PHENO 2021

AFTER WINTER COMES SPRING

Search for long-lived particles in CMS

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UNIVERSIDAD DE CANTABRIA

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Introduction: Long-lived particles

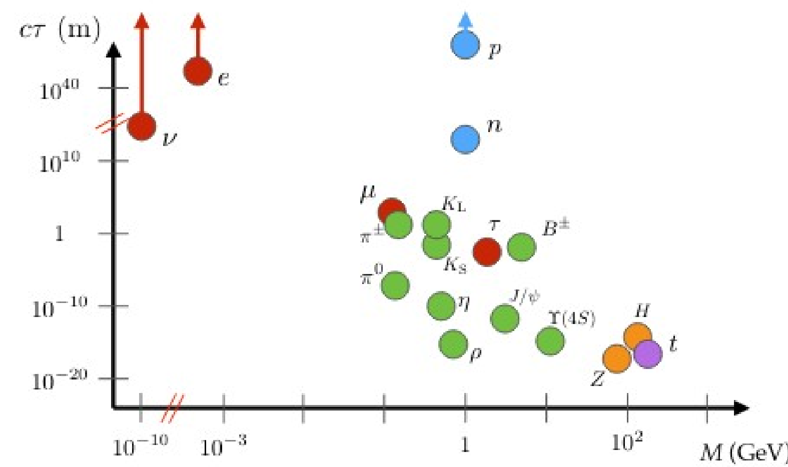
New physics could be hiding in particles with high lifetimes → **long-lived particles (LLPs).**

LLPs arise in a wide variety of **BSM theories** and covering different regions of the phase space due to

- Small couplings
- Very compressed spectra
- Heavy off-shell mediators

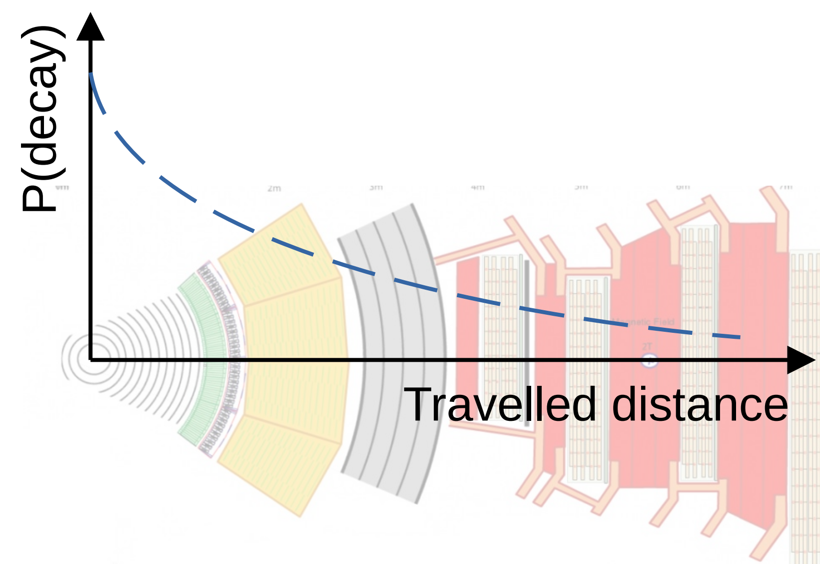
$$\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$$

$$\frac{2\pi h}{\tau} = \frac{f_{\pi}^{2}}{256\pi m_{\pi}} \left[\frac{G_F^2}{M_W^2} \frac{m_{\mu}}{m_{\pi}} (m_{\pi}^2 - m_{\mu}^2) \right]^2$$

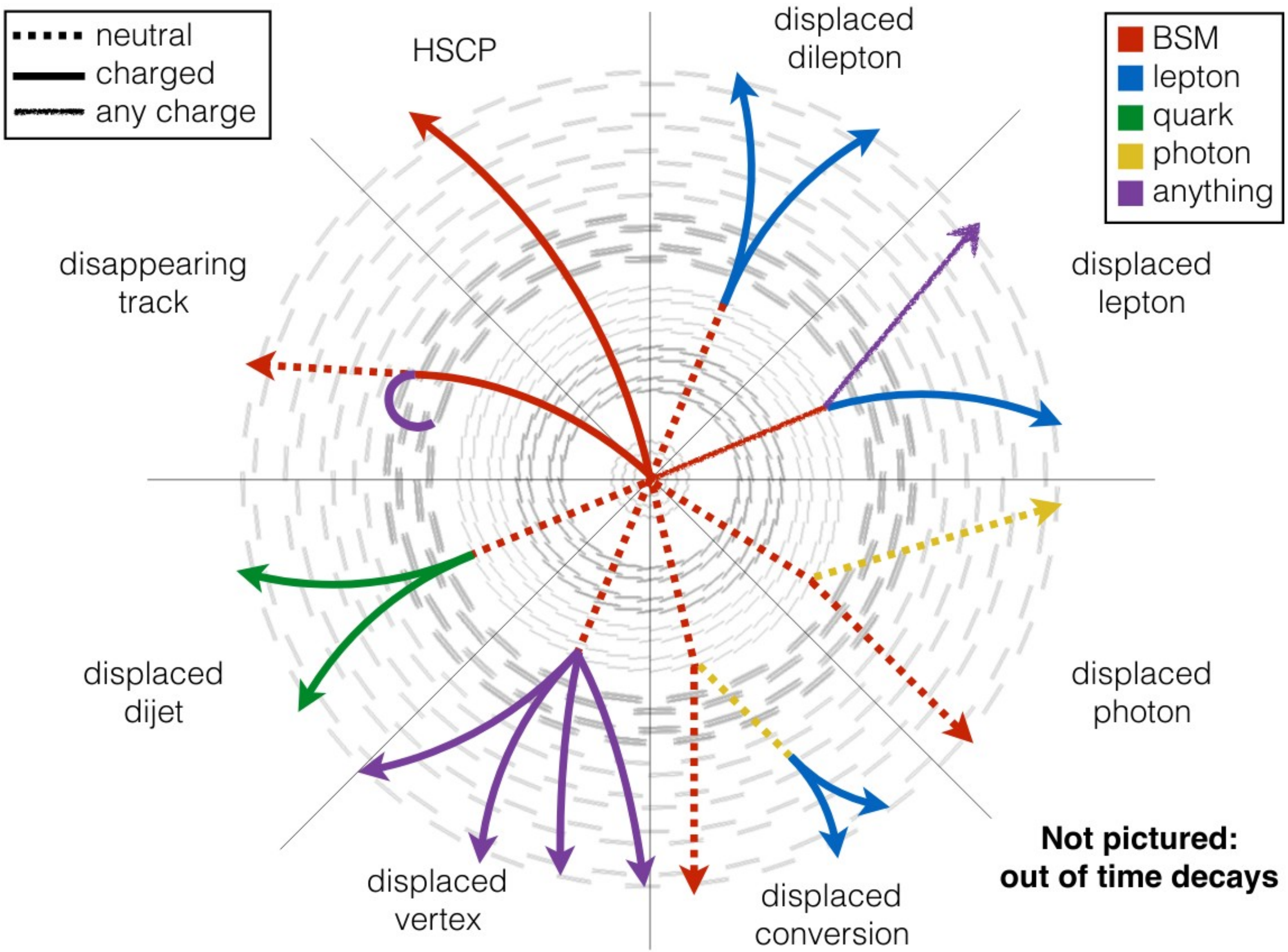


They may decay far away from the interaction point, which makes them **challenging to detect and analyse**:

- Dedicated triggers and reconstructions
- Non-standard analysis methods
- Atypical backgrounds



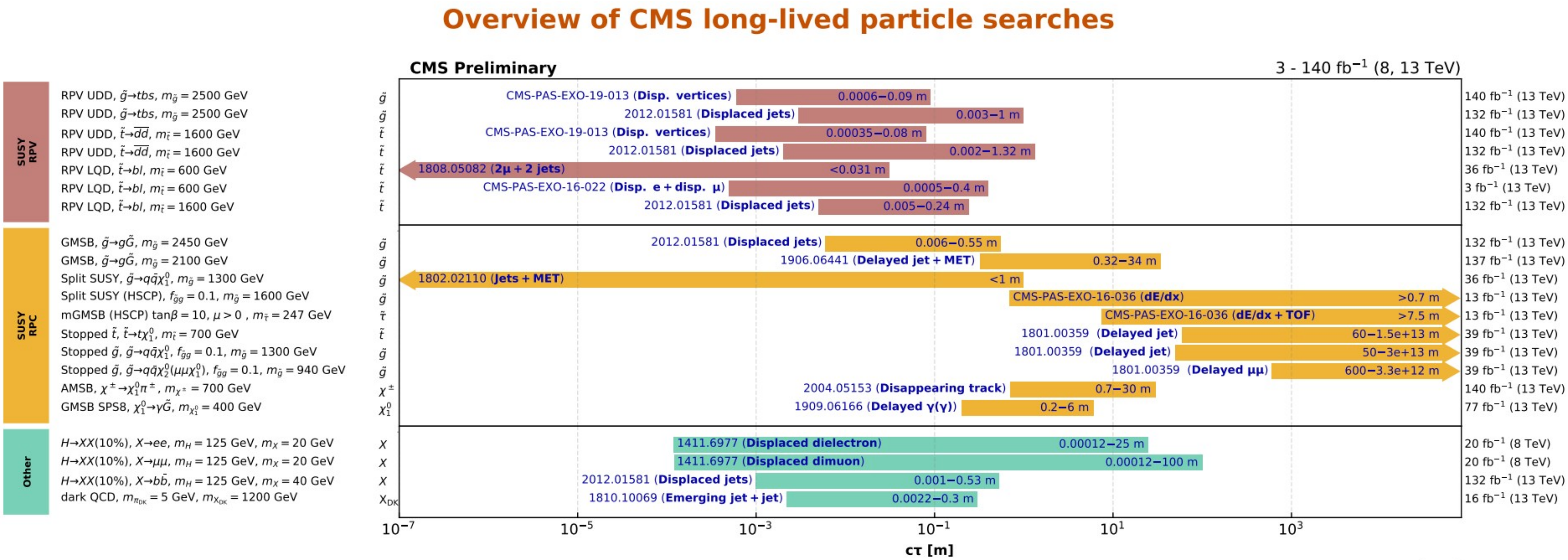
The long-lived signature



Not pictured: out of time decays

J. Antonelli

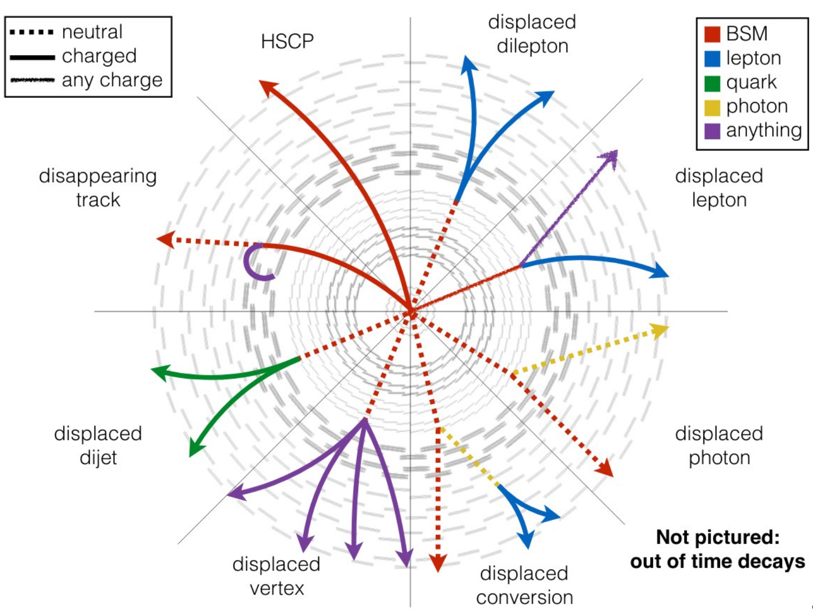
Overview of CMS LLP searches



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.

In this talk, the latest CMS results will be reviewed:

- ✗ Search for disappearing tracks
- ✗ Search for displaced jets
- ✗ Search for displaced vertices



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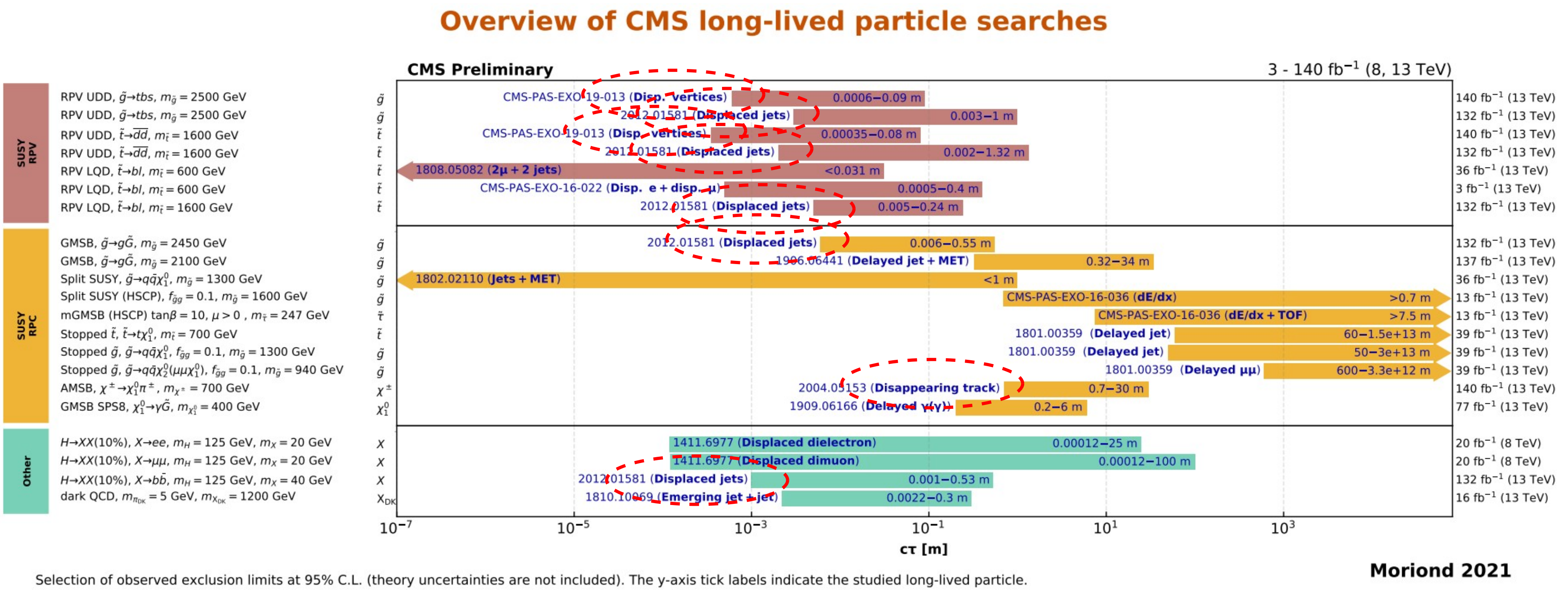

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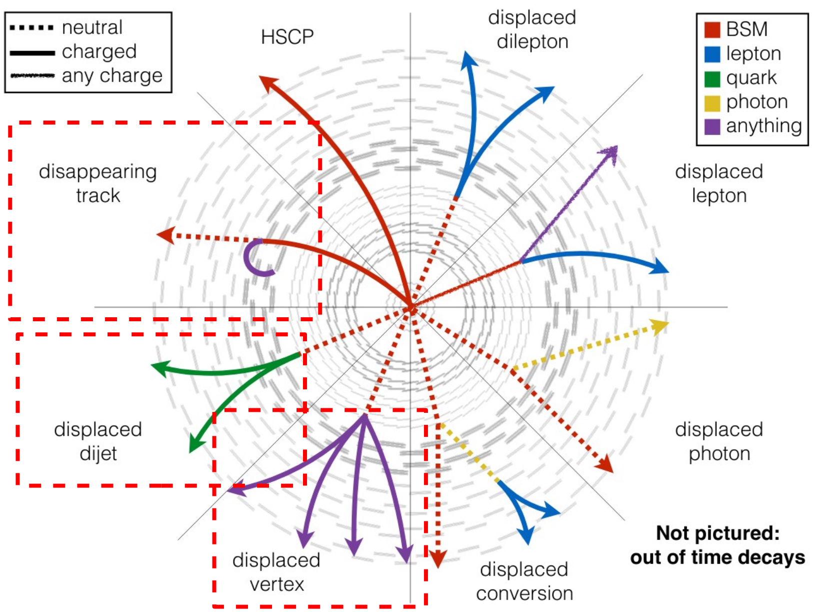


Recent long-lived searches in CMS

These 3 searches look for decays occuring within the CMS Tracker at **different ranges**:

→ Triggers used:

- MET trigger: Disappearing tracks
- Jet triggers: Displaced jets and Displaced vertices (higher p_T^{min})

→ Disappearing tracks and Displaced jets search for **at least one LLP** in the event.

→ Displaced vertices is sensitive to LLPs produced in **pairs**.

→ <u>The three analyses:</u>

- Deploy **dedicated reconstructions** to target the displaced objects in each case
- Estimate the background using **data-driven methods**

Search for disappearing tracks

CMS-EXO-19-010
2004.05153

Target: Charged LLPs that decay within the silicon tracker volume into undetected decay products.

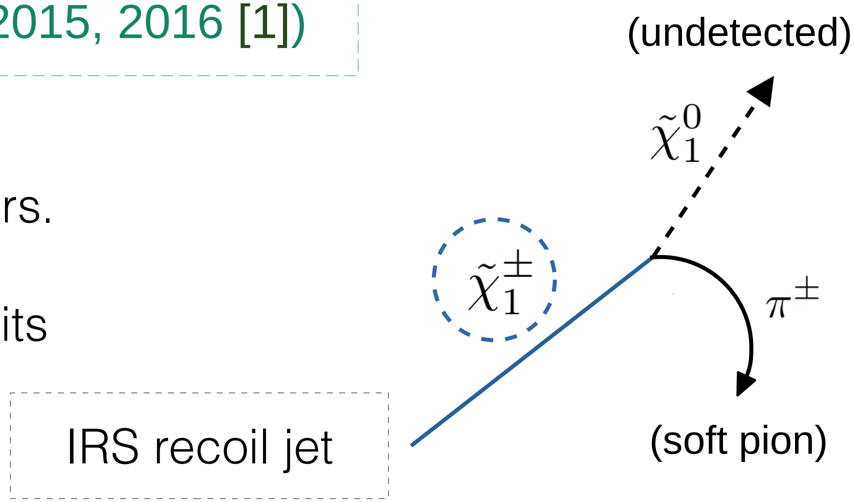
2017, 2018 (+ 2015, 2016 [1])

Signature: Disappearing track

Isolated track with
→ $p_T > 55$ GeV $|\eta| < 2.1$,

- Missed hits in outermost layers.
- Little energy in calo and no hits in muon detector.

Jet with $p_T > 110$ GeV, $|\eta| < 2.4$



→ Search interpreted in the context of Anomaly-mediated-supersymmetry-breaking AMSB models:

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$$

→ **Backgrounds** of this search are spurious reconstructed tracks and leptons. Both of them are estimated from data:

✗ Estimated probability that the lepton reconstruction fails but the track is still observed and counted in the signal region.
✗ Estimated fake track event probability.

Search for disappearing tracks

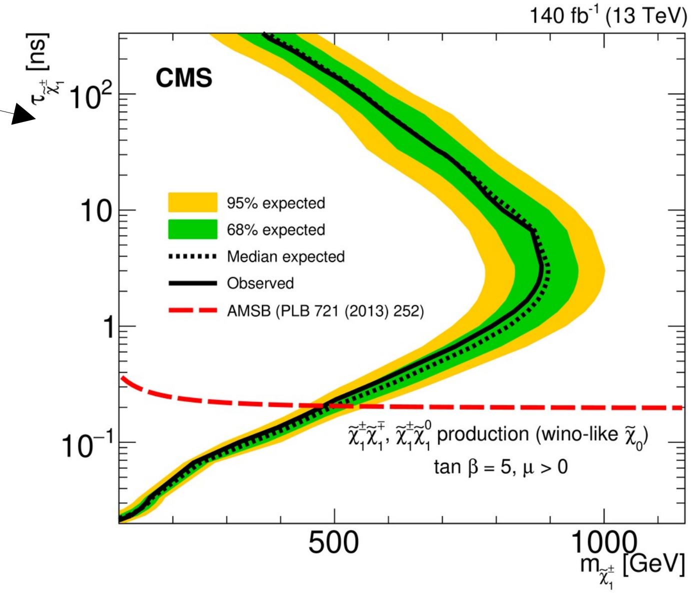
CMS-EXO-19-010
2004.05153

Upper limits are set, obtaining:

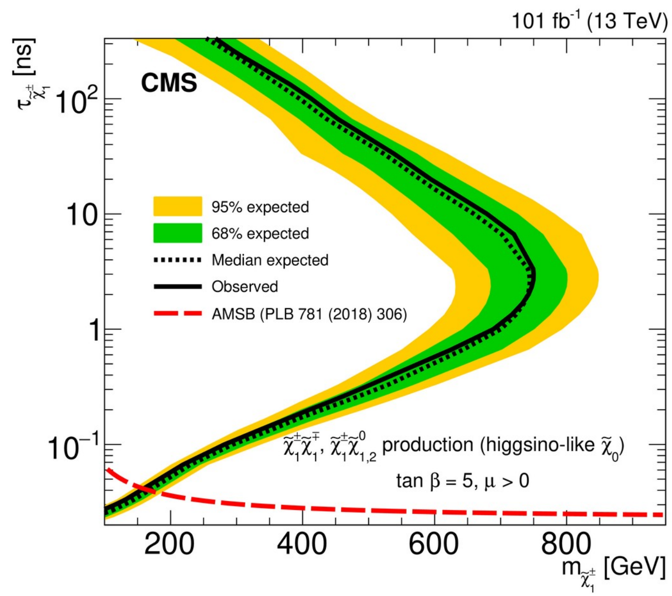
Full Run 2

The most stringent constraints to date for charginos with LSP wino.

- ✗ Charginos with lifetime of 3 (0.2) ns are excluded up to a mass of 884 (474) GeV



(2017 + 2018)



The first results to constrain chargino masses with LSP higgsino with disappearing track signature.

- ✗ Charginos with lifetime of 3 (0.05) ns are excluded up to a mass of 750 (175) GeV

Search for displaced jets

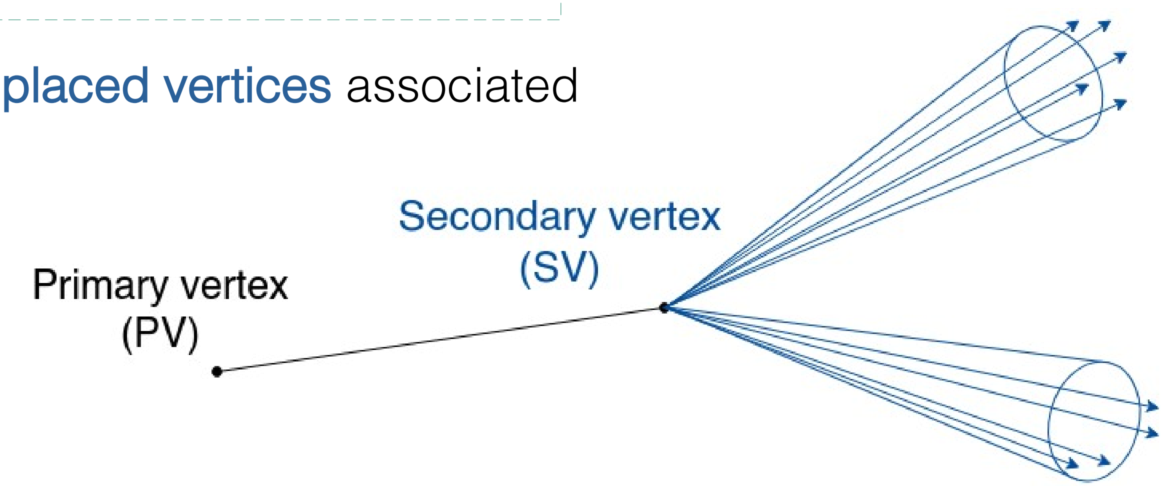
Target: LLPs decaying into jets having a displaced decay vertex within the tracker acceptance.

CMS-EXO-19-021
Submitted to PRD

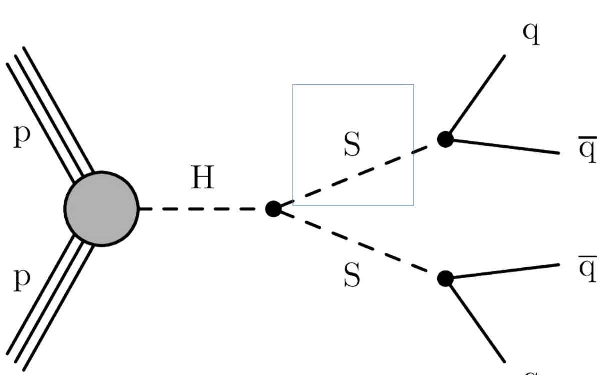
2017, 2018 (+ 2016 [1])

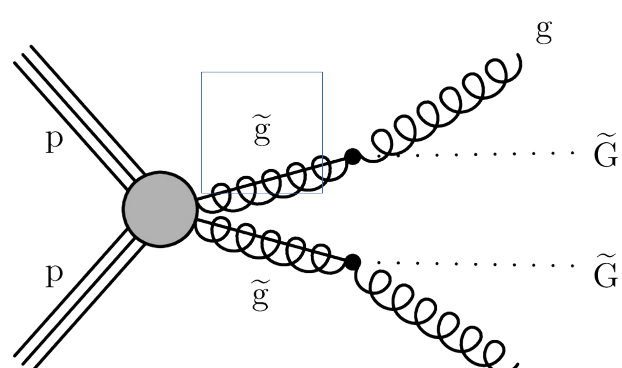
Signature: Displaced tracks and displaced vertices associated with a **dijet system**.

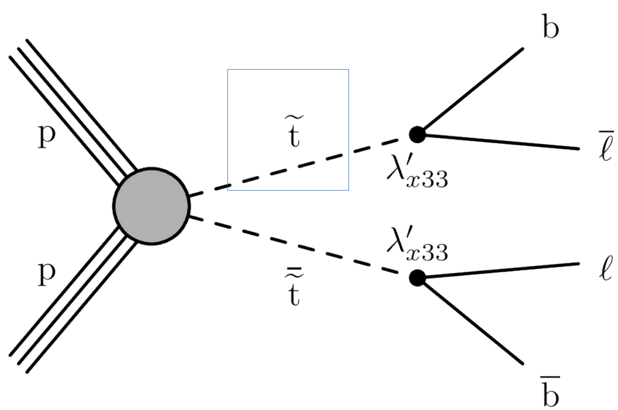
- Jet pairs with p_T > 50/80* GeV, |η| < 2.0
- SV reconstructed from displaced tracks (IP_{2D} > 0.5 mm and Sig[IP_{2D}] > 5.0)



→ The search is interpreted in the context of a wide variety of **BSM scenarios** e.g. SM-like Higgs models, GMSB SUSY, RPV SUSY and others.







* p_T threshold depends on fired triggers in each event

Search for displaced jets

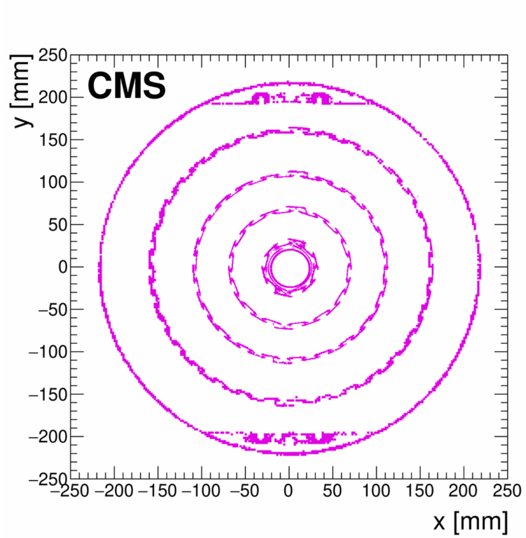
CMS-EXO-19-021
Submitted to PRD

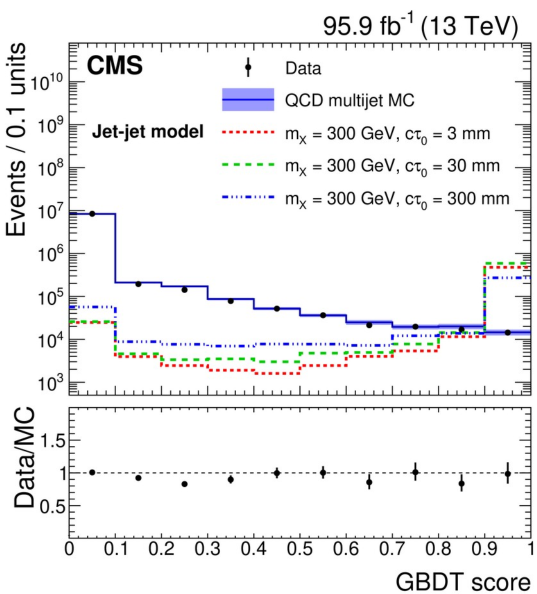
Background sources include **nuclear interactions (NIs)** between outgoing particles and detector material, **long-lived SM hadrons**, **misreconstructed displaced SVs** and **QCD**.

→ Estimated from data in Control Regions

Analysis strategy

- ✗ Events triggered with both a displaced and an inclusive **jet triggers**.
- ✗ One SV is reconstructed from the displaced tracks of each **dijet candidate**.
- ✗ Dedicated variables to provide signal-to-background discrimination (second highest track Sig[IP_{2D}], fraction of dijet energy associated to SV, charged energy fraction associated to Pvs...)
- ✗ NI-veto map to reduce NIs
- ✗ Gradient Boosted Decision Tree to discriminate signal from QCD.
- ✗ → **Signal region:**
  - score > 0.988
  - ≤ 3 tracks in jets with IP_{3D} < 0.3 mm

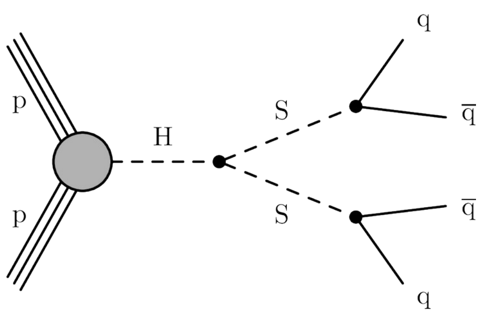




Search for displaced jets

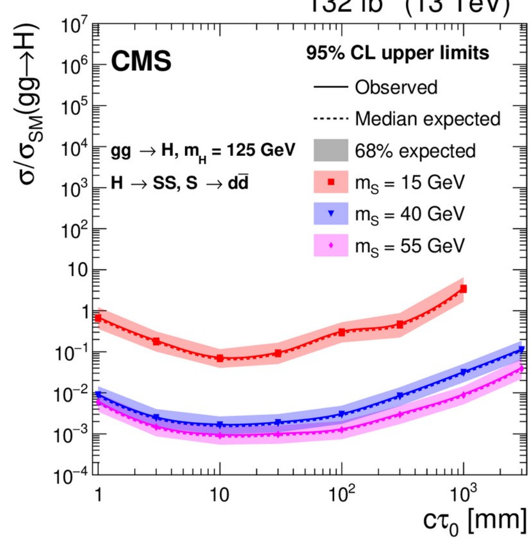
Most stringent limits to date in SM-like Higgs and SUSY models e.g.

CMS-EXO-19-021
Submitted to PRD

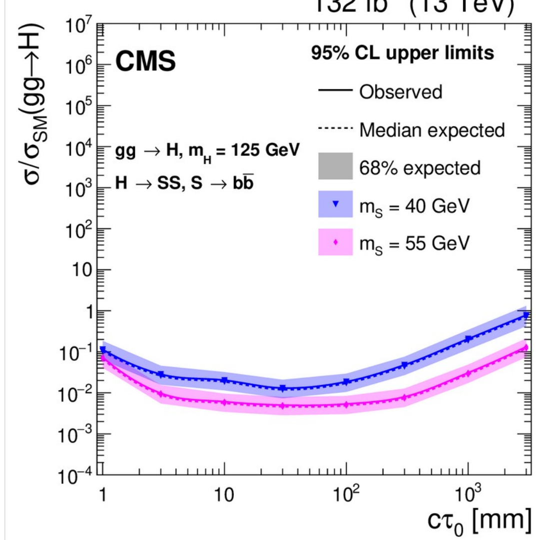


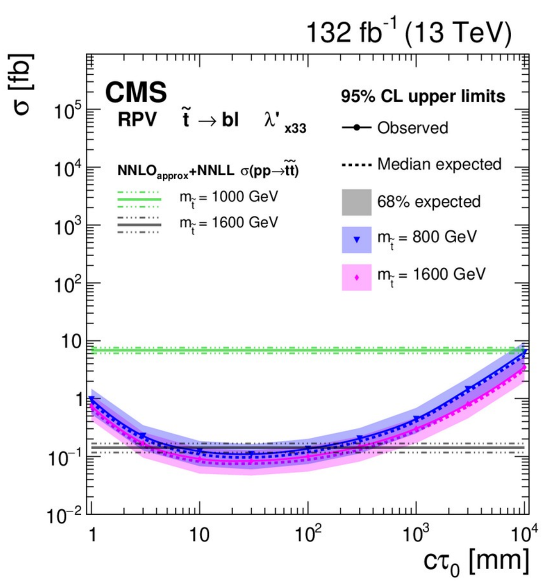
Branching fractions larger than 1% are excluded for $1 < c\tau < 530$ mm with $m_S \geq 40$ GeV,

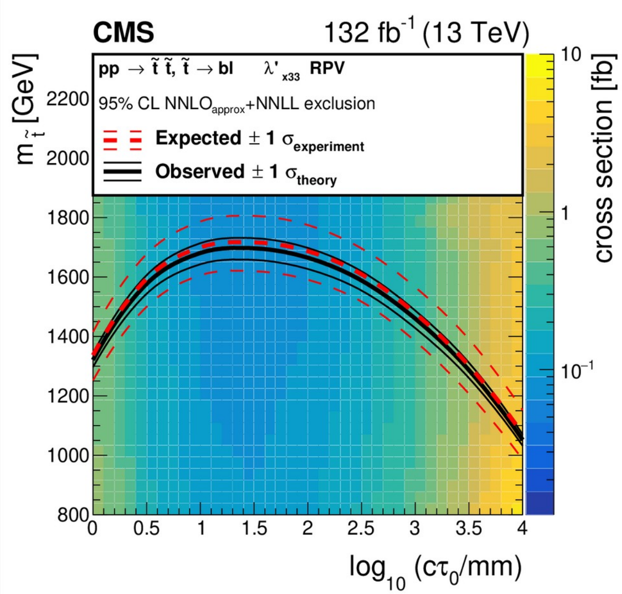
S → dd

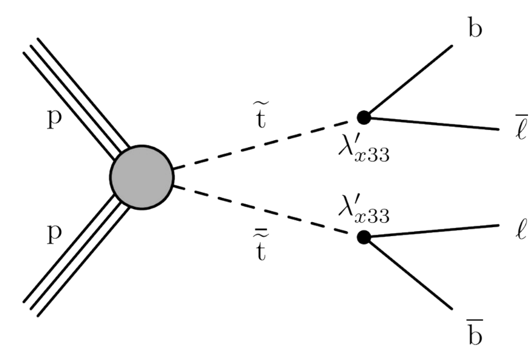


S → bb









Largest top squark mass excluded is 1720 GeV with $c\tau = 30$ mm

Search for displaced vertices

CMS-EXO-19-013
Submitted to PRD

Target: LLPs produced in pairs decaying into final states with multiple jets.

2017, 2018 (+ 2015, 2016 [1])

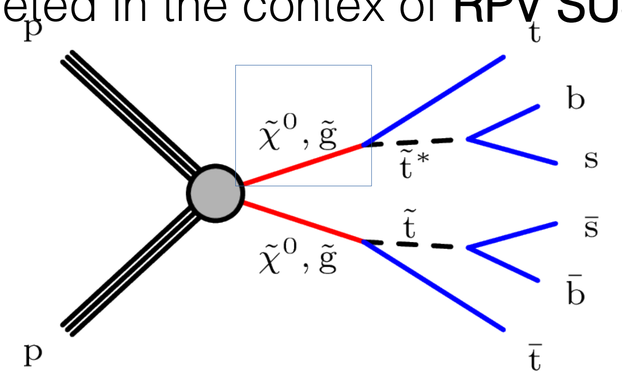
Signature: Two vertices reconstructed from the intersection of the charged particles trajectories. Displaced up to the beam pipe radius (22mm).

→ Additional selection: ≥4 jets with $p_T > 20$ GeV and $|\eta| < 2.5$

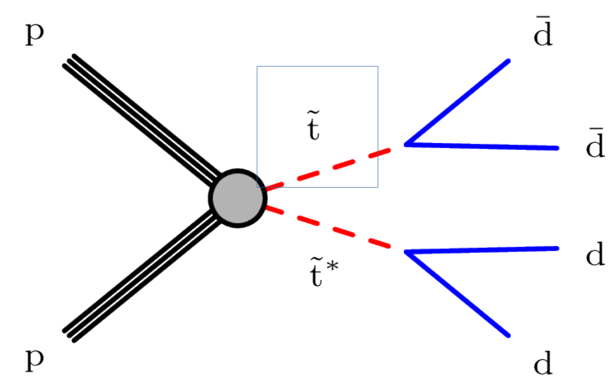
→ The displaced vertices are reconstructed with a custom vertex reconstruction algorithm:

1) Reconstruct vertices from pairs of selected displaced tracks by using the Kalman filter method.
2) Merge pairs of vertices iteratively until no vertices share a track.
3) Select good quality displaced vertices at least by 100 µm from beam axis.

Interpreted in the contex of **RPV SUSY models**:



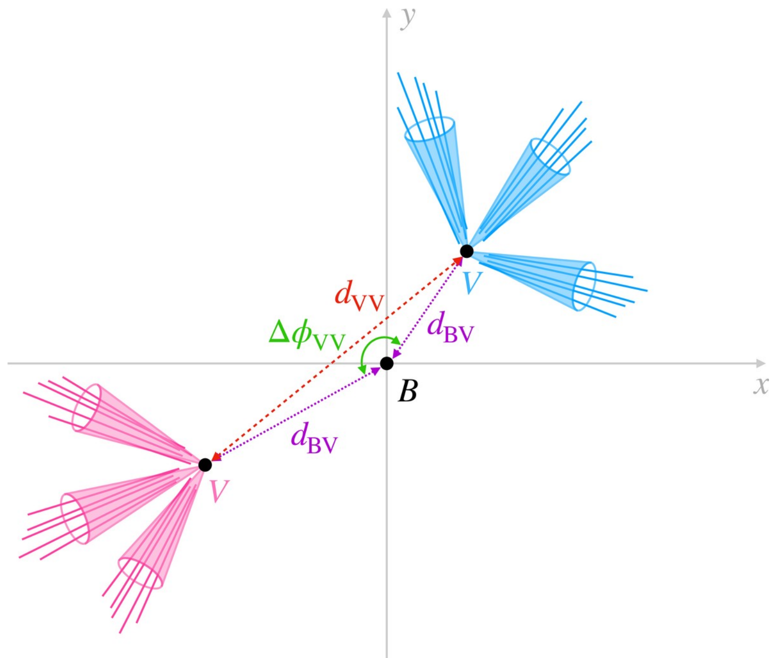
Multijet signal



Dijet signal

Search for displaced vertices

CMS-EXO-19-013
Submitted to PRD



Used the **distance between vertices d_{VV}** as a discriminant:

✗ Large for displaced signals (simulated)
✗ Small in background events (data-driven)

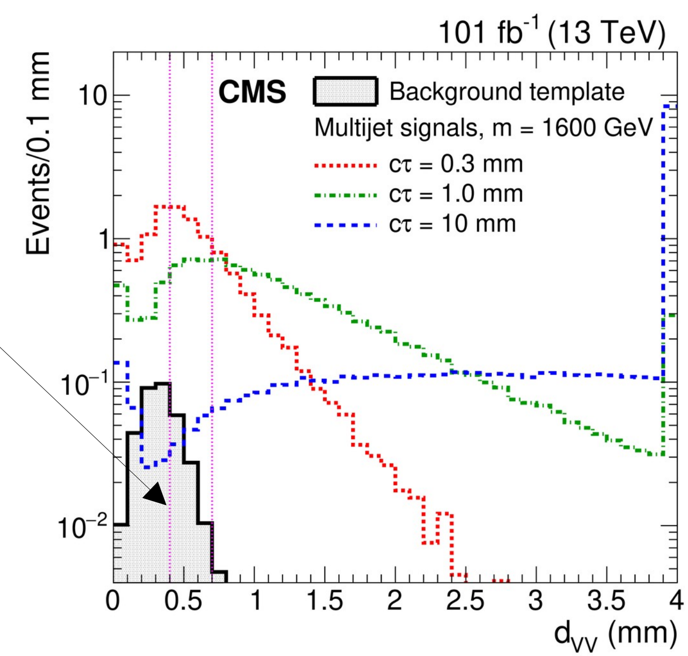
Fit to d_{VV} distribution in bins: [0, 0.4, 0.7, 40] mm

Background composed of spurious vertices from jets from **QCD** and **pair produced top quarks**.

→ Estimated from a template constructed from control **data events**.

→ **New technique** to supress background vertices from accidental track intersections (40% reduction):

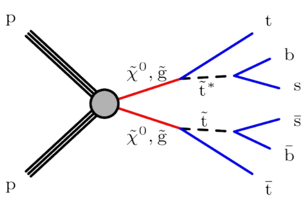
Evaluate shift introduced by each track by refitting the vertex without it → remove the track if shift is > 50 µm

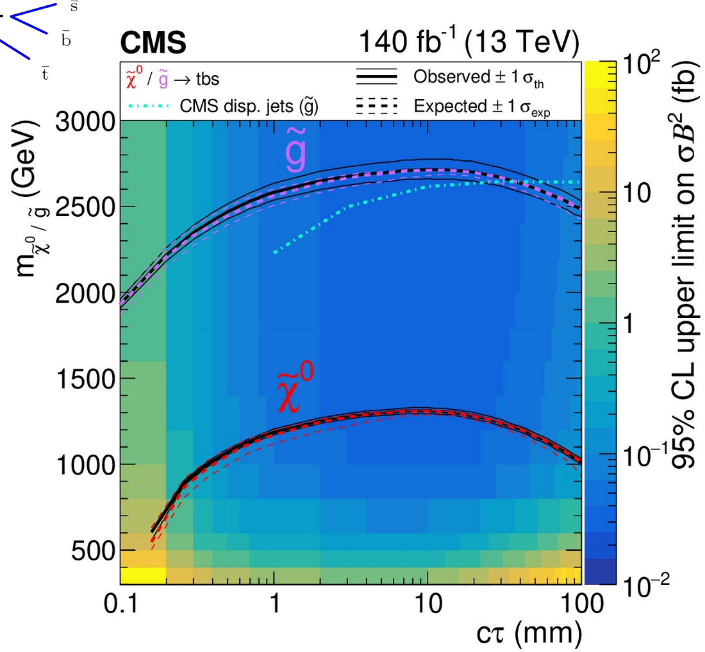


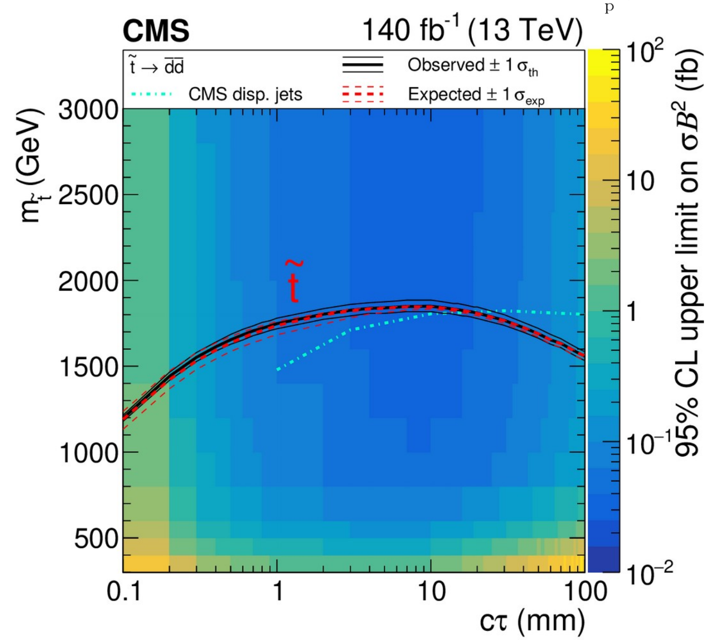
Search for displaced vertices

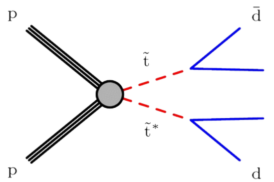
CMS-EXO-19-013
Submitted to PRD

→ Upper limits on the product of cross section and branching fraction squared for the multijet (left) and dijet (right) signals:









✗ Exclusions **250-300 GeV higher** that those of the previous analysis (2015+2016).

✗ The **most stringent bounds** on these models for **cτ between 0.1 and 15 mm for all masses considered**.

Looking towards Run 3

Long-lived analyses are exploiting all the tools available in Run 2 but there is room for improvement towards **Run 3**:

→ **Standard triggers are optimized for prompt signals** (vertex constraints, worse resolution, low efficiency… etc)

- → **Critical** because trigger decides which physics is left
- → Huge effort ongoing to **increase both L1 and HLT performance**

→ **Standard reconstructions are also optimized for prompt physics objects**, so there are ongoing developments on dedicated displaced-reconstructions which would:

- → Improve **efficiency** at high displacement
- → Not rely on **constraints** (e.g. vertex constraints) that may affect to measurements resolution
- → Introduce the possibility to deploy **new and innovative analysis strategies**

Conclusions

- ✗ Three of the **last long-lived searches** have been presented.
  - ✗ And **more long-lived searches are still yet to come** with Run 2 data. (e.g. displaced leptons, HNL, inelastic dark matter…)
- ✗ Long lifetimes provide a handle to **reduce background and gain sensitivity**.
  - ✗ But at the same time are **challenging to detect and analyse**.
  - ✗ Run 2 analyses have **exploited all the tools available**.
- ✗ There is **room for improvement towards Run 3** and a huge effort ongoing:
  - ✗ **Improving triggers** to gain sensitivity at lower masses and even larger lifetimes
  - ✗ **Optimizing offline reconstructions** to improve their performance at high displacement