Reinterpreting the ATLAS HHH(6b) search in CheckMATE and Rivet

Krzysztof Rolbiecki
University of Warsaw

Work in progress in collaboration with Tomek Procter and Andrzej Siódmok

HHH Workshop, Dubrovnik
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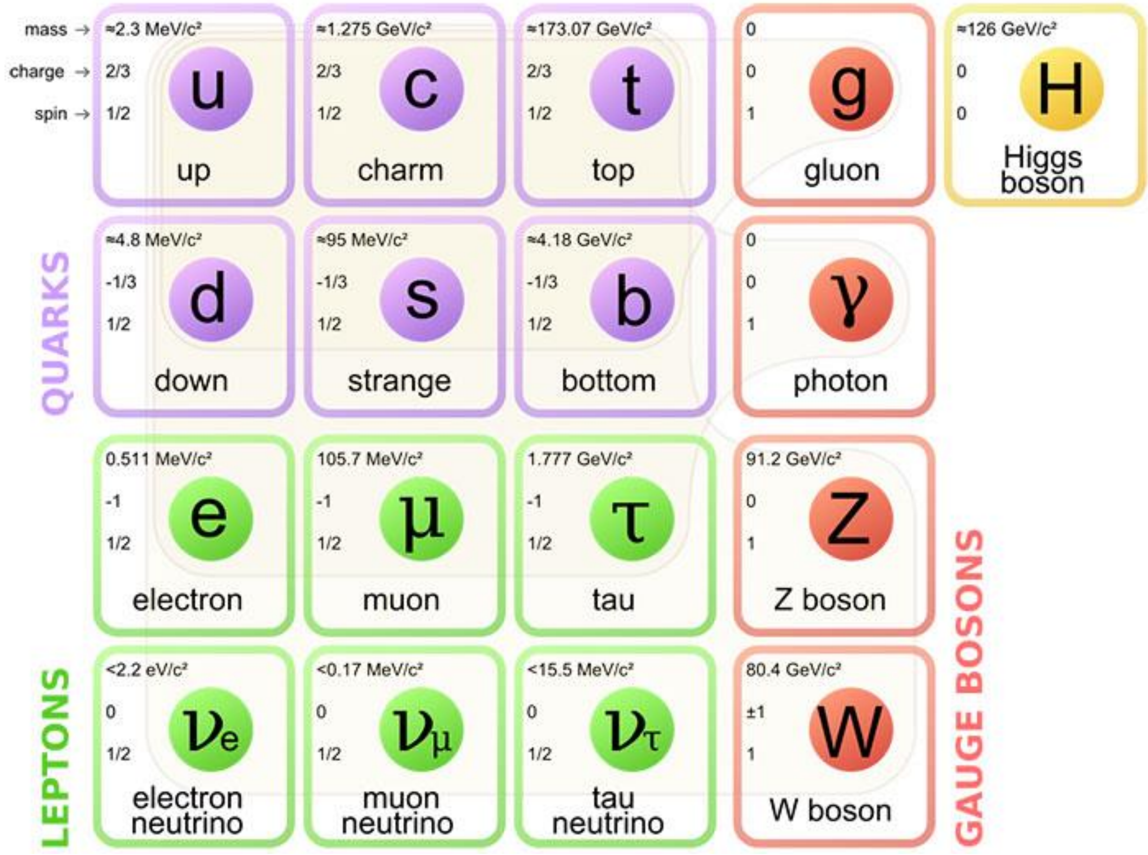
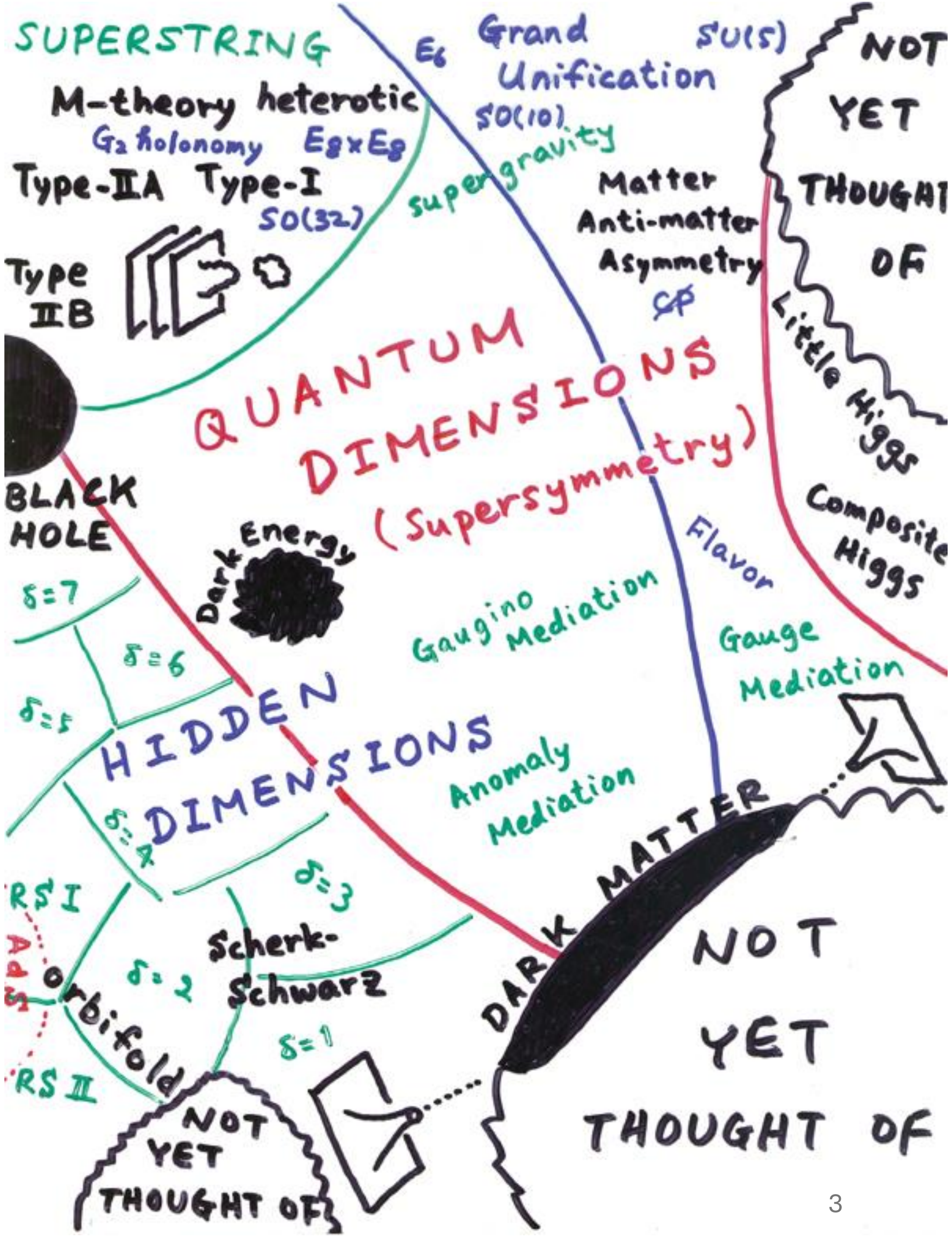
NATIONAL SCIENCE CENTRE
POLAND

Contents


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

?


SUPERSTRING
M-theory
heterotic
G₂ holonomy
E₈×E₈
Type-IIA
Type-I
SO(32)
Type IIB
E₆
Grand Unification
SU(5)
SO(10)
Supergravity
NOT YET THOUGHT OF
Matter Anti-matter Asymmetry
CP
QUANTUM DIMENSIONS
(Supersymmetry)
Little Higgs
Composite Higgs
BLACK HOLE
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
HIDDEN DIMENSIONS
Anomaly Mediation
RS I
AdS
orbifold
RS II
Scherk-Schwarz
DARK MATTER
NOT YET THOUGHT OF
NOT YET THOUGHT OF

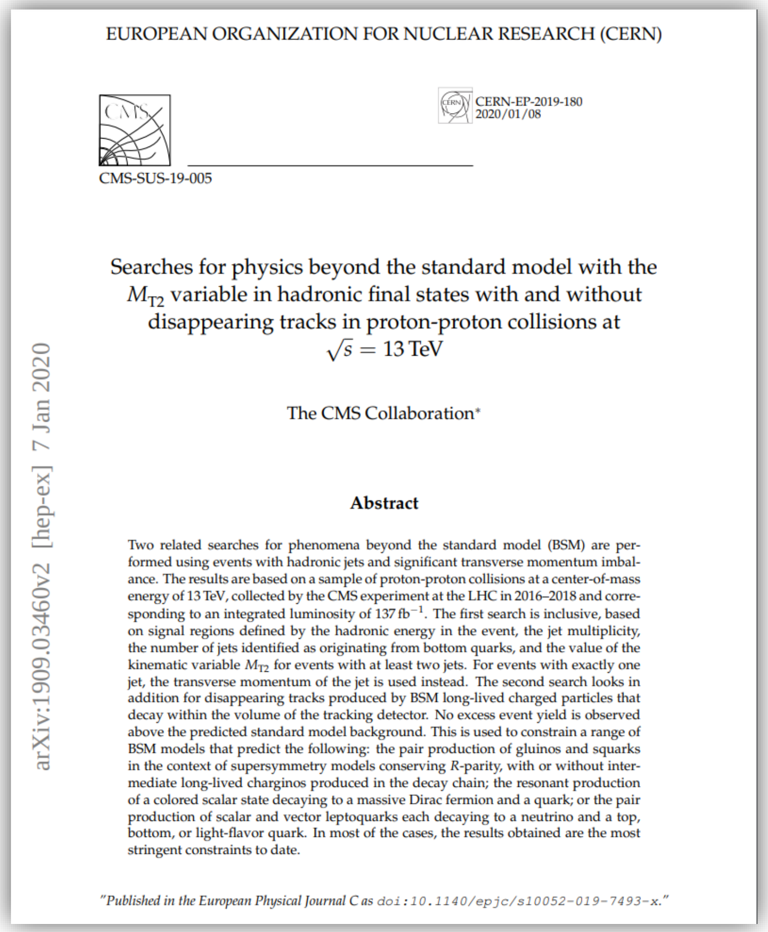
Monte Carlo tools & discoveries at the LHC

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

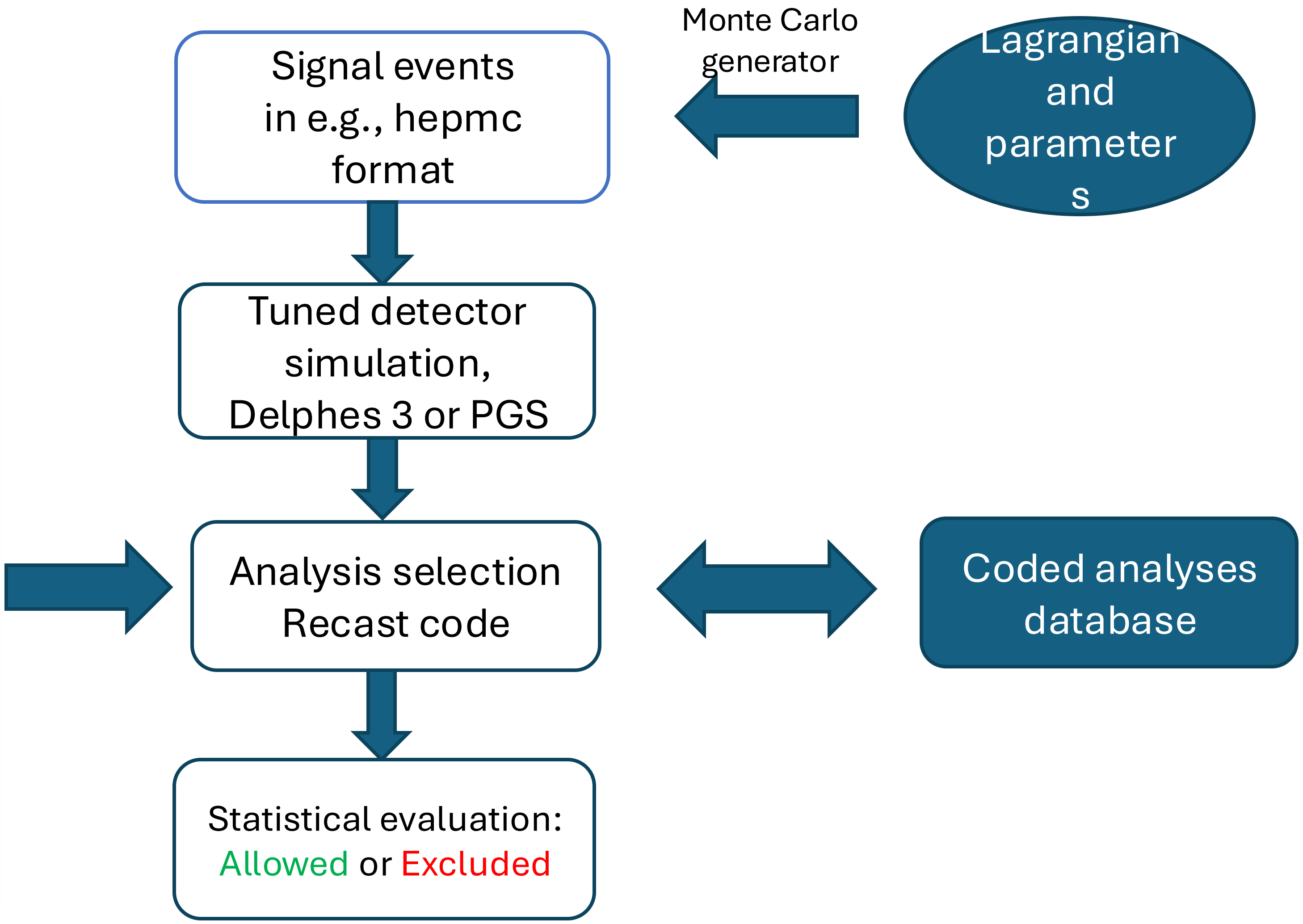
The CMS Collaboration*

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



LHC Reinterpretation Working Group

The purpose of the REI WG is to discuss topics related to the BSM (re)interpretation of LHC data, including the development of the necessary public recasting tools and related infrastructure, and to provide a platform for a continued interaction between theorists and with the experiments. The recent topics:

- the publication and reuse of statistical models
- the reinterpretation of analyses that employ machine learning
- global analyses and global fits
- preservation of data and methods for replication/reanalysis in future: for a once in a lifetime experiment we want to make sure all the necessary information is provided and understandable for people outside of a particular analysis

(Re)interpretation of the LHC results for new physics

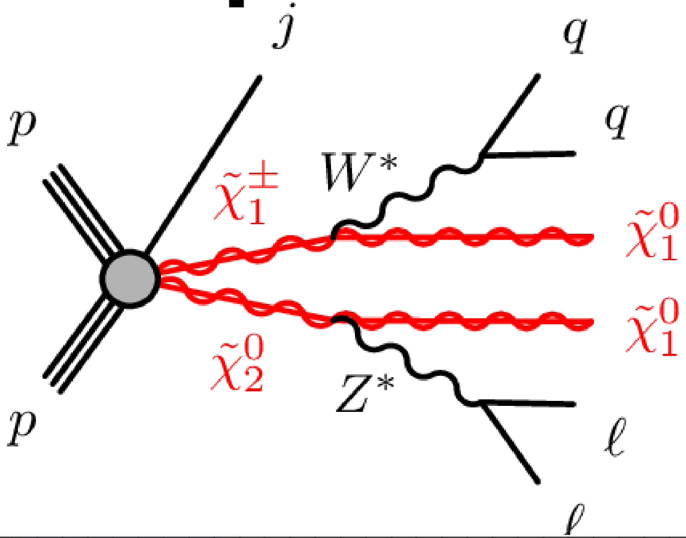
Feb 25 – 28, 2025
CERN
Europe/Paris timezone

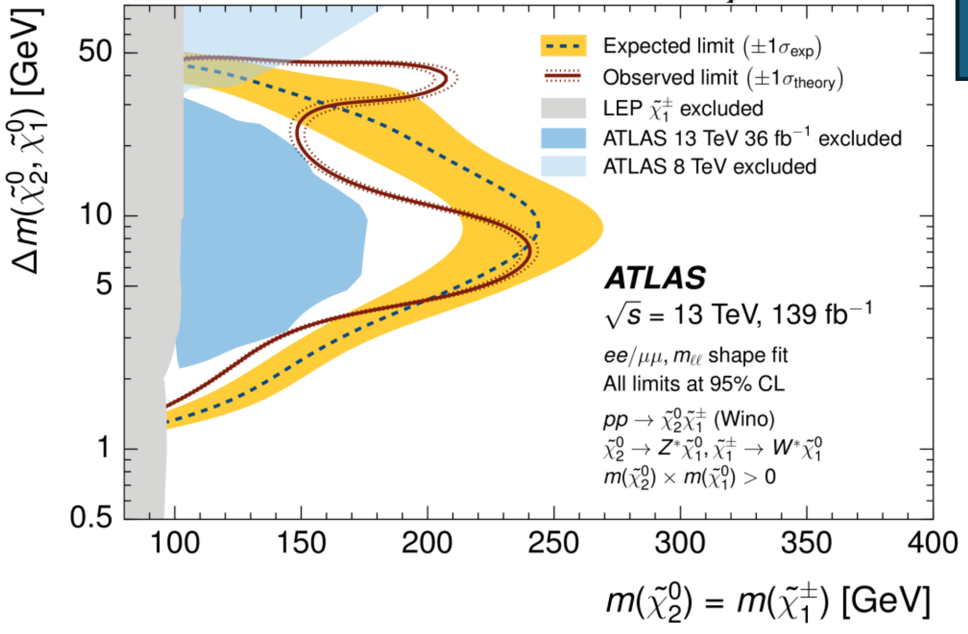
Overview
Timetable

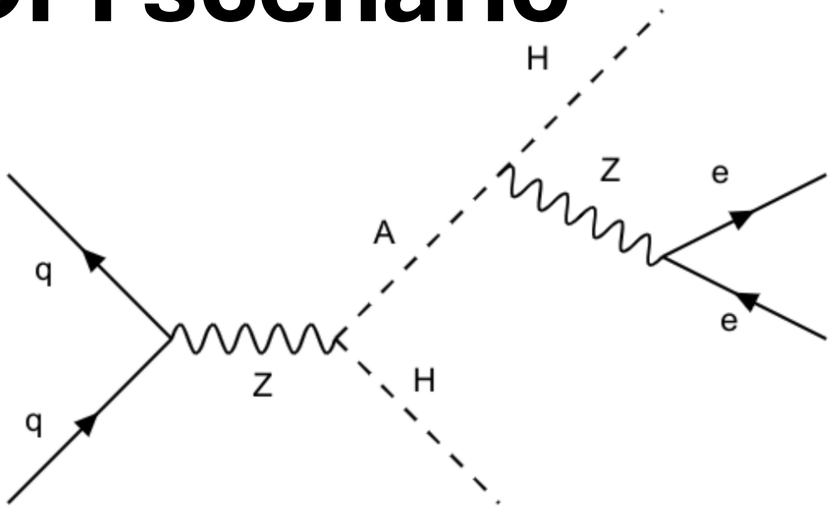
Participant List
130 participants

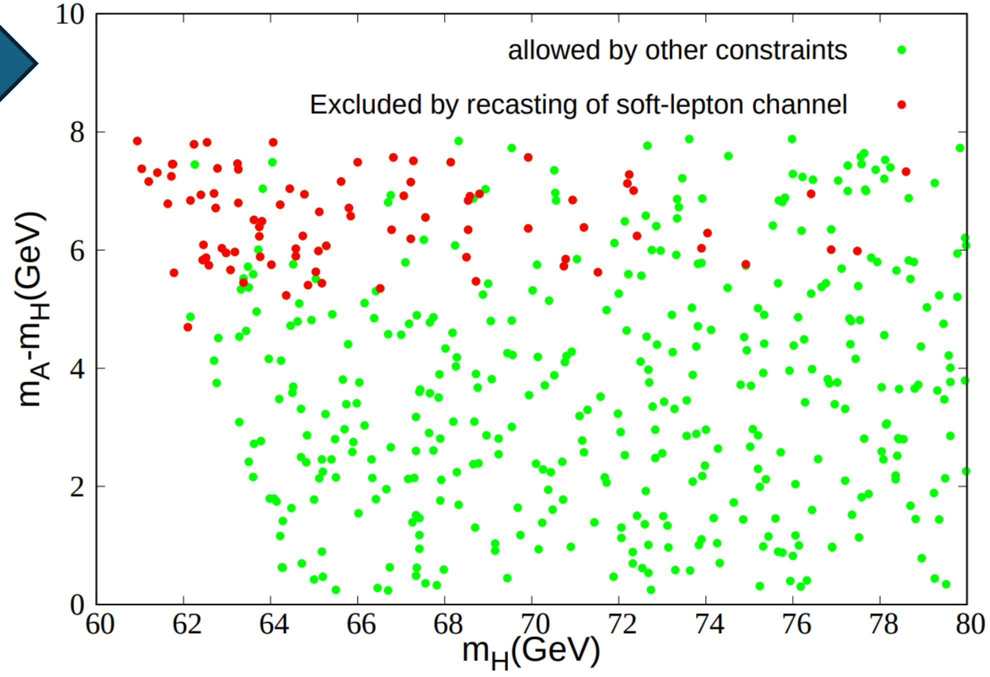
https://indico.cern.ch/event/1466101/

Example: SUSY search in IDM scenario









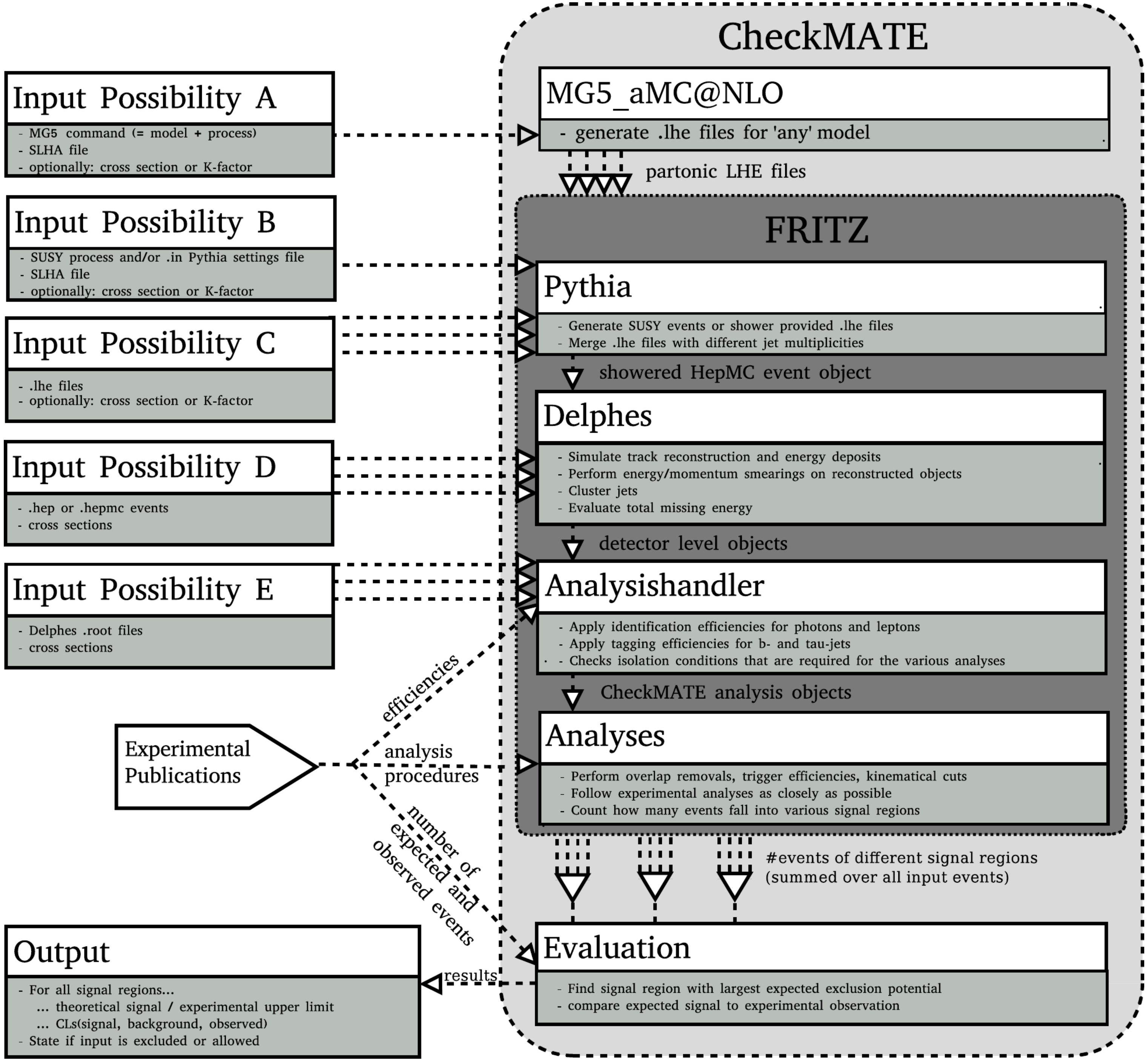
SUSY-2018-16

J. Lahiri, T. Robens, KR, to appear

Contents

CHECKMATE

- 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
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
#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-factor
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

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

DELPHES
fast simulation

CheckMATE improvements

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

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	14	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
atlas_2006_05880	28	Search for top squarks in events whith a Higgs or a Z boson	139
atlas_2111_08372	23	dark matter and invisible Higgs with Z boson	139
atlas_2202_07953	17	invisible Higgs decays in VBF	139
atlas_2209_13935	59	search for charginos and sleptons in 2-lepton final states	139
atlas_2102_10874	26	monojet	139
atlas_2411_02040	5	triple Higgs search	126

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 much shorter compared to ATLAS...

- From start CheckMATE was based on collaboration with ATLAS so the ties are still stronger
- ATLAS is by default releasing reinterpretation material for all SUSY searches: cutflows, simplified analysis code, efficiencies etc., what makes recasting much easier
- Many searches very similar (on the other hand combinations are tempting...)

Contents

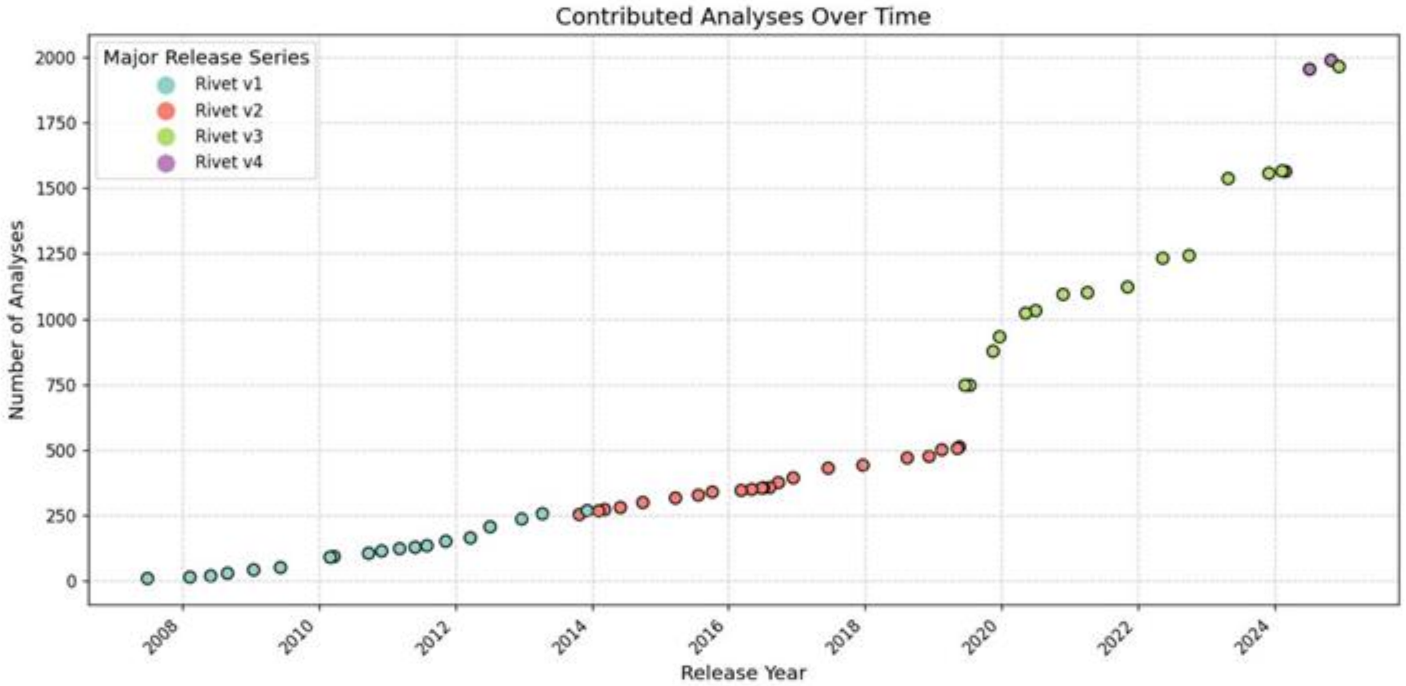
What is Rivet (1)?

→Paper, →Webpage

- **R**obust **I**ndependent **V**alidation of **E**xperiment & **T**heory
- A tool to preserve the **logic** of particle physics data analyses and encourage expt-pheno collaboration
- Validation of MC tools
- Put simply, Rivet replicates the experiments' event analysis on "truth" MC.
  - Simple, intuitive "event loop" to apply selections.
  - Event graphs (from different tools) are complex! Put all tools in one place.
  - Normally starts from **hepmc**
    - For certain analyses, can run from LHE.
    - Within ATLAS, can be run on EVNT
    - Easy to run "on-the-fly" from several generators (Pythia, Sherpa, ++)
  - Avoid cheating! Use fiducial final state where possible.

What is Rivet (2)?

- **Vast library of measurements** of final state particles, and derived variables
  - Mostly collider physics (not just LHC!), some cosmic-ray.
  - Originally designed for MC generator val/tuning
  - More than 2000 total analyses!
    (lots of examples to help get you started!)
- C++ core with Python executables
- The **"LHC standard" MC analysis toolkit**
  - Central to ecosystem of analysis reinterpretation tools, linking experiment to theory



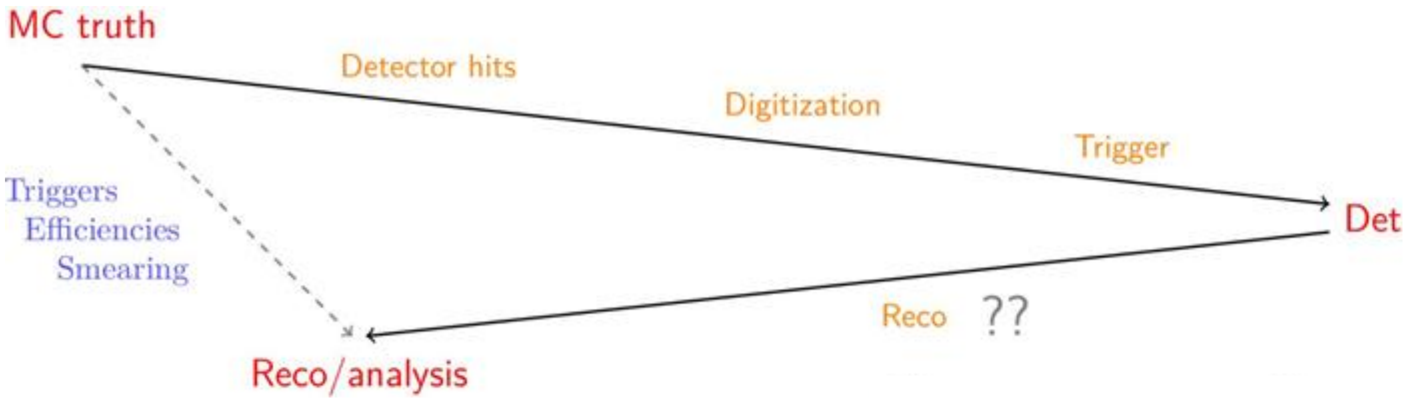
→YODA

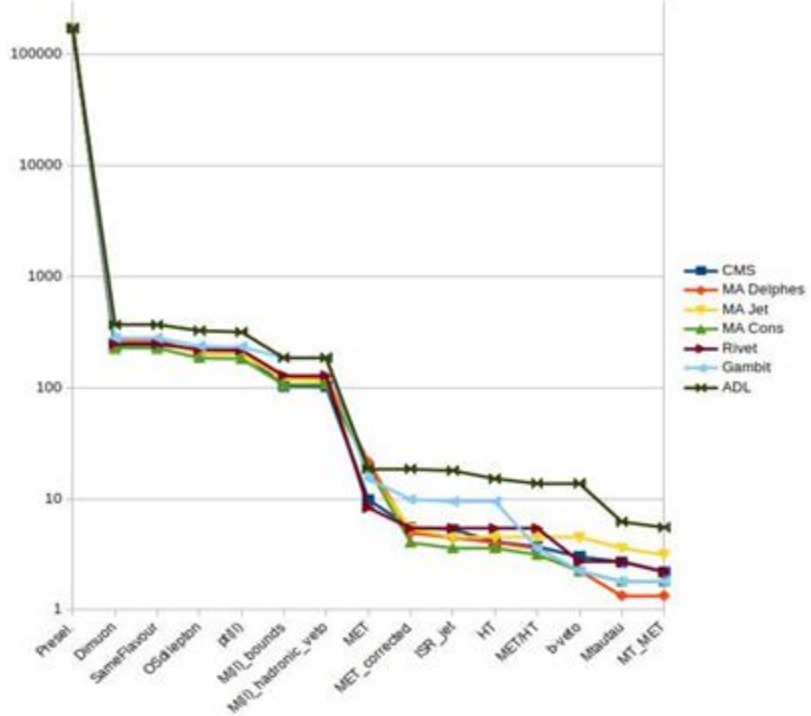
→Contur

→Professor

Rivet: not just for unfolded measurements!

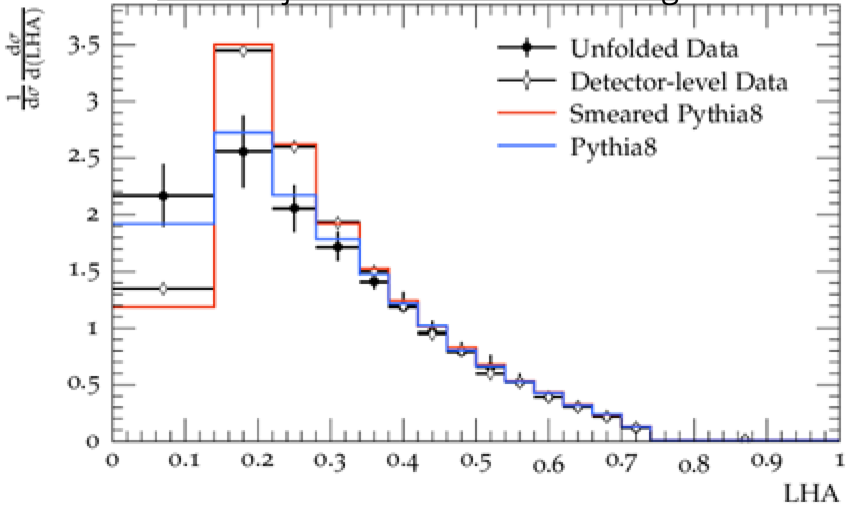
- → **detector smearing available (and performs well!)**





→ Many easy-to-use defaults for ATLAS/CMS, fully customisable if required.

→ "Tuned" jet-substructure smearing



- Easy-to-use interface to ONNX for NNs and BDTs*
  → E.g. ATLAS_2022_I2182381(SUSY multi-b jets with NN)

*including MVAUtils BDTs and lwtnn NNs via petrifyML!

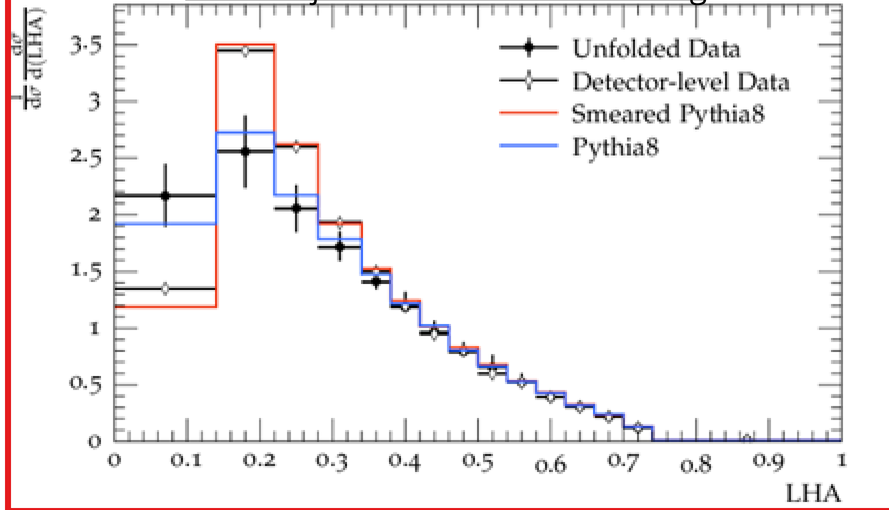
Rivet: not just for unfolded measurements!

- → **Example: jet substructure**
  - ATLAS published unfolded *and* detector-level substructure measurements in one paper (1903.02942)
  - Great testing ground for RIVET smearing functions!

- Process:
  - Implement selections (with/without smearing)
  - Implement substructure variables (LHA, D2, ECF,++)
  - Run on our own MC to get results (very good!)

- If we want to use this for BSM predictions:
  - Run our BSM MC sample through the analysis
  - Get an output histogram
  - Compare to measured data and expected SM background to get
    an exclusion!
  - (n.b. the unfolded version of this analysis is used in CONTUR)

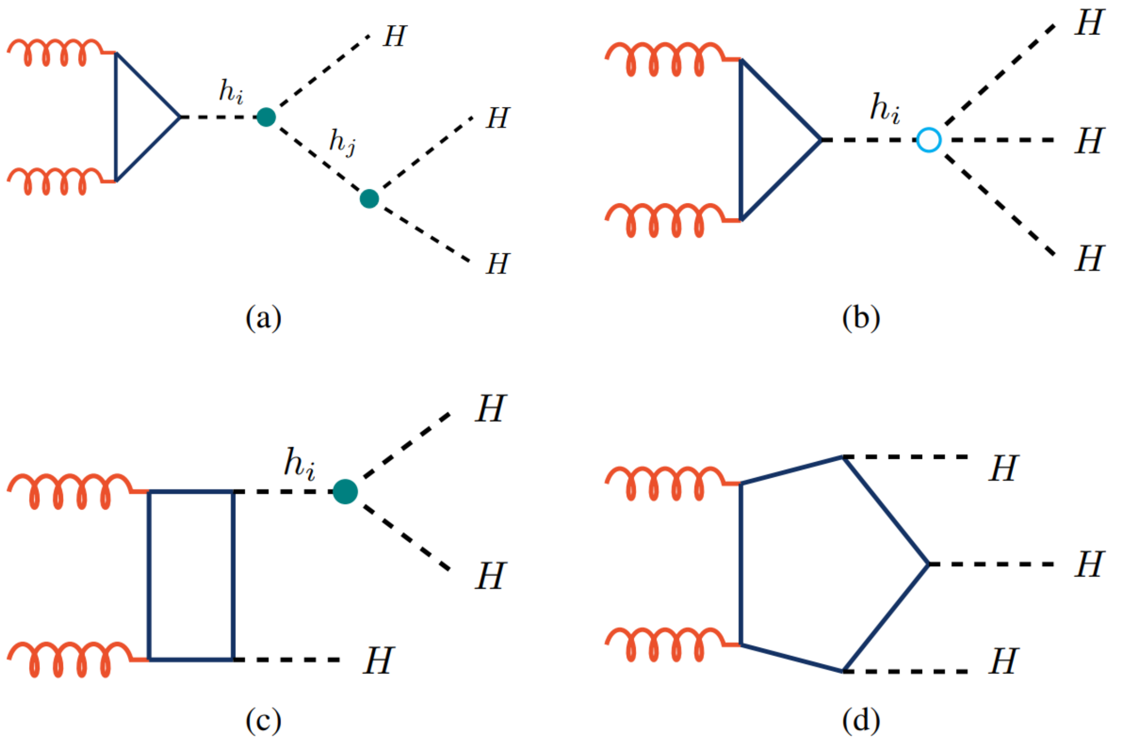
→ "Tuned" jet-substructure smearing



Contents

ATLAS HHH->6b

Key features:
NN based in 3 scenarios:
SM – nonresonant
TRSM – resonant and nonresonant
simplified – heavy resonant



ATLAS provided:

- the statistical model in HS3 format;
- the NN in ONNX format;
- SimpleAnalysis code

see more: Osama Karkout talk

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGP-2024-32/

ATLAS HHH->6b: recasting challenges

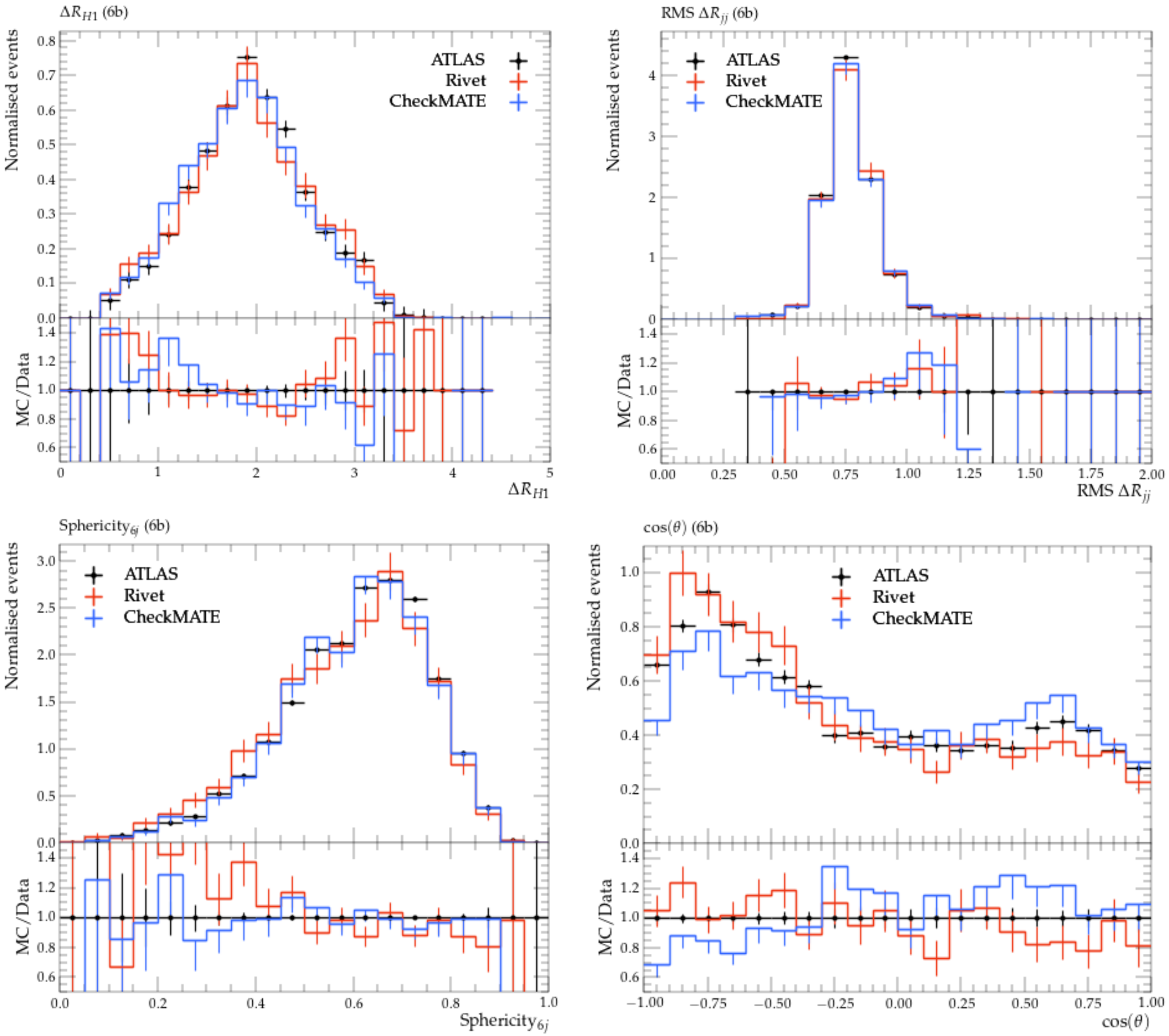
- Complex input variables for NN – but poorly described

$\cos\theta$	In the (m_{H1}, m_{H2}, m_{H3}) coordinate system, θ is the angle between the vector from the origin to the event's reconstructed mass of the Higgs boson candidates, and the vector from the origin to (120, 115, 110) GeV.		✓	
Aplanarity$_{6j}$	The fraction of p_T from the 6 jets selected lying outside the plane formed by the 2 highest p_T jets .	✓	✓	✓
Sphericity$_{6j}$	Isotropy of the momenta of the 6 jets selected to reconstruct the 3 Higgs boson candidates .		✓	
Transverse Sphericity$_{6j}$	Isotropy of the p_T of the 6 jets used for Higgs reconstruction, within the $x - y$ plane .	✓		
Sphericity	Isotropy of the momenta of all jets in the event .			✓

- First use of HS3 format in recasting:

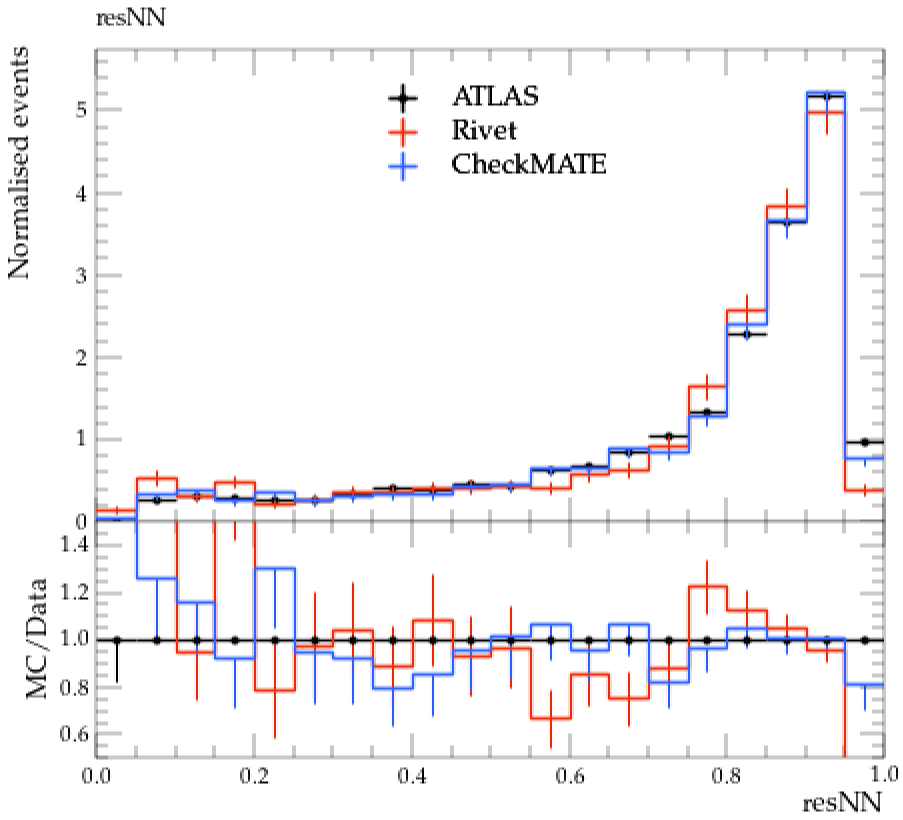
  The **HS3 (HEP Statistics Serialization Standard)** is an emerging, language-agnostic, and software-independent format designed to standardize statistical models, datasets, and analysis components for High Energy Physics (HEP). Its format is **JSON-based**, making it human-readable while also being machine-readable for direct use by statistical software across different frameworks. The goal of HS3 is to improve **interoperability and data preservation** by providing a common, machine-readable representation for sharing and preserving statistical analysis components like models, datasets, and likelihoods

Validation: getting input variables right

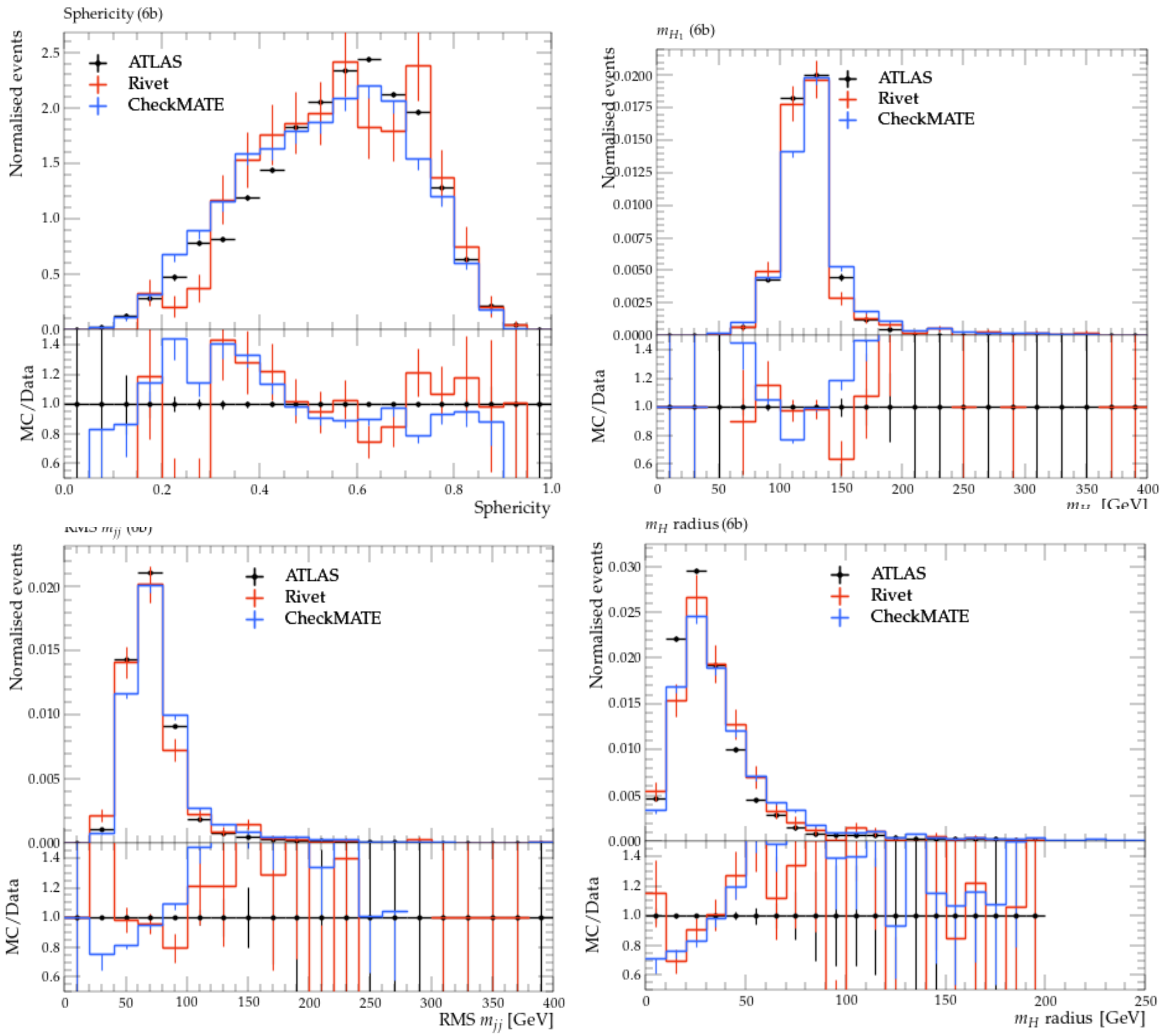


Resonant model:

(mS, mX) = (275, 400)

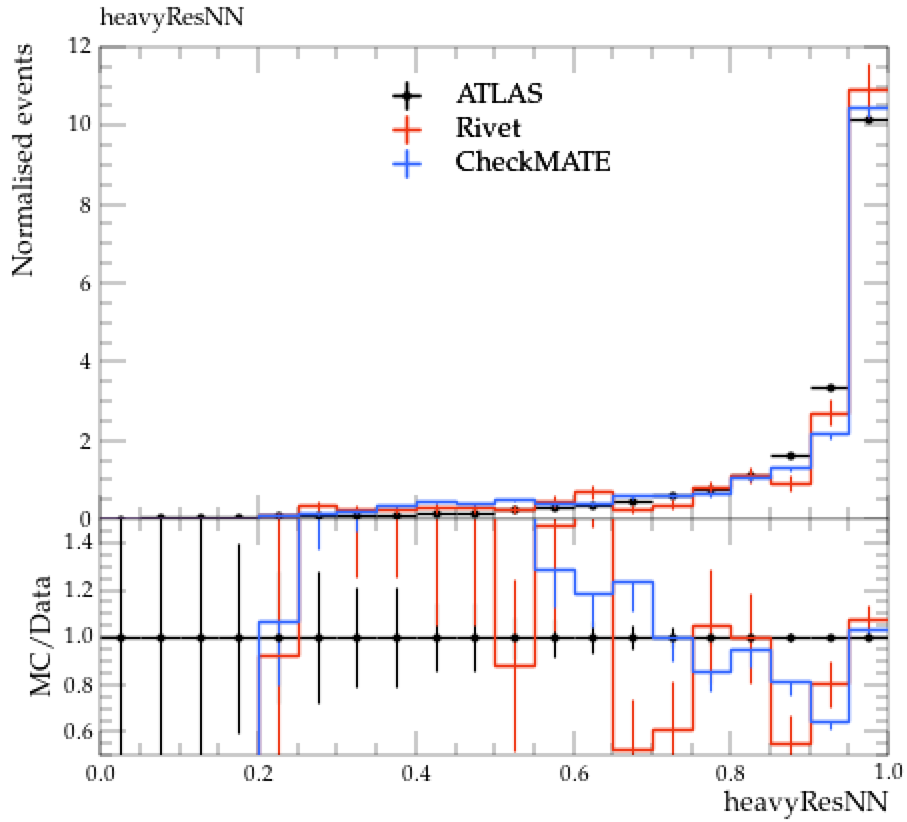


Validation: getting input variables right

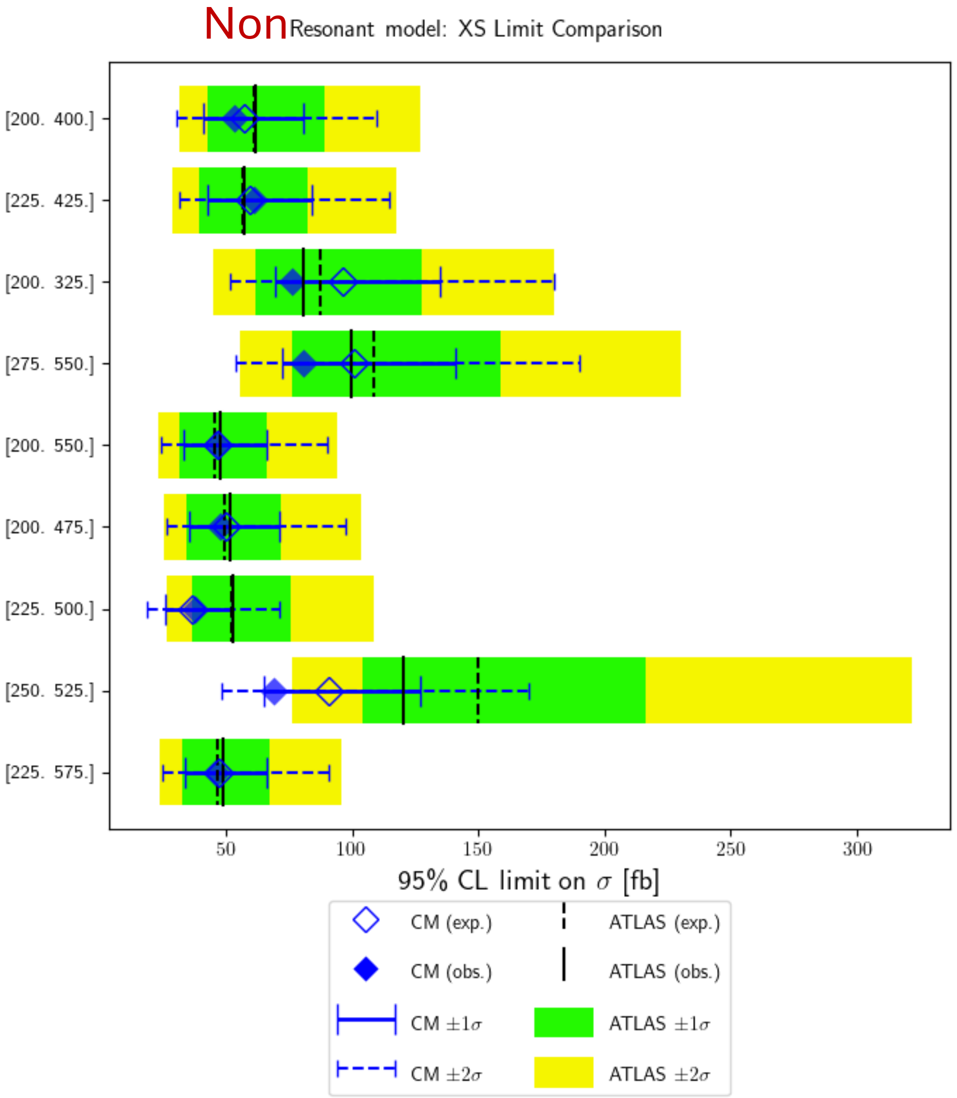


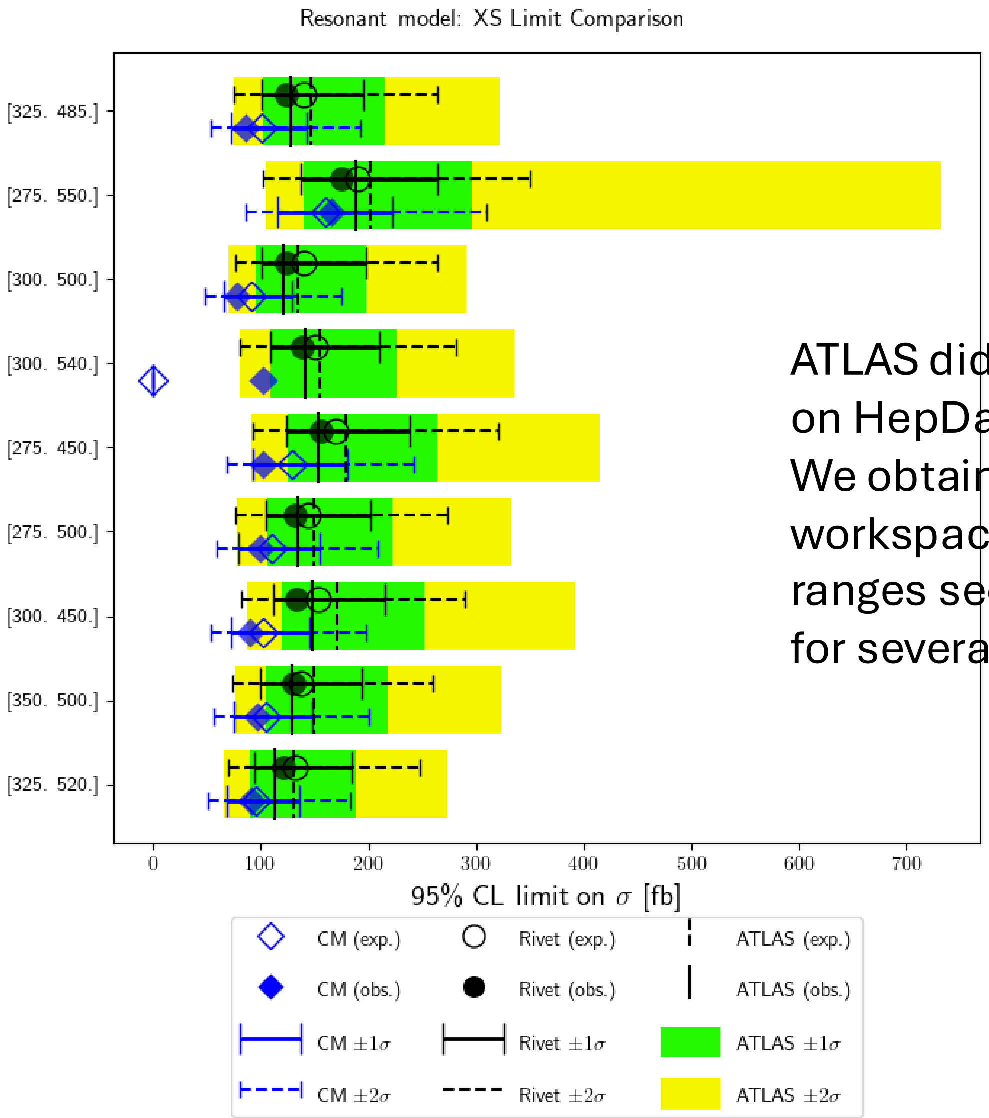
Heavy resonant model:

(mS, mX) = (700, 400)



Validation: limits on cross section





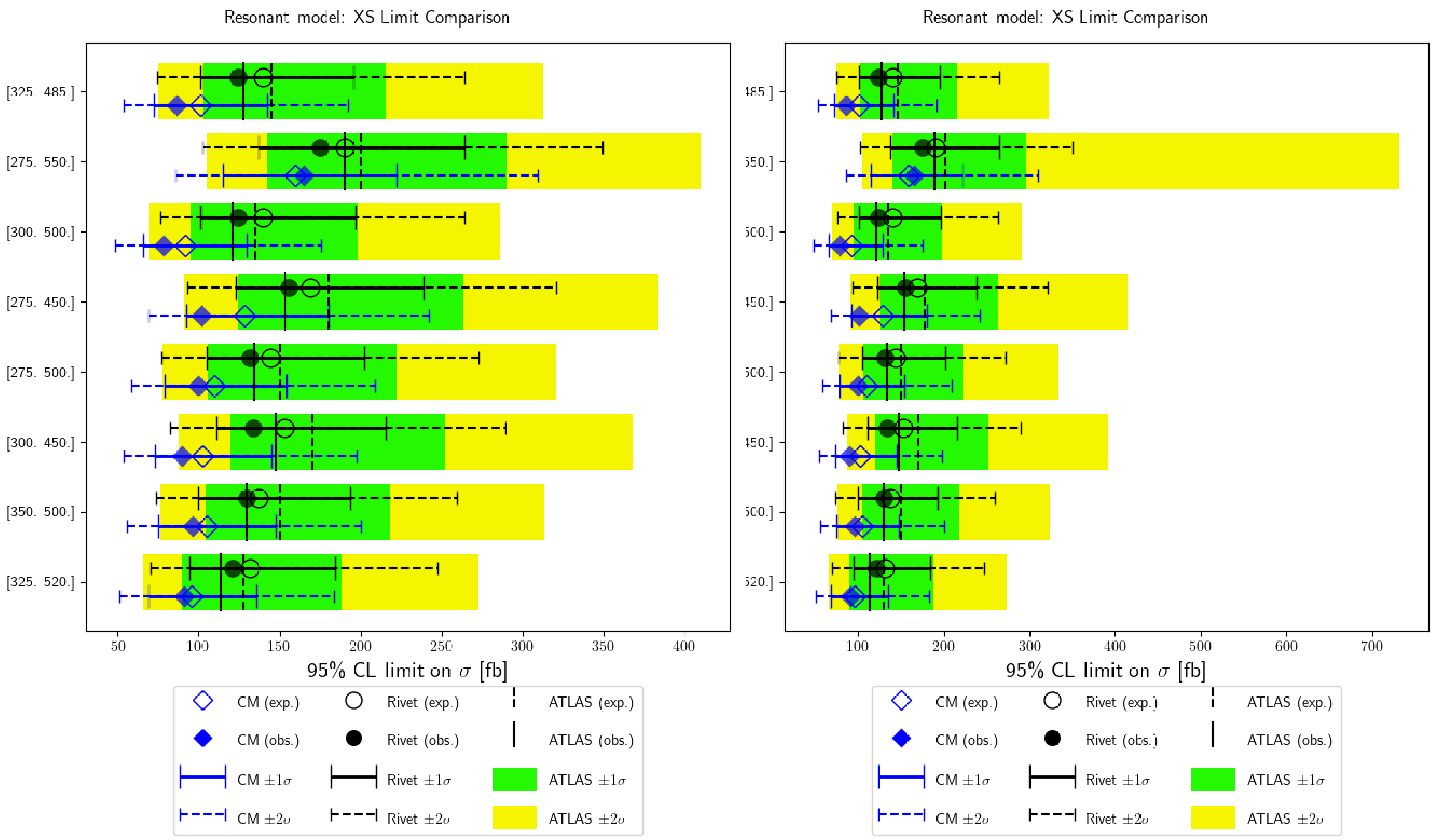
ATLAS did not publish errors on HepData
We obtain errors from root workspaces – 2sigma ranges seem somewhat off for several points

Summary and outlook

- Implementation almost ready in CheckMATE and Rivet
- Good agreement in NN input variables
- Limits reproduced within 1sigma uncertainty (mostly)
- Ready for physics studies: TRSM, HEFT, other ideas?
- Recasting CMS 3H(6b) is very interesting, possible?

		expected			observed	
m_S	m_X	ATLAS	CM	Rivet	ATLAS	CM
225	575	$46.5^{+21,+50}_{-14,-22}$	$47.0^{+20,+44}_{-13,-22}$		49.0	46.0
250	525	$150.0^{+66,+172}_{-46,-74}$	$90.5^{+36,+80}_{-25,-42}$		120.5	69.0
225	500	$52.0^{+24,+56}_{-16,-26}$	$36.4^{+16,+35}_{-11,-17}$		53.0	37.5
200	475	$49.5^{+22,+54}_{-15,-24}$	$50.1^{+21,+47}_{-14,-24}$		51.5	48.0
200	550	$45.5^{+20,+48}_{-14,-22}$	$46.5^{+20,+44}_{-13,-22}$		48.0	46.5
275	550	$108.5^{+50,+121}_{-32,-53}$	$101.0^{+40,+89}_{-28,-47}$		99.5	80.5
200	325	$87.5^{+40,+92}_{-26,-42}$	$96.5^{+38,+84}_{-27,-45}$		81.0	76.5
225	350	$74.5^{+34,+81}_{-22,-36}$	$0.0^{+0,+0}_{-0,-0}$		71.5	0.0
225	425	$56.5^{+26,+61}_{-17,-27}$	$59.5^{+24,+55}_{-17,-28}$		57.5	61.0
250	425	$345.9^{+229,+\infty}_{-111,-172}$	$179.5^{+71,+208}_{-50,-84}$		311.5	186.0
250	375	$123.5^{+55,+132}_{-37,-60}$	$0.0^{+0,+0}_{-0,-0}$		125.0	0.0
275	400	$805.2^{+\infty,+\infty}_{-305,-452}$	$333.5^{+206,+\infty}_{-98,-158}$		798.6	273.9
250	475	$210.0^{+109,+619}_{-62,-102}$	$137.0^{+54,+119}_{-38,-64}$		165.5	73.0
200	400	$61.0^{+28,+66}_{-18,-30}$	$57.5^{+24,+53}_{-16,-27}$		62.0	53.5

		expected			observed	
m_S	m_X	ATLAS	CM	Rivet	ATLAS	CM
350	475	$165.5^{+78,+209}_{-51,-81}$	$110.5^{+44,+100}_{-32,-52}$		145.5	96.0
325	520	$130.0^{+58,+144}_{-40,-64}$	$96.0^{+40,+88}_{-27,-45}$		113.5	91.0
350	500	$150.0^{+68,+174}_{-46,-74}$	$105.0^{+42,+95}_{-30,-49}$		129.5	96.5
300	450	$171.0^{+81,+221}_{-52,-84}$	$102.5^{+43,+95}_{-29,-48}$		147.5	89.5
275	500	$150.0^{+72,+182}_{-44,-72}$	$110.0^{+44,+99}_{-31,-52}$		134.5	100.0
275	450	$178.5^{+85,+236}_{-54,-88}$	$128.5^{+52,+114}_{-36,-60}$		153.5	101.5
300	540	$155.0^{+72,+181}_{-46,-75}$	$0.0^{+0,+0}_{-0,-0}$		141.5	101.5
300	500	$135.0^{+63,+156}_{-40,-66}$	$92.0^{+37,+84}_{-26,-43}$		121.0	78.5
275	550	$202.0^{+95,+530}_{-62,-97}$	$159.5^{+63,+150}_{-45,-74}$		189.0	165.0
300	425	$200.0^{+102,+546}_{-60,-98}$	$145.5^{+58,+134}_{-41,-68}$		175.5	123.0
325	485	$146.5^{+69,+176}_{-44,-72}$	$101.0^{+41,+91}_{-29,-47}$		127.5	86.5
280	420	$210.0^{+109,+614}_{-63,-102}$	$140.0^{+56,+126}_{-40,-66}$		181.0	121.5
325	450	$167.5^{+79,+210}_{-50,-82}$	$97.0^{+41,+92}_{-28,-46}$		147.5	92.5



Resonant model: XS Limit Comparison
Resonant model: XS Limit Comparison
[325. 485.]
[275. 550.]
[300. 500.]
[275. 450.]
[275. 500.]
[300. 450.]
[350. 500.]
[325. 520.]
50
100
150
200
250
300
350
400
95% CL limit on σ [fb]
100
200
300
400
500
600
700
95% CL limit on σ [fb]
CM (exp.)
Rivet (exp.)
ATLAS (exp.)
CM (obs.)
Rivet (obs.)
ATLAS (obs.)
CM $\pm1\sigma$
Rivet $\pm1\sigma$
ATLAS $\pm1\sigma$
CM $\pm2\sigma$
Rivet $\pm2\sigma$
ATLAS $\pm2\sigma$

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