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Physics Beyond the Standard Model

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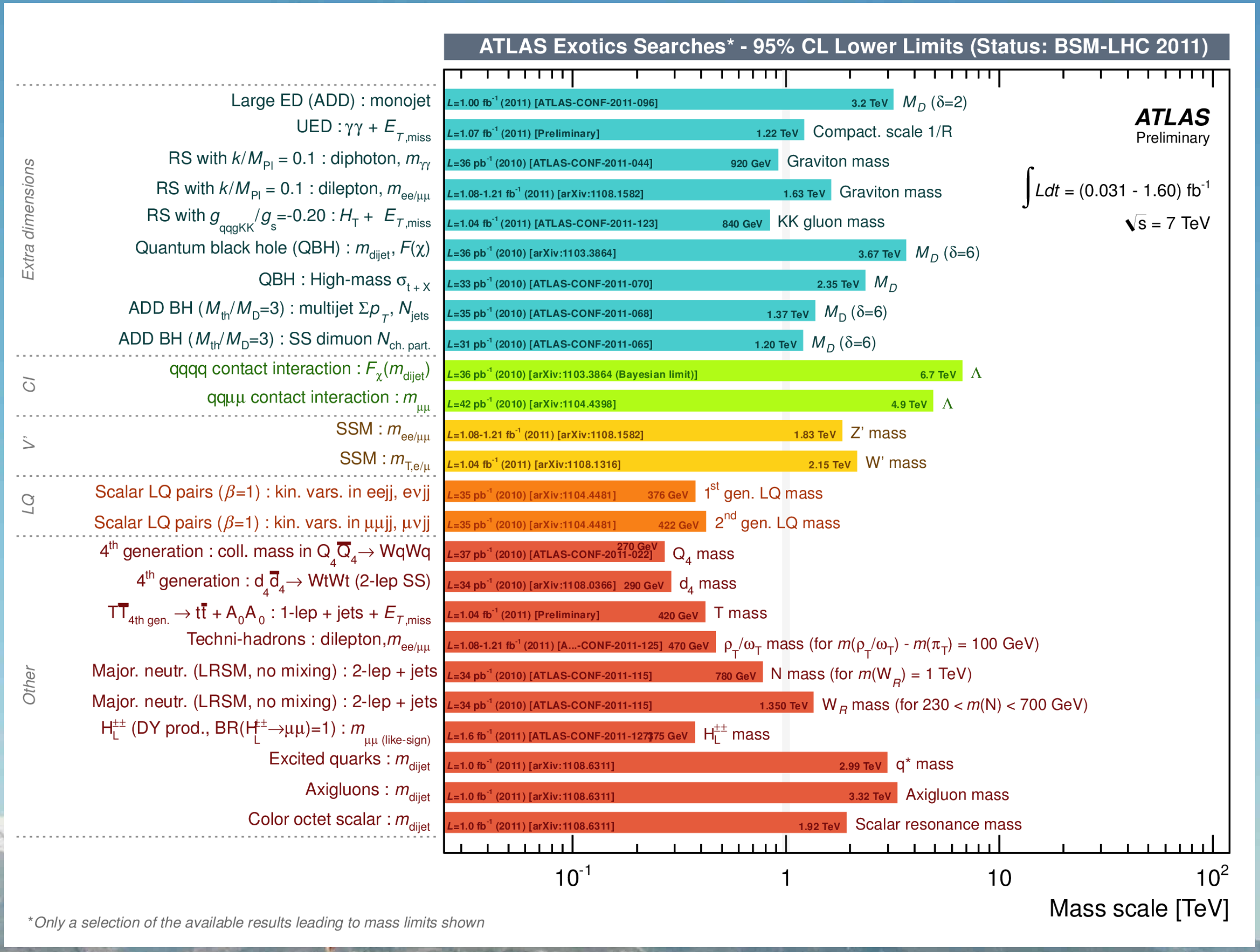
Beyond the SM Physics?

- One of the most common sentences in LHC experimental talks: no signs of new physics found (yet)



Beyond the SM Physics?

- One of the most common sentences in LHC experimental talks: no signs of new physics found (yet)
- And not because they are not looking …
  - Many (sophisticated) analyses
  - Luminosity increasing fast
- Time to give up on BSM physics?

Absolutely not!

  - EWSB sector still unexplored
  - Models of new physics not as accessible (did we really think they would be?)
- BSM physics more exciting than ever!

Outline

- Why physics beyond the standard model (BSM)?
- Which kind of physics BSM?
  - Not seen at LEP
  - Hierarchy problem
- NP “in pairs”
- “Single” NP
- “Disguised” NP
- Importance of the Higgs sector
- Summary and Outlook

The Standard Model

- Spontaneously broken gauge theory

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_Q$$

- Most general renormalizable Lagrangian with field content:

$$G_\mu^a,\ W_\mu^I,\ B_\mu$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R \times 3 \text{ families}$$

$$\phi = e^{\mathrm{i}\pi\cdot\sigma/(\sqrt{2}v)} \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

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All experimentally observed except for the Higgs boson

Why BSM at the LHC?

- Electroweak symmetry breaking (Hierarchy problem)
  - Elementary scalars (Higgs) are quadratically sensitive to UV physics: v=246 GeV highly unnatural
  - Can be protected by new symmetries (SUSY, LH,...) or replaced by new structures (Compositeness)

Hint: no elementary scalars found in nature

Why BSM at the LHC?

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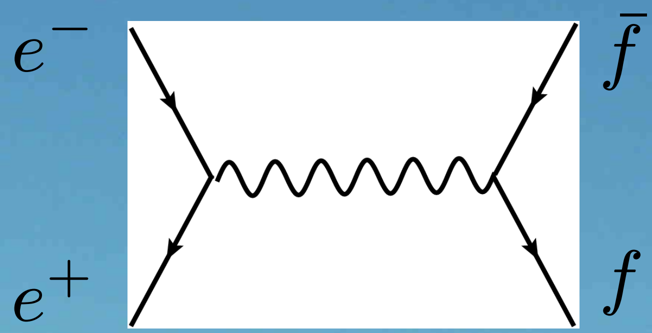
  - Can be protected by new symmetries (SUSY, LH,...) or replaced by new structures (Compositeness)
- Not only hierarchy problem
  - Dark matter, family replication, structure of masses and mixing angles, baryon asymmetry, …
- Not only LHC
  - Tevatron, flavor, neutrinos, astro-particles, ...

Which kind of NP?

- Not discovered at LEP



Measured with precision $\mathcal{O}(10^{-2} - 10^{-3})$

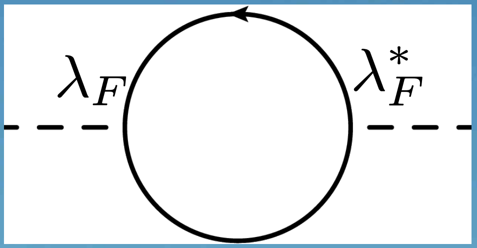
- Typical ways to evade constraints:
  - Loop suppression: weak coupling $\dfrac{g^2}{16\pi^2} \sim \mathcal{O}(10^{-2} - 10^{-3})$
  - Heavy NP with small couplings to SM

$$\frac{g^2 v^2}{M^2} \sim \mathcal{O}(10^{-2} - 10^{-3}) \text{ for } \frac{M}{g} \sim 7 - 8 \text{ TeV}$$

Can we still solve the hierarchy problem?

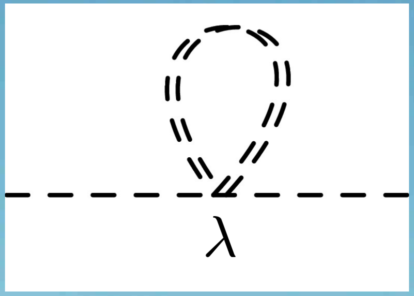
Hierarchy problem

- The hierarchy problem arises at the quantum level

$\delta m_H^2 \sim$ 

$\sim -2|\lambda_F|^2 \frac{\Lambda^2 N_c}{16\pi^2} + \ldots$

- As long as NP enters at the loop level, it can cancel the quadratic sensitivity

$\delta m_{H,NP}^2 \sim$ 

$\sim \lambda \frac{\Lambda^2 N_c}{16\pi^2} + \ldots$

- Impose a symmetry that forbids couplings with an odd number of new particles: no tree level effects but same one loop effects.
- Extra Higgs symmetry protection needed if NP scale is high

NP “in pairs”

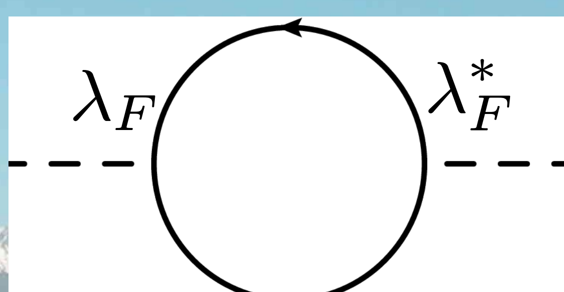
Supersymmetry (SUSY)

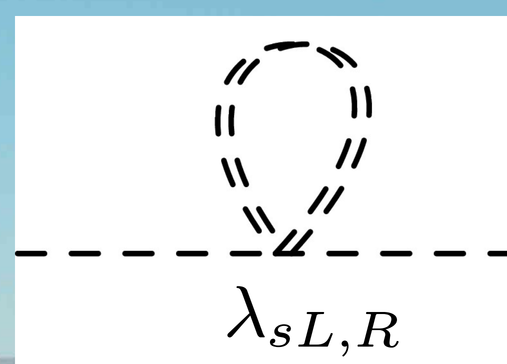
- Supersymmetry: fermion ⟷ boson symmetry.
  - Each particle has a supersymmetric partner with opposite statistics

Fermions		Sfermions
Gauge bosons	⟷	Gauginos
Higgs boson		Higgsinos

  - Chiral symmetry protects the Higgs mass

$$\delta m_H^2 = \frac{\Lambda^2 N_c}{16\pi^2}\left[-2|\lambda_F|^2 + \lambda_{sL} + \lambda_{sR}\right] + \ldots$$





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- SUSY $\Rightarrow \lambda_{sL} = \lambda_{sR} = |\lambda_F|^2$
- If SUSY spontaneously broken (must: no sparticles found)

$$\delta m_H^2 \approx -\frac{2N_c}{16\pi^2}|\lambda_t|^2 m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

Sparticles cannot be too heavy

Supersymmetry (SUSY)

- R-parity:

$$\text{particles} \to R = +$$
$$\text{sparticles} \to R = -$$

- Only loop effects at low energies
- Only pair production
- Lightest Supersymmetric Particle (LSP) stable: DM candidate

- Phenomenology extremely rich (studied for many years):

SUSY not in the Exotics group

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- Phenomenology extremely rich (studied for many years):
  - MSSM: $\mathcal{O}(120)$ free parameters (just parameterization of SUSY breaking)
  - Many models of SUSY breaking
  - Many different possible spectra
  - Searches typically interpreted in terms of models with minimal number of independent parameters (mSUGRA, cMSSM, ...): very constrained experimentally (doesn't make SUSY close to be ruled out).

Supersymmetry (SUSY)

- Typical assumptions:
  - Sparticles produced in pairs
  - LSP corresponds to partner of SM particle
  - Colored sparticles (squarks and gluinos) heavier than uncolored ones (but light enough to be produced)
- Typical implications:
  - Large production cross sections of colored particles with cascade decays down to SM particles and two LSPs.
  - Standard SUSY search: large $\not{E}_T$, large number of hard jets and leptons

Common in many models of SUSY breaking

Nothing found yet!

Might need to revise our assumptions

Little Higgs models (LH)

- Higgs: pseudo-Goldstone boson

Massless at tree level but quadratic sensitivity at one loop

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Massless at tree level but quadratic sensitivity at one loop

Cancels the quadratic sensitivity at one loop

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$$G/H \times G'/H' \Rightarrow \pi^a, \pi^{a\,\prime}$$

$$\downarrow$$

$$G \oplus G'$$

Explicit breaking by gauge and Yukawa couplings

V_L would-be Goldstone bosons

h^i pseudo-Goldstones IF both groups simultaneously broken

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Explicit breaking by gauge and Yukawa couplings

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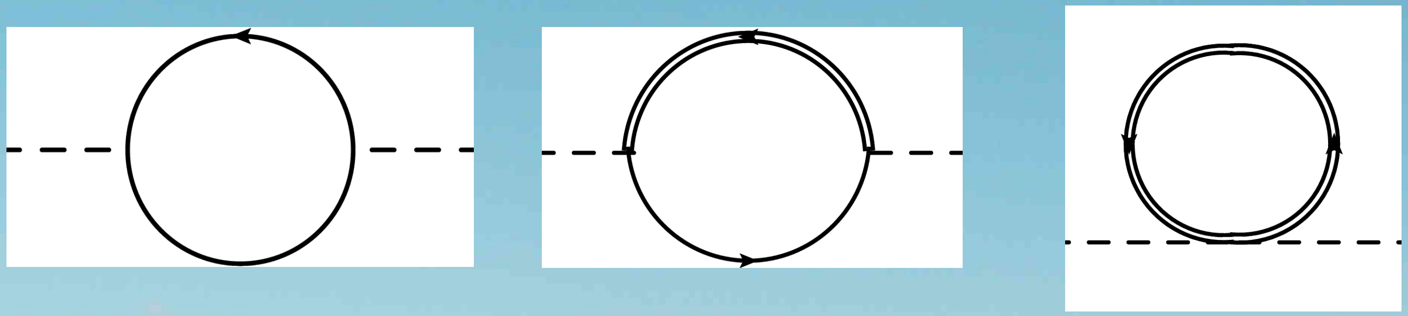
Quadratic sensitivity canceled at one loop (can be extended to higher orders)

$$\delta m_H^2 \sim$$



Cancellations from same statistics particles (Clebsch-Gordan coefficients)

Little Higgs models (LH)

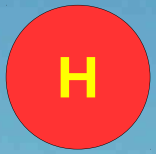
- LEP constraints force new particles heavy unless one imposes an exchange T-symmetry with similar implications to R-parity
  - Pair production
  - Missing energy signatures

- Despite differences many collider implications dictated by the discrete symmetry (also in other models like Universal Extra Dimensions): might be difficult to disentangle in a first round of discoveries!
- But
  - Not a complete theory: $\Lambda \sim 10\ \mathrm{TeV}$ UV completion?
  - No “gluon partners”

NP “singly produced”

New Structures: Compositeness

- If NP can couple linearly it must be relatively heavy and couple weakly to light SM fermions
- Archetype: Composite Higgs
  - Higgs: composite state of a new strongly coupled interaction



Higgs mass protected by its finite size
Extra protection if Higgs is a pseudo Goldstone boson

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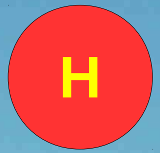

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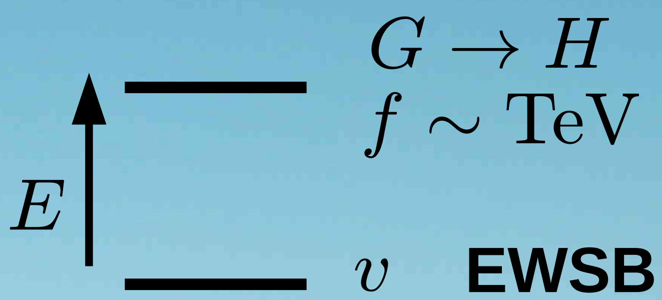

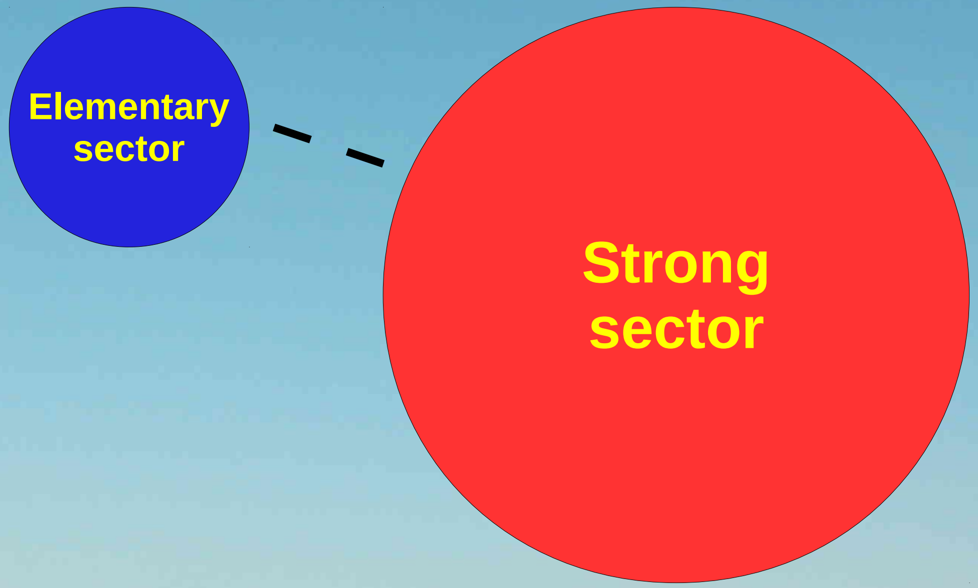

$\mathrm{SM} \subset H$

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H

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E

$G \to H$

$f \sim \mathrm{TeV}$

v **EWSB**

$\mathrm{SM} \subset H$

$f \lll M_{\mathrm{Pl}}$ **Strong sector conformal**

$m_{NP} \sim g_c f \gg f$ **Heavy NP**

$m_h \sim \frac{g_e}{4\pi} m_{NP} \ll m_{NP}$ **pNGB Higgs**

Just like QCD (almost)

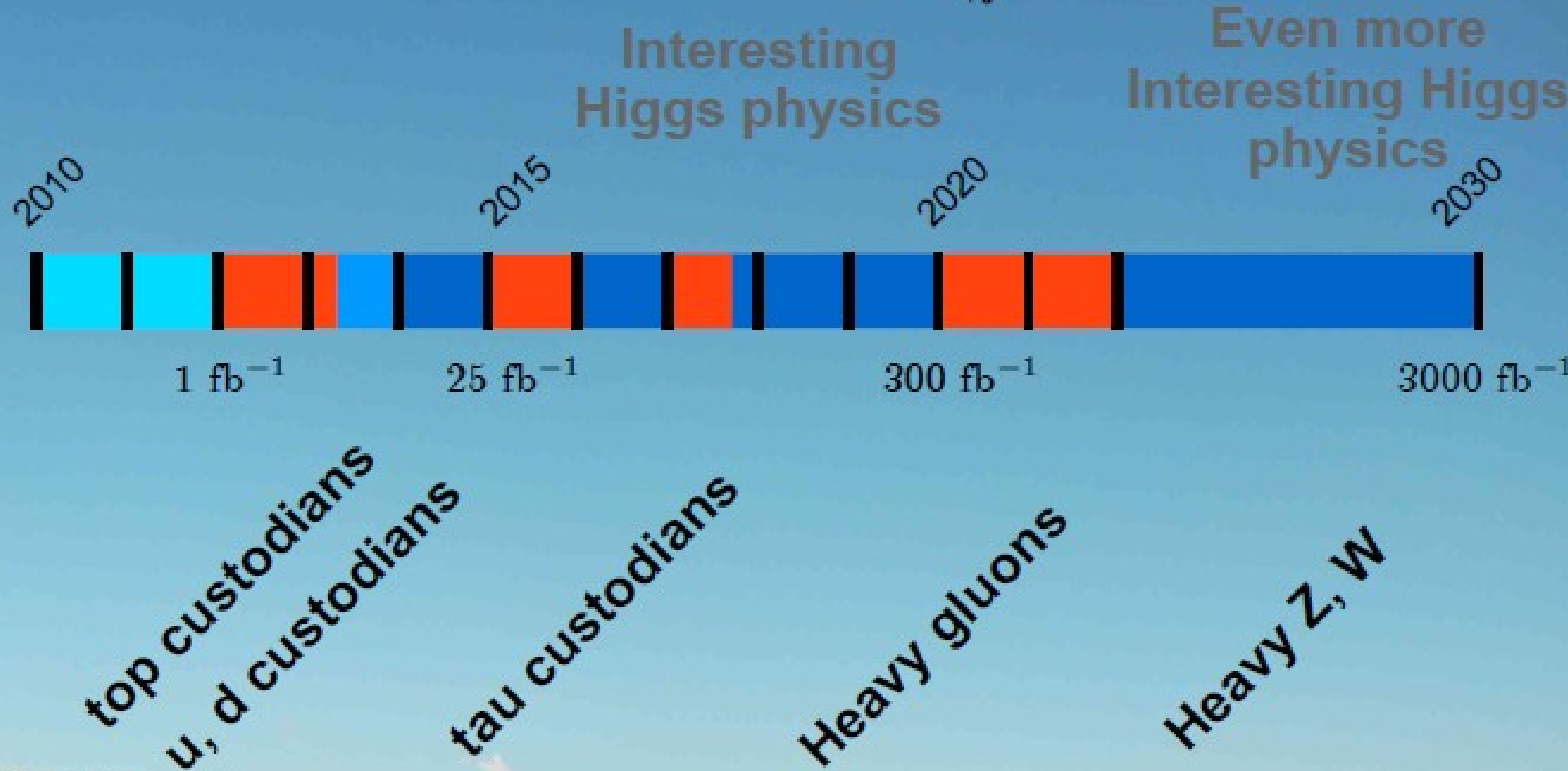
New Structures: Compositeness

- LHC implications
  - New particles heavy ~ few TeV
  - Strong coupling: wide resonances
  - Top likely composite: (boosted) top rich final states
  - Light SM fermion partners (top, tau custodians) likely, but models without custodial symmetry (thus without custodians) also possible
  - Modified Higgs couplings: suppressed couplings, fermiophobic Higgs, ...
  - Phenomenology quite different from previous cases but it was not expected to show up this early

Difficult at 7 TeV LHC!

Warped Extra Dimensions at the LHC

LHC schedule taken from talks by M. Lamont (pLHC2010) and F. Zimmermann (KEK)



New Structures: Compositeness

- What if no Higgs at all?
  - Composite Higgs allows for an interpolation between the SM ($f \to \infty$) and Higgsless models ($f \to v$)
  - Higgsless models still allowed:
  - Models with warped extra dimensions give weakly coupled duals (calculable because of large N)
    - Vector resonances will be probed soon (cannot be too heavy to unitarize longitudinal gauge boson scattering)
  - Technicolor models: difficult to give definite predictions
    - Low N theories might be promising but it is difficult to make quantitative statements.

Disguised NP

Disguised New Physics

- NP could be even lighter than expected but hidden:

  - Stealth gluon scenario
    - Massive (700-900 GeV) gluon with small axial couplings to light quarks and large couplings to the RH top.
    - New vector-like quarks increase its width to 0.5-0.7 M
    - Can explain the Tevatron top FB anomaly
    - Difficult to see unless tailored analyses are performed
    - See today's talk by Mikael Chala
  - Many other options of (unexpected) new physics

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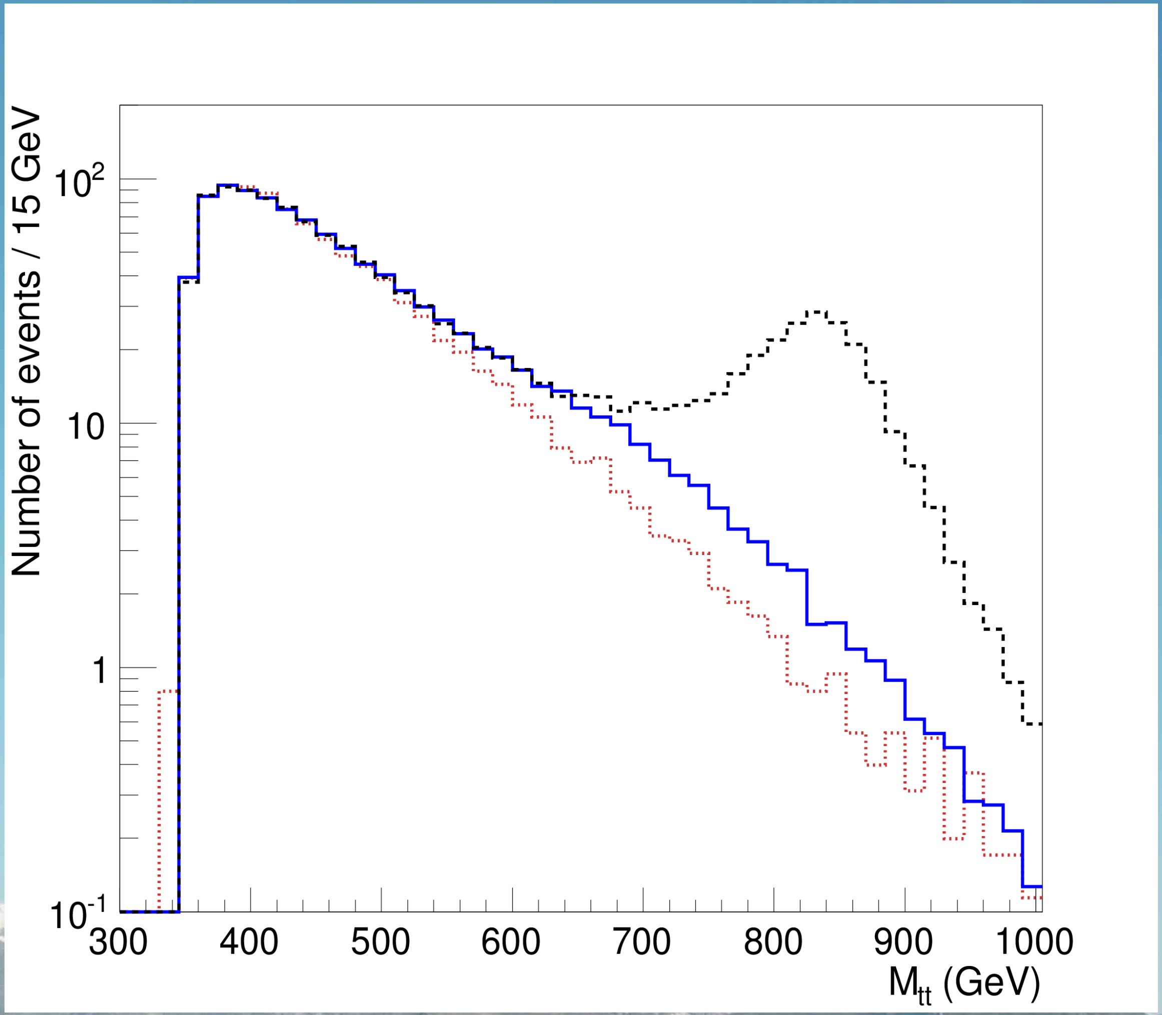

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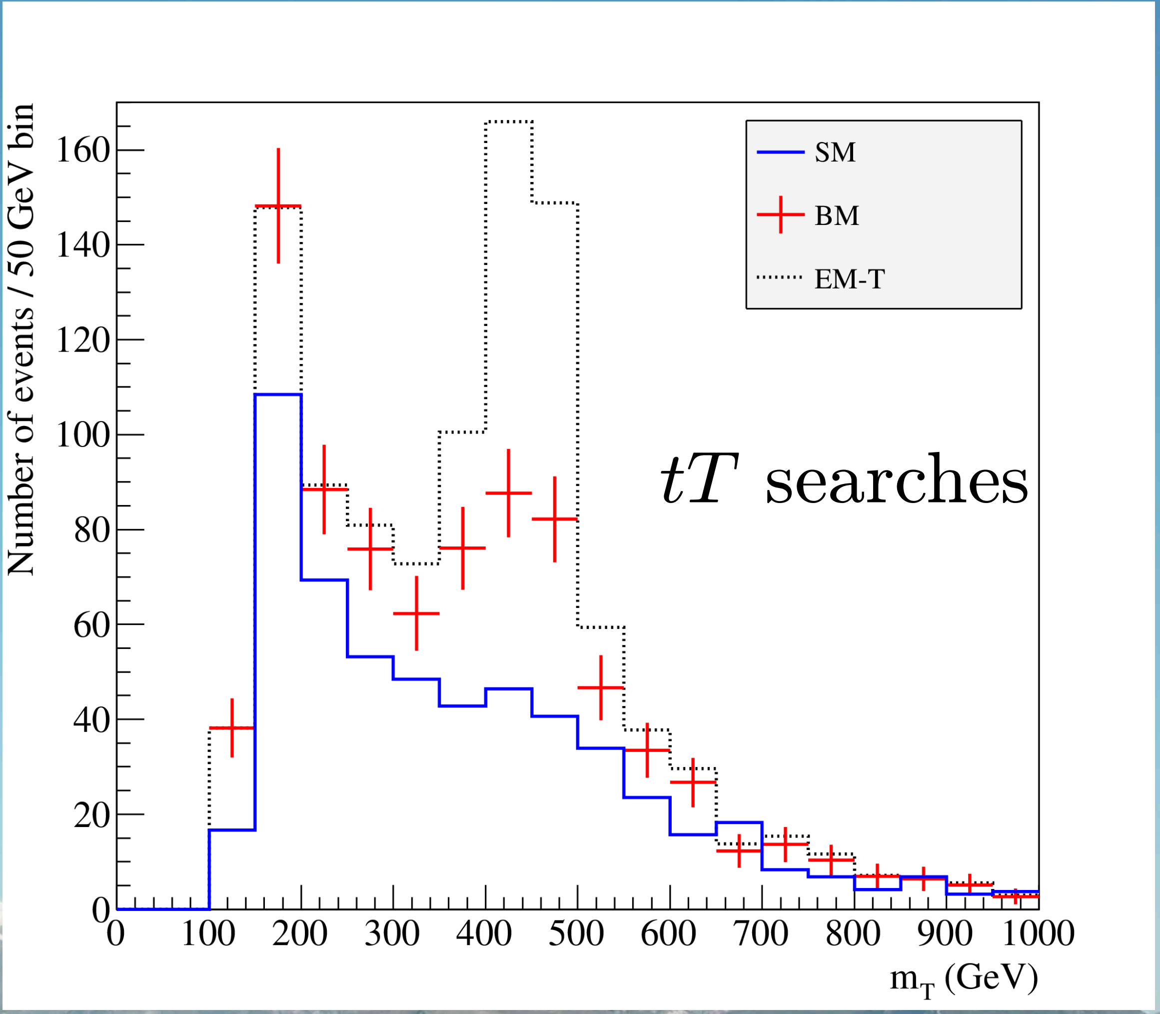

Situation at the LHC

- LHC phenomenology very rich
  - Many different phenomenological implications are possible
  - Different models can have similar (on a first look) implications
  - Signatures not as immediately visible as some expected
    - Standard assumptions are common but violations are also common
    - Some models of new physics still out of reach
- We have focused on the sectors that solve the hierarchy problem but the crucial test is the Higgs itself
  - Extended Higgs structures needed in certain extensions (SUSY) but not exclusive to these extensions
  - Couplings easily modified with dramatic phenomenological changes

Importance of the Higgs sector

- Besides being a remnant of EWSB in the SM the Higgs unitarizes longitudinal gauge boson scattering.
- The theory is unitary, the question is whether unitarization occurs at weak or strong coupling.
- Is EWSB weak or strong?

$$\frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left[1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right]-m\bar{\psi}_L\Sigma\left(1+c\frac{h}{v}\right)+\mathrm{h.c.}$$

- $V_L V_L \to V_L V_L (HH)$ Crucial (but very difficult) test
- A SM-like Higgs should be accessible by next year. A detailed study of its properties is essential to disentangle the mechanism of EWSB

Importance of the Higgs sector

- A SM-like Higgs should be accessible by next year. A detailed study of its properties is essential to disentangle the mechanism of EWSB.
  - Is there a Higgs at all?
  - Is it SM-like?
    - Expected couplings (production and branching ratios)
    - No extra scalars (charged Higgses, extra neutral ones)
    - Is it an impostor? (Dilaton, radion, ...)
  - Plausible option (in my view): SM-like but not quite
- Surely we will have to review our assumptions once again.

Summary and Outlook

- BSM physics more interesting than ever:
  - Many different options still possible
  - Many models with similar phenomenology
  - NP not as “exhibitionist” as expected (by some)
- EWSB is the main motivation for BSM physics
  - Detailed study of the Higgs sector (or its replacement) is crucial
  - Should start to have information next year but might need more energy and luminosity to be conclusive
  - Combine information on Higgs sector and searches/discoveries of its “companions”

Word of Caution

- Do not only look far at the horizon, new physics might be right underneath our feet!