Checkmating New Physics at the LHC

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arXiv:1611.09856, 2104.04542, 1503.01123

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Contents

Check **M**odels **A**t **T**erascale **E**nergies

`http://checkmate.hepforge.org`

1. What is `CheckMATE`?
2. Testing models against current LHC results
3. Testing new ideas for future LHC results

Minimal Running Example

- Step 1: Decide on a parameter point `benchmark1.slha`
- Step 2: Set up parameters `param.dat`

```
[Parameters]
SLHAFile: /scratch/benchmark1.slha

[squ_asq]
Pythia8Process: p p > sq sq~
MaxEvents: 1000
```

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- Step 1: Decide on a parameter point `benchmark1.slha`
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- Wait.

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SLHAFile: /scratch/benchmark1.slha

[squ_asq]
Pythia8Process: p p > sq sq~
MaxEvents: 1000
```

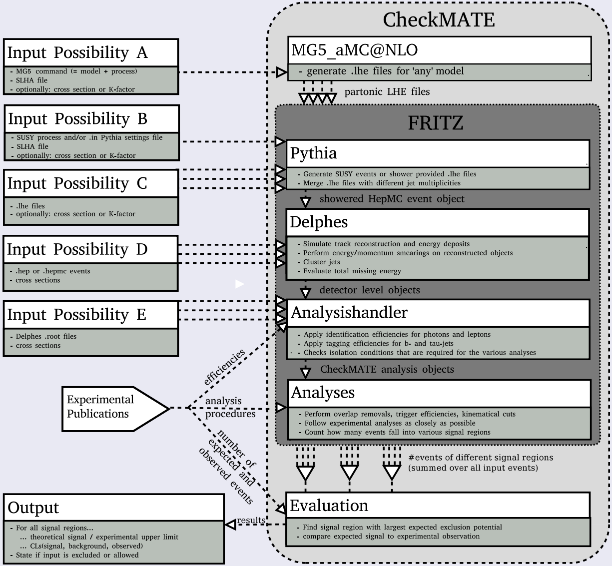
```
Result:  Allowed
Result for r: r_max = 0.74
SR: atlas_conf_2013_047 - ET
```

or

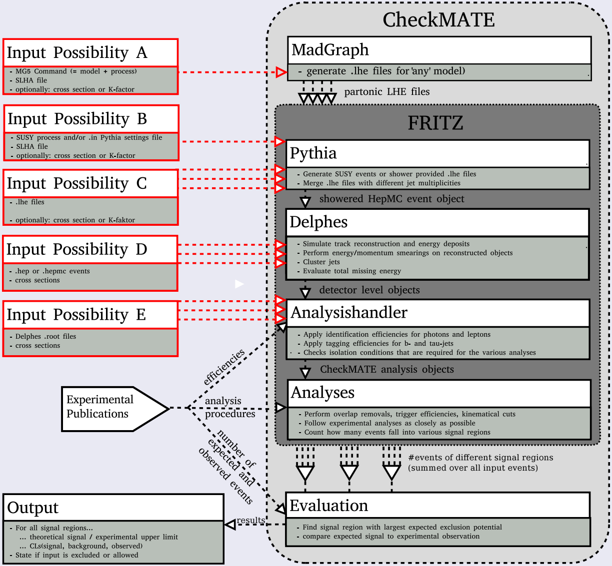
```
Result: Excluded
Result for r: r_max = 1.33
SR: atlas_conf_2013_047 - A
```

You quickly know if your model has been excluded or not by current LHC results

Overview: Data Flow



Input



CheckMATE
MadGraph
- 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
#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
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-faktor
Input Possibility D
- .hep or .hepmc events
- cross sections
Input Possibility E
- Delphes .root files
- cross sections
Experimental Publications
efficiencies
analysis procedures
number of expected and observed events
results
Output
- For all signal regions...
... theoretical signal / experimental upper limit
... CLs(signal, background, observed)
- State if input is excluded or allowed

Different Input Methods

checkmate_input_parameter.dat

```
[Parameters]
SLHAFile: /scratch/point.slha

[squ_asq]
Pythia8Process: p p > sq sq~

[squ_squ]
MGCommand: import model mssm
    define sq = ~ul ~ur ~dl ~dr ~sl ~
    generate p p > sq sq

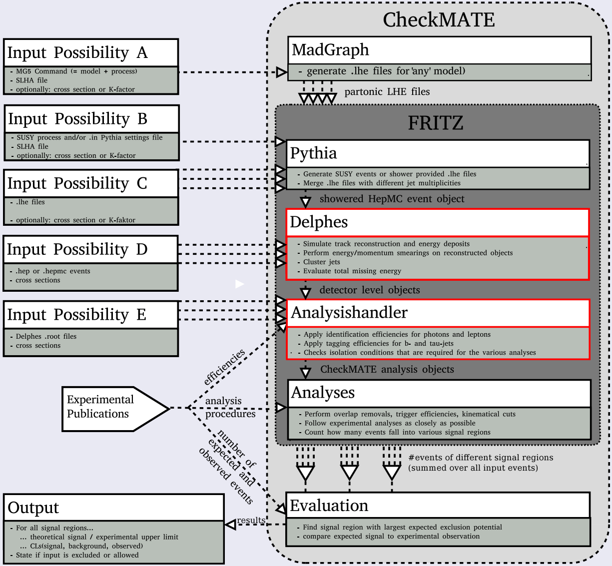
[glu_glu]
Events: /scratch/glu_glu.lhe

[glu_sq]
Events: /scratch/glu_squ_1.hepmc,
        /scratch/glu_squ_2.hepmc
XSect: 0.75 fb
```

Possibilities

1. Internal Pythia8 for parton event generation and parton showering (*Limited to certain BSM models*)
2. Internal MG5_aMC@NLO for parton event generation, Pythia8 for parton showering (*Works for 'any' BSM model*)
3. External parton event generation, internal Pythia8 for parton showering
4. External parton showered events

Detector simulation



Detector Simulation

Delphes 3.4 / 3.5

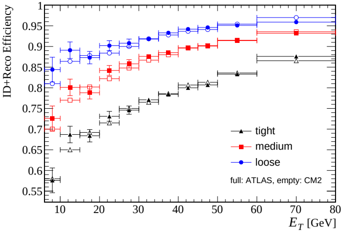
- Simulates tracking and energy deposition
- Applies efficiencies for photons and leptons
- Clusters jets
- Performs energy/momentum smearing of all reconstructed objects
- Evaluates total missing energy
- Checks isolation conditions for photons and leptons
- Applies b-/ tau-tag on jets

CheckMATE improvements

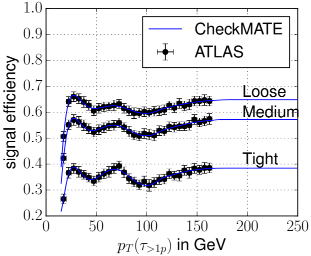
- Added identification and isolation flags
- Tuned to reproduce LHC detectors:
  - ATLAS for 13 TeV Run; updates in progress
  - CMS work in progress

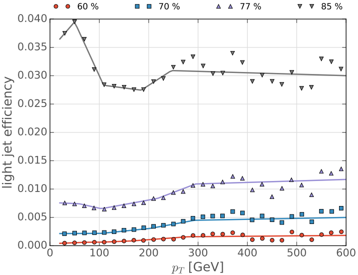
Detector Tuning — Examples

e reconstruction eff.

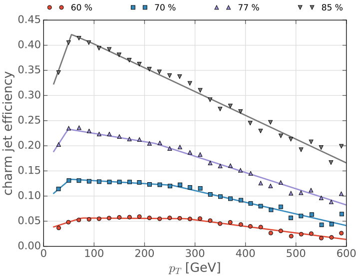


τ-jet eff.



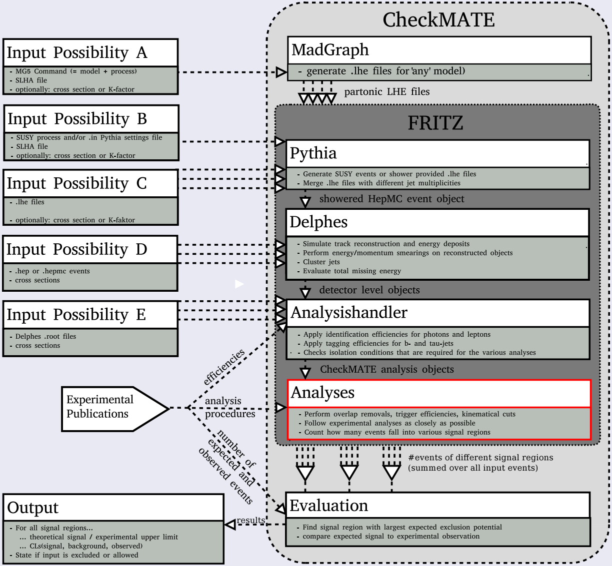


light jet eff.



c-jet eff

Step 2: Analyses



Analyses

A CheckMATE analysis does the following

- Choose the objects of interest (leptons, jets,...)
- Filter objects (efficiency and isolation flags, kinematical cuts, overlap removals, ...)
- Check event vetoes (Too many/few objects, trigger efficiencies, ...)
- Check various signal region criteria (total $\not{E}_T$, # and energy of objects, ...)
- Count number of input events that fall into each signal region
- Make plots, save additional data etc.

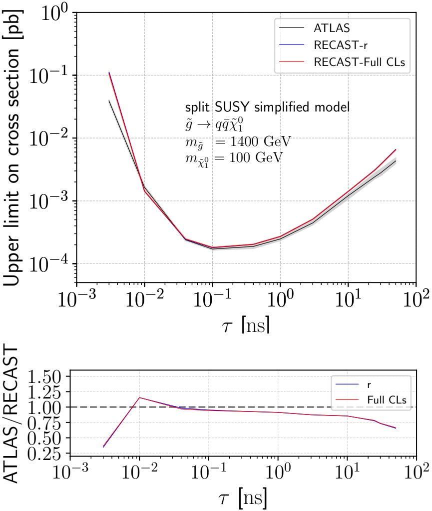
Validation

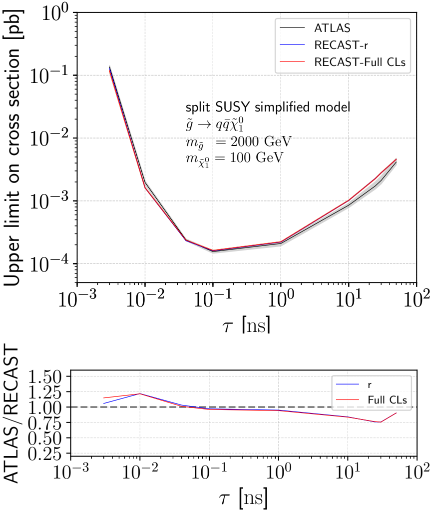
- how do we know an implementation is correct?
- comparison with cutflows if published by a collaboration
- many validation notes are public with MC files

	Selection	$m_{\tilde{q}} = 1200$ GeV $m_{\tilde{\chi}_1^0} = 600$ GeV		$m_{\tilde{q}} = 1400$ GeV $m_{\tilde{\chi}_1^0} = 600$ GeV		$m_{\tilde{q}} = 1600$ GeV $m_{\tilde{\chi}_1^0} = 400$ GeV	
		ATLAS	CM	ATLAS	CM	ATLAS	CM
Generated MC events		10000	10000	6000	10000	6000	10000
Common Requirements	Preselection, $E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV, $p_T(j_1) > 200$ GeV, $m_{\mathrm{eff}} > 800$ GeV	1763	1780	541	546	174	176
	jet multiplicity ≥ 2	1763	1780	541	546	174	176
	Cleaning cuts	1746	–	535	–	173	–
SR-2j-1600	$\Delta\phi(j_{1,2,(3)}, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.8$	1433	1434	431	433	136	139
	$\Delta\phi(j_{i>3}, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$	1377	1353	411	410	129	130
	$p_T(j_2) > 250$ GeV	853	850	311	310	111	112
	$\lvert\eta(j_{1,2})\rvert < 2.0$	836	832	306	305	109	110
	$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T} > 16$ GeV$^{1/2}$	568	554	228	227	86.4	87.3
	$m_{\mathrm{eff}}(\mathrm{incl.}) > 1600$ GeV	366	362	202	195	83.5	84.2

More validation

- reproduction of exclusion limits for benchmark models





More validation

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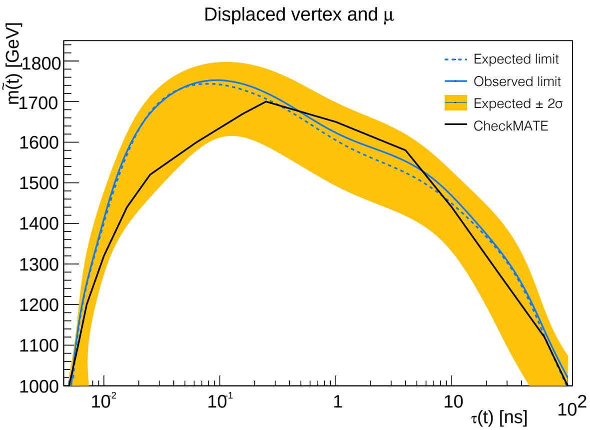


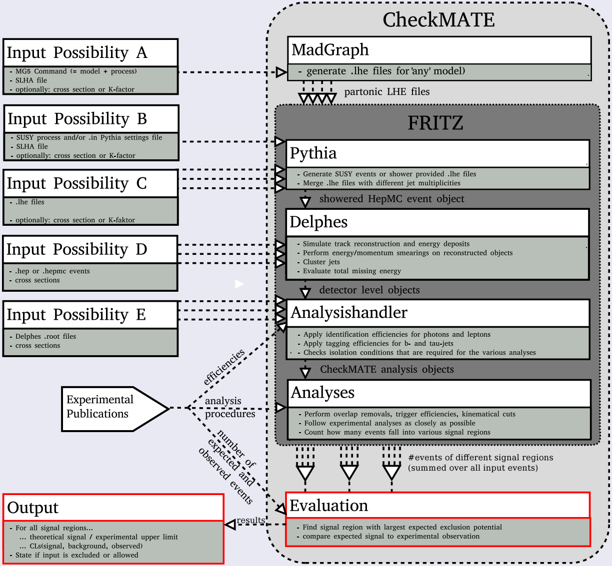
Example Output

```
# ATLAS-CONF-2013-047
# 0 leptons, 2-6 jets, etmiss
# sqrt(s) = 8 TeV
# int(L) = 20.3 fb^-1

Inputfile:         /hdd/results/cMSSM/delphes/000_delphes.root
XSect:             4.35 fb
 Error:            1.22086 fb
MCEvents:          5000
 SumOfWeights:     5000
 SumOfWeights2:    5000
 NormEvents:       87.9518

SR   Sum_W   Sum_W2   Acc      N_Norm
AL   1315    1315     0.263    23.1313
AM   71      71       0.0142   1.24892
BM   98      98       0.0196   1.72385
BT   2       2        0.0004   0.0351807
CM   505     505      0.101    8.88313
CT   9       9        0.0018   0.158313
D    184     184      0.0368   3.23663
EL   613     613      0.1226   10.7829
EM   398     398      0.0796   7.00096
```

Step 3: Evaluation



Evaluation

Input and Setup

- We have number of expected signal $S \pm \Delta S$ in each signal region
- `CheckMATE` has a reference card with experimental results:
  - observed events O
  - expected background plus uncertainty $B \pm \Delta B$
  - (in most cases) translated 95% upper limit on signal S^{95}_{max}

Evaluation

Input and Setup

- We have number of expected signal $S \pm \Delta S$ in each signal region
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  - observed events O
  - expected background plus uncertainty $B \pm \Delta B$
  - (in most cases) translated 95% upper limit on signal S^{95}_{max}

User can choose

- Directly compare S to S^{95}_{max}
- If $r^{\text{c}} = \frac{S-2\Delta S}{S^{95}_{\text{max}}} > 1$: Excluded!
- Quick and easy for limit setting

- Evaluate $\text{CL}_s(O, B, \Delta B, S, \Delta S)$
- If $\text{CL}_s < 0.05$: Excluded!
- Slower, but limits can be set to different confidence levels

Selected public analyses at 13 TeV (total $\sim$ 90 available)

Name	Search designed for	L	N_{SR}
atlas_1807_07447	general search for new phenomena	3.2	633
atlas_1609_01599	ttV cross section measurement at 13 TeV	3.2	9
atlas_conf_2016_050	stops in events with an isolated lepton, jets and $\not{E}_T$	13.3	5
atlas_conf_2016_054	1 lepton + (b) jets + $\not{E}_T$	14.8	10
atlas_conf_2016_076	SUSY with 2 leptons + jets + $\not{E}_T$	13.3	6
atlas_conf_2017_019	search for stops with Higgs or Z	36.1	6
atlas_conf_2017_040	mono-Z: Z + $\not{E}_T$	36.1	2
atlas_1710_11412	dark matter with bottom or top quarks	36.1	1
atlas_1704_03848	monophoton dark matter search	36.1	5
atlas_1802_03158	search for GMSB with photons	36.1	7
atlas_1708_07875	electroweakino search with taus and $\not{E}_T$	36.1	2
atlas_1706_03731	same-sign or 3 leptons RPC and RPV SUSY	36.1	19
atlas_1803_02762	electroweakino with two or three leptons	36.1	20
atlas_1908_08215	charginos/sleptons, 2 leptons + $\not{E}_T$	139	16
atlas_1909_08457	search for squarks and gluinos with same-sign leptons	139	5
atlas_conf_2019_040	search for squarks and gluinos in $\not{E}_T$ + jet final states	139	70
atlas_conf_2019_020	chargino-neutralino with electroweak mass splittings	139	2
atlas_conf_2018_041	gluinos decaying via 3rd gen; multi b-jets and MET	79.8	10
atlas_2101_01629	squarks/gluinos, 1 lepton, jets, MET	139	32
atlas_conf_2020_048	Search for dark matter with monojets	139	26
atlas_2004_14060	stops, leptoquarks, 0 lepton	139	9
atlas_1908_03122	0 leptons, 3 or more b-jets, sbottoms	139	10
atlas_1911_12606	search for sleptons and electroweakinos with soft leptons	139	87
atlas_2103_11684	Search for SUSY in events with four or more leptons	139	2
atlas_2004_10894	EWino search in Higgs (diphoton) and met	139	12
atlas_2106_09609	Search for RPV SUSY with leptons and many jets	139	21
atlas_1911_06660	search for direct stau production	139	2
atlas_2202_07953	invisible Higgs decays in VBF	139	17
cms_sus_16_025	electroweakino and stop compressed spectra	12.9	14
cms_sus_16_039	electrowekinos in multilepton final state	35.9	158
cms_sus_16_048	soft opposite sign leptons	35.9	20

High Luminosity phase

- several ATLAS projections for Run 3 and High Luminosity

Name	Search designed for	L	N_{SR}
atlas_phys_pub_2013_011	1 lepton + jets + Etmiss (Stop)	3000	4
atlas_2014_010_hl_3l	3 leptons + Etmiss (char+neut)	3000	1
atlas_phys_2014_010_300	2-6 jets + Etmiss	300	10
atlas_phys_2014_010_sq_hl	2-6 jets + Etmiss	3000	10
atl_phys_pub_2014_010_sbottom	0 leptons + 2 b-jets + Etmiss	300	6
atlas_phys_2014_007	monojet	3000	21

Long-lived particles branch

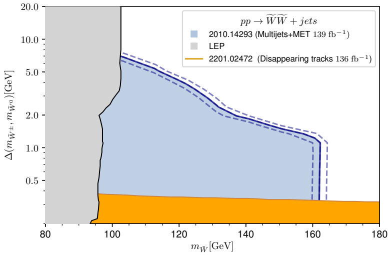
- searches for LLP gained new momentum recently
- a dedicated branch was developed - to be merged in near future
- covered signals:
  - displaced leptons
  - displaced vertex and $\not{E}_T$
  - displaced vertex and muon
  - heavy charged particles
  - disappearing track

Name	Search designed for	L	N_{SR}
atlas_1712_02118	search for disappearing track	36.0	2
atlas_1710_04901	search for displaced vertex	32.8	1
atlas_1902_01636	heavy charged long-lived particles	36.1	8
atlas_2003_11956	long-lived particles decaying to hadrons and displaced muon	136.0	2
cms_pas_exo_16_022	displaced leptons search (13 TeV)	2.6	3
cms_1409_4789	displaced lepton (8 TeV)	36.0	1

Examples

Recasted `arXiv:2010.14293` – search for squarks and gluinos in final states with jets and missing transverse momentum

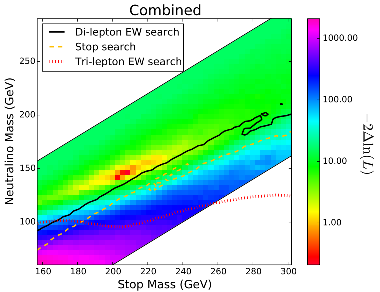
- $pp \to \widetilde{W}^{\pm}\widetilde{W}^{0}, \widetilde{W}^{+}\widetilde{W}^{-}$
- quasi-degenerate wino dark matter (LSP + NLSP)
- $\widetilde{W}^{\pm} \to \widetilde{W}^{0} W^{*} \to \widetilde{W}^{0} + (\text{soft SM})$
- the new exclusion on top of LEP and long-lived charged wino limits
- includes new feature: improved statistical treatment – multibin fit with `HistFitter`



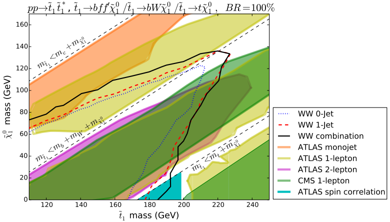
not quite expected: multijet search more sensitive than monojet

Examples

What if a signal is seen? Fit of the model parameters.
Ambulance chasing example – alleged stop production
Combination of excesses in several measurements SM + BSM at 7 TeV
arXiv:1406.0858



...or exclude parts missed by other searches; WW @ CMS 8 TeV
arXiv:1505.05523



Coming next

- obviously: more full-lumi analyses
- several new features/improvements planned for not-so-far future:
- improving statistical packages, e.g. implementation of pyhf, HistFitter
- support of ML based ATLAS and CMS searches (weights from experiments needed)
- parallelisation of CM, in particular the Pythia handler
- support of jet structure analyses, multiple jet definitions
- CMS detector tuning
- implementation of the ILC module (essentially ready); next: future colliders

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What if an analysis is not listed or doesn't exist yet?

- Use `AnalysisManager` to create a new one
- Answer questions to setup framework
- Code in C++ actual selections

Running the Analysis Manager

- Run `make AnalysisManager; /bin/AnalysisManager`

```
  ____ _               _    __  __    _  _____ _____
 / ___| |__   ___  ___| | _|  \/  |  / \|_   _| ____|
| |   | '_ \ / _ \/ __| |/ / |\/| | / _ \ | | |  _|
| |___| | | |  __/ (__|   <| |  | |/ ___ \| | | |___
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                  /--\| )(_||\/_)|_)  |  |(_|| )(_|(_)(-|
                             /                      _/

 What would you like to do?
   -(l)ist all analyses,
   -(a)dd a new analysis to CheckMATE,
   -(r)emove an analysis from CheckMATE
```

The Analysis Manager

Adding an analysis

```
    a
This will collect all necessary information to create a full analysis and
Takes care for the creation and implementation of the source files into the code.
Please answer the following questions.
Attention: Your input is NOT saved before you finish this questionnaire.
1. General Information to build analysis
Analysis Name:
       ATLAS_1234_5678
Description (short, one line):
       ATLAS: many leptons, few jets
Description (long, multiple lines, finish with ';;' on a new line):
       ATLAS
       many leptons, few jets
       sqrt(s) = 9 TeV
       int(L) = 42 fb^-1
       ;;
Luminosity (in fb^-1):
       42
Do you plan to implement control regions to that analysis? [(y)es, (n)o)
       n
```

The Analysis Manager

Adding an analysis

```
2. Information on Signal Regions
List all signal regions (one per line, finish with ';;' on a new line):
 1l
 2l
[...]
Is the SM expectation B known? [(y)es, (n)o]?
```

```
 y
You now have to add the
numbers for each of the
given signal regions.
1l
obs:
 100
bkg:
 90
bkg_err:
 15
2l
obs:
 200
bkg:
 180
bkg_err:
 30
[...]
```

```
 n
Signal regions are registered but without any
numbers associated to them.
IMPORTANT: The analysis will be created and can
then be used like any other analysis.
CheckMATE will skip the model exclusion
tests as long as the expectation is not
known. You can e.g. use CheckMATE on background
samples to estimate B and dB. As soon as
you know these numbers, run the
AnalysisManager again and use the (e)dit
feature to add them.
```

The Analysis Manager

Adding an analysis

```
2. Information on Signal Regions
List all signal regions (one per line, finish with ';;' on a new line):
 11
 21
[...]
Is the SM expectation B known? [(y)es, (n)o]?
```

```
  y
You now have to add the
numbers for each of the
```

```
  n
Signal regions are registered but without any
numbers associated to them.
IMPORTANT: The analysis will be created and can
```

Add a published analysis

- Provide results straight away
- Typical mode for 8 and 13 TeV
- Compare with existing distributions

```
[...]
```

Add a new analysis

- run on SM backgrounds first
- add these results to CM
- Typical mode to project to 13 and 14 TeV and to invent new cutflows or observbles

The Analysis Manager

Adding an analysis

```
3. Settings for Detector Simulation
3.1: Miscellaneous
To which experiment does the analysis correspond? (A)TLAS, (C)MS
 A
3.2: Electron Isolation
Do you need any particular isolation criterion? [(y)es, (n)o]
 y
Isolation 1:
Which objects should be considered for isolation? [(t)racks, (c)alo objects?
 t
What is the minimum pt of a surrounding object to be used for isolation? [in GeV]
 5
What is the dR used for isolation?
 0.4
Is there an absolute or a relative upper limit for the surrounding pt? [(a)bsolute, (r)elative]
 a
What is the maximum surrounding pt used for isolation [in GeV]?
 20

Do you need more isolation criteria? [(y)es, (n)o]
 n
3.3: Muon Isolation
Do you need any particular isolation criterion? [(y)es, (n)o]
 n
3.4: Photon Isolation
Do you need any particular isolation criterion? [(y)es, (n)o]
 n
```

The Analysis Manager

Adding an analysis

```
3.5: Jets
Which dR cone radius do you want to use for the FastJet algorithm?
 0.4
What is the minimum pt of a jet? [in GeV]
 10
Do you need a separate, extra type of jet? [(y)es, (n)o]
 n
Do you want to use b-tagging? [(y)es, (n)o]
 y

b-Tagging 1:
What is the signal efficiency to tag a b-jet? [in %]
 70
Do you need more b tags? [(y)es, (n)o]
 y

b-Tagging 2:
What is the signal efficiency to tag a b-jet? [in %]
 40
Do you need more b tags? [(y)es, (n)o]
 n

Do you want to use tau-tagging? [(y)es, (n)o]
 n
```

Some example lines

```
void Atlas_1609_01599::analyze() {
  missingET->addMuons(muonsCombined);
  electronsMedium = filterPhaseSpace(electronsMedium, 7., -2.47, 2.47, tru
  muonsCombined = filterPhaseSpace(muonsCombined, 7., -2.4, 2.4);
  jets = filterPhaseSpace(jets, 25., -2.5, 2.5);
  [...]
  if ( muonsCombined.size() > 1 && muonsCombined[0]->Charge*muonsCombined[
    if ( nbjets > 1 ) countCutflowEvent("muSS_04_bjets>0");
    else return;
    if ( muSS && electronsMedium.size() == 0 && muonsCombined.size() == 2)
    else return;
    if (muSS && muonsCombined[1]->PT > 25.) countCutflowEvent("muSS_06_pT>
    else return;
    if (muSS && MET > 40.) countCutflowEvent("muSS_07_met>40");
    else return;
    if (muSS && ht > 240. ) {
      countCutflowEvent("muSS_08_ht>240");
      countSignalEvent("2muSS");
    }
  }
```

Conclusions

- CheckMATE is a very simple to use LHC-phenomenology tool
- It is fully model independent
- Enables testing against many BSM searches and SM measurements
- It can be used to check against existing results **or** to do prospective studies
- many root functionalities directly available, eg. histograms for differential distributions

http://checkmate.hepforge.org/

More stuff

https://checkmate.hepforge.org/

Installation:

https://checkmate.hepforge.org/tutorial/ver2/start.php

Tutorial:

https//checkmate.hepforge.org/online_tutorial/2018_MC4BSM/

GitHub:

https://github.com/CheckMATE2/checkmate2

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interplay of theory and collider experiments

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