# DARK SECTOR THEORY AT LHC

**Felix Yu**
**Johannes Gutenberg University, Mainz**

Light Dark Matter 2017
Isola d’Elba, May 26, 2017

# Goal of this overview

**What underpins dark sector searches at LHC?**

# WIMP legacy

- Only nontrivial SM gauge quantum number for dark matter is an electrically neutral SU(2)xU(1) charge
  - *Weakly* interacting massive particle has correct parametric dependence to fit the measured relic abundance measured by Planck

$$\Omega h^2 \approx 8.76 \times 10^{-11} \mathrm{GeV}^{-}2 \left[ \int_{T_0}^{T_F} g_*^{1/2} \langle \sigma v \rangle \frac{dT}{m_\chi} \right]^{-1}$$

Arcadi, et. al. [1703.07364]

$$\Omega h^2 = 0.1198 \pm 0.0026$$

Planck [1502.01589]

- Separately, new physics at the weak scale strongly motivated by **naturalness**

# WIMP legacy

- R-parity conserving MSSM (minimal supersymmetric SM) is a canonical example
  - Elegantly solves hierarchy problem and provides a dark matter candidate neutralino
    - Neutralino is fermionic superpartner of weak gauge bosons

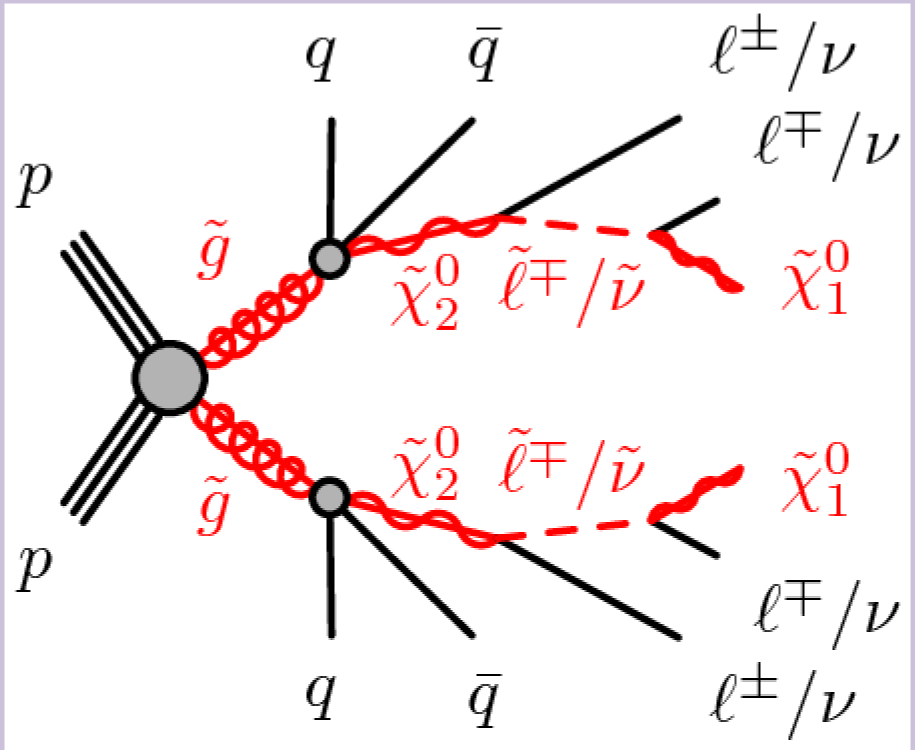
(cf. Cheung, Hall, Pinner, Ruderman [1211.4873])

  - DM gauge representations extended to consider beyond triplets of SU(2), other spins

Cirelli, Fornengo, Strumia [0512090]

# WIMP legacy

- R-parity conserving MSSM (minimal supersymmetric SM) is a canonical example
  - Spectacular cascade decay collider signals – jets, leptons, and missing transverse energy (MET)

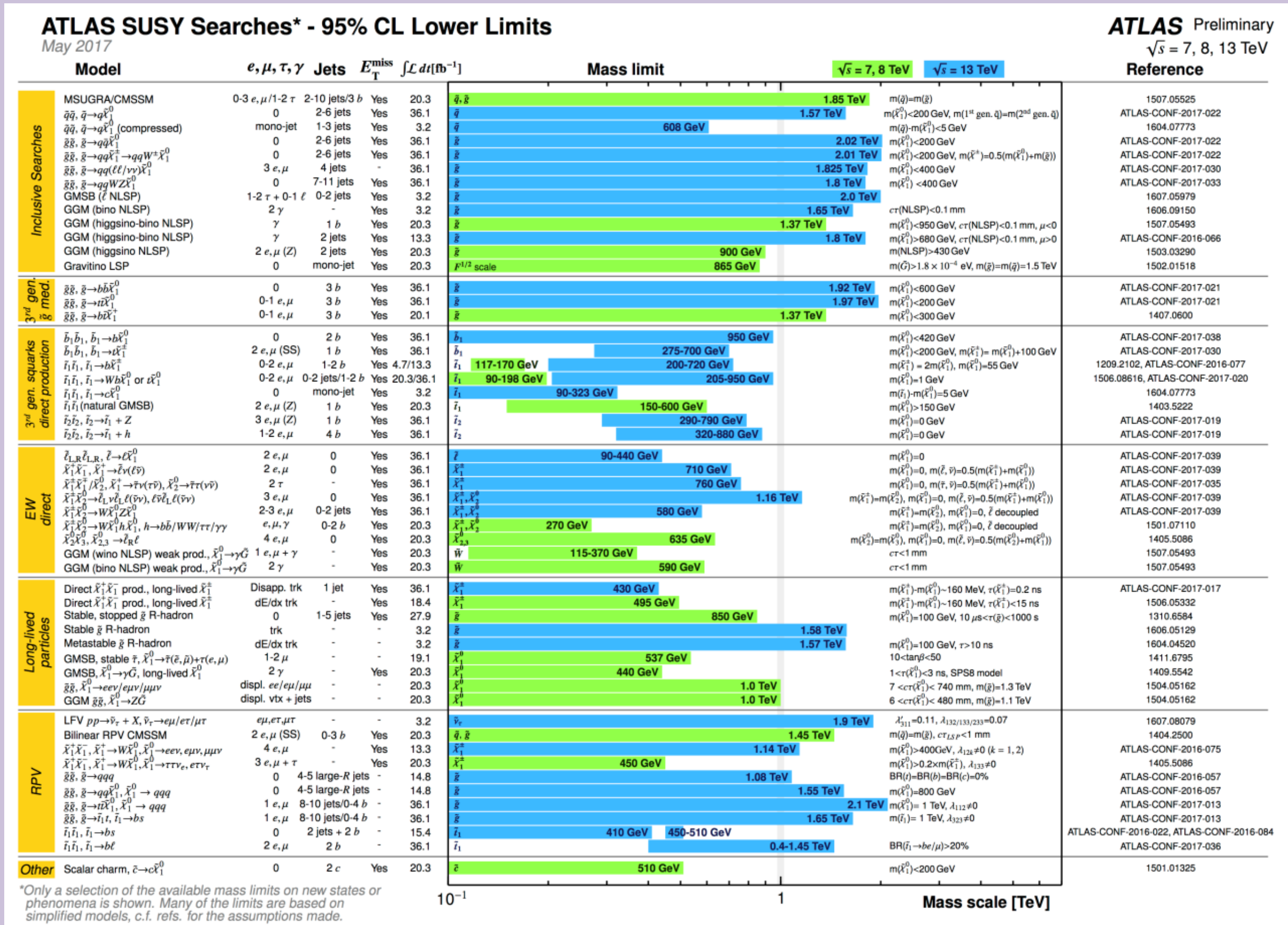



ATLAS-CONF-2017-030

# WIMP legacy

- R-parity conserving MSSM (minimal supersymmetric SM) is a canonical example

But no signals have been seen yet



# Beyond WIMPs at and beyond LHC

- Thermal vs. non-thermal mechanism
  - Simplified model
  - Coannihilation
- Dark sector vs. dark matter
  - Cascade decays
  - Probe mediators directly
- Effective operators for new, invisible particles
  - Complete parametric ignorance
- Symmetry mechanism
- Mass generation
- (Self-interactions)

LHC most powerful when dark sector particles charged under SM color

↓

Next jumps in reach for SM weak interactions

↓

Mediators searched as resonances

↓

Marginal operators more difficult

# Beyond WIMPs → effective operators

- Give up on $\Omega h^2$ connection, simply characterize gauge-invariant fermion bilinears with SM operators at lowest order
- Use initial state radiation (jet, photon, etc.) to generate mono-X + MET signal ("mono-mania")

At LHC, must control jet mismeasurement and neutrino MET tail

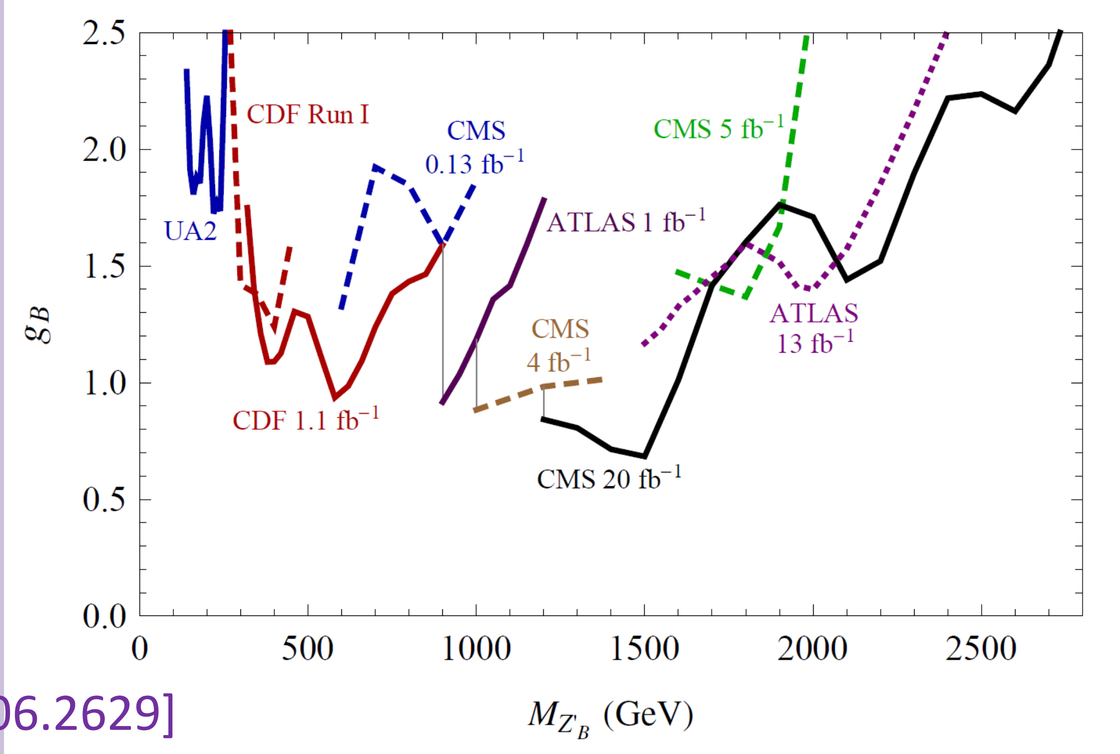
$$\mathcal{L} = G_\chi \, [\bar{\chi}\Gamma^\chi \chi] \times [\bar{q}\Gamma^q q]$$

| Name | Type | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | 1 | 1 |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | 1 |
| M3 | $qq$ | $im_q/2M_*^3$ | 1 | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | 1 | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | 1 | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

Goodman, et. al. [1005.1286, 1008.1783], Bai, Fox, Harnik [1005.3797]

# Beyond WIMPs → beyond effective operators → simplified models

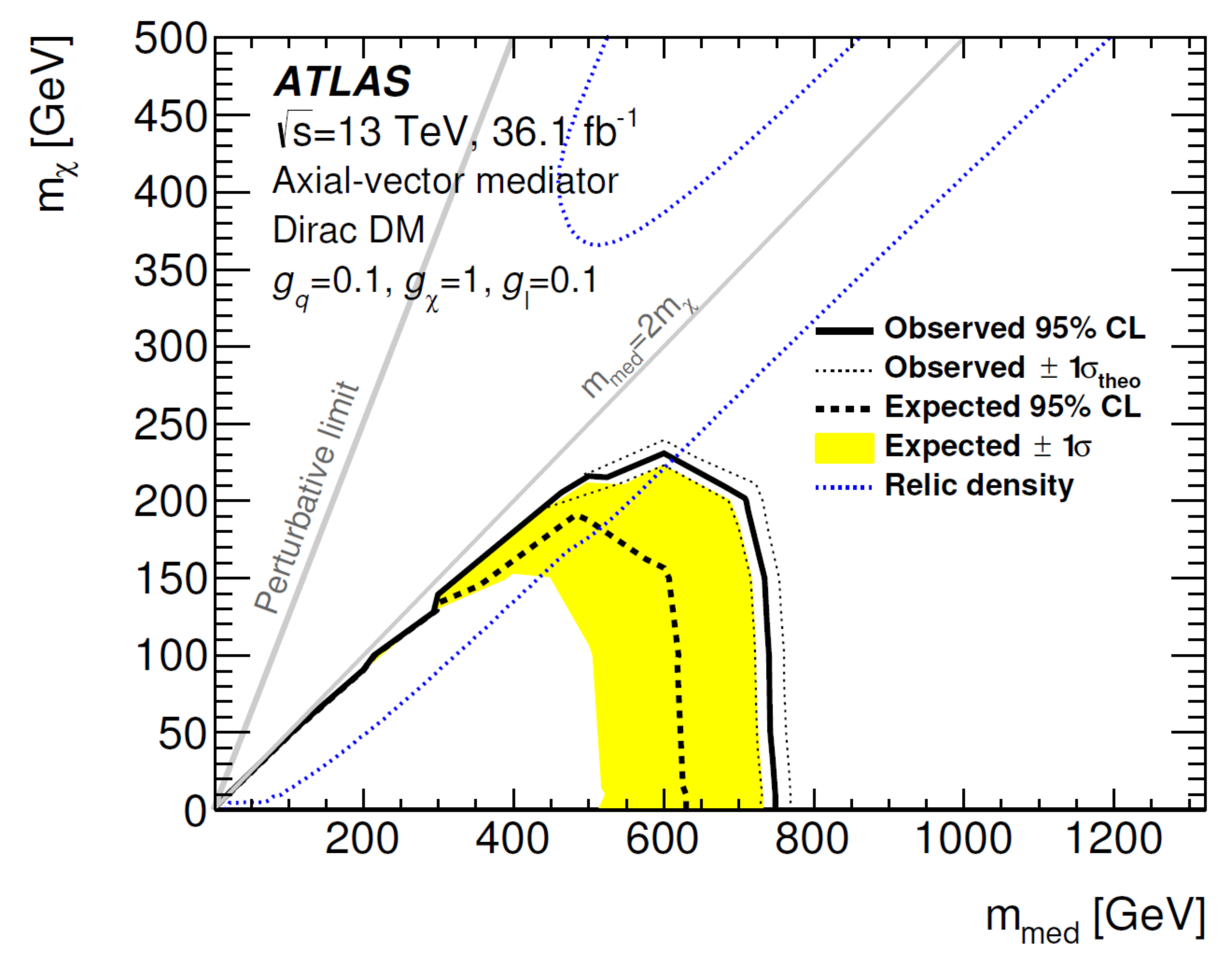
- Divorce dark matter from weak interactions
  - $\Omega h^2$ from weak-like (i.e. perturbative) couplings and O(100) GeV masses
- Easiest situation: mediator is leptophobic – $Z'_B$




Dobrescu, FY [1306.2629]

# Beyond WIMPs → beyond effective operators → simplified models

- Straightforward, tree-level mediator leads to a dijet resonance




ATLAS [1611.03568]

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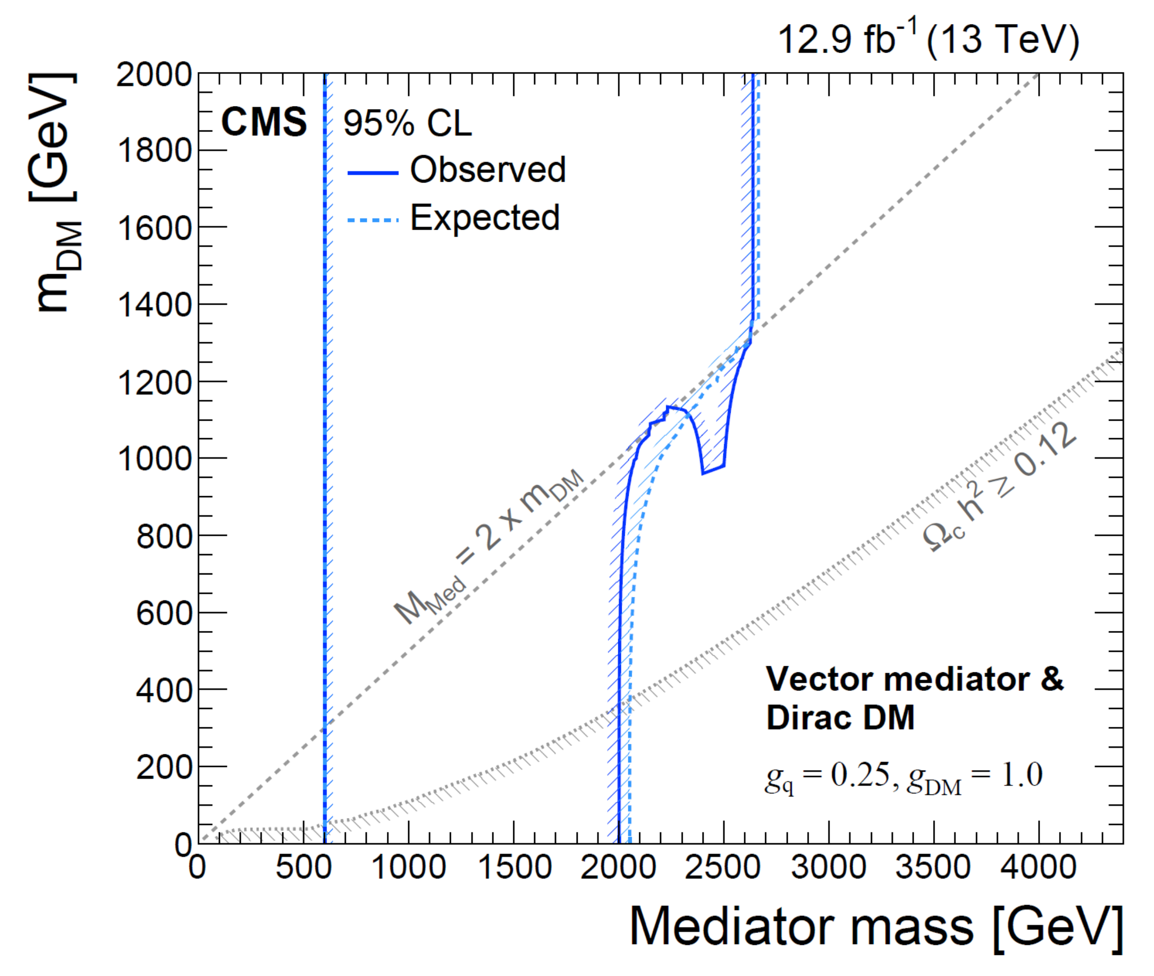
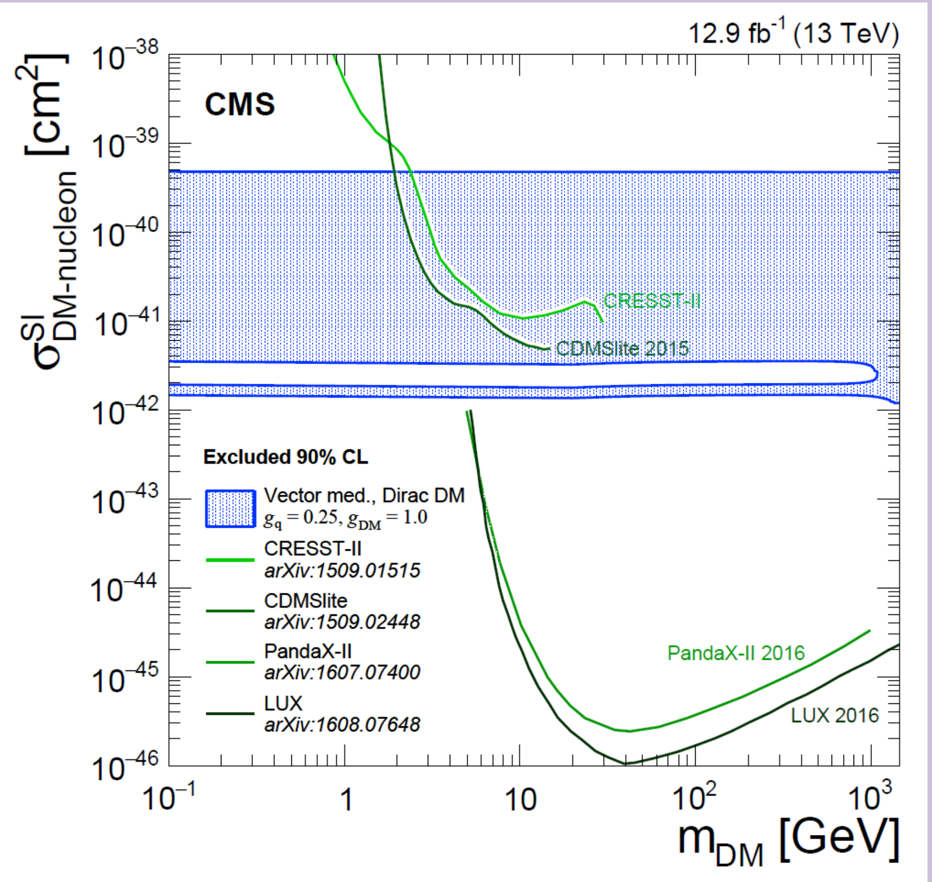



CMS [1611.03568]

# Beyond WIMPs → beyond effective operators → simplified models

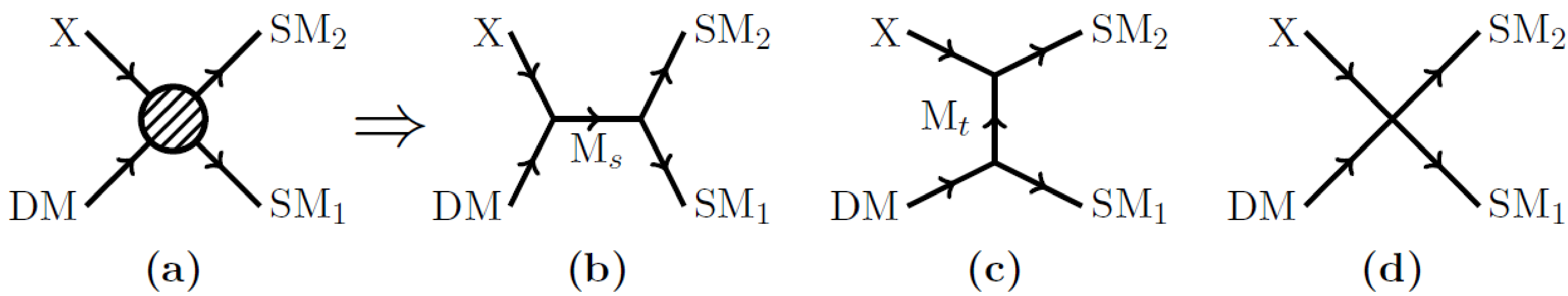
- Translating LHC limits to, *e.g.*, direct detection plane requires complete model specification and astrophysical assumptions




CMS [1611.03568]

# Even further → coannihilating simplified models

- Tree-level mediator for DM coannihilation instead of DM pair annihilation



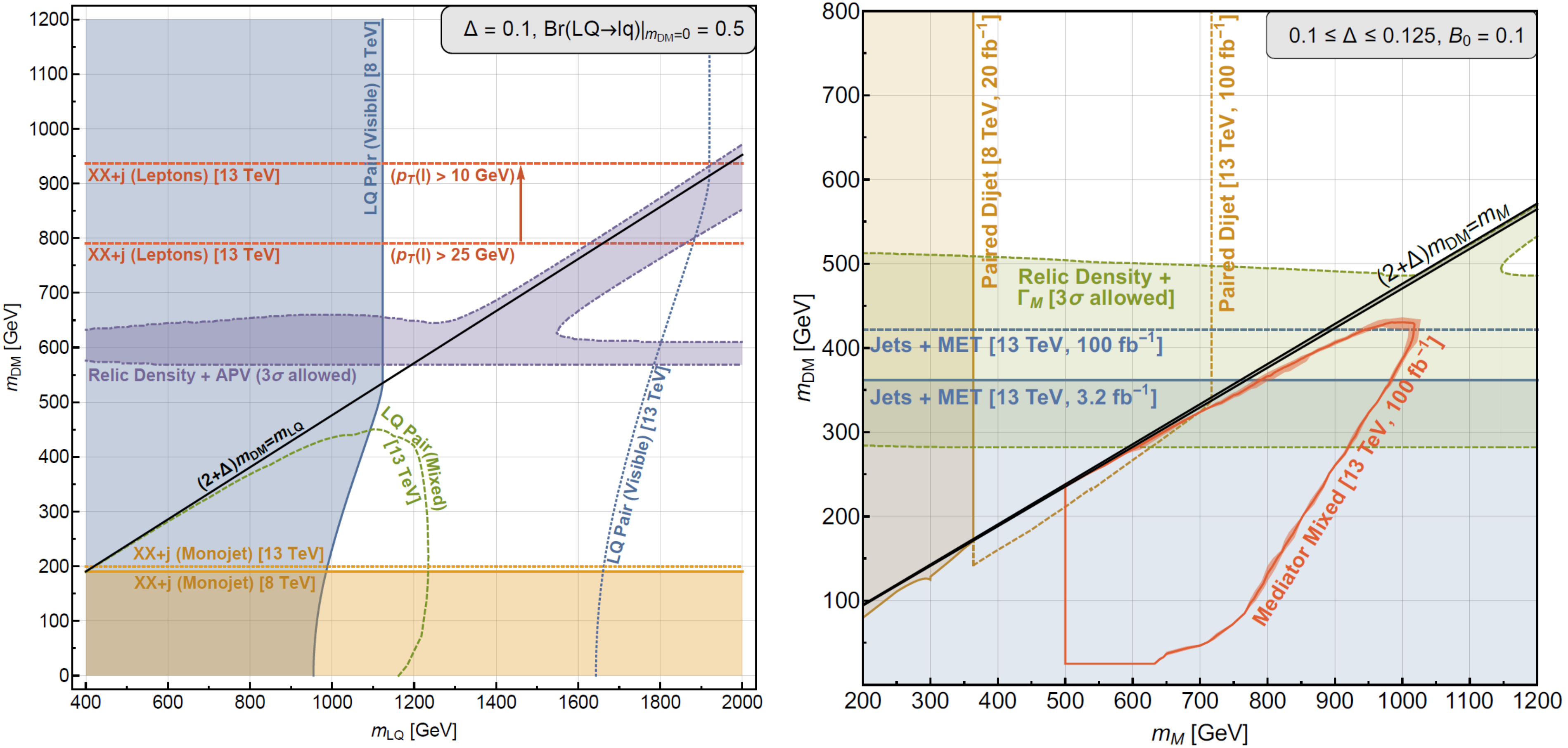

- Mediator strongly produced, leads to resonance + MET signatures
  - Identified leptoquark + MET and diquark + MET signatures as new channels for LHC searches

The Coannihilation Codex (Baker, [FY] et. al.) [1510.03434], [1605.0805]

# Even further → coannihilating simplified models

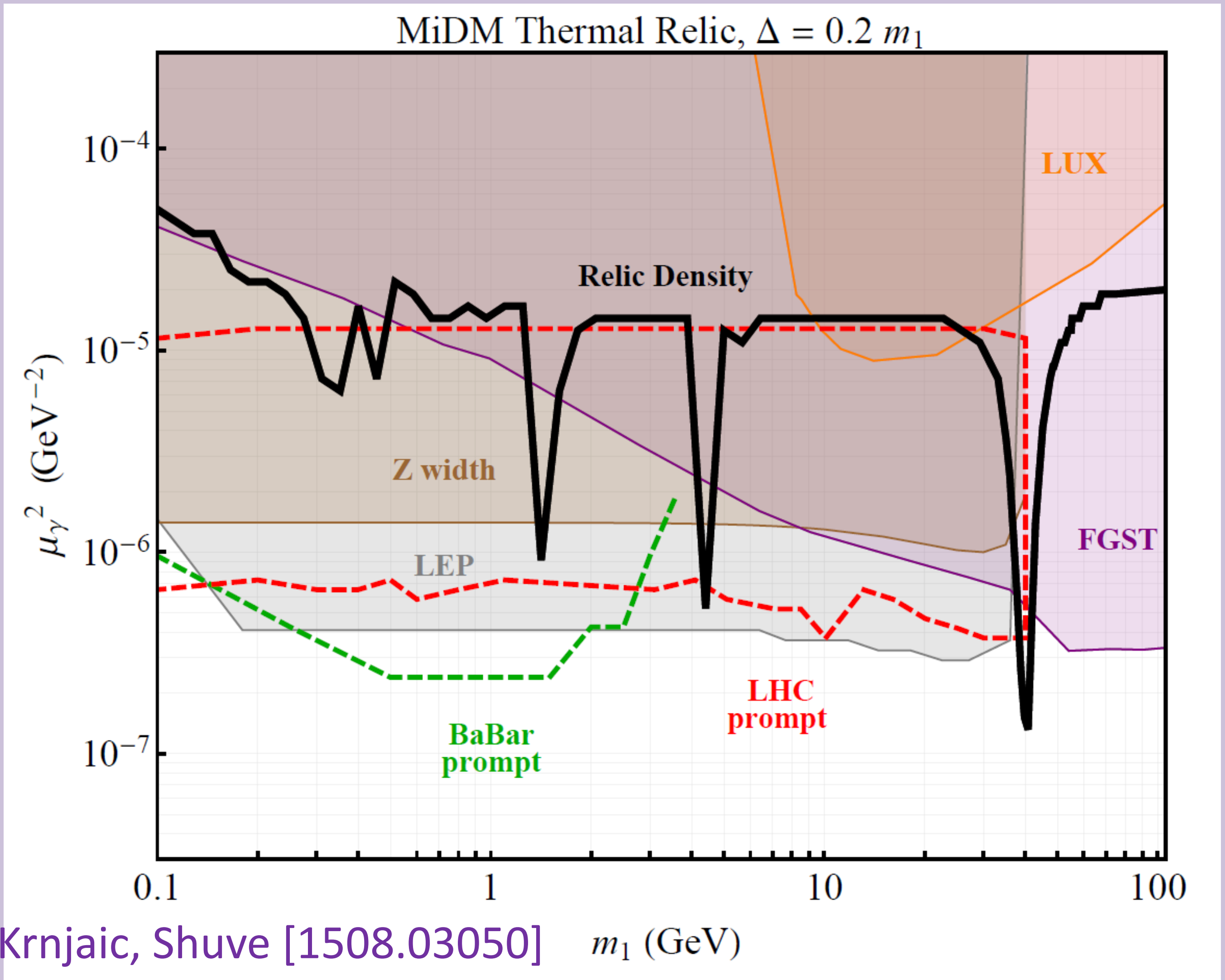
The Coannihilation Codex (Baker, [FY] et. al.) [1510.03434], [1605.0805]

Complementary reach from LHC in mediator and dark sector searches, overlay preferred region from $\Omega h^2$



# Even further → coannihilating simplified models

- Tag soft decays from coannihilation partner




Izaguirre, Krnjaic, Shuve [1508.03050]

# Beyond WIMPs → marginal operators

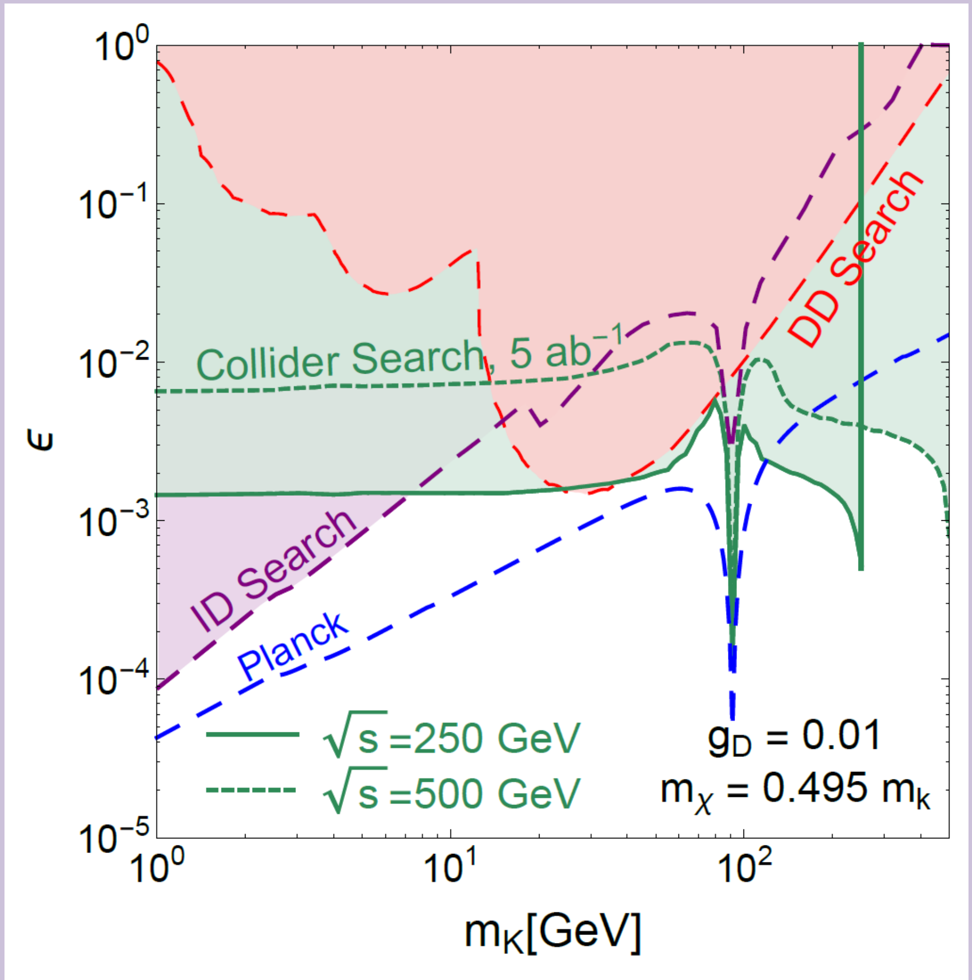
- Divorce dark sector from all SM gauge interactions
  - $\Omega h^2$ from weak-like (i.e. perturbative) couplings and O(100) GeV masses
- Leading interactions at dim-4
  - Scalar Higgs portal $(\mu\phi + \lambda\phi^2)H^\dagger H$
  - Neutrino portal $y_n LHN$
  - Kinetic mixing portal $-\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu}F'^{\mu\nu}$
- Dimension-5
  - Axion portal $\dfrac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$

High COM energy for LHC tends to win only when other experiments lose kinematic reach

# Beyond LHC

- Study dark scalar Higgs and dark U(1)’ gauge boson prospects at future $e^+e^-$ collider

Emphasizes ***complementary reach*** from direct detection, indirect detection, Planck, and colliders




Liu, Wang, FY [1704.00730]

# Summary: collider dark matter

- LHC has special opportunity to test relic density mechanism via direct production of mediators
  - Many classes of models (within kinematic reach of LHC) with new particles charged under SM gauge symmetries
- Combination of production and decay rates will measure underlying Lagrangian parameters
  - Powerful post-discovery possibilities
- Must keep in mind
  - Timescale for collider stability ≠ cosmological stability
  - Dark matter stability ≠ parity
  - Model dependent and astrophysical assumptions to translate constraints to, *e.g.* nucleon cross section