Implications of a SM like Higgs for a natural NMSSM with low cutoff

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in collaboration with
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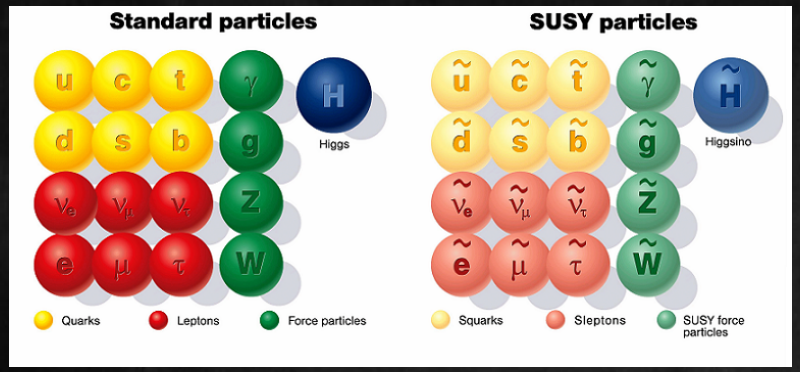
[to appear soon]

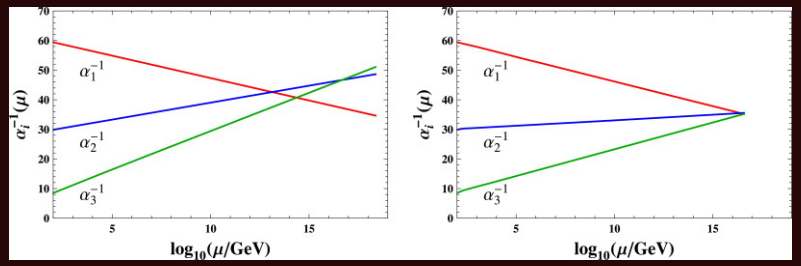
THE UNIVERSITY OF MELBOURNE

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

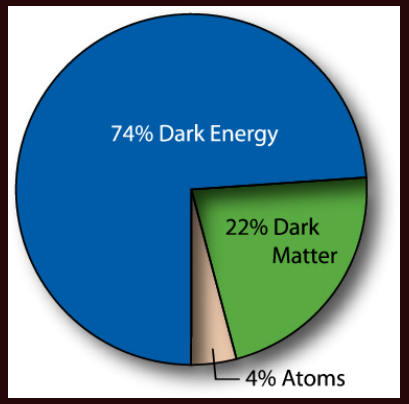
Low-energy Supersymmetry



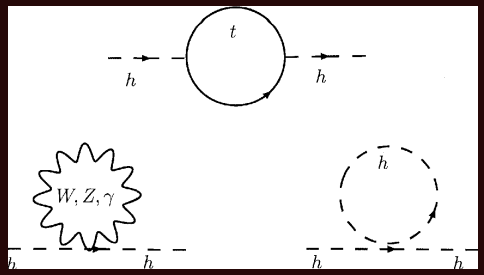
Gauge coupling unification



DM candidate



Solution to hierarchy problem



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln\frac{\Lambda_{UV}}{m_S} + \dots\right]$$

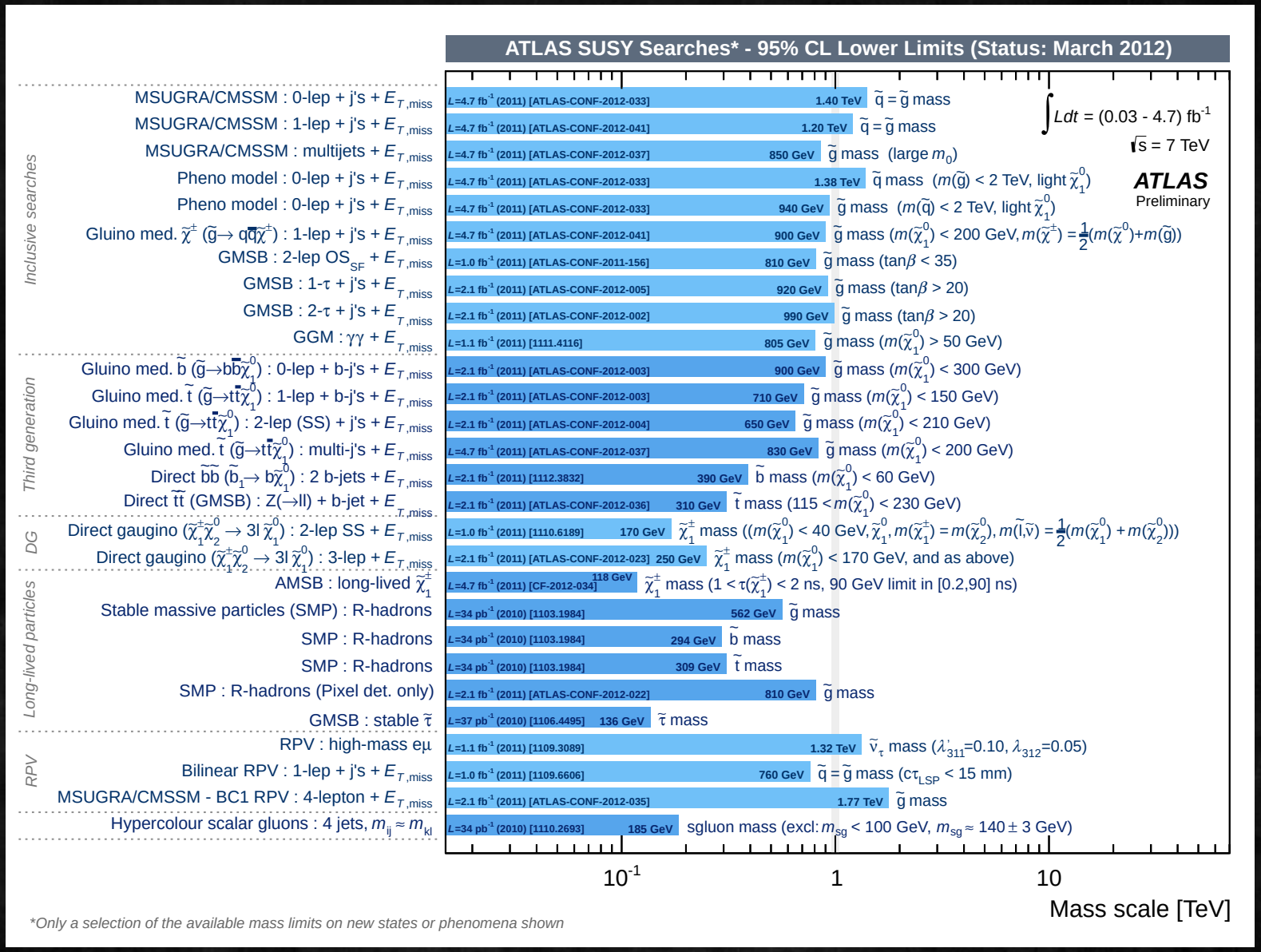
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{16\pi^2}\left[\Lambda_{UV}^2 + \dots\right]$$

Higgs mass prediction

At tree level

$$m_{h^0} < m_Z |\cos 2\beta|$$

CMSSM and Co.


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 2012)
Inclusive searches
MSUGRA/CMSSM : 0-lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1-lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : multijets + $E_{T,miss}$
Pheno model : 0-lep + j's + $E_{T,miss}$
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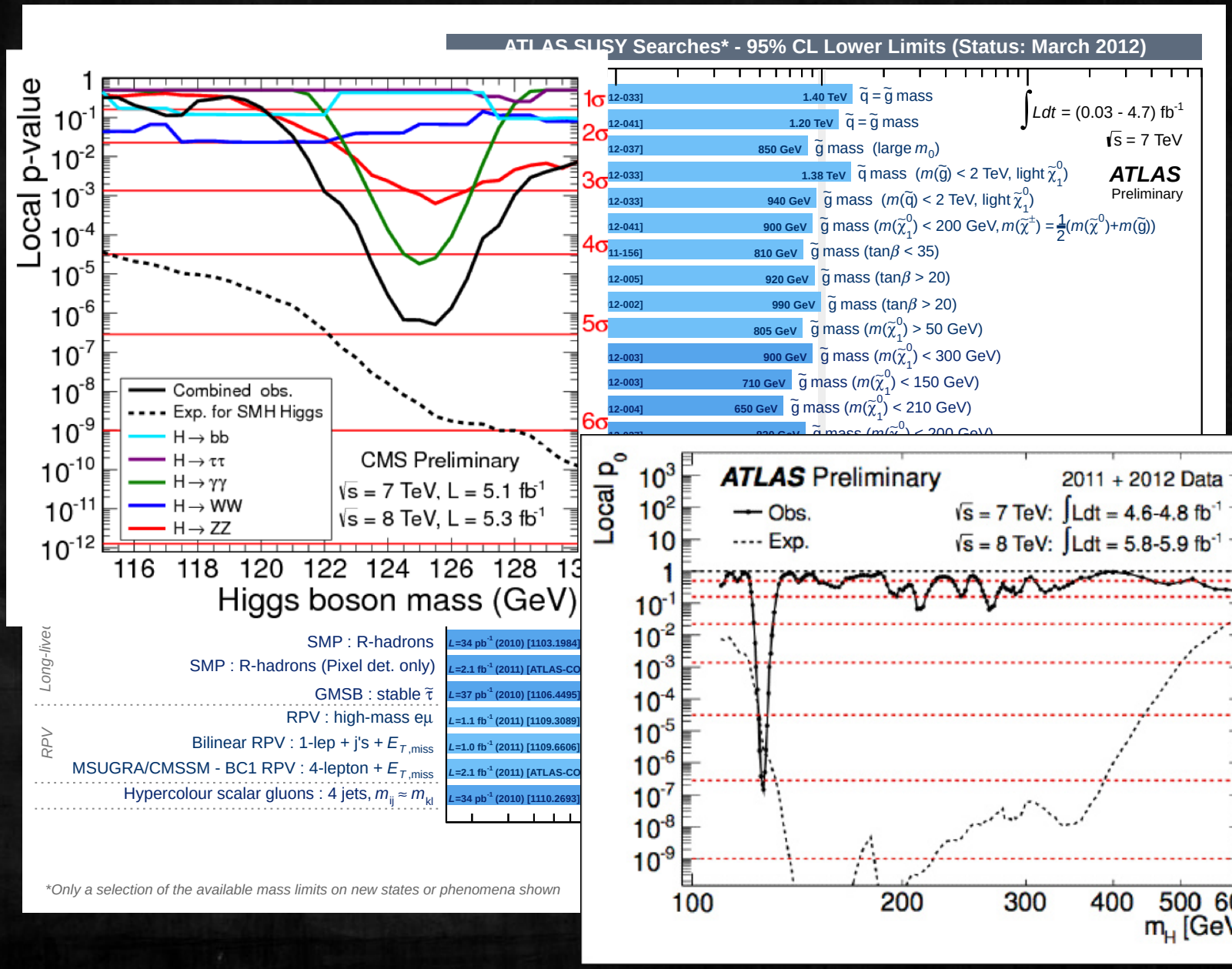
Gluino med. $\tilde{\chi}^{\pm}$ ($\tilde{g} \to q\bar{q}\tilde{\chi}^{\pm}$) : 1-lep + j's + $E_{T,miss}$
GMSB : 2-lep OS_{SF} + $E_{T,miss}$
GMSB : 1-τ + j's + $E_{T,miss}$
GMSB : 2-τ + j's + $E_{T,miss}$
GGM : γγ + $E_{T,miss}$
Third generation
Gluino med. $\tilde{b}$ ($\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$) : 0-lep + b-j's + $E_{T,miss}$
Gluino med. $\tilde{t}$ ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$) : 1-lep + b-j's + $E_{T,miss}$
Gluino med. $\tilde{t}$ ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$) : 2-lep (SS) + j's + $E_{T,miss}$
Gluino med. $\tilde{t}$ ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$) : multi-j's + $E_{T,miss}$
Direct $\tilde{b}\tilde{b}$ ($\tilde{b}_1 \to b\tilde{\chi}_1^0$) : 2 b-jets + $E_{T,miss}$
Direct $\tilde{t}\tilde{t}$ (GMSB) : Z(→ll) + b-jet + $E_{T,miss}$
DG
Direct gaugino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3l\,\tilde{\chi}_1^0$) : 2-lep SS + $E_{T,miss}$
Direct gaugino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3l\,\tilde{\chi}_1^0$) : 3-lep + $E_{T,miss}$
Long-lived particles
AMSB : long-lived $\tilde{\chi}_1^{\pm}$
Stable massive particles (SMP) : R-hadrons
SMP : R-hadrons
SMP : R-hadrons
SMP : R-hadrons (Pixel det. only)
GMSB : stable $\tilde{\tau}$
RPV
RPV : high-mass eμ
Bilinear RPV : 1-lep + j's + $E_{T,miss}$
MSUGRA/CMSSM - BC1 RPV : 4-lepton + $E_{T,miss}$
Hypercolour scalar gluons : 4 jets, $m_{ij} \approx m_{kl}$
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-033] 1.40 TeV $\tilde{q} = \tilde{g}$ mass
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-041] 1.20 TeV $\tilde{q} = \tilde{g}$ mass
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-037] 850 GeV $\tilde{g}$ mass (large m_0)
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-033] 1.38 TeV $\tilde{q}$ mass ($m(\tilde{g})$ < 2 TeV, light $\tilde{\chi}_1^0$)
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-033] 940 GeV $\tilde{g}$ mass ($m(\tilde{q})$ < 2 TeV, light $\tilde{\chi}_1^0$)
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-041] 900 GeV $\tilde{g}$ mass ($m(\tilde{\chi}_1^0)$ < 200 GeV, $m(\tilde{\chi}^{\pm}) = \frac{1}{2}(m(\tilde{\chi}^0)+m(\tilde{g}))$)
L=1.0 fb^{-1} (2011) [ATLAS-CONF-2011-156] 810 GeV $\tilde{g}$ mass (tanβ < 35)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-005] 920 GeV $\tilde{g}$ mass (tanβ > 20)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-002] 990 GeV $\tilde{g}$ mass (tanβ > 20)
L=1.1 fb^{-1} (2011) [1111.4116] 805 GeV $\tilde{g}$ mass ($m(\tilde{\chi}_1^0)$ > 50 GeV)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-003] 900 GeV $\tilde{g}$ mass ($m(\tilde{\chi}_1^0)$ < 300 GeV)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-003] 710 GeV $\tilde{g}$ mass ($m(\tilde{\chi}_1^0)$ < 150 GeV)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-004] 650 GeV $\tilde{g}$ mass ($m(\tilde{\chi}_1^0)$ < 210 GeV)
L=4.7 fb^{-1} (2011) [ATLAS-CONF-2012-037] 830 GeV $\tilde{g}$ mass ($m(\tilde{\chi}_1^0)$ < 200 GeV)
L=2.1 fb^{-1} (2011) [1112.3832] 390 GeV $\tilde{b}$ mass ($m(\tilde{\chi}_1^0)$ < 60 GeV)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-036] 310 GeV $\tilde{t}$ mass (115 < $m(\tilde{\chi}_1^0)$ < 230 GeV)
L=1.0 fb^{-1} (2011) [1110.6189] 170 GeV $\tilde{\chi}_1^{\pm}$ mass (($m(\tilde{\chi}_1^0)$ < 40 GeV, $\tilde{\chi}_1^0$, $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0)$, $m(\tilde{l},\tilde{\nu}) = \frac{1}{2}(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$))
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-023] 250 GeV $\tilde{\chi}_1^{\pm}$ mass ($m(\tilde{\chi}_1^0)$ < 170 GeV, and as above)
L=4.7 fb^{-1} (2011) [CF-2012-034] 118 GeV $\tilde{\chi}_1^{\pm}$ mass (1 < τ($\tilde{\chi}_1^{\pm}$) < 2 ns, 90 GeV limit in [0.2,90] ns)
L=34 pb^{-1} (2010) [1103.1984] 562 GeV $\tilde{g}$ mass
L=34 pb^{-1} (2010) [1103.1984] 294 GeV $\tilde{b}$ mass
L=34 pb^{-1} (2010) [1103.1984] 309 GeV $\tilde{t}$ mass
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-022] 810 GeV $\tilde{g}$ mass
L=37 pb^{-1} (2010) [1106.4495] 136 GeV $\tilde{\tau}$ mass
L=1.1 fb^{-1} (2011) [1109.3089] 1.32 TeV $\tilde{\nu}_{\tau}$ mass (λ'_{311}=0.10, λ_{312}=0.05)
L=1.0 fb^{-1} (2011) [1109.6606] 760 GeV $\tilde{q} = \tilde{g}$ mass ($c\tau_{LSP}$ < 15 mm)
L=2.1 fb^{-1} (2011) [ATLAS-CONF-2012-035] 1.77 TeV $\tilde{g}$ mass
L=34 pb^{-1} (2010) [1110.2693] 185 GeV sgluon mass (excl: m_{sg} < 100 GeV, $m_{sg} \approx 140 \pm 3$ GeV)
$\int Ldt$ = (0.03 - 4.7) fb^{-1}
$\sqrt{s}$ = 7 TeV
ATLAS
Preliminary
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

CMSSM and Co.


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 2012)
1σ
2σ
3σ
4σ
5σ
6σ
12-033] 1.40 TeV q̃ = g̃ mass
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∫Ldt = (0.03 - 4.7) fb-1
√s = 7 TeV
ATLAS
Preliminary
Local p-value
Combined obs.
Exp. for SMH Higgs
H→ bb
H→ ττ
H→ γγ
H→ WW
H→ ZZ
CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
Higgs boson mass (GeV)
Long-live
SMP : R-hadrons
SMP : R-hadrons (Pixel det. only)
GMSB : stable τ̃
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RPV : high-mass eμ
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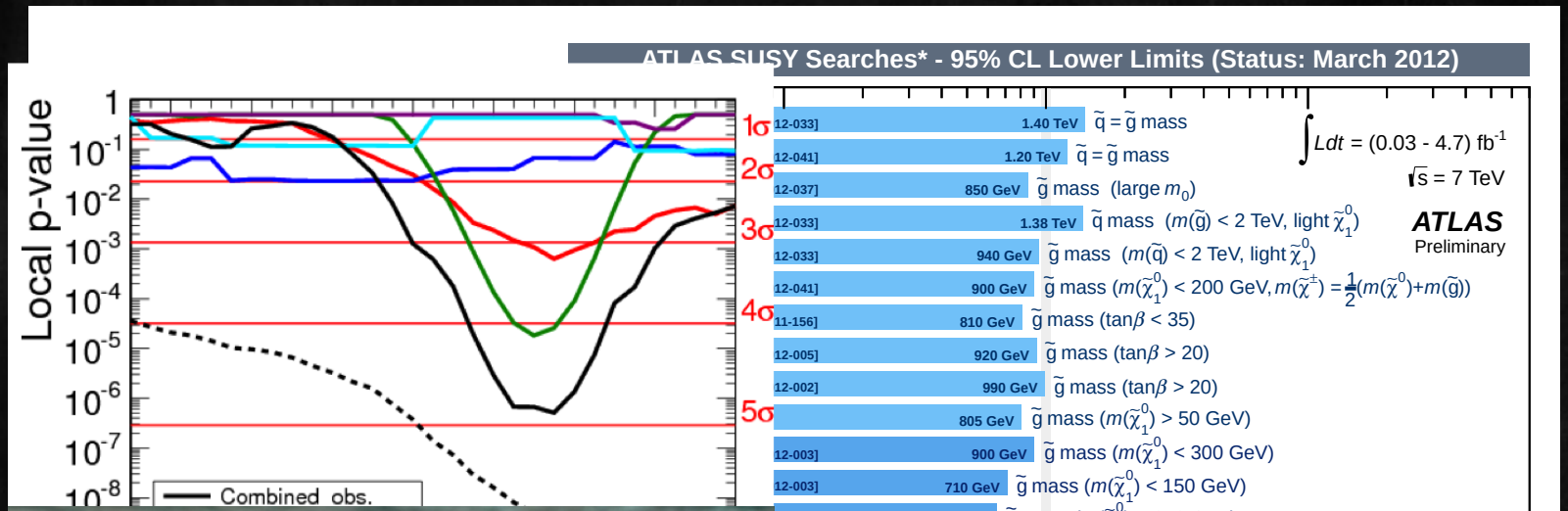
ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Local p0
0σ
1σ
2σ
3σ
4σ
5σ
6σ
mH [GeV]

CMSSM and Co.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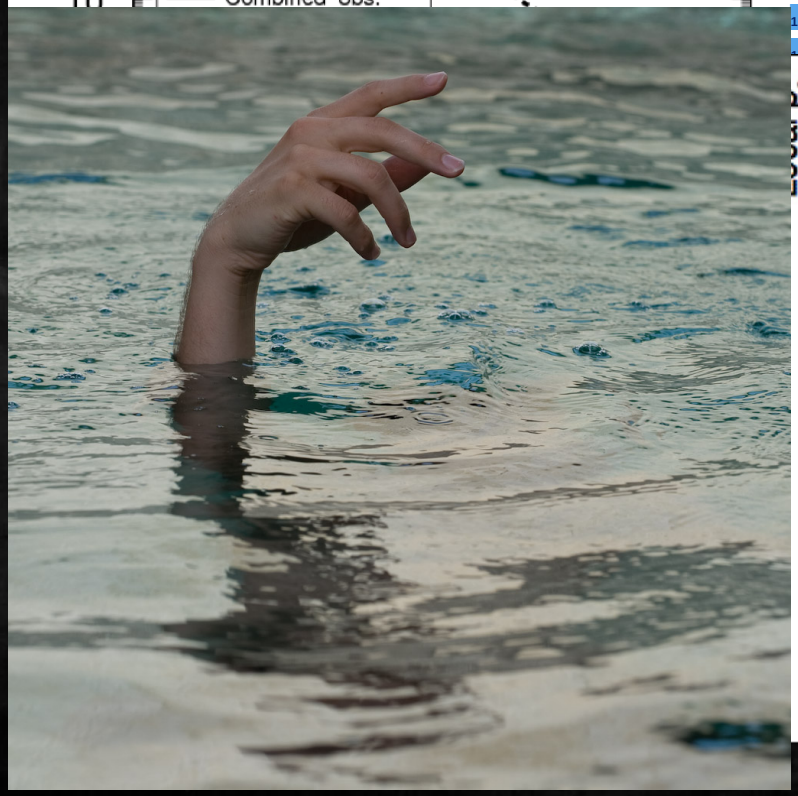
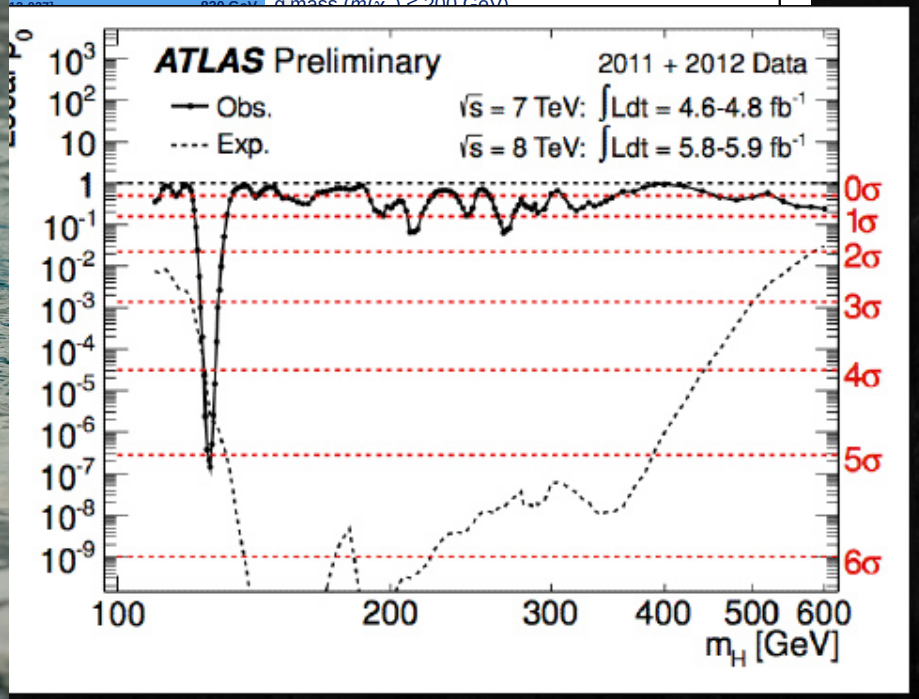
Preliminary

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1σ
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Saving SUSY [Many people...]

Drop one of the assumptions in the (C)MSSM

- give up on small fine-tuning

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  - compressed particle spectrum
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  → proton decay?

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- Why is the Higgs heavy despite tree level relation $m_{h^0} < m_Z |\cos 2\beta|$?

  - light stops with large $A_t \Rightarrow$ large mass splitting
  - Extend MSSM to modify Higgs mass prediction

  → e.g. at tree level in NMSSM: introduce gauge singlet S

Outline

Outline

Literature: NMSSM and 125/126 GeV Higgs

- **"A Natural SUSY Higgs Near 126 GeV"**
  L. J. Hall, D. Pinner and J. T. Ruderman.
  arXiv:1112.2703 [hep-ph]
  JHEP **1204**, 131 (2012)
- **"Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale"**
  U. Ellwanger and C. Hugonie.
  arXiv:1203.5048 [hep-ph]
- **"The 125 GeV Higgs in the NMSSM in light of LHC results and astrophysics constraints"**
  D. A. Vasquez, G. Belanger, C. Boehm, J. Da Silva, P. Richardson and C. Wymant.
  arXiv:1203.3446 [hep-ph]
- **"A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM"**
  J. Cao, Z. Heng, J. M. Yang, Y. Zhang and J. Zhu.
  arXiv:1202.5821 [hep-ph]
  JHEP **1203**, 086 (2012)
- **"NMSSM Higgs Benchmarks Near 125 GeV"**
  S. F. King, M. Muhlleitner and R. Nevzorov.
  arXiv:1201.2671 [hep-ph]
  Nucl. Phys. B **860**, 207 (2012)
- **"The Constrained NMSSM and Higgs near 125 GeV"**
  J. F. Gunion, Y. Jiang and S. Kraml.
  arXiv:1201.0982 [hep-ph]
  Phys. Lett. B **710**, 454 (2012)
- **"A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM"**
  U. Ellwanger.
  arXiv:1112.3548 [hep-ph]
  JHEP **1203**, 044 (2012)
- **"The fine-tuning of the generalised NMSSM"**
  G. G. Ross and K. Schmidt-Hoberg.
  arXiv:1108.1284 [hep-ph] **"The generalised NMSSM at one loop: fine tuning and phenomenology"**
  G. G. Ross, K. Schmidt-Hoberg and F. Staub.
  arXiv:1205.1509 [hep-ph]
- ...

NMSSM

Superpotential

$$W_{NMSSM} = \lambda S H_d H_u + \frac{\kappa}{3} S^3$$

NMSSM

Superpotential

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Soft breaking terms

$$V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_s^2 |S|^2 + (a_\lambda S H_d H_u + \frac{a_\kappa}{3} S^3 + h.c.)$$

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Bound on lightest Higgs mass m_h

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \rightarrow \begin{cases} m_Z^2 \cos^2 2\beta & \text{large } \tan\beta \\ \lambda^2 v^2 \sin^2 2\beta & \text{small } \tan\beta \end{cases}$$

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- No gain for large $\tan\beta$ compared to MSSM $\rightarrow$ small $\tan\beta$

$\rightarrow$ relatively large $\lambda \gtrsim 0.6$ or additional stop loop contribution

$\rightarrow$ Landau pole below GUT scale $\rightarrow$ low cutoff required

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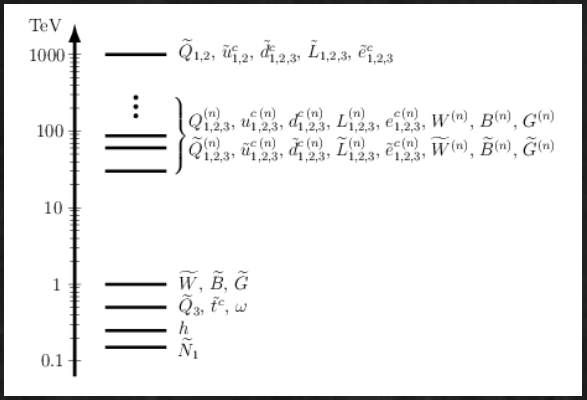
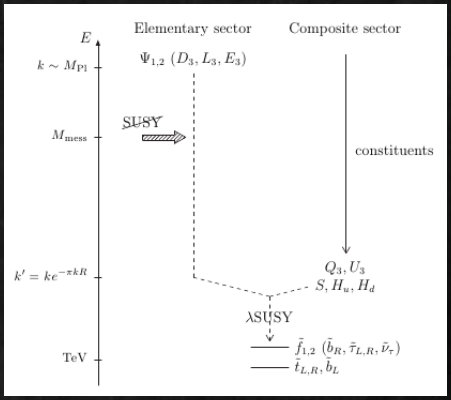


[Gherghetta, v.Harling, Setzer (2011)]



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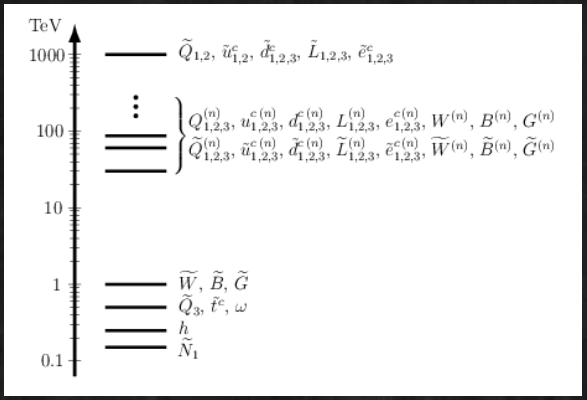

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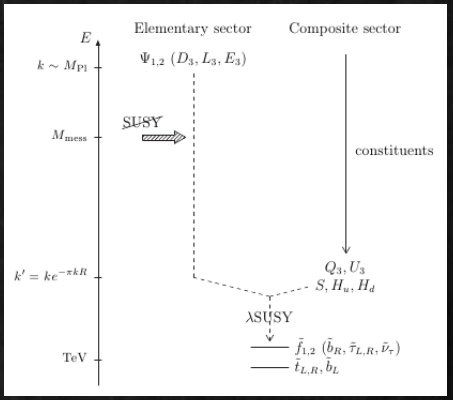

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Our Study

- Aim: Find the "Golden Region" of small fine-tuning (better 10%)
- assuming "SM-like" Higgs with $m_h \approx 126\,\text{GeV}$ [$(124 - 127)\,\text{GeV}$]

NMSSM with low Cutoff $\Lambda = 10\,\text{TeV}$ – Our Study

Assumptions

- Fine tuning better 10% $\Rightarrow \Sigma < 10$
- $124\,\text{GeV} < m_h < 127\,\text{GeV}$
- "SM-like" Higgs: $|R_{ZZh} - 1| < 0.05$ and $|R_{u\bar{u}h} - 1| < 0.05$
- no invisible Higgs decays
- no CP violation
- First two generations of squarks and all sleptons decoupled
- Neutralino LSP
- No Landau pole below cutoff scale $\Lambda = 10\,\text{TeV}$

Fine-tuning Measure

$$\Sigma_\xi^v \equiv \left| \frac{d \log v^2}{d \log \xi} \right| = \left| \frac{\xi}{v^2} \frac{dv^2}{d\xi} \right| < \Sigma$$

[Barbieri,Giudice (1988)]

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- No Landau pole below cutoff scale $\Lambda = 10\,\text{TeV}$

Fine-tuning Measure

$$\Sigma_\xi^v \equiv \left| \frac{d \log v^2}{d \log \xi} \right| = \left| \frac{\xi}{v^2} \frac{dv^2}{d\xi} \right| < \Sigma$$

[Barbieri,Giudice (1988)]

Analysis

- Markov-Chain Monte-Carlo
- modified version of NMHDECAY[Ellwanger, Gunion, Hugonie]

Analysis

Constraints

- LEP bounds on particle masses
- Flavour constraints
  - $b \to s\gamma$
  - $B_s \to \mu\mu$
  - $B^+ \to \tau^+\nu_\tau$
  - $\Delta M_{s,d}$
- Electroweak precision tests (S and T):
  - Higgs sector
  - full Neutralino-Chargino sector
  - T_{stsb} from stop-sbottom

  $\to$ S_{stsb} is small

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Range of input values

Input values

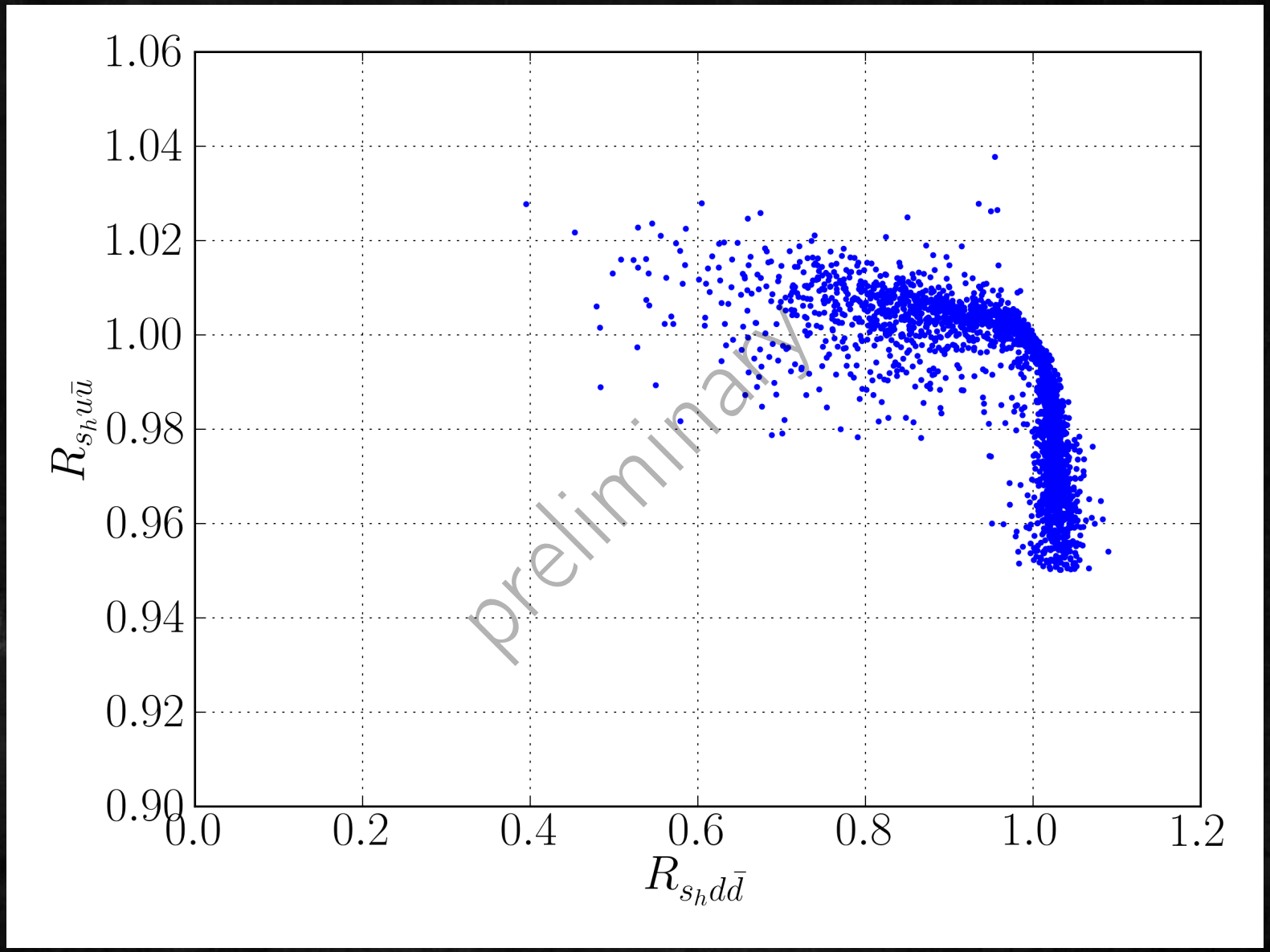
$$M_{1,2} < 3\,\text{TeV}$$
$$700\,\text{GeV} < M_3 < 3\,\text{TeV}$$
$$m_{Q_3,\,u_3,\,d_3} < 3\,\text{TeV}$$
$$|A_{\lambda,\,\kappa,\,t,\,b}| < 3\,\text{TeV}$$
$$\lambda > 0$$
$$a_\kappa = \kappa\, A_\kappa \geq 0$$
$$\tan\beta > 0.5$$

are specified at SUSY scale

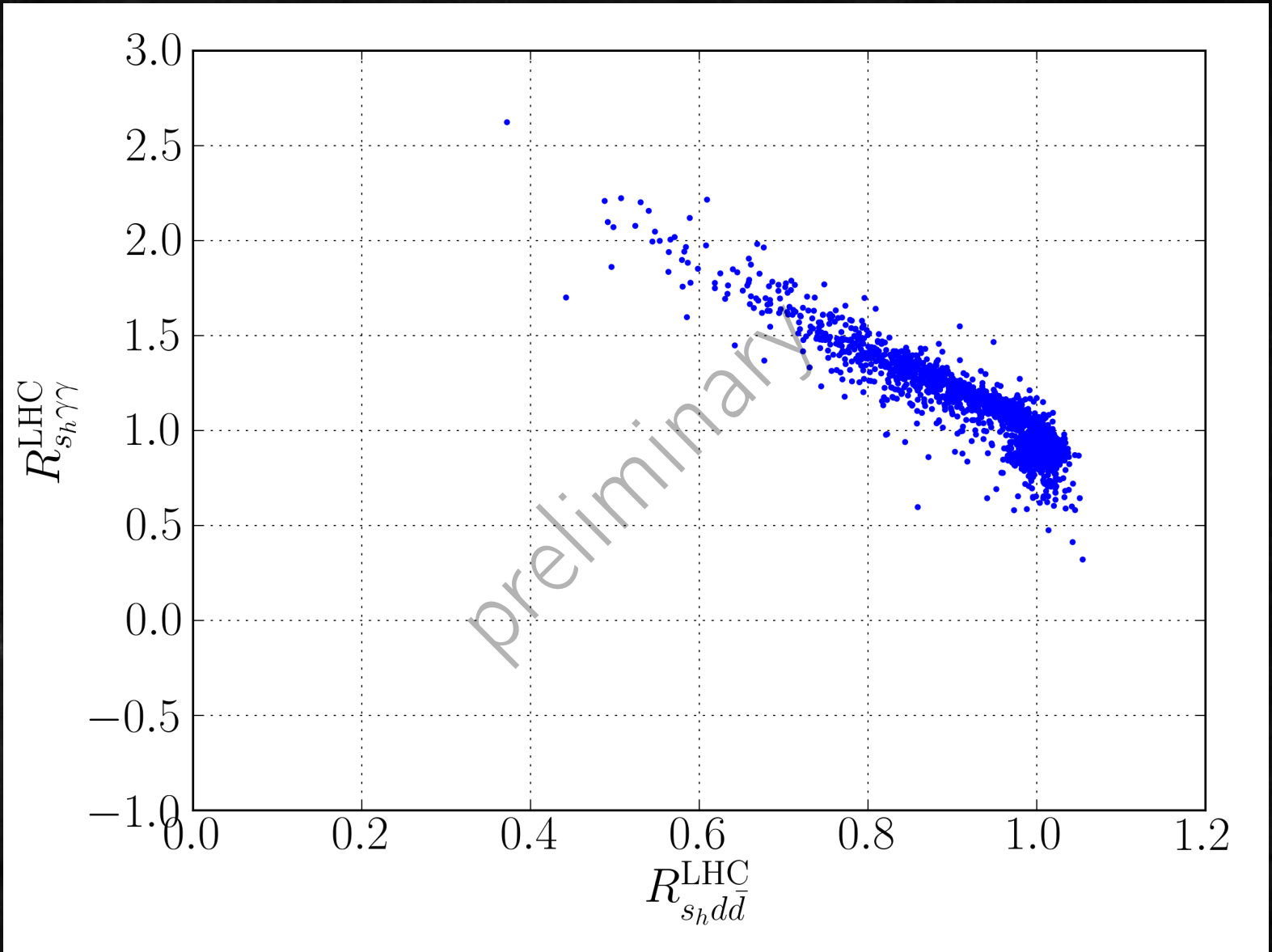
$$M^2_{SUSY} = \frac{1}{4} \sum_{i=\tilde{t}_{1,2},\,\tilde{b}_{1,2}} m_i^2$$

Outline

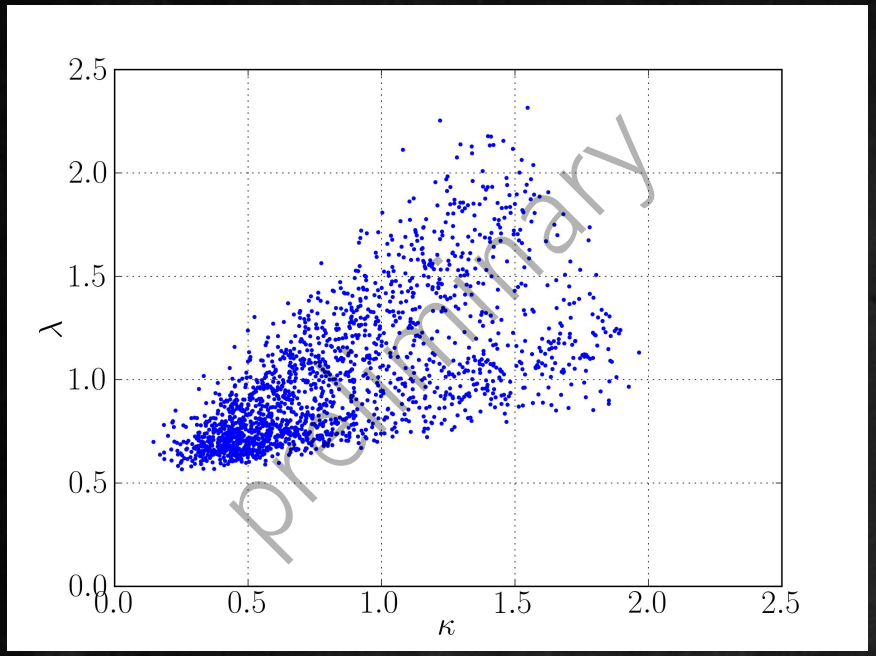
Higgs couplings

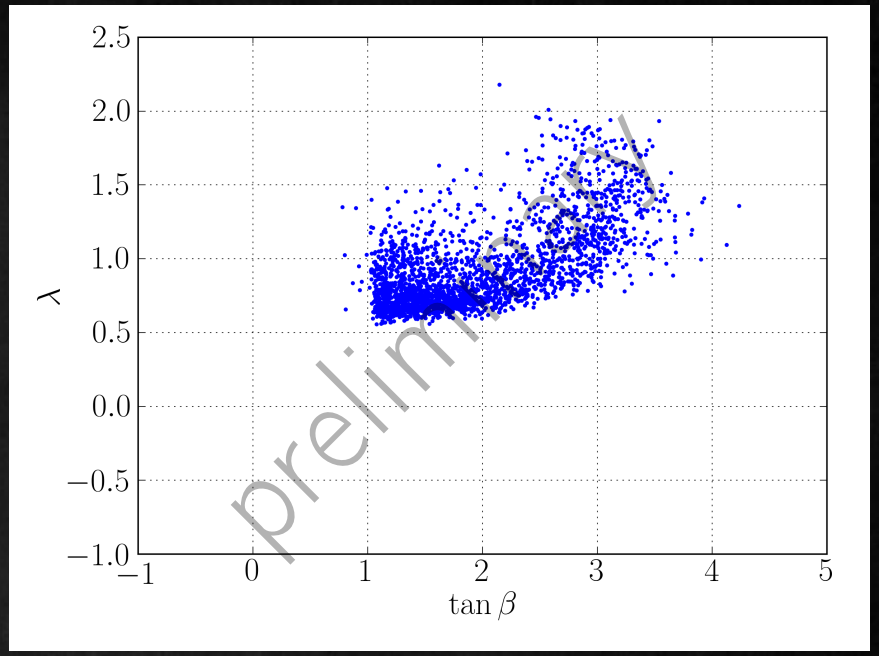


Higgs couplings II



$\lambda - \kappa$





- $0.6 \lesssim \lambda \lesssim 2.3$ and $\max \kappa < \max \lambda \Leftarrow$ running of κ stronger than λ

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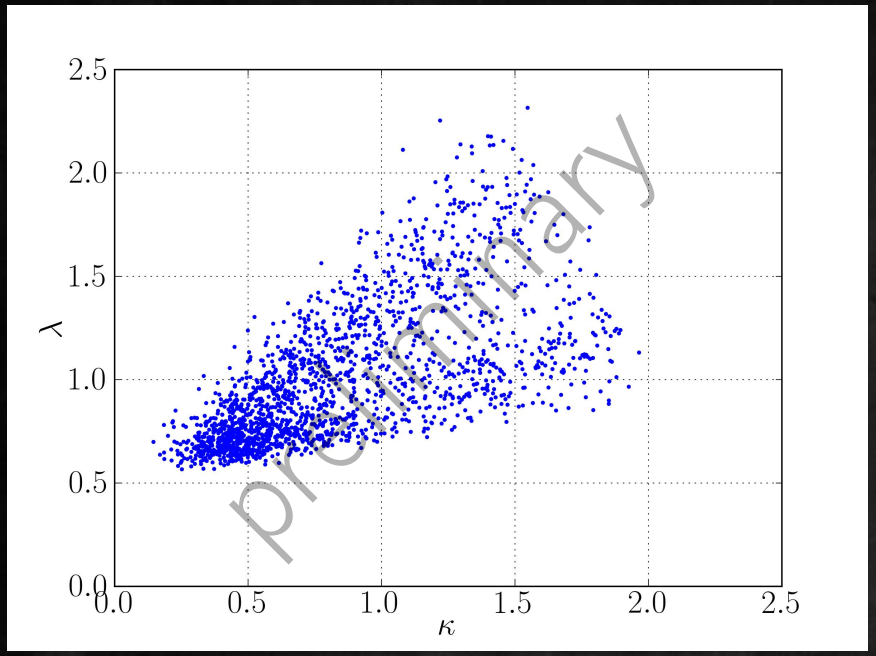

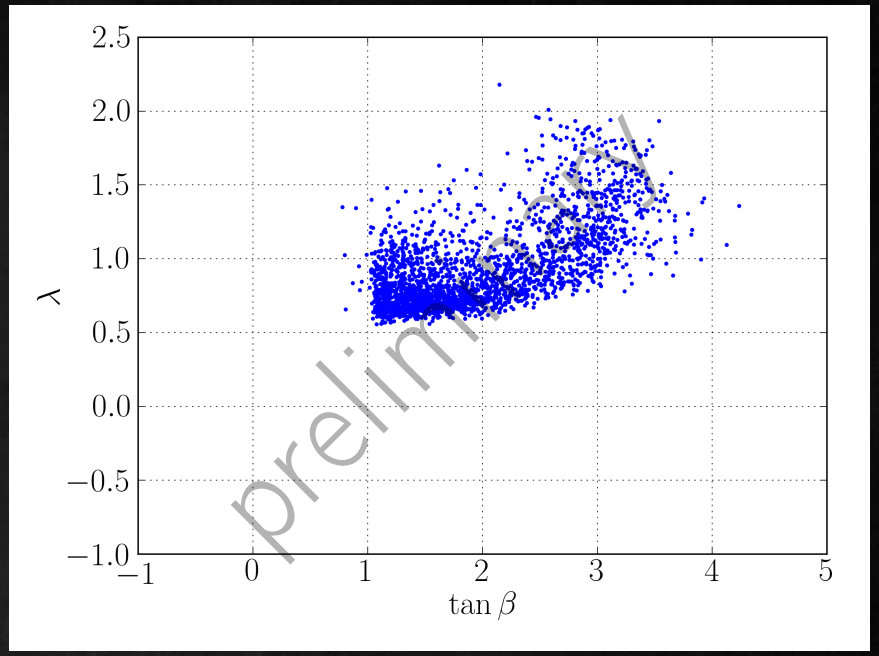

- $0.6 \lesssim \lambda \lesssim 2.3$ and $\max \kappa < \max \lambda \Leftarrow$ running of κ stronger than λ
- $\lambda \sim \kappa$ [Larsen,Nomura,Roberts] because EWSB requires $B_\mu \sim \mu^2$:

$$B_\mu = \mu \left(A_\lambda + \frac{\kappa}{\lambda} \mu \right)$$

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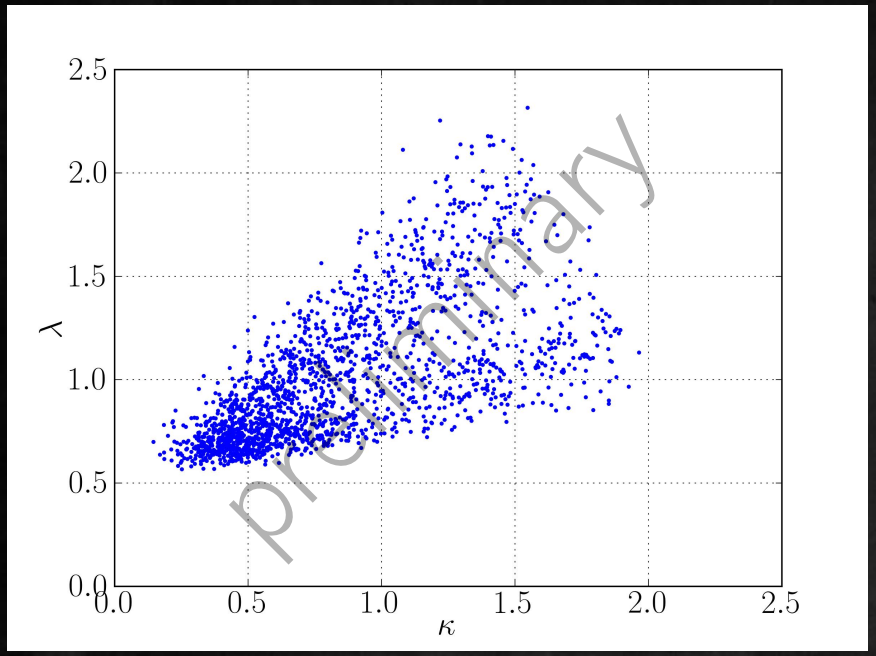

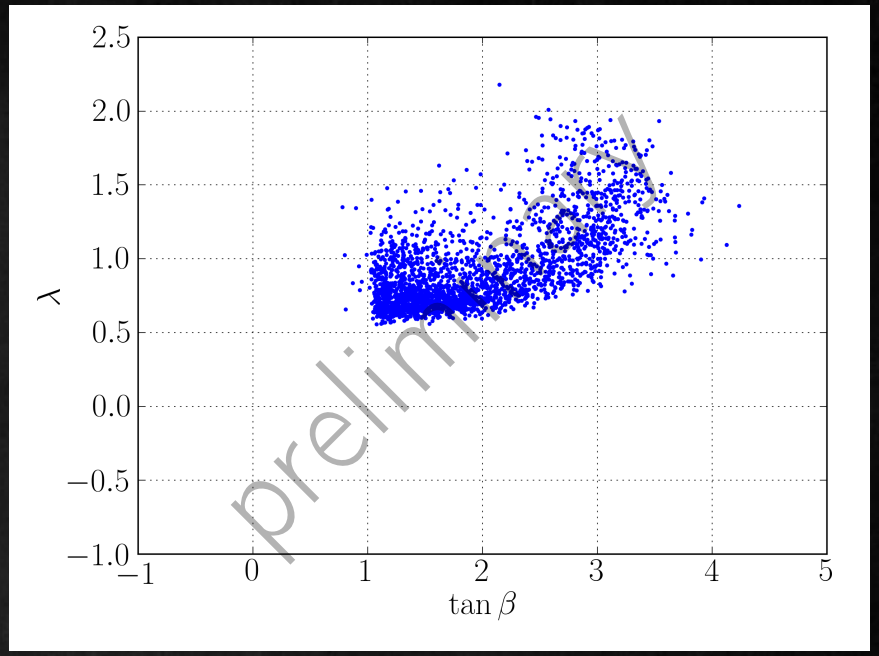

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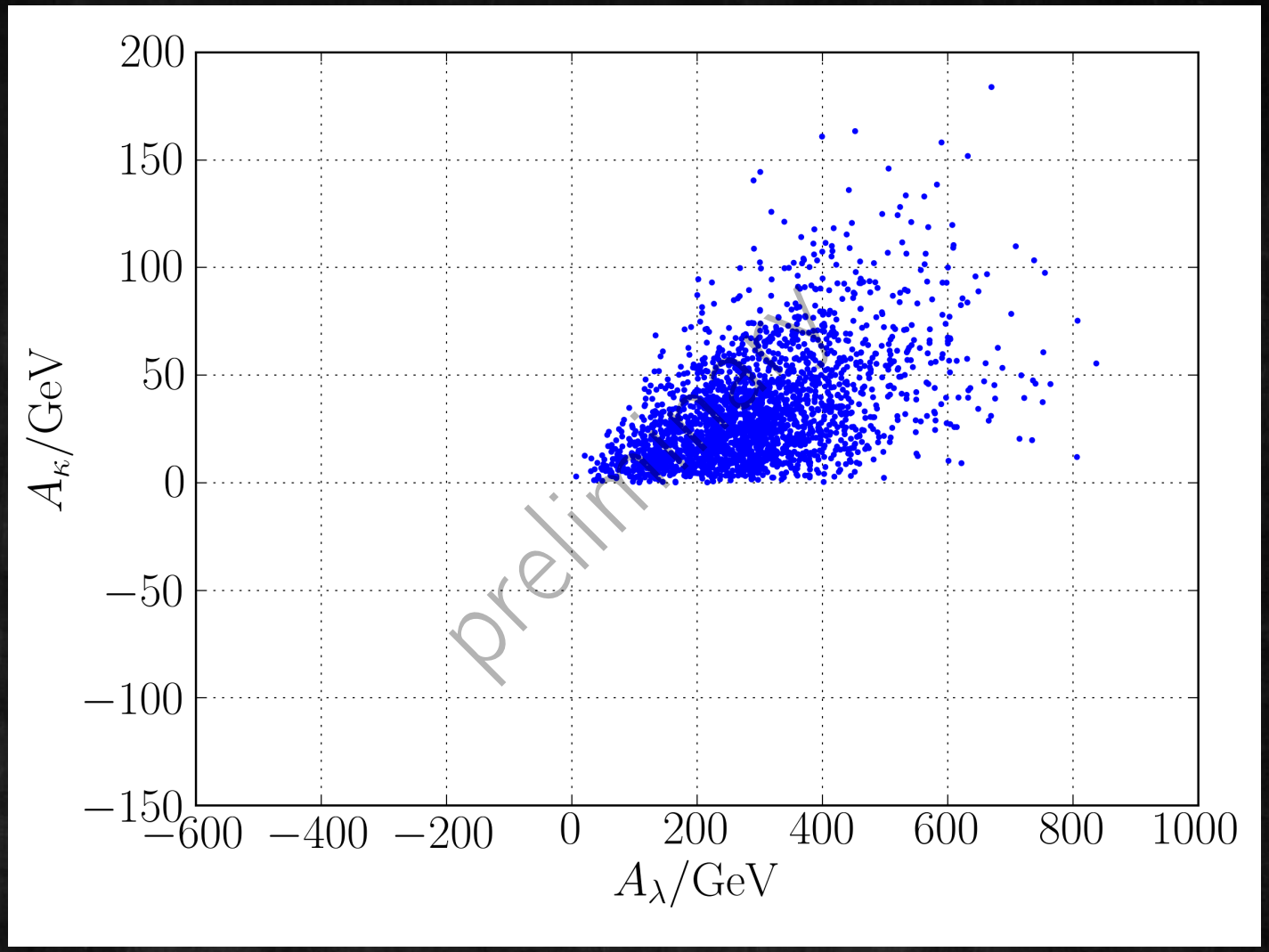
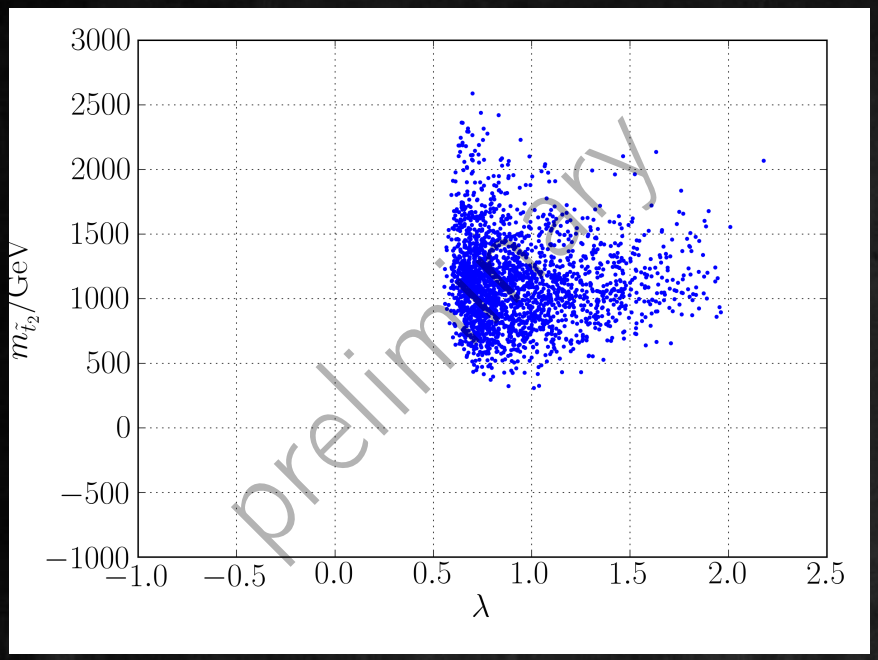
- $\tan\beta \lesssim 4.5$ [Barbieri, Hall, Nomura, Rychkov] because large $\tan\beta$
  $\Rightarrow$ large higgsino-singlino mixing ($\sim \lambda \tan\beta$)
  $\Rightarrow$ large contribution to T parameter

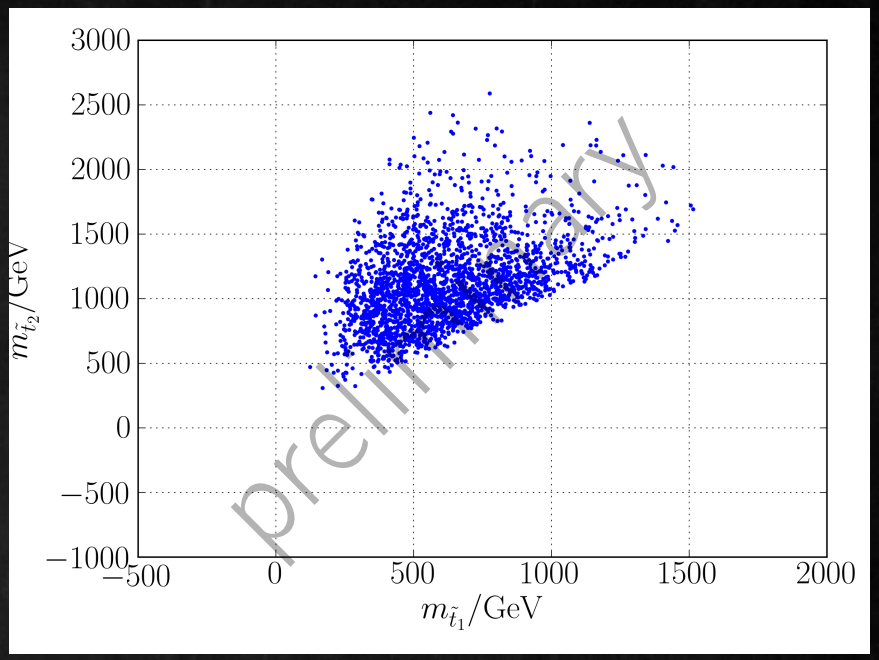
$A_\lambda - A_\kappa$



- small A terms: $A_\kappa \lesssim A_\lambda \lesssim 800\,\text{GeV}$

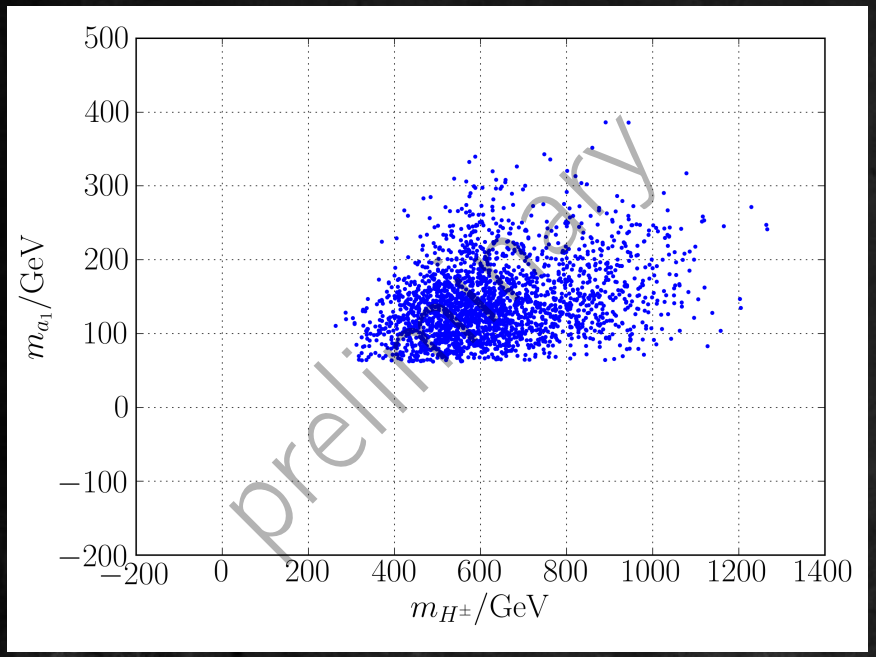
Stop masses

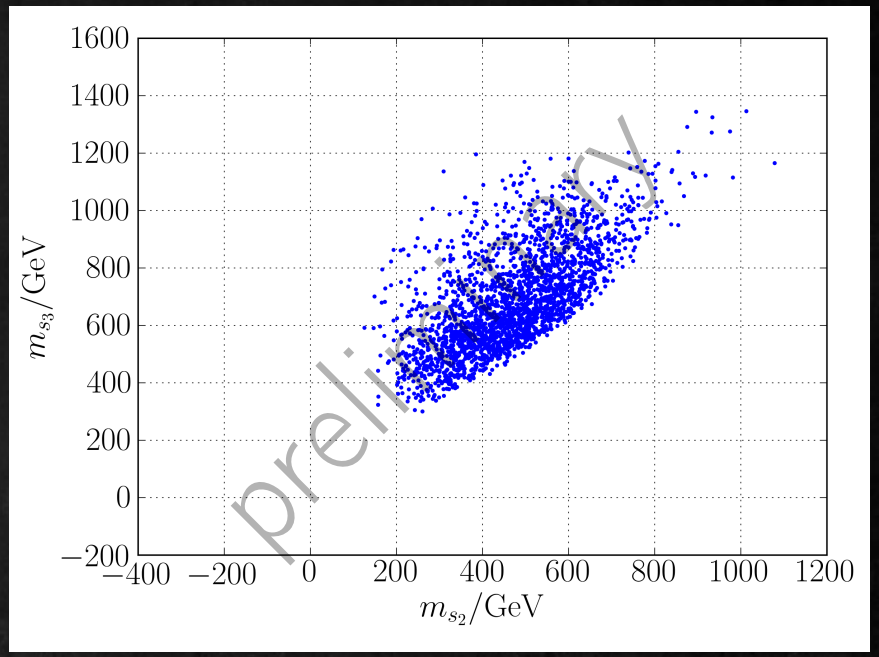




- $m_{\tilde{t}_2} \lesssim 2.5\,\text{TeV}$
- naturalness does not require light stops
- consistent with results obtained for
  $W_{NMSSM} = \lambda S H_u H_d + \hat{\mu} H_u H_d + \frac{M}{2} S^2$ [Hall, Pinner, Ruderman (2011)]

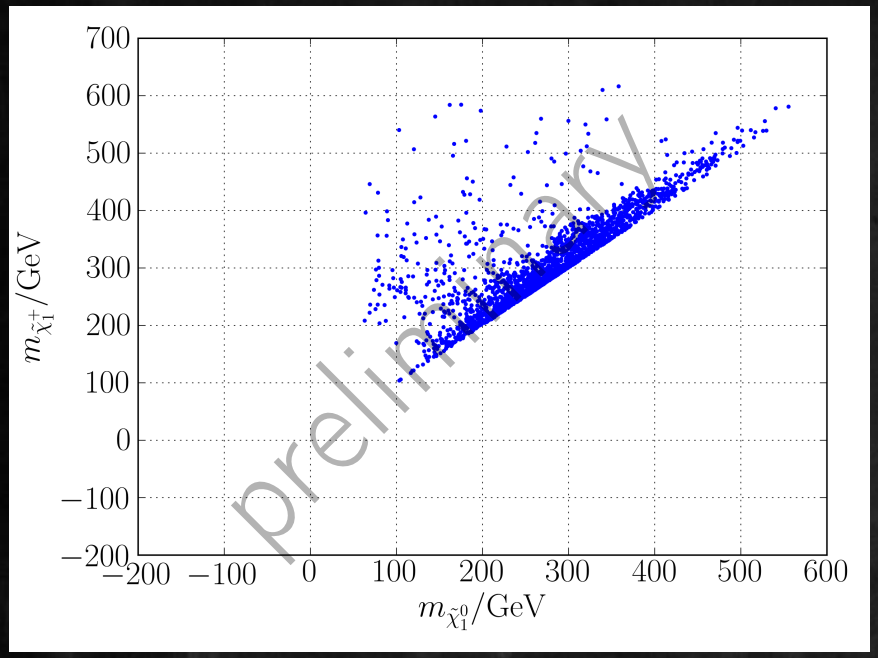
What is light? – Higgs sector

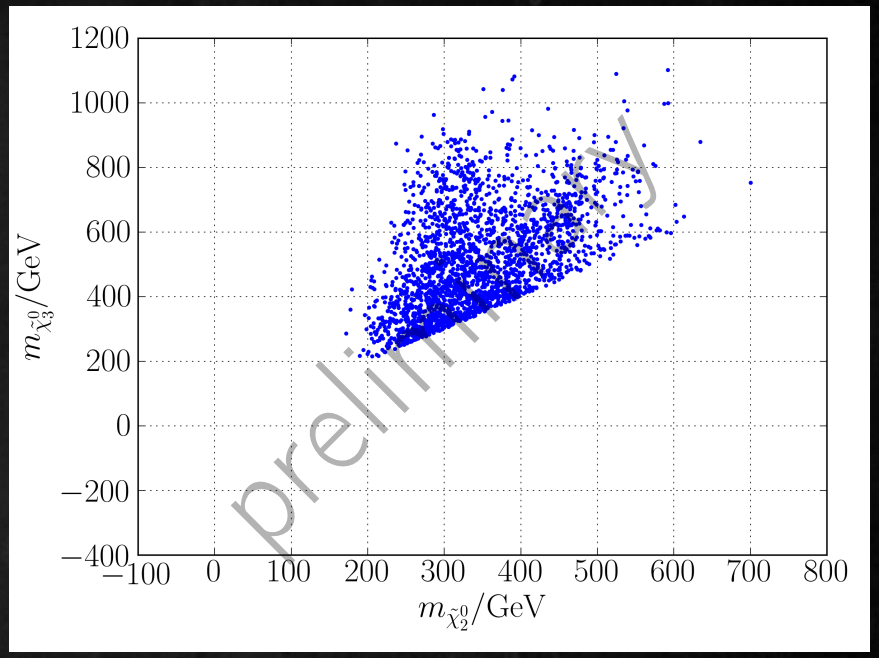




- one CP odd Higgs $\lesssim$ 400 GeV
- at least two CP even Higgs $\lesssim$ 1 TeV

What is light? – Neutralino-Chargino sector





- imposed condition of a neutralino LSP: $m_{\chi_1^\pm} > m_{\chi_1^0}$
- several light neutralinos ($< 1\,\text{TeV}$)
- lightest chargino $m_{\chi_1^\pm} < 700\,\text{GeV}$

Outline

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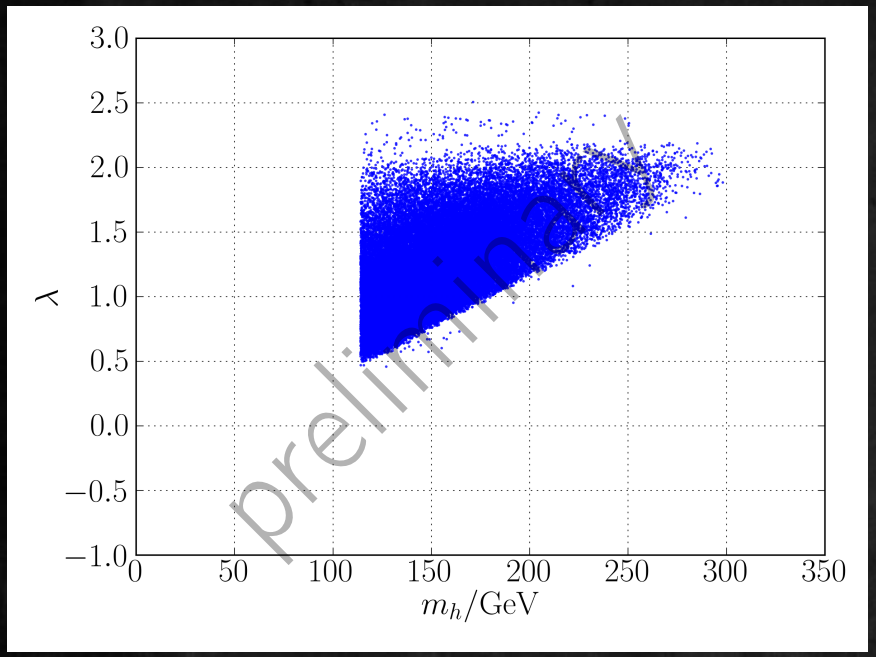
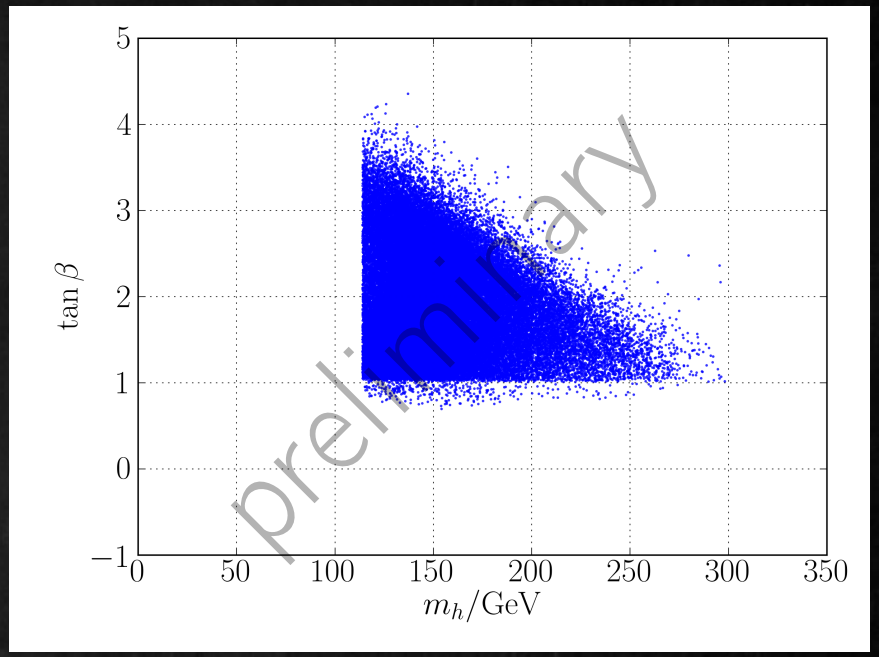
$\Rightarrow$ difficult to test the parameter space of natural SUSY at the LHC

Thank you very much for your attention.

Backup Slides

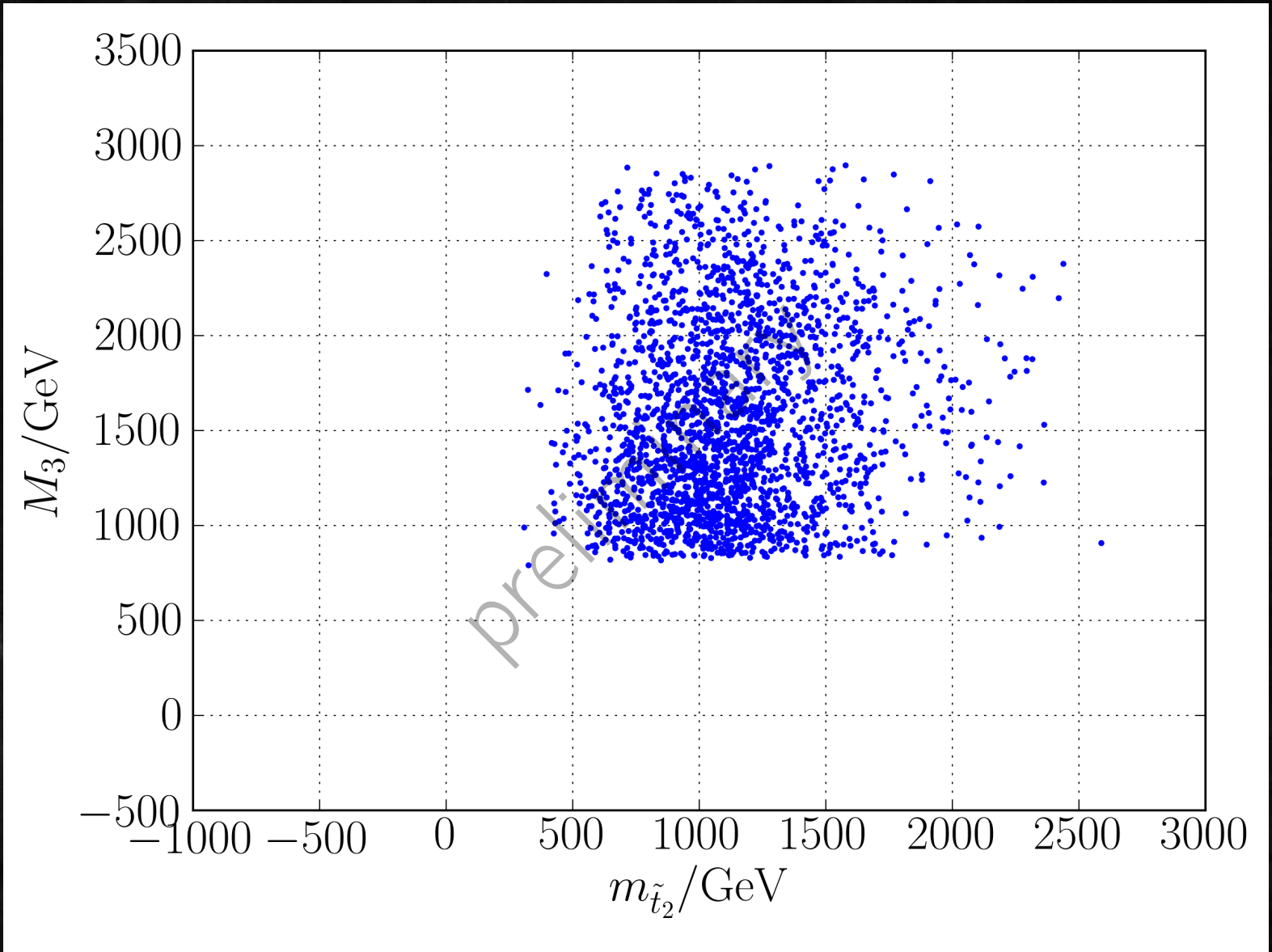
Higgs mass





- large Higgs mass m_h requires large λ and small $\tan\beta$
- Higgs defined as CP even scalar with largest H_u component (not necessarily lightest CP even scalar)

Gluino mass


3500
3000
2500
2000
1500
1000
500
0
−500
M_3/GeV
−1000
−500
0
500
1000
1500
2000
2500
3000
$m_{\tilde{t}_2}$/GeV
preliminary

Neutralinos and T parameter

Neutralinos

$$\begin{pmatrix} M_1 & 0 & -\cos\beta\sin\theta_W m_Z & \sin\beta\sin\theta_W m_Z & 0 \\ . & M_2 & \cos\beta\cos\theta_W m_Z & -\sin\beta\cos\theta_W m_Z & 0 \\ . & . & 0 & -\mu & -\lambda v\sin\beta \\ . & . & -\mu & 0 & -\lambda v\cos\beta \\ . & . & . & . & -2\frac{\kappa}{\lambda}\mu \end{pmatrix}$$

in gauge-eigenbasis $\psi^0 = (\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$

- $\tan\beta \lesssim 4.5$ limited by stop contribution to T [Barbieri, Hall, Nomura, Rychkov]

$\rightarrow$ Higgsino-Singlino mixing restricted