New sensitivity of LHC measurements to Composite Dark Matter

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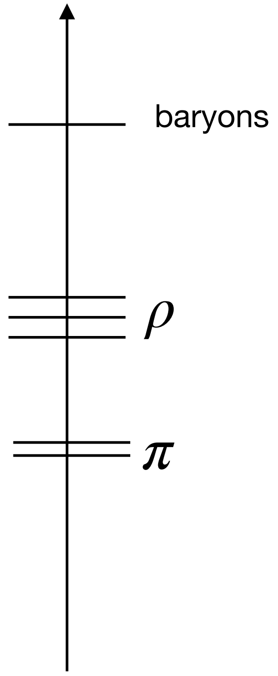
26 July 2021

Introduction

Dark Spectrum



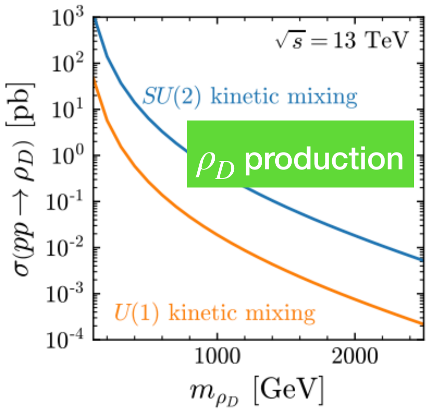
- What if **dark matter** is a **composite particle** arising from **non-Abelian dynamics**?
- Theory under consideration: SU(N_D) [N_D = 4, N_f = 4] gauge theory - confines at some scale Λ_{dark}
- Low energy theory: bound states of mesons and baryons, masses computed by lattice calculations
    - Simplest case, **dark pions** π_D and **dark rho** ρ_D, in addition to dark baryons (DM candidates)—> **Heavy Dark Mesons**
- Dark fermions transform under electroweak part of the Standard Model
    - Allows communication with SM
- There are no direct searches for this model by ATLAS or CMS
    - ***We propose instead to constrain this model using the bank of existing LHC measurements using the CONTUR method***
    - ***We can then link the constraints back to DM phenomenology using existing lattice calculations***

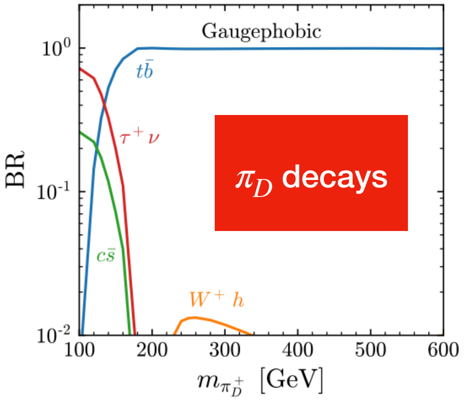
arXiv:2105.08494

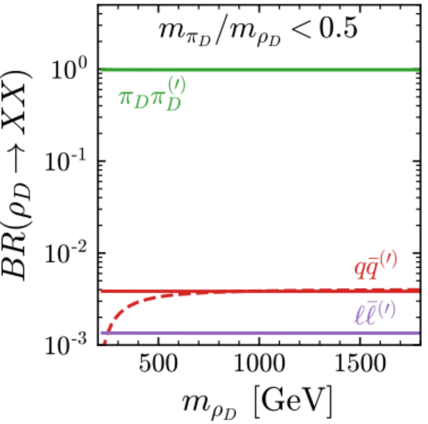
For other Composite DM scenarios, featuring semi-visible jets, see talk by S. Kulkarni on Tuesday: https://indico.desy.de/event/28202/contributions/105527/)

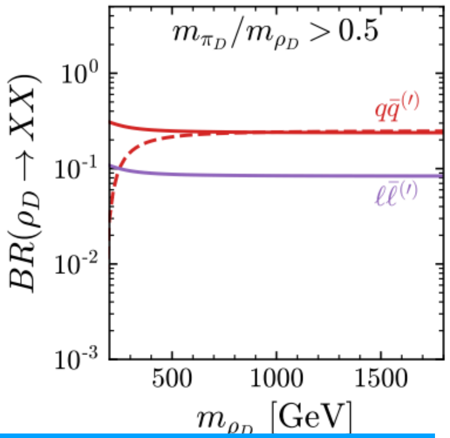
Heavy Dark Meson phenomenology at the LHC

Dark meson phenomenology at the LHC









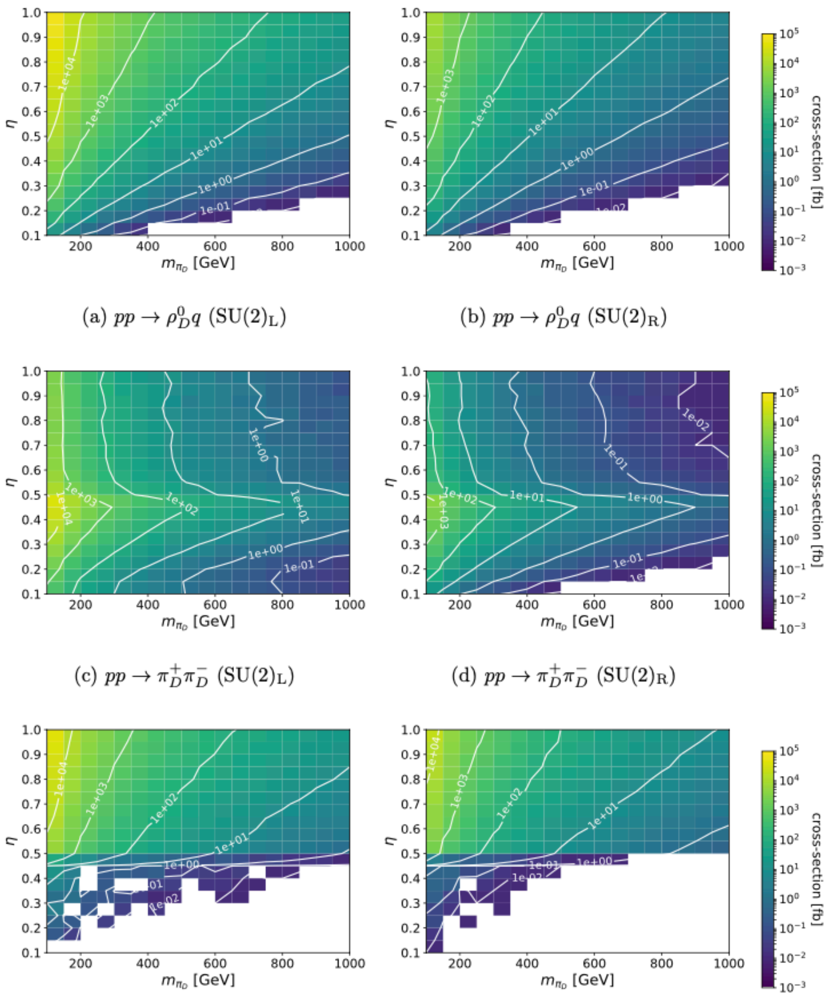
ρ_D decays: depends on mass hierarchy

Kribs et al. arXiv:1809.10183

- Distinguish two cases for Dark Sector:
  - *"Left-handed case"*: DS gauged under SM SU(2)$_L$, mix with SM W/Z/ɣ. Gives Three ρ_D with charges 0, +1, -1
  - *"Right-handed case":* SM U(1) -> ρ_D mixing only with SM ɣ, only have neutral ρ_D.

- Phenomenology depends on π_D/ρ_D mass hierarchy
- If ρ_D cannot decay to π_D, it chiefly decays to leptons: Z' like resonance signature
- If ρ_D can decay to π_D, it will almost always do so
- Dark pion decays feature a variety of final states specially featuring third generation SM fermions

Dark meson phenomenology at the LHC



(a) $pp \to \rho_D^0 q$ (SU(2)$_\mathrm{L}$)　(b) $pp \to \rho_D^0 q$ (SU(2)$_\mathrm{R}$)

(c) $pp \to \pi_D^+ \pi_D^-$ (SU(2)$_\mathrm{L}$)　(d) $pp \to \pi_D^+ \pi_D^-$ (SU(2)$_\mathrm{R}$)

(e) s-channel $pp \to \rho_D \to l^+ l^-$ (SU(2)$_\mathrm{L}$)　(f) s-channel $pp \to \rho_D \to l^+ l^-$ (SU(2)$_\mathrm{R}$)

- Define $\eta = m_{\pi_D}/m_{\rho_D}$
- Above η > 0.5, ρ_D can decay to diquark/dilepton pairs, expect this model to be picked up by High-mass Drell-Yan measurements (and the smeared particle-level HDMY search which is in CONTUR)
- Below, η < 0.5, ρ_D decays almost exclusively to π_D
    - Chiefly decay to τν for π_D below 200 GeV, and *tb* above.
        - Missing energy and multiple (b-)jets
        - Or take advantage of single-pion production with a W or Z: Missing energy, jets, leptons

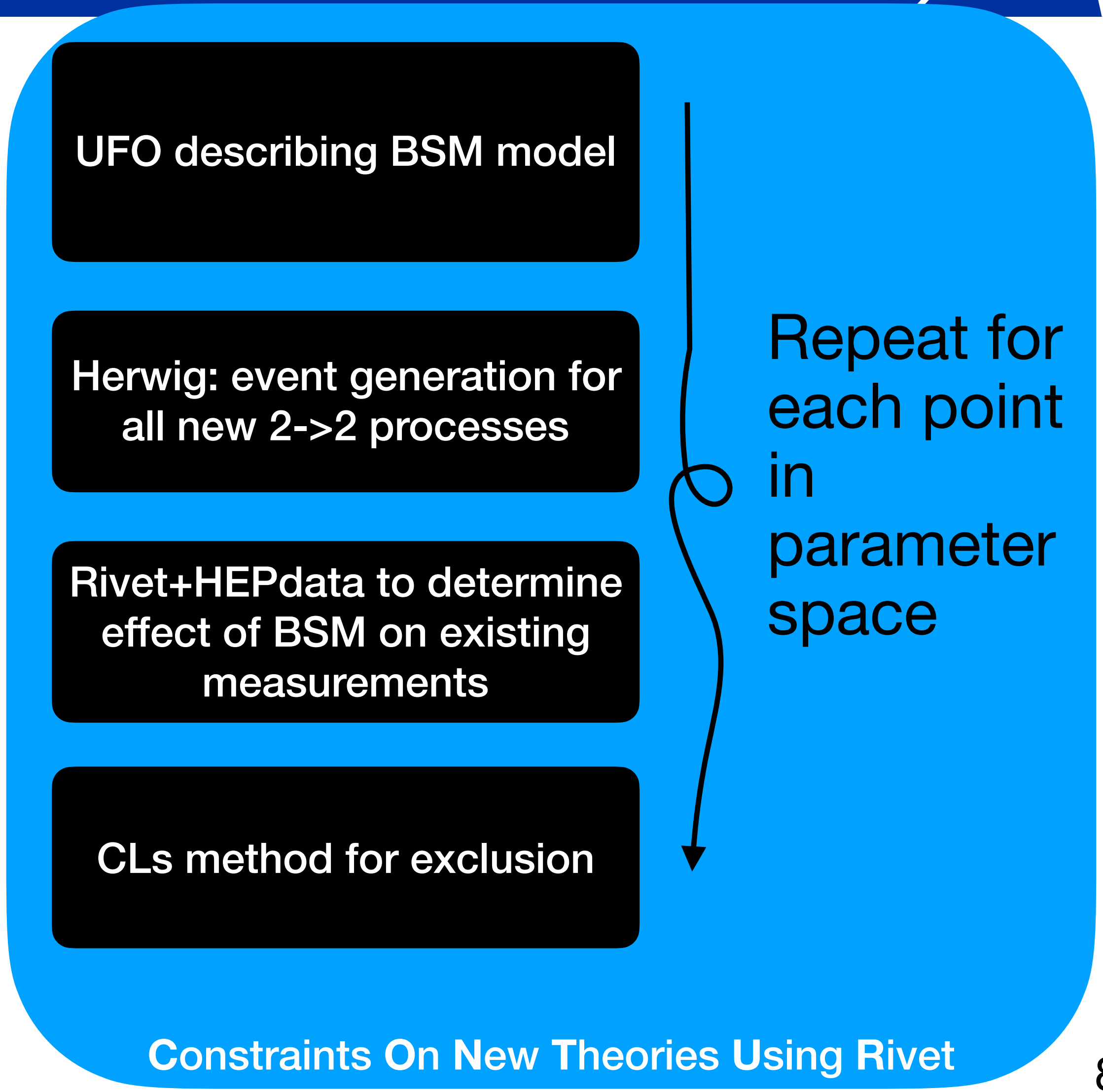
The CONTUR method

CONTUR 101

- The LHC programme often focuses on most spectacular signature of a new model…
- But many models might already be ruled out because they would cause visible distortions in spectra of ‘’standard” processes!
- Challenge is **figuring out how a new model might impact hundreds of measured distributions…**
- …and understanding **whether the model is consistent with the measured data within uncertainties**
- **We already have this technology:** MC event generator comparison and tuning framework (Rivet + HEPData)… Hundreds of LHC measurements are available!

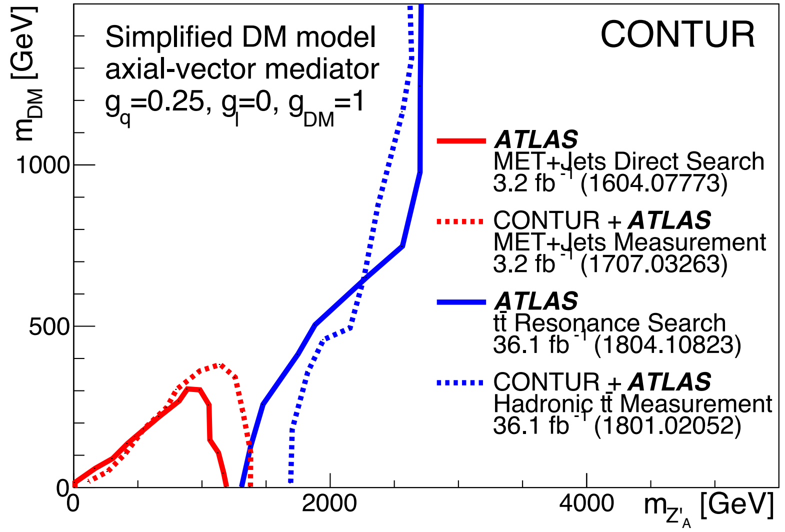
Overview of the CONTUR method

- CONTUR uses bank of LHC results preserved in Rivet to rapidly check if new models already ruled out
- Input: Universal Feynrules Object (new physics Lagrangian coded up in python by theorists)
- MC Generation of events. By default, Herwig to inclusively generate events involving new particles
- Pass through ~150 Rivet routines from particle-level LHC results: quick since everything is at particle-level! Routines categorised into ‘pools’ grouped by √s and final state to ensure orthogonality
- Compare size of deviation to reference data from HEPData (including correlations!) to check if signal would already have been seen or whether it is OK within errors -> CLs value



Do measurements really give comparable exclusions?

- For the same final state and luminosity, searches and measurements have roughly the same exclusion power.
- Not surprising:
    - Searches and measurements would both use similar calibrations, reco techniques, etc…
- A search might use machine-learning or other optimisation to eke out sensitivity to benchmark models (at the cost of model dependence)
    - Can be quite hard to recast search results in terms of other models or other parameter choices.
- A measurement would have the advantage of being performed in a BSM-agnostic way, but typically unfolded to particle-level and has analysis logic preserved. **Potential hit in sensitivity, but easy to re-use!**



Dedicated search to probe some BSM models takes ~2 years…

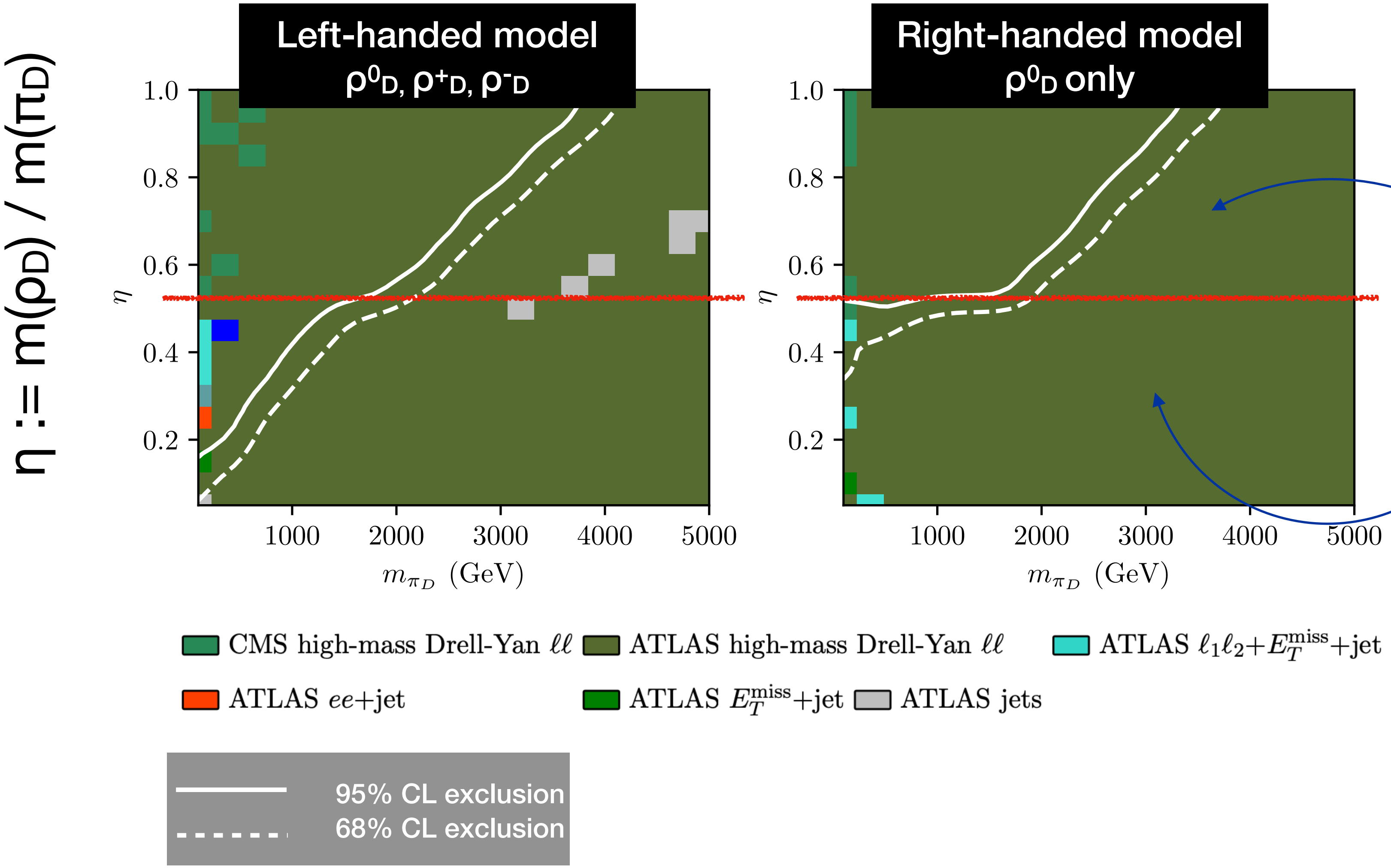
… but running a CONTUR grid of 200 points with 30,000 events each takes <24h on standard batch farm, and yields comparable exclusions

CONTUR results for Heavy Dark Mesons

Methodology

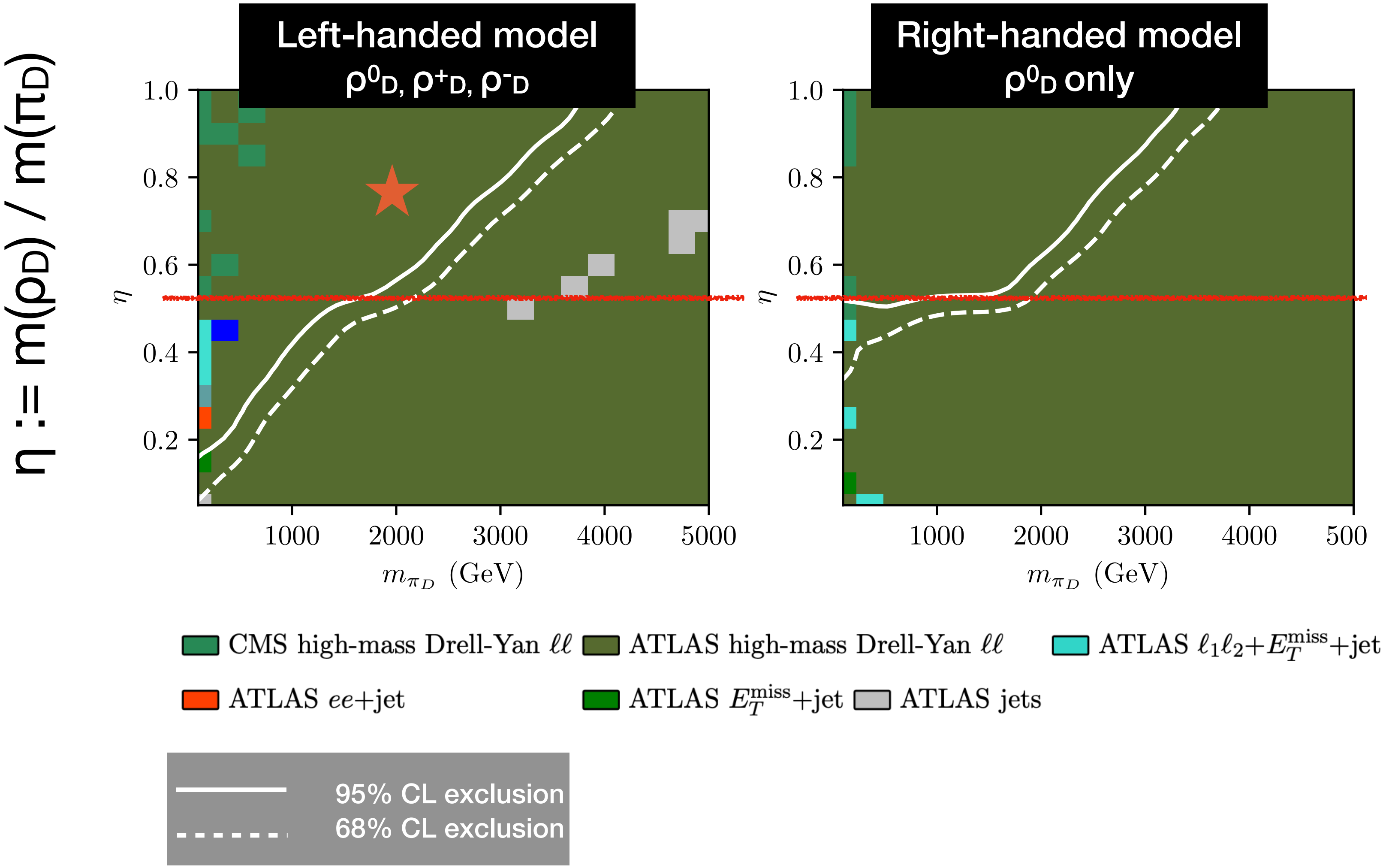
- Use Heavy Dark Meson UFO files : models for left- and right-handed scenarios
  - Define grid of 400 points in η vs m_{π_D}
  - At each point, use Herwig7 to generate all $2 \to 2$ processes involving a BSM particle in external leg or propagator, separately at 7, 8 and 13 TeV. 30,000 events / point (roughly equivalent 139/fb for typical cross-section)
  - Pipe output into Rivet, which filters events through the >150 LHC analyses preserved as runnable code snippets.
    - Automatically compare to analysis results from HEPData
  - Derive CLs exclusions at each point, and extract dominant analysis type

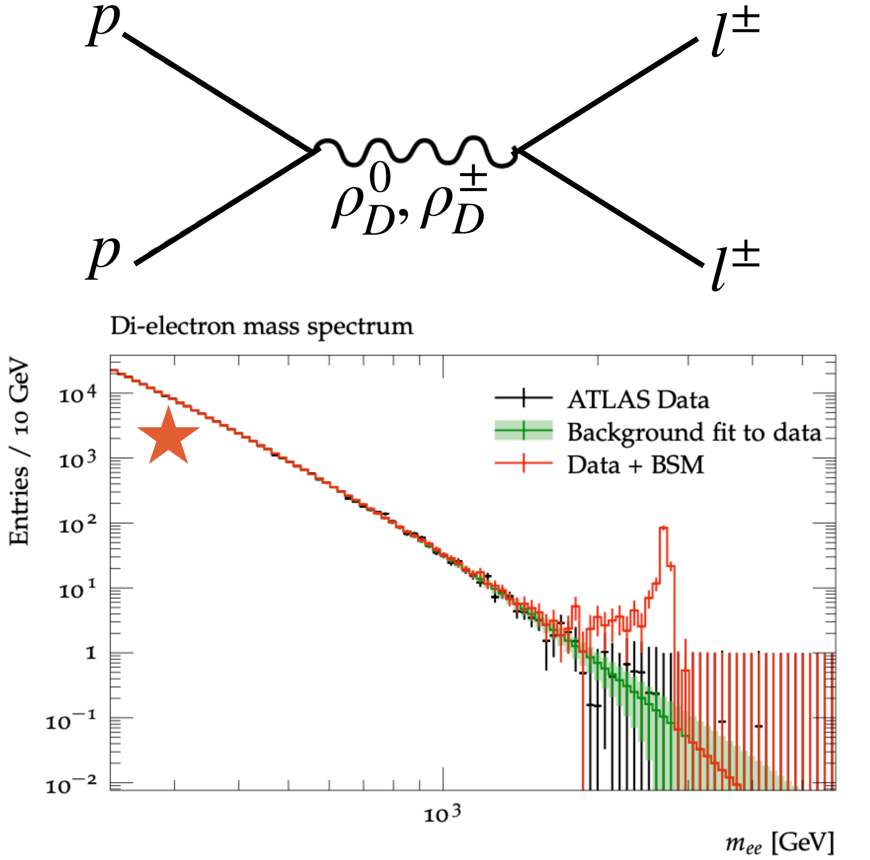
CONTUR results



Colour in each cell represents the "type" of LHC analysis which gives best sensitivity for each parameter point

CONTUR results

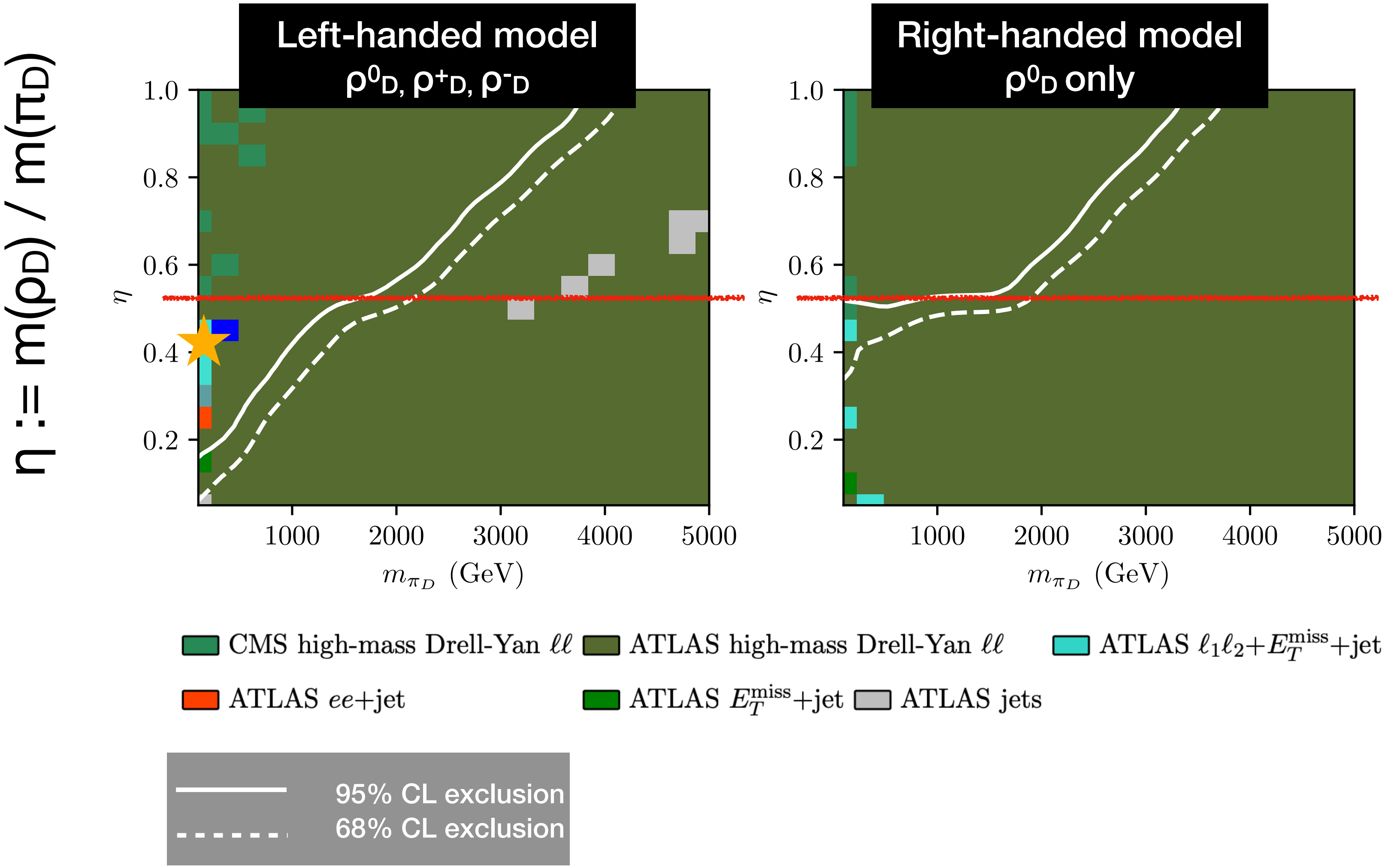


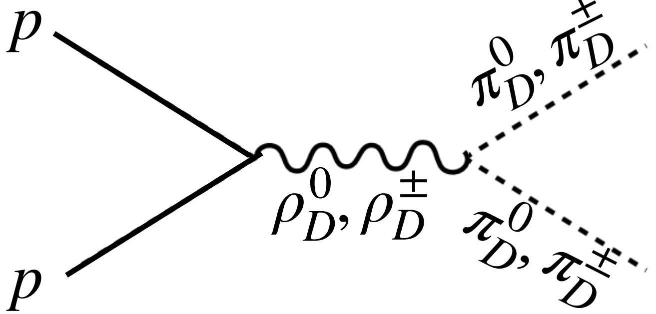


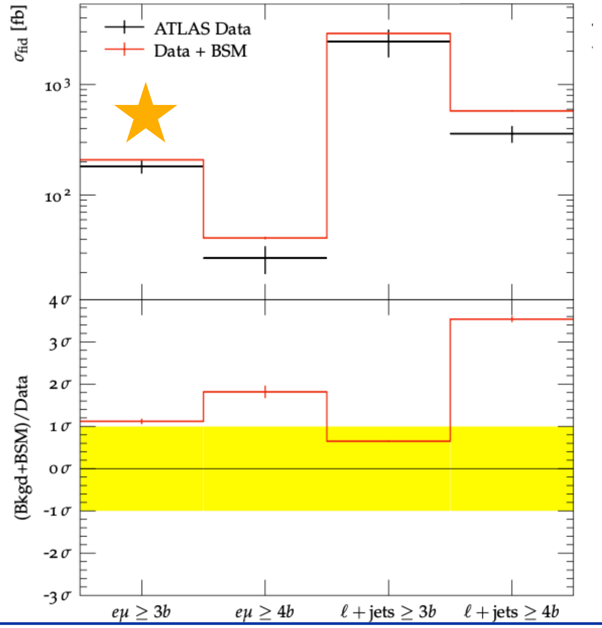
Search for high-mass dilepton resonances using 139/fb pp collision data collected at 13 TeV with the ATLAS detector
https://arxiv.org/abs/1903.06248

One of a few detector-level analyses in Rivet thanks to dedicated smearing functions!

CONTUR results







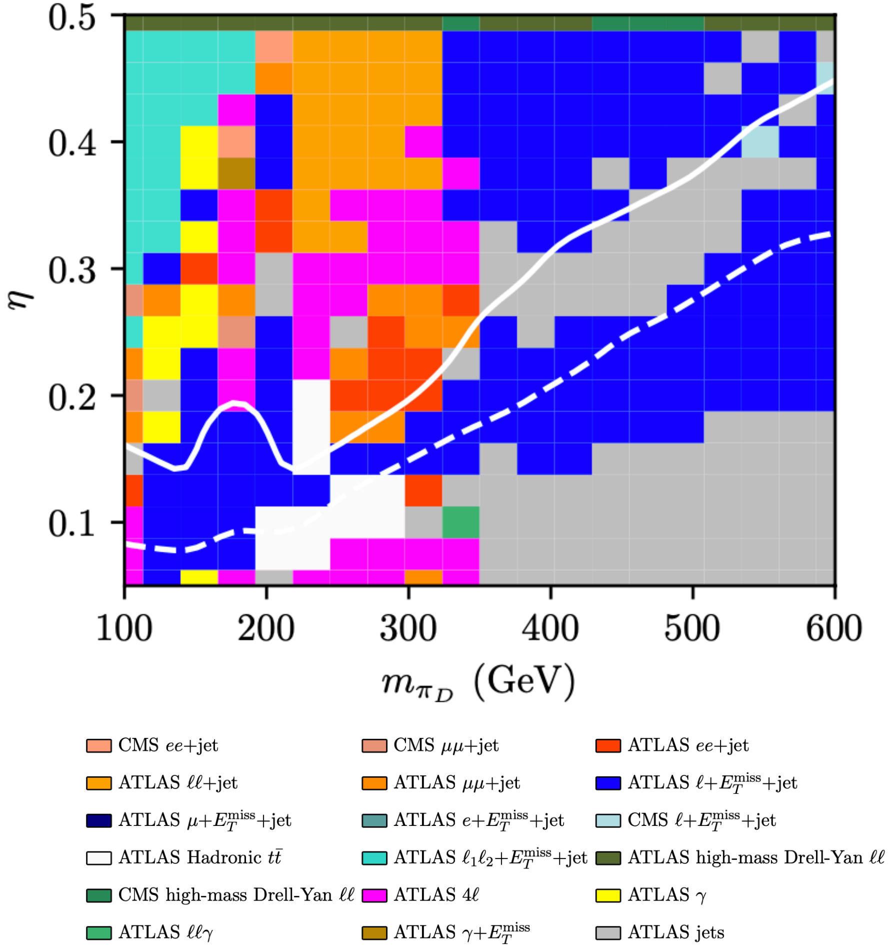
Measurements of fiducial and differential cross-sections of tt production with additional heavy-flavour jets in proton-proton collisions at 13 TeV with the ATLAS detector (36/fb)
https://arxiv.org/abs/1811.12113

ttbb final state (both dark pions decay to tb)

CONTUR results: zoom on low-η region

Left-handed model
ρ^0_D, ρ^+_D, ρ^-_D

95% CL exclusion
68% CL exclusion

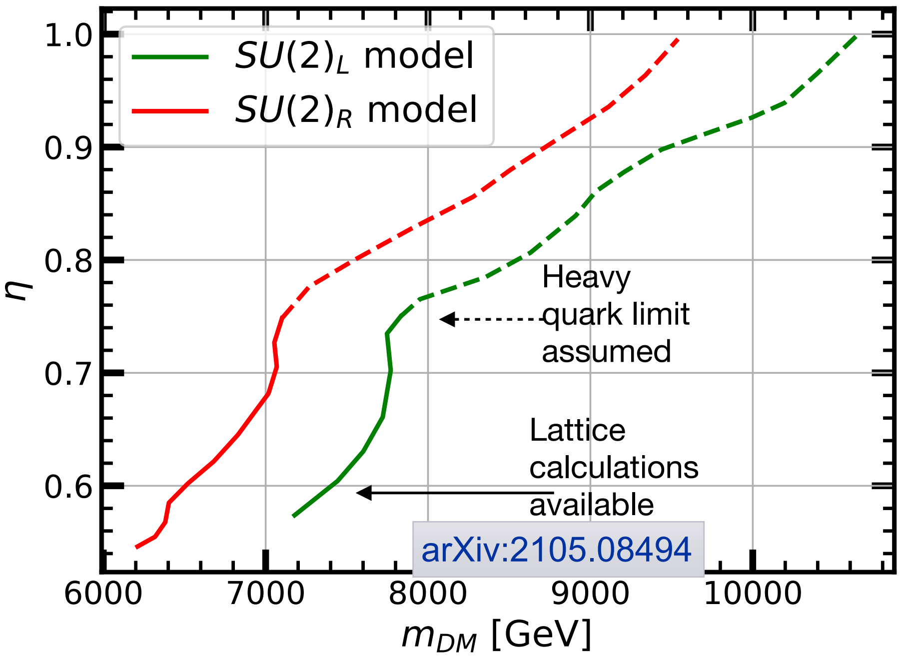


- Excluding the most sensitive analysis
  - DY resonant search: *because signal would not cause a "bump" in this region*

- CONTUR still excludes large areas of this region . What measurements contribute?
  - Higgs mass bin, contributions from ɣɣ measurements, as π_D->ɣɣ becomes important even if decay mode is suppressed
  - Boosted hadronic tt measurements play a role around m(π_D) 200 GeV: expected from dominant decay of pions to *tb*, and the fact they are boosted at that mass
  - Lots of sensitivity from tt-like measurements
  - Further High-mass Drell-Yan measurements, in particular of **ττ** + jets, could be helpful in future!

Linking to Dark Matter phenomenology

Translating results to limits of m_{DM}



η	$amps$	amv	$amS0$	f_f^{DM}
0.77	0.3477	0.4549	0.9828	0.153
0.70	0.2886	0.4170	0.8831	0.262
0.50	0.2066	0.3783	0.7687	0.338

Appelquist et al (arXiv:1503.04203)

- Follow similar strategy to Appelquist et al (arXiv:1503.04203) to connect collider limits to DM analysis: connect non-DM signatures (π_D) to DM via fundamental SU(4) representation, which fixes mass scales, and lattice calculations

$$m_{\mathrm{DM}}(\eta) = \frac{amS0(\eta)}{amps(\eta)} \times m_{\pi_D}(\eta)$$

Lattice dimensionless mass prediction for dark baryon

Lattice dimensionless mass prediction for pseudo-scalar

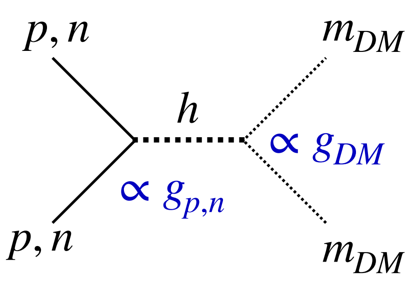
Appelquist et al (arXiv:1503.04203)

- LHC exclusions together with the lattice results push the dark matter mass limits to multi-TeV mass range. Results interpolated between different η scenarios.

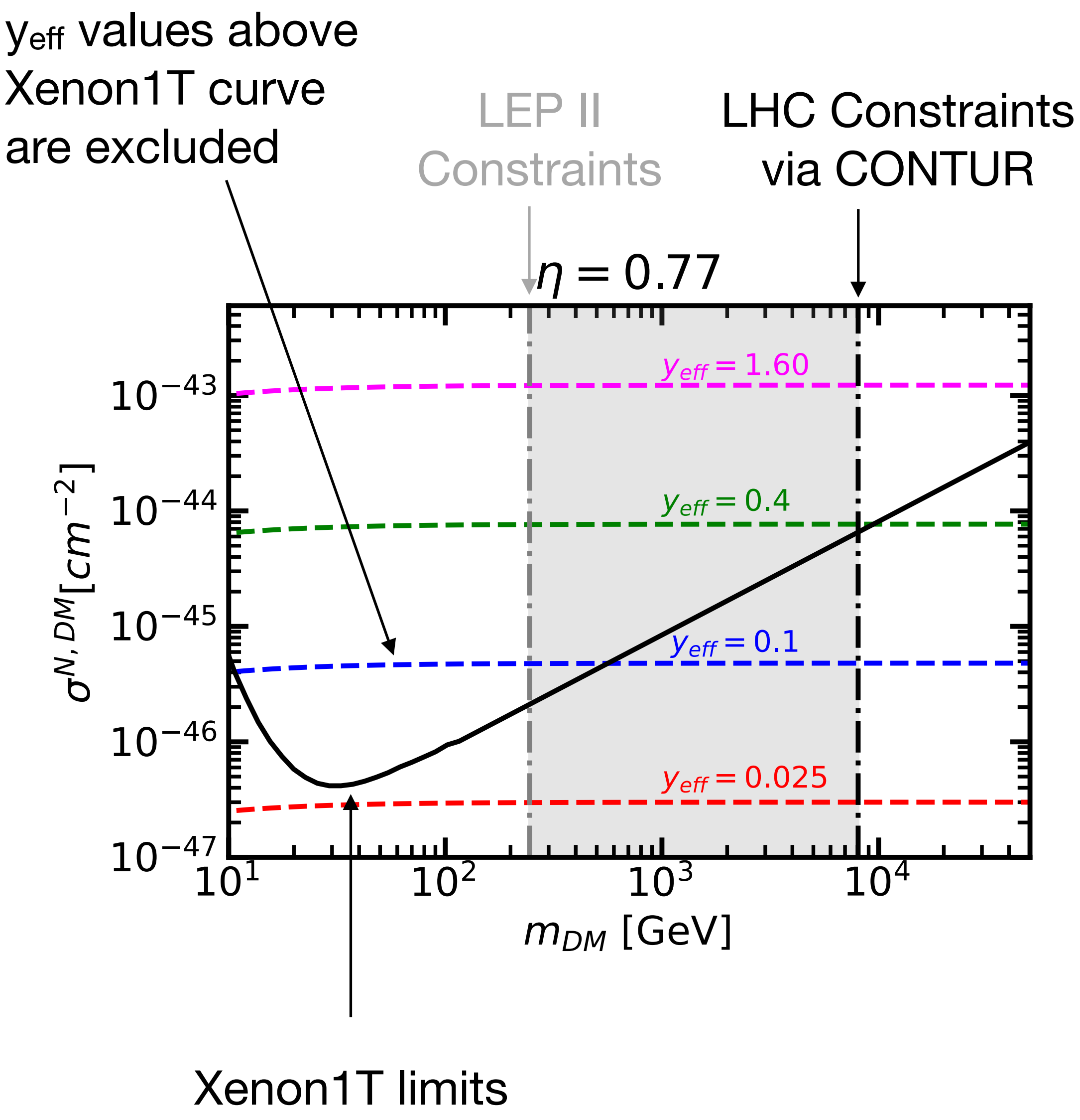
Combining with Direct Detection results

$$\mathcal{M}_{p,n} = \frac{g_{p,n}\, g_{DM}}{m_h^2}$$

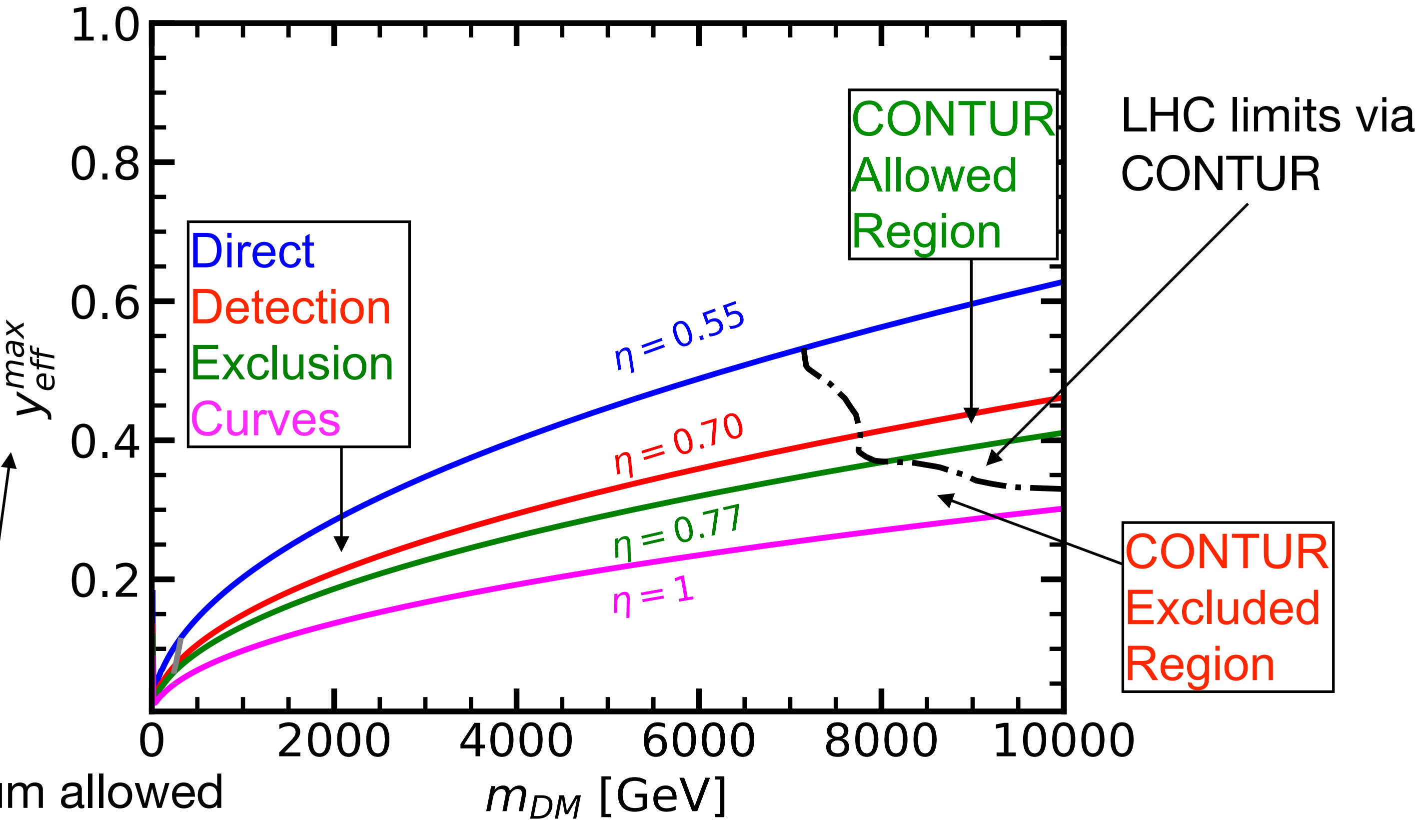
$$g_{\mathrm{DM}} \simeq y_{\mathrm{eff}} \times f_f^{\mathrm{DM}}$$



- Higgs-mediated DM production cross-section related to effective dark quark - Higgs coupling y_{eff}
  - Using inputs from lattice, eg f_f^{DM}
- LHC CONTUR limits, which are independent can be used to compare to Xenon1T constraints
  - Can then extract maximum allowed y_{eff} for each DM mass hypothesis



Bringing Direct Detection and LHC limits together



Maximum allowed coupling between dark quarks and Higgs

Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Summary

- CONTUR method allows new-physics models to automatically be confronted with a large bank of LHC measurements. Code is public and manual (https://arxiv.org/abs/2102.04377) and tutorials available !
  - Only requirement: need a UFO file for the BSM model!

- New paper uses this method to study Heavy Dark Mesons in a Composite DM model (https://arxiv.org/abs/2105.08494 —> Submitted to PRD)
  - LHC CONTUR limits translated to DM/Dark Baryon mass limits using existing lattice calculations
  - In combination with direct detection limits, provided an updated constraints on dark quark coupling to the Higgs and on the masses of DM bound state

home.cern

Details of Heavy Dark Meson model

Microscopic theory (custodially symmetric)
$SU(N_D)$, $N_D = 4$, $N_f = 4$, **Weyl Fields** $F_L, \hat{F}_L, F_R, \hat{F}_R$
Vector-like mass $m(1+\Delta)F_L\hat{F}_L$, $m(1-\Delta)F_R\hat{F}_R$
Chiral mass $y(1+\epsilon)F_L H \hat{F}_R$, $y(1-\epsilon)\hat{F}_L H F_R$
Δ splits vector mass, yv splits chiral mass,
$|\epsilon| \ll |y|$, $yv \ll m$

↓

Macroscopic theory
$N_f^2 - 1 = 15$ mesons
$15 \to (3,1) \oplus (2,2)_a \oplus (2,2)_b \oplus (1,3) \oplus (1,1)$

- π_L^D, ρ_L^D — $SU(2)_L$ Triplet (3 pions, 3 rho)
- π_R^D, ρ_R^D — $SU(2)_R$ Triplet (3 pions, 3 rho)
- Two bi-doublet K^D, singlet η_s^D + Dark scalar baryon (DM)

Gauge SU(2)L
Three dark rho bosons mix with three SM gauge bosons
LHC DY **production** of three dark rho

Gauge SU(2)R
(Equivalent to gauging $U(1)_Y$)
Neutral dark rho boson mixes with SM neutral gauge boson
LHC DY **production** of neutral dark rho

Dark pions mix with SM Higgs, Goldstones
Mixing suppressed by $\sim m_h^2/m_{K_D}^2$
→ Gaugephobic interactions

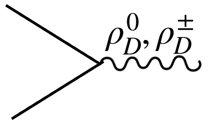
SU(2)L gaugephobic
Linear
$\Delta \ll yv$
Dark quark Dirac mass splitting dominated by electroweak symmetry breaking

SU(2)R gaugephobic
Quadratic
$\Delta \gg yv$
Dark quark Dirac mass splitting dominated by vector-like mass splitting

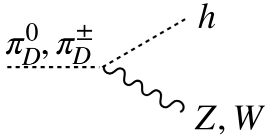
⇒ High scale model

⇒ Low scale model
Meson content from symmetries
Particle spectrum from lattice ($m_{q_D} \sim \Lambda_{dark}$ regime)

⇒ Dictates chiral Lagrangian,
dark mesons production mechanism



⇒ Defines dark pion decays



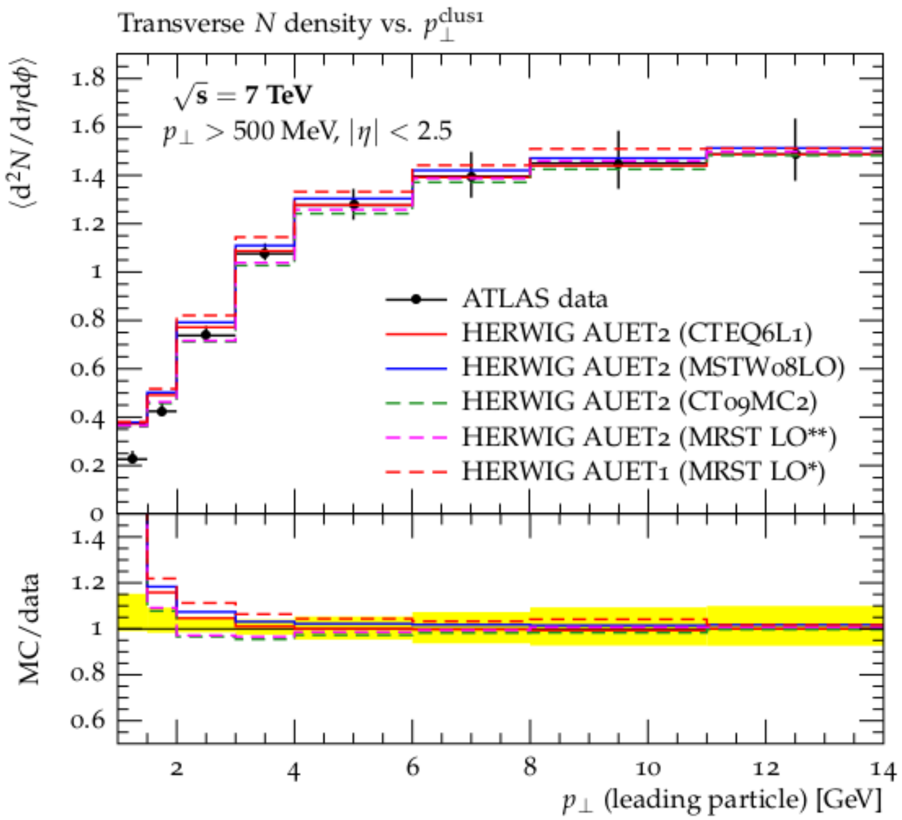
Aim: constrain dark sector - SM portal i.e. constrain value of Higgs - dark quark Yukawa coupling

Important: Lattice does not predict absolute masses but bound state mass in terms of common mass scale of free choice

Kribs et al. arXiv:1809.10183

We have the technology

- We **already have the infrastructure to make rapid particle-level Data/MC comparisons**.
- We use it all the time: it's called **Rivet** (Robust Independent Validation of Experiment and Theory)
    - Preserve fiducial selection logic in runnable code snippet, automatic comparison to experimental results stored on HEPData
    - Originally for MC Generator comparisons of SM predictions, and tuning
    - <u>**Trivial to switch out so we compare to a SM+BSM prediction!**</u>
- We have 100s of measurements preserved in this way in Rivet. Optimised for speed and efficiency: run all the Rivet routines for a given sqrt(S) at the same time.
- More Analyses being added all the time: having a Rivet routine is part of the ATLAS (and now CMS) approval procedure



CONTUR Steering

- CONTUR provides the book-keeping and steering machinery to repeat this process over a grid of parameter values
- Run grid for 7, 8, 13 TeV separately, then combine by taking most sensitive measurement from orthogonal analysis pools