Mediator-Induced Decay Chains and Multi-Jet Signatures of Non-Minimal Dark Sectors at Colliders

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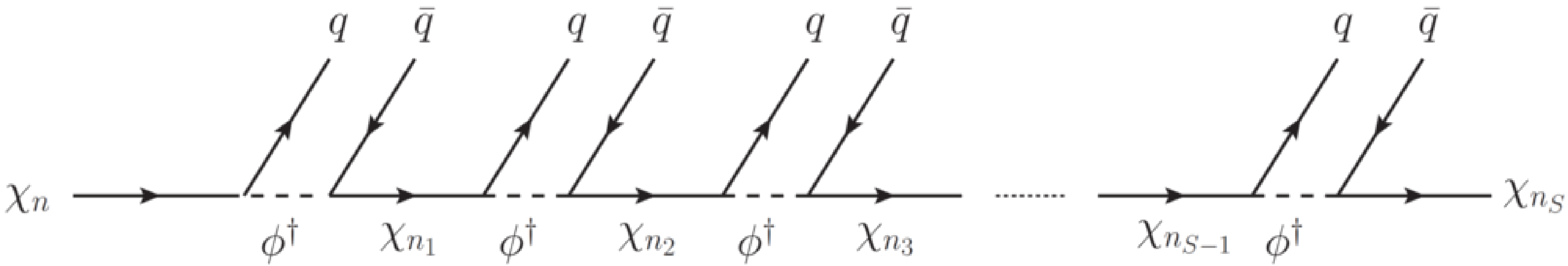


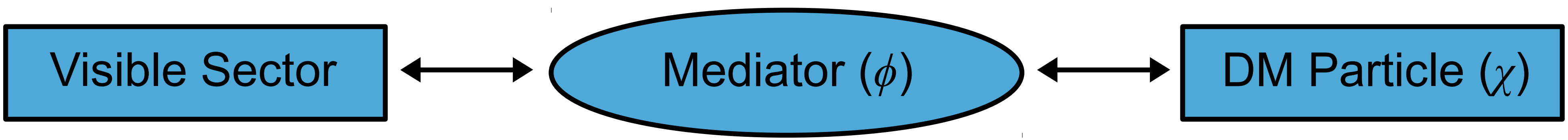
Based on work done in collaboration with:

- **Keith Dienes, Doojin Kim, Huayang Song, Shufang Su, and David Yaylali [arXiv:1910.01129]**

PHENO 2021, May 24th, 2021

Portals to the Dark Sector

- Dark matter communicates with the visible sector through gravity, but the hope is that it also communicates with the visible sector in other ways.
- One possibility is that the dark sector couples to the visible sector via some ***mediator particle***, which provides a non-gravitational portal through which the two sectors can comminicate.



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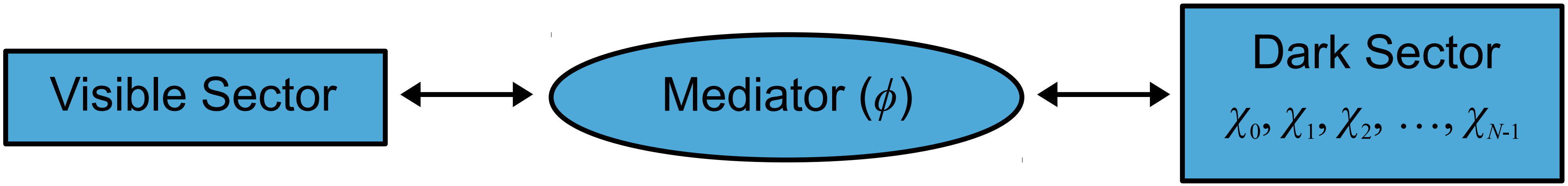


- The situation can become far richer in scenarios involving not merely a single dark-matter particle, but an entire ***dark sector***.
- For example, consider the case wherein there exist ***multiple dark-sector fields*** with ***similar quantum numbers*** which can couple to the mediator.

In such scenarios, the mediator not only facilitates interactions via which the χ_n can be ***produced*** experimentally/cosmologically, but also generically gives rise to ***decay processes*** which render the heavier χ_n unstable.

→ Striking signatures at colliders and beyond!

An Example Model

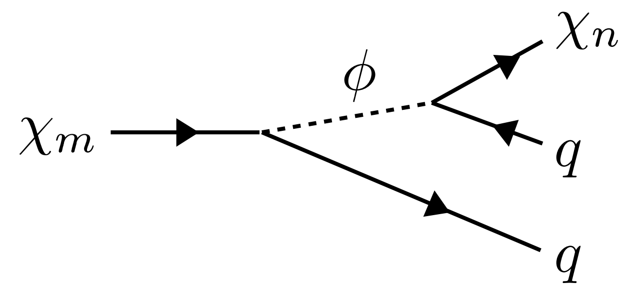
- For concreteness, let's consider a example model in which the χ_n are SM-singlet ***Dirac fermions*** which couple to SM quarks q via a mediator ϕ which is a ***Lorentz scalar*** and a triplet under $SU(3)$ color.
- To suppress flavor-changing effects, we take ϕ to be a triplet under the approximate $U(3)_u$ flavor symmetry of the right-handed up-type quarks and assume that ϕ and these quarks share a common mass eigenbasis.

→ Mass eigenstates $\{\phi_u, \phi_c, \phi_t\}$ essentially each couple to a ***single flavor***.

coupling constants

$$\mathcal{L}_{\text{int}} = \sum_{q\in\{u,c,t\}} \sum_{n=0}^{N-1} \left[c_{nq}\phi_q^\dagger \overline{\chi}_n P_R q + \text{h.c.}\right]$$

Decay:



- For simplicity, we take $m_{\phi_u} \ll m_{\phi_c}, m_{\phi_t}$ for now, so only u matters (we'll revisit this later). For simplicity, we'll refer to ϕ_u as "ϕ" and m_{ϕ_u} as "m_ϕ".
- In practice, this is tantamount to taking $c_{nc} = c_{nt} = 0$, while $c_n \equiv c_{nu} \neq 0$.

An Example Model

- The masses and couplings for the individual χ_n are not arbitrary, but determined by ***scaling relations*** that hold across the dark sector.

Masses

$$m_n = m_0 + n^\delta \Delta m$$

Controls how density of states scales w/ n

Mass of the lighest state

Mass-splitting parameter

Couplings

$$c_n = c_0 \left(\frac{m_n}{m_0}\right)^\gamma$$

Controls how c_n scales w/ n

Coupling for lighest state

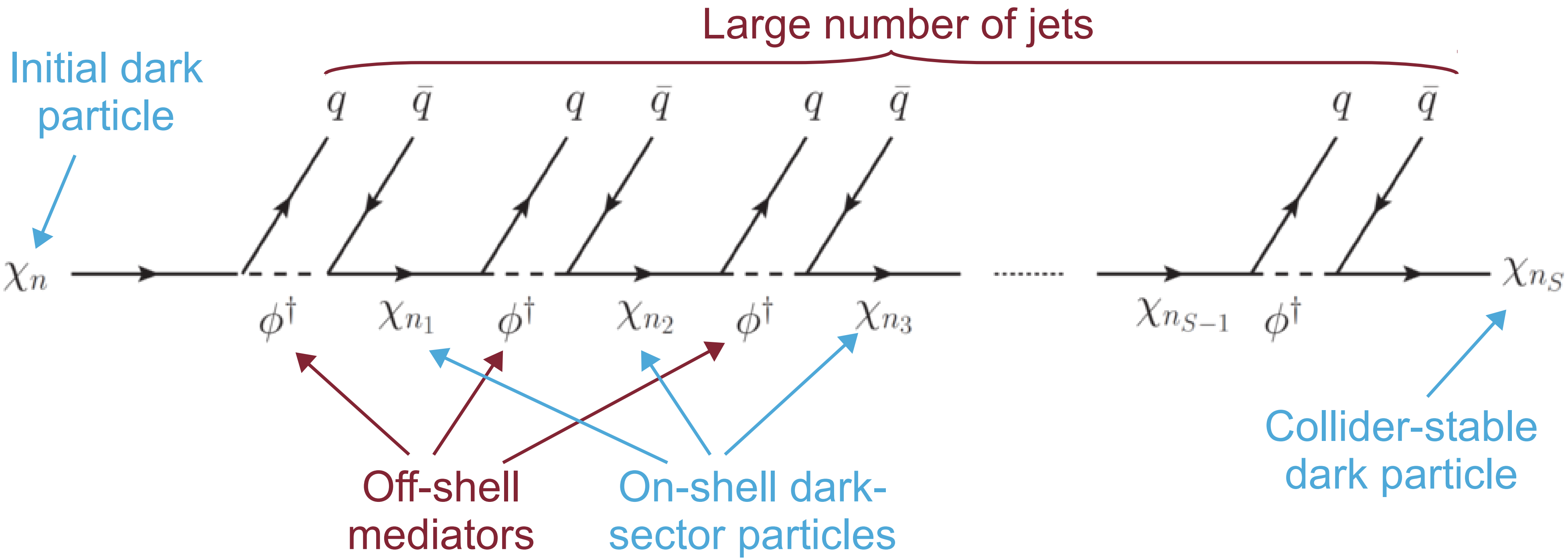
- Scaling relations of this sort arise in many top-down scenarios with extended dark sectors. **[Dienes, BT: 1107.0721; Dienes, Fennick, Kumar BT: 1601.05094,1712.09919; Buyukdag, Dienes, Gherghetta, BT: 1912.10588]**

- For simplicity, take N such that all possible states with $m_n < m_\phi$ given by the mass-scaling relation exist, but no states with $m_n \geq m_\phi$.

Free parameters: $\{m_\phi, m_0, \Delta m, c_0, \delta, \gamma\}$

Collider Phenomenology

- Once a heavy dark-sector particle is produced at a collider, it precipitates a series of decays.



<u>**Mediator-induced decay chains**</u> with potentially many steps

→

Striking signals involving <u>***large numbers of hadronic jets***</u> and <u>***missing energy***</u>!

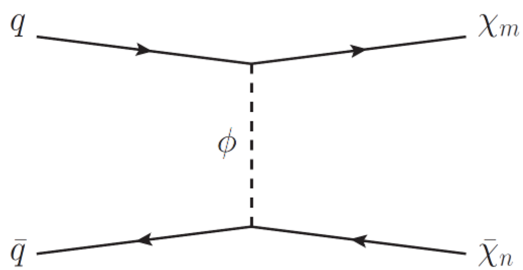
Production Channels

- Several different processes contribute to the overall production rate for mediator-induced decay chains. There are **three main classes**:

1 $pp \to \chi_m \overline{\chi}_n$

(no on-shell mediators)

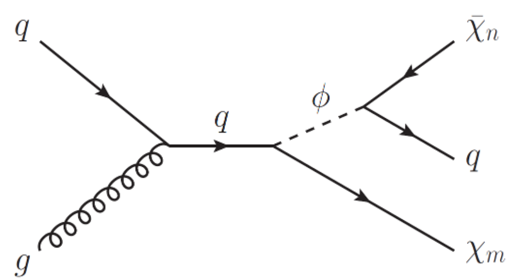
$$\sigma(pp \to \chi_m \chi_n) \propto c_0^4$$



2 $pp \to \chi_m \phi$

(one on-shell mediator)

$$\sigma(pp \to \chi_m \chi_n) \propto c_0^2$$



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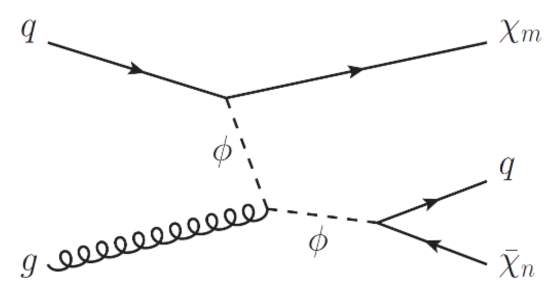


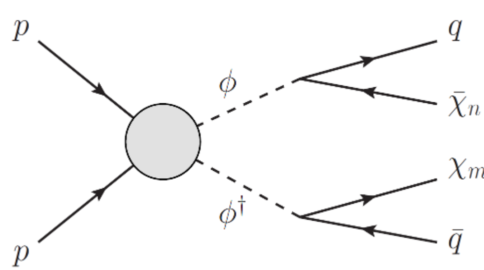
, …

3 $pp \to \phi^\dagger \phi$

(two on-shell mediators)

$$\sigma(pp \to \chi_m \chi_n) \propto 1$$

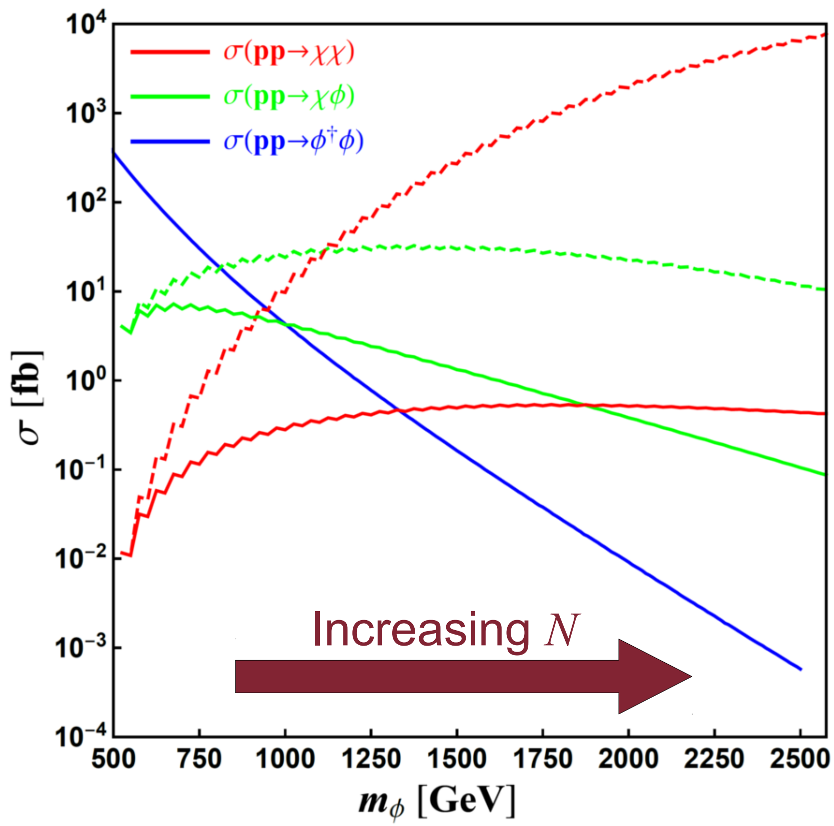
i.e., independent of c_0



Production Cross-Sections

- Different production channels dominate the production rate in different regions of parameter space.
- Define the *total* cross-sections for each channel:

$$\sigma_{\chi\chi} \equiv \sum_{m,n=0}^{N-1} \sigma(pp \to \chi_m \overline{\chi}_n) \qquad \sigma_{\phi\chi} \equiv \sum_{n=0}^{N-1} \sigma(pp \to \phi\chi_n) \qquad \sigma_{\phi\phi} \equiv \sigma(pp \to \phi\phi)$$



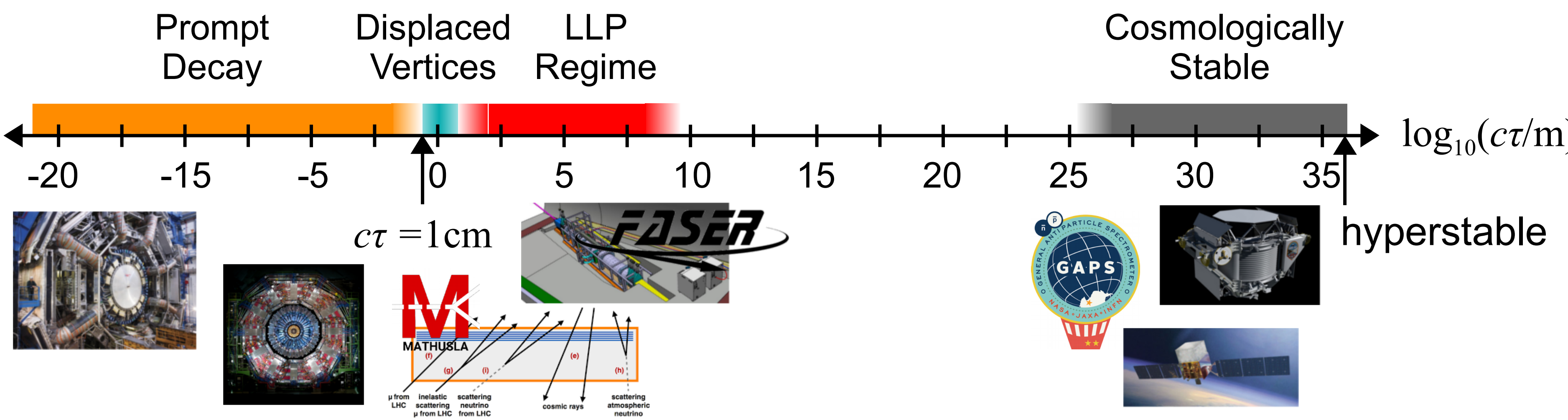
$$m_0 = 500 \text{ GeV}$$
$$\Delta m = 50 \text{ GeV}$$
$$\delta = 1$$
$$c_0 = 0.1$$

$\gamma = 3$ (dashed)

$\gamma = 1$ (solid)

Decay Lengths

- The collider phenomenology of this scenario also depends on the lifetimes τ_n (or decay lengths $c\tau_n$) of the individual χ_n.



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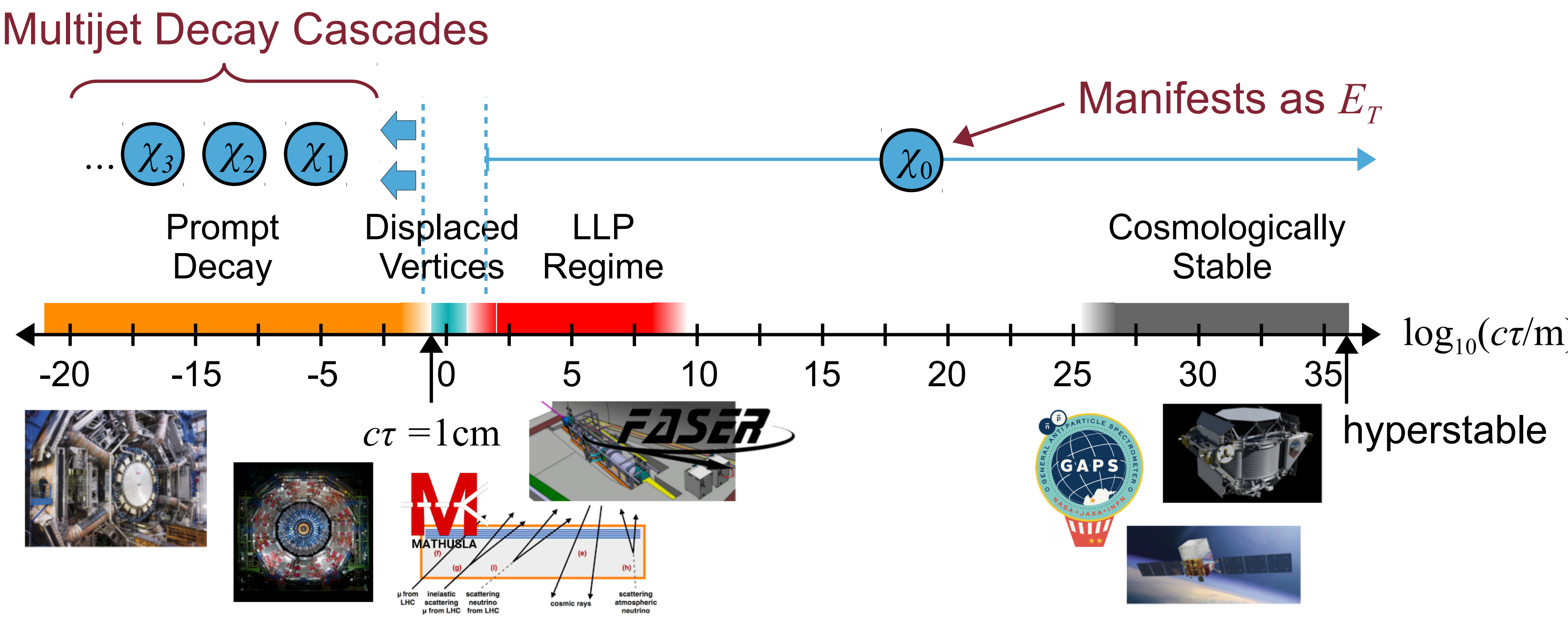

- In this talk, we'll focus on the case in which all χ_n with $n > 0$ decay ***promptly*** ($c\tau_n \lesssim 1$ cm), while χ_0 is at least collider-stable. Places an effective upper bound on c_0 for any combination of m_ϕ, m_0, Δm, δ, and γ.

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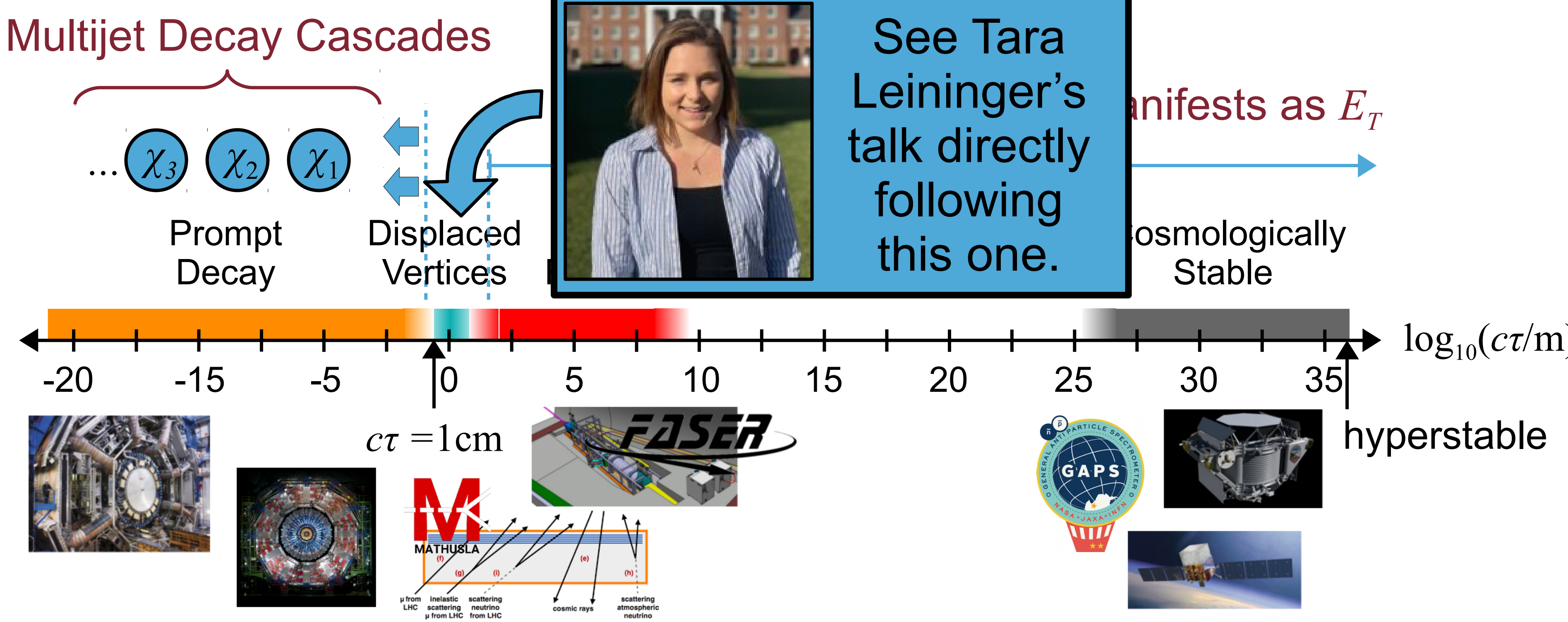

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- However, the case in which one or more of the χ_n have characteristic decay lengths in the ***displaced-vertex regime*** is interesting too!

Decay Chains: Statistical Properties

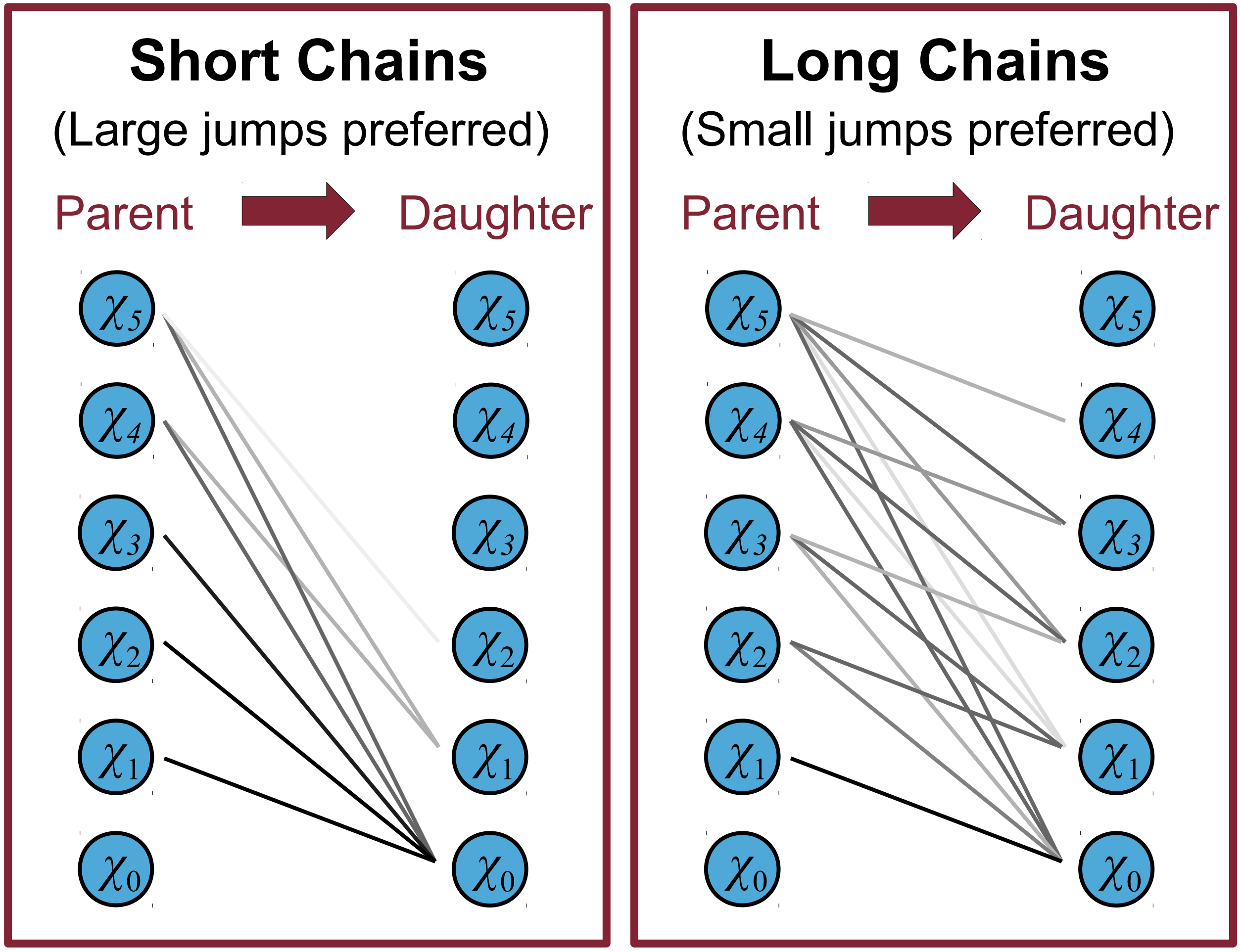
- The ***mediator-induced decay chains*** which arise in this scenario can in principle give rise to collider signatures involving ***large jet multiplicities***.

- In practice, however, having a sizable population of signal events depends of the statistical properties of these decay chains.

- These properties are ultimately dictated by the ***branching fractions*** for the individual decay steps:

$$\mathrm{BR}_{\phi n} \equiv \Gamma(\phi \to q\chi_n)/\Gamma_\phi$$

$$\mathrm{BR}_{n\ell} \equiv \Gamma(\chi_n \to qq\chi_\ell)/\Gamma_n$$



- Since we're interested in extended decay chains with many decays, we want decays with ***small $n - \ell$*** to dominate.

Decay Chains: Statistical Properties

- Let's now consider the statistical properties of ***sequences*** of decays.
- The probability that a decay chain has precisely S steps may be written schematically as

$$\hat{\mathcal{P}}(S) = \sum_{n_0, n_1, \ldots, n_{S-1}}^{N-1} \mathrm{BR}_{n_0}^{\mathrm{prod}} \mathrm{BR}_{n_0,n_1} \ldots \mathrm{BR}_{n_{S-1},0}$$

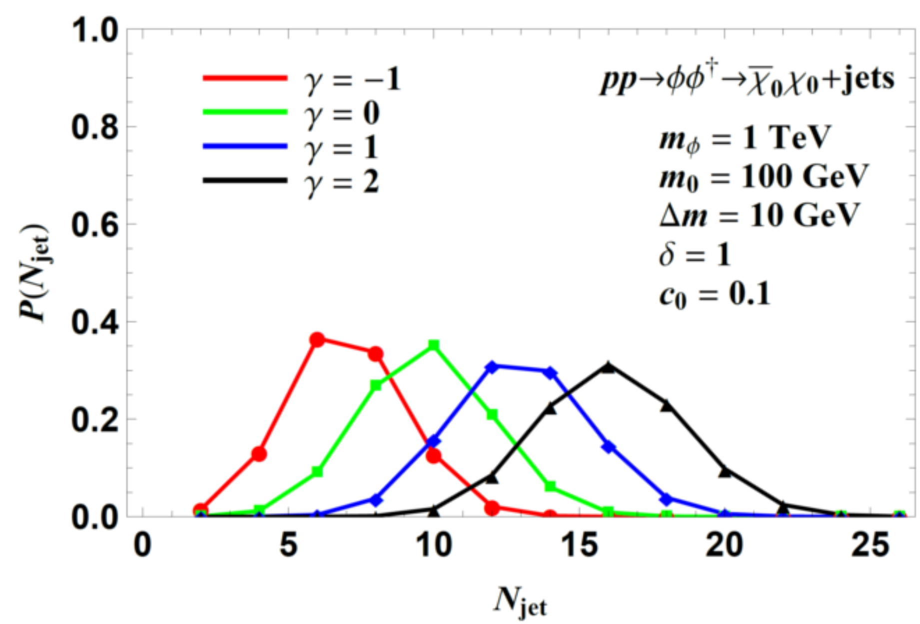
  - $\mathrm{BR}_{n_0}^{\mathrm{prod}}$: probability that χ_{n_0} is initially produced
  - $\mathrm{BR}_{ij} = 0$ for $j \geq i$

- The probability that a decay chain will yield N_{jet} SM quarks is then

$$P(N_{\mathrm{jet}}) = \sum_{S_1=0}^{(N_{\mathrm{jet}}-\zeta)/2} \hat{\mathcal{P}}(S_1)\hat{\mathcal{P}}\left(\frac{N_{\mathrm{jet}}}{2} - \frac{\zeta}{2} - S_1\right)$$

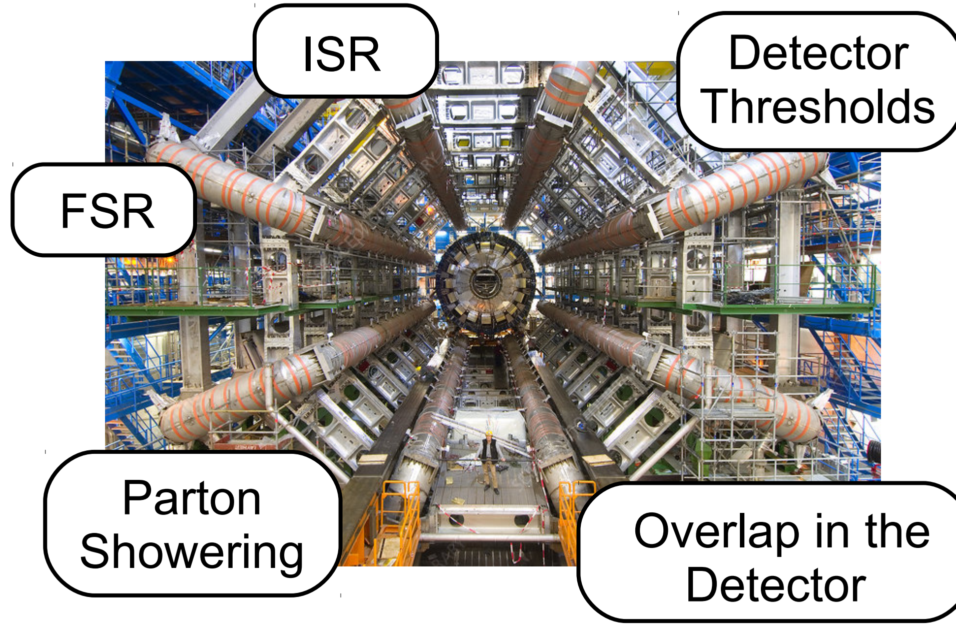
- Indeed, at least at the parton level, mediator-induced decay chains routinely give rise to events with ***large numbers ($N_{\mathrm{jet}} > 10$) of "jets."***

Jet-Number Probabilities



When You're a Jet, Are You a Jet All the Way?

- Of course, in going from the parton level ot the ***detector level***, a lot of effects can modify the distribution of N_{jet} (and other collider variables).
- In order to examine how things are modified at the detector level, we define three ***benchmark points*** within our model-parameter space.



Parameter-Space Benchmarks

Benchmark	m_ϕ	m_0	Δm	δ	γ	c_0
A	1 TeV	500 GeV	50 GeV	1	1	0.1
B	1 TeV	500 GeV	50 GeV	1	3	0.1
C	2 TeV	500 GeV	50 GeV	1	1.5	0.1

- A: $pp \to \phi^\dagger \phi$, $pp \to \phi^\dagger \chi_n$ dominate
- B: $pp \to \phi^\dagger \chi_n$ dominates
- C: $pp \to \chi_m \overline{\chi}_n$ dominates

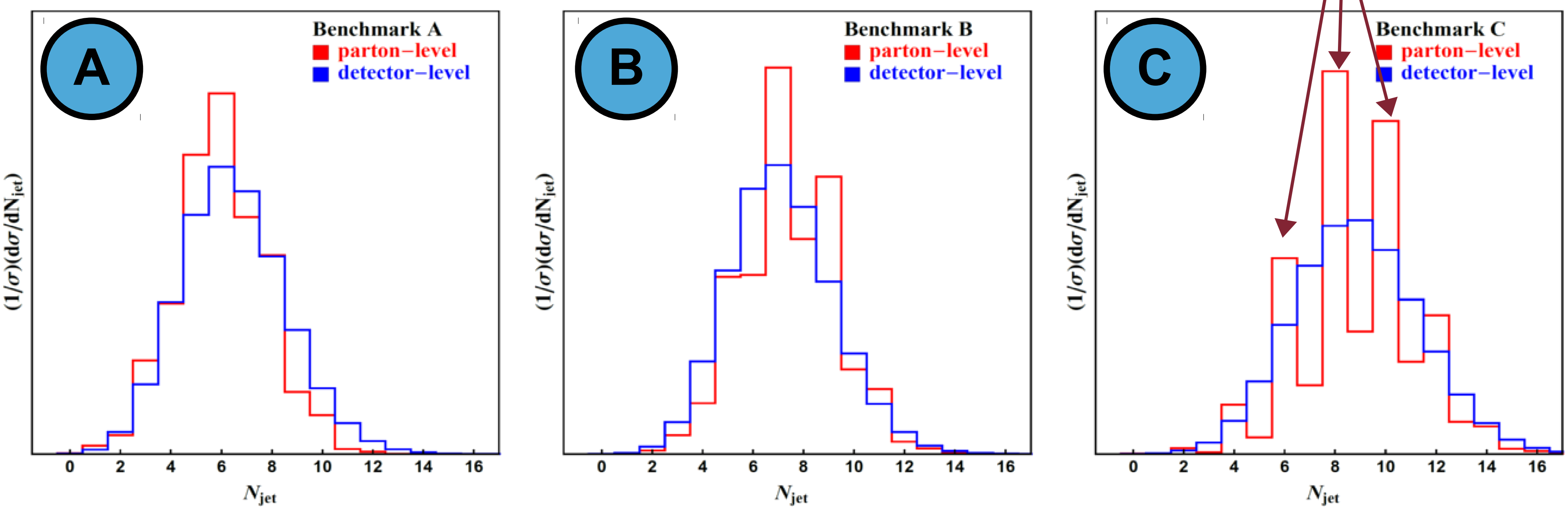
- Note that a different production channel dominates the event rate for each of these three benchmarks.

N_{jet} Distributions

- We'll begin with a comparison of the N_{jet} distributions. Contributions from all channels are included and weighted by their cross-sections.
- **Parton level**: Each quark, gluon which passes cuts counts as a "jet." No additional cuts on p_{Tj}, η_j, etc., or separation ΔR_{jj} from other "jets."
- **Detector level**: Jets requires to satisfy $p_{Tj} > 20\ \text{GeV}$, $|\eta_j| < 5$, and separation of at least $\Delta R_{jj} > 0.4$ from all more energetic jets.

The Upshot: N_{jet} distributions at the detector level are smoother and slightly broader, but not drastically different.

$pp \to \chi_m \overline{\chi}_n$ yields peaks at even N_{jet}



Event-Selection: Multi-Jet Channel

- Searches wherein events are selected primarily on the basis of $\not{E}_T$ and N_{jet} are ideal for probing our parameter-space region of interest. For our ***multi-jet search*** along these lines, we impose the following cuts:

(Modeled after Sirunyan et al.: 1708.02794)

- Basic trigger cuts: $p_{T_j} > 50$ GeV, $|\eta_j| < 5$, $\Delta R_{jj} > 0.4$
- $\frac{\not{E}_T}{\sqrt{H_T}} > 5\ \text{GeV}^{1/2}$
  - Use only $|\eta_j| < 4.5$ in computing $\not{E}_T$
  - Use only $p_{T_j} > 40$ GeV, $|\eta_j| < 2.8$ in computing H_T
- No heavy-flavor tagging.
- We also define the parameters:
  - N_{jet}^{50} : # of jets with $p_{T_j} > 50$ GeV
  - N_{jet}^{80} : # of jets with $p_{T_j} > 80$ GeV

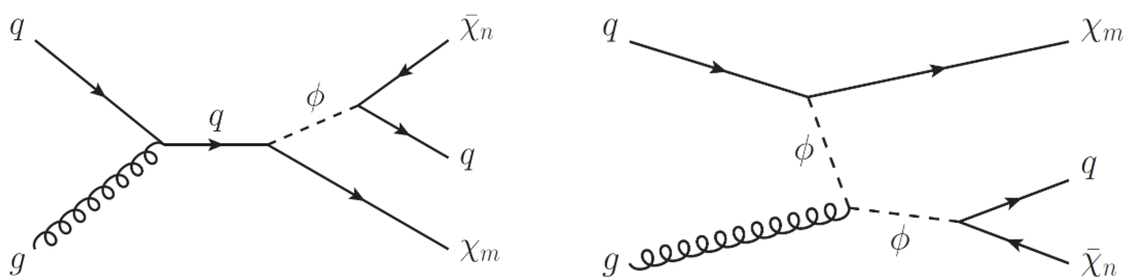
… and perform an inclusive search within the signal regions

$$N_{\text{jet}}^{50} \geq \{8, 9, 10, 11\} \qquad N_{\text{jet}}^{80} \geq \{7, 8, 9\}$$

Event-Selection: Monojet Channel

- We must also be careful in our analysis to ensure that our model isn't already excluded by searches in other detection channels.
- One of these is the ***monojet + $\not{E}_T$ channel***:

e.g., from



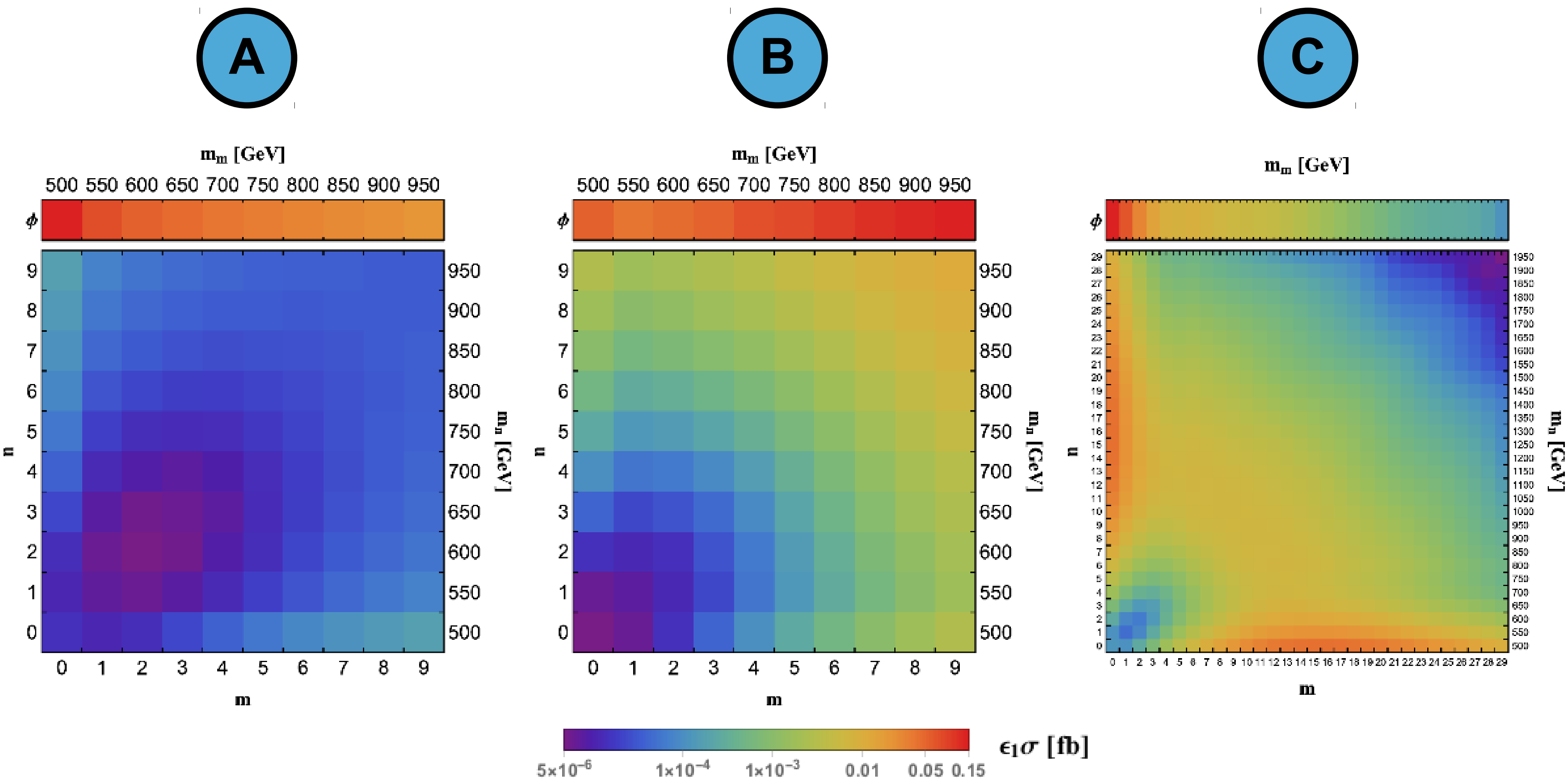
with $m = n = 0$

- We adopt the following cuts in assessing the event rate in the monojet channel: **(Modeled after Aaboud et al.: arXiv:1711.03301)**
  - Basic trigger cuts: $p_{T_j} > 50$ GeV, $|\eta_j| < 5$, $\Delta R_{jj} > 0.4$
  - $\not{E}_T > 250$ GeV
  - $p_{T_j} > 250$ GeV, $|\eta_j| < 2.4$ for leading jet
  - No more than 4 jets with $p_{T_j} > 30$ GeV, $|\eta_j| < 2.8$
- In addition, we also consider constraints from multi-jet searches with more ***moderate jet multiplicities*** ($N_{\text{jet}} = 2 - 6$) and large $\not{E}_T$.

Contributions from Individual Processes

- We begin by examining the cross-sections for the individual production processes $pp \to \phi\chi_m$ and $pp \to \chi_m\bar{\chi}_n$ for our three benchmarks after each set of cuts is applied.

Monojet Cuts



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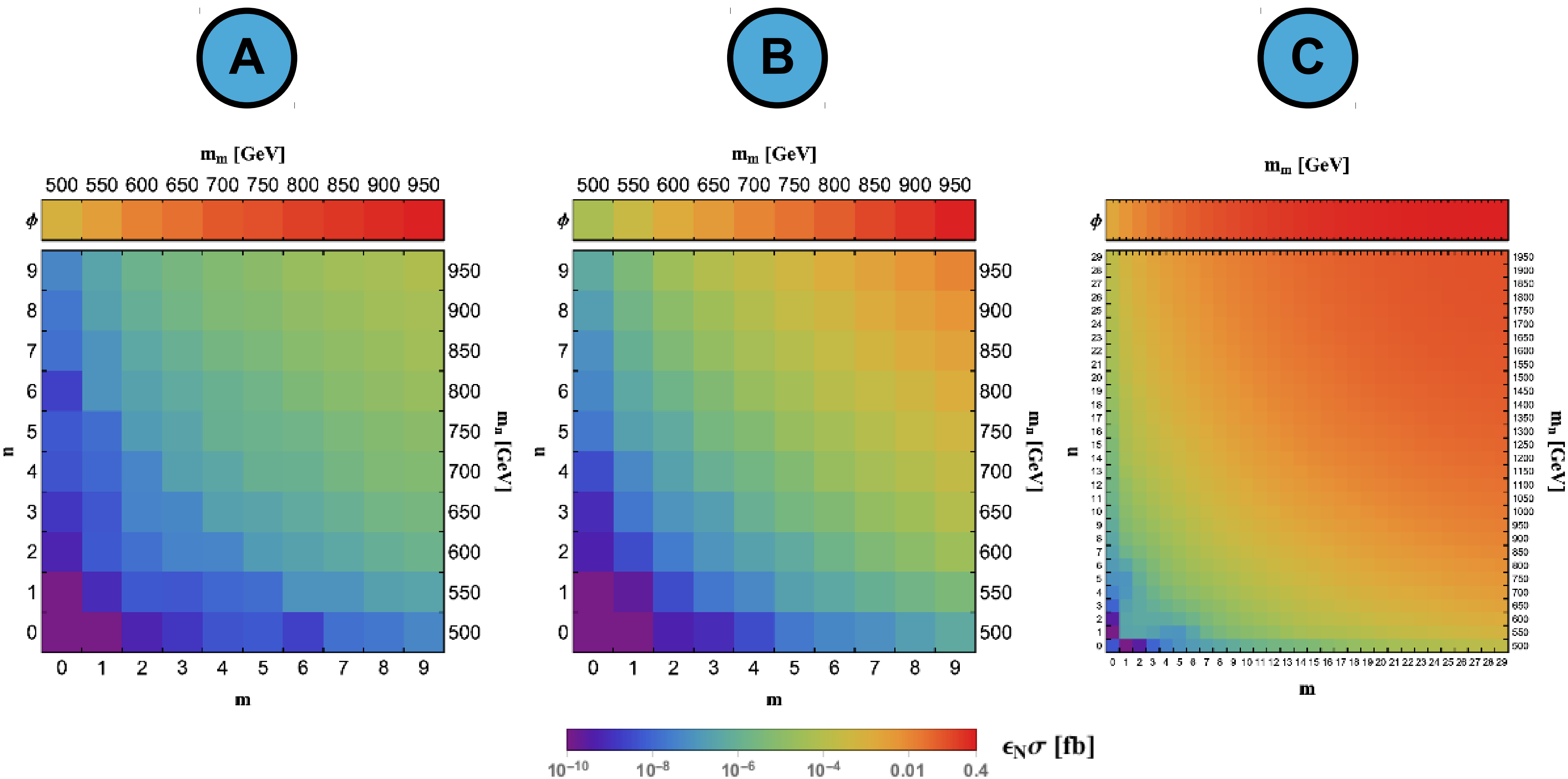
Multijet Cuts



Aggregate Contributions

- We now compare the ***total cross-sections*** for our benchmark points for each of the three main production channels, before and after cuts.

ε_1 and ε_N: cut efficiencies for monojet and multi-jet channels

Total Cross-Sections

	Before Cuts			After Monojet Cuts			After Multi-Jet Cuts		
Benchmark	$\sigma_{\chi\chi}$ (fb)	$\sigma_{\phi\chi}$ (fb)	$\sigma_{\phi\phi}$ (fb)	$\epsilon_1\sigma_{\chi\chi}$ (fb)	$\epsilon_1\sigma_{\phi\chi}$ (fb)	$\epsilon_1\sigma_{\phi\phi}$ (fb)	$\epsilon_N\sigma_{\chi\chi}$ (fb)	$\epsilon_N\sigma_{\phi\chi}$ (fb)	$\epsilon_N\sigma_{\phi\phi}$ (fb)
A	0.28	4.19	4.29	0.015	0.41	0.32	7.6×10^{-4}	0.058	0.12
B	9.72	23.9	4.29	0.32	0.77	0.10	0.10	0.87	0.24
C	3.06	0.92	9.1×10^{-3}	0.065	6.0×10^{-3}	1.4×10^{-5}	0.62	0.34	4.6×10^{-3}
LHC Limit				531			7.2		

Current (as of April, 2020) limit from LHC searches (in fb)

- All three benchmarks are consistent with LHC limits from both monojet and multi-jet searches, yet a different process dominates for each one.

The upshot: Despite stringent limits, there is still potential for mediator-induced decay chains to manifest themselves at colliders.

Results

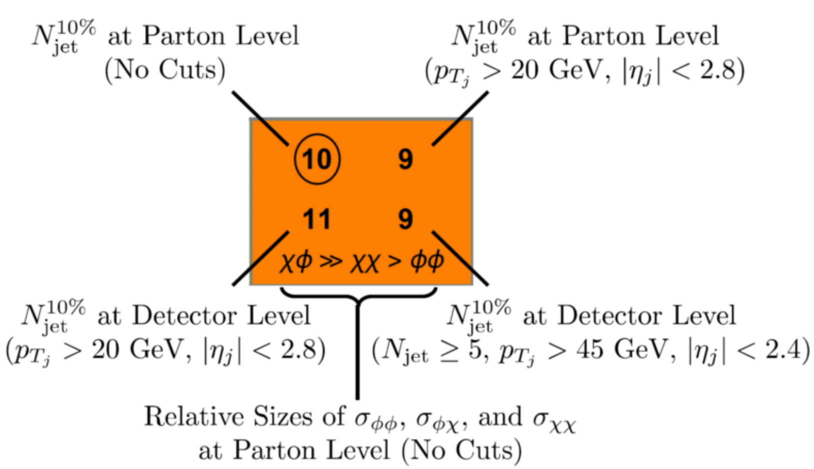
- We perform a parameter-space survey, varying γ and m_ϕ and holding all other parameters fixed.

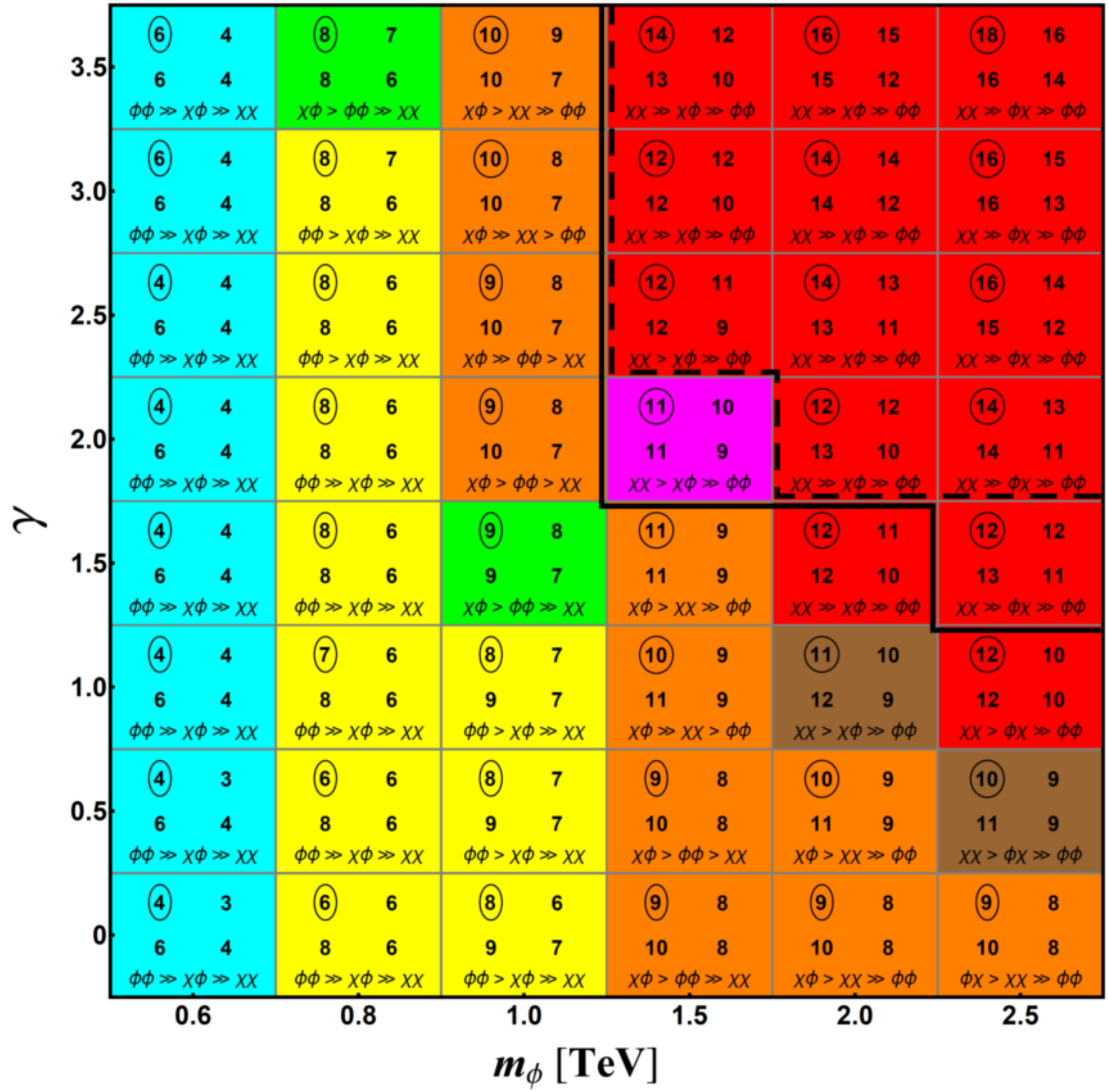
$$m_0 = 500\ \text{GeV} \qquad \delta = 1$$
$$\Delta m = 50\ \text{GeV} \qquad c_0 = 0.1$$

—— Multi-jet search limit

------- Moderate N_{jet} search limit

(Monojet searches not constraining here)





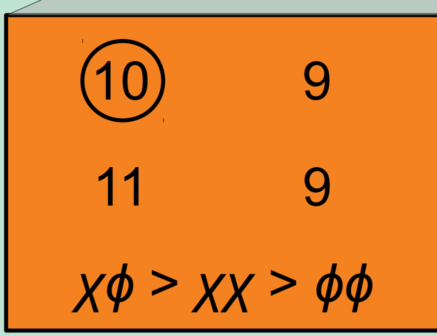
	Dominant Process After Specified Cuts			
	Parton Level (No Cuts)	Basic Trigger (p_T>20 GeV, $|\eta|$<2.8)	Multi–Jet Trigger (N_{jet}≥5, p_T>45 GeV, $|\eta|$<2.4)	Multi–Jet ($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, N_{jet}^{50}≥8)
	χχ	χχ	χχ	χχ
	χχ	χχ	χχ	χϕ
	χχ	χχ	χϕ	χϕ
	χϕ	χχ	χϕ	χϕ
	χϕ	χϕ	ϕϕ	ϕϕ
	ϕϕ	χϕ	ϕϕ	ϕϕ
	ϕϕ	ϕϕ	ϕϕ	ϕϕ

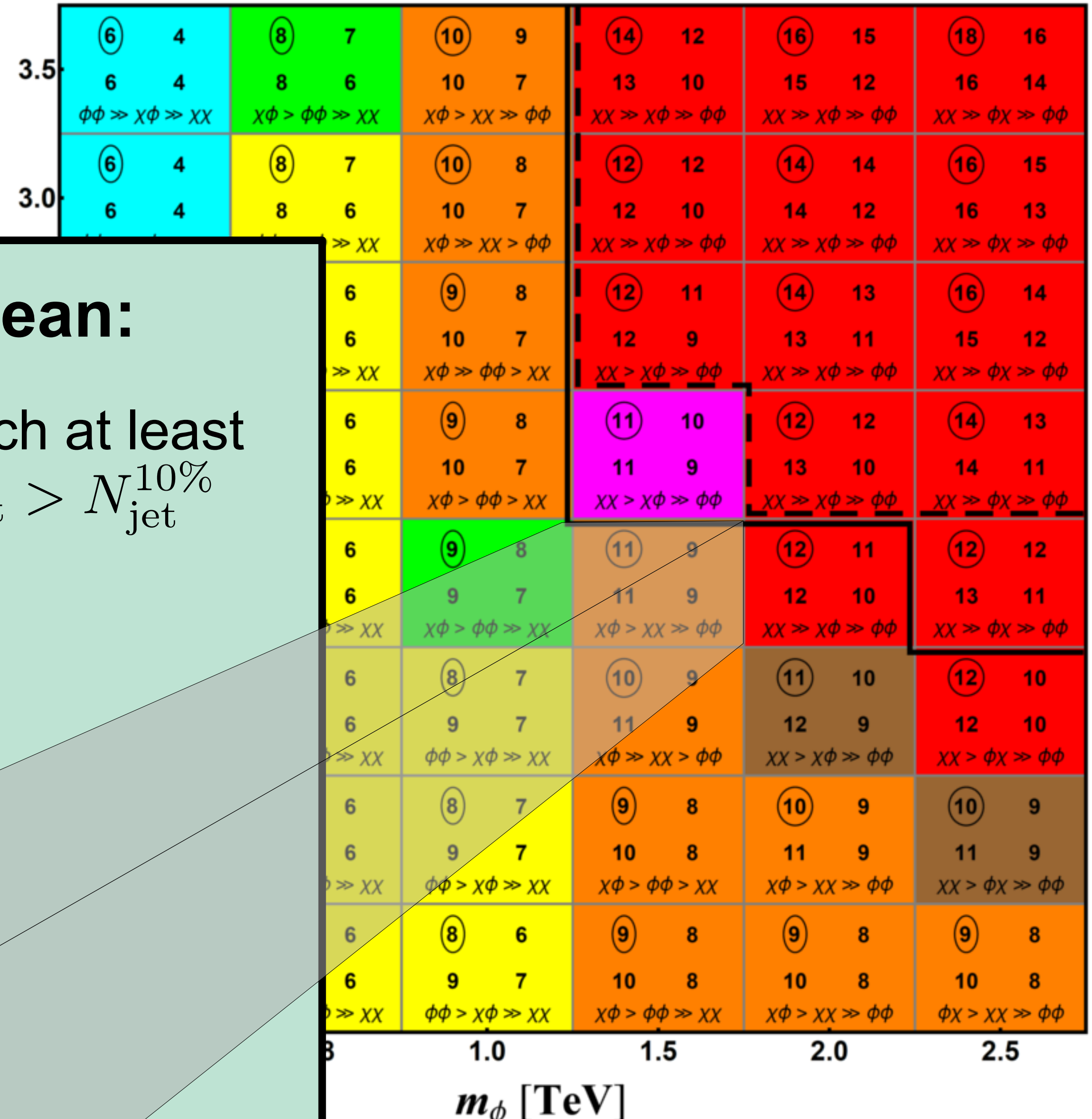
Results

- We perform a parameter-

What the Entries Mean:

$N_{\rm jet}^{10\%}$: max value of $N_{\rm jet}$ for which at least 10% of signal events have $N_{\rm jet} > N_{\rm jet}^{10\%}$





Dominant Process After Specified Cuts		
Basic Trigger	Multi–Jet Trigger	Multi–Jet
$_T$>20 GeV, $\|\eta\|$<2.8)	($N_{jet}\geq5$, p_T>45 GeV, $\|\eta\|$<2.4)	($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, $N_{jet}^{50}\geq8$)
χχ	χχ	χχ
χχ	χχ	χϕ
χχ	χϕ	χϕ
χχ	χϕ	χϕ
χϕ	ϕϕ	ϕϕ
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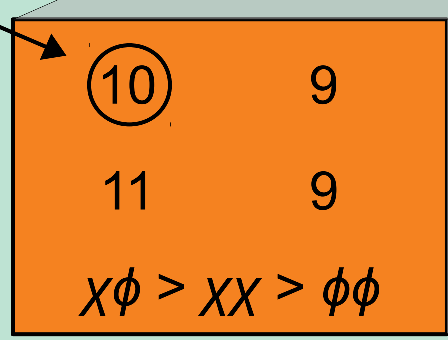
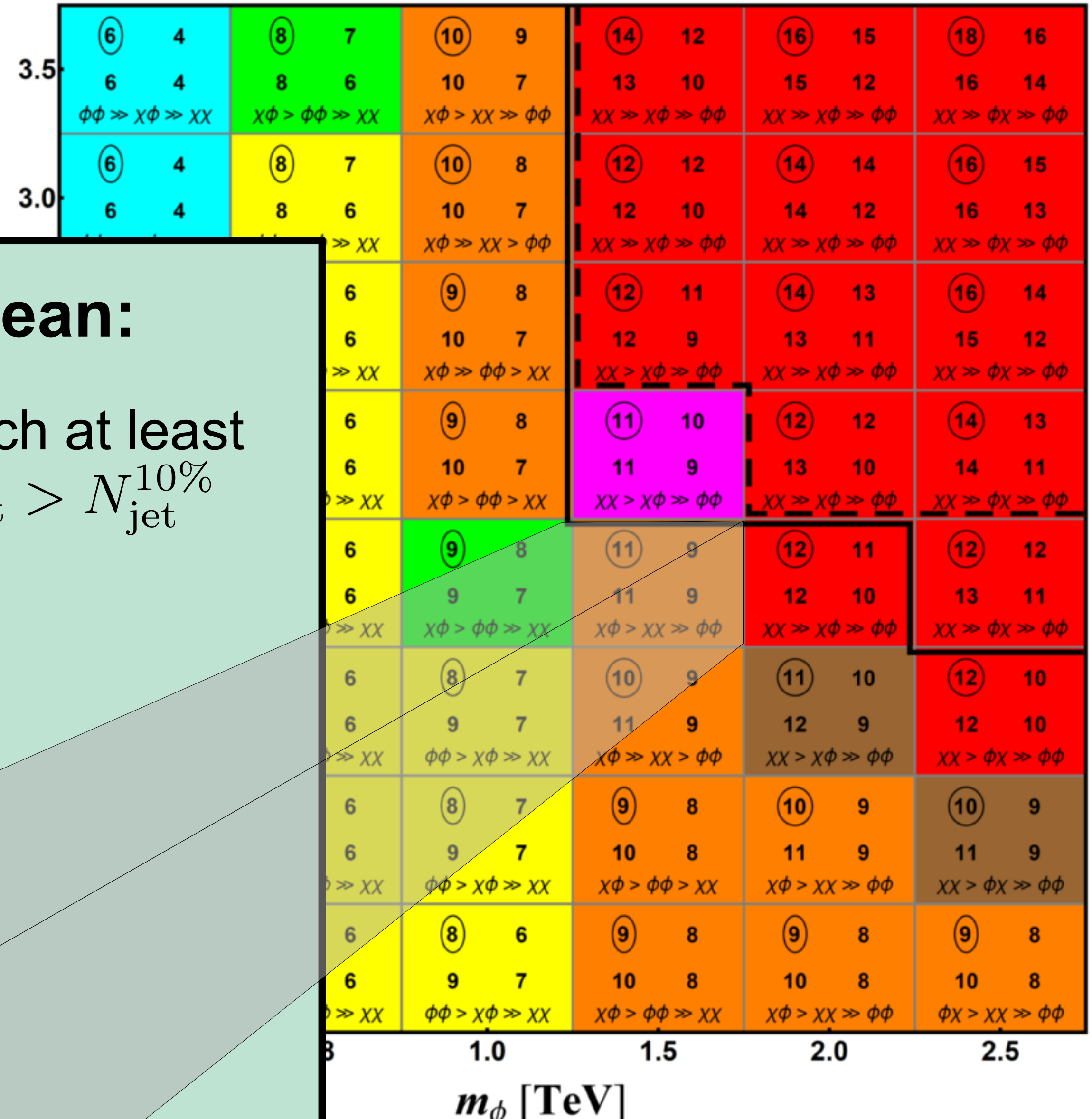
$N_{\text{jet}}^{10\%}$: max value of N_{jet} for which at least 10% of signal events have $N_{\text{jet}} > N_{\text{jet}}^{10\%}$

$N_{\text{jet}}^{10\%}$ at parton level (no cuts)





Dominant Process After Specified Cuts		
Basic Trigger (p_T>20 GeV, $\lvert\eta\rvert$<2.8)	Multi–Jet Trigger (N_{jet}≥5, p_T>45 GeV, $\lvert\eta\rvert$<2.4)	Multi–Jet ($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, N_{jet}^{50}≥8)
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χϕ	ϕϕ	ϕϕ
χϕ	ϕϕ	ϕϕ
ϕϕ	ϕϕ	ϕϕ

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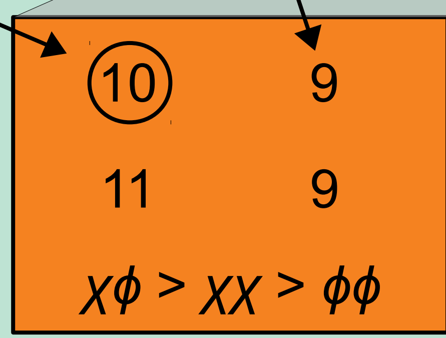
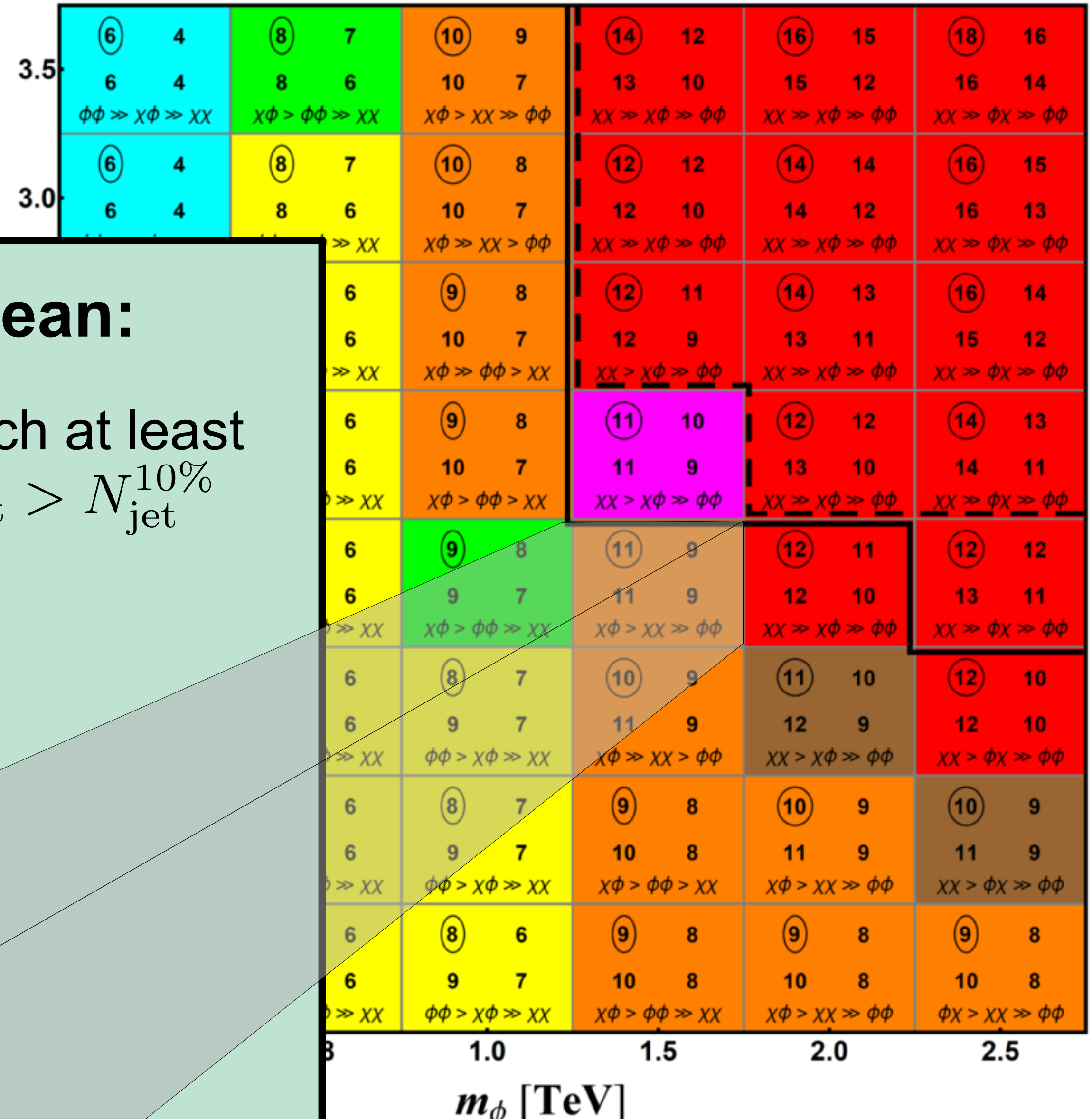
$N_{\rm jet}^{10\%}$ at parton level ($p_{T_j} > 20$ GeV, $|\eta_j| < 2.8$)

$N_{\rm jet}^{10\%}$ at parton level (no cuts)





Dominant Process After Specified Cuts		
Basic Trigger (…T>20 GeV, |η|<2.8)	Multi–Jet Trigger ($N_{\rm jet}$≥5, p_T>45 GeV, |η|<2.4)	Multi–Jet ($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, $N_{\rm jet}^{50}$≥8)
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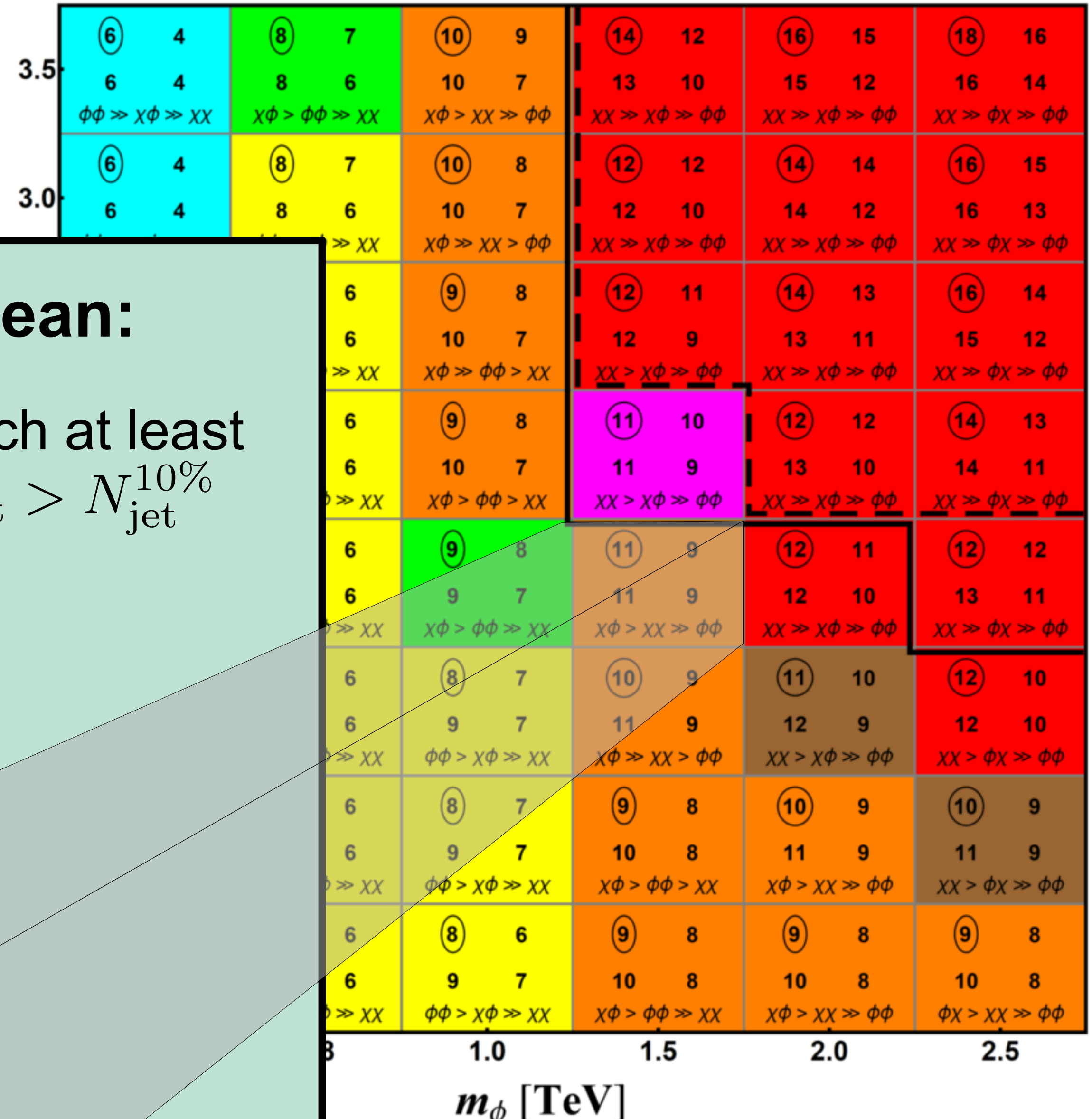

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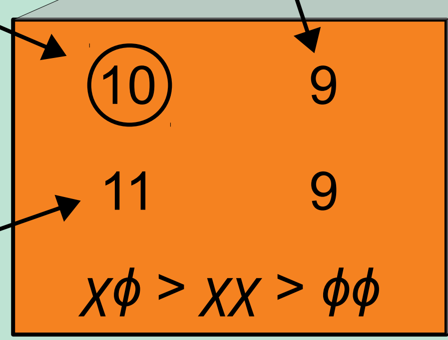
$N_{\rm jet}^{10\%}$: max value of $N_{\rm jet}$ for which at least 10% of signal events have $N_{\rm jet} > N_{\rm jet}^{10\%}$

$N_{\rm jet}^{10\%}$ at parton level ($p_{T_j} > 20$ GeV, $|\eta_j| < 2.8$)

$N_{\rm jet}^{10\%}$ at parton level (no cuts)

$N_{\rm jet}^{10\%}$ at detector level ($p_{T_j} > 20$ GeV, $|\eta_j| < 2.8$)



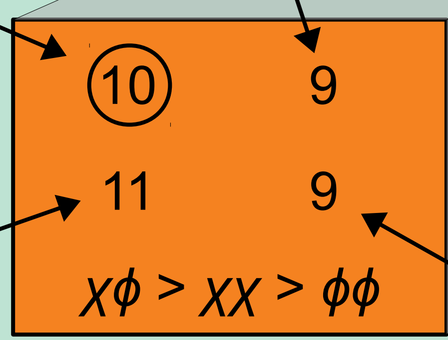
Dominant Process After Specified Cuts		
Basic Trigger ($_T$>20 GeV, $|\eta|$<2.8)	Multi–Jet Trigger ($N_{\rm jet}\geq5$, p_T>45 GeV, $|\eta|$<2.4)	Multi–Jet ($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, $N_{\rm jet}^{50}\geq8$)
χχ	χχ	χχ
χχ	χχ	χϕ
χχ	χϕ	χϕ
χχ	χϕ	χϕ
χϕ	ϕϕ	ϕϕ
χϕ	ϕϕ	ϕϕ
ϕϕ	ϕϕ	ϕϕ

Results

- We perform a parameter-

What the Entries Mean:

$N_{\rm jet}^{10\%}$: max value of $N_{\rm jet}$ for which at least 10% of signal events have $N_{\rm jet} > N_{\rm jet}^{10\%}$

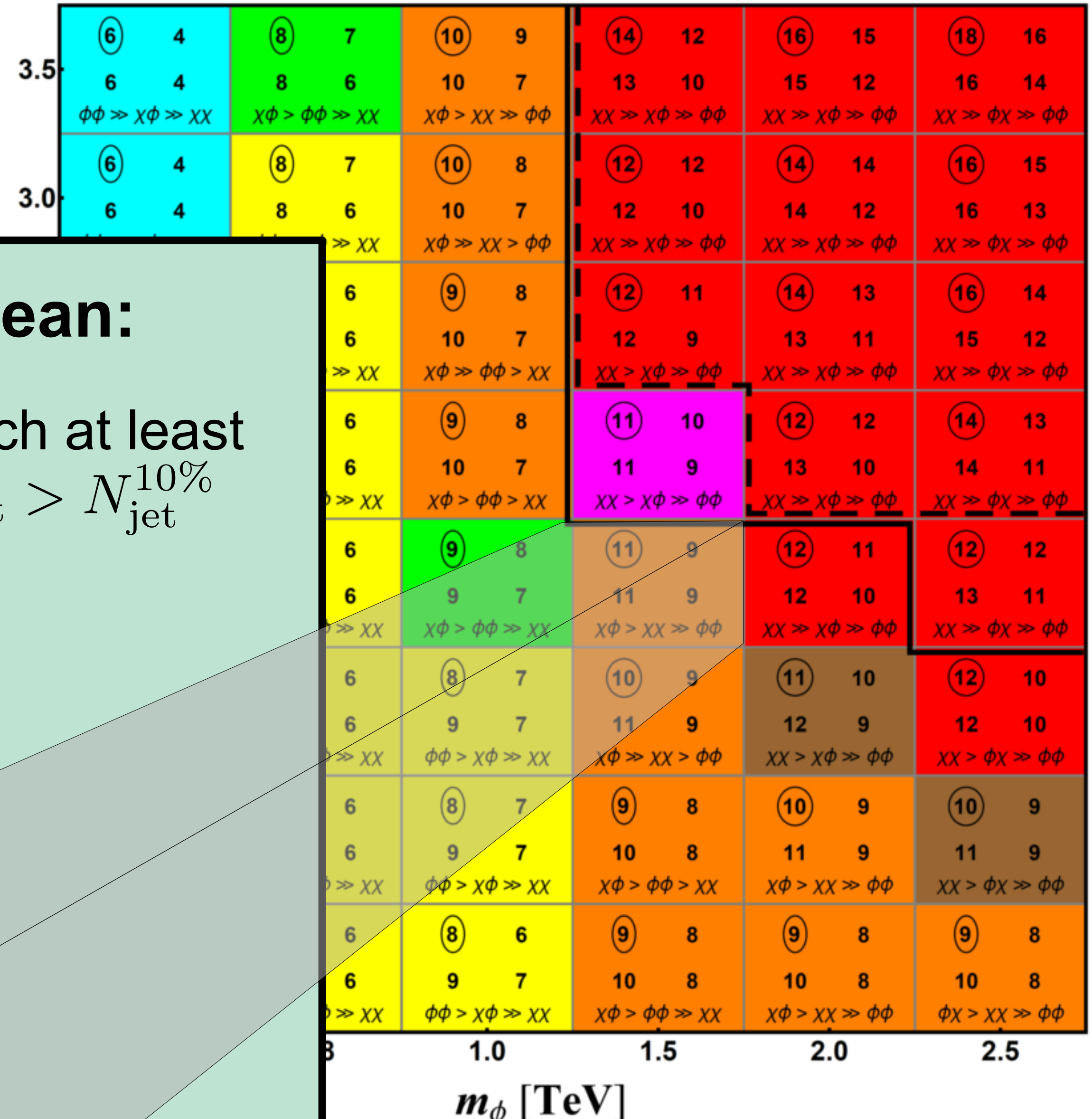


$N_{\rm jet}^{10\%}$ at parton level (no cuts)

$N_{\rm jet}^{10\%}$ at parton level ($p_{T_j} > 20$ GeV, $|\eta_j| < 2.8$)

$N_{\rm jet}^{10\%}$ at detector level ($p_{T_j} > 20$ GeV, $|\eta_j| < 2.8$)

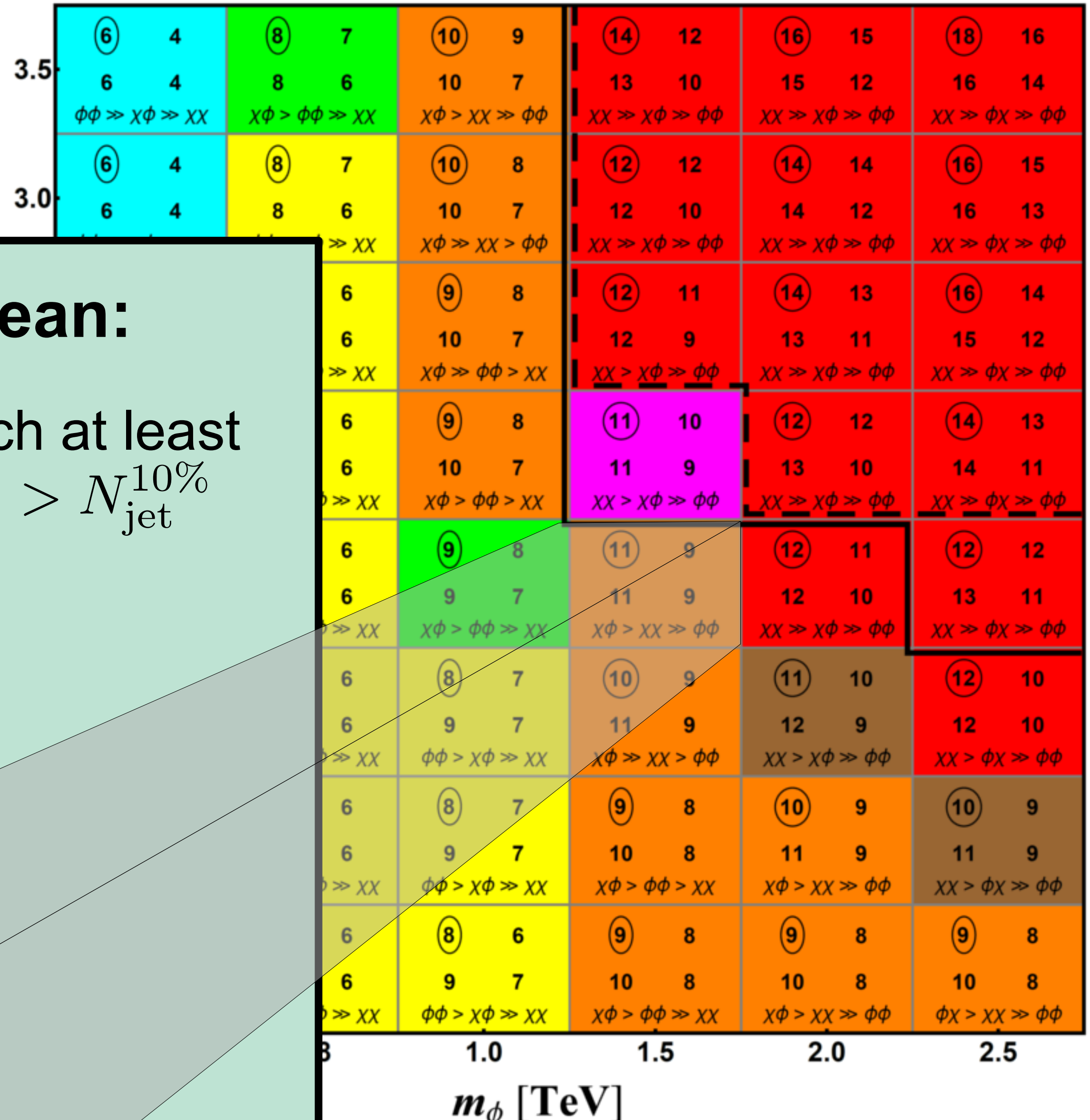
$N_{\rm jet}^{10\%}$ at detector level ($p_{T_j} > 45$ GeV, $|\eta_j| < 2.4$, $N_{\rm jet} \geq 5$)

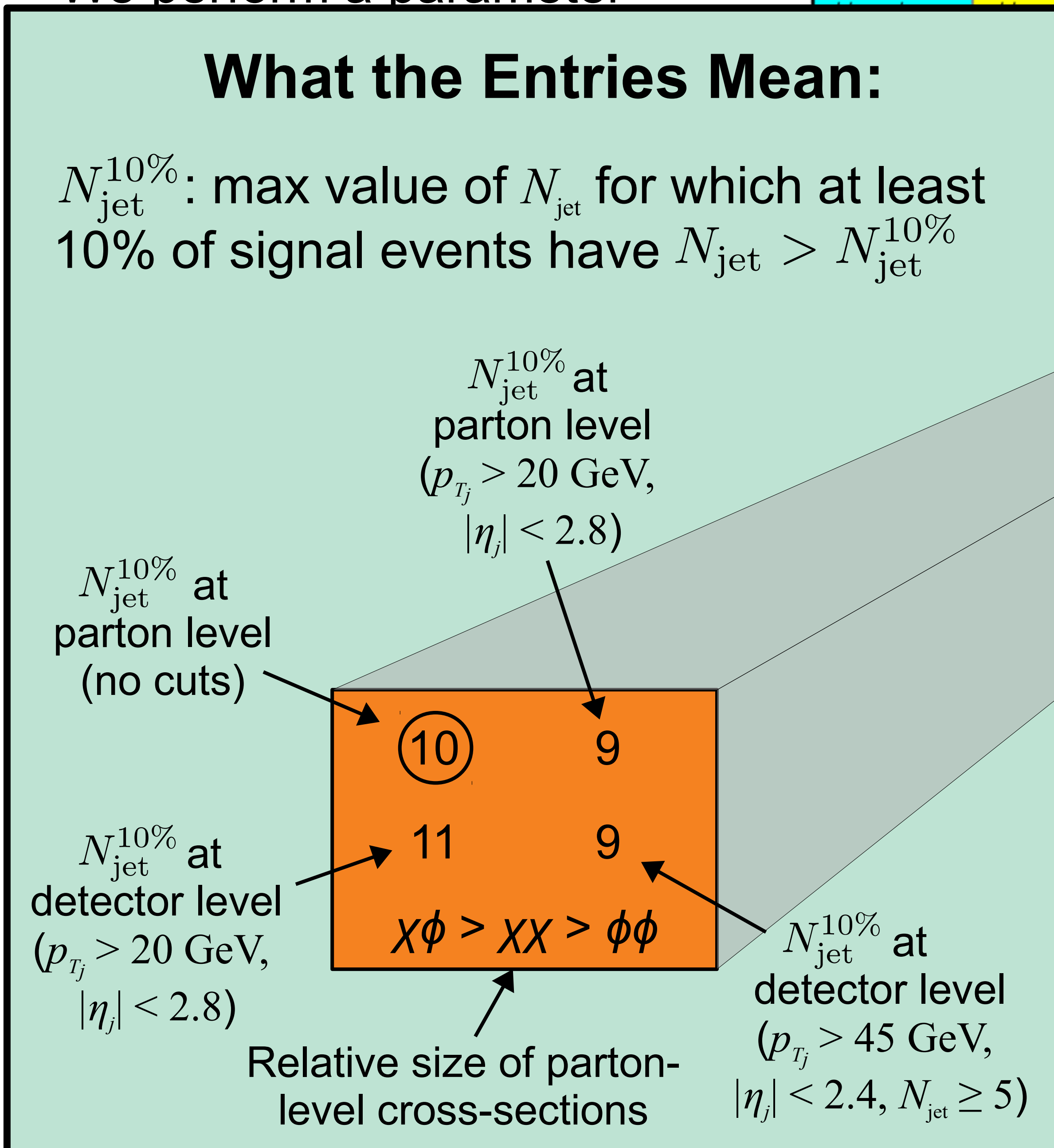


Dominant Process After Specified Cuts		
Basic Trigger (p$_T$>20 GeV, $|\eta|$<2.8)	Multi–Jet Trigger ($N_{\rm jet}\geq5$, p_T>45 GeV, $|\eta|$<2.4)	Multi–Jet ($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, $N_{\rm jet}^{50}\geq8$)
χχ	χχ	χχ
χχ	χχ	χϕ
χχ	χϕ	χϕ
χχ	χϕ	χϕ
χϕ	ϕϕ	ϕϕ
χϕ	ϕϕ	ϕϕ
ϕϕ	ϕϕ	ϕϕ

Results

- We perform a parameter-





Dominant Process After Specified Cuts		
Basic Trigger	Multi–Jet Trigger	Multi–Jet
$_T$>20 GeV, $\|\eta\|$<2.8)	($N_{\rm jet}$≥5, p_T>45 GeV, $\|\eta\|$<2.4)	($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, $N_{\rm jet}^{50}$≥8)
χχ	χχ	χχ
χχ	χχ	χφ
χχ	χφ	χφ
χχ	χφ	χφ
χφ	φφ	φφ
χφ	φφ	φφ
φφ	φφ	φφ

Results

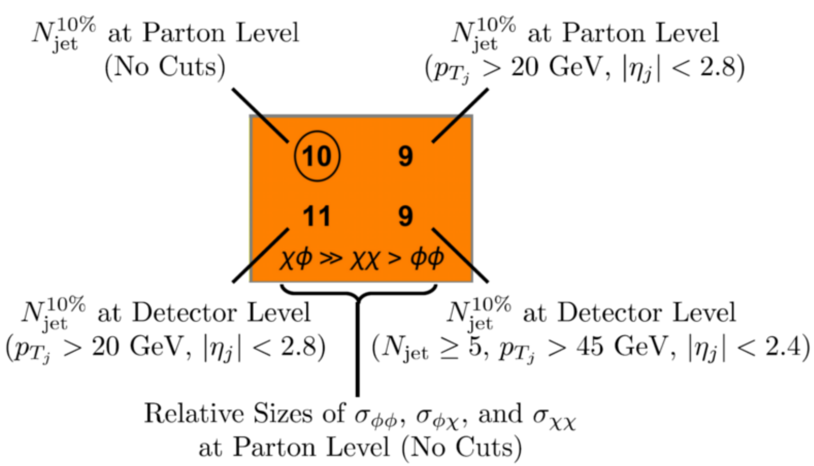
- We perform a parameter-space survey, varying γ and m_ϕ and holding all other parameters fixed.

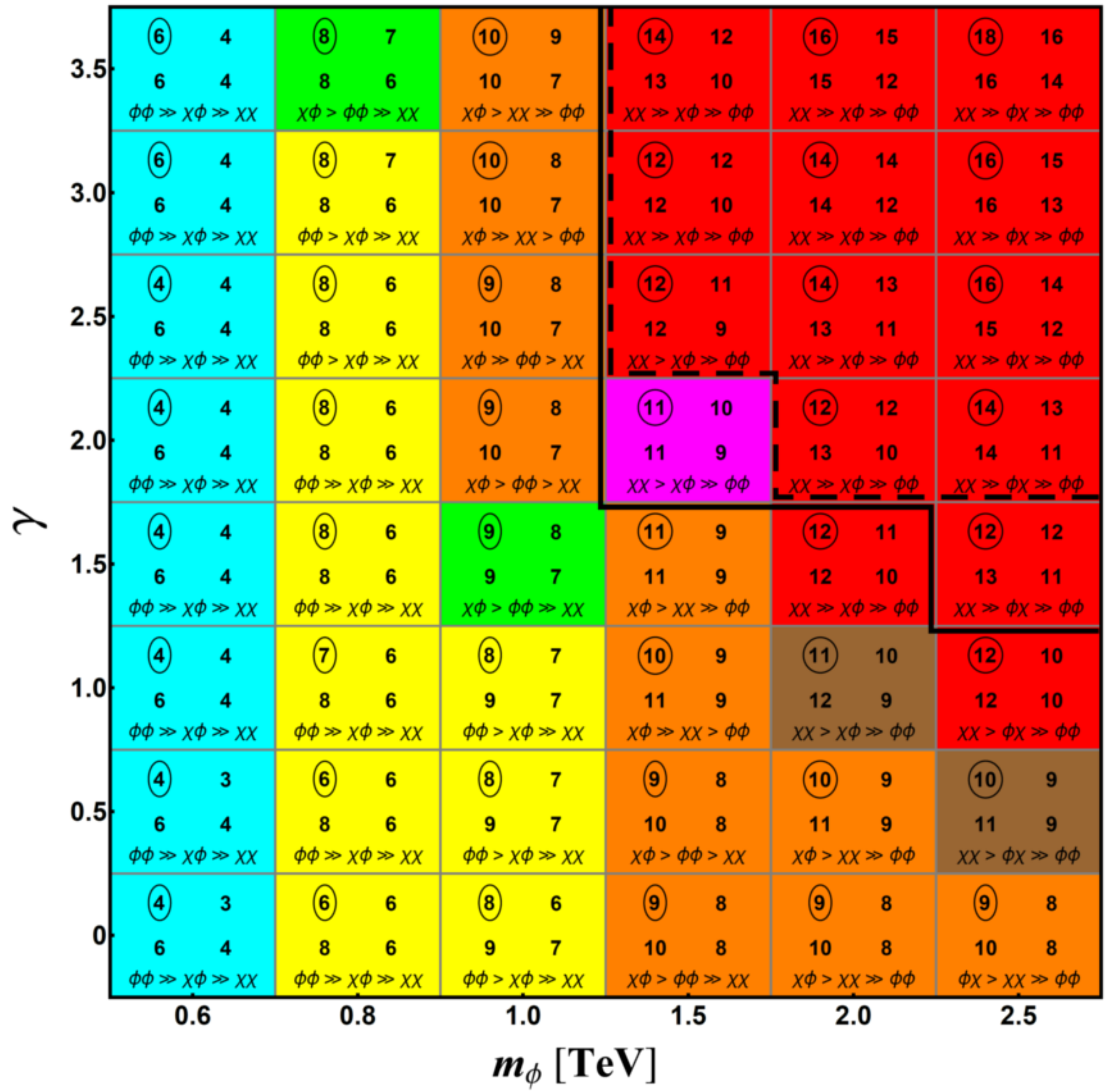
$$m_0 = 500\ \text{GeV} \qquad \delta = 1$$
$$\Delta m = 50\ \text{GeV} \qquad c_0 = 0.1$$

—— Multi-jet search limit

------- Moderate N_{jet} search limit

(Monojet searches not constraining here)





	Dominant Process After Specified Cuts			
	Parton Level (No Cuts)	Basic Trigger (p_T>20 GeV, $\|\eta\|$<2.8)	Multi–Jet Trigger (N_{jet}≥5, p_T>45 GeV, $\|\eta\|$<2.4)	Multi–Jet ($\not{E}_T/\sqrt{H_T}$ >5 GeV$^{1/2}$, N_{jet}^{50}≥8)
red	χχ	χχ	χχ	χχ
magenta	χχ	χχ	χχ	χφ
brown	χχ	χχ	χφ	χφ
orange	χφ	χχ	χφ	χφ
green	χφ	χφ	φφ	φφ
yellow	φφ	χφ	φφ	φφ
cyan	φφ	φφ	φφ	φφ

Summary

- In a variety of dark-matter scenarios, interactions between the dark-matter particle and the fields of the visible sector are facilitated by a ***mediator particle***.
- In the context of non-minimal dark sectors, mediators. not only provide a portal between the visible and dark sectors, but also can render the dark-sector states ***unstable***.
- These mediators can give rise to ***extended decay chains*** at coliders involving large numbers of SM particles.
- We have examined the ***multi-jet signatures*** which arise from decay chains of this sort in the case in which the SM particles which couple to the mediator are light quarks.
- While constraints on mediator-induced decay chains are quite stringent, there is still a ***discovery window*** for such processes at the LHC.
- In addition, the lightest dark-sector state in these scenarios can potentially serve as a dark-matter candidate.