Implementation of multi-bin searches in CheckMATE

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Most BSM searches are interpreted in terms of a small set of signal models in the original publications.

Reinterpretation of the results in terms of other BSM models require the full statistical model. → Computationally very expensive and not always available.

Alternatives:
• Calculate limits with single bin signal regions. Only total event rate is needed and signal contamination in the CRs is ignored. Drawbacks: underestimates the true exclusion power and less robust against statistical fluctuations.
• In this talk: Use a reasonable simplification of the statistical model to reduce computational cost retaining the use of multi-binned SR bins.
Current CheckMATE version bases test on the SR with the largest expected exclusion potential. We use only a fraction of the available data which could cause a loss of sensitivity.

Our goal is to implement multibinned analysis in the CheckMATE framework.

We build a simplified statistical model based on the CheckMATE output and make the hypothesis test within the PYHF environment.
We build the simplified likelihood following the prescription in ATL-PHYS-PUB-2021-038:

• "In the simplified likelihood introduced herein, the background model is approximated with a single background sample, representing the total SM background rate in the different analysis channels."

• "The pre-fit sample rate of the total background sample is set to the total post-fit background rate obtained in the background-only fit in the full likelihood"

• "...the complete set of nuisance parameters in the original full likelihood is reduced to a single constrained parameter... . It is constrained by a Gaussian $G(\alpha = 0 | \alpha, \sigma = 1)$ and is correlated over all bins in each channel"
PYHF implementation
API to implement HistFactory statistical models in a python framework.

• Simplified model in JSON format including:
  • Single channel including signal and background samples.
    
    Signal modifiers: statistical error (from CheckMATE output), luminosity error (optional input), systematics (optional input).
    
    Background modifiers: fully correlated background error.
  
  • Parameter of interest: \( \mu \) (signal strength of the model)
  
• Hypothesis test:
  
  Option to choose between asymptotic calculator or toy based.

We compared the results of this implementation with the results obtained in with an implementation on HistFitter finding equivalent results.
Results format:

**Observed CLs for \( \mu = 1 \):** \( 3.120639681359277 \times 10^{-06} \)

**Expected CLs band for \( \mu = 1 \):** \([1.6443160871263e-07, 5.531920389481112e-06, 0.00015700059417103602, 0.0032331969351591075, 0.03843474510134974]\)

**Upper limit (obs):** \( \mu = 0.2255 \)

**Expected 2-sigma band:** \([0.2134, 0.2960, 0.4337, 0.6556, 0.9610]\)

**Observed upper limit over signal strength**
(point is excluded if \( \mu < 1 \))

The point tested in this case is **excluded!**
Validation

• Several ATLAS searches featuring multibinned analysis were recasted:

  • Squarks and gluinos to jets and missing transverse momentum. *JHEP* 02 (2021) 143 (2010.14293)


  • Sbottom to higgs bosons, b-jets and missing transverse momentum. *JHEP* 12 (2019) 060 (1908.03122)

  • More in preparation ...
3 Sets of binned signal regions (not orthogonal between them!)

Orthogonal binning within each set in terms of $m_{\text{eff}}$ and $E_{T}^{\text{miss}}/\sqrt{H_T}$

For each point, we calculate the expected upper limit based on each of the three SR-sets and we select the observed limit obtained from this SR-set.

- Simulation of squark/gluino + to 2 additional partons with MadGraph5_aMC@NLO_v3.4.1
- PYTHIA v8.306 for parton showering and hadronization.
- CKKW-L merging scheme.
- NNPDF2.3LO pdf set was used.
\( \tilde{q}\tilde{q} \) production, \( B(\tilde{q} \rightarrow q\chi^0_1) = 100\% \)

Points where energetic jets came from initial state radiation are more challenging to simulate.

Good agreement for points with large squark-neutralino hierarchy:
Energetic jets originated from squark decay

Limits using only best signal region.
Limits using only best signal region. \( B(\tilde{g} \rightarrow qq\tilde{\chi}^0_1) = 100\% \)

Good agreement in general. Slightly worse in the compressed region.
Search for direct stau production in events with two hadronic $\tau$-leptons in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector

The ATLAS Collaboration

2 disjoint signal regions separated by the requirement on missing transverse momentum.

Simulation of stau pair production + to 2 additional partons with MadGraph5_aMC@NLO_v3.4.1
PYTHIA v8.306 for parton showering and hadronization.
MLM merging scheme.
NNPDF2.3LO pdf set
Limits using only best signal region.

Increased exclusion power with the multibin analysis.
3 Sets of signal regions (not orthogonal between them!). SRA and SRC binned.

Orthogonal binning within each set in terms of meff and "S" (object-based MET -significance)

For each point, we calculate the expected upper limit based on each of the three SR-sets and we select the observed limit obtained from this SR-set.

• Simulation of sbottom + to 2 additional partons
  with MadGraph5_aMC@NLO_v3.4.1
• PYTHIA v8.306 for parton showering and hadronization.
• MLM merging scheme.
• NNPDF2.3LO pdf set was used.
Multibin analysis improves the limits obtained by CheckMATE and gives a better agreement with ATLAS result.

\[ \tilde{b}_1 \tilde{b}_1 \text{ production; } \tilde{b}_1 \rightarrow b \tilde{\chi}^0_2 \rightarrow bh \tilde{\chi}^0_1; \quad m(\tilde{\chi}^0_1) = 60 \text{ GeV} \]
\( \tilde{b}_1 \tilde{b}_1 \) production; \( \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0 \); \( \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \) GeV

Better agreement with ATLAS with the multibin analysis.

Worse performance in points where neither the sbottom decay nor the 2nd neutralino decay produce hard b-jets.
Summary

• The use of simplifications of statistical models of the LHC searches facilitates the use of multibinned analysis in recasted analysis.

• Multibinned analysis utilizing the additional information with respect to best SR approach lead to more robust results and generally stricter limits.

• A PYHF based implementation of this approach is in preparation for CheckMATE

• Several ATLAS searches featuring multibinned analysis have been recasted with good agreement with ATLAS results.
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Understanding the Early Universe:
interplay of theory and collider experiments

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