Exotica Searches at the LHC
Lecture 1 of 3

Greg Landsberg

Taller de Altas Energías 2014

Benasque, Spain

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Outline

- Why Search for BSM Physics?
- The Hierarchy Problem
- Possible Solutions
- SUSY Primer
- Technicolor: RIP
- Extra Dimensions

What I'll Cover

- Searches for BSM physics are vast
- For example, in CMS they are organized within three physics groups: SUSY (SUS), Exotica (EXO), and Beyond Two Generations (B2G)
  - While "bread-and-butter" EXO searches (W', Z', extra dimensions, LQs, etc.) are winding down, a lot of attention is shifting to B2G searches with b and t quarks, as well as searches in the boosted topologies
  - SUS searches moved toward "natural" SUSY models and Higgs production in the SUSY decay chains
- In these lectures, I'll highlight some of these recent results
- I'll also cover one particular result in a lot of details - as a pedagogical introduction to searches for new physics

Motivation

MOTIVATION

Some people need more than others...

As Confucius Once Said...

… about SUSY searches in the XXI century?..

It’s very hard to find a black cat ...

As Confucius Once Said...

… in a dark room … … about SUSY searches in the XXI century?..

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As Confucius Once Said...

… in a dark room … **… about SUSY searches in the XXI century?..**

It’s very hard to find a black cat …

… especially if he is not there…

Why Motivate Yourselves?

- Searching for new physics is not for weak at heart:
  - Some 200 searches have been carried out by the ATLAS and CMS experiments so far, and all came empty-handed
  - A likelihood for any given search to find something interesting is close to zero…
  - ..yet, the only way to find something is to keep looking!
- It's much easier to do the analysis if you are motivated
  - …not [just] by your advisor, but by the physics you are doing!
- Remember, every search is a potential discovery, and only if it fails, it becomes a limit setting exercise
- "Pier is a disappointed bridge" - James Joyce
  - Set out to build bridges, not piers!

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Real Motivation: the Hierarchy Problem

[Matthew Ritchie, 2003; Guggenheim Museum]

Large Hierarchies Tend to Collapse…

SM:10^{-34}
fine-tuning

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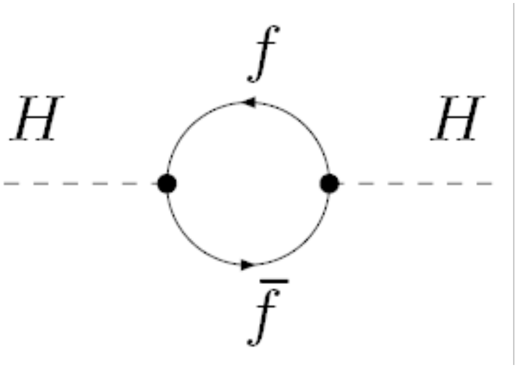
The Hierarchy Problem

- Higgs boson mass receives corrections from fermion loops:



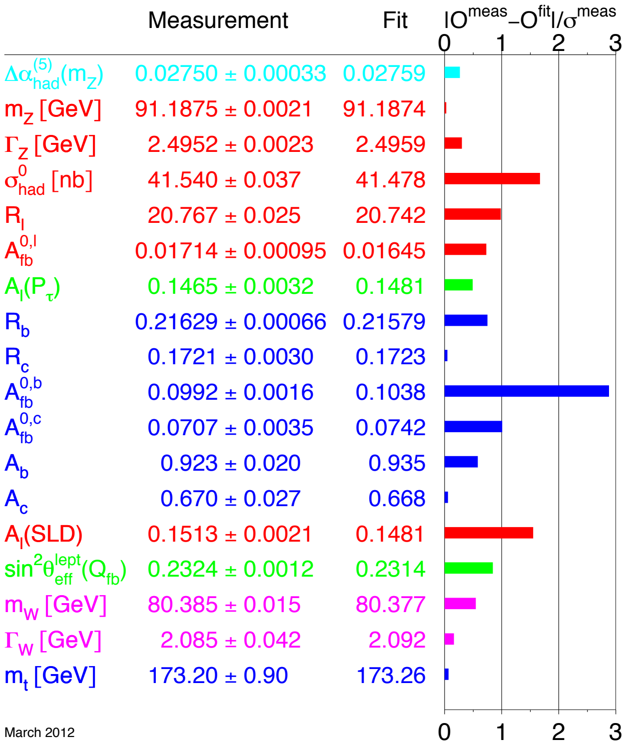
- The size of corrections is ~ to the UV cutoff (Λ) squared:

$$\Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + M_H^2) + \ldots$$

- In order for the Higgs boson mass to be finite, a fine tuning (cancellation) of various loops is required to a precision $\sim(M_H/\Lambda)^2 \sim 10^{-34}$ for $\Lambda \sim M_{Pl}$
- This is known as a “hierarchy problem” stemming from a large hierarchy between the electroweak symmetry breaking and Planck scales, and it requires new physics at Λ ~ 1-10 TeV

Standard Model: Beauty & the Beast

Beauty…

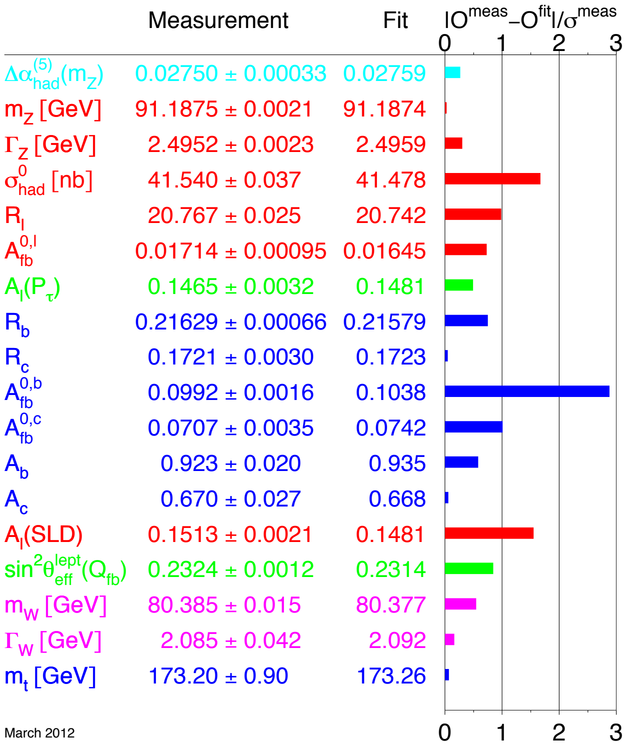


	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.385 ± 0.015	80.377	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.26	

March 2012

Standard Model: Beauty & the Beast

Beauty… and the Beast



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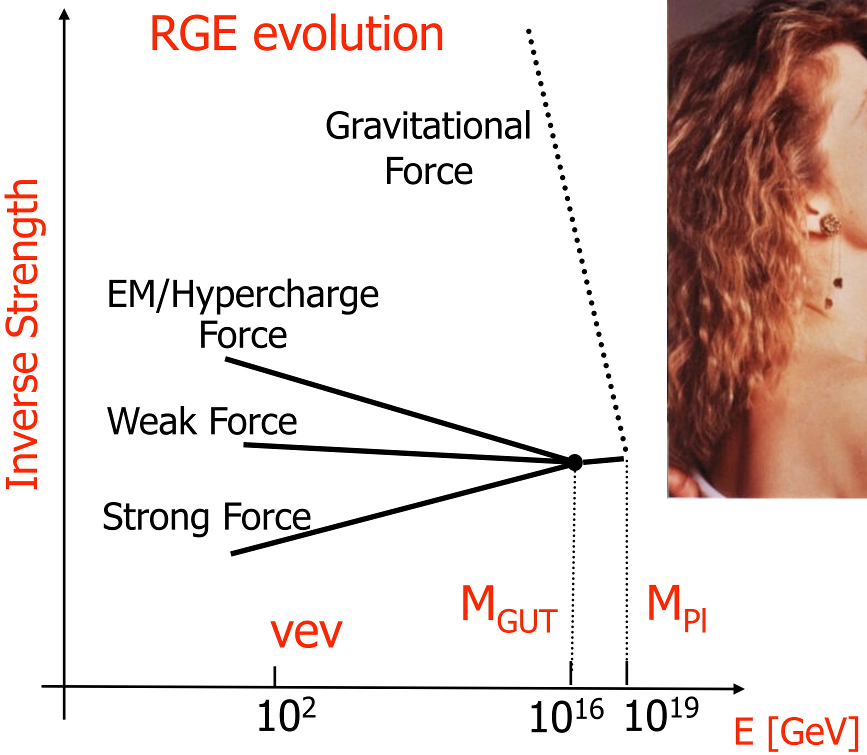
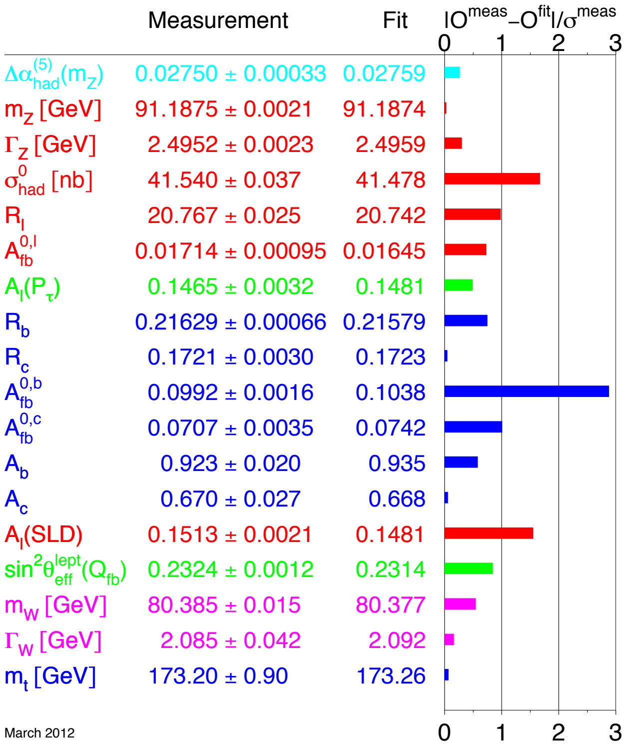


$M_{GUT} \sim M_{Pl} \gg$ vev

Standard Model: Beauty & the Beast

- Physics beyond the SM may get rid of the beast while preserving SM's natural beauty!

Beauty… and the Beast



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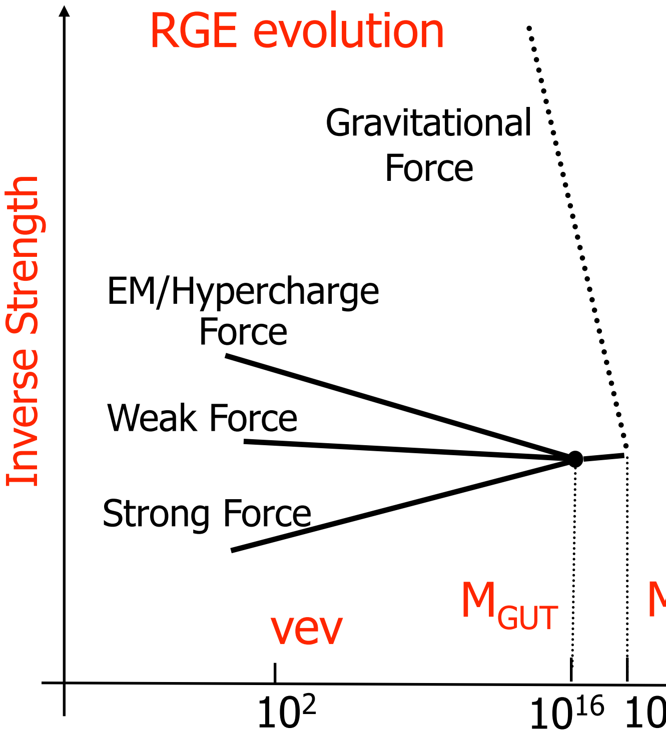

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- Nevertheless: beware of the *anthropic principle*
  - Properties of the universe are so special because we happen to exist and be able to ask these very questions
  - Is it time to give up science for philosophy? – So far we've been able to explain the universe entirely with science!

Beyond the Standard Model

Beyond the Standard Model

- Apart from the naturalness argument:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses (i.e., the values of the Yukawa couplings to the Higgs field)
  - It doesn't provide natural explanation for the:
    - Neutrino masses
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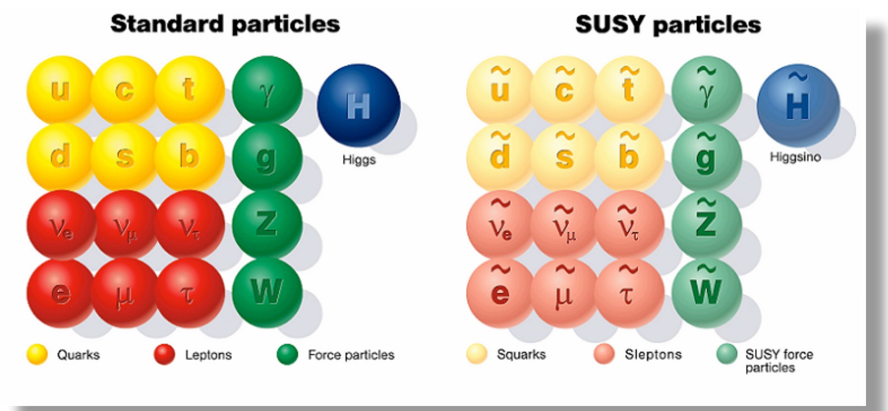
  - It doesn't provide natural explanation for the:
    - Neutrino masses
    - Cold dark matter
- Logical conclusion:
  - Standard model is an effective theory – a low-energy approximation of a more complete theory, which ultimately explains the above phenomena
  - This new theory must take off at a scale of ~1 TeV to avoid significant amount of fine tuning
  - Three classes of solutions:
    - Ensure automatic cancellation of divergencies (SUSY/Little Higgs)
    - Eliminate fundamental scalar and/or introduce intermediate scale Λ ~ 1 TeV (Technicolor/Higgsless models) - basically dead now
    - Reduce the highest physics scale to ~1 TeV (Extra Dimensions)

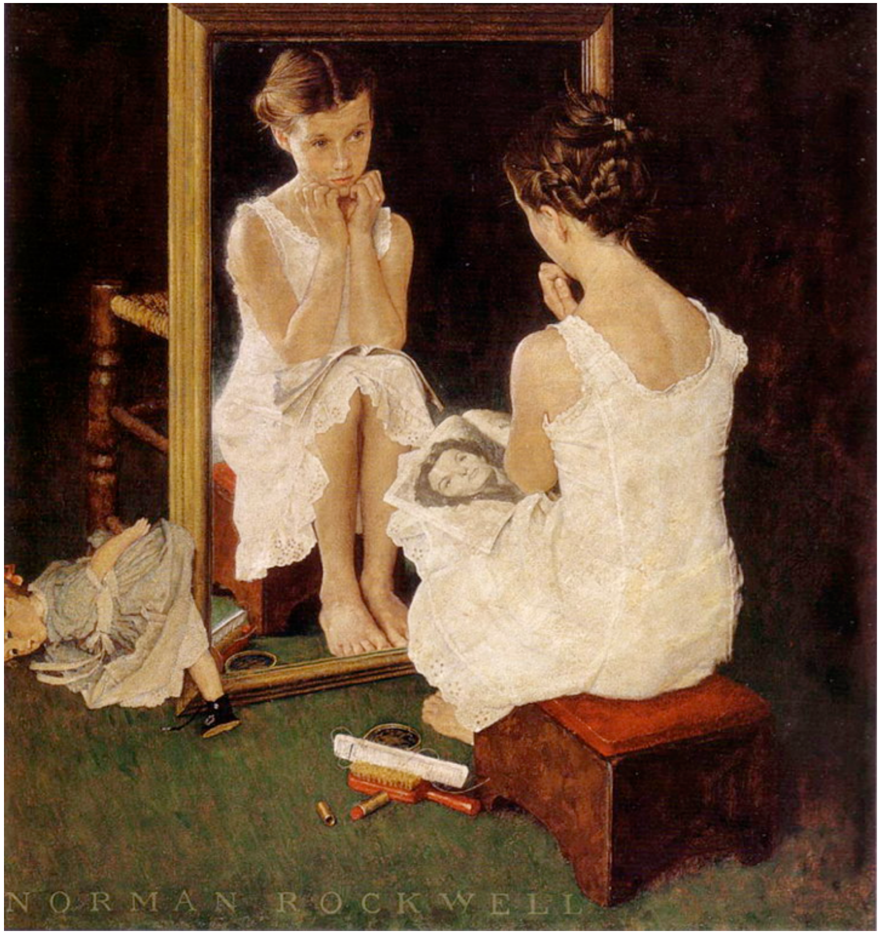
Looking for SUSY

- See more motivational details in Dominik Stöckinger’s lectures:
  - What is SUSY?
  - Three SUSY miracles
  - Supersymmetric particle zoo
  - “Natural” SUSY
- SUSY and Higgs - the marriage made in heaven
  - What did we learn about SUSY in the aftermath of the Higgs discovery?

The Beauty in the Mirror

- The mirror world: discrete symmetry of spin
  - Every Standard Model (SM) fermion has a bosonic “superpartner,” and vice versa, e.g.:
    - Quark (J = ½) → Squark (J = 0)
    - Photon (J = 1) → Photino (J = ½)
- Supersymmetry must be “broken” as we do not see a selectron with the mass of 0.5 MeV!
- To avoid multiple constraints, typically introduce conserved R-parity [Farrar, Fayet, Phys. Lett. B **76** (1978) 575]:
  - $R = (-1)^{3B+L+2S} = +1$ (SM) and -1 (SUSY)
- This leads to the lightest supersymmetric particle (LSP) being stable and pair-production of SUSY as the only possible mechanism





Norman Rockwell “Girl at Mirror”

The LSP is an excellent Dark Matter (DM) Candidate

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SUSY: Gauge Sector

- Higgses: two complex doublets (8 degrees of freedom)
  - One gives masses to down-type, and another one – to up-type quarks
  - Ratio of vacuum expectation values is conventionally called ***tanβ***
  - 3 d.o.f. are “eaten” by massive Z, $W^\pm$
  - 5 remaining d.o.f. become physical states: h^0, H^0, $H^\pm$, A^0
  - $M_H > M_h$ by definition; $M_h < 135$ GeV
  - A is a CP-odd Higgs
  - Supersymmetric partners of the two Higgs doublets mix with the partners of SM EW gauge bosons to give four neutral (neutralinos) and two pairs of charged (charginos) gauginos
- Gluino remains unmixed

$\tilde{Z}^0, \tilde{\gamma}, \tilde{h}_1^0, \tilde{h}_2^0$

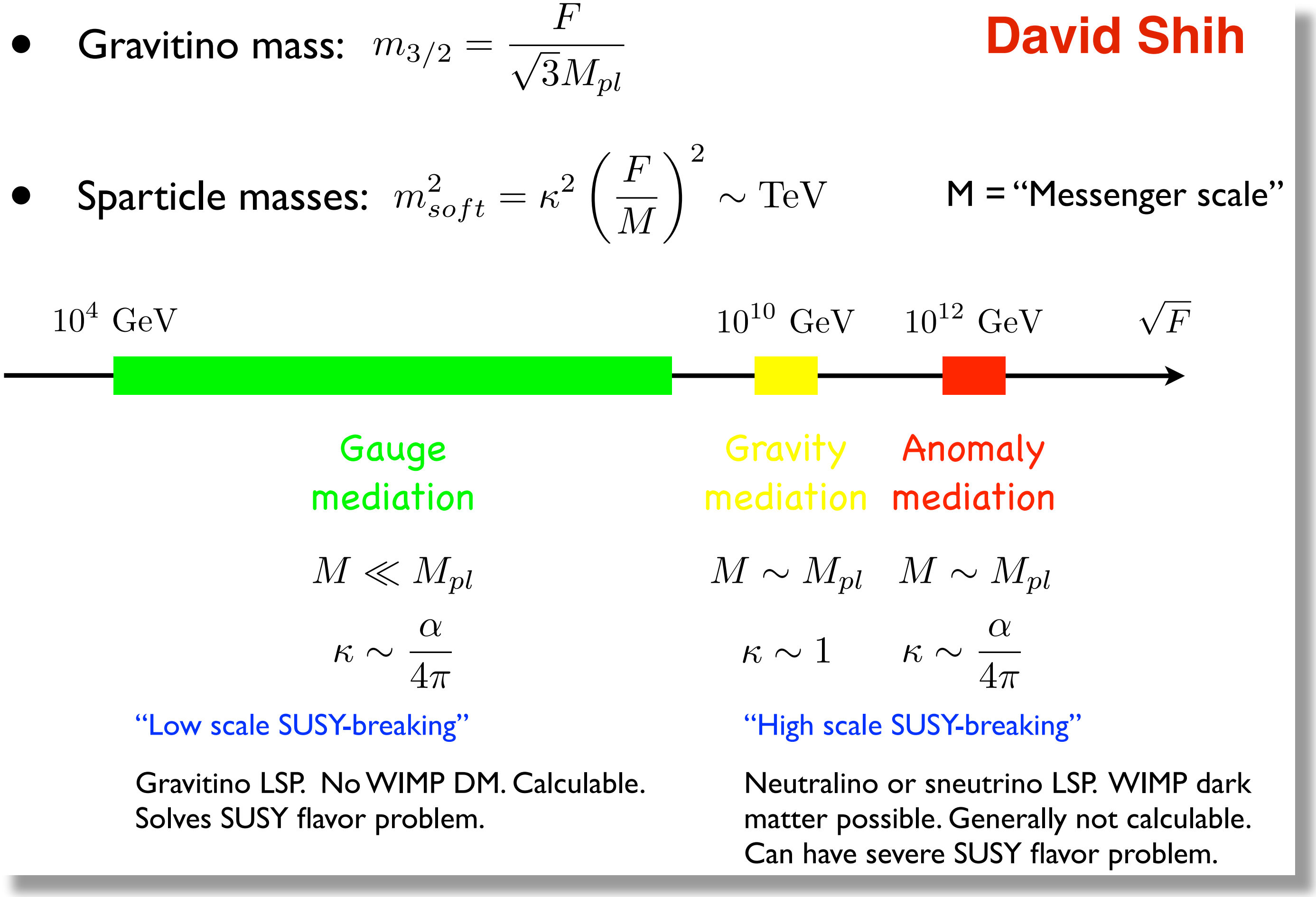
$\tilde{W}^\pm, \tilde{h}^\pm$

$\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$

$\chi_1^\pm, \chi_2^\pm$

Supersymmetry Breaking

- We know that SUSY is a broken symmetry, but we do not know how it is broken
- Several theoretical models exist:



David Shih

- Gravitino mass: $m_{3/2} = \frac{F}{\sqrt{3}M_{pl}}$
- Sparticle masses: $m^2_{soft} = \kappa^2 \left(\frac{F}{M}\right)^2 \sim \text{TeV}$

M = "Messenger scale"

Gauge mediation	Gravity mediation	Anomaly mediation
$M \ll M_{pl}$	$M \sim M_{pl}$	$M \sim M_{pl}$
$\kappa \sim \frac{\alpha}{4\pi}$	$\kappa \sim 1$	$\kappa \sim \frac{\alpha}{4\pi}$

"Low scale SUSY-breaking"

Gravitino LSP. No WIMP DM. Calculable. Solves SUSY flavor problem.

"High scale SUSY-breaking"

Neutralino or sneutrino LSP. WIMP dark matter possible. Generally not calculable. Can have severe SUSY flavor problem.

MSSM and cMSSM

- SUSY is a renormalizable and calculable theory and has been thoroughly studied theoretically over the last four decades
- MSSM has just two Higgs doublets; nevertheless the number of parameters describing the model is still very large: 124
  - 18 are the SM ones + Higgs boson mass (now known!)
  - 105 genuinely new parameters:
    - 5 real parameters and 3 CP-violating phases in gaugino sector
    - 21 squark/slepton masses and 36 mixing angles
    - 40 CP-violating phases in the sfermion sector
- This makes it very challenging to search for generic SUSY, and simplifying assumptions are typically made
- One of these simplifications is constrained MSSM, or cMSSM, which assumes gaugino unification and degenerate squark/slepton masses at high energy (typical of gravity-mediated SUSY breaking)
  - That results in just five parameters fixing all the SUSY interactions: common scalar and fermion masses M_0, $M_{1/2}$, ratio of the vacuum expectations of the two Higgs doublets **$\tan\beta$**, sign of Higgsino mass term **$sign(\mu)$**, and trilinear coupling A_0

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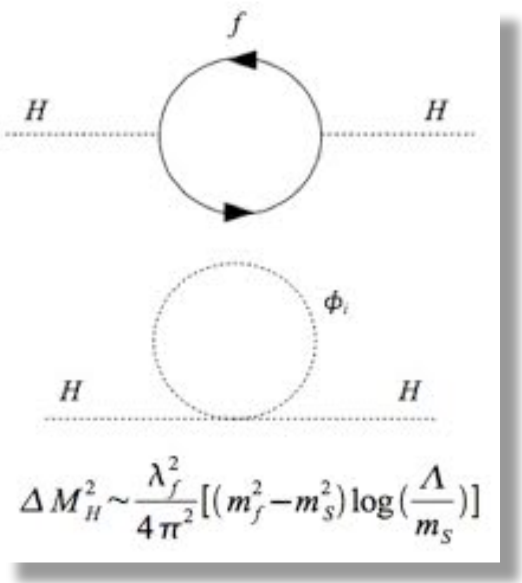
Typically most important

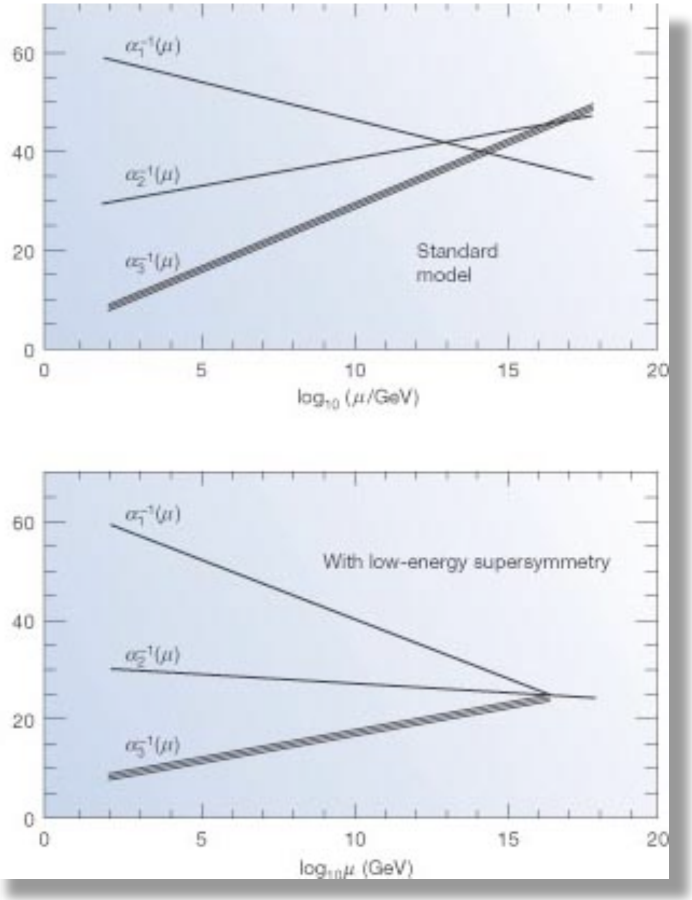
Three Miracles of SUSY



$$\Delta M_H^2 \sim \frac{\lambda_f^2}{4\pi^2}[(m_f^2 - m_S^2)\log(\frac{\Lambda}{m_S})]$$

- Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)

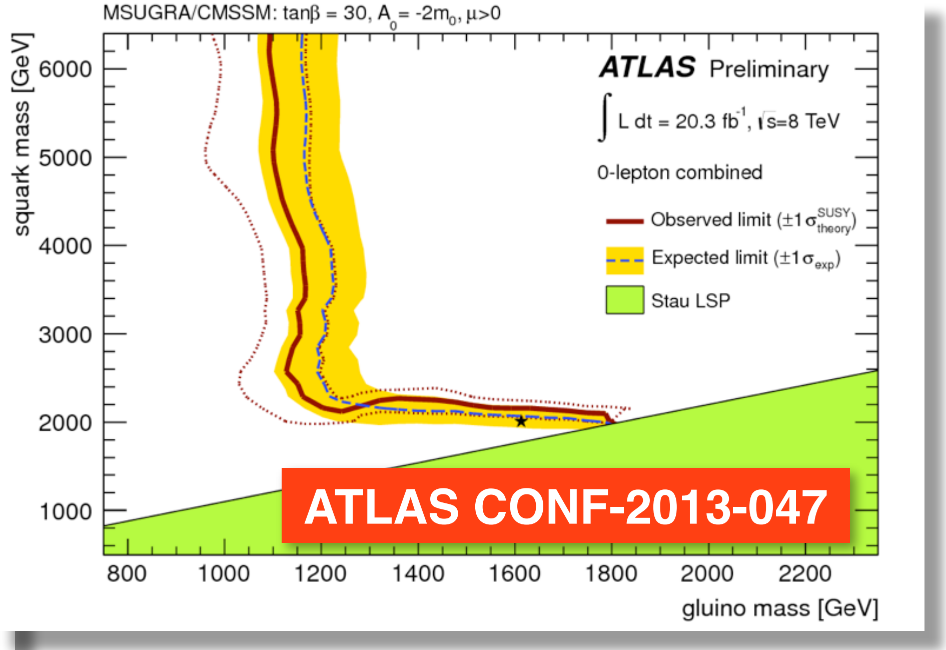
- Gauge unification



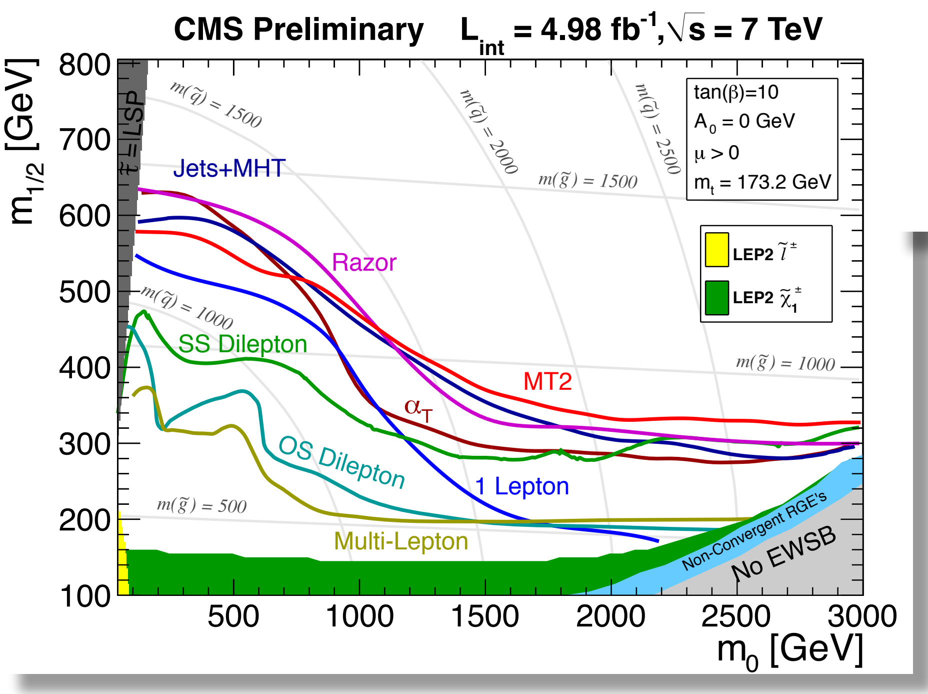
- Dark matter candidate with the right abundance

SuperSymmetry or SuperCemetery?

- Excluded squarks to ~2.0 TeV and gluinos to ~1.2 TeV - or did we?



ATLAS CONF-2013-047



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Read the fine print!

What SUSY Have We Excluded?

- We set strong limits on squarks and gluinos, and yet we have not excluded SUSY
  - Moreover, we basically excluded VERY LITTLE!
- We ventured for an "easy-SUSY" or "lazy-SUSY" and we basically failed to find it
  - So what? - Nature could be tough!
- What we probed is a tiny sliver of multidimensional SUSY space, simply most "convenient" from the point of view of theory
- All it takes to avoid these limits is to give up squark degeneracy!

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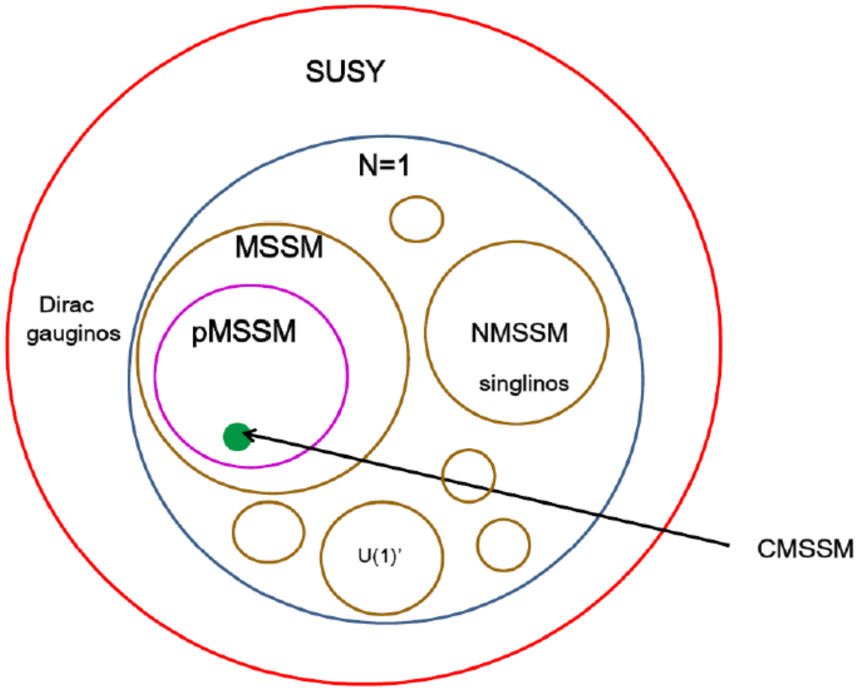
SUSY Theory phase space



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

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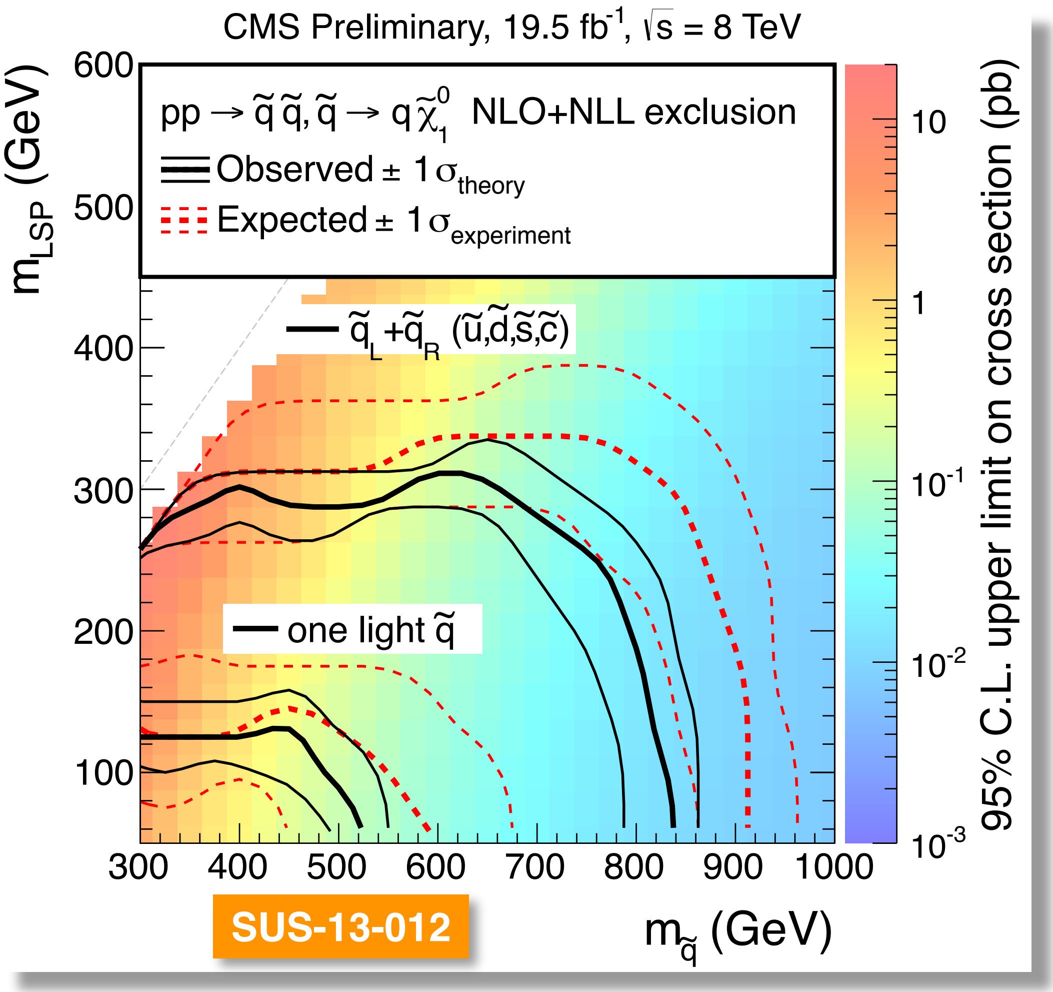

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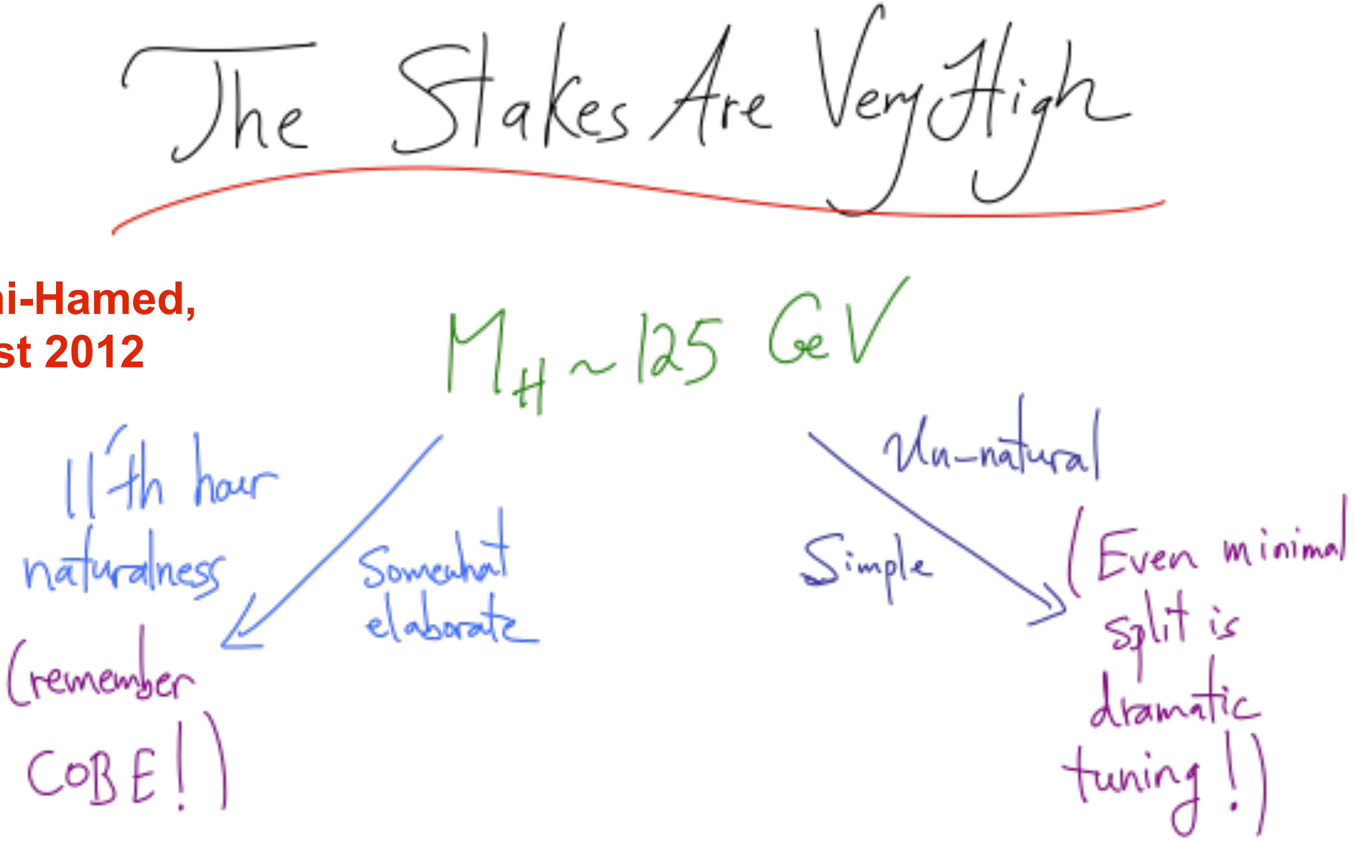
We are at a SUSY Crossroad

- Light 125 GeV Higgs boson strongly prefers SUSY as the fundamental explanation of the EWSB mechanism (via soft SUSY-breaking terms and radiative corrections)
- But what kind of SUSY?



Nima Arkani-Hamed, SavasFest 2012

Implies: light stops/sbottom, reasonably light gluinos and charginos/neutralinos

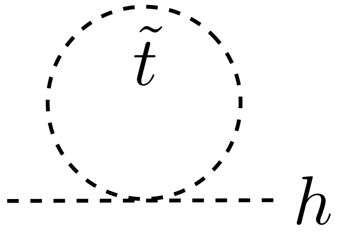
Likely: long-lived particles, light neutralino, multi-TeV Z′, ...

Fine-Tuning in (p)MSSM

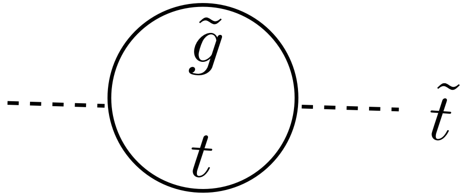
- Fine-tuning: cancellation of two or more large numbers
- In pMSSM: $m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \frac{2}{\tan^2\beta}(m_{H_d}^2 - m_{H_u}^2) + \mathcal{O}(1/\tan^4\beta)$

|μ| is small → light higgsinos

m^2_{Hu} is small → lights stops (at one-loop level) and gluinos (at two-loop level)



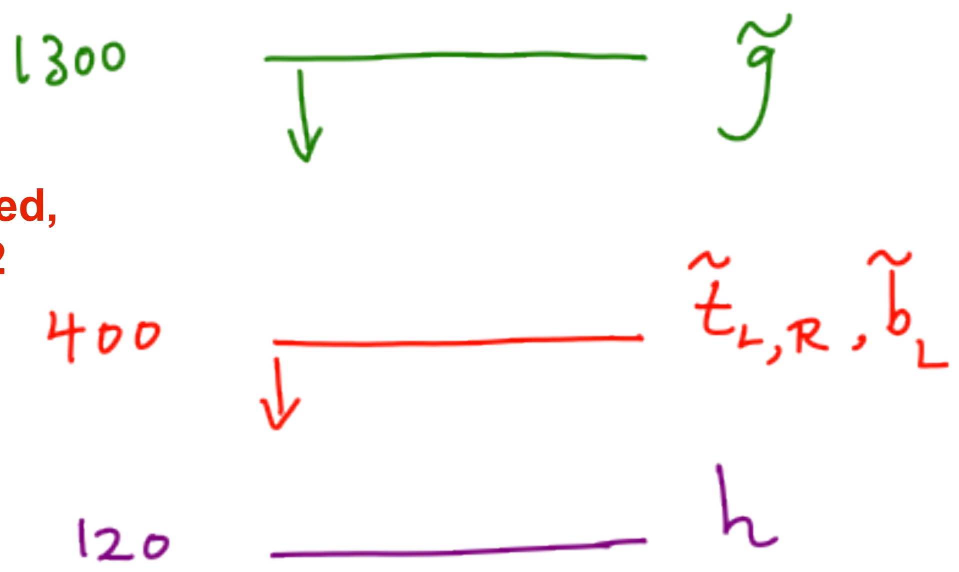
$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(\underbrace{m_{Q_3}^2 + m_{u_3}^2}_{\text{stops}} + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$



gluino-top loop drives the stop mass further up

Natural SUSY Spectrum

Compulsory Natural SUSY



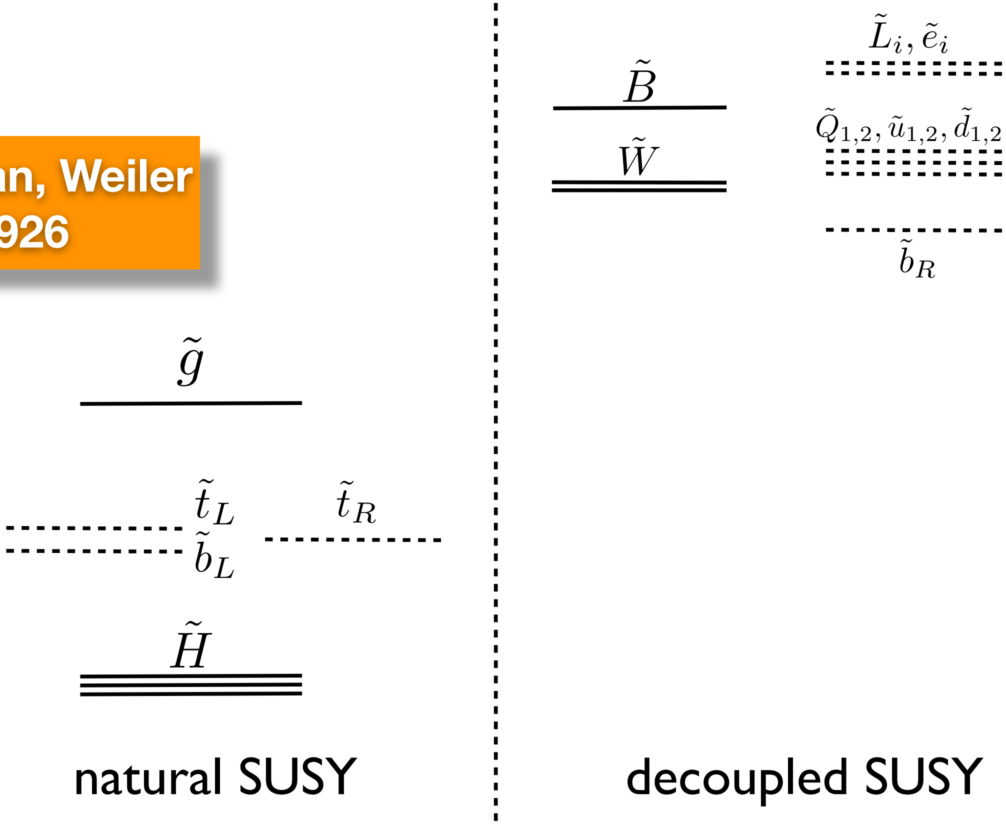
Nima Arkani-Hamed, SavasFest 2012

Unavoidable tunings: $\left(\frac{400}{m_{\tilde t}}\right)^2, \left(\frac{4 m_{\tilde t}}{M_{\tilde g}}\right)^2$

Natural SUSY

- If SUSY is natural, we should find it soon:
  - And we most likely will find it by observing 3rd generation SUSY particles first!
- Requires shifting of the SUSY search paradigm: going for the third generation partners, push gluino reach, and look for EW boson partners

Papucci, Ruderman, Weiler
arXiv:1110.6926



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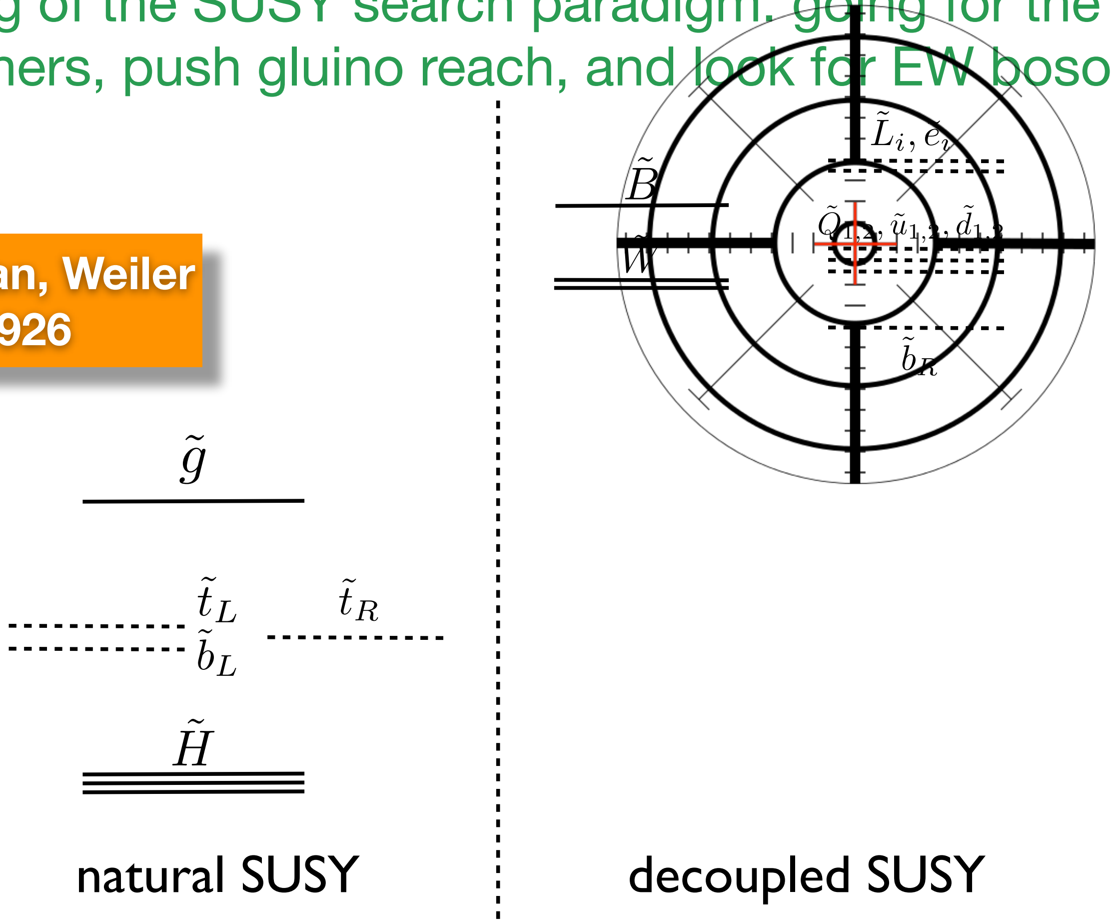

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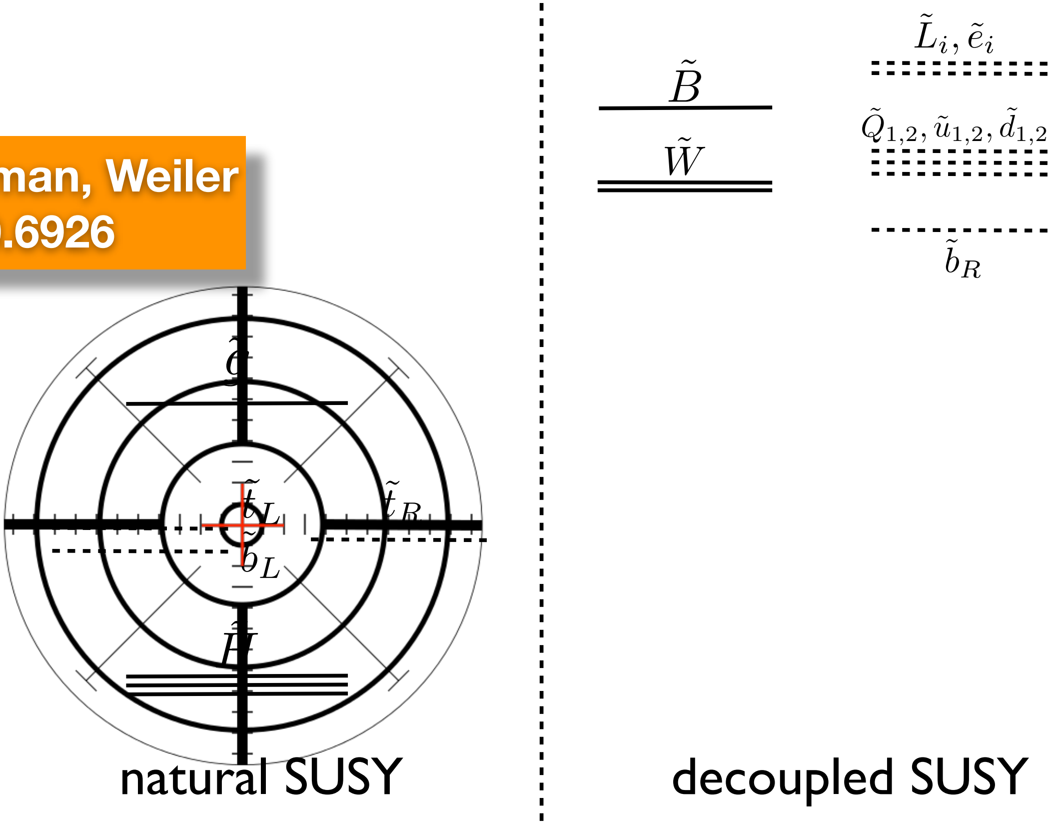
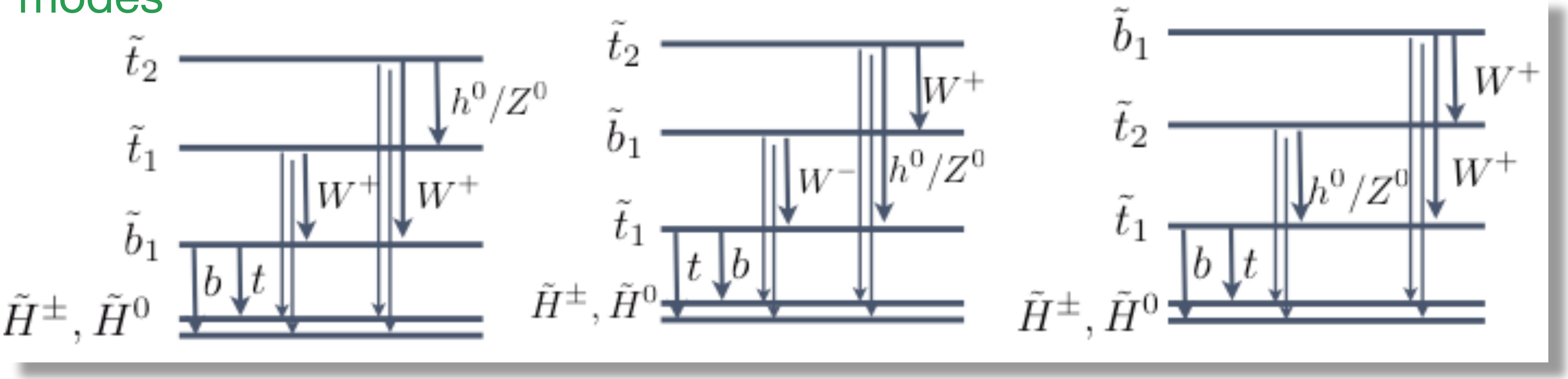


Natural SUSY Spectra

- Once we focus on natural SUSY, the spectra and the signatures become rather simple – almost like “simplified model spectra”
- Basically have to consider three types of spectra and related decay modes



Abbreviation	Decay mode	Conditions
T_t	$\tilde{t} \to t\chi^0$	$m_{\tilde{t}} > m_t + m_{\chi^0}$
T_b	$\tilde{t} \to b\chi^+ \to bW^+\chi^0$	$m_{\tilde{t}} > m_b + m_{\chi^+}, \quad m_{\chi^+} > m_{\chi^0} + m_W$
$T_{b'}$	$\tilde{t} \to b\chi^+ \to bW^{+*}\chi^0$	$m_{\tilde{t}} > m_b + m_{\chi^+}, \quad m_{\chi^+} < m_{\chi^0} + m_W$
$T_{t'}$	$\tilde{t} \to t^*\chi^0 \to bW^+\chi^0$	$m_{\tilde{t}} < m_t + m_{\chi^0}, \quad m_{\tilde{t}} < m_{\chi^+} + m_b$
T_c	$\tilde{t} \to c\chi^0$	$m_{\tilde{t}} < m_t + m_{\chi^0}, \quad m_{\tilde{t}} < m_{\chi^+} + m_b$
B_b	$\tilde{b} \to b\chi^0$	
B_t	$\tilde{b} \to t\chi^- \to tW^-\chi^0$	$m_{\tilde{b}} > m_t + m_{\chi^-}, \quad m_{\chi^-} > m_{\chi^0} + m_W$
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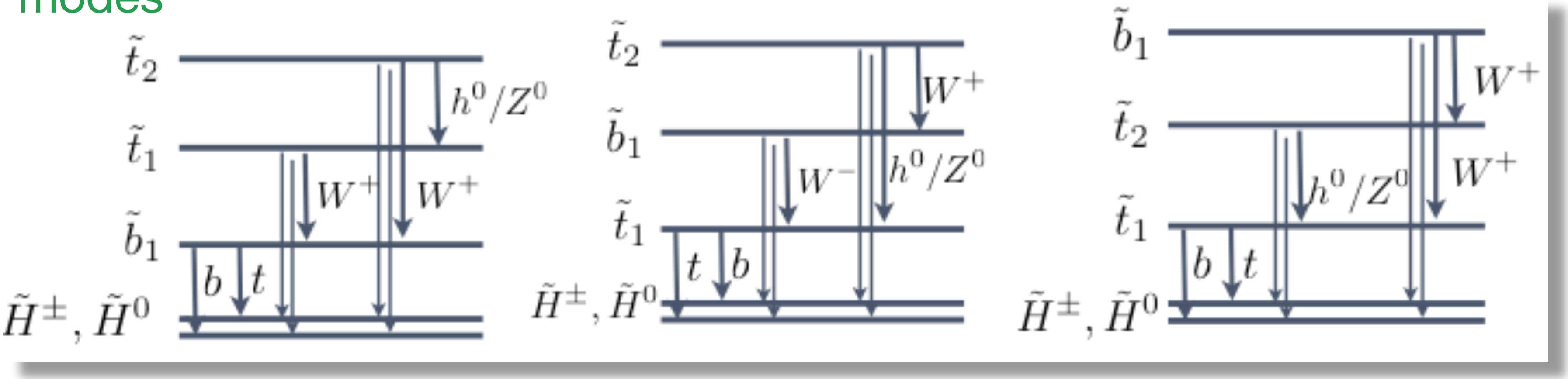

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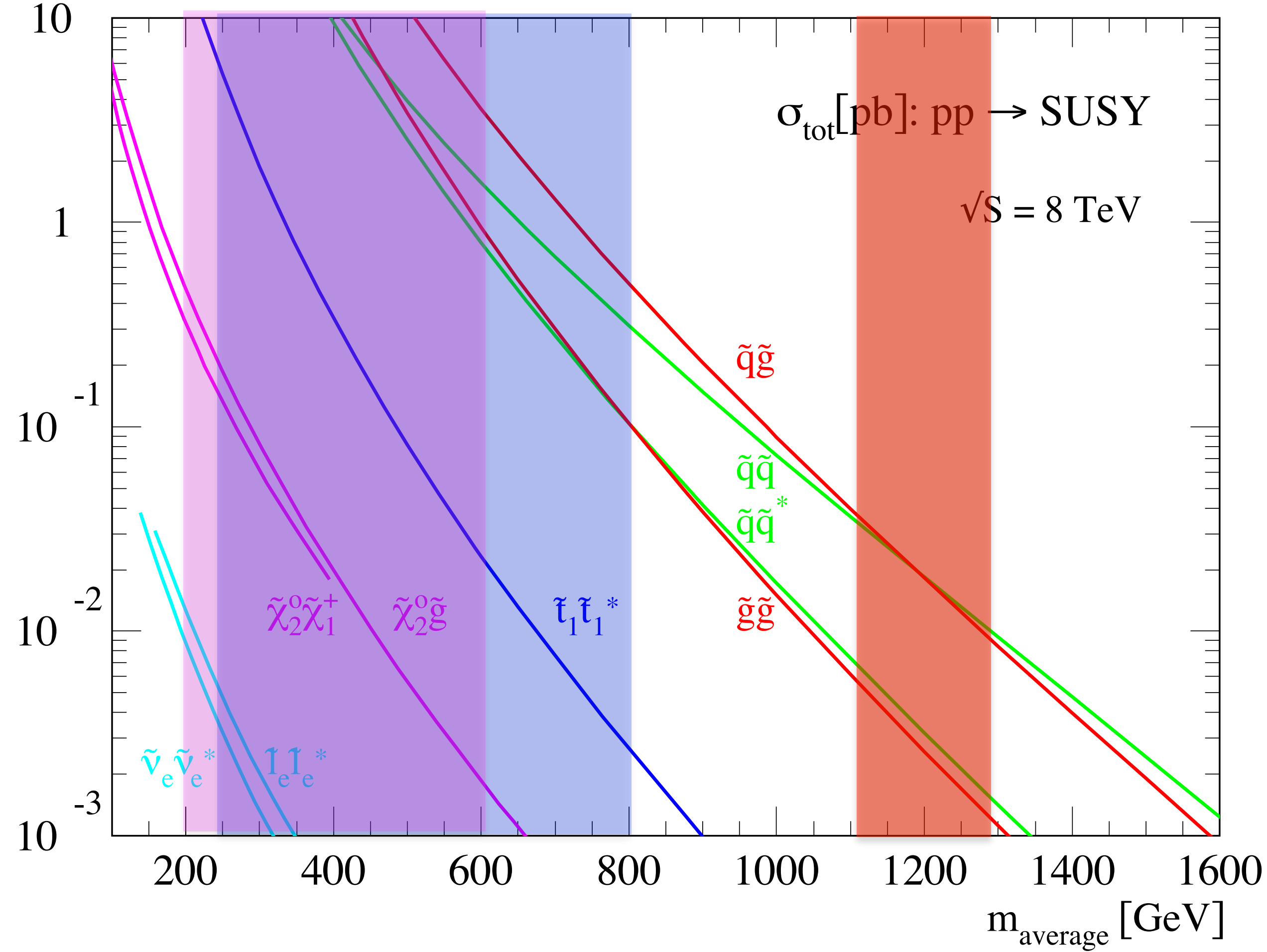
Natural SUSY Reach

- With ∫Ldt ~ 20/fb^{-1} and 1 fb cross section produce 20 events; typically 1-10 events observed after acceptance/efficiencies

http://www.thphys.uni-heidelberg.de/~plehn/



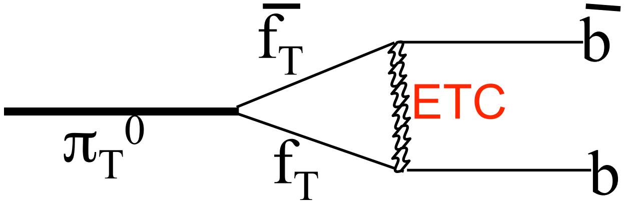
$\tilde{g}\tilde{g}$: M($\tilde{g}$) ≲ 1.3 TeV

$\tilde{t}_1\tilde{t}_1$: M($\tilde{t}_1$) ≲ 0.8 TeV

$\tilde{\chi}\tilde{\chi}$: M($\tilde{\chi}$) ≲ 0.6 TeV

Strong Dynamics

- New, QCD like force with “pions” at ~ 100 GeV and a number of QCD meson-like bound state
- No fundamental Higgs particle; global EW symmetry is broken dynamically, which results in nearly massless Goldstone bosons, analogous to pions in QCD
  - Three degrees of freedom are consumed by the longitudinal W/Z modes; the rest become physical meson-like particles
  - This is the way chiral symmetry is broken in QCD
  - To explain observed W/Z masses, need new techniparticles to be ~10^3 times heavier than the QCD particles
  - The role of Higgs boson in SM is played by a condensate of fermion-antifermion pair (e.g., new pion), resembling superconductivity
- Several realizations, e.g. technicolor
  - Excluded by LEP precision measurements in its simplest form
  - Cures: walking technicolor, topcolor assisted TC, extended TC



Analogous to the Higgs decay

  - Still, EW corrections are ~$(M_W/M_{TC})^2$ – hard to satisfy LEP constraints for M_{TC} ~ 1 TeV
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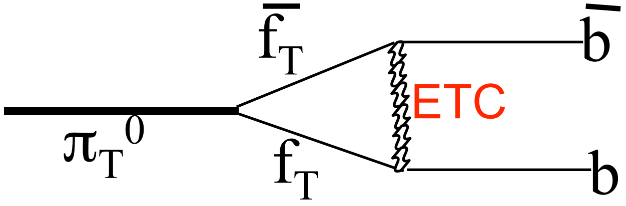
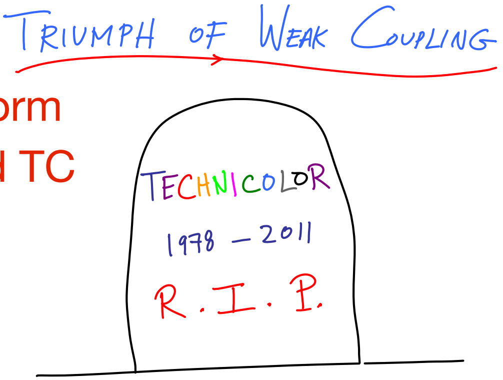


Analogous to the Higgs decay



N. Arkani-Hamed, Savasfest

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- Observation of a scalar Higgs boson with properties close to the SM ones really kills TC

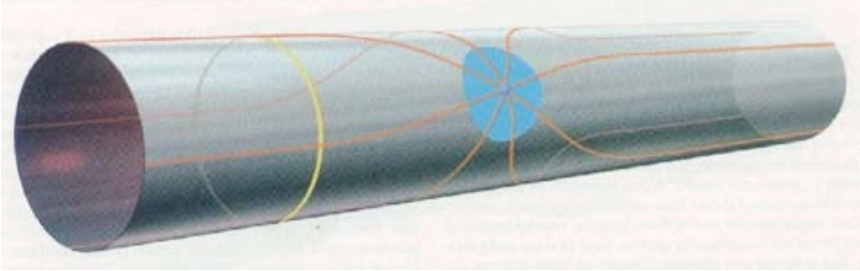
1998: Large Extra Dimensions

- But: what if there is no other scale, and SM model is correct up to M_{Pl}?
  - Give up naturalness: inevitably leads to anthropic reasoning
  - Radically new approach – Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998): maybe the fundamental Planck scale is only ~ 1 TeV?!!
- Gravity is made strong at a TeV scale due to existence of *large* (r ~ 1mm – 1fm) extra spatial dimensions:
  - –SM particles are confined to a 3D "brane"
  - –Gravity is the only force that permeates "bulk" space
- What about Newton's law?

$$\boxed{V(\rho) = \frac{1}{M_{\rm Pl}^2}\frac{m_1 m_2}{\rho^{n+1}} \rightarrow \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{\rho^{n+1}}}$$

- Ruled out for infinite ED, but does not apply for the compact ones:

$$\boxed{V(\rho) \approx \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^n \rho}, \mathrm{for} \rho \gg r}$$



- Gravity is fundamentally strong force, but we do not feel that as it is diluted by the large volume of the bulk space $G'_N = 1/(M_{\rm Pl}^{[3+n]})^2$ = $1/M_D^2$; $M_D \sim 1$ TeV

$$\boxed{M_D^{n+2} \sim M_{\rm Pl}^2/r^n}$$

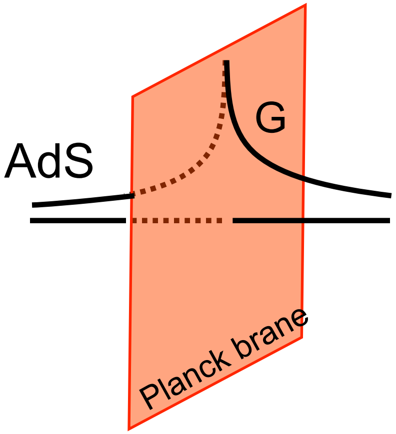
- More precisely, from Gauss's law:

$$\boxed{r = \frac{1}{\sqrt{4\pi}M_D}\left(\frac{M_{\rm Pl}}{M_D}\right)^{2/n} \sim \begin{cases} 8\times 10^{12} m, & n=1 \\ 0.7mm, & n=2 \\ 3nm, & n=3 \\ 6\times 10^{-12} m, & n=4 \end{cases}}$$

- Amazing as it is, but as of 1998 no one has tested Newton's law to distances less than ~ 1mm! (Even now it's been tested to only 37 μm!)
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

1999: Randall-Sundrum Model

- Randall-Sundrum (RS) model [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - –One + brane – no low energy effects
  - –Two + and – branes – TeV Kaluza-Klein modes of graviton
  - –Low energy effects on SM brane are given by Λ_π; for kr ~ 10, Λ_π ~ 1 TeV and the hierarchy problem is solved naturally



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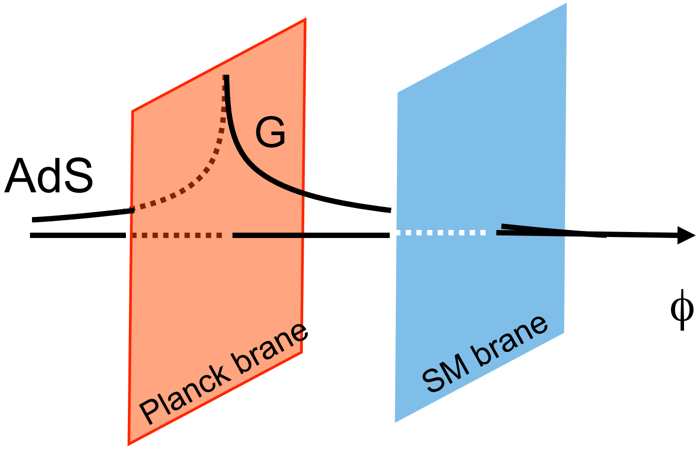

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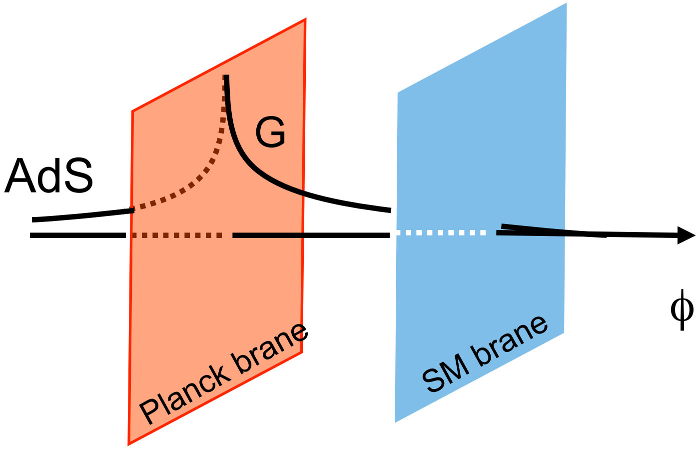
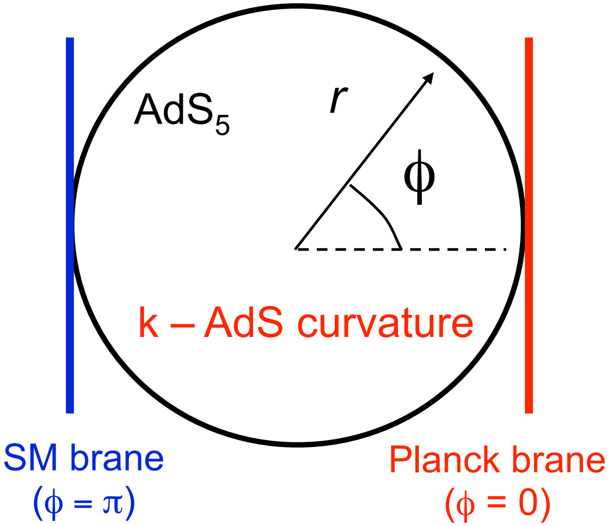




Anti-deSitter space-time metric:

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

$$\Lambda_\pi = \overline{M}_{\rm Pl} e^{-kr\pi}$$

Reduced Planck mass:

$$\boxed{\overline{M}_{\rm Pl} \equiv M_{\rm Pl}/\sqrt{8\pi}}$$

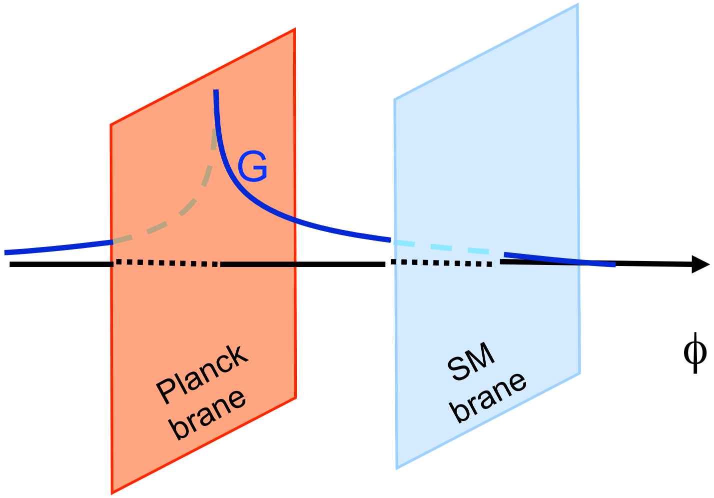
Extra Dimensions: a Brief Summary

ADD Paradigm:

- Pro: “Eliminates” the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the “bulk” space
- Size of ED’s (n=2-7) between ~100 μm and ~1 fm
- Black holes at the LHC and in the UHE cosmic rays
- Con: Doesn’t explain why ED are so large

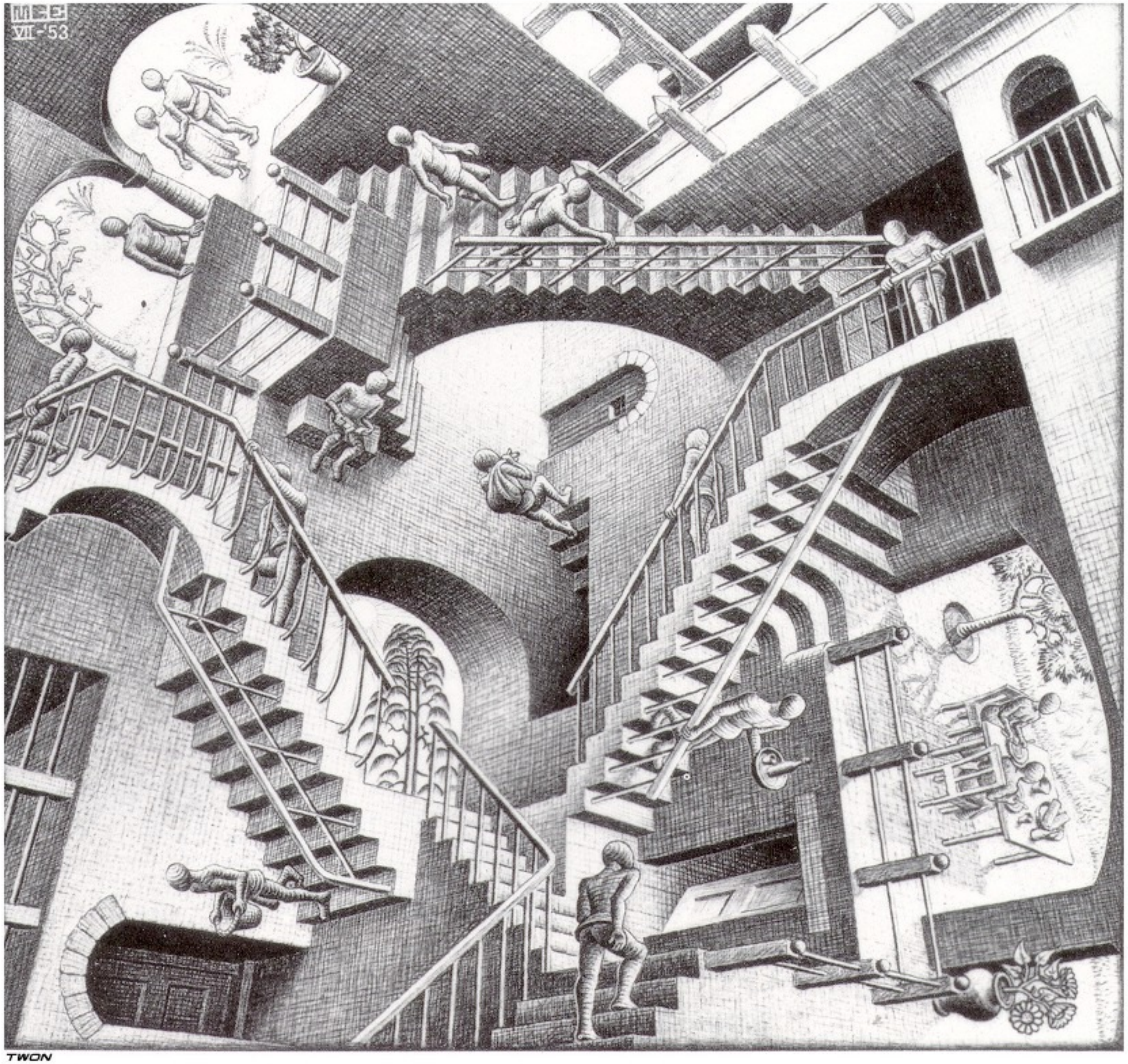
RS Model:

- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



Examples of Compact Dimensions

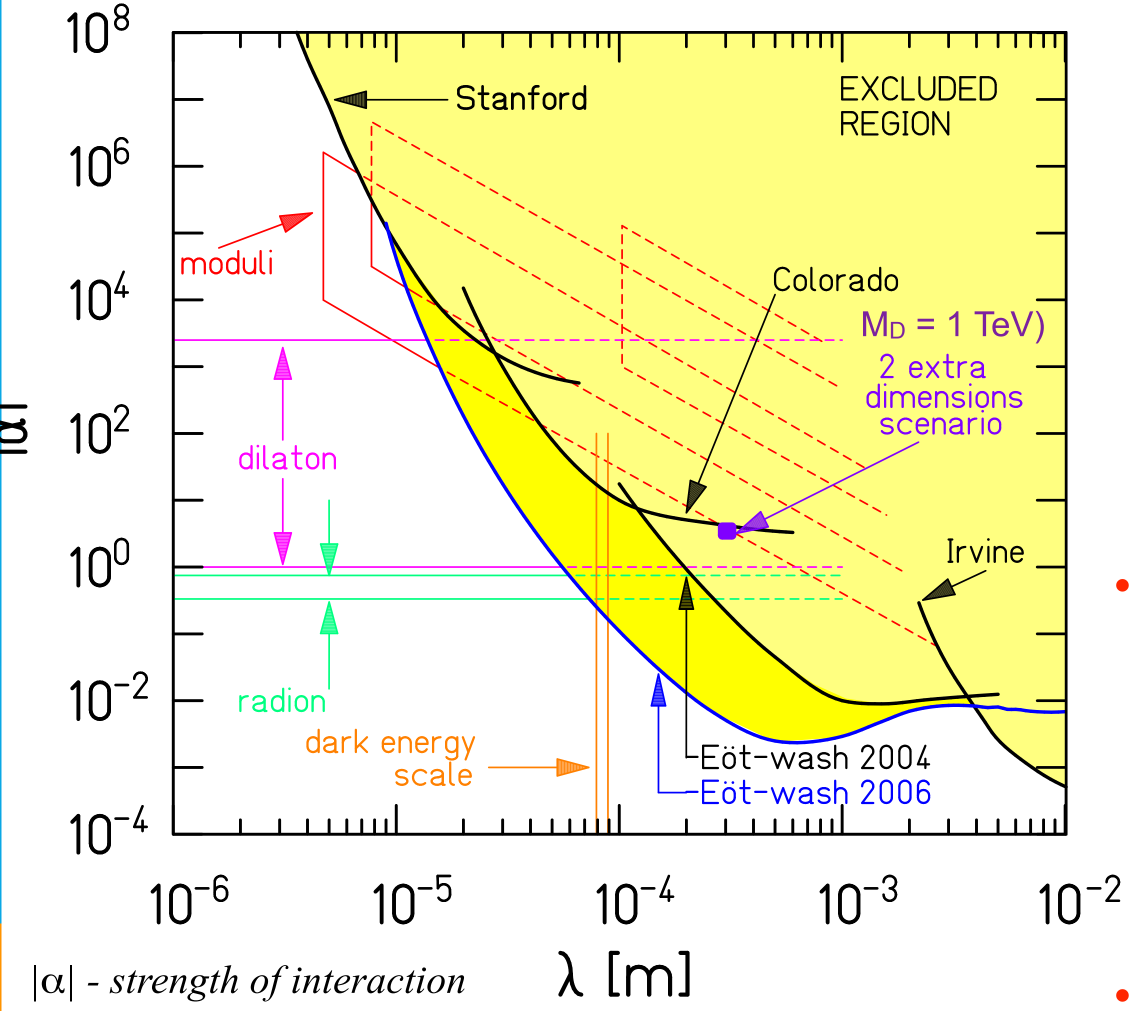
[M.C.Escher, Mobius Strip II (1963)]



[M.C.Escher, Relativity (1953)]

Large ED: Gravity at Short Distances

D. Kapner et al., PRL 98 (2007) 0211001



|α| - strength of interaction relative to Newtonian gravity

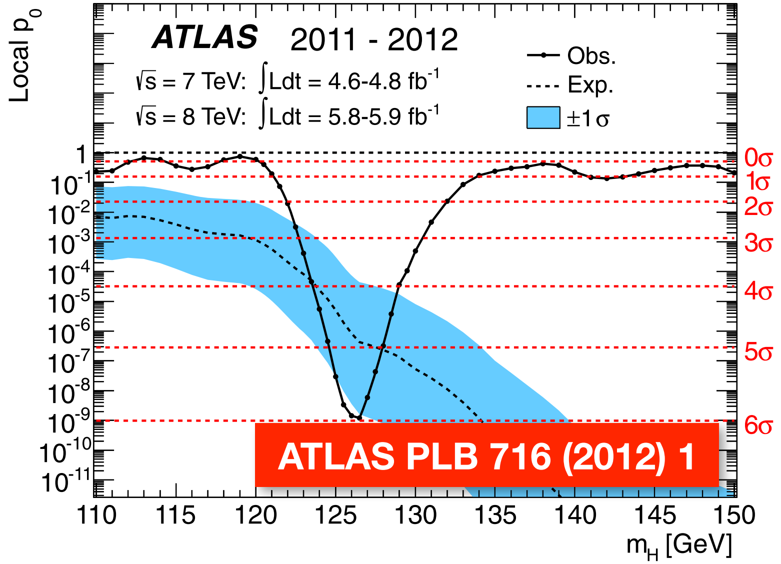
- Sub-millimeter gravity measurements could probe *only* n=2 case *only* within the ADD model
  - The best sensitivity so far have been achieved in the U of Washington torsion balance experiment – a high-tech “remake” of the 1798 Cavendish experiment
    - R $\lesssim$ 37 μm ($M_D \gtrsim$ 2 TeV)
- Sensitivity vanishes quickly with the distance – can’t push limits further down significantly
  - Started restricting ADD with 2 extra dimensions; can’t probe any higher number
- No sensitivity to the RS models

Higgs Leads the Way

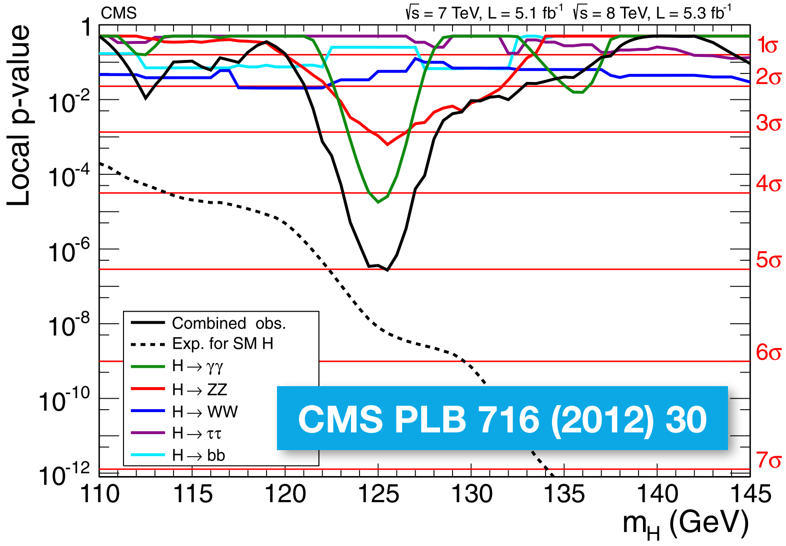
4th of July 2012 Fireworks

A New Boson Discovery

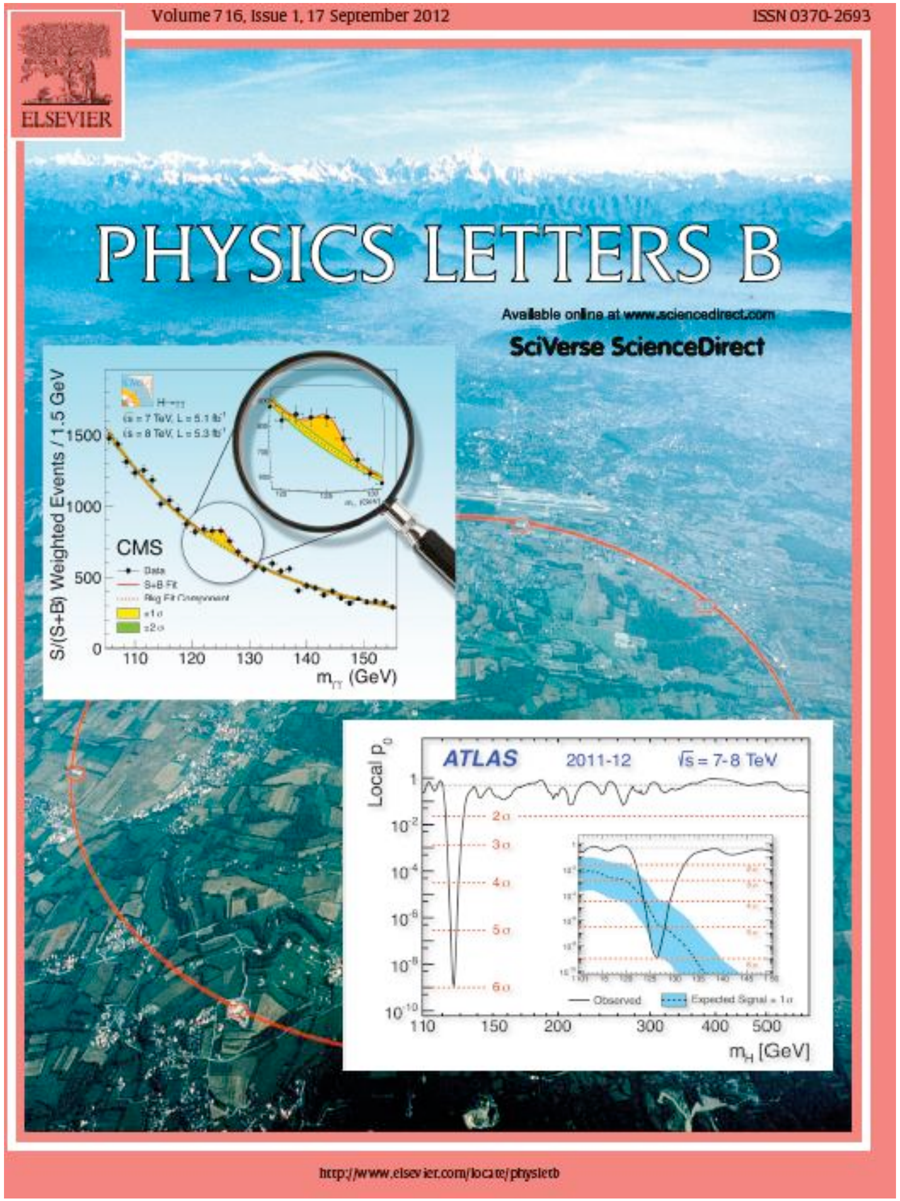
- Phys. Lett. B **716** (2012) 1-29 and 30-61



ATLAS PLB 716 (2012) 1

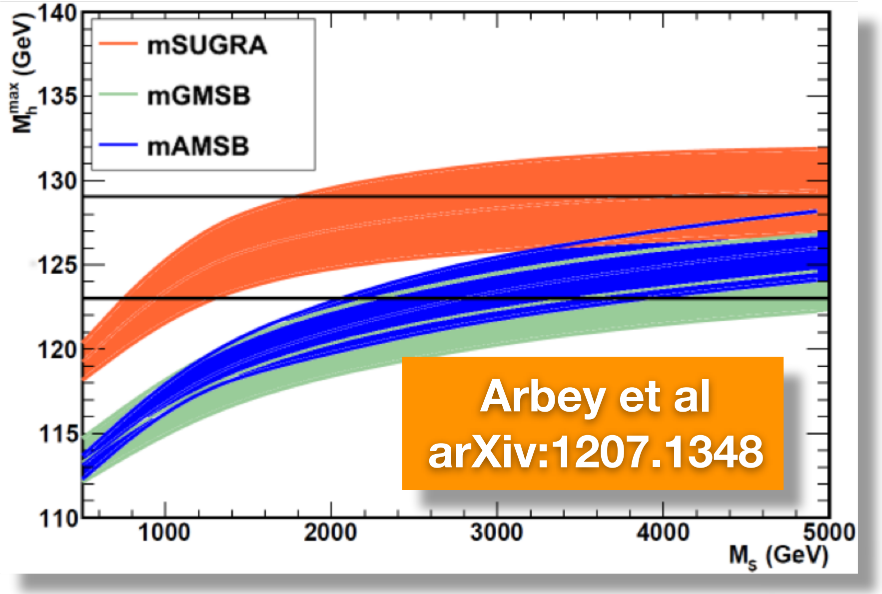


CMS PLB 716 (2012) 30

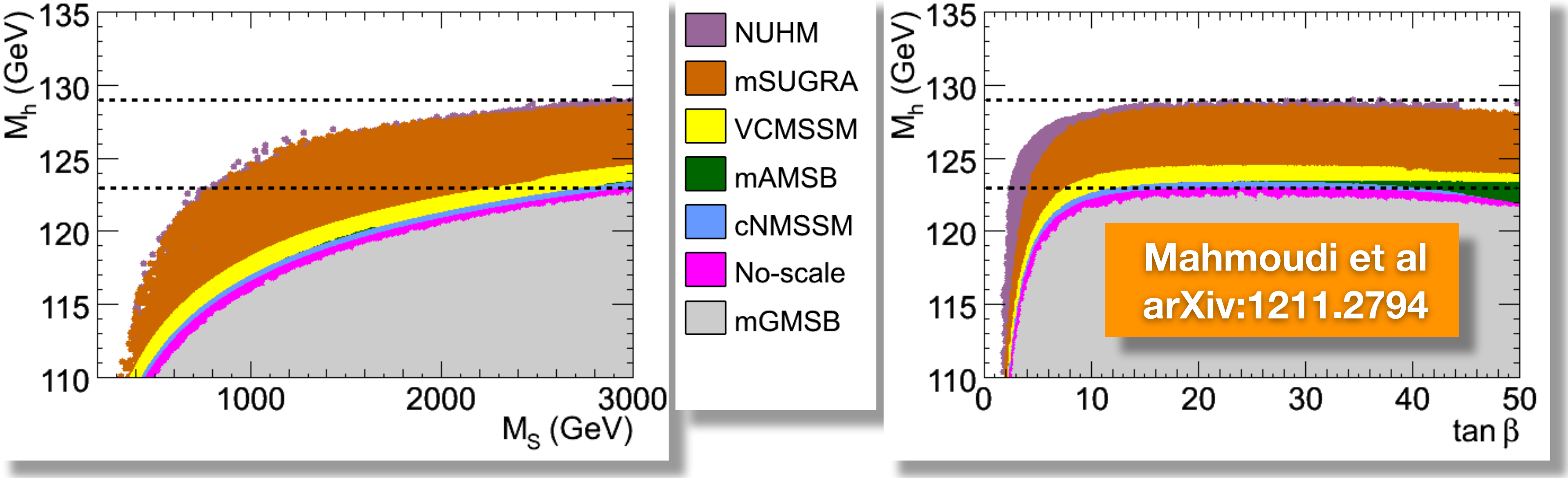


SUSY: the Higgs Aftermath

- ✦ A 125 GeV Higgs boson is challenging to accommodate in (over)constrained versions of SUSY, particularly for "natural" values of superpartner masses
  - ◉ Started to constrain some of the simpler models
- ✦ Big question: if SUSY exists, can it still be "natural", i.e. offer a non-fine-tuned solution to the hierarchy problem
  - ◉ If not, we would be giving up at least one of the three SUSY "miracles"



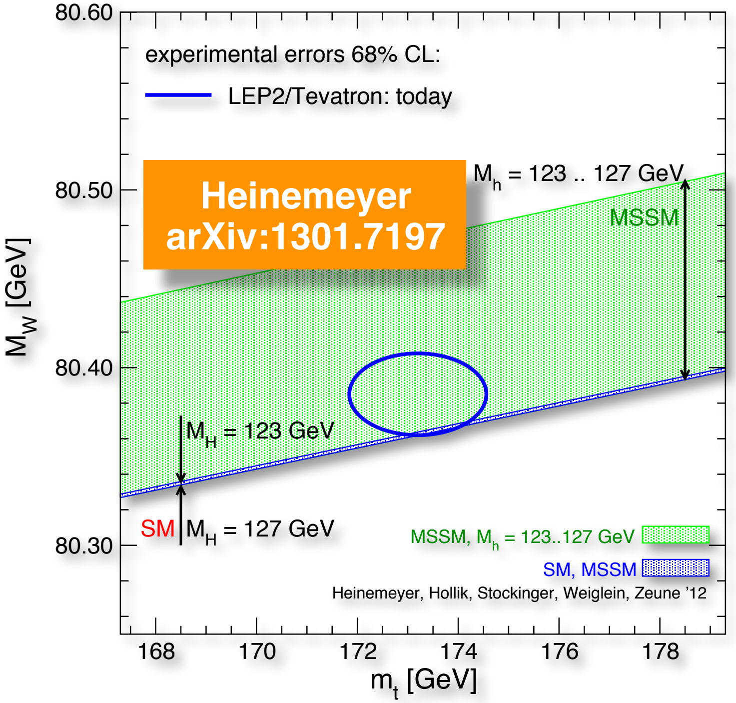
Arbey et al arXiv:1207.1348



Mahmoudi et al arXiv:1211.2794

SUSY & Higgs

- Existence of several Higgs bosons is the key prediction of low-scale SUSY
    - Higgs & SUSY - a marriage made in heaven!
- The lightest one looks largely like the SM Higgs and has to be light (≲135 GeV); the other ones could be relatively heavy
- Discovery of the Higgs boson at 125-126 GeV was the crucial missing proof that low-scale SUSY can still exists, despite the fact that we haven't seen it yet
    - Precision EW data does prefer MSSM over SM (only by 1 standard deviation)
    - Had the Higgs boson been just 10% heavier, I wouldn't be even including SUSY in this talk!

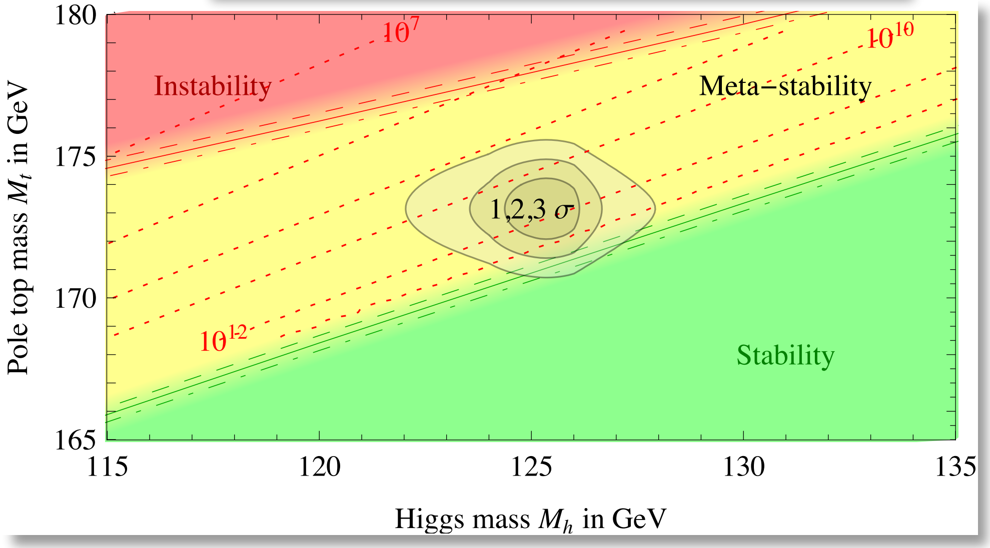


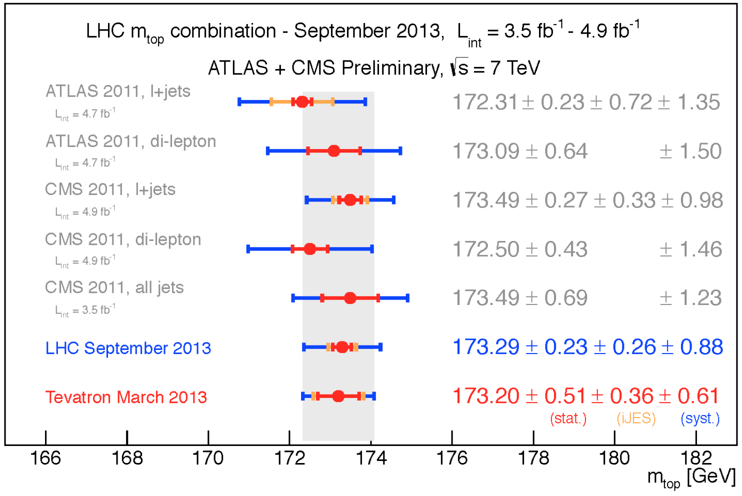
Heinemeyer arXiv:1301.7197

Just-So Higgs?

- The simultaneous measurement of the Higgs boson and top quark masses allowed for the first time to infer properties of the very vacuum we leave in!
  - We are in a highly fine-tuned situation: the vacuum is at the verge of being either stable or metastable!
  - ~1 GeV in either the top-quark or the Higgs boson mass is all it takes to tip the scales!
- Perhaps Nature is trying to tell us something here?
  - Very important to improve on the precision of top quark mass measurements, including various complementary methods and reduction of theoretical uncertainties
  - Tevatron is still leading with the new combined M_t result, but LHC is catching up quickly!

Degrassi et al, arXiv:1205.6497





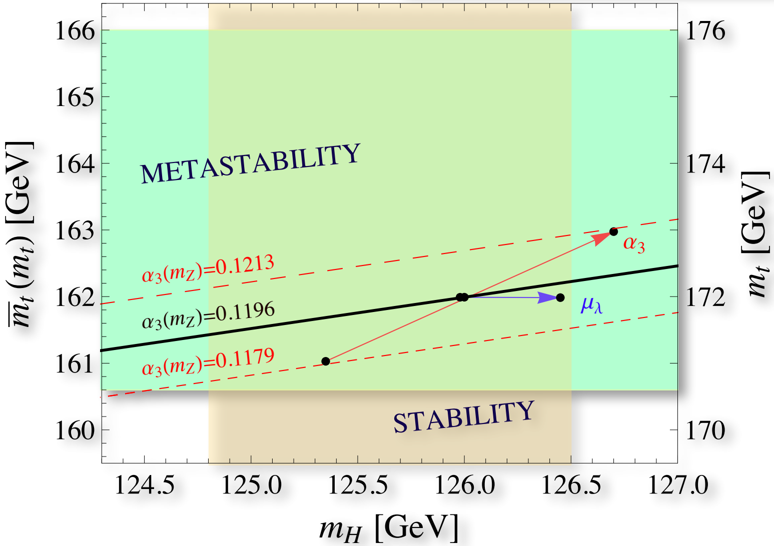
CMS PAS TOP-13-005
ATLAS-CONF-2013-110

What Vacuum Do We Live In?

- Stable vacuum?

- Metastable vacuum?

Masina
arXiv:1301.2175



- Unstable vacuum?

Thank You!