Signal region combination in CheckMATE

Pyhf Users and Developers Workshop

CERN - December 2023

Contents

1. CheckMATE overview
2. Implementation of searches with multibin SRs
3. Example of application: pushing limits for electroweakinos.
4. Summary and outlook

CHECKMATE

- CheckMATE is a general tool for recasting arbitrary models.
- Accepts events as .hepmc, .lhe; also integration with Pythia and MadGraph -> From SLHA file to the limit in one click.
- Based on Delphes for detector simulation.
- Using existing LHC searches calculates a limit on a given parameter space point.
- One can easily constrain models that were not covered in the original ATLAS/CMS search.
- Also brach dedicated to long-lived particles.
- https://github.com/CheckMATE2/checkmate2 & https://checkmate.hepforge.org/

CheckMATE: ATLAS analyses (@13TeV)

#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_conf_2019_018	2	Search for direct stau production in events with two hadronic tau leptons	139
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_conf_2020_048	26	Search for dark matter with monojets	139
atlas_2004_14060	9	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

CheckMATE: CMS analyses (@13TeV)

#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 is shorter than for ATLAS but expanding. Three new full luminosity searches added recently.

Contents

Signal region combination

Older CheckMATE versions based the test on the SR with the largest expected exclusion, using only a fraction of the available data -> loss of sensitivity.

New CheckMATE release will include multi-bin based limits within Checkmate. ATLAS and CMS provide the instructions and information to implement those limits at different levels:

- ATLAS is publishing the Full statistical model in .json format. Also provides prescription to build a simplified likelihood.
- CMS gives covariance matrices of the fitted background among the SRs.

ATLAS multibin searches

- Implementation based on pyhf
- Most searches available with full and simplified likelihoods
- By default CheckMATE calculates upper limit over signal streng th using a scan.
- Full likelihood evaluation is very time consuming -> option to change to CLs-only calculation for given point.
- Full hadronic search 2010.14293 has all control regions implemented

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}	4, 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	11, 78	✓
atlas_2004_14060	Search for stops in hadronic final states with E_T^{miss}	2, 9	✗
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}	8, 32	✓
atlas_2106_01676	Search for chargino–neutralino production in final states with 3 leptons and E_T^{miss}	2, 72	✓

ATL-PHYS-PUB-2021-038

ATL-PHYS-PUB-2019-029

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

- Implementation with ROOT workspace in python3

$$\mathcal{L}_S(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu \cdot s_i + b_i + \theta_i)^{n_i} e^{-(\mu \cdot s_i + b_i + \theta_i)}}{n_i!} \cdot \exp\left(-\frac{1}{2}\boldsymbol{\theta}^T \mathbf{V}^{-1} \boldsymbol{\theta}\right)$$

Performance is not particularly stable -> Very often we find problems with convergence.

- Optional constraint for signal numbers: for many bins it's difficult to get reasonable statistics which results in large MC-related errors.

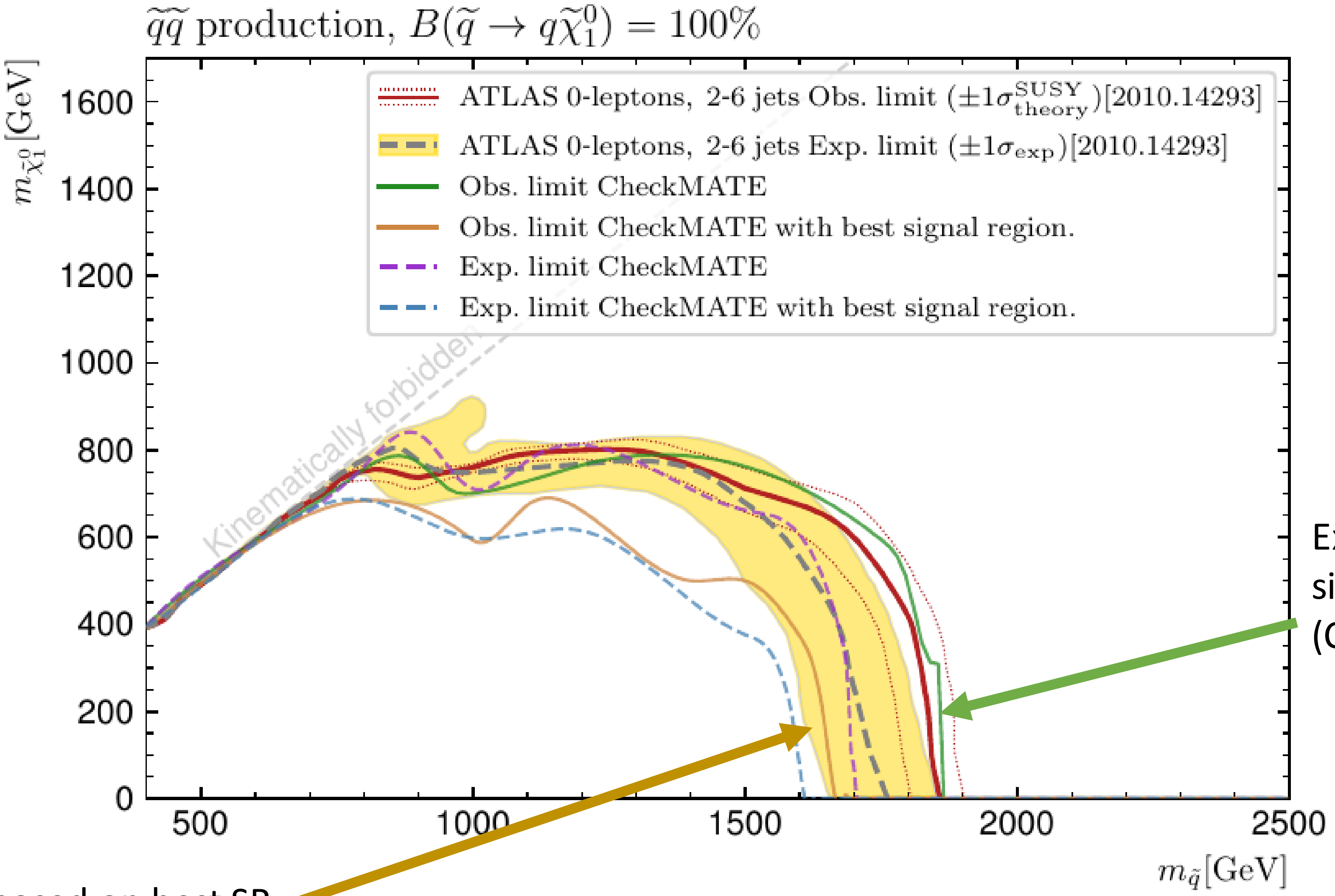
CMS multibin searches

Additional features:

- Spey wrapper – very good stability compared to ROOT implementation, good agreement between both methods
- Possible extension to combine different searches/experiments with Spey
- Some flexibility left regarding error treatment

Some examples...

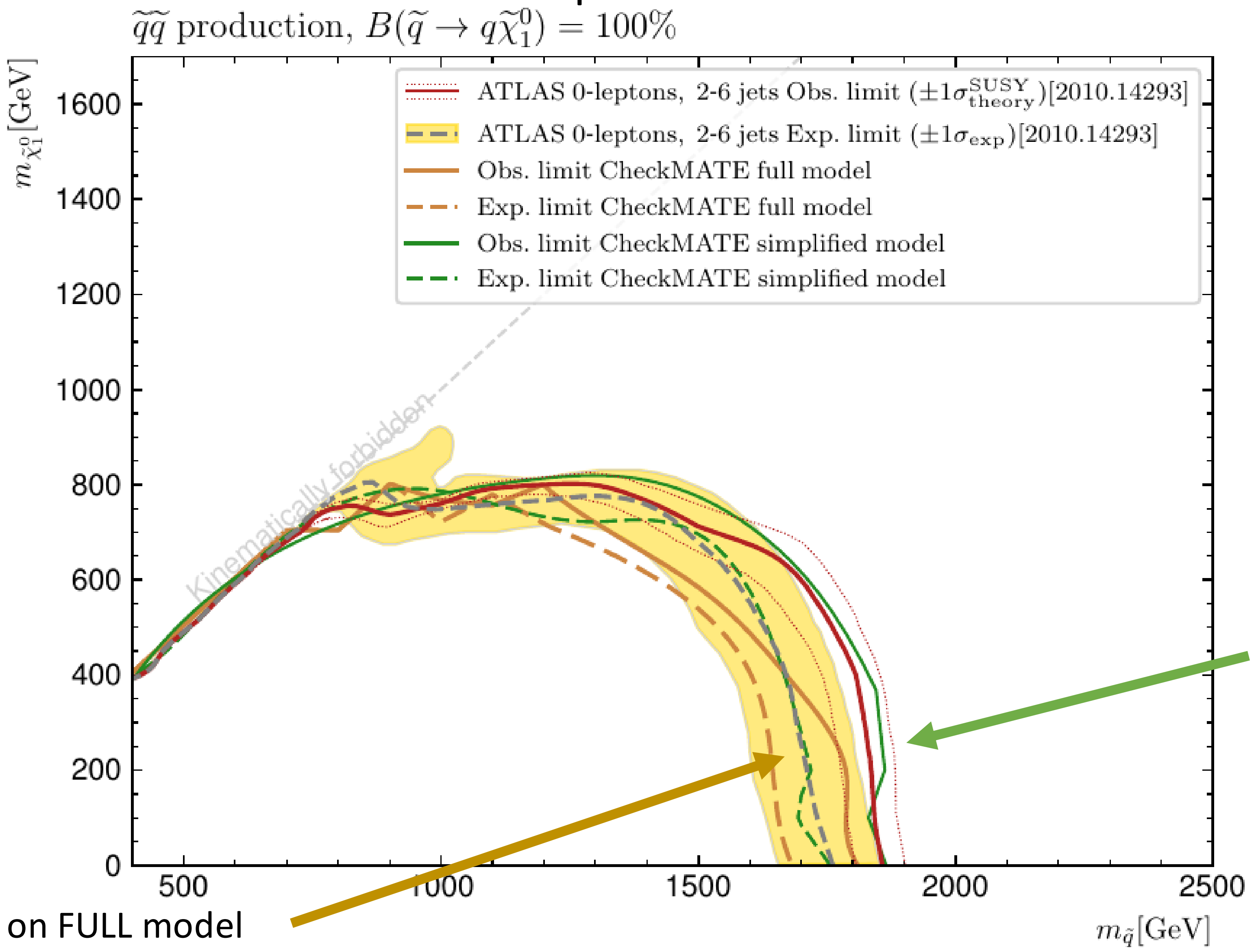
Comparison between the best SR and simplified-Likelihood fit



Exclusion based on simplified Likelihood (CheckMATE)

Exclusion based on best SR (CheckMATE)

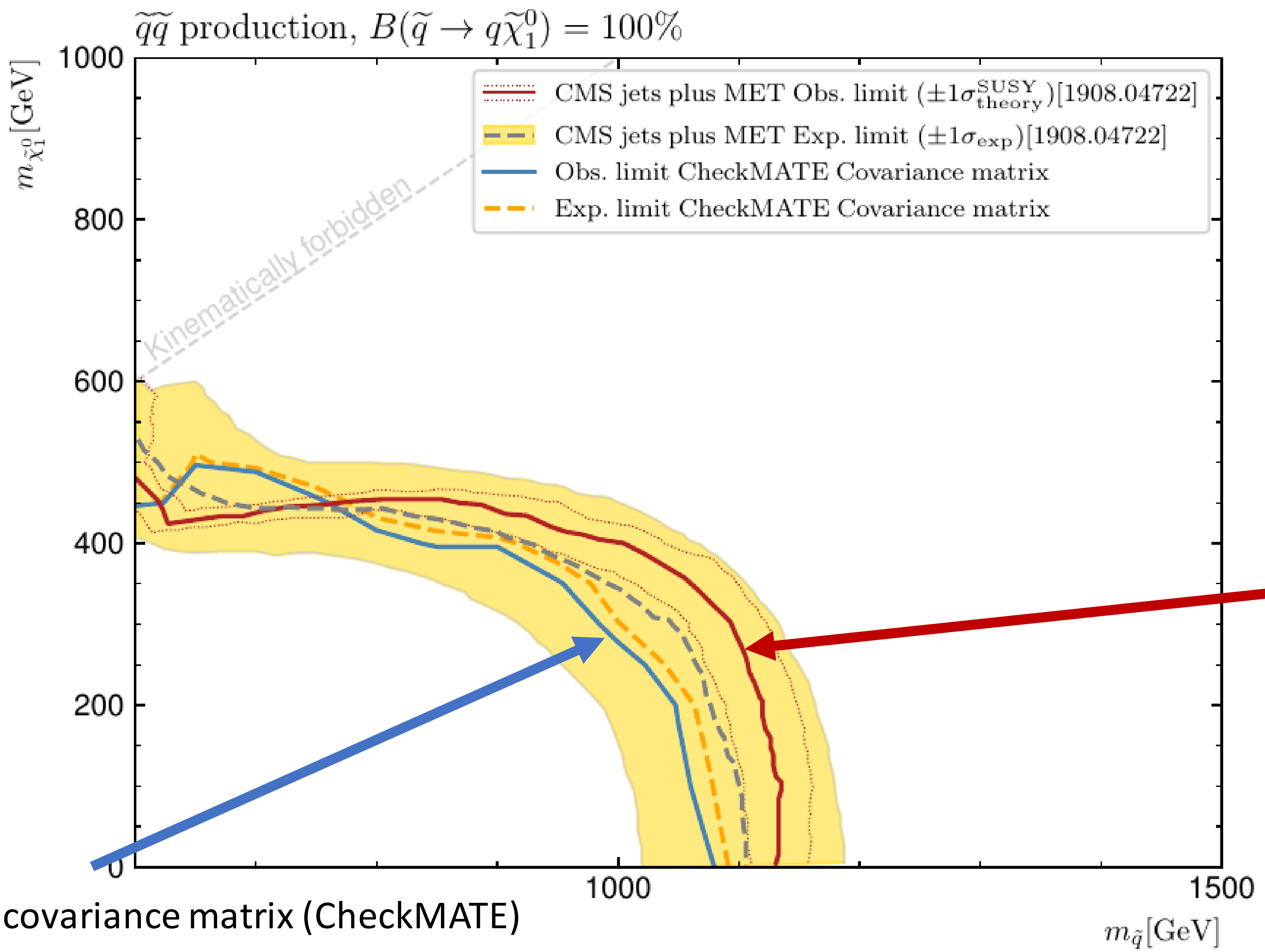
Comparison between the simplified and full model.



Exclusion based on simplified Likelihood (CheckMATE)

Exclusion based on FULL model (CheckMATE)

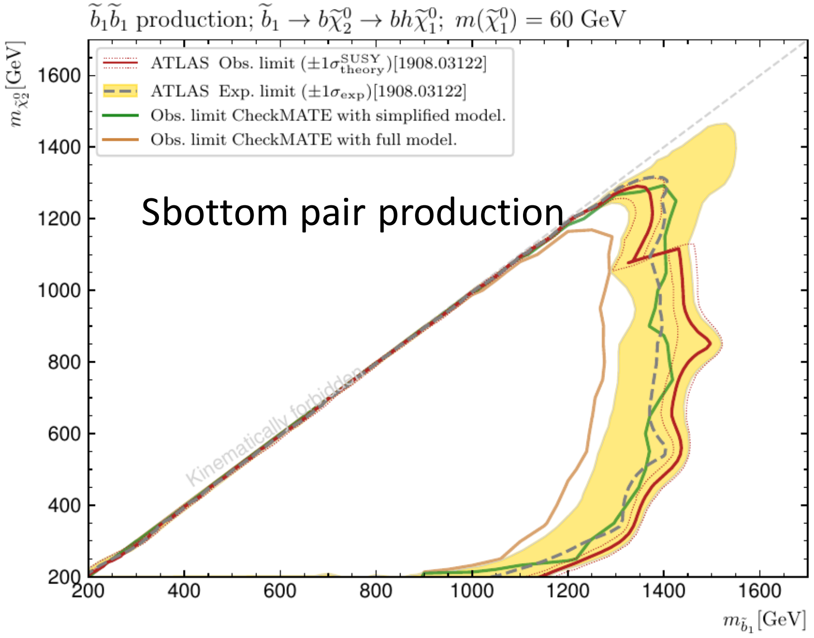
Comparison between the Simplified model + Covariance matrix vs official limit.

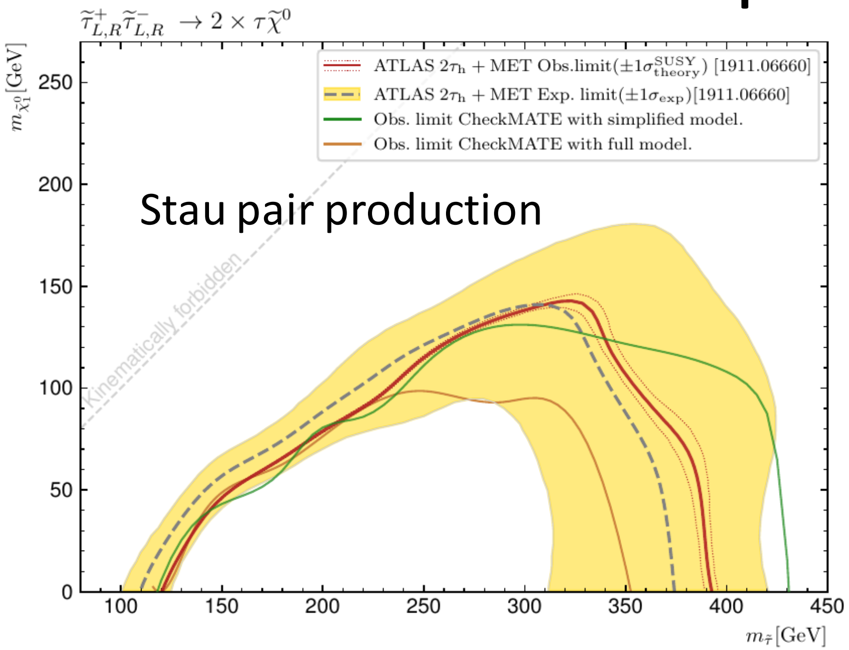


CMS observed limit.

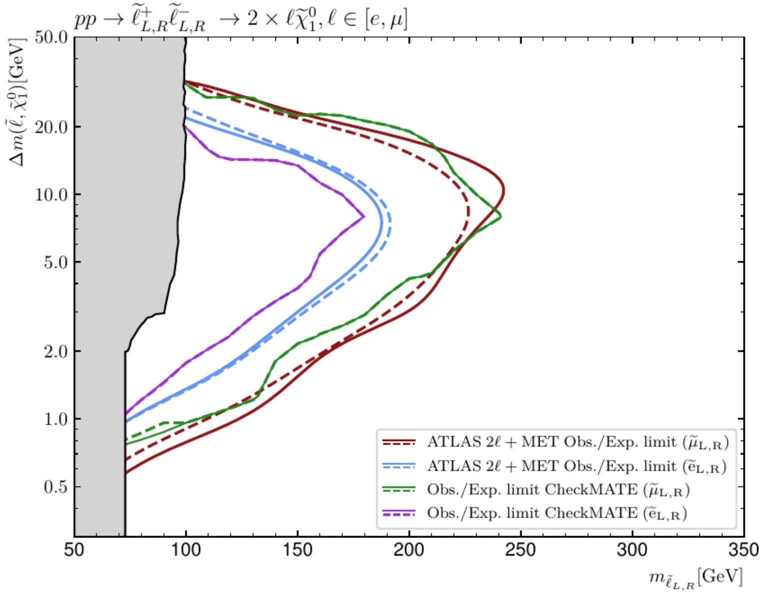
Exclusion using covariance matrix (CheckMATE)

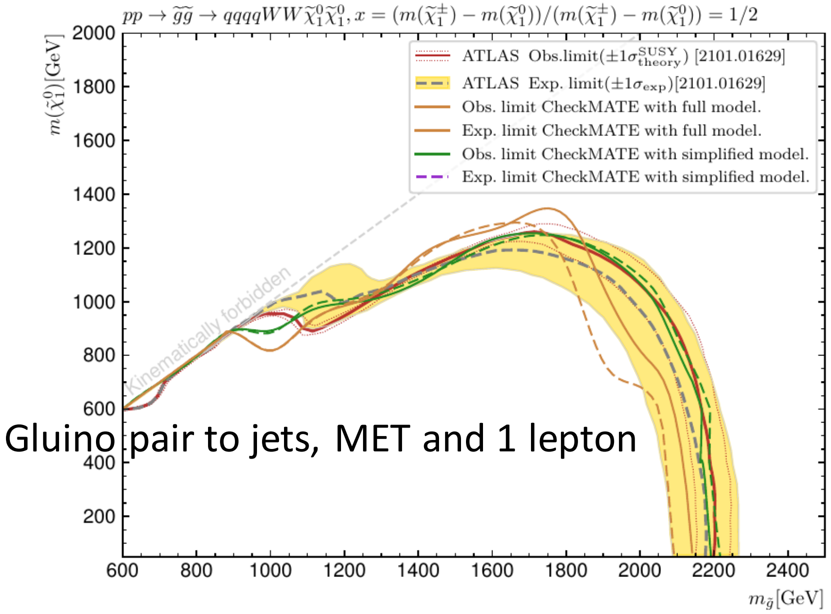
Other ATLAS searches implemented

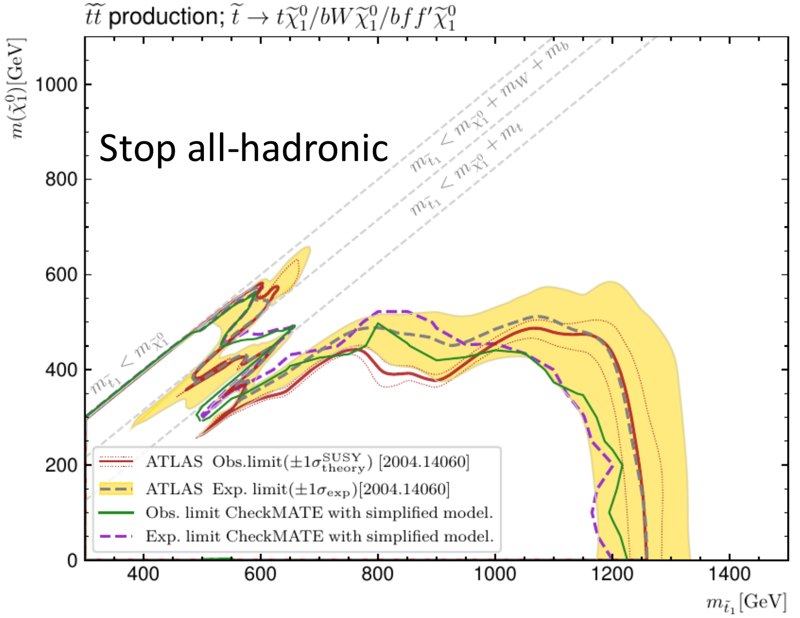




Slepton pair-> Soft leptons

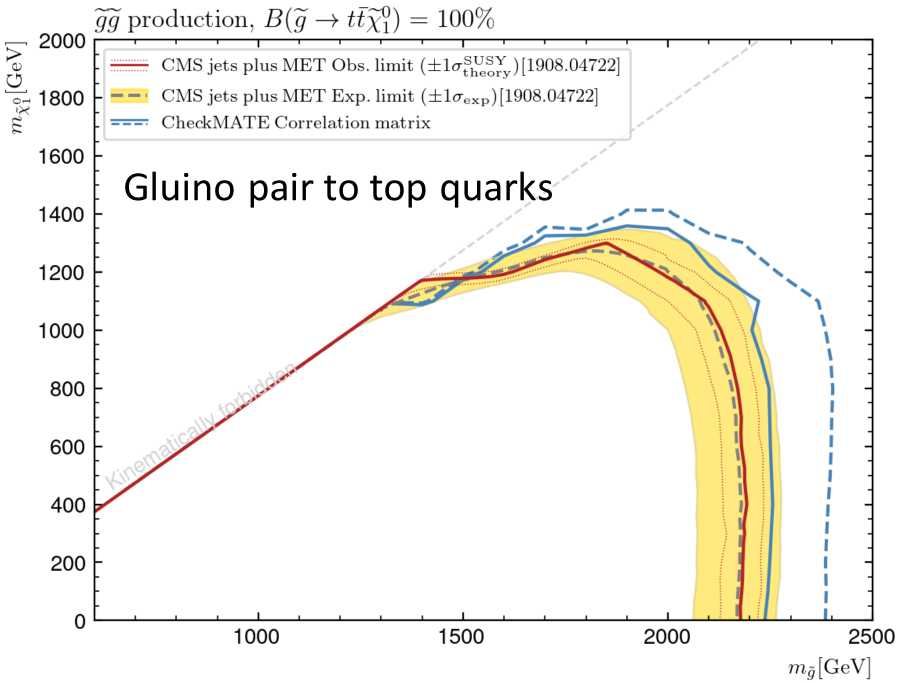


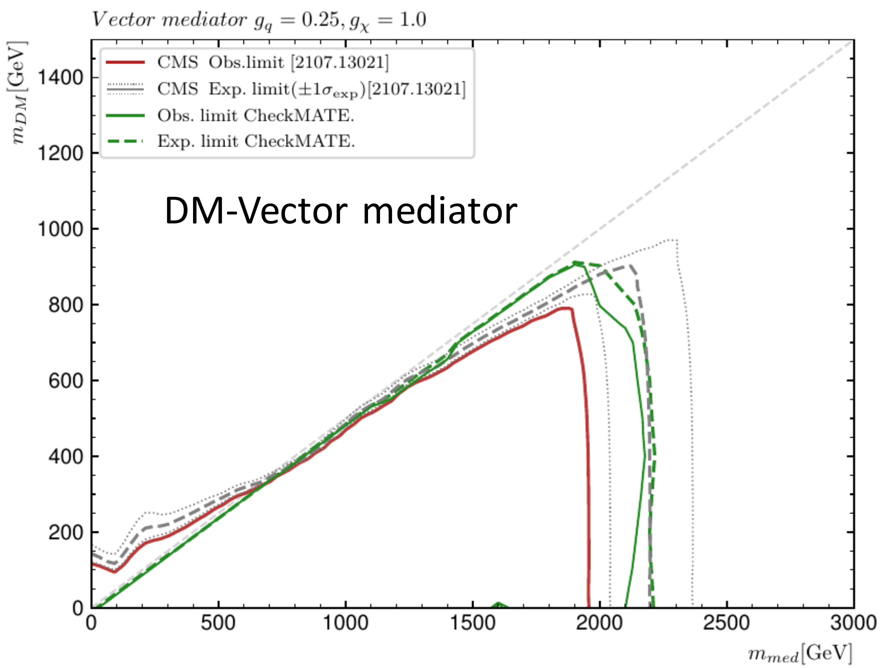




And more...

Other CMS searches implemented





And more in process...

Contents

1. CheckMATE overview
2. Implementation of searches with multibin SRs
3. Example of application: pushing limits for electroweakinos.
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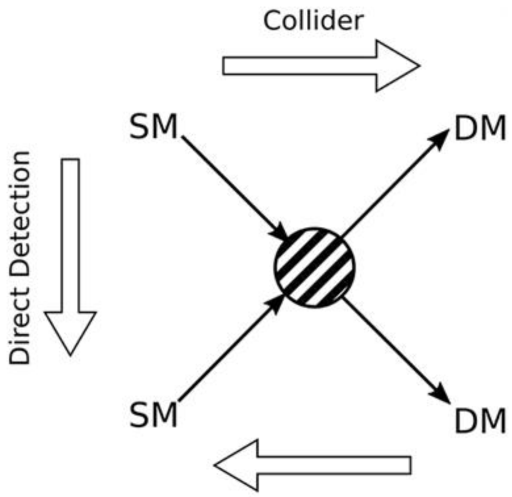
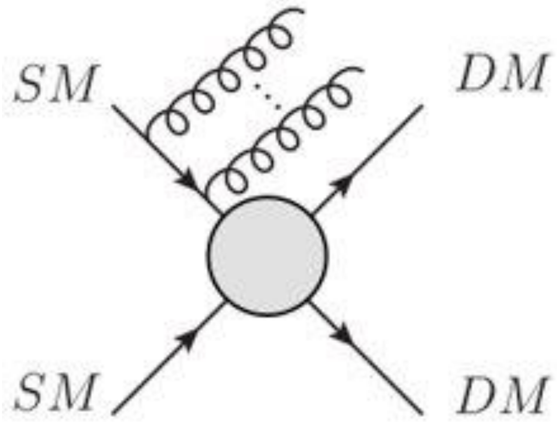
Case of study: Supersymmetric DM

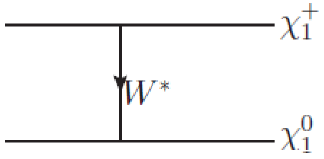


- Superparners of gauge and Higgs bosons justified at LHC reach as DM candidates.
- Hadron colliders may produce DM particles in pairs, associated with a few high pT jets originating from initial state QCD radiation

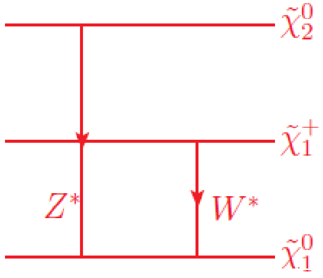


bino-wino: almost mass degenerate winos and bino LSP

wino LSP: $M_2 \ll M_1, \mu$, two quasi-degenerate states: χ_1^0, $\chi_1^\pm$

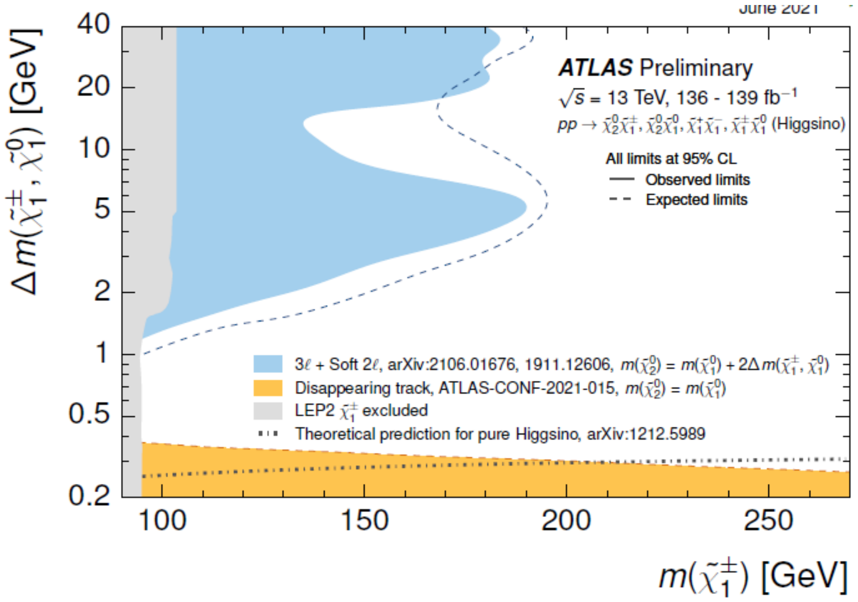


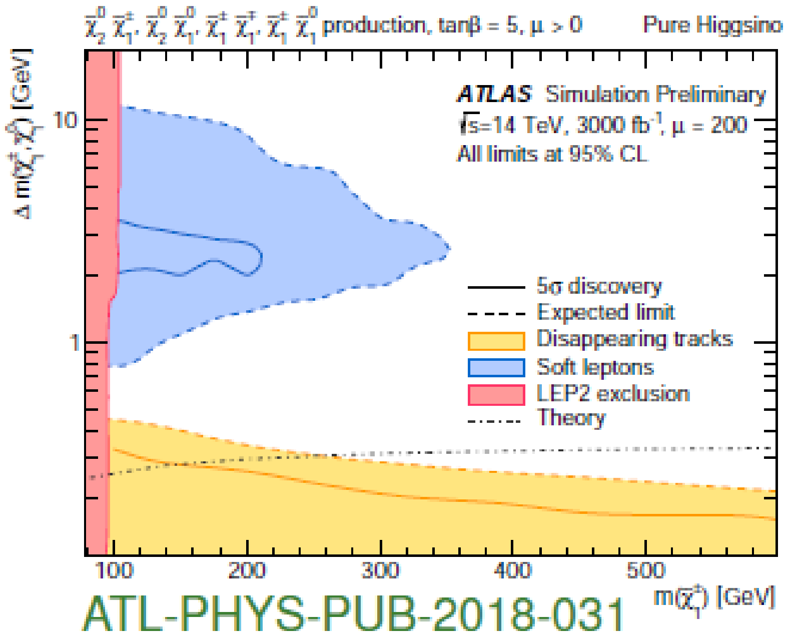
higgsino LSP, $\mu \ll M_1, M_2$, three quasi-degenerate states: $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$



Mass splitings of order 100-1000 MeV

At the LHC this scenarios has been constrained focusing on:

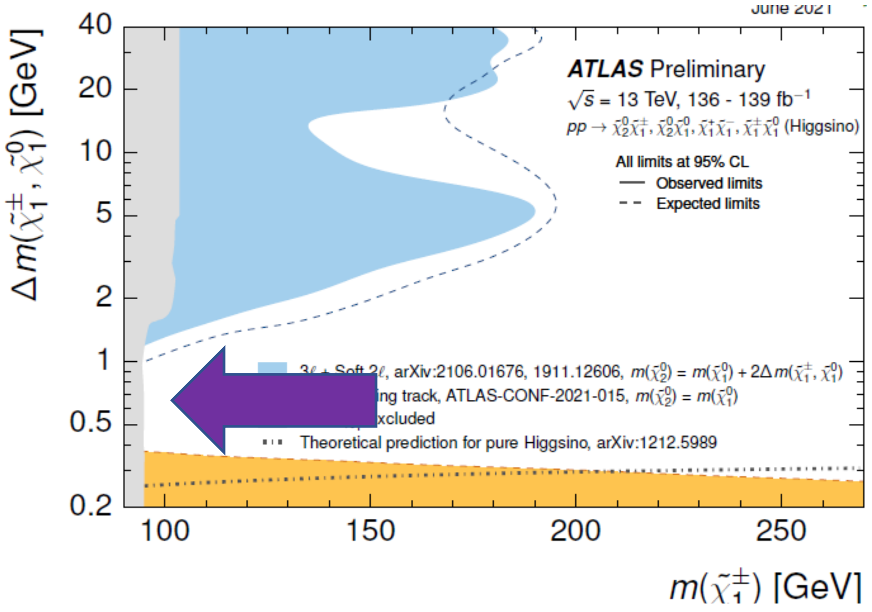


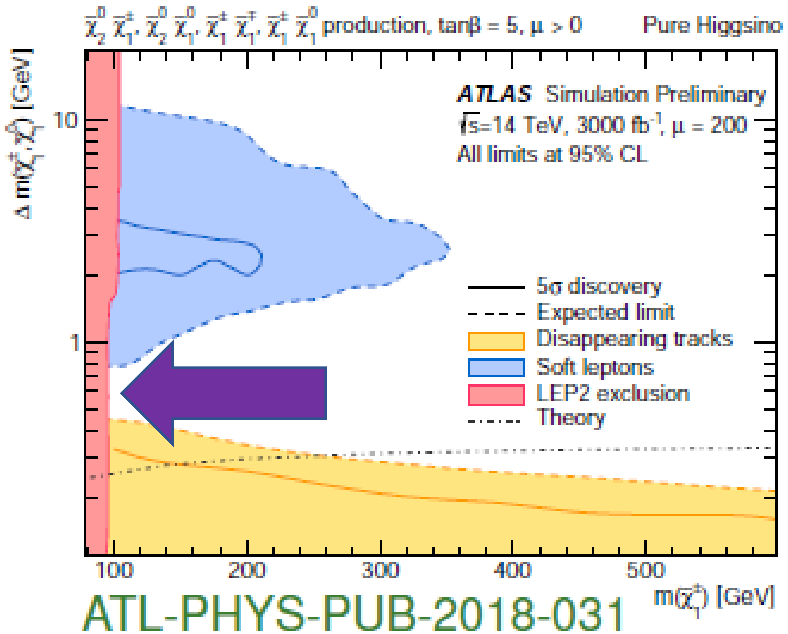


ATL-PHYS-PUB-2018-031

- Disappearing tracks: for sufficiently small mass gap, heavier states are long-lived.
- Soft leptons: For a mass difference ≳1 GeV look for soft decay products.
- Long-standing limit at ~ 100 GeV from LEP

At the LHC this scenarios has been constrained focusing on:





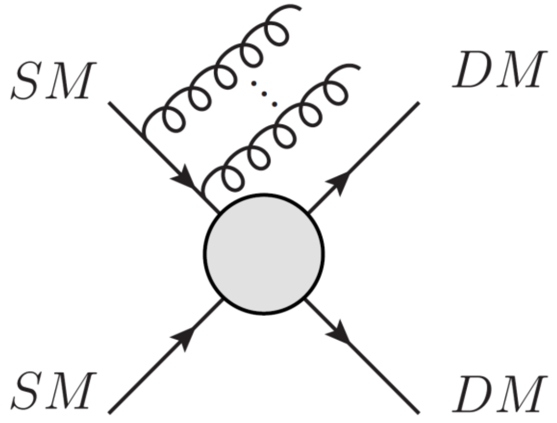
ATL-PHYS-PUB-2018-031

- Disappearing tracks: for sufficiently small mass gap, heavier states are long-lived.
- Soft leptons: For a mass difference ≳1 GeV look for soft decay products.
- Long-standing limit at ∼ 100 GeV from LEP.

GAP between the two LHC searches. Use Mono/few-jets searches on this region.

Monojet searches from ATLAS and CMS are not sensitive (yet) to *electroweakino* DM. More than one jet emitted is possible, thus *more-than-one-jet* searches may be used also.

- We recast with CheckMATE a general search for squarks and gluinos, arXiv:2010.14293, in total 70 signal regions.
- Basic (preselection) signal requirements:
  - no electrons or muons.
  - 2–6 jets
  - large missing energy > 300 GeV
  - hard leading jet p_T > 200 GeV
  - large effective mass > 800 GeV



- Some overlap of the final states with “mono”-jet.
- We focus on bins with the largest sensitivity (originally intended for squark pair production):

2–3 jets, $p_T^{\mathrm{jet1}}, p_T^{\mathrm{jet2}} > 250$ GeV
effective mass > 1600 GeV
$E_T^{\mathrm{miss}}/\sqrt{H_T} > 16\sqrt{\mathrm{GeV}}$

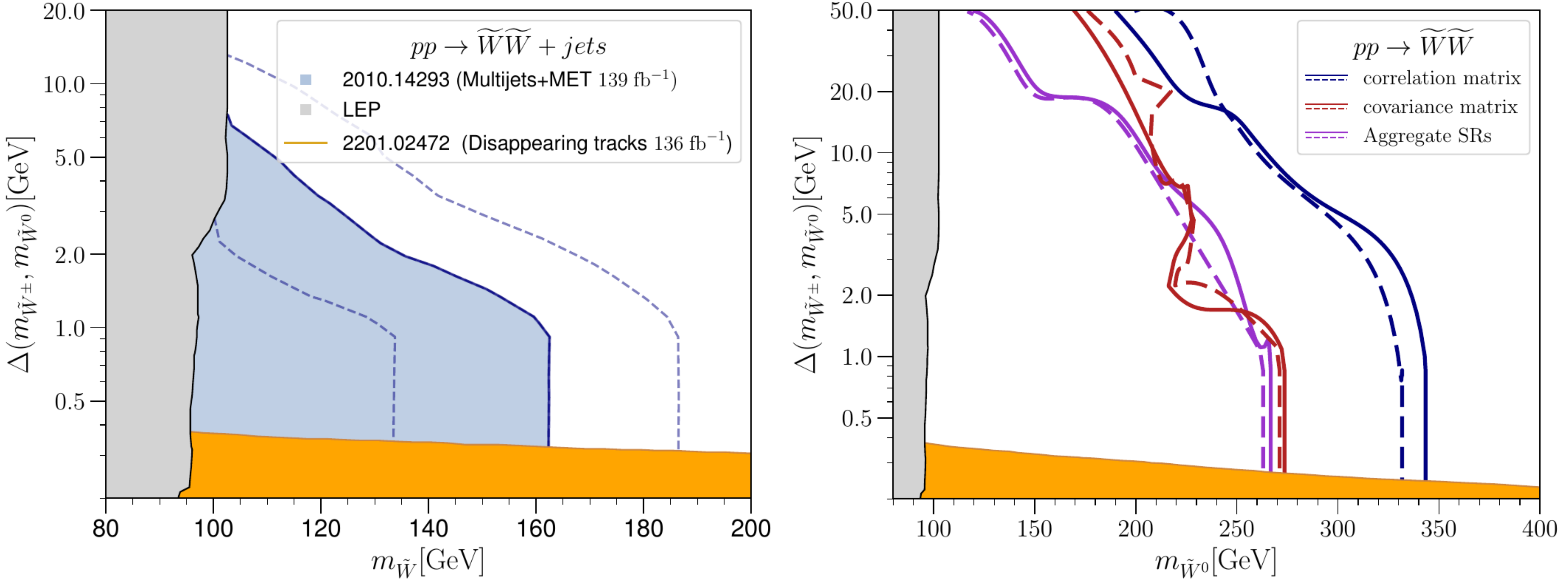
- Multi-bin fit over ortogonaly binned signal regions

Also test with CMS multijet:

- CMS-SUS-19-006 with multibin for – different selections wrt ATLAS

  - $N_{\text{jet}} \geq 2$, where jets must appear within $|\eta| < 2.4$;
  - $H_T > 300\,\text{GeV}$, where H_T is the scalar p_T sum of jets with $|\eta| < 2.4$;
  - $H_T^{\text{miss}} > 300\,\text{GeV}$, where H_T^{miss} is the magnitude of $\vec{H}_T^{\text{miss}}$, the negative of the vector p_T sum of jets with $|\eta| < 5$; an extended η range is used to calculate H_T^{miss} so that it better represents the total missing momentum in an event;
  - $H_T^{\text{miss}} < H_T$, because events with $H_T^{\text{miss}} > H_T$ are likely to arise from mismeasurement;
  - no identified isolated electron or muon candidate with $p_T > 10\,\text{GeV}$;
  - no isolated track with $m_T < 100\,\text{GeV}$ and $p_T > 10\,\text{GeV}$ ($p_T > 5\,\text{GeV}$ if the track is identified as a PF electron or muon), where m_T is the transverse mass [52] formed from $\vec{p}_T^{\text{miss}}$ and the isolated-track p_T vector, with $\vec{p}_T^{\text{miss}}$ the negative of the vector p_T
  - $\Delta\phi_{H_T^{\text{miss}},j_i} > 0.5$ for the two highest p_T jets j_1 and j_2, with $\Delta\phi_{H_T^{\text{miss}},j_i}$ the azimuthal angle between $\vec{H}_T^{\text{miss}}$ and the p_T vector of jet j_i; if $N_{\text{jet}} \geq 3$, then, in addition, $\Delta\phi_{H_T^{\text{miss}},j_3} > 0.3$ for the third-highest p_T jet j_3; if $N_{\text{jet}} \geq 4$, then, yet in addition, $\Delta\phi_{H_T^{\text{miss}},j_4} > 0.3$ for the fourth-highest p_T jet j_4; all considered jets must have $|\eta| < 2.4$; these requirements

New limits based on recasted analysis:



Summary and Outlook

- New version of CheckMATE will include upper limit calculation based on SR combinations. Implemented in 12 ATLAS and CMS searches.
- Implementation based on pyhf (for ATLAS) and ROOT/Spey (for CMS).
- In most cases runs in a reasonable amount of time. Option to calculate just CLs for specific point to seed calculation.
- Reasonable agreement with ATLAS/CMS published limits.
- New limits from hadronic final states on electroweakinos are very promising – important for future colliders.

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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