Searching for dark sector parton showers at the LHC

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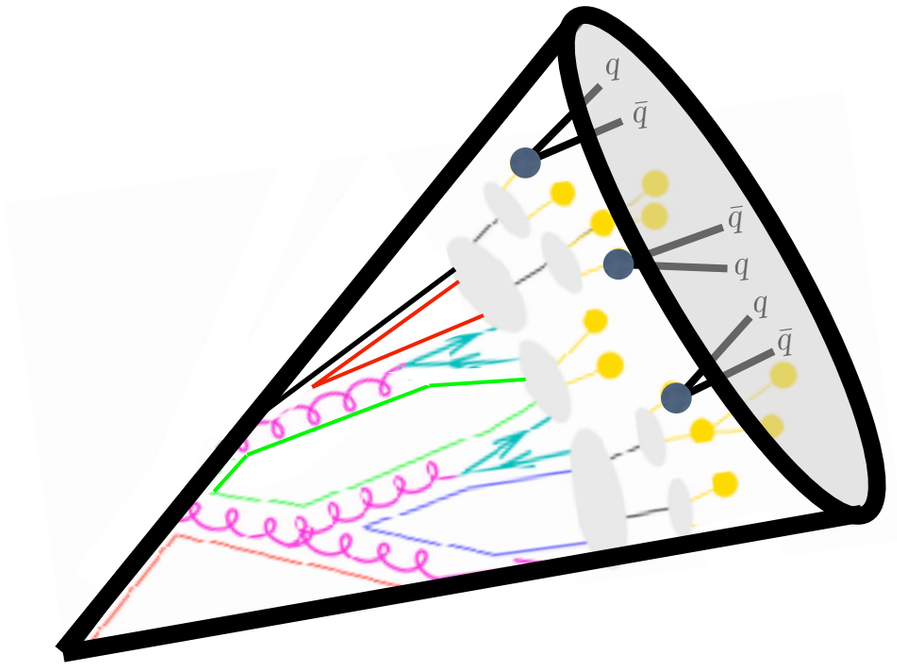
Based on work with:
T. Cohen, M. Lisanti and H.K. Lou
[1707.05326]



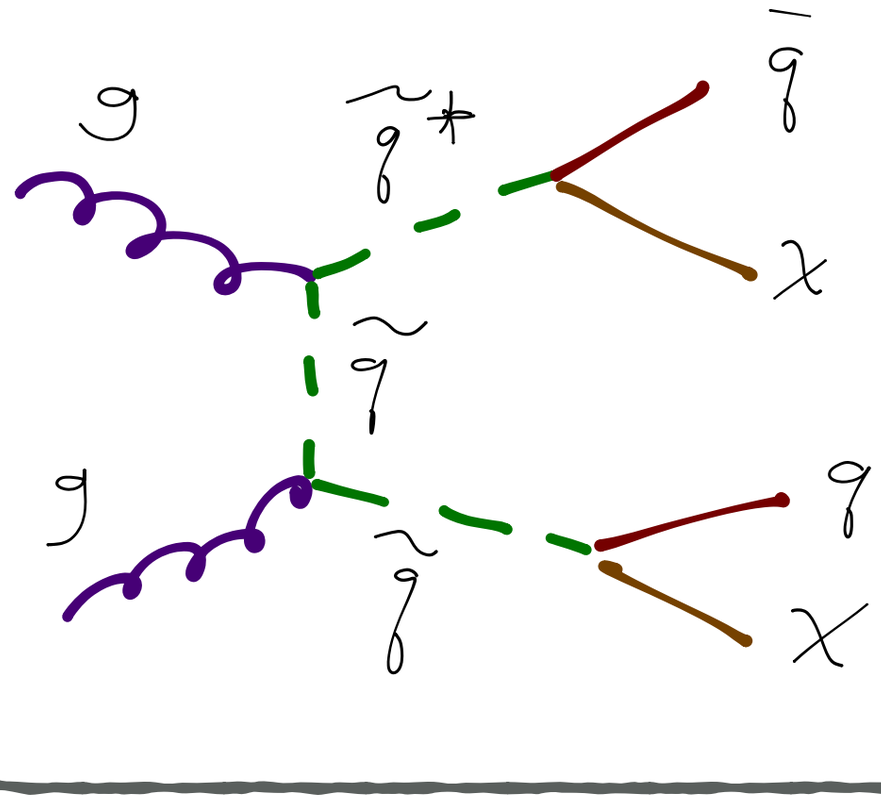
LHC LLP Workshop
October 20, 2017

PRINCETON UNIVERSITY

“WIMP” Signals

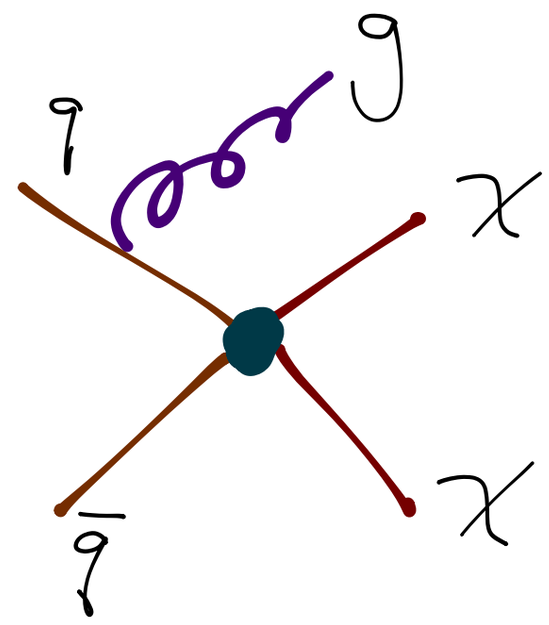
New physics in Jets + $\not{E}_T$

Simplified Model



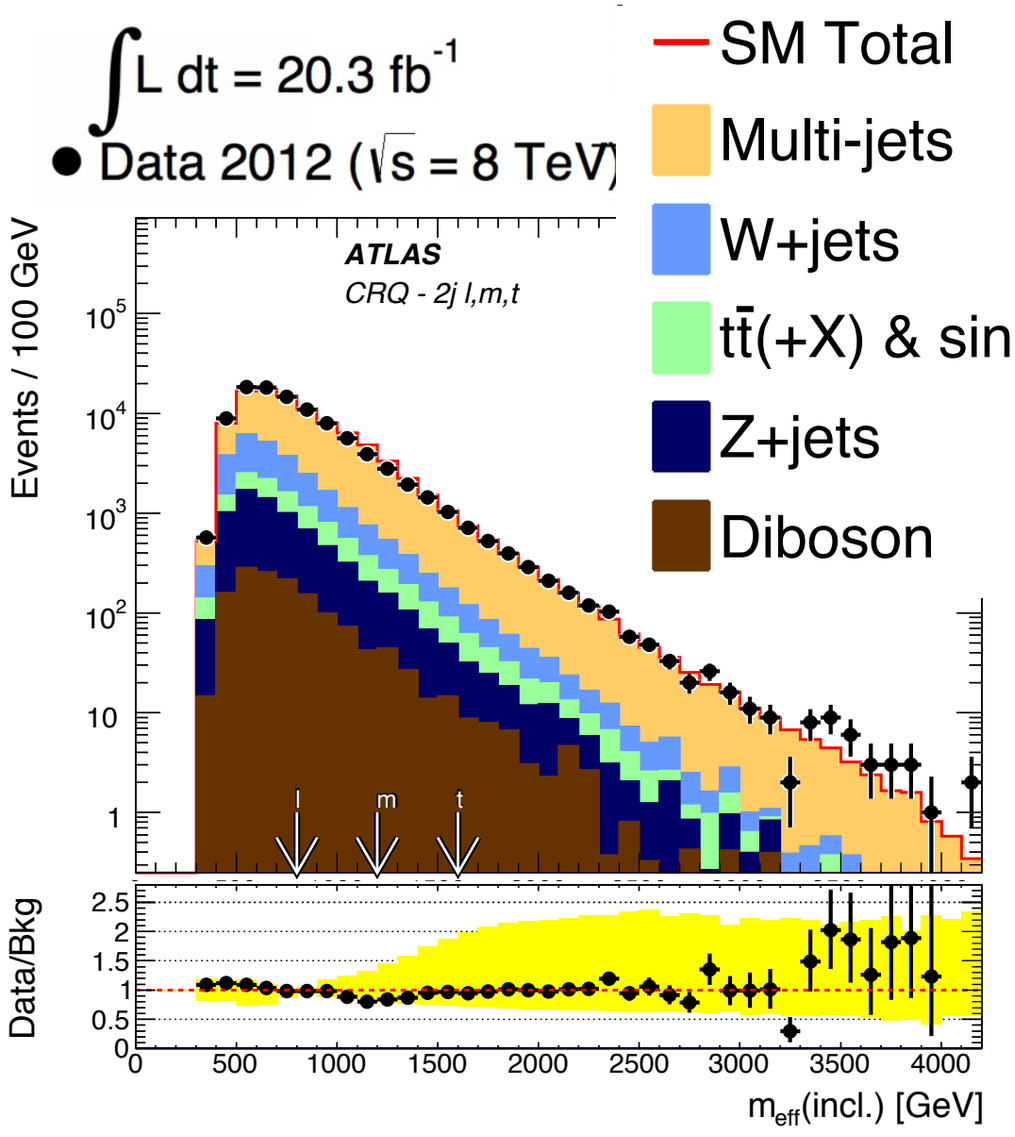
Alwall, Le, Lisanti, Wacker [arXiv:0809.3294]
Alwall, Schuster, Toro [arXiv:0810.3921]
LHC New Physics Working Group [arXiv:1105.2838]

Contact operator



Fox, Harnik, Kopp, Tsai [arXiv:1109.4398]
Rajaraman, Shepherd, Tait, Wijangco [arXiv:1108.1196]

Backgrounds in WIMP searches



ATLAS Collaboration [arXiv:1405.7875]

QCD background:

$\not{E}_T$ from jet mismeasurement.

Background $\not{E}_T$ aligned with jets.

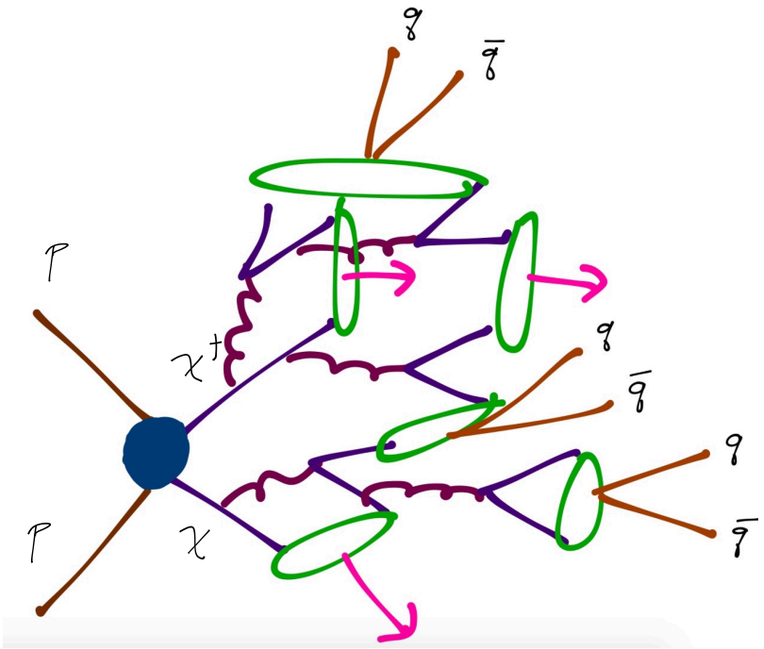
Cut on

$$\min\left[\Delta\phi(\text{jets}, \not{E}_T)\right] \gtrsim 0.4$$

Dark shower

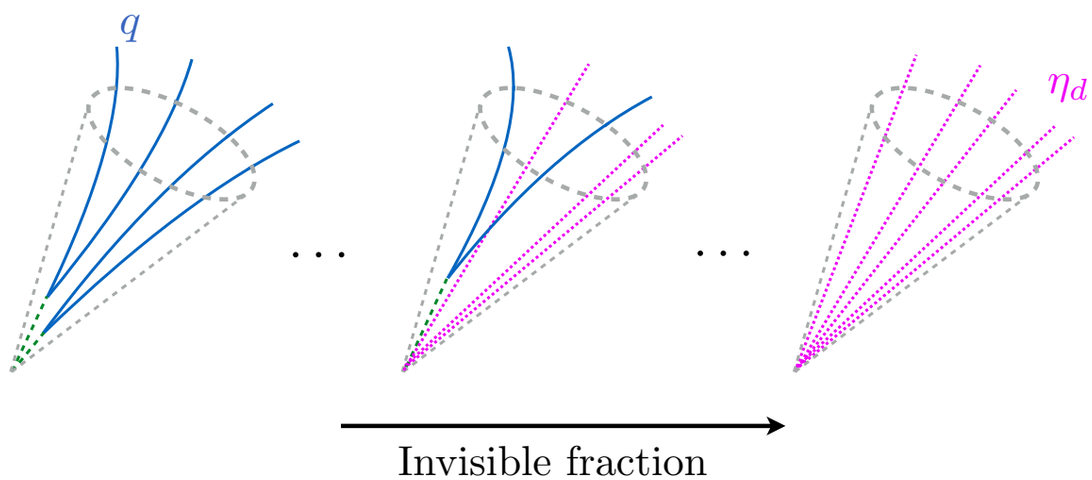
Signature made classic by “Hidden Valley” models.

Strassler, Zurek [arXiv:hep-ph/0604261]

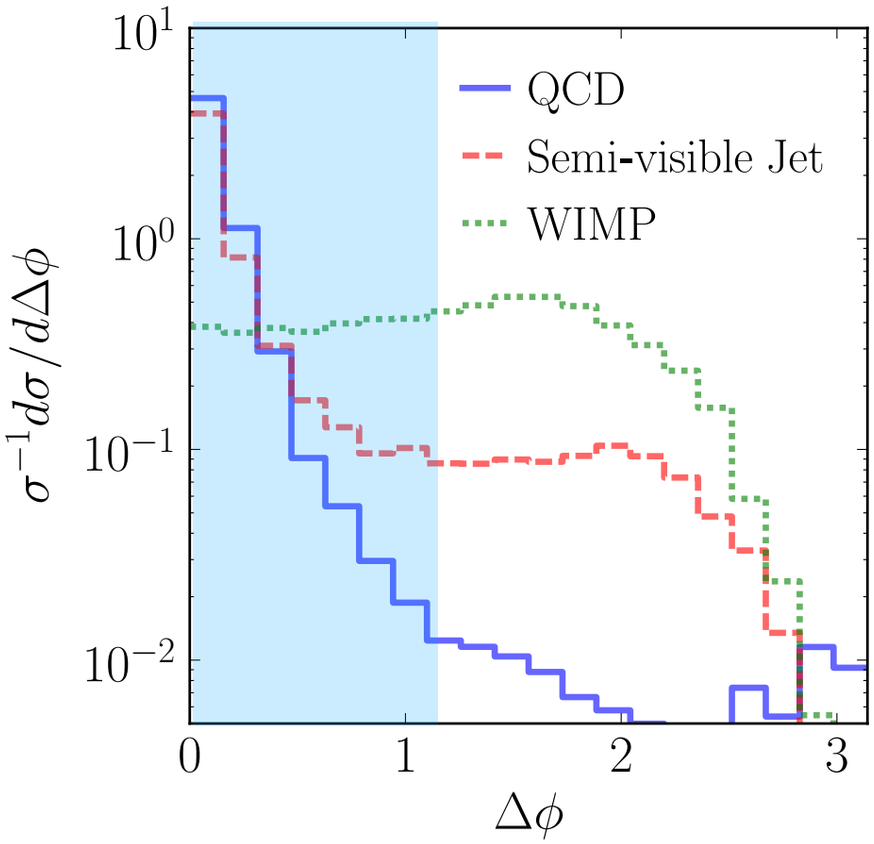


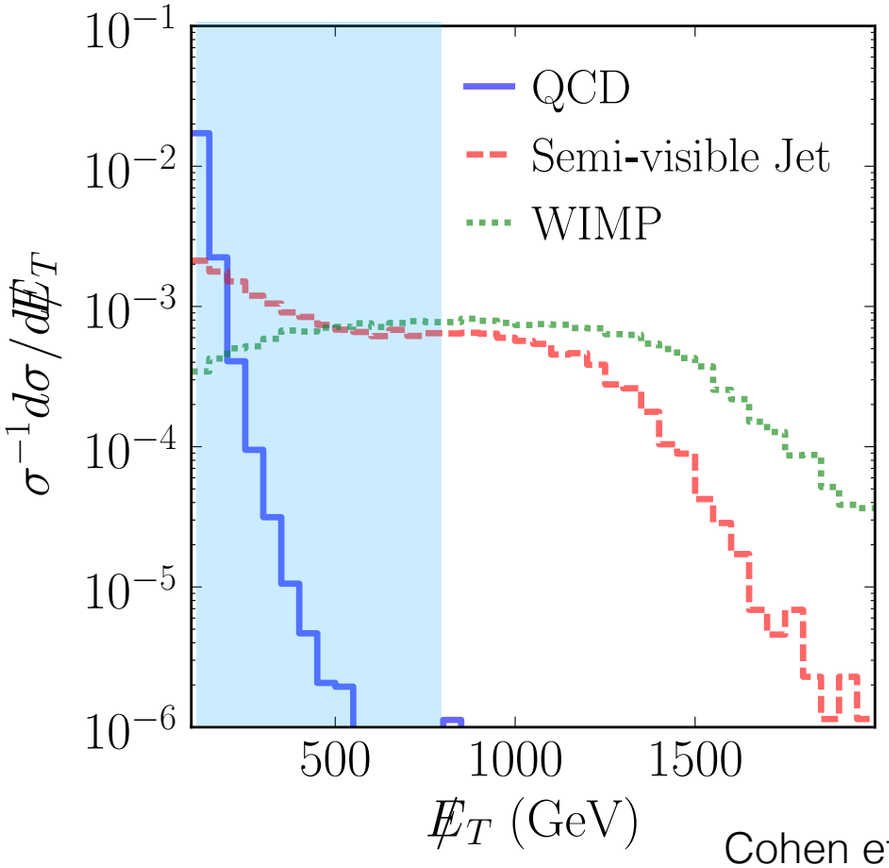
Jet of visible matter and dark matter: “semi-visible” jet

Anatomy of a semi-visible jet



WIMP vs Semi-visible jet distributions

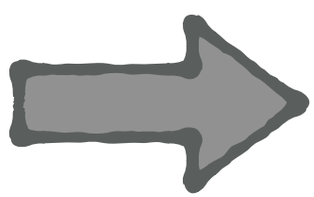




Cohen et. al. [1503.00009]

$\not{E}_T > 800$ GeV

$\min\left[\Delta\phi(\text{jets}, \not{E}_T)\right] \gtrsim 0.4$



Efficiencies:

$\sim 40\%$ WIMP

$\sim 1\%$ Semi-visible jets

No stone unturned

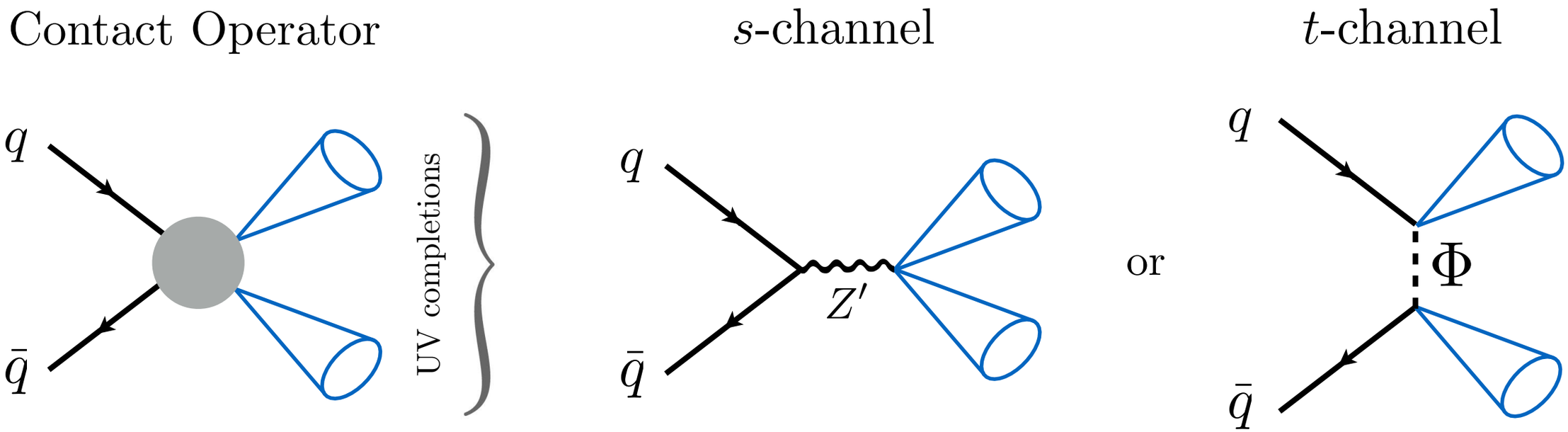
Want to ensure discovery of new physics.

Nothing stopping the dark sector from being complicated.

Goal: **minimal parametrization to cover broad class of models.**

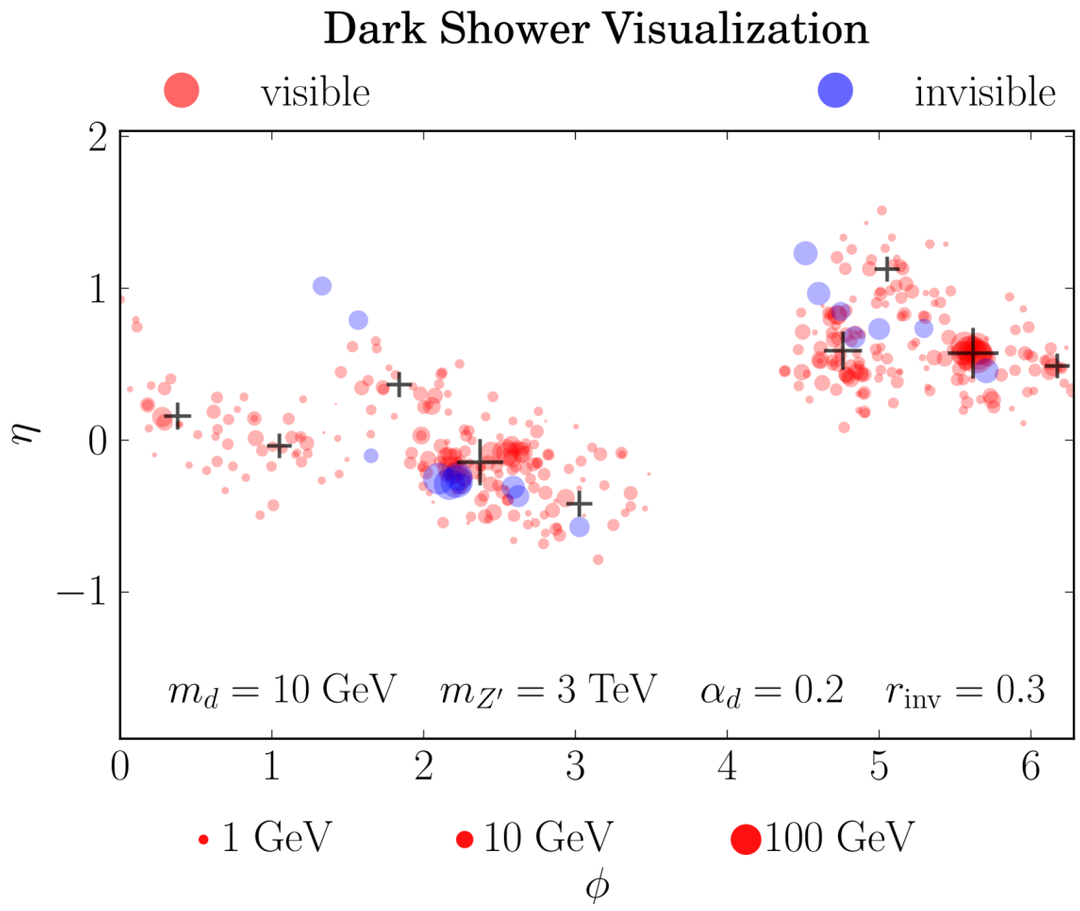
Portals

Simulation: Pythia8 hidden valley module (modified to include running couplings) piped through DELPHES (CMS card) at 13 TeV.

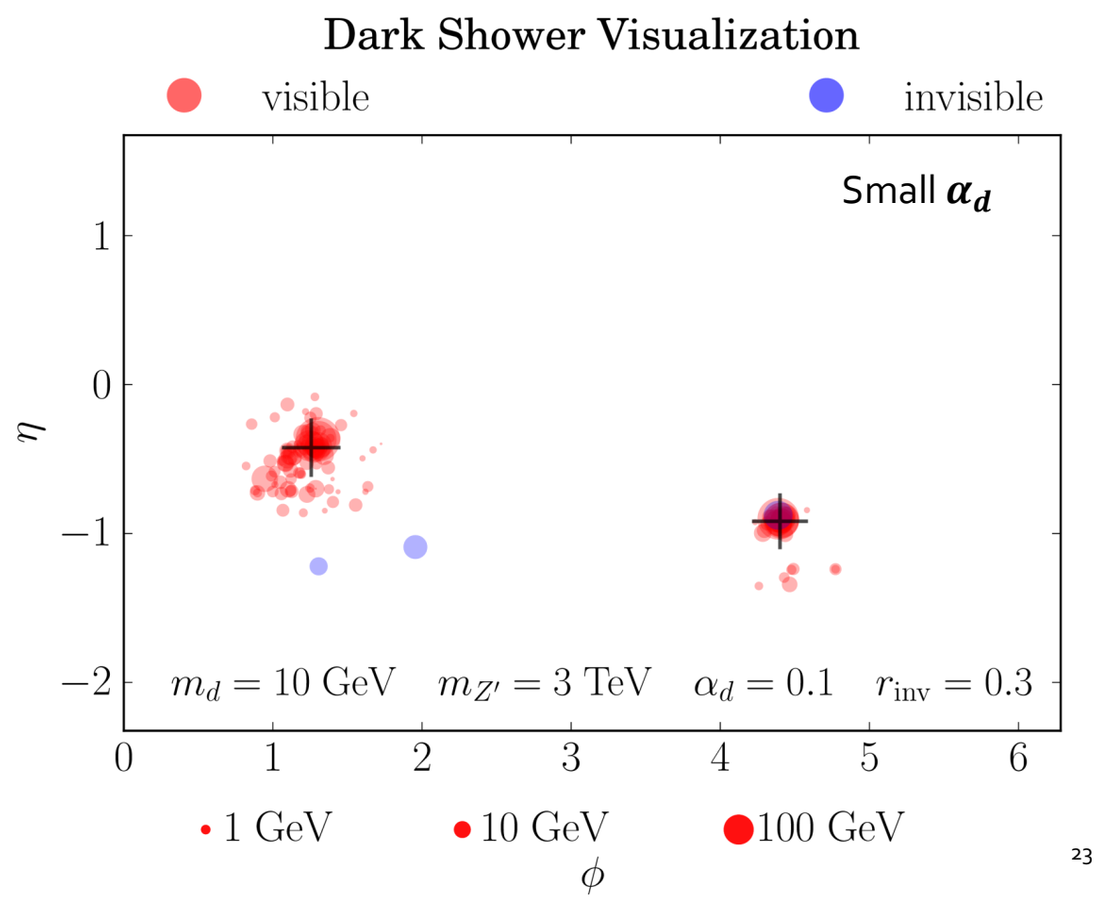


Parameterization: α_d

Dark quark coupling strength: parameterizes "strength" of shower



Larger α_d

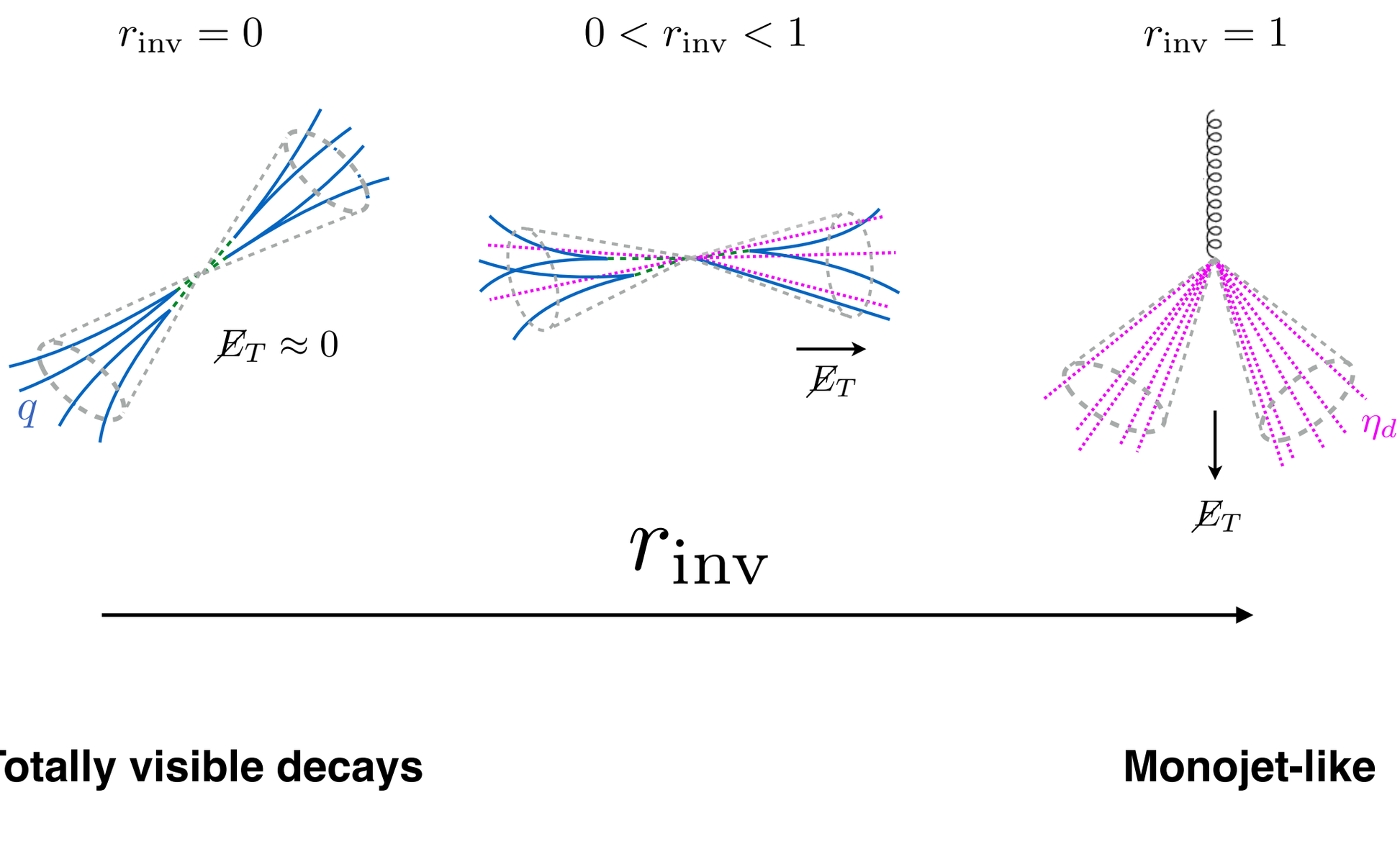


Smaller α_d

23

Parameterization: r_{inv}

Invisible ratio: parameterizes ratio of invisible to total number of hadrons



Totally visible decays

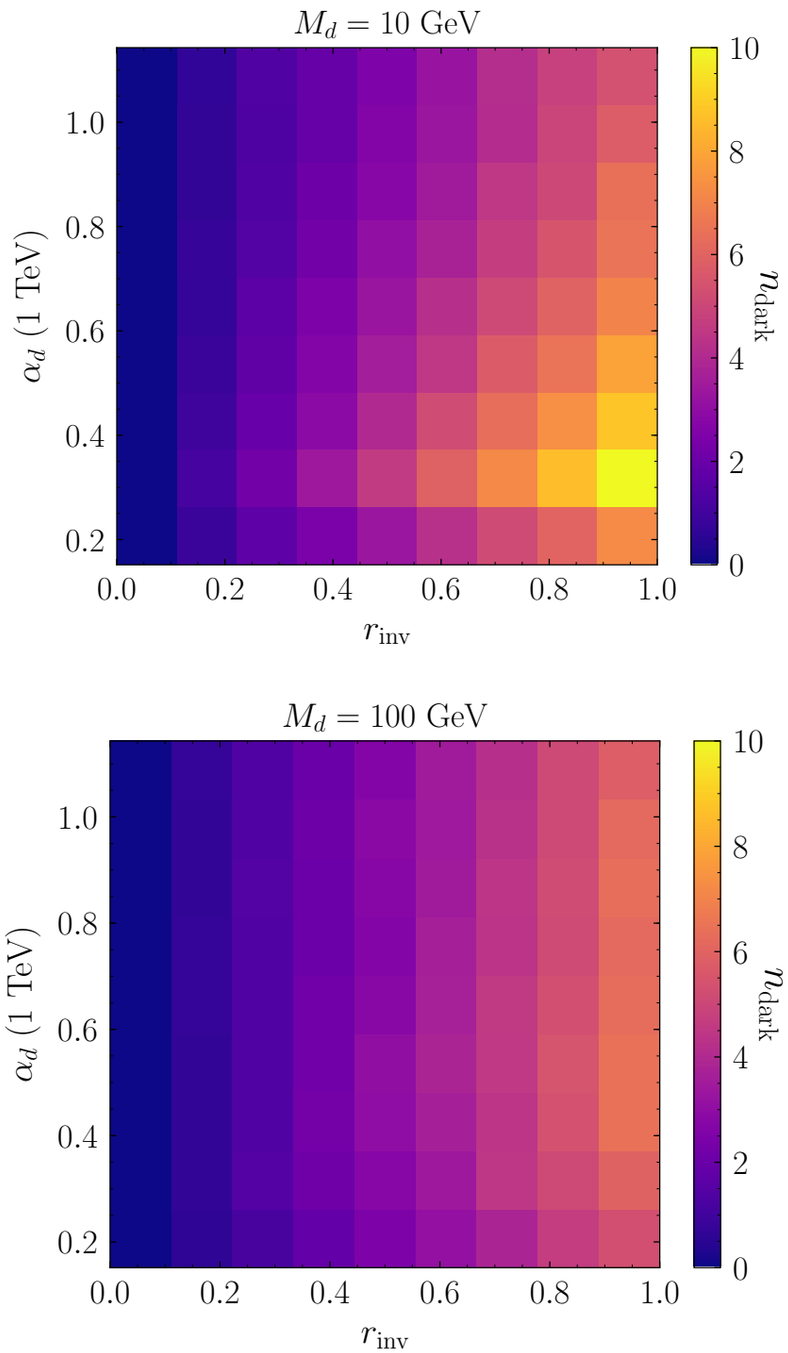
Monojet-like

Parameter summary

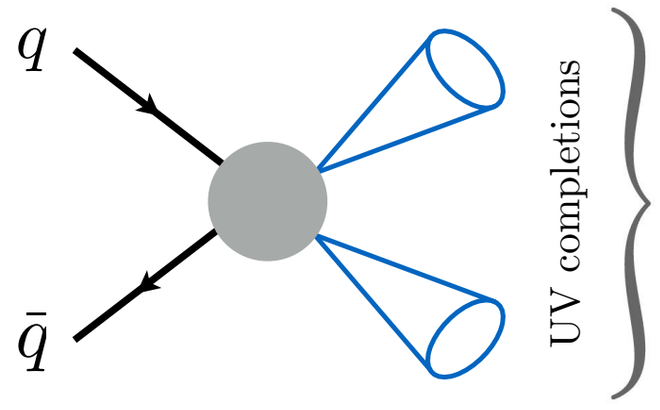
Shower Strength	Invisible ratio
$\alpha_d(\mathbf{1TeV})$	r_{inv}
larger $\alpha_d(\Lambda)$	larger r_{inv}

+ dark quark mass, m_d

Number of dark mesons / event:



Contact operator search



Follow "mono-*X*" strategy.

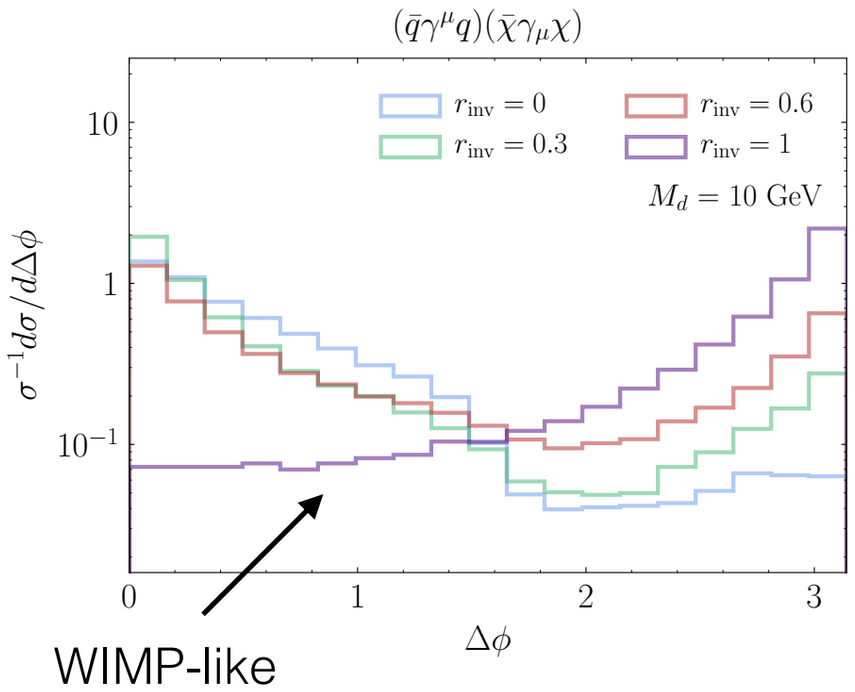
Focus on the vector-vector contact operator:

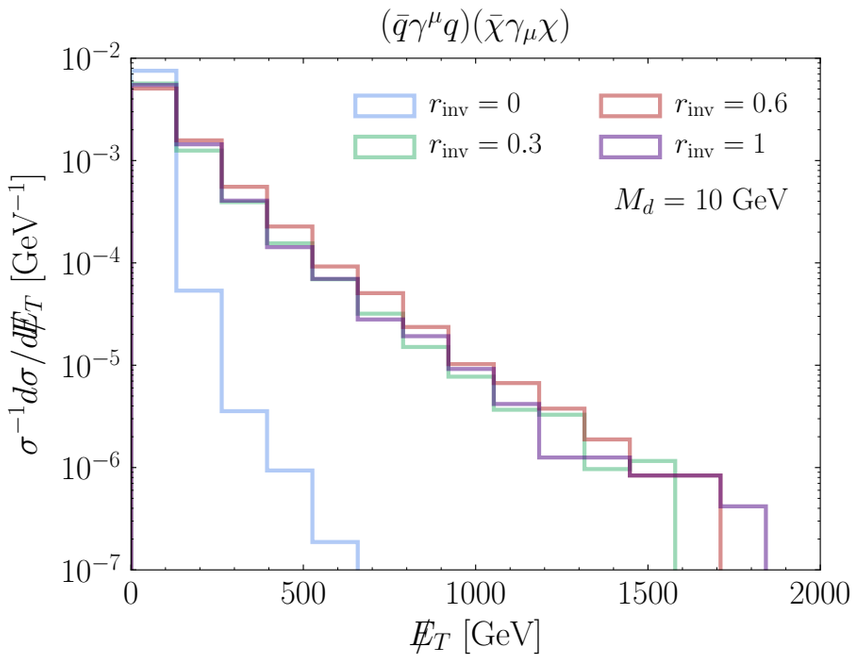
$$\frac{1}{\Lambda^2}\left(\bar{q}\gamma^\mu q\right)\left(\bar{\chi}\gamma_\mu\chi\right)$$

Then UV complete into model with *s*- or *t*-channel exchange.

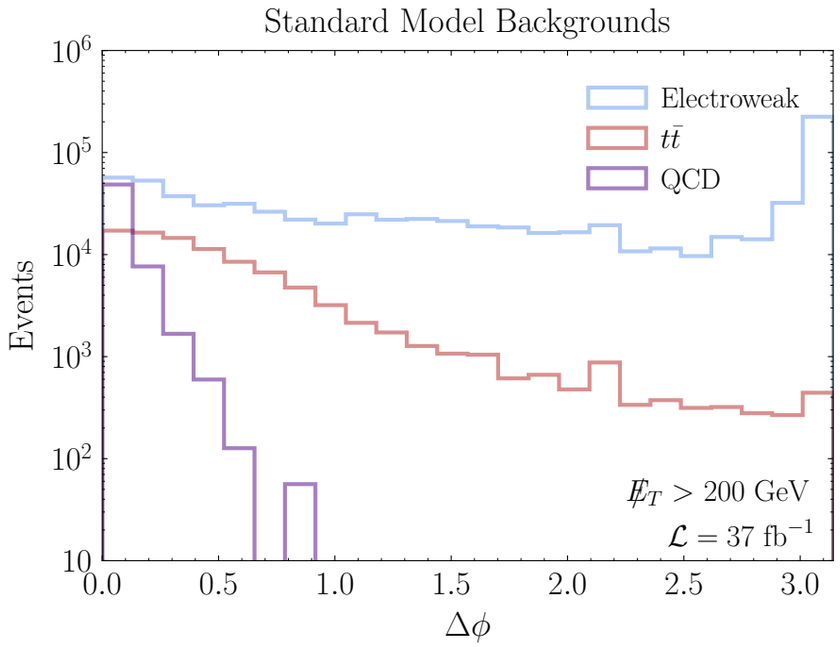
Distributions

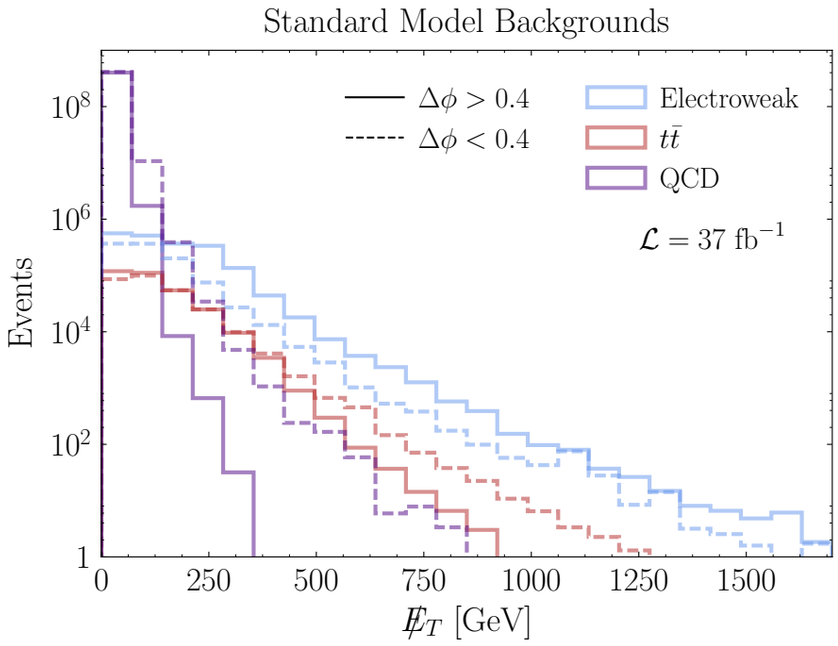
Signal distributions





Background distributions

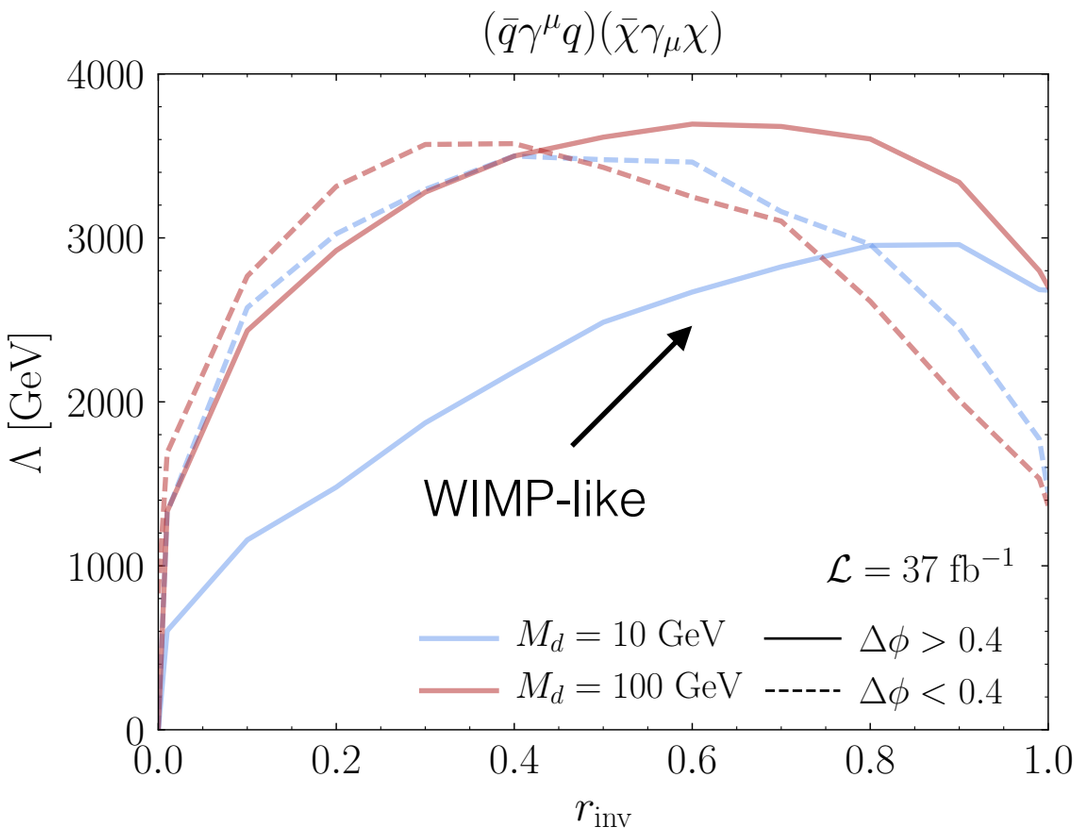


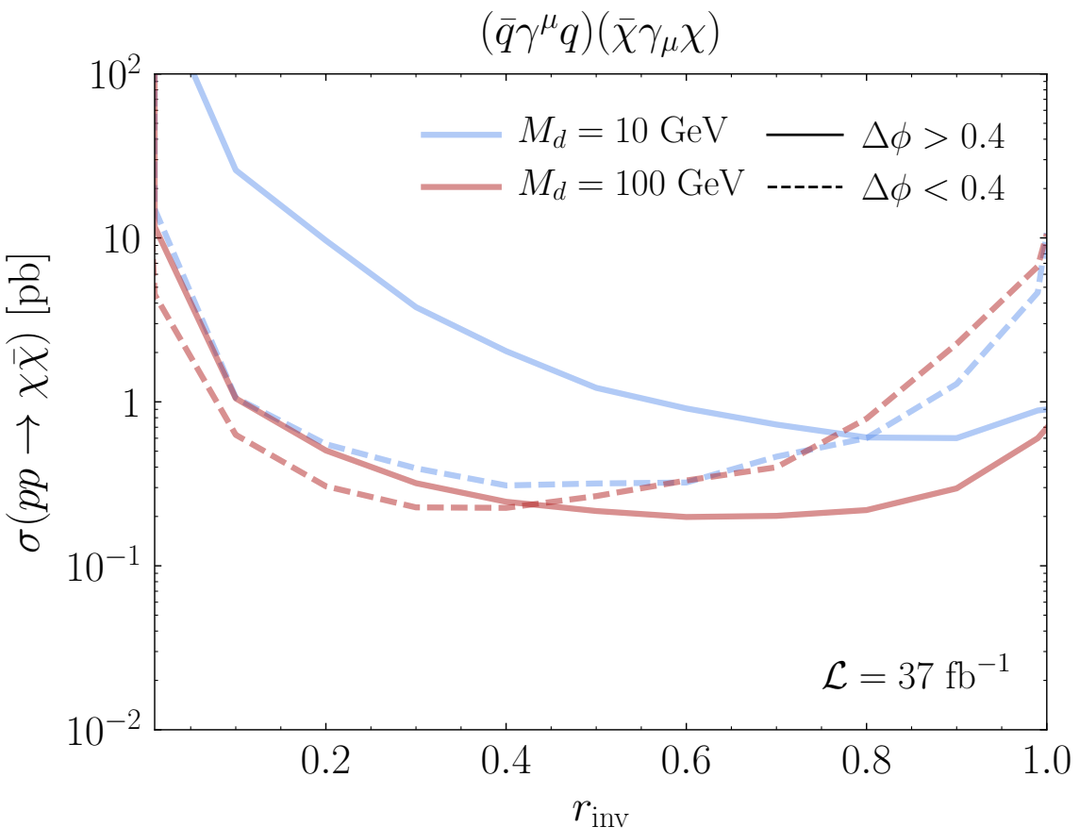


Projected reach

Contact operator

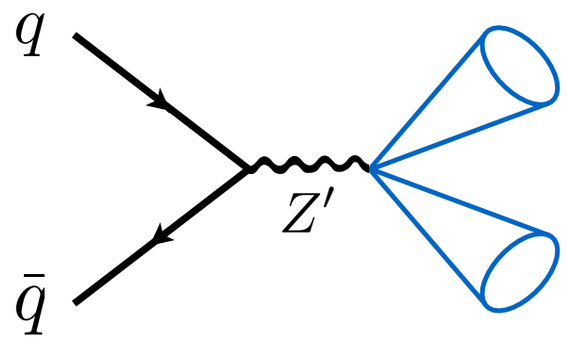
	Cuts	Signal (r_{inv}) 0.1	0.5	0.9	Background $Z+\text{jets}$	$W^{\pm}+\text{jets}$	$t\bar{t}+\text{jets}$	QCD
	Trigger and presel.	2000[2.58]	4920[6.34]	2340[3.02]	2.3×10^5	2.5×10^5	6.9×10^4	5.7×10^4
	$\not{E}_T > 800$	43[1.01]	174[3.94]	108[2.49]	1160	536	80	0
Traditional →	$\Delta\phi > 0.4$	0[0]	31[0.89]	73[2.0]	1050	209	8	0
	or	Low efficiency						
Reversed →	$\Delta\phi < 0.4$	42[1.81]	142[5.57]	35[1.51]	110	326	72	0





s-channel UV completion

$$\mathcal{L}_{s\text{-channel}} \supset -Z'_\mu \sum_{i,a} \left(g_q \, \overline{q}_i \gamma^\mu q_i + g_\chi \, \overline{\chi}_a \gamma^\mu \chi_a \right)$$

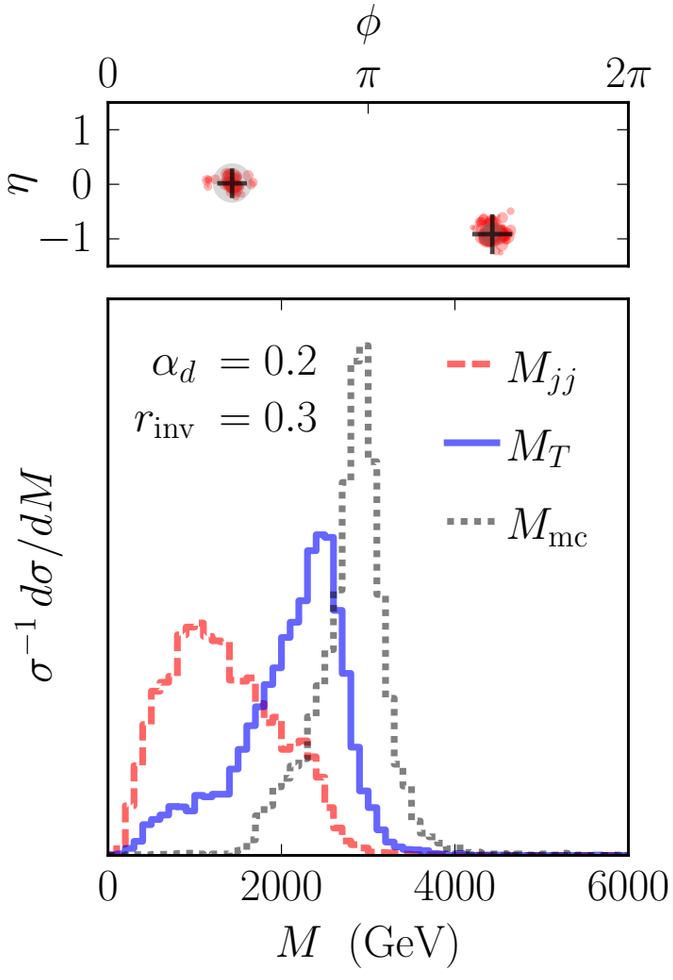


Looking for a resonance.

Di-jet like.

Jets are fatter than QCD jets.

Non-zero $\not{E}_T$ (also washes out resonance).



Cohen et. al. [1503.00009]

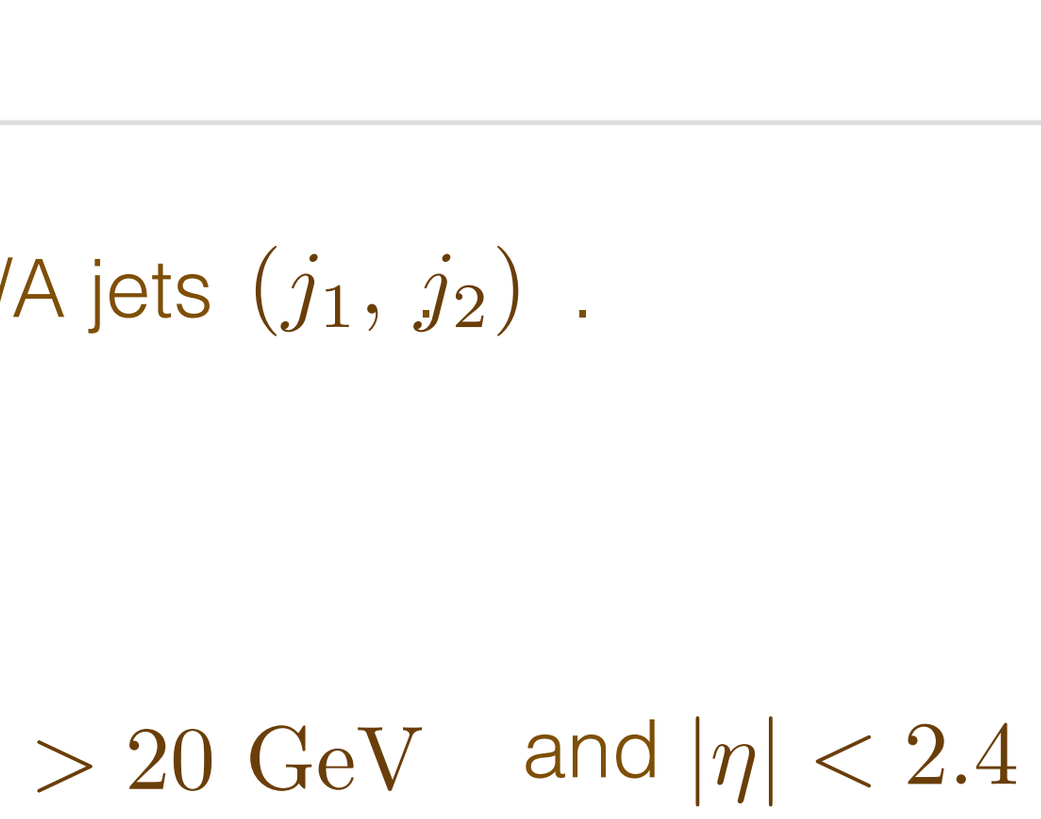
Try the transverse mass:

$$M_T^2 = M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{Tjj}^2}\not{E}_T - \vec{p}_{Tjj} \cdot \vec{\not{E}}_T\right)$$

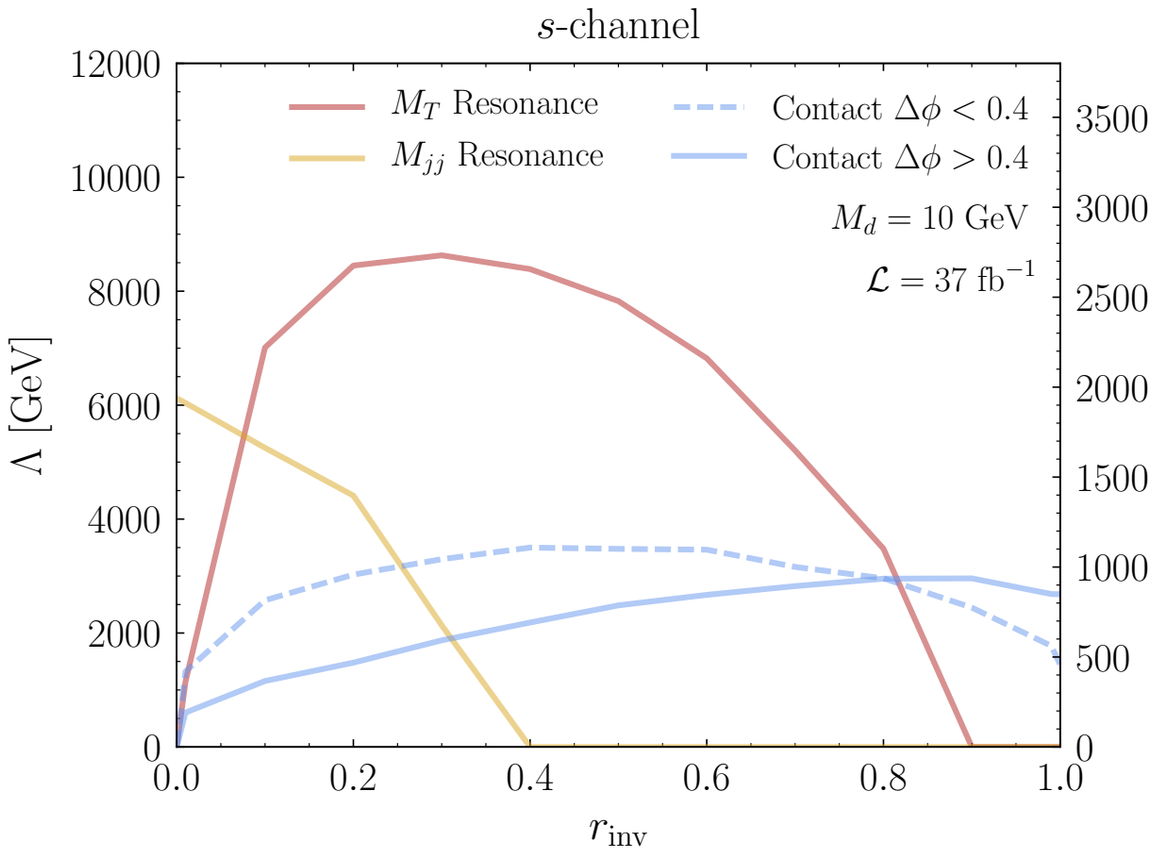
Cuts

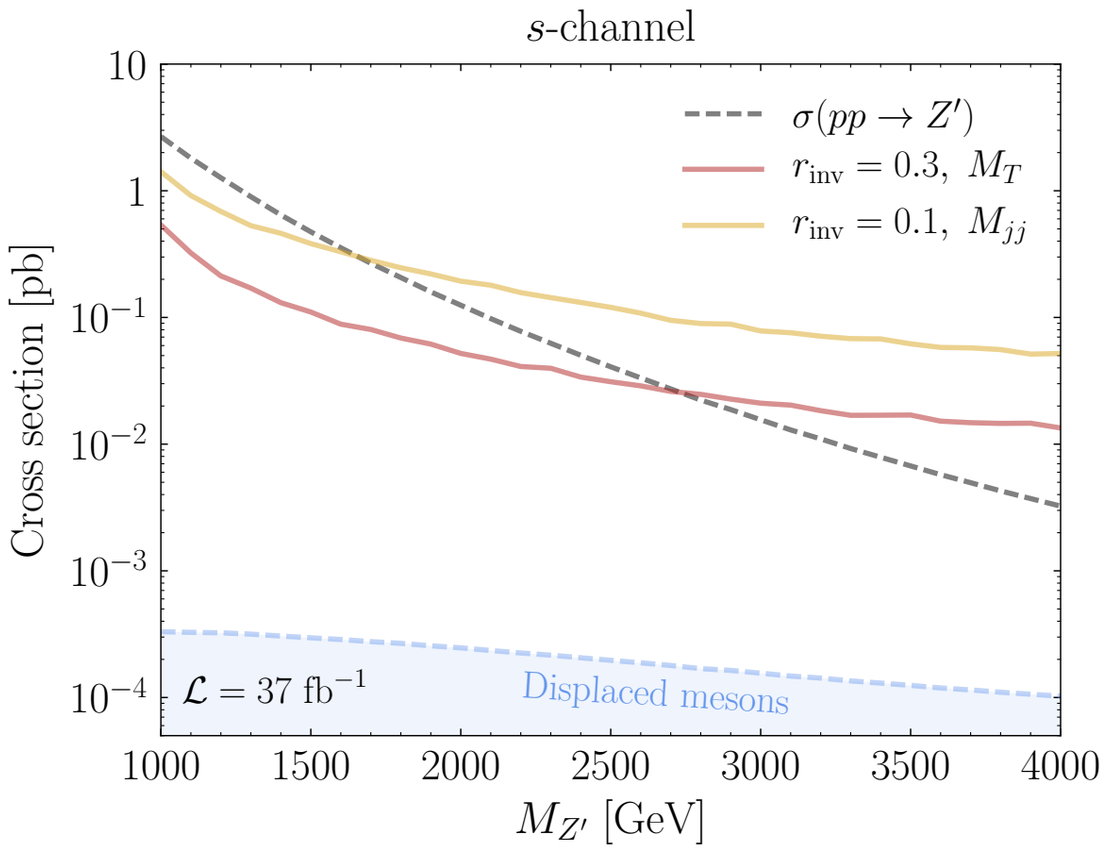
- Reclusters jet into $R = 1.1$ C/A jets (j_1, j_2) .
- Require $\left|\eta_{j_1} - \eta_{j_2}\right| < 1.1$.
- Require $\Delta\phi < 1$.
- Veto isolated $e^{\pm}/\mu^{\pm}$ with $p_T > 20$ GeV and $|\eta| < 2.4$.
- Require $\not{E}_T/M_T > 0.15$.

Then bump hunt in M_T :



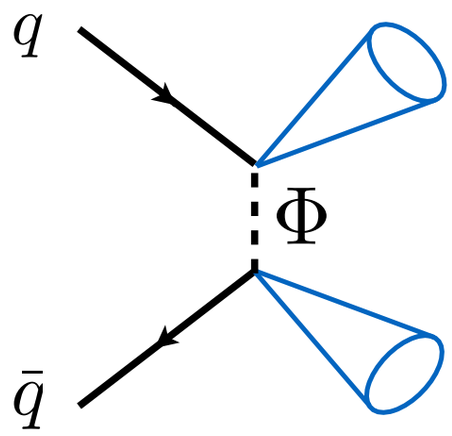
Projected reach





Dedicated search beats contact operator search

t-channel UV completion



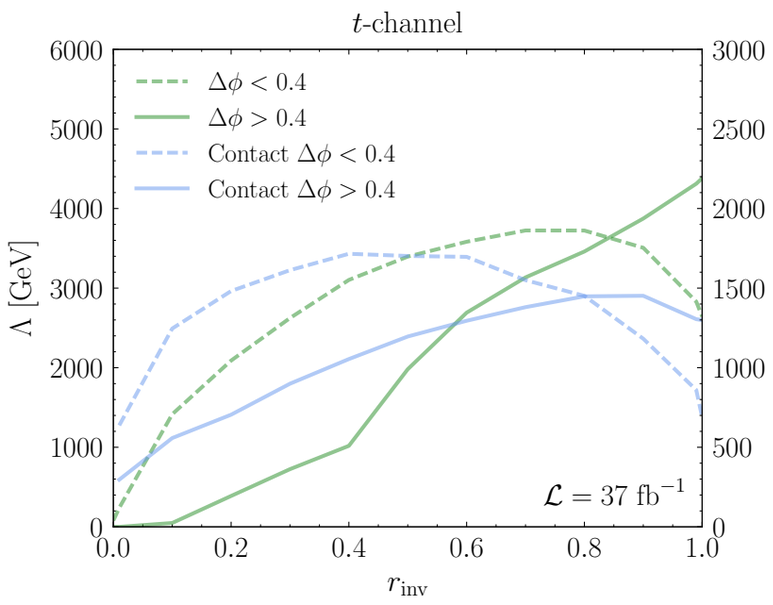
$$\mathcal{L}_{t\text{-channel}} \supset \sum_{i,j,a,b} \lambda_{ijab}\, \overline{\chi}_a\, \Phi^*_{bi}\, q_{Rj}$$

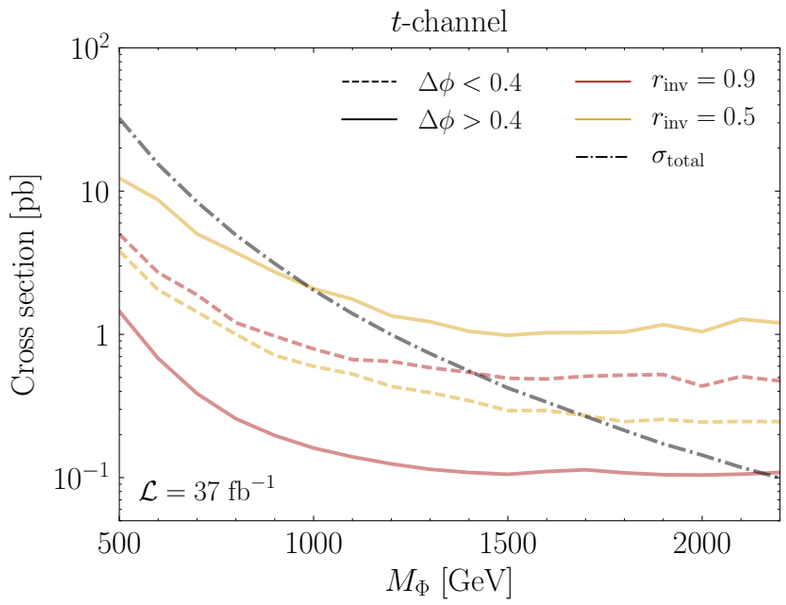
Variety of production modes — details in paper!

Similar benchmark strategy to contact operator case

t-CHANNEL

Cuts	**Signal** (r_{inv}, M_Φ [GeV]) (0.5, 1500)	**Signal** (r_{inv}, M_Φ [GeV]) (0.9, 2000)	**Background** $Z+\text{jets}$	**Background** $W^\pm+\text{jets}$	**Background** $t\bar{t}+\text{jets}$	**Background** QCD
Trigger and presel.	2091[2.7]	467[0.6]	2.3×10^5	2.5×10^5	6.9×10^4	5.7×10^4
$\not{E}_T > 800$	50[1.17]	96[2.22]	1160	536	80	0
$\Delta\phi > 0.4$	13[0.38]	64[1.77]	110	326	72	0
or						
$\Delta\phi < 0.4$	36[1.57]	31[1.35]	1050	209	8	0





Direct detection

Weakly coupled DM

Direct detection fully correlated with LHC signatures.

LHC

$$\frac{1}{\Lambda^2}\left(\bar{q}\gamma^\mu q\right)\left(\bar{\chi}\gamma_\mu\chi\right)$$

→

DD

$$\frac{1}{\Lambda^2}\left(\bar{q}\gamma^\mu q\right)\left(\bar{\chi}\gamma_\mu\chi\right)$$

Composite DM

Direct detection depends on UV completion.

LHC

$$\frac{1}{\Lambda^2}\left(\bar{q}\gamma^\mu q\right)\left(\bar{\chi}\gamma_\mu\chi\right)$$

→

DD

$$\frac{1}{\Lambda^2_{\rm DD}}\left(\bar{q}\gamma^\mu q\right)\left(\bar{\pi}_d\gamma_\mu\pi_d\right)$$

χ are dark quarks.

π_d are dark mesons.

Implication: *s*-channel model has vanishing DD (to leading order)!

Conclusions

Strongly coupled dark sector could yield semi-visible jets.

Useful parametrization of dark sector properties:
$(\Lambda_d, M_d, r_{\rm inv})$

Many portal possibilities:

Contact operator limit

s/t-channel

Direct detection depends on UV completion

Simplified parametrization allows for optimization, and useful way to present limits.