PROSPECTS FOR THE LHC ERA

JOSEPH LYKKEN

FERMILAB

The LHC Era has begun!

- Effectively the LHC era has begun in 2010, with ~ 35 pb-1 of 7 TeV data per experiment being analyzed by ATLAS and CMS
- 2011 is likely to be the most exciting year of the LHC era, since most the discovery reach (in some metric) will be covered by the first few fb-1 of 8 TeV data
- What will the LHC experiments discover???
- The canonical discovery program is based on the expectation of a more-or-less SM-like Higgs and on TeV scale supersymmetry
- Many of us have voted with our feet that these are good bets

Discoveries in Physics

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z, W
AGS Brookhaven (1960)	π N interactions	2 kinds of neutrinos, Time reversal non-symmetry, New form of matter (4^{th} Quark)
FNAL Batavia (1970)	Neutrino physics	*5^{th} Quark, 6^{th} Quark*
SLAC Spear (1970)	ep, QED	Partons, 4^{th} Quark, 3^{rd} electron
ISR CERN (1980)	PP	*Increasing PP Cross section*
PETRA Hamburg (1980)	6^{th} Quark	*Gluon*
Super Kamiokande (2000)	Proton decay	Neutrinos have mass
Hubble Space Telescope	Galactic survey	*Curvature of the universe, dark energy*

Exploring a new territory with a precision instrument is the key to discovery.

The LHC is a precision machine

- The LHC era will last a long time
- Consider the Tevatron, celebrating its 25th year of operations and still doing exciting frontier physics
- LHC (with upgrades) will be the same
- Nominally the LHC pp physics program is 300 fb-1, but it will eventually be more
- This huge amount of data, combined with the amazing capabilities of the ATLAS and CMS detectors, will allow us to overcome the intrinsic messiness of pp collisions
- We should therefore be very ambitious about the physics goals of the long-term LHC program

The LHC Era: looking ahead

J.L. complaining at a 2005 MCTP workshop:

> "Why do almost all LHC studies by theorists and experimenters assume 30 to 100 fb-1? We should have a lot more people thinking about 100 pb-1 to 1 fb-1"

J.L. complaining at a 2010 MCTP workshop:

> "Why do almost all LHC studies by theorists and experimenters assume 100 pb-1 to 1 fb-1? We should have a lot more people thinking about 300 fb-1 to 3000 fb-1"

Tevatron history: a full-scale joint CDF-D0-theorist analysis of Tevatron Higgs sensitivity with 20 fb-1 was completed in 1998, a time when the Tevatron data set was ~100 pb-1, and Run II was defined as 2 fb-1

Two kinds of scenarios that imply thinking about the later stages of the LHC era:

- Relatively early discoveries that then raise many challenging follow-up questions
- Discoveries/measurements that intrinsically require very large data sets

Relatively early discoveries that imply many challenging follow-up questions

1. Discovery of a 120 GeV resonance consistent with being a SM Higgs boson
2. No Higgs boson found
3. Discovery of some new heavy particles consistent with supersymmetry
4. Discovery (at LHC or elsewhere) of new sources of flavor/CP violation
5. Discovery of a missing energy signature/s consistent with WIMP dark matter

Discovery a 120 GeV resonance consistent with a SM Higgs

Some immediate questions:

- Is it spin 0?
- Is it CP even? To what extent can you exclude a CP odd component?
- Does it come from a weak doublet?
- Are its couplings proportional to masses?
- Is it composite or an elementary scalar?
- Are there other neutral or charged resonances?
- Does other things decay into it?
- Did you look at all possible associated production of it?

Discovery a 120 GeV resonance consistent with a SM Higgs

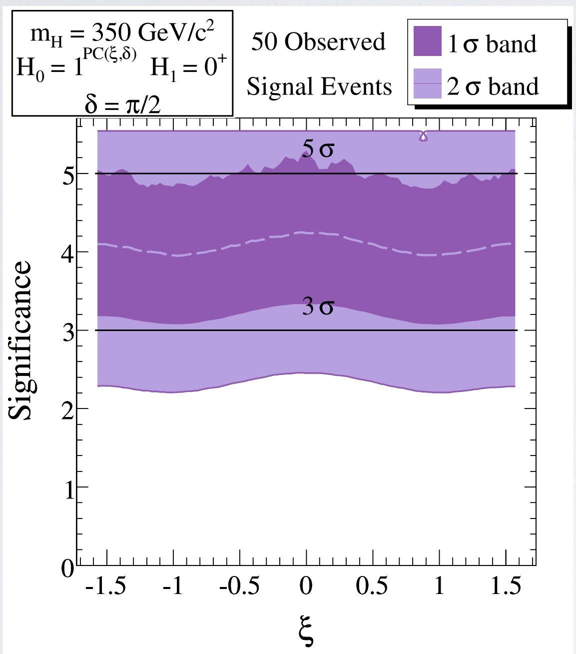
Partial list of things we need to do then:

- Measure h-> bb
- Measure h -> WW and h-> ZZ
- Measure h-> tautau
- Measure h -> Z gamma
- Measure h-> mumu
- Measure h-> cc (?)
- Measure h-> gg (how?)
- Measure/constrain h-> invisible
- Measure/constrain h-> cascade
- Measure/constrain self-couplings of h

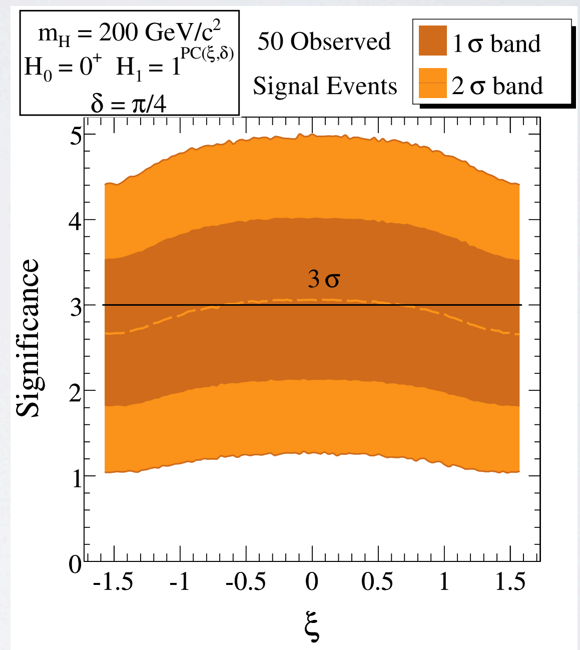
Some of this may happen around the moment of discovery

Example: ZZ -> 4 lepton final state:
0+ neutral resonance versus any spin 1 look-alike

how well do I exclude arbitrary spin 1 when in fact I have a SM Higgs?



how well do I exclude an SM Higgs when in fact I have some arbitrary spin 1?



A. De Rujula, J.L., M. Pierini, C. Rogan, M. Spiropulu, arXiv:1001.5300

- for 145 GeV SM Higgs we can exclude the general spin one hypothesis at 5 sigma with 60 signal events

Some of these will require huge LHC data sets

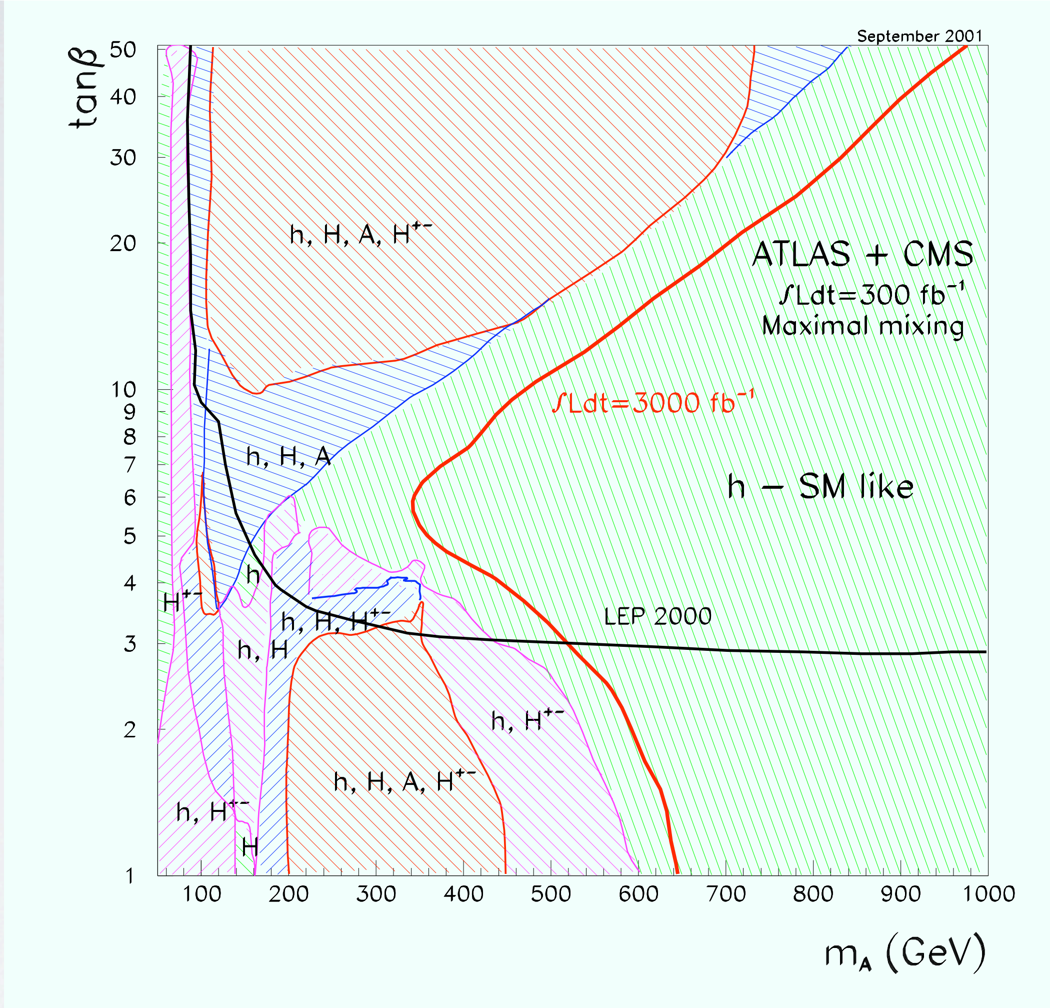
Table 6: Expected signal significance of a SM $gg \rightarrow H \rightarrow \mu\mu$ signal for various mass values, as obtained by combining ATLAS and CMS and for an integrated luminosity of 3000 fb^{-1}per experiment [19]. The expected statistical accuracy on the measurement of the product of cross-section times BR is also given.

m_H (GeV)	$S/\sqrt{B}$	$\frac{\delta\sigma\times\mathrm{BR}(H\rightarrow\mu\mu)}{\sigma\times\mathrm{BR}}$
120 GeV	7.9	0.13
130 GeV	7.1	0.14
140 GeV	5.1	0.20
150 GeV	2.8	0.36

F. Gianotti, M. Mangano, T. Virdee, et al, hep-ph/0204087

- Note this assumes 3000 fb-1 ATLAS and CMS combined
- Assumes can use Z-> ee to get precise prediction for Z-> mumu background

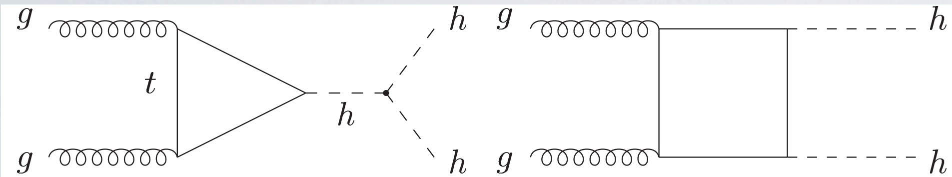
Discovery of the extra heavy Higgses of the MSSM

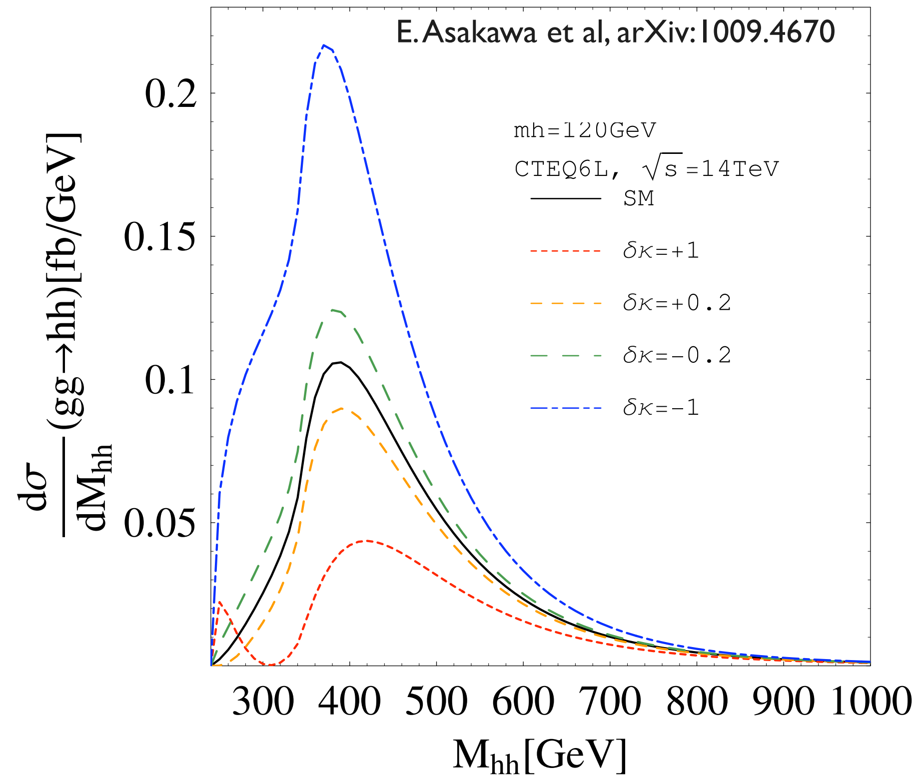


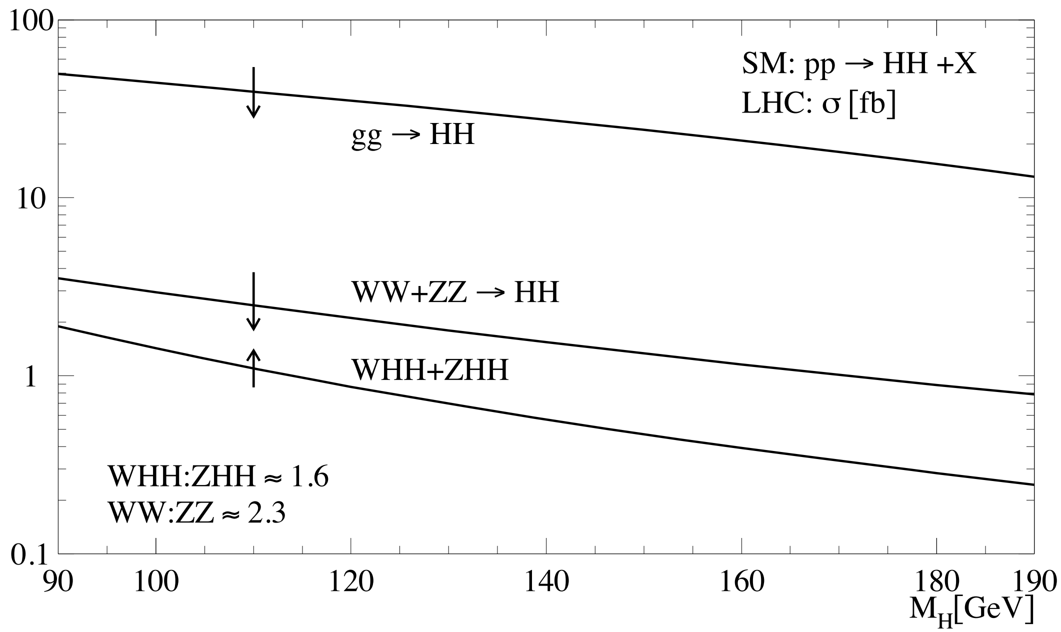
F. Gianotti, M. Mangano, T. Virdee, et al, hep-ph/0204087

Fig. 10: Regions of the MSSM parameter space where the various Higgs bosons can be discovered at $\geq 5\sigma$ at the LHC (for 300 fb^{-1} per experiment and both experiments combined) through their decays into SM particles. In the dashed regions at least two Higgs bosons can be discovered, whereas in the dotted region only h can be discovered at the LHC. In the region to the left of the rightmost contour at least two Higgs bosons can be discovered at the SLHC (for 3000 fb^{-1} per experiment and both experiments combined).

Measuring the "Higgs" self-couplings







F. Gianotti, M. Mangano, T. Virdee, et al, hep-ph/0204087

Is the "Higgs" composite?

$\xi = v^2/f^2$

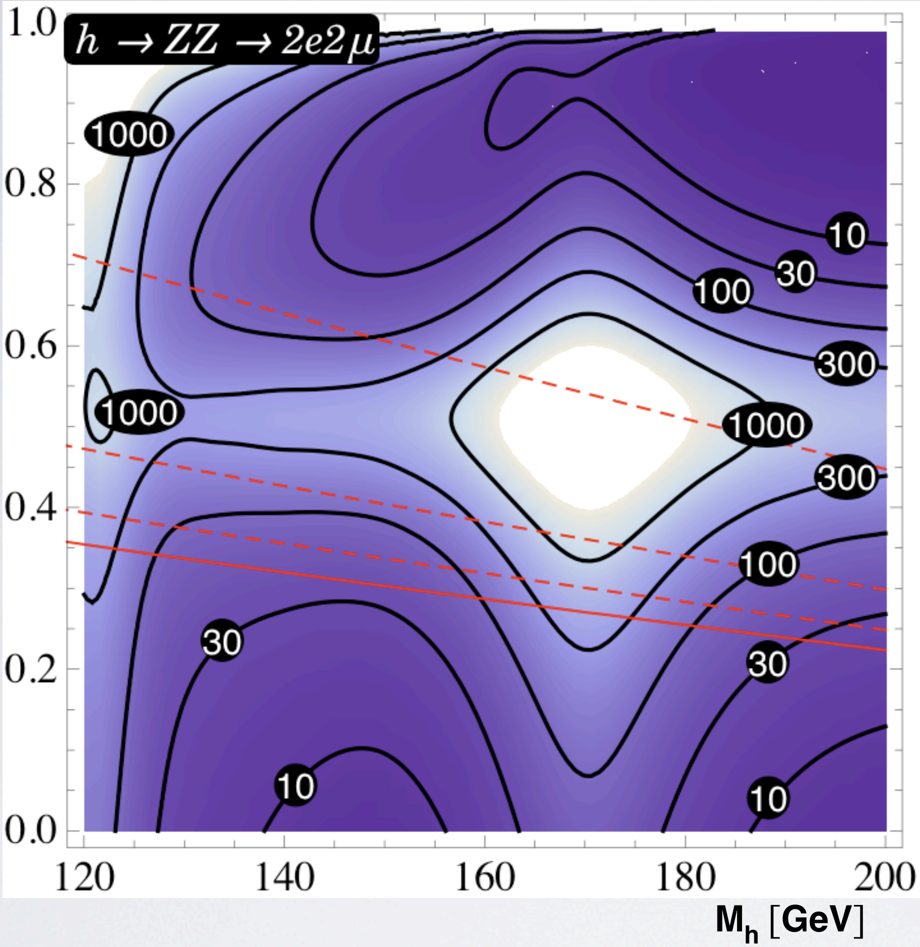


Figure 3: Luminosity (in fb^{-1}) needed for discovery in the most promising channels with the CMS detector [111] as a function of the Higgs mass (horizontal axis, in GeV) and the parameter $\xi = v^2/f^2$ (vertical axis), measuring the amount of compositeness of the Higgs boson. These contour plots correspond to the minimal composite Higgs model of Ref. [80] with fermion in fundamental representations. Strictly speaking, these results are fuly consistent only below the plain red curve that delineates the 99% C.L. region of the parameters space favored by EW precision constraints (with a cutoff scale fixed at 2.5 TeV). Above, some amount of cancellation in the oblique parameters is needed (from the bottom to the top, the dashed red lines indicate regions with 10%, 25% and 50% cancellation in S and T), and the physics at the origin of this cancellation might also affect the Higgs production cross sections and decay rates. From Ref. [112].

C. Grojean, arXiv:0910.4976

No Higgs found

Some immediate questions:

- Do you have enough data / good enough analyses?
- Is it a non-SM Higgs with invisible and/or cascade decays? Is it lighter than the LEP SM lower bound?
- Are you in a “Higgsless” scenario where Kaluza-Klein tree-level exchanges replace Higgs exchange in unitarizing WW and WZ scattering? [See talk by Csaba Csaki]
- Are you in a “technicolor” scenario where new strong dynamics takes over before you reach the ~1.6 TeV unitarity bound? Do you see techni-resonances?
- Is quantum field theory the wrong way to think about this problem?

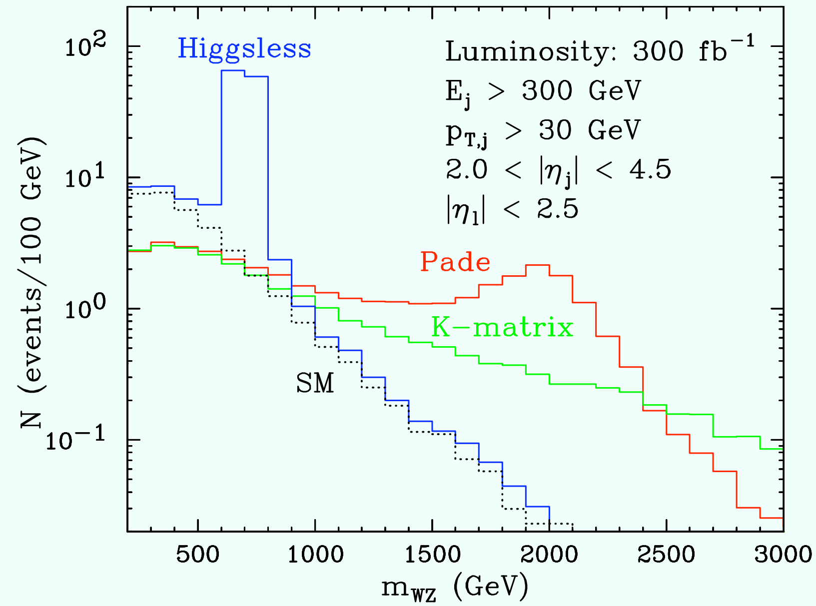
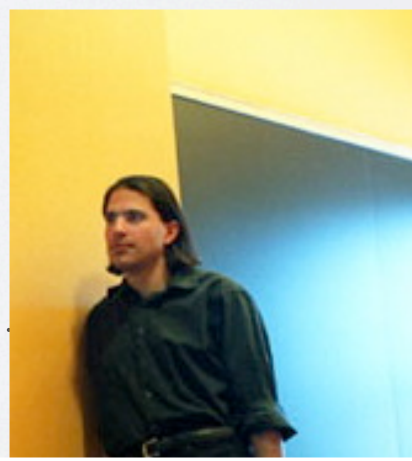


FIG. 4. The number of events per 100 GeV bin in the $2j + 3\ell + \nu$ channel at the LHC with an integrated luminosity of 300 fb^{-1} and cuts as indicated in the figure. The model assumptions and parameter choices are the same as in Fig. 2.

A. Birkedal, K. Matchev, M. Perelstein, hep-ph/0412278



Discovery of new heavy particles consistent with supersymmetry

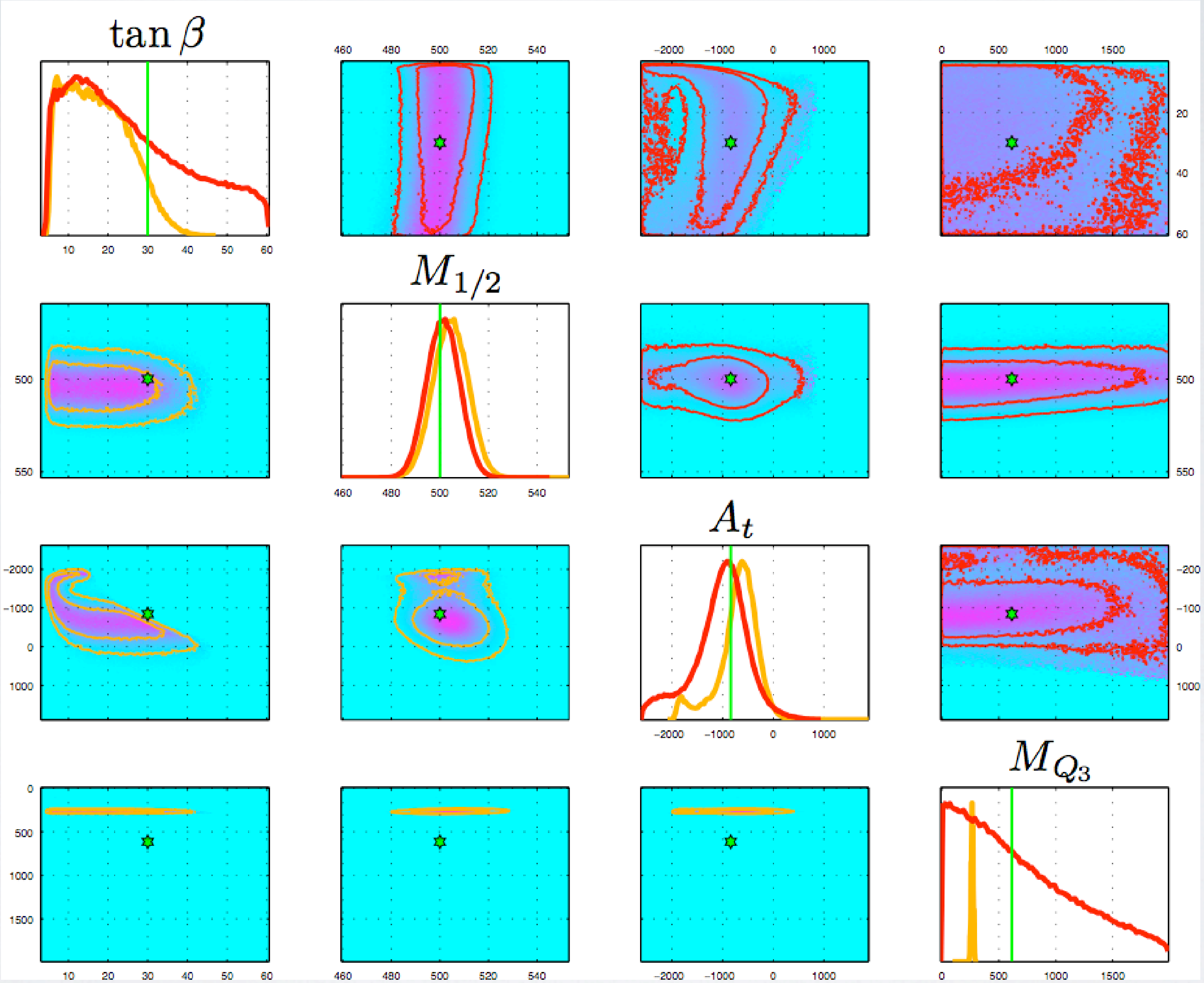
Some immediate questions:

N. Arkani-Hamed, G. Kane, J. Thaler, L-T Wang, hep-ph/0512190
J. Hubisz, J.L., M. Pierini, M. Spiropulu, arXiv:0805.2398
etc.

- Is it really SUSY? (The look-alike problem)
- If it is SUSY, what kind of SUSY? What is the soft-breaking mechanism? (The look-alike problem again, distinguishing different "footprints")
- Can you reconstruct all the decay chains and production mechanisms? [See talk by Ben Gripaios]
- Can you make an unambiguous mapping back to the parameters of the soft-breaking Lagrangian? (The inverse problem) [See talk by Brent Nelson]

Can we please use all the information in the LHC data?

[See talk by Maria Spiropulu]

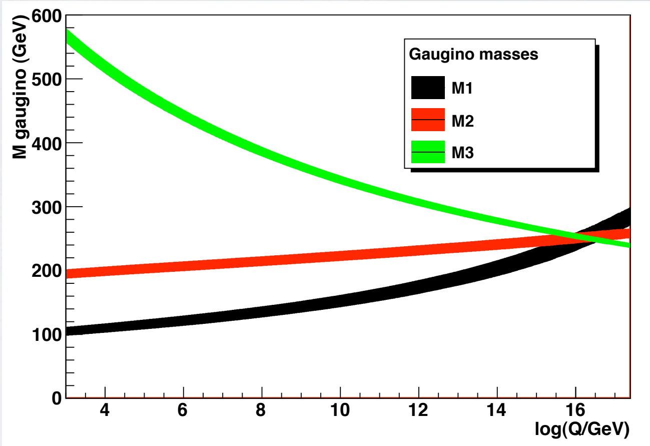


S. Fichet and S. Kraml, Les Houches 2009

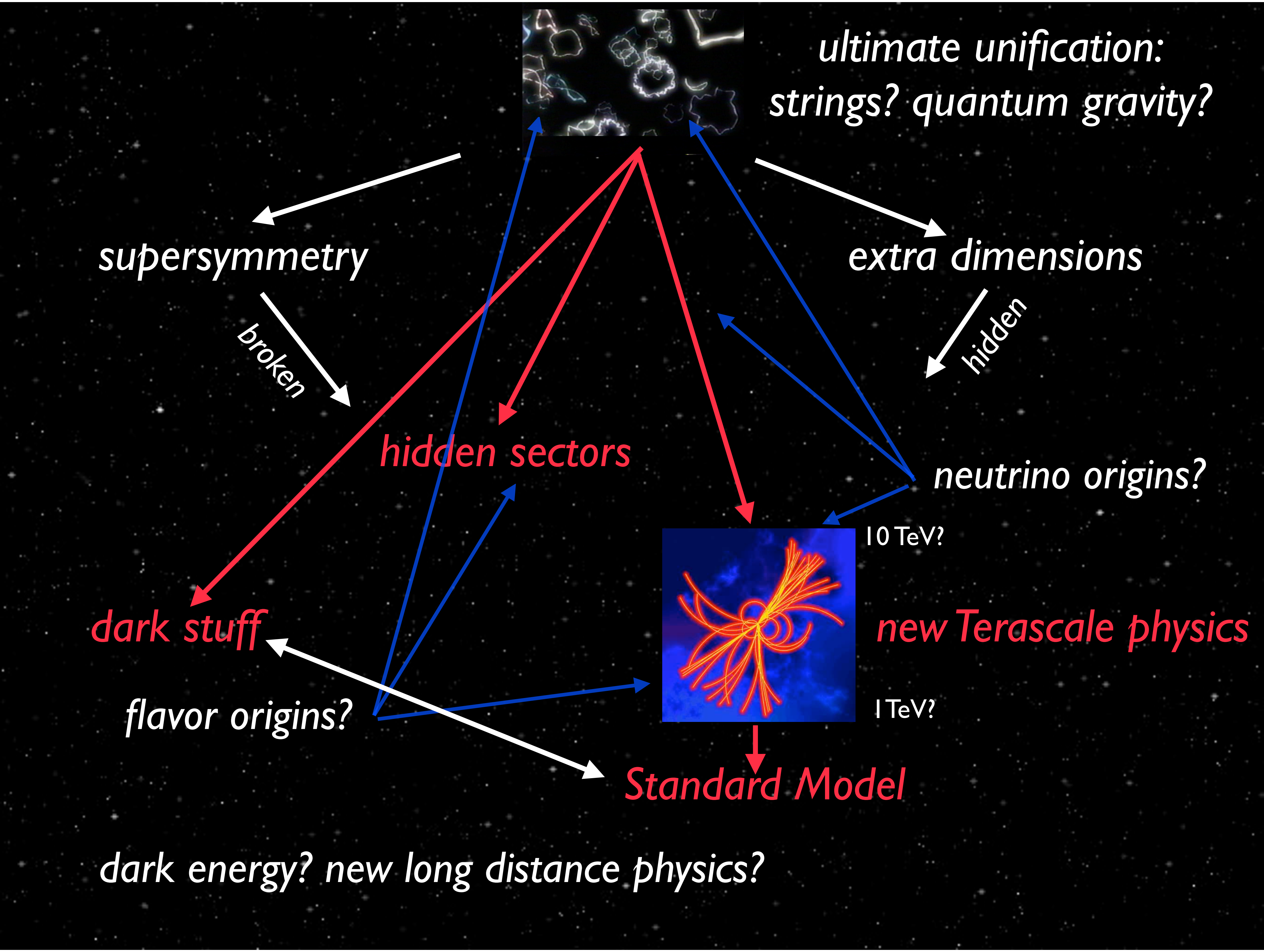
Discovery of new heavy particles consistent with supersymmetry

After you answer the previous questions, try these:

- What can you say about super-high energy scales?



  - Force unification?
  - Matter unification?
  - Connection to neutrino see-saw and leptogenesis?
  - What string compactification do we live in? [See talk by Brent Nelson]


ultimate unification:
strings? quantum gravity?
supersymmetry
broken
extra dimensions
hidden
hidden sectors
neutrino origins?
10 TeV?
dark stuff
new Terascale physics
flavor origins?
1 TeV?
Standard Model
dark energy? new long distance physics?

What can you say about flavor and the origin of matter?

- Minimal flavor violation or new sources?
- New sources of CP violation?
- Why are EDMs so small and FCNC so suppressed?
- Compositeness?
- Baryogenesis or Leptogenesis?
- Do fermion masses come from Yukawa couplings to a Higgs, or are the real couplings to the Higgs vev hierarchical? Are other vevs and/or condensates involved?
- So far warped extra dimensions seems like our best candidate for a natural theory of flavor. How to prove this even if it is true?

Dark matter at the LHC?

- What can you say about dark matter candidates and the dark sector? [See talks by Brent Nelson and Neal Weiner]
- Do you have evidence for a WIMP dark matter candidate?
- What is its mass?
- What kind of particles decay into it?
- Can you see direct production or associated production?
- Does it carry electroweak charge and/or some new charge?
- What is its spin?
- What are the LHC predictions for direct DM detection, indirect DM detection, and early universe cosmology (e.g. relic abundances)?

Direct neutralino production

Example: LM5 mSUGRA benchmark model

- LSP mass 144 GeV
- gluino mass 850 GeV
- squark masses ~750 GeV
- LSP-LSP pair production cross section 130 fb (at 7 TeV)
  - asking for a hard ISR monojet knocks this down to ~10 fb
- LSP-gluino associated production 10 fb
- LSP-squark associated production 24 fb

We should be able to see direct WIMP DM production as long as the couplings are not *too* weak and the mass is reasonably light

Some new particles may be detected only rather late in the LHC program. Why?

- They are very heavy (factor of 10 integrated luminosity ~ factor of 2 in energy):
  - Heavy resonances
  - Heavy pair production (or pairs of resonances [See talk by Bogdan Dobrescu])
  - Heavy associated production
- They are weakly coupled to partons inside the proton (need integrated luminosity)
- Their signatures have large SM backgrounds with few handles for discrimination (need to be smarter, but also need to have lots of data to do data-driven tests of new discriminators and/or to allow you to cut hard on the signal if necessary)
- Their signatures involve special features that are difficult to reconstruct and/or trigger on (e.g. quirks, displaced decays, top jets, lepton jets, dependence on color flow, etc.)

Heavy resonances: Z-primes

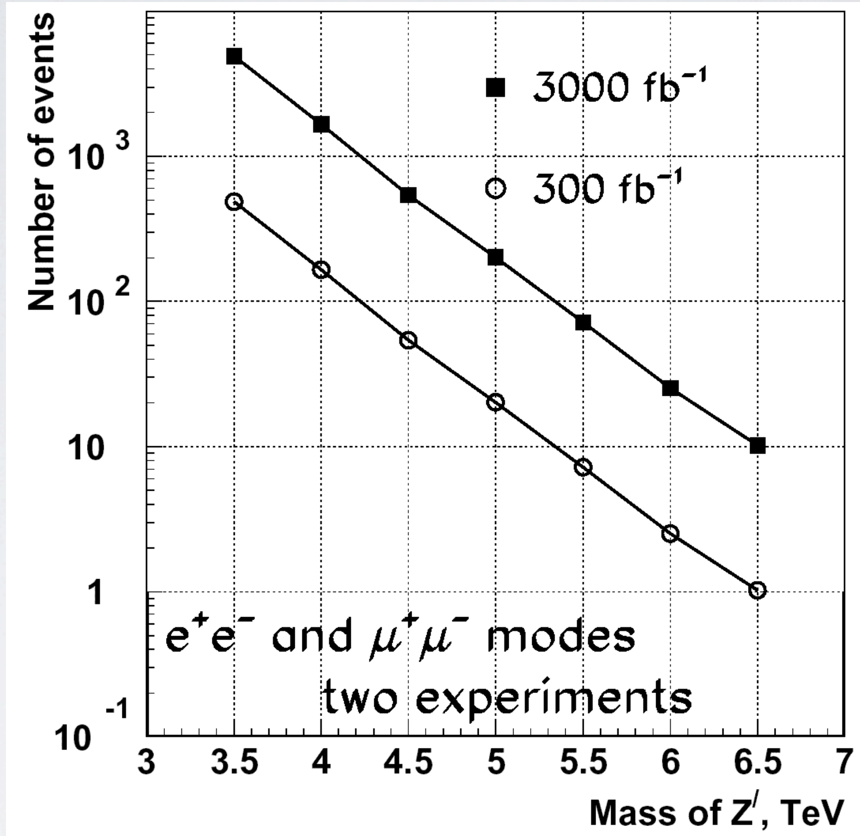
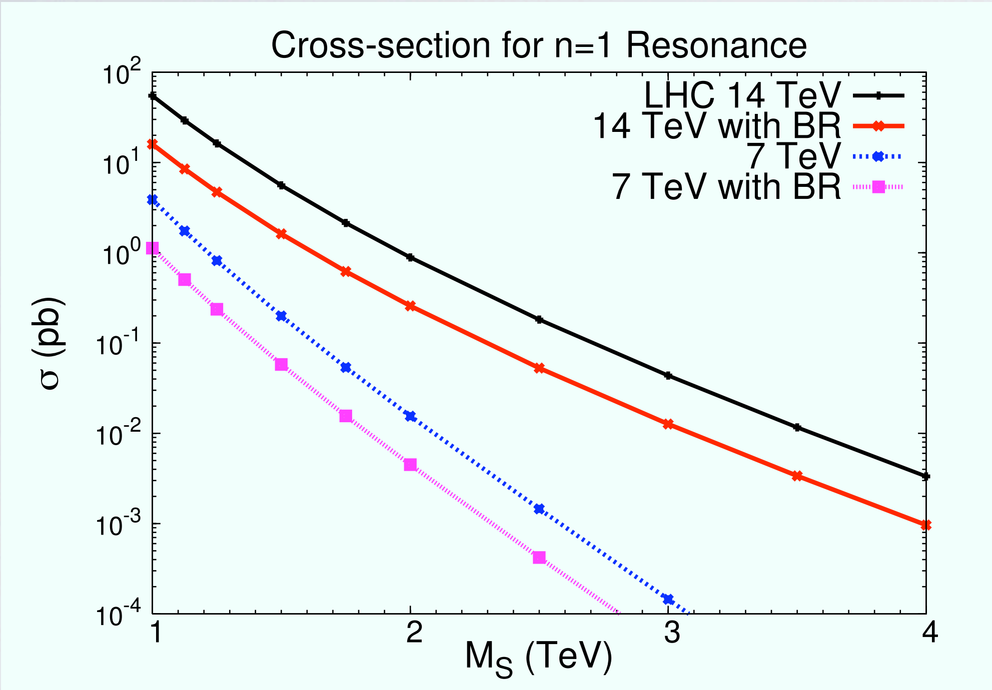


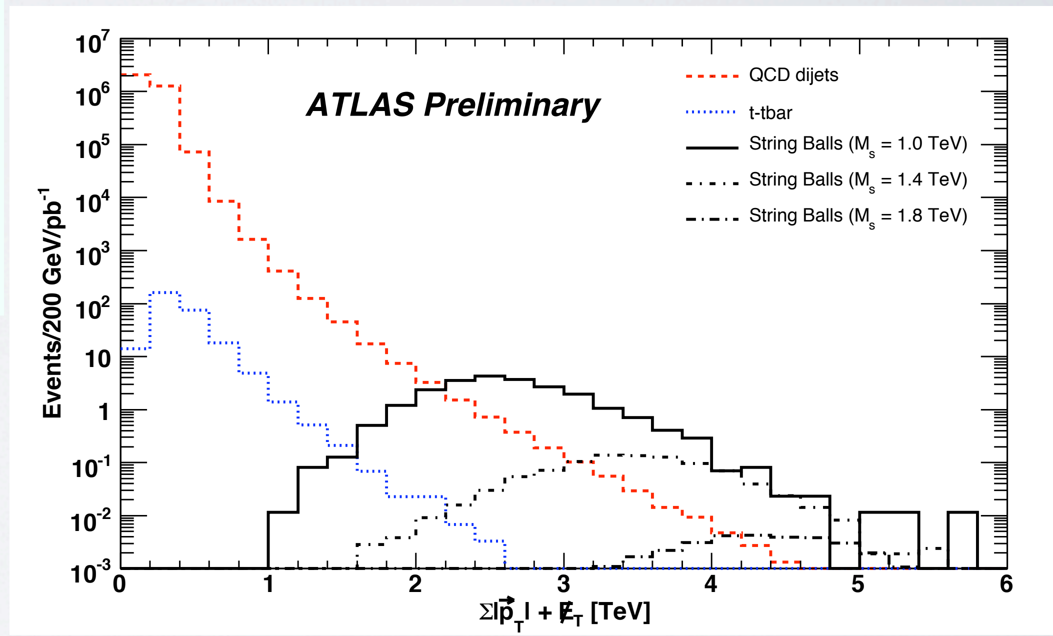
Figure 6. Event rates for a Z' with Standard Model couplings, at the LHC and sLHC.

M. Mangano, arXiv:0910.0030

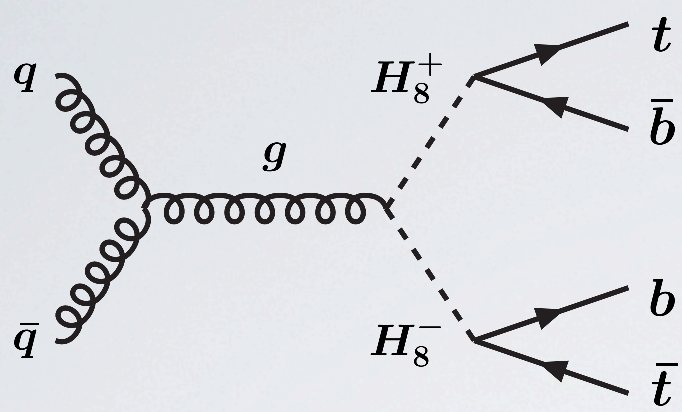
Heavy resonances: string excitations and black holes



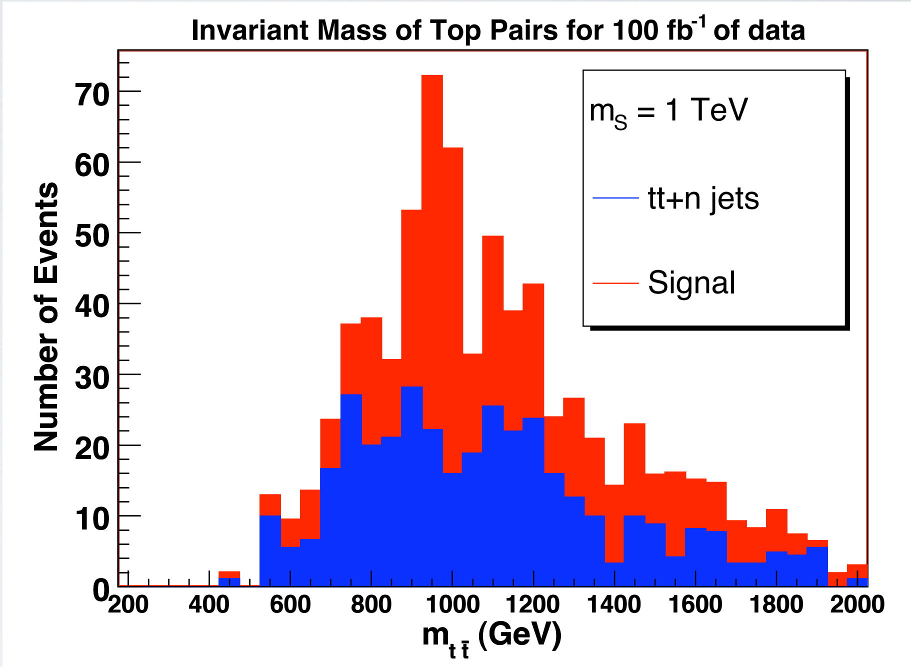
Z. Dong, T. Han, M. Huang, G. Shiu, arXiv:1004.5441



ATLAS 10 TeV study ATL-PHYS-PUB-2009-011

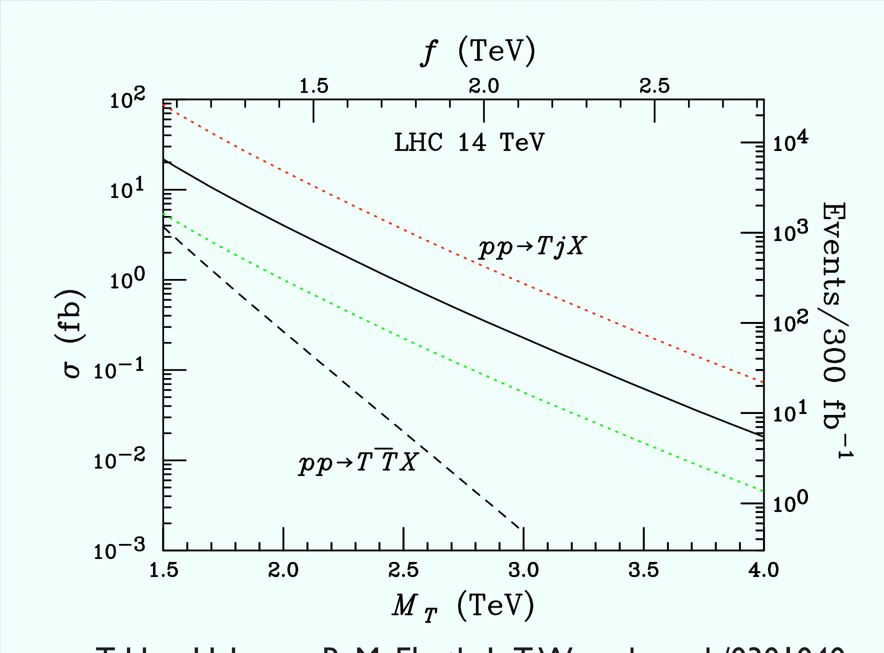


M. Gerbush, T. Khoo, D. Phalen,
A. Pierce, D. Tucker-Smith, 0710.3133



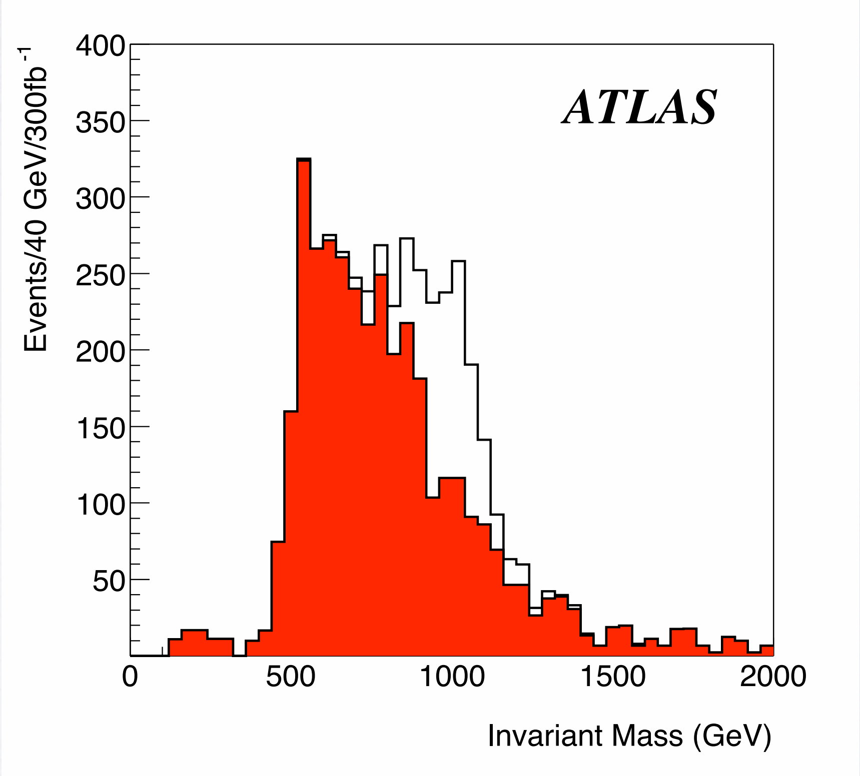
- Aaron: This analysis is already obsolete, should be able to do better with new jet reclustering techniques

Single production of new heavy quarks



T. Han, H. Logan, R. McElrath, L-T Wang, hep-ph/0301040

5 sigma reach for T mass < 2.0 - 2.5 TeV



G. Azuelos et al, hep-ph/0402037

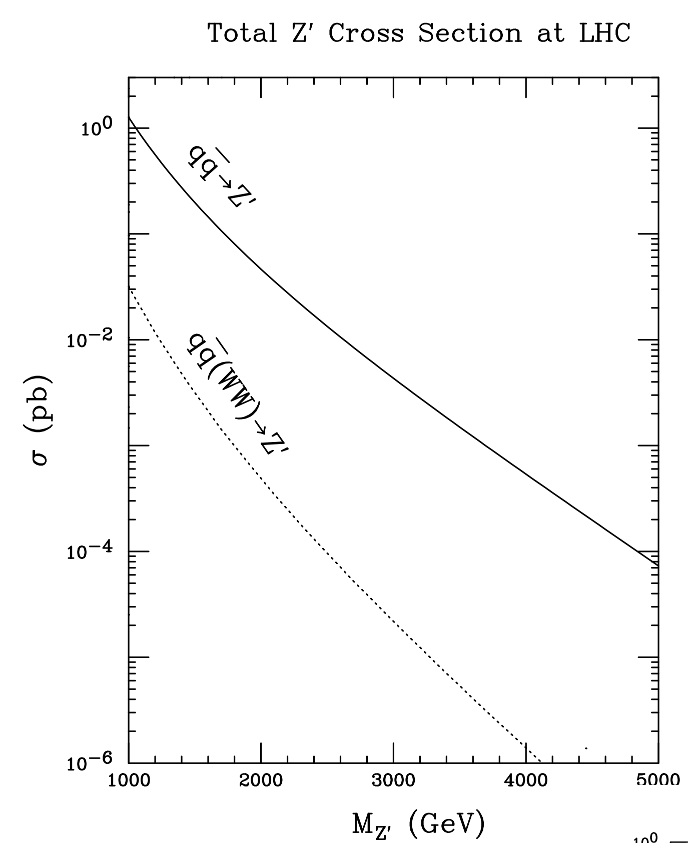
- At least one charged lepton with p_T >100 GeV.
- One b-jet with $p_T > 200$ GeV.
- No more than 2 jets with $p_T > 30$ GeV.
- Mass of the pair of jets with the highest p_T is greater than 200 GeV.
- $\not{E}_T$ >100 GeV.

Does the LHC have enough energy?

- Leon Lederman's original supercollider proposal was 20 TeV (ten times Tevatron)
- SSC was 40 TeV
- LHC design is 14 TeV, people talk about an upgrade to 28 TeV
- So far we have 7 TeV
- The technical upper limit for a proton collider with more-or-less proven technology is 100 - 200 TeV

Case study: a warped extra dimension

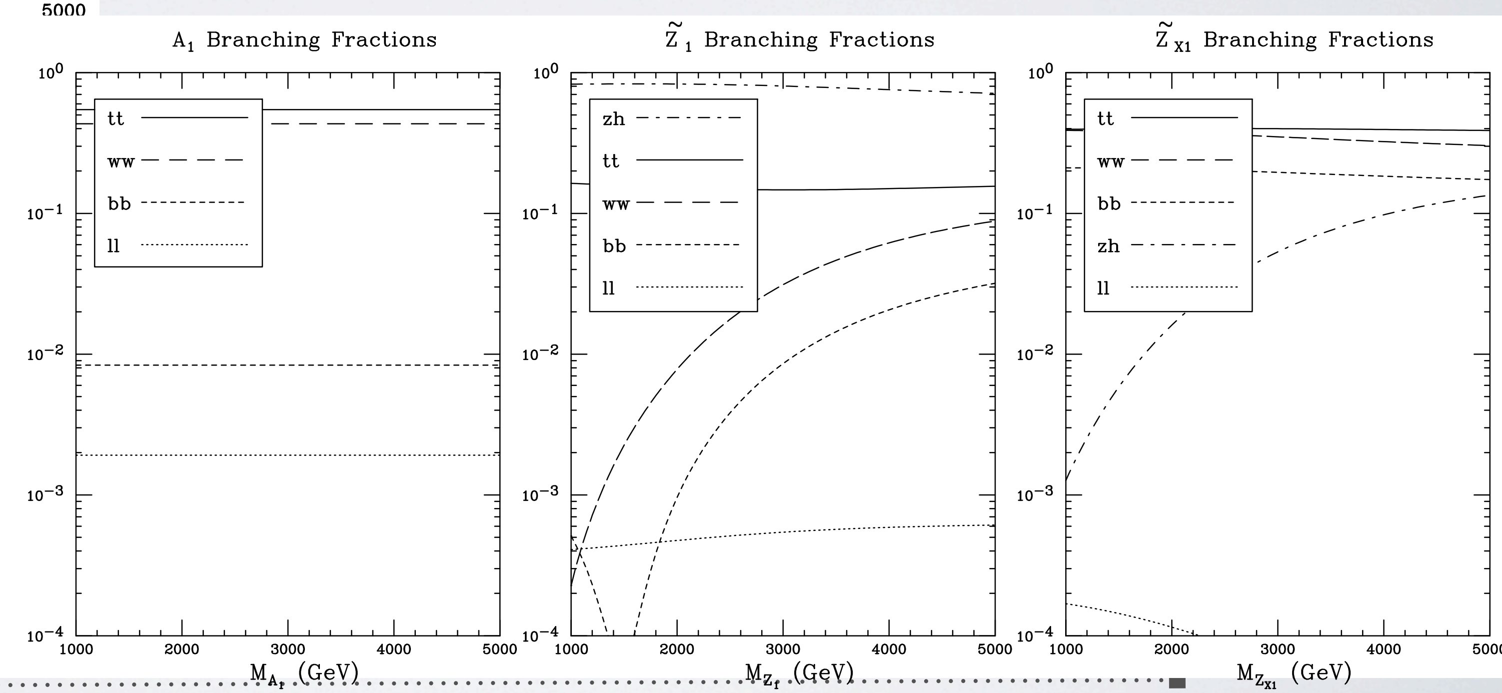
- A possible output of string theory
- Complementary to SUSY: generic Randall-Sundrum solves hierarchy problem but not the Higgs naturalness problem
- A viable theory of flavor:
  - Higgs localized at the IR brane
  - Quarks and leptons localized different places in the 5th dimension
  - Order one "anarchic" inputs can give observed SM flavor hierarchies
  - Dual 4d description: gauge bosons and fermions come in both elementary and composite varieties; mass eigenstates are different mixtures of elementary and composite states
- **Could we verify any of this at the LHC?**



Heavy KK gauge bosons from a warped extra dimension

Z' Channel	$M_{Z'}$ (TeV)	$\mathcal{L}$ (fb^{-1})	$\frac{S}{B}$	Significance (σ)
$W\,W \to \ell\nu j\,j$	3	1000	0.2	4.6
$m_h = 120$: $Z\,h \to \ell\ell b\bar{b}$	3	1000	2	5.7
$m_h = 150$: $Z\,h \to (jj)\,(jj)\,\ell\nu$	3	300	1.2	4.7

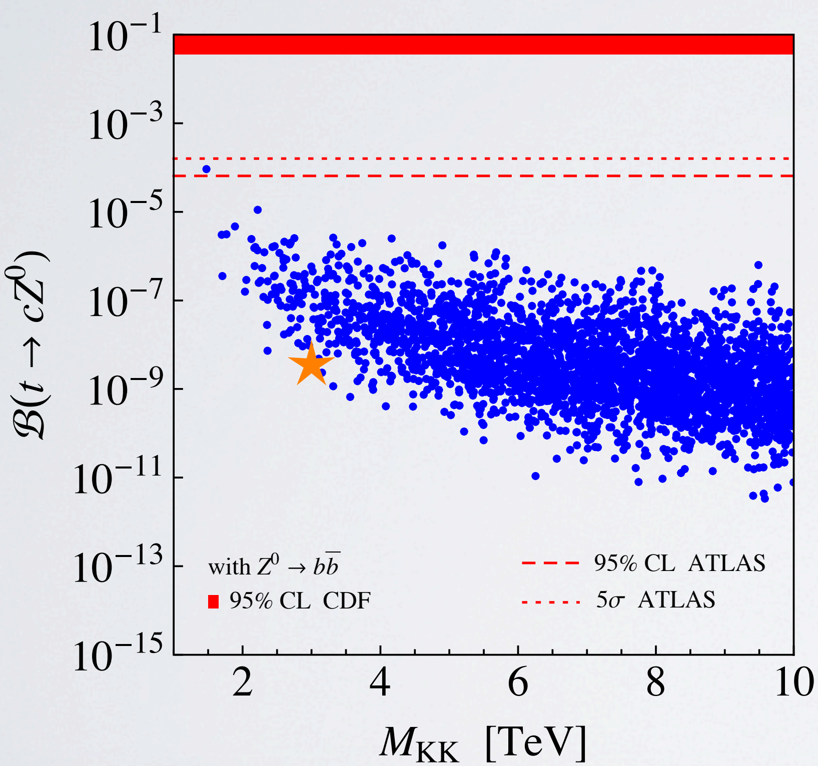
K. Agashe, H. Davoudiasl, S. Gopalakrishna, T. Han, G-Y Huang, G. Perez, Z-G Si, A. Soni arXiv:0709.0007
H. Davoudiasl, S. Gopalakrishna, E. Ponton, J. Santiago arXiv:0908.1968

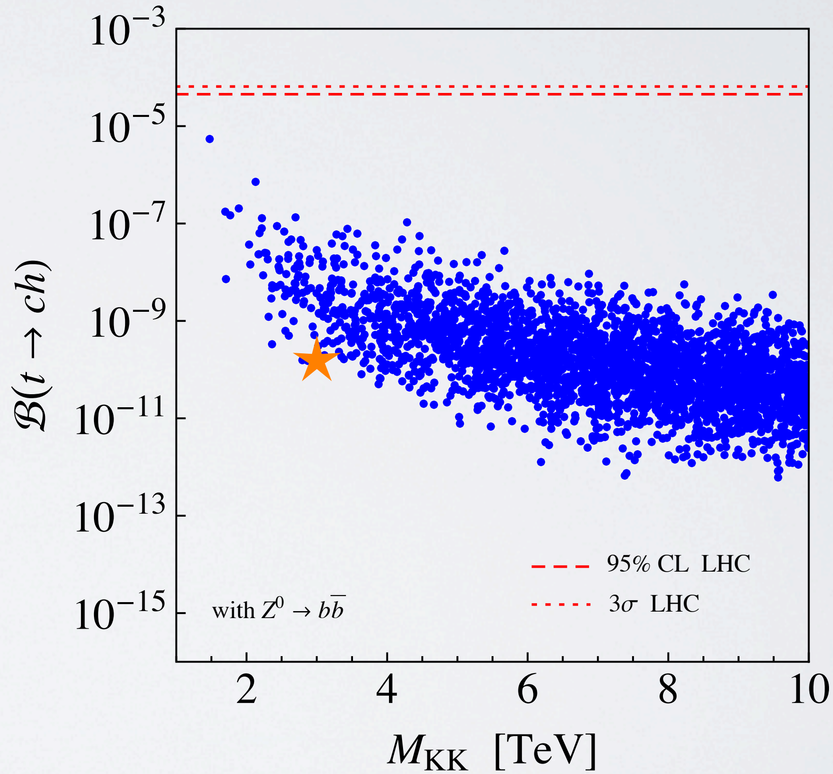


- Masses and decay fractions are model dependent
- "Realistic" masses are > 3 TeV
- Even for most favorable decay channels, this is a challenge

Rare top decays from a warped extra dimension

- In "generic" warped models, top is heavy because its wave function is localized close to the IR brane, thus having a larger overlap with the Higgs
- For the same reason top is more mixed with the extra KK/composite fermions, inducing FCNC rare decays
- With 100 fb-1 at 14 TeV, ATLAS projects sensitivities down to a few times 10^-5
- This is impressive but still not good enough!





S. Casagrande, F. Goertz, U. Haisch, M. Neubert, T. Pfoh, arXiv:0807.4937

Lots of opportunities for theorists and experimentalists!!!

- Relatively early discoveries (2011?) will raise many challenging follow-up questions --- attack them now!

- Discoveries/measurements that intrinsically require large data sets and/or new analysis techniques -- be ambitious!