Searches for unconventional signatures at CMS

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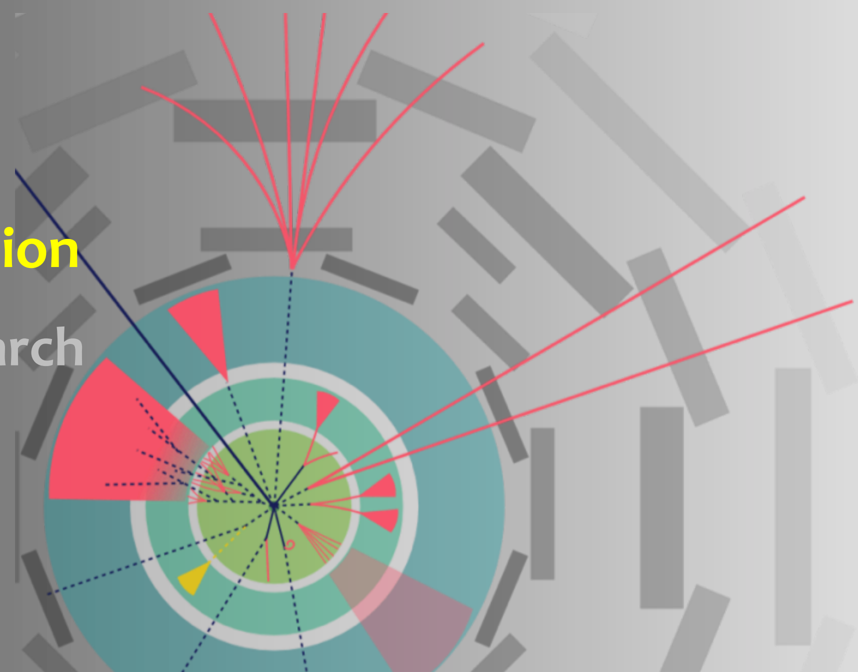
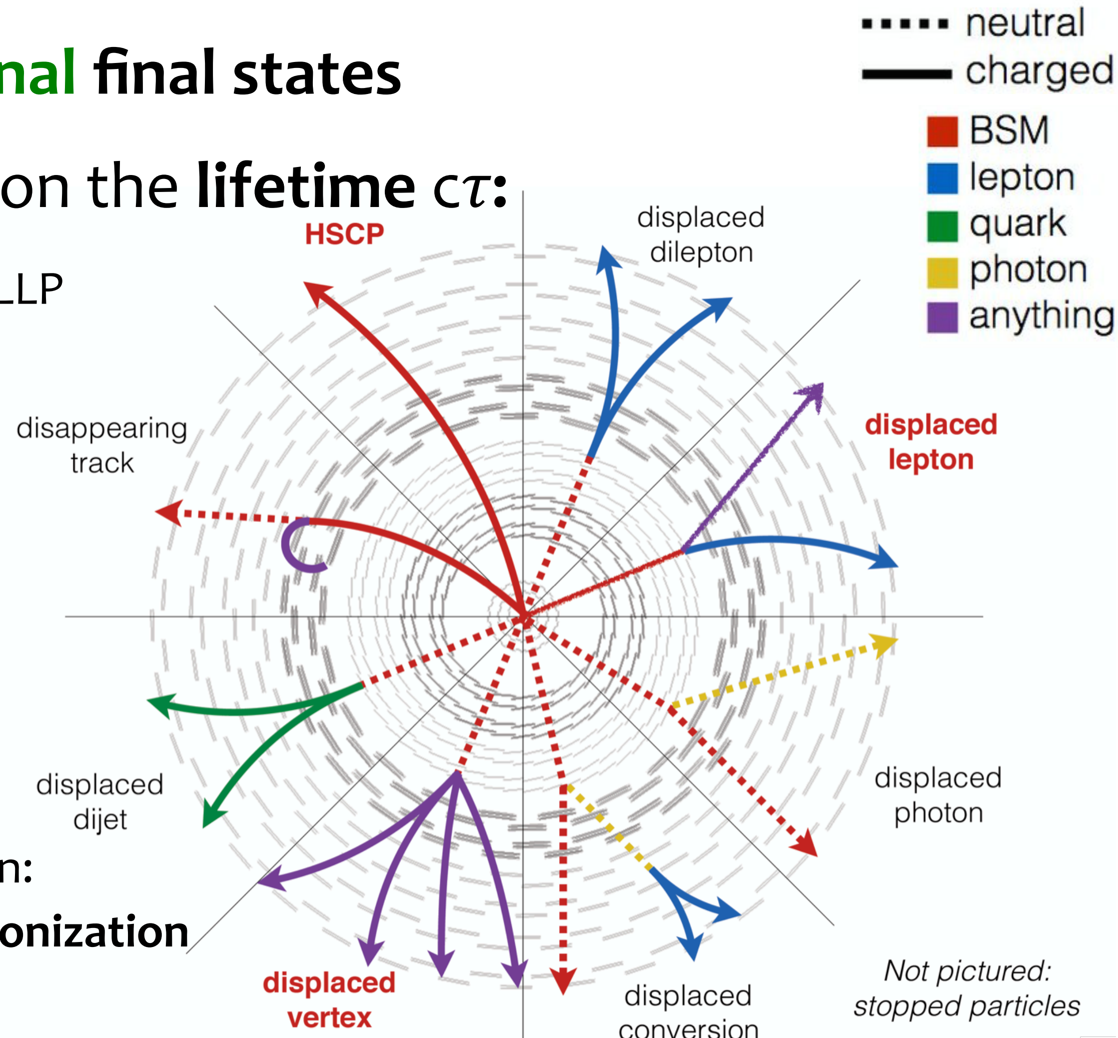


Compact Muon Solenoid
experiment at the CERN's LHC

Phenomenology Symposium, PHENO 2020
4-6 May 2020
University of Pittsburgh, USA

Searches for long-lived particles

- **LLPs** have **unconventional final states**
- **LLPs signature** depend on the **lifetime** $c\tau$:
  - **Cross** the detector: quasi-stable LLP
  - **Decay inside** the detector: displaced, delayed or disappearing objects
  - **Challenging** from the experimental point of view:
    - Often difficult triggering
    - Non-standard reconstruction: **displacements, timing** and **ionization**

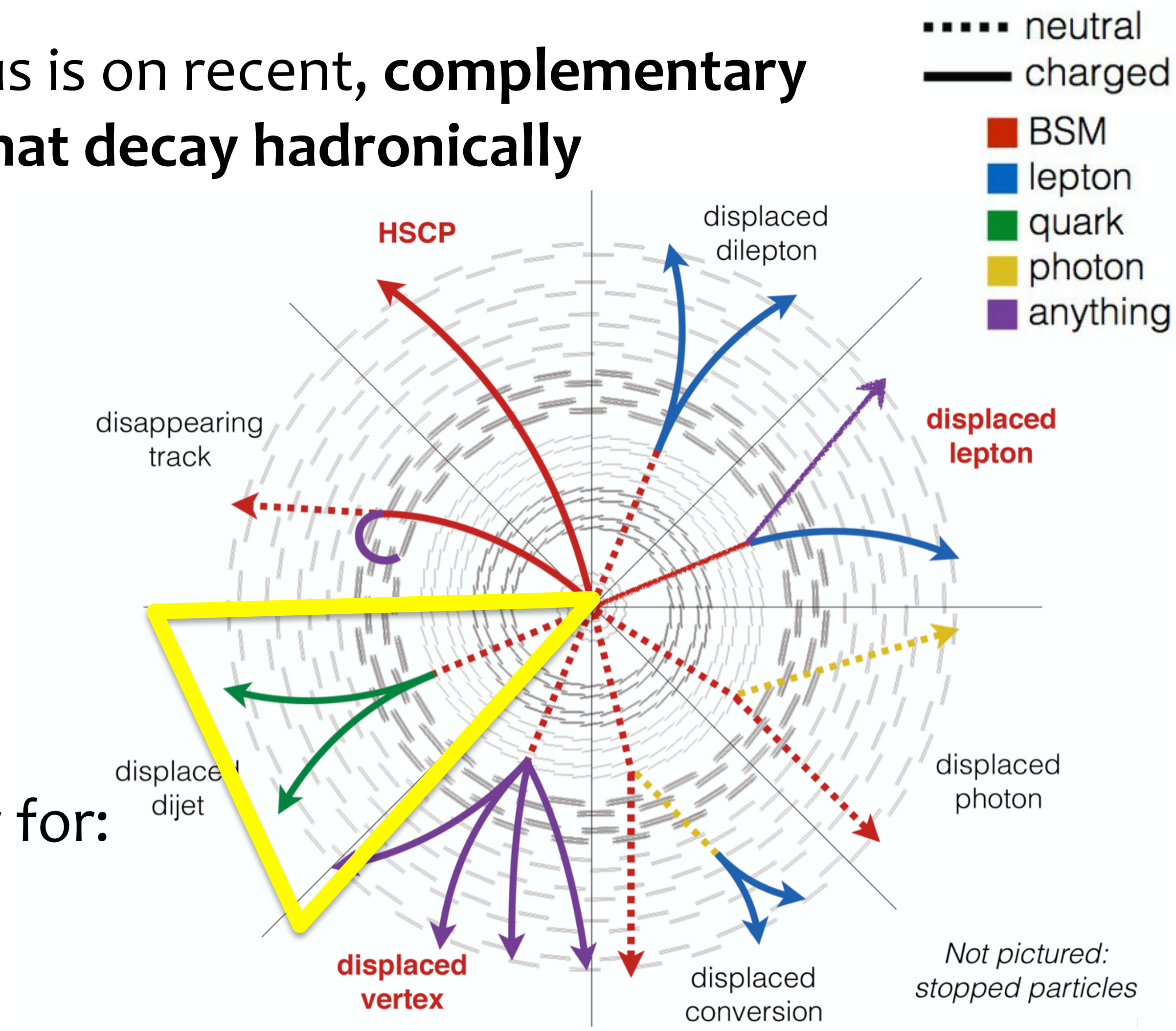


- **Non-standard backgrounds to challenges**
  detector noise, cosmic rays, reco failures – can be estimated from data

Searches for LLPs

- In this talk, the focus is on recent, **complementary** searches for **LLPs that decay hadronically**

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



- The search strategy for:
  - **Displaced** jets
  - **Delayed** jets

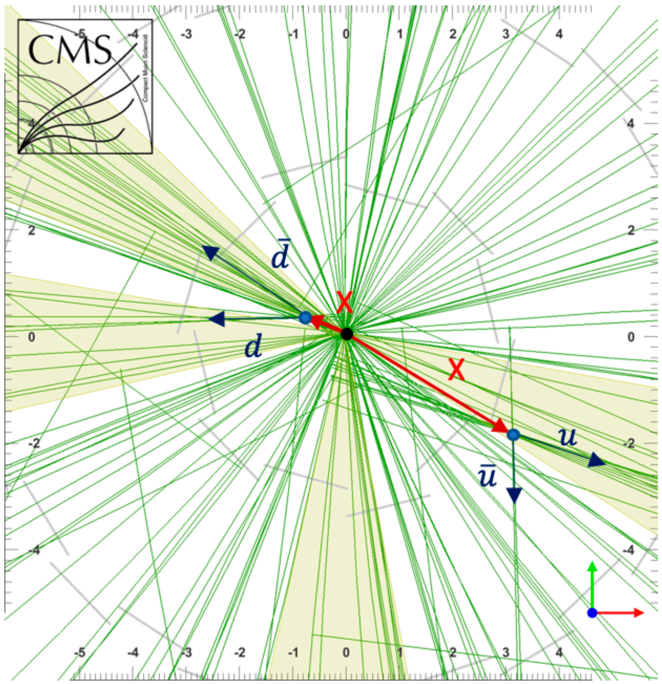
Displaced Jets

- 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

Calo jet

Calo jet



Calo jet

New results with 132/fb!

Full Run 2

- 2017/2018: **95.9/fb**
  Preliminary: EXO-19-021
  https://cds.cern.ch/record/2717071
- 2016: **36/fb**
  Phys. Rev. D 99 (2019) 032011

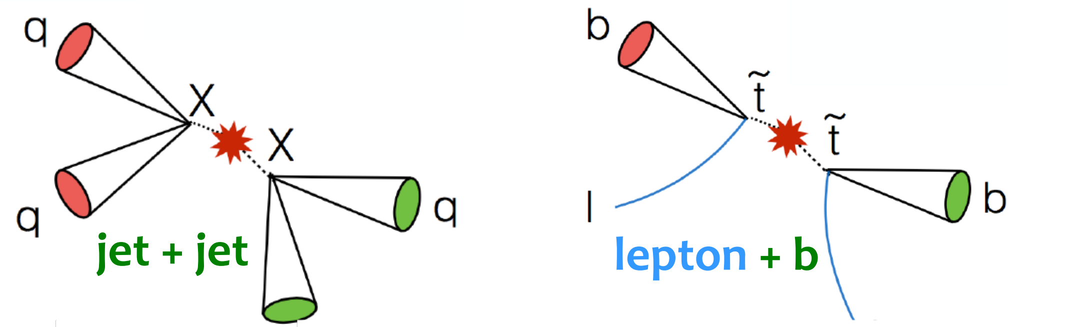
Calo jet is formed from energy deposits in the calorimeters

EXO-19-021

Displaced Jets - signal

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

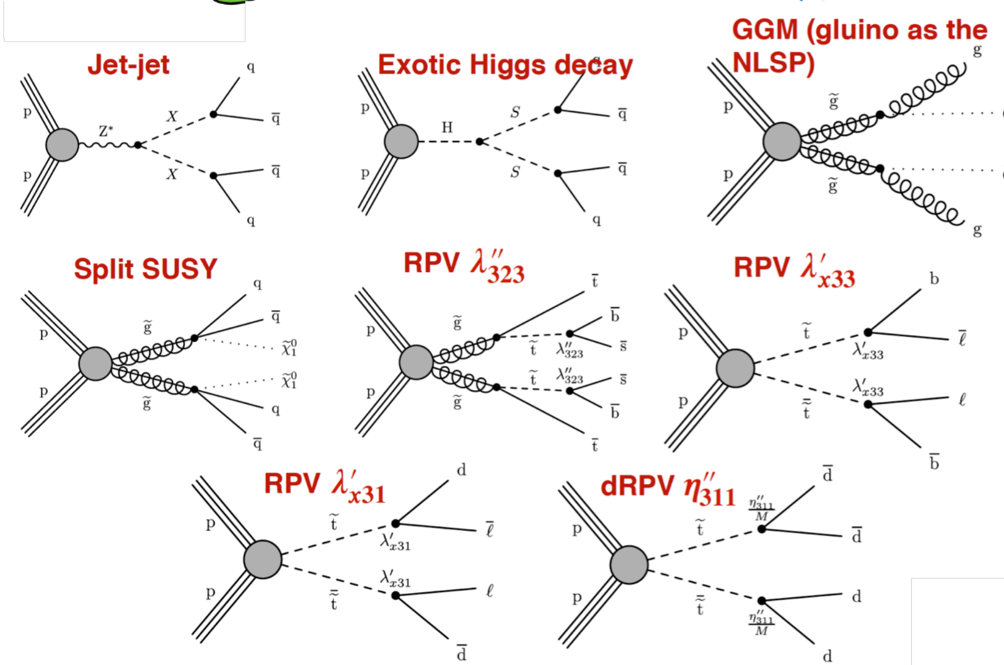
Hypothetical **SIGNAL:**



- **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



EXO-19-021

Displaced Jets – pre-selection

- Dedicated **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
    - H_T trigger threshold required if no selection on displaced object is significantly higher
  - ≥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

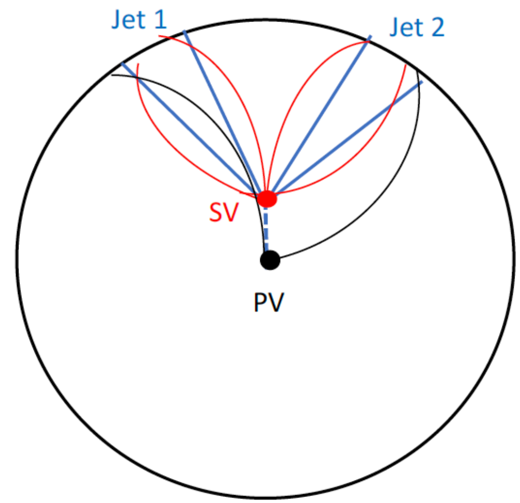
H_T – a scalar sum of p_T of all jets with p_T > 40GeV and |η| < 2.5 in the event

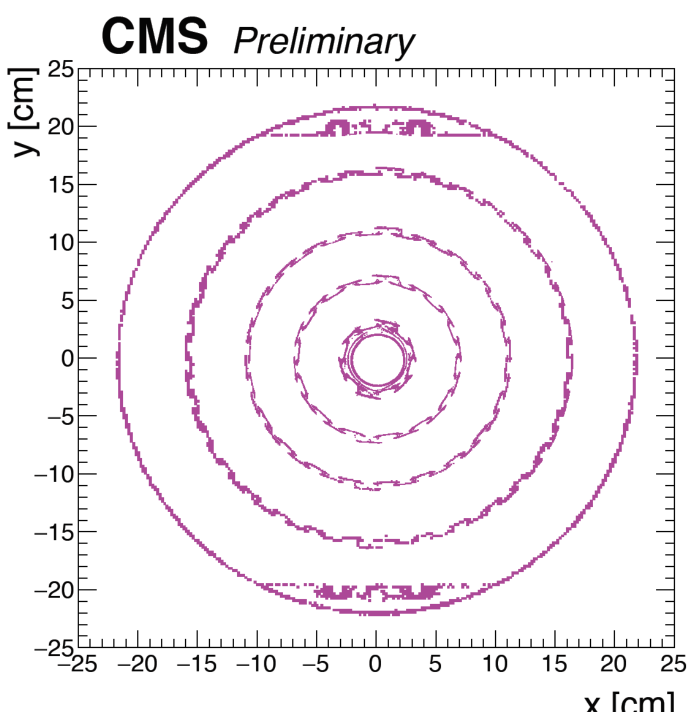
- Basic event selections:
  - If passes the ***displaced*** (***inclusive***) trigger:
    Calo **H_T>500 (700) GeV**, Calo jets **p_T>50 (80) GeV**, |η|<2.0
  - Track-jet association, tracks are matched to jets within R<0.5
  - Tracks are required to high-purity and have p_T>1GeV

Displaced Jets – SV reco

Secondary vertex reconstruction

- For all possible pairs of jets
- **Tracks** associated with the **dijet candidate** have $IP_{2D} > 0.5$mm, $Sig[IP_{2D}] > 5.0$ (w.r.t. the **leading PV**)
- Fit a **SV** with requirement of $\chi^2/ndof < 5.0$
- Vertex $\mathbf{Mass_{inv}} > 4$ GeV and **vertex** $\mathbf{p_T} > 8$ GeV





Pixel tracker

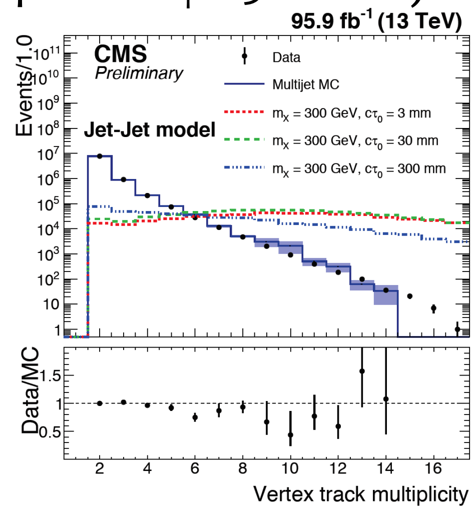
- Background events arise from nuclear interactions (NI) with the inner tracker material
- NI vertex candidates reflect a structure of the pixel tracking system and beam pipe
- **Any secondary vertex candidate that overlaps with the NI-veto map is rejected**
- The loss of the fiducial volume within r < 30 cm is around 4%
- Efficiencies for signal events to pass this selection are generally well above 90%

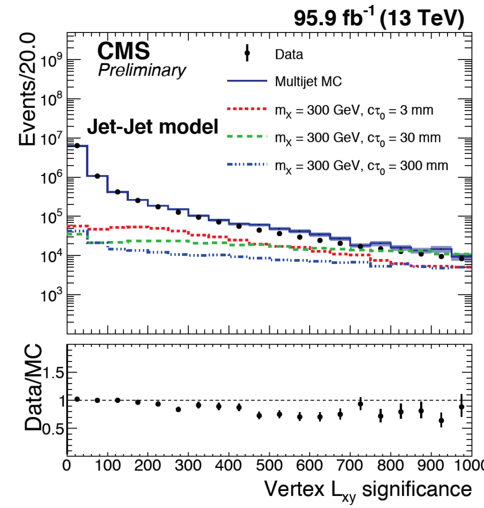
EXO-19-021

Displaced Jets – background

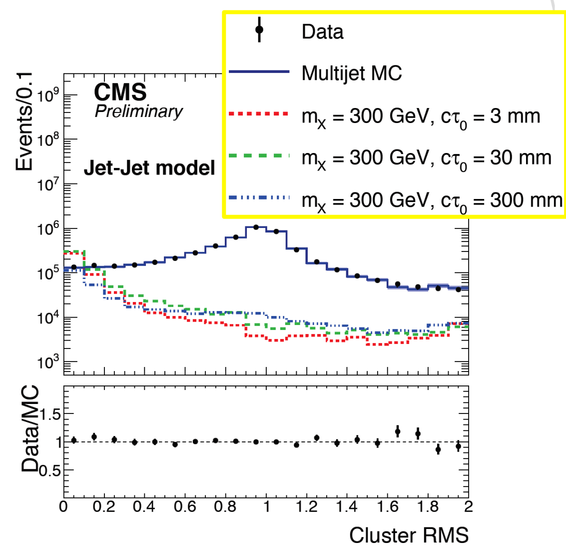
- **QCD multijet process dominates the background**
  given the large cross section (~4 x 10^4 pb for H_T > 500 GeV)

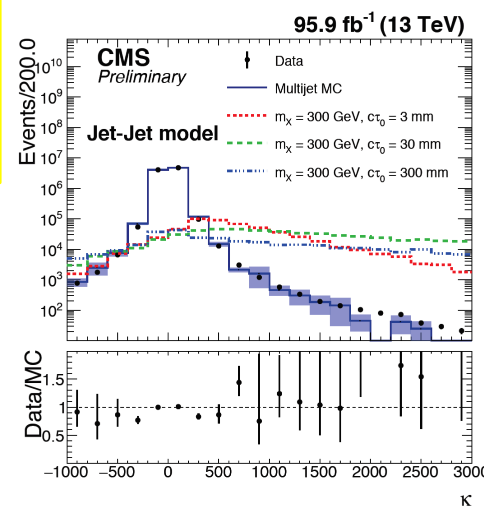
- **Gradient Boosted Decision Tree (GBDT)** as the discriminant on four variables:
  1. vertex track multiplicity
  2. cluster RMS
  3. vertex Lxy significance
  4. |κ| $\kappa = \sum_{i=1}^{6} \mathrm{Sig}[\mathrm{IP}_{2D}(\mathrm{track}_i)]$





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





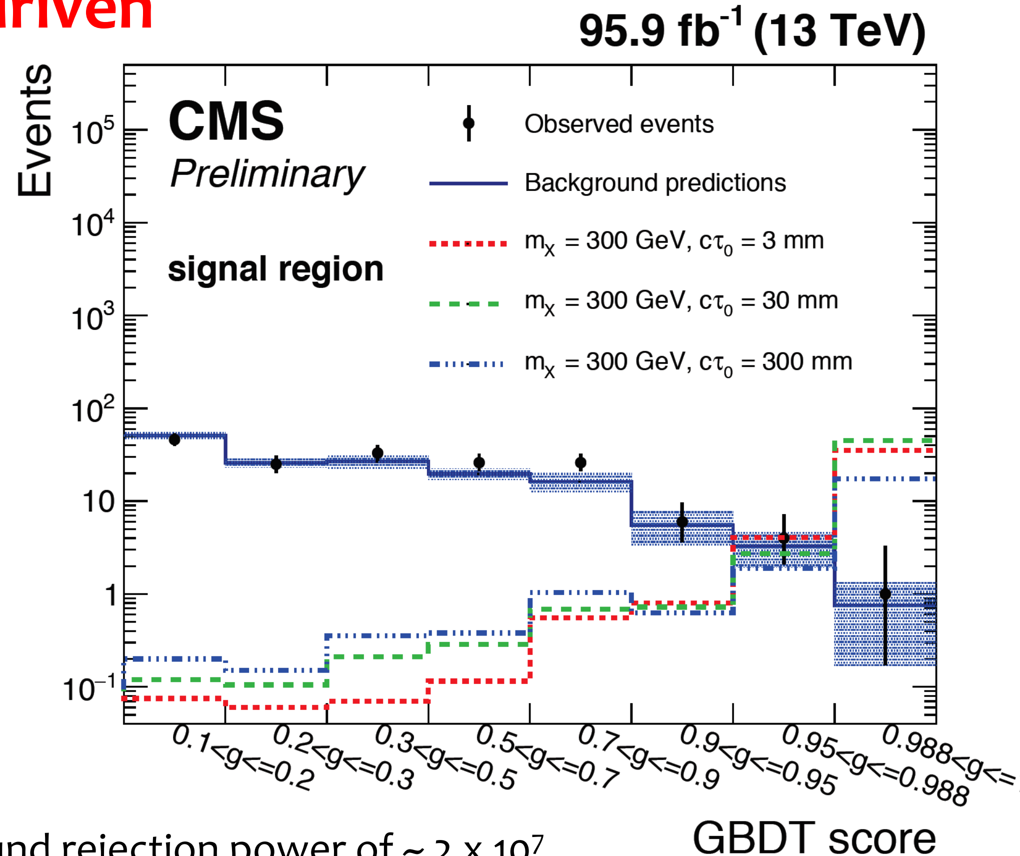
- Signal distributions almost do not depend on mass and ctau

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



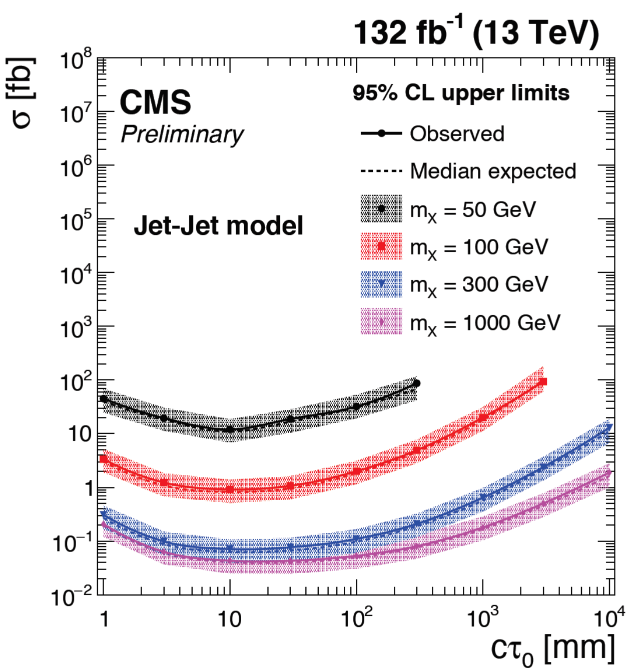
- Offline selections:
  - provide an extremely strong background rejection power of ~ 2 x 10^7
  - are highly efficient for signals (can be ~70% - 80%)
  - inclusive to different long-lived models with different final-state topologies

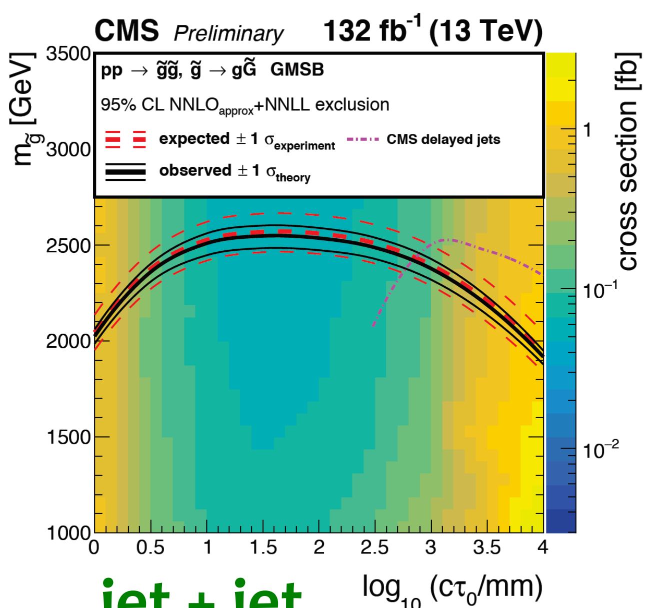
- Predicted background in the final signal region: **0.75 ± 0.44(stat) ± 0.39(syst)**
- Number of observed events: **1 event** (H_T = 570 GeV, SV with Lxy ~26 cm and 8 assigned tracks)

New limits with displaced jets

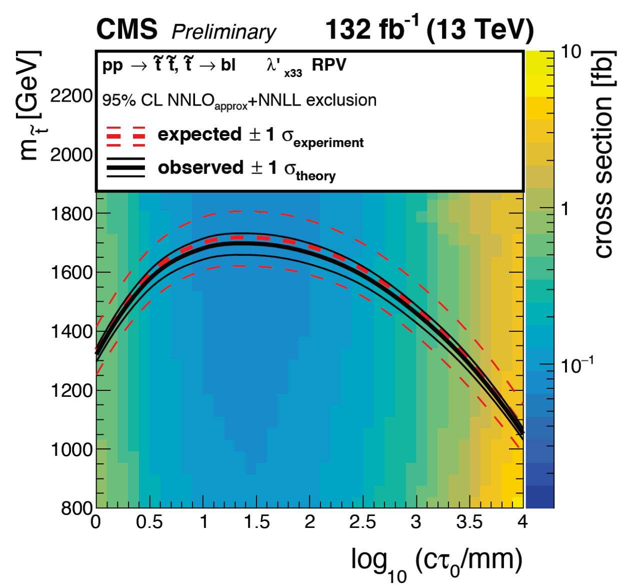
Combined results for Full Run 2 data (2016 + 2017/18) :

- 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





jet + jet



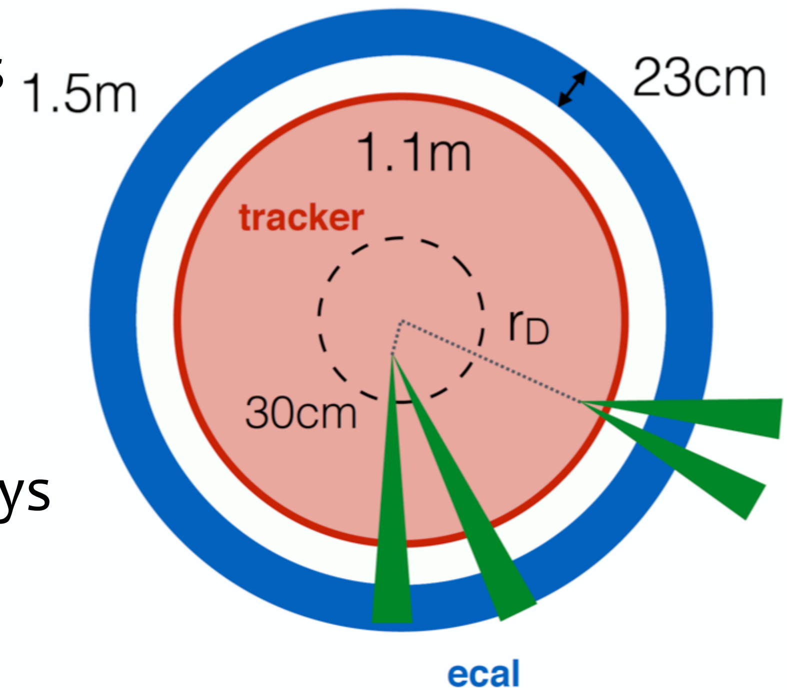
lepton + b

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)



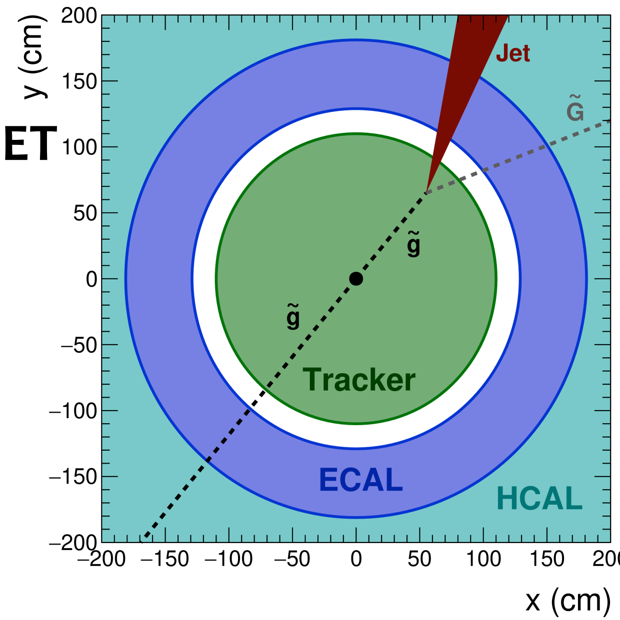
- **ECAL:** **jet time** is a median time of all ECAL cells in jet with energy > 0.5 GeV and |time| < 20ns, ΔR(cell, jet) < 0.4
- time resolution per cell (crystal+APD) ~200 ps

2016-18: 137/fb

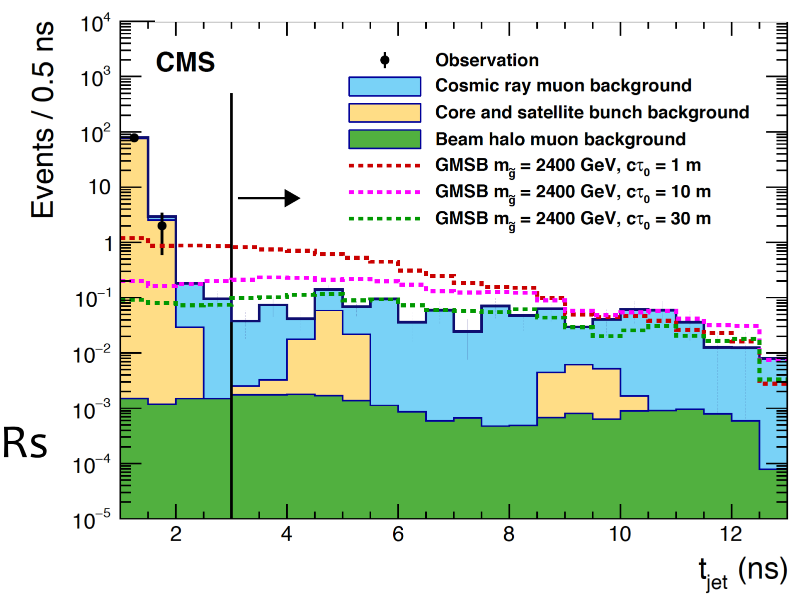
Phys. Lett. B 797 (2019) 134876, EXO-19-001

Delayed Jets

- **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

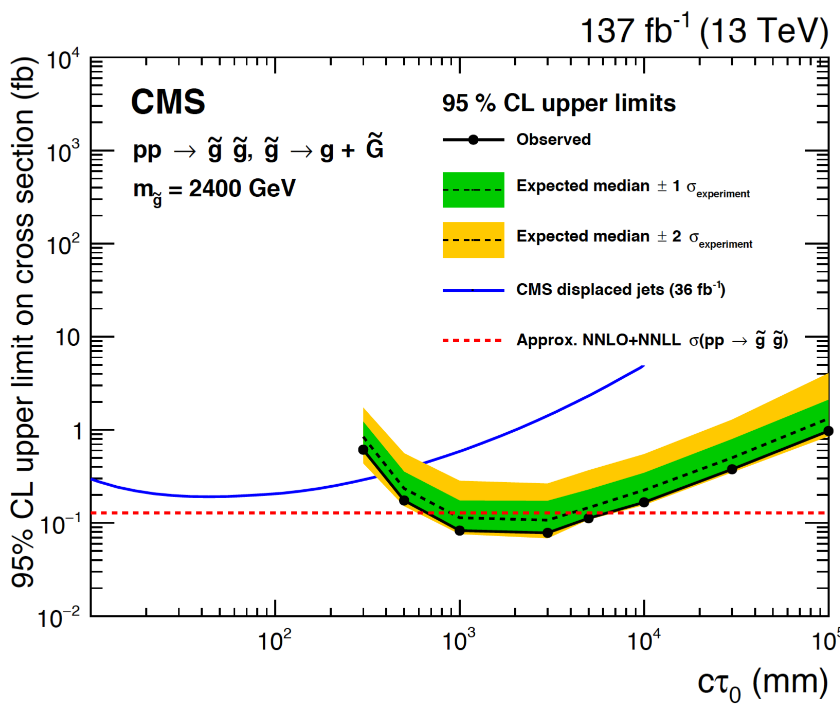
Delayed Jets

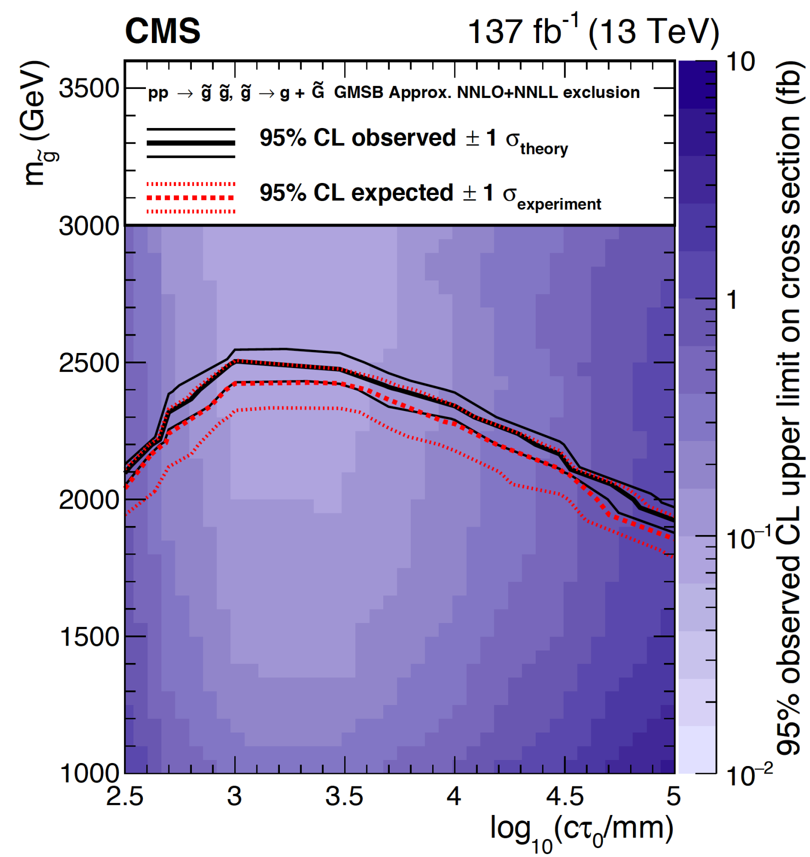
- **Observed: 0 events** in agreement with bckg. prediction of **1 evt**
- **Results (GMSB):**

  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)

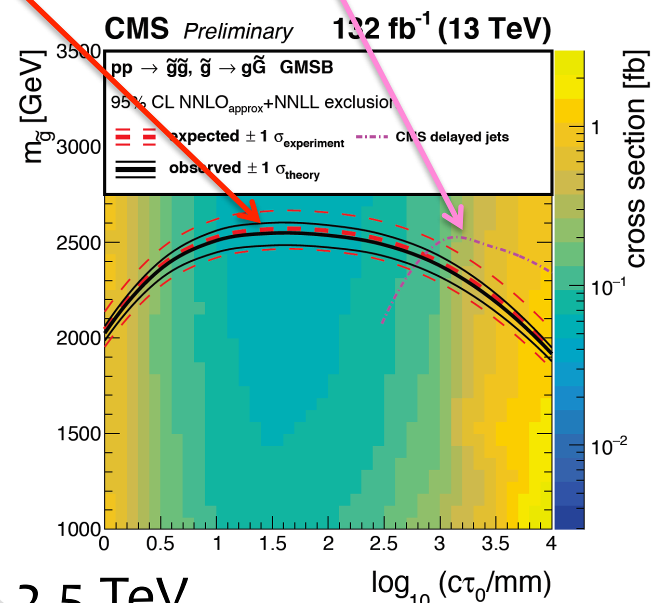
Background source	Events predicted
Beam halo muons	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunch collisions	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmic ray muons	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)





LLP at CMS summary

- **Unconventional** signatures of **displaced** or **delayed** jets is a powerful tool in searches different LLPs in a model independent way
  - Searches are complementary



- **New results for full Run 2 data pushed limits on LLPs**
  - Exclude new LLPs with masses up to 2.5 TeV
  - Sensitive to decay lengths from 1 mm
  - Any detected signal of LLP would be a clear indication of a new physics

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

Thank you!

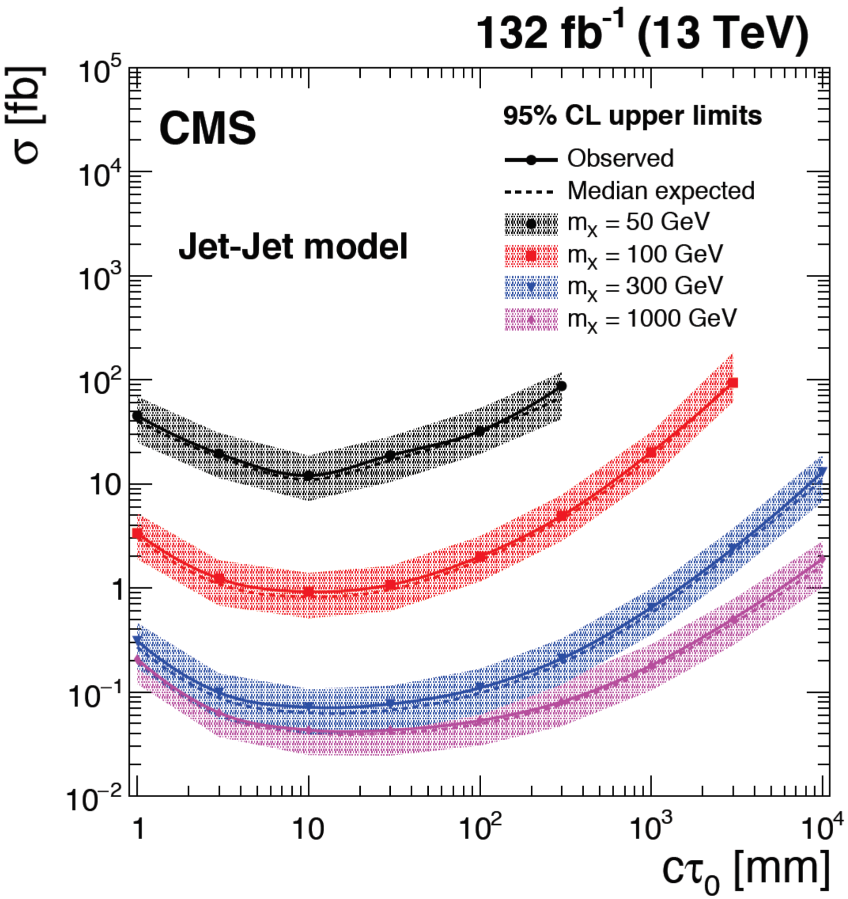
Supported in part by the NCN grant:
2014/15/B/ST2/03998

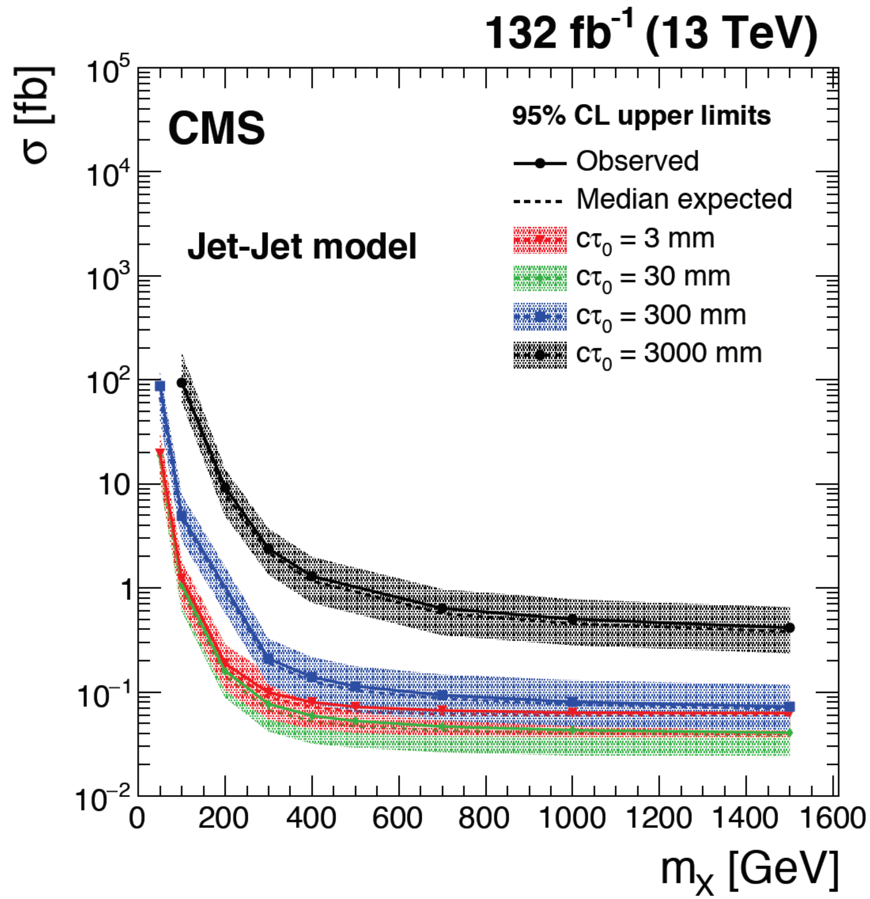
Backup

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

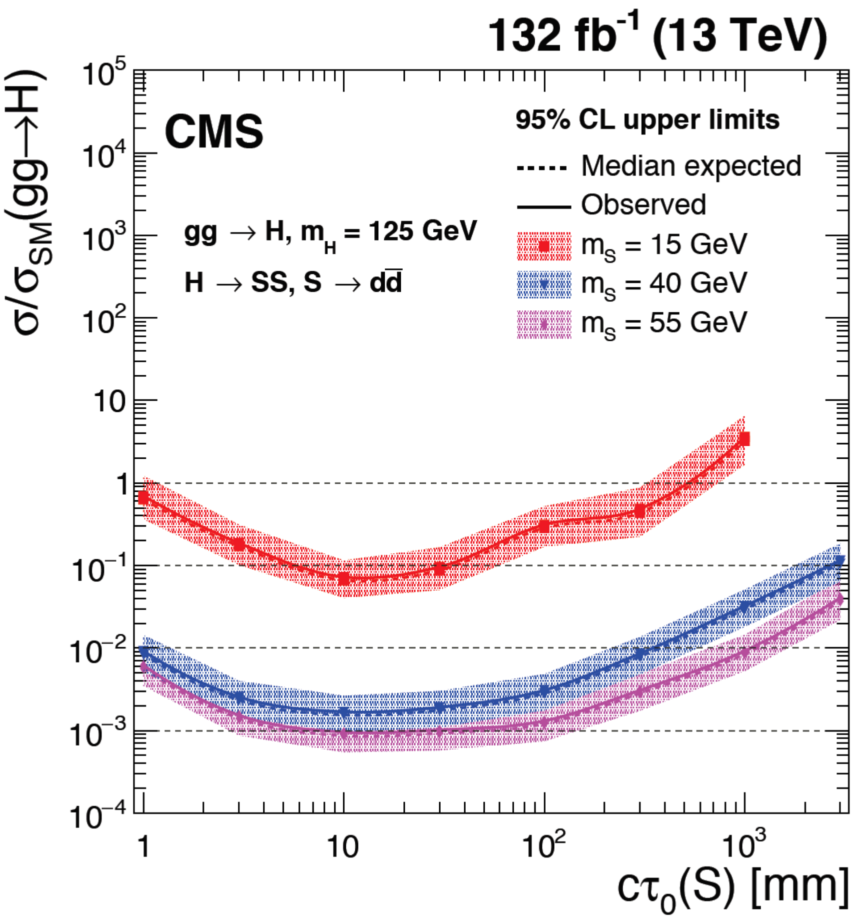


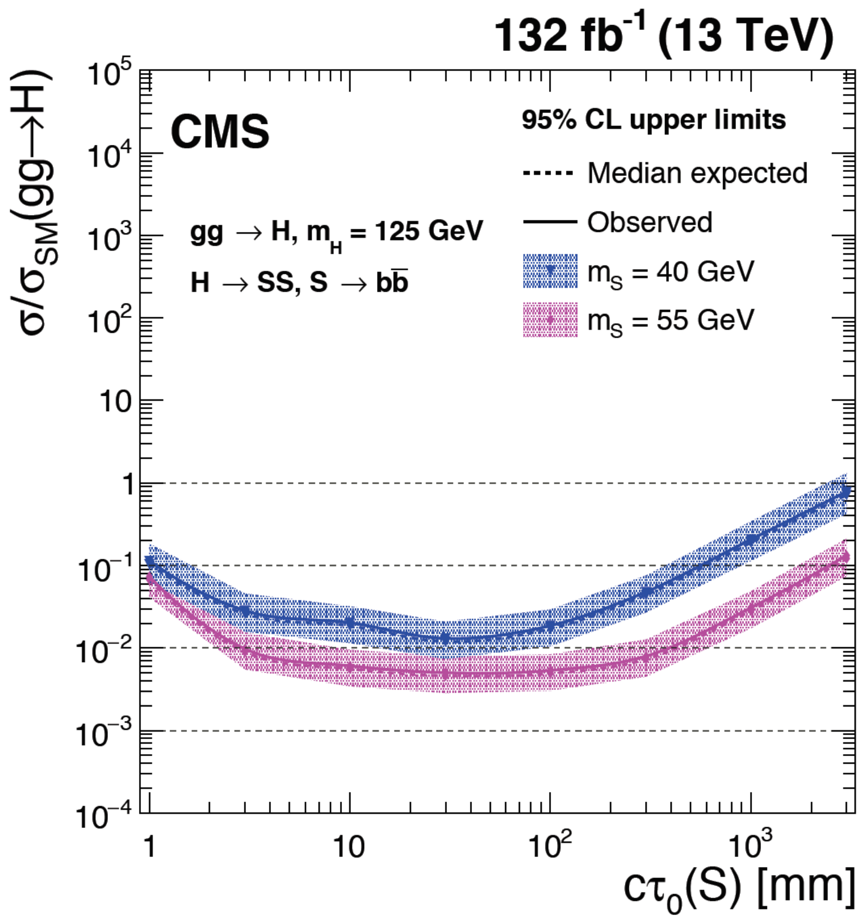


New limits with displaced jets

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

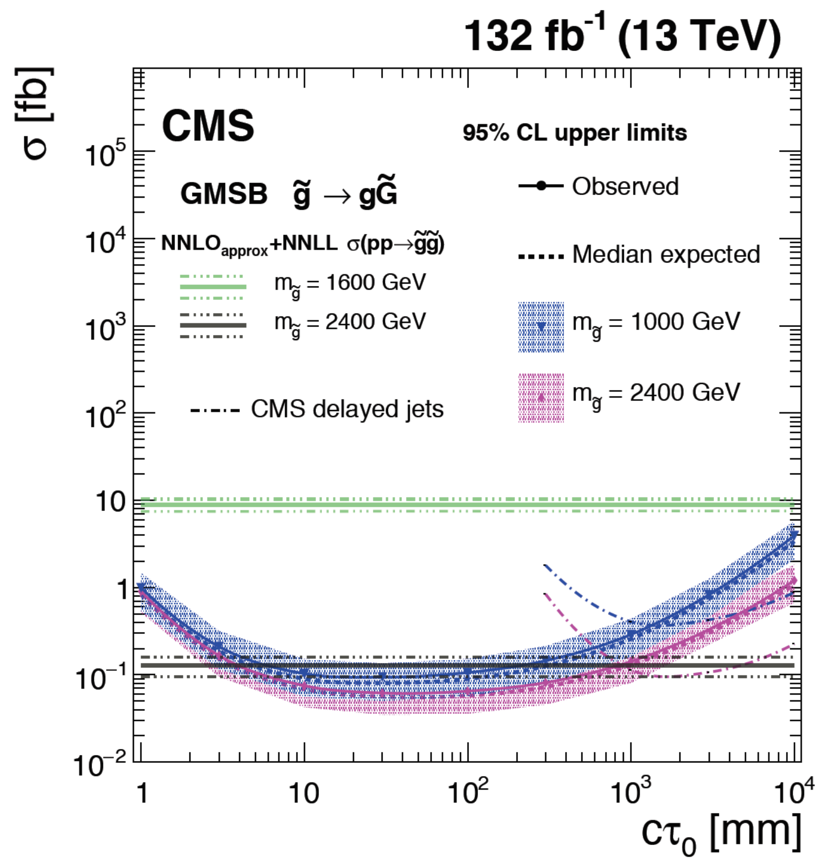
- For SM Higgs boson decays 2 LL Scalars and each LLS decays to a qq pair, the branching fractions for the **exotic Higgs decay larger than 1% are excluded at 95% CL for $c\tau_0$ between 1mm and 1 m** when scalar mass is 40 or 55GeV

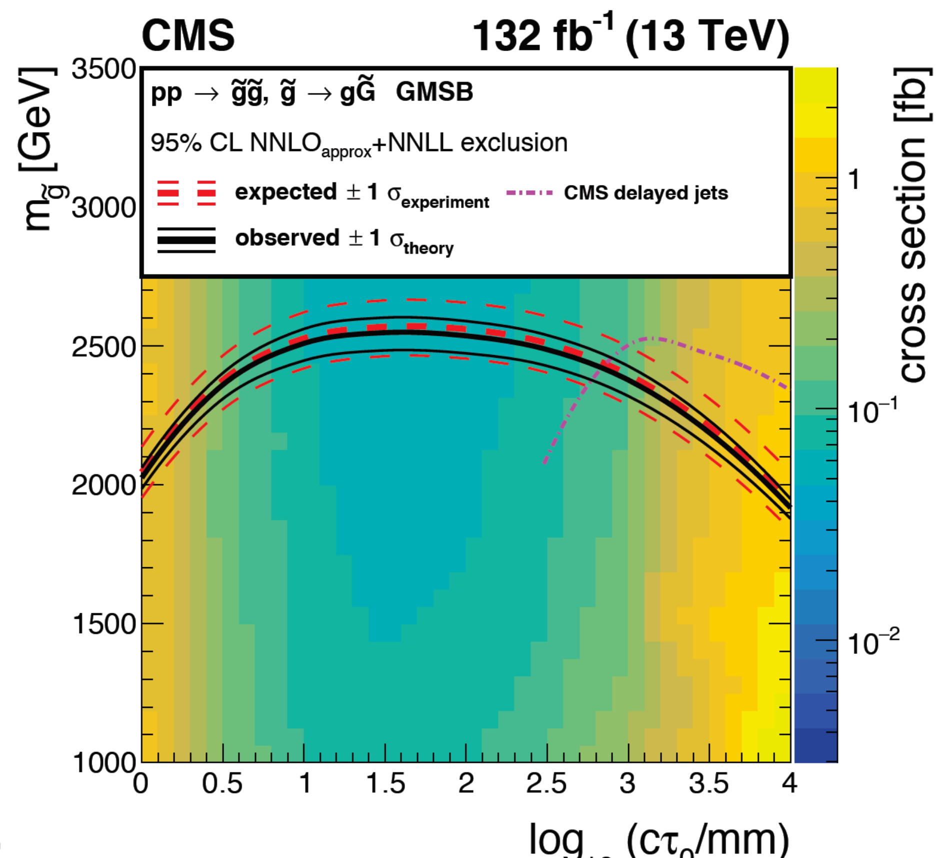




New limits with displaced jets

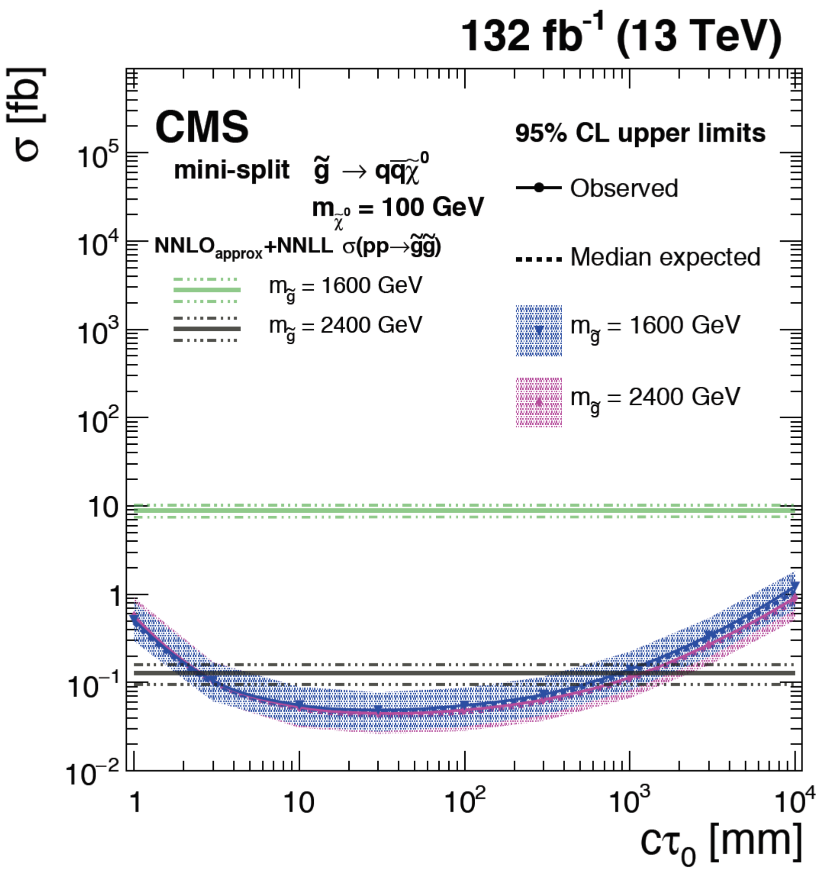
- **GMSB:** pair-produced **LL gluinos** lighter than **2450 GeV** are excluded for $c\tau_0$ between 6 – 550 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 7 – 600 mm
- the largest gluino mass excluded is 2560 GeV with a $c\tau_0$ of 30 mm

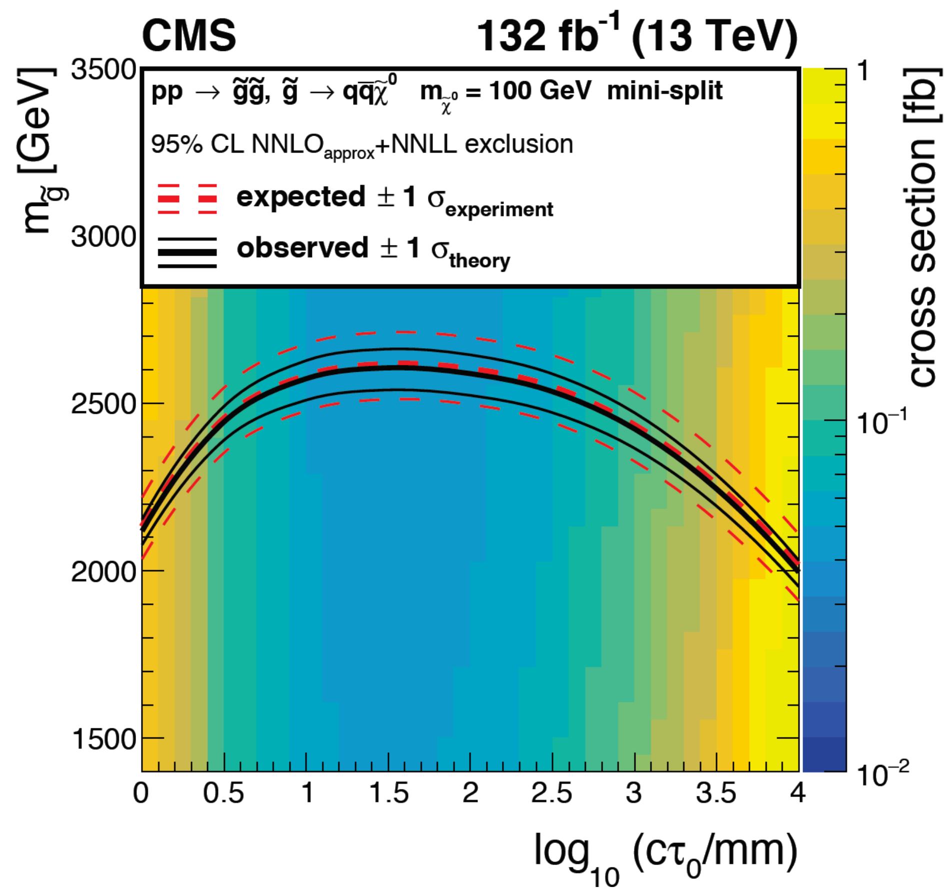




New limits with displaced jets

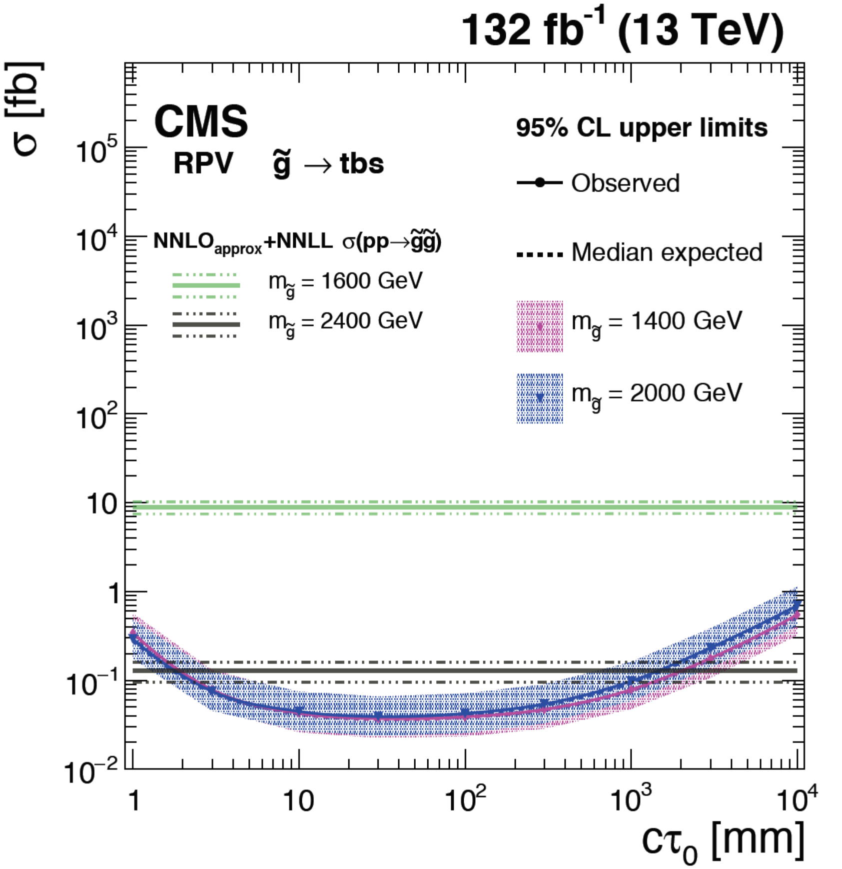
- **Mini Split:** pair-produced **LL gluinos** lighter than **2500 GeV** are excluded for $c\tau_0$ between 5 – 520 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 3 – 900 mm
- the largest gluino mass excluded is 2610 GeV with a $c\tau_0$ of 30 mm

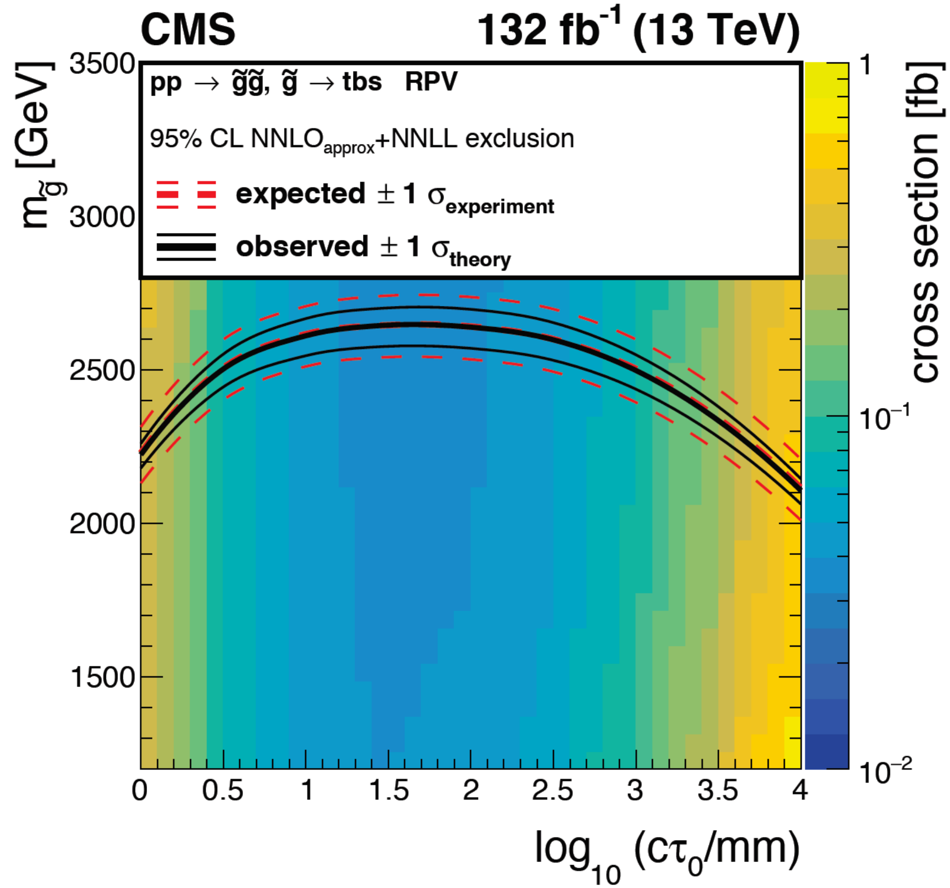




New limits with displaced jets

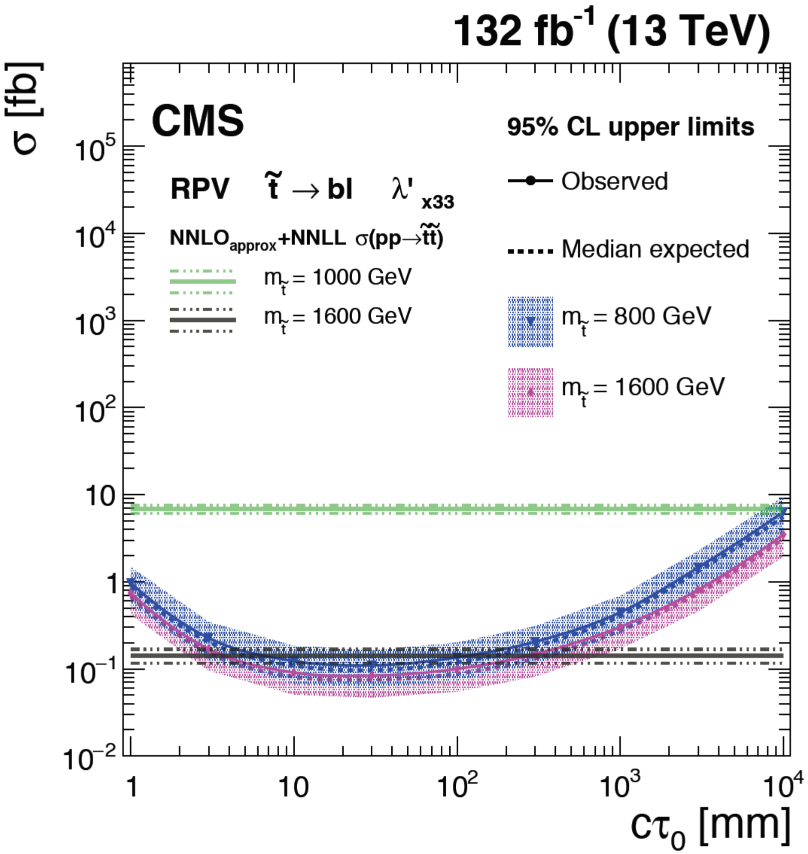
- **RPV tbs:** pair-produced **LL gluinos** lighter than **2400 GeV** are excluded for $c\tau_0$ between 3 – 1000 mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 3 – 1490 mm
- the largest gluino mass excluded is 2640 GeV with a $c\tau_0$ of 30 mm

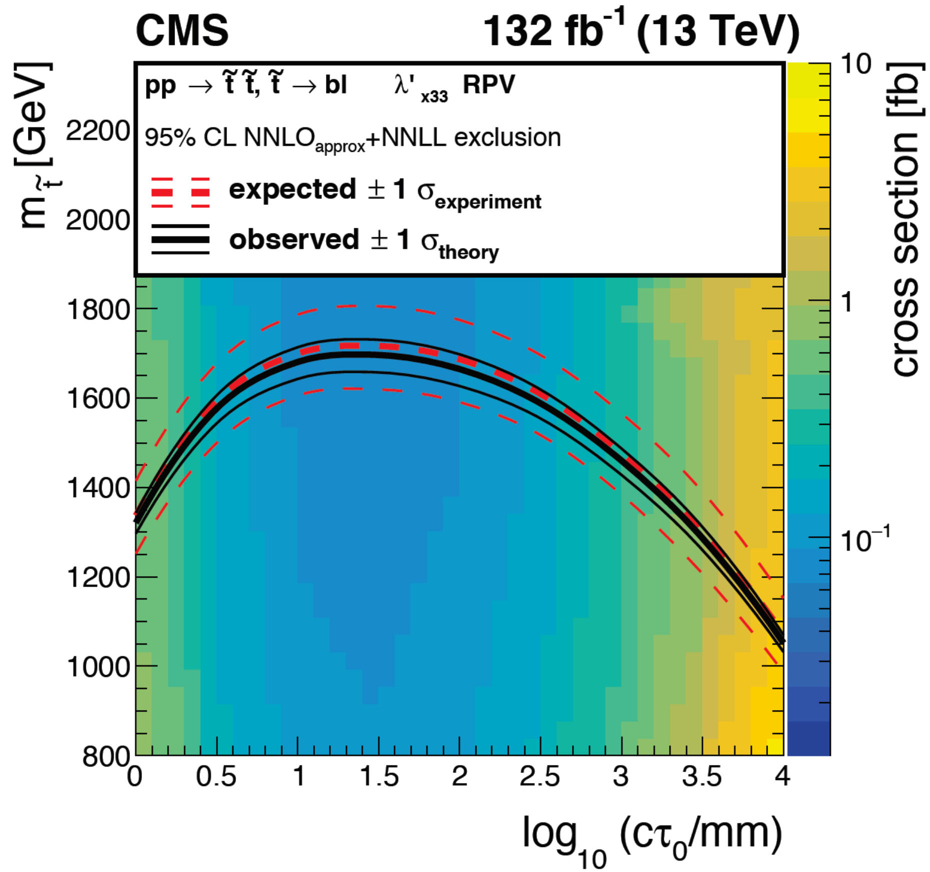




New limits with displaced jets

- **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





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