New developments in CheckMATE

Krzysztof Rolbiecki

in collaboration with Iñaki Lara Perez

University of Warsaw

(Re)interpretation of the LHC results for New Physics

27 February 2025

NATIONAL SCIENCE CENTRE POLAND

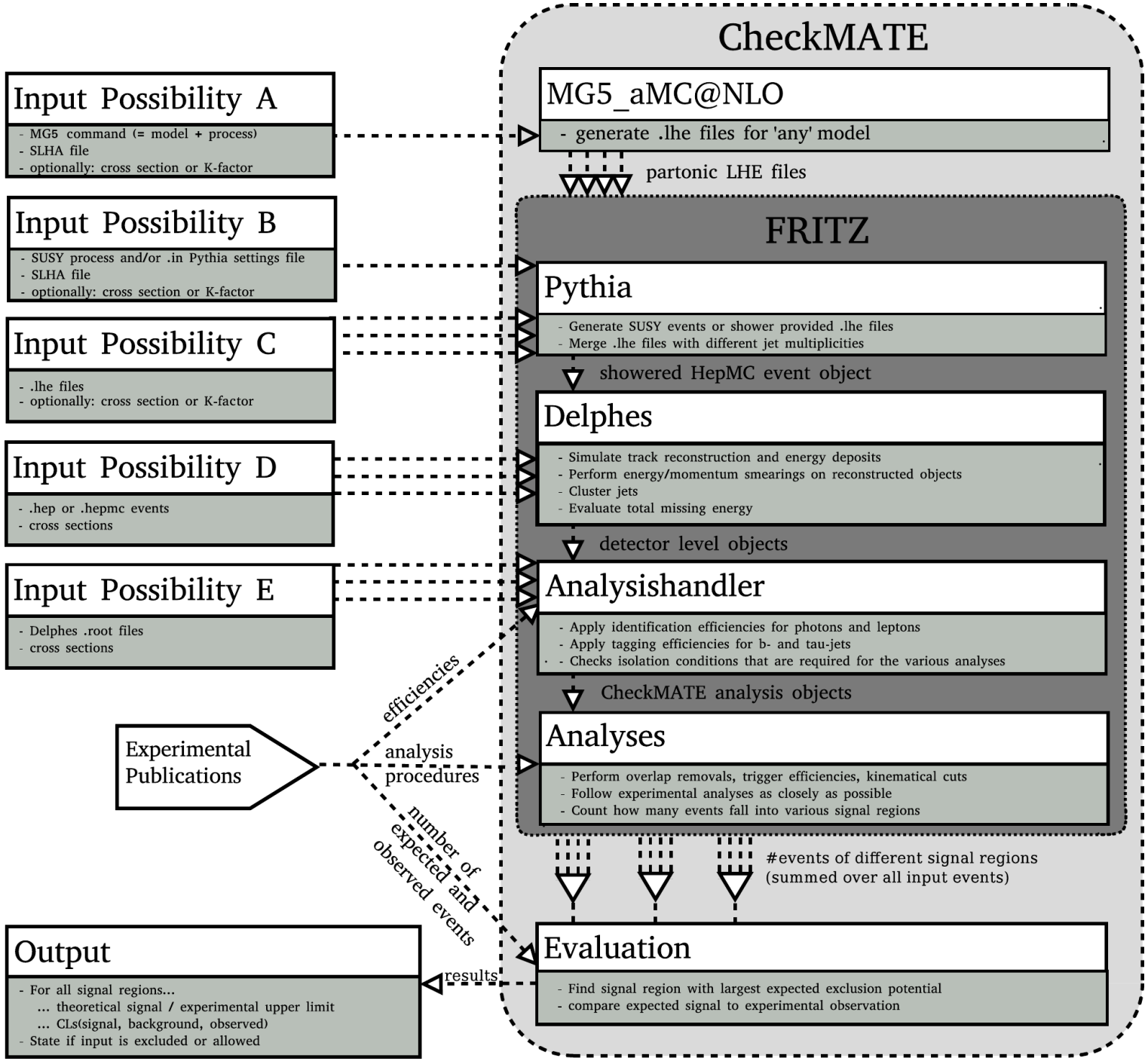
Contents

1. CheckMATE overview
2. Implementation of statistical models
3. Validation examples
4. ML implementation
5. Summary and outlook

Current Members: Manimala Chakraborti, Nishita Desai, Florian Domingo, Jong Soo Kim, Krzysztof Rolbiecki, Roberto Ruiz de Austri, Ipsita Saha, Liangliang Shang, Mangesh Sonawane, Zeren Simon Wang, Yuanfang Yue

Former Members: Daniel Dercks, Manuel Drees, Herbert Dreiner, Frederic Ponzca, Jamie Tattersall, Thorsten Weber

- CheckMATE is a general tool for recasting arbitrary model
- Accepts events as .hepmc, .lhe; integration with Pythia and MadGraph
- based on Delphes for detector simulation
- using existing LHC searches calculates a limit on a given parameter point
- From SLHA file to the limit in one click
- one can easily constrain models that were not covered in the original ATLAS/CMS search
- currently more than 40 searches at 13 TeV coded, including 14 with full luminosity
- long-lived particles branch
- https://checkmate.hepforge.org/ and https://github.com/CheckMATE2/checkmate2
- new features branch: https://github.com/CheckMATE2/checkmate2/tree/cms_sus_19_005


CheckMATE
Input Possibility A
- MG5 command (= model + process)
- SLHA file
- optionally: cross section or K-factor
Input Possibility B
- SUSY process and/or .in Pythia settings file
- SLHA file
- optionally: cross section or K-factor
Input Possibility C
- .lhe files
- optionally: cross section or K-factor
Input Possibility D
- .hep or .hepmc events
- cross sections
Input Possibility E
- Delphes .root files
- cross sections
MG5_aMC@NLO
- generate .lhe files for 'any' model
partonic LHE files
FRITZ
Pythia
- Generate SUSY events or shower provided .lhe files
- Merge .lhe files with different jet multiplicities
showered HepMC event object
Delphes
- Simulate track reconstruction and energy deposits
- Perform energy/momentum smearings on reconstructed objects
- Cluster jets
- Evaluate total missing energy
detector level objects
Analysishandler
- Apply identification efficiencies for photons and leptons
- Apply tagging efficiencies for b- and tau-jets
- Checks isolation conditions that are required for the various analyses
CheckMATE analysis objects
Analyses
- Perform overlap removals, trigger efficiencies, kinematical cuts
- Follow experimental analyses as closely as possible
- Count how many events fall into various signal regions
efficiencies
Experimental Publications
analysis procedures
number of expected and observed events
#events of different signal regions (summed over all input events)
Output
- For all signal regions...
... theoretical signal / experimental upper limit
... CLs(signal, background, observed)
- State if input is excluded or allowed
results
Evaluation
- Find signal region with largest expected exclusion potential
- compare expected signal to experimental observation

CheckMATE: ATLAS analyses

#Name	NSR	Description	Lumi
atlas_1604_01306	1	photon + MET search at 13 TeV	3.2
atlas_1605_09318	8	>= 3 b-jets + 0-1 lepton + Etmiss	3.3
atlas_1609_01599	9	ttV cross section measurement at 13 TeV	3.2
atlas_1704_03848	5	monophoton dark matter search	36.1
atlas_conf_2015_082	1	leptonic Z + jets + Etmiss	3.2
atlas_conf_2016_013	10	4 top quark (1 lepton + jets, vector like quark search)	3.2
atlas_conf_2016_050	5	1-lepton + jets + etmiss (stop)	13.3
atlas_conf_2016_054	10	1-lepton + jets + etmiss (squarks and gluino)	14.8
atlas_conf_2016_076	6	2 leptons + jets + etmiss	13.3
atlas_conf_2016_096	8	2-3 leptons + etmiss (electroweakino)	13.3
atlas_conf_2017_060	20	monojet search	36.1
atlas_conf_2016_066	2	search for photons, jets and met	13.3
atlas_1712_08119	39	electroweakinos search with soft leptons	36.1
atlas_1712_02332	24	squarks and gluinos, 0 lepton, 2-6 jets	36.1
atlas_1709_04183	14	stop pair production, 0 leptons	36.1
atlas_1802_03158	7	search for GMSB with photons	36.1
atlas_1708_07875	2	electroweakino search with taus and MET	36.1
atlas_1706_03731	19	same-sign or 3 leptons RPC and RPV SUSY	36.1
atlas_1908_08215	16	charginos/sleptons, 2 leptons + MET	139
atlas_1909_08457	5	search for squarks and gluinos with same-sign leptons	139
atlas_conf_2019_020	2	Search for chargino-neutralino production with mass splittings near the electroweak scale	139
atlas_1803_02762	20	Search for electroweakino production in final states with two or three leptons	36.1
atlas_2101_01629	32	squarks/gluinos, 1 lepton, jets, MET	139
atlas_2004_14060	14	stops, leptoquarks, 0 lepton	139
atlas_1908_03122	10	0 leptons, 3 or more b-jets, sbottoms	139
atlas_1911_12606	87	search for sleptons and electroweakinos with soft leptons	139
atlas_1807_07447	633	general search for new phenomena	3.2
atlas_2103_11684	2	Search for SUSY in events with four or more leptons (gravitino SR)	139
atlas_2004_10894	12	EWino search in Higgs (diphoton) and met	139
atlas_2106_09609	21	Search for RPV SUSY in final states with leptons and many jets	139
atlas_1911_06660	2	search for direct stau production	139
atlas_2010_14293	78	search for squarks and gluinos in MET_jet final states	139
atlas_2211_08028	22	search for gluinos decaying via 3rd gen; multi b-jets and MET	139
atlas_2106_01676	72	electroweakinos, 3 leptons, WZ, Wh, on+off-shell	139
atlas_2006_05880	28	Search for top squarks in events whith a Higgs or a Z boson	139
atlas_2111_08372	23	dark matter and invisible Higgs with Z boson	139
atlas_2202_07953	17	invisible Higgs decays in VBF	139
atlas_2209_13935	59	search for charginos and sleptons in 2-lepton final states	139
atlas_2102_10874	26	monojet	139

CheckMATE: CMS analyses

#Name	NSR	Description	Lumi
cms_pas_sus_15_011	47	CMS, 13 TeV, 2 leptons + jets + MET	2.2
cms_sus_16_039	158	electrowekinos in multilepton final state	35.9
cms_sus_16_025	14	electroweakino and stop compressed spectra	12.9
cms_sus_16_048	20	two soft opposite sign leptons	35.9
cms_sus_19_005	303	hadronic final states with MT2	137.0
cms_1908_04722	186	hadronic final states with HT, post-fit and simple fitting	137.0
cms_2107_13201	88	monojet with multibin	137.0
cms_2205_09597	40	search for electroweakinos in hadronic final states	137.0

The list shorter than for ATLAS but expanding, with three new full luminosity searches added recently

Contents

1. CheckMATE overview
2. Implementation of statistical models
3. Validation examples
4. ML implementation
5. Summary and outlook

Implemented statistical models

ATLAS simplified likelihoods ATL-PHYS-PUB-2021-038

- Histogram fitting – overall normalization, no control regions
- Can be built without public full likelihood
- Sacrifices accuracy for speed

ATLAS full likelihoods ATL-PHYS-PUB-2019-029

- Full statistical model can be bulky and slow
- Limited coverage of control regions in the current searches
- Expected better accuracy than simplified likelihoods

CMS covariance matrix CMS-NOTE-2017-001

- Simplified approach, lowest order approximation
- Fast calculation
- Problems with data quality

User control and what's calculated

Parameter card		Terminal	X	Description and available choices
`Multibin:`	`X`	`-mb X`	`none`	No signal region combination is performed (default).
			`select`	Calculates user selected statistics.
			`scan`	Calculates observed CL_s; fast and reliable for quick assessment of exclusion.
			`detailed`	Calculates observed and expected upper limits and CL_s.
`Expected:`	`False`	`-exp`		Selects calculation of expected limits.
`CLs:`	`False`	`-cls`		Selects calculation of CL_s.
`Uplim:`	`False`	`-uplim`		Selects calculation of upper limits.
`Statonly:`	`False`	`-so`		Calculates statistical combinations without event-level analysis provided the analysis and evaluation steps were already completed.

Methods

- Default calculation using Spey
- Enables straightforward combination of searches and signal regions

`Model: X`	`-mod X`	`simple`	The simplified likelihood model for ATLAS searches (default).
		`full`	The Spey interface to the full likelihood model for ATLAS searches.
		`fullpyhf`	The full likelihood model for ATLAS searches with `pyhf` interface.

Different backends enabled:

- numpy - extremely slow
- pytorch is recommended (order of magnitude faster)
- full model can take O(10) minutes to evaluate

`Backend: X`	`numpy`
	`pytorch`
	`tensorflow`

Implemented ATLAS multibin searches

Name	Description	#SR	N_{bin}	Full
atlas_1908_03122	Search for bottom squarks in final states with Higgs bosons, b-jets and E_T^{miss}	2	7	✓
atlas_1908_08215	Search for electroweak production of charginos and sleptons in final states with 2 leptons and E_T^{miss}	1	52	✓
atlas_1911_06660	Search for direct stau production in events with two hadronic taus	1	2	✓
atlas_1911_12606	Search for electroweak production of supersymmetric particles with compressed mass spectra	2	76	✓
atlas_2004_14060	Search for stops in hadronic final states with E_T^{miss}	3	14	✗
atlas_2006_05880	Search for top squarks in events with a Higgs or Z boson	3	23	✗
atlas_2010_14293	Search for squarks and gluinos in final states with jets and E_T^{miss}	3	60	✓
atlas_2101_01629	Search for squarks and gluinos in final states with one isolated lepton, jets, and E_T^{miss}	1	26	✓
atlas_2106_01676	Search for chargino–neutralino production in final states with 3 leptons and E_T^{miss}	2	72	✓
atlas_2111_08372	Search for associated production of a Z boson with an invisibly decaying Higgs boson or dark matter candidates	1	22	✗

Control regions fully implemented in 1911.06660 and 2010.14293

Implemented CMS multibin searches

Name	Description	N_{bin}
cms_1908_04722	Search for supersymmetry in final states with jets and E_T^{miss}	174
cms_1909_03460	Search for supersymmetry with M_{T2} variable in final states with jets and E_T^{miss}	282
cms_2107_13021	Search for new particles in events with energetic jets and large E_T^{miss}	66
cms_2205_09597	Search for production of charginos and neutralinos in final states containing hadronic decays of WW, WZ, or WH and E_T^{miss}	35

1909.03460 is actually divided into 2 parts (the full 282x282 matrix wasn't positive definite...) and then combined

The hadronic searches are on my wish list for Combine implementation

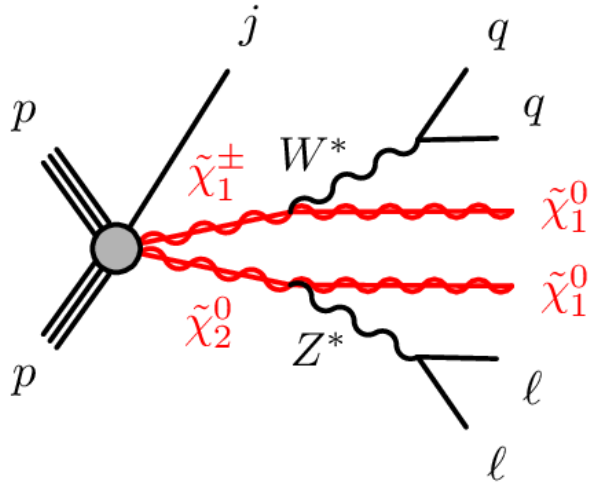
Contents

1. CheckMATE overview
2. Implementation of statistical models
3. Validation examples
4. ML implementation
5. Summary and outlook

arXiv:1911.12606 - EW with soft leptons

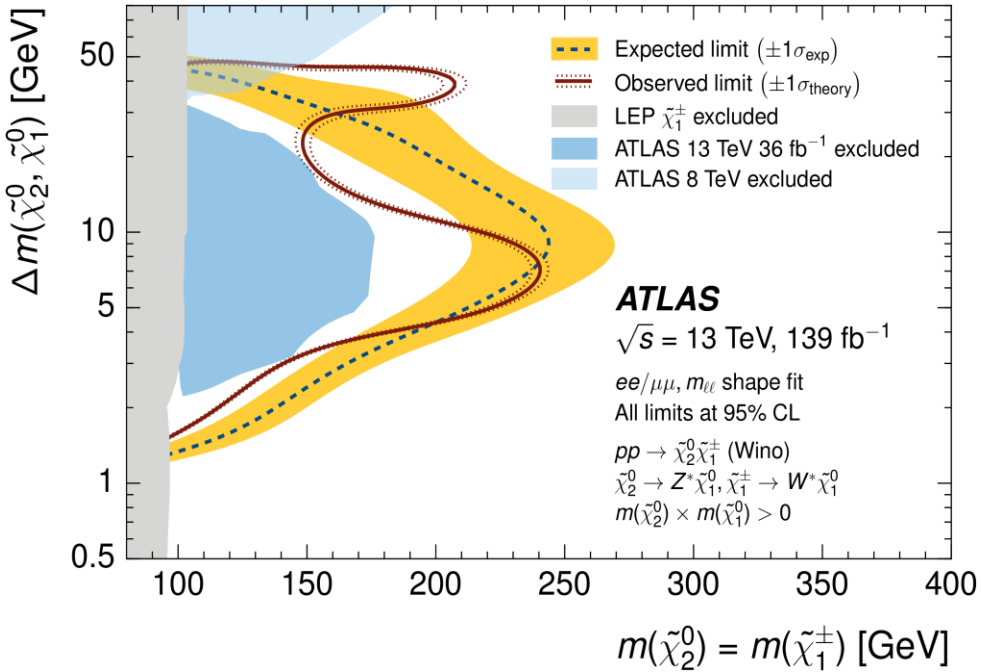
Covers mass-degenerate models of:

- wino-type chargino/neutralino
- higgsino-type chargino/neutralino + neutralino pairs
- sleptons
- direct and VBF (not in CM) production modes



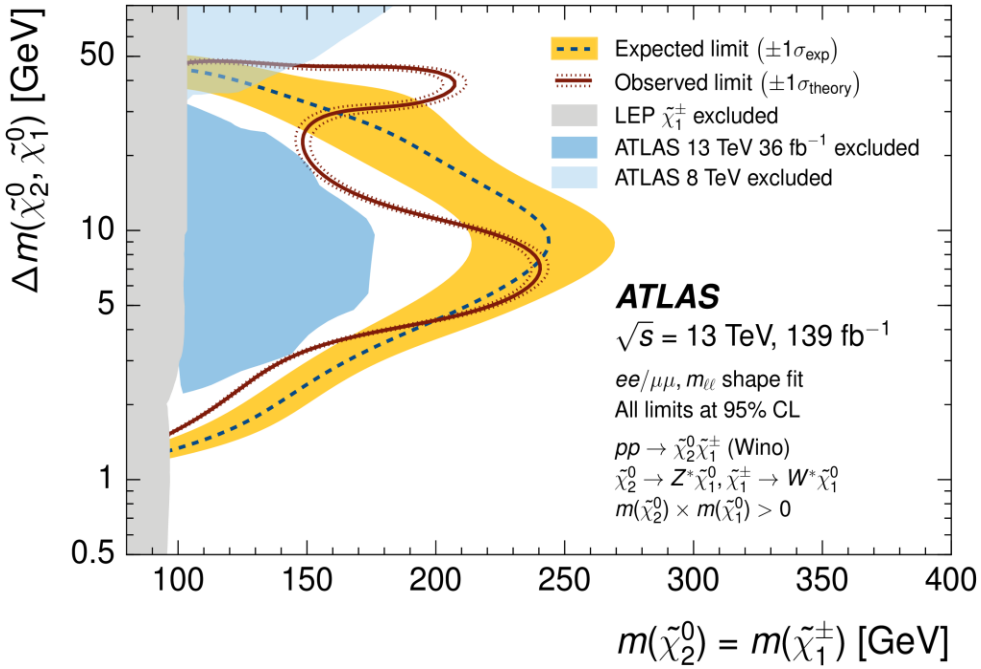
Challenging for recasting:

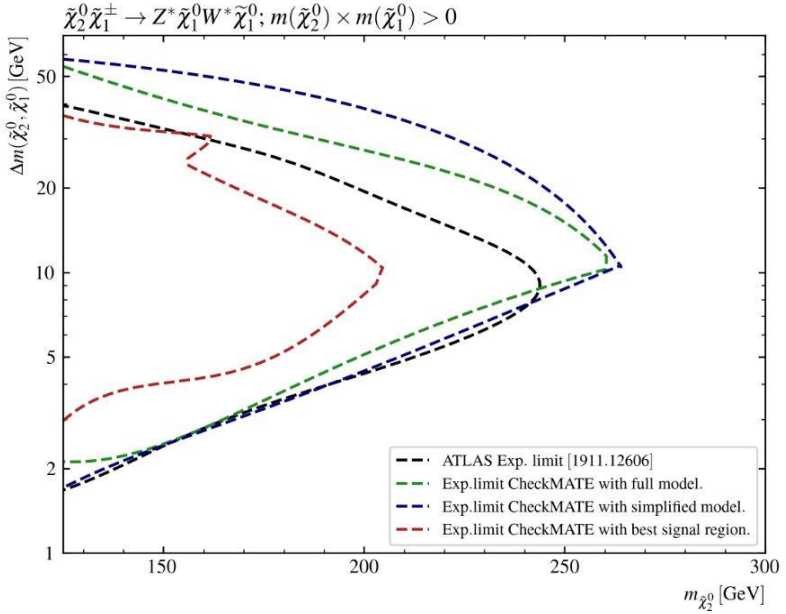
- needs special treatment of soft leptons
- lepton (track) down to pT > 3 GeV (1 GeV)
- many finely binned signal regions
- momentum resolution important
- large fluctuations in the observed number of events
- difficult MC modelling: crucial role of ISR and decay kinematics

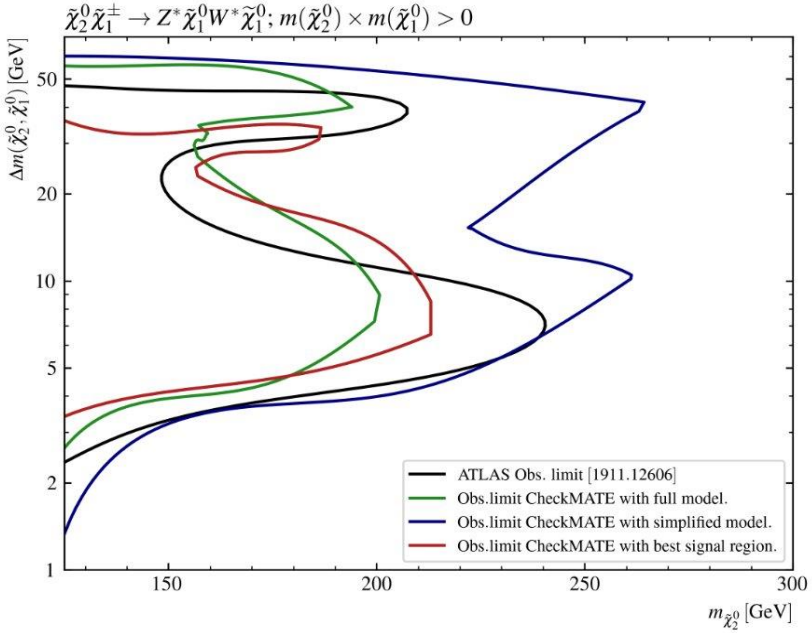


arXiv:1911.12606

Same parity wino-bino:
difficult reinterpretation due to apparent excesses and deficits in observed data
Legened:
black: CMS; green: full likelihood; blue: simplified; red: best signal region

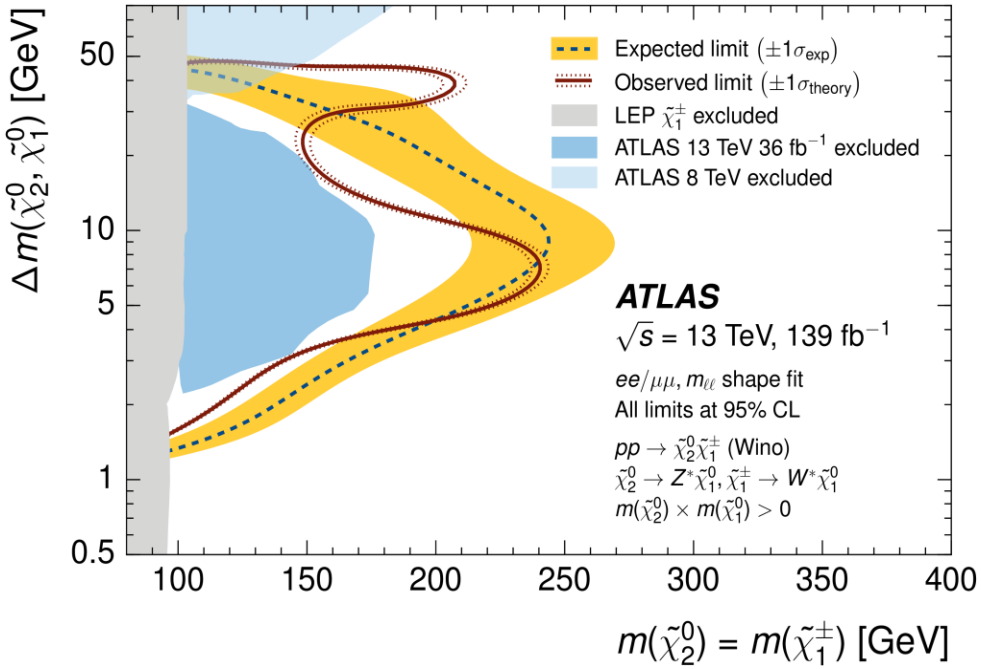




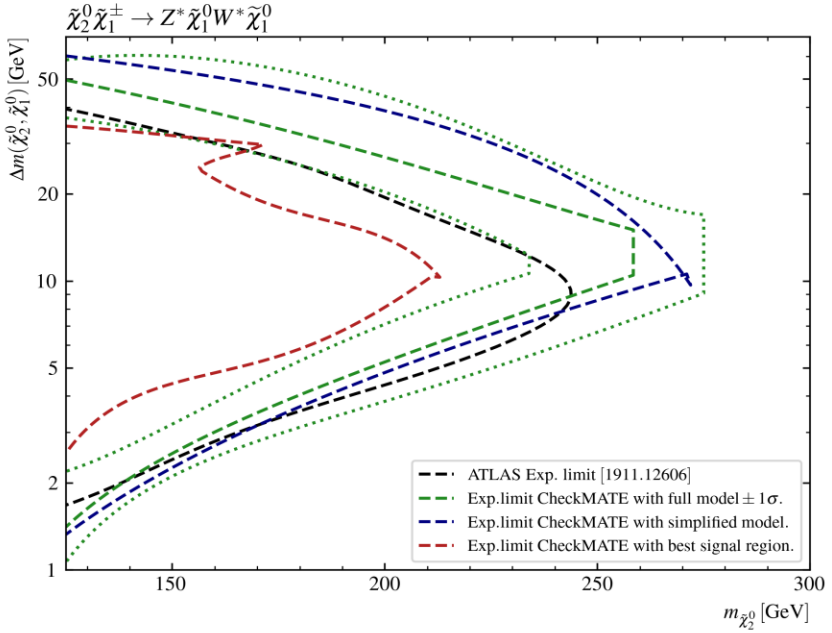


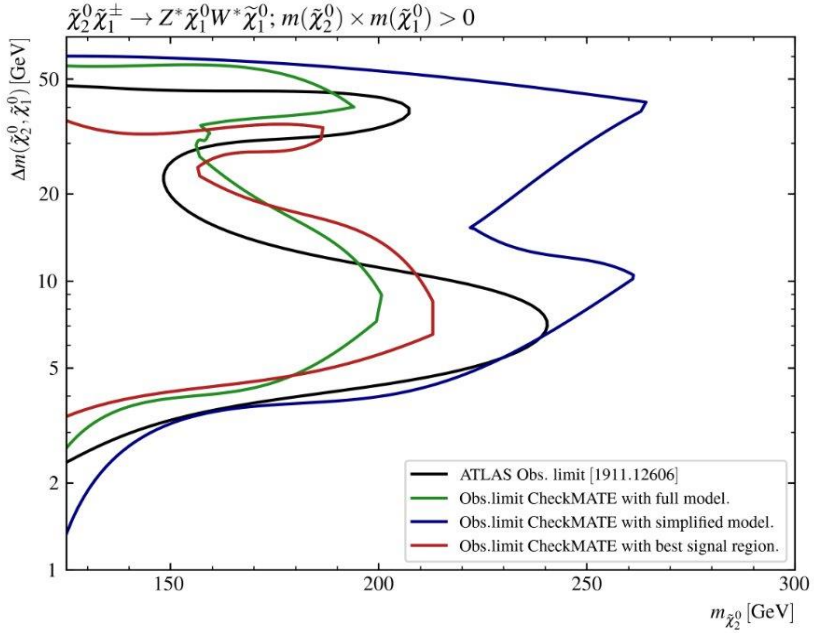
arXiv:1911.12606

Same parity wino-bino:
difficult case reinterpretation case due to
apparent excesses and deficits in observed data



uncertnty (1sigma) around CM prediction:

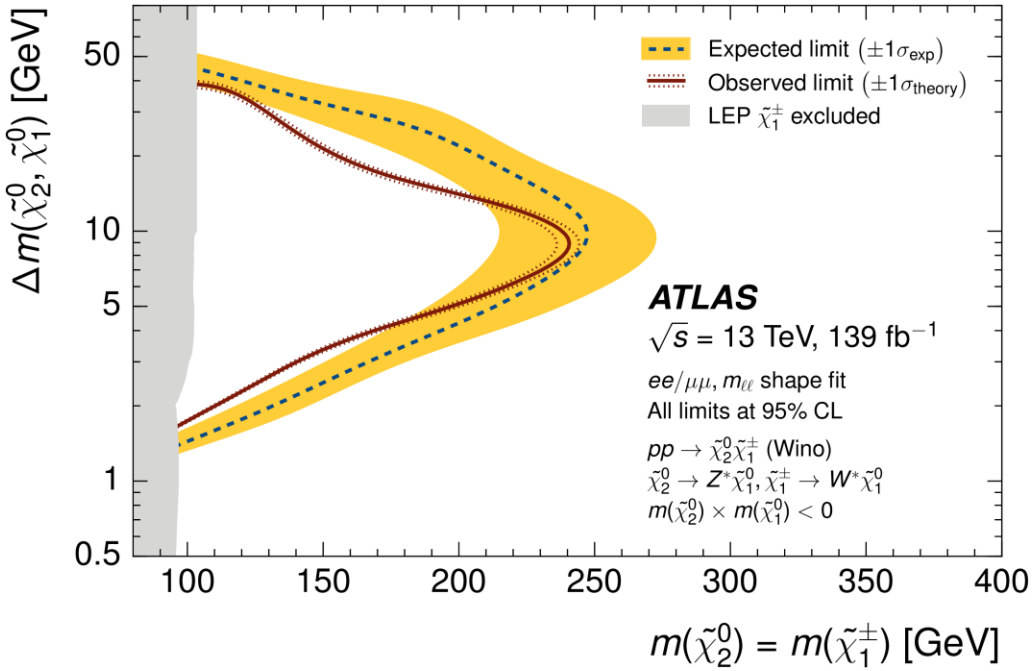


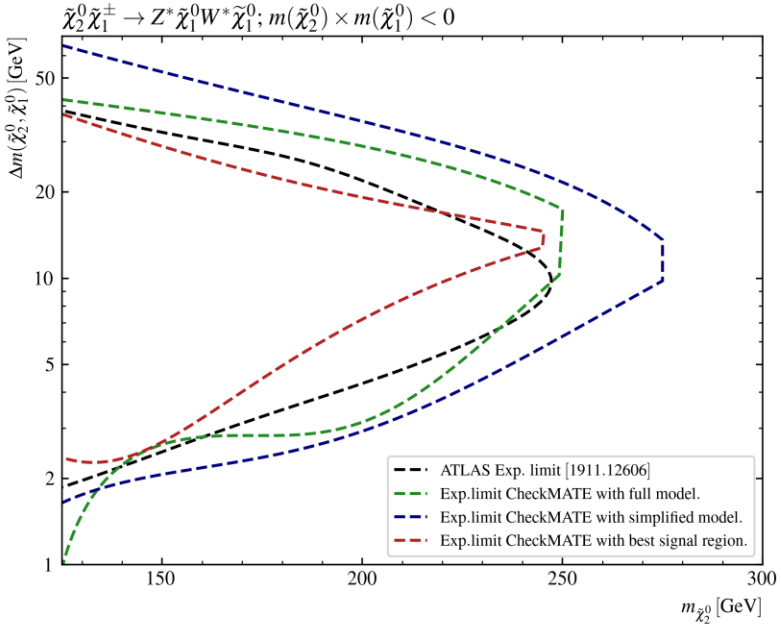


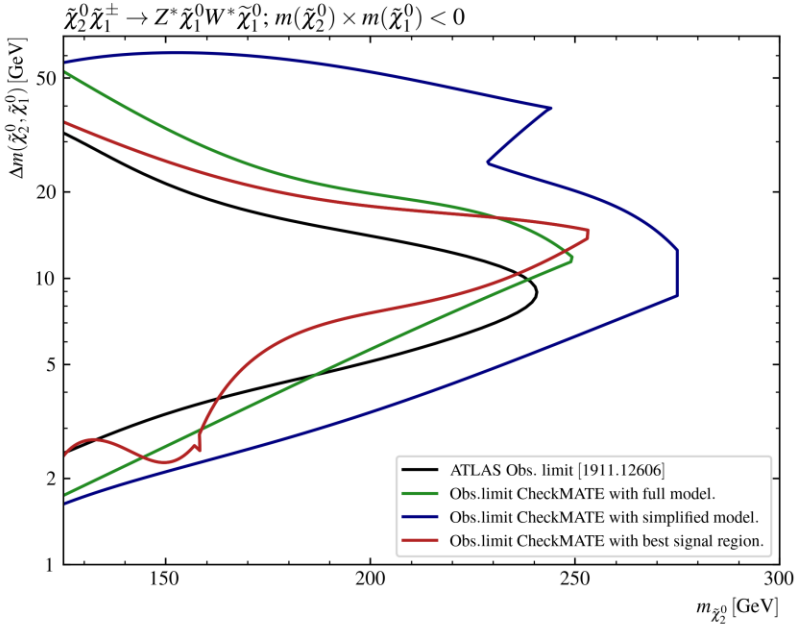
arXiv:1911.12606

Opposite parity wino-bino:

More smooth behavior of exclusion curves

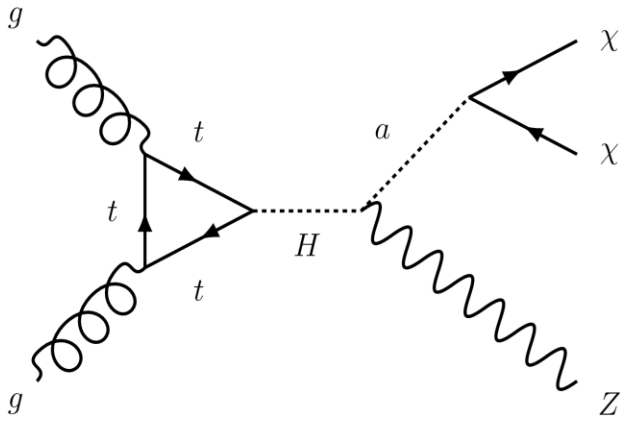


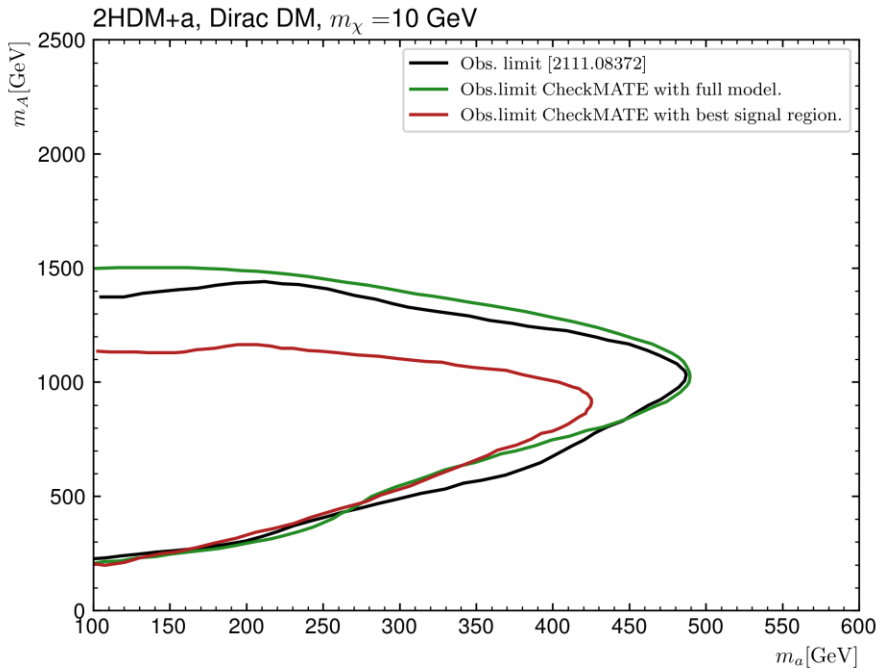


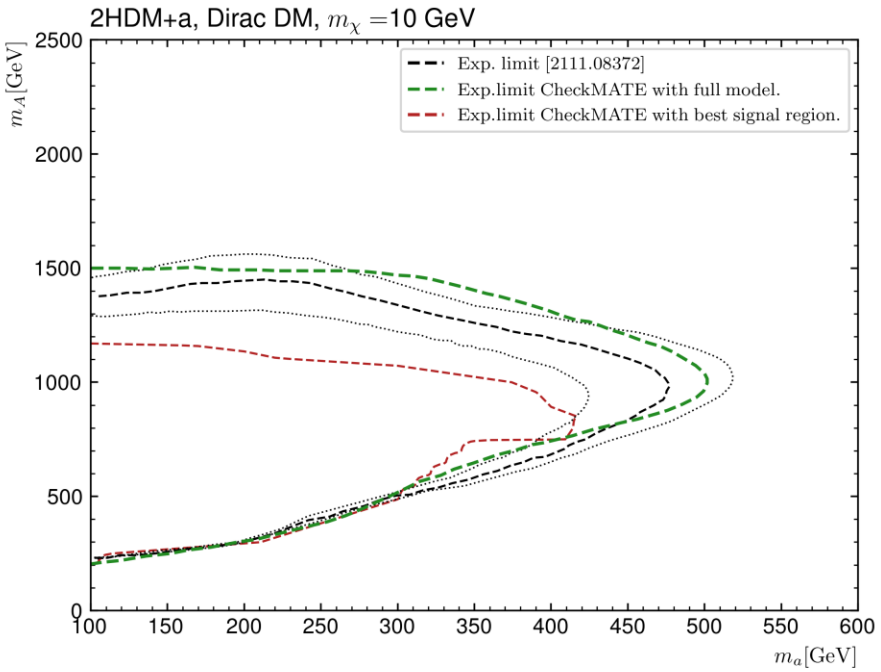


arXiv:2111.08372 - invisible Higgs decays

- ATLAS simplified likelihood: mT distribution
- mono-Z search
- see also: Jayita Lahiri talk tomorrow

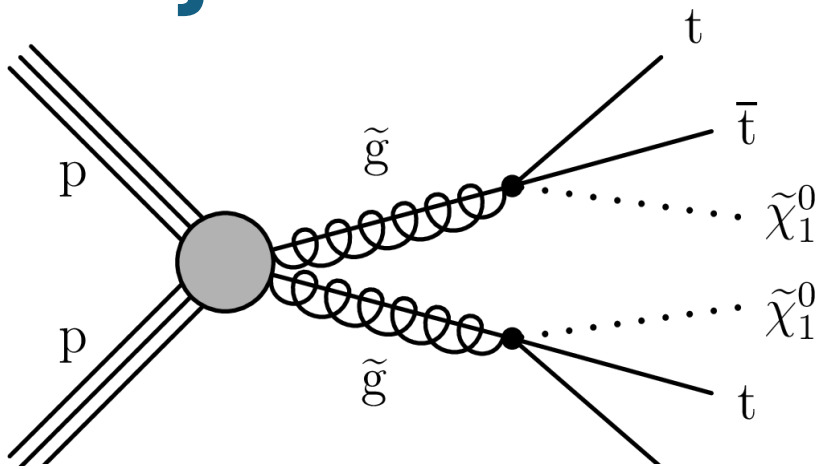


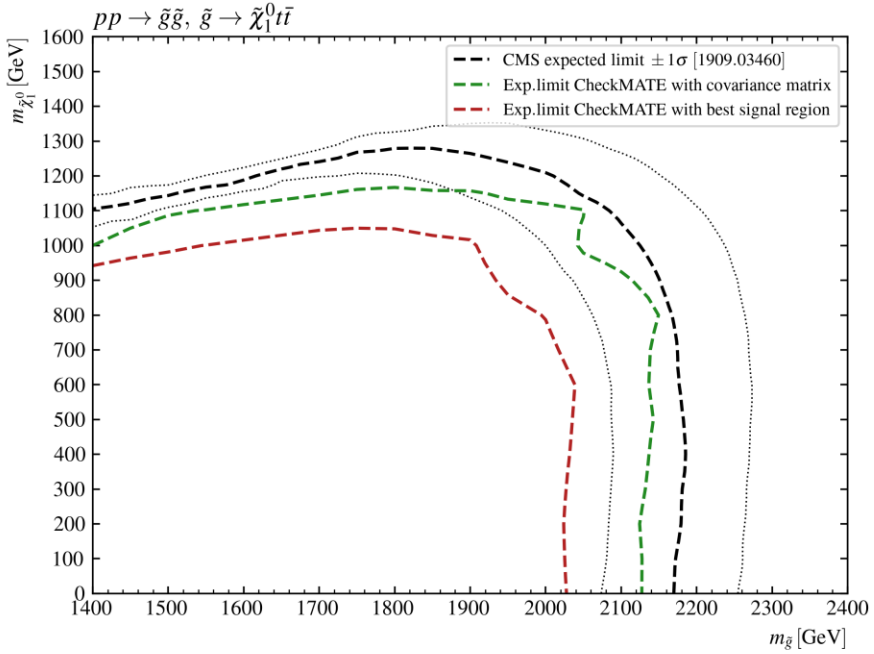


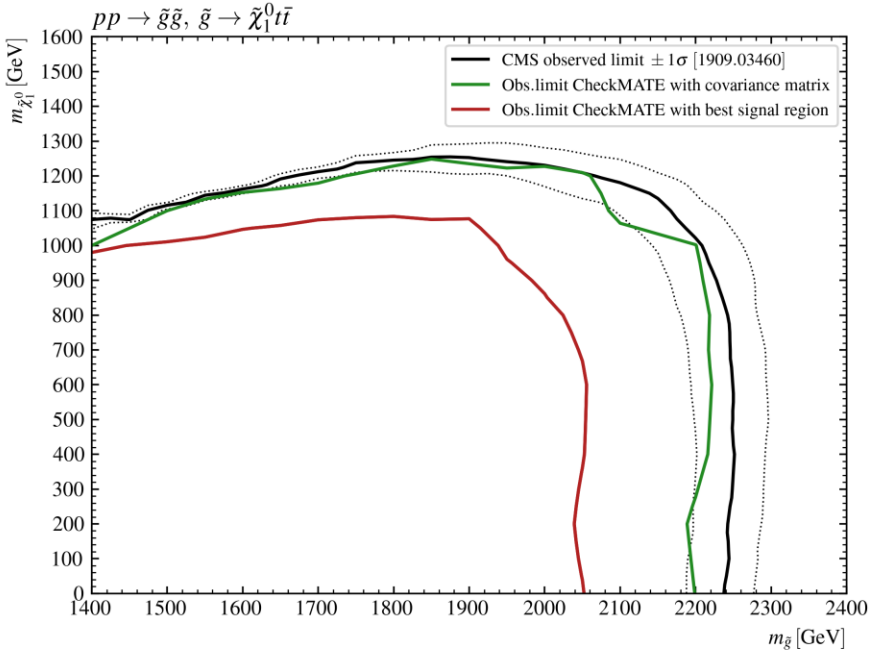


arXiv:1909.03460 - multijet MT2 variable

- CMS covariance matrix
- 282 signal regions
- 21 super signal regions
- covers mono-jets, SUSY, LQs

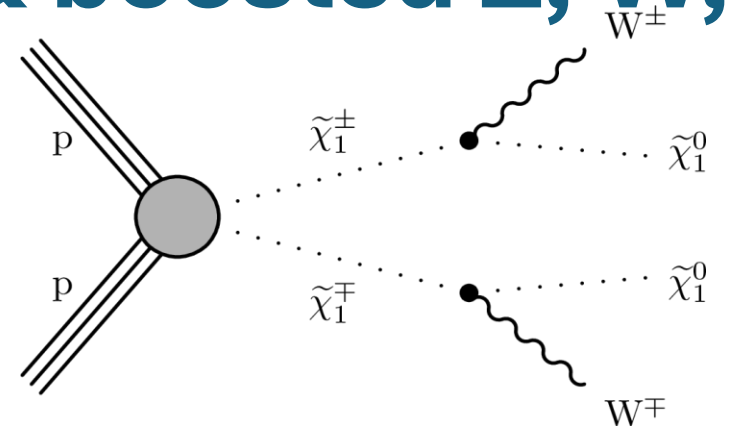


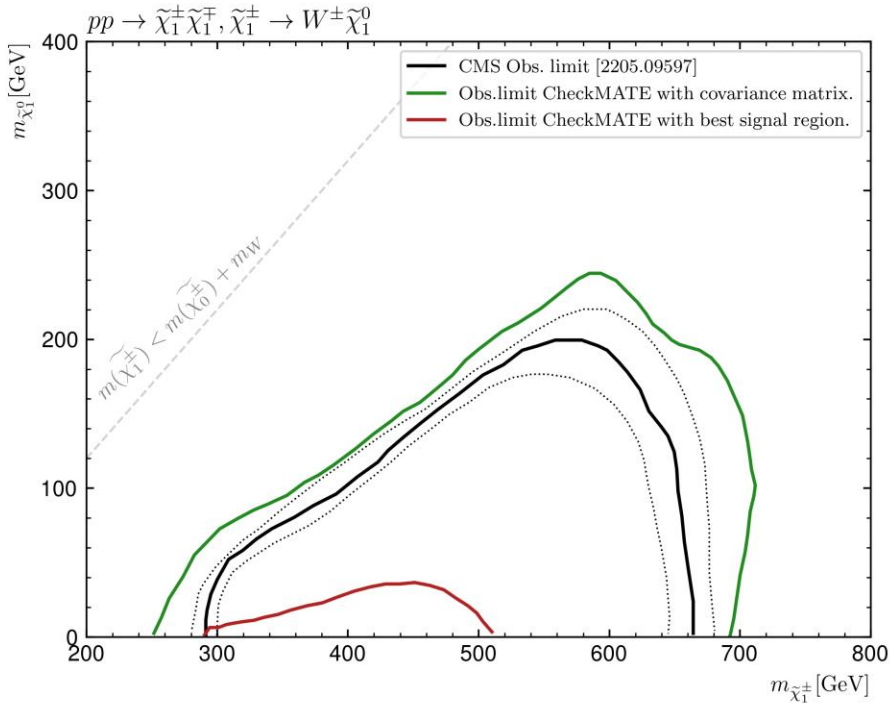


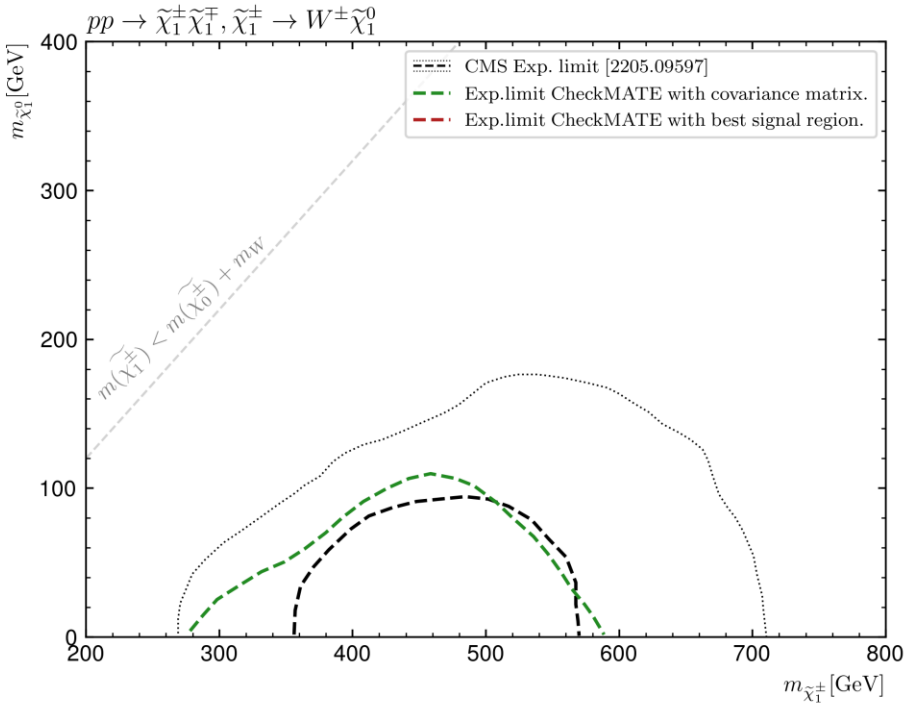


arXiv:2205.09597 - SUSY & boosted Z, W, H

- CMS covariance matrix
- search for chargino and neutralino production with boosted hadronic gauge/H bosons and dedicated taggers







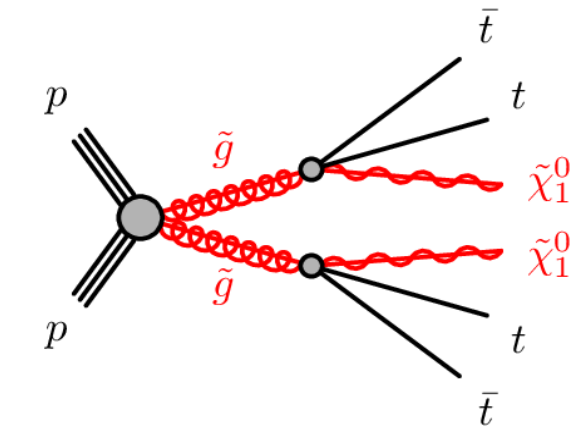
Contents

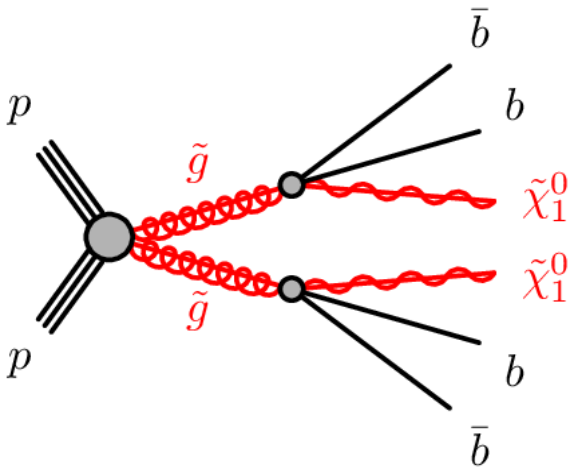
1. CheckMATE overview
2. Implementation of statistical models
3. Validation examples
4. ML implementation
5. Summary and outlook

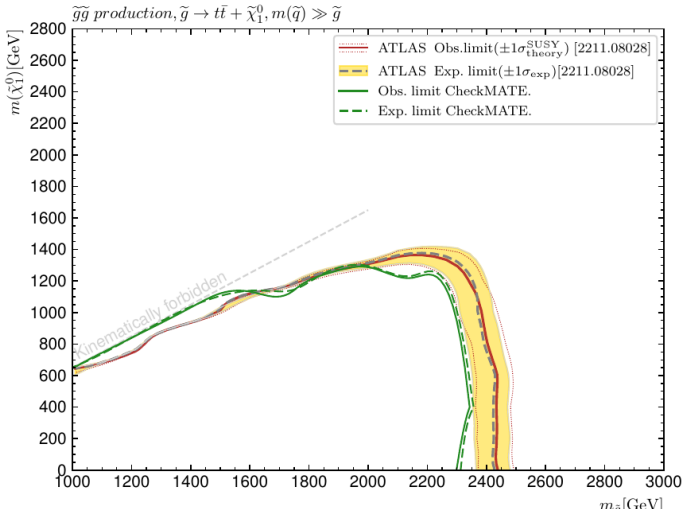
Searches with ML implementation (ATLAS)

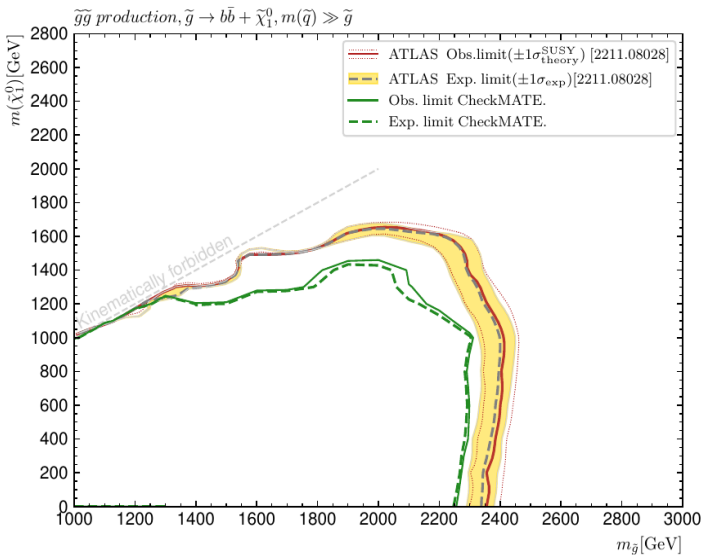
- NN, RPV SUSY, arxiv:2106.09609, SUSY-2019-04
  using ONNX
- NN, SUSY, b-jets+MET, arXiv:2211.08028, SUSY-2018-30
  using ONNX
- BDT, SUSY, jets+MET, arxiv:2010.14293, SUSY-2018-22
  using ROOT BDT with .xml files
- BDT, EW chargino/neutralinos, arXiv:2209.13935, SUSY-2019-02
  using MVAUtils with .root files

arXiv:2211.08028 - SUSY, many b-jets







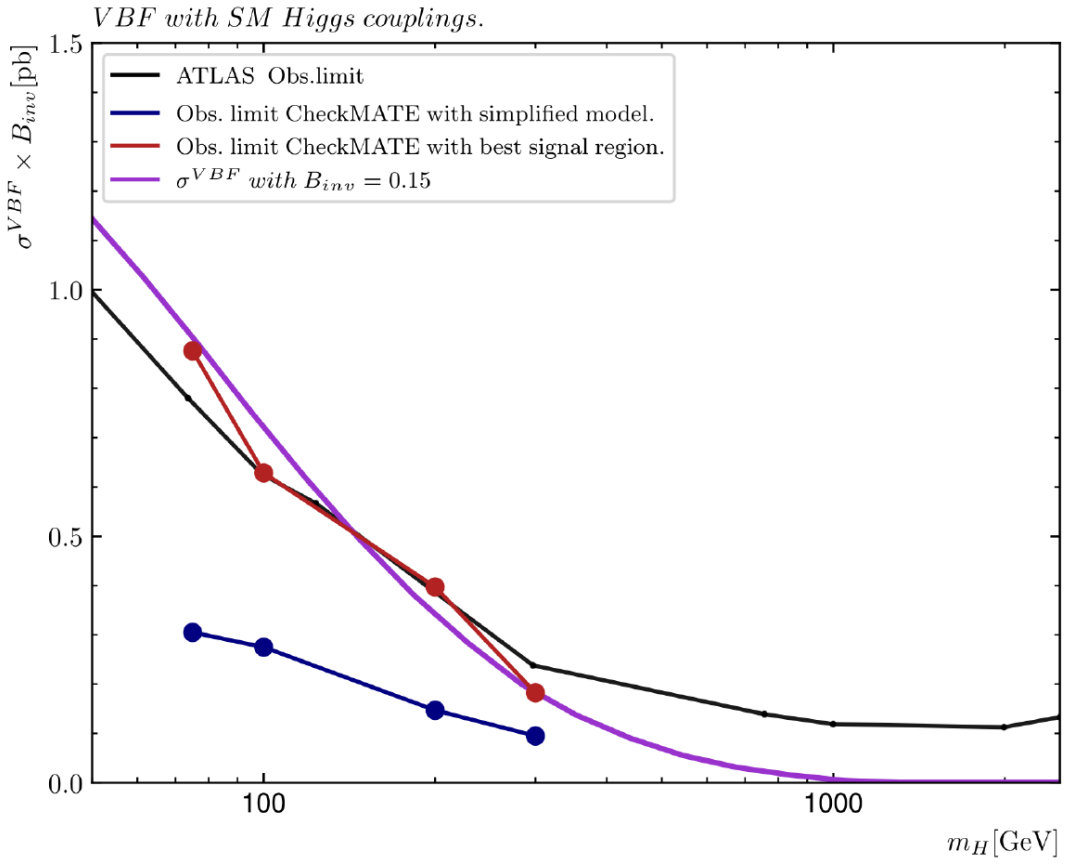


Contents

1. CheckMATE overview
2. Implementation of statistical models
3. Validation examples
4. ML implementation
5. Summary and outlook

Summary and Outlook

- Statistical models available in 15 ATLAS and CMS searches
- Good agreement with published results
- Several choices for evaluation method
- Possible combination of different searches/experiments straightforward – based on Spey
- 4 searches using ML (and 3 different implementations…)
- I'm strongly motivated to merge everything into the master branch very soon

When simplified likelihood fails

- arXiv:2202.07953 - VBF + MET
- search for invisible Higgs decays in VBF production
- no likelihood provided
- attempted simplified likelihood, but it fails badly