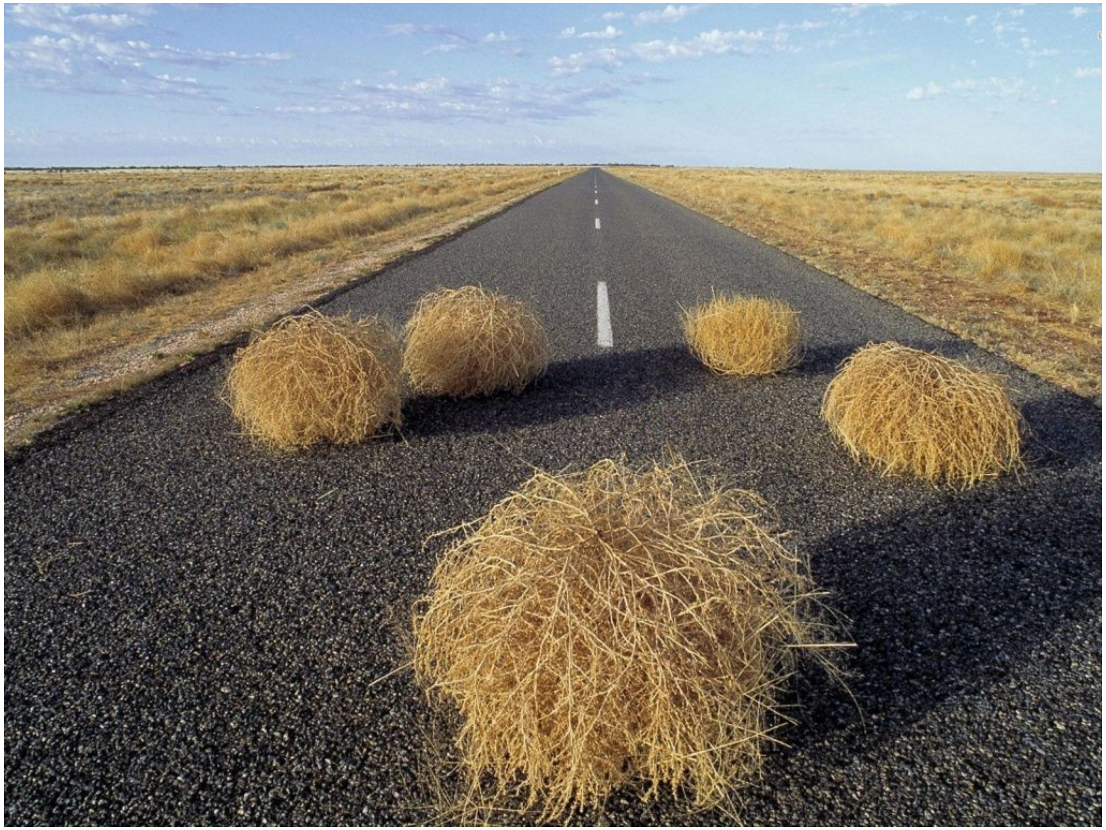
Tumblers: A Novel Collider Signature for Long-Lived Particles



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Based on work done in collaboration with:

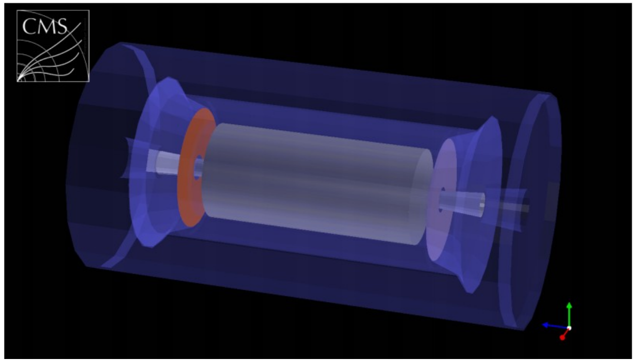
- **Keith Dienes, Doojin Kim, and Tara Leininger [arXiv:2108.02204]**

Mitchell Workshop 2022, May 25th, 2022

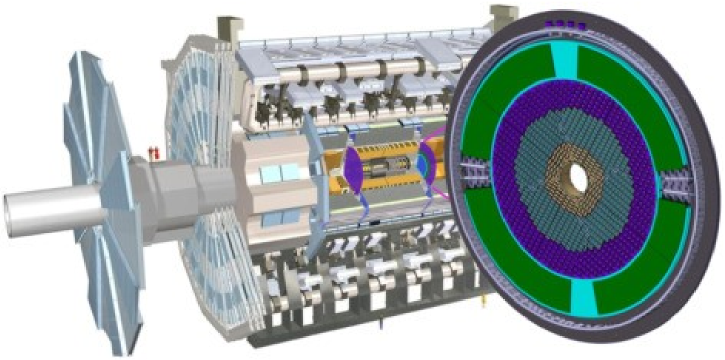
Long-Lived Particles

- Long-lived particles (LLPs) arise in many extensions of the SM.
- LLPs with lifetimes $\mathcal{O}(1\ \mathrm{mm}) \lesssim c\tau \lesssim \mathcal{O}(100\ \mathrm{m})$ can give rise to macroscopically ***displaced vertices*** (DVs) at colliders.
- Search channels involving DVs have very ***low SM backgrounds*** and thus represent a promising experimental probe of new physics.
- Several dedicated searches for excesses in channels involving one or more DVs have already been performed at the LHC.
- During the HL-LHC upgrade, additional apparatus will be installed in both the ATLAS and CMS detectors which enhances their physics performance with regard to DVs. [Liu, Liu, Wang: 1805.05957; Liu, Liu, Wang, Wang: 2005.10836; Flowers, Meier, Rogan, Kang, Park: 1903.05825]

CMS: Barrel Timing Layer, High-Granularity Calorimeters

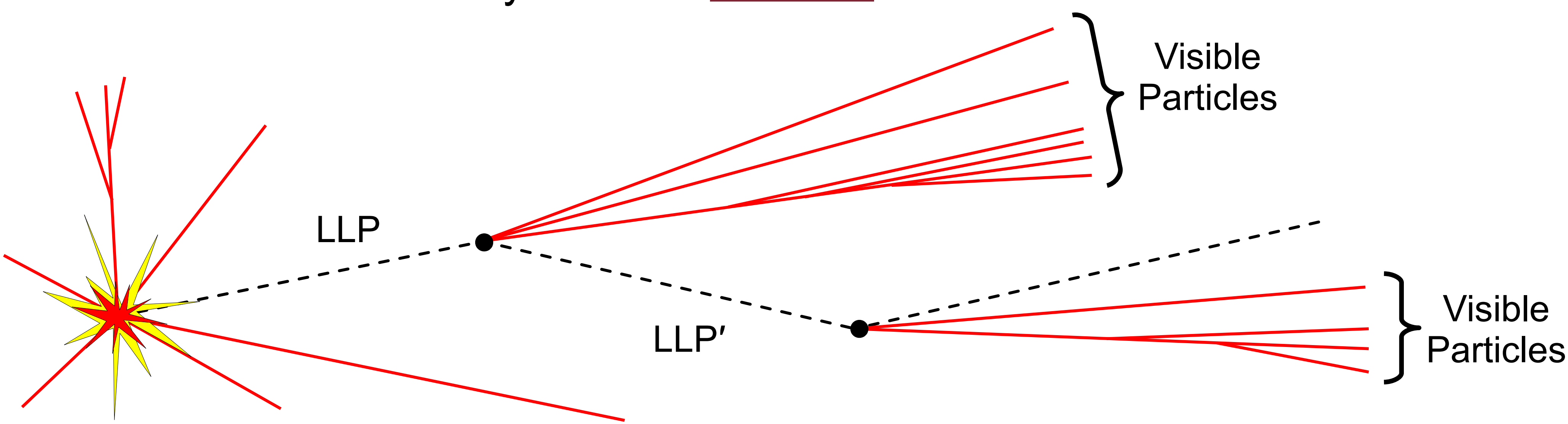


ATLAS: Encap Timing Detectors, High-Granularity Calorimeters



Tumblers

- The analysis of LLP signatures has generally focused on the case in which each LLP decays to final states involving one or more detectable SM particles – plus perhaps additional invisible particles.
- However, in scenarios in which there exist ***multiple LLP species***, another possibility arises: LLPs which decay to finals states involving both SM particles and ***other, lighter LLPs***.
- Multiple, sequential decays of different LLP species along the same decay chain can give rise to multiple DVs.
- We call a sequence of DVs which result from successive decays of LLPs within the same decay chain a "***tumbler***."

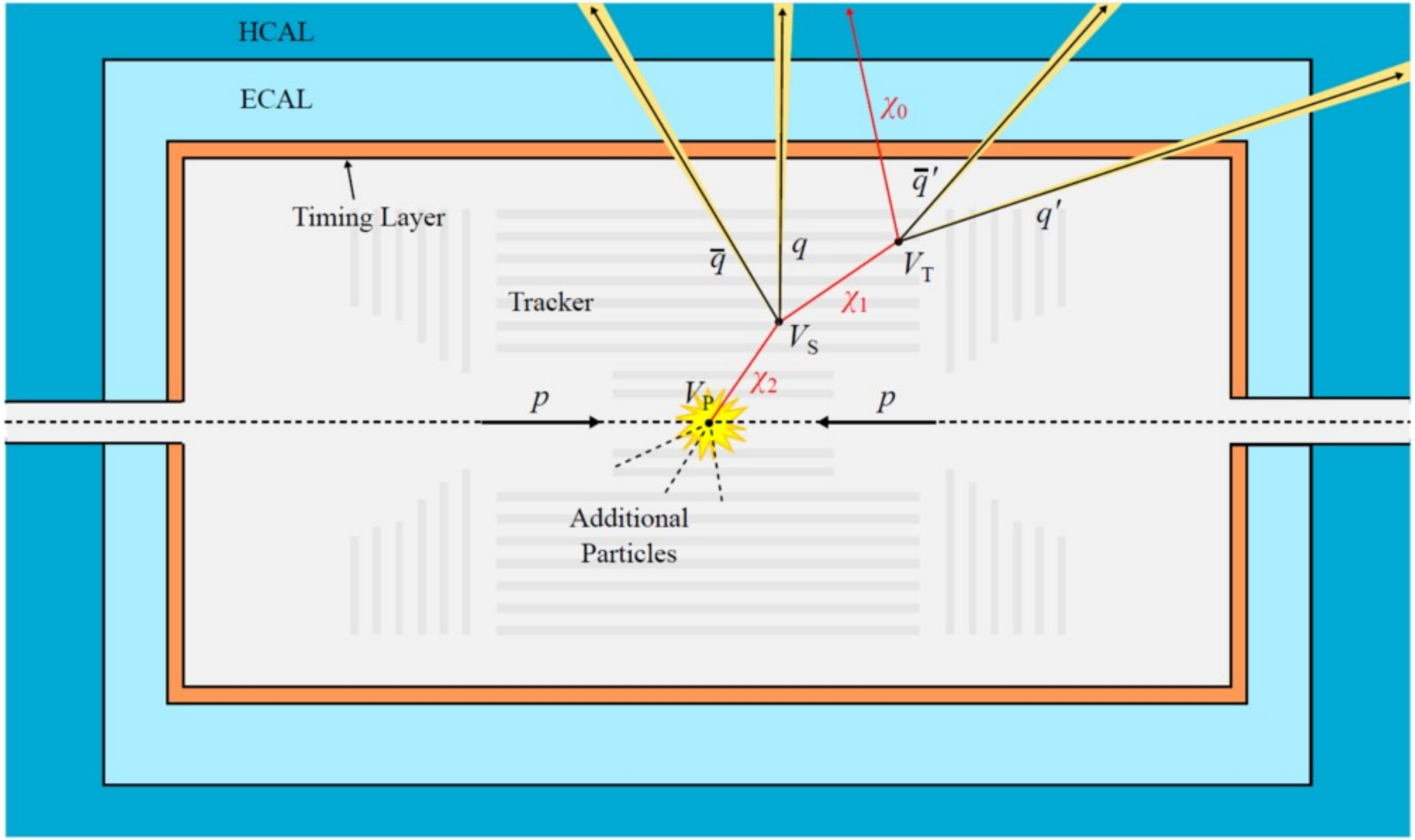


Tumblers

- Tumblers can arise in a number of scenarios for new physics, including...
  - Hidden-valley scenarios [Strassler, Zurek: hep-ph/0604261; Strassler: hep-ph/0607160; Juknevich: 0911.5616; Juknevich, Melnikov, Strassler: 0903.0883; Craig, Katz, Strassler, Sundrum: 1501.05310]
  - Compressed SUSY [Martin: hep-ph/0703097]
  - Scenarios involving emerging jet, semi-visible jets, dark jets, or soft bombs [Schwaller, Stolarski, Weiler: 1502.05409; Cohen, Lisani, Lou: 1503.00009; Park, Zhang: 1712.09279; Knapen, Pagan Griso, Papucci, Robinson: 1612.00850]
  - Models involving large numbers of additional degrees of freedom with disorder in their mass matrix [D’Agnolo, Low: 1902.05535]
  - Extended dark-sector scenarios with mediator-induced decay chains [Dienes, Kim, Song, Su, BT, Yaylali: 1910.01129]
- As we shall see, precision timing provides us with a tool that we can use in order to exploit the ***distinctive kinematics*** of tumbler events and distinguish tumblers from other kinds of events involving multiple DVs.

Tumblers: An Example

- For purposes of illustration, let's focus on the simplest example of a tumbler – an example which involves ***two DVs***.
- An LLP χ_2 is produced at the primary vertex and decays into a lighter LLP χ_1, which itself decays to a collider-stable, invisible particle χ_0. Each decay is macroscopically displaced. Each decay ***also produces SM particles*** – here a $\bar{q}q$ pair which manifests as a pair of hadronic jets.



A Concrete Model for Tumblers

- For concreteness, let's consider a model in which there exist three SM-singlet ***Dirac fermions*** χ_0, χ_1, and χ_2.
- These χ_n 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.

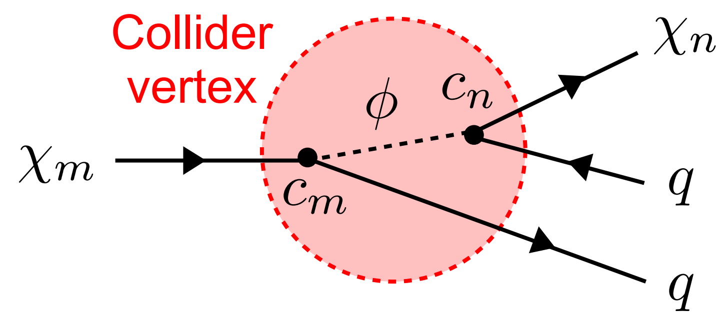
→ Mass eigenstates $\{\phi_u, \phi_c, \phi_t\}$ essentially each couple to a ***single flavor***.

coupling constants

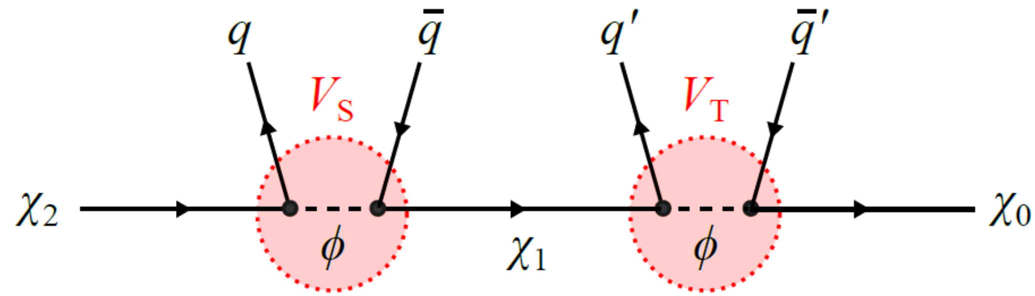
$$\boxed{\mathcal{L}_{\rm int} = \sum_{q\in\{u,c,t\}} \sum_{n=0}^{2} \left[c_{nq}\phi_q^\dagger \overline{\chi}_n P_R q + \text{h.c.}\right]}$$

- For simplicity, we take $m_{\phi_u} \ll m_{\phi_c}, m_{\phi_t}$ so that only ϕ_u. 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 $c_n \equiv c_{nu} \neq 0$.

Decays and Displaced Vertices



- Both χ_1 and χ_2 are unstable in this model and decay via three-body processes of the form $\chi_m \to \chi_n qq$ involving a virtual ϕ.



- Tumblers arise when χ_2 is produced at the primary vertex and decays to χ_1, which in turn decays to χ_0.

- Partial widths of χ_m scale like $\Gamma_{mn} \propto c_m^2 c_n^2$. For χ_1 and χ_2 to be sufficiently long-lived that they both yield DVs, we need small couplings $c_n \ll 1$.

- For concreteness, we take the three c_n to scale according to relation

Coupling for lighest state

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

Controls how c_n scales w/ n

- By contrast, partial widths for ϕ scale like $\Gamma_{\phi n} \propto c_n^2$, which in this regime implies $\Gamma_{\phi n} \gg \Gamma_{mn}$. As a result, in the regime where χ_1 and χ_2 typically decay inside the tracker of a collider detector, ϕ decay is typically prompt.

Production Channels

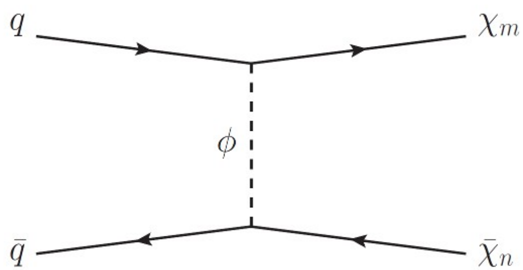
- Several different processes contribute to the overall production rate ftumblers in this scenario. There are **three main classes**:

1

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

(no on-shell mediators)

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

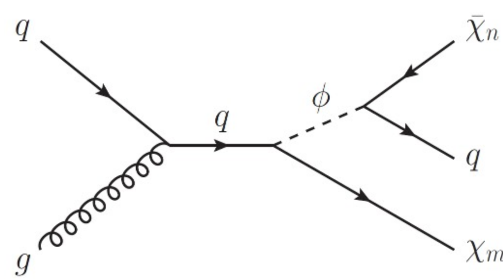


2

$$pp \to \chi_m \phi$$

(one on-shell mediator)

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



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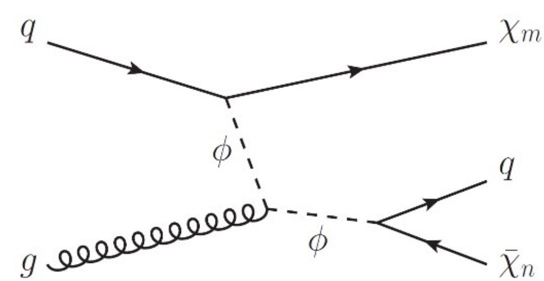


, ...

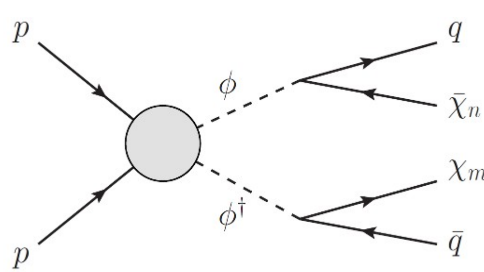
3

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

(two on-shell mediators)

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

i.e., independent of c_0



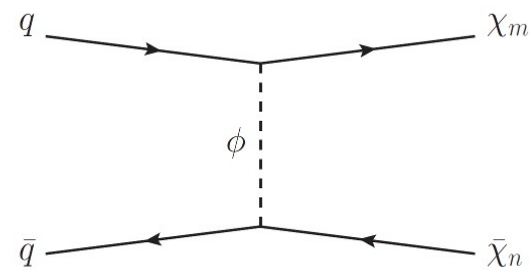
Production Channels

- Several different processes contribute to the overall production rate ftumblers in this scenario. There are **three main classes**:

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

(no on-shell mediators)

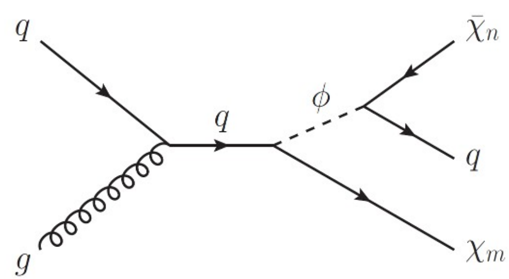
$$\boxed{\sigma(pp \to \chi_m \chi_n) \propto c_0^4}$$



2 $pp \to \chi_m \phi$

(one on-shell mediator)

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



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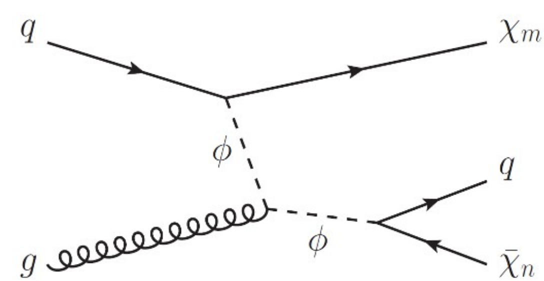

, ...

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

(two on-shell mediators)

$$\boxed{\sigma(pp \to \chi_m \chi_n) \propto 1}$$

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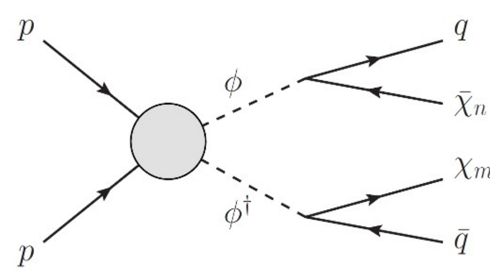


In the regime where $c_n \ll 1$, this process vastly dominates the production rate. We therefore focus on this contribution.

Parameter-Space Regions of Interest

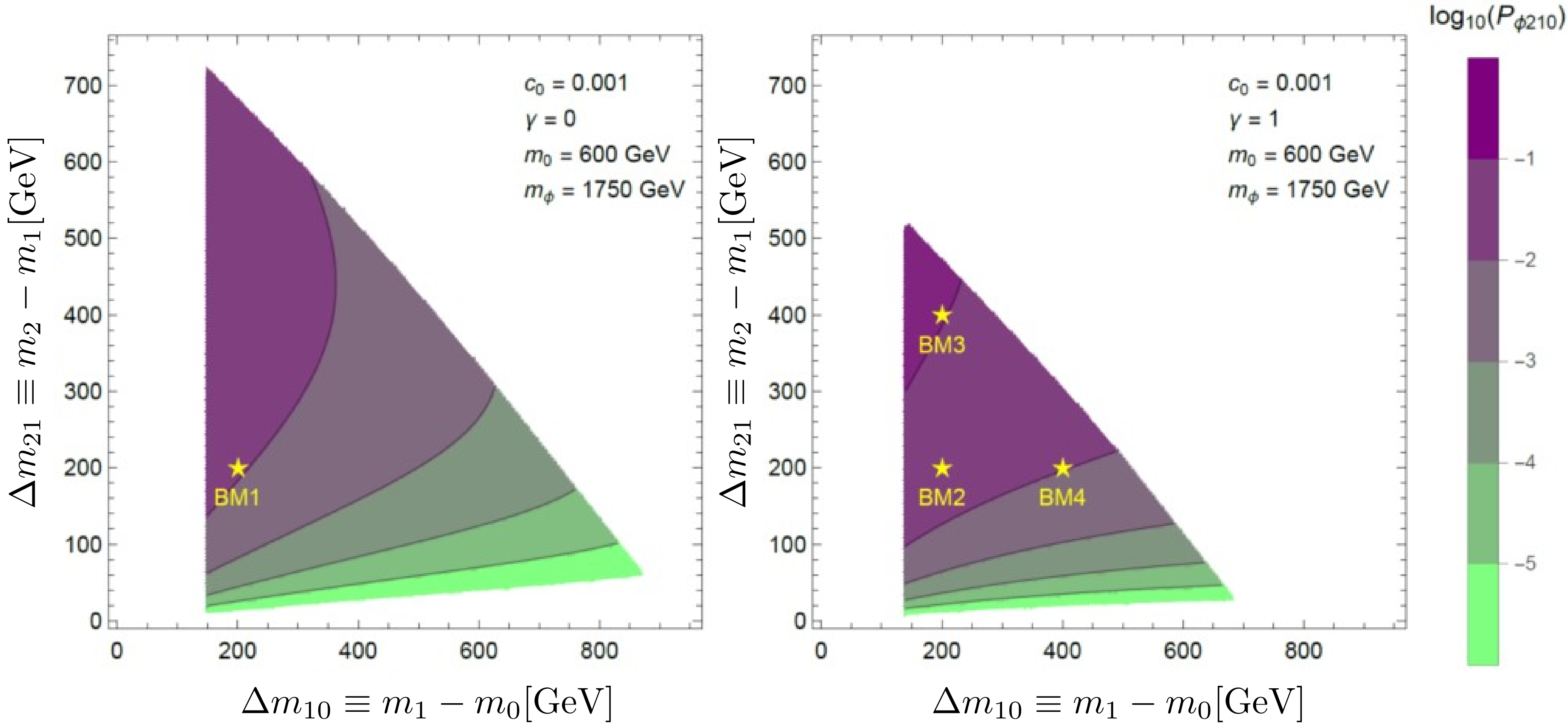
- Not all decay chains give rise to tumblers, however. The probability that a given decay chain yields a tumbler depends on the set of branching fractions $\mathrm{BR}_{\phi n} \equiv \mathrm{BR}(\phi^\dagger \to \chi_n \bar{q})$ and $\mathrm{BR}_{mn} \equiv \mathrm{BR}(\chi_m \to \chi_n q\bar{q})$.
- Since $pp \to \phi^\dagger\phi$ production dominates, most tumbler decay chains begin with the (prompt) decay of ϕ or $\phi^\dagger$. The probability that such a chain will yield a tumbler is

$$\boxed{\begin{aligned} P_{\phi 210} &= \mathrm{BR}_{\phi 2}\mathrm{BR}_{21}\underbrace{\mathrm{BR}_{10}}_{\mathrm{BR}_{10}=1} \\ &= \mathrm{BR}_{\phi 2}\mathrm{BR}_{21} \end{aligned}}$$

- Generally speaking, the regions of our parameter space which are of interest for tumbler phenomenology are those within which $P_{\phi 210}$ is large.
- Our parameter space is six-dimensional:

$$\boxed{\text{Free parameters: } \{m_\phi, m_0, m_1, m_2, c_0, \gamma\}}$$

Results for $P_{\phi 210}$ and Benchmarks



- Based on these results, we define four parameter-space benchmarks (indicated by the yellow stars above).

Benchmark	Input Parameters						Mass Splittings		Proper Decay Lengths	
	c_0	γ	m_0 (GeV)	m_1 (GeV)	m_2 (Gev)	m_ϕ (GeV)	Δm_{10} (GeV)	Δm_{21} (GeV)	$c\tau_1$ (m)	$c\tau_2$ (m)
BM1	0.001	0	600	800	1000	1750	200	200	2.42	8.33×10^{-2}
BM2	0.001	1	600	800	1000	1750	200	200	1.36	2.89×10^{-2}
BM3	0.001	1	600	800	1200	1750	200	400	1.36	2.14×10^{-3}
BM4	0.001	1	600	1000	1200	1750	400	200	3.15×10^{-2}	2.89×10^{-3}

Constraints from LHC Searches

- Current LHC results constrain new-physics contributions to the event rates in several detection channels for our model. These include...

- ***Multijet + $\not{E}_T$***: [Sirunyan et al.: 1908.04722, 1909.03560; Aad et al.: 201014293]
  - Since ϕ and χ_n have the same quantum numbers as $\widetilde{q}$ and $\widetilde{N}$ in SUSY, bounds are similar to those on squark/neutralino models.
  - Constraints satisfied when $m_\phi \gtrsim 1250\ \mathrm{GeV}$ and $m_{\chi_n} \gtrsim 500\ \mathrm{GeV}$.

- ***Monojet + $\not{E}_T$***: [Aad et al.: 2012.10874]
  - Constraints within our parameter-space region of interest are subleading in comparison with multijet constraints.

- ***Displaced-Jet Channels***: [Sirunyan et al.: 1906.06441, 2012.01581, 2104.13474]
  - Constrains the product of production cross-section $\sigma_{\chi\chi}$ and the square of the LLP branching fraction $\mathrm{Br}_{\chi j}$ into relevant final states.
  - Bound is $\sigma_{\chi\chi}\mathrm{BR}_j^2 \lesssim 0.05 - 0.5\ \mathrm{fb}$ for $10^{-4}\ \mathrm{m} < c\tau_\chi < 10\ \mathrm{m}$.

We must ensure that our model is consistent with these bounds within our region of interest, while at the same time yields a significant number of tumbler events at the HL-LHC or proposed future colliders.

Effective Cross-Sections

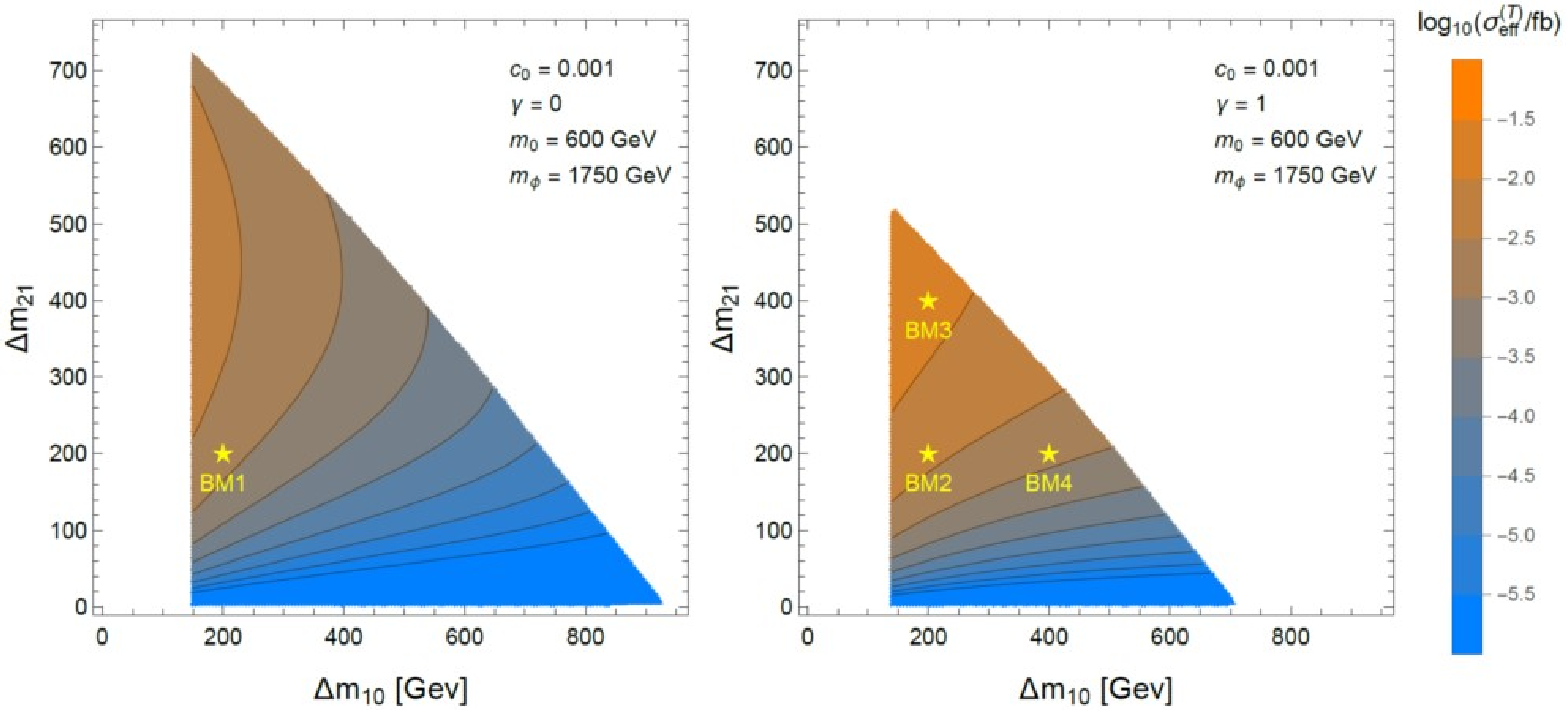
- We define a set of ***effective cross sections*** $\sigma_{\text{eff}}^{(\alpha)}$ which incorporate contributions to the event rate for a particular class of processes that arise in our model.
  - **Tumbler Class:** $\sigma_{\text{eff}}^{(\text{T})}$
    Processes involving at least one tumbler
  - **DV Class:** $\sigma_{\text{eff}}^{(\text{DV})}$
    Processes which yield at least one DV, whether or not it is part of a tumbler
  - **Multi-Jet Class:** $\sigma_{\text{eff}}^{(Nj)}$
    Processes which yield two or more hard jets, but no DV
  - **Monojet Class:** $\sigma_{\text{eff}}^{(1j)}$
    Processes which involve one hard jet and no DV

Possible Event Topolgies

First Chain	Second Chain	Tumblers	Displaced Vertices	Prompt Jets
From $pp \to \phi\phi$ Production				
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\phi \to \chi_2 \to \chi_1 \to \chi_0$	2T		$2j$
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\phi \to \chi_2 \to \chi_0$	T	DV	$2j$
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\phi \to \chi_1 \to \chi_0$	T	DV	$2j$
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\phi \to \chi_0$	T		$2j$
$\phi \to \chi_2 \to \chi_0$	$\phi \to \chi_2 \to \chi_0$		2DV	$2j$
$\phi \to \chi_2 \to \chi_0$	$\phi \to \chi_1 \to \chi_0$		2DV	$2j$
$\phi \to \chi_2 \to \chi_0$	$\phi \to \chi_0$		DV	$2j$
$\phi \to \chi_1 \to \chi_0$	$\phi \to \chi_2 \to \chi_0$		2DV	$2j$
$\phi \to \chi_1 \to \chi_0$	$\phi \to \chi_1 \to \chi_0$		DV	$2j$
$\phi \to \chi_0$	$\phi \to \chi_0$			$2j$
From $pp \to \phi\chi_n$ Production				
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\chi_2 \to \chi_1 \to \chi_0$	2T		j
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\chi_2 \to \chi_0$	T	DV	j
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\chi_1 \to \chi_0$	T	DV	j
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	χ_0	T		j
$\phi \to \chi_2 \to \chi_0$	$\chi_2 \to \chi_1 \to \chi_0$	T	DV	j
$\phi \to \chi_2 \to \chi_0$	$\chi_2 \to \chi_0$		2DV	j
$\phi \to \chi_2 \to \chi_0$	$\chi_1 \to \chi_0$		2DV	j
$\phi \to \chi_2 \to \chi_0$	χ_0		DV	j
$\phi \to \chi_1 \to \chi_0$	$\chi_2 \to \chi_1 \to \chi_0$	T	DV	j
$\phi \to \chi_1 \to \chi_0$	$\chi_2 \to \chi_0$		2DV	j
$\phi \to \chi_1 \to \chi_0$	$\chi_1 \to \chi_0$		2DV	j
$\phi \to \chi_1 \to \chi_0$	χ_0		DV	j
$\phi \to \chi_0$	$\chi_2 \to \chi_1 \to \chi_0$	T		j
$\phi \to \chi_0$	$\chi_2 \to \chi_0$		DV	j
$\phi \to \chi_0$	$\chi_1 \to \chi_0$		DV	j
$\phi \to \chi_0$	χ_0			j
From $pp \to \chi_m\chi_n$ Production				
$\chi_2 \to \chi_1 \to \chi_0$	$\chi_2 \to \chi_1 \to \chi_0$	2T		
$\chi_2 \to \chi_1 \to \chi_0$	$\chi_2 \to \chi_0$	T	DV	
$\chi_2 \to \chi_1 \to \chi_0$	$\chi_1 \to \chi_0$	T	DV	
$\chi_2 \to \chi_1 \to \chi_0$	χ_0	T		
$\chi_2 \to \chi_0$	$\chi_2 \to \chi_0$		2DV	
$\chi_2 \to \chi_0$	$\chi_1 \to \chi_0$		2DV	
$\chi_2 \to \chi_0$	χ_0		DV	
$\chi_1 \to \chi_0$	$\chi_1 \to \chi_0$		2DV	
$\chi_1 \to \chi_0$	χ_0		DV	
χ_0	χ_0			

Effective Tumbler Cross-Sections

- Within our parameter-space region of interest, $\sigma_{\rm eff}^{(\rm T)}$ is indeed large enough to provide a significant number of events at the HL-LHC.



Results

- We evaluate $\sigma_{\text{eff}}^{(\text{DV})}$, $\sigma_{\text{eff}}^{(Nj)}$, and $\sigma_{\text{eff}}^{(1j)}$ as well as $\sigma_{\text{eff}}^{(\text{T})}$ for all of our benchmarks. However, we find that $\sigma_{\text{eff}}^{(1j)}$ is always subleading.

Effective Cross-Sections and Expected Tumbler Event Counts

Benchmark	$\sigma_{\text{eff}}^{(\alpha)}$ (fb)			Tumbler Events	
	Tumblers	DV	Multi-Jet + $\not{E}_T$	LHC Run 2 (137 fb^{-1})	HL-LHC (3000 fb^{-1})
BM1	1.5×10^{-3}	5.3×10^{-2}	1.1×10^{-2}	0.4	9.2
BM2	4.3×10^{-3}	6.1×10^{-2}	4.0×10^{-3}	1.1	25.6
BM3	1.3×10^{-2}	6.0×10^{-2}	4.3×10^{-3}	3.7	76.1
BM4	1.4×10^{-3}	6.1×10^{-2}	3.9×10^{-3}	0.4	8.1

$\sigma_{\text{eff}}^{(\text{DV})} \gg \sigma_{\text{eff}}^{(\text{T})}$

Consistent with current bounds

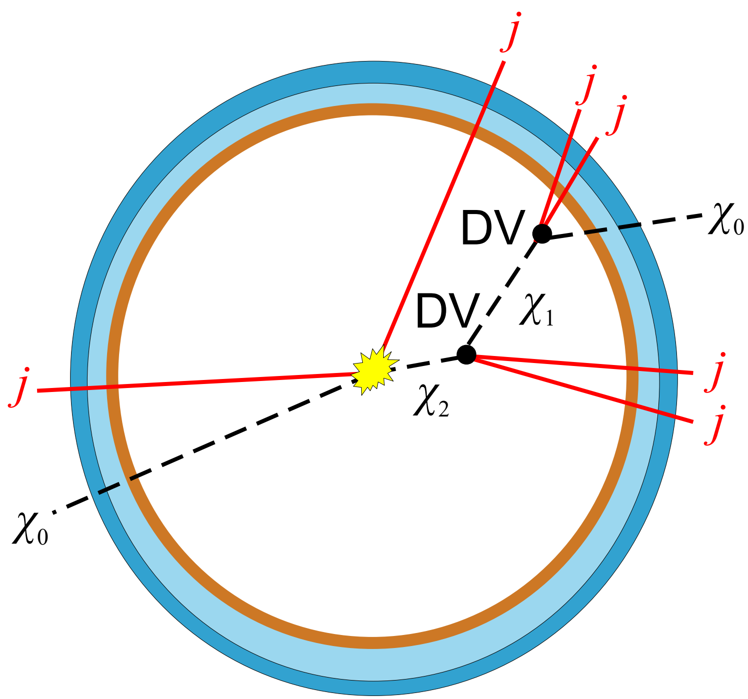
Good detection prospects

- All four of our benchmarks are consistent with current LHC limits from monojet, multi-jet, and DV searches.
- Moreover, all of these benchmarks are expected to yield a significant number of tumbler events at the HL-LHC.

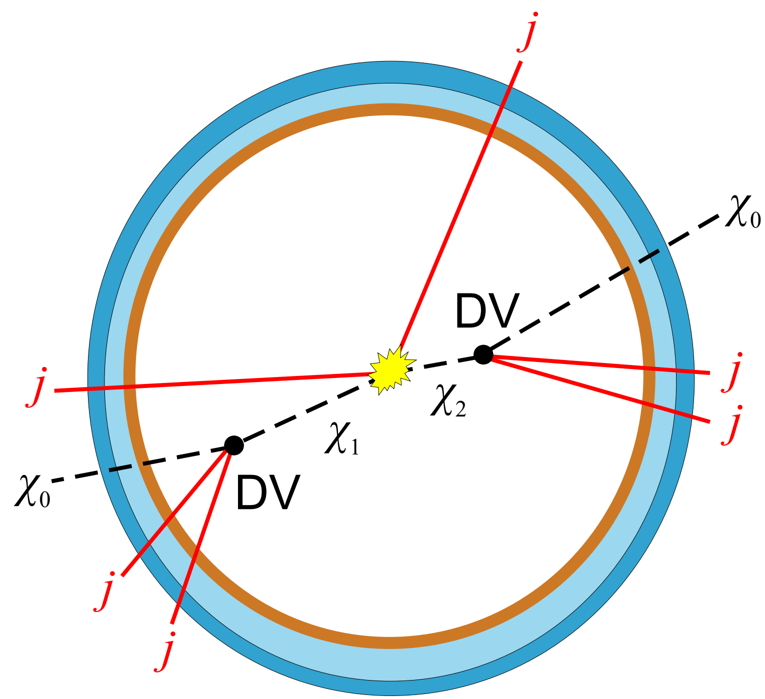
<u>The upshot</u>: Despite stringent limits, there is still potential for mediator-induced decay chains to manifest themselves at colliders.

The Next Step: Distinguishing Tumblers

- There is, however, another issue we must address. Up to this point, our analysis does not distinguish between tumbler events and other, non-tumbler events which likewise include multiple DVs.
- Moreover, we have seen that a “background” of such non-tumbler events arises even within the context of our model!
- Thus, in order to claim a discovery of tumblers, we must develop a ***method for distinguishing them*** from non-tumbler events.



Tumbler



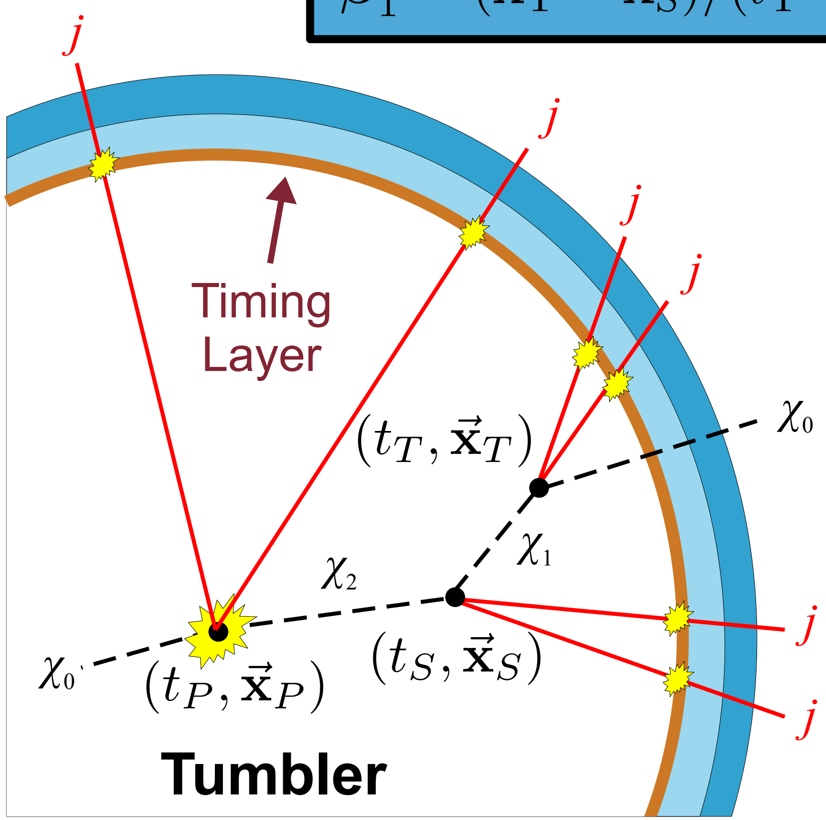
Non-Tumbler

Event-Selection Through Mass-Reconstruction

- Fortunately, the ***distinctive kinematics*** of tumblers can serve as a basis for distinguishing between tumbler and non-tumbler events.
- ***Timing and momentum information*** can be used to reconstruct the positions and times of the primary and displaced vertices.
- From this information, the velocities $\vec{\beta}_1$ and $\vec{\beta}_2$ of χ_1 and χ_2 can be reconstructed, and from these, in turn, the ***masses*** m_0, m_1, and m_2.

$$\vec{\beta}_1 = (\vec{\mathbf{x}}_{\mathrm{T}} - \vec{\mathbf{x}}_{\mathrm{S}})/(t_{\mathrm{T}} - t_{\mathrm{S}})$$

$$\vec{\beta}_2 = (\vec{\mathbf{x}}_{\mathrm{S}} - \vec{\mathbf{x}}_{\mathrm{P}})/(t_{\mathrm{S}} - t_{\mathrm{P}})$$



Reconstructed masses

$$m_2 = \frac{\left|\vec{\mathbf{p}}_q + \vec{\mathbf{p}}_{\bar{q}} - \vec{\beta}_1\left(|\vec{\mathbf{p}}_q| + |\vec{\mathbf{p}}_{\bar{q}}|\right)\right|}{\gamma_2|\vec{\beta}_1 - \vec{\beta}_2|}$$

$$m_1 = \frac{\left|\vec{\mathbf{p}}_q + \vec{\mathbf{p}}_{\bar{q}} - \vec{\beta}_2\left(|\vec{\mathbf{p}}_q| + |\vec{\mathbf{p}}_{\bar{q}}|\right)\right|}{\gamma_1|\vec{\beta}_1 - \vec{\beta}_2|}$$

$$m_0^2 = m_1^2 - 2\gamma_1 m_1\left[|\vec{\mathbf{p}}_{q'}| + |\vec{\mathbf{p}}_{\bar{q}'}| - \vec{\beta}_1 \cdot (\vec{\mathbf{p}}_{q'} + \vec{\mathbf{p}}_{\bar{q}'})\right] + 2\left(|\vec{\mathbf{p}}_{q'}||\vec{\mathbf{p}}_{\bar{q}'}| - \vec{\mathbf{p}}_{q'} \cdot \vec{\mathbf{p}}_{\bar{q}'}\right)$$

Event-Selection Through Mass-Reconstruction

- For tumblers, this procedure nevertheless typically yields a sensible set of reconstructed masses and velocities – *i.e.*, a set for which:
  - m_1 and m_2 are real and positive
  - m_0^2 is real
  - $|\vec{\mathbf{p}}_0|$ is real and positive
  - $0 < |\vec{\beta}_n| < 1$ for $n = 1, 2$
  - $m_2^2 > m_1^2 > m_0^2$
- By contrast, non-tumbler events, which have a different kinematic structure, typically fail to satisfy one or more of these criteria.
- Moreover, the kinematic distributions of m_0, m_1, and m_2 for tumbler events should all exhibit ***peaks*** at the correspondin true mass values. By contrast, non-tumbler events should exhibit no such peaks.

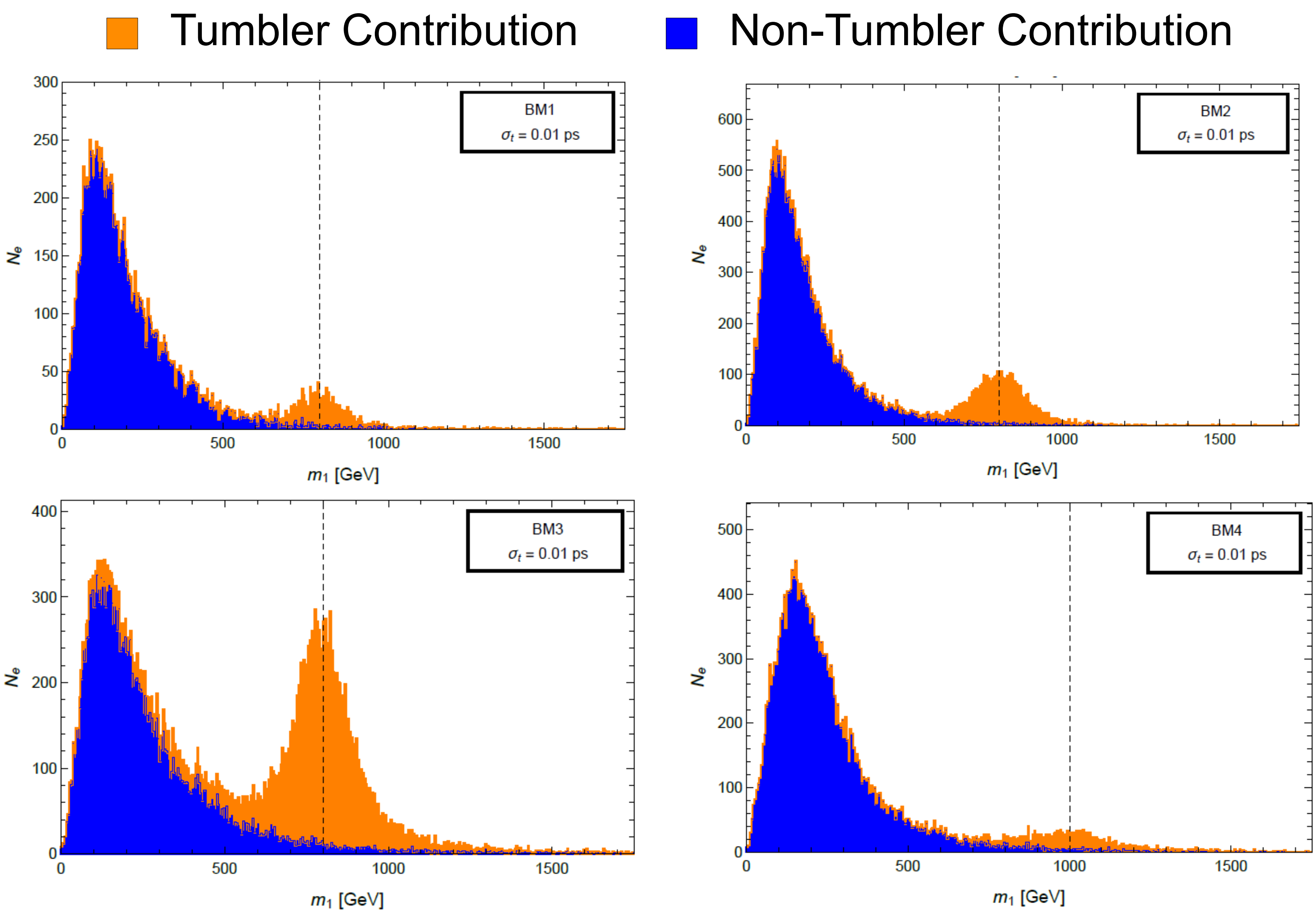
The plan: apply these event-selection criteria in order to amplify the ratio of tumbler to non-tumbler events in the data, then identify the peaks in order to detect/distinguish tumblers.

Monte-Carlo Simulation

- In order to examine how this work in practice, we perform a Monte-Carlo analysis of $pp \to \phi^\dagger \phi$ production and subsequent mediator decay.
- We work at parton level, but take into account the relevant uncertainties as follows:
  - **Timing uncertainty**: smear the time at which each jet hits the timing layer by a Gaussian with uncertainty σ_t.
  - **Jet-energy uncertainty**: smear the energy E_j of each jet by a Gaussian with an energy-dependent uncertainty $\sigma_E(E_j)$ modeled after the CMS-detector response.
- The *direct* effect of the jet-direction uncertainties σ_η and σ_ϕ on the reconstructed m_n through the $\vec{\mathbf{p}}_j$ are subleading compared to that of σ_E.
- However, their *indirect* effect through $\vec{\beta}_1$ and $\vec{\beta}_2$, which depend on $\vec{\mathbf{x}}_{\mathrm{P}}$, $\vec{\mathbf{x}}_{\mathrm{S}}$, and $\vec{\mathbf{x}}_{\mathrm{T}}$ can be more significant and need to be accounted for.
  - **Vertex-location uncertainty**: shift the position of each vertex by a random vector whose magnitude is distributed according to a Gaussian with uncertainty $\sigma_r = 30\ \mu\mathrm{m}$.

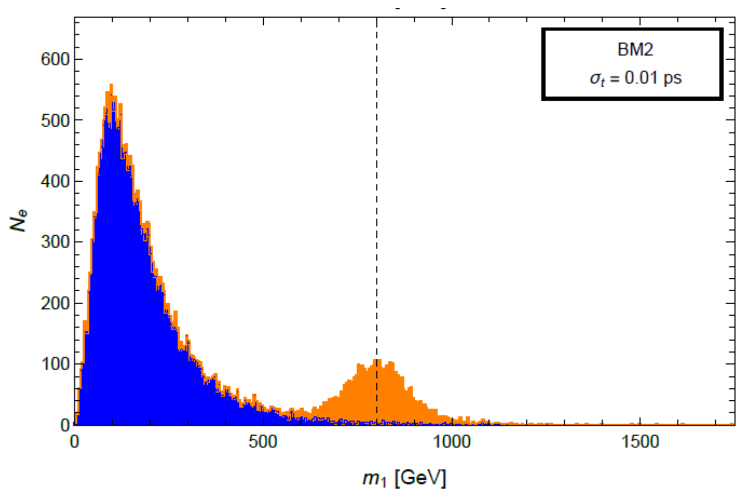
The Reconstructed m_n Distributions

- Indeed, for sufficiently low σ_t, the distributions of reconstructed m_1 values exhibit a discernable ***tumbler peak*** around the true m_1 value, along with a residual background of non-tumbler events at low m_1.



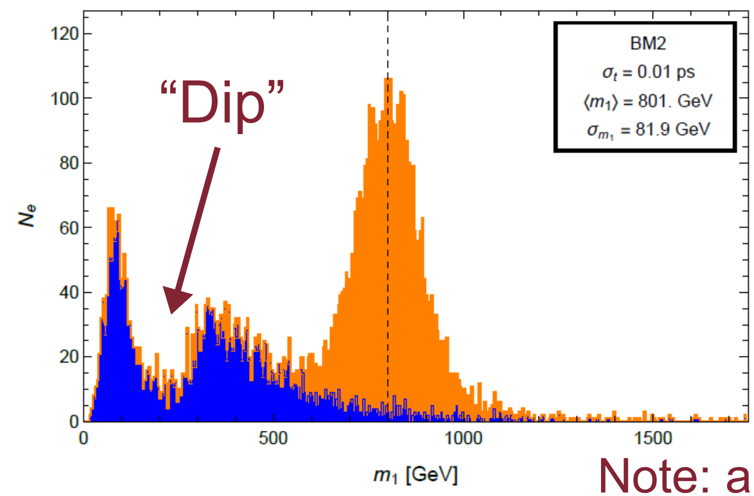
One Additional Cut

- Finally, we'll impose one additional requirement: $m_0^2 > 0$. This cut reduces the background even further (by a factor of ~10 for all BMs) and also alters the ***shapes*** of the m_1 distributions.



$m_0^2 > 0$

cut



Note: always fails when $m_1 = E^*_{jj}$

- The dip arises because our $m_0^2 > 0$ criterion fails whenever

Energy of the $\bar{q}'q'$ system in the χ_1 frame

$$\boxed{E^*_{jj} - \sqrt{(E^*_{jj})^2 - m^2_{jj}} \leq m_1 \leq E^*_{jj} + \sqrt{(E^*_{jj})^2 - m^2_{jj}}}$$

- Moreover, three-body decay kinematics imposes a constraint on the range of E^*_{jj}:

$$\boxed{\frac{m_1^2 - m_0^2}{2m_1} \leq E^*_{jj} \leq m_1 - m_0}$$

- For example, for BM1, E^*_{jj} lies within the narrow range

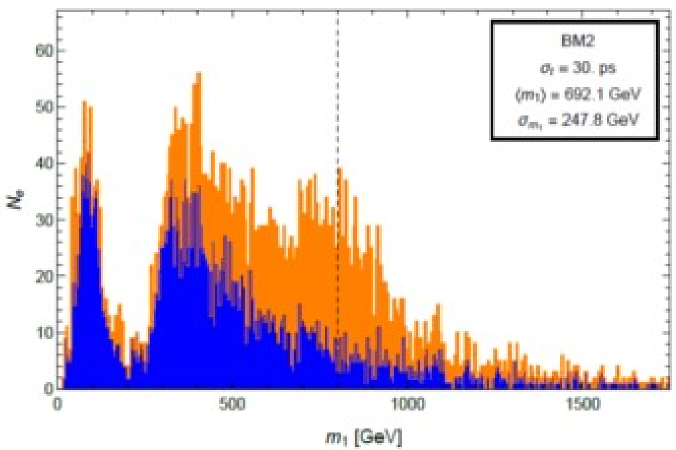
$$175 \text{ GeV} \leq E^*_{jj} \leq 200 \text{ GeV}$$

Location of the dip

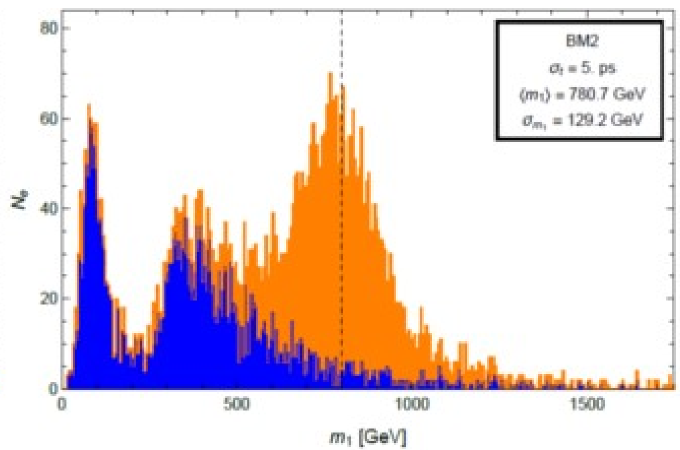
The Impact of Timing Resolution

- We can also examine how improvements in timing resolution would impact our ability to resolve the tumbler peak in the m_1 distribution.

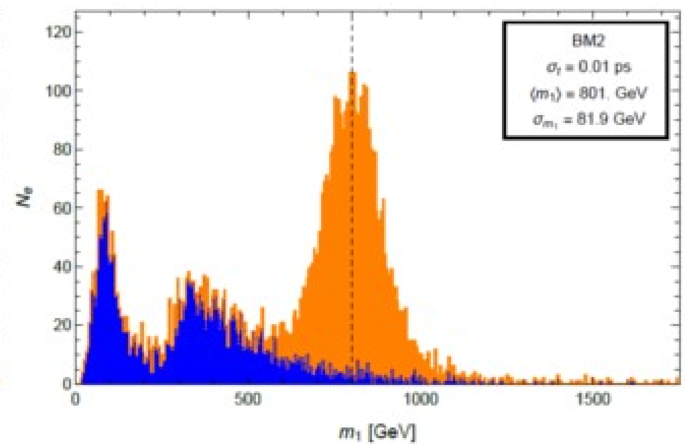
Decreasing σ_t



$\sigma_t = 30$ ps
(CMS Timing Layer)



$\sigma_t = 5$ ps
(Modest Improvement)



$\sigma_t = 0.01$ ps
(σ_E and σ_r Dominate)

The Upshot:

Even a moderate improvement in σ_t would significantly enhance the prospects for distinguishing tumblers at the LHC or at future colliders.

Other Benchmarks

- The m_1 distributions for our other benchmarks depend similarly on σ_t.

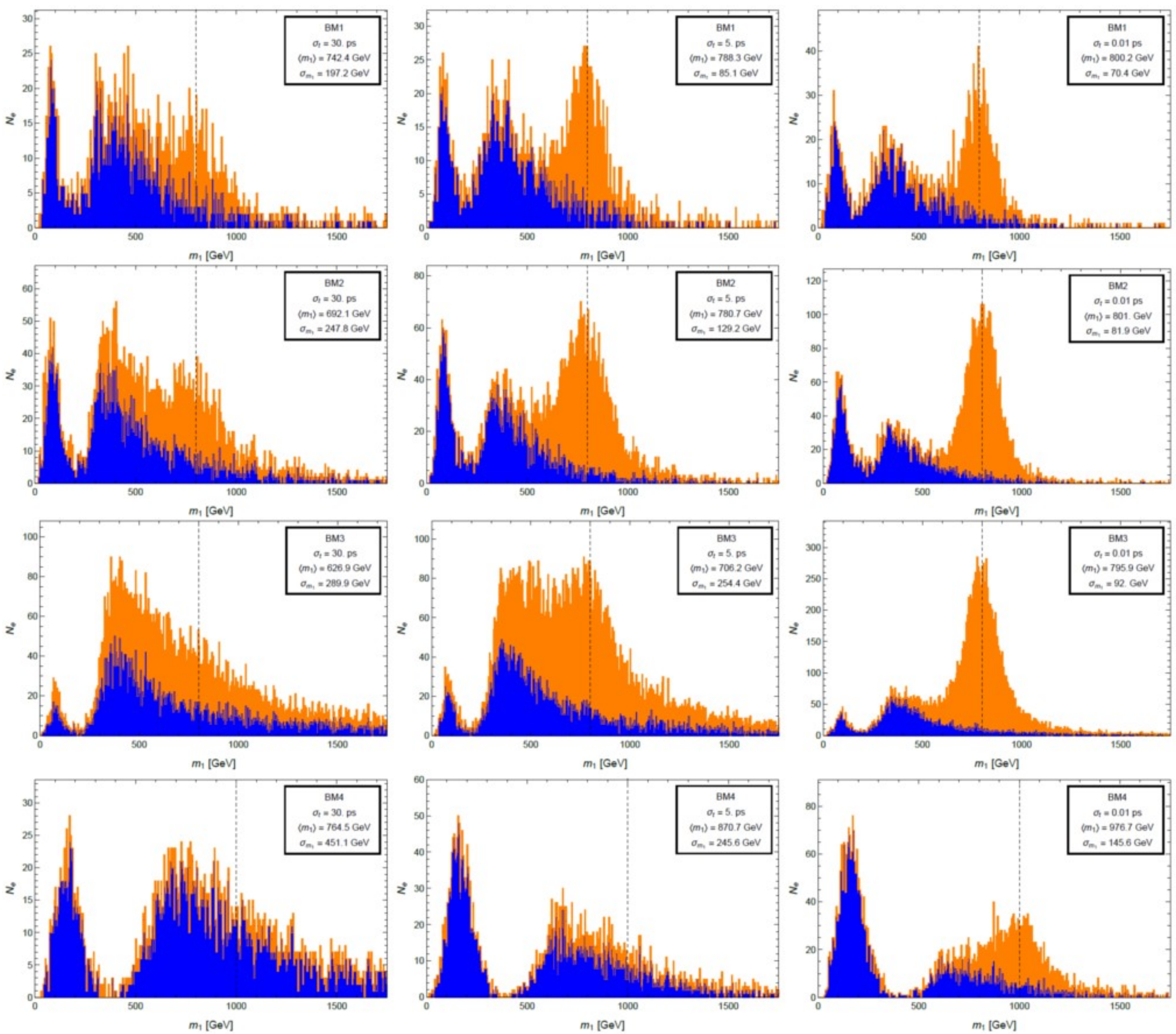
$\sigma_t = 30$ ps $\quad \sigma_t = 5$ ps $\quad \sigma_t = 0.01$ ps

BM1

BM2

BM3

BM4



Realistic Event Counts

- At a collider similar to HL-LHC, with twice the integrated luminosity.

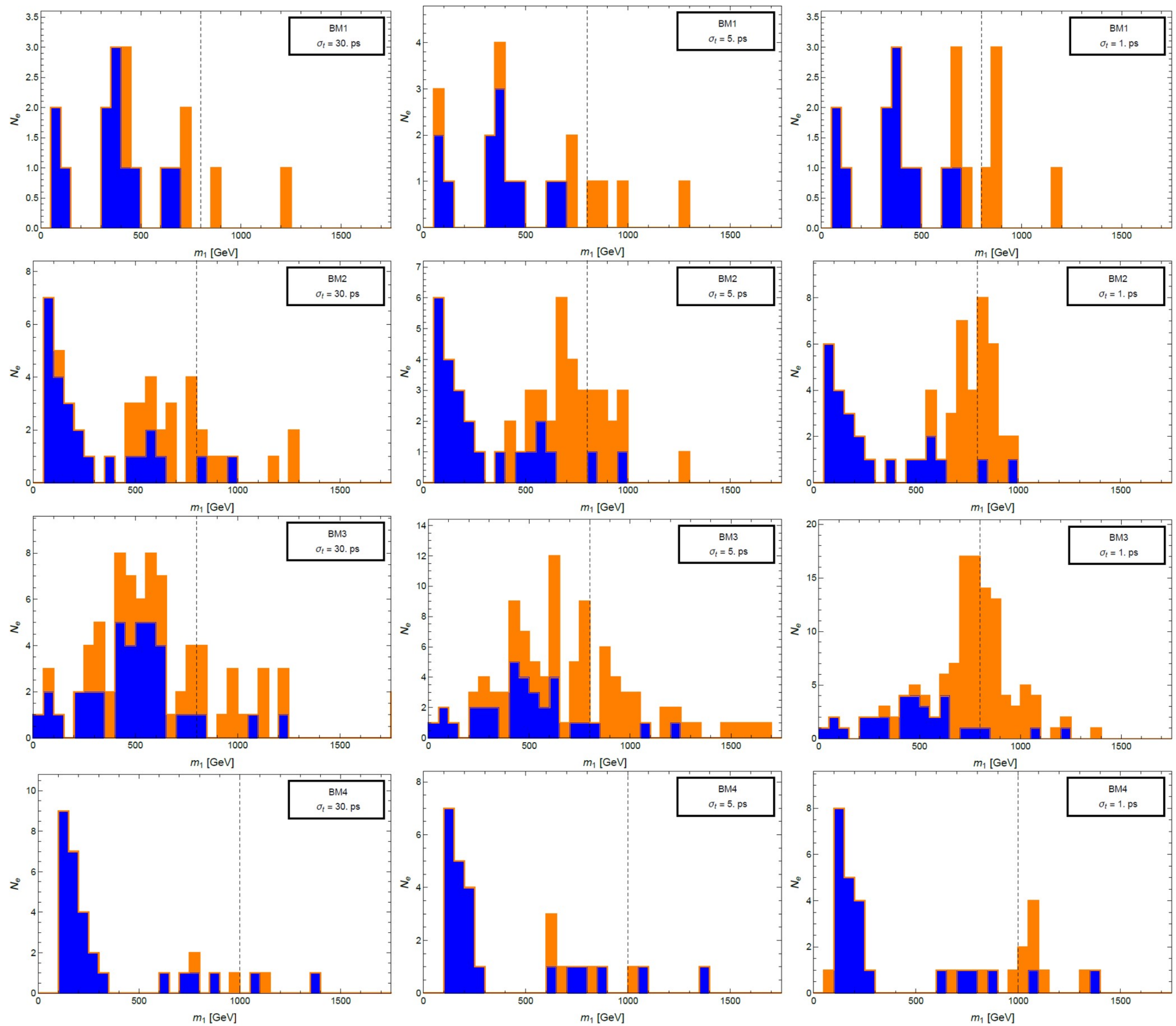
$\sigma_t = 30$ ps $\quad \sigma_t = 5$ ps $\quad \sigma_t = 0.01$ ps

BM1

BM2

BM3

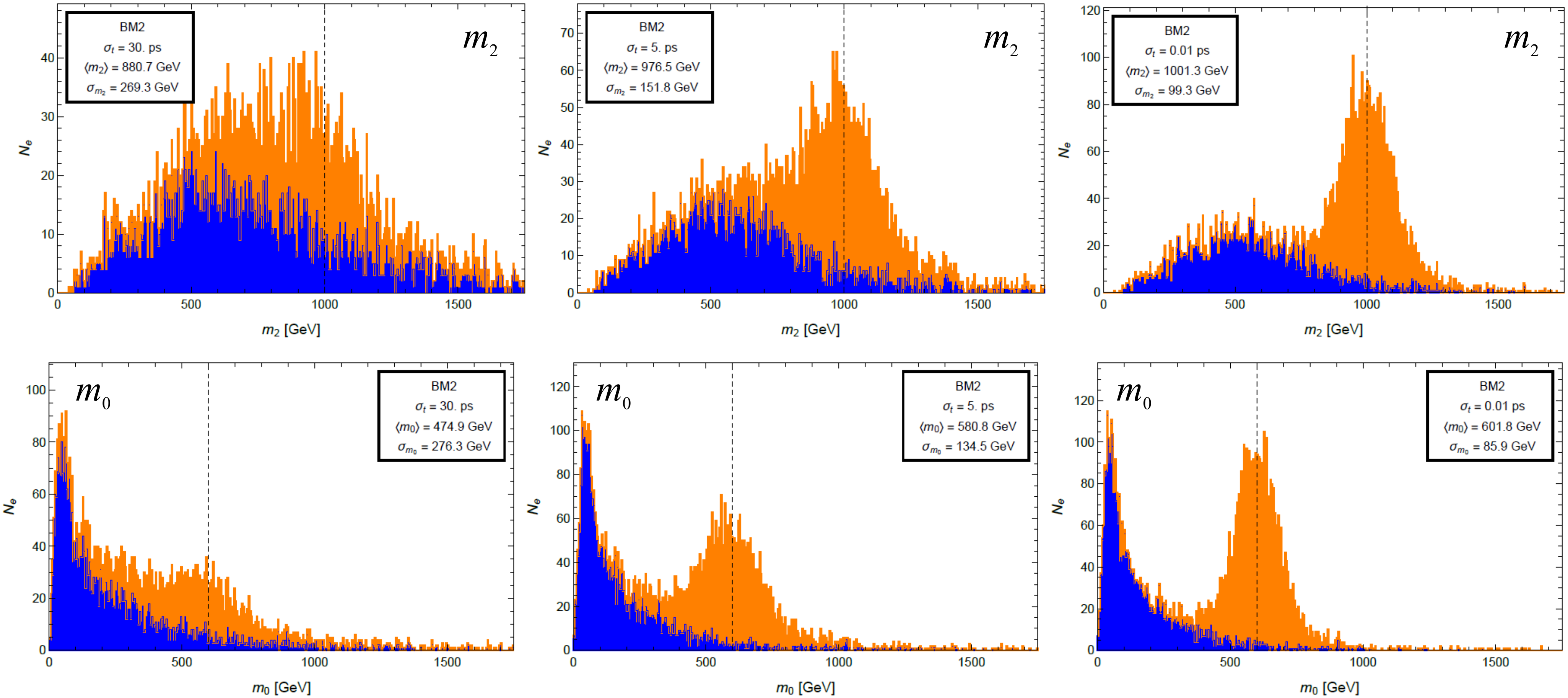
BM4



Peaks still readily apparent

Other Masses

- The m_2 and m_0 distributions exhibit a similarly dependence on σ_t.
- However these distibutions do not exhibit a “dip” akin to the one which appears in the m_1 distribution.



$\sigma_t = 30$ ps $\sigma_t = 5$ ps $\sigma_t = 0.01$ ps

Once again, even a moderate improvement in σ_t would have a huge impact.

Other Masses

- The m_2 and m_0 distributions exhibit a similarly dependence on σ_t.
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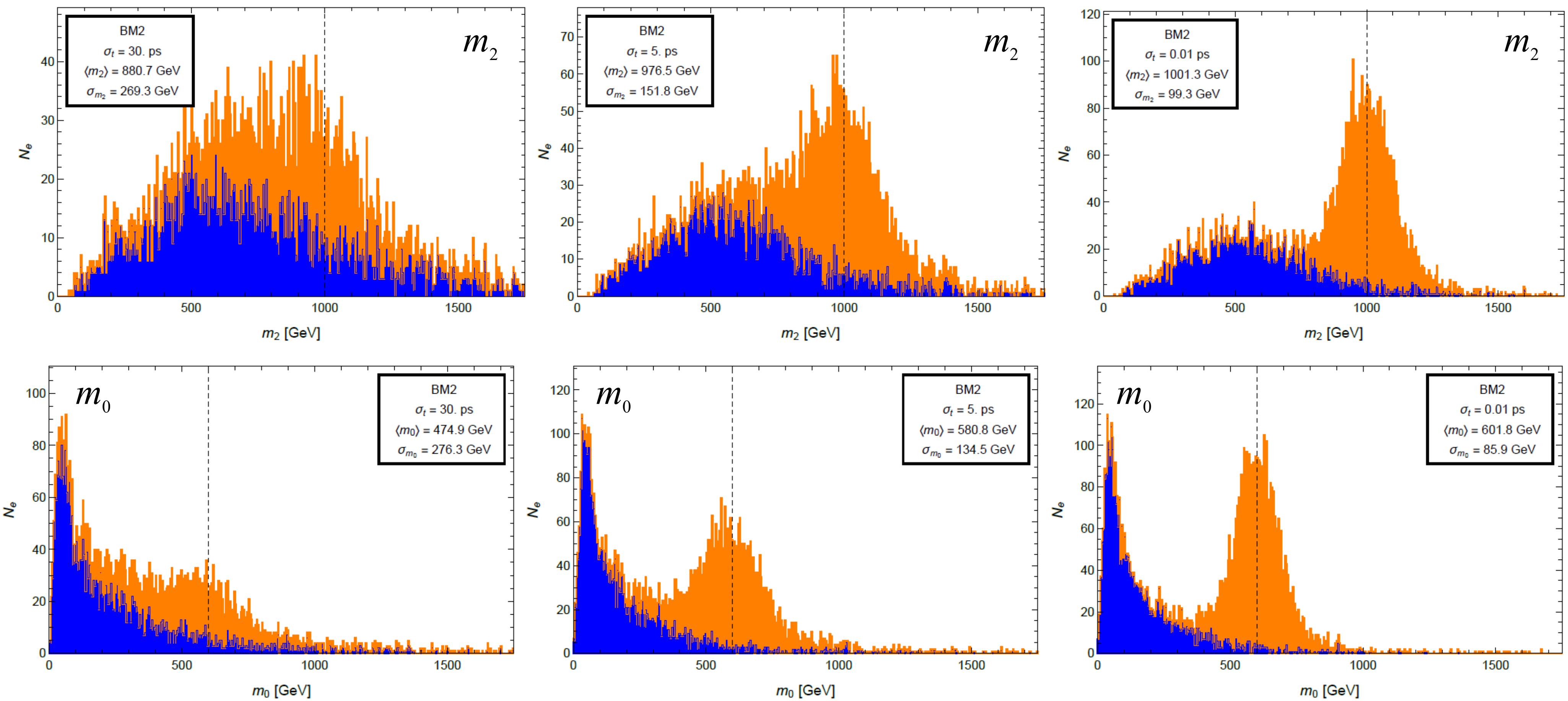


$\sigma_t = 30$ ps | $\sigma_t = 5$ ps | $\sigma_t = 0.01$ ps

Once again, even a moderate improvement in σ_t would have a huge impact.

Lifetime Reconstruction

- Timing and vertex-position information likewise allows us to determine the lifetimes of the decaying LLPs.
- Proper decay times t_1 and t_2 can also be reconstruct for χ_1 and χ_2 in each event, given timing information.

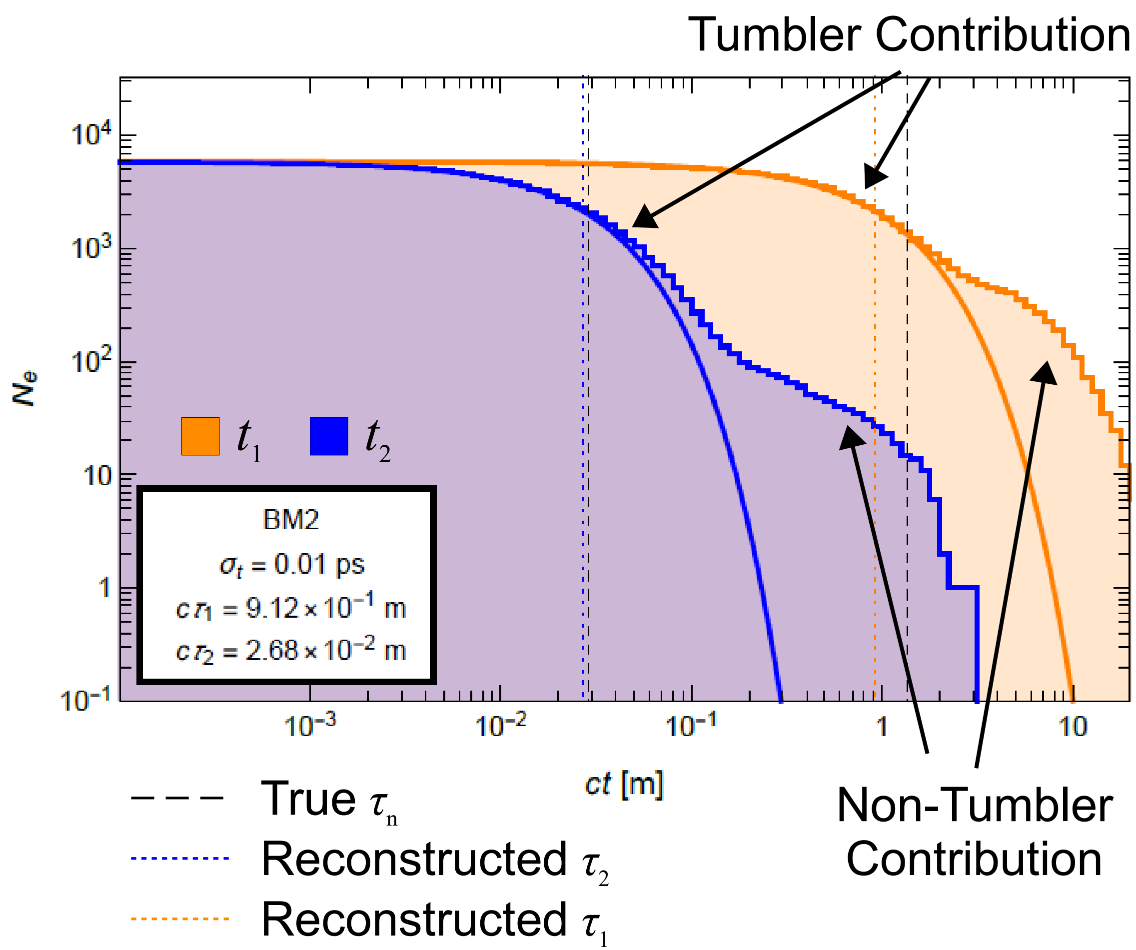
Proper Decay Times

$$t_1 = (t_\mathrm{T} - t_\mathrm{S})(1 - |\vec{\beta}_1|^2)^{1/2}$$
$$t_2 = (t_\mathrm{S} - t_\mathrm{P})(1 - |\vec{\beta}_2|^2)^{1/2}$$

- For $n = 1,2$, we define the total number of events $N_n(t)$ which have a proper decay time t_n longer than t.
- Fitting the $N_n(t)$ distributions (after cuts) to exponential functions of the form

$$\boxed{N_n(t) = N_n(0)e^{-t/\tau_n}}$$

yields a reasonably accurate estimate for the τ_n.



Summary

- Tumblers are a novel collider signature in which ***multiple DVs*** arise in the same event as a consequence of ***sequential decays*** along the same decay chain.
- Such signatures arise naturally in new-physics scenarios in which LLPs themselves decay into final states involving other LLPs.
- These mediators can give rise to ***extended decay chains*** at coliders involving large numbers of SM particles.
- Event-selection criteria based on the reconstruction of the LLP masses can efficiently discriminate between tumblers and other kinds of events involving multiple DVs.
- A ***moderate enhancement in timing resolution*** relative to the ~30 ps that will be provided by the CMS barrel timing layer could pay huge dividends in terms of our ability to distinguish between different event topologies involving multiple displaced vertices.