Recasting long-lived particle searches at the LHC with CheckMATE 2

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arXiv:2104.04542

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https://github.com/CheckMATE2/checkmate2-LLP

Nov 11th, 2021

Tenth workshop of the LLP Community

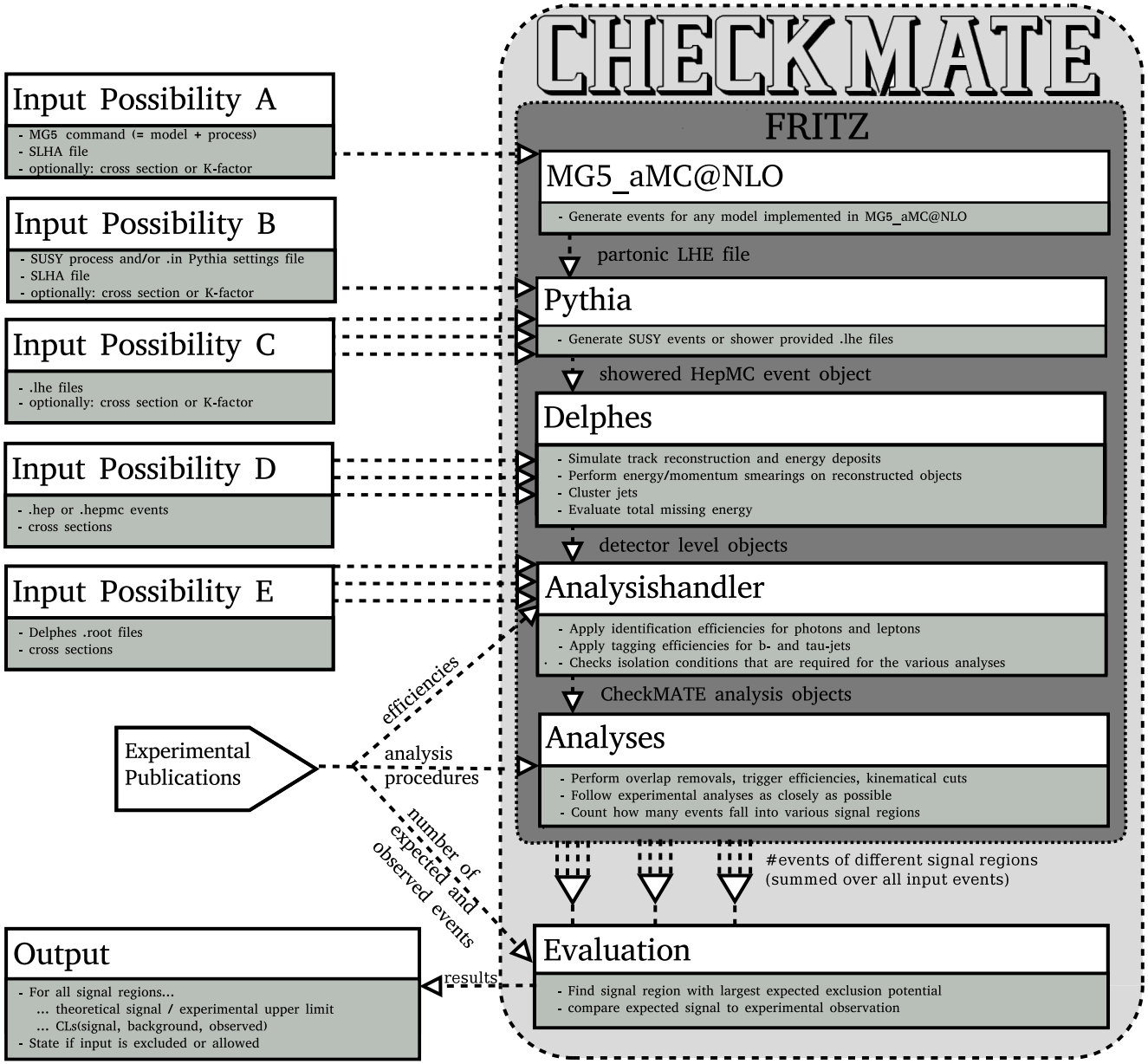
NTHU

Motivation

- Experimentalists have performed multiple LLP searches
- Experimental papers constrained limited class of models only

Recast:

1. Follow event selections of experimental searches step by step to reproduce the published cutflow and exclusion limits (validation)
2. Apply the same search on your favorite new-physics model to get constraints (reinterpretation)
3. Focus on the recasting tool `CheckMATE2`



arXiv:1611.09856

Identification of the LLPs at the detector level

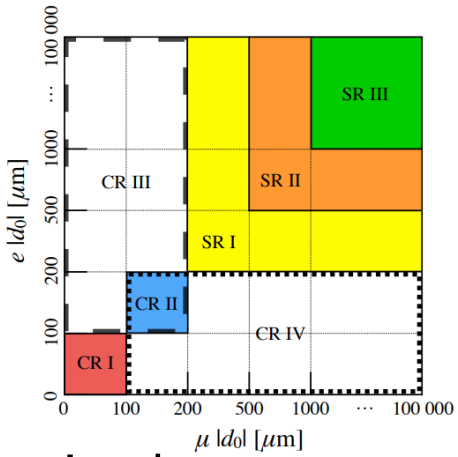
- Different from recasting prompt searches
- There are no standard LLP identification algorithms like those available for the identification of standard objects, such as leptons, b- and τ-tagged jets
- For now, apply the signal efficiencies published by the experimental collaborations on truth-level objects for the recast

Recast of 5 LLP searches

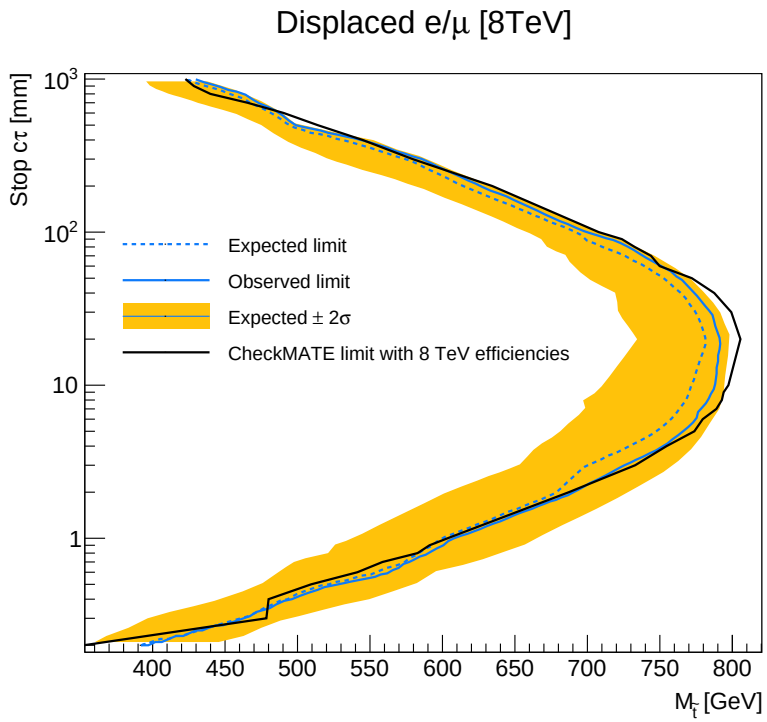
1. *Displaced Leptons* (CMS, arXiv:1409.4789, CMS-PAS-EXO-16-022)
2. *Displaced Vertex + MET* (ATLAS, arXiv:1710.04901)
3. *Displaced Vertex + μ* (ATLAS, arXiv:2003.11956)
4. *Heavy Charged Particles* (ATLAS, arXiv:1902.01636)
5. *Disappearing track* (ATLAS,arXiv:1712.02118)

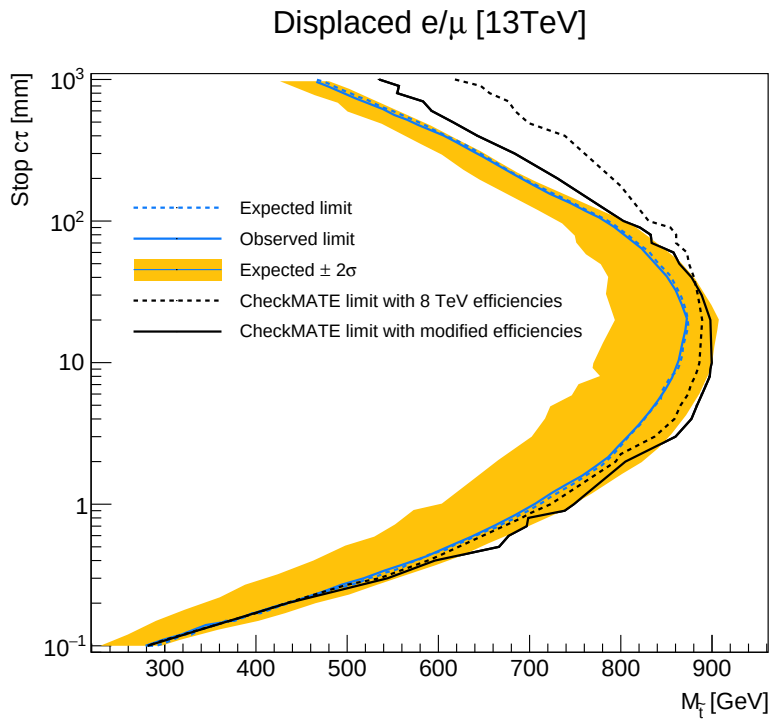
Displaced leptons searches at CMS

- arXiv:1409.4789: 8 TeV, 19.7 fb^{-1}
- CMS-PAS-EXO-16-022: 13 TeV, 2.6 fb^{-1}
- $pp \to \tilde{t}_1 \tilde{t}_1^*,\ \tilde{t}_1^{(*)} \to e/\mu + b$ (RPV)

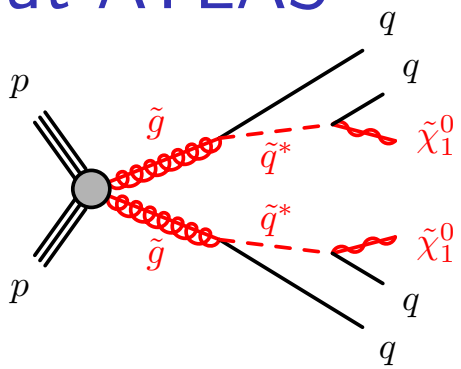


- Require exactly one e and one μ with opposite electric charges





Displaced vertex + MET searches at ATLAS



- arXiv:1710.04901: 13 TeV, 32.8 fb^{-1}

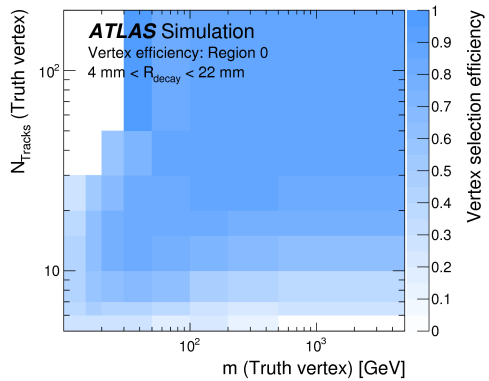
Event selections:

- Split SUSY
- $pp \to \tilde{g}\tilde{g}$ long-lived gluino decaying to light quarks and stable $\tilde{\chi}_1^0$
- Require large missing E_T at the truth-level
- DV reconstruction: ≥ 1 DV in the fiducial volume, containing ≥ 5 stable and charged decay products, at the truth-level

- Applications of parameterized efficiencies for:

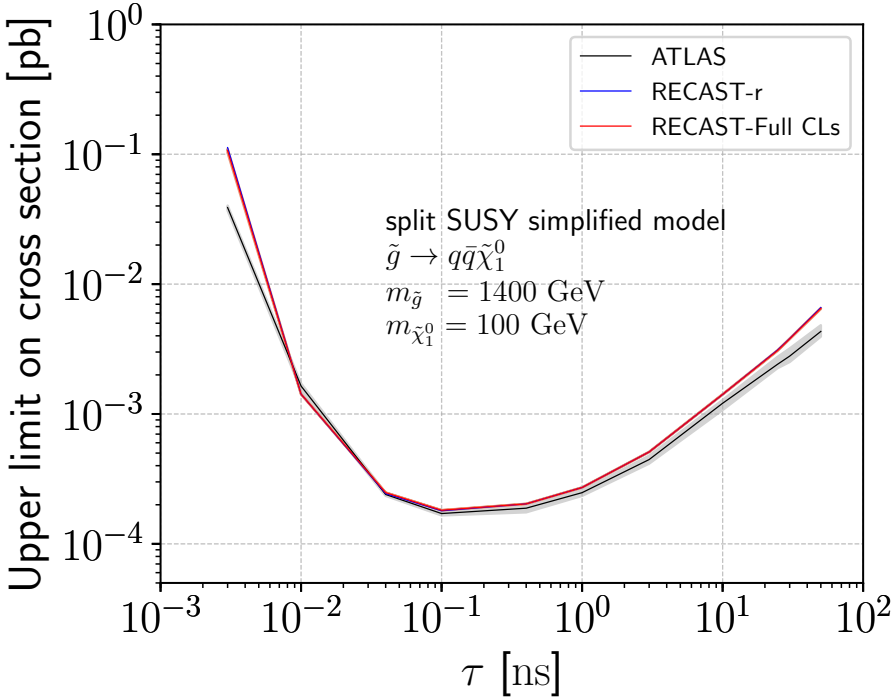
1) correcting $E^{\text{miss}}_{\text{T,true}}$,
2) reconstructing the DV,

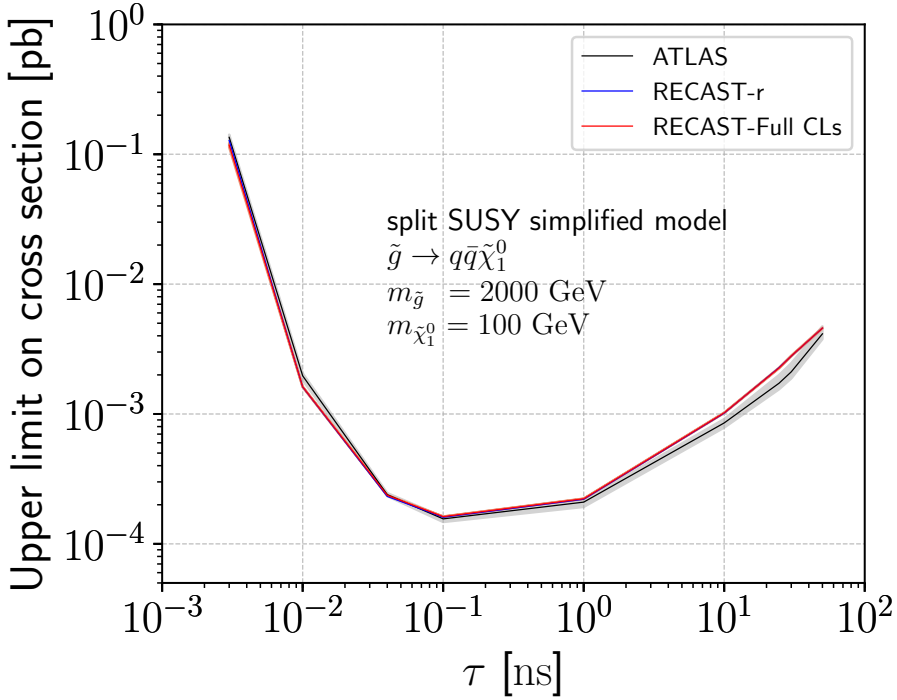
provided by the experimental collaboration



Displaced vertex + MET searches: results

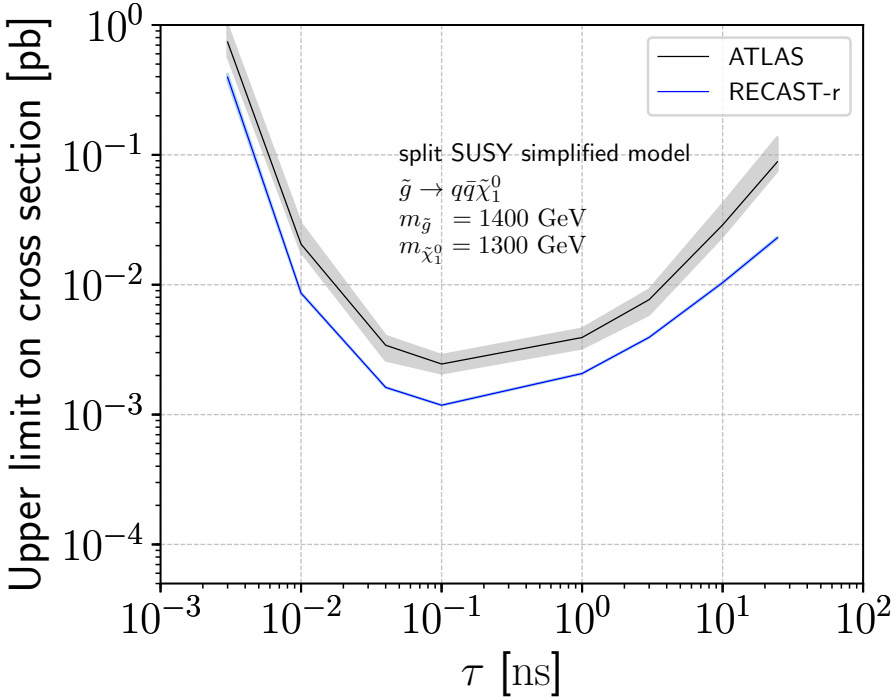
Satisfactory performance of the recast strategy in scenarios involving a sizable mass-splitting between the LLP and the LSP:

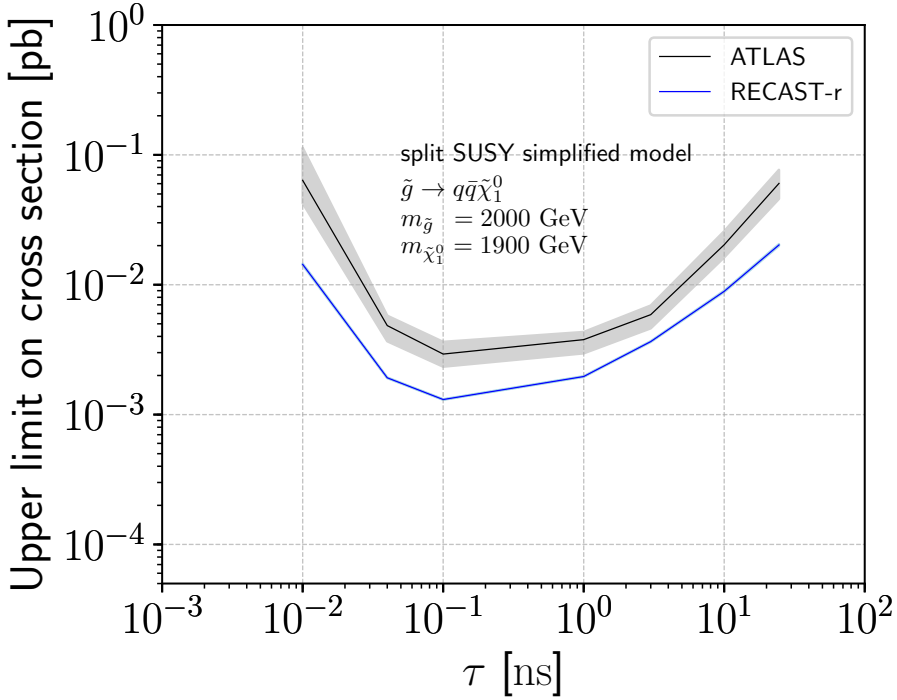




Displaced vertex + MET searches: inconsistencies

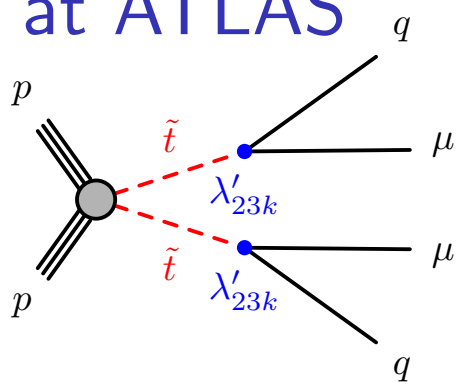
A compressed spectrum → large deviations: (seen also in other groups)





Maybe due to the impact of R-hadronization on the definition of the MET

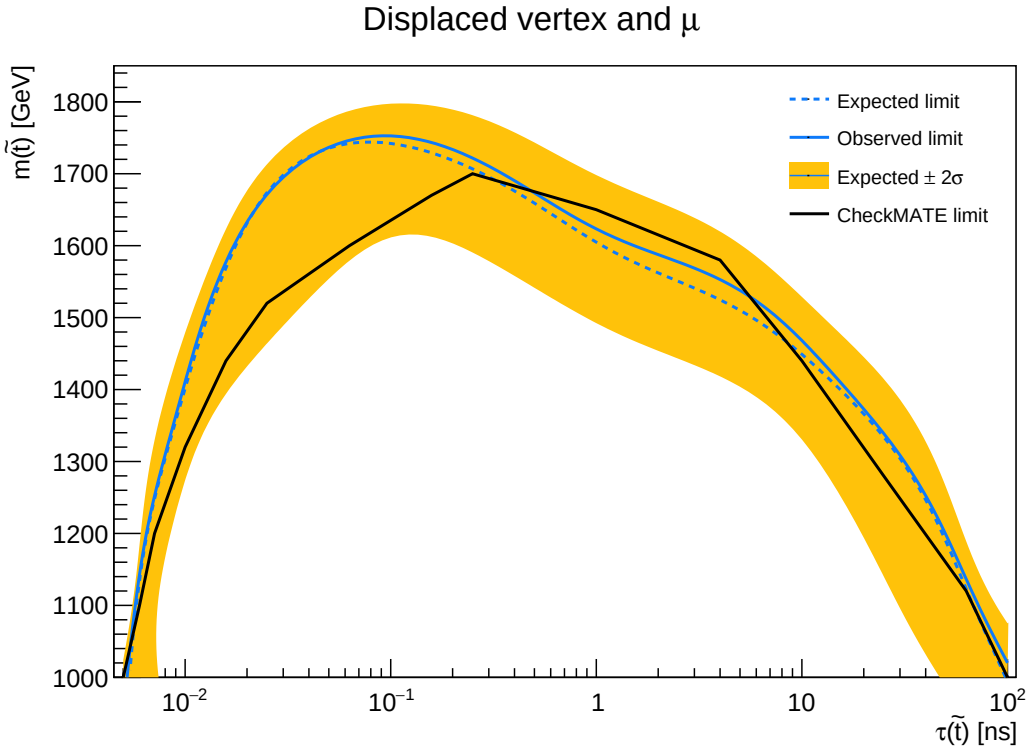
Displaced vertex + muon searches at ATLAS



- arXiv:2003.11956: 13 TeV, 139 fb^{-1}

Event selections:

- $pp \to \tilde{t}_1 \tilde{t}_1$ with the stops displaced-decaying to a light quark and a muon via a RPV vertex



Heavy charged particles searches at ATLAS

- arXiv:1902.01636: 13 TeV, 36.1 fb^{-1}
- Implemented EW searches: $\tilde{\chi}^+\tilde{\chi}^-$ & $\tilde{\tau}^+\tilde{\tau}^-$ stable at the detector level
- Charginos (∼winos) in mAMSB and Staus in GMSB
- HCP passed the full ATLAS detector before decaying
- $E_{\text{T}}^{\text{miss}}$ and single-muon triggers with efficiencies provided by ATLAS

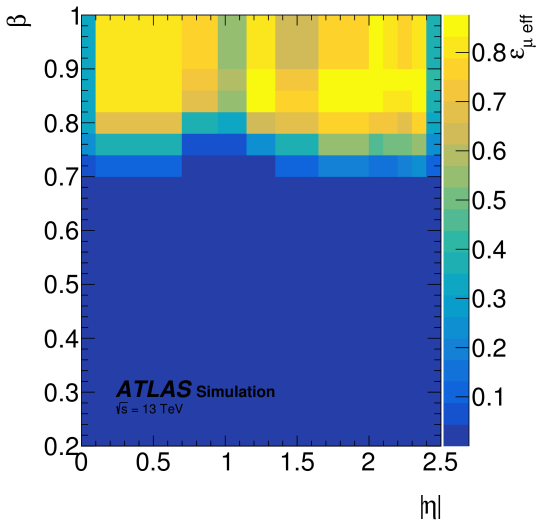


Figure: Single-muon trigger efficiency

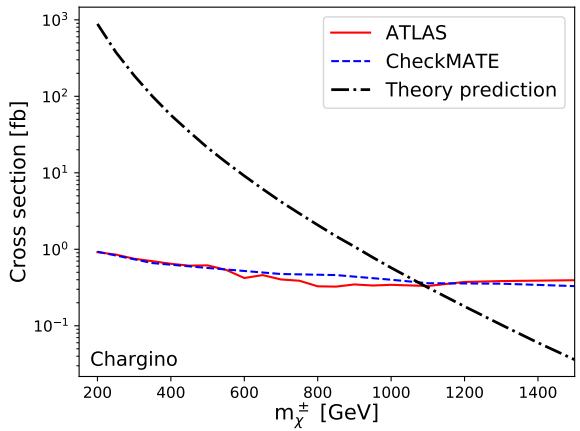


Figure: Excluded $m_{\chi^\pm} \lesssim 1090$ GeV

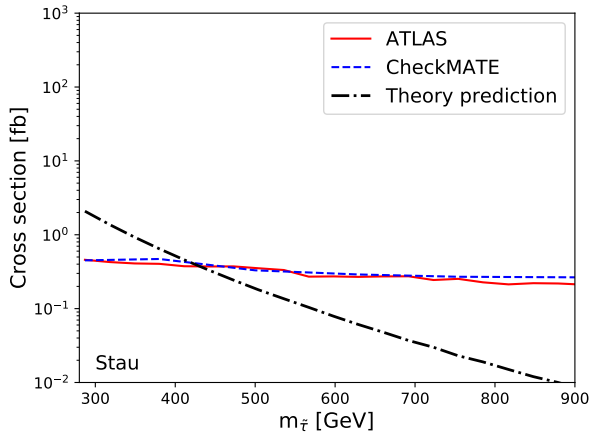
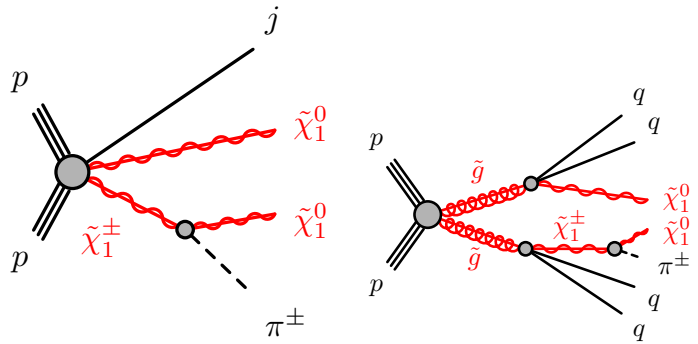
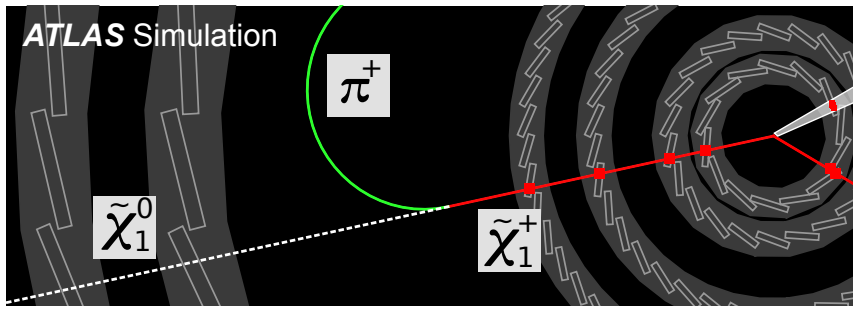


Figure: Excluded $m_{\tilde{\tau}} \lesssim 430$ GeV

Disappearing track searches at ATLAS

- arXiv:1712.02118: 13 TeV, 36.1 fb^{-1}
- Chargino and neutralino nearly mass degenerate, wino triplet





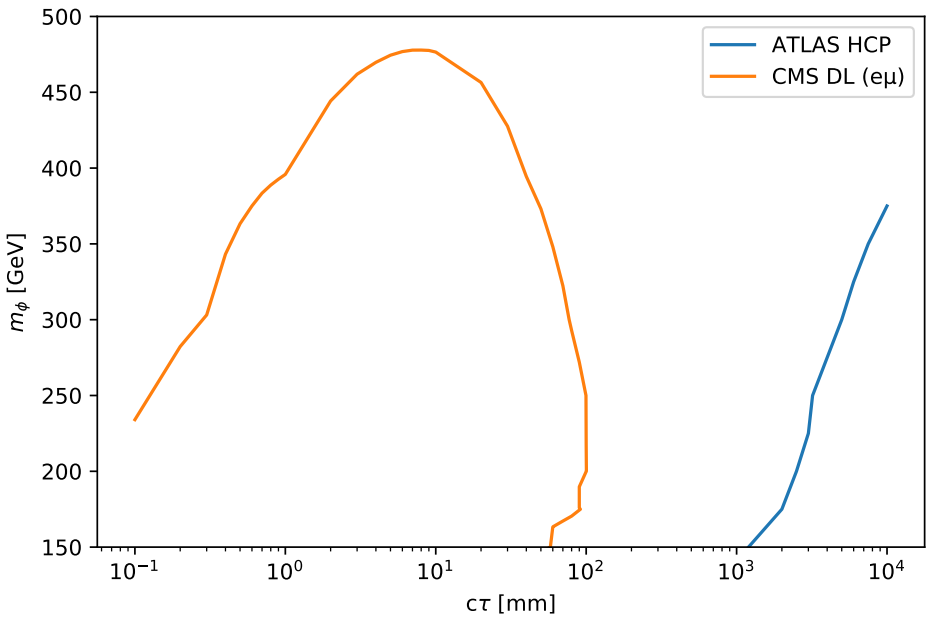
- Benchmark points for the winos:
  - EW: $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (400\,\text{GeV},\ 0.2\,\text{ns})$
  - Strong: $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (1600\,\text{GeV},\ 500\,\text{GeV},\ 0.2\,\text{ns})$

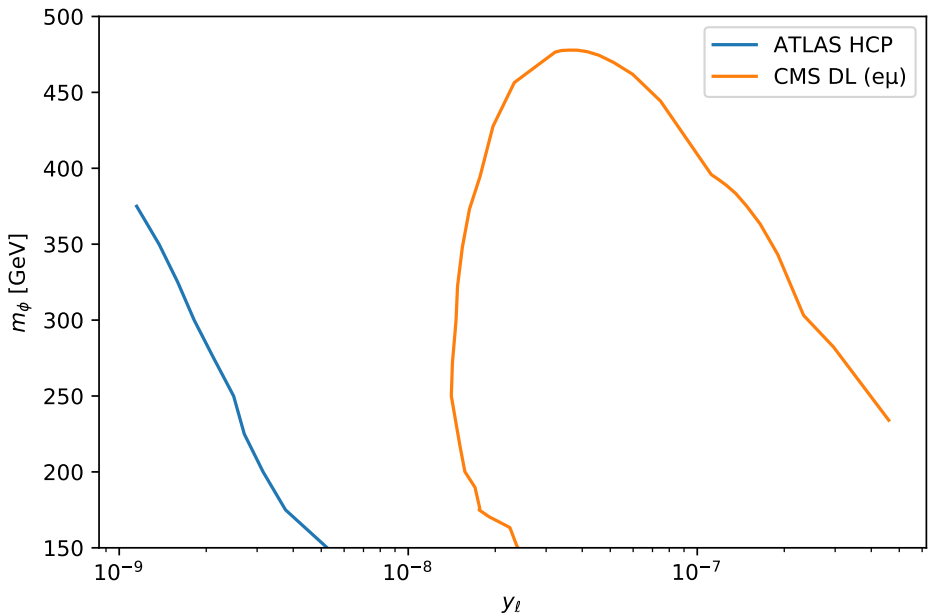
	CM $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$	CM $\tilde{\chi}_1^+\tilde{\chi}_1^0$	CM $\tilde{\chi}_1^-\tilde{\chi}_1^0$	CM all channels	ATLAS
Trigger	445.1	624.0	274,4	1343.5	1276
Lepton Veto	423.4	608.5	267.3	1308.2	1181
MET and jet requirements	164.2	229.6	101.0	494.8	579
EW SR	5.2	4.4	1.6	11.2	13.5

	CM	ATLAS
Trigger	289	285
Lepton Veto	277	278
MET and jet requirements	216	202
strong SR	11	11

Electroweak LLP

- A scalar ϕ: $U(1)_Y$, like a l_R, and a SM-singlet Dirac fermion (χ)
- $y_\ell \phi \bar{\chi} \ell_R$, toy model of e.g., DM
- $pp \to \phi^* \phi$ with $\phi \to l\chi$ and χ being stable
- $y_e = y_\mu, m_\chi = 10$ GeV

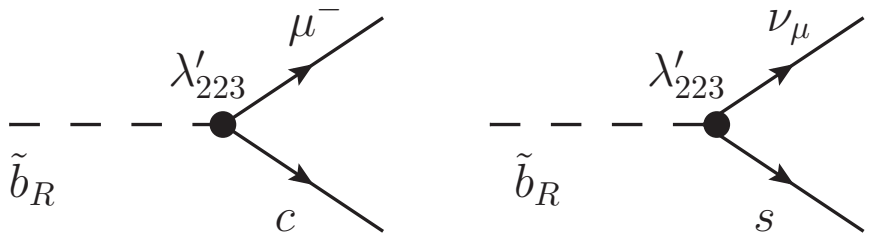




- Current prompt limits are at 250 GeV with full run 2 data
- Disappearing track search insensitive

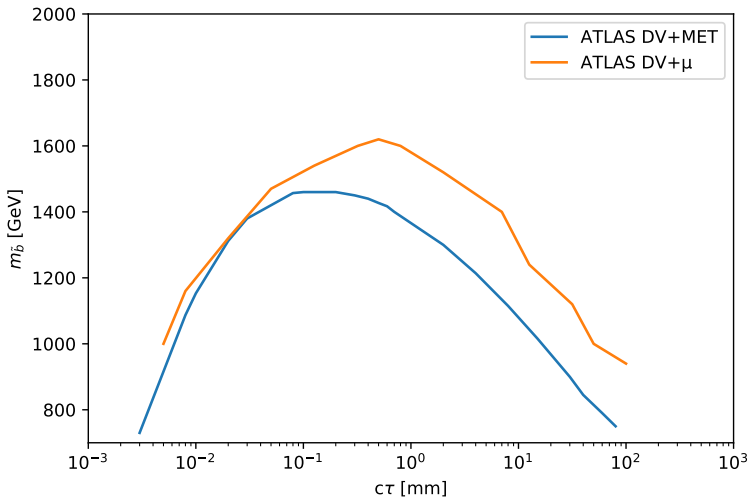
Strong LLP

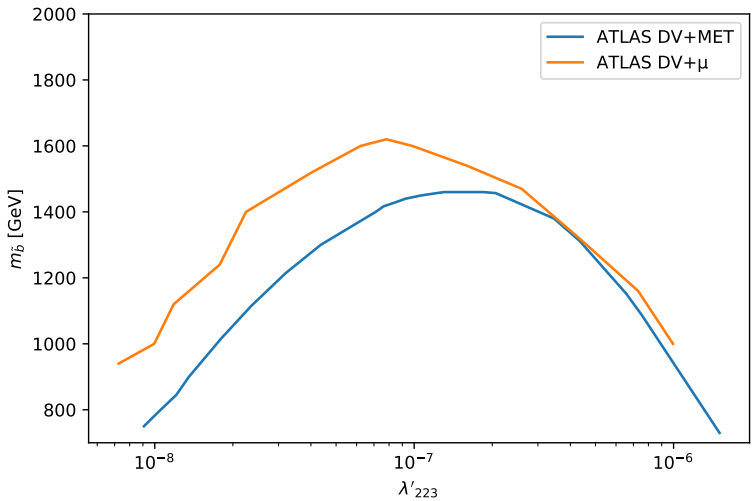
- $\lambda'_{223} L_2 Q_2 \bar{D}_3$, long-lived right-handed sbottom: $\tilde{b}_1 \to \mu c$ or $\tilde{b}_1 \to \nu s$



connected to B-anomalies

- $pp \to g \to \tilde{b}_1 \tilde{b}_1^*$





- RPC sbottom prompt limit: 1270 GeV ($\tilde{b} \to b\chi$, χ massless)
- Not taking the HCP search given uncertainty in $\tilde{b}$ hadronization
- Disappearing-track search insensitive because of hard displaced jets

Summary

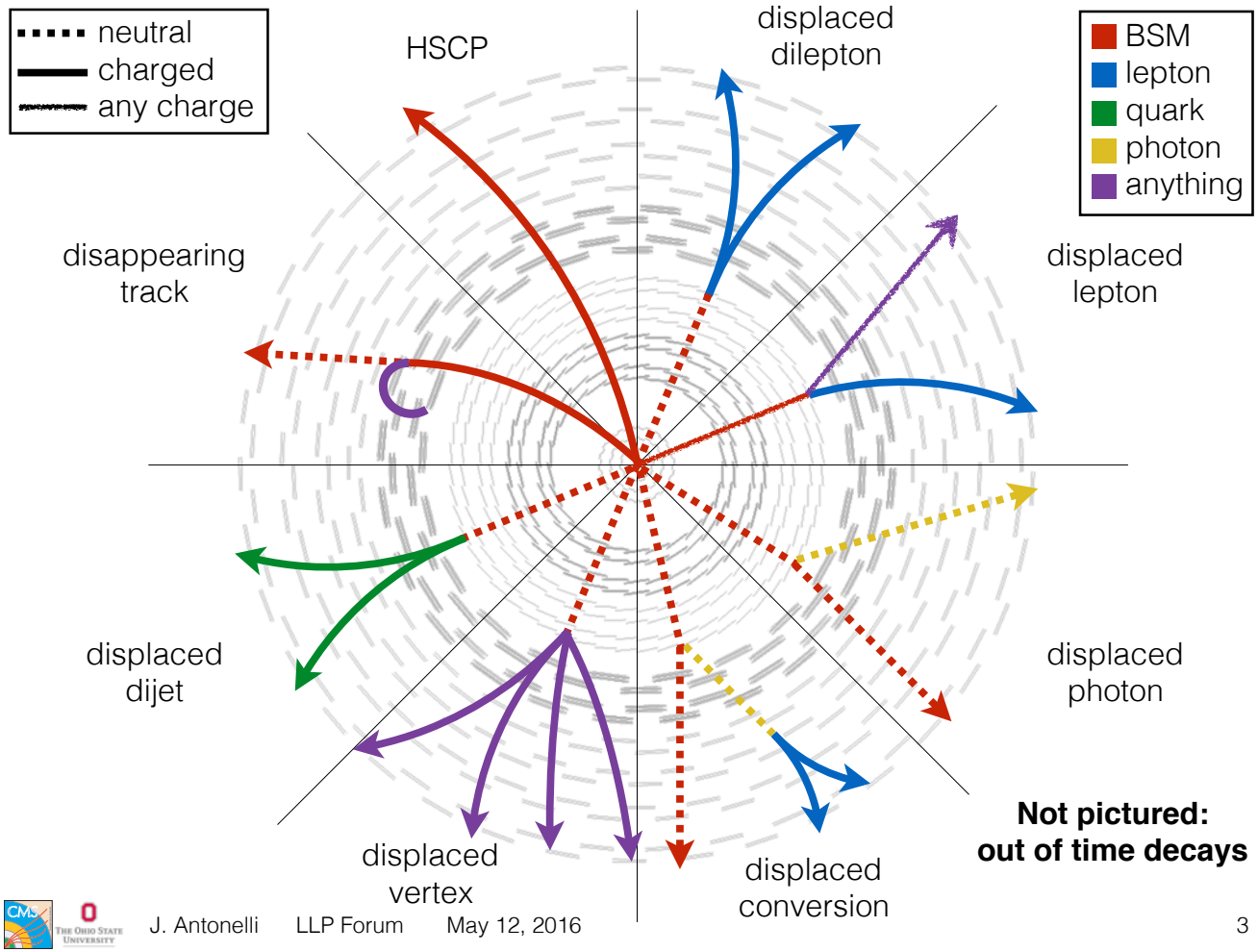
- LLP searches are becoming increasingly important
- We *recast* multiple LHC LLP searches in CheckMATE2:
- Given the absence of standardized objects in such searches, such recast depends heavily on the parameterized efficiencies published by the experiments to be applied on truth-level objects
- Validation shown to give comparatively good results
- Considered two toy models of LLPs to exemplify the constraining power and complementarity of these searches

Thank You!

Back-up slides

Collider signatures of LLPs

- LLP signatures depend on charge, decay modes, & lifetime, . . .
- Exponential distribution of decay position



J. Antonelli, talk @LHC LLP Mini-workshop May 12, 2016

(Incomplete) categorization of LLP signatures

- Categorization according to the LLP decay modes:
  1. neutral LLP $\rightarrow$ invisible or neutral stable particles: *missing momentum*
  2. neutral LLP $\rightarrow$ charged leptons: *leptons with large impact parameter (i.e. "displaced" leptons)*
  3. neutral LLP $\rightarrow$ coloured particles: *displaced vertices, or emerging jets*
  4. stable, charged LLP: *charged track (with its time of flight dependent on mass and boost)*
  5. charged LLP $\rightarrow$ invisible: *"disappearing" track*
  6. charged LLP $\rightarrow$ other charged stable object(s): *kink-track or displaced vertex*

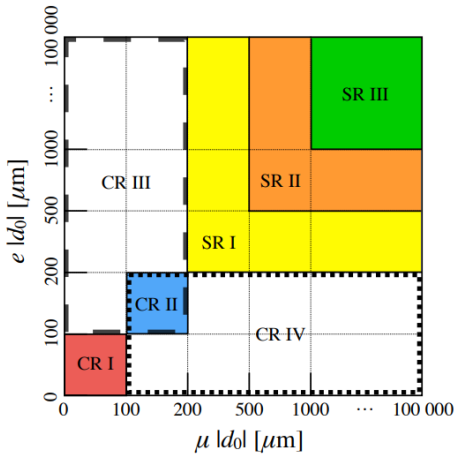
CheckMATE in one slide

- CheckMATE: a public tool that allows the reinterpretation of a wide variety of ATLAS and CMS search results for new physics models
- Consists of an engine written in C++ that runs each analysis cut-by-cut in order to assess the final number of expected events satisfying the requirements of the corresponding analysis
- The engine can also use external libraries like Madgraph5 and Pythia8 in order to generate events, and Delphes3 for detector simulation
- The User Interface and the statistical analyses are provided by a collection of Python scripts (including AnalysisManager that guides the users through the implementation of their own analyses)

$$r = \frac{S - 1.64 \cdot \Delta S}{S95} \rightarrow \begin{cases} r \geq 1 \Rightarrow \text{excluded} \\ r < 1 \Rightarrow \text{allowed} \end{cases}$$

Displaced leptons searches at CMS

- arXiv:1409.4789: 8 TeV, 19.7 fb^{-1}
- CMS-PAS-EXO-16-022: 13 TeV, 2.6 fb^{-1}



Event selections:

- $pp \to \tilde{t}_1 \tilde{t}_1^*$, and long-lived $\tilde{t}_1^{(*)} \to e/\mu + b$ via RPV vertices
- Require exactly one e and one μ with opposite electric charges
- e and μ: high p_T and well isolated
- 3 signal regions with diff. ranges of the leptonic impact parameter d_0
- Identification and fiducial acceptances applied on generator-level events and provided by the experimental collaboration

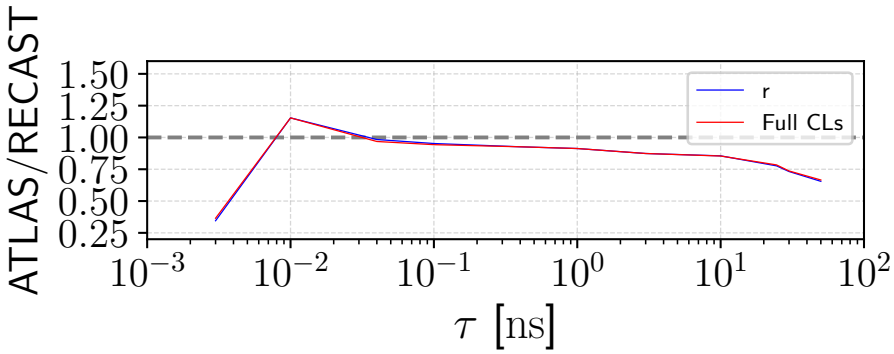
Selection criteria for the displaced vertex + MET searches

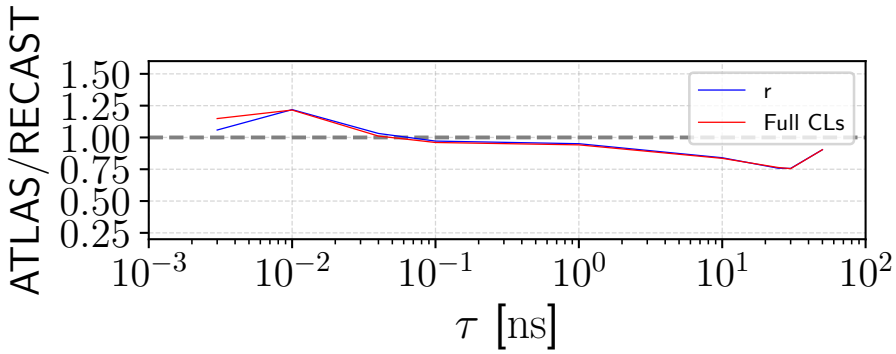
Event selections:

- Require $E^{\text{miss}}_{\text{T,true}} > 200$ GeV
- Jet requirements on 75% of the events:
  - either one truth jet with $p_T > 70$ GeV or ≥ 2 jets with $p_T > 25$ GeV, satisfying in both cases a trackless requirement:
    - Scalar sum of the charged particle p_T in the jet should not exceed 5 GeV for particles with small impact parameter (d_0)
- Reconstruct DV from stable charged particles:
  - At least one DV in the fiducial volume
  - The DV's should contain at least 5 selected decay products, i.e. stable and charged particles with $p_T > 1$ GeV and an approximate transverse impact parameter $d_0 > 2$ mm
- Efficiencies of two origins are considered: one corrects $E^{\text{miss}}_{\text{T,true}}$ and one for the reconstruction of the DV. Both are provided by the experimental collaboration

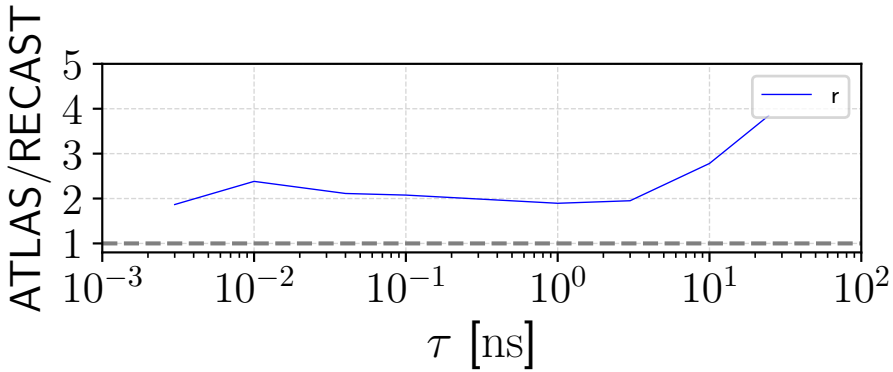
Exclusion limits' ratios

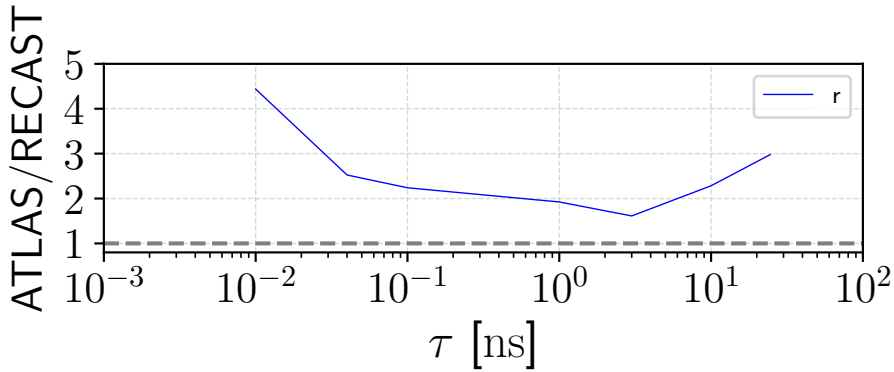
First spectrum:





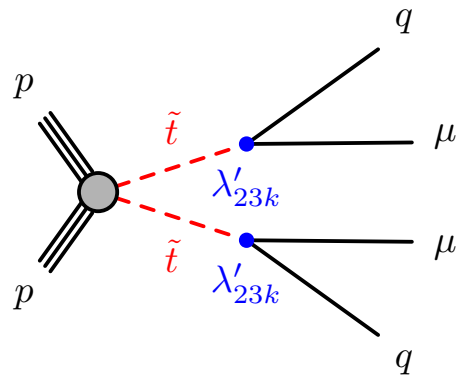
Compressed spectrum:





Displaced vertex + muon searches at ATLAS

- arXiv:2003.11956: 13 TeV, 139 fb^{-1}



Event selections:

- $pp \to \tilde{t}_1 \tilde{t}_1$ with the stops displaced-decaying to a light quark and a muon via a RPV vertex
- Two mutually exclusive trigger-based signal regions:
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ Trigger SR: large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Muon Trigger SR: muon trigger and low $E_{\mathrm{T}}^{\mathrm{miss}}$
- At least 1 DV reconstructed in the fiducial volume
- The dense detector material veto applied as a flat rejection probability on each reconstructed displaced vertex

Selection criteria for the displaced vertex + μ searches

- $pp \to \tilde{t}_1 \tilde{t}_1$ with the stops displaced-decaying to a light quark and a muon via a RPV vertex
- Two mutually exclusive trigger-based signal regions:
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ Trigger SR: $E_{\mathrm{T}}^{\mathrm{miss}} > 180$ GeV and a muon with $p_T^{\mu} > 25$ GeV
  - Muon Trigger SR: $p_T^{\mu} > 60$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} < 180$ GeV
- Muon vertex at least 2 mm away from IP
- One DV at least 4 mm away from IP, with ≥ 3 associated tracks and its visible invariant mass calculated from the four-momenta of the associated tracks $m_{\mathrm{DV}} > 20$ GeV
- DV's reconstructed internally by CheckMATE using a DVfinder class
- The material veto applied as a flat rejection probability on each reconstructed displaced vertex

Displaced vertex + muon searches: results

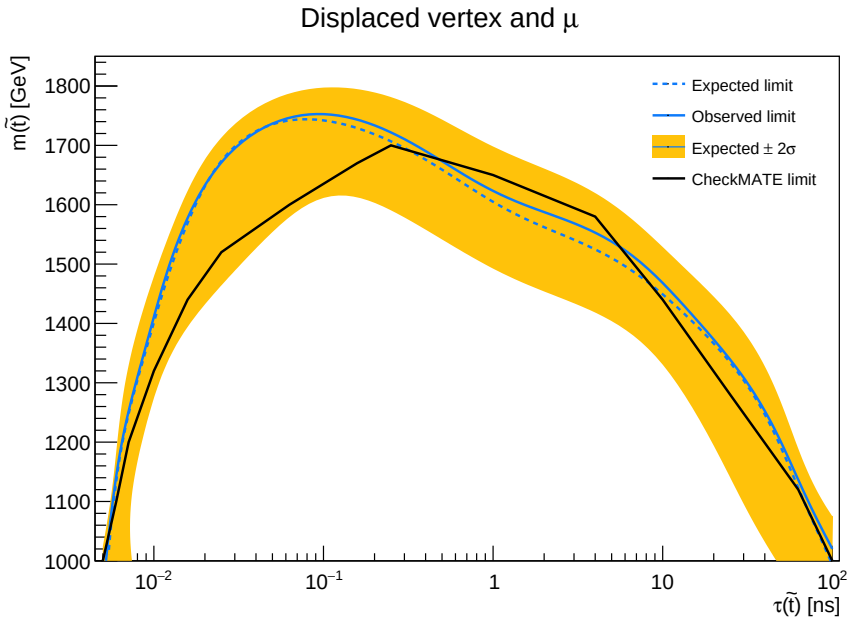


Figure: Sensitivity limits

Selection	$\tau = 0.01$ ns		$\tau = 0.1$ ns		$\tau = 1$ ns	
	ATLAS	CM	ATLAS	CM	ATLAS	CM
All	64.2	64.2	64.2	64.2	64.2	64.2
E_T^{miss} trigger	63.0	63.2	63.0	63.3	62.7	63.2
$E_T^{\text{miss}} > 180$ GeV	60.9	61.2	61.0	61.3	60.6	61.0
$\geq 1\mu$; $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$	57.8	60.8	58.7	61.0	52.5	60.6
$2 < \lvert d_0(\mu)\rvert < 300$ mm	11.3	12.8	49.1	52.5	49.5	59.2
$\lvert z_0(\mu)\rvert < 500$ mm	11.3	12.8	49.1	52.5	49.3	58.1
Fake/HF/cosmic veto	9.1	9.9	40.0	42.4	39.4	48.1
At least one DV	8.5	4.4	37.6	29.8	32.6	39.6
DV fiducial volume	8.4	3.7	37.1	29.1	31.2	32.7
Material veto	5.3	2.2	31.0	16.9	22.2	19.0
$n_{\text{tracks}}^{\text{DV}} \geq 3$	3.8	1.8	26.0	15.5	13.7	17.3
$m_{\text{DV}} > 20$ GeV	3.4	1.2	22.7	11.9	10.3	14.0

Table 8: Cutflow for the displaced vertex + muon search in the missing transverse energy SR.

Figure: cutflow for $m_{\tilde{t}} = 1.4$ TeV in MET SR.

Selection criteria for the disappearing track search

EW SR	strong SR
at least one jet with $p_T > 140$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 140$ GeV $\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}(p_T > 50\ \mathrm{GeV})) > 1.0$ cuts on charged LLP with $p_T > 100$ GeV	$p_T(j_1) > 100$ GeV, $p_T(j_2) > 50$ GeV, $p_T(j_3) > 50$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV $\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}(p_T > 50\ \mathrm{GeV})) > 0.4$ cuts on charged LLP with $p_T > 100$ GeV

Table: Summary of the selection criteria for signal events for direct electroweakino production and the strong channel channel where the chargino is produced in gluino decays.

R-parity and the RPV-MSSM

In general, the MSSM superpotential includes the following operators:

$$W_{\not R_p} = \mu_i H_u \cdot L_i + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Lepton Number Violation & Baryon Number Violation

$\Rightarrow$ too fast proton decay rate!

$\Rightarrow$ An implicit ingredient of the MSSM: R_p conservation (RPC)

$$R_p = (-1)^{3(B-L)+2S}$$

B : *baryon number*, L : *lepton number*, S : *spin*

- SM fields: $R_p = +1$, superpartners: $R_p = -1$
- Forbids all the terms in $W_{\not R_p}$
- Renders the lightest supersymmetric particle (LSP) a stable cold DM candidate

Outlook

- Standardize displaced objects into fast full-detector simulation tools such as Delphes3
- New types of LLP signature?
- Recast more collider searches in CM2 or other software frameworks
- Exploring/pushing the limits of such recast process?
- Extend the recast framework to include far-detector programs and future lepton colliders