Signal region combination and other new features in CheckMATE

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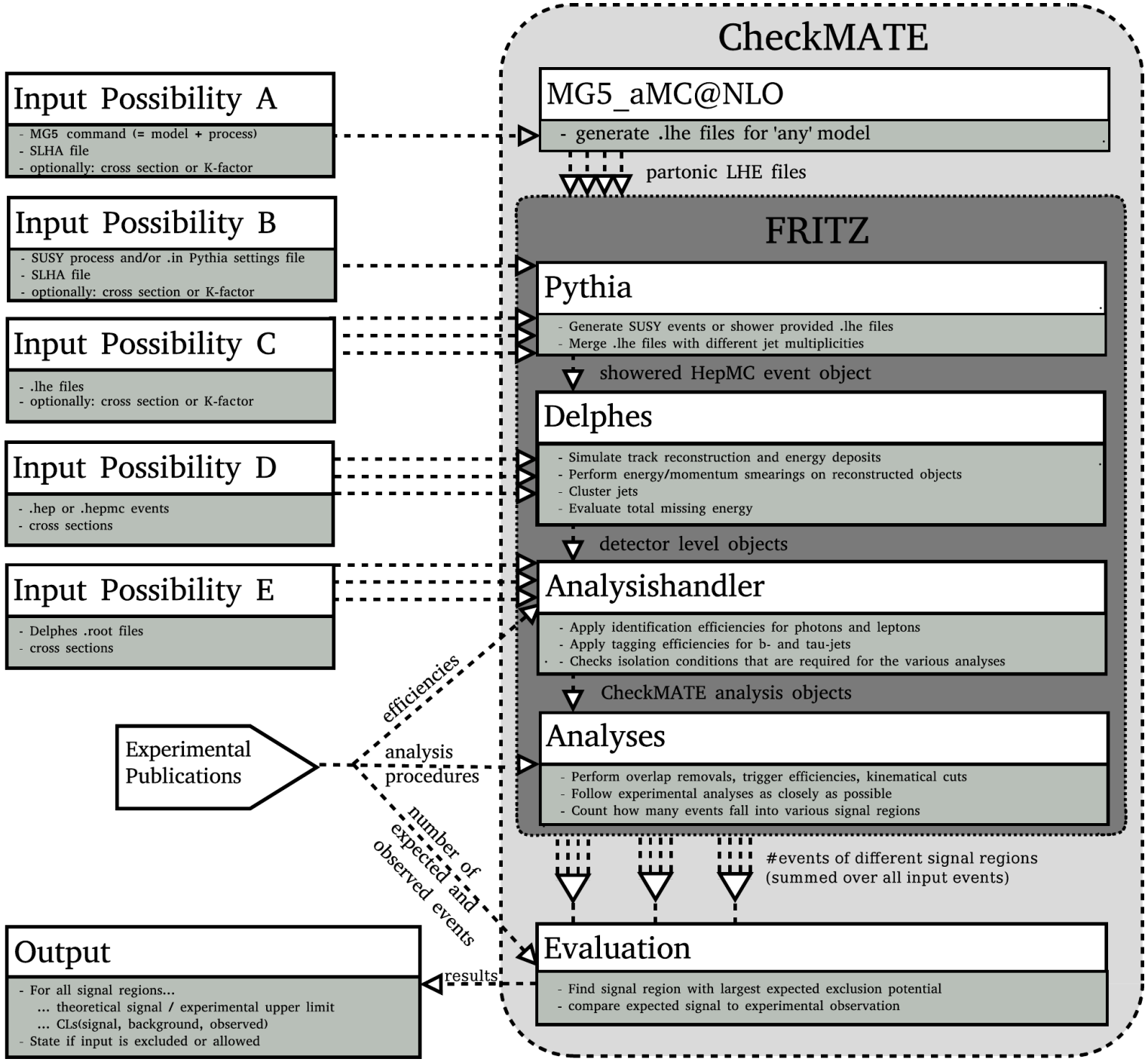
- CheckMATE is a general tool for recasting arbitrary model
- Accepts events as .hepmc, .lhe; integration with Pythia and MadGraph
- based on Delphes for detector simulation
- using existing LHC searches calculates a limit on a given parameter point
- From SLHA file to the limit in one click
- one can 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


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_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

#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

ATLAS multibin searches

- Implementation using pyhf
- Most searches available with full and simplified likelihoods
- Full likelihood evaluation tends to be time consuming, one can opt for CLs-only calculation
- 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 (not particularly stable)

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

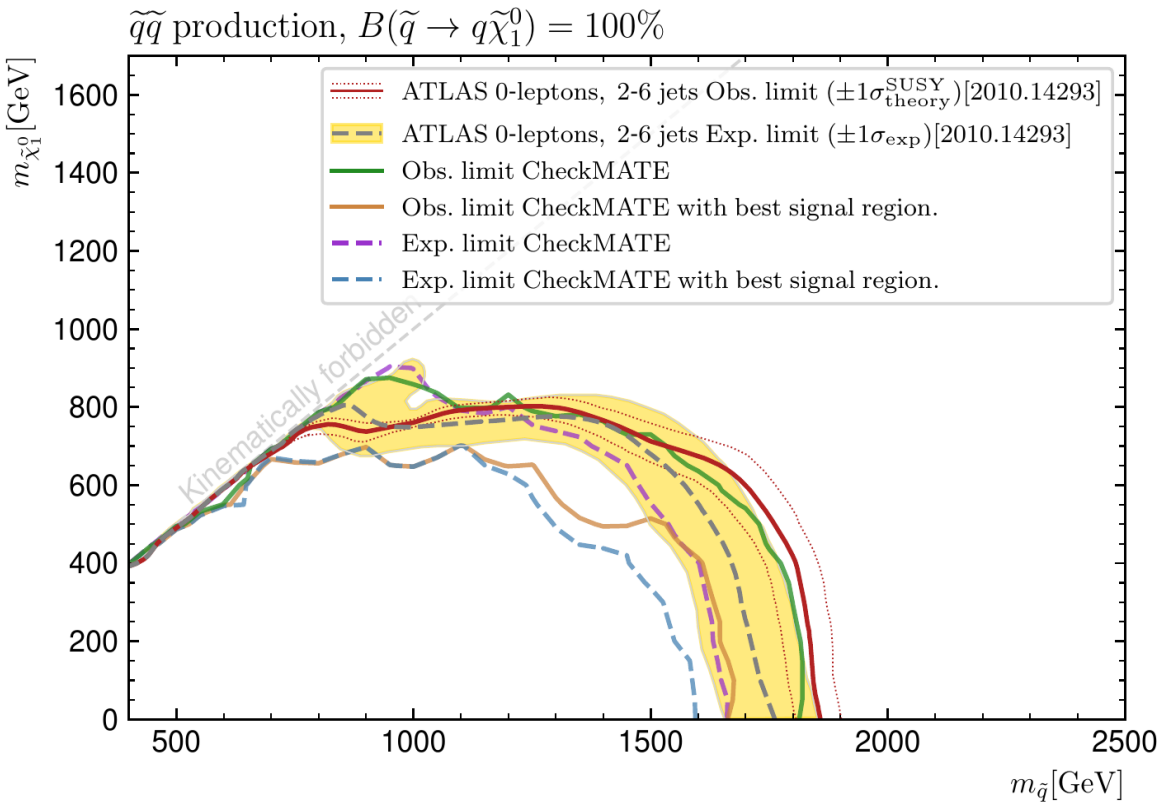
- Optional constraint for signal numbers: for many bins it's difficult to get reasonable statistics which results in large MC-related errors

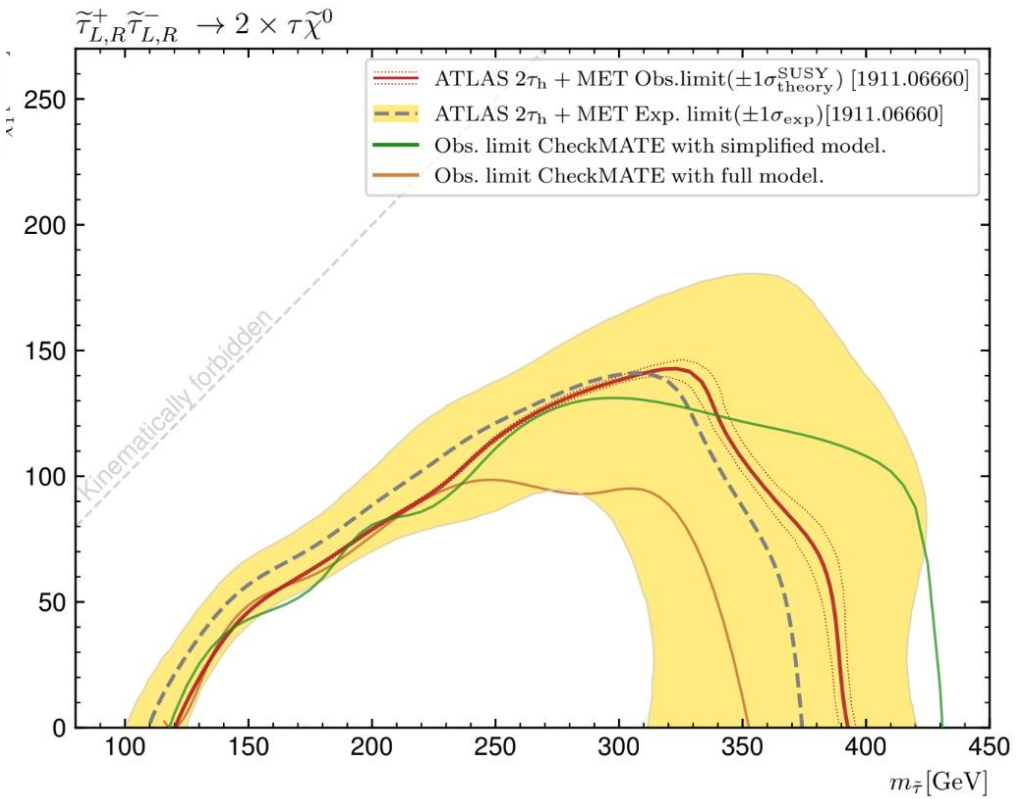
CMS multibin searches

Additional features:

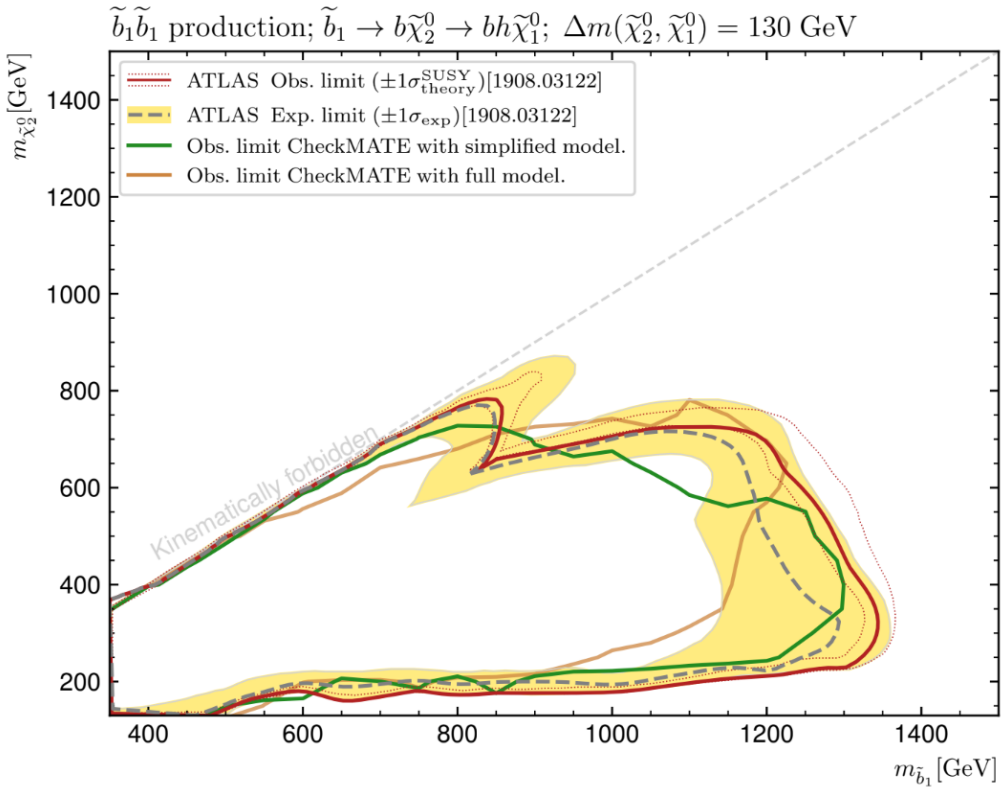
- Spey wrapper – very good stability compared to ROOT implementation, good agreement between both methods
- Possible extension to combine different searches/experiments with Spey
- Some flexibility left regarding error treatment

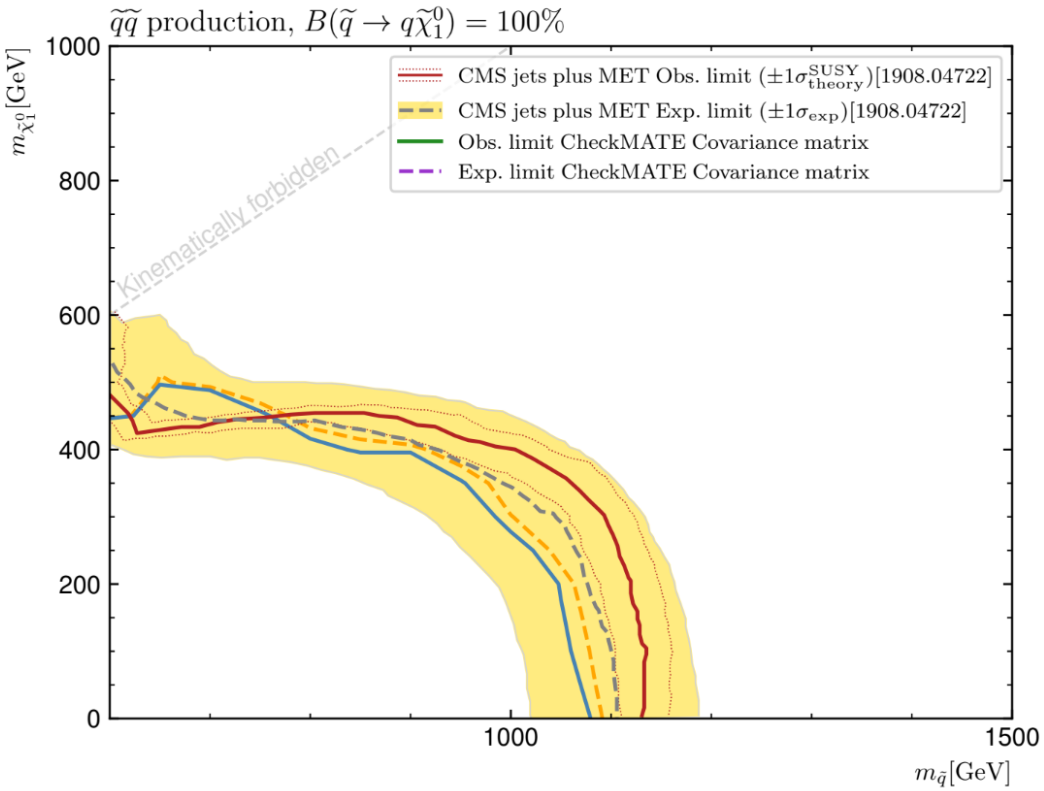
Validation


$\widetilde{q}\widetilde{q}$ production, $B(\widetilde{q} \to q\widetilde{\chi}_1^0) = 100\%$
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
$m_{\widetilde{\chi}_1^0}$[GeV]
$m_{\widetilde{q}}$[GeV]


$\widetilde{\tau}^+_{L,R}\widetilde{\tau}^-_{L,R} \to 2 \times \tau\widetilde{\chi}^0$
ATLAS $2\tau_{\mathrm{h}}$ + MET Obs.limit($\pm 1\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$) [1911.06660]
ATLAS $2\tau_{\mathrm{h}}$ + MET Exp. limit($\pm 1\sigma_{\mathrm{exp}}$)[1911.06660]
Obs. limit CheckMATE with simplified model.
Obs. limit CheckMATE with full model.
Kinematically forbidden
$m_{\widetilde{\tau}}$[GeV]

Validation

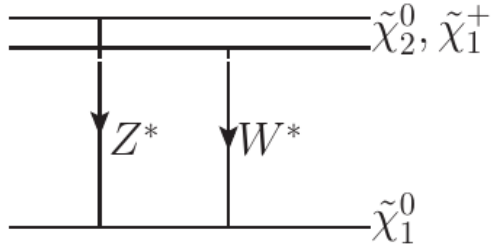

$\widetilde{b}_1\widetilde{b}_1$ production; $\widetilde{b}_1 \to b\widetilde{\chi}_2^0 \to bh\widetilde{\chi}_1^0$; $\Delta m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^0) = 130$ GeV
ATLAS Obs. limit ($\pm 1\sigma_{\text{theory}}^{\text{SUSY}}$)[1908.03122]
ATLAS Exp. limit ($\pm 1\sigma_{\text{exp}}$)[1908.03122]
Obs. limit CheckMATE with simplified model.
Obs. limit CheckMATE with full model.
Kinematically forbidden
$m_{\tilde{\chi}_2^0}$[GeV]
$m_{\tilde{b}_1}$[GeV]
200
400
600
800
1000
1200
1400


$\widetilde{q}\widetilde{q}$ production, $B(\widetilde{q} \to q\widetilde{\chi}_1^0) = 100\%$
CMS jets plus MET Obs. limit ($\pm 1\sigma_{\text{theory}}^{\text{SUSY}}$)[1908.04722]
CMS jets plus MET Exp. limit ($\pm 1\sigma_{\text{exp}}$)[1908.04722]
Obs. limit CheckMATE Covariance matrix
Exp. limit CheckMATE Covariance matrix
Kinematically forbidden
$m_{\tilde{\chi}_1^0}$[GeV]
$m_{\tilde{q}}$[GeV]
0
200
400
600
800
1000
1000
1500

Contents

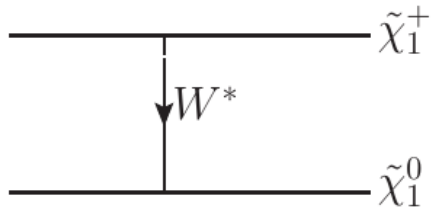
Light SUSY dark matter

- bino-wino: almost mass degenerate winos and bino LSP



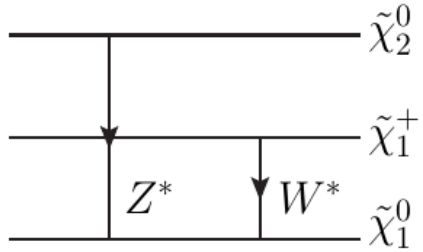
bino-wino

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



wino

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



higgsino

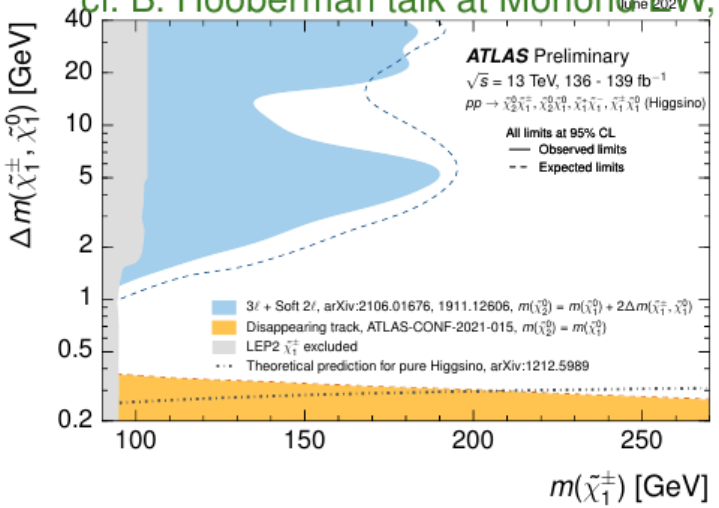
- mass splittings of order 100–1000 MeV

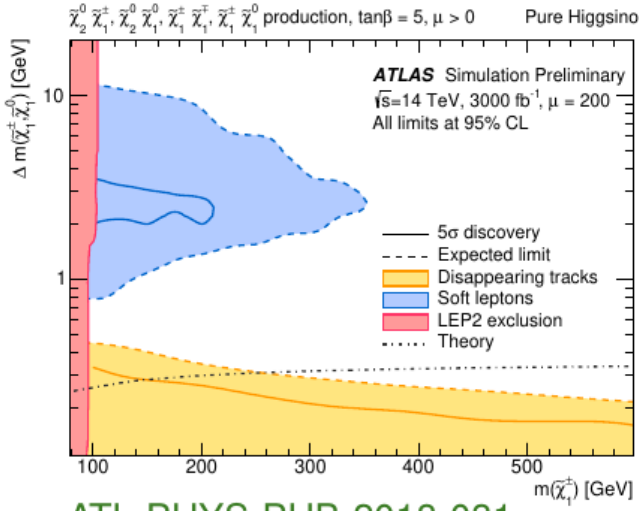
Search strategies

- for sufficiently small mass gap a long-lived massive particle travels macroscopic distance in the detector
- possible signatures: displaced vertex, heavy charged track, displaced jet etc.
- for a larger mass difference (> 1 GeV) look for soft decay products

- at HL the gap remains
- for winos no exclusion in soft ℓ search!

cf. B. Hooberman talk at Moriond EW, 14.03.22





ATL-PHYS-PUB-2018-031

"Multijet" search by ATLAS

- 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
- note 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, $p_{\mathrm{T}}^{\mathrm{jet1}}, p_{\mathrm{T}}^{\mathrm{jet2}} > 250$ GeV
  - effective mass > 1600 GeV
  - $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 16\sqrt{\mathrm{GeV}}$
  - perform a multibin fit using HistFitter

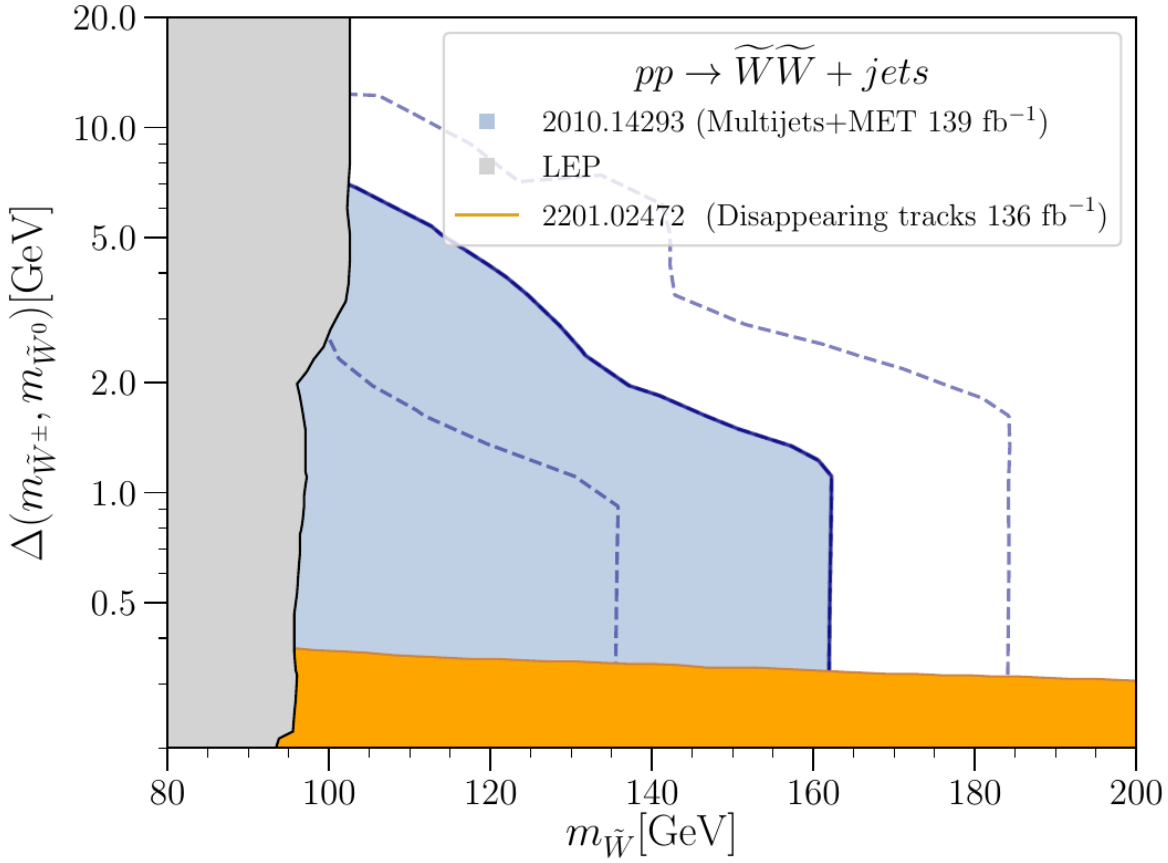
Also try CMS multijet

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

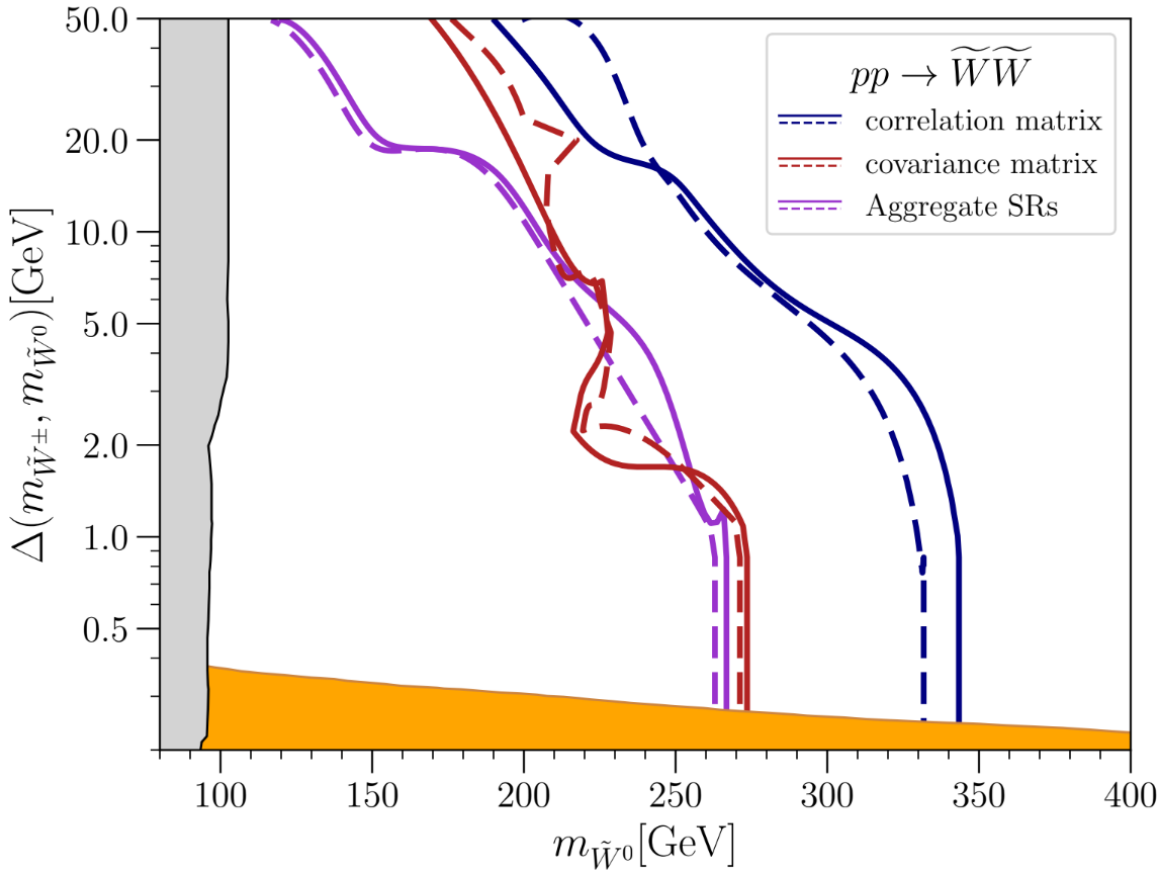
  - $N_{\text{jet}} \geq 2$, where jets must appear within $|\eta| < 2.4$;
  - $H_{\text{T}} > 300\,\text{GeV}$, where H_{T} is the scalar p_{T} sum of jets with $|\eta| < 2.4$;
  - $H_{\text{T}}^{\text{miss}} > 300\,\text{GeV}$, where $H_{\text{T}}^{\text{miss}}$ is the magnitude of $\vec{H}_{\text{T}}^{\text{miss}}$, the negative of the vector p_{T} sum of jets with $|\eta| < 5$; an extended η range is used to calculate $H_{\text{T}}^{\text{miss}}$ so that it better represents the total missing momentum in an event;
  - $H_{\text{T}}^{\text{miss}} < H_{\text{T}}$, because events with $H_{\text{T}}^{\text{miss}} > H_{\text{T}}$ are likely to arise from mismeasurement;
  - no identified isolated electron or muon candidate with $p_{\text{T}} > 10\,\text{GeV}$;
  - no isolated track with $m_{\text{T}} < 100\,\text{GeV}$ and $p_{\text{T}} > 10\,\text{GeV}$ ($p_{\text{T}} > 5\,\text{GeV}$ if the track is identified as a PF electron or muon), where m_{T} is the transverse mass [52] formed from $\vec{p}_{\text{T}}^{\text{miss}}$ and the isolated-track p_{T} vector, with $\vec{p}_{\text{T}}^{\text{miss}}$ the negative of the vector p_{T}
  - $\Delta\phi_{H_{\text{T}}^{\text{miss}},\text{j}_\text{i}} > 0.5$ for the two highest p_{T} jets j_1 and j_2, with $\Delta\phi_{H_{\text{T}}^{\text{miss}},\text{j}_\text{i}}$ the azimuthal angle between $\vec{H}_{\text{T}}^{\text{miss}}$ and the p_{T} vector of jet j_i; if $N_{\text{jet}} \geq 3$, then, in addition, $\Delta\phi_{H_{\text{T}}^{\text{miss}},\text{j}_3} > 0.3$ for the third-highest p_{T} jet j_3; if $N_{\text{jet}} \geq 4$, then, yet in addition, $\Delta\phi_{H_{\text{T}}^{\text{miss}},\text{j}_4} > 0.3$ for the fourth-highest p_{T} jet j_4; all considered jets must have $|\eta| < 2.4$; these requirements

Head-to-head comparison

MT2 search preliminary results also very strong (not shown in the plot)



ATLAS



CMS

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Summary and Outlook

- Multibin limits available in 12 ATLAS and CMS searches
- Good agreement with published results
- In most cases reasonable evaluation time - for parameter space scans
- Extension to combinations of different searches/experiments straightforward
- New limits from hadronic final states on electroweakinos are very promising – important for future colliders
- More to come from CMS MT2 hadronic search

Norway grants

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

Comparison of different error treatment