

Seeking a coherent explanation of LHC excesses for compressed spectra

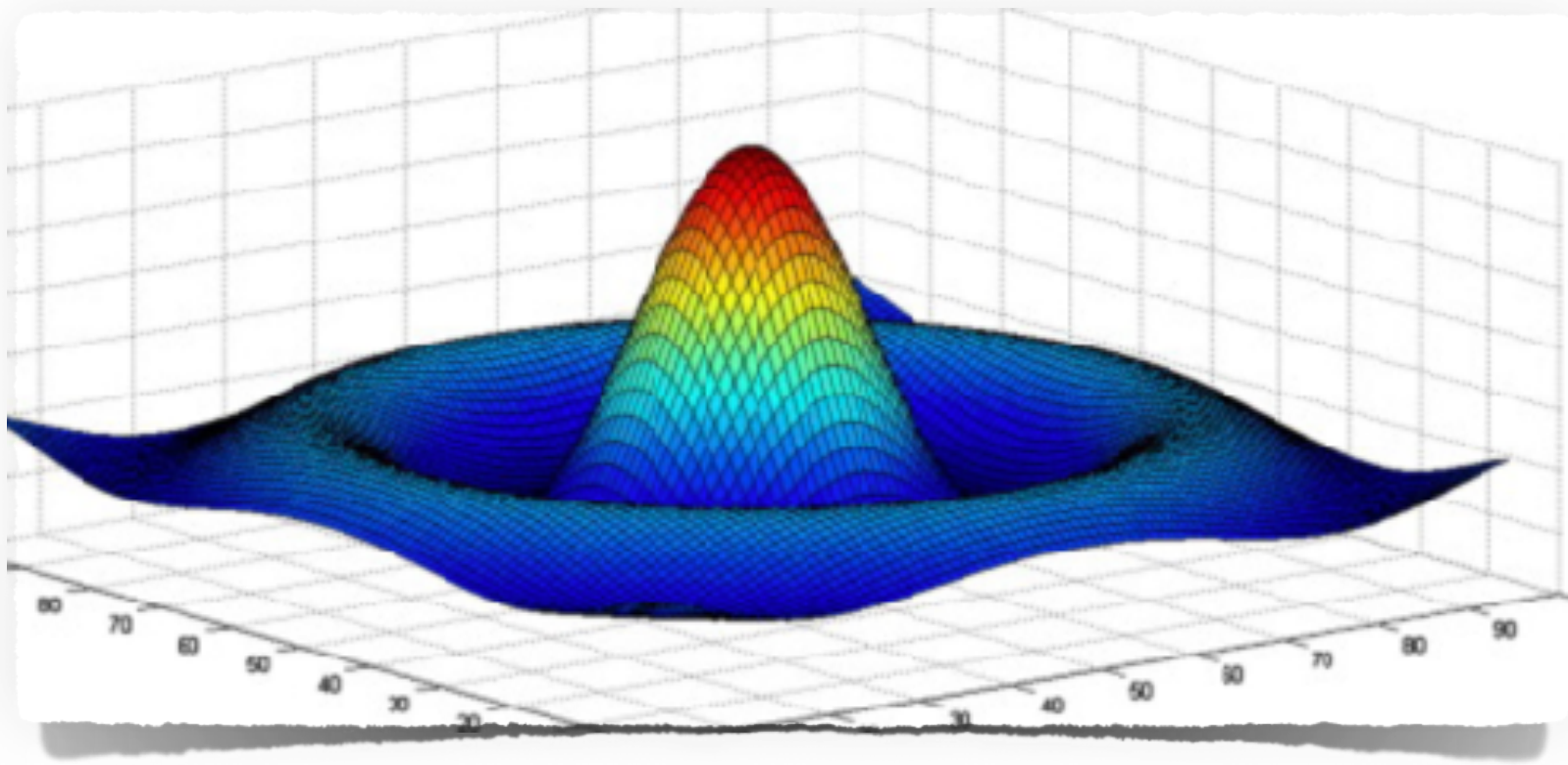
Benjamin Fuks

LPTHE / Sorbonne Université

High-energy physics seminar

Institut Jožef Stefan – 23 October 2025

Going beyond the Standard Model?



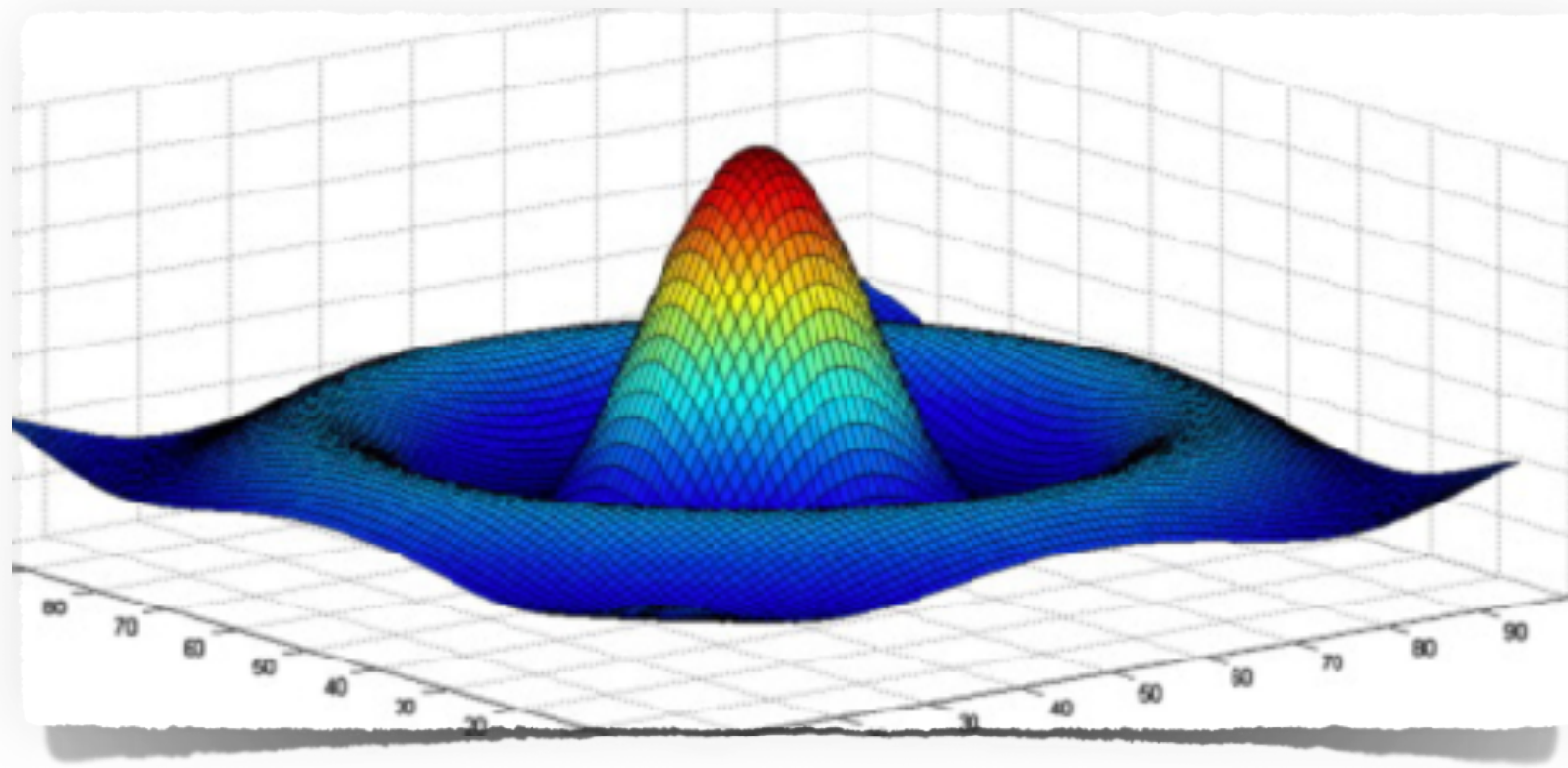
SM extremely successful

- Agreement with a century of data
- No clear sign of new phenomena

Why going beyond ?

- Practical limitations
- Conceptual issues
- Few experimental anomalies

Going beyond the Standard Model?



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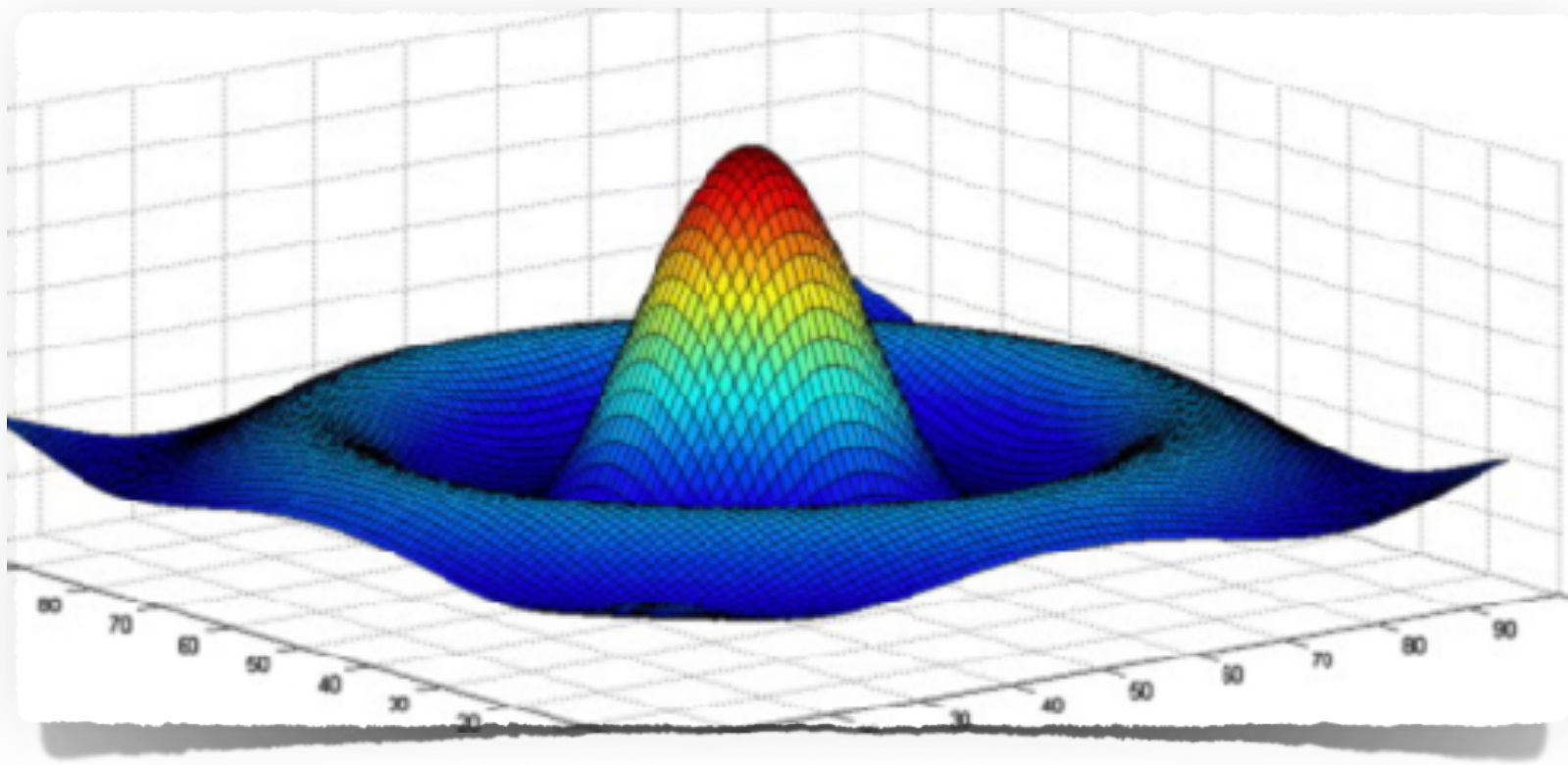
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Some issues of the SM

- Naturalness of the theory / hierarchy problem
- Neutrino masses
- Dark matter
- Gauge structure of the theory
- Origins of CP violation
- Matter/antimatter asymmetry
- Lepton/quark mixings and masses
- Dark energy
- Four-dimensionality of space-time
- Gravity

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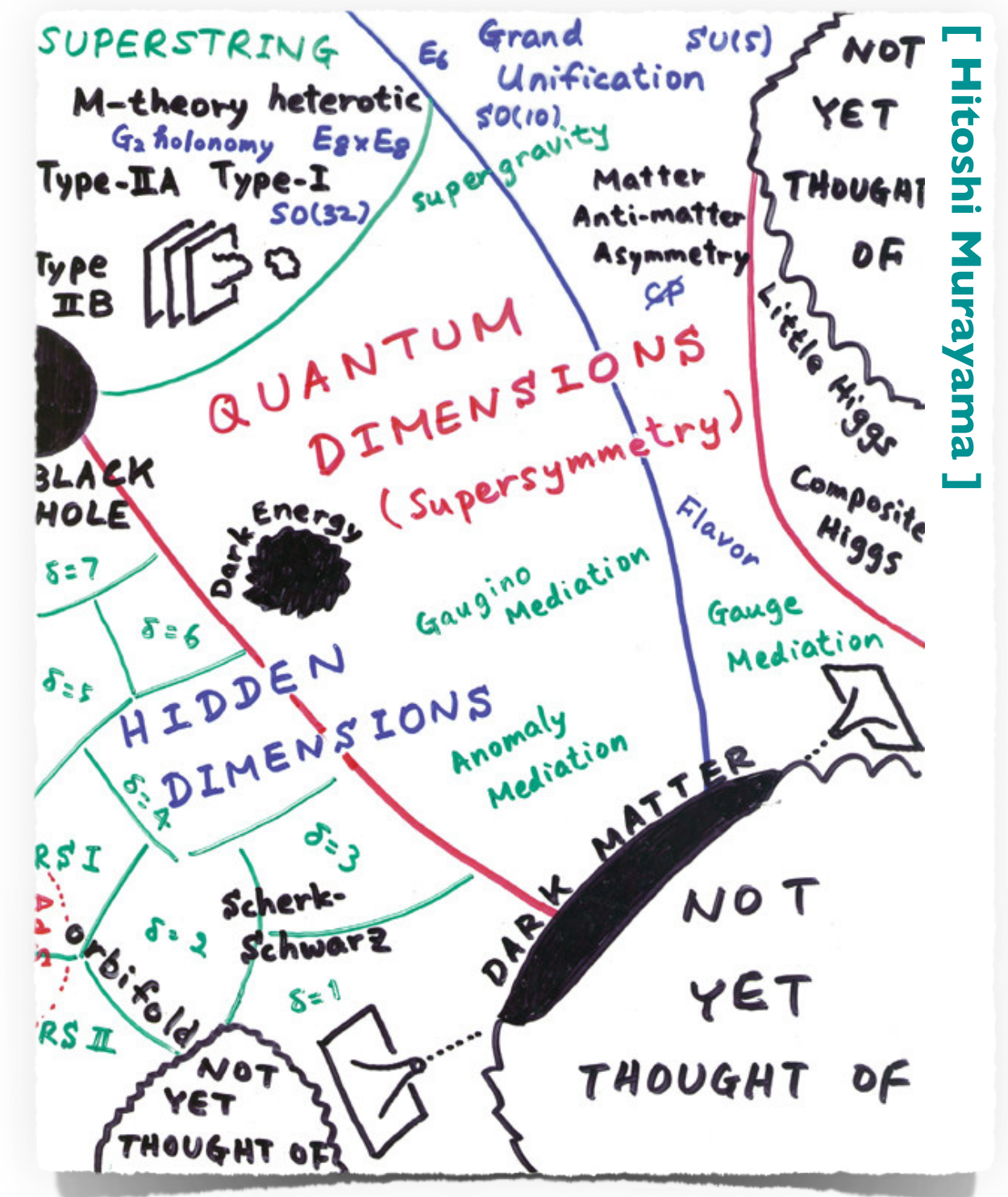
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SM $\equiv$ tip of the iceberg

- BSM exploration to solve its issues
- No clear path
 - Supersymmetry / Dark matter $\equiv$ (excellent) ways
 - Collider signals comprising missing transverse energy

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Supersymmetry as a general QFT

Most general quantum field theory

- SUSY natural in any generic QFT with a generic symmetry
- Noether and spin-statistics $\rightarrow$ the Poincaré superalgebra
- **Unification of the external and internal symmetries**
 $\rightarrow$ Algebra: $\mathfrak{iso}(1,3) \times \mathfrak{g}_{\text{int}} \oplus$ fermionic part

[Coleman, Mandula (PhysRev '67)]

[Haag, Lopuszanski, Sohnius (NPB '75)]

[BF (Habilitation Thesis, 2014)]

$$\begin{aligned} [M^{\mu\nu}, M^{\rho\sigma}] &= -i(\eta^{\nu\sigma} M^{\rho\mu} - \eta^{\mu\sigma} M^{\rho\nu} + \eta^{\nu\rho} M^{\mu\sigma} - \eta^{\mu\rho} M^{\nu\sigma}) , \\ [M^{\mu\nu}, P^\rho] &= -i(\eta^{\nu\rho} P^\mu - \eta^{\mu\rho} P^\nu) , \\ [T_a, T_b] &= if_{ab}{}^c T_c , \\ [Q_\alpha, M^{\mu\nu}] &= \sigma^{\mu\nu}{}_\alpha{}^\beta Q_\beta , \quad [\bar{Q}^\alpha, M^{\mu\nu}] = \bar{\sigma}^{\mu\nu}{}^{\dot{\alpha}}{}_{\dot{\beta}} \bar{Q}^{\dot{\beta}} , \\ \{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} &= 2\sigma^\mu{}_{\alpha\dot{\alpha}} P_\mu , \\ [Q_\alpha, R] &= Q_\alpha , \quad [\bar{Q}_{\dot{\alpha}}, R] = -\bar{Q}_{\dot{\alpha}} , \\ [P^\mu, P^\nu] &= [P_\mu, Q_\alpha] = [P_\mu, \bar{Q}_{\dot{\alpha}}] = \{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = 0 , \\ [T_a, P^\mu] &= [T_a, M^{\mu\nu}] = [Q_\alpha, T_a] = [\bar{Q}_{\dot{\alpha}}, T_a] = 0 . \end{aligned}$$

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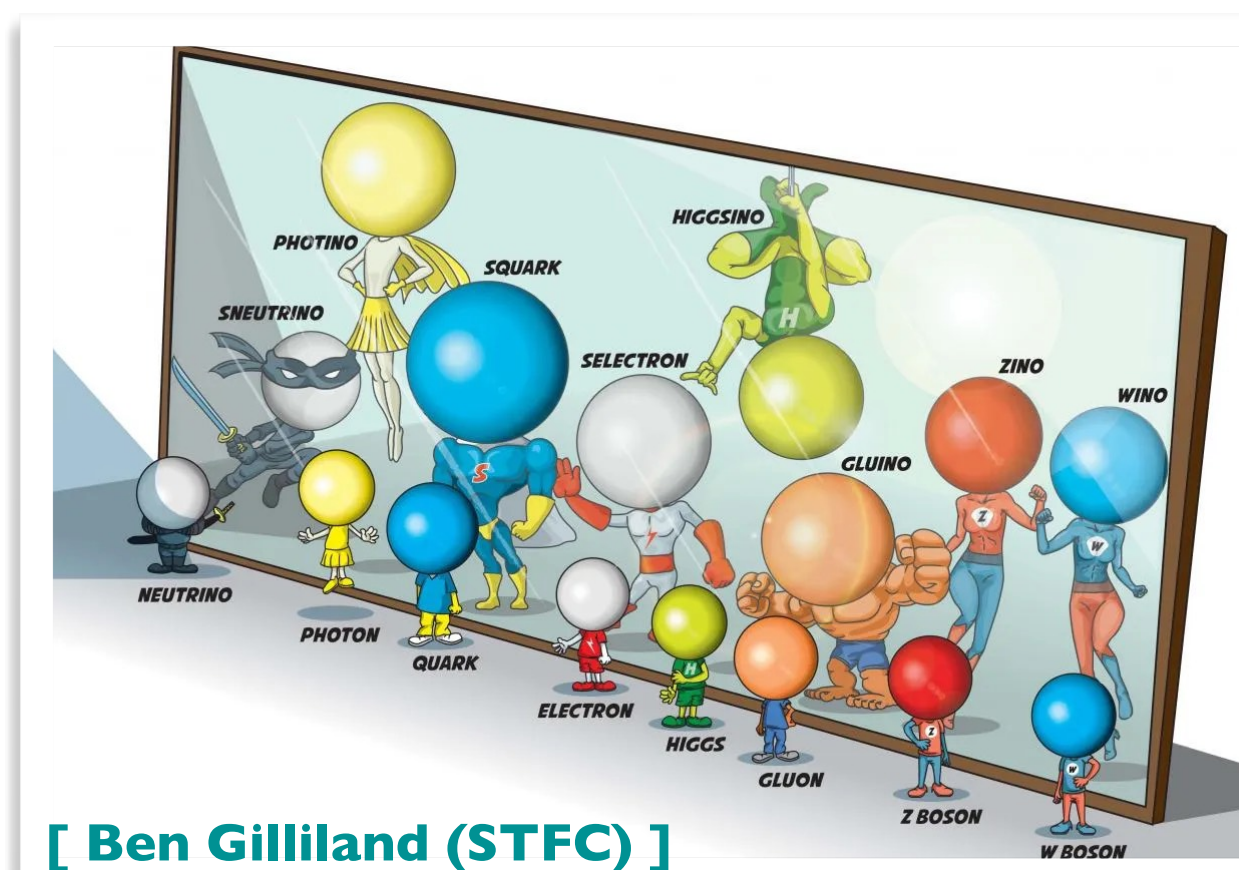
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Representations of the Poincaré superalgebra

- Minimality: 1 supercharge
- SM states associated with superpartners of opposite statistics

$$Q|F\rangle = |B\rangle \quad Q|B\rangle = |F\rangle$$



[Ben Gilliland (STFC)]

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Supersymmetry broken

- No observation of a SUSY state with a SM mass
- Unknown breaking mechanism
 $\rightarrow$ **100s free parameters**
 $\rightarrow$ Simplest options: 5–10 parameters (supergravity, gauge mediation, ...)

SUSY as a cure to the SM problems

Scalar masses protected with respect to quantum corrections

- Hierarchy problem fixed
- SUSY breaking soft
- Superpartners not too heavy $\rightarrow$ strong motivation for the LHC

[Witten (NPB '81)]

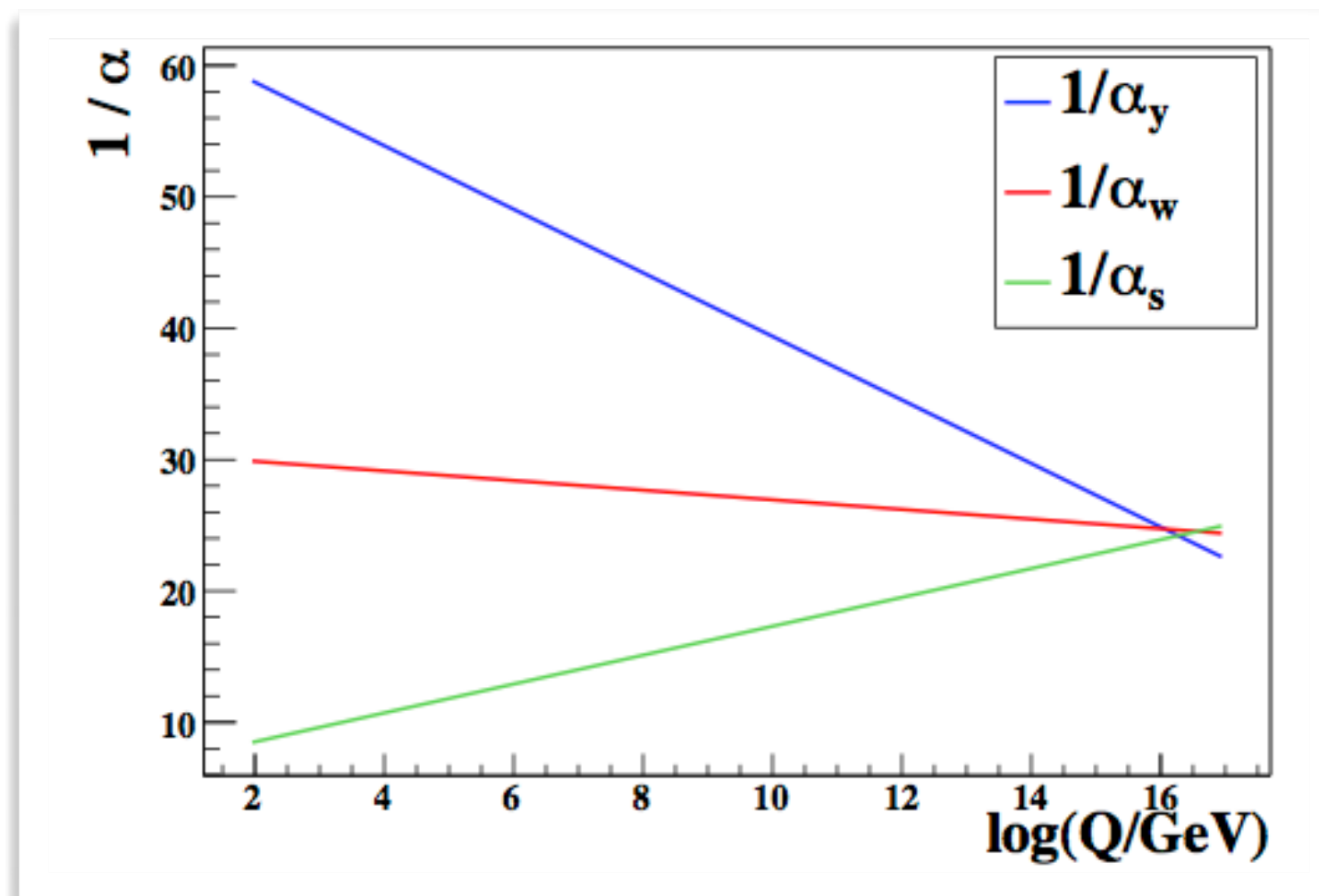


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RG running of the gauge couplings

- Superpartners in the loops
- Unification at high energies

[Ibanez, Ross (PLB '81)]

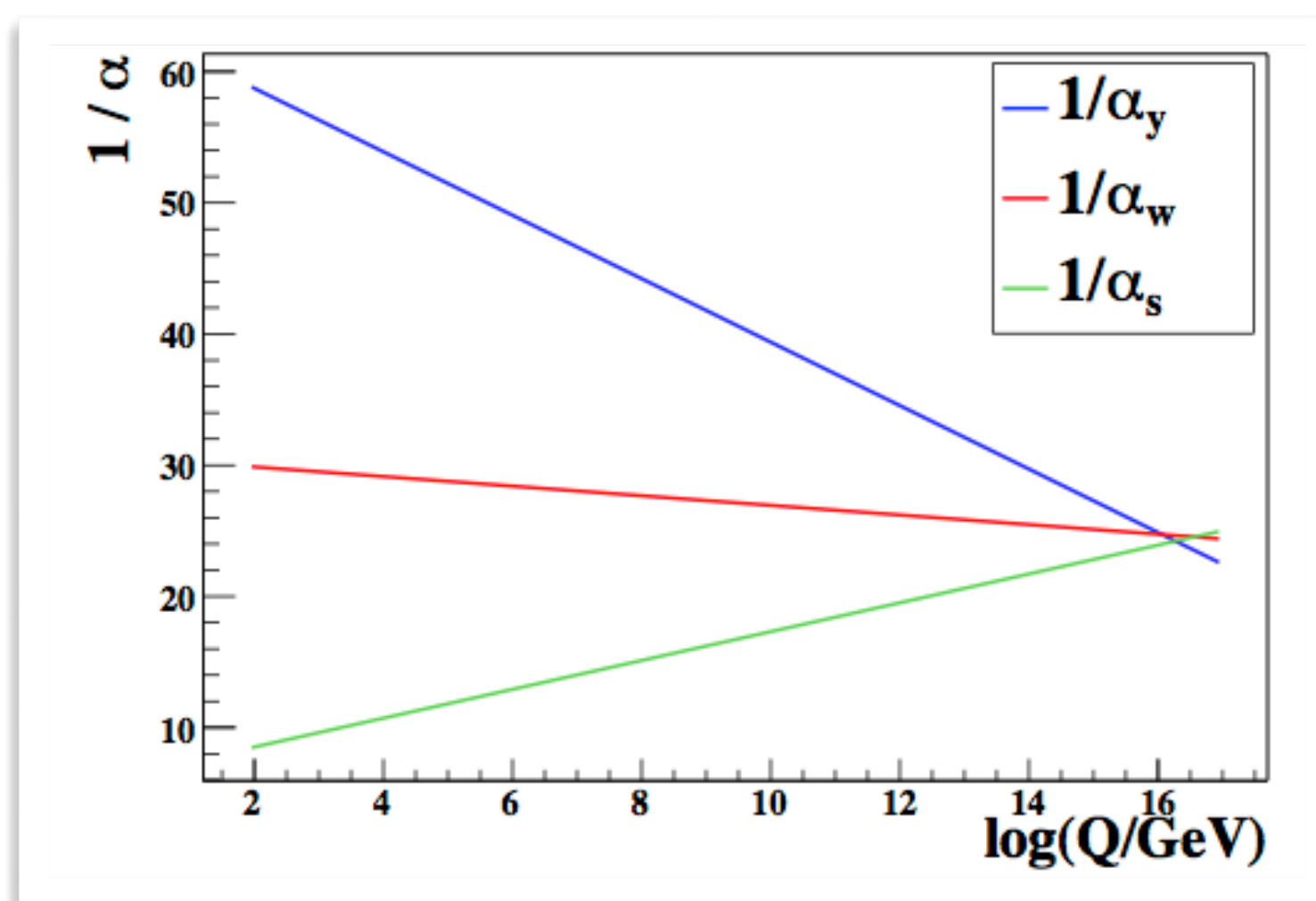
[Dimopoulos, Raby, Wilczek (PRD '81)]

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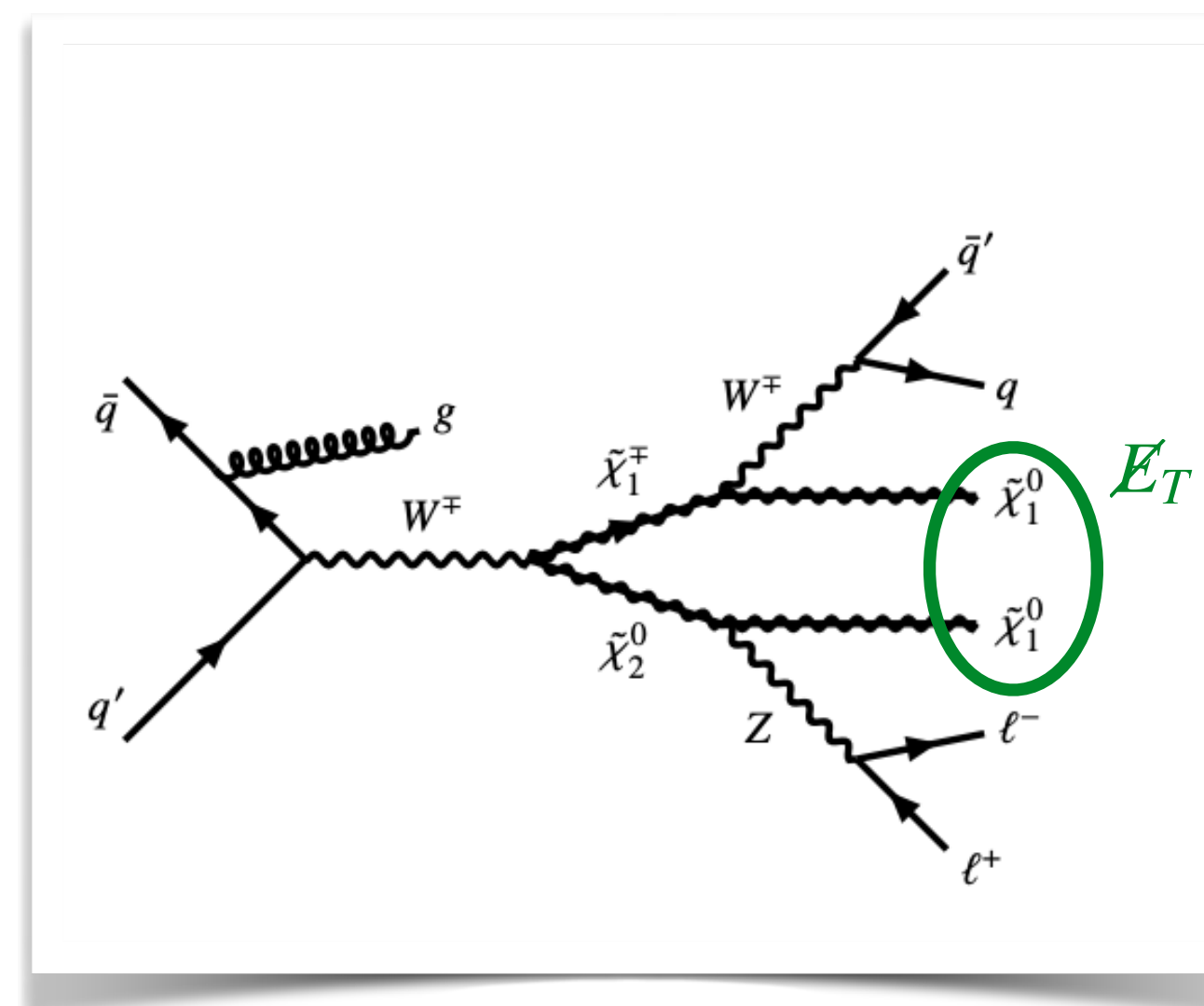
[Ibanez, Ross (PLB '81)]

[Dimopoulos, Raby, Wilczek (PRD '81)]

R-parity conservation

[Farrar, Fayet (PLB'78)]

- SM states: $R=+1$ / SUSY partners: $R = -1$
- Proton stability
- Lightest SUSY state: **DM candidate** (if neutral/colourless)
- **Missing transverse energy** and pair production at colliders

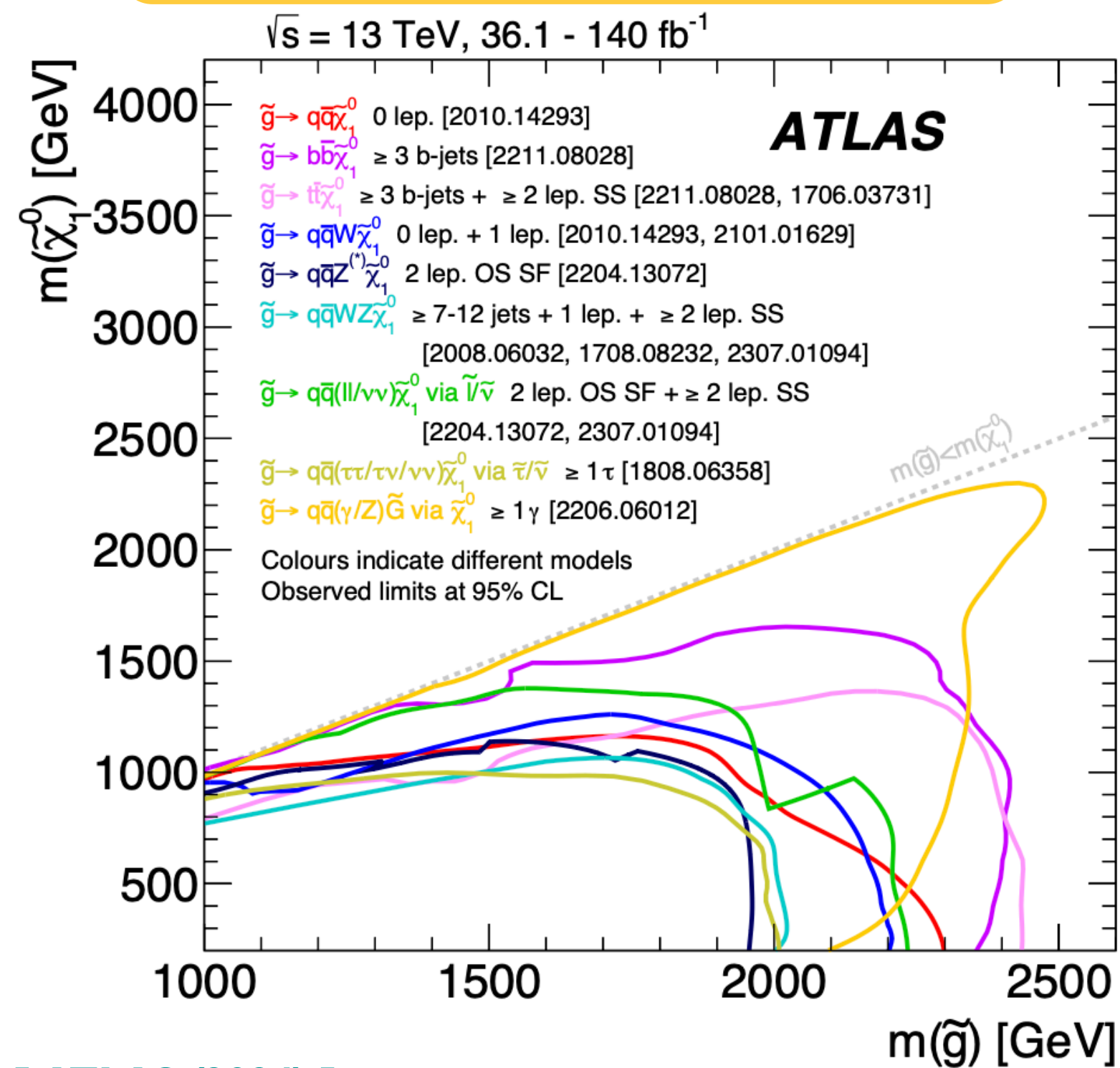


Where are we with supersymmetry (and simplified models)?

Typical MSSM searches at the LHC (with R -parity)

- Missing energy and visible objects (jets, leptons, etc.)
 - **Stringent bounds** deep in the TeV regime
 - Both for strong and EW superpartners

$\tilde{g}$ constraints with jets, leptons and MET

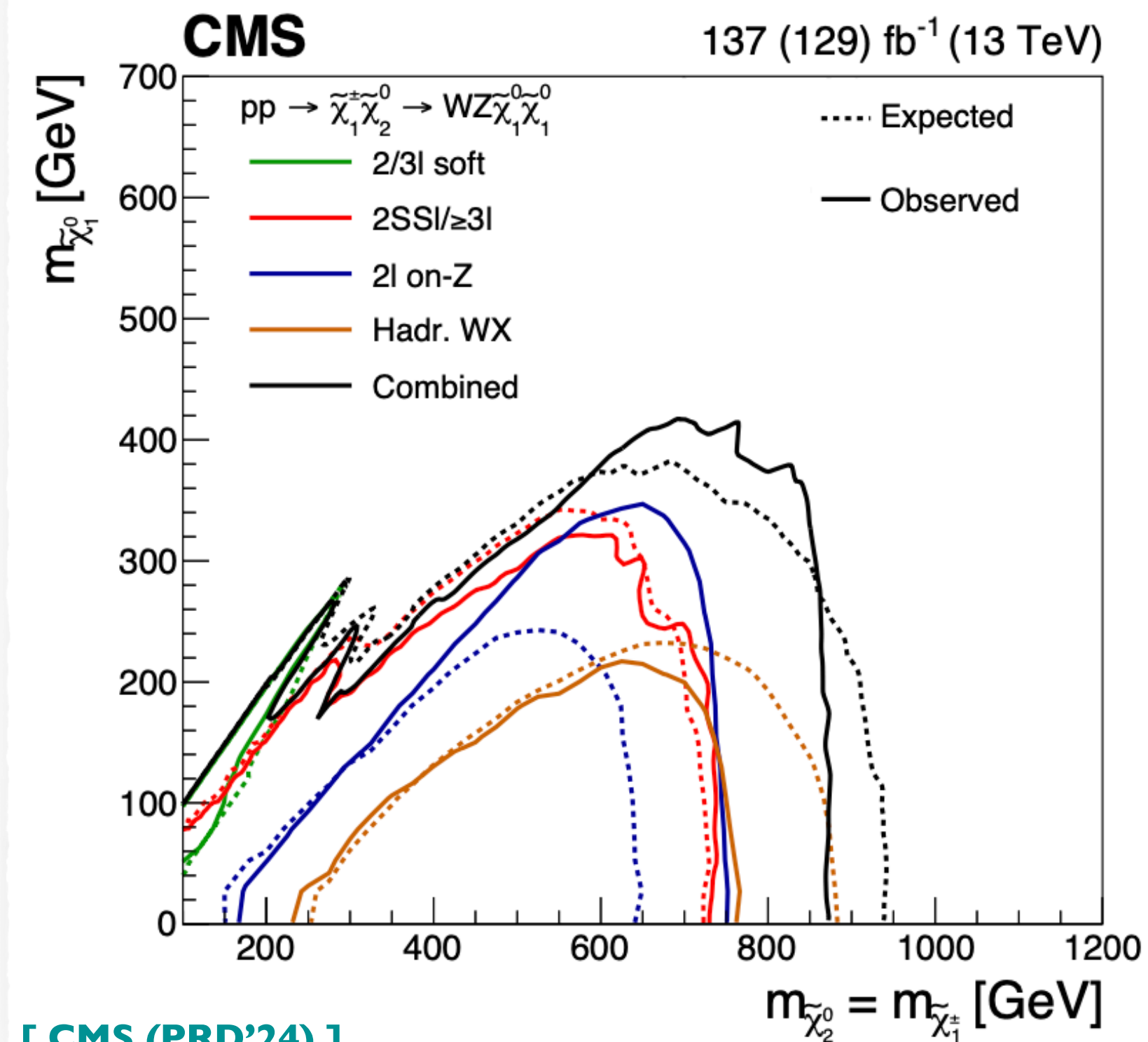


[ATLAS (2024)]

Interpretation on simplified models

- SM + few states
 - Generally **2 or 3 free parameters** (masses)

$\tilde{W}/\tilde{B}$ constraints with jets, leptons and MET



[CMS (PRD'24)]

Is SUSY dead ?

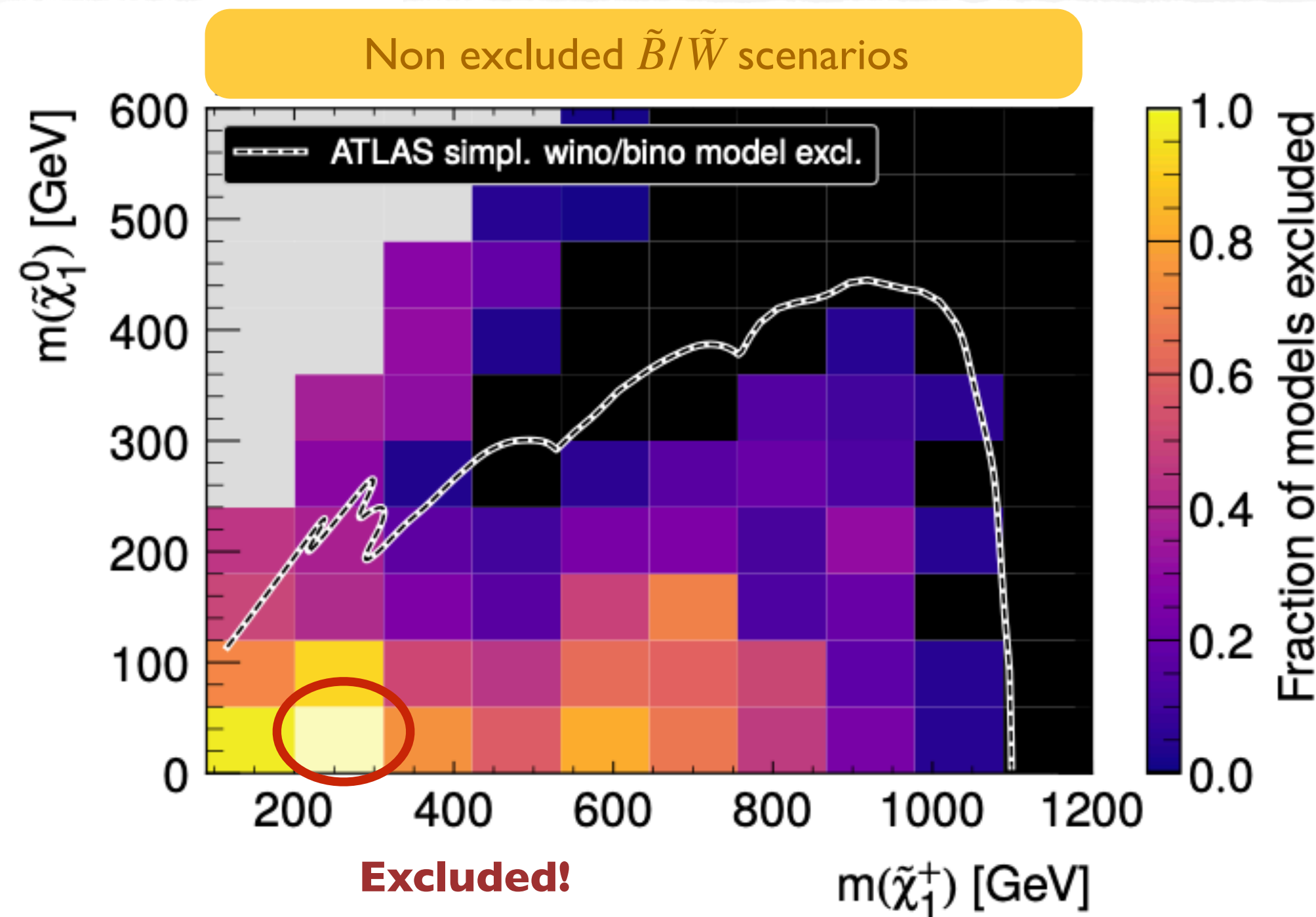
Is SUSY in bad shape ?

- **Not really:** MSSM-inspired simplified models
 - Most superpartners decoupled
 - Specific decay table
- Signatures typically more complex
 - **Constraints not necessarily that strong**

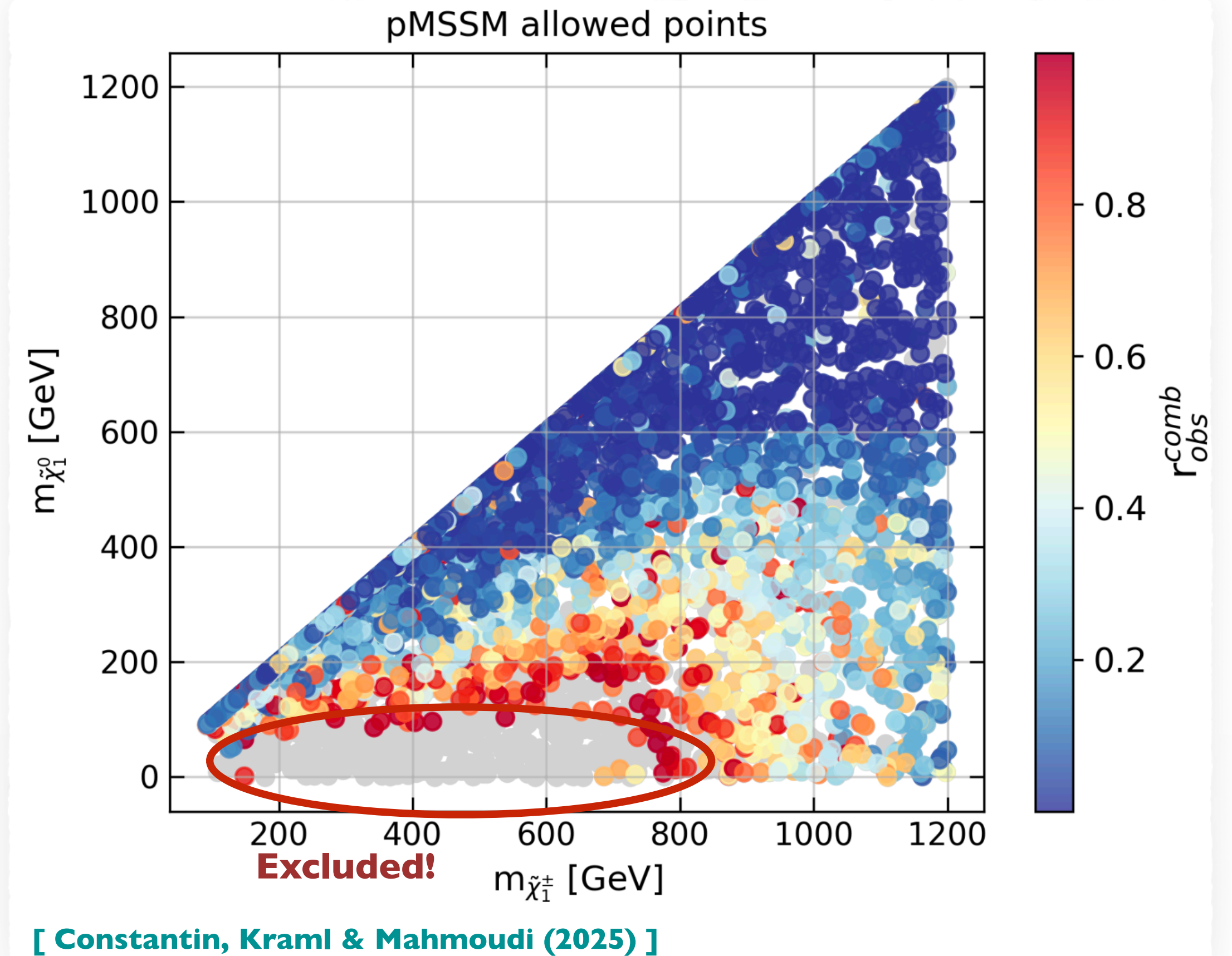
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[ATLAS (JHEP'24)]



Example: ATLAS pMSSM scan (20,000 scenarios)

- Points survival (almost) at all masses
- Combining analyses not too helpful to kill SUSY

What's next?

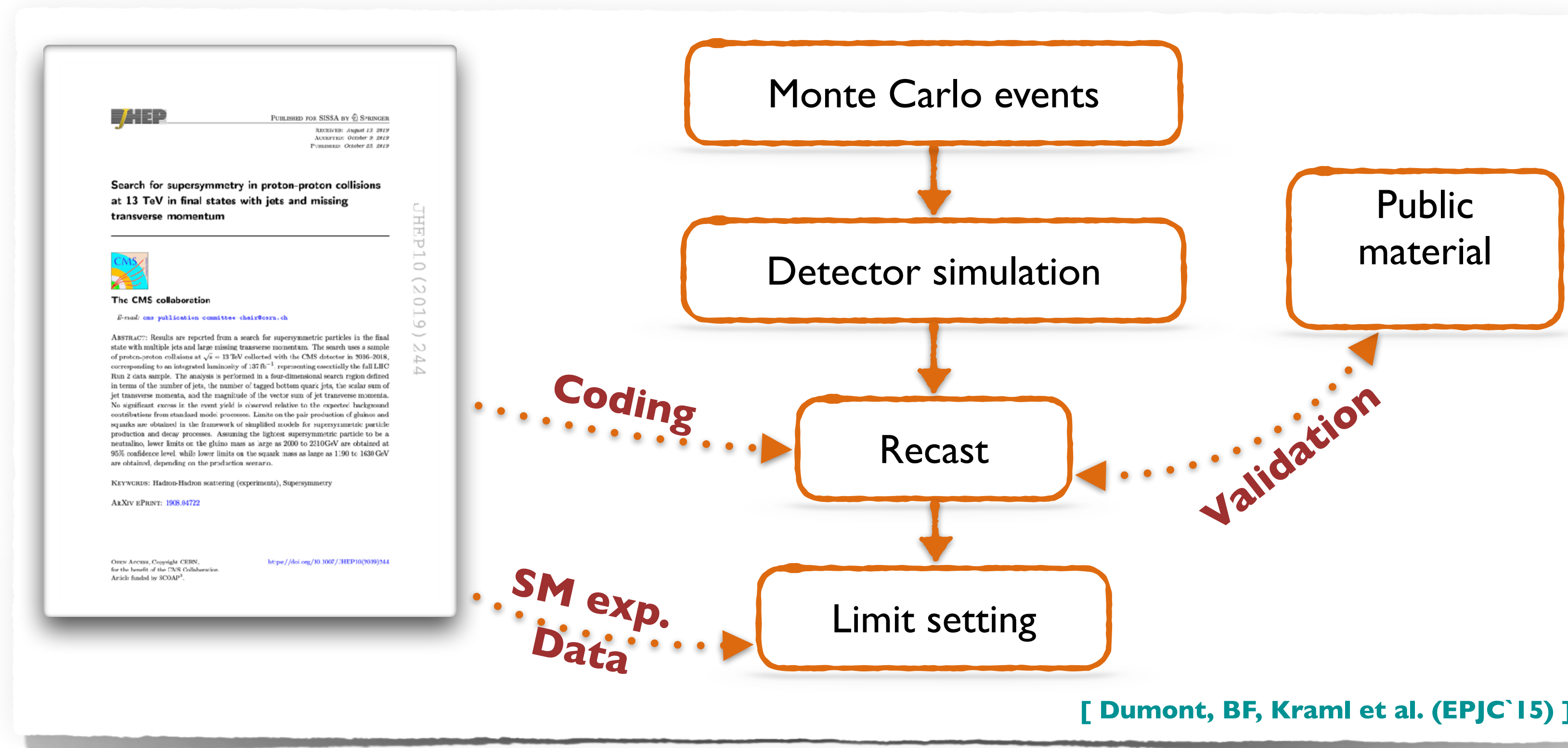
Searches for SUSY will continue (during Run 3 and beyond)

- **Great:** SUSY $\leftrightarrow$ test ground for many BSM theories
 - Shared signatures with numerous models
- Requires **ability to reproduce/recycle the analyses**

What's next? → reinterpretations (in the hard way)

Reinterpretation based on simulations

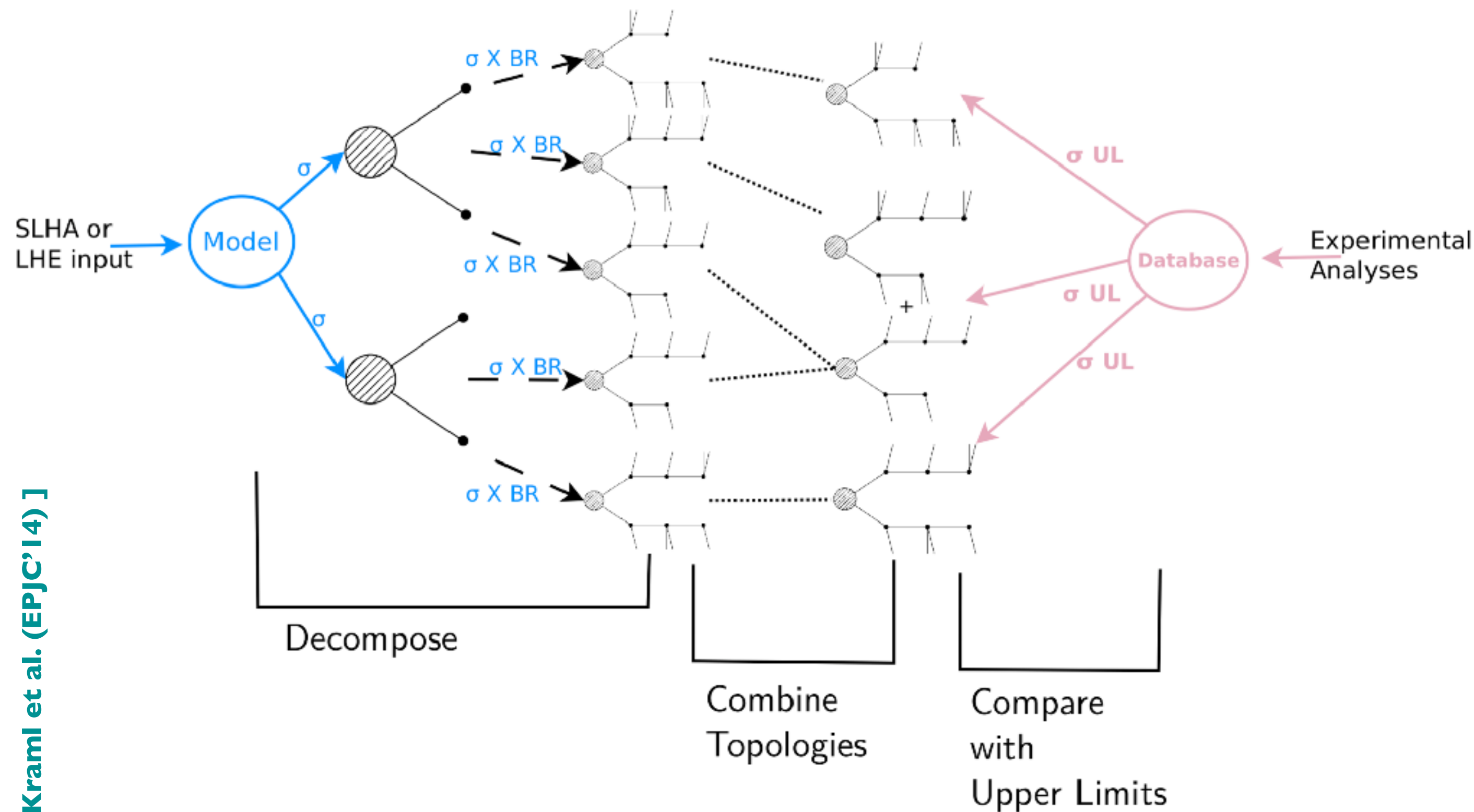
- **Detector modelling** mimicking ATLAS / CMS
- Development of full frameworks
 - Implementations of searches (and validation)
 - Event yields from simulated signals



What's next? → reinterpretations (quick and conservative)

Reinterpretation based on Simplified Model Spectra (SMS)

- Decomposition of theory signatures into SMS signatures
- Fiducial cross sections on the basis of public **efficiency maps**
- Comparison to published **upper bounds**
 - Validation: reproduction of existing bounds



- Often **conservative**
 - $\neq$ kinematics, asymmetric decays
 - Rather **fast**
 - Fair estimates of bounds

[Kraml et al. (EPJC'14)]

Analysis implementations in tools – how to

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.)
- Detailed **cut-flows** for well-defined benchmarks
 - Information for all SRs
 - Exact definition of benchmarks (spectra)
 - Event generation information (cards, tunes)
- **Digitised histograms** (e.g. on HEPDATA)
- Reproduction of exclusion contours

! Essential
✗ Often difficult!

Analysis implementations in tools – challenges

Wishlist for high-quality recasts

- **Background estimates**
 - ➔ usually provided (not systematic)
- **Efficiencies**
 - ➔ To be provided as tables / functional forms
 - ➔ To be broken down in sub-efficiencies (trigger, etc.)
 - ➔ Efficiency maps for SMS-based recasting
- **Validation material** (crucial):
 - ➔ SLHA files, MG5_aMC cards, PYTHIA8 cards, etc.
 - ➔ Cut-flows for given benchmarks
 - ➔ **Not systematic** (sequence, details, all SRs)

Improved recast material over the years

- Publications clearer, HEPDATA widely used
- Better EXP/TH communication
- **Still improvable**

[The Reinterpretation Forum (SciPost`20)]

 SciPost

SciPost Phys. 9, 022 (2020)

**Reinterpretation of LHC results for new physics:
status and recommendations after run 2**

The LHC BSM Reinterpretation Forum

Abstract

We report on the status of efforts to improve the reinterpretation of searches and measurements at the LHC in terms of models for new physics, in the context of the LHC Reinterpretation Forum. We detail current experimental offerings in direct searches for new particles, measurements, technical implementations and Open Data, and provide a set of recommendations for further improving the presentation of LHC results in order to better enable reinterpretation in the future. We also provide a brief description of existing software reinterpretation frameworks and recent global analyses of new physics that make use of the current data.

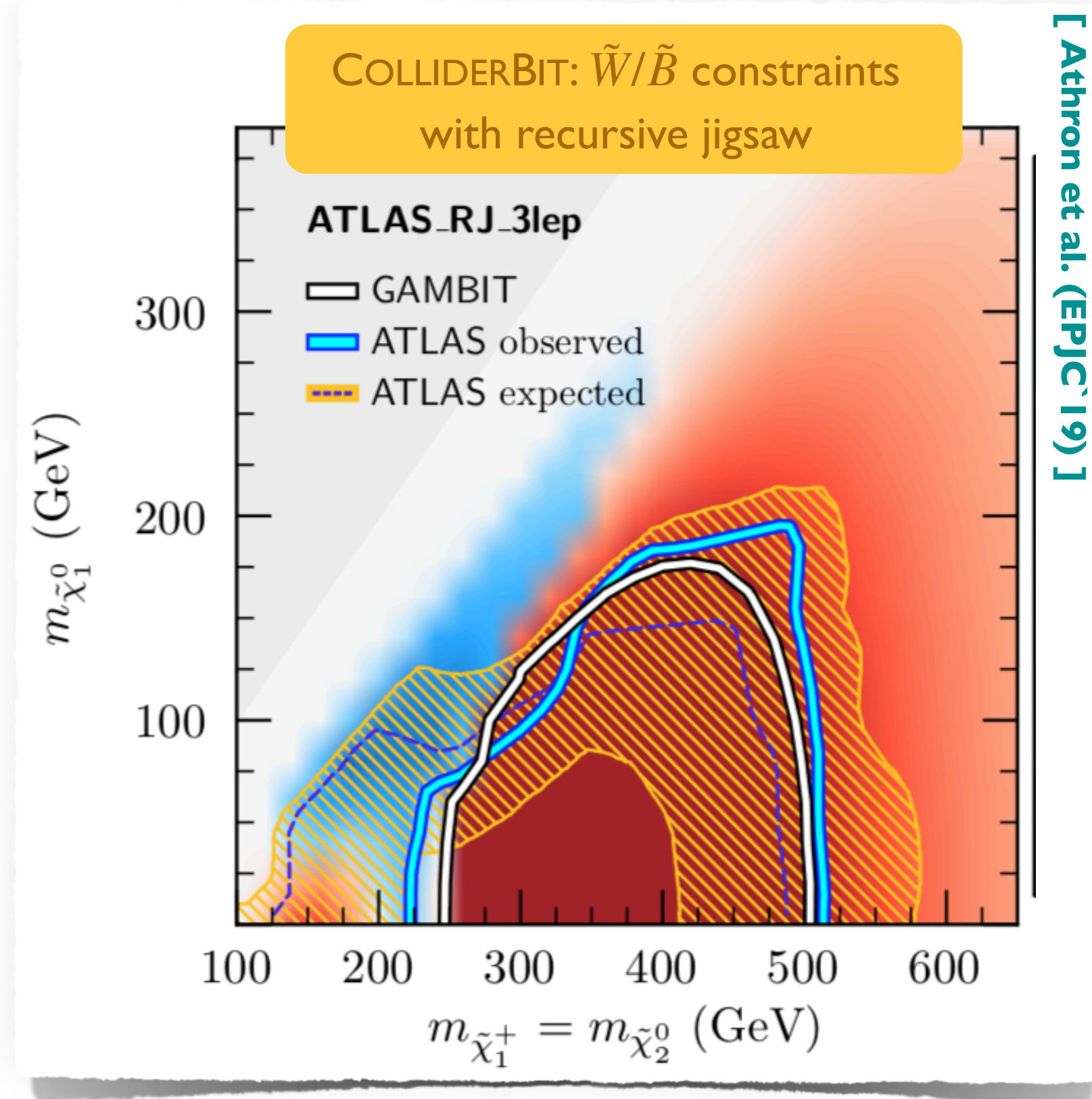
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 Check for updates

Waleed Abdallah^{1,2}, Shehu AbdusSalam³, Azar Ahmadov⁴, Amine Ahrich^{5,6}, Gaël Alguero⁷, Benjamin C. Allanach^{8*}, Jack Y. Araz⁹, Alexandre Arbey^{10,11}, Chiara Arina¹², Peter Athron¹³, Emanuele Bagnaschi¹⁴, Yang Bai¹⁵, Michael J. Baker¹⁶, Csaba Balazs¹³, Daniele Barducci^{17,18}, Philip Bechtle^{19*}, Aoife Bharucha²⁰, Andy Buckley^{21†}, Jonathan Butterworth^{22*}, Haiying Cai²³, Claudio Campagnari²⁴, Cari Cesarotti²⁵, Marcin Chrzasczcz²⁶, Andrea Coccaro²⁷, Eric Conte^{28,29}, Jonathan M. Cornell³⁰, Louie D. Corpe²², Matthias Danninger³¹, Luc Darmé³², Aldo Deandrea¹⁰, Nishita Desai^{33*}, Barry Dillon³⁴, Caterina Doglioni³⁵, Matthew J. Dolan¹⁶, Juhi Dutta^{1,36}, John R. Ellis³⁷, Sebastian Ellis³⁸, Matthew Feickert⁴⁰, Nicolas Fernandez⁴⁰, Sylvain Fichet⁴¹, Thomas Flacke⁴², Benjamin Fuks^{43,44*}, Achim Geiser⁴⁵, Marie-Hélène Genest⁷, Akshay Ghalsasi⁴⁶, Tomas Gonzalo¹³, Mark Goodsell⁴³, Stefania Gori⁴⁶, Philippe Gras⁴⁷, Admir Greljo¹¹, Diego Guadagnoli⁴⁸, Sven Heinemeyer^{49,50,51}, Lukas A. Heinrich^{11*}, Jan Heisig^{12*}, Deog Ki Hong⁵², Tetiana Hryn'ova⁵³, Katri Huitu⁵⁴, Philip Ilten⁵⁵,

Validating LHC recast in public tools

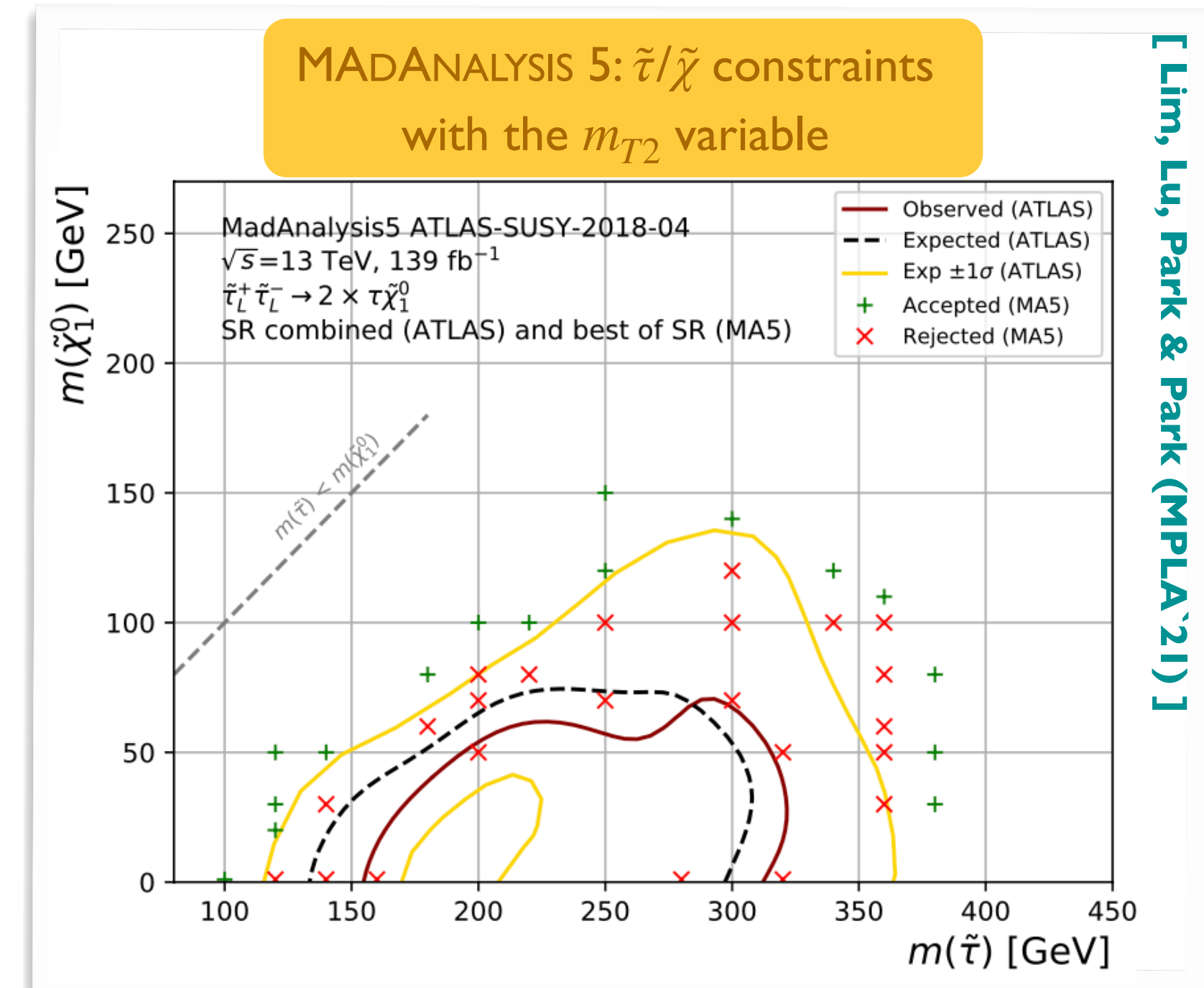


Excellent agreement with ATLAS

- Wino/bino scenarios ($\tilde{W}$ decays into EW bosons)
- Not necessarily easy to get
- Using the '*best expected region*'
→ Works well here

Excellent agreement with ATLAS

- Stau-neutralino scenario ($\tilde{\tau} \rightarrow \tau \tilde{\chi}$ decays)
- Using the '*best expected region*'
→ Often off when correlations matter



Validating LHC recast in public tools

Better limit settings procedures

- Signal region combination
 - CMS correlation matrices (Gaussian-approximate likelihoods)

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

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

- ATLAS (full) PYHF likelihoods [Heinrich, Feickert, Stark & Cranmer (JOSS'21)]

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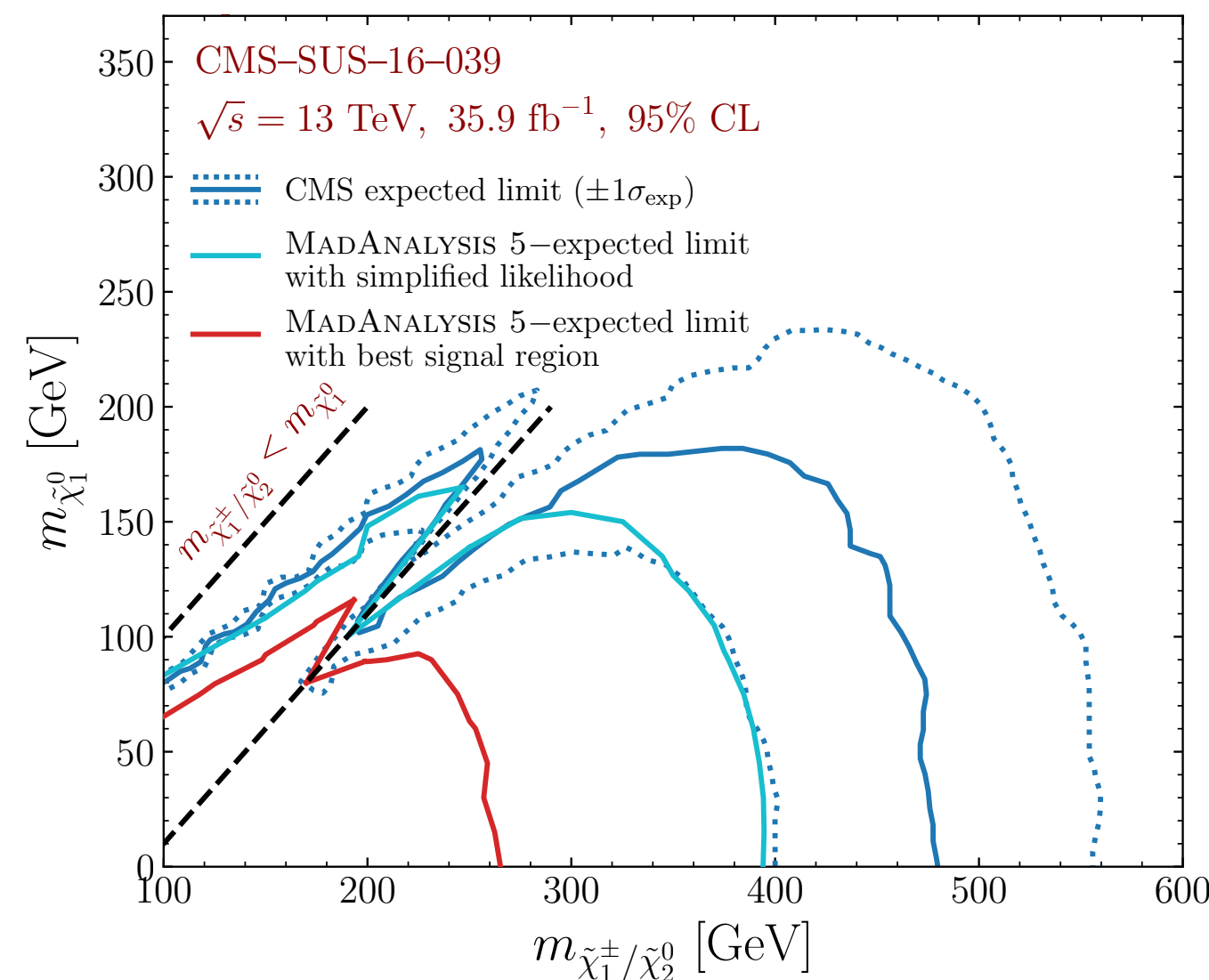
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Combination mandatory

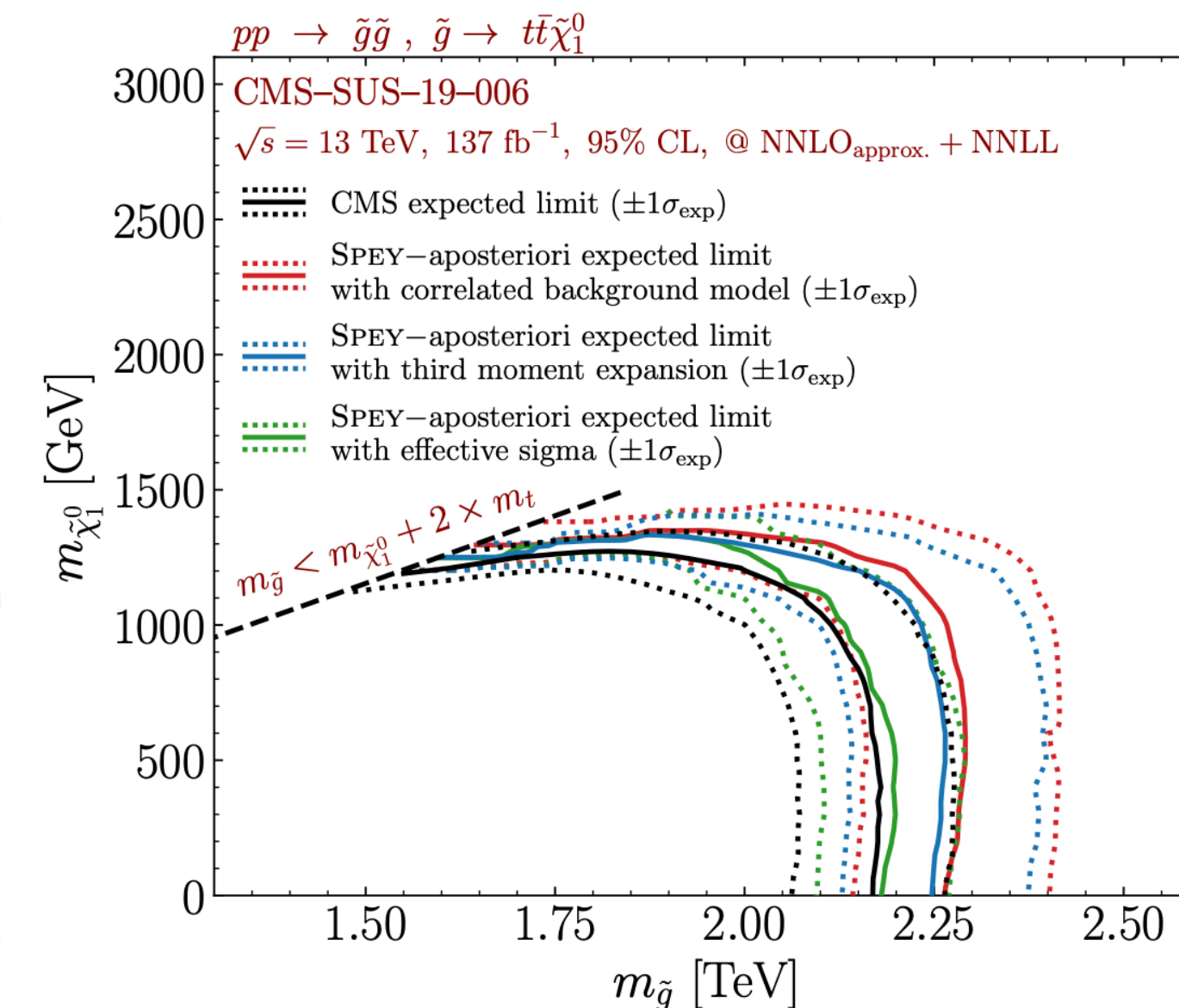
- Wino/bino scenarios ($\tilde{W}$ decays into EW bosons)
- Top-philic gluino scenarios ($\tilde{g}$ decays into top and E_T^{miss})
- 100+ SRs; signal over $\neq$ SRs
- Sensitivity reduced with the 'best region' only
- Covariance matrices and PyHF models crucial

MADANALYSIS5: $\tilde{W}/\tilde{B}$ constraints with standard ewkino variables



[Alguero, Araz, BF & Kraml (SciPost'22)]

Gluino search with jets and MET



[Araz (SciPost'24)]

SMS-based public tools

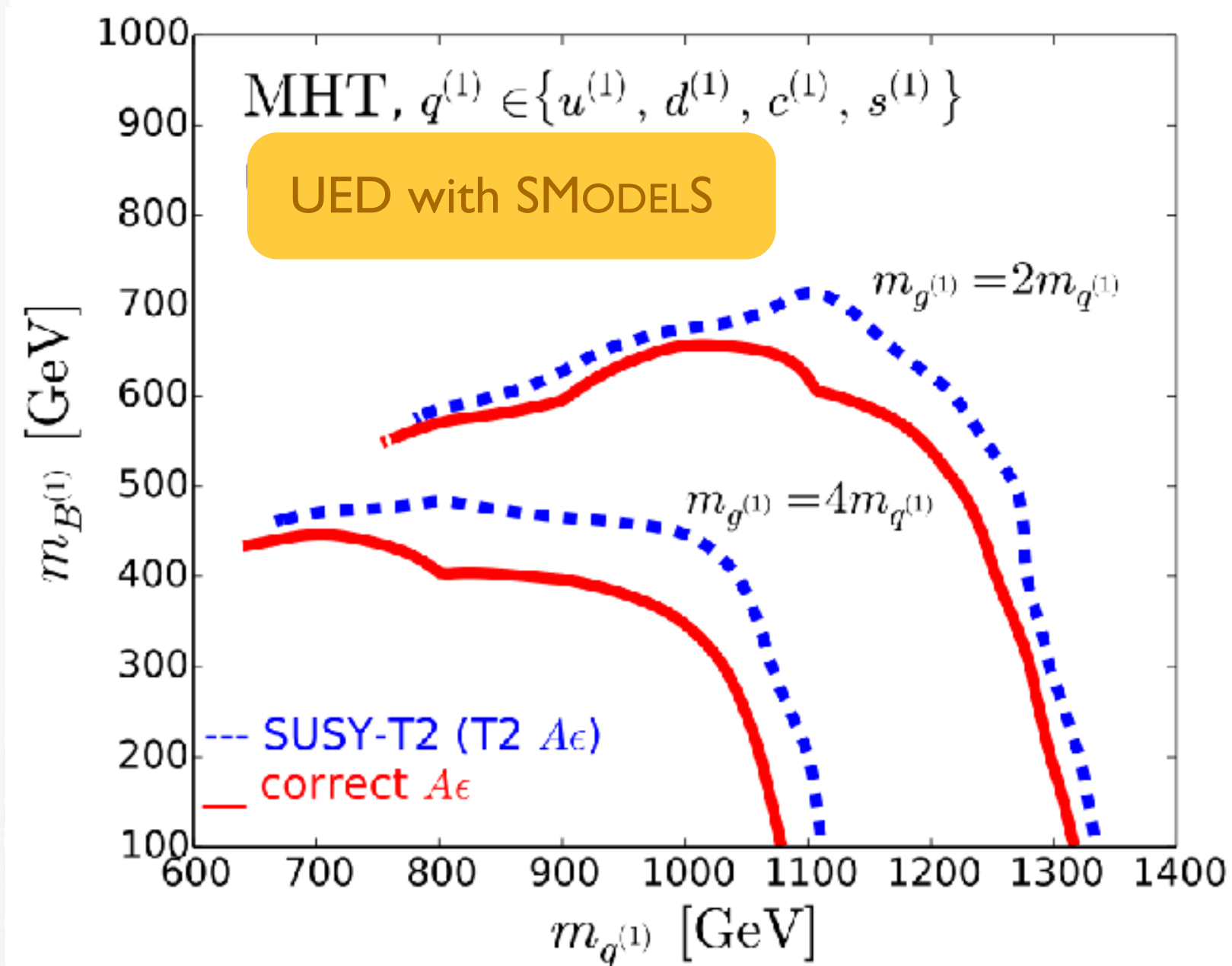
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 - **PYHF model crucial**
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 - [Altakach et al. (SciPost'24)]
- Dark photons: DARKCAST [from [GITLAB](#)] [Ilten et al. (JHEP'18)]

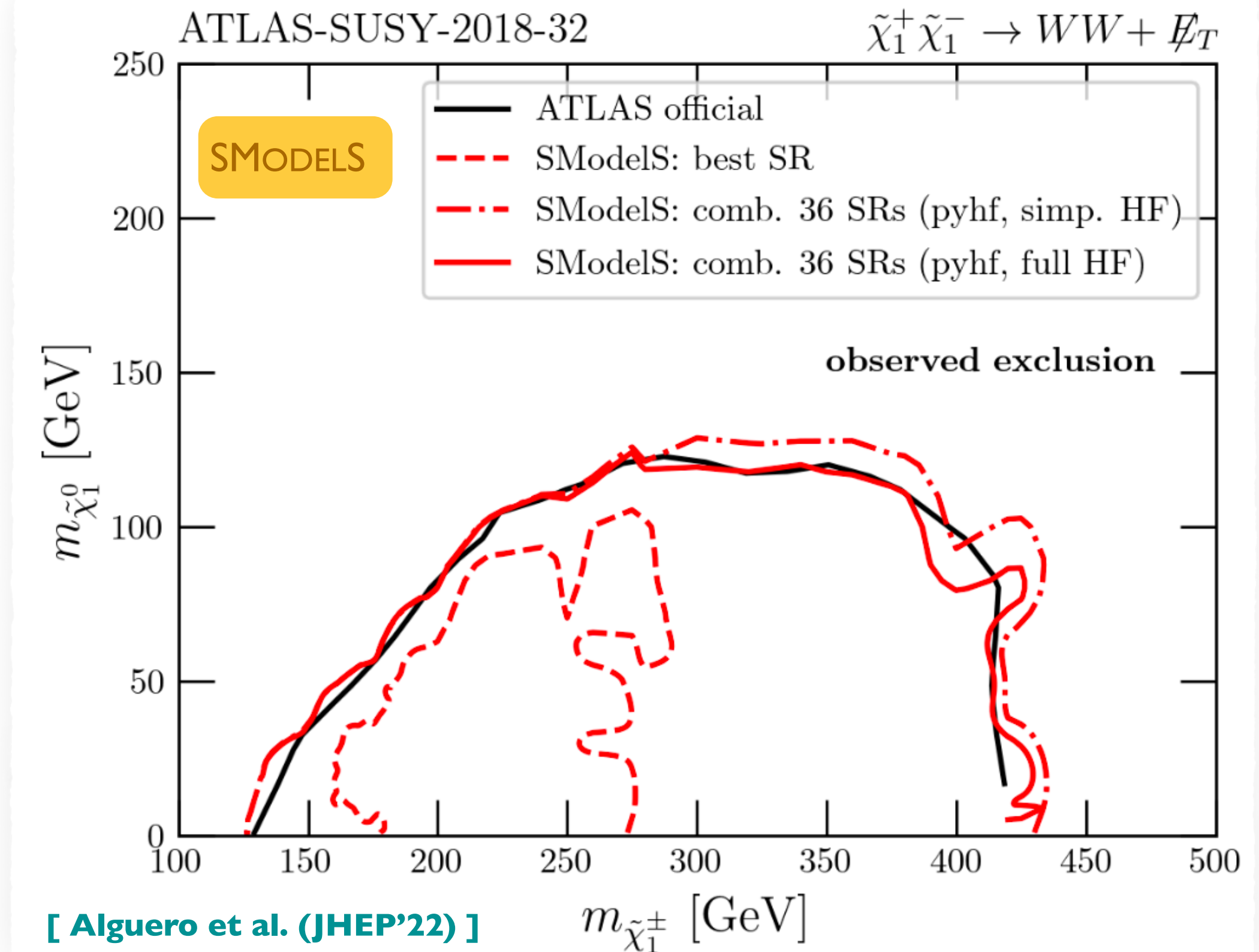
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[[Edelhäuser, Krämer, Sonneveld \(JHEP'15\)](#)]



[[Alguero et al. \(JHEP'22\)](#)]

Simulation-based public tools - transfer functions

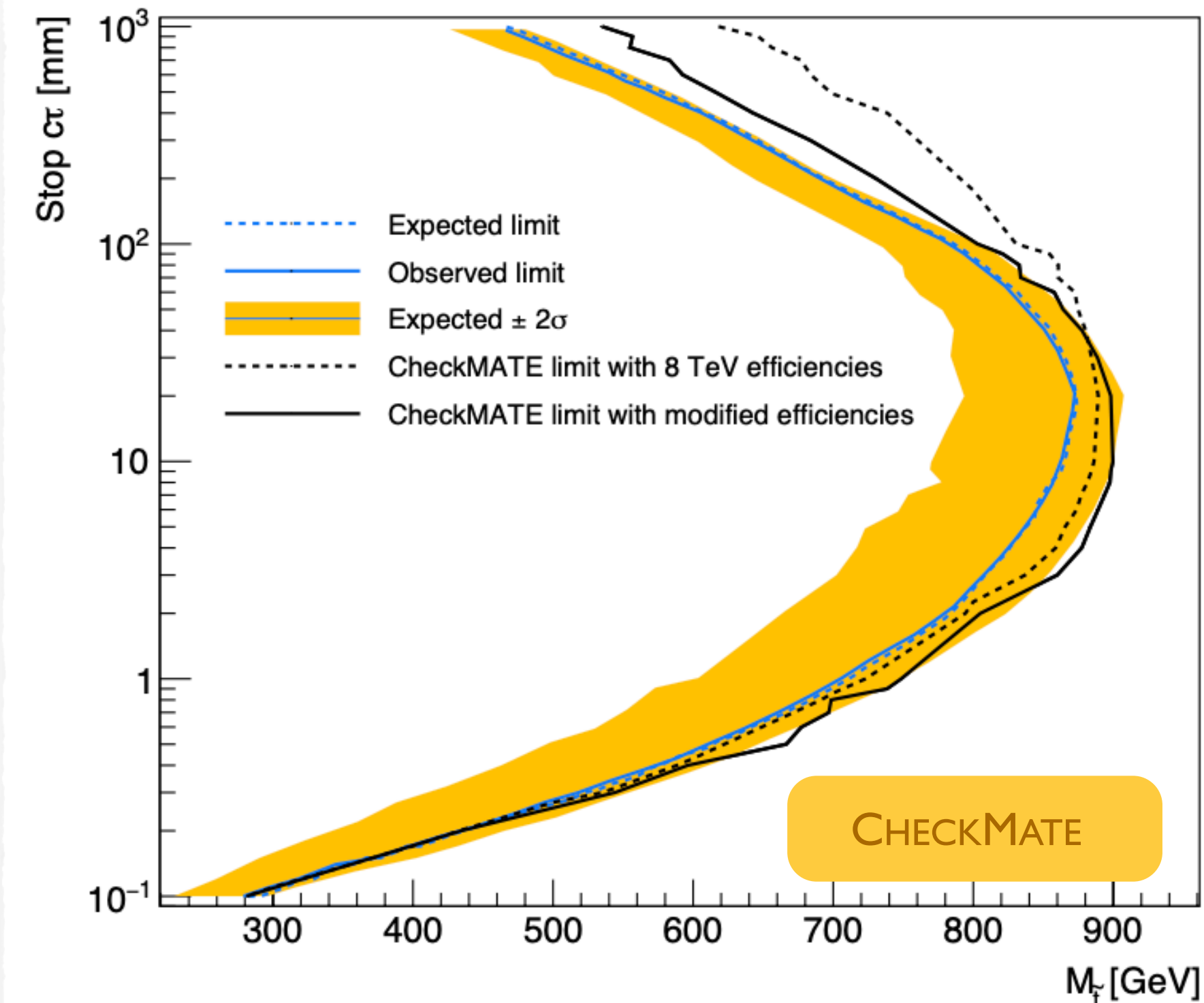
Simulation-based; detector modelling with transfer functions

- COLLIDERBIT [$O(40)$ analyses, from [HEPFORGE](#)] [Balász et al. (EPJC`17)]
- HACKANALYSIS [$O(10)$ analyses, from [IN2P3](#)] [Goodsell & Priya (EPJC`22)]
 - ★ Validation example (CMS-EXO-19-010)
 - ➔ Disappearing tracks and winos
 - ➔ Cut-flow comparisons
- MADANALYSIS5/SFS [$O(15)$ analyses, from [GITHUB/MA5DATAVERSE](#)] [Araz, BF & Polykratis (EPJC`21) ; Araz, BF, Goodsell & Utsch (EPJC`22)]
- RIVET [$O(30)$ analyses, from [HEPFORGE](#)] [Buckley et al. (2010); Bierlich et al. (SciPost`20)]

Cut	700 GeV, 10 cm, region 2018A		
	HACKANALYSIS ϵ_i^{CMS}	$\epsilon_i^{\text{sim}}, \text{HEPMC}$	$\epsilon_i^{\text{sim}}, \text{HEPMC}, \text{no pileup}$
Total	$1.0^{+0.00}_{-0.00}$	$1.0^{+0.00}_{-0.00}$	$1.0^{+0.00}_{-0.00}$
Trigger	$1.5^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
Passes p_T^{miss} filters	$1.4^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
$p_T^{\text{miss}} > 120 \text{ GeV}$	$1.4^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 jet with $p_T > 110 \text{ GeV}$ and $ \eta < 2.4$	$1.3^{+0.02}_{-0.02} \times 10^{-1}$	$1.3^{+0.01}_{-0.01} \times 10^{-1}$	$1.3^{+0.01}_{-0.01} \times 10^{-1}$
$\Rightarrow 0$ pairs of jets with $\Delta\phi_{\text{jet, jet}} > 2.5$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
$ \Delta\phi(\text{leading jet}, \mathbf{p}_T^{\text{miss}}) > 0.5$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 track with $ \eta < 2.1$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 track with $p_T > 55 \text{ GeV}$	$4.7^{+0.10}_{-0.10} \times 10^{-2}$	$4.6^{+0.06}_{-0.06} \times 10^{-2}$	$4.6^{+0.06}_{-0.06} \times 10^{-2}$
≥ 1 track passing fiducial selections	$3.1^{+0.08}_{-0.08} \times 10^{-2}$	$3.6^{+0.05}_{-0.05} \times 10^{-2}$	$3.6^{+0.05}_{-0.05} \times 10^{-2}$
≥ 1 track with ≥ 4 pixel hits	$1.7^{+0.06}_{-0.06} \times 10^{-2}$	$2.7^{+0.05}_{-0.05} \times 10^{-2}$	$2.7^{+0.05}_{-0.05} \times 10^{-2}$
≥ 1 track with no missing inner hits	$1.7^{+0.06}_{-0.06} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$
≥ 1 track with no missing middle hits	$1.5^{+0.05}_{-0.05} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$
≥ 1 track with relative track isolation $< 5\%$	$5.3^{+0.34}_{-0.34} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
≥ 1 track with $ d_{xy} < 0.02 \text{ cm}$	$5.1^{+0.34}_{-0.34} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
≥ 1 track with $ d_z < 0.5 \text{ cm}$	$5.1^{+0.31}_{-0.31} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
≥ 1 track with $\Delta R(\text{track}, \text{jet}) > 0.5$	$4.9^{+0.31}_{-0.31} \times 10^{-3}$	$5.9^{+0.22}_{-0.22} \times 10^{-3}$	$6.1^{+0.23}_{-0.23} \times 10^{-3}$

[Goodsell & Priya (EPJC`22)]

Simulation-based public tools - DELPHES



[Desai et al. (EPJC'21)]

Simulation-based; DELPHES 3 detector modelling

- MADANALYSIS 5 [O(50) analyses, from [GITHUB/MA5DATAVERSE](#)]
- CHECKMATE [O(50) analyses, from [GITHUB](#)]

★ Validation example (CMS-EXO-16-022)

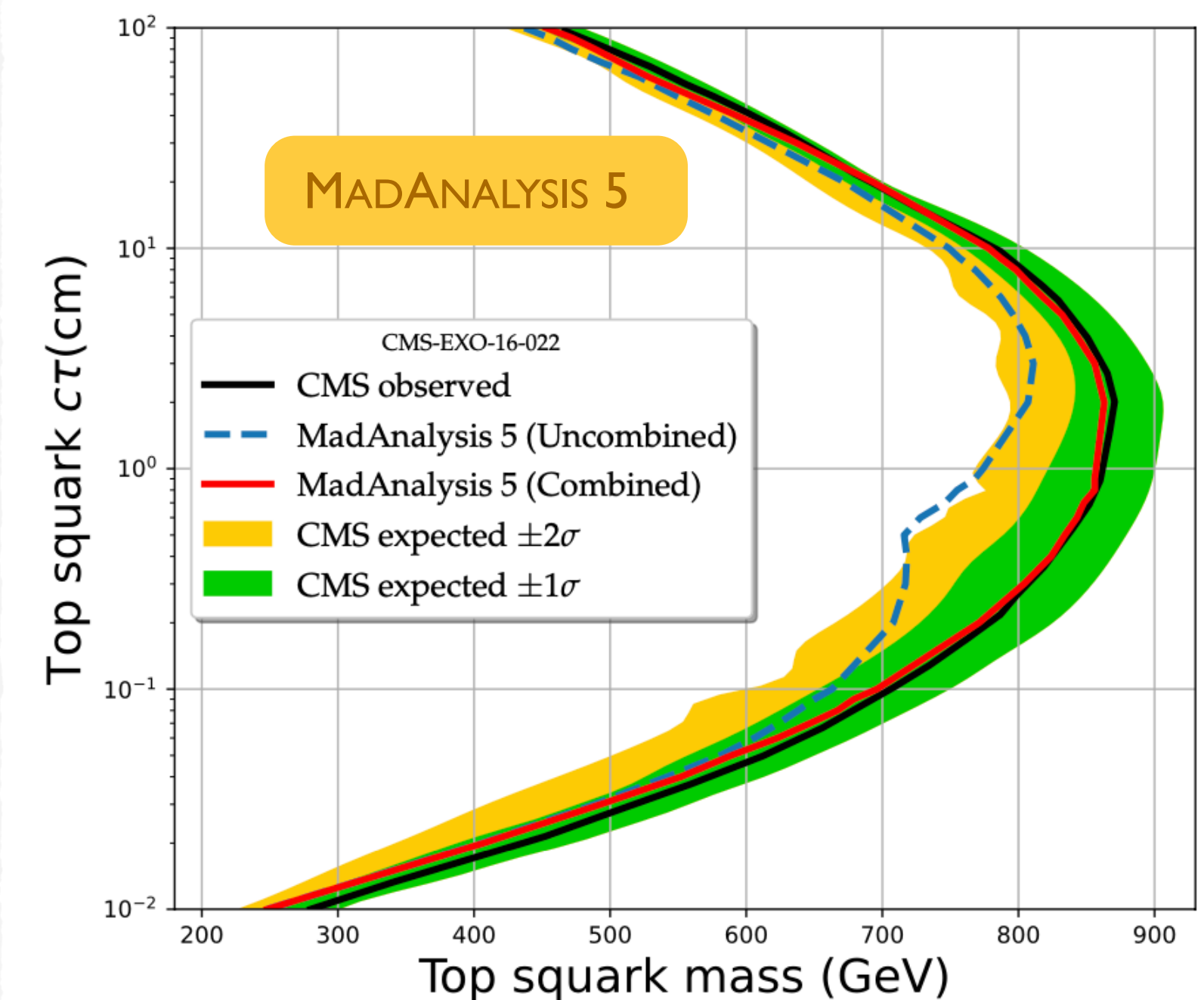
→ Displaced stop in an $e\mu$ pair

→ Detailed information crucial

[Dumont, BF, Kraml et al. (EPJC'15)]

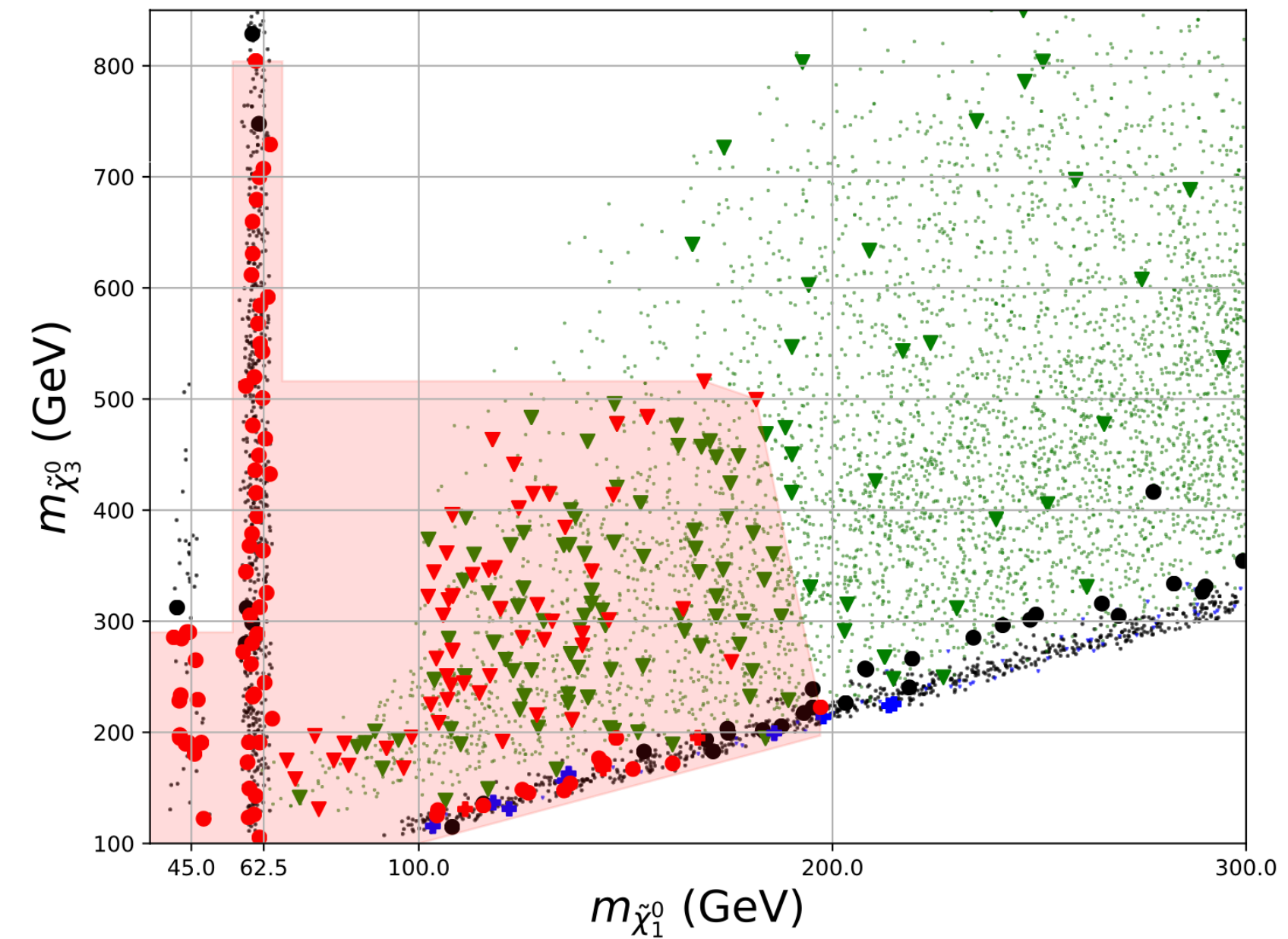
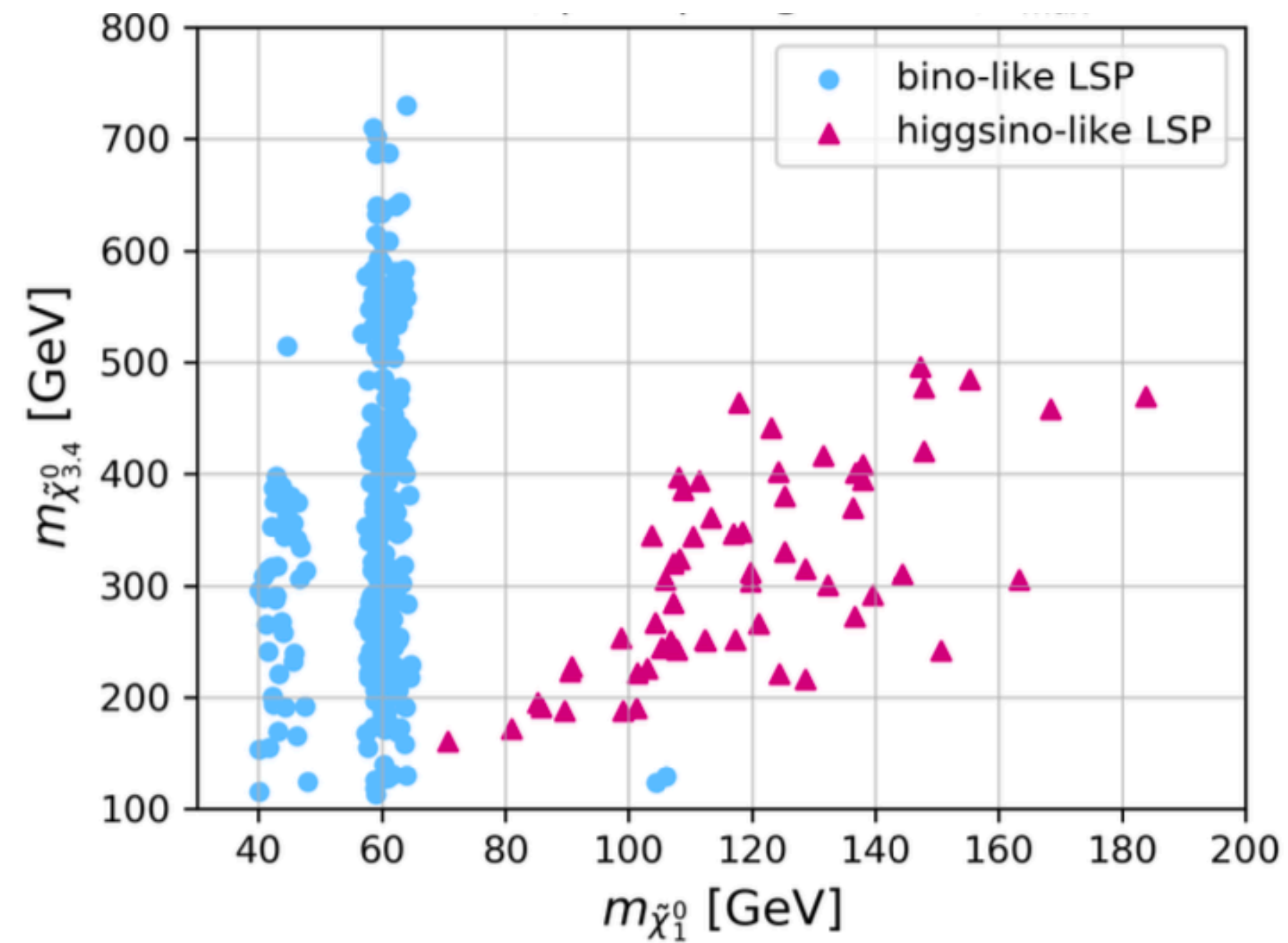
[Conte & BF (IJMPA'19)]

[Derks et al. (CPC'17)]



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

SMS-based public tools - limitations



[Goodsell, Kraml, Reyes-González & Williamson (SciPost'20)]

Application: Dirac gauginos at the LHC

- Model not considered by ATLAS/CMS
 - Full scan of the EW sector of the model
 - Constraints (EWPT, relic density, etc.)

Model's coverage at the LHC

- Points excluded by SMODELS (with $r \geq 1$)
 - DM funnels
 - Larger set of analyses than other tools
- Comparison with full recasts (from MADANALYSIS 5)
 - SMS approach **more conservative and faster**
 - Full recasts sensitive to **complex spectra/signatures**

Recasting SUSY searches to study... SUSY?

LHC recasting

- Constraining SUSY models
 - Beyond those addressed in LHC searches
 - Minimal and non-minimal setups

Excesses in SUSY searches at the LHC

- Quantifying
- Interpreting
- Tools needed!



Compressed ewkino excesses at the LHC

Numerous LHC searches for ewkinos with leptons and $\cancel{E}_T$

- Many signatures
 - 3 leptons + $\cancel{E}_T$ (ATLAS-SUSY-2019-09, CMS-SUS-19-012)
 - 2 soft leptons + $\cancel{E}_T$ (ATLAS-SUSY-2018-16, CMS-SUS-18-004)
 - Combination (CMS-SUS-21-008)
- Even more analyses now (conventional dilepton + $\cancel{E}_T$)

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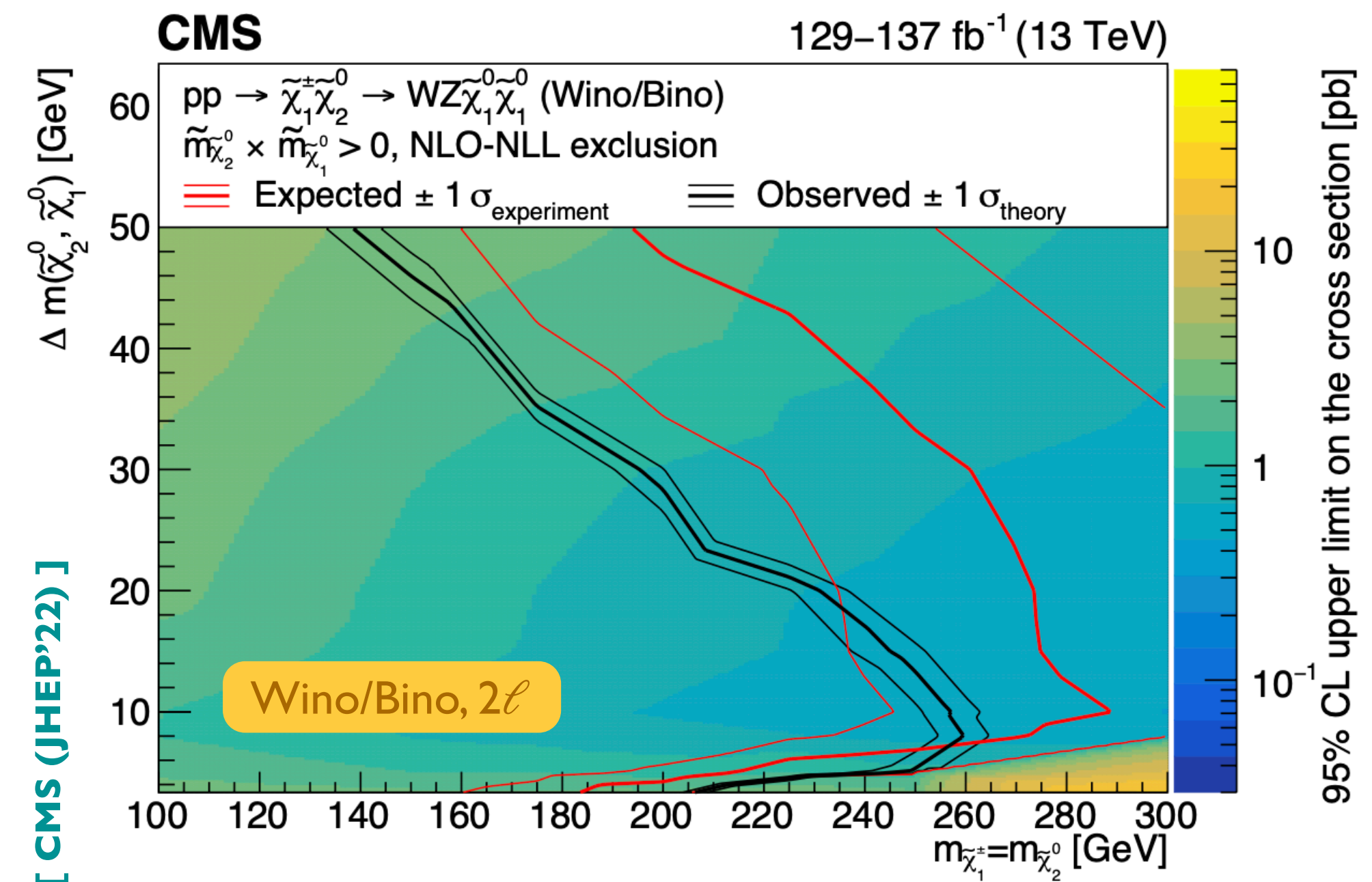
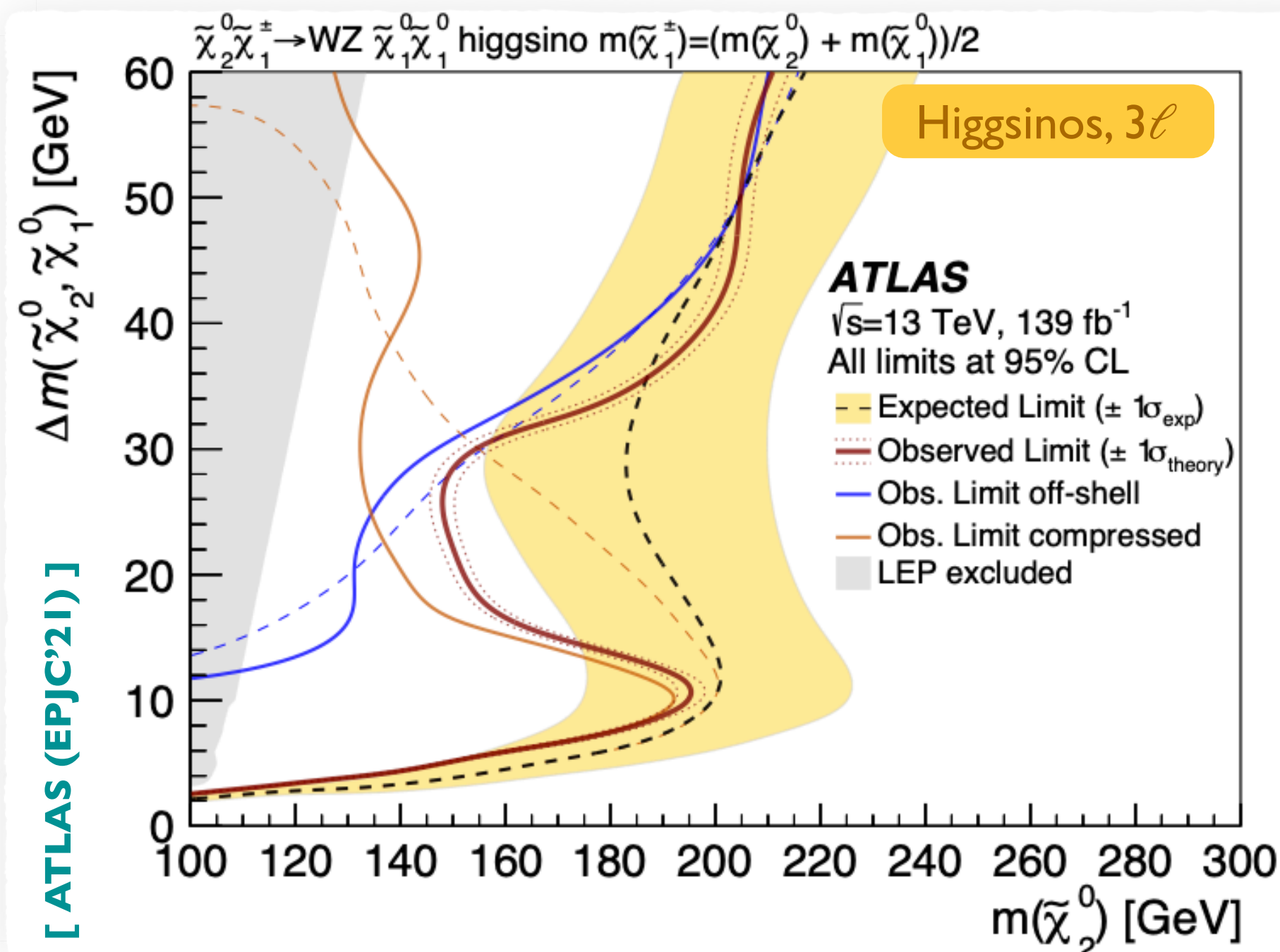
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Interpretations of the results

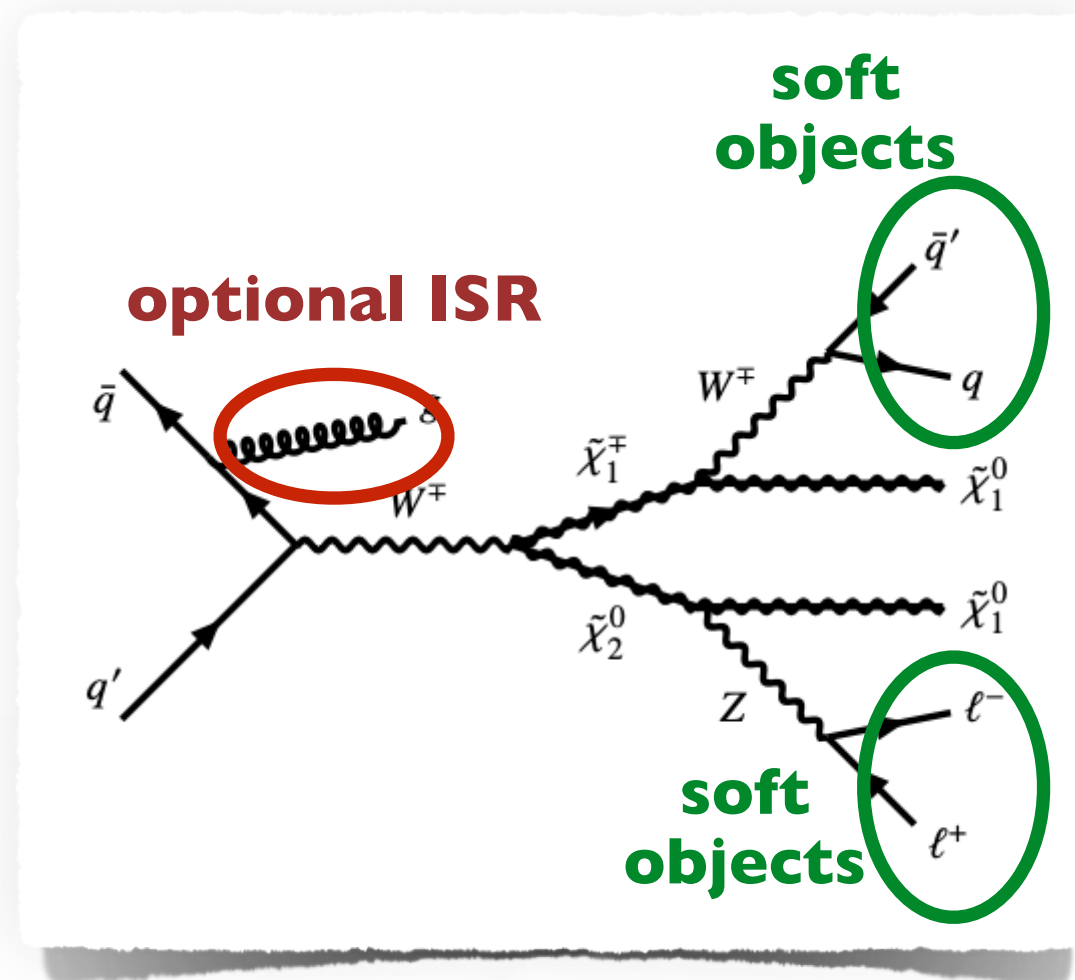
- Interpretations in various simplified models
 - Light higgsinos
 - Light bino/wino (+/- $\equiv$ sign of the mass)

$$\tilde{\chi}_{1,2}^0 \sim -\frac{1}{\sqrt{2}} \left(\mp \tilde{H}_u^0 + \tilde{H}_d^0 \right), \quad \tilde{\chi}_1^\pm \sim \tilde{H}_{u,d}^\pm$$

$$\tilde{\chi}_1^0 \sim i\tilde{B}, \quad \tilde{\chi}_2^0 \sim i\tilde{W}^3, \quad \tilde{\chi}_1^\pm \sim \tilde{W}^\pm$$



But no (known) monojet excesses!



Excesses compatible with a compressed spectrum

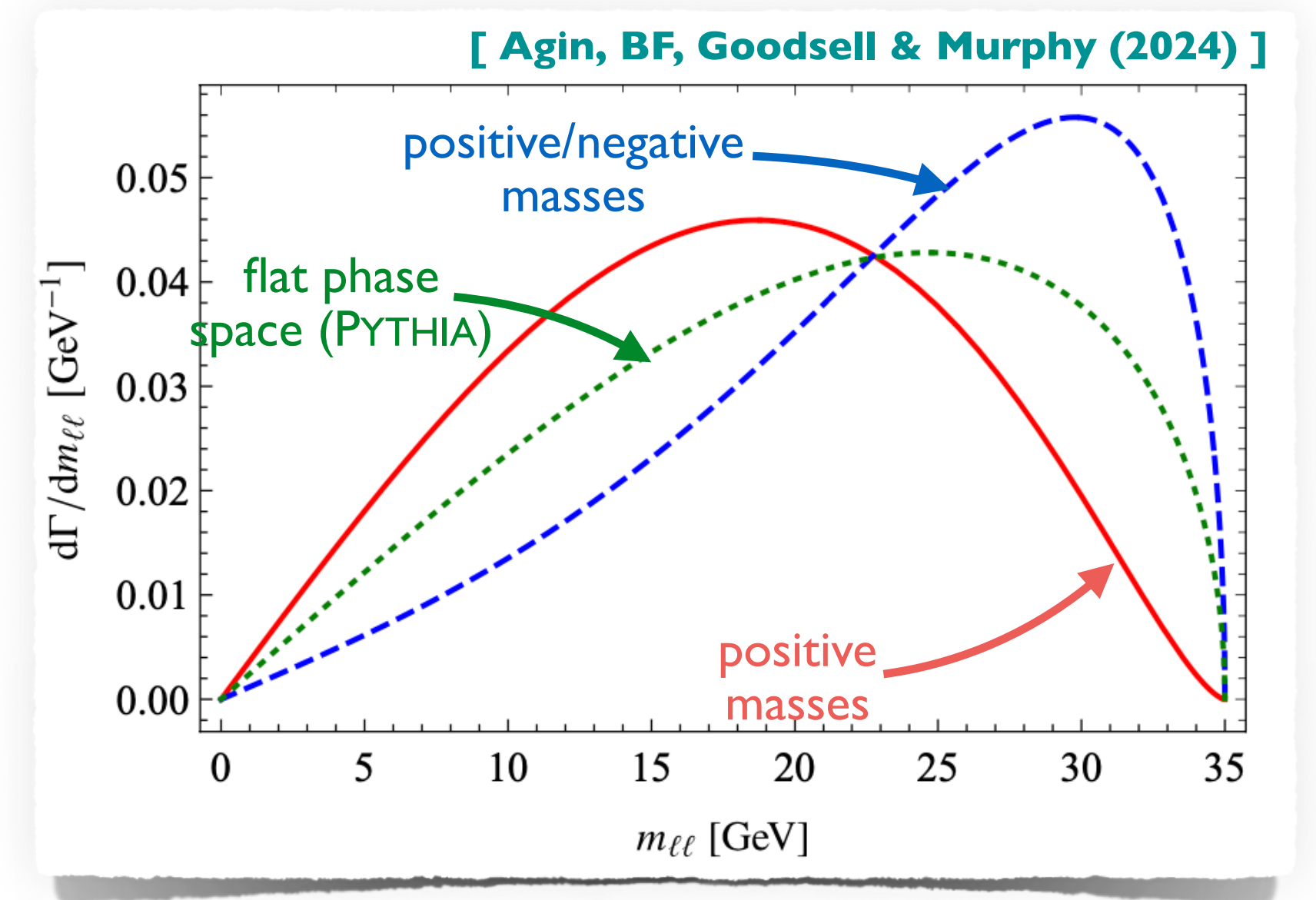
- Mass differences of 10-30 GeV
- **Overlapping** excesses?
- What about **monojets**?
- What about **complete models**?

Use LHC recasting to check out!

A few words on soft lepton excess recasts

ATLAS-SUSY-2018-16: Soft di-lepton + E_T

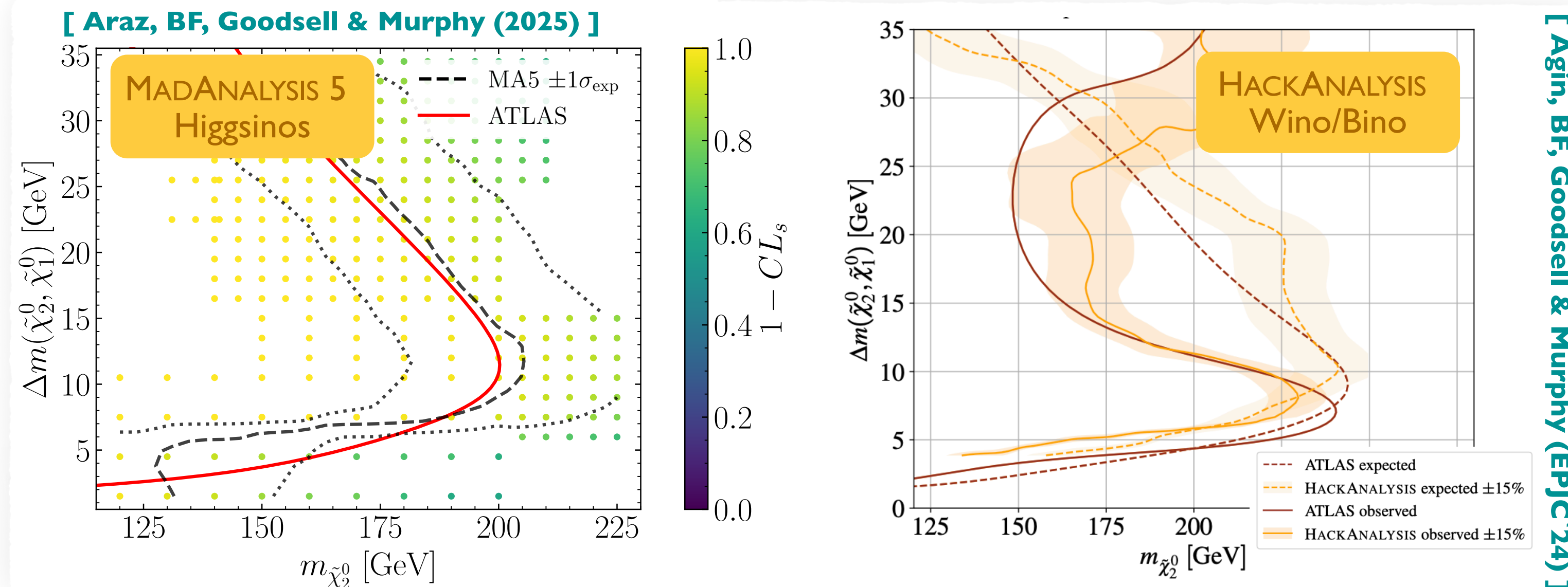
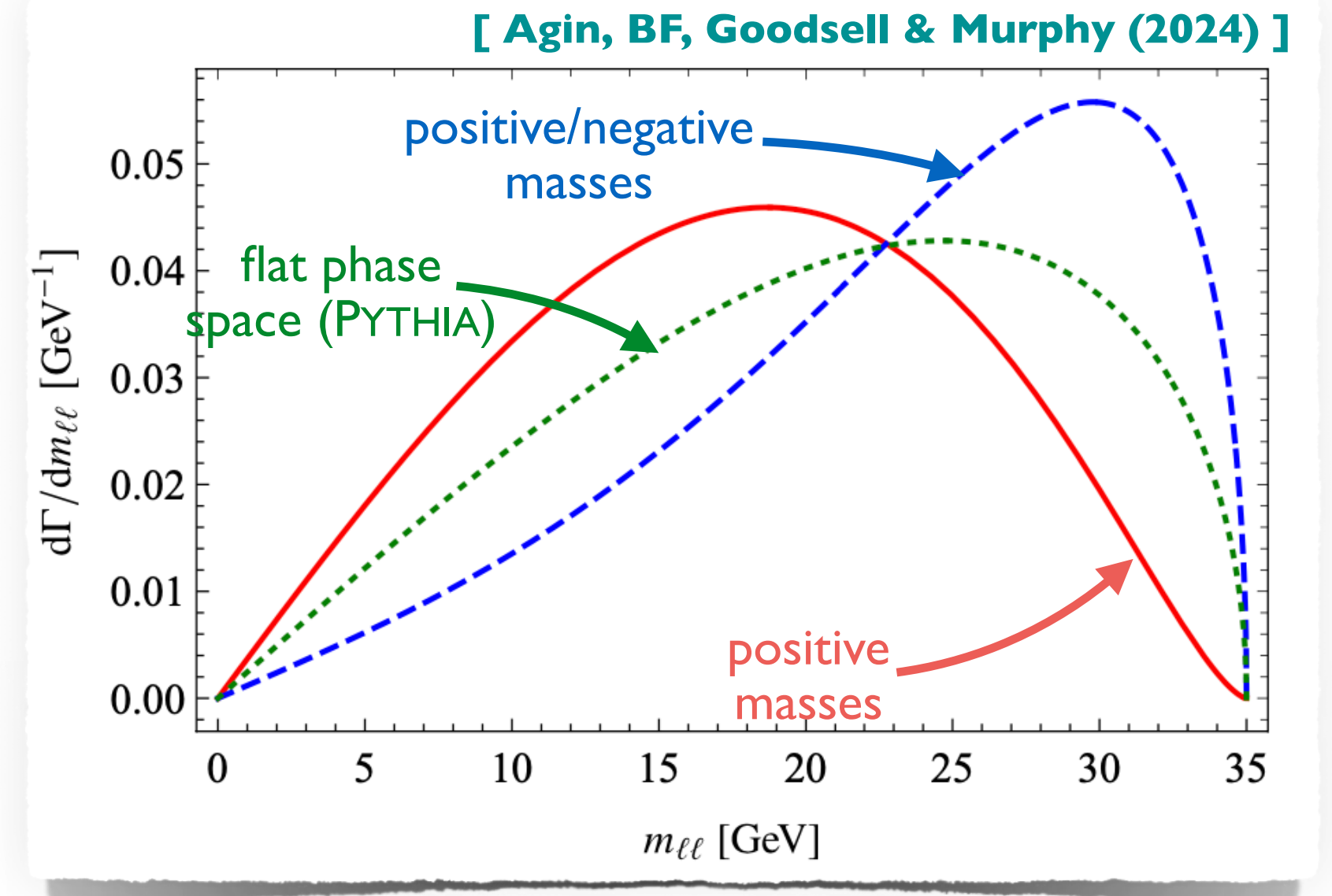
- Selection (the second lepton could be a track)
 - IOSSF pair + E_T + at least 1 hard jet
 - Object isolation, m_T , jigsaw, etc.; bins in $m_{\ell\ell}$
 - PYHF model file
- Recasting challenges
 - Using **RESTRAMES** (cf. jigsaw variables) $\equiv$ strong impact on exclusions
 - **Event generation details** important for compressed spectra
 - Validated recast in HACKANALYSIS / MADANALYSIS5
- Equivalent CMS search: CMS-SUS-18-004



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Recast validation

- Agreement both for exp. and obs. results
 - at 1σ
- **Simulation details crucial**
 - Ewkino decays
 - Multipartonic matrix element merging
- Cross section normalisations important
 - NLO+NLL rates (via RESUMMINO)
- Numerical accuracy important
 - Low efficiencies $\leftrightarrow$ 3-20 Mevents / scenario

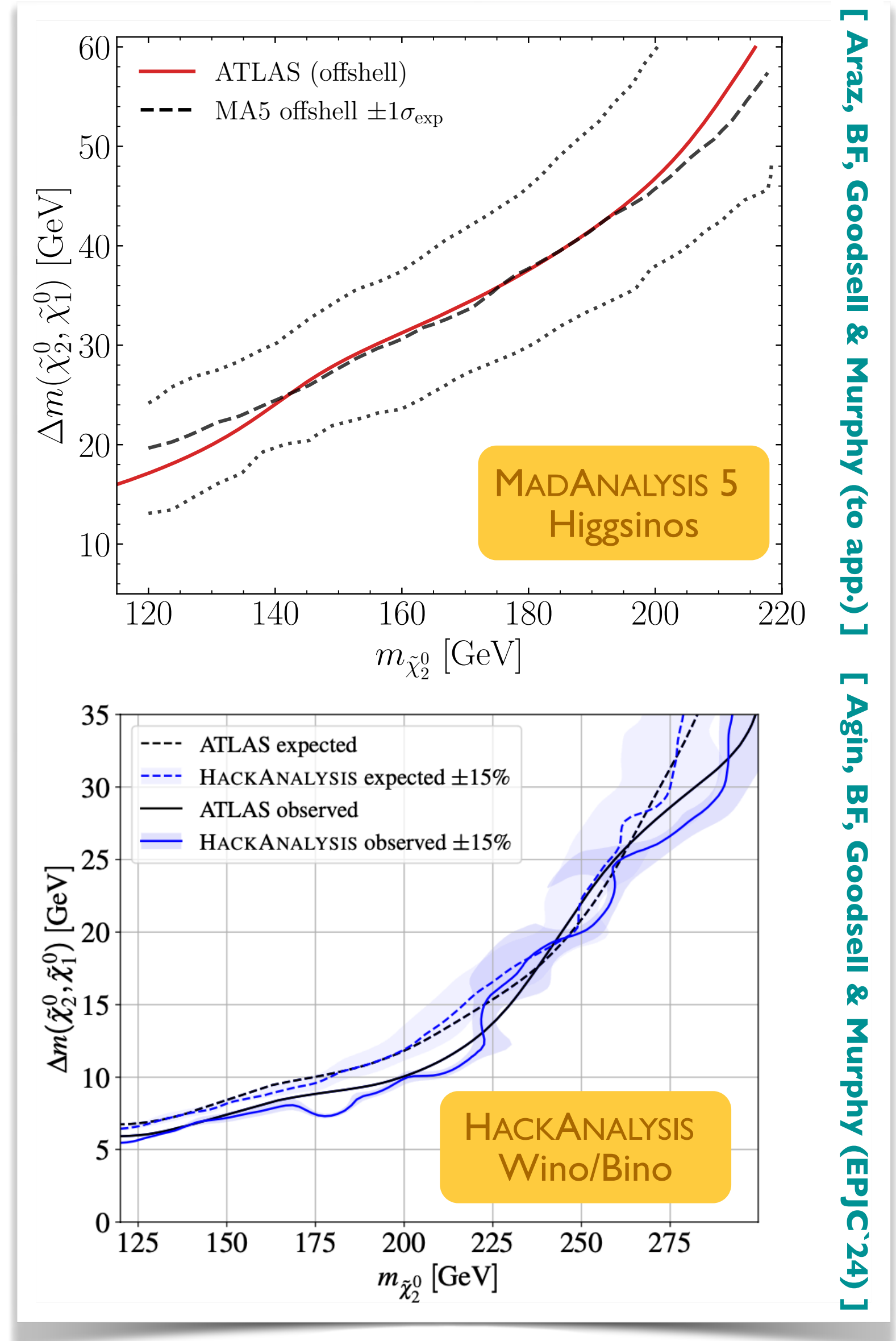
More words on soft lepton excesses...

ATLAS-SUSY-2019-09: 3 leptons + E_T

- Selection
 - 3 leptons including 1 OSSF pair + small/large E_T + with/without jets
 - Object isolation, lepton properties, on-shell/off-shell Z boson; bins in $m_{\ell\ell}$
 - PYHF model file
- Recasting challenges
 - Event generation details important for compressed spectra
 - Validated recast in HACKANALYSIS and MADANALYSIS5
- Equivalent CMS search: CMS-SUS-19-012

Recast validation

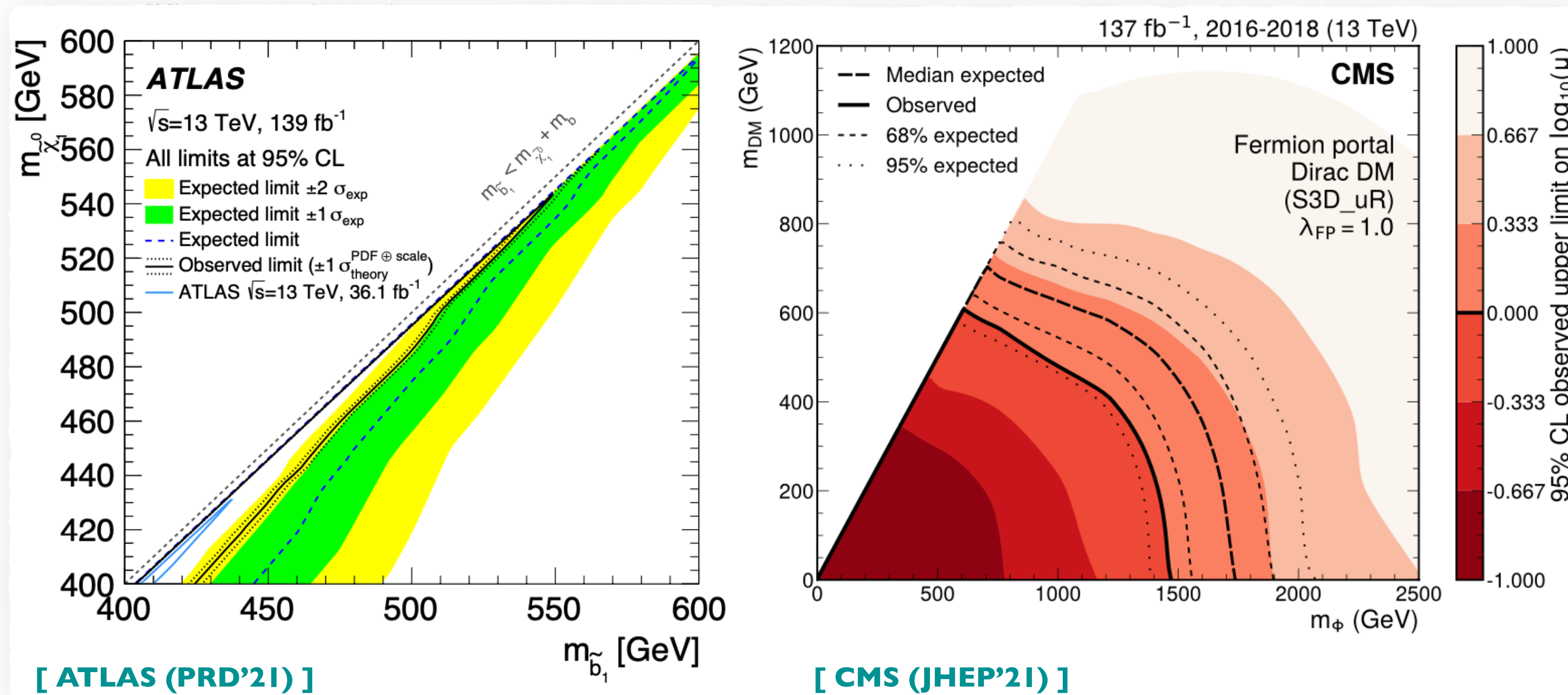
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- Numerical accuracy important
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Recasting searches for monojets

Monojet excesses: CMS-EXO-20-004 & ATLAS-EXOT-2018-06

- Selection
 - ATLAS: **up to 3 jets**, exclusive and inclusive $\cancel{E}_T$ bins
 - CMS: large $\cancel{E}_T$, **at least one hard jet**
- Signal region combination
 - No PYHF model file (ATLAS)
 - **Correlation matrix** (CMS) ↔ more realistic bounds expected
- Excesses in fact clearly visible!



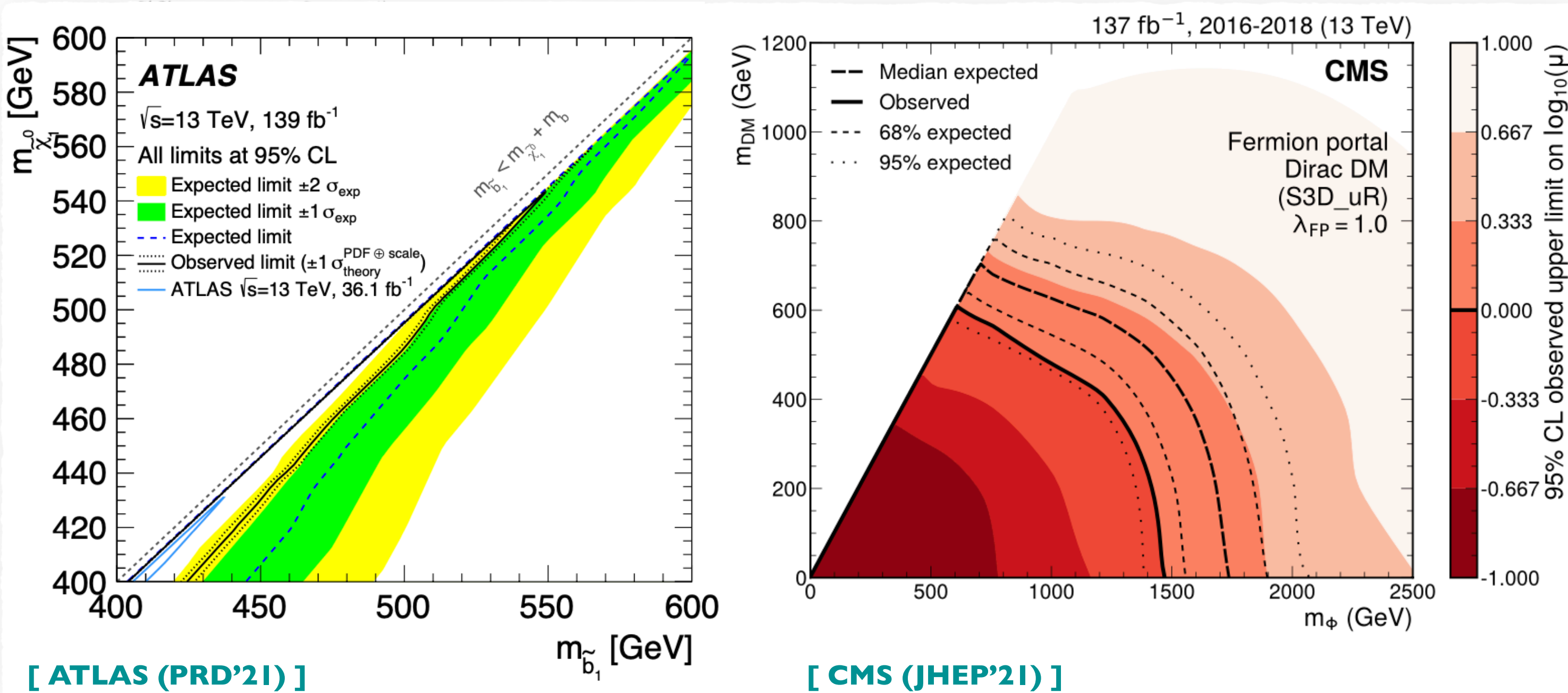
Recasting searches for monojets

Monojet excesses: CMS-EXO-20-004 & ATLAS-EXOT-2018-06

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- Signal region combination
 - No PYHF model file (ATLAS)
 - **Correlation matrix** (CMS) ↔ more realistic bounds expected
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Recast validation

- CMS implementation achieved by CMS 🥰
 - Including correlations
- ATLAS implementation
 - Several cut-flows (fair agreement with ATLAS)
 - Varied exclusion contours
 - **No PyHF information**

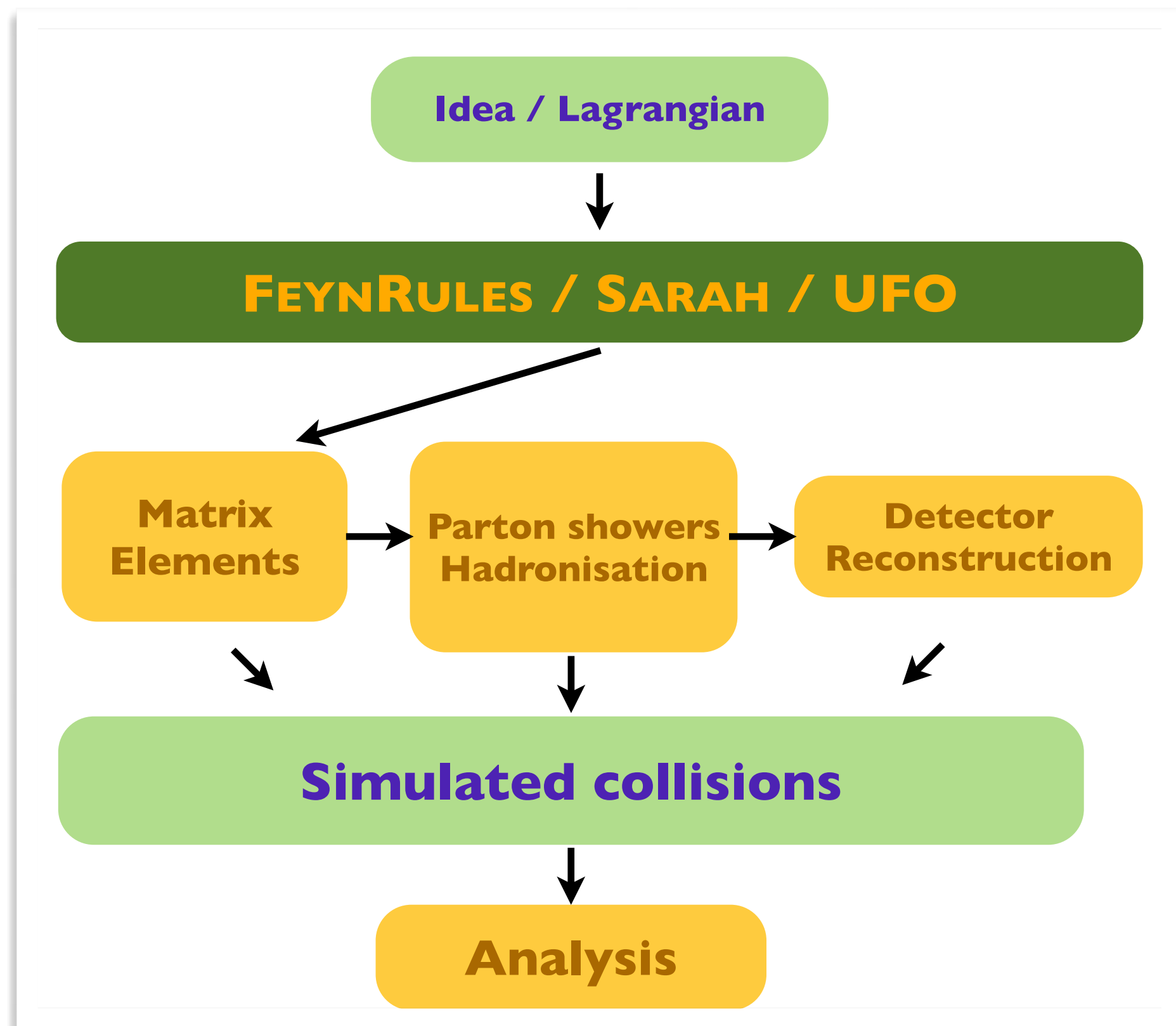


[Agin (2024)]

	ATLAS			MadAnalysis 5-SFS				
	Events	ε [%]	ε_{cut} [%]	Events	ε [%]	δ [%]	ε_{cut} [%]	R_{gap} [%]
Initial (truth $E_T^{\text{miss}} > 150$ GeV)	39598	-	100	89529	-	0.17	100	-
Lepton veto	37547	94.82	94.82	85417	95.41	0.17	95.41	0.62
$N_{\text{jets}} \leq 4$	35412	89.43	94.31	76195	85.11	0.18	89.20	4.38
$\min[\Delta\phi(\text{jets}, E_T^{\text{miss}})]$ cut	33319	84.14	94.10	69253	77.35	0.18	91.00	8.07
Leading jet > 150 GeV and $ \eta < 2.4$	23134	58.42	69.43	47157	52.67	0.20	68.10	9.84
$E_T^{\text{miss}} > 200$ 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
EM4	2618	6.61	-	5847	6.53	-	-	1.21
EM5	1352	3.41	-	2895	3.23	-	-	5.28

Connecting ideas to simulations...

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC 11)]



Scan and constraints

- Scan: BSMArt
- LHC constraints: SMODELS
- Higgs constraints: HIGGSTOOLS
- DM constraints: MICROMEAS
- Cross sections: RESUMMINO

- Model building / spectrum  FEYNRULES, SARAH/SPHENO
UFO
- Hard scattering
 - ★ Feynman diagram and amplitude generation
 - ★ Monte Carlo integration  MG5_AMC
CALCHEP (cf. MICROMEAS)
 - ★ Event generation
- QCD environment
 - ★ Parton showering
 - ★ Hadronisation  PYTHIA 8
 - ★ Underlying event
- Detector simulation
 - ★ Simulation of the detector response  DELPHES
HACKANALYSIS
MADANALYSIS 5 – SFS/DELPHES
 - ★ Object reconstruction
- Event analysis
 - ★ Signal/background analysis  HACKANALYSIS / MADANALYSIS 5 / SPEY
 - ★ LHC recasting

Higgsinos in the MSSM

Spectrum:

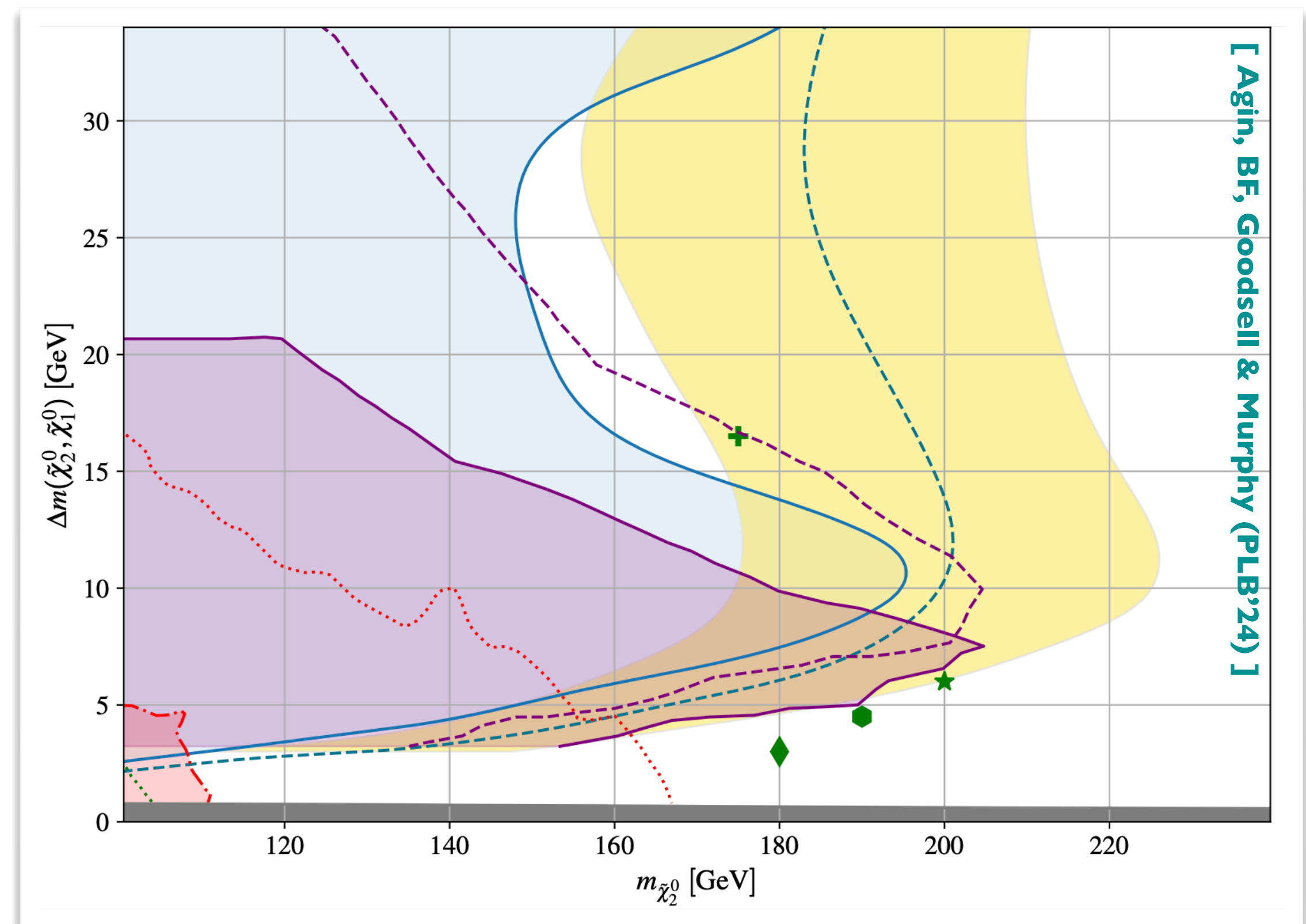
- Two light neutralinos
- One chargino with mass half-way

$$m_{\tilde{\chi}_1^\pm} = \frac{1}{2} (m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0})$$

ATLAS/CMS ewkino searches with leptons

- Clear **excesses** in both experiments
 - $\Delta m \in [10, 30]$ GeV
 - $m_{\tilde{\chi}_2^0} \sim 180$ GeV

- CMS EWino expected
- CMS EWino observed
- ATLAS EWino expected $\pm 1\sigma_{\text{exp}}$
- ATLAS EWino observed



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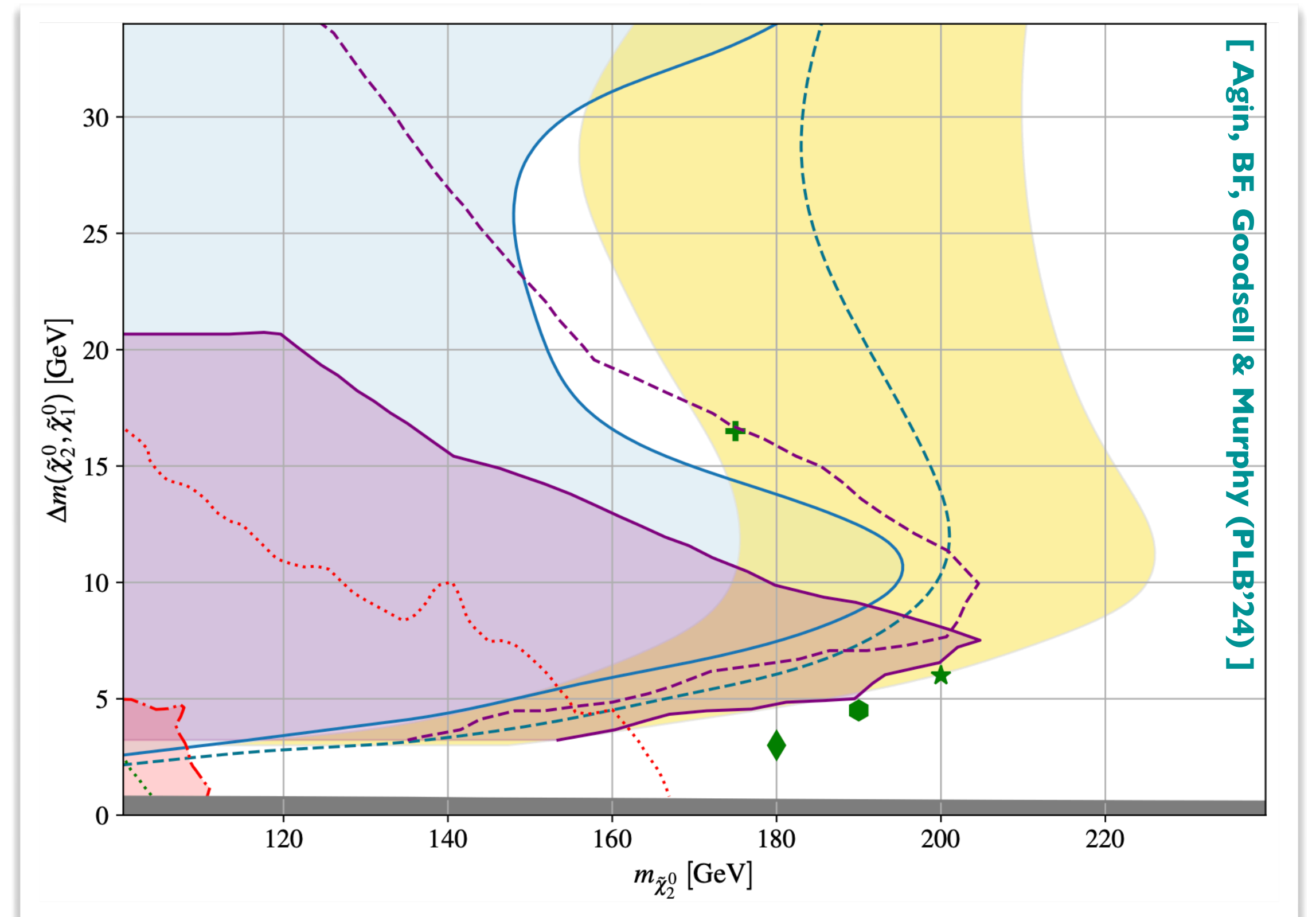
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Significant excess in the CMS monojet search

- ATLAS monojet search insensitive (but also with excess)
 - Not exploitable in a good way (as expected)

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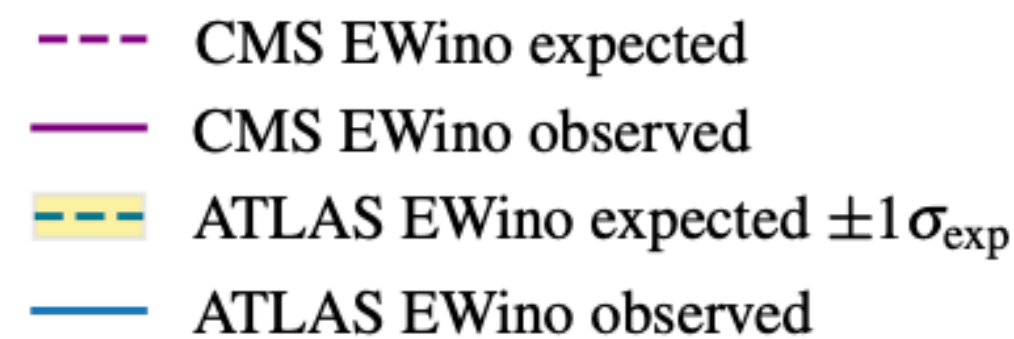
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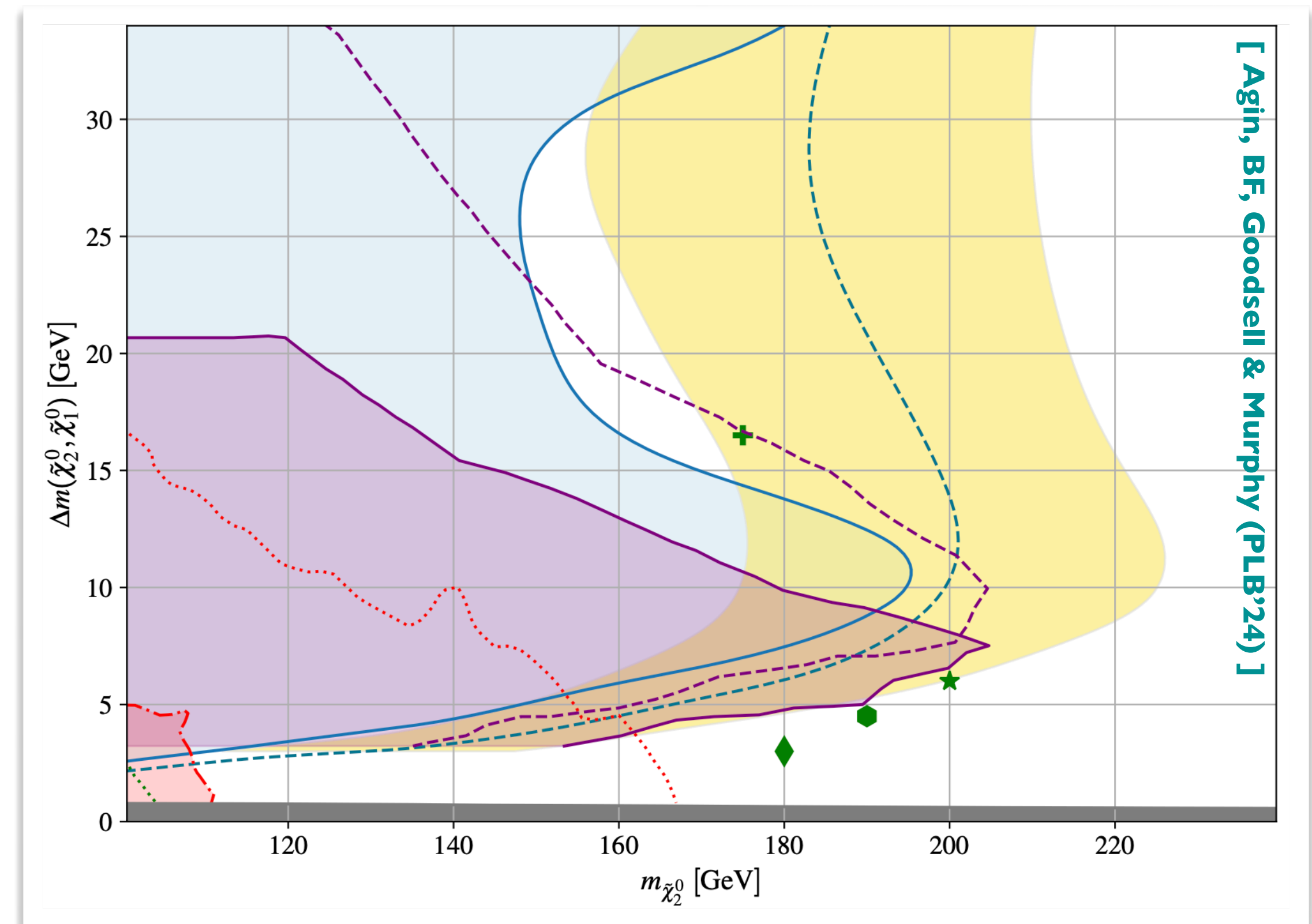
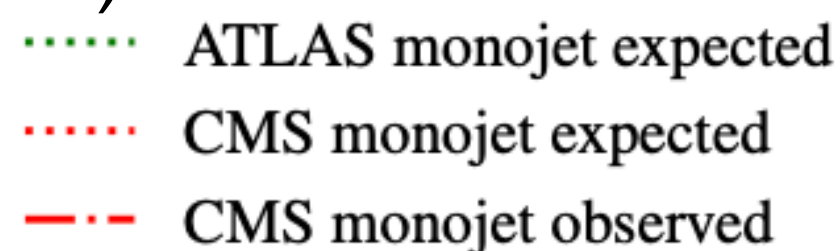
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Significant excess in the CMS monojet search

- ATLAS monojet search insensitive (but also with excess)
 - Not exploitable in a good way (as expected)
- Special monojet points
 - Best fit (♦): $\mu \sim 1; p \sim 0.05$
 - Most significant (◆): $\mu \sim 1.4; p \sim 0.02$
 - Other good point (+): $\mu \sim 1.5; p \sim 0.04$
- **Overlap** with the multi-leptonic excesses not trivial
 - **Very few multilepton events** in the special scenarios
 - Beyond simplified models
 - Favoured by DM



Realistic wino-bino scenarios

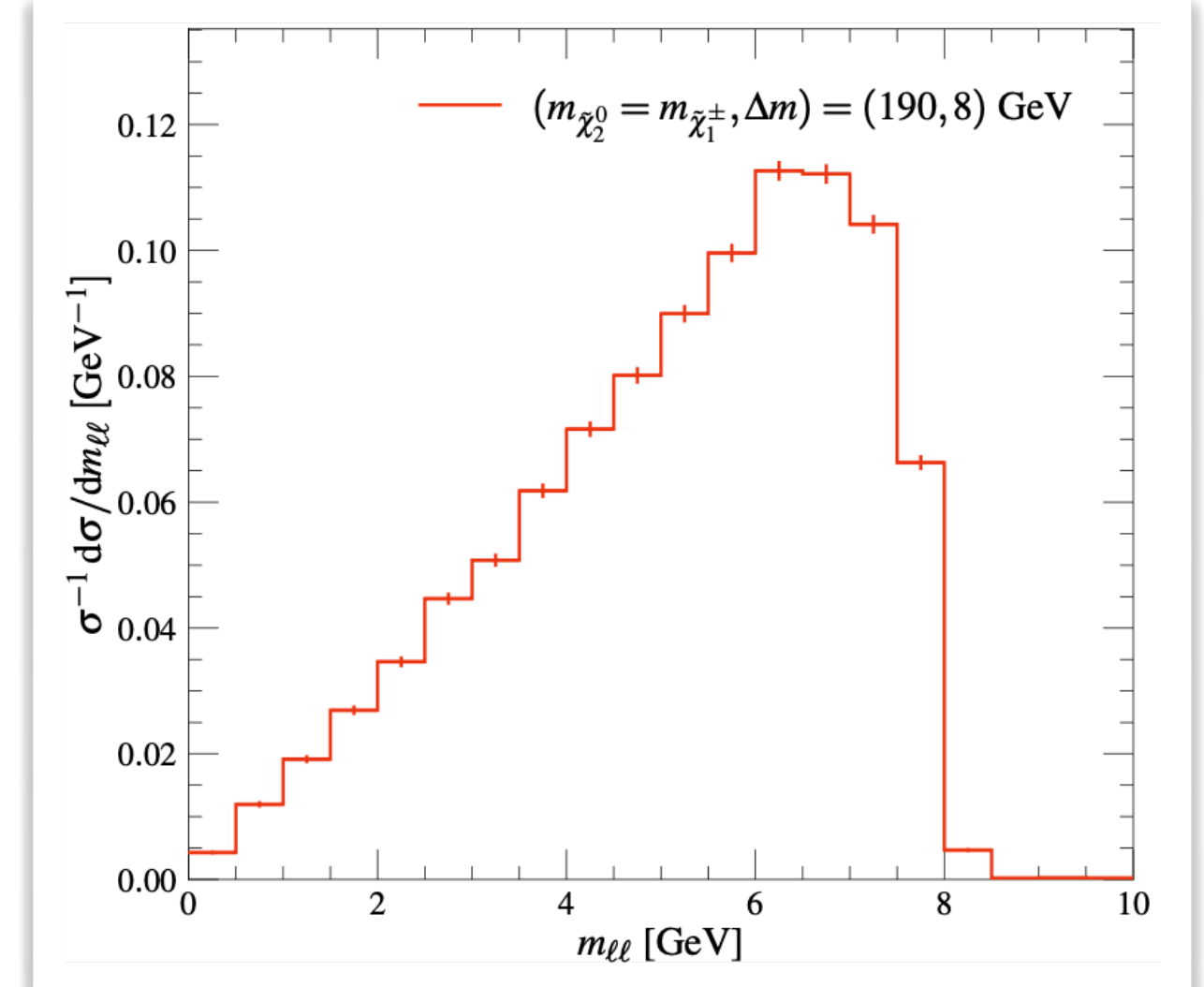
[Agin, BF, Goodsell & Murphy (EPJC'24)]

Wino-bino models

- Dark matter: bino LSP with mixings and compression
 - Sub-GeV co-annihilating DM (unlike Higgsinos)
 - **20 GeV mass splitting** needed ↔ region of interest
- Mass spectrum featuring $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$
- Constraints: Higgs bosons; other LHC signals
- Scan of the ewkino parameter space (mainly M_1, M_2)

Signal features

- Excess in some $m_{\ell\ell}$ bins
 - Need for $m_{\ell\ell}$ in [5, 20] GeV
 - Tails not populated
- **3-body decays mandatory**



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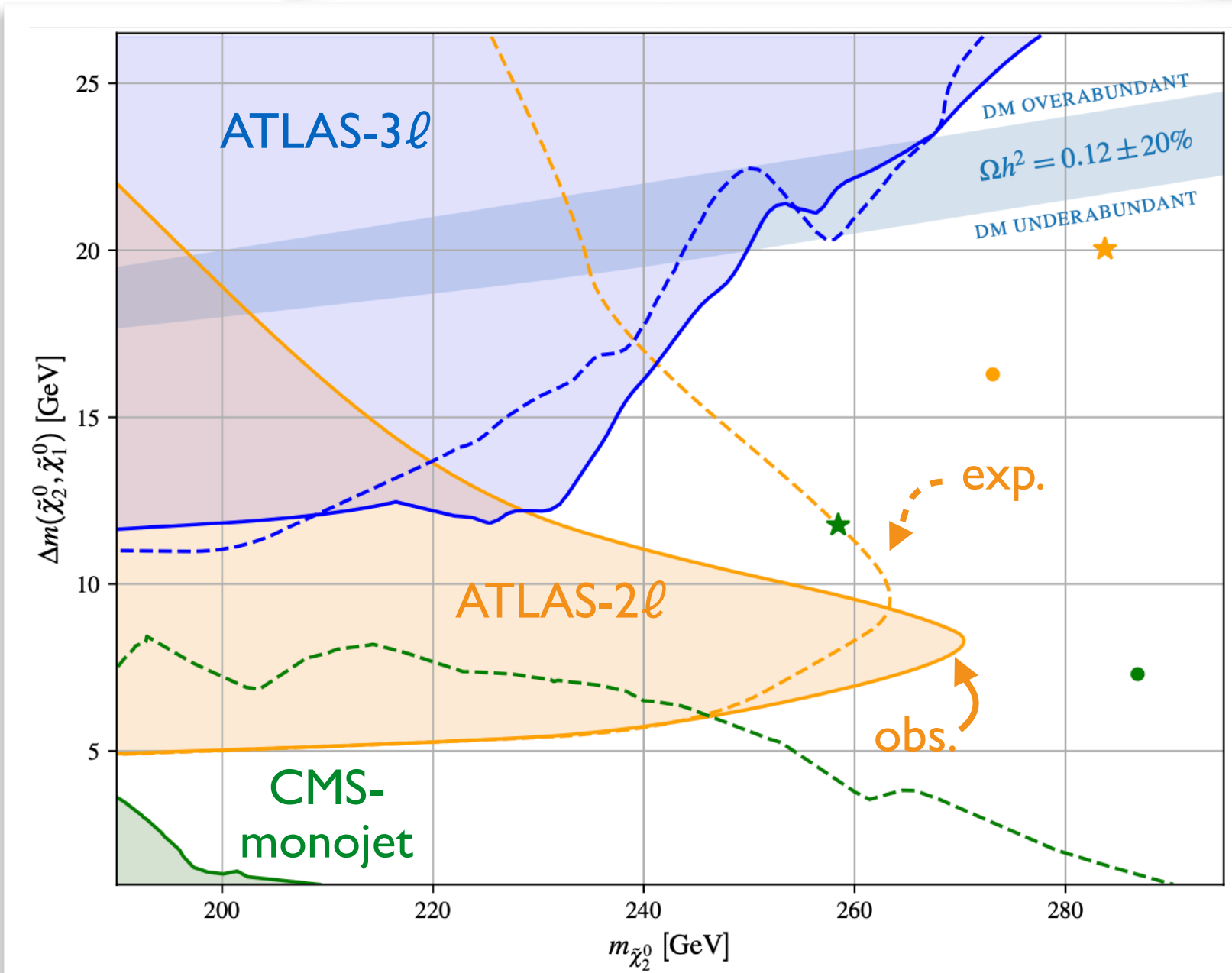
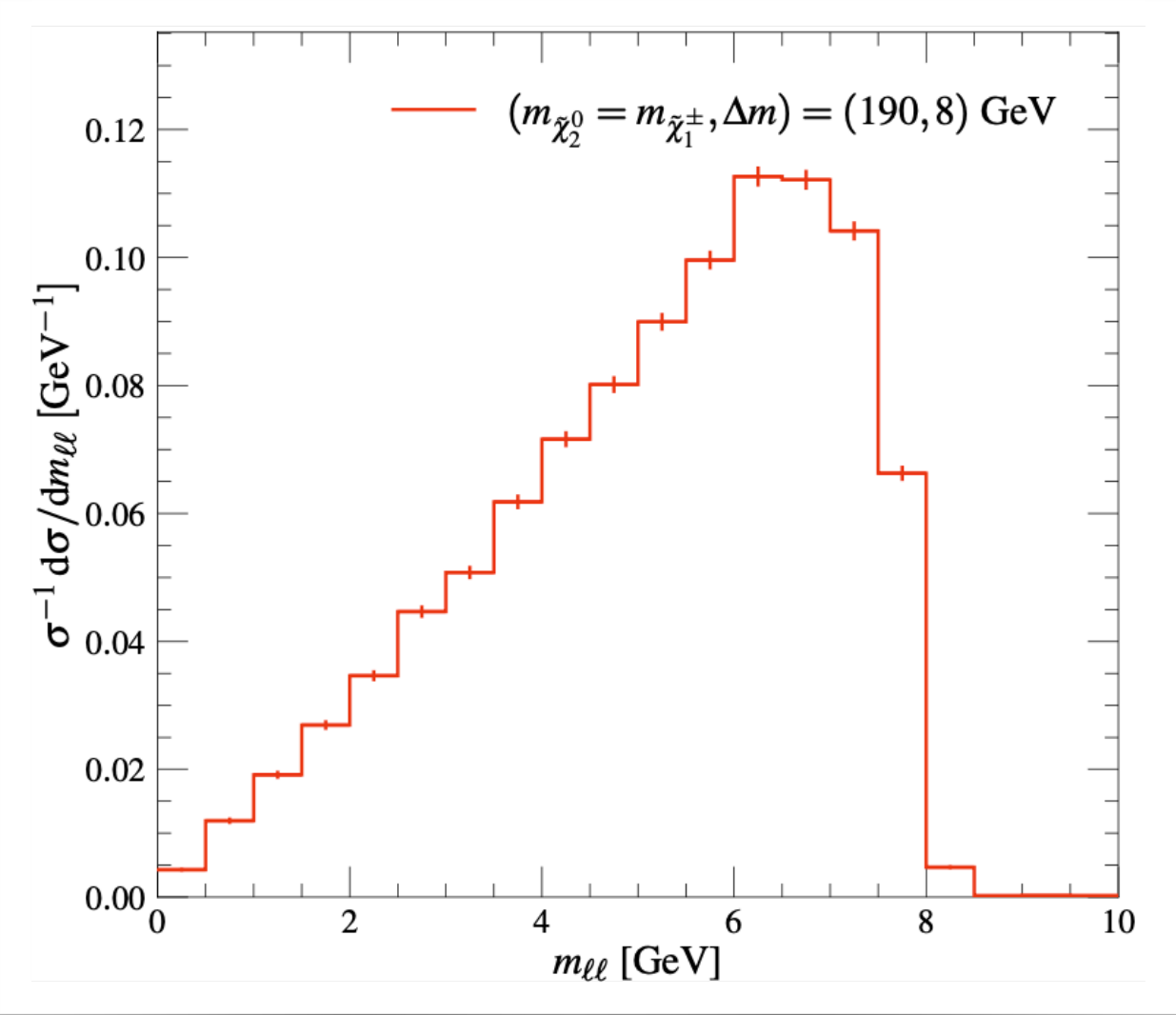
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Overlapping excess?

- Significant ATLAS-2 ℓ /CMS-monojet excesses
- Individual special points shown
 - $m_{\tilde{\chi}_2^0} \sim 260 - 290$ GeV; $\Delta m \in [7, 20]$ GeV
- ATLAS-2 ℓ best fit point:
 - Signal strength close to 1, some **overlap with monojets**
 - Not very far from the **DM band**!
- CMS best monojet points insensitive to leptonic signals

Signal features

- Excess in some $m_{\ell\ell}$ bins
 - Need for $m_{\ell\ell}$ in $[5, 20]$ GeV
 - Tails not populated
- **3-body decays mandatory**



Point ($m_{\tilde{\chi}_2^0}, \Delta m$) [GeV]	● ATLAS 2 ℓ best fit (273, 16.3)	★ ATLAS 2 ℓ most significant (284, 20.0)	● CMS monojet best fit (287, 7.30)	★ CMS monojet most significant (258, 11.8)
($p, \hat{\mu}$) [ATLAS 2 ℓ]	(0.047, 1.12)	(0.041, 1.26)	(> 0.5, < 0.1)	(0.290, 0.30)
($p, \hat{\mu}$) [ATLAS 3 ℓ]	(> 0.5, < 0.1)	(0.426, < 0.1)	(> 0.5, < 0.1)	(> 0.5, < 0.1)
($p, \hat{\mu}$) [CMS monojet]	(0.098, 1.58)	(0.065, 2.33)	(0.049, 1.15)	(0.044, 1.40)
($p, \hat{\mu}$) [ATLAS monojet]	(0.277, 1.21)	(0.163, 2.44)	(0.127, 1.53)	(0.277, 0.879)

NMSSM singlino-higgsino setups

[Agin, BF, Goodsell & Murphy (EPJC`24)]

Singlino+higgsino models

- NMSSM $\leftrightarrow$ solution to the μ problem
- Singlino LSP with small higgsino mixing (4 light ewkinos)
 - $\rightarrow$ No higgsino DM under-abundance
 - $\rightarrow$ Annihilations into EW bosons; co-annihilations to quarks
- LHC signals: mostly higgsino-driven
- Constraints: properties of Higgs bosons; other LHC exclusions
- Scan of the singlino/higgsino parameter space

$$\mathcal{W}_{\text{NMSSM}} \supset \lambda S \mathcal{H}_u \mathcal{H}_d + \frac{1}{3} \kappa S^3$$

$$V_{\text{NMSSM}}^{\text{soft}} \supset A_\lambda \lambda S \mathcal{H}_u \mathcal{H}_d + \frac{1}{3} A_\kappa \kappa S^3$$

$$\mu_{\text{eff}} \in [100, 250] \text{ GeV}$$

$$\kappa \in [1, 20] \times 10^{-3}$$

$$\delta \in [0.01, 0.20] \text{ such that } \lambda = (2 + \delta)\kappa$$

$$\tan \beta \in [8, 20]$$

$\tilde{S}/\tilde{H}$ mixing

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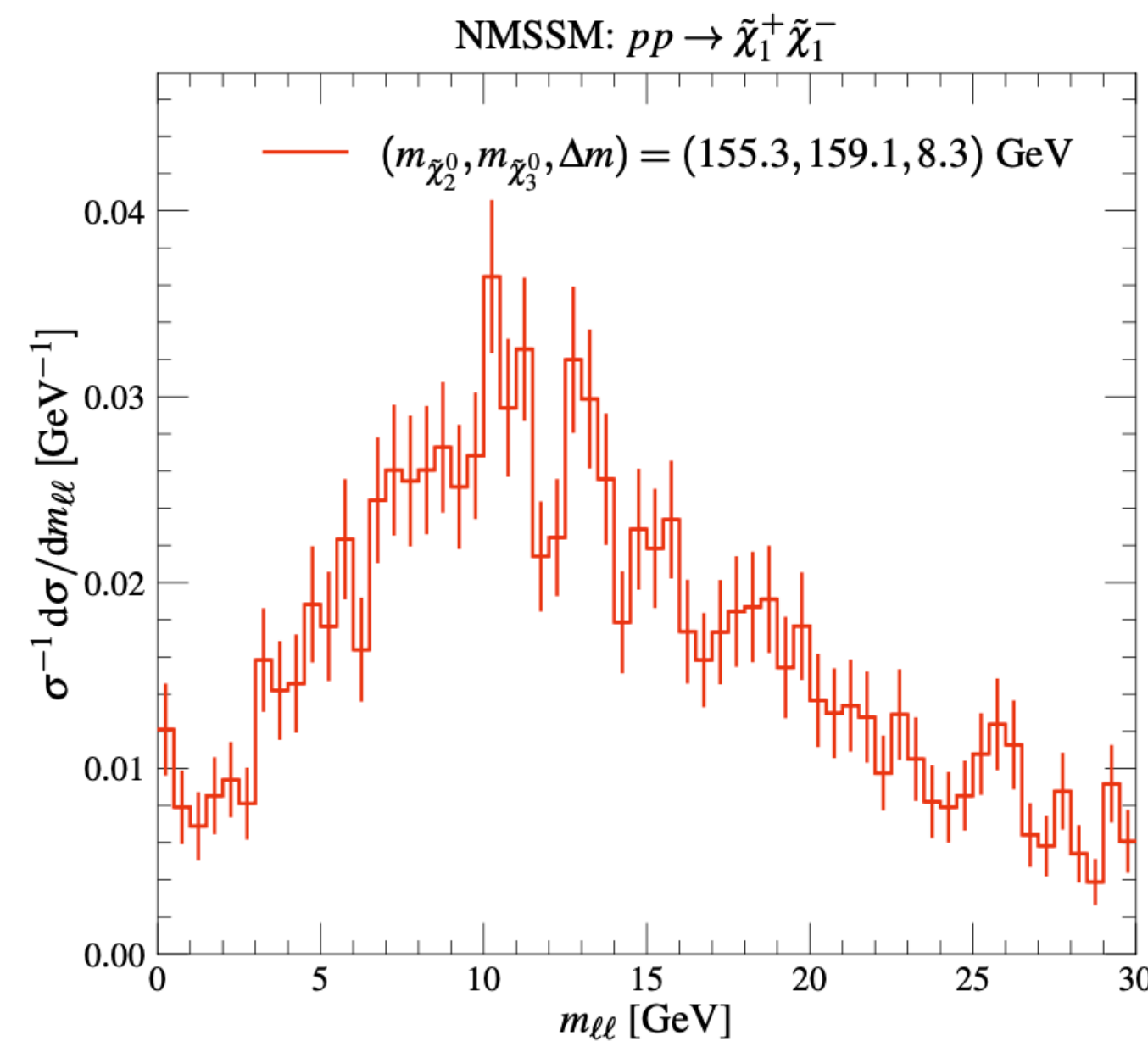
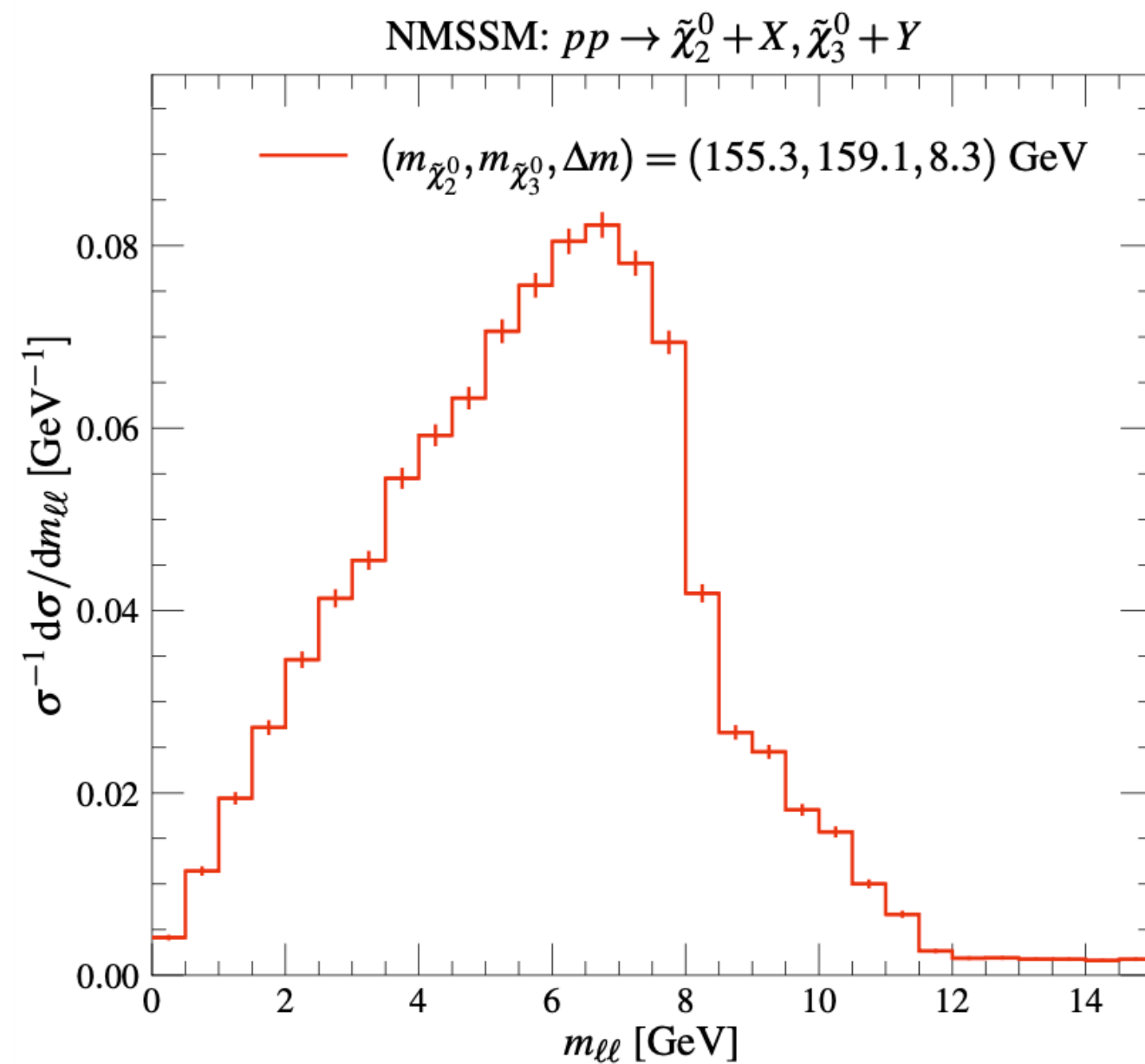
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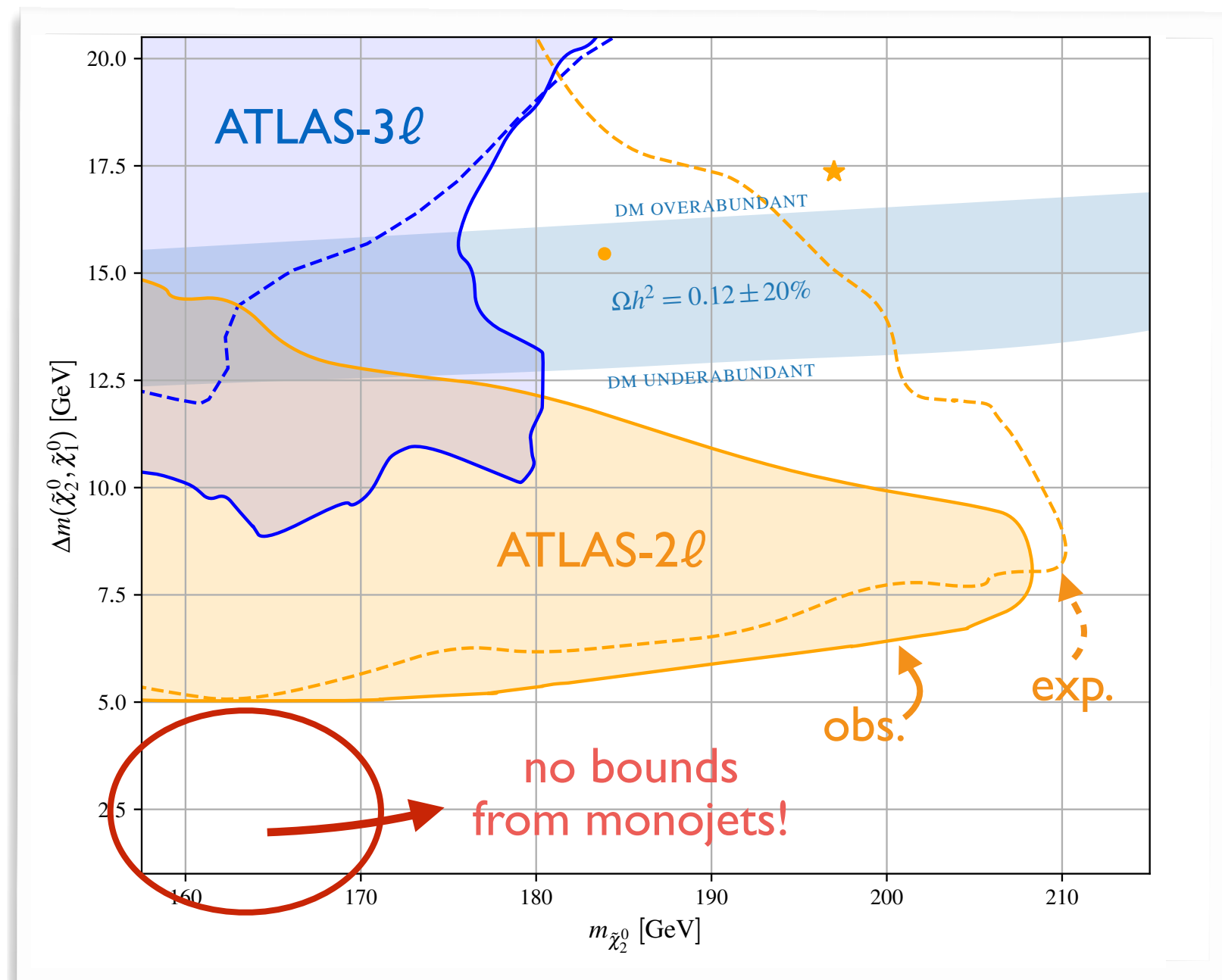


Signal features

- Tail in chargino pair production
 - $\rightarrow$ Challenge for excess explanation?
- Neutralino channels
 - $\rightarrow$ Good $m_{\ell\ell}$ features?

EWkino excesses in the NMSSM

[Agin, BF, Goodsell & Murphy (EPJC'24)]



Point ($m_{\tilde{\chi}_2^0}, \Delta m$) [GeV]	★ ATLAS 2ℓ best (197, 17.4)	● ATLAS 2ℓ second best (184, 15.5)	● CMS monojet best fit (205, 6.66)	★ CMS monojet most significant (179, 16.3)
($p, \hat{\mu}$) [ATLAS 2ℓ]	(0.041, 0.97)	(0.044, 0.80)	(0.435, < 0.1)	(0.071, 0.64)
($p, \hat{\mu}$) [ATLAS 3ℓ]	(0.446, 0.12)	(> 0.5, 0.12)	(> 0.5, 0.71)	(> 0.5, 0.13)
($p, \hat{\mu}$) [CMS monojet]	(0.132, 3.00)	(0.129, 2.65)	(0.712, 1.91)	(0.051, 3.79)
($p, \hat{\mu}$) [ATLAS monojet]	(0.277, 2.44)	(0.277, 2.02)	(0.127, 2.96)	(0.277, 2.08)

Overlapping excess?

- Stronger constraints from ATLAS- 3ℓ
- Tension between soft dilepton and monojet points
 - Not enough monojet cross section
 - Poor monojet fit
- ATLAS- 2ℓ points ↔ interesting DM candidates
- No overlap between excesses...

NMSSM scan

- $\tilde{S}$ -like LSP (cf. DM) ↔ 4 light ewkinos
- Excess compatibility can accommodate DM
 - cf. best fit points
- Monojet bounds in principle complementary
 - Existing excesses
 - No constraints!

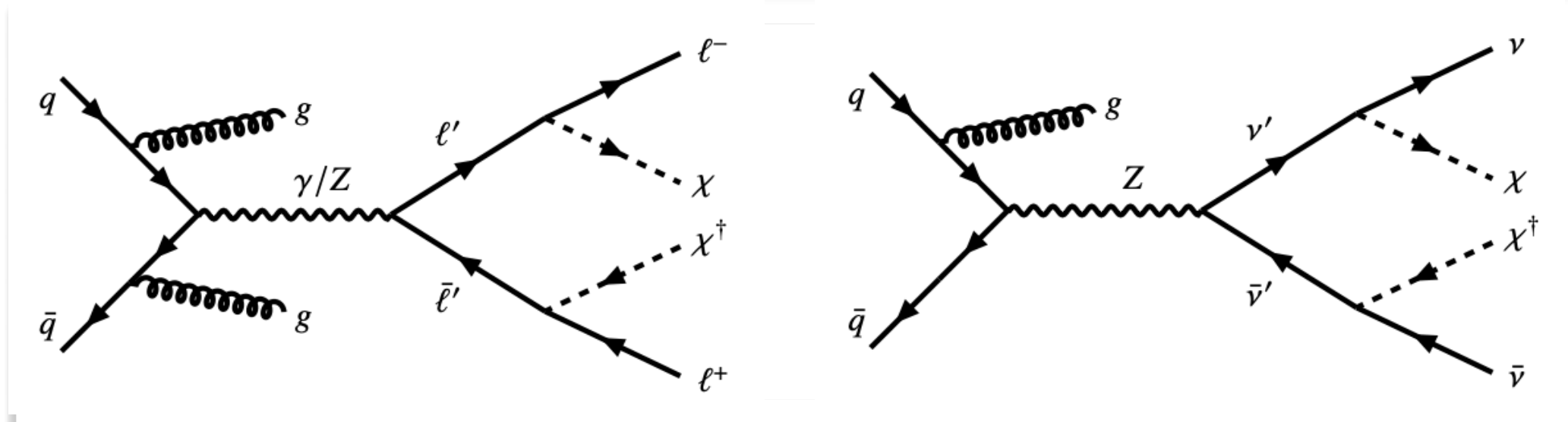
Non-supersymmetric explanations?

[Agin, BF, Goodsell & Murphy (EPJC`24)]

Scalar DM with a doublet vector-like leptons

$$\mathcal{L} \supset \lambda_I \chi (\bar{\nu}' \nu_{LI} + \bar{\ell}' \ell_{LI}) + \text{H.c.}$$

- Non-SUSY higgsino-like setup (**fermionic weak doublet**)
- LHC signals: **two-body decays** to leptons



- Spectrum of interest: compressed by [0, 30] GeV
→ Soft leptons at the LHC

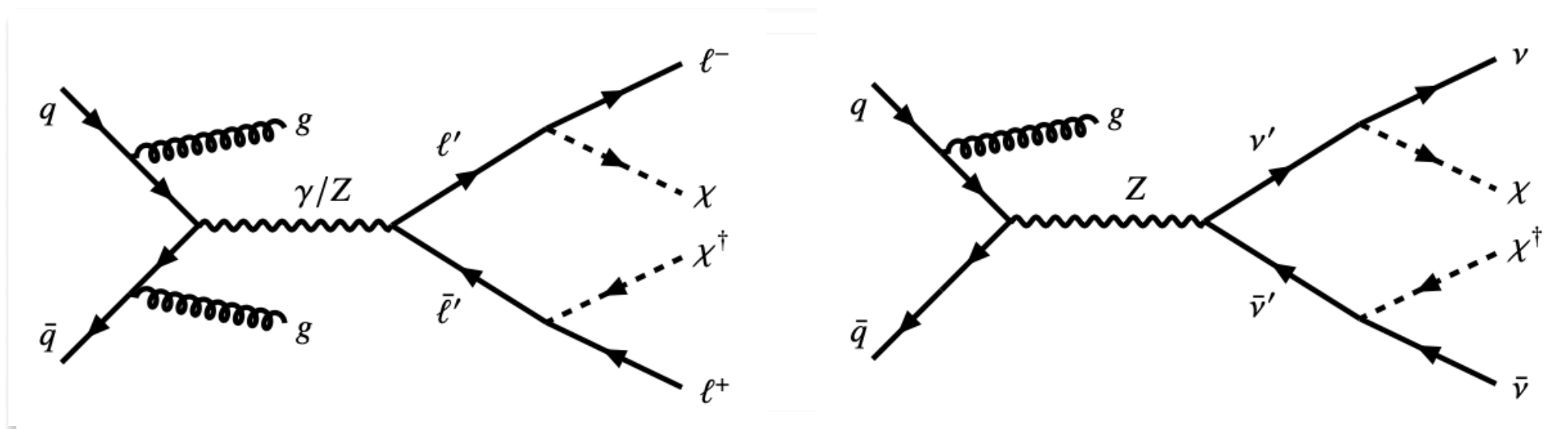
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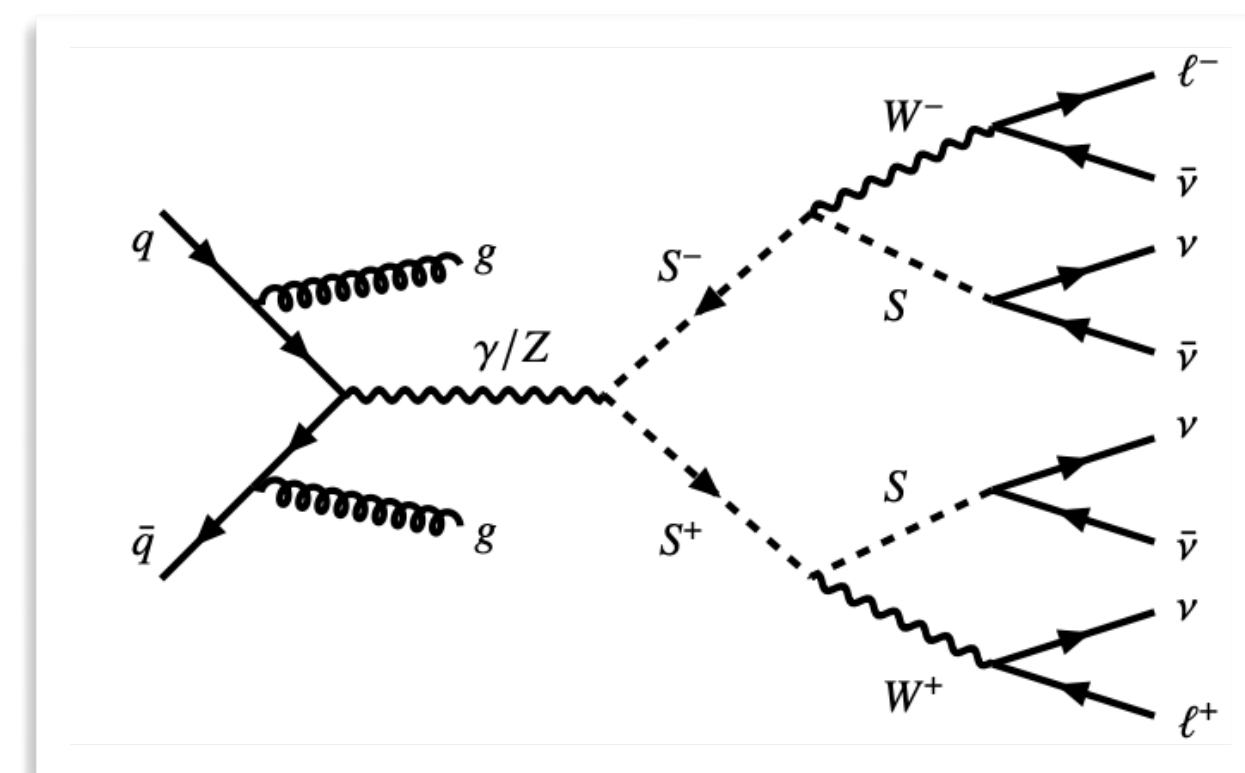
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- Spectrum of interest: compressed by [0, 30] GeV
 ➔ Soft leptons at the LHC

Type II Seesaw

- Neutrino mass modelling
- Non-SUSY wino-like setup (**scalar weak triplets**)
 ➔ 1 SM Higgs field ϕ + 1 BSM scalar Δ
 ➔ 4 CP-even scalars ($h, S, S^\pm, S^{\pm\pm}$)
 ➔ Small splitting possible $\leftrightarrow$ small ϕ/Δ mixing
- LHC signals: **cascade-decays** to leptons
 ➔ Via off-shell weak bosons
 ➔ Many (too many?) soft leptons

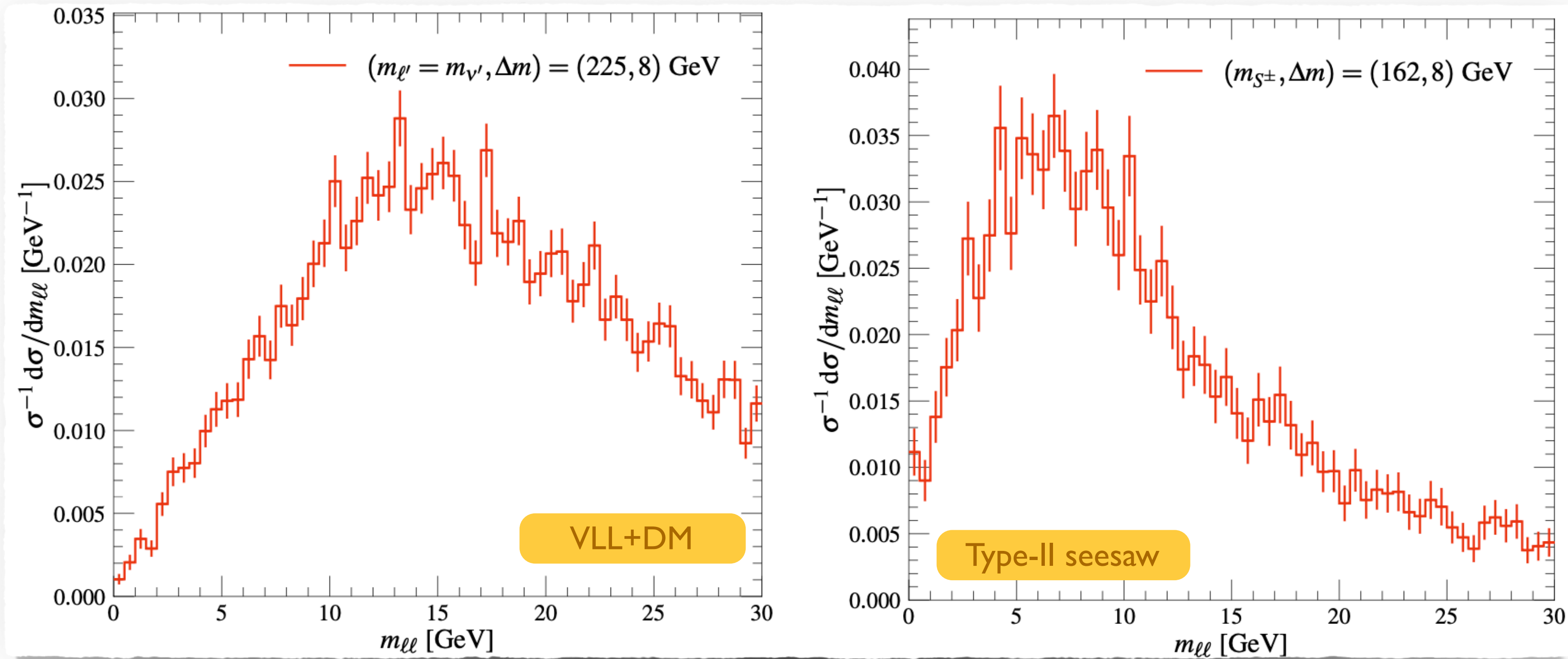


Non-supersymmetric explanations: not so far!

[Agin, BF, Goodsell & Murphy (EPJC`24)]

Too hard tails in the dilepton invariant mass spectra

- VLL+DM: events expected to populating high $m_{\ell\ell}$ bins
- Type-II: similar to ewkino models

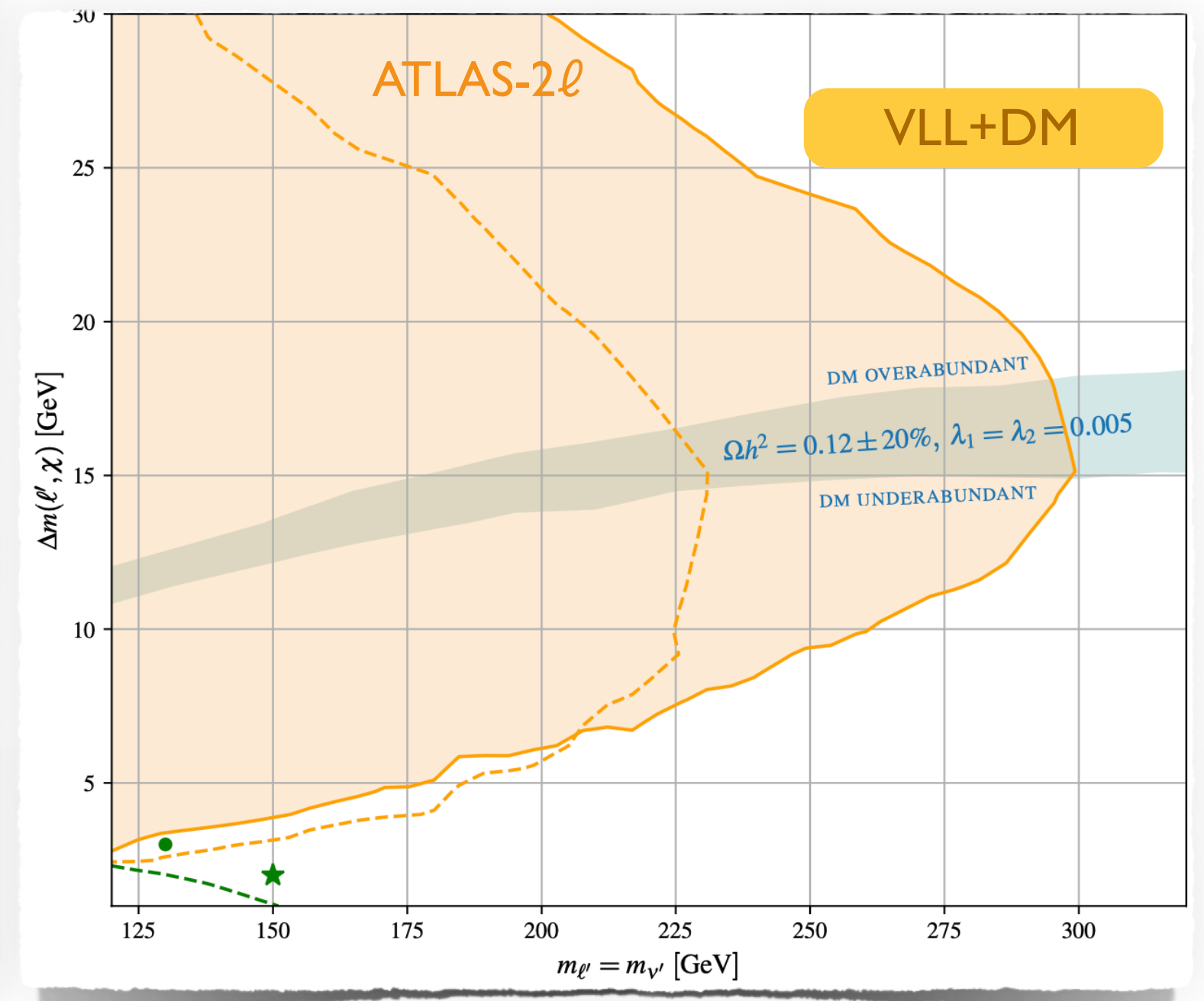
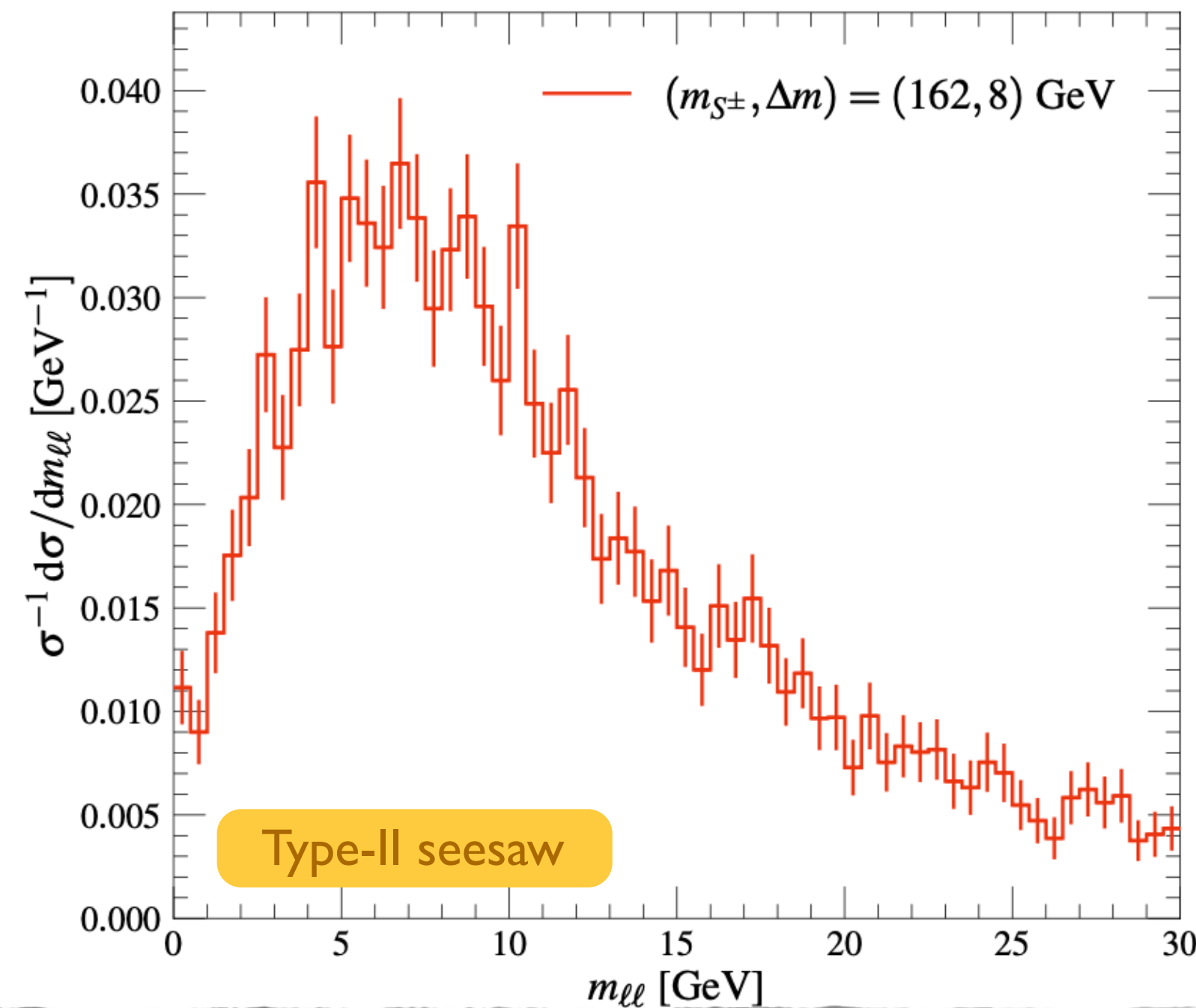
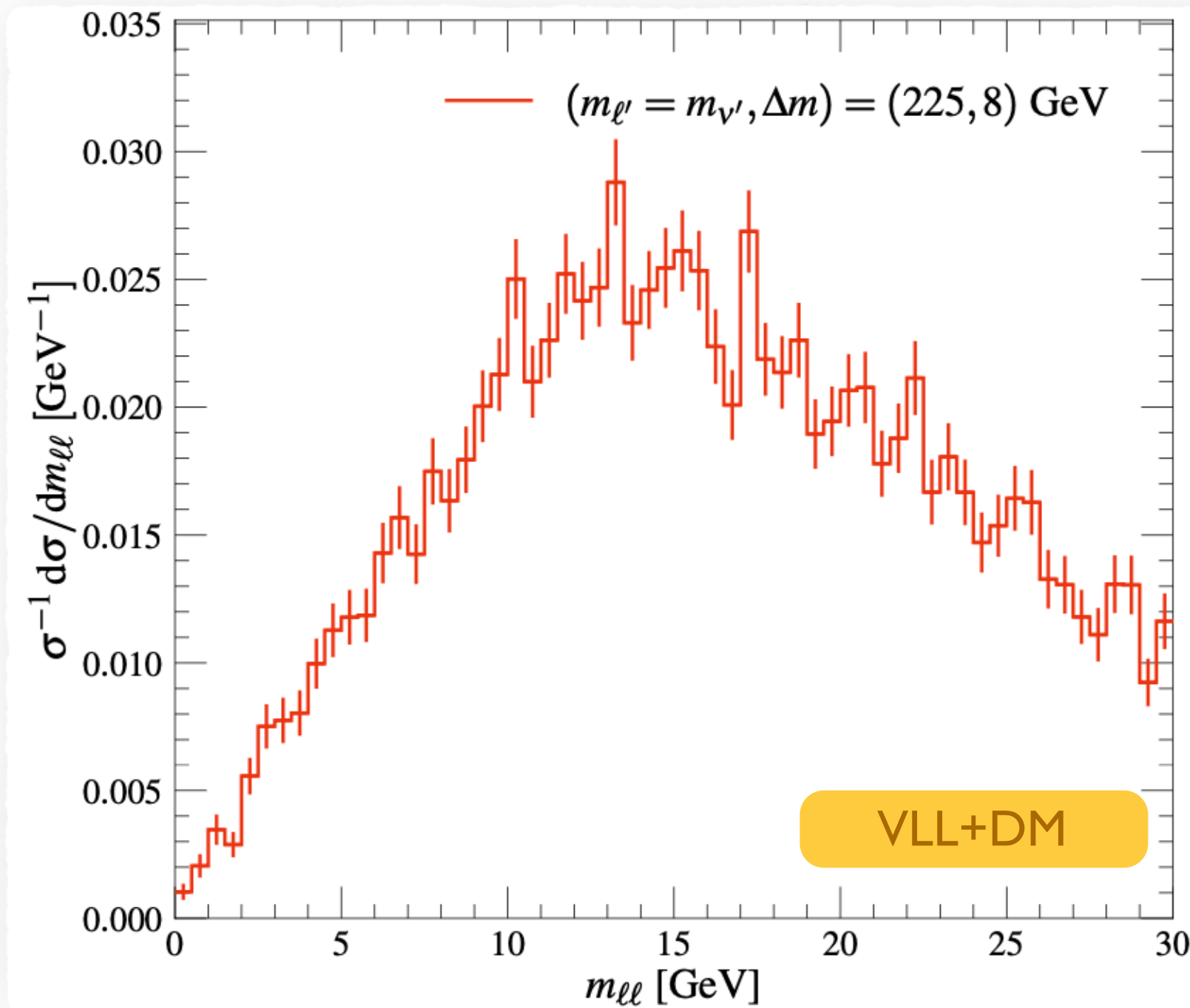


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VLL+DM model

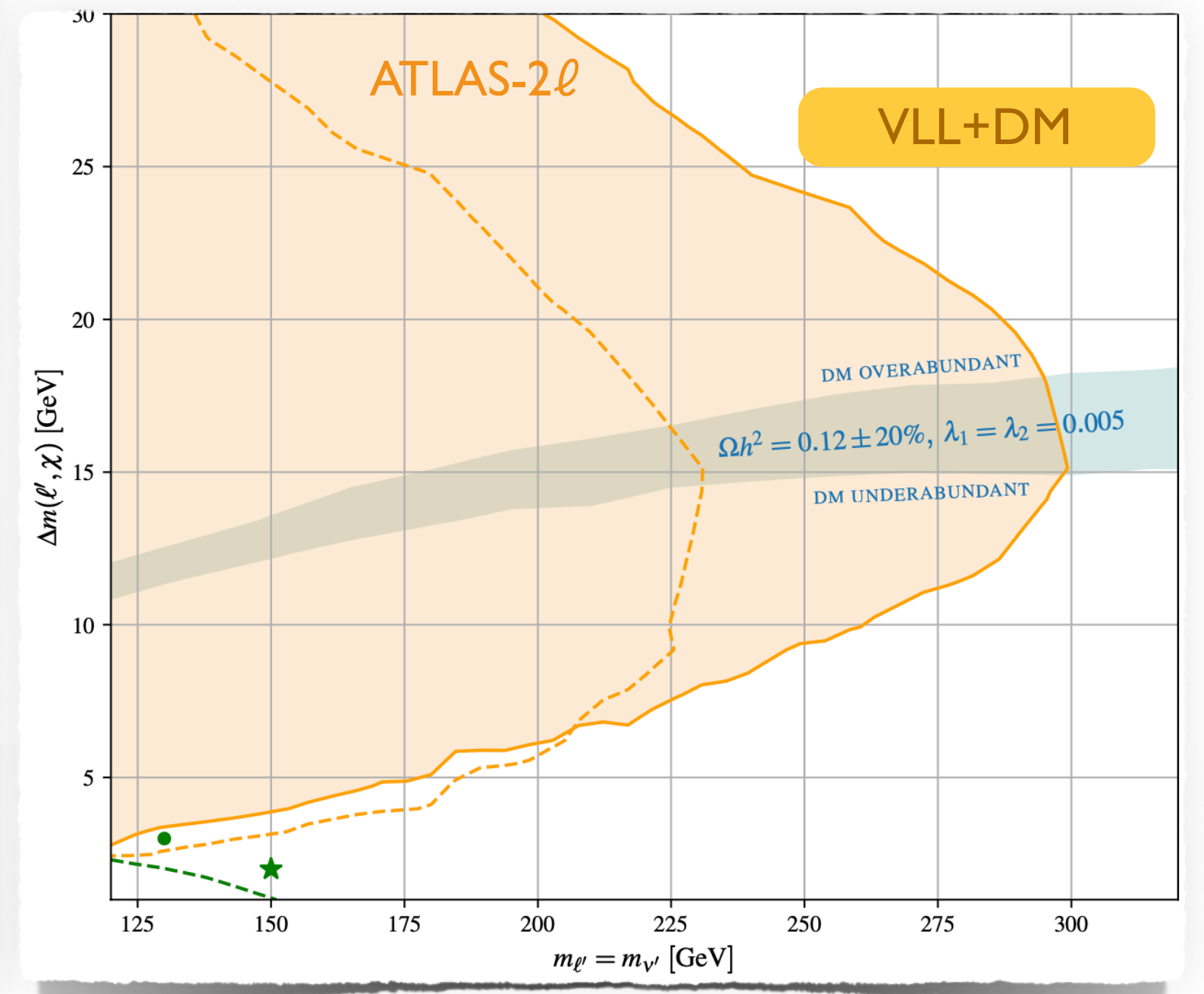
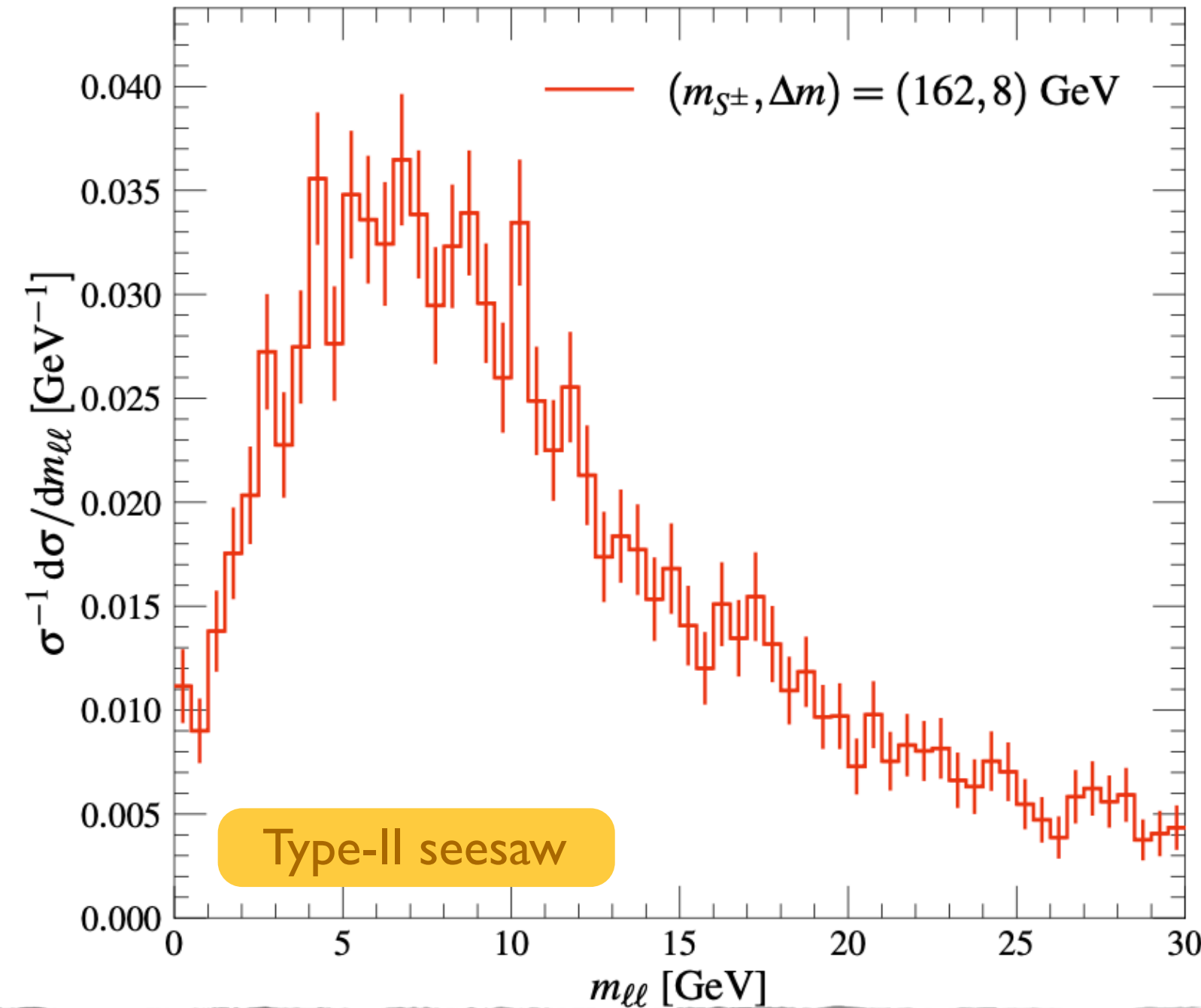
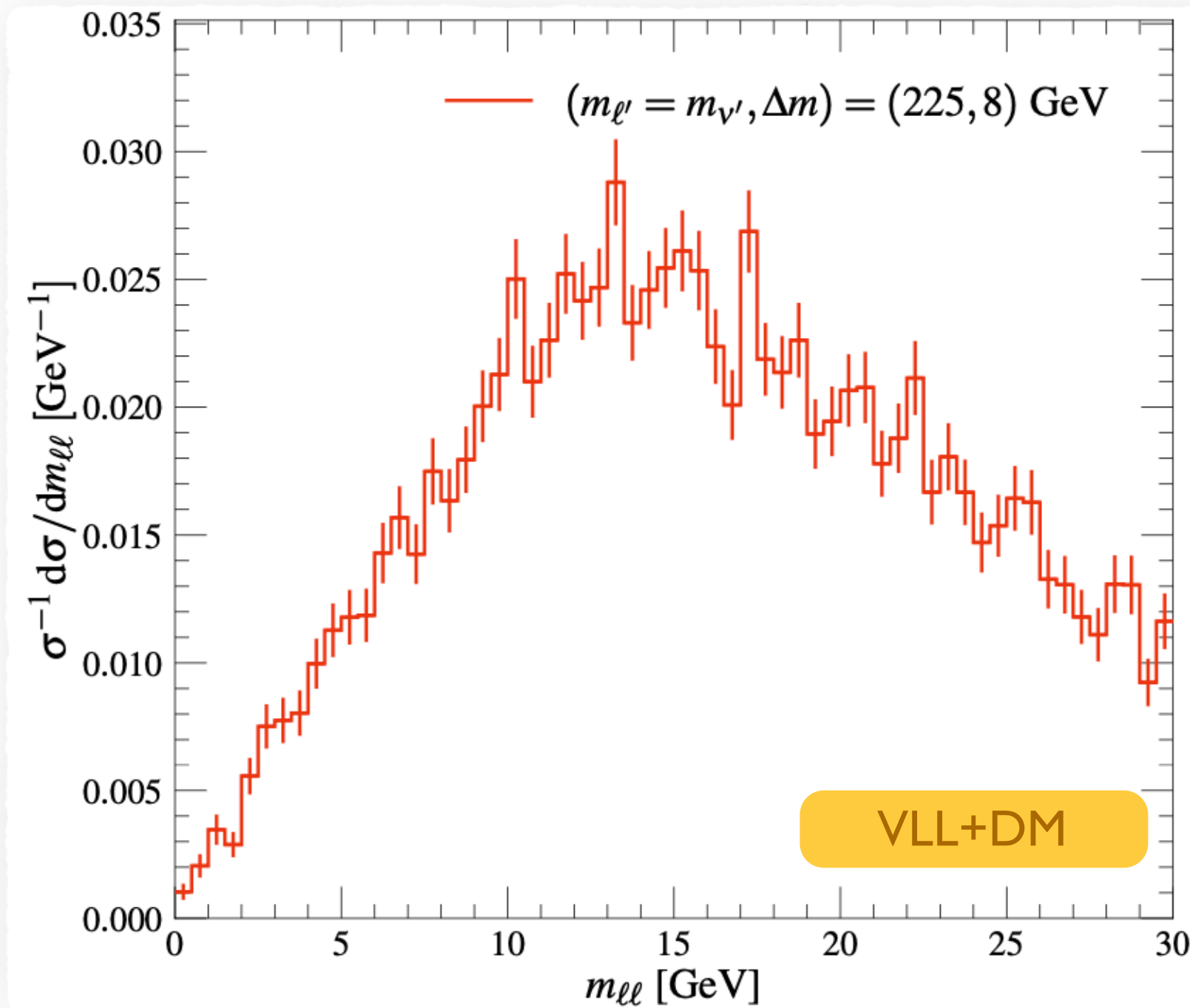
- No leptonic excess, strong exclusion
 - 3-body BSM decays in order
- Survival of the **monojet excess!**
 - Very light BSM states ($\mu \sim 1.1 - 1.25$; $p \sim 0.04$)

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Type-II model

- No sensitivity ($CL_s > 0.05$)
 - Busy final states ↔ small efficiencies
- **Excess present!**
 - Dedicated analyses hard

	CL_s^{exp}	CL_s^{obs}	p -value	$\hat{\mu}$
ATLAS 2 ℓ	0.387	0.620	0.050	2.06
ATLAS 3 ℓ	0.611	0.615	≥ 0.5	0.62
CMS monojet	0.270	0.395	0.081	1.17
ATLAS monojet	0.553	0.399	0.277	0.72

Combinations of LHC analyses



Theory-driven combinations

- Beyond those done in experiments
- Could be done in a good enough manner
 - Has to be conservative
 - Ideas on global status of models

Combining all lepton + E_T^{miss} & monojet searches

[Agin, BF, Goodsell & Murphy (EPJC'25)]

Combination: likelihood products and impact on the wino/bino plane

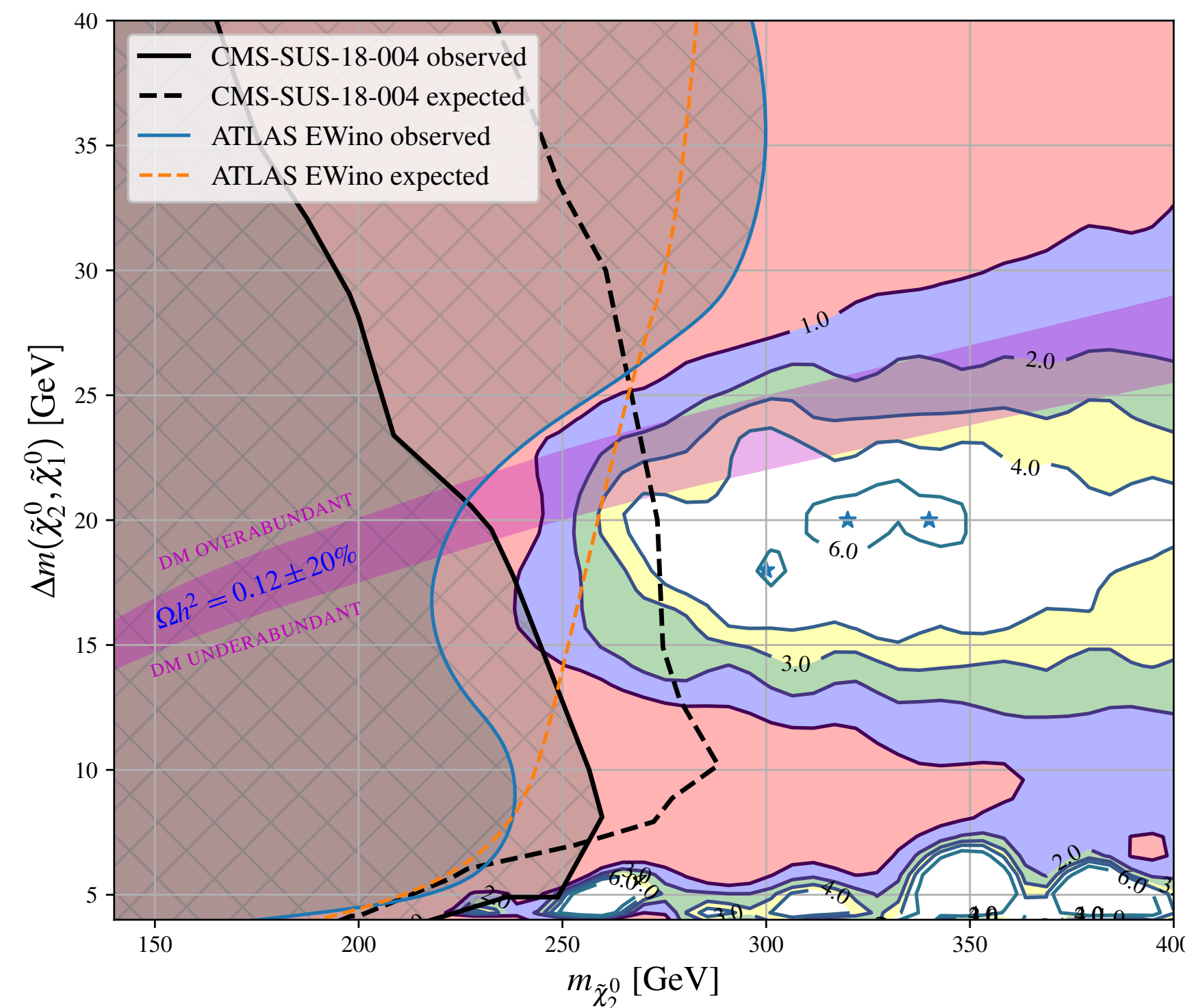
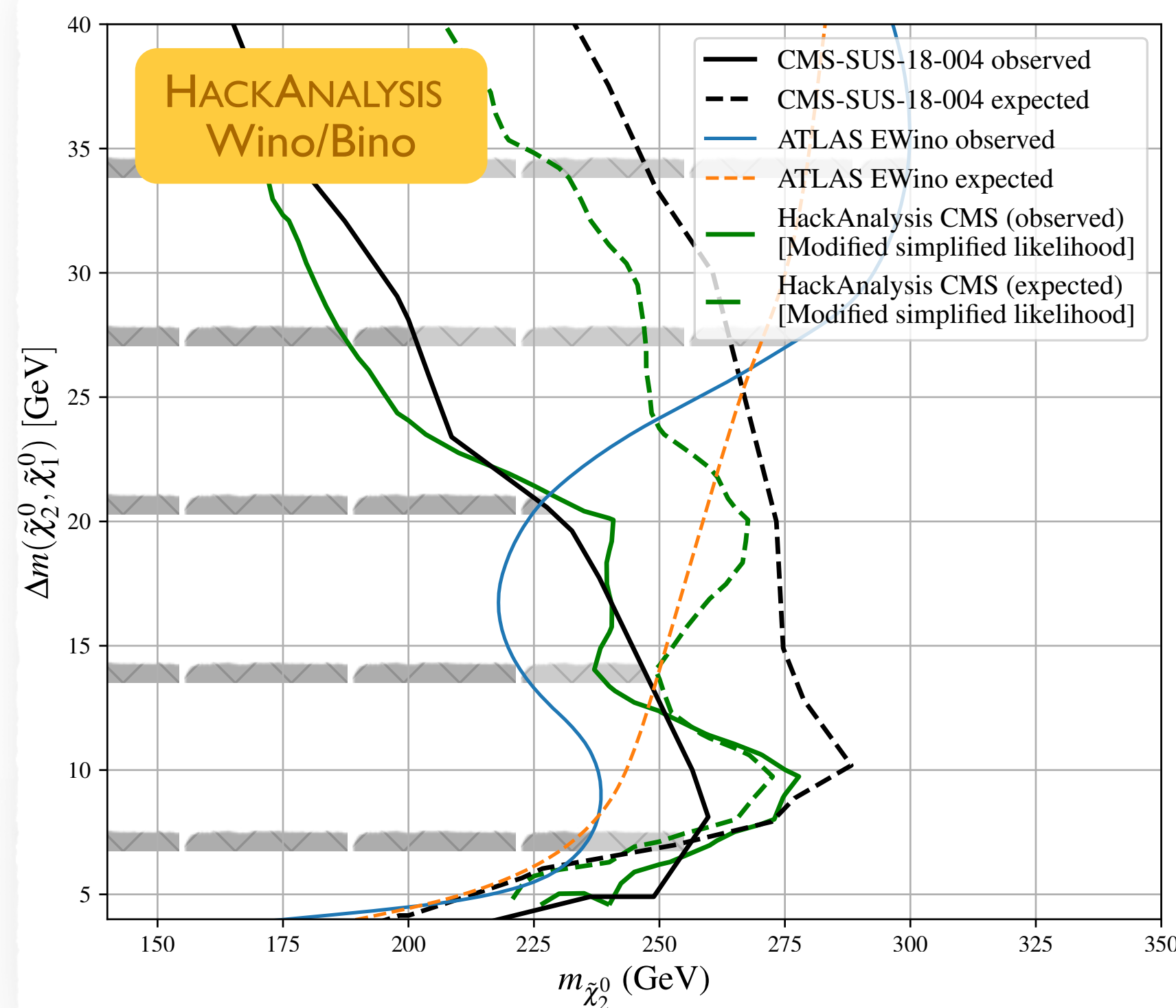
- Inclusion of CMS-SUS-18-004 (2/3 soft leptons and missing transverse momentum)
- All relevant searches now available

Identification of the preferred region of the parameter space

- Bayes factors: ratio of evidences for a new-physics scenario to the SM
 - Quantitative measurement of whether a new model is (dis)favoured compared to the SM
 - $B_{10} > 1$ ↔ evidence for the new model stronger than that for the SM

Best points

- $m_{\tilde{\chi}_2^0} \sim 300$ GeV
- $\Delta m \sim 20$ GeV
- $B_{10} \sim 6$ or 7



Summary - outlook

SUSY searches ↔ excellent templates for BSM searches

- Large set of shared signatures with numerous models
- **Crucial to reproduce analyses** (aka *LHC recasting*)

LHC recasting paves the way to interesting studies

- Non-simplified models; non-minimal models
- Understanding excesses [soft leptons? monojets?]

A lot of development over the past decade

- Two classes of public tools (SMS or simulation based)
- **Validation ↔ detailed material**
 - Great progress over the years!
 - Being transparent crucial
- Combination of SRs/analyses now possible
- ML-based searches ↔ the next frontier
 - ONNX-released networks
 - Already available in some tools [*not covered here*]

Reproducibility

- Key principle in the scientific method
- Need for the TH/EXP communities to move together

