Next-to-minimal Gauge Mediation and Displaced Vertices

by

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- NMGMSB Scenario
- LHC Limits
- Run II Prospects

Motivation

Gauge mediation is nice because of *predictivity in soft breaking terms* and desirable *flavour properties*. However, when embedded in the MSSM, it typically predicts m_h too low. Also, $B/\mu \sim F/M$ is too large by 1/loop factor.

A mGMSB scan[1] (10 TeV$\leq \Lambda \leq 1000$ TeV, 1$\leq M/\Lambda \leq 10^{11}$, $1 \leq \tan\beta \leq 60$, $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} < 3$ TeV) yields

$$m_h < 118 \text{ GeV}.$$

$\mathcal{Q}$: Can the NMSSM help?

[1] Arbey, Battaglia, Djouadi, Mahmoudi, PLB 708 (2012) 162, arXiv:1112.3028

NMGMSB

Z_3 NMSSM superpotential

$$W_N = \lambda N H_d H_u - \frac{k}{3} N^3$$

forbids bare μ term. Effective μ and B terms now generated by low energy dynamics: $\mu = \lambda < N >$, $B = \lambda < F_N > \sim < N >^2$, evading B/μ problem.

However, in NMGMSB[2]: $< N >$ is too small because we need $m_N^2 < 0$ or large trilinears. Thus, electroweak symmetry does not break correctly.

[2] Dine, Nelson, PRD48 (1993) 1277, arXiv:hep-ph/9303230

DGS Model

To fix this, DGS proposed[3] a NMGMSB model with $5_i \oplus \bar{5}_i = \Phi_i + \bar{\Phi}_i$ messengers of $SU(5)$.

$$W_\Phi = \kappa X \sum_{i=1}^{2} \bar{\Phi}_i \Phi_i + \xi N \bar{\Phi}_i \Phi_i + W_N,$$

where $X = M + \theta^2 F$ is a background non-dynamical field.

Once the messengers are integrated out, this yields one-loop A_λ, A_k and two-loop m_N^2, yielding successful SUSY breaking.

[3] Delgado, Giudice, Slavich, PLB 653 (2007) 424, arXiv:0706.3873

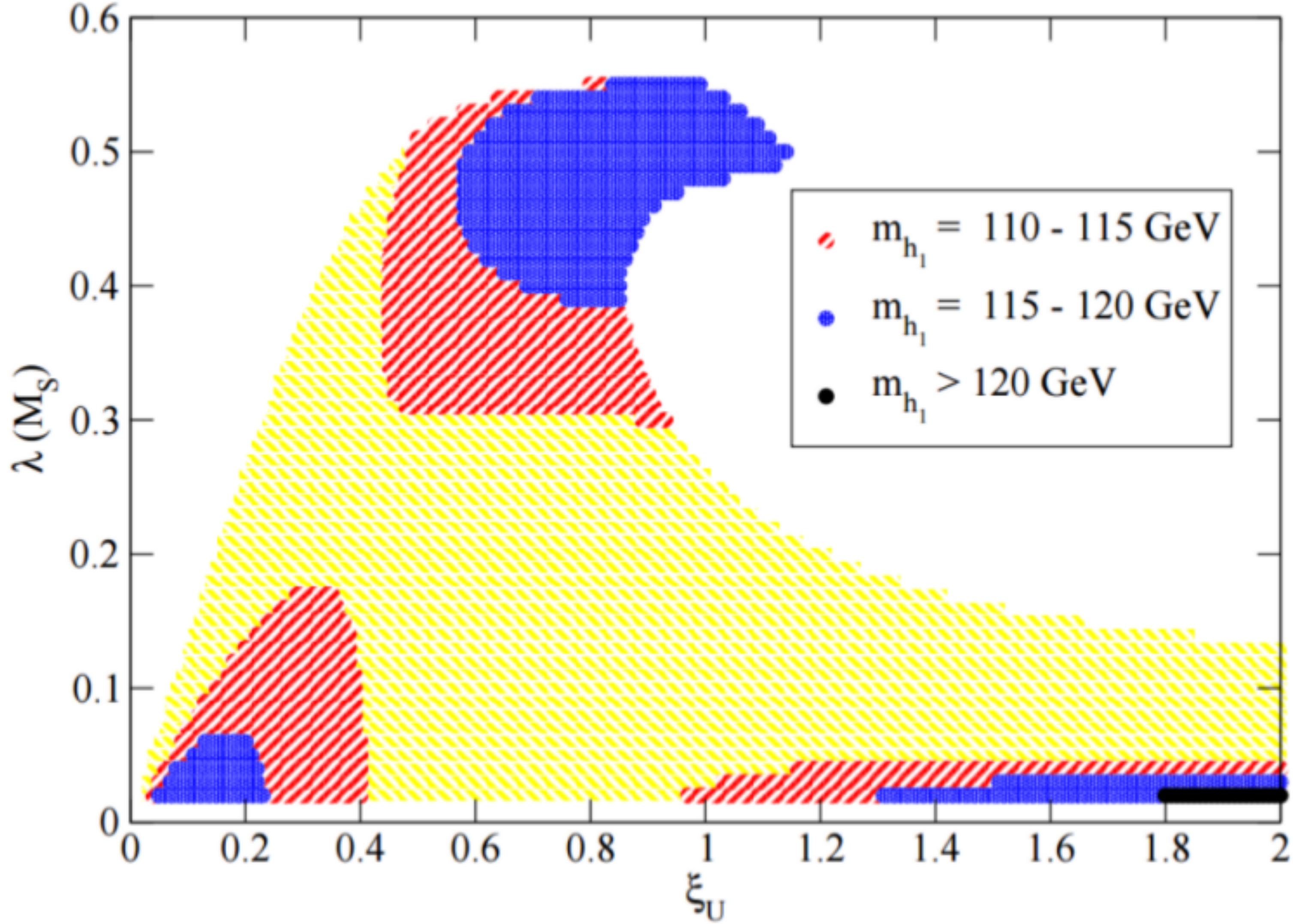


Figure 2: Mass of the lightest CP-even Higgs boson h_1 in the $\xi_U - \lambda(M_S)$ plane, for $M = 10^{13}$ GeV and $F/M = 1.72 \times 10^5$ GeV.

Post Higgs Discovery [4]

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m_{mix}^2 + m_{loop}^2.$$

m_{mix} comes from mixing terms with other two CP-even Higgs states. Can reach up to $m_h^2 - m_{loop}^2 \approx (99 \text{ GeV})^2$ for large $\tan\beta$ if the mixing contribution is large and positive⇒the singlet state is lighter than the SM-like Higgs.

[4] BCA, Badziak, Hugonie, Ziegler, PRD 92 (2015) 015006, arXiv:1502.05836.

Maximising Tree m_{h_2}

Fixes $m_{h_1} \approx 94$ GeV and the singlet-Higgs mixing $\cos\theta \approx 0.88$. Neglecting RG effects and expanding EWSB conditions in terms of large $< N >$,

$$\xi \sim \frac{m_{h_1}}{4\sqrt{2} g_3 \tilde{m}} \sim .01, \qquad \lambda \sim \frac{m_{h_2}^2 - m_{h_1}^2}{4 v \tilde{m}} \sin 2\theta \sim .01,$$

where $\tilde{m} = F/(16\pi^2 M)$.

Small $\lambda, \xi \Rightarrow$ small $|A_\lambda| = |A_\kappa|/3 = \tilde{m}(2\xi_D^2 + \xi_T^2)$.

A Light Pseudoscalar/Singlino

EWSB$\Rightarrow \kappa \ll \lambda$ and large $\tan\beta \sim \lambda/\kappa$. Small A_κ and $\kappa \Rightarrow$ light pseudoscalar

$$m_{a_1} \sim \sqrt{\frac{45\sqrt{8}\xi}{32 g_3}} m_{h_1} \in \{20,\ 40\} \text{ GeV}.$$

$$m^2_{\tilde{S}} \approx m^2_{h_1} + \frac{1}{3} m^2_{a_1} \sim 100 \text{ GeV}.$$

LSP is gravitino, NLSP is dominantly singlino.

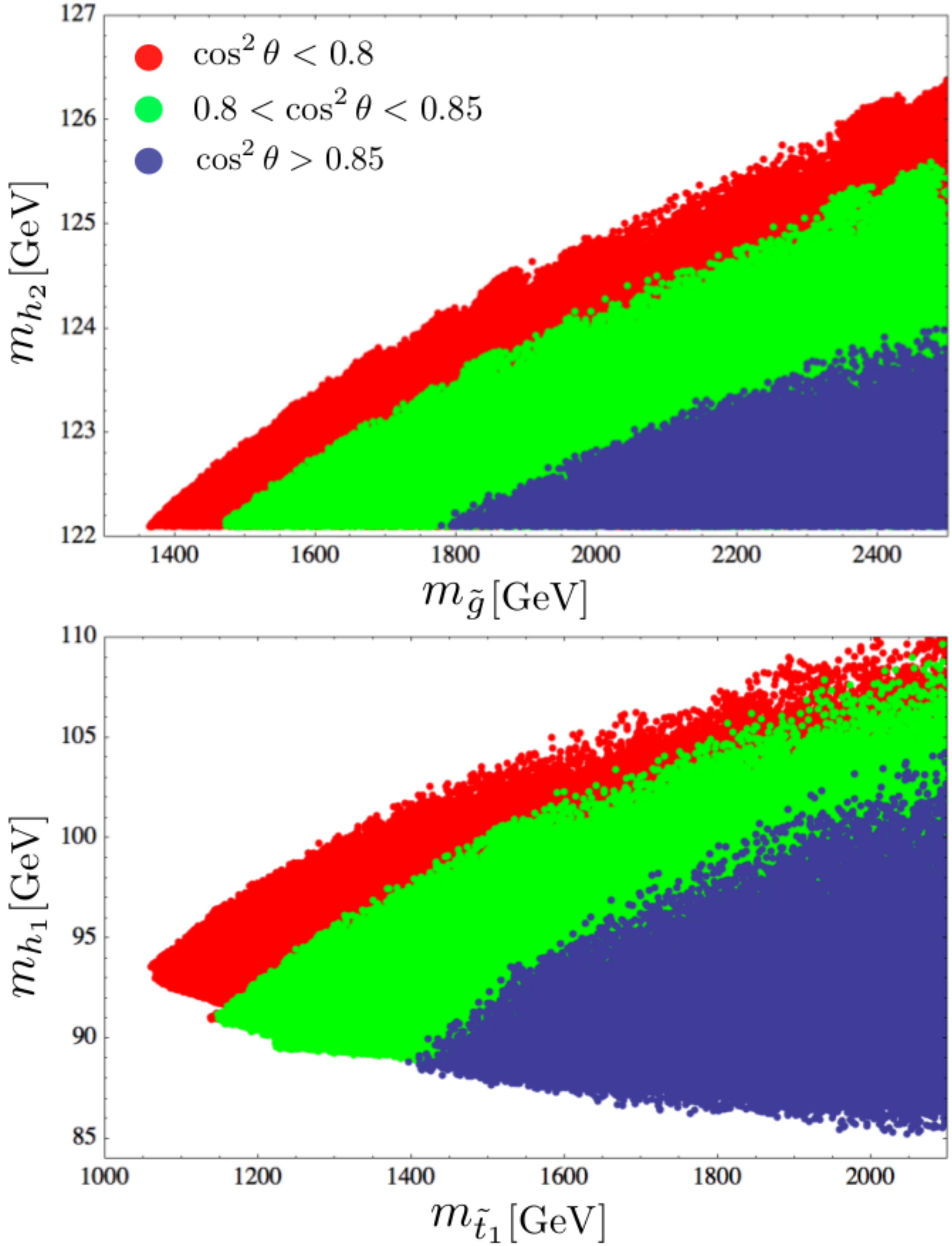
Higgs Properties

For $m_{h_1} \sim 98$ GeV, we explain a small 2σ excess in the LEP II Higgs search, which has a reduced coupling to the Z^0 boson.

Stop masses can be lighter and still get $m_{h_2} \sim 125$ GeV because of the singlet-Higgs mixing.

$\{\xi,\ \lambda,\ \tilde{m}\}$ fixed by setting $\{m_{h_1},\ m_{h_2},\ \theta\}$. Leaves messenger scale M.

For numerical analysis, we use `NMSSMTools`, checked with `SOFTSUSY3.4.1`.


$\cos^2\theta < 0.8$
$0.8 < \cos^2\theta < 0.85$
$\cos^2\theta > 0.85$
m_{h_2} [GeV]
127
126
125
124
123
122
1400
1600
1800
2000
2200
2400
$m_{\tilde{g}}$ [GeV]
m_{h_1} [GeV]
110
105
100
95
90
85
1000
1200
1400
1600
1800
2000
$m_{\tilde{t}_1}$ [GeV]

Messenger scale M

$$m_{3/2} = 38 \text{ eV} \left(\frac{\tilde{m}}{\text{TeV}}\right) \left(\frac{M}{10^6 \text{ GeV}}\right).$$

- $M \stackrel{<}{\sim} 10^8$ GeV: $\tilde{\tau}_R$ is NNLSP.
- 10^9 GeV $\stackrel{<}{\sim} M$: $\tilde{B}$ NNLSP.
- $10^8 \stackrel{<}{\sim} M/$ GeV $\stackrel{<}{\sim} 10^9$: either $\tilde{\tau}_R$ or $\tilde{B}$.

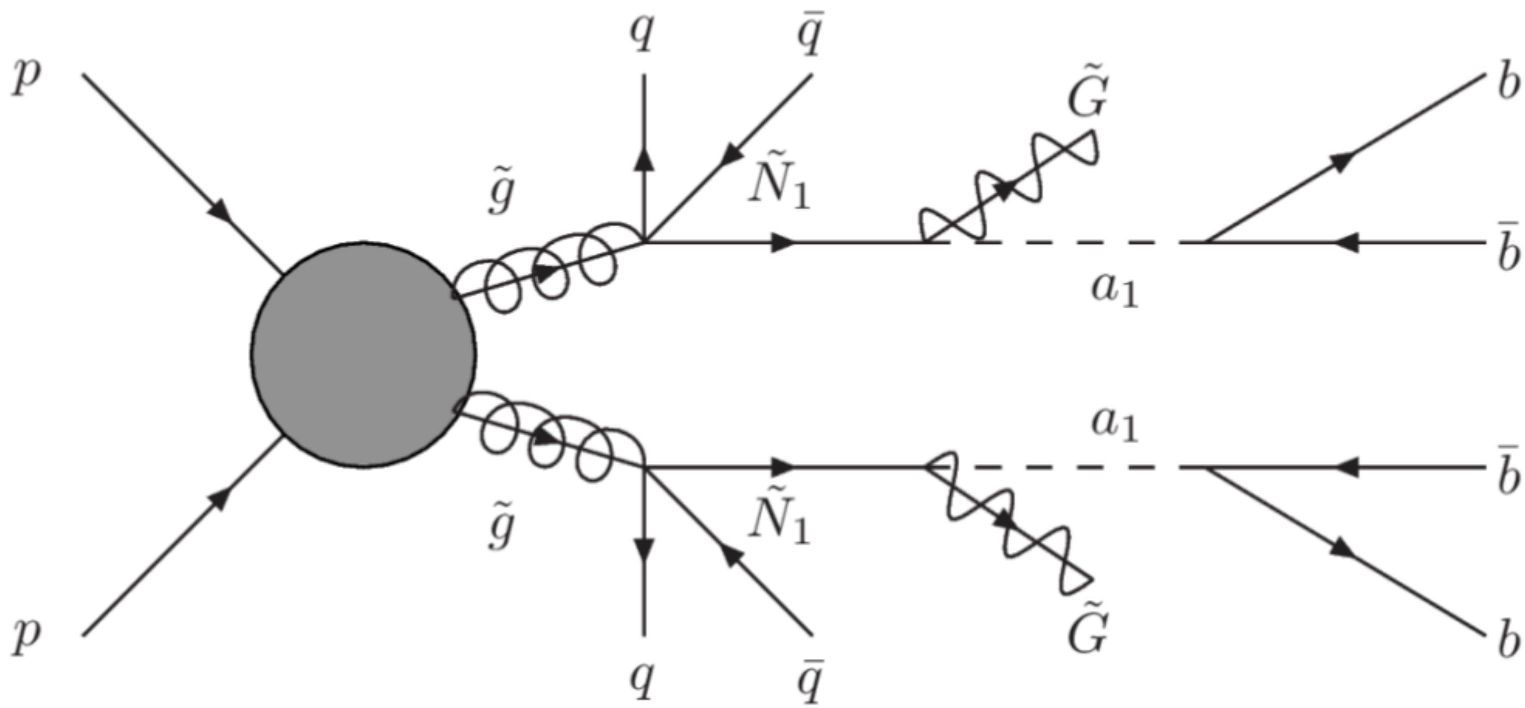
NLSP Decays

At the end of decay chains, $\tilde{N}_1 \to a_1 \to b\bar{b}\tilde{G}$.

$$c\tau_{\tilde{N}_1} \approx 2.5\,\text{cm} \left(\frac{100\,\text{GeV}}{M_{\tilde{N}_1}}\right)^5 \left(\frac{M}{10^6\,\text{GeV}}\right)^2 \left(\frac{\tilde{m}}{\text{TeV}}\right)^2 .$$

Hence, we have displaced decays, but for $M > 10^{10}$ GeV, it decays outside of the detector.

LHC Detection

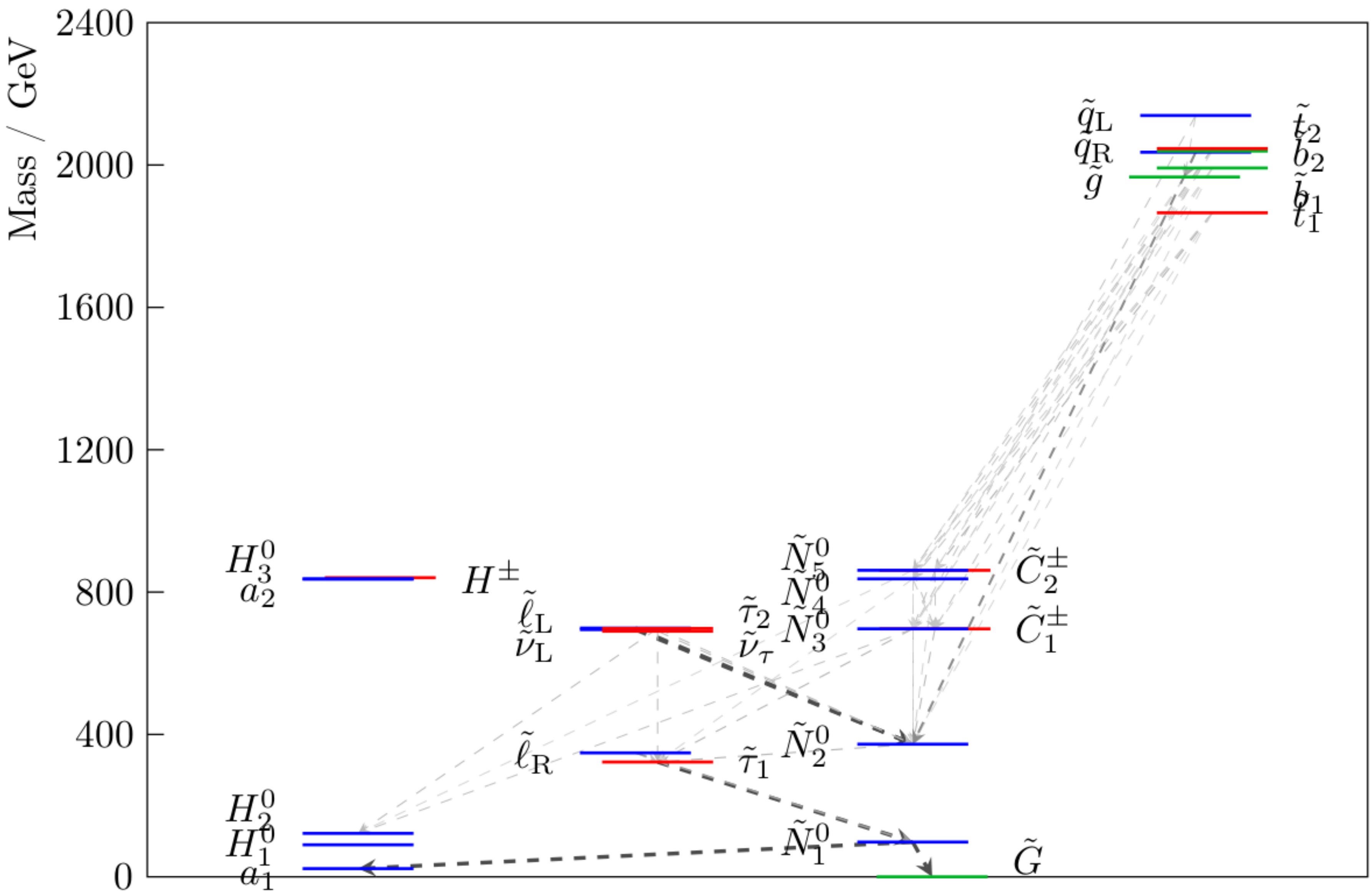


Simulate[5] with SOFTSUSY3.6.1 for ATLAS validation, PYTHIA8.2, FASTJET3.1.3, SDECAY1.5, SLHA2,

[5] BCA, Badziak, Cottin, Desai, Hugonie, Ziegler, EPJ C76 (2016) 482, arXiv:1606.03099

PROSPINO2.1.

$\xi = 0.01, \lambda = .009, M = 1.4 \times 10^6$ **GeV,** $\tilde{m} = 863$ **GeV,** $\tan\beta = 28.8, c\tau = 99$**mm**



$m_{H_1^0}$	$m_{H_2^0}$	m_{a_1}	$m_{\tilde{N}_1}$	$m_{\tilde{N}_2}$	$m_{\tilde{e}_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{g}}$	$m_{\tilde{u}_R}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$	$m_{\tilde{G}}$
90	122.1	23	97.6	373	348	323	1966	2045	1992	1866	5×10^{-8}

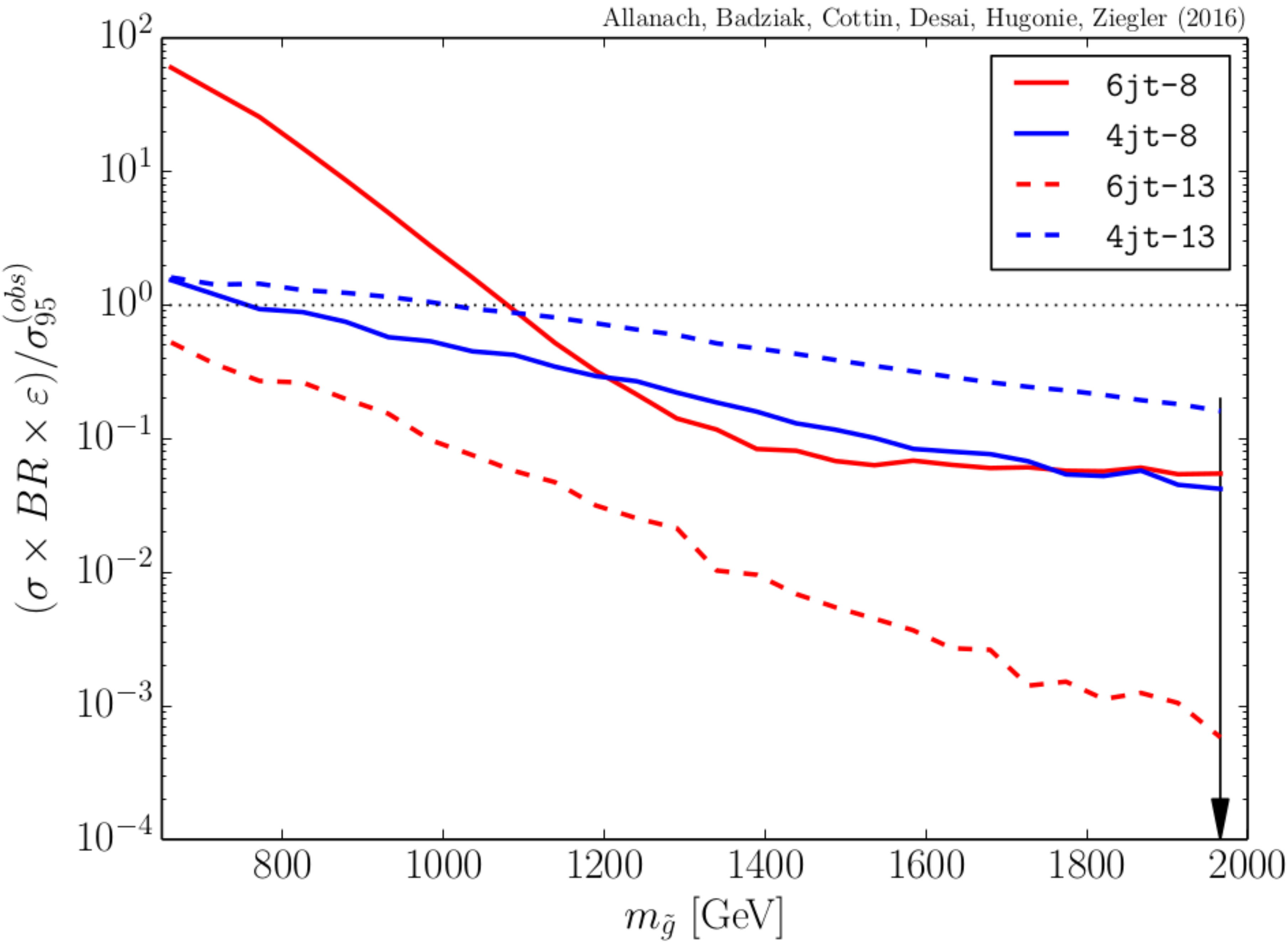
Detector Response

Jet response: $p_T(j)$ is smeared by a gaussian with 20% resolution of energy for $E_j < 50$ GeV falling linearly to 10% up to 100 GeV and then a flat 10%. A further scale correction of 1% is applied for $|\eta_j| < 2$, 3% for $\eta \geq 2$.

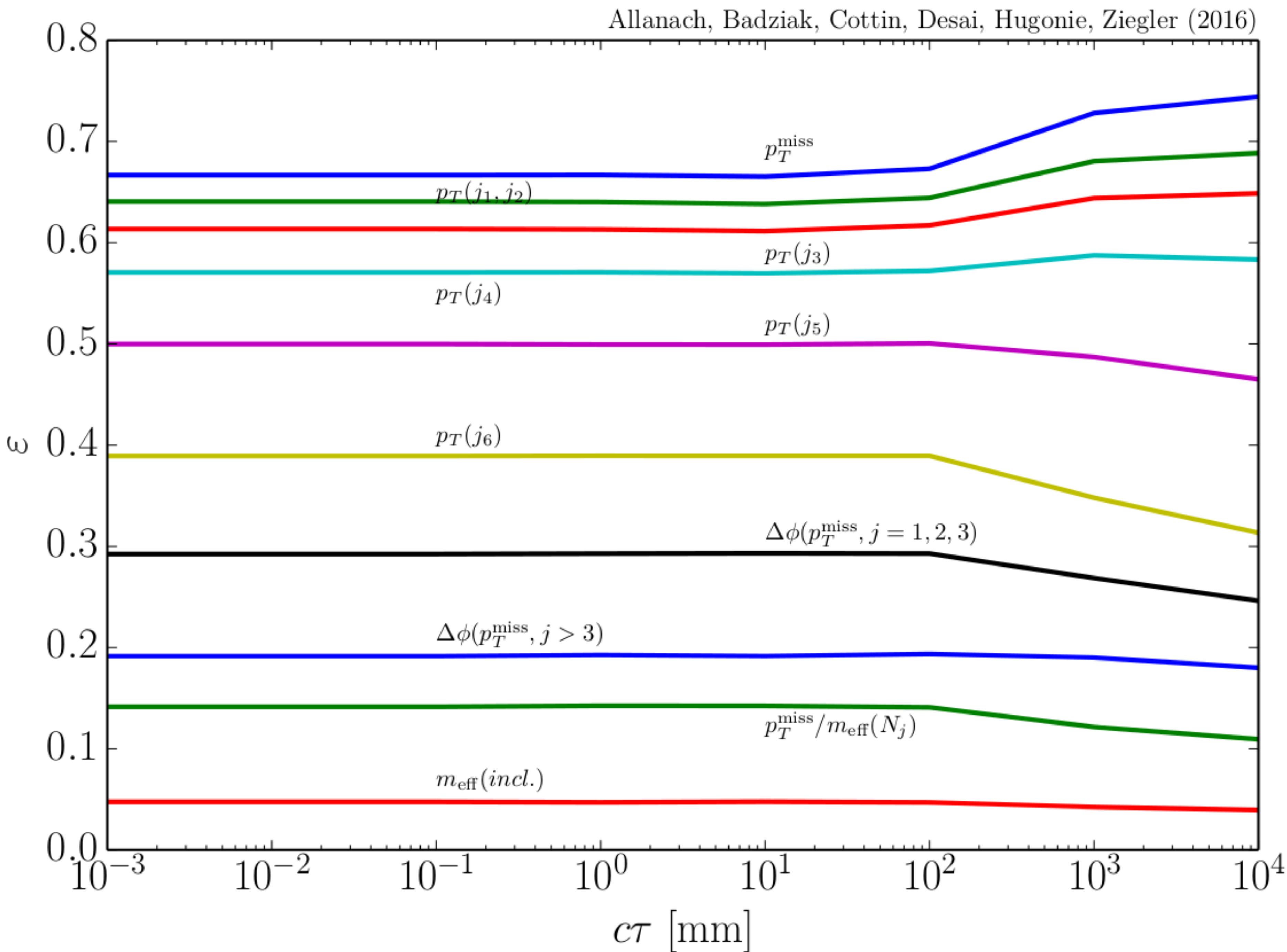
Eg cuts for jets+$\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ ATLAS at 13 TeV 4jt-13: $\vec{p}_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV, $p_T(j_i)$/GeV $> \{200, 100, 100, 100\}$. $\Delta\phi(j_{1,2,3}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$, $\Delta\phi(j_4, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}/m_{eff}(N_j) > 0.2$, $m_{eff} > 2.2$ TeV.

$\sigma_{95}^{obs} < 2.7$fb.

Gluino Bounds

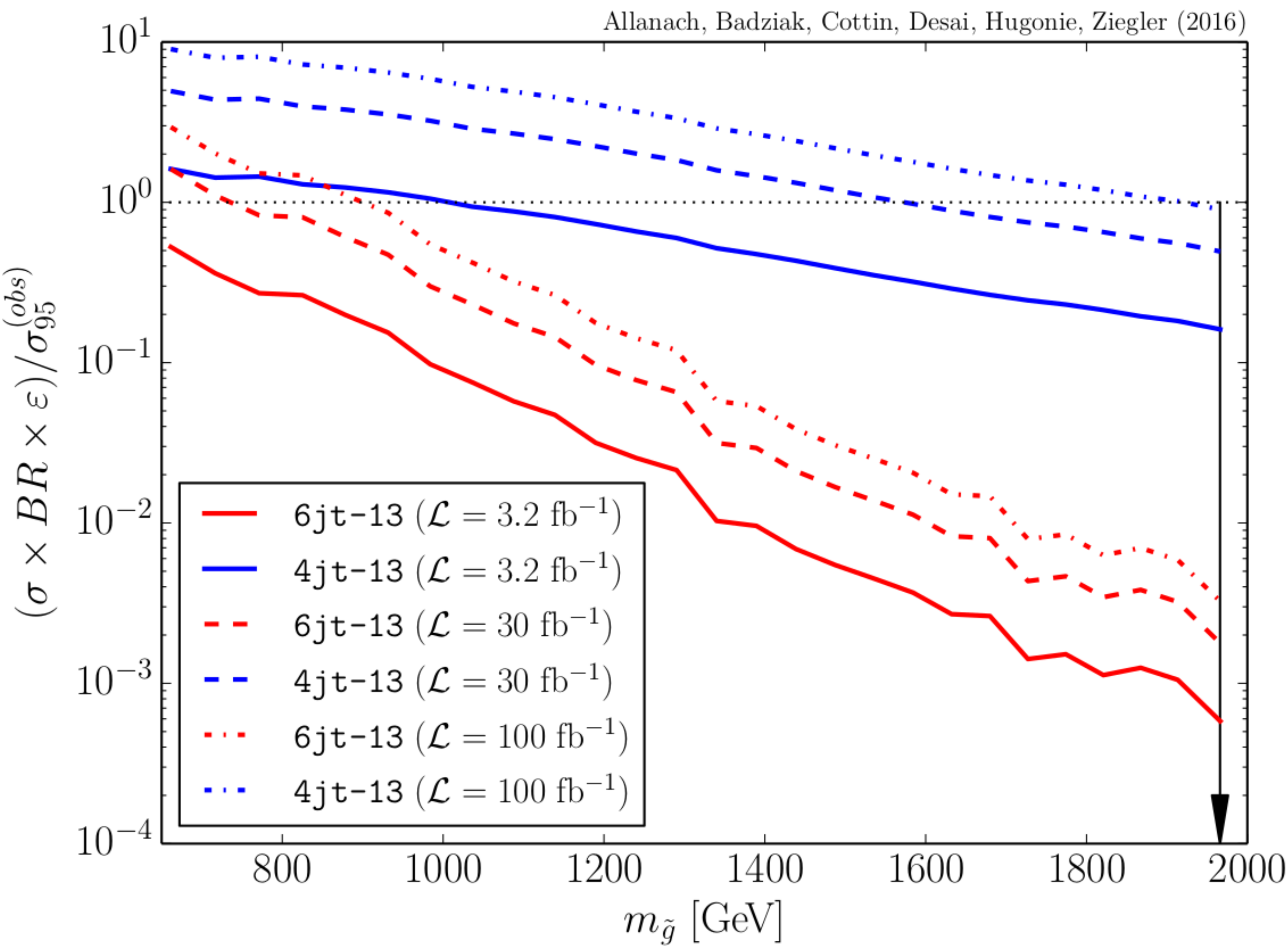


Lifetimes

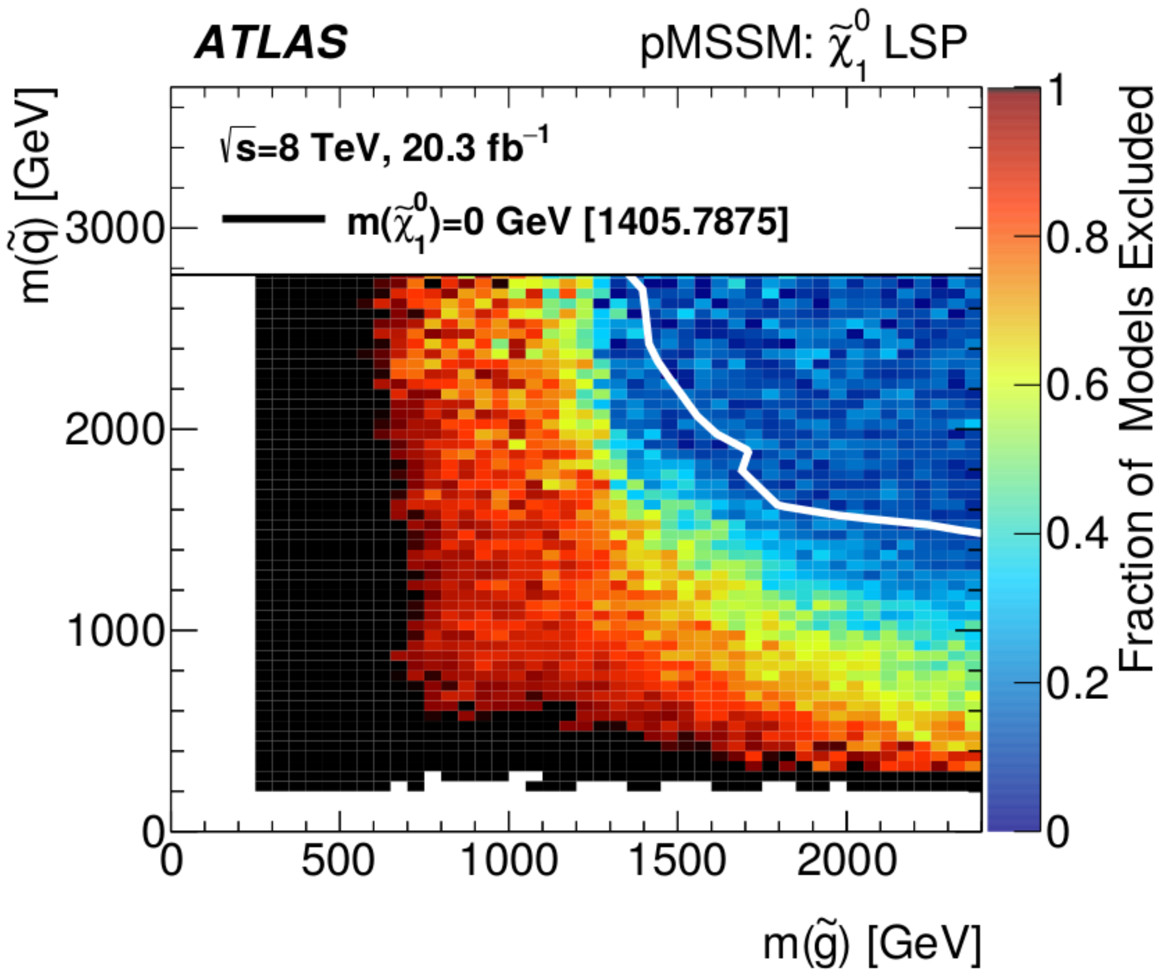


Allanach, Badziak, Cottin, Desai, Hugonie, Ziegler (2016)
$p_T^{\rm miss}$
$p_T(j_1, j_2)$
$p_T(j_3)$
$p_T(j_4)$
$p_T(j_5)$
$p_T(j_6)$
$\Delta\phi(p_T^{\rm miss}, j = 1, 2, 3)$
$\Delta\phi(p_T^{\rm miss}, j > 3)$
$p_T^{\rm miss}/m_{\rm eff}(N_j)$
$m_{\rm eff}(incl.)$
ε
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
$c\tau$ [mm]

Run II Reach $\sigma_{95}^{obs} \propto 1/\sqrt{\mathcal{L}}$



Possible Low[6] $m_{\tilde{g}}$



(a) All LSP types

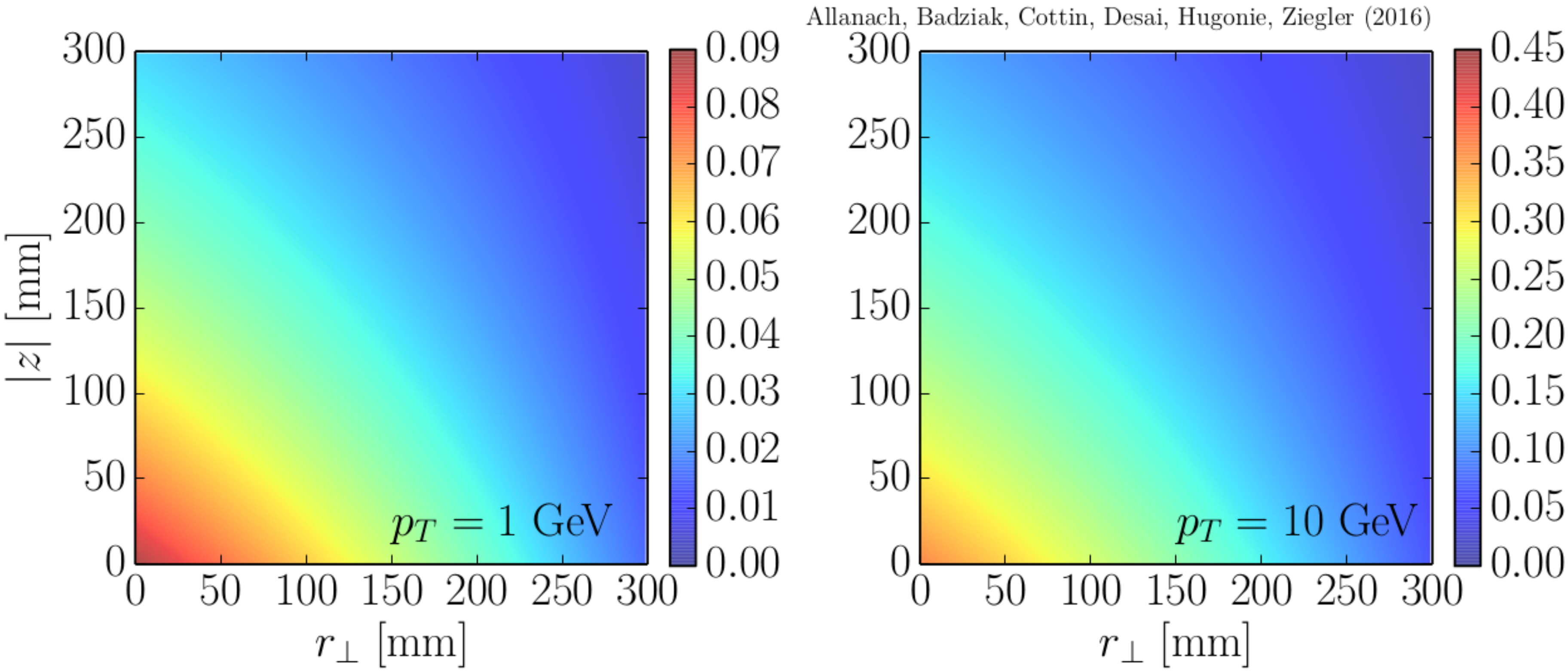
[6] ATLAS, JHEP 10 (2015) 134, arXiv:1508.06608; Barr, Liu

Displaced Vertices

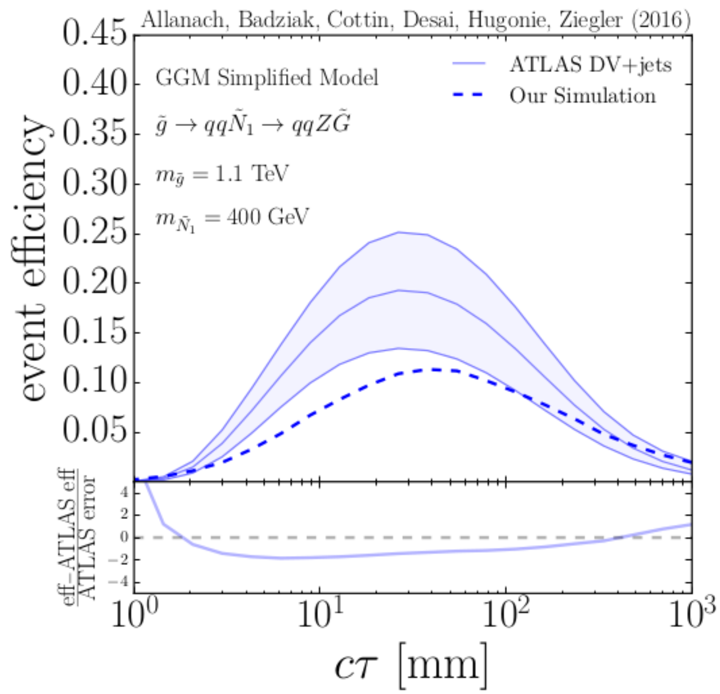
We need to model the detector response.

DV jets	4 or 5 or 6 jets with $\|\eta\| < 2.8$ and $p_T > 90, 65, 55$ GeV, each.
DV reconstruction	DV made from tracks with $p_T > 1$ GeV, $\|\eta\| < 2.5$ and $\|d_0\| > 2$ mm, satisfying a tracking efficiency given by equation 2. Vertices within 1 mm are merged.
DV fiducial	DV within 4 mm $< r_{DV} <$ 300 mm and $\|z_{DV}\| <$ 300 mm.
DV material	No DV in regions near beampipe or within pixel layers: Discard tracks with $r_{DV}/\text{mm} \in \{[25,38], [45,60], [85,95], [120,130]\}$.
N_{trk}	DV track multiplicity ≥ 5.
m_{DV}	DV mass $>$ 10 GeV.

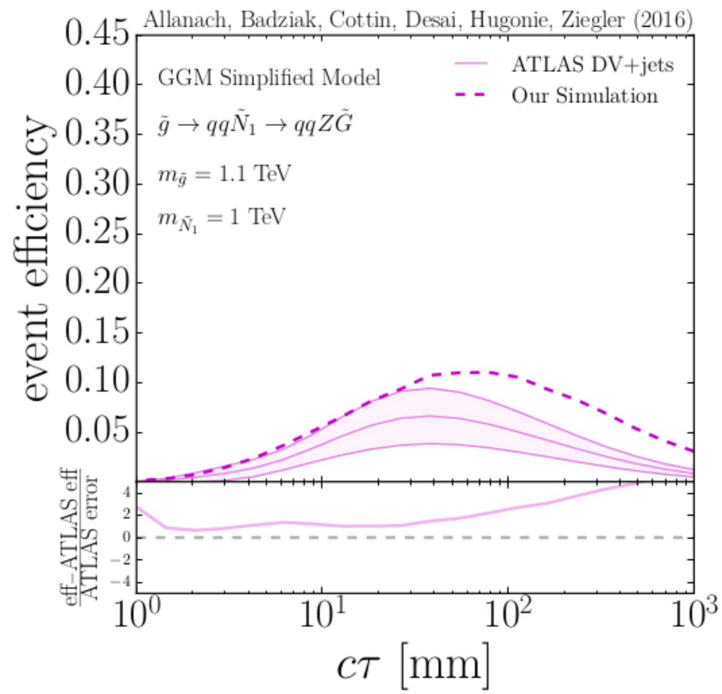
We fit a form of track efficiency to 3 ATLAS benchmarks: 2 GGM, RPV.



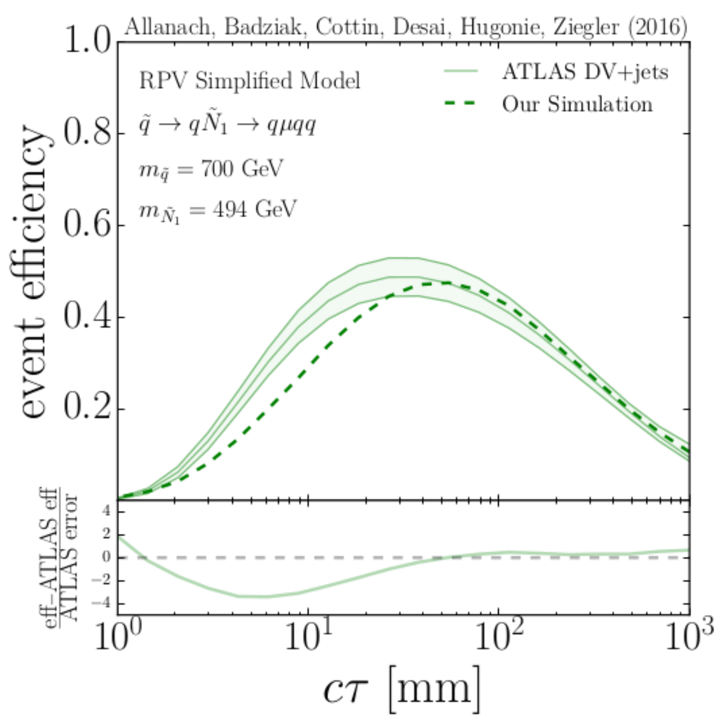
$$\begin{aligned}\varepsilon_{\rm trk} \;=\;& 0.5 \times (1 - \exp(-p_T/[4.0\ \mathrm{GeV}])) \\ & \times \exp(-z/[270\ \mathrm{mm}]) \\ & \times \max(-0.0022 \times r_\perp/[1\ \mathrm{mm}] + 0.8, 0),\end{aligned}$$



(a) GGM1



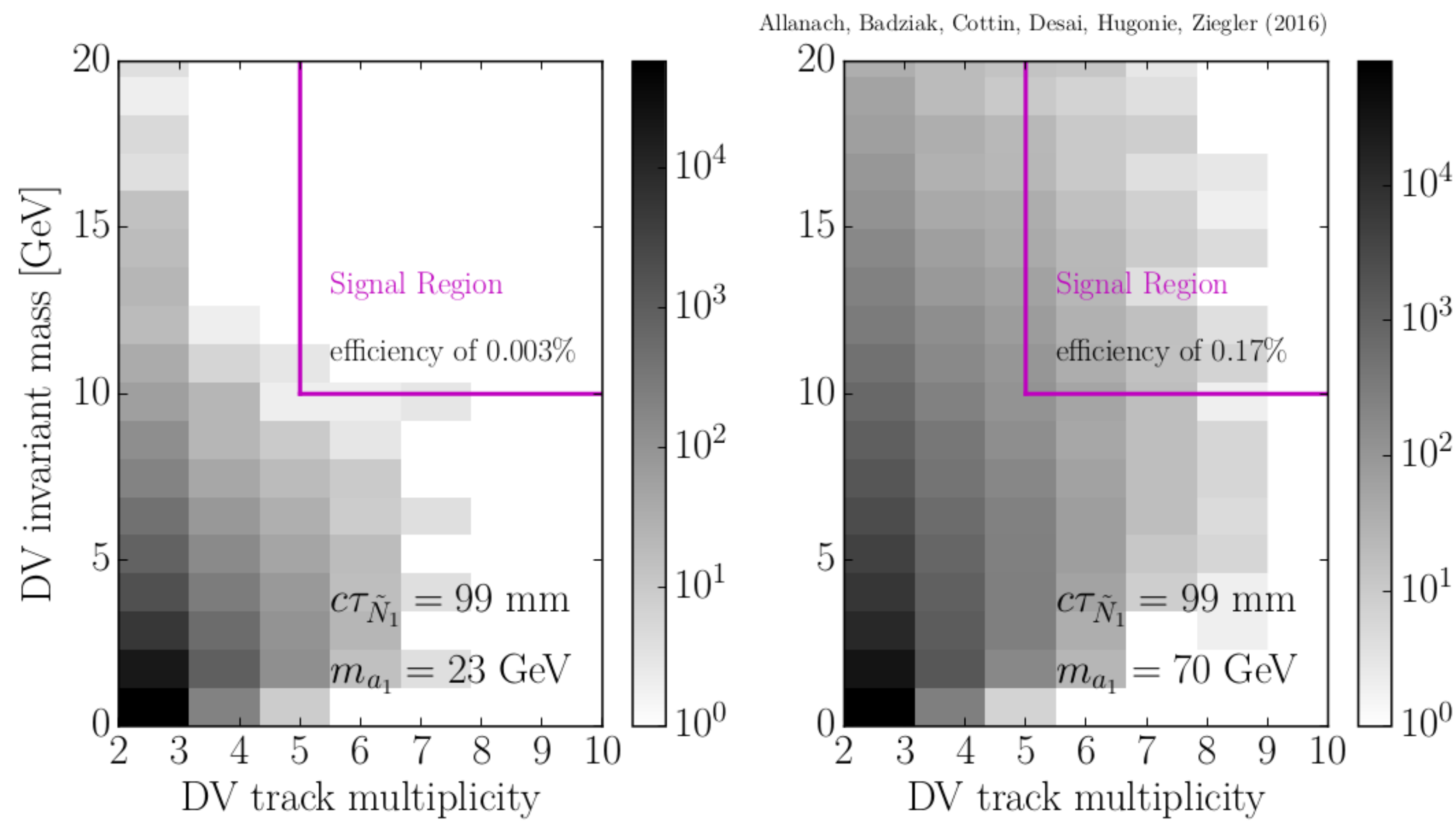
(b) GGM2



(c) RPV

	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 13$ TeV	
	N	ϵ [%]	N	ϵ [%]
All events	100000	100.	100000	100.
DV jets	96963	97.	98306	98.3
DV reconstruction	16542	17.1	16542	16.8
DV fiducial	16459	99.5	16460	99.5
DV material	16146	98.1	16210	98.5
$N_{\rm trk}$	584	3.6	544	3.4
$m_{\rm DV}$	4	0.7	3	0.6

Table 3 Numbers of simulated events N and relative efficiencies ϵ (i.e. defined with respect to the previous cut) for our NMGMSB model (P0 benchmark) with $c\tau_{\tilde{N}_1} = 99$ mm at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV for the ATLAS selection of cuts in Table 2.

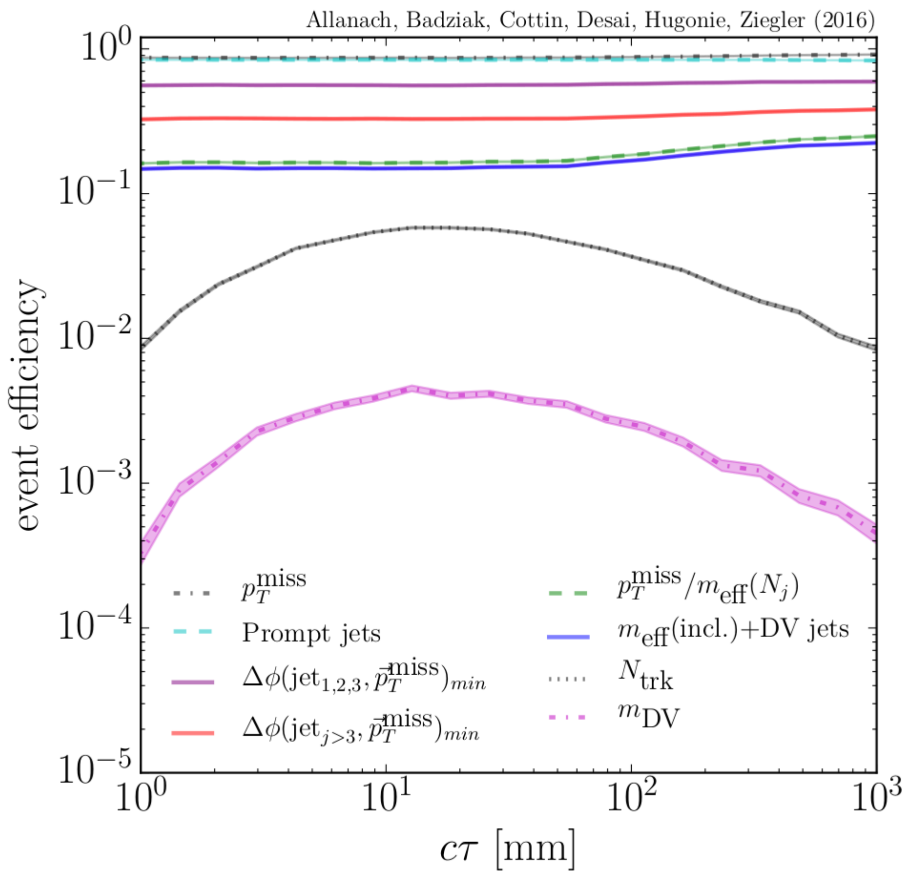


Why so bad?

Topology of $b\bar{b}\tilde{G}$ involves further displacements from B mesons, each with less than 5 tracks. ATLAS only merges them if tracks start within 1 mm of each other. Benchmark: displaced track $\epsilon = 0.06$, average number of track from displaced b is 18.1$\Rightarrow 18.1 \times 0.06 = 1.2$ visible tracks per displaced b.

Higher m_{a_1} means collimated daughters and $b-$hadron vertices are more likely to be close to each other.

	$\sqrt{s} = 8$ TeV N	ϵ [%]	$\sqrt{s} = 13$ TeV N	ϵ [%]
All events	100000	100.	100000	100.
Prompt $p_T^{\mathrm{miss}\,*}$	91709	91.7	87737	87.7
Prompt jets*	72075	78.6	84178	95.9
Prompt $\Delta\phi(\mathrm{jet}_{1,2,3}, \mathbf{p}_T^{\mathrm{miss}})_{min}{}^*$	49095	68.1	57261	68.
Prompt $\Delta\phi(\mathrm{jet}_{j>3}, \mathbf{p}_T^{\mathrm{miss}})_{min}{}^*$	27315	55.6	33832	59.1
Prompt $p_T^{\mathrm{miss}}/m_{\mathrm{eff}}(N_j)^*$	6670	24.4	18409	54.4
Prompt $m_{\mathrm{eff}}(\mathrm{incl.})^*$	6636	99.5	16848	91.5
DV jets	6636	100.	16848	100.
DV reconstruction†	1524	23.	3850	22.9
DV fiducial	1516	99.5	3825	99.4
DV material	1494	98.5	3750	98.
$N_{\mathrm{trk}} \geq 2$	1494	100.	3750	100.
$m_{\mathrm{DV}} > 5$ GeV	88	5.9	265	7.1



Summary

- NMGMSB has nice Higgs properties with a relatively light SUSY spectrum.
- One gets concurrent prompt jets plus $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ plus displaced signatures
- LHC at 8 TeV$\Rightarrow m_{\tilde{g}} > 1080$ GeV in prompt searches. Can reach $m_{\tilde{g}} \sim 2$ TeV with 300 fb^{-1}.
- Displaced signatures have very low efficiencies due to: light a_1 and B-meson decays
- One can increase efficiencies by loosening displaced cuts while imposing stricter prompt cuts.

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