

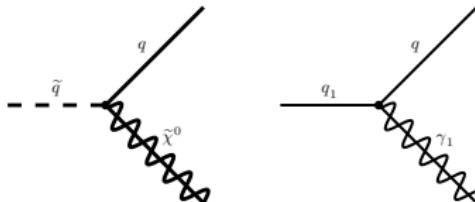
Limits and Fits from Simplified Models for supersymmetry and same-spin models

Lisa Edelhäuser Jan Heisig Michael Krämer Lennart Oymanns
Jory Sonneveld Wolfgang Waltenberger

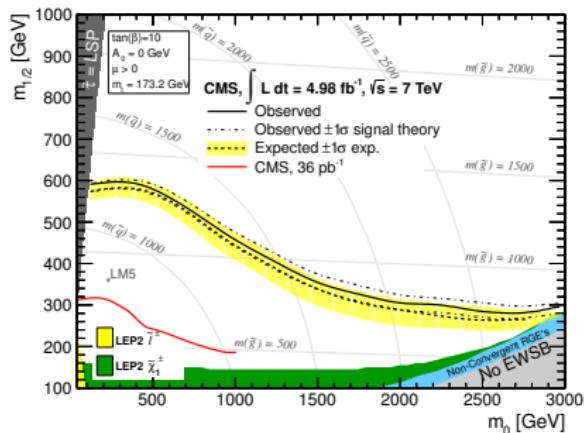
RWTH Aachen and HEPHY Vienna

Terascale Alliance Meeting, DESY Hamburg, December 2014

Based on [arXiv:1410.0965](https://arxiv.org/abs/1410.0965) and work in progress



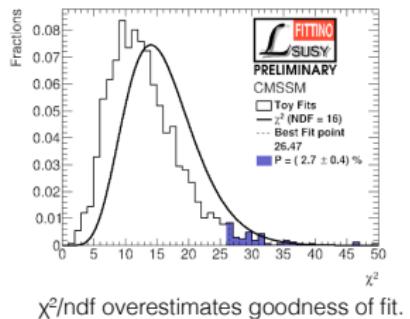
Limits: 2012 vs 2014



From CMS: [CMS-SUS-12011: arXiv:1207.1898](#)

Fittino

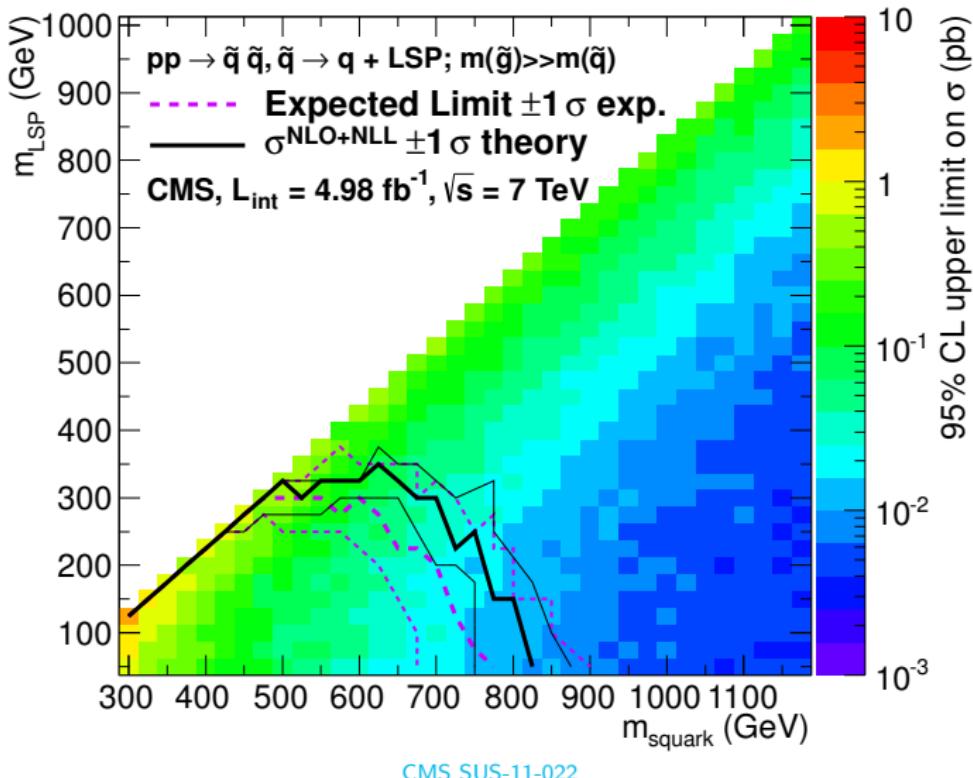
World's first *very preliminary!*
p-value for the CMSSM



χ^2/ndf overestimates goodness of fit.

From Björn Sarrazin: [ICHEP, SUSY14](#)

Simplified Models: for general limits

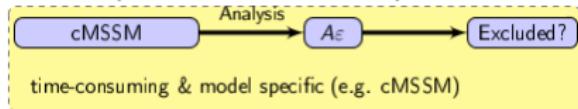


Can we translate this to limits for e.g. the MSSM?

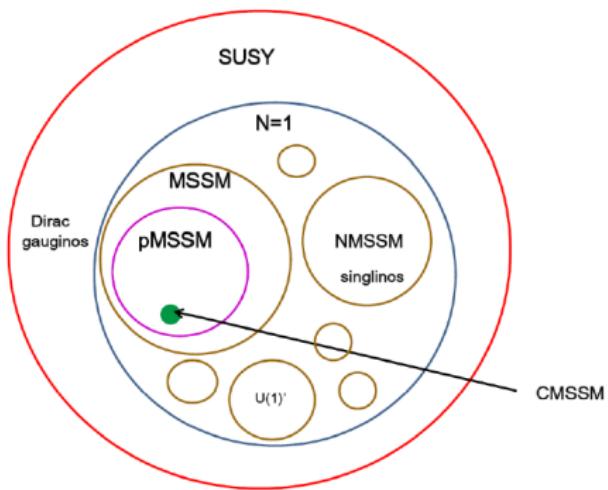
Simplified Models: Why?

Or, use simplified modules:

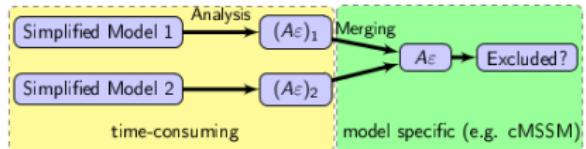
Usual (time-consuming) approach:



SUSY Theory phase space

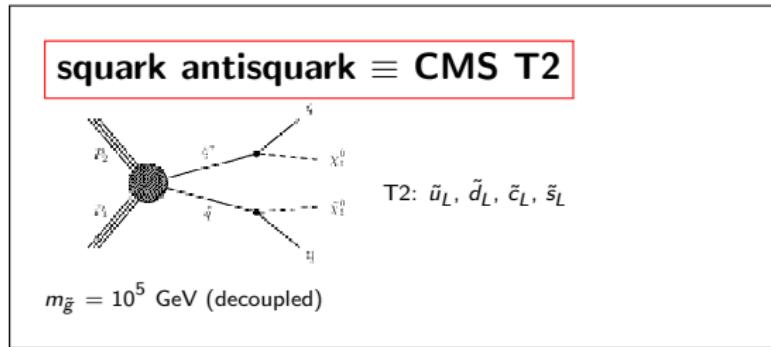


T. Rizzo (SLAC Summer Institute, 01-Aug-12)



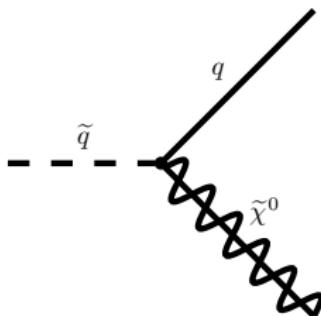
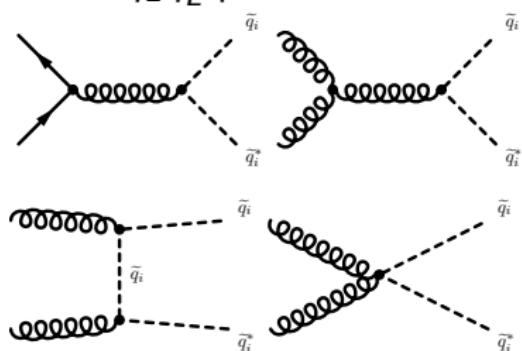
model name	prod. mode	decay	visibility
T1	$\tilde{g} \tilde{g}$	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0$	hadronic
T2	$\tilde{q} \tilde{q}^*$	$\tilde{q} \rightarrow q\tilde{\chi}^0$	hadronic
T1zz	$g g$	$g \rightarrow q\bar{q}\tilde{\chi}^0$ di-leptons multi-leptons	hadronic di-leptons multi-leptons
T3w	$\tilde{g} \tilde{g}$	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0$ $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^\pm, \tilde{\chi}^\pm \rightarrow W^\pm \tilde{\chi}^0$	single lepton
T5lnu	$\tilde{g} \tilde{g}$	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^\pm, \tilde{\chi}^\pm \rightarrow \ell\nu\tilde{\chi}^0$	di-leptons
T3lh	$g g$	$g \rightarrow q\bar{q}\tilde{\chi}^0$ $\tilde{g} \rightarrow q\bar{q}\ell^\pm \ell^- \tilde{\chi}^0$	di-leptons
T2bb	$b b^*$	$b \rightarrow b \tilde{\chi}^0$	hadronic
T2tt	$t t^*$	$t \rightarrow t \tilde{\chi}^0$	hadronic
T1bbbb	$\tilde{g} \tilde{g}$	$\tilde{g} \rightarrow b \bar{b} \tilde{\chi}^0$	hadronic
T1tttt	$g g$	$\tilde{g} \rightarrow t \bar{t} \tilde{\chi}^0$	hadronic(b) single-leptons(b) di-leptons(b) inclusive(b)
TChiSlepSlep	$\tilde{\chi}_2^{\pm} \tilde{\chi}_2^0$	$\tilde{\chi}_2^0 \rightarrow \ell^\pm \ell^\mp, \ell \rightarrow \ell \tilde{\chi}^0$ $\tilde{\chi}_2^\pm \rightarrow v \bar{v}, \bar{v} \rightarrow \ell \tilde{\chi}^0$	multi-leptons
TChiwz	$\tilde{\chi}_2^{\pm} \tilde{\chi}_2^0$	$\tilde{\chi}_2^{\pm} \rightarrow W^\pm \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}^0$	multi-leptons
TChizz	$\tilde{\chi}_2^0 \tilde{\chi}_3^0$	$\tilde{\chi}_2^0 \tilde{\chi}_3^0 \rightarrow Z \tilde{\chi}^0$	multi-leptons
T5gg	$\tilde{g} \tilde{g}$	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$	photons
T5Wg	$\tilde{g} \tilde{g}$	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$ $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^\pm, \tilde{\chi}^\pm \rightarrow W^\pm \tilde{\chi}_1^0$	photons

A simplified model: T2



CMS SUS-11-016; arXiv:1301.2175 (CMS Simplified Models)

$\tilde{q}_L \tilde{q}_L^*$ production:

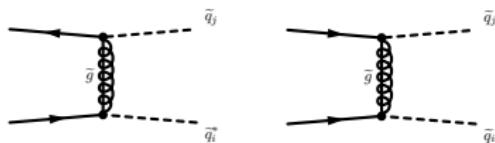


one decay (100% Br. - no mixing!)

What T2 is not

Not included in T2:

- right-handed squarks \tilde{q}_R
- gluinos, resulting in production:

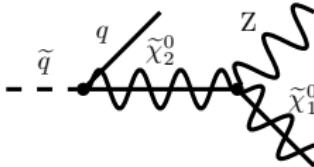
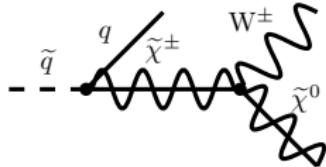


→ Effect on limits when including:

- production channels like $\tilde{q}_L \tilde{q}_L$, $\tilde{q}_L \tilde{q}_R$, $\tilde{q}_L \tilde{q}_R^*$;
- a non-decoupled gluino?

Not included in T2, not considered here:

- decays such as



no mixing!

Limits for MSSM-like model

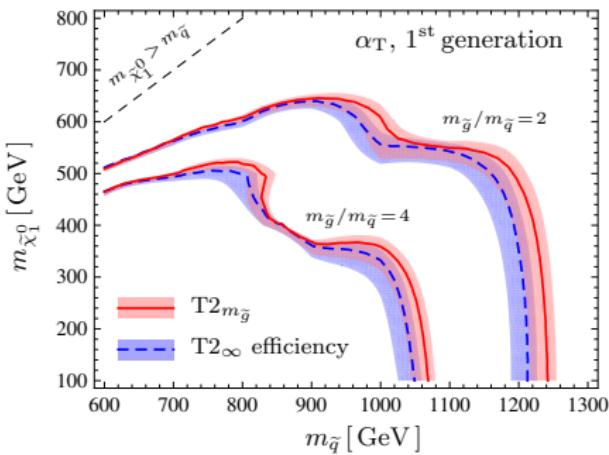
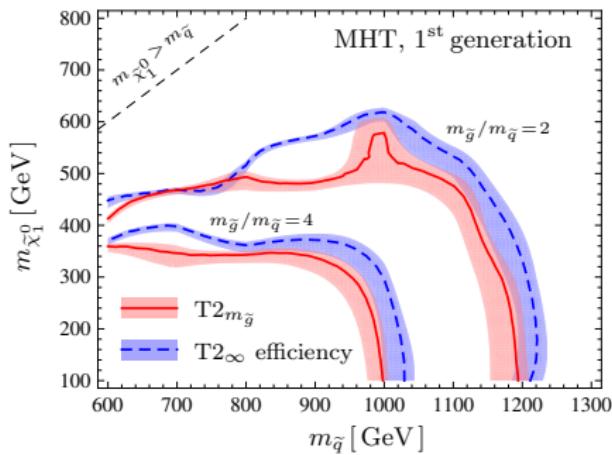
A_{ε} : % events left after cuts

- **MSSM-like:** Limits using (correct) $\sigma \equiv A_{\varepsilon} \times$ cross section:

$$2\sigma_{\tilde{q}_L\tilde{q}_L} + 2\sigma_{\tilde{q}_L\tilde{q}_L^*} + \sigma_{\tilde{q}_L\tilde{q}_R} + 2\sigma_{\tilde{q}_L\tilde{q}_R^*}$$

- **T2:** Limits using (incorrect) A_{ε} from simplified model T2

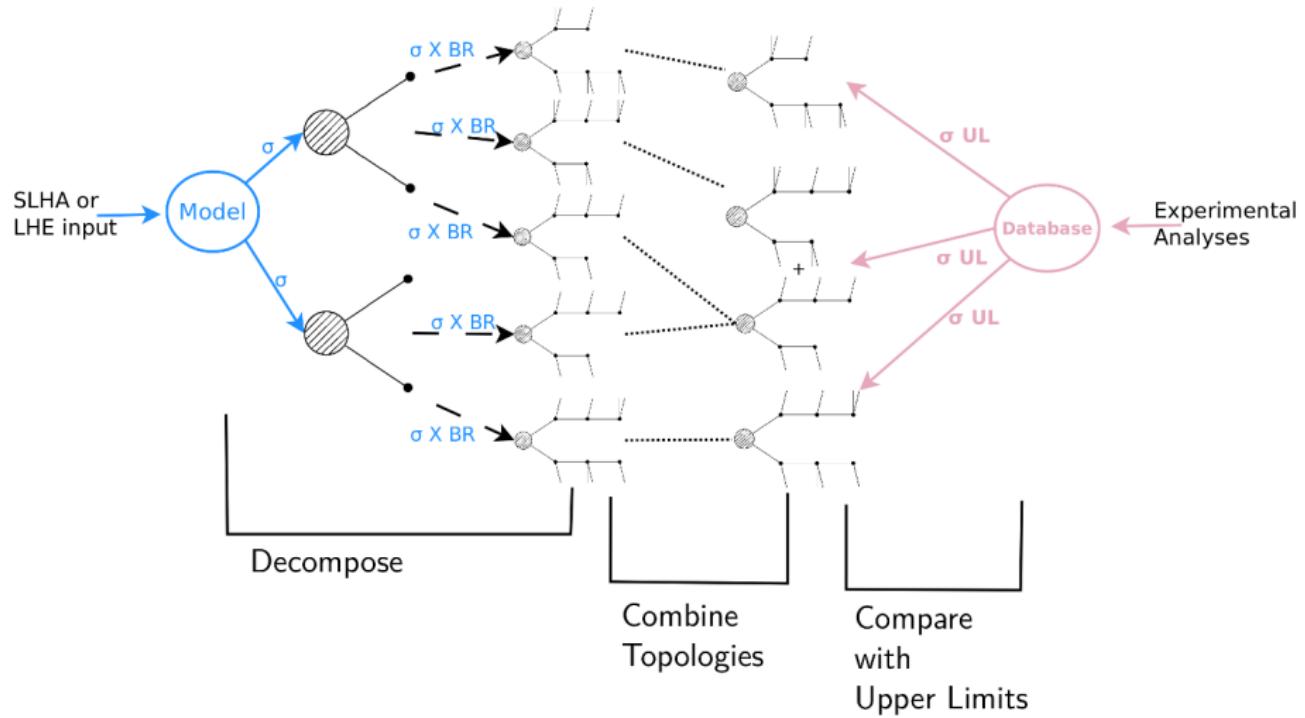
arXiv:1410.0965



CMS SUS-13-012: arXiv:1402.4770

CMS SUS-12-028: arXiv:1303.2985

SModelS: translating simplified model limits



arXiv:1312.4175

Sabine Kraml et al.

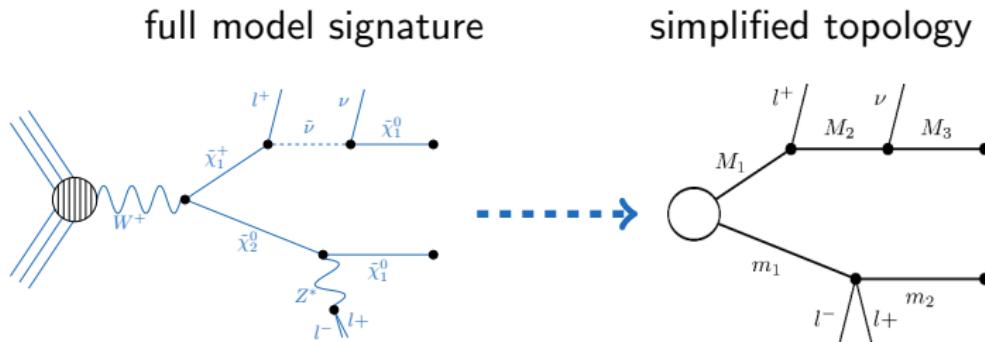
Jory Sonneveld (RWTH Aachen)

Limits and Fits from Simplified Models

Physics at the Terascale, 2014

8 / 15

SModelS: simplifies topologies



- requires a \mathbb{Z}_2 symmetry (R-parity, KK-parity) resulting in pair production and \cancel{E} ;
- ignores color and spin.

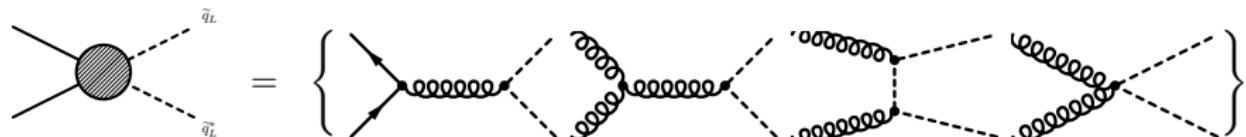
SModelS arXiv:1312.4175

Sabine Kraml et al.

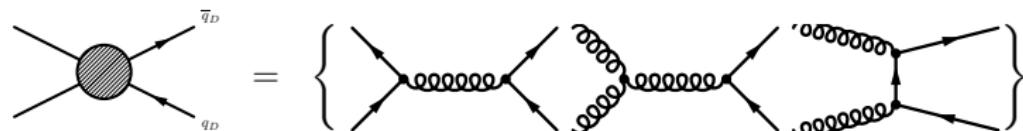
SModelS website

Same-spin models

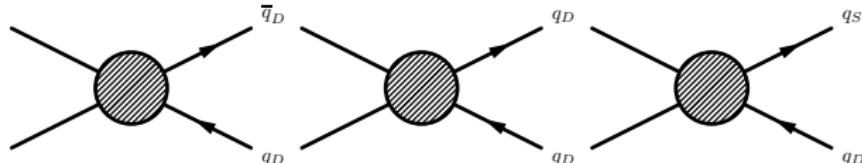
SUSY



Same-spin Model (as SM)



Same-spin production modes (UED):

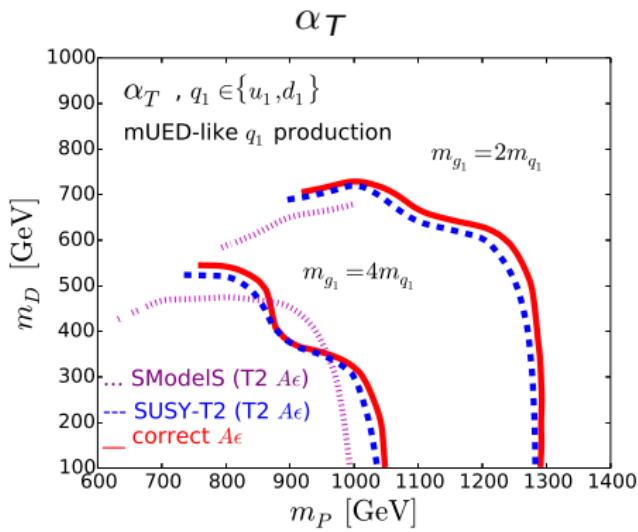
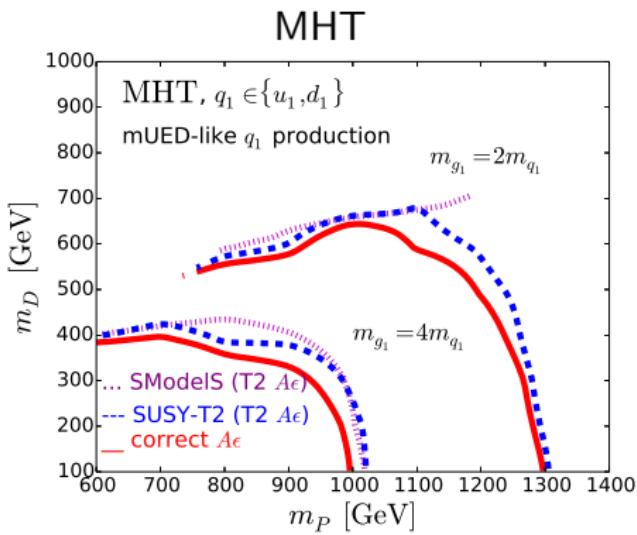


q_D/q_S : first KK mode SU(2) doublet/singlet quark

[in preparation] Limits: UED-like model

$$\text{UED-like} = 2(q_D q_D + q_D \bar{q}_D + q_D \bar{q}_S) + q_D q_S.$$

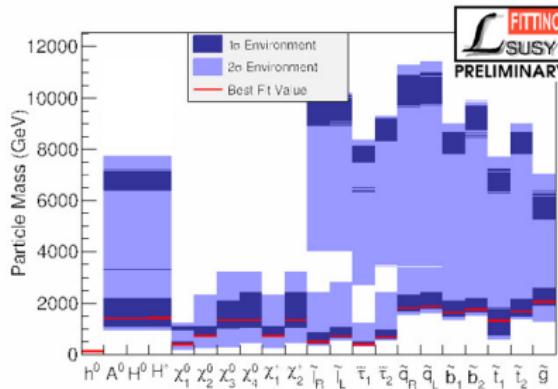
$q_{D(S)}$: first KK mode SU(2) doublet (singlet) quark



Global Fits

Example: Fittino results for cMSSM sparticle masses

Predicted mass spectrum



- squark and gluino masses at best fit point about 2 TeV
- But now also masses of 10 TeV allowed at 1 sigma

From Björn Sarrazin: [ICHEP, SUSY14](#)

Fittino: [arXiv:1204.4199](#)

Fittino: 1 analysis only

Higgs boson properties and searches

- Higgs limits via `HiggsBounds`
- Higgs signals via `HiggsSignals`

Direct sparticle searches

- LEP chargino mass limit
- ATLAS MET + jets + 0 lepton search (20fb^{-1})

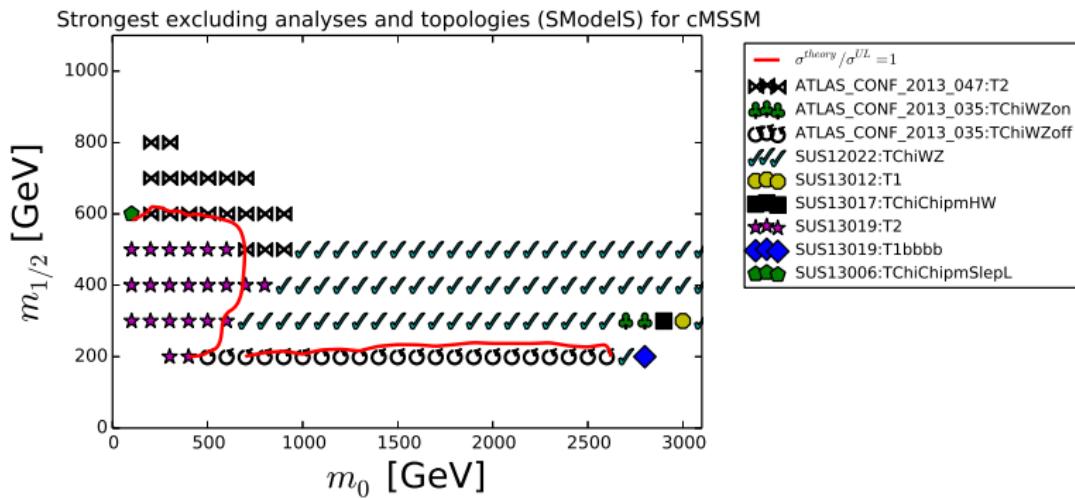
Astrophysical observables

- We require χ_1^0 to be the LSP
- $\Omega_{\text{CDM}} h^2 = 0.1187 \pm 0.0017 \pm 0.0119_{\text{theo}}$ (Planck '13)
- Direct detection limit from LUX

From Björn Sarrazin: [ICHEP, SUSY14](#)

SModelS: which analyses are where important?

[Preliminary]



Goal: use SModelS to

- Determine regions of analyses for input of χ^2
- Calculate χ^2 for more general models
- Combine analyses using likelihoods

Summary and Future work

Simplified models are a good approximation in limit setting

- for a general SUSY model such as the MSSM; [arXiv:1410.0965](https://arxiv.org/abs/1410.0965)
- for same-spin models [in preparation].

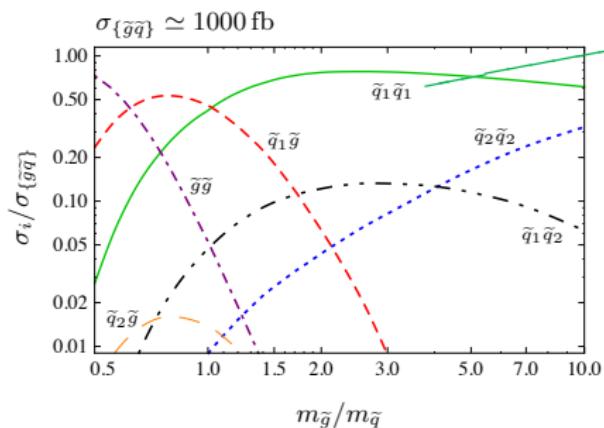
Accuracy is analysis dependent, but can indicate interesting search regions.

Next, collaborate with [SModels](#) for:

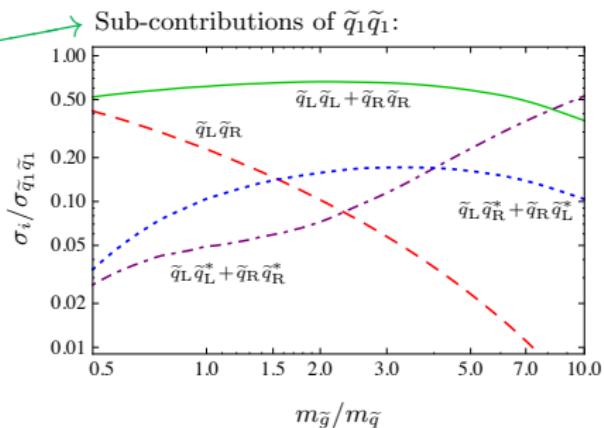
- Global fit of the cMSSM
- Global fit of a more general SUSY model
- Combining analyses

Backup

Squark production



1st and 2nd generation



1st generation

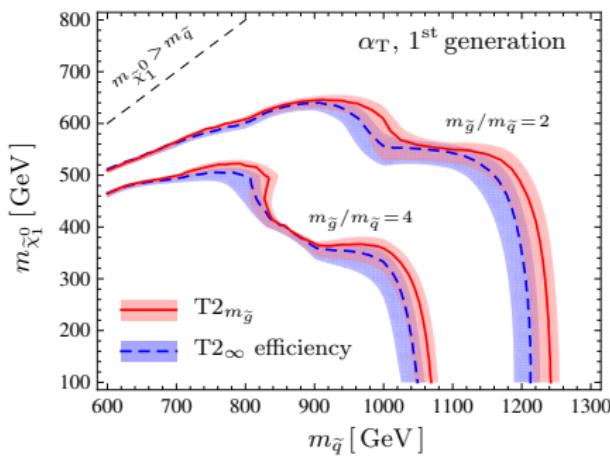
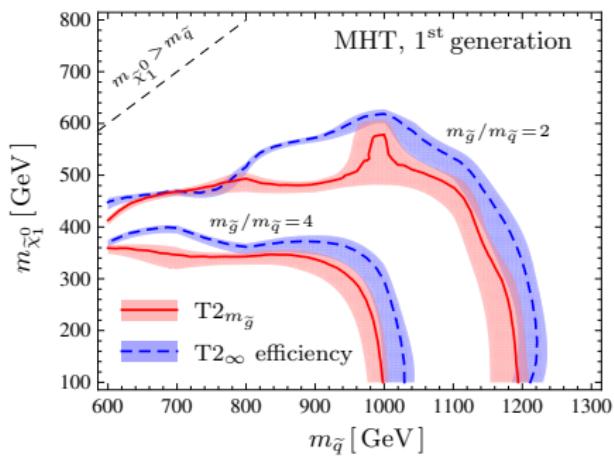
Limits MSSM-like vs T2, 1st generation

- **MSSM-like:** Limits using (correct) $\sigma \equiv A_\varepsilon \times$ cross section:

$$2\sigma_{\tilde{q}_L\tilde{q}_L} + 2\sigma_{\tilde{q}_L\tilde{q}_L^*} + \sigma_{\tilde{q}_L\tilde{q}_R} + 2\sigma_{\tilde{q}_L\tilde{q}_R^*}$$

- **T2:** Limits using (incorrect) A_ε from T2

arXiv:1410.0965



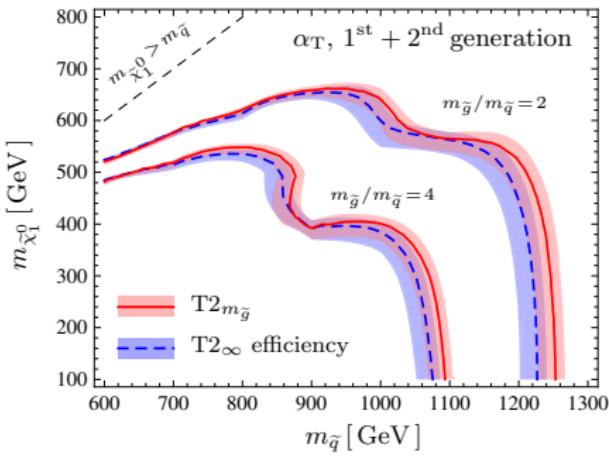
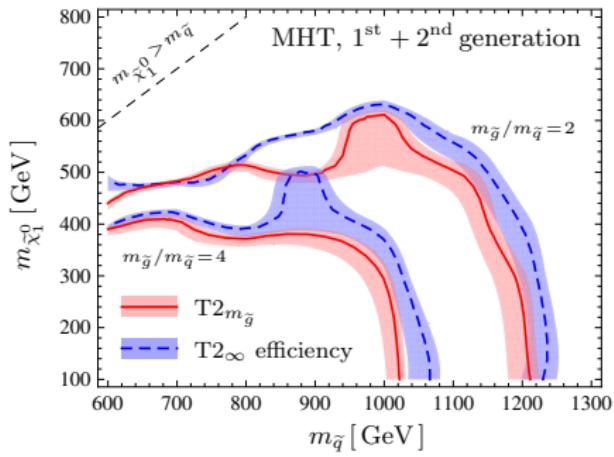
Limits MSSM-like vs T2, all light squarks

- **MSSM-like:** Limits using (correct) $\sigma \equiv A_\varepsilon \times$ cross section:

$$2\sigma_{\tilde{q}_L\tilde{q}_L} + 2\sigma_{\tilde{q}_L\tilde{q}_L^*} + \sigma_{\tilde{q}_L\tilde{q}_R} + 2\sigma_{\tilde{q}_L\tilde{q}_R^*}$$

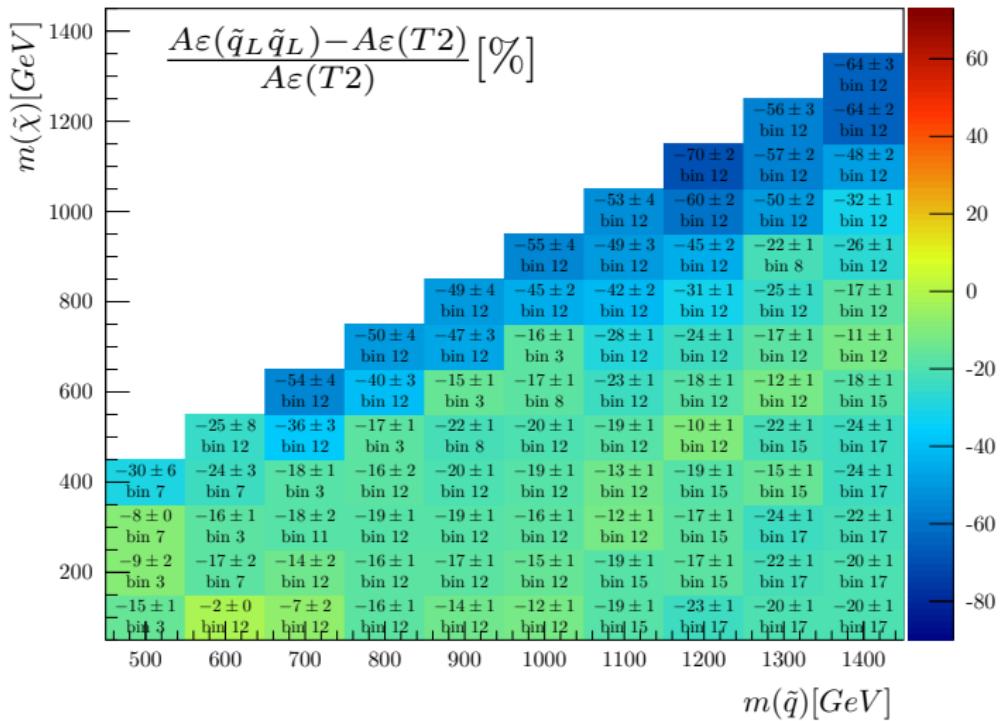
- **T2:** Limits using (incorrect) A_ε from T2

arXiv:1410.0965



$A\varepsilon$ differences: \mathcal{H}_T

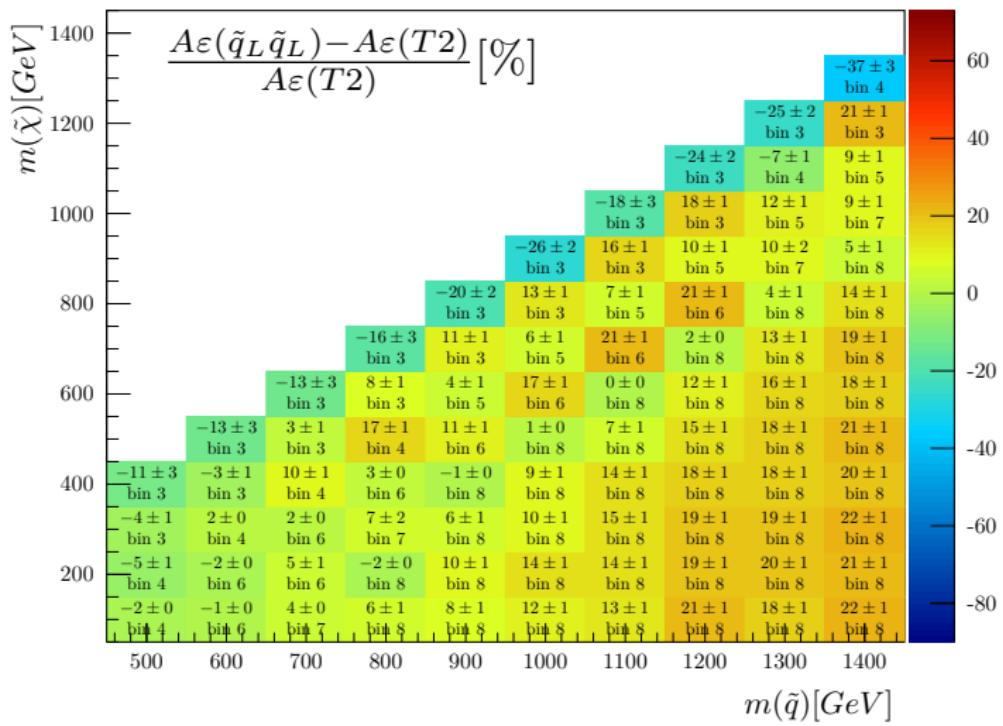
$$pp \rightarrow \tilde{q}_L \tilde{q}_L \ m(\tilde{g}) = 2m(\tilde{q})$$



arXiv:1410.0965

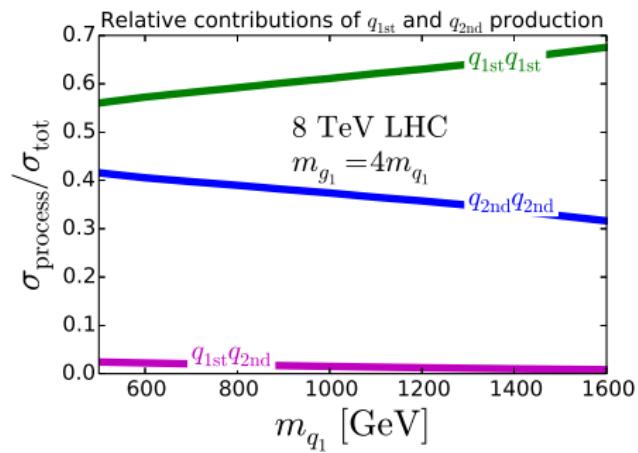
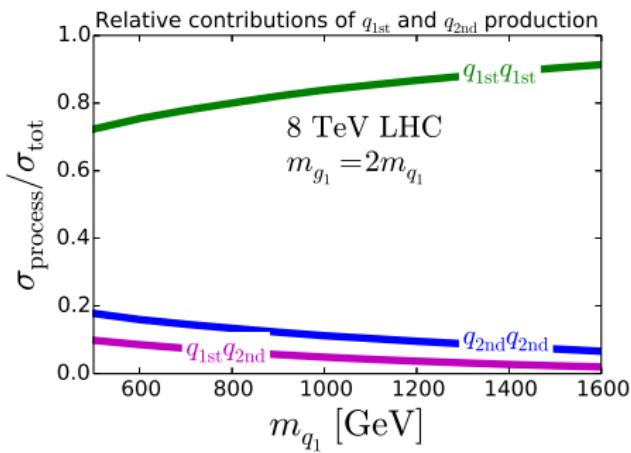
$A\varepsilon$ differences: α_T

$$pp \rightarrow \tilde{q}_L \tilde{q}_L \ m(\tilde{g}) = 2m(\tilde{q})$$

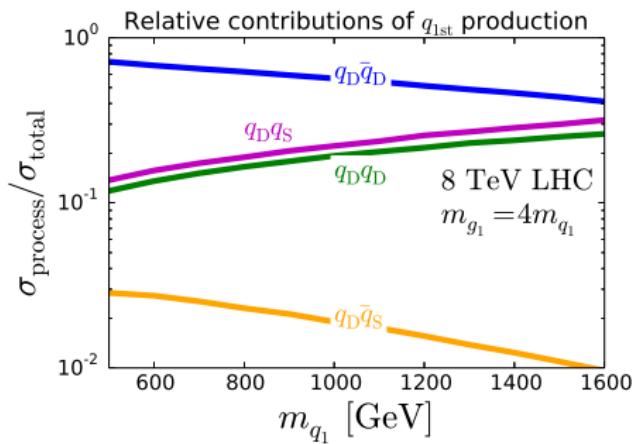
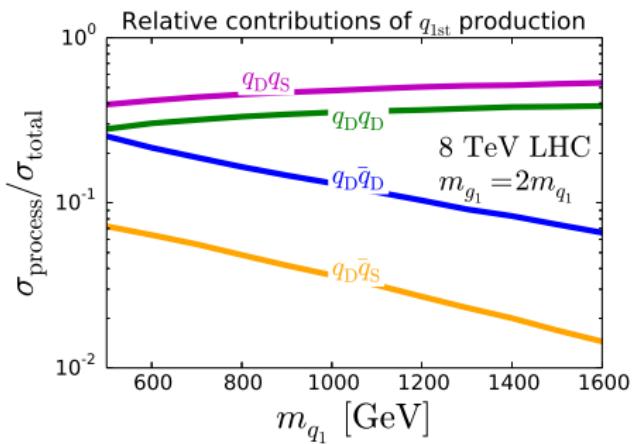


arXiv:1410.0965

[in preparation] KK quark production



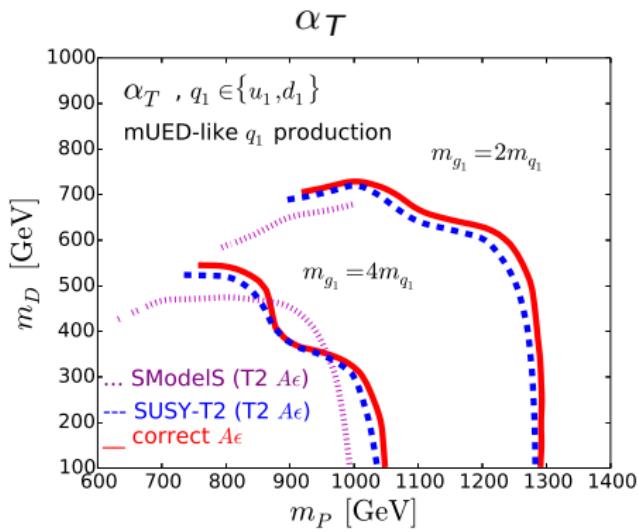
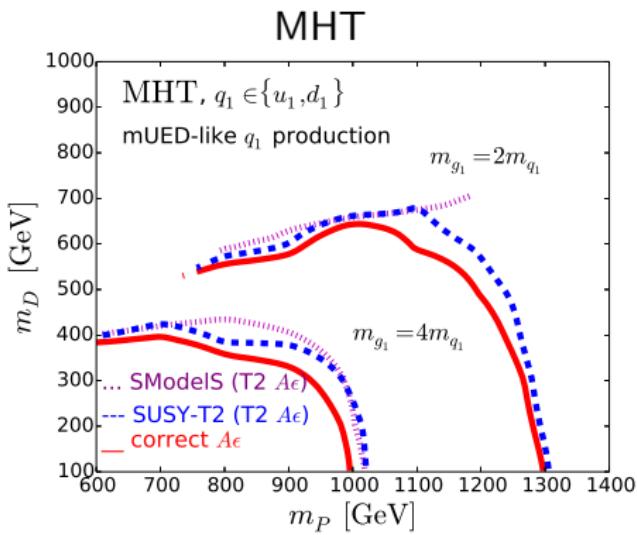
[in preparation] KK quark production (first generation)



[in preparation] Limits: UED-like model

$$\text{UED-like} = 2(q_D q_D + q_D \bar{q}_D + q_D \bar{q}_S) + q_D q_S.$$

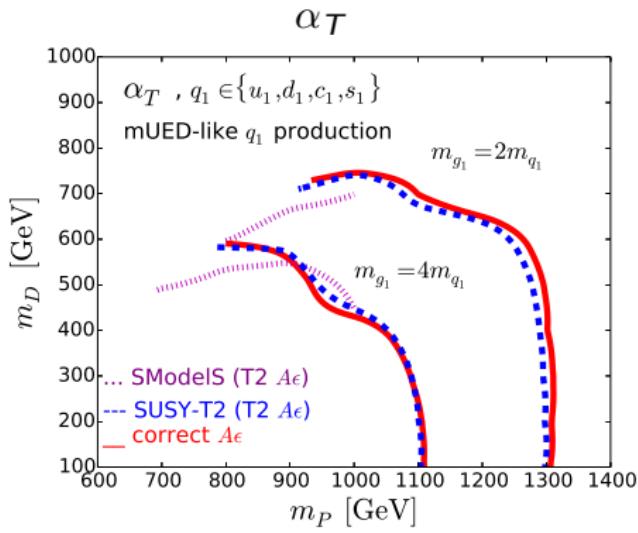
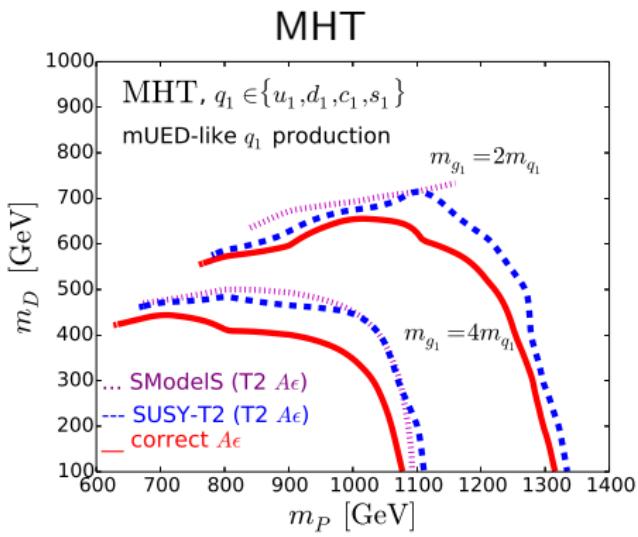
$q_{D(S)}$: first KK mode SU(2) doublet (singlet) quark



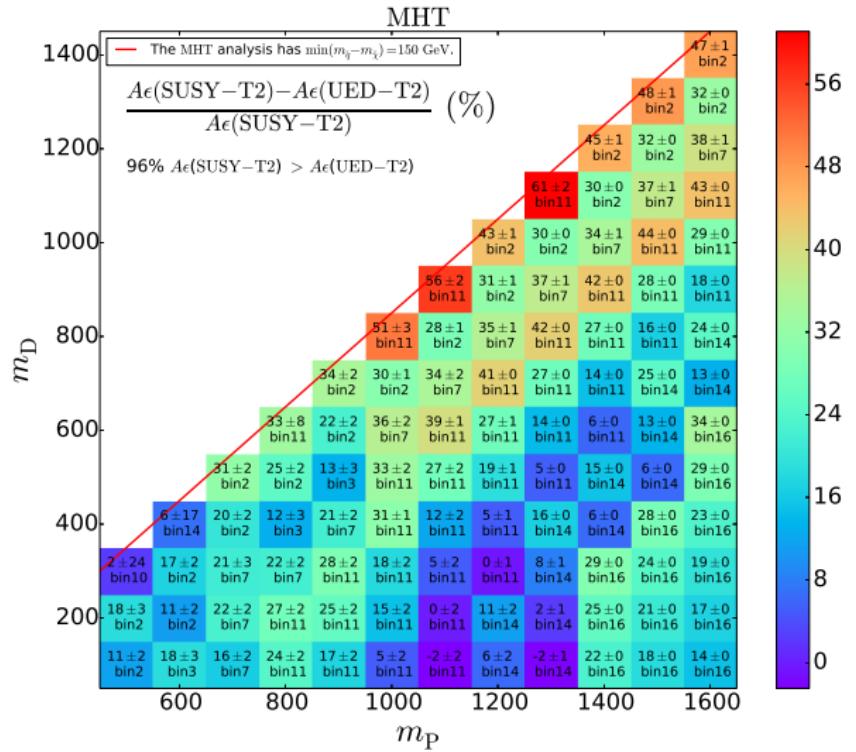
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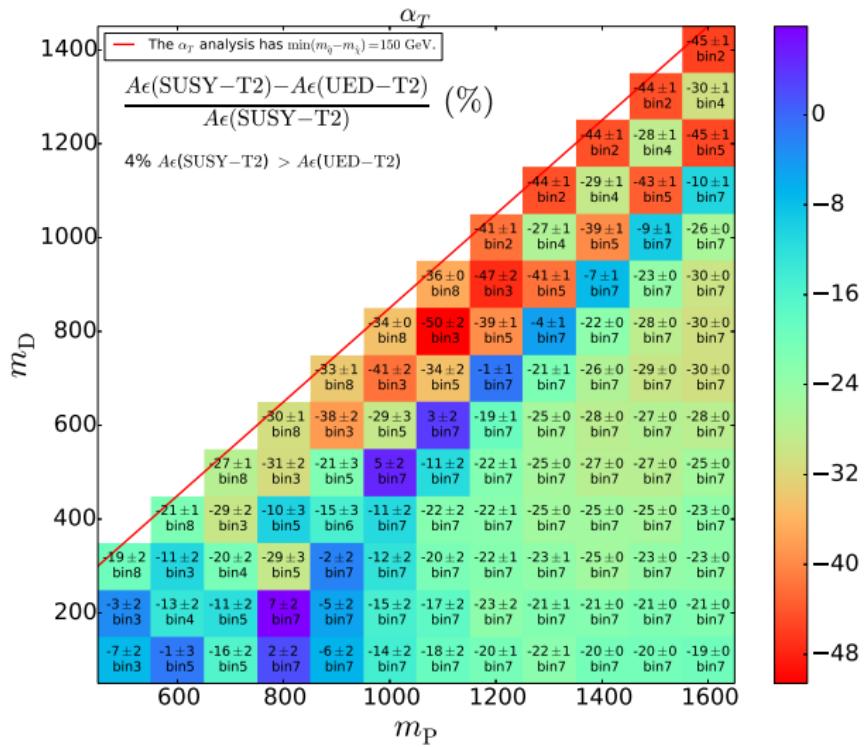
$q_{D(S)}$: first KK mode SU(2) doublet (singlet) quark



[in preparation] UED-T2 vs SUSY-T2, MHT



[in preparation] UED-T2 vs SUSY-T2, α_T



α_T variable

2 jets

$$\alpha_T = \frac{E_T^{j_2}}{M_T}$$

$$M_T = \sqrt{\left(\sum_{i=1}^2 E_T^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_x^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_y^{j_i}\right)^2}$$

> 2 jets

Combination of jets into two pseudojets minimizing $|E_T|$ difference between pseudojets:

$$\alpha_T = \frac{1}{2} \times \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not{H}_T^2}} = \frac{1}{2} \times \frac{1 - (\Delta H_T / H_T)}{\sqrt{1 - (\not{H}_T / H_T)^2}}$$

$$H_T = \sum_{i=1}^{n_{\text{jet}}} E_T^{j_i}$$

$$\not{H}_T = |\sum_{i=1}^{N_{\text{jet}}} \not{p}_T^{j_i}|$$

The α_T analysis

CMS SUS-12-028: arXiv:1303.2985

- Jets are required to have $E_T > 50$ GeV $|\eta| < 3.0$;
- Events with electron or muon $p_T > 10$ GeV are vetoed;
- Events with photon $p_T > 25$ GeV are vetoed;
- The highest- E_T jet must have $|\eta| < 2.5$;
- The two highest- E_T jets must have $E_T > 100$ (73 and 87 GeV for bin 0 and bin 1, resp.);
- Events with any additional jet having $E_T > 50$ and $|\eta| > 3$ are vetoed;
- Events must have $H_T > 275$ GeV;
- It is required that $H_T/\cancel{E}_T < 1.25$;
- $\alpha_T < 0.55$;
- For focus on T2, events are required to have 0 b quarks and 2-3 jets.

8 bins in H_T :

- 2 bins of width 50 GeV in $275 < H_T < 375$ GeV;
- 5 bins of width 100 GeV in $375 < H_T < 875$ GeV.
- 1 bin with $H_T > 875$ GeV.

The \cancel{H}_T analysis

CMS SUS-13-012: arXiv:1402.4770

- Jets are required to have $p_{T,j} > 30$ GeV and $|\eta_j| < 5$;
- Events must contain 3 jets with $p_T > 50$ GeV and $|\eta| < 2.5$;
- An azimuthal angle difference between a jet axis and the \cancel{H}_T direction $|\Delta\phi(J_n, \cancel{H}_T)| > 1.5$ rad, $n = 1, 2$ and $|\Delta\varphi(J_3, \cancel{H}_T)| > 0.3$ rad, with J_n the jet axis of jet n and n indicating the ranking of the jet in p_T from highest to lowest
- No isolated muons or electrons:
 - $p_T > 10$ GeV for muons and electrons;
 - $|\eta| < 2.4$ for muons;
 - $|\eta| \leq 1.44$ or $1.57 \leq |\eta| < 2.5$ for electrons;
- $H_T > 500$ GeV;
- $\cancel{H}_T > 200$ GeV;
- Events should contain 3-5 jets.

17 bins in H_T and \cancel{H}_T and 3-5 jets:

- 500-800, 800-1000, and 1000-1250 GeV in H_T , and 200-300, 300-450, 450-600, and > 600 GeV for \cancel{H}_T (bins 0-11, resp.);
- 1250-1500 GeV in H_T with \cancel{H}_T binned into 200-300, 300-450, and > 450 GeV (bins 12-14, resp.);
- > 1500 GeV in H_T with \cancel{H}_T binned into 200-300 and > 300 GeV (bins 15-16, resp.).

Limits for combined models

Combining models A and B:

$$A\varepsilon_{\text{combined}} = \frac{\sigma_A (A\varepsilon)_A + \sigma_B (A\varepsilon)_B}{\sigma_A + \sigma_B}$$

Events passed for A and B combined:

$$N = (\sigma_A + \sigma_B) \times A\varepsilon_{\text{combined}} \times \mathcal{L}$$

MSSM-like squark production

$$\text{MSSM - like} = 2\widetilde{q}_L\widetilde{q}_L + 2\widetilde{q}_L\widetilde{q}_L^* + \widetilde{q}_R\widetilde{q}_R + 2\widetilde{q}_R\widetilde{q}_R^*.$$

for $\widetilde{q}_L\widetilde{q}_L \equiv \sigma_{\widetilde{q}_L\widetilde{q}_L} \times A\varepsilon_{\widetilde{q}_L\widetilde{q}_L}$ and $m_{q_L} = m_{q_R}$ so that $\widetilde{q}_L\widetilde{q}_L = \widetilde{q}_R\widetilde{q}_R$.

Use SModelS for χ^2 to fit

Fittino:

$$\chi_{\text{bound}}^2 = \sum_{i=1}^{N_{\text{bound}}} \left(\frac{O_{\text{limit}}^i - O_{\text{pred}}^i(\vec{P})}{\sigma^i} \right)^2$$

parameters
(e.g. masses)

Upper limit from experiment Theory prediction of signal

- Want: O_{limit}^i
- Available in SModelS: σ_{obs}^{UL} and σ_{exp}^{UL}

Then for one given limit:

$$\text{SModelS : } \chi_{\vec{P}}^2 = \left(\frac{\sigma_{\text{pred}}^{\text{theo}}(\vec{P}) - \sigma(\sigma_{\text{obs}}^{UL}, \sigma_{\text{exp}}^{UL})}{\omega(\sigma_{\text{obs}}^{UL}, \sigma_{\text{exp}}^{UL})} \right)^2 ,$$

Gaussian approximation of likelihood

[Based on Azatov, Contino and Galloway: [arXiv:1202.3415](https://arxiv.org/abs/1202.3415)]

- Approximate likelihood: $\sigma = \frac{n - b}{\mathcal{L}}$, $\omega = \frac{\sqrt{n}}{\mathcal{L}}$:

$$p(\sigma_{\text{pred}}^{\text{theo}} | \sigma_{\text{obs}}^{\text{UL}}, \sigma_{\text{exp}}^{\text{UL}}) \propto e^{-(\sigma_{\text{pred}}^{\text{theo}} - \sigma)^2 / (2\omega^2)}.$$

(\mathcal{L} = luminosity, n = observed data, b = background)

- σ : deviation of n from b
- solve by requiring 95% CL:

$$0.95 = \int dx \ p(x | \sigma_{\text{obs}}^{\text{UL}}) \simeq \frac{\int_0^{\sigma_{\text{obs}}^{\text{UL}}} dx \ e^{-\frac{(x-\sigma)^2}{2\omega_{\text{obs}}^2}}}{\int_0^{\infty} dx \ e^{-\frac{(x-\sigma)^2}{2\omega_{\text{obs}}^2}}}.$$

- σ_{exp} from $\sigma_{\text{exp}}^{\text{UL}}$ as above, $n = b \rightarrow \sigma = 0 \rightarrow \frac{\sigma_{\text{exp}}^{\text{UL}}}{1.96}$.
- approximate $\sigma_{\text{obs}} \approx \sigma_{\text{exp}}$