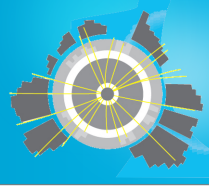


Dark Matter and Co-annihilation

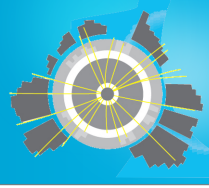
Yi Cai

The University of Melbourne

July 11, 2013

w/ N. F. Bell and A. Medina(in progress)

Outline



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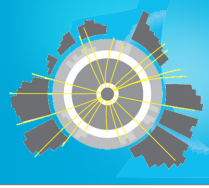
Outline



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Crucial Facts of Dark Matter

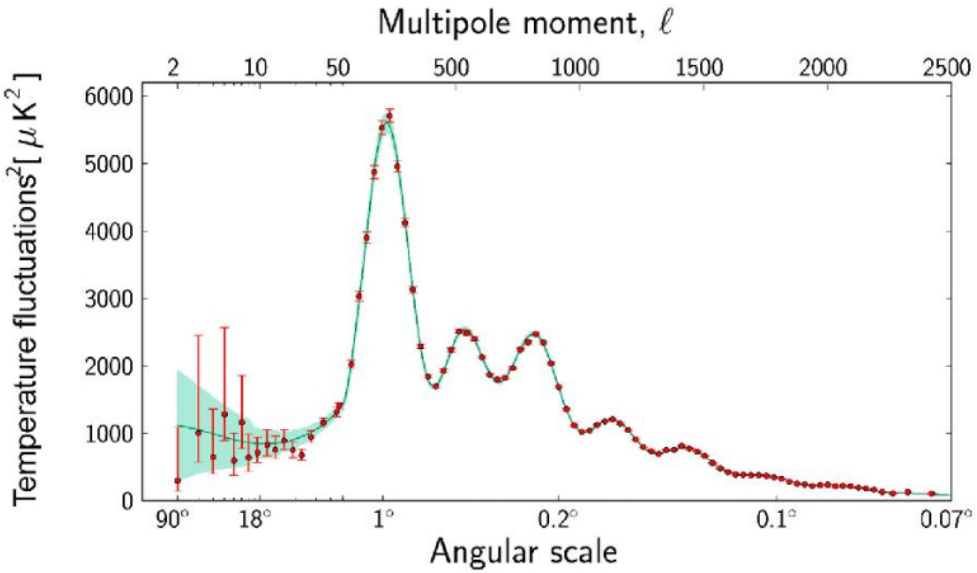
Story told more than $\mathcal{O}(10^3)$ times

Wide Range of Proofs of the Existence of DM

- Different scales: from galactic to cosmological
- Different ages: from the early universe to the present

Mere Knowledge of DM Properties

- Dark
- Massive
- Beyond the SM
- Ωh^2



Planck 2013

Search for Dark Matter

Direct Detection

DM particle scatters off nuclei at the Earth.

Low event rate

Indirect Detection

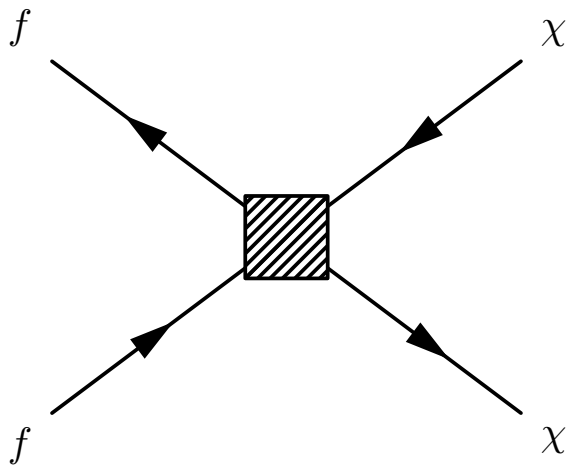
DM particles annihilate at the high density area.

Astrophysical complexities

Collider Search

DM are produced and escape from the detector. MET will be observed.

Impossible to identify



Observations from different experiments may or may not be the results of the same operators.

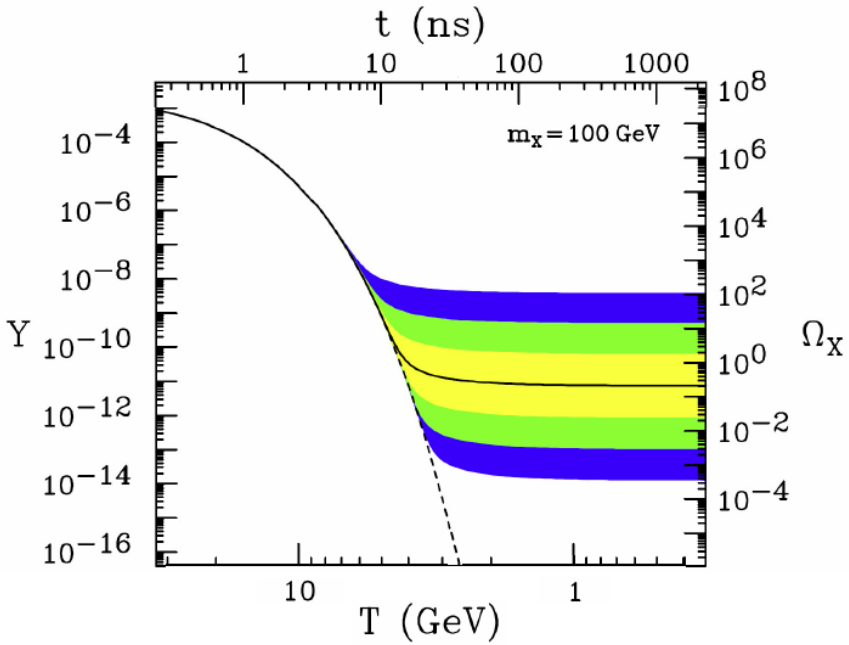
Candidates for Dark Matter

WIMP Miracle

- Weak scale mass
- Weak scale interaction strength

$$\Downarrow$$

$$\Omega h^2 \sim \mathcal{O}(0.1)$$



Other Candidates

- Axions
- Gravitinos
- Sterile neutrinos $\cdots$

Another approach? the EFT.

Effective Operators

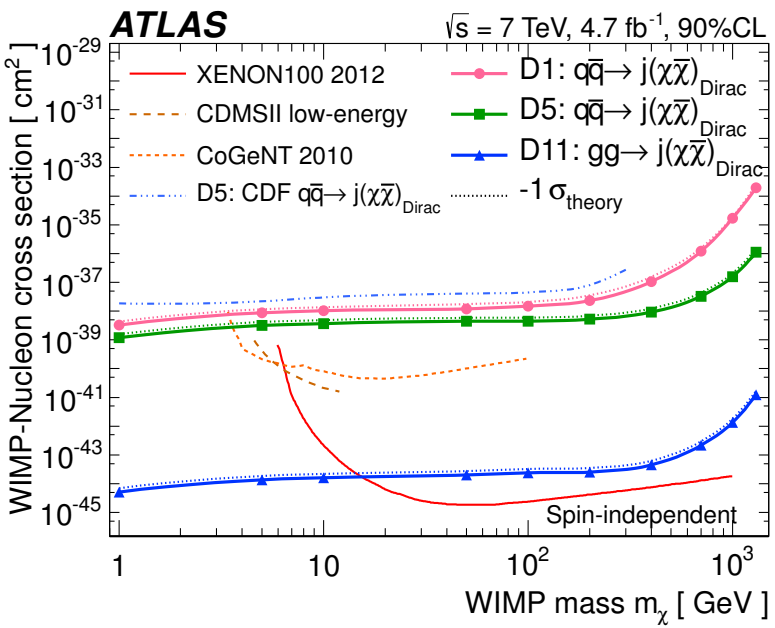
Certain operators describe the physics at both colliders and direct detection experiments.

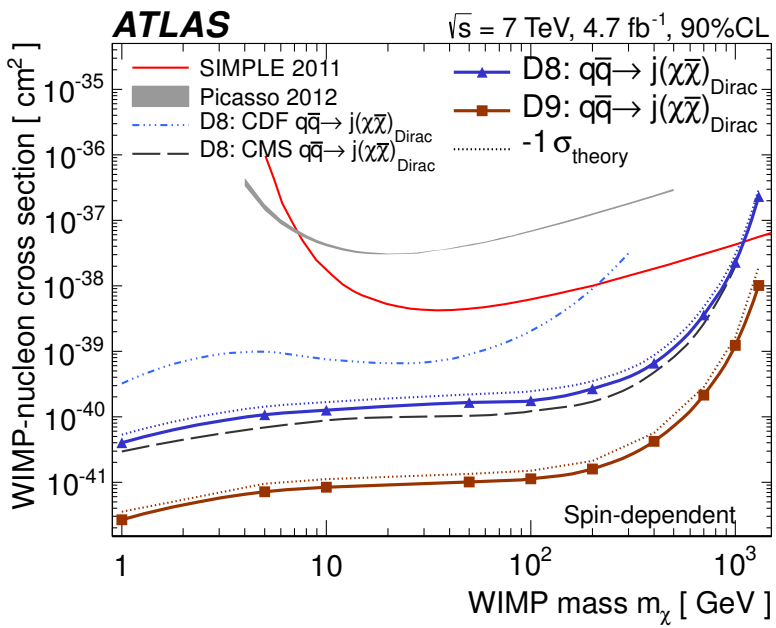
Example

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$$

Comparison

$$\sigma_{SI/SD} \sim \frac{1}{\Lambda^4} \sim \sigma_{pp\to j+MET}$$





Possible Issues

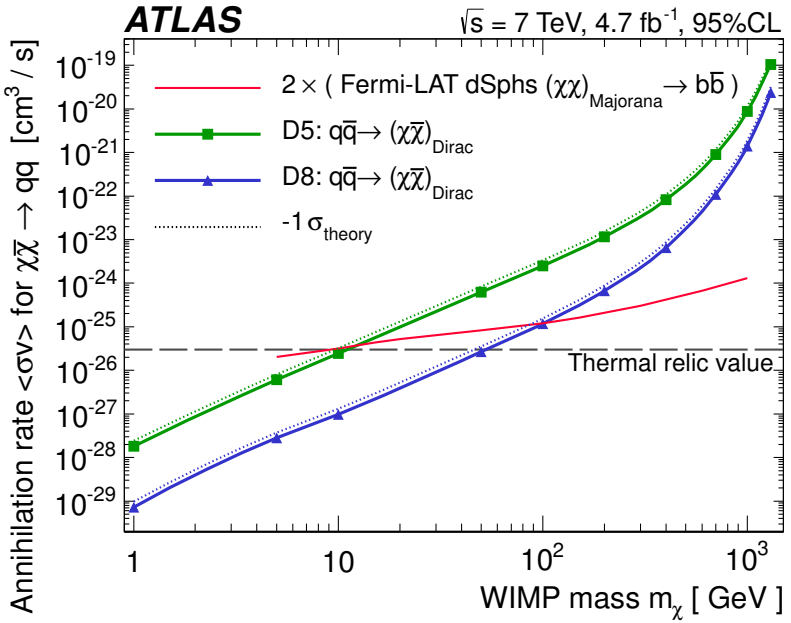
Breakdown of the EFT and the Relic Abundance

Effective Theory

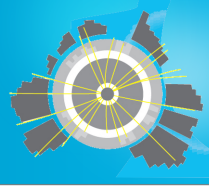
- Momentum transfer: MeV in DD v.s. TeV at colliders
- $\Lambda = \frac{M}{\sqrt{g_\chi g_q}} \Rightarrow M \sim$ TeV from perturbativity
  The particle can be produced on shell.
- Unitarity $\Rightarrow \sqrt{s} \lesssim$ TeV

Relic Abundance

- Usually can not produce the required amount
- Other operators needed



Outline



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How to get Ωh^2?

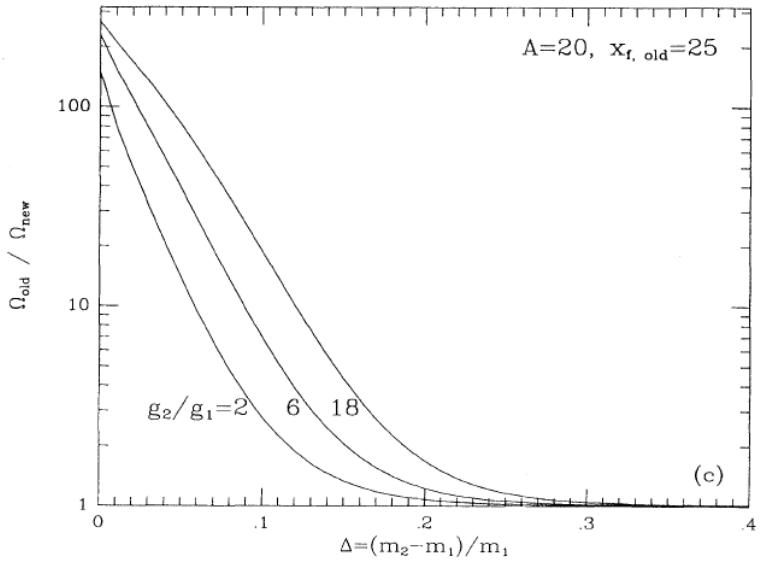
Coannihilation

- Boltzmann equation $\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$
- The effective cross section for the whole dark sector

$$\sigma_{\text{eff}} = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}^2} (1 + \Delta_i)^{\frac{3}{2}} (1 + \Delta_j)^{\frac{3}{2}} \times e^{-x(\Delta_i + \Delta_j)}$$

Example

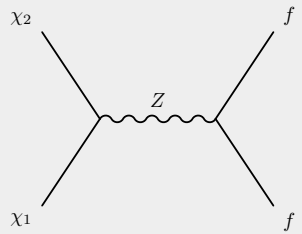
- Two particles: $\chi_{1,2}$
- $\sigma_{22} = A\sigma_{12} = A^2\sigma_{11}$
- Sizable effect as long as $\Delta < 10\%$



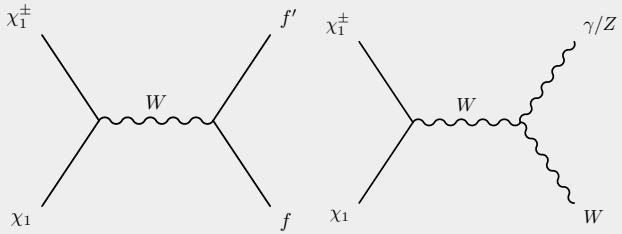
Models with Coannihilating DM

Co-annihilation of DM can be important in many frameworks.

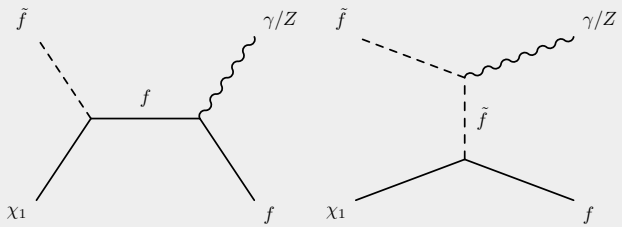
SUSY



higgsino-like LSP

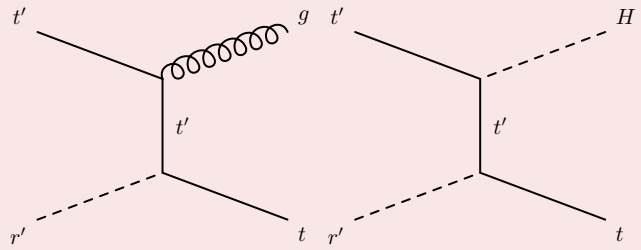


higgsino- and wino-like LSP



$\tilde{f}$ slightly heavier than χ_1

Extra Dimensions



radion and the first KK top excitation

Many other examples in the literature

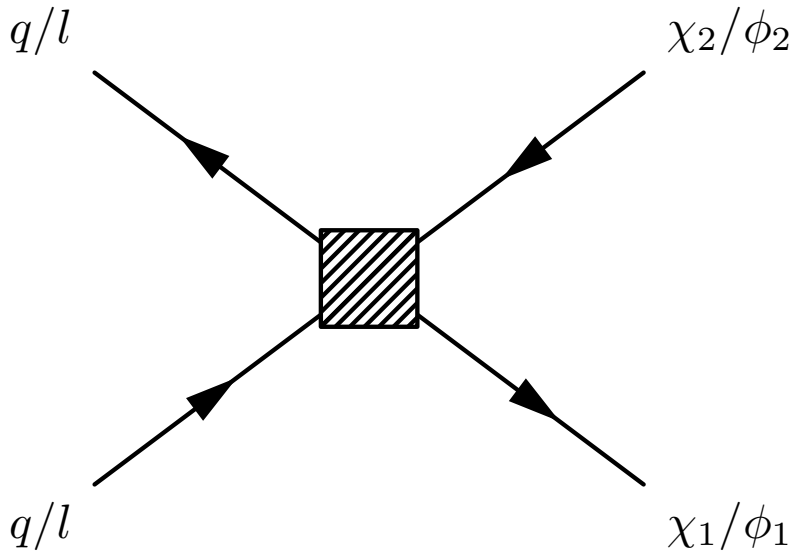
Effective Operator Description

Assumption

Only coannihilation is relevant.

Scalar	Vector
$\frac{\bar{\chi}_1\chi_2\bar{q}q}{\Lambda_q^2}$	$\frac{\bar{\chi}_1\gamma^\mu\chi_2\bar{q}\gamma_\mu q}{\Lambda_q^2}$
$\frac{\bar{\chi}_1\gamma_5\chi_2\bar{q}\gamma_5 q}{\Lambda_q^2}$	$\frac{\bar{\chi}_1\gamma^\mu\gamma_5\chi_2\bar{q}\gamma_\mu\gamma_5 q}{\Lambda_q^2}$
$\frac{\bar{\chi}_1\gamma_5\chi_2\bar{q}q}{\Lambda_q^2}$	$\frac{\bar{\chi}_1\gamma^\mu\gamma_5\phi_2\bar{q}\gamma_\mu q}{\Lambda_q^2}$
$\frac{\bar{\chi}_1\chi_2\bar{q}\gamma_5 q}{\Lambda_q^2}$	$\frac{\bar{\chi}_1\gamma^\mu\chi_2\bar{q}\gamma_\mu\gamma_5 q}{\Lambda_q^2}$

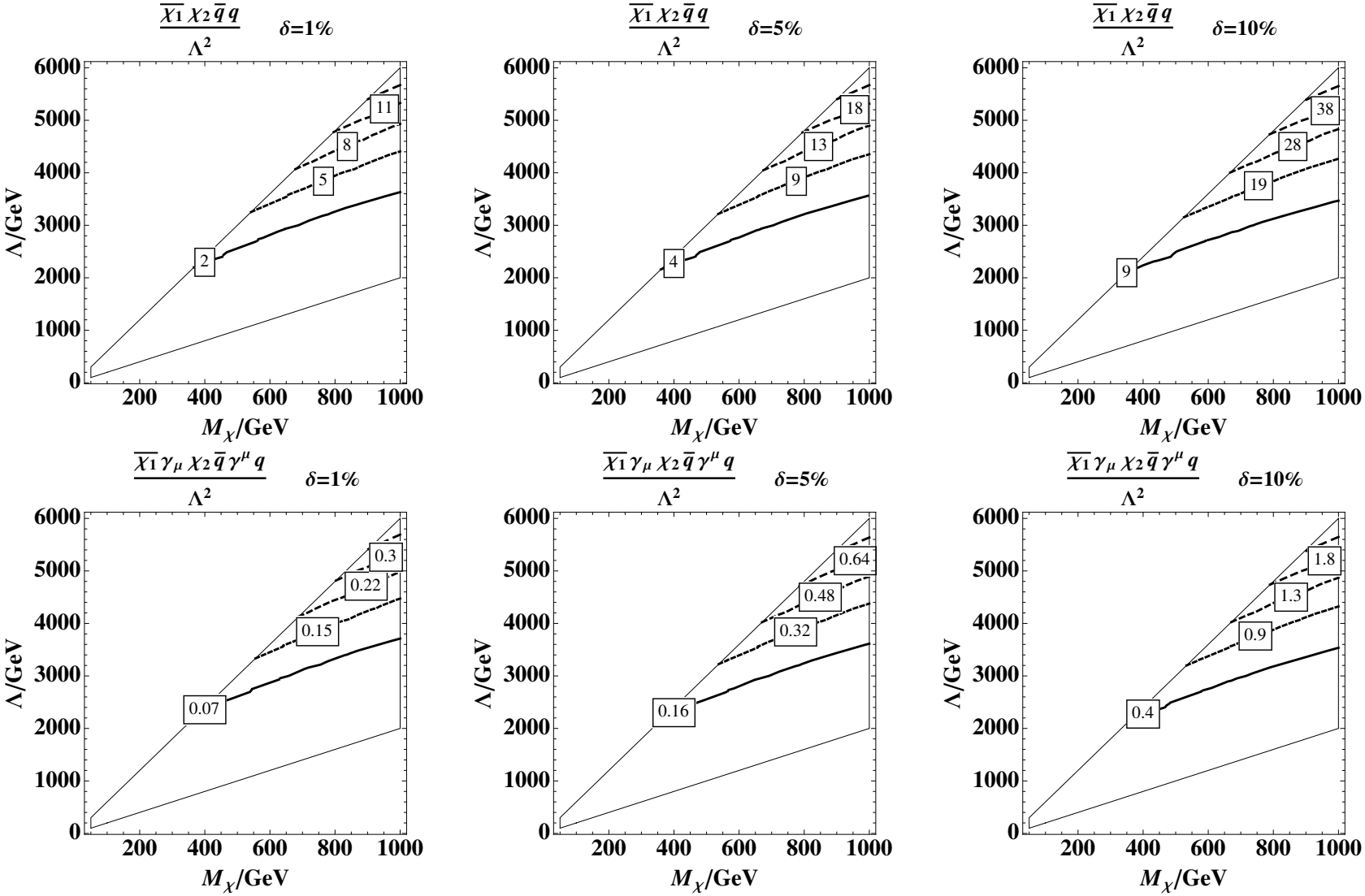
The same set of operators can exist for leptonic couplings with Λ_l .



Parameters: Λ, M_{χ_1}/M_{ϕ_1} and Δ

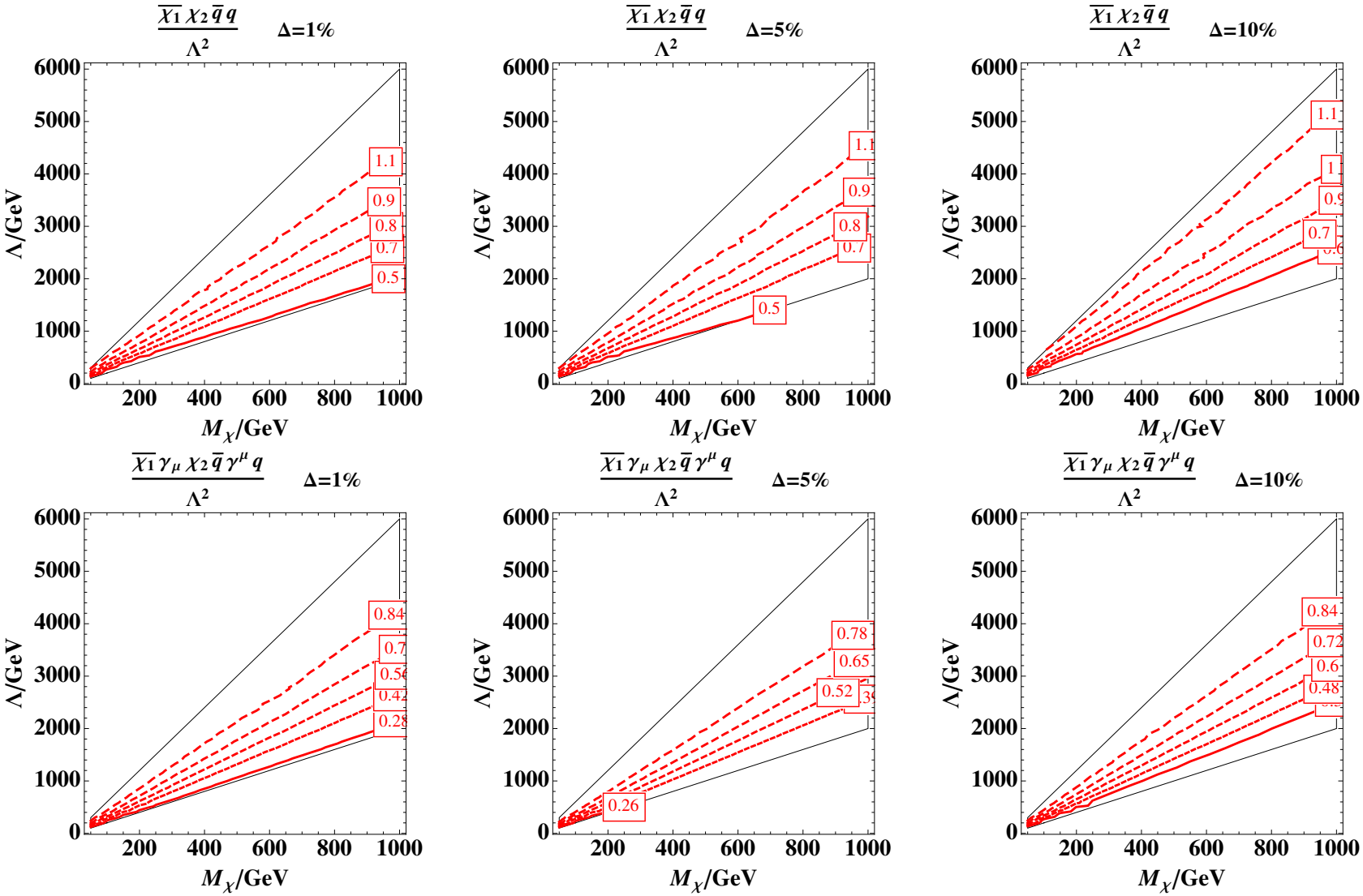
Relic Abundance

Prelim.

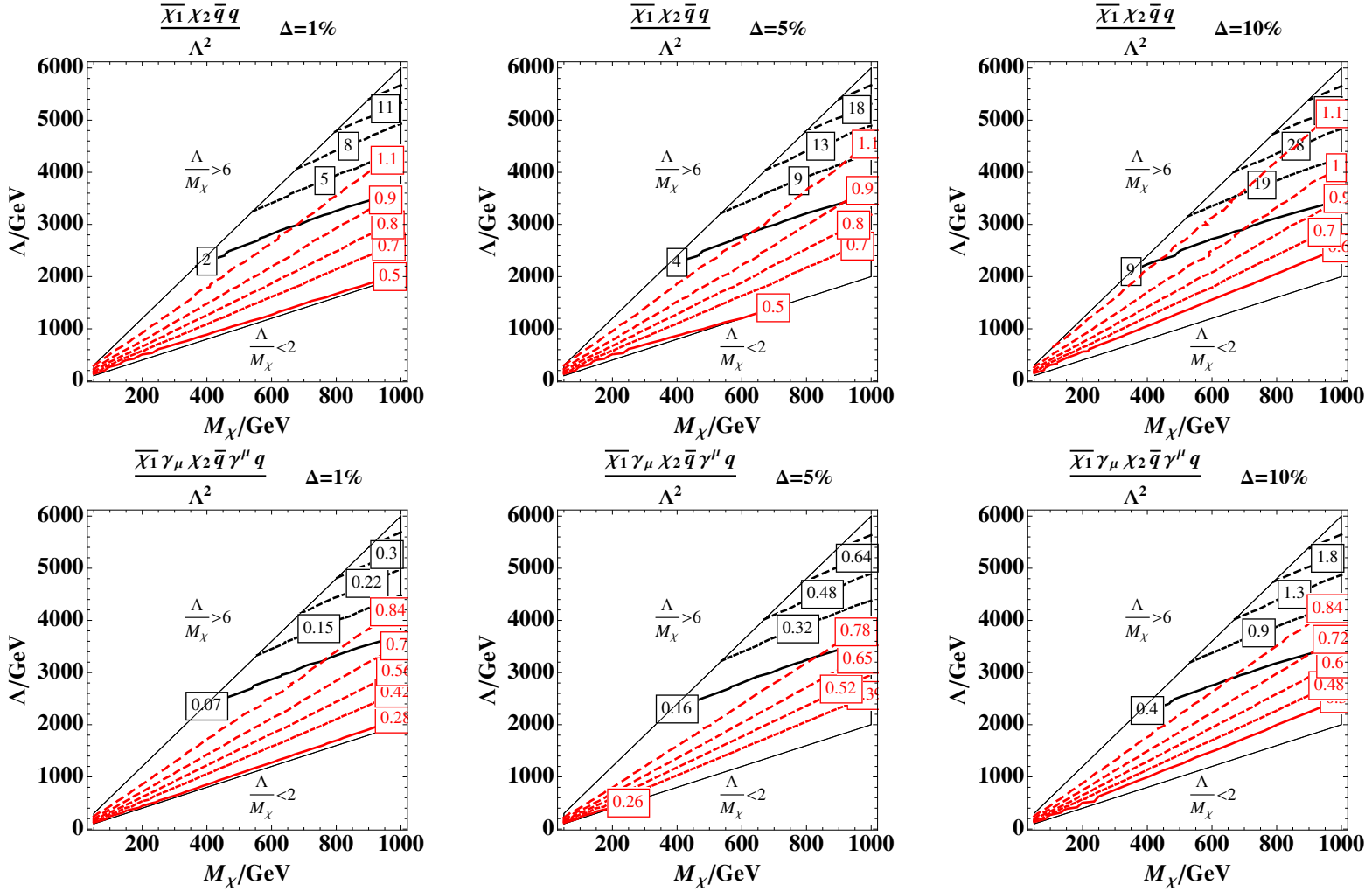


How effective is the EFT?

$\Omega h^2_{Full}/\Omega h^2_{EFT}$



The Right Description

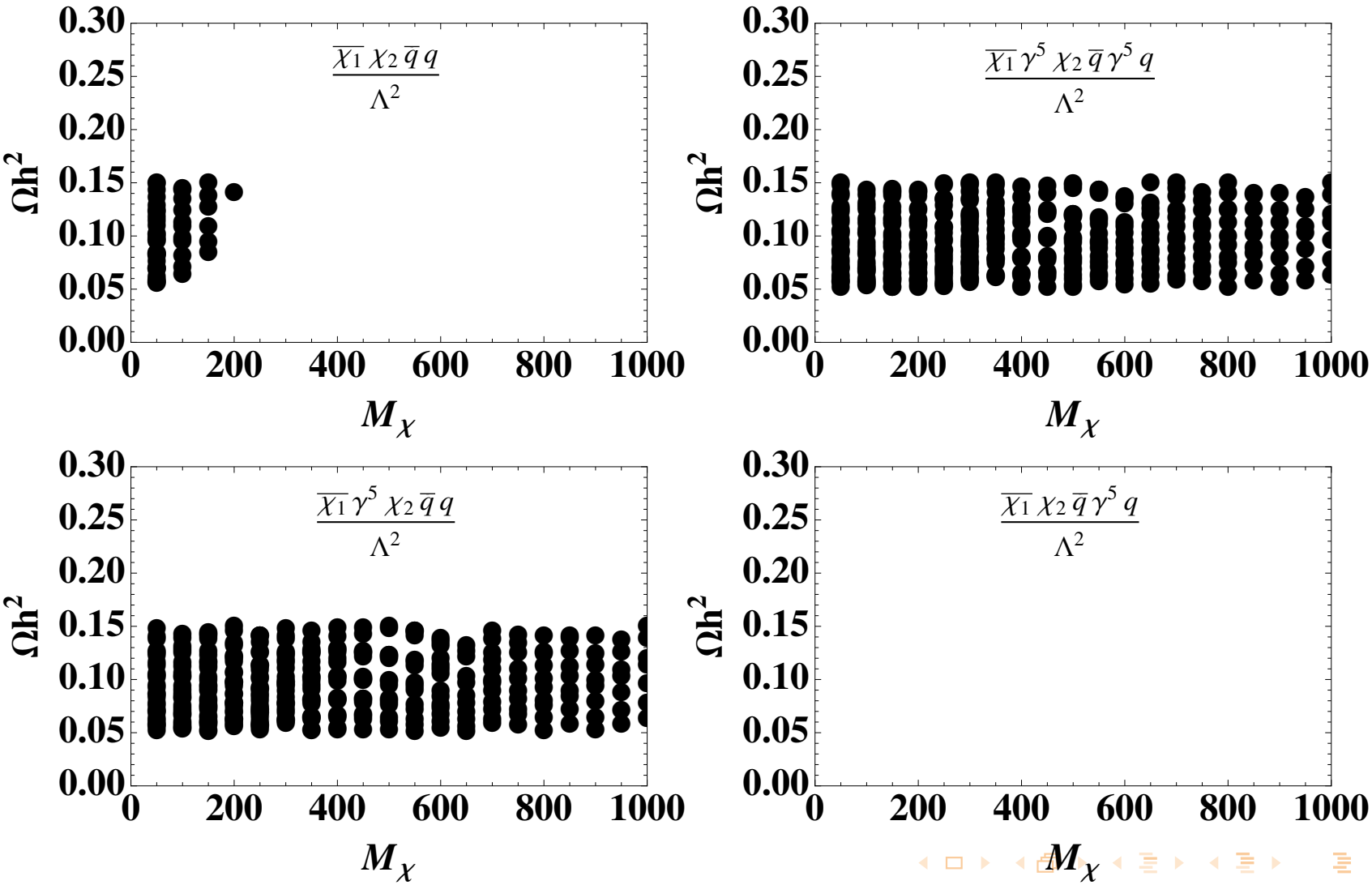


$$\Omega h^2 = 0.11$$

$$\frac{\Omega h^2_{Full}}{\Omega h^2_{EFT}} > 0.8$$

Plausible Models

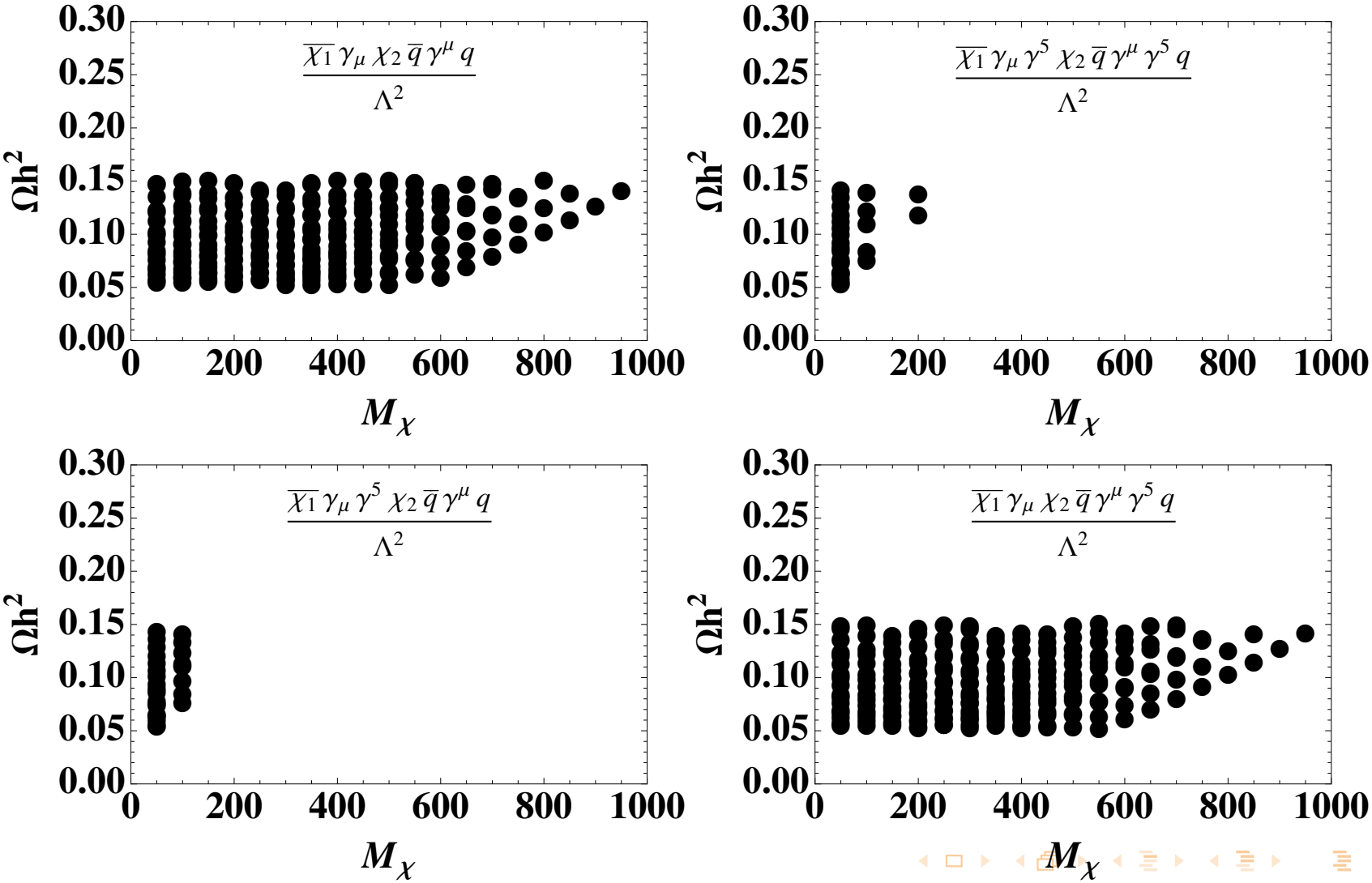
Scalar-like



Plausible Models

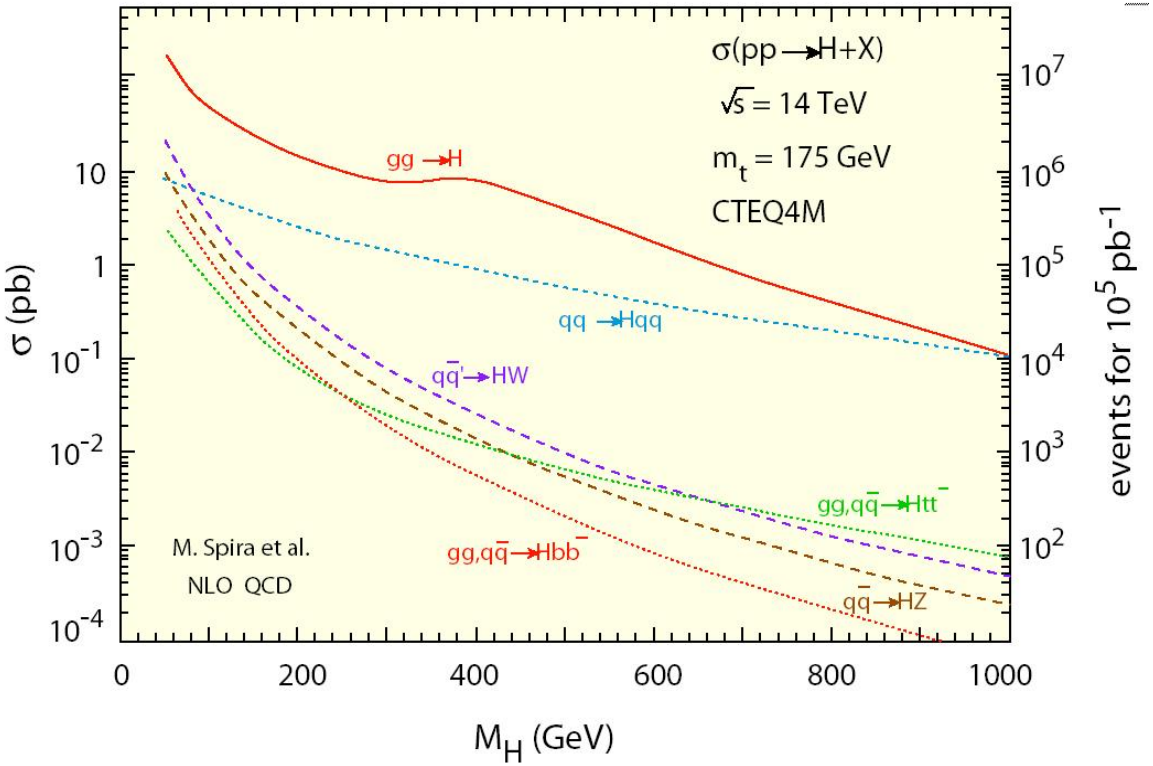
Vector-like

Vector-like



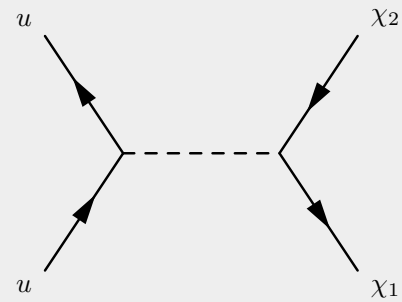
Dark Matter Production

In the full theory with couplings set to 1

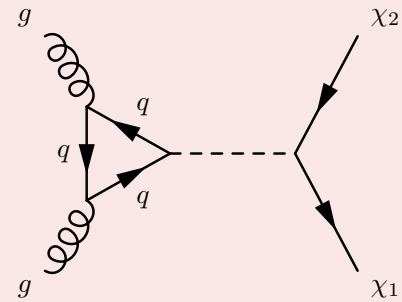


$$\frac{\sigma_\phi^{gg}}{\sigma_\phi^{q\bar{q}}} = \frac{\sigma_\phi^{gg}/\sigma_H^{gg}}{\sigma_\phi^{q\bar{q}}/\sigma_H^{q\bar{q}}} \frac{\sigma_H^{gg}}{\sigma_H^{q\bar{q}}} \sim 10^{-6}$$

Scalar-like: Tree



Scalar-like: Loop



relevant if the couplings to the first generation quarks are suppressed as the Yukawa couplings

Detection

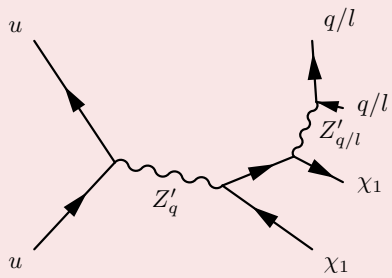
Still under construction

Testable Models at colliders

$$\sigma_{2j/2l+MET} \sim 1 fb^{-1} \Rightarrow \Lambda = \frac{M}{\sqrt{g_\chi g_q}} \text{ can not be too large}$$

$p_t > 20/10$ GeV for jets/leptons

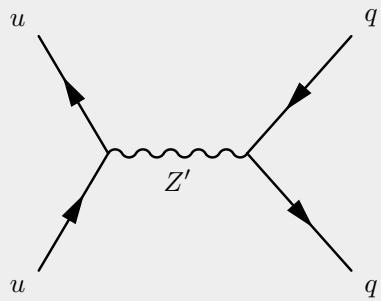
Signal: 2j/2l + MET



$\sim g_\chi g_q$

- 2j:only VV type operator gives sizable σ
  $M_\chi = 100$ GeV, $\Delta = 0.15$, $\Lambda_q = 300$ GeV, $p_t \sim 100$ GeV
- 2l: softer cuts($p_t > 10$ GeV) and the only hope

Constraint: dijet mass distribution



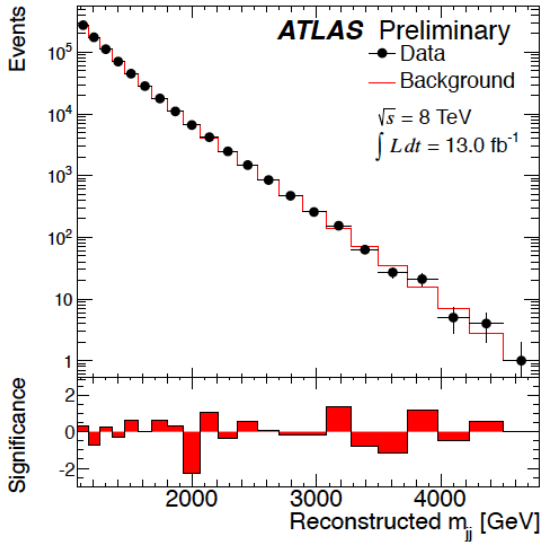
$\sim g_q^2$

the constrains coming from Z' or extra scalar searches can be evaded by making the direct couplings to first generations small while increasing the coupling to χ_1 χ_2

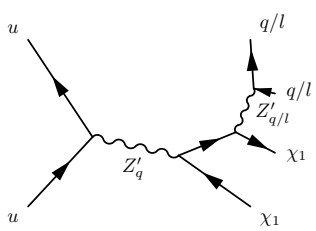
Potentially Interesting Models

Tension

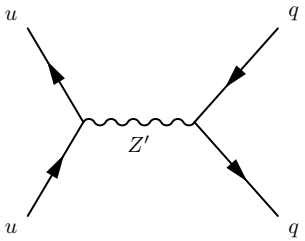
Operator	M_{χ_1}	M_{χ_2}	Λ	σ/fb^-
$\frac{\bar{\chi}_1\chi_2\bar{q}q}{\Lambda^2}$	50	53	300	.6
$\frac{\bar{\chi}_1\gamma^5\chi_2\bar{q}\gamma^5 q}{\Lambda^2}$	50	59	300	.15
$\frac{\bar{\chi}_1\gamma^5\chi_2\bar{q}q}{\Lambda^2}$	50	59	300	.15



also for the vector-like operators



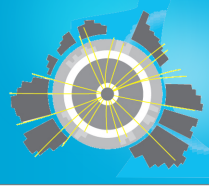
$\sim g_\chi g_q$



$\sim g_q^2$

- $g_q \downarrow$, $g_\chi \uparrow \Rightarrow \sqrt{g_q g_\chi}$ and M fixed
- $g_q \downarrow$, $g_\chi \uparrow$, $M \downarrow \Rightarrow \Lambda$ fixed
- $\cdots$ more to play with full collider simulation

Outline



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Summary

- Effective operators are not perfect description at colliders and the required relic abundance can't be produced via the same operators.
- Coannihilation enhances the annihilation cross section and the dark matter candidate is not constrained from the direct detection searches.
- Collider searches put strong constraints on these coannihilating operators(in progress).