Implementation of multi-bin searches in CheckMATE

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Most BSM searches are interpreted in terms of a small set of signal models in the original publications.

Reinterpretation of the results in terms of other BSM models require the full statistical model. ➔ Computationally very expensive and not always available.

Alternatives:

- Calculate limits with single bin signal regions. Only total event rate is needed and signal contamination in the CRs is ignored.
  Drawbacks: underestimates the true exclusion power and less robust against statistical fluctuations.
- In this talk: Use a reasonable simplification of the statistical model to reduce computational cost retaining the use of multi-binned SR bins.

CHECKMATE

Current CheckMATE version bases test on the SR with the largest expected exclusion potential. We use only a fraction of the available data which could cause a loss of sensitivity.

Our goal is to implement multibinned analysis in the CheckMATE framework.

We build a simplified statistical model based on the CheckMATE output and make the hypothesis test within the PYHF environment.

We build the simplified likelihood following the prescription in ATL-PHYS-PUB-2021-038:

- *"In the simplified likelihood introduced herein, the background model is approximated with a single background sample, representing the total SM background rate in the different analysis channels. "*

- *"The pre-fit sample rate of the total background sample is set to the total post-fit background rate obtained in the background-only fit in the full likelihood"*

- *"…the complete set of nuisance parameters in the original full likelihood is reduced to a single constrained parameter… . It is constrained by a Gaussian $G(a = 0|\alpha, \sigma = 1)$ and is correlated over all bins in each channel"*

PYHF implementation

API to implement HistFactory statistical models in a python framework.

- Simplified model in JSON format including:
  - Single channel including *signal* and *background* samples.

    Signal modifiers: statistical error (from CheckMATE output), luminosity error (optional input), systematics (optional input).

    Background modifiers: fully correlated background error.
  - *Parameter of interest : μ (signal strength of the model)*
  - *Hypothesis test:*

    Option to choose between *asymptotic calculator* or *toy based.*

We compared the results of this implementation with the results obtained in with an implementation on HistFitter finding equivalent results.

Results format:

Observed CLs for μ = 1: 3.120639681359277e-06

Expected CLs band for μ = 1: [1.64443160871263e-07, 5.531920389481112e-06, 0.00015700059417103602, 0.0032331969351591075, 0.03843474510134974]

Upper limit (obs): μ = 0.2255

Expected 2-sigma band = [0.2134,0.2960,0.4337,0.6556,0.9610]

Observed p-value of the hypothesis μ=1

2-sigma band for the **Expected** p-value assuming μ=1

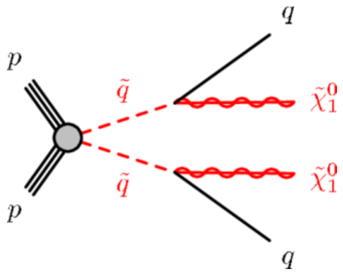
Observed upper limit over signal strength
(point is excluded if μ<1)
The point tested in this case is excluded!

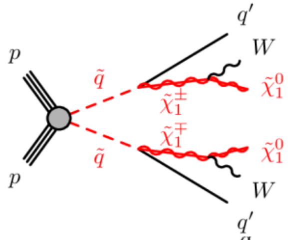
2 sigma band of the expected limit over the signal strength for the point tested.

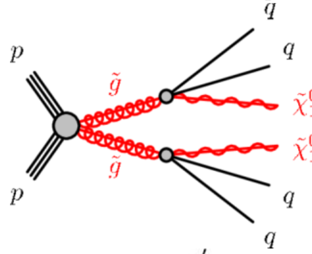
Validation

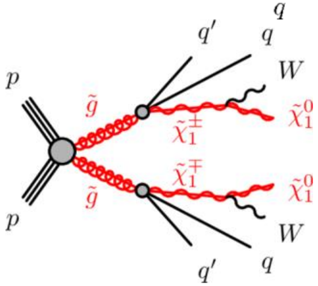
- Several ATLAS searches featuring multibinned analysis were recasted:
  - Squarks and gluinos to jets and missing transverse momentum. *JHEP 02 (2021) 143 (*2010.14293*)*
  - Staus to 2 hadronic τ-leptons and missing transverse momentum. *Phys. Rev. D 101 (2020)* 032009 (1911.06660)
  - Sbottom to higgs bosons, b-jets and missing transverse momentum. *JHEP 12 (2019) 060* (1908.03122)
  - More in preparation ...

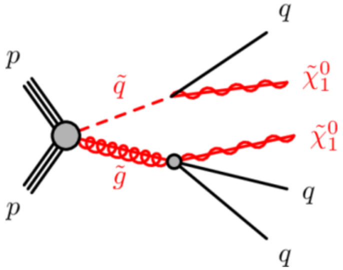
Search for squarks and gluinos in final states with jets and missing transverse momentum using 139 fb^{-1} of $\sqrt{s}$ =13 TeV pp collision data with the ATLAS detector











3 Sets of binned signal regions (not orthogonal between them!)

Orthogonal binning within each set in terms of **meff** and $E_T^{miss}/\sqrt{H_T}$

For each point, we calculate the expected upper limit based on each of the three SR-sets and we select the observed limit obtained from this SR-set.

- Simulation of squark/gluino + to 2 additional partons with MadGraph5_aMC@NLO_v3.4.1
- PYTHIA v8.306 for parton showering and hadronization.
- CKKW-L merging scheme.
- NNPDF2.3LO pdf set was used.

MB-SSd

$N_j = [2,3]$, $p_T(j_{i=1,2}) > 250$ GeV		m_{eff} [TeV]					
		[1.0, 1.6)	[1.6, 2.2)	[2.2, 2.8)	[2.8, 3.4)	[3.4, 4.0)	[4.0, ∞)
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	[10, 16)						
	[16, 22)						
	[22, 28)					$N_j = [2, \infty)$	$N_j = [2, \infty)$
	[28, ∞)					$N_j = [2, \infty)$	$N_j = [2, \infty)$

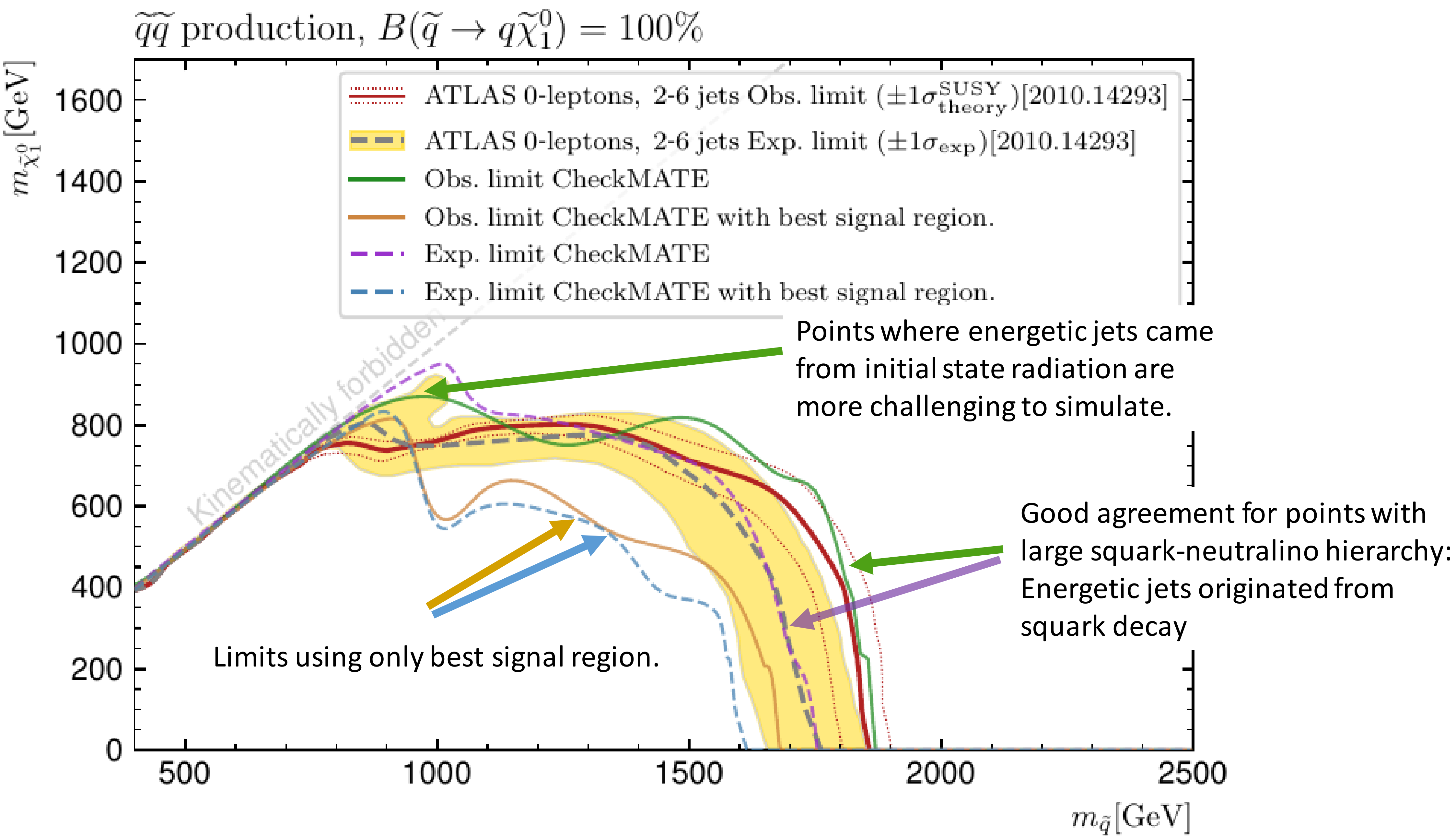
$N_j = [4, \infty)$		m_{eff} [TeV]			
		[1.0, 1.6)	[1.6, 2.2)	[2.2, 2.8)	[2.8, ∞)
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	[10, 16)				
	[16, 22)				
	[22, ∞)				$m_{eff} = [2.8, 3.4)$

MB-GGd

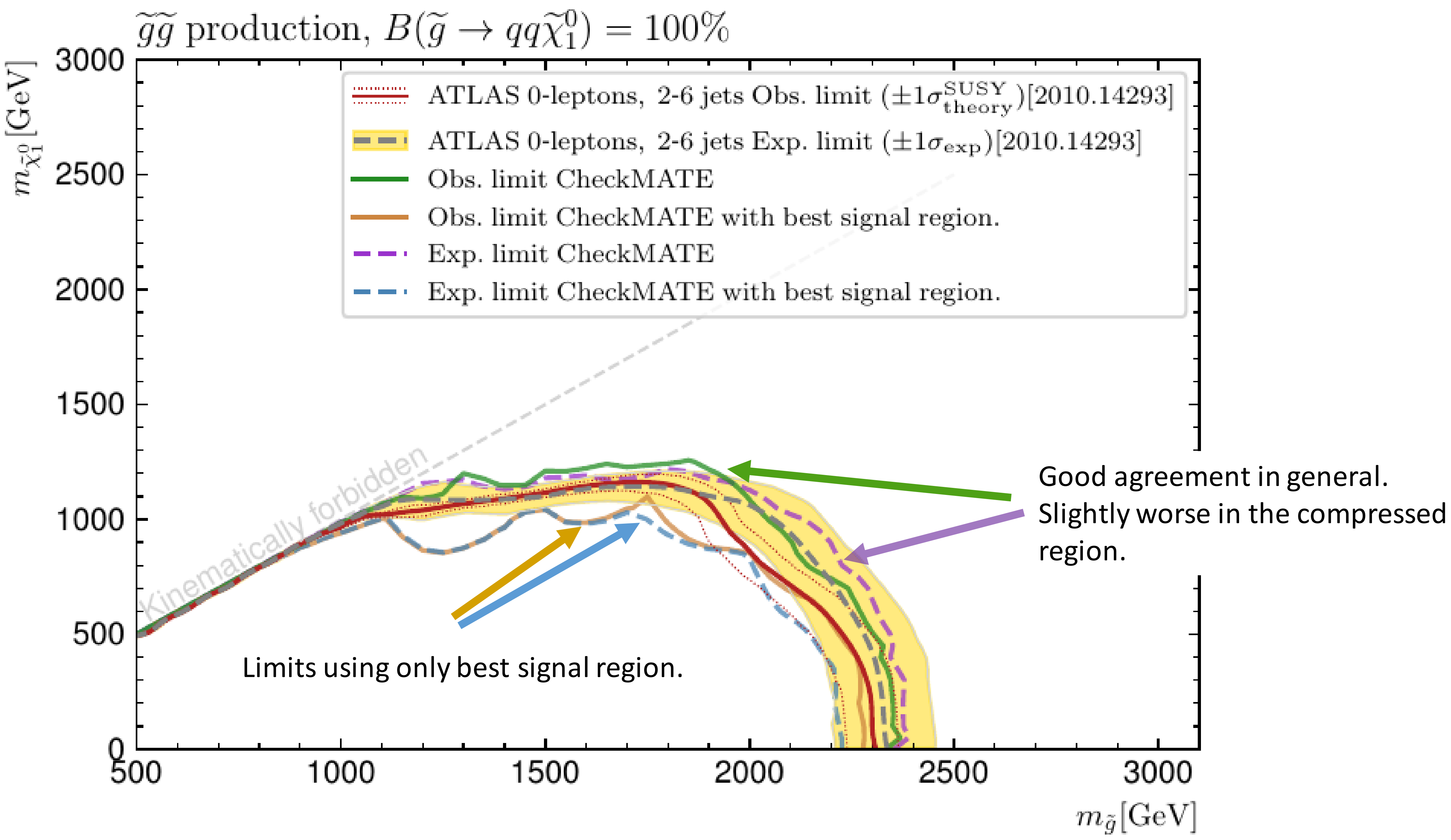
$N_j = [4, \infty)$		m_{eff} [TeV]					
		[1.0, 1.6)	[1.6, 2.2)	[2.2, 2.8)	[2.8, 3.4)	[3.4, 4.0)	[4.0, ∞)
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	[10, 16)						
	[16, 22)						
	[22, ∞)						

MB-C

$N_j = [2,3]; 4; [5, \infty)$		m_{eff} [TeV]		
		[1.6, 2.2)	[2.2, 2.8)	[2.8, ∞)
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	[16, 22)			
	[22, ∞)			

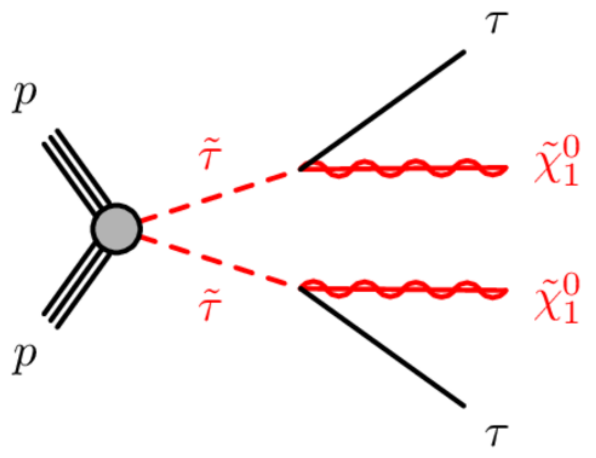


$\tilde{q}\tilde{q}$ production, $B(\tilde{q} \rightarrow q\tilde{\chi}_1^0) = 100\%$
ATLAS 0-leptons, 2-6 jets Obs. limit ($\pm 1\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$)[2010.14293]
ATLAS 0-leptons, 2-6 jets Exp. limit ($\pm 1\sigma_{\mathrm{exp}}$)[2010.14293]
Obs. limit CheckMATE
Obs. limit CheckMATE with best signal region.
Exp. limit CheckMATE
Exp. limit CheckMATE with best signal region.
Kinematically forbidden
$m_{\tilde{\chi}_1^0}$[GeV]
$m_{\tilde{q}}$[GeV]
0
200
400
600
800
1000
1200
1400
1600
500
1000
1500
2000
2500
Points where energetic jets came from initial state radiation are more challenging to simulate.
Good agreement for points with large squark-neutralino hierarchy: Energetic jets originated from squark decay
Limits using only best signal region.


$\tilde{g}\tilde{g}$ production, $B(\tilde{g} \to qq\tilde{\chi}_1^0) = 100\%$
ATLAS 0-leptons, 2-6 jets Obs. limit ($\pm1\sigma^{\rm SUSY}_{\rm theory}$)[2010.14293]
ATLAS 0-leptons, 2-6 jets Exp. limit ($\pm1\sigma_{\rm exp}$)[2010.14293]
Obs. limit CheckMATE
Obs. limit CheckMATE with best signal region.
Exp. limit CheckMATE
Exp. limit CheckMATE with best signal region.
Kinematically forbidden
$m_{\tilde{\chi}_1^0}$[GeV]
$m_{\tilde{g}}$[GeV]
0
500
1000
1500
2000
2500
3000
Good agreement in general.
Slightly worse in the compressed region.
Limits using only best signal region.

Search for direct stau production in events with two hadronic τ-leptons in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration



SR-lowMass	SR-highMass
2 tight τ (OS) asymmetric di-τ trigger	2 medium τ (OS) , $\geq$ 1 tight τ di-τ+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
τ p_{T} cut described in Section 5	
light lepton veto and 3rd medium τ veto	
b-jet veto	
Z/H veto ($m(\tau_1, \tau_2) > 120$ GeV)	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 0.8$	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$m_{\mathrm{T2}} > 70$ GeV	

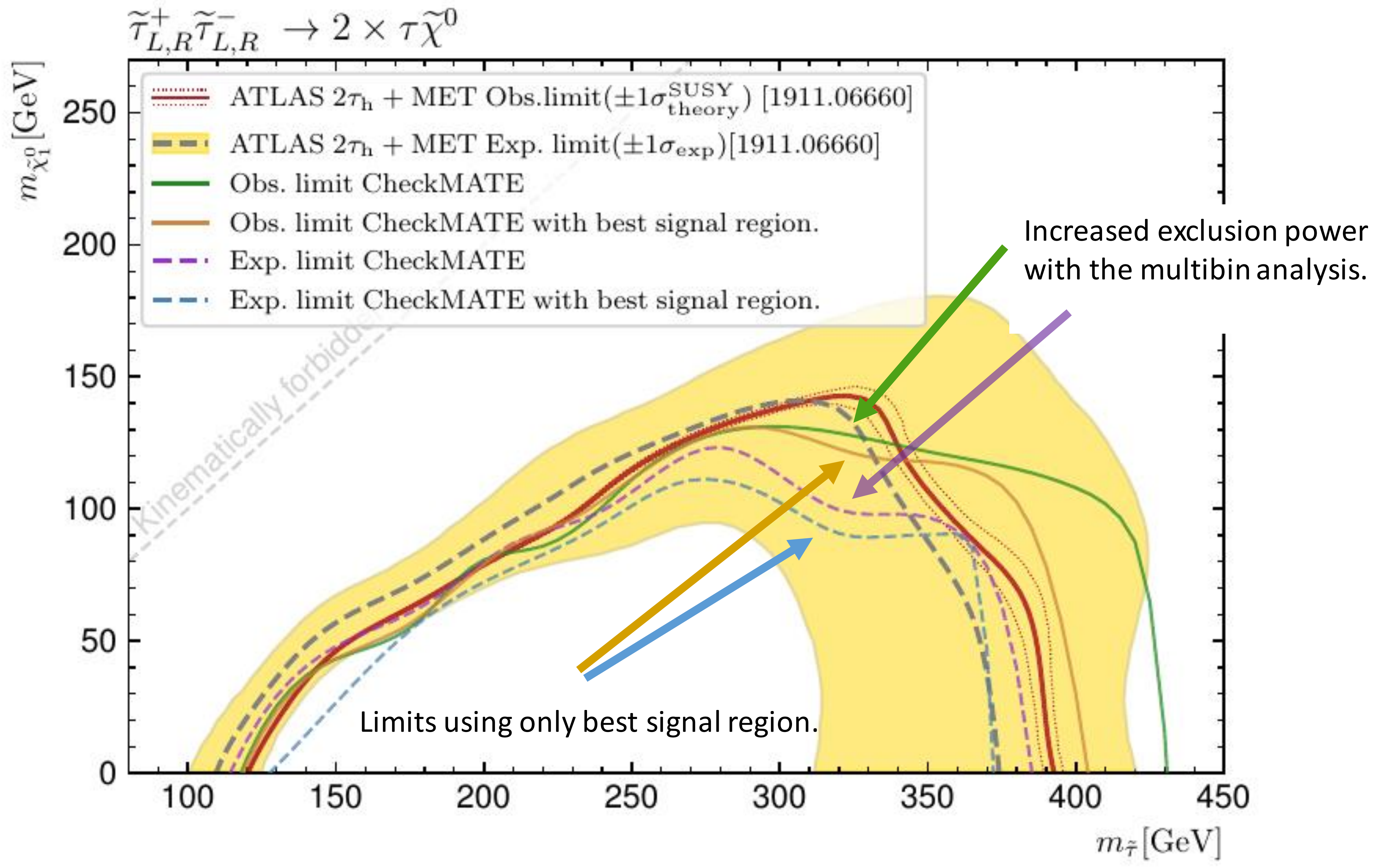
2 disjoint signal regions separated by the requirement on missing transverse momentum.

Simulation of stau pair production + to 2 additional partons with MadGraph5_aMC@NLO _v3.4.1

PYTHIA v8.306 for parton showering and hadronization.

MLM merging scheme.

NNPDF2.3LO pdf set

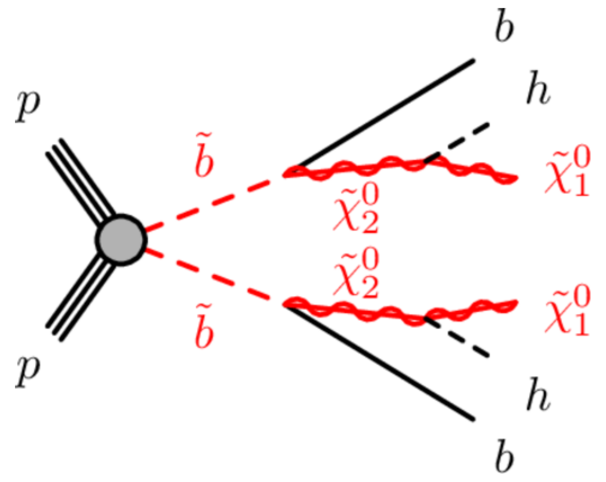


$\tilde{\tau}^{+}_{L,R}\tilde{\tau}^{-}_{L,R} \rightarrow 2 \times \tau\tilde{\chi}^0$
ATLAS $2\tau_h$ + MET Obs.limit($\pm 1\sigma^{SUSY}_{theory}$) [1911.06660]
ATLAS $2\tau_h$ + MET Exp. limit($\pm 1\sigma_{exp}$)[1911.06660]
Obs. limit CheckMATE
Obs. limit CheckMATE with best signal region.
Exp. limit CheckMATE
Exp. limit CheckMATE with best signal region.
Kinematically forbidden
Increased exclusion power with the multibin analysis.
Limits using only best signal region.
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{\tau}}$ [GeV]

Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, *b*-jets and missing transverse momentum

The ATLAS Collaboration

Variable	SRA	SRA-L	SRA-M	SRA-H
N_{leptons} (baseline)	$= 0$		$= 0$	
N_{jets}	≥ 6		≥ 6	
$N_{b\text{-jets}}$	≥ 4		≥ 4	
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 350		> 350	
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]	> 0.4		> 0.4	
τ veto	Yes		Yes	
$p_{\text{T}}(b_1)$ [GeV]	> 200		> 200	
$\Delta R_{\text{max}}(b,b)$	> 2.5		> 2.5	
$\Delta R_{\text{max-min}}(b,b)$	< 2.5		< 2.5	
$m(h_{\text{cand}})$ [GeV]	> 80		> 80	
m_{eff} [TeV]	> 1.0	$\in [1.0, 1.5]$	$\in [1.5, 2.0]$	> 2.0



Variable	SRB
N_{leptons} (baseline)	$= 0$
N_{jets}	≥ 5
$N_{b\text{-jets}}$	≥ 4
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 350
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]	> 0.4
τ veto	Yes
$m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ [GeV]	$\in [75, 175]$
Leading jet not b-tagged	Yes
$p_{\text{T}}(j_1)$ [GeV]	> 350
$\lvert\Delta\phi(j_1, E_{\text{T}}^{\text{miss}})\rvert$ [rad]	> 2.8
m_{eff} [TeV]	> 1

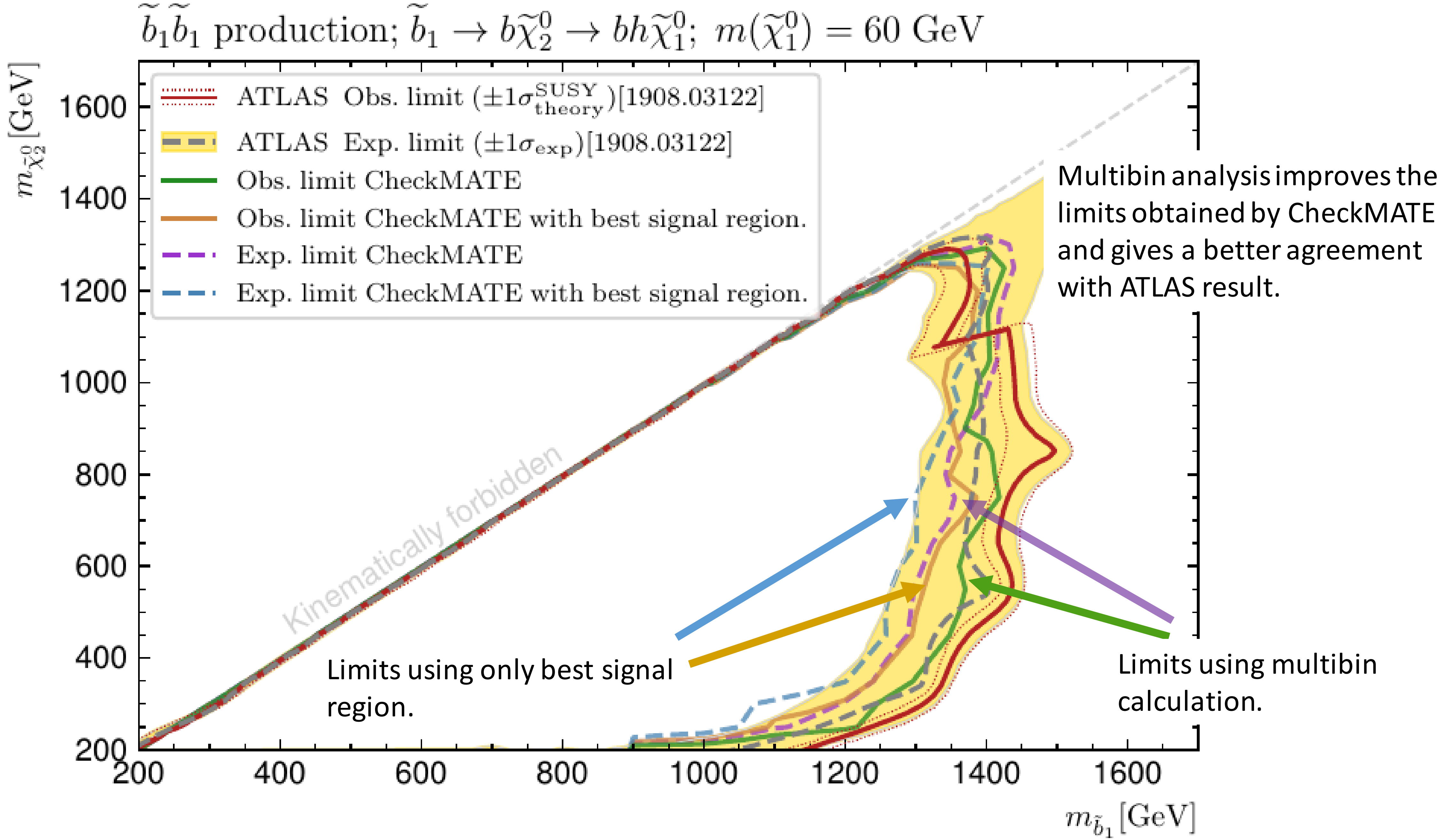
Variable	SRC	SRC22	SRC24	SRC26	SRC28
N_{leptons} (baseline)	$= 0$			$= 0$	
N_{jets}	≥ 4			≥ 4	
$N_{b\text{-jets}}$	≥ 3			≥ 3	
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 250			> 250	
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_{\text{T}}^{\text{miss}})$ [rad]	> 0.4			> 0.4	
$\mathcal{S}$	> 22	$\in [22, 24]$	$\in [24, 26]$	$\in [26, 28]$	> 28

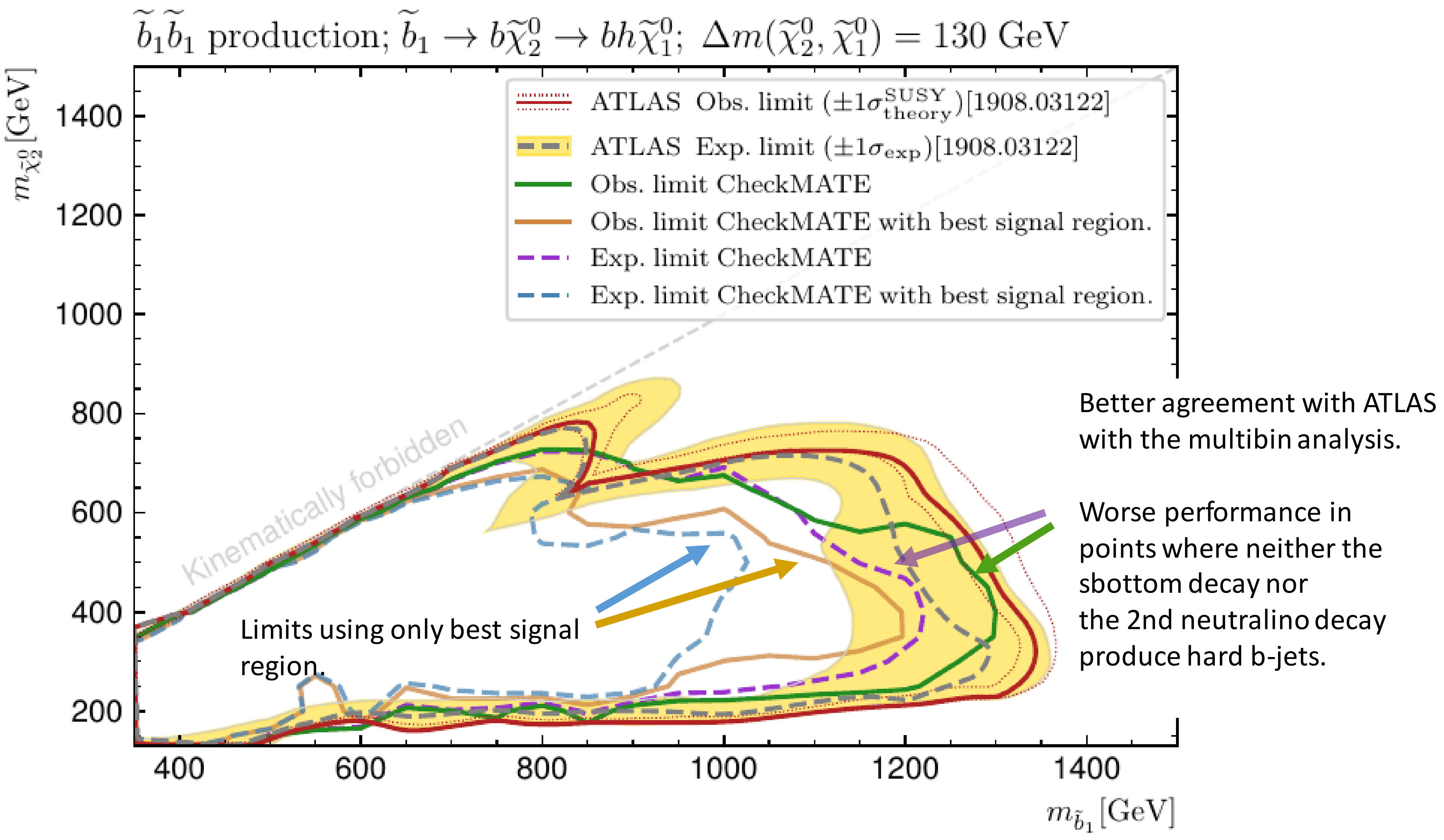
3 Sets of signal regions (not orthogonal between them!). SRA and SRC binned.

Orthogonal binning within each set in terms of **meff** and "**S**" (object-based MET -significance)

For each point, we calculate the expected upper limit based on each of the three SR-sets and we select the observed limit obtained from this SR-set.

- Simulation of sbottom + to 2 additional partons with MadGraph5_aMC@NLO_v3.4.1
- PYTHIA v8.306 for parton showering and hadronization.
- MLM merging scheme.
- NNPDF2.3LO pdf set was used.


$\tilde{b}_1\tilde{b}_1$ production; $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$; $m(\tilde{\chi}_1^0) = 60$ GeV
ATLAS Obs. limit ($\pm 1\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$)[1908.03122]
ATLAS Exp. limit ($\pm 1\sigma_{\mathrm{exp}}$)[1908.03122]
Obs. limit CheckMATE
Obs. limit CheckMATE with best signal region.
Exp. limit CheckMATE
Exp. limit CheckMATE with best signal region.
Kinematically forbidden
$m_{\tilde{\chi}_2^0}$ [GeV]
$m_{\tilde{b}_1}$ [GeV]
200
400
600
800
1000
1200
1400
1600
Multibin analysis improves the limits obtained by CheckMATE and gives a better agreement with ATLAS result.
Limits using only best signal region.
Limits using multibin calculation.



$\tilde{b}_1\tilde{b}_1$ production; $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$; $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV
$m_{\tilde{\chi}_2^0}$ [GeV]
$m_{\tilde{b}_1}$ [GeV]
ATLAS Obs. limit ($\pm 1\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$)[1908.03122]
ATLAS Exp. limit ($\pm 1\sigma_{\mathrm{exp}}$)[1908.03122]
Obs. limit CheckMATE
Obs. limit CheckMATE with best signal region.
Exp. limit CheckMATE
Exp. limit CheckMATE with best signal region.
Kinematically forbidden
Limits using only best signal region.
Better agreement with ATLAS with the multibin analysis.
Worse performance in points where neither the sbottom decay nor the 2nd neutralino decay produce hard b-jets.

Summary

- The use of simplifications of statistical models of the LHC searches facilitates the use of multibined analysis in recasted analysis.
- Multibinned analysis utilizing the additional information with respect to best SR approach lead to more robust results and generally stricter limits.
- A PYHF based implementation of this approach is in preparation for CheckMATE
- Several ATLAS searches featuring multibined analysis have been recasted with good agreement with ATLAS results.

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NATIONAL SCIENCE CENTRE POLAND

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Understanding the Early Universe:
interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen