Exploring a Composite Dark Matter Model Using CONTUR and MadAnalysis5

Clarisse Prat
Benjamin Fuks, Louie Dartmoor Corpe

LHC Reinterpretation Forum 2025

CONTUR

Constraints On New Theories Using RIVET

- Toolkit designed to probe BSM theories using **measurements** at particle colliders
- We have a vault of information from SM measurements and BSM searches that have been performed at the LHC
- How can we use this information to search for BSM physics?
- CONTUR produces cross-section limits derived from comparisons between theoretical BSM simulations and ***unfolded*** data at particle-level

MadAnalysis5

- Framework for phenomenological analyses based on **searches** at the LHC
  - Utilise MC simulations to generate new physics signals emerging from a given model
- Includes accurate modelling of detector effects
  - **Simplified Fast Detector Simulation (SFS)**: efficiency functions and smearing techniques to map hadron-level MC truth to reconstructed objects used in analyses
- Calculates exclusion limits, expected and observed cross-sections via uncorrelated signal regions
- **Public Analysis Database (PAD):** validated LHC analyses to use in recasting

CONTUR and MA5 workflow

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UFO describing BSM model

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MadGraph5 for the event generation, Pythia8 for showering

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Repeat for each point in the parameter space!

LO Model - DM Whitepaper

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Inspiration from theories with DM and partial compositeness:
Top mass from mixing SM with two VLQ partners - $SU(2)_L$ doublet and an $SU(2)_L$ singlet
Scalar dark matter candidate X

$$Q_{L,R} = \begin{pmatrix} T_{L,R} \\ B_{L,R} \end{pmatrix} \qquad \tilde{T}_{L,R}$$

Simplified Model:

- Three mediators $T_{L,R}$ $\tilde{T}_{L,R}$ $B_{L,R}$
- One dark matter candidate X

$$\mathcal{L}_{\mathrm{BSM}} = \mathcal{L}_{\mathrm{kin}} - M_T \overline{T}\, T - M_B \overline{B}\, B - M_{\tilde{T}} \overline{\tilde{T}}\, \tilde{T} - \frac{1}{2} M_X X^2 + \left(\lambda_Q [\, \overline{T_R}\, t_L + \overline{B_R}\, b_L \,] X + \lambda_T \overline{\tilde{T}_L}\, t_R\, X + \mathrm{H.c.} \right)$$

free parameters: four masses and two couplings

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Computing in HEP and Applications CNRS-Africa Lectures

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FURTHER Simplified Model:

All VLQ masses are equal: $M_Y = M_T = M_B = M_{\tilde{T}}$

All BSM couplings are equal: $\lambda = \lambda_Q = \lambda_T$

Left with three parameters:

- VLQ mass M_Y
- DM mass M_X
- BSM coupling λ

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Simplification assumption is just to get started!

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Simpli
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t-channel Dark Matter Models – A Whitepaper IN PREPARATION

Diyar Agin,[1] Chiara Arina★,[2] Emanuele Bagnaschi,[3] Kehang Bai,[4] Michael J. Baker†,[5] Mathias Becker,[6,7,8] Alexander Belyaev,[9,10] Ferdinand Benoit,[1] Monika Blanke,[11,12] Jackson Burzynski,[13] Jonathan M. Butterworth,[14] Lorenzo Calibbi,[15] Linda M. Carpenter,[16] Emanuele Copello,[6] Alan S. Cornell†,[17] Louie Corpe,[18] Francesco D'Eramo,[7,8] Aldo Deandrea,[17,19] Aman Desai,[20,21] Benjamin Fuks★[a],[1] Mathias Garny,[22] Mark D. Goodsell,[1] Julia Harz,[6] Jan Heisig†,[23] Alejandro Ibarra,[22] Alberto Orso Maria Iorio,[24,25] Deepak Kar,[26,27] Shaaban Khalil,[28] Mohan Kirtiman,[29] Sabine Kraml,[30] Andre Lessa,[31] Laura Lopez-Honorez,[32,33] Benedikt Maier†,[34] Alberto Mariotti,[35,33] Alexander Moreno Briceño,[36] Léandre Munoz-Aillaud,[1] Taylor Murphy,[1,37] Anele M. Ncube,[17] Wandile Nzuza,[26] Luca Panizzi★,[38,39] Rute Pedro†,[40] Clarisse Prat,[26] Thobani Sangweni,[41] Dipan Sengupta,[42] Will Shepherd,[43] Andrea Thamm,[5] and Dominique Trischuk†[44]

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UFO model: DMSimp_t-F3S_VLQ

But how do we actually run this?

Parameter space scan over different VLQ and DM masses **for a fixed λ**

- $\lambda = 1$
- $M_X = 50 - 500$ GeV
- $M_Y = 500 - 2000$ GeV

Hard processes and VLQ decays done in **MG5aMC**
Parton showering and hadronisation with **Pythia8**
Exclusions from **CONTUR** and **MA5**

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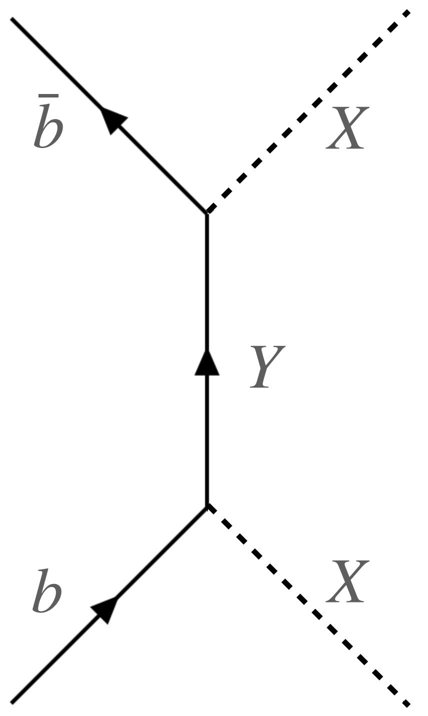
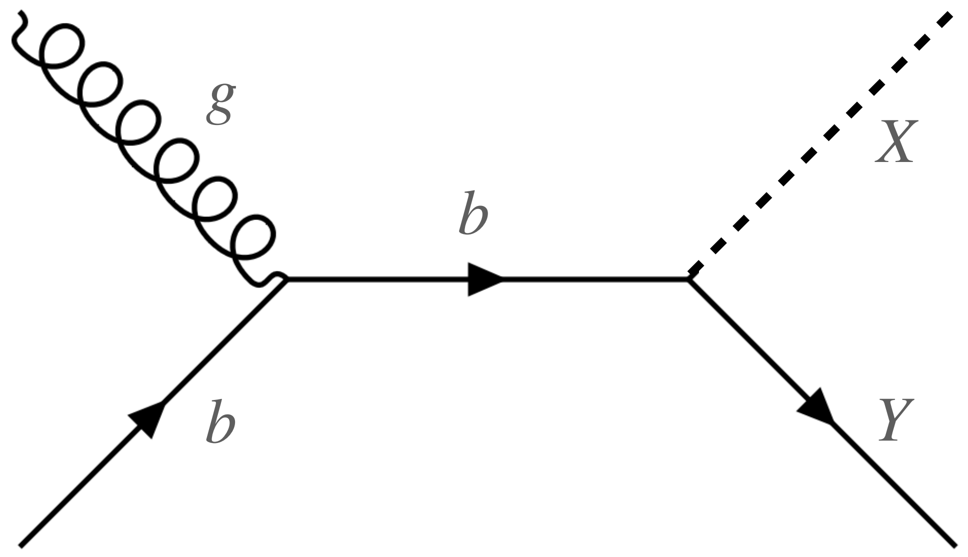
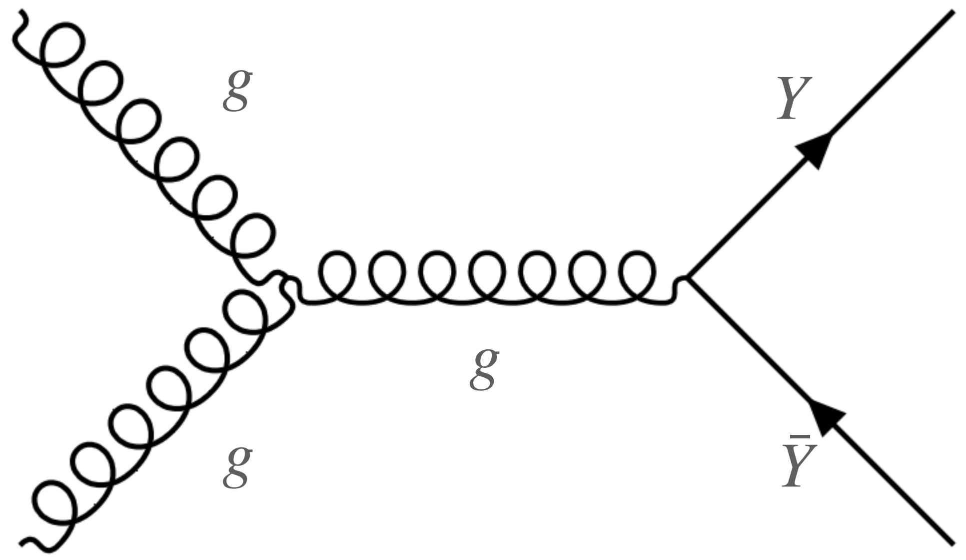


Pair of DM states



Associated production of DM particle and mediator



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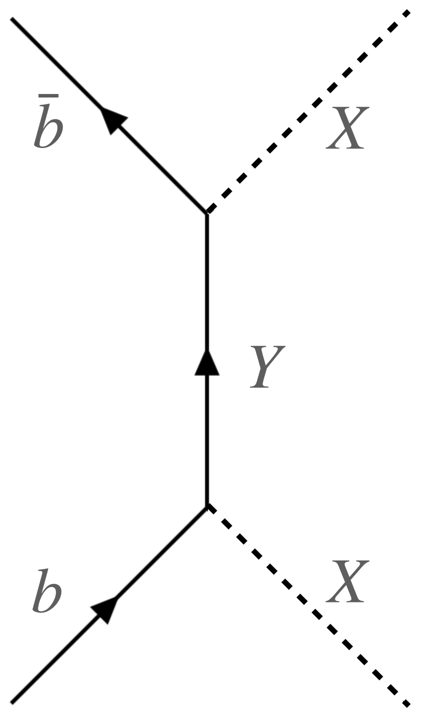

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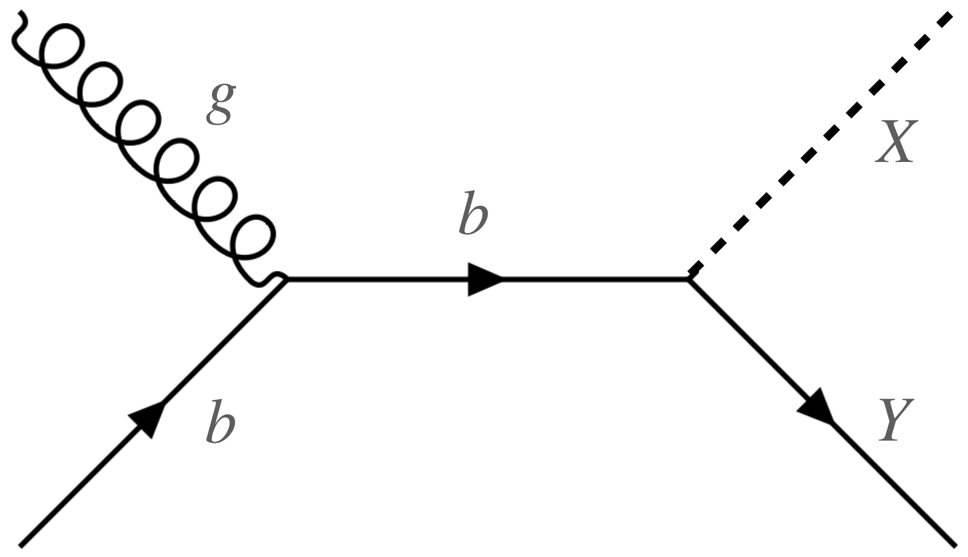

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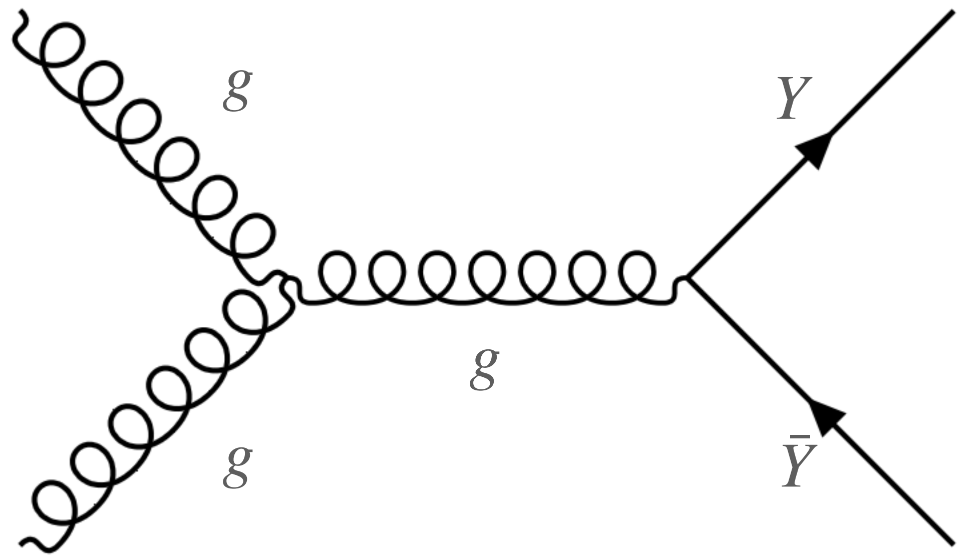
VLQ pair production is the only one that really contributes to the exclusion for this λ



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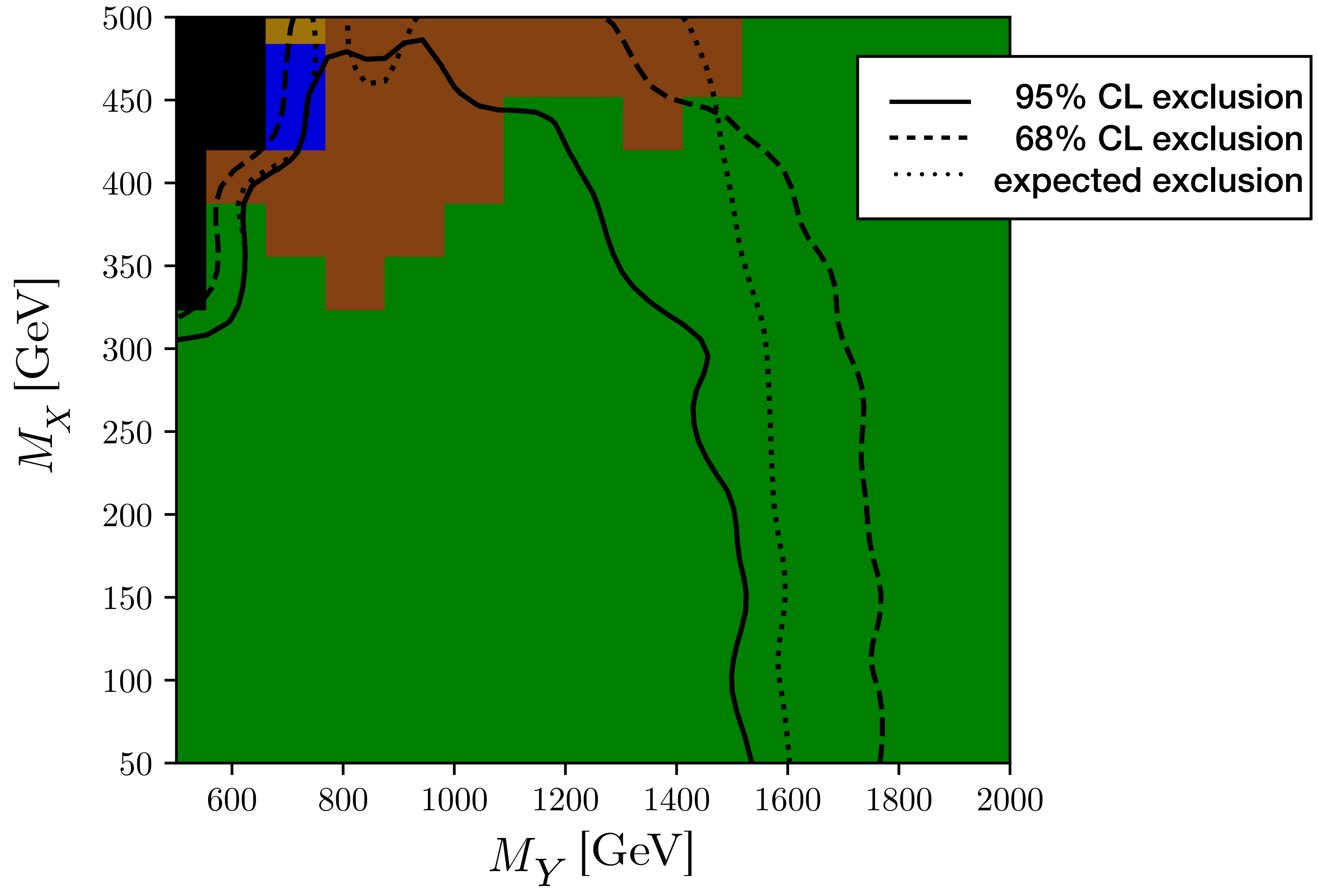
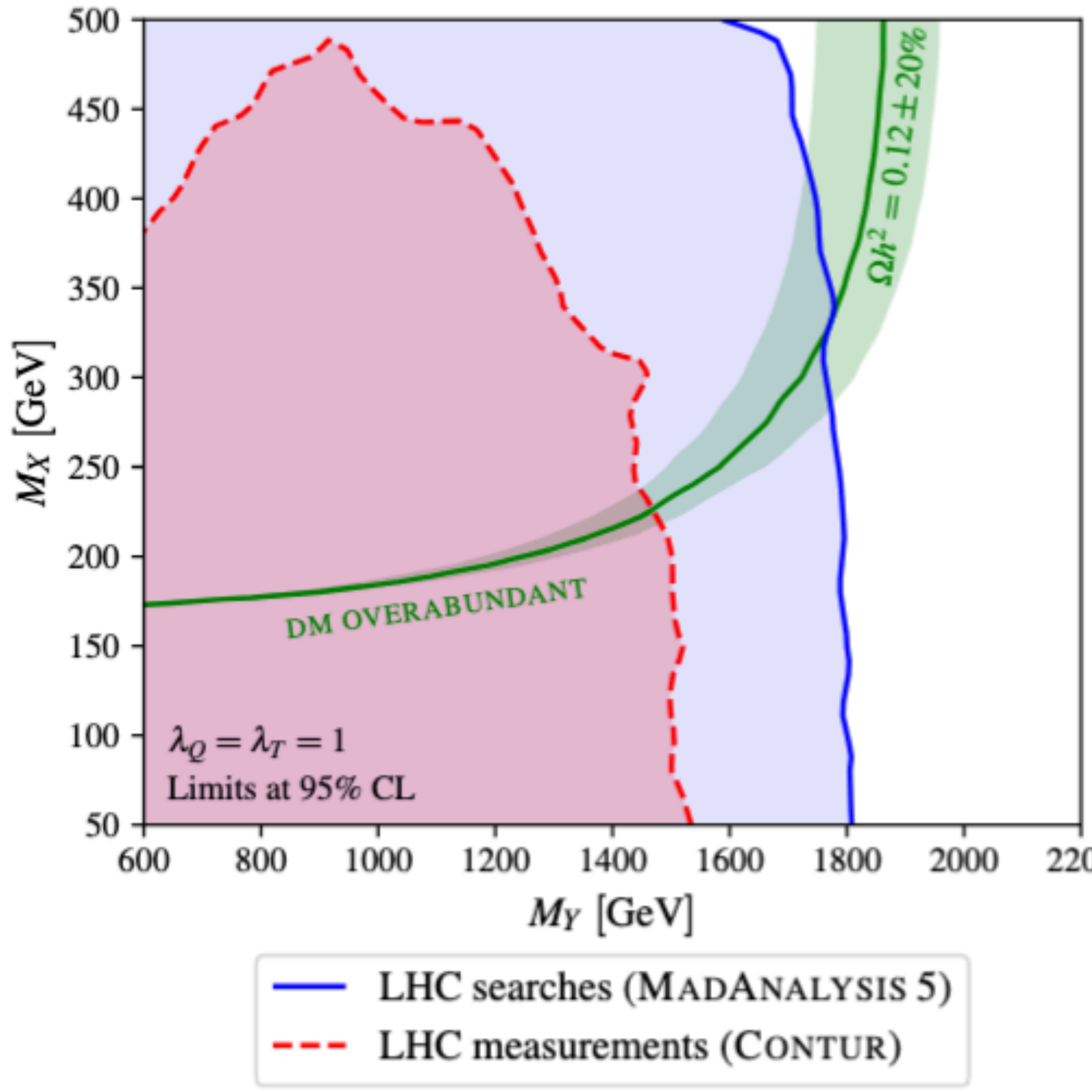
LO Results - DM Whitepaper

CONTUR exclusions with the most sensitive analysis pool



- E_T^{miss} + jets
- Hadronic $t\bar{t}$
- $l^+l^- + E_T^{miss}$ + jets
- $l^+l^-\gamma$

95% CONTUR exclusion and MA5 exclusion



Extending the Initial Project

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Why stick to LO when you can do NLO too?

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Running it gets a lot more complicated…

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MadSTR plugin to handle resonant contributions appearing at NLO

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If you want to compare LO with NLO - need to split up the VLQ pair production into different components

$$\sigma_{\mathrm{BSM}} = \lambda^2 \sigma_{XY} + \lambda^4 \sigma_{XX} + \sigma_{Y\bar{Y}_{\mathrm{QCD}}} + \lambda^4 \sigma_{Y\bar{Y}_t} + \lambda^2 \sigma_{Y\bar{Y}_i} + \lambda^4 \sigma_{YY_t} + \lambda^4 \sigma_{\bar{Y}\bar{Y}_t}$$

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Full process described in the white paper shown earlier that should be coming out soon :)

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QCD diagrams

tChannel DM exchange diagrams

Interference

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Each sub-process cross-section scales differently with λ

running with $\lambda = 1$ for now, expect different contributions once we scale this

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QCD diagrams

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So what you end up with is essentially **13 different processes to run** - 6 at NLO and 7 at LO

need to go calculate the k-factor for the NLO interference process and scale the LO cross-section accordingly

$$K_{Y\bar{Y}_i} \equiv \sqrt{K_{Y\bar{Y}_t}\, K_{Y\bar{Y}_{\mathrm{QCD}}}} = \sqrt{\frac{\hat{\sigma}^{\mathrm{NLO}}_{Y\bar{Y}_t}}{\hat{\sigma}^{\mathrm{LO}}_{Y\bar{Y}_t}} \frac{\hat{\sigma}^{\mathrm{NLO}}_{Y\bar{Y}_{\mathrm{QCD}}}}{\hat{\sigma}^{\mathrm{LO}}_{Y\bar{Y}_{\mathrm{QCD}}}}}$$

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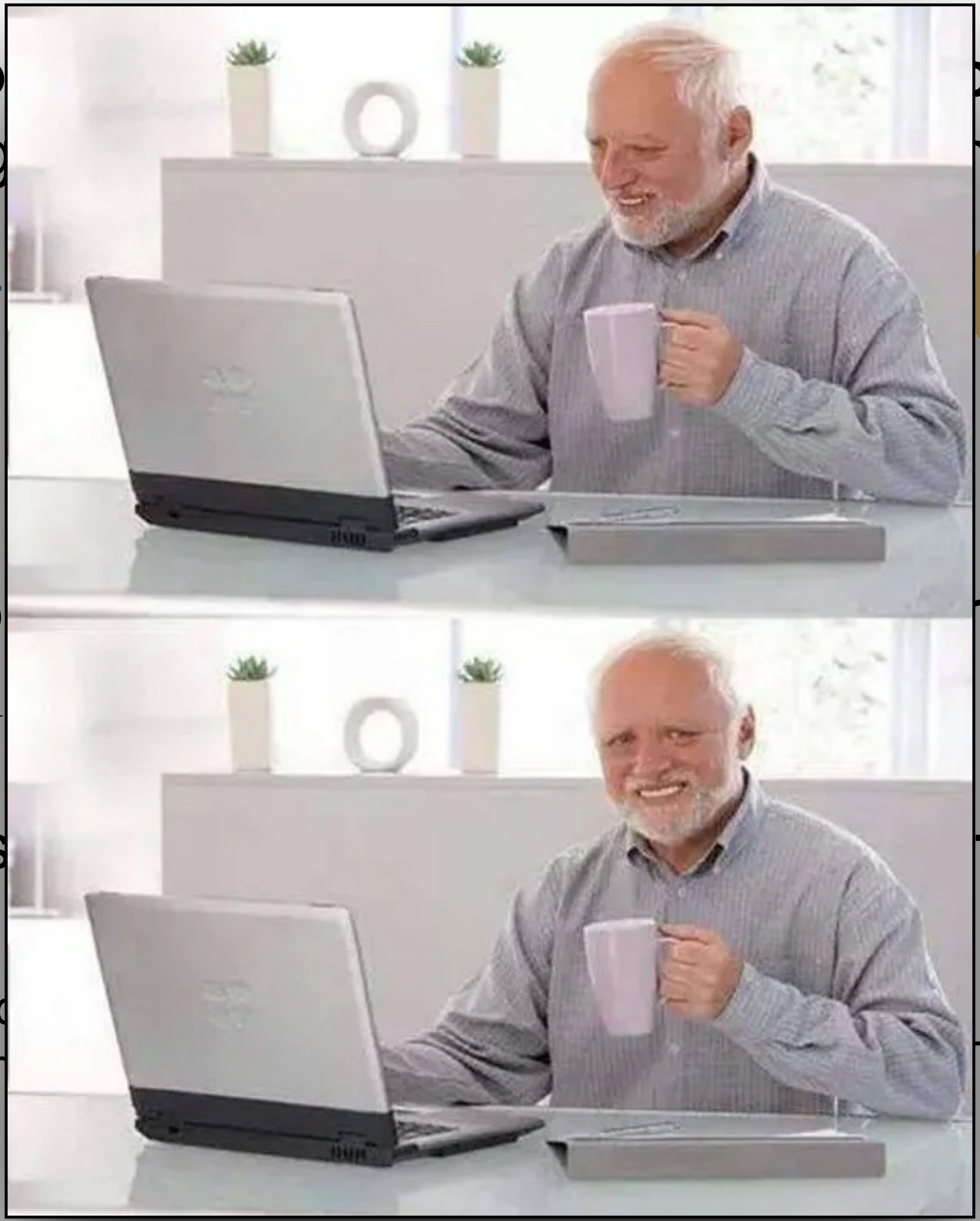

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QCD Contributions - CONTUR

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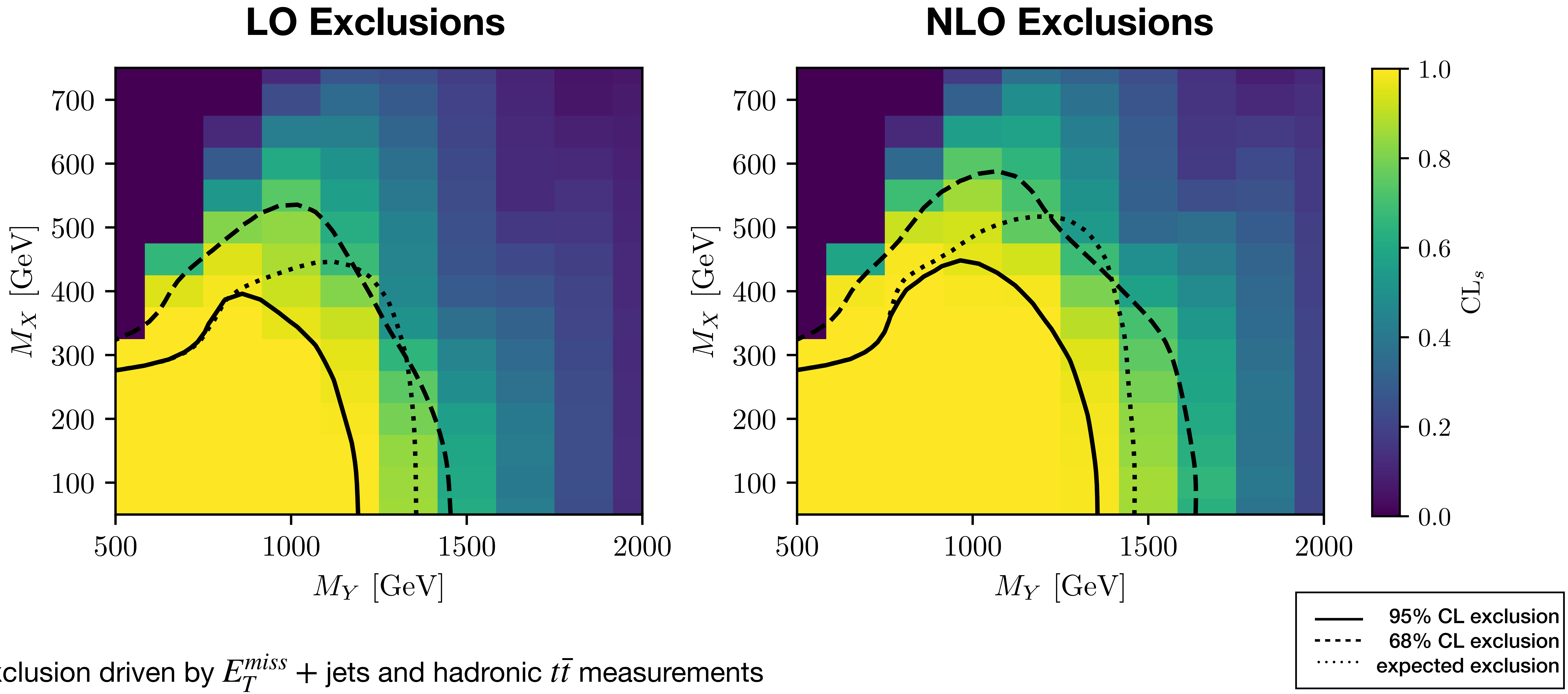

Exclusion driven by E_T^{miss} + jets and hadronic $t\bar{t}$ measurements

Expected better than observed?

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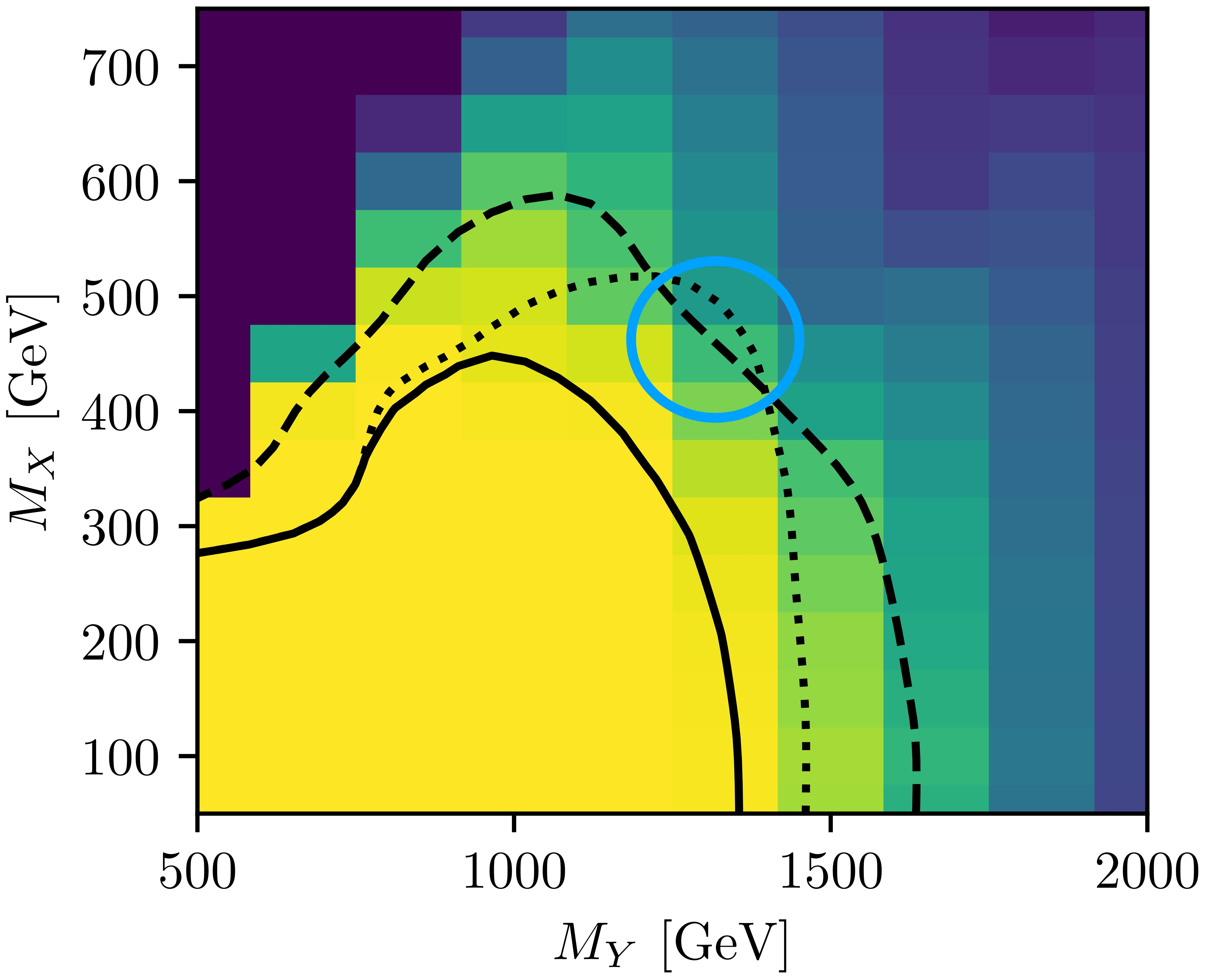
Why is the expected exclusion better than the actual 68% exclusion?



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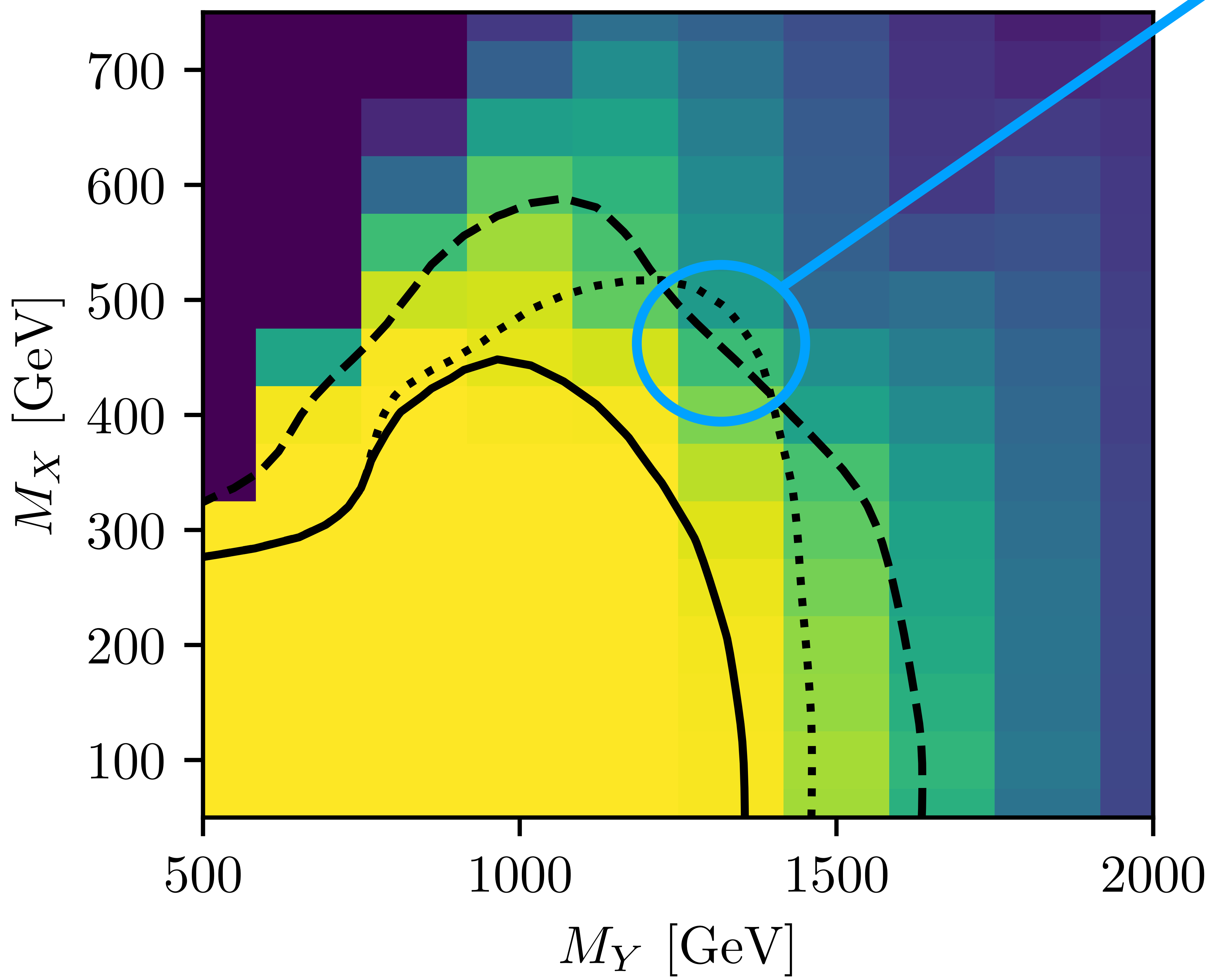
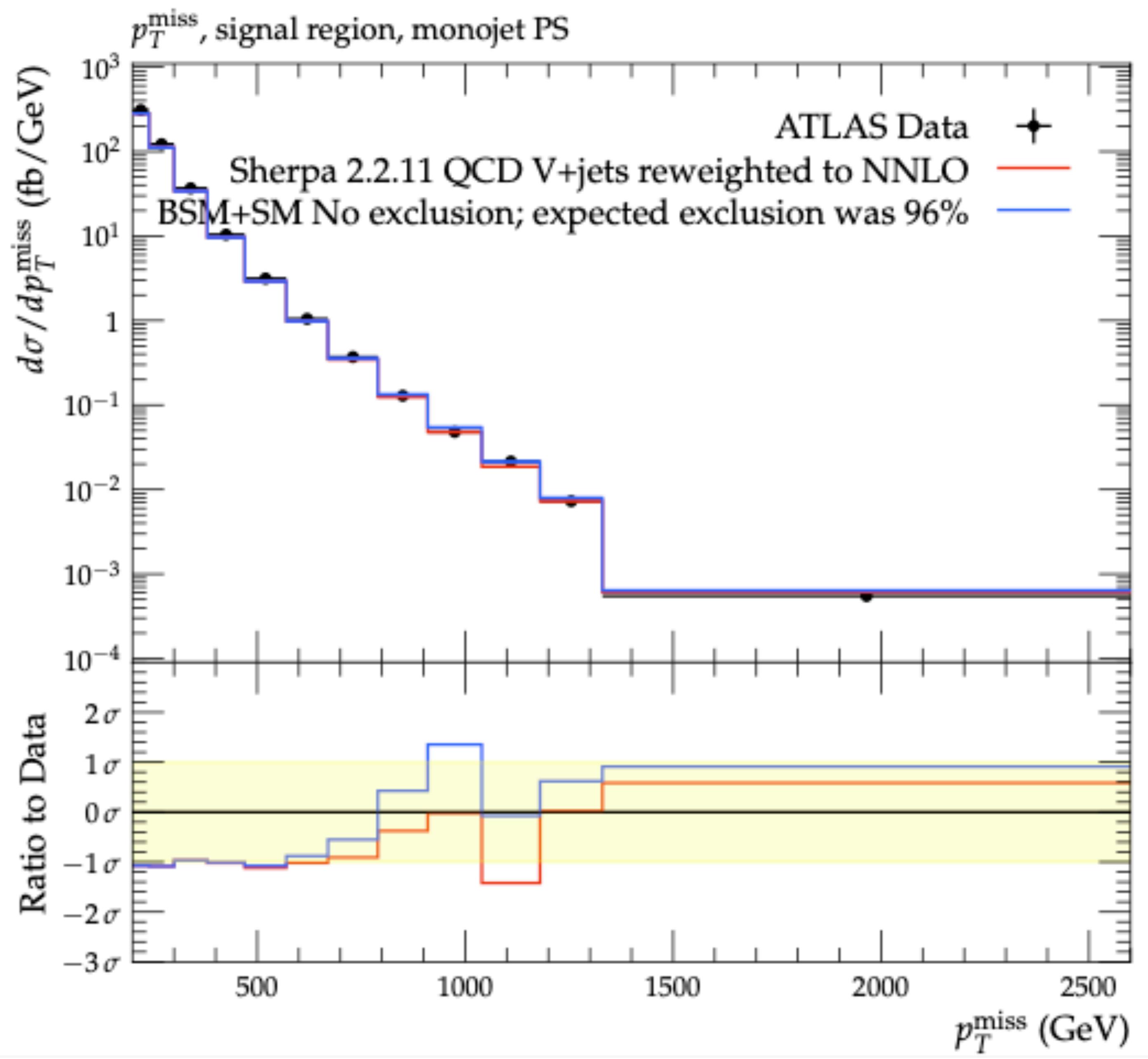
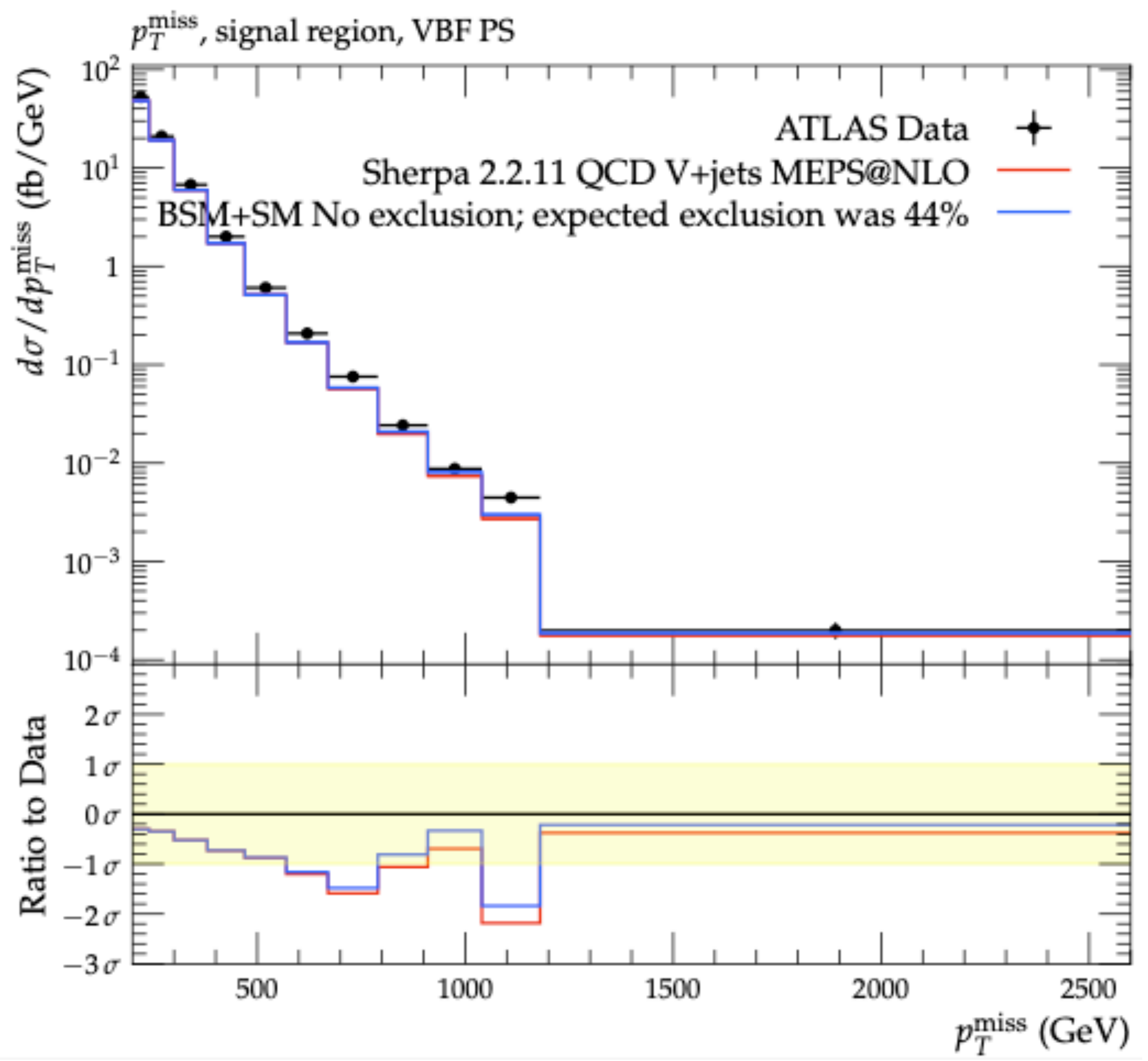


CONTUR has a great command where you can go make the RIVET plots that contribute to the exclusion at a point!





ATLAS MET-Jet measurement
(STDM_2018_55)

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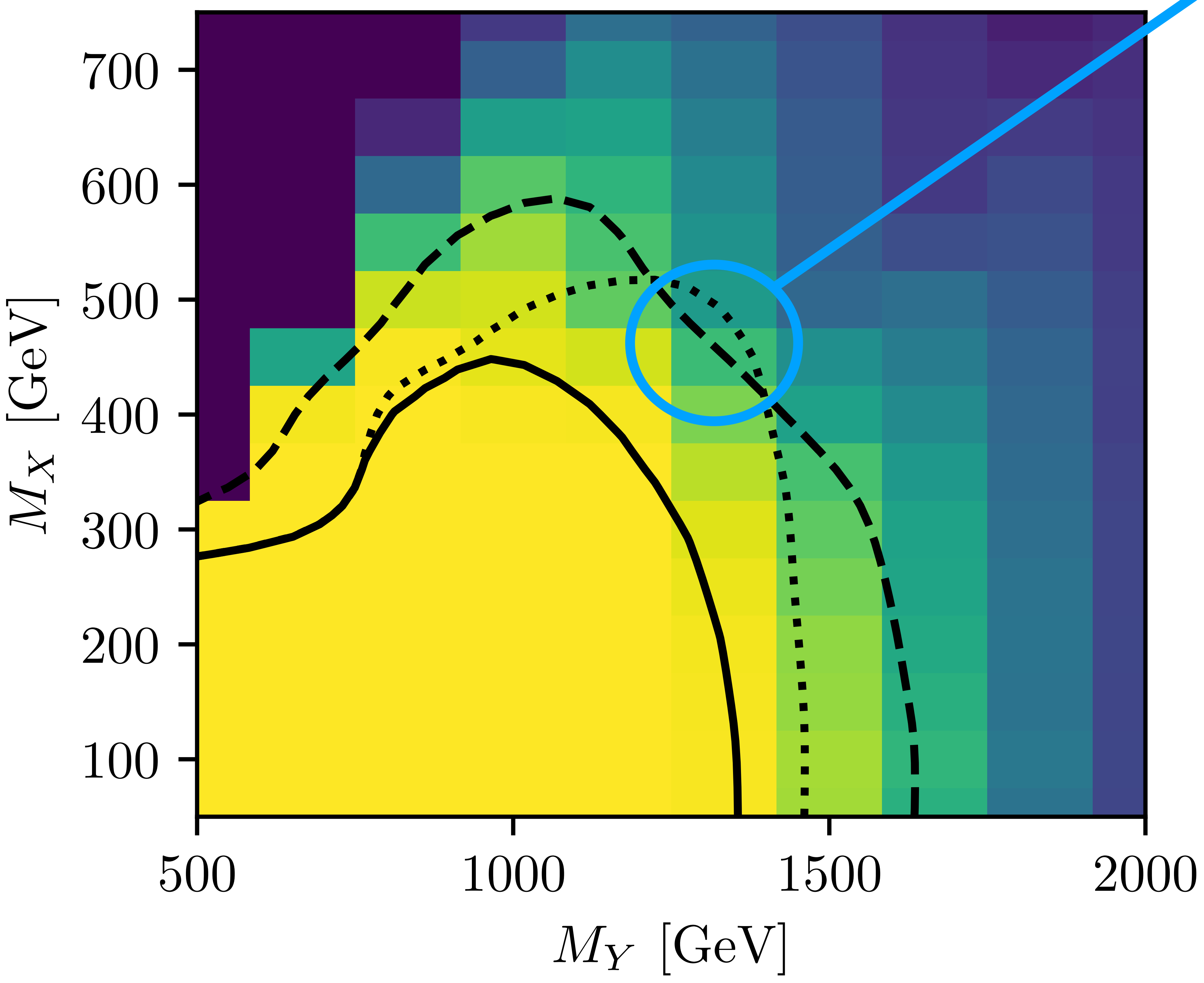

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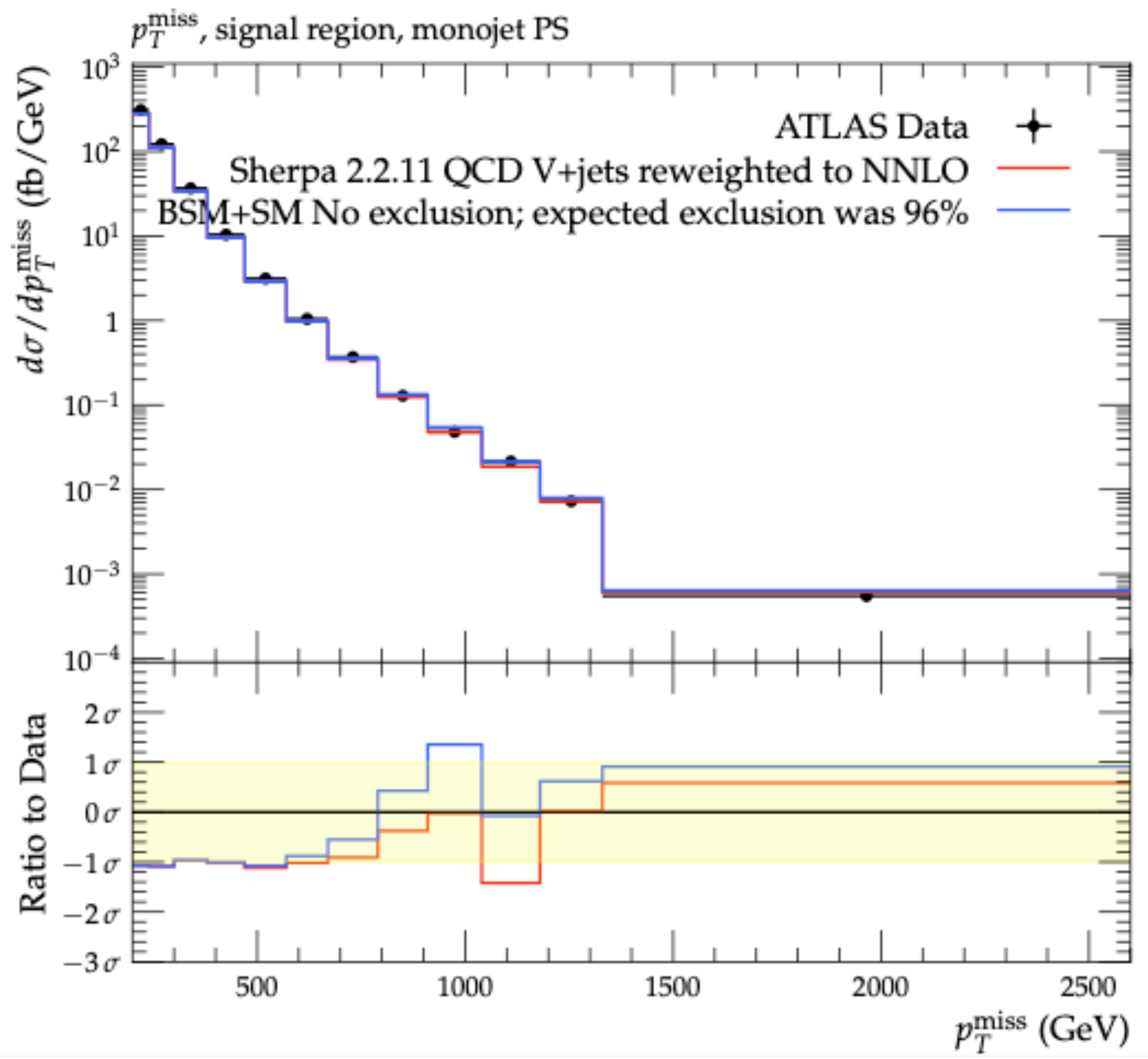

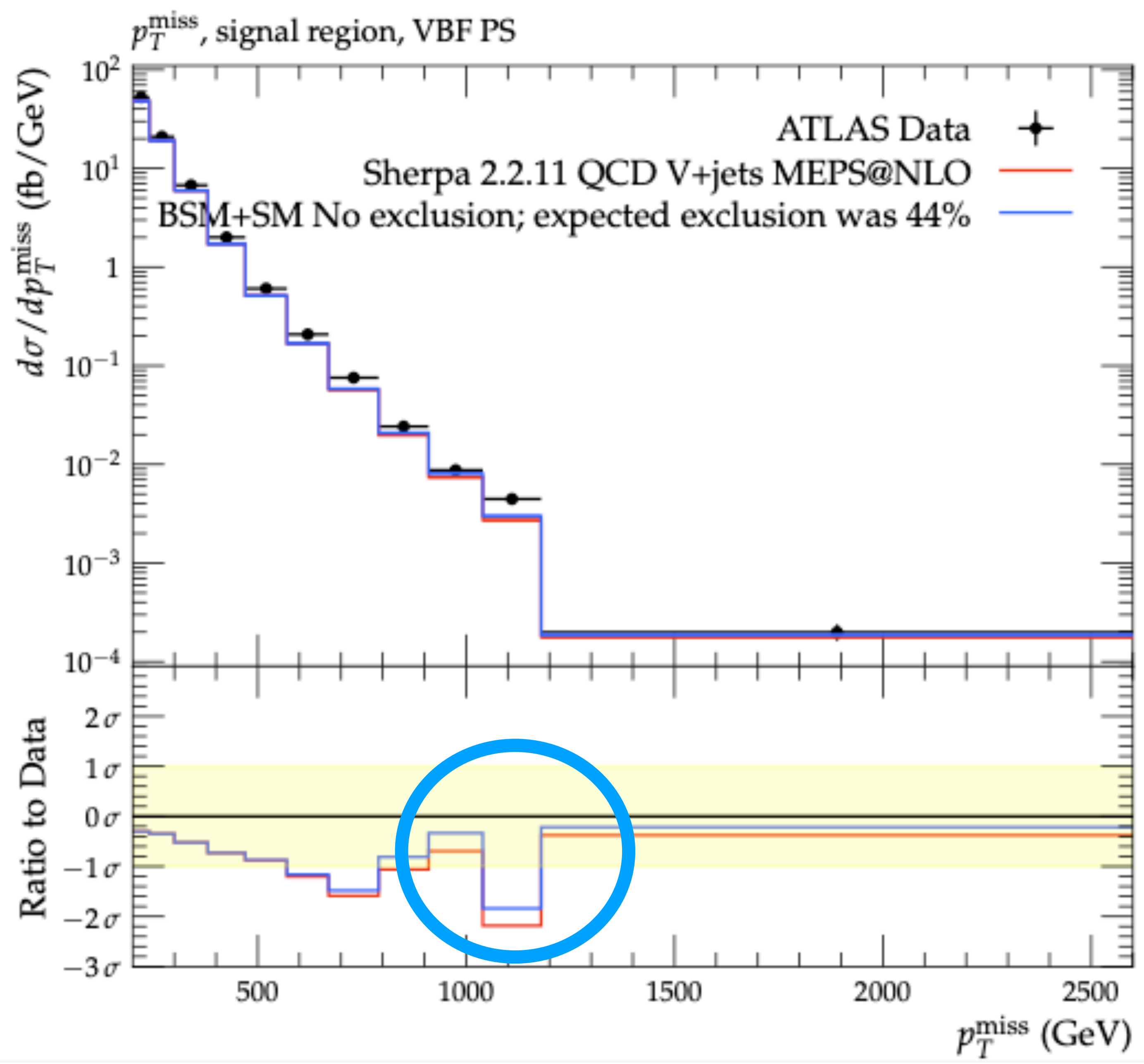

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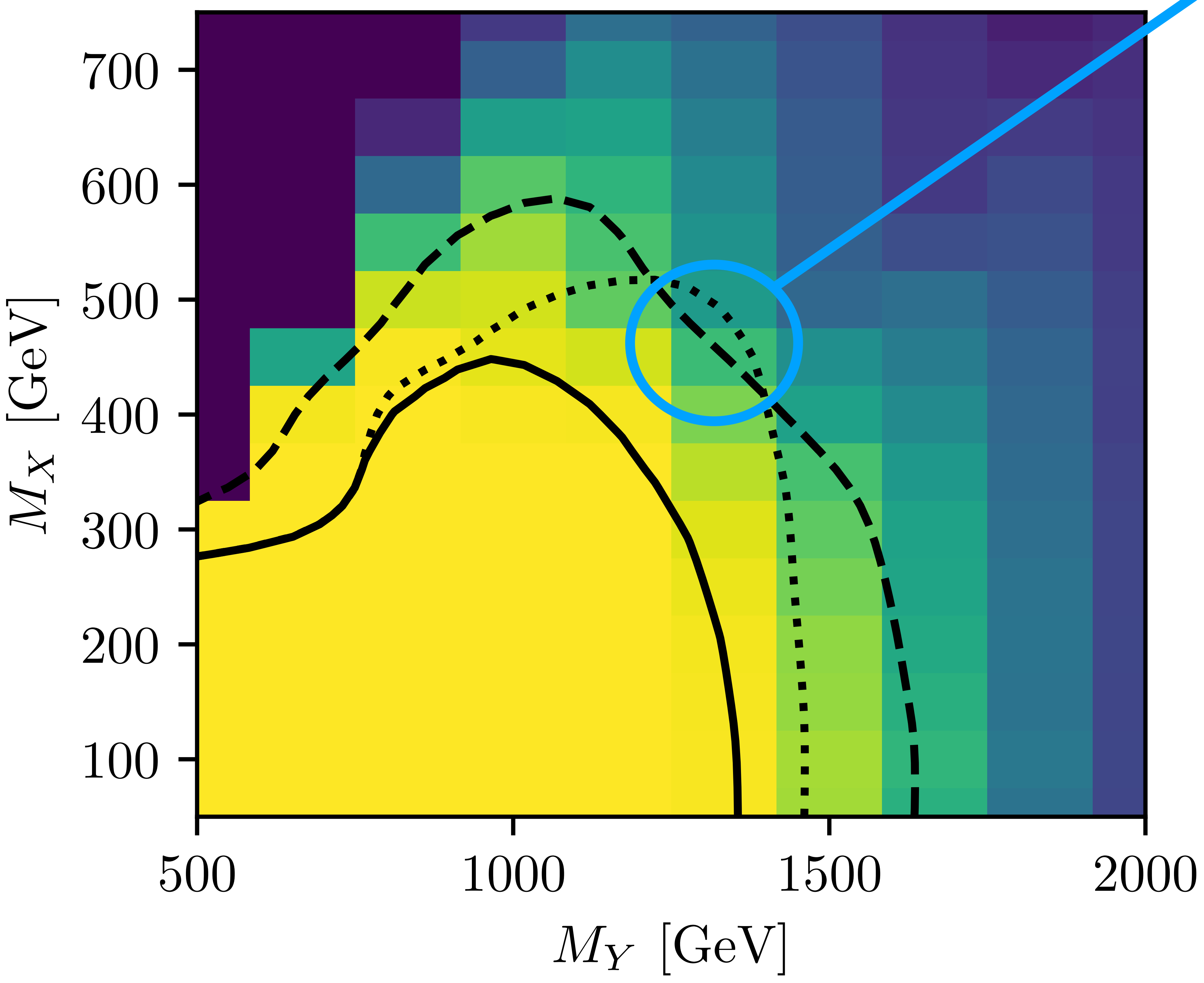

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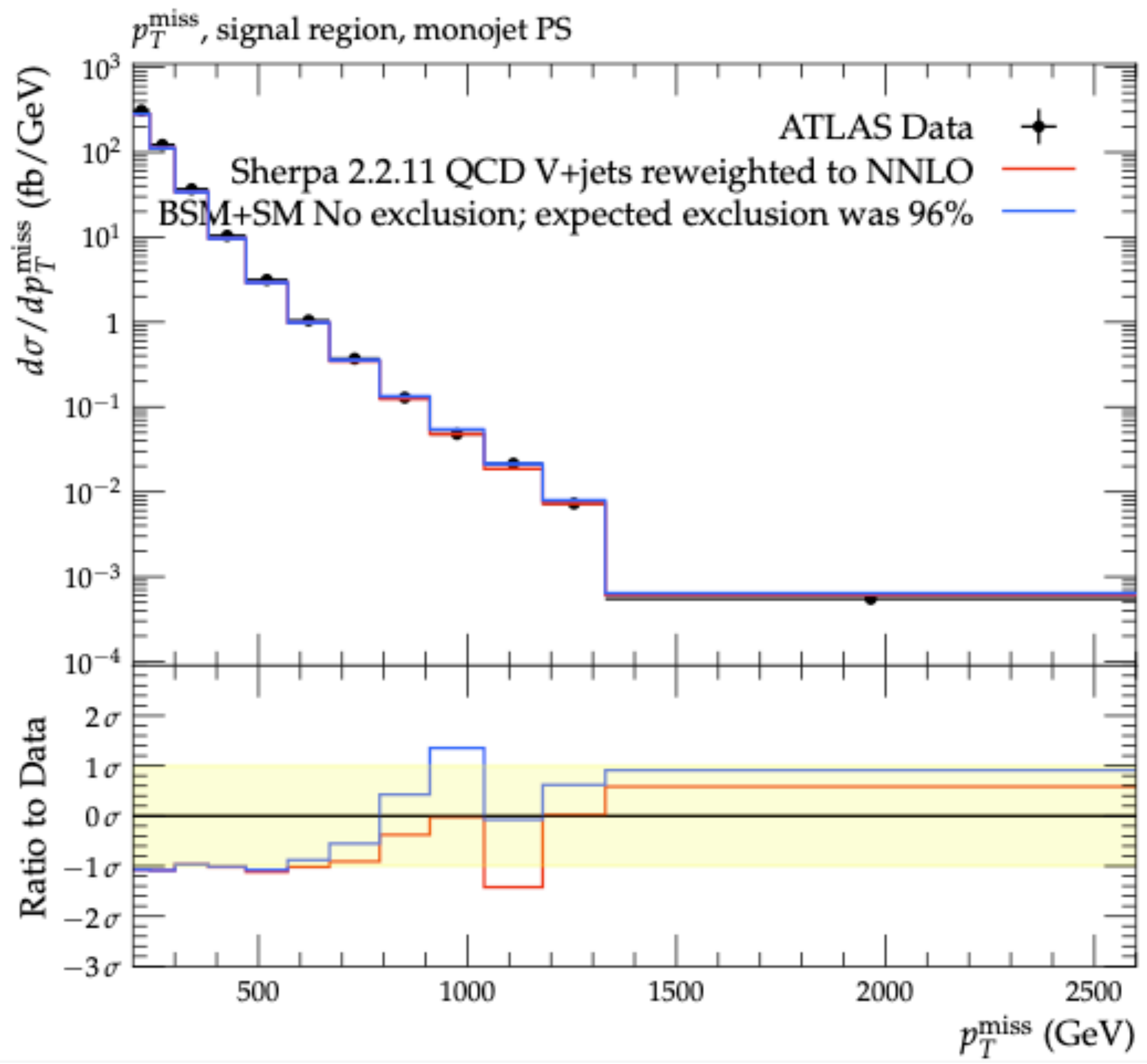

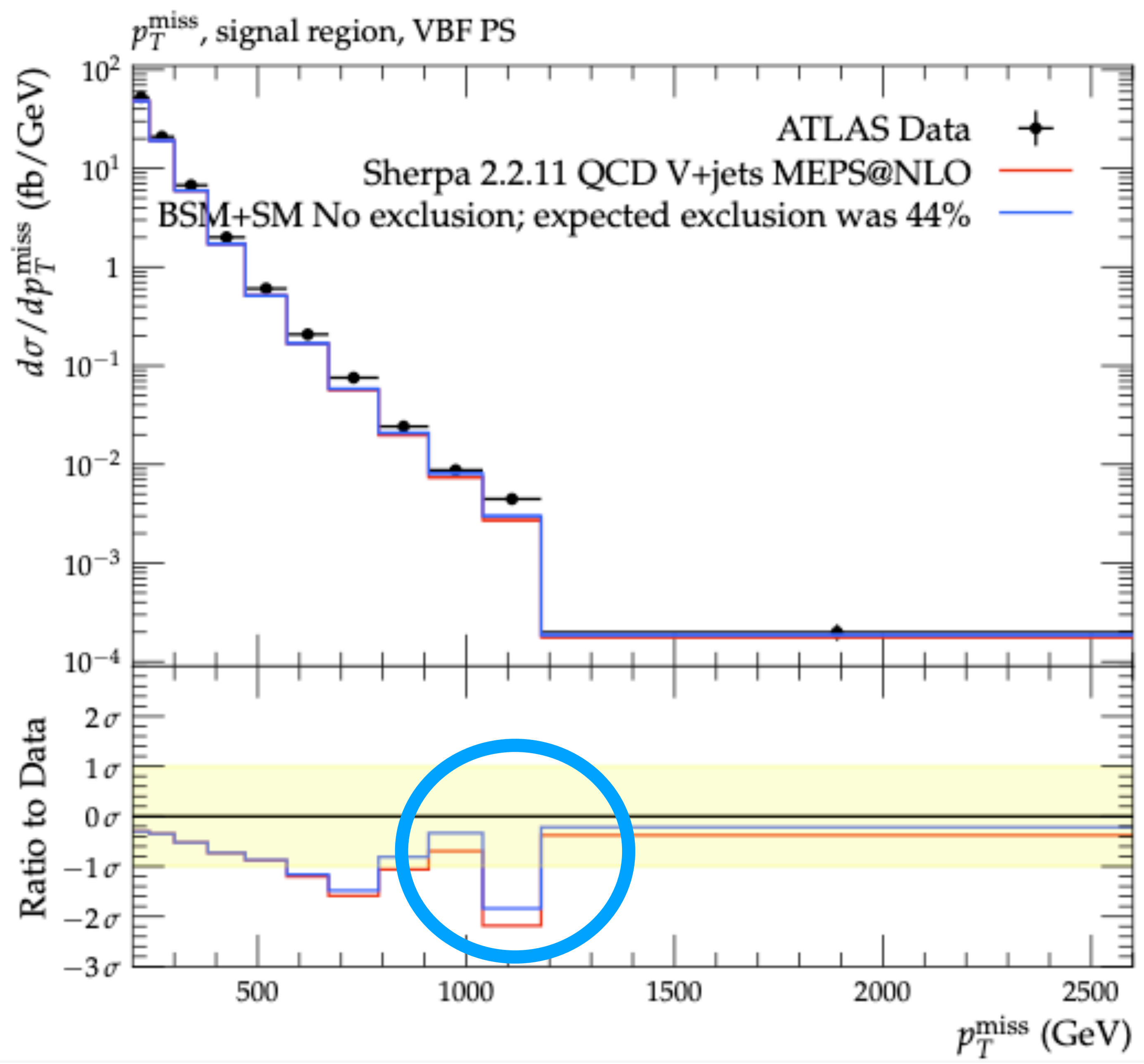

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Also in the monojet search at the same place

Effect of the Interference Term - LO

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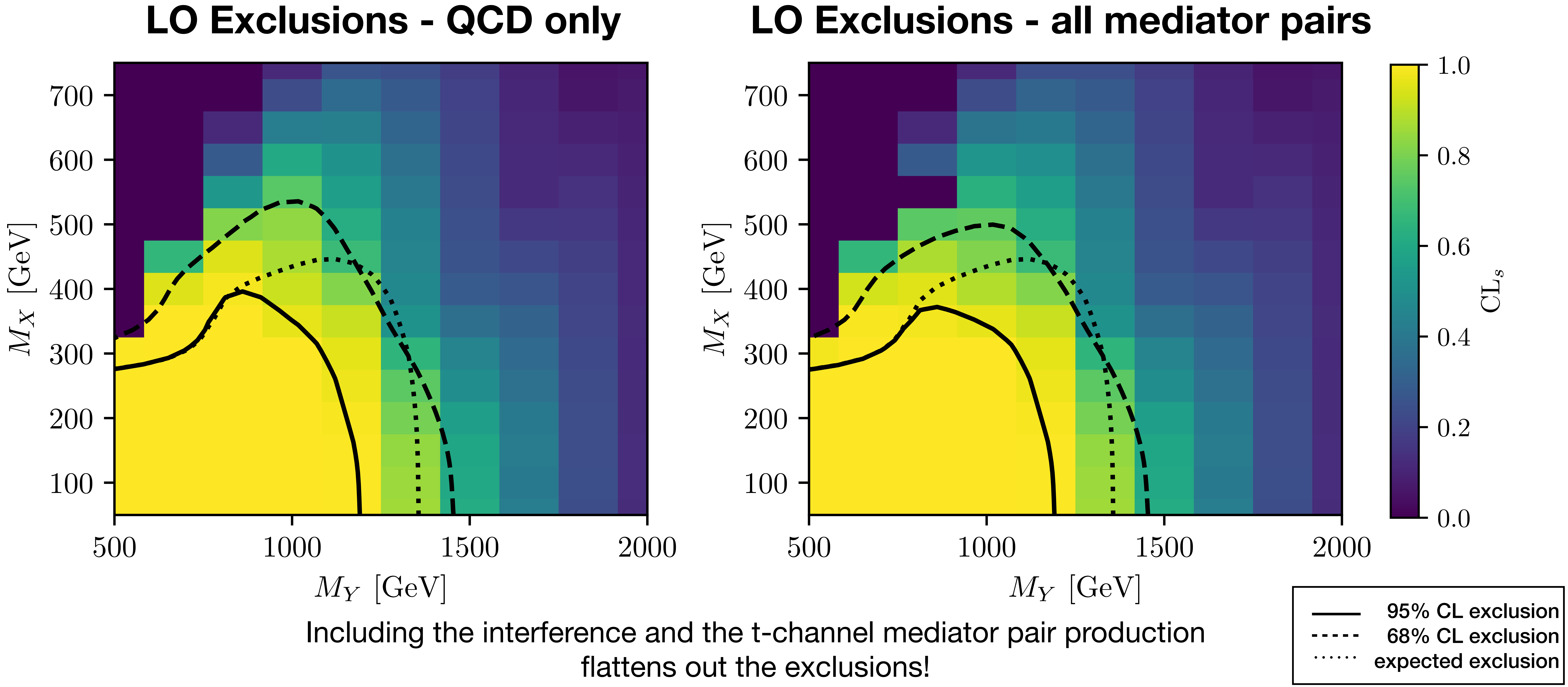

Including the interference and the t-channel mediator pair production flattens out the exclusions!

Effect of the Interference Term - NLO

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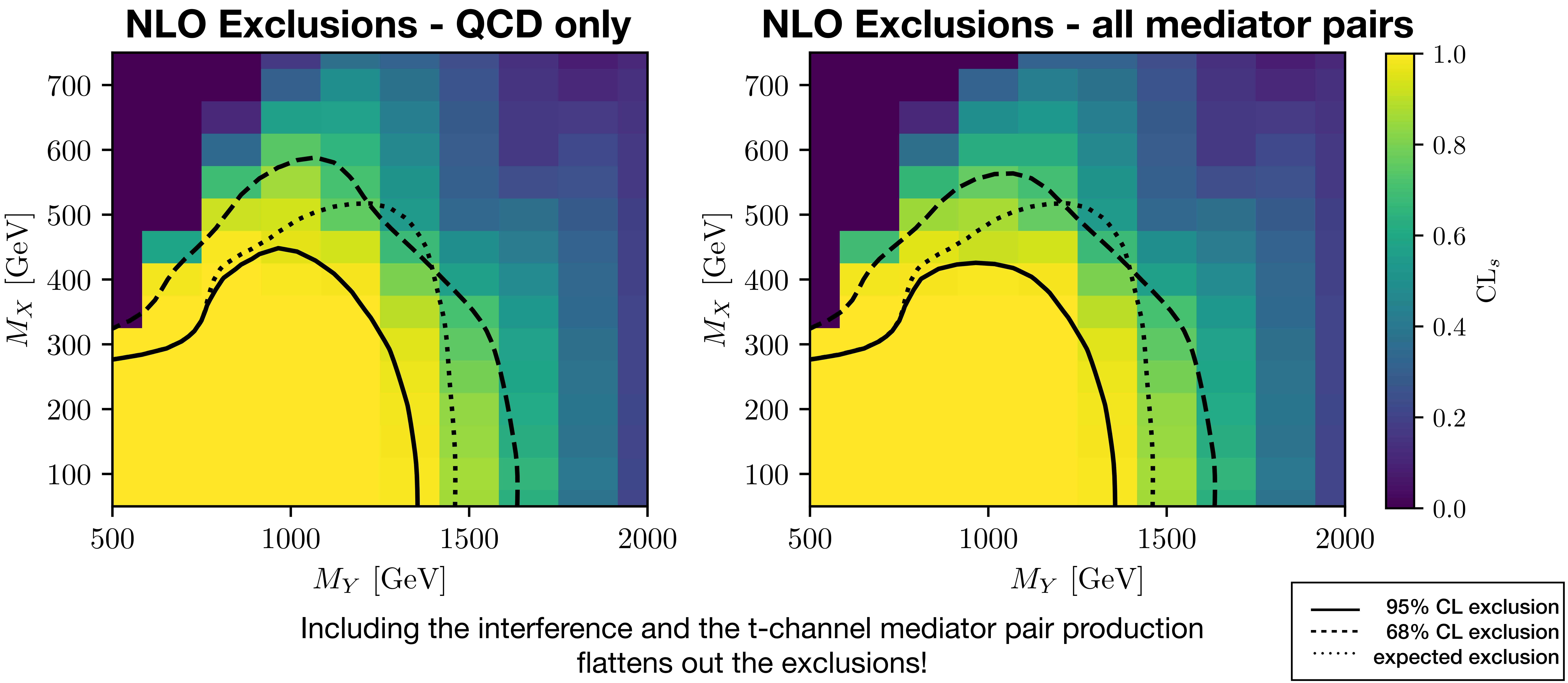

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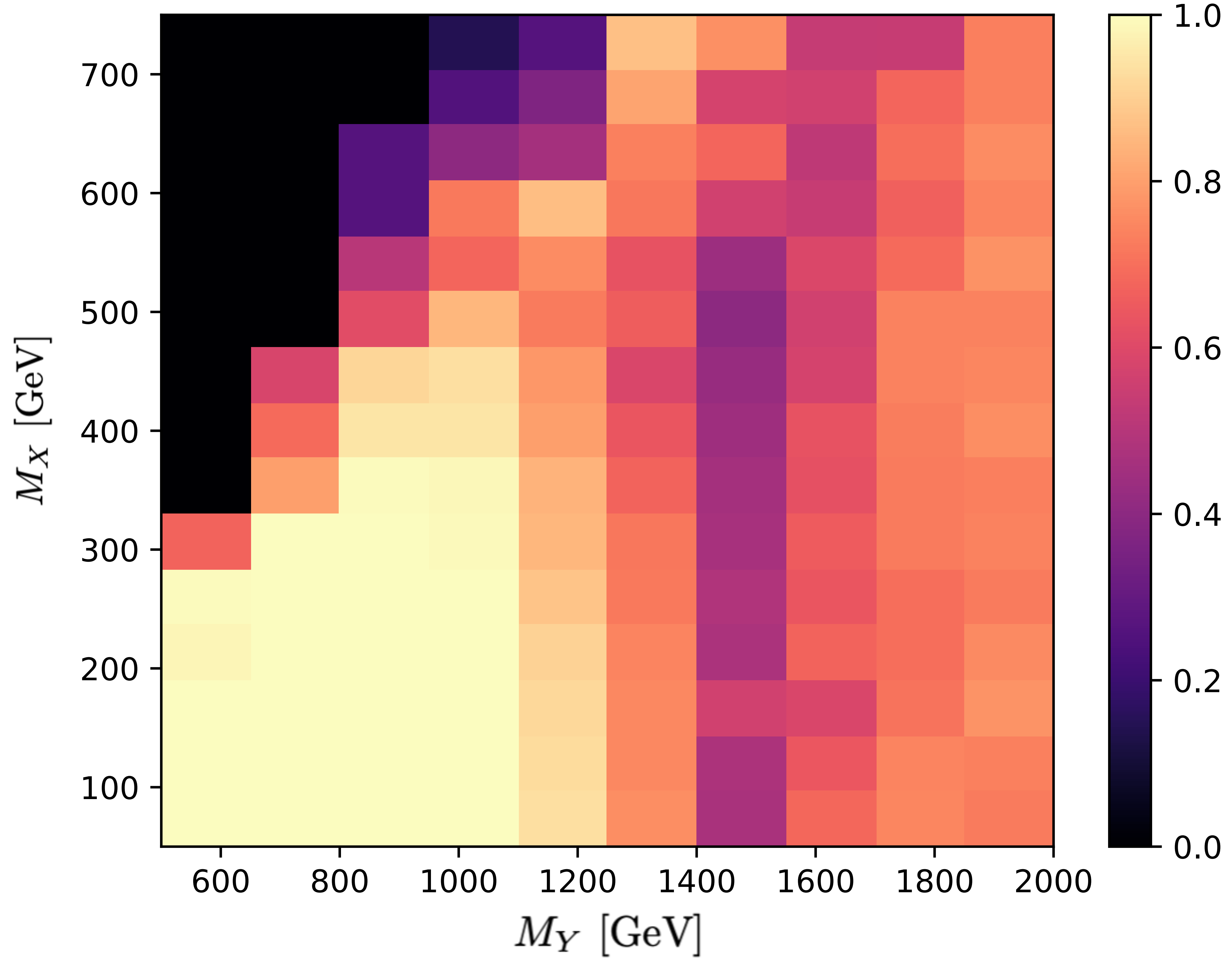

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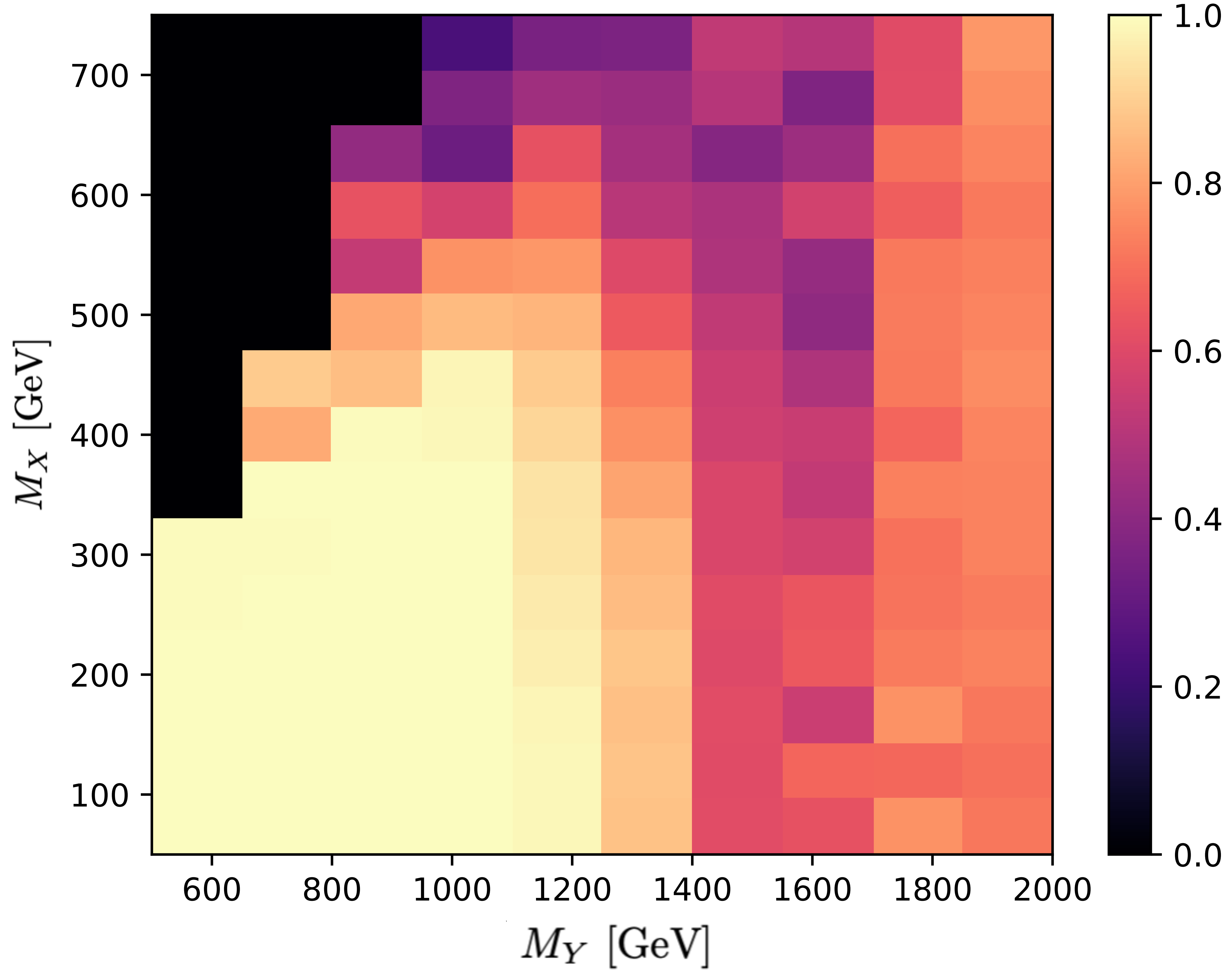

NLO does extend the exclusion!

Exclusions driven by **ATLAS_CONF_2019_040** (jet + MET final states) and **CMS_EXO_20_004** (energetic jets and large MET)

Summary

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Possible (and fun) to compare LO and NLO exclusions in CONTUR and MA5!

- Current scan with $\lambda = 1$: QCD contributions dominate
- Can see the effect of the interference term

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Quite a bit of work still to do:

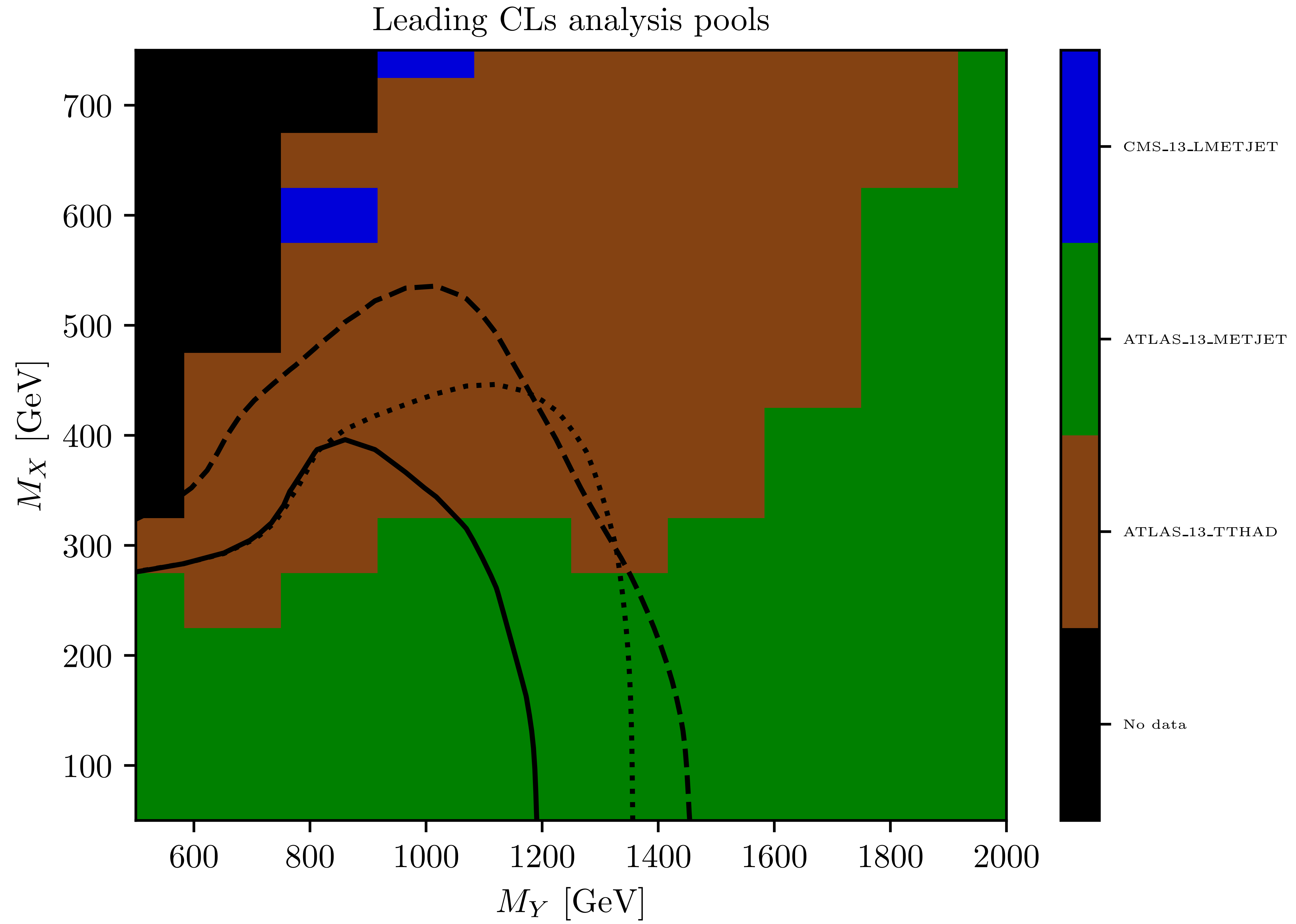
- MA5 on all of the samples
- Plan is to perform a scan over different λ values to see at which point the other processes contribute more to overall cross-section (and exclusion)
- Looking at the cosmological side of the model, and UV completion of the model
- Publication forthcoming :))

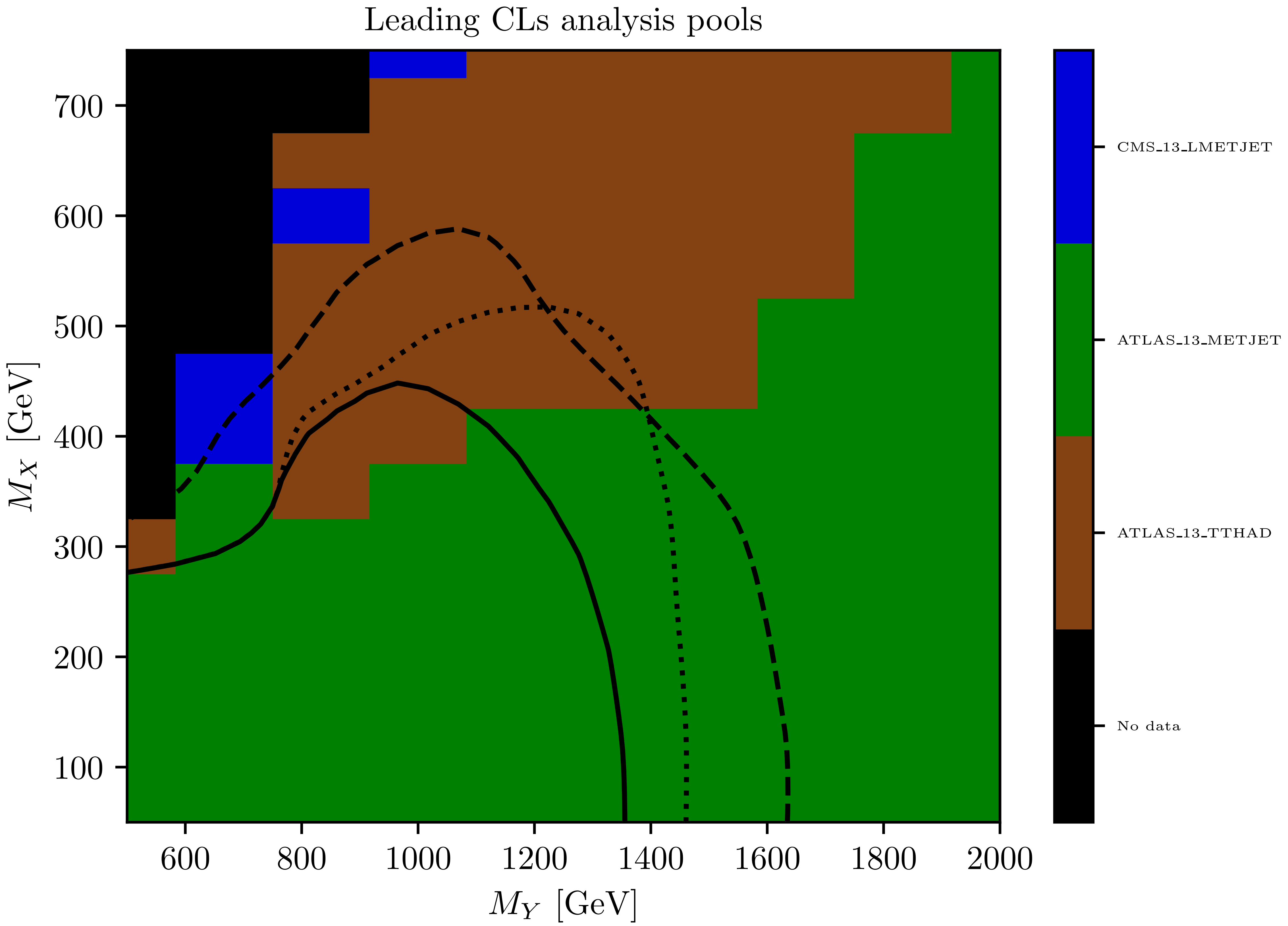
Backup Slides

Cross-sections of a single runpoint

	XX [fb]	XY [fb]	YY (total) [fb]	YY (QCD) [fb]	YY (t-channel) [fb]	YY (Int) [fb]
LO	0.06909	20.55062	1081.7836	1081.396	0.7436	-0.3560
NLO	0.07840	38.74542	1562.6919	1562.046	1.1862	-0.5404

Most sensitive analyses - CONTUR





- E_T^{miss} + jets
- Hadronic $t\bar{t}$

- $l^+l^- + E_T^{miss}$ + jets