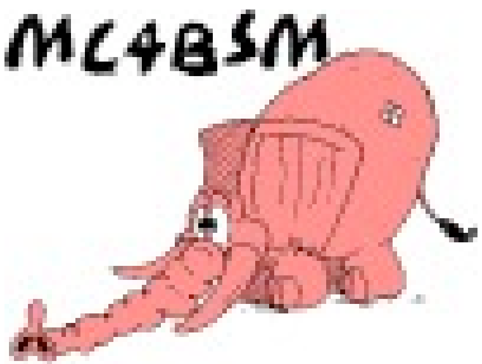
# MC4BSM-3: Welcome and Orientation




G. Azuelos, U. Montreal/ATLAS
C. Grojean, CERN/Theory
J. Hubisz, ANL/Theory
B. Kersevan, Jozef Stefan/ATLAS
J. Lykken, FNAL/Theory
F. Maltoni, UCL/Theory
K. Matchev, U. Florida/Theory
F. Moortgat, ETH Zurich/CMS
S. Mrenna, FNAL/Theory
M. Perelstein, Cornell/Theory
P. Skands, CERN+FNAL/Theory
J. Wells, CERN+Michigan/Theory

# WORKSHOP INFO

- LAPTOPS need to be registered with CERN:

  https://network.cern.ch/sc/fcgi/sc.fcgi?Action=VisitorRegistration

- COFFEE BREAKS in TH common room (3rd floor)
- RECEPTION tonight at
- After-workshop event TOURS Wed 12 Mar
  - CMS at 10:00
  - ATLAS at 14:45
- A few spaces still left! People interested in joining either should contact Peter Skands in the coffee breaks

# BSM Physics Overview

"A (brief and not unweighted) random walk through the theory landscape"

M. Perelstein, Cornell

MC4BSM-3 Workshop, CERN, March 10 2008

# Introduction

- Standard Model: Electroweak gauge symmetry SU(2)xU(1) is fundamental, but spontaneously broken at low energies down to e&m U(1)

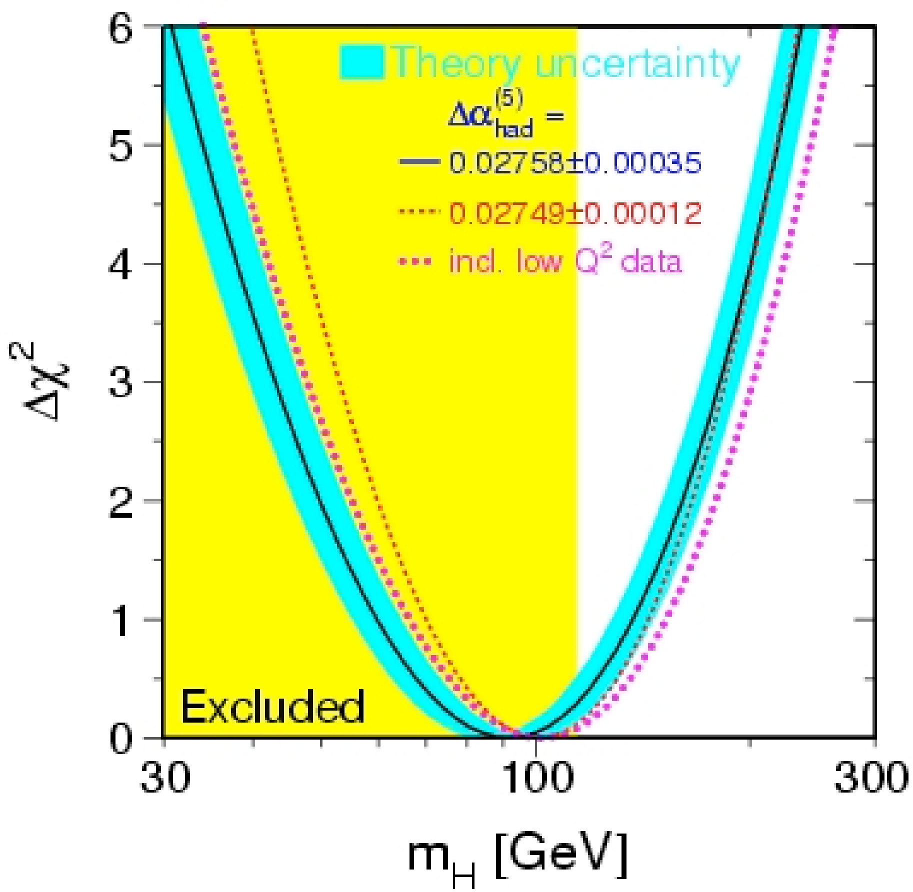
- Uncovering the mechanism of electroweak symmetry breaking (EWSB) is the central question for the LHC

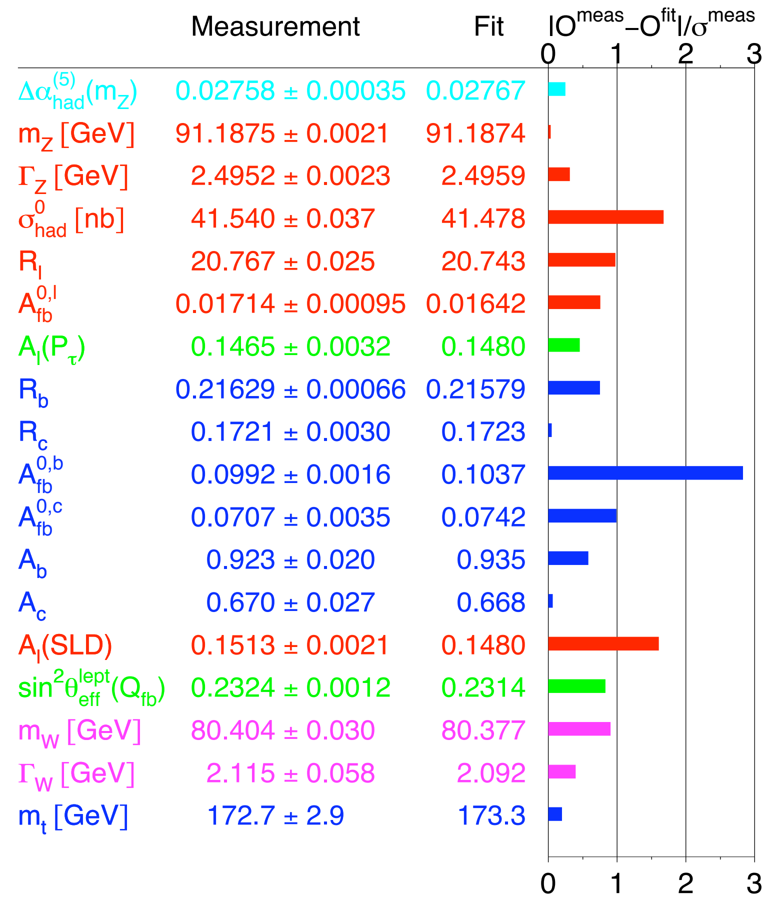
- The Standard Model explanation of EWSB: Higgs phenomenon

- Postulate a new particle - the Higgs boson - of spin 0

- Vacuum is filled with Higgs condensate, which breaks the symmetry

# Is the Higgs Really There?




- Standard Model with a light Higgs provides a good fit to all data, indirect determination of H mass:

$$M_H < 186 \text{ GeV} \quad (95\% \text{ c.l.})$$

# Light Higgs ➔ New Physics

- No elementary spin-0 particles are known to exist: scalar mass is unstable with respect to radiative corrections

- If SM is valid up to some UV scale $\Lambda$ where new physics occurs and divergent loop integrals are cut off, we expect

$$\mu^2(M_{\rm ew}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2}\Lambda^2 + c_2 \frac{1}{16\pi^2} \log\left(\frac{\Lambda}{M_{\rm ew}}\right) + \text{finite}$$

with $c_1 \sim 1$

- Unless the 1st and 2nd terms cancel each other precisely ("fine-tuning"), we should get $\mu \sim \Lambda/(4\pi)$

- New physics must occur at ~1 TeV scale!

# Supersymmetry

- Supersymmetry, with superpartners around 1 TeV, would do the job
- The minimal SUSY model - the MSSM - is the best-studied by far of the BSM models: successful gauge unification, etc.
- However, non-observation of the Higgs at LEP2 presents a significant problem for the MSSM
- At tree level, there is a firm upper bound on the mass of the lightest of the two CP-even Higgs bosons:

$$m(h^0) < M_Z$$

- Experimentally, $m(h^0) > 114 \text{ GeV}$
- Either the MSSM is wrong, or loop corrections to $m(h^0)$ are large (25%)

# Supersymmetry and Tuning

- Loop corrections to the Higgs potential change the Higgs vev, not just its mass!
- Parameters can always be adjusted to reproduce the known Higgs vev...
- BUT, if the loop contribution to the vev is BIG, it would need to be cancelled precisely by other terms ⇨ classic example of fine-tuning!
- So: need loops to change Higgs mass by a lot while not changing the Higgs vev by a lot ⇨ difficult!
- Fine-tuning of at least 1% is needed to make things work
- If SUSY is realized, it may very well be a non-minimal version (e.g. extra scalars coupled to the Higgs sector)

# Non-Minimal Supersymmetry

- Models with one extra singlet studied extensively (NMSSM)

$$W = \lambda S H_1 H_2 + \frac{\kappa}{3} S^3$$

- Typically large $\lambda$ is required to raise $m_h$; $\lambda$ hits Landau pole before the GUT scale, extra structure is required to preserve coupling unification (e.g. "Fat Higgs")
- Both scalars and inos are affected: singlino admixture in neutralinos!
- Example of a realistic simulation in NMSSM: Cornell 2007 LHC Olympics Black Box
- Used Madgraph/Madevent; took ~hour to "add" the model
- MG/ME → (BRIDGE) → LHA file → PYTHIA → (PGS): realistic events within hours!
- More complex models are easily possible - flexibility is key!!

# Quantum Gravity at TeV

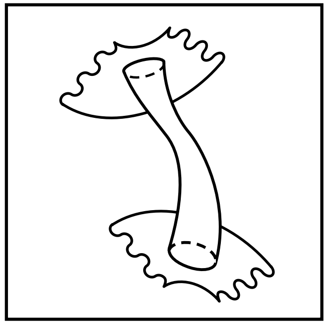
- At Planck scale, SM has to be embedded into a theory with quantum gravity - string theory?
- It is believed that that theory must be finite - all divergences cut off at $M_{\rm Pl}$
- If $M_{\rm Pl} \sim 1~{\rm TeV}$, there is no hierarchy problem!
- ADD model: SM on a 4D brane inside higher-D space, with extra dimensions compactified with
$$R \sim M_{\rm Pl}^{-1} \left( \frac{M_{\rm Pl,4}}{M_{\rm Pl}} \right)^{2/n} \gg M_{\rm Pl}^{-1}$$
- At $E < M_{\rm Pl}$, model-independent missing energy signature due to graviton emission into the extra dimensions
- If two partons collide at super-plankian energies $E \gg M_{\rm Pl}$, a black hole must form!

[see talk by Godang]

# String Theory at TeV

- Given existing constraints on $M_{\rm Pl}$ , it seems pretty unlikely that the LHC will probe the region $E \gg M_{\rm Pl}$
- In any (weakly coupled) string theory, Regge excitations of SM particles lie below Planck scale

$$M_n = \sqrt{n} M_S, \qquad M_S \ll M_{\rm Pl}$$



- Reggeons appear as s-channel resonances in SM scattering processes!
- Easy to see, more realistic target than BHs
- But need to be distinguished from Zprimes etc.
- Excited Reggeons have spin > 2 ⟹ at present not handled by the general-purpose MC generators!

# QCD Redux: Composite Higgs, Technicolor, and Their Cousins

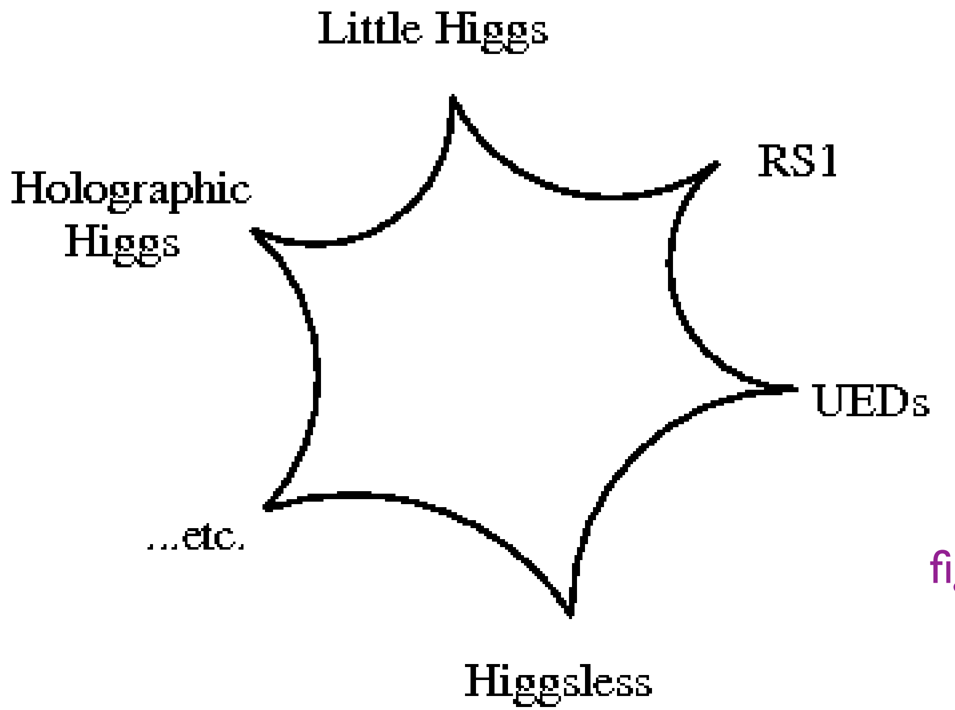



figure credit: Ian Low

- All these models involve new strong dynamics at TeV, a la QCD confinement (but with interesting twists)
- They can be "continuously deformed" into each other ("little M-theory")

# Composite Higgs

- Many spin-0 particles exist in nature - mesons
- They are composite, made of spin-1/2 quarks, bound by QCD strong force
- Above the QCD confinement scale, the good degrees of freedom are quarks ⇒ no hierarchy problem!
- Can the Higgs be a meson bound by a new strong force?
- Old idea, but difficult to build models - non-perturbative physics!
- New insight: AdS/CFT duality ⇒ some strongly coupled 4D models are "dual" to weakly coupled, calculable models with an extra dimension!
- Setup: Randall-Sundrum (RS) 5D model

# Warped (RS) Extra Dimension

- Original model had the SM on the TeV brane
- It was subsequently realized that models with SM gauge fields and fermions in the "bulk" are more interesting:

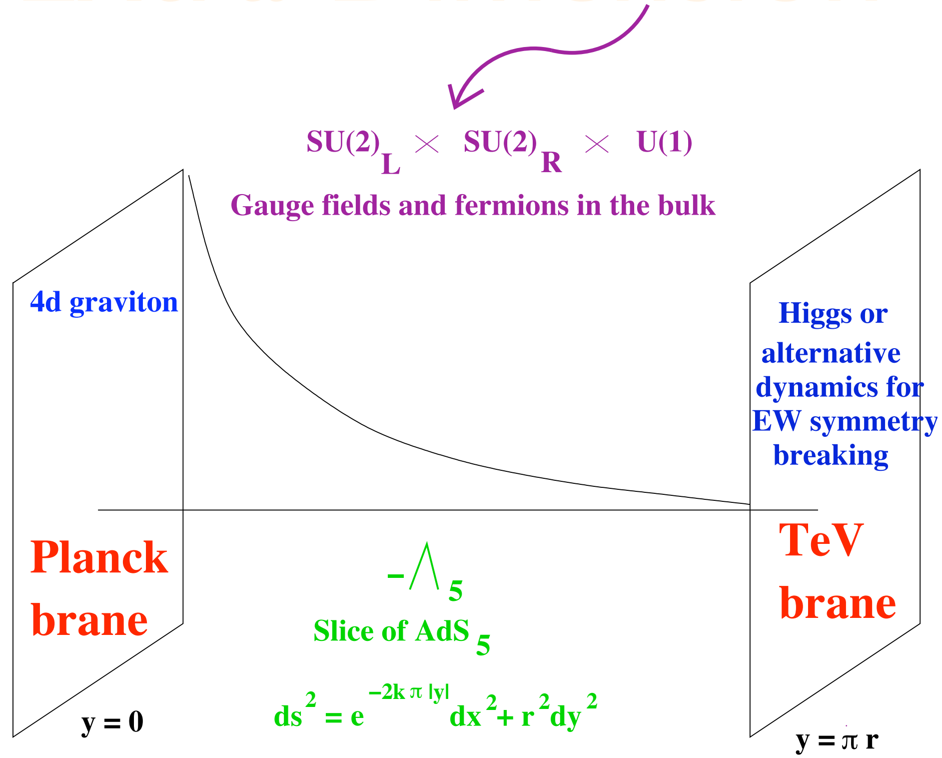



figure credit: G. Servant

- natural solution to fermion mass hierarchy problem
- natural suppression of flavor-changing neutral currents
- possibility of gauge coupling unification, as in the MSSM

NB: collider pheno is different from the "SM on the brane" model, e.g. small KK-graviton coupling to light quarks/leptons!

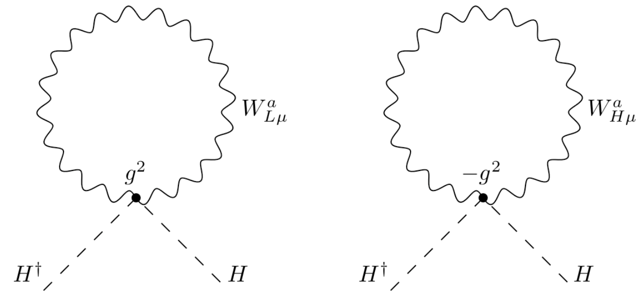
[see talks by Randall, Perez, Lee]

# Universal Extra Dimensions and KK Parity

- UED is a model with flat extra dimension(s) of $R^{-1} \sim 1\ \mathrm{TeV}$ , all SM fields (including Higgs) propagate in the bulk
- Natural discrete symmetry, KK parity: first-level KK states are odd, lightest odd state (LKP) is stable, typically heavy photon
- Interesting pheno: faking SUSY at the LHC, dark matter
  [see talk by Przysniezniak]
- Disadvantage 1: strongly coupled at $\Lambda \sim 10\ \mathrm{TeV}$ , needs a "UV completion" e.g. to address gauge coupling unification
- Disadvantage 2: $m_h \sim 0.01\Lambda$ requires 1% fine-tuning ("little hierarchy")
- An interesting alternative that addresses these issues: a warped RS-style extra dimension with KK parity
  [Agashe, Falkowski, Low, Servant, 12/07]

# Gauge-Higgs Unification

- A zero-mass photon does not require fine-tuning - mass is protected by gauge symmetry
- In a 5D theory, the gauge field $A_M(x) \to A_\mu(x), A_5(x)$
- If the 5th dimension is infinite, $A_5$ is naturally massless!
- After compactification, $m(A_5) \sim 1/R$ ⇨ good if $1/R \sim M_W$
- Higgs mass quadratic divergences are canceled by KK modes:



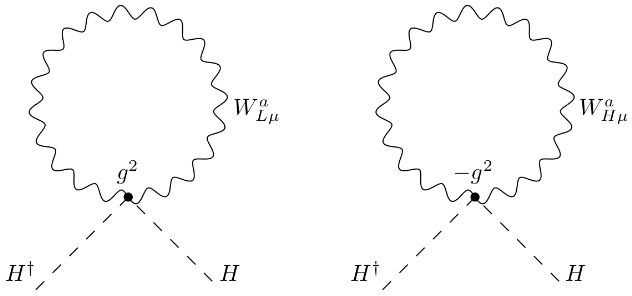

- A realistic GHU implementation, using a warped extra dimension, predicts $m_h < 140$ GeV and KK states at 2 TeV

[Agashe, Contino, Pomarol, 12/04]

# Little Higgs

- Quadratic divergence cancellation by same-spin states can also occur in a purely 4D theory - Little Higgs

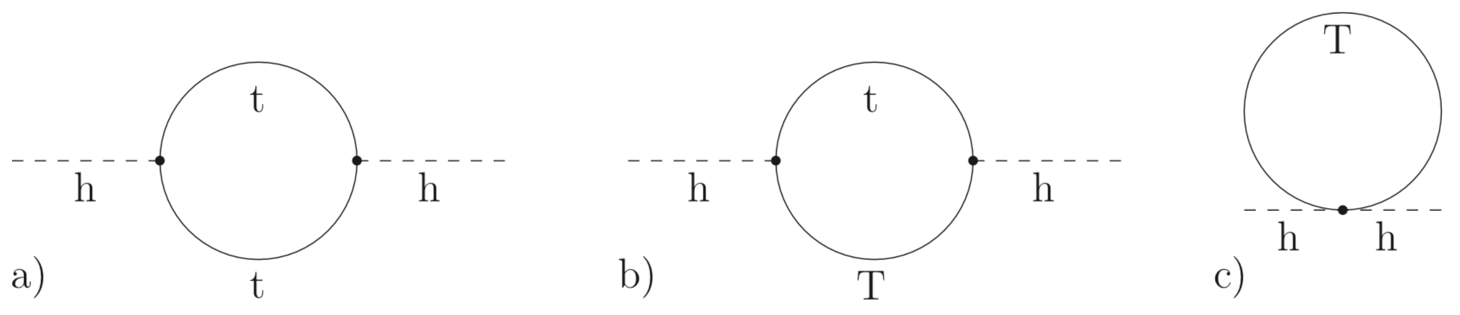
[LH ⇔ effective theory of the first two KK modes in GHU!]




- In LH, Higgs is a Goldstone boson arising from a global symmetry breaking [a la pions in QCD]
- If the global symmetry is exact, $m_h = 0$ naturally!
- Goldstones only interact derivatively ⇒ need to break the global symmetry explicitly by gauge and Yukawa interactions
- Generically explicit breaking reintroduces quadratic divergences
- “Collective” breaking pattern in LH avoids quad. div. at one loop

# EWSB in Littlest Higgs Model

- Higgs mass is dominated by top and Top loops:




- This contribution is log-divergent and negative:

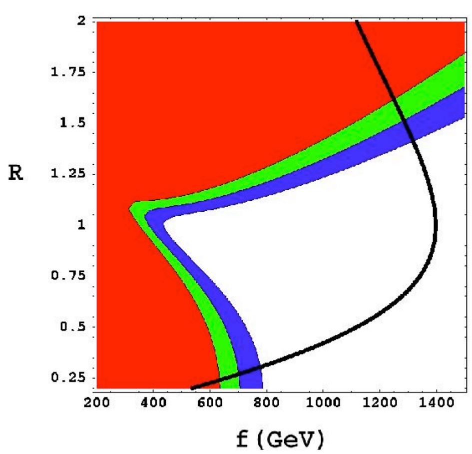
$$m_t^2(H) = -\frac{3\lambda_t^2 M_T^2}{8\pi^2} \log \frac{\Lambda^2}{M_T^2} \; .$$

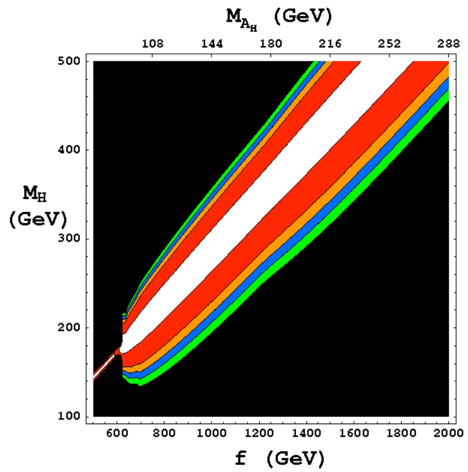
- Quadratically divergent 2-loop contributions are of order $\frac{g^2 y_t^2 M_T^2}{16\pi^2}$ , no log enhancement ➡ subdominant
- 1-loop gauge contribution down by $g^2/y_t^2 \sim 0.25$
- EWSB is triggered radiatively - simple mechanism!

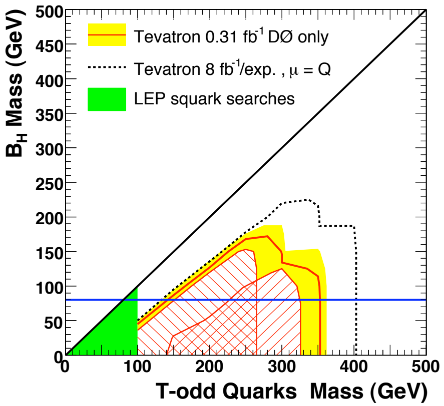
# Little Higgs and T Parity

- LH models are weakly coupled at the TeV scale, predictive!
- The "first-generation" LH models strongly disfavored by precision electroweak data
- Best solution: introduce "T Parity": new TeV-scale particles T-odd and only appear in loops in PEWO [a la R parity of the MSSM]
- Littlest Higgs with T Parity (LHT) a benchmark model, many pheno studies: missing energy signatures at the LHC and the Tevatron, dark matter candidate, ...

[see talk by Figi]



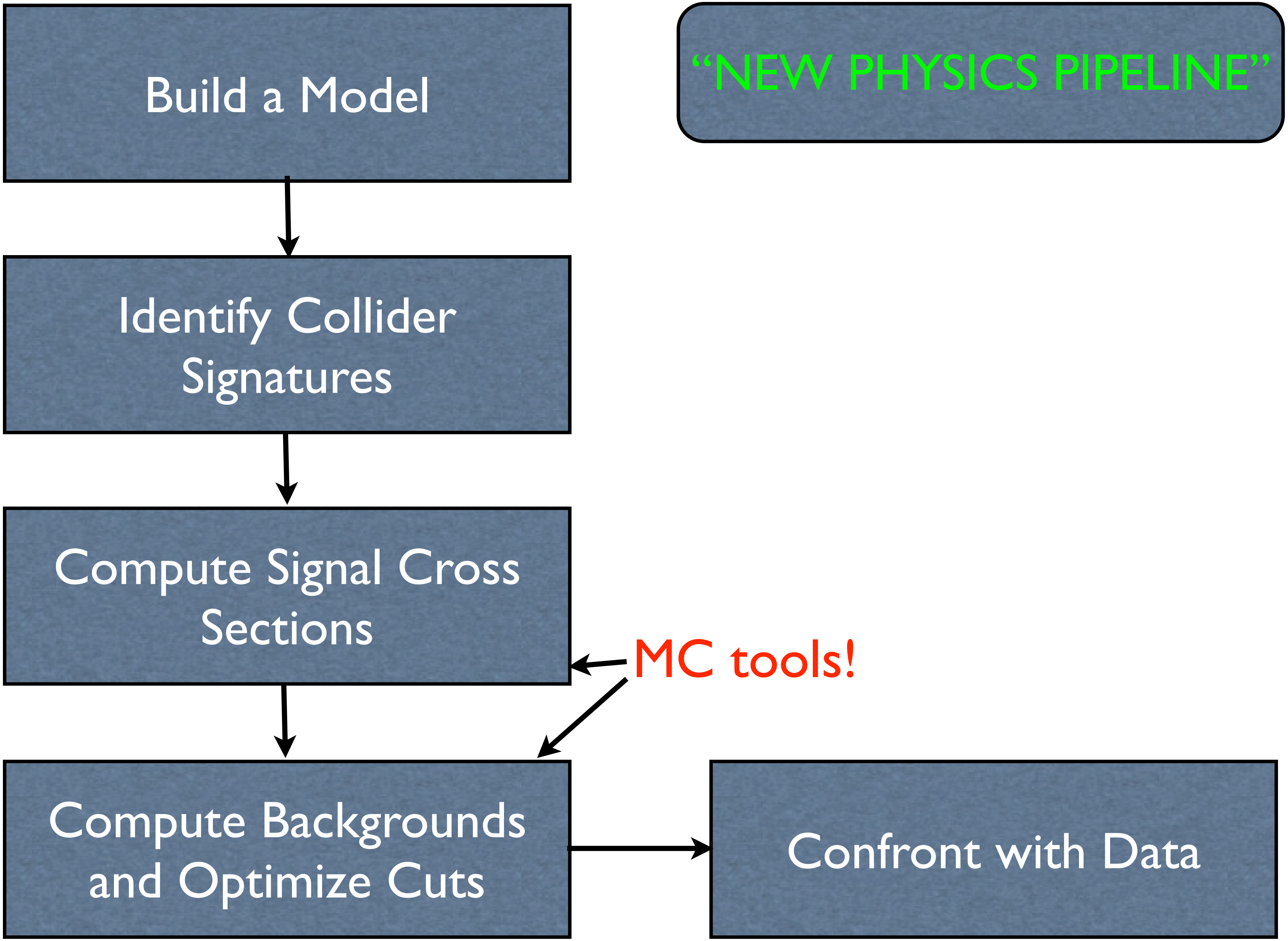
# What if There is No Higgs?

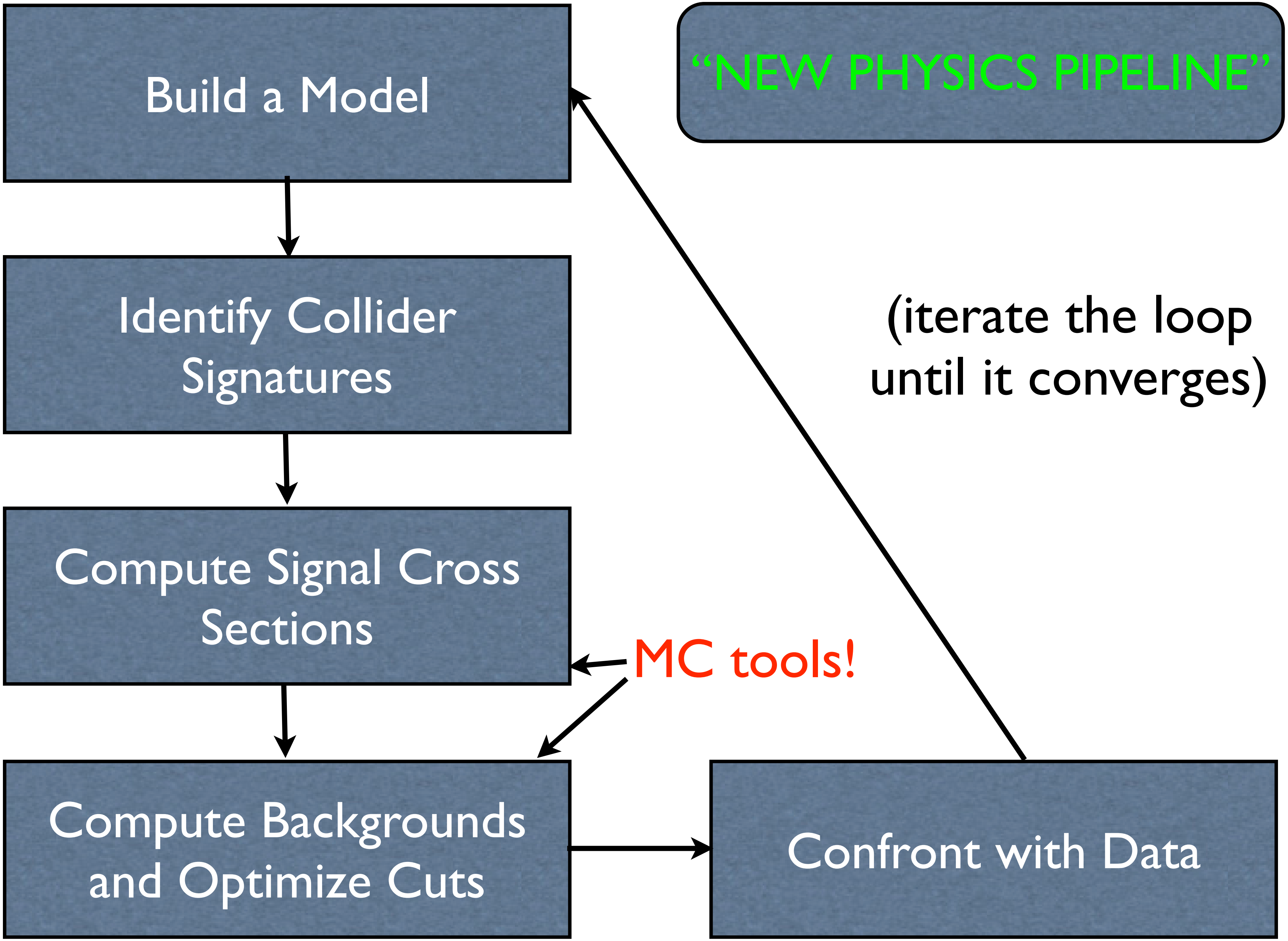
- If physics at TeV scale is strongly coupled, a symmetry-breaking condensate can exist without a physical Higgs boson in the theory - technicolor!
- TC with QCD-like dynamics at TeV is ruled out by precision electroweak data
- Difficult to explore model space due to strong coupling
- New insight: AdS/CFT duality ⇨ some strongly coupled 4D models are "dual" to weakly coupled, calculable models with an extra dimension!
- 5D "Higgsless" models have been constructed, can pass precision electroweak tests with ~1% fine-tuning
- Renewed interest in 4D TC model-building

[see talk by Foadi]

# Conclusions and Outlook

- The mechanism which breaks electroweak symmetry remains a fundamental, unsolved mystery
- It must involve new physics at the TeV scale
- Several theoretical ideas for what new physics might be have been proposed: supersymmetry, dynamical symmetry breaking, extra dimensions, little higgs, ...
- True model is unknown: only indirect constraints and theoretical prejudice to guide us at this point...
- All models predict discoveries at the LHC - theory will be confronted with data soon!
- Detailed predictions will be needed for theoretical interpretation of the data


Build a Model
"NEW PHYSICS PIPELINE"
Identify Collider Signatures
Compute Signal Cross Sections
MC tools!
Compute Backgrounds and Optimize Cuts
Confront with Data


Build a Model
"NEW PHYSICS PIPELINE"
Identify Collider Signatures
(iterate the loop until it converges)
Compute Signal Cross Sections
MC tools!
Compute Backgrounds and Optimize Cuts
Confront with Data

- Since models will change "in real time", flexibility is the key desired feature of the BSM MC tools
- In the past, general-purpose MC tools had a small number of models (or processes) hard-wired, with significant effort and expert-level coding required to add a new model/process
- Now: any new physics model can be realistically simulated within hours by a physicist with rudimentary software skills (e.g. myself) as long as:
  - all new particles are spin <=2
  - couplings of "known" Lorentz structures only
  - no new long-lived colored states or exotic color rep's
- Full implementation of such models ahead of data seems unnecessary; removing these limitations is more useful