Collider Phenomenology & LHC Recasting with MadAnalysis 5

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IRN Terascale
July 5th, 2021

Durham University

Science & Technology Facilities Council

MCnet

IP3

Outline

- Introduction
- Latest developments
  - Simplified - Fast detector Simulations
  - Theoretical uncertainties and HL extrapolations
  - Simplified/Full likelihoods
- Outlook & ongoing developments
- Conclusion & Summary

Introduction

Why designing & recasting is important?

- Exploiting the full potential of LHC (for new physics)
  - *Designing* new analyses (based on MC simulations)
  - *Recasting* LHC analyses (The LHC legacy)
- Data preservation in HEP is mandatory
  - Going beyond raw data via analyses
- Related tools need to be supported by the entire community
  - Both theorists & experimentalists
- Universal recasting tool

Les Houches Recommendations (EPJC '12)

Reinterpretation Forum Report (SciPost '20)

MadAnalysis 5

What is MadAnalysis 5?

- A framework for phenomenological analyses
- Any level of sophistication: partonic, hadronic, detector, reconstructed
- Several input formats: STDHEP, HEPMC, LHE, LHCO, ROOT (from Delphes)
- User-friendly, flexible & Fast!!!
- Interfaces several HEP packages: MadGraph, FastJet, Delphes, pyhf

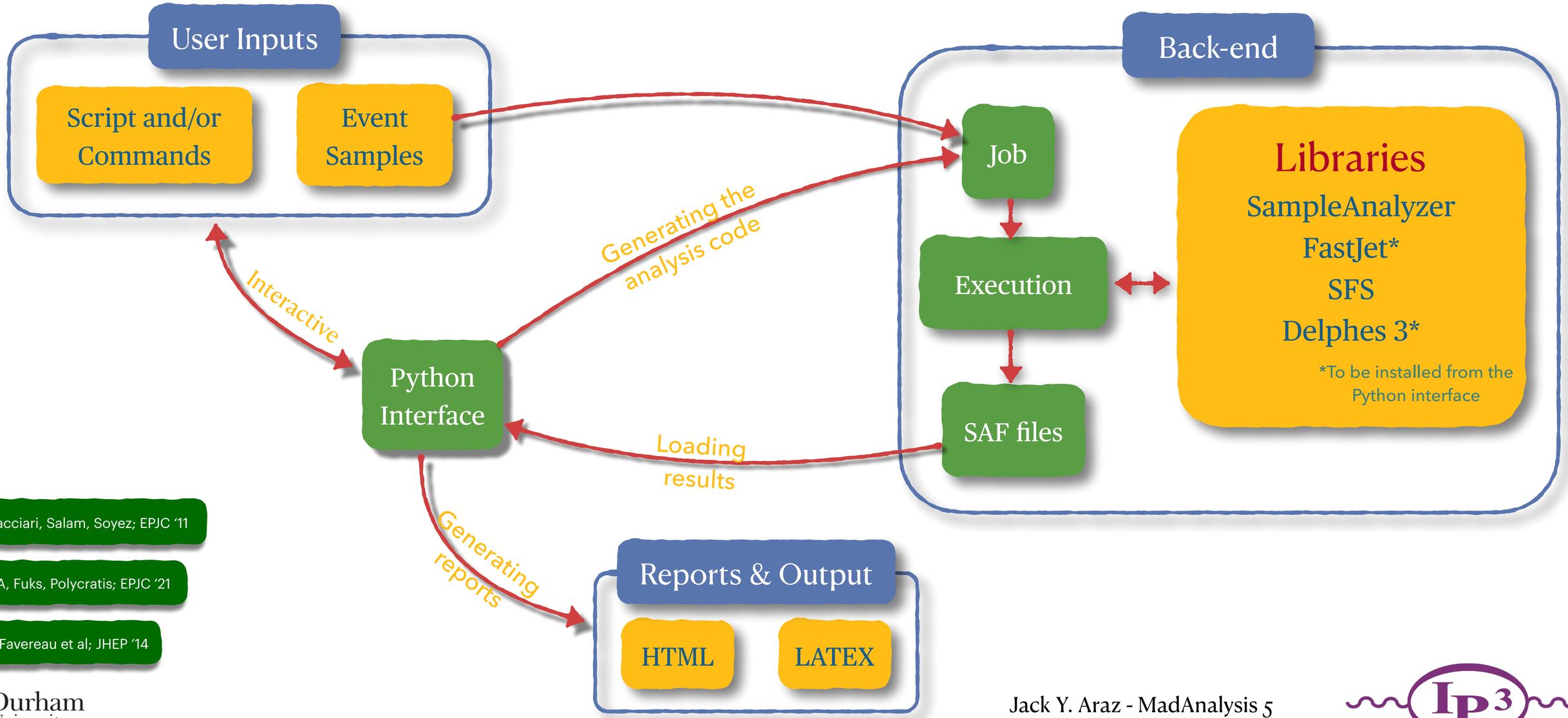
Normal Mode

- Intuitive commands typed in the Python interface
- Analysis performed behind the scenes (black box)
- Human readable output: HTML and LaTeX

Expert Mode

- C++ programing with the SampleAnalyzer framework
- Support for multiple sub-analyses, an efficient way for handling cuts and histograms, etc.

MadAnalysis 5: Normal Mode

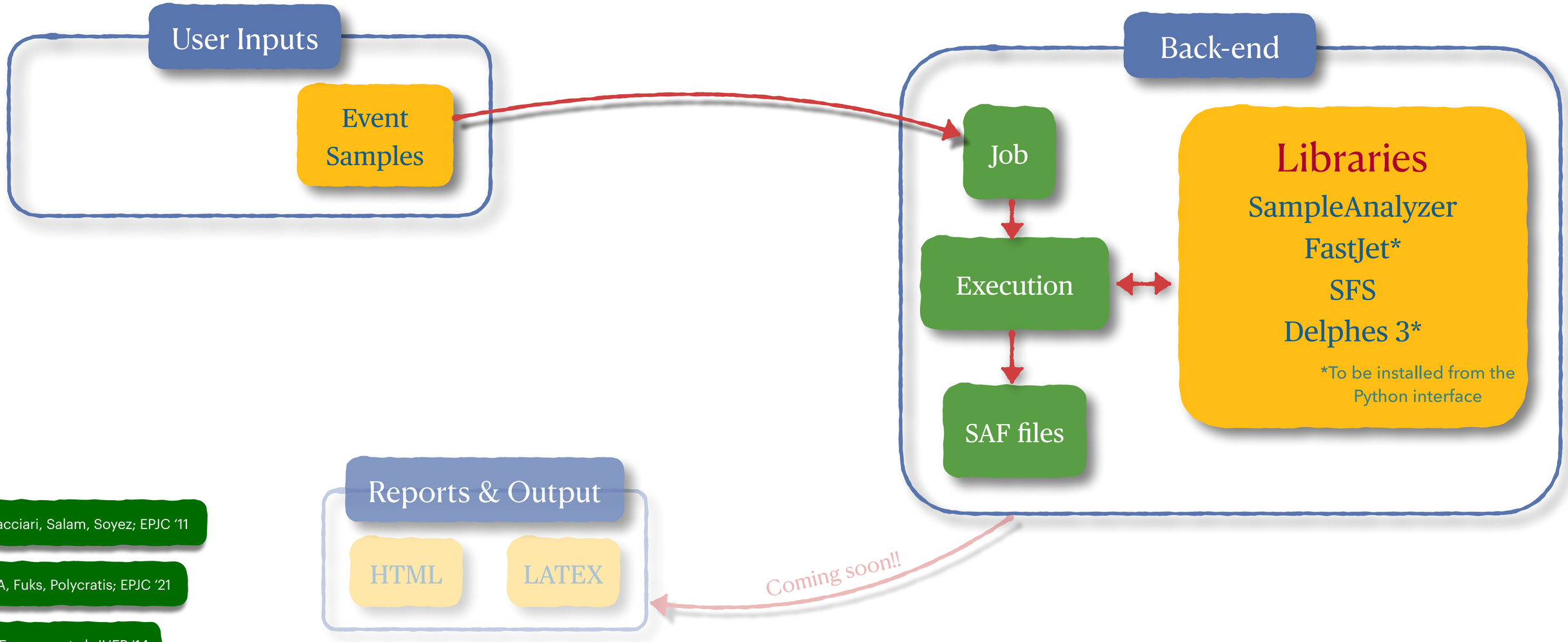


Cacciari, Salam, Soyez; EPJC '11

JYA, Fuks, Polycratis; EPJC '21

De Favereau et al; JHEP '14

MadAnalysis 5: Expert Mode



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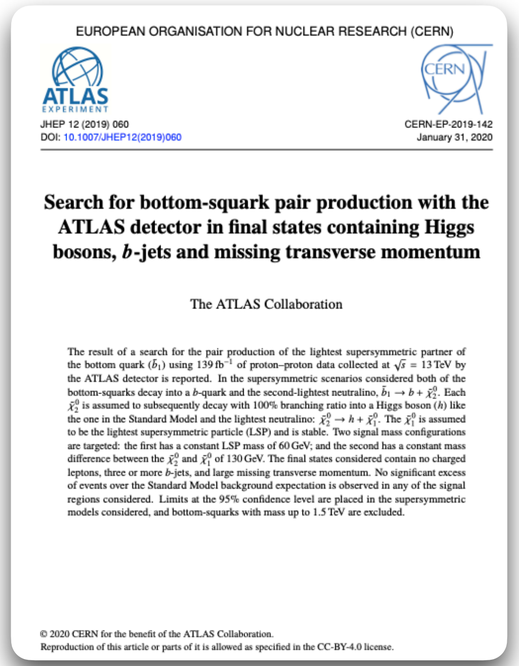
Latest Developments

Reimplementing an analysis in MadAnalysis 5



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

JHEP 12 (2019) 060
DOI: 10.1007/JHEP12(2019)060

CERN-EP-2019-142
January 31, 2020

Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, *b*-jets and missing transverse momentum

The ATLAS Collaboration

The result of a search for the pair production of the lightest supersymmetric partner of the bottom quark ($\tilde{b}_1$) using 139 fb^{-1} of proton–proton data collected at $\sqrt{s}$ = 13 TeV by the ATLAS detector is reported. In the supersymmetric scenarios considered both of the bottom-squarks decay into a *b*-quark and the second-lightest neutralino, $\tilde{b}_1 \to b + \tilde{\chi}_2^0$. Each $\tilde{\chi}_2^0$ is assumed to subsequently decay with 100% branching ratio into a Higgs boson (h) like the one in the Standard Model and the lightest neutralino: $\tilde{\chi}_2^0 \to h + \tilde{\chi}_1^0$. The $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle (LSP) and is stable. Two signal mass configurations are targeted: the first has a constant LSP mass of 60 GeV; and the second has a constant mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ of 130 GeV. The final states considered contain no charged leptons, three or more *b*-jets, and large missing transverse momentum. No significant excess of events over the Standard Model background expectation is observed in any of the signal regions considered. Limits at the 95% confidence level are placed in the supersymmetric models considered, and bottom-squarks with mass up to 1.5 TeV are excluded.

Signal Events
(STDHEP or HEPMC format)

SFS@Ma5 or Delphes

Detector Simulation

C++

Recast

Validation

Public Analysis Database ++;

Exclusion limit calculation

Cut-flows uncertainties

TH uncertainties, HL extrapolations, simplified/full likelihoods

Dumont, Fuks, Kraml, et. al. EPJC '15

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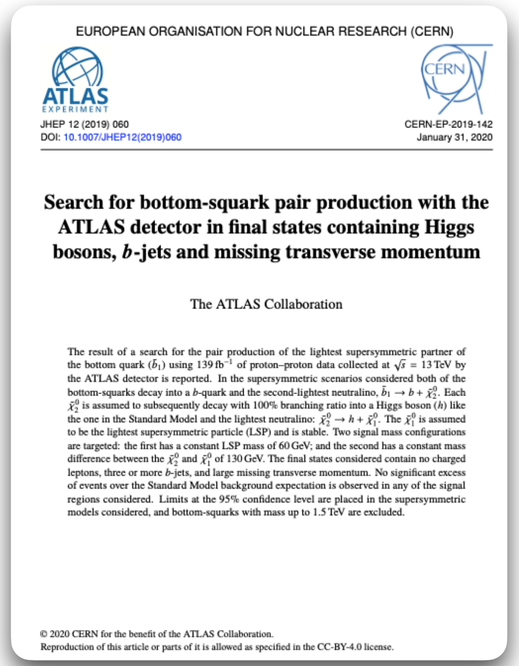

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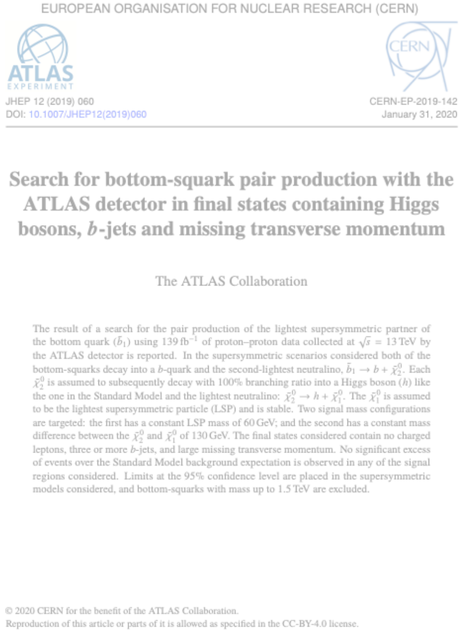

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Simplified - Fast Detector Simulation with MadAnalysis 5

JYA, Fuks, Polykratis EPJC '21

- Prerequisite : Beginner level English
- Simulation based on reconstruction efficiencies, four momentum smearing and flexible particle (mis)tagging for FS jets, leptons, photons & tracks.
  - Smearer
  - Reconstruction efficiencies
  - (mis)Tagger
  - Observable Scaling (JES, energy scaling, general scaling)
  - Substructure smearing
- Fully integrated to Public Analysis Database `ma5> install PAD`
- Example?

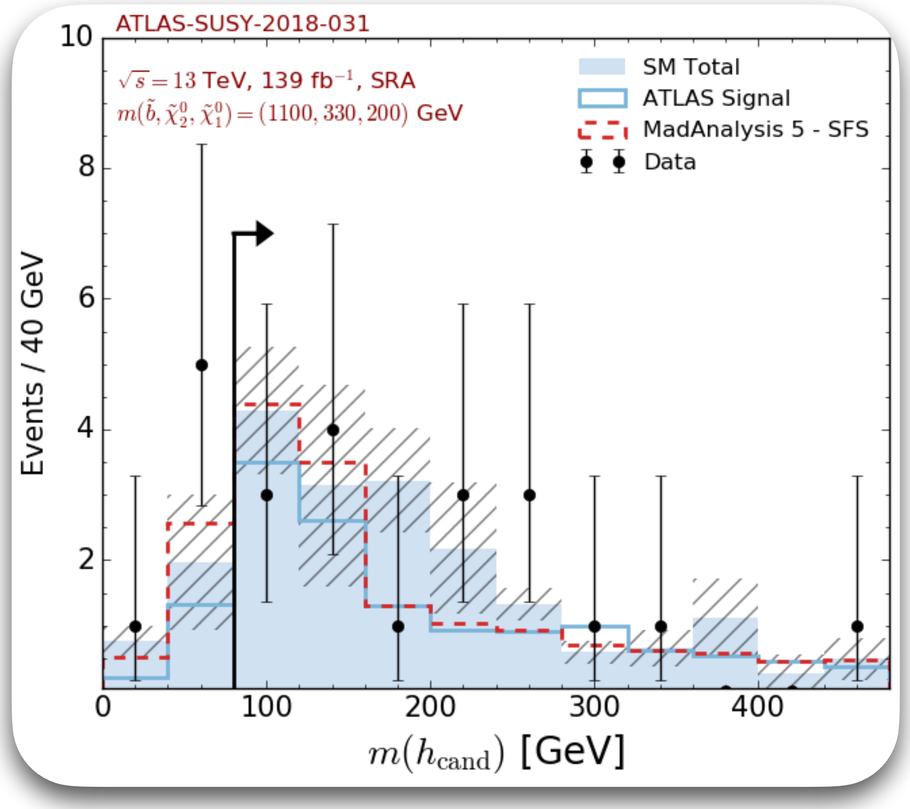
- ✓ ATLAS - SUSY - 2018 - 31
- ✓ ATLAS - CONF - 2019 - 40
- ✓ ATLAS - SUSY - 2016 - 07
- ✓ CMS - SUS - 2016 - 48

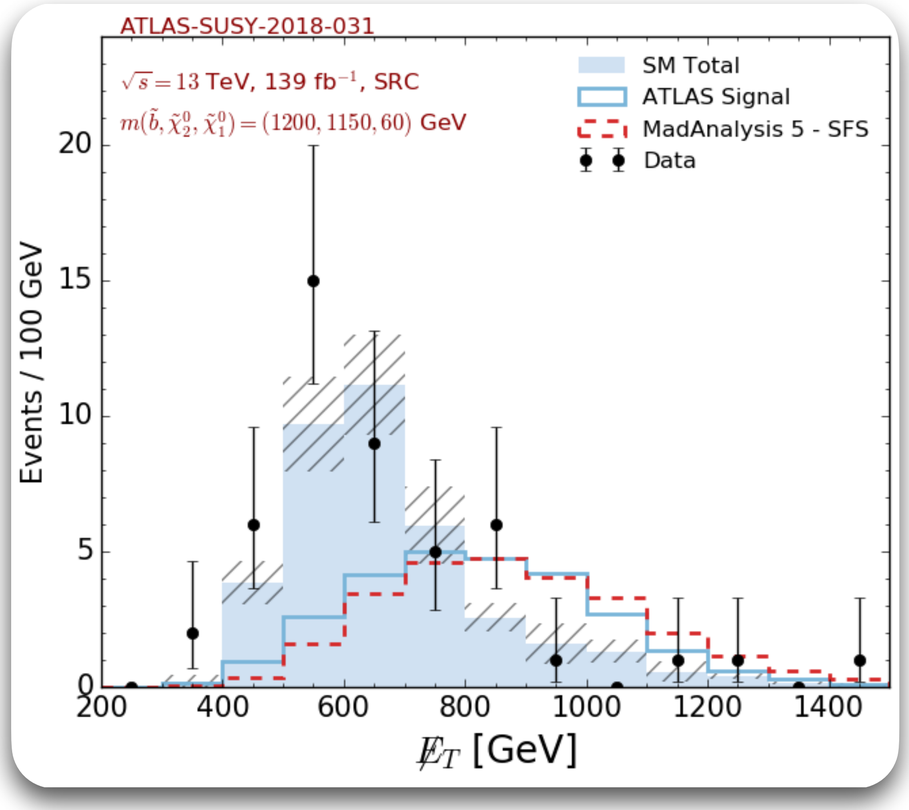
```
ma5>define smearer j with E (exp(pt)/cosh(eta))^2  [ (abseta > 2.5 or pt < 10) and pt > 100 ]
```

Random equation — Random domain

Simplified - Fast Detector Simulation with MadAnalysis 5

Comparison with ATLAS-SUSY-2018-031

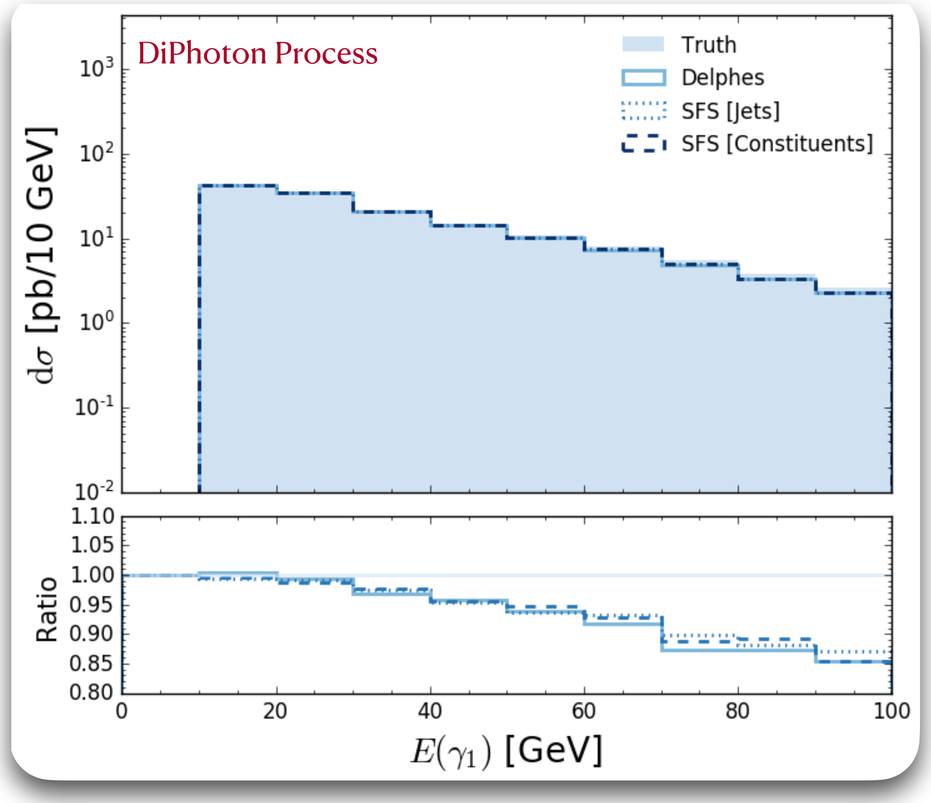


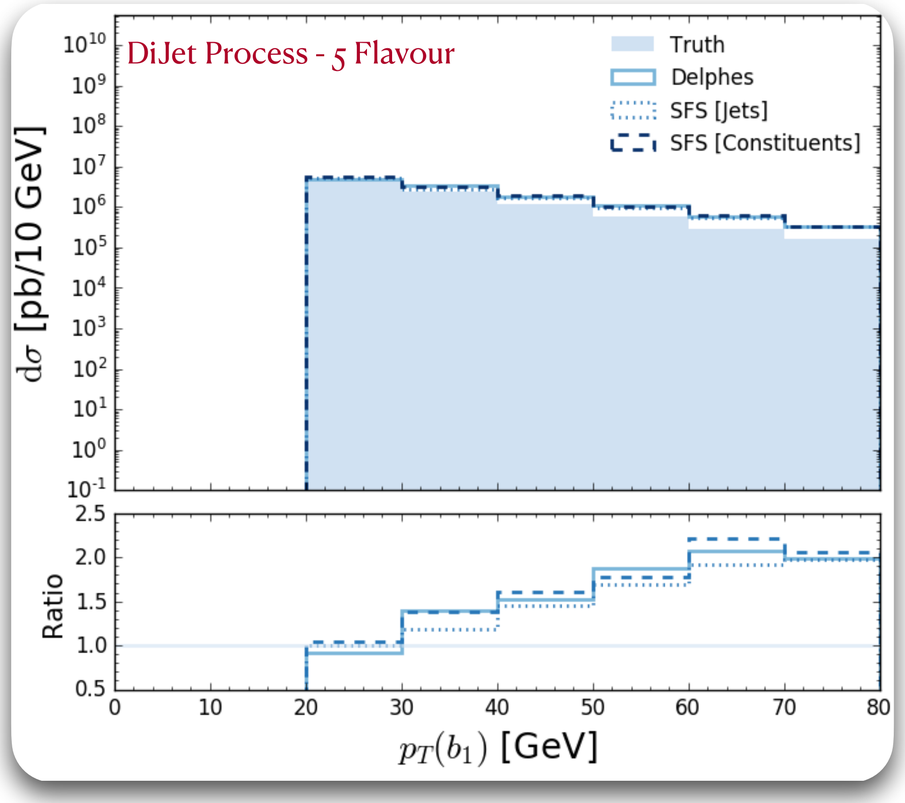


JYA et. al. Mod.Phys.Lett.A '21

Simplified - Fast Detector Simulation with MadAnalysis 5

Comparison with Delphes





JYA, Fuks, Polykratis EPJC'21

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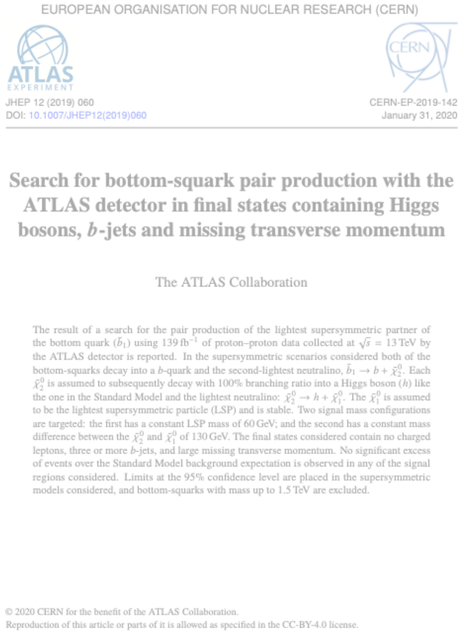
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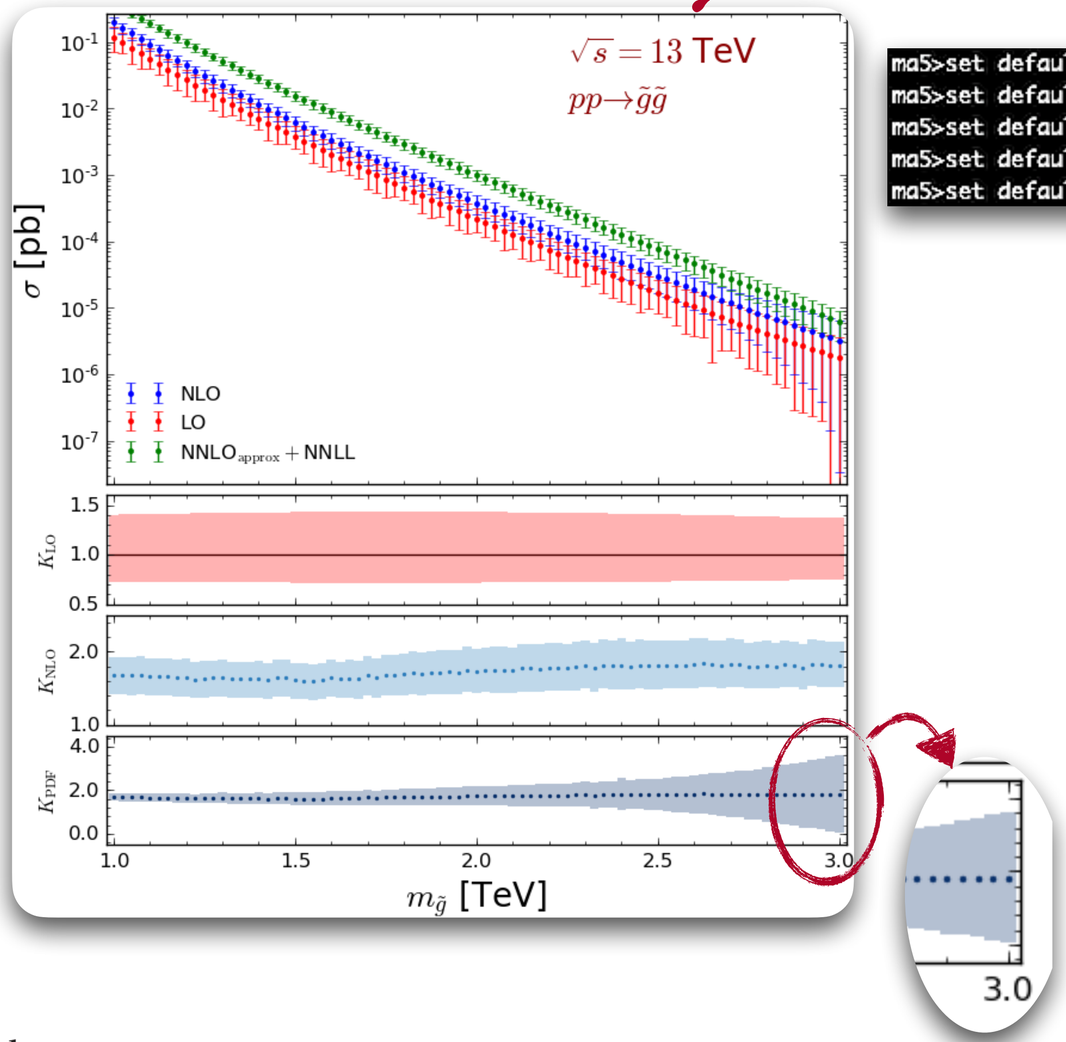
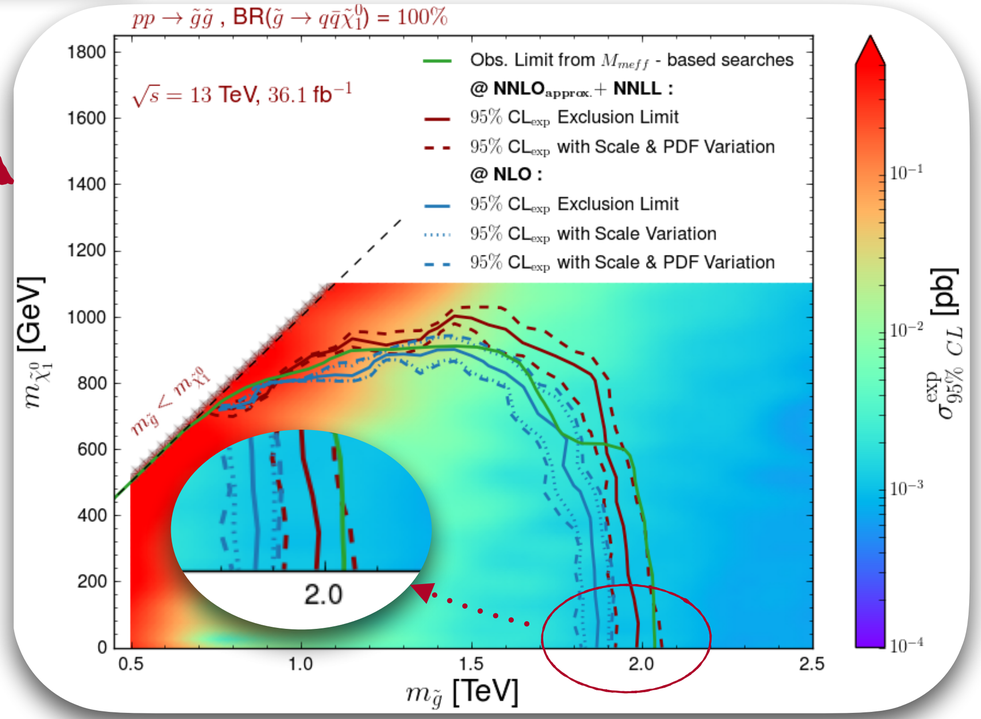
Theoretical uncertainties & HL extrapolations

JYA, Frank, Fuks EPJC '20




```
ma5>set defaultset.xsection = 1.8524788535e-06
ma5>set defaultset.scale_up_variation = 0.388
ma5>set defaultset.scale_down_variation = 0.262
ma5>set defaultset.pdf_up_variation = 0.131
ma5>set defaultset.pdf_down_variation = 0.131
```

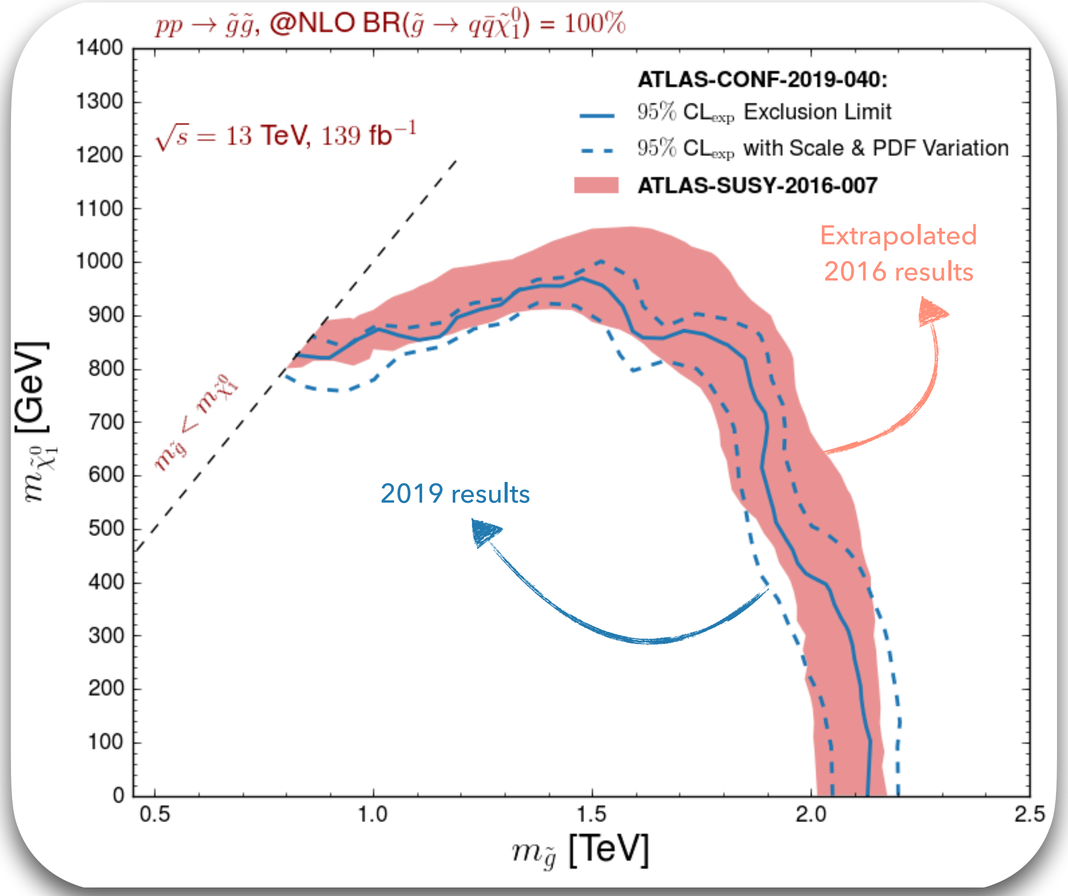
ATLAS-SUSY-2016-07

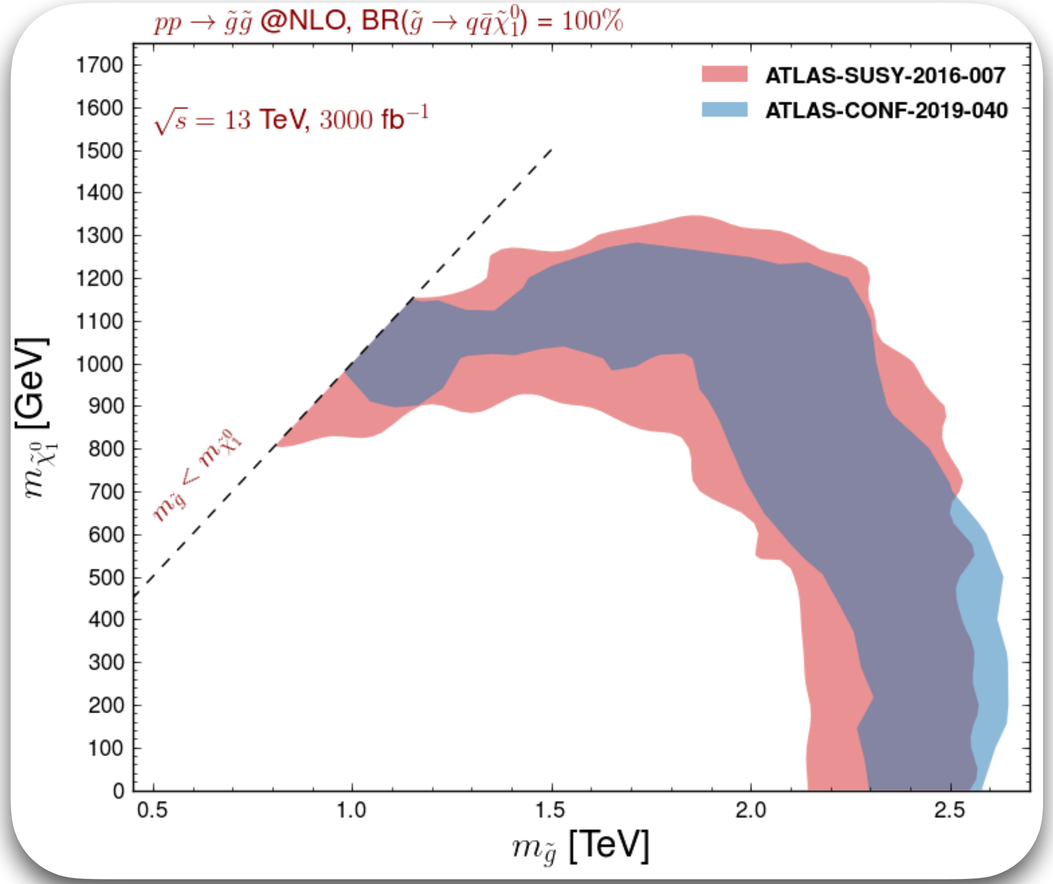


Theoretical uncertainties & HL extrapolations

```
ma5>set main.recast.add.extrapolated_luminosity = 300 3000
```

JYA, Frank, Fuks EPJC '20





Simplified/Full likelihoods

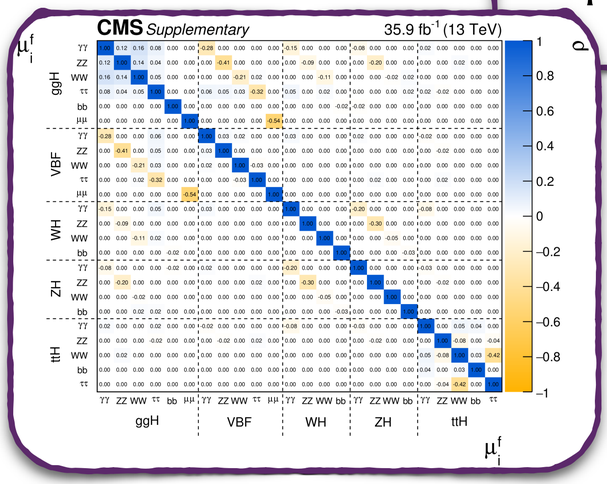
Why important?

ATLAS SUSY and Exotics workshop
S. Kraml '20

- The mathematical description of the analysis is provided within its statistical model.
- The likelihood profile enables the standard statistical approaches to extract information.
- *i.e.* how reasonably aligned the theoretical predictions with the experimental observations?

Les Houches Recommendations (EPJC '12)

Simplified likelihoods from CMS



CMS-NOTE-2017-001

Full likelihoods from ATLAS

pyhf
differentiable Likelihoods

```
ma5> install pyhf
```

ATL-PHYS-PUB-2019-029

SModelS: Alguero, Kraml, Waltenberg '20

Gael's talk just before this one

Simplified/Full likelihoods

Alguero, JYA, Fuks, Kraml, Waltenberger '20

Simplified likelihoods and pyhf interface has been fully integrated in MadAnalysis 5 - v1.9_beta

- ATLAS - SUSY - 2018 - 31
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- ATLAS - SUSY - 2018 - 14

- CMS - SUS - 2016 - 39
- CMS - SUS - 2017 - 01
- CMS - SUS - 2019 - 06
- CMS - PAS - EXO - 20 - 004

NEW!!! By Andreas Albert; see his talk at RAMP#3

Ma5 best SR

Image credit: Mark Goodsell

Ma5 with pyhf

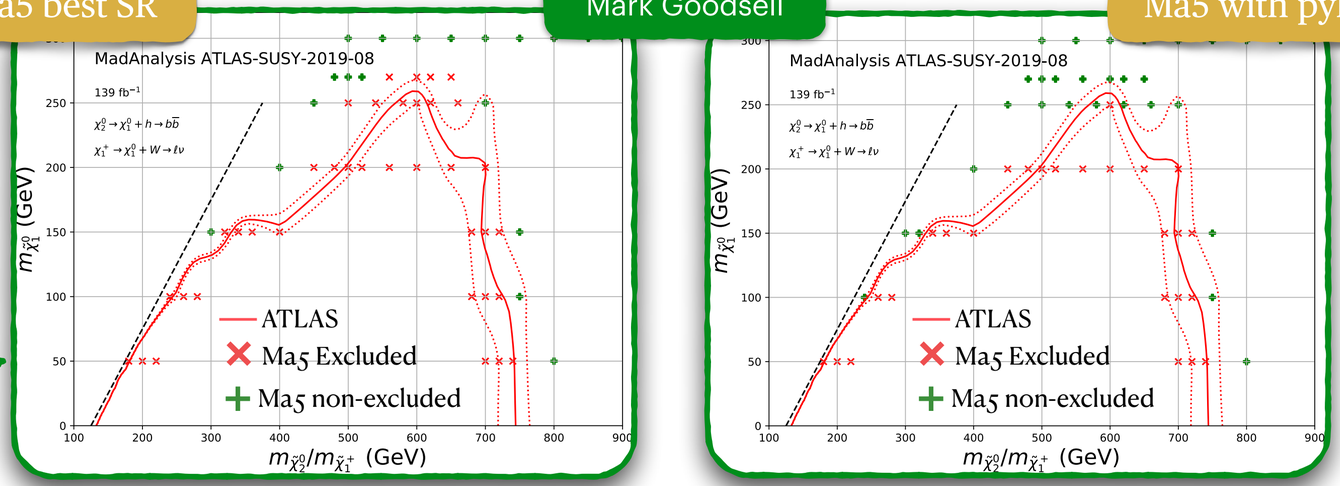
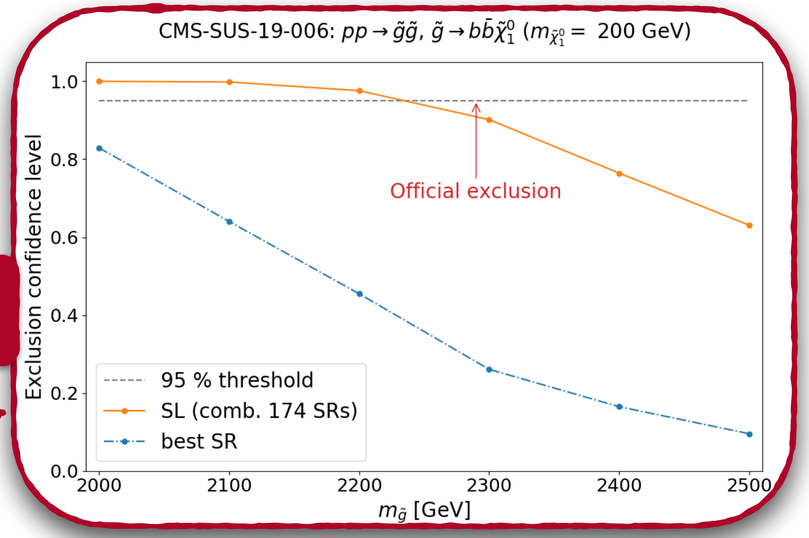


Image credit: Gael Alguero



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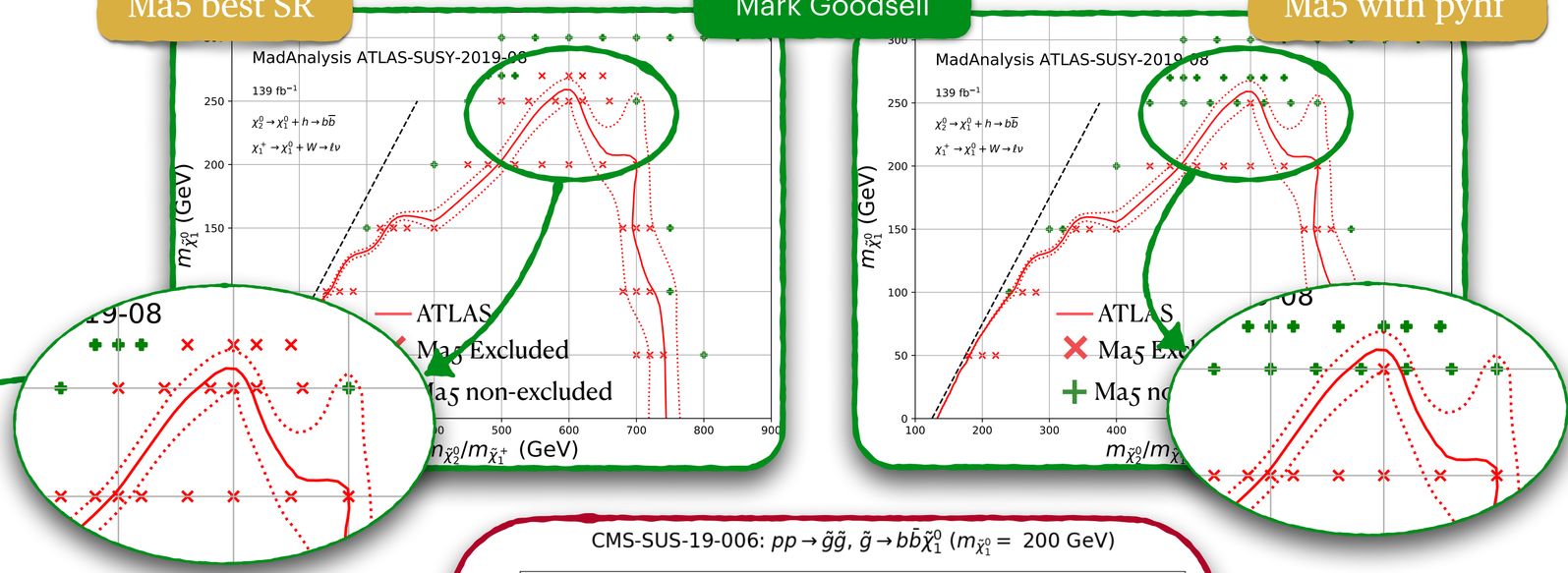

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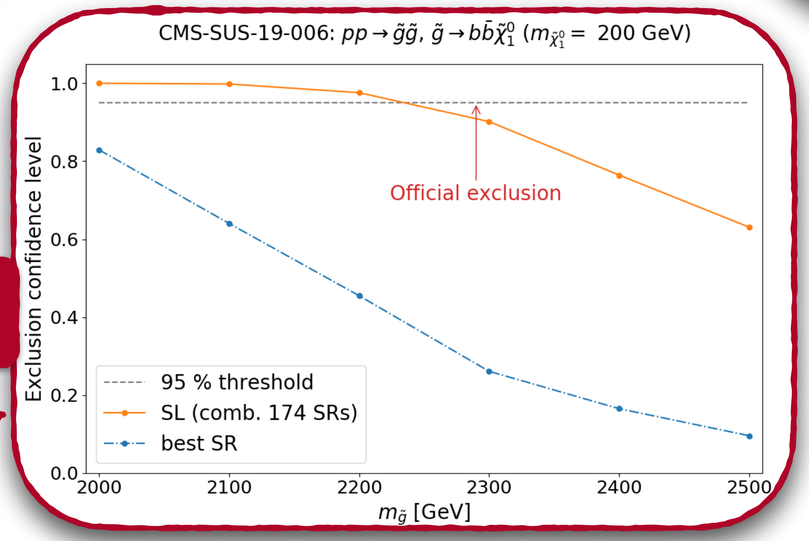

Outlook & ongoing developments

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- SFS@Ma5 with Particle Propagator module for LLP analyses available in ma5_v1.9

JYA, Fuks, Goodsell, Utsch; Ongoing

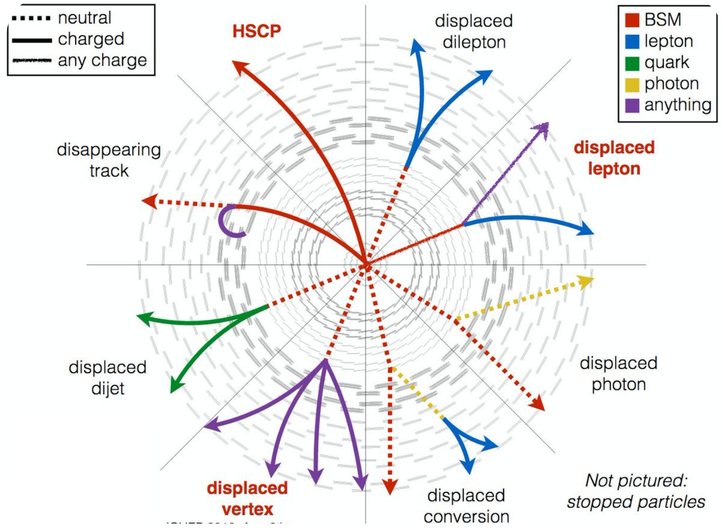
✓ CMS - EXO - 2016 - 22

✓ ATLAS - SUSY - 2017 - 04

By Manuel Utsch

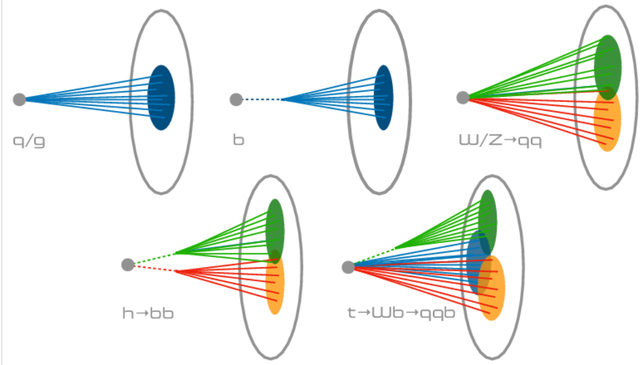
✓ CMS - EXO - 2019 - 10

For more details see Mark's talk at RAMP#3



- Multi-Jet Clustering & Substructure tools will be available with a toolbox for VLQ searches
- Alpha version of SFS@Ma5 for substructure tools available in this link.

JYA, Flacke, Fuks, Jueid, Panizzi; Ongoing



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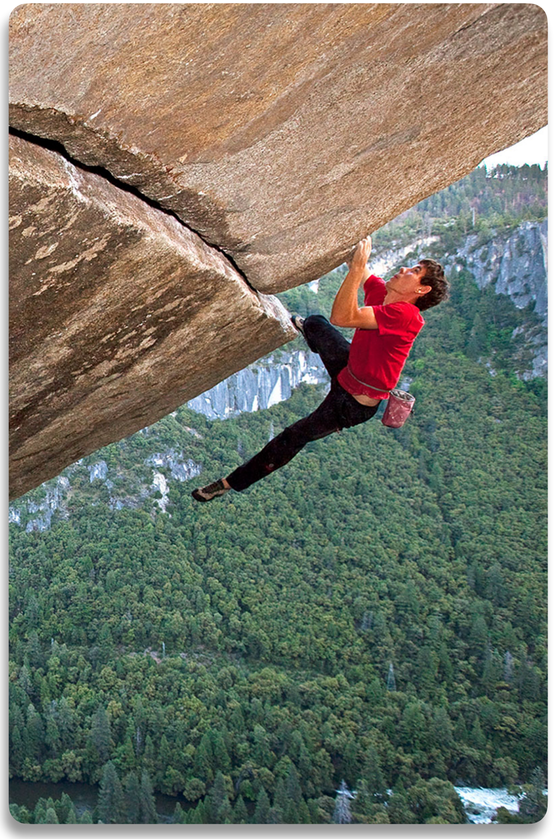
Scheduled Developments

- ❖ Event-by-event theoretical uncertainty estimation.
- ❖ Independent report generator will be available for Expert Mode.
- ❖ Option to add pile-up in SFS.
- ❖ More generic signal region implementation (thanks to Andreas Albert for the valuable comments!).
- ❖ More optimization, more speed!

Conclusion

- ☑ Theoretical (scale & PDF) and experimental uncertainties are crucial for an accurate (re)interpretation of an analysis.
  - ☑ Usage of pyhf (ATLAS) & simplified likelihoods (CMS) are fully compatible with the new interface.
- ☑ Simple and fast analysis recasting/designing now available with SFS@Ma5 and fully integrated with PAD.
- ☑ Fully analytic particle propagator is available with `SFS@Ma5v1.9_beta`
  - ☐ More LLP analyses are coming to PAD.
- ☐ Jet Substructure analyses will soon be available through SFS@Ma5 and PAD frameworks. (Alpha version is ready to use.)

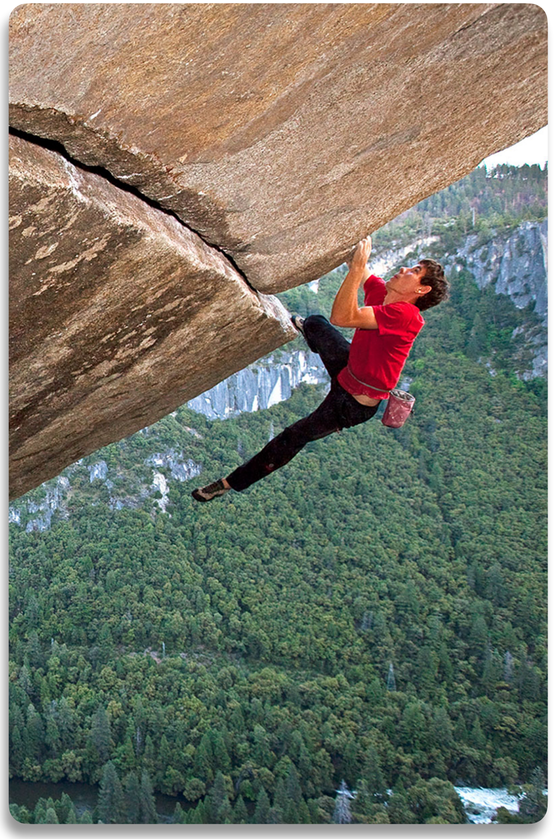


Conclusion

WANTED: Analysis codes

Scientific reproducibility and data preservation solely depend on preserving analysis logic in a reinterpretable form. You can contribute to the HEP community by sharing the LHC recast you have implemented in the MadAnalysis 5 framework, through Public Analysis Database! Please send us your analysis code, detector card, info file and validation note to be included in PAD for public use.

More information and examples can be found in the proceedings of the second MadAnalysis 5 Workshop on LHC recasting in Korea. Analysis codes have been published, documented and got a DOI so that they can now be cited.



Backup

Theoretical uncertainties & HL extrapolations

JYA, Frank, Fuks [EPJC '20]

- Theoretical uncertainties & error combination (scale & PDF)
- Systematic uncertainties
- HL extrapolation
- Experimental error extrapolation (systematic or statistical)
- Experimental error extrapolation assumption

```
ma5>set main.recast.THerror_combination = quadratic
```

ma5> `set main.recast.THerror_combination` : How to combine theoretical uncertainties, linearly or in quadrature.

ma5> `set main.recast.add.systematics` : Add desired possible systematic uncertainty values on the signal

```
ma5>set main.recast.add.systematics = 0.15
ma5>set main.recast.add.systematics = 0.2
```

ma5> `set main.recast.add.extrapolated_luminosity`: Add desired luminosity values (in fb^{-1}) for the results to be extrapolated

```
ma5>set main.recast.add.extrapolated_luminosity = 300 3000
```

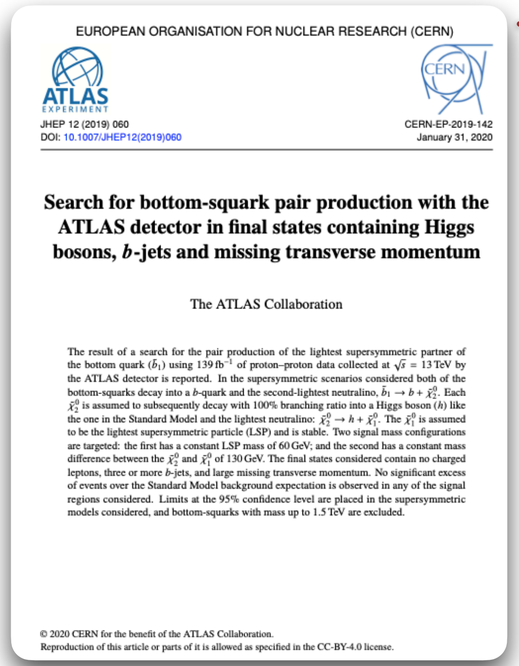
ma5> `set main.recast.error_extrapolation` : How to extrapolate error on the background to higher luminosity.

- Linear: Uncertainties on the background are assumed to be dominated by systematical error
- Sqrt: Uncertainties on the background are assumed to be dominated by statistical error
- Experimental error assumptions : $\sqrt{\kappa_1^2 + \frac{\kappa_2^2}{n_b}}$ where κ_1 is the estimation of systematic uncertainty and κ_2 is the estimation of statistical uncertainty; e.g.

```
ma5> set main.recast.error_extrapolation = 0.2 0.15
```

```
ma5>set main.recast.error_extrapolation = sqrt
```

Introduction : Reimplementing an analysis in Ma5



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CERN

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Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, *b*-jets and missing transverse momentum

The ATLAS Collaboration

The result of a search for the pair production of the lightest supersymmetric partner of the bottom quark ($\tilde{b}_1$) using 139 fb^{-1} of proton–proton data collected at $\sqrt{s}$ = 13 TeV by the ATLAS detector is reported. In the supersymmetric scenarios considered both of the bottom-squarks decay into a *b*-quark and the second-lightest neutralino, $\tilde{b}_1 \to b + \tilde{\chi}_2^0$. Each $\tilde{\chi}_2^0$ is assumed to subsequently decay with 100% branching ratio into a Higgs boson (h) like the one in the Standard Model and the lightest neutralino: $\tilde{\chi}_2^0 \to h + \tilde{\chi}_1^0$. The $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle (LSP) and is stable. Two signal mass configurations are targeted: the first has a constant LSP mass of 60 GeV; and the second has a constant mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ of 130 GeV. The final states considered contain no charged leptons, three or more *b*-jets, and large missing transverse momentum. No significant excess of events over the Standard Model background expectation is observed in any of the signal regions considered. Limits at the 95% confidence level are placed in the supersymmetric models considered, and bottom-squarks with mass up to 1.5 TeV are excluded.

Relatively easy to read and understand

Often difficult to exploit detector efficiencies

Detector Simulation

SFS@Ma5 or Delphes

Relatively easy

Recast

Exclusion limit calculation

Validation material can be hard to come by;

- Detailed cut-flows
- Exact definitions of the benchmarks
- Event generation information
- Digitized histograms

Les Houches Recommendations (EPJC '12)

Les Houches Recommendations 2019