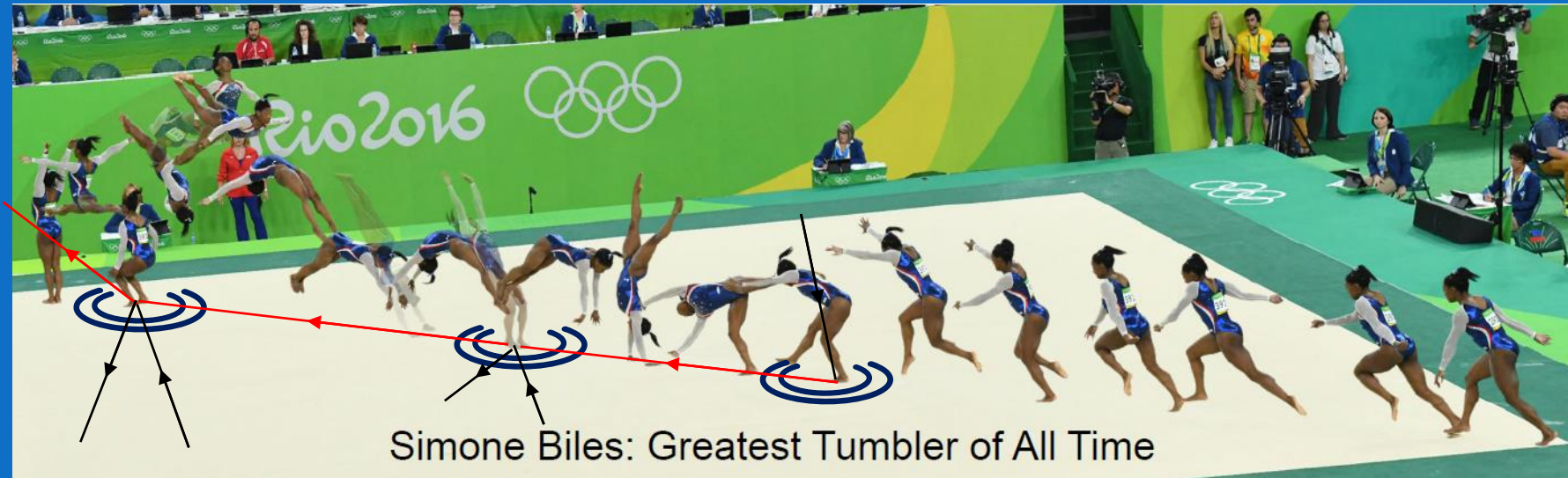


Tumblers

A Novel Collider Signature for Long-Lived Particles



Doojin Kim (doojin.kim@tamu.edu)

Snowmass EF09 Meeting, September 17th, 2021

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

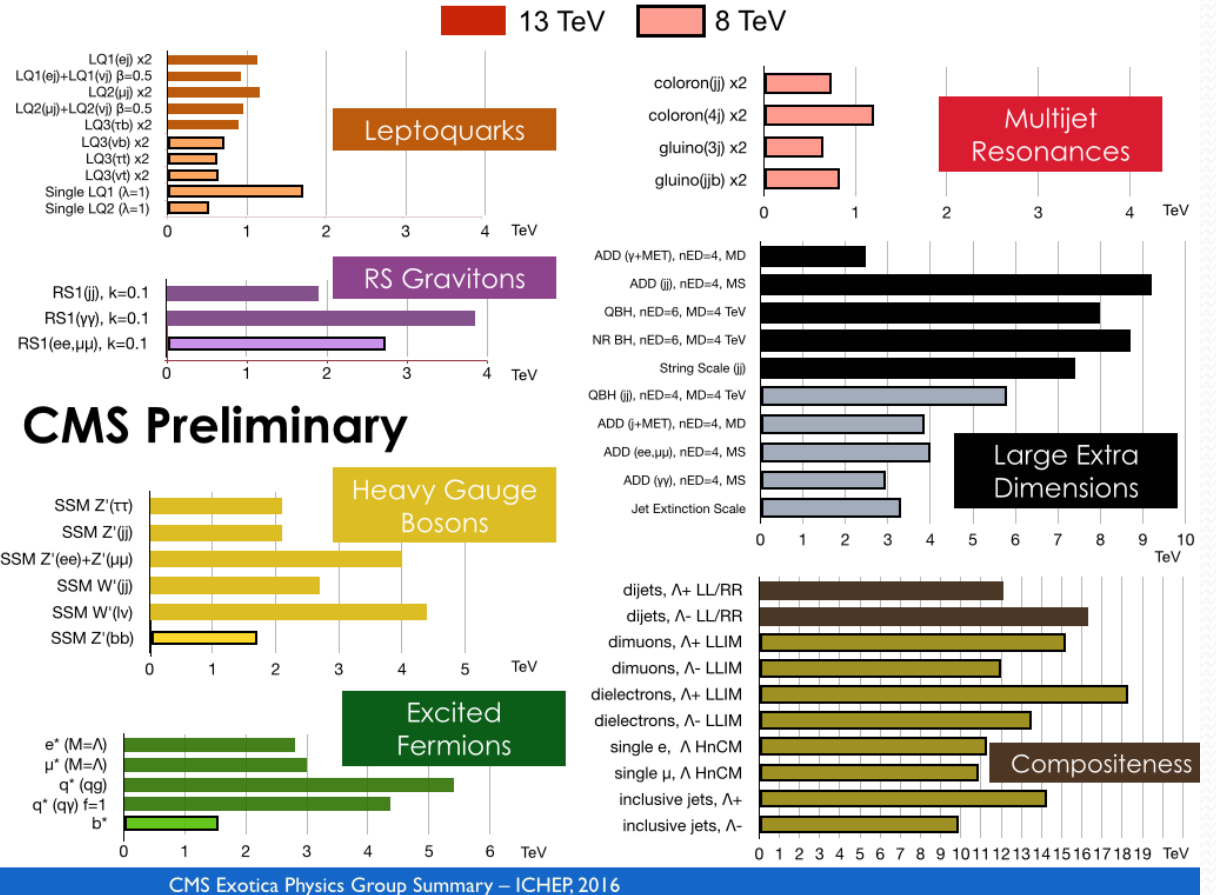
BSM Search Efforts at Colliders: No Conclusive Evidence!

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
 Status: May 2020

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{\mu\nu} + g^2$	0, 1, 2	Yes	36.1	$M_{\text{Pl}} > 2.7 \text{ TeV}$	1711.03007
ADD non-resonant $\gamma\gamma$	2, 2	-	-	36.1	$M_{\text{Pl}} > 3.6 \text{ TeV}$	1707.34147
ADD GBH	-	2	-	37.0	$M_{\text{Pl}} > 3.9 \text{ TeV}$	1710.09217
ADD BH high \sqrt{s}	0, 1, 2, 2	2	-	3.2	$M_{\text{Pl}} > 6.2 \text{ TeV}$	1606.02011
ADD BH multi	0, 1, 2, 2	2	-	3.6	$M_{\text{Pl}} > 6.5 \text{ TeV}$	1614.00545
RS1 $G_{\mu\nu} + g^2$	2, 2	-	-	36.7	$M_{\text{Pl}} > 3.0 \text{ TeV}$	1707.34147
Sub FS $G_{\mu\nu} + WW + ZZ$	multi-channel	-	-	36.1	$M_{\text{Pl}} > 2.3 \text{ TeV}$	1606.02011
Sub FS $G_{\mu\nu} + WY + WZ$	1, 2, 2	2	Yes	130	$M_{\text{Pl}} > 2.0 \text{ TeV}$	1604.14601
Sub FS $G_{\mu\nu} + WZ$	1, 2, 2	2, 2	Yes	36.1	$M_{\text{Pl}} > 2.3 \text{ TeV}$	1604.14601
SUED-1 RPP	1, 2, 2	2, 2	Yes	36.1	$M_{\text{Pl}} > 2.3 \text{ TeV}$	1604.14601
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2, 2	-	139	$M_{Z'} > 2.42 \text{ TeV}$	1603.26014
SSM $Z' \rightarrow \tau\tau$	2, 2	-	-	36.1	$M_{Z'} > 2.1 \text{ TeV}$	1603.26014
Leptoquark $Z' \rightarrow \ell\nu$	0, 1, 2	2, 2	Yes	139	$M_{Z'} > 4.1 \text{ TeV}$	1604.05110
Leptoquark $Z' \rightarrow \ell\nu$	0, 1, 2	2, 2	Yes	139	$M_{Z'} > 4.1 \text{ TeV}$	1604.05110
SSM $W' \rightarrow \ell\nu$	1, 2	-	-	139	$M_{W'} > 6.8 \text{ TeV}$	1604.05110
SSM $W' \rightarrow \ell\nu$	1, 2	-	-	36.1	$M_{W'} > 3.7 \text{ TeV}$	1604.05110
HVT $Z' \rightarrow WZ$ or WZ model B	1, 2, 2	2, 2	Yes	139	$M_{Z'} > 4.3 \text{ TeV}$	1604.14601
HVT $Z' \rightarrow WZ$ or WZ model B	1, 2, 2	2, 2	Yes	139	$M_{Z'} > 3.8 \text{ TeV}$	1604.14601
HVT $Z' \rightarrow WZ$ or WZ model B	multi-channel	-	-	36.1	$M_{Z'} > 2.9 \text{ TeV}$	1604.14601
HVT $Z' \rightarrow WZ$ or WZ model B	1, 2, 2	2, 2	Yes	139	$M_{Z'} > 3.2 \text{ TeV}$	1604.14601
LRSM $W_{\mu} \rightarrow \ell\nu$	multi-channel	-	-	36.1	$M_{W_{\mu}} > 3.2 \text{ TeV}$	1607.16475
LRSM $W_{\mu} \rightarrow \ell\nu$	2, 2	2, 2	-	80	$M_{W_{\mu}} > 3.8 \text{ TeV}$	1604.14601
CI	Chiral	2	-	37.0	$M_{\text{CI}} > 21.8 \text{ TeV}$	1707.34147
CI $\ell\ell$	2, 2	-	-	139	$M_{\text{CI}} > 30.8 \text{ TeV}$	1604.05110
CI $\ell\nu$	2, 2	2, 2	Yes	36.1	$M_{\text{CI}} > 2.87 \text{ TeV}$	1604.05110
DM	Axial vector mediator (Dirac DM)	0, 1, 2	Yes	36.1	$M_{\text{DM}} > 1.35 \text{ TeV}$	1711.03007
Colored scalar mediator (Dirac DM)	0, 1, 2	Yes	36.1	$M_{\text{DM}} > 1.67 \text{ TeV}$	1711.03007	
$\nu\nu_{\text{eff}}$ EFT (Dirac DM)	0, 1, 2	Yes	3.2	$M_{\text{DM}} > 700 \text{ GeV}$	1606.02011	
Scalar reson. $\phi \rightarrow \ell\nu$ (Dirac DM)	0, 1, 2	Yes	36.1	$M_{\phi} > 3.4 \text{ TeV}$	1603.26014	
LO	Scalar LQ 1 st gen	1, 2	Yes	36.1	$M_{LQ} > 1.8 \text{ TeV}$	1606.02011
Scalar LQ 2 nd gen	1, 2	Yes	36.1	$M_{LQ} > 1.88 \text{ TeV}$	1606.02011	
Scalar LQ 3 rd gen	2, 2	Yes	36.1	$M_{LQ} > 1.23 \text{ TeV}$	1606.02011	
Scalar LQ 3 rd gen	3, 3	Yes	36.1	$M_{LQ} > 0.76 \text{ TeV}$	1606.02011	
Heavy bosons	VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.27 \text{ TeV}$	1606.02011
VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.34 \text{ TeV}$	1606.02011	
VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.34 \text{ TeV}$	1606.02011	
VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.58 \text{ TeV}$	1606.02011	
VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.65 \text{ TeV}$	1606.02011	
VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.21 \text{ TeV}$	1606.02011	
VLG $Z' \rightarrow \ell\ell$	2, 2	Yes	36.1	$M_{Z'} > 1.21 \text{ TeV}$	1606.02011	
Excited fermions	Excited quark $q^* \rightarrow q\ell$	2	Yes	139	$M_{q^*} > 6.2 \text{ TeV}$	1610.03007
Excited quark $q^* \rightarrow q\ell$	2	Yes	36.7	$M_{q^*} > 5.3 \text{ TeV}$	1707.34147	
Excited quark $q^* \rightarrow q\ell$	2	Yes	36.1	$M_{q^*} > 3.8 \text{ TeV}$	1606.02011	
Excited quark $q^* \rightarrow q\ell$	2	Yes	36.1	$M_{q^*} > 3.8 \text{ TeV}$	1606.02011	
Excited lepton $\ell^* \rightarrow \ell\nu$	2	Yes	36.1	$M_{\ell^*} > 3.8 \text{ TeV}$	1606.02011	
Excited lepton $\ell^* \rightarrow \ell\nu$	2	Yes	36.1	$M_{\ell^*} > 3.8 \text{ TeV}$	1606.02011	
Other	Type III Seesaw	1, 2, 2	Yes	39.8	$M_{\text{seesaw}} > 660 \text{ GeV}$	1606.02011
LRSM Majorana ν	2, 2	Yes	36.1	$M_{\text{seesaw}} > 3.2 \text{ TeV}$	1606.02011	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4	Yes	36.1	$M_{H^{\pm\pm}} > 870 \text{ GeV}$	1606.02011	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4	Yes	36.1	$M_{H^{\pm\pm}} > 870 \text{ GeV}$	1606.02011	
Multi-charged particles	2, 3, 4	Yes	36.1	$M_{\text{multi}} > 1.22 \text{ TeV}$	1606.02011	
Magnetic monopoles	2, 3, 4	Yes	36.1	$M_{\text{mono}} > 3.37 \text{ TeV}$	1606.02011	

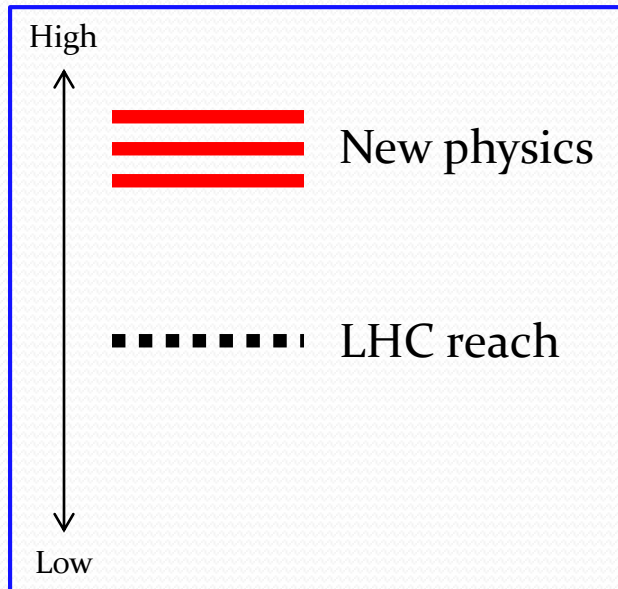
*Only a selection of the available mass limits on new states or phenomena is shown.
 †Small radius (large-exotic) jets are denoted by the letter J.



Why Long-Lived Particles (LLPs)?

BSM beyond the reach of LHC

⇒ Go with future colliders

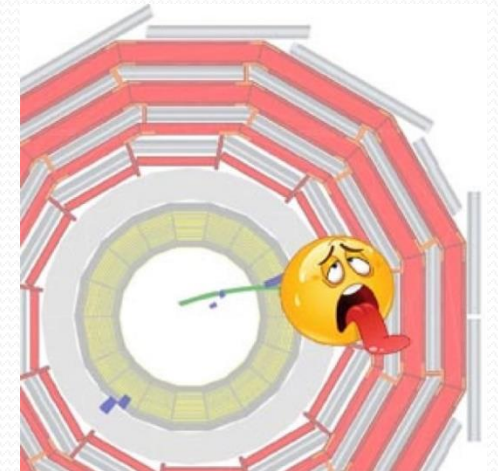


BSM hidden in the parameter space to which the existing searches are less sensitive

⇒ Explore channels/ways receiving less attention



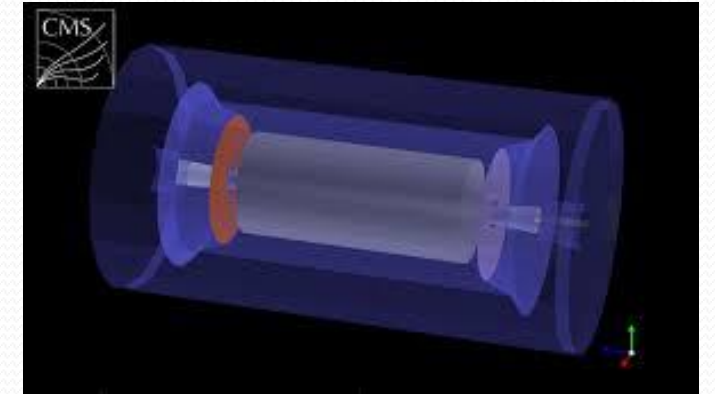
- LLPs is one such way.
- Most conventional searches are designed, assuming promptly decaying new resonances.



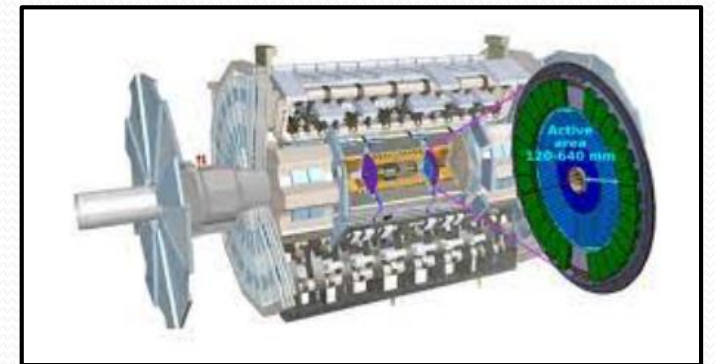
Searching for Long-Lived Particles

- ❑ 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]

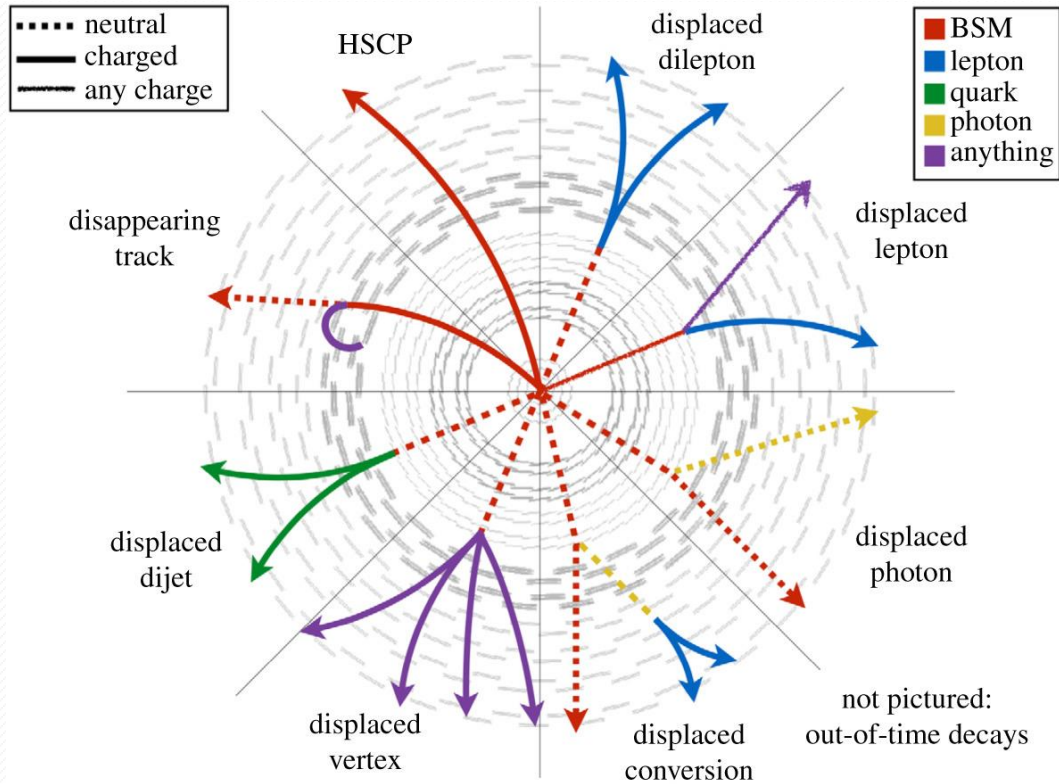


[CMS: Barrel timing layer, high-granularity calorimeters]



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

Existing LLP Searches at the LHC



Other possibilities?

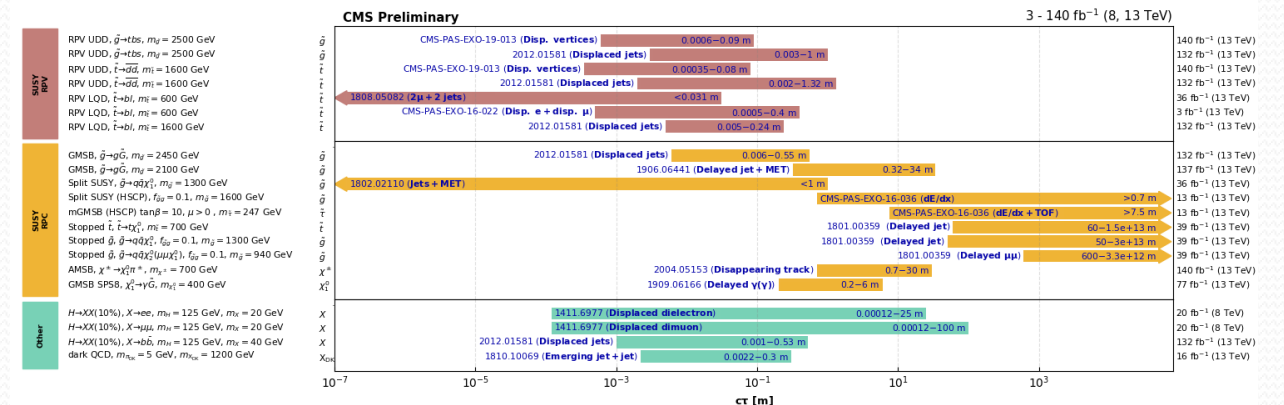
ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: May 2020

ATLAS Preliminary
 $\int \mathcal{L} dt = (18.4 - 136) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Lifetime limit	Reference	
SUSY	RPV $\tilde{t} \rightarrow \mu q$	136	\tilde{t} lifetime: 0.003-6.0 m	$m(\tilde{t}) = 1.4 \text{ TeV}$ 2003.11956	
	RPV $\chi_1^0 \rightarrow e e \nu / \mu \nu / \mu \mu \nu$	32.8	χ_1^0 lifetime: 0.003-1.0 m	$m(\tilde{g}) = 1.6 \text{ TeV}, m(\chi_1^0) = 1.3 \text{ TeV}$ 1907.10037	
	GGM $\chi_1^0 \rightarrow Z \tilde{C}$	32.9	χ_1^0 lifetime: 0.029-18.0 m	$m(\tilde{g}) = 1.1 \text{ TeV}, m(\chi_1^0) = 1.0 \text{ TeV}$ 1808.03057	
	GMSB	non-pointing or delayed γ	20.3	\tilde{g} lifetime: 0.06-5.4 m	SPSB with $\Lambda = 200 \text{ TeV}$ 1409.5542
	AMSB $pp \rightarrow \chi_1^+ \chi_1^0 \chi_1^+ \chi_1^-$	20.3	χ_1^+ lifetime: 0.22-3.0 m	$m(\chi_1^+) = 450 \text{ GeV}$ 1310.3675	
	AMSB $pp \rightarrow \chi_1^+ \chi_1^0 \chi_1^+ \chi_1^-$	36.1	χ_1^+ lifetime: 0.057-1.53 m	$m(\chi_1^+) = 450 \text{ GeV}$ 1712.02118	
	AMSB $pp \rightarrow \chi_1^+ \chi_1^0 \chi_1^+ \chi_1^-$	18.4	χ_1^+ lifetime: 1.31-9.0 m	$m(\chi_1^+) = 450 \text{ GeV}$ 1506.05332	
	Stealth SUSY	2 MS vertices	36.1	\tilde{S} lifetime: 0.1-519 m	$B(\tilde{g} \rightarrow \tilde{S} g) = 0.1, m(\tilde{g}) = 500 \text{ GeV}$ 1811.07370
	Split SUSY	large pixel dE/dx	36.1	\tilde{g} lifetime: > 0.9 m	$m(\tilde{g}) = 1.8 \text{ TeV}, m(\chi_1^0) = 100 \text{ GeV}$ 1808.04095
	Split SUSY	displaced vtx + E_T^{miss}	32.8	\tilde{g} lifetime: 0.03-13.2 m	$m(\tilde{g}) = 1.8 \text{ TeV}, m(\chi_1^0) = 100 \text{ GeV}$ 1710.04901
Split SUSY	0 $\ell, 2 - 6$ jets + E_T^{miss}	36.1	\tilde{g} lifetime: 0.0-2.1 m	$m(\tilde{g}) = 1.8 \text{ TeV}, m(\chi_1^0) = 100 \text{ GeV}$ ATLAS-CONF-2018-003	

Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

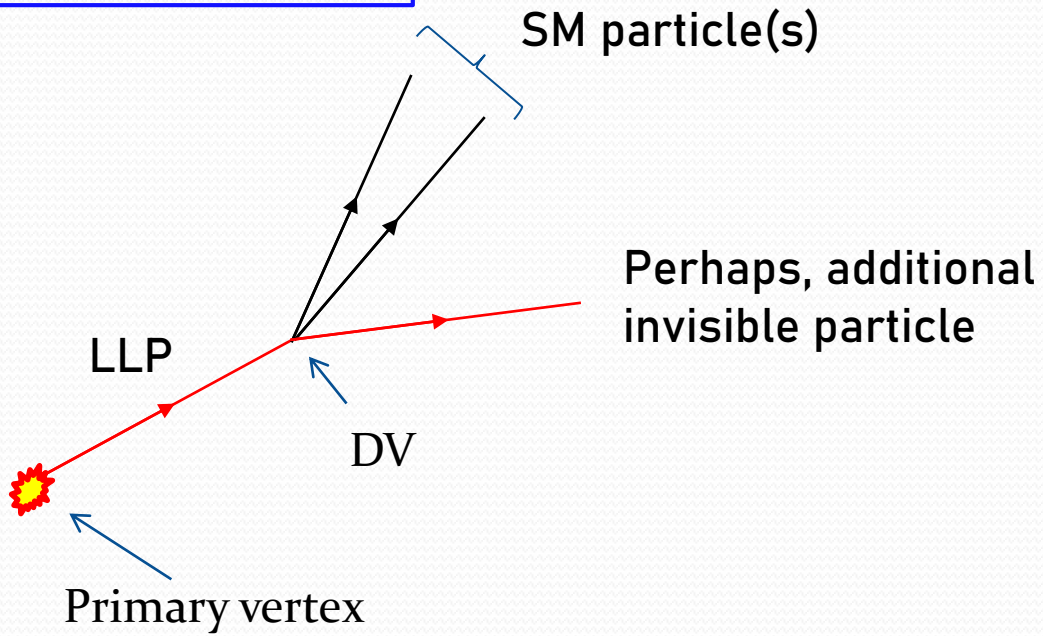
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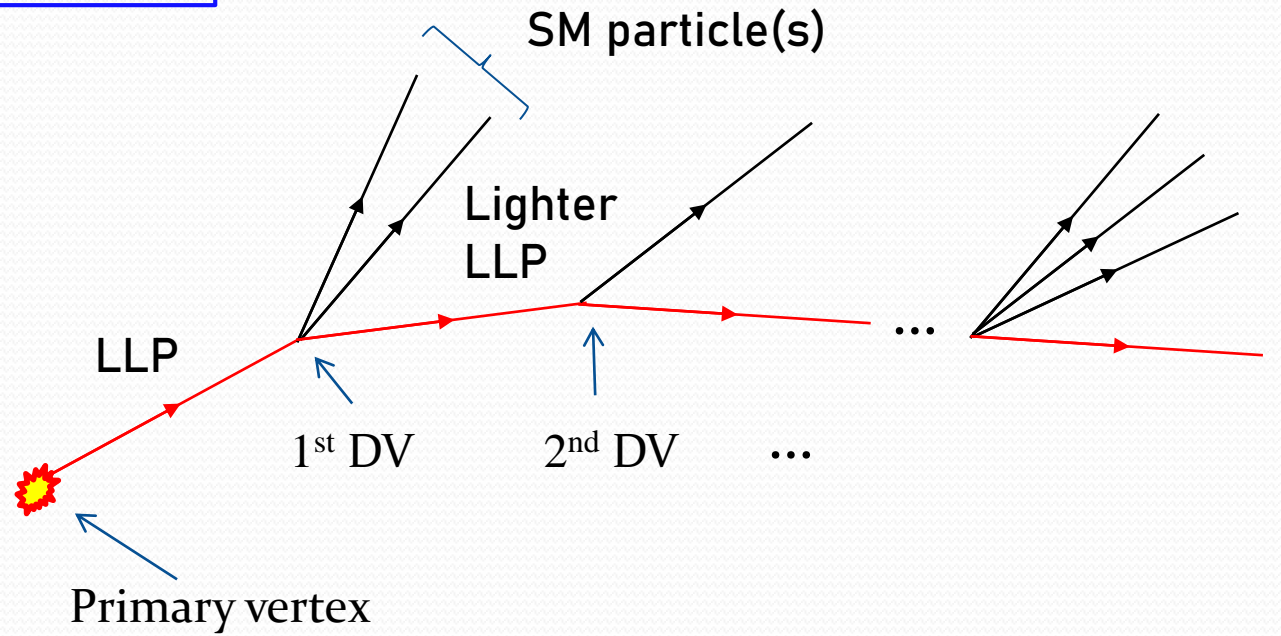
Tumblers

Tumblers: A New Collider Signature for LLPs

Conventional DVs



Tumblers

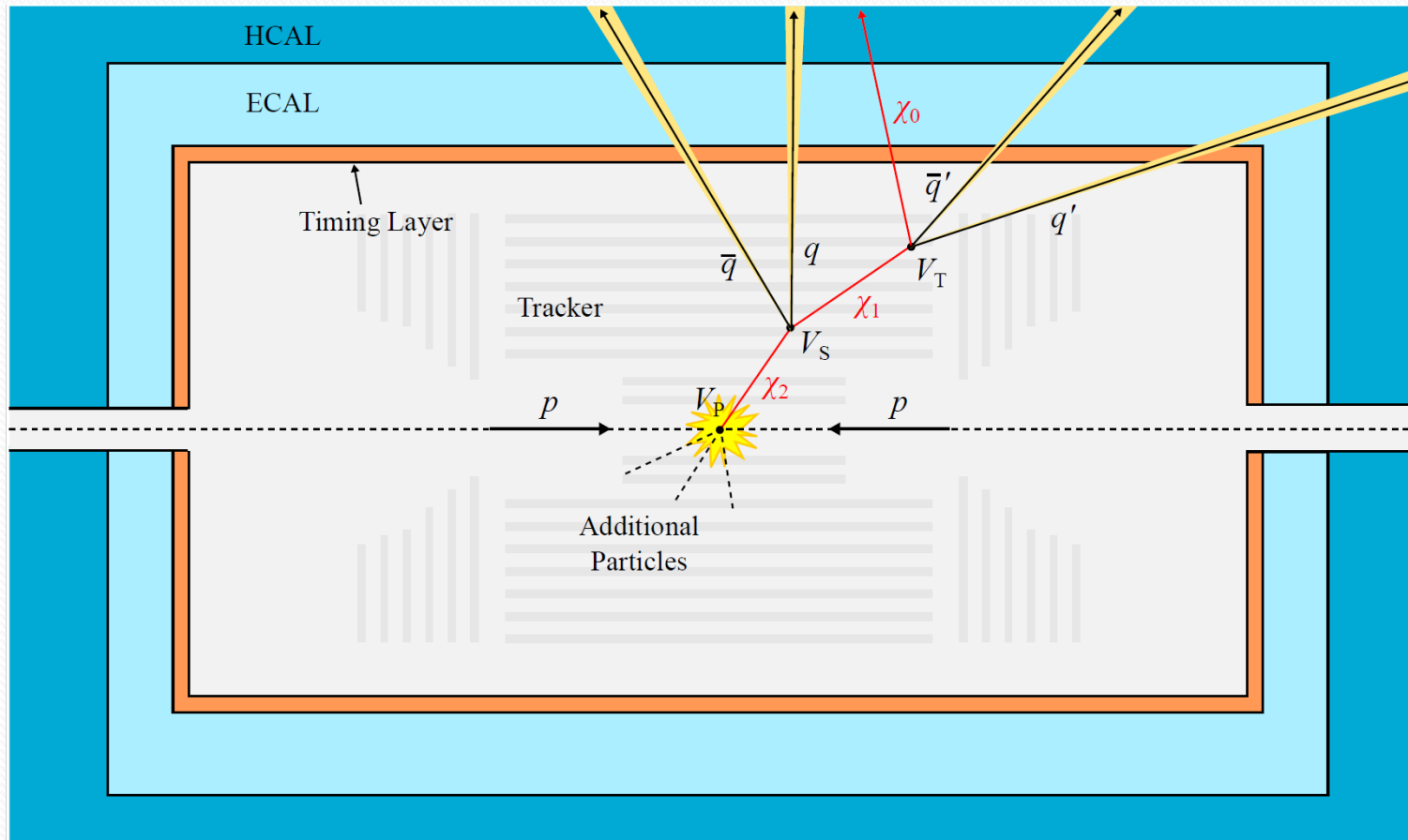


- **“Tumbler”**: A sequence of DVs which result from successive decays of LLPs within the same decay chain

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]

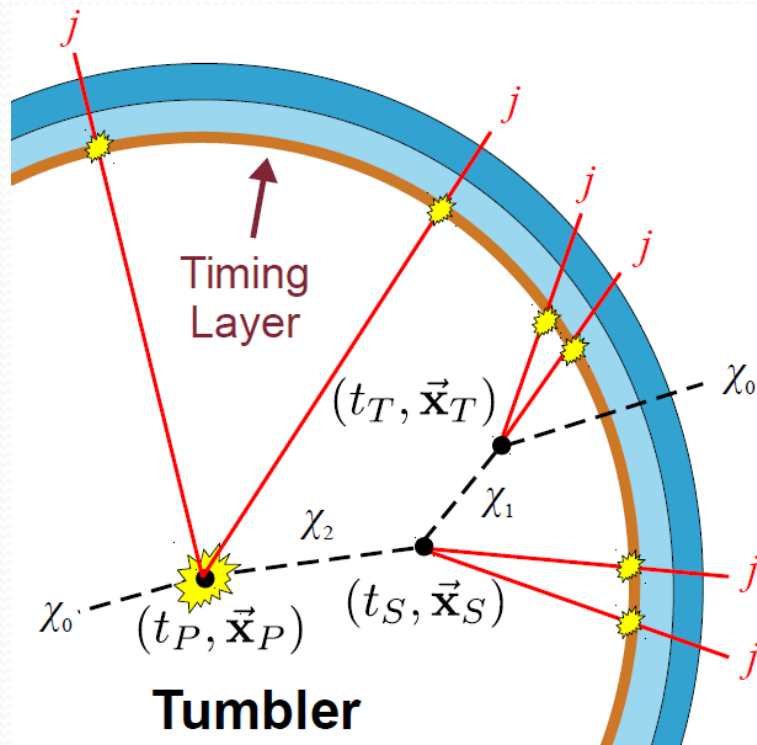
Tumblers: An Example



- 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.)



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

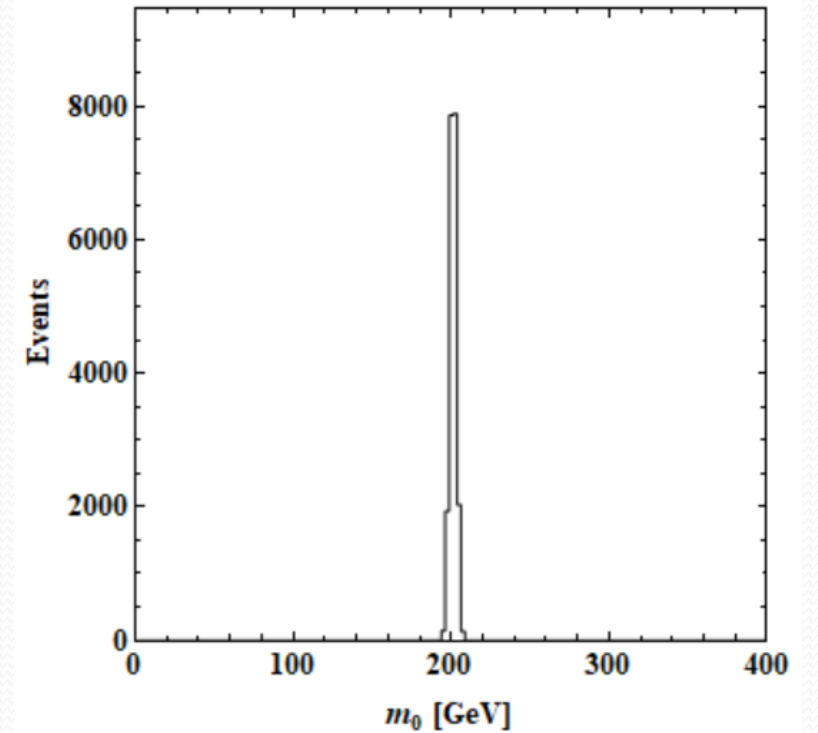
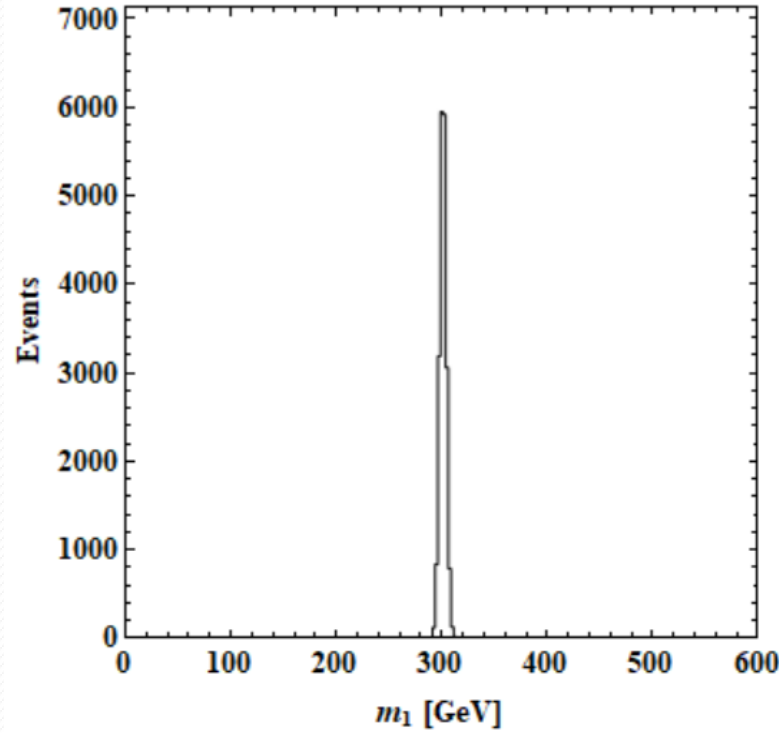
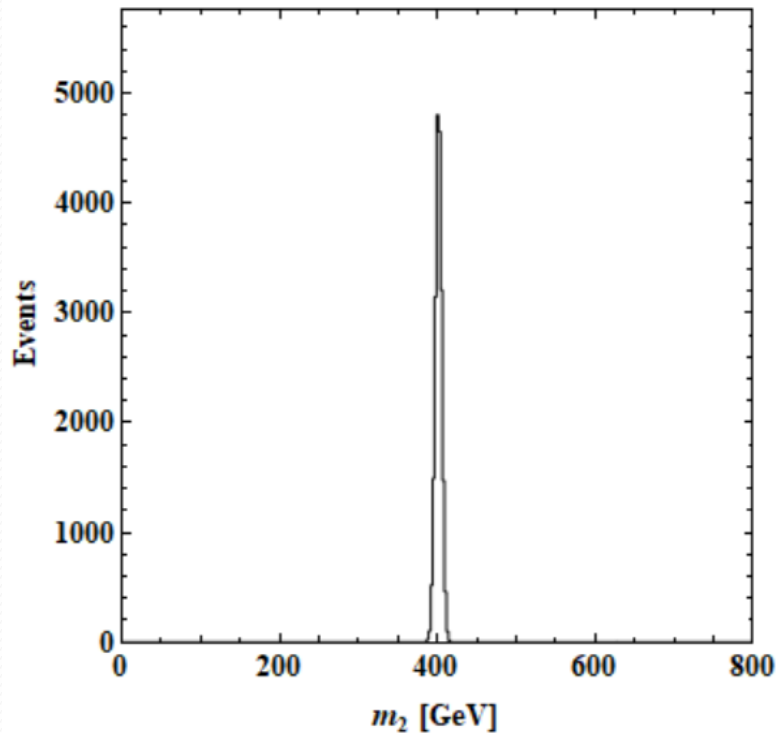
$$m_2 = \frac{|\vec{p}_q + \vec{p}_{\bar{q}} - \vec{\beta}_1(|\vec{p}_q| + |\vec{p}_{\bar{q}}|)|}{\gamma_2 |\vec{\beta}_1 - \vec{\beta}_2|}$$

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

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

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

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

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

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 $m_2 > m_1 > m_0$

SM quarks interacting with new particles

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

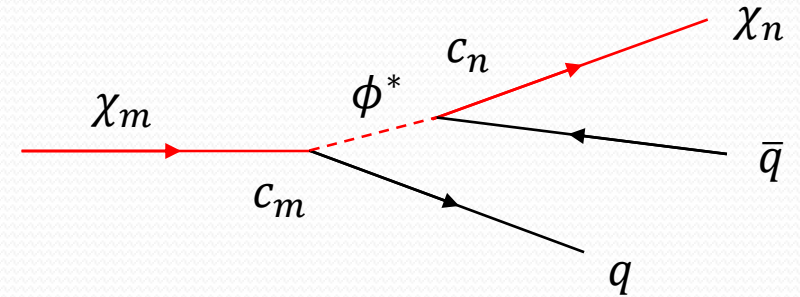
Decays and Displaced Vertices

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

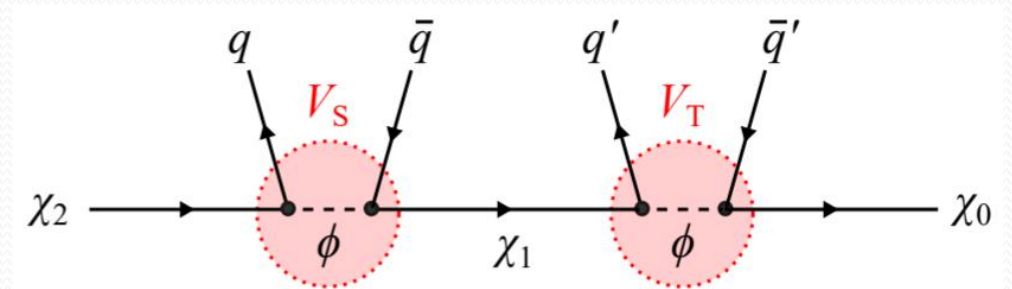
$$\Gamma_{nl} = \frac{3c_n^2 c_\ell^2 m_\phi}{256\pi^2 r_{\phi n}^3} \left[f_{\phi nl}^{(1)} - f_{\phi nl}^{(2)} \ln(r_{nl}) + f_{\phi nl}^{(3)} \ln\left(\frac{1 - r_{\phi n}^2}{1 - r_{\phi n}^2 r_{nl}^2}\right) \right], \quad (4.2)$$

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

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



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

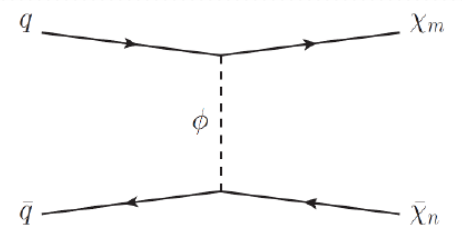


- Partial decay widths scale like $\Gamma_{mn} \propto c_m^2 c_n^2$. If $c_n \ll 1$, both χ_2, χ_1 can be long-lived and hence yield DVs. (cf. $\Gamma_{\phi n} \propto c_n^2$, so ϕ decay is typically prompt in this coupling regime.)

Production Channels

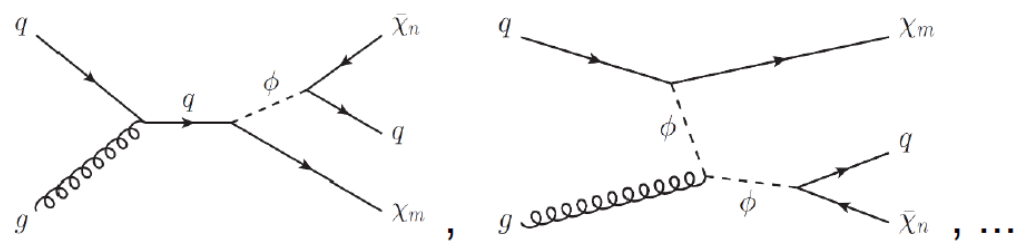
- ① $pp \rightarrow \chi_m \bar{\chi}_n$
(no on-shell mediators)

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



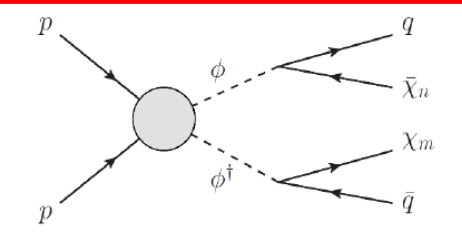
- ② $pp \rightarrow \chi_m \phi$
(one on-shell mediator)

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



- ③ $pp \rightarrow \phi^\dagger \phi$
(two on-shell mediators)

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

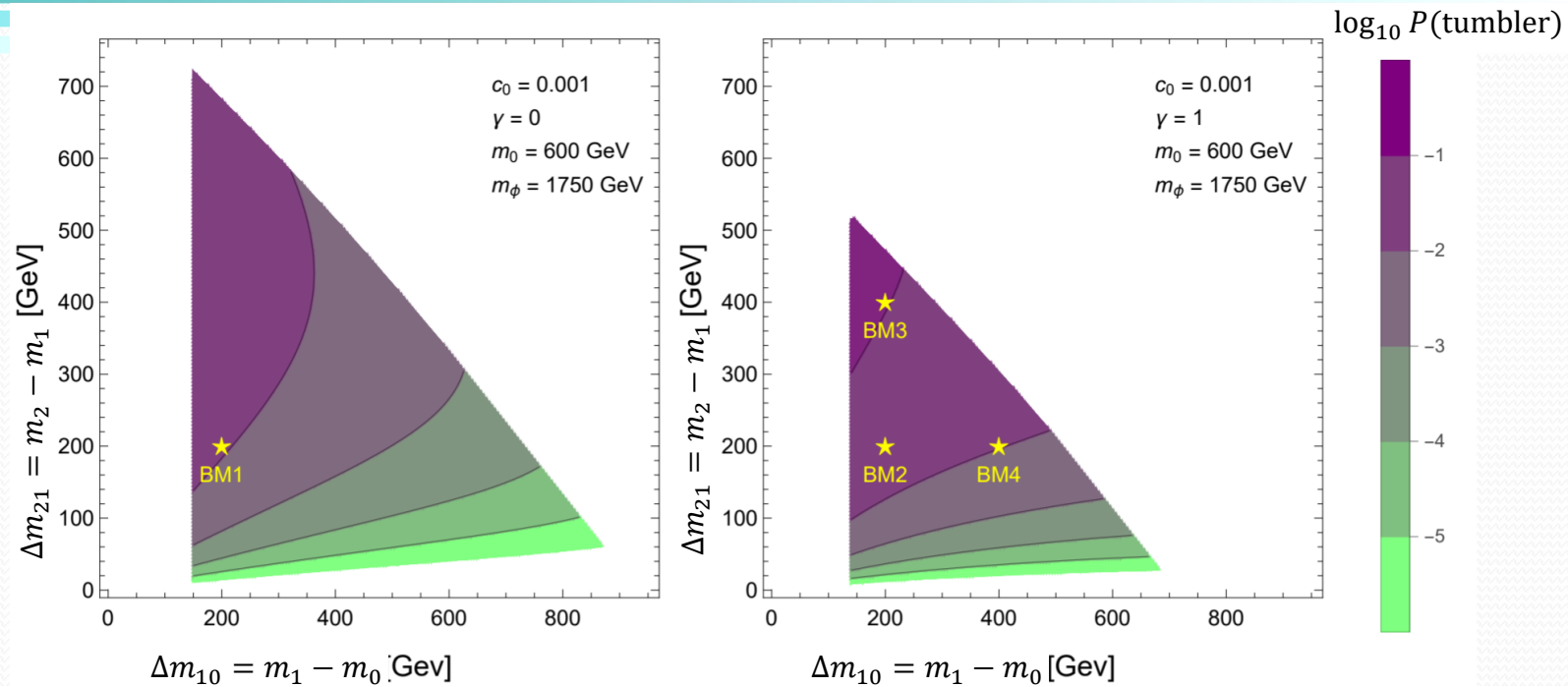


i.e., independent of c_0

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

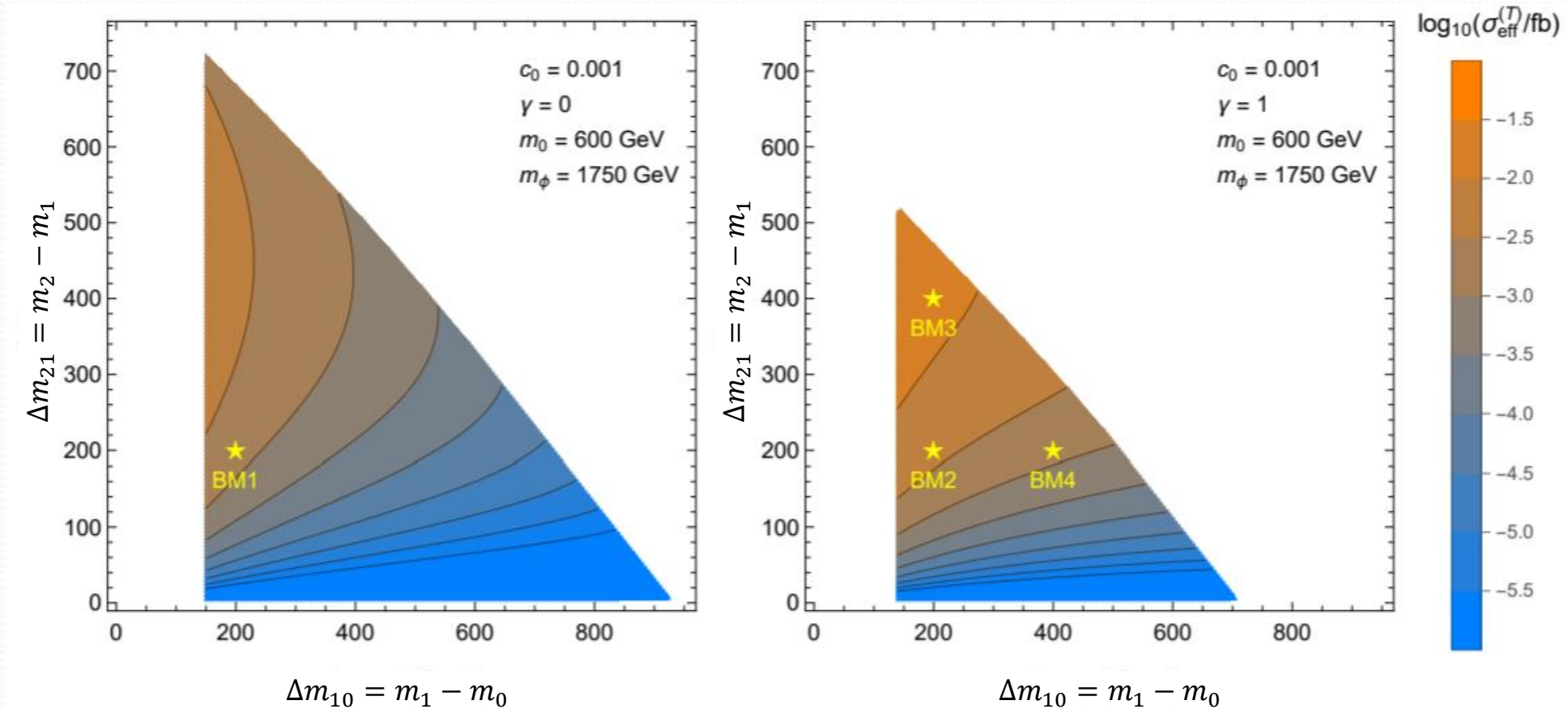


Benchmark Points



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



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

Results

Benchmark	$\sigma_{\text{eff}}^{(\alpha)}$ (fb)			Tumbler Events	
	Tumblers	DV	Multi-Jet + \cancel{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 $\sigma_{\text{eff}}^{(1j)}$ is always subleading.]

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

Consistent with current bounds

Good detection prospects

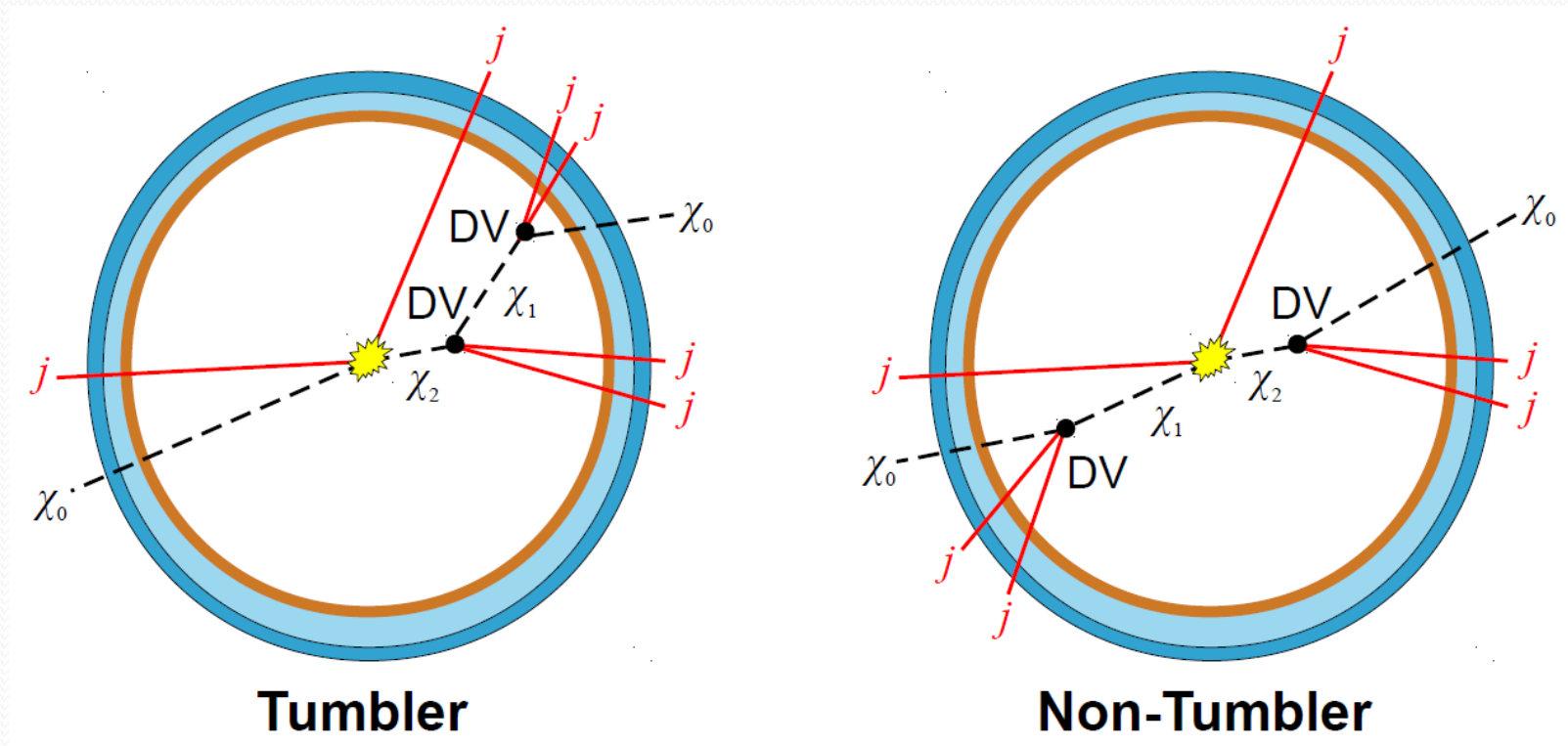
- Despite stringent limits, there is still potential for mediator-induced decay chains to manifest themselves at colliders in the displaced-vertex search channels.
- Nevertheless, tumbler events could be buried in non-tumbler (i.e., mere DVs) events.



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 needed to claim a discovery of tumblers!

Event Selection through Mass Reconstruction

Recall the mass reconstruction formulae

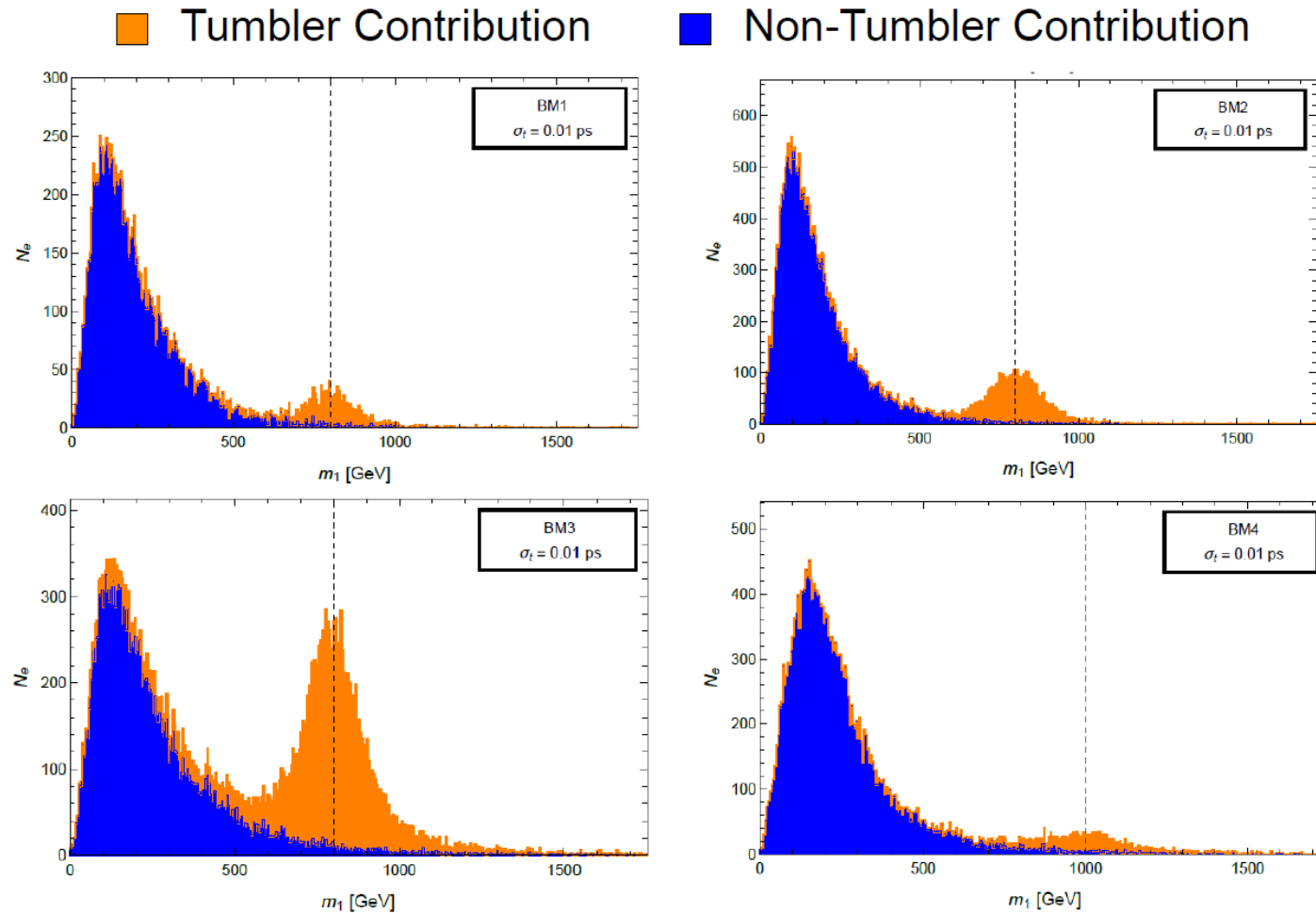
$$m_2 = \frac{|\vec{p}_q + \vec{p}_{\bar{q}} - \vec{\beta}_1 (|\vec{p}_q| + |\vec{p}_{\bar{q}}|)|}{\gamma_2 |\vec{\beta}_1 - \vec{\beta}_2|}$$
$$m_1 = \frac{|\vec{p}_q + \vec{p}_{\bar{q}} - \vec{\beta}_2 (|\vec{p}_q| + |\vec{p}_{\bar{q}}|)|}{\gamma_1 |\vec{\beta}_1 - \vec{\beta}_2|}$$
$$m_0^2 = m_1^2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

- 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,
 - $0 < |\vec{\beta}_i| < 1$ 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

- $pp \rightarrow \phi\phi^\dagger$ simulation with MG5 and ϕ decay cascades with our own simulation code
- A few crucial detector effects are parameterized/simulated.
 - **Timing uncertainty, σ_t** : smear the time at which each jet hits the timing layer by a Gaussian with uncertainty σ_t
 - **Jet-energy uncertainty, σ_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 $\sigma_r = 30 \mu\text{m}$

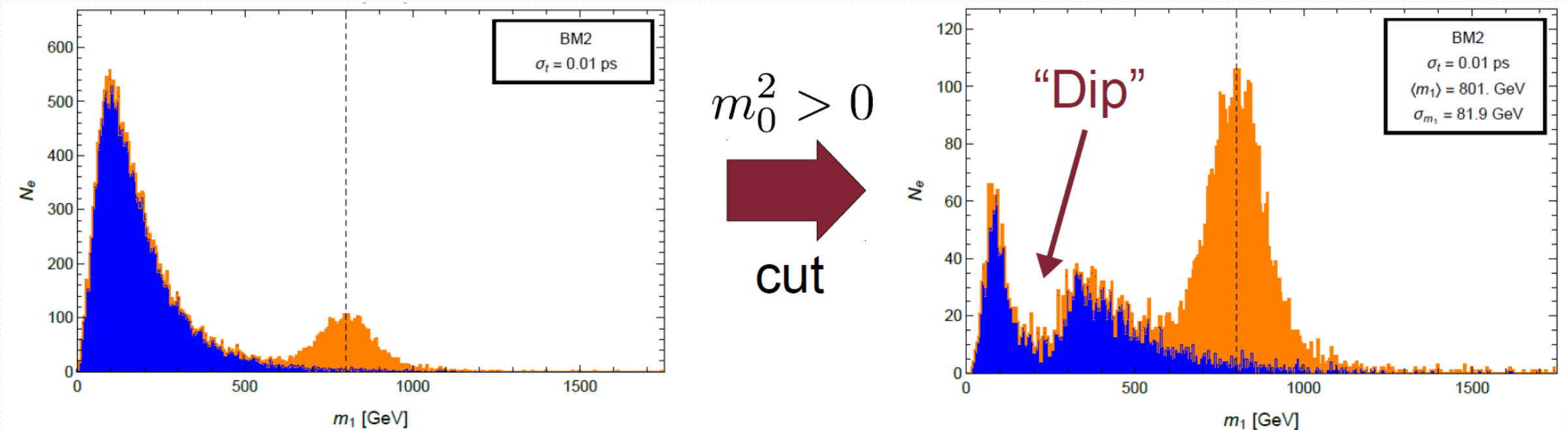
Reconstructed Mass Distributions



- 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 .

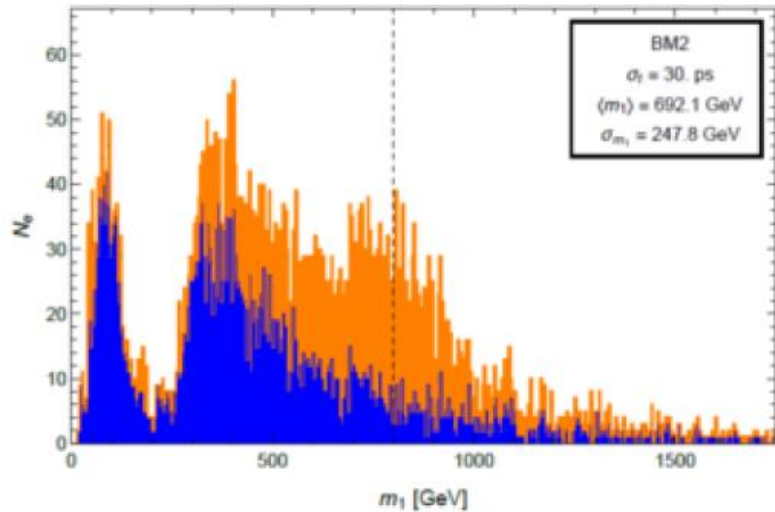
One Additional Cut

- 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.

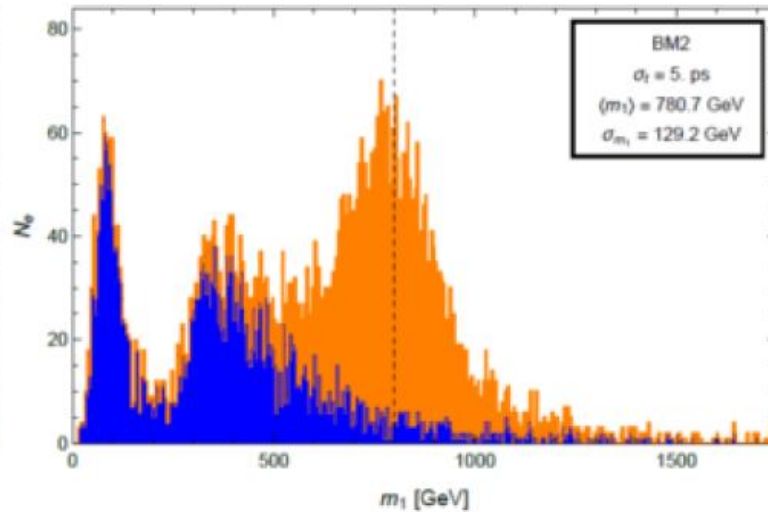


The Impact of Timing Resolution

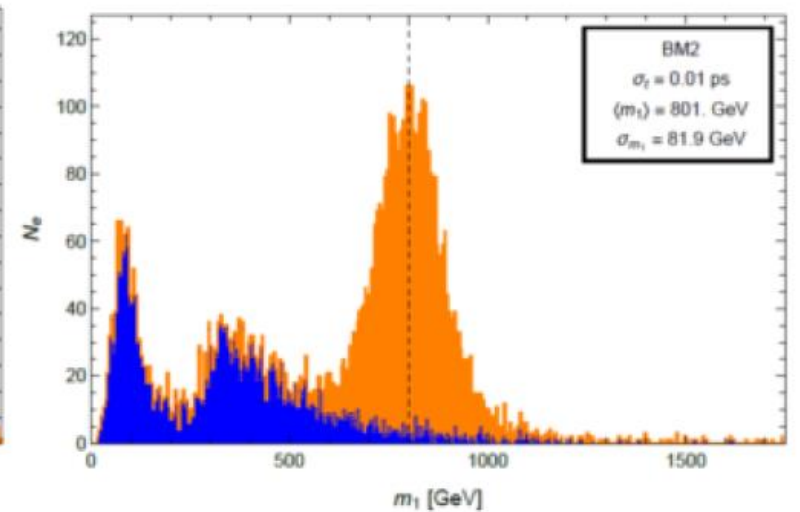
Decreasing σ_t →



$\sigma_t = 30 \text{ ps}$
(CMS Timing Layer)



$\sigma_t = 5 \text{ ps}$
(Modest Improvement)



$\sigma_t = 0.01 \text{ ps}$
(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 $pp \rightarrow \phi\phi^\dagger$ production dominates, most tumbler decay chains begin with the (prompt) decay of ϕ .

$$\begin{aligned} P(\text{tumbler}) &= \text{BR}(\phi \rightarrow \chi_2)\text{BR}(\chi_2 \rightarrow \chi_1)\text{BR}(\chi_1 \rightarrow \chi_0) \\ &= \text{BR}(\phi \rightarrow \chi_2)\text{BR}(\chi_2 \rightarrow \chi_1) \underbrace{\hspace{10em}}_{=1} \end{aligned}$$

- We are generally interested 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^{miss} [Syrunyan et al., 1908.04722, 1909.03560; Aad et al., 2010.14293]
⇒ Constraints satisfied when $m_\phi \gtrsim 1250$ GeV and $m_n \gtrsim 500$ GeV.
- ❑ Mono-jet + E_T^{miss} [Aad et al., 2012.10874]
⇒ 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]
⇒ Bound is $\sigma_{\chi\chi} \text{BR}_j^2 \lesssim 0.05 - 0.5$ fb for 10^{-4} m < $c\tau_\chi$ < 10 m.

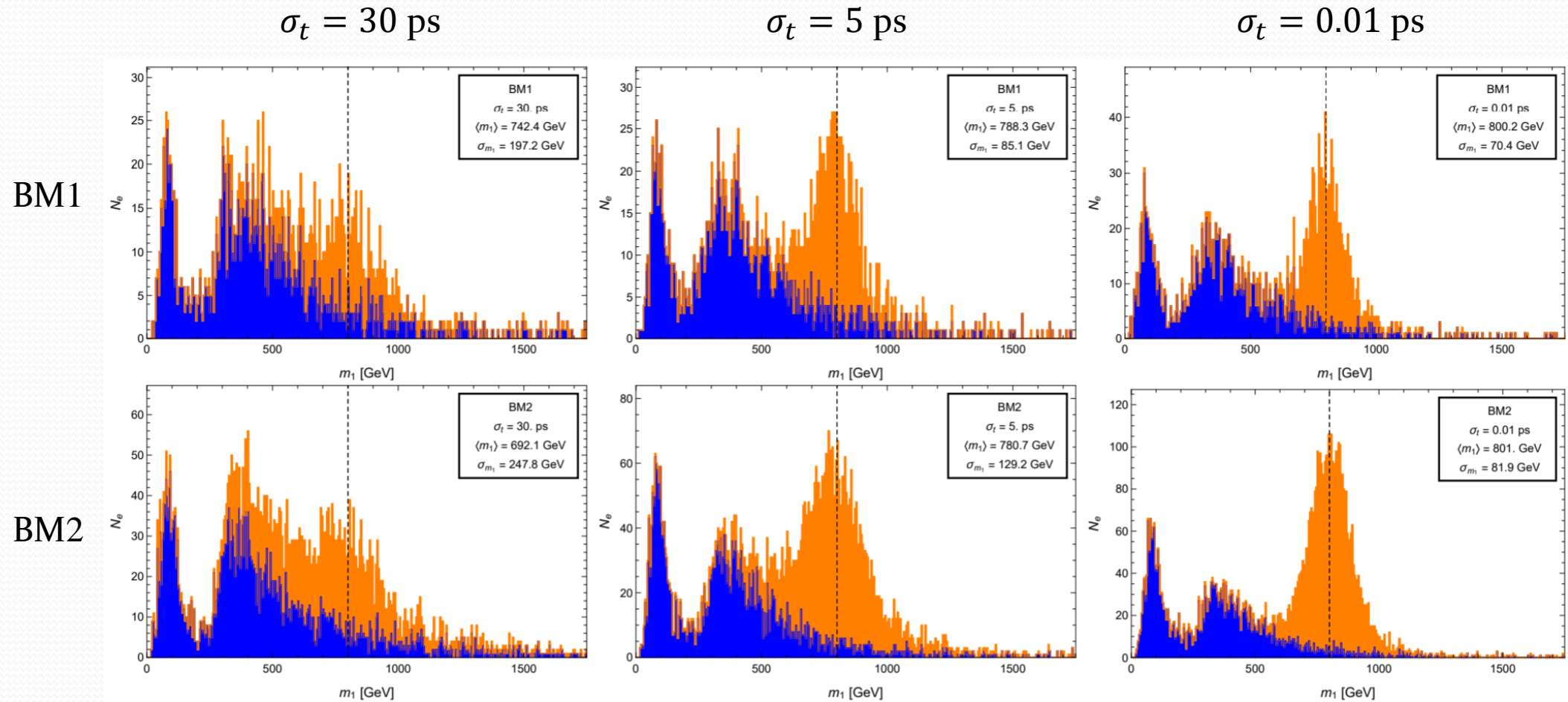
Effective Cross-Sections

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.

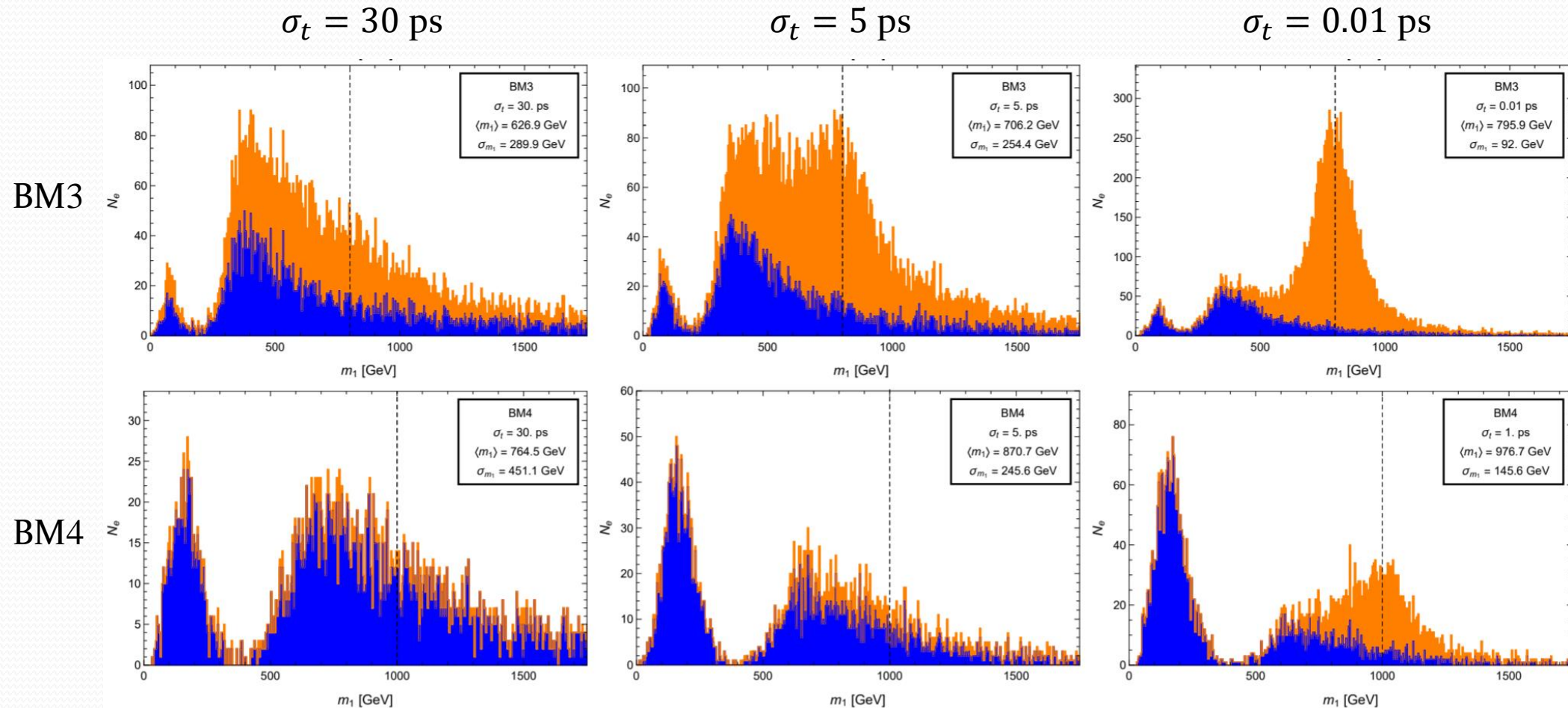
- **Tumbler class, $\sigma_{\text{eff}}^{(T)}$** : Processes involving at least one tumbler
- **DV class, $\sigma_{\text{eff}}^{(DV)}$** : Processes which yield at least one DV, whether or not it is part of a tumbler
- **Multi-jet class, $\sigma_{\text{eff}}^{(Nj)}$** : Processes which yield two or more 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 $pp \rightarrow \phi\phi$ Production				
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	2T		2j
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\phi \rightarrow \chi_2 \rightarrow \chi_0$	T	DV	2j
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\phi \rightarrow \chi_1 \rightarrow \chi_0$	T	DV	2j
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\phi \rightarrow \chi_0$	T		2j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	$\phi \rightarrow \chi_2 \rightarrow \chi_0$		2DV	2j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	$\phi \rightarrow \chi_1 \rightarrow \chi_0$		2DV	2j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	$\phi \rightarrow \chi_0$		DV	2j
$\phi \rightarrow \chi_1 \rightarrow \chi_0$	$\phi \rightarrow \chi_2 \rightarrow \chi_0$		2DV	2j
$\phi \rightarrow \chi_1 \rightarrow \chi_0$	$\phi \rightarrow \chi_1 \rightarrow \chi_0$		DV	2j
$\phi \rightarrow \chi_0$	$\phi \rightarrow \chi_0$			2j
From $pp \rightarrow \phi\chi_n$ Production				
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	2T		j
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_0$	T	DV	j
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$	T	DV	j
$\phi \rightarrow \chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	χ_0	T		j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$		DV	j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_0$		2DV	j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$		2DV	j
$\phi \rightarrow \chi_2 \rightarrow \chi_0$	χ_0		DV	j
$\phi \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	T	DV	j
$\phi \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_0$		2DV	j
$\phi \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$		2DV	j
$\phi \rightarrow \chi_1 \rightarrow \chi_0$	χ_0		DV	j
$\phi \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	T		j
$\phi \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_0$		DV	j
$\phi \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$		DV	j
$\phi \rightarrow \chi_0$	χ_0			j
From $pp \rightarrow \chi_m\chi_n$ Production				
$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	2T		
$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_0$	T	DV	
$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$	T	DV	
$\chi_2 \rightarrow \chi_1 \rightarrow \chi_0$	χ_0	T		
$\chi_2 \rightarrow \chi_0$	$\chi_2 \rightarrow \chi_0$		2DV	
$\chi_2 \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$		2DV	
$\chi_2 \rightarrow \chi_0$	χ_0		DV	
$\chi_1 \rightarrow \chi_0$	$\chi_1 \rightarrow \chi_0$		2DV	
$\chi_1 \rightarrow \chi_0$	χ_0		DV	
χ_0	χ_0			

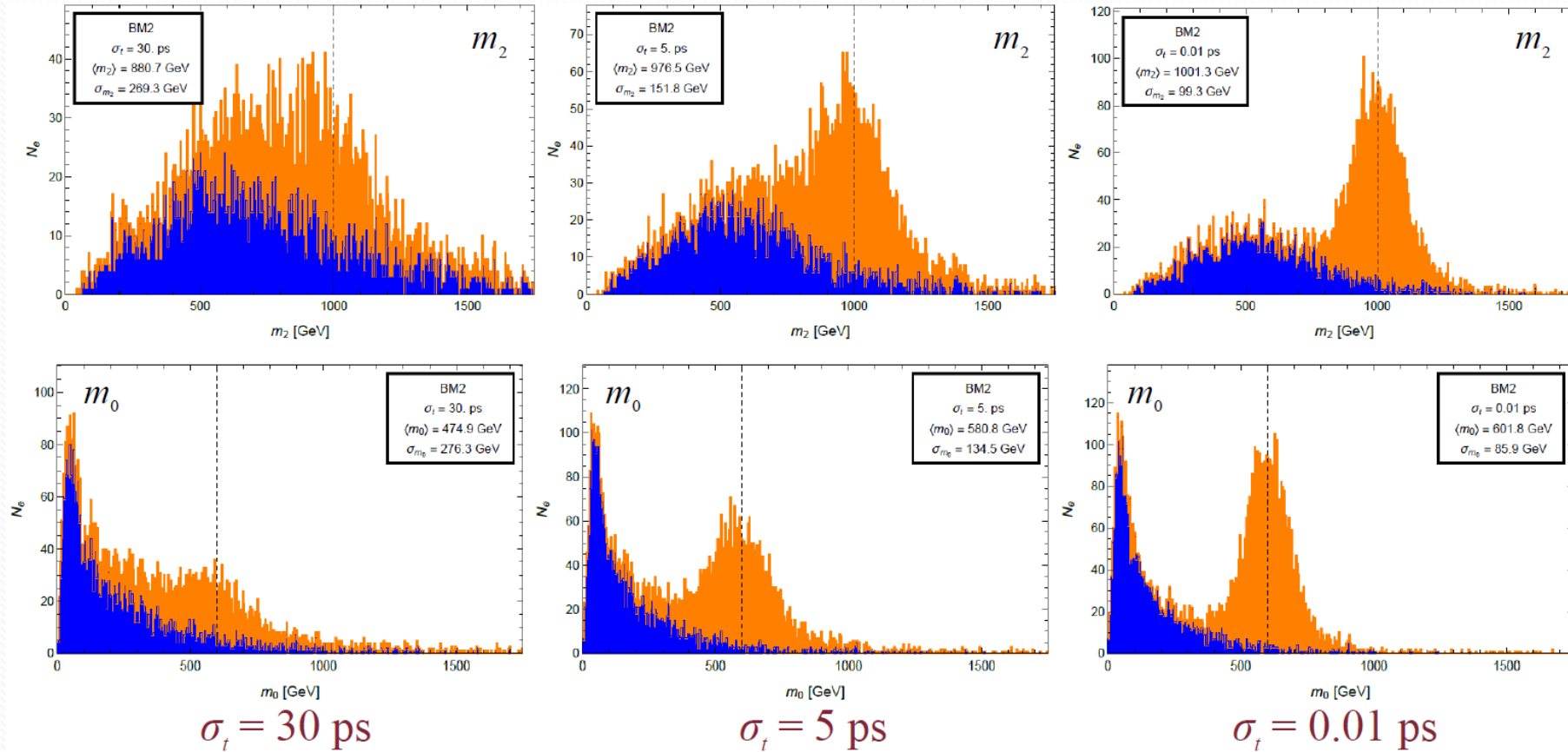
Other Benchmark Points



Other Benchmark Points



Other Masses



No “dips”
developed!

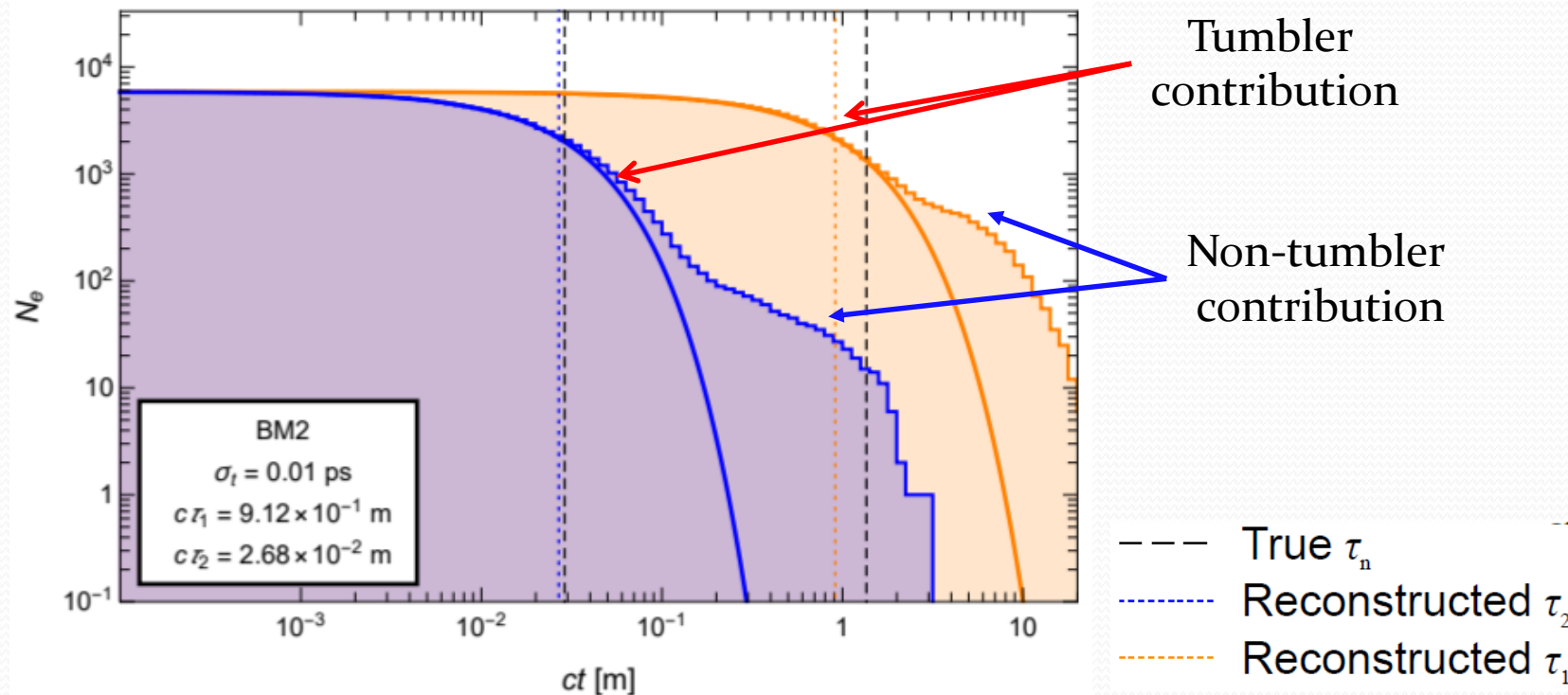
Once again, even a moderate improvement in σ_t would have a huge impact!

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

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