(Re)interpretation for new physics: Transferring insights from LHC to EIC

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Thomas Jefferson National Accelerator Facility

Electroweak and beyond the standard model physics at the EIC
Institute for Nuclear Theory, University of Washington
February 15th, 2024

Outline

(Re)interpretation of the LHC results for new physics

29 August 2023 to 1 September 2023
Durham University

8th workshop of the series

- Preservation of experimental analyses
- Public Likelihoods
- Towards global sensitivity
- Reusable ML-based analyses
- Conclusion

Preservation of Experimental Analyses

Preservation of experimental analyses

- Exploiting the full potential of the experiments (for new physics)
  - *Designing* new analyses (based on MC simulations)
  - *Recasting* analyses (The legacy of the experiment)
- 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)

Searches for BSM

Lagrangian

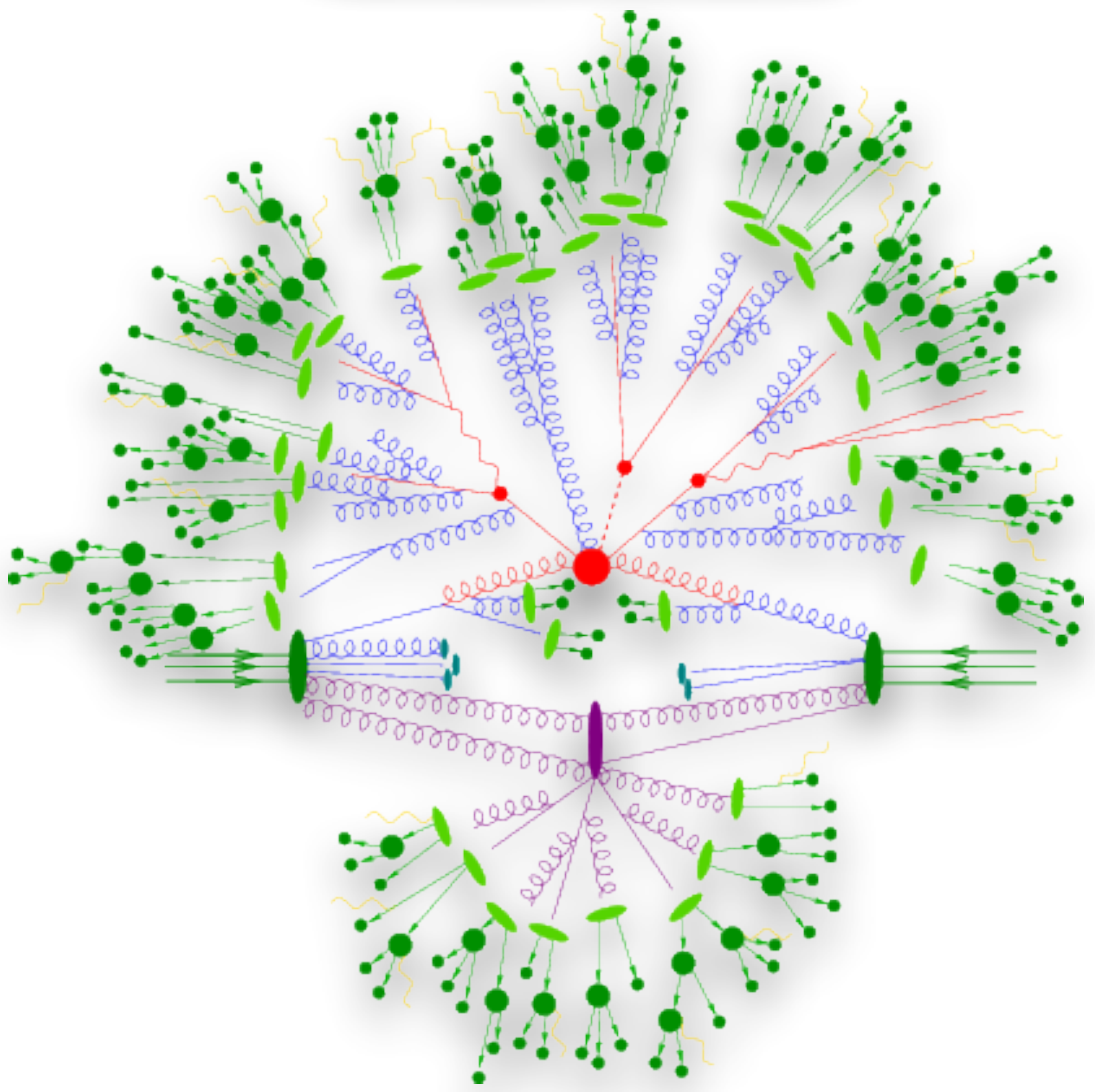
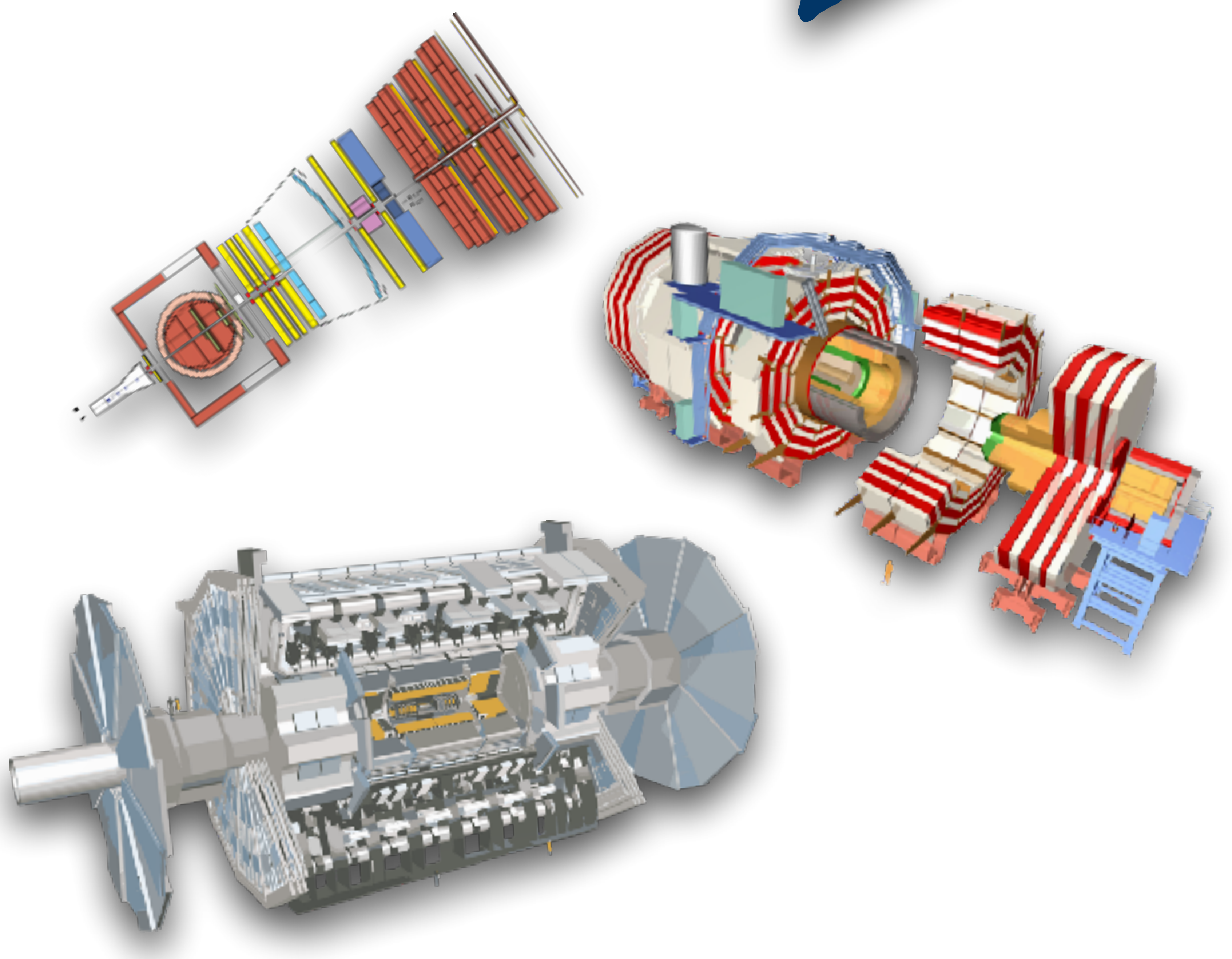
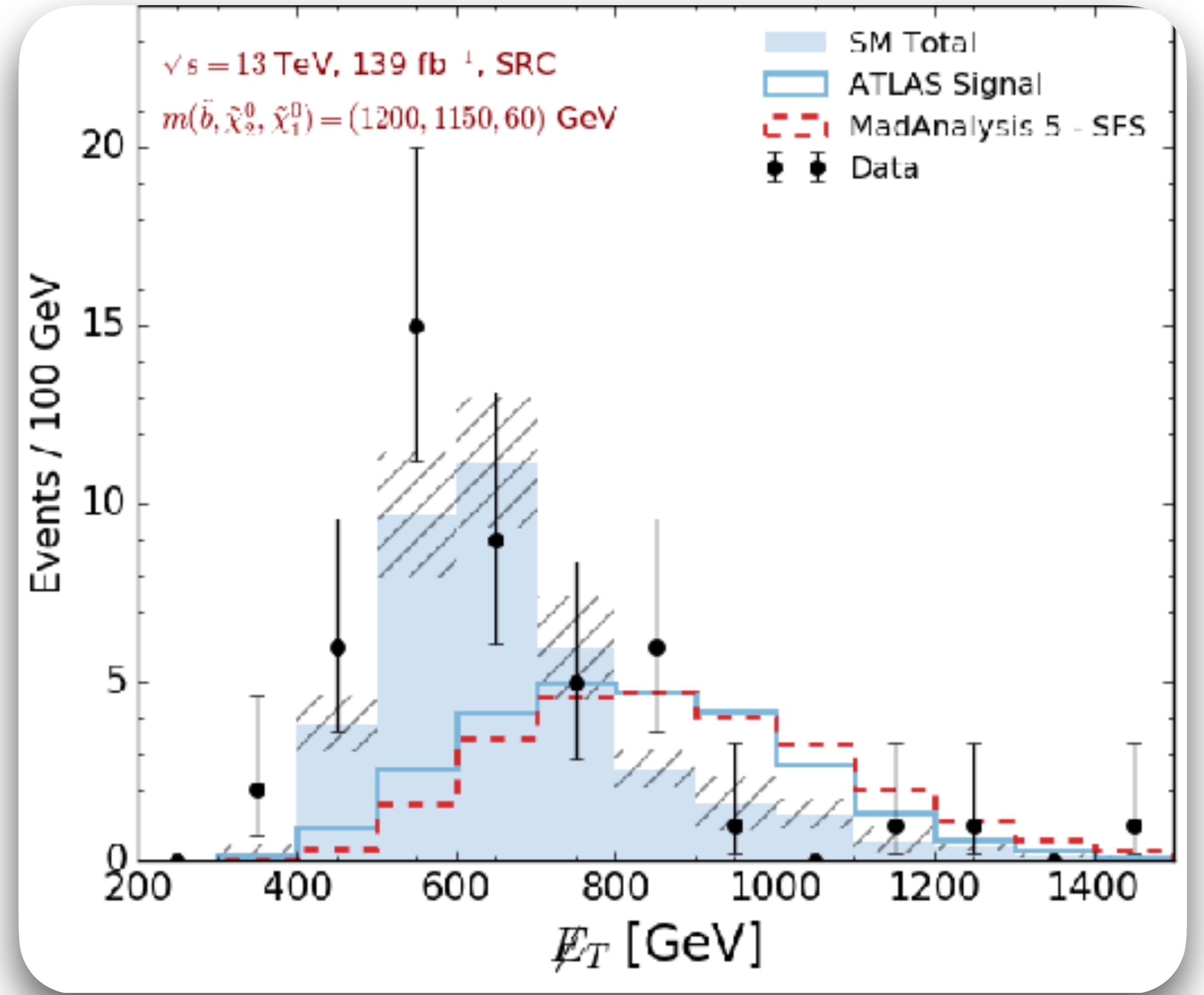


Image credit: Sherpa

Smearing

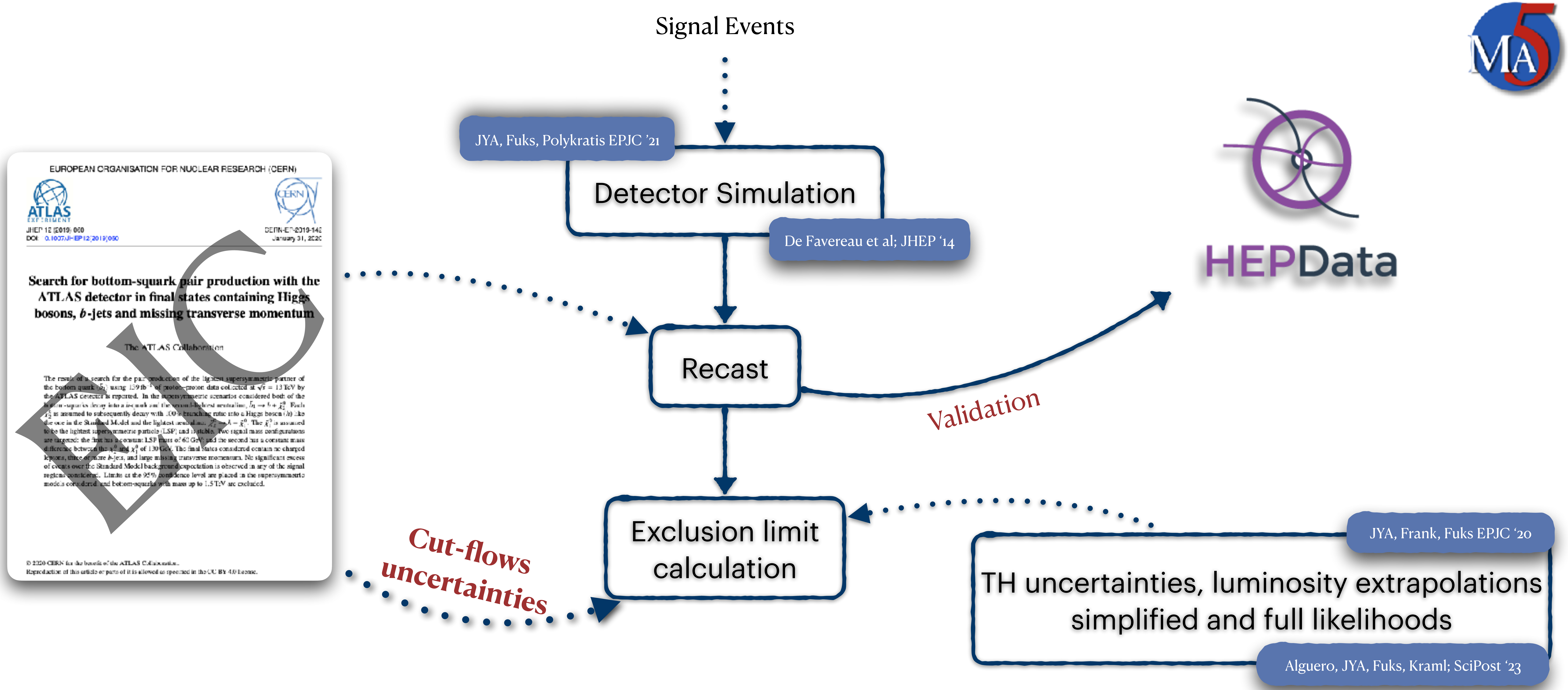




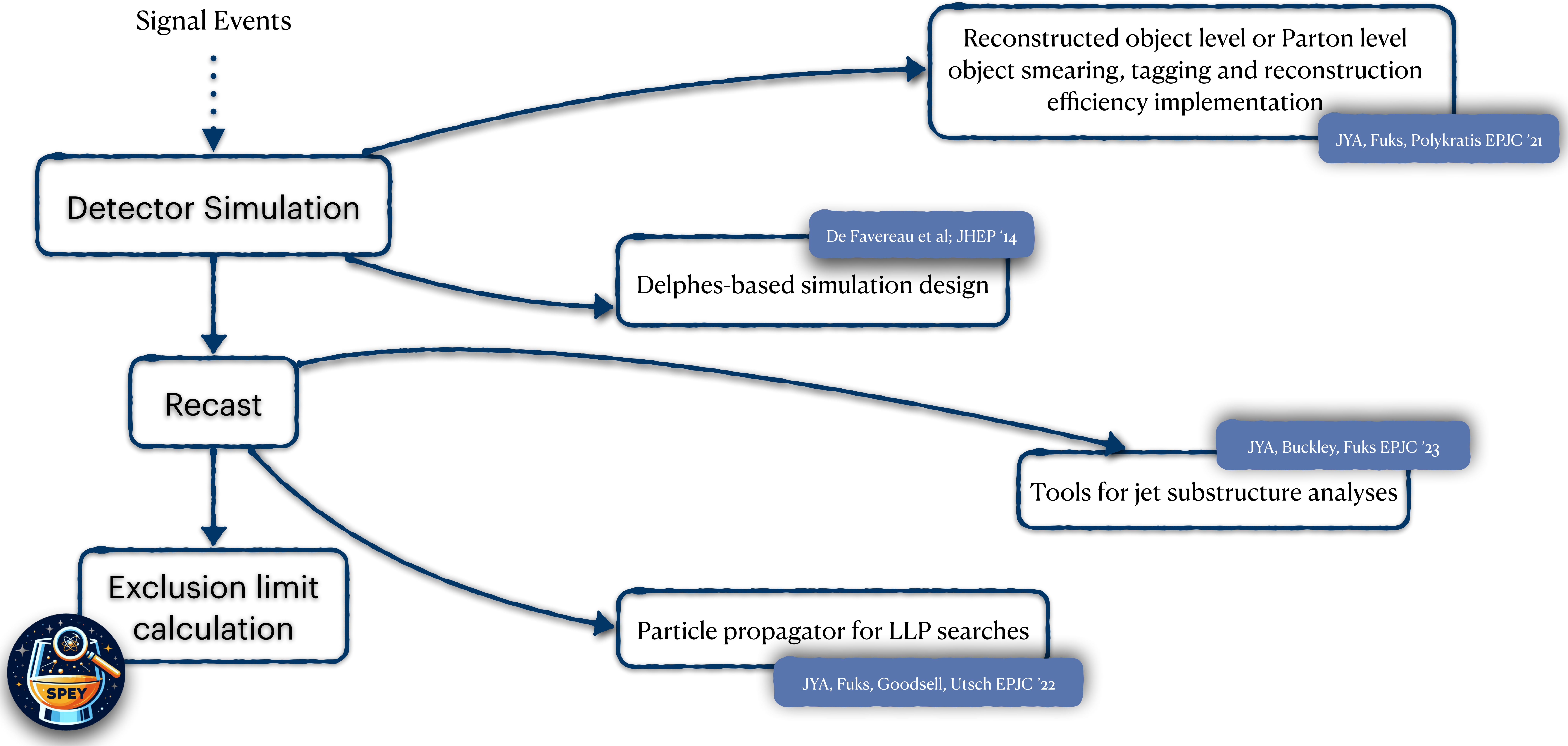
Smeared MC + observed data

Jack Y. Araz

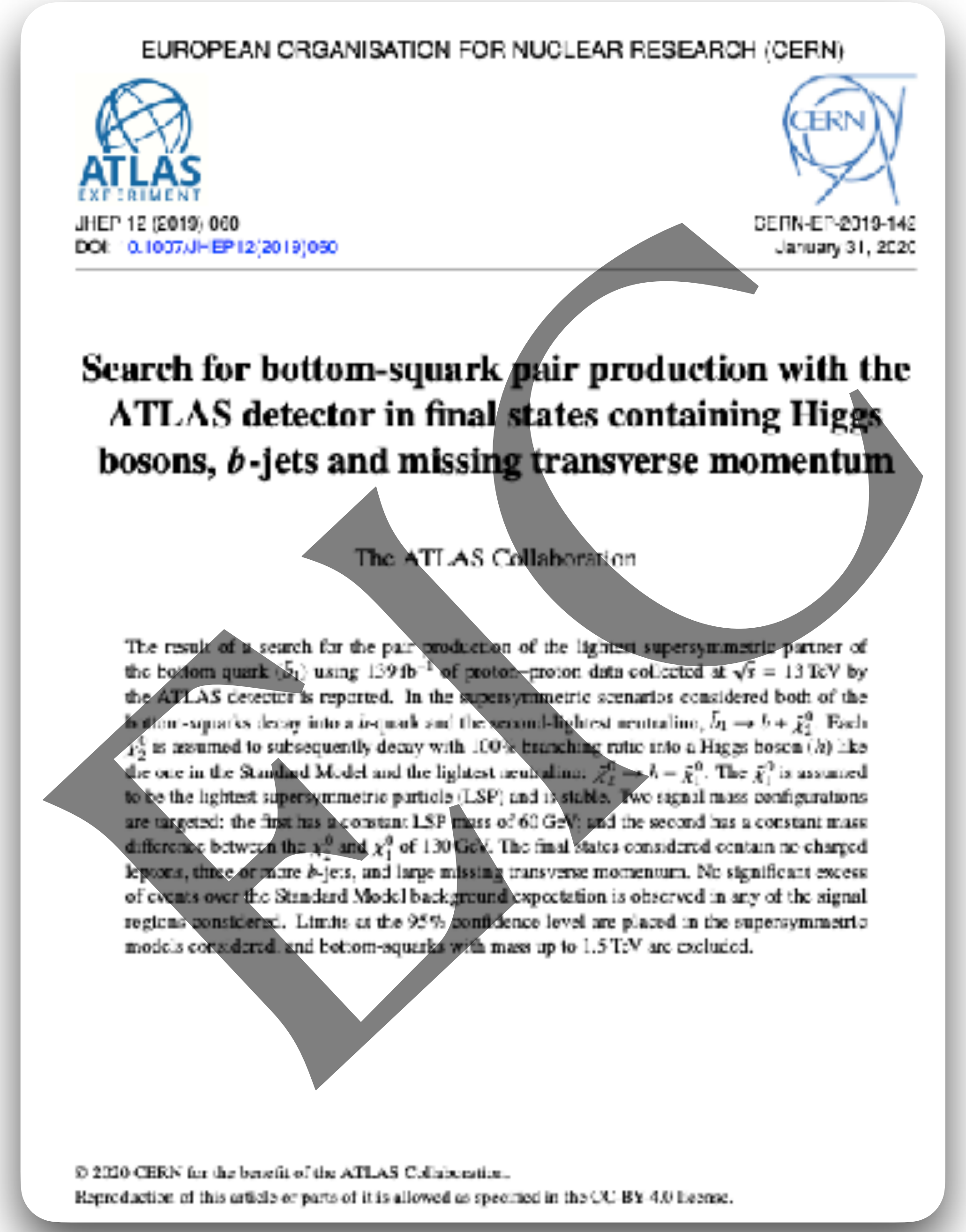
(Re)interpretation of an analysis

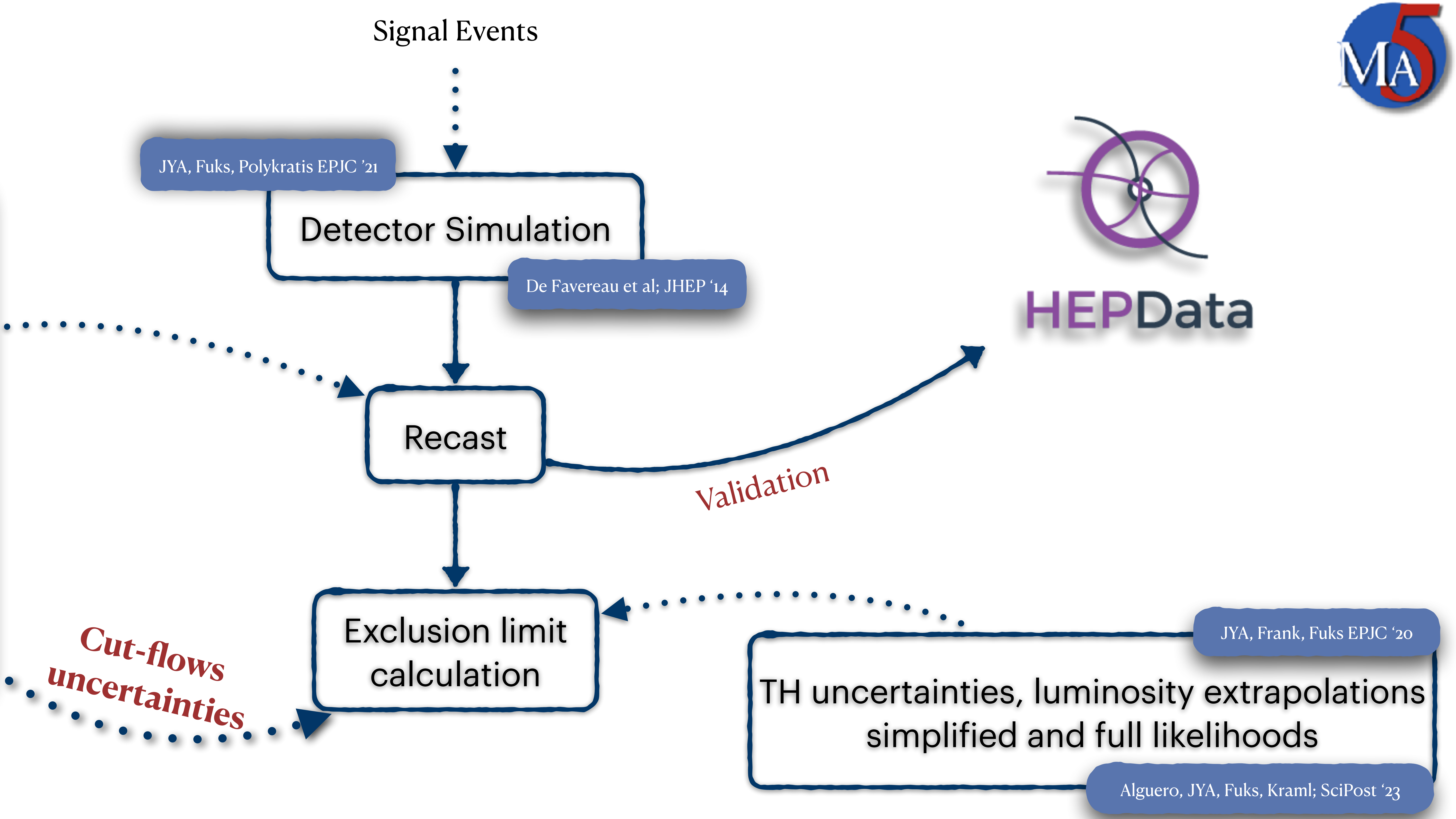


(Re)interpretation of an analysis

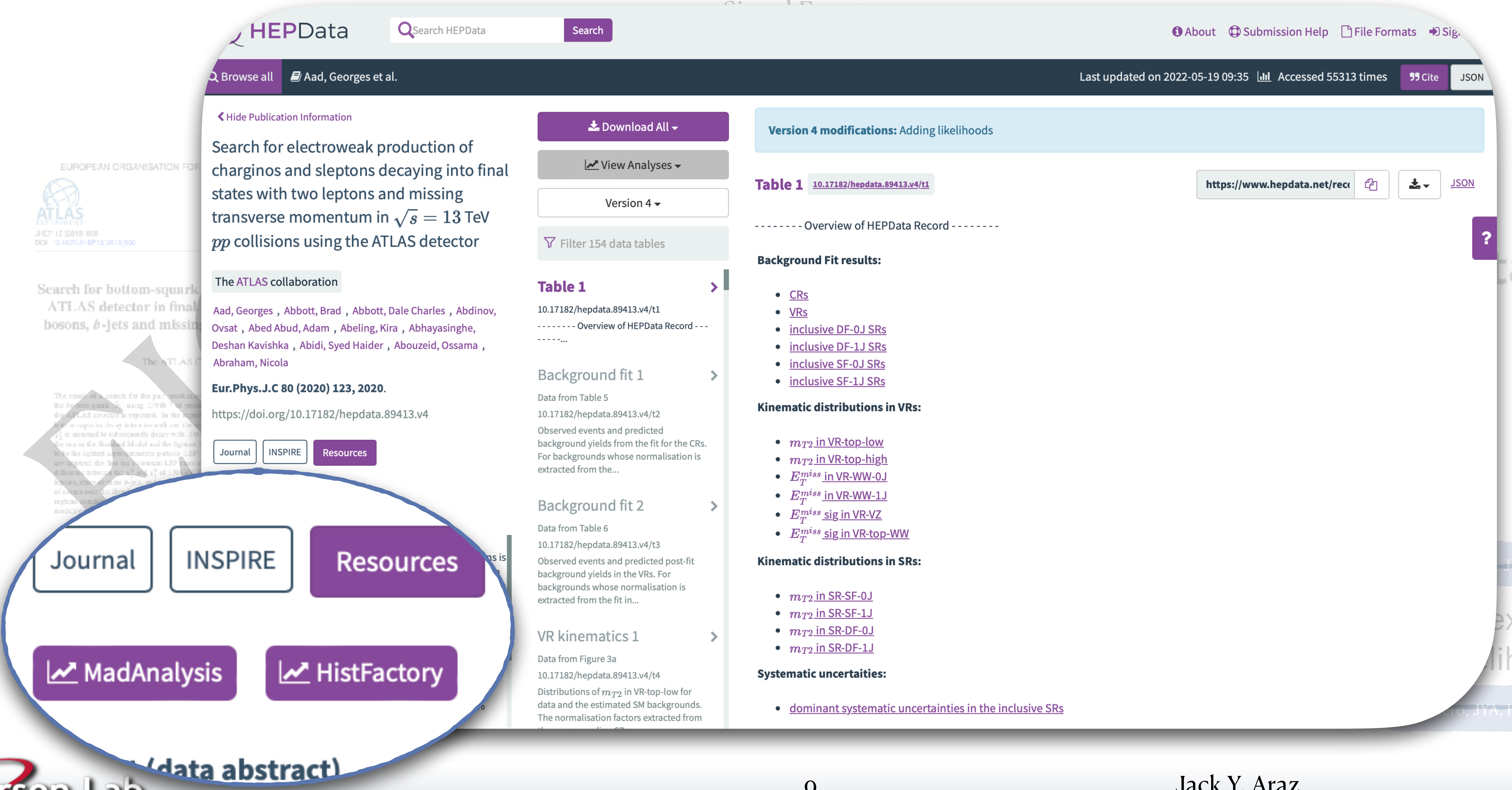


(Re)interpretation of an analysis

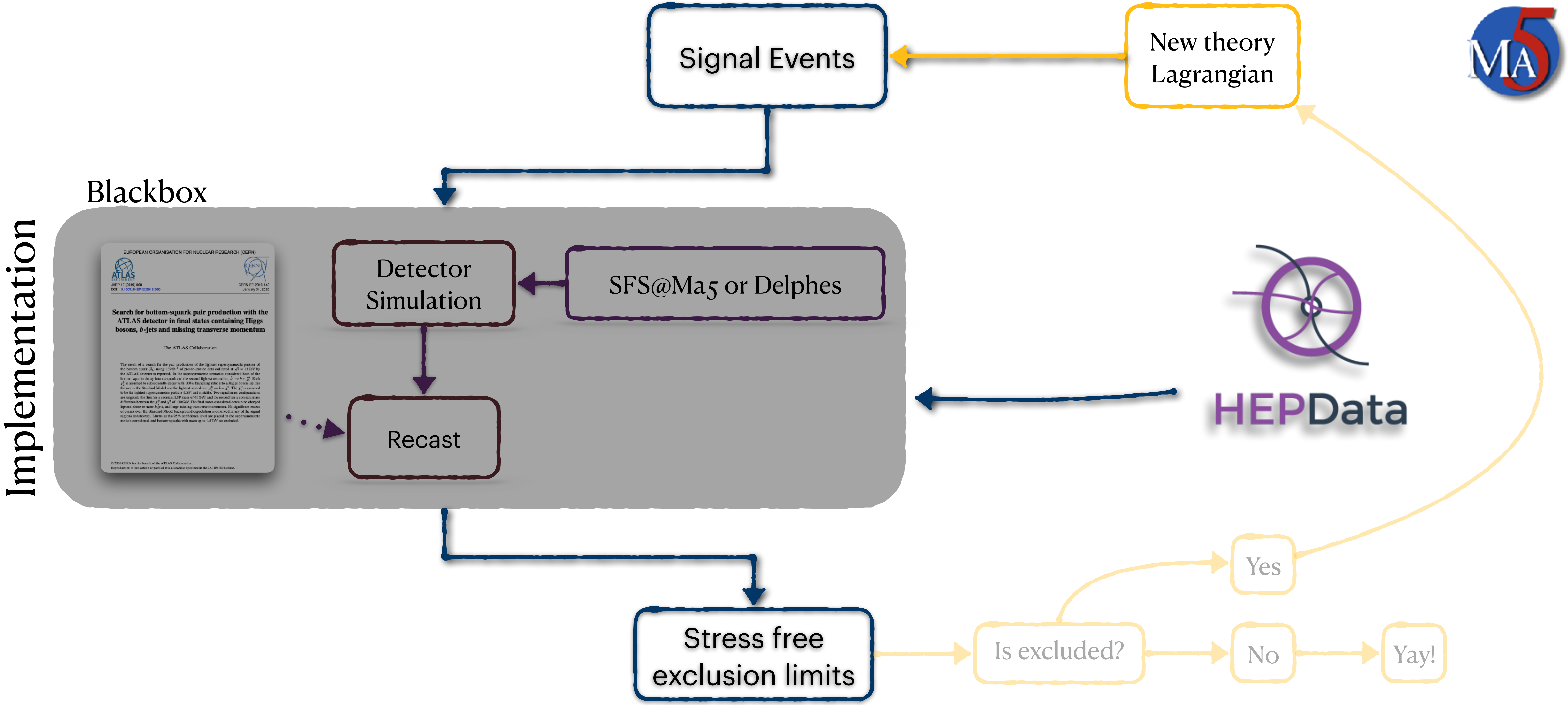




(Re)interpretation of an analysis



Reusable analysis framework



Why reusable analysis framework?

Measurements can be used to exclude new physics.
They have shown compatible results to searches!

SciPost Physics — arXiv: 2111.15406 — Submission

Probing a leptophobic top-colour model with cross section measurements and precise signal and background predictions: a case study

M. M. Altakach[1,2,4], J. M. Butterworth[3], T. Ježo[2], M. Klasen[2], I. Schienbein[1]

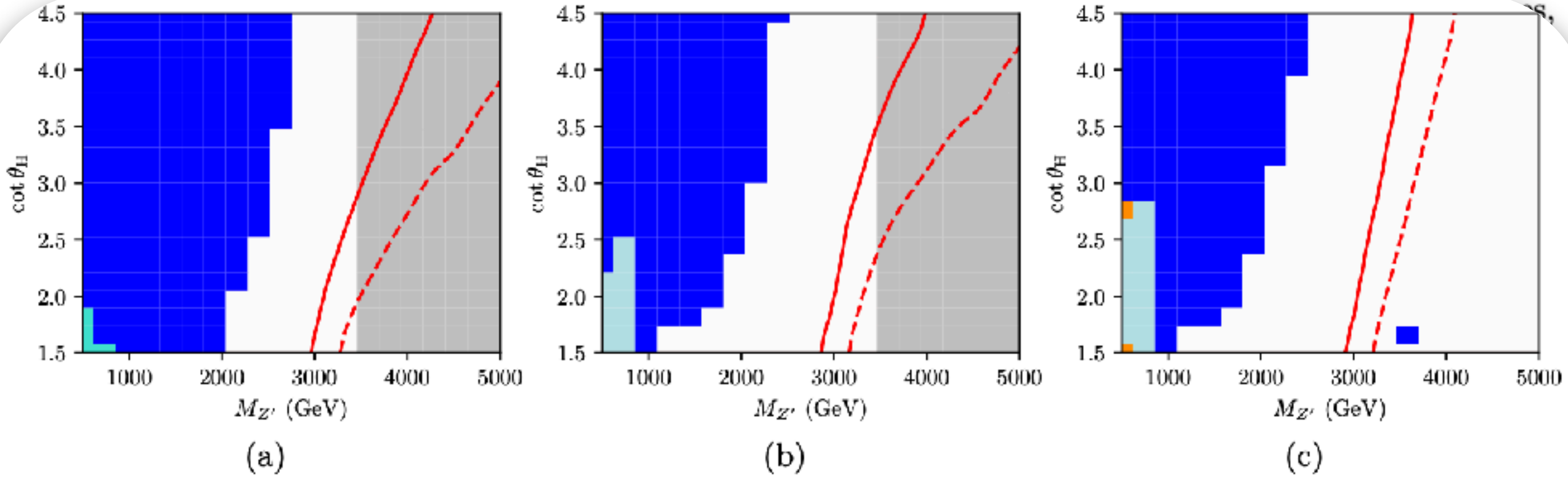


Figure 4: Exclusions derived using Herwig. (a) As Fig. 1b but only using those measurements for which SM predictions are available. (b) Expected limit. (c) Measured limits using the SM predictions as background.

ATLAS $\ell+E_T^{\rm miss}$+jet | ATLAS Hadronic $t\bar{t}$ | CMS $\ell+E_T^{\rm miss}$+jet | ATLAS jets | ATLAS $\mu\mu$+jet

From their conclusion:

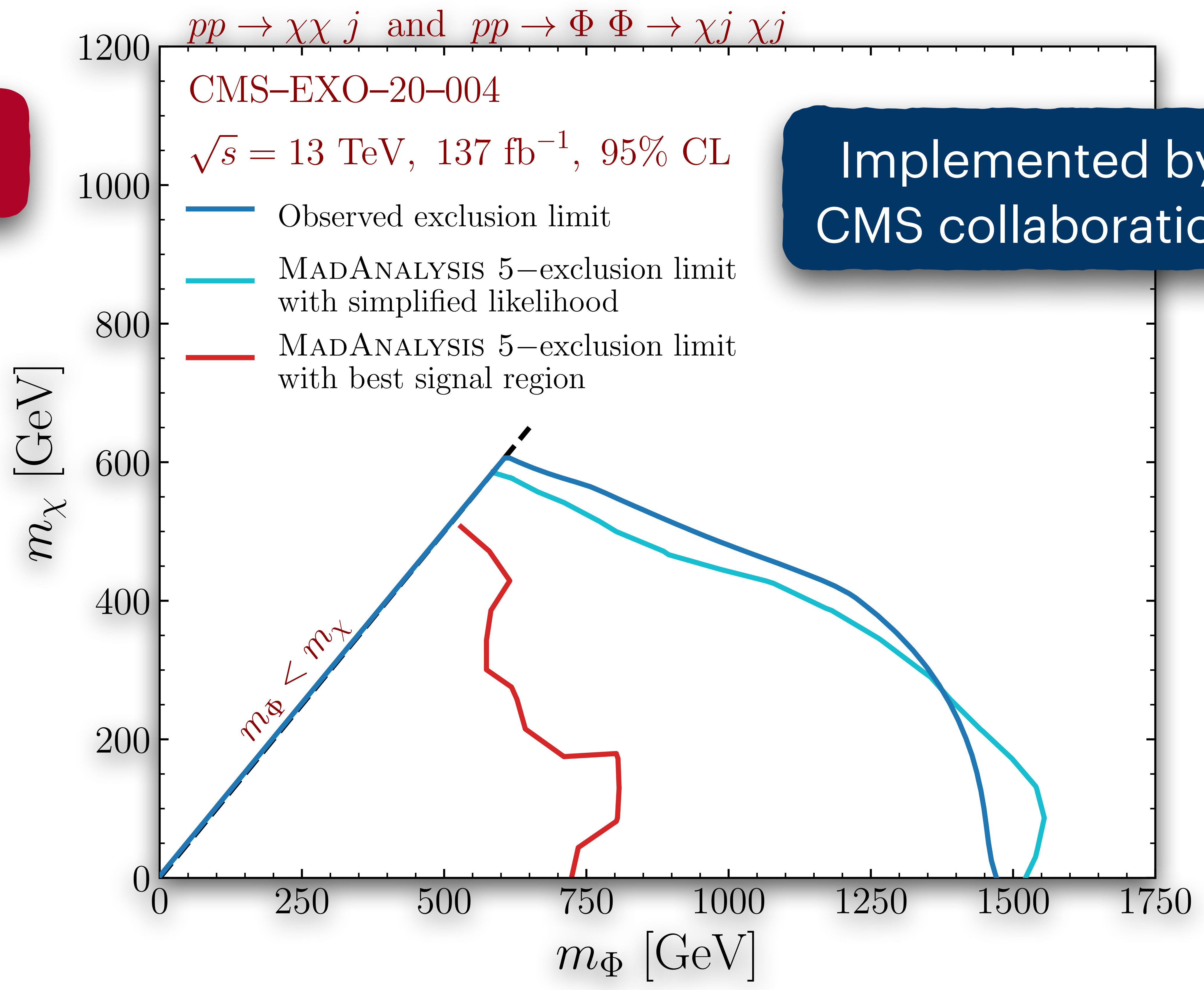
Our exclusions can be compared to the strongest limits to date on this model, coming from resonance searches by ATLAS and CMS. CMS [20] excludes the TC Z' boson below 3.80, 5.25, and 6.65 TeV for 1, 10, and 30% widths respectively, using leptonic and hadronic decays of the top in 35.9/fb of data. ATLAS [17] excludes it below 3.9 and 4.7 TeV for decay widths of 1 and 3% respectively using the fully hadronic decay channel only in 139/fb of integrated luminosity. An earlier ATLAS search [15], using the semileptonic decay mode in 36.1/fb of integrated luminosity excludes the Z' bosons with $M_{Z'}$ below 3 (3.8) TeV for 1% (3%) decay width. In [16], using the fully hadronic decay mode in 36.1/fb of integrated luminosity, ATLAS excludes Z' bosons with mass below 3.1 (3.6) TeV for 1% (3%) decay width.

What will we need from EIC?

- Detailed cutflows
- Accurate detector parametrisation (see the EIC technical report)
- Collaboration with experimentalists is essential to develop reliable tools.
- Numbers published by the experimental collaborations are typically far away from being a complete representation of the statistical model.

See Ernst's talk from Tuesday

Extended SM with a generic DM, χ, and mediator, Φ



Implemented by CMS collaboration

Alguero, JYA, Fuks, Kraml; SciPost, arXiv: 2206.14870

Public Likelihoods

Public Likelihoods

MASSIMO CORRADI:

Does everyone agree on this statement, to publish likelihoods?

LOUIS LYONS:

Any disagreement? Carried unanimously. That's actually quite an achievement for this workshop.

Slide from Kyle Cranmer


CERN 2000–005
30 May 2000

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

WORKSHOP ON CONFIDENCE LIMITS

CERN, Geneva, Switzerland
17–18 January 2000

PROCEEDINGS

Editors: F. James, L. Lyons, Y. Perrin

Public Likelihoods

(PUBLIC) Exotics + SUSY Reinterpretations: Theorist Feedback

Thursday 24 Sept 2020, 14:00 → 17:00 Europe/Zurich

Carl Gwilliam (University of Liverpool (GB)), Federico Meloni (Deutsches Elektronen-Synchrotron (DE)), Laura Jeanty (University of Oregon (US)), Oliver Stelzer-Chilton (TRIUMF (CA))

Why public likelihoods

- The statistical model of an experimental analysis provides the complete mathematical description of that analysis

  $p(o|\alpha)$ relating the observed quantities o to the parameters α

- Given the likelihood, all the standard statistical approaches are available for extracting information from it

- Essential information for any detailed interpretation of experimental results

  = determining the compatibility of the observations with theoretical predictions

Les Houches Recommandations (2012)

3b: When feasible, provide a mathematical description of the final likelihood function in which experimental data and parameters are clearly distinguished, either in the publication or the auxiliary information. Limits of validity should always be clearly specified.

3c: Additionally provide a digitized implementation of the likelihood that is consistent with the mathematical description.

arXiv:1203.2489

Slide from Sabine Kraml

First implementations:

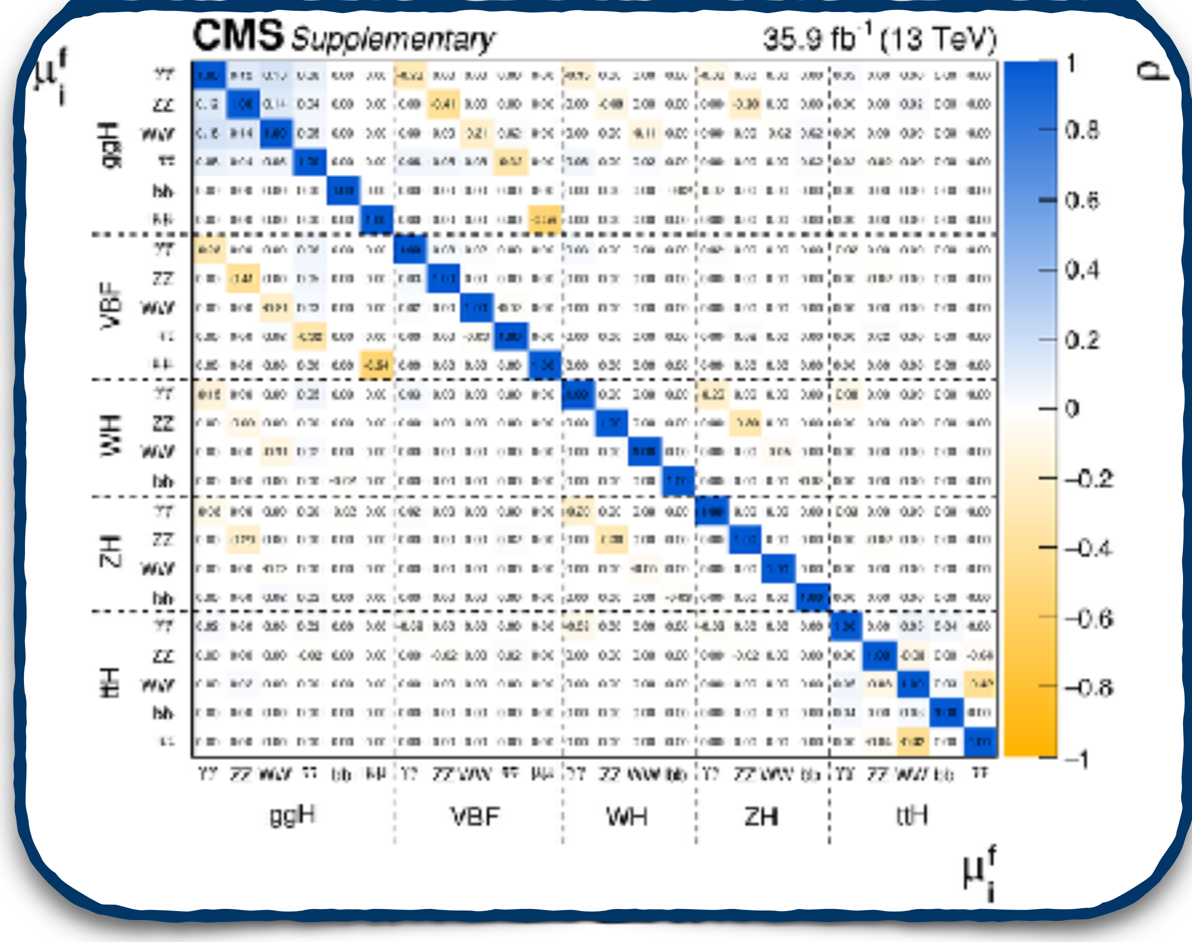
- Alguero, Kraml, Waltenberg arXiv: 2009.01809
- Alguero, JYA, Fuks, Kraml; SciPost, arXiv: 2206.14870

Public Likelihoods

- Experimental searches often employ the Likelihood for parameter estimation in some underlying physics model (also for discovery and setting limits)
- Searches often consider multiple channels and bins simultaneously.
- We are interested in POI, μ (e.g. signal strength or Wilson coefficients).
- Additional parameters (θ) account for systematic uncertainties in the model (nuisance parameters) - these are often constrained in some external measurement/by theory/additional data, $\mathscr{C}(\theta)$

$$\mathscr{L}(\mu,\theta) = \prod_{i\in\text{channels}} \prod_{j\in\text{bins}} \mathscr{M}(n_{ij} | \lambda_{ij}(\mu,\theta)) \cdot \prod_{k\in\text{nui}} \mathscr{C}(\theta_k)$$

Simplified likelihoods from CMS



CMS-NOTE-2017-001

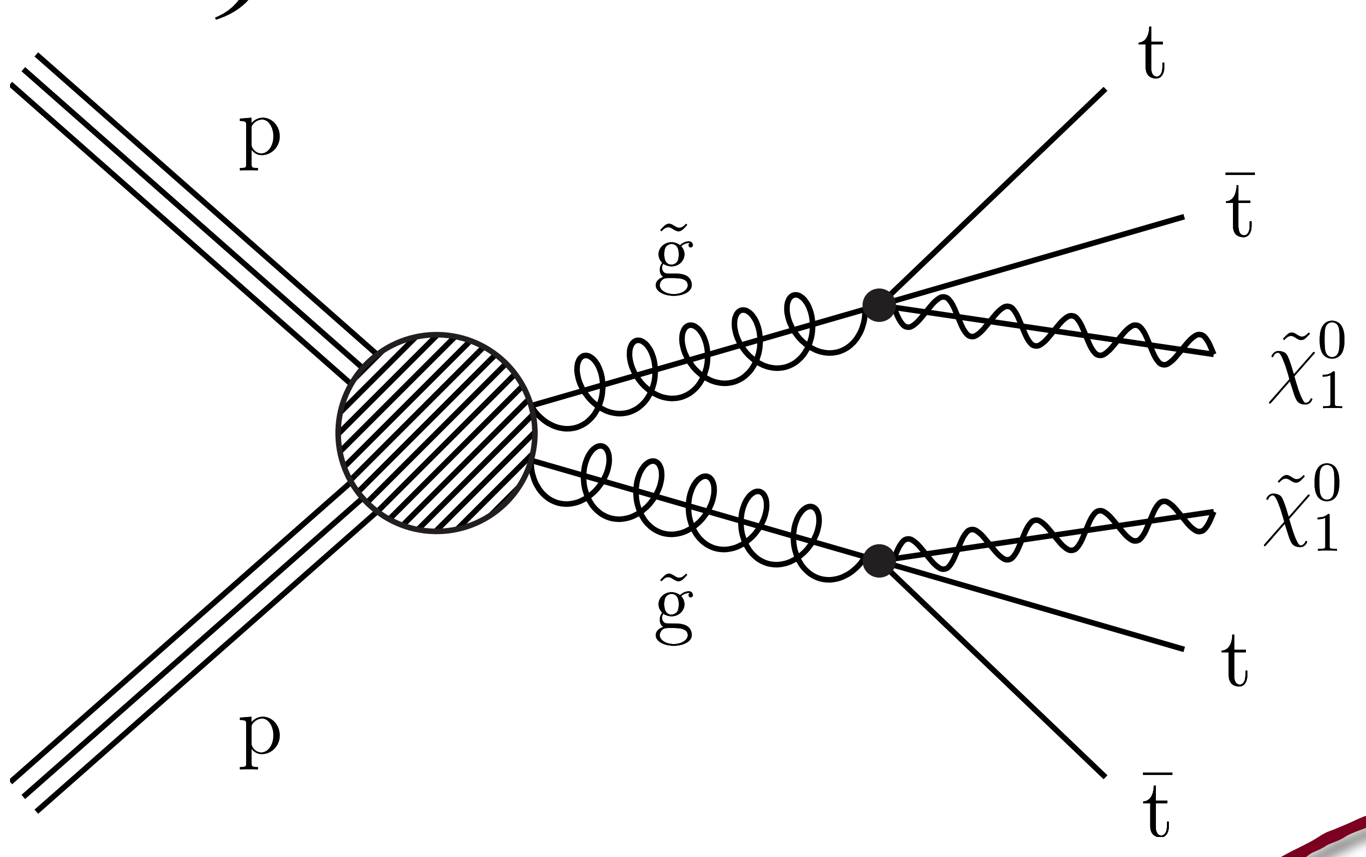
Full likelihoods from ATLAS

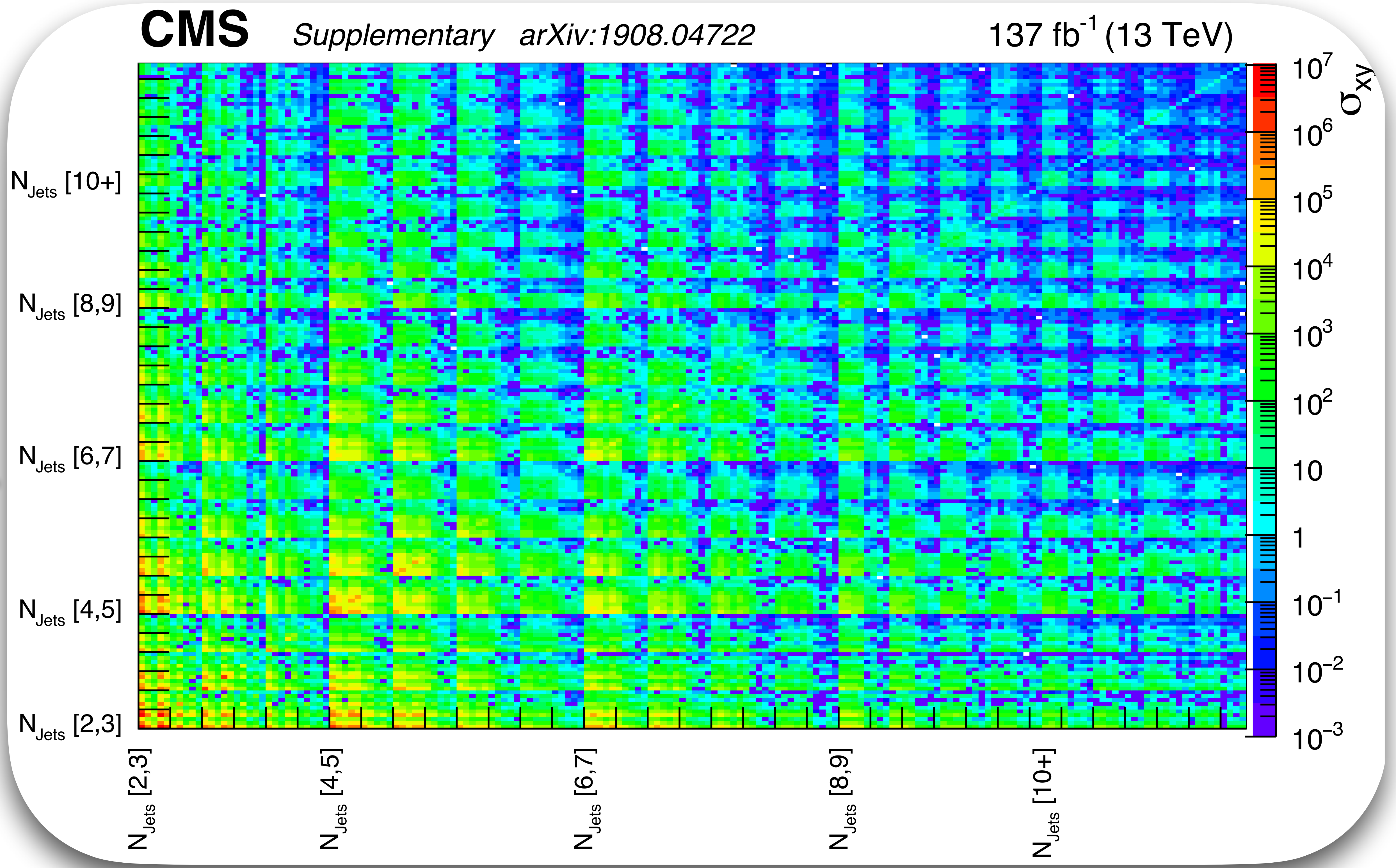
pyhf ∂ifferentiable Likelihoods

ATL-PHYS-PUB-2019-029

Simplified likelihoods

CMS-SUS-19-006





$$\mathscr{L}(\mu,\theta) = \left[\prod_{i\in \text{bins}} \text{Poiss}\left(n^i \,|\, \mu n_s^i + n_b^i + \theta^i \sigma_b^i\right)\right] \cdot \mathcal{N}\left(\theta \,|\, 0,\rho\right)$$

CMS-NOTE-2017-001

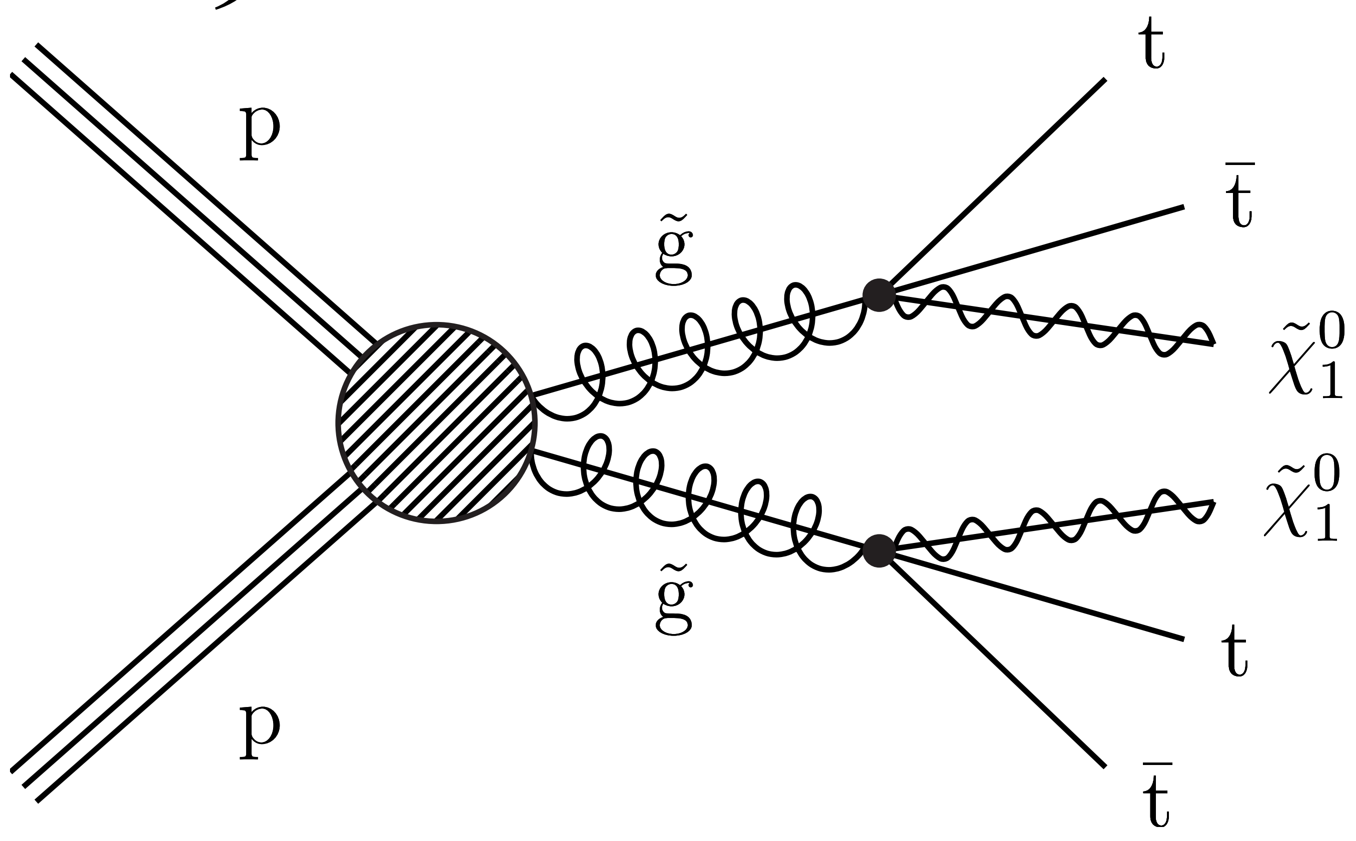
186 signal regions!

Simplified likelihoods

Alguero, JYA, Fuks, Kraml; SciPost, arXiv: 2206.14870

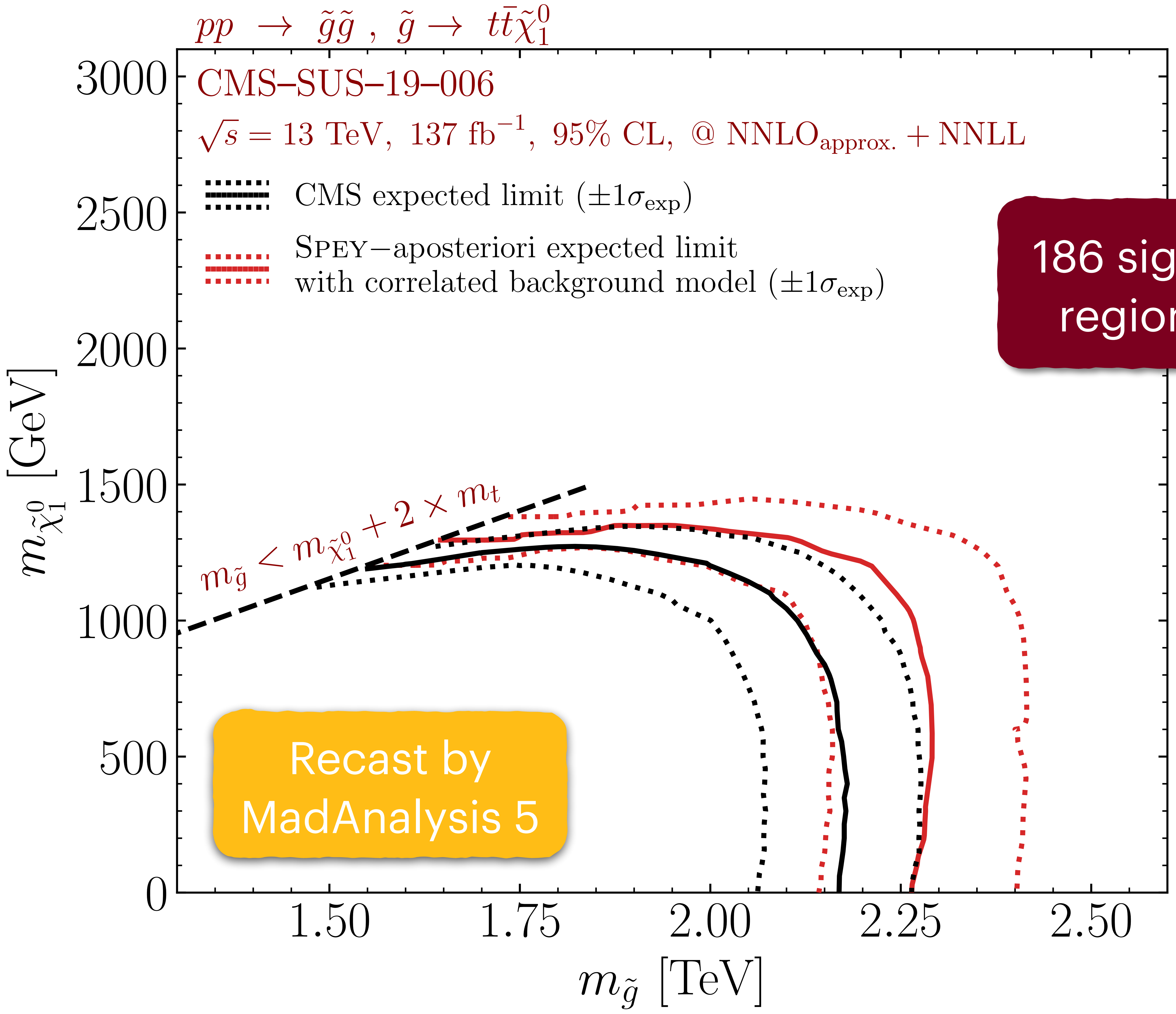
JYA, SciPost; arXiv: 2307.06996

CMS-SUS-19-006



$$\mathscr{L}(\mu,\theta) = \left[\prod_{i\in \text{bins}} \text{Poiss}\left(n^i \,|\, \mu n_s^i + n_b^i + \theta^i \sigma_b^i\right)\right] \cdot \mathcal{N}\left(\theta \,|\, 0, \rho\right)$$

CMS-NOTE-2017-001

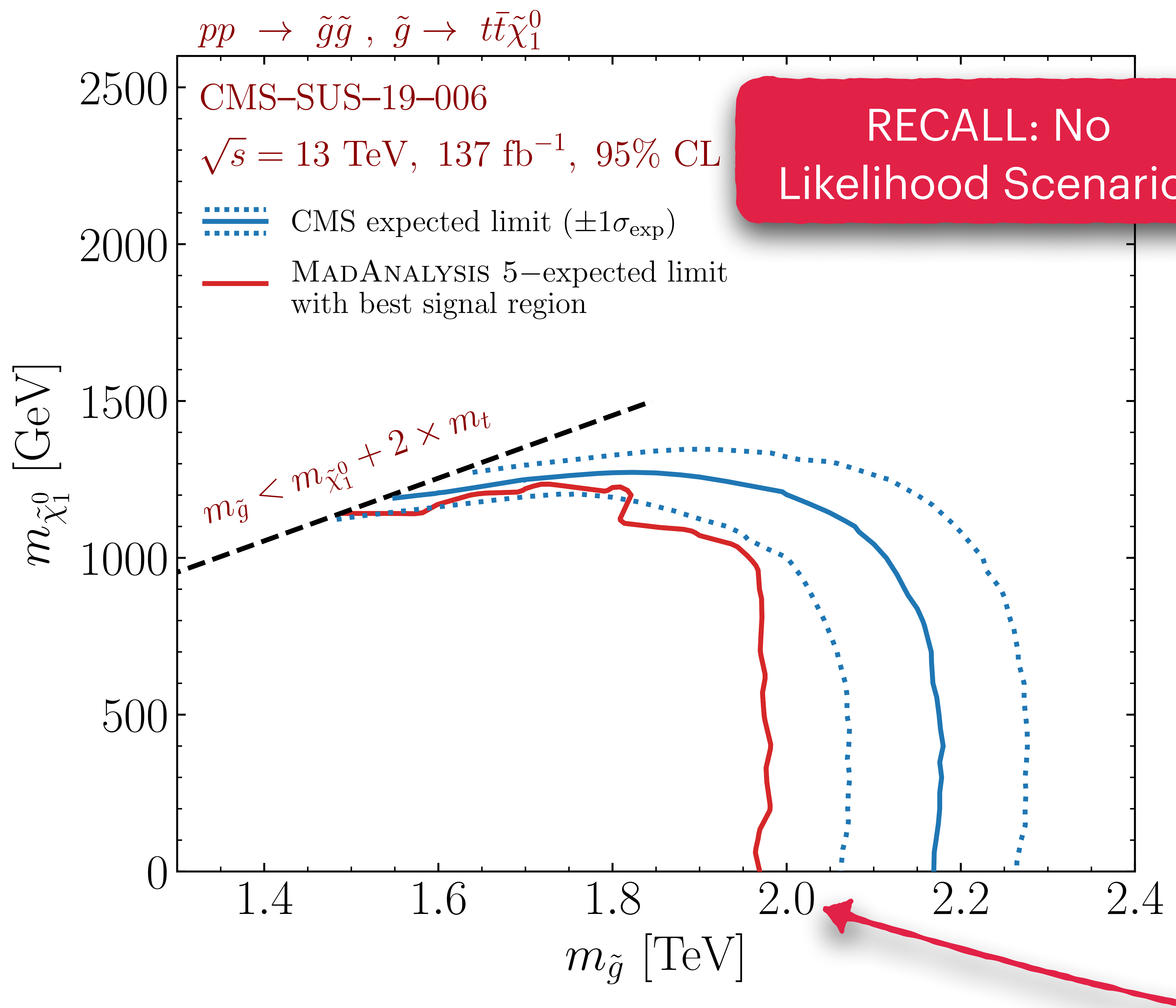


186 signal regions

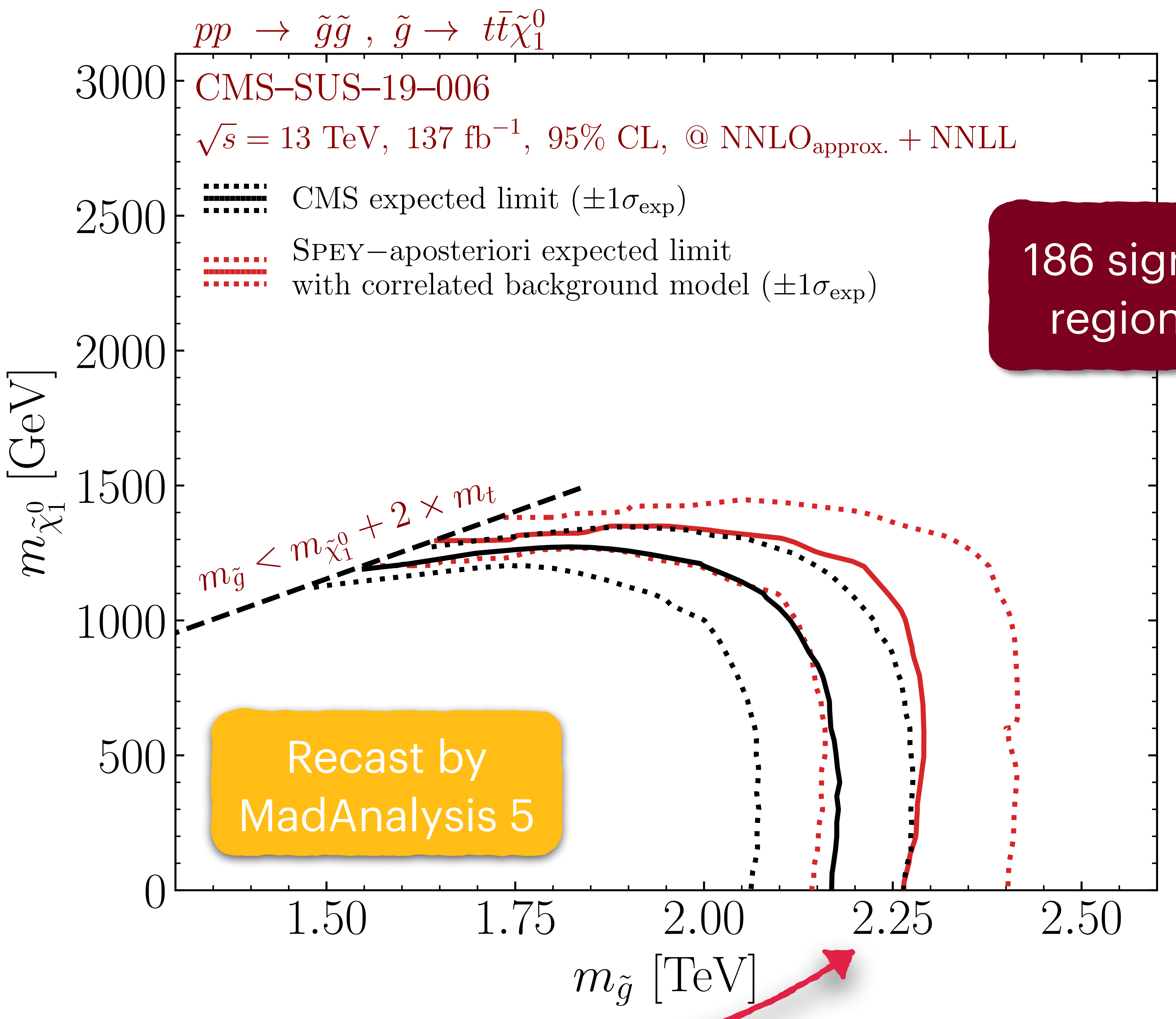
Simplified likelihoods

Alguero, JYA, Fuks, Kraml; SciPost, arXiv: 2206.14870

JYA, SciPost; arXiv: 2307.06996



RECALL: No Likelihood Scenario!



186 signal regions

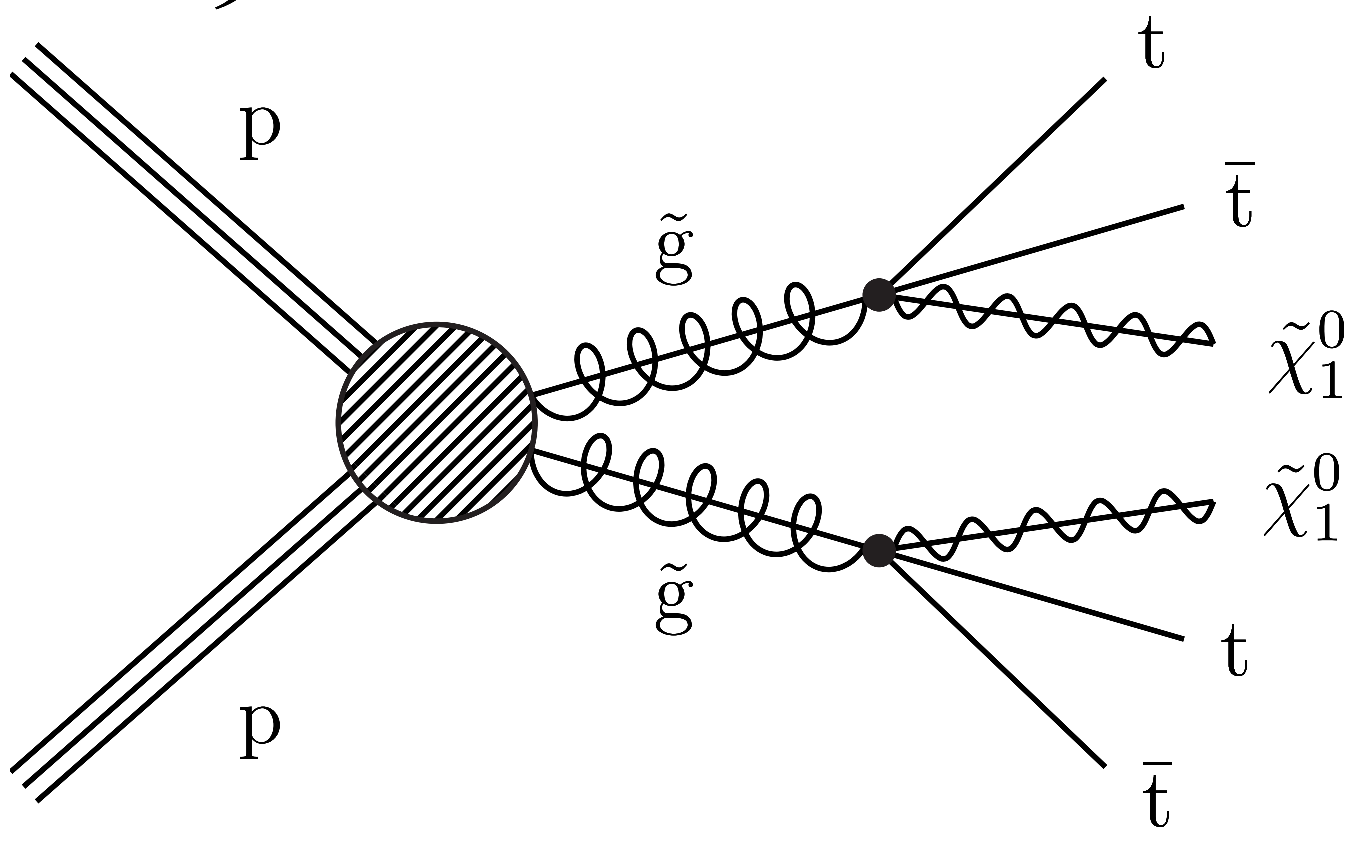
Recast by MadAnalysis 5

Third moment expansion

Alguero, JYA, Fuks, Kraml; SciPost, arXiv: 2206.14870

JYA, SciPost; arXiv: 2307.06996

CMS-SUS-19-006

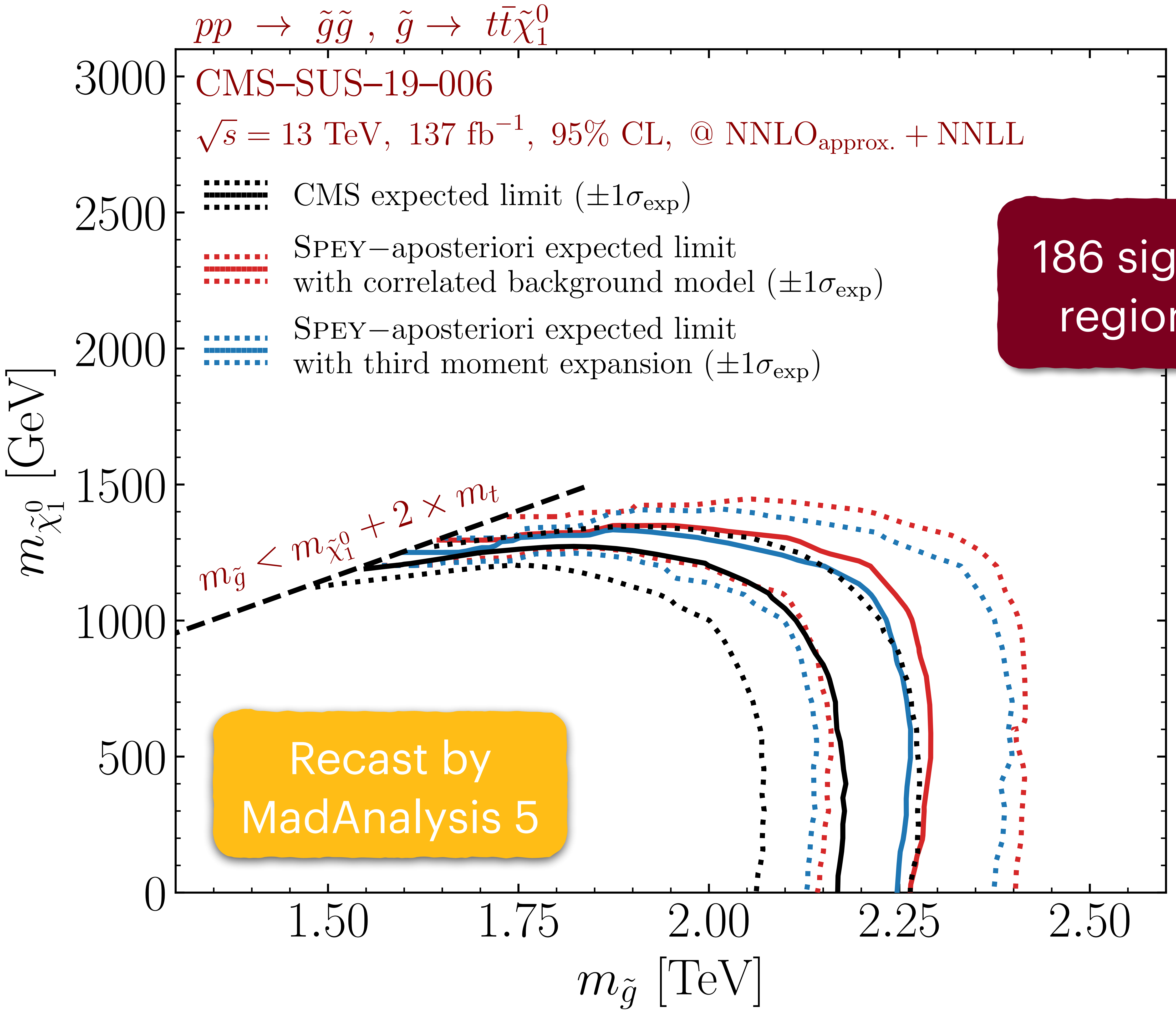


$$\mathscr{L}(\mu,\theta) = \left[\prod_{i\in \text{bins}} \text{Poiss}\left(n^i \,|\, \mu n_s^i + \bar{n}_b^i + A_i\theta_i + C_i\theta_i^2\right)\right] \cdot \mathcal{N}\left(\theta \,|\, 0, \bar{\rho}\right)$$

$\bar{n}_b^i$:= the central value of the background

A_i := the effective sigma of the background uncertainty

C_i := asymmetry of the background uncertainty



186 signal regions

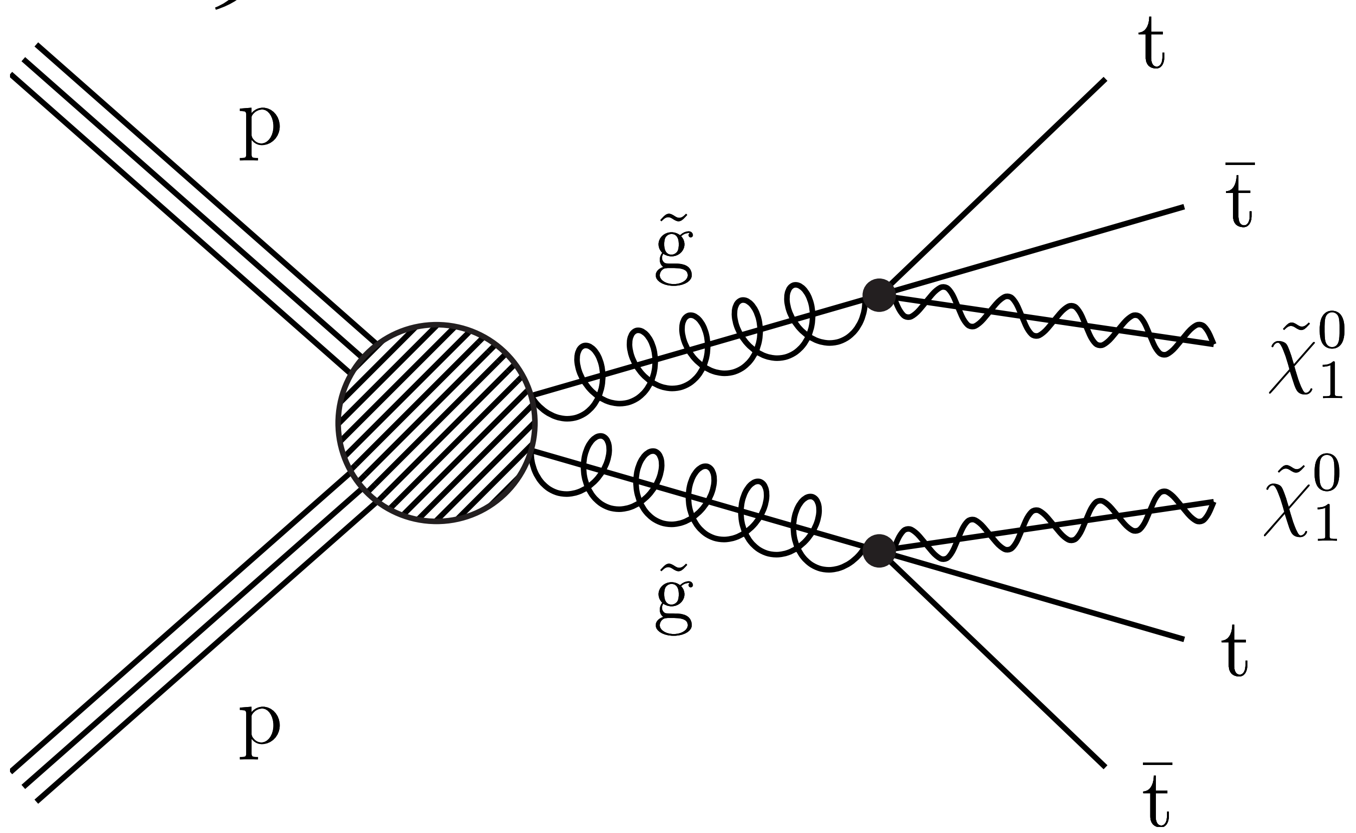
Recast by MadAnalysis 5

Buckley, Citron, Fichet, Kraml, Waltenberger, Wardle; JHEP '18

Asymmetric Uncertainties

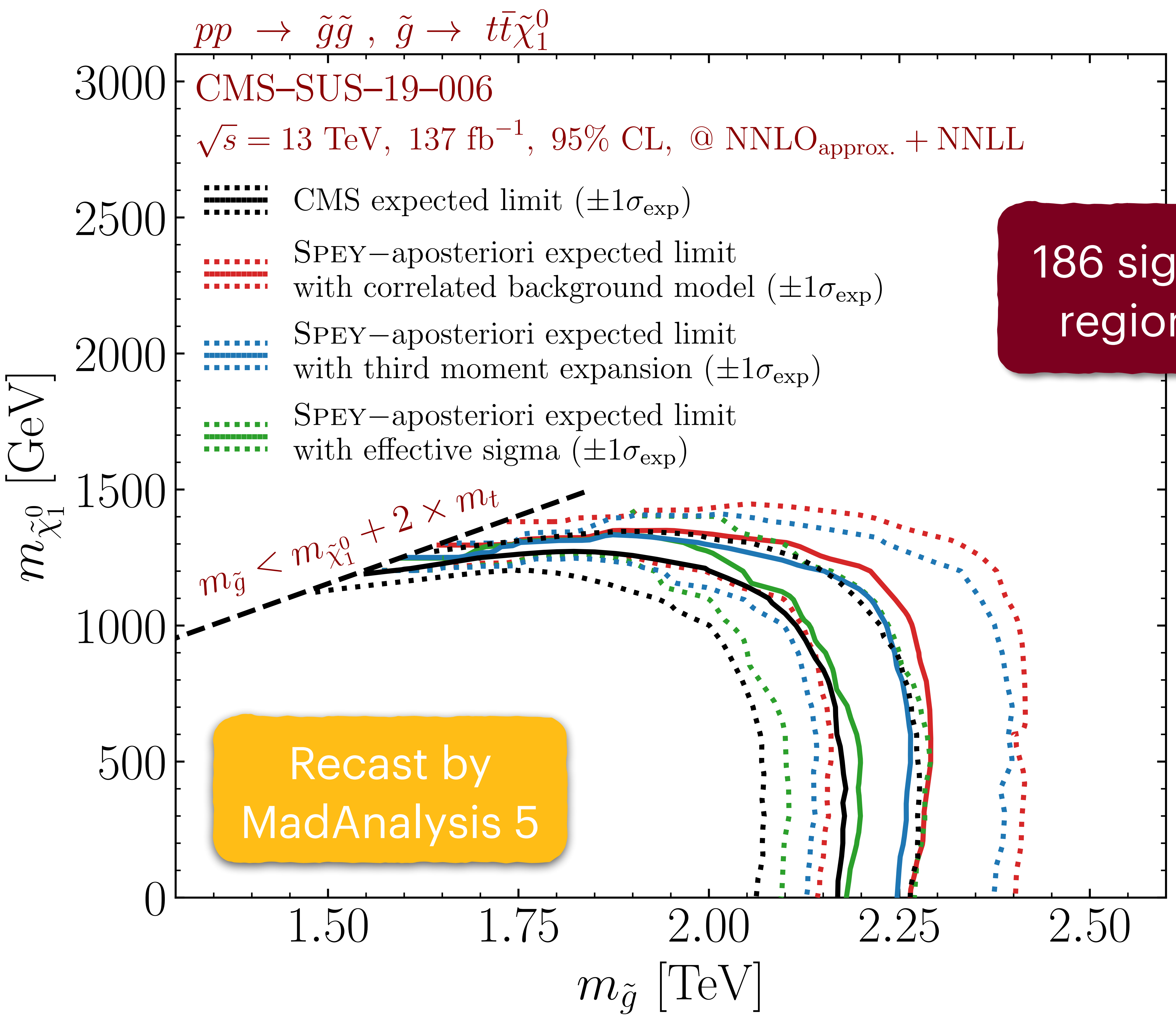
JYA, SciPost; arXiv: 2307.06996

CMS-SUS-19-006



$$\mathscr{L}(\mu,\theta) = \left[\prod_{i\in \text{bins}} \text{Poiss}\left(n^i \,|\, \mu n_s^i + n_b^i + \theta^i \sigma_{\text{eff}}^i(\theta^i)\right)\right] \cdot \mathscr{N}\left(\theta \,|\, 0, \rho\right)$$

$$\sigma_{\text{eff}}^i(\theta^i) = \sqrt{\sigma_i^+\sigma_i^- + (\sigma_i^+ - \sigma_i^-)(\theta^i - n_b^i)}$$

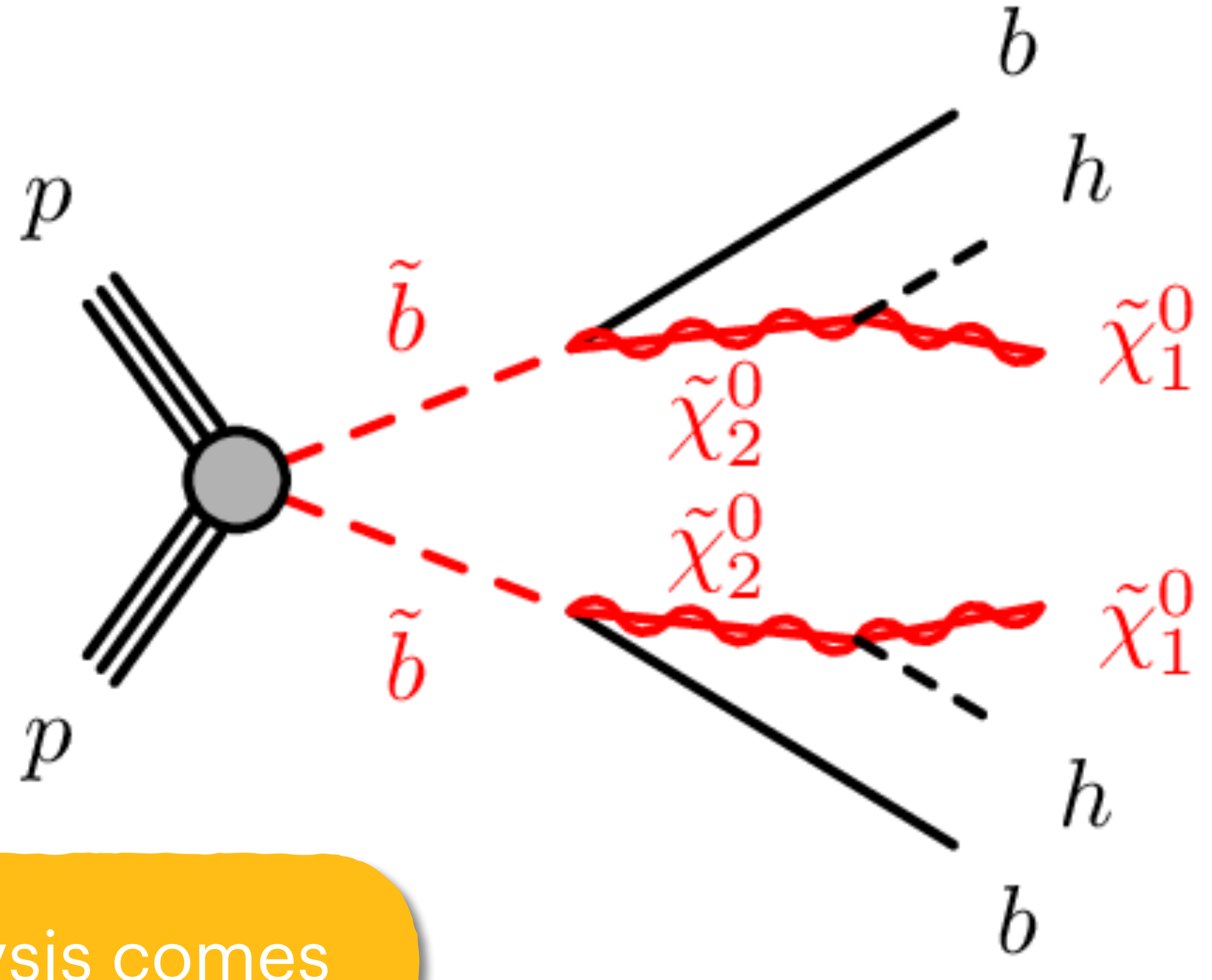


186 signal regions

Full likelihoods

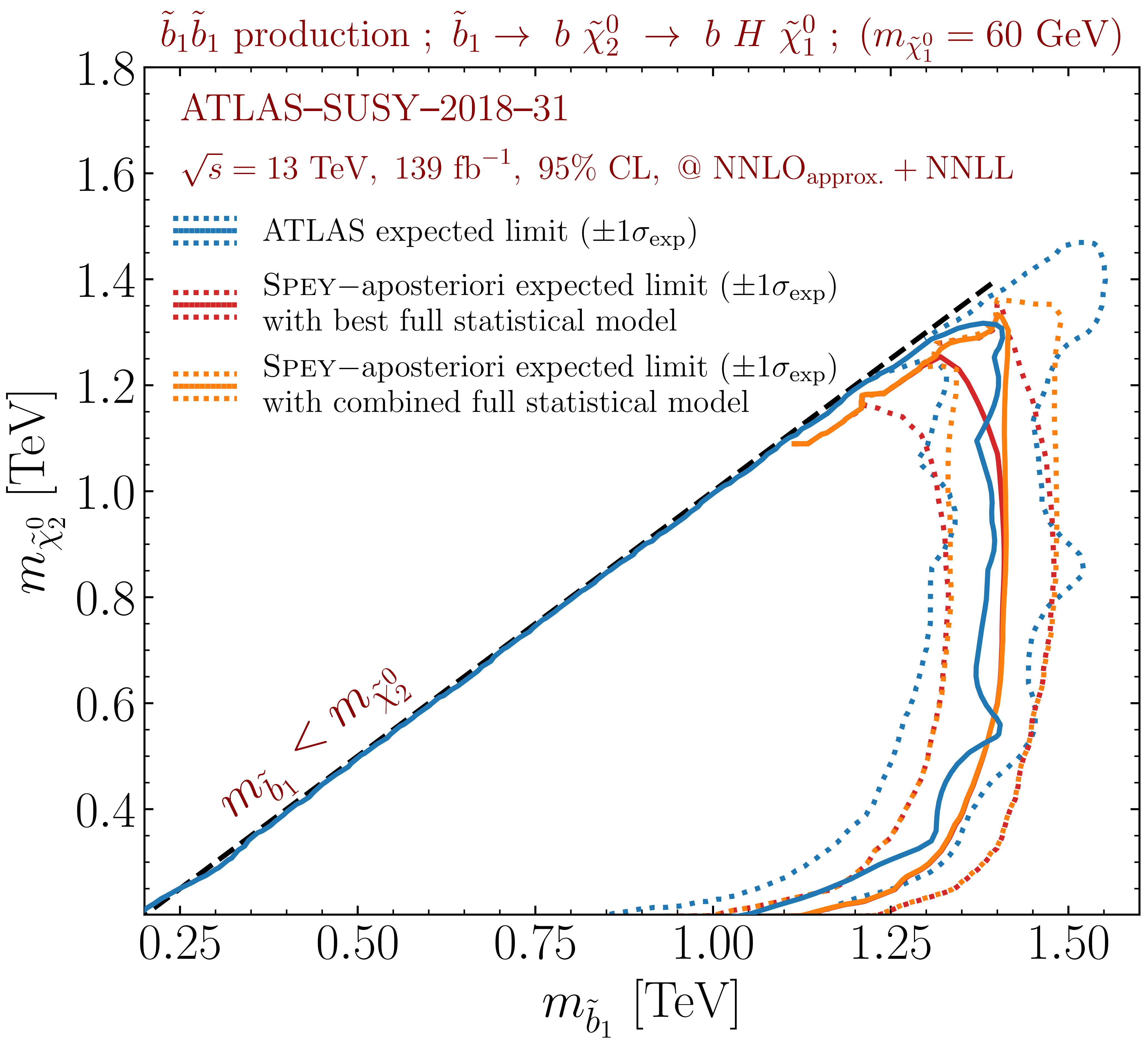
Alguero, JYA, Fuks, Kraml; SciPost, arXiv: 2206.14870

JYA, SciPost; arXiv: 2307.06996



This analysis comes with three different super regions!

Full likelihoods include all the necessary information to mix and match nuisance parameters to combine them!



Recast by MadAnalysis 5

Full Likelihoods

(Re)interpretation of the LHC results for new physics

29 August 2023 to 1 September 2023
Durham University

What we want

- A descriptive, domain-specific language for serializing models, and it should be
  - feature-complete with respect to ROOT (and all other common frameworks)
  - human-readable (at least in principle)
  - machine-readable with little effort
  - well documented to the point where someone implementing a new tool can reproduce the functionality with just the documentation
- Ideally, it should be suitable to
  - exchange models between analysts inside collaborations & outside
  - capable of being published on HEPdata or similar places
  - usable and modifiable by outsiders with little to no domain knowledge
  - useful for outreach and teaching activities
  - carry the legacy of the LHC experiments & their publications

technische universität dortmund

HS^3

High Energy Physics

Statistics Serialization Standard

Carsten Burgard

Tomas Dado, Jonas Eschle, Matthew Feickert, Cornelius Grunwald, Alexander Held, Robin Pelkner, Jonas Rembser, Oliver Schulz

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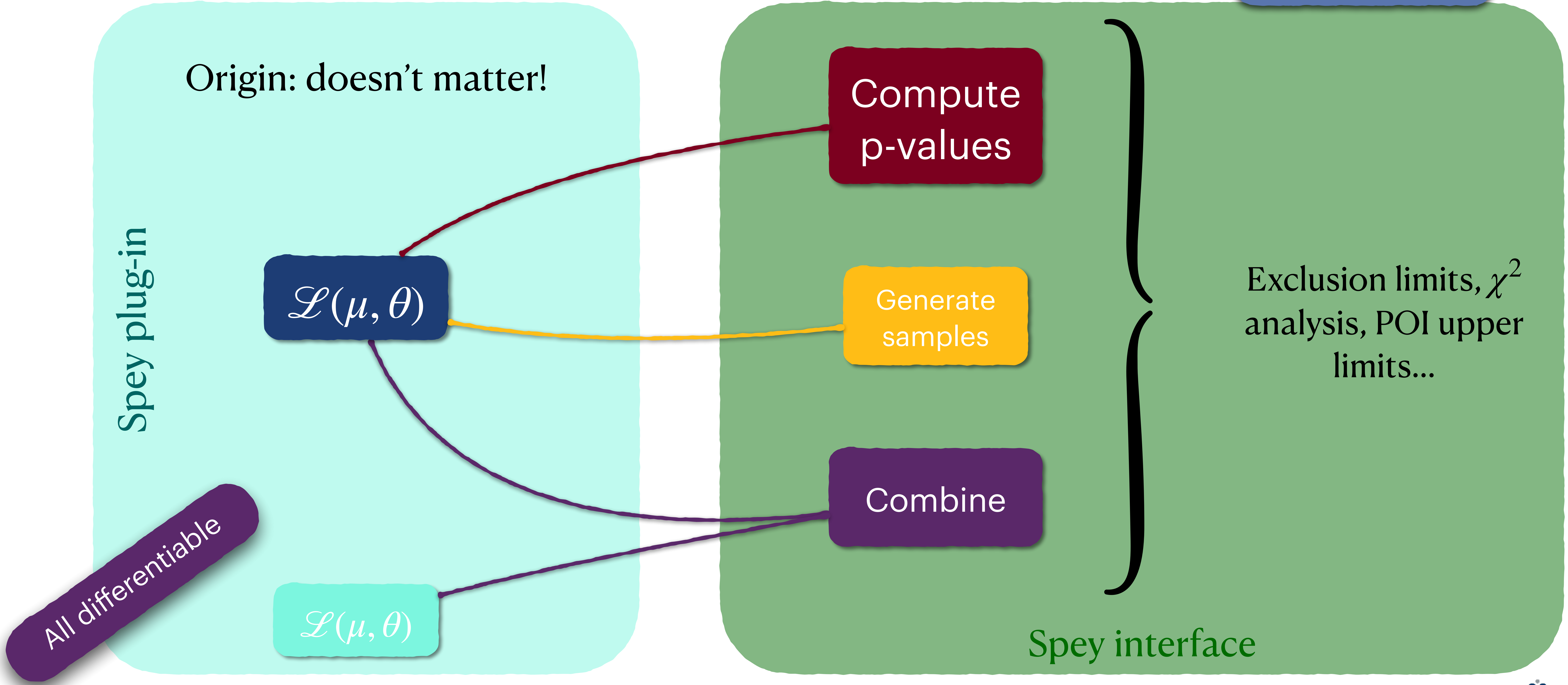
Towards global sensitivity

$$\mathscr{L}' = \mathscr{L}_{\rm ATLAS} \oplus \mathscr{L}_{\rm CMS} \oplus \underline{\mathscr{L}_{\rm EIC}} \oplus \mathscr{L}_{\rm Cosmology} \oplus \cdots$$

Add your favourite experiment here

Towards global sensitivity

JYA, SciPost; arXiv: 2307.06996



Towards global sensitivity

JYA, SciPost; arXiv: 2307.06996

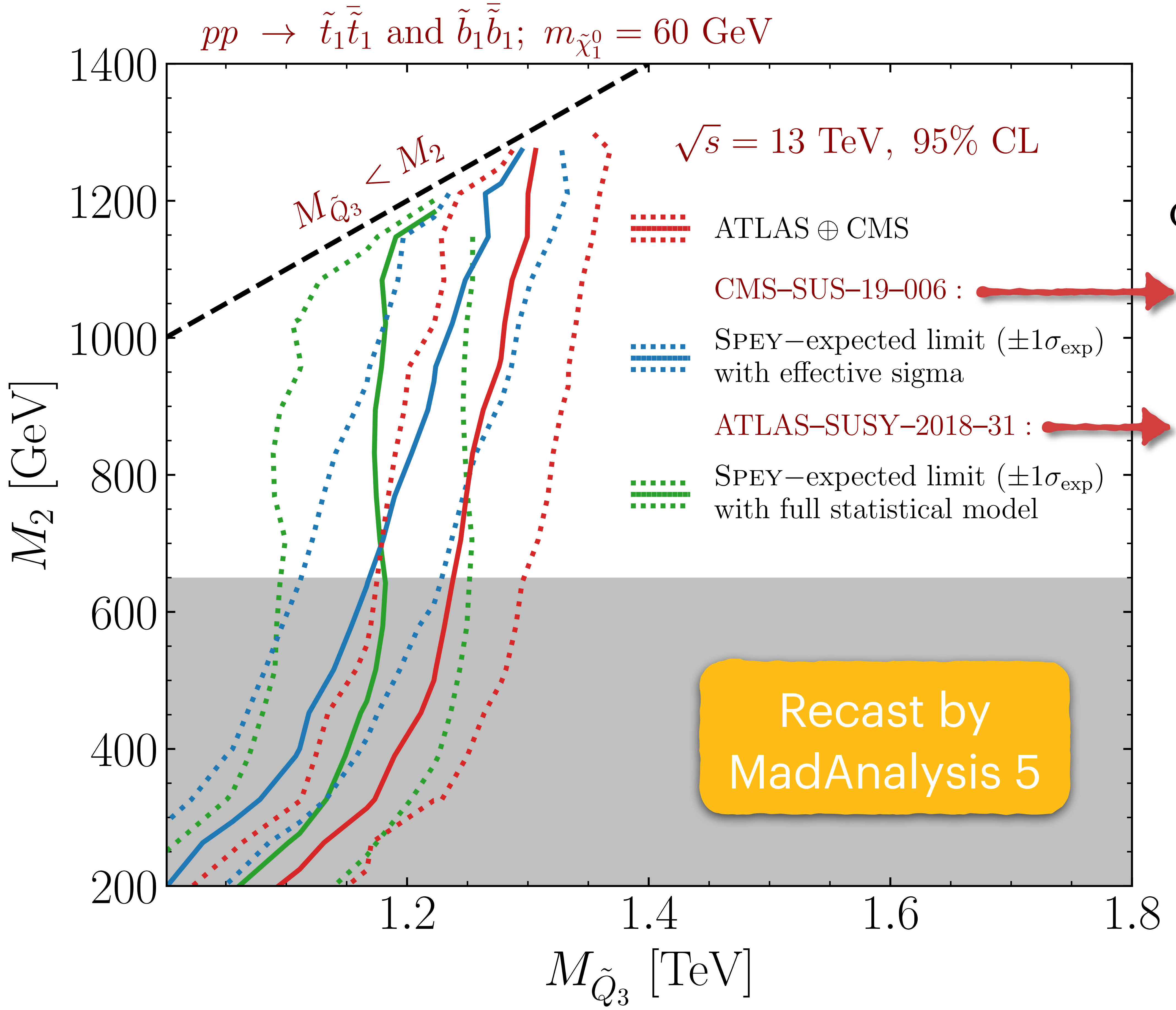
$$\mathscr{L}' = \mathscr{L}_{\rm ATLAS} \oplus \mathscr{L}_{\rm CMS}$$

Full likelihood

Simplified likelihood with effective sigma model

A combination of analyses, rather than regions, contains much more information!

MSSM: $M_1 = M_2 = M_3 = M_{\tilde{Q}}$ at GUT scale



Original analysis:

$pp \to \tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$

$pp \to \tilde{b}_1\bar{\tilde{b}}_1(\to bh\tilde{\chi}_2^0)$

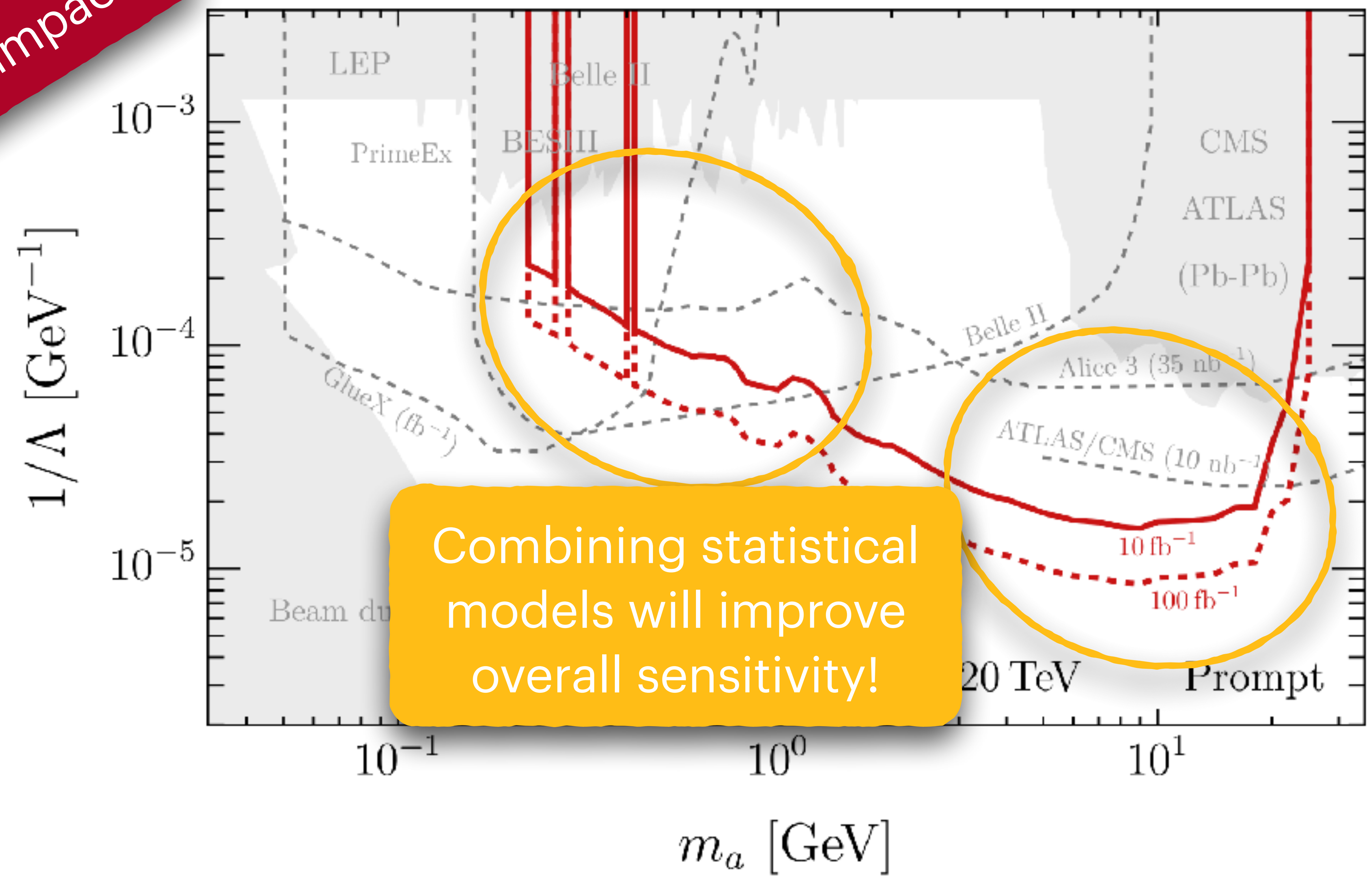
Towards global sensitivity

JYA, SciPost; arXiv: 2307.06996

See Hongkai's talk from Monday

EIC projections: prompt searches

Potential impact



Combining statistical models will improve overall sensitivity!

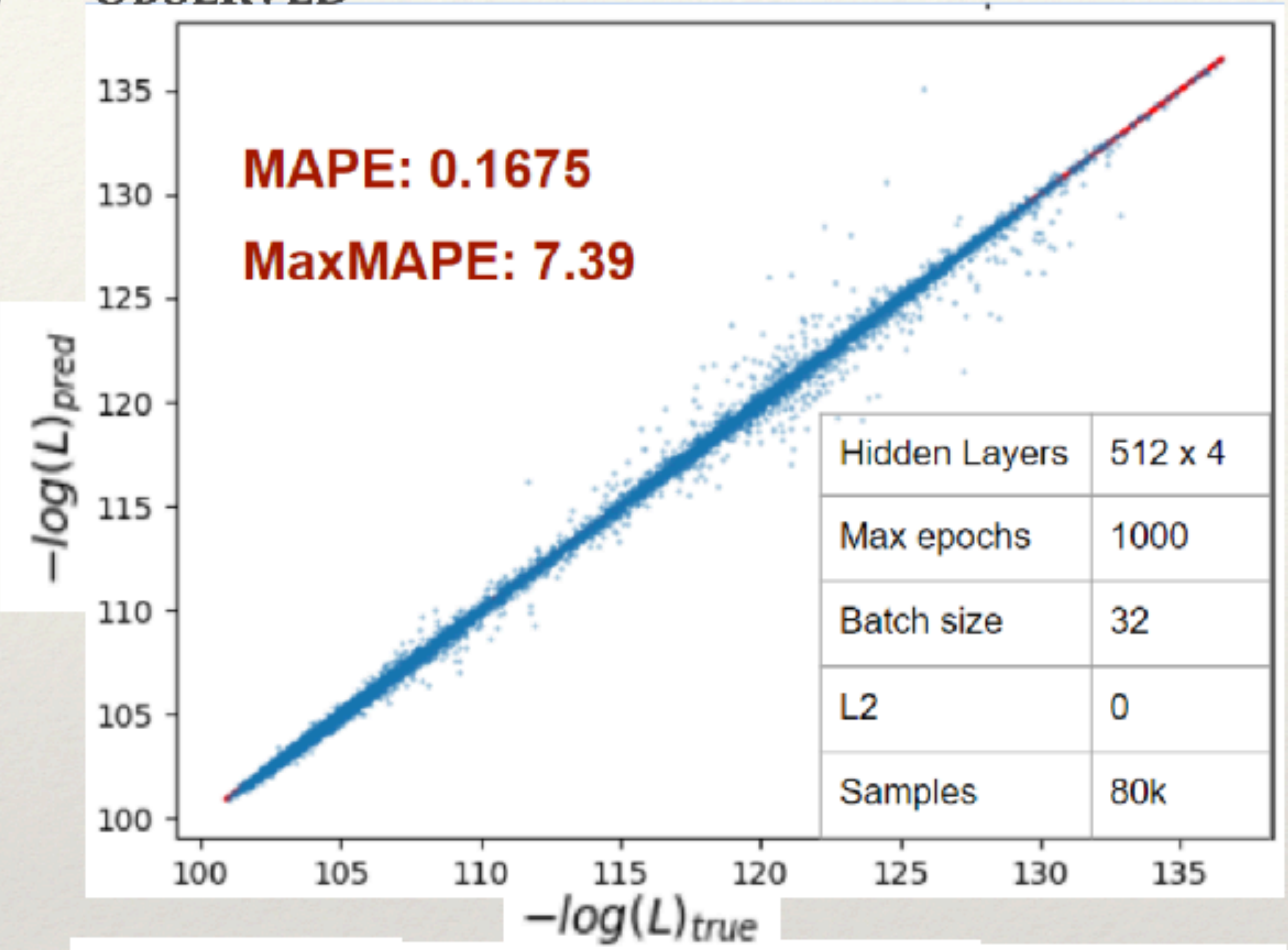
Going beyond: Machine learned likelihoods

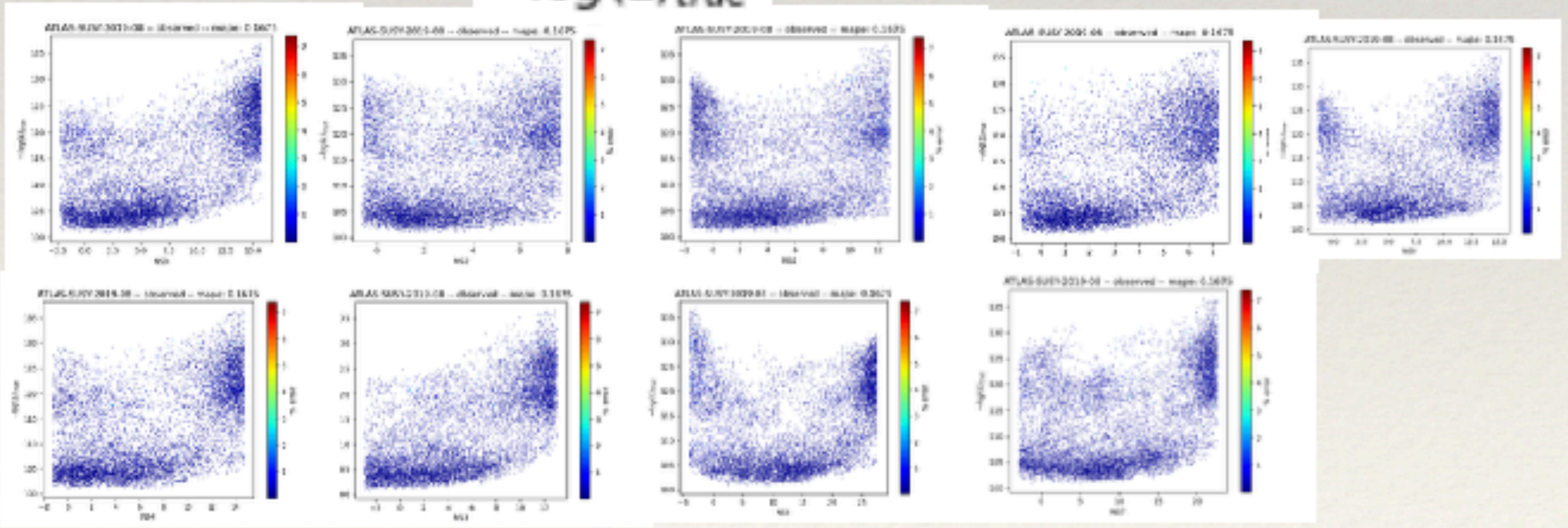
JYA, Reyes, Maselek, Kraml, Waltenberger; arXiv: 24xx.xxxxx

Preliminary

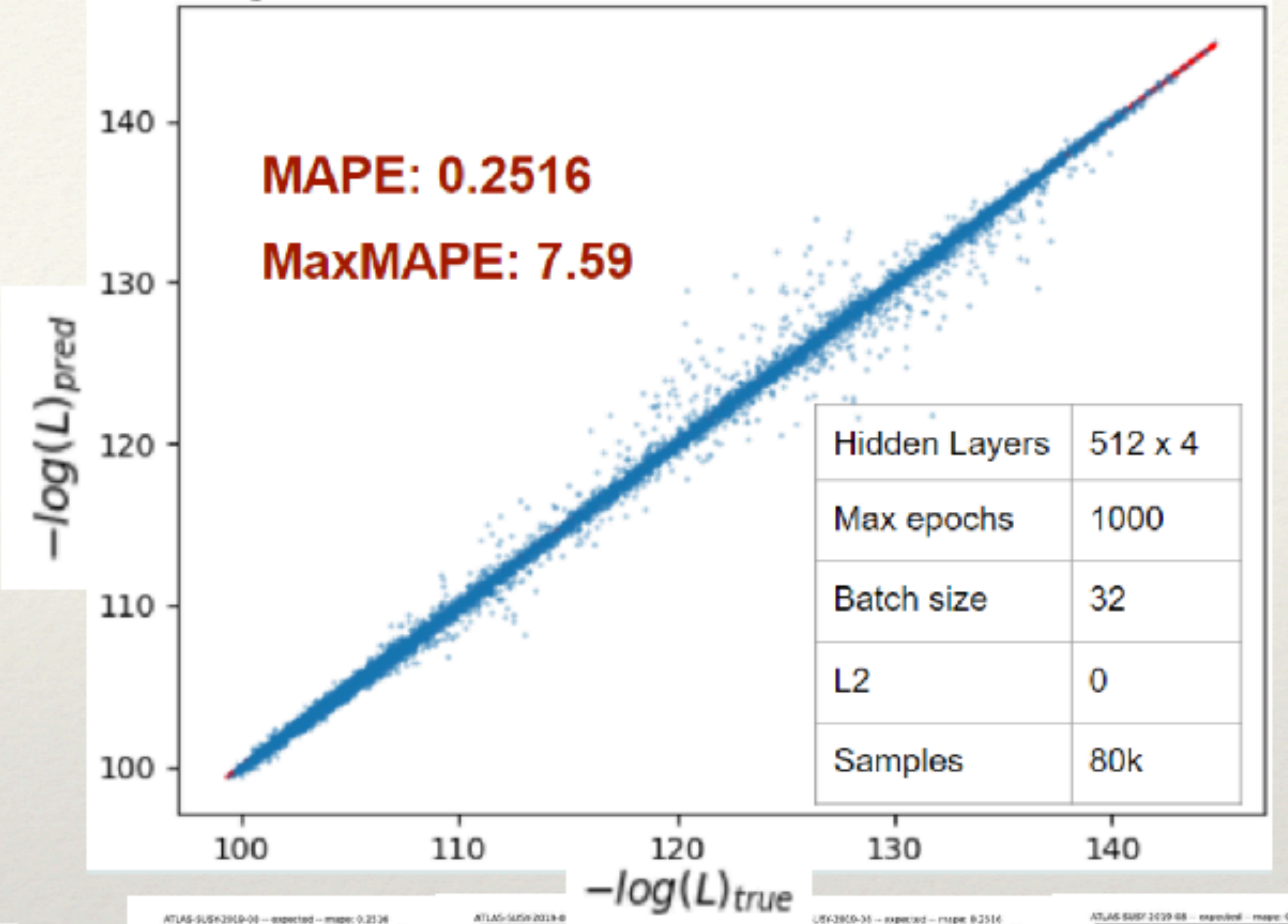
Results: ATLAS-SUSY-2019-08, 9 SRS

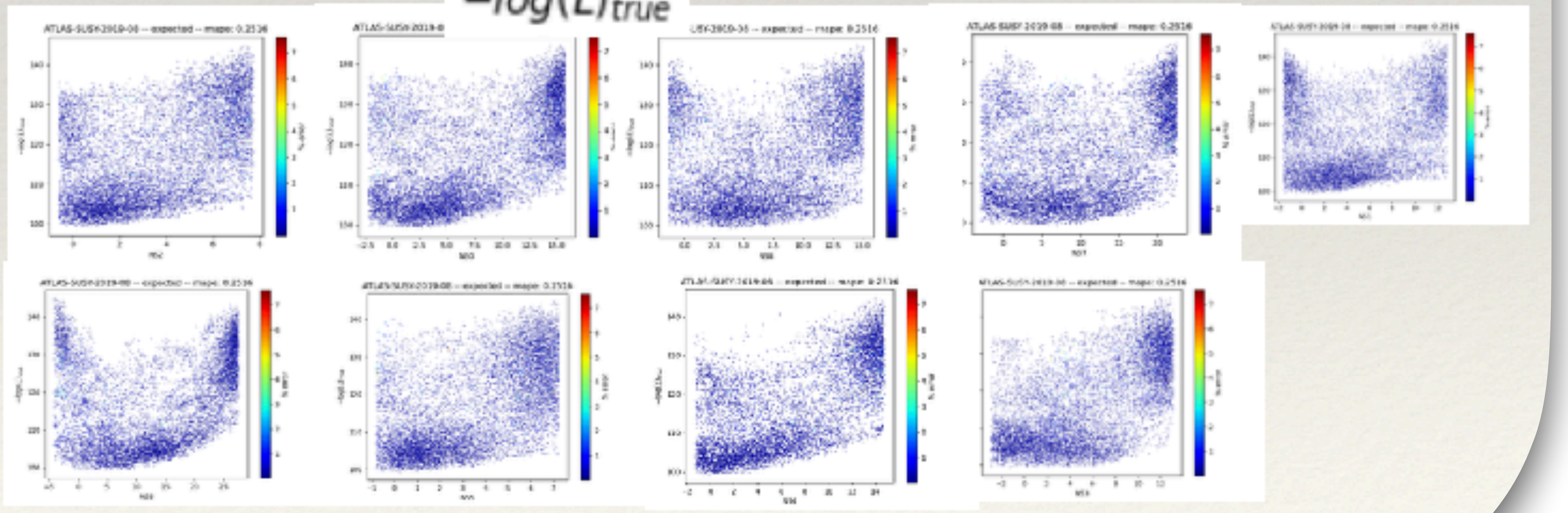
OBSERVED





EXPECTED





Slide from Humberto Reyes

Reusable ML-based analyses

You can reproduce the results of ML if I give you the weights and architecture, can't you?

Spoiler alert: No!

Reusable ML-based analyses

Snowmass 2021: Data and Analysis Preservation, Recasting, and Reinterpretation

Reinterpretation and Recasting Recommendations

5.1: Encourage that reinterpretability and reuse be kept in mind early on in the analysis design. This concerns, for instance, the choice of input parameters in ML models, the full specification of the fiducial phase space of a measurement in terms of the final state, including any vetos applied, and generally the choice of non-overlapping regions and standard naming of shared nuisances to facilitate the combination of analyses.

Why not? E.g. Extrapolation with ML

- Any observable that is used as a feature in ML has to be accurately reconstructable, e.g. b-tagged input with imperfect smearing.
- Unknown boundaries for input features.

Recommendation highlights

- Input features should not include detector-specific arguments, such as hits. If this is needed, the analysis should be shipped with a surrogate model.
- Extensive metadata, which specifies the domain limits of the input parameters, is needed.
- The model should be shipped in ONNX format, which is resistant with respect to the version dependencies.

JYA, Buckley, Kasiecka, et al.; arXiv: 2312.14575

Conclusion

Conclusion

- Reinterpretable analyses are essential for the preservation of the experimental results.
- Providing the full or simplified likelihoods allows for a much more accurate representation of the results.
- ML has a very important role in data analysis. Reusability should be kept in mind early on.
- MadAnalysis collaboration is taking the necessary steps to provide the toolset needed for reusable analyses by the HEP community, and we are happy to work with experimentalists to enable a reinterpretable workflow early on for EIC.