Signal region combination in CheckMATE

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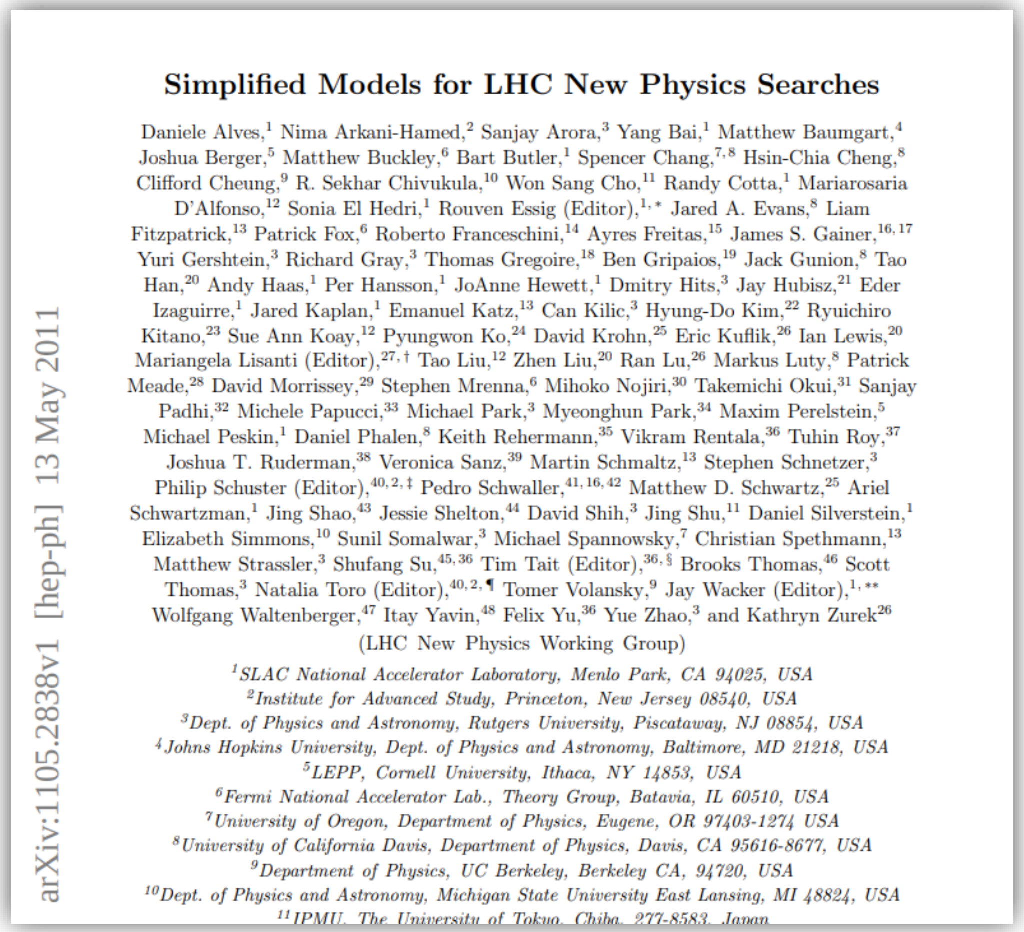
Conference of Norwegian Financial Mechanism "Early Universe", Warszawa 9.10.2023

Contents

Why simplified models?

- Realistic new physics models tend to involve many new parameters, for example the Minimal Supersymmetric Standard Model ~ 100
- This makes the interpretation and design of searches difficult
- The purpose of simplified models is to reduce the number of parameters: include only a few particles and interactions of a full model with fixed branching fractions



arXiv:1105.2838v1 [hep-ph] 13 May 2011

Simplified Models for LHC New Physics Searches

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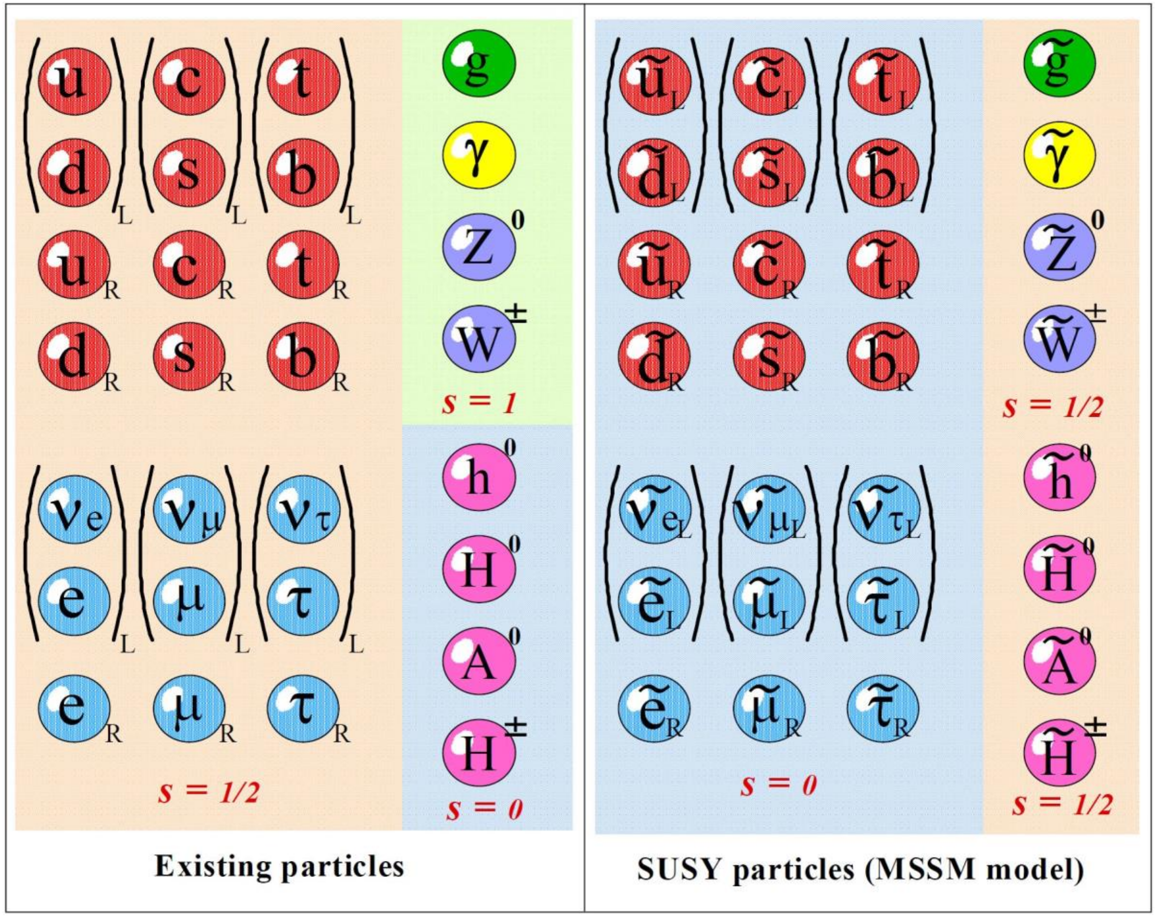
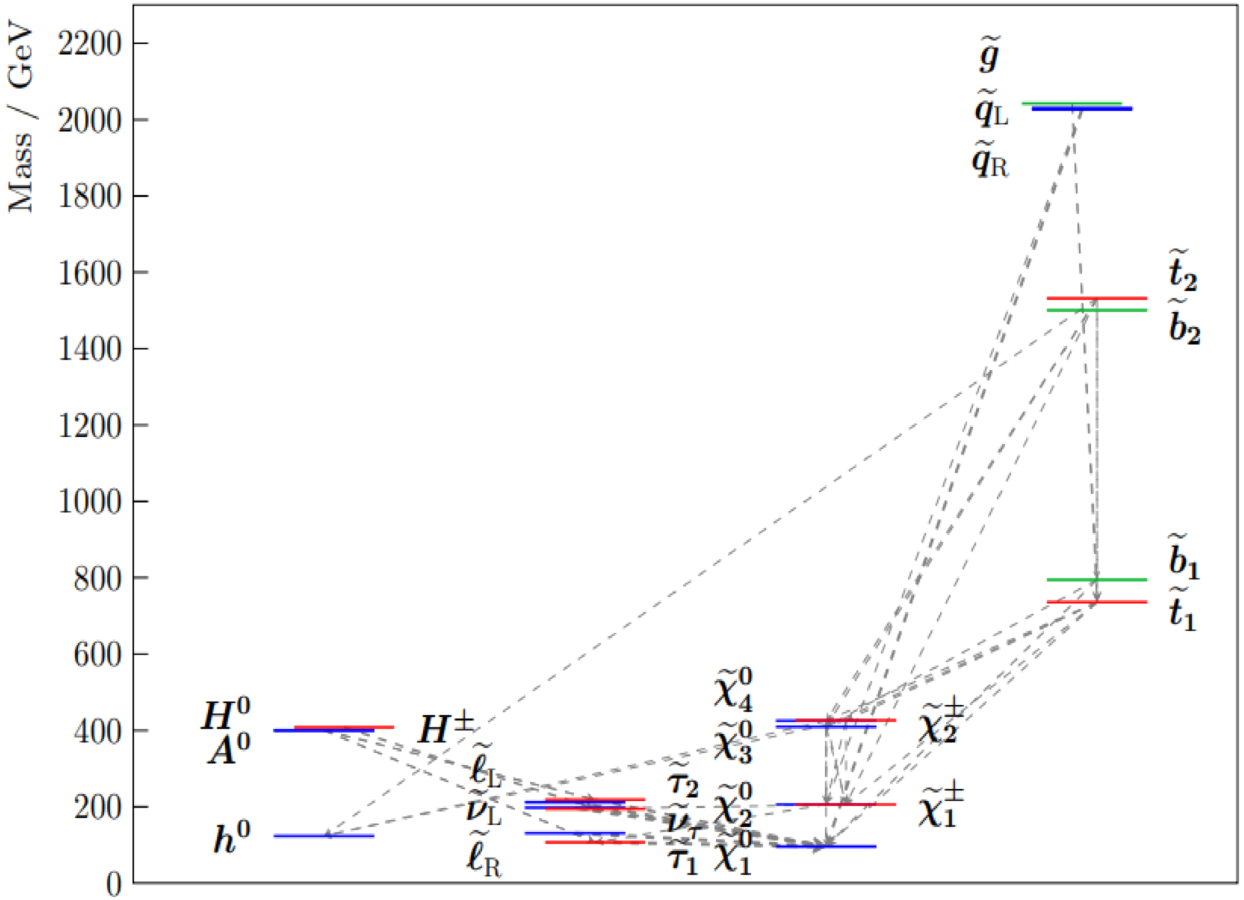
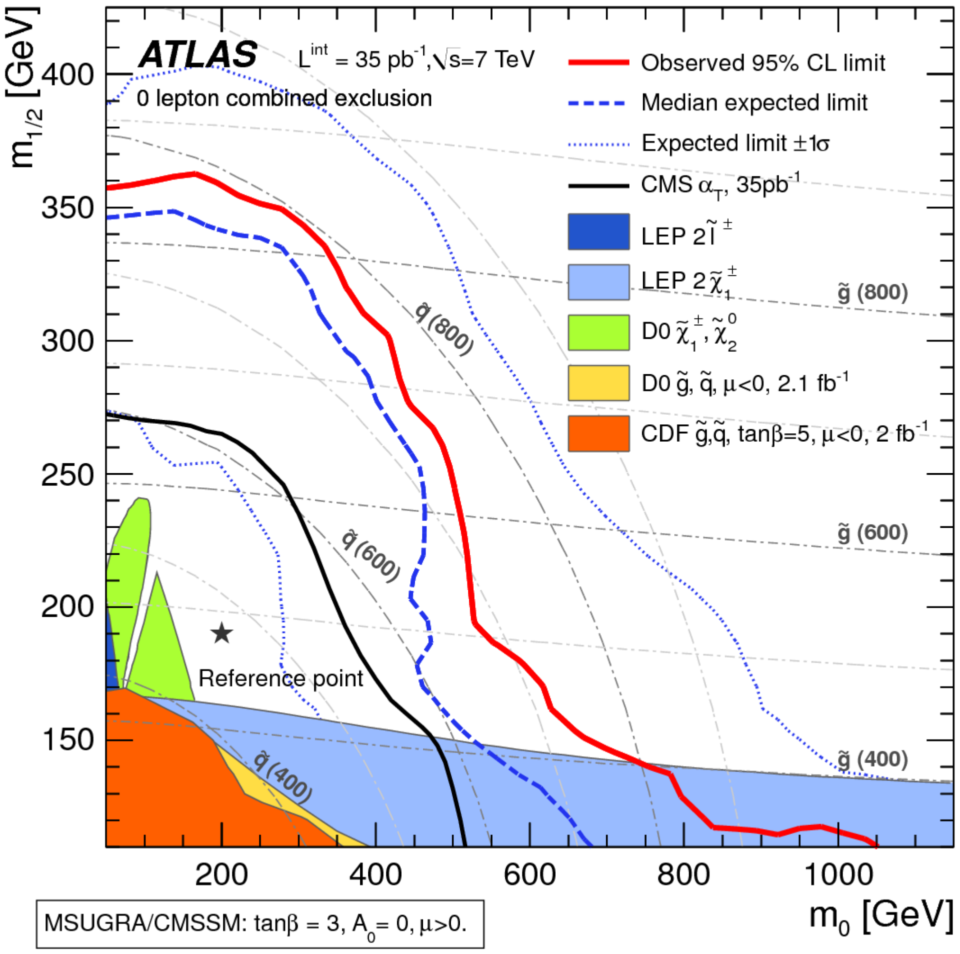
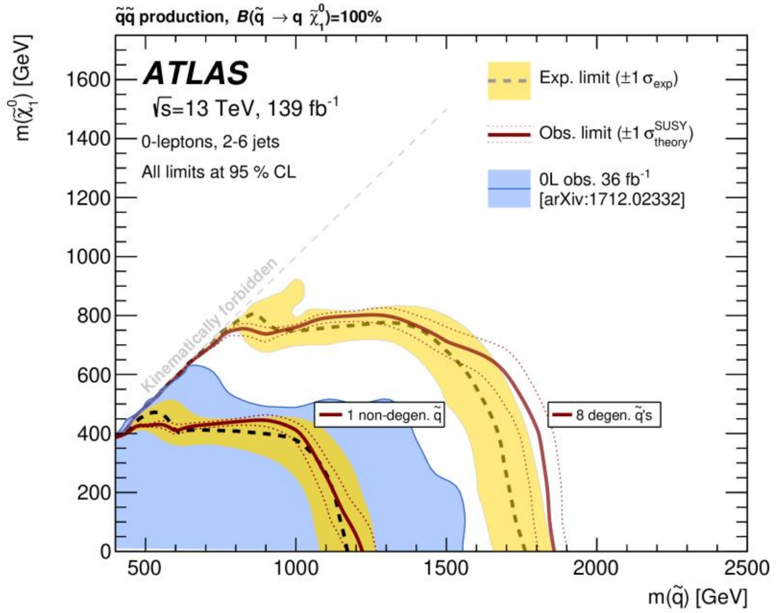
Benchmark MSSM example

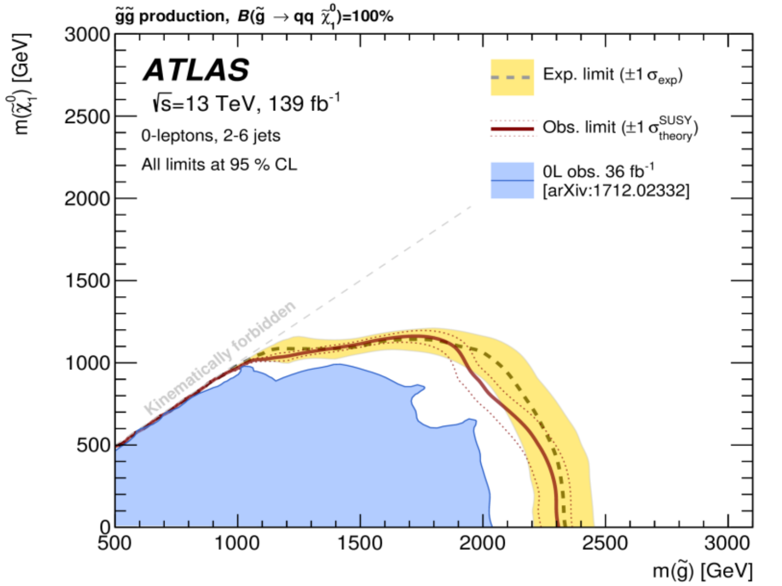




Example: supersymmetry





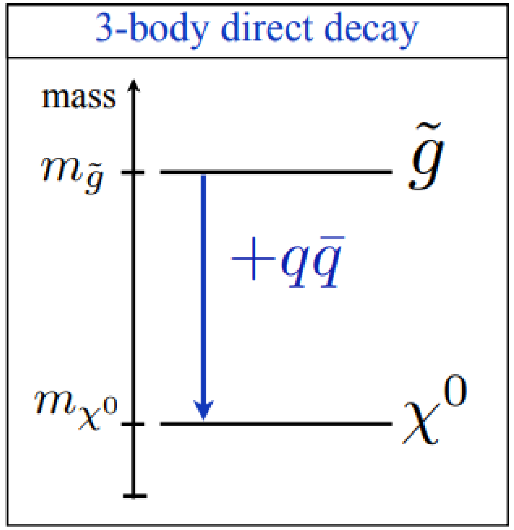


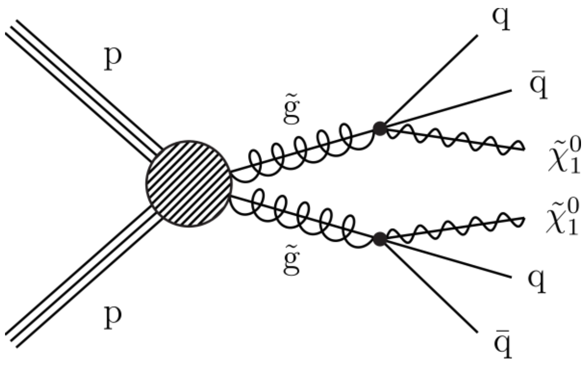
The purpose of simplified models

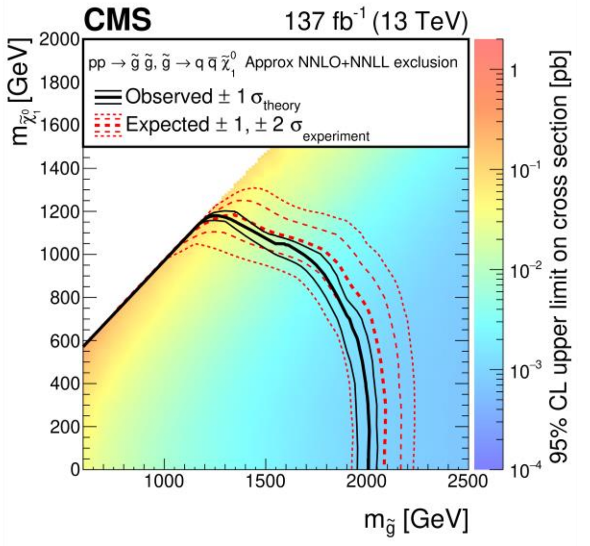
A simplified model is specifically designed to involve only a few new particles and interactions. They are limits of more general new physics scenarios, where all but a few particles are integrated out.

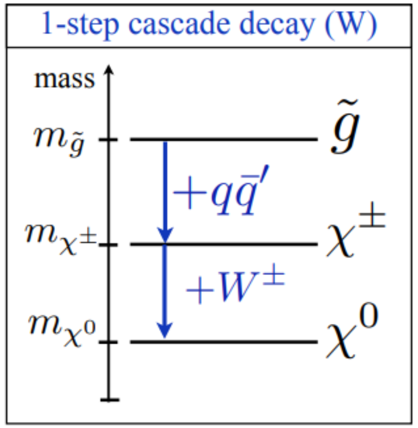
- **Identifying the boundaries of search sensitivity:**
  one- and two-dimensional slices within a simplified model can illustrate these boundaries very clearly and help to identify kinematic ranges
- **Characterizing new physics signals:**
  simplified models can be a starting point for identification of observed signal with different realistic models
- **Deriving limits on more general models:**
  the initial assessment within a simplified model should be followed by a dedicated recasting study

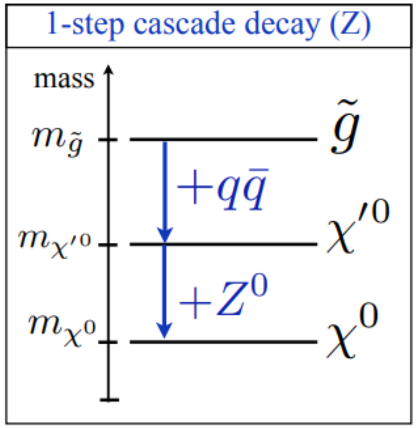
Example: gluino simplified models – jets+MET

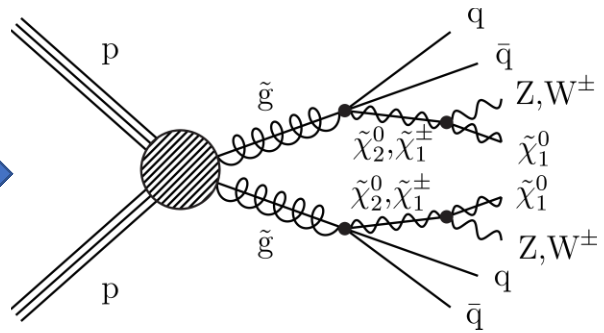


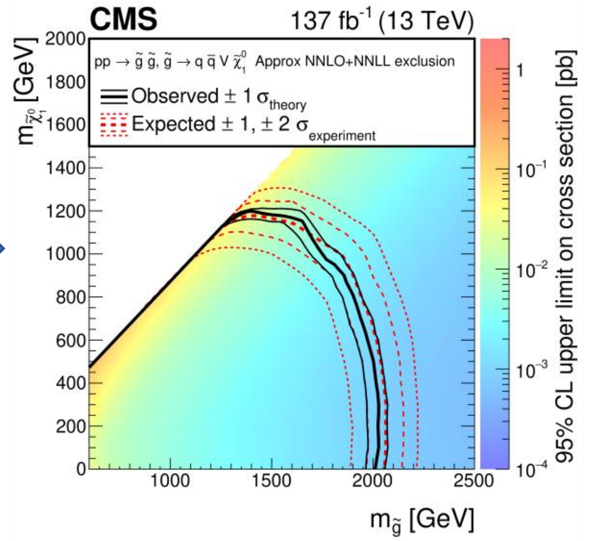












Simplified model summary

- Simplified models cover a small and often unrealistic part of the models and parameters landscape
- Simplified models provide an easy parametrization in terms of just a few parameters e.g., 2-3 masses, perhaps a branching fraction (but often 100%)
- Hundreds of searches for supersymmetry but other models used to be less popular (this is changing though)
- Provide a clear link in terms of limits between particular topologies and final states e.g.: jets + MET, jets + lepton + MET, jets + lepton...
- Simplified models were never meant as a final word in searches for TeV-scale physics
- A quick way of recasting searches optimized for simplified models is essential in the quest for new physics

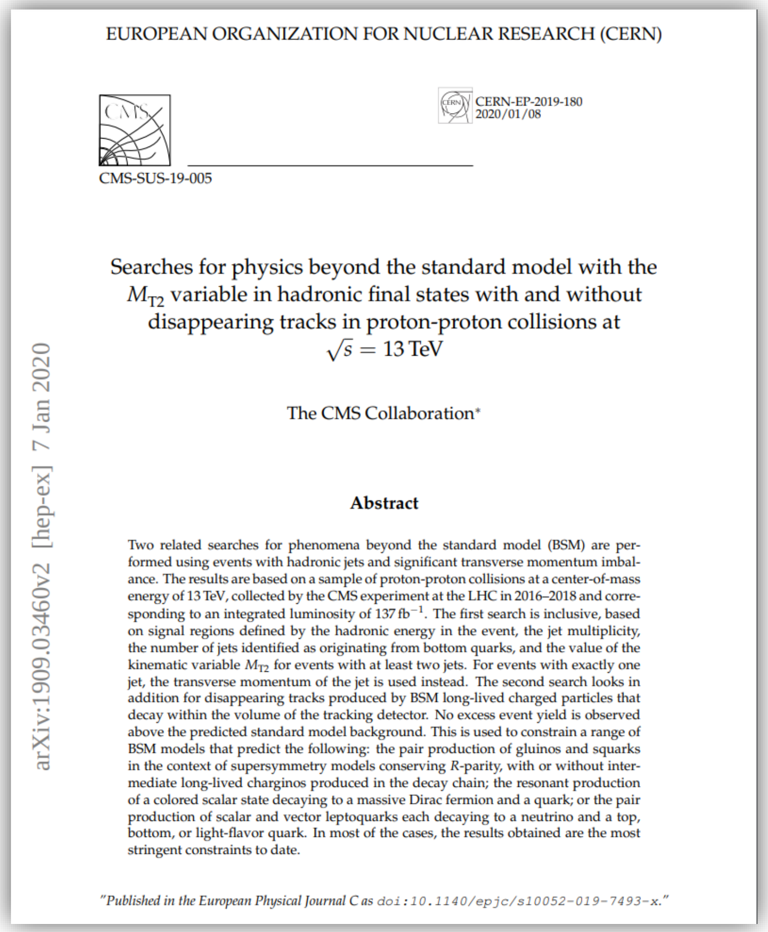
Monte Carlo tools & discoveries at the LHC

Searches for new TeV-scale physics still one of the main goals in the coming years

- Theoretical model building offers a vast number of models with particles in the LHC reach
- Experimental papers cover only a small fraction of existing models
- We need tools to cover the gap and: assess viability of models, guide future searches, looking for blind spots
- Computer tools are essential: Monte Carlo generators, fast detector simulators, cross section calculators
- We need tools to analyze MC output easily and compare it quickly and reliably with existing experimental exclusions

This is the main purpose of recasting tools

Reinterpretation/recasting in a nutshell


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-180
2020/01/08

CMS-SUS-19-005

Searches for physics beyond the standard model with the M_{T2} variable in hadronic final states with and without disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV

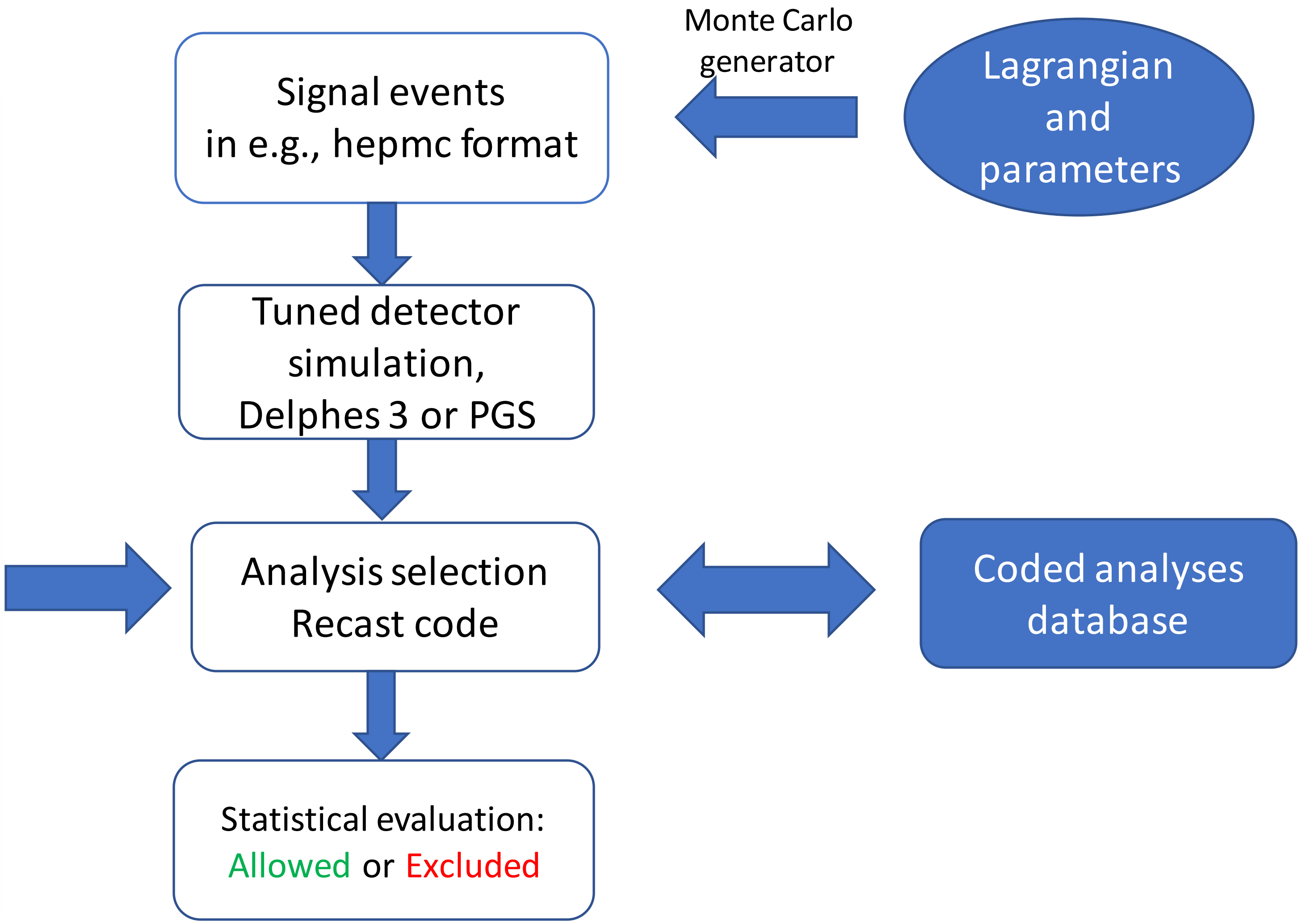
The CMS Collaboration*

Abstract

Two related searches for phenomena beyond the standard model (BSM) are performed using events with hadronic jets and significant transverse momentum imbalance. The results are based on a sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment at the LHC in 2016–2018 and corresponding to an integrated luminosity of 137 fb^{-1}. The first search is inclusive, based on signal regions defined by the hadronic energy in the event, the jet multiplicity, the number of jets identified as originating from bottom quarks, and the value of the kinematic variable M_{T2} for events with at least two jets. For events with exactly one jet, the transverse momentum of the jet is used instead. The second search looks in addition for disappearing tracks produced by BSM long-lived charged particles that decay within the volume of the tracking detector. No excess event yield is observed above the predicted standard model background. This is used to constrain a range of BSM models that predict the following: the pair production of gluinos and squarks in the context of supersymmetry models conserving *R*-parity, with or without intermediate long-lived charginos produced in the decay chain; the resonant production of a colored scalar state decaying to a massive Dirac fermion and a quark; or the pair production of scalar and vector leptoquarks each decaying to a neutrino and a top, bottom, or light-flavor quark. In most of the cases, the results obtained are the most stringent constraints to date.

"Published in the European Physical Journal C as doi:10.1140/epjc/s10052-019-7493-x."

arXiv:1909.03460v2 [hep-ex] 7 Jan 2020



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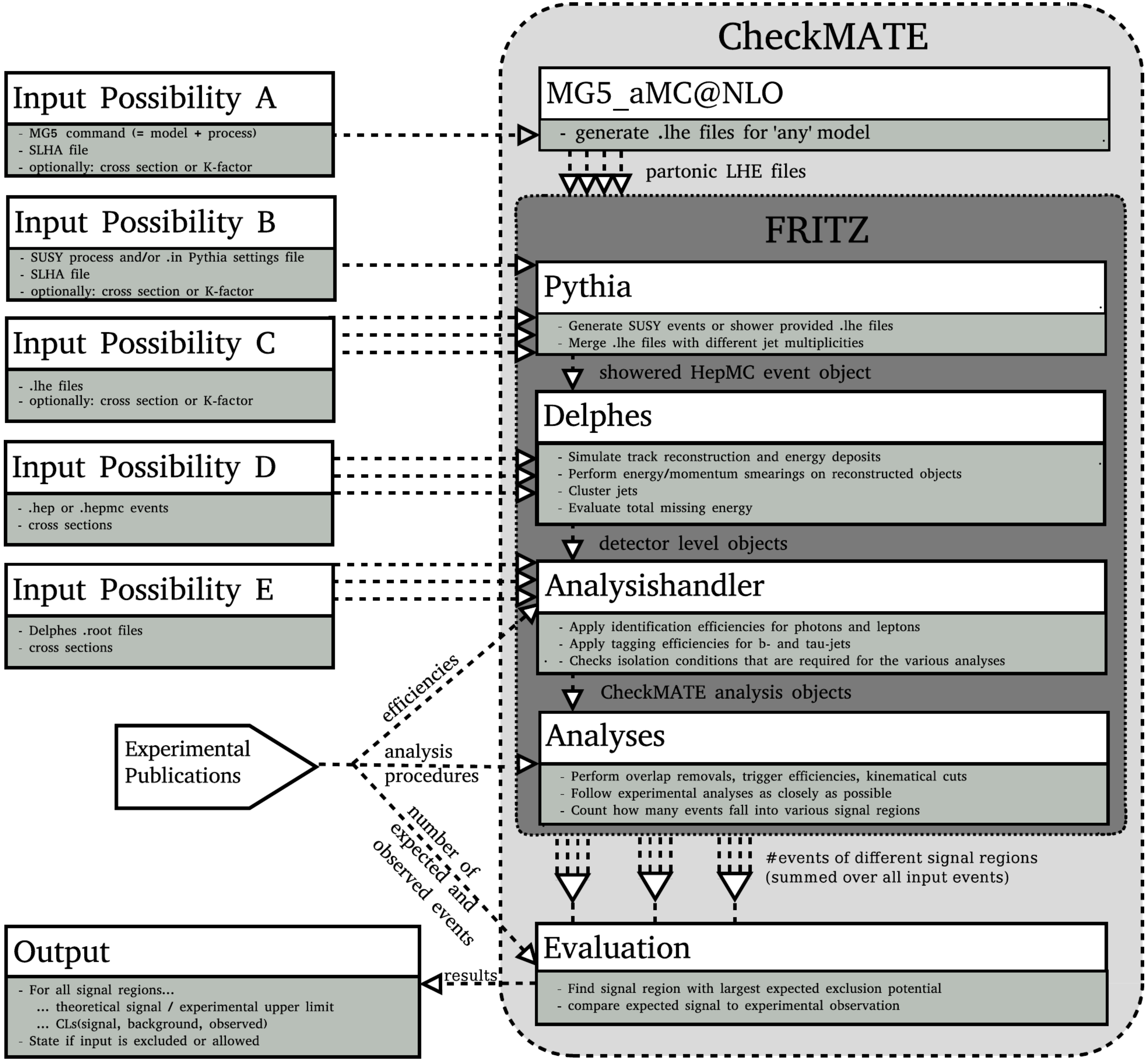
3. Implementation of searches with multibin SRs
4. Application: pushing limits for electroweakinos
5. Summary and outlook

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



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
Experimental Publications
efficiencies
analysis procedures
number of expected and observed events
#events of different signal regions (summed over all input events)
Evaluation
- Find signal region with largest expected exclusion potential
- compare expected signal to experimental observation
results
Output
- For all signal regions...
... theoretical signal / experimental upper limit
... CLs(signal, background, observed)
- State if input is excluded or allowed

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

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

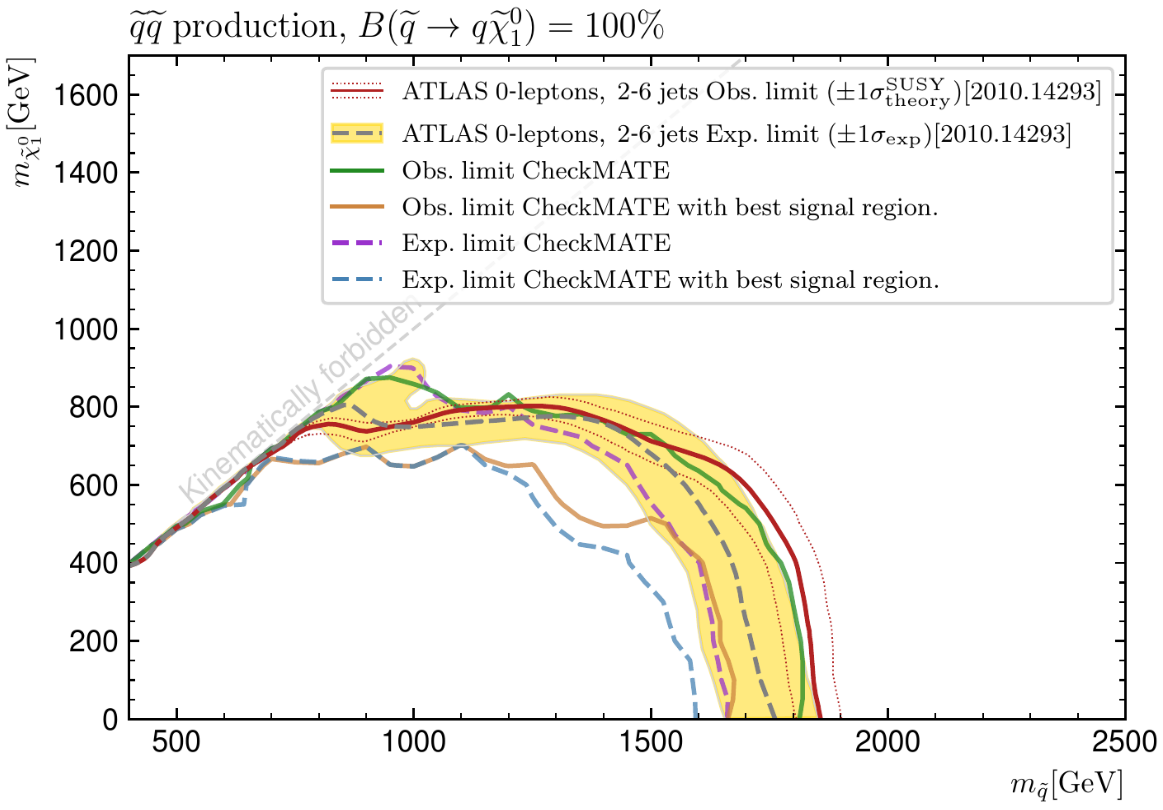
- Optional constraint for signal numbers: for many bins it's difficult to get reasonable statistics which results in large MC-related errors

CMS multibin searches

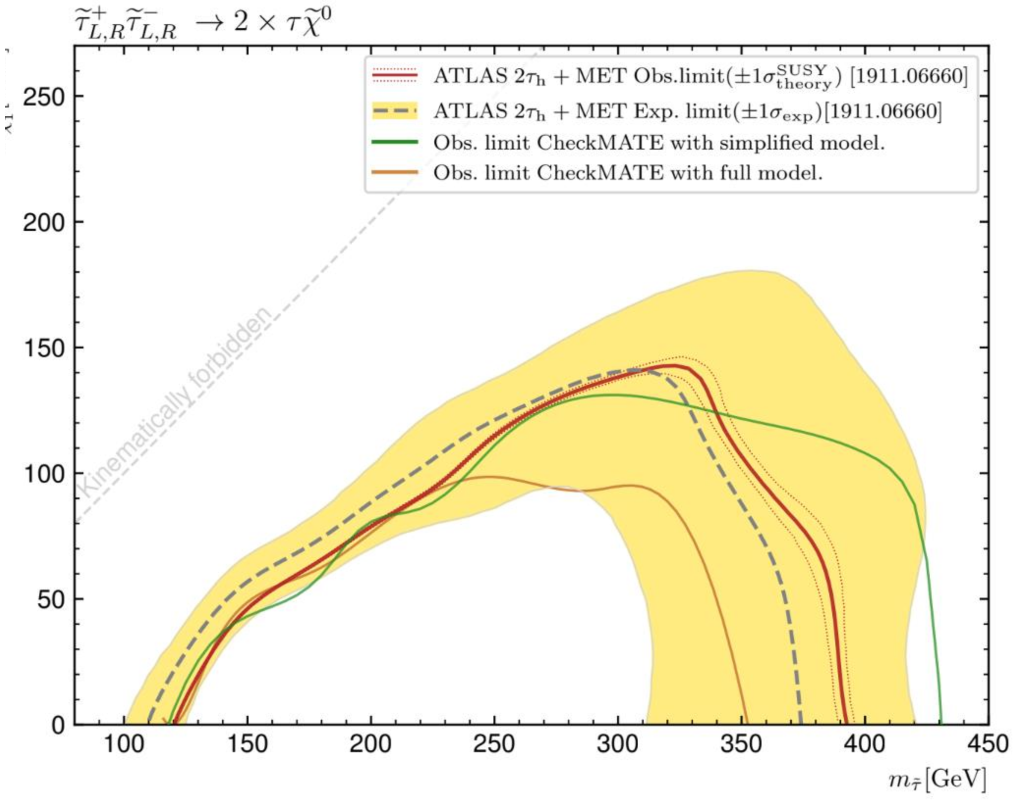
Additional features:

- 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

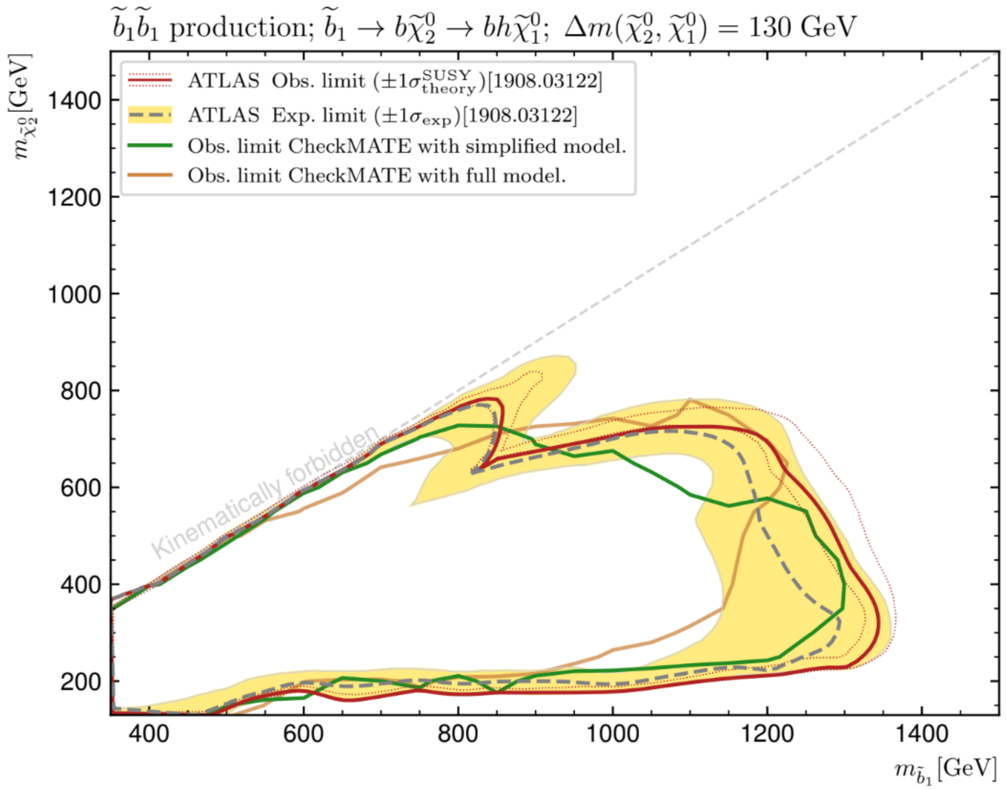


$\widetilde{q}\widetilde{q}$ production, $B(\widetilde{q} \to q\widetilde{\chi}_1^0) = 100\%$
ATLAS 0-leptons, 2-6 jets Obs. limit ($\pm 1\sigma_{\mathrm{theory}}^{\mathrm{SUSY}}$)[2010.14293]
ATLAS 0-leptons, 2-6 jets Exp. limit ($\pm 1\sigma_{\mathrm{exp}}$)[2010.14293]
Obs. limit CheckMATE
Obs. limit 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]

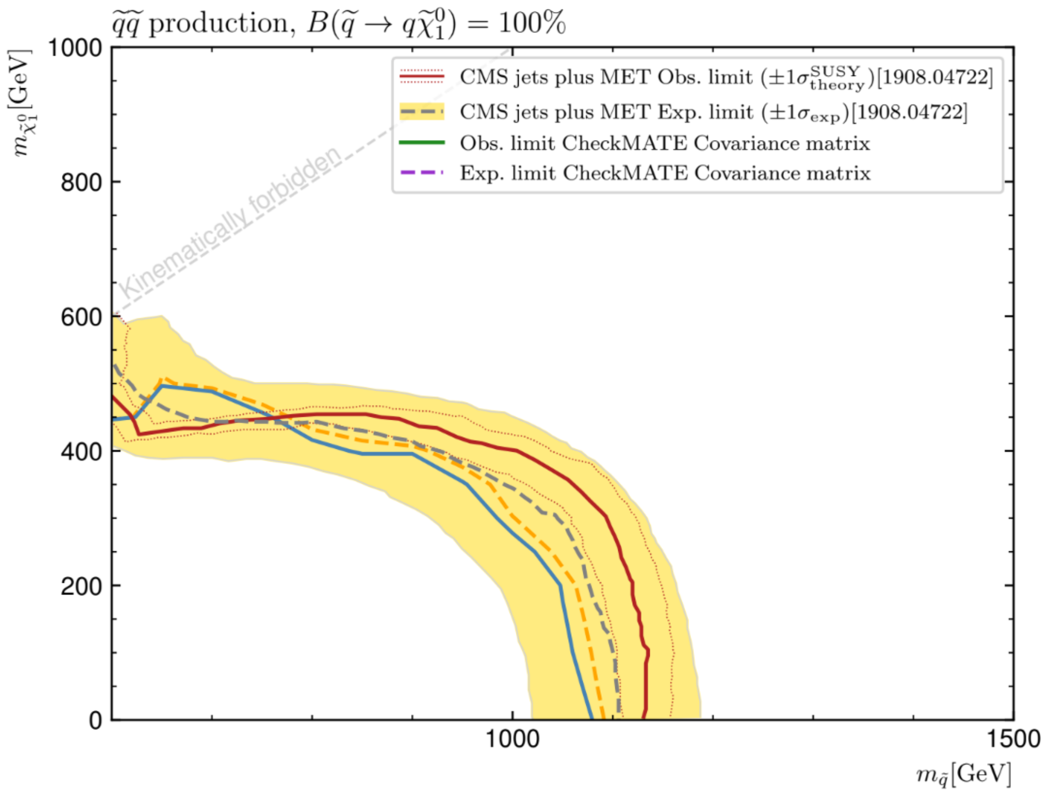


$\widetilde{\tau}_{L,R}^{+}\widetilde{\tau}_{L,R}^{-} \to 2 \times \tau\widetilde{\chi}^0$
ATLAS $2\tau_h$ + MET Obs.limit($\pm 1\sigma_{\mathrm{theory}}^{\mathrm{SUSY}}$) [1911.06660]
ATLAS $2\tau_h$ + MET Exp. limit($\pm 1\sigma_{\mathrm{exp}}$)[1911.06660]
Obs. limit CheckMATE with simplified model.
Obs. limit CheckMATE with full model.
Kinematically forbidden
$m_{\tilde{\tau}}$[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 ($\pm 1\sigma_{\rm theory}^{\rm SUSY}$)[1908.03122]
ATLAS Exp. limit ($\pm 1\sigma_{\rm exp}$)[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]
1400
1200
1000
800
600
400
200
400
600
800
1000
1200
1400

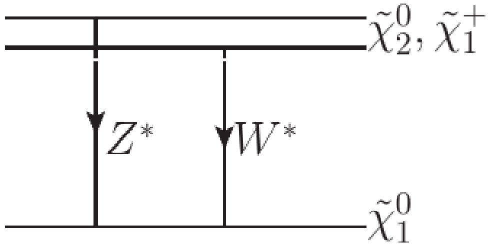


$\widetilde{q}\widetilde{q}$ production, $B(\widetilde{q} \to q\widetilde{\chi}_1^0) = 100\%$
CMS jets plus MET Obs. limit ($\pm 1\sigma_{\rm theory}^{\rm SUSY}$)[1908.04722]
CMS jets plus MET Exp. limit ($\pm 1\sigma_{\rm exp}$)[1908.04722]
Obs. limit CheckMATE Covariance matrix
Exp. limit CheckMATE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

Contents

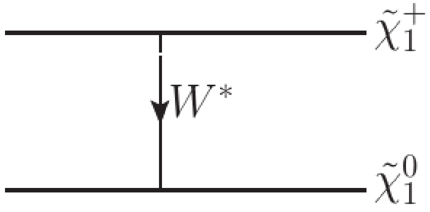
Light SUSY dark matter

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



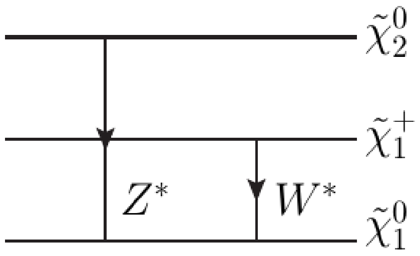
bino-wino

- 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

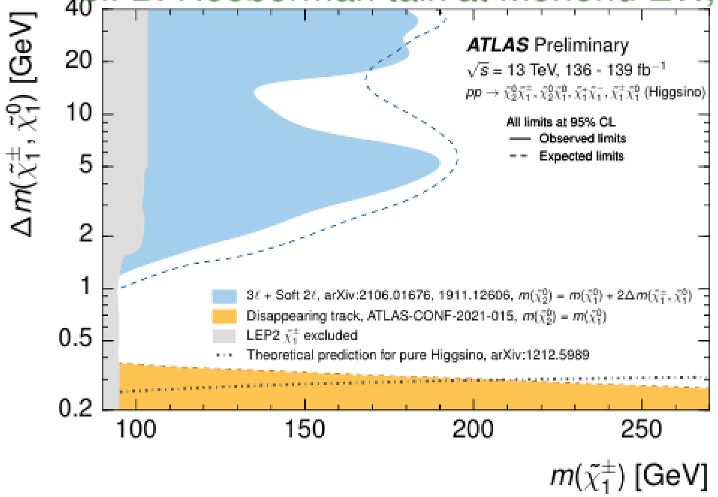
- mass splittings of order 100–1000 MeV

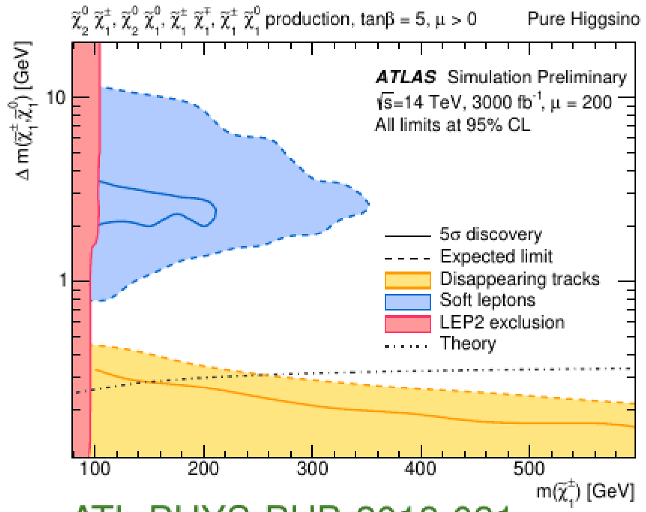
Search strategies

- 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

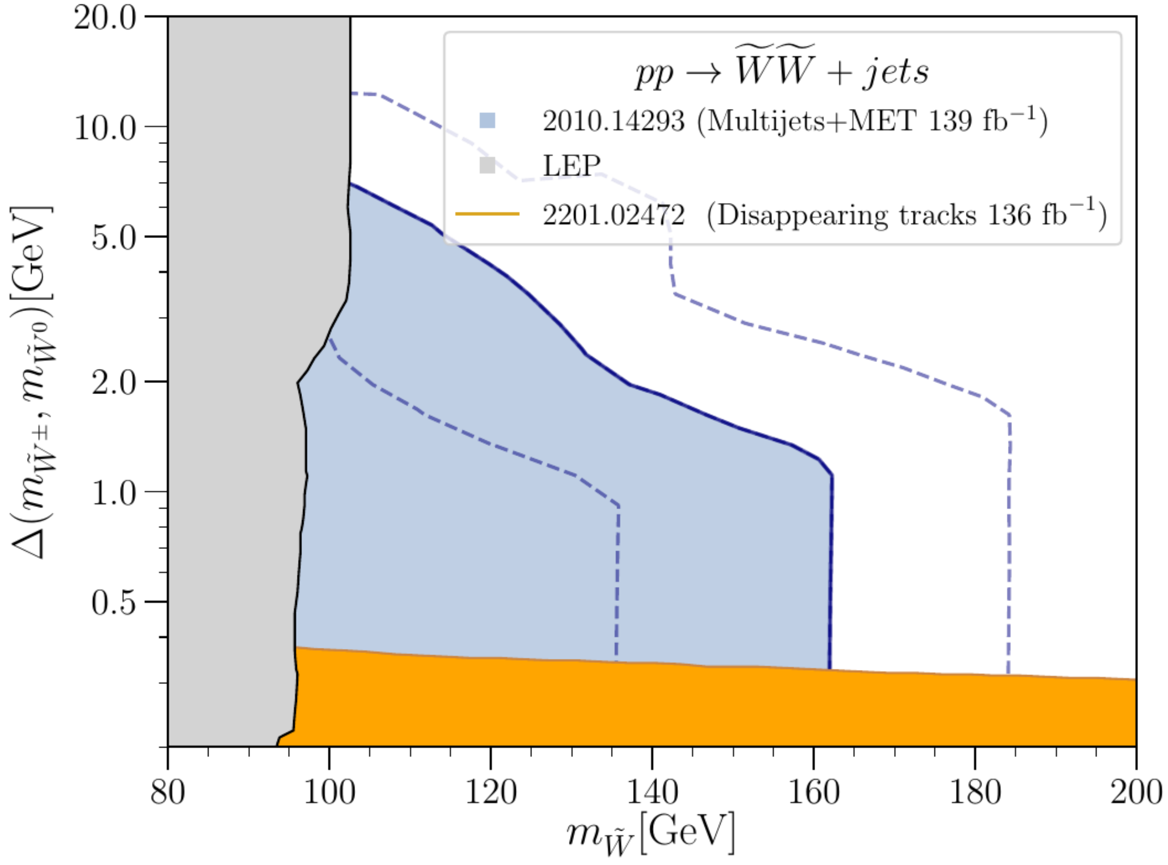
Also try CMS multijet

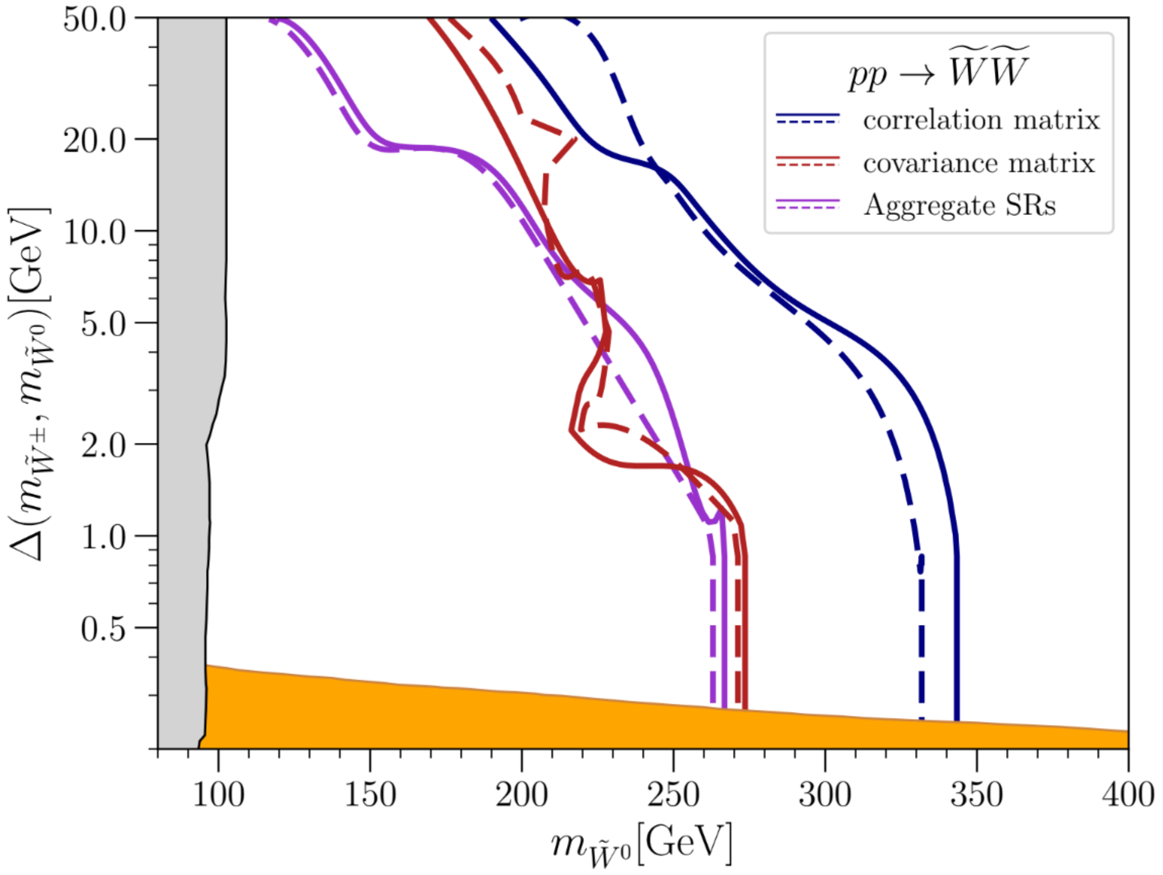
- CMS-SUS-19-006 with multibin for – different selections wrt ATLAS

  - $N_{\text{jet}} \geq 2$, 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}
  - $\Delta\phi_{H_{\text{T}}^{\text{miss}},\text{j}_i} > 0.5$ for the two highest p_{T} jets j_1 and j_2, with $\Delta\phi_{H_{\text{T}}^{\text{miss}},\text{j}_i}$ 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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4. Application: pushing limits for electroweakinos
5. Summary and outlook

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

The research leading to the results presented in this talk has received funding from the Norwegian Financial Mechanism for years 2014-2021, grant nr 2019/34/H/ST2/00707

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