

Semi-visible Topologies at the LHC

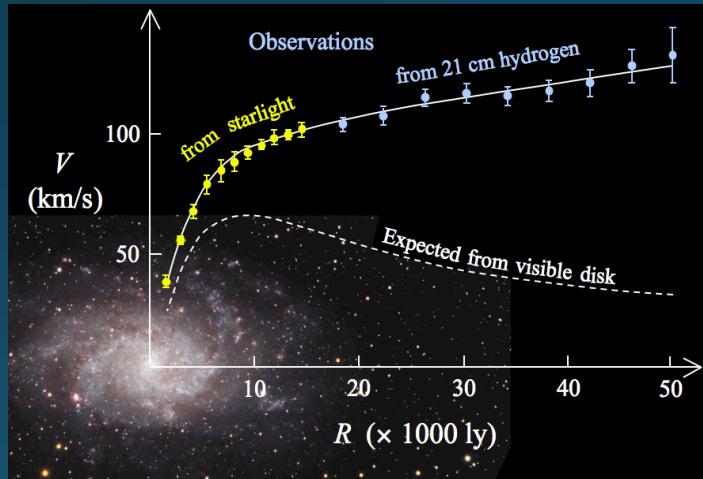
Hou Keong (Tim) Lou

Collaborators: Timothy Cohen, Mariangela Lisanti, Siddharth Mishra Sharma

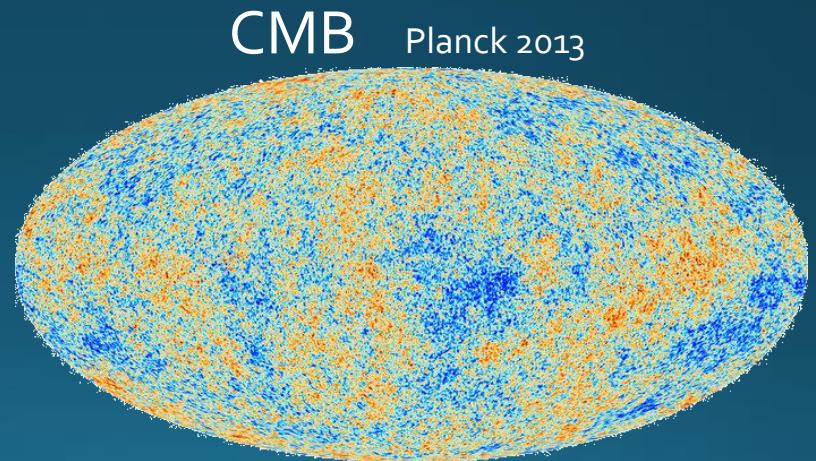
Dark Matter

- Overwhelming evidence for existence of Dark Matter
- One of LHC's primary experimental objectives
- Needs comprehensive search strategies

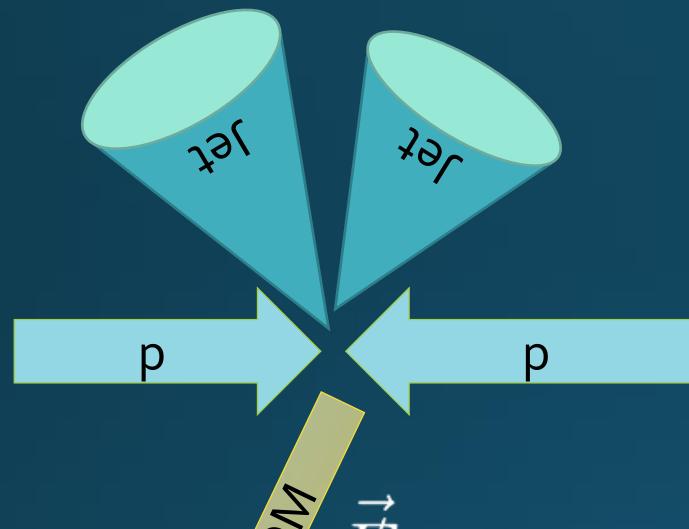
Galaxy rotation curves



E. Corbelli, P. Salucci , astro-ph/9909252

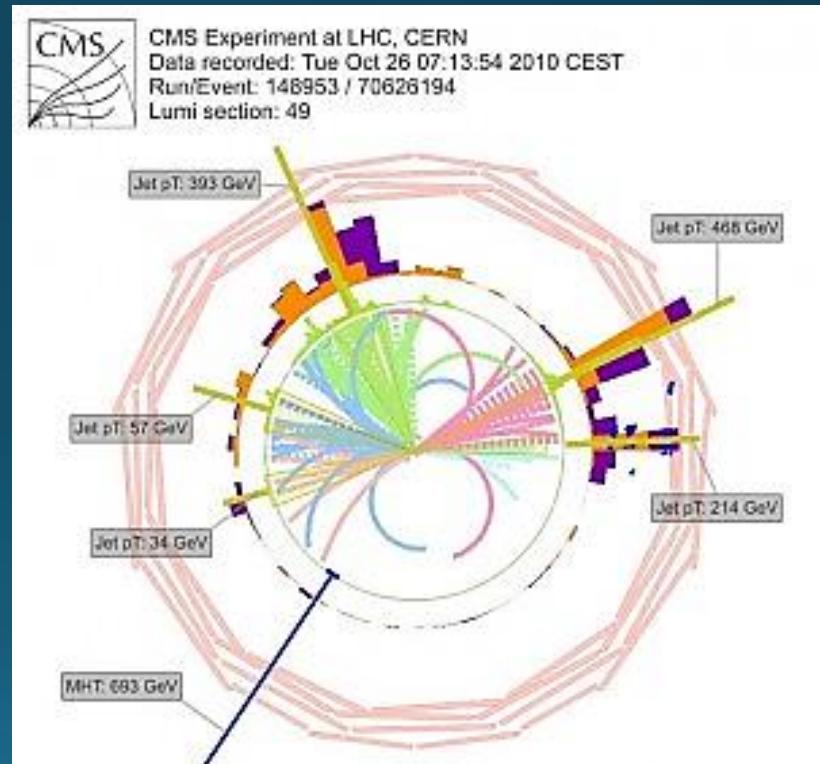


WIMP at the LHC



- Large \vec{E}_T
- Large jet- \vec{E}_T separation

CMS Jet + \vec{E}_T event



Beyond WIMP

- What if DM has hidden (strong) interactions?
- Example:
 - Asymmetric DM S.Nussinov Phys. Lett. B 165 (1985)
 - Hidden-Valley M. Strassler, K. Zurek , arXiv/o6o4261
 - SIMPs Y. Hochberg, E. Kuflik, H Murayama, T. Volansky, J. G. Wacker
arXiv:1402.5143, arXiv:/o6o4261
- DM production may NOT be isolated

Toy Model

- QCD-like dark hidden (dark) sector

$$\mathcal{L}_H = -\frac{1}{2}\text{tr}(G_D^{\mu\nu})^2 - \frac{1}{4}(Z'_{\mu\nu})^2 + \bar{\chi}_i(iD - m_{ij})\chi_j + gZ'_\mu J_B^\mu$$

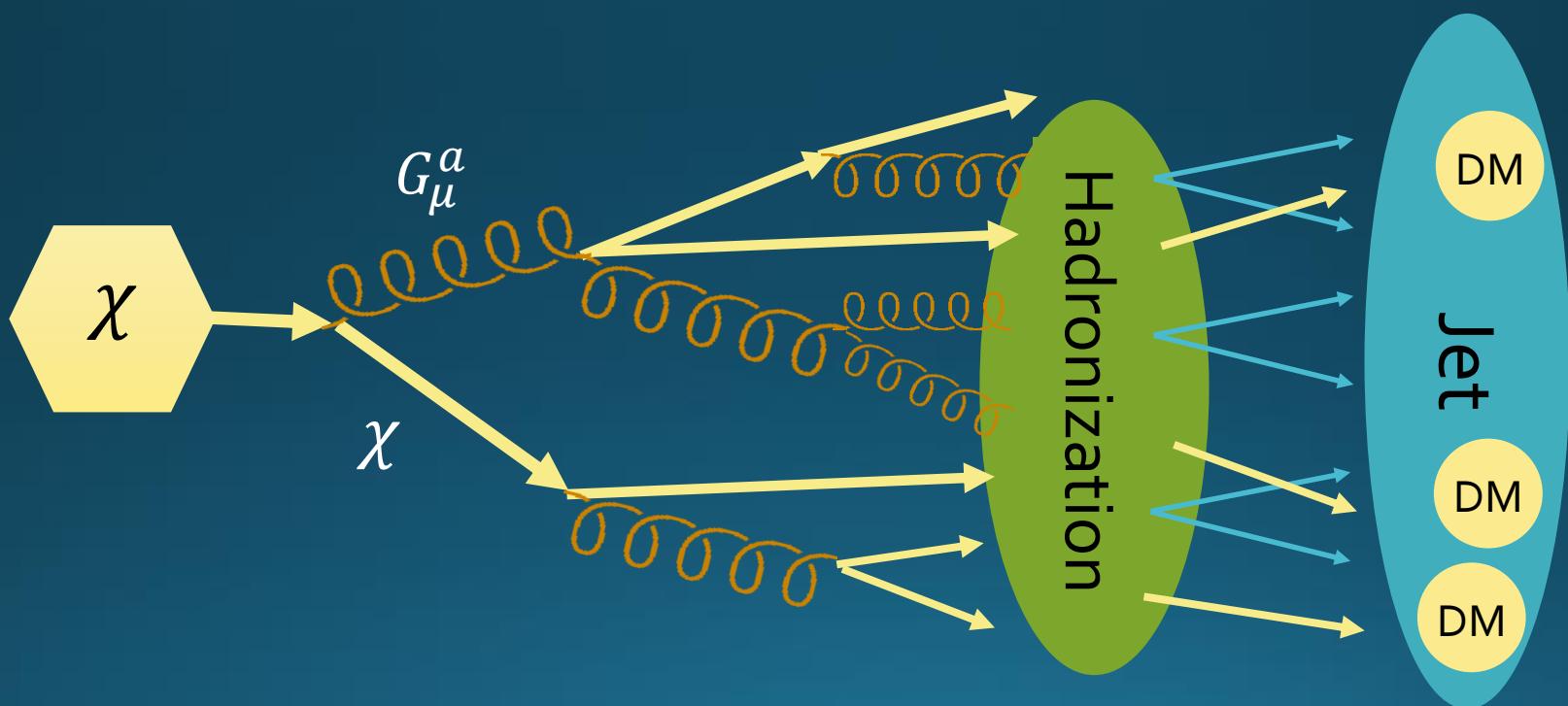
- Dark hadrons:

$$\pi_D, \rho_D, b_D \dots$$

- Some are stable (DM), others will decay back to SM
- Many possible gauge groups and strong interactions

Semi-visible Jet

- When χ s are produced, they shower in the dark sector



Generalization

- Can involve leptons
- Can lead to heavy flavor content (c/b-jets)
- Can lead to displaced decays
- Can have exotic showering patterns
- Particle multiplicity can vary from small to very large

Simplified Scenario

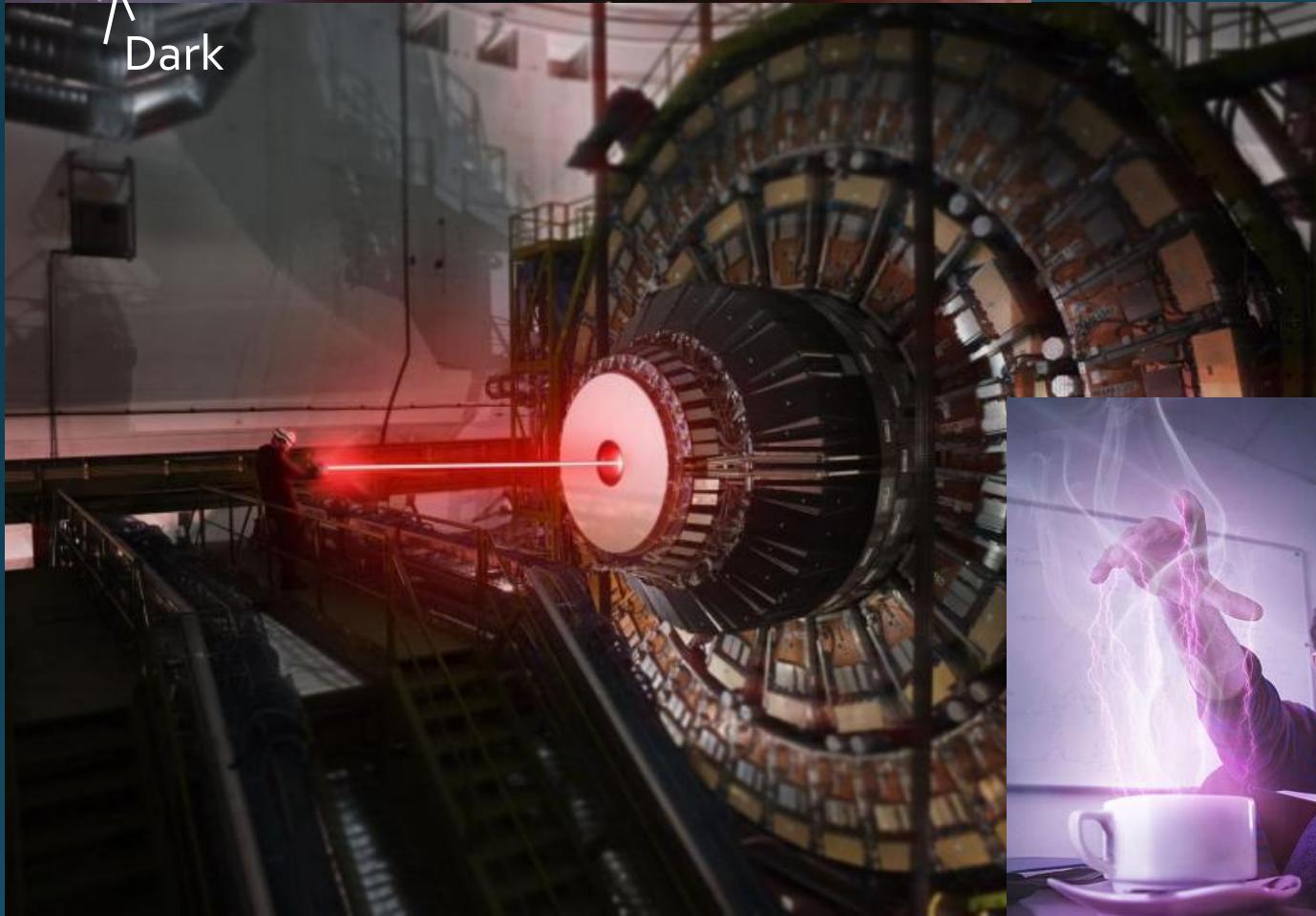
- QCD like dark sector $\Lambda_D \simeq 10 \text{ GeV}$
- $r_{\text{inv}} = \left\langle \frac{\# \text{ of stable hadrons}}{\text{total } \# \text{ of hadrons}} \right\rangle$
- r_{inv} parameterizes the average missing momentum in a semi-visible jet
- Example:
 - Asymmetric DM: only the baryon is stable, $r_{\text{inv}} = \text{average baryon content}$, $r_{\text{inv}} \simeq 0.1$
 - SIMP-like, $r_{\text{inv}} = \text{average fraction of stable } \pi_D$, $r_{\text{inv}} \approx 1.0$

How to Look for Dark Sector?

CERN researchers confirm existence of the Force

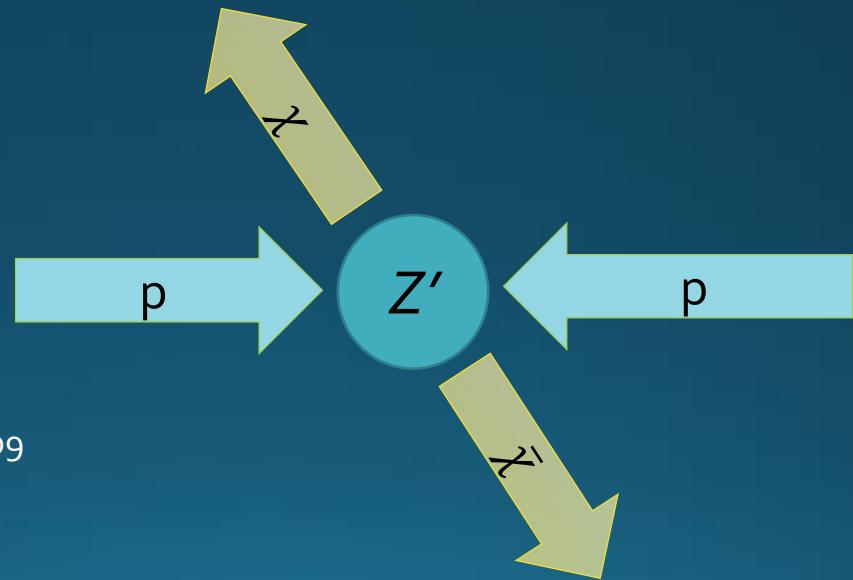
1 Apr 2015

Dark



On-shell Z'

- Decays into $\chi, \bar{\chi}$, and showers in the Hidden sector
- \vec{E}_T somewhat cancels out
- Parameterization:
 - $M_{Z'}$,
 - $\sigma \times \text{Br}(Z' \rightarrow \chi\bar{\chi})$
 - r_{inv}

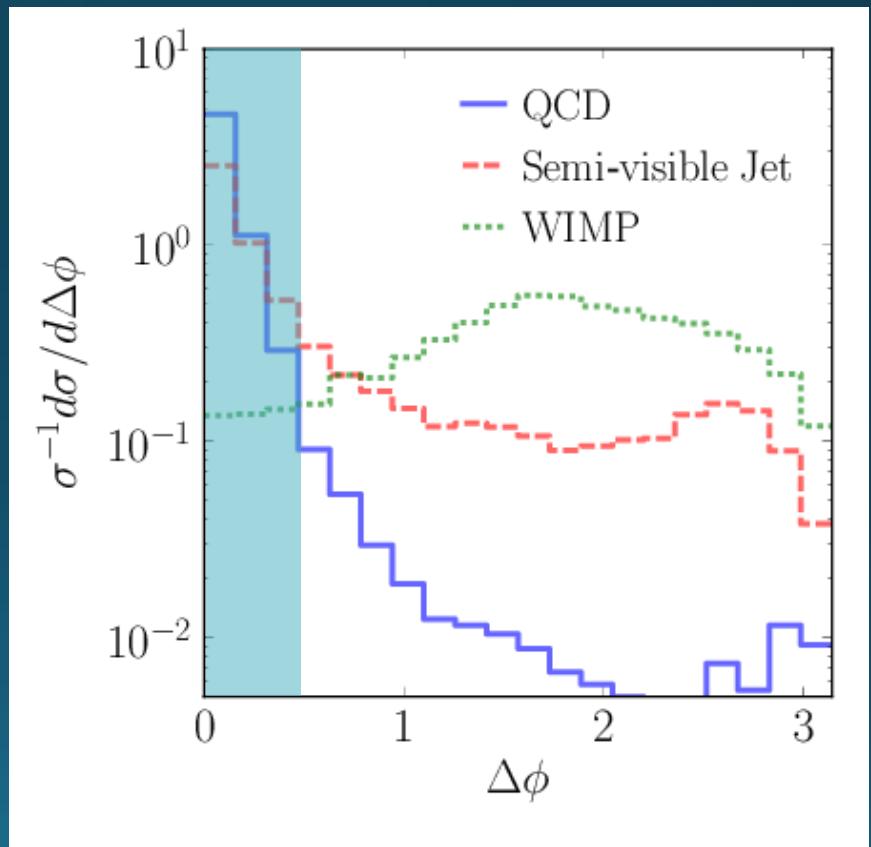
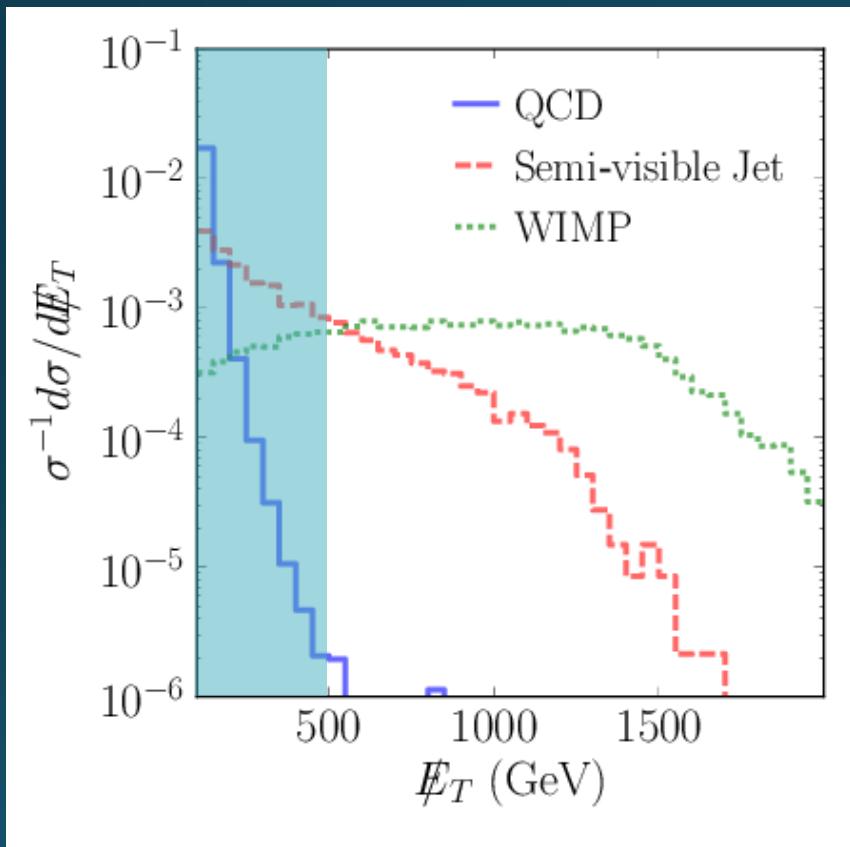


T. Cohen, M. Lisanti, HL, arXiv/1503.00009

Z' Benchmark

$M_{Z'} = 3 \text{ TeV}$

$r_{\text{inv}} = 0.3$



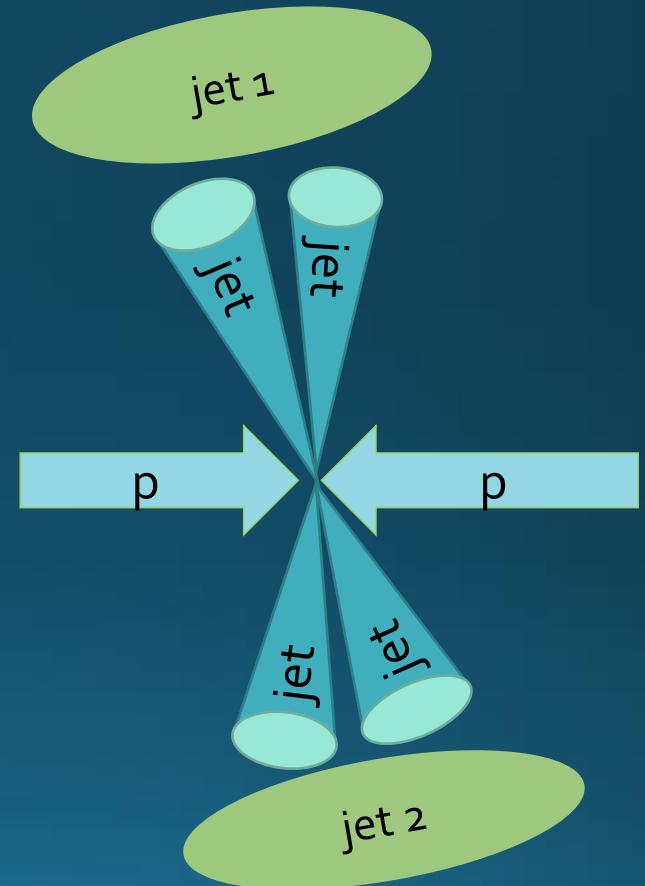
Strategy

- Resonance hunt (only works for moderate r_{inv})
- Re-cluster narrow jets into j_1, j_2
 - CA jets $R = 1.1$

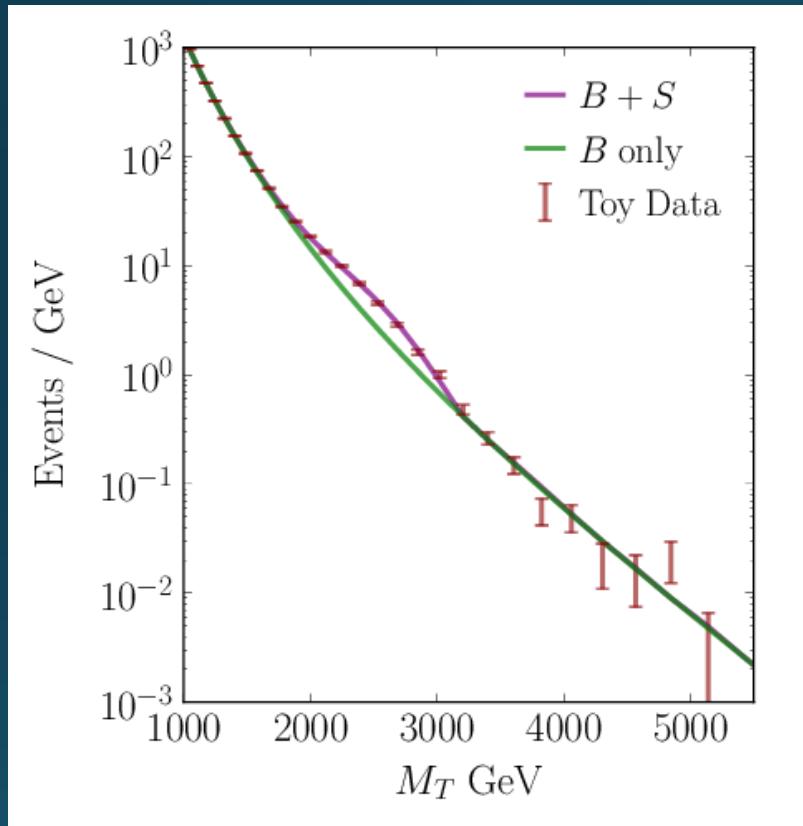
- Edge hunt

$$M_{jj}^2 = (p_{j_1}^\mu + p_{j_2}^\mu)^2$$

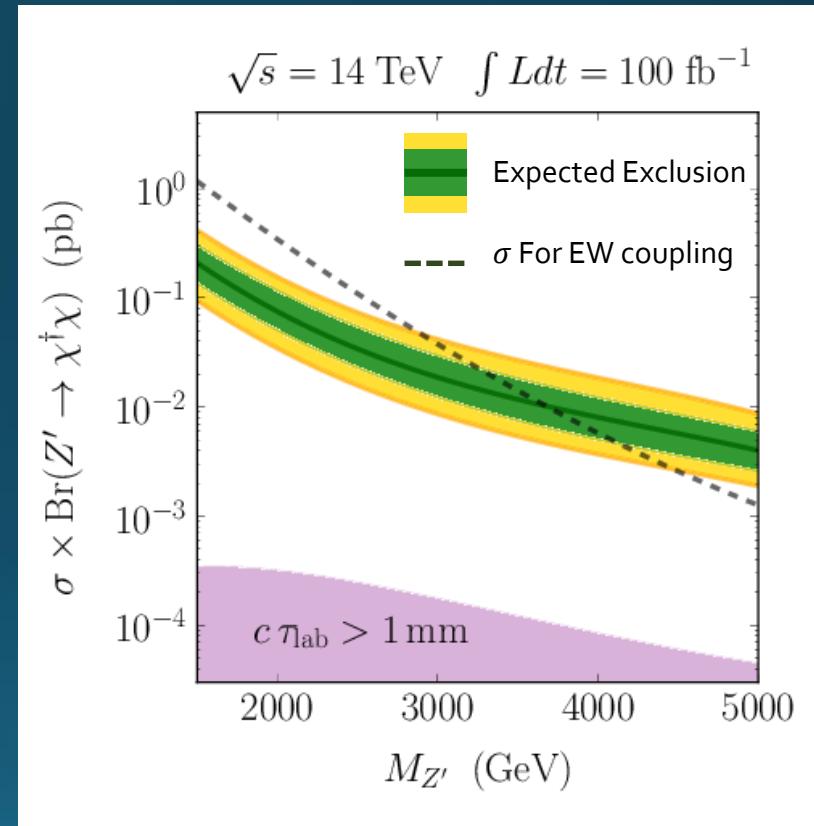
$$M_T^2 = M_j j^2 + 2(E_{jj}^T p_{jj}^T - \vec{p}_{jj}^T \cdot \vec{E}_T)$$



Projection



Cuts: Lepton veto, $\Delta\phi < 1.0$ and $\vec{E}_T > 0.15 M_T$

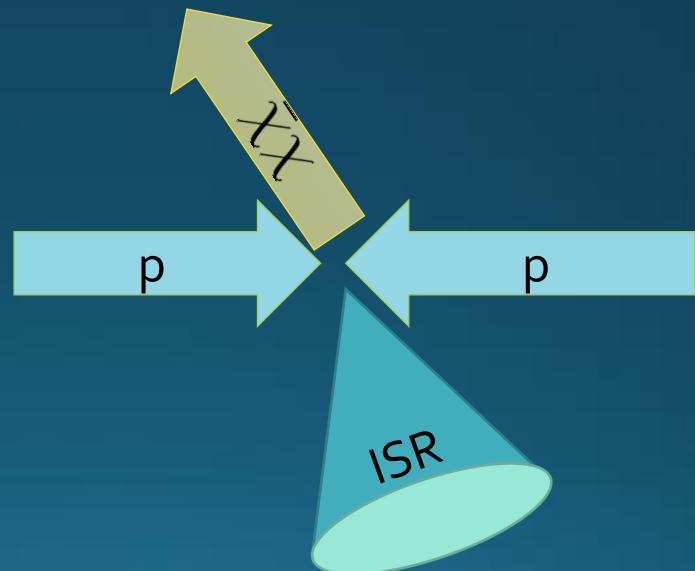


See details in arXiv/1503.00009

Off-shell Z'

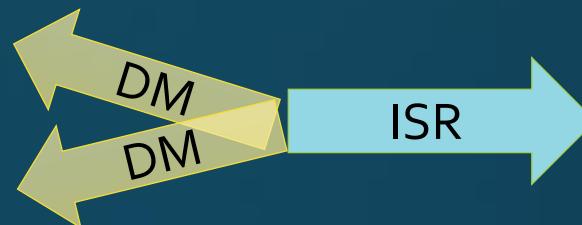
- Resonance cannot be reconstructed
- Effective operator $(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma^\mu q)/\Lambda_{\text{eff}}^2$

- Produced with ISR
- Shower into hidden sector
- Different regimes depending on r_{inv}

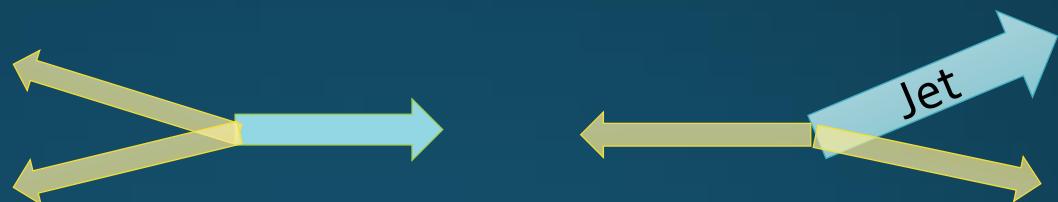


Signal Topology

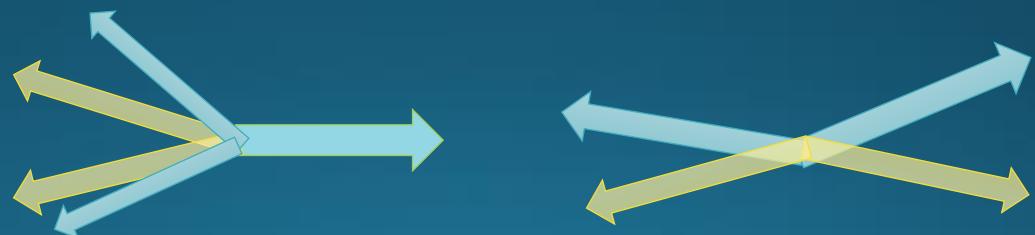
- $r_{\text{inv}} = 1.0$



- $r_{\text{inv}} \lesssim 1.0$

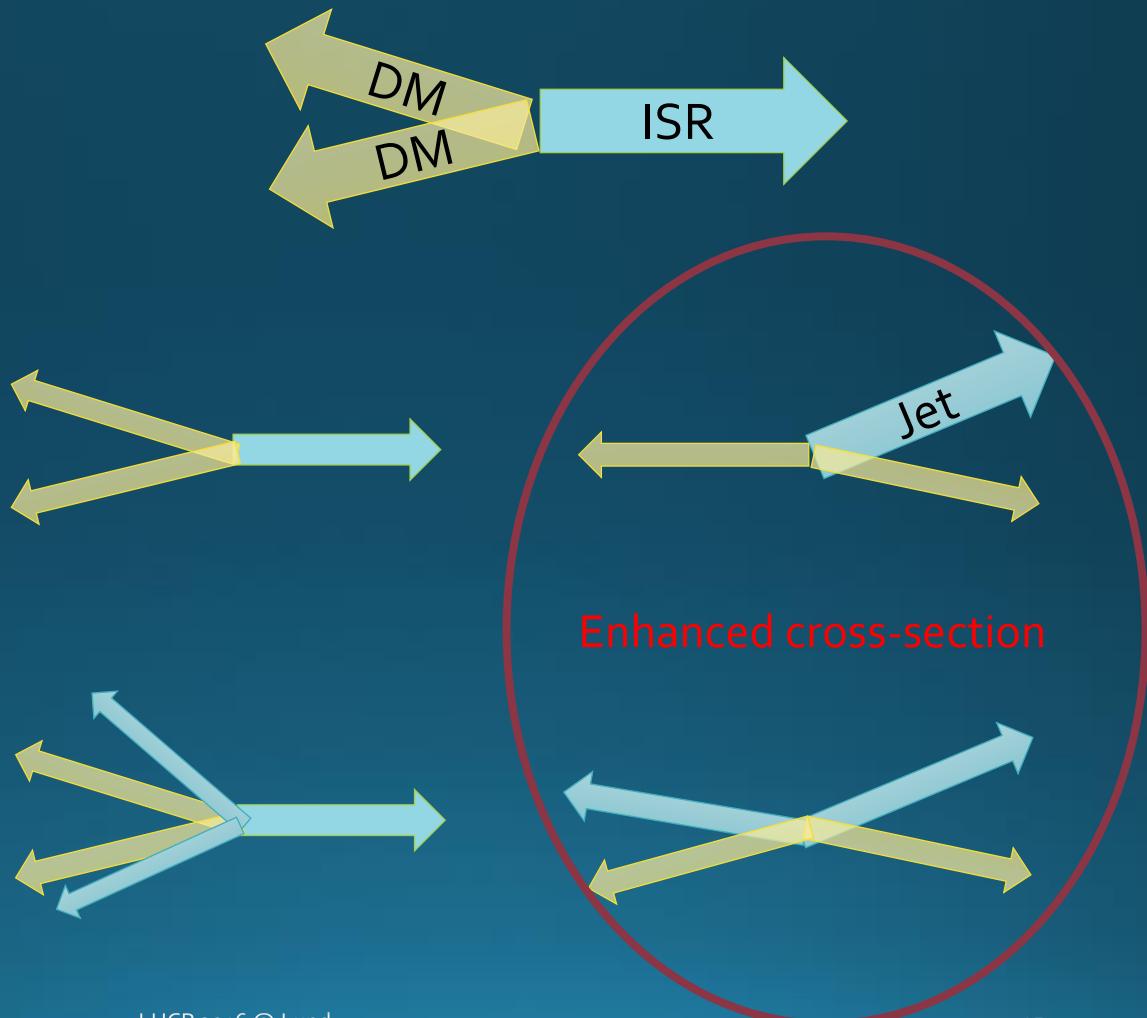


- $r_{\text{inv}} \sim 0.5$



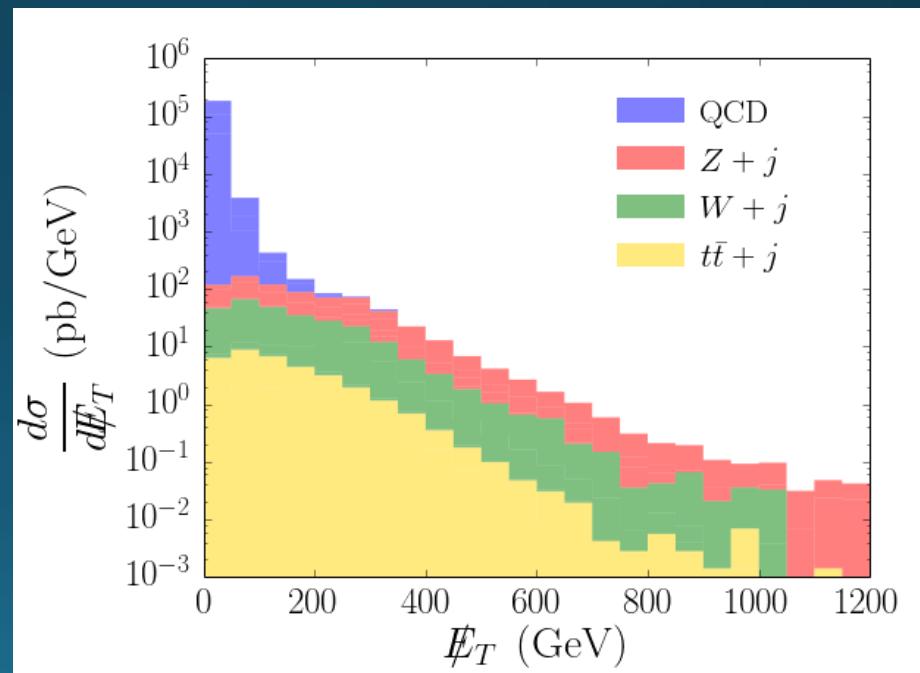
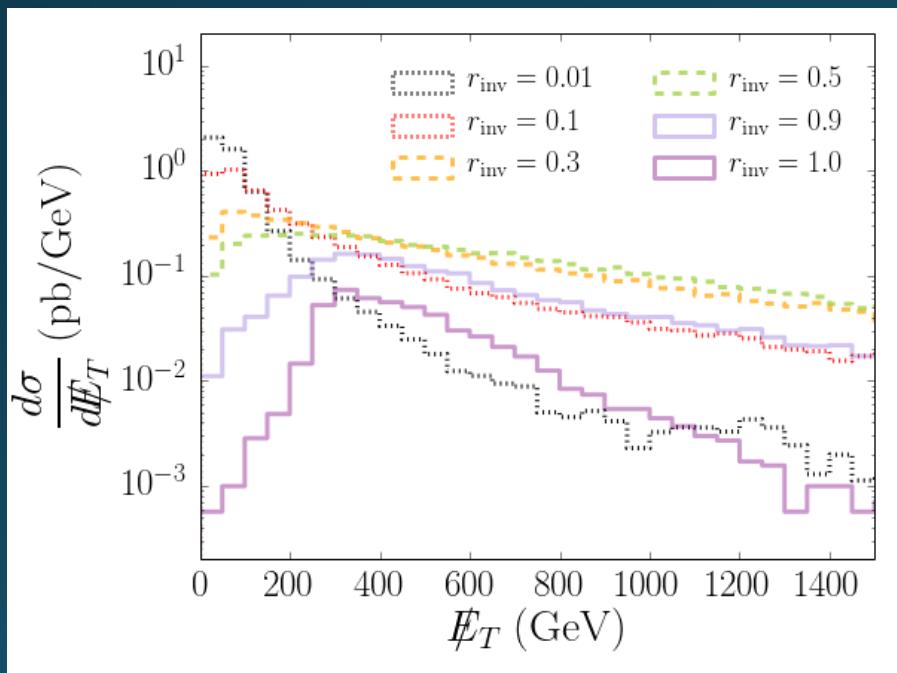
Signal Topology

- $r_{\text{inv}} = 1.0$
- $r_{\text{inv}} \lesssim 1.0$
- $r_{\text{inv}} \sim 0.5$



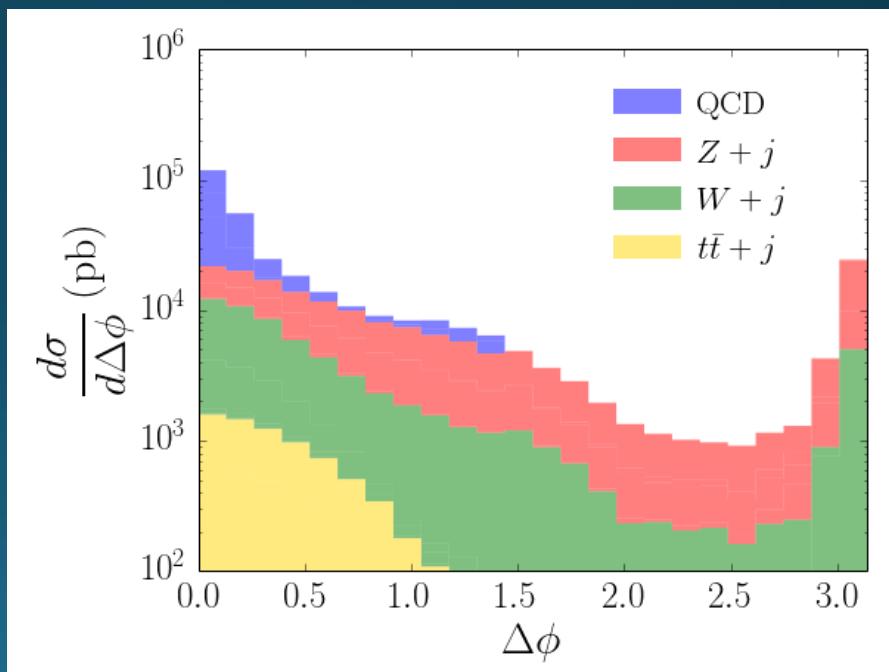
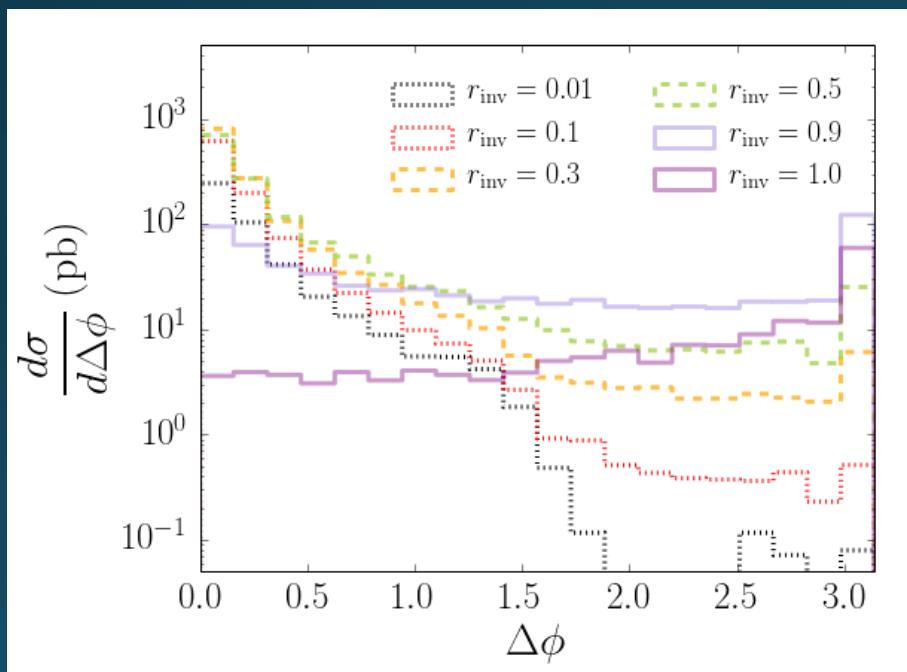
Benchmark

- $\Lambda_{\text{eff}} = 5 \text{ TeV}$
- \cancel{E}_T maximized for $r_{\text{inv}} \simeq 0.5$
- Cut: Lepton veto $p_{T,j_1} > 250 \text{ GeV}$



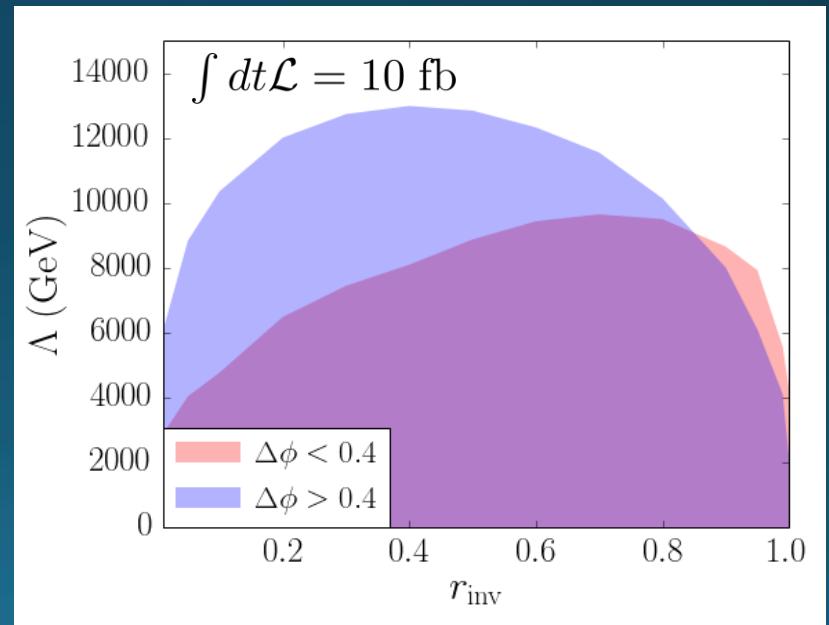
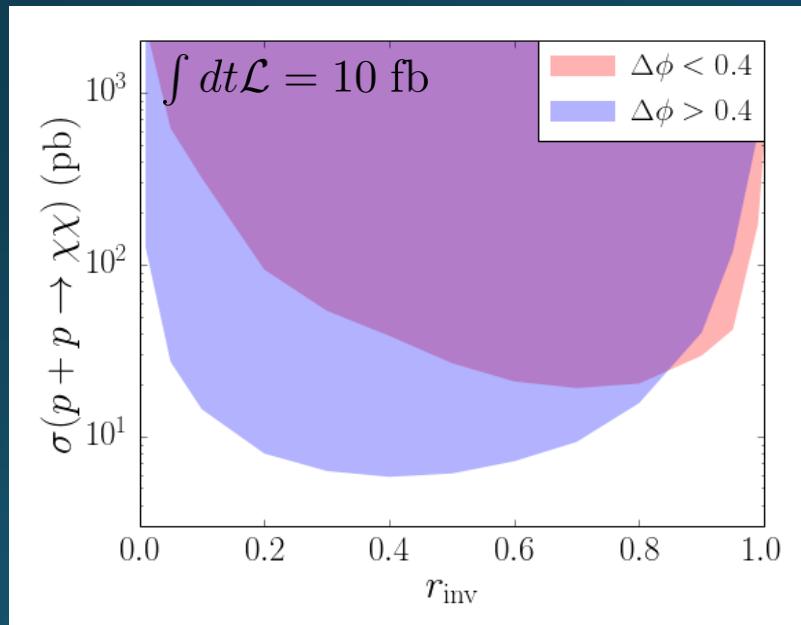
Benchmark

- $\Lambda_{\text{eff}} = 5 \text{ TeV}$
- E_T maximized for $r_{\text{inv}} \simeq 0.5$
- Cut: $p_{T,j_1} > 250 \text{ GeV}$
- $E_T > 100 \text{ GeV}$



Projection

- Initial cut $\cancel{E}_T > 800 \text{ GeV}$
- Optimize
 $1200 \text{ GeV} > \cancel{E}_{T,\text{cut}} > 800 \text{ GeV}$
- Assume QCD does not contribute



Conclusion

- Strongly coupled DM is phenomenologically relevant and can lead to novel signatures at the LHC
- Opportunities beyond traditional mono-jet and SUSY searches
- Simple adjustments to existing searches can lead to strong constraints

On-going/Future directions

- Light Z' can be produced with a boost, and the resonance can be reconstructed if r_{inv} is moderate
 - Boosted Higgs decaying into semi-visible jets
- π_D decay preferentially to heavy quarks, can lead to multiple b -mesons in a semi-visible jet
- Jet-substructure
 - Depends on the details of the showering