Searches for long-lived particles at CMS

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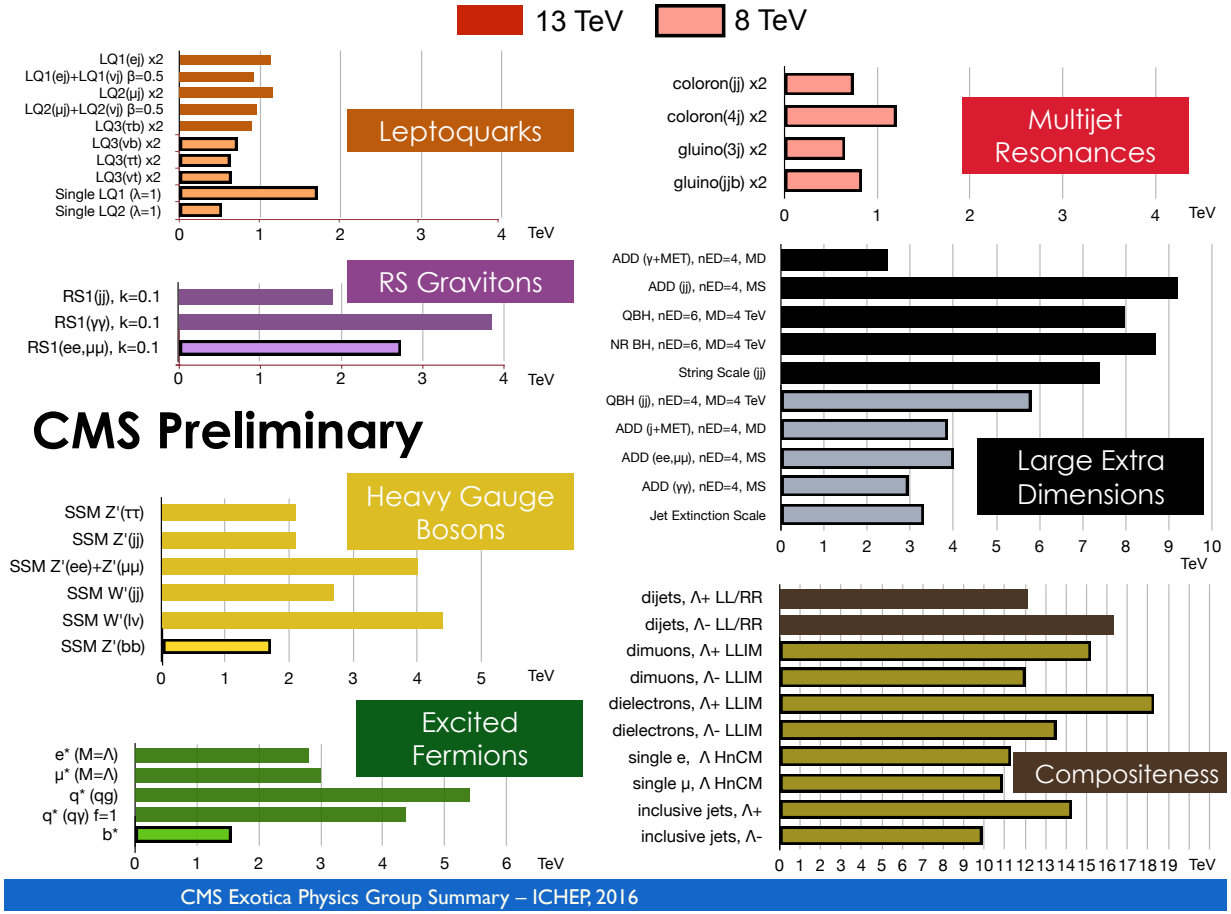
May 16, 2017

Why long-lived particles (LLP)?

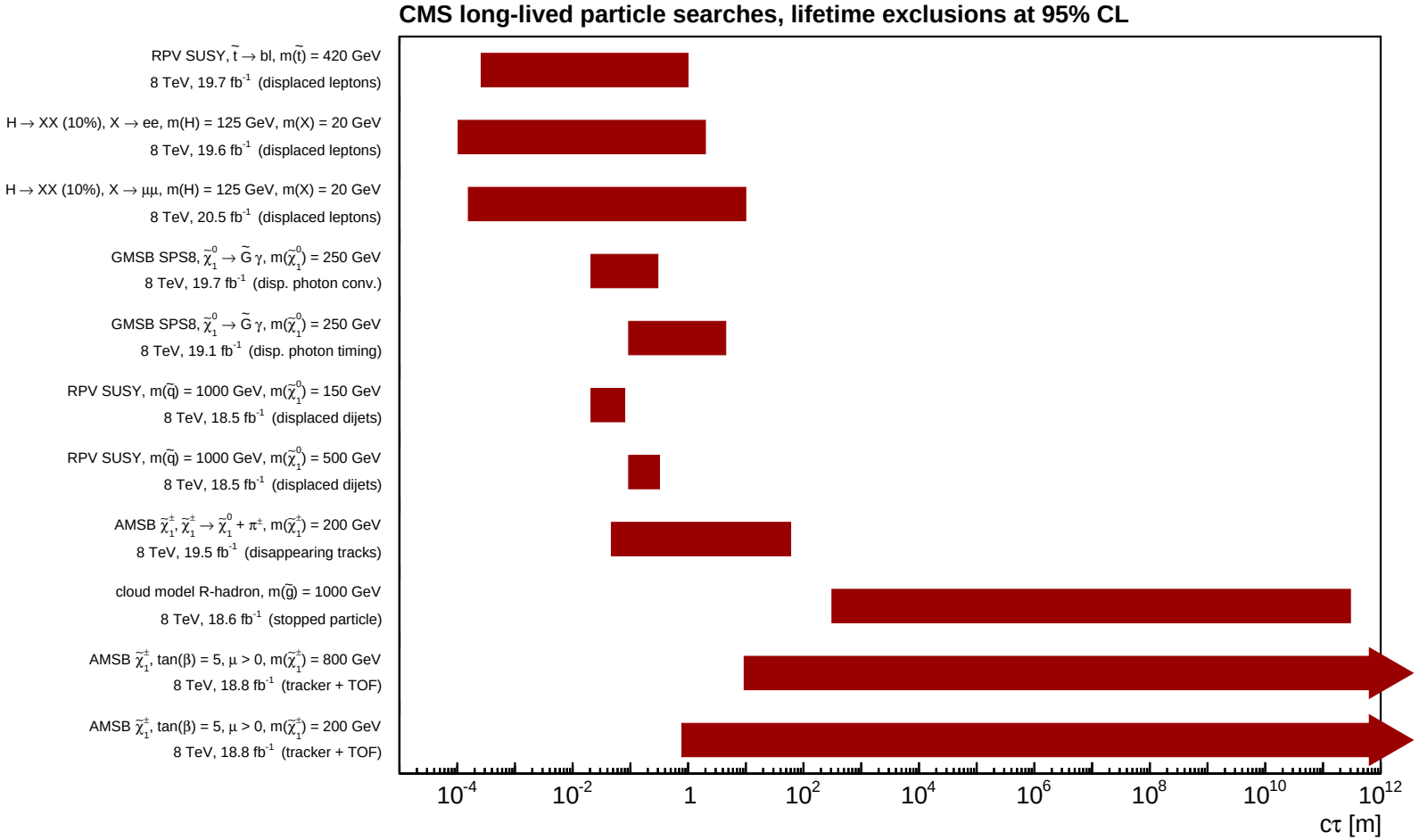
- Dozens of searches over past 6 years have failed to find evidence of BSM physics at the LHC.
- More important than ever to explore ways new physics could have escaped the attention of all these searches.

- LLPs is one such way.
- Most searches assume promptly decaying new particles.



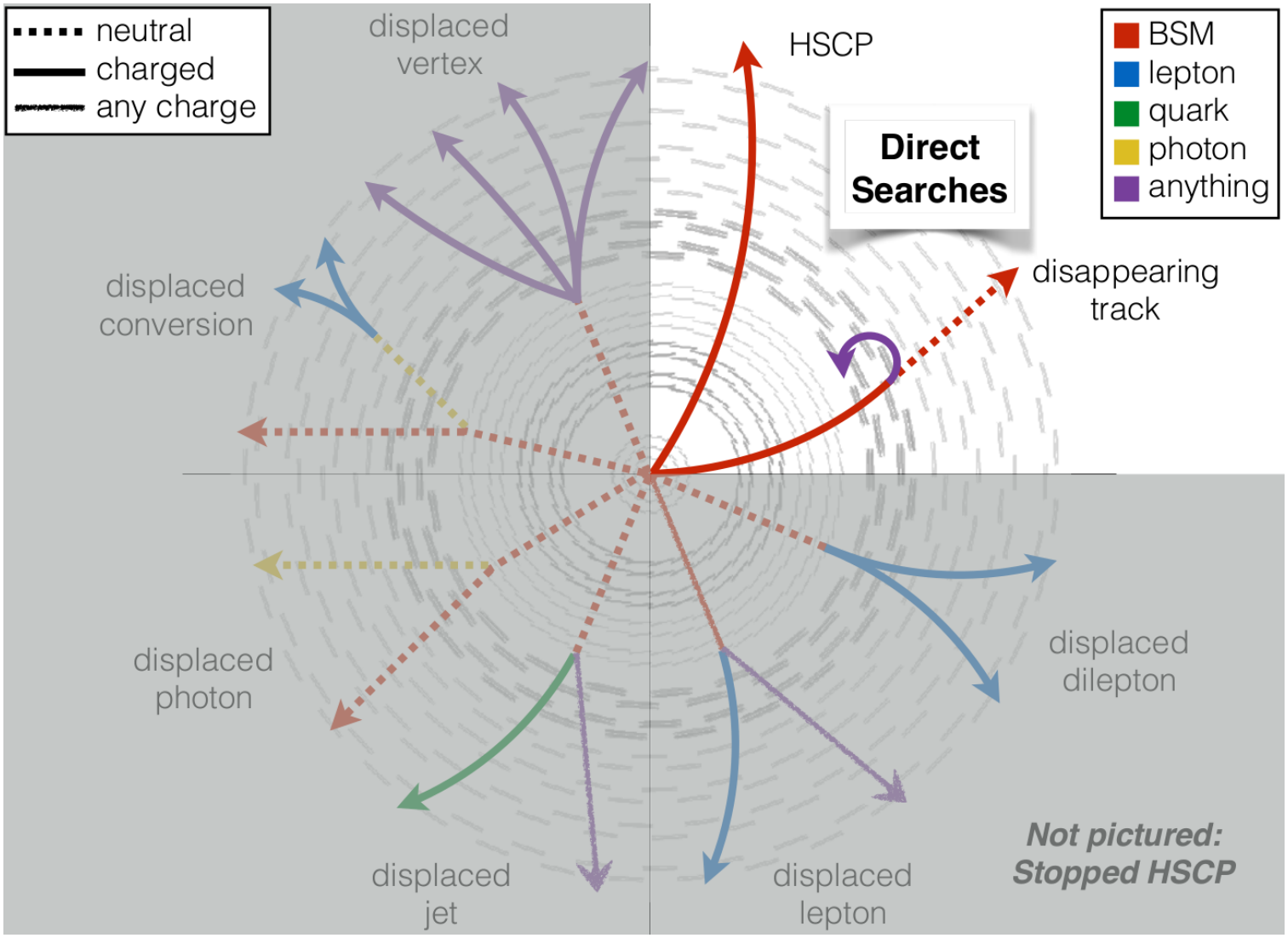
LLP searches

- CMS already has a rich programme of LLP searches.
- Several searches place limits on models with baryon/lepton number violation, typically as R-parity violation (RPV):
  - very small RPV couplings is a well-motivated way of making the LSP long-lived in SUSY models



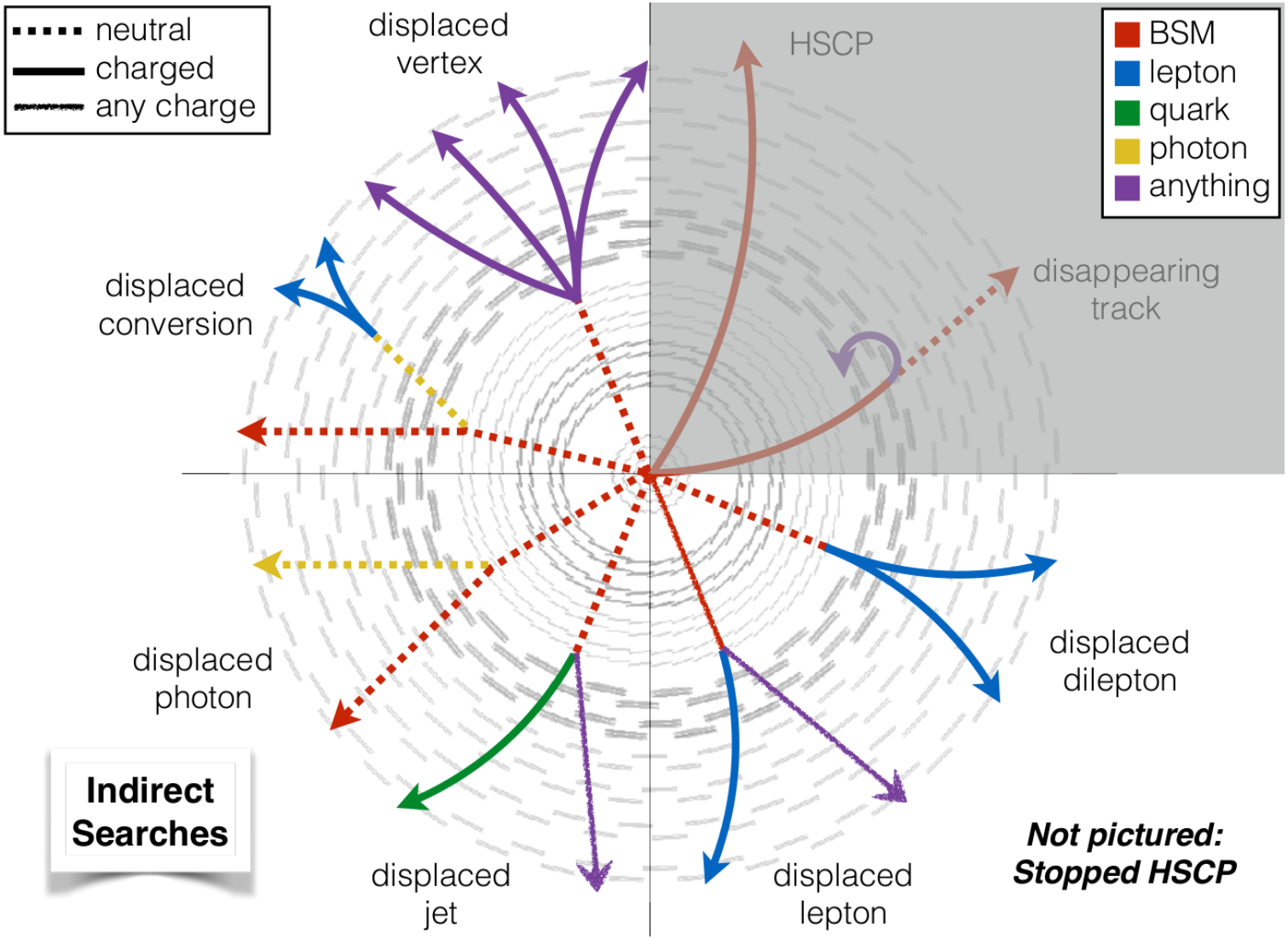
Types of LLP searches – direct

- observe LLP directly
- better for **long lifetimes**
- good for **charged LLPs**



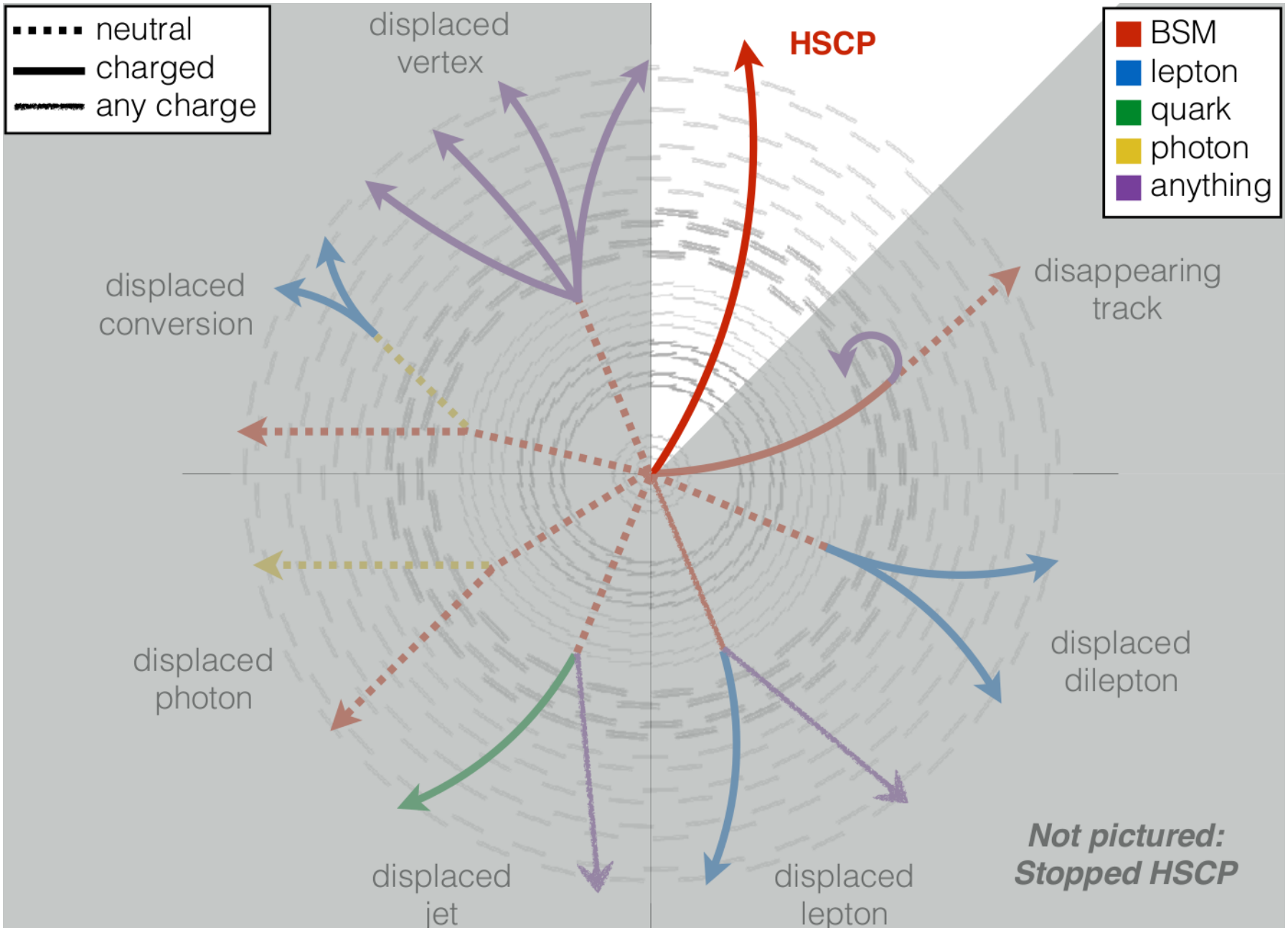
Types of LLP searches – indirect

- observe LLP decay products
- better for **short lifetimes**
- good for **neutral LLPs**



Heavy stable charged particle (HSCP) search

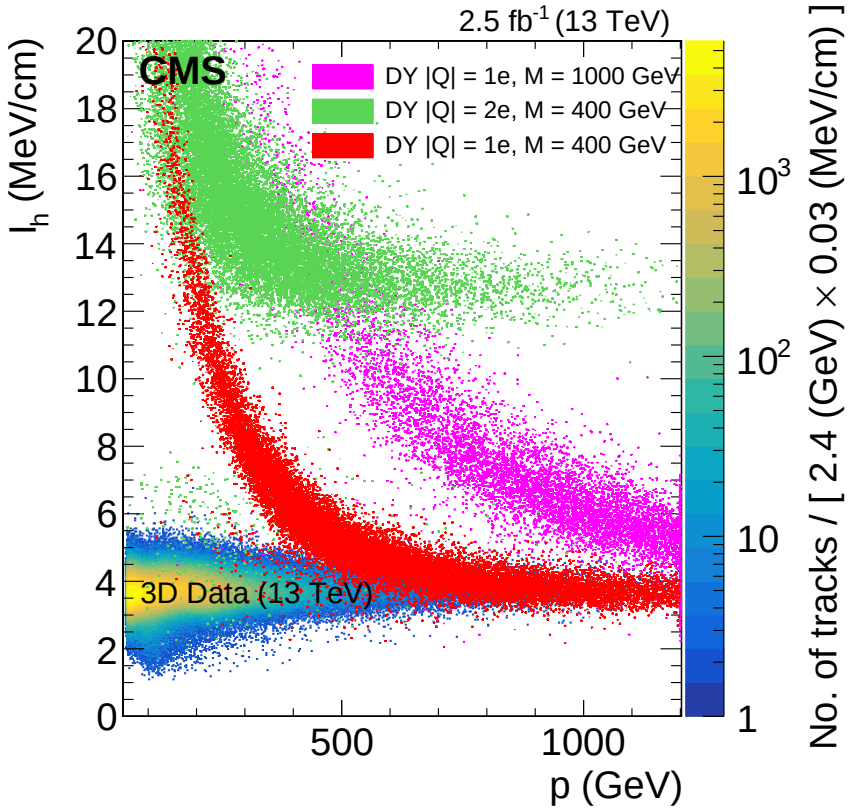
CMS-EXO-16-036



Heavy stable charged particle (HSCP) search

CMS-EXO-16-036

- Most mature LLP search at CMS:
  - results at 7, 8, and 13 TeV
- Two main discriminating variables:
  - I_h (a.k.a. dE/dx): ionization energy loss in tracker
  - β^{-1}: time of flight (TOF) to muon chambers
- Two channels maximize sensitivity to strongly-interacting HSCPs that may become neutral via interactions in the tracker:
  - tracker-only
  - tracker + TOF

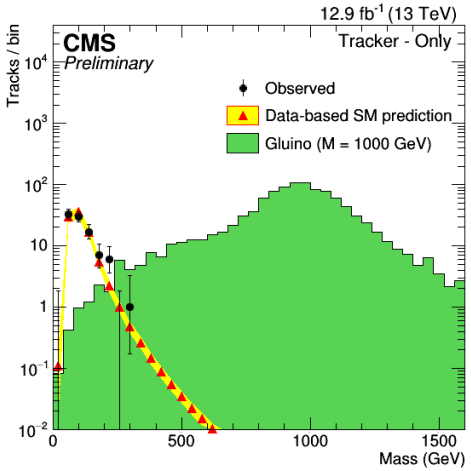


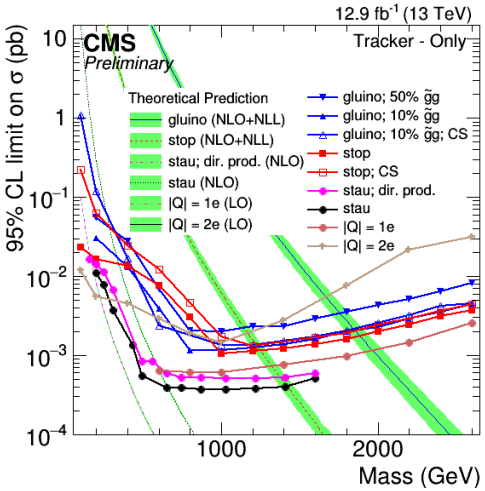
Limits set on variety of models

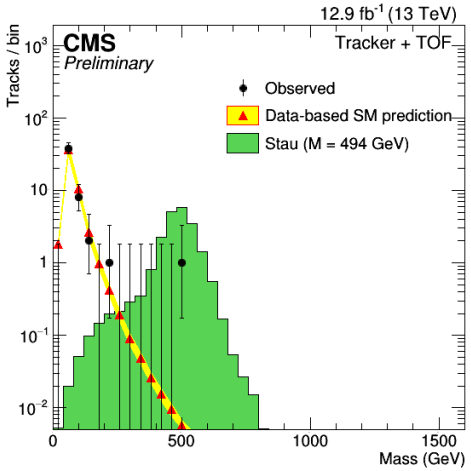
CMS-EXO-16-036

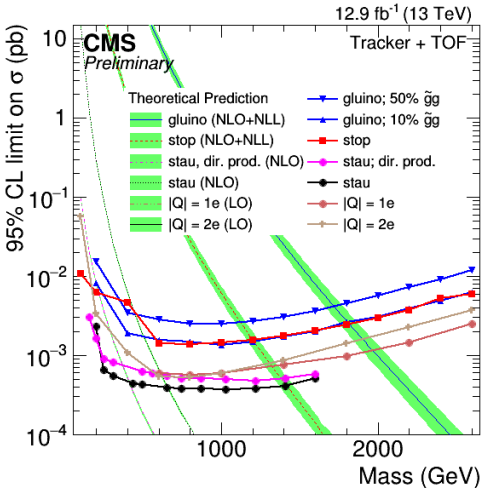
- No excess at high mass in either channel.
- Limits placed on wide range of models:
  - cross section limits down to 1∼10 fb
  - mass limits up to 1.8 TeV

	Selection cuts				Numbers of events 2016	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
Trk-only	> 65	> 0.3	-	> 0	92.4 ± 18.9	94
				> 100	43.2 ± 8.9	46
				> 200	4.3 ± 0.9	7
				> 300	0.86 ± 0.18	0
				> 400	0.25 ± 0.05	0
Trk+TOF	> 65	> 0.175	> 1.250	> 0	53.1 ± 10.6	50
				> 100	7.7 ± 1.5	8
				> 200	0.82 ± 0.17	2
				> 300	0.15 ± 0.03	1
				> 400	0.04 ± 0.01	1



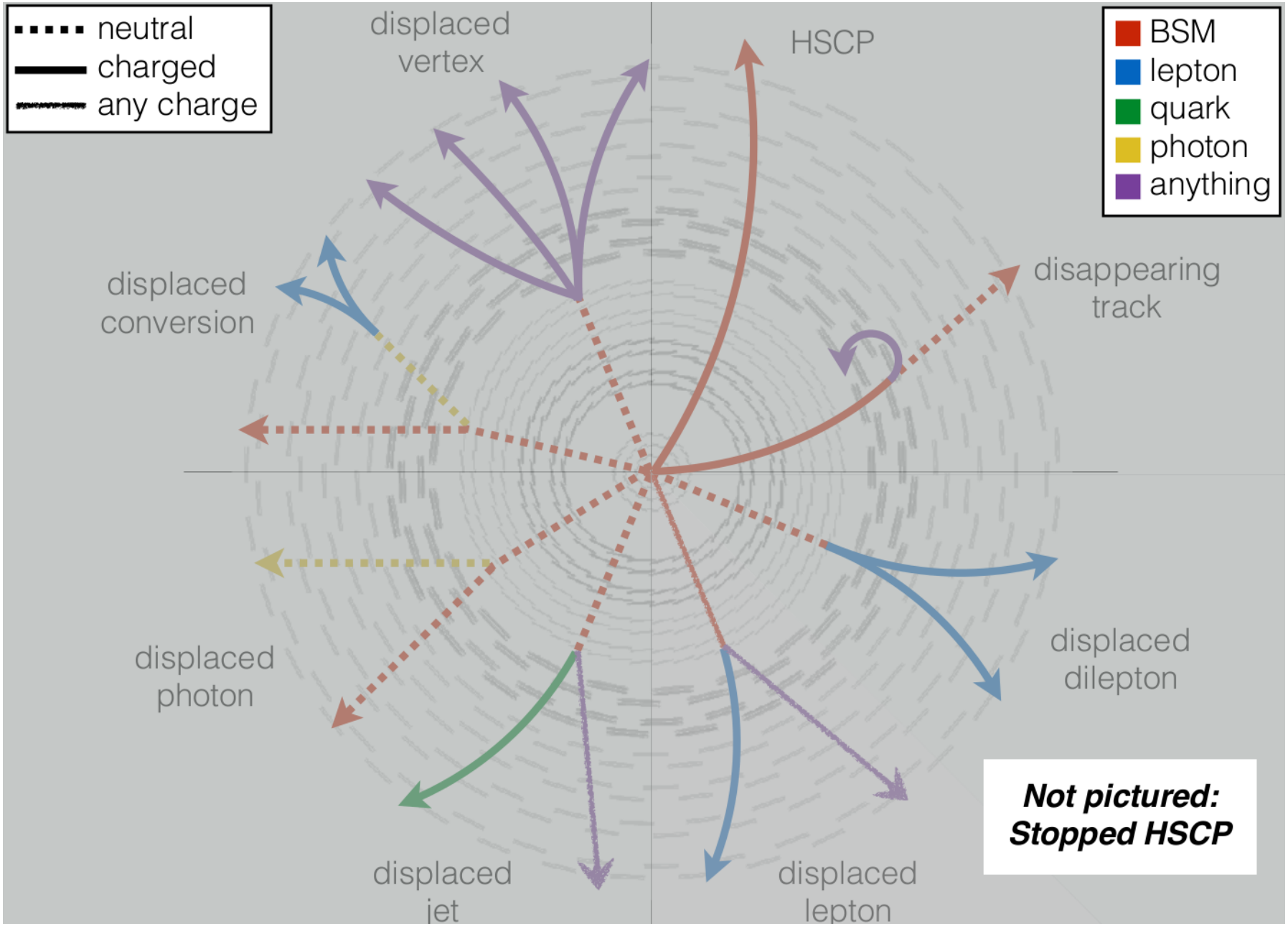






Stopped particles

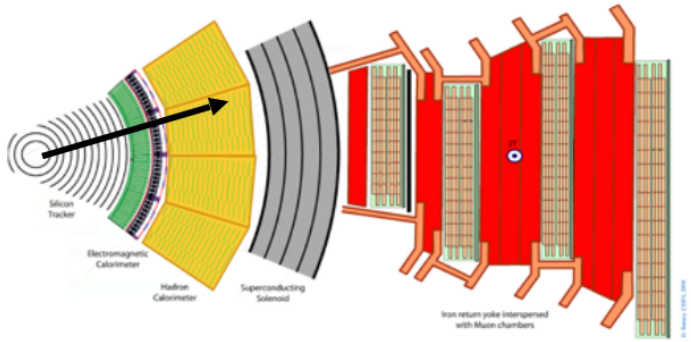
New CMS-EXO-16-004

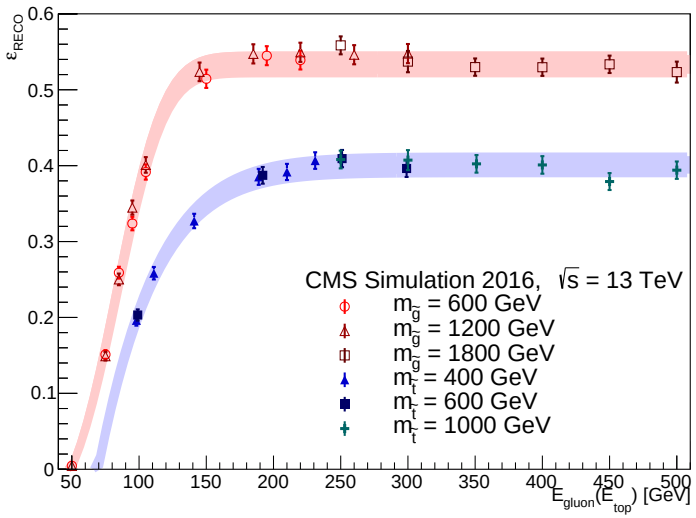


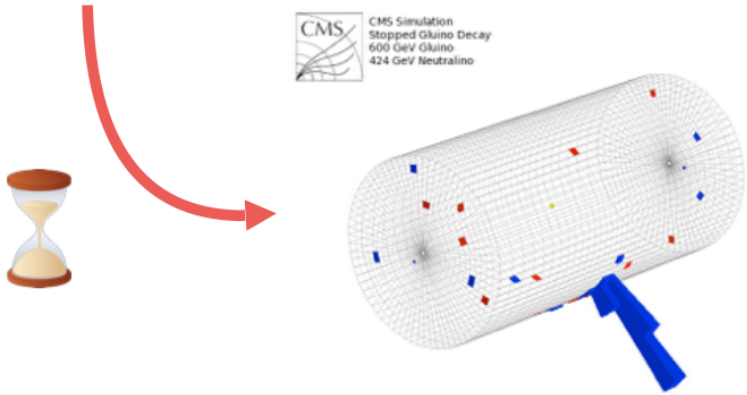
Stopped particles

New CMS-EXO-16-004

- Update of mature search done at 7 TeV and 8 TeV.
- Out-of-time events selected with a high-p_{T} jet.
- Vetoes applied to reject dominant sources of out-of-time calo. activity:
  - calo. noise
  - bremsstrahlung from beam halo muons
  - bramsstrahlung from cosmic muons



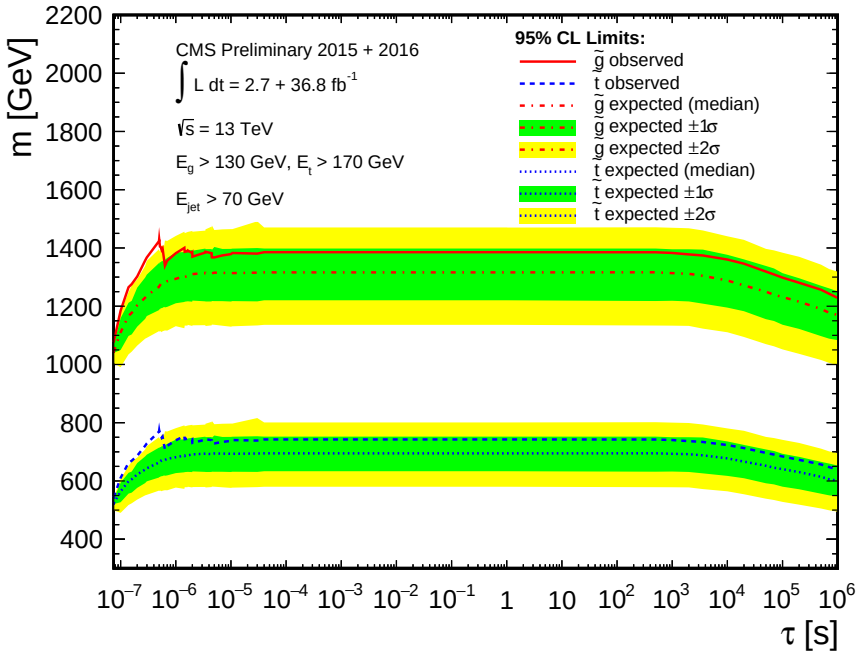




Limits placed up to $\tau \gtrsim 11\,\mathrm{days}$

New CMS-EXO-16-004

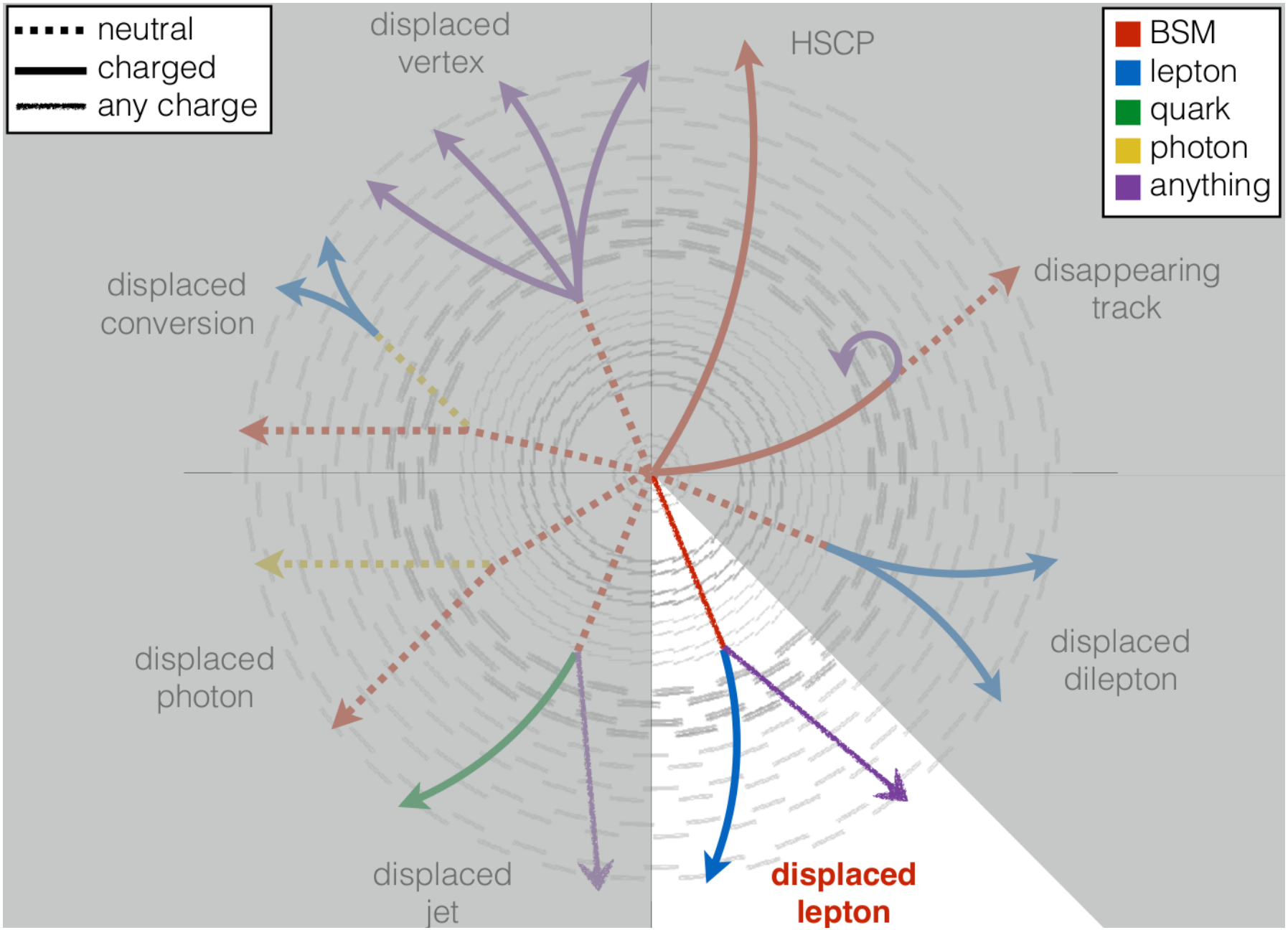
- Observed numbers of events consistent with expected backgrounds.
- Limits placed on long-lived gluinos and stops:
  - mass limits up to $1.4\,\mathrm{TeV}$ ($740\,\mathrm{GeV}$) for long-lived gluinos (stops)
  - limits placed over 13 decades of τ



Period	Livetime (hrs)	Noise	Cosmics	Halo	Total	Observed
2015 control	-	$0.3^{+2.4}_{-0.3}$	1.7 ± 0.6	0	-	2
2015	135	$0.4^{+2.9}_{-0.4}$	2.6 ± 0.9	1.1 ± 0.1	$4.1^{+3.0}_{-1.0}$ (the median is 6.2)	4
2016 control	-	$0^{+2.2}_{-0}$	2.5 ± 0.9	0	-	2
2016	586	$0^{+9.8}_{-0}$	8.8 ± 3.1	2.6 ± 0.2	$11.4^{+10.3}_{-3.1}$ (the median is 17.4)	13

Displaced $e\mu$ search

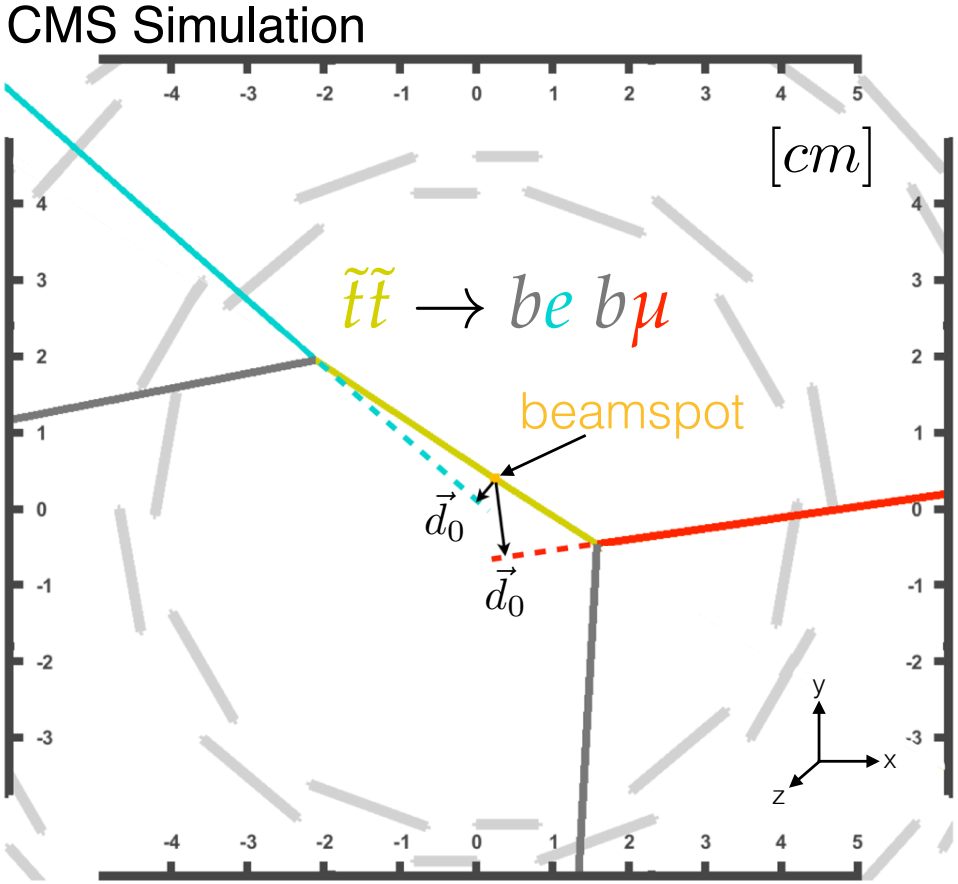
CMS-EXO-16-022

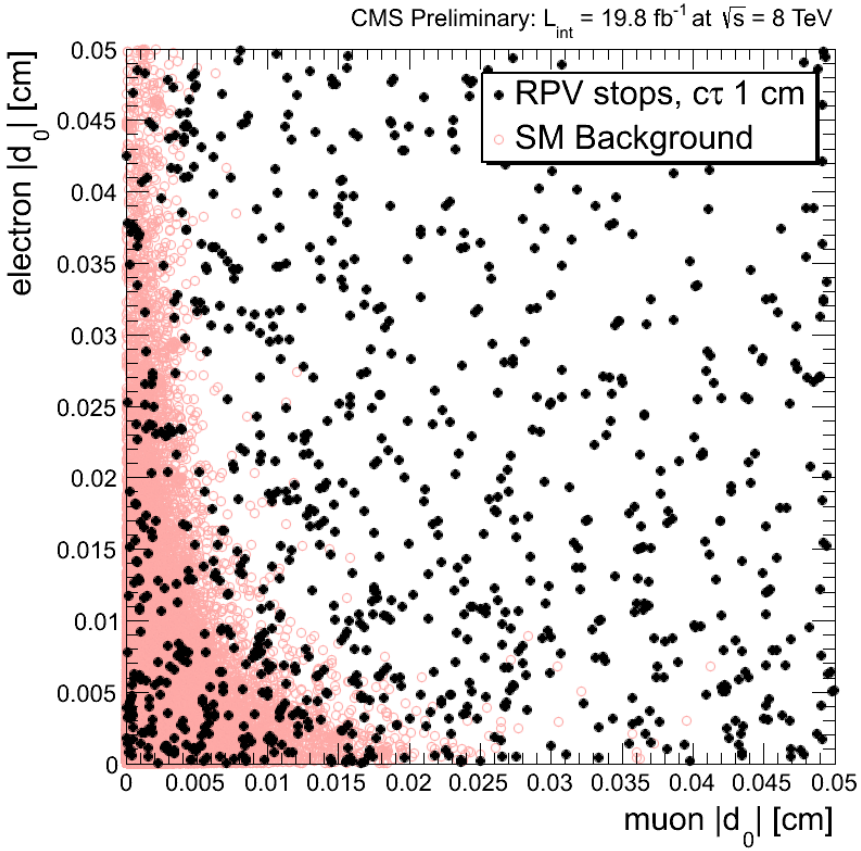


Displaced $e\mu$ search

CMS-EXO-16-022

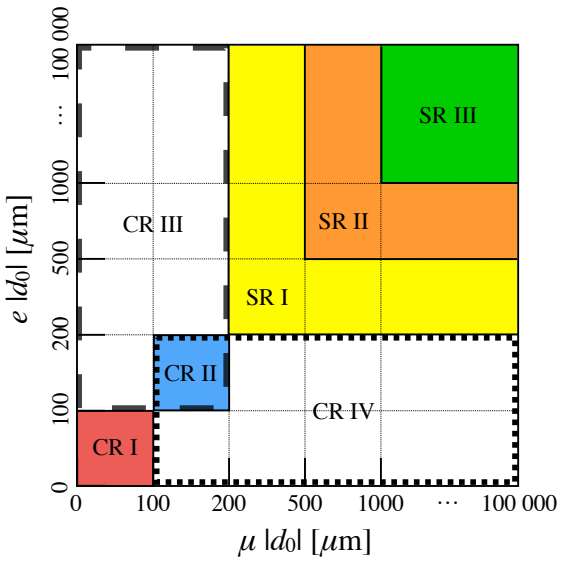
- Update of 8 TeV search.
- Benchmark model of RPV $\tilde{t} \to b l^{\pm}$ pair production.
- d_0 of electron and muon used as discriminating variables.
- Events selected with one oppositely-charged $e\mu$ pair.





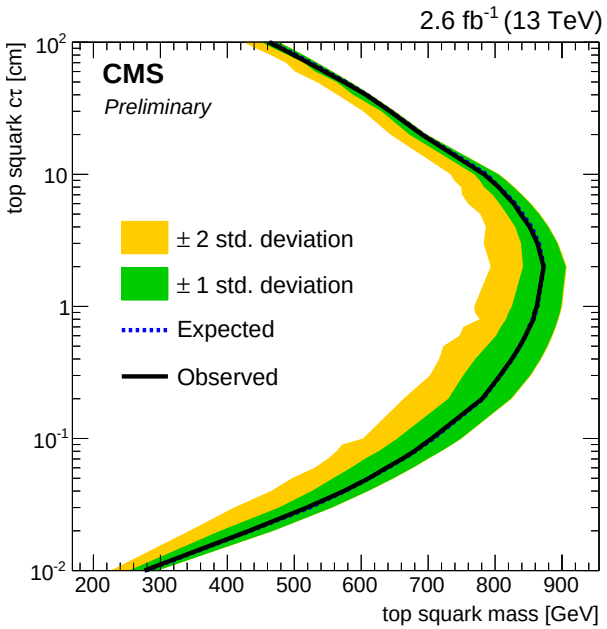
Limits placed over 4 decades in $c\tau$

CMS-EXO-16-022



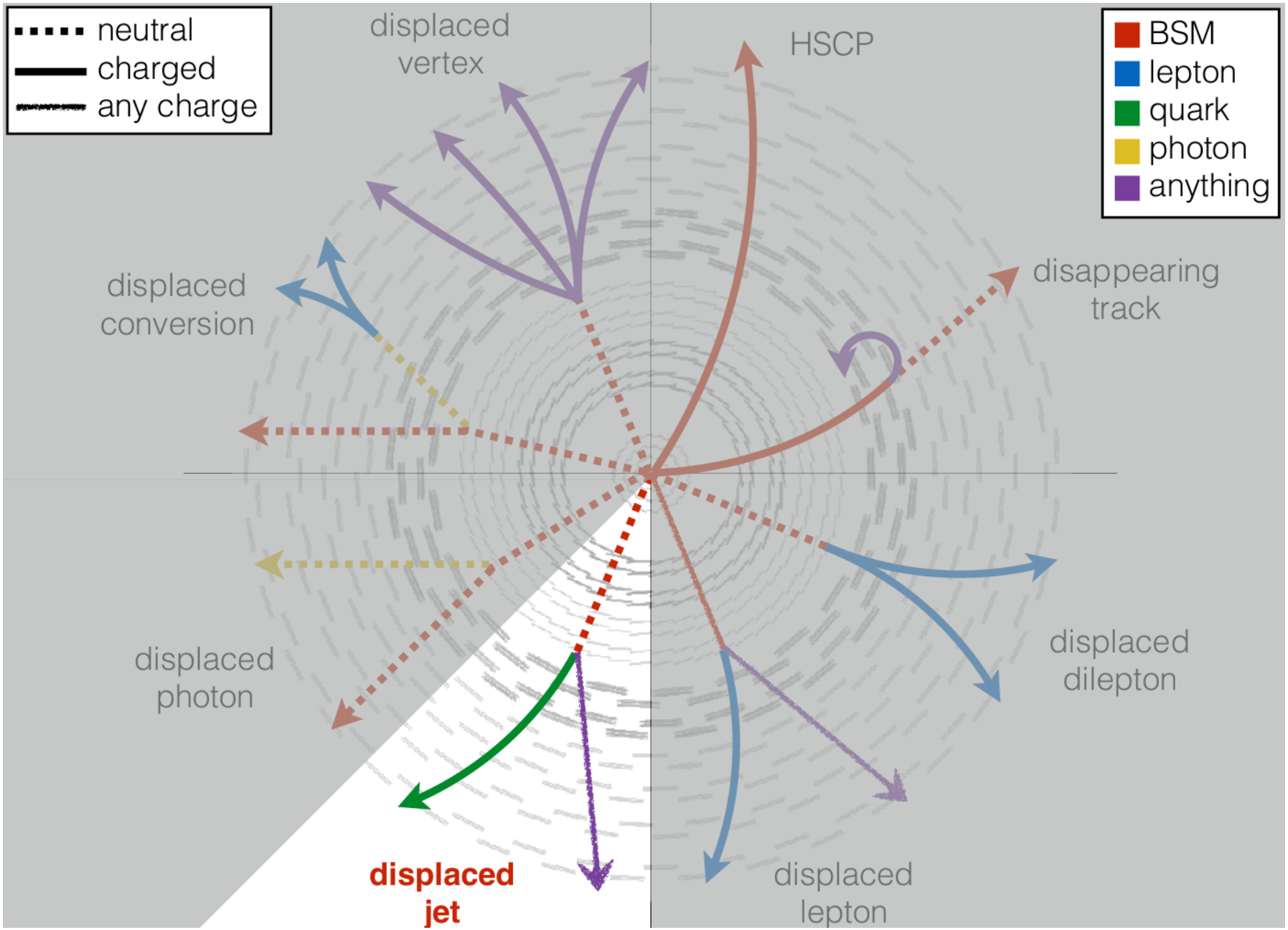
- Three mutually exclusive search regions: $200\,\mu\mathrm{m} < d_0 < 10\,\mathrm{cm}$.
- Observation consistent with expected background in each region.
- Sensitivity limited by:
  - prompt backgrounds and $d_0 > 200\,\mu\mathrm{m}$ criterion at small $c\tau$
  - lepton reco. eff. at large $c\tau$

Event Source	Search Region I	Search Region II	Search Region III
non-HF sum	$(203 \pm 26) \times 10^{-3}$	$(410 \pm 170) \times 10^{-5}$	$(82 \pm 71) \times 10^{-5}$
data-driven HF	< 3.0	< 0.50	< 0.019
total background	< 3.2	< 0.50	< 0.020
observation	1	0	0
$pp \to \tilde{t}_1\tilde{t}_1^*(M_{\tilde{t}_1} = 700\,\mathrm{GeV})$			
$c\tau = 0.1\,\mathrm{cm}$	3.8 ± 0.2	0.94 ± 0.06	0.16 ± 0.02
$c\tau = 1\,\mathrm{cm}$	5.2 ± 0.4	4.1 ± 0.3	7.0 ± 0.3
$c\tau = 10\,\mathrm{cm}$	0.8 ± 0.1	1.0 ± 0.1	5.8 ± 0.2
$c\tau = 100\,\mathrm{cm}$	0.009 ± 0.005	0.03 ± 0.01	0.27 ± 0.03



Displaced jet search

CMS-EXO-16-003

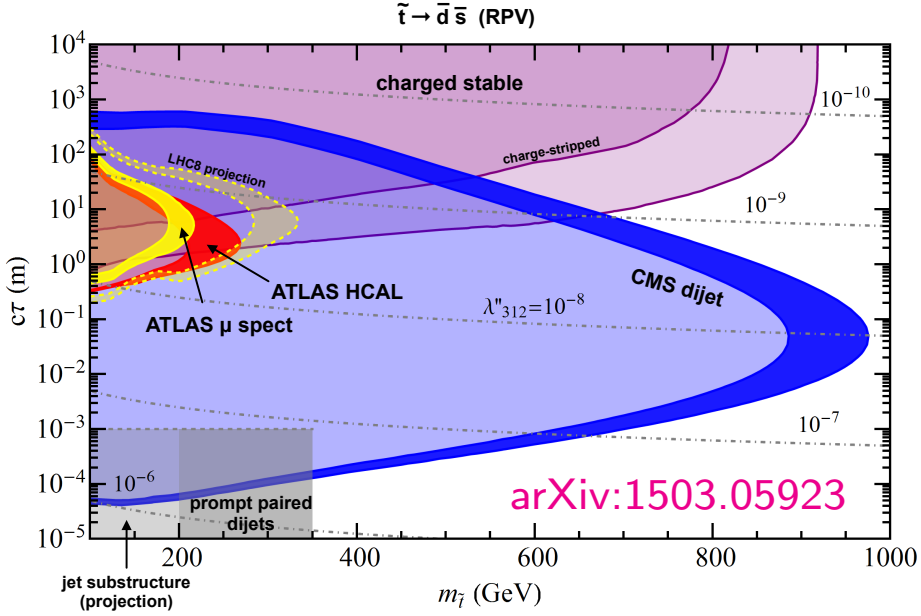


Displaced jet search

CMS-EXO-16-003

Run 1

- Search for dijets sharing a common, displaced vertex.
- Generated a lot of interest from the pheno. community:
  - able to exclude huge swaths of parameter space for several models



Run 2

- Displaced jet-based tagging strategy developed:
  - sensitive now to single displaced jets
  - able to place limits on RPV $\tilde{t} \to \mathrm{bl}^{\pm}$ model from displaced $\mathrm{e}\mu$ search

Jet tagging variables

CMS-EXO-16-003

- vertex α: fraction of jet's track p_{T} associated to vertex
  - cut on highest α vertex
- track $\mathrm{IP}_{\mathrm{sig}}^{\mathrm{2D}}$: transverse impact parameter of track wrt. PV divided by its error
  - cut on median $\mathrm{IP}_{\mathrm{sig}}^{\mathrm{2D}}$ for jet
- track Θ_{2D}: angle between track p_{T} and vector from PV to track's innermost hit
  - cut on median Θ_{2D} for jet

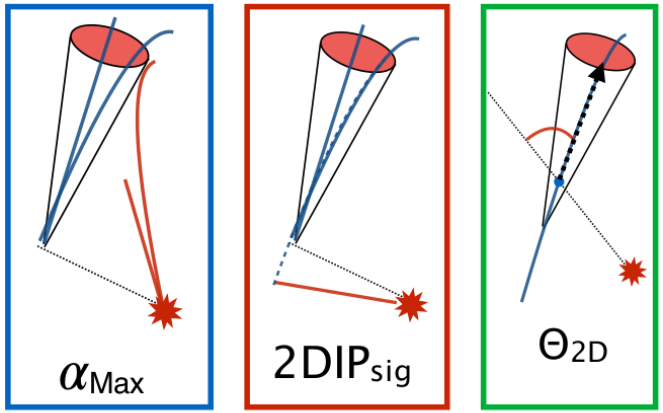
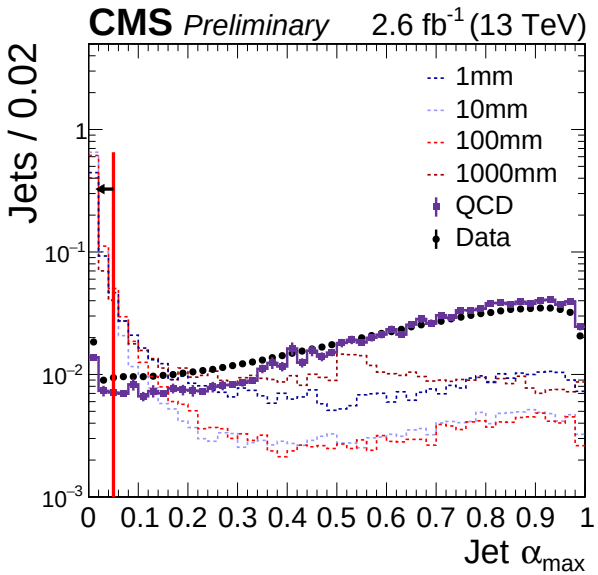
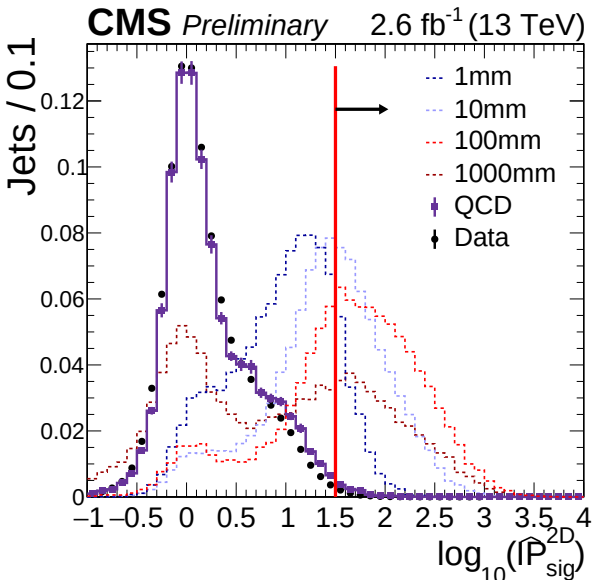
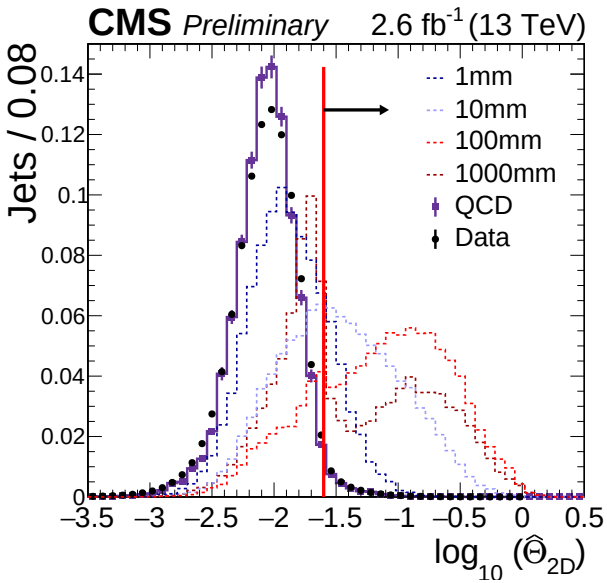


image credits: J. Hardenbrook





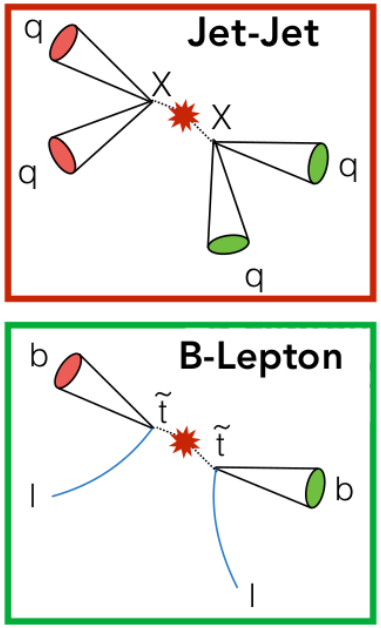


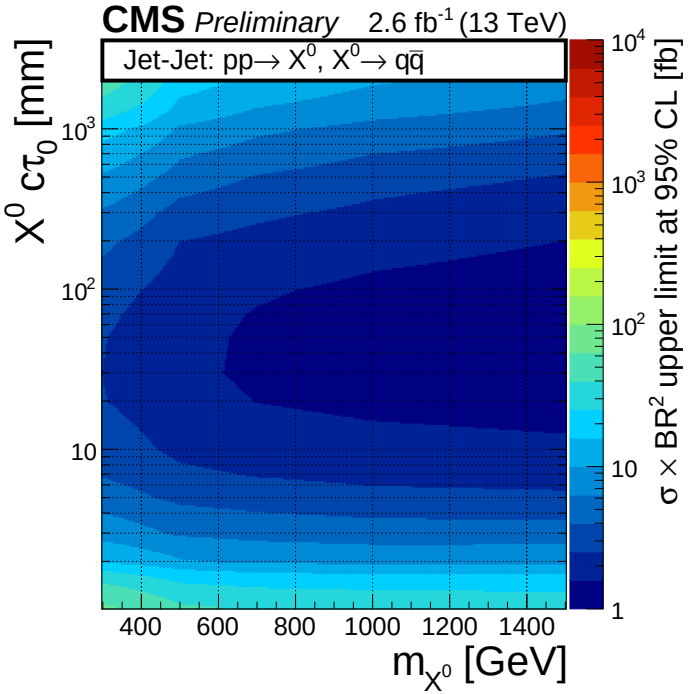
Lot of parameter space excluded

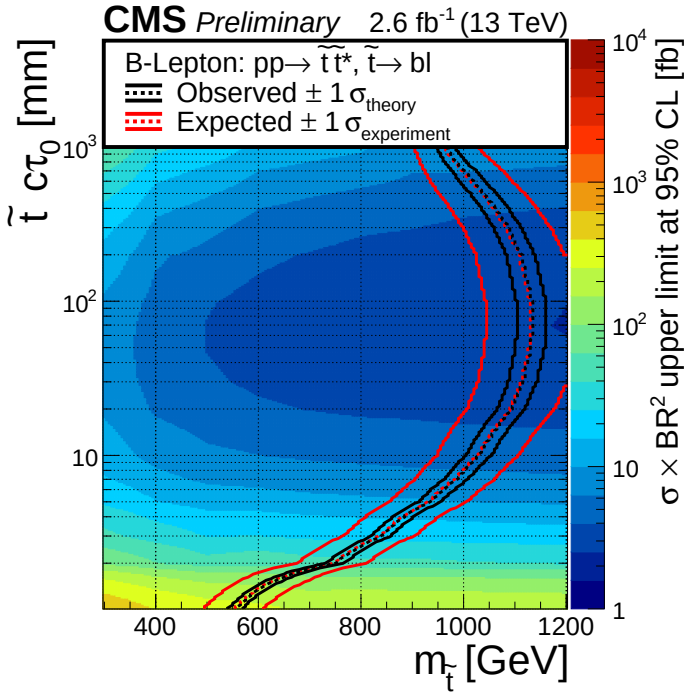
CMS-EXO-16-003

- Expected backgrounds are very small:
  - observation is consistent
- Limits placed on multiple models as a function of LLP mass and lifetime.

N_{tags}	Expected	Observed
2	1.09 ± 0.16	1
≥ 3	$(4.9 \pm 1.0) \times 10^{-4}$	0







Conclusion

- Many more results with current $38.5\,\mathrm{fb}^{-1}$ $13\,\mathrm{TeV}$ dataset in pipeline.
- The 2017 run will offer even more interesting possibilities for some analyses:
  - CMS now has an upgraded pixel detector with a new 4th barrel layer and 3rd endcap disk on each side

final state	$13\,\mathrm{TeV}$ result
displaced $\mathrm{ee}/\mu\mu$ pairs	
displaced $\mu\mu$ pairs in muon sys.	
displaced $\mathrm{e}\mu$ pairs	CMS-EXO-16-022
displaced $\mu\mu$ pairs (dark photons)	CMS-HIG-16-035
displaced γ using ECAL timing	
displaced γ using conversions	
displaced vertices	
displaced jets	CMS-EXO-16-003
disappearing tracks	
short, highly ionizing disapp. trks.	
kinked tracks	
fractionally charged particles	
HSCP	CMS-EXO-15-010 (2015) CMS-EXO-16-036 (2016)
stopped particles	CMS-EXO-16-004
delayed muons	

- Many well-motivated LLP topologies have yet to be explored.
- Big discoveries could be lurking in the data, just waiting to be found!