Dark Matter at the HE/HL LHC

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Dark Matter at Colliders

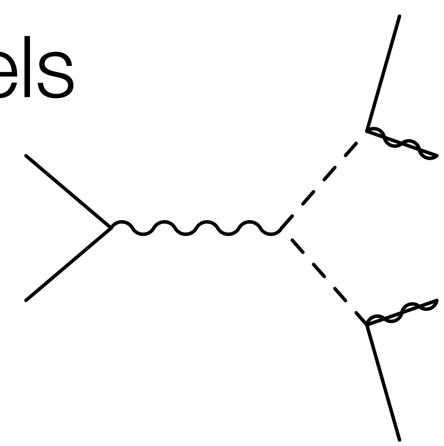
- From the organizers:

"Given the level of expertise of the audience we would prefer you focus on details and not general introduction/motivation."

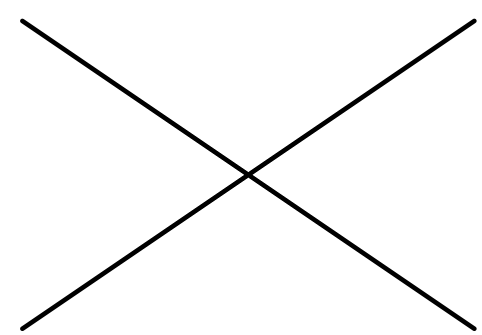
- So I'll assume we all know that dark matter exists, why we want to look for it, and the complementary probes we can use to get at dark matter.
    - Colliders, direct detection, indirect detection…

Dark Matter at Colliders

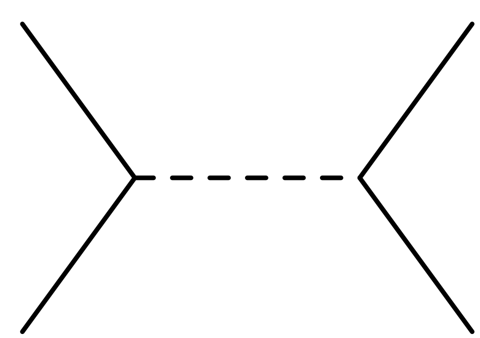
- We all know the diversity of ways that we theorists can put dark matter into a theory:
    - UV-complete models



    - Effective operators

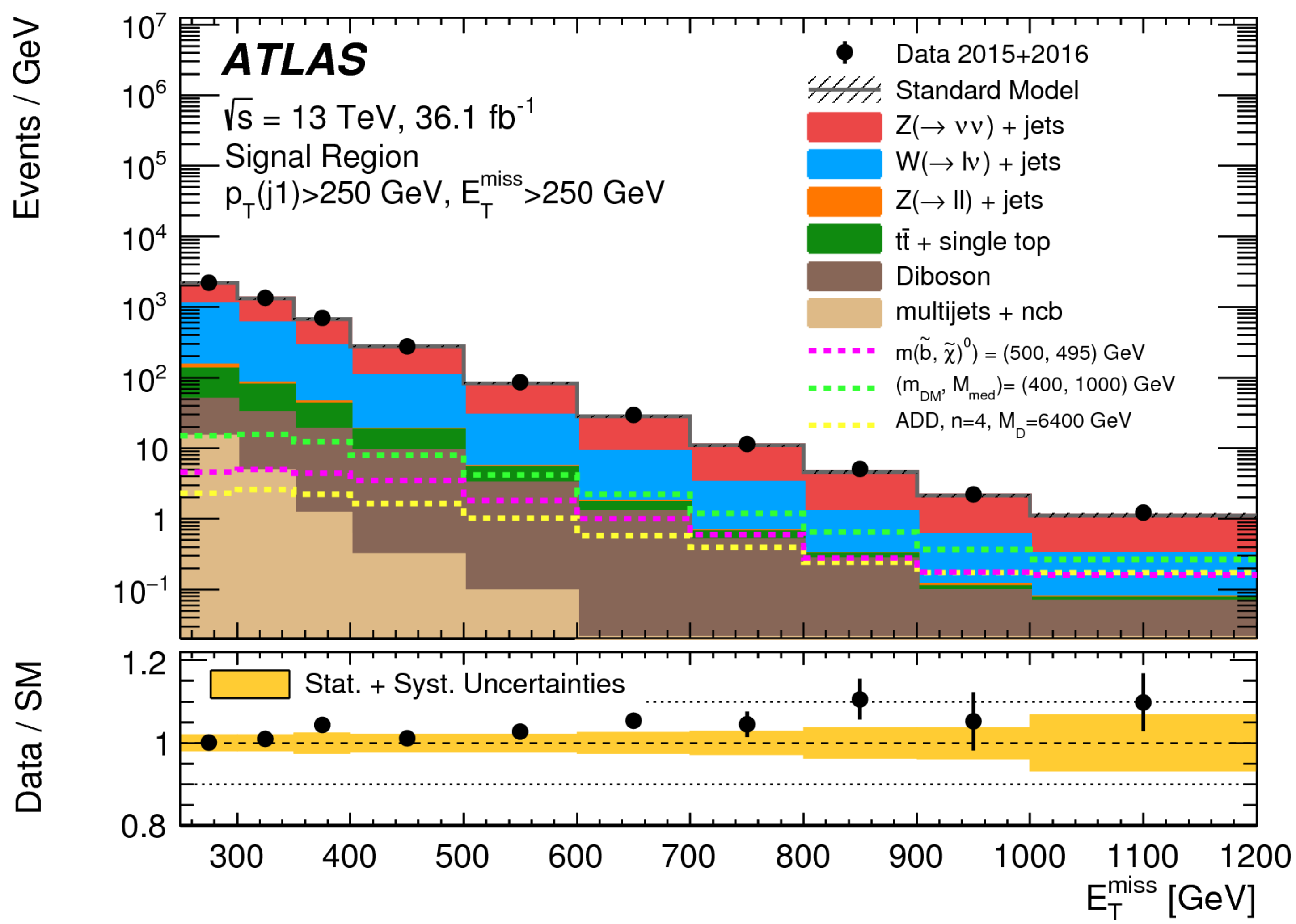


    - Simplified models



Dark Matter at Colliders

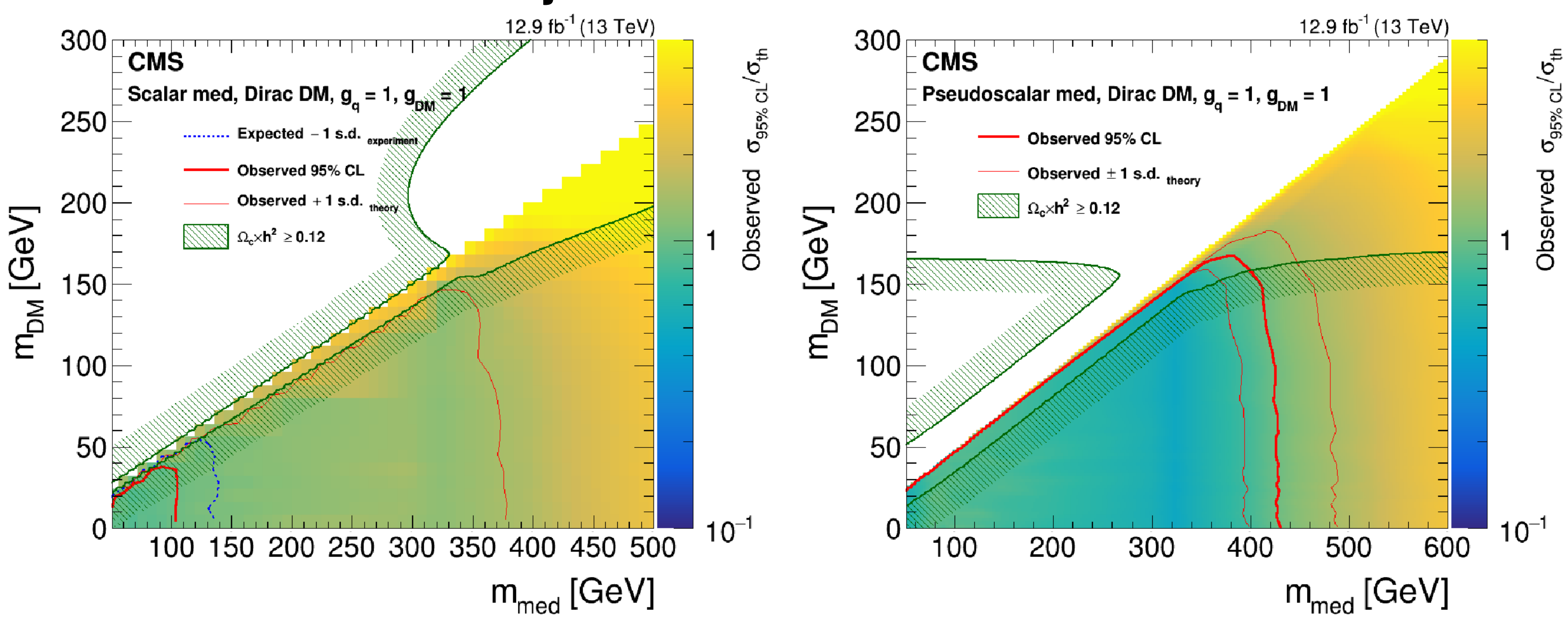
- Searches typically rely on tails of MET distributions.



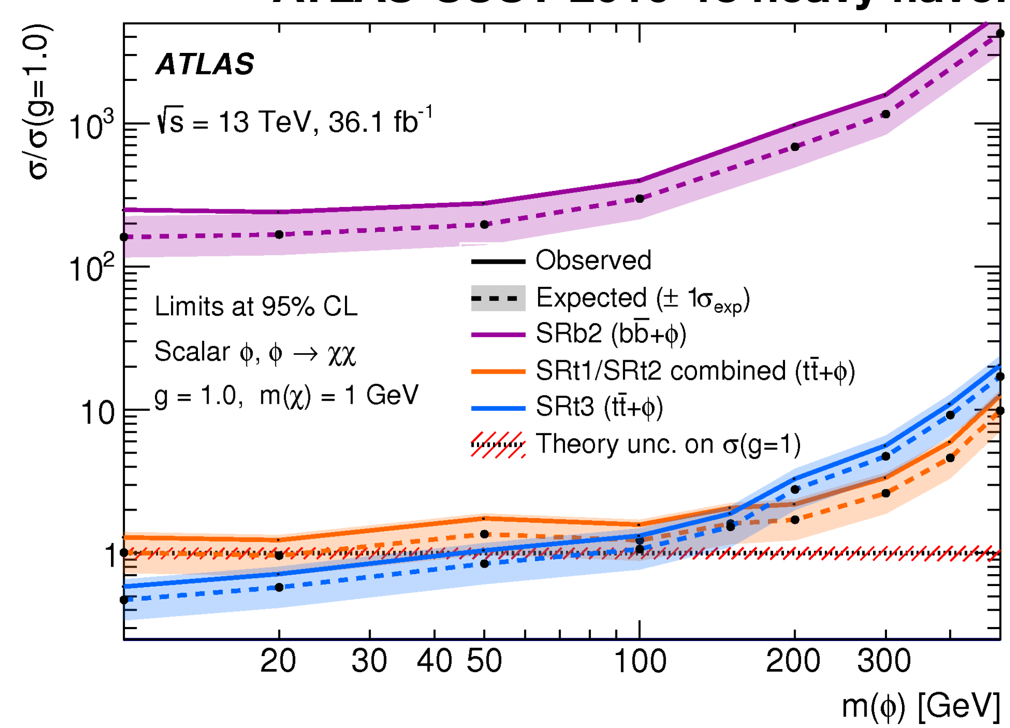
ATLAS 1711.03301

Examples of the State of the Art

CMS-EXO-16-037 monojets

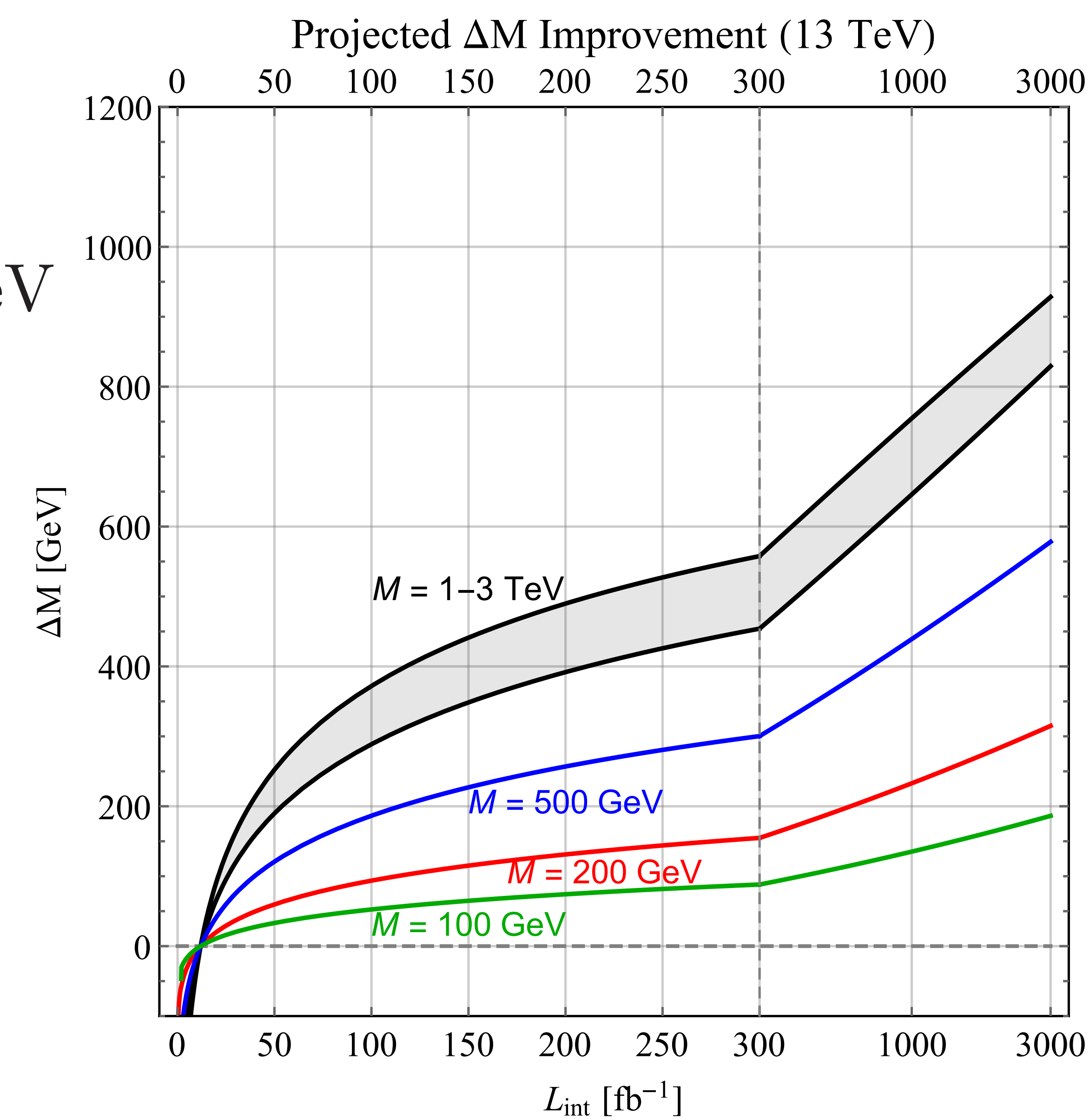


ATLAS-SUSY-2016-18 heavy flavor



High Luminosity

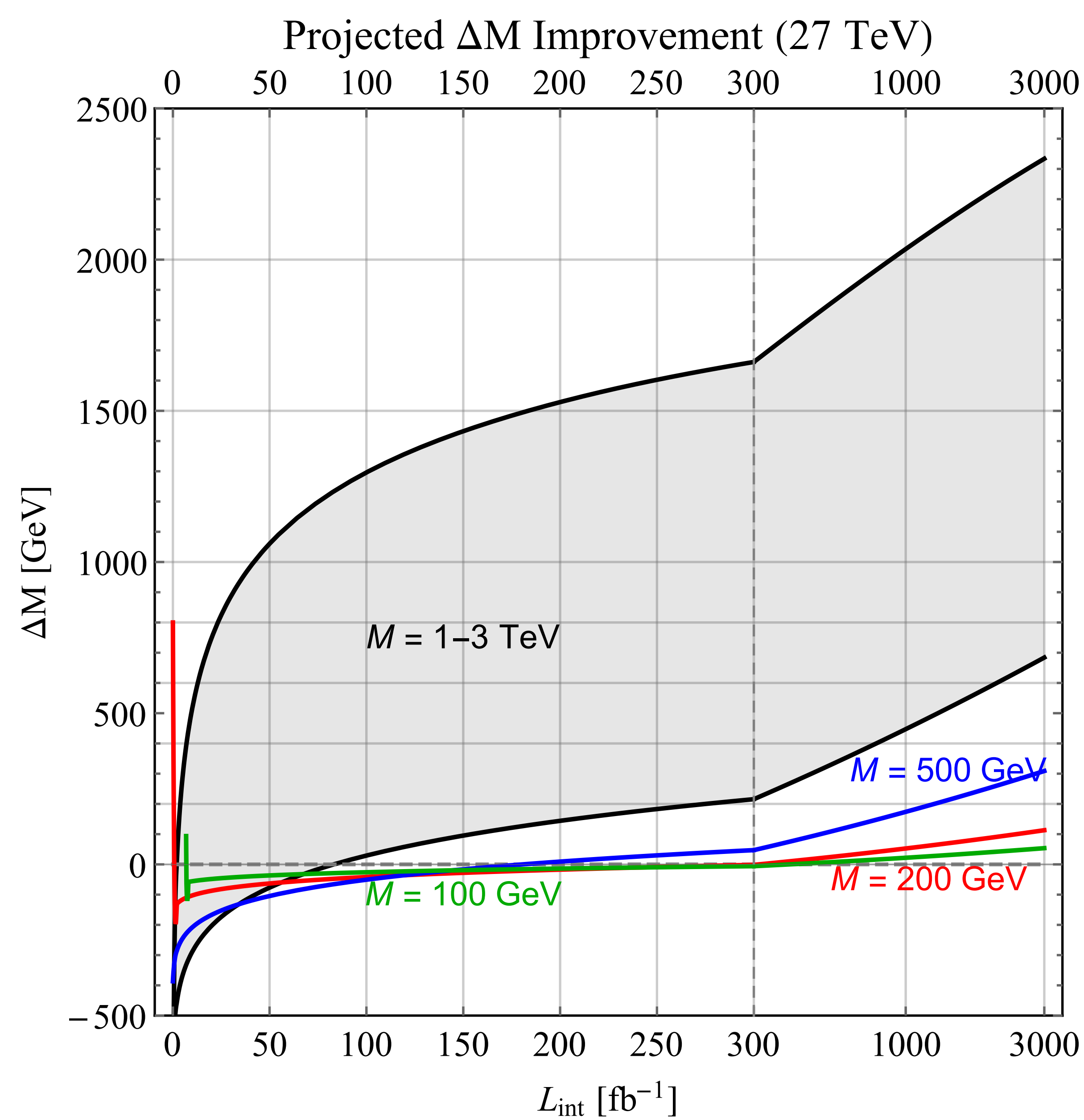
- Rough projection of limits as luminosity is increased.
  - Relative to 12 fb^{-1} $\sqrt{s} = 13\ \mathrm{TeV}$
  - Assumes a single mass
  - Assumes signal efficiencies and background counts are held constant.
  - Assumes statistics is the major limiting factor



Buckley *et al*, 1610.08059

High Energy

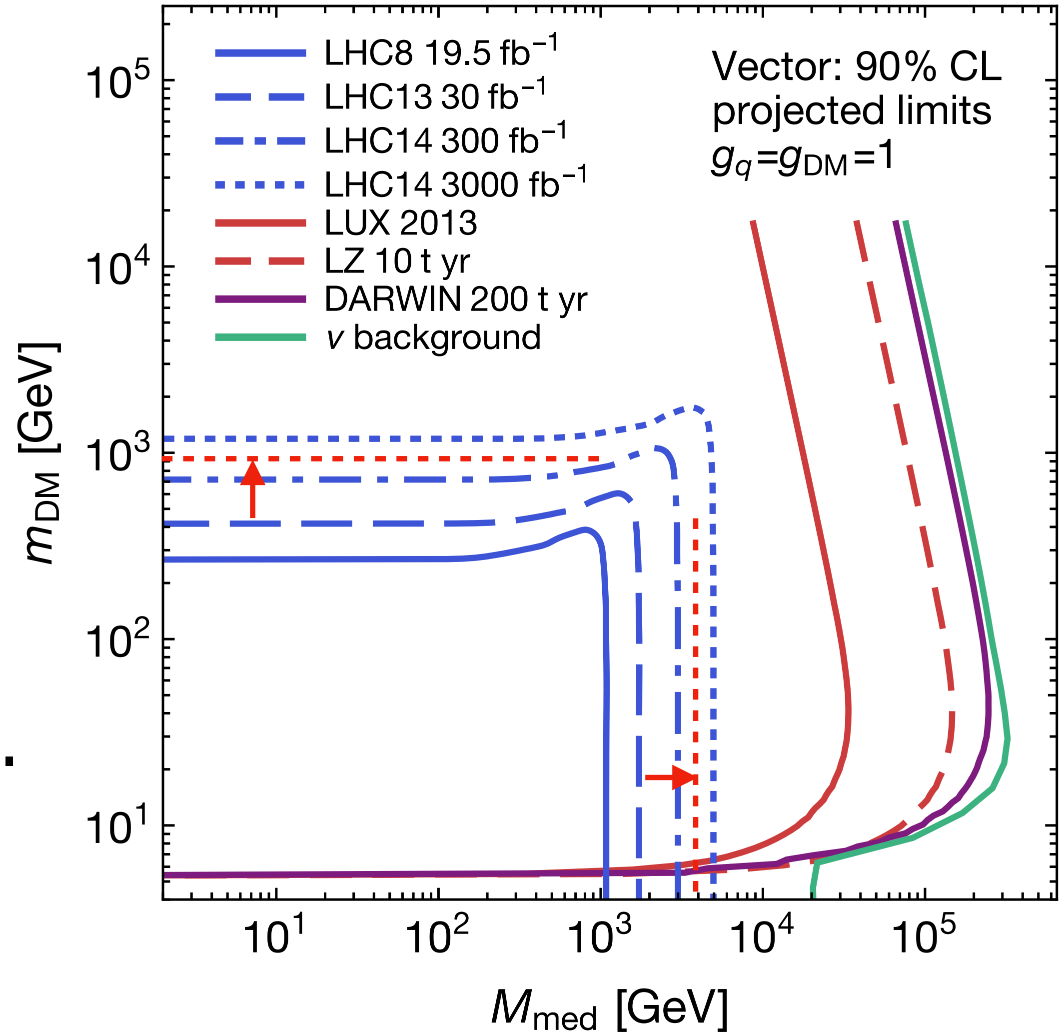
- What does going to high-energy net us?
    - Relative to 3000 fb^{-1} of $\sqrt{s} = 13\ \text{TeV}$ data
    - Big improvement at high mass range
    - Marginal improvements for low masses



Using code from
Buckley *et al*, 1610.08059

More Realistic Estimates

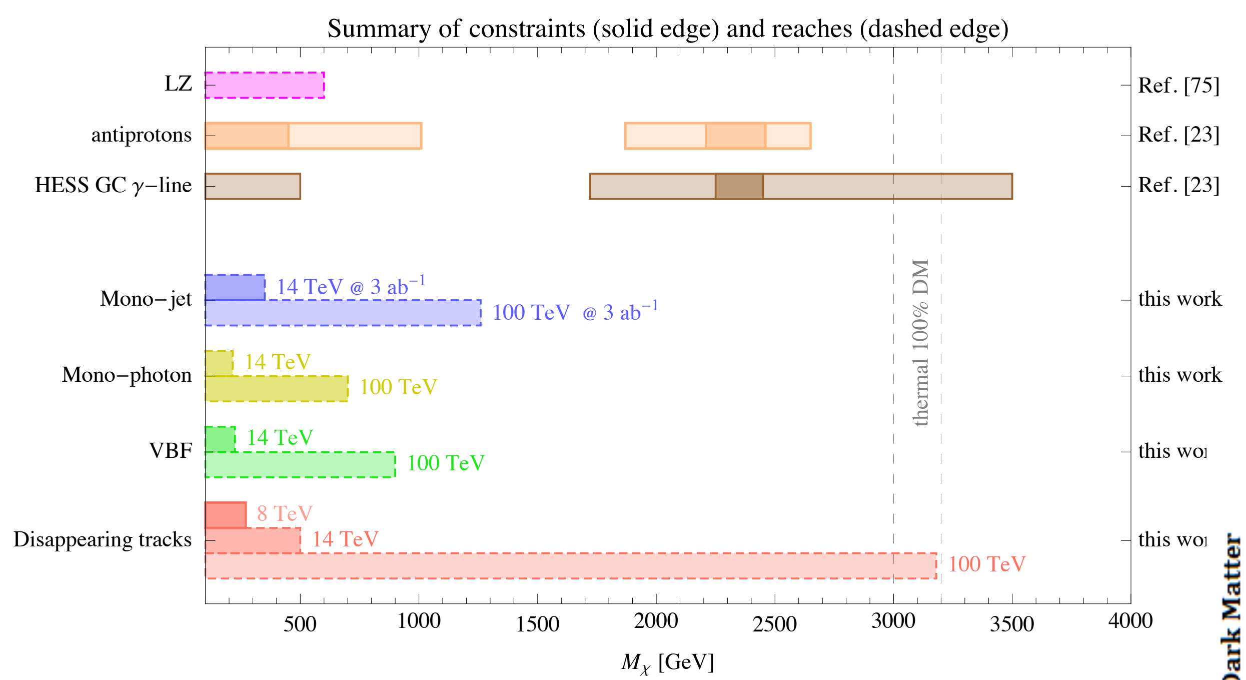
- Our back-of-the-envelope calculations aren't a terrible estimator as compared to the more detailed analysis.
- We could make significant advances in ruling out thermal relic dark matter, but not all of it.
    - (as far as I know the required plot doesn't exist)



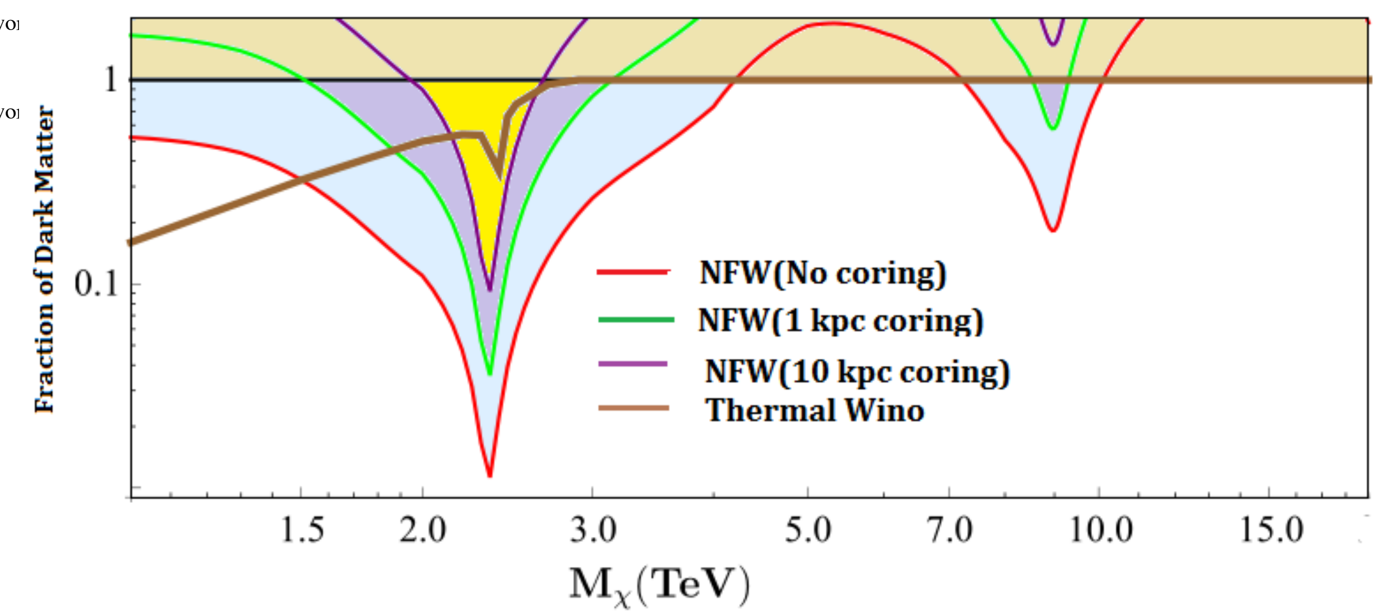
Malik *et al*, 1409.4075

Wino Dark Matter

- Wino dark matter will very difficult to fully exclude
- Indirect Detection perhaps necessary?



Cirelli, Sala, Taosa 1407.7058



Baumgart, Rothstein, Vaidya 1412.8698

Tracking Down Systematics

- What am I most worried about?
  - Systematics.
  - Not the systematics from increased pile-up
- Many dark matter search regions are *already* systematics dominated.

$\sqrt{67100} = 259$ $\sqrt{27640} = 166$

Exclusive Signal Region	EM2	EM4	EM6	EM8	EM9
Observed events (36.1 fb^{-1})	67475	27843	2975	512	223
SM prediction	67100 ± 1400	27640 ± 610	2825 ± 78	463 ± 19	213 ± 9
$W(\rightarrow e\nu)$	5510 ± 140	1789 ± 59	147 ± 9	18 ± 1	8 ± 1
$W(\rightarrow \mu\nu)$	6120 ± 200	2021 ± 82	173 ± 9	21 ± 5	11 ± 1
$W(\rightarrow \tau\nu)$	13680 ± 310	4900 ± 110	397 ± 11	55 ± 5	29 ± 2
$Z/\gamma^*(\rightarrow e^+e^-)$	0.03 ± 0	0.02 ± 0.02	–	–	–
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	167 ± 8	36 ± 2	2.0 ± 0.2	0.4 ± 0.1	0.5 ± 0.1
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	185 ± 6	68 ± 4	5.1 ± 0.3	0.3 ± 0.1	0.31 ± 0.04
$Z(\rightarrow \nu\bar{\nu})$	37600 ± 970	17070 ± 460	1933 ± 57	337 ± 12	153 ± 7
$t\bar{t}$, single top	2230 ± 200	848 ± 86	43 ± 6	4 ± 1	1.3 ± 0.4
Diboson	1327 ± 90	874 ± 64	124 ± 16	26 ± 5	10 ± 2
Multijet background	170 ± 160	13 ± 13	1 ± 1	1 ± 1	0.1 ± 0.1
Non-collision background	71 ± 71	18 ± 18	–	–	–

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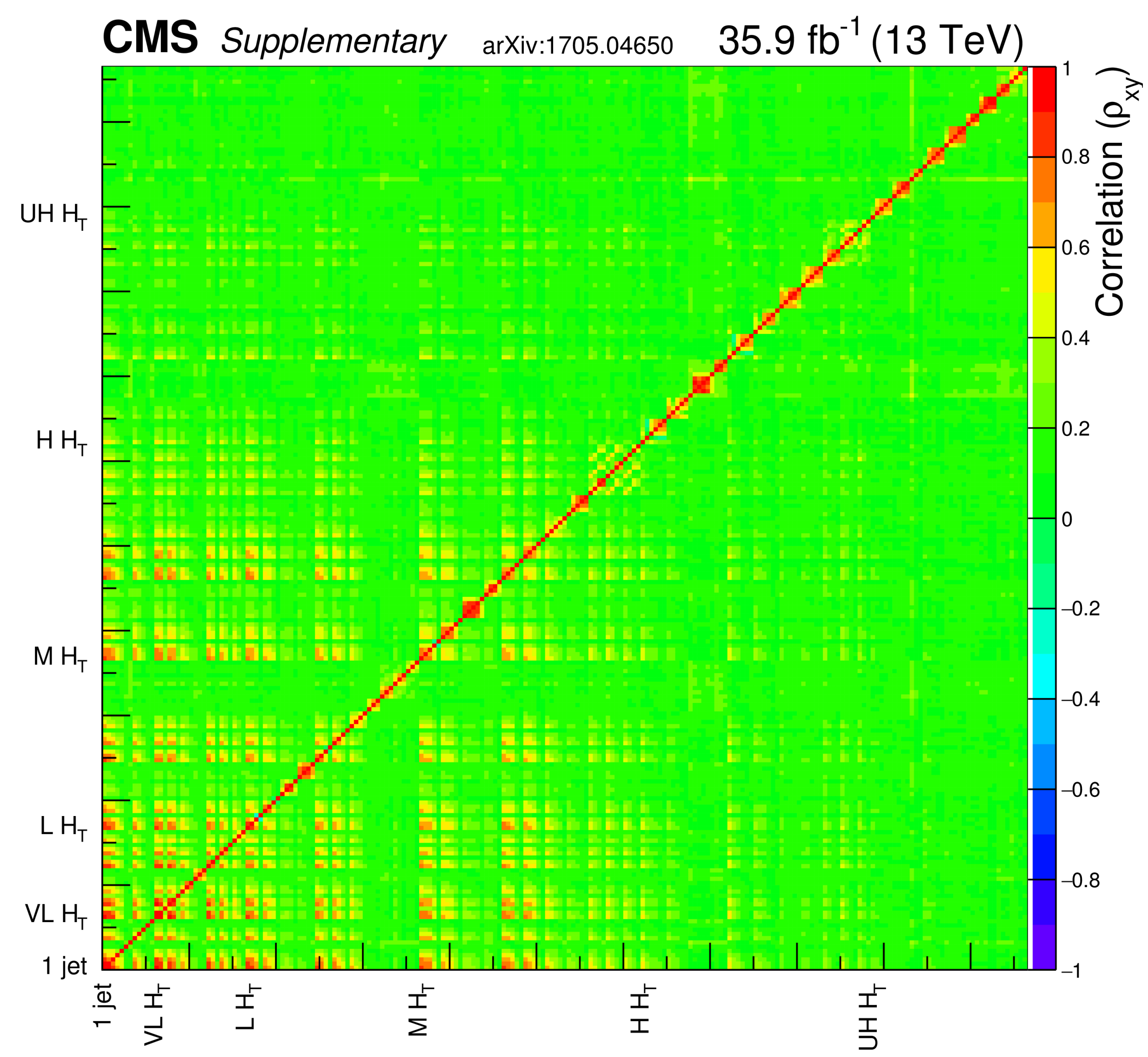
Tracking Down Systematics

- Systematics are correlated across signal regions.

- Depending where your sought-after signal lives, the “post-fit” error can be greatly reduced.

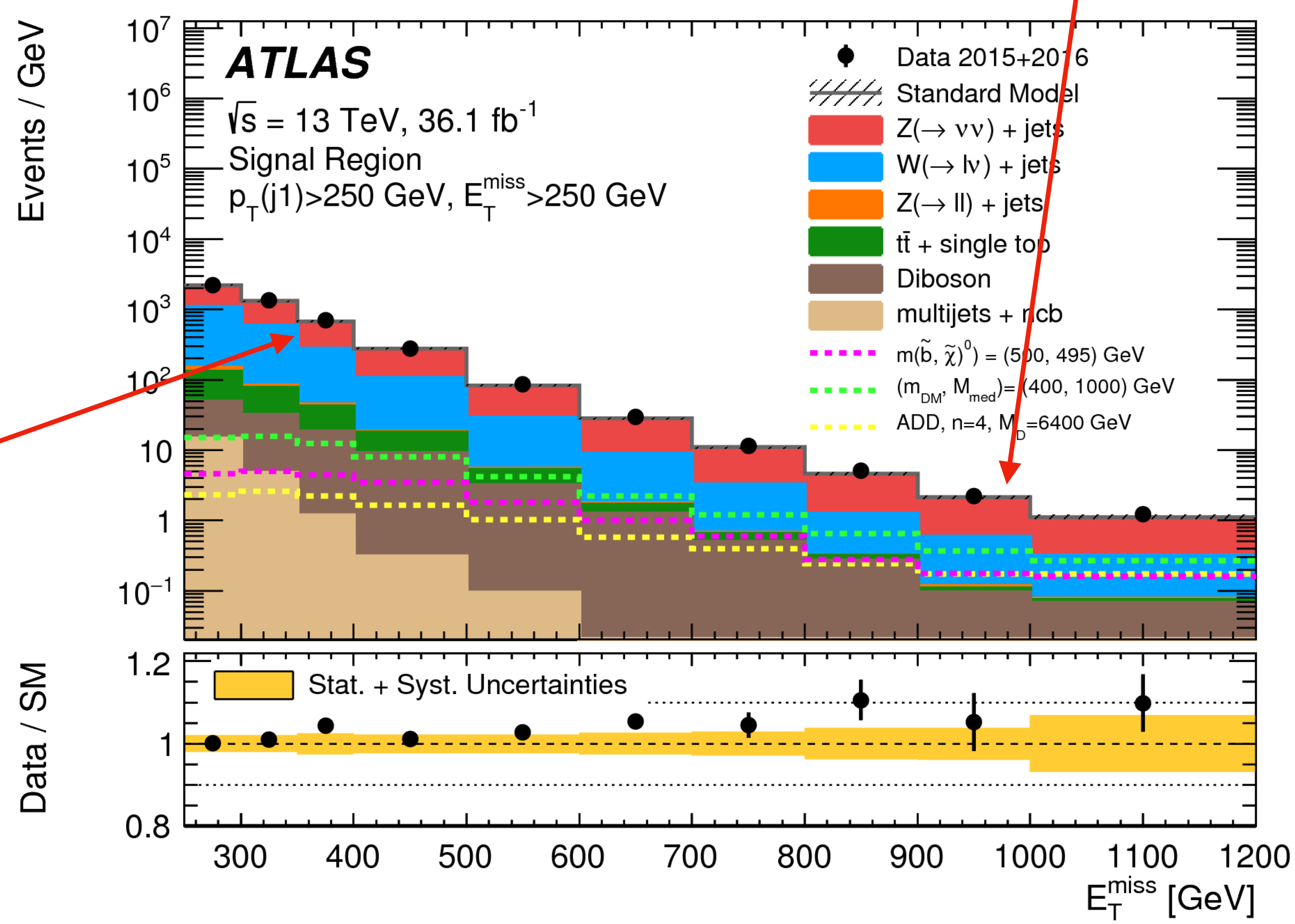


The Effects of Systematics

- Where does this matter?

Not in limits that are set by these events

Limits that are set by these



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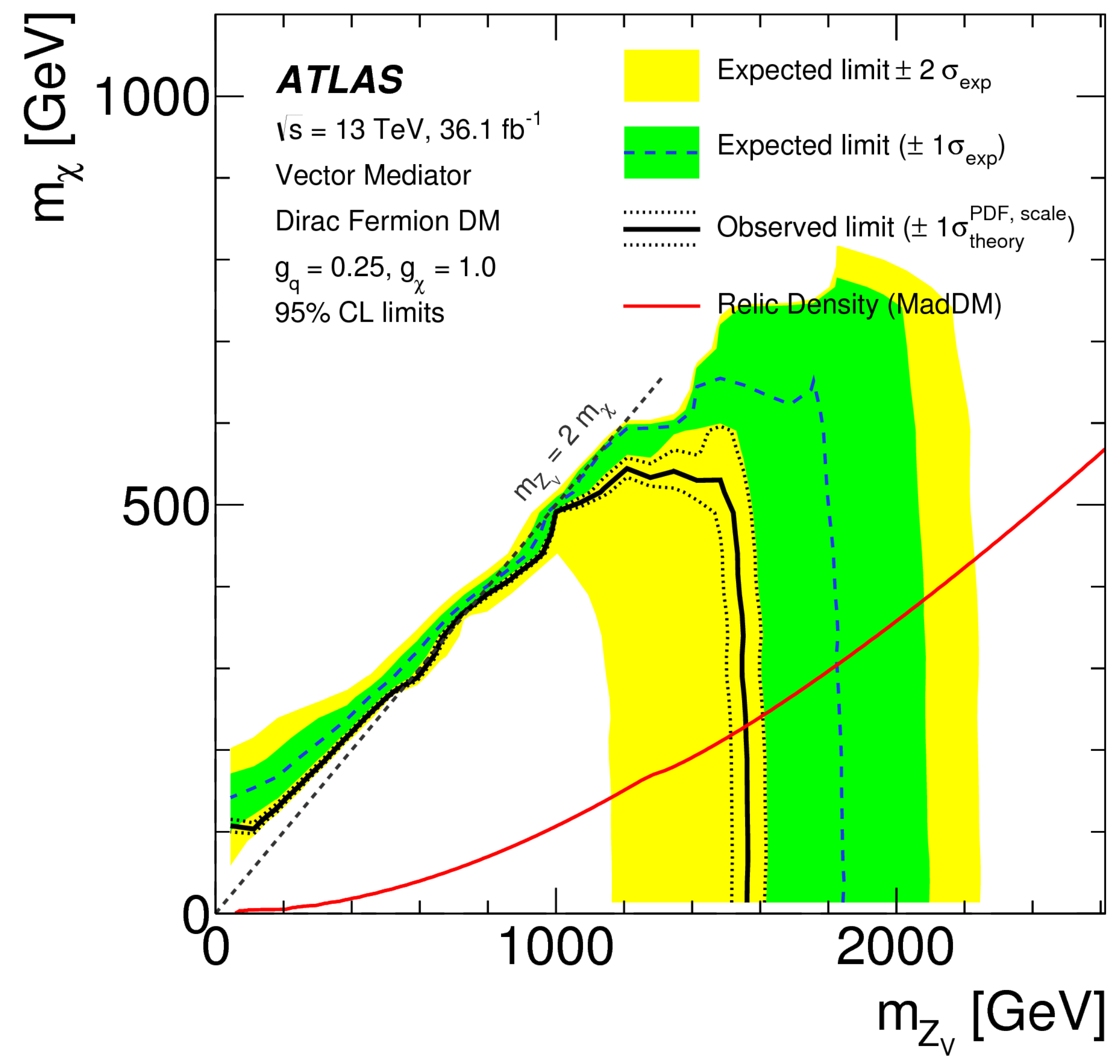
The Effects of Systematics

- Limits set at the "edge" of available parameter space are mostly statistics-dominated.
- Set by the highest MET bins
- We know how to deal with deviations here: more statistics.



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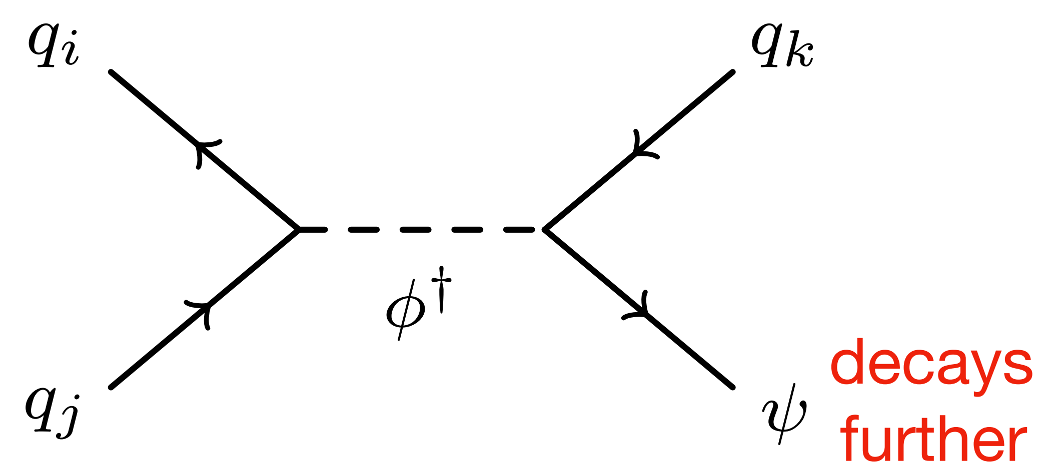
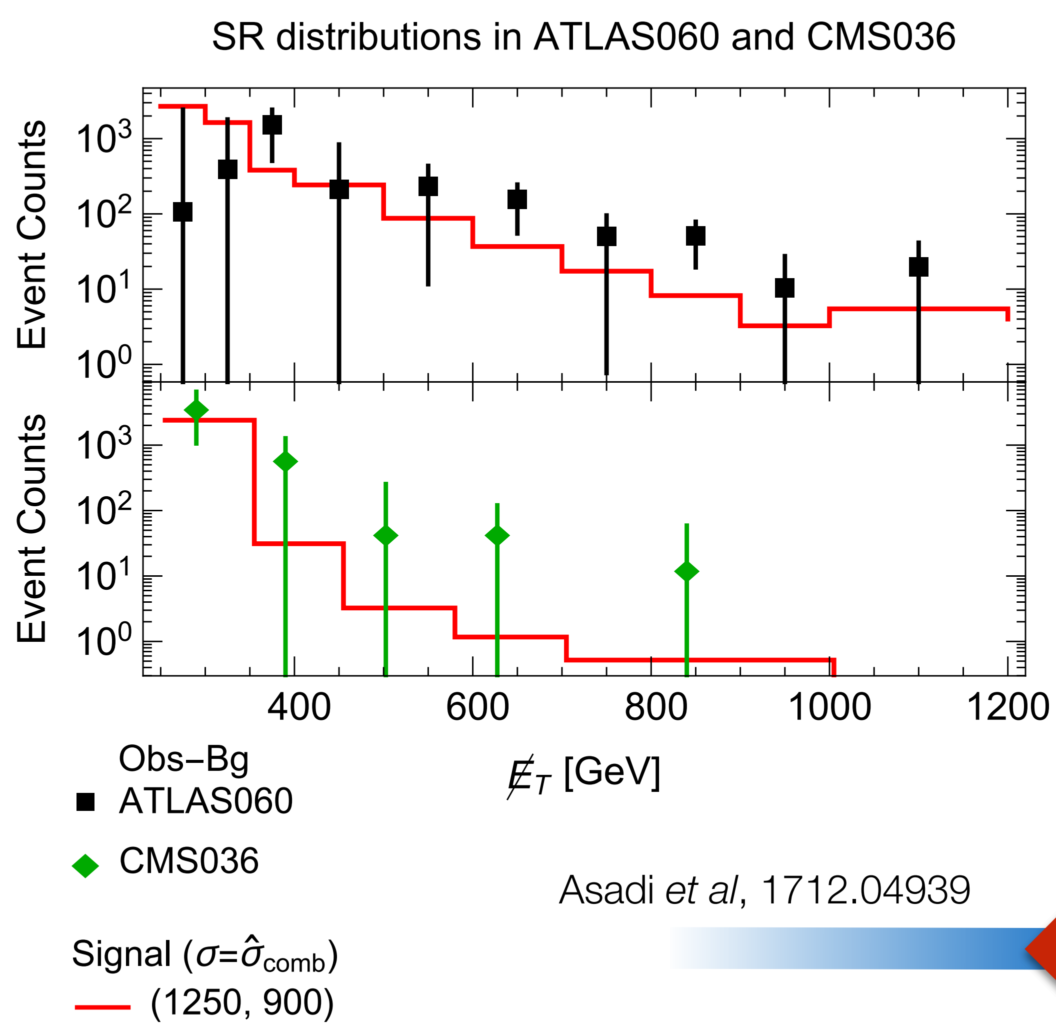
Planning for Anomalies

- What about unusual results in systematics dominated regions?
  - Not what you'd find in analyses that are pushing the edge of the limit curve.

- Here's an example.
  - Doesn't fit into a pre-existing simplified model
- Won't be (dis)proven by more data — requires new kinematic cuts or reducing systematics.





Asadi *et al*, 1712.04939

What's the Lesson?

- Pushing the edge of the limit plots is a laudable goal.
- But it shouldn't be the *only* goal.
  - Natural Supersymmetry, simplified models, *etc.* provide benchmarks against which to compare data.
  - But they may not be the right answer for dark matter.

- As we pursue high-luminosity/energy, need to keep our eyes open for what's in the data.
  - Need plan for anomalies: how do we respond and reduce the uncertainties when we're systematics dominated?

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