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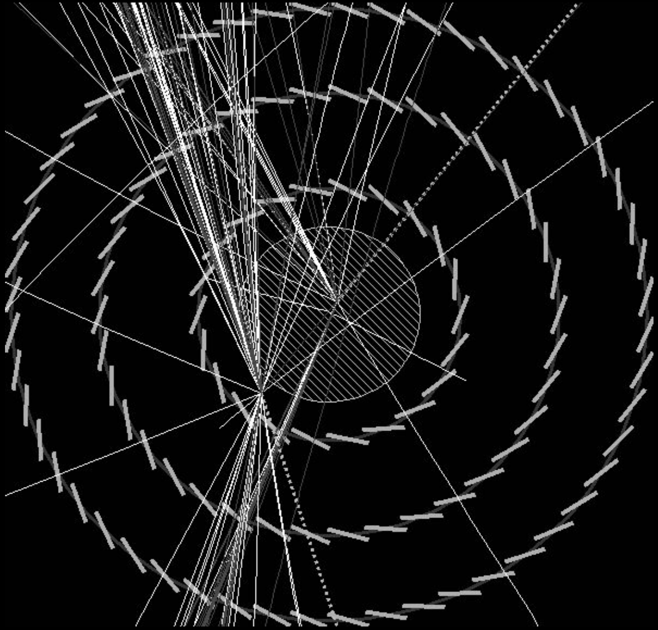
Long-Lived Neutral Particles decaying to b's: Reinterpretation of LHC displaced vertex searches



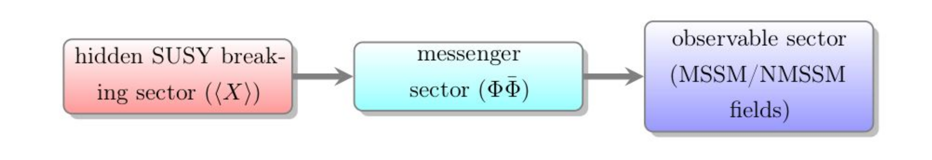
Giovanna Cottin

Based on Eur.Phys.J. C76 (2016) with B.C. Allanach, M. Badziak, N. Desai, C. Hugonie, R. Ziegler
and our LHC-LLP Community White paper (J. Beachman et al, 1903.04497)

Long-Lived Particles and the Third Generation Workshop
Higgs Centre for Theoretical Physics, University of Edinburgh
November 2019

Next-to-minimal Supersymmetry with Gauge Mediation predicts neutral long-lived particles in decay chains ending in b-quarks

A 125 GeV higgs constraints SUSY model building.
Light sparticle spectrum possible in non-minimal models.
In this talk the focus is the DGS Model:



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

$$W_{\rm GM} = X \sum_{i=1,2} \left(\kappa_i^D \bar{\Phi}_i^D \Phi_i^D + \kappa_i^T \bar{\Phi}_i^T \Phi_i^T \right)$$

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

Only 4 free parameters !

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

NMSSM +Gauge Mediation+Direct Singlet Messenger Couplings = DGS Model

Delgado, Giudice, Slavich
Phys. Lett. B 653 (2007) 424

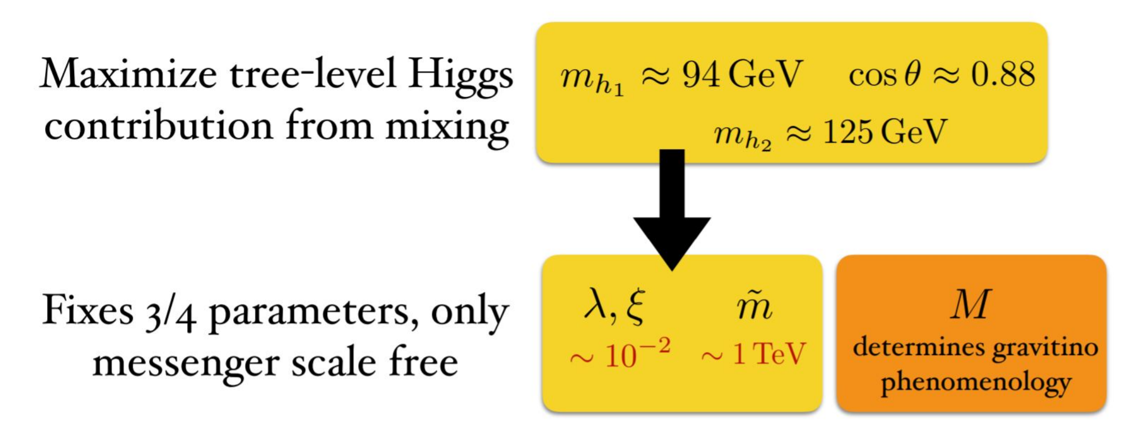
In the DGS model, a new contributions to the Higgs mass appears

Allanach, Badziak, Hugonie, Ziegler
Phys.Rev. D92 (2015) 1, 015006

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m^2_{h,\text{mix}} + m^2_{h,\text{loop}}$$

singlet-Higgs mixing contribution giving substantial contributions to the tree-level Higgs mass

With thanks to R. Ziegler

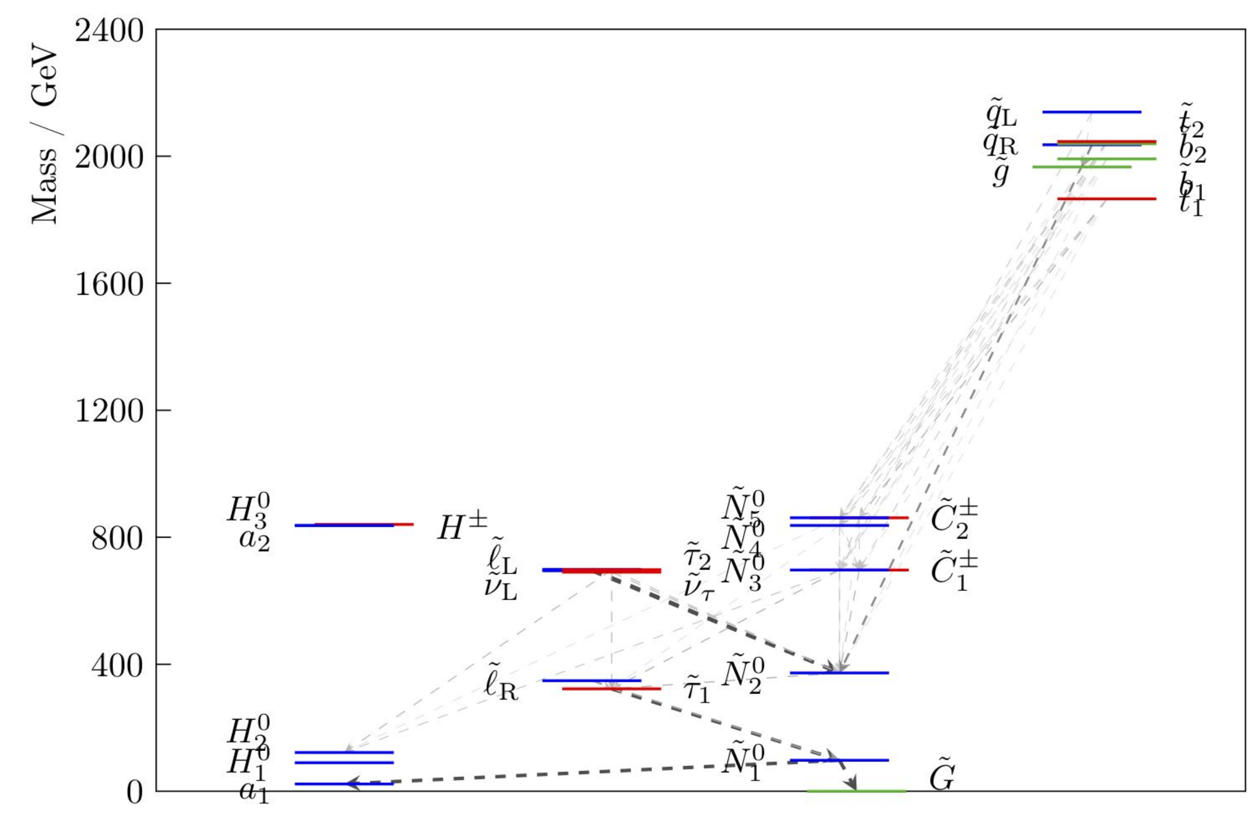


This leads to a very light singlet-like pseudo scalar(~20 GeV) and a ~100 GeV singlino NLSP

DGS Model Spectrum

Generated with NMSSM Tools

Allanach, Badziak, Cottin, Desai, Hugonie, Ziegler
Eur.Phys.J. C76 (2016)



Light singlet-like pseudo scalar (~20 GeV) and a ~100 GeV singlino-like neutralino NLSP. Gluino of 1.9 TeV

ctau_N1 = 99 mm

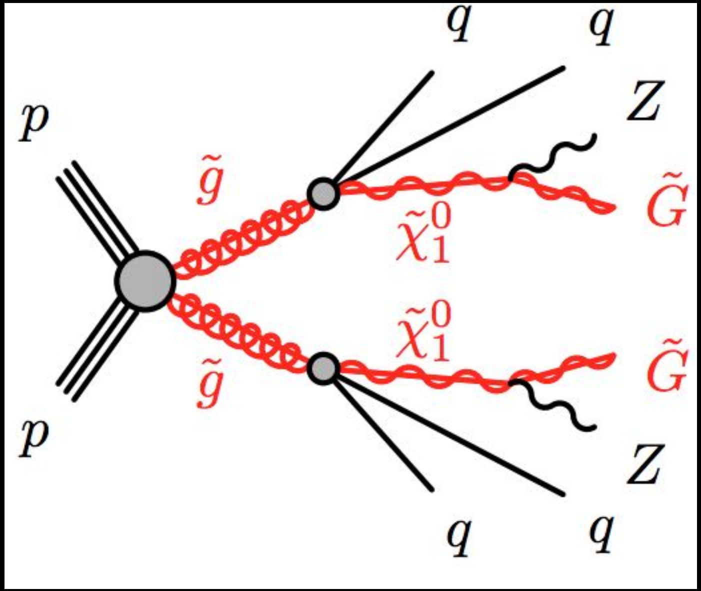
NOTE: Further studies on the model rules out points with small enough gluino mass that has a long-lived neutralino

M. Badziak, N. Desai, C. Hugonie, R. Ziegler
Eur.Phys.J. C79 (2019) 67

Gauge Mediation

GMSB Displaced Phenomenology

GGM:
G. F. Giudice and R. Rattazzi, Phys. Rept. 322 (1999)



$$c\tau \simeq 130 \left(\frac{100\ \text{GeV}}{m_{\tilde{\chi}_1^0}} \right)^5 \left(\frac{\sqrt{F}}{100\ \text{TeV}} \right)^4 \times 10^{-3}\ \text{mm}$$

Decays to gravitino suppressed by SUSY-breaking scale

Displaced GGM:
A. Delgado, G. F. Giudice, P. Slavic, Phys. Lett. B653 (2007)

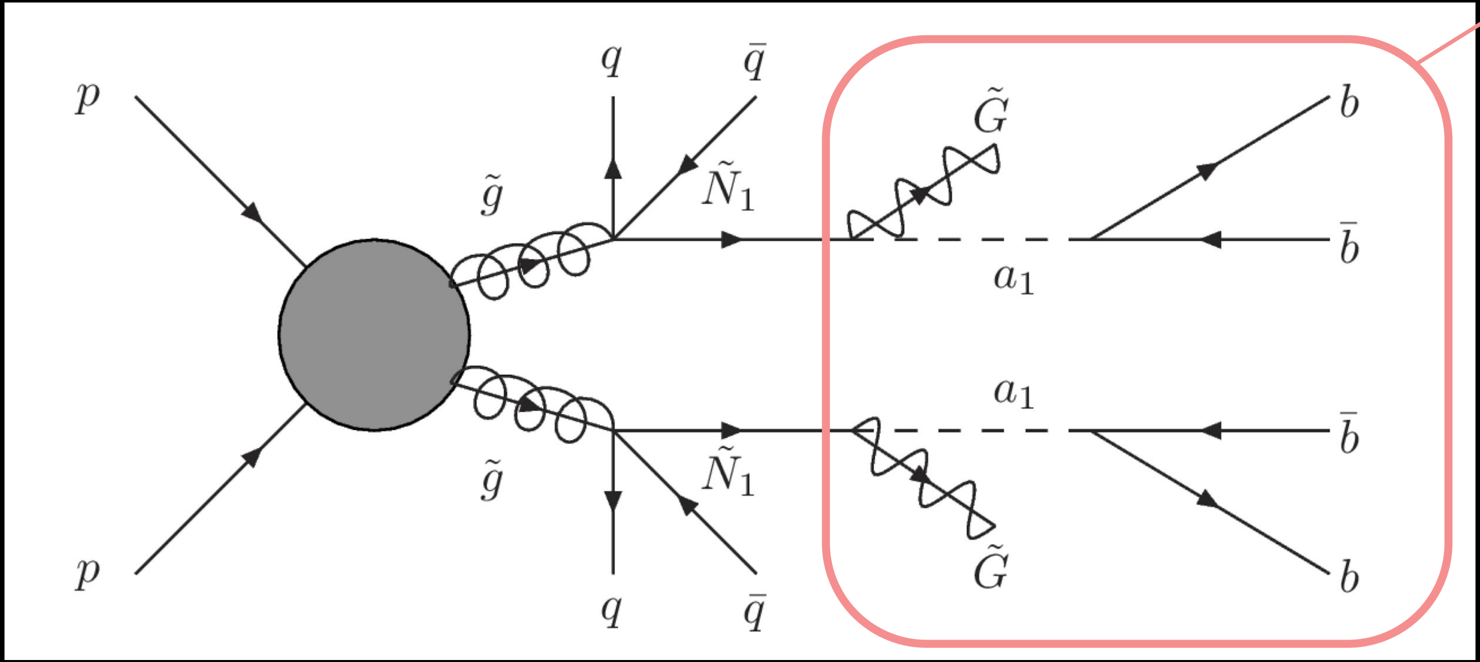
Eur.Phys.J. C76 (2016)

NMSSM+ Gauge Mediation

NGMSB Displaced Phenomenology

The only free parameter is the messenger scale, which controls the phenomenology

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

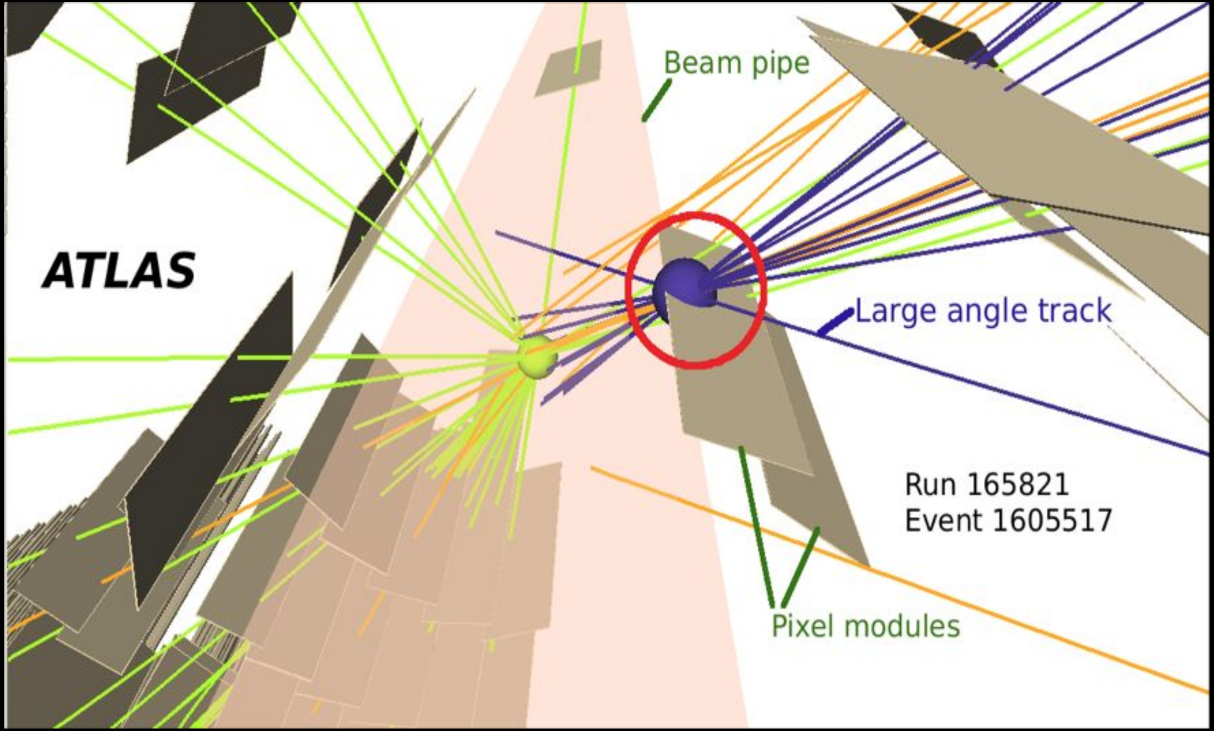


Singlino alters SUSY decay chains as compared to the MSSM, leading to additional *b*-jets

Decay is long-lived !

Displaced Searches @ the LHC

ATLAS Multitrack DV 8 TeV search PRD92 (2015) 7, 072004



Event Display arXiv:1109.2242

Signatures inside inner tracker (lifetimes of order picosecond to a nanosecond)

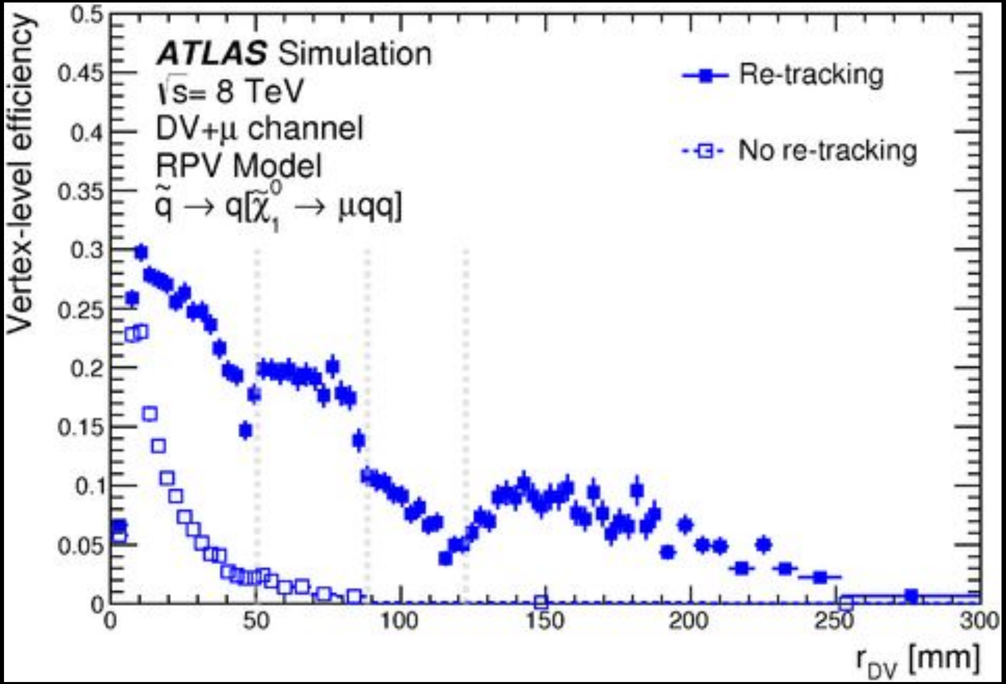
Analysis strategy

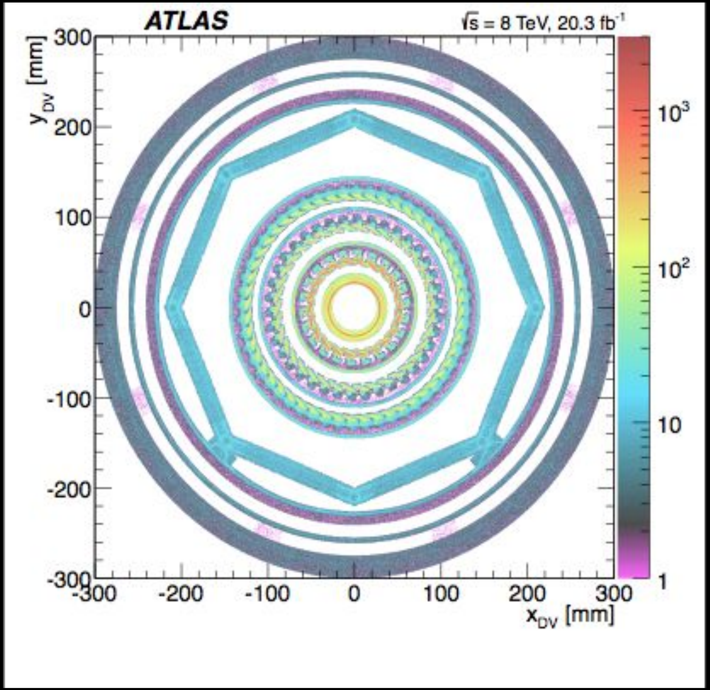
Look for high-mass and track multiplicity DVs ($m_{DV} > 10$ GeV, $nTrk > 5$)

ATLAS Multitrack DV 8 TeV search PRD92 (2015) 7, 072004

Standard tracking algorithms are re-run with looser cuts to gain efficiency for displaced (high-d0) tracks

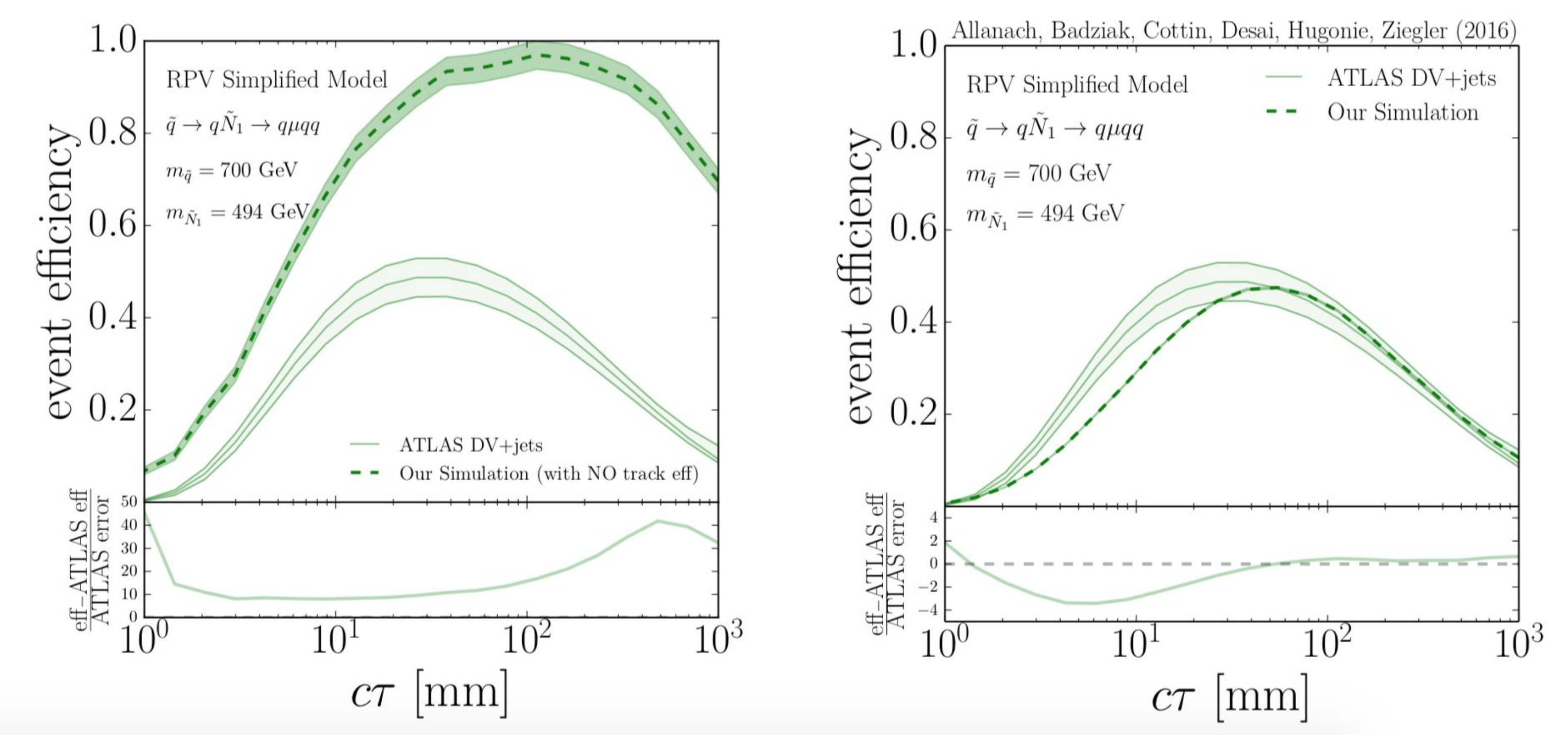
Veto vertices in material layers (dominant background) with a 3D material. Zero background search





Standard objects (jets, electrons, muons, tracks) are not so standard anymore if they are/come from a LLP. Reconstruction efficiencies have a strong dependence on LLP decay position/boost, which are hard to model within custom/publicly available simulation tools

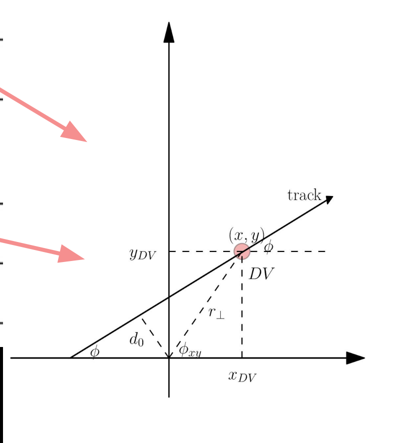
Risk of dangerous extrapolations. Validation is KEY!



Our Recast

We implement a custom made toy detector simulation* and (model independent) vertex reconstruction algorithm** inspired by the ATLAS multi-track DV analysis

DV jets	4 or 5 or 6 jets with $\lvert\eta\rvert < 2.8$ and $p_T > 90, 65, 55$ GeV, each.
DV reconstruction	DV made from tracks with $p_T > 1$ GeV, $\lvert\eta\rvert < 2.5$ and $\lvert d_0\rvert > 2$ 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 $\lvert z_{DV}\rvert < 300$ 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.

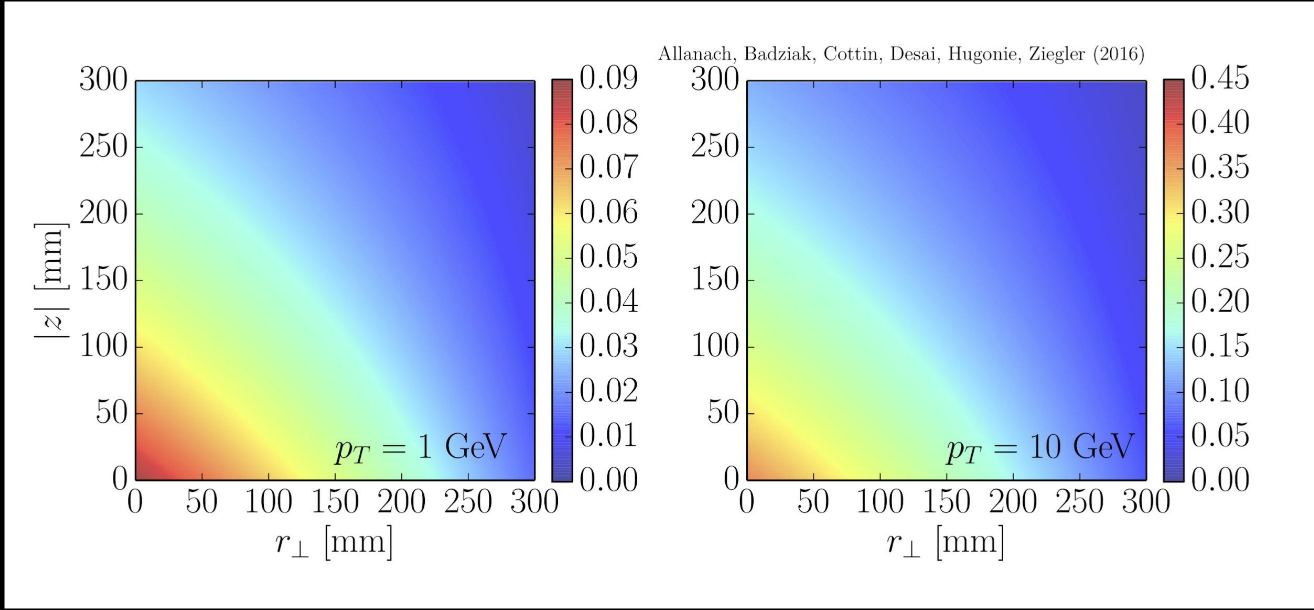


* Made inside Pythia8. Particles decaying outside ID are considered stable. FastJet for jet reconstruction.
** DV algorithm takes displaced tracks as input. It compares and clusters the tracks origins until each track is assigned to a single vertex. After merging vertices, the DV position is defined as the average position of all track origins in the cluster.

Track Efficiency Parameterization

Eur.Phys.J. C76 (2016)

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

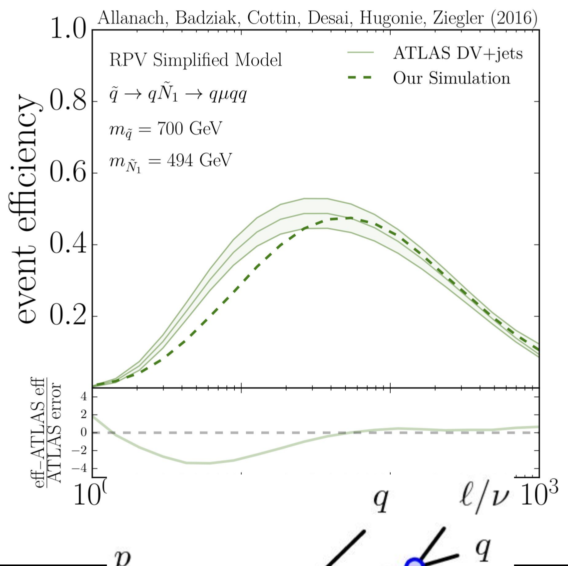


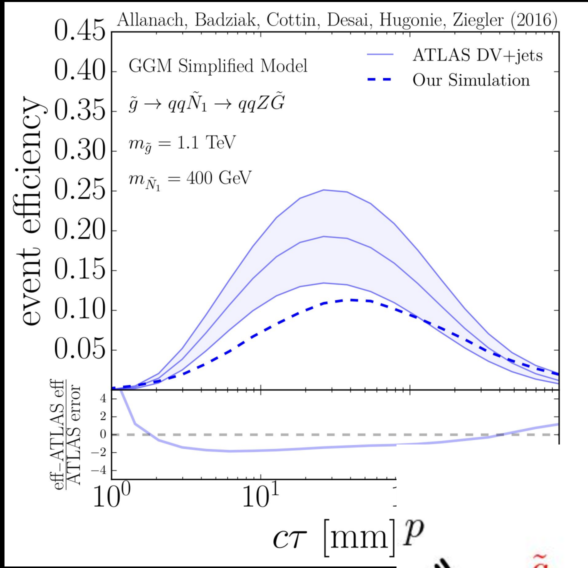
Eur.Phys.J. C76 (2016)

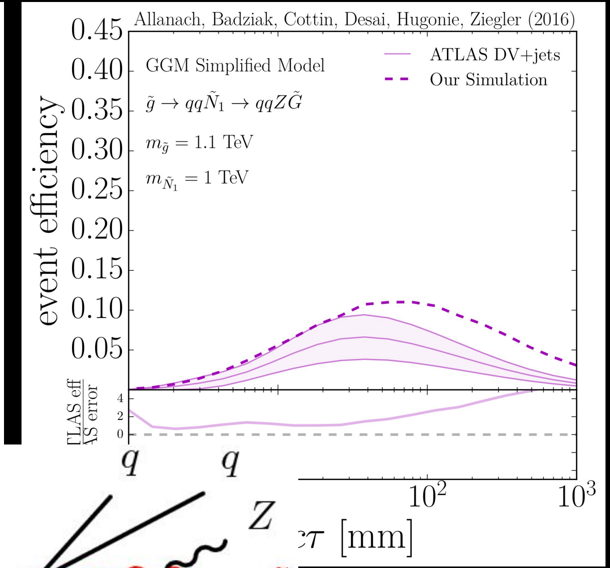
Validation against the ATLAS benchmarks

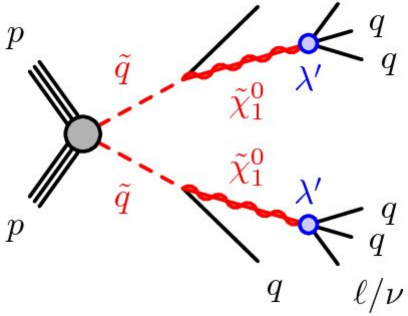
$$\varepsilon_{\rm trk} = 0.5 \times (1 - \exp(-p_T/[4.0\ \text{GeV}])) \times \exp(-z/[270\ \text{mm}]) \times \max(-0.0022 \times r_\perp/[1\ \text{mm}] + 0.8, 0)$$

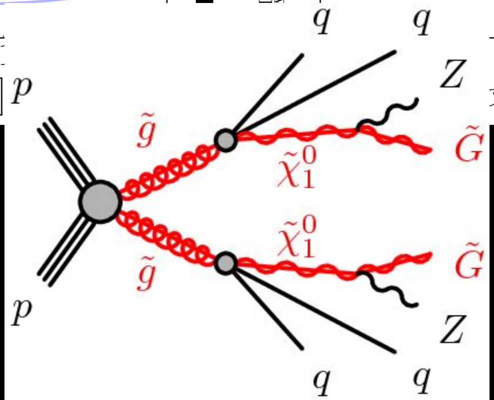
The previous functional form gives the best fit to three of the ATLAS benchmarks









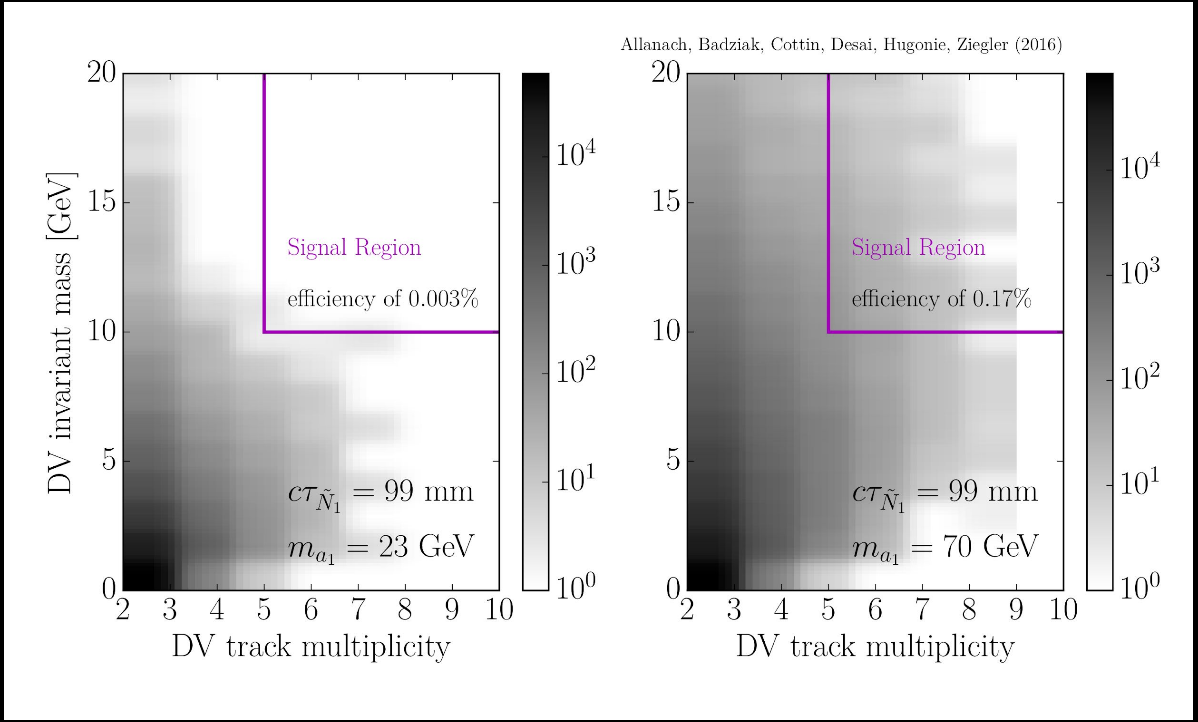


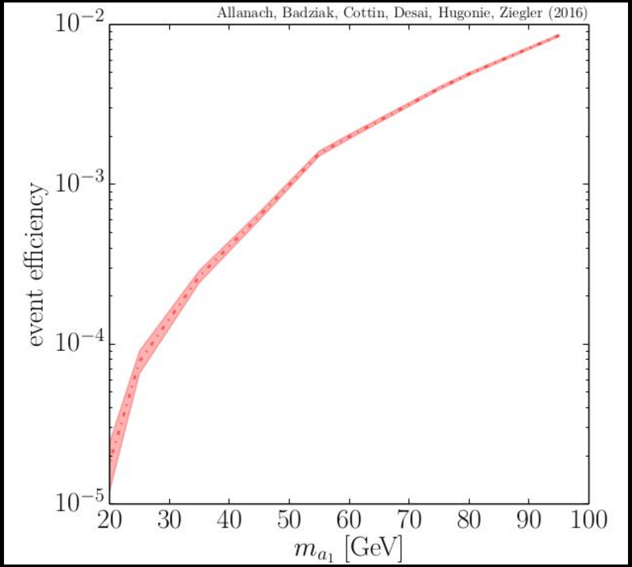
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2014-02/

[Eur.Phys.J. C76 (2016)]

Model Sensitivity

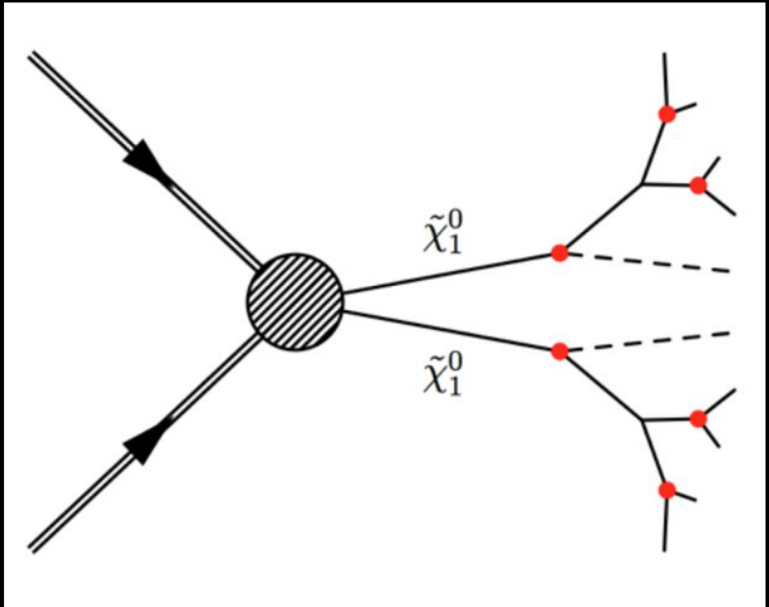
Sensitivity is affected due to low pseudo scalar mass and the presence of b's.
Low a1 mass means softer b's, which produce fewer tracks, making hard to satisfy a large vertex invariant mass





Sensitivity is affected due to the presence of additional displaced b-vertices

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



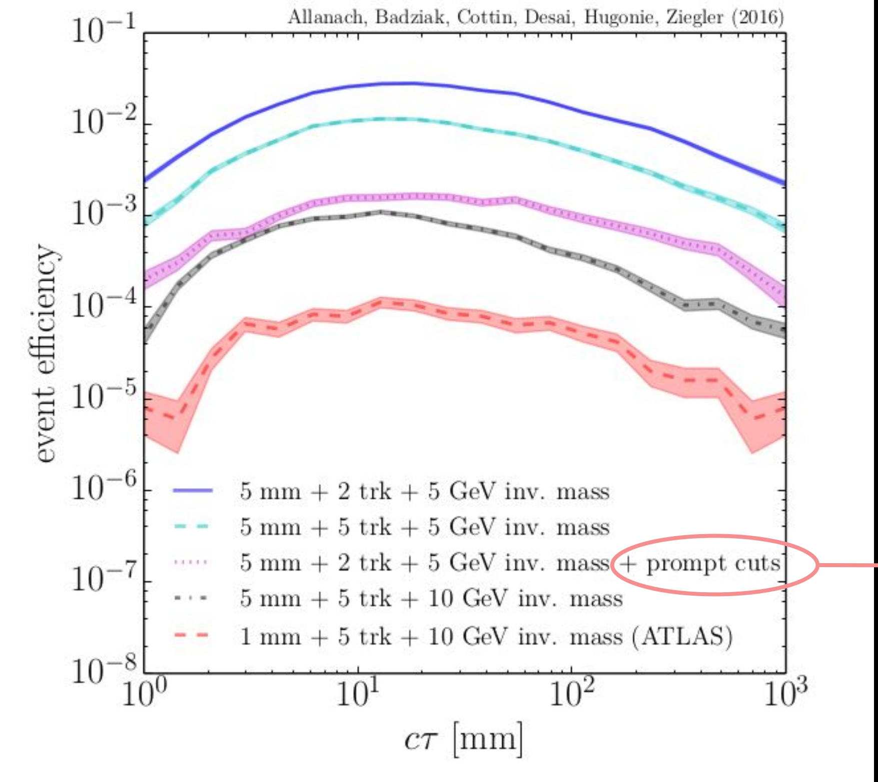
b-hadrons are themselves long-lived, and both b's from the neutralino decay have less than 5 tracks* and are almost always more than 1 mm apart. Displaced-displaced vertices !

* 18.1 (tracks after hadronisation) x 0.06 (displaced track efficiency) $=$ 1.2 visible tracks per displaced b

Tuning the DV cuts to enhance sensitivity

Eur.Phys.J. C76 (2016)

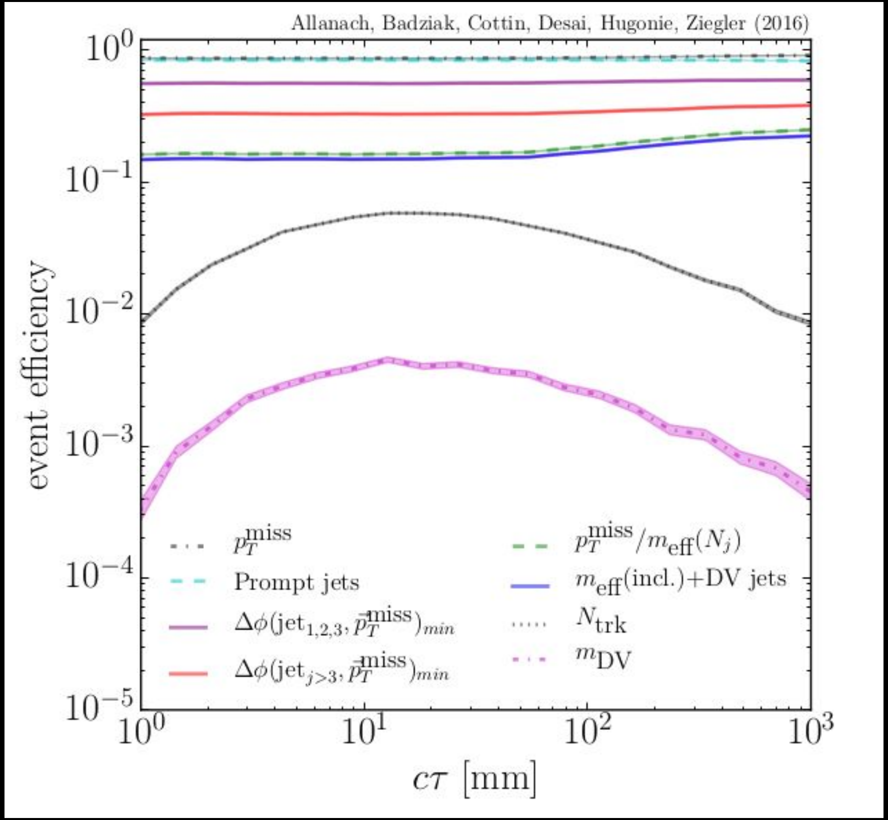
Loosen up invariant mass and track multiplicity cuts. Increase merging distance of DV reconstruction to 5mm to catch both b' in same vertex. Control backgrounds (such as random track crossings) by adding standard jet+MET prompt searches cuts (ATLAS Eur. Phys. J. C (2016) 76: 39)



$\sqrt{s}$	8 TeV		13 TeV	
Signal region	4jt-8	6jt-8	4jt-13	6jt-13
p_T^{miss}/GeV >	160	160	200	200
$p_T(j_1)$/GeV >	130	130	200	200
$p_T(j_2)$/GeV >	60	60	100	100
$p_T(j_3)$/GeV >	60	60	100	100
$p_T(j_4)$/GeV >	60	60	100	100
$p_T(j_5)$/GeV >	–	60	–	50
$p_T(j_6)$/GeV >	–	60	–	50
$\Delta\phi(\text{jet}_{1,2,3}, \mathbf{p}_T^{miss})_{min}$ >	0.4			
$\Delta\phi(\text{jet}_{j>3}, \mathbf{p}_T^{miss})_{min}$ >	0.2			
$p_T^{miss}/m_{eff}(N_j)$ >	0.25		0.2	
m_{eff}(incl.)/GeV >	2200	1500	2200	2000
σ_{95}^{obs} (fb)	0.15	0.32	2.7	1.6

Eur.Phys.J. C76 (2016)

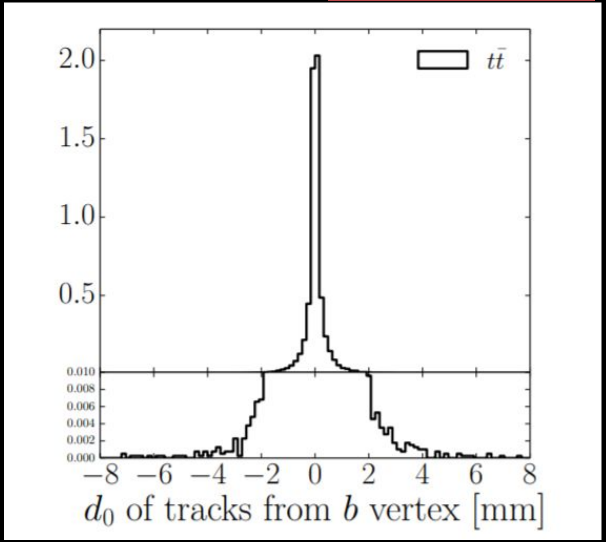
Recommendations for DV searches @ 13 TeV



DVL+4jt region gives eff ~ 0.2% at benchmark

Ideal to relax cuts further, but doing so requires a full estimation from DV background (heavy flavour, material interactions and random crossing of tracks)
Estimation from heavy flavour decays gives zero events in 3.2 fb-1.

G. Cottin 10.17863/CAM.12237



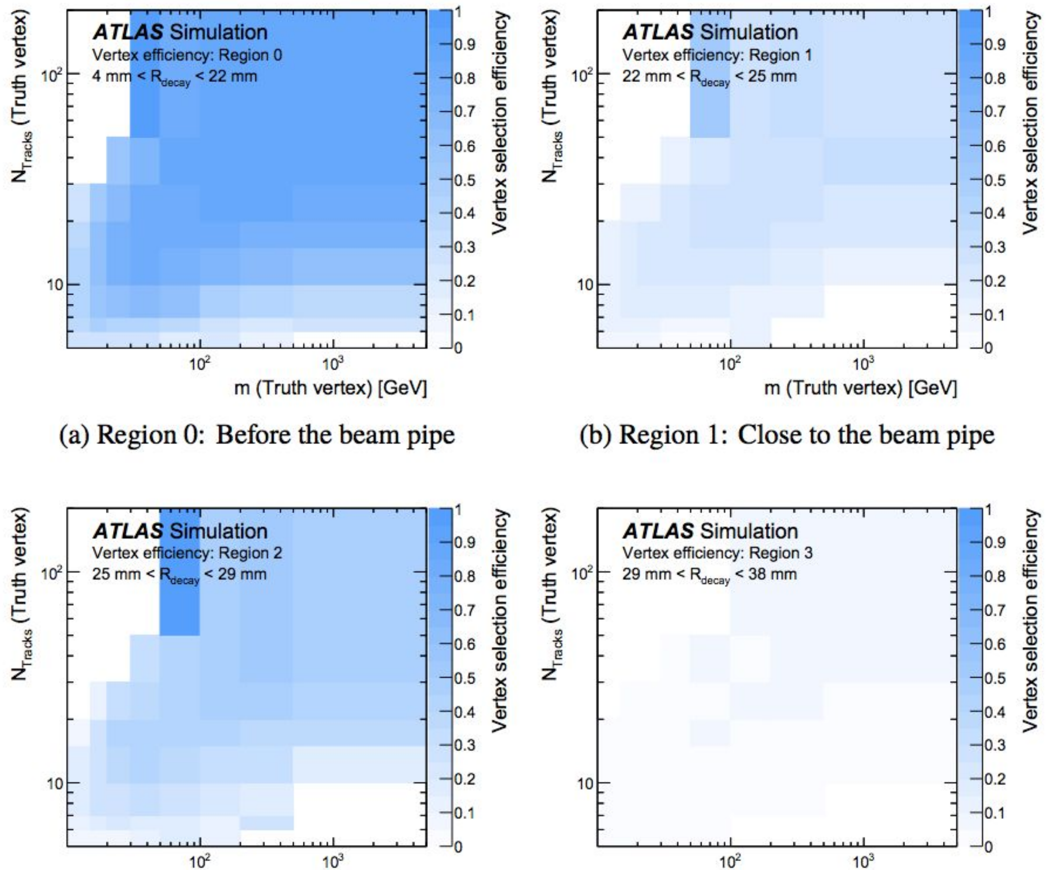
Can discover NMSSM+GM with 100/fb @13 TeV.
This is better than a prompt strategy alone! Further bkg. optimizations motivates experimental studies !

Relevant updates to the ATLAS DV search @ 13 TeV [Phys. Rev. D 92, 072004 (2015)]

Public ATLAS efficiency grids at 13 TeV to model detector response to DVs.

Can be applied to truth-level MC (nTrk, mDV, rDV) instead of track efficiency parametrization we did

NOTE: These maps assume all tracks from LLP decay are prompt. So would need much care if 3rd gen. comes from the DV (ex. we avoided this in : G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D97 (2018))



(a) Region 0: Before the beam pipe

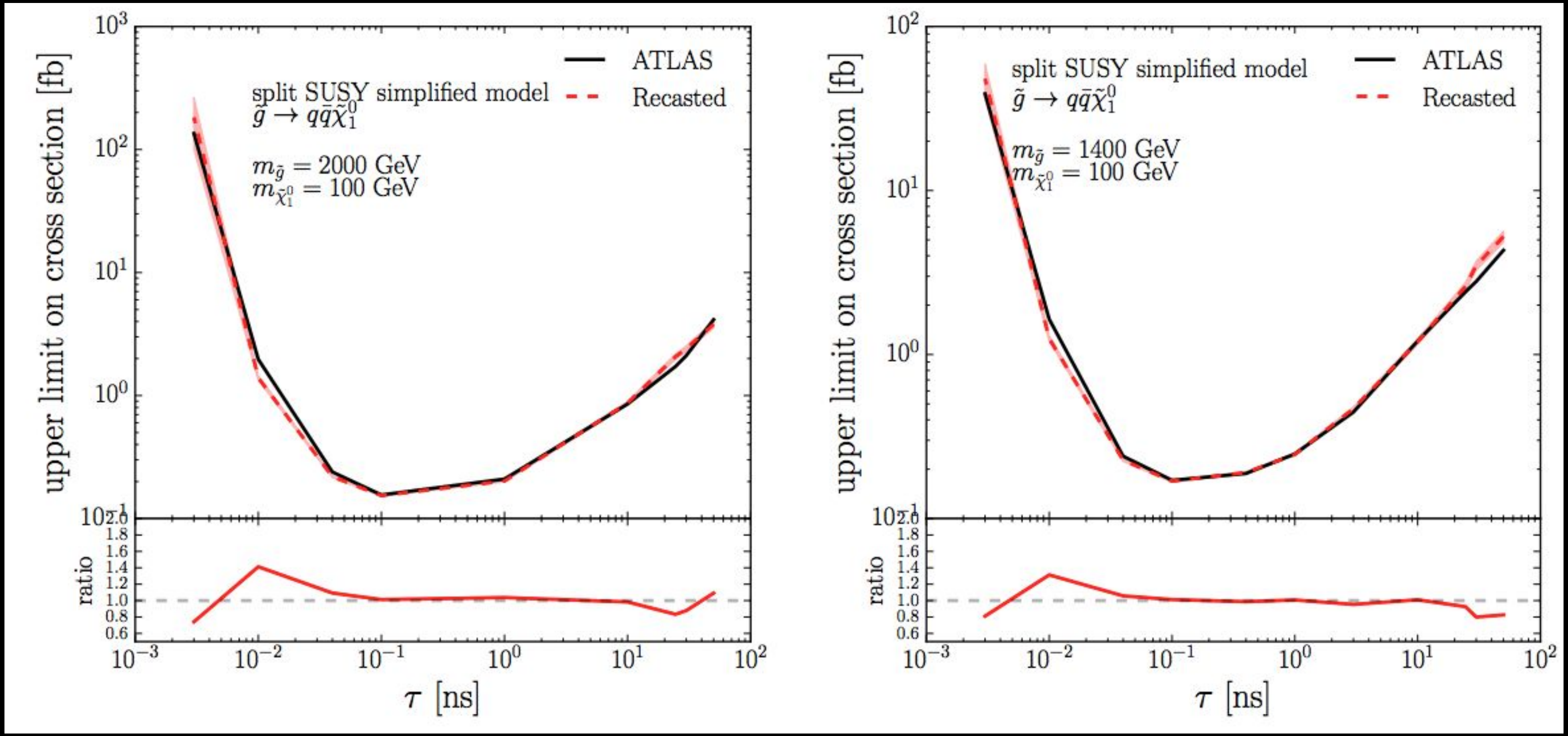
(b) Region 1: Close to the beam pipe

(c) Region 2: Before the IBL

(d) Region 3: Close to the IBL

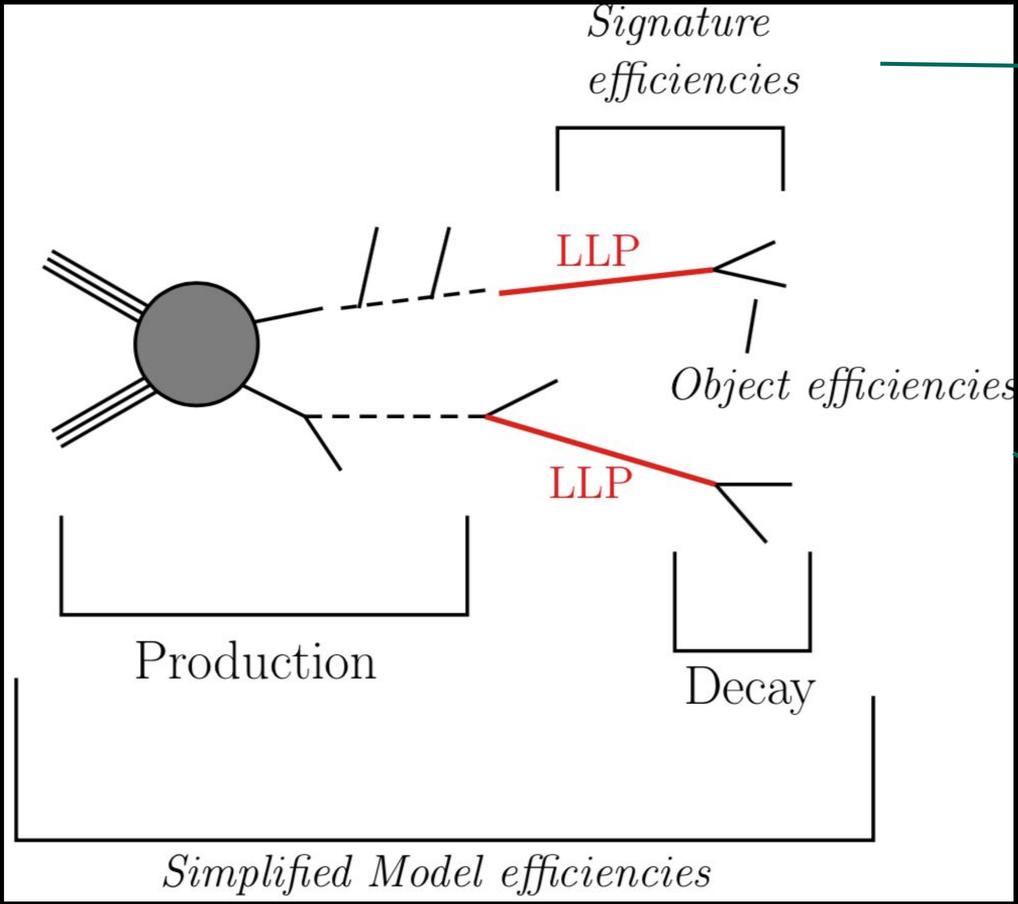
Improvements in the available experimental information makes the DV search validation much straightforward!

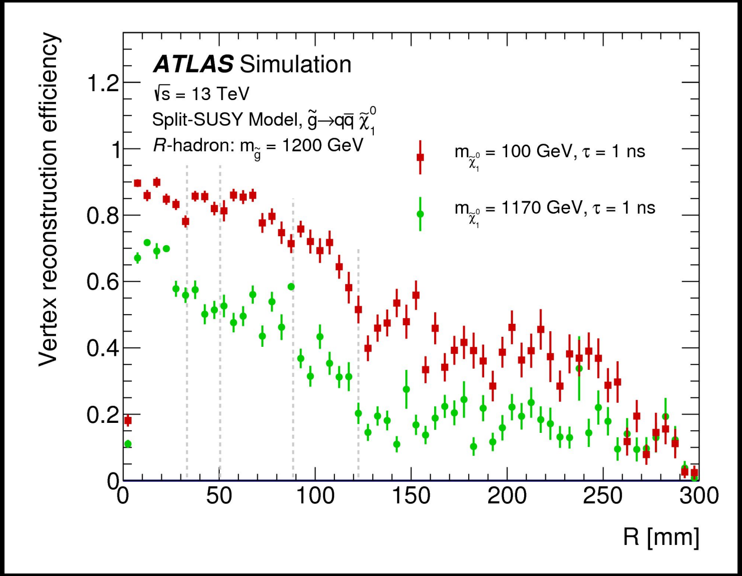
Limits Looking MUCH alike for Les Houches 2018 ! G. Cottin, N. Desai, J. Heisig and A. Lessa ([1803.10379] C17-06-05.2)



Lessons Learned from Recast: Different levels of Information

arXiv:1710.04901



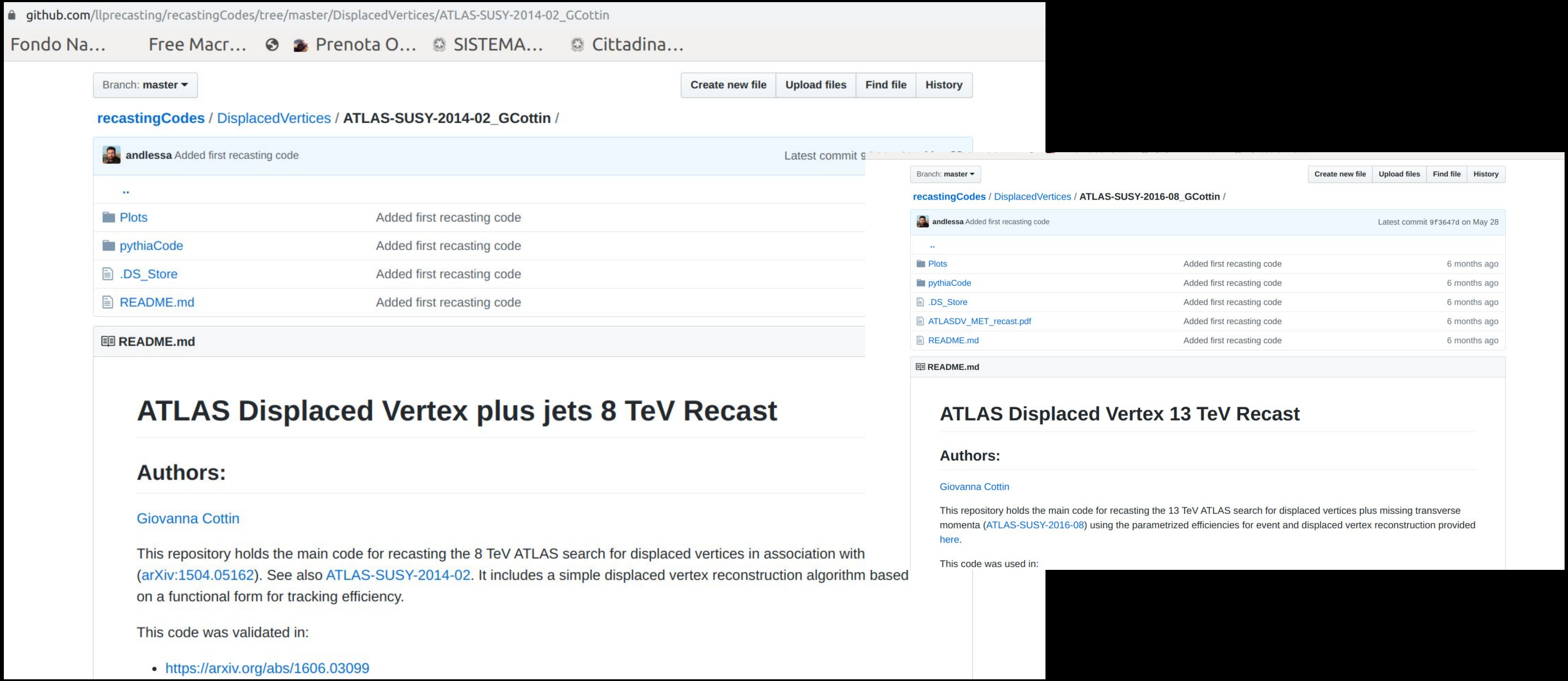


$$\varepsilon_{\mathrm{trk}} = 0.5 \times \left(1 - \exp\left(\frac{-p_T}{4.0\ \mathrm{GeV}}\right)\right) \times \exp\left(\frac{-z_{\mathrm{DV}}}{270\ \mathrm{mm}}\right) \times \max\left(-0.0022 \times \frac{r_{\mathrm{DV}}}{1\ \mathrm{mm}} + 0.8, 0\right),$$

LHC-LLP community whitepaper
arXiv:1903.04497

Going Open : LLP GitHub with these Reinterpretations !

An LHC LLP Community Initiative



Summary

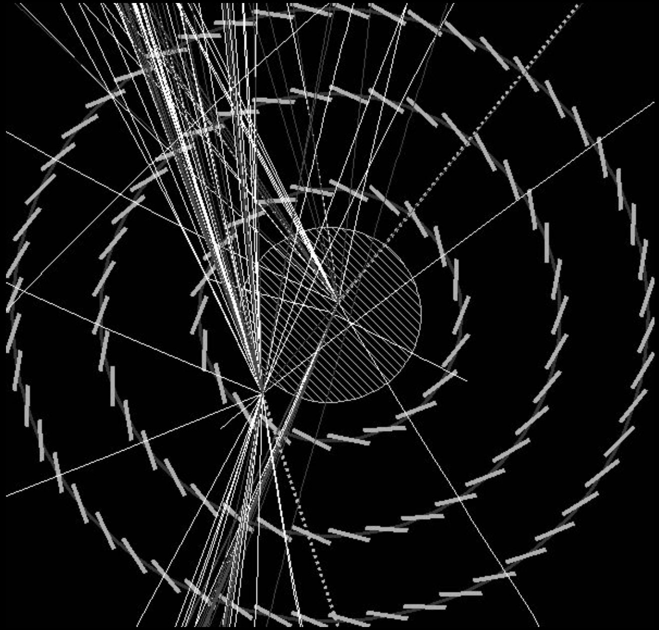
We have applied LHC constrains on a NMGMSB model with light sparticles producing displaced decays to b-quarks in the final state

There is low sensitivity for current displaced LHC searches. Low pseudo scalar mass and b-quarks affects efficiency dramatically ! Can have signatures of ‘displaced-displaced’ vertices. A larger merging requirement (5mm) helps merge the two b’s. A higher mass would produce more collimated daughters and b-hadron vertices are more likely to be close to each other. Relaxed DV+prompt cuts boosts the efficiency. This can get better with proper bkg. studies

Long-lived/displaced searches are very challenging for LHC experiments. More public information ideal for phenomenologists trying to recast (special care with 3rd gen on how to use the available information). Several recommendations for the presentation of LLP search results in our whitepaper arXiv:1903.04497!

Scope for improvement from our side as well (ex. LLP Recast GitHub going public to help the community).

Backup



How to get a natural 125 GeV Higgs in SUSY ?

	Naturally accomodate a 125 GeV Higgs via	with Gauge Mediation
MSSM	**large At**	**large At can not happen without new Higgs-messenger couplings**
NMSSM	**new contributions to Higgs mass**	**soft terms are too small, unless direct Singlet-messengers couplings are introduced**

this talk,
DGS Model !

Motivations for NMSSM

In the NMSSM, the supersymmetric Higgs mass parameter is promoted to a gauge-singlet superfield S

$$\mu \hat{H}_u \hat{H}_d \longrightarrow \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{k\hat{S}^3}{3}$$

The NMSSM solves the μ problem, which is the puzzle of why the SUSY mass scale is of the same order of the SUSY breaking scale if they have a conceptually different origin?

The problem is solved in the NMSSM since an effective term is generated

$$\mu_{eff} = \frac{\lambda v_s}{\sqrt{2}} \sim Q_{EW}$$

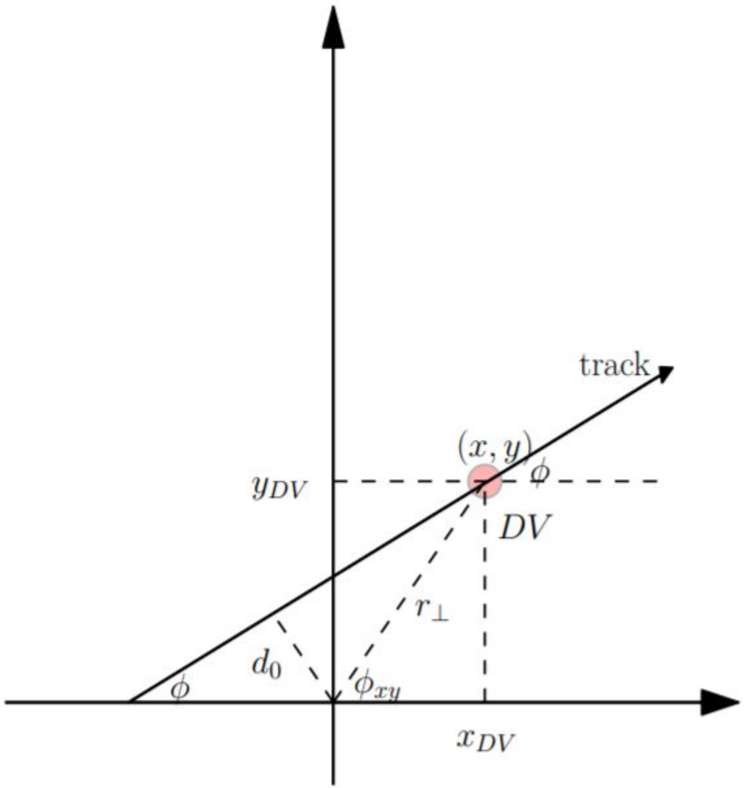
The vev is determined by minimizing a potential that depends on soft supersymmetry-breaking terms. So in this way, the value of the effective parameter is no longer conceptually distinct from the mechanism of supersymmetry breaking.

DV CutFlows

	$\sqrt{s} = 8$ TeV N	ϵ [%]	$\sqrt{s} = 13$ TeV 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_{trk}	584	3.6	544	3.4
m_{DV}	4	0.7	3	0.6

	$\sqrt{s} = 8$ 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

Structure of a Displaced Decay



$$r_\perp = \sqrt{x^2 + y^2}$$

$$\tan\phi = p_y/p_x$$

$$d_0 = r_\perp \times \sin(\phi_{xy} - \phi)$$