THE OHIO STATE UNIVERSITY

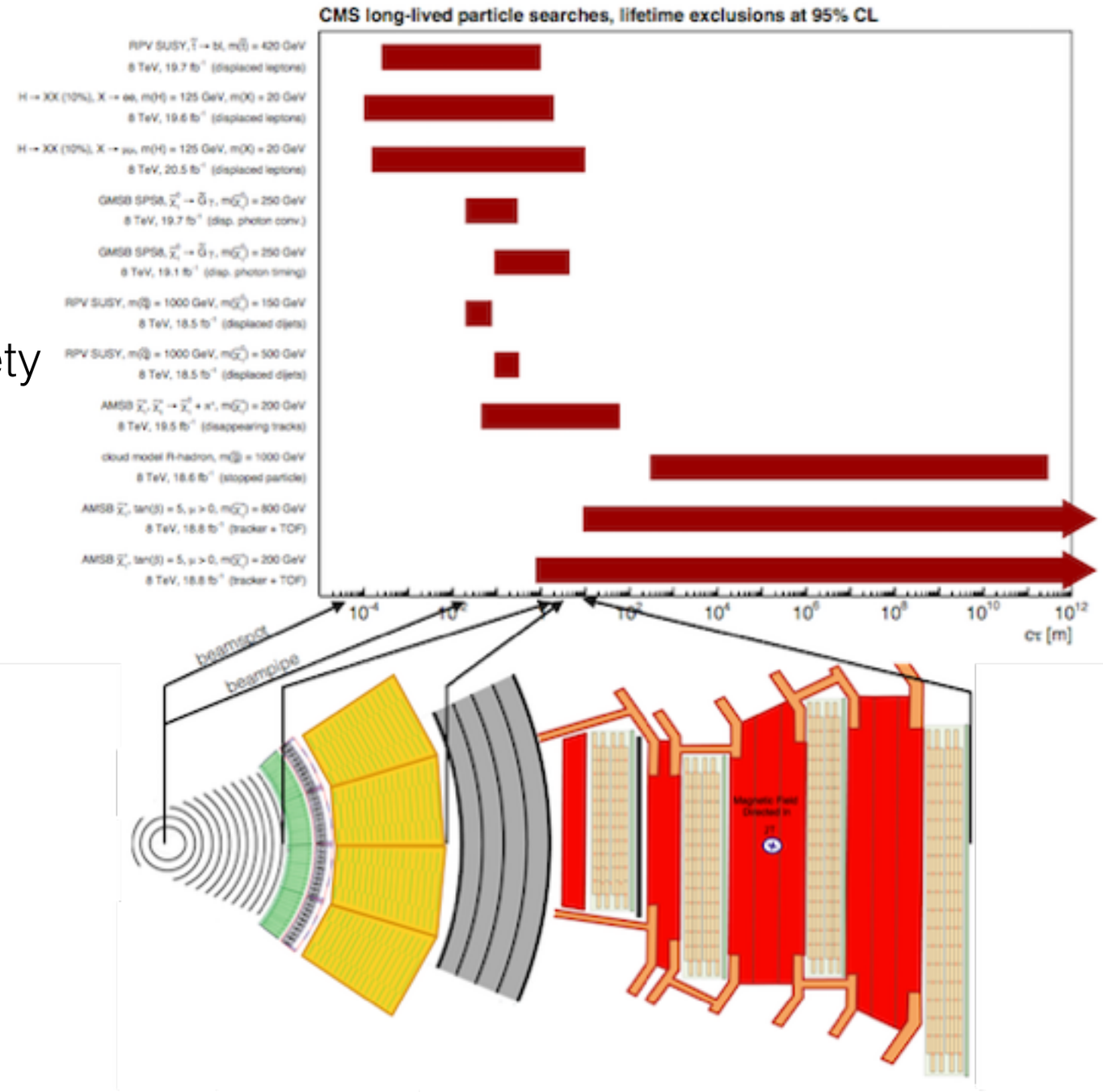
Search for long-lived particles at CMS

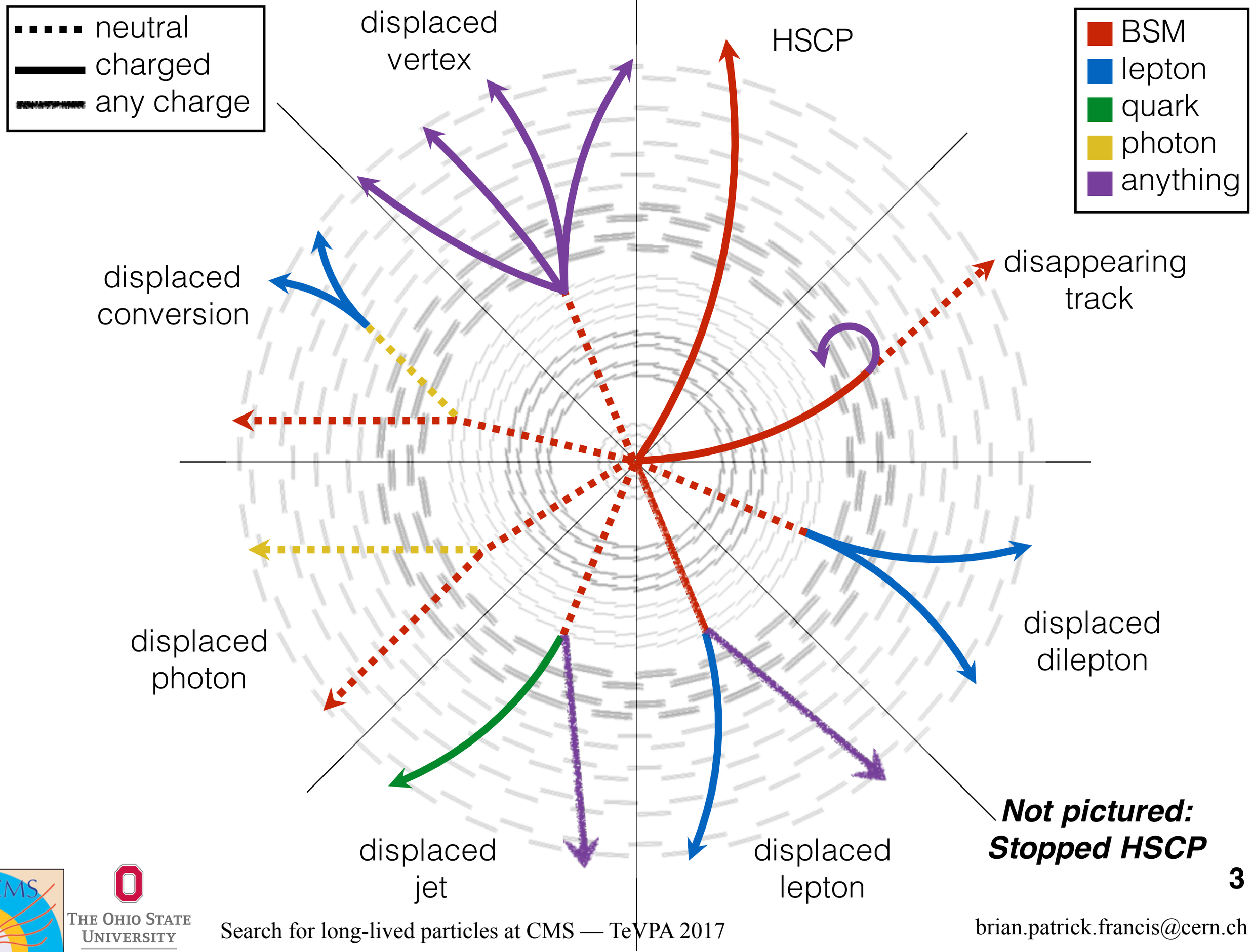
TeVPA 2017

Brian Francis
for the CMS Collaboration

Long-lived particles (LLP) at CMS

- Despite best efforts, no evidence yet of BSM physics at the LHC
- If it's not where we've looked, hugely important to consider where we haven't!
- LLPs ($c\tau$ > ~5 microns) offer a wide variety of non-conventional signatures
  - Many models predict LLPs: split/RPV SUSY, hidden valleys, magnetic monopoles…
  - Non-prompt signatures are easily missed by prompt searches
- CMS is already sensitive to a *very* wide range of particle lifetimes
  - From well beyond the first and last active layers

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BSM
lepton
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displaced vertex
HSCP
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disappearing track
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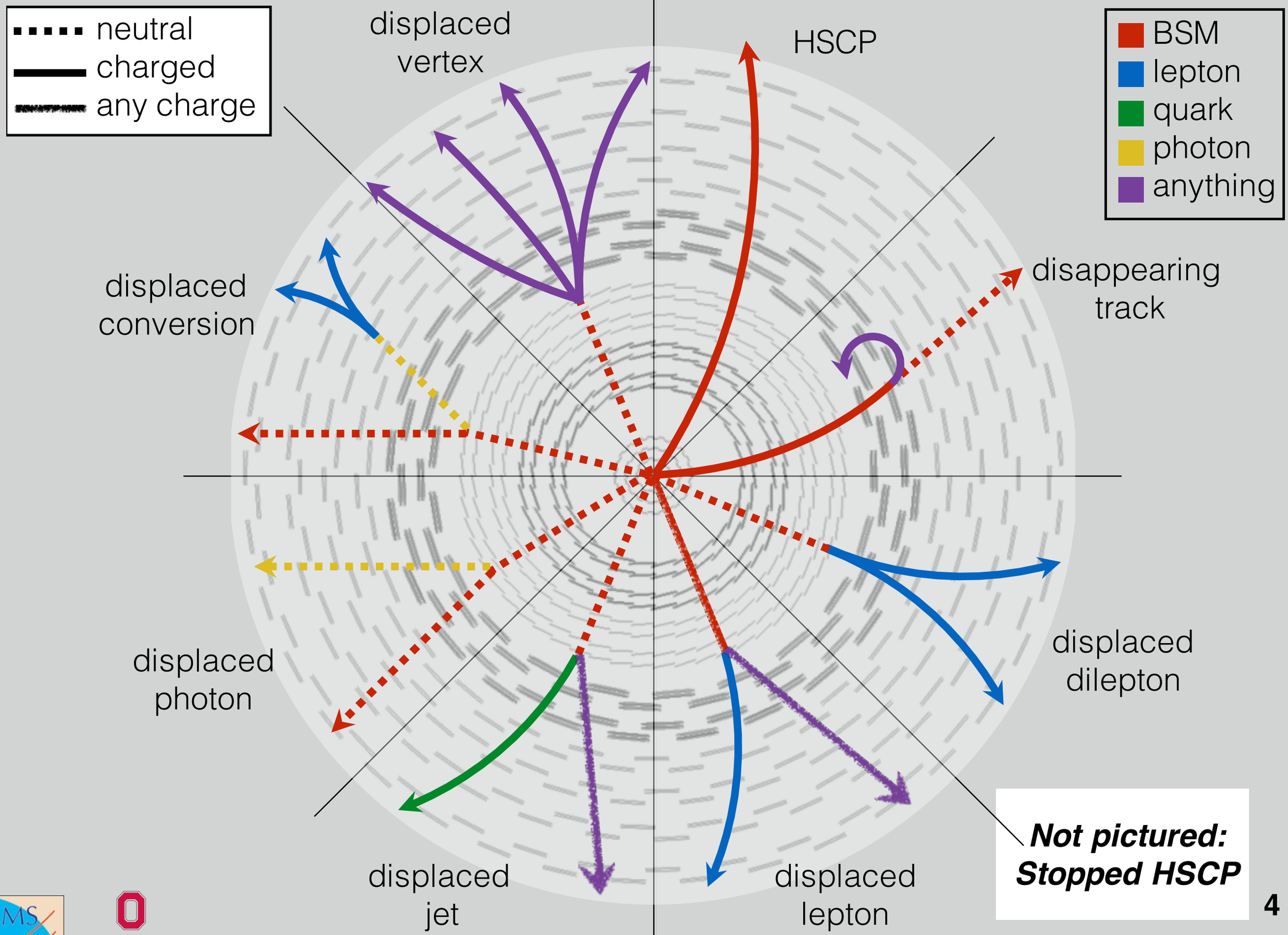
Not pictured: Stopped HSCP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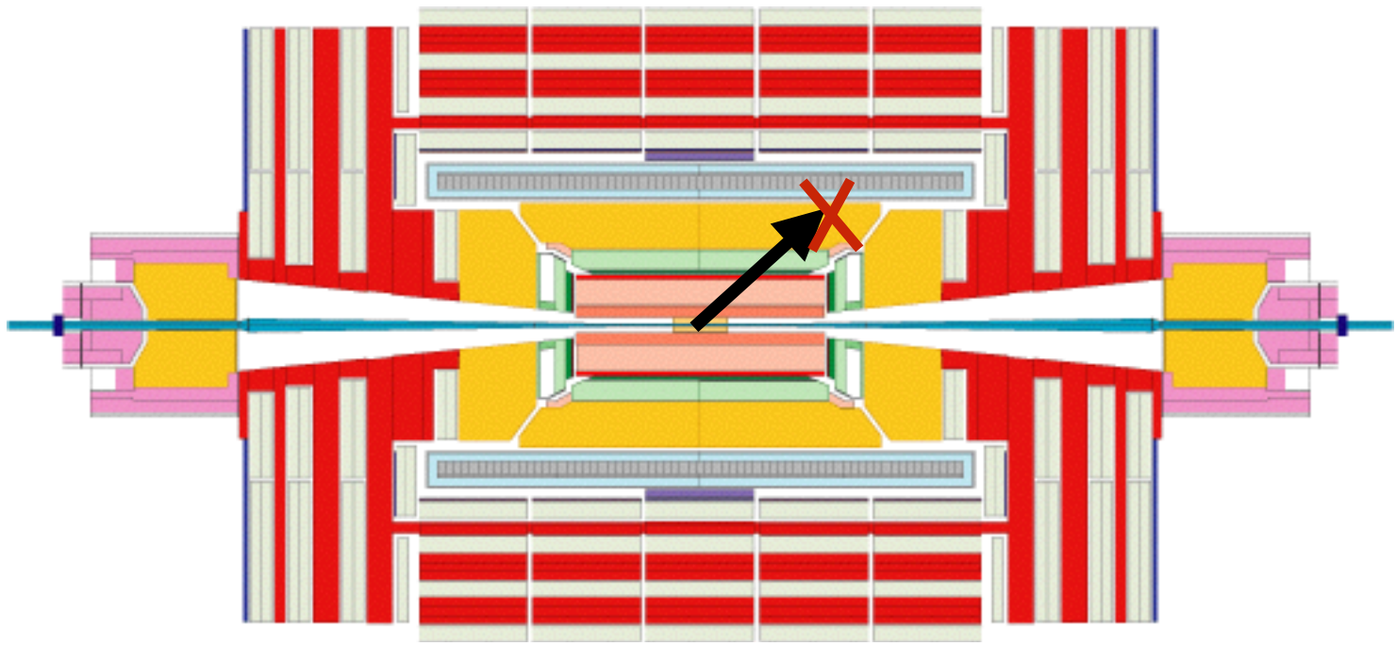
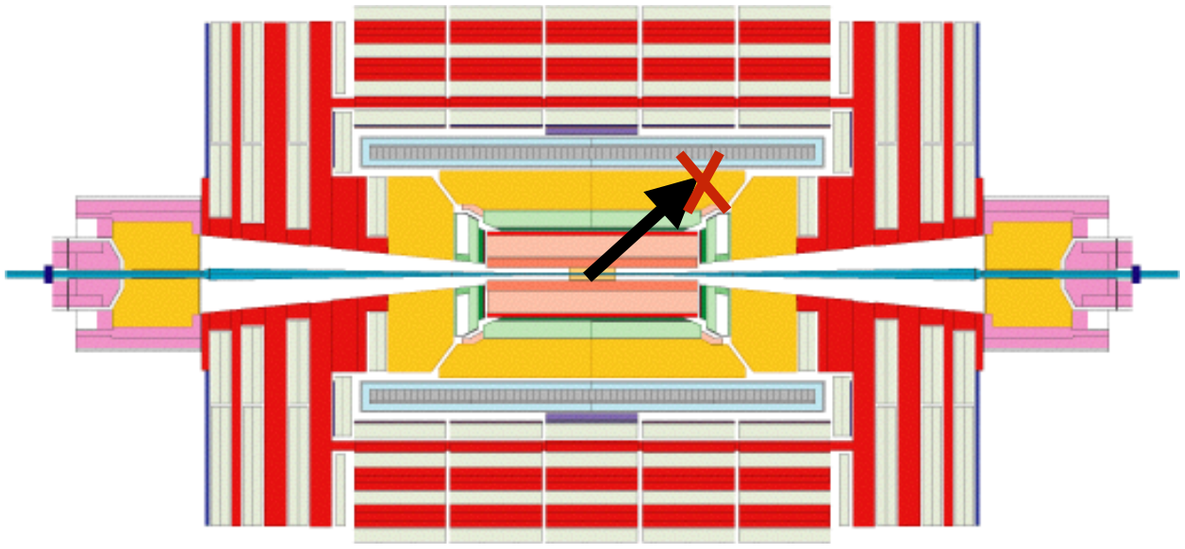
Stopped Particle Search

- Considers HSCPs that become completely stopped within the detector
- May decay *much* later
- Two signatures searched for:
  - Calorimeter (jets) — 2264688
  - Muon system (muons) — 2273460
- Both search in combined 2015+2016 dataset
- Search for decays out-of-time with colliding protons
- Backgrounds:
  - Cosmic rays
  - Beam halo
  - Detector noise

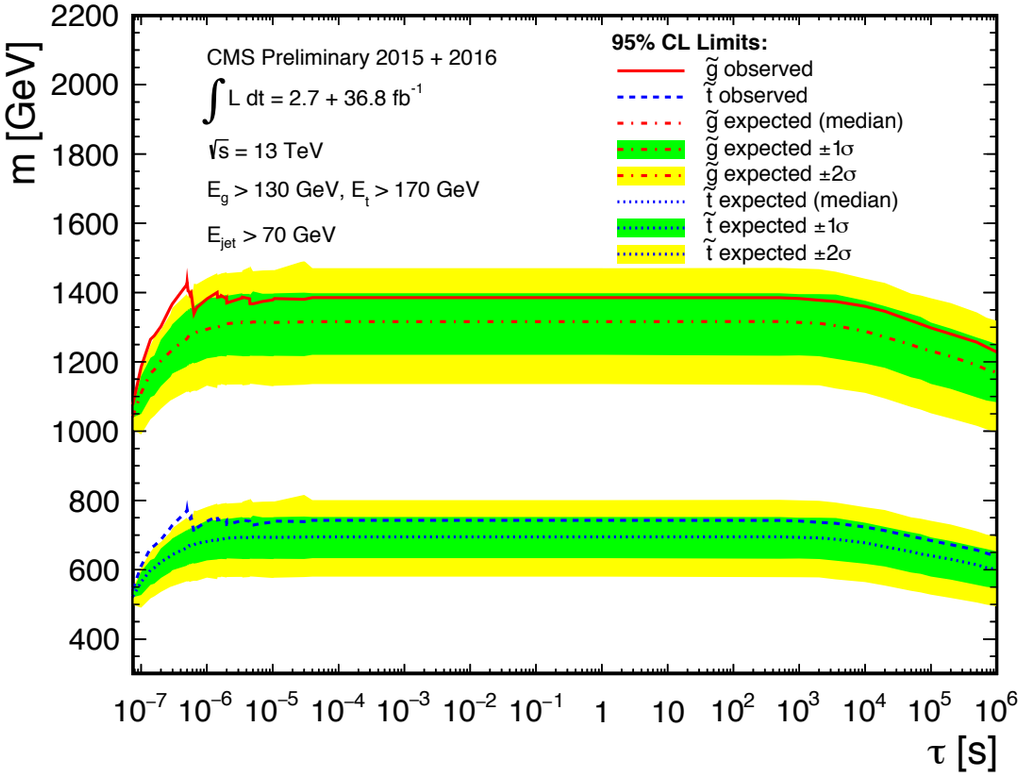


Stopped Particle Search: Calorimeter Signature

2264688



- Trigger on events out-of-time with proton collisions (≥ 2 bunch crossings)
- Energetic jet (E > 70 GeV)
- Data collected over 721 hours of trigger livetime
- Data-driven background estimation
- No excess observed
- Places limits on gluino and stop lifetimes up to ~11 days

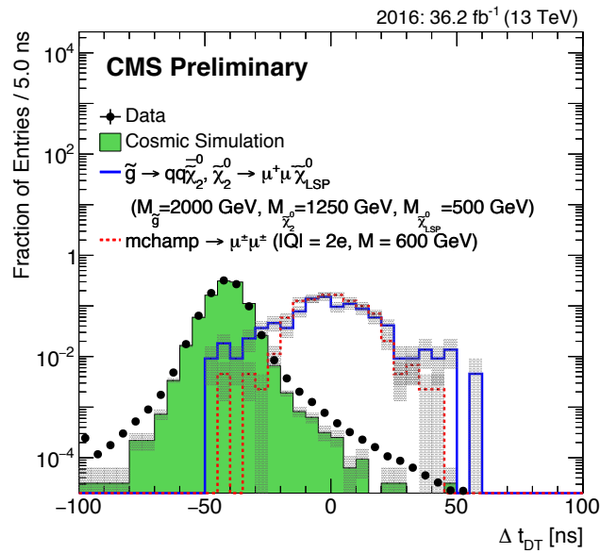


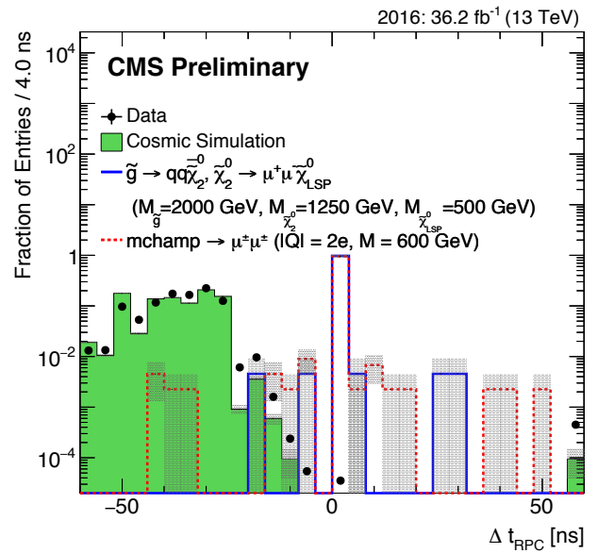
Period	Livetime (hrs)	Noise	Cosmics	Halo	Total	Observed
2015 control	-	$0.3^{+2.4}_{-0.3}$	1.7 ± 0.6	0	-	2
2015	135	$0.4^{+2.9}_{-0.4}$	2.6 ± 0.9	1.1 ± 0.1	$4.1^{+3.0}_{-1.0}$ (the median is 6.2)	4
2016 control	-	$0^{+2.2}_{-0}$	2.5 ± 0.9	0	-	2
2016	586	$0^{+9.8}_{-0}$	8.8 ± 3.1	2.6 ± 0.2	$11.4^{+10.3}_{-3.1}$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

Stopped Particle Search: Muon Signature

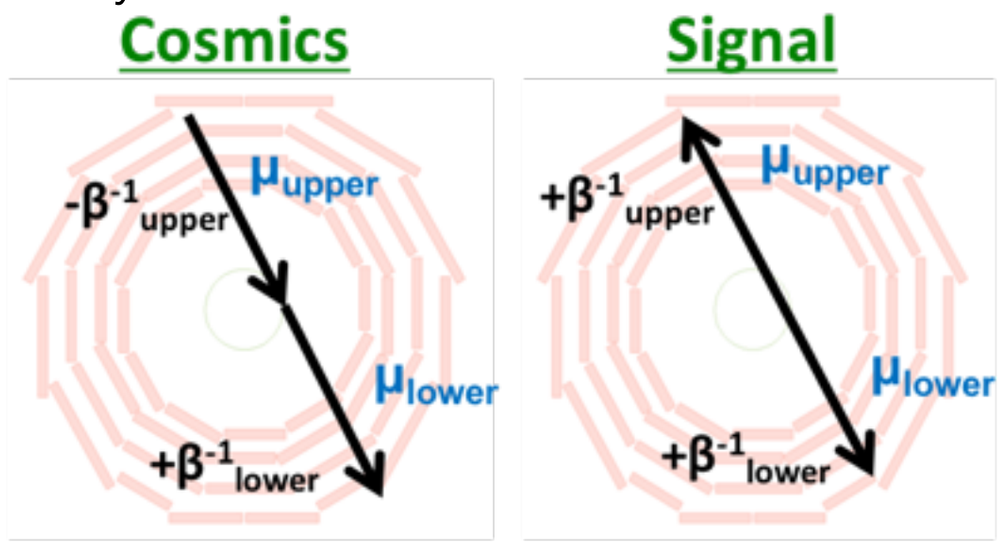
[2273460](#)

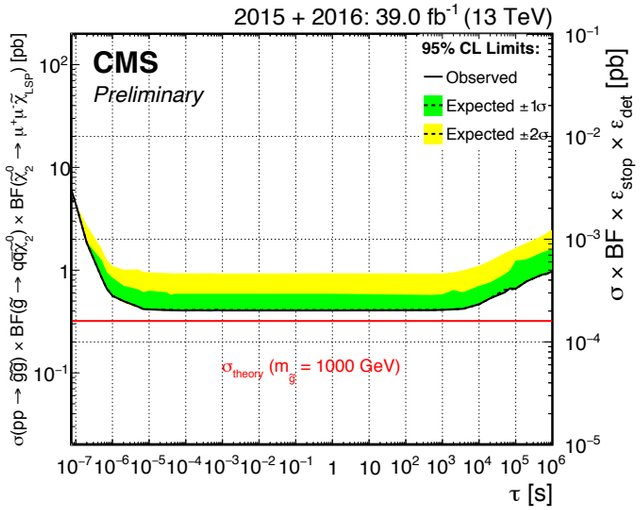
- Requires two muons out-of-time with proton collisions (≥2 bunch crossings), one each in upper/lower hemispheres
  - Unique reconstruction with no beamspot constraints
- Distinguish signal from cosmic muons by:
  - Direction of each muon
  - Time of flight difference between muons
- Data taken over 744 hours of trigger livetime

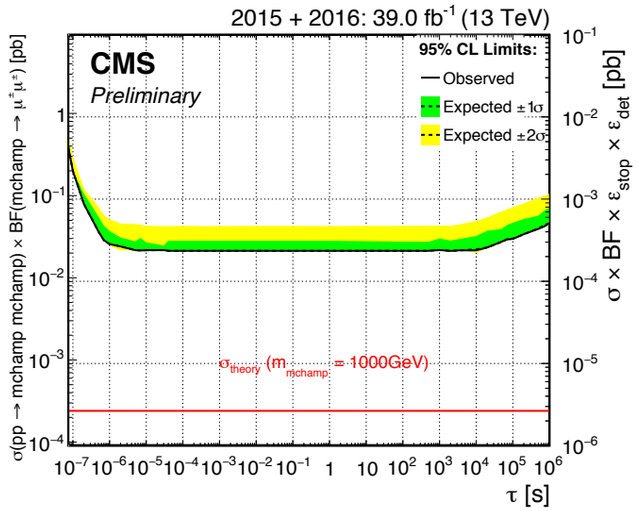


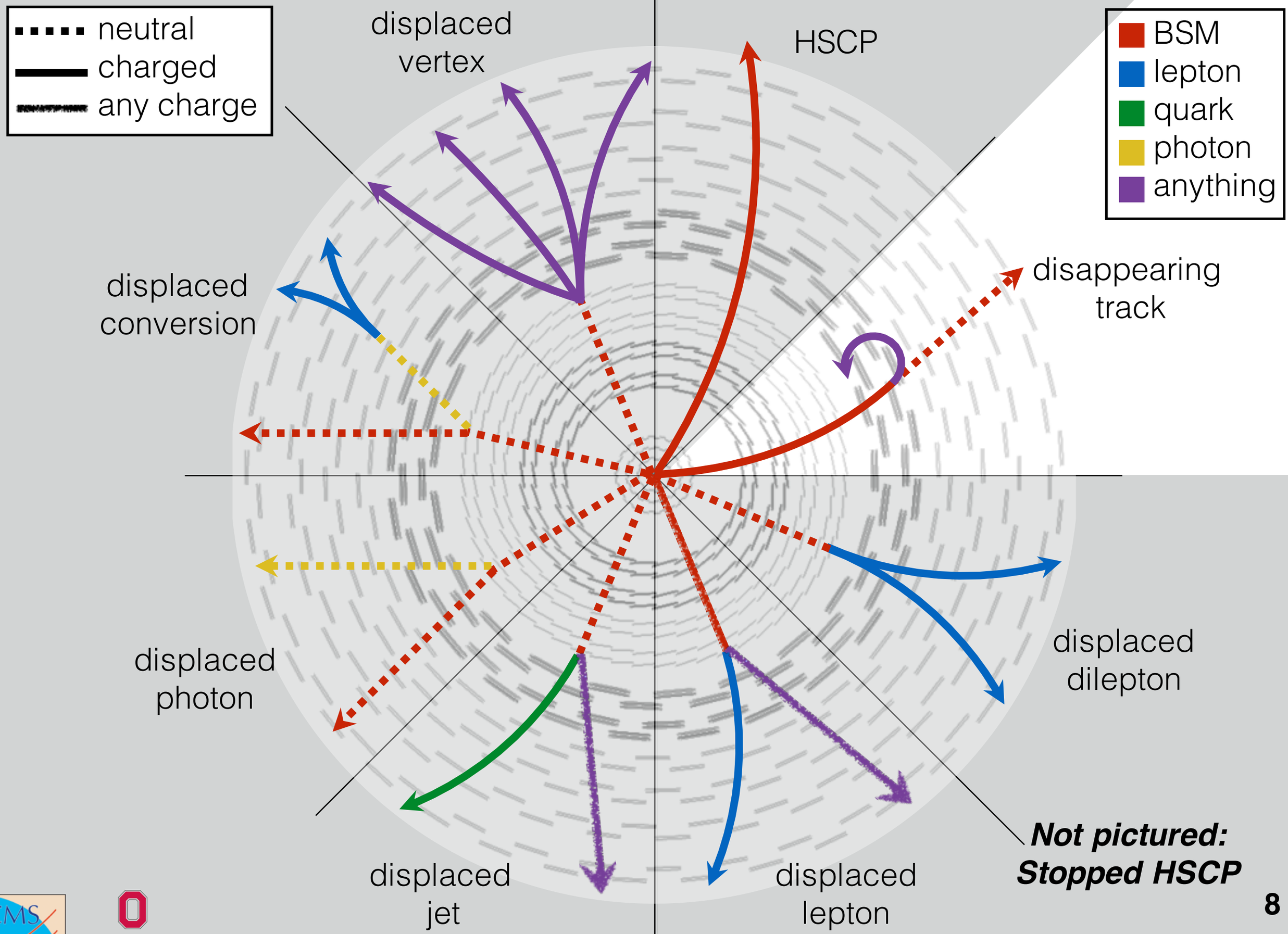


- No events observed
- Limits placed on gluino and stop lifetimes up to ~10 days









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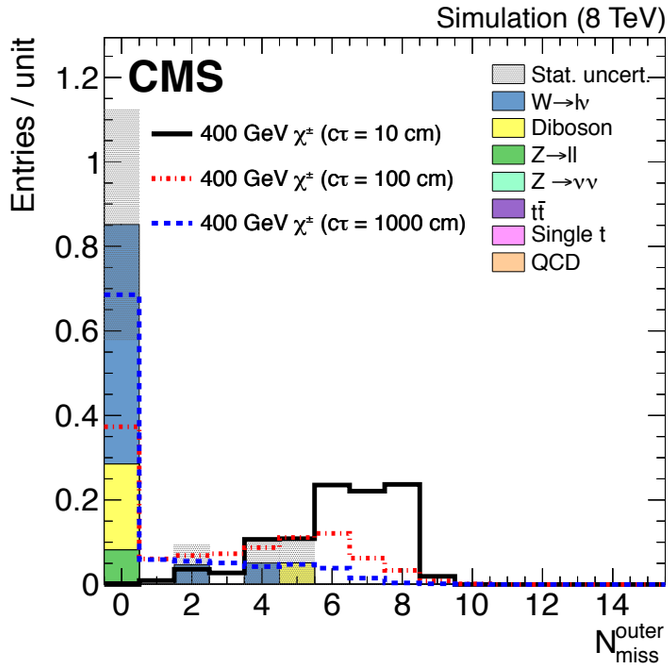
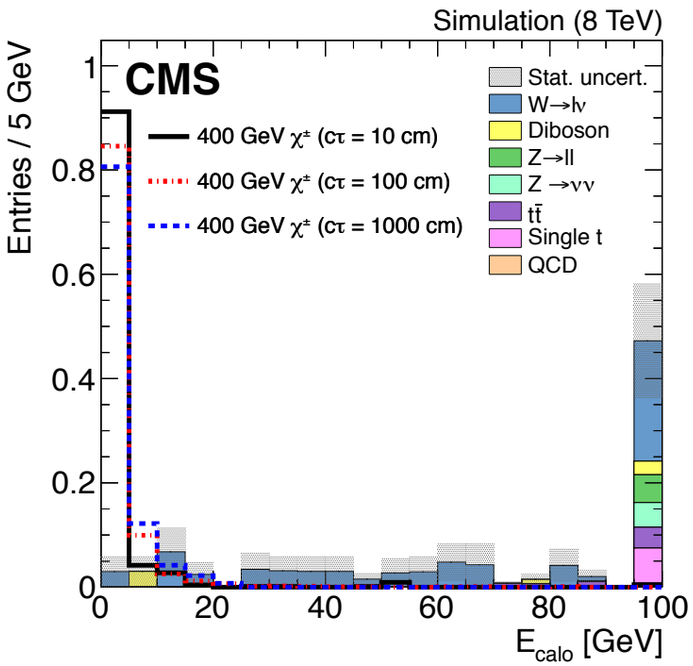
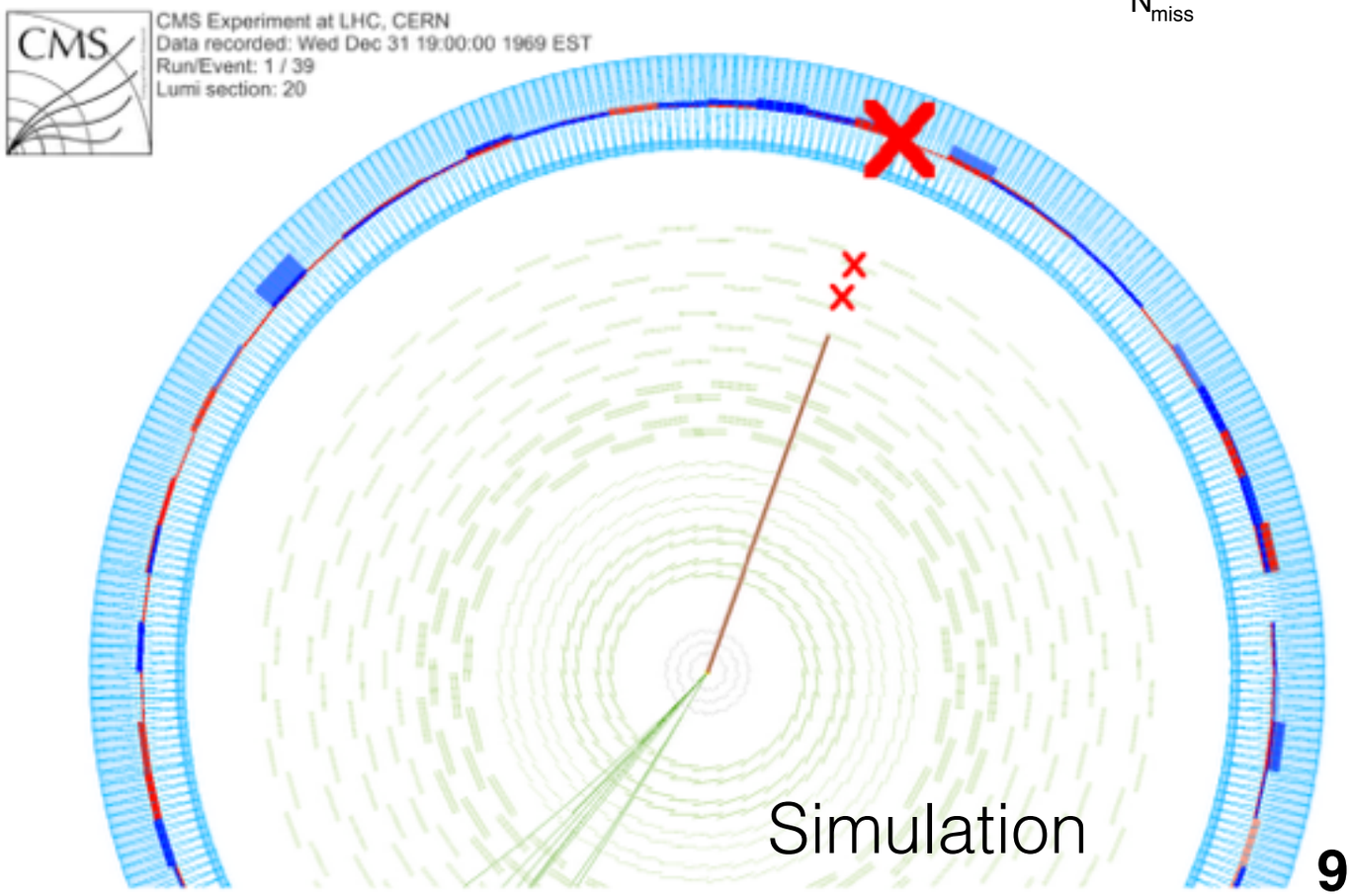
Disappearing Tracks Search

arXiv:1411.6006 (Run I)

- Charged LLPs decaying in the inner tracker to neutral or un-reconstructed particles
- Striking signature of a disappearing track:
  - Missing outer hits in the inner tracker
  - Very small associated calorimeter energy
  - No hits in the muon system
- Trigger on MET from radiated jet

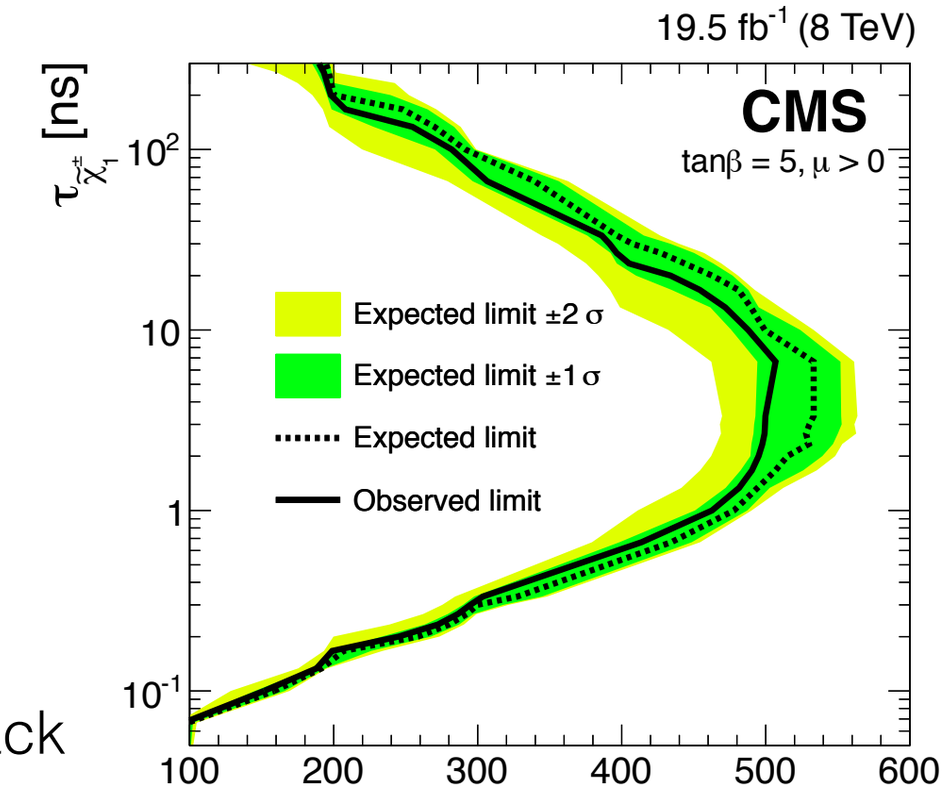




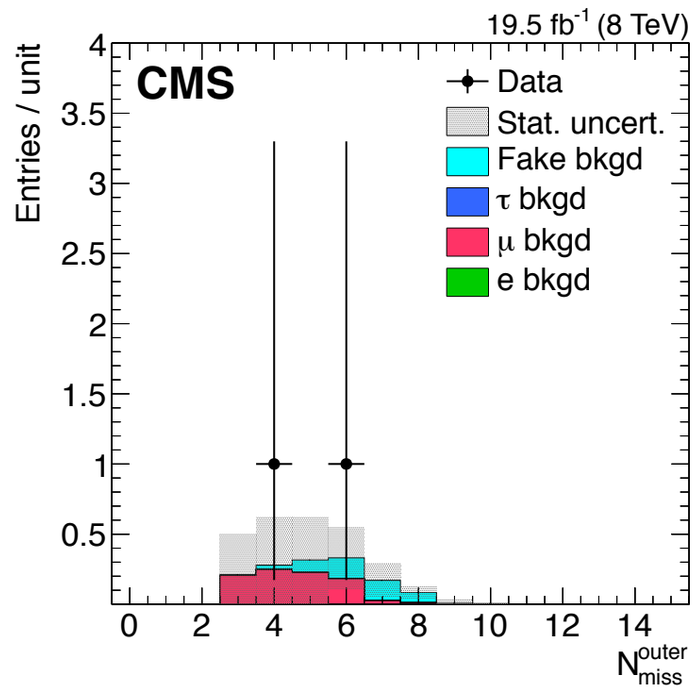


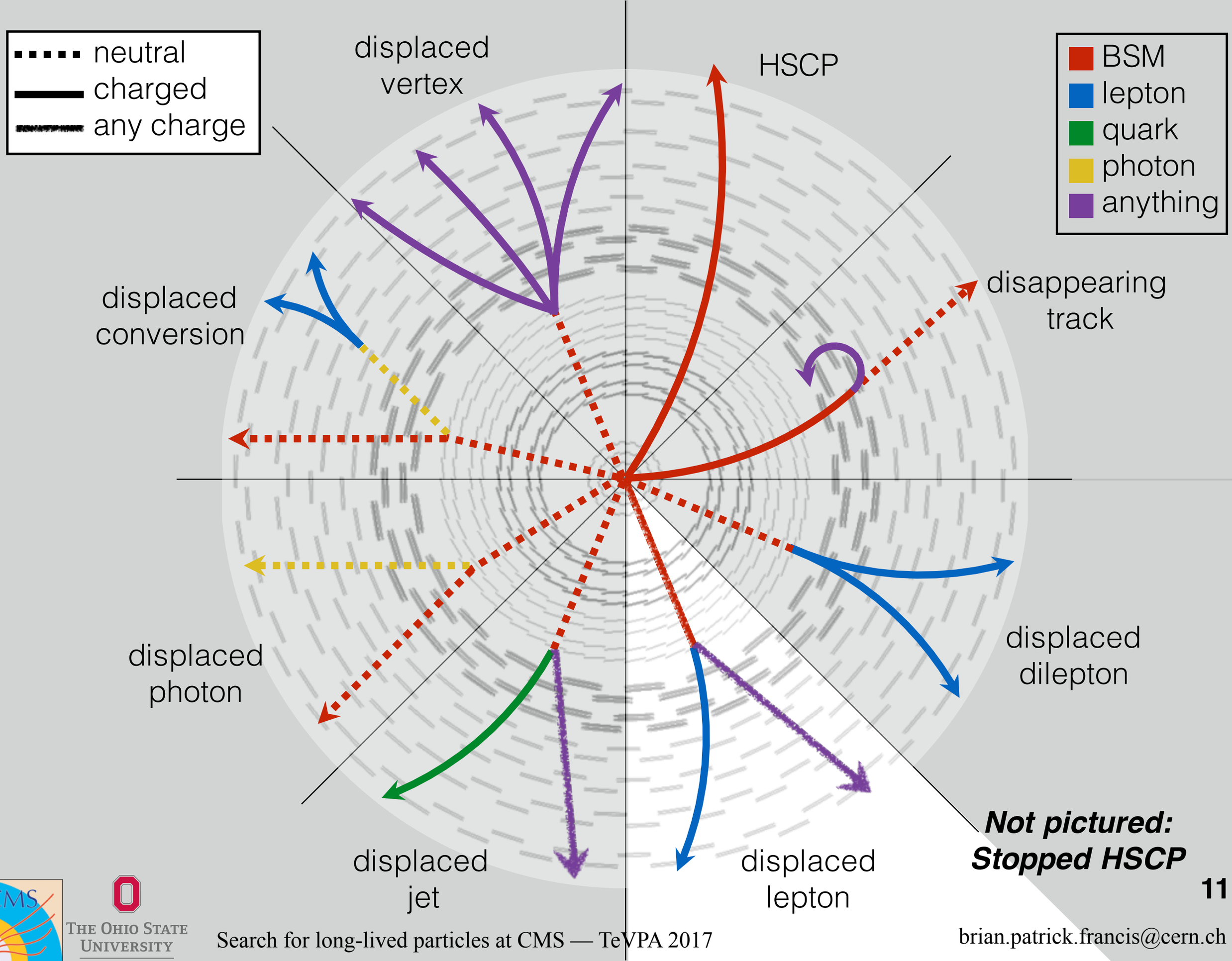
Disappearing Tracks Search arXiv:1411.6006 (Run I)

- Very small instrumental backgrounds:
  - Un-reconstructed charged leptons
  - ‘Fake’ tracks — tracker hit combinations not produced by a single particle
- No excess observed in 8 TeV (Run I) data
  - Cross section limits placed on AMSB chargino production
- The Run II analysis is well under way!
  - Specialized trigger requiring MET and isolated track
  - Completely data-driven background estimation
- Pixel tracker upgrade: additional layer since 2017!



Event source	Yield
Electrons	<0.49 (stat) <0.50 (stat+syst)
Muons	$0.64^{+1.47}_{-0.53}$ (stat) $\pm$ 0.32 (syst)
Taus	<0.55 (stat) <0.57 (stat+syst)
Fake tracks	$0.36^{+0.47}_{-0.23}$ (stat) $\pm$ 0.13 (syst)
Data	2

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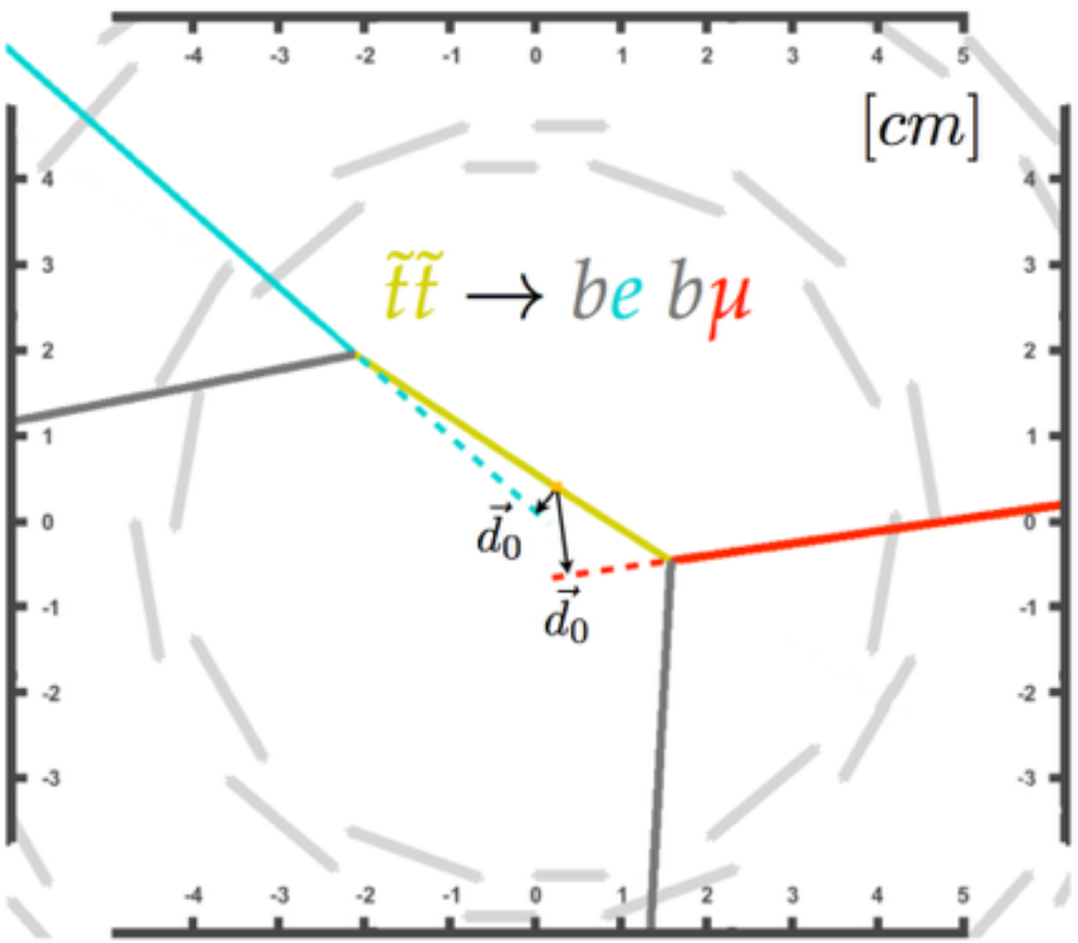
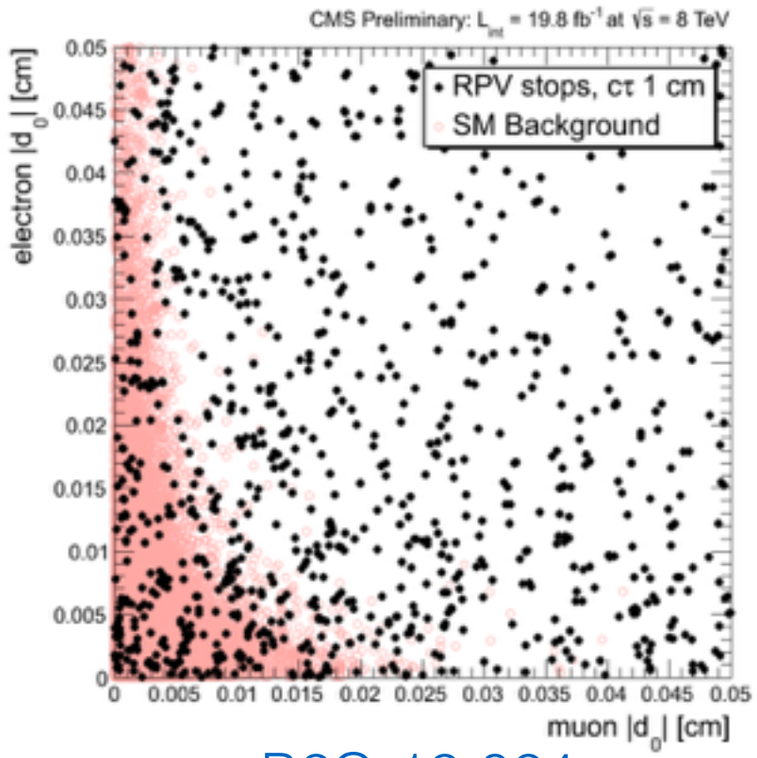
Displaced eμ Search [2205146]



[B2G-12-024]

- Targets RPV $\tilde{t} \to bl^{\pm}$ pair production
- Requires an e-μ pair with opposite charge
- Discriminates from SM backgrounds with lepton impact parameter (d_0)

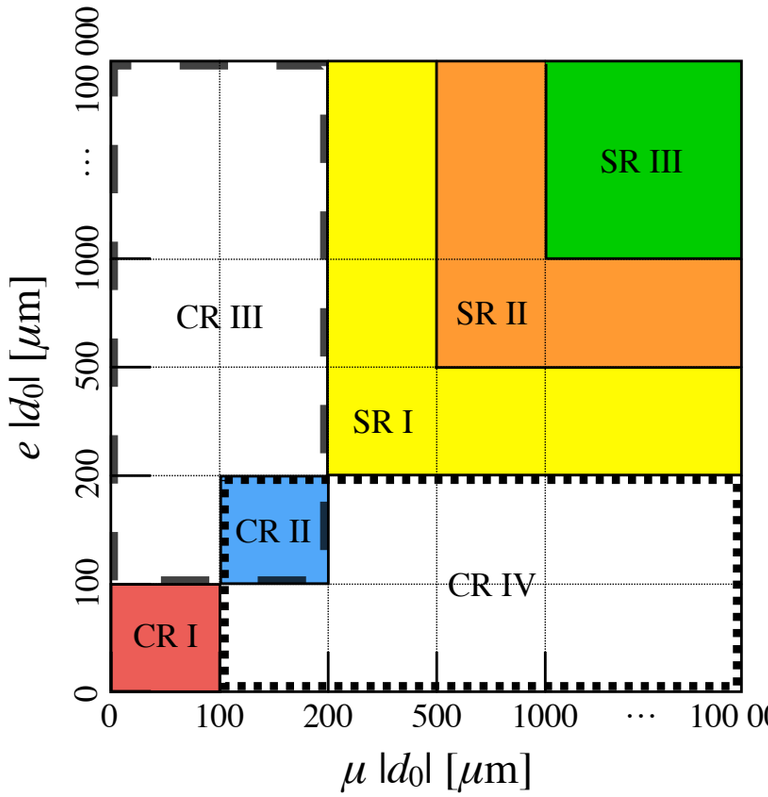


[B2G-12-024]

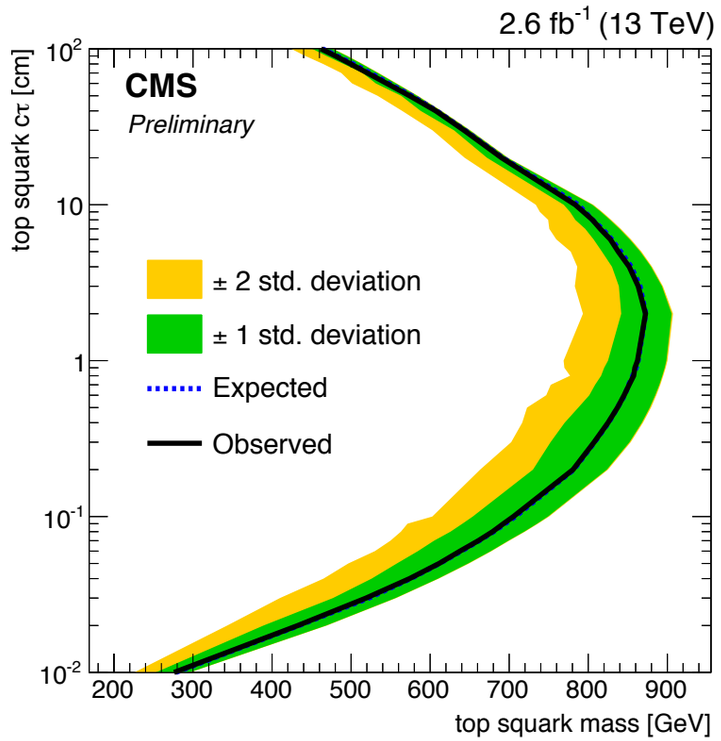
Displaced eμ Search

2205146

- No excess observed in 3 orthogonal search regions 200 μm < d_0 < 10 cm
- Currently updating with 2016 data
  - Expanding search to include ee, μμ decays
- Will also benefit from 2017 pixel tracker upgrade



Event Source	Search Region I	Search Region II	Search Region III
$W \to l\nu$	$(1.1 \pm 0.5) \times 10^{-3}$	$(2.4 \pm 1.7) \times 10^{-5}$	$(0.25 \pm 0.29) \times 10^{-5}$
single top	$(8.4 \pm 1.2) \times 10^{-3}$	$(35 \pm 12) \times 10^{-5}$	$(1.50 \pm 0.91) \times 10^{-5}$
diboson	$(18.2 \pm 5.8) \times 10^{-3}$	$(39 \pm 25) \times 10^{-5}$	$(4.0 \pm 4.6) \times 10^{-5}$
$Z \to ll$	$(115 \pm 25) \times 10^{-3}$	$(100 \pm 160) \times 10^{-5}$	$(69 \pm 71) \times 10^{-5}$
$t\bar{t}$	$(60.6 \pm 5.1) \times 10^{-3}$	$(226 \pm 25) \times 10^{-5}$	$(8.0 \pm 1.6) \times 10^{-5}$
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
$pp \to \tilde{t}_1\tilde{t}_1^*(M_{\tilde{t}_1} = 700\,\text{GeV})$			
$c\tau = 0.1\,\text{cm}$	3.8 ± 0.2	0.94 ± 0.06	0.16 ± 0.02
$c\tau = 1\,\text{cm}$	5.2 ± 0.4	4.1 ± 0.3	7.0 ± 0.3
$c\tau = 10\,\text{cm}$	0.8 ± 0.1	1.0 ± 0.1	5.8 ± 0.2
$c\tau = 100\,\text{cm}$	0.009 ± 0.005	0.03 ± 0.01	0.27 ± 0.03



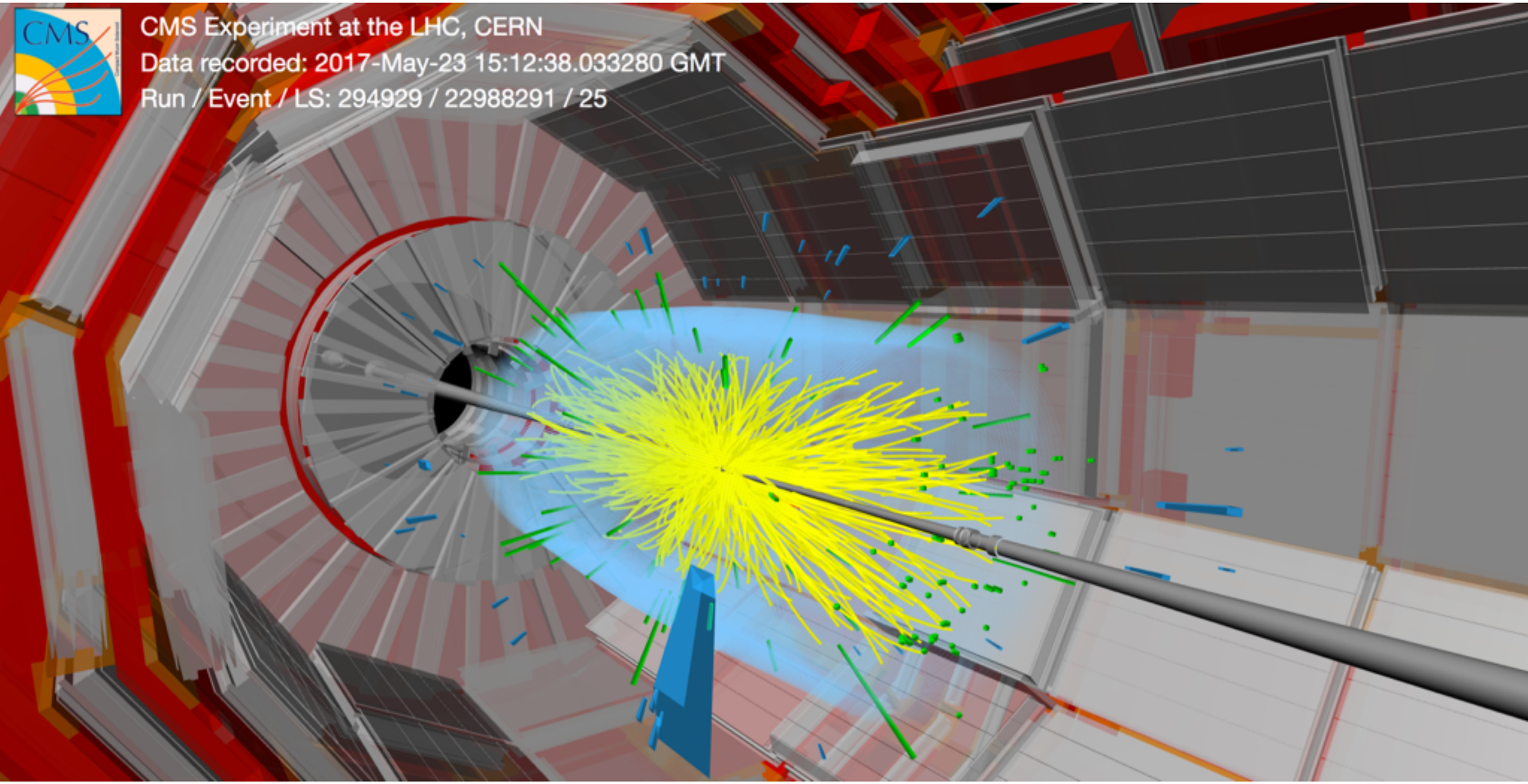
Summary and Outlook

- More important than ever to search where we haven't before
- Many signatures require non-conventional analysis techniques
- Many upcoming results from CMS with the current 38.5/fb 13 TeV dataset
- 2017 is well under way!
  - Upgraded pixel detector with new 4th barrel layer and 3rd endcap disk on each side

	Final state	13 TeV
1	displaced ee/μμ pairs	
2	displaced μμ pairs in muon system	
3	displaced eμ pairs	2205146
4	displaced μμ pairs (dark photons)	2232052
5	displaced photons using ECAL timing	
6	displaced photons using conversions	
7	displaced vertices	
8	displaced jets	2256654
9	short, highly ionizing disappearing tracks	
10	disappearing tracks	
11	kinked tracks	
12	fractionally charged particles	
13	HSCPs	2114818 (2015) 2205281 (2016)
14	stopped particles	2264688 (jets) 2273460 (muons)
15	delayed muons	
16	…many more!	

Backups

2017 Proton Collisions



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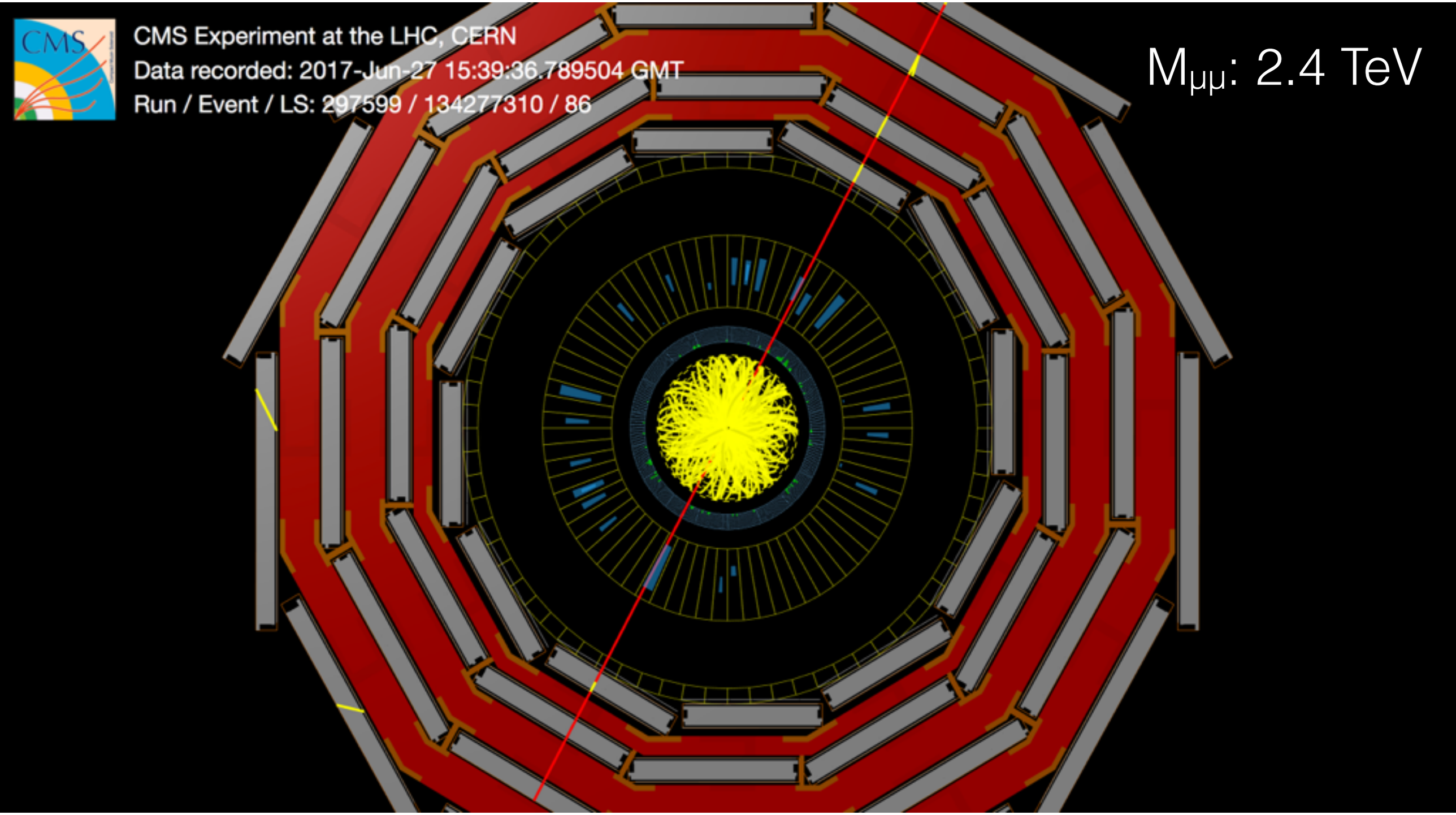

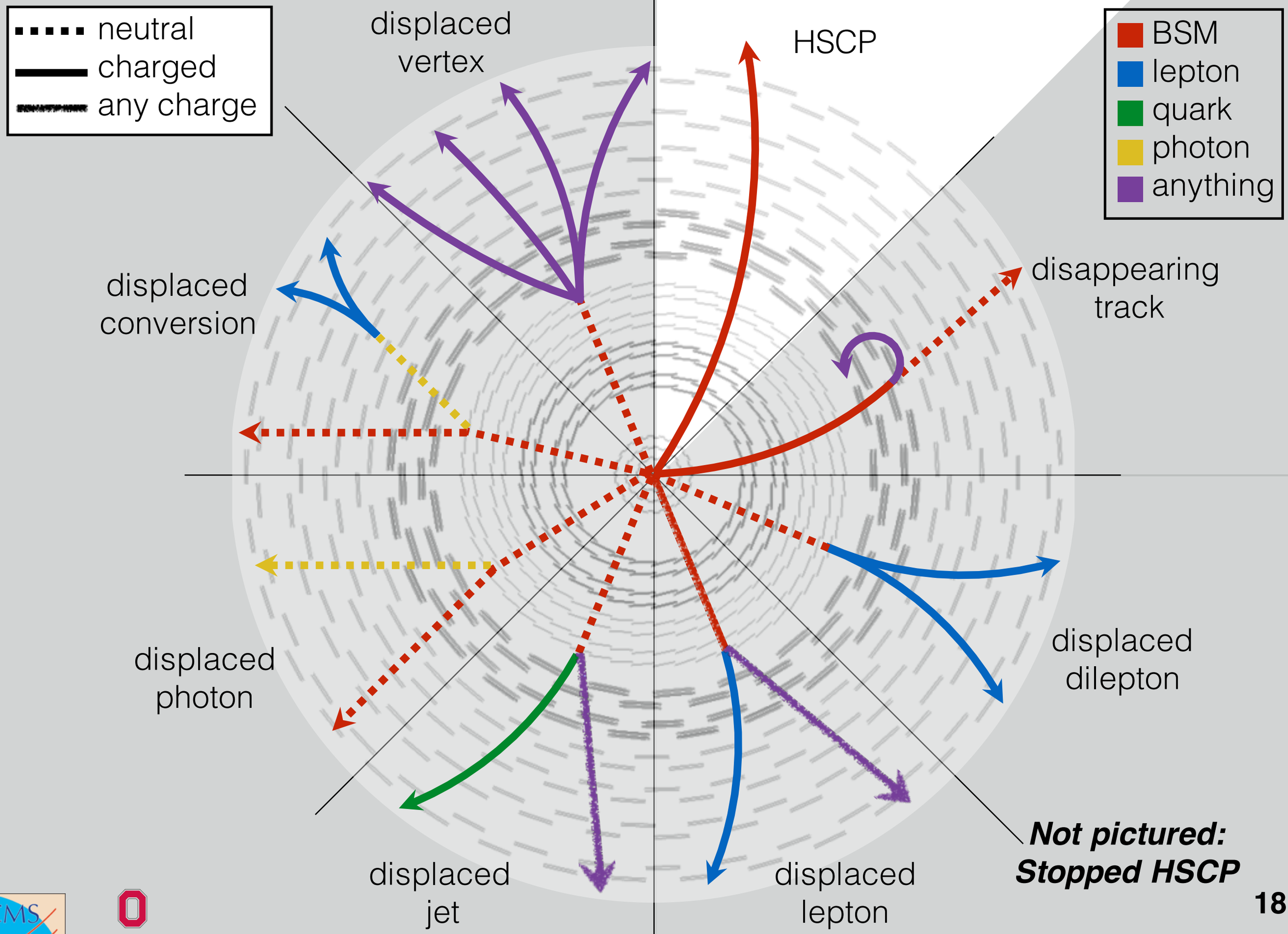

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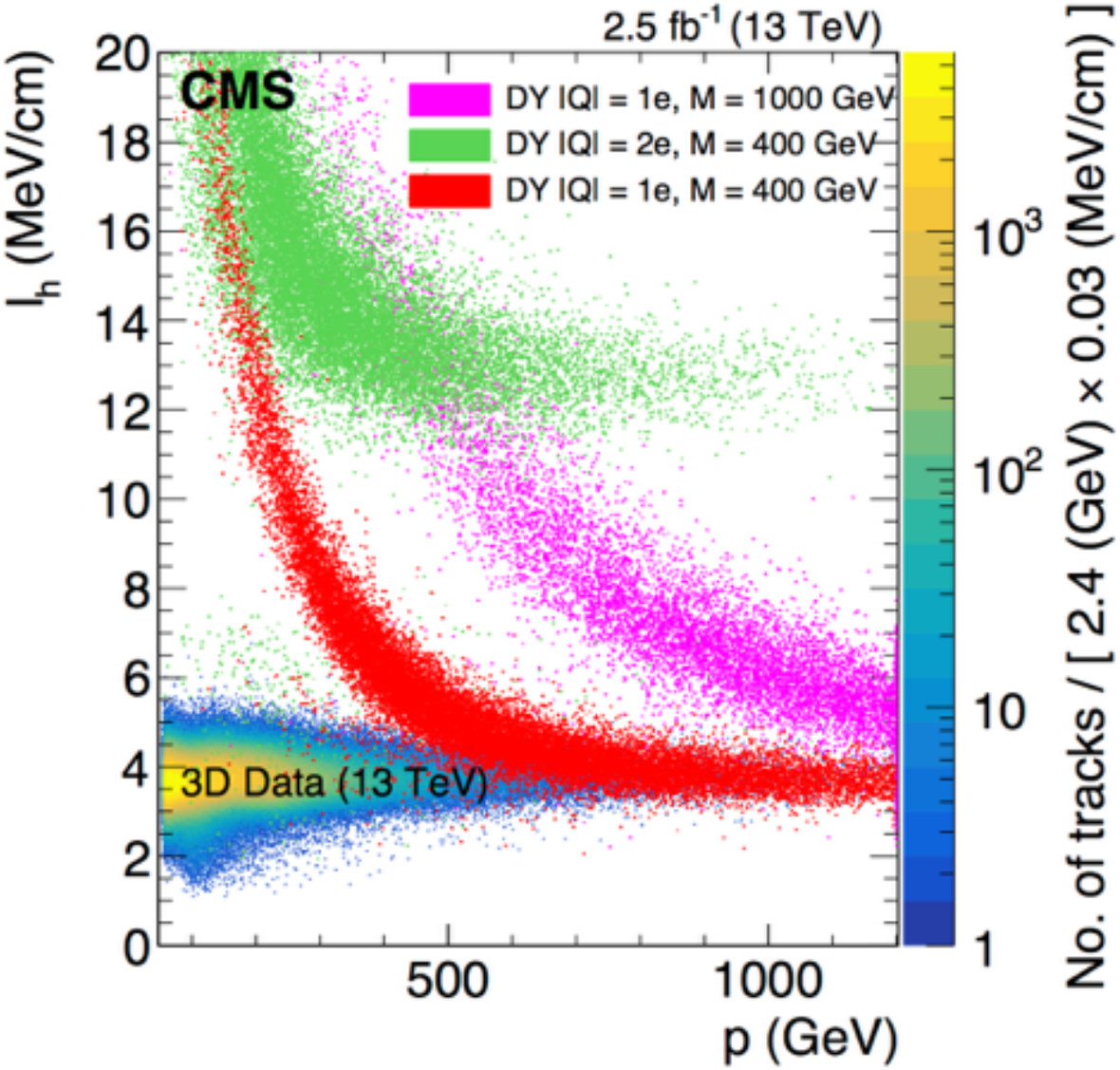
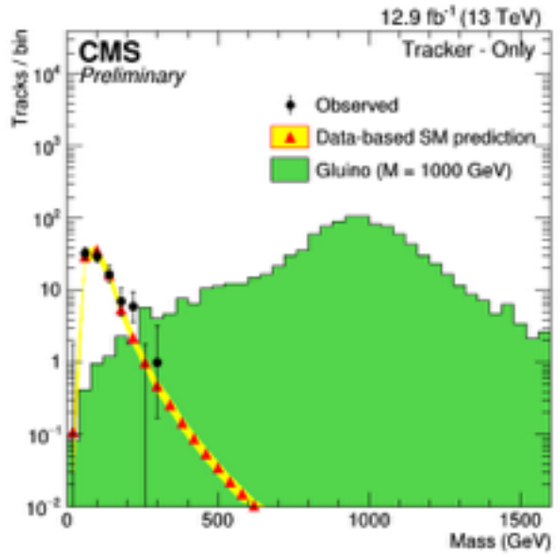
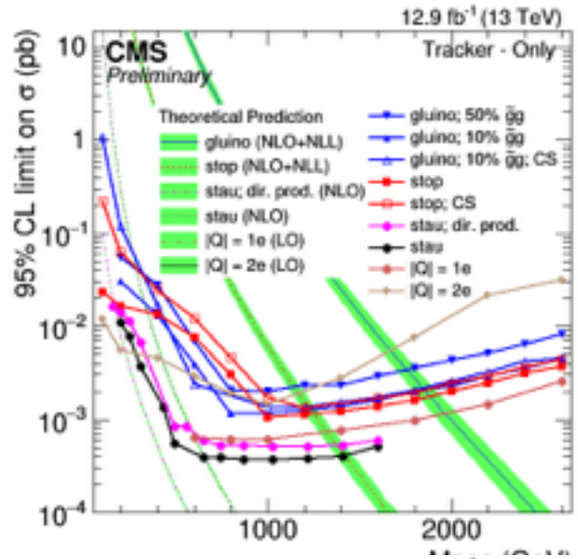
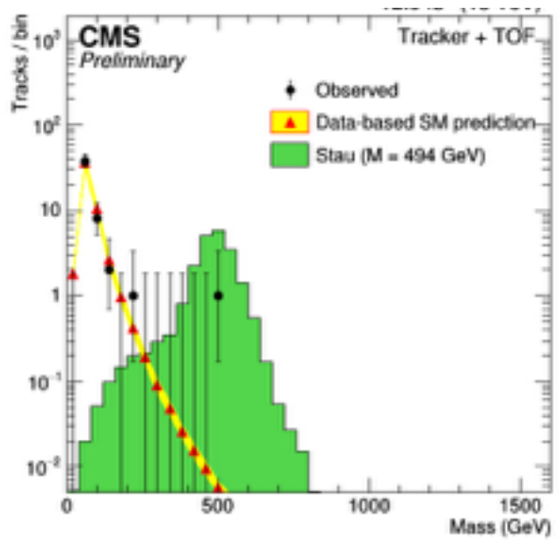
Heavy Stable Charged Particle (HSCP) search

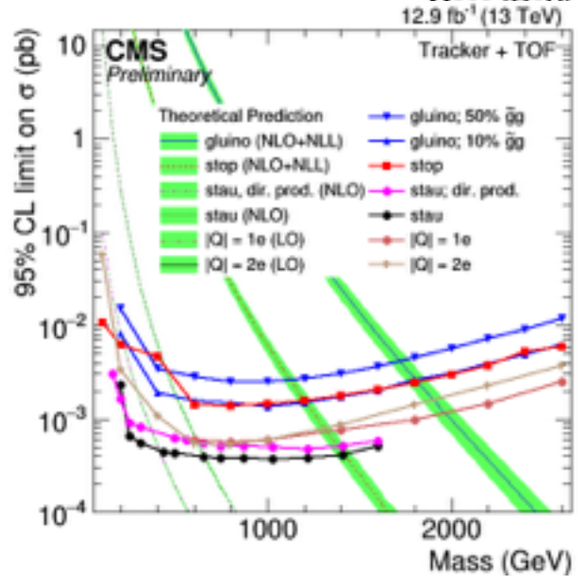
- Very unique signature:
  - Large ionization energy loss in detectors (***dE/dx*** or I_h)
  - Long time-of-flight to muon detectors (β^{-1})



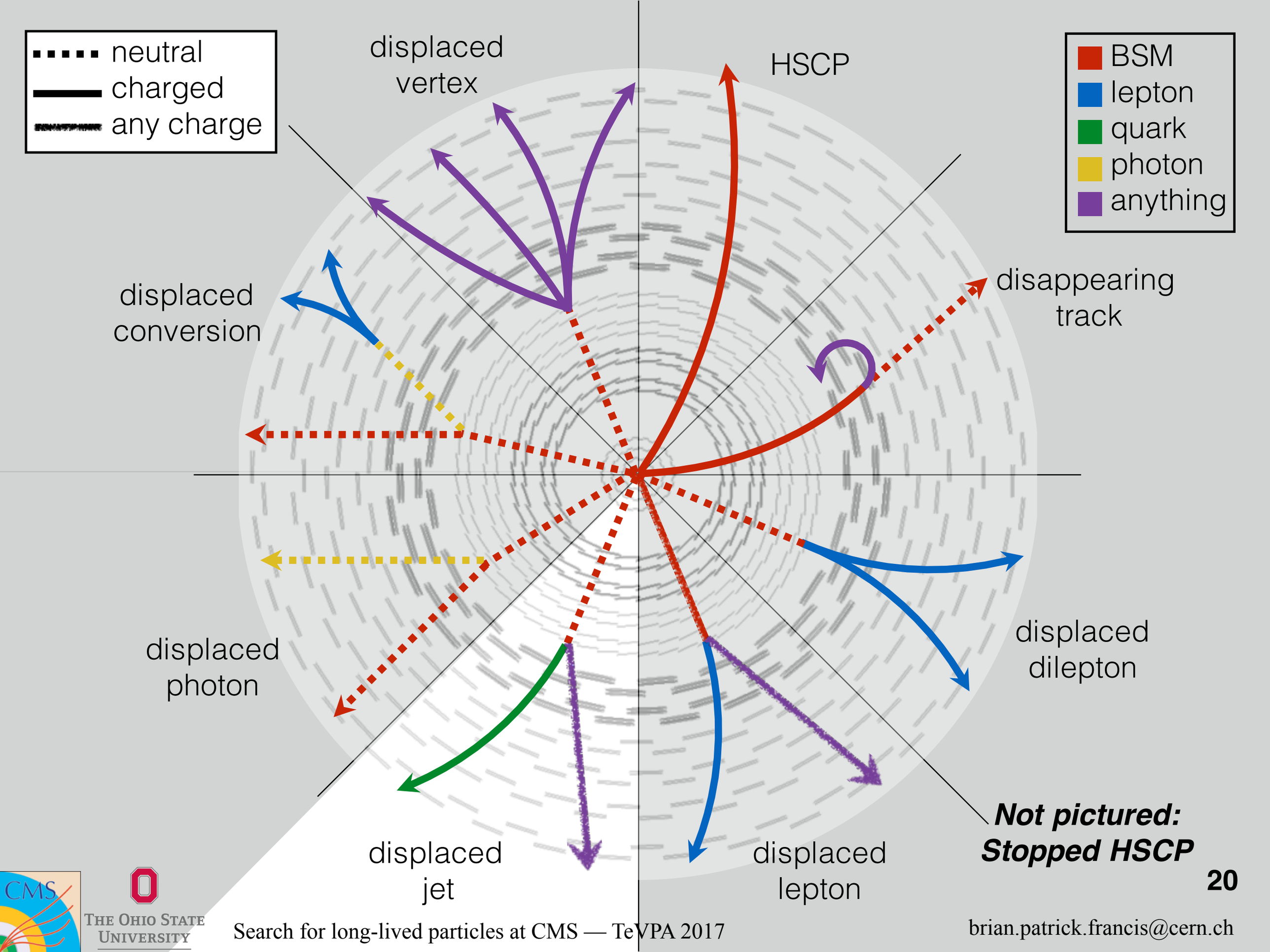








[2205281]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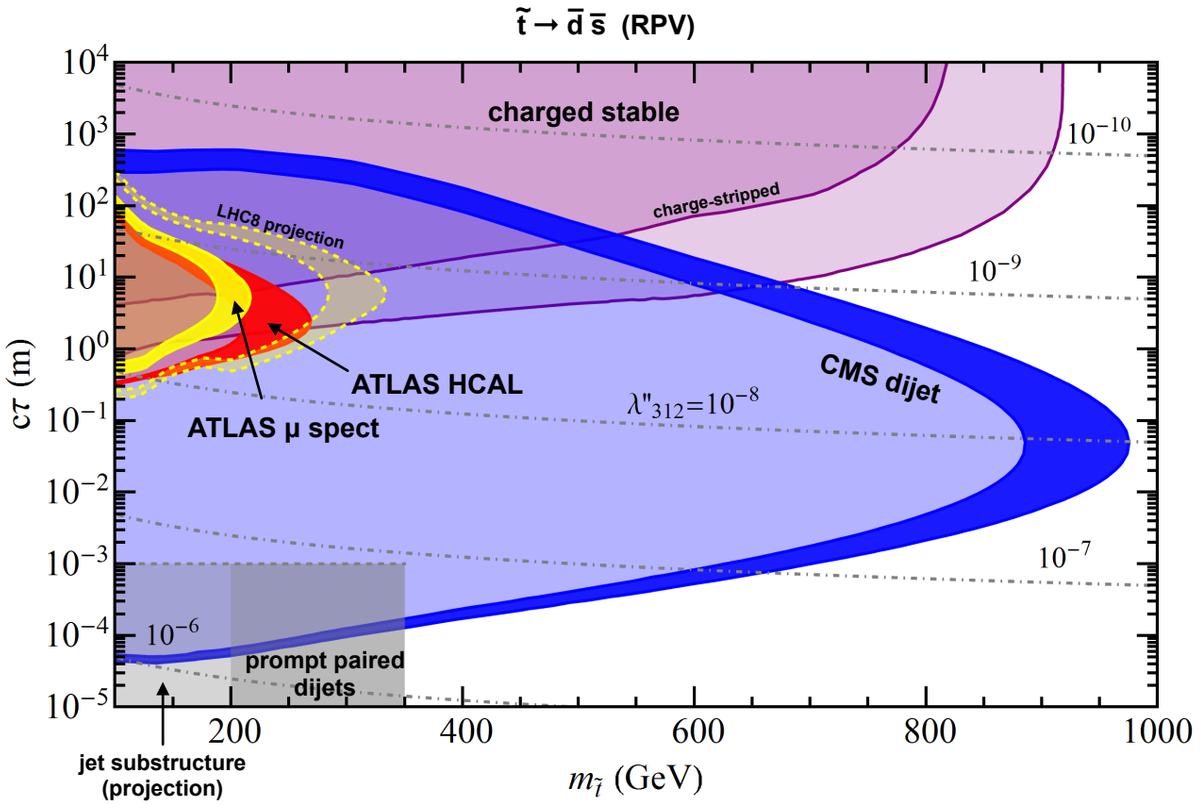
Displaced Jets Search [2256654]



[arXiv:1503.05923]

- Long-lived neutral particles decaying to a jet (or jets) within the detector
- Highly sensitive Run I analysis searched for dijets sharing a displaced vertex
- Run II analysis developed a jet-based tagging strategy
  - Now sensitive to single displaced jets
  - Able to place limits on RPV stop models

Displaced Jets Search 2256654

- Jet tagging variables:
  - **Vertex α**: fraction of jet's track PT associated to vertex (cut on highest α vertex)
  - **Track IP_{sig}**: transverse impact parameter wrt PV, divided by its error
    - Cut on median IP^{2D}_{sig} for the jet
  - **Track Θ**: angle between track PT and the direction from the PV and the track's innermost hit
    - Cut on median Θ_{2D} for jet

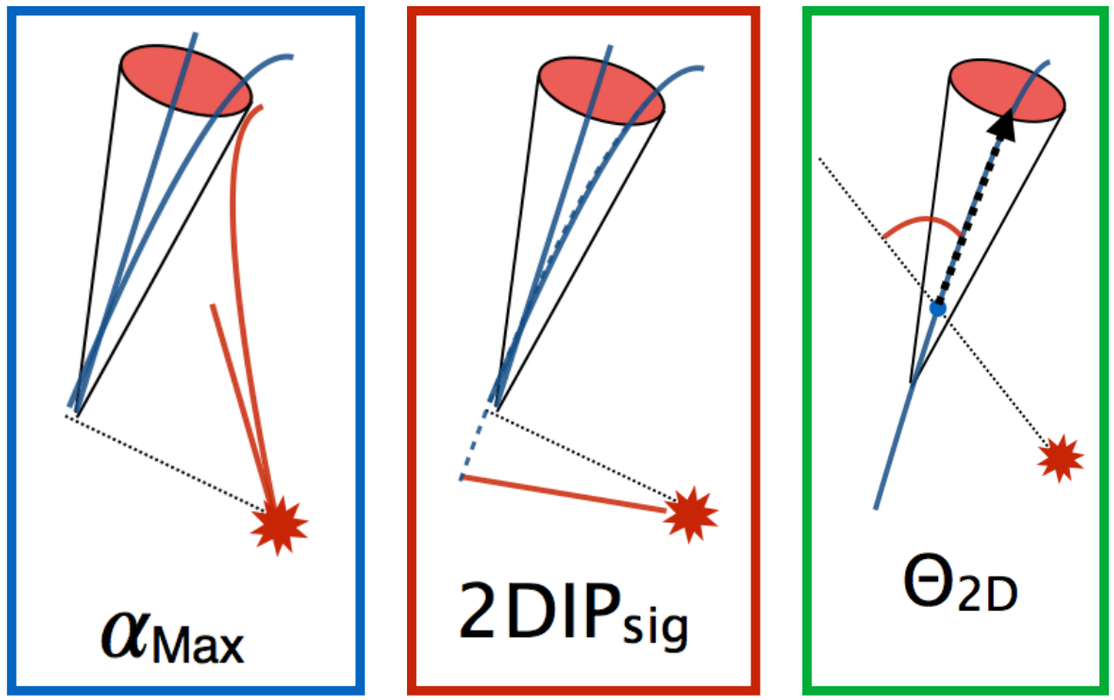
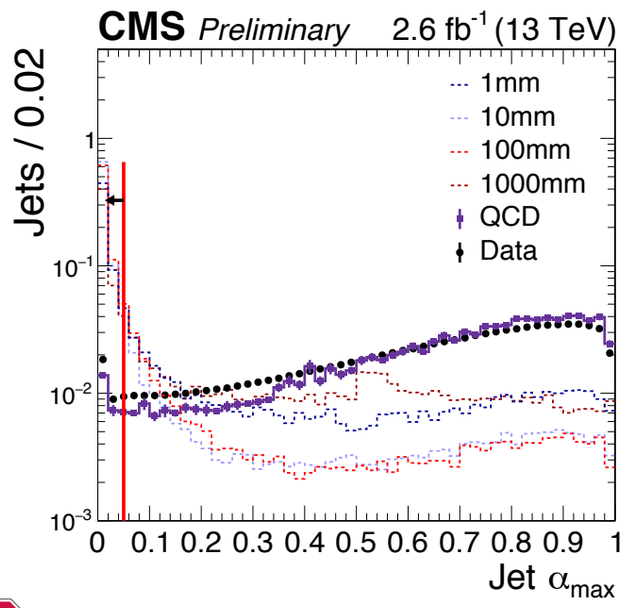
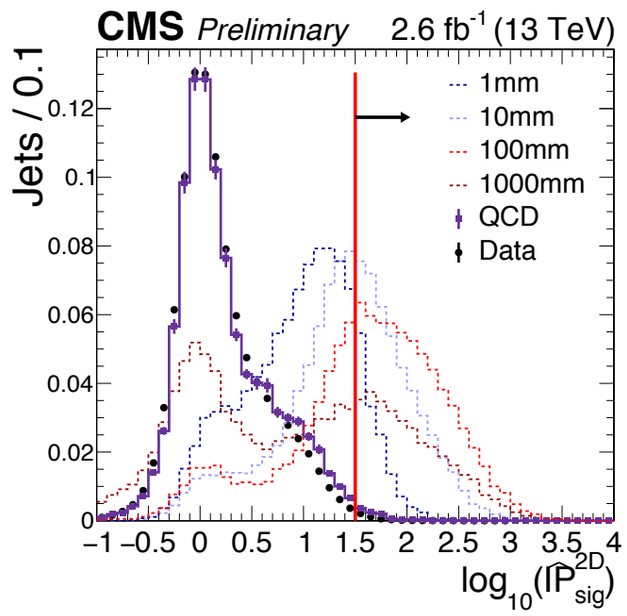
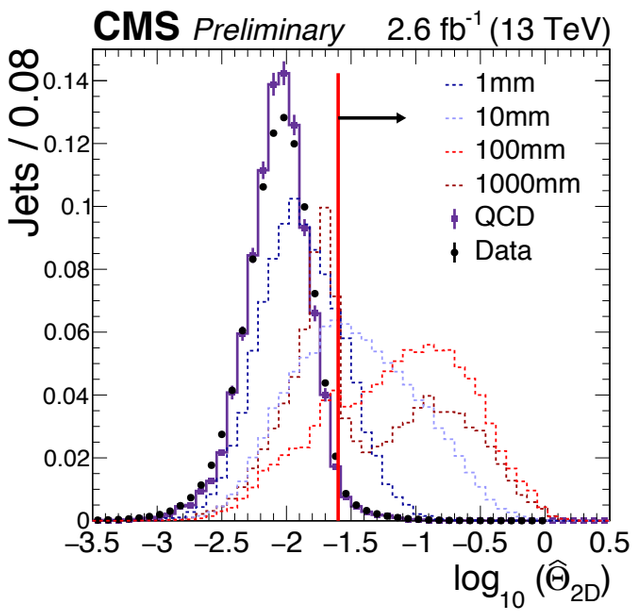


Image credit: J. Hardenbrook

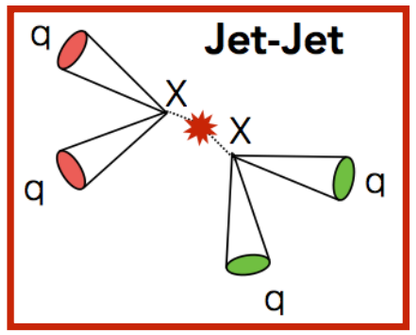


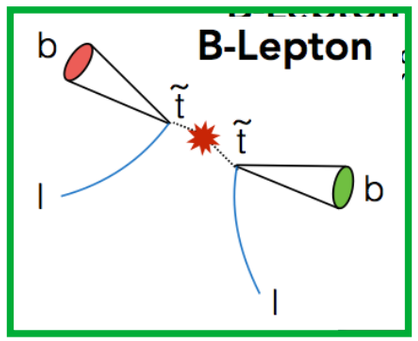


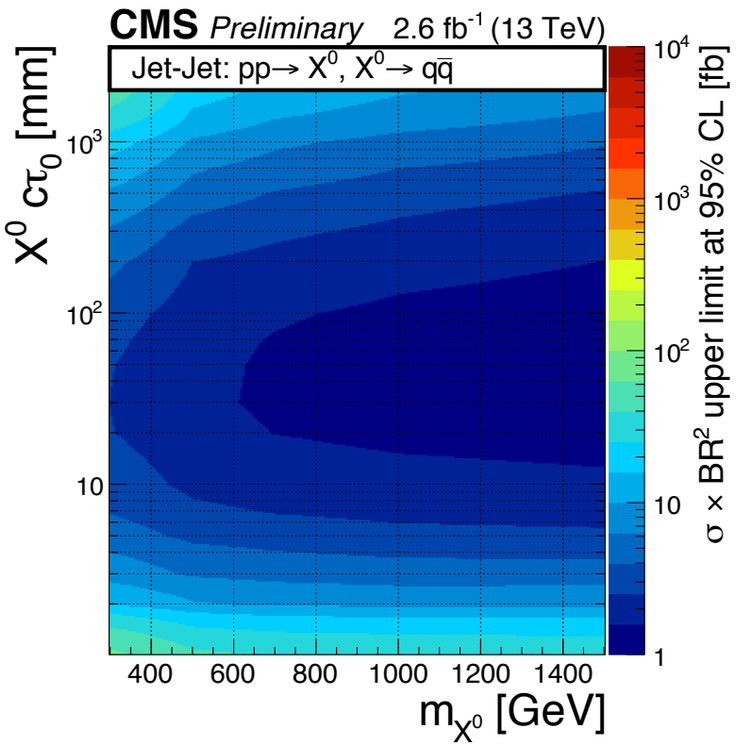


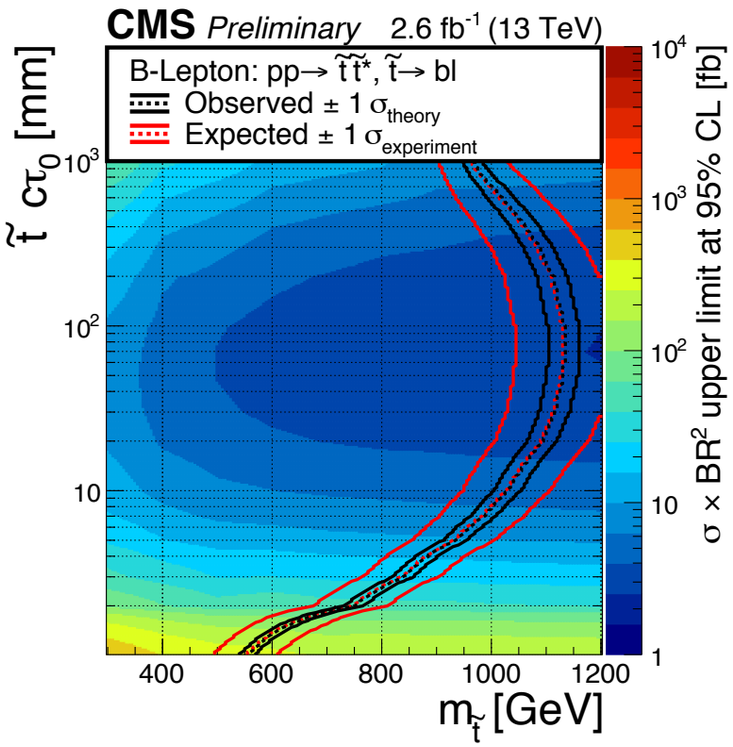
Displaced Jets Search

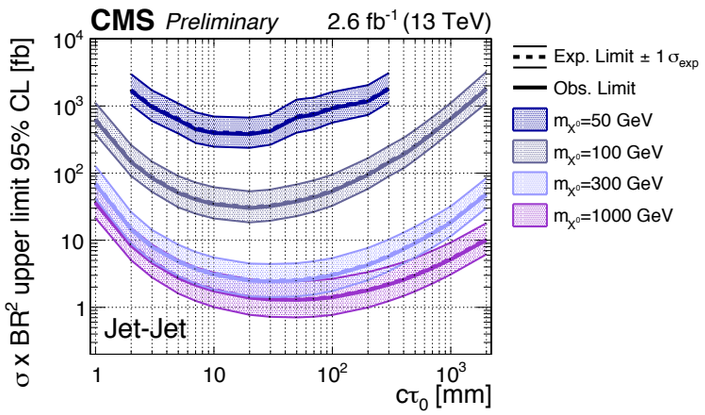
2256654

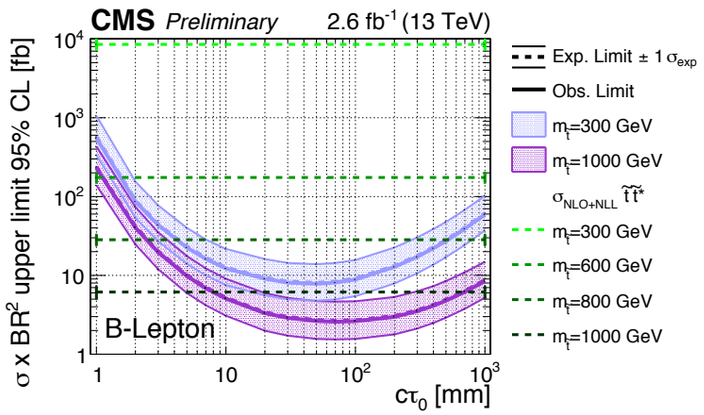












- Very small backgrounds
- No excess observed
- Limits set on several models as a function of particle lifetime and mass

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