SEARCHING FOR DARK PARTON SHOWERS AT THE LHC

Tim Cohen
University of Oregon

based on
Phys. Rev. Lett. 115, 171804 (2015)
[arXiv: 1503.00009]
with M. Lisanti, H. K. Lou
and in progress
with M. Lisanti, H. K. Lou, S. Mishra-Sharma

CERN-CKC Workshop:
"What's Going on at the Weak Scale?"
Jeju Island, South Korea
June 2, 2015

WHAT IS DARK MATTER?!?

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WHAT IS DARK MATTER?!?

WHAT IS DARK MATTER?!?

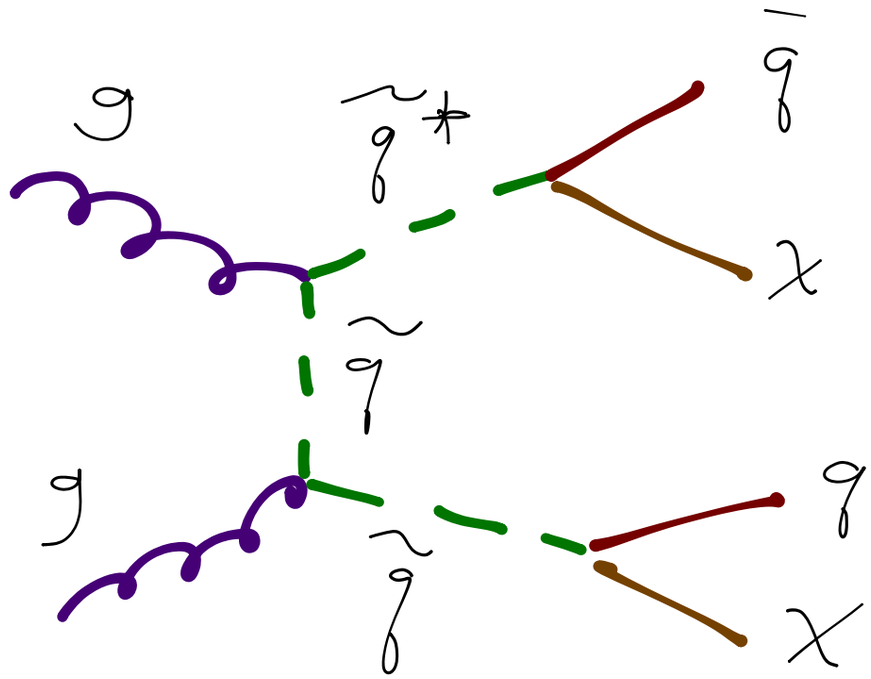
How do we ensure discovery????

Can we better optimize searches????

"WIMP" SIGNALS

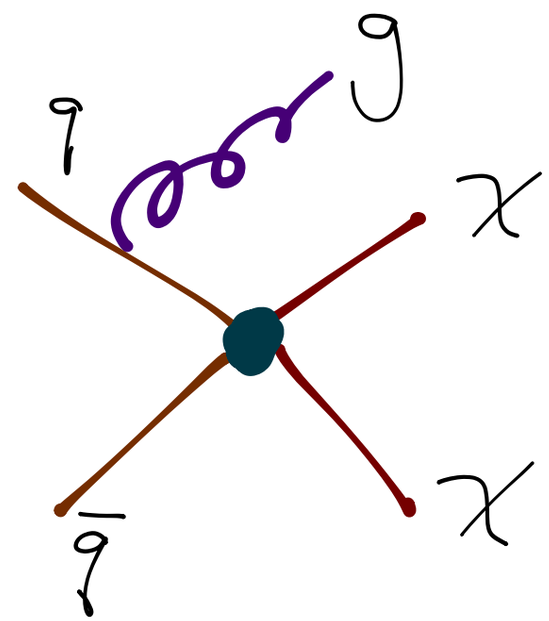
New physics in Jets + $\not{E}_T$.

Simplified Model



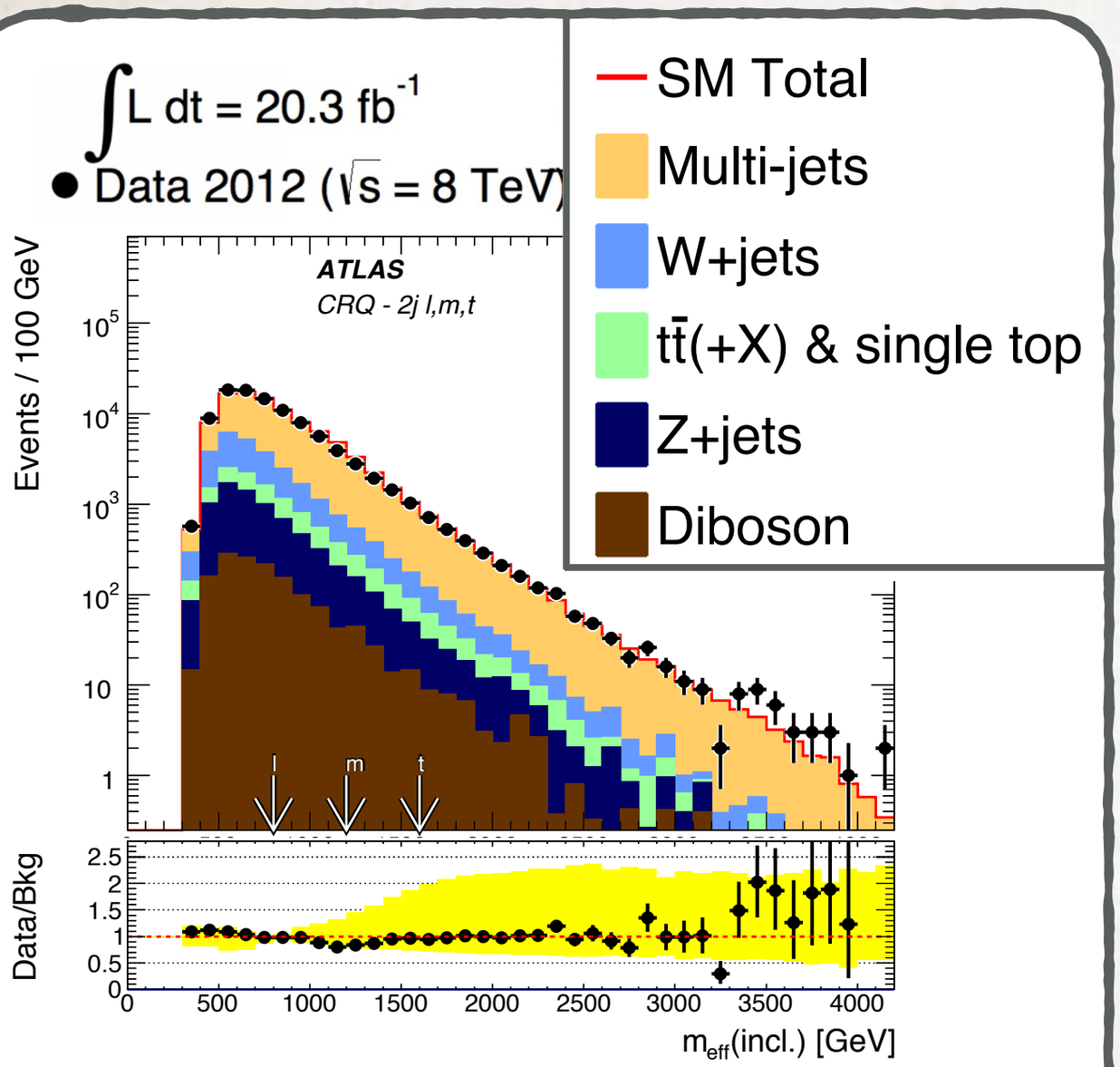
Alwall, Le, Lisanti, Wacker [arXiv:0809.3294]
Alwall, Schuster, Toro [arXiv:0810.3921]
LHC New Physics Working Group [arXiv:1105.2838]

Contact operator



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

BACKGROUNDS



Control region: $\Delta\phi(\text{jets}, \not{E}_T)$ cut reversed.

ATLAS Collaboration [arXiv:1405.7875]

QCD background:

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

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

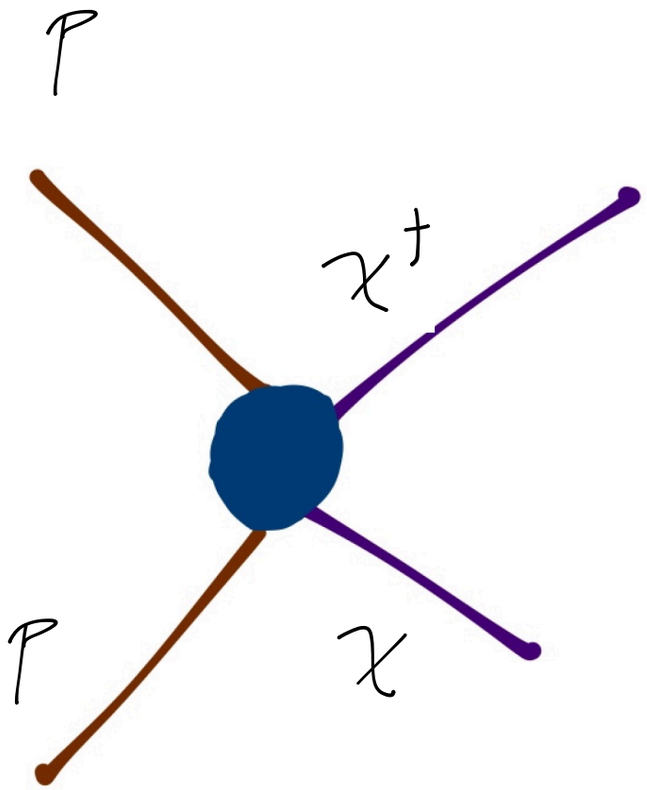
Cut on

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

DARK SHOWER

Signature made classic by "Hidden Valley" models.

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



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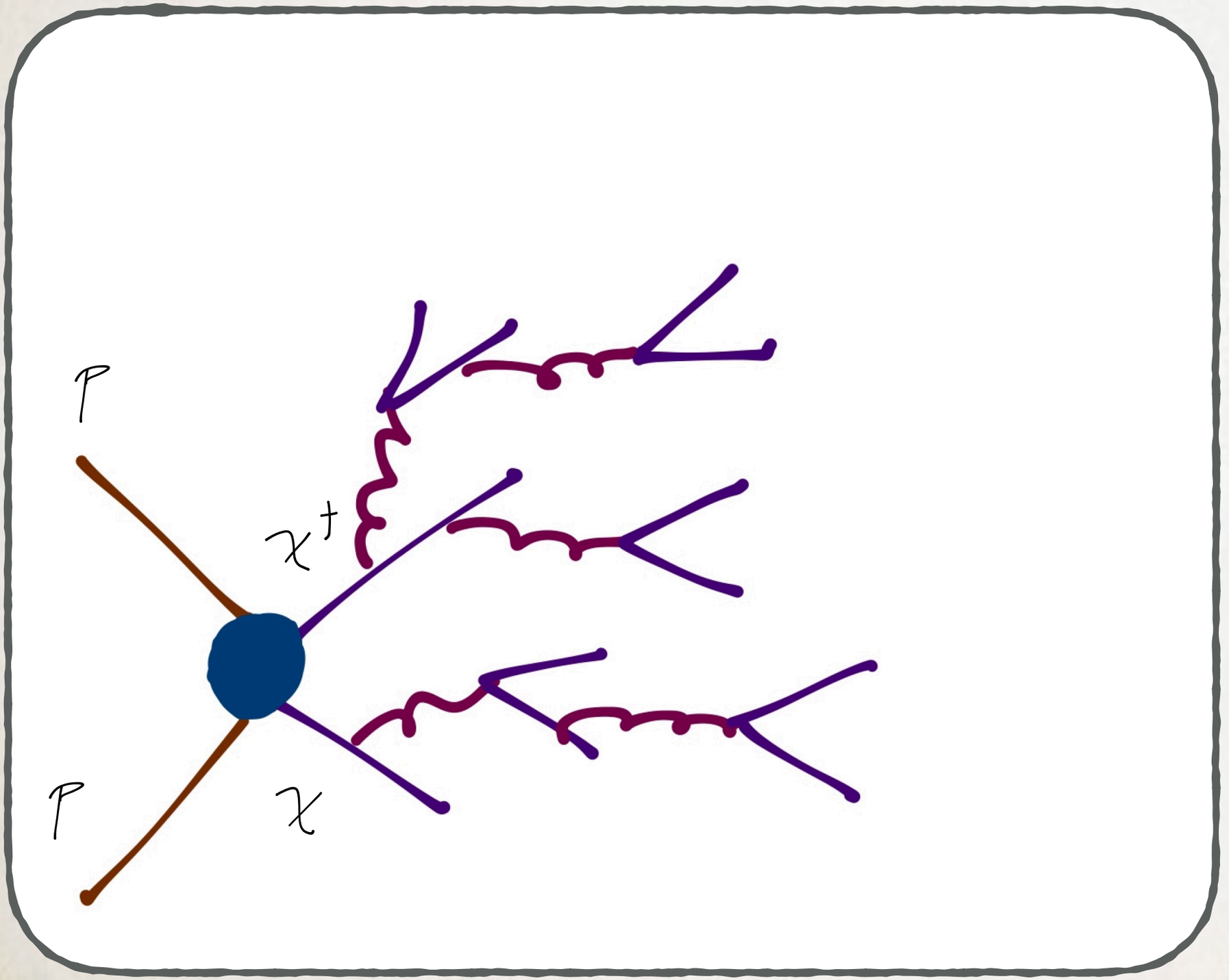

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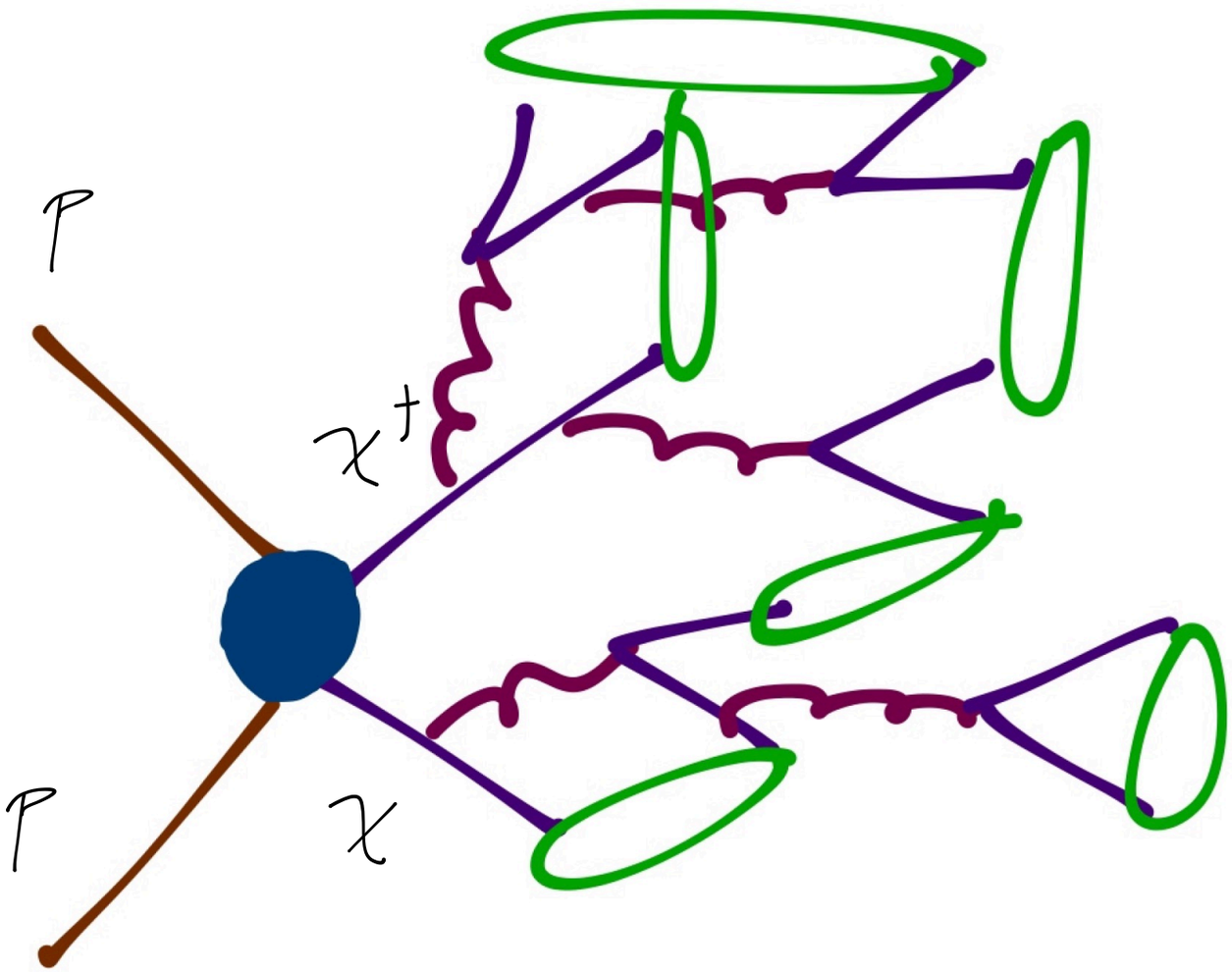

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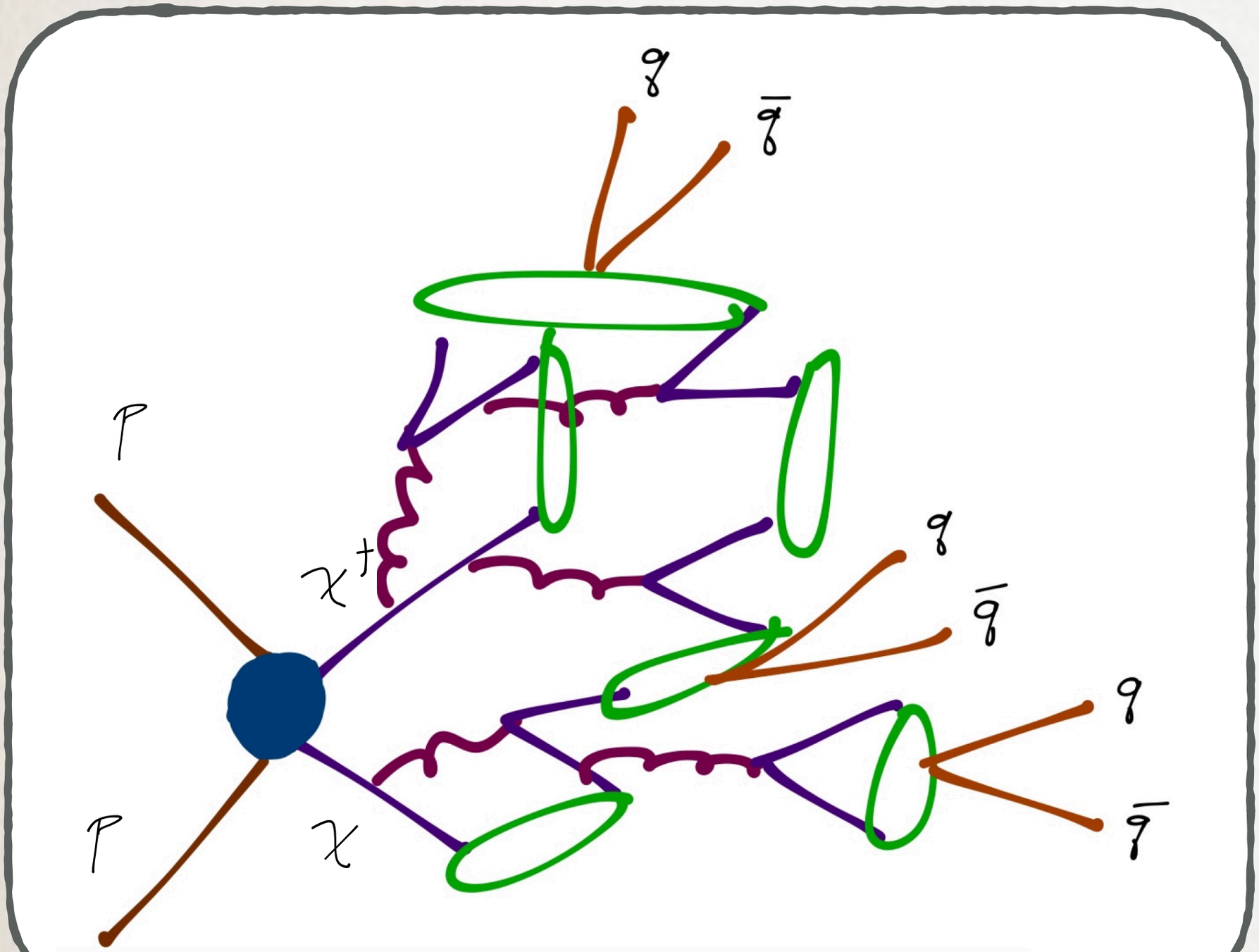

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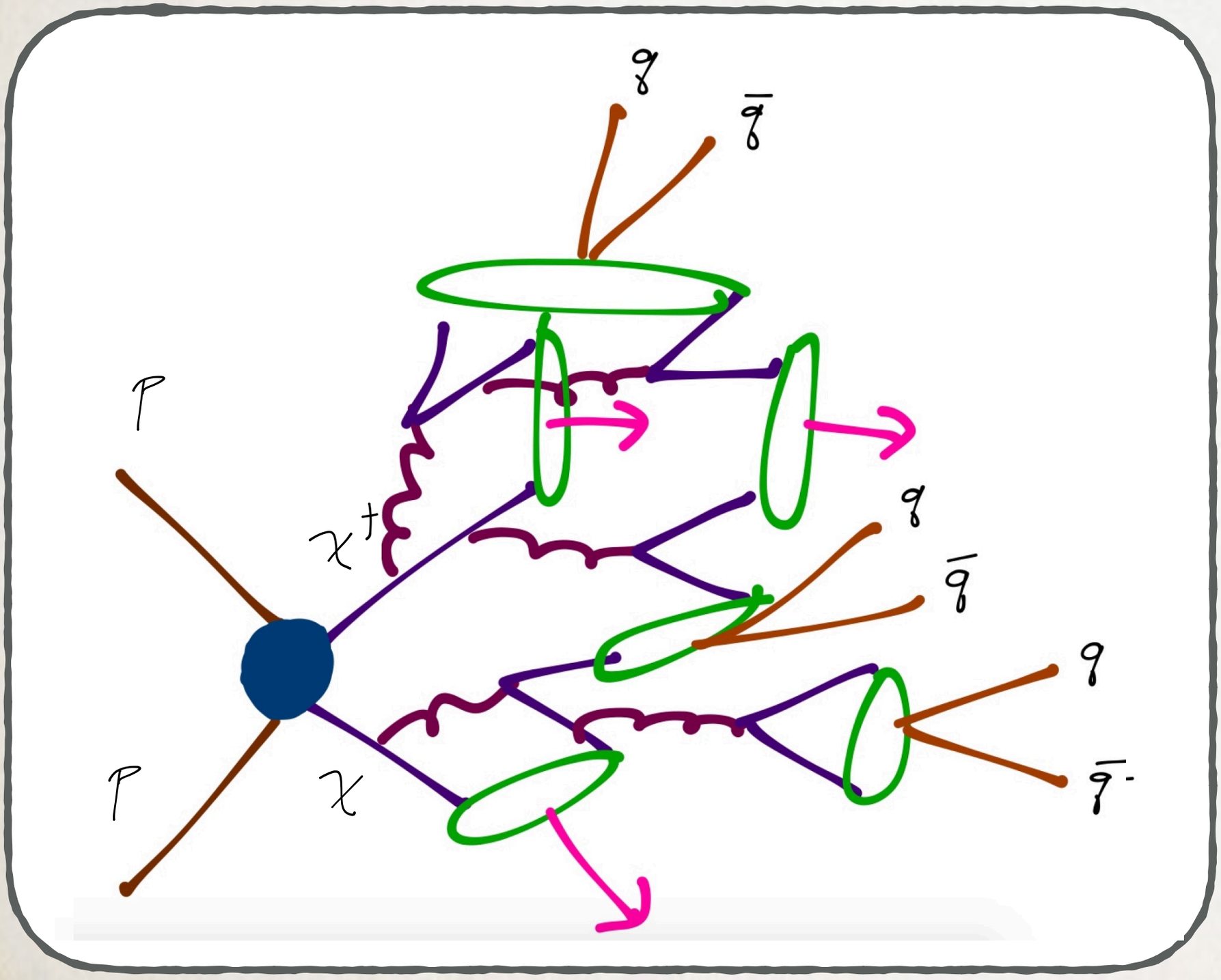

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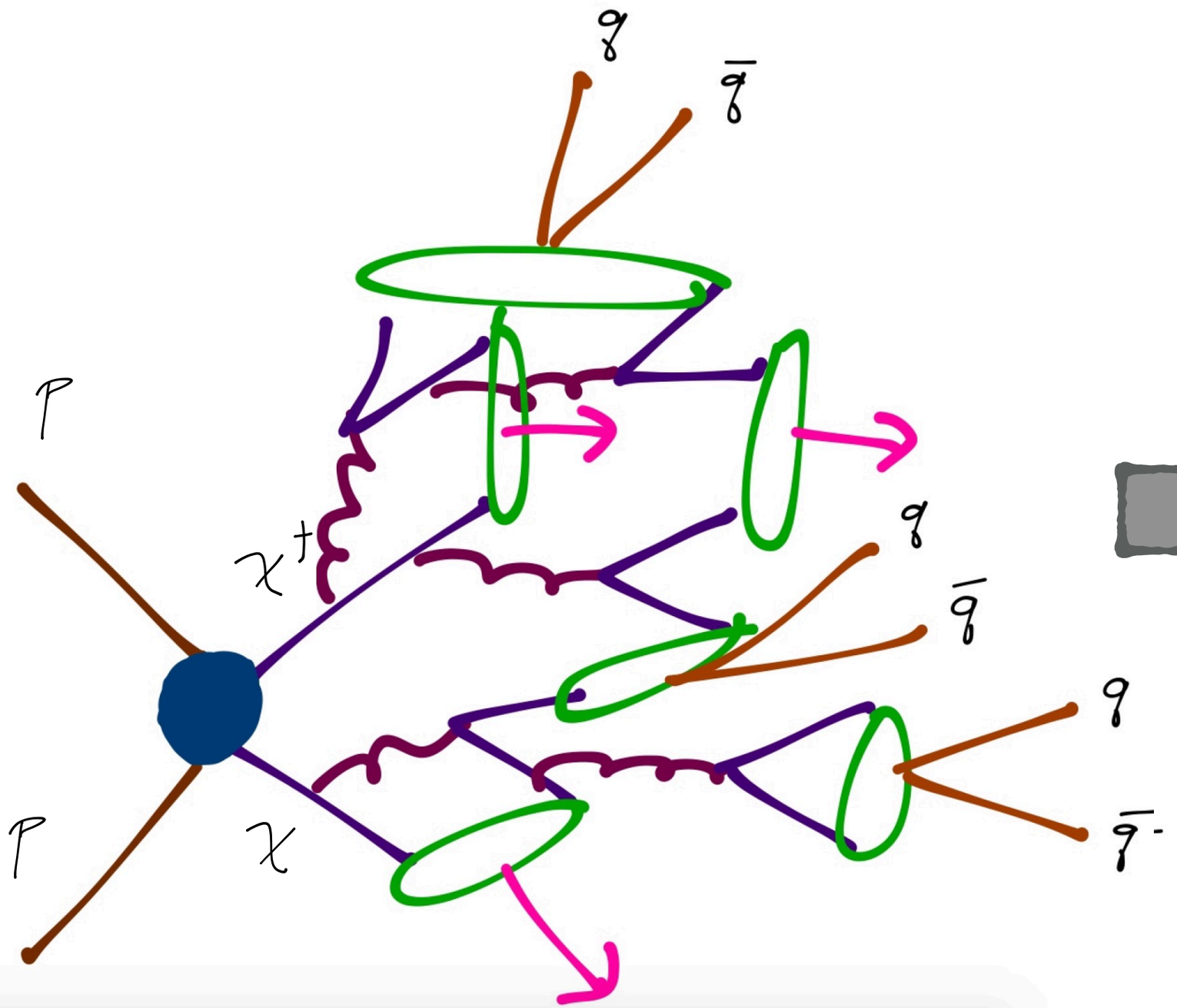
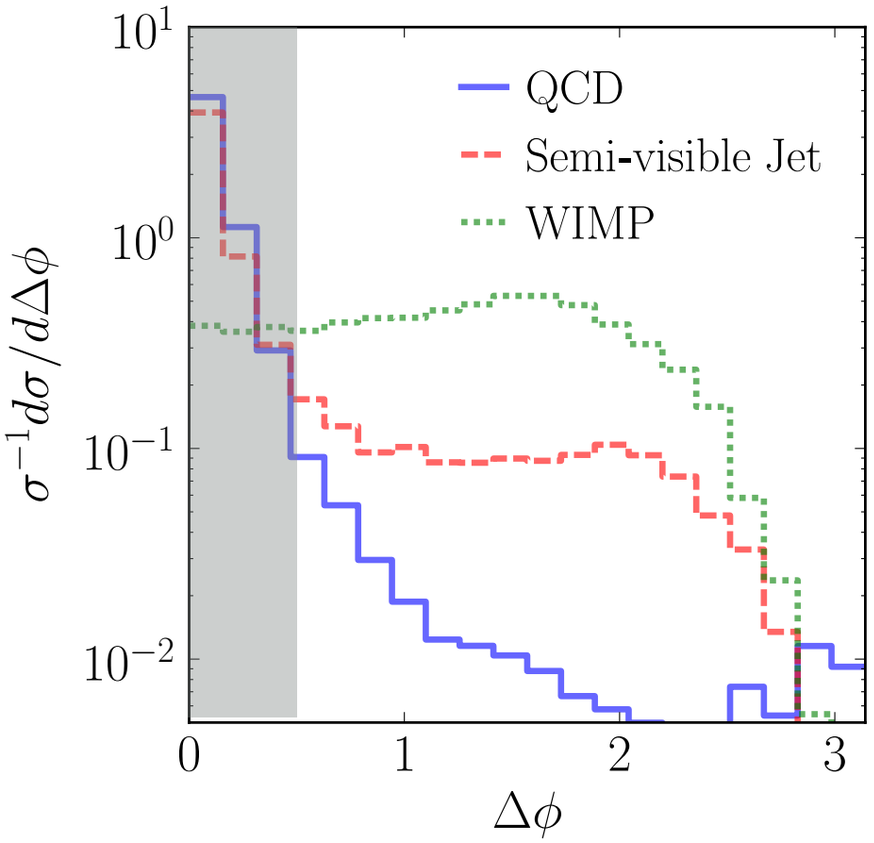


Jet of visible matter and dark matter: "semi-visible" jet

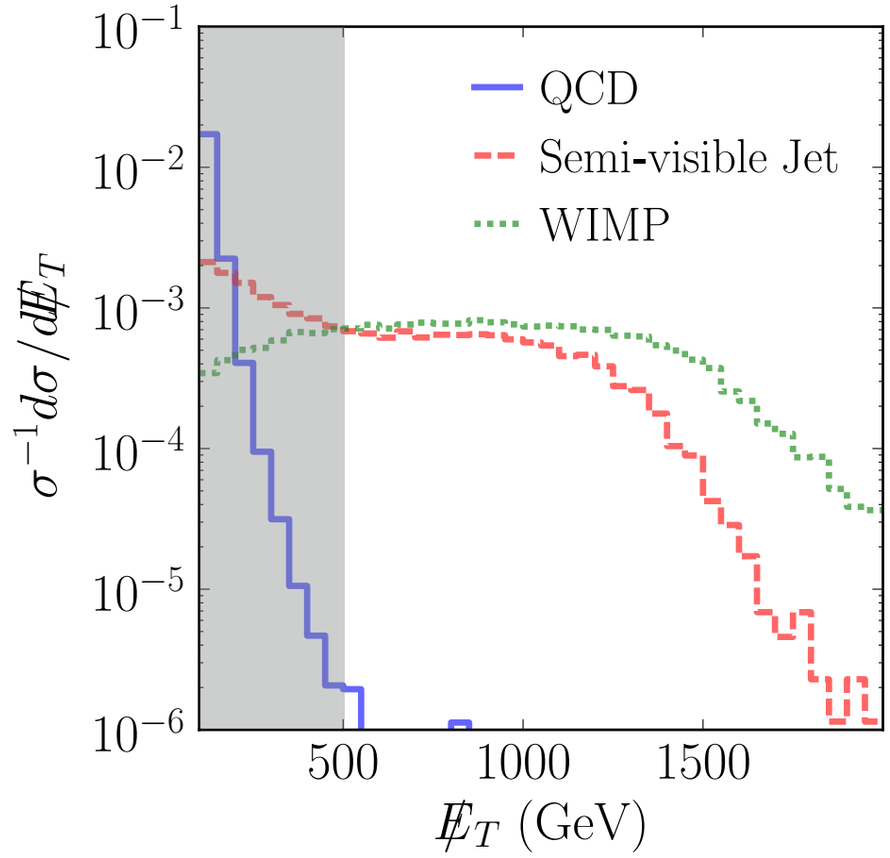
DISTRIBUTIONS



"Standard" cuts:

$$\not{E}_T \gtrsim 500 \text{ GeV}$$

$$\Delta\phi \gtrsim 0.4$$



Efficiencies:

$\sim 40\%$ WIMP

$\sim 1\%$ Semi-visible jets

NO STONE UNTURNED

Want to ensure discovery of new physics.

Nothing stoping the dark sector from being complicated.

Goal: minimal parametrization to cover broad class of models.

OUTLINE

MODELS

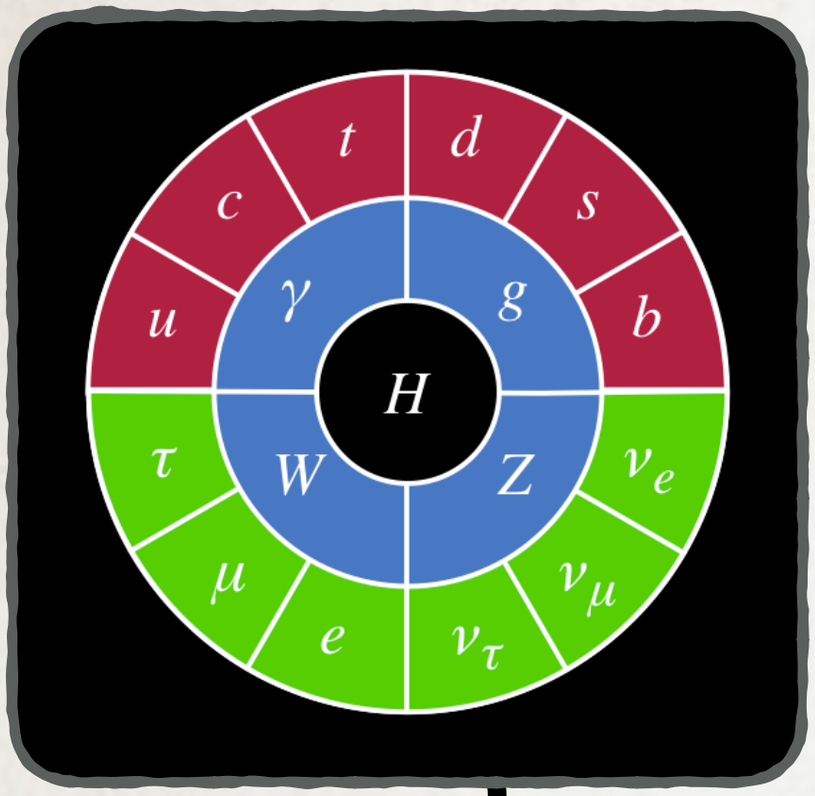
SEARCHES

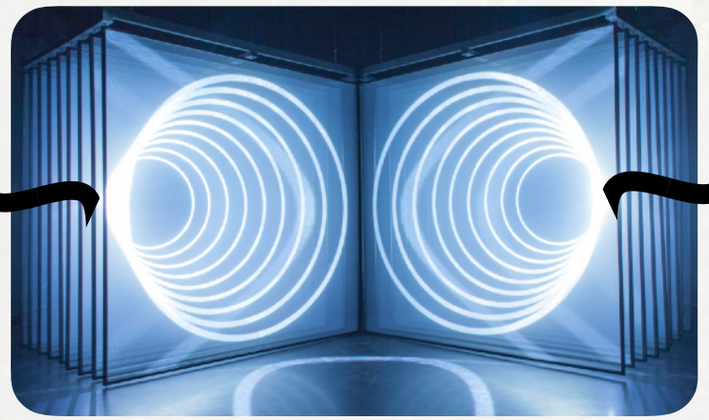
OUTLOOK

MODELS

Simulation: pythia8 hidden valley module (modified to include running couplings) piped through DELPHES (CMS card) at 14 TeV.

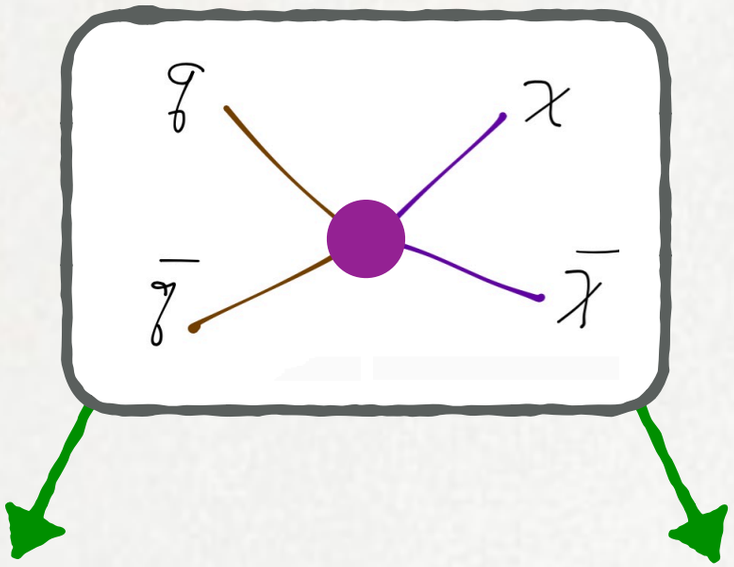
PORTAL INTO THE DARK SECTOR



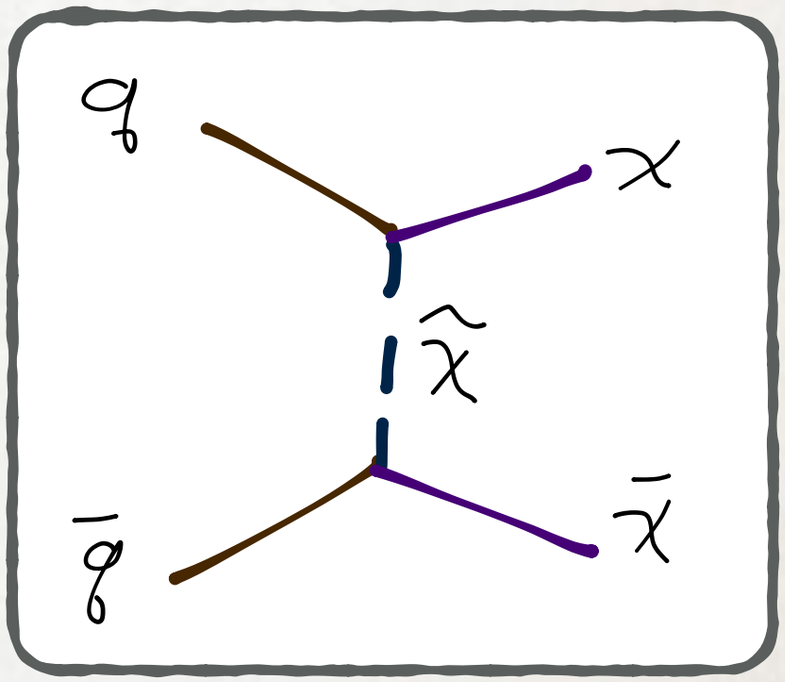


PORTALS

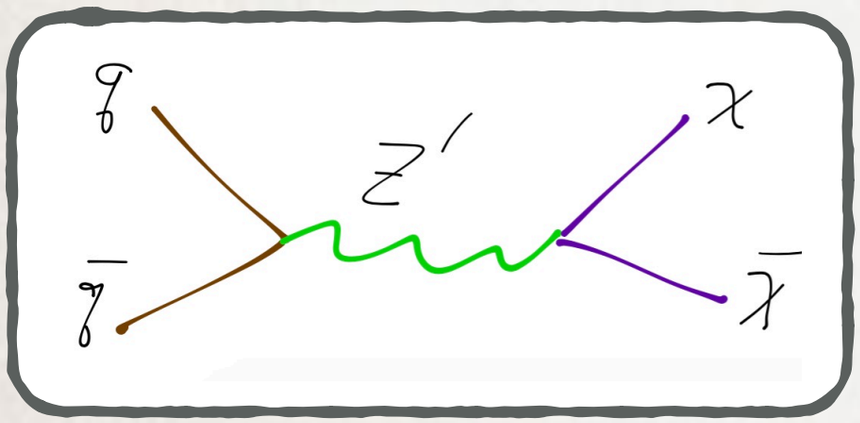
Contact operator



t-channel

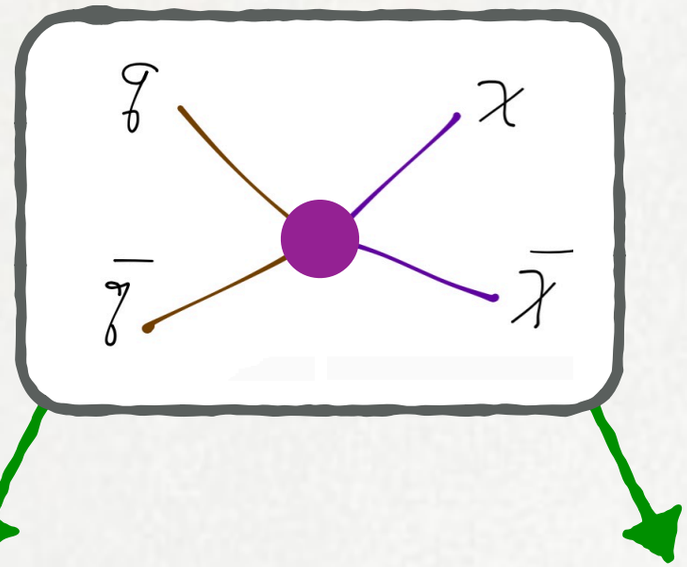


s-channel

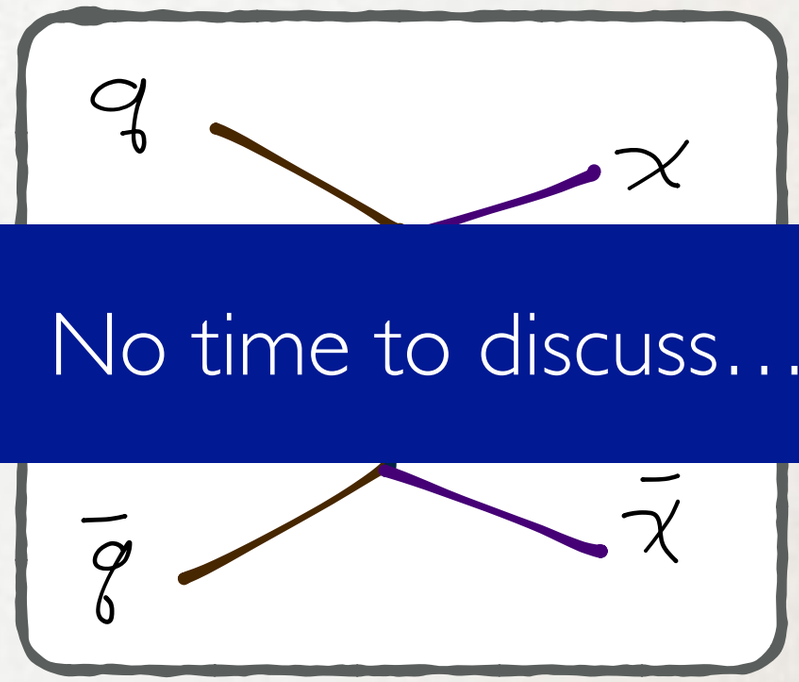


PORTALS

Contact operator

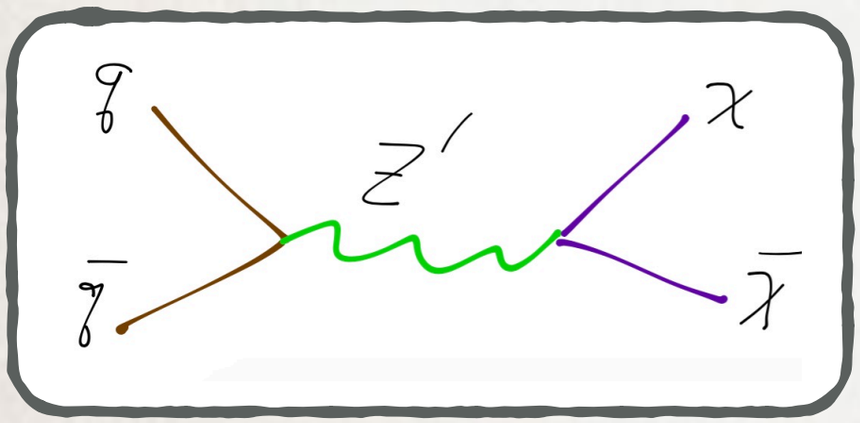


t-channel



No time to discuss…

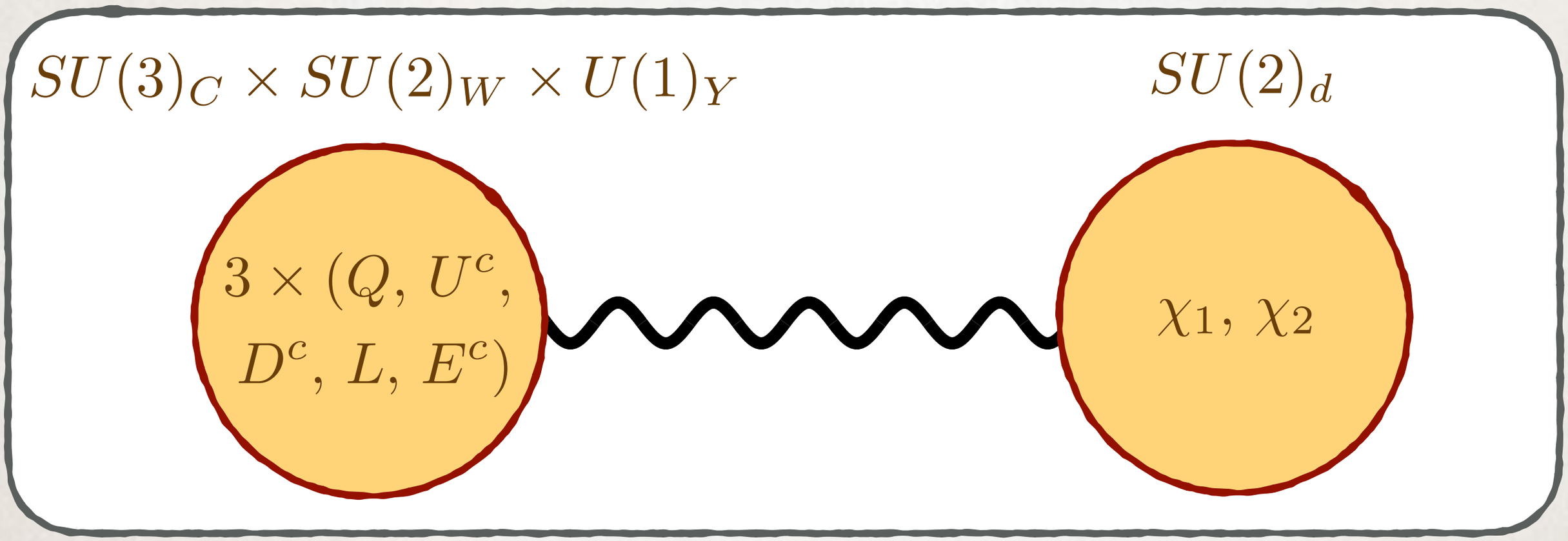
s-channel



DARK SECTOR

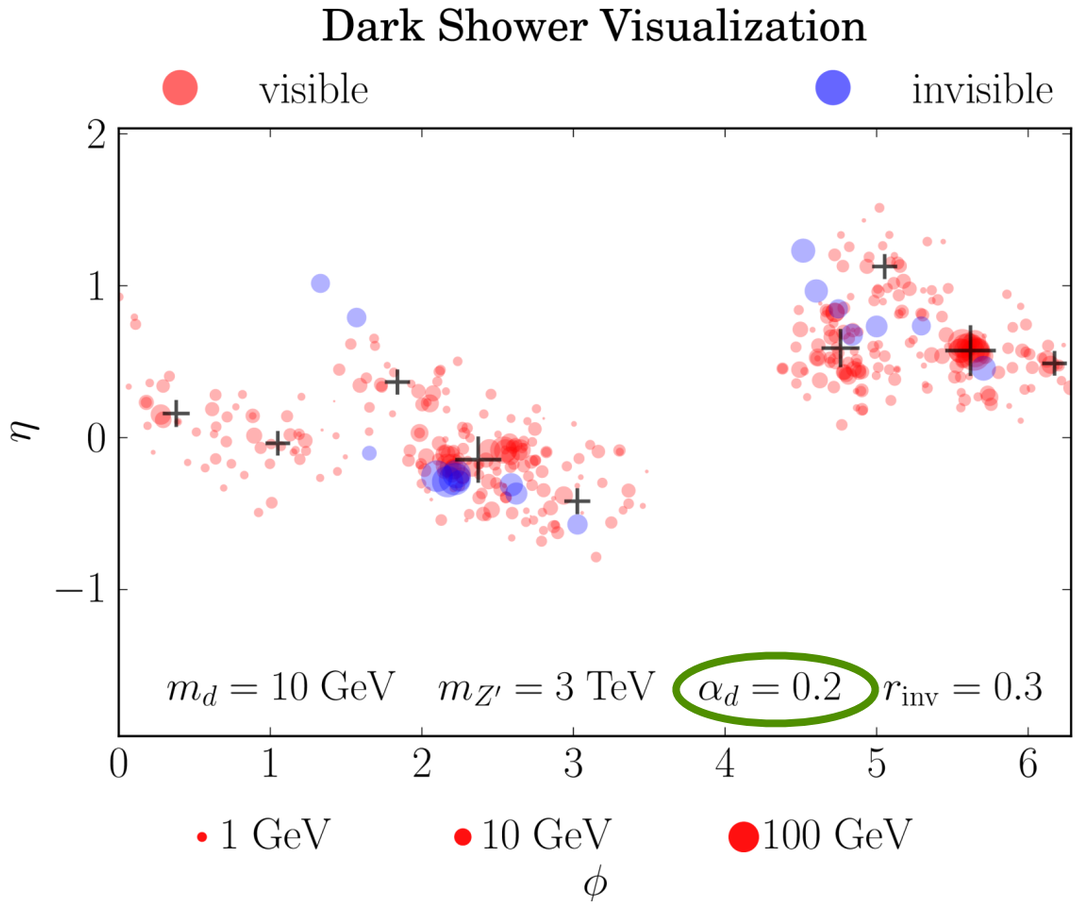
Dark force: $SU(2)_d \Longrightarrow \alpha_d$ or equivalently Λ_d.

Dark quarks: χ_1, χ_2.

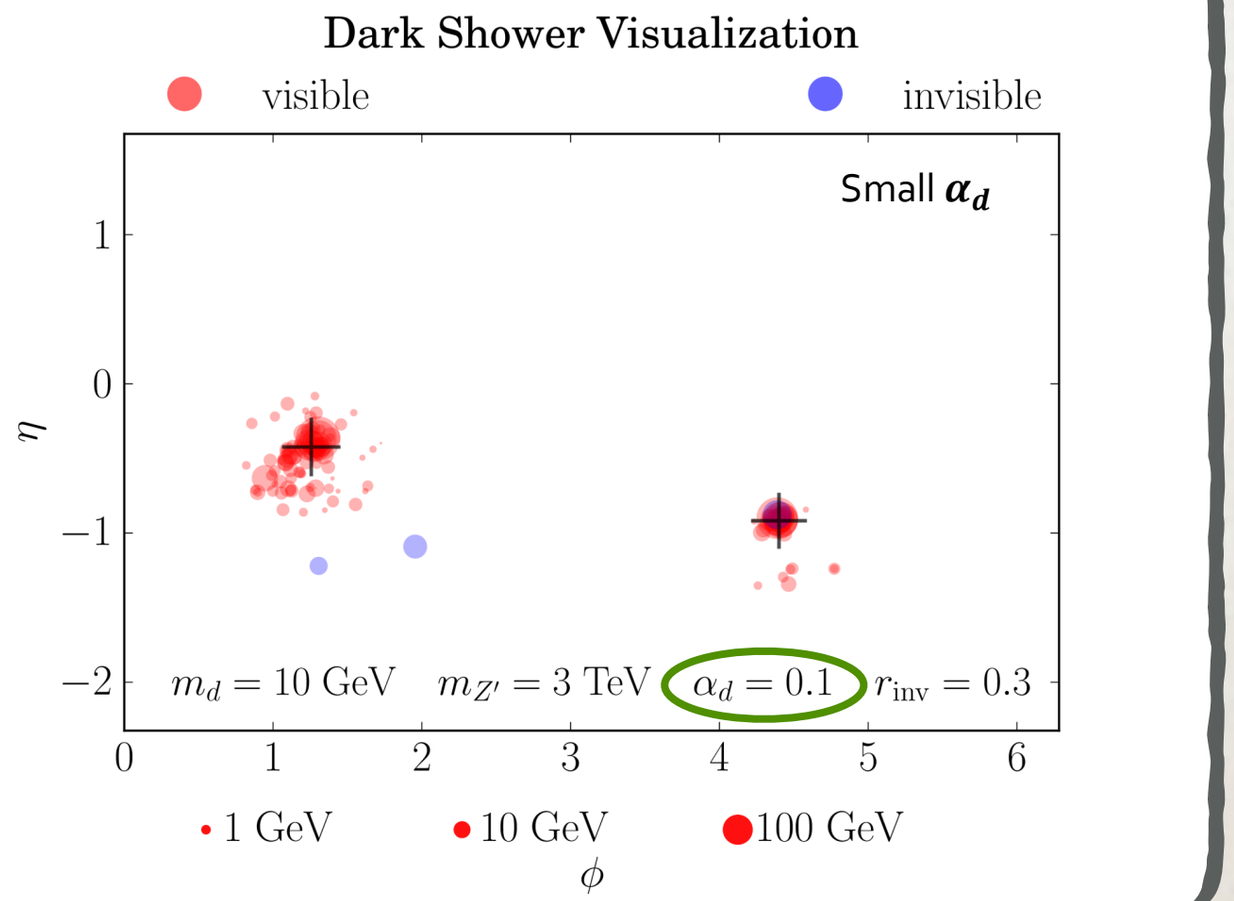


$$\Lambda_D \ll \Lambda_{\text{contact}}$$

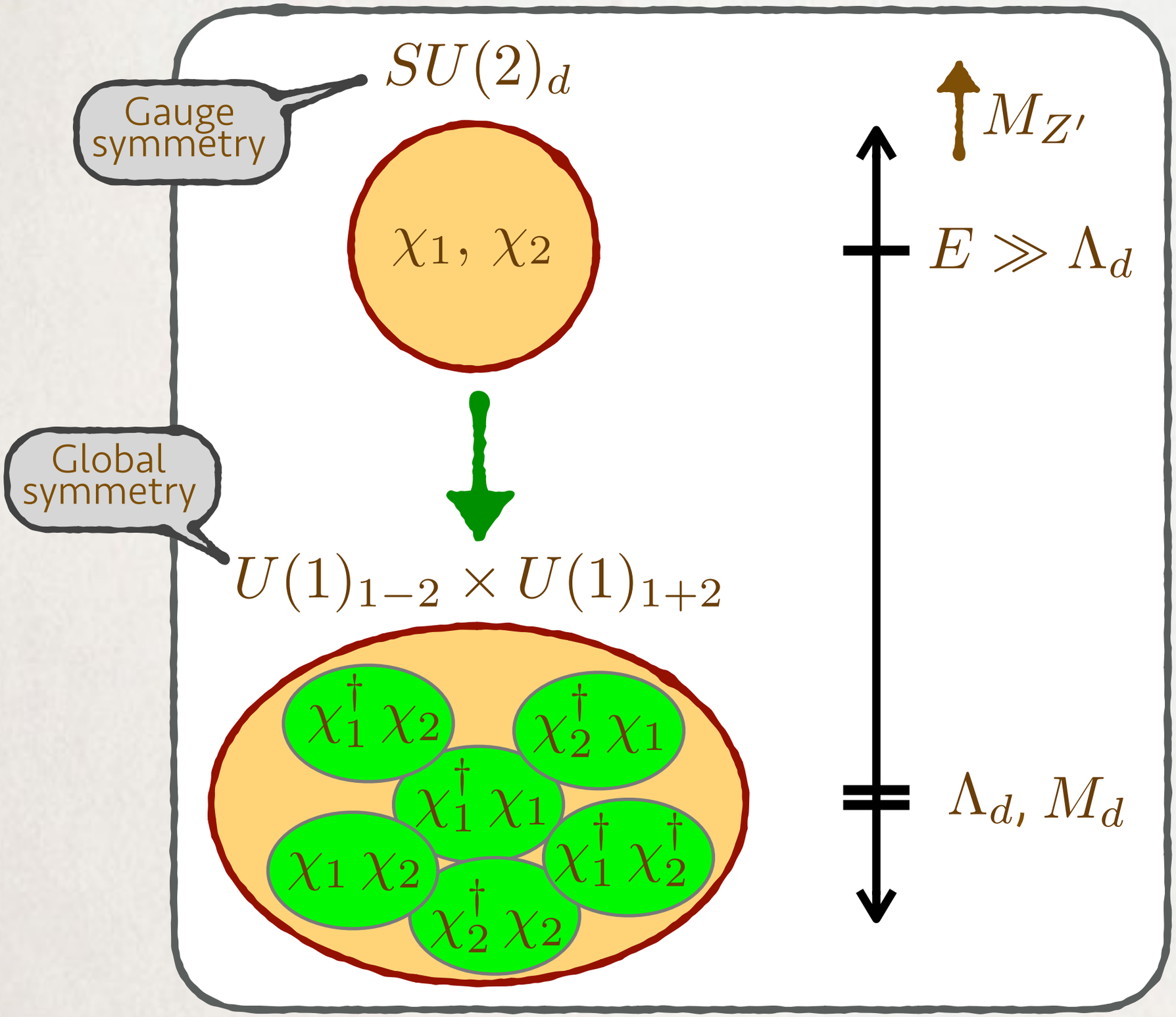
DARK SHOWER STRENGTH



Dark gauge coupling, α_d, unknown parameter.



DARK HADRONS



DARK HADRONS

Two global symmetries:

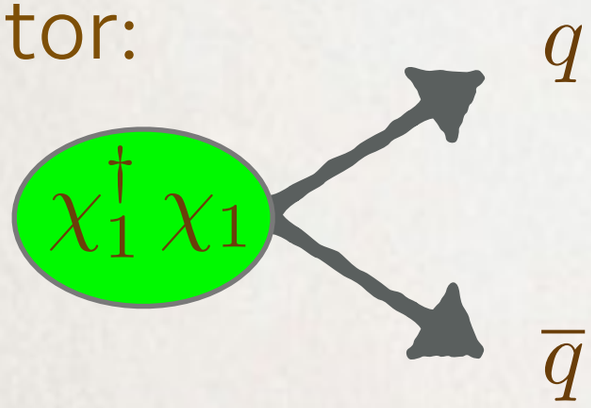
$U(1)_{1-2}$ and $U(1)_{1+2}$

Dark isospin

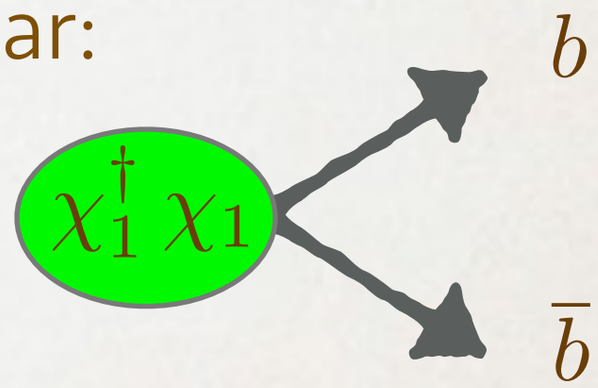
Dark baryon number

	Hadrons		$U(1)_{1-2}$	$U(1)_{1+2}$
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	$+2, -2$

Vector:



Scalar:



INVISIBLE BR PARAMETER

$$r_{\rm inv} \equiv \left\langle \frac{\#\ \text{stable}}{\text{total}} \right\rangle$$

Fragmentation rate: $T \sim \exp\left(-\frac{4\,\pi|M_2^2 - M_1^2|}{\Lambda_d^2}\right)$

Andersson, Gustafson, Ingelman, Sjostrand [Phys. Rept. 97 (1983)]

2 flavors with $M_1^2 = M_2^2$ ⟶ $r_{\rm inv} \simeq 0.5$

2 flavors with $M_1^2 \ll M_2^2$ ⟶ $r_{\rm inv} \to 0$

(ignoring baryons)

INVISIBLE BR PARAMETER

$$r_{\rm inv} \equiv \left\langle \frac{\#\ \text{stable}}{\text{total}} \right\rangle$$

Naively counting:

N_F singlet combinations $\chi_i^\dagger \chi_i$.

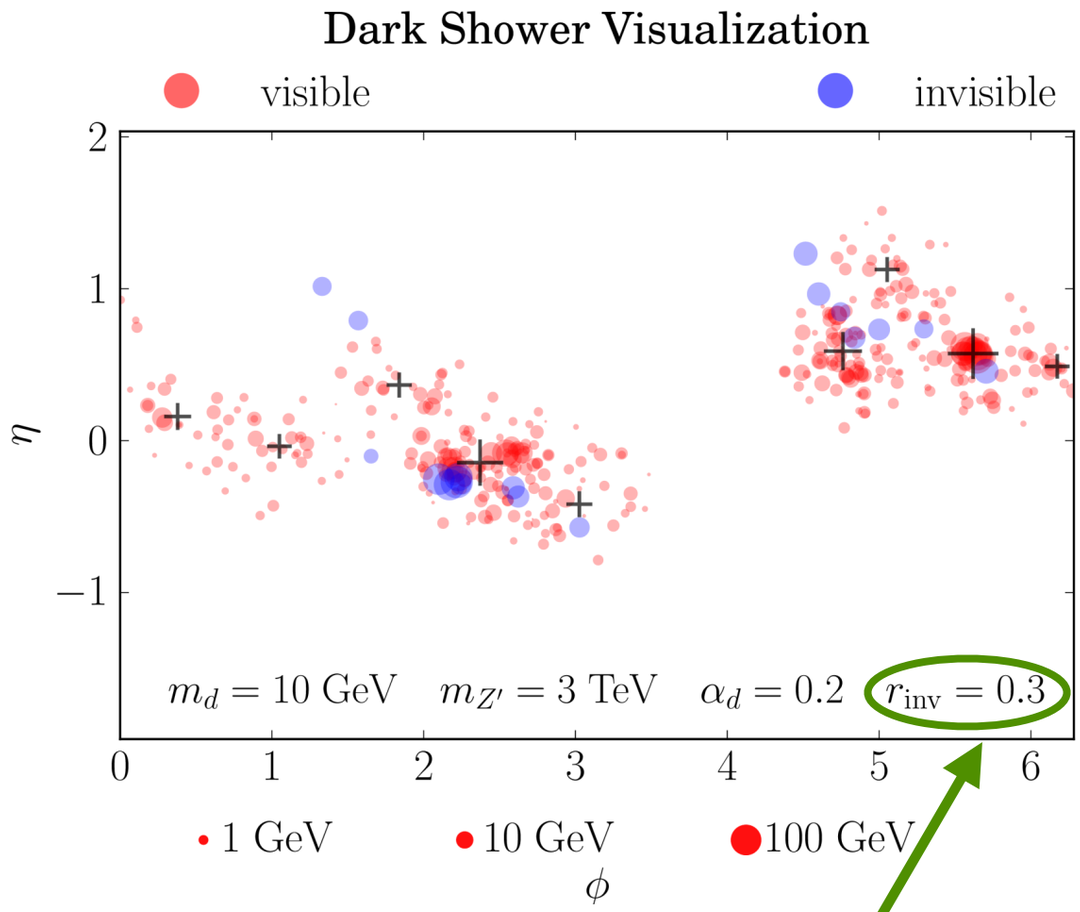
$\frac{N_F(N_F-1)}{2}$ "charged" combinations $\chi_i^\dagger\, \chi_j$ with $i \neq j$.

Number of (possibly) stable particles grows as $N_F \to \infty$

$$\Rightarrow r_{\rm inv} \to 1$$

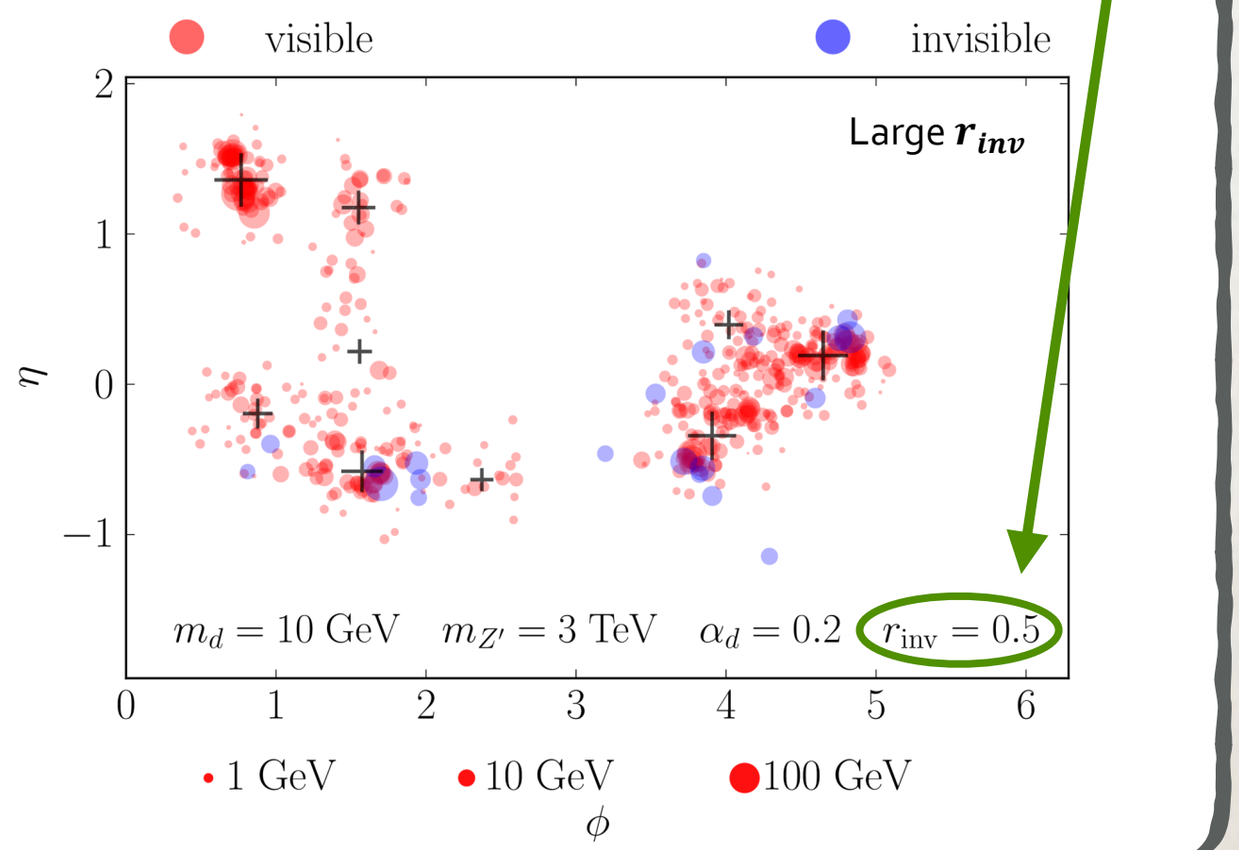
$$0 < r_{\rm inv} < 1$$

LEGO PLOTS

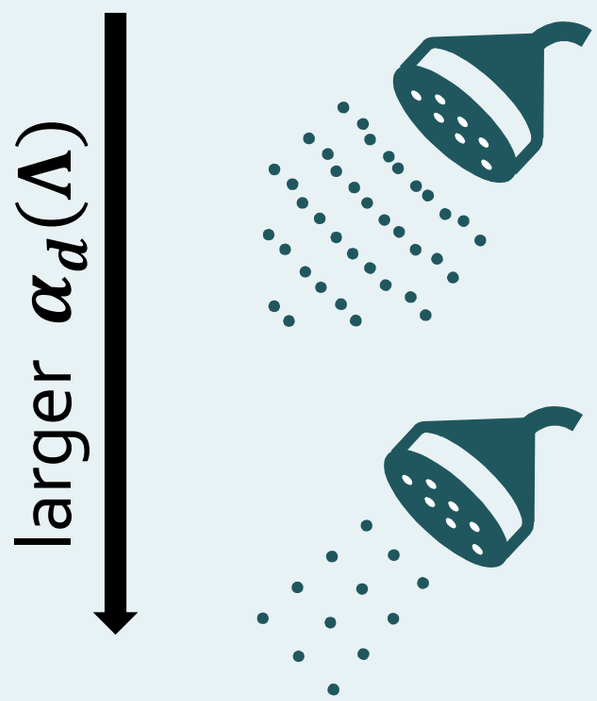
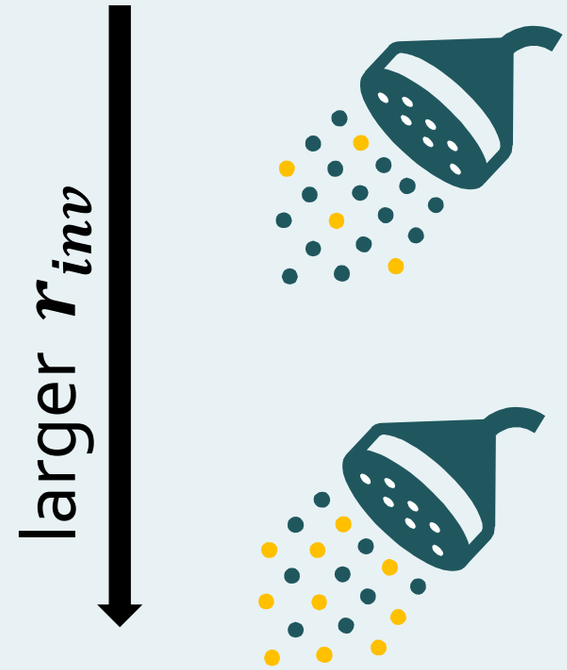


$r_{\rm inv} = 0.3$

$r_{\rm inv} = 0.5$



PARAMETER SUMMARY

Shower Strength	Invisible ratio
$\alpha_d(1\text{TeV})$	r_{inv}
	

Dark meson mass, m_d ,and production rate: $\sigma \times \text{BR}$.

SEARCHES

CONTACT OPERATOR SEARCH

Follow "mono-*X*" strategy.

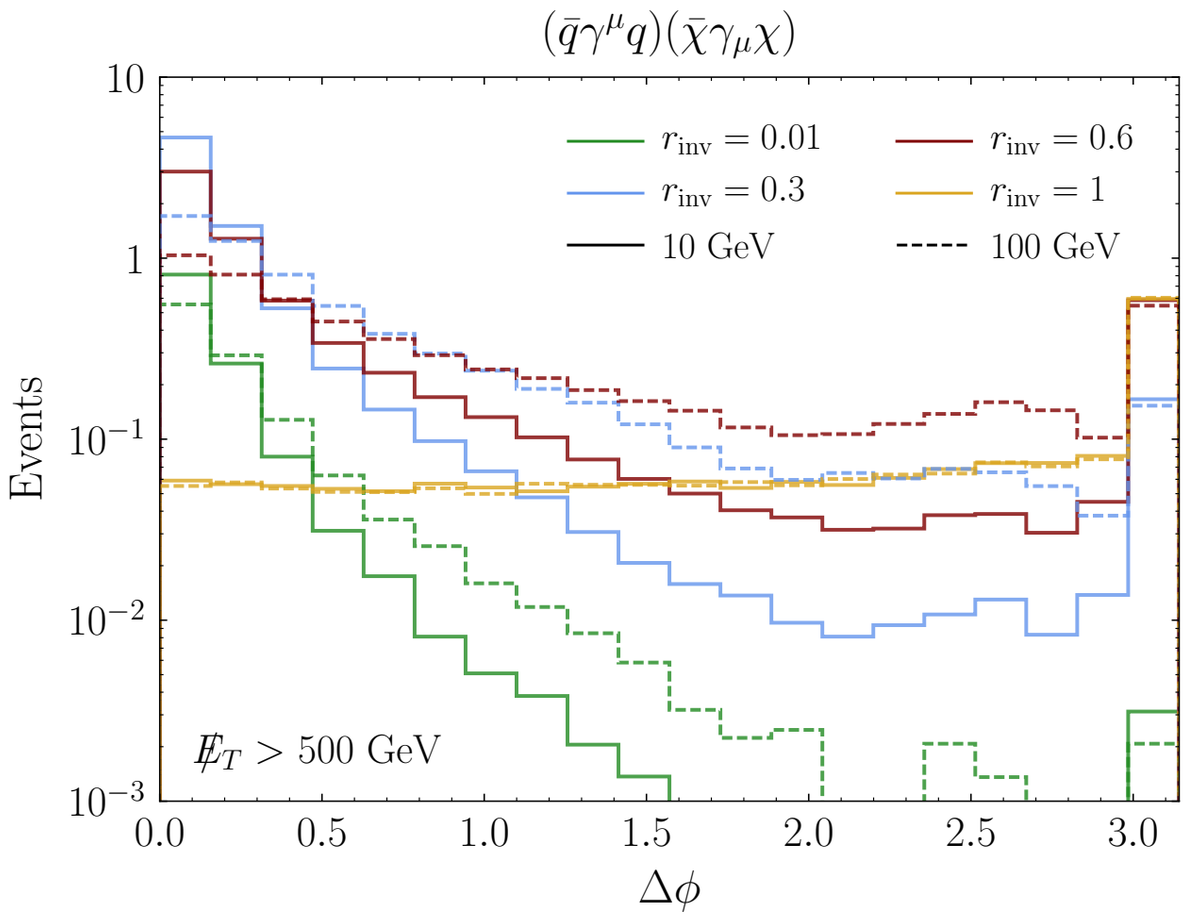
Focus on the vector-vector contact operator:

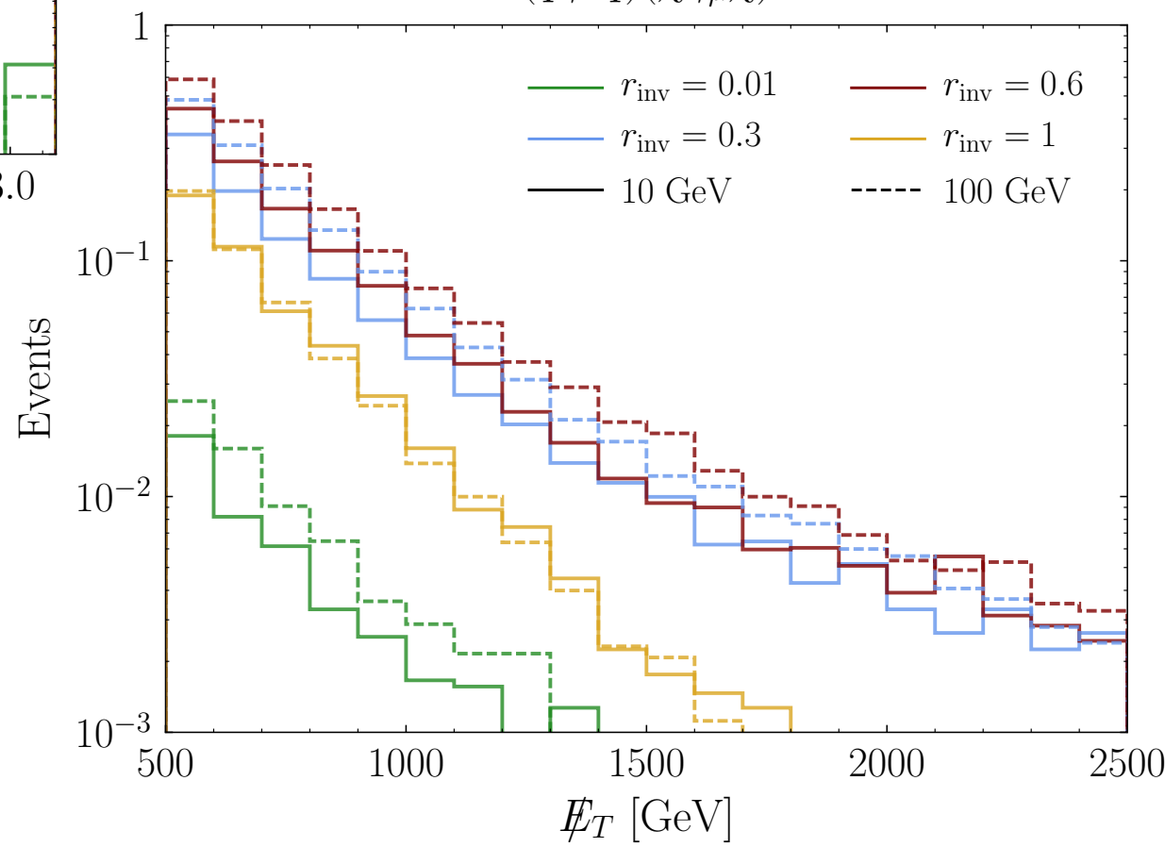
$$\frac{1}{\Lambda^2}\left(\bar{q}\gamma^\mu q\right)\left(\bar{\chi}\gamma_\mu\chi\right)$$

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

(For *t*-channel model, see paper.)

DISTRIBUTIONS





CUTS

Trigger:

- At least one jet with $|\eta| < 2.5$ and $p_T > 250\ \mathrm{GeV}$.
- Veto leptons.

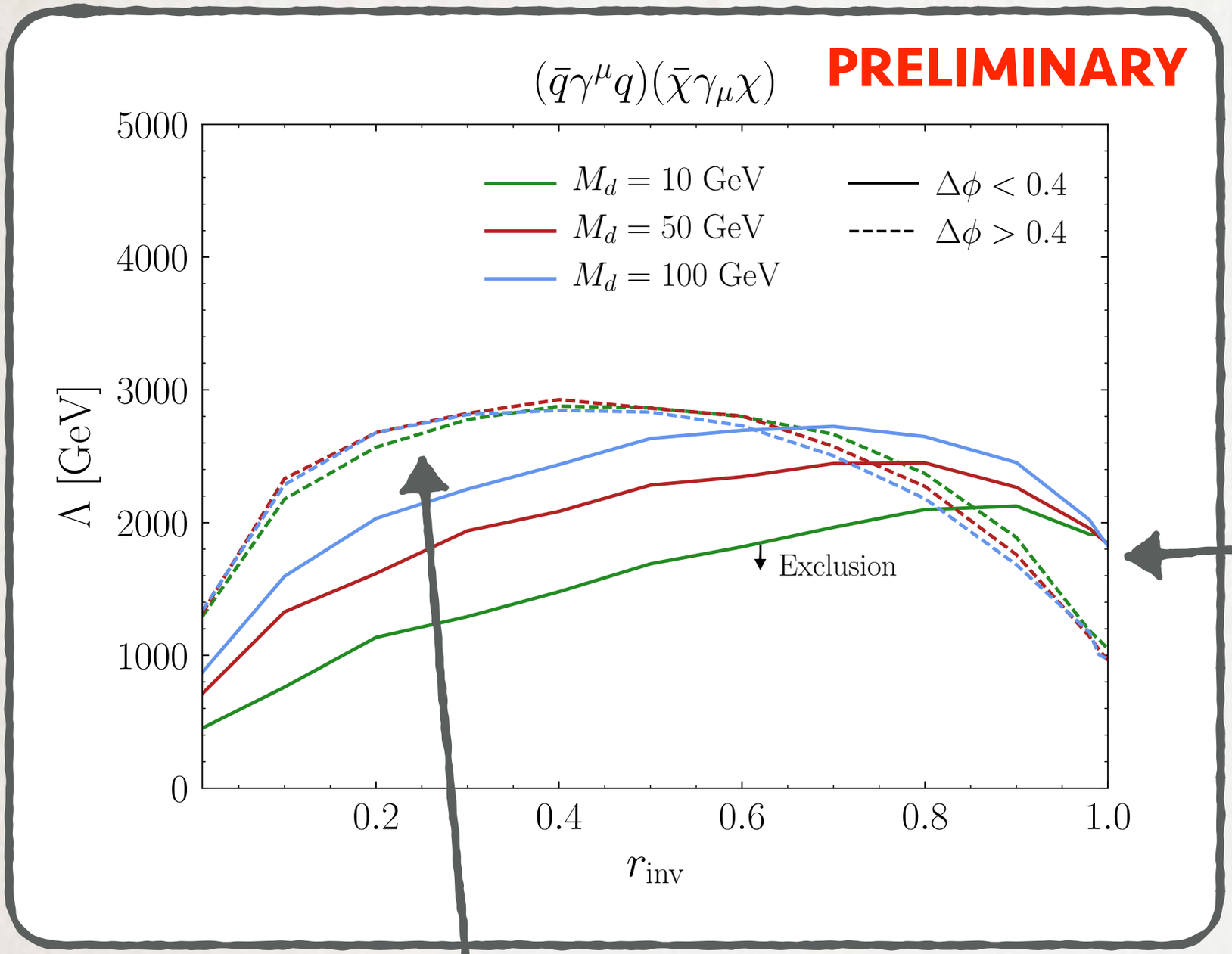
Signal Regions:

- Require $\not{E}_T > 800, 900, 1000\ \mathrm{GeV}$.
- Require either $\Delta\phi > 0.4$ or $\Delta\phi < 0.4$.

Standard cut.

"Semi-visible" cut.

PROJECTED REACH



Invisible dark shower

Semi-visible jet search dominates

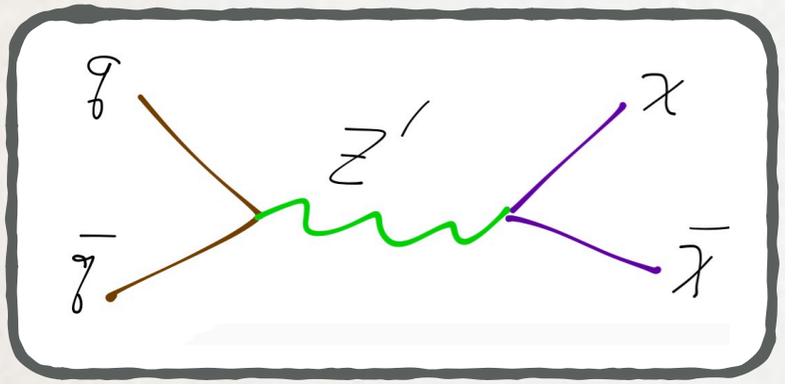
S-CHANNEL UV COMPLETION: HOW DOES SENSITIVITY CHANGE?

Z′ SEARCH

Couple a Z' to quarks.

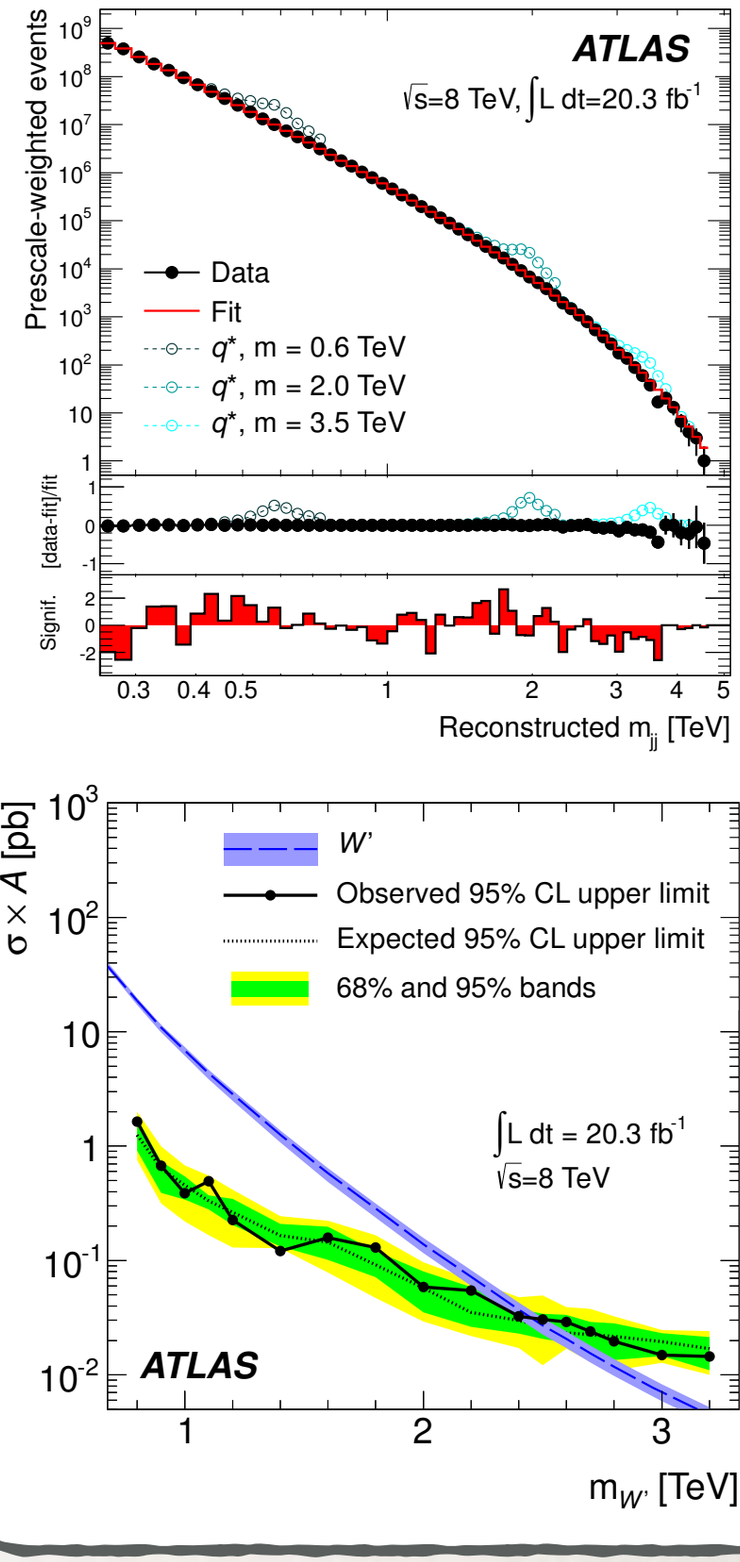
Produced resonantly at LHC.

$$\sigma \times \mathrm{BR}$$

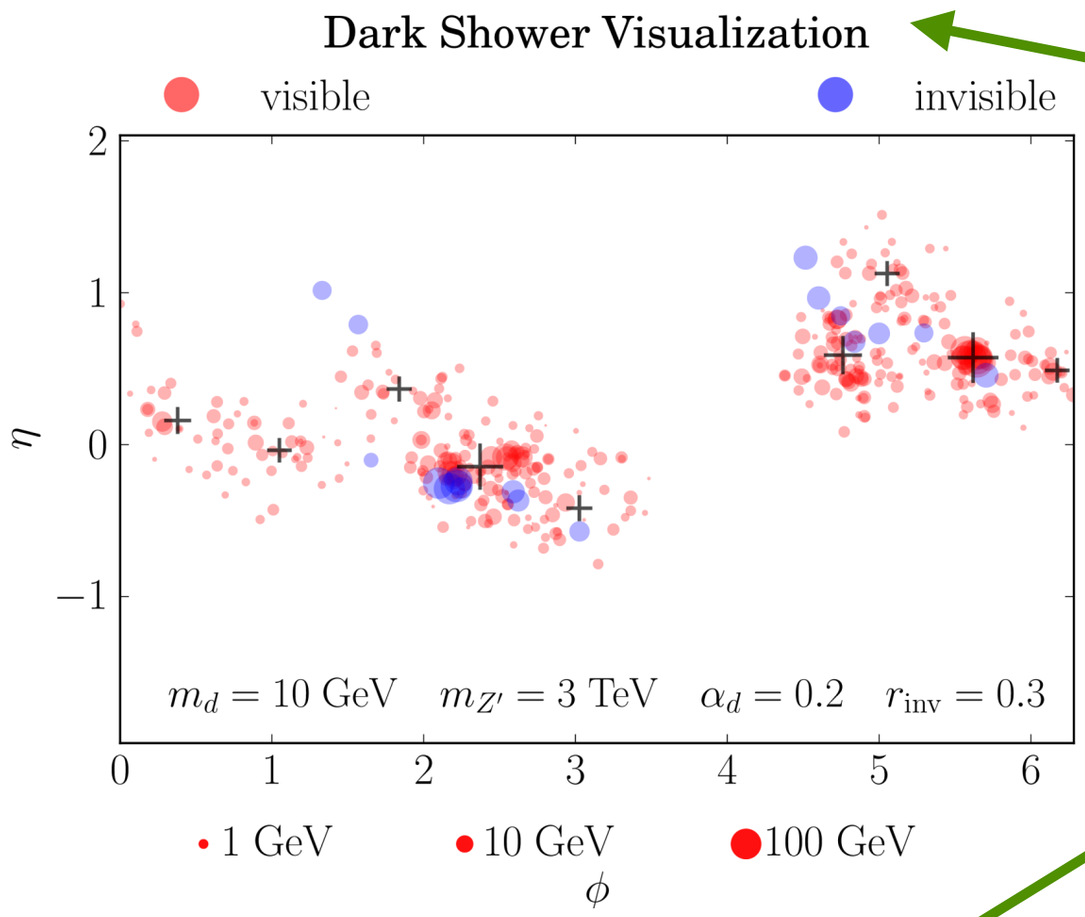


At partonic center of mass energy

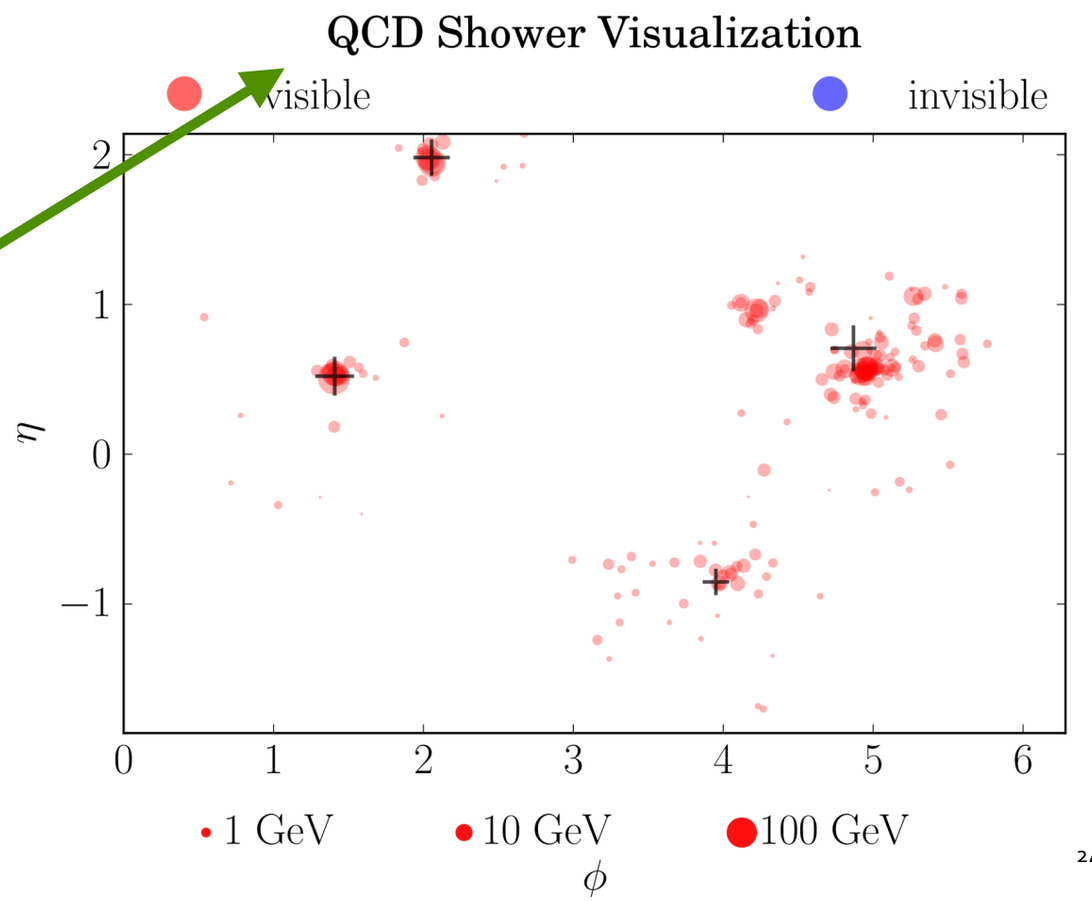
$$\sqrt{\hat{s}} \simeq M_{Z'}$$



SIGNAL VERSUS BACKGROUND



Dark shower



QCD shower

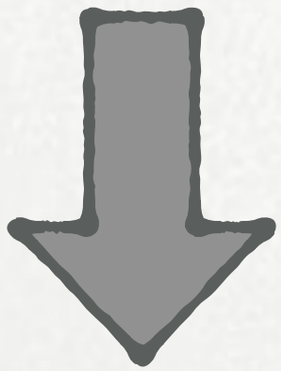
BUMP HUNT

Looking for a resonance.

Di-jet like.

Jets are fatter than QCD jets.

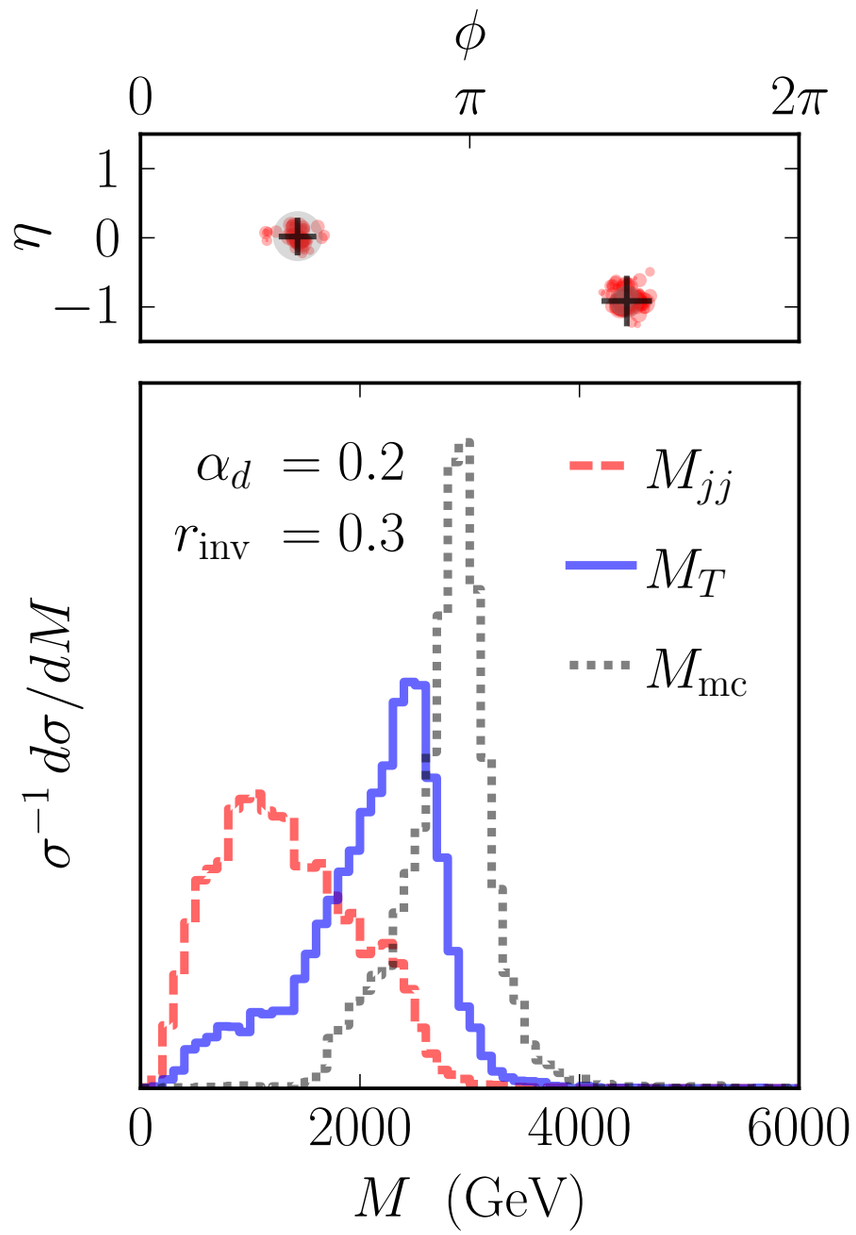
Non-zero $\not{E}_T$ (also washes out resonance).



Try the transverse mass:

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

BUMP HUNT



Cluster into $R = 0.5$ anti- k_T jets.

Re-cluster into $R = 1.1$ C/A jets.

Compute M_T using the fat jets.

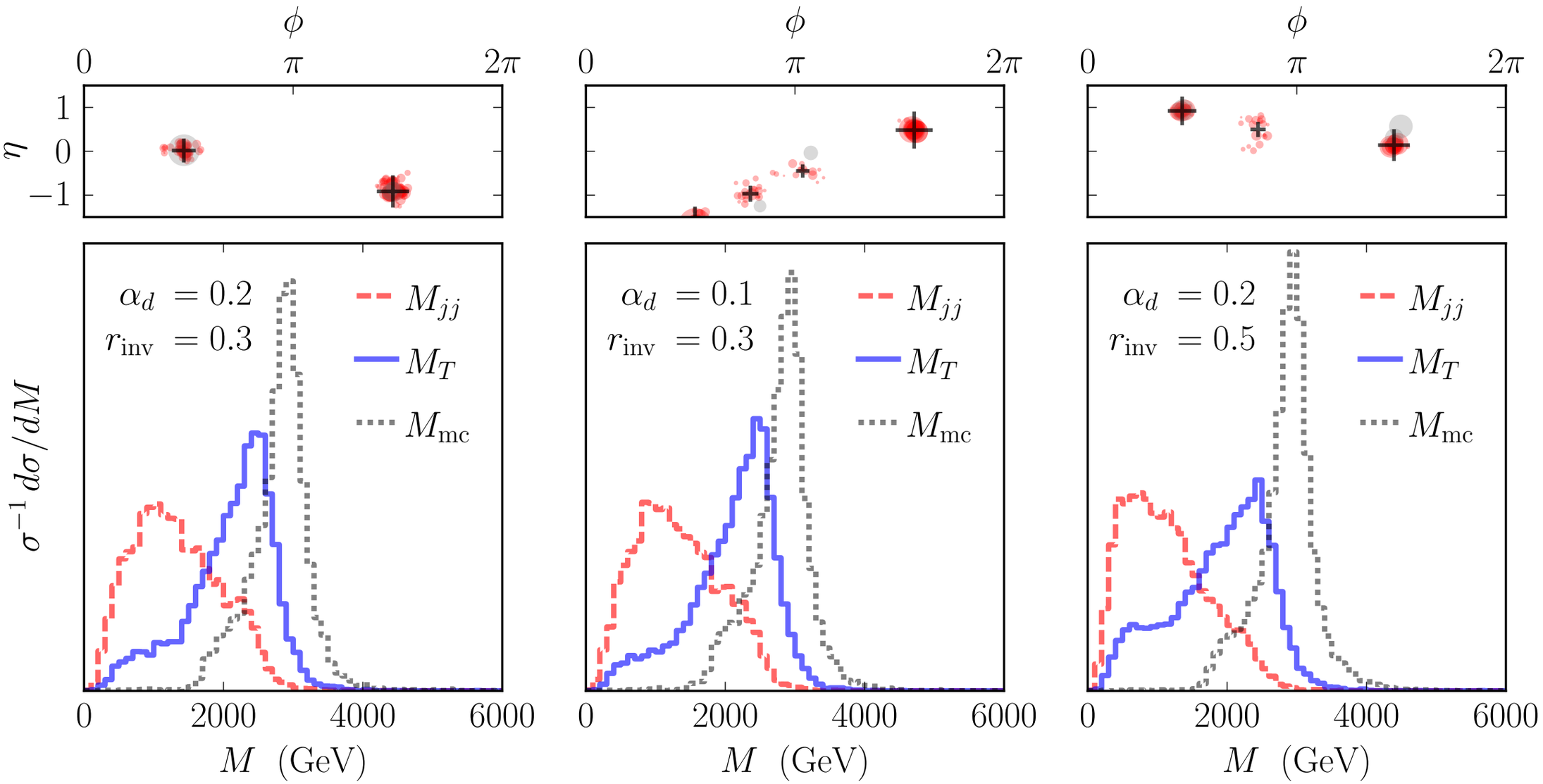
$$M_{jj} \leq M_T \leq M_{Z'}$$

Di-fat jet invariant mass

True invariant mass. Mocked up by $M_{\rm mc}$: computed using visible and invisible 4-vectors.

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

VARY PARAMETERS



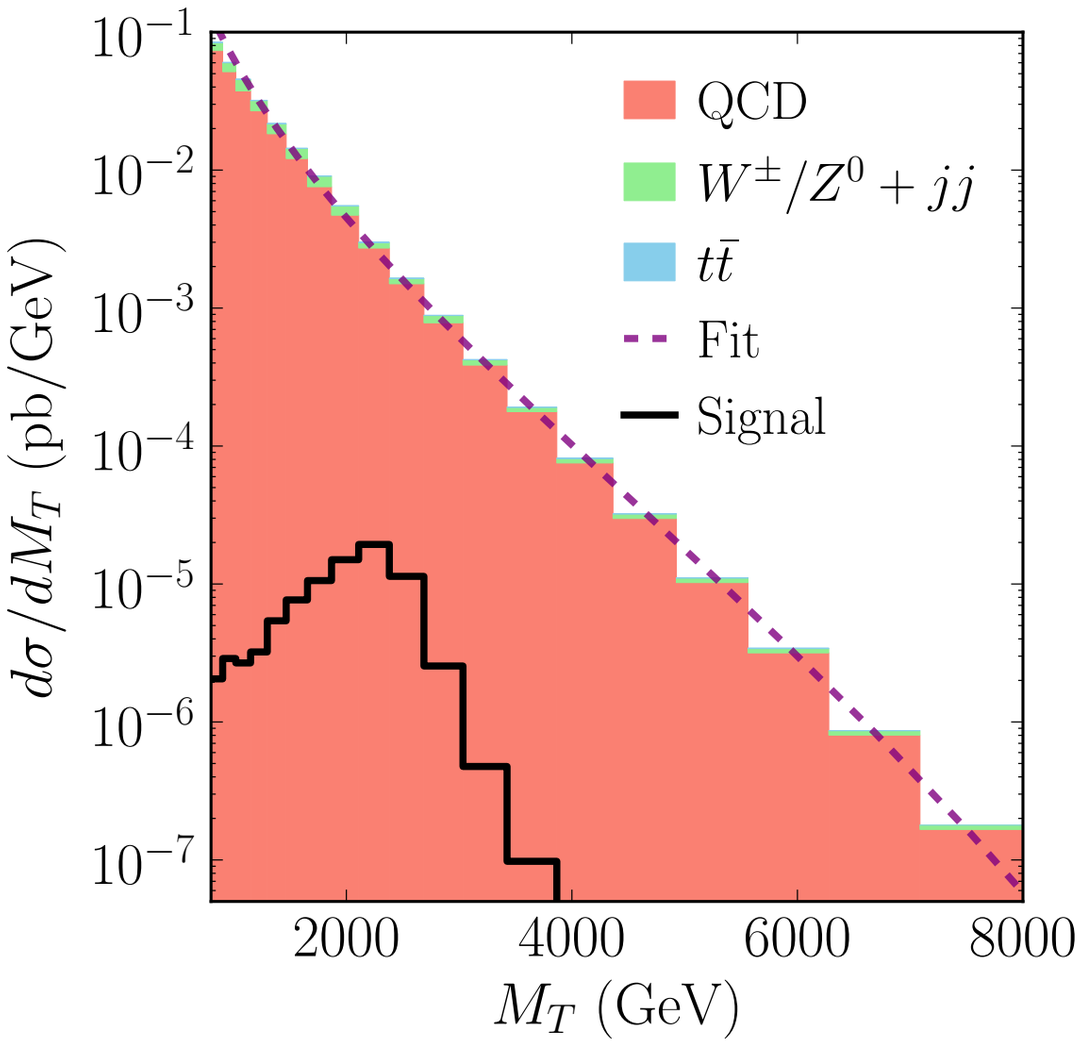
CUTS

- 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 $p_T > 20\ \mathrm{GeV}$ and $|\eta| < 2.4$.
- Require $\not{E}_T/M_T > 0.15$.

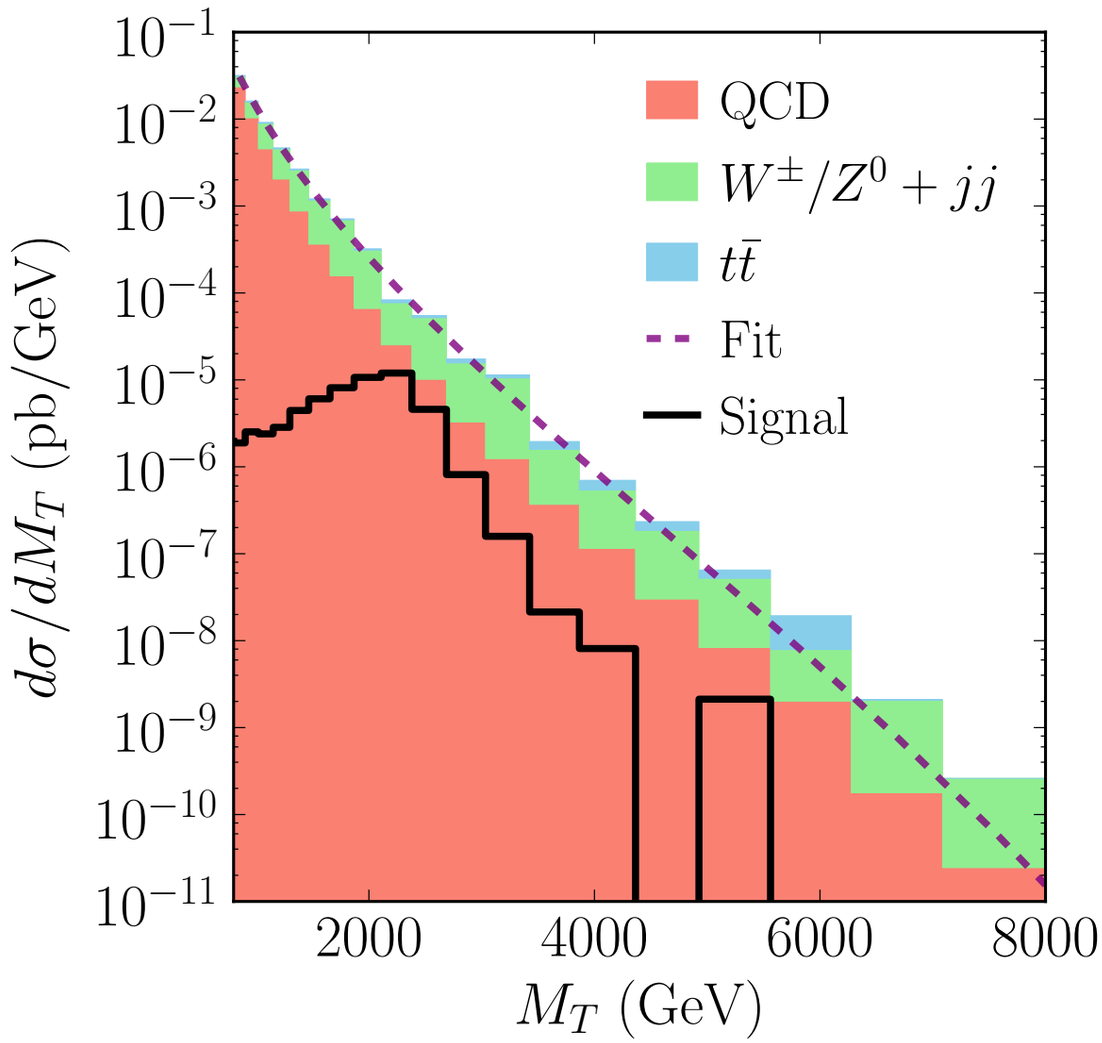
Then bump hunt in M_T.

DISTRIBUTIONS

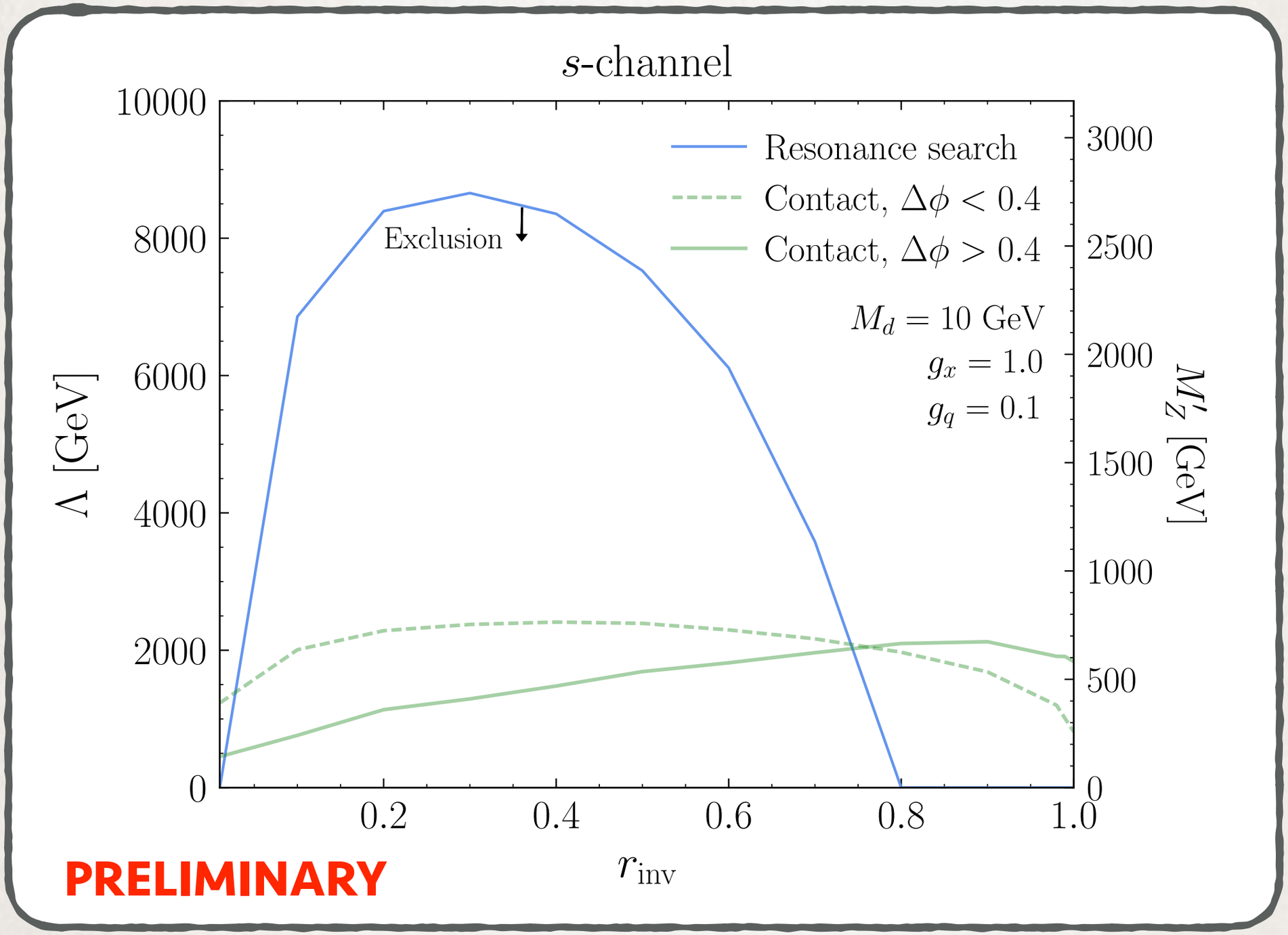
After pre-selection



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



PROJECTED REACH



OUTLOOK

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

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

χ are dark quarks.

π_d are dark mesons.

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

RELIC DENSITY

Symmetric abundance

Large annihilation cross section yields small relic density.

Some spectra could use "forbidden channel" mechanism.

Correlation between relic density and $r_{\rm inv}$.

Are such spectra possible?

Asymmetric abundance

Straightforward to implement.

Relate global symmetry charge to baryon or lepton number.

Big symmetric annihilation cross section.

CONCLUSIONS

Strongly coupled dark sector could yield semi-visible jets.

Useful parametrization of dark sector properties:

$$(\Lambda_d, M_d, r_{\text{inv}})$$

Many portal possibilities:

Contact operator limit

s-channel: Z' resonance search

(t-channel : will be presented in paper)

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

Direct Detection is UV completion dependent.