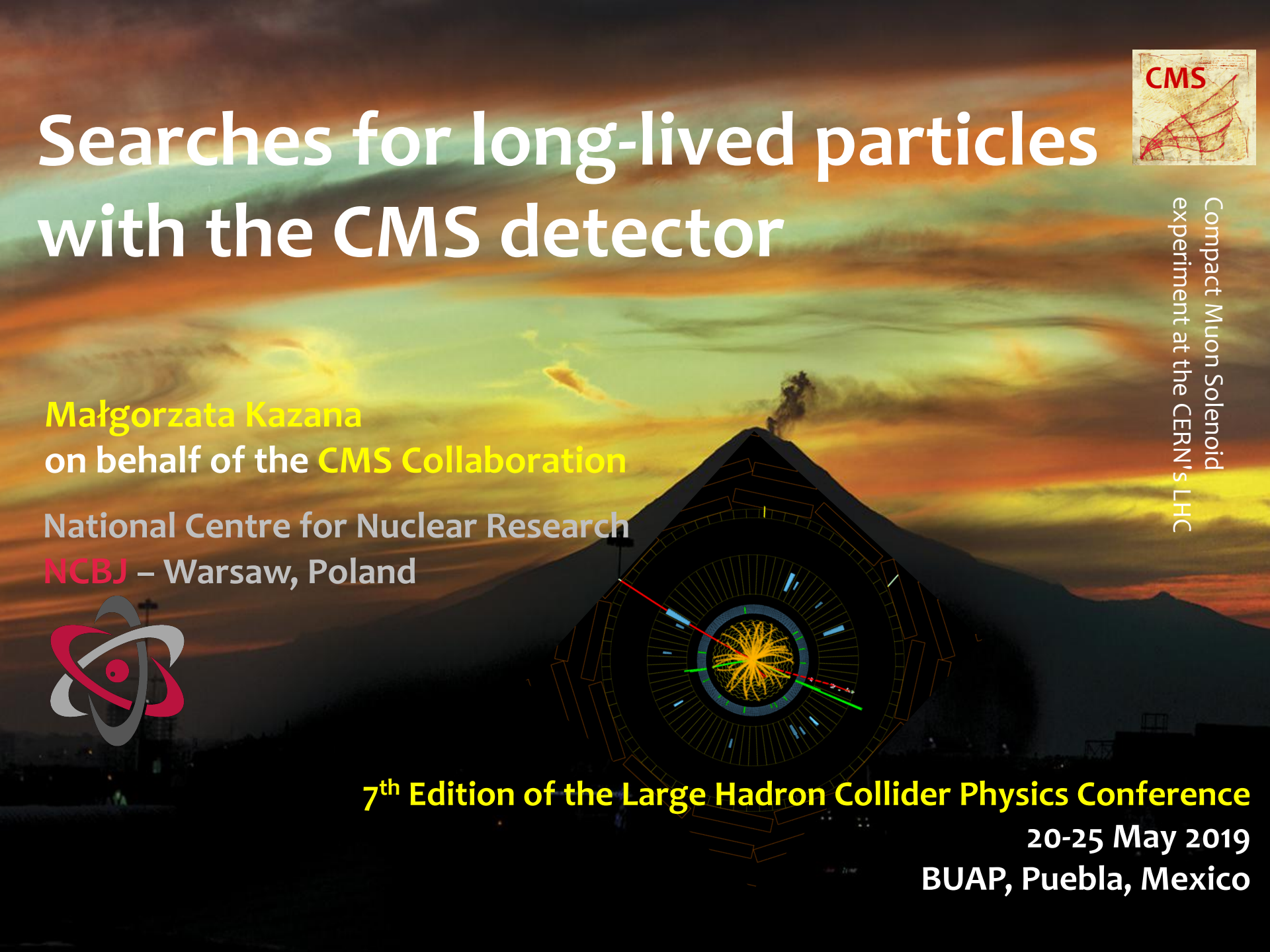
Searches for long-lived particles with the CMS detector



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NCBJ – Warsaw, Poland

7th Edition of the Large Hadron Collider Physics Conference
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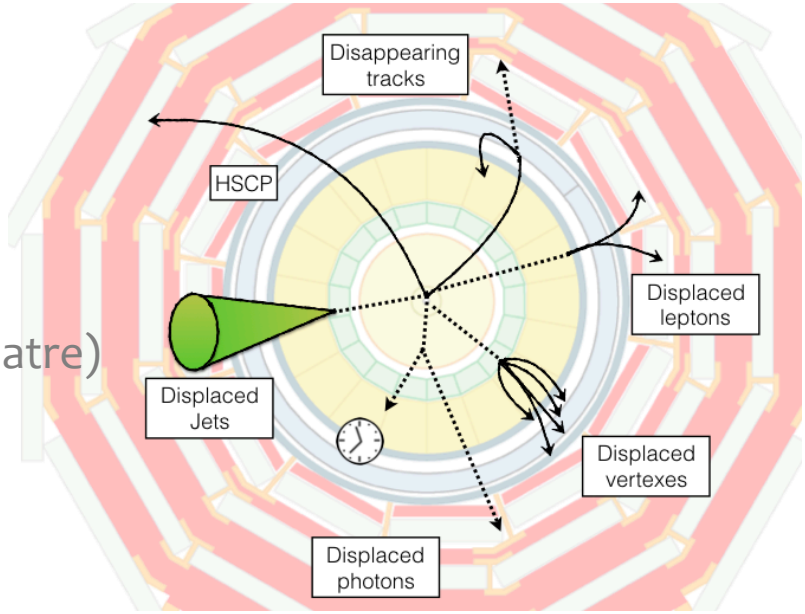
Outline

- **Highlights** from **signature-driven searches for LLPs** in the LHC Run 2 at CMS
  - The search strategy for:

    LLP Signatures:
    - **Displaced** vertices or jets
    - **Emerging** jets (presented by J. Duatre)
    - **Disappearing** tracks
    - **Delayed** jets
    - **Stopped** particles

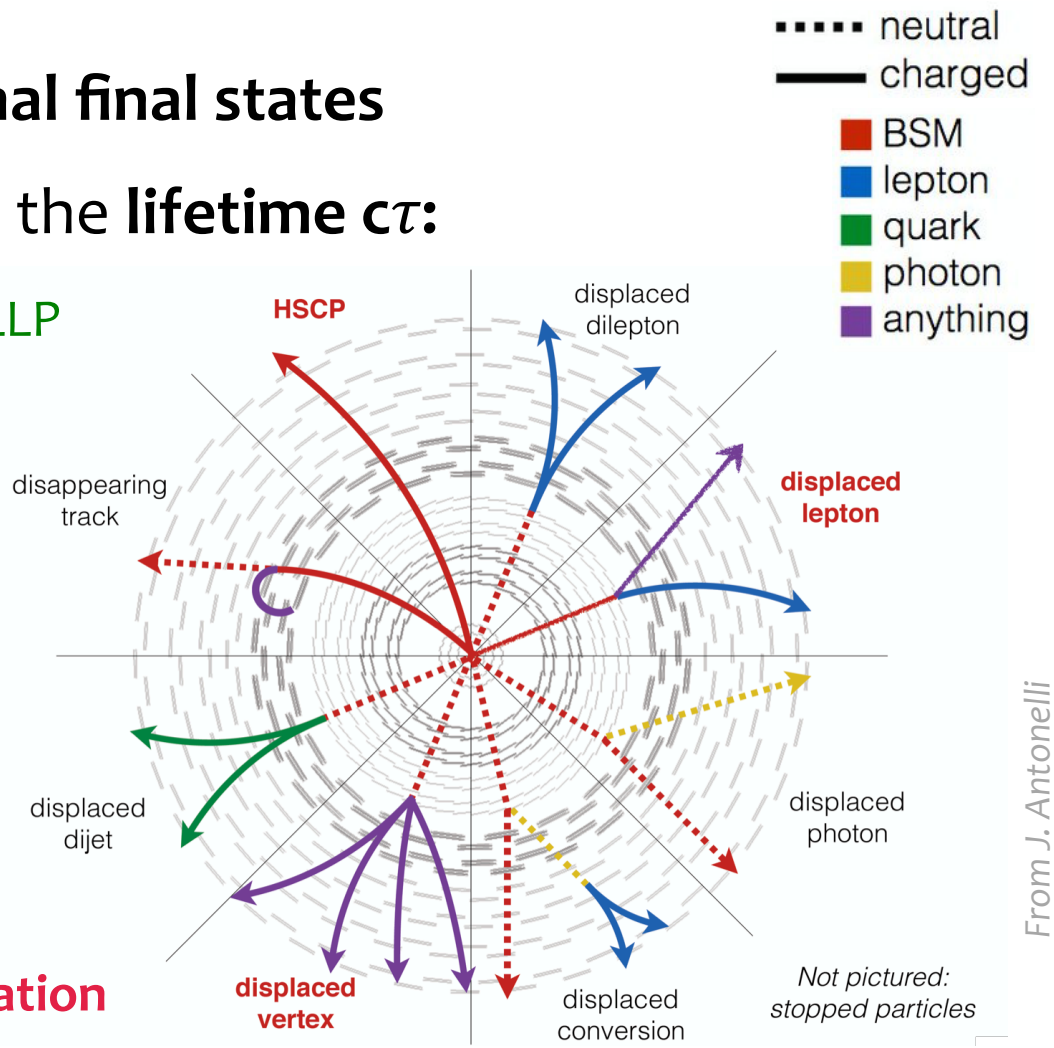


  - Results and limits on xsec, mass & lifetime

- **CMS data collected at 13 TeV** in **Run II** up to **137/fb** from **2016 – 36/fb, 2017 – 41/fb, 2018 – 60/fb**
  - In this talk, the focus is on recently published CMS results

Secret life of Long-Lived Particles

- **LLPs** have **non conventional final states**
- **LLPs signature** depend on the **lifetime cτ:**
  - **Cross** the detector quasi-stable LLP
  - **Decay or are produced inside** the detector
    Displaced or disappearing objects, stopped particles
- **Challenging** from the experimental point of view:
  - Often difficult triggering
  - Non-standard reconstruction:
    displacements, timing and **ionization**



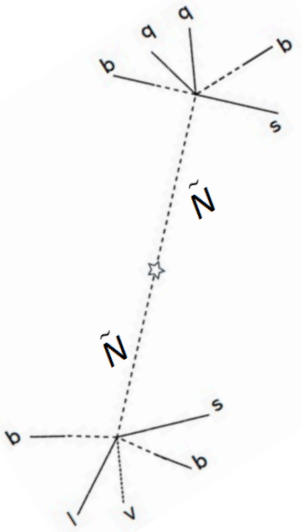
- **Not much SM background,** no such objects in SM, mostly detector noise, cosmic rays, reco failures – can be estimated from data

Phys. Rev. D 98, 092011 (2018), arXiv:1808.03078, EXO-17-018

Displaced vertices in multijet events

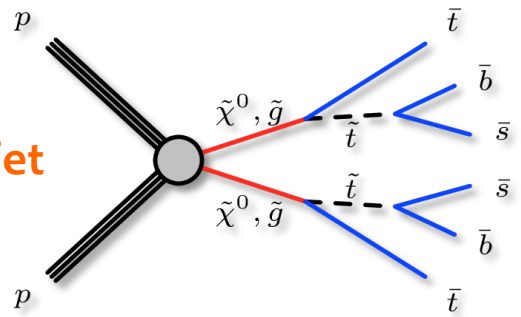
- **Signature: displaced jets** in the region of a beam pipe

- **Analysis strategy:**
  - reconstruct displaced vertices from tracks in events with jets
  - focus on intermediate lifetimes **cτ** (100 μm to 10 cm)
    - first tracking (pixel) layer: 4.4 cm radius
  - distinguish **signal in two-vertex events** using **the distance d_{vv}** between vertices
  - SM background: prompt vertices in events with lots of jets

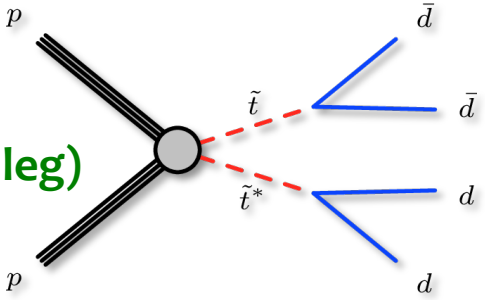


- **Benchmark:**
  - Pair-produced long-lived neutralinos/gluinos or stops in RPV SUSY

Multijet



Dijet (per leg)



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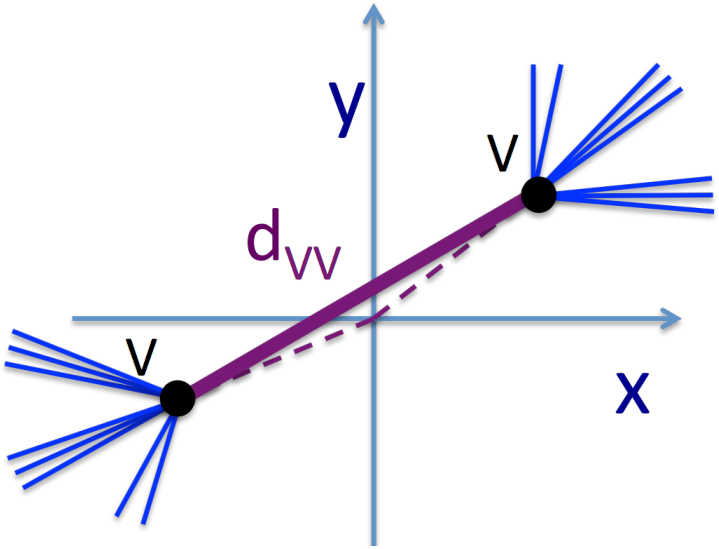
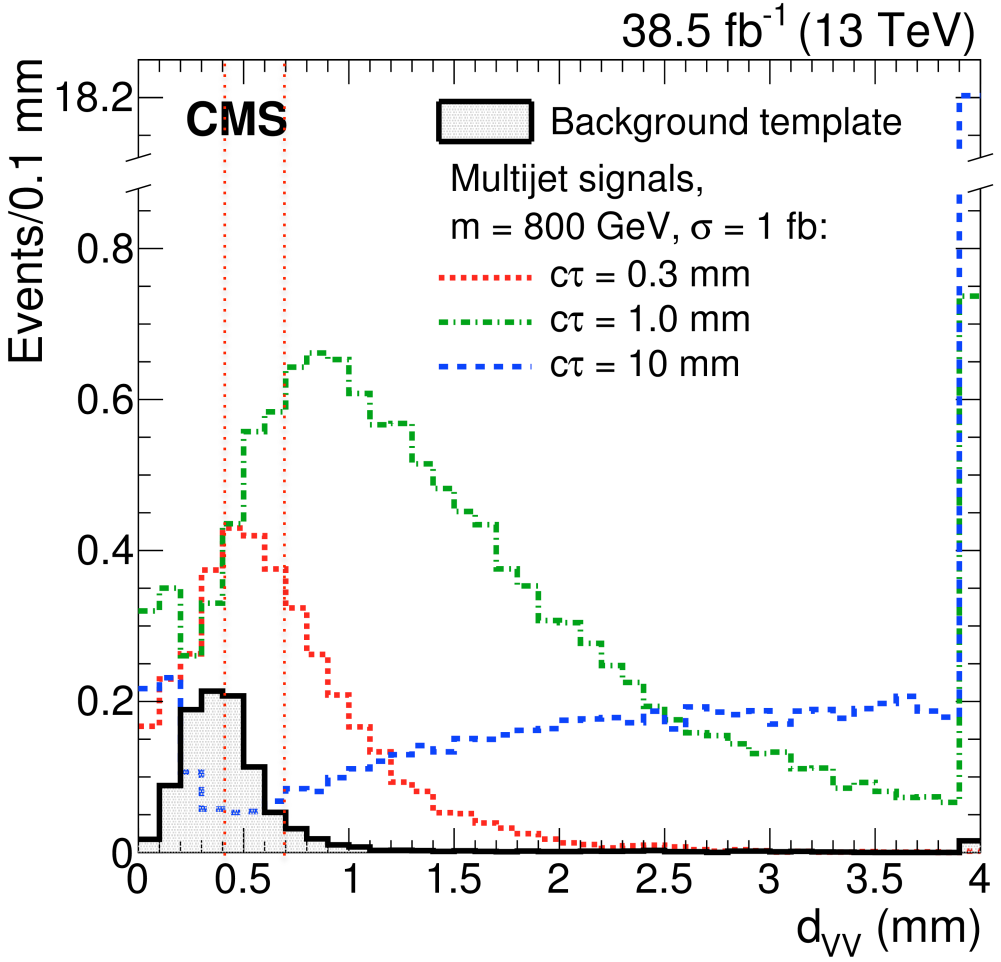
Displaced vertices in multijet events

- **Search variable: d_{VV}** – xy distance between vertices

- **Search regions:** 3 bins
  - 0.0 – 0.4 mm
  - 0.4 – 0.7 mm
  - 0.7 – 40 mm

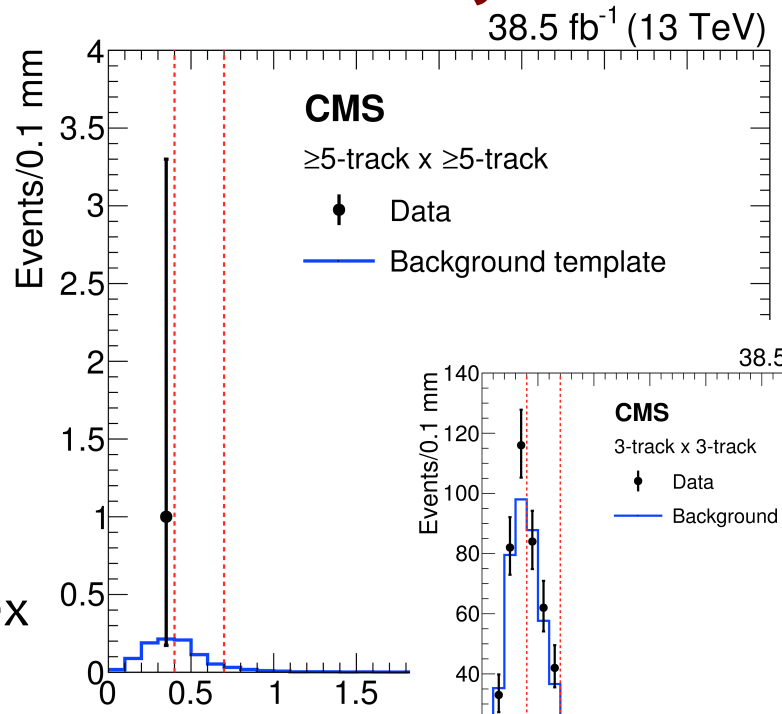




Phys. Rev. D 98, 092011 (2018), arXiv:1808.03078, EXO-17-018

Displaced vertices in multijet events

- **Trigger:**
  standard HT = $\Sigma^{N_{jets}} E_T$ > 800 GeV
- **Selection:** ≥ 4 jets
- **Signal region:**
  - ≥5-track two-vertex events
- **Background:**
  - estimated from ≥5-track one-vertex
- **Control samples:**
  - events with 3-track and 4-track vertices

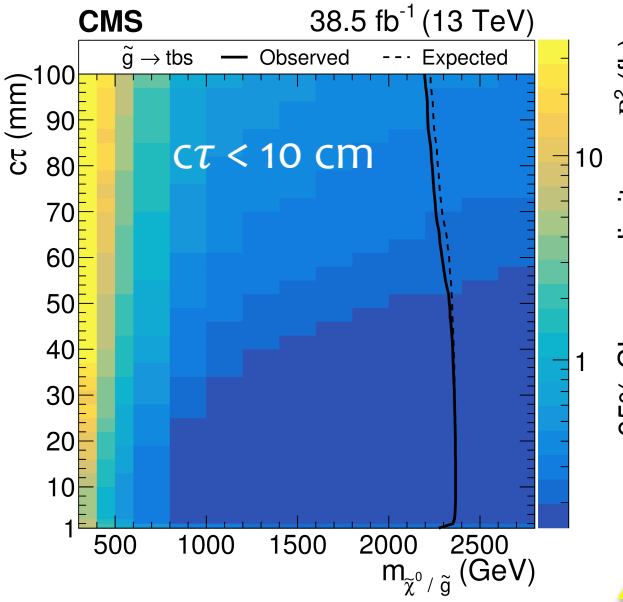


- **Results:** 1 event observed (≥5-track two-vertex) with d_{VV} = 396 μm

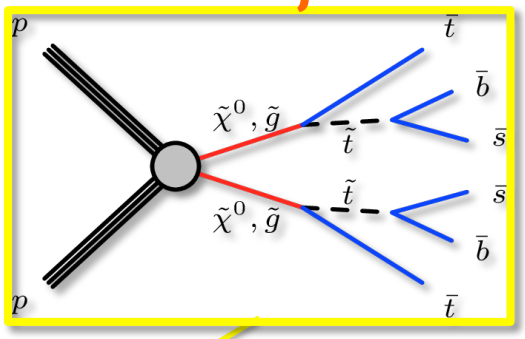
d_{VV} range	Fitted background yield	Observed	Predicted multijet signal yields 0.3 mm	1.0 mm	10 mm
0–0.4 mm	$0.51 \pm 0.01\,(\text{stat}) \pm 0.13\,(\text{syst})$	1	2.8 ± 0.7	3.5 ± 0.8	1.0 ± 0.2
0.4–0.7 mm	$0.37 \pm 0.02\,(\text{stat}) \pm 0.09\,(\text{syst})$	0	2.0 ± 0.5	3.7 ± 0.9	0.5 ± 0.1
0.7–40 mm	$0.12 \pm 0.02\,(\text{stat}) \pm 0.08\,(\text{syst})$	0	1.1 ± 0.3	11 ± 3	31 ± 7

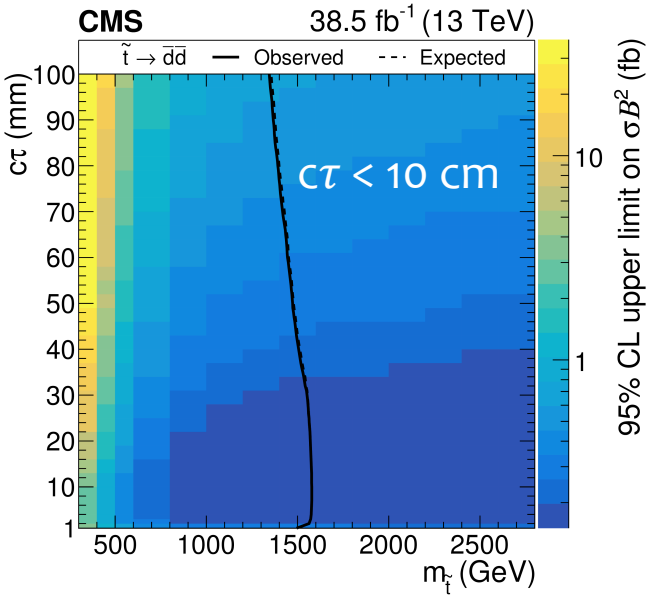
Phys. Rev. D 98, 092011 (2018), arXiv:1808.03078, EXO-17-018

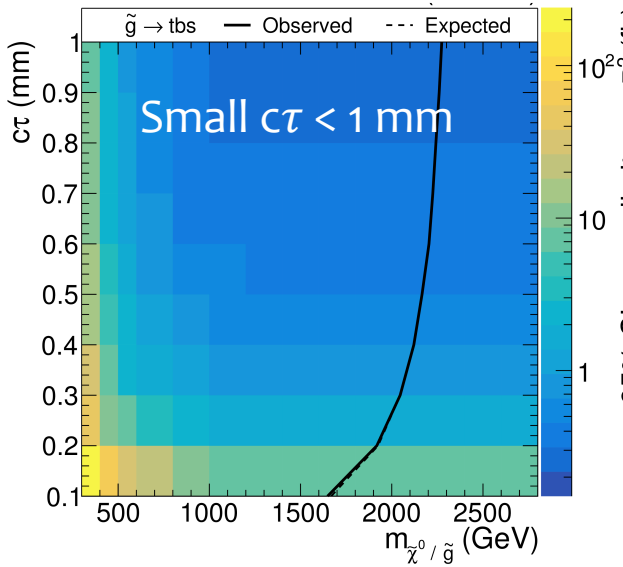
Displaced vertices in multijet events

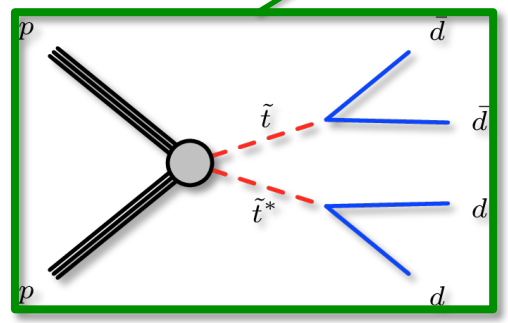


Multijet

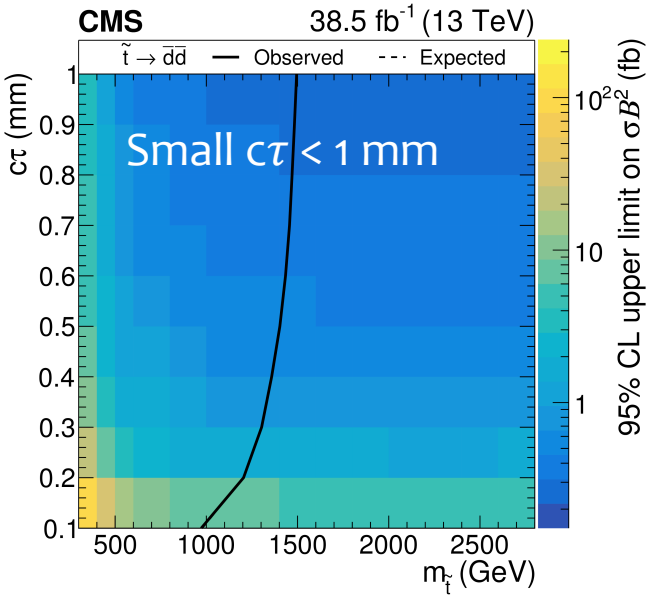






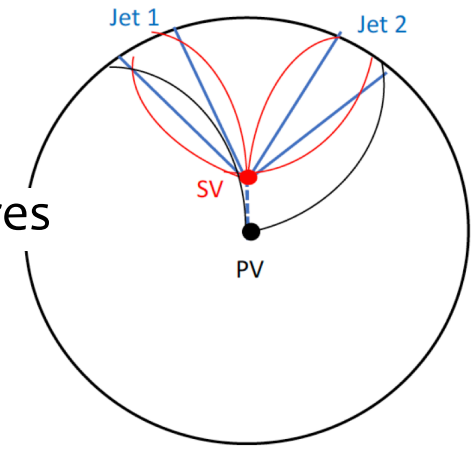


Dijet per leg



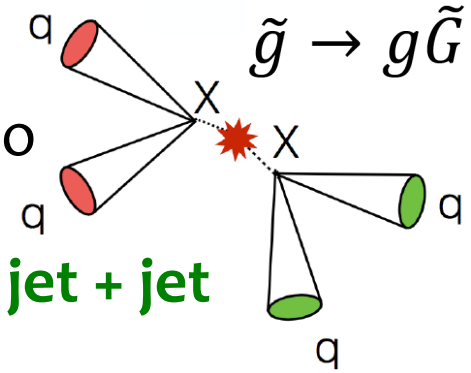
Phys. Rev. D 99 (2019) 032011, arXiv:1811.07991, EXO-18-007

Inclusive displaced jets

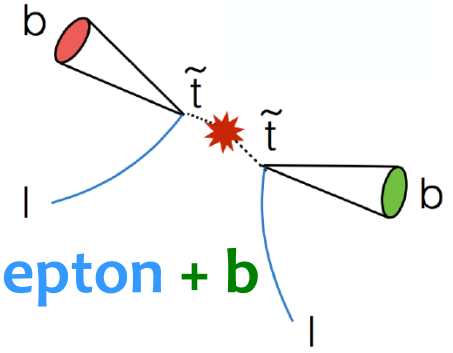


- **Signature: displaced jets** in the tracker
- **Analysis strategy:** utilize the properties of jets, tracks and **secondary vertices** to tag **displaced jet** signatures
- **Inclusive analysis:**
  - one displaced vertex is sufficient
  - not requires SV containing tracks from both jets
  - no missing hit requirement, therefore LLPs could be charged
- **Benchmark:**
  pair produced LLP with **cτ** from **1mm** to **1 m** decaying to jets or leptons which are displaced

GMSB gluino



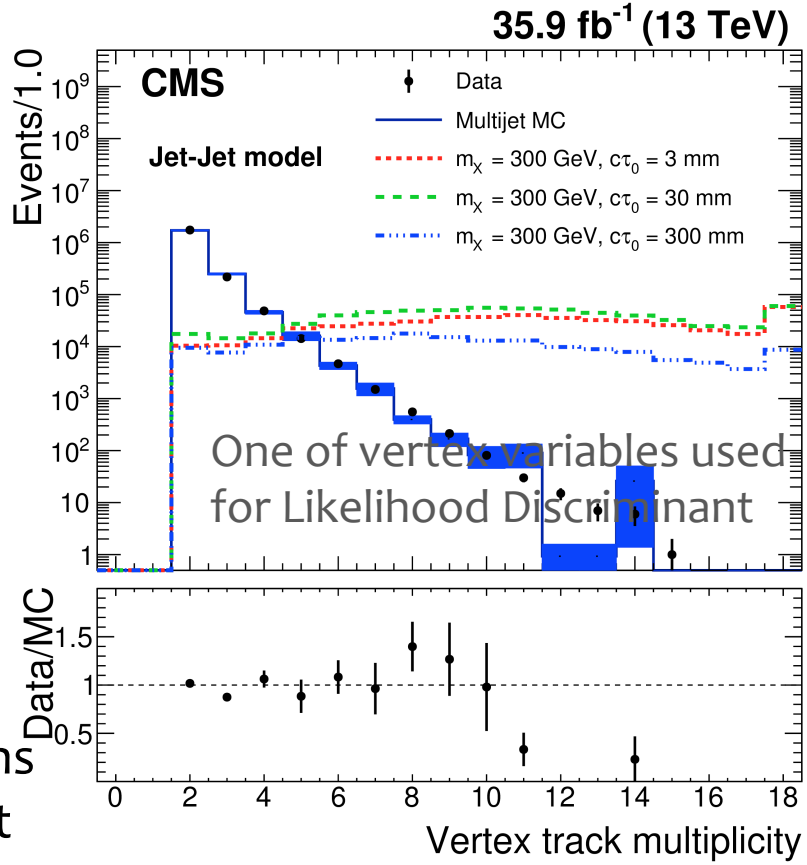
RPV stop quarks



Phys. Rev. D 99 (2019) 032011, arXiv:1811.07991, EXO-18-007

Inclusive displaced jets

- **Dedicated *displaced* trigger:**
  - Calo HT > 350 GeV
  - ≥2 calo jets with pT > 40 GeV, |η| <2.0
  - ≥1 displaced track for each jet pair
  - ≤2 prompt tracks for each jet pair
- **Offline kinematics selection:**
  - Calo HT > 400 GeV
  - pT>50 GeV, |eta| < 2.0 for calo jets in dijet candidates
- **Background:**
- Data driven estimate using control regions built from track, secondary vertex and jet information as a likelihood discriminant
- **4 Signal Regions:**

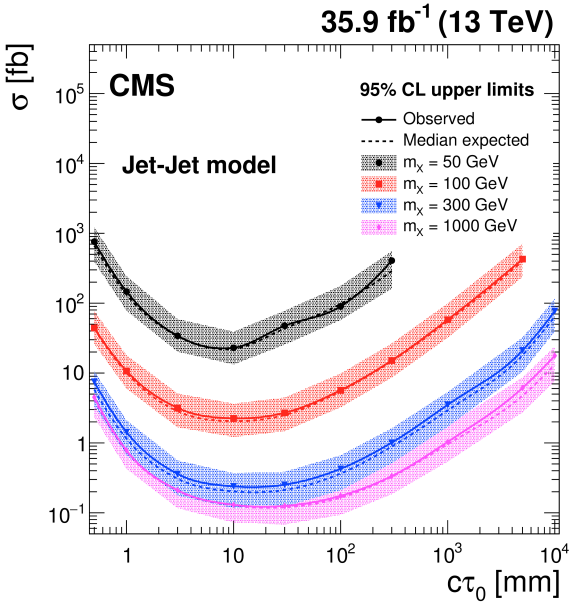


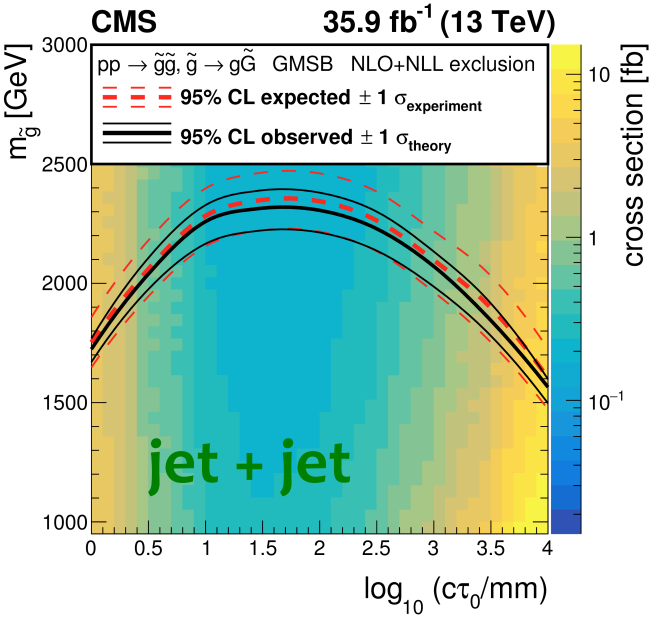
Selection on H_T	Number of dijets	Expected	Observed
$400 < H_T < 450$ GeV	1	0.42 ± 0.14 (stat) ± 0.01 (syst)	0
$450 < H_T < 550$ GeV	1	0.23 ± 0.08 (stat) ± 0.07 (syst)	0
$H_T > 550$ GeV	1	0.19 ± 0.07 (stat) ± 0.05 (syst)	1
—	>1	0.16 ± 0.11 (stat) ± 0.06 (syst)	0

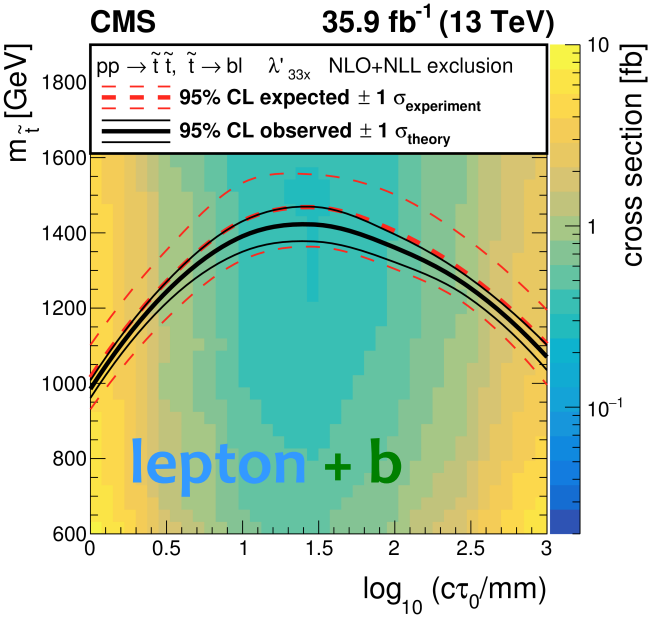
Phys. Rev. D 99 (2019) 032011, arXiv:1811.07991, EXO-18-007

Inclusive displaced jets

Limits:





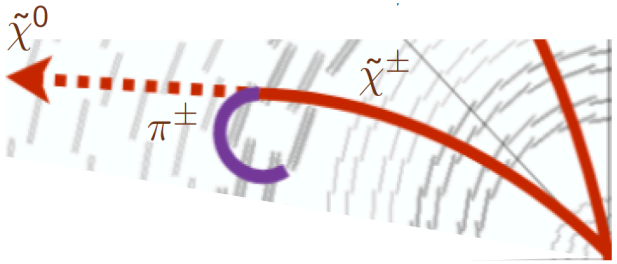


Exclusion limits on the cross-section on **new neutral LLPs** decaying to two jets:, eg
0.2 fb at high mass (m_X>1000 GeV) for $c\tau_0$ from 3 to 130 mm

GMSB: pair-produced
LL gluinos < 2300 GeV
are excluded for
$c\tau_0$ between 20 and 110 mm

RPV SUSY: pair-produced
LL top squarks < 1350 GeV
are excluded for
$c\tau_0$ between 7 and 110 mm

Disappearing tracks

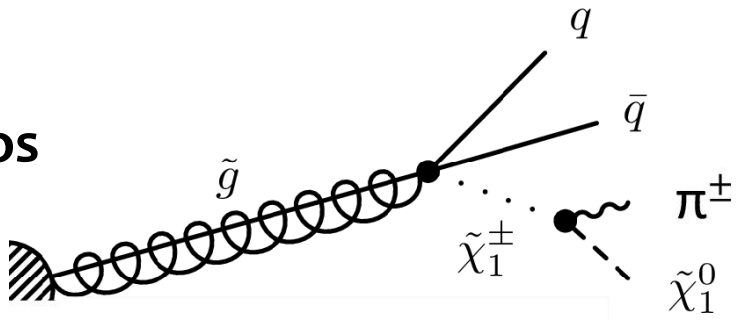


- **Signature** of **short track (ST)** in the tracker

→ **charged soft pion hard to be reconstructed**

- **Benchmark:** compressed SUSY
  where in a decay chain **long-lived charginos** will be seen as **STs** in the tracker

  because of small mass splitting with the LSP neutralino, $\Delta m(\tilde{\chi}^{\pm 1}, \tilde{\chi}^{0}_{1}) \sim 100$ MeV, $c\tau(\tilde{\chi}^{\pm 1}) \sim 50$ cm



- **Analysis strategy:** classic SUSY **inclusive M_{T2} search adopted** to disappearing track search for events with at least 2 jets

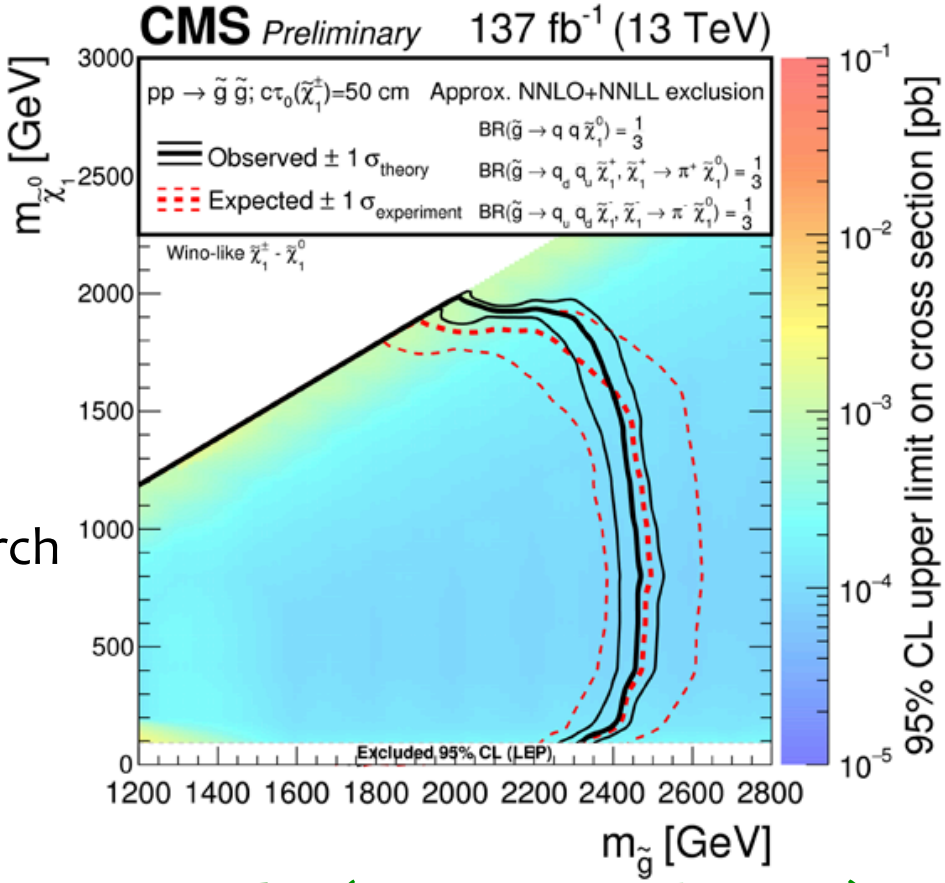
- **Profit:** SM background is significantly further suppressed by presence of disappearing tracks

2016-18: 137/fb

PAS-SUS-19-005

Disappearing tracks

- **Short Track:** high quality track with missing outer hits w/o associated calo or muon hits
- **Selection:** ≥2 jets,
  events converted to 2 pseudo-jets with M_{T2} > 200 GeV and at least 1 ST
- **Trigger:** identical to inclusive M_{T2} search based on pT, MET, HT and HTM
- **Background:**
  Data-driven estimation for main backgrounds: fake rate applied to ST events from poorly reconstructed charged pions and leptons
- **Search regions:**
  68 regions in Njet, HT, the ST length, the ST pT

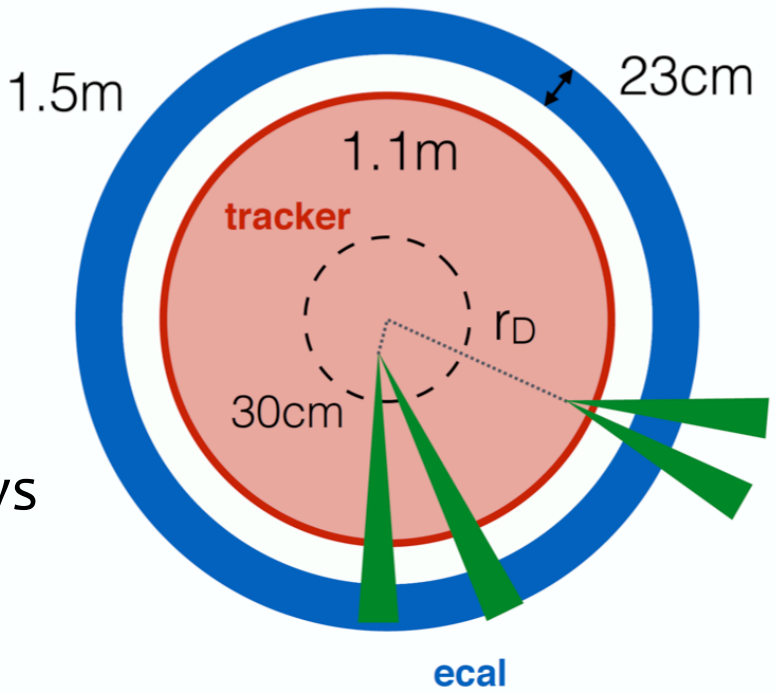


Results (compressed SUSY)
for cτ =50 cm
Exclude $m_{\tilde{g}}$ < 2.46 TeV and $m_{\tilde{\chi}^0}$ < 2.0 TeV

Delayed Jets

NEW! Usage of ECAL timing for calo jets

- **Signature:** Calorimeter deposits of displaced jets from massive LLPs are **delayed** wrt. jets from prompt decays
- **Strategy:** use ECAL timing to find ***delayed jets***
- **Profit:** increased acceptance for decays beyond tracker (0.3 - 1.5 m)

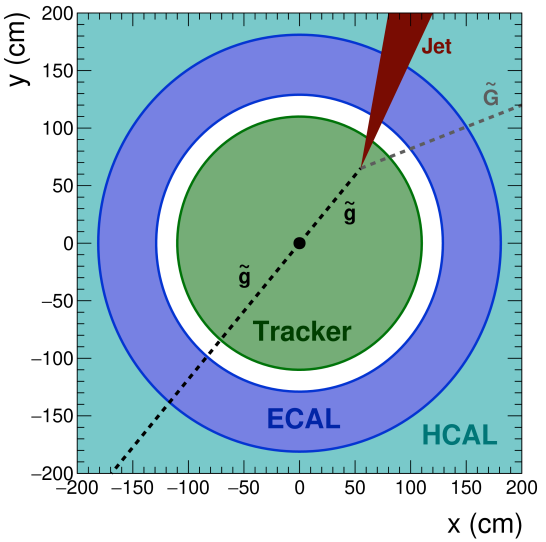


- **ECAL: jet time** is a median time of all ECAL cells in jet with energy > 0.5 GeV and |time| < 20ns, $\Delta R(\text{cell, jet}) < 0.4$
- time resolution per cell (crystal+APD) ~200 ps

2016-18: 137/fb

PAS-EXO-19-001

Delayed Jets



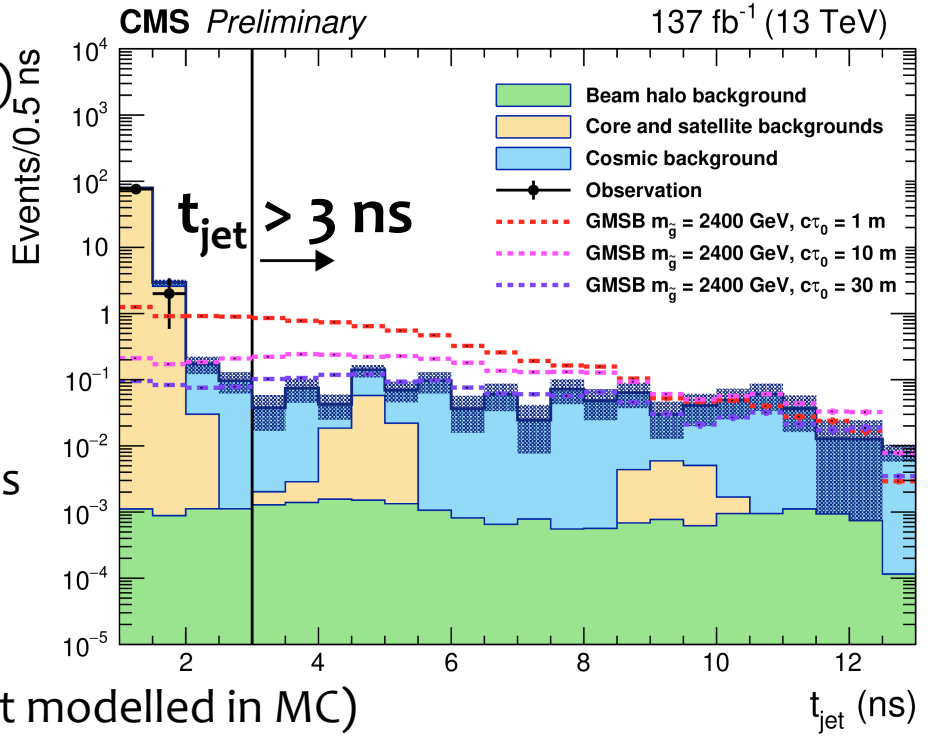
- **Benchmark model:**

  GMSB **long-lived gluino** → gluon + gravitino

Selection SR:

- ≥ 1 delayed calo jet

  (t > 3ns, pT > 30 GeV, E > 70 GeV, |η| < 1.48)
- Calo MET > 300 GeV
- **Trigger:** MET > 120 GeV



Background:

- **Cleaning selections reject** contributions from dominant backgrounds:

  beam halo, cosmics, satellite bunches
- Bkg. prediction from data using ABCD (not modelled in MC)

PAS-EXO-19-001

Delayed Jets

- **Observed:** 0 events in agreement with bkg. prediction of 1 evt
- **Results (GMSB):**

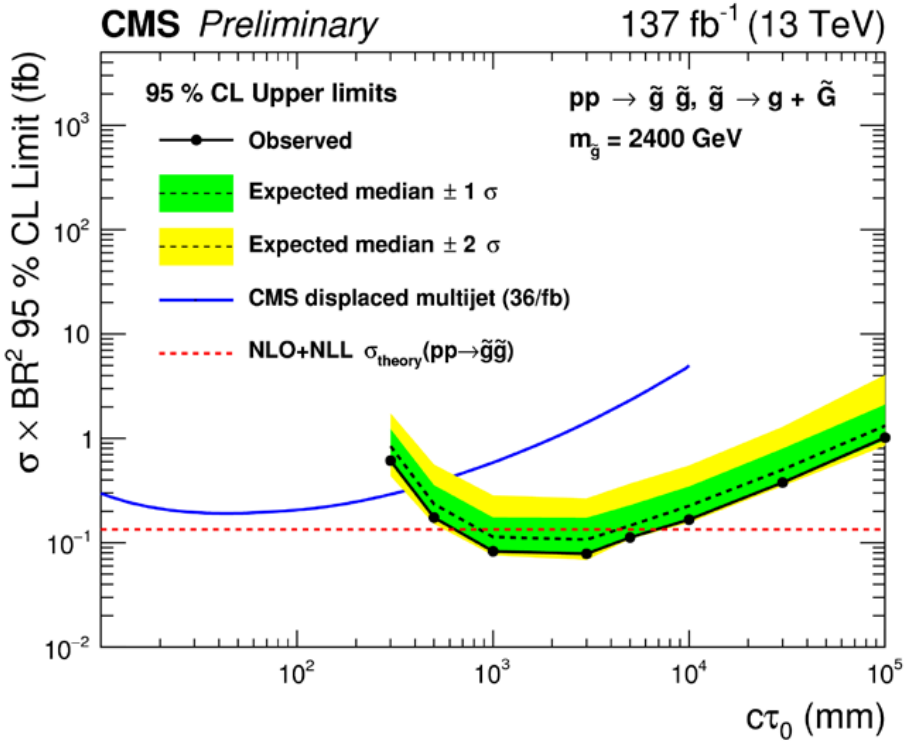
  Exclude $m_{\tilde{g}} < 2.50$ TeV for $c\tau_0 \sim 1$ m

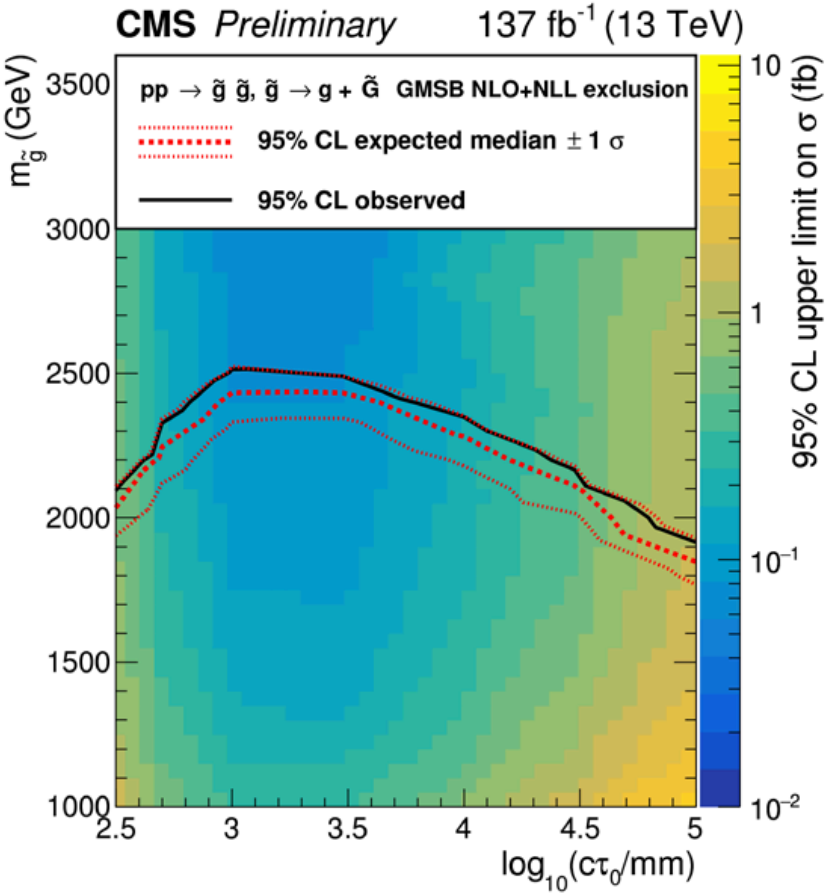
  or $m_{\tilde{g}} < 2.15$ TeV for $c\tau_0 \sim 30$ m

→ **Significantly extends reach for $c\tau_0 \geq 1$ m**

(vs. tracker-based searches)

Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunches	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmics	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)

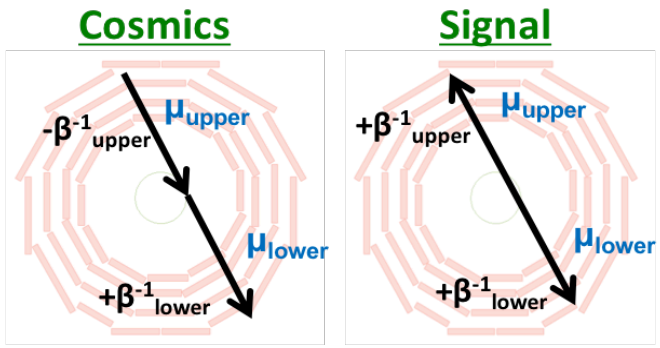


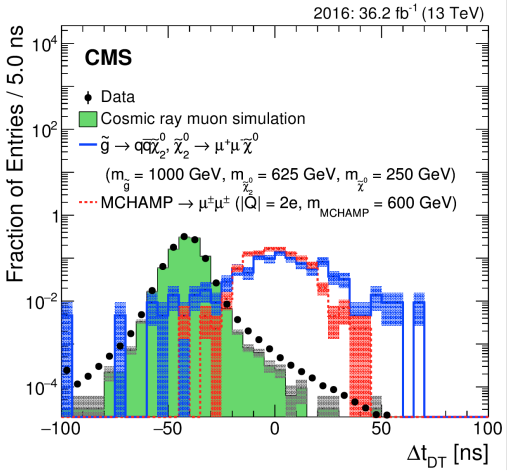


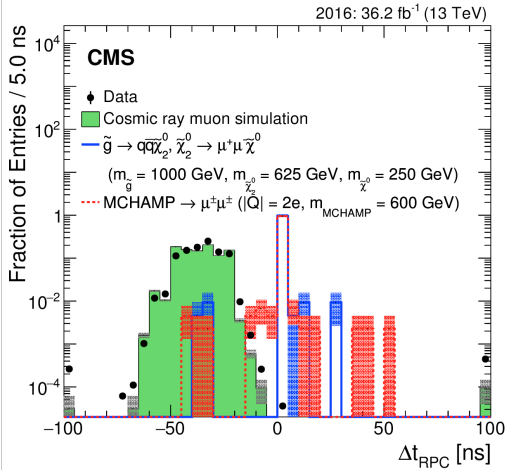
EXO-17-004, EXO-16-004, JHEP 05 (2018) 127

Stopped particles

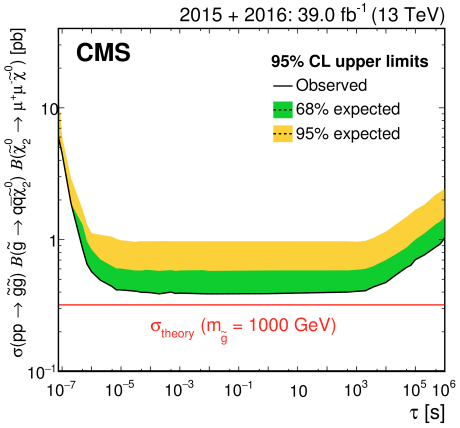
- **R-hadrons from Split SUSY** (gluino or |Q|=2e) are **stopped inside the detector** and **decay to muons or have hadronic decays** from rest after unknown time (sensitivity to lifetimes between 0.1 μs and 10^6 s)
- Events recorded **out-of-time with collisions** with the custom trigger

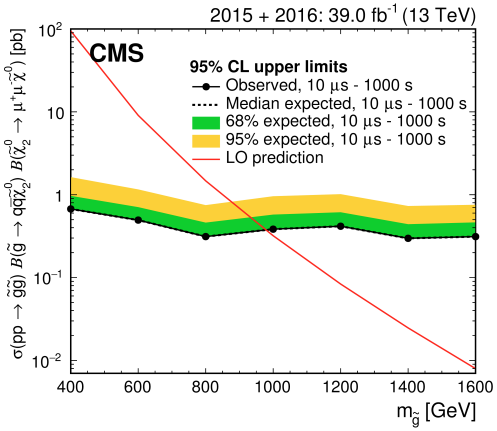






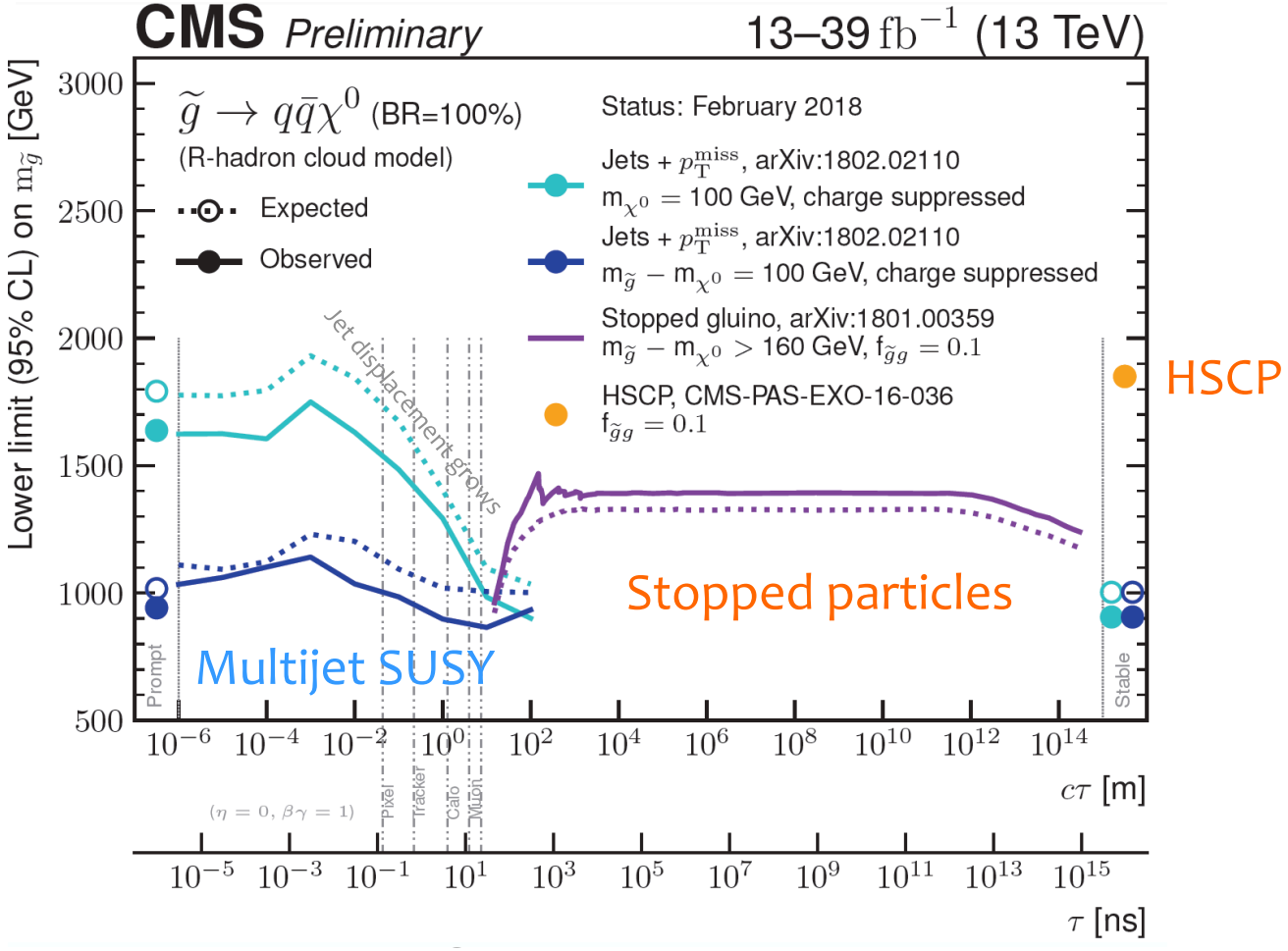
- **No events** observed
- 13 orders of magnitude of the lifetime tested
- **Excluded gluinos** with mass between 400 and 970 GeV, assuming 100% BF to muons





Re-interpretation of prompt SUSY searches

- A fraction of **long-lived particles** can be detected in **prompt searches**
  - If the reco object is not too much displaced or delayed
- Prompt searches **complement the sensitivity** to dedicated LLP searches



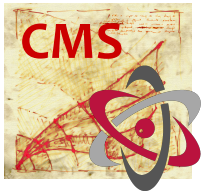
LLP at CMS summary

- **CMS** has an **extensive search program** for **different signatures** of LLPs
  - CMS provides **HepData records** with tables of acceptances, efficiencies and signal cross sections, etc. for the **model independent** studies

- **No LLP particle has been observed… yet…**
  - Exclude LLPs with masses up to 1 – 2.5 TeV
  - Sensitive to proper decay lengths from 1 mm
  - Any detected signal of LLP would be a clear indication of a new physics

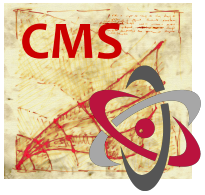
- **Improvements** on sensitivity to LLP is expected with
  - **Advanced techniques of reconstruction** displacement, timing and ionization and triggering
  - **New topologies** are being included
  - **Complementary prompt searches**
  - Increasing luminosity – Run II dataset **(~140/fb** in total) coming soon

- SUSY CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO



Thank you!

Supported in part by the NCN grant:
2014/15/B/ST2/03998

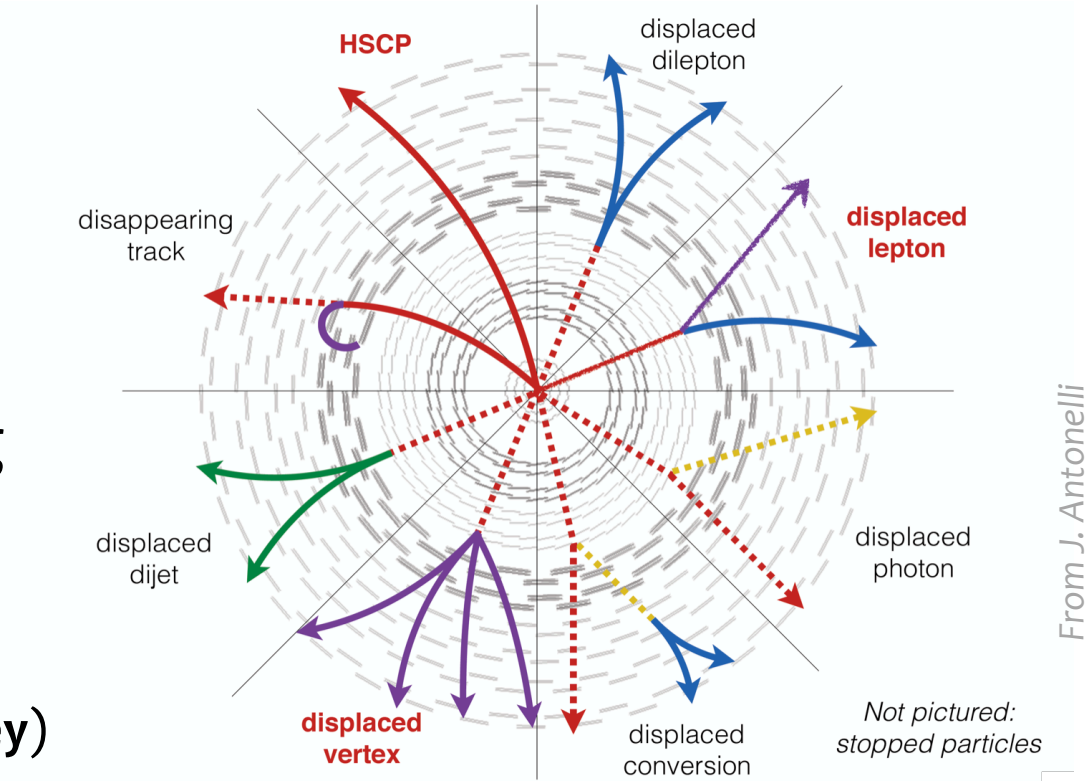


BACKUP

Secret life of Long-Lived Particles

LLPs sources:

- Small couplings in decay chain
  - **RPV SUSY**
  - **GMSB** small coupling to the lightest gravitino
- small phase space/mass splitting (**AMSB**)
- massive particle mediating the decay (**Split SUSY,** R-hadrons (gluino/stop))
- hidden sectors (**Hidden Valley**)
- **Dark QCD** and more



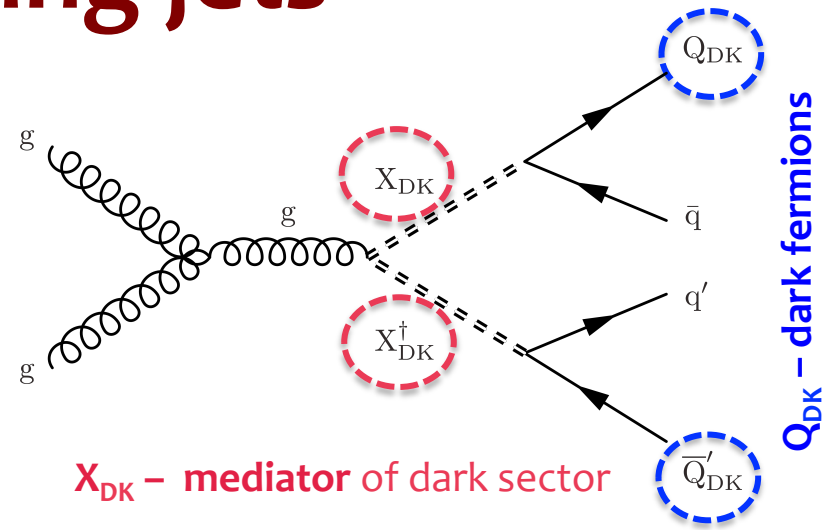
From J. Antonelli

JHEP 02 (2019) 179, EXO-18-001, arXiv:1810.10069

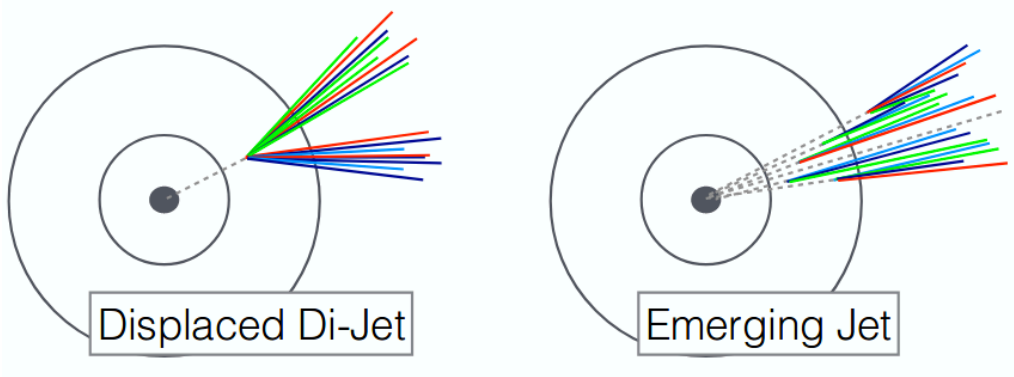
Emerging jets

- The **Dark QCD** model with
  long-lived dark-pions,
  which can decay to SM particles

- **Signal:**
  2 prompt jets and **2 emerging jets**



X_{DK} – **mediator** of dark sector



Emerging jets are produced in the hadronization of Q_{DK} to dark hadrons (π_{DK}) which form dark jets, and contain **multiple displaced vertices** from the **decay of dark-pions**

Signal model parameters	List of values
Dark mediator mass $m_{X_{DK}}$ [GeV]	400, 600, 800, 1000, 1250, 1500, 2000
Dark pion mass $m_{\pi_{DK}}$ [GeV]	1, 2, 5, 10
Dark pion decay length $c\tau_{\pi_{DK}}$ [mm]	1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000

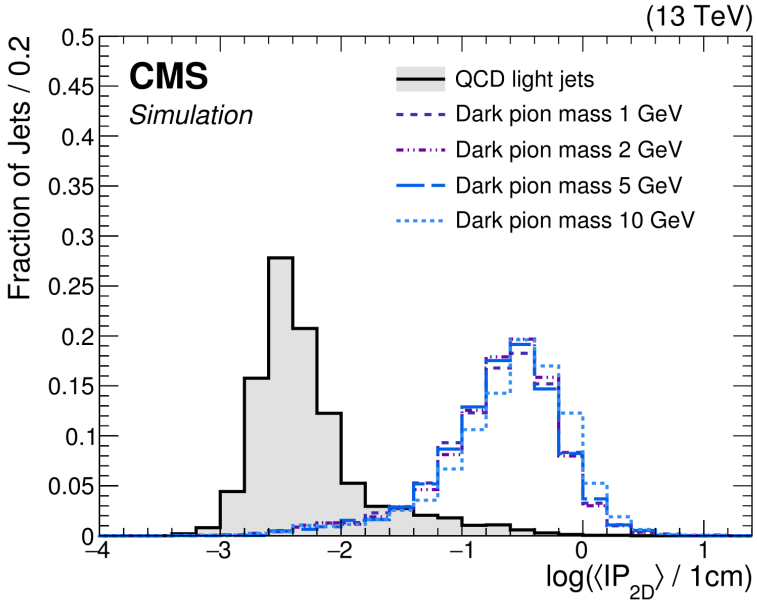
focus on lifetimes of
1 mm < $c\tau$ < 1 m

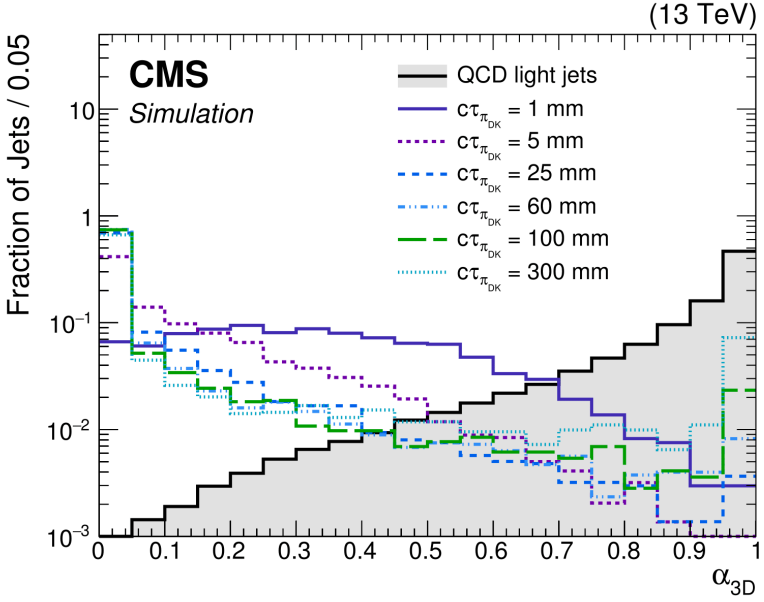
336 signal hypotheses

JHEP 02 (2019) 179, EXO-18-001, arXiv:1810.10069

Emerging jets

- **Data: 16/fb** – part of 2016
  due to saturation-induced dead time present in the readout of the silicon strip tracker
- **HLT Trigger: HT** > 900 GeV
- **Strategy:** extension of the displaced jet search and tagger for emerging jets – *emerging jets identification:*





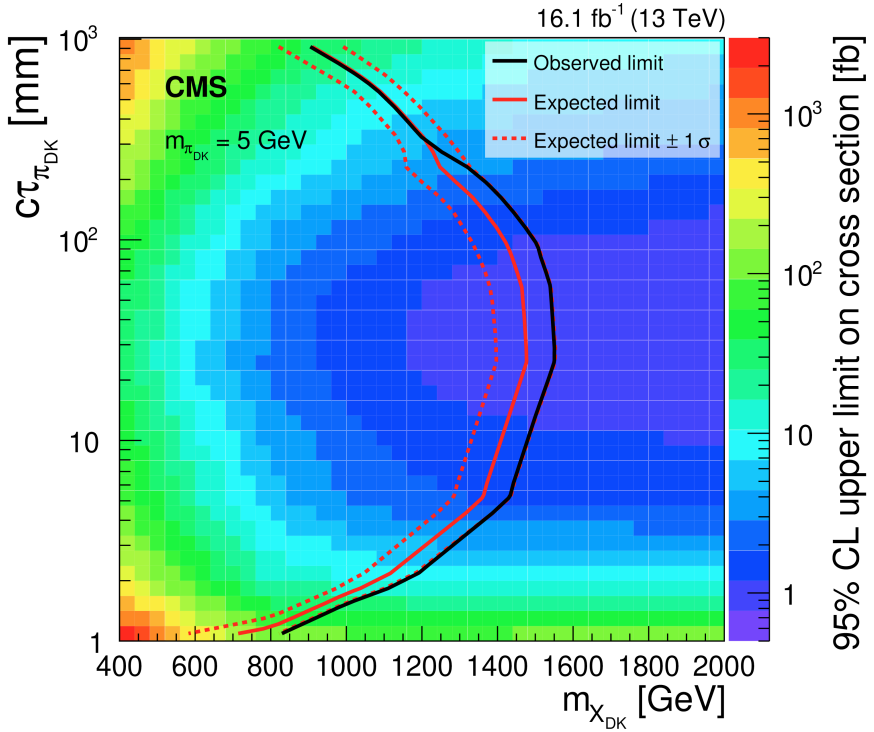
- **7 Different selections sets** are used with:
  - optimized kinematic cuts on HT, p_T of jets, MET
  - optimized emerging jet tag cuts

JHEP 02 (2019) 179, EXO-18-001, arXiv:1810.10069

Emerging jets

- **Results:** Observed events agree with bkg. expectation in all 7 selection sets

	Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
Signal Regions	1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
	2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
	3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
	4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
	5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
	6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
	7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

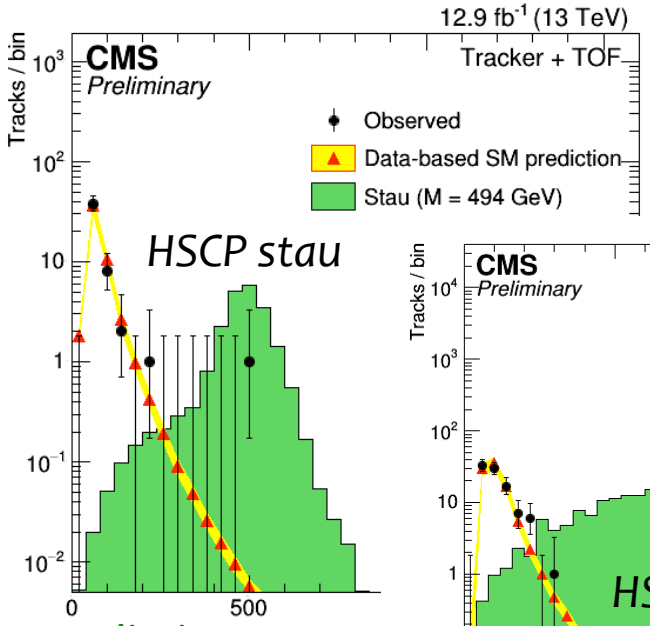


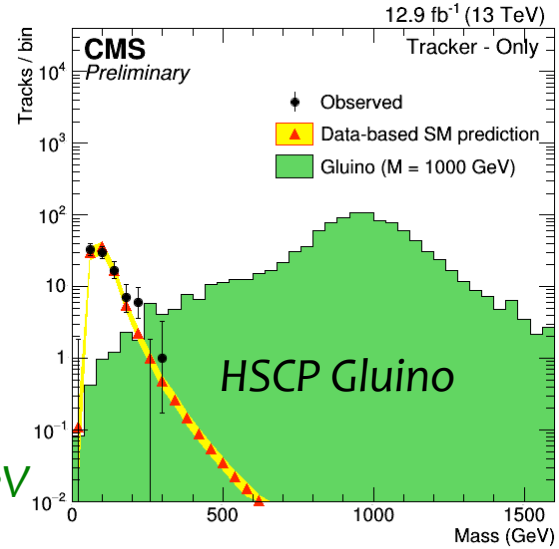
- **First emerging jets search at colliders!**
- **First Dark QCD results**
- Limits do not depend strongly on mass of dark pion π_{DK}
- Exclude dark-mass mediator X_{DK} mass between **400 and 1250 GeV** for $c\tau$ (π_{DK}) between **5 and 225 mm**

EXO-16-036, PRD 94 (2016) 112004

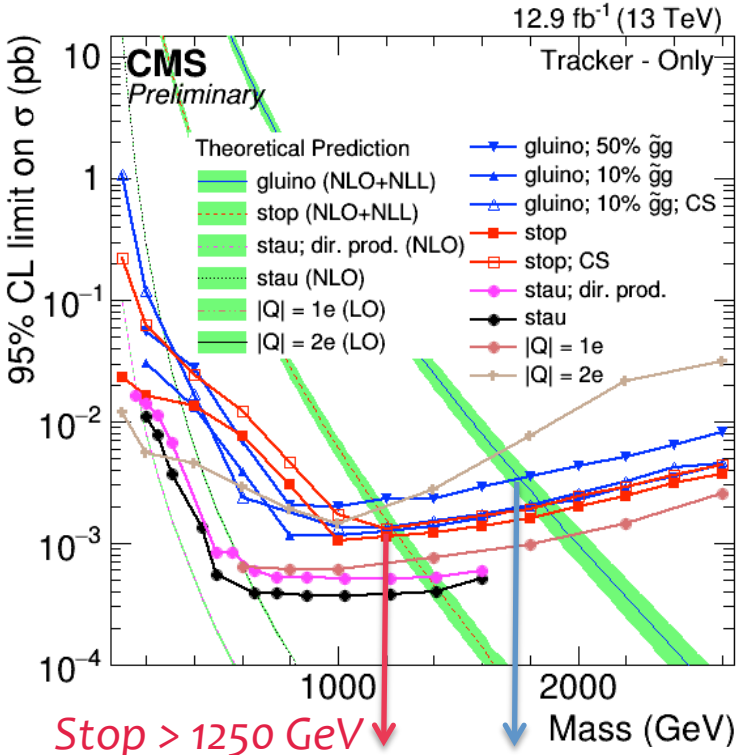
Heavy quasi-stable charged particles

- HSCPs (R-hadrons, GMSB staus and MCHAMPs) cross the detector
- **Signature: high ionization** (dE/dx) in the tracker
  delay in the muon system – long-time of flight (TOF: 1/β measured)
  → **mass measurement** from dE/dx
- **Trigger:** MET (>170 GeV) or single muon (pT > 50 GeV)
- **Background** estimated from data using pT, dE/dx discriminator, 1/β





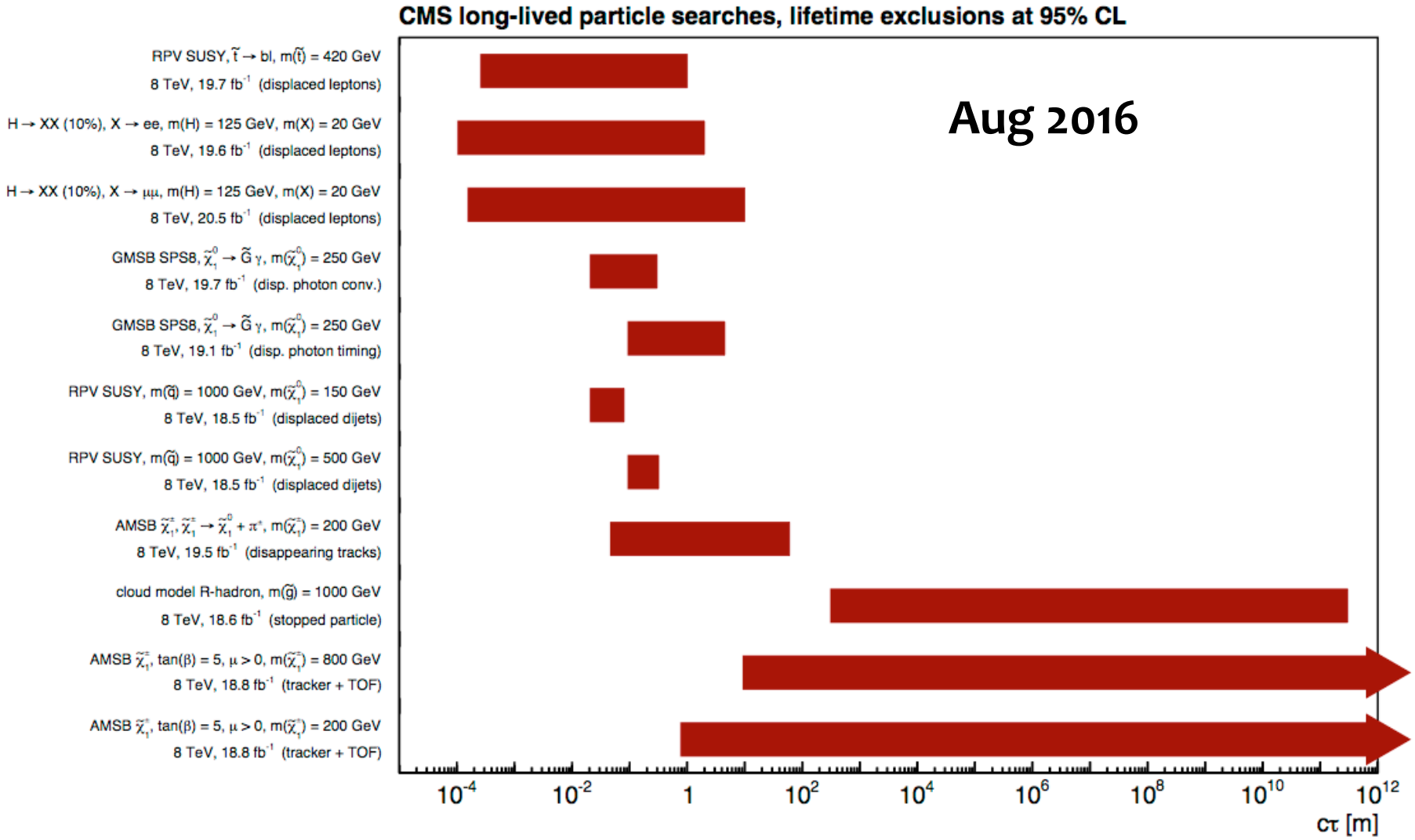
Mass limit on GMSB stau > 660 GeV



Stop > 1250 GeV

Gluino > 1850 GeV

LLP limits


CMS long-lived particle searches, lifetime exclusions at 95% CL
Aug 2016
RPV SUSY, $\tilde{t} \rightarrow bl$, $m(\tilde{t})$ = 420 GeV
8 TeV, 19.7 fb^{-1} (displaced leptons)
$H \rightarrow XX$ (10%), $X \rightarrow ee$, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 19.6 fb^{-1} (displaced leptons)
$H \rightarrow XX$ (10%), $X \rightarrow \mu\mu$, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 20.5 fb^{-1} (displaced leptons)
GMSB SPS8, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, $m(\tilde{\chi}_1^0)$ = 250 GeV
8 TeV, 19.7 fb^{-1} (disp. photon conv.)
GMSB SPS8, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, $m(\tilde{\chi}_1^0)$ = 250 GeV
8 TeV, 19.1 fb^{-1} (disp. photon timing)
RPV SUSY, $m(\tilde{q})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 150 GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
RPV SUSY, $m(\tilde{q})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 500 GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
AMSB $\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$, $m(\tilde{\chi}_1^\pm)$ = 200 GeV
8 TeV, 19.5 fb^{-1} (disappearing tracks)
cloud model R-hadron, $m(\tilde{g})$ = 1000 GeV
8 TeV, 18.6 fb^{-1} (stopped particle)
AMSB $\tilde{\chi}_1^\pm$, tan(β) = 5, μ > 0, $m(\tilde{\chi}_1^\pm)$ = 800 GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
AMSB $\tilde{\chi}_1^\pm$, tan(β) = 5, μ > 0, $m(\tilde{\chi}_1^\pm)$ = 200 GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
cτ [m]

Regions of LLP decay/production in CMS