Extended Gauge Mediation in the NMSSM with Displaced LHC Signals

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Based on:
MB, N. Desai, C. Hugonie, R. Ziegler, arXiv:1810.05618
B. Allanach, MB, G. Cottin, N. Desai, C. Hugonie, R. Ziegler, arXiv:1606.03099
B. Allanach, MB, C. Hugonie, R. Ziegler, arXiv:1502.05836

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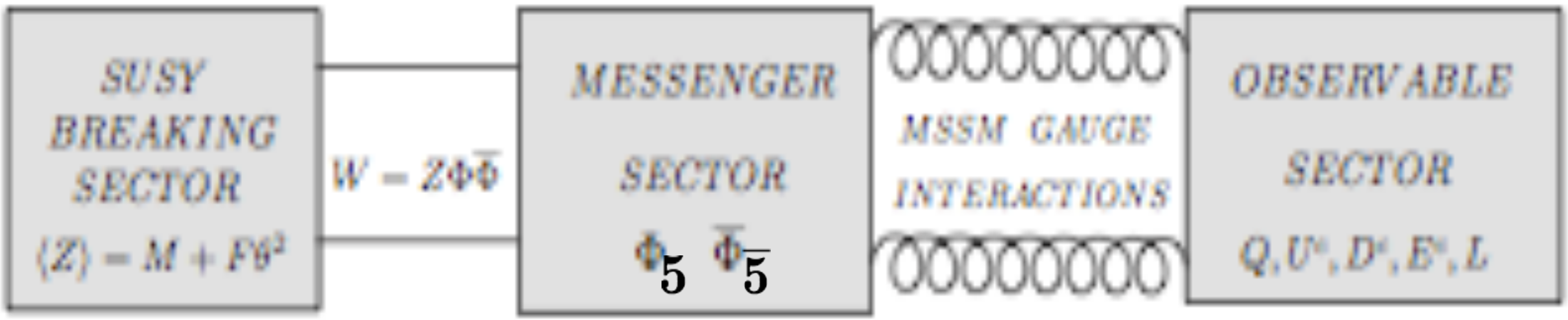
Minimal GM with 125 GeV Higgs



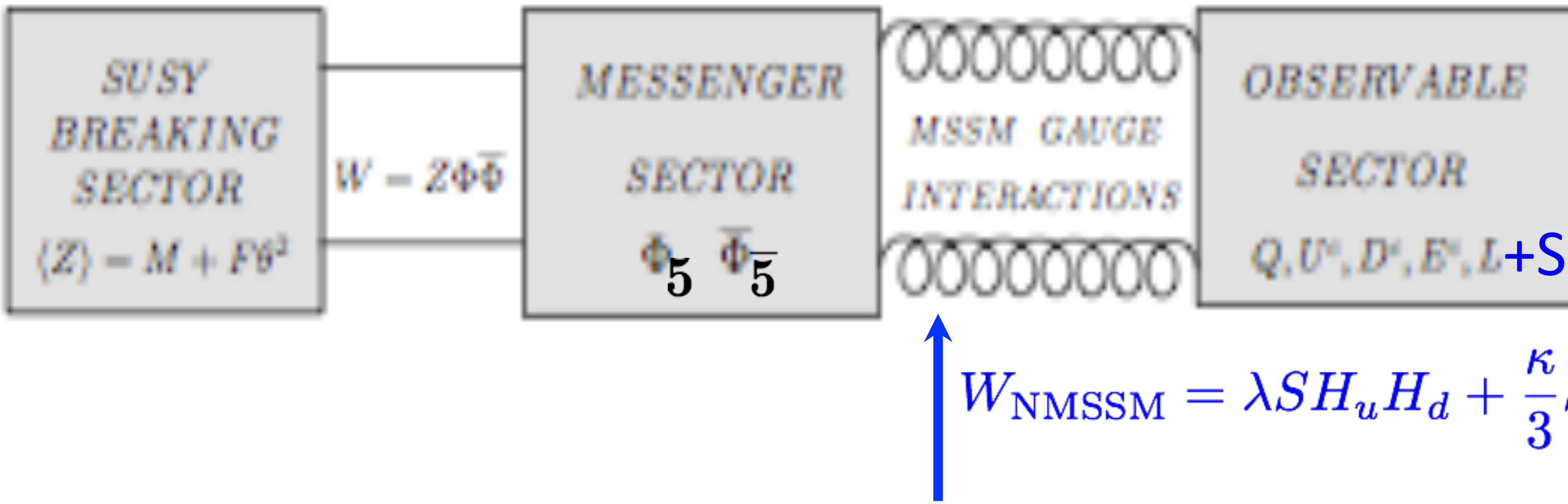
Very predictive framework that solves SUSY flavor problem

But with other problems:

- A-terms suppressed: very unnatural sparticle spectrum with no chance to be probed at the LHC
- μ and B_μ typically generated at same loop order, therefore B_μ too large for correct EWSB (μ-B_μ problem)

Need to go to non-minimal models of gauge mediation ⟶ NMSSM

Next-to-minimal gauge mediation



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

- New contributions to the Higgs mass
- μ and B_μ generated dynamically

However: naive combination NMSSM + minimal GM does not provide correct EWSB (because singlet soft mass too small)

The minimal model of gauge mediation in NMSSM:

Delgado, Giudice, Slavich '07

Main ingredient:

direct coupling of the singlet to (two pairs) of messengers

$$W_{\rm DGS} = S\left(\xi_D \bar{\Phi}_1^D \Phi_2^D + \xi_T \bar{\Phi}_1^T \Phi_2^T\right) \qquad \xi_D(M_{\rm GUT}) = \xi_T(M_{\rm GUT}) \equiv \xi$$

generates NMSSM A-terms and singlet masses (correct EWSB)

very predictive model with only 4 parameters:

$$\lambda, \xi, \tilde{m}, M$$

soft SUSY breaking scale ($\tilde{m}$)

messenger scale (M)

Note: $\tan\beta$ is NOT a free parameter

The minimal model of gauge mediation in NMSSM

Delgado, Giudice, Slavich ' 07

Conclusion of the original DGS paper: sparticles are heavier than in Minimal Gauge Mediation in MSSM due to the Higgs mass constraint

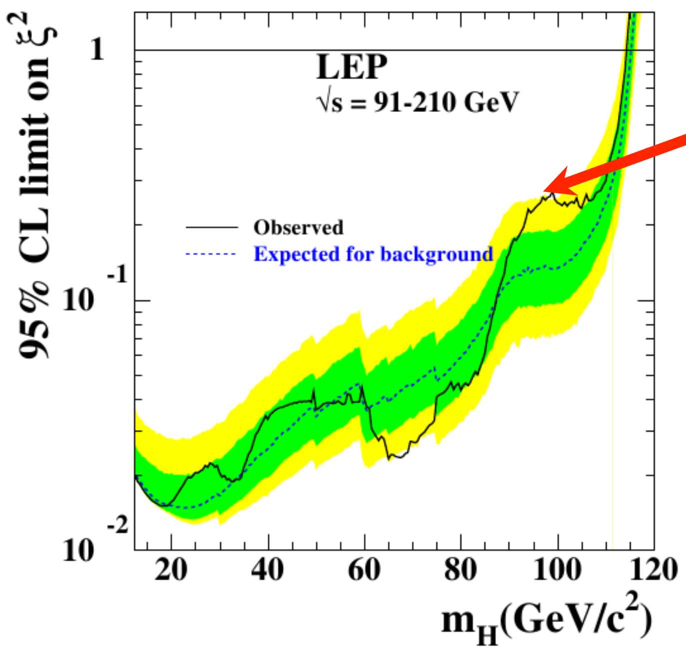
Caveat:

The above assumes singlet heavier than the Higgs

Enhanced Higgs mass from mixing with a light singlet

$$\begin{pmatrix} m_h^2 & m_{hs}^2 \\ m_{hs}^2 & m_s^2 \end{pmatrix} \xrightarrow{m_h^2 > m_s^2} m_{h_2}^2 \approx m_h^2 + \frac{m_{hs}^4}{m_h^2}$$

can be large close to the LEP excess



How large the mixing contribution to the Higgs mass can be?

$$M^2 = \begin{pmatrix} M^2_{hh} & M^2_{hs} \\ M^2_{hs} & M^2_{ss} \end{pmatrix}$$

MSSM Higgs mass

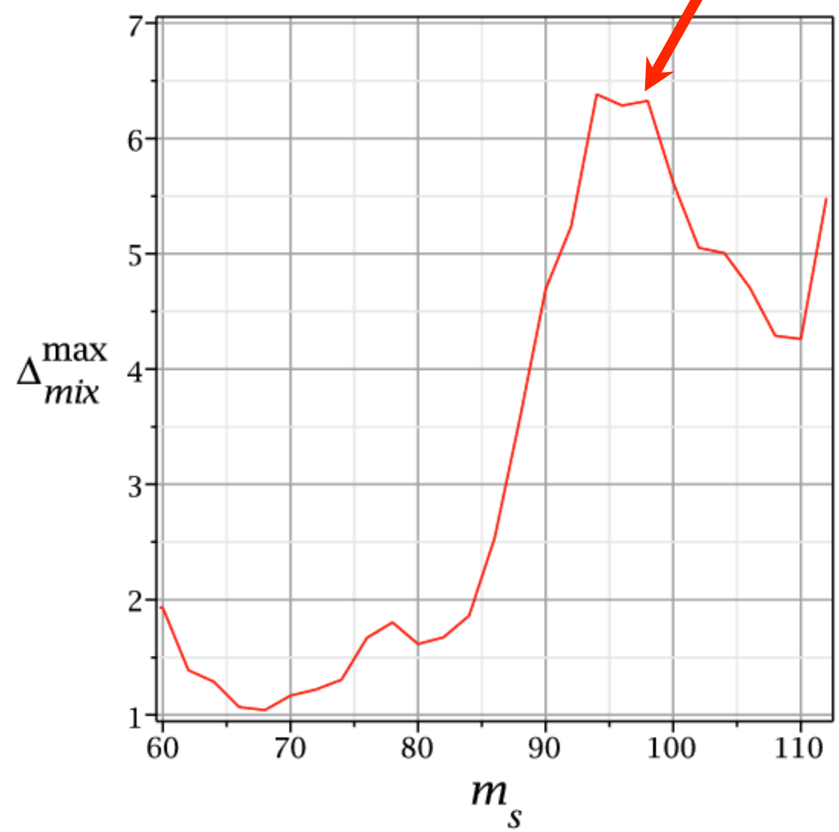
$$m_h \equiv M_{hh} + \Delta_{\rm mix}$$

$$\Delta_{\rm mix} \approx \frac{\bar{g}_s^2}{2}\left(m_h - \frac{m_s^2}{m_h}\right)$$

5-6 GeV correction to the Higgs mass is possible when m_s close to the LEP excess

MB, Olechowski, Pokorski '13

the LEP excess



Light singlet scenario in DGS model

Allanach, MB, Hugonie, Ziegler '15

Maximizing the contribution to the Higgs mass from mixing essentially fixes most model parameters

$\cos\theta \approx 0.9 \longrightarrow \lambda \sim 10^{-2}$

$m_{h_1} \approx 90 - 100\,\mathrm{GeV} \longrightarrow \xi \sim 10^{-2}$

$\Big\} \longrightarrow$ 100 GeV Singlino NLSP, 20-40 GeV pseudoscalar

$m_{h_2} \approx 125\,\mathrm{GeV} \longrightarrow \tilde{m} \sim 1\,\mathrm{TeV}$

Only the messenger scale remains free and determines collider phenomenology

The 125 GeV Higgs mass obtained for stops and gluinos below 2 TeV

LHC Phenomenology

new feature is Singlino NLSP & Gravitino LSP

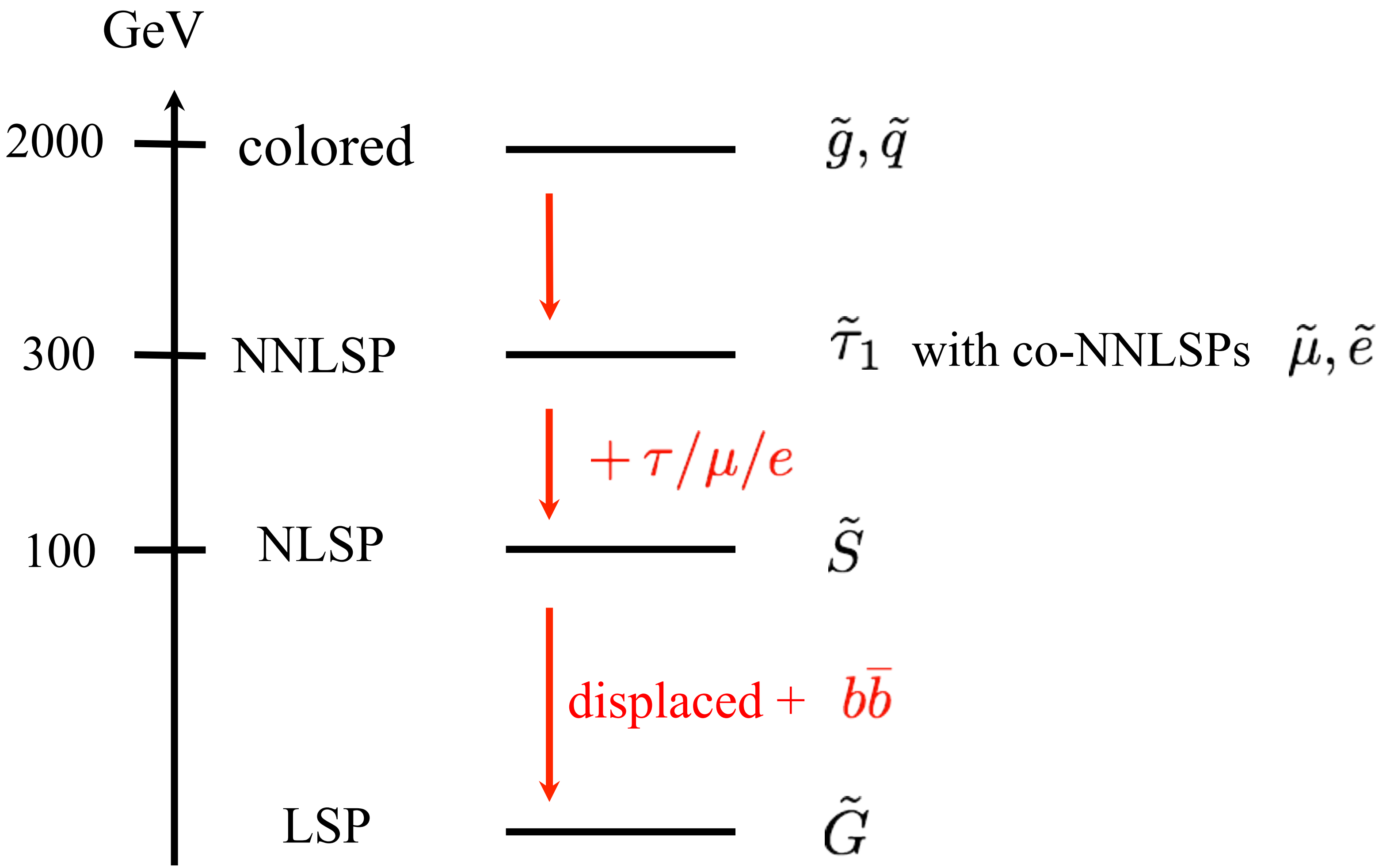
$$\tilde{N}_1 \to a_1 \tilde{G} \to b\bar{b}\tilde{G}$$

Messenger scale determines NNLSP (bino or stau) and singlino decay length

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

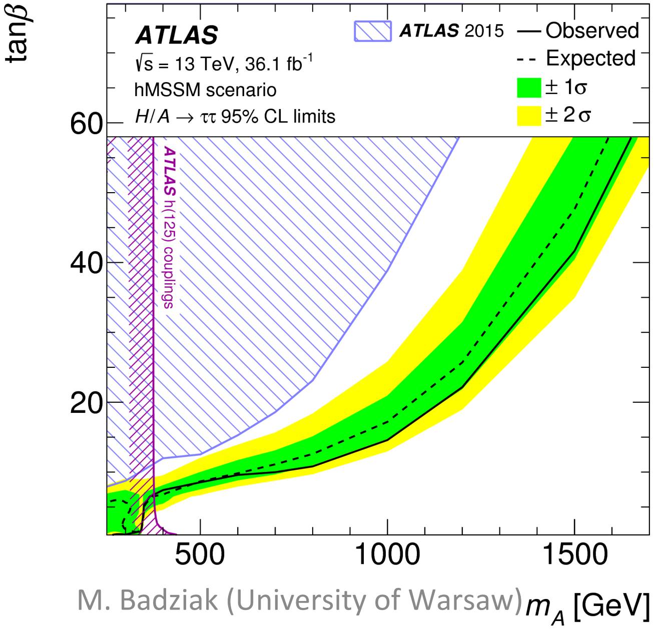
Singlino and Gravitino essentially decoupled: all SUSY decay chains to LSP proceed through NNLSP and NLSP

Displaced vertices from long-lived singlino for M < 10^7 GeV



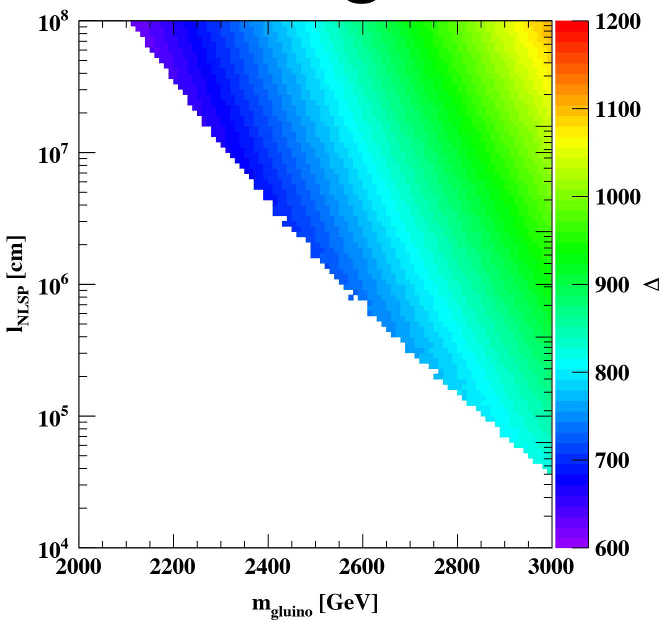
Heavy Higgs searches hurt DGS model

- The DGS model in a light singlet scenario predicts large $\tan\beta \gtrsim 30 \div 40$
- The MSSM-like Higgses are strongly constrained by the LHC searches



Heavy Higgs searches hurt DGS model

- Correlation between MSSM-like Higgs and sparticle masses results in a strong lower limit on gluino mass



Gluino mass is pushed above 3 TeV for singlino lifetimes leading to displaced vertices

Extended gauge mediation in NMSSM

MB, Desai, Hugonie, Ziegler ' 18

For direct Higgs-messenger couplings e.g.

$$\Delta W = \lambda_{ij} Q_i U_j \Phi_{H_u}$$

- Sparticle masses may not be correlated with MSSM-like Higgs mass
- The Higgs mass may be additionally enhanced via stop mixing due to contribution to A-terms

The U model

One pair of messengers:

5 free parameters (1 more than DGS):

$\lambda, \tilde{m}, M, \lambda_t, \lambda_{S_d}$

$$W_{\rm U} = \lambda_t Q_3 U_3 \Phi_u + \lambda_{S_d} S \Phi_u H_d$$

- Large λ_t makes the MSSM-like Higgs heavier:

$$m_{a_2}^2 \approx -m_{H_u}^2 \supset 9 y_t^2 \lambda_t^2 \tilde{m}^2$$

- allows for stop-mixing correction to the Higgs mass

$$A_t \supset -3\lambda_t^2 \tilde{m}$$

- supresses $\tan\beta$ (e.g. due to RG effect of A_t on A_λ)

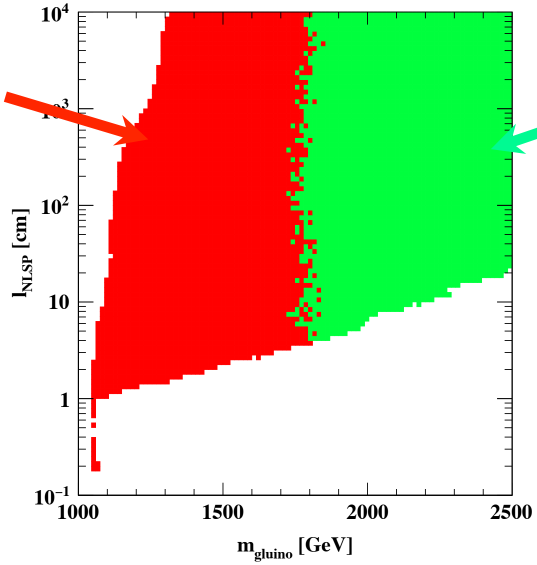
Heavy Higgs searches no longer constrain SUSY spectrum!

The U model

Very light gluinos allowed by the (light and heavy) Higgs data

Excluded

Allowed



- Gluino mass down to 1.7 TeV allowed by SUSY searches at the LHC
- singlino decay length as small as O(1 cm)

The DGSU model

Combines U model with DGS model (2 pairs of messengers):

$$W_{\rm DGSU} = S\left(\xi_D \Phi_u^{(1)} \Phi_d^{(2)} + \xi_T \Phi_T^{(1)} \Phi_{\overline{T}}^{(2)}\right) + \lambda_t Q_3 U_3 \Phi_u^{(2)} + \lambda_{S_d} S \Phi_u^{(2)} H_d$$

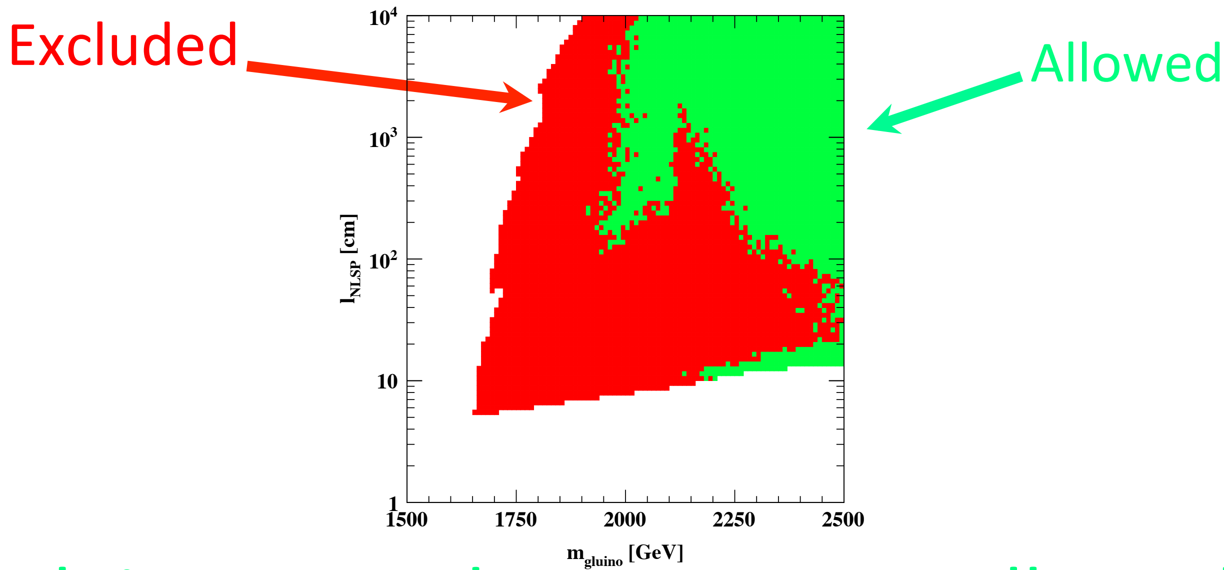
$$\xi_D(M_{\rm GUT}) = \xi_T(M_{\rm GUT}) \equiv \xi$$

$$\lambda_{S_d}(M) y_t(M) = \lambda_t(M) \lambda(M)$$

Higgs-messenger mixing condition

- Very predictive (5 free parameters)
- The same singlino/singlet sector leading to displaced pheno as in the DGS model but with much lighter colored sparticles!

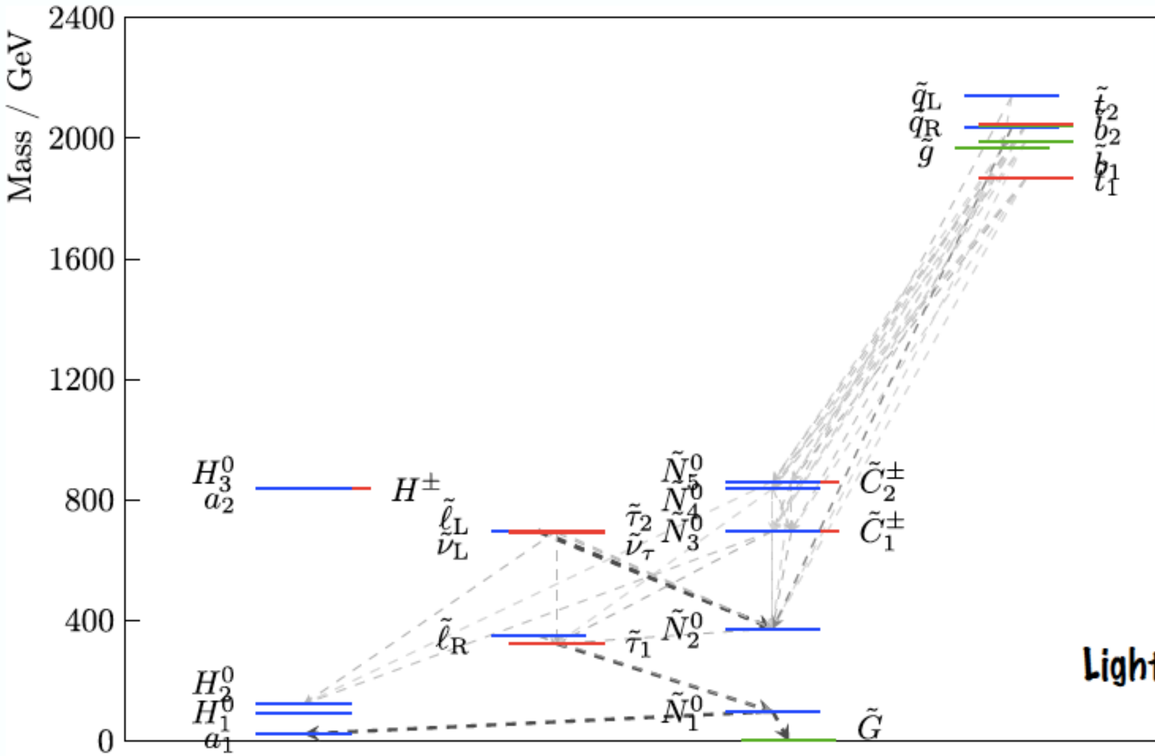
The DGSU model



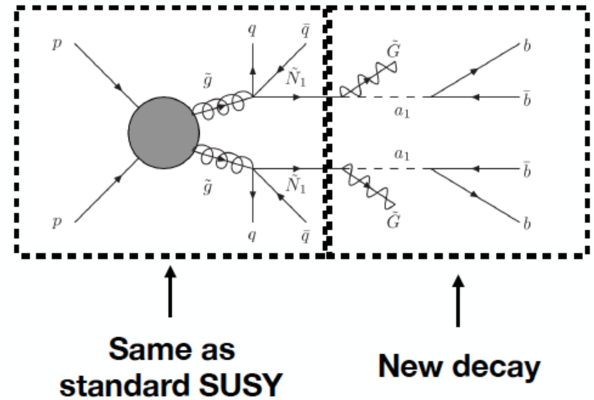
- Gluino mass down to 2 TeV allowed by SUSY searches at the LHC (the limit is stronger than in the U model due to lighter squarks)
- singlino decay length as small as O(1 m)

Looking for the displaced signature at the LHC: benchmark spectrum

Allanach, MB, Cottin, Desai, Hugonie, Ziegler '16



$m_{H_1^0}$	$m_{H_2^0}$	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}

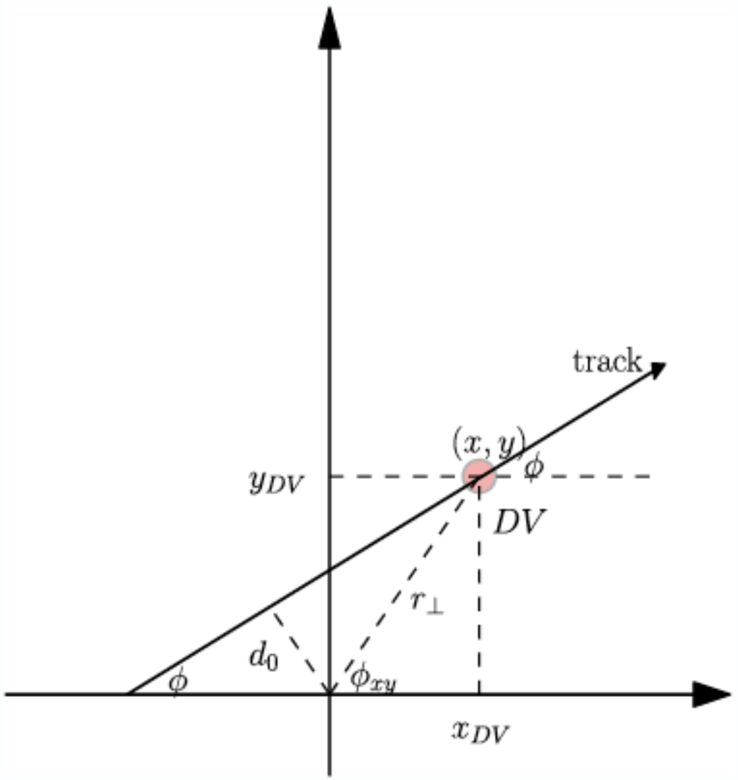


Lightest neutralino not stable

a_1 decays mainly to bb, decay is long lived!

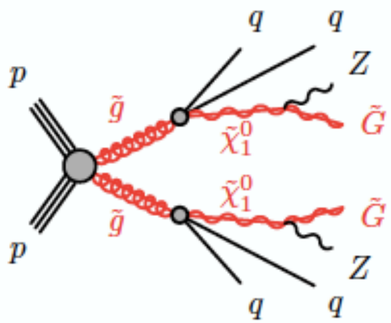
The displaced vertex search

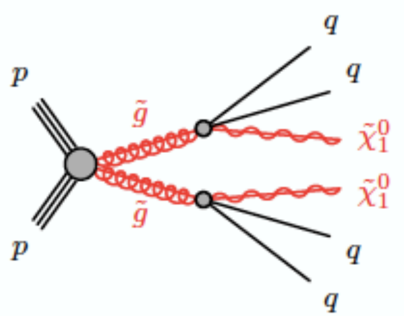
ATLAS Coll. Phys. Rev. D (2015)



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
	Vertices within 1 mm are merged
DV fiducial	DV within 4 mm $< r_{\rm DV} <$ 300 mm and $\|z_{\rm DV}\| <$ 300 mm
DV material	No DV in regions near beampipe or within pixel layers:
	Discard tracks with $r_{\rm DV}/{\rm mm} \in \{[25, 38], [45, 60], [85, 95], [120, 130]\}$
$N_{\rm trk}$	DV track multiplicity ≥ 5
$m_{\rm DV}$	DV mass >10 GeV

Gauge Mediated benchmarks





RPV benchmark

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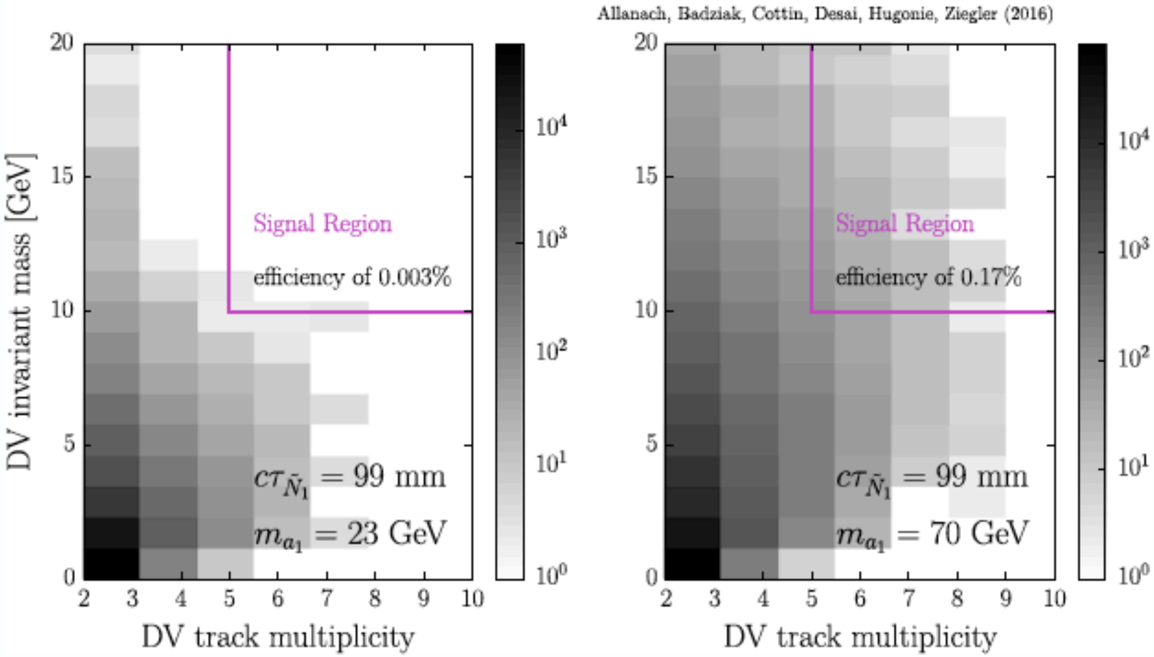
Dependence on DV mass and N_{trk}



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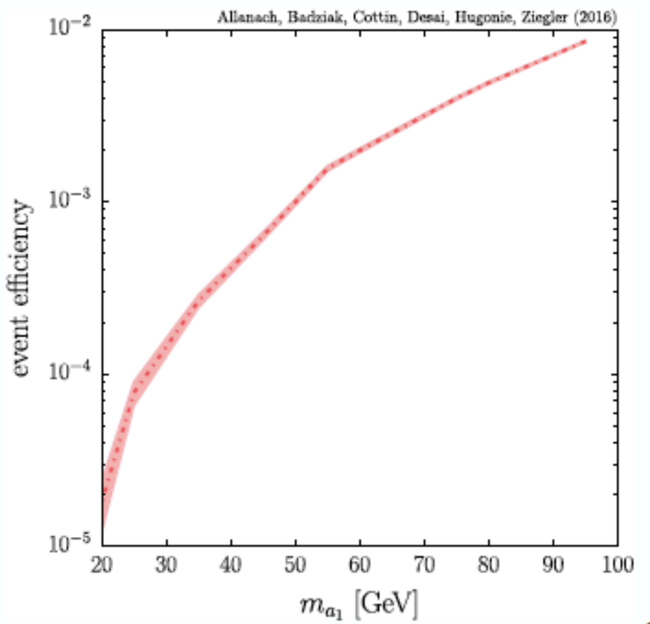
Our model fails to satisfy the DV cuts because of long lived B-mesons in the final state.

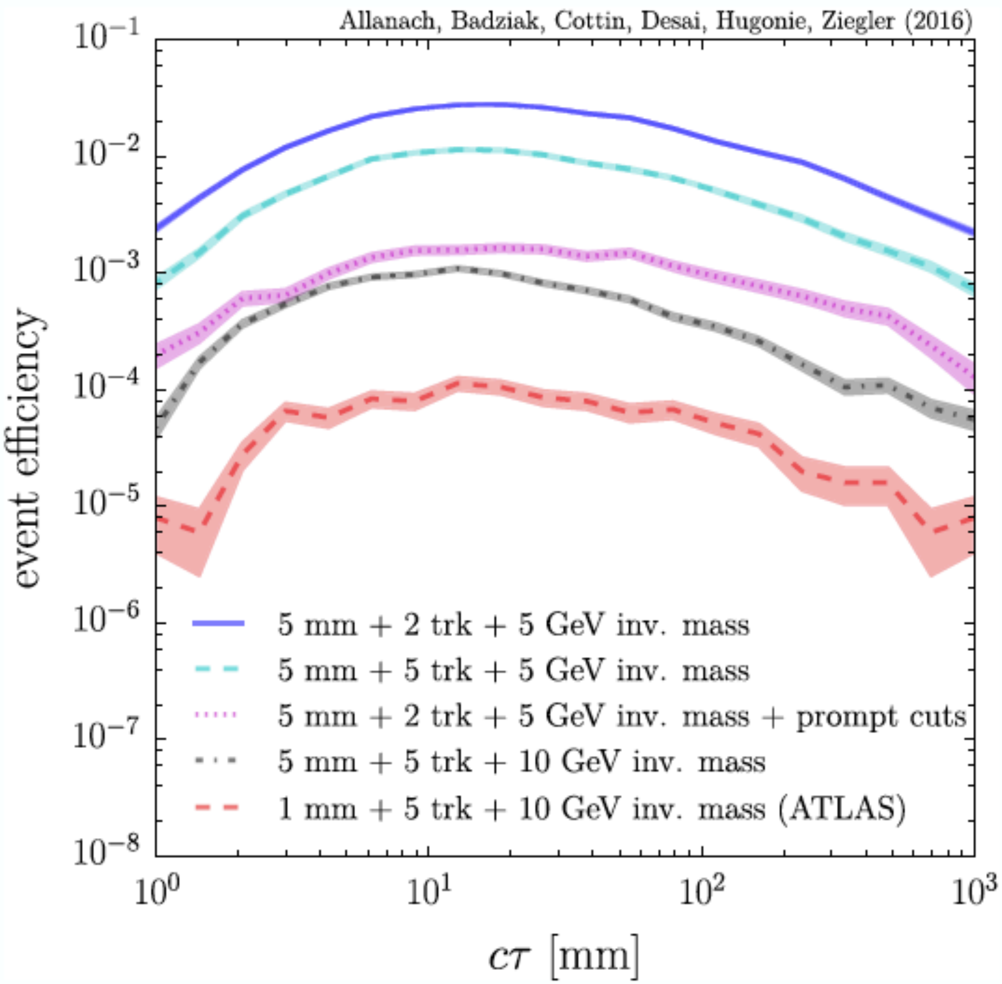
➡ B-mesons themselves give displaced vertices (not enough tracks < 1mm)

➡ Small momentum transfer

This improves with heavier a_1.



Modifying the displaced vertex criteria



- It is possible to significantly improve efficiency by relaxing cuts
- Not easy to estimate background for these changes
- Our solution: combine prompt cuts + DV cuts & use prompt background estimate as a conservative upper limit
- Much better sensitivity possible with better estimate of background

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Summary

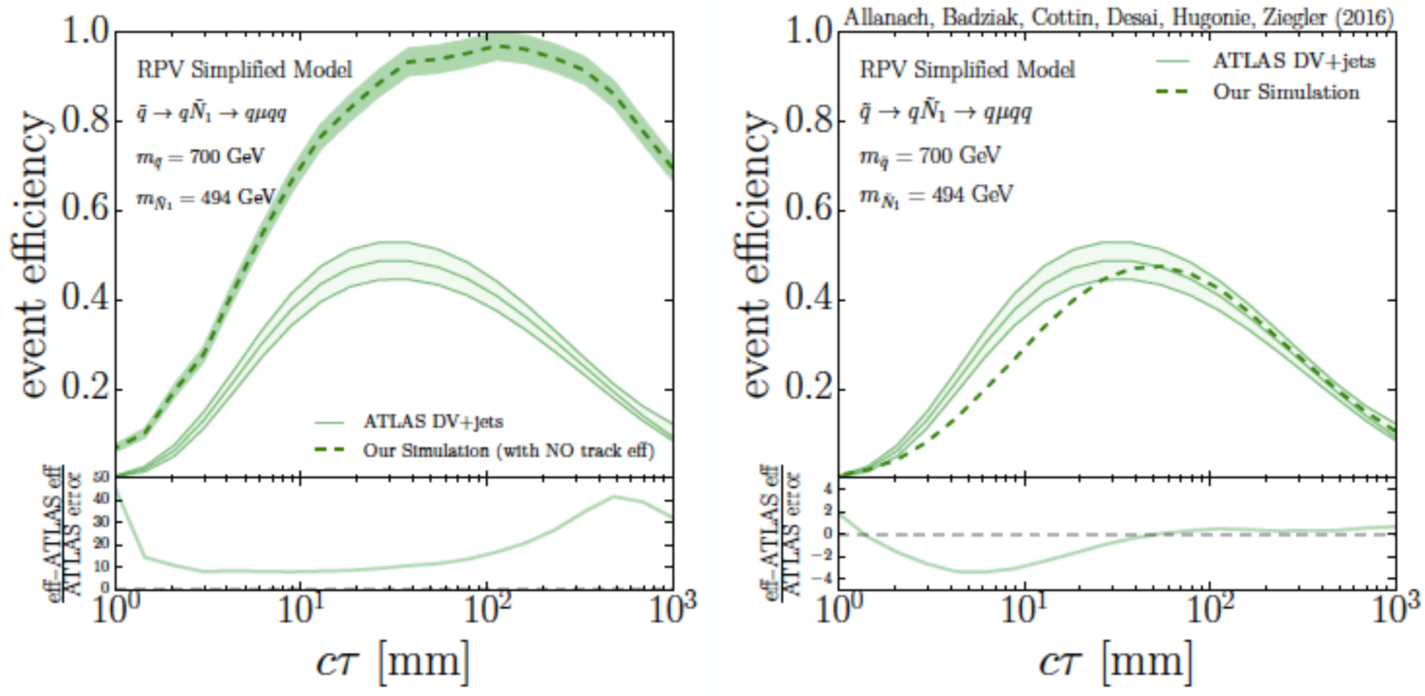
- Light NMSSM singlet (which explains the LEP excess) solves the problems of minimal gauge mediation in MSSM
  - Direct singlet-messenger couplings is crucial for correct EWSB
  - Sparticle masses close to present experimental bounds thanks to Higgs-messenger couplings
- Novel signatures from decays of long-lived singlino NLSP to displaced b-quarks
  - Displaced vertex signature with hard prompt cuts improves sensitivity of analysis + points to underlying model
  - Much more optimisation of this search possible with a dedicated background estimate

BACKUP

Benchmarks for U and DGSU models

	P1	P2	P3	P4	P5	P6
$\tilde{m}$ [TeV]	1.7	1.5	1.5	0.87	1.0	1.0
M [GeV]	2.8×10^6	3.1×10^6	2.5×10^6	5.6×10^6	5.1×10^6	1.6×10^6
λ	4.6×10^{-3}	4.4×10^{-3}	1.1×10^{-3}	4.9×10^{-3}	5.4×10^{-3}	2.5×10^{-3}
κ	1.4×10^{-4}	1.2×10^{-4}	4.3×10^{-5}	1.5×10^{-4}	2.1×10^{-4}	6.5×10^{-5}
λ_t	-0.33	-0.48	-0.73	-0.64	-0.38	0.76
λ_{S_d}	0.022	0.028	0.17	-	-	-
ξ	-	-	-	0.012	0.010	0.010
$\tan\beta$	18	11	10	9.1	17	8.7
$m_{\tilde{g}}$ [TeV]	2.0	1.7	1.8	2.0	2.3	2.2
$m_{\tilde{d}_R}$ [TeV]	2.6	2.2	2.3	2.0	2.4	2.3
$m_{\tilde{t}_1}$ [TeV]	2.1	1.7	2.2	1.8	2.0	2.2
$m_{\tilde{N}_1}$ [GeV]	95	96	200	96	97	106
$m_{\tilde{N}_2}$ [GeV]	370	320	330	380	440	430
m_{a_1} [GeV]	26	32	290	26	24	26
m_{a_2} [TeV]	1.7	1.9	2.7	1.6	1.4	2.1
m_{h_1} [GeV]	89	89	110	89	91	101
$m_{\mu L}$ [GeV]	960	830	820	710	840	790
$m_{\mu R}$ [GeV]	480	430	520	390	420	450
$m_{\chi_1^\pm}$ [GeV]	720	620	640	720	840	830
$m_{H_u}^2$ [TeV^2]	-2.2	-2.8	-6.8	-2.2	-1.5	-3.9
$m_{H_d}^2$ [TeV^2]	0.75	0.62	0.59	0.47	0.58	0.58
m_S^2 [GeV^2]	-4.3×10^3	-4.3×10^3	7.8×10^3	-4.3×10^3	-4.5×10^3	-5.3×10^3
A_λ [GeV]	64	130	180	150	52	210
A_κ [GeV]	-4.9	-7.2	-280	-4.8	-3.9	-4.3
$c\tau_{\tilde{N}_1}$ [cm]	200	200	10	200	200	12
Δ	530	680	37000	440	310	720

Finding the track efficiency



Tracking efficiency determined by fitting parameters of an empirical function

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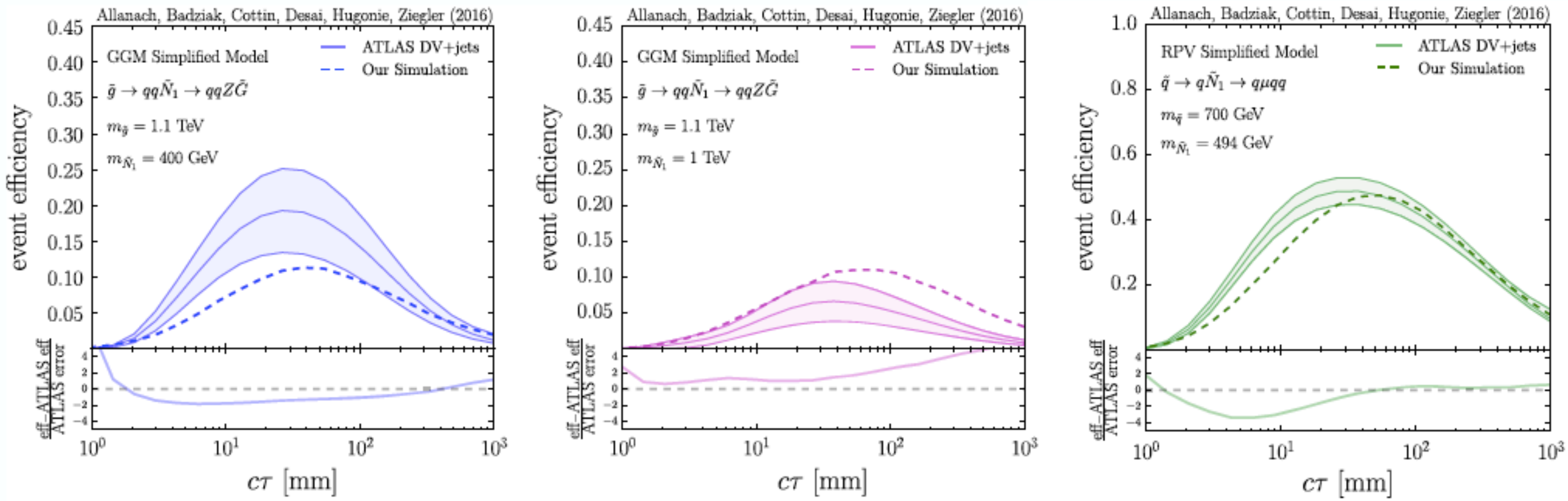
$$\varepsilon_{\rm trk} = 0.5 \times (1 - \exp(-p_T/[4.0\ \text{GeV}]))$$ Remove low p_T

$$\times \exp(-z/[270\ \text{mm}])$$ Dependence on z of DV (i.e. truth of decay vertex)

$$\times \max(-0.0022 \times r_\perp/[1\ \text{mm}] + 0.8, 0).$$ Dependence on radial distance of DV

Finding the track efficiency



- Fitting any one benchmark gives vary bad fit for others
  - ➡ Not the right parameters? (we tried d_0, z_0 with no improvement)
  - ➡ Hidden dependence on extra variables?

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- Three benchmarks used to fit tracking parameters as a compromise