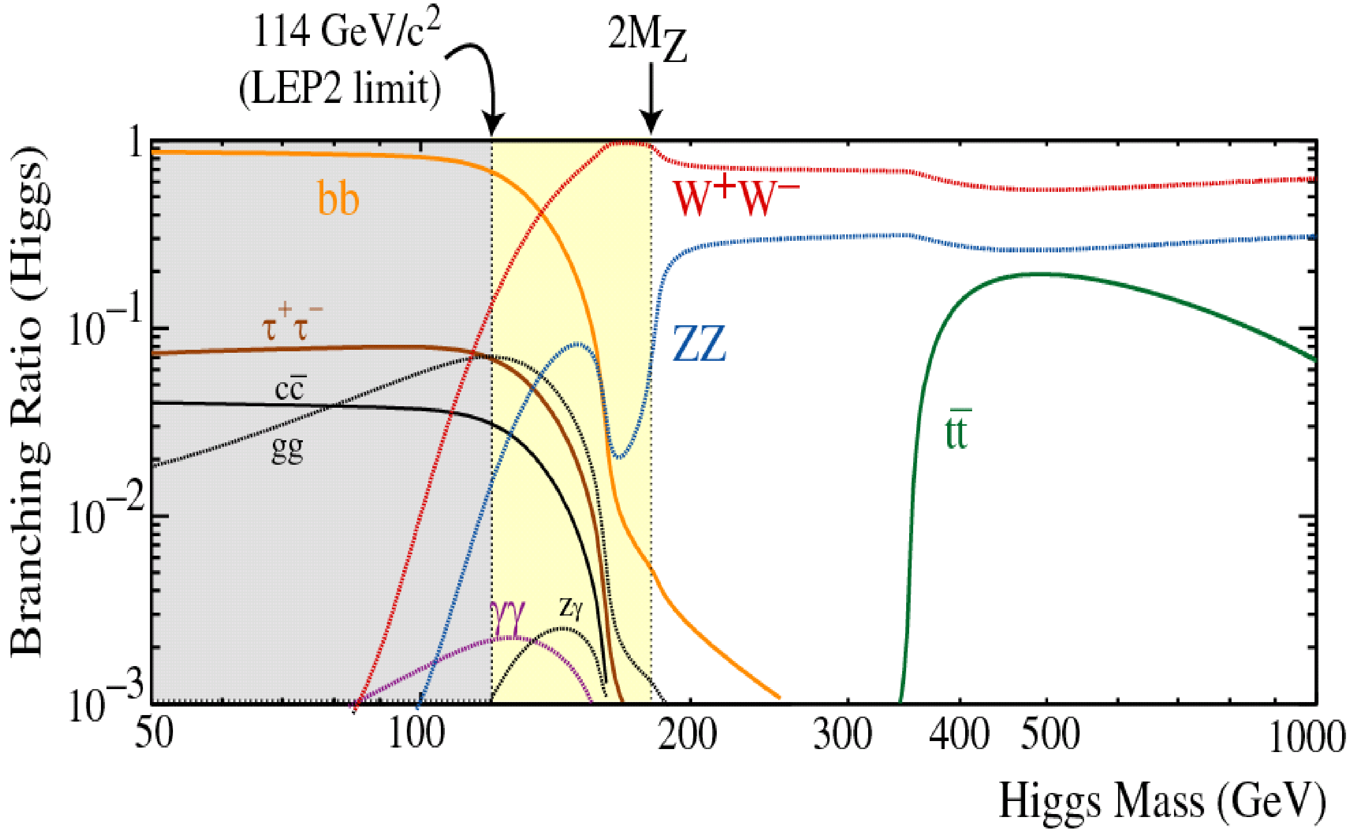
Sub-leading Process (VBF)





Main Decay Modes

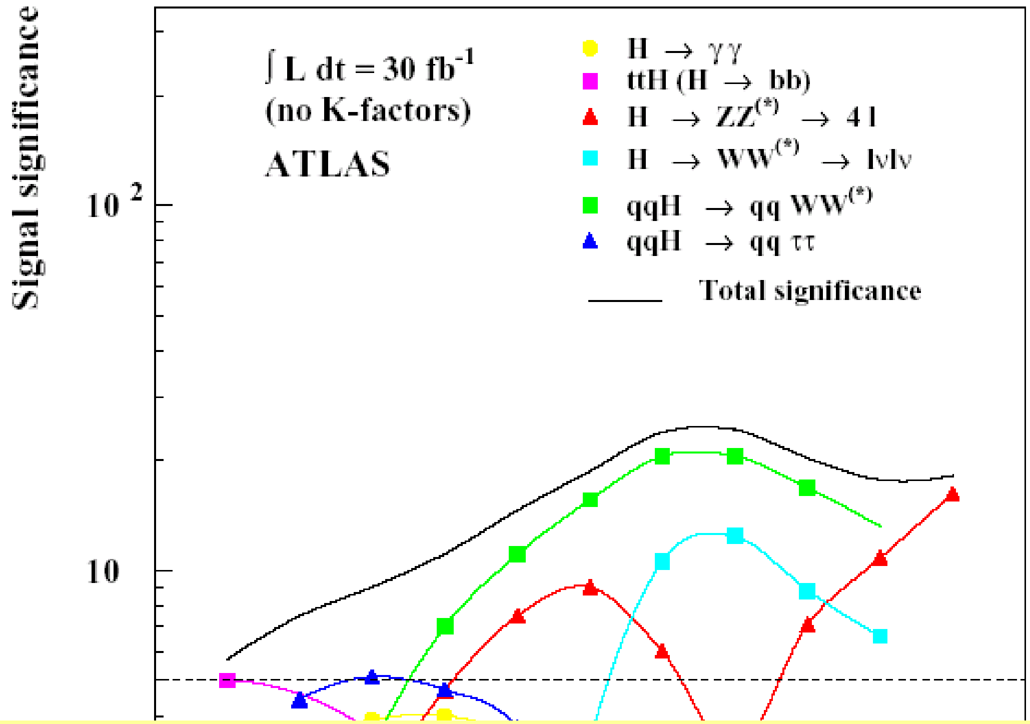
200 GeV Higgs is very different from 120 Gev Higgs



Close to LEP limit: $H \to \gamma\gamma, \tau\tau, bb$

For $M_H > 140$ GeV: $H \to WW^{(*)}, ZZ^{(*)}$

Higgs Discovery Prospects

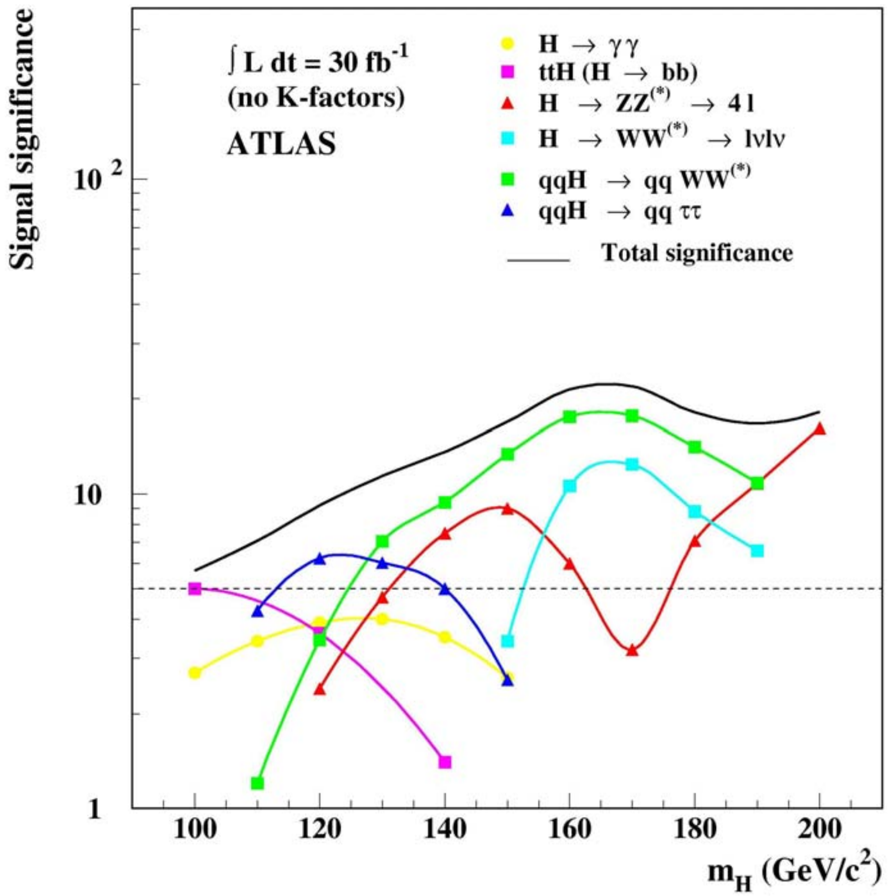


- Generally need O(10) fb^{-1} for 5σ discovery
- Possible exception WW→ll νν at ~ 155-180 GeV (systematics?)
- Exclusion limits on large region of SM Higgs (H →ZZ,WW)

LHC will find Standard Model Higgs

CERN Large Hadron Collider (LHC)

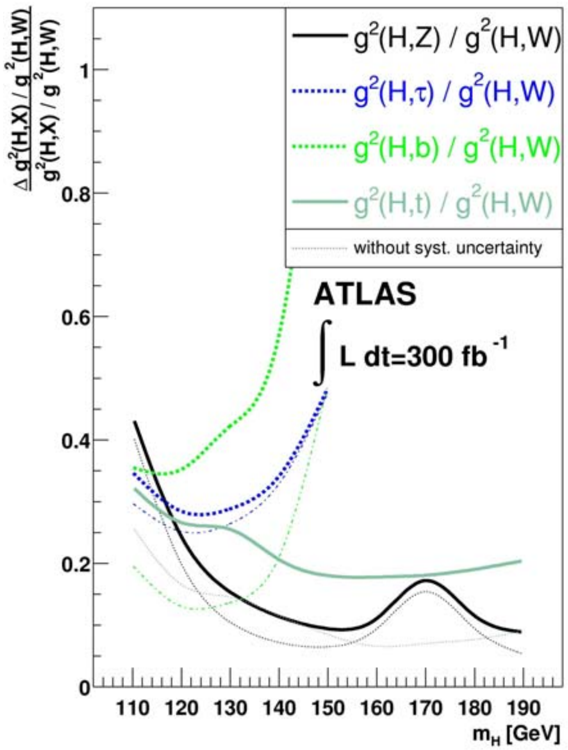
- pp interactions at $\sqrt{s}$ =14 TeV
- LHC will discover Higgs boson if it exists
- Sensitive to M_h from 100-1000 GeV
- Higgs signal in just a few channels
- Physics circa 2007



Discovery happens quickly!

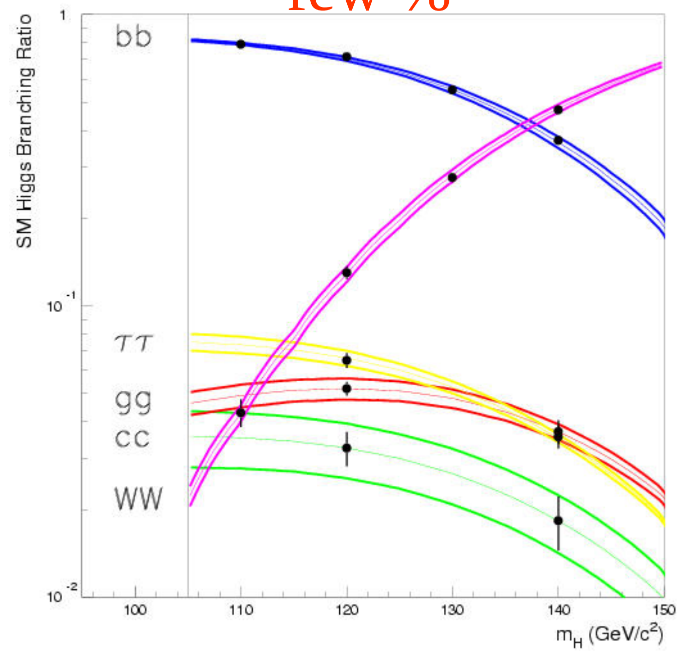
Once we find the Higgs, we need to measure its couplings

Ratios of coupling constants measured quite precisely at LHC



Duhrssen, ATL-PHYS-2003-030

LC measures couplings to a few %



e^+e^- LC at $\sqrt{s}$=350 GeV

L=500 fb^{-1}, M_H=120 GeV

Battaglia & Desch, hep-ph/0101165

Linear Collider is the place!

Discovery isn't enough….

- Is this a Higgs or something else?
- Linear Collider can answer critical questions
  - Does the Higgs generate mass for the W,Z bosons?
  - Does the Higgs generate mass for fermions?
  - Does the Higgs generate its own mass?

Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

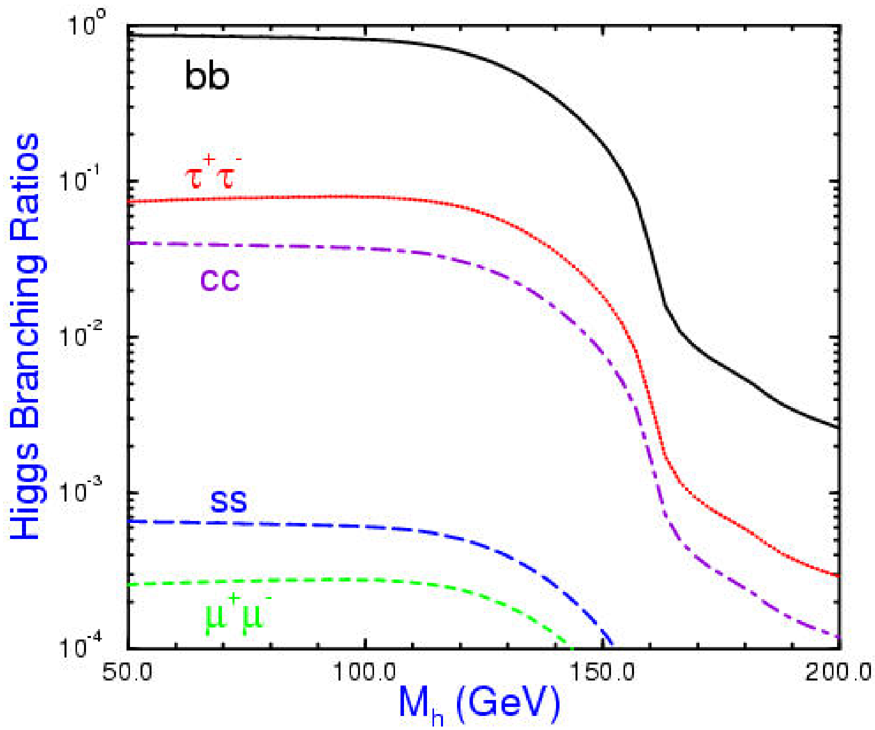
$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

- Measure self interactions

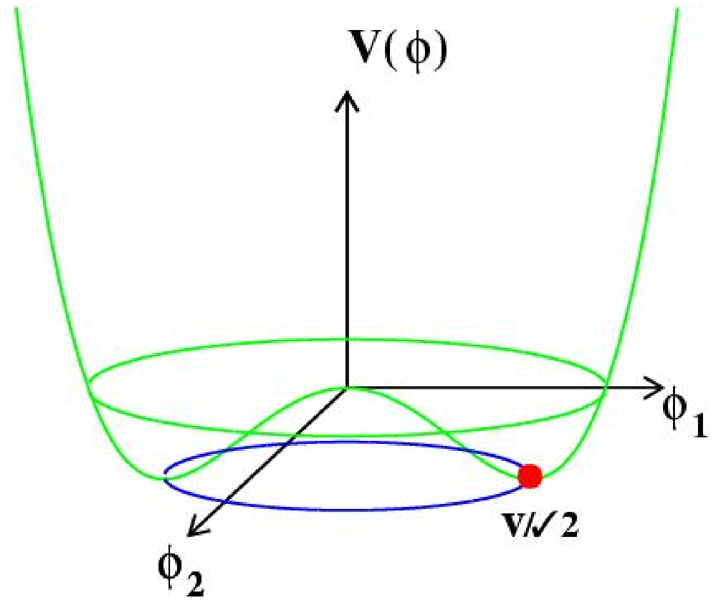
$$V = \frac{M_h{}^2}{2}h + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$



Does the Higgs generate its own mass?

Can we reconstruct the Higgs potential?

$$V = \frac{M_h{}^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$
$$+ \sum_n C_n \frac{(h^2 - v^2)^n}{\Lambda^{(2n-4)}}$$

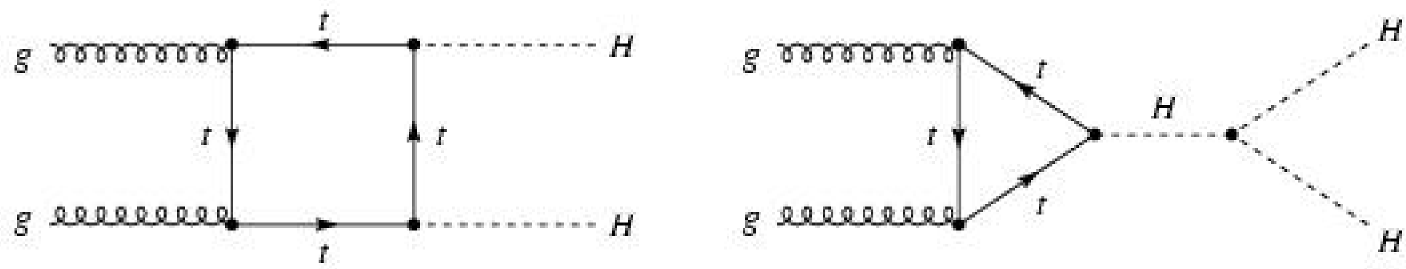


Fundamental test of model!

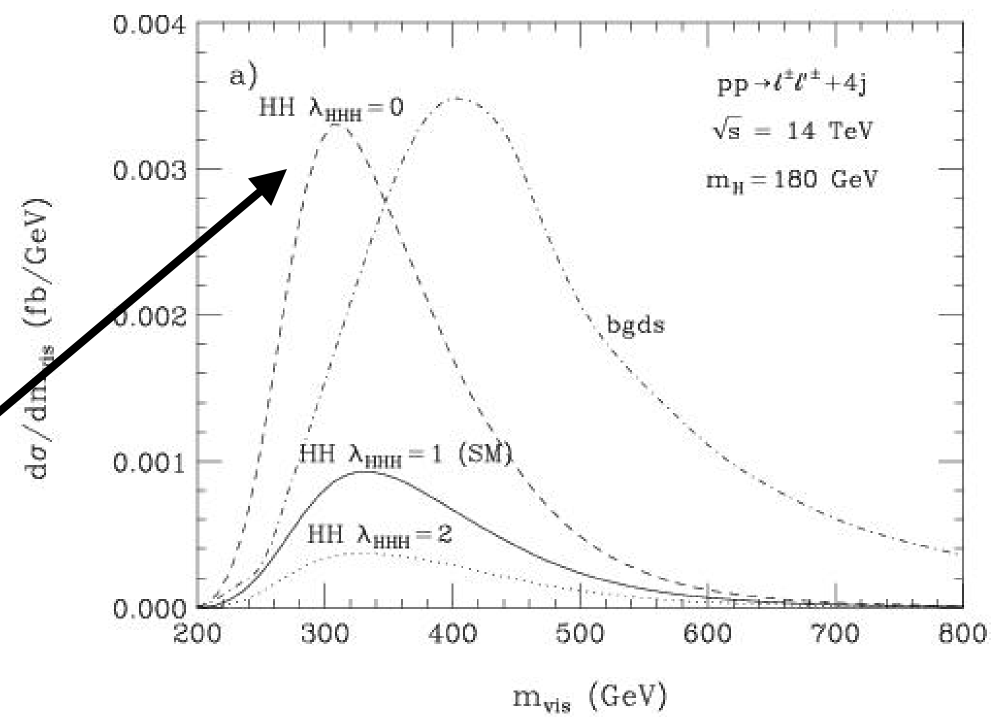
SM: $\lambda_3 = \lambda_4 = M_h^2/2v^2$

We need both λ_3 and λ_4

Reconstructing the Higgs potential



- λ_3 requires 2 Higgs production



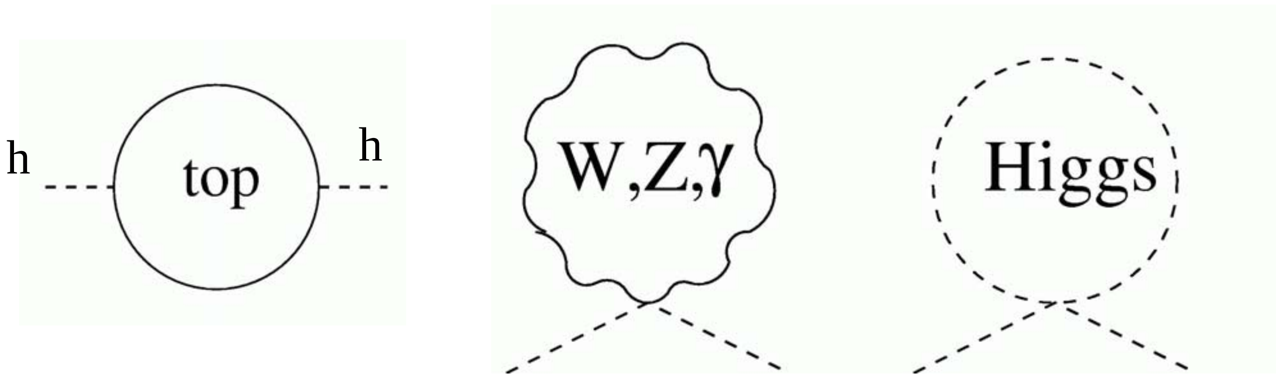
Can determine whether λ_3=0 at LHC

Baur, Plehn & Rainwater, hep-ph/0304015

What is wrong with the Standard Model?

Light Scalars are Unnatural

- Higgs mass depends sensitively on physics at higher scales, Λ (*a priori* $\Lambda = M_{pl}$)



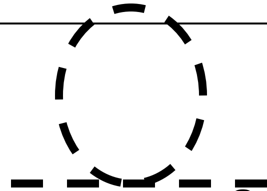
$$\delta M_h^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_h^2 - 12M_t^2\right)$$

$$= -\left(\frac{\Lambda}{0.7\ \text{TeV}}\ 200\ \text{GeV}\right)^2$$

$M_h \leq 200$ GeV requires large cancellations…..Used as argument for new physics at the TeV scale

Quantum Corrections Connect Weak and Planck Scales

Quantum corrections drag weak scale to Planck scale



$$\delta M_H^2 \approx M_{Pl}^2$$

Tevatron/LHC Energies

Problem with this picture…

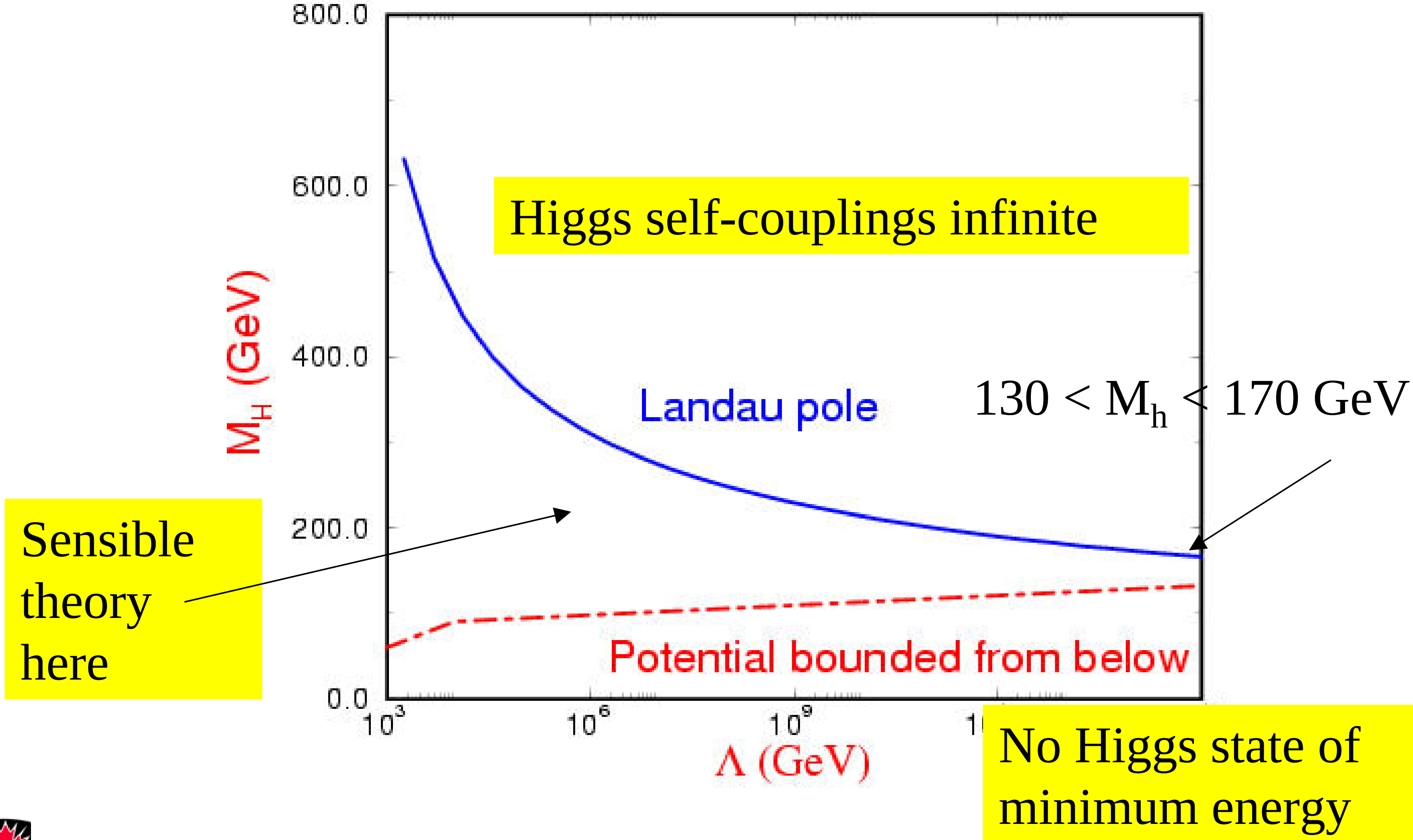
- Fundamental Higgs is not natural
- Quantum corrections to M_h are quadratically divergent

$$\delta M_h^2 \approx \Lambda^2$$

- So enormous fine-tuning needed to keep Higgs light

$$\delta M_h^2 \backslash M_h^2 \approx M_W^2 \backslash M_{pl}^2 \approx 10^{-32}$$

Higgs mass and scale of new physics correlated.....

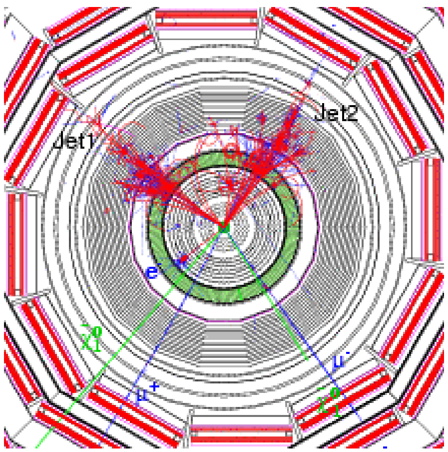


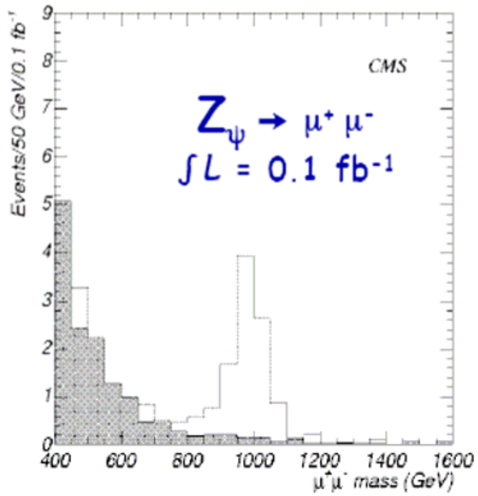
Why New Physics at TeV ?

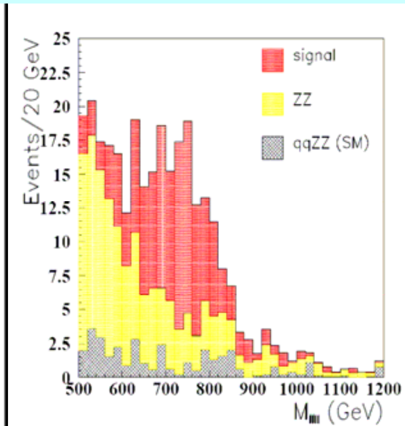
- Believe standard model is low energy effective theory
- Expect some form of new physics to exist beyond the SM
- Don't know what it is
- Need experiments to to show the way

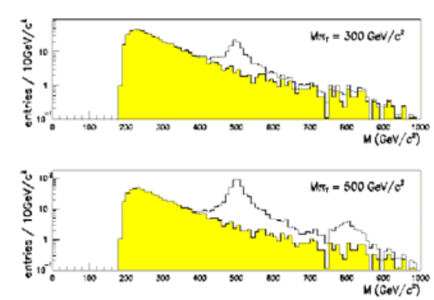
BSM Physics at the LHC

Supersymmetry? New Gauge Bosons? ZZ/WW resonances? Technicolor?

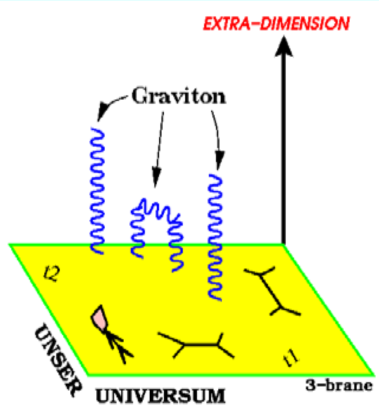


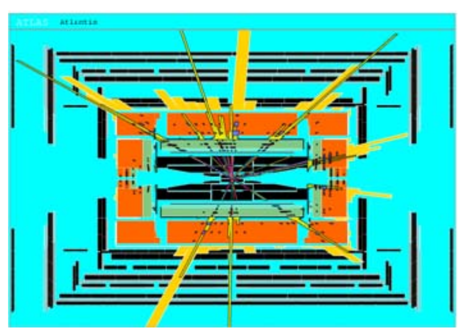


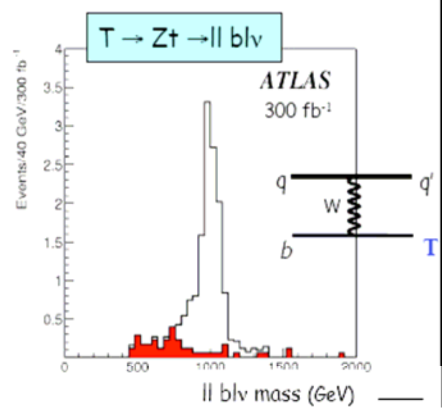




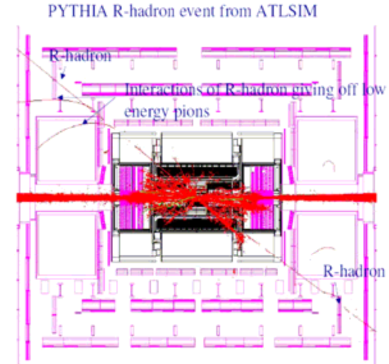
Extra Dimensions? Black Holes??? Little Higgs? Split Susy?







PYTHIA R-hadron event from ATLSIM



Supersymmetry is one solution

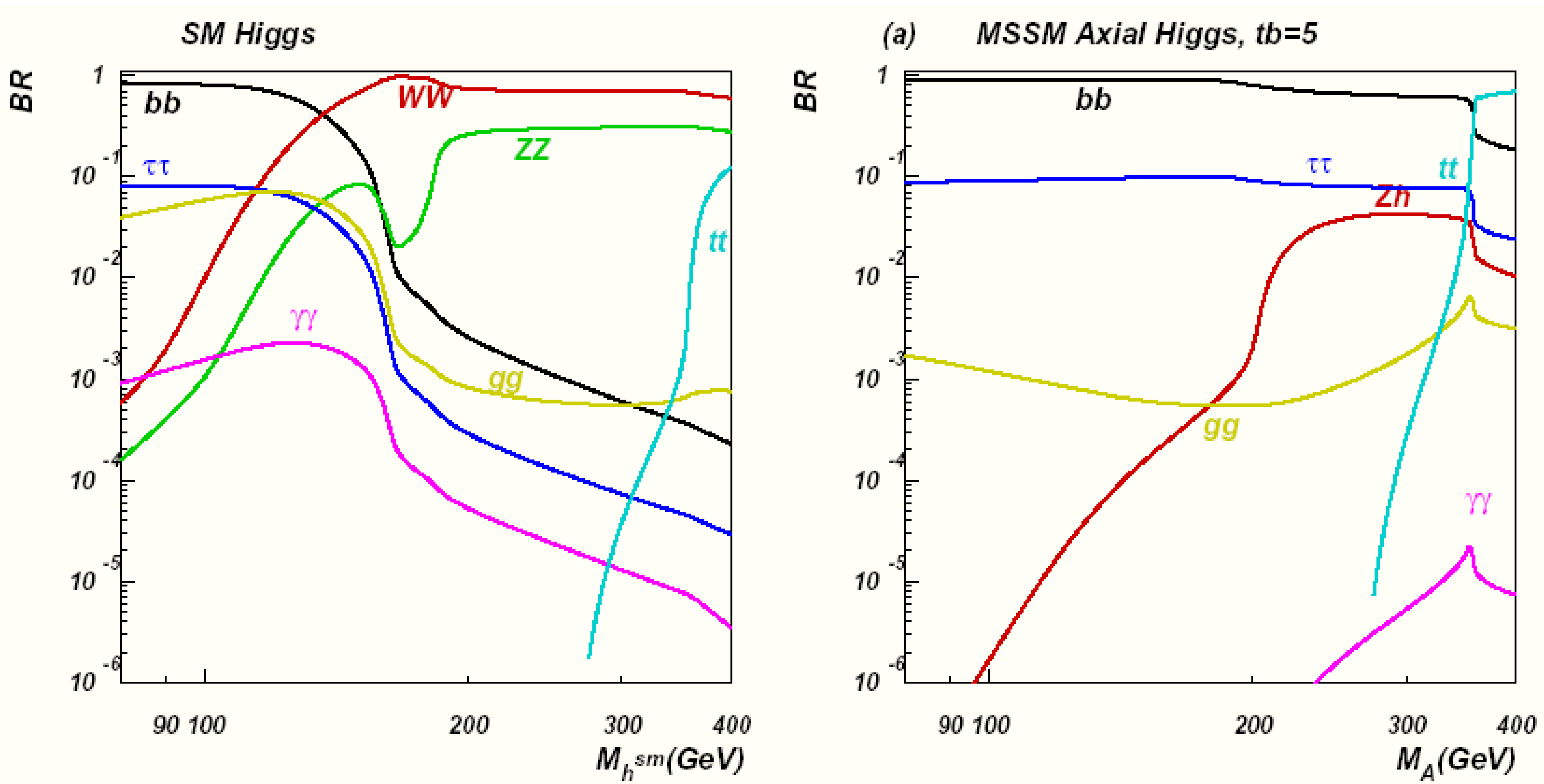
- Provides cancellation of quadratic divergences
- Unification of gauge couplings

- Each ordinary fermion (boson)
  is paired with a new boson (fermion)

- Two Higgs doublets
  - 8 degrees of freedom
    - 3 give W and Z mass
    - Two neutral CP even states: h, H
    - One neutral CP odd state: A
    - Two charged states: $H^{+/-}$

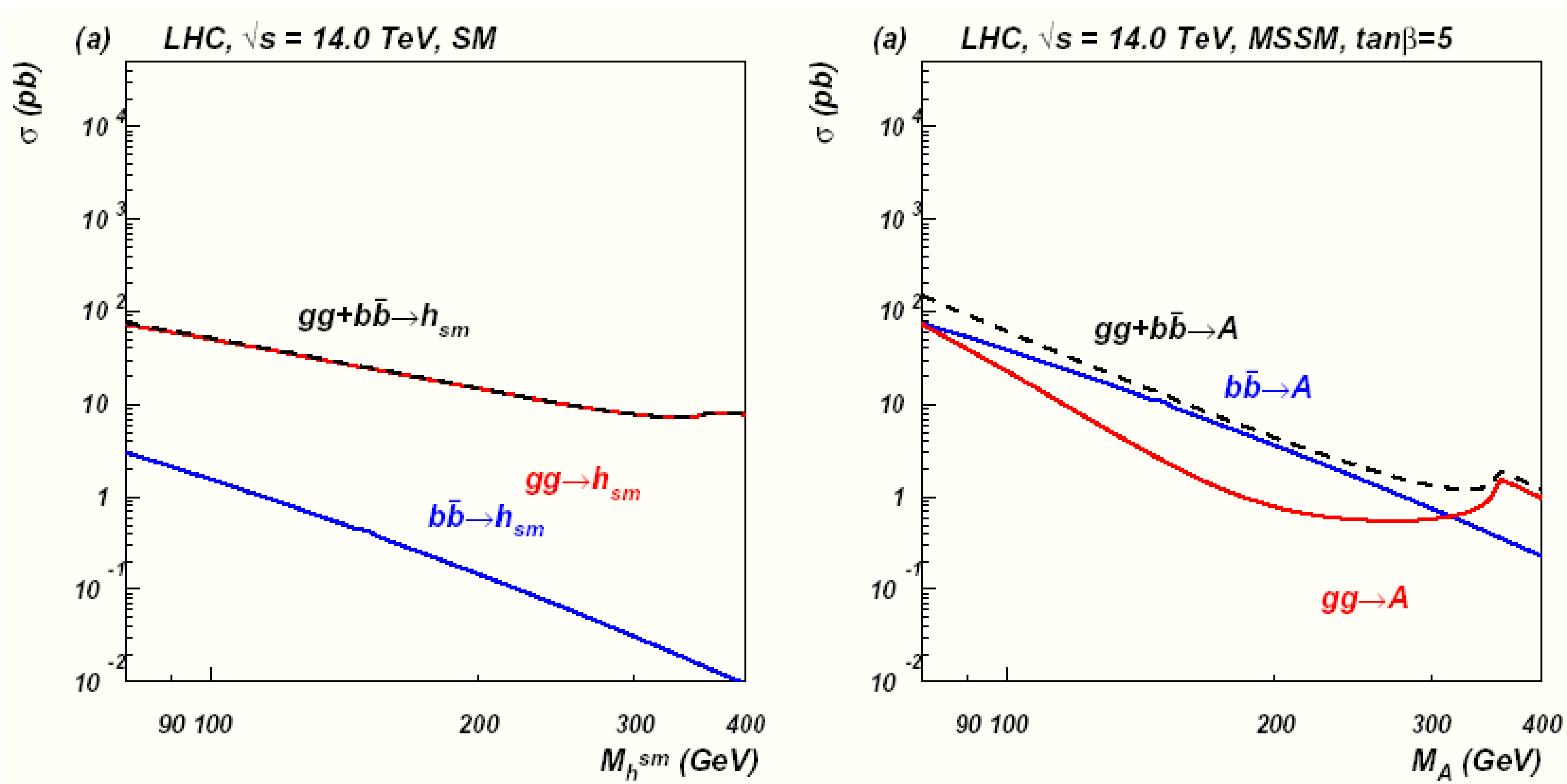
Alterations to SM couplings

Alterations of couplings changes widths and BR's

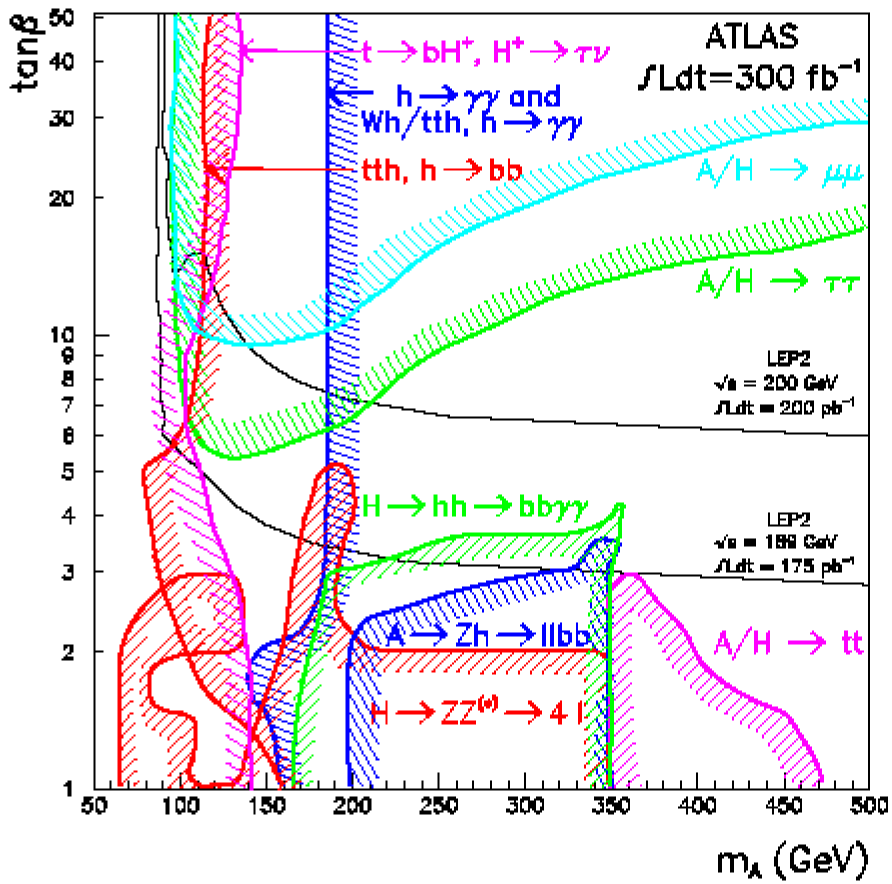


Sensitive to tanβ

•B-quark loop enhanced
•Enhanced bottom-Higgs couplings makes bb->H significant



SUSY Search



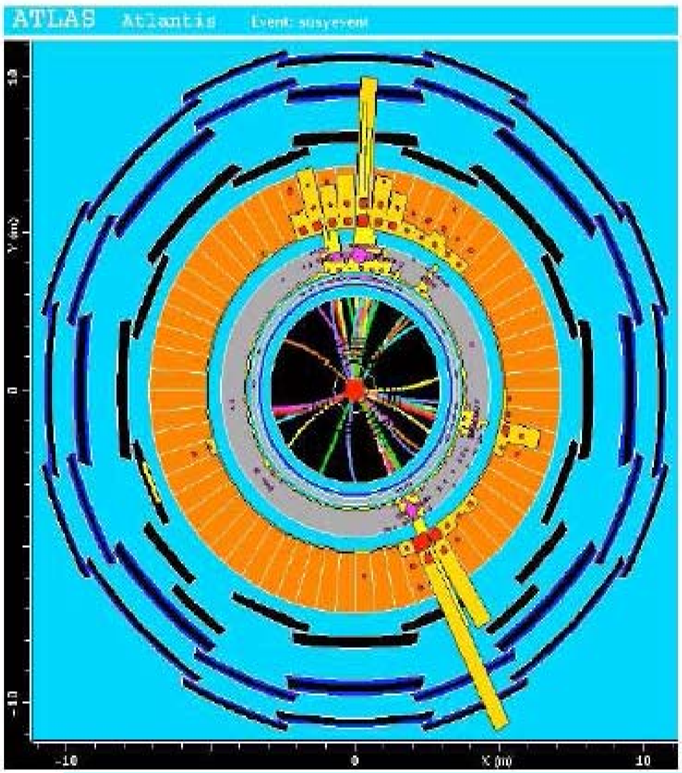
ATLAS
∫Ldt=300 fb⁻¹
t → bH⁺, H⁺ → τν
h → γγ and
Wh/tth, h → γγ
tth, h → bb
A/H → μμ
A/H → ττ
LEP2
√s = 200 GeV
∫Ldt = 200 pb⁻¹
H → hh → bbγγ
LEP2
√s = 189 GeV
∫Ldt = 175 pb⁻¹
A → Zh → llbb
A/H → tt
H → ZZ(*) → 4 l
tanβ
m_A (GeV)

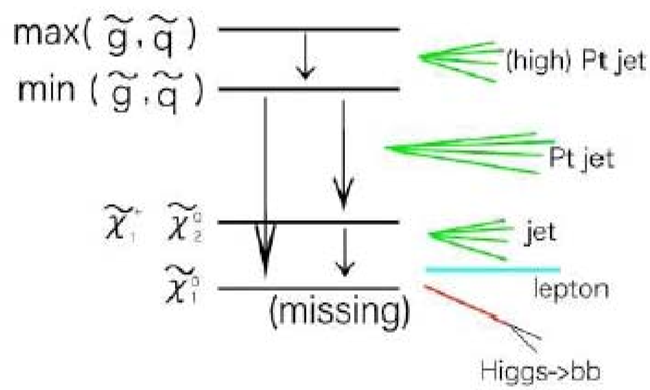
Supersymm

SUSY could be at the rendez-vous very early on!

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

$10 fb^{-1}$





event topologies of SUSY

multi leptons

$\not{E}_T$ + High P_T jets + b-jets

τ-jets

Therefore:
SUSY one of the priorities of the "search" program

Main signal: lots of activity (jets, leptons, taus, missing E_T)
Needs however good understanding of the detector & SM processes!!

Note: establishing that the new signal is SUSY will be more difficult!

Supersymm

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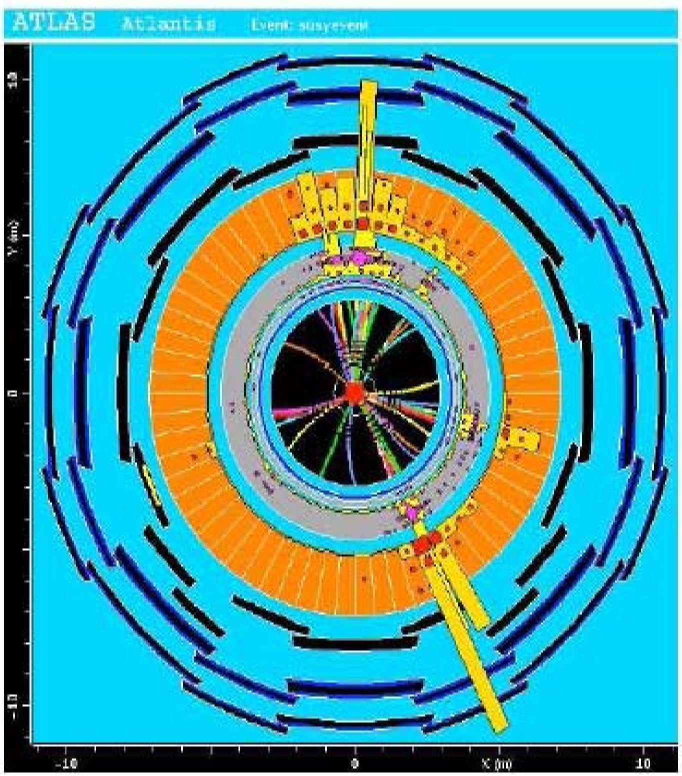
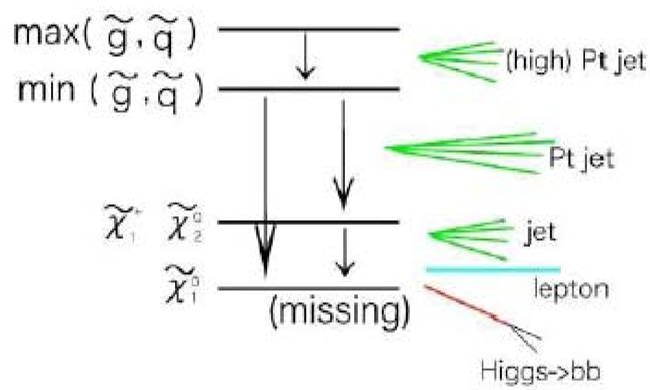




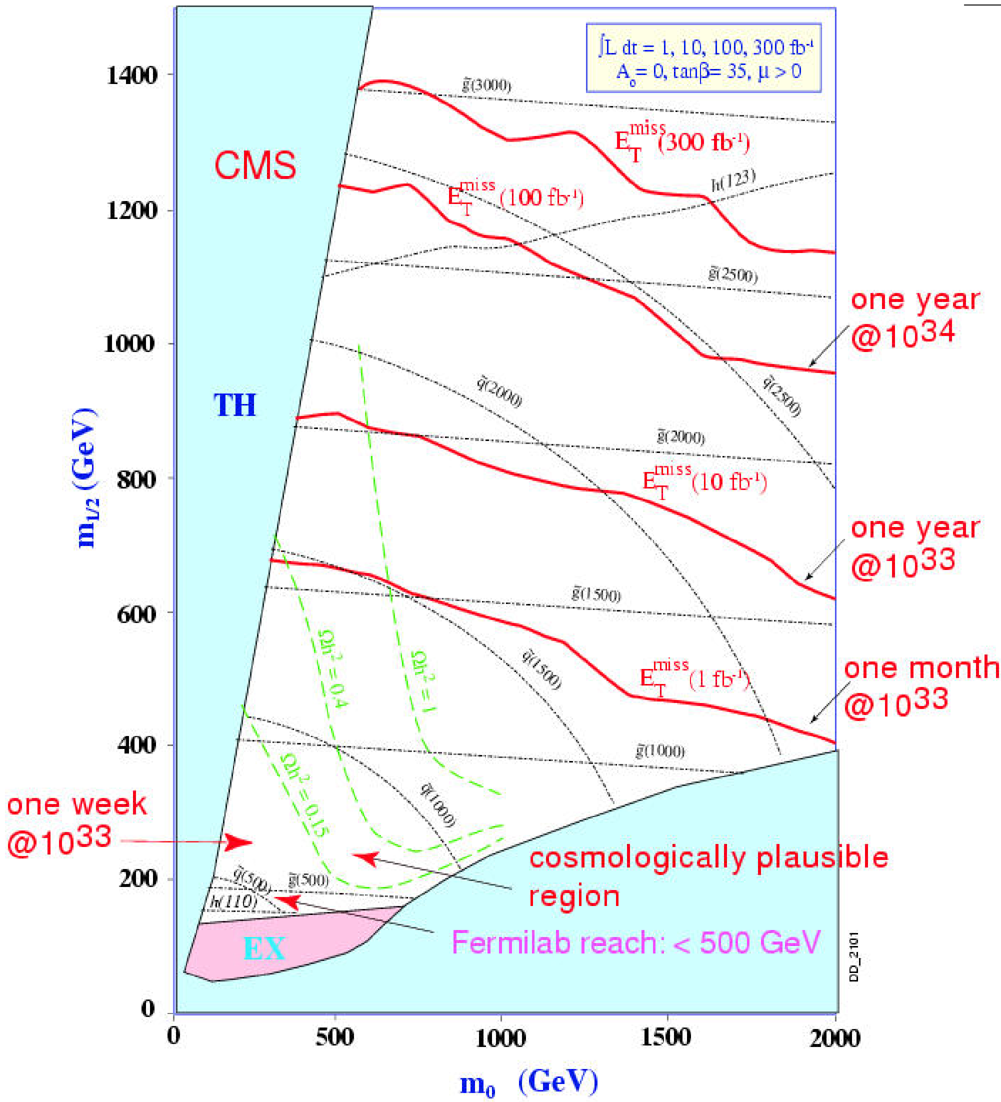
event topologies of SUSY

multi leptons
$\not{E}_T$ + High P_T jets + b-jets
τ-jets

Main signal: lots of activity (jets, leptons, taus, missing E_T)

In many cases: evidence for new physics will be very prominent

LHC/Tevatron will find SUSY



Catania, CMS

Catania 18

Discovery of many SUSY particles is straightforward

Untangling spectrum is difficult

⇒ all particles produced together

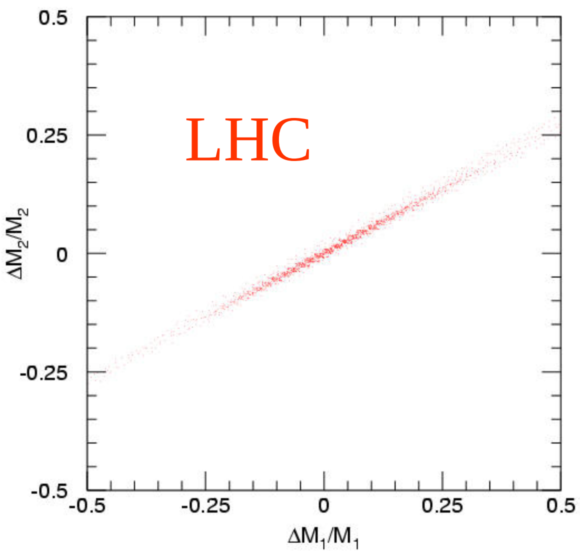
SUSY mass differences from complicated decay chains;eg

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^+ l^- q$$

$M_{\chi 0}$ limits extraction of other masses

LHC & LC improves SUSY mass resolution

- Lightest SUSY particle mass constrained at LHC at 10% level



Bachacou, Hinchliffe, Paige, hep-ph/9907518

⇒LC input improves accuracy significantly

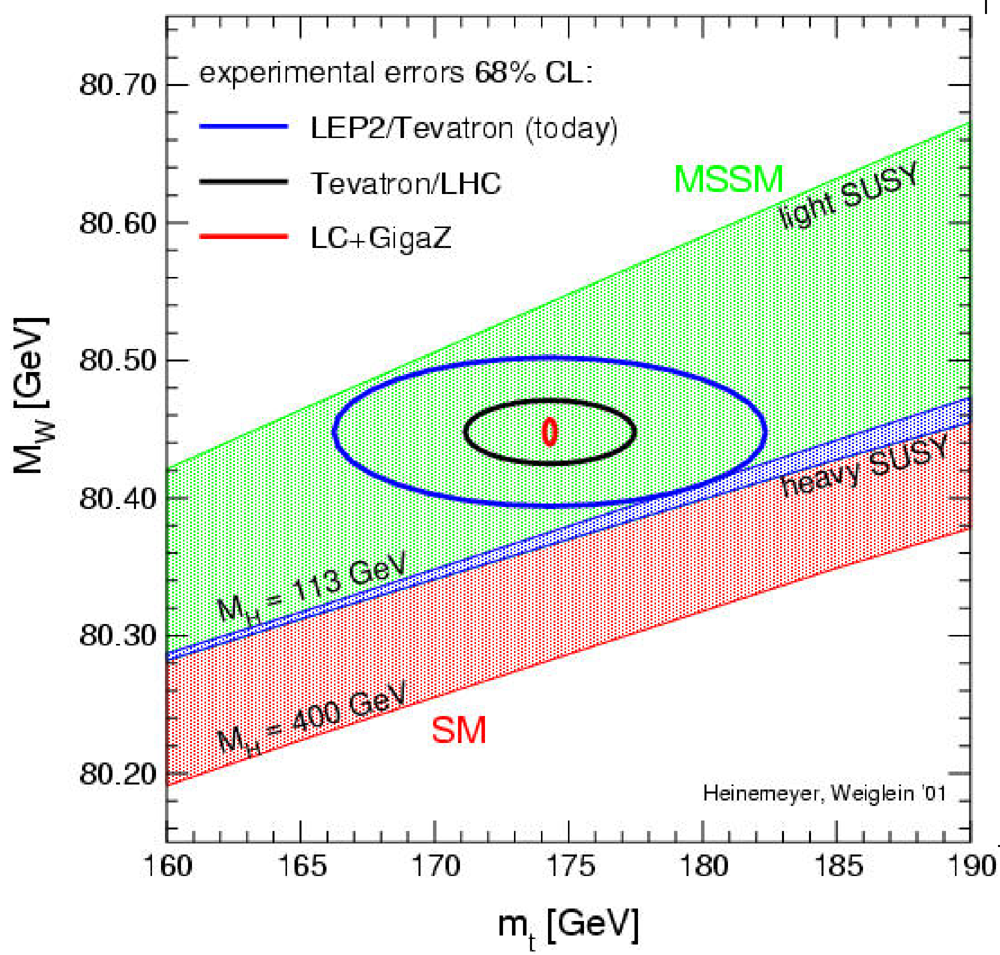
⇒Precision measurements tell us about underlying theory at Planck scale

- Take Lightest SUSY particle mass as input from Linear Collider

(GeV)	LHC	LHC+ LC(.2%)	LHC+ LC (1%)
$\Delta m(\tilde{\chi}_1^0)$	9.2	.2	1
$\Delta m(\tilde{l}_R)$	9.2	.5	1
$\Delta m(\tilde{\chi}_2^0)$	9.0	.3	1
$\Delta m(\tilde{b}_1)$	23	17	17
$\Delta m(\tilde{q}_L)$	15	5	5

Weiglein, LHC/LC Study

Light SUSY consistent with Precision Measurements



- SUSY predicts light Higgs

$$M_h^{SUSY} < 130\,GeV$$

- SUSY predicts 5 scalars

$$h^0, H^0, A^0, H^\pm$$

- For $M_A \rightarrow \infty$, SUSY Higgs sector looks like SM

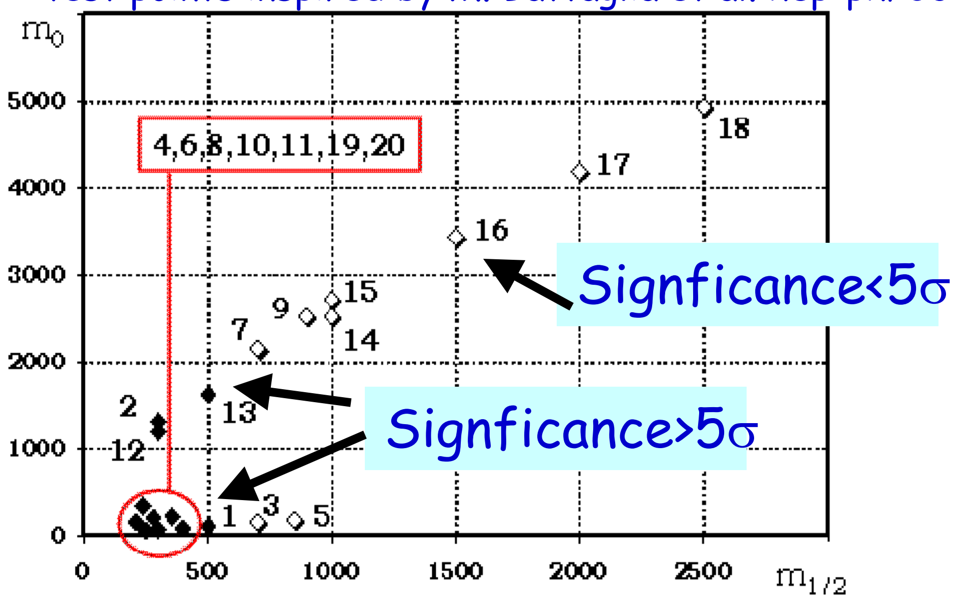
Supersymmetry: in…

$\tilde{\chi}_1^0 \nu_\mu$
$\tilde{\nu}_{\mu L} \mu^+$
$\tilde{\chi}_1^+ d$
$pp \rightarrow \tilde{g}\tilde{u}_L + X$
$\tilde{t}_1 t$
$\tilde{\chi}_1^+ b$
$\tilde{\nu}_{\mu L} \mu^+$
$\tilde{\chi}_1^0 \nu_\mu$

Cuts:
2 same sign isolated muons, 1 or 2 jets and missing E_T

set	miss. E_T, GeV	E_{T,jet_1}, GeV	E_{T,jet_3}, GeV	P_{T,μ_1}, GeV	P_{T,μ_2}, GeV
1	> 200	> 0	> 170	> 20	> 10
2	> 100	> 300	> 100	> 10	> 10

test points inspired by M. Battaglia et al. hep-ph/0306



Study signal excess expected over SM background

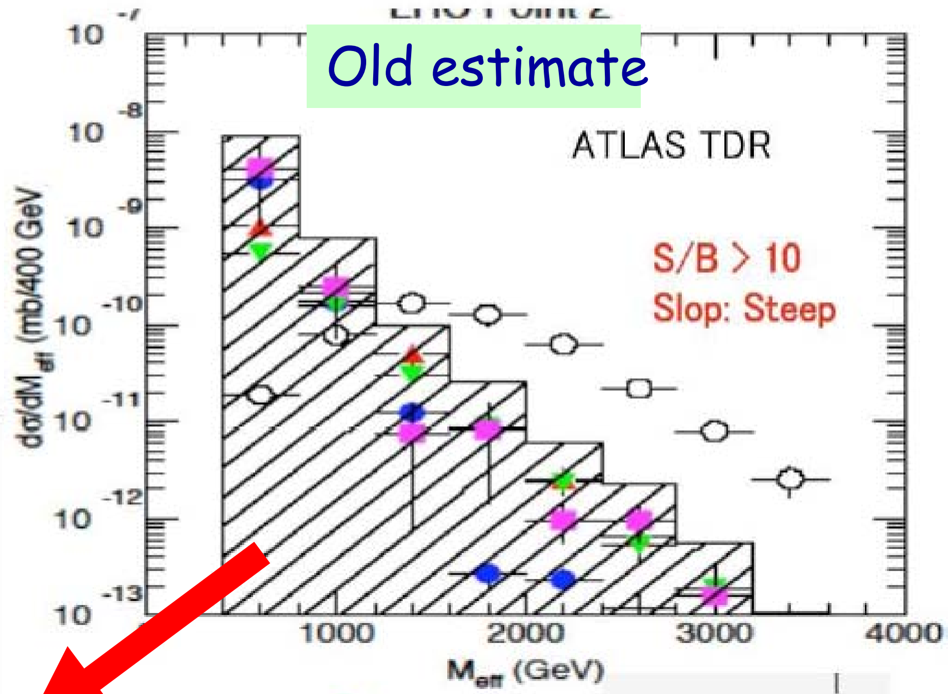
m_0 Universal scalar mass at GUT scale
$m_{1/2}$ Universal gaugino mass at GUT scale

A 5σ discovery is possible for $m_{1/2}$ < 650 GeV with 10 fb

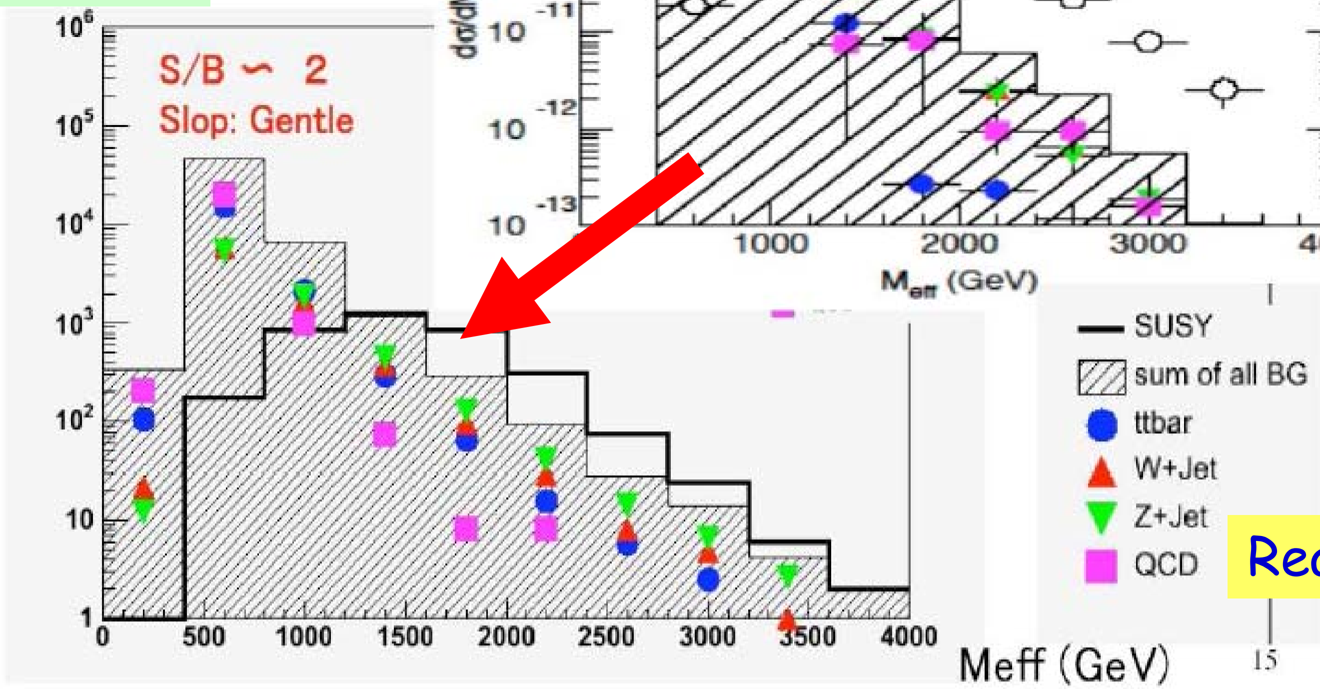
Old PYTHIA BG
New ALPGEN BG

ME vs PS

Old estimate



New estimate...



All jets
Final state

Reach lower?

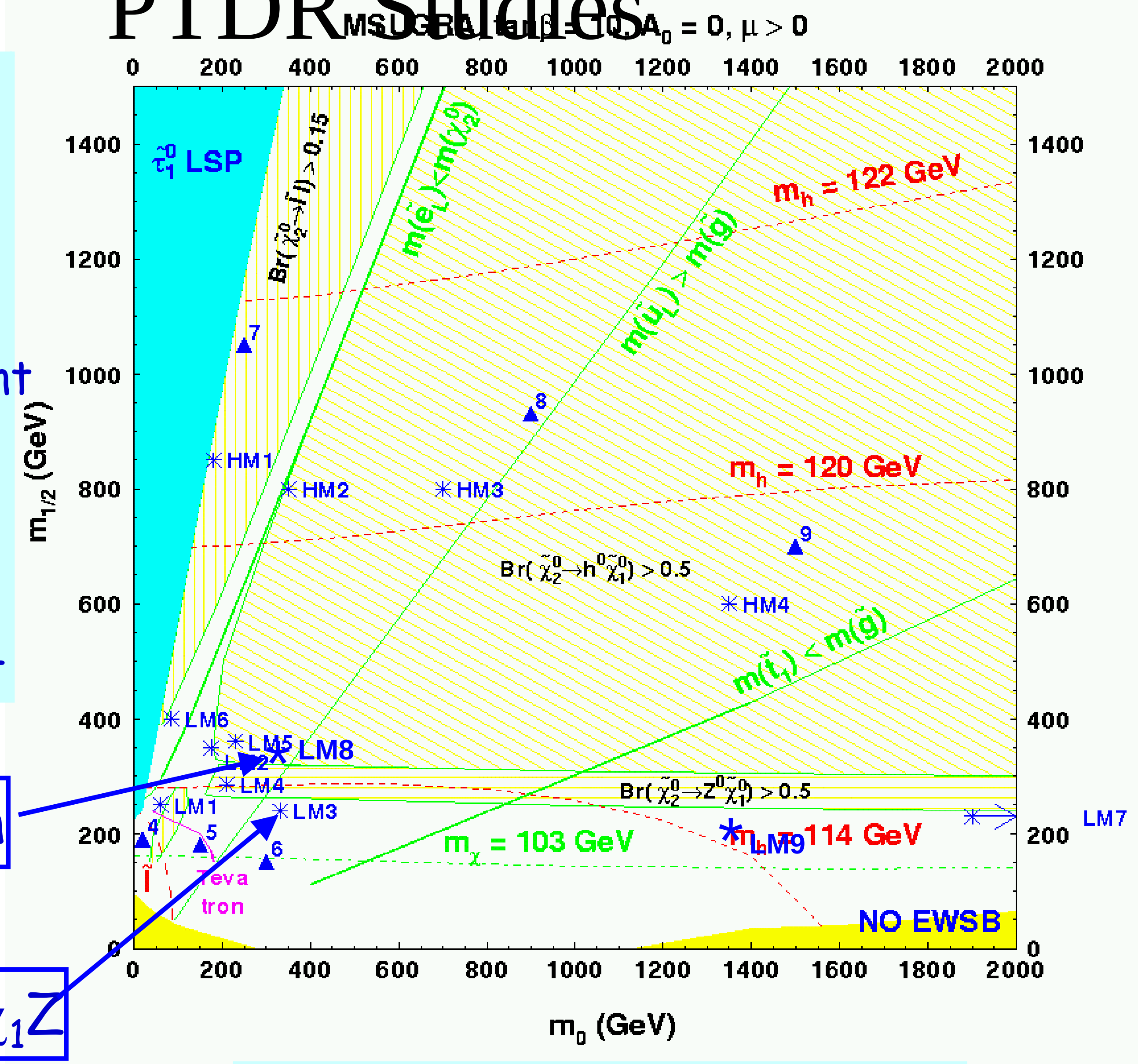
$$M_{\text{eff}} = \Sigma_i |p_{T(i)}| + \not{E}_T$$

SUSY Benchmark Points for PTDR Studies

CMS: preparation for Physics TDR (2006)

Important: different topologies/decay modes, i.e. on different signatures

Selection of 13 Points
Low mass LM1→LM9
High mass HM1→HM4



$\chi_2 \rightarrow \chi_1 h$

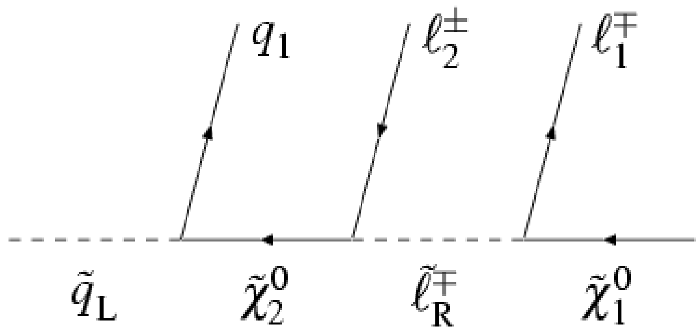
$\chi_2 \rightarrow \chi_1 Z$

Not on CMSSM WMAP lines!

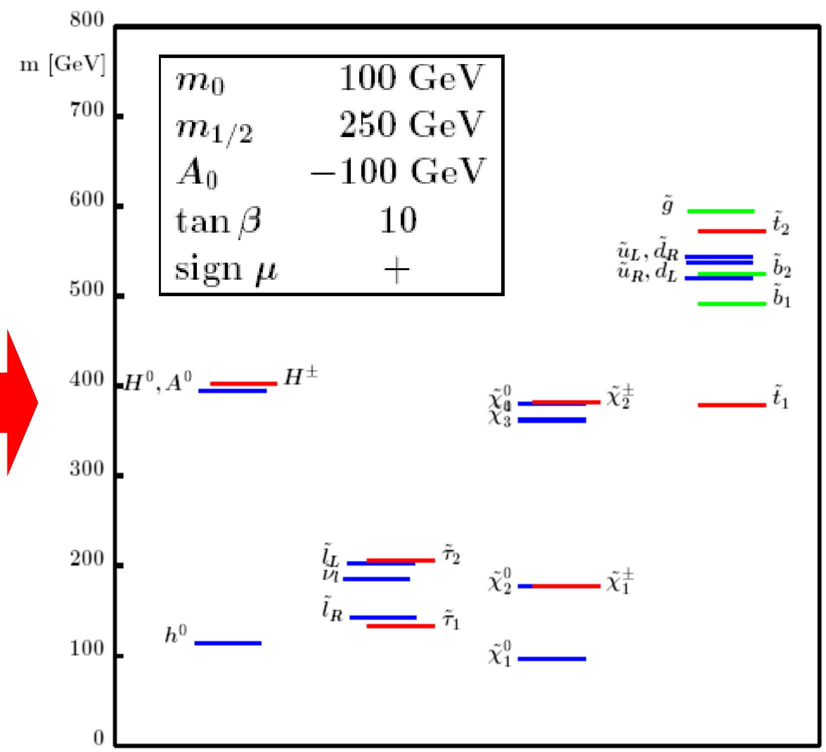
⇒Details in benchmark talk on Monday

SUSY studies: Benchmark points

LHC: complicated by decay chains for squarks and gluons



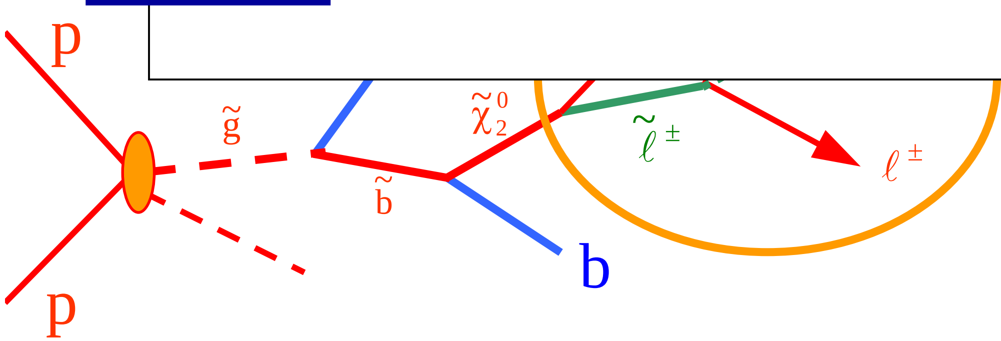
Examples worked out for SPS1a (point B) in ATLAS/CMS



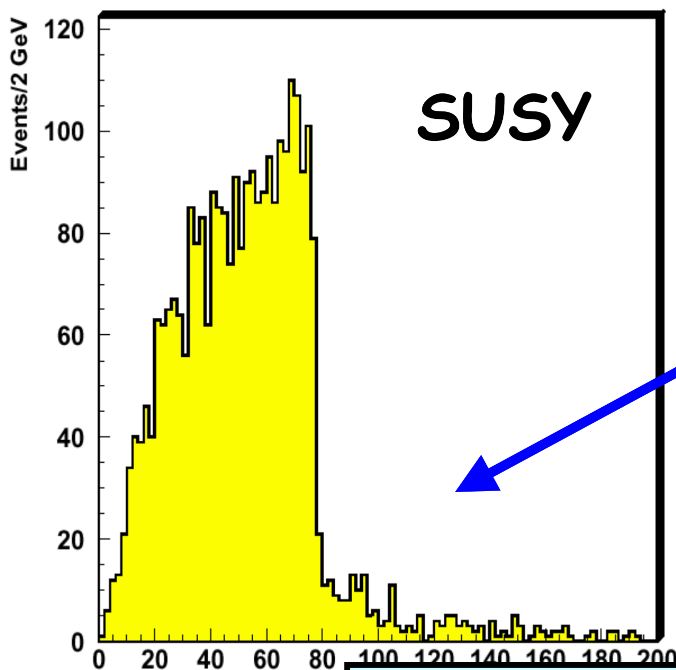
LHC will see all squarks, H,A and may see most gauginos

Sparticle Reconstruction

Example



Problem χ_1^0 measurement!
It escapes detection like a neutrino!
Use kinematic formulae…



$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}_1^0})}}{M_{\tilde{\ell}}}$$

$M(e^+e^-) + M(\mu^+\mu^-)$

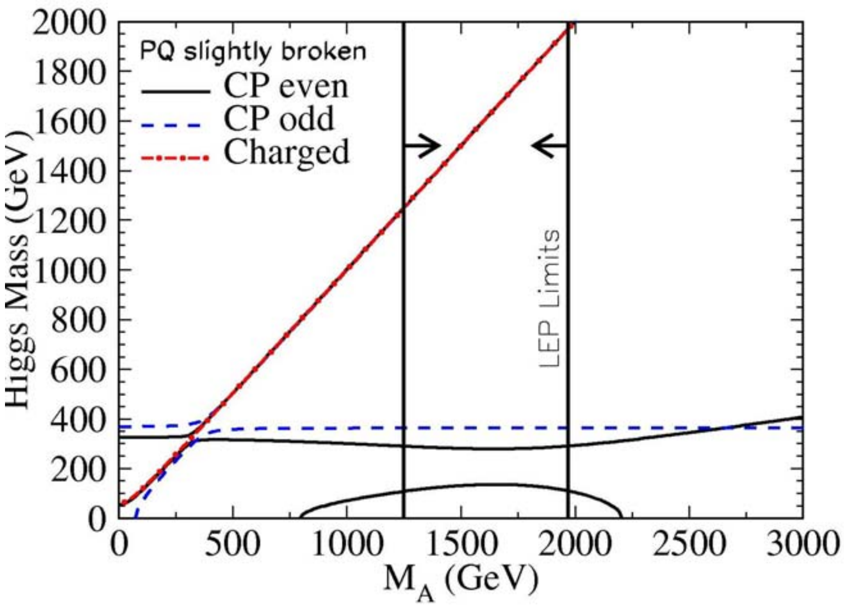
Don't be afraid of endpoints
(it's kinematics) !

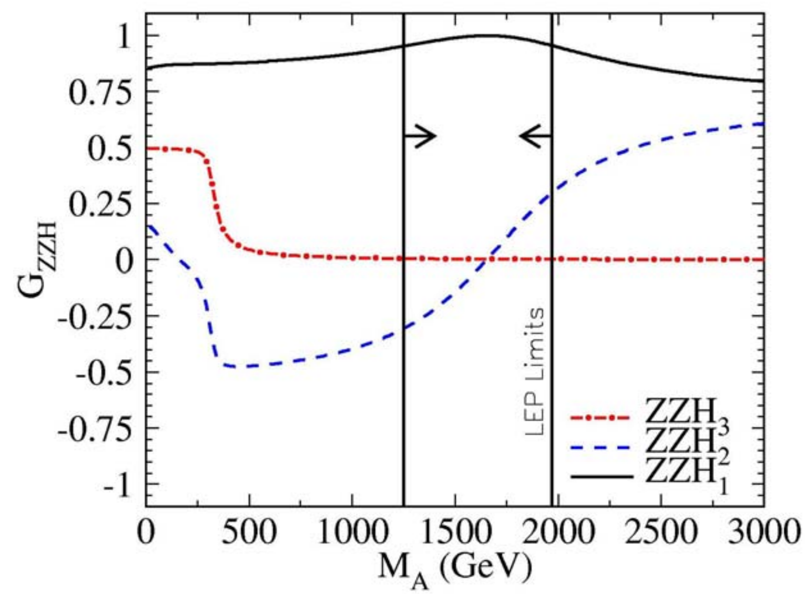
NMSSM Higgs Mass Spectrum

ZZH couplings suppressed

Typical Scenario:

(Evade LEP bounds on M_H)





- Spectrum of light Higgs: 2 light scalars, 1 light pseudoscalar

- Heavy, roughly degenerate H_3, A_2, $H^\pm$

New Decays:

$A_1 \rightarrow H_1 H_1$, $H_2 \rightarrow A_1 A_1$

Very different from MSSM!

Ellwanger, Gunion, Hugonie, hep-ph/0503203

Miller, Nevzorov, Zerwas, hep-ph/0304049

Choi, Miller, Zerwas, hep-ph/0407209

Models of New Physics

- Little Higgs
- Extra dimensions (ADD, RS, UED…)
- Higgsless Model
- Extended gauge sectors (S. Nandi)
  - Extra U(1) factors: $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\psi$
  - Left-Right symmetric model: $SU(2)_L \times SU(2)_R \times U(1)$
- Technicolour
- Topcolour
- Non-Commutative theories

Many, many models

What do these models have in common?

How do we distinguish them?

Alternative Models of EWSB:

Dynamical Symmetry Breaking (Technicolour)

- Scalars are composite
- New asymptotically free strong interaction
- Resulting condensate breaks EW symmetry
- Additional Nambu-Goldstone bosons: "Technipions"

Little Hierarchy Problem
Problem #2 with SM light Higgs Picture

- Need new physics at 1 TeV to get light Higgs
- Much possible new physics is excluded at this scale
  - Look at possible dimension 6 operators
    - Many more operators than shown here
  - Limits depend on what symmetry is violated

New operators	Experimental limits
$\frac{(\bar{d}s)(\bar{d}s)}{\Lambda^2}$	$\Lambda > 1000\ TeV$
$\frac{m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)}{\Lambda^2}$	$\Lambda > 50\ TeV$
$\frac{(h^+ D_\mu h)^2}{\Lambda^2}$	$\Lambda > 5\ TeV$
$\frac{(D^2 h^+ D^2 h}{\Lambda^2}$	$\Lambda > 5\ TeV$

New Physics must be at scale $\Lambda > 5$ TeV

Schmaltz, hep-ph/0502182

The Higgs as a Goldstone Boson

- Little Higgs models
- Basic idea:
  - Break continuous global symmetry spontaneously
  - Higgs is Goldstone boson of broken symmetry
  - Many variants
- Littlest Higgs model: non-linear σ model based on SU(5)/SO(5)
  - Global SU(5) $\rightarrow$ Global SO(5) with $<\Sigma>$ $\Sigma = e^{2i\Pi/f}\langle\Sigma\rangle$
  - Gauged $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$

    $\rightarrow SU(2) \times U(1)_{SM}$

General feature: Extra gauge bosons

Littlest Higgs Model, continued

- Quadratic contributions to Higgs mass cancelled at one-loop by new states
  - $W, Z, B \leftrightarrow W_H, Z_H, A_H$
  - $t \leftrightarrow T$
  - $H \leftrightarrow \phi$
- Cancellation between states with same spin statistics
  – Naturalness requires f ~ few TeV
- Symmetries only allow Higgs mass at 2-loops
  – $\delta M_H^2 \sim (g^2/16\pi^2)^2 \Lambda^2$
  – Allows scale to be raised to Λ ~10 TeV

Solving the Little Hierarchy Problem with Little Higgs Models

←Weak Coupling | Strong Coupling→

$\Lambda_{weak} = \frac{g^2 f}{4\pi}$ $gf = 1-3\ TeV$ $\Lambda = 4\pi f$

Weak

10^3 GeV

Higgs gets mass at 2-loops

Quadratic divergences cancelled by new states

10 TeV

Higgs is pseudo Goldstone boson from global symmetry breaking at Λ

EW data limit new physics at TEV Scale

- Try to add new physics with dimension 6 operators

$$L \approx \sum \frac{c_i}{\Lambda^2} O_i$$

- Precision measurements already limit Λ > 5-10 TeV

$\bar{e}\gamma_\mu e \bar{l}\gamma^\mu l$	Λ > 4.5 – 6 TeV
$\bar{e}\gamma_\mu\gamma_5 e \bar{b}\gamma^\mu\gamma_5 b$	Λ > 3 – 4 TeV
$(H^+\tau^a H)W_{\mu\upsilon} B^{\mu\upsilon}$	Λ > 10 TeV

- Flavor violating couplings even more tightly constrained

"Little Hierarchy Problem"

Hard to get new physics at the TeV Scale

Giudice

I want to focus on predictions of the models; NOT the theoretical nitty gritty details

(Dimopolous)

So start with a rather superficial overview of some recent models

To sort out the models we need to elucidate and complete the TeV particle spectrum

Many types of new particles:

- Extra gauge bosons
- Vector resonances
- New fermions
- Extended Higgs sector
- Pseudo Goldstone bosons
- Leptoquarks…

Little Higgs

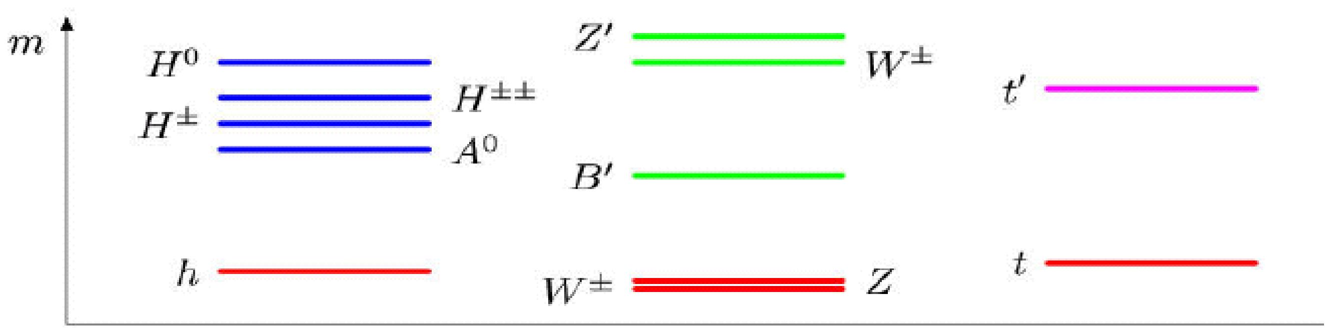
Arkani-Hamed et al hep-ph/0206021

- The little Higgs models are a new approach to stabilize the weak scale against radiative corrections

10 TeV — New Strong Dynamics
Global Symmetry

1 TeV — Symmetries Broken
Pseudo-Goldstone Scalars
New Gauge Bosons related to SU(2): $W_H^{\pm}$ Z_H B_H
New Heavy Top cancels quadratic divergences

100 GeV — Light Higgs
SM vector bosons & fermions



Parameters:
f~vev
s, s': GB mixing angles

Extra Dimensions

In most scenarios our 3-dimensional space is a 3-brane embedded in a D-dimensional spacetime

Basic signal is KK tower of states corresponding to a particle propagating in the higher dimensional Space-time

The details depend on geometry of extra dimensions

Many variations

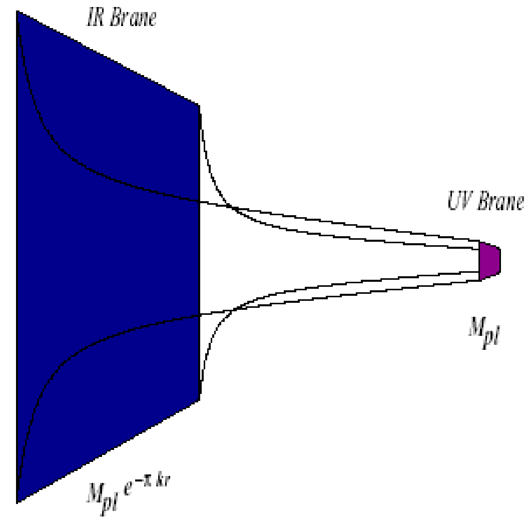
ADD Type of Extra Dimensions

(Arkani-Hamed Dimopoulos Dvali)

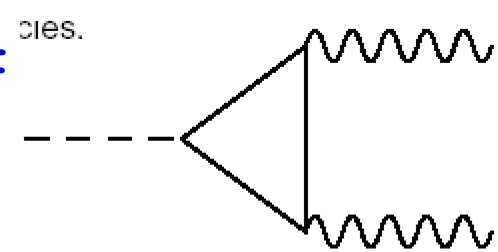
- Have a KK tower of graviton states in 4D which behaves like a continuous spectrum
- Graviton tower exchange effective operators: $i\frac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$
- Leads to deviations in $e^+e^- \to f\bar{f}$ dependent on λ and s/M_H
- Also predicts graviscalars and gravitensors propagating in extra dimensions
- Mixing of graviscalar with Higgs leads to significant invisible width of Higgs

Randall Sundrum Model

- 2 3+1 dimensional branes separated by a 5th dimension
- Predicts existence of the ***radion*** which corresponds to fluctuations in the size of the extra dimension



- Radion couplings are very similar to SM Higgs except for anomalous couplings to gluon and photon pairs
  - Radion can mix with the Higgs boson
  - Results in changes in the Higgs BR's from SM predictions
- Also expect large couplings for KK states of
  - Expect supression of $h \to WW,\ ZZ$
  - Enhancement of $h \to gg,\ \gamma\gamma$

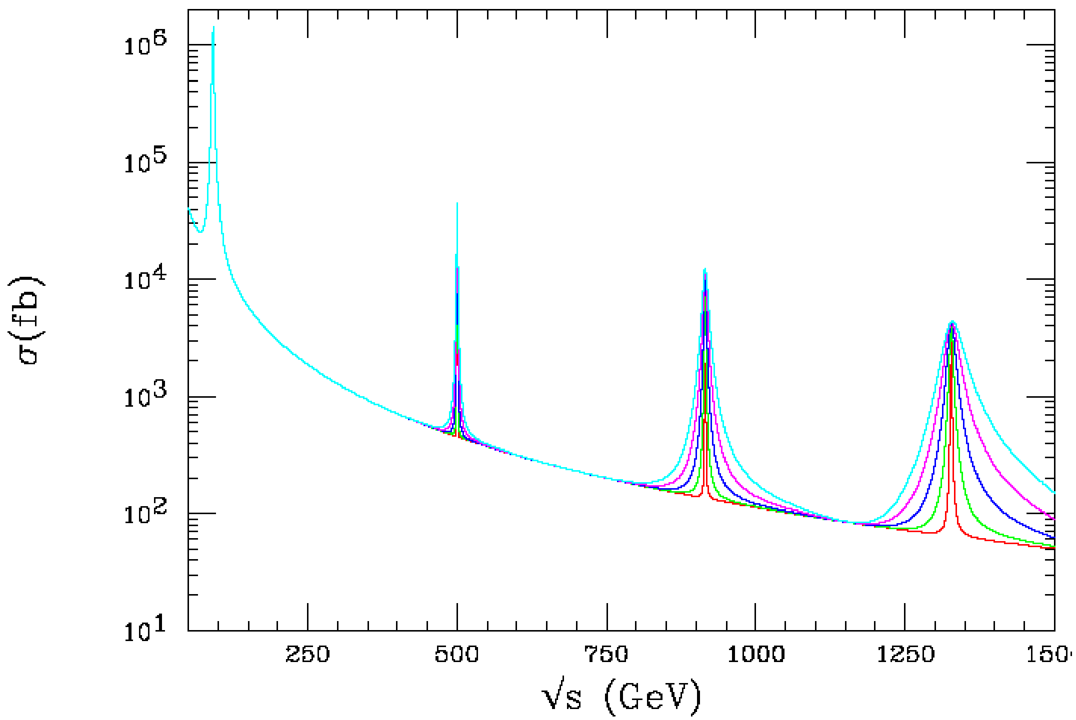


Randall-Sundrum Gravitons:

- The spectrum of the graviton KK states is discrete and unevenly spaced

- Expect production of TeV scale graviton resonances in 2-fermon channels

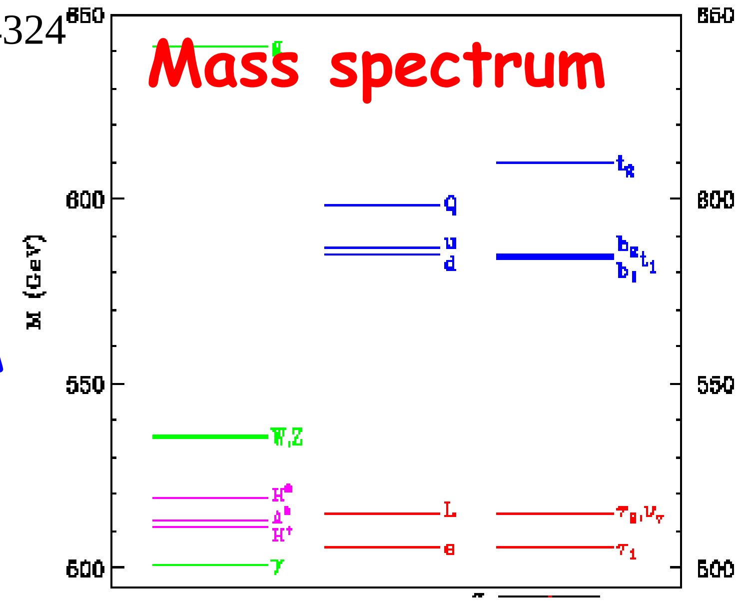
Has 2 parameters;
- mass of the first KK state
- coupling strength of the graviton (controls the width)

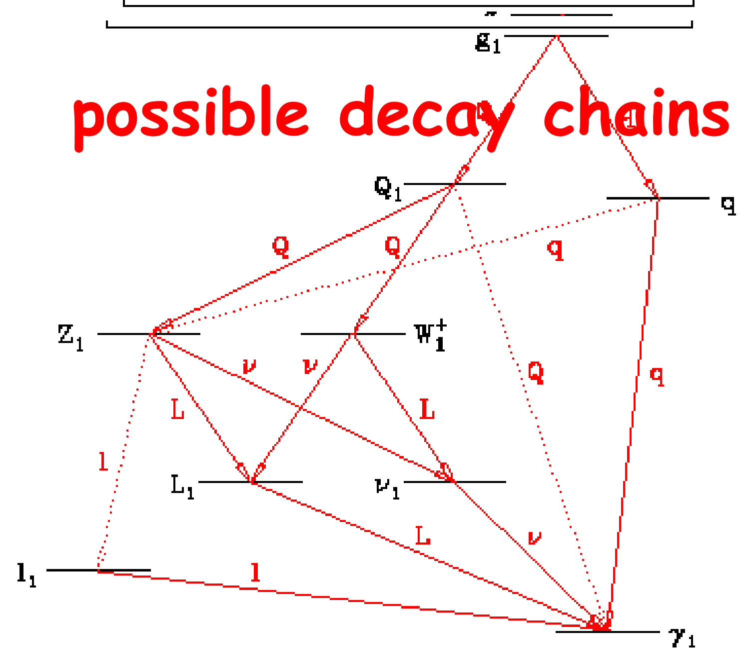


Universal Extra Dimensions

Appelquist, Cheng, Dobrescu, hep-ph/0012100
Cheng, Matchev, Schmaltz, hep-ph/0204324

- All SM particles propagate in the bulk
- KK towers for SM particles with spin quantum numbers identical to SM particles
- Spectrum resembles that of SUSY
- Have conservation of KK number at tree level leading to KK parity = $(-1)^n$
- Ensures that lightest KK partners are always pair produced
- So lightest KK particle is stable



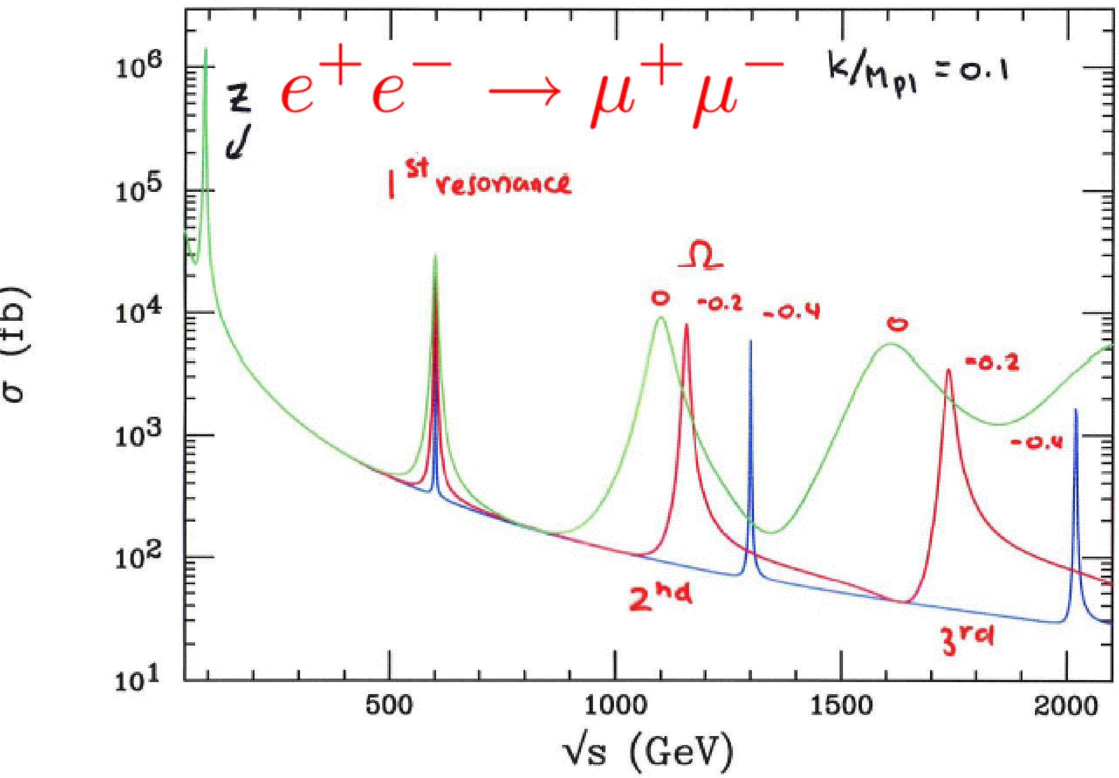


Higher Curvature TeV-scale Gravity

Rizzo [hep-ph/0503…]

- EH is at best an effective theory below M_*
- Terms from UV completion (strings?) may be important as we approach M_*

- Implications are:
  - KK mass shifts
  - New features in Black hole production



Summary of Model Predictions

Models Predict:

- Extra Higgs (doublets & triplets)
- Radions, Graviscalars
- Gravitons
- KK excitations of γ, Z, W …
- Extra gauge bosons

What do these models have in common?

- Almost all of these models have new s-channel structure at ~TeV scale
- Either from extended gauge bosons or new resonances

How do we distinguish the models?

Need to map out the low energy particle content

New Vector Bosons

Appear in many models:

- Z′ in string inspired models
- Z′, W′ in extended gauge sectors
- Z_R, W_R in left-right symmetric models
- Z_{KK}, γ_{KK}, W_{KK}, in theories with extra dimensions
- Z_H, W_H in Little Higgs Models

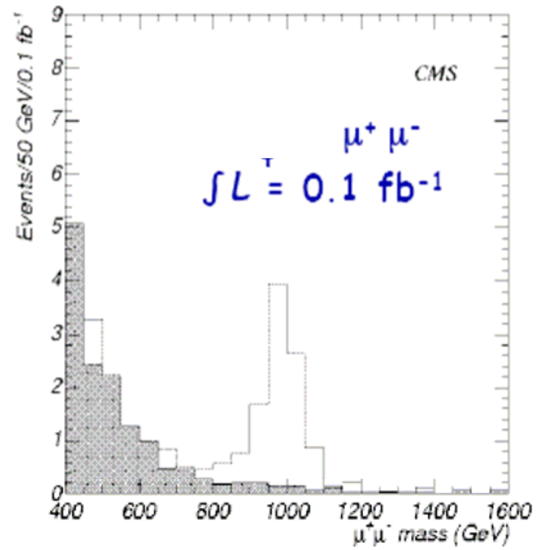
Also possible higher spin states:

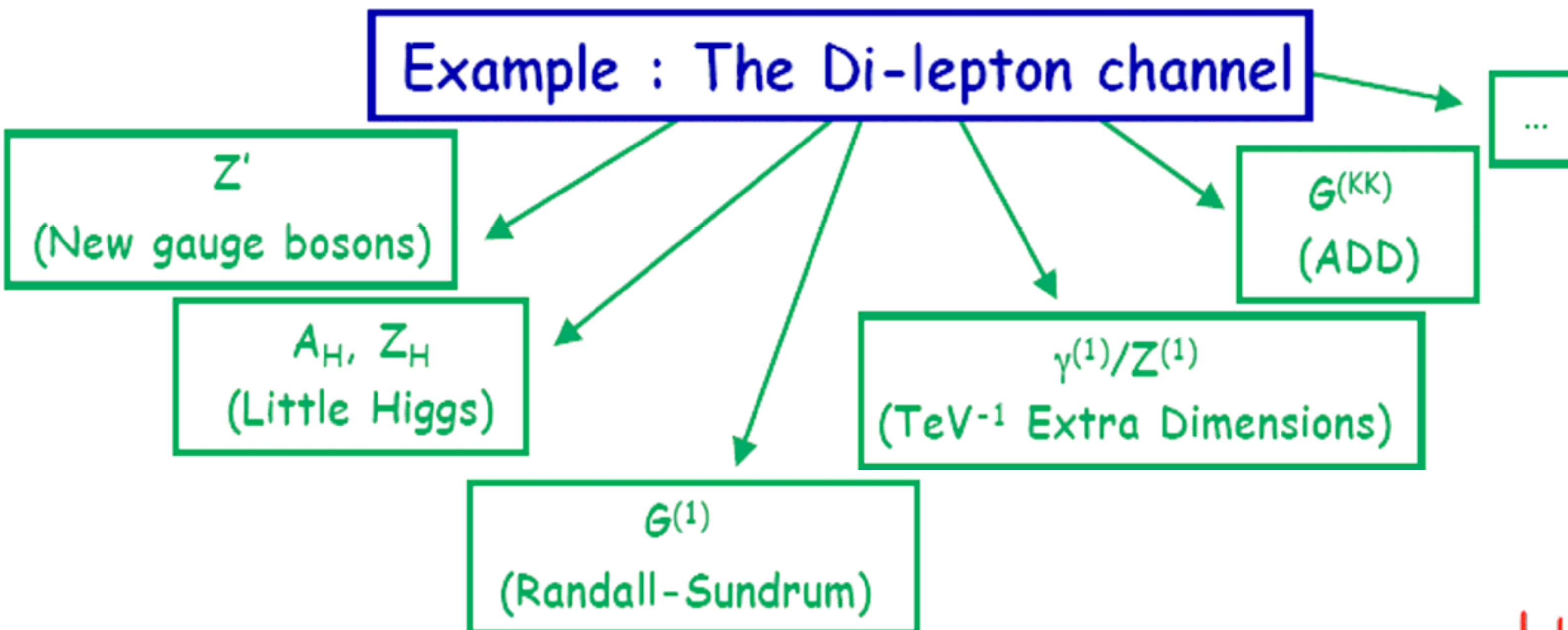
- Gravitons in theories with extra dimensions
- String resonances

Discovery of New Vector Bosons

Discovery of Dilepton Resonance

May be seen very early: first weeks

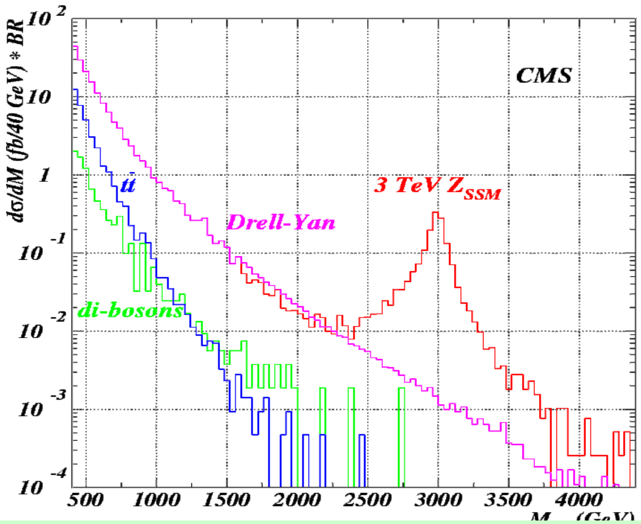




New Z' Gauge Bosons

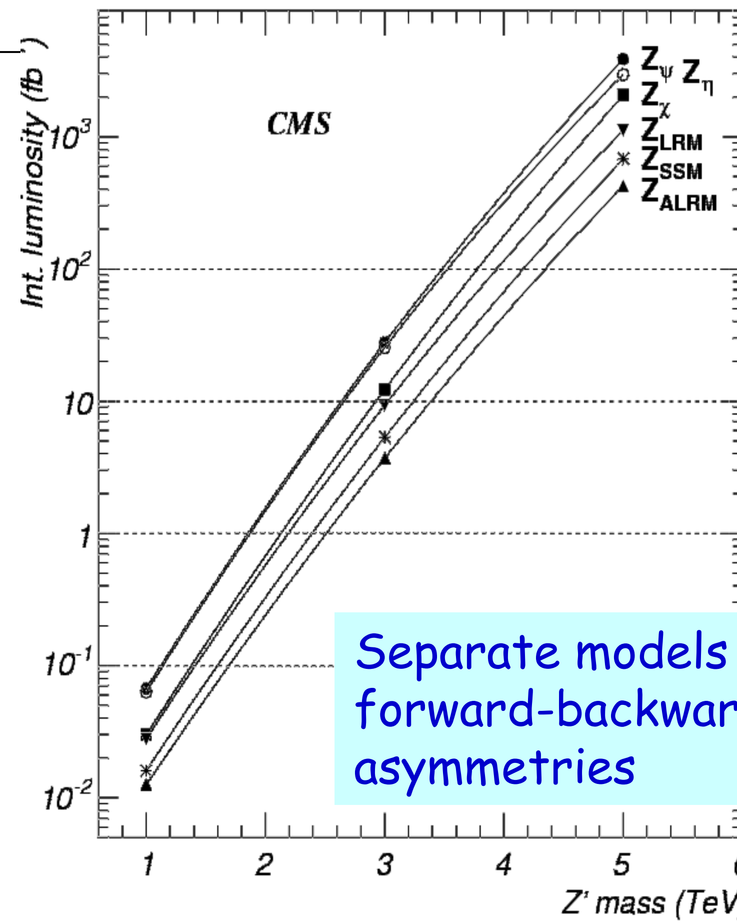
R. Cousins et al.

Z'→μμ production



Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

Z' → $\mu^+\mu^-$: 5σ significance curves



Separate models with forward-backward asymmetries

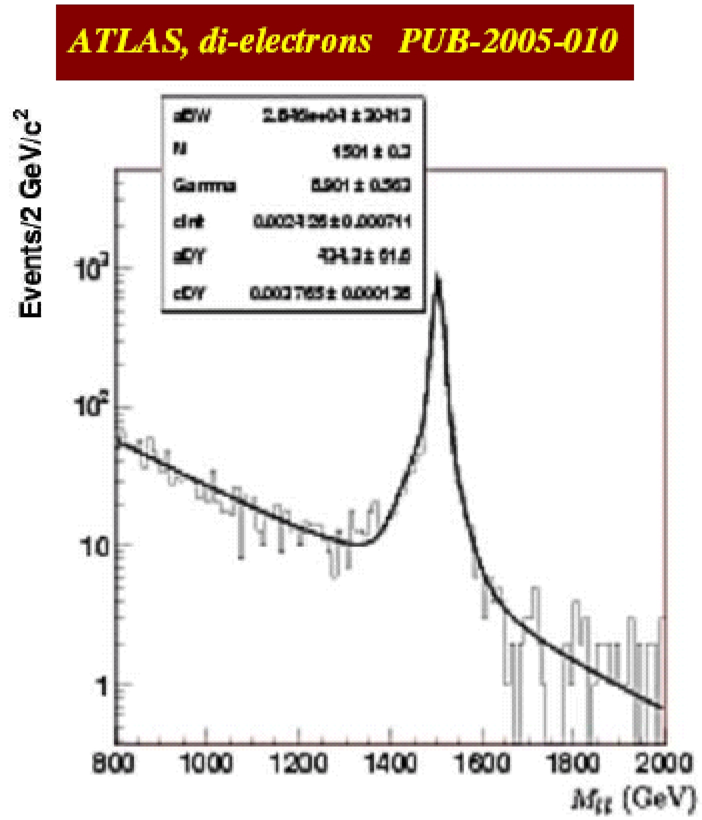
- Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible, beyond Tevatron run-
- High lumi 100 fb^{-1}: extend range to 3.4-4.3 TeV

Di-lepton Resonance: Search

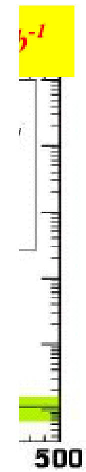
- Select 2 opposite sign high p_T isolated leptons
- Examine invariant mass distribution
- Worry about SM backgrounds

- If you find a peak:
  - quantify its significance
  - Measure its σ x BR

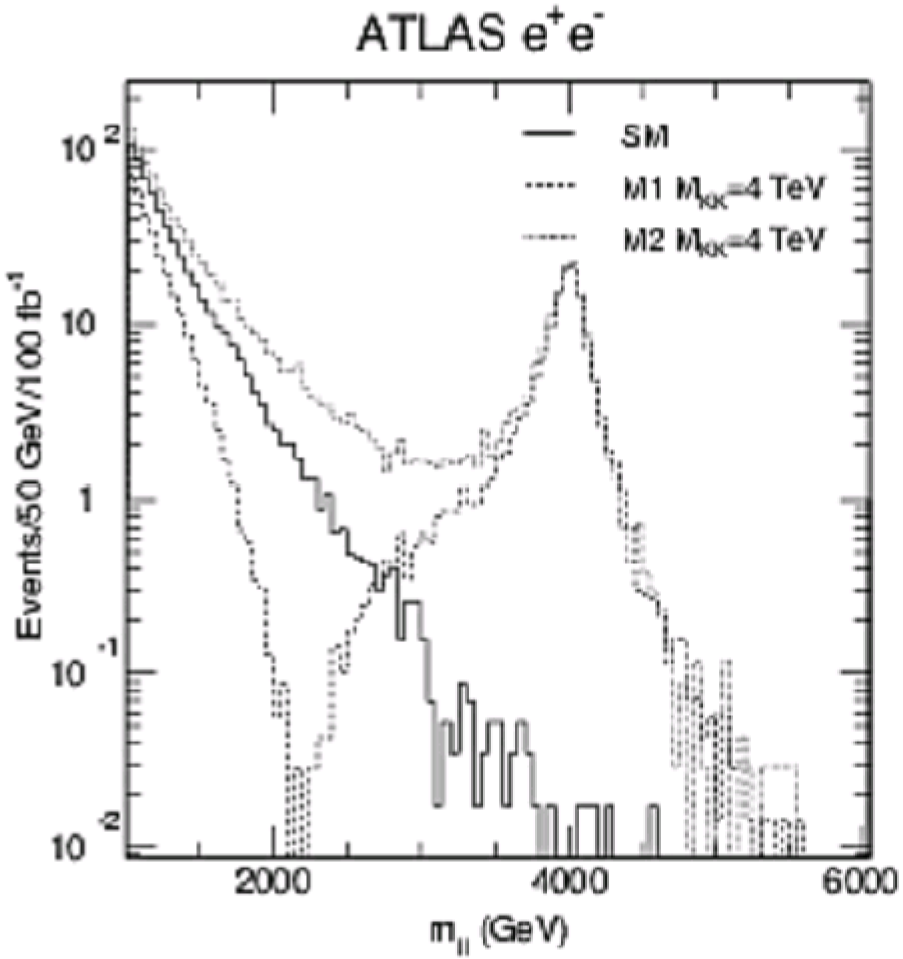
- If you don't:
  - Derive upper limit on σ x BR
  - Constrain models



(a) Z'_η model - $M = 1.5$ TeV



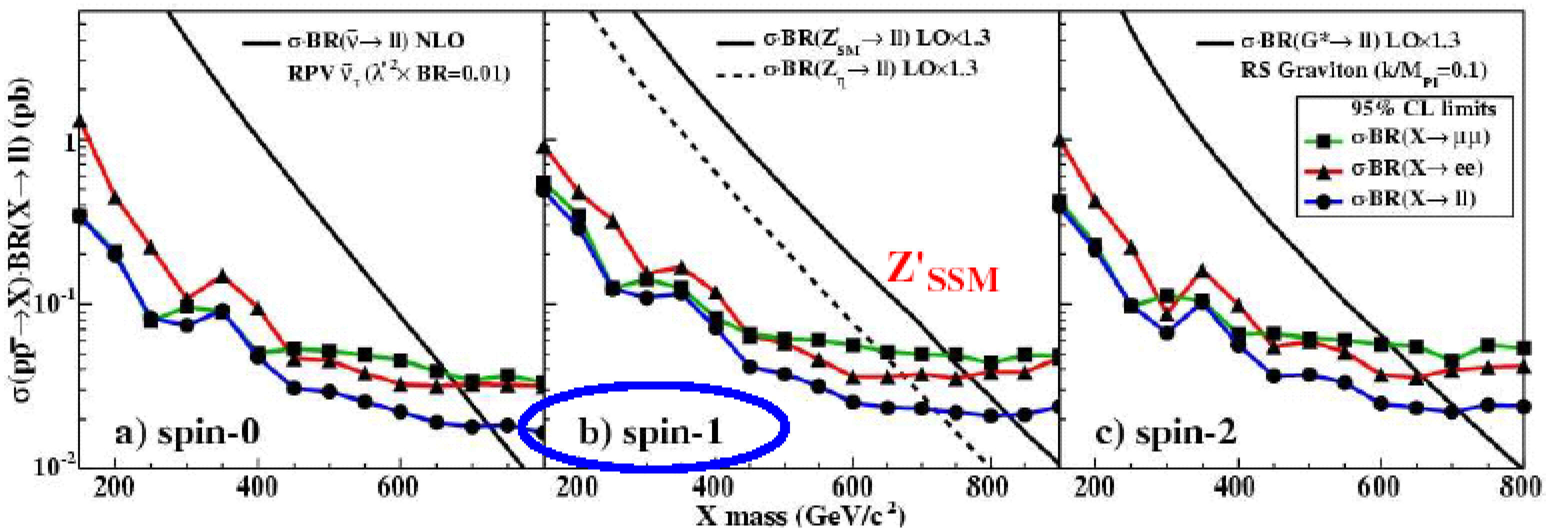
Azuelos & Polesello, Eur. Phys. J C39, s2, s1 (2004)



Z′ Mass

CDF, di-electrons and di-muons combined, 200 pb-1

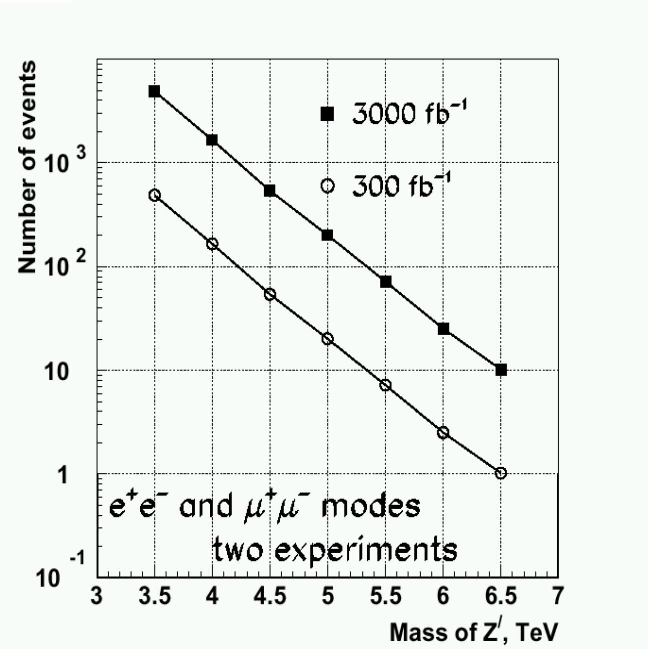
hep-ex/0507104



SLHC: New Z′ Gauge Bosons

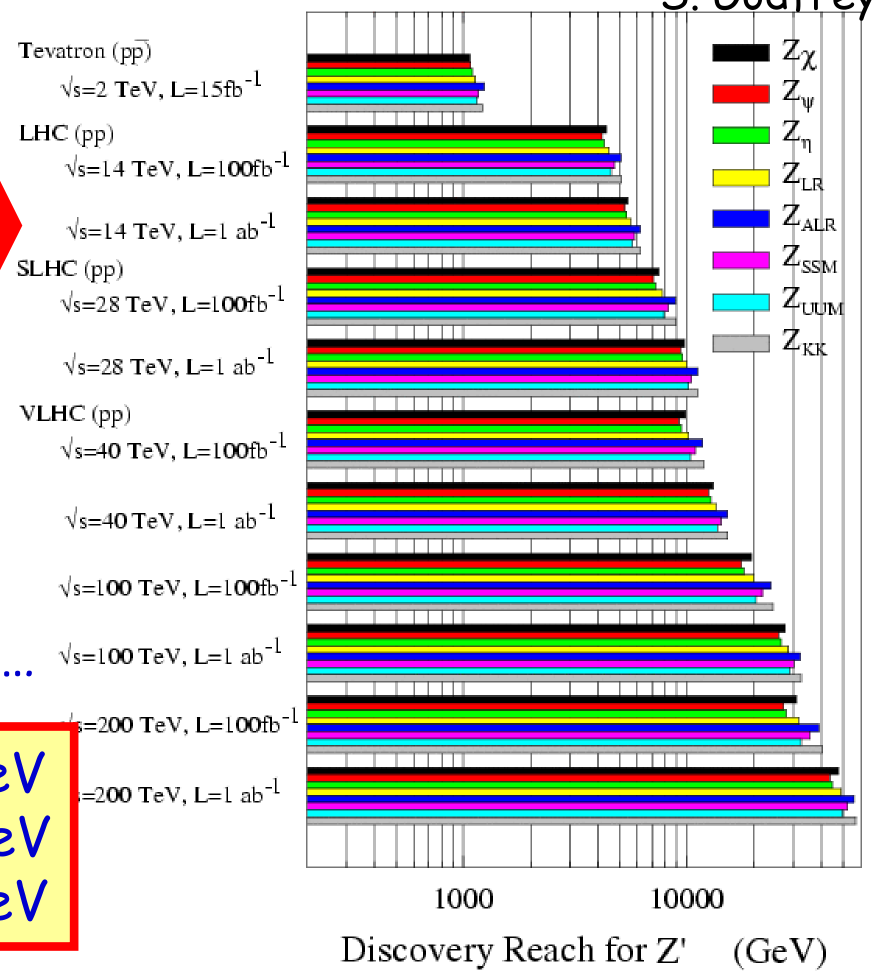
Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

with Z-like couplings



Includes pile-up, ECAL saturation…

S. Godfrey

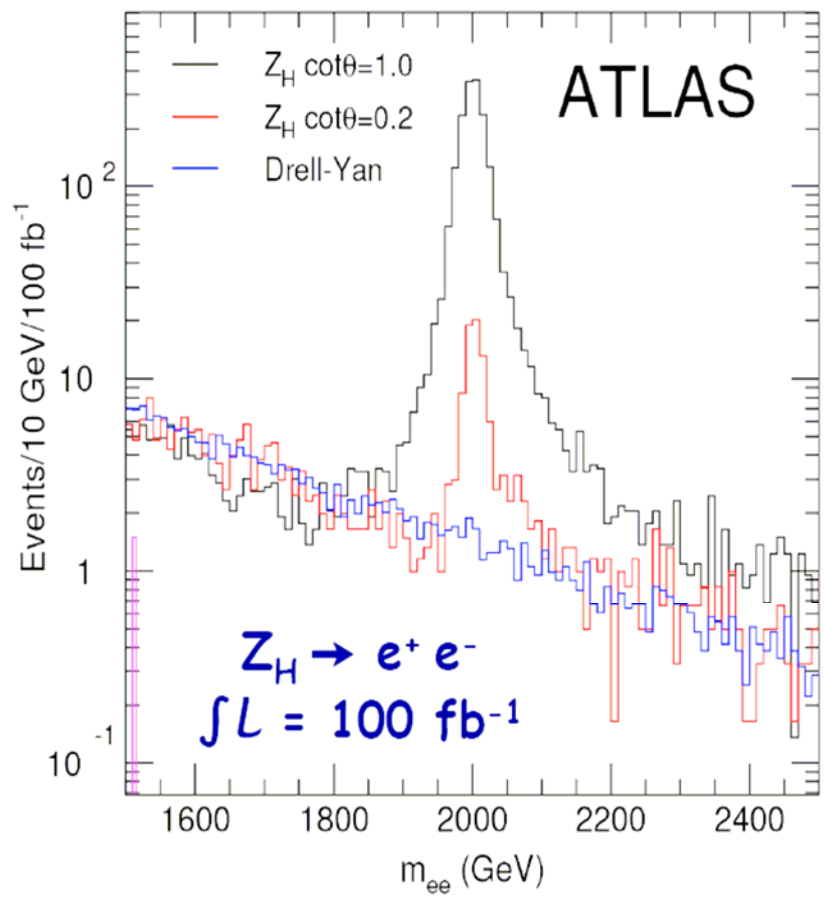


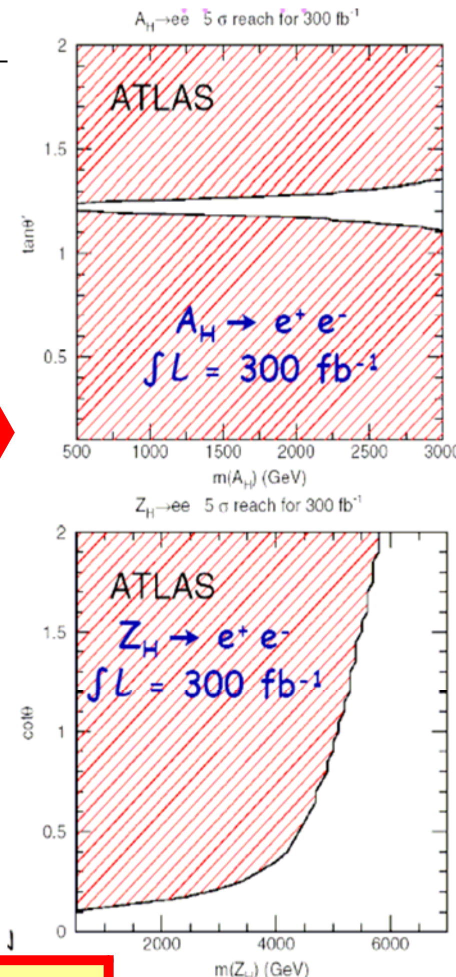
Reach:		
	LHC/600 fb^{-1}	5.3 TeV
	SLHC/6000 fb^{-1}	6.5 TeV
	LHC-28TeV/600 fb^{-1}	8 TeV

Model A_H and Z_H

Signal : di-lepton resonance

Littlest Higgs Model
Arkani-Hamed et al., Han et a

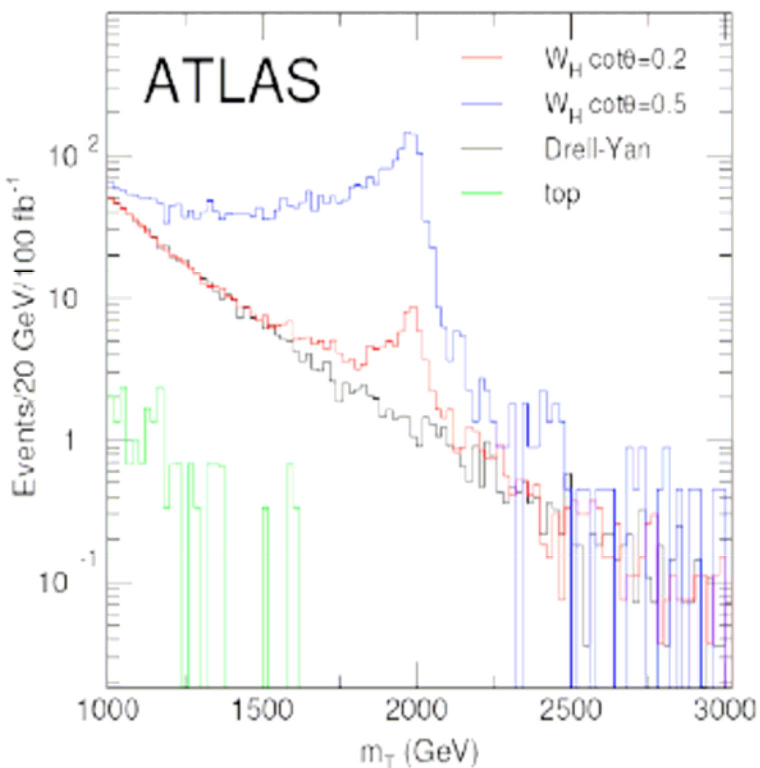




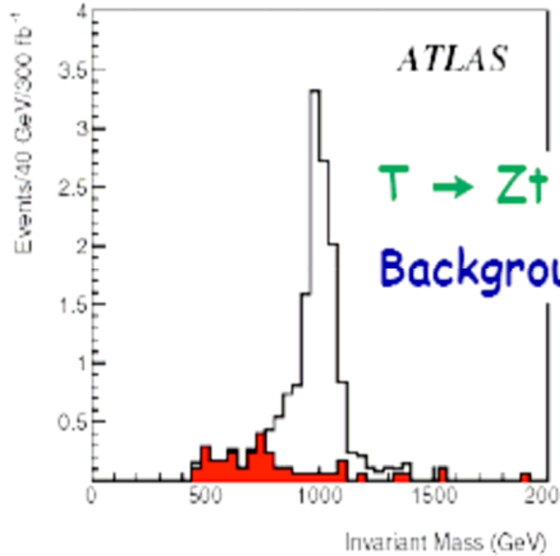
Reach up to 5.7 TeV depending on the θ angle

$W_H \to e\nu$

Background: $l\nu$ via virtual W, labeled Drell-Yan



M_{WH} = 2 TeV, $\int L$ = 100 fb^{-1}

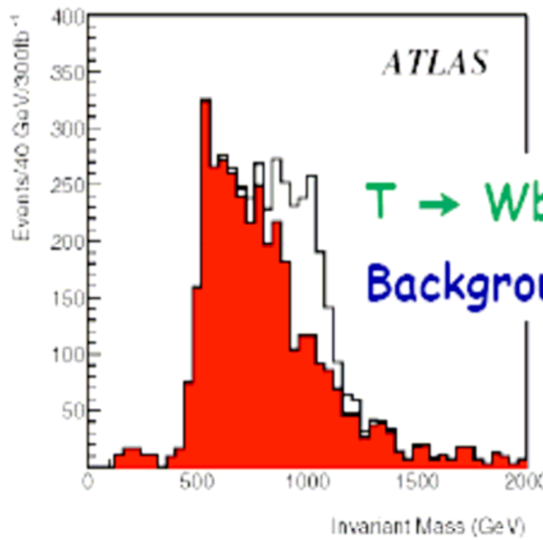


$T \to Zt \to l^+l^-l\nu b$

Background: tbZ, WZ

M_T = 1 TeV,

$\int L$ = 300 fb^{-1}



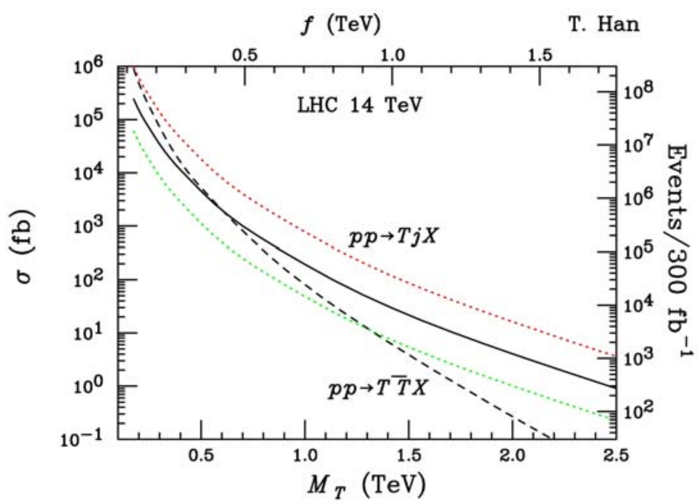
$T \to Wb \to l\nu b$

Background: single t, $t\bar{t}$

Little Higgs Models

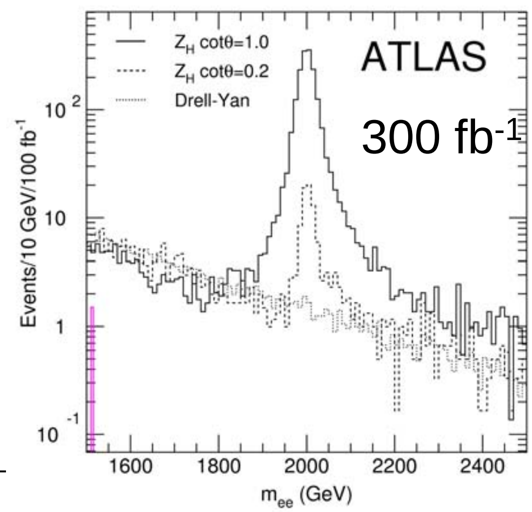
- All models have at least one vector-like quark and extra gauge bosons and scalars at TeV scale

Single T to 2 TeV



Han, Logan, McElrath, Wang, hep-ph/0301040

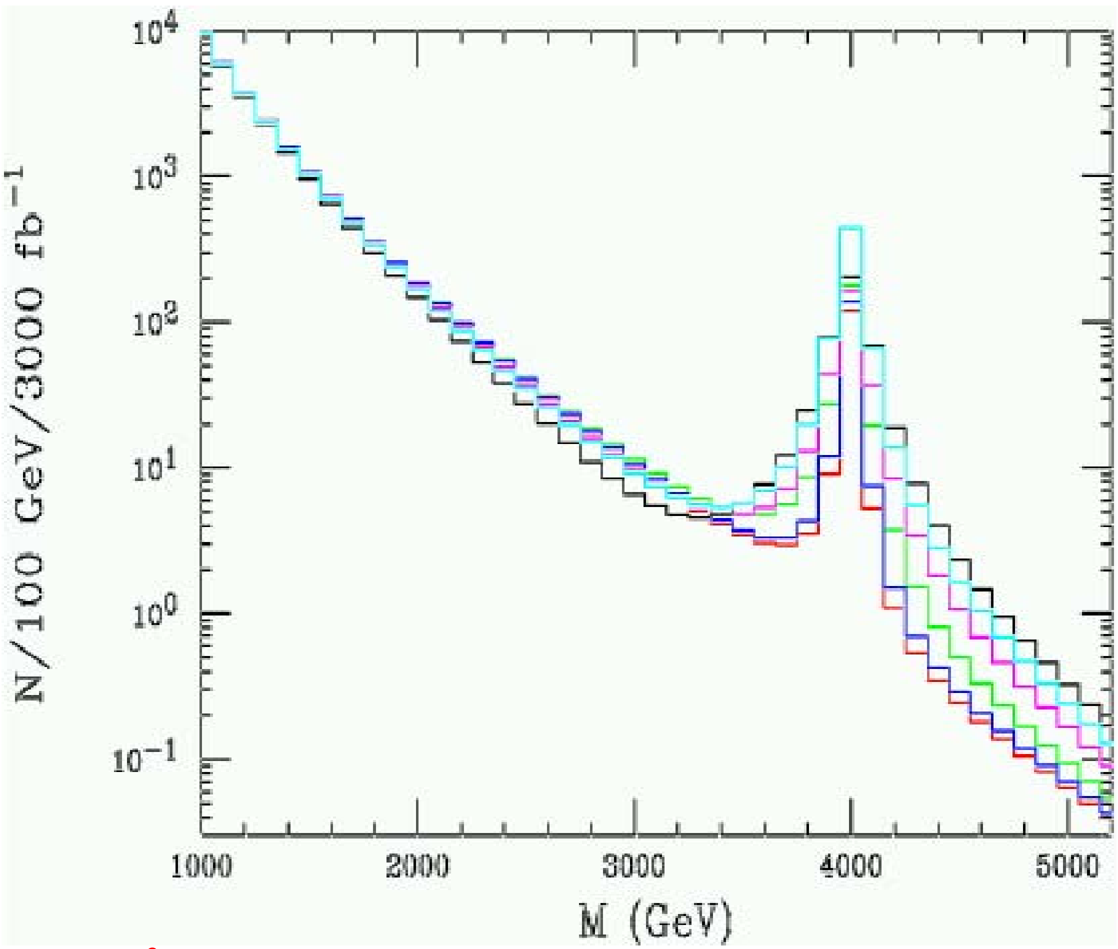
Z_H to 2 TeV



Look for $Z_H \to Z H$

Azuelos et al, hep-ph/0402037

LHC Discovers S-channel Resonance !!



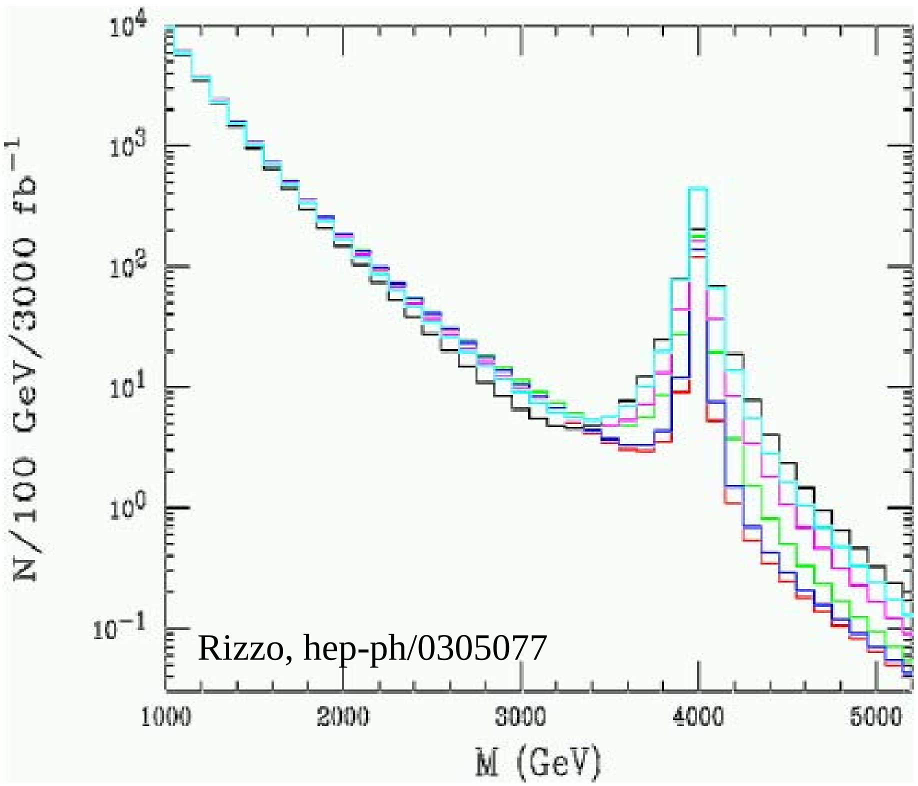
What is it?

Many possibilities for an s-channel resonances:

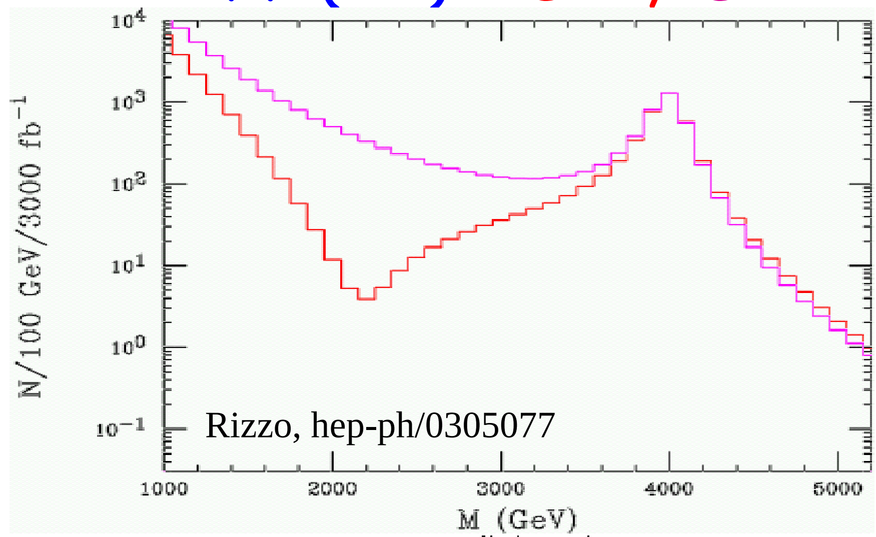
graviton, KK excitations, Z' …

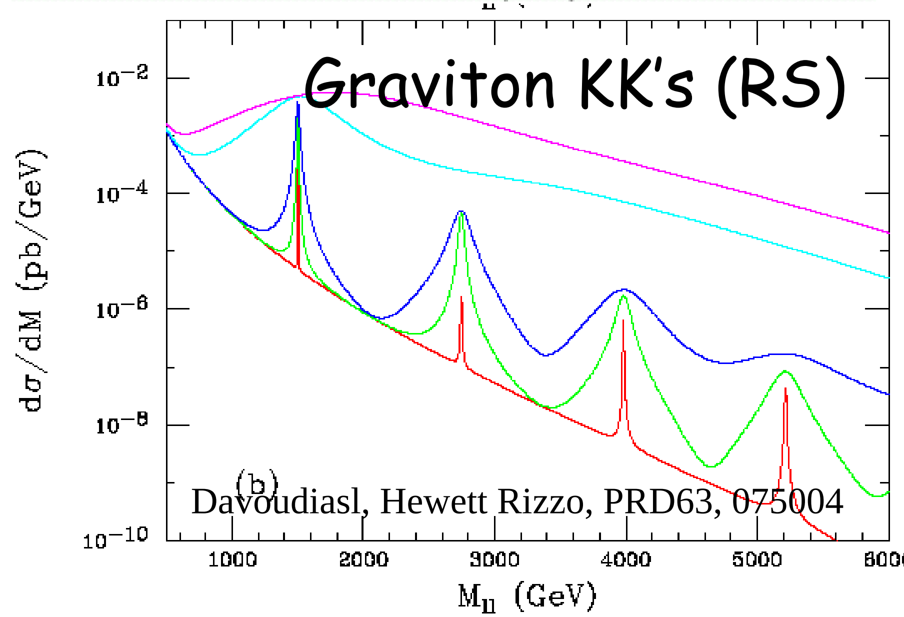
LHC can give some information:

Z': ψ, χ, η, LR, ALR, SSM

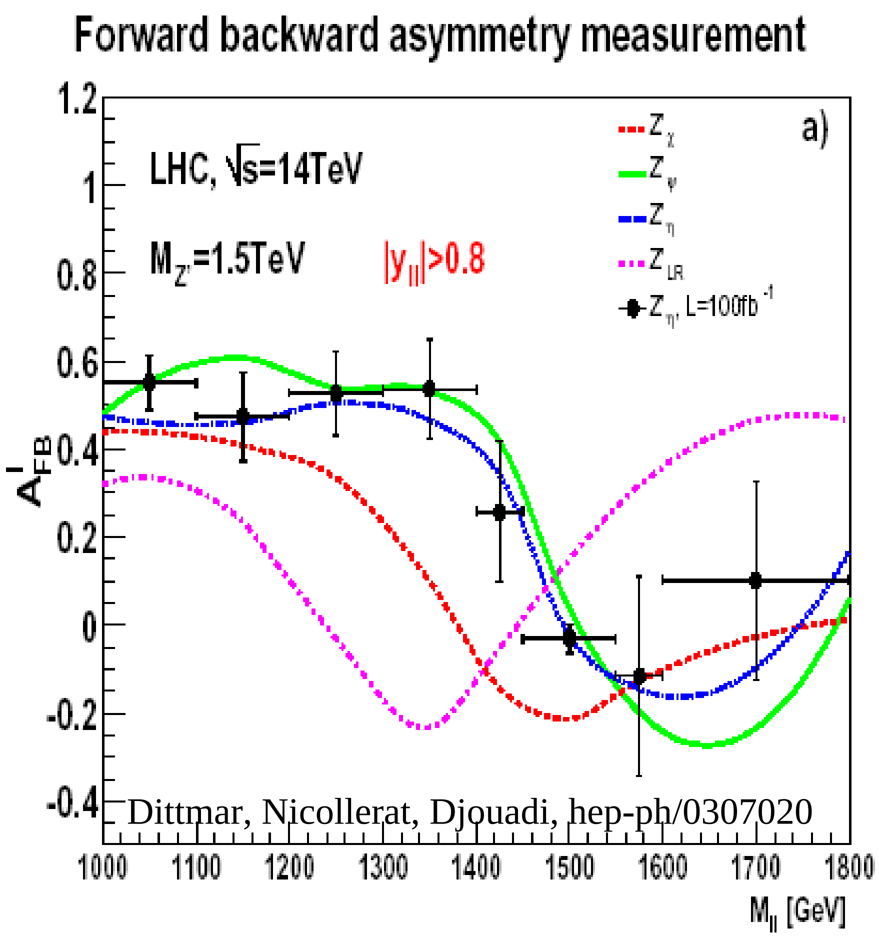


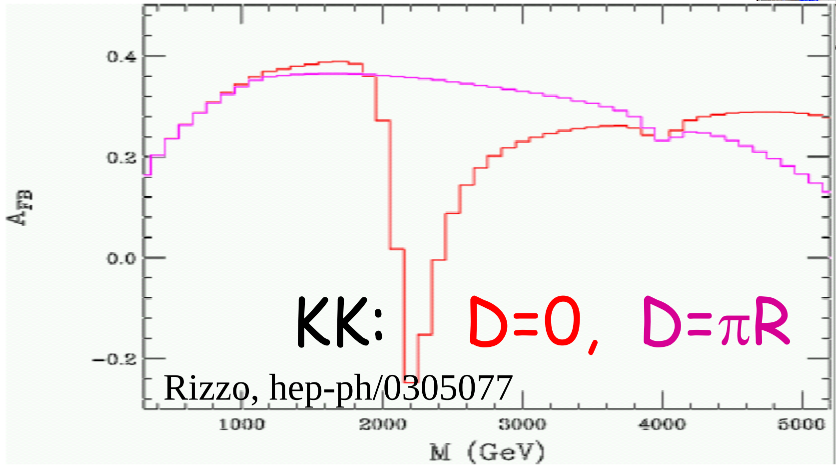
KK (RS): D=0, D=πR

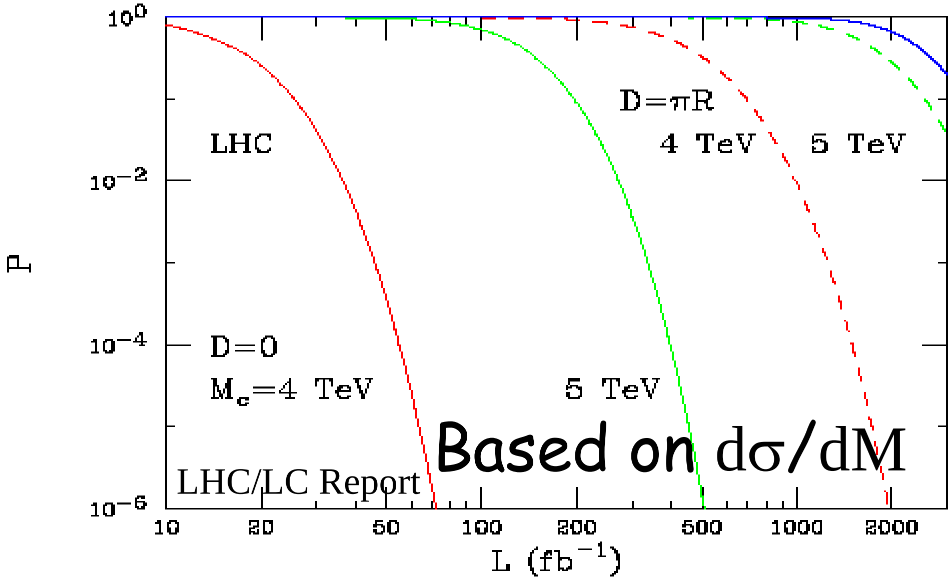




Forward Backward Asymmetries



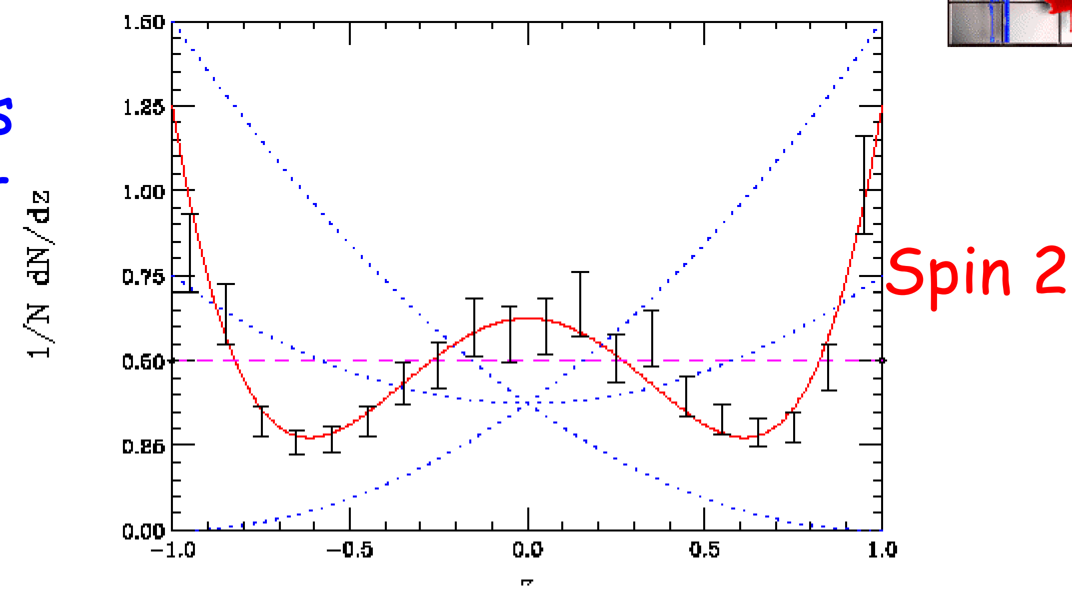




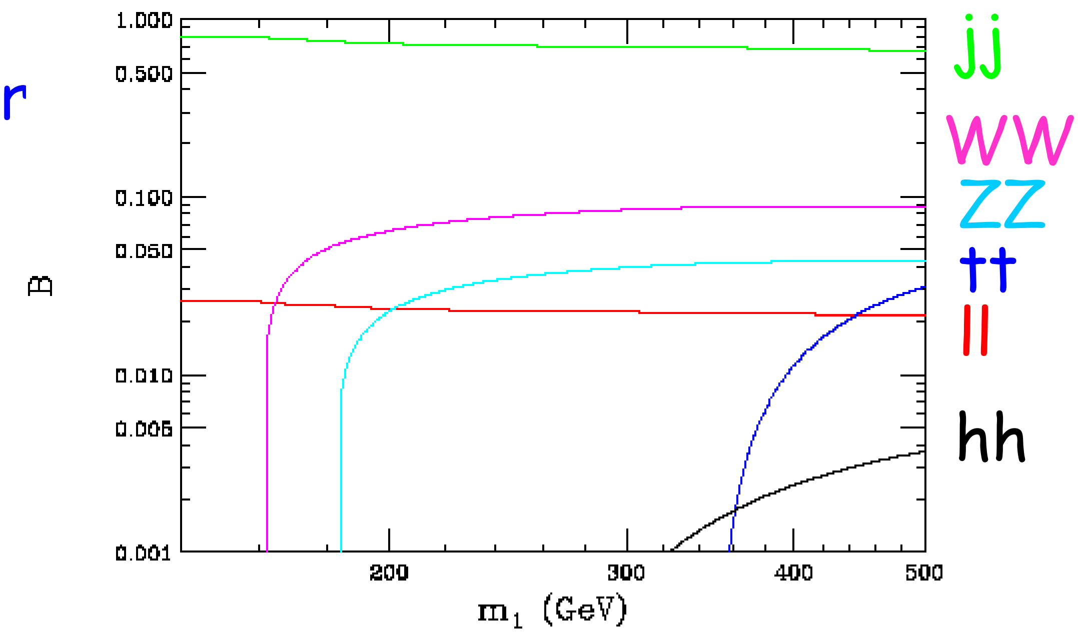
LHC can resolve to some extent but requires significant luminosity

On resonance production of (RS) Gravitons

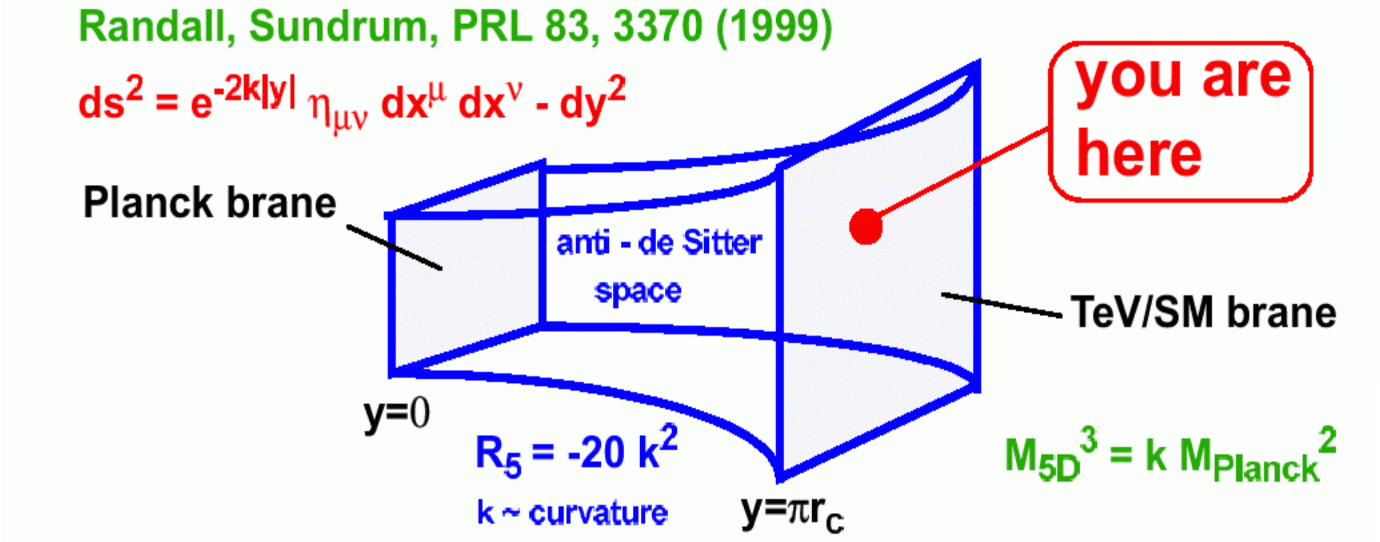
Use angular distributions to test against different spin hypothesis



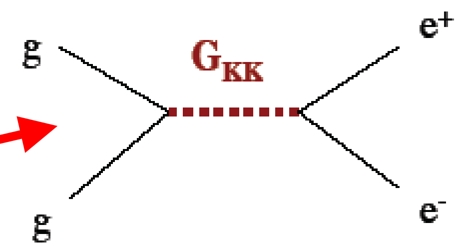
Measure BR's to test for Universal couplings



Curved Space: RS Extra

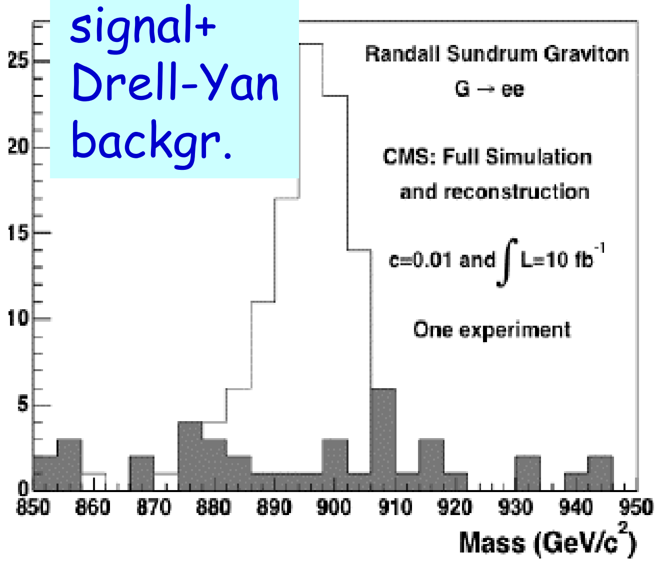


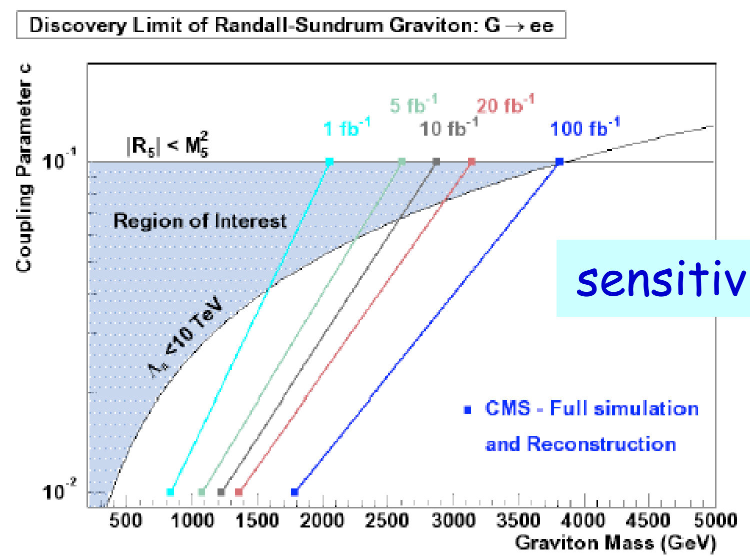
phenomenology



Study the channel pp→Graviton→ e+e-

signal+
Drell-Yan
backgr.





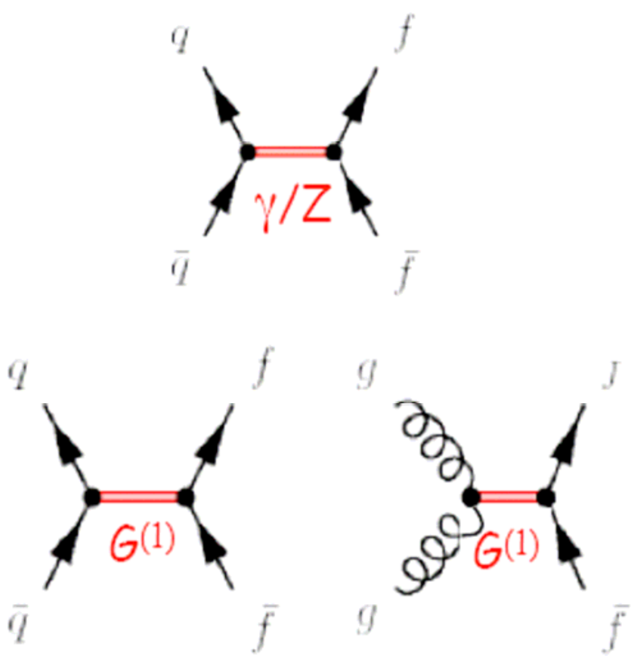
sensitivity

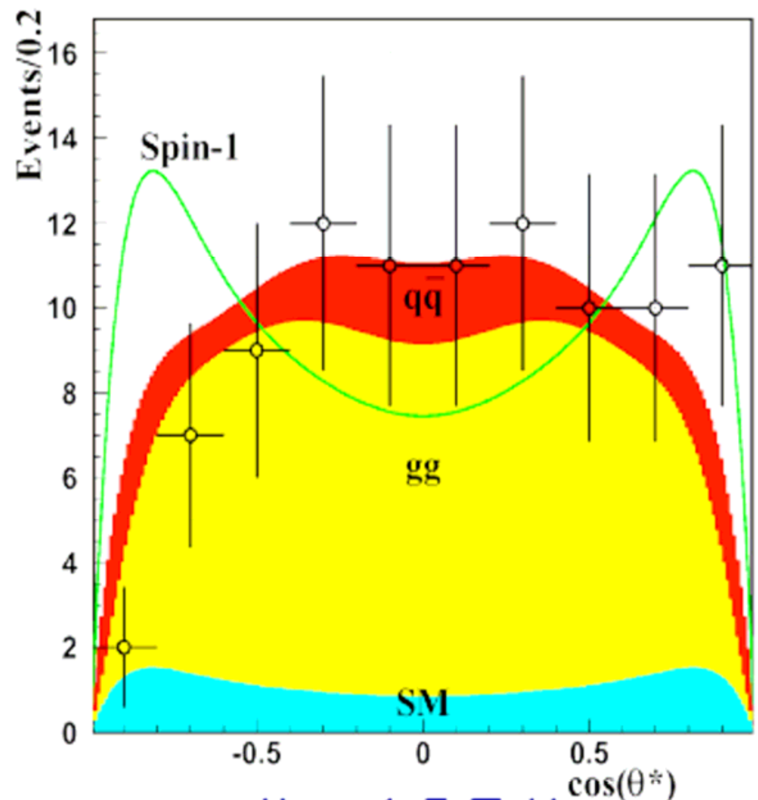
Randall Sundrum EDs

We observe a peak in di-lepton spectrum

Is it a new gauge boson or a RS KK excitation

$\Rightarrow$ Study the spin of the object: spin 1 versus spin 2



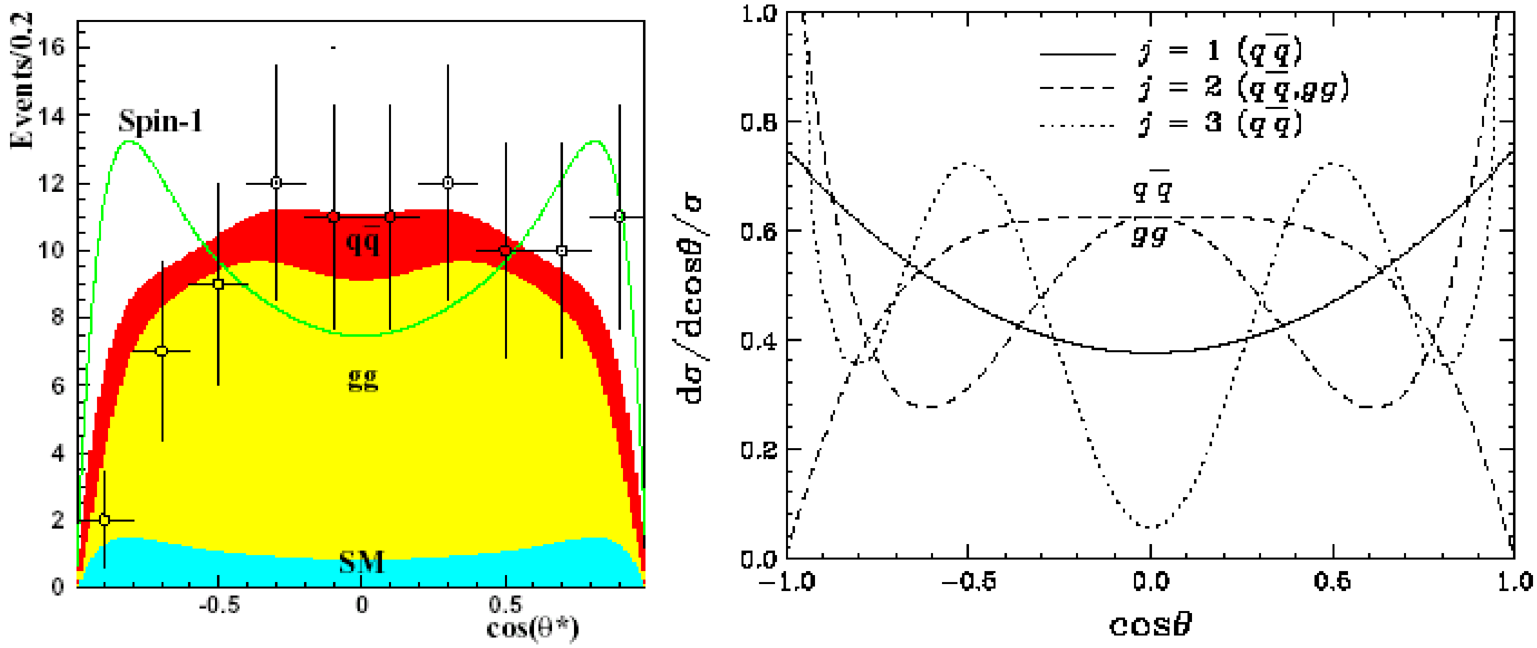


M_G = 1.5 TeV

$\int L$ = 100 fb^{-1}

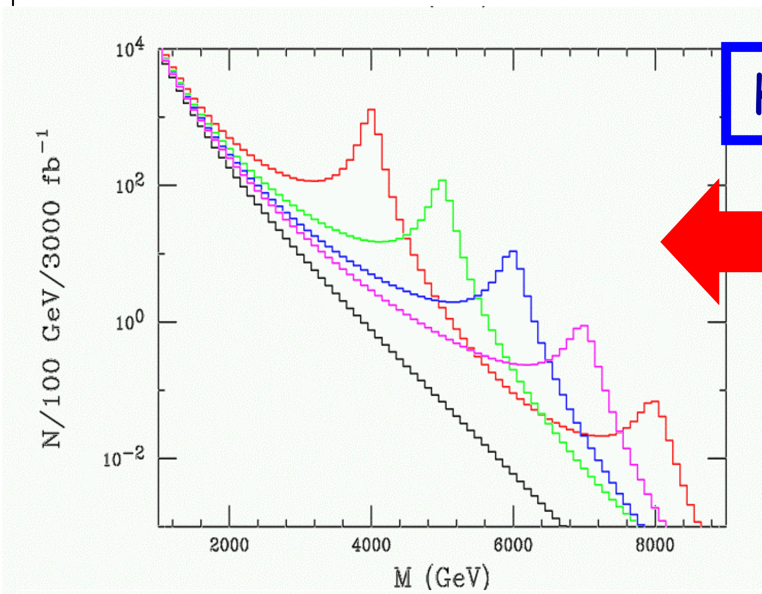
Identification of New Vector Bosons

Use polar angular distributions to find j

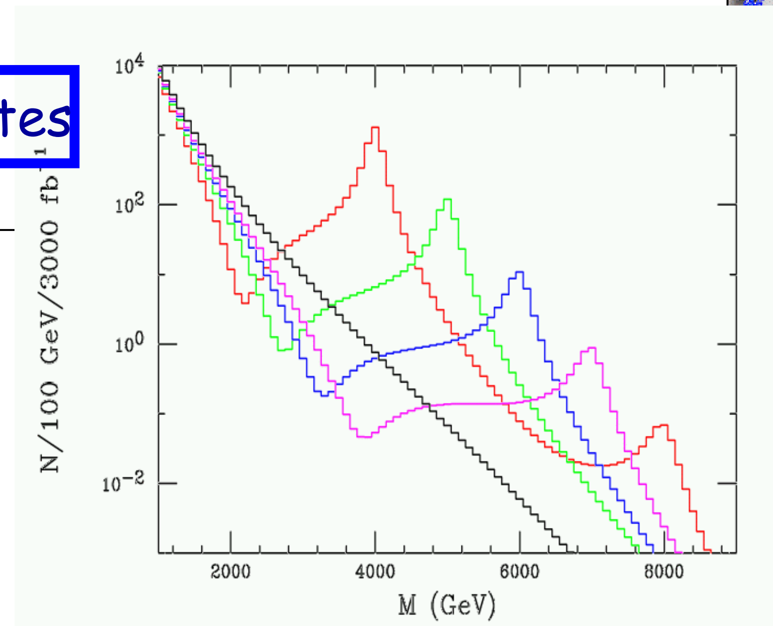


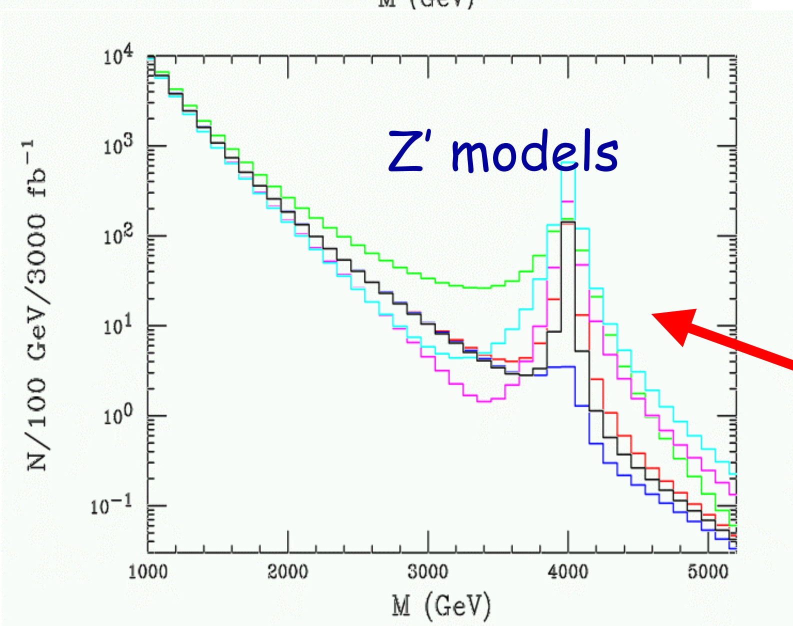
Straightforward angular measurements and fitting.

Allanach et al., hep-ph/0006114; Burikham et al., hep-ph/0411094.



KK states





LEP: M > 4 TeV (indirect)

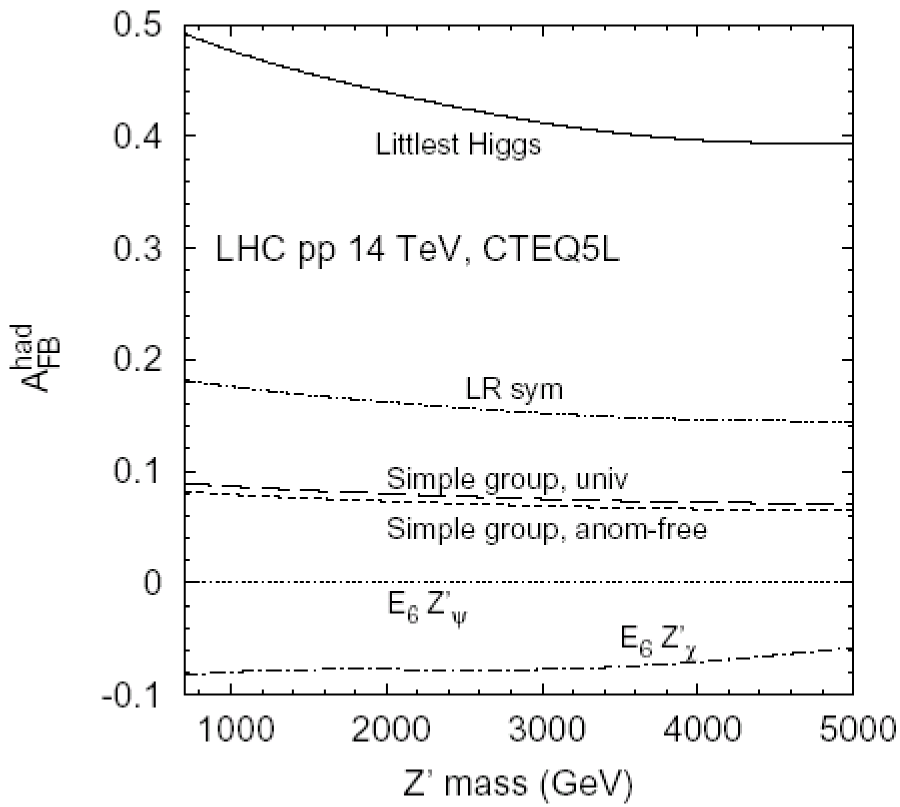
Sensitivity of the LHC

- Direct up to 5.8 TeV for 300 fb
- Indirect up to 13 TeV for 300 fb

How to distinguish from a Z'?
E.g. use Forw-Backw assymetries
T. Rizzo (hep-ph/0305077)

Forward Backward Asymmetry

$$A_{FB}^{i,f} = \frac{3}{4} A_i A_f, \qquad A_i = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}.$$



Langacker, Rosner, Robinett (1984); Carena, Daleo, Dobrescu, Tait, hep-ph/0408098; Hewett, Rizzo; Han, Logan, Wang, hep-ph/0506313.

Strongly Interacting "Electroweak" Vector Bosons

$$\mathcal{L}_{\text{scalar}} = (D^\mu\Phi)^\dagger D_\mu\Phi - \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

- At high mass the Higgs self-coupling becomes strong

$$\lambda = \frac{M_H^2}{2v^2}$$

and interaction becomes strongly interacting

- Goldstone-boson scattering diverges for large M_H or absence of Higgs

Standard Model is Effective Low Energy Theory

- We don't know what's happening at high energy
- Effective theory approach:

$$L \approx \frac{v^2}{4} Tr D^{\mu}\Sigma^{+} D_{\mu}\Sigma + \sum_i \alpha_i \frac{O_i}{\Lambda^2} + \ldots \qquad \Sigma = e^{i\omega_i \tau_i / v}$$

ω_i are longitudinal components of W,Z

- Compute deviations from SM due to new operators and compare with experimental data
- In any given model, compute coefficients of operators
- Global fit to 21 flavor and CP conserving operators
  - Some linear combinations of operators are very weakly constrained (below 1 TeV)
  - Apply analysis to bound new Z'> 2 TeV

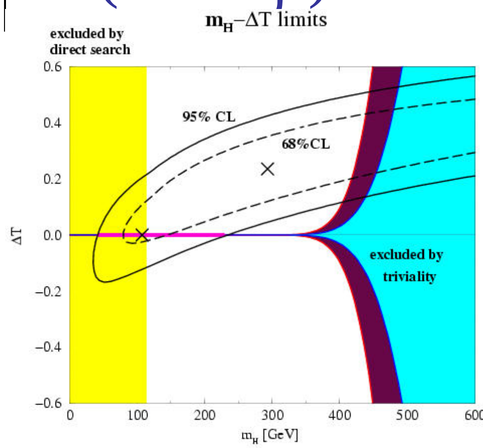
New Result

Han & Skiba, hep-ph/0412166

Barbieri, Pomarol, Rattazzi, Strumia, hep-ph/0405040

Higgs can be heavy with new physics

- Specific examples of heavy Higgs bosons in Little Higgs and Triplet Models
- $M_H \approx$ 450-500 GeV allowed with large isospin violation ($\alpha\Delta T=\rho$) and higher dimension operators



Chivukula, Holbling, hep-ph/0110214

$$L' = c_1\left(Tr\Sigma^+\tau_3 D_\mu \Sigma\right)^2 + c_2 Tr\left(B_{\mu\nu}\Sigma^+ W^{\mu\nu}\Sigma\right)$$

Generates large isospin violation

We don't know what the model is which produces the operators which generate large ΔT

Effective Lagrangian Approach

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

- Model independent approach to bound coefficients
- Model dependent approach coefficients are predicted by specific models

Chiral Lagrangian Approach

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

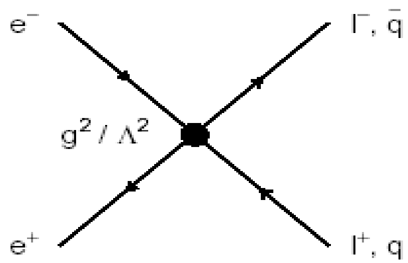
- Model independent approach to bound coefficients
- Model dependent approach coefficients are predicted by specific models

Precision Measurements and Effective Lagrangians

W. Kilian
P. Osland, A. Pankov & N. Paver

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

Contact Interactions:



- New interactions can be parametrized in terms of 4-fermion interactions if √s « Λ

$$L = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} \left(\bar{f}_i \gamma^\mu f_i\right)\left(\bar{F}_i \gamma^\mu F_i\right) \quad \Lambda \sim M_{Z'}$$

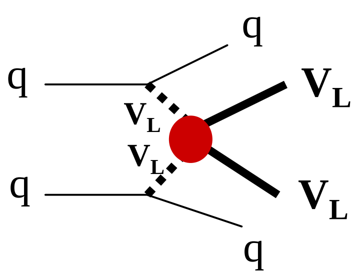
- Contact terms related to Z' parameters

$$\frac{\eta_{LL}}{\Lambda^2} \frac{\eta_{RR}}{\Lambda^2} = \frac{\eta_{LR}}{\Lambda^2} \frac{\eta_{RL}}{\Lambda^2} \approx \frac{g_L^e}{M_{Z'}} \frac{g_L^F}{M_{Z'}} \frac{g_R^e}{M_{Z'}} \frac{g_R^f}{M_{Z'}}$$

- Obtain similar expressions for leptoquark exchange etc

Strongly Coupled Vector Boson System

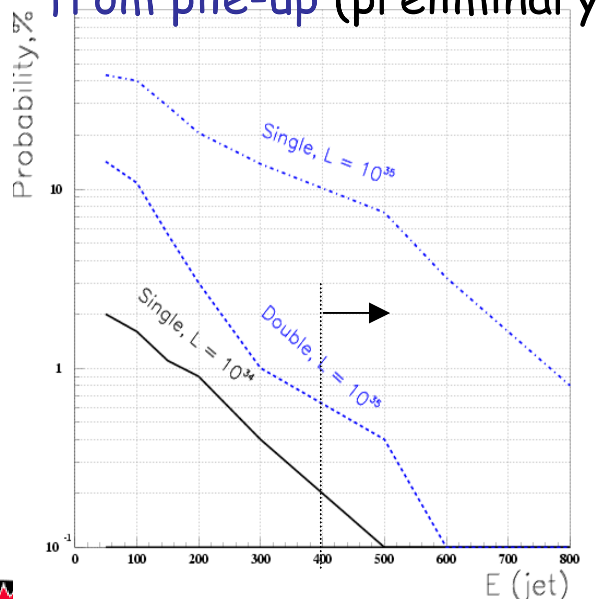
If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at $\sqrt{s} \approx$ TeV



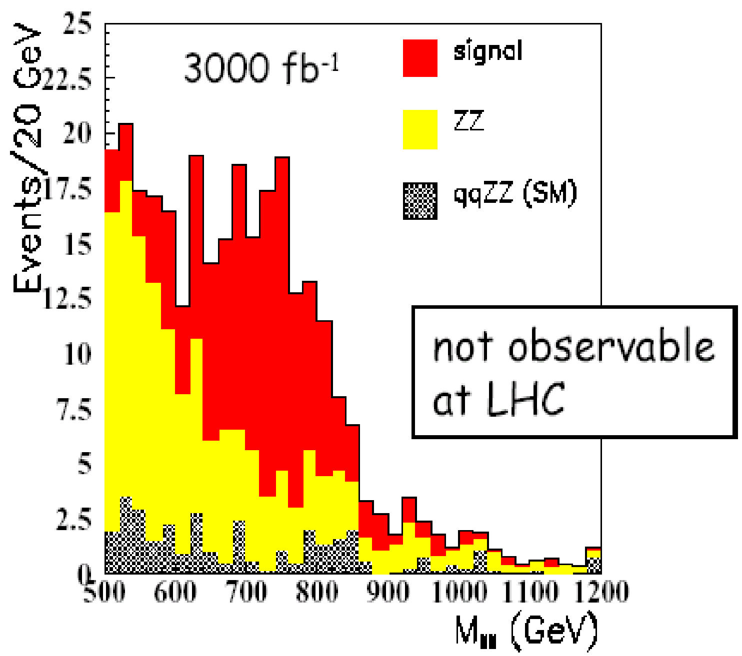
May be difficult at LHC. What about SLHC?

- degradation of fwd jet tag and central jet veto due to huge pile
- BUT : factor ~ 10 in statistics → 5-8σ excess in W^+_L W^+_L scatte
  - → other low-rate channels accessible

Fake fwd jet tag (|η| > 2) probability from pile-up (preliminary ...)



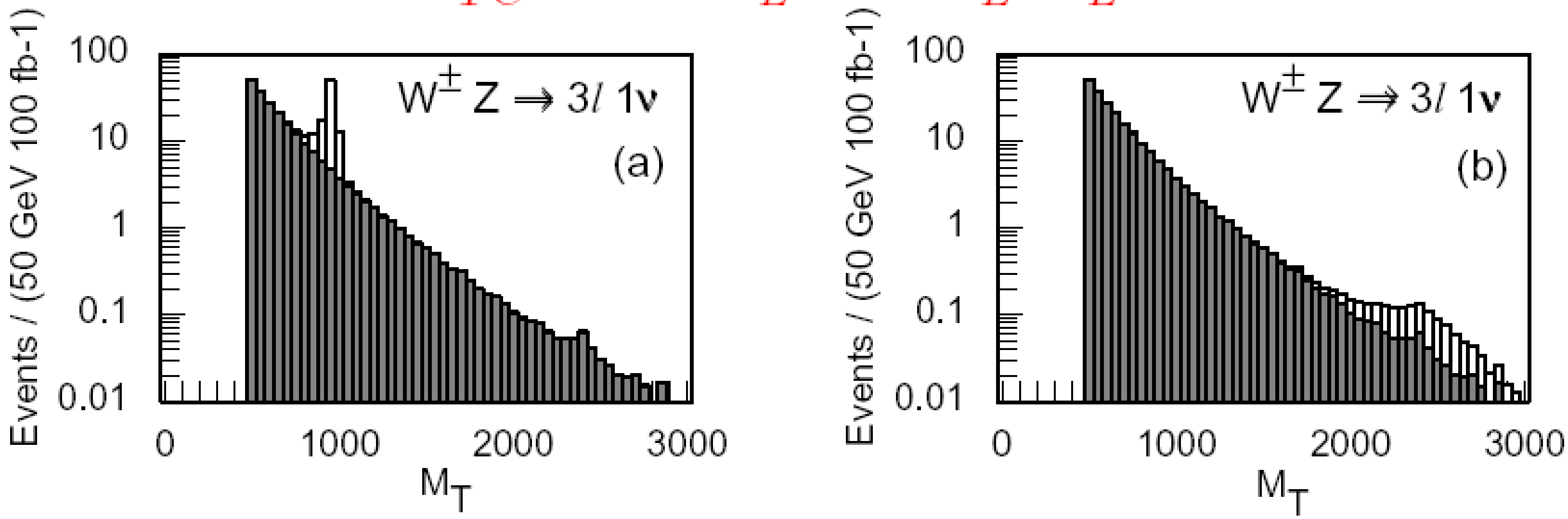
Scalar resonance $Z_L Z_L \to 4\ell$



Strongly Interacting "Electroweak" Vector Bosons

$$q\bar{q} \to \rho_{TC}^{\pm,0} \to W_L^{\pm} Z_L,\ W_L^{+} W_L^{-},\ t\bar{t},\ t\bar{b};$$

$$qq \to qq\ \rho_{TC}^{\pm,0} \to qq\ W_L^{\pm} Z_L,\ W_L^{+} W_L^{-},\ t\bar{t},\ t\bar{b}.$$



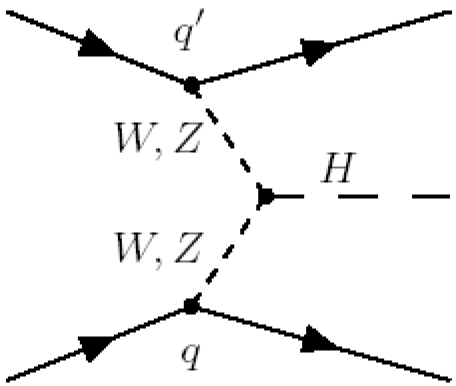
Bagger et al., PRD (1995.)

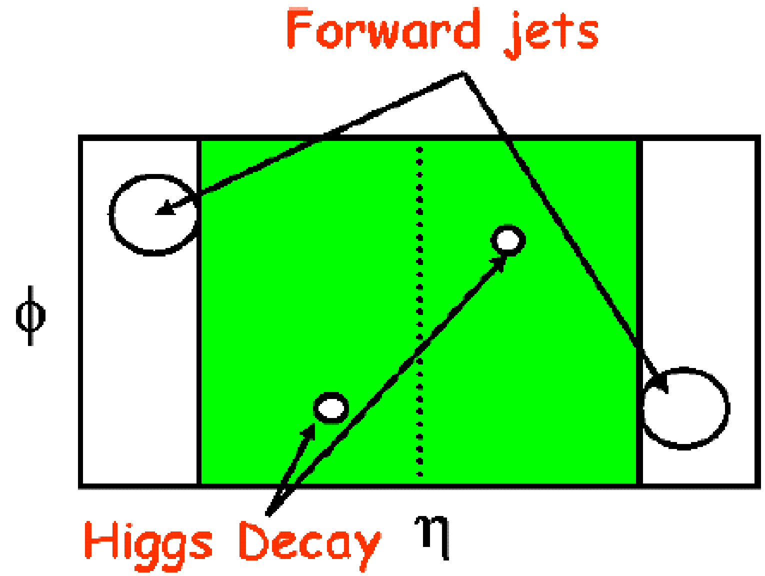
Colored bosons: $\eta_8,\ \pi_8,\ \rho_8,\ Z_8 \to t\bar{t}.$

$\Gamma \gtrsim 20\%\ M_V, \quad \sigma \sim \sigma_{QCD}(t\bar{t}).$ Eichten, Lane; Hill, Parke (1993)

Challenge is to beat down SM WW, WZ, tt backgrounds

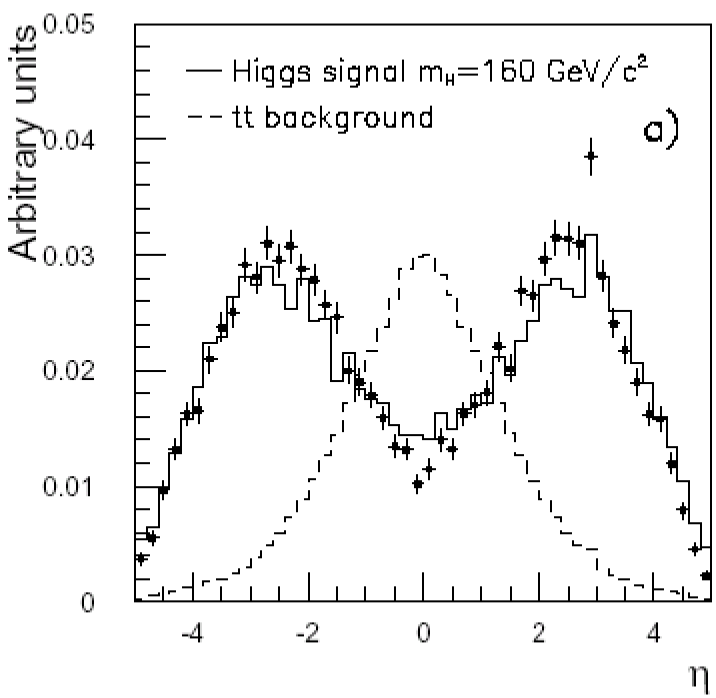
Vector Boson Fusion





Enhance signal with tagging jets:

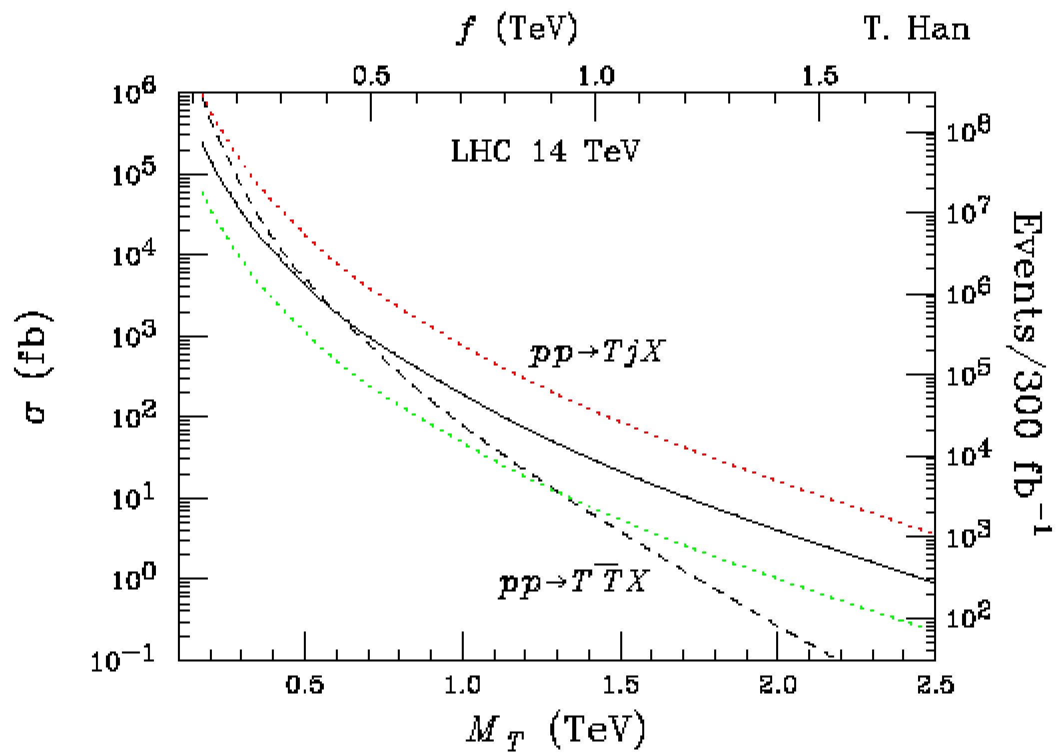
- 2 high p_T forward jets (large $\Delta\eta$)
- Jet veto in central region
- Large M_{jj} ~0.5-1 TeV
- Higgs decay products between jet tags



Discover New Heavy Quarks

Appear in:

- T in topcolour type models
- T, U, D in Little Higgs models



General strategy toward understanding the underlying theory

(SUSY as an example …)

Discovery phase: inclusive searches … as model-independent as possible

First characterization of model: from general features: Large E_T^{miss} ? Many leptons ?
Exotic signatures (heavy stable charged particles, many γ's, etc.) ? Excess of b-jets or τ's ? …

Interpretation phase:

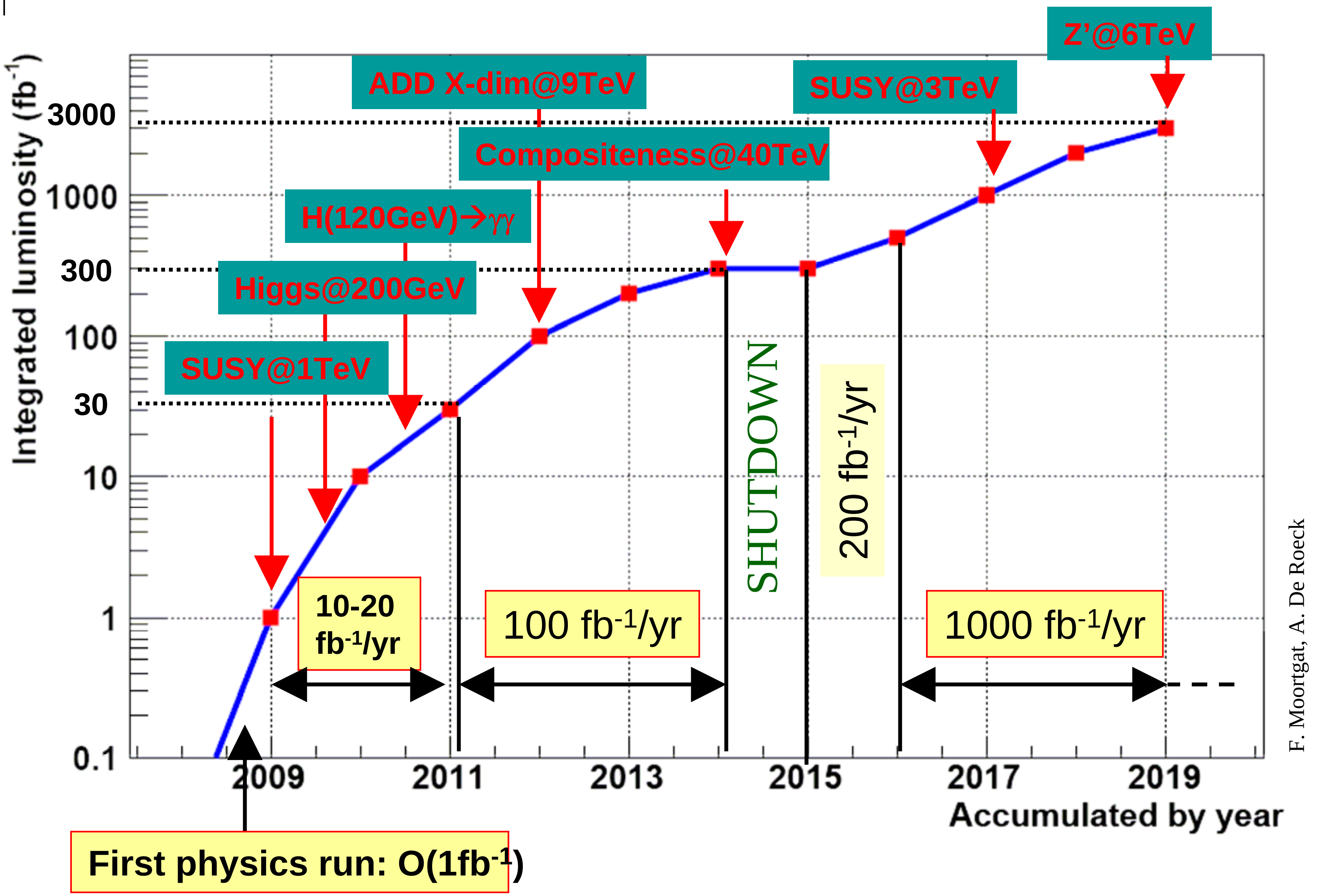
- reconstruct/look for semi-inclusive topologies, eg.:
  - -- h $\rightarrow$ bb peaks (can be abundantly produced in sparticle decays)
  - -- di-lepton edges
  - -- Higgs sector: e.g. A/H $\rightarrow \mu\mu, \tau\tau \Rightarrow$ indication about tanβ, measure masses
  - -- tt pairs and their spectra $\Rightarrow$ stop or sbottom production, gluino $\rightarrow$ stop-top
- determine (combinations of) masses from kinematic measurements (e.g. edges …)
- measure observables sensitive to parameters of theory (e.g. mass hierarchy)

At each step narrow landscape of possible models and get guidance t

- lot of information from LHC data (masses, cross-sections, topologi
- consistency with other data (astrophysics, rare decays, etc.)
- joint effort theorists/experimentalists will be crucial

F. Gianotti
LP05

Discoveries?



Recap: Challenge to Theorists

- Understand SM processes with higher order corrections
- Classify typical signals for new physics
- Develop strategies to disentangle the underlying theory

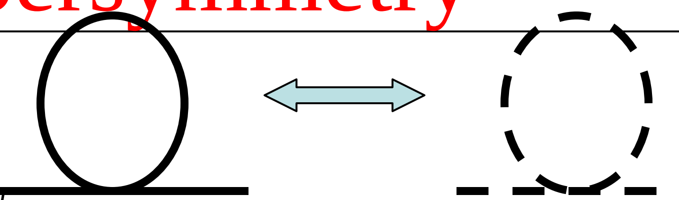
Standard Model is Unsatisfactory

- Despite phenomenological successes
  - Gauge invariant masses for W, Z, fermions
  - Unitarity conservation
  - Agreement with precision electroweak measurements

The SM with a light Higgs can't be the whole story

Quantum Corrections and Supersymmetry

$\delta M_H^2 \approx -M_{Pl}^2$



$\delta M_H^2 \approx M_{Pl}^2$

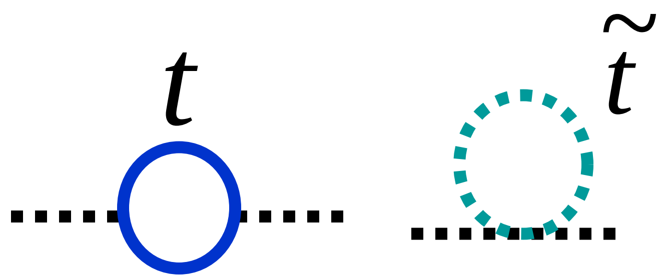
Tevatron/LHC Energies

10^3 GeV **10^{16}** **10^{19} GeV**

Quantum corrections cancel order by order in perturbation theory

SUSY….Our favorite model

- Quadratic contributions to Higgs mass cancelled automatically if SUSY particles at TeV scale
- Cancellation result of ***supersymmetry***, so happens at every order

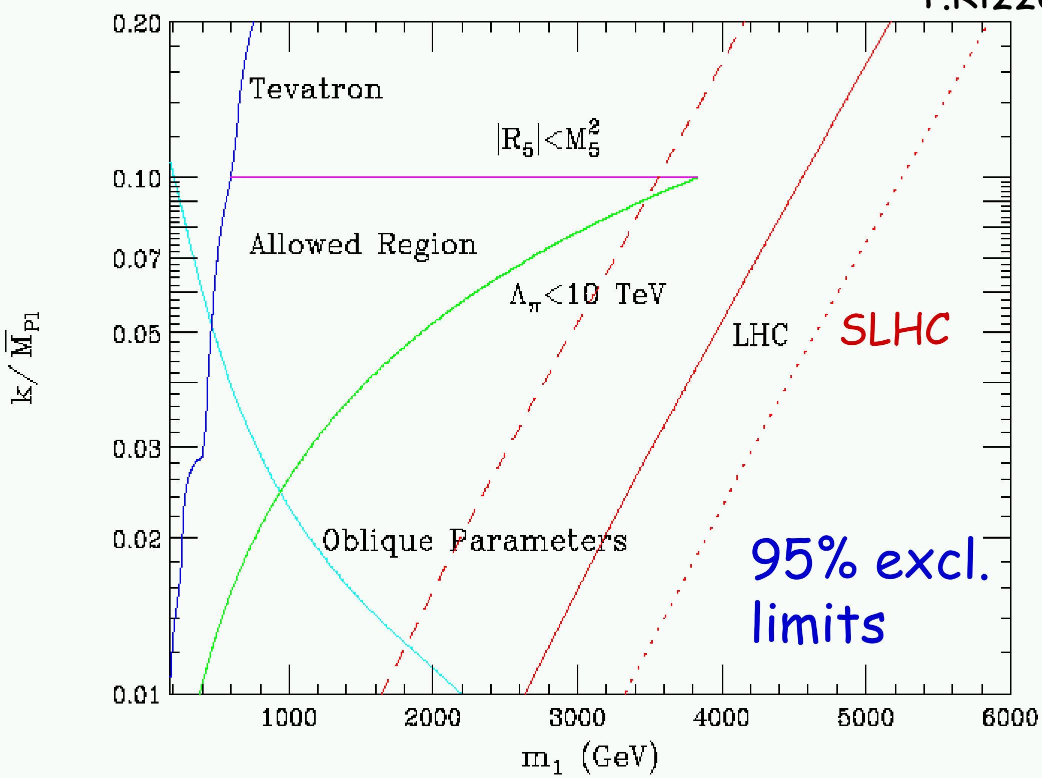


$$\delta M_h^{\ 2} \approx (....) G_F \Lambda^2 (M_t^{\ 2} - M_{\tilde{t}}^{\ 2})$$

SLHC: Extra Dimension Scenarios

Randall Sundrum model

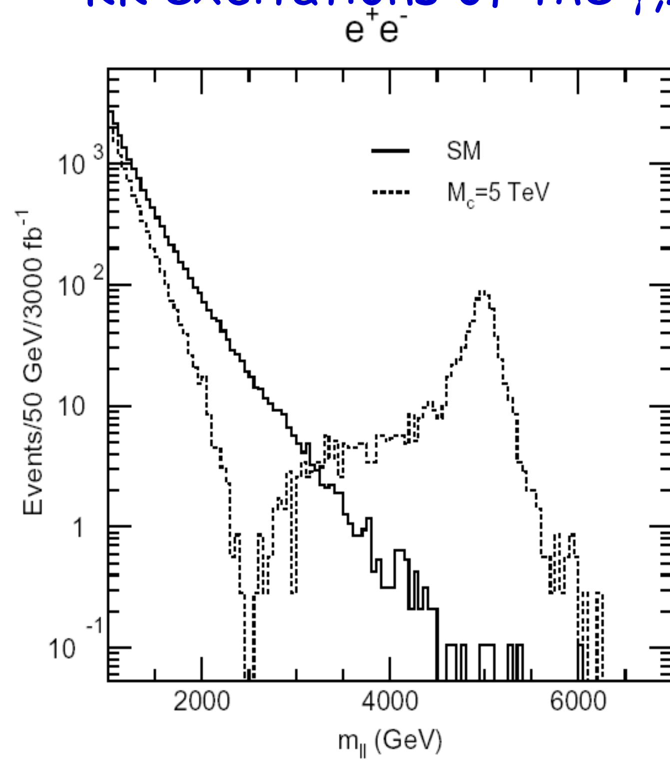
- Predicts KK graviton resonances
- k= curvature of the 5-dim. Space
- m_1 = mass of the first KK state



$100\rightarrow1000$ fb^{-1}: Increase in reach by 25

TeV scale ED's

- KK excitations of the γ,Z



Direct: LHC/600 fb^{-1} 6 TeV

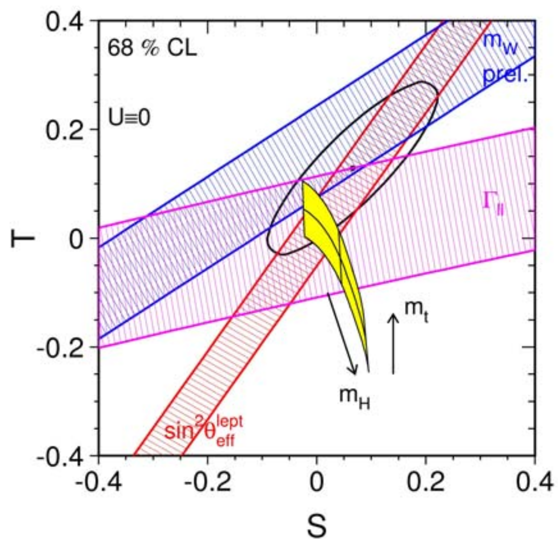
SLHC/6000 fb^{-1} 7.7 TeV

Interf:SLHC/6000 fb^{-1} 20

EWSB without a Higgs

- As Higgs gets heavy, electroweak predictions get further and further from data

SM



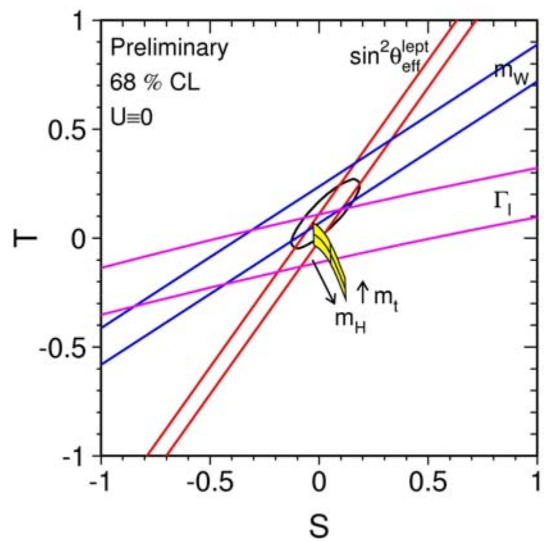
2005

Fit assumes M_H=150 GeV

- Heavy Higgs gives too large value of S, too small value for T
- EW precision measurements are a problem in Higgsless models
- Usually, light KK modes give too large contribution to S

What if no light Higgs?

- Excluded by EW fits?
- Must confront unitarity violation
- What about Higgsless models with EW symmetry broken by boundary conditions?
  - Unitarize scattering amplitudes by exchange of new heavy W and Z bosons
  - Need mechanism with positive ΔT



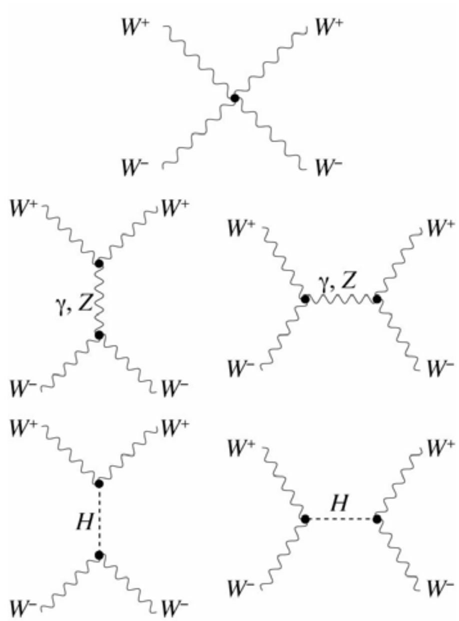
LEP EWWG 2004

Models without Higgs have difficulties with Unitarity

- Without Higgs, *W*-boson scattering grows with energy

  $A \sim G_F s$

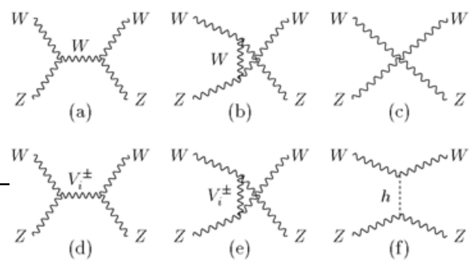
  – Violates unitarity at 1.8TeV
- SM Higgs has just the right couplings to restore unitarity
- Extra D models have infinite tower of Kaluza-Klein states
- Need cancellations both in s and s^2 contributions to amplitudes
- Arrange couplings to make this happen



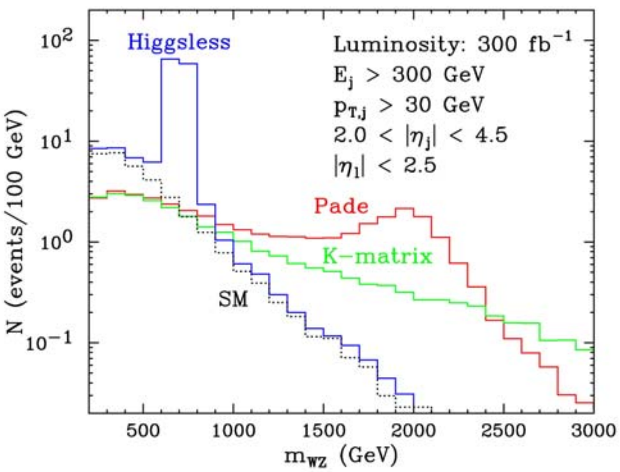
Look for heavy gauge bosons

Experimental Signatures of Higgsless Models

- Weakly coupled Kaluza Klein particles are generic feature of Higgsless Models
- Look for massive W, Z, γ like particles in vector boson fusion
  - Need small couplings to fermions to avoid precision EW constraints
  - Narrow resonances in WZ channel



LHC



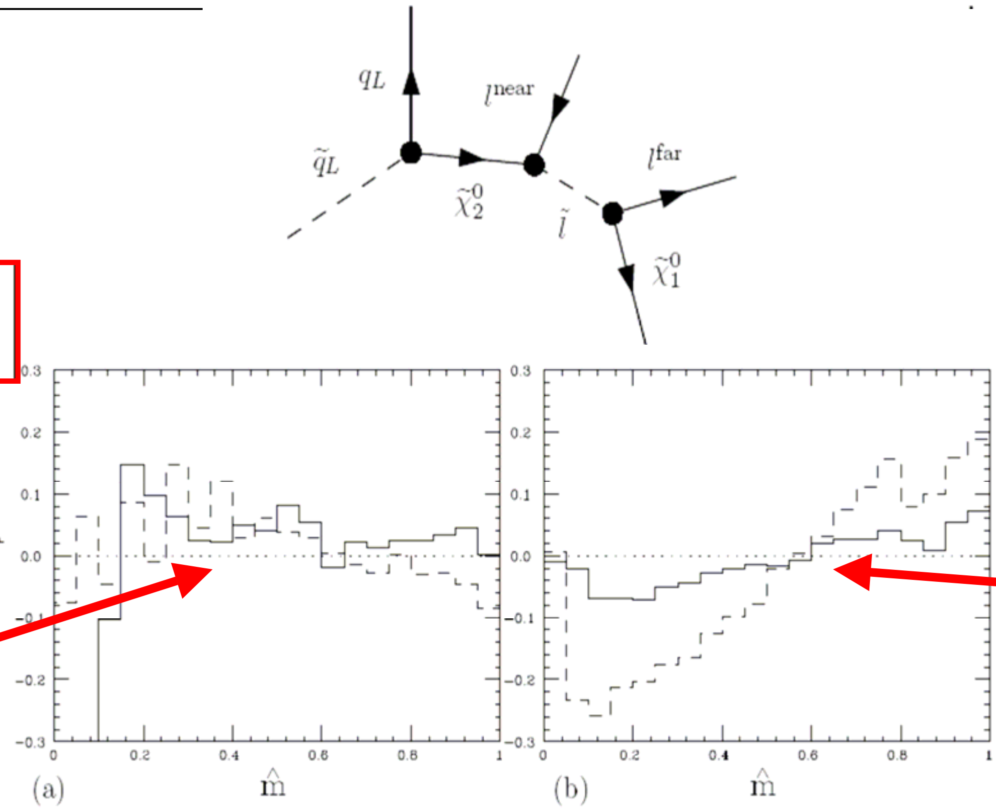
Different resonance structure from SM!

Birkedal, Matchev, Perelstein, hep-ph/0412278

•Top quark plays leading role in dynamical symmetry breaking models, other new physics models

Look for variables sensitive to the particle spin eg. lepton charge asymmet
in squark/KKquark decay chains Barr hep-ph/0405052; Smillie & Webber hep-ph/05

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$



KK like Spectrum (small mass Splitting)

SPS1a benchmark type spectrum

Method works better or worse depending mass differences between the par

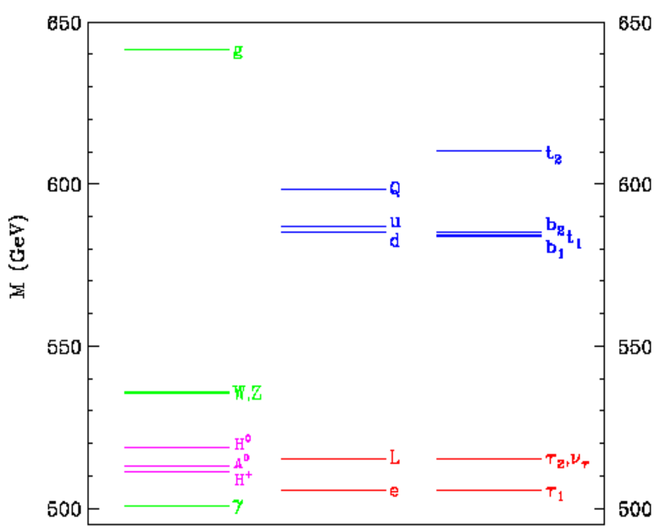
More ideas/variables for determining the spin @LHC welcome!

Universal Extra Dimensions

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

UED⇒ all particles in the bulk
Phenomenology: a KK tower pattern from
ED's which looks like supersymmetry:
Can the LHC tell distinguish?

Tools: spin of the "sparticles"/ No heavy higgses/mass splitting small/ pattern repeates at higher energies…



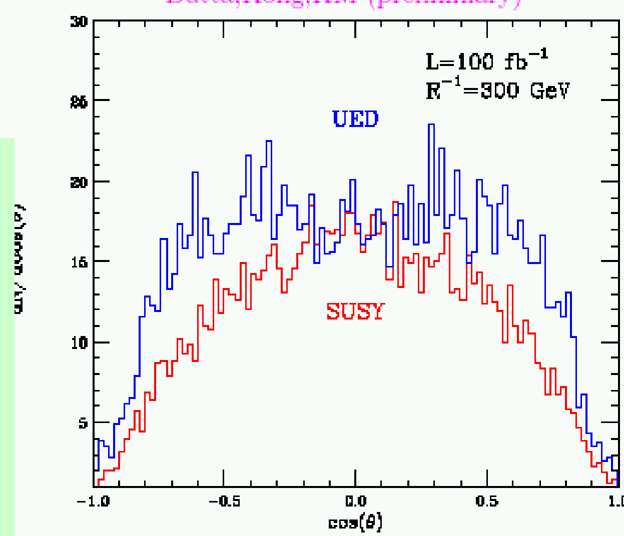
Study muon angular distribution in (approx.) smuon rest frame

First result looks encouraging
Also: A. Bar hep-ph/0405052 lepton charge asymmetry

SUSY versus UED at the LHC

- Cuts:
  - $E_{\mu^+} + E_{\mu^-} > 40$ GeV (similar with 60 and 80 GeV).
  - $|\eta(\mu)| < 2.5$.
- We can recover to some extent the difference in shapes!

Datta,Kong,KM (preliminary)



- Backgrounds? Other tricks? Strong KK production?

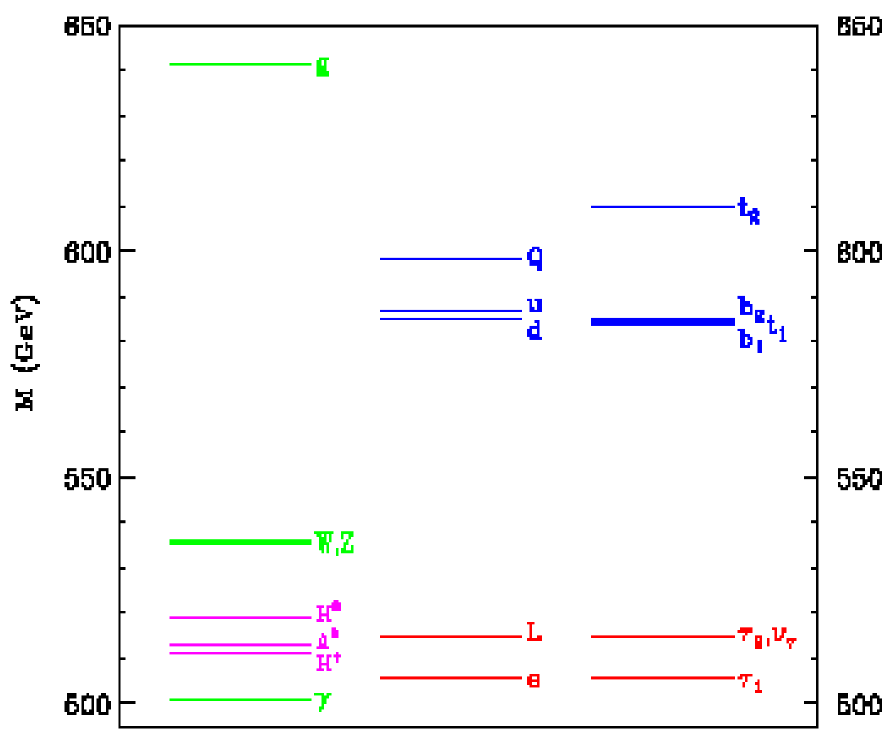
Studies of spin sensitive variables neede

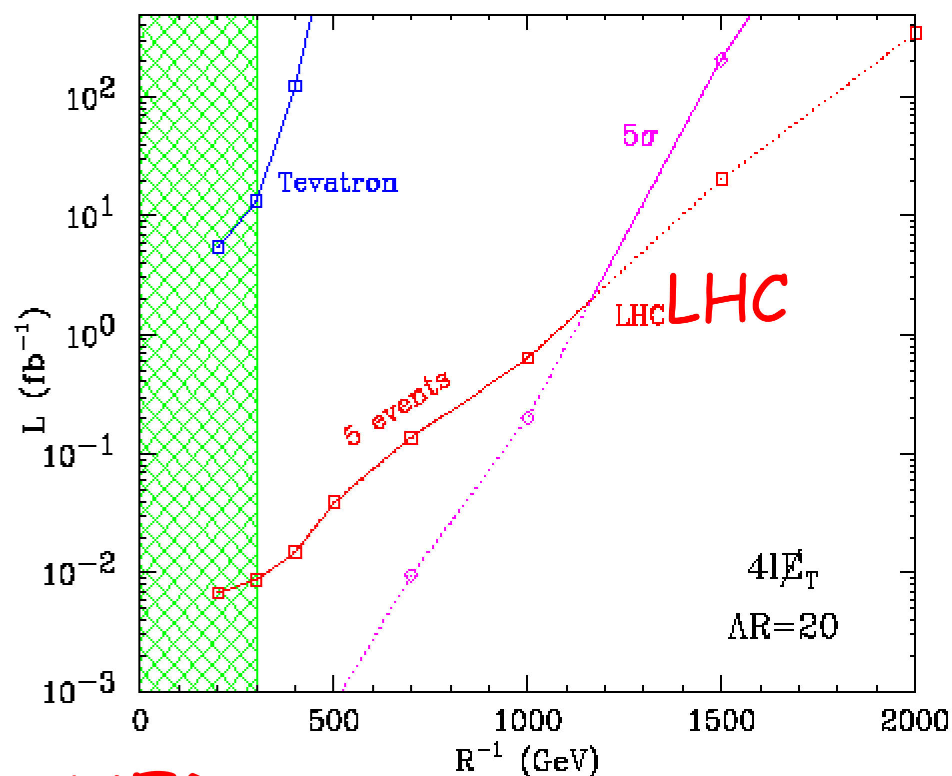
UED

K.C. Kong [hep-ph/0502041]

The KK spectrum in UED resembles that of SUSY

Discovery Reach at LHC in $Q_1 Q_2 \to Z_1 Z_1 \to 4\ell + \not{E}_T$





SUSY or UED?