Reinterpretation of LHC searches for new physics

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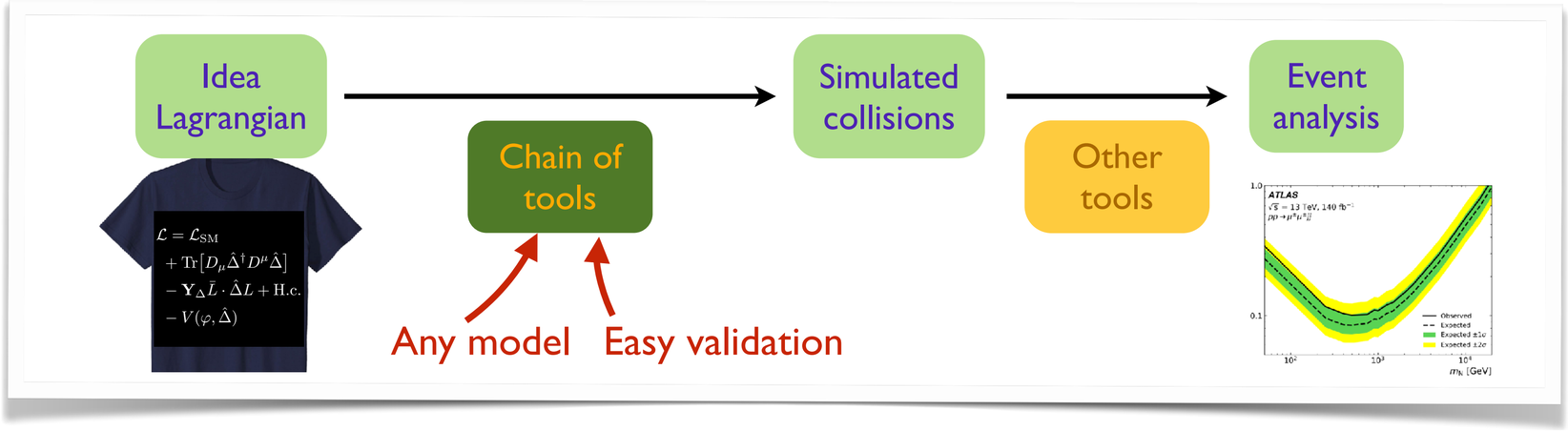
Chacal 2024 – 22 January 2024

From Lagrangians to events… and back!

Monte Carlo simulations standard today

- 20 − 25 years of developments ➙ LO simulations ≡ bread and butter
- Simulations at NLO (at least QCD) easily achieved



Let's reverse the chain…

LHC recasting - some context

First steps in the SUSY context, from SUGRA to the 19-dim pMSSM

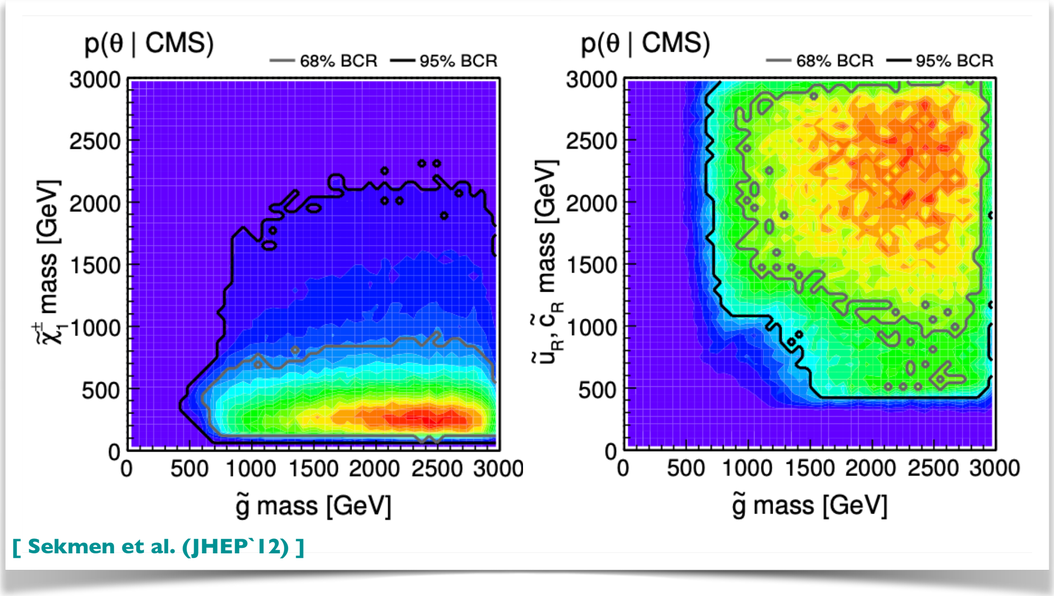
- ‘Interpreting LHC SUSY searches in the phenomenological MSSM’
- ‘Supersymmetry without prejudice’

[Conley, Gainer, Hewett, Le, Rizzo (EPJC`10)]

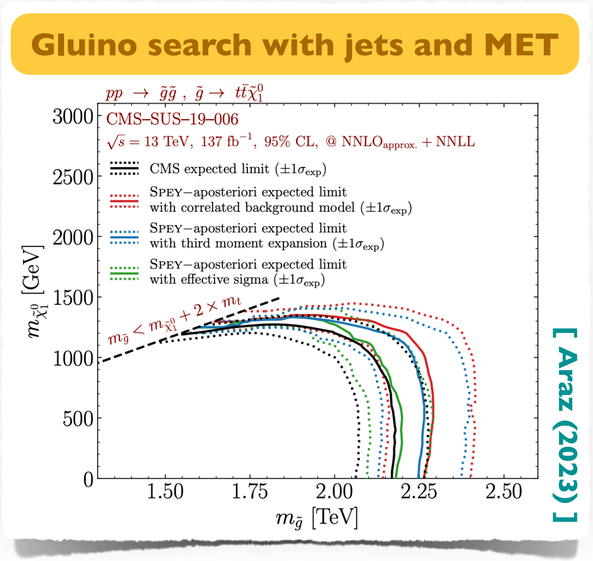
[Sekmen et al. (JHEP`12)]

Exploit the full potential of the LHC (for new physics)

- Designing new analyses ➙ probing new ideas
- Recasting LHC analyses ➙ studying new models



[Sekmen et al. (JHEP`12)]



Data preservation in high-energy physics mandatory

- Going beyond raw data ➙ analyses

Related tools need to be supported by the entire community

- Both theorists and experimentalists

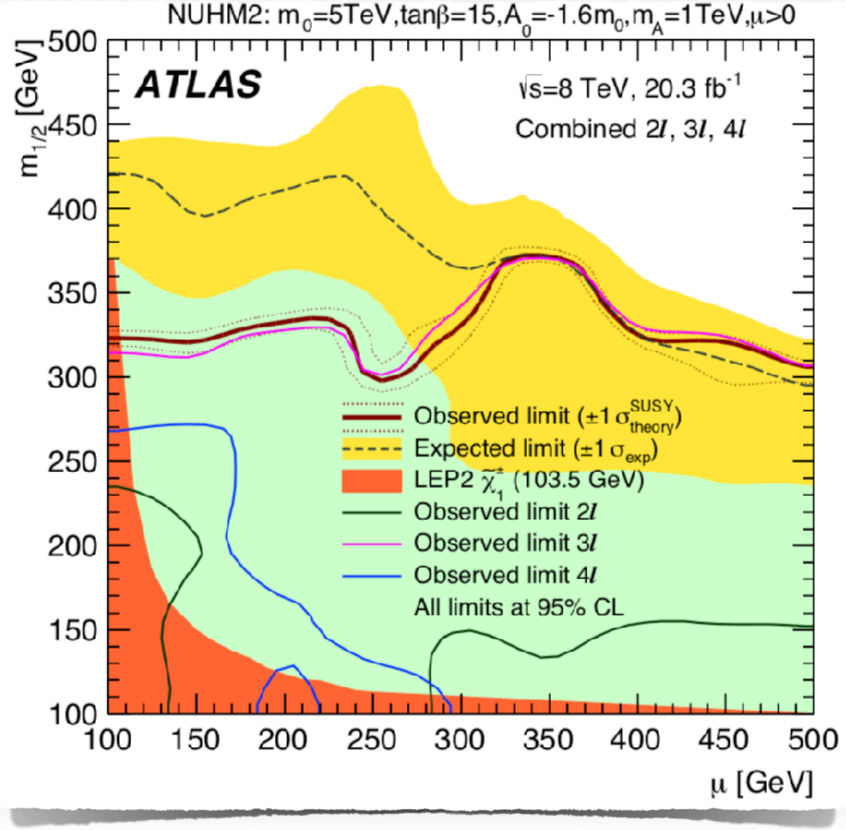
[Les Houches Recommendations (EPJC’12)]

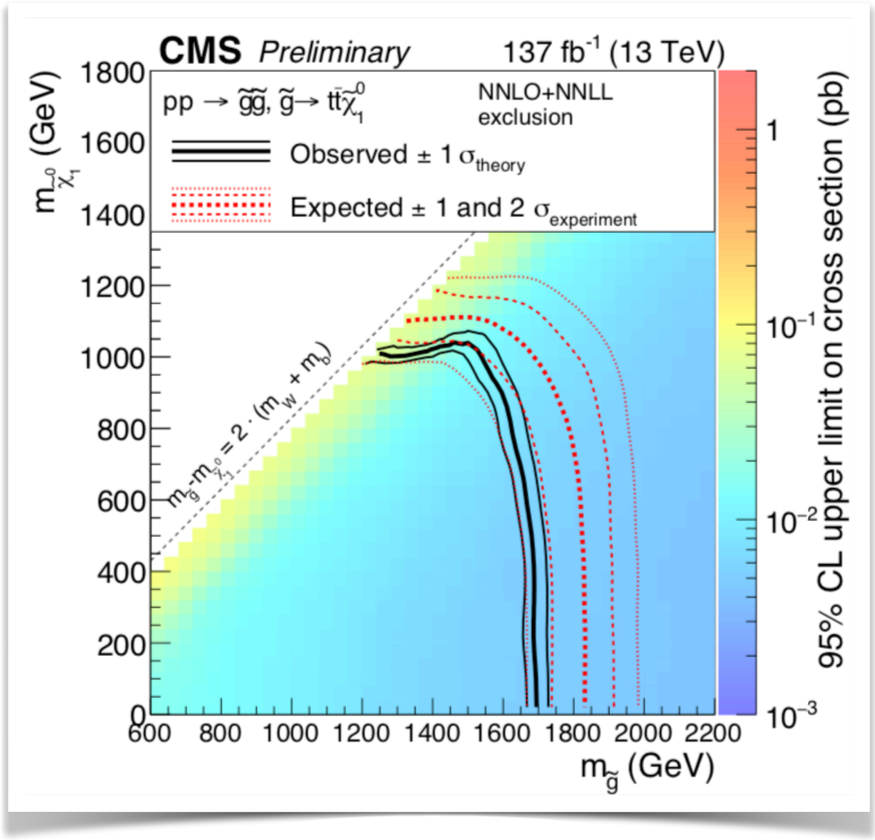
[ReInterpretation Forum (SciPost`20)]

New physics results at the LHC

LHC ≡ discovery machine

- Many ATLAS and CMS searches for new physics
- Interpretation within popular frameworks and simplified models
  ➙ for instance, supersymmetry-inspired





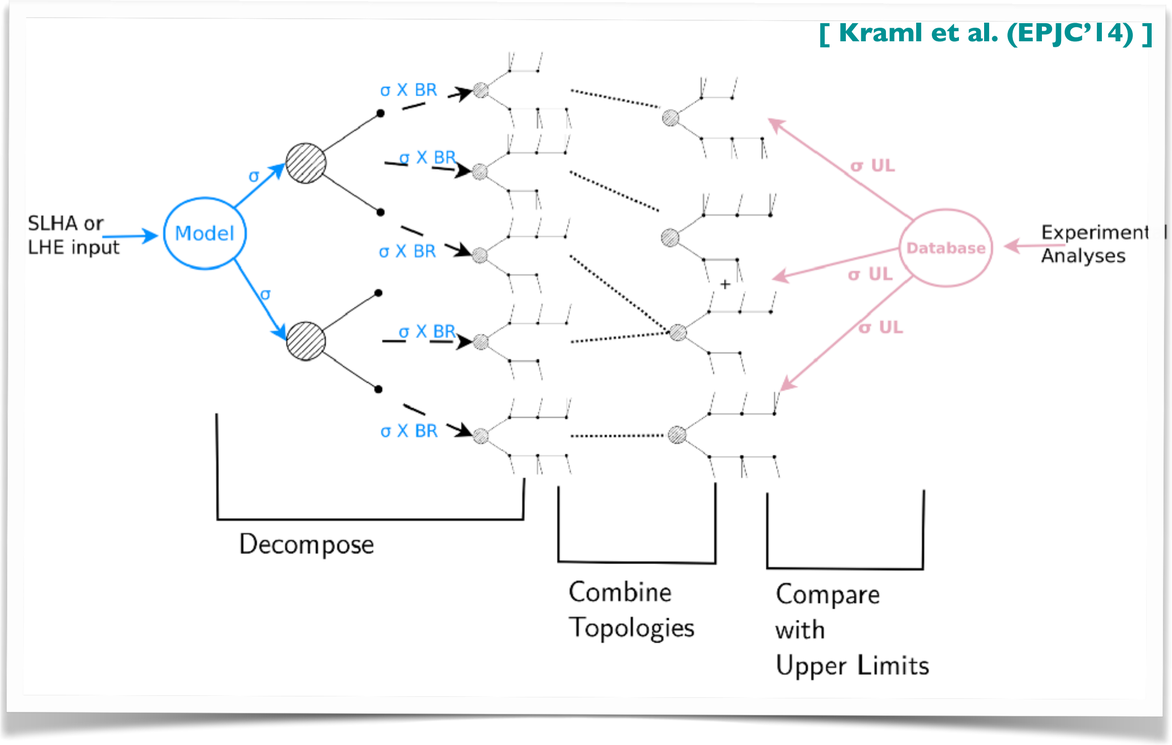
Need for interpretations in all kinds of models

The Simplified Model Spectra (SMS) approach

Simplified Model Spectra (SMS)

The SMS-based reinterpretation framework

- Decomposition of all signatures of a theory into SMS signatures
- Fiducial cross sections on the basis of public efficiency maps
- Comparisons to published upper bounds



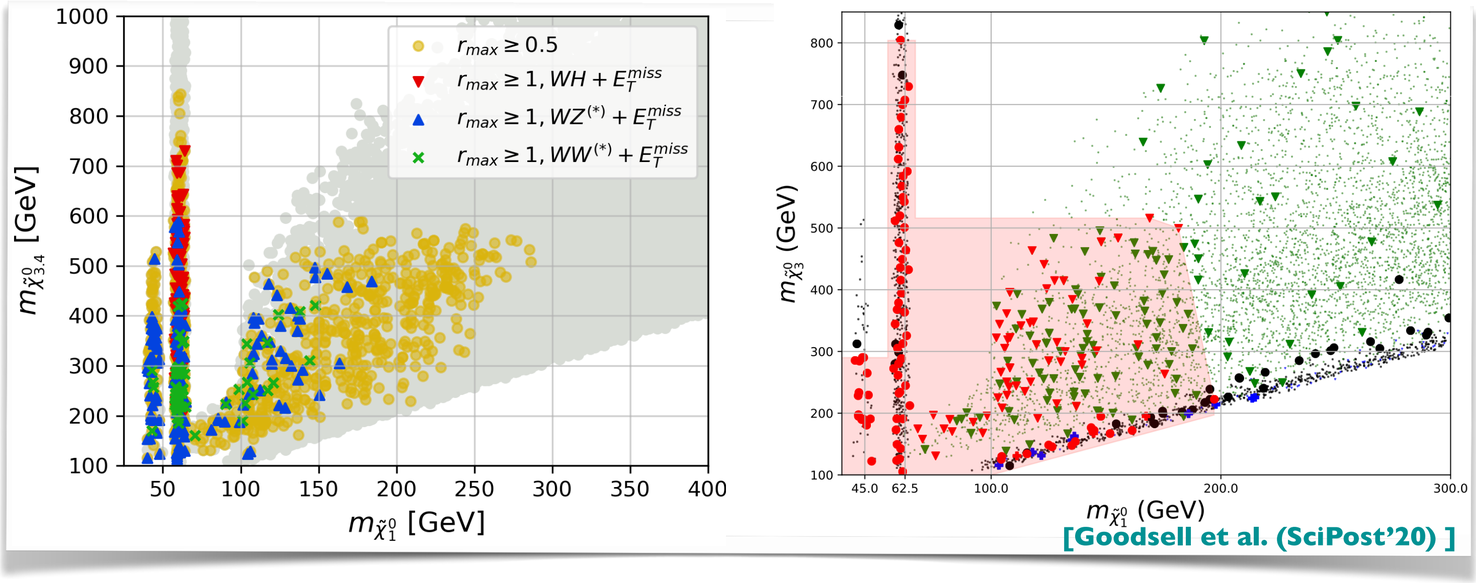
Main features

- Often conservative
  - ⋆ Different kinematics
  - ⋆ Asymmetric decays
- Rather fast
- Usually fair estimates
  - ➙ Possibly too conservative (complex models)

Existing tools

- A generic program: SmodelS
  - ⋆ *O*(100) available analyses
  - ⋆ Prompt and LLP decays [Kraml et al. (EPJC'14)]
  - ⋆ Available from GitHub [Alguero et al. (JHEP'22)]
- Dark photons: DarkCast
  - ⋆ Available from GitLab [Ilten et al. (JHEP'18)]

SMS reinterpretation tools - examples



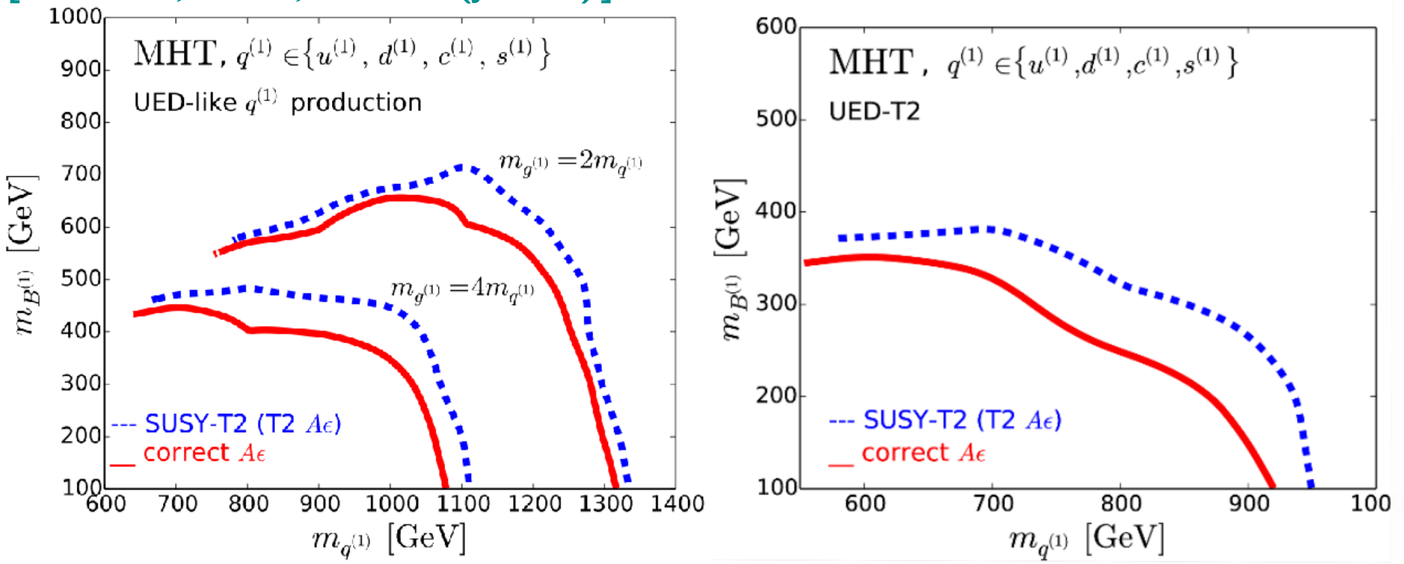
DGMSSM at the LHC

- Exploring SUSY with Dirac gauginos
- Models not considered by ATLAS/CMS
- Left: points excluded by SModelS (with $r \geq 1$)
- Right: comparison with full recasts (from MadAnalysis 5)
  - ➞ SMS approach fair enough
  - ➞ Far from full recasts
- SMS approach faster

SUSY *vs* extra dimensions

- SUSY searches to constrain KK excitations
  - ➞ Blue: SMS approach
  - ➞ Red: full recast
- Efficiencies depend on particle spins
  - ➞ SMS approach fair enough
  - ➞ however: too aggressive as well

[Edelhäuser, Krämer, Sonneveld (JHEP'15)]



The fastsim-based approach

Beyond the SMS approach

SMS often not sufficient to study all interesting new physics realisations

- More accurate detector simulations
  - ➙ mimicking ATLAS / CMS
- New frameworks for LHC re-interpretations
  - ➙ Easy implementations of searches
  - ➙ Test of signals fully automated

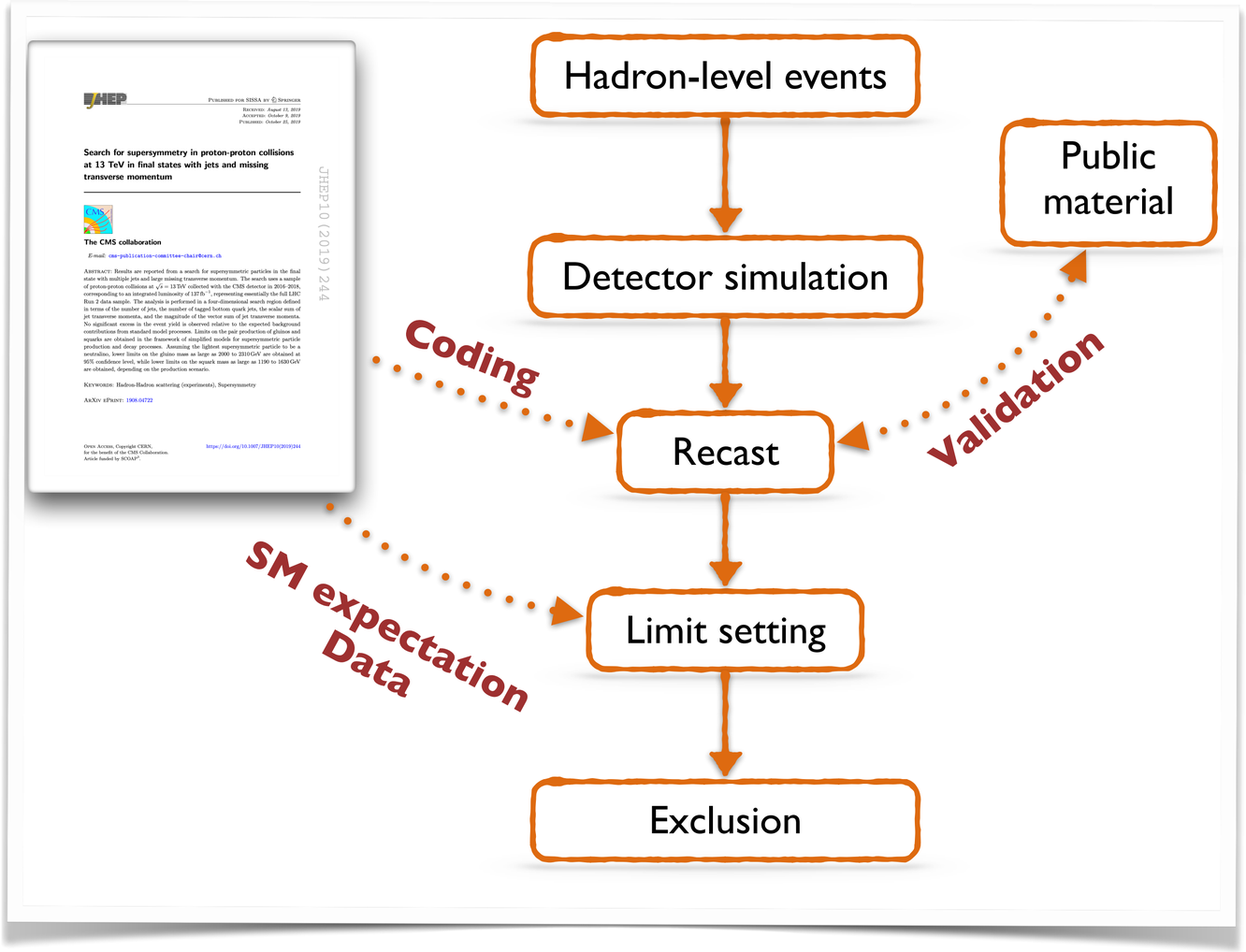
Detector ≡ key difference

- Close to a real detector (slower)
  - ➙ from particles to tracks/hits
  - ➙ resolutions, efficiencies, *etc.*
  - ➙ *à la Delphes 3* **[de Favereau et al. (JHEP`14)]**
- Based on transfer functions (faster)
  - ➙ From MC particles
  - ➙ Resolutions, efficiencies, …
  - ➙ *à la* RIVET, MADANALYSIS 5 − SFS

[Araz, BF & Polykratis (EPJC`21)]
[Araz, BF, Goodsell & Utsch (EPJC`22)]
[Bierlich et al. (SciPost`20)]

- Unfolding
  - ➙ No need for a detector

See Jon's lecture



Public programs based on DELPHES 3

Detector based on (customised) DELPHES 3

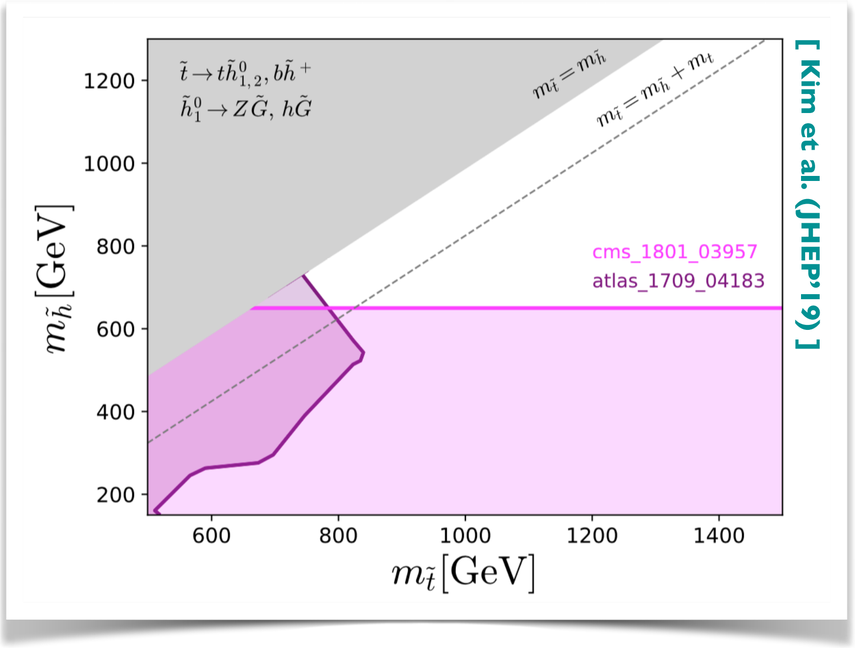
- CHECKMATE [*O(50)* analyses, from GITHUB]
- MADANALYSIS 5 [*O(50)* analyses, from GITHUB and the MA5 DATAVERSE]

[Derks et al. (CPC`17)]

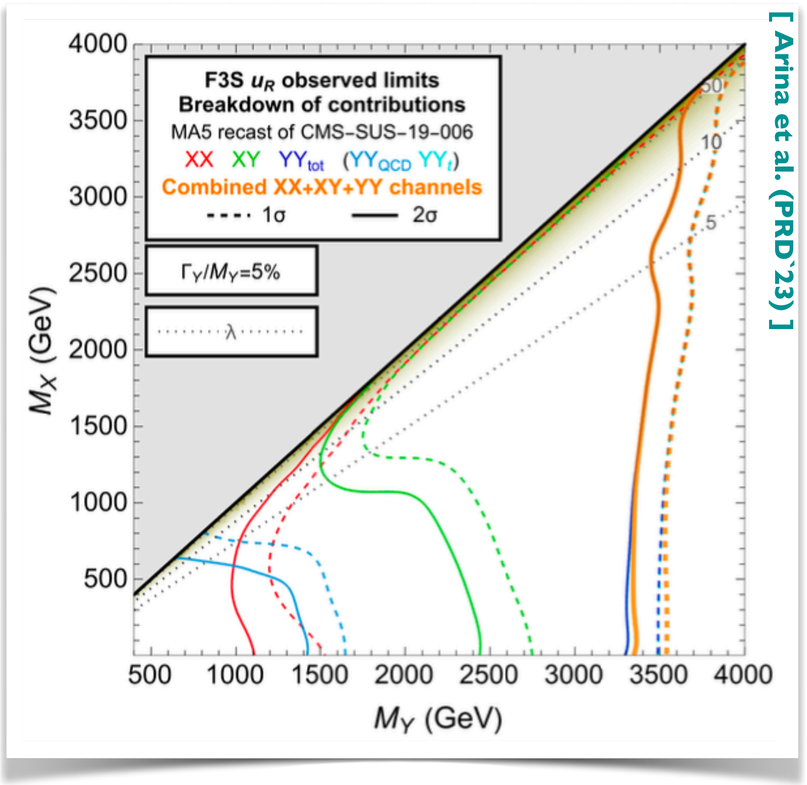
[Dumont, BF, Kraml et al. (EPJC`15); Conte & BF (IJMPA`19)]
[Araz, Conte & BF (in prep)]

Constraining *t*-channel dark matter with jets + MET (in MADANALYSIS 5)

- SM ⊕ coloured fermion (Y) ⊕ scalar DM (X) ⊕ coupling to u_R
- Signal modelling crucial: XX, YY and XY production @ NLO



[Kim et al. (JHEP'19)]



[Arina et al. (PRD`23)]

Constraining stops, higgsinos and gravitinos (in CHECKMATE 2)

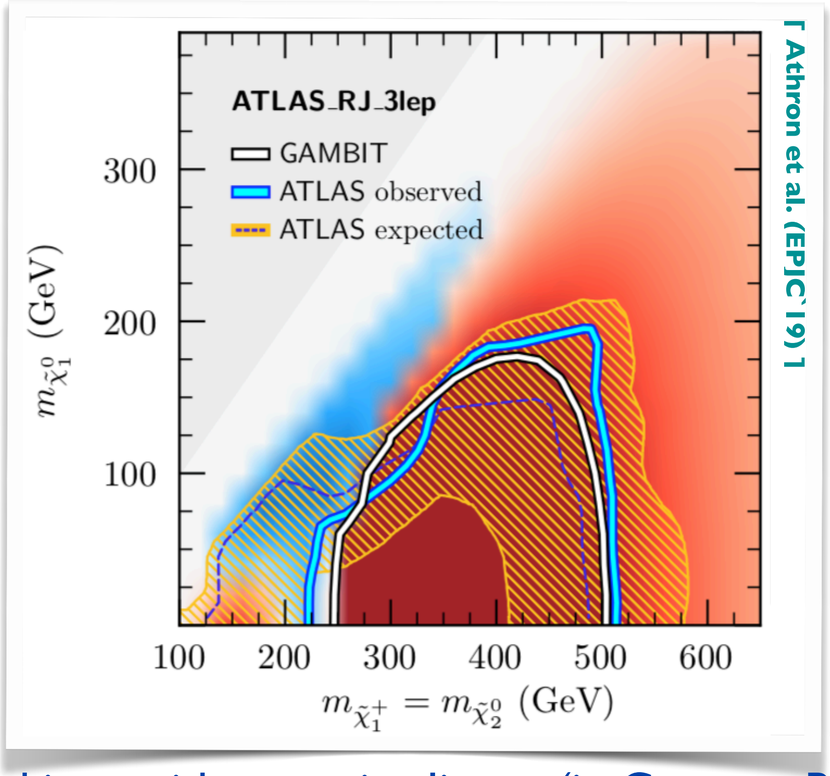
- Simplified model based on GMSB SUSY models
- Overlaying searches targeting stops (ATLAS) and GMSB ewkinos (CMS)

Public programs based on transfer functions

Detector based on transfer functions

- ColliderBit [*O(40)* analyses, from HepForge]
- MadAnalysis 5 - SFS [*O(10)* analyses, from GitHub and the MA5-DataVerse]
- Rivet [*O(30)* analyses, from HepForge]

[Balász et al. (EPJC`17)]
[Araz, BF & Polykratis (EPJC`21)]
[Araz, BF, Goodsell & Utsch (EPJC`22)]
[Buckley et al. (2010); Bierlich et al. (SciPost`20)]



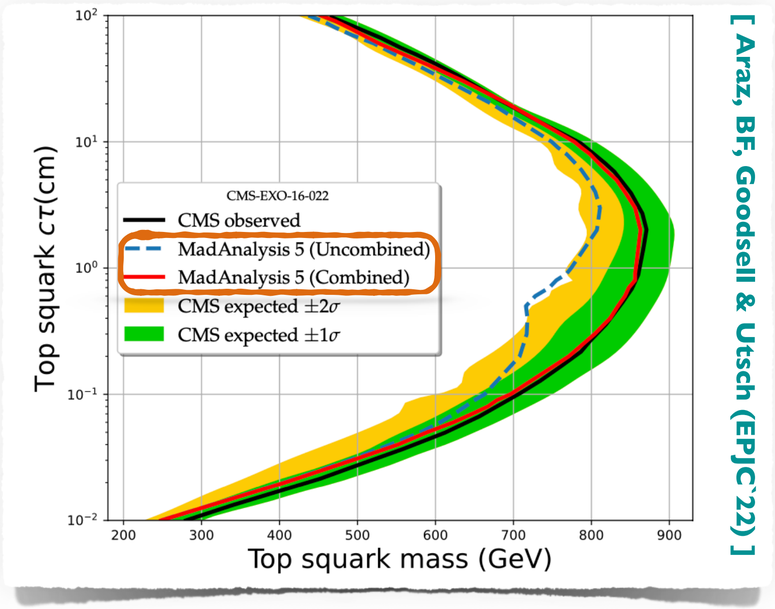
[Athron et al. (EPJC`19)]

Ewkinos with recursive Jigsaw (in ColliderBit)

- Validation ≡ closure test

Long-lived stops decaying to *bl* systems (in MadAnalysis 5)

- SR combination useful



[Araz, BF, Goodsell & Utsch (EPJC`22)]

The challenges

Implementing a new recast

Picking up an experimental publication

- Reading
- Understanding

✅ Relatively easy

Writing the analysis code in the tool internal language

Accurate information for proper validation

- Efficiencies (trigger, $e^{\pm}$, $\mu^{\pm}$, *b*-tagging, JES, *etc.*)
  - ➙ including p_T/η dependence
- Detailed cutflows for well-defined benchmarks
  - ➙ Region per region information
  - ➙ Exact definition of benchmarks (spectra)
  - ➙ Event generation information (cards, tunes)
- Digitised histograms (e.g. on HEPDATA)

⚠️ Essential
❌ Often difficult!

A 2012 TH-wishlist for high-quality recasts (1/2)

- Clear description of cuts and their sequence
- Efficiencies ($e^{\pm}$, $\mu^{\pm}$, jets, τ_h, *b*-tagging, *etc.*)
  - ➙ Including p_T/η dependence
- Efficiencies for triggers, event cleaning, *etc.*
  - ➙ Effects not manageable in fast simulations
- Special variable definitions (razor, aM_{T2}, *etc.*)
  - ➙ Snippets of code

A 2012 TH-wishlist for high-quality recasts (2/2)

- Benchmark scenarios
  - ➙ Spectra / decay tables (SLHA-form)
  - ➙ Several scenarios
- Monte Carlo configuration
  - ➙ Cards, tunes, matching information, *etc.*
- Detailed cutflows (with correct cut ordering)
  - ➙ Including (pre)selection steps (more is better)
- Kinematical distributions at different cuts
  - ➙ Extra cross-checks

[Les Houches Recommendations (EPJC'12)]

10 years later…

Much better material

- Publications much clearer
- HEPDATA widely used
- Improved communication between the EXP/TH communities
- Sometimes works amazingly well: e.g. ATLAS *multijet+MET*
- Still improvable: e.g. ATLAS *dE/dx* [HSCP with large ionisation]

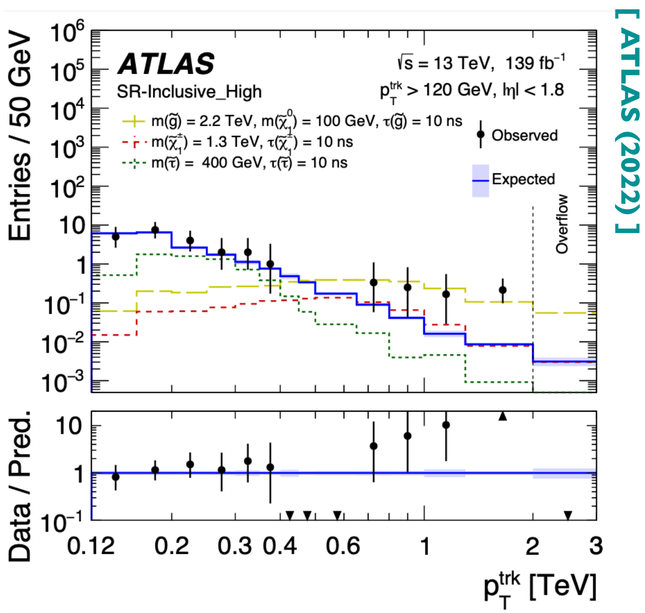
A 2020 TH-wishlist for high-quality recasts

- Background estimates: usually provided (not systematic)
- Efficiencies
  - ➙ Should be provided as tables / functional forms
  - ➙ Should be broken down in sub-efficiencies (trigger, *etc.*)
- Efficiency maps: necessary for SMS-based recasting
- Monte Carlo: still very minimal
  - ➙ SLHA files, MG5_aMC cards, PYTHIA cards, *etc.*
  - ➙ Crucial for the validation (*cf.* MC bias)
- Cut-flows for given benchmarks
  - ➙ not systematic (sequence, details, all SRs)

[The Reinterpretation Forum (SciPost`20)]

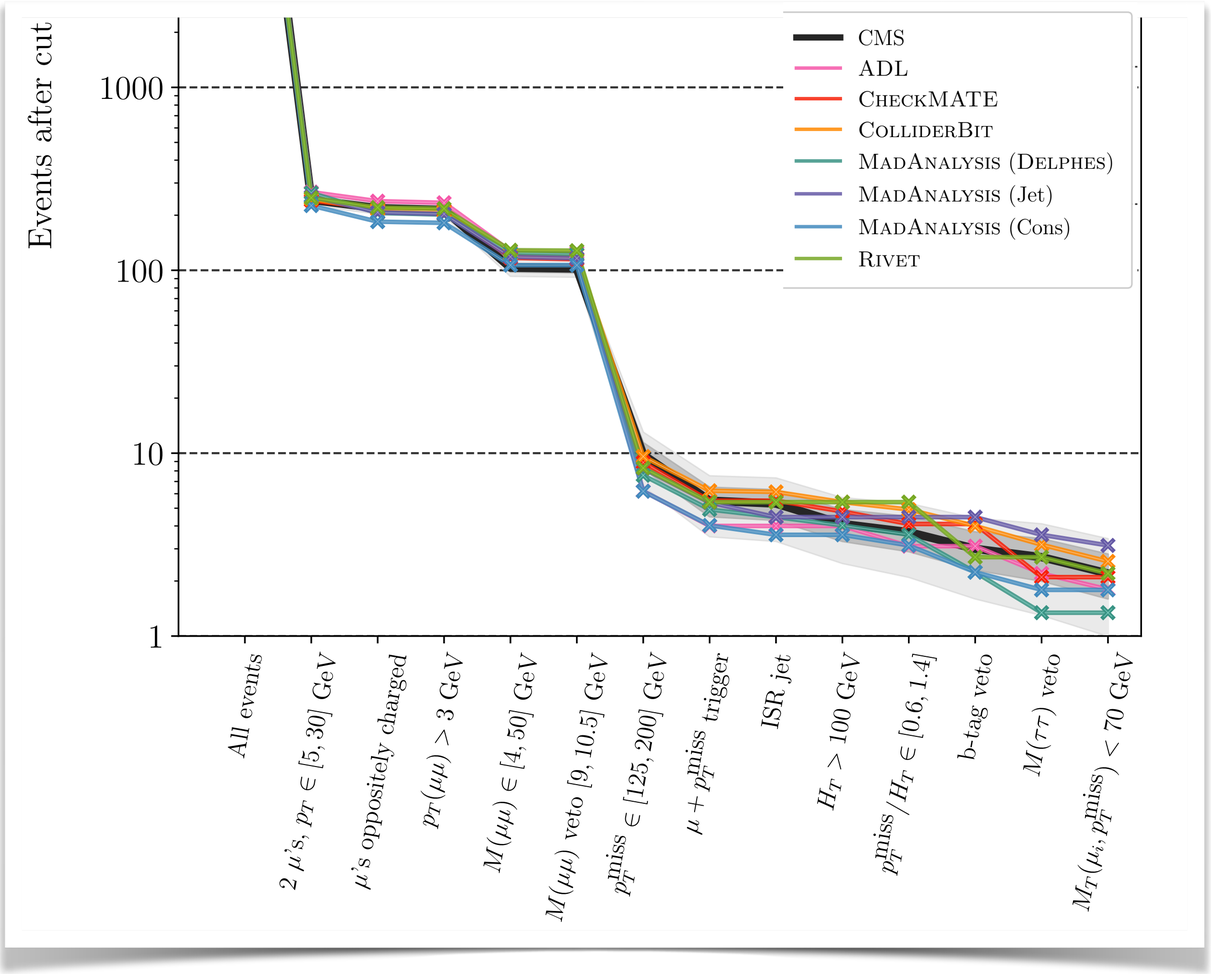
	ATLAS			MadAnalysis 5-SFS				
	Events	ε [%]	ε_{cut} [%]	Events	ε [%]	δ [%]	ε_{cut} [%]	R_{gap} [%]
Initial (truth $E_T^{miss} > 150$ GeV)	39598	-	100	89529	-	0.17	100	-
Lepton veto	37547	94.82	94.82	85417	95.41	0.17	95.41	0.62
$N_{jets} \leq 4$	35412	89.43	94.31	76195	85.11	0.18	89.20	4.38
$\min[\Delta\phi(jets, E_T^{miss})]$ cut	33319	84.14	94.10	69253	77.35	0.18	91.00	8.07
Leading jet > 150 GeV and $\lvert\eta\rvert < 2.4$	23134	58.42	69.43	47157	52.67	0.20	68.10	9.84
$E_T^{miss} > 200$ GeV	18801	47.48	81.30	39183	43.77	0.20	83.10	7.81
EM0	4488	11.34	-	8509	9.50	0.22	-	16.23
EM1	3789	9.57	-	7946	8.88	-	-	7.21
EM2	2857	7.21	-	6226	6.95	-	-	3.61
EM3	2111	5.33	-	4621	5.16	-	-	3.19

[Again with MADANALYSIS 5]



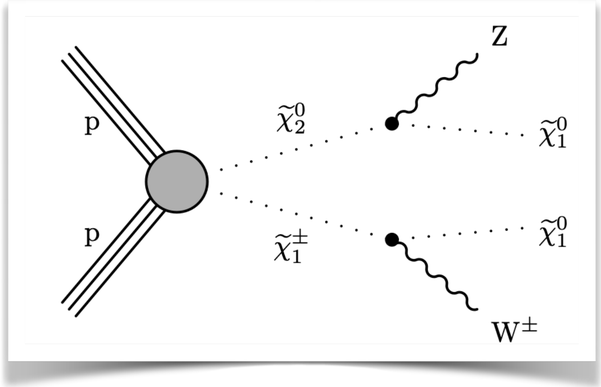
[ATLAS (2022)]

Does it really work?



Example: LH 2019

- CMS-SUS-16-048
- Supersymmetry with soft leptons
  ➙ sleptons / ewkinos



- Reasonable agreement with CMS
  ➙ Not achieved in 10 min
  ➙ Validation is crucial
  ➙ Having different frameworks help

Validation important, rarely easy, not always possible

Novelties

Covariances and correlations

Limit setting: "Best signal region"

- Exclusion from the best region of an analysis
- Often off compared with CMS/ATLAS
  ➙ Correlations rarely negligible

Better limit settings procedures

- Signal region combination (within an analysis):
  ➙ CMS correlation matrices
  (likelihoods in Gaussian approximation)

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

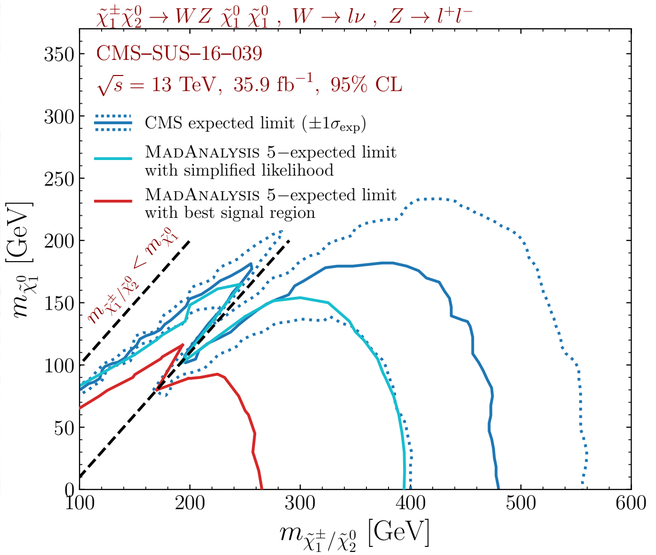
[CMS-NOTE-2017-001; Buckley et al. (JHEP`19)]

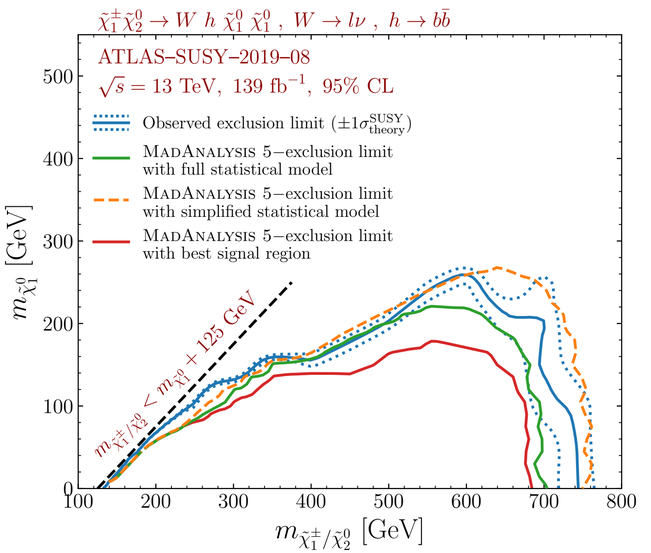
  ➙ ATLAS (full) PyHF likelihoods
  (to be further simplified for speed reasons)

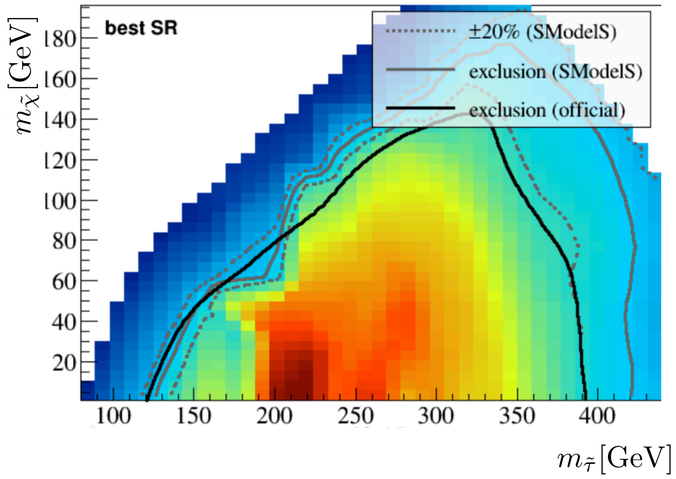
[ATLAS-PHYS-PUB-2019-029]

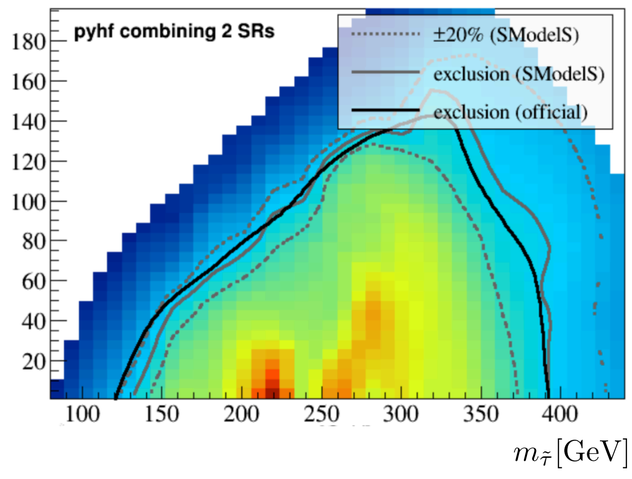
- More realistic reinterpretations
- Support by SModelS, MadAnalysis5, ColliderBit

ATLAS and CMS searches for ewkinos/sleptons









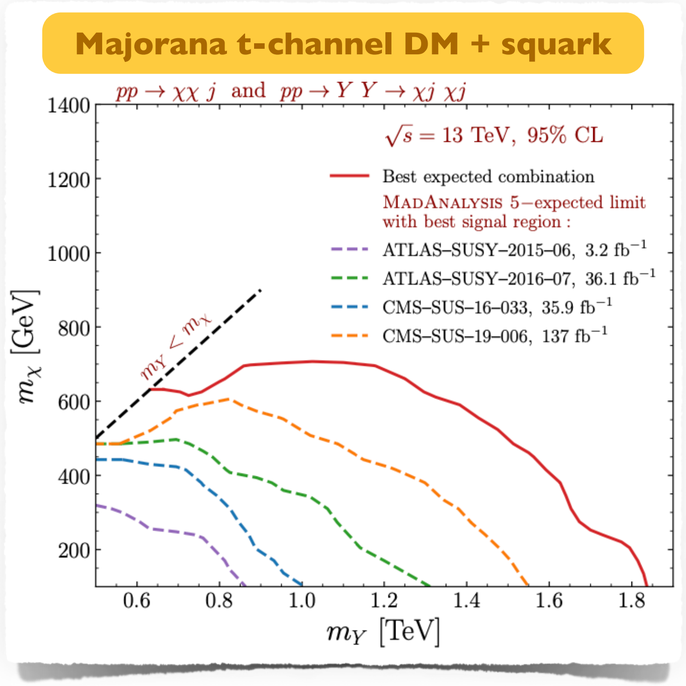
[Alguero, Araz, BF & Kraml (SciPost`22); Alguero, Kraml, Waltenberger (CPC`21)]

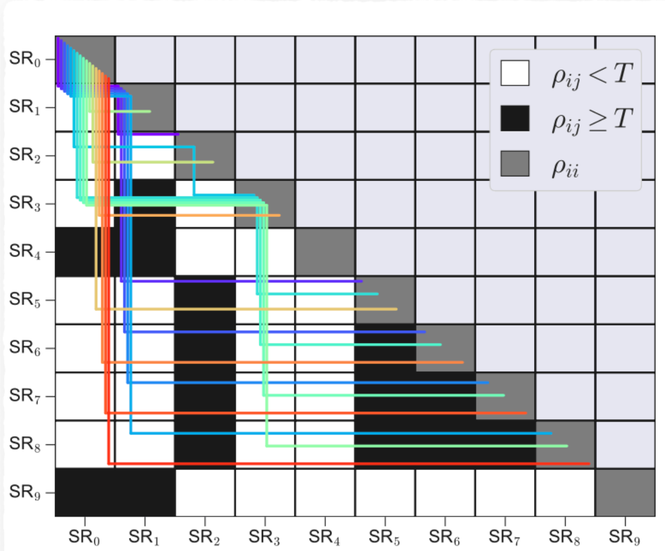
Analysis combination - the TACO approach

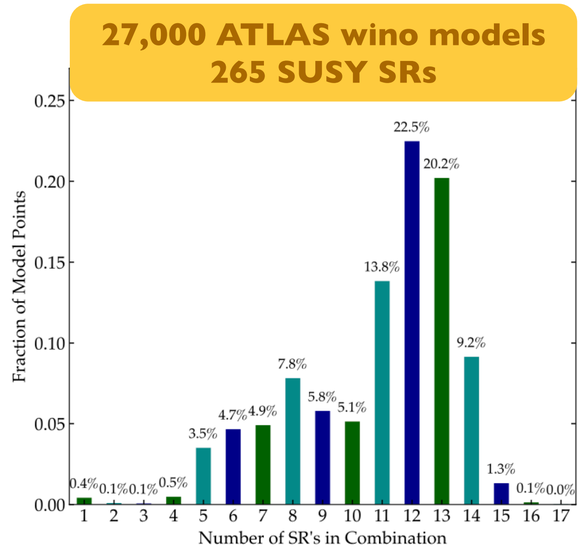
[Araz, Buckley, BF et al. (SciPost`23)]

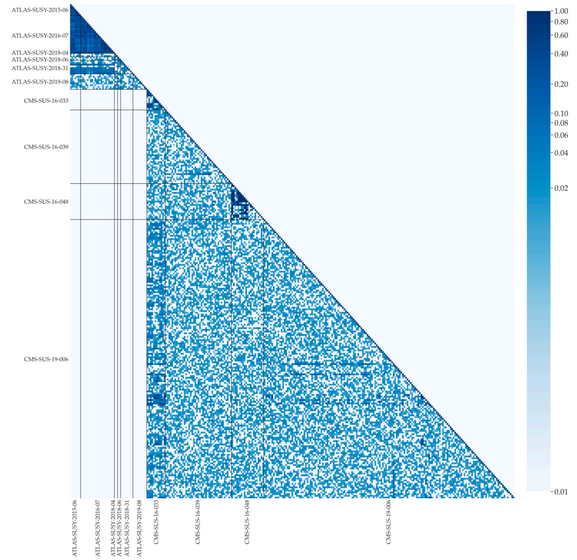
The TACO approach - testing analysis correlations

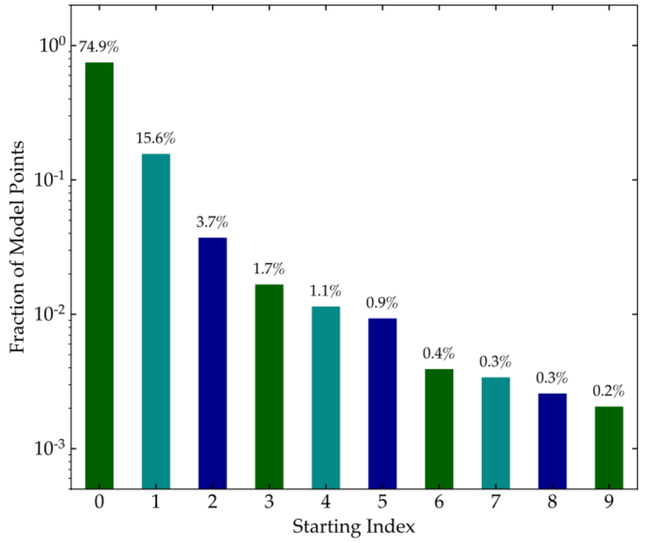
- One step further: combination of analyses
  - ➙ Overlap matrix ≡ approximate correlation matrix
  - ➙ Path finding (set of non-overlapping regions) [weighted hereditary depth-first search algorithm]
- Out of 100s of signal regions, a few usually sufficient
  - ➙ Going beyond just combining ATLAS with CMS
  - ➙ Sensitivity largely driven by a specific SR





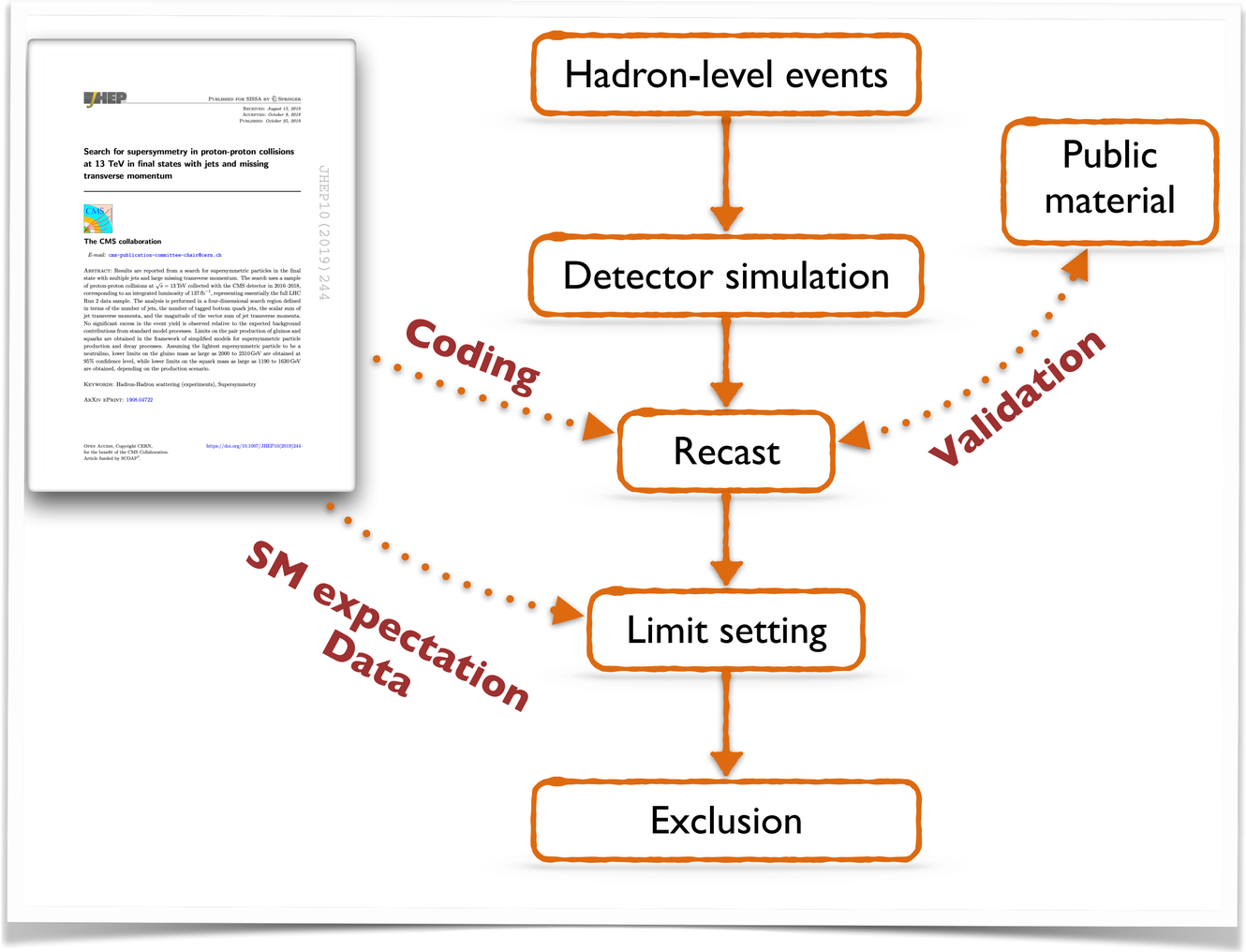






Summary

Summary



The LHC legacy

- Reinterpretation of the LHC results crucial
  - ➙ Several complementary approaches
  - ➙ Active field of research
- Exciting on-going developments: combining & correlating

Final last words

- **Reproducibility** ≡ ability to reproduce an experiment (possibly by an independent theoretical study)
- Need for the TH and EXP communities to move together!