Searching for Hidden Dark Sectors at the LHC

Mariangela Lisanti

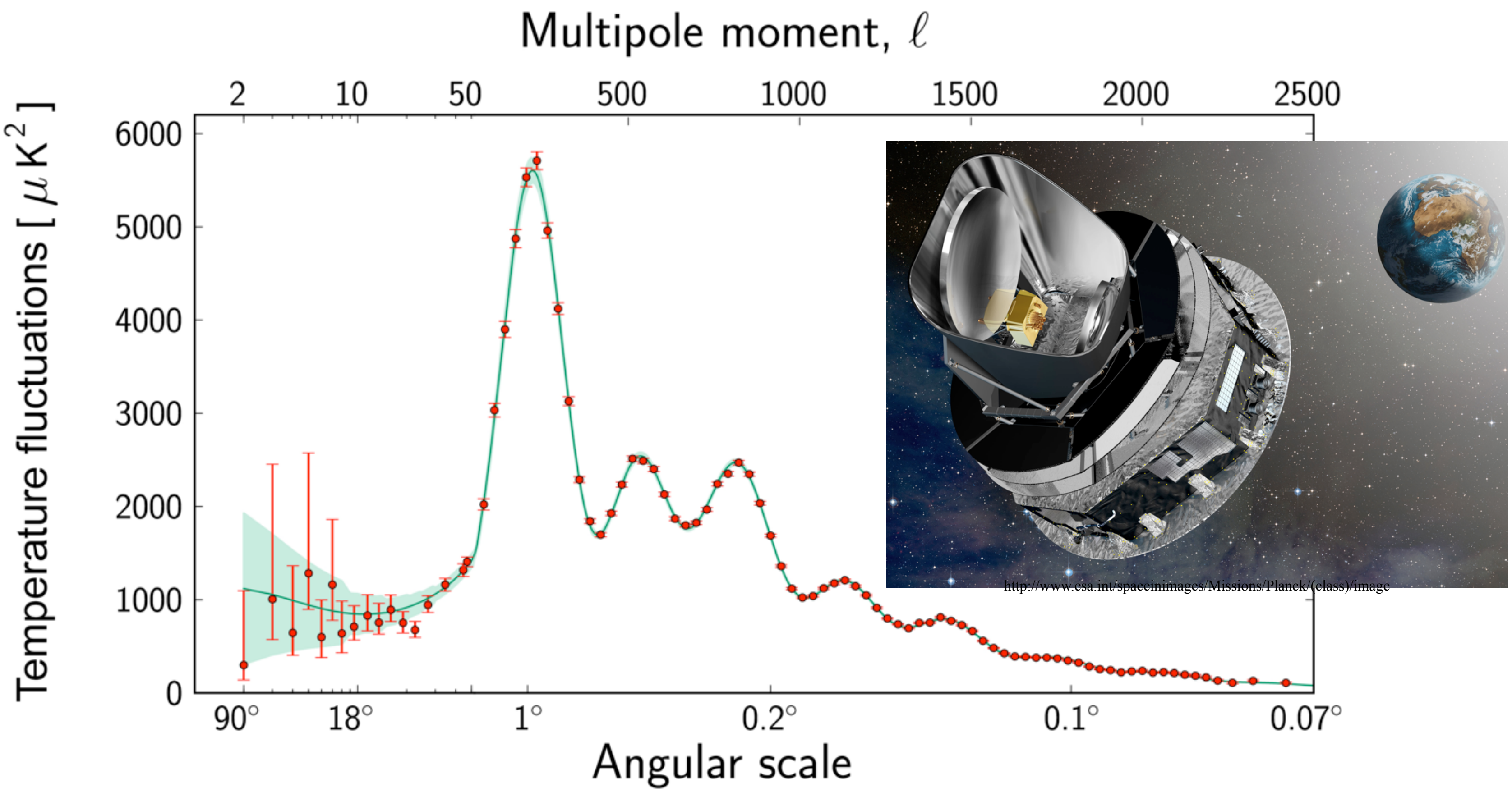
Princeton University

1503.00009 with Tim Cohen, Tim Lou

Work in progress with Tim Cohen, Tim Lou, and Siddharth Sharma

Matter Accounting

83% Dark, 17% Baryonic



Planck Collaboration [1303.5076]

Outline

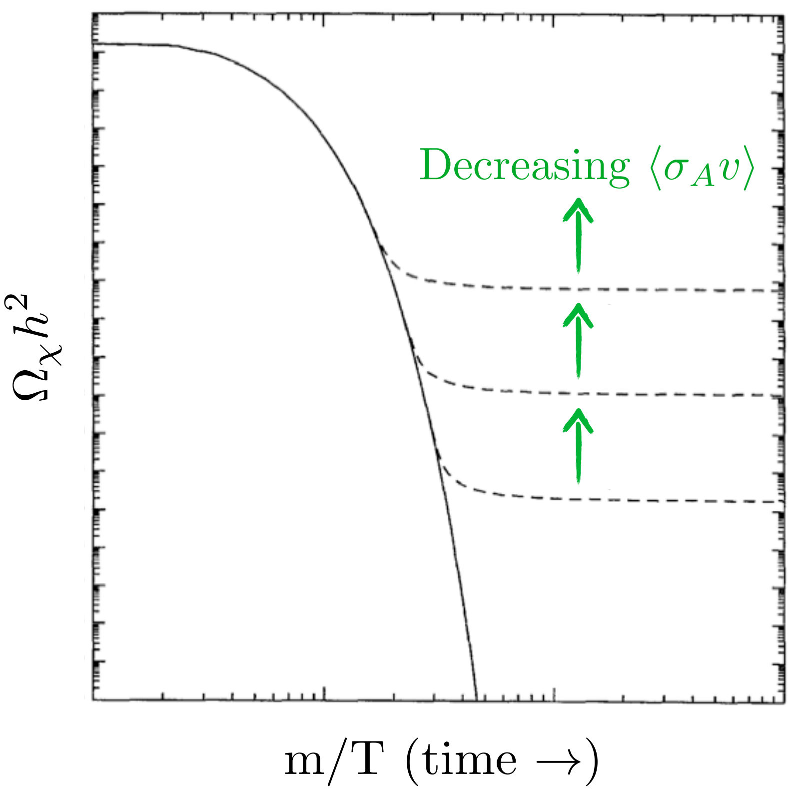
Status of Dark Matter Searches at LHC

Hidden Dark Sectors

Discovering Semi-Visible Jets

WIMP Paradigm

Dark matter is in thermal equilibrium in early Universe, until its interactions "freeze-out"



$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb}}{\langle\sigma_A v\rangle}$$

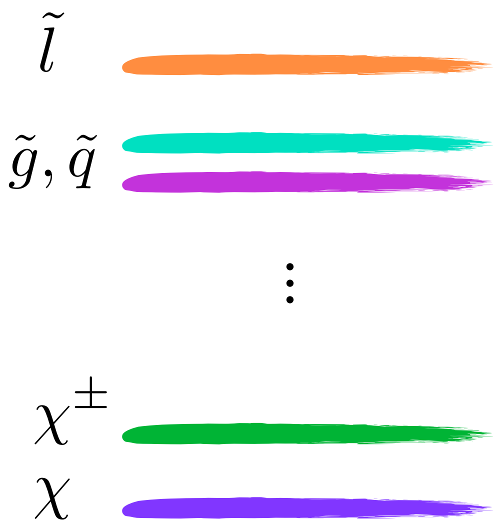
$$\simeq 0.1 \cdot \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

WMAP: $\Omega_\chi h^2 = 0.1109 \pm 0.0056$

- Single, Stable Particle
- Weakly Interacting
- Mass is $\mathcal{O}(100\ \mathrm{GeV})$

A Minimal Model

supersymmetry-inspired



Dark matter is a Majorana fermion and SM singlet

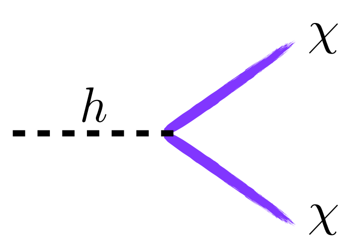
$$\chi = c_1 \widetilde{B} + c_2 \widetilde{W} + c_3 \widetilde{H}_u^0 + c_4 \widetilde{H}_d^0$$

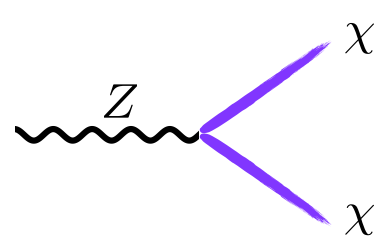
gauginos higgsinos

Also include an additional SM triplet

$$\chi^{\pm} = a_1 \widetilde{W}^{\pm} + a_2 \widetilde{H}^{\pm}$$

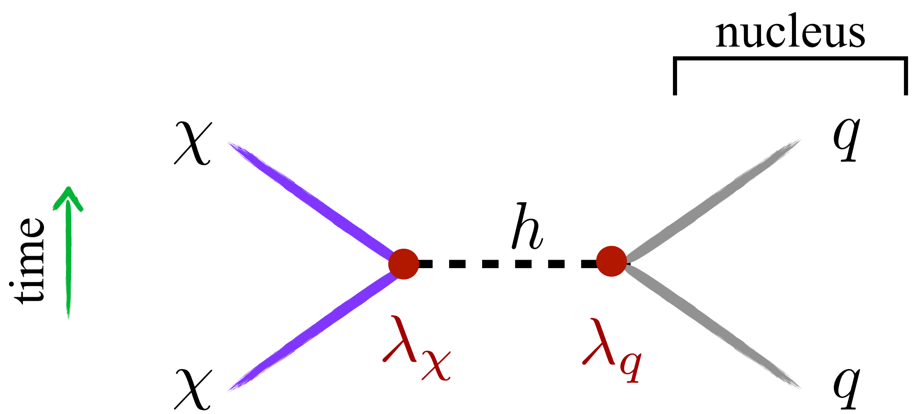
Dark matter couples to the SM through Higgs and Z bosons





Scattering Cross Section

Example: spin-independent interaction due to Higgs exchange

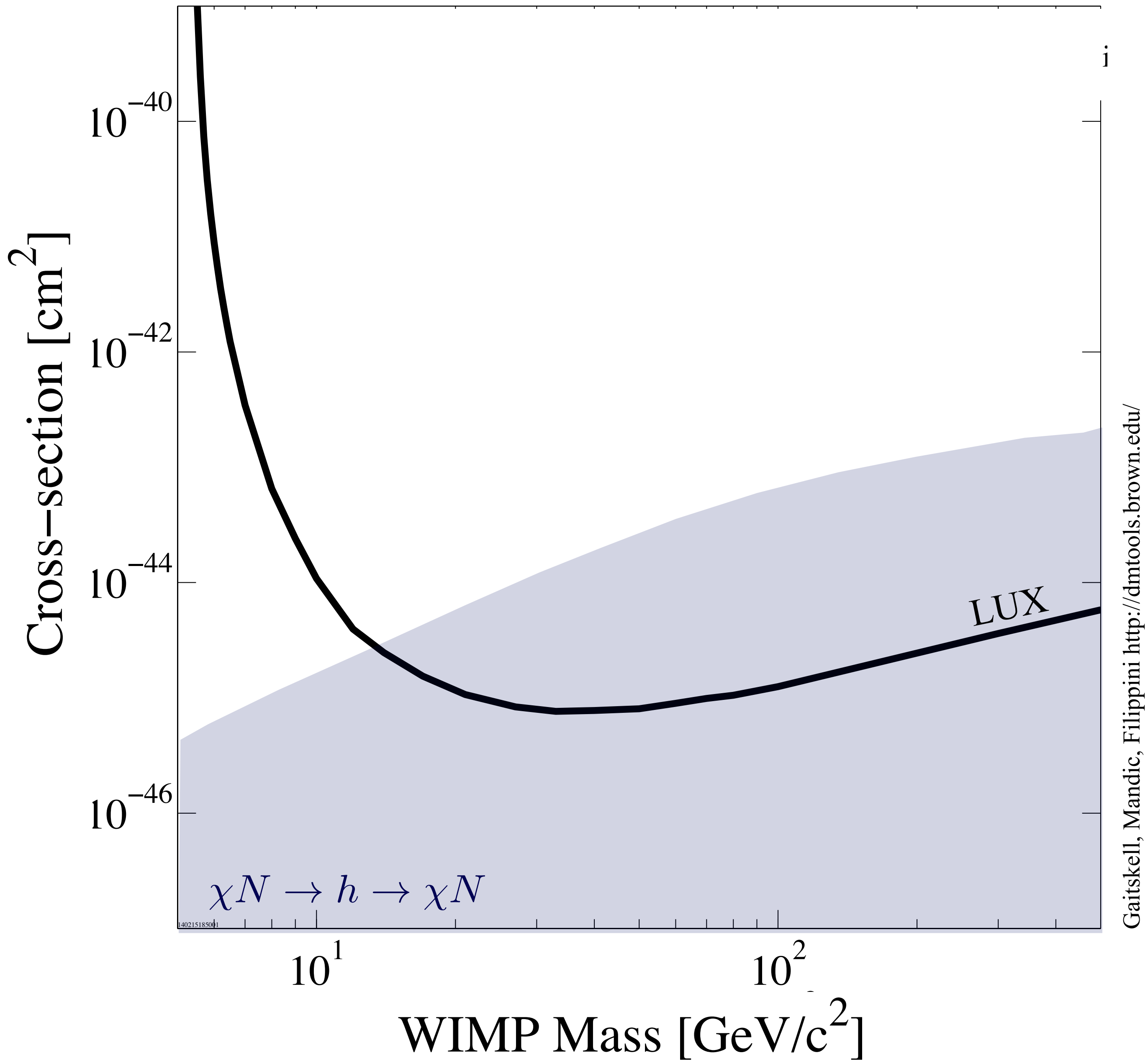


$$\sigma_{\chi N \to \chi N} \simeq \frac{\lambda_\chi^2 \lambda_q^2}{4 m_h^4} \cdot \mu_{\chi N}^2$$

$$\sim (7 \times 10^{-44}\ \mathrm{cm}^2) \cdot \lambda_\chi^2$$

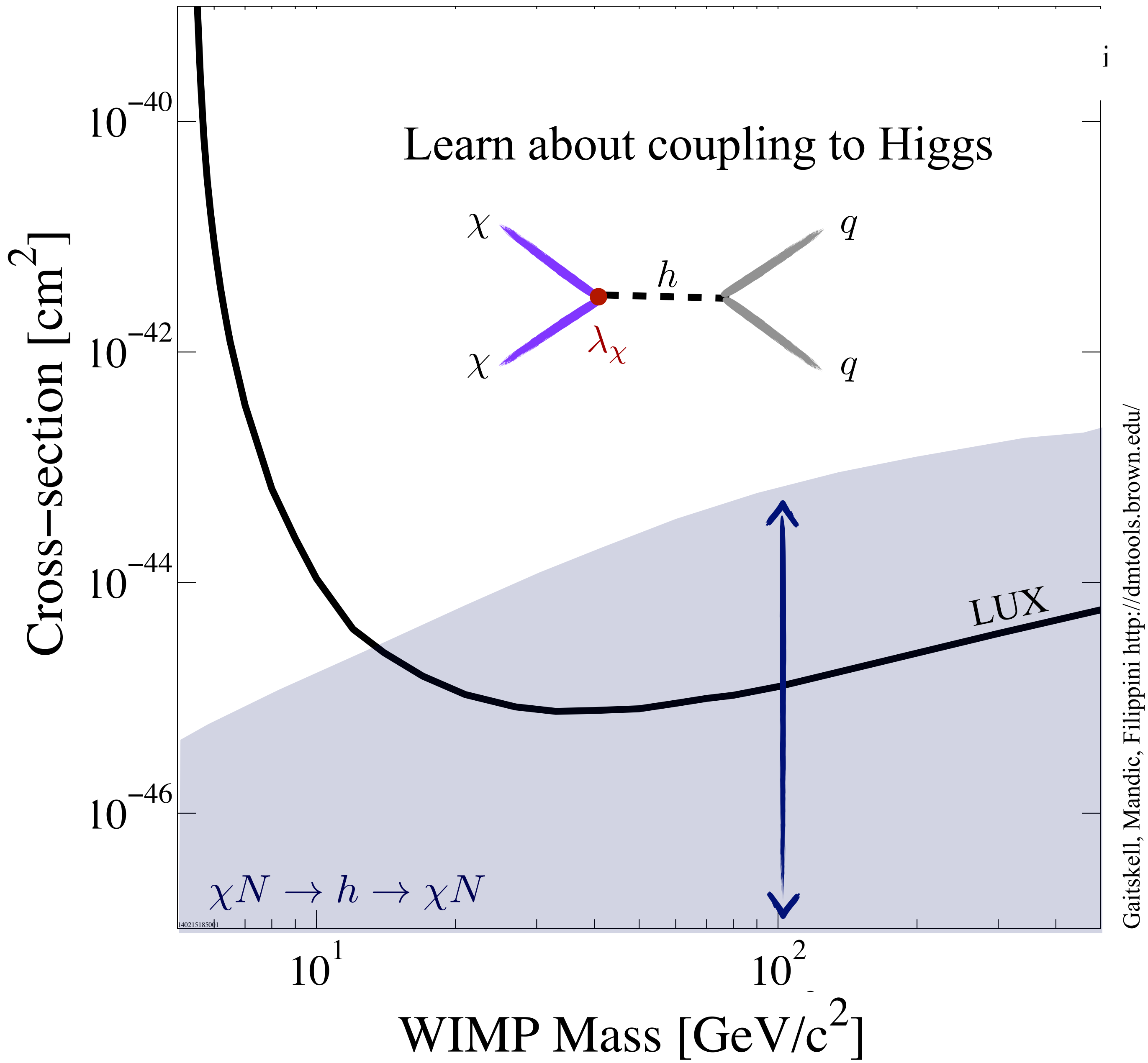
for Xe target, 125 GeV Higgs, 100 GeV DM

Spin-Independent Limit



LUX Collaboration [1310.8214]

Spin-Independent Limit



LUX Collaboration [1310.8214]

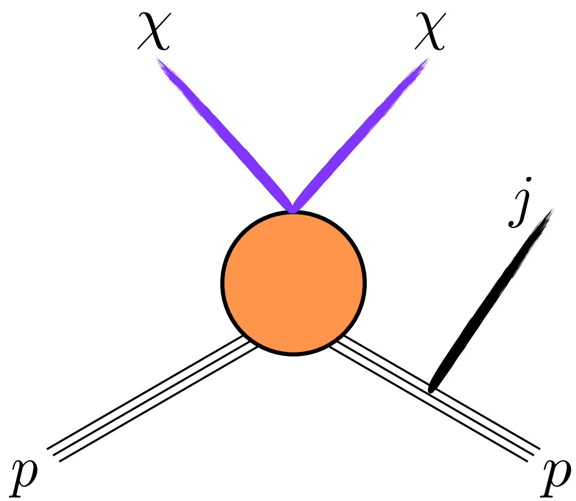
LHC Tests

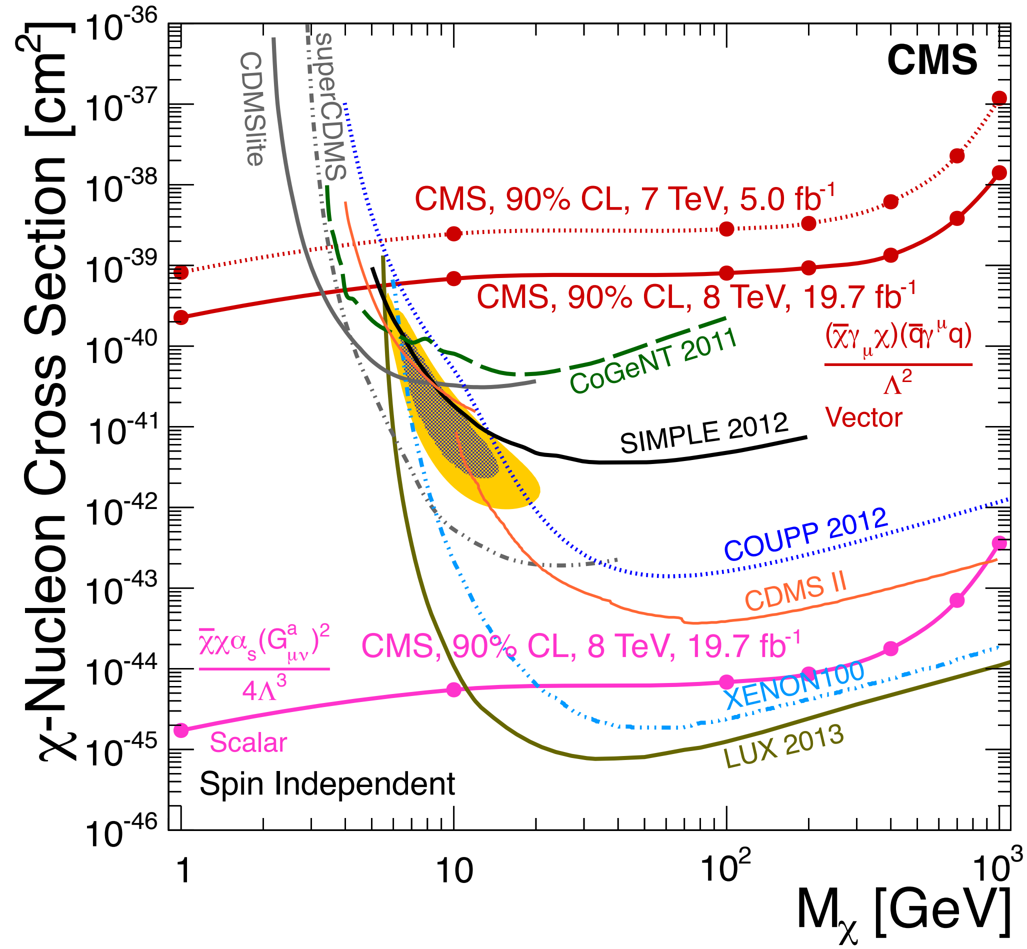
LHC can set model-independent limits on this minimal scenario

Monojet searches are particularly relevant:

P. Fox, R. Harnik, J. Kopp, Y. Tsai [1109.4398]

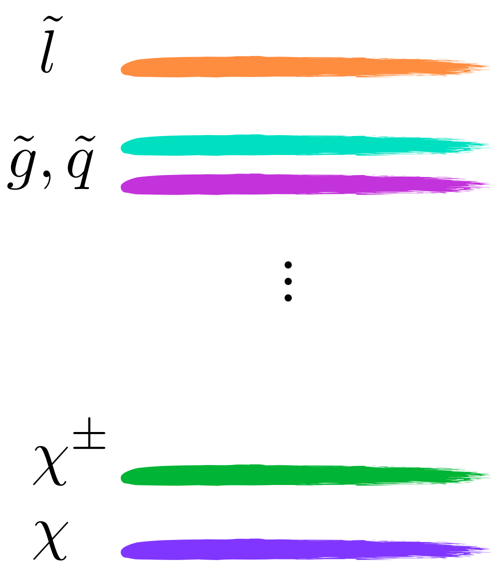
A. Rajaraman, W. Shepherd, T. Tait, A. Wijangco [1108.1196]





New Colored States

Introduce colored states such as squarks or gluinos in the spectrum

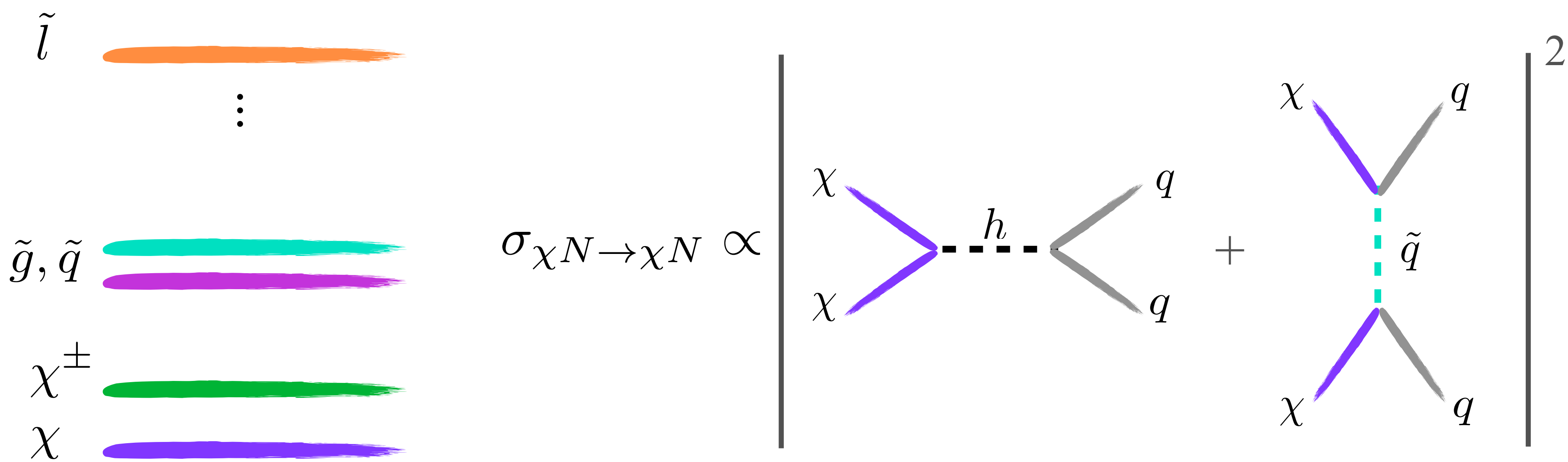


New Colored States

Introduce colored states such as squarks or gluinos in the spectrum

Additional contributions to scattering cross section

May weaken LUX bounds in certain regions of parameter space



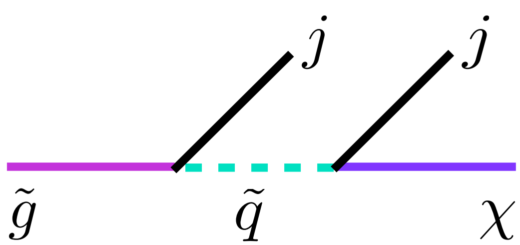
New Colored States

Dark matter produced in decays of colored particles

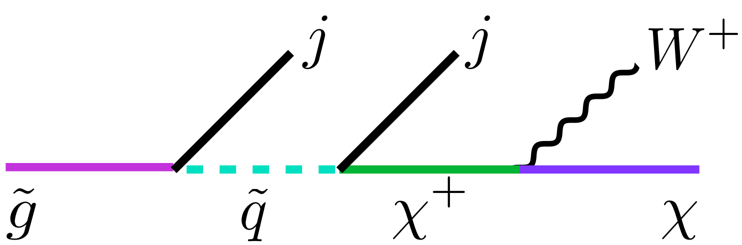
Takes advantage of large colored production cross section

Events typically have several jets and missing energy

Example: Gluino Pair Production



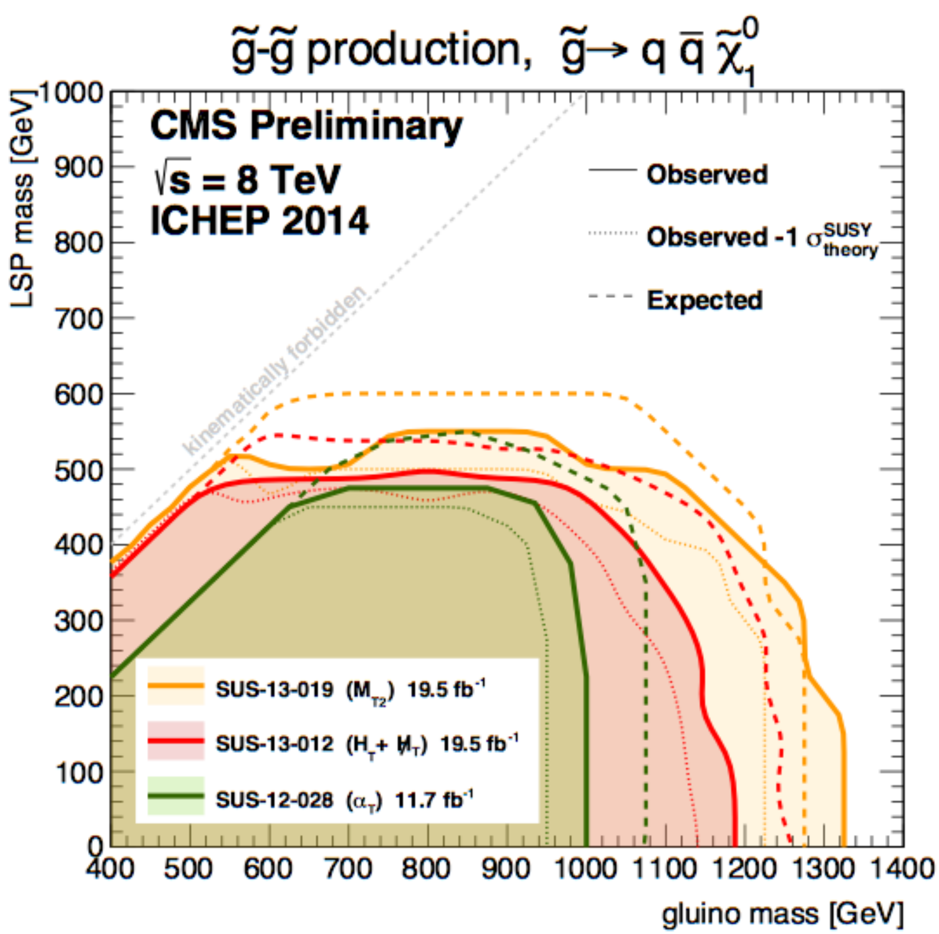
4 jets

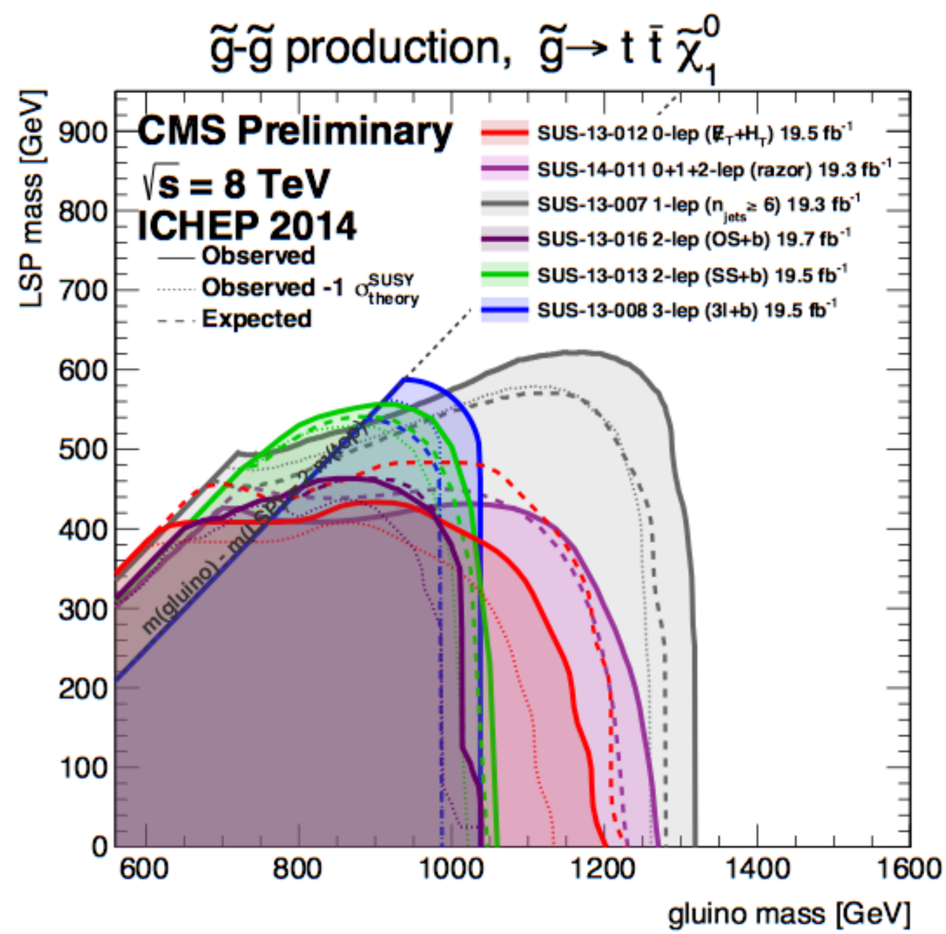


4-8 jets, 0-2 leptons

LHC Bounds

Current searches probing gluino masses up to ~1.3 TeV,
LSP masses up to ~550 GeV





Typically, LHC dark matter searches are cast in terms of

- simplified models for supersymmetry
- effective theory of dark matter interactions

WIMP paradigm has been the primary motivator for current dark matter program at LHC

Important to consider other well-motivated dark matter scenarios to ensure that all possibilities are fully explored

Maybe minimality is not necessarily the best guide in the search for dark matter

Why should 5% of the mass density have all the fun?

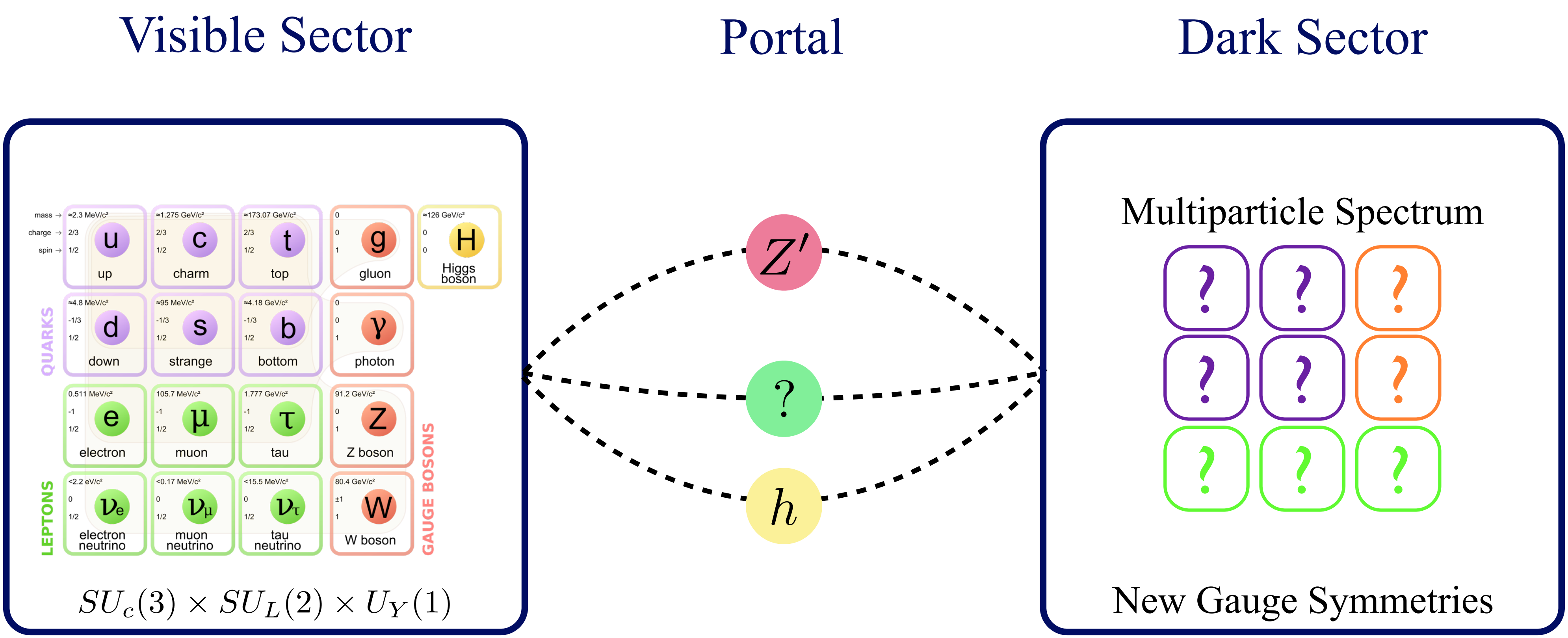
Outline

Status of Dark Matter Searches at LHC

Hidden Dark Sectors

Discovering Semi-Visible Jets

Hidden Dark Sector



Higgs Portal

Does the Higgs serve as a portal to physics
beyond the Standard Model?

Due to low dimension of the Higgs field, it admits operators like

$$|H|^2\mathcal{O}$$

where dimension of $\mathcal{O}$ is less than or equal to 2

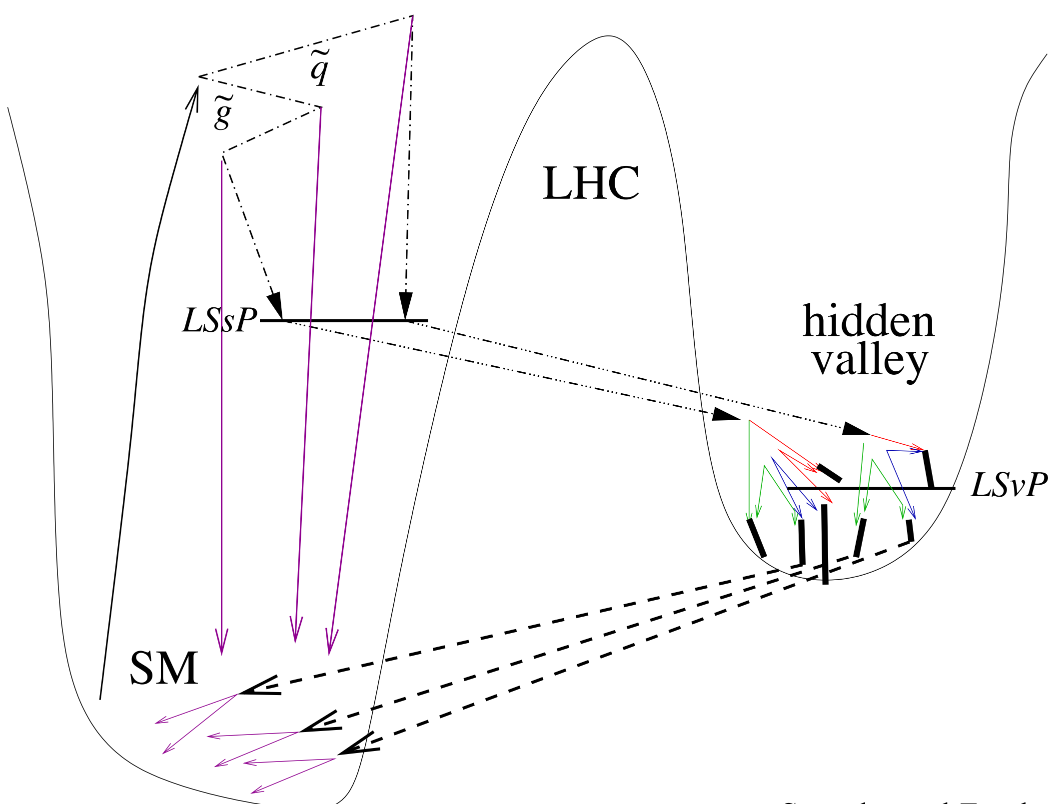
For example, dark sector can consist of new scalar field:

$$\mathcal{O} = \phi^2$$

Hidden Valleys

Standard Model particles remain neutral under new, non-abelian symmetry in a "hidden valley"

Higher dimension operators enable TeV-scale fields to mediate interactions between the two sectors



Strassler and Zurek [hep-ph/0604261] ; Zurek [1001.2563]

Novel Phenomenology

If the dark-sector states are produced at the LHC, they can lead to novel phenomenology such as:

displaced vertices

large particle multiplicities

multiple resonances

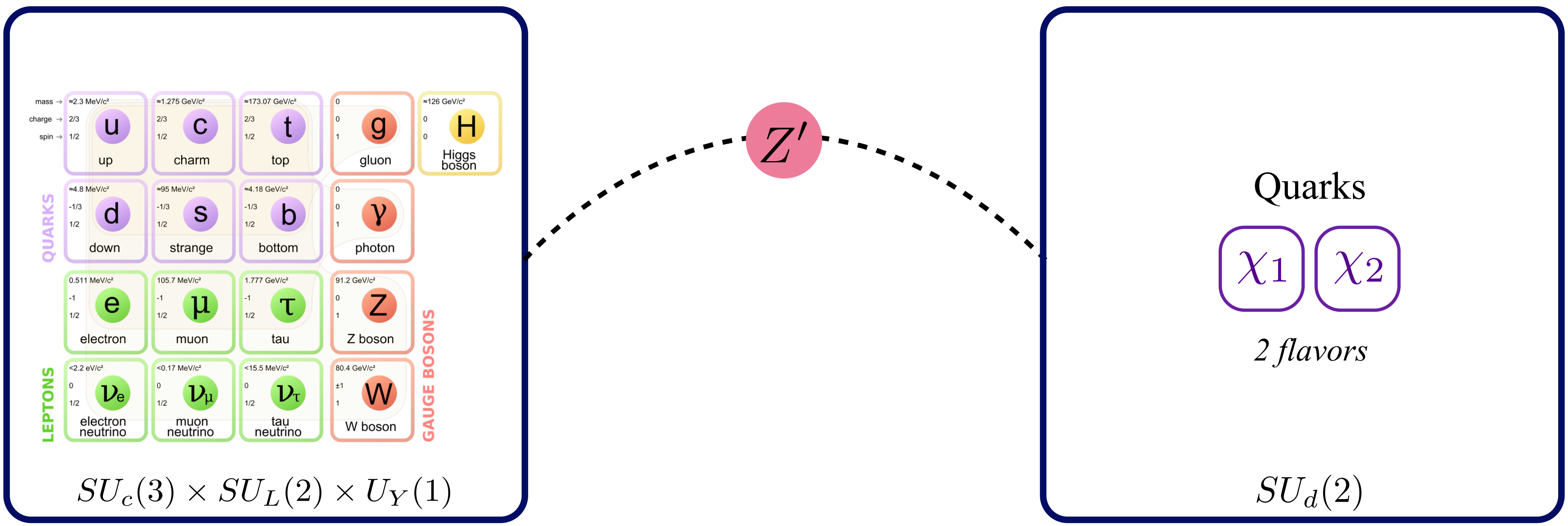
lepton or photon jets

Phenomenological Model

Portal consists of new TeV-scale, leptophobic gauge boson

$$\mathcal{L} \supset -\frac{1}{4}\, Z'^{\mu\nu}\, Z'_{\mu\nu} - \frac{1}{2}\, M^2_{Z'}\, Z'_{\mu}\, Z'^{\mu} - g^{\rm SM}_{Z'}\, Z'_{\mu}\, J^{\mu}_{\rm SM}$$

Visible Sector | Portal | Dark Sector



Dark Sector

$SU_d(2)$ confines at scale $\Lambda_d \ll M_{Z'}$

Results in a QCD-like spectrum of dark mesons and baryons

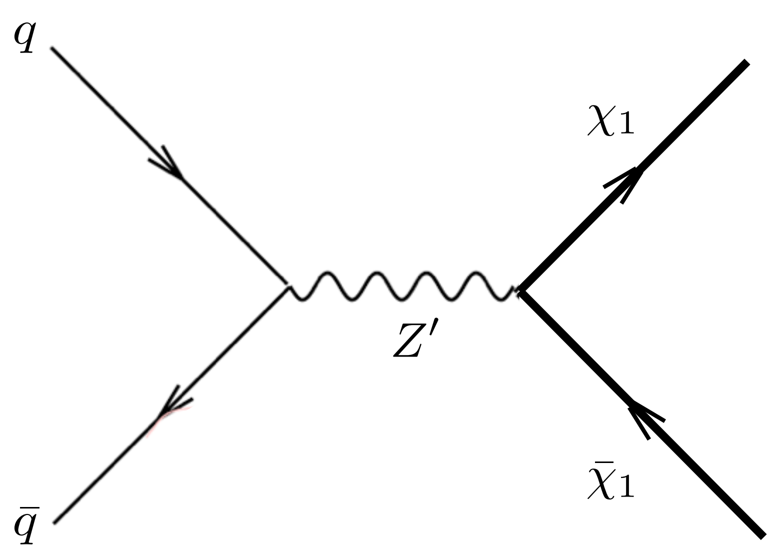
Use symmetry arguments to say something about spectrum...

Dark Isospin → $U(1)_{1-2}$

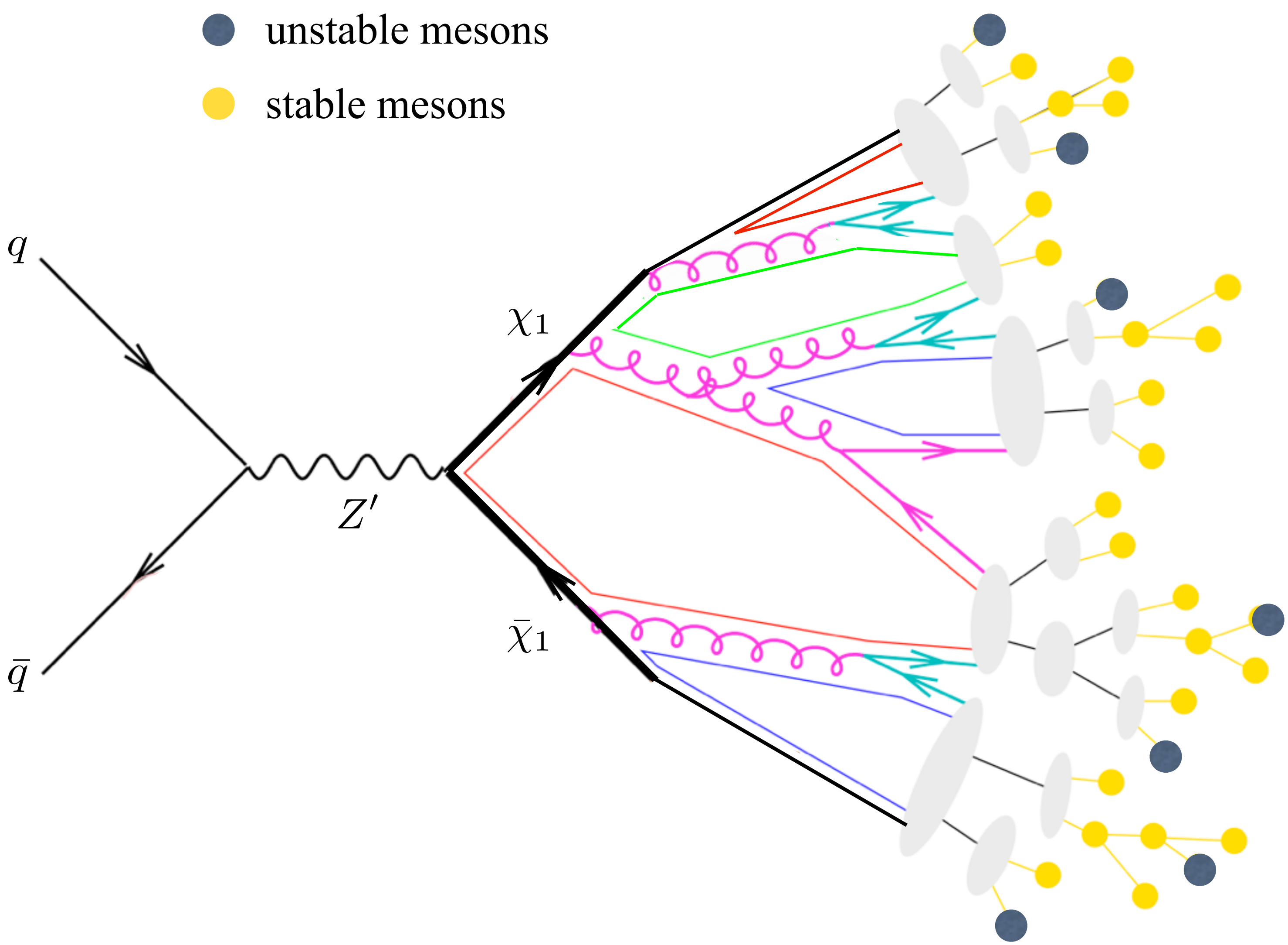
Dark Baryon Number → $U(1)_{1+2}$

Hadrons	Constituents	$U(1)_{1-2}$	$U(1)_{1+2}$
unstable meson	$\chi_1^\dagger \chi_1$ $\chi_2^\dagger \chi_2$	0	0
stable meson	$\chi_1 \chi_2^\dagger$ $\chi_1^\dagger \chi_2$	$+2, -2$	0
baryon	$\chi_1 \chi_2$ $\chi_1^\dagger \chi_2^\dagger$	0	$+2, -2$

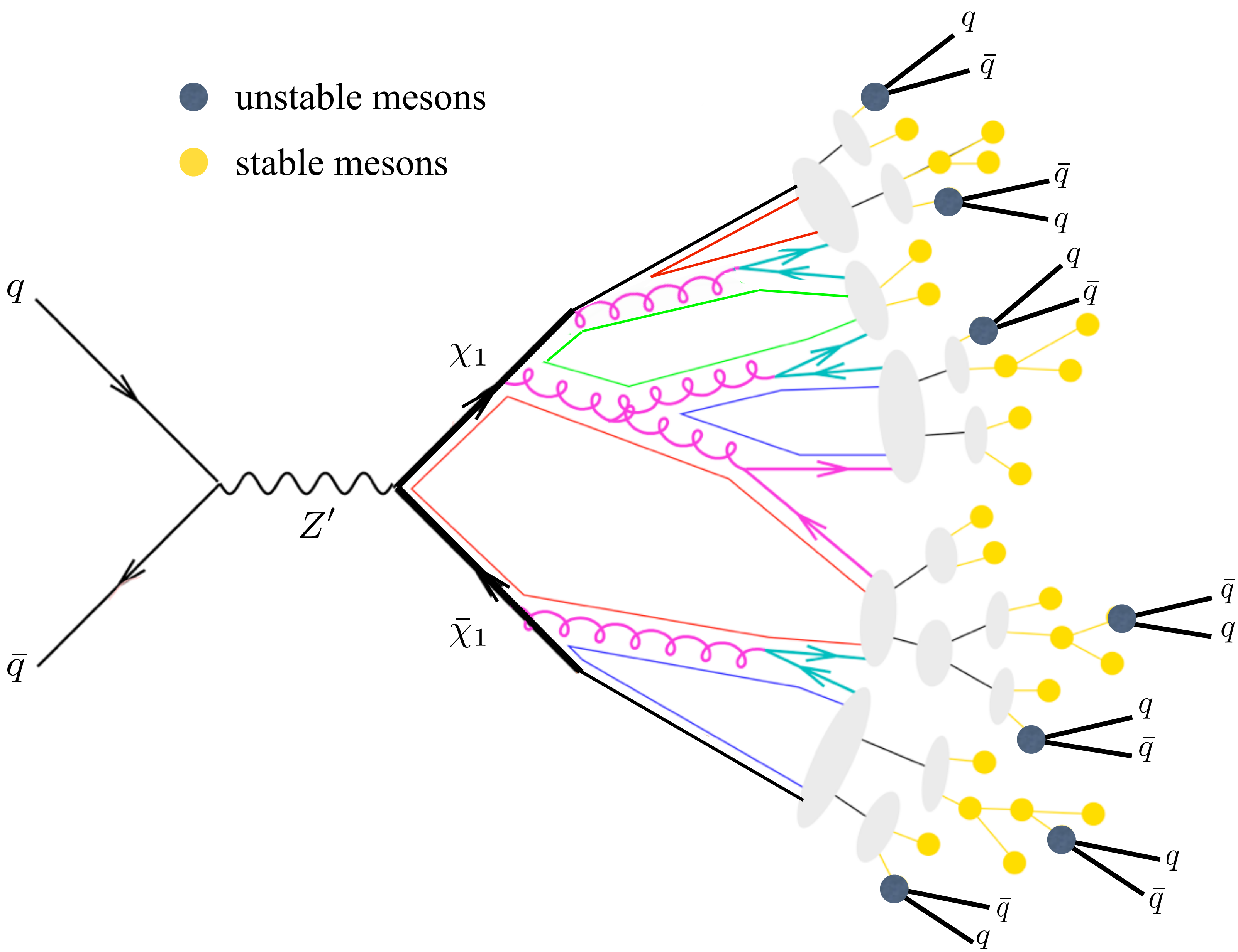
Anatomy of a Signal



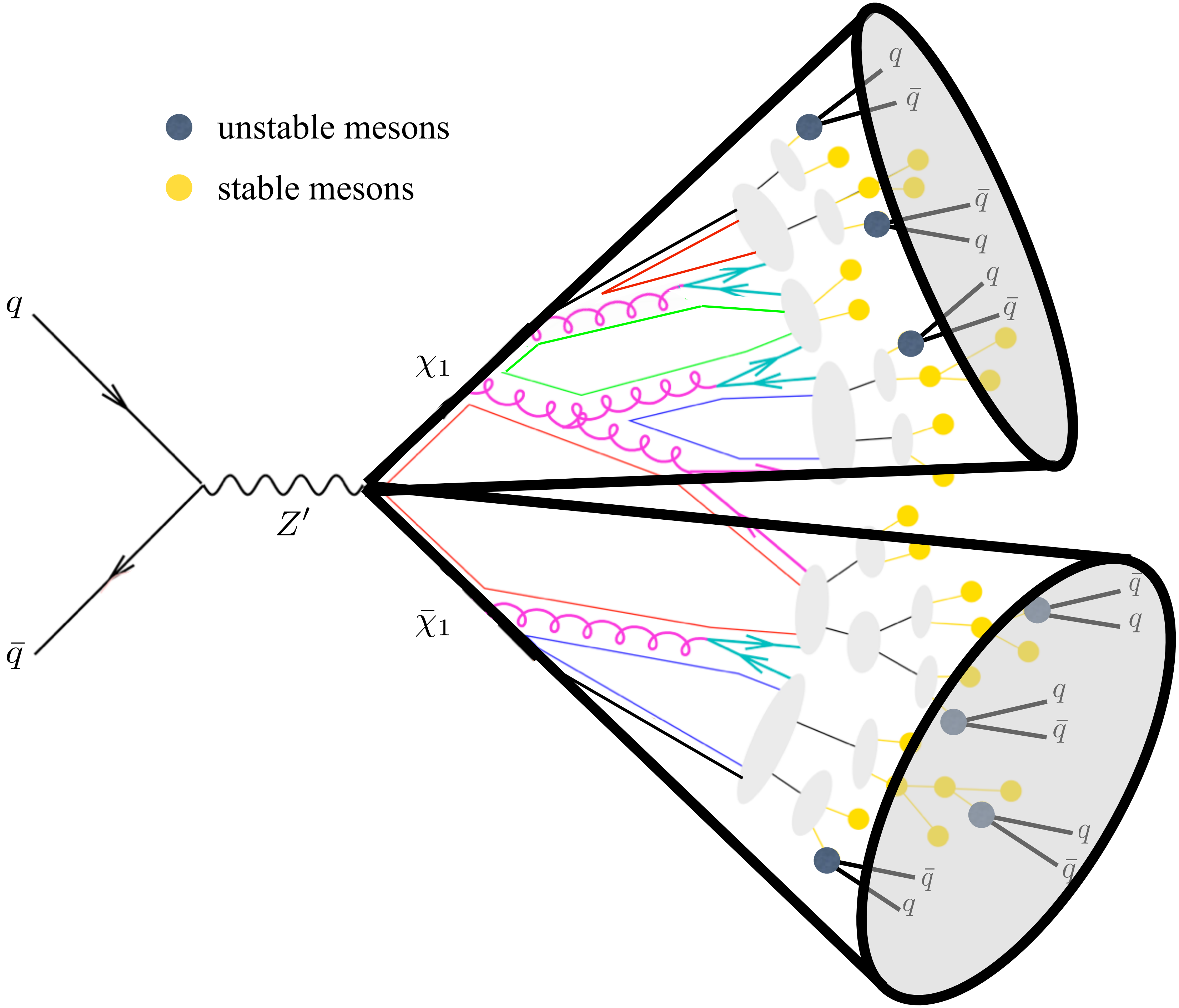
Anatomy of a Signal



Anatomy of a Signal

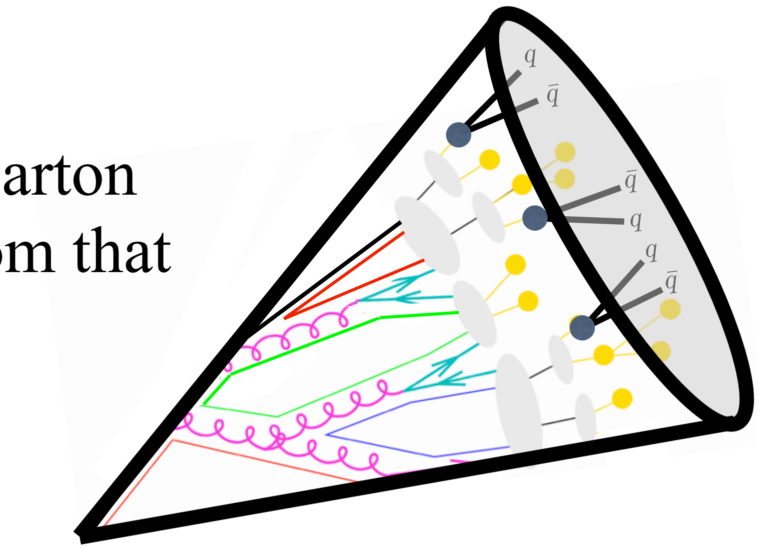


Anatomy of a Signal



Semi-Visible Jets

Dark matter is produced in a QCD-like parton shower along with other degrees of freedom that decay hadronically



Observed as a hadronic jet that also contains invisible particles

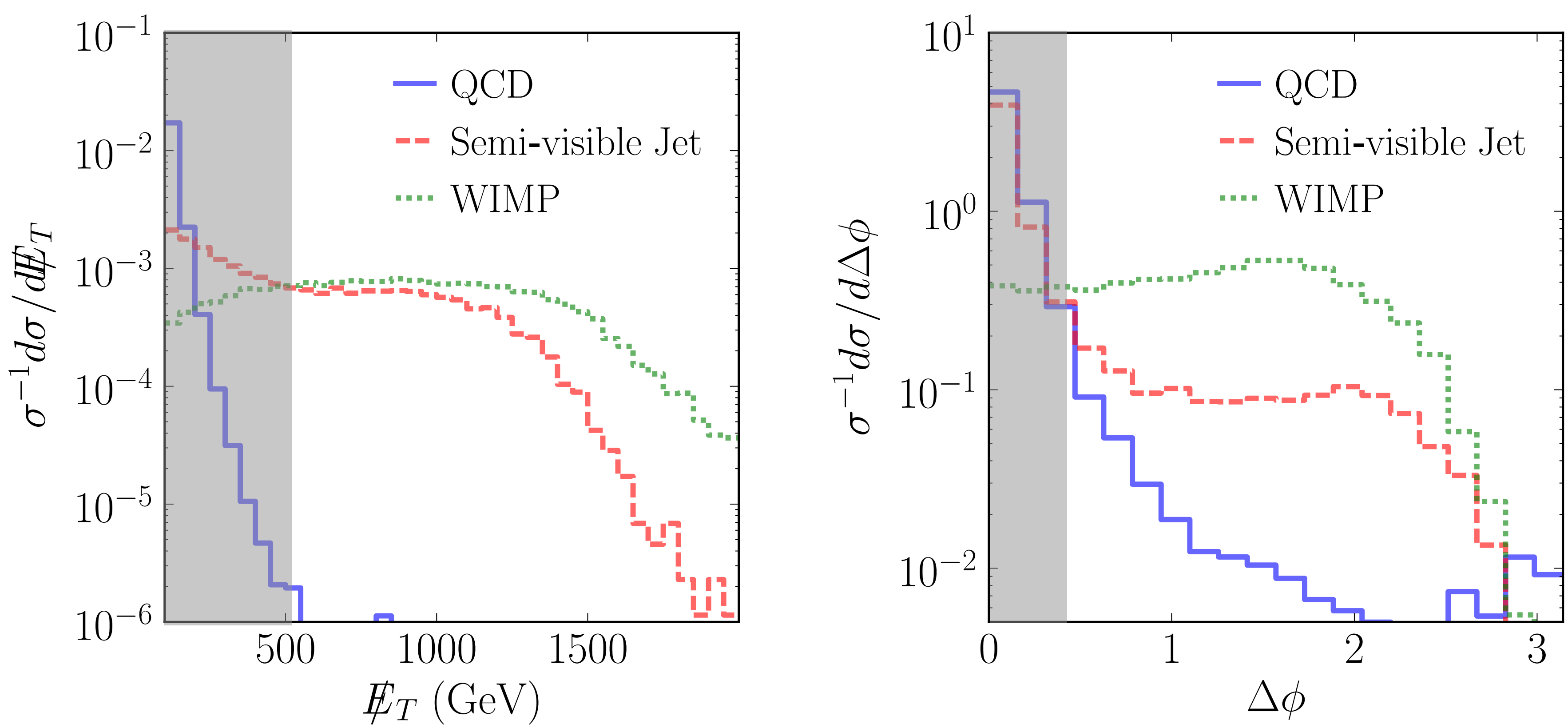
multijet+MET signature where one of the jets is closely aligned with the direction of missing energy

Semi-Visible Jets

Typical LHC searches require $\Delta\phi \gtrsim 0.4$

Acceptance after $\Delta\phi \gtrsim 0.4$ & $\mathrm{MET} > 500\ \ \mathrm{GeV}$:

$\sim 70\%$ WIMP $\sim 7\%$ Semi-visible jet



Outline

Status of Dark Matter Searches at LHC

Hidden Dark Sectors

Discovering Semi-Visible Jets

Simplified Model Approach

Seemingly infinite possibilities for the dark sector

At first glance, may seem impossible to develop a systematic search strategy to scan relevant parameter space

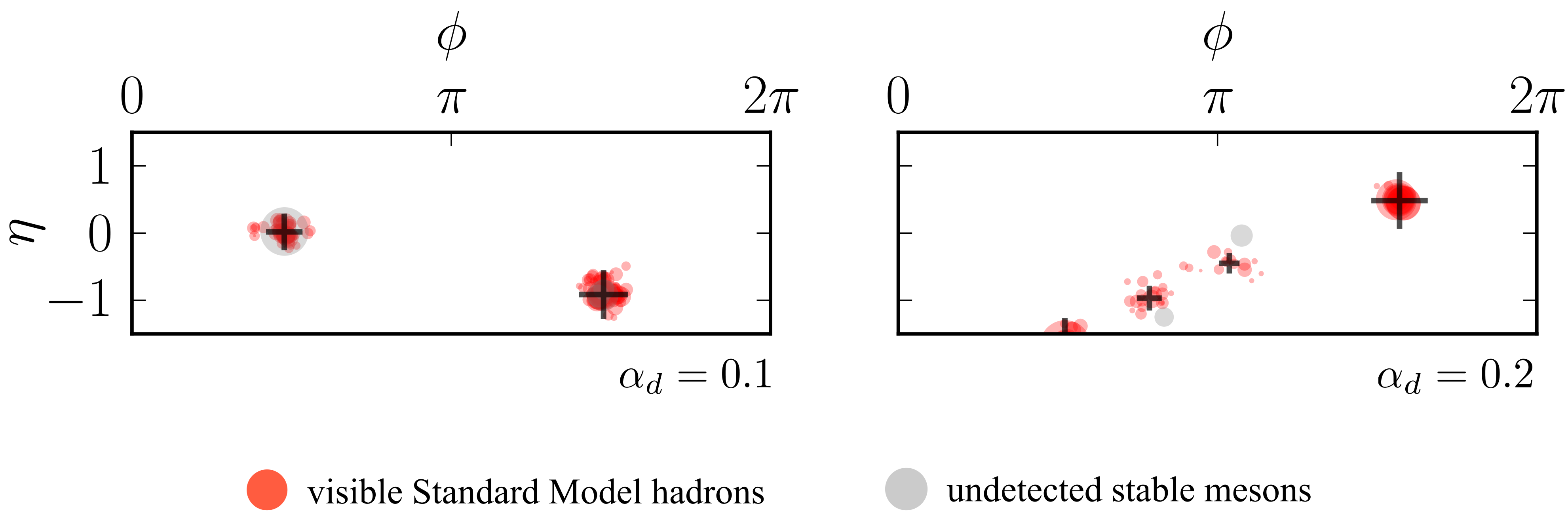
However, many of the details of the dark sector spectrum are not relevant for quantities measured in the detector

Focus on dark sector parameters that are most important for observable quantities

Dark-Sector Gauge Coupling

α_d parametrizes the strength of the dark shower

Increasing α_d increases the number of dark hadrons emitted in the shower, as well as their p_T distributions

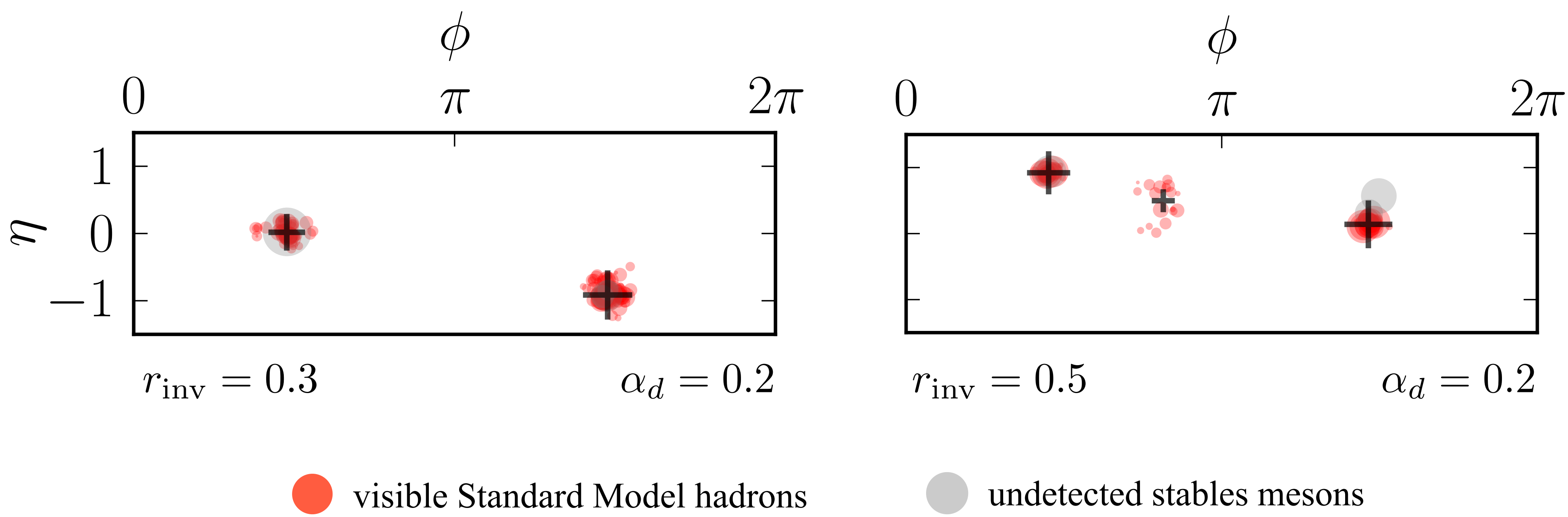


Invisible Ratio

Parametrize uncertainty in # of dark matter particles produced in shower using

$$r_{\text{inv}} = \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$

Depending on the details of the dark sector spectrum, r_{inv} = [0,1]



Parametrization

		DESCRIPTION	BENCHMARK
Portal	$\sigma \times \mathrm{Br}$	cross section $\times$ branching ratio	80 fb
	$M_{Z'}$	Z' pole mass	3 TeV
Dark Sector	M_d	dark hadron mass scale	20 GeV
	$\alpha_d(1\ \mathrm{TeV})$	running dark coupling	0.2
	r_{inv}	ratio of stable to unstable	0.3

Monte Carlo

Z' events generated in PYTHIA8 and dark sector shower simulated with the Hidden Valley module

$\mathrm{QCD},\ W^{\pm}/Z^{0} + \mathrm{jets},\ t\bar{t}$ events generated at the parton-level with MADGRAPH, then showered and hadronized in PYTHIA8

Resulting particles processed through DELPHES3, with default CMS settings

QCD backgrounds and MET distributions validated against the published results from CMS

Cut Flow

Two R=1.1 Cambridge/Achen jets (j_1, j_2)

Large jets capture wider radiation patterns

Require $|\eta_{j_1} - \eta_{j_2}| < 1.1$

To remove t-channel QCD

Require alignment between jet p_T and missing energy

Veto isolated muons and electrons

To suppress electroweak backgrounds

Require $\not{E}_T / M_T > 0.15$

Effective MET requirement to suppress QCD

Transverse Mass

Two semi-visible jet final state

Invariant Mass, M_{jj}

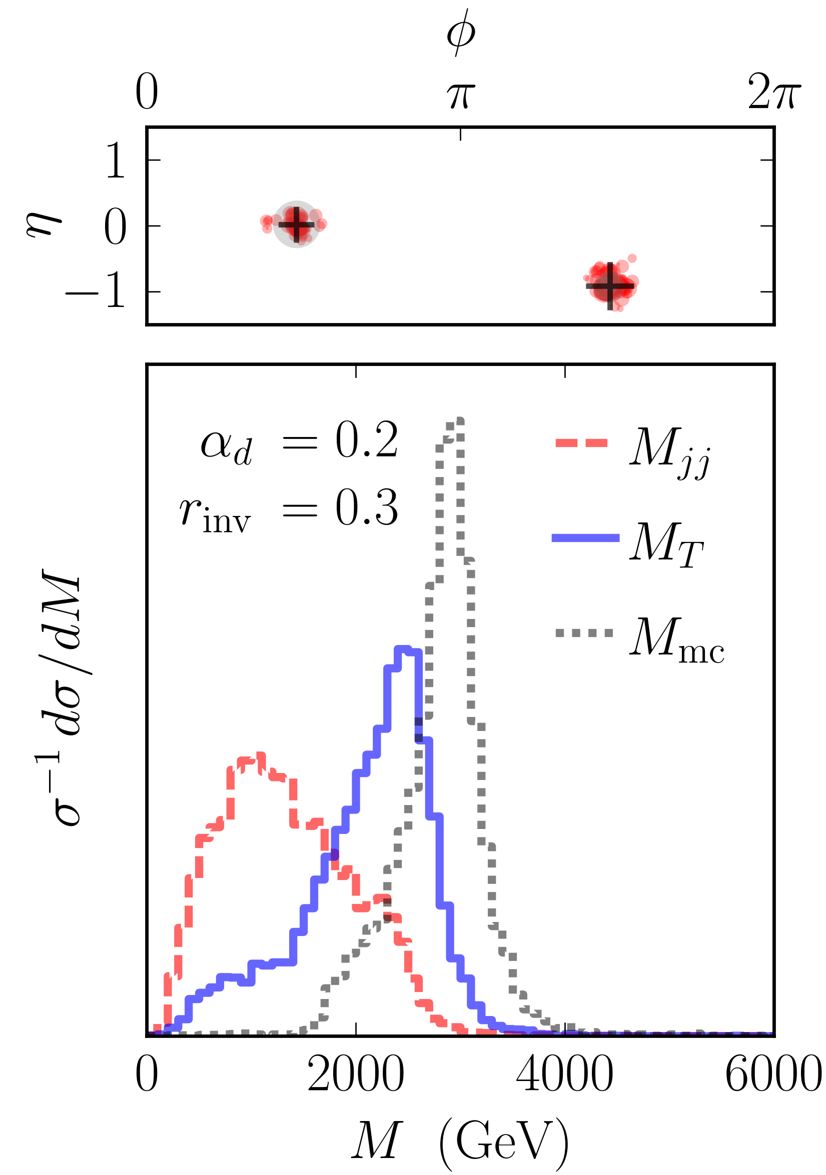
$$M_{jj}^2 = (p_{j_1} + p_{j_2})^2$$

Transverse Mass, M_T

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

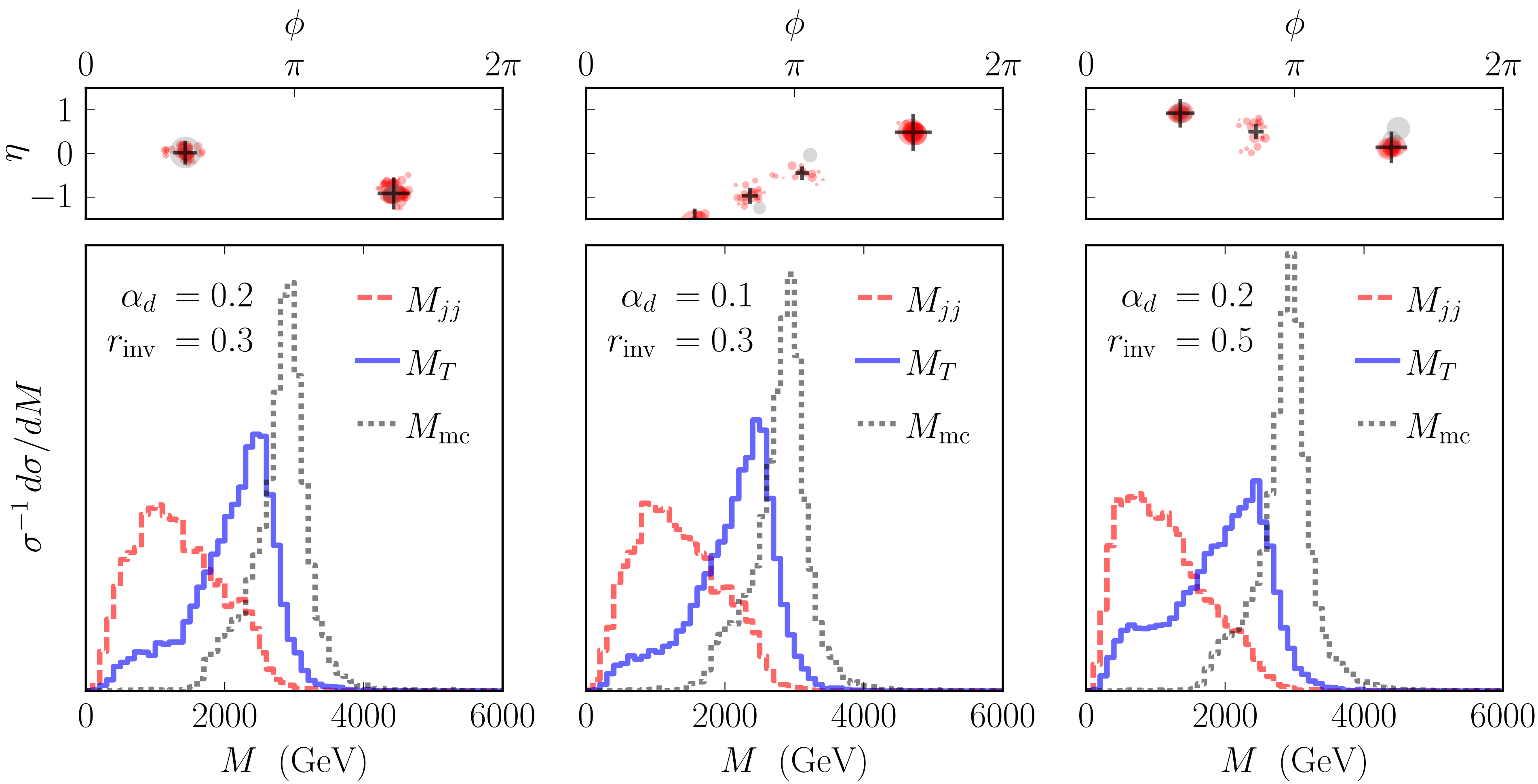
Truth-level Mass, M_{mc}

Reconstructed $M_{Z'}$ from all reclustered jets and truth-level dark-matter four vectors



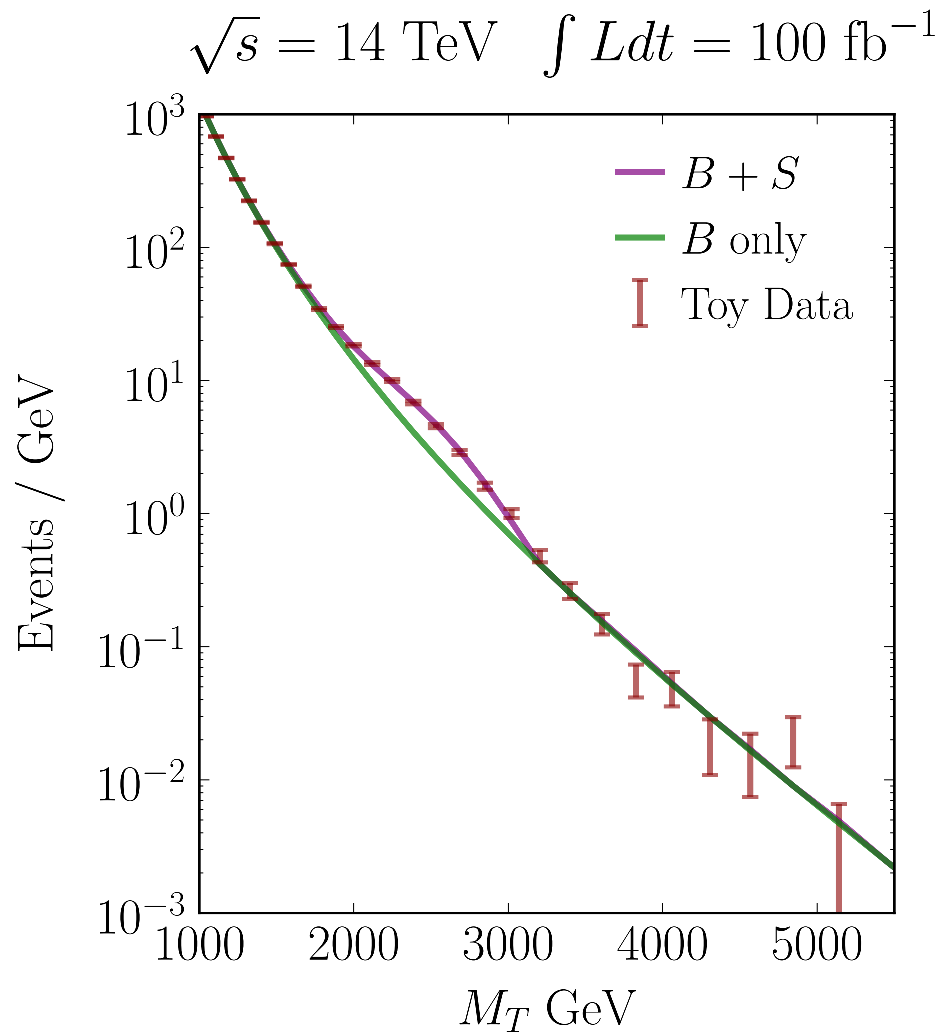
Transverse Mass

M_T can yield a narrower, more prominent peak than M_{jj}, depending on α_d and r_{inv}

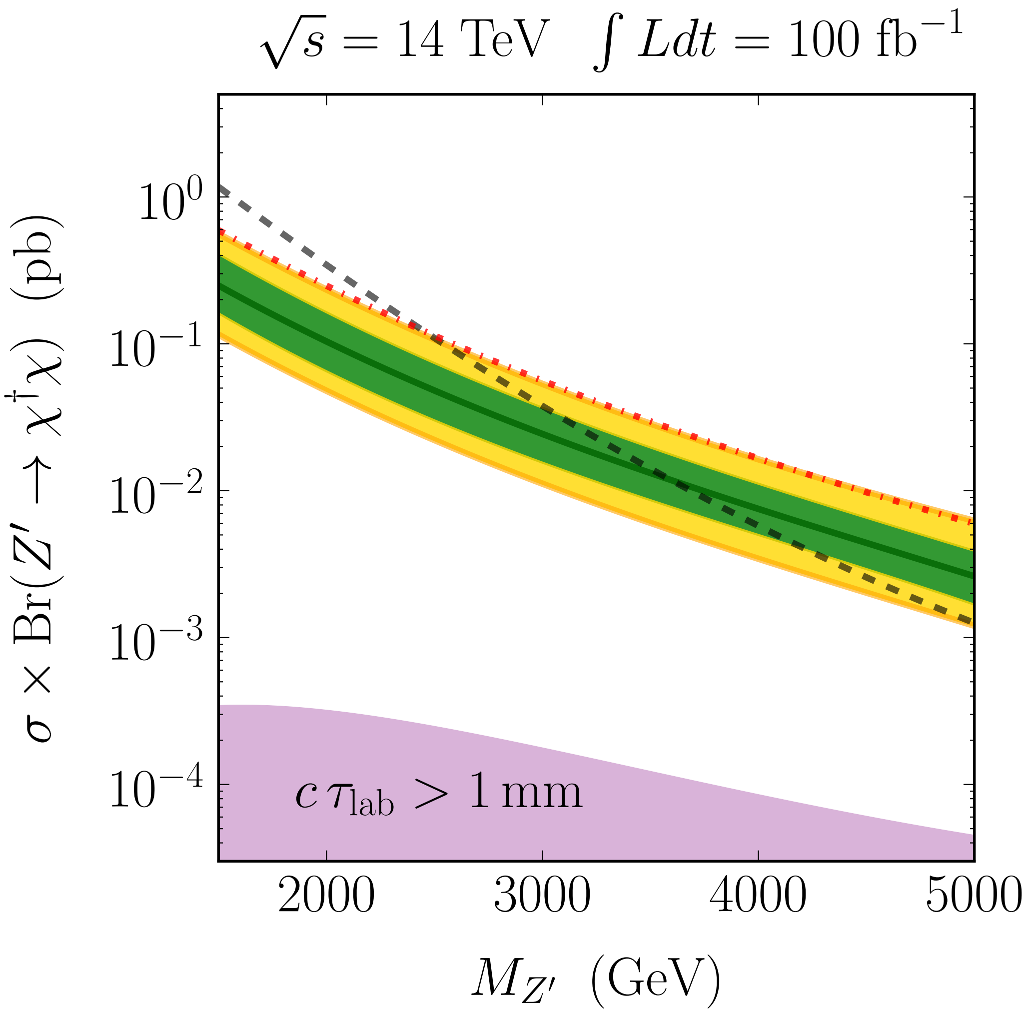


Bump Hunt

Use of transverse mass effectively turns this search into a massive resonance bump hunt



Projected Sensitivity



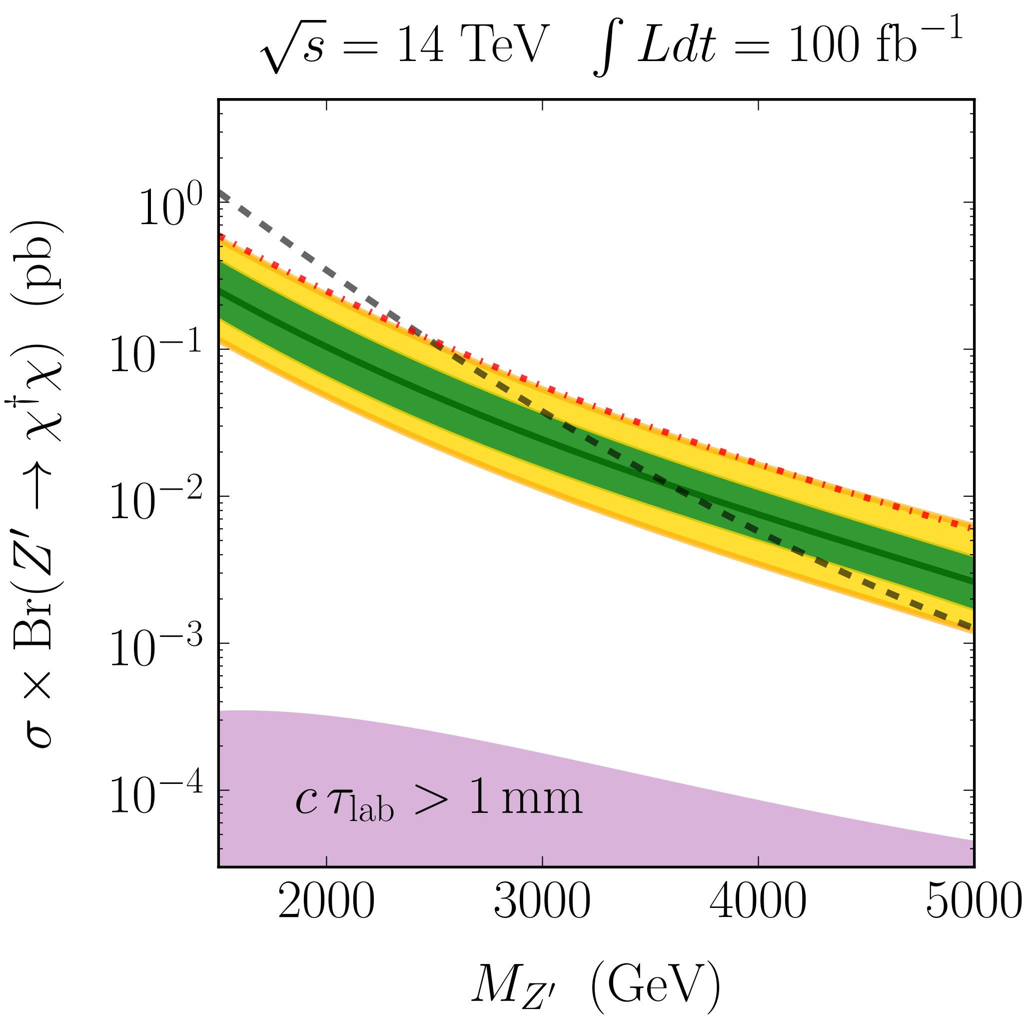
$(M_d = 20$ GeV, $\alpha_d = 0.2, r_{\mathrm{inv}} = 0.3)$

σ×Br for Z' with the same coupling to quarks as the SM Z^0

Projected limits for signal benchmark

Z' with SM couplings can be probed up to masses of ~3.5 TeV

Projected Sensitivity



Dijet limit on σ×Br(Z′→qq) comparable to that for dark-sector decay mode

Branching ratio to dark sector varies from 80% to 50% along expected exclusion bound

Discovered in semi-visible dijet channel first

Conclusions

Hidden dark sectors arise in many new-physics models and can lead to interesting phenomenology

Semi-visible jets are one so-far unexplored possibility

Semi-visible jets from the decay of a heavy resonance can be discovered by doing a “bump hunt” in transverse mass

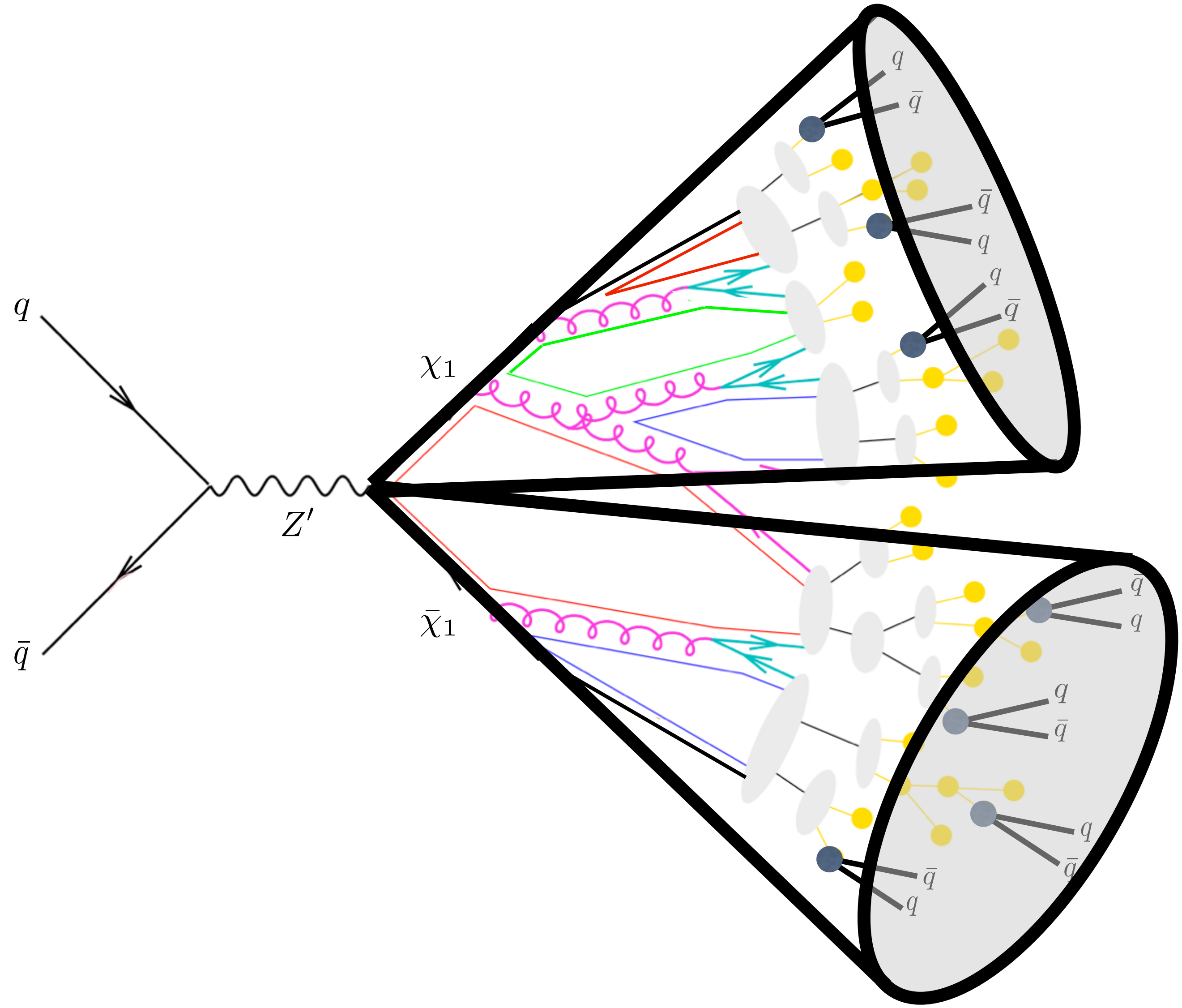
Next Steps

Develop a systematic search strategy to cover the wide array of possibilities for dark-sector physics

Strategies to cover all possible...

production modes

decay channels



Backup Slides

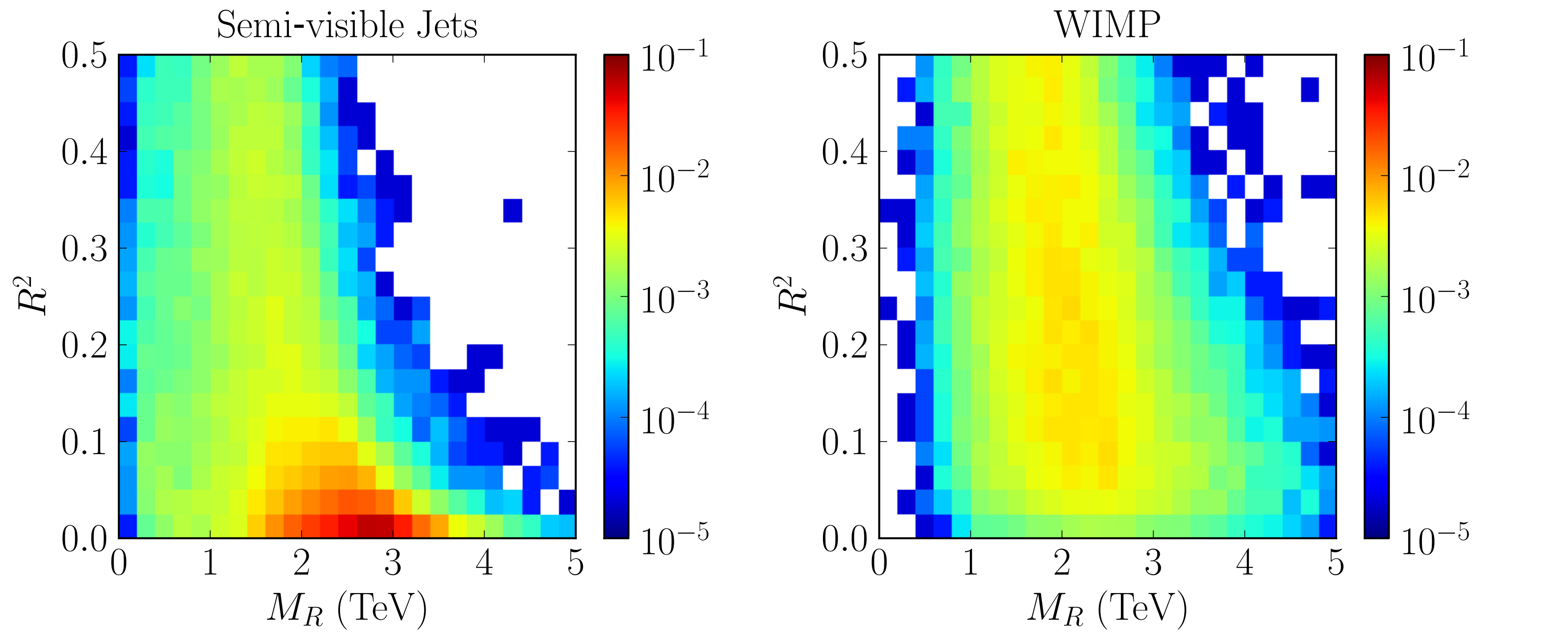


FIG. S1: The R^2 vs. M_R distribution for the strongly coupled *(left)* and weakly coupled *(right)* dark-matter models from Figure 1 in the main Letter. The color scale denotes the fraction of events in each bin.

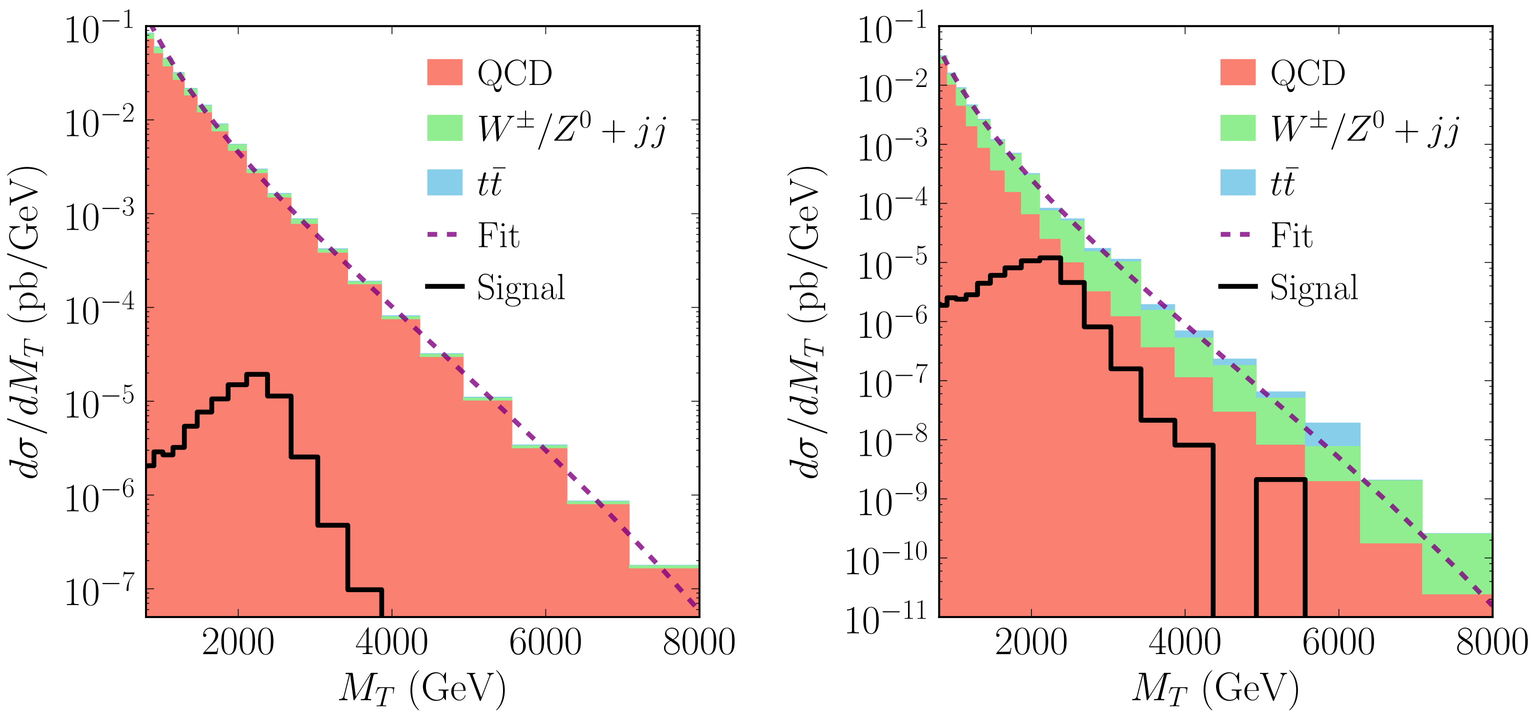


FIG. S2: M_T distribution before *(left)* and after *(right)* an $\not\!\!E_T/M_T > 0.15$ requirement. (All other selection criteria are applied for both panels.) The QCD, $W^{\pm}/Z^0 + jj$, and $t\bar{t}$ backgrounds are shown in red, green, and blue, respectively, and are stacked. The dashed purple curve is an analytic fit to the total background using Eq. S3. The solid black curve corresponds to the benchmark signal, with parameters listed in Table I.