Long-lived Colored Scalars at the LHC

Alejandro de la Puente

TRIUMF, Theory Group

Portoroz 2015: Particle Phenomenology from the Early Universe to High Energy Colliders

Portoroz, Slovenia

April 7, 2015

- Motivation.

- Simplified Models.

- Prompt Searches.

- Long-lived Searches.

- Constraints and Reach.

- Summary.

- Collider signatures from long-lived massive particles are relatively free from SM backgrounds.
- Conventional searches are limited to impact parameters below ~ 1mm.

- Collider signatures from long-lived massive particles are relatively free from SM backgrounds.
- Conventional searches are limited to impact parameters below ~ 1mm.
  - Heavy flavor (500 μm).
  - tau decays (87 μm).

- Collider signatures from long-lived massive particles are relatively free from SM backgrounds.
- Conventional searches are limited to impact parameters below ~ 1mm.
  - Heavy flavor (500 μm).
  - tau decays (87 μm).

- Most searches incorporate track quality cuts with requirements on the impact parameter.
- Use impact-parameter-based tagging (b's).

- Signatures from decays of long-lived particles require dedicated triggers and non-conventional particle reconstructions methods.
- Most searches are signature driven:
  - R-parity violation..
  - SUSY breaking (AMSB, GMSB)
  - Hidden valleys, Mini-split, etc...

- Signatures from decays of long-lived particles require dedicated triggers and non-conventional particle reconstructions methods.

- Most searches are signature driven:
  - R-parity violation..
  - SUSY breaking (AMSB, GMSB)
  - Hidden valleys, Mini-split, etc...

- Recast long-lived searches to more general frameworks (Complementary with prompt searches and compressed spectra).

- Long-lived colored electroweak-singlet scalar coupled to the right-handed top quark and a dark fermion.

$$\mathcal{L} = \lambda \phi^* \bar{X} P_R t + \text{ H.c}$$

- Long-lived colored electroweak-singlet scalar coupled to the right-handed top quark and a dark fermion.

$$\mathcal{L} = \lambda \phi^* \bar{X} P_R t + \text{ H.c}$$

$$\phi : (3, 1, 2/3)$$

- Long-lived colored electroweak-singlet scalar coupled to the right-handed top quark and a dark fermion.

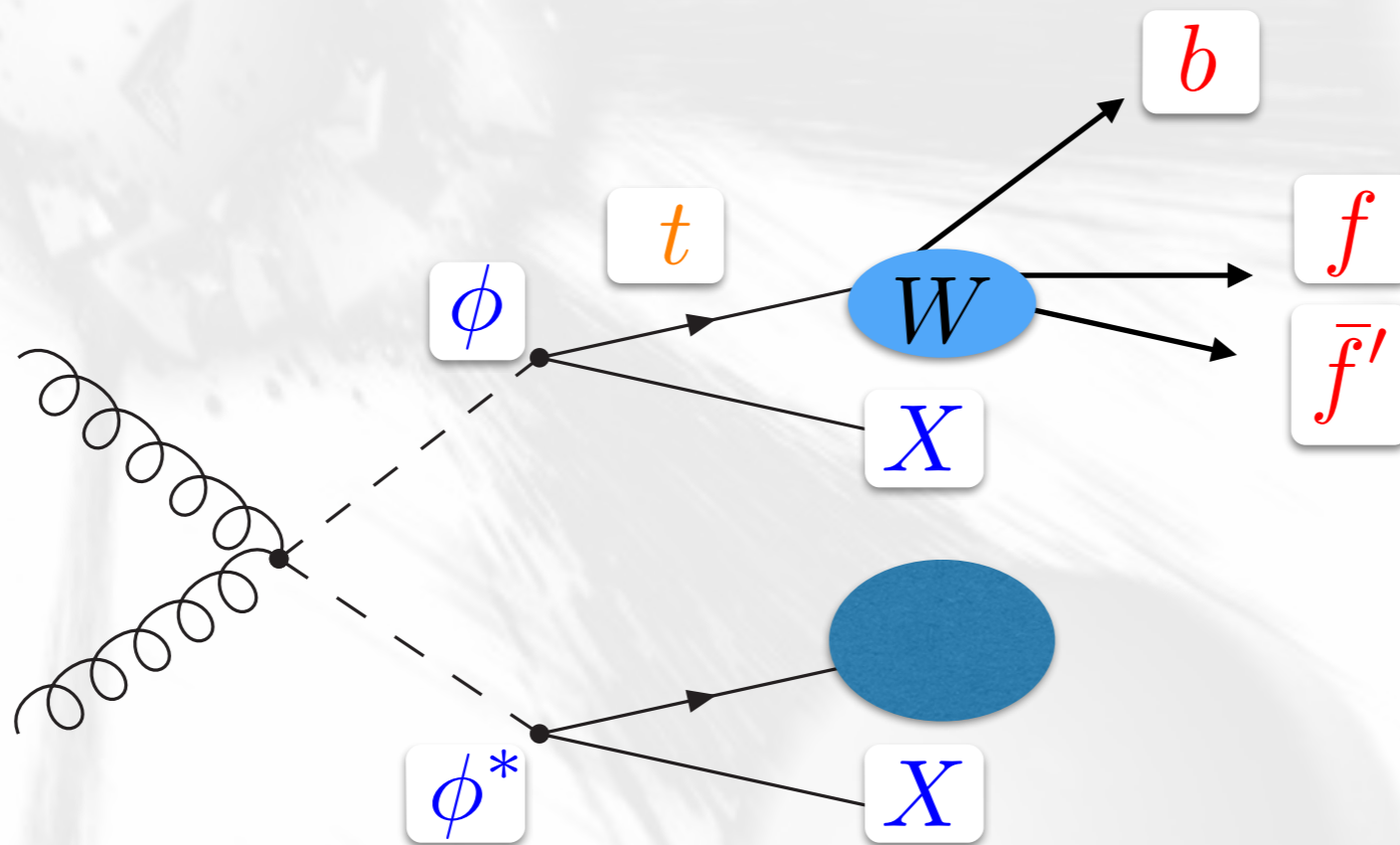$$\mathcal{L} = \lambda \phi^* \bar{X} P_R t + \text{ H.c}$$

$$\phi : (3, 1, 2/3)$$

$$X : (1, 1, 0)$$

- Lifetime depends on coupling and/or spectrum.

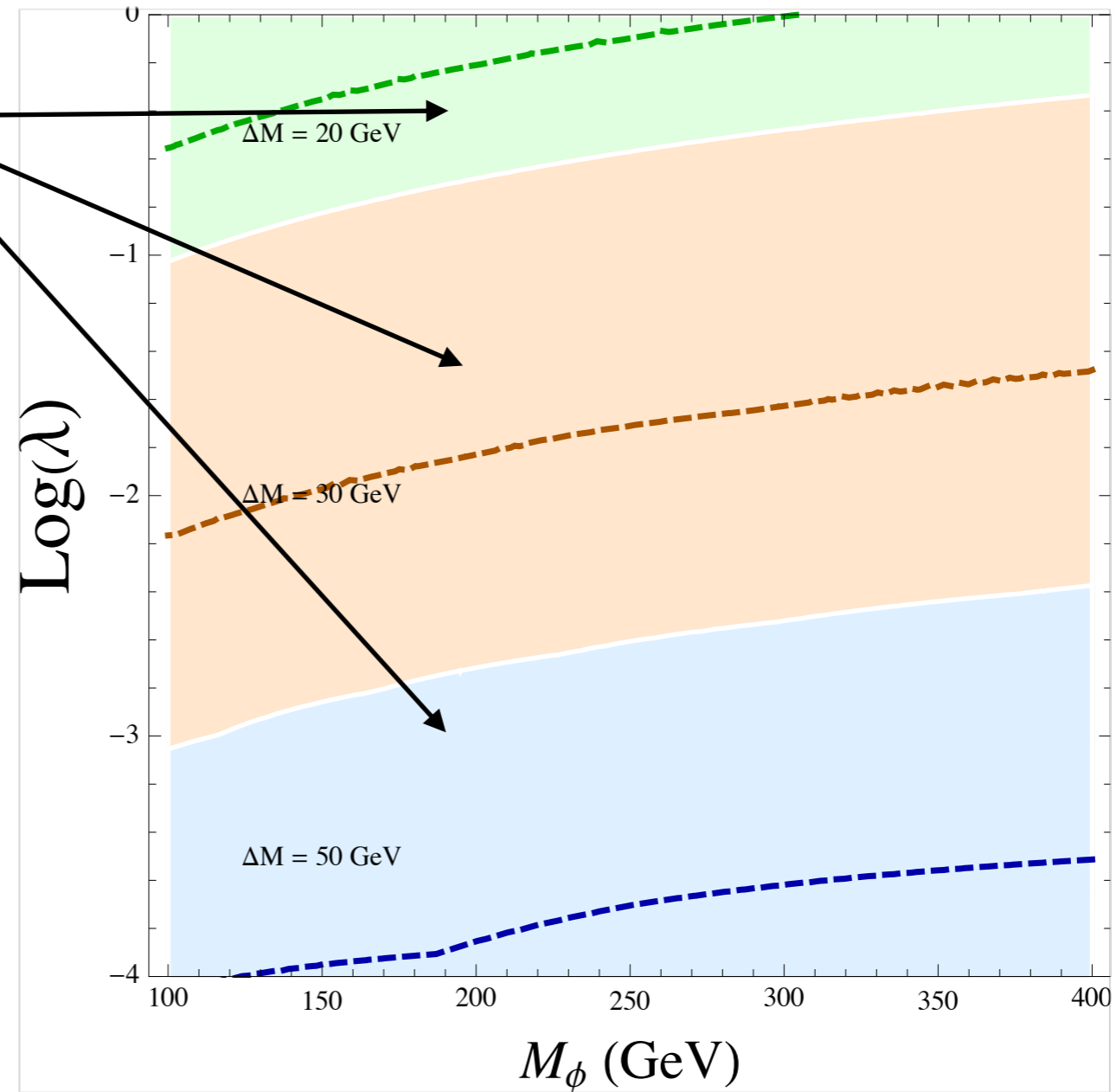# Simplified Model

- ## Lifetime depends on coupling and/or spectrum.

Regions correspond to lifetimes in the range 0.1 - 10 mm/c.

Dashed lines denote a decay length of 0.1 mm.

- For lifetimes between 0.1 and 100 mm, colored scalar has enough time to hadronize. Additional jets in the decay can be expected.

- Focus on parton-level analysis to probe this range of decay lengths at CMS and ATLAS.

- For lifetimes between 0.1 and 100 mm, colored scalar has enough time to hadronize. Additional jets in the decay can be expected.

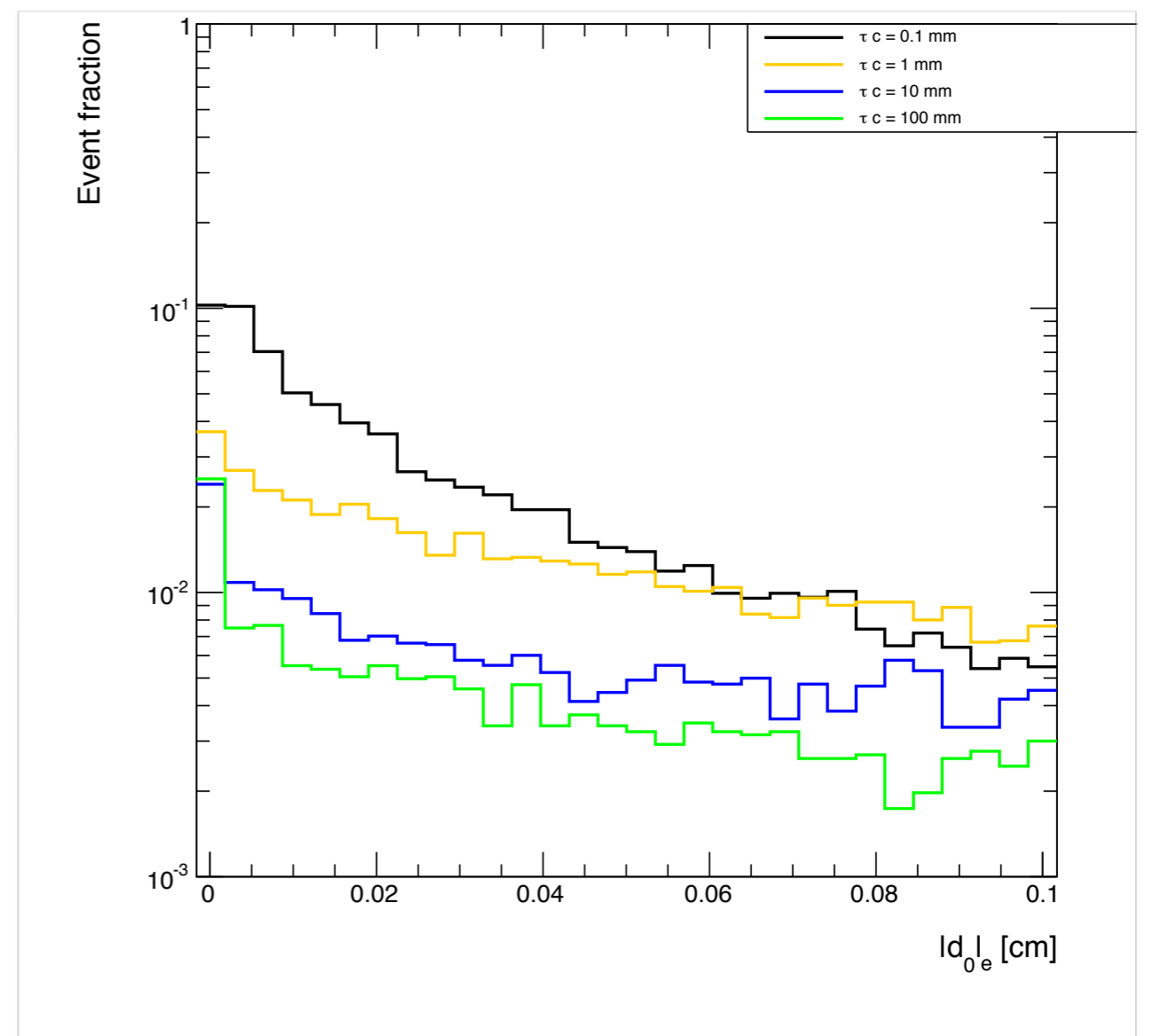- Expect prompt SUSY searches to have suppressed sensitivity…

- Conventional searches are limited to impact parameters below ~ 1mm.

  - CMS lepton performance for reconstruction efficiency.
  - Isolation, $I_e < 10\%$ within cone of 0.3.

- Conventional searches are limited to impact parameters below ~ 1mm.

- CMS lepton performance for reconstruction efficiency.
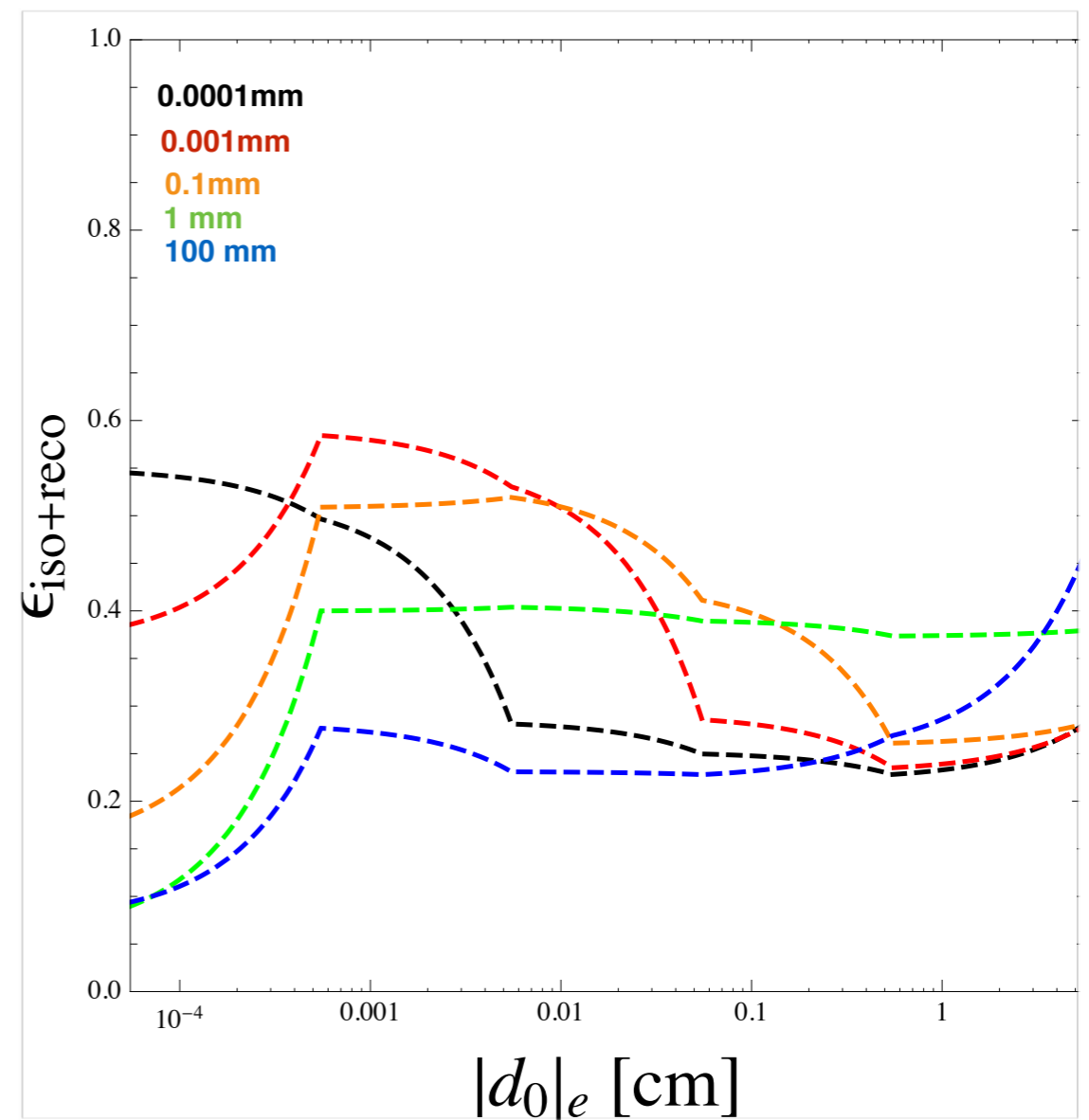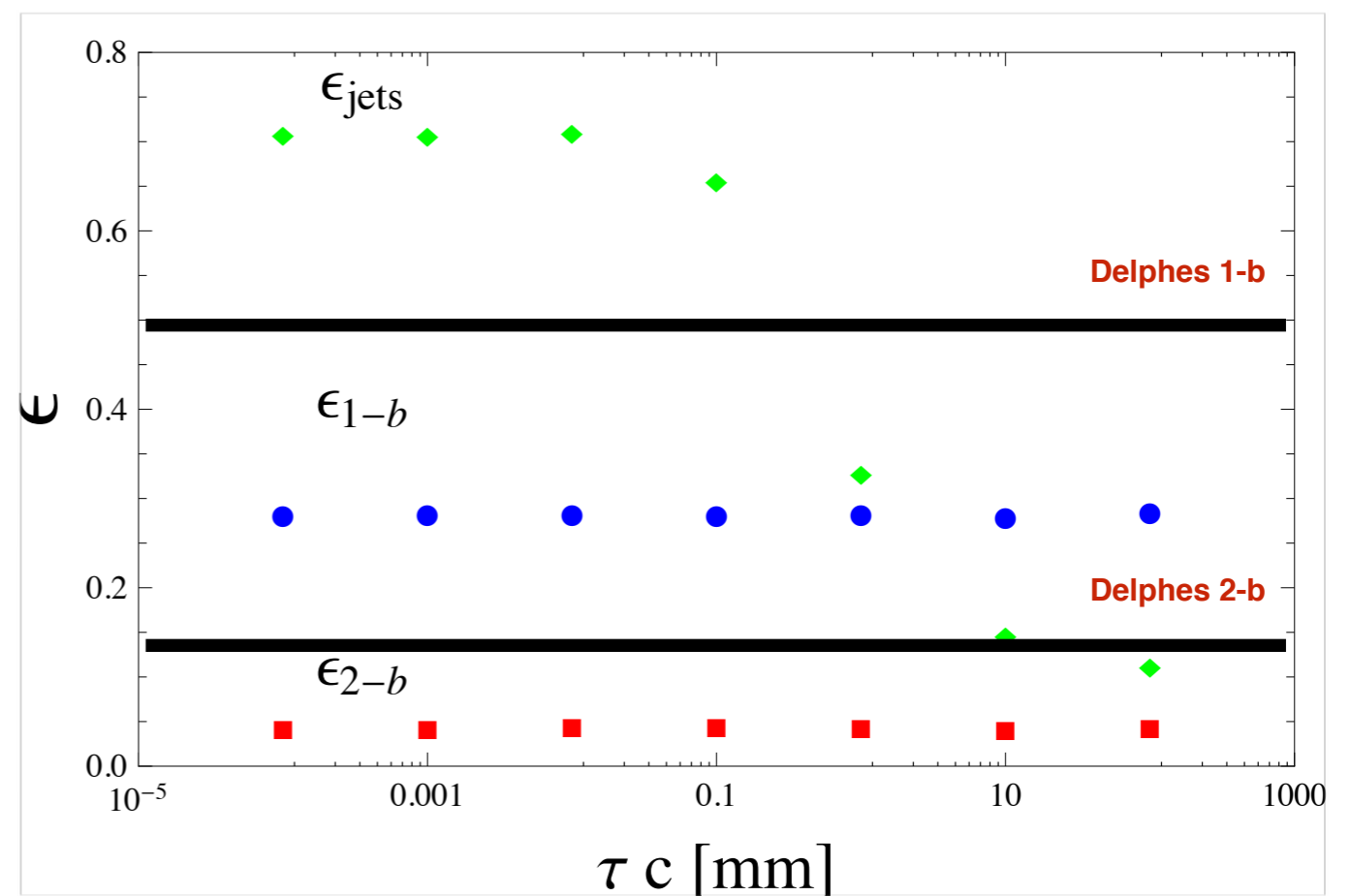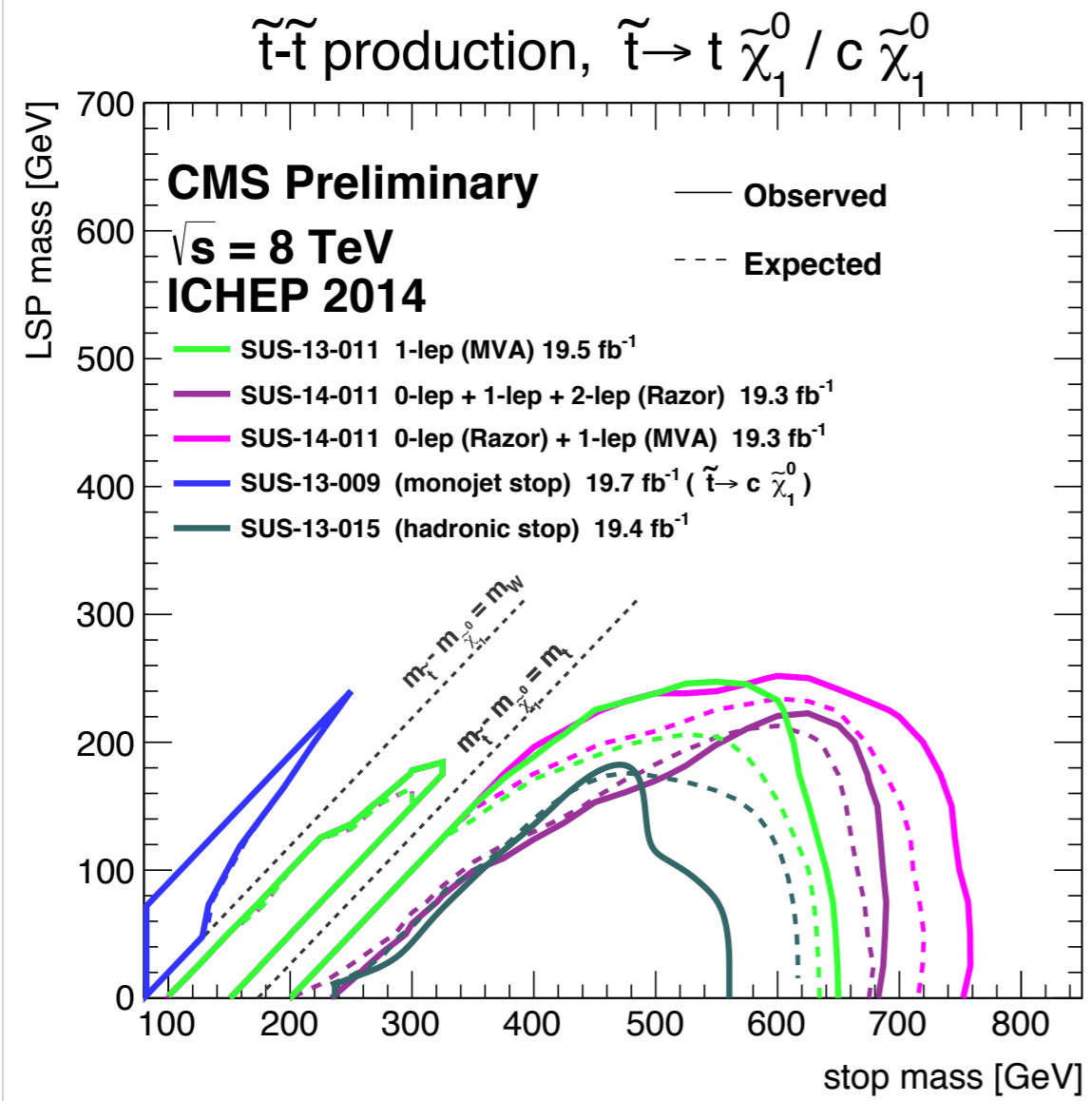- Isolation, I_l<10% within cone of 0.3.

- Most searches incorporate track quality cuts with requirements on the impact parameter.
- Use impact-parameter-based tagging.

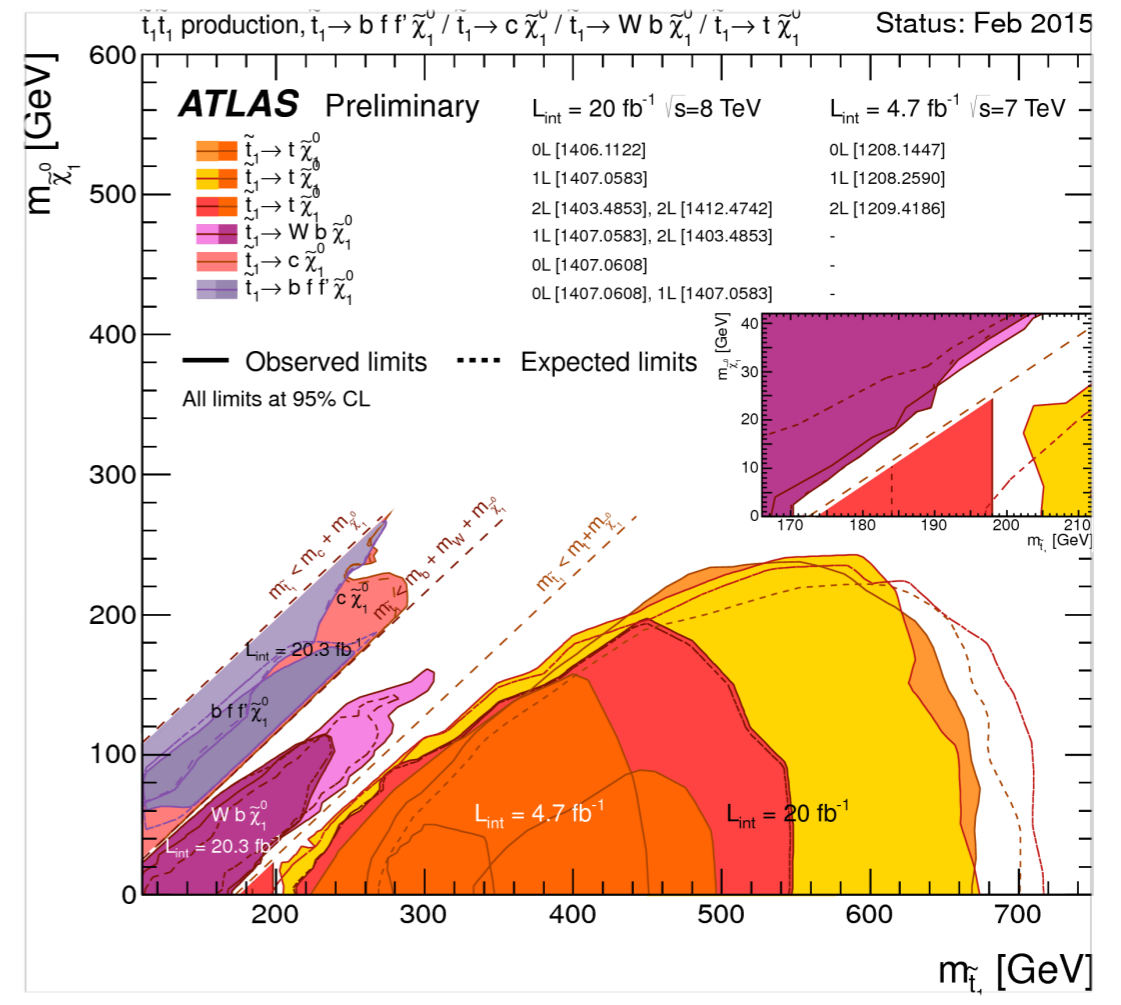- Jet must have at least one well-reconstructed charged track.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

- Use validated analyses from Checkmate for third-generation scalar quark pair production.
  1. 1l + ≥ 4j + MET (ATLAS-CONF-2012-104)
  2. 0l + 6(2b-jets) + MET (CONF-2013-024)
  3. 2-6 jets + MET (CONF-2013-047)
  4. 2l + jets + MET(razor) (CONF-2013-089)
  5. 2jets + b-jet mult. + MET(α_T) (CMS-1303-2085)
  6. monojet + MET (CONF-2012-147)

CheckMate-arXiv:1312.2591

CERN-PH-EP/2013-037
2013/10/30

CMS

CMS-SUS-12-028

Search for supersymmetry in hadronic final states with missing transverse energy using the variables α_T and b-quark multiplicity in pp collisions at $\sqrt{s} = 8\,\text{TeV}$
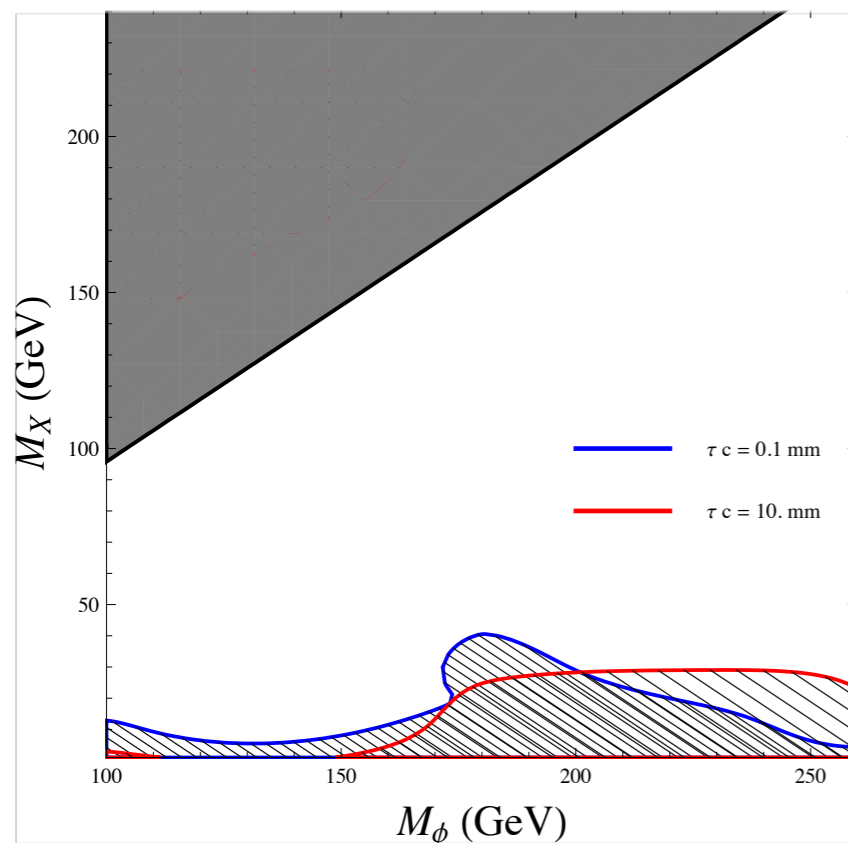
The CMS Collaboration*

Table 4: Event yields observed in data and fit results with their associated uncertainties in bins of H_T for events in the signal region that are categorised according to n_jet and n_b. The final $H_T > 375\,\text{GeV}$ bin is inclusive for the $n_\text{jet} \geq 4$ and $n_\text{b} \geq 4$ category.

	n_jet	n_b	275–325	325–375	375–475	475–575	575–675	675–775	775–875	875–∞
SM	2–3	0	6235^{+100}_{-67}	2900^{+60}_{-54}	1955^{+34}_{-39}	558^{+14}_{-15}	186^{+11}_{-10}	$51.3^{+3.4}_{-3.8}$	$21.2^{+2.3}_{-2.2}$	$16.1^{+1.7}_{-1.7}$
Data	2–3	0	6232	2904	1965	552	177	58	16	25
SM	2–3	1	1162^{+37}_{-29}	481^{+18}_{-19}	341^{+15}_{-16}	$86.7^{+4.2}_{-5.6}$	$24.8^{+2.8}_{-2.7}$	$7.2^{+1.1}_{-1.0}$	$3.3^{+0.7}_{-0.7}$	$2.1^{+0.5}_{-0.5}$
Data	2–3	1	1164	473	329	95	23	8	4	1
SM	2–3	2	224^{+15}_{-14}	$98.2^{+8.4}_{-6.4}$	$59.0^{+5.2}_{-6.0}$	$12.8^{+1.6}_{-1.6}$	$3.0^{+0.9}_{-0.7}$	$0.5^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$
Data	2–3	2	222	107	58	12	5	1	0	0
SM	≥4	0	1010^{+34}_{-24}	447^{+19}_{-16}	390^{+19}_{-15}	250^{+12}_{-11}	111^{+9}_{-7}	$53.3^{+4.3}_{-4.3}$	$18.5^{+2.4}_{-2.4}$	$19.4^{+2.5}_{-2.7}$
Data	≥4	0	1009	452	375	274	113	56	16	27
SM	≥4	1	521^{+25}_{-17}	232^{+15}_{-12}	188^{+12}_{-11}	106^{+6}_{-6}	$42.1^{+4.1}_{-4.4}$	$17.9^{+2.2}_{-2.0}$	$9.8^{+1.5}_{-1.4}$	$6.8^{+1.2}_{-1.1}$
Data	≥4	1	515	236	204	92	51	13	13	6
SM	≥4	2	208^{+17}_{-9}	103^{+9}_{-7}	$85.9^{+7.2}_{-6.9}$	$51.7^{+4.6}_{-4.7}$	$19.9^{+3.4}_{-3.0}$	$6.8^{+1.2}_{-1.3}$	$1.7^{+0.7}_{-0.4}$	$1.3^{+0.4}_{-0.3}$
Data	≥4	2	204	107	84	59	24	5	1	2
SM	≥4	3	$25.3^{+5.0}_{-4.2}$	$11.7^{+1.7}_{-1.8}$	$6.7^{+1.4}_{-1.2}$	$3.9^{+0.8}_{-0.8}$	$2.3^{+0.6}_{-0.6}$	$1.2^{+0.3}_{-0.4}$	$0.3^{+0.2}_{-0.1}$	$0.1^{+0.1}_{-0.1}$
Data	≥4	3	25	13	4	2	2	3	0	0
SM	≥4	≥4	$0.9^{+0.4}_{-0.7}$	$0.3^{+0.2}_{-0.2}$	$0.6^{+0.3}_{-0.3}$	–	–	–	–	–
Data	≥4	≥4	1	0	2	–	–	–	–	–

- Use validated analyses from Checkmate for third-generation scalar quark pair production.
  1. $1l + \geq 4j + MET$ (ATLAS-CONF-2012-104)
  2. $0l + 6(2b\text{-jets}) + MET$ (CONF-2013-024)
  3. 2-6 jets + MET (CONF-2013-047)
  4. $2l + jets + MET$(razor) (CONF-2013-089)
  5. 2jets + b-jet mult. + MET(α_T) (CMS-1303-2085)
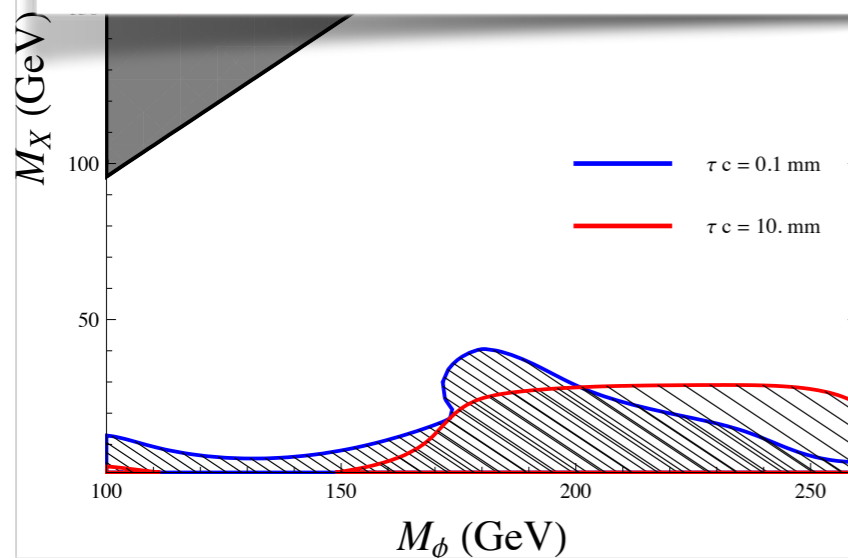 6. monojet + MET (CONF-2012-147)

CMS   CERN-PH-EP/2013-037
2013/10/30

CMS-SUS-12-028

Search for supersymmetry in hadronic final states with missing transverse energy using the variables α_T and b-quark multiplicity in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

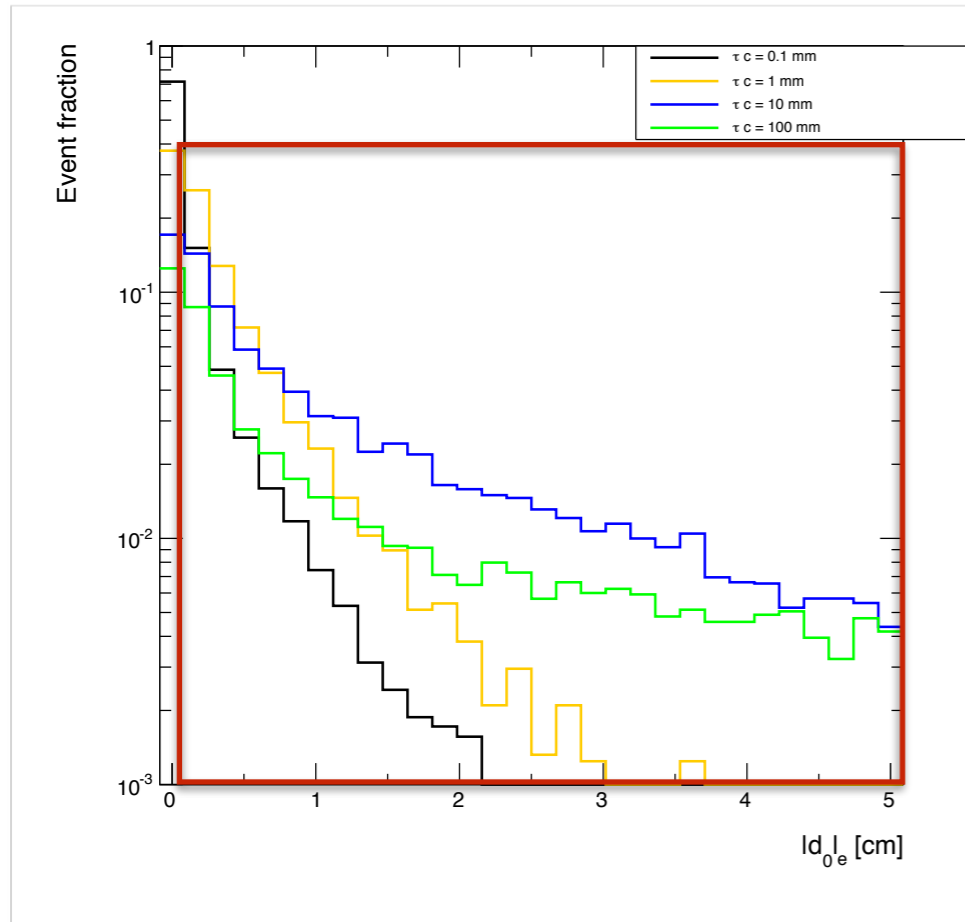- Promising for light stop window of the MSSM (Delgado,Giudice, Isidori,Pierini, Strumi; Kriska, Kumar, Morrissey).

...s in bins
...The final

| | | | | | $5-\infty$ | | |
					$1.1^{+1.7}_{-1.7}$		
SM	2–3	1	1162^{+37}_{-29}	481^{+18}_{-19}	341^{+15}_{-16}	$86.7^{+4.2}_{-5.6}$	$24.8^{+2.8}_{-2.7}$	$7.2^{+1.1}_{-1.0}$	$3.3^{+0.7}_{-0.7}$	$2.1^{+0.5}_{-0.5}$
Data	2–3	1	1164	473	329	95	23	8	4	1
SM	2–3	2	224^{+15}_{-14}	$98.2^{+8.4}_{-6.4}$	$59.0^{+5.2}_{-6.0}$	$12.8^{+1.6}_{-1.6}$	$3.0^{+0.9}_{-0.7}$	$0.5^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$
Data	2–3	2	222	107	58	12	5	1	0	0
SM	≥ 4	0	1010^{+34}_{-24}	447^{+19}_{-16}	390^{+19}_{-15}	250^{+12}_{-11}	111^{+9}_{-7}	$53.3^{+4.3}_{-4.3}$	$18.5^{+2.4}_{-2.4}$	$19.4^{+2.5}_{-2.7}$
Data	≥ 4	0	1009	452	375	274	113	56	16	27
SM	≥ 4	1	521^{+25}_{-17}	232^{+15}_{-12}	188^{+12}_{-11}	106^{+6}_{-6}	$42.1^{+4.1}_{-4.4}$	$17.9^{+2.2}_{-2.0}$	$9.8^{+1.5}_{-1.4}$	$6.8^{+1.2}_{-1.1}$
Data	≥ 4	1	515	236	204	92	51	13	13	6
SM	≥ 4	2	208^{+17}_{-9}	103^{+9}_{-7}	$85.9^{+7.2}_{-6.9}$	$51.7^{+4.6}_{-4.7}$	$19.9^{+3.4}_{-3.0}$	$6.8^{+1.2}_{-1.3}$	$1.7^{+0.7}_{-0.4}$	$1.3^{+0.4}_{-0.3}$
Data	≥ 4	2	204	107	84	59	24	5	1	2
SM	≥ 4	3	$25.3^{+5.0}_{-4.2}$	$11.7^{+1.7}_{-1.8}$	$6.7^{+1.4}_{-1.2}$	$3.9^{+0.8}_{-0.8}$	$2.3^{+0.6}_{-0.6}$	$1.2^{+0.3}_{-0.4}$	$0.3^{+0.2}_{-0.1}$	$0.1^{+0.1}_{-0.1}$
Data	≥ 4	3	25	13	4	2	2	3	0	0
SM	≥ 4	≥ 4	$0.9^{+0.4}_{-0.7}$	$0.3^{+0.2}_{-0.2}$	$0.6^{+0.3}_{-0.3}$	–	–	–	–	–
Data	≥ 4	≥ 4	1	0	2	–	–	–	–	–

Long-lived searches

Many recent results

**LL particle may be
neutral or charged (or both)**
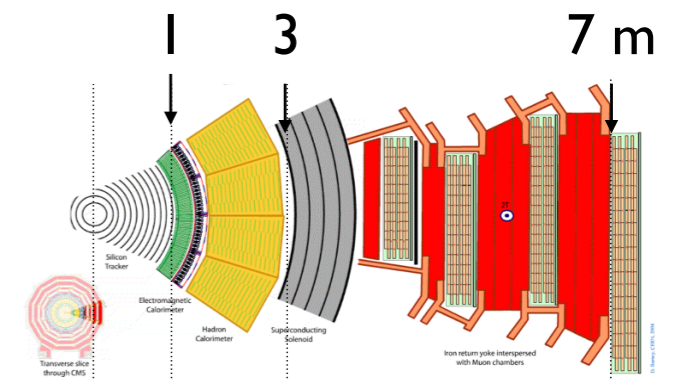
Region of BSM particle decay

displaced jets	Phys. Rev. D 91, 012007 (2015) / Phys. Lett. B 743, 15 (2015) / ATLAS Preliminary
lepton jets	JHEP 11, 088 (2014)
displaced leptons	arXiv:1411.6977 & EXO-14-012 PAS / Phys. Rev. Lett. 114, 061801 (2015)
displaced vertices	ATLAS Preliminary (paper in preparation)
displaced / delayed photons	Phys. Rev. D 90, 112005 (2014)
prompt RPV	arXiv:1502.05686 & arXiv:1503.04430 / ATLAS-CONF-2015-015
stopped particles	Phys. Rev. D 88, 112006 (2013) / arXiv:1501.05603
heavy stable charged particles	JHEP 07 (2013) 122 / JHEP 01, 068 (2015) / ATLAS-CONF-2015-013 & ATLAS Preliminary
disappearing tracks	Phys. Rev. D 88, 112003 (2013) / JHEP 01 (2015) 096
reinterpretations	ATLAS-CONF-2014-037 / arXiv:1502.02522

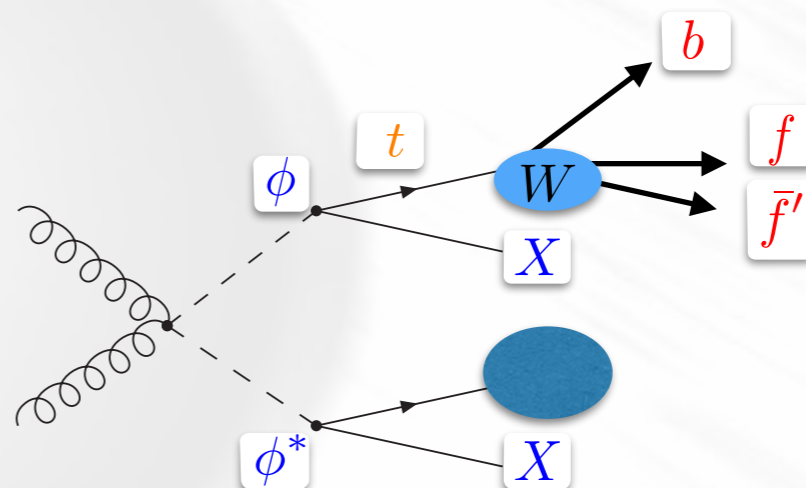**Wells Wulsin, Moriond 2015**

- Some backgrounds are difficult to simulate... most are data driven...

- Search for long-lived neutral particles decaying to quark-anitquark pairs (CMS-EXO-12-038)
    - H_T >325 GeV.
    - Jets with p_T >60 GeV.
    - At least two jets cannot have more than two tracks with $|d_0|$ <0.3 mm.
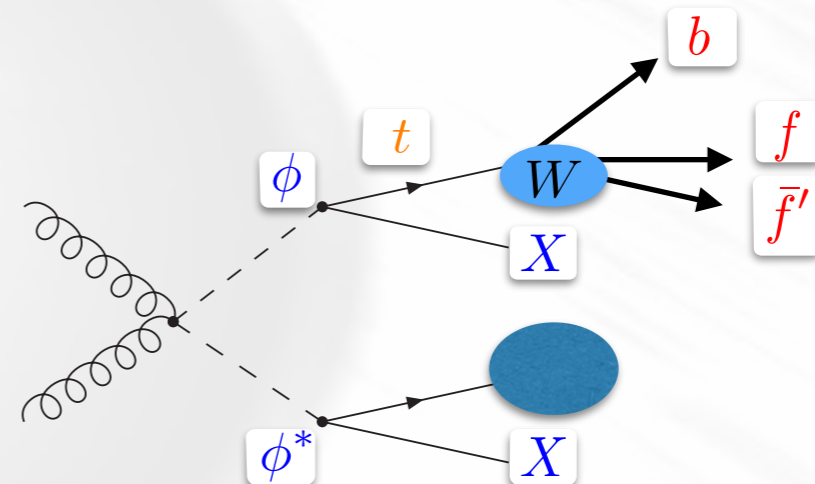   - No more than 15% of energy is carried away by tracks with impact parameter below 0.5 mm.
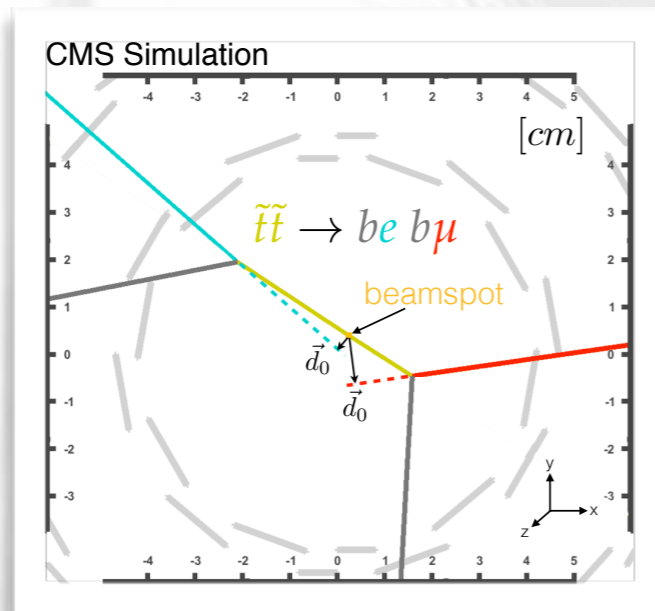
- Search for long-lived heavy particles in final states with a muon and a multitrack displaced vertex (ATLAS-CONF-2013-092)
  - Reconstructed muon with $p_T>55$ GeV from a displaced vertex (only muon chamber).
  - >4 tracks from displaced vertex.
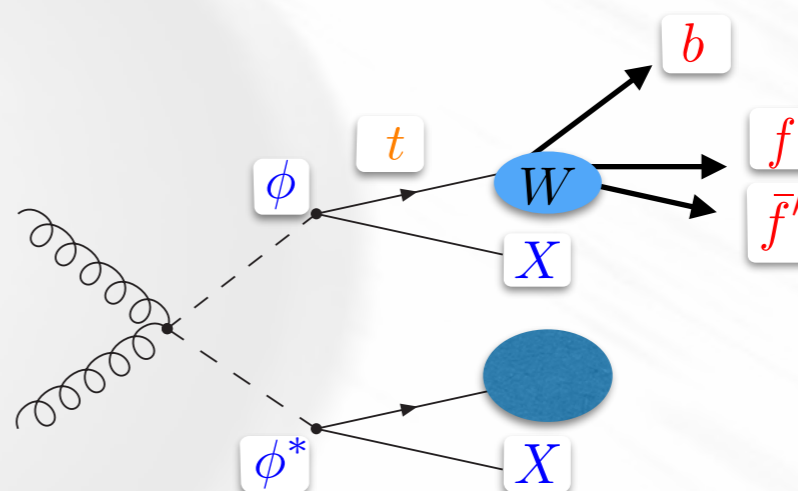
- Search for displaced SUSY in events with an electron and a muon with large impact parameters (B2G-12-024).

  - Opposite-sign lepton pair with large impact parameters.

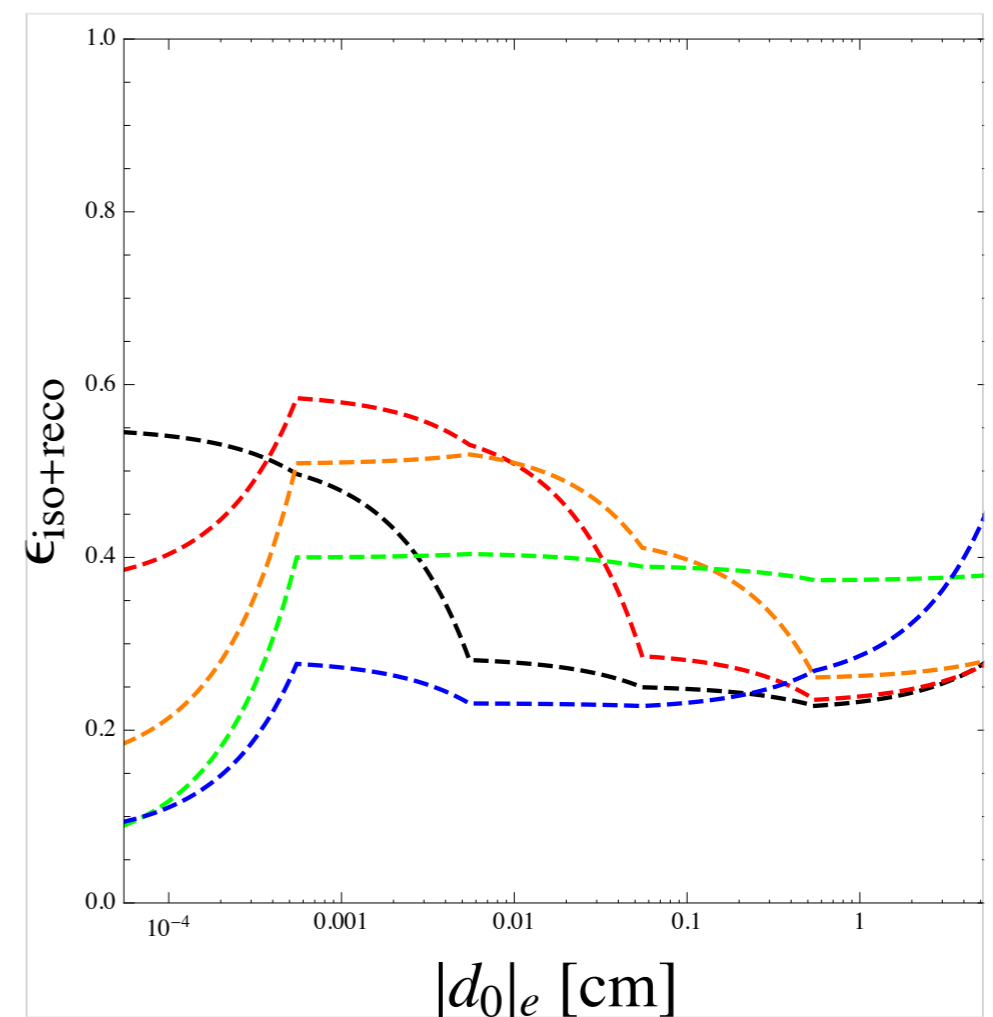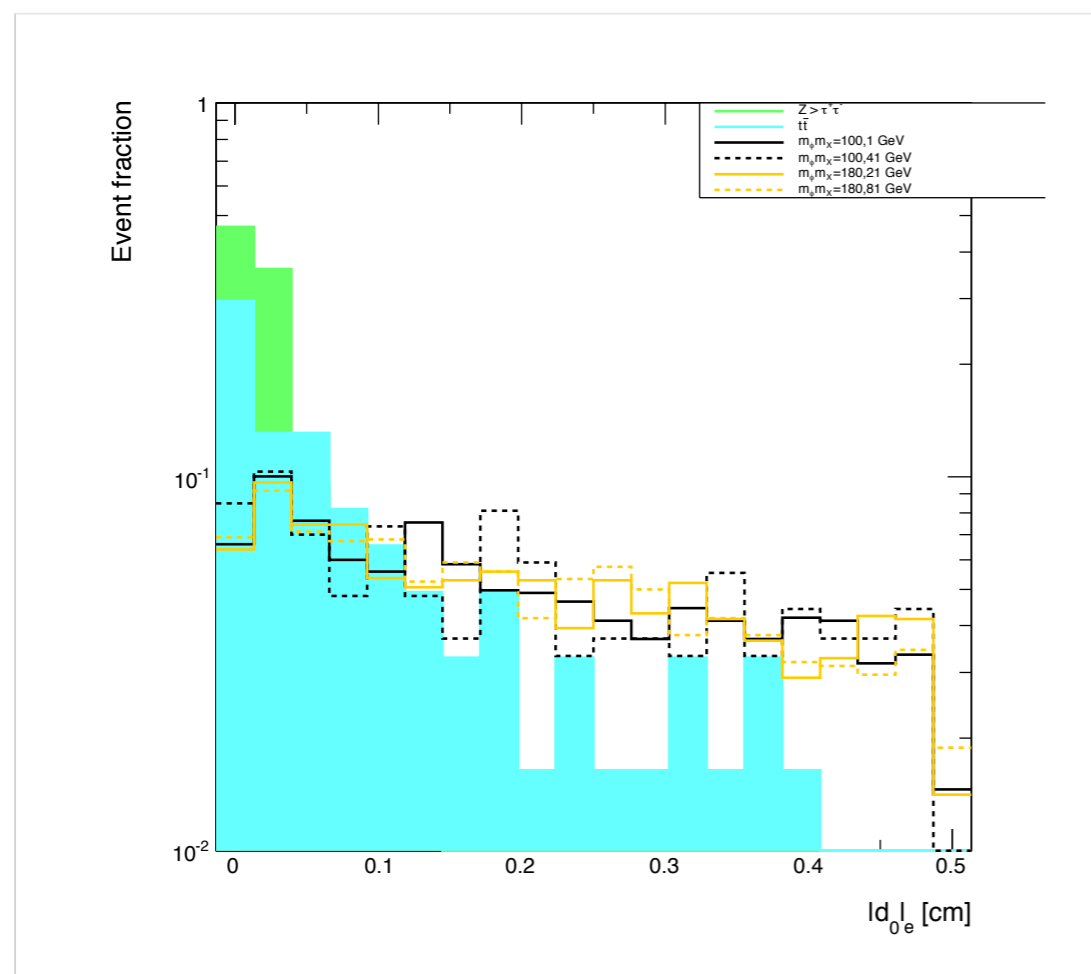 - No requirement on vertex formation, hadronic activity or MET.

CMS Simulation

$[cm]$

$\tilde{t}\tilde{t} \rightarrow b e\, b \mu$

beamspot

$\vec{d_0}$

$\vec{d_0}$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12024

Long-lived searches

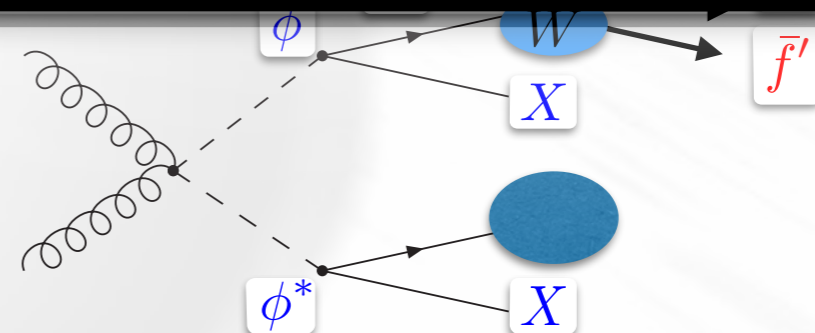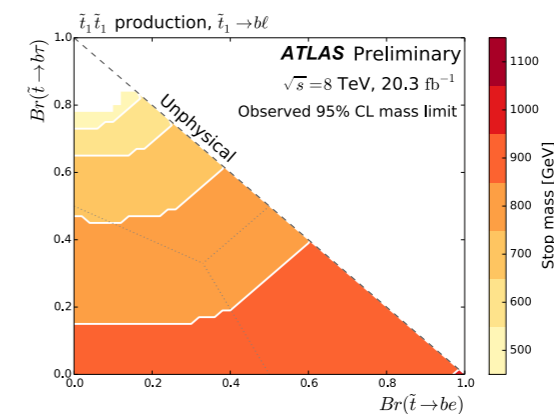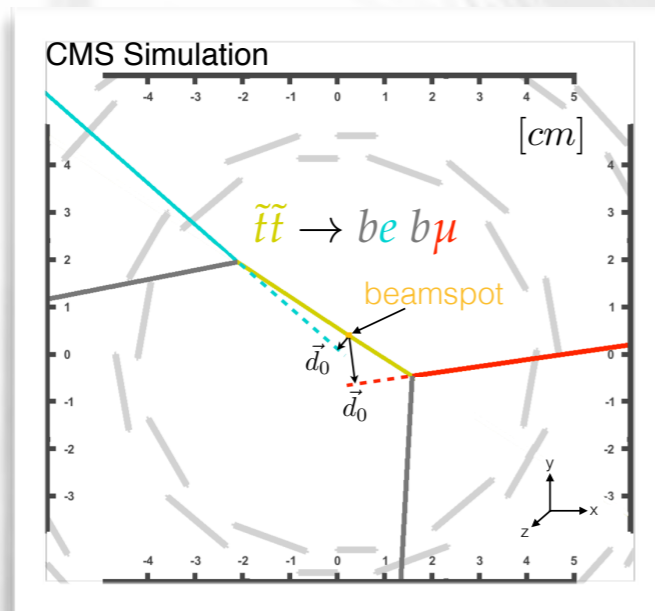| SM background	$0.02 < |d_0|_{e,\mu} < 0.05$ cm	$0.05 < |d_0|_{e,\mu} < 0.1$ cm	$0.1 < |d_0|_{e,\mu} < 2.$ cm
Total Expected Background	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observed Events	19	0	0
95% CL$_s$	13.68	2.93	2.42

- Search for displaced SUSY in events with an electron and a muon with large impact parameters (B2G-12-024).

  - Opposite-sign lepton pair with large impact param...

  - No requireme... hadronic activ...

CMS Simulation

$\tilde{t}\tilde{t} \rightarrow be\ b\mu$

beamspot

$\vec{d_0}$

$\vec{d_0}$

$[cm]$

- ATLAS search (ATLAS-CONF-2015-015), geared for prompt decays, requires 2 b-jets.

$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b\ell$

ATLAS Preliminary
$\sqrt{s} = 8$ TeV, 20.3 fb^{-1}
Observed 95% CL mass limit

Unphysical

$Br(\tilde{t} \rightarrow b\tau)$

$Br(\tilde{t} \rightarrow be)$

Stop mass [GeV]

ϕ

W

$\bar{f}'$

X

ϕ^*

X

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12024
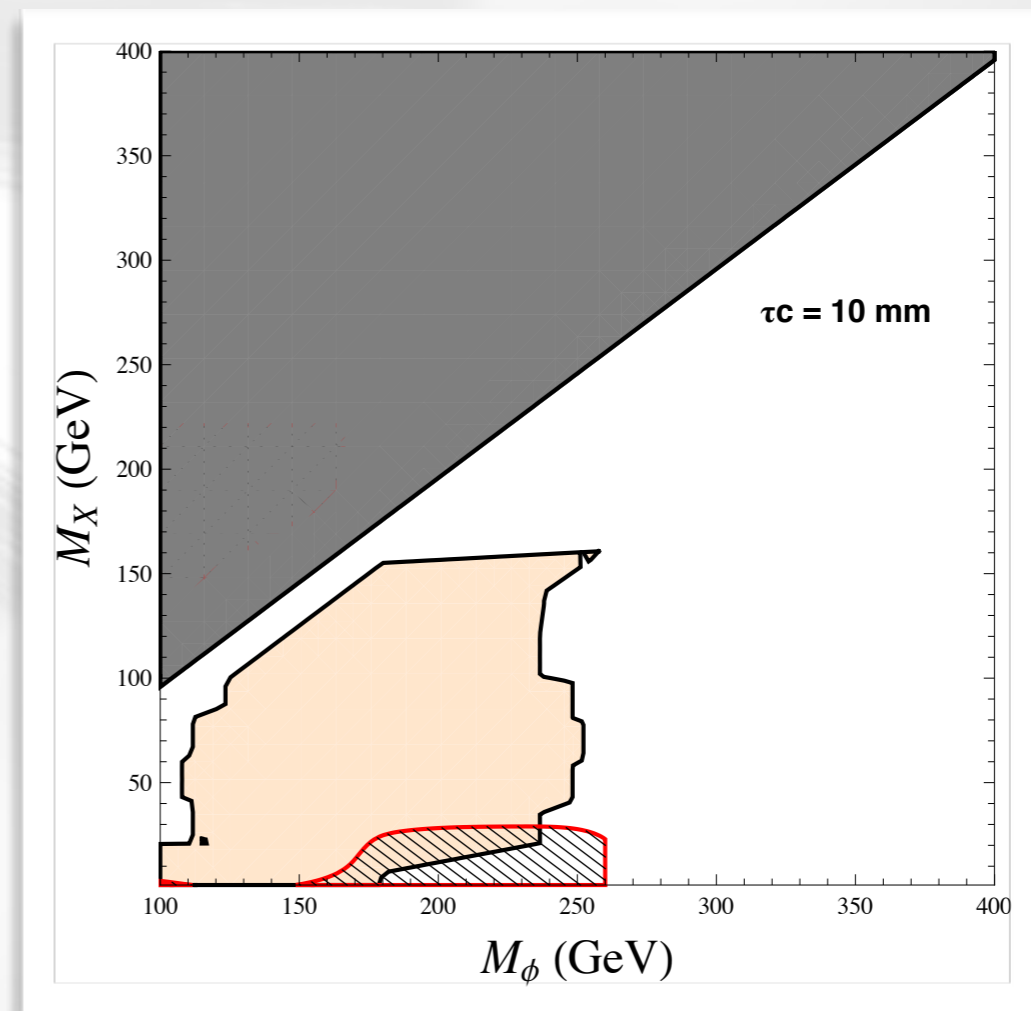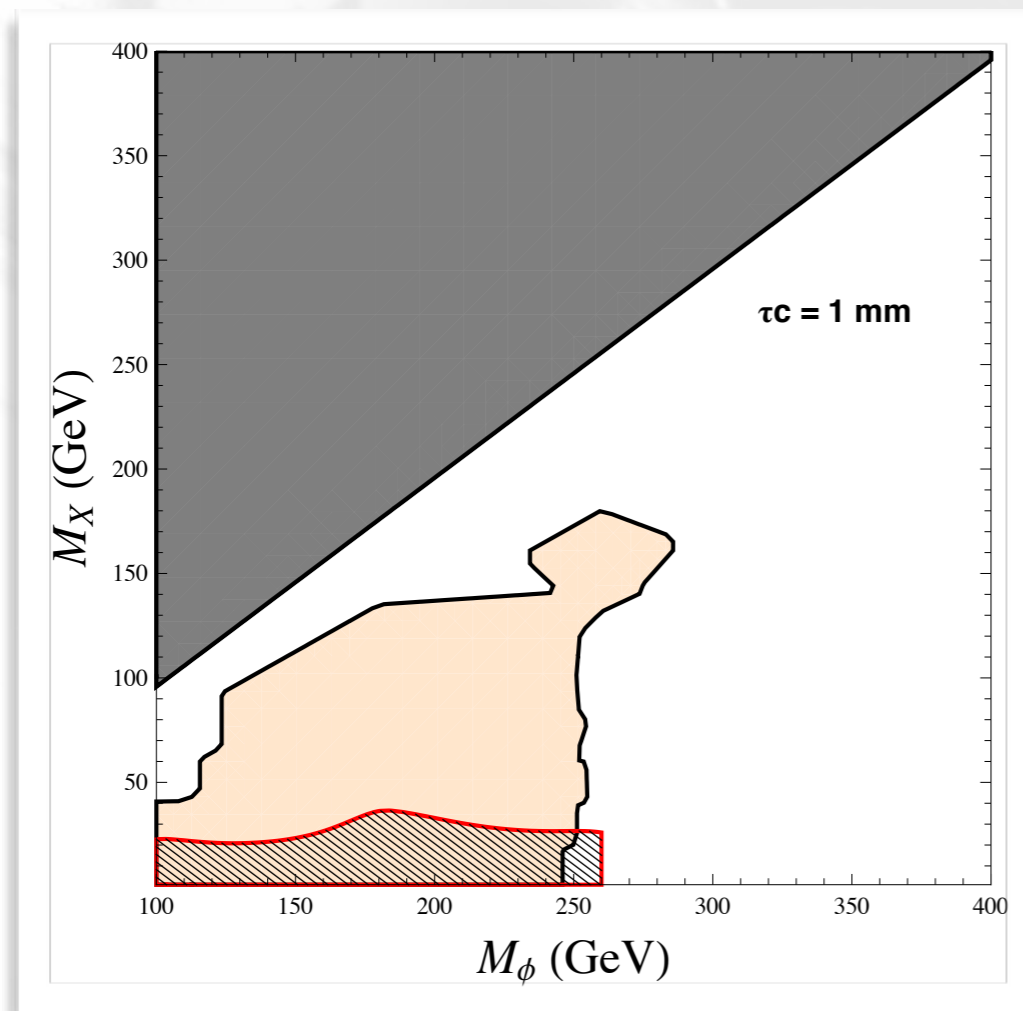
- Largest reach from CMS displaced muon and electron search...

- Region of interest is one where both prompt and long-lived searches seem to fail...
- "Save the light stop..." (Delgado, Giudice, Isidori, Pierini, Strumi; Kriska, Kumar, Morrissey).

- Apply same lepton criteria but require enough MET to suppress QCD background from mis-reconstructed jets...

- Require one b-jet; further suppress Z to $\tau\tau$. Signal is lost as well...

b-jet	$\not{E}_T$ (GeV)	$|d_0|_\mu$ (cm)	σ_{Zj} (pb)	σ_{signal} (pb)	$\frac{N_{signal}}{\sqrt{N_{signal}+N_{background}}}$
-	> 50	$0.01 < |d_0| < 2.$	0.53	5.54×10^{-3}	$0.75, 1.31, 4.13$
-	> 100	$0.01 < |d_0| < 2.$	7.49×10^{-3}	1.71×10^{-3}	$1.69, 2.92, 9.25$
1	> 50	$0.01 < |d_0| < 2.$	5.52×10^{-3}	9.41×10^{-4}	$1.11, 1.93, 6.10$
1	> 100	$0.01 < |d_0| < 2.$	3.94×10^{-4}	~ 0	$-$
-	> 50	$0.01 < |d_0| < 0.1$	0.46	5.48×10^{-3}	$0.79, 1.37, 4.35$
-	> 100	$0.01 < |d_0| < 0.1$	5.52×10^{-3}	1.71×10^{-3}	$1.89, 3.25, 10.29$
1	> 50	$0.01 < |d_0| < 0.1$	4.73×10^{-3}	9.42×10^{-4}	$1.18, 2.04, 6.47$
1	> 100	$0.01 < |d_0| < 0.1$	3.94×10^{-4}	~ 0	$-$

τc = 0.1 mm
L = 10 fb⁻¹

τc = 0.1 mm
L = 30 fb⁻¹
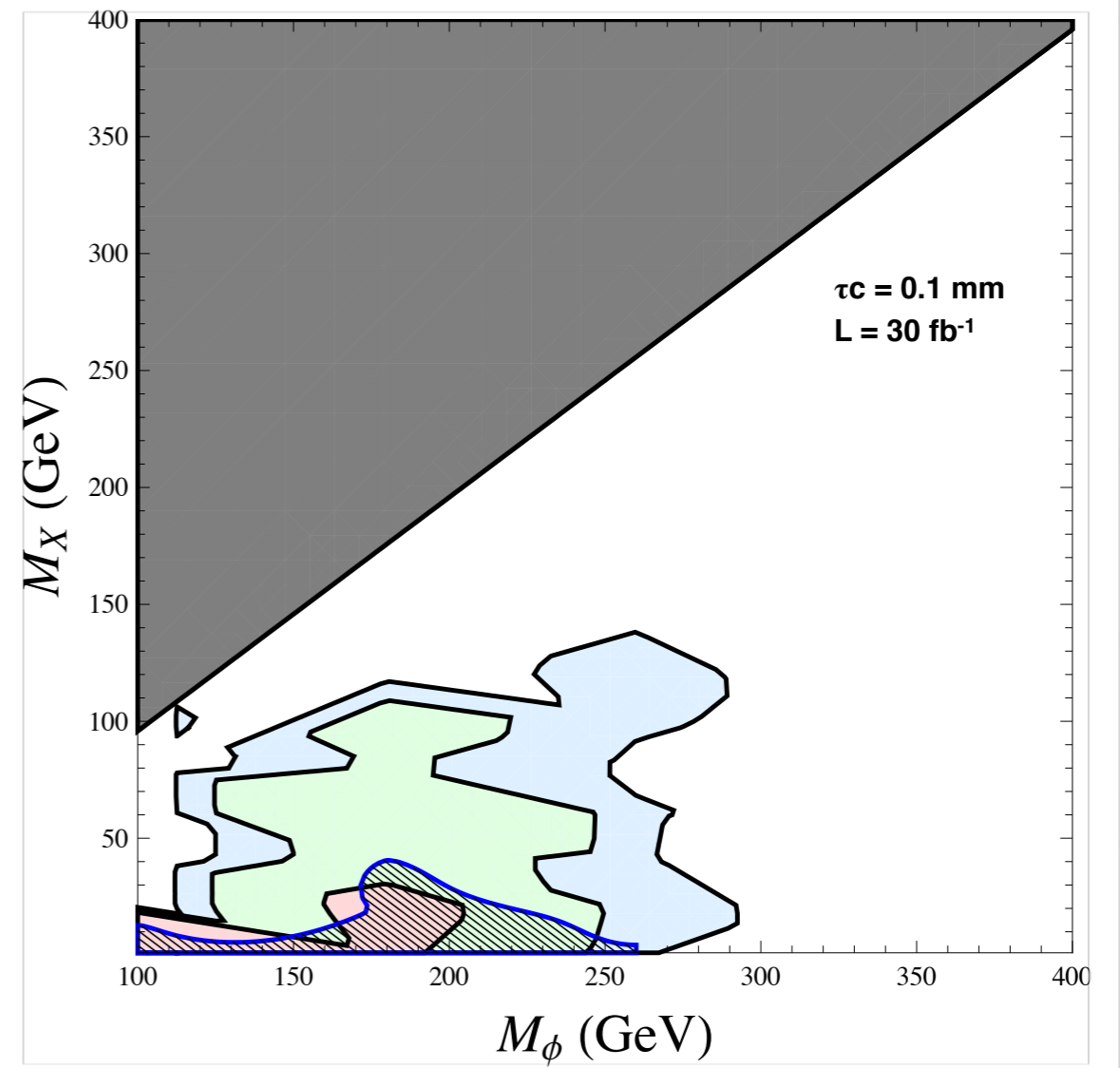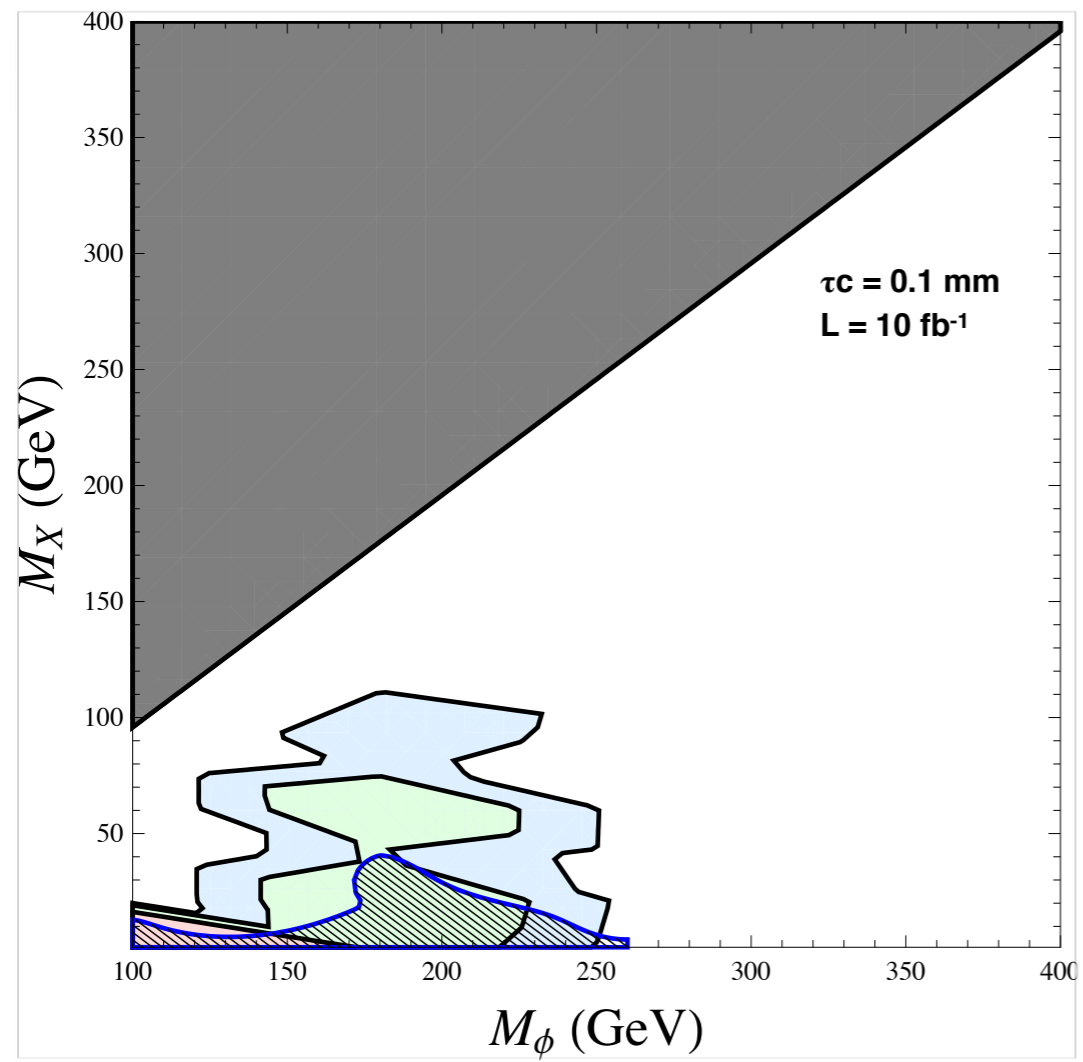
- Direct sensitivity to a light stop with decay length in the heavy-flavor range.
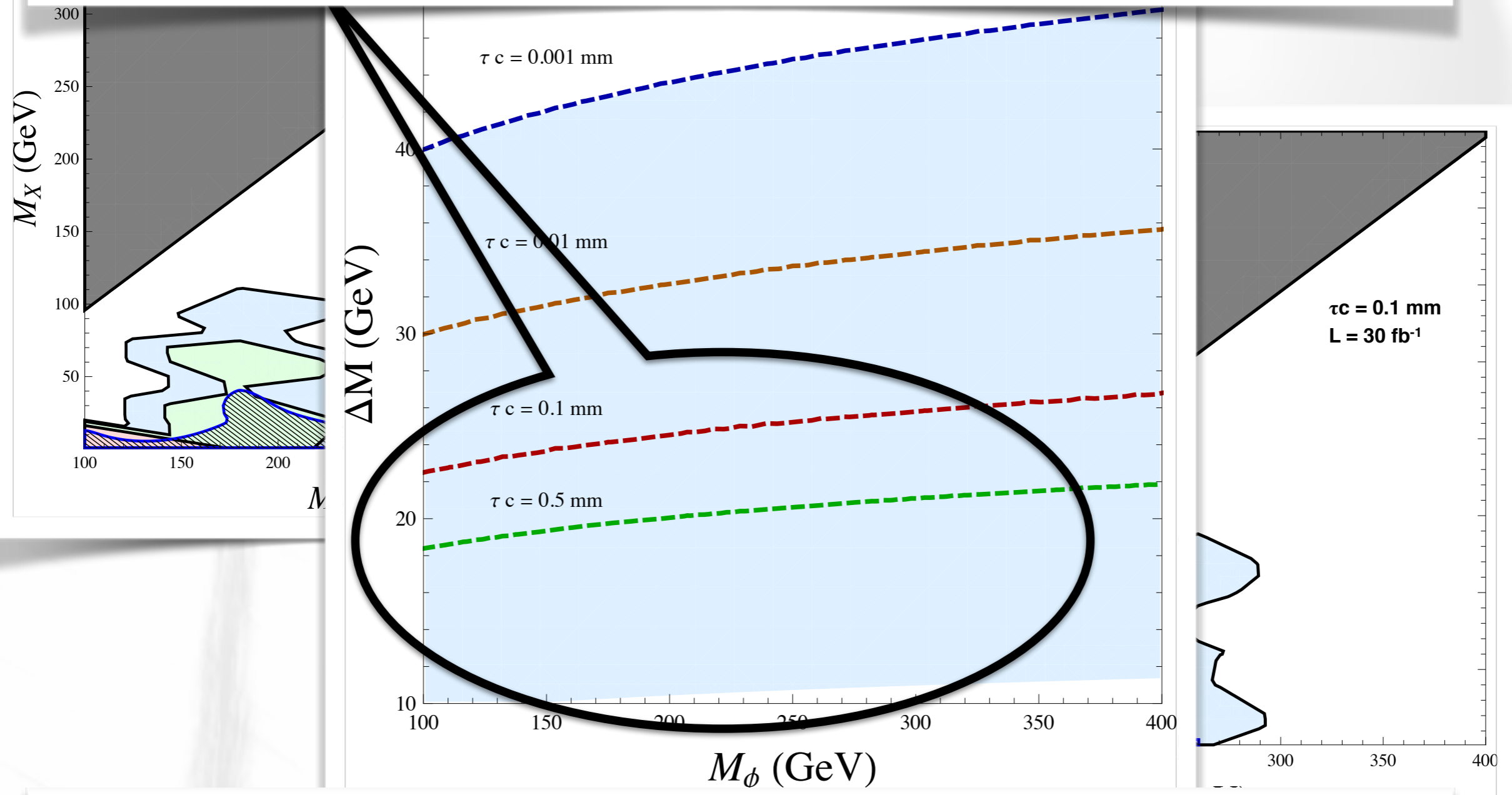
- Light Stop window of the NMSSM with two-body FV decay with $\Theta_{tc} \sim 10^{-5}$.

<u>Summary</u>

- Long-lived particles appear in a large class of models.
- Decays in the tracker range from prompt-sensitive to the need for specialized triggers.
- Existing long-lived searches are signature driven.
- Exciting opportunities for recasting and new proposals for Run II.
- However, to enhance efficiencies, we to better trigger on displaced particles (decay products).

- Light stop window of MSSM not necessarily dead for masses below 200 GeV.
- New exotic hadrons can be expected...