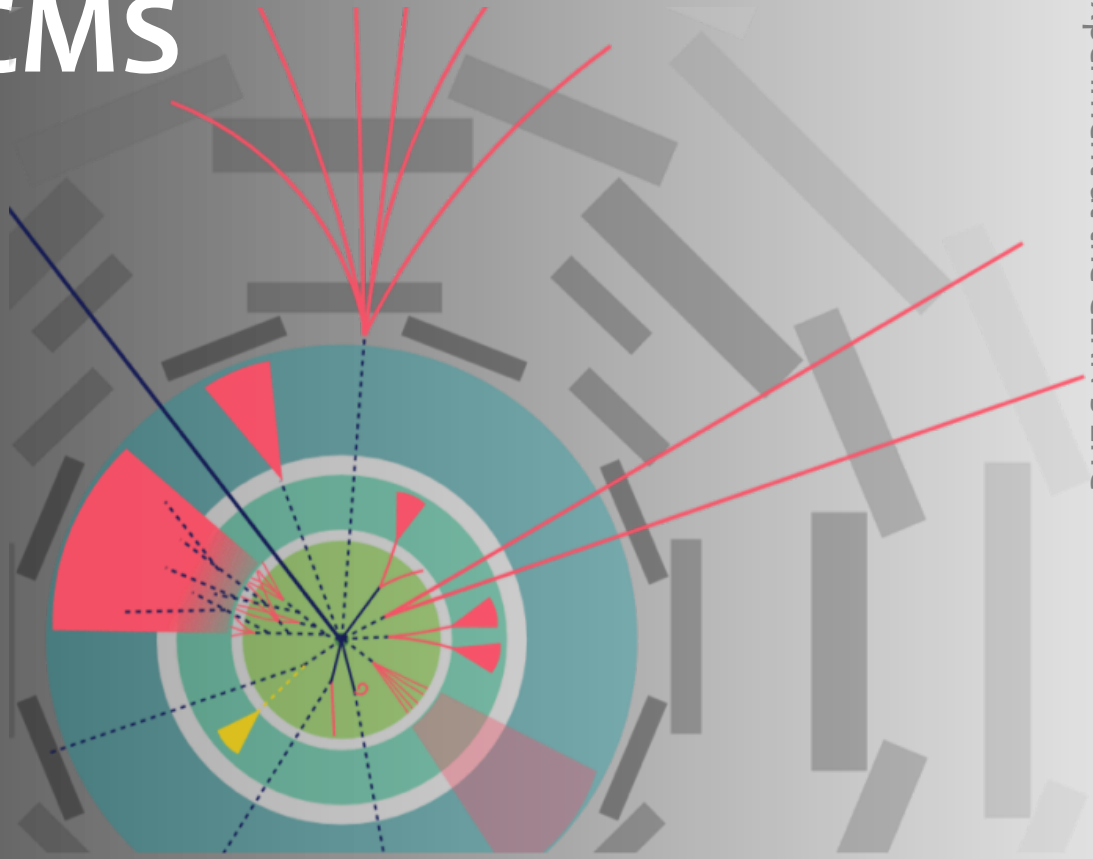
Searches for long-lived particles at CMS

Małgorzata Kazana
CMS Collaboration

NCBJ National Centre for Nuclear Research



Compact Muon Solenoid experiment at the CERN's LHC

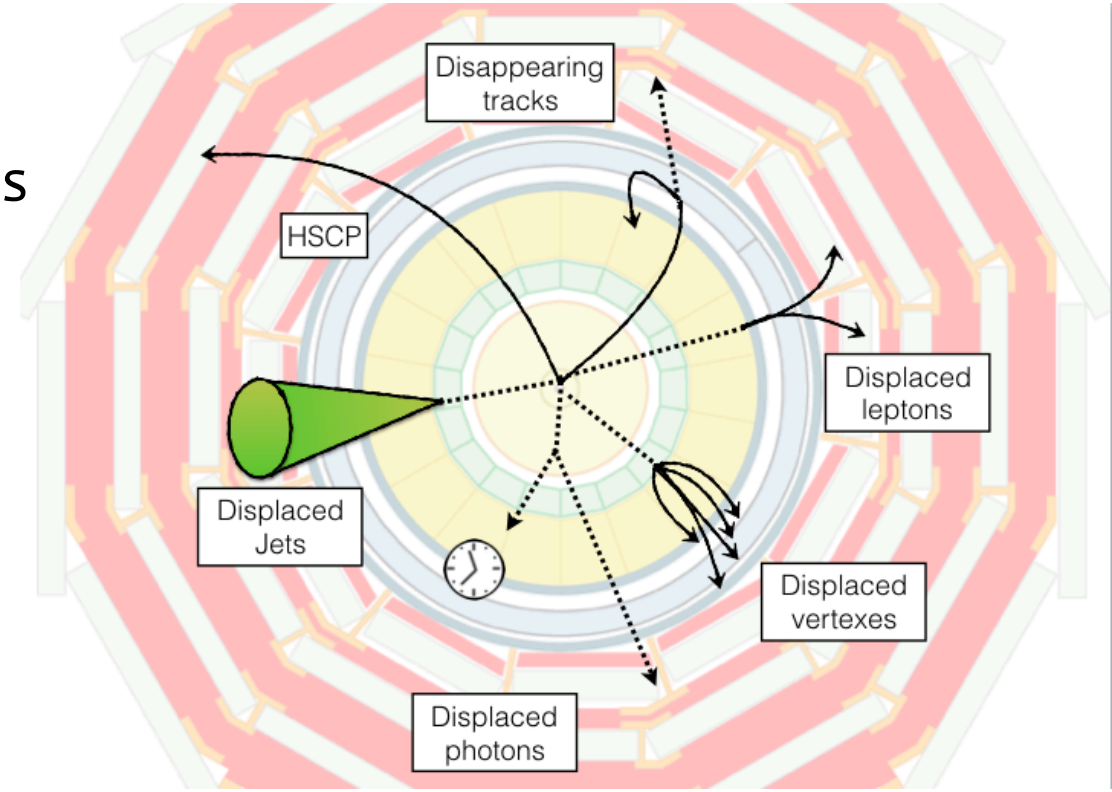
HEP Seminar
14 May 2021
University of Warsaw, PL

Searches for long lived particles

- Wilde array of possible exotic **signatures** and search **strategies**

- In this talk, the focus is on recently published analyses for **long lived particles**

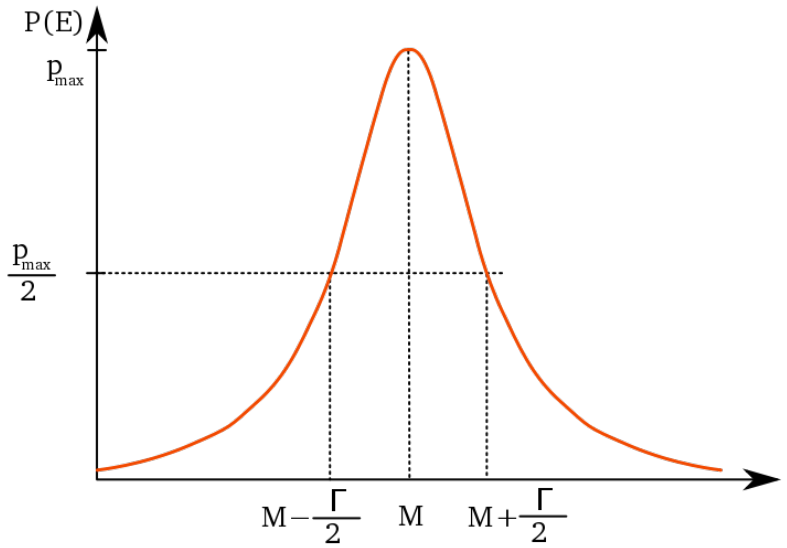
- CMS data collected at pp collisions at 13 TeV in **Run 2 up to 137/fb:**
  - 2016 – 36/fb,
  - 2017 – 41/fb,
  - 2018 – 60/fb



Long Lived Particles (LLPs)

- Particles with a **macroscopic lifetime, $c\tau \gtrsim 1$ mm** ($\tau \gtrsim$ ~3 pico sec)

- Particles have: **mass (M)** and **width (Γ)**
- **Γ** is determined by how the particle decays
  - ***proper lifetime*: $\tau \sim 1/\Gamma$**



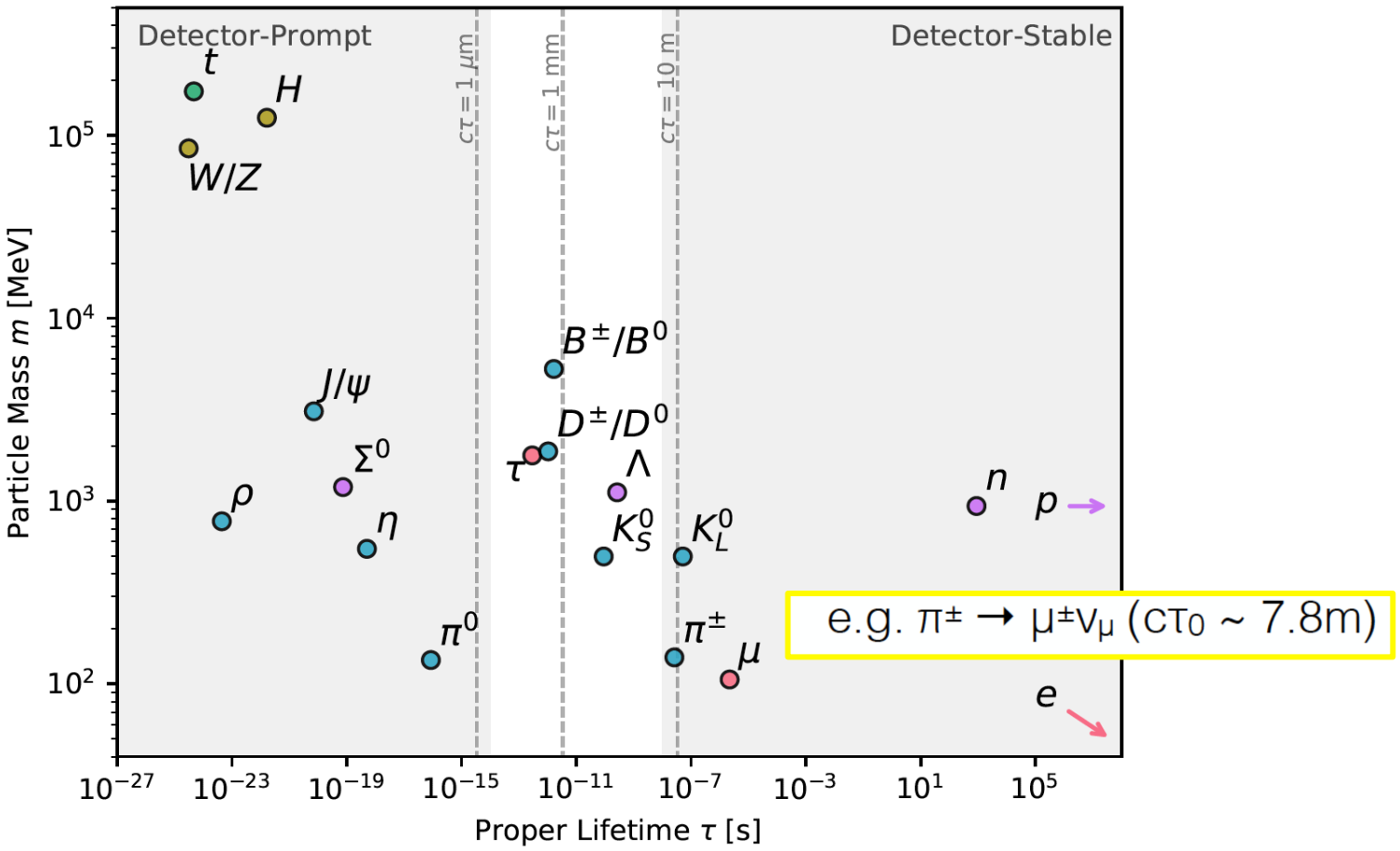
- Particles can gain a large lifetime (small **Γ**) whenever a particle decays via:
  - small couplings (**ε**),
  - high scale operators (**Λ**) (*heavy mediator*)
  - small phase space (**Φ**) (*compressed spectra*)

$$\Gamma \sim \varepsilon^2 \left(M/\Lambda\right)^{2n} \Phi$$

LLPs in SM

- The SM contains a large number of metastable particles

[JPPNP 3695 (2019)]

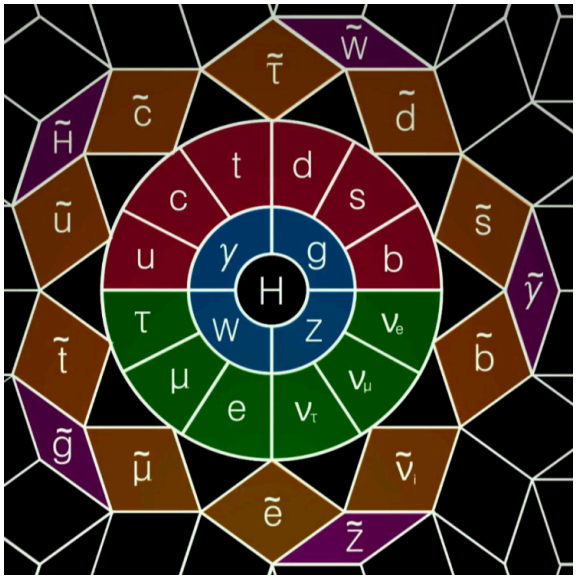


Decade of the LHC exlcusions

- **$m_H \approx 125$ GeV**

  Higgs Naturalness problem in SM:

  quantum corrections suggest m_H should be many orders of magnitude larger

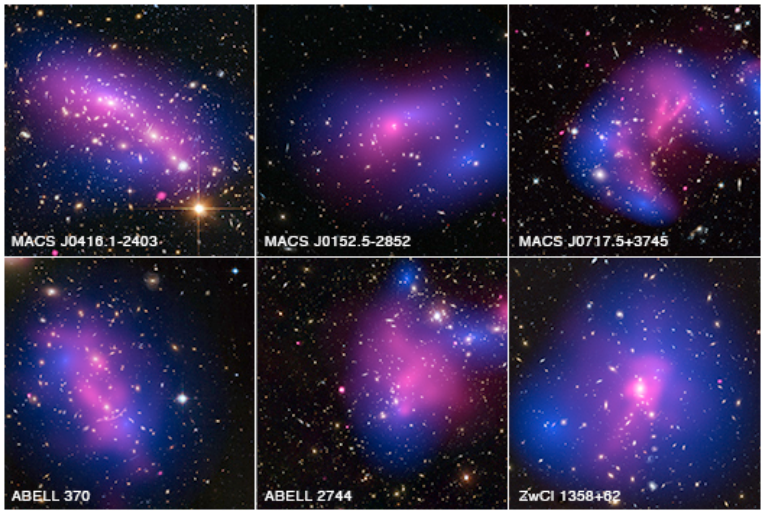


- **Nature is quite unkind!**

- **LHC has been looking intensively to find new particles:**
  - Supersymmetry
  - Leptoquarks
  - And much more…
  - Heavy Bosons
  - Multijet Resonanses
  - Exited Fermions
  - Extra Dimensions

- BUT, the only competition is which experiment (ATLAS or CMS) put the exclusion limits higher…

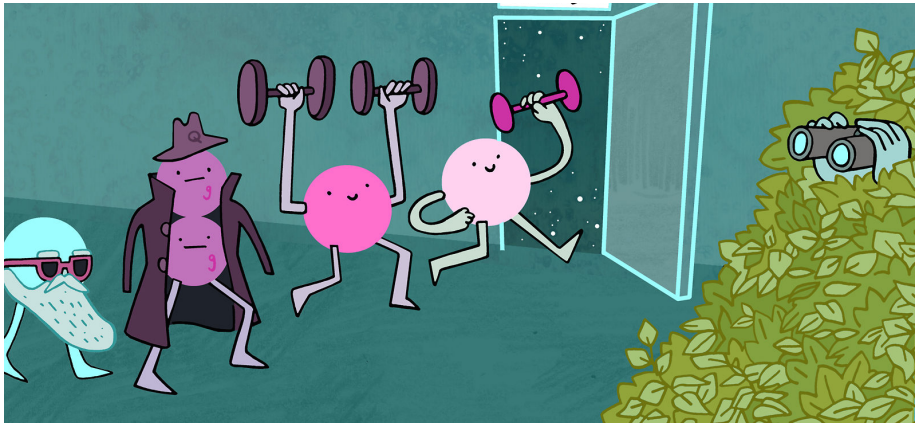
New physics



Galaxy cluster collisions (by Hubble and Chandra)

- *Dark Matter*: **no candidate in SM**

X-ray observations of revealed the **hot X-ray gas** within the galaxy clusters — gas that would have drifted away if it weren't for the **cluster's dark matter**, which **gravitationally holds it in place**

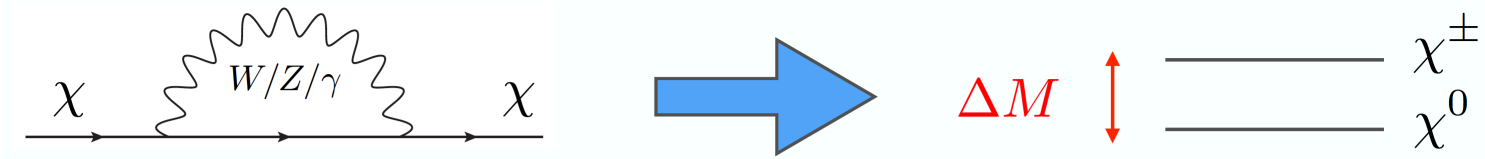


- ***Are we looking well enough?***

- **Long lived particles** produce **unique signatures** which may have been **overlooked by** more **traditional searches** for new physics

Why LLPs in BSM?

- Small phase space in **Supersymmetry**
- *Example*: new electroweak multiplets (doublets, triplets, etc)
- **Mass splitting** set by electroweak **radiative corrections**



$$\Gamma(\chi^{\pm} \to \chi^{0}\pi^{\pm}) \sim \frac{g_W^4 f_\pi^2 \Delta M^3}{M_W^4}$$

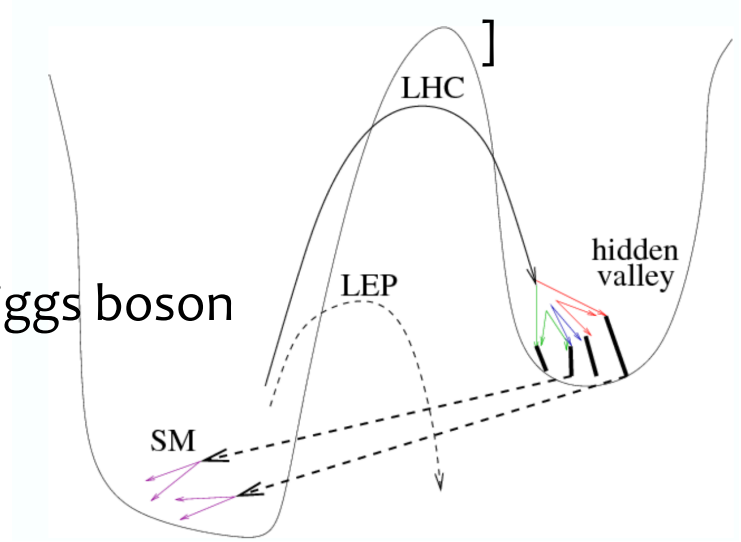
$$c\tau_{\chi^{\pm}} \sim 5 \text{ cm} \quad \text{(triplet)}$$
$$\sim 5 \text{ mm} \quad \text{(doublet)}$$

Why LLPs in BSM?

- Hierarches in **Hidden Valleys**
  - Present in any multi-component hidden sector, whether weakly or strongly interacting
  - **Dark sectors** communicates with SM only via Higgs boson

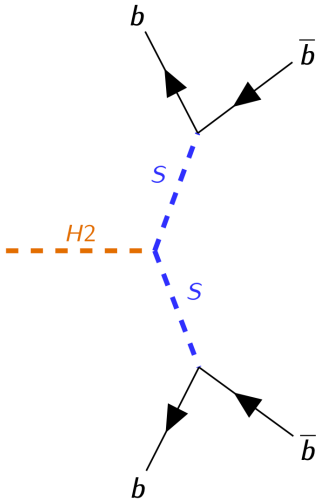
    → **solves the Higgs mass divergences!**
  - **Decay rate suppressed** by ratios of masses

[0912.3259]



- **Example:** Hidden SU(3) glueball (twin Higgs, etc)

$$c\tau \sim 18\ \mathrm{m} \left(\frac{10\ \mathrm{GeV}}{M}\right)^7$$



- **Example:**

BSM Higgs:
H2 → *SS* → *bbbb*
S is long lived
H2 can also be the SM Higgs

Bunch of LLPs in BSM

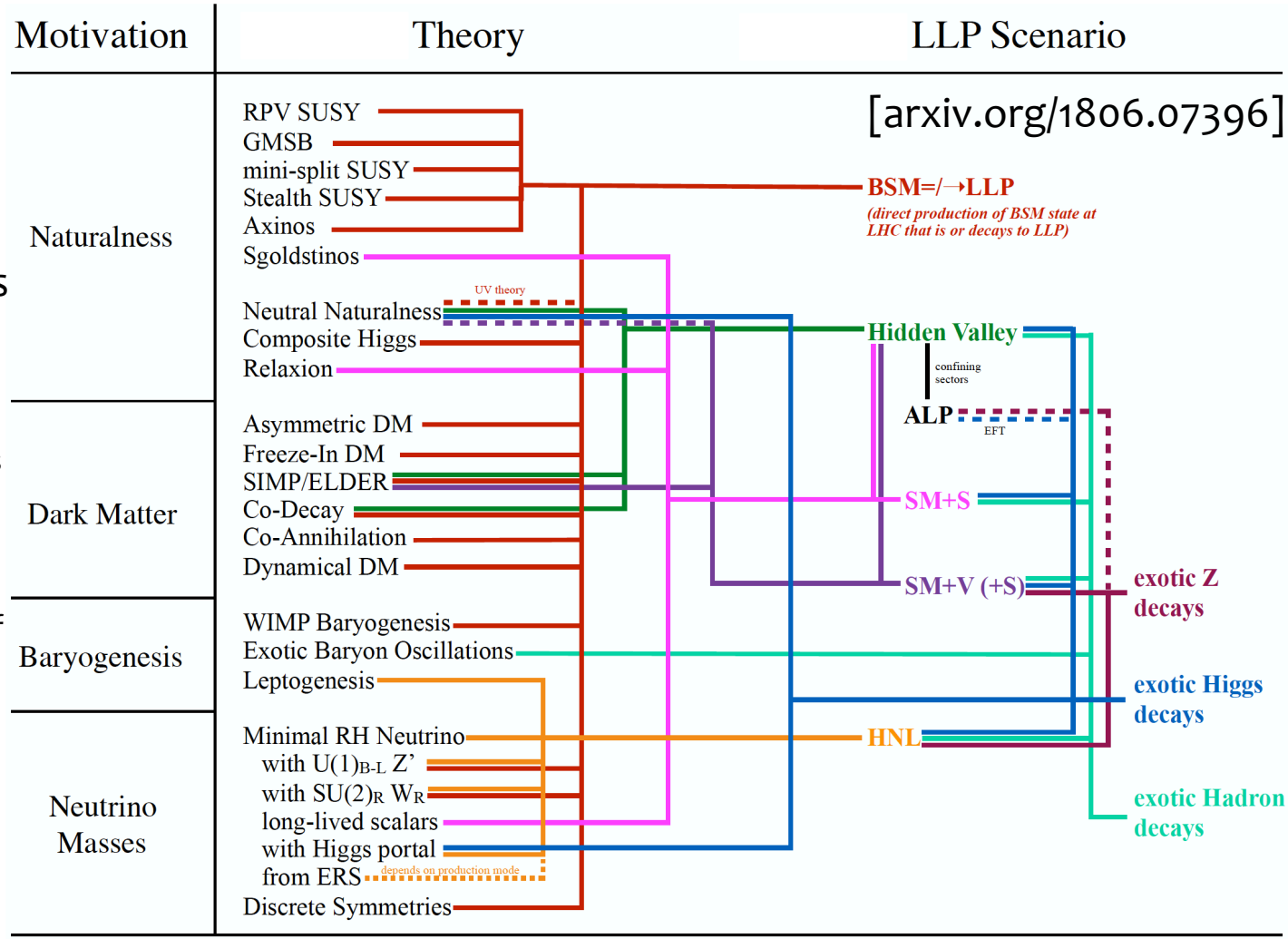
- The **long lifetime** is quite a common feature in new physics models

Discrete symmetry stabilizing Higgs mass

E.g. Freeze-in via decay requires LLPs with SM couplings

Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry

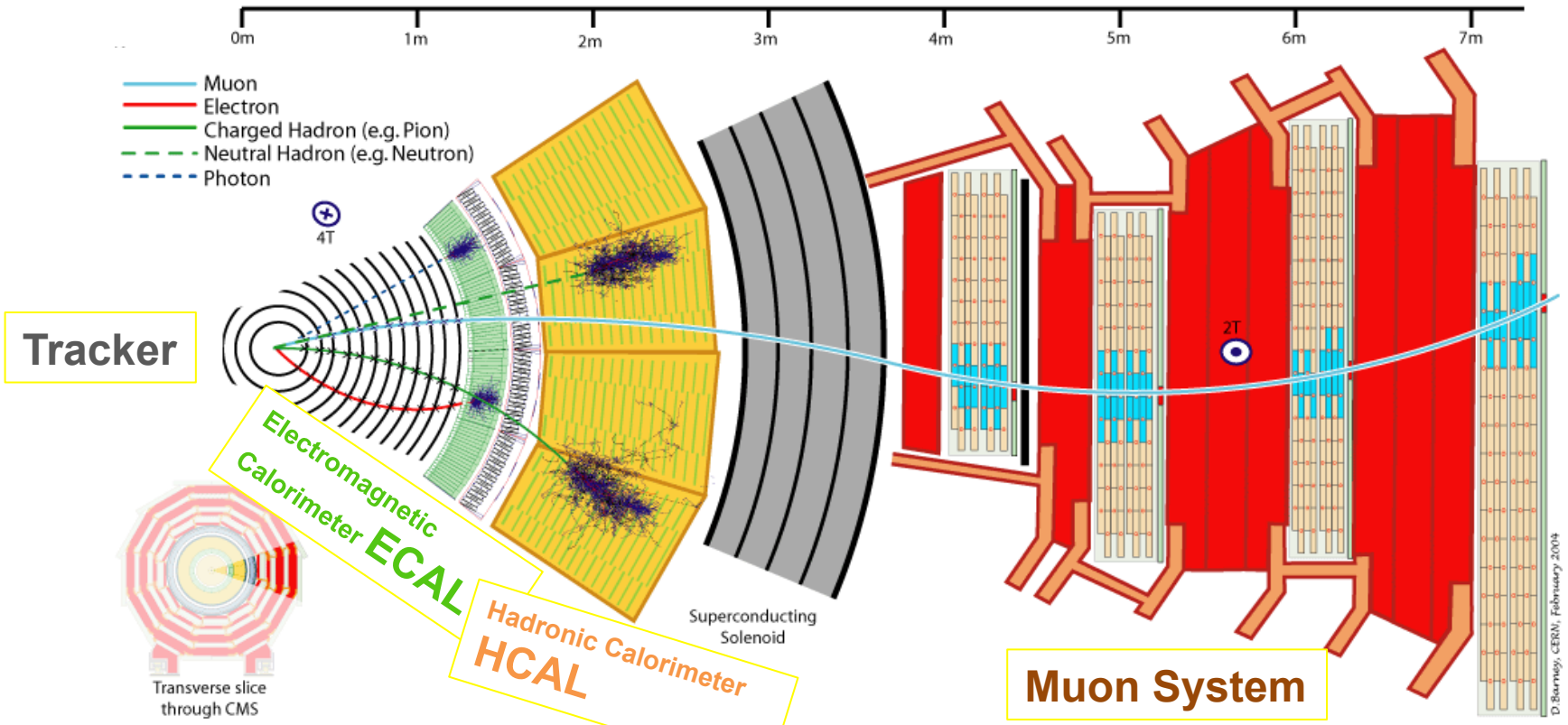
Tiny mixing between ν_L L and ν_R makes ν_R LLPs



Detector design vs LLPs

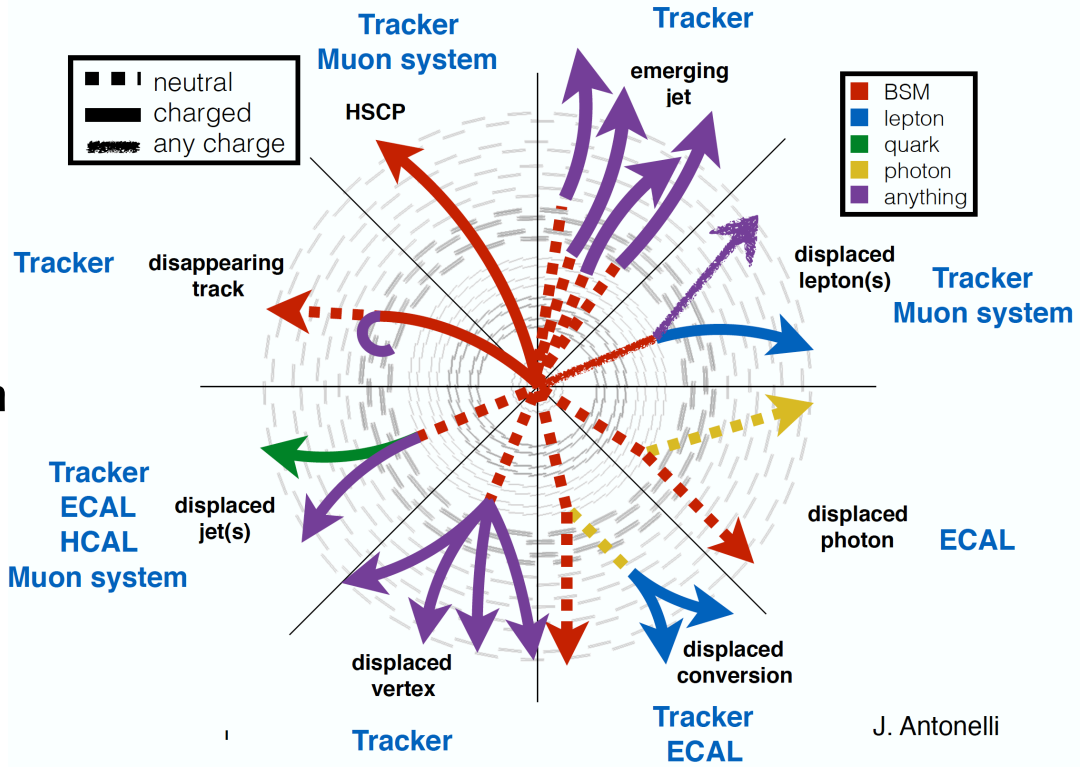
- **CMS: reconstruction** algorithms, cylindrical **geometry**, **trigger** all designed assuming ***particles emerge from the collision point***

- **LLPs signature** depend on the **lifetime** $c\tau$**:**
  - **Decay inside various regions of the detector**: *meta-stable LLP*
  - **Cross** the detector: *quasi-stable LLP*

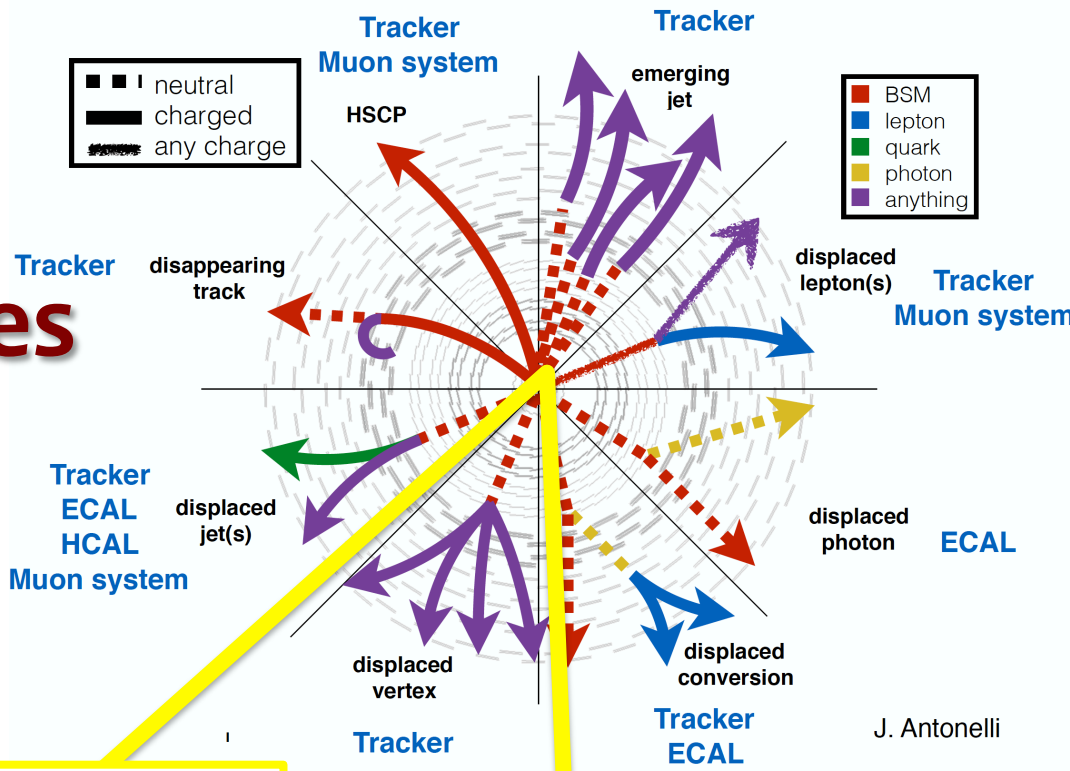


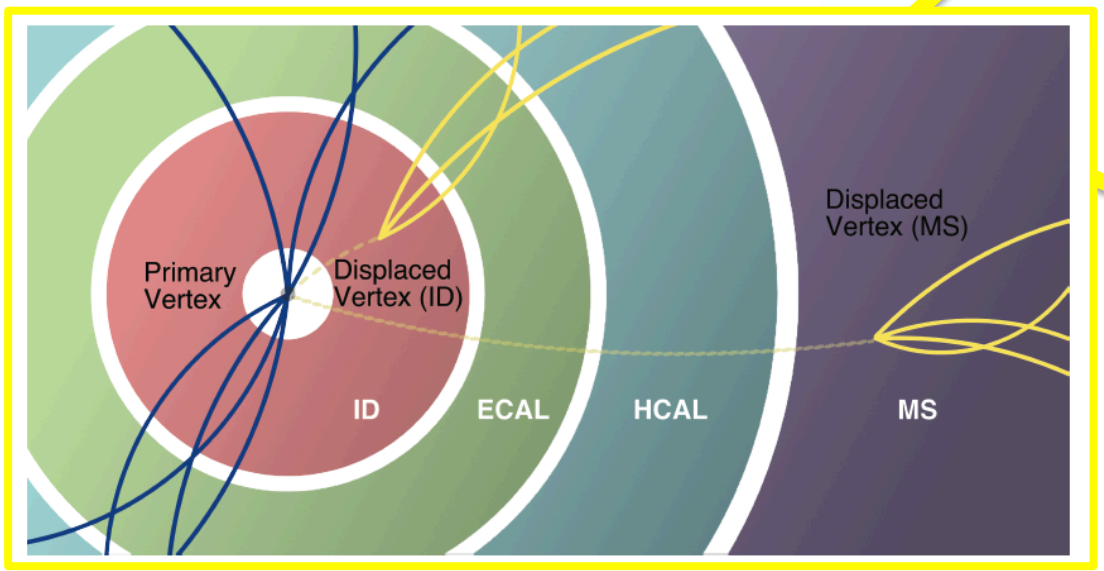
Signatures of LLPs

- **LLPs** have **unusual** final states that require **innovative** techniques
- **Challenging** from the experimental point of view:
- **Dedicated** physics object **identification** and **reconstruction**
  - Displacements
  - Short tracks
  - Jet structure
  - Timing
  - Ionization
- Triggering weird/low energy signatures
- **Atypical** (non collisional) **backgrounds**
  detector noise, cosmic rays, reco failures – can be estimated from data



Displaced Vertices

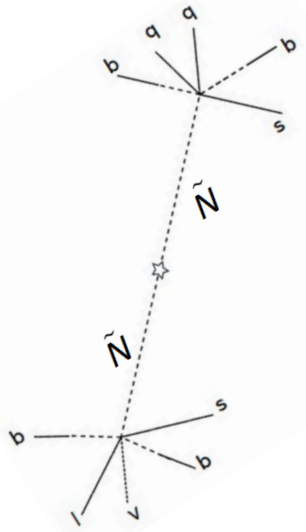




Displaced vertices in multijet events

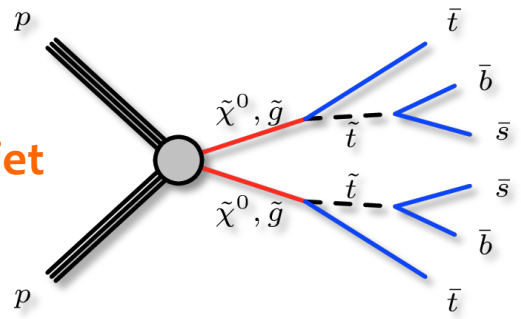
- **Signature: displaced jets** in the region of a beam pipe

- **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

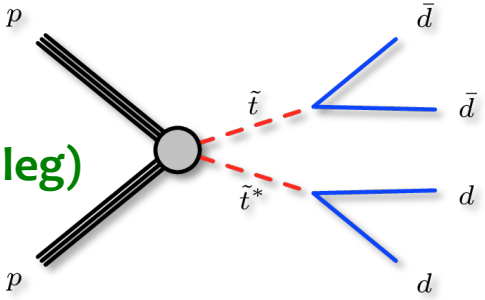


- **Benchmark:**
  - Pair-produced long-lived neutralinos/gluinos or stops in RPV SUSY

Multijet



Dijet (per leg)

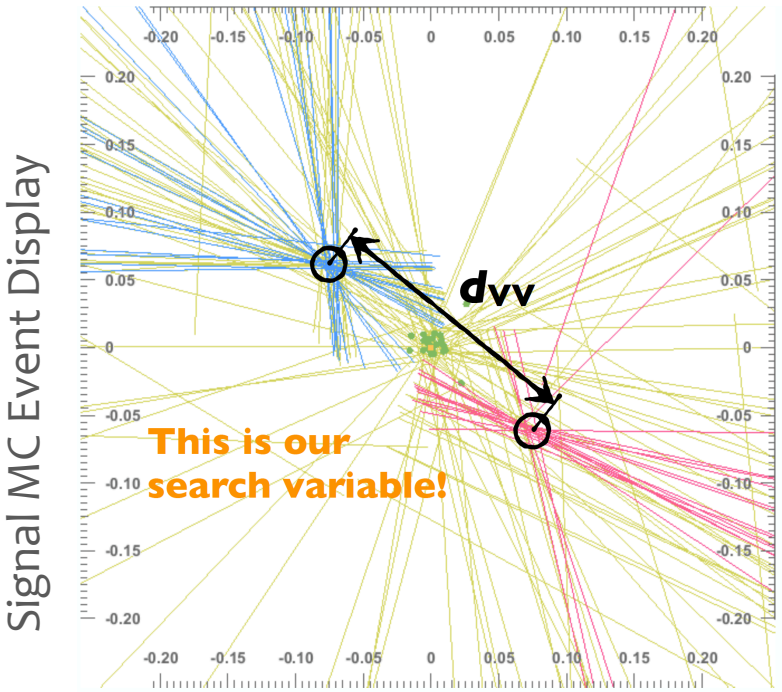


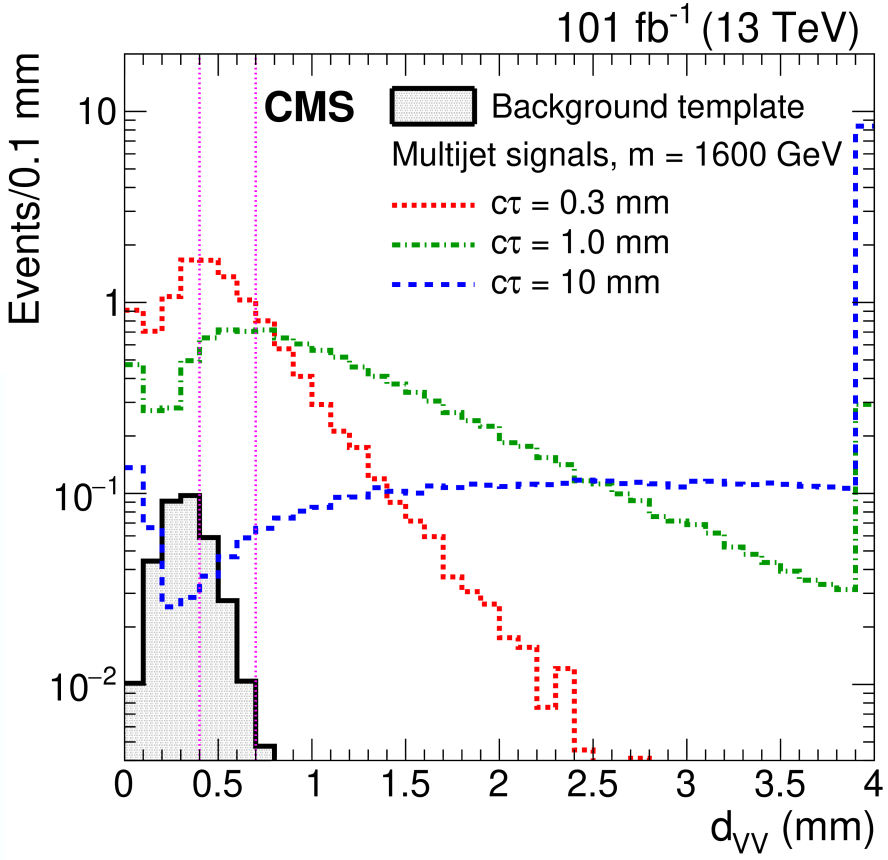
EXO-19-013, submitted to PRD

Displaced vertices - variable

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

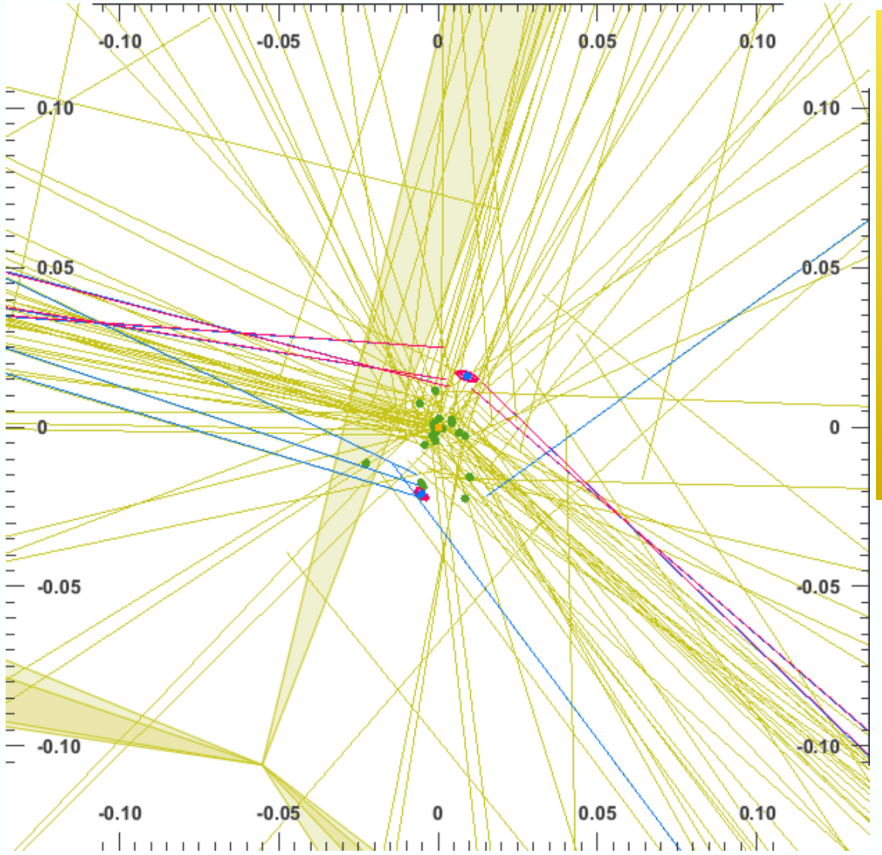
- **Search regions:** 3 bins
  - 0.0 – 0.4 mm
  - 0.4 – 0.7 mm
  - 0.7 – 40 mm





Displaced vertices - bkg

- **Background vertices** arise due to misreconstructed tracks with non-negligible transverse impact parameters
- Two-vertex background events are independent rare coincidences of two background vertices from separate misreconstructions in one event
- No guarantee that MC can faithfully reproduce such effects
- **Use data-driven method** to construct background template that models two-vertex background shape



Phys. Rev. D 98, 092011 (2018)

2016 DATA event observed

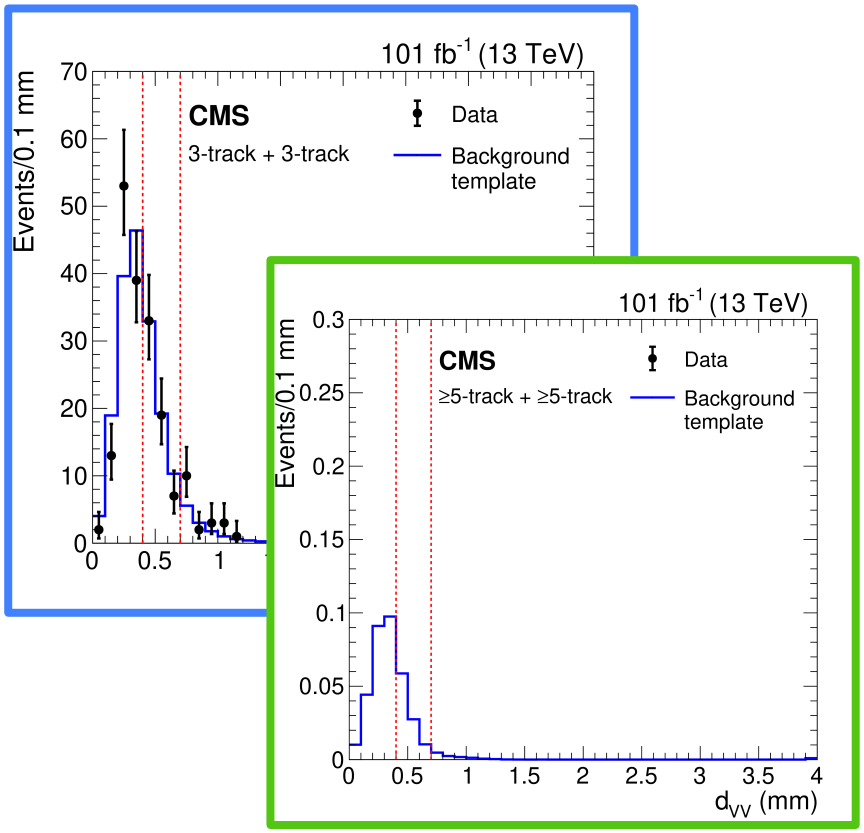
(≥5-track two-vertex) with d_{VV} = 396 µm

EXO-19-013, submitted to PRD

Displaced vertices - results

- **Trigger:** on events with large jet acctivity
  standard HT = $\Sigma^{Njets} E_T$ > 1050 GeV
- **Selection:** ≥ 4 jets

- **Control samples:**
  - events with 3-track & 4-track vertices
- **Background:**
  - estimated from ≥5-track one-vertex
- **Signal region:**
  - ≥5-track two-vertex events



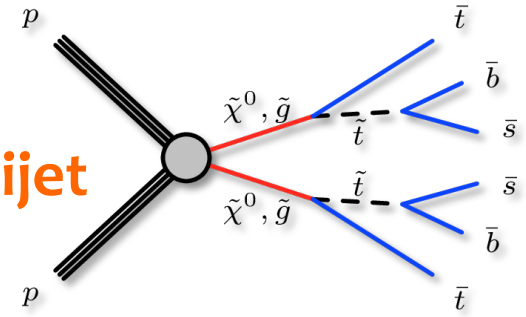
- **Results:** 0 event observed (≥5-track two-vertex)

		Predicted multijet signal yields			
d_{VV} range	Predicted background yield	0.3 mm	1.0 mm	10 mm	Observed
0–0.4 mm	0.243 ± 0.003 (stat) ± 0.061 (syst)	4.4 ± 0.5	1.5 ± 0.1	0.26 ± 0.02	0
0.4–0.7 mm	0.097 ± 0.003 (stat) ± 0.032 (syst)	4.1 ± 0.5	2.1 ± 0.2	0.14 ± 0.01	0
0.7–40 mm	0.012 ± 0.001 (stat) ± 0.006 (syst)	3.0 ± 0.3	7.6 ± 0.7	12 ± 1	0

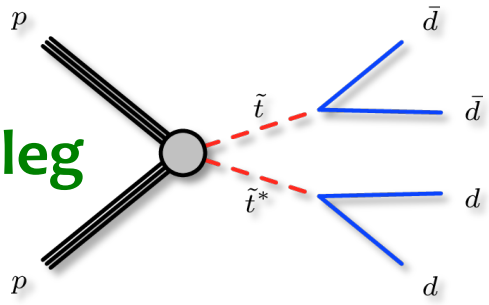
EXO-19-013, submitted to PRD

Displaced vertices - intepretation

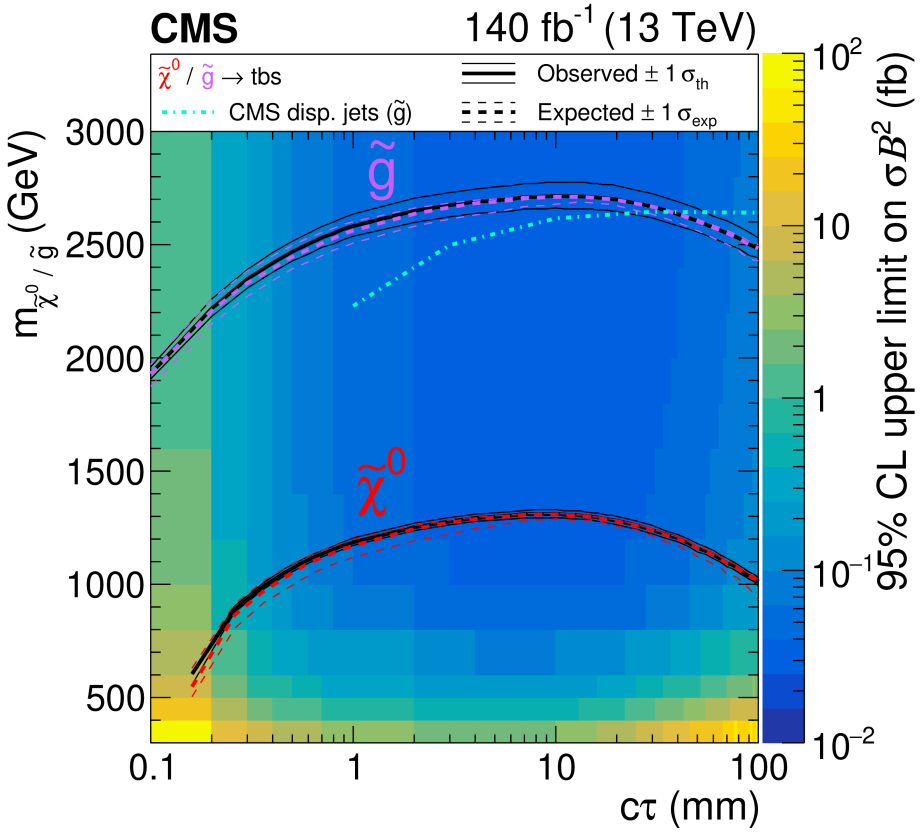
Multijet

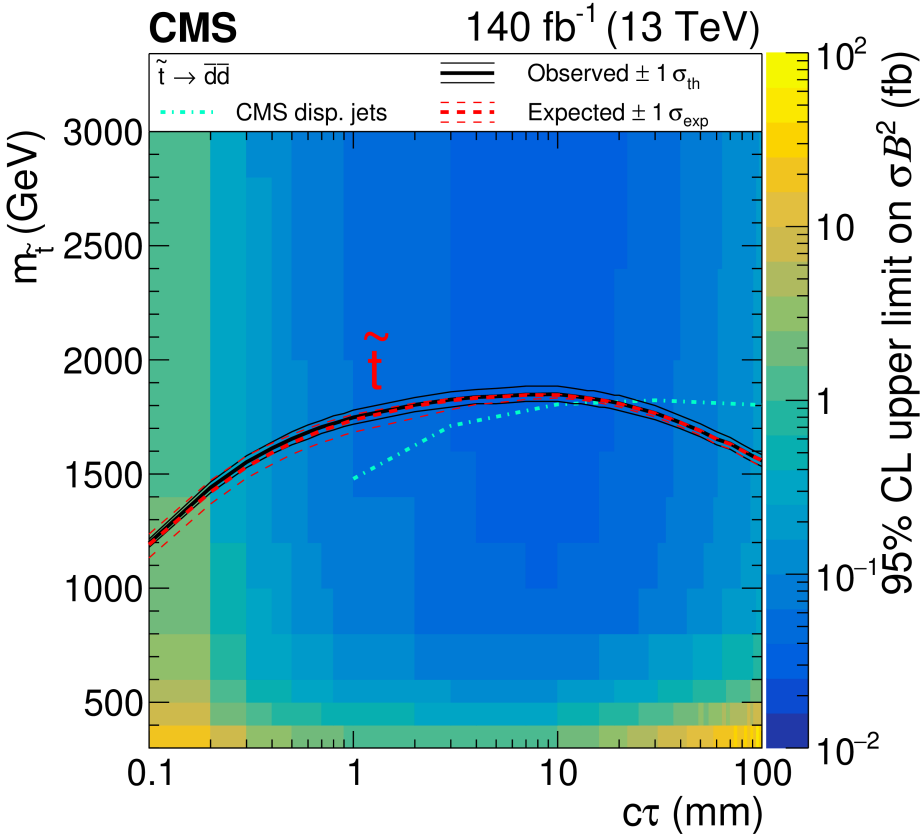


Dijet per leg

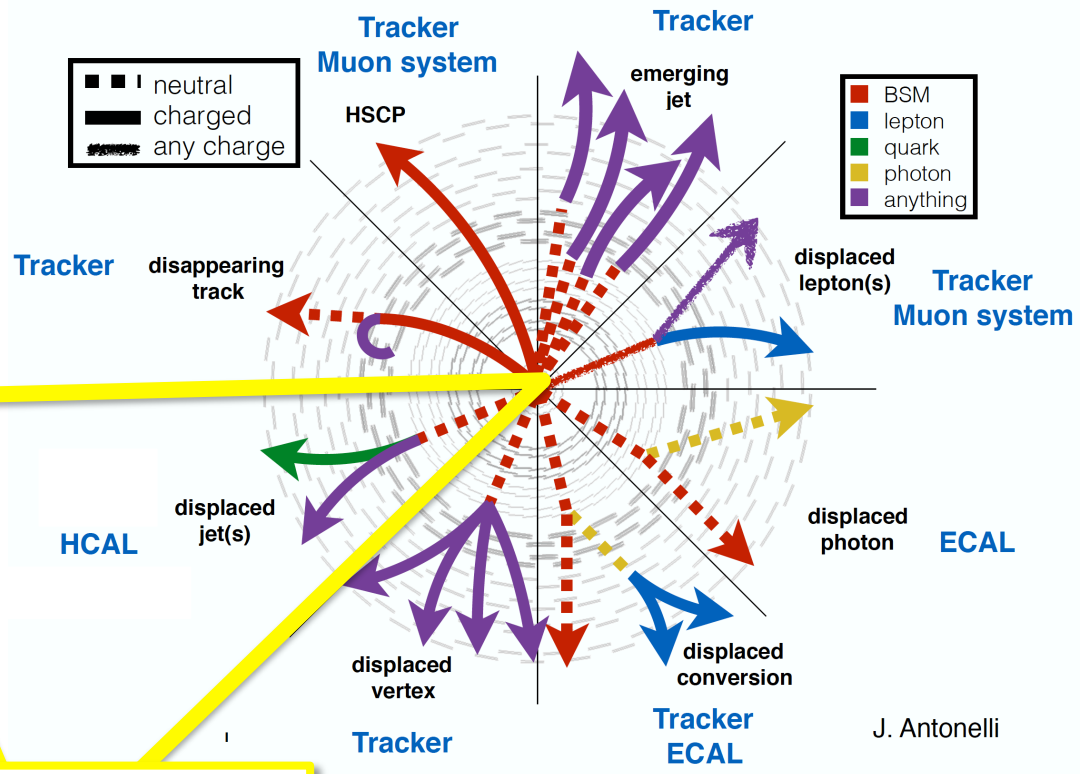


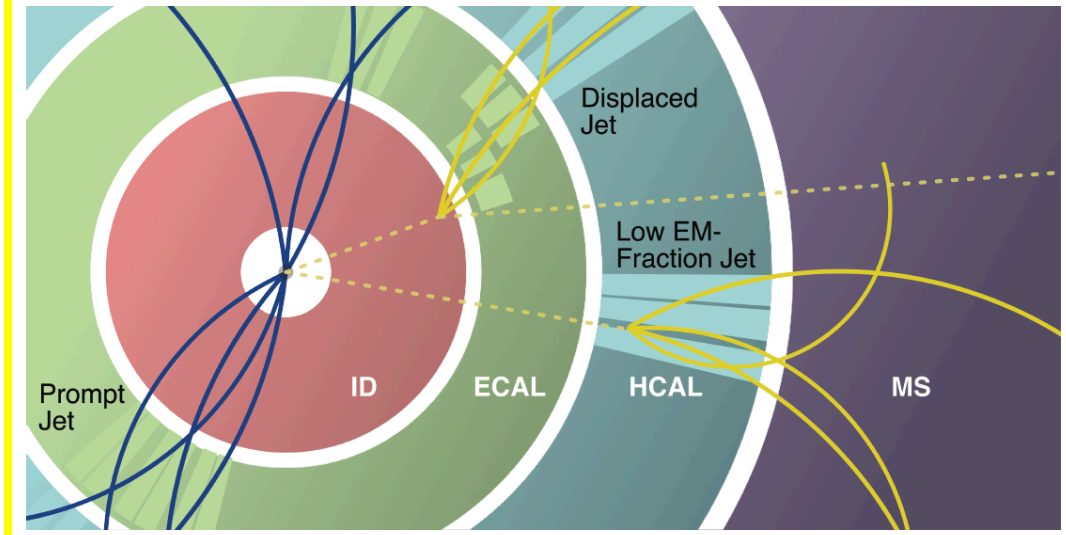
Full Run 2





Displaced Jets



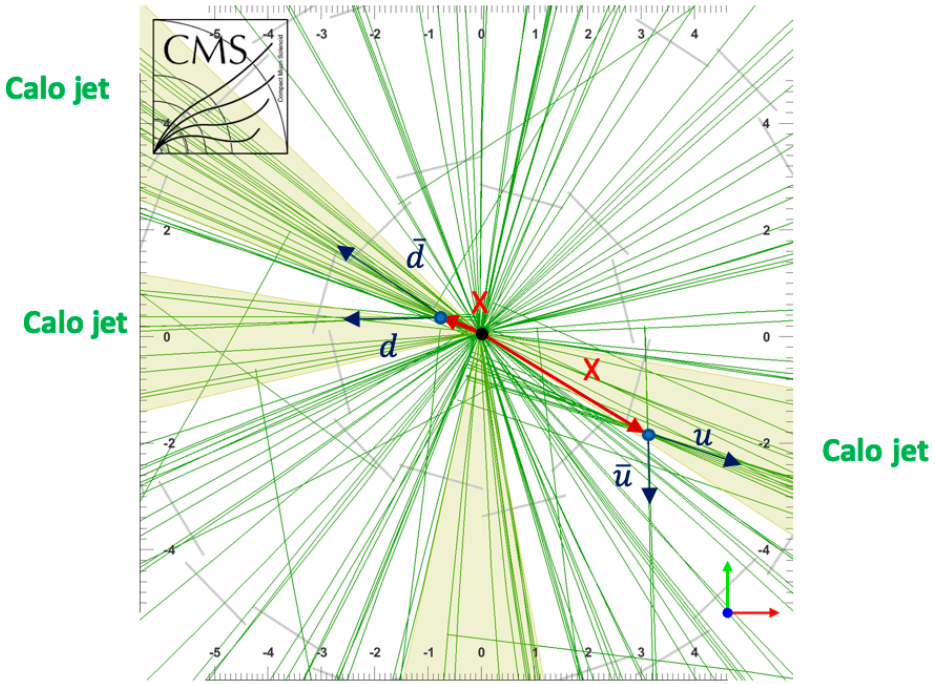


EXO-19-021, submitted to PRD

Displaced Jets

- Distinctive **topology:**
  pair of jets originating at a **secondary vertex displaced**
  from the production vertex by up to around 55 cm in the transverse plane
- inclusive search for LLPs decaying into jets, with **at least one displaced vertex**

Reconstructed tracks (and CALO jets) in a simulated LLP event



Full Run 2

- 2017/2018: **95.9/fb**
- 2016: **36/fb**

Phys. Rev. D 99 (2019) 032011

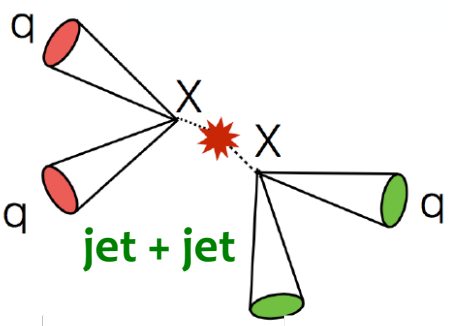
Calo jet is formed from energy deposits in the calorimeters

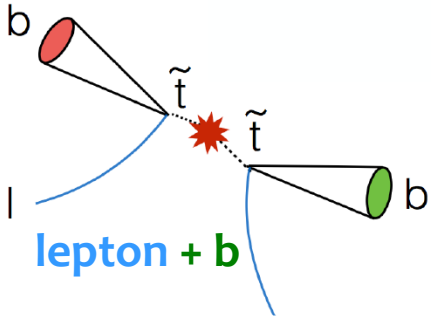
Displaced Jets - signal

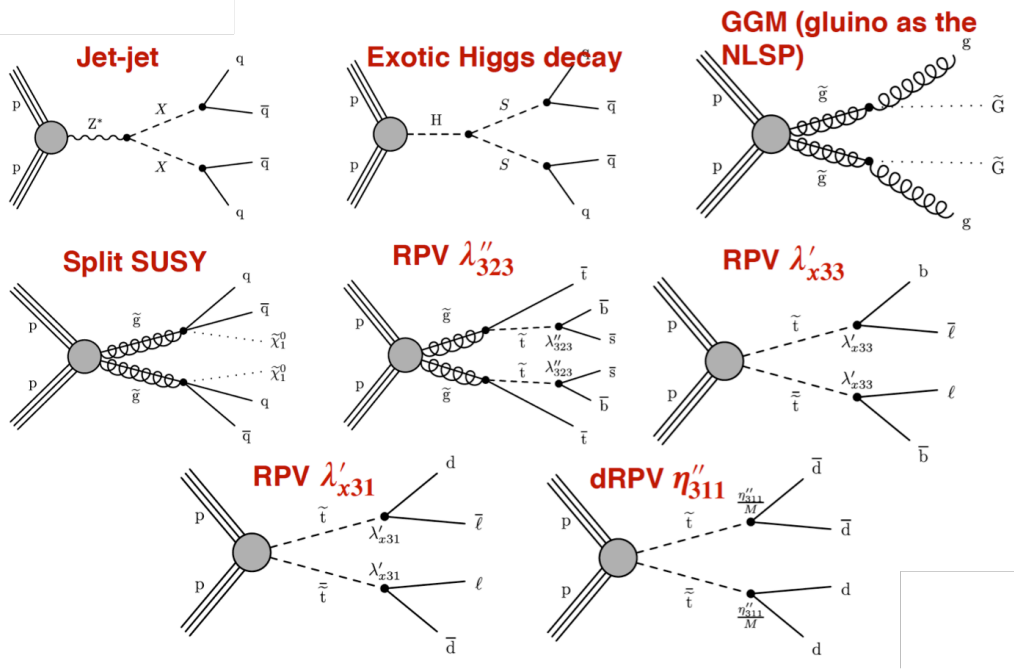
- Distinctive **topology:**
  pair of jets originating at a **displaced vertex**

Hypothetical **SIGNAL:**

- **Long-lived massive neutral particles** decaying to quark-antiquark pairs
- **Jet-jet** benchmark model:
  gg → (non-SM) H → 2X, X → qq
  where **$c\tau_X$ ~ 1mm to 10m**
- **BMS models:**
  Hidden Valley Higgs, Split SUSY, General Gauge Mediated SUSY, RPV SUSY







Displaced Jets – pre-selection

- Two **triggers:**
  the ***displaced* trigger** has better efficiency for low-mass LLPs,
  while the ***inclusive* trigger** recovers efficiency for high mass LLPs
  with small cτ (< ~3mm) and large cτ (> ~300mm)

- with algo for **jet displacement tagging**
  - H_T > 430 (**650**) GeV
  - ≥2 jets with pT > 40 (**60**) GeV, |η| <2.0
  - ≥1 displaced track (**no requirement on the number of displaced tracks**)
  - ≤2 (**associated**) prompt tracks

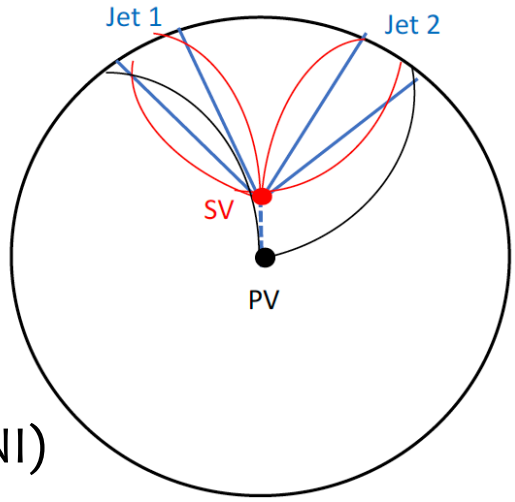
H_T – a scalar sum of p_T of all jets with p_T > 40GeV and |η| < 2.5 in the event

- Basic event selections:
  - If passes the ***displaced*** (***inclusive***) trigger:
    Calo **H_T>500 (700) GeV**, Calo jets **p_T>50 (80) GeV**, |η|<2.0
  - Track-jet association, tracks are matched to jets within R<0.5
  - Tracks are required to high-purity and have p_T>1GeV

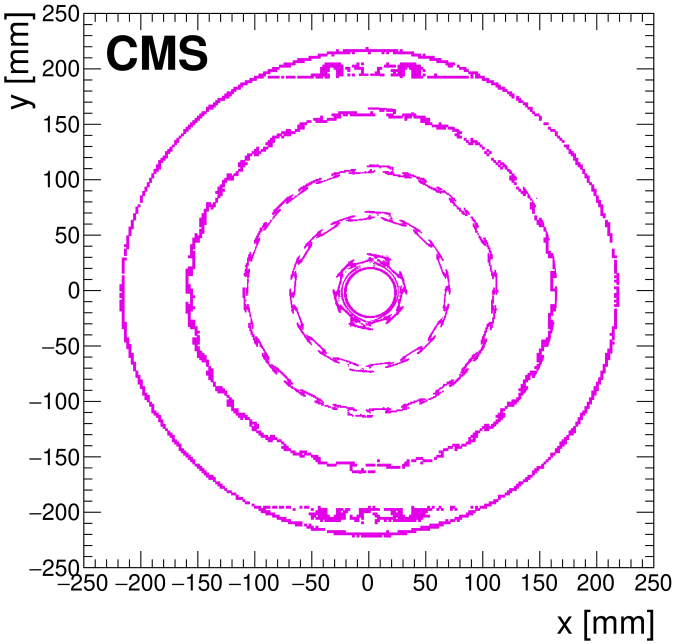
Displaced Jets – SV reco

Secondary vertex reconstruction

- For all possible pairs of jets
- **Tracks** associated with the **dijet candidate**
- Fit a **SV** position
- Vertex **Mass$_{inv}$** > 4 GeV and **vertex p$_T$** > 8 GeV



Background events arise from nuclear interactions (NI) with the **inner pixel tracker** material



Pixel tracker

- NI vertex candidates reflect a structure of the pixel tracking system and beam pipe
- **Any secondary vertex candidate that overlaps with the NI-veto map is rejected**

Displaced Jets – background

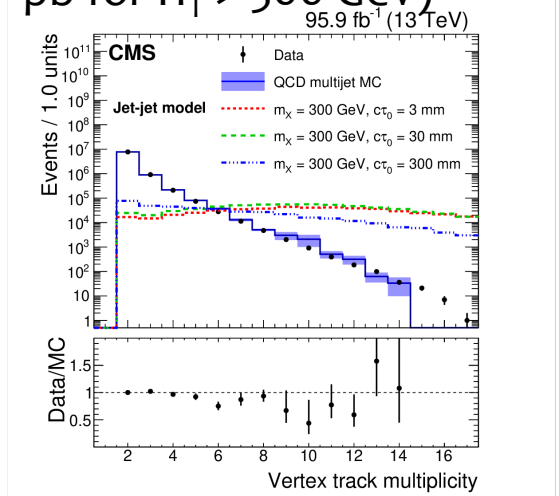
- **QCD multijet process dominates the background**
  given the large cross section (~4 x 10^4 pb for H_T > 500 GeV)

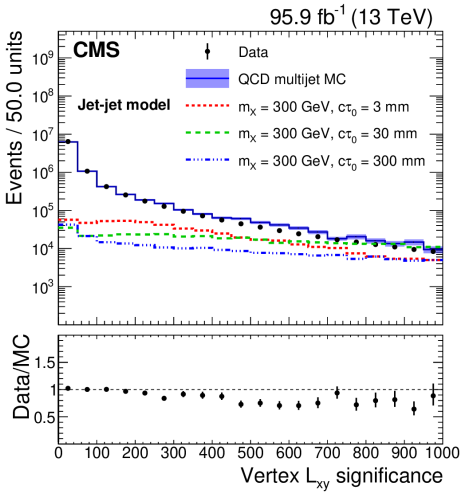
- **Gradient Boosted Decision Tree (GBDT)** as the discriminant on four variables:
  1. vertex track multiplicity
  2. cluster RMS
  3. vertex Lxy significance
  4. |κ|

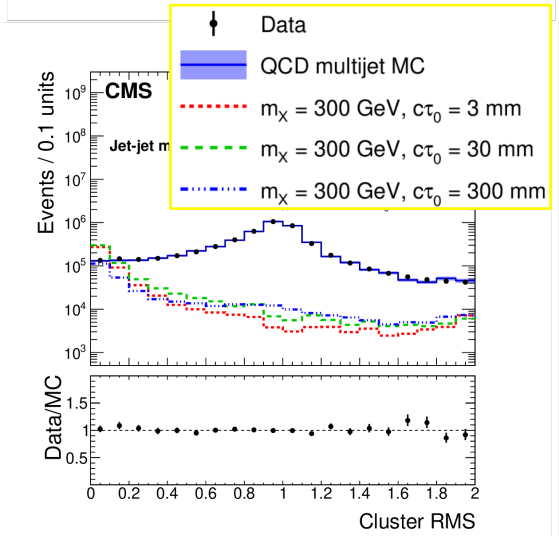
$$\kappa = \sum_{i=1}^{6} \mathrm{Sig}[\mathrm{IP}_{2D}(\mathrm{track}_i)]$$

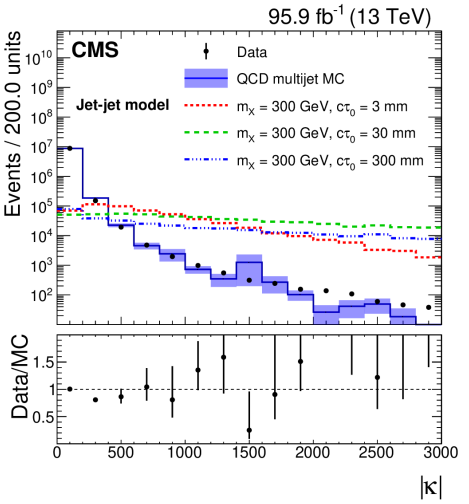
- Control region for GBDT training:
  - selection on the SV track energy fraction inverted
  - NI-veto removed

- Signal distributions almost do not depend on mass and ctau



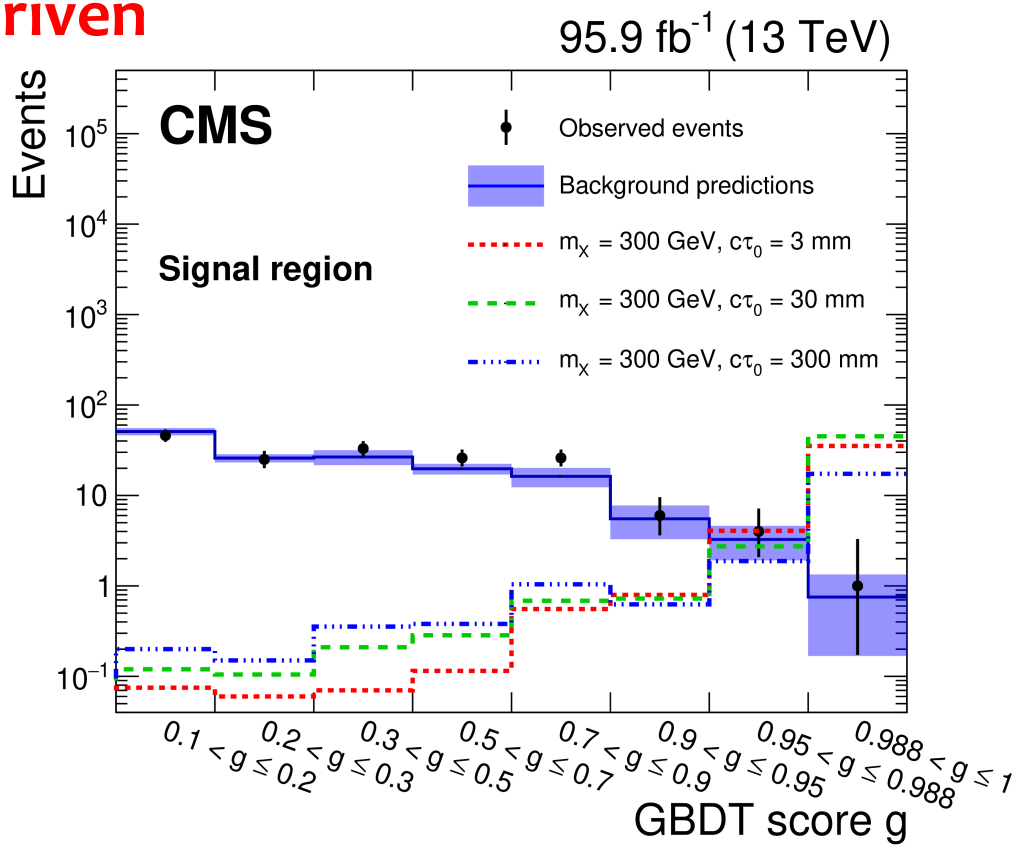






Displaced Jets – bckg. prediction

- Background is **purely data-driven**
- with extended ABCD method predictions in 8 regions for 3 selection options:
  - no of prompt tracks for 1st jet ≤2
  - no of prompt tracks for 2nd jet ≤2
  - GBDT>0.988
- **Signal region:**
  - all selection criteria applied
  - no of prompt tracks for both jets ≤2
  - GBDT>0.988

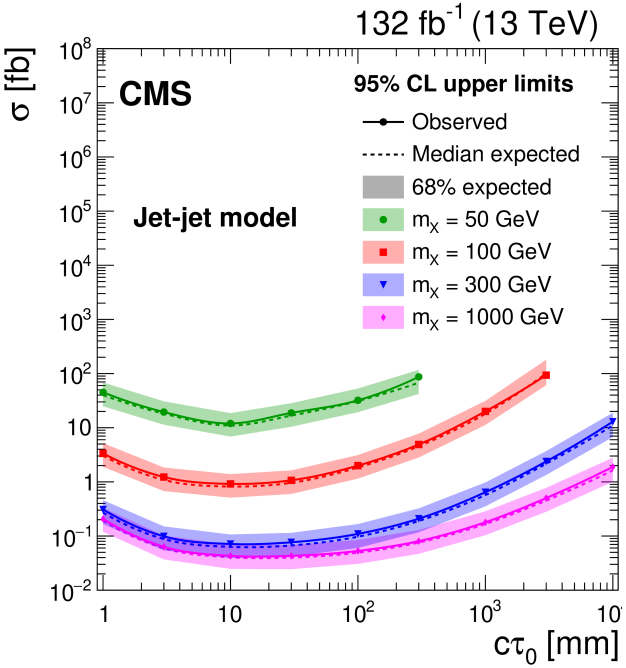


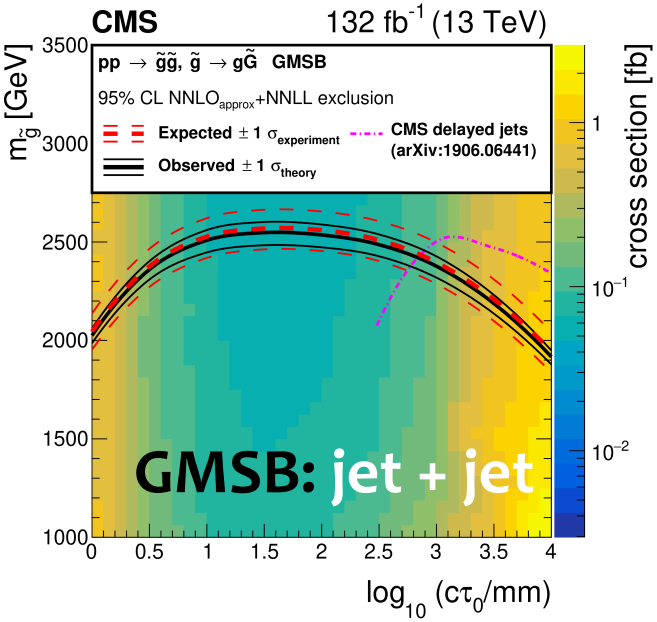
- **Predicted background** in the final signal region: **0.75 ± 0.44(stat) ± 0.39(syst)**
- Number of **observed events: 1 event** (H_T = 570 GeV, SV with Lxy ~26 cm and 8 assigned tracks)

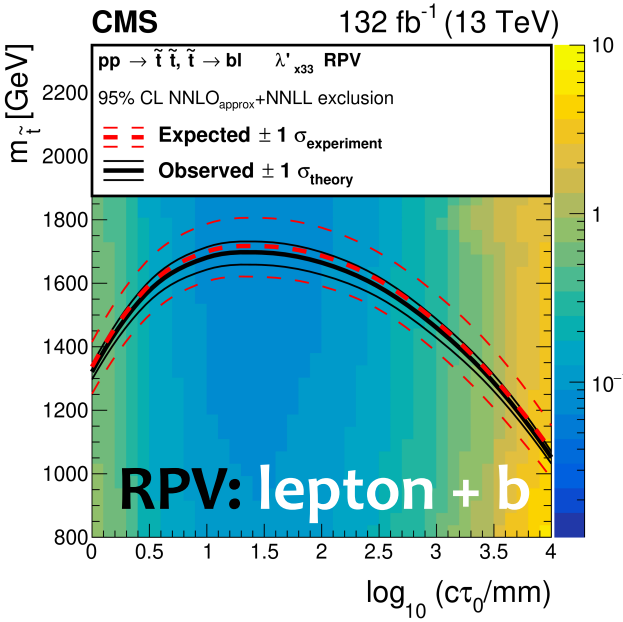
New limits with displaced jets

Combined results for Full Run 2 data (2016 + 2017/18) :

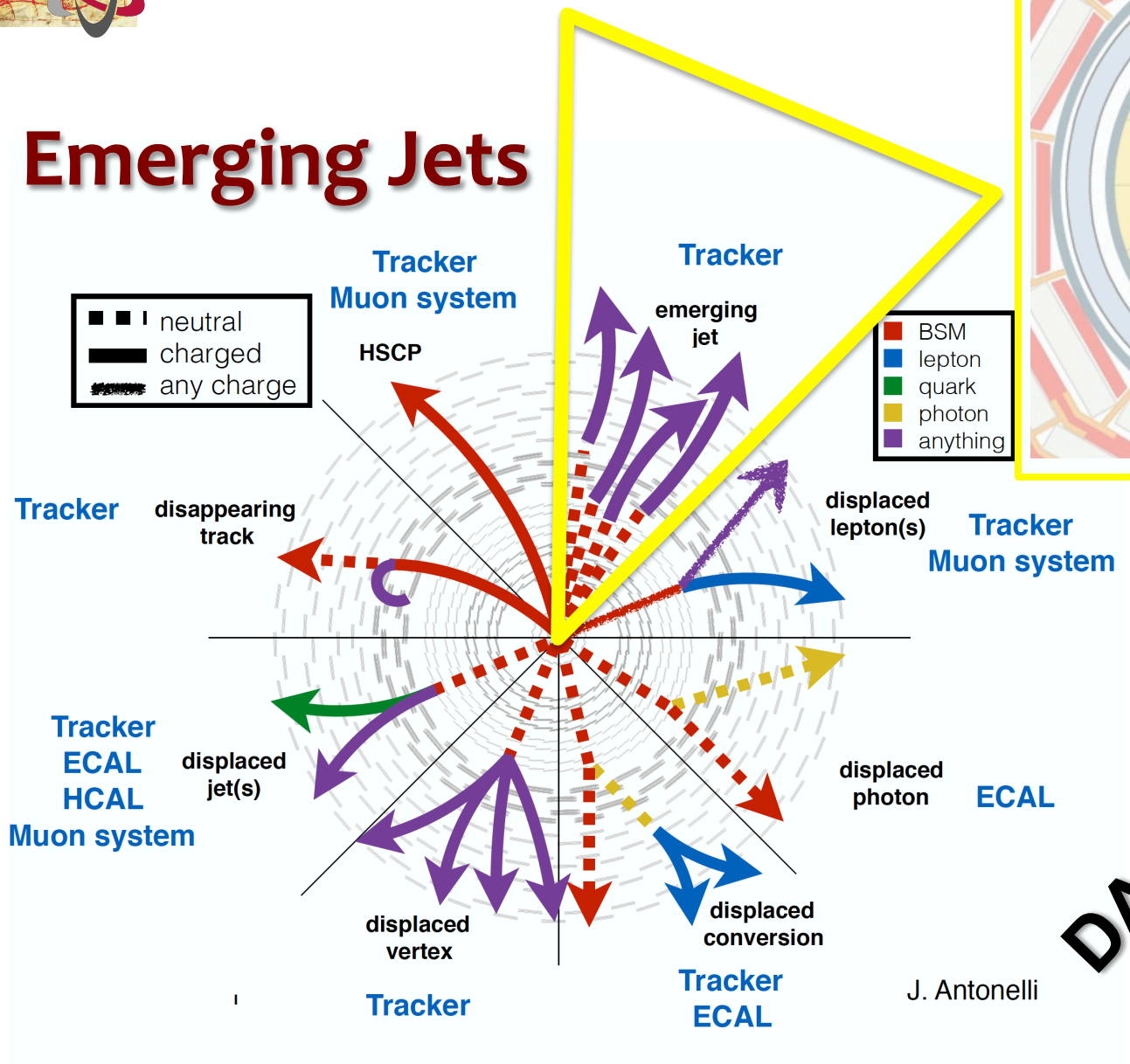
- Exclusion limits on the cross-section on **new neutral LLPs** decaying to two jets, 0.04 fb at high mass (m_X>1000 GeV) for $c\tau_0$ = 30 mm
- **GMSB:** pair-produced **LL gluinos** lighter than **2450 GeV** are excluded for $c\tau_0$ between 6 and 550 mm
- **RPV SUSY:** pair-produced **LL top squarks** lighter than ~1600 GeV are excluded for $c\tau_0$ between 2 and 1320 mm

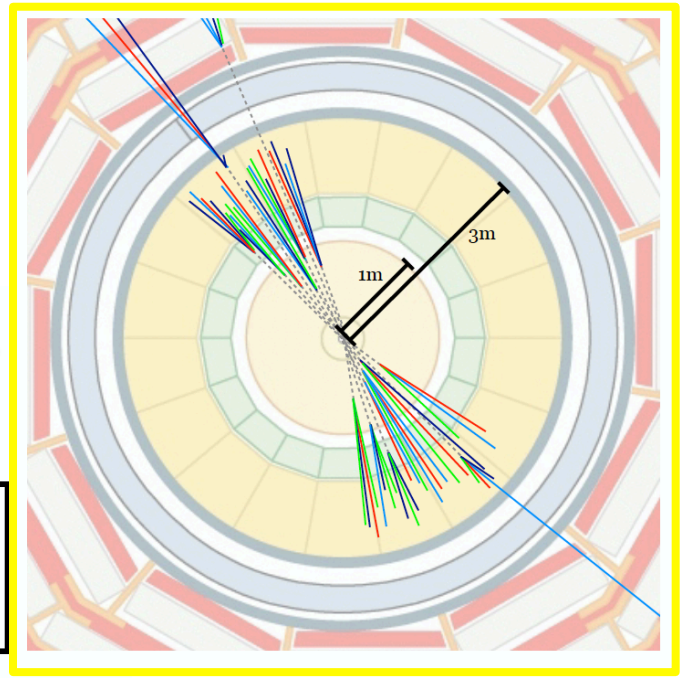






Emerging Jets





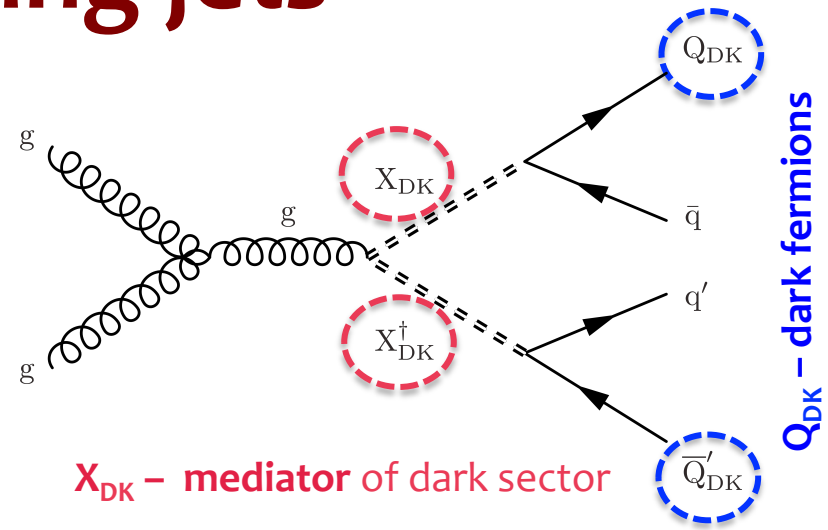
DARK SHOWERS
of Hidden Valley
[Knapen et al., arXiv:1612.00850]

JHEP 02 (2019) 179, EXO-18-001

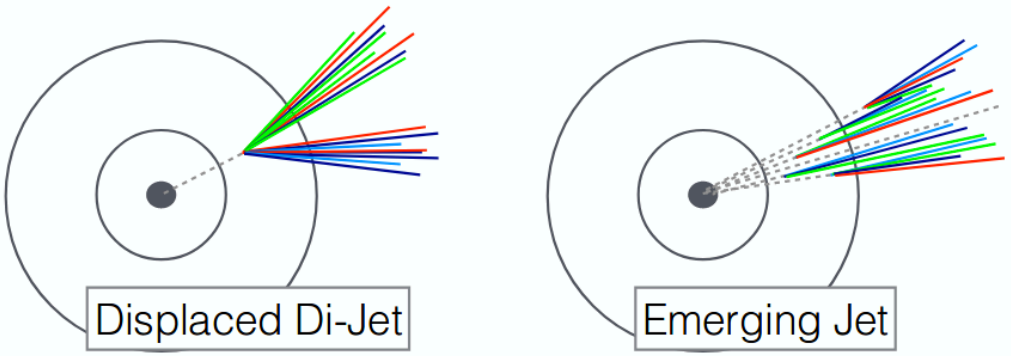
Emerging jets

- 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

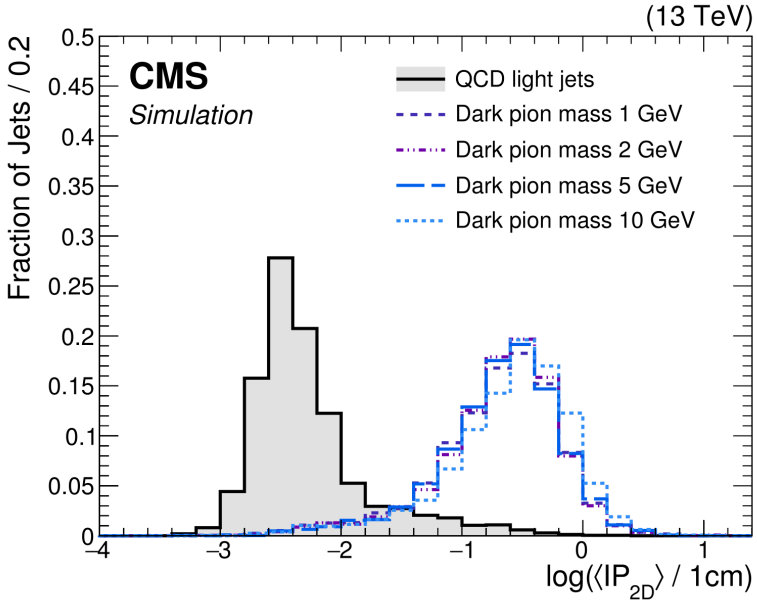
focus on lifetimes of
1 mm < $c\tau$ < 1 m

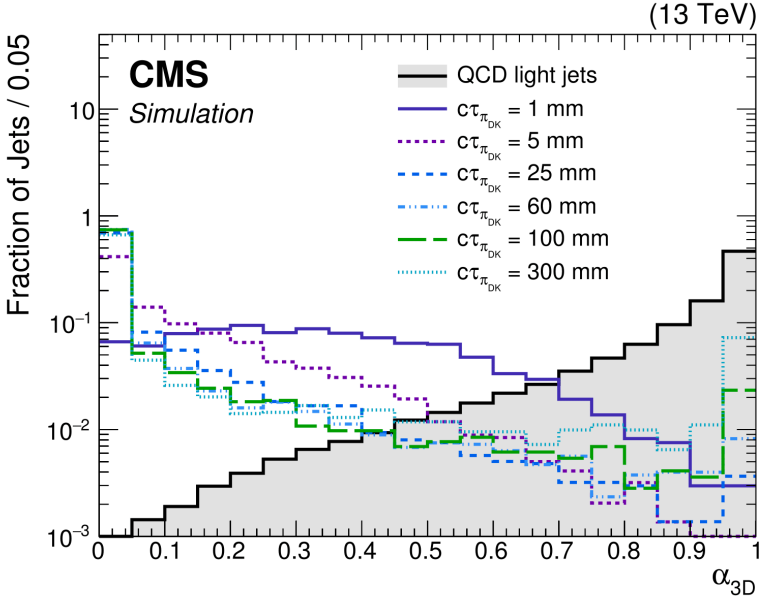
336 signal hypotheses

JHEP 02 (2019) 179, EXO-18-001

Emerging jets – stratedy

- **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:*





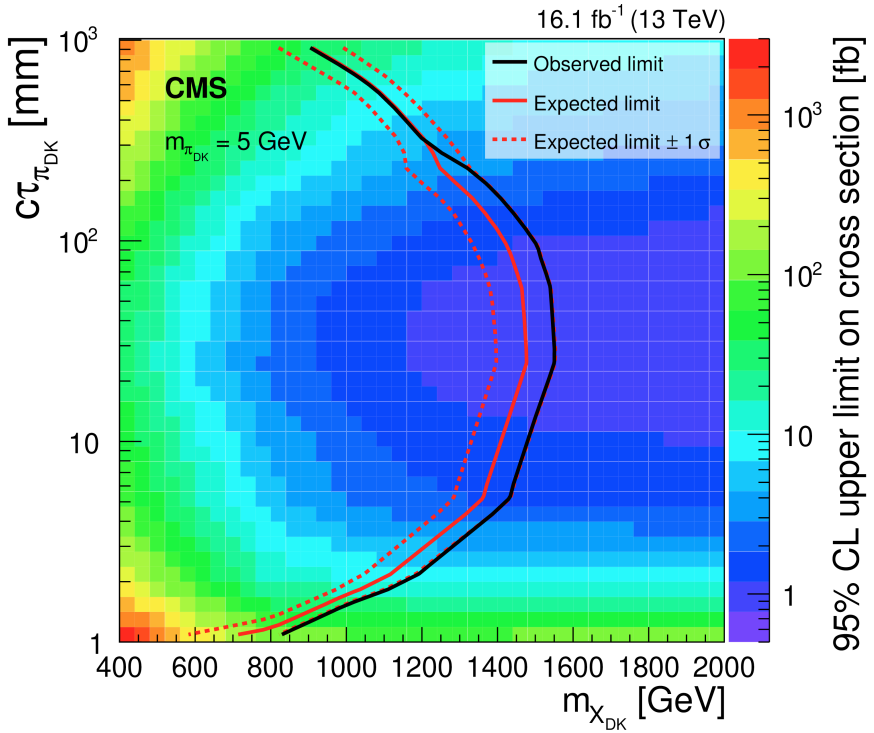
- **7 Different selections sets** are used with:
  - optimized kinematic cuts on HT, p_T of jets, MET
  - optimized emerging jet tag cuts

JHEP 02 (2019) 179, EXO-18-001

Emerging jets - limits

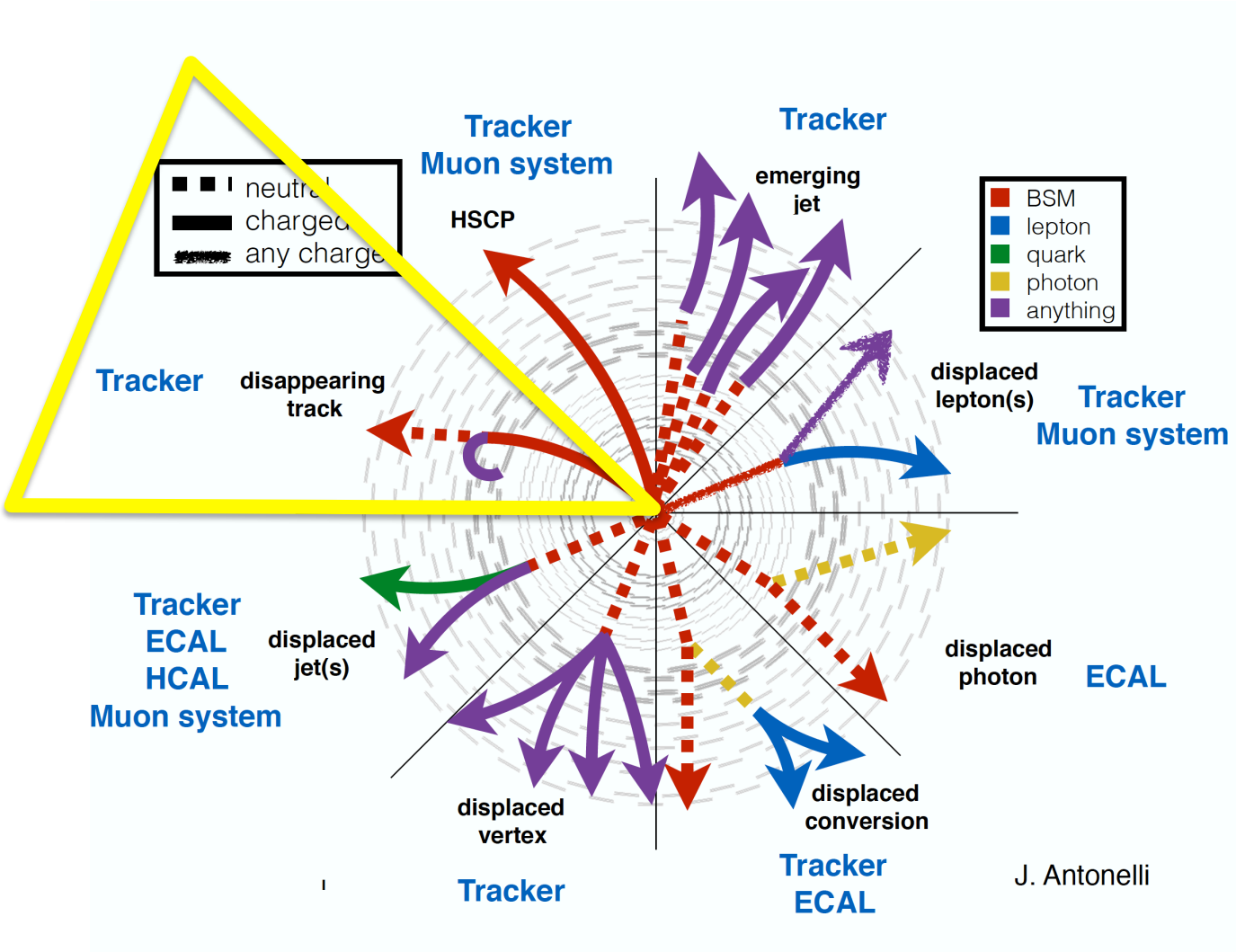
- **Results:** Observed events agree with bkg. expectation in all 7 selection sets

	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



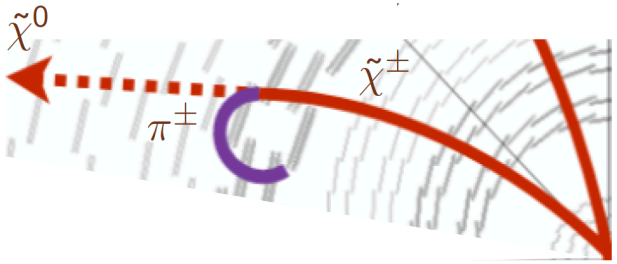
- **First emerging jets search at colliders!**
- **First Dark QCD results**
- Limits do not depend strongly on mass of dark pion π_{DK}
- Exclude dark-mass mediator X_{DK} mass between **400 and 1250 GeV** for $c\tau$ (π_{DK}) between **5 and 225 mm**

Disappearing track



EPJC 80 (2020) 3, SUS-19-005

Disappearing tracks



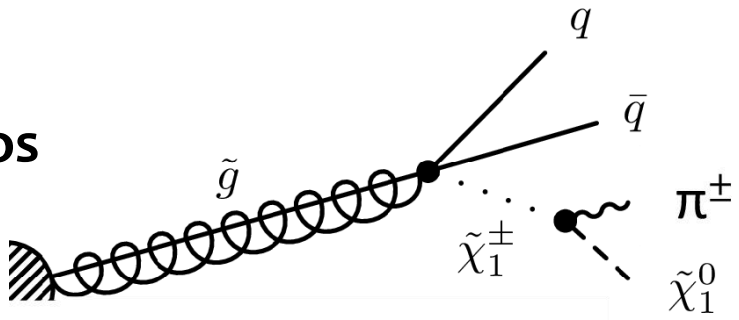
- **Signature** of **short track (ST)** in the tracker

→ **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



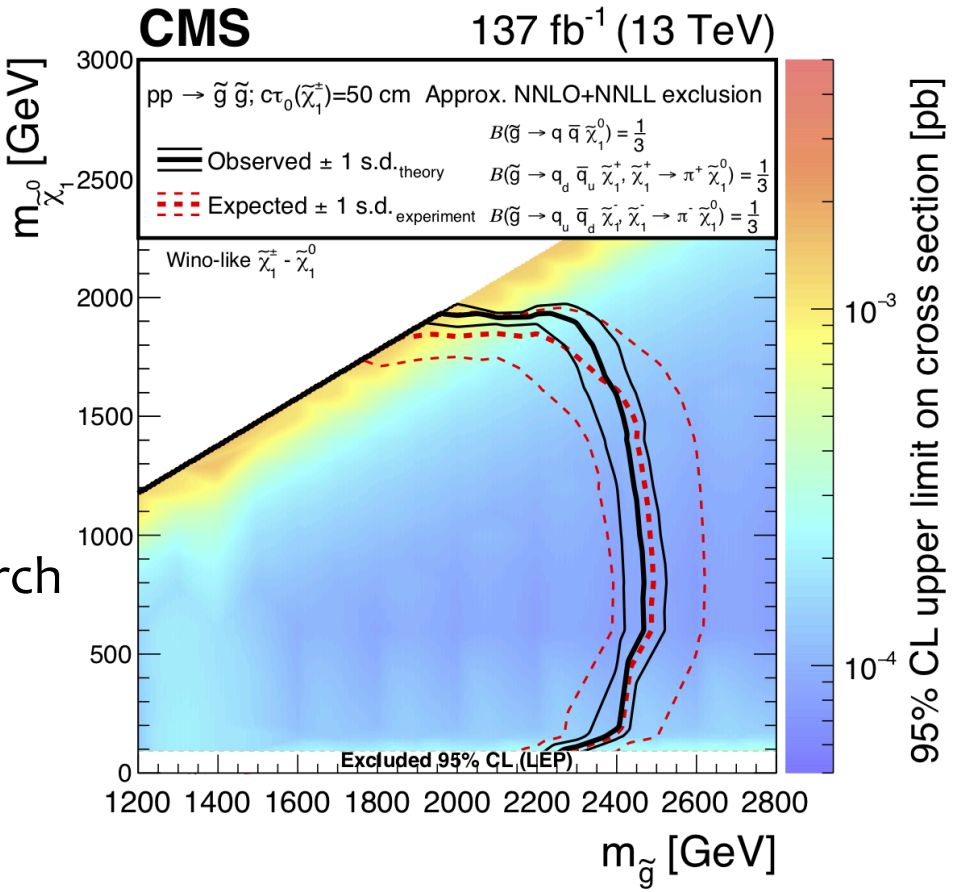
- **Analysis strategy:** classic SUSY **inclusive M_{T2} search adopted** to disappearing track search for events with at least 2 jets

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

EPJC 80 (2020) 3, SUS-19-005

Disappearing tracks - results

- **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

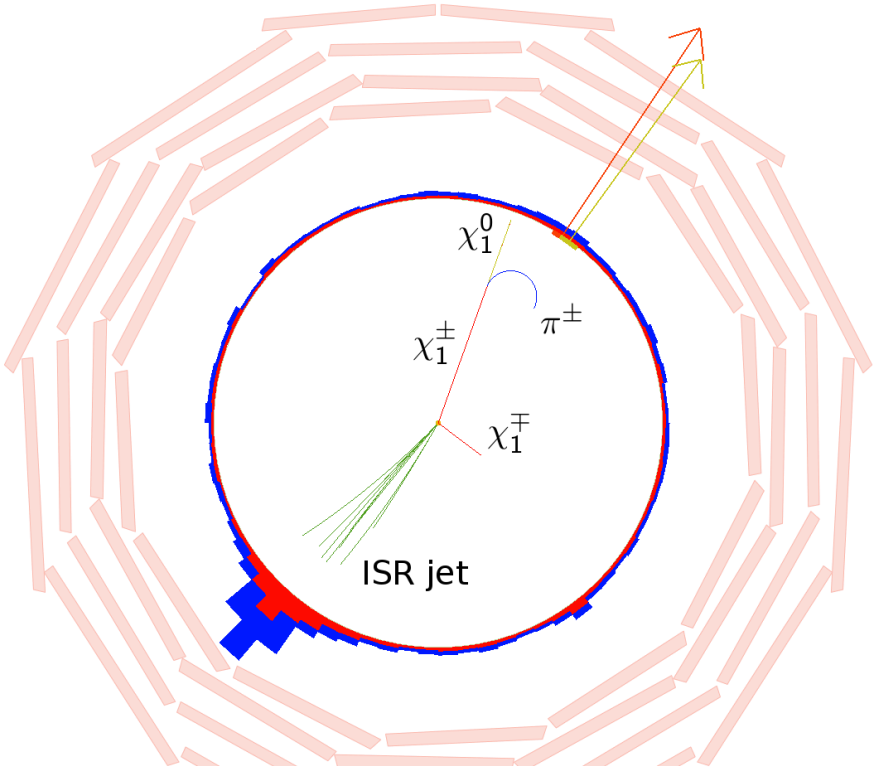


Results (compressed SUSY)
for cτ =50 cm
Exclude $m_{\tilde{g}}$ < 2.46 TeV and $m_{\tilde{\chi}^0}$ < 2.0 TeV

PLB 806 (2020) 135502, EXO-19-010

Disappearing tracks II

- **Complementary search** for LLP decay within the tracker
- **Benchmark:** AMSB (anomaly mediated SUSY)
- **Dedicated Trigger:** on **MET from ISR jets** and **isolated track** and other inclusive MET paths



Signal MC Event Display

- **Disappearing track selection:**
- Candidate track that disappears:
  - Ecalo < 10 GeV within ΔR < 0.5
  - ≥ 3 missing outer hits
  - Number of tracker layers $\mathbf{n_{lay}}$ **=4,5,≥6,** that have hits associated to the track which correspond to track lengths of >20,30,40 cm
- **Background** data driven:

  lepton can appear as a disappearing track or **fake tracks**

$$47.8^{+2.7}_{-2.3}\ (\text{stat}) \pm 8.1\ (\text{syst})$$

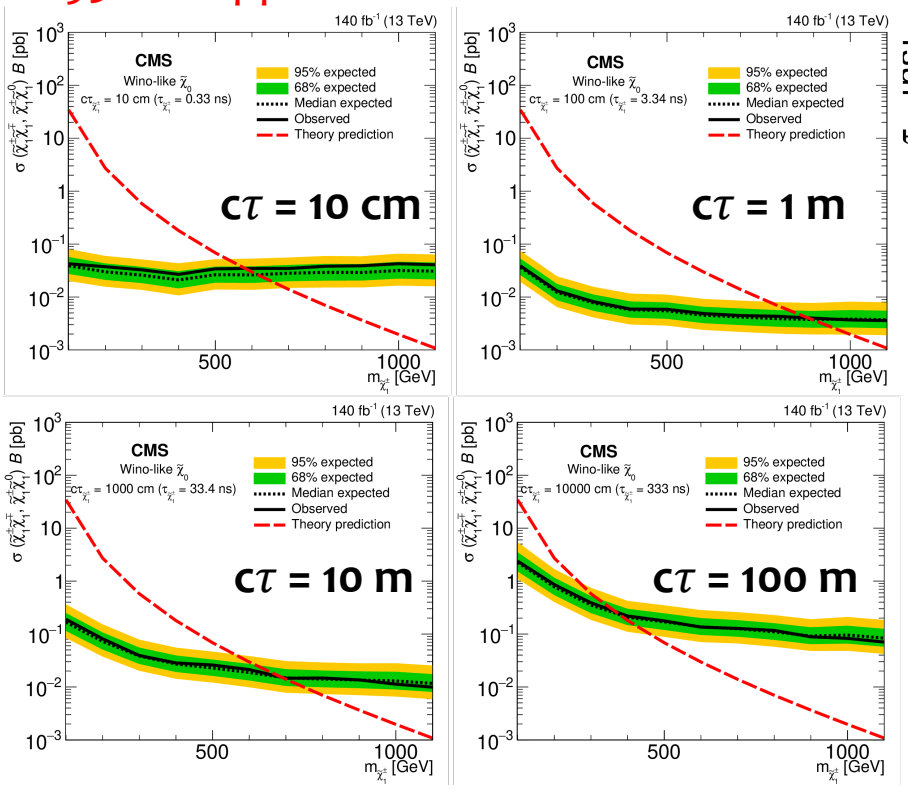
- **Observed 48 events**

PLB 806 (2020) 135502, EXO-19-010

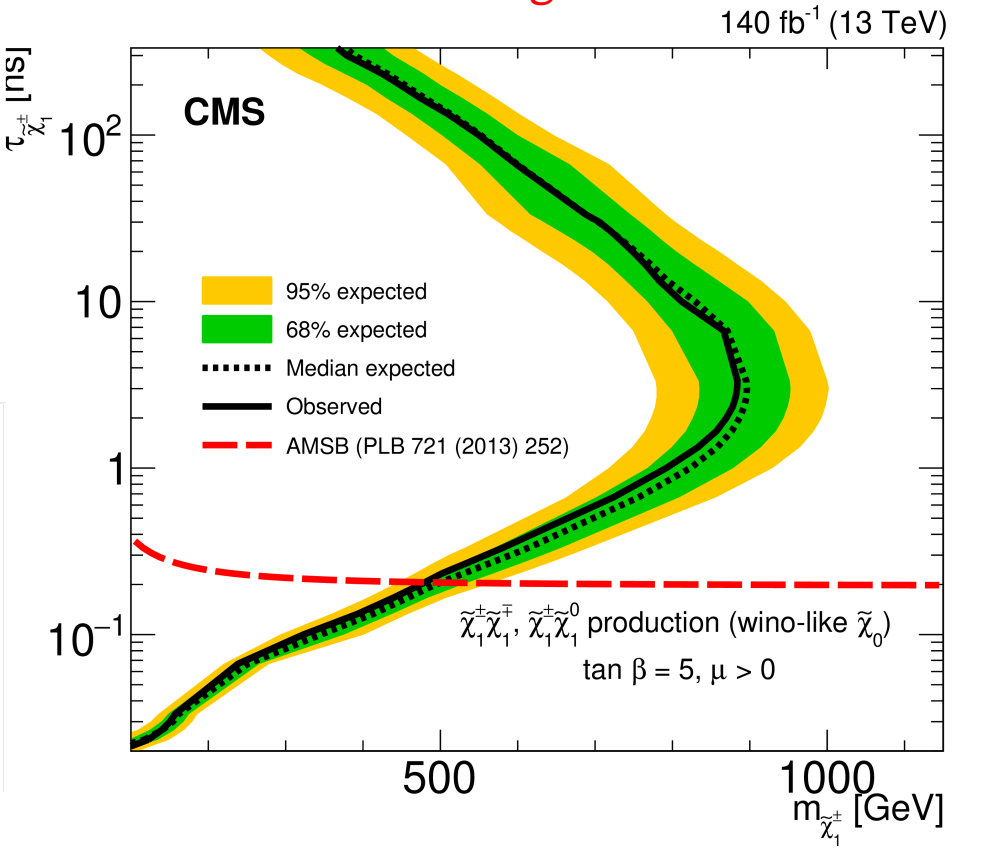
Disappearing tracks II - interpretation

- **AMSB:** Chargino masses for a purely wino-like neutralino:
  - Excluded below **884 GeV for τ = 3 ns**
  - Excluded below **474 GeV for τ = 0.2 ns**

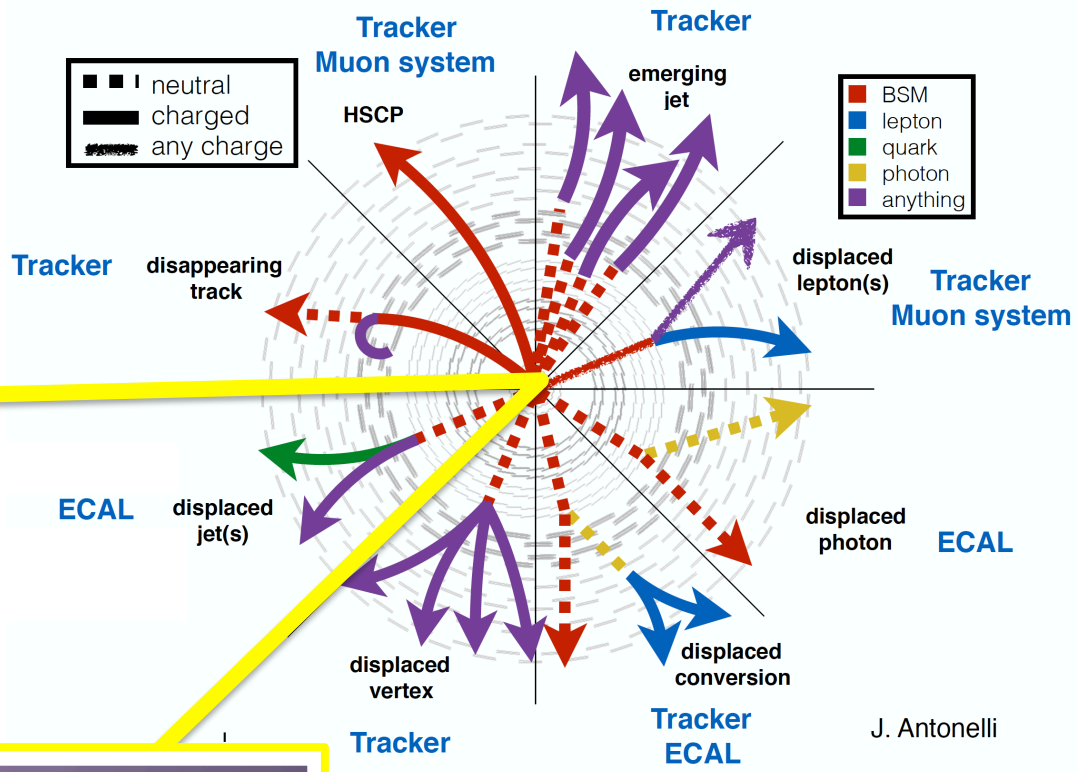
95% CL upper limits on cross section x BR

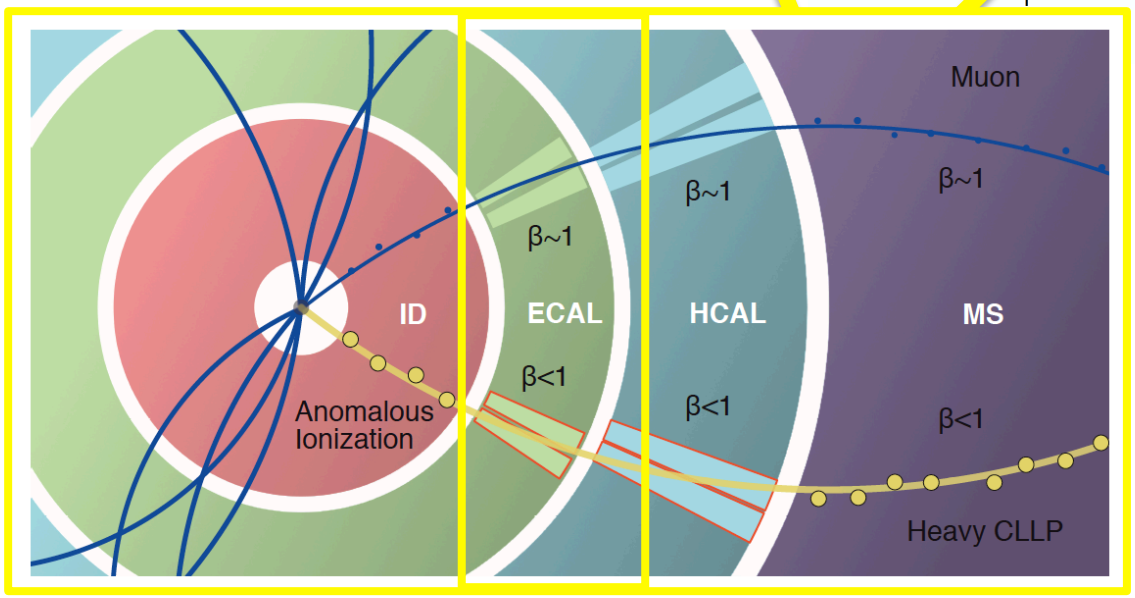


Constraints on chargino lifetime and mass



Delayed Jets





Phys. Lett. B 797 (2019) 134876, EXO-19-001

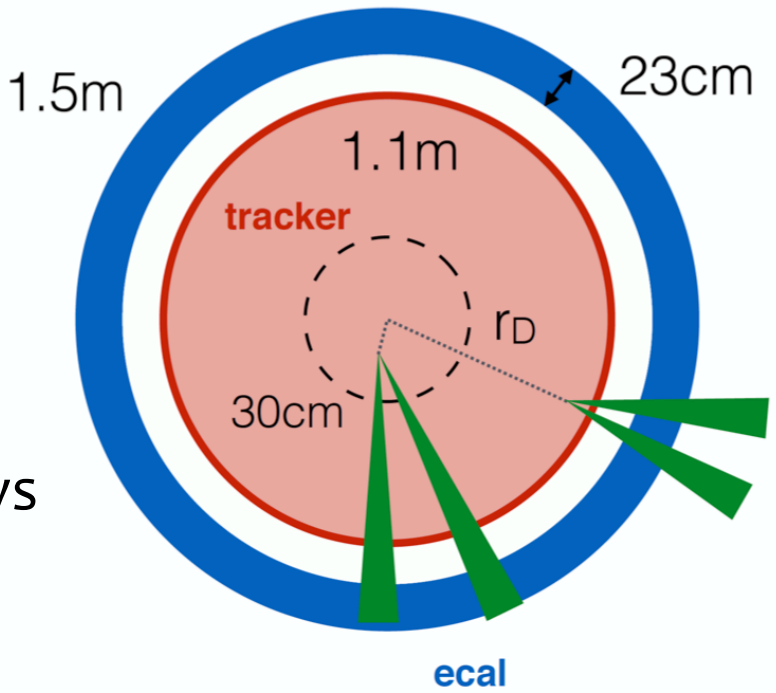
Delayed Jets

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)

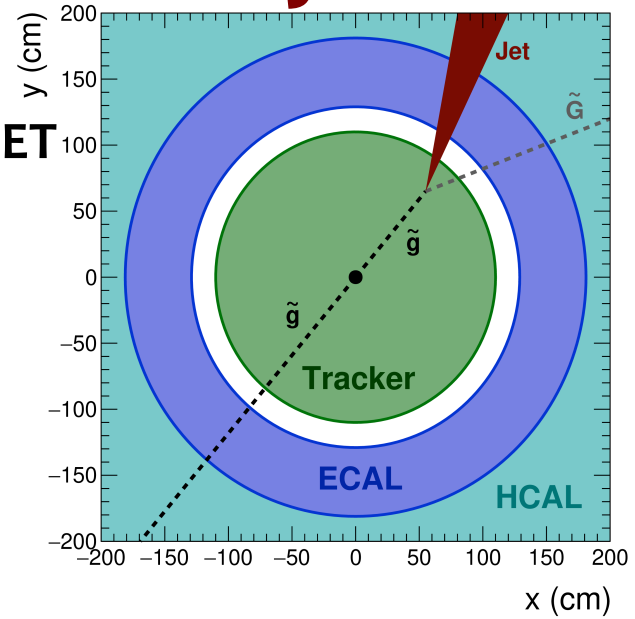


- **ECAL: jet time** is a median time of all ECAL cells in jet with energy > 0.5 GeV and |time| < 20ns, $\Delta R(\text{cell, jet}) < 0.4$
- time resolution per cell (crystal+APD) ~200 ps

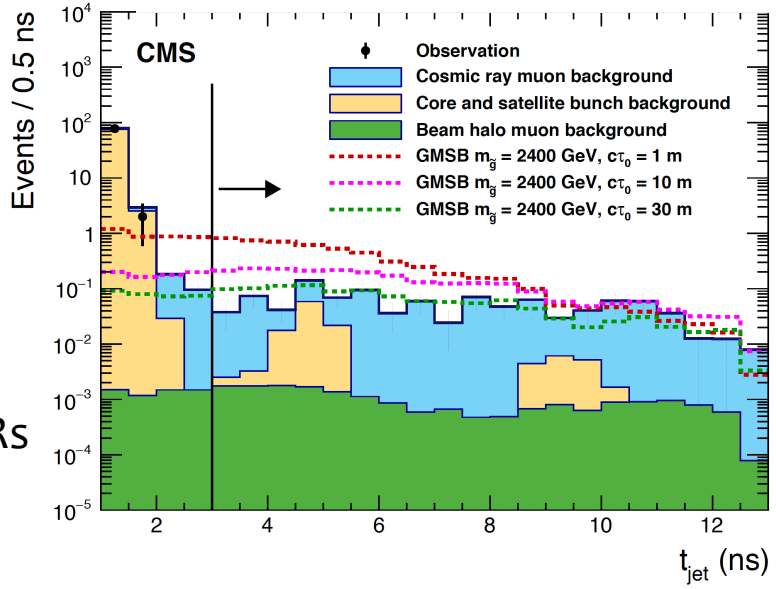
Phys. Lett. B 797 (2019) 134876, EXO-19-001

Delayed Jets – stratedy

- **Signal:** GMSB **long-lived gluinos** or
  Split SUSY **R-hadrons** decaying to **displaced jets + MET**



- **Selection:**
  - ≥ 1 delayed calo jet
    (t > 3ns, pT > 30 GeV, E > 70 GeV, |η| < 1.48)
  - MET > 300 GeV
- **Trigger:** MET > 120 GeV
- **Candidate event cleaning:**
  - beam halo rejected by muon CSC & HCAL
  - satellite bunches & mismeasurements veto
  - cosmics vetoed by muon DT and RPC
  - pileup & APD hits rejected by ECAL timing



- **Background:**
  Data-driven by invert cleaning cuts to form data CRs
- **Search region:** $N_{jet} \geq 1$, $t_{jet} > 3$ ns

Phys. Lett. B 797 (2019) 134876, EXO-19-001

Delayed Jets - results

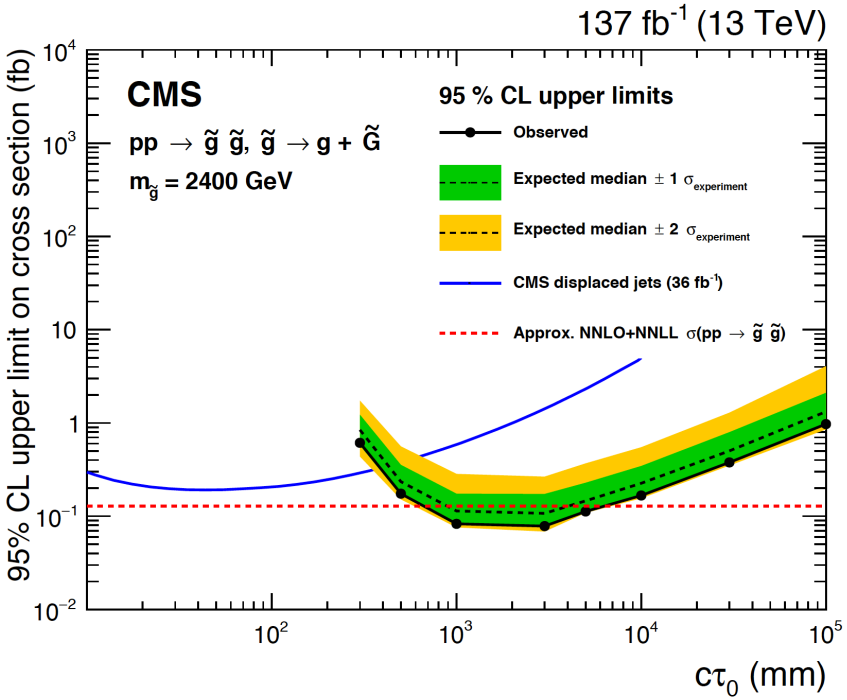
- **Observed: 0 events** in agreement with bckg. prediction of **1 evt**
- **Results (GMSB):**

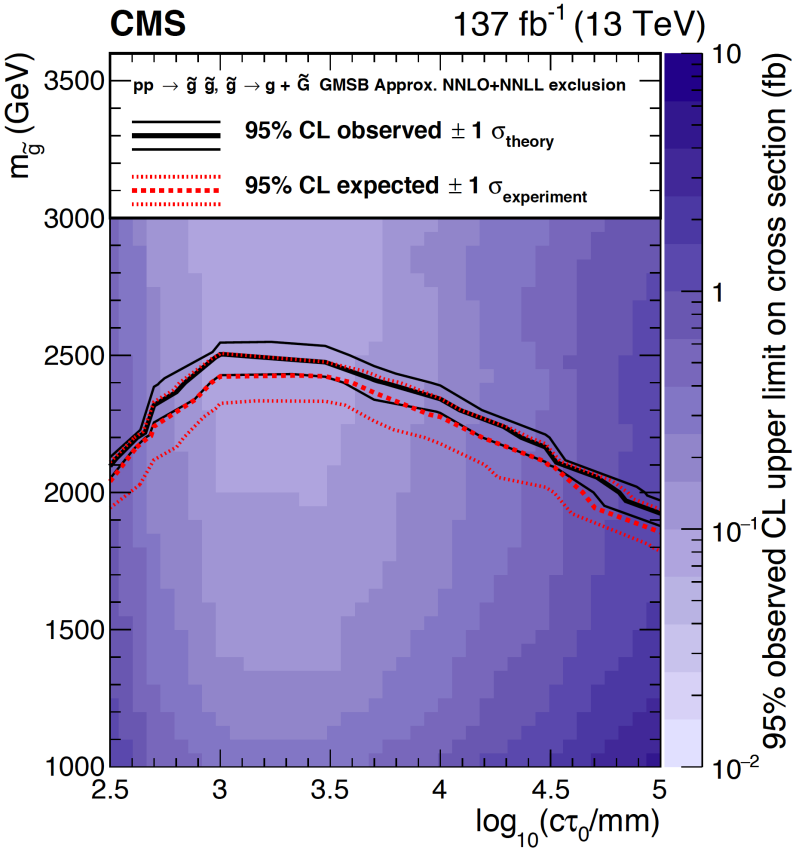
  Exclude $\mathbf{m_{\tilde{g}} < 2.50}$ **TeV for** $\mathbf{c\tau_0 \sim 1}$ **m**

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

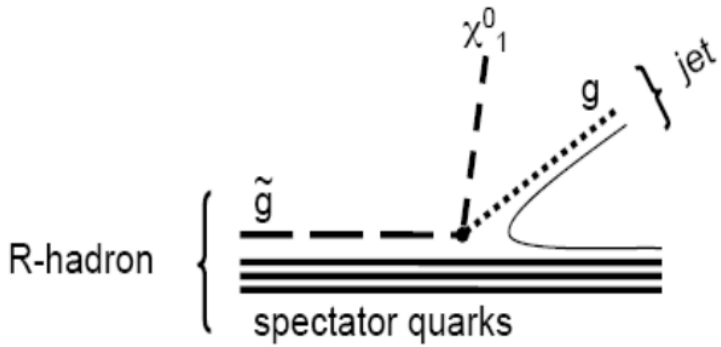
→ Significantly extends reach for $c\tau_0 \geq 1$ m (vs. tracker-based searches)

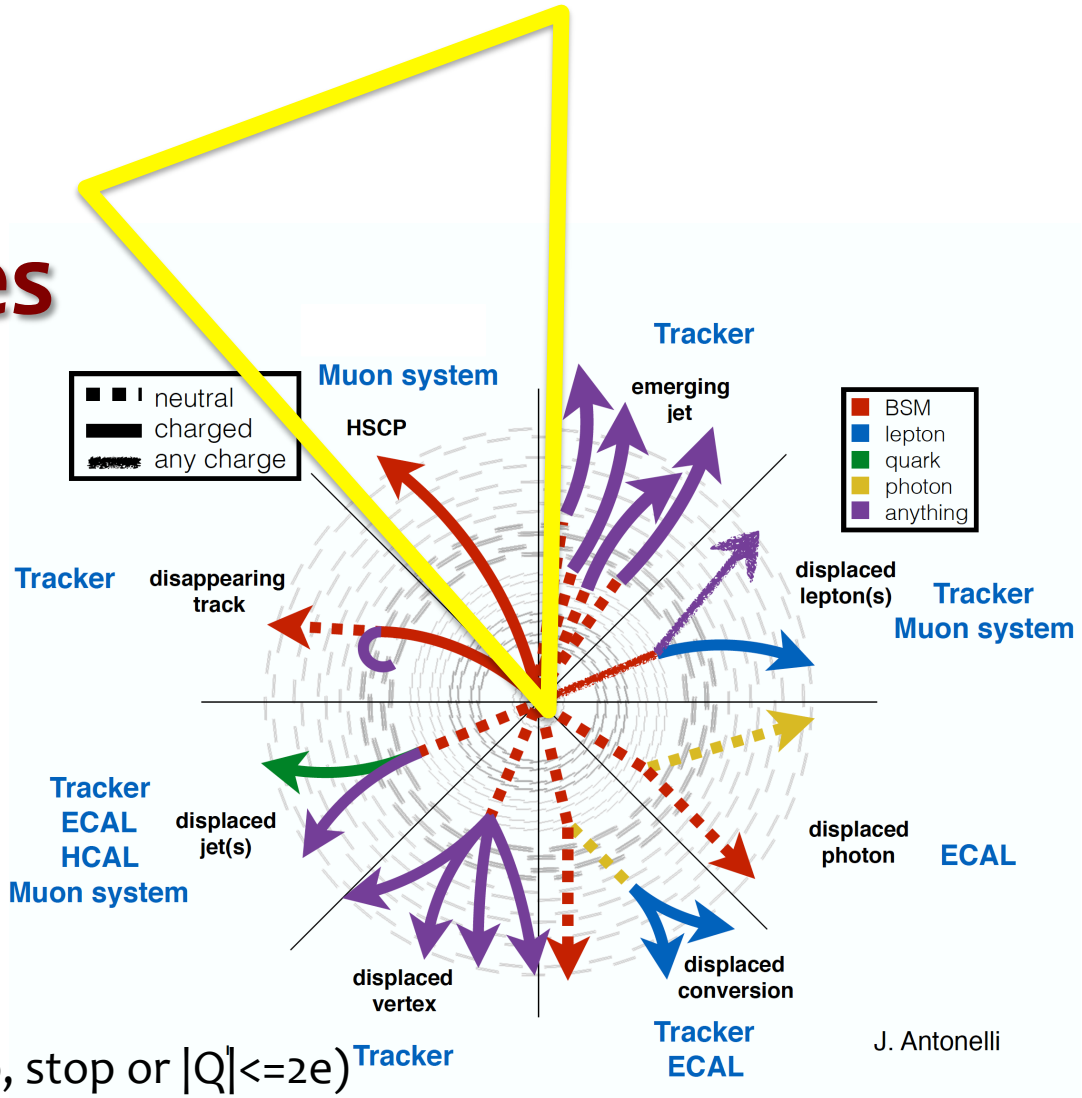
Background source	Events predicted
Beam halo muons	$0.02^{+0.06}_{-0.02}\,(\text{stat})^{+0.05}_{-0.01}\,(\text{syst})$
Core and satellite bunch collisions	$0.11^{+0.09}_{-0.05}\,(\text{stat})^{+0.02}_{-0.02}\,(\text{syst})$
Cosmic ray muons	$1.0^{+1.8}_{-1.0}\,(\text{stat})^{+1.8}_{-1.0}\,(\text{syst})$





Stopped Paricles





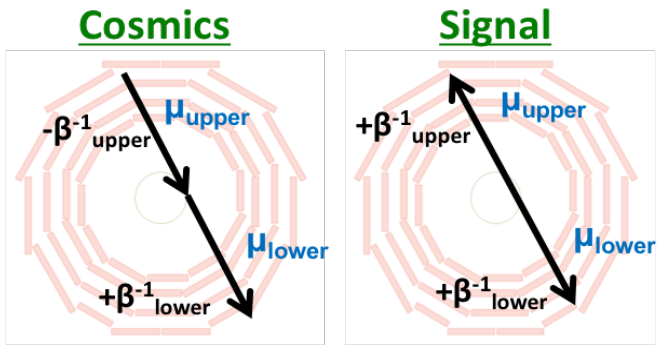
R-hadrons from Split SUSY (gluino, stop or |Q|<=2e)

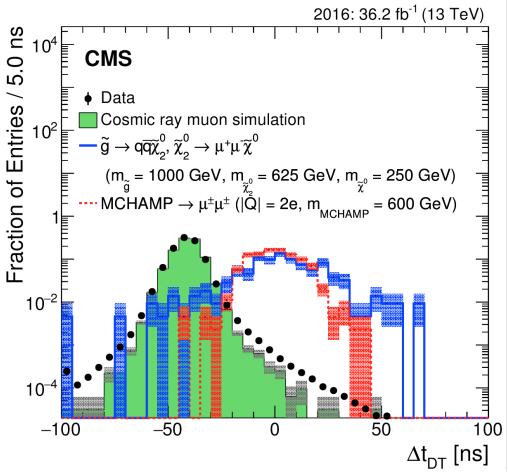
- heavy coloured particles that interactions with matter
- can change their sign
- decay are suppressed by a heavy squark making them **LLPs**

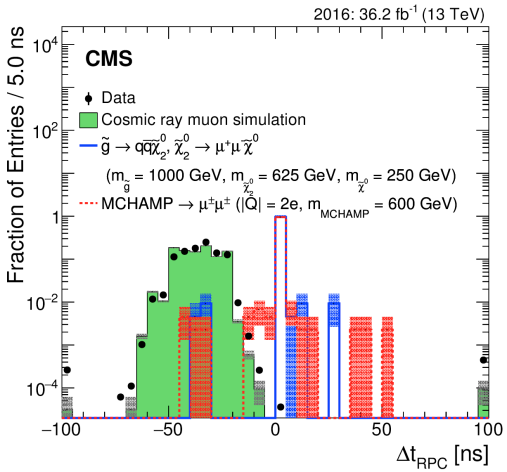
EXO-17-004, EXO-16-004, JHEP 05 (2018) 127

Stopped particles

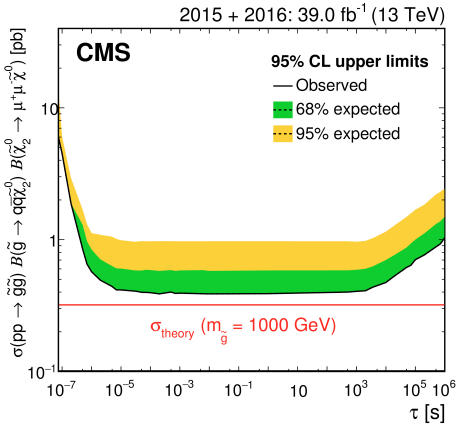
- **R-hadrons** are **stopped inside the detector** and **decay to muons** or **have hadronic decays** from rest after unknown time
  (sensitivity to lifetimes between 0.1 μs and 10^6 s)
- Events recorded **out-of-time with collisions** with the custom trigger

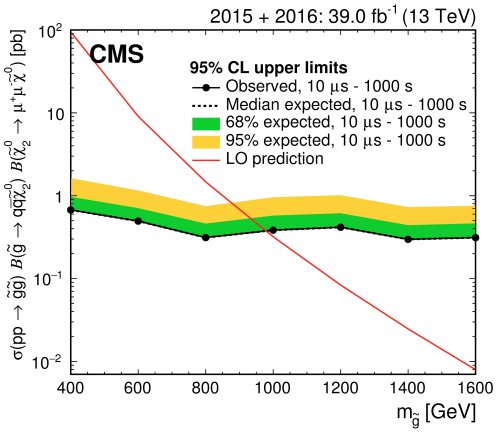






- **No events** observed
- 13 orders of magnitude of the lifetime tested
- **Excluded gluinos** with mass between 400 and 970 GeV, assuming 100% BF to muons





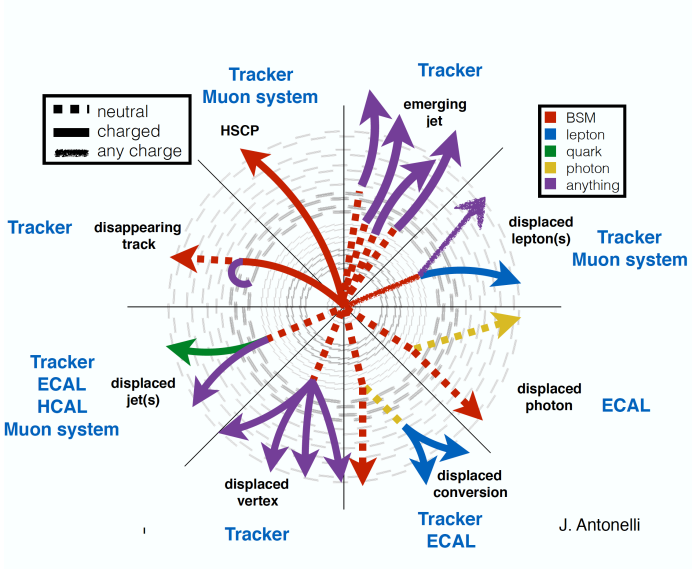
Future developments: LLP triggering in Run3

L1 trigger

- **Hardware** based, information from **calorimeters and muon systems only** (regional triggers combined to global)
- First pattern recognition and raw measurements
- Fixed latency: 4 μs to accept/reject
- Skims rate to 100 kHz (in total)

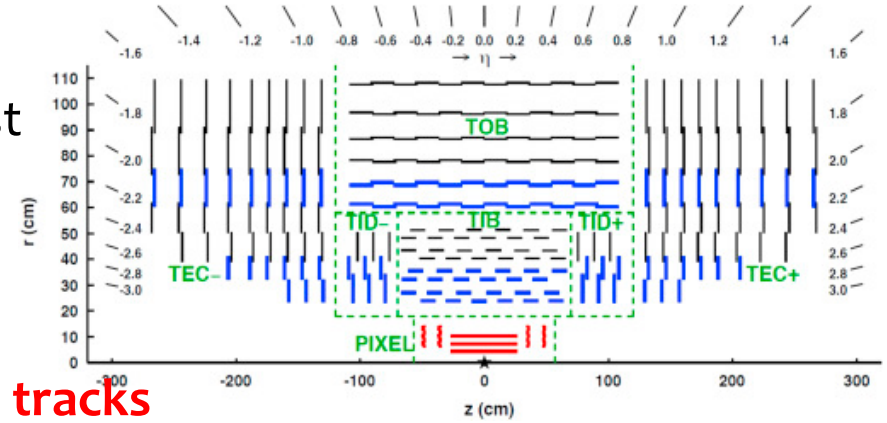
High level trigger (HLT)

- Fully **software**, includes **info from tracker**
- Similar algorithms as those applied offline
- Latency: 300 ms/events
- Skims rate to 1 kHz max (in total)



Displaced tracking for Run3

- CMS reconstruction designed for particles produced close to the collision point
  - Displacement → loss of efficiency
  - Displaced tracks and vertices are lost



- **Tracking @ HLT**
  - *Current baseline:*
    - **single iteration seeded by pixel tracks**
  - *Developments:*
    - use **strip-seeded iteration** to recover efficiency for larger displacement
    - used in Run2 for dedicated HLT triggers (not standard tracking)

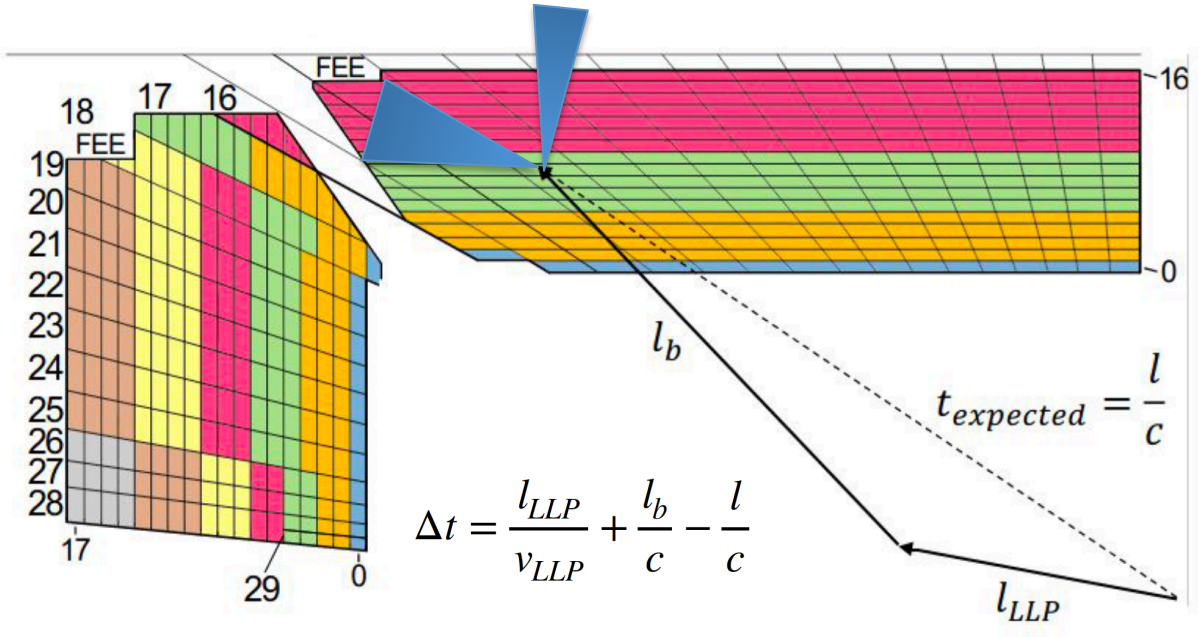
- **Tracking offline**
  - New iteration using predefined **Regions of Interest (ROI)**
    - pairwise tracks combined together into vertices
    - vertices clustered in spherical ROIs, radius 1 cm, tagged with an MVA
    - tagged ROIs used in tracking algorithm

Trigger for LLPs in Calorimeters

- Hadronic sampling calorimeter **(HCAL)**: plastic scintillator and brass
- Some first level L1 trigger possibilities not fully exploited so far:
  - **Timing information** (resolution 0.5 ns)

  → **delay** due to kinks/heavy LLP mass
  - **Longitudinal depth** (4 layers in barrel, 7 layers in endcaps)

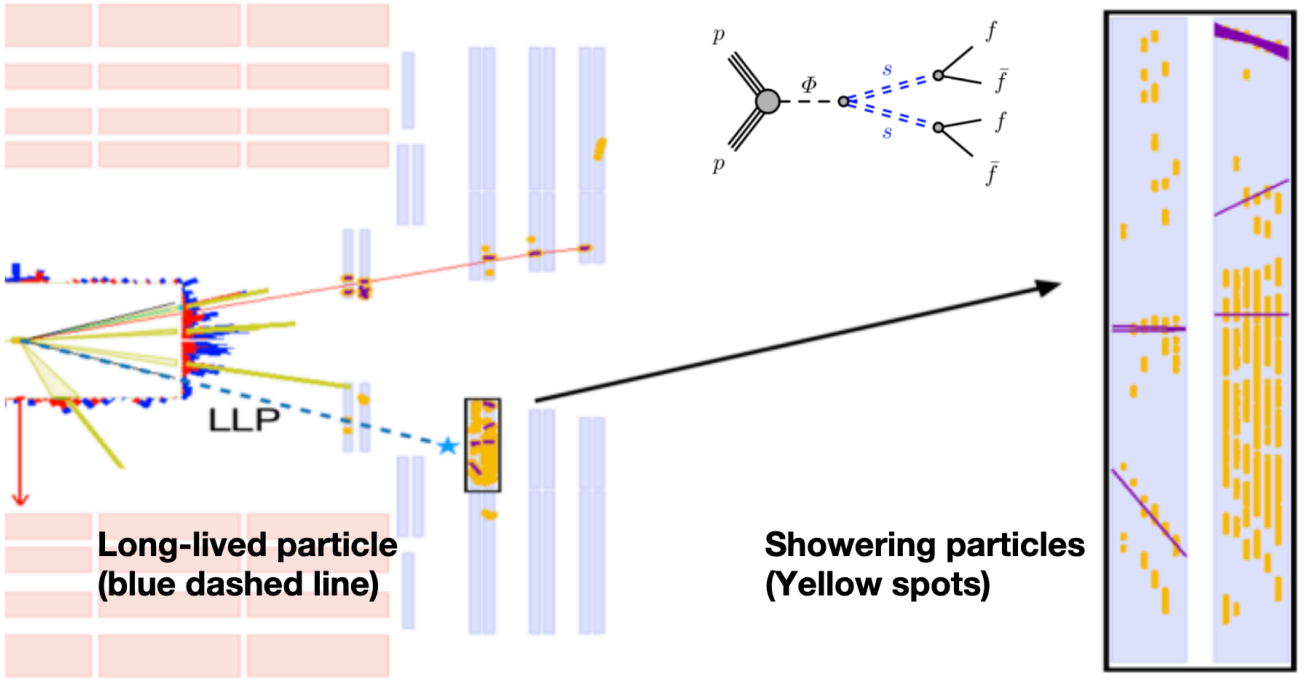
  → S/B discrimination (deeper showers)
- **Energy ratio** E_{HCAL}/E_{ECAL} → successful at **killing multi-jet background**, lower rate



Trigger for LLPs in Muon System

- Cathode Strip Chambers **(CSC)** in the endcaps: L1 triggering
- **Trigger on displaced muons**
  - Improved FPGAs → better resolution (x4) and bending (x3) wrt Run2
- **Trigger on showers (hit clusters from jets)**
  - **Count** cathode/anode **hits**

    → **threshold** optimised for S/B and for reasonable L1 trigger rates
  - Can be improved the missing energy approach of Run2 by a factor >10



LLP at CMS summary

- **New results for full Run 2 data pushed limits on LLPs**
  - **exclude** hypothetical **LLPs** with masses up to **2.5 TeV**
  - Sensitive to **decay lengths from 1 mm**
  - **Searches are complementary**

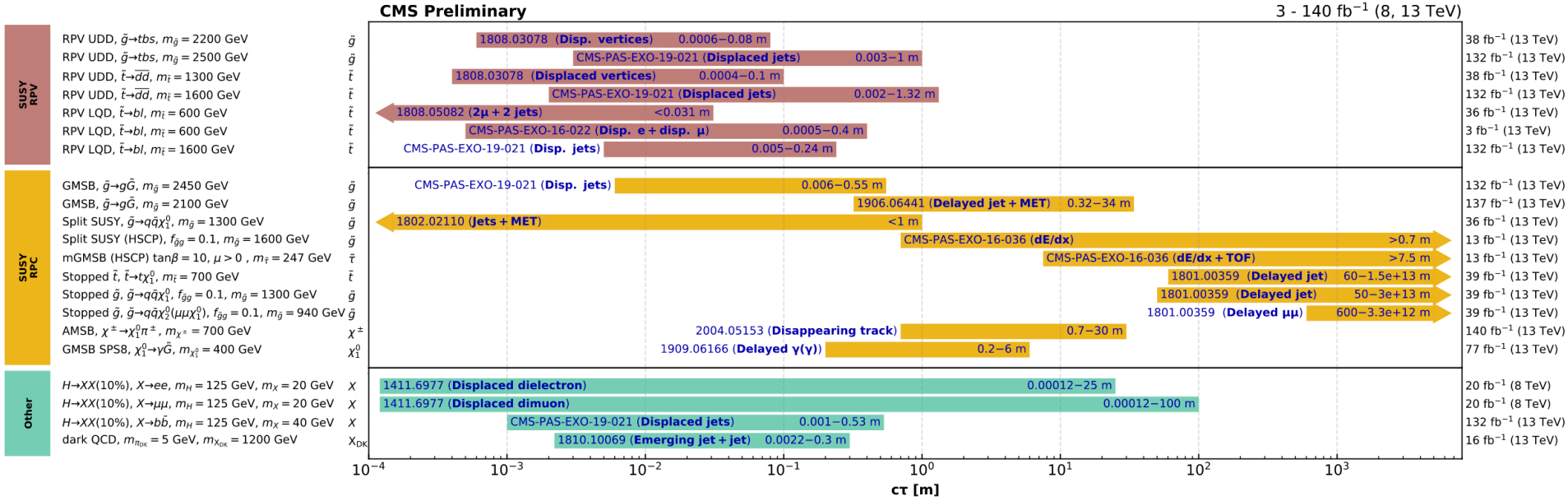
- **Unconventional signatures and measurements (timing, ionisation) are powerful tools** in searches for different LLPs in a model independent way

- **Any detected signal of LLP would be a clear indication of a new physics**
  - Therefore, the CMS experiment make an effort *(detector upgrades)* to enhance his sensitivity to cached the LLPs by new algorithms of reco and **triggering especially at the L1 for Run 3**

- *EXO CMS public results:* *http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/LLP.html*

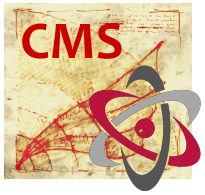
Thank you!

Selection of LLP searches at CMS



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.

https://twiki.cern.ch/twiki/pub/CMSPublic/SummaryPlotsEXO13TeV/barplot_RPV_RPC_OLL.svg

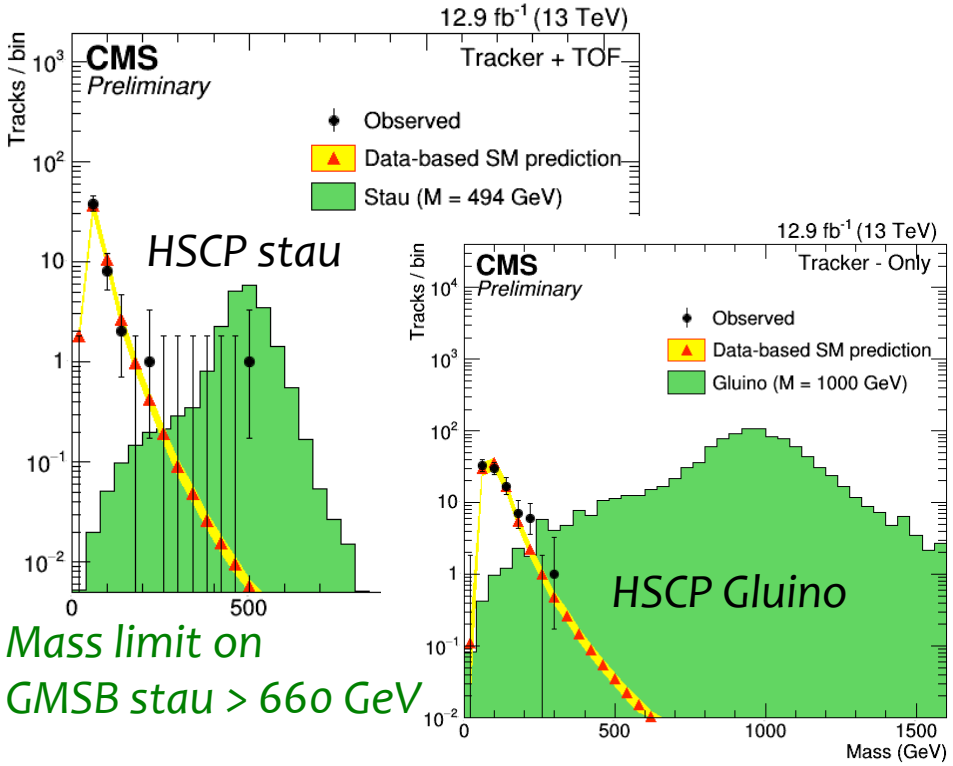


Backup

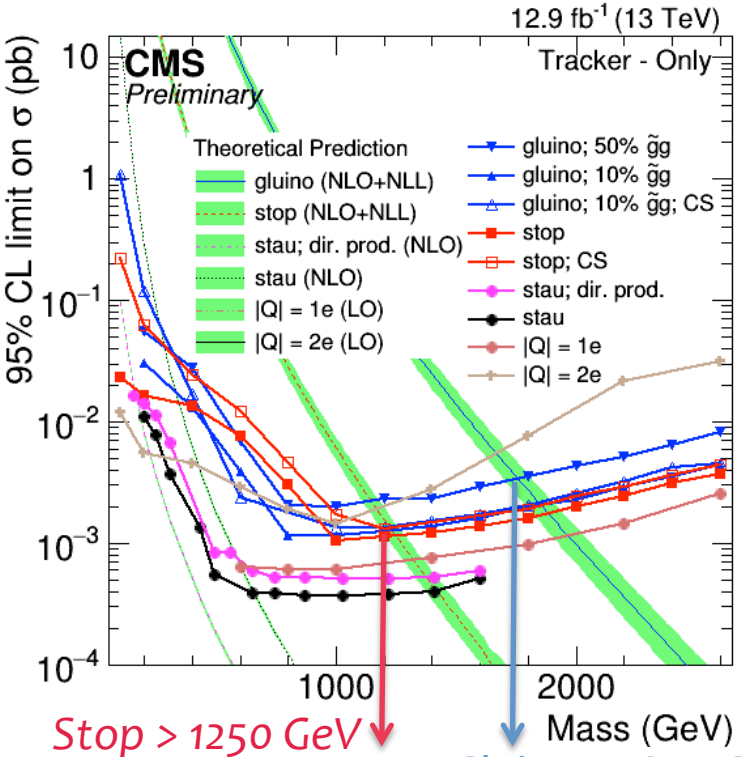
EXO-16-036, PRD 94 (2016) 112004

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

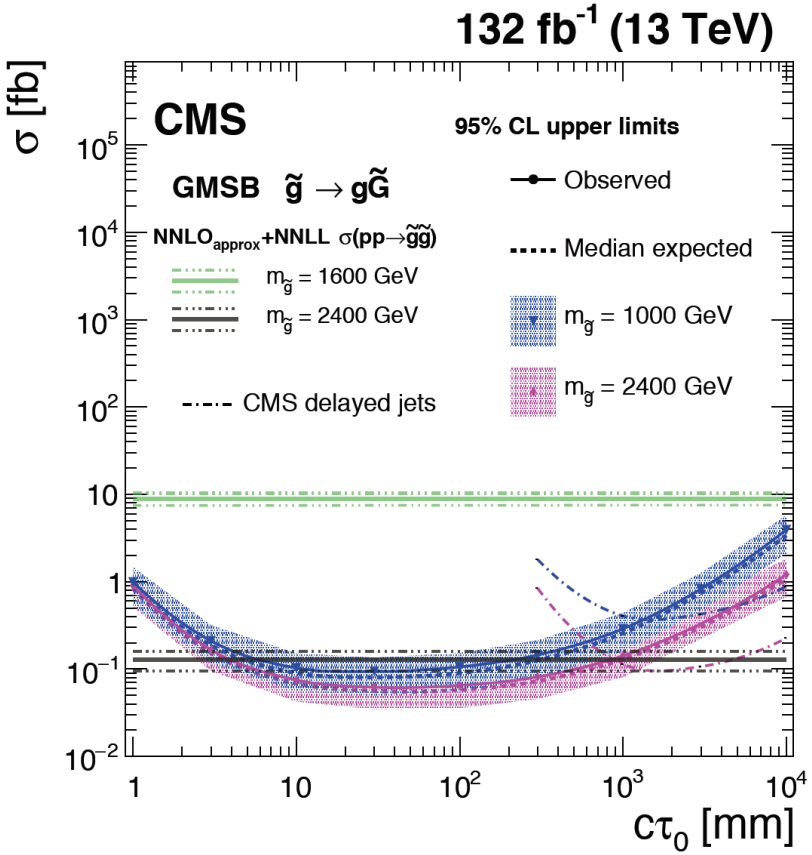


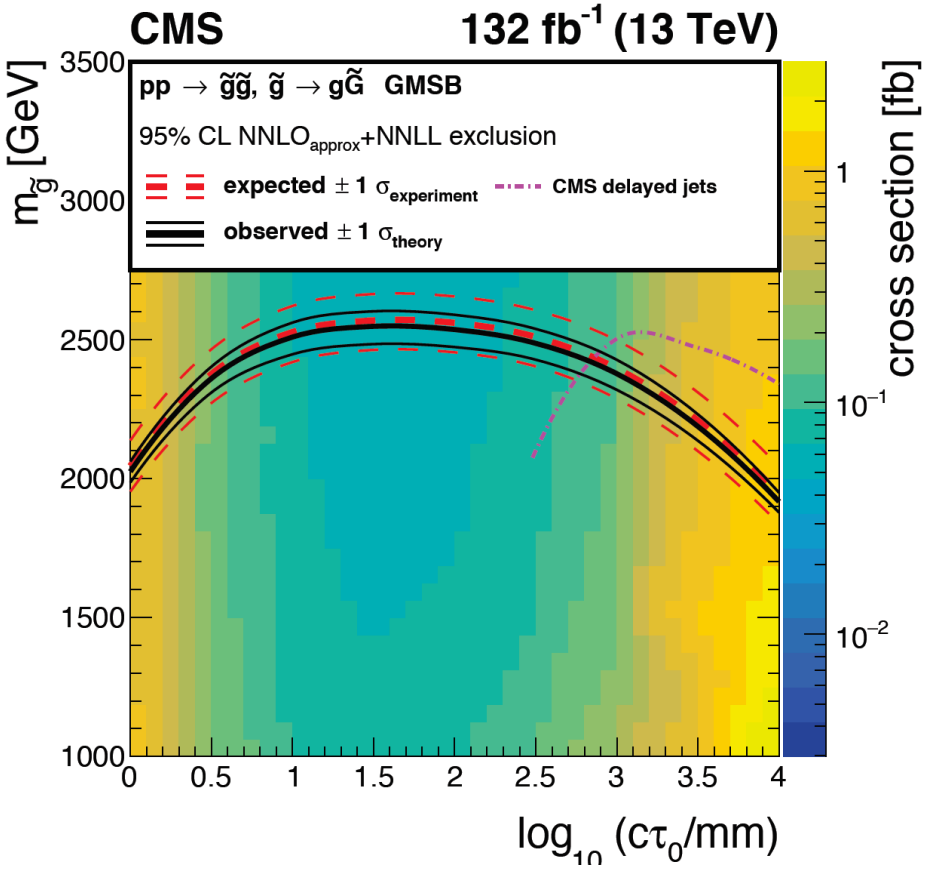
Stop > 1250 GeV

Gluino > 1850 GeV

New limits with displaced jets

- **GMSB:** pair-produced **LL gluinos** lighter than **2450 GeV** are excluded for $c\tau_0$ between 6 – 550 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 7 – 600 mm
- the largest gluino mass excluded is 2560 GeV with a $c\tau_0$ of 30 mm

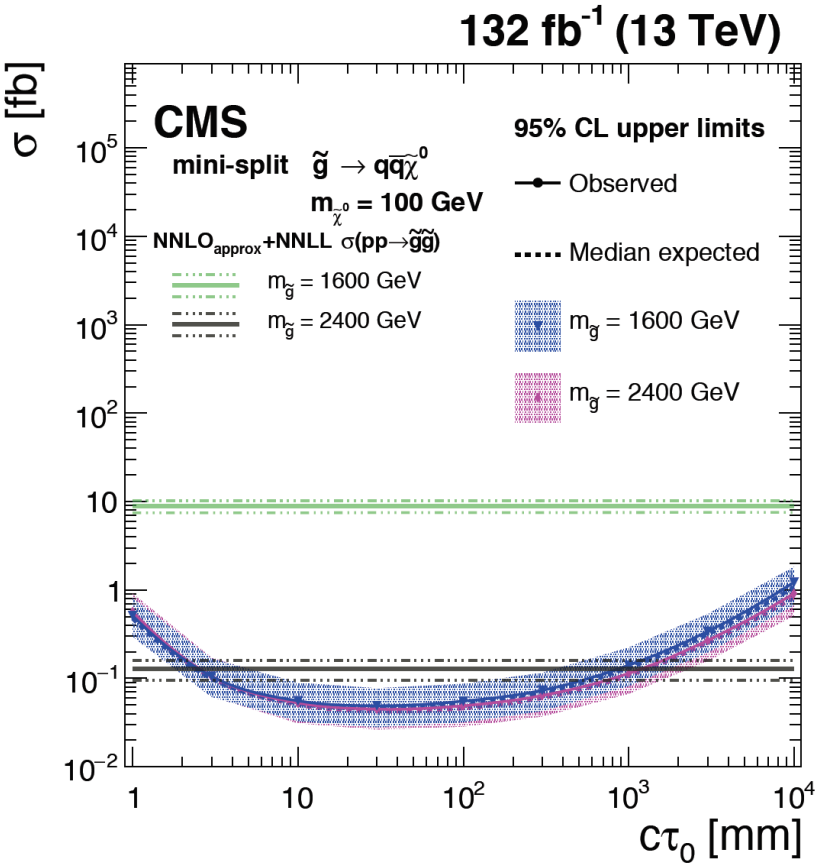


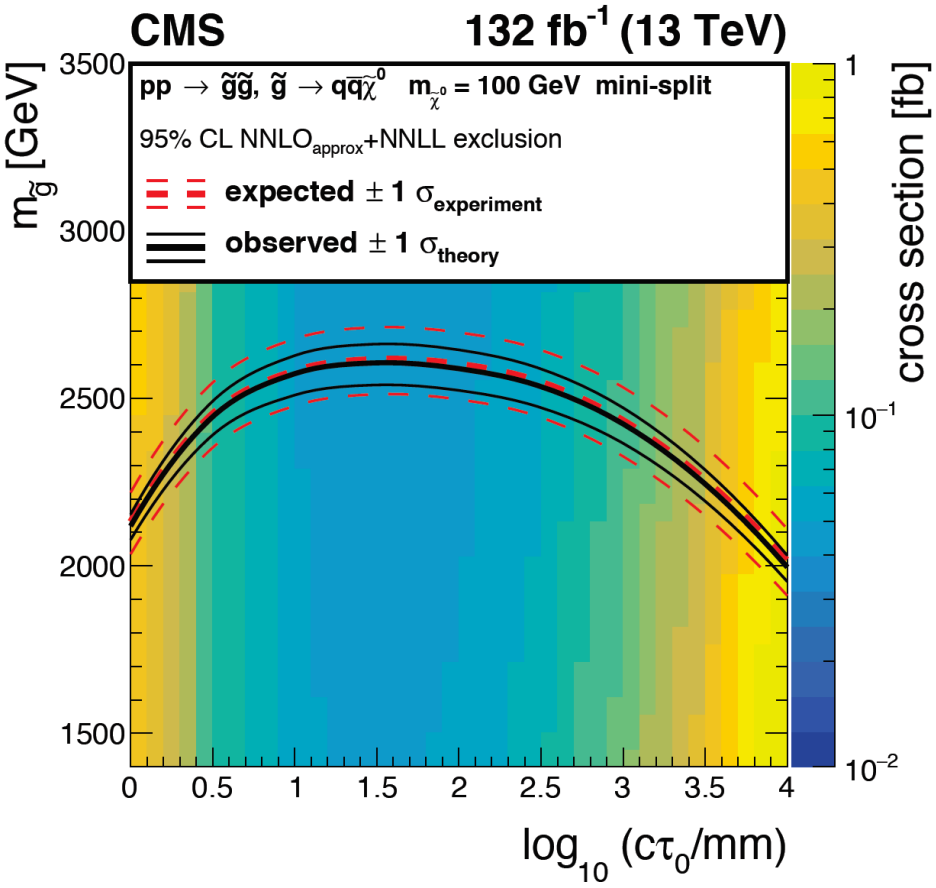


EXO-19-021

New limits with displaced jets

- **Mini Split:** pair-produced **LL gluinos** lighter than **2500 GeV** are excluded for $c\tau_0$ between 5 – 520 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 3 – 900 mm
- the largest gluino mass excluded is 2610 GeV with a $c\tau_0$ of 30 mm

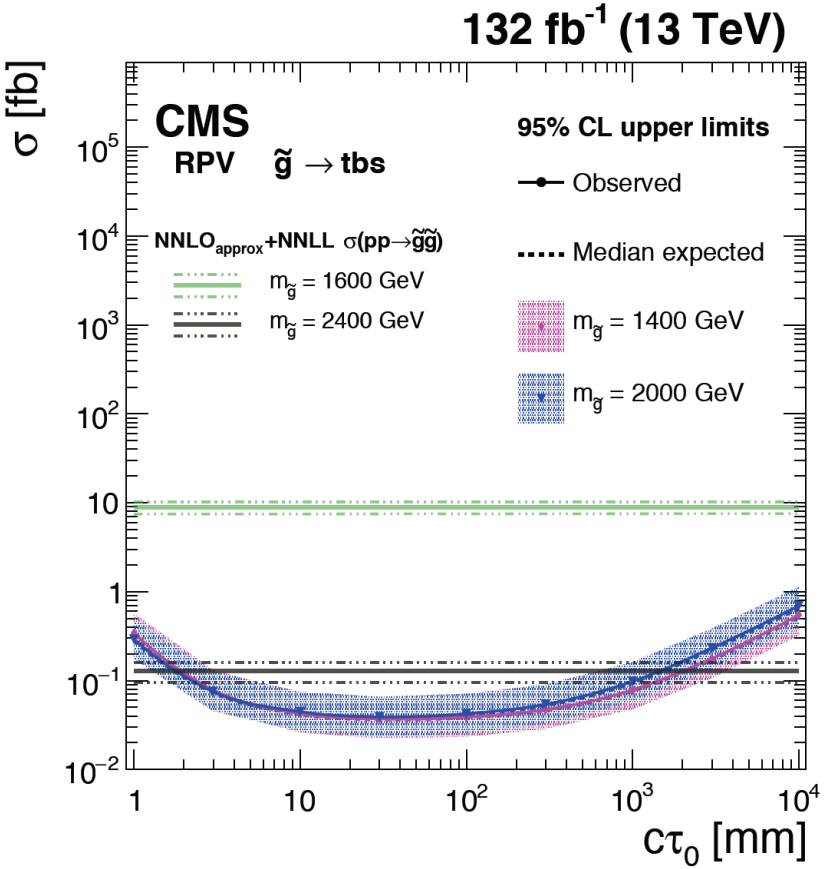


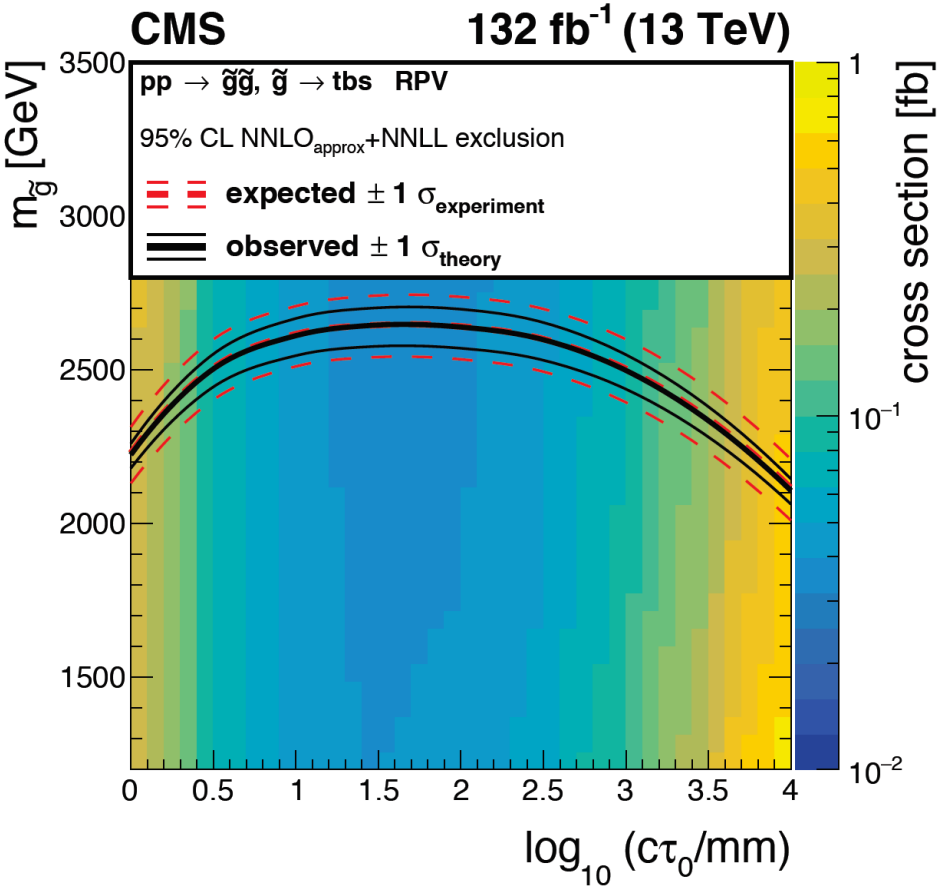


EXO-19-021

New limits with displaced jets

- **RPV tbs:** pair-produced **LL gluinos** lighter than **2400 GeV** are excluded for $c\tau_0$ between 3 – 1000 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 3 – 1490 mm
- the largest gluino mass excluded is 2640 GeV with a $c\tau_0$ of 30 mm

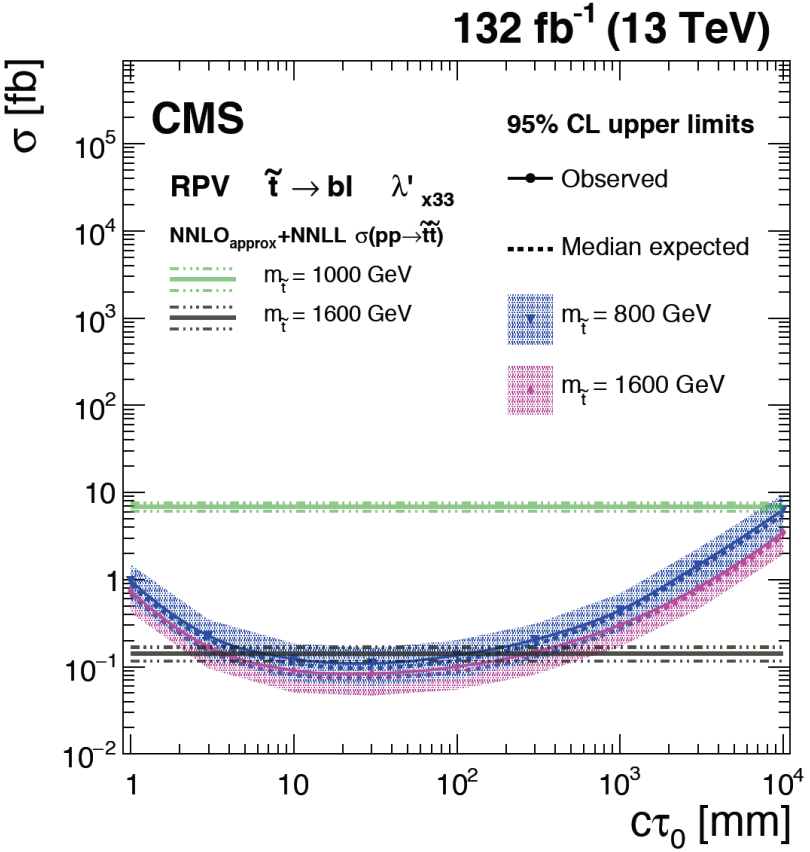


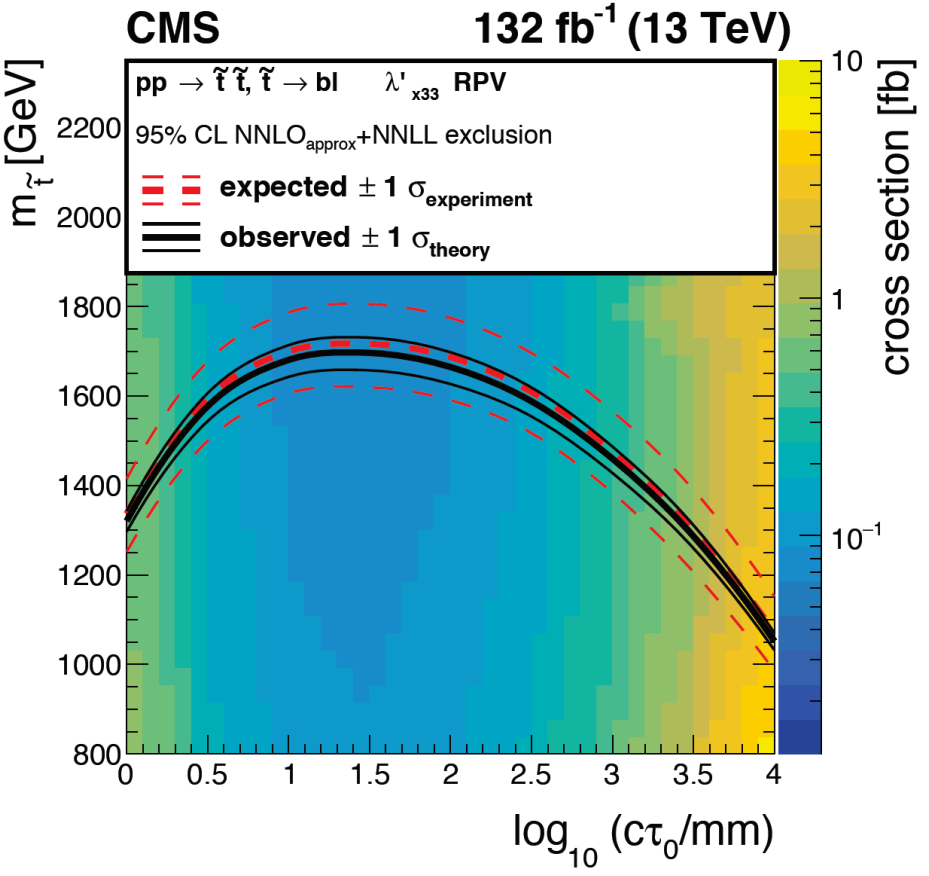


EXO-19-021

New limits with displaced jets

- **RPV bl:** pair-produced **LL gluinos** lighter than **1600 GeV** are excluded for $c\tau_0$ between 3 – 340 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 8 – 160 mm
- the largest gluino mass excluded is 1720 GeV with a $c\tau_0$ of 30 mm

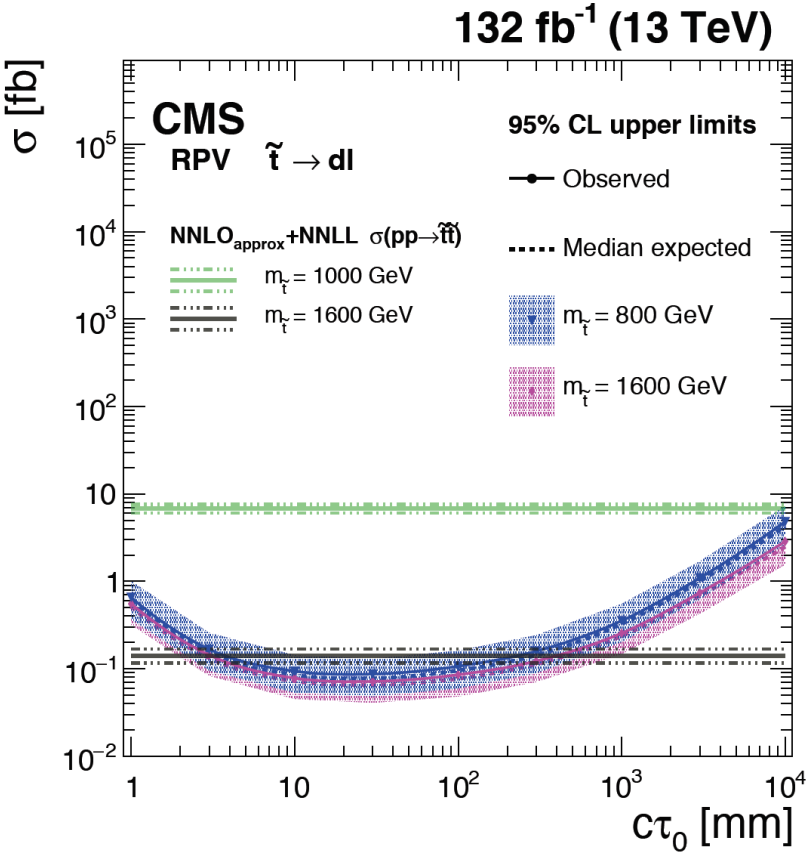


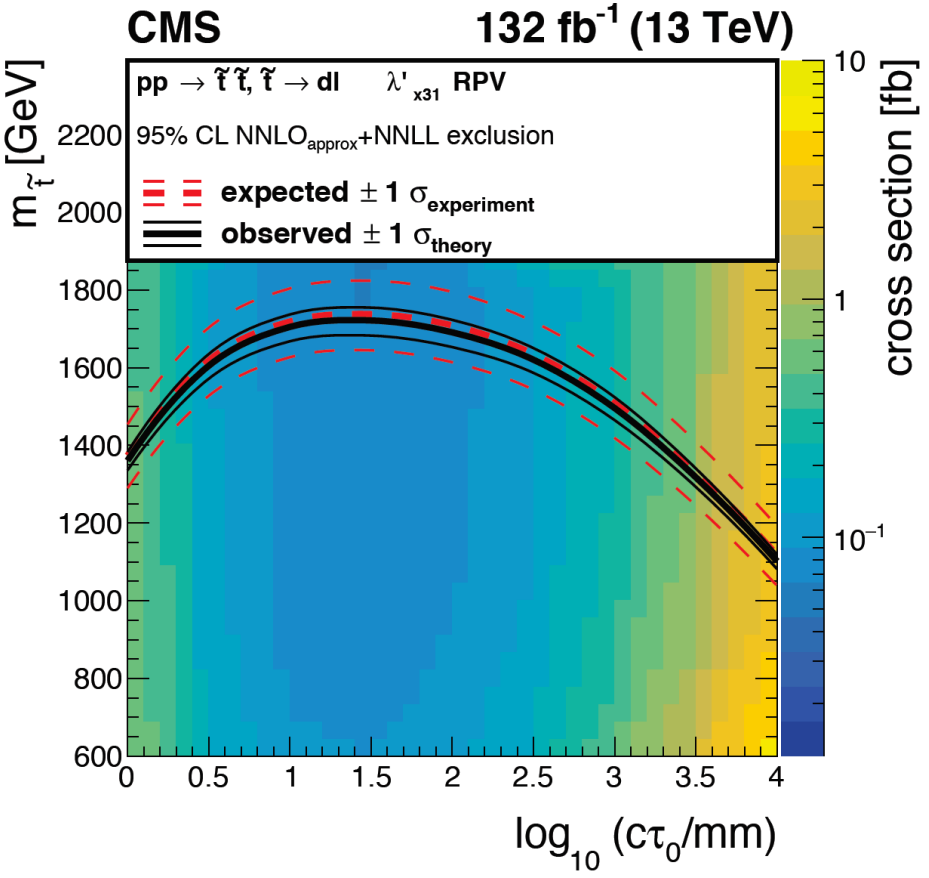


EXO-19-021

New limits with displaced jets

- **RPV dl:** pair-produced **LL gluinos** lighter than **1600 GeV** are excluded for $c\tau_0$ between 3 – 430 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 7 – 220 mm
- the largest gluino mass excluded is 1740 GeV with a $c\tau_0$ of 30 mm





EXO-19-021

New limits with displaced jets

Combined results for Full Run 2 data (2016 + 2017/18) :

- Exclusion limits on the cross-section on **new neutral LLPs** decaying to two jets, 0.04 fb at high mass (m_X>1000 GeV) for $c\tau_0$ = 30 mm