Tumblers
A Novel Collider Signature for Long-Lived Particles

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Physics & Astronomy

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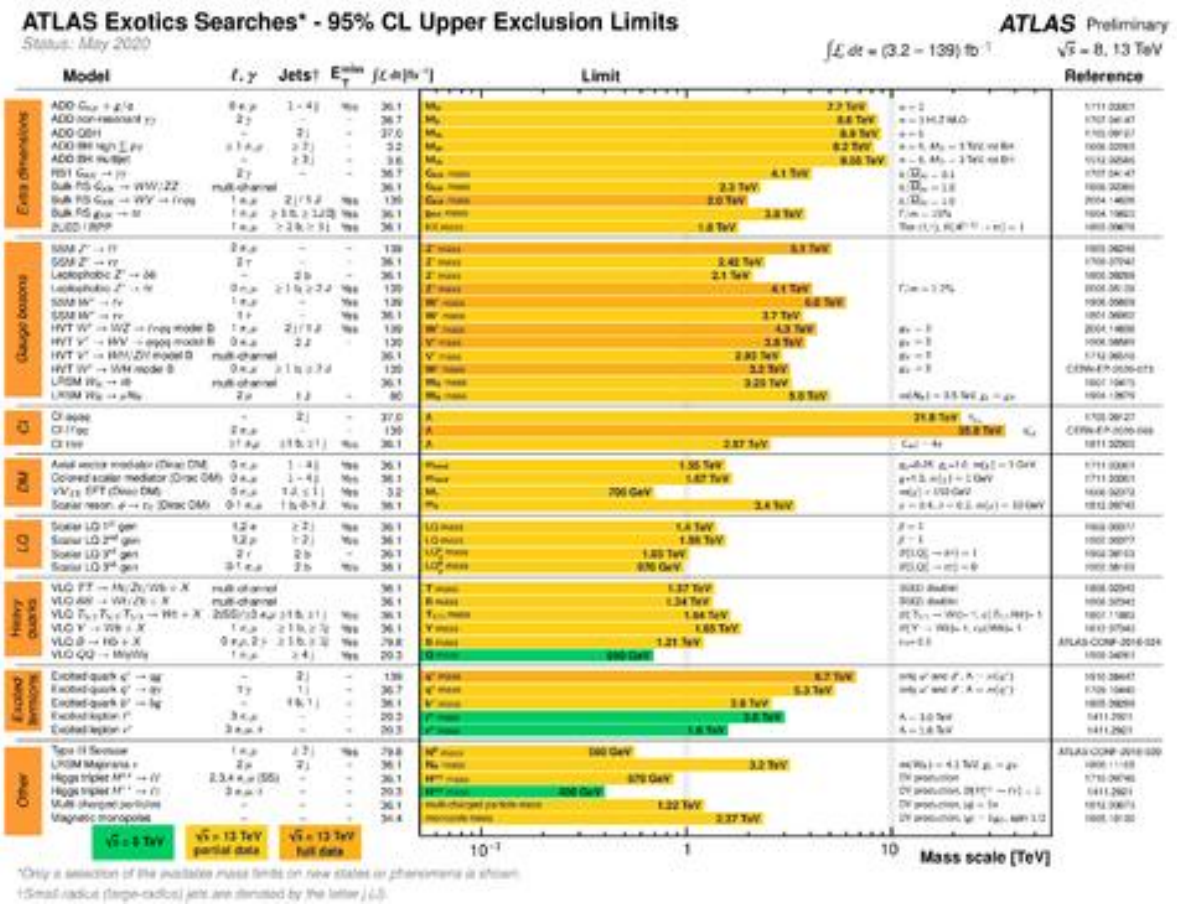
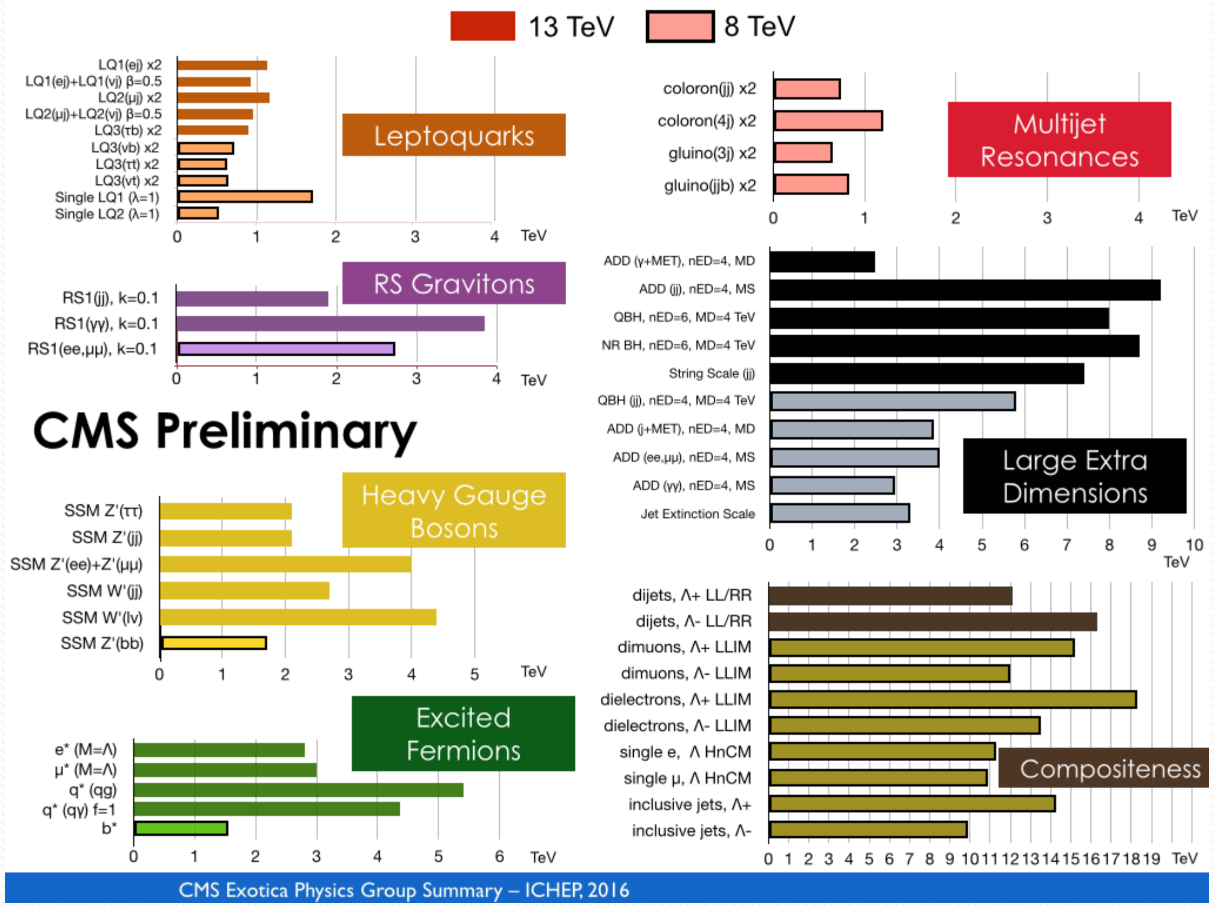
In collaboration with Keith Dienes, Tara Leininger, and Brooks Thomas, arXiv:2108.02204

BSM Search Efforts at Colliders: No Conclusive Evidence!

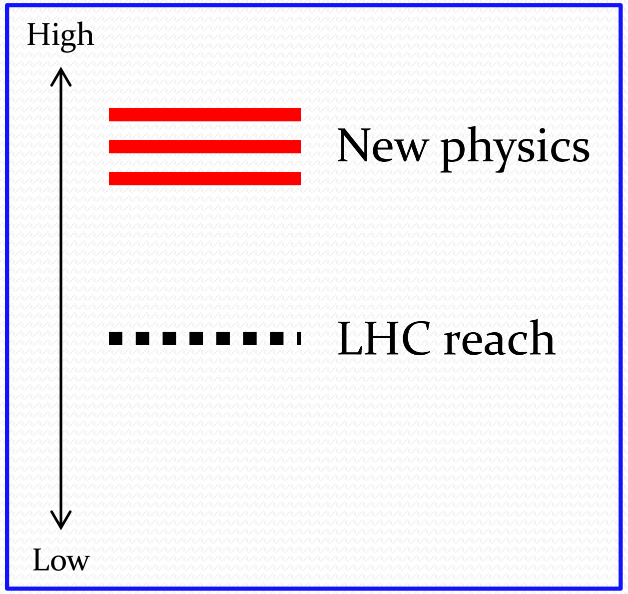




Why Long-Lived Particles (LLPs)?

BSM beyond the reach of LHC

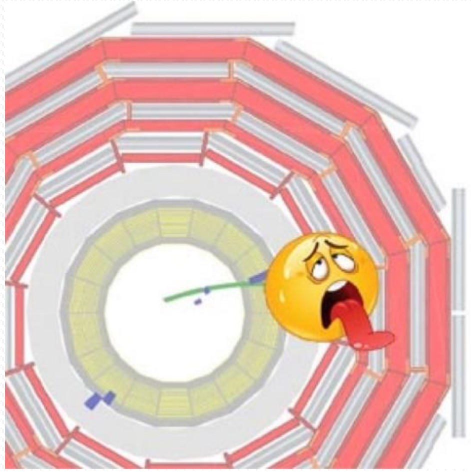
⇒ Go with future colliders



BSM hidden in the parameter space to which the existing searches are less sensitive

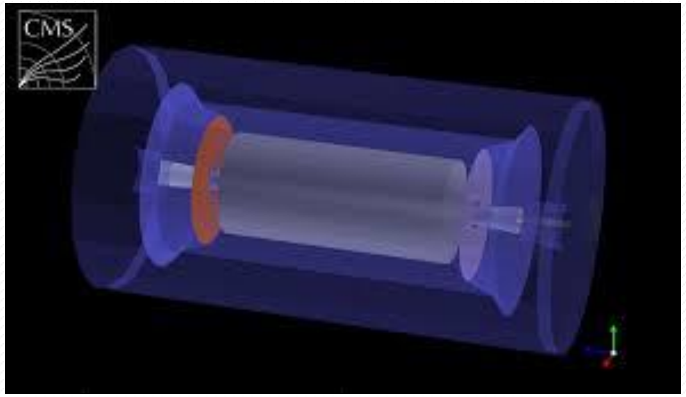
⇒ Explore channels/ways receiving less attention

- LLPs is one such way.
- Most conventional searches are designed, assuming promptly decaying new resonances.

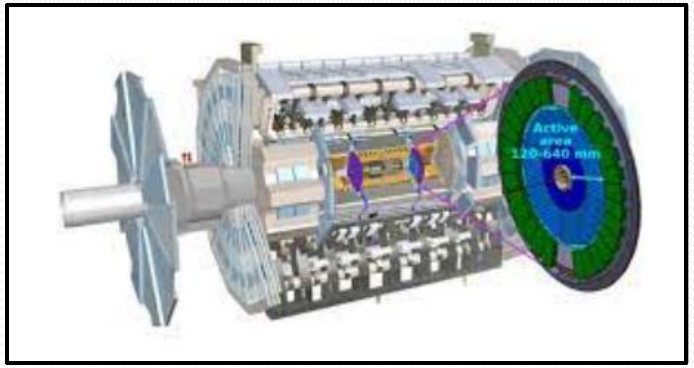


Searching for Long-Lived Particles

- LLPs arising in many extensions of the SM, e.g., RPV SUSY
- Macroscopically **displaced vertices** (DVs) at colliders by LLPs with lifetimes
- Very **low SM backgrounds** in the search channels involving DVs
- Additional apparatus installed in both the ATLAS and CMS detectors during the HL-LHC upgrade 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]

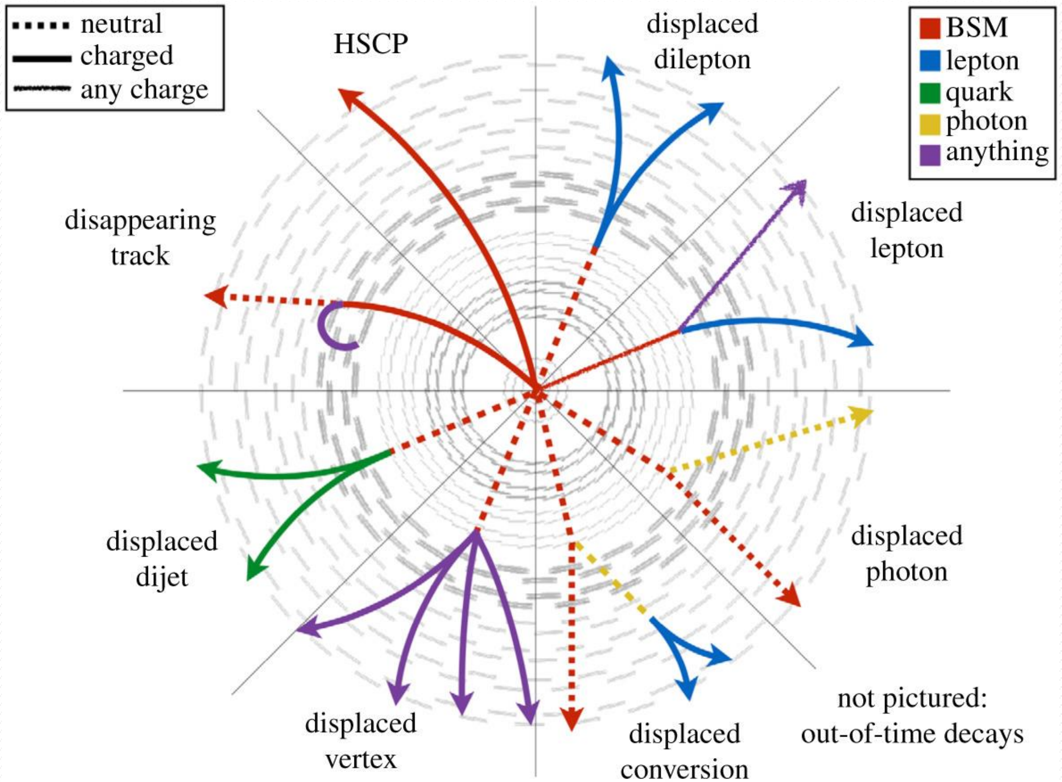


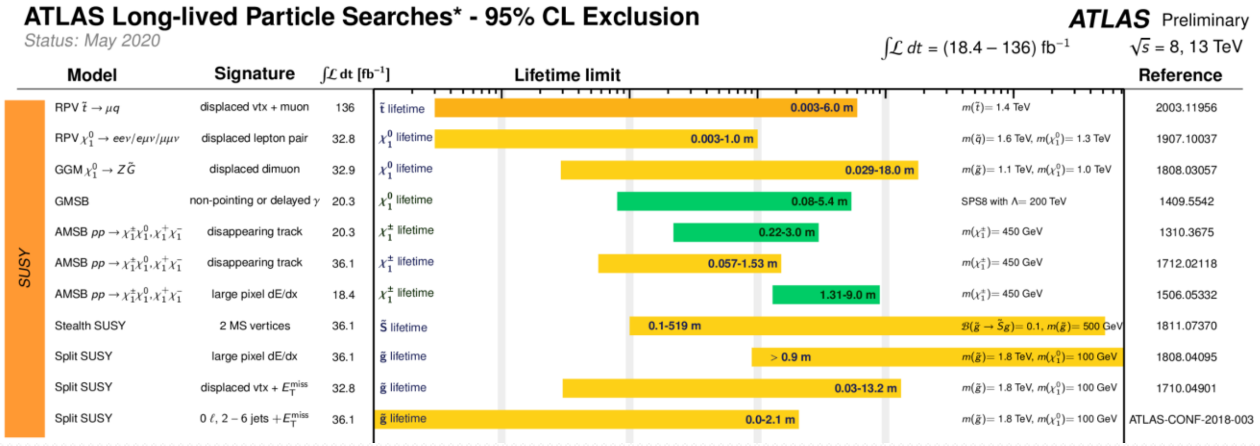
[CMS: Barrel timing layer, high-granularity calorimeters]

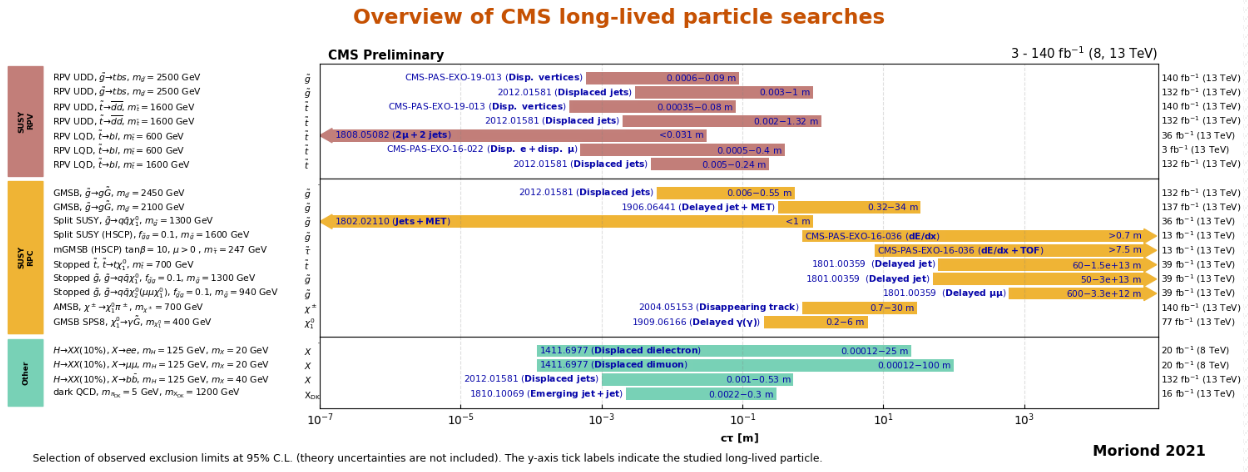


[ATLAS: Endcap timing detectors, high-granularity calorimeters]

Existing LLP Searches at the LHC



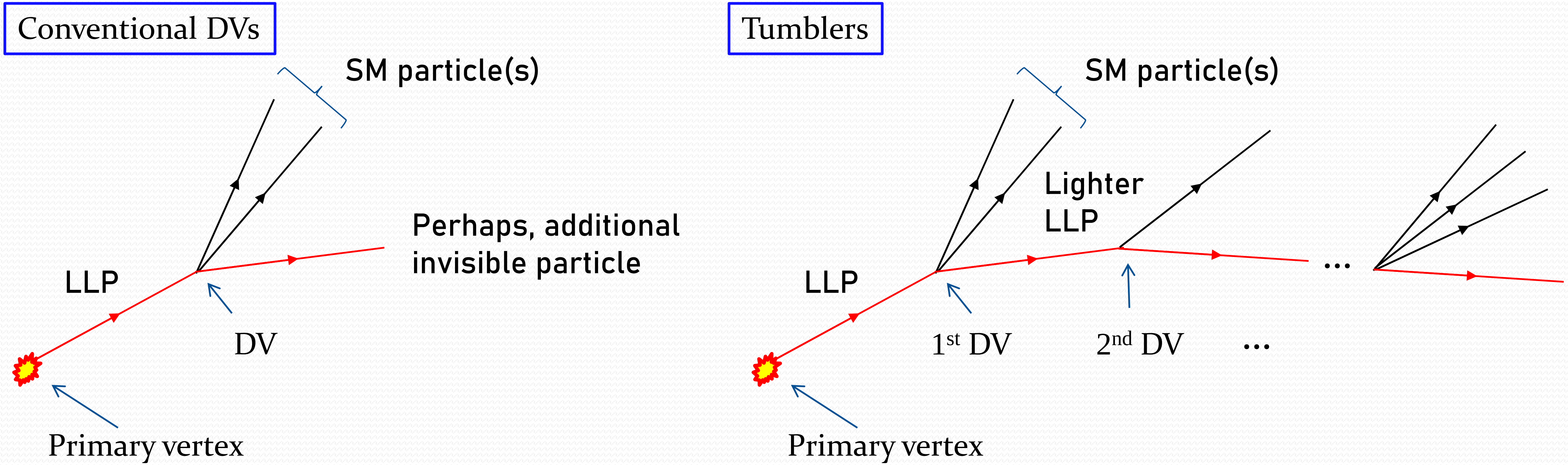




Other possibilities?

Tumblers

Tumblers: A New Collider Signature for LLPs

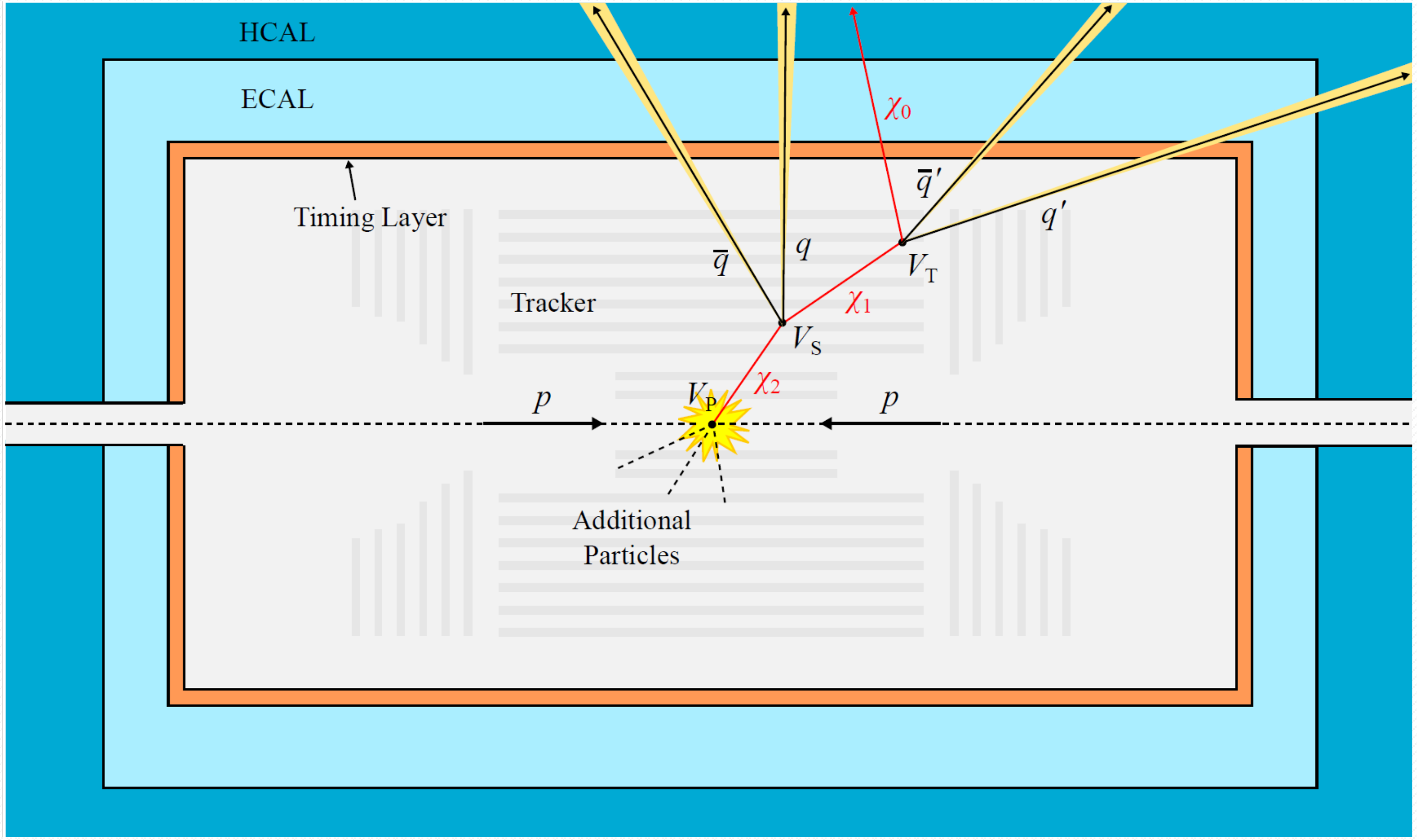


- "**Tumbler**": A sequence of DVs which result from successive decays of LLPs within the same decay chain

What Models Give Rise to Tumblers?

- New physics **models/scenarios with multiple LLPs**
- Example scenarios
  - Compressed SUSY [Martin, hep-ph/0703097]
  - 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, **DK**, Song, Su, Thomas, Yaylali, 1910.01129]

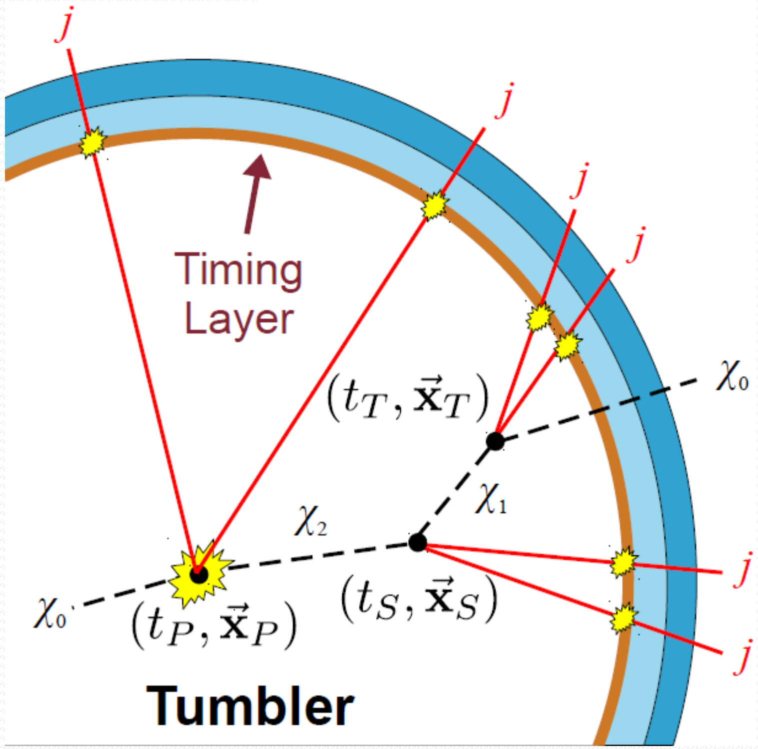
Tumblers: An Example



- Simplest tumbler signal: **two sequential DVs** for purposes of illustration.
- Each decay **produces SM particles**, here a $q\bar{q}$ pair which manifests as a pair of hadronic jets.

Resonance Mass Reconstruction

- Timing information together with momentum information allows us to reconstruct the masses of the three resonances event-by-event. (see also [Bae, Park, Zhang, 2001.02142] for the event-by-event mass reconstruction in the DV events involving ISR.)

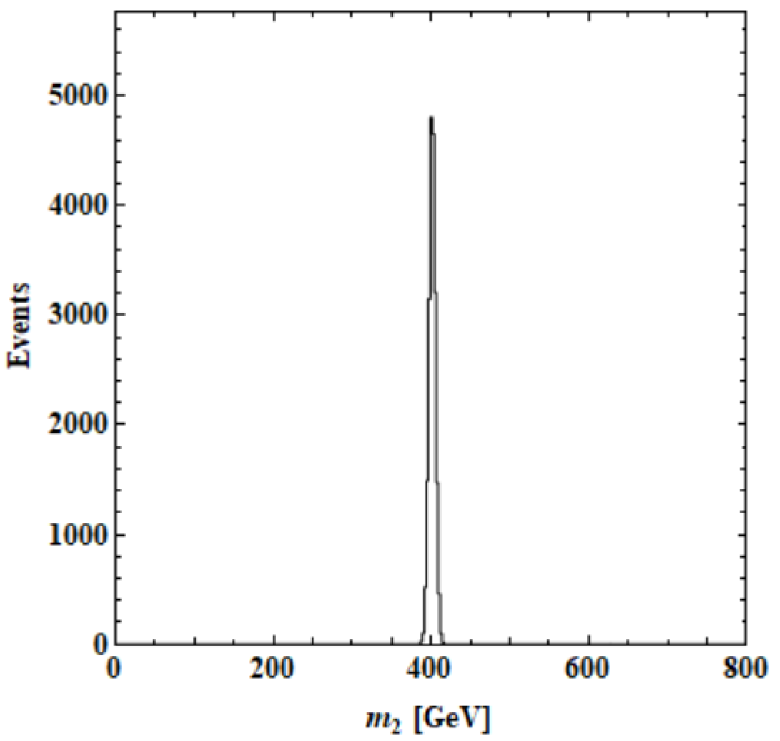


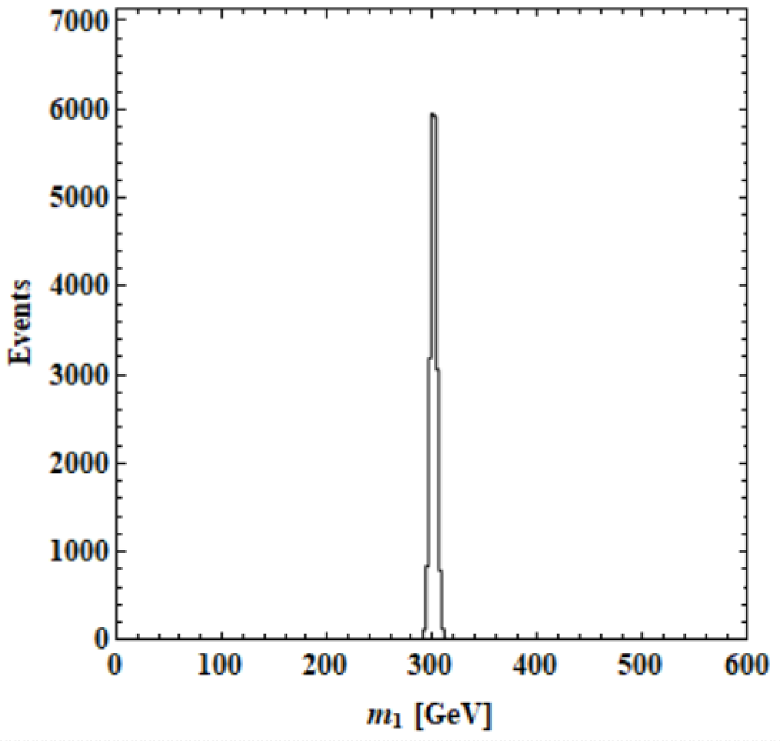
$$\vec{\beta}_1 \equiv (\vec{\mathbf{x}}_T - \vec{\mathbf{x}}_S)/(t_T - t_S) \text{ and } \vec{\beta}_2 \equiv (\vec{\mathbf{x}}_S - \vec{\mathbf{x}}_P)/(t_S - t_P)$$

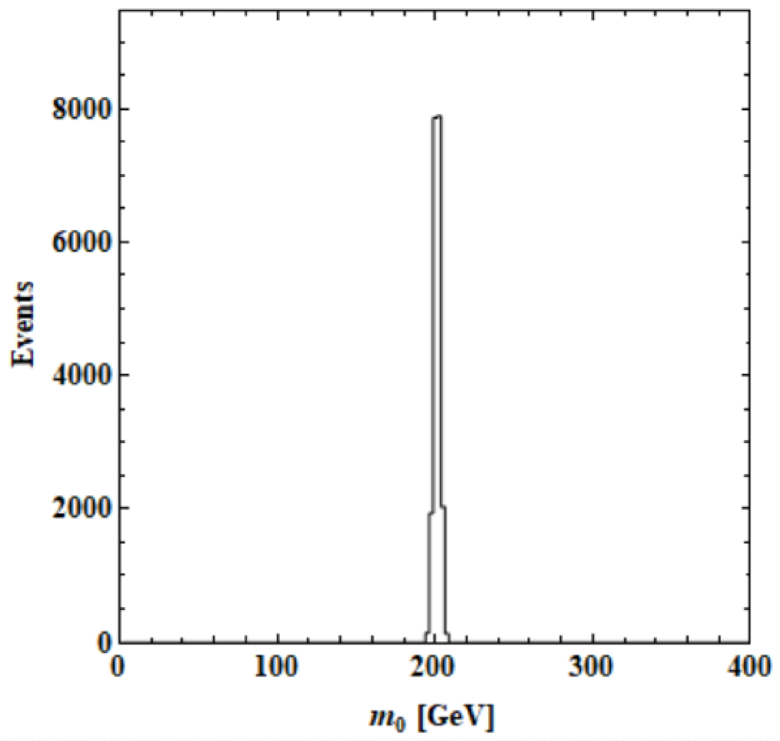
$$\begin{aligned} m_2 &= \frac{\left|\vec{\mathbf{p}}_q + \vec{\mathbf{p}}_{\bar{q}} - \vec{\beta}_1\left(|\vec{\mathbf{p}}_q| + |\vec{\mathbf{p}}_{\bar{q}}|\right)\right|}{\gamma_2|\vec{\beta}_1 - \vec{\beta}_2|} \\ m_1 &= \frac{\left|\vec{\mathbf{p}}_q + \vec{\mathbf{p}}_{\bar{q}} - \vec{\beta}_2\left(|\vec{\mathbf{p}}_q| + |\vec{\mathbf{p}}_{\bar{q}}|\right)\right|}{\gamma_1|\vec{\beta}_1 - \vec{\beta}_2|} \\ m_0^2 &= m_1^2 - 2\gamma_1 m_1\left[|\vec{\mathbf{p}}_{q'}| + |\vec{\mathbf{p}}_{\bar{q}'}| - \vec{\beta}_1\cdot(\vec{\mathbf{p}}_{q'} + \vec{\mathbf{p}}_{\bar{q}'})\right] \\ &\quad +2\left(|\vec{\mathbf{p}}_{q'}||\vec{\mathbf{p}}_{\bar{q}'}| - \vec{\mathbf{p}}_{q'}\cdot\vec{\mathbf{p}}_{\bar{q}'}\right) . \end{aligned}$$

Reconstructed Mass Distributions

- Distributions of reconstructed mass values with a 1% mass resolution
- Input mass: $\{m_2, m_1, m_0\} = \{400, 300, 200\}$ GeV







Tumblers in an Example Model

A Concrete Model for Tumblers

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

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

SM quarks interacting with new particles

Lorentz scalar mediator

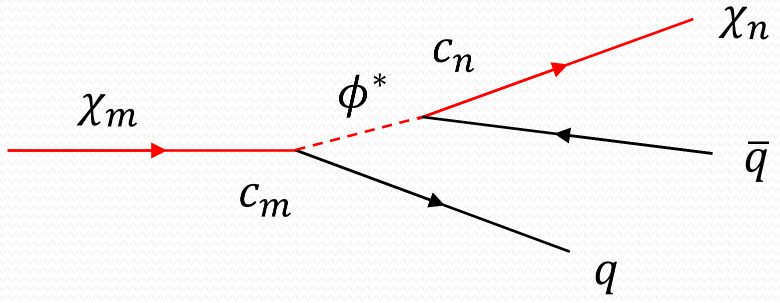
- SU(3) color triplet
- Triplet under the approximate U(3) flavor symmetry to suppress the flavor-changing effects
- ϕ and quarks sharing a common mass eigenbasis
- For simplicity, $m_\phi \equiv m_{\phi_u} \ll m_{\phi_c}, m_{\phi_t}$

Three SM-singlet Dirac fermions, χ_2, χ_1, and χ_0 with $m_2 > m_1 > m_0$

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

Decays and Displaced Vertices

- χ_2, χ_1 are unstable and decay to lighter states via a virtual ϕ.

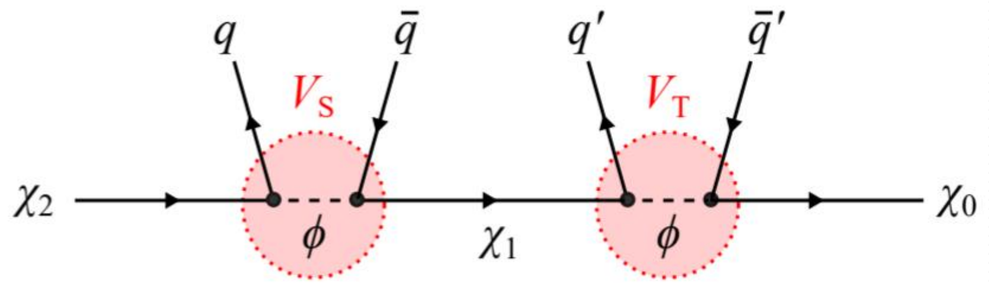


$$\Gamma_{n\ell} = \frac{3c_n^2 c_\ell^2}{256\pi^2} \frac{m_\phi}{r_{\phi n}^3} \left[f_{\phi n\ell}^{(1)} - f_{\phi n\ell}^{(2)} \ln(r_{n\ell}) + f_{\phi n\ell}^{(3)} \ln\left(\frac{1 - r_{\phi n}^2}{1 - r_{\phi n}^2 r_{n\ell}^2} \right) \right], \qquad (4.2)$$

where $r_{n\ell} \equiv m_\ell / m_n$, where $r_{\phi n} \equiv m_n / m_\phi$, and where

$$\begin{aligned} f_{\phi n\ell}^{(1)} &\equiv 6r_{\phi n}^2(1 - r_{n\ell}^2) - 5r_{\phi n}^4(1 - r_{n\ell}^4) \\ &\quad + 2r_{\phi n}^6 r_{n\ell}^2 (1 - r_{n\ell}^2) \\ f_{\phi n\ell}^{(2)} &\equiv 4r_{\phi n}^8 r_{n\ell}^4 \\ f_{\phi n\ell}^{(3)} &\equiv 6 - 8r_{\phi n}^2(1 + r_{n\ell}^2) - 2r_{\phi n}^8 r_{n\ell}^4 \\ &\quad + 2r_{\phi n}^4(1 + 4r_{n\ell}^2 + r_{n\ell}^4) \, . \end{aligned} \qquad (4.3)$$

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



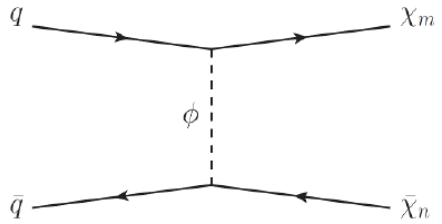
- Partial decay widths scale like $\Gamma_{mn} \propto c_m^2 c_n^2$. If $c_n \ll 1$, both χ_2, χ_1 can be long-lived and hence yield DVs. (cf. $\Gamma_{\phi n} \propto c_n^2$, so ϕ decay is typically prompt in this coupling regime.)

Production Channels

① $pp \to \chi_m \overline{\chi}_n$

(no on-shell mediators)

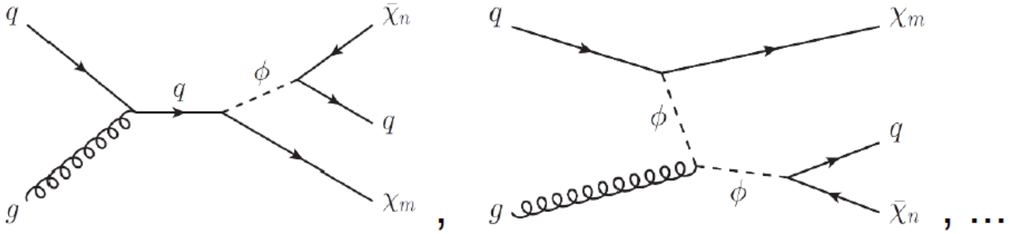
$\sigma(pp \to \chi_m \chi_n) \propto c_0^4$



② $pp \to \chi_m \phi$

(one on-shell mediator)

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

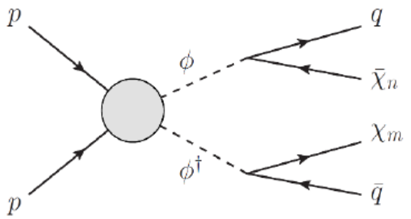


③ $pp \to \phi^\dagger \phi$

(two on-shell mediators)

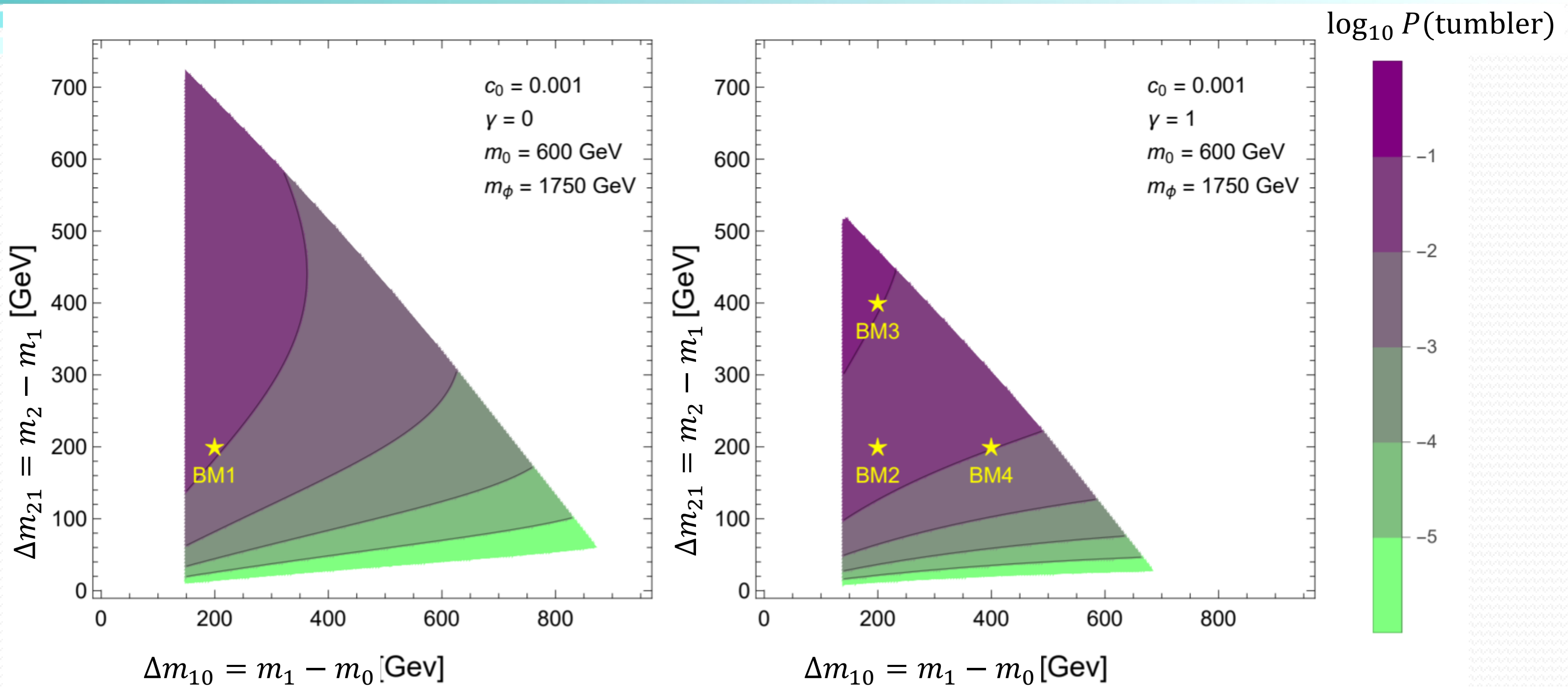
$\sigma(pp \to \chi_m \chi_n) \propto 1$

i.e., independent of c_0



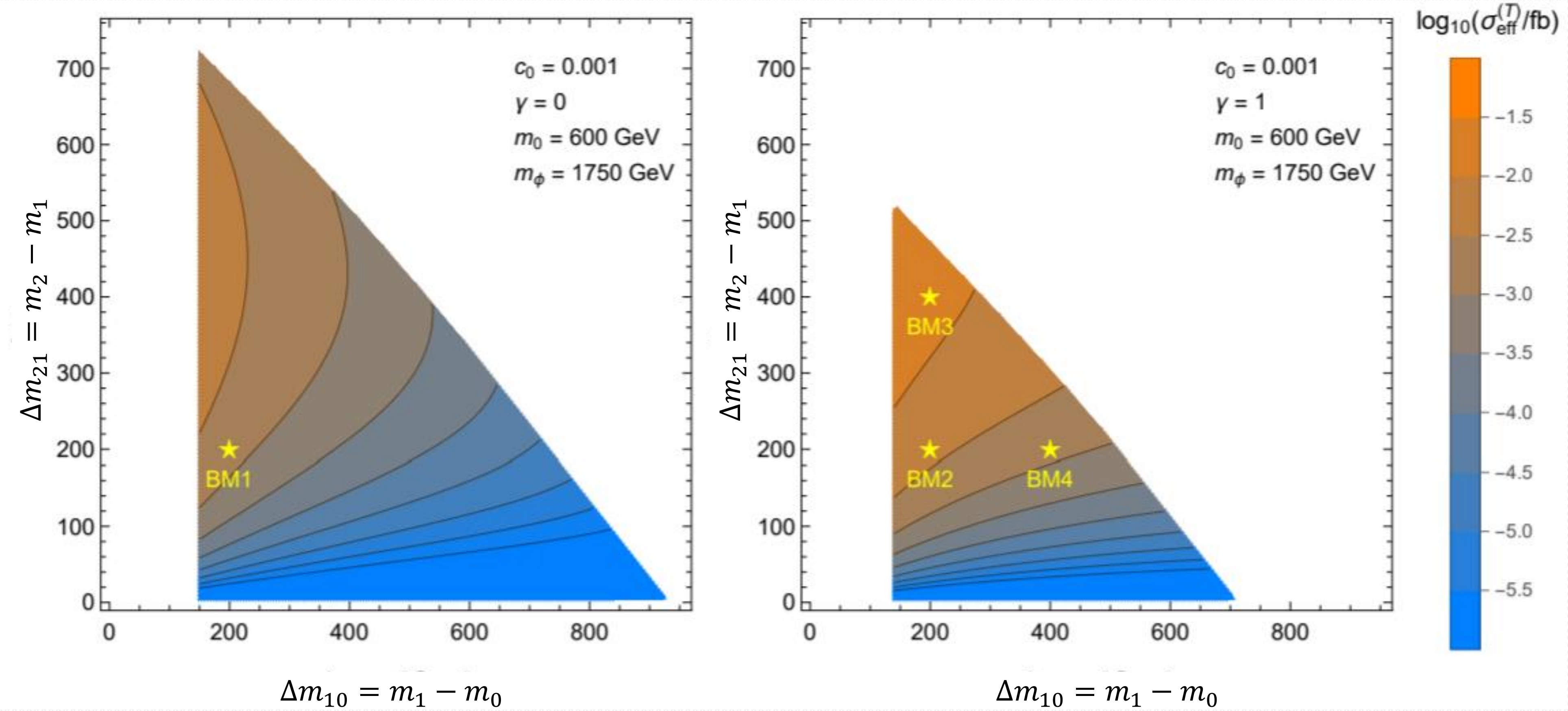
In the regime where $c_n \ll 1$, this process vastly dominates the production rate. We therefore focus on this contribution.

Benchmark Points



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}

Effective Tumbler Cross-Sections



$\sigma_{\rm eff}^{(T)}$ is large enough to provide a significant number of events at the HL-LHC!

Results

Benchmark	$\sigma_{\rm eff}^{(\alpha)}$ (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

[We find that $\sigma_{\rm eff}^{(1j)}$ is always subleading.]

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

Consistent with current bounds

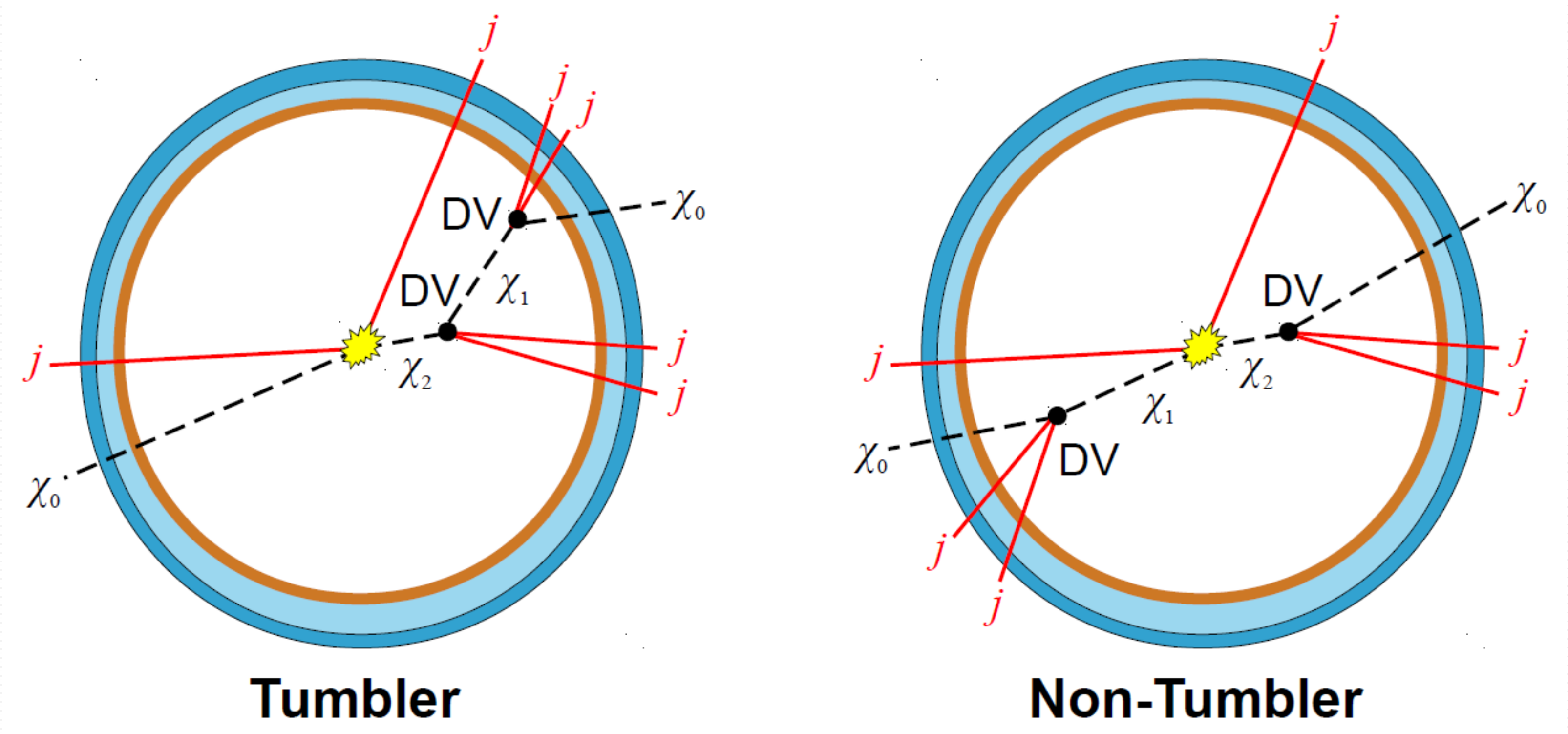
Good detection prospects

- Despite stringent limits, there is still potential for mediator-induced decay chains to manifest themselves at colliders in the displaced-vertex search channels.
- Nevertheless, tumbler events could be buried in non-tumbler (i.e., mere DVs) events.

Tumblers vs. Non-Tumblers

Tumblers vs. Non-Tumblers

- The model under consideration can give rise to not only tumbler events but non-tumbler events.



A method for distinguishing them is need to claim a discovery of tumblers!

Event Selection through Mass Reconstruction

Recall the mass reconstruction formulae

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

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

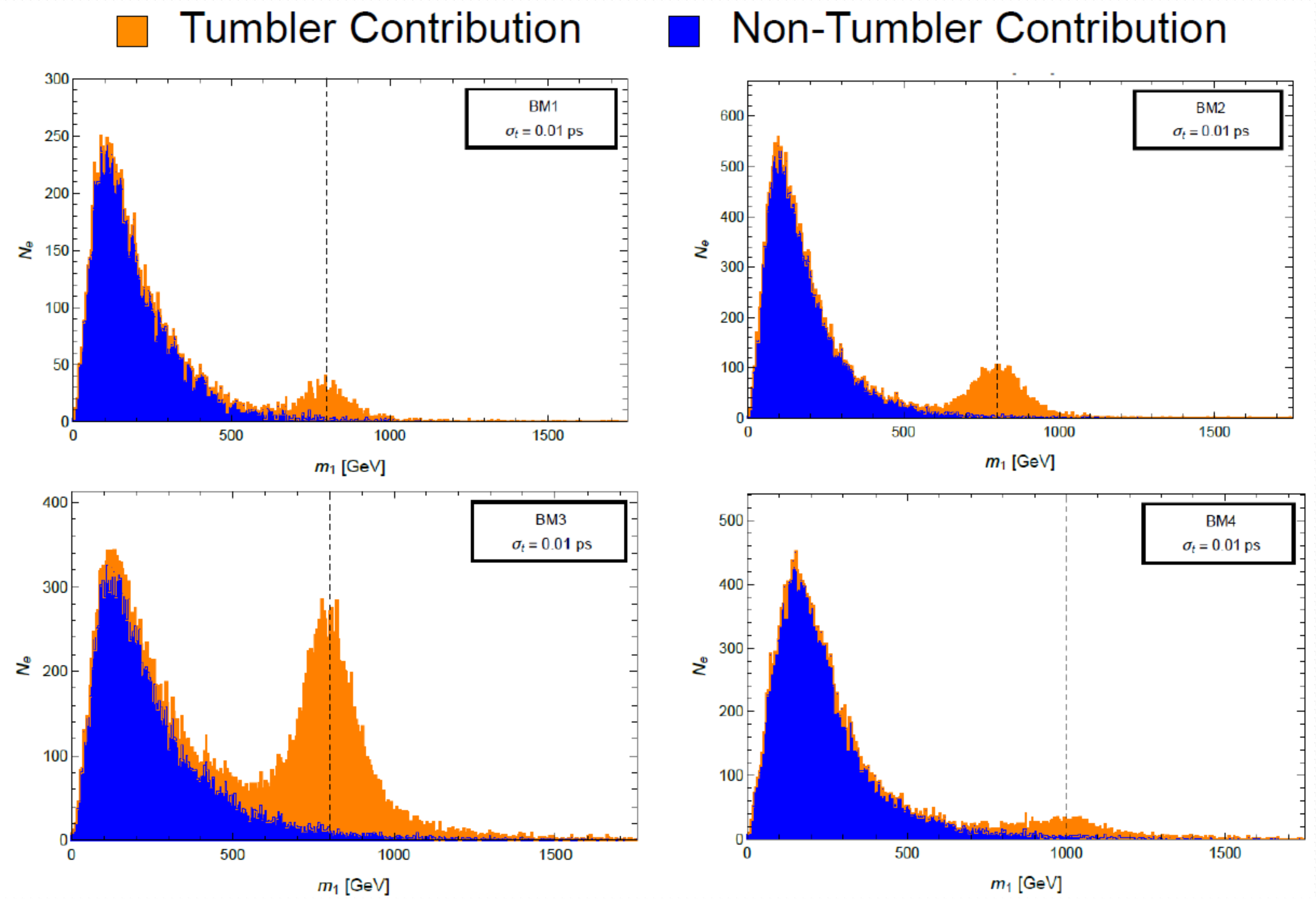
$$m_0^2 = m_1^2 - 2\gamma_1 m_1\left[|\vec{\mathbf{p}}_{q'}| + |\vec{\mathbf{p}}_{\bar{q}'}| - \vec{\beta}_1 \cdot (\vec{\mathbf{p}}_{q'} + \vec{\mathbf{p}}_{\bar{q}'})\right] + 2\left(|\vec{\mathbf{p}}_{q'}||\vec{\mathbf{p}}_{\bar{q}'}| - \vec{\mathbf{p}}_{q'} \cdot \vec{\mathbf{p}}_{\bar{q}'}\right)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

- If an event comes from the true decay topology, i.e., tumblers,
  - m_1 and m_2 are real and positive,
  - m_0^2 is real,
  - $|\vec{p}_0|$ is real and positive,
  - $0 < \left|\vec{\beta}_i\right| < 1$ for $i = 1,2$,
  - $m_2^2 > m_1^2 > m_0^2$
- Non-tumbler events may fail in satisfying some of the above criteria.

Monte Carlo Simulation Scheme

- ❑ $pp \to \phi\phi^\dagger$ simulation with MG5 and ϕ decay cascades with our own simulation code
- ❑ A few crucial detector effects are parameterized/simulated.
  - **Timing uncertainty, $\boldsymbol{\sigma_t}$**: smear the time at which each jet hits the timing layer by a Gaussian with uncertainty σ_t
  - **Jet-energy uncertainty, $\boldsymbol{\sigma_E}$**: 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 (cf. uncertainty in jet direction is subleading)
  - **Vertex-location uncertainty, σ_r**: shift the position of each vertex by a random vector whose magnitude is distributed according to a Gaussian with uncertainty $\sigma_r = 30\ \mu m$

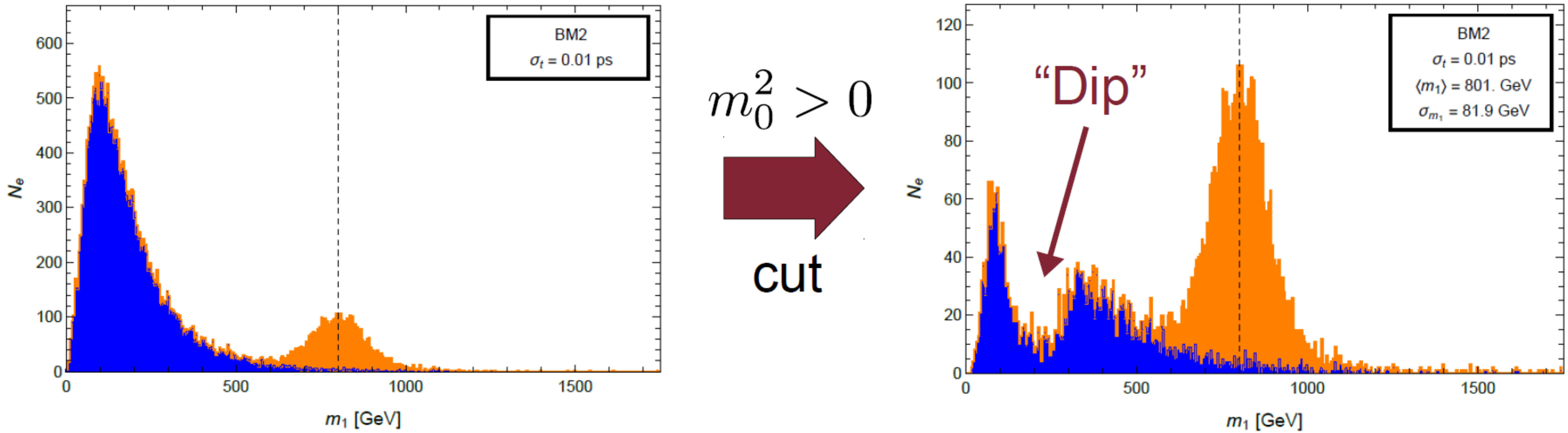
Reconstructed Mass Distributions



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

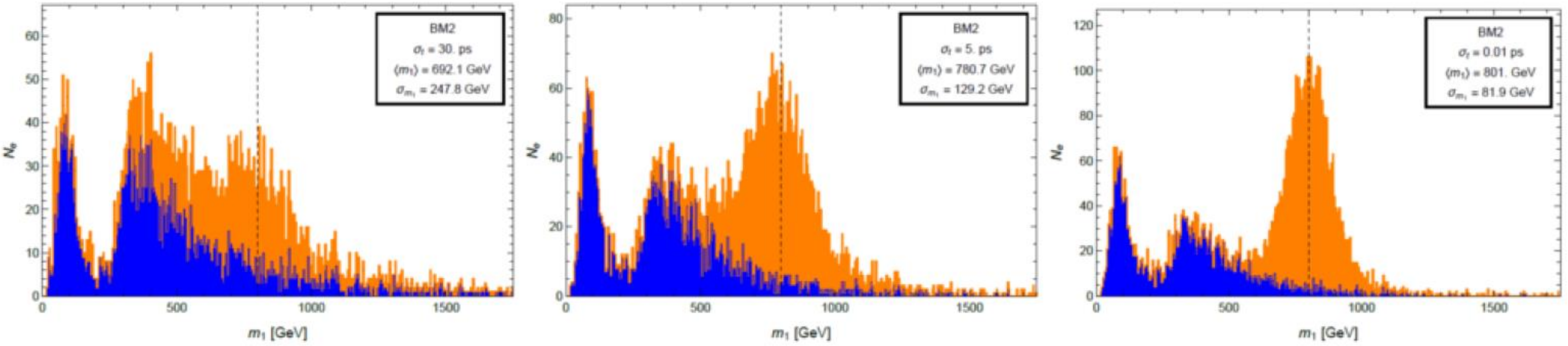
One Additional Cut

- Finally, we 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.



The Impact of Timing Resolution

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)

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

Conclusions

- 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 colliders 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.

Thank you!

Back-up

Parameter-Space Regions of Interest

- Since $pp \to \phi\phi^\dagger$ production dominates, most tumbler decay chains begin with the (prompt) decay of ϕ.

$$P(\text{tumbler}) = \text{BR}(\phi \to \chi_2)\text{BR}(\chi_2 \to \chi_1)\underbrace{\text{BR}(\chi_1 \to \chi_0)}_{=1}$$

$$= \text{BR}(\phi \to \chi_2)\text{BR}(\chi_2 \to \chi_1)$$

- We are generally interest in the regions of parameter space where $P(\text{tumbler})$ is large.
- Our parameter space is six-dimensional: $\{m_\phi, m_2, m_1, m_0, c_0, \gamma\}$

Constraints from LHC Searches

- Multi-jet $+E_T^{\text{miss}}$ [Syrunyan et al., 1908.04722, 1909.03560; Aad et al., 2010.14293]

  $\Rightarrow$ Constraints satisfied when $m_\phi \gtrsim 1250$ GeV and $m_n \gtrsim 500$ GeV.

- Mono-jet $+E_T^{\text{miss}}$ [Aad et al., 2012.10874]

  $\Rightarrow$ Constraints within our parameter-space region of interest are subleading in comparison with multi-jet constraints.

- Displaced-jet channel [Syrunyan et al., 1906.06441, 2012.01581, 2104.13474]

  $\Rightarrow$ Bound is $\sigma_{\chi\chi}\text{BR}_j^2 \lesssim 0.05 - 0.5$ fb for 10^{-4} m $< c\tau_\chi <$ 10 m.

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, $\sigma_{\text{eff}}^{(T)}$: Processes involving at least one tumbler
- DV class, $\sigma_{\text{eff}}^{(DV)}$: 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
- Mono-jet class, $\sigma_{\text{eff}}^{(1j)}$: Processes which involve one hard jet and no DV

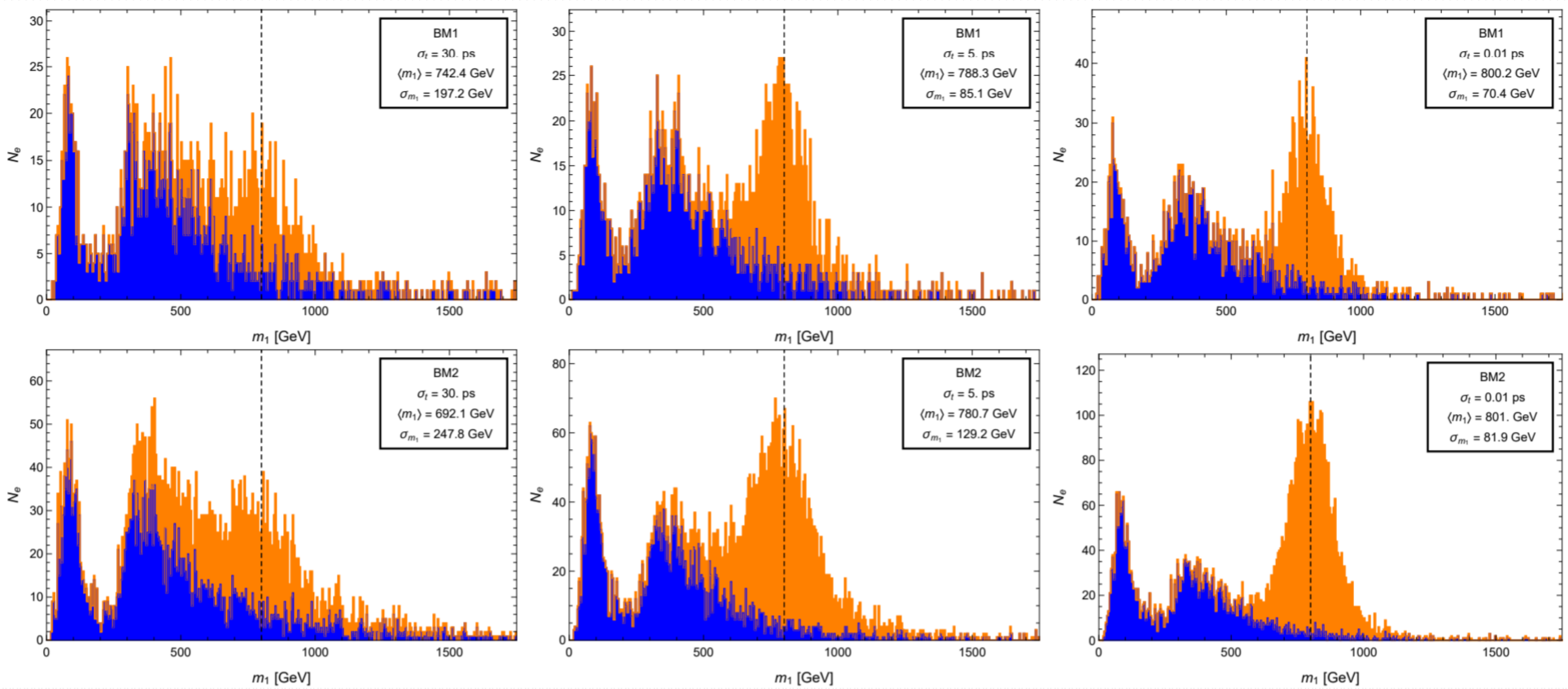
First Chain	Second Chain	Tumblers	Displaced Vertices	Prompt Jets
From $pp \to \phi\phi$ Production				
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\phi \to \chi_2 \to \chi_1 \to \chi_0$	2T		$2j$
$\phi \to \chi_2 \to \chi_1 \to \chi_0$	$\phi \to \chi_2 \to \chi_0$	T	DV	$2j$
$\phi \to \chi_2 \to \chi_1 \to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

Other Benchmark Points

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

BM1

BM2

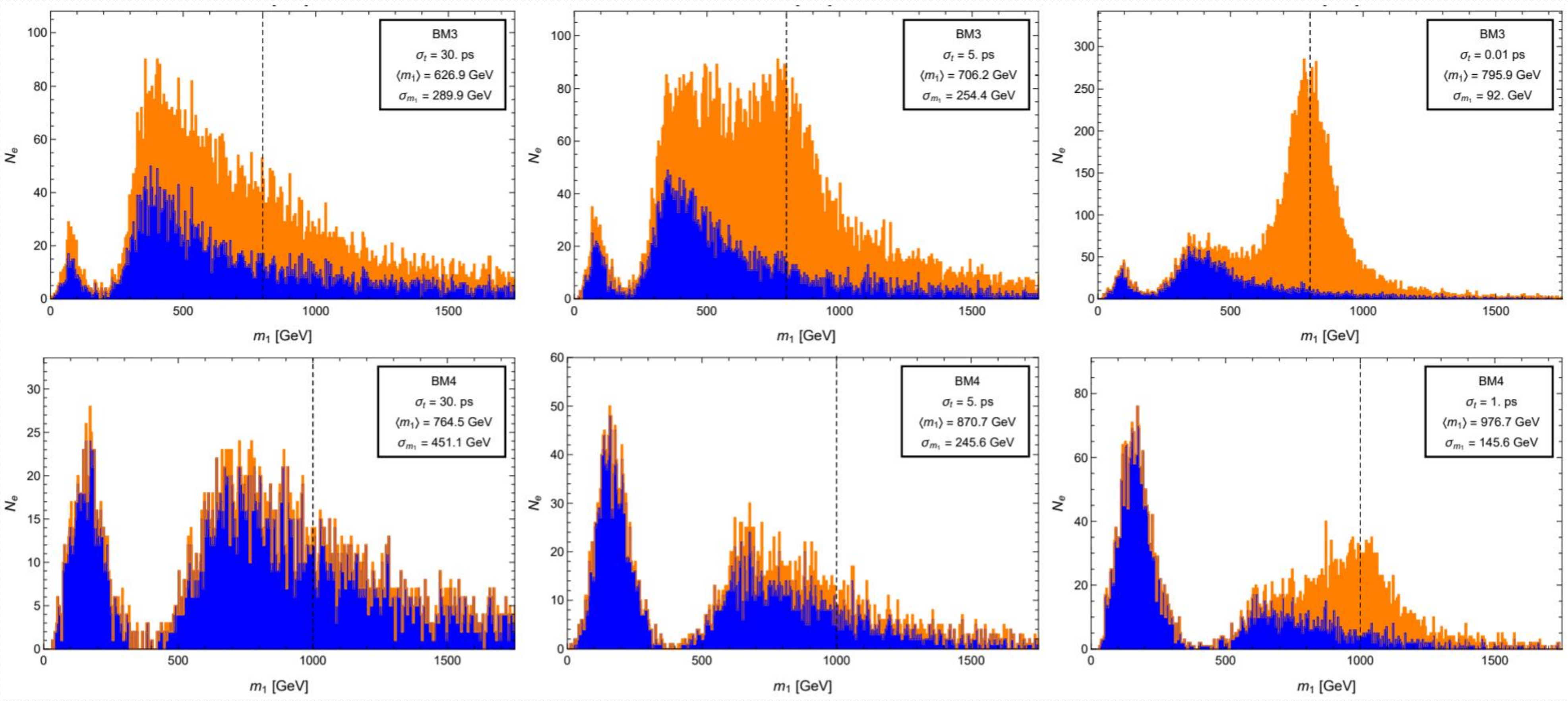


Other Benchmark Points

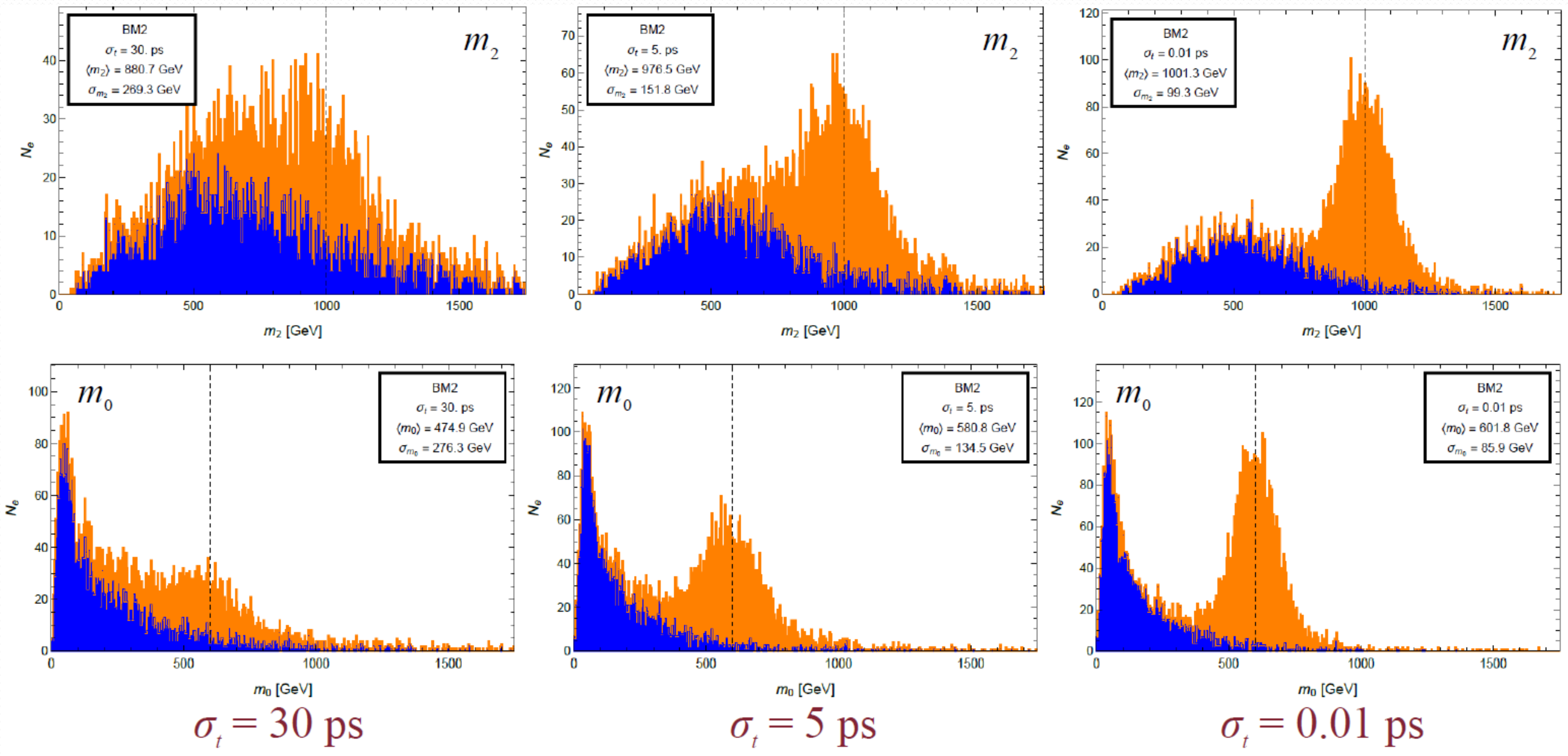
$\sigma_t = 30$ ps | $\sigma_t = 5$ ps | $\sigma_t = 0.01$ ps

BM3

BM4



Other Masses



No "dips" developed!

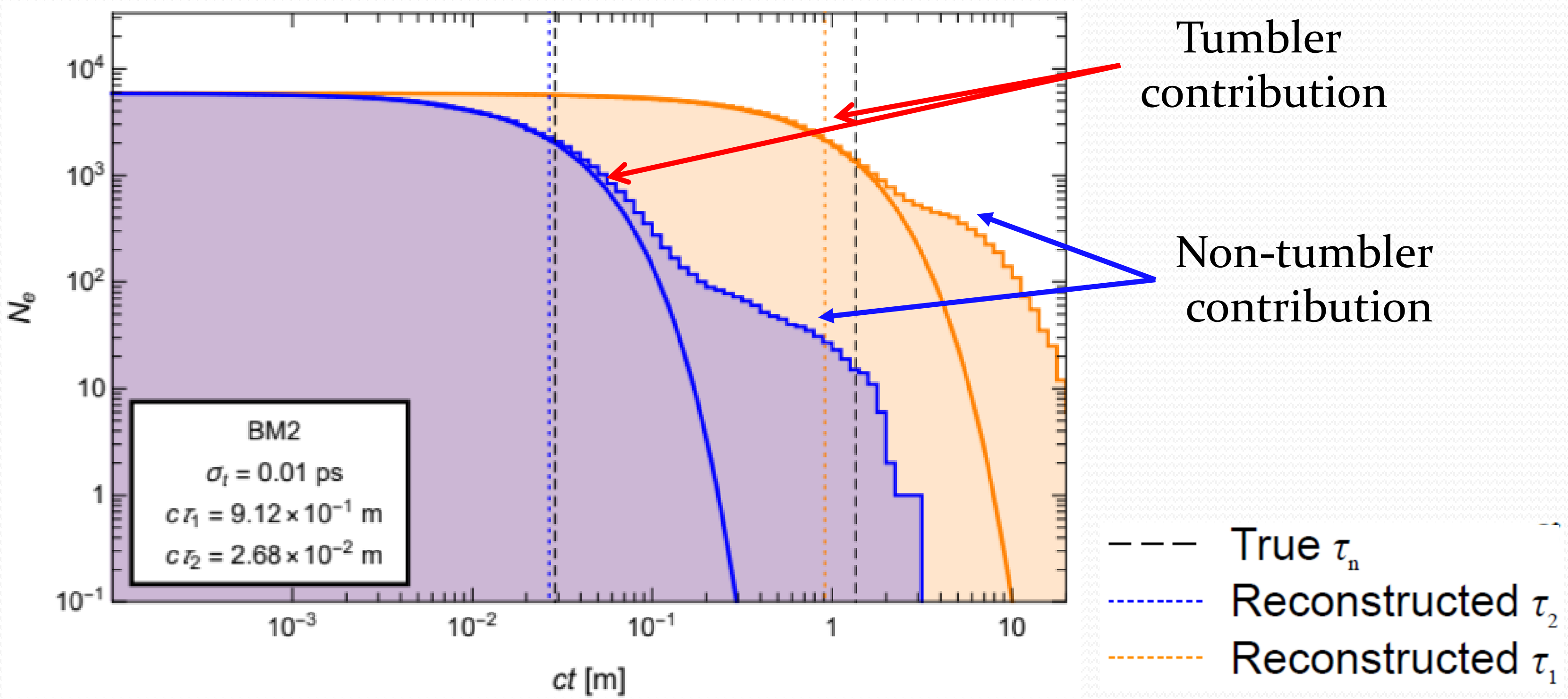
Once again, even a moderate improvement in σ_t would have a huge impact!

Lifetime Reconstruction

- We define the total number of events $N_i(t)$ $(i = 1,2)$ which have a proper decay time t_i longer than t.

Proper decay times

$$t_1 = (t_T - t_S)/\gamma_1 \text{ and } t_2 = (t_S - t_P)/\gamma_2$$



- Fit of the $N_i(t)$ distributions (after cuts) to exponential functions of the form

$$N_i(t) = N_0(t)e^{-t/\tau_i}$$