Theoretical Prophesies on Electroweak Symmetry Breaking

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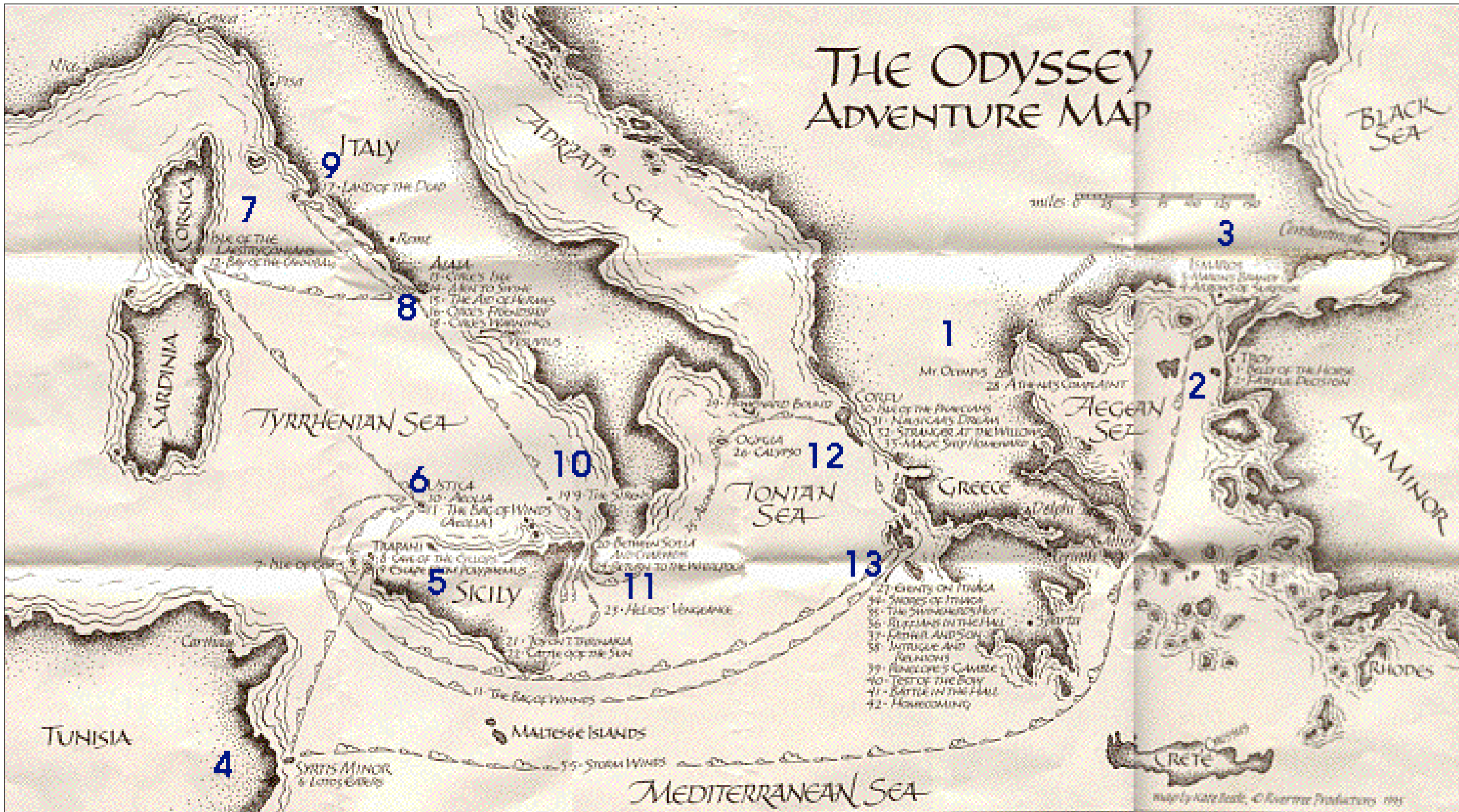
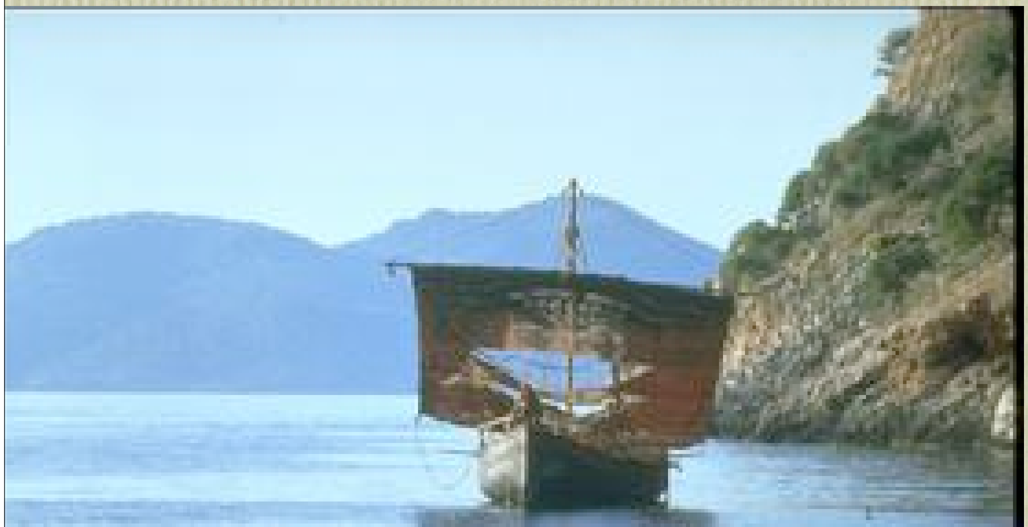
outline

- the Odyssey of EWSB
- are theorists useful?
- the General Motors approach to building models
- what do we really think?
- what do we need to know about Higgs?
- what are we getting nervous about?
- the not-so-minimal SSM
- CPV, Higgs, and baryogenesis
- the not-so-little Higgs
- less Higgslessness
- prophesy



- his arrogance angered the Gods
- who doomed him to wander for 10 years
- does this story have a familiar ring?

the Odyssey of EWSB

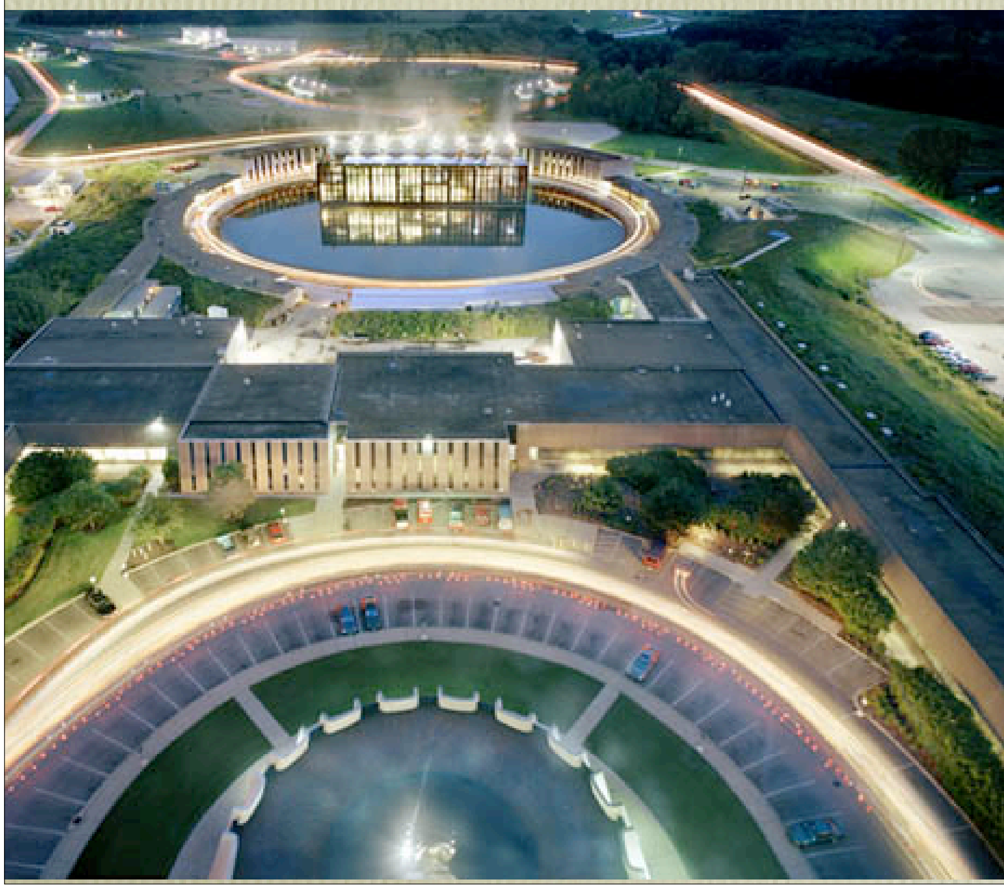


we have been wandering "beyond the standard model" for 20+ years

but the source of EWSB remains hidden from us

getting close

- only 754 days until LHC
- don’t discount possibility of surprises from Tevatron, B factories, wimp searches, EDM expts, etc



are theorists useful?

theorists engage in
two types of activity:

- playing around with new/old/stolen ideas for going beyond the standard paradigm
(easy, fun, richly rewarded, but potentially useless)

- calculating things within the standard paradigm
(useful, but difficult, tedious, and poorly rewarded)

SM theory to-do list for LHC

- work together to assemble the basic set of "Standard Model Candles", with fully documented uncertainties
- compute a whole bunch of critical processes at NLO + EW corrections, and a few at NNLO
- finish and validate the new tools that will be used for LHC analyses (Herwig++, Pythia8, MC@NLO, Sherpa, MCFM, Vircol, Alpgen, etc etc)
- make the tools modular and document them

note: nobody will discover anything at LHC unless (most of) this gets done

SM benchmarks for the LHC start

A key point: standard candles must be fully understood by LHC experiments to believe any claim of new physics (unless spectacularly clear)

- $t\bar{t}$ production
- W and Z production (possibly with jets)
- Single-inclusive jet and dijet production
- Photon and di-photon production

Issues to be addressed here:

- Predicted cross sections, and their uncertainties
- Standard candles as luminometers

Some remarks:

- Must improve understanding of power-suppressed effects in jet production
- Single-inclusive photons still not well understood
- For which processes do we really need NNLO results?

W and Z production

Theoretical predictions under fairly good control

- Fully-differential NNLO results
- NLO results matched with parton showers
- q_T, joint resummations
- $W + n$ jets observables sensibly predicted by Monte Carlos
- EW corrections available (more later)

Best candidates as luminometers? We do need precision here, if we have to improve mass measurements of LEP and Tevatron

PDF uncertainties

Pre-LHC results from Tevatron and HERA are essential. Recent progress

- Three-loop AP kernels computed exactly (Moch, Vermaseren, Vogt)
- PDF uncertainties are routinely used

Issues to be addressed here:

- How will HERA II and Tevatron Run II improve the current situation?
- Will we be able to get a consistent NNLO picture by the start of LHC?
- Do we need it?
- Are EW corrections relevant? If so, for which processes? (estimate $\Delta\mathrm{PDF} \sim 0.3\%(1\%)$ for $x < 0.1(0.4)$)

Systematic comparisons between CTEQ and MRST will be made during the workshop (other sets with errors?)

1 (Many-)Particle production at NLO

A lot of processes with $n \geq 3$ particles in final states only known at LO
$\hookrightarrow$ enormous amount of homework for theorists

State-of-the-art for NLO in theory:

- techniques for $2 \to 3$ processes established;
  results known for several processes at hadron colliders:

  $$\mathrm{pp} \to 3\mathrm{jets}, V{+}2\mathrm{jets}, V\mathrm{b}\bar{\mathrm{b}}, \gamma\gamma{+}\mathrm{jet}, \mathrm{t}\bar{\mathrm{t}}\mathrm{H}, \mathrm{b}\bar{\mathrm{b}}\mathrm{H}$$

  $\hookrightarrow$ calculations still demanding

- $2 \to 4$ processes are technical frontier;
  only two results for EW corrections in $\mathrm{e}^+\mathrm{e}^-$ physics:

  $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{HH}$, GRACE-1loop (Boujema et al.) '04

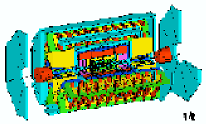
  $\mathrm{e}^+\mathrm{e}^- \to 4f$ Denner et al. '05

  \+ some partial or toy-model results Bern et al., Binoth et al.

  $\hookrightarrow$ calculations very challenging + lenghty !

$\Rightarrow$ Theorists need a clear list of important processes
including arguments for "why calculating what !?"

Joey Huston’s wish list:



Experimental priority list

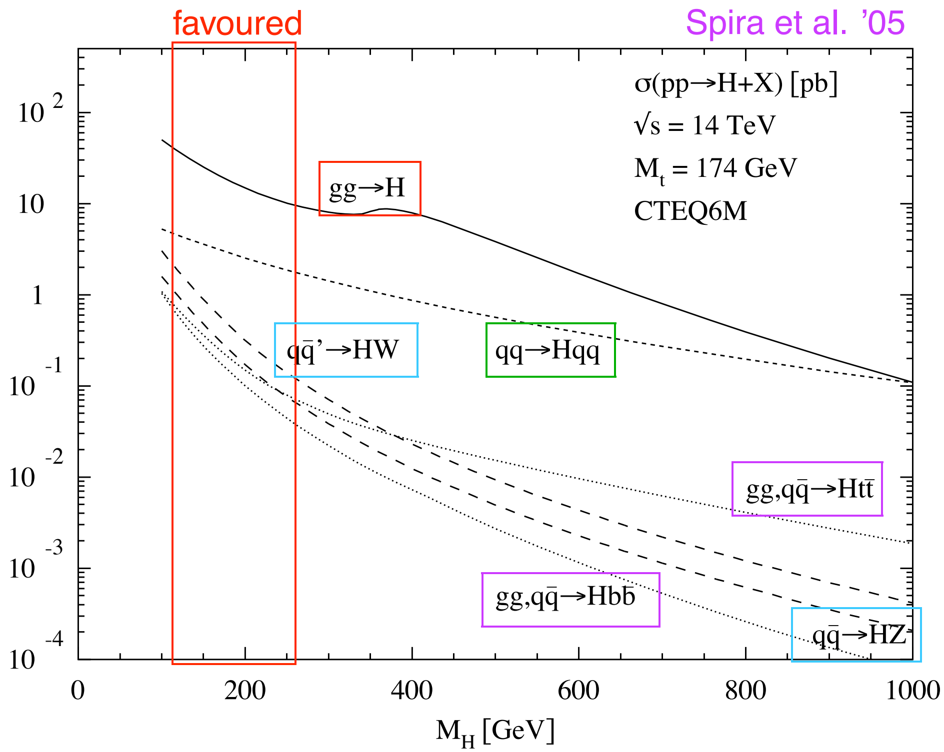
- Note have to specify how inclusive final state is
  - what cuts will be made?
  - how important is b mass for the observables?
- How uncertain is the final state?
  - what does scale uncertainty look like at tree level?
  - new processes coming in at NLO?
- Some information may be available from current processes
  - pp->tT j may tell us something about pp->tTbB?
    - j=g->bB
  - CKKW may tell us something about higher multiplicity final states

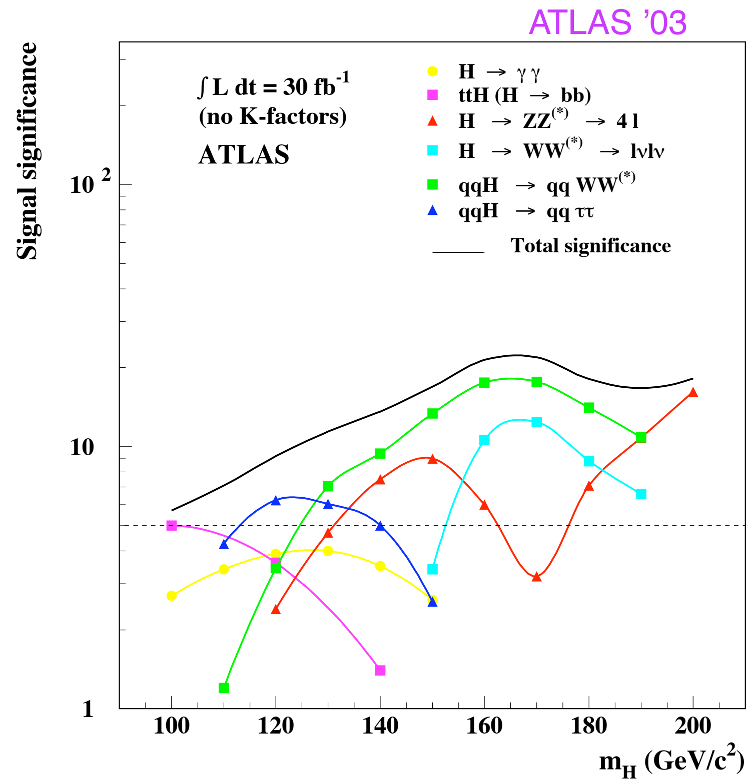
1. pp->WW jet
2. pp->tT bB
   1. background to tTH
3. pp->tT + 2 jets
   1. background to tTH
4. pp->WWbB
5. pp->V V + 2 jets
   1. background to WW->H->WW
6. pp->V + 3 jets
   1. beneral background to new physics
7. pp->V V V
   1. background to SUSY trilepton

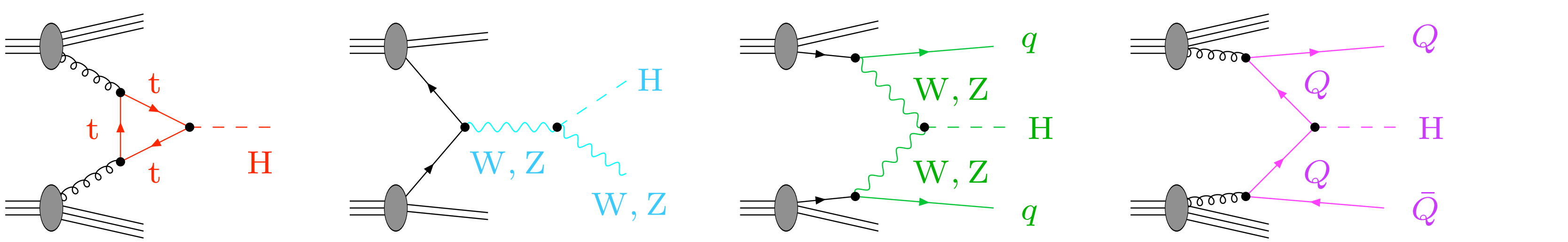
Beyond the SM Workshop at Columbia

2 Predictions for SM Higgs-boson production at the LHC

Overview of cross sections and significance of the Higgs signal at the LHC

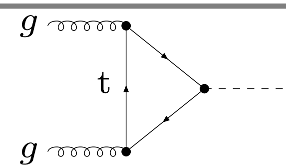






Stefan Dittmaier, Les Houches 05

Higgs production via gluon fusion



- complete NLO QCD correction known

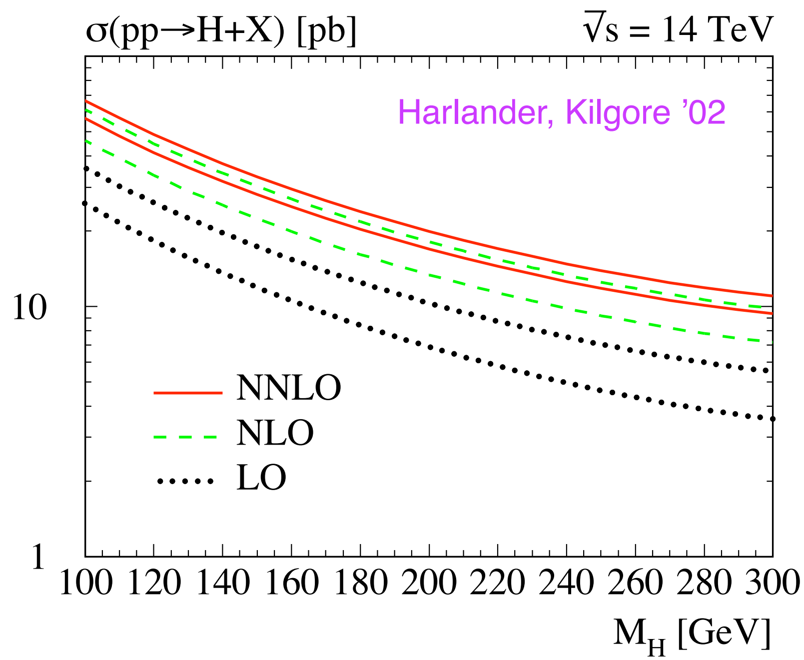
  Graudenz, Spira, Zerwas '93
  Spira, Djouadi, Graudenz, Zerwas '95

- NNLO QCD correction known in limit $m_t \to \infty$

  Harlander, Kilgore '02
  Anastasiou, Melnikov '02
  Ravindran, Smith, van Neerven '03

$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

$\hookrightarrow$ scale uncertainty reduced to $\sim 10\%$



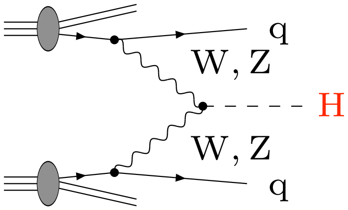
- improvements by soft-gluon resummations

  Krämer, Laenen, Spira '96; Balazs, Yuan '00
  Catani, de Florian, Grazzini, Nason '03

- electroweak $\mathcal{O}(\alpha)$ correction completed recently

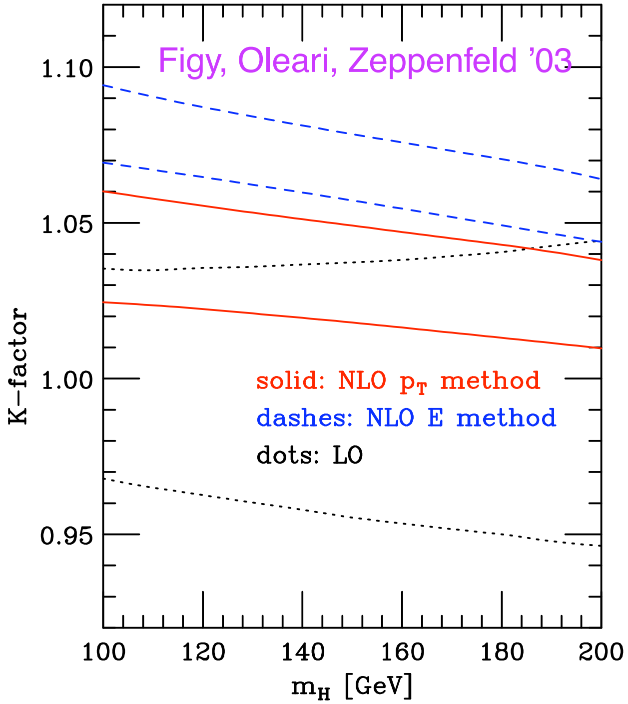
  Aglietti, Bonciani, Degrassi, Vicini '04
  Degrassi, Maltoni '05

  $\hookrightarrow$ corrections $\sim$ 5–8% for $115\,\mathrm{GeV} \lesssim M_{\mathrm{H}} \lesssim 2M_{\mathrm{W}}$



Higgs production via vector-boson fusion

- NLO QCD corrections known
  - ◇ for total cross section
    Han, Valencia, Willenbrock '92
    ↪ small corrections
    (suppressed colour exchange between the two quark lines)
  - ◇ for differential cross sections
    Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
    ↪ larger corrections and
    distortion of distributions

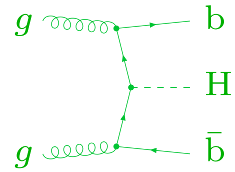


band widths:

$$Q_i/2 < \mu_{\rm ren} = \mu_{\rm fact} < 2Q_i$$

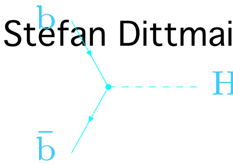
- electroweak corrections not yet known
  ↪ expected to be of the order of QCD
  scale uncertainty or larger

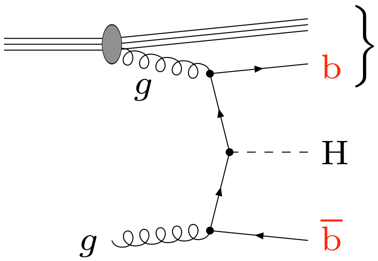
Higgs production with $\mathrm{b\bar{b}}$ pairs



versus

Stefan Dittmaier, Les Houches 05





small b transversal momenta lead to potentially large corrections

$\propto \ \alpha_{\mathrm{s}} \ln(m_{\mathrm{b}}/\mu_{\mathrm{fact}})$

resummation of higher orders necessary !

Two complementary approaches:

- Four-flavour scheme:

  splitting $g \to \mathrm{b\bar{b}}$ appears outside proton

  $\hookrightarrow$ (N)LO calculation as for $\mathrm{t\bar{t}H}$
  (apart from running b-mass in Yukawa coupling)

  ◇ 2 tagged b's — Dittmaier, Krämer, Spira '03; Dawson, Jackson, Reina, Wackeroth '03

  no large log's if $p_{\mathrm{T,b}} > \text{several GeV}$

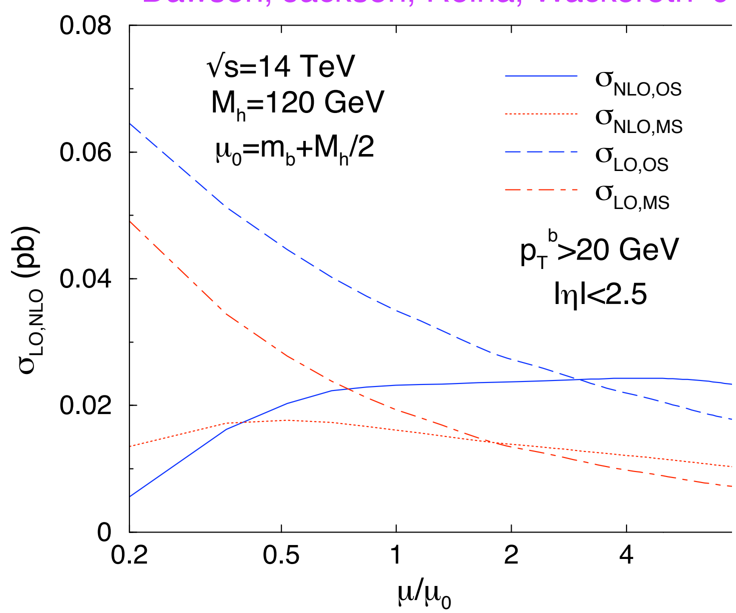
  $\hookrightarrow$ perturbative approach ok !

  ◇ inclusive b's — Dittmaier, Krämer, Spira '03

  corrections $\propto \ \alpha_{\mathrm{s}} \ln(m_{\mathrm{b}}/\mu_{\mathrm{fact}})$ with $\mu_{\mathrm{fact}} \sim M_{\mathrm{H}}/4$

  $\hookrightarrow$ resummations needed (but not included yet)

Dawson, Jackson, Reina, Wackeroth '03



summary of BSM frameworks for EWSB:

summary of BSM frameworks for EWSB:

- there are too many models
- none of them are any good

the General Motors approach to model building

the General Motors approach to model building

- build as many different kinds of models as you can dream up
- advertise them heavily
- get the customers to buy a new one before they have a chance to figure out that the last model you sold them was a lemon

what do we really think?

- there is a Higgs
- it is probably lighter than 200 GeV
- the Higgs sector is probably not simple
- the Higgs naturalness problem is solved by new physics at the TeV scale
- SUSY with radiative EWSB is probably involved
- SUSY gauge coupling unification, and $\mathbf{m_t \simeq \langle v \rangle / \sqrt{2}}$ are probably not coincidences
- SUSY is only part of the answer
- there is room for big surprises

what do we need to know about Higgs?

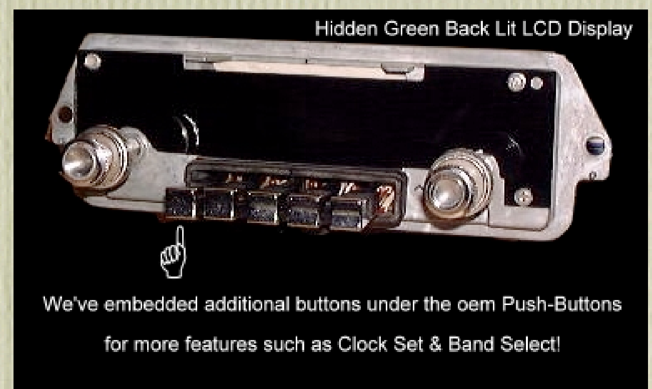
- what is its mass?
- how does it couple to SM particles?
- who else does it couple to?
- what other scalars does it does it mix with?
- is it a composite?
- is it a CP eigenstate?
- why is it light?
- what does it tell us about new physics at the TeV scale?
- what does it tell us about new physics at higher scales?

what are we getting nervous about?

- why haven't we already seen clear/clearer signals of new TeV scale physics?
- if SUSY, why haven't we already seen the Higgs?
- is the new stuff all heavy, or is some of it light but you have to be more clever to see it?
- why is flavor such a mess?
- why doesn't string theory help us understand anything?
- what does dark energy mean for particle physics?

the history of tuning

the Philco



the push button car radio

the scanner

tuned or scanned?

- if your “fundamental” theory has unexplained tunings or hierarchies, usually means that you are missing some underlying mechanism
- but not always: sometimes it just means that you are mistaken about which observables are “fundamental”, e.g. earth-sun distance
- is there a criterion for the exceptions in particle physics?

is the MSSM fine tuned?

no Higgs at LEP -> heavy-ish stop,
no direct or indirect signs of superpartners
(except g-2?)

but this formula still has to hold:

$$\begin{aligned} M_Z^2 \quad = \quad & -1.8\mu^2(\mathrm{UV}) + 5.9M_3^2(\mathrm{UV}) - 0.4M_2^2(\mathrm{UV}) - 1.2m_{H_U}^2(\mathrm{UV}) \\ & +0.9m_{Q_3}^2(\mathrm{UV}) + 0.7m_{U_3}^2(\mathrm{UV}) - 0.6A_t(\mathrm{UV})M_3(\mathrm{UV}) \\ & -0.1A_t(\mathrm{UV})M_2(\mathrm{UV}) + 0.2A_t^2(\mathrm{UV}) + 0.4M_2(\mathrm{UV})M_3(\mathrm{UV}) + \ldots \end{aligned}$$

looks like this requires ~1% cancellations
of the high scale mu term and soft SUSY parameters

is the MSSM fine tuned?

- the MSSM has 124 parameters
- the real high scale SUSY theory presumably has fewer
- matching this to the MSSM will produce "mysterious" relations between the MSSM parameters, at the high scale

$$
\begin{aligned}
M_Z^2 \quad = \quad & -1.8\mu^2(\mathrm{UV}) + 5.9M_3^2(\mathrm{UV}) - 0.4M_2^2(\mathrm{UV}) - 1.2m_{H_U}^2(\mathrm{UV}) \\
& +0.9m_{Q_3}^2(\mathrm{UV}) + 0.7m_{U_3}^2(\mathrm{UV}) - 0.6A_t(\mathrm{UV})M_3(\mathrm{UV}) \\
& -0.1A_t(\mathrm{UV})M_2(\mathrm{UV}) + 0.2A_t^2(\mathrm{UV}) + 0.4M_2(\mathrm{UV})M_3(\mathrm{UV}) + \ldots
\end{aligned}
$$

such relations are not tunings

is the MSSM fine tuned?

- the problem is that nobody has a believable model to relate, e.g. the μ parameter to $\mathbf{M_3}$
- and the RGE running down from the high scale is (usually) a pretty big effect -> “fine” tuning
- combining the above, it has become fashionable to call the MSSM fine tuned.

$$\begin{aligned} M_Z^2 \;\; = \;\; & -1.8\mu^2(\mathrm{UV}) + 5.9M_3^2(\mathrm{UV}) - 0.4M_2^2(\mathrm{UV}) - 1.2m_{H_U}^2(\mathrm{UV}) \\ & +0.9m_{Q_3}^2(\mathrm{UV}) + 0.7m_{U_3}^2(\mathrm{UV}) - 0.6A_t(\mathrm{UV})M_3(\mathrm{UV}) \\ & -0.1A_t(\mathrm{UV})M_2(\mathrm{UV}) + 0.2A_t^2(\mathrm{UV}) + 0.4M_2(\mathrm{UV})M_3(\mathrm{UV}) + \ldots \end{aligned}$$

possible solutions

- tree level UV relations, with no tuning; in this case we are running out of room and superpartners should be discovered soon Kane, JL, Nelson, Wang
- the "high scale" is not so high, e.g. 10-100 TeV
  Casas, Espinosa, Hidalgo; Harnik, Kribs, Larson, Murayama; Nomura, Tweedie
- the Higgs sector of the SSM is not minimal
- the superpartners are all 10 TeV but the EW scale is determined by something else, e.g. little Higgs
- there are 10^{120} parallel universes, so anything can happen, e.g. split SUSY

nonminimal SSM
as a Higgs mass booster

- you expect a nonminimal SSM anyway
- the only problem is that there are many possibilities
- nicely summarized in recent paper of Batra, Delgado, Kaplan, and Tait:

nonminimal SSM
as a Higgs mass booster

- want to increase the tree level value of the Higgs quartic coupling
- e.g. the NMSSM has a singlet S: if S is light, it solves the mu problem; if it is heavy, integrating it out gives a Higgs quartic coupling $\lambda_s S H \bar{H} \rightarrow |\lambda_s|^2 |H \bar{H}|^2$
- other singlets or SU(2) triplets could also do this
- new gauge interactions in the Higgs sector, U(1) or nonabelian, could also do this, from new D terms

- problem: the contributions to the Higgs quartic coupling are infrared free
- so you will hit a Landau pole at some energy scale
- making the Higgs heavier will tend to make this energy scale lower
- e.g. in the pure NMSSM version, avoiding the Landau pole up to the GUT scale restricts $\mathbf{m_h < 160}\ \mathrm{GeV}$
- one solution is extra nonabelian gauge interactions that give asymptotically free contributions; this can raise the Higgs mass bound to 250 - 350 GeV.
- another solution is that there is Higgs compositeness/ new strong dynamics, at a lower scale...

fat Higgs

Harnik, Kribs, Larson, Murayama

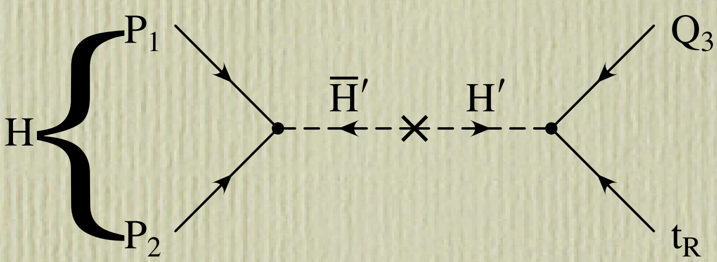
Superfields	$SU(2)_L$	$SU(2)_H$
$(T^1, T^2) \equiv T$	$\mathbf{2}$	$\mathbf{2}$
(T^3, T^4)	$\mathbf{1}$	$\mathbf{2}$
(T^5, T^6)	$\mathbf{1}$	$\mathbf{2}$
P	$\mathbf{2}$	$\mathbf{1}$
Q	$\mathbf{1}$	$\mathbf{1}$
S	$\mathbf{1}$	$\mathbf{1}$
S'	$\mathbf{1}$	$\mathbf{1}$

- SUSY + gauge coupling unification
- but add new strong interaction at an intermediate scale $\mathbf{\Lambda \sim 1000}$ TeV
- produces 4 neutral and 2 charged Higgs as mesons of the confining (almost superconformal) theory
- lightest Higgs can be 450 GeV
- nonstandard production, e.g.

  $\mathbf{gg \rightarrow h}$ but not $\mathbf{qq \rightarrow Wh}$

fat Higgs, fat top

Delgado, Tait



$$\lambda_{\text{eff}} \sim \frac{\lambda_{\text{preon}}\lambda_{\text{SM}}}{4\pi}\,\frac{\Lambda}{M_{H'}}$$

	$SU(3)_s$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
P_3	$\square$	$\square$	$\mathbf{1}$	0	$+$
P_1	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-2/3$	$-$
$\overline{P}_2$	$\overline{\square}$	$\mathbf{1}$	$\square$	$+1/6$	$-$
$\overline{P}_1$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$+2/3$	$+$
$\overline{P}_{\tilde{1}}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$-$
P'	$\square$	$\mathbf{1}$	$\mathbf{1}$	$+1/3$	$-$
$\overline{P}'$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$-$

- how to generate SM fermion masses?
- introduce heavy fundamental Higgs doublets with Yukawa couplings to both SM fermions and the preons
- problem: $\mathbf{m_t \simeq \langle v \rangle/\sqrt{2}}$ is now a complete coincidence
- solution: tweak the strong dynamics and preon content to get composite $\mathbf{t_L},\ \mathbf{b_L},\ \mathbf{t_R}$

CP violation

$$0.015(0.011) \lesssim \Omega_B\, h^2 \lesssim 0.026(0.038)$$

- we need new sources of CP violation to explain the basic fact of our own existence
- from Sakharov, good to look where you also already have sources of B or L violation, plus the possibility of it all happening out of thermal equilibrium
- two good prospects:

  * leptogenesis from heavy neutrinos

  * electroweak baryogenesis

electroweak baryogenesis

- in the EW phase transition, violation of B+L comes for free from sphalerons
- the big challenges are:

  * identify a new source of large CP violation in the EW sector, Arg(phases) ~ 0.1 - 1

  * make the EW phase transition strongly enough first order, to get out of equilibrium

CP violating SUSY

reviewed in Phys. Rep. by Chung, Everett, Kane, King, JL, Wang

- the MSSM has 43 new physical phases, coming from the sfermion mixings, and other soft parameters:
- the 1st+2nd generation phases are constrained to have arg <~ .01 - .00001 by FCNC data
- the phases relevant to EW baryogenesis are constrained by nonobservation of EDMs
- estimates of upper bounds on these phases range from .01 to 1
- can also relax EDM constraints by assuming 1st+2nd gen. sfermions have multi-TeV masses

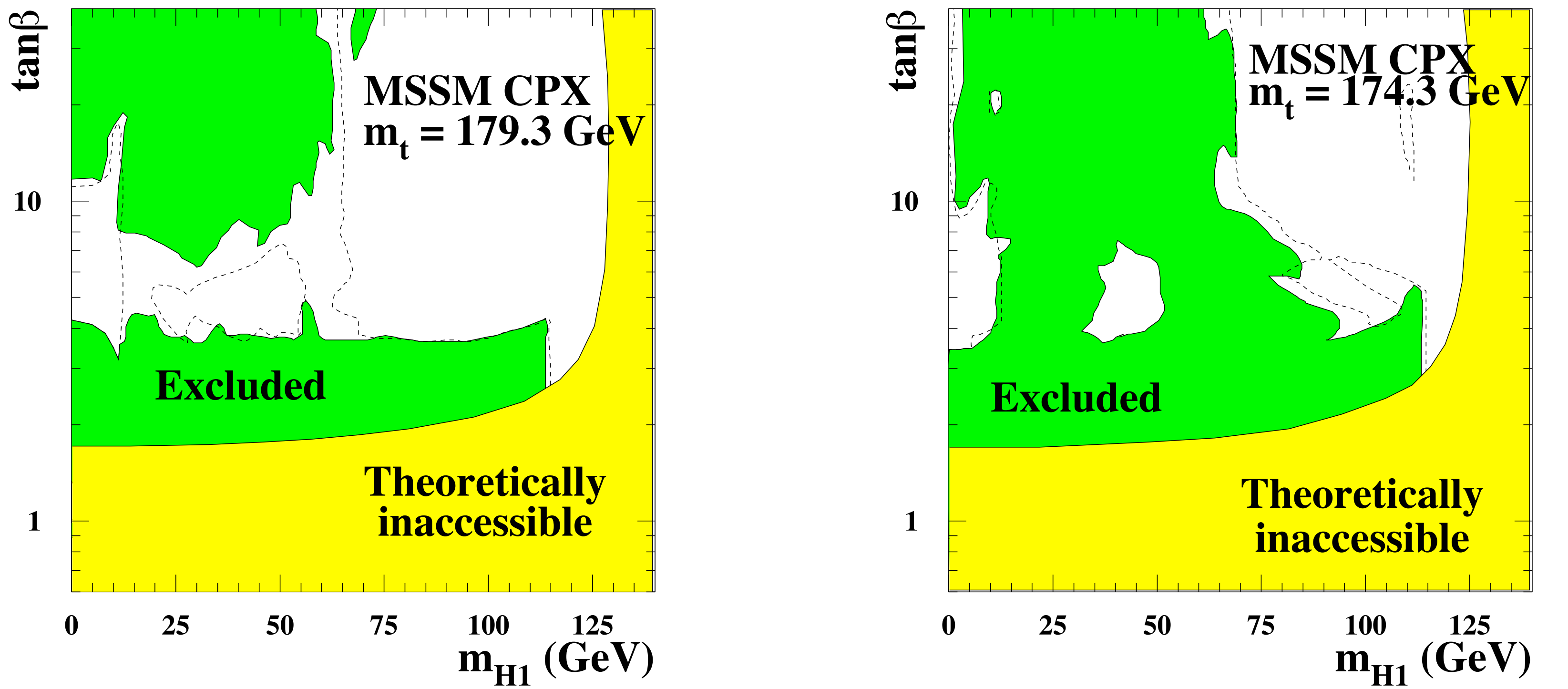
CP violating SUSY

- we need better convergence on what the EDMs imply for MSSM electroweak baryogenesis
- ditto for MSSM extensions
- a new round of EDM experiments in the next few years are supposed to have 10 -100 times better sensitivity
- if EW baryogenesis makes any sense, these expts should see EDMs.

CP violating SUSY Higgs

for more info, see talks at TeV4LHC and Les Houches 05

- CP violation creates important challenges for sparticle production and decay at LHC
- CP violating SUSY will feed into the MSSM Higgs sector at the loop level
- CPV in the MSSM means $\mathbf{h_0,\ H_0,\ A_0 \rightarrow h_1,\ h_2,\ h_3}$
- CPV in the NMSSM means $\mathbf{h_0,\ H_0,\ A_0,\ S \rightarrow h_1,\ h_2,\ h_3,\ h_4,\ h_5}$
- could have big impact on both Higgs production and decay



- in the CPX MSSM scenario, $\mathbf{ZZh_1}$ coupling is suppressed, $\mathbf{Zh_2}$ production is kinematically marginal
- conclusion for LEP depends on whether you use a D0 or a CDF top mass

electroweak baryogenesis

* identify a new source of large CP violation in the EW sector, Arg(phases) ~ 0.1 - 1

* make the EW phase transition strongly enough first order, to get out of equilibrium

- in first challenge, big question is what SUSY models give large enough phases w/o violating EDM bounds
- in second challenge, big question is how to sift through many possibilities:

ways to make the EW phase transition more strongly first order

- a very light Higgs (ruled out by LEP?)
- a light stop — Carena, Quiros, Wagner
- trilinear scalar couplings in extended Higgs sector — Kang, Langacker, Li, Liu
- low scale cutoff induces dimension 6 operator in the Higgs potential — Grojean, Servant, Wells
- new TeV scale fermions with strong couplings to Higgs — Carena, Megevand, Quiros, Wagner
- slinky inflation gives a larger expansion rate during the EW phase transition — Barenboim, JL

not-so-little Higgs

- Little Higgs models with conserved T parity are alive and well and add to the “confusion” problem for LHC
  Hubisz, Meade
- Little Higgs models w/o T parity have generic problems with precision EW constraints
- new strategy (Katz, Nelson, Walker): retreat to “intermediate” Higgs models
- just add new vectorlike quarks to cancel the 1-loop top quark quadratic divergence, forget about cancelling the gauge boson contributions
- gives a natural theory for a cutoff scale up to 6 TeV

less Higgslessness

- Higgless models arise from the observation that the Kaluza-Klein mechanism is an alternative to the Higgs mechanism, saturating the same sum rules that restore unitarity to the SM

- 5d warped Higgless models, and "deconstructed" 4d relatives, have been much studied

- they have generic problems with precision EW data

- the experts are now pushing:

- 5d warped models with an extra TeV brane and AdS_5 bulk space, just for the third generation — Cacciapaglia, Csaki, Grojean, Reece, Terning

- deconstucted models with delocalized fermions — Chivukula, Simmons, He, Kurachi, Tanabashi

- this does not look good...

prophesy

- EWSB is an old problem, but it won't be solved by old people
- new heroes will emerge in the golden era of the LHC