BSM Physics at the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Barcelona, 09/2010

1. Introduction
2. Introduction to Supersymmetry
3. Supersymmetry at the LHC
4. More BSM phenomenology at the LHC
5. Conclusions

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BSM Physics at the LHC (III)

More BSM Phenomenology at the LHC

1. Z' models

2. 4th generation models

3. Extra dimensions

4. Little Higgs models

1. Z' models

Z' is the gauge boson of an additional $U(1)$

$\longrightarrow$ remnant of a larger gauge symmetry

$$\begin{aligned} SO(10) &\to SU(5) \otimes U(1) \\ &\to SU(3) \otimes SU(2) \otimes U(1) \otimes U(1) \\ E_6 &\to SO(10) \\ &\to SU(5) \otimes U(1) \\ \ldots &\to \ldots \end{aligned}$$

$\Rightarrow$ many^2 possibilities!

. . . all with slightly different couplings of the Z'

Z' mass:

$$M^2_{ZZ'} = \begin{pmatrix} M_Z^2 & \Delta^2 \\ \Delta^2 & M_{Z'}^2 \end{pmatrix}$$

$$M_1^2 = M_Z^2 - \frac{\Delta^4}{M_{Z'}^2} \ll M_2^2$$

$$M_2^2 \approx M_{Z'}^2$$

$$\theta_{ZZ'} \approx -\frac{\Delta^2}{M_{Z'}^2}$$

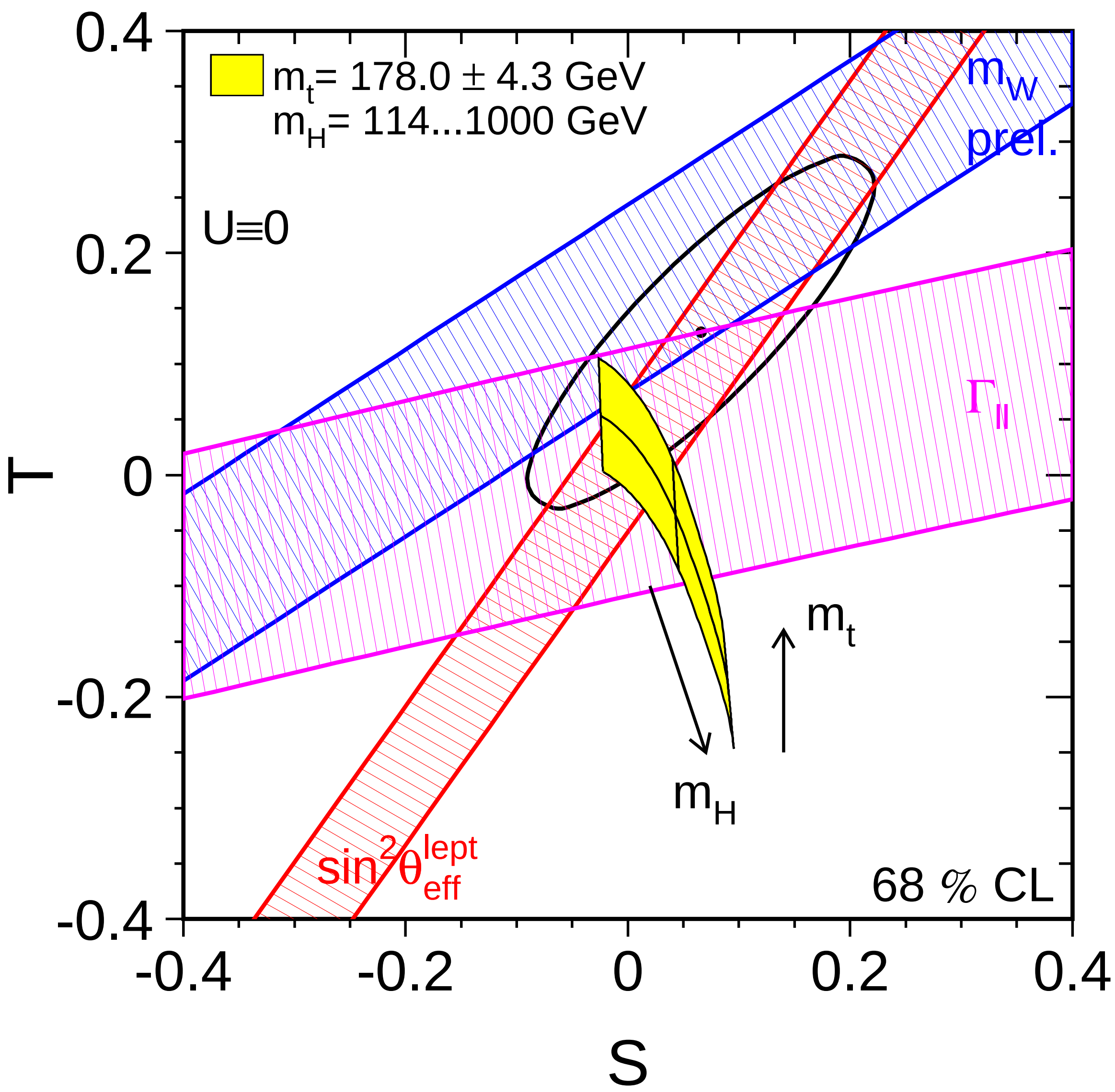
ρ parameter:

$$\rho \equiv \frac{M_W^2}{M_1^2 c_\mathrm{W}^2} \sim T$$

$\Rightarrow$ strong constraints from electroweak precision data

(Z pole experiments have little sensitivity to Z_2 exchange)

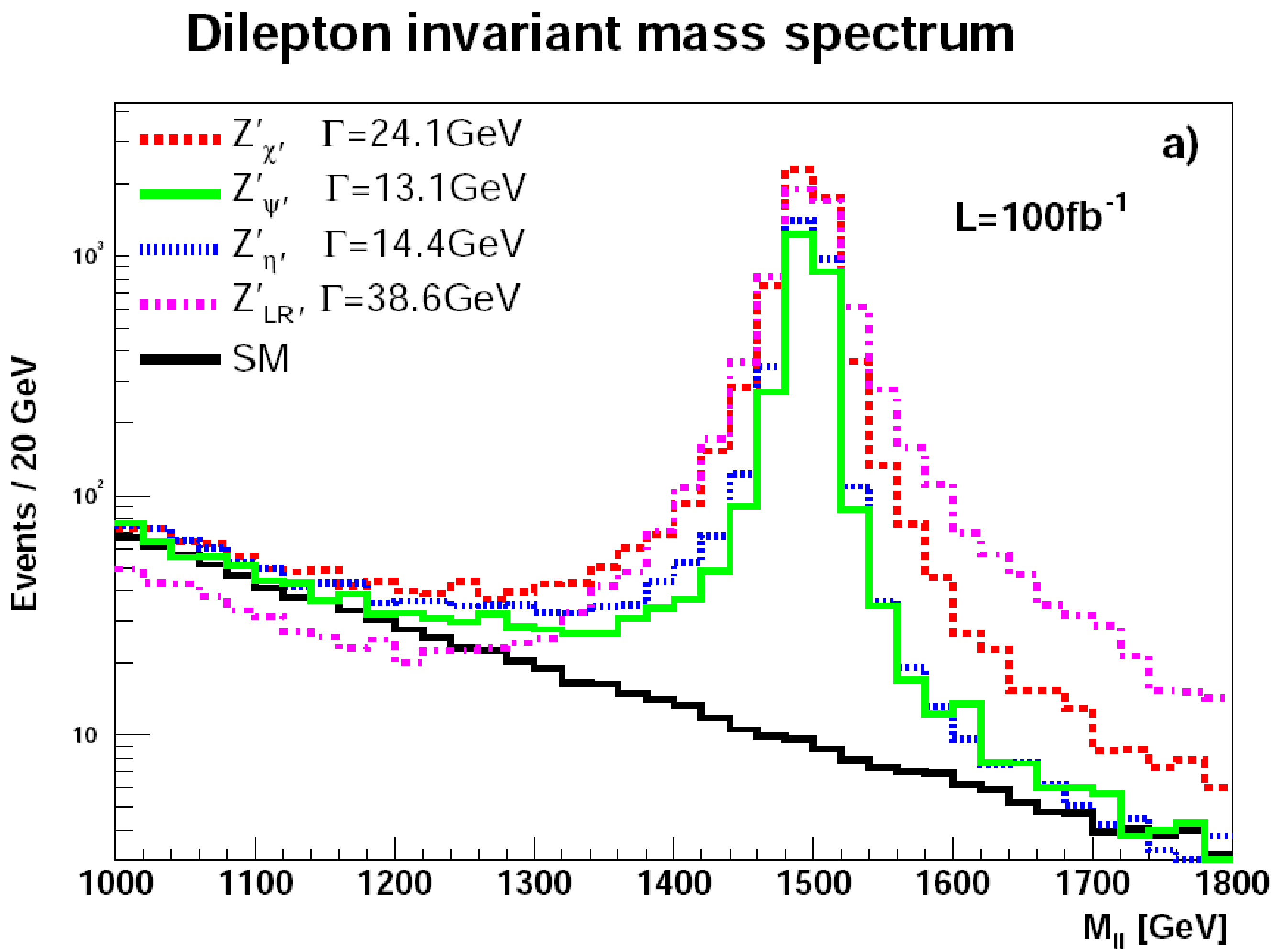
Electroweak precision constraints:



Z' compatible with heavier Higgs boson!

Golden channel: $Z' \to \ell\ell$ ($\ell = e, \mu$)

[*M. Dittmar, A. Nicollerat, A. Djouadi '03*]

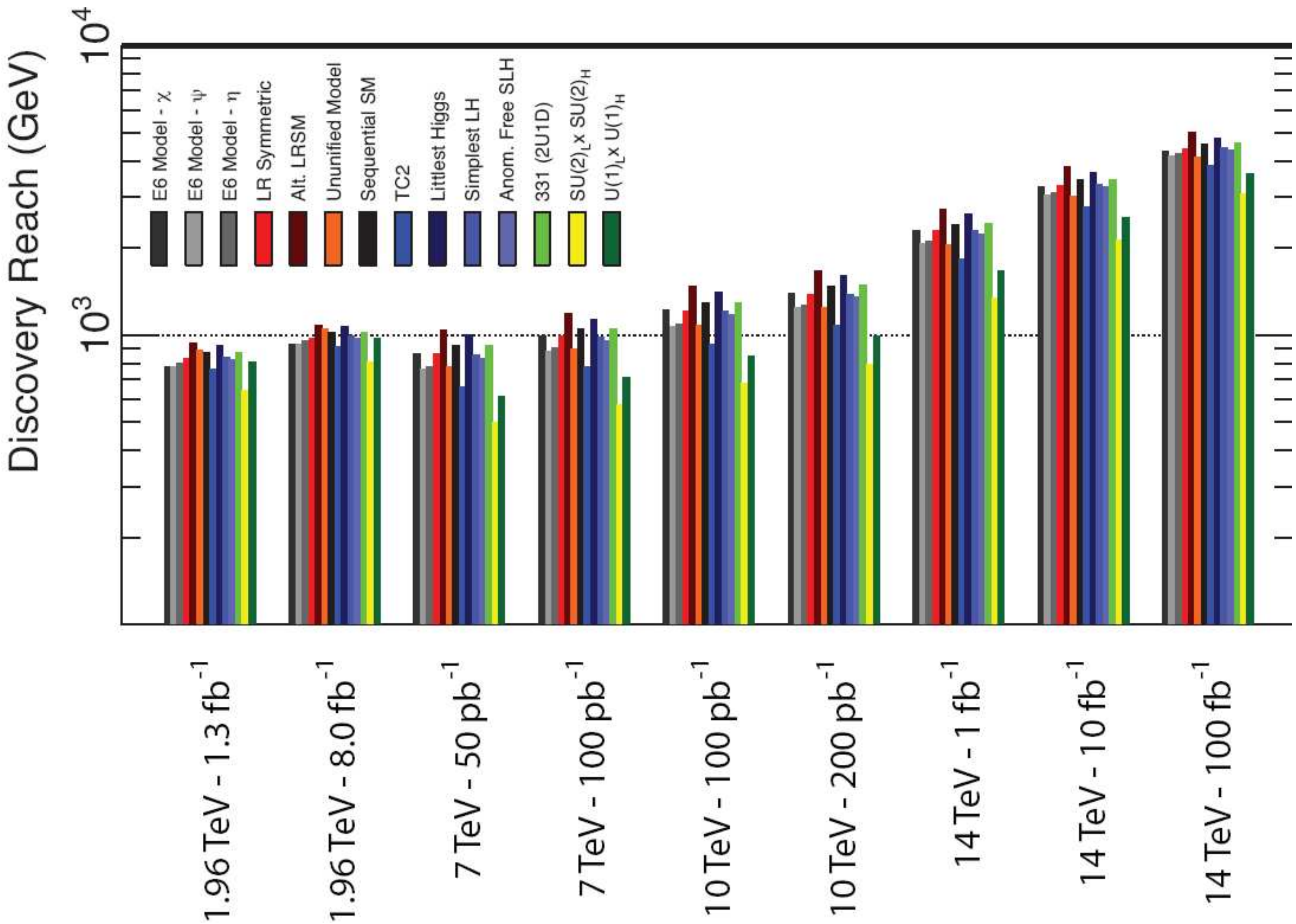


$M_{Z'} = 1.5$ TeV, $\sqrt{s} = 14$ TeV, $\mathcal{L}_{\text{int}} = 100$ fb^{-1}

$\Rightarrow$ "easy" signal

Reach for various Z' models:

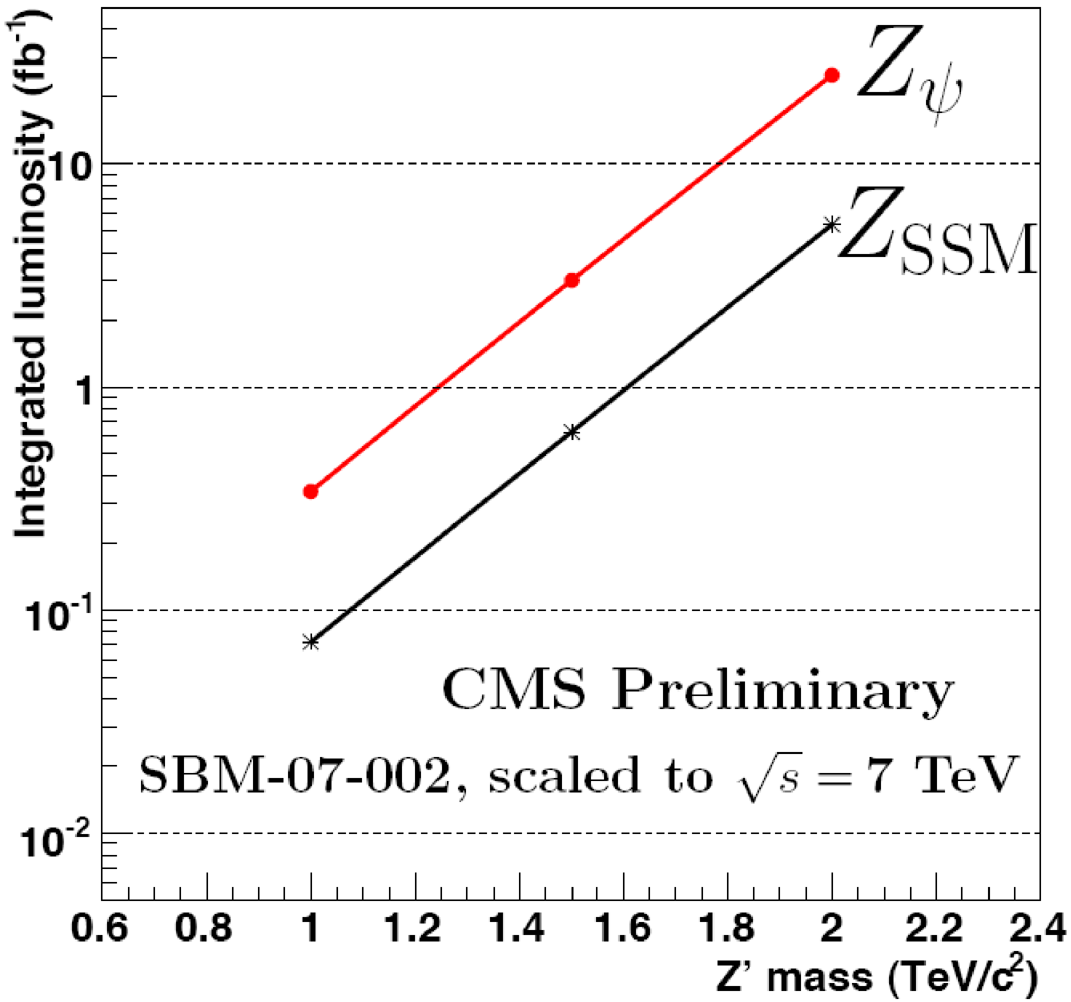
[*R. Diener, S. Godfrey, T. Martin '09*]



$\Rightarrow$ large reach with low luminosity

Reach for two Z' models:

[*CMS '10*]



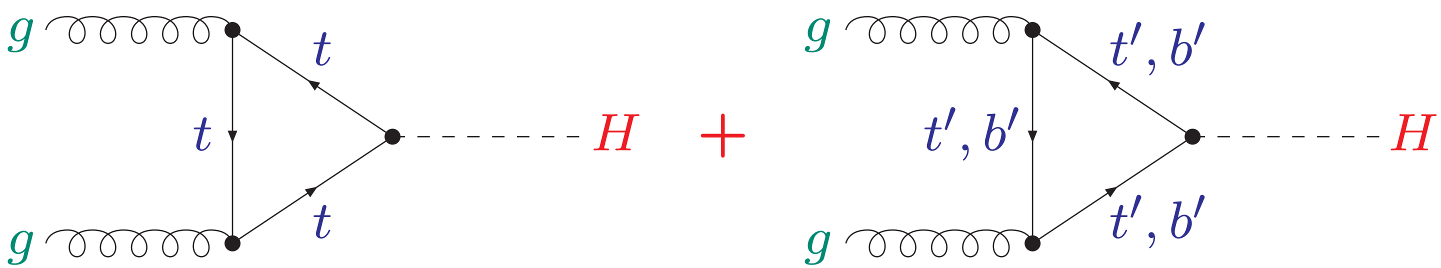
$\Rightarrow$ large reach with low luminosity, already at $\sqrt{s} = 7$ TeV

2. 4th generation models

Assume the SM with a 4th generation of heavy fermions
(SM4 = SM + 4th generation of quarks and leptons)

Relevant changes:

1. additional contribution to $gg \to H$:



$\Rightarrow$ factor of ~ 9 in Higgs production cross section

2. $\Rightarrow$ factor of ~ 9 in $\Gamma(H \to gg)$

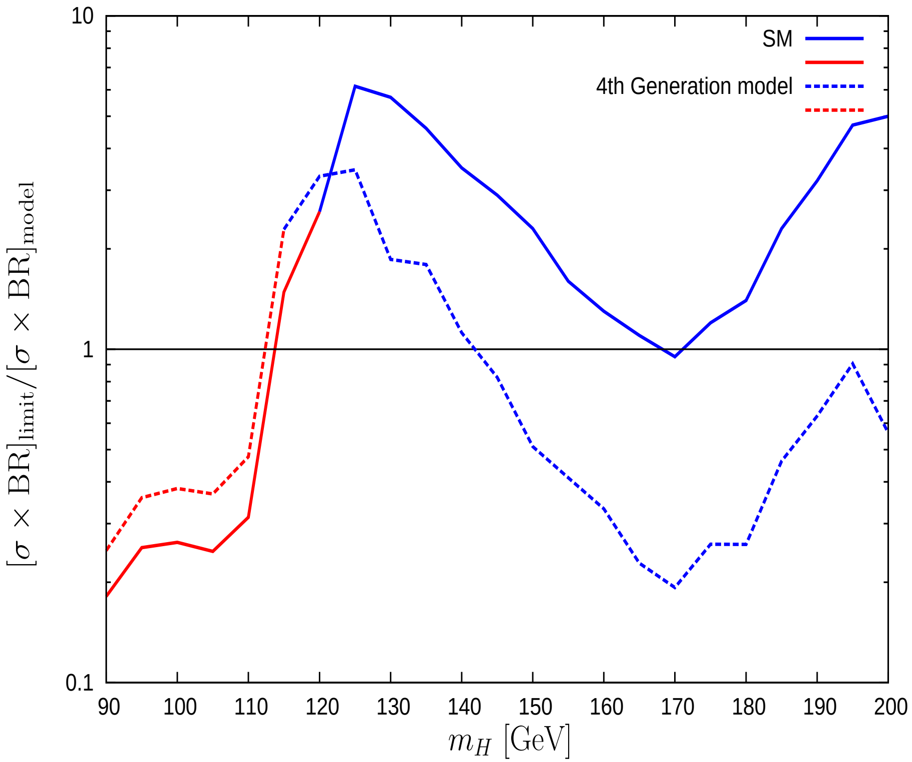
$\Rightarrow$ reduced BR($H \to b\bar{b}$), BR($H \to \tau^+\tau^-$)

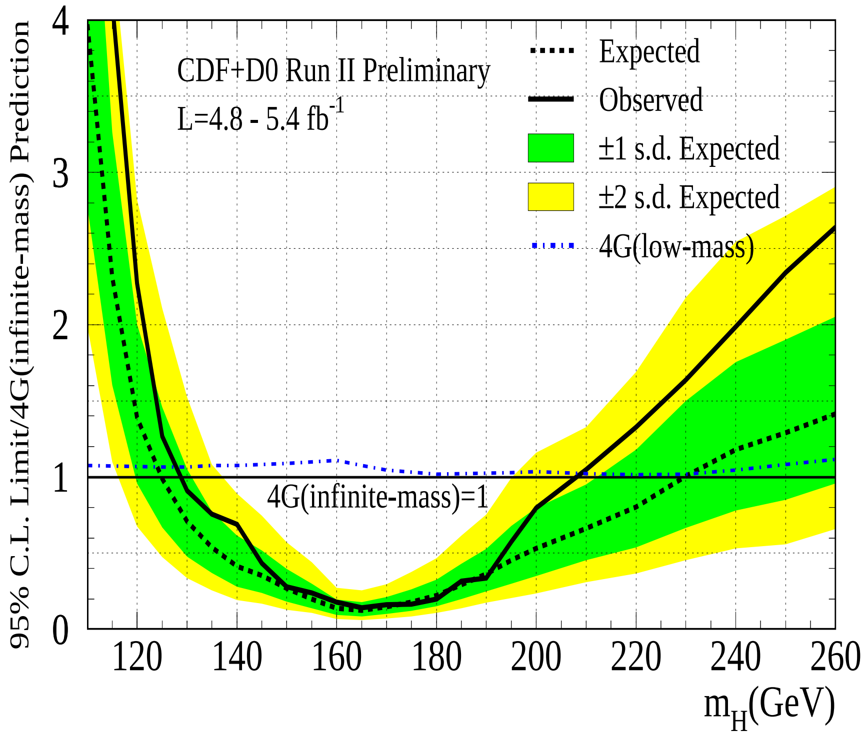
Simple approximation recently confirmed by explicit calculation
[*C. Anastasiou, R. Boughezal, E. Furlan '10*]

Limits on M_H from LEP and Tevatron searches

[P. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08] [CDF, DØ '10]

code: HiggsBounds



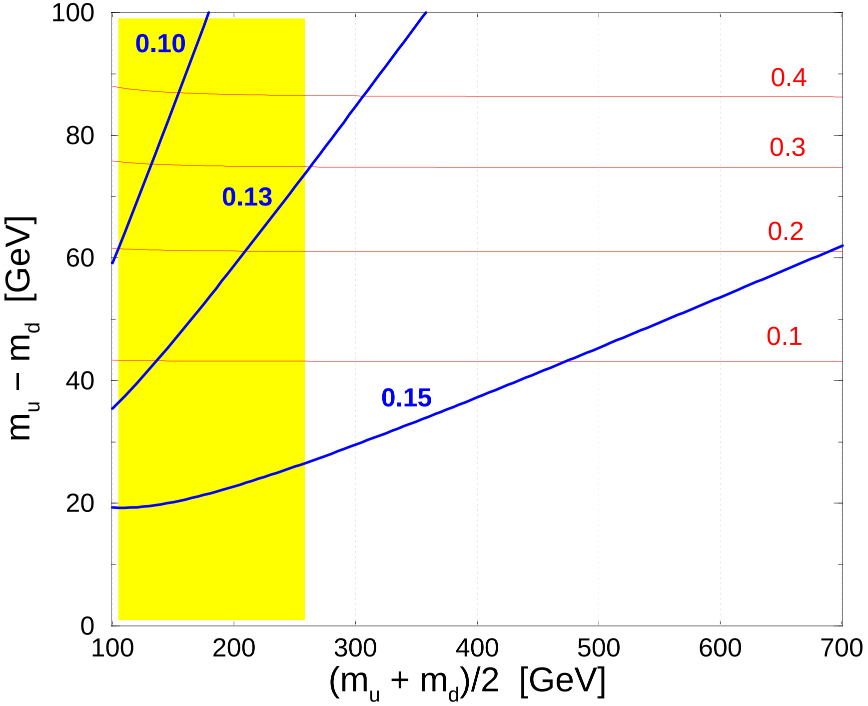


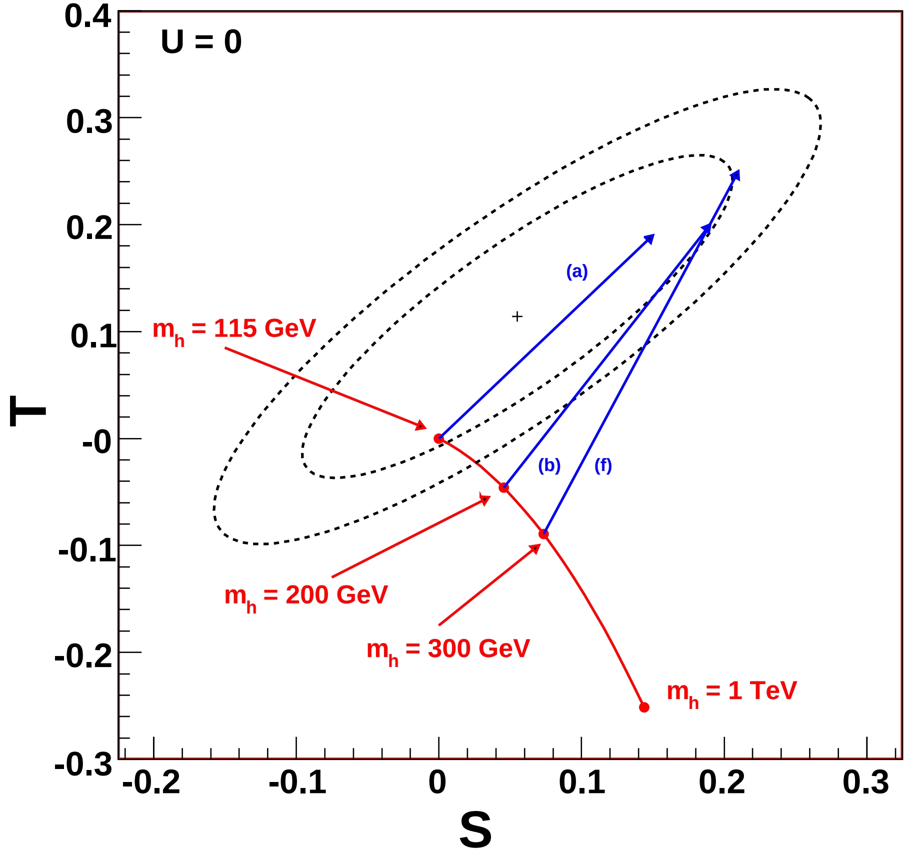
⇒ only 112 GeV $\lesssim M_H \lesssim$ 130 GeV, $M_H \gtrsim$ 210 GeV still allowed

⇒ tested soon by the Tevatron ??

Electroweak precision data for SM4:

[*G. Kribs, T. Plehn, M. Spannowsky, T. Tait '07*]



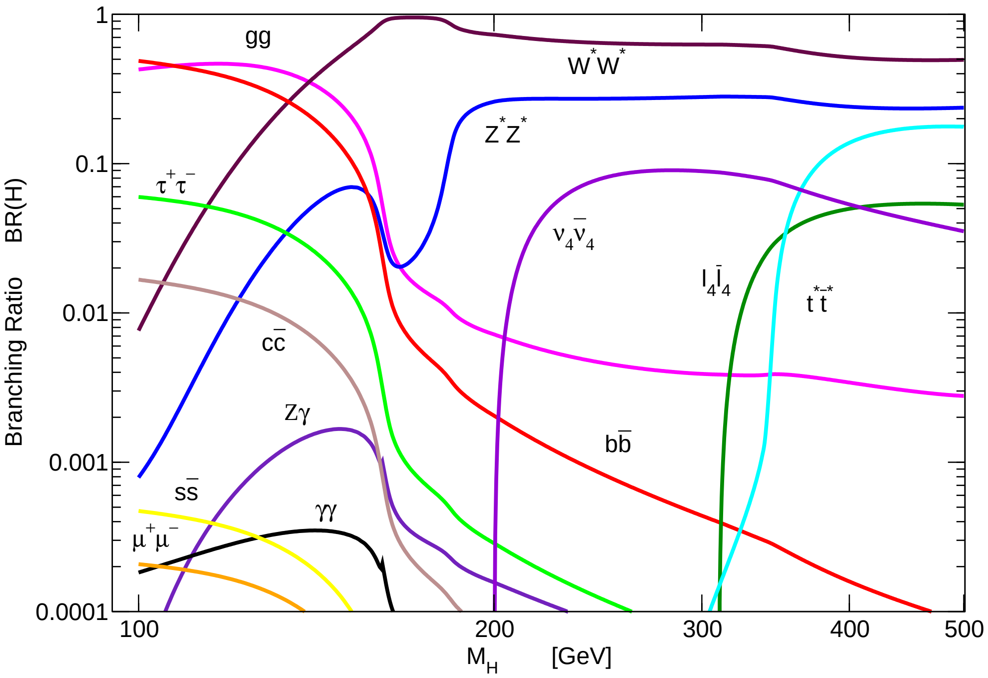


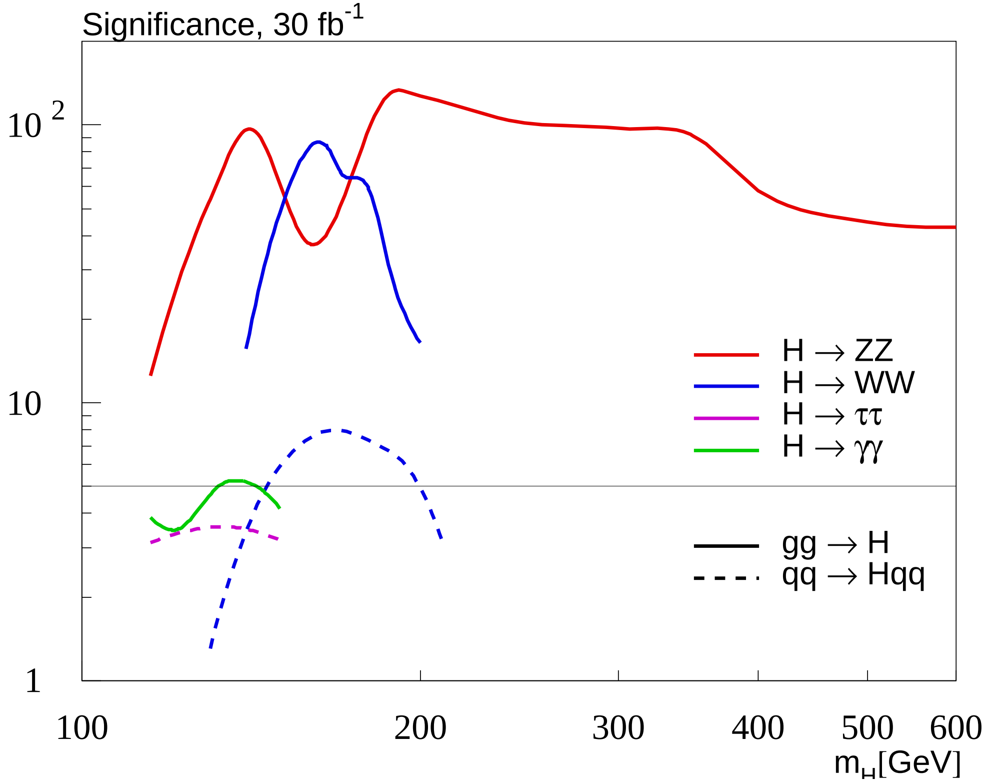
$\Rightarrow$ heavy Higgs can be accommodated

. . . by some fine-tuning of 4th generation masses

SM4 Higgs physics at the LHC:

[*G. Kribs, T. Plehn, M. Spannowsky, T. Tait '07*]



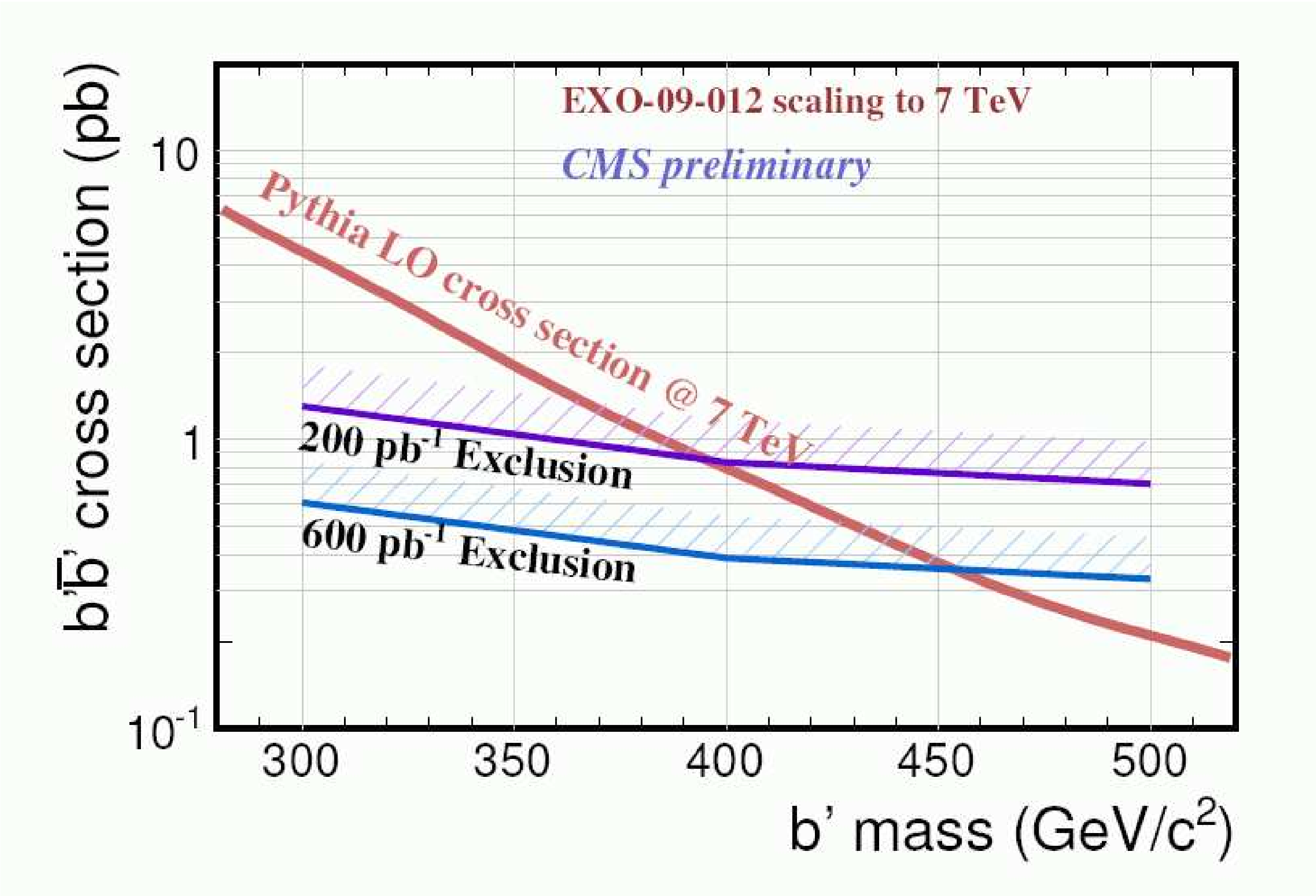


⇒ modified branching ratios

but BR($H \to WW^{(*)}$) and BR($H \to ZZ^{(*)}$) still strong

⇒ discovery possible with 30 fb^{-1}

Reach for b' quarks: [CMS '10]



⇒ large reach with low luminosity, already at $\sqrt{s} = 7$ TeV

3. Extra dimensions

Two general types:

1. flat (or factorizable) geometry

   $\rightarrow$ any number of (additional) dimensions:
   3+1 space-time + (D-4) extra dimensions

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (\mu, \nu = 0, 1, 2, 3, \ldots D)$$

2. warped (or non-factorizable) geometry

   $\rightarrow$ "warp factor" (for one extra dimension:) $a(y)$

$$ds^2 = a(y)(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2 \quad (\mu, \nu = 0, 1, 2, 3)$$

Size of the extra dimensions:

For flat geometries the extra dimensions must be small, i.e. compact

Compactifying extra dimensions leads to periodicity conditions

One extra dimension:

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{k=+\infty} \phi^{(k)}(x_\mu) e^{iky/R}$$

R: inverse compactification size / radius

→ Kaluza-Klein (KK) modes $\phi^{(k)}(x_\mu)$
→ infinite number of KK modes!

Masses of KK modes:

$$m_k^2 = m_0^2 + \frac{k^2}{R^2}$$

Many options: which field sits where?

- ADD:
  n compactified extra dimensions with flat geometry $\to$ bulk
  only gravity propagates in the full D dimensional space-time
  SM fields live in the 4-dim subspace $\to$ brane
- TeV^{-1}:
  one or more compactified extra dimensions with flat geometry and sizes of $\mathcal{O}\left(10^{-19}\right)$ m, i.e. of TeV scale
  SM fields live in the 4-dim subspace $\to$ brane
- UED:
  $\to$ Universal Extra Dimensions
  also SM gauge bosons and fermions can propagate in the bulk
- RS:
  only gravity propagates in a 5-dim warped bulk
  one compactified extra dim $+$ two 4-dim branes:
  – SM fields live in the "TeV brane"
  – other: "Planck brane"

  $\to$ adding a scalar field to the warped bulk to stabilize the brane distance

ADD at the LHC (I):

solution to the hierarchy problem:

$$M^2_{\text{Pl}(4)} = M^{n+2}_{\text{Pl}(4+n)}\, R^n \quad \Rightarrow \quad M_{\text{Pl}(4)} = \mathcal{O}(1\ \text{TeV})$$

mass difference of KK gravitons:

$$\Delta m \approx \left(\frac{M_{\text{Pl}(4)}}{1\ \text{TeV}}\right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}}$$

$\Rightarrow$ very close to each other

$\Rightarrow$ very characteristic for ADD

Possible detection modes:

– direct KK graviton production

– indirect KK graviton effects as quantum corrections

ADD at the LHC (II):

direct KK graviton production

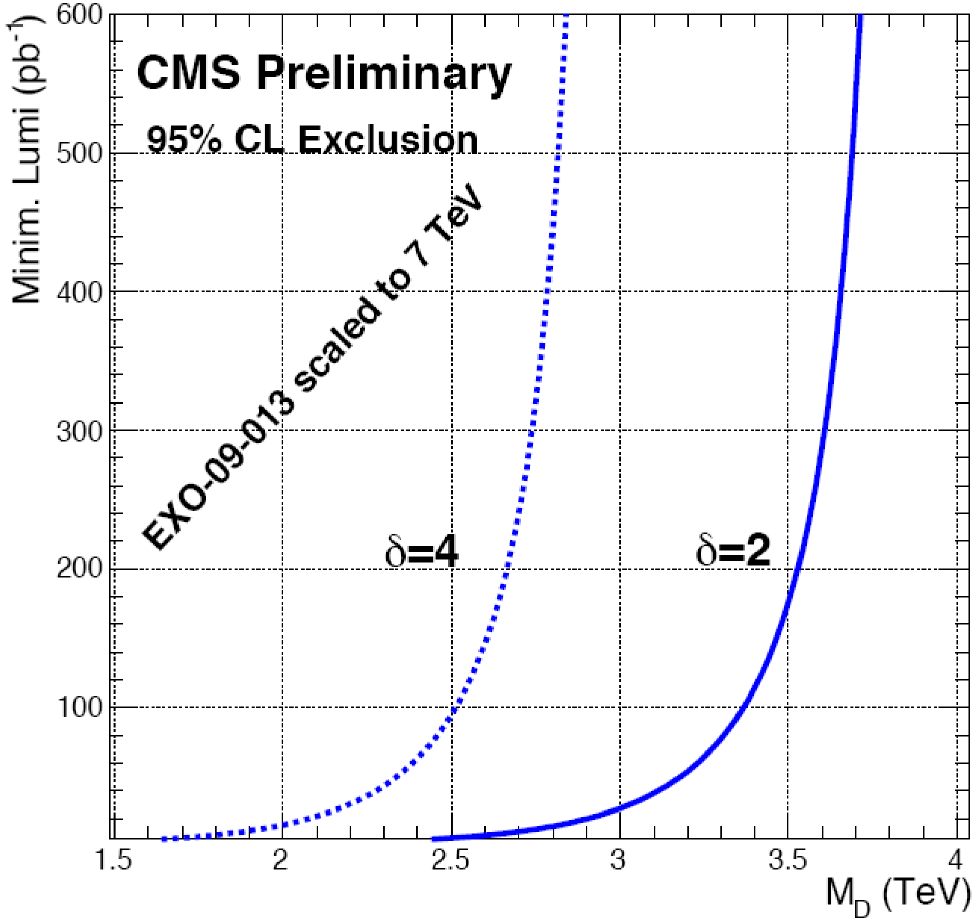
$$pp \to G_n G_n + \{g, \gamma, Z\}$$

G_n escape undetected

$\Rightarrow$ signature: $\{g, \gamma, Z\}$
$+$ missing energy

$(n \leftrightarrow \delta,\ M_D \leftrightarrow M_{\mathrm{Pl}(4)})$

$\Rightarrow$ exclusion potential



ADD at the LHC (III):

direct KK graviton production

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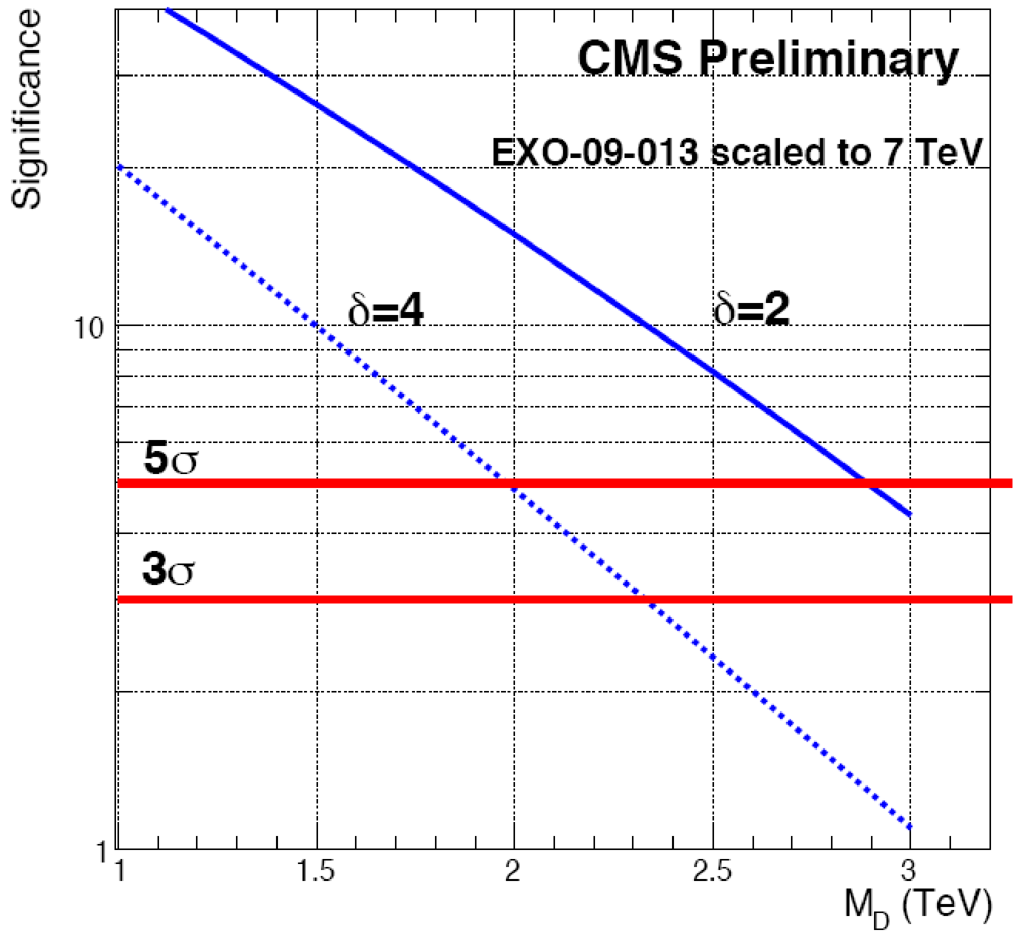
$(n \leftrightarrow \delta,\ M_D \leftrightarrow M_{\mathrm{Pl}(4)})$

$\Rightarrow$ discovery potential



UED at the LHC (I):

KK 0^{th} modes are identified with 4-dim SM particles

each SM particles has its 1^{st} KK mode

⇒ part of the spectrum is similar to the MSSM → T

"KK parity" conserved:

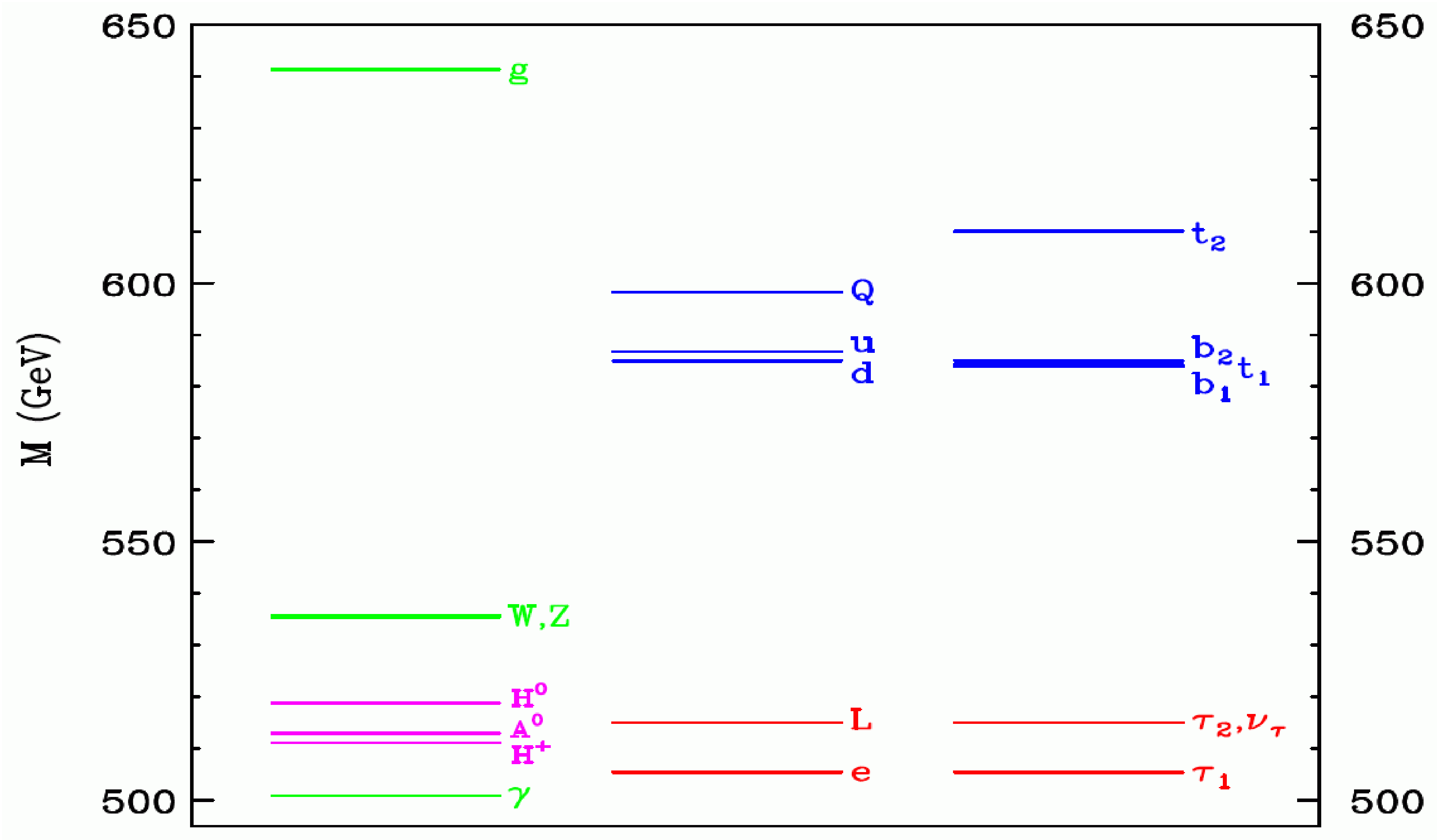
⇒ light UED KK modes are pair produced
light UED KK modes decay to SM particle
and other light UED KK mode

⇒ LKP (lightest Kaluza-Klein particle) is stable, DM candidates: γ_1, ν_1

⇒ phenomenology very similar to MSSM

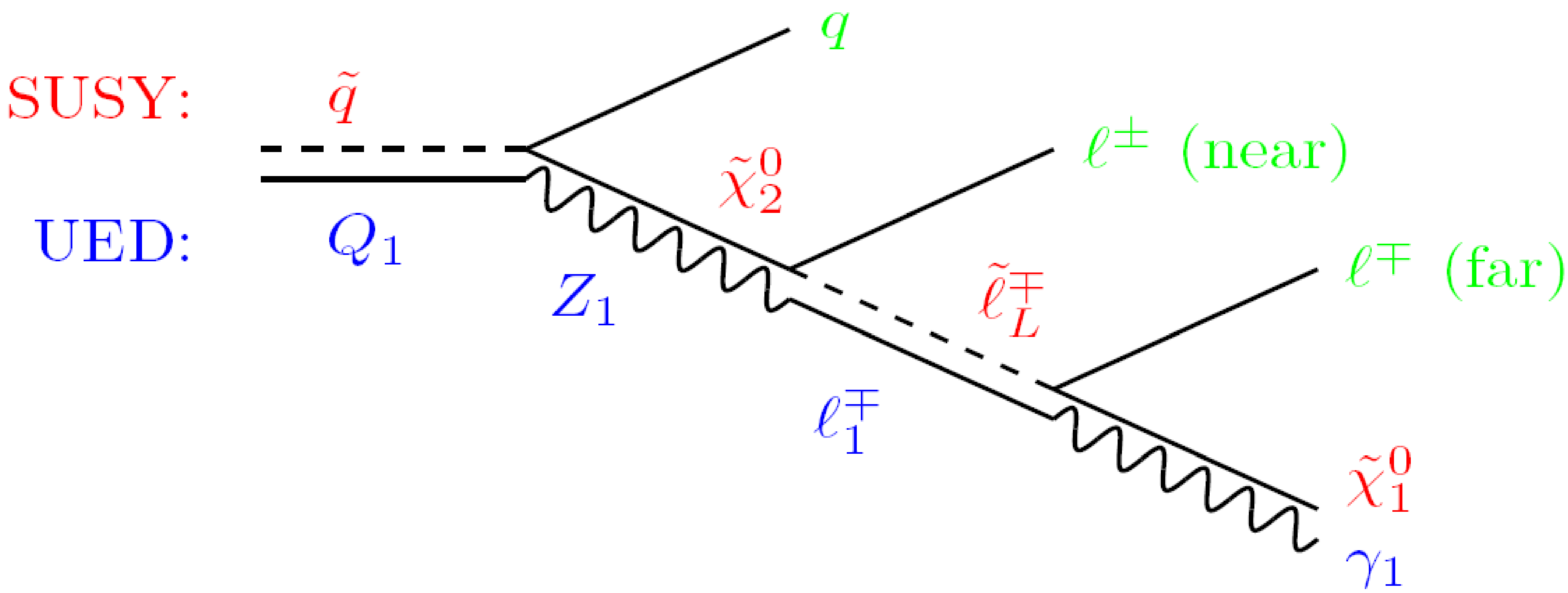
⇒ very similar decay chains

UED particle spectrum:



Comparison of SUSY with e.g. Extra Dimensions:

⇒ cascades may look very similar:



UED at the LHC (II):

Possibilities for distinction of UED and SUSY:

1. size of cross section:

   colored SM particles: quarks
   SUSY partners: scalar quarks
   UED partners: fermionic KK states

$$\text{scalar}: \quad \sigma \propto (1 - \cos^2\theta)$$
$$\text{fermion}: \quad \sigma \propto (1 + \cos^2\theta)$$

   ⇒ UED has larger cross sections for same masses than MSSM

2. search for 2$^{\text{nd}}$ KK mode:

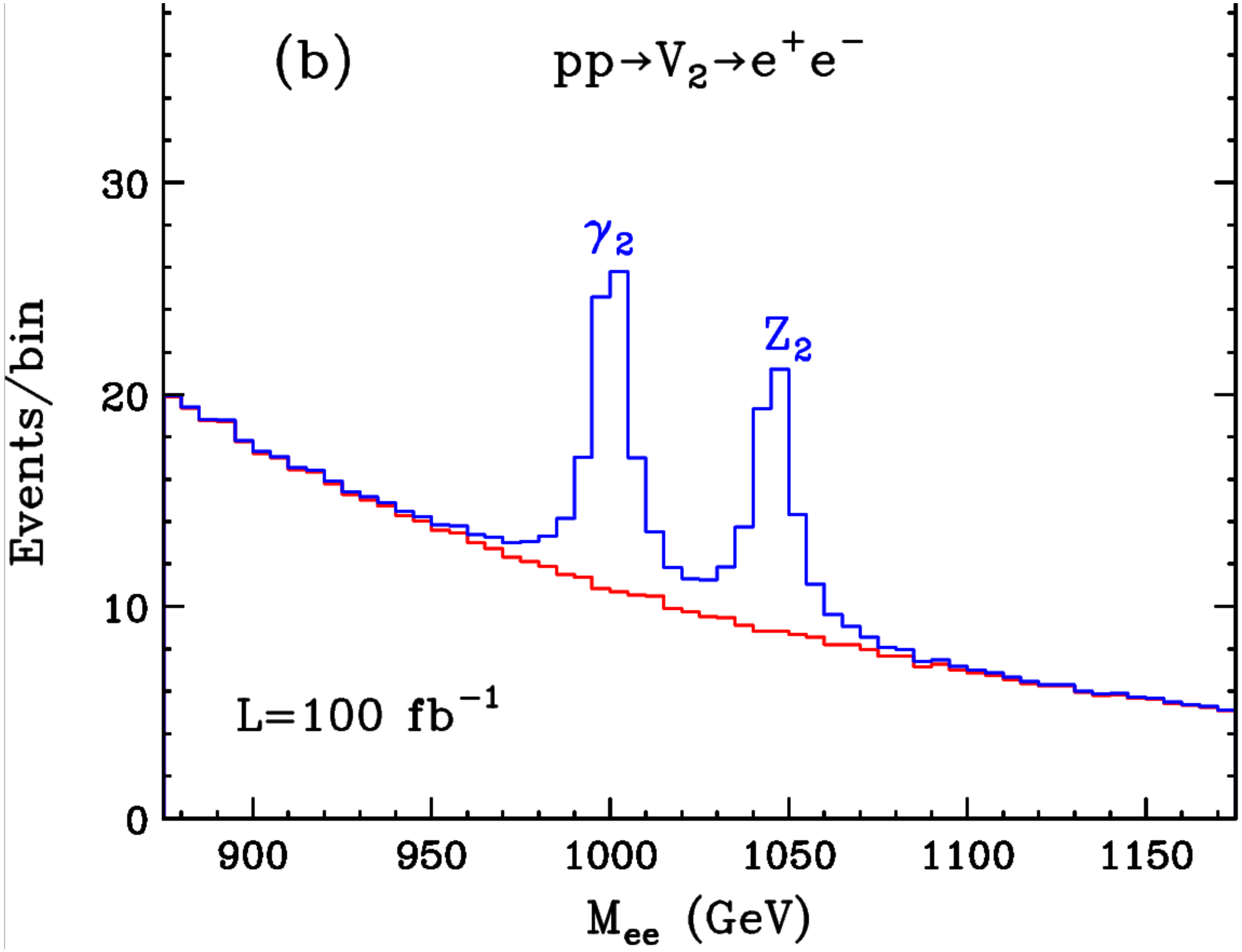
   possible:

$$pp \to V_2 \to \ell\ell \quad (V_2 = \gamma_2, Z_2,\ \ell = e, \mu)$$

3. measurement of mass differences, spin, . . .

UED at the LHC (III):

[*A. Datta, K. Kong, T. Matchev '05*]



$R^{-1} = 500$ GeV, $\sqrt{s} = 14$ TeV, $\mathcal{L}_{\text{int}} = 100$ fb^{-1} $\Rightarrow$ clear signal

RS at the LHC (I):

search mode: $pp \to G_{\mathsf{KK}} \to \gamma\gamma$

Parameter dependence:

– graviton mass: G_{KK}

– coupling strength: $\tilde{k} = k/\overline{M}_{\mathsf{Pl}}$

RS at the LHC (II):

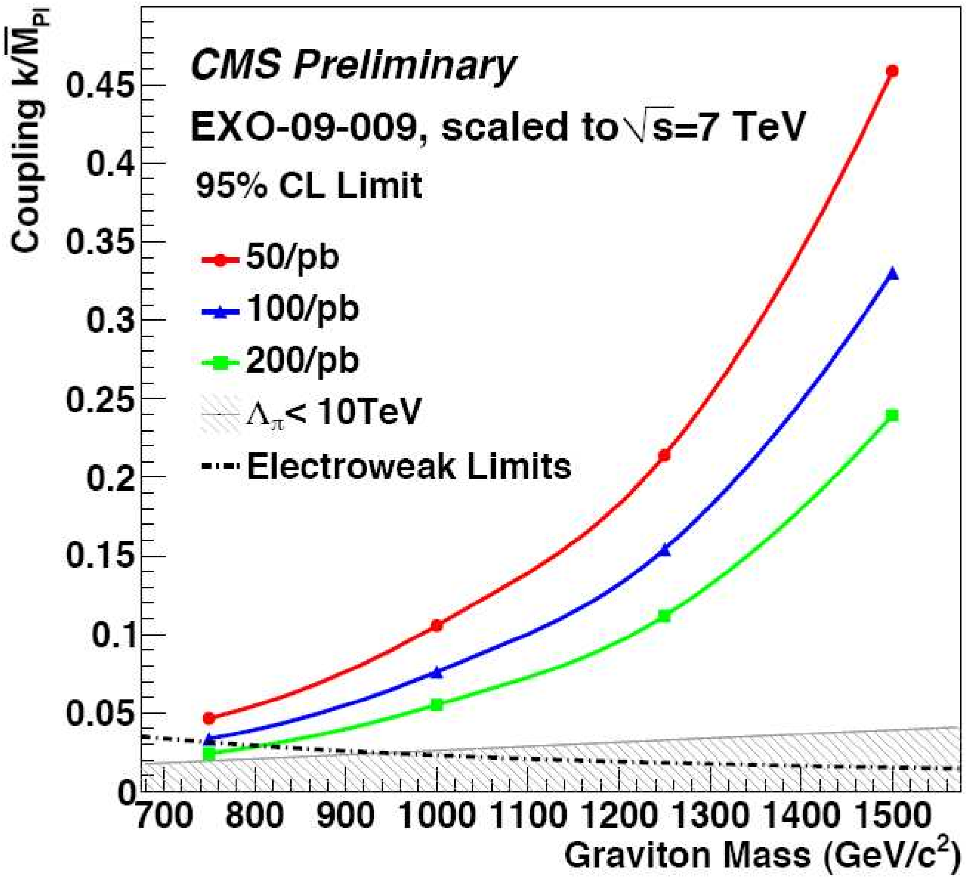
di-photon channel:

$$pp \to G_{\mathsf{KK}} \to \gamma\gamma$$

⇒ peak in the invariant

di-photon mass spectrum

⇒ exclusion potential



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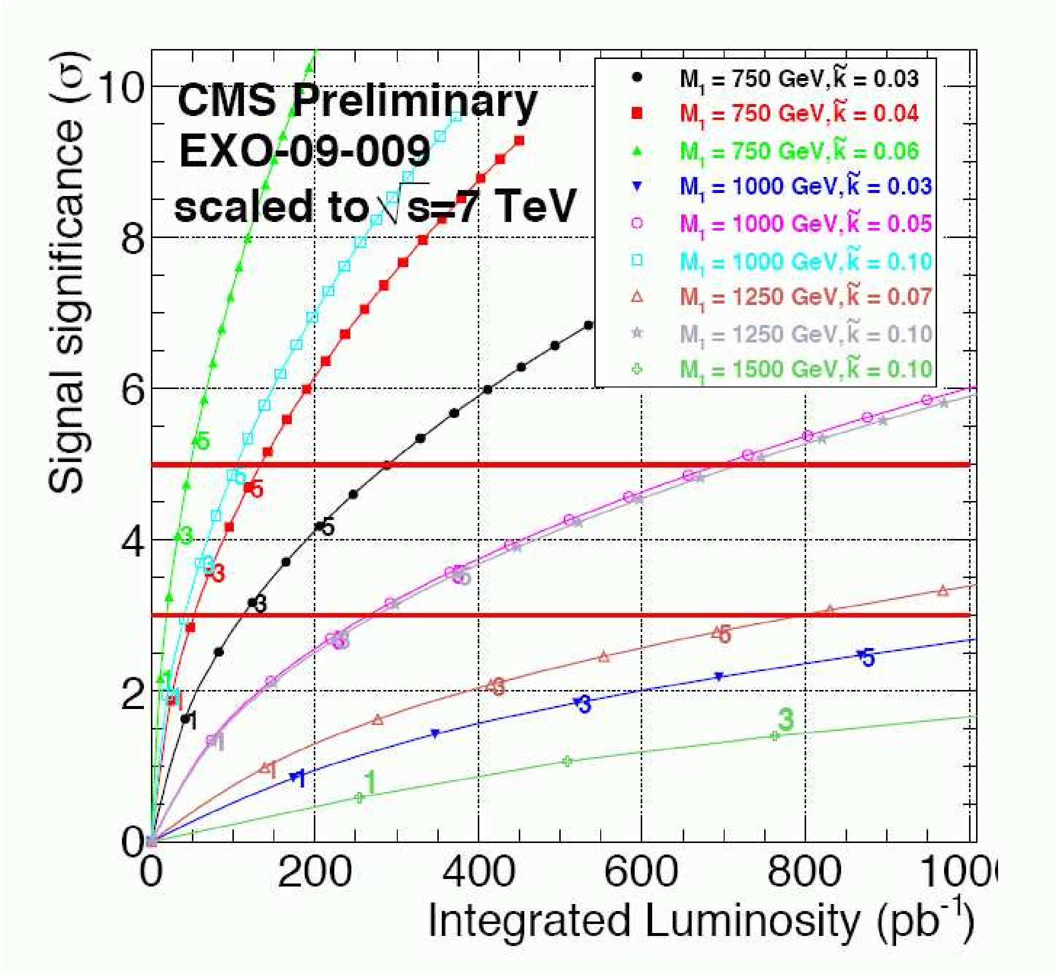
$\Rightarrow$ peak in the invariant

di-photon mass spectrum

$\Rightarrow$ discovery potential



4. Little Higgs models

Main idea of Little Higgs (LH):
light Higgs boson as a Nambu-Goldstone boson
of an approximate symmetry

Breaking of a gauge group:

$$G \to H \quad \text{at the scale } f$$

(with H being e.g. the SM gauge group)

Problem:
this set-up induces via gauge boson loops (quadratic divergences)

$$v \approx f$$

EWPO: $f = \mathcal{O}(1\text{ TeV})$

+ quadratic divergences from top loops

$\Rightarrow$ simple idea does not work

Solution in LH models: "collective symmetry breaking"

consider a gauge group G such that

$$G \supset G_1 \times G_2$$

and each G_i contains the SM gauge group

Now after

$$G \to H \quad \text{at the scale } f$$

the gauge bosons of the extended gauge group (with $M \approx g\,f$) cancel the quadratic divergences and

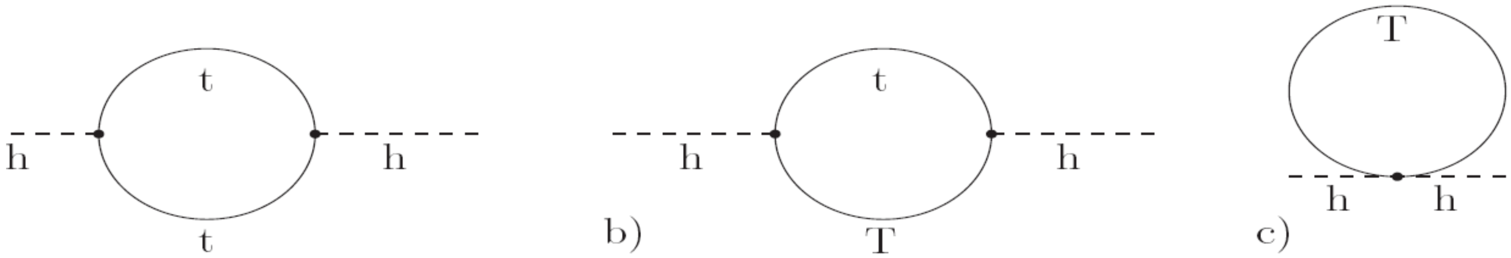
$$v \ll f$$

is possible

Still a problem: quadratic divergences from top loops

Still a problem: quadratic divergences from top loops

⇒ introduction of vectorial top-partner T fermions



Quadratic divergences:

– removed at one-loop
– not removed at two-loop
– log-divergences already at one-loop

⇒ theory valid up to $\Lambda = 4\pi f$

Little Higgs models:

Model depends on the gauge group G:

$$[SU(3)_L \times SU(3)_R]^4 : \text{ minimal moose model}$$

$$SU(5), SO(5) : \text{ littlest Higgs}$$

$$[SU(3) \times U(1)]^2 : \text{ simplest LH}$$

Common features:

– new gauge bosons
– new top partners (and possibly other partners)
– often additional scalar states . . .

General problem of LH models: EWPO!

New gauge bosons mix with SM gauge bosons
$\Rightarrow$ large tree-level contributions to EWPO

Solution 1:
$\Rightarrow$ make f large, $f =$ several TeV
($\to$ little hierarchy problem)

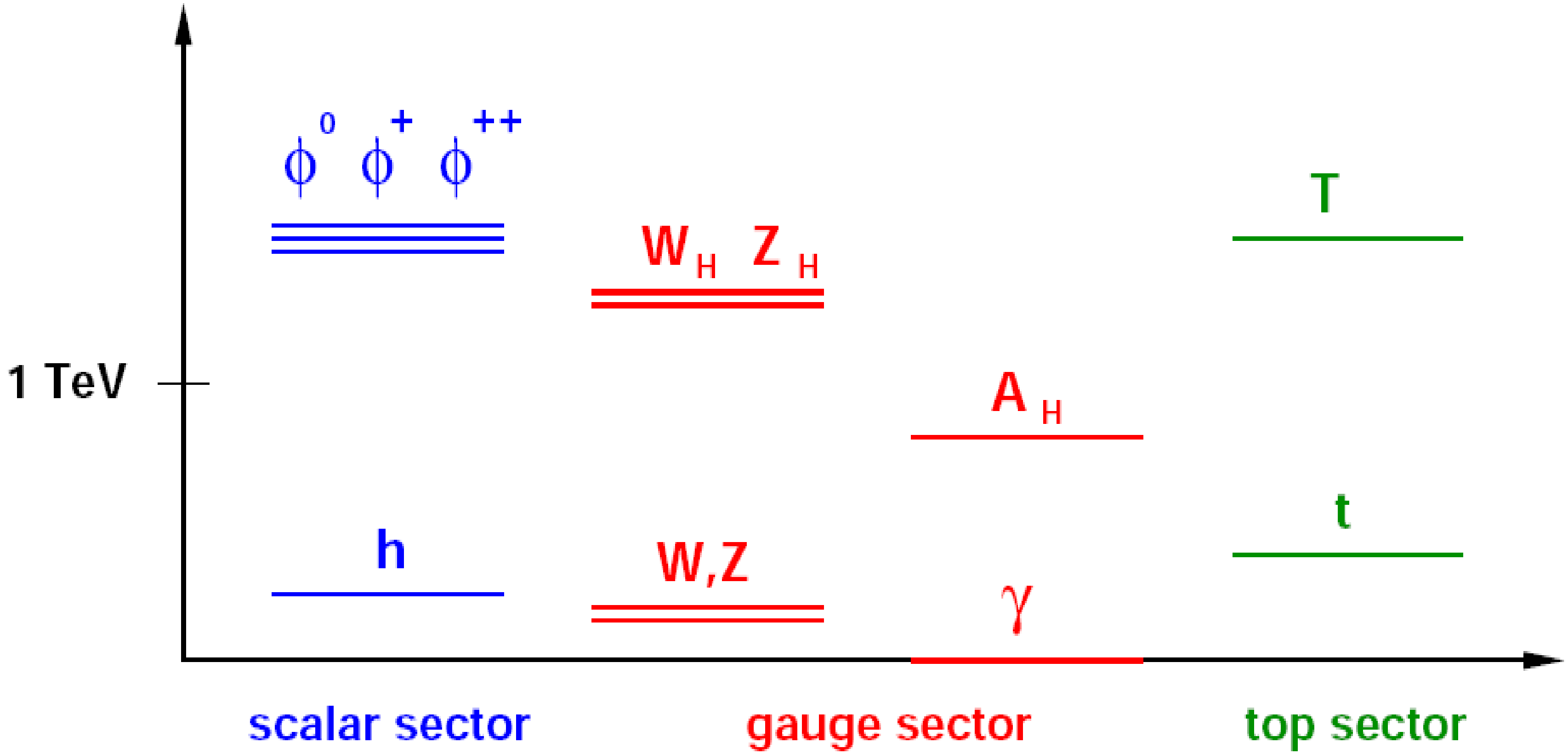
Solution 2:
new discrete symmetry: T parity (Z_2 symmetry)

SM: $T = +1$
LH: $T = -1$ $\Rightarrow$ no mixing between SM and new gauge bosons

additional heavy top states: allow for "heavy" Higgs boson

LTP is stable $\Rightarrow B_H$ is DM candidate

Generic Little Higgs particle spectrum:



LHC phenomenology of LH models:

very different for LH with or without T parity

LH with T parity:

QCD pair production: $pp \to TT$

with (cascade) decays of T: $T \to tB_H$
$\Rightarrow$ signal: missing energy

LH without T parity:

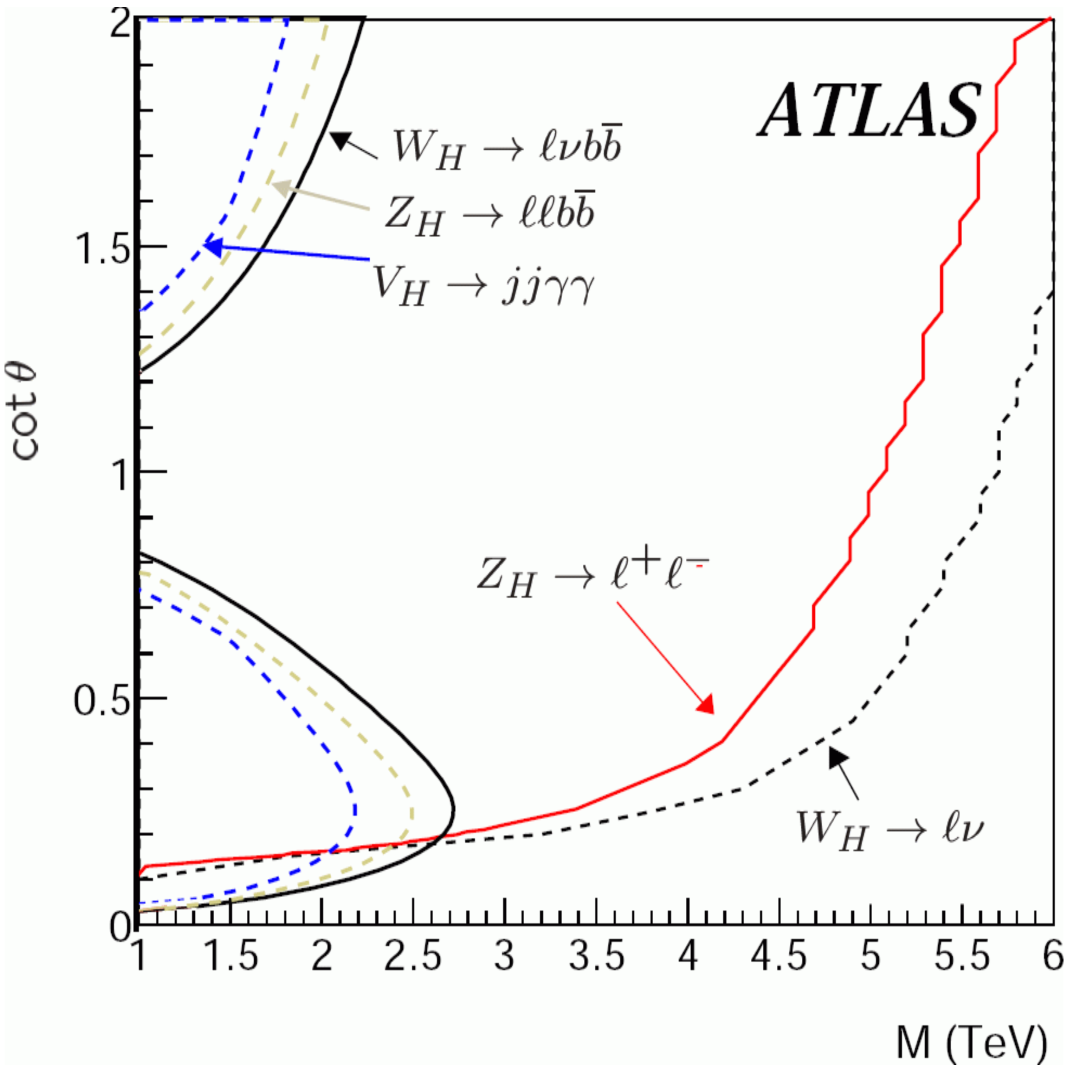
single production of T, B_H, Z_H, W_H, ...
with subsequent decay to SM particles
$\Rightarrow$ no missing energy

LHC phenomenology of LH models:

very different for LH with or without T parity

LH without T parity:

single production and decay of new LH particles possible



Outlook

- First the LHC has to re-discover the SM
  Important improvements for the W boson, top quark, B physics . . .
  $\Rightarrow$ sensitive test of the SM

- The Higgs mechanism continues to be our best bet for EWSB

- Low-energy Supersymmetry continues to be our best bet for physics beyond the Standard Model

- Within the next years the LHC will bring a decisive test of our ideas about SM extensions and the Higgs

- Data rules:

  We need experimental information from Tevatron, LHC, ILC,
  ν experiments, dark matter searches, low-energy experiments, . . .
  to verify / falsify our ideas about electroweak symmetry breaking,
  the Higgs, extensions of the SM, . . .

$\Rightarrow$ Very exciting prospects for the coming years

Expect the unexpected!

Interested in Theory Predictions?

Interested in

- theory predictions for the Tevatron?
- theory predictions for the LHC?
- theory predictions for the ILC?
- phenomenology analyses in Higgs/SUSY?

⇒ You can do your PhD at IFCA (Santander, Spain)

contact: Sven.Heinemeyer @ cern.ch

Santander, Spain: (15 minutes by foot from the institute :-)

contact: Sven.Heinemeyer @ cern.ch