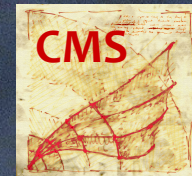


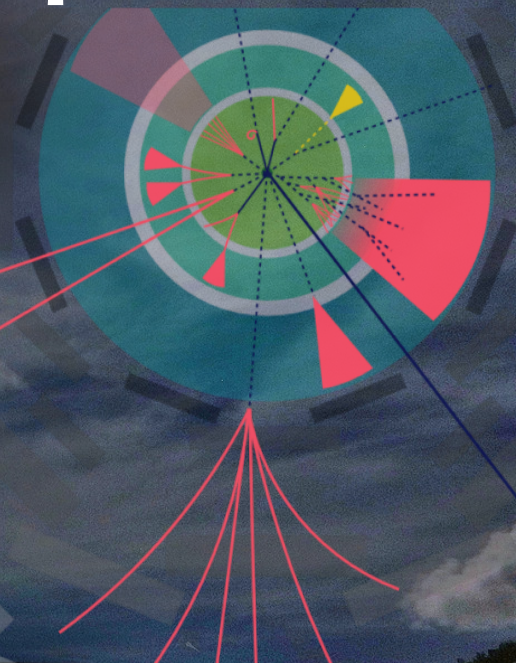
Searches for long-lived particles with the CMS detector



Compact Muon Solenoid
experiment at the CERN's LHC

Małgorzata Kazana
on behalf of the **CMS Collaboration**

National Centre for Nuclear Research
NCBJ – Warsaw, Poland



25th Anniversary Conference of the Rencontres du Vietnam
Windows on the Universe: Particle Physics

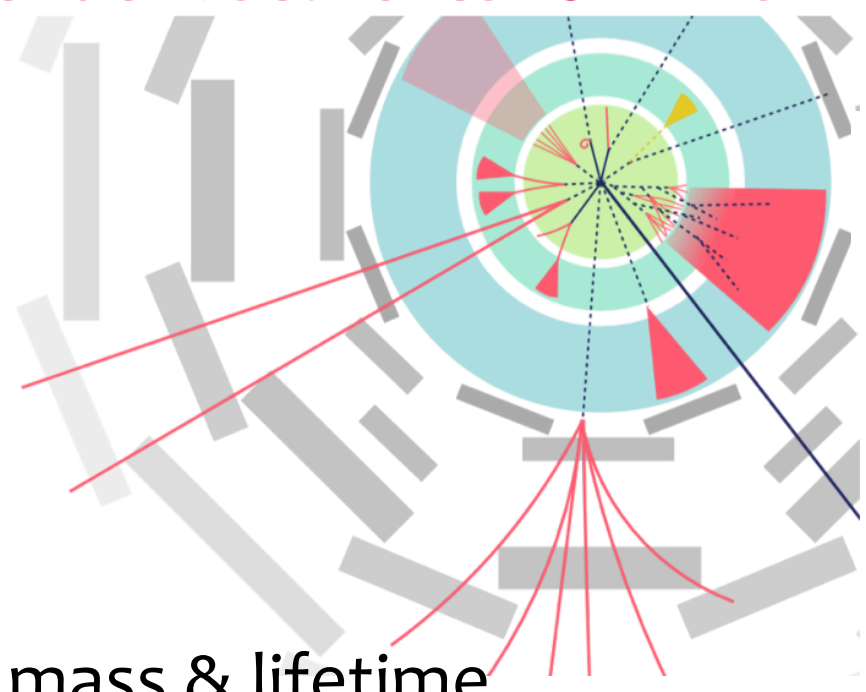
5-11 Aug 2018

Quy Nhon, ICISE, Vietnam



Outline

- **Highlights** from **model independent searches for LLPs** in the LHC Run 2 at CMS
 - The search strategy for:
 - **Displaced** vertices or jets
 - **Emerging** jets
 - **Disappearing** tracks
 - **Quasi-stable** particles
 - **Stopped** particles
 - Results and limits on σ , mass & lifetime
- **CMS data collected at 13 TeV in 2016 – 36/fb**
 - Not many new results this year, waiting for the full Run 2 statistics
 - In this talk, the focus is on recently published CMS results

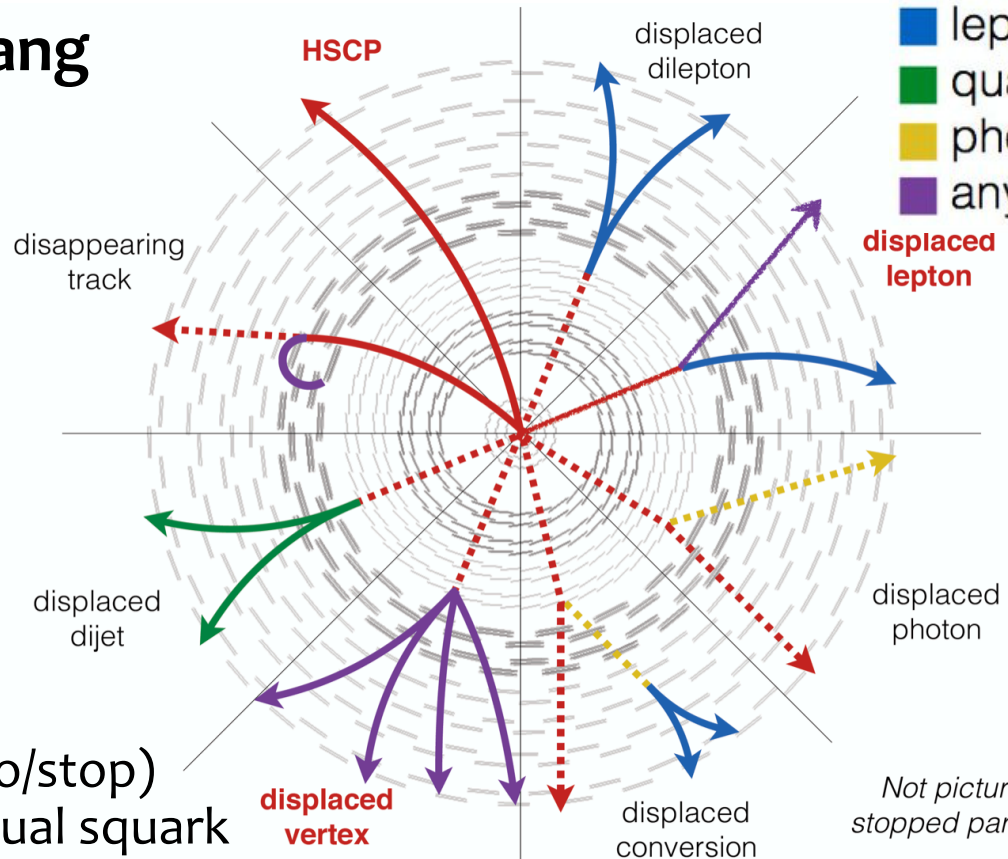




Secret life of Long-Lived Particles

- neutral
- charged
- BSM
- lepton
- quark
- photon
- anything

- **Dark Matter** can be a product of an **exotic LLP**
- **LLPs** can improve **big bang nucleosynthesis** model
- Various theoretical models predict **LLPs**:
 - **RPV SUSY** small couplings
 - **GMSB** small coupling to the lightest gravitino
 - **AMSB** small mass splitting
 - **Split SUSY** R-hadrons (gluino/stop) due to massive mediating virtual squark
 - **Hidden Valley** (sector), **Dark QCD** and more



Not pictured:
stopped particles

From J. Antonelli



Secret life of Long-Lived Particles

■ LLPs have non conventional final states

■ LLPs signature depend on the lifetime $c\tau$:

■ 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:

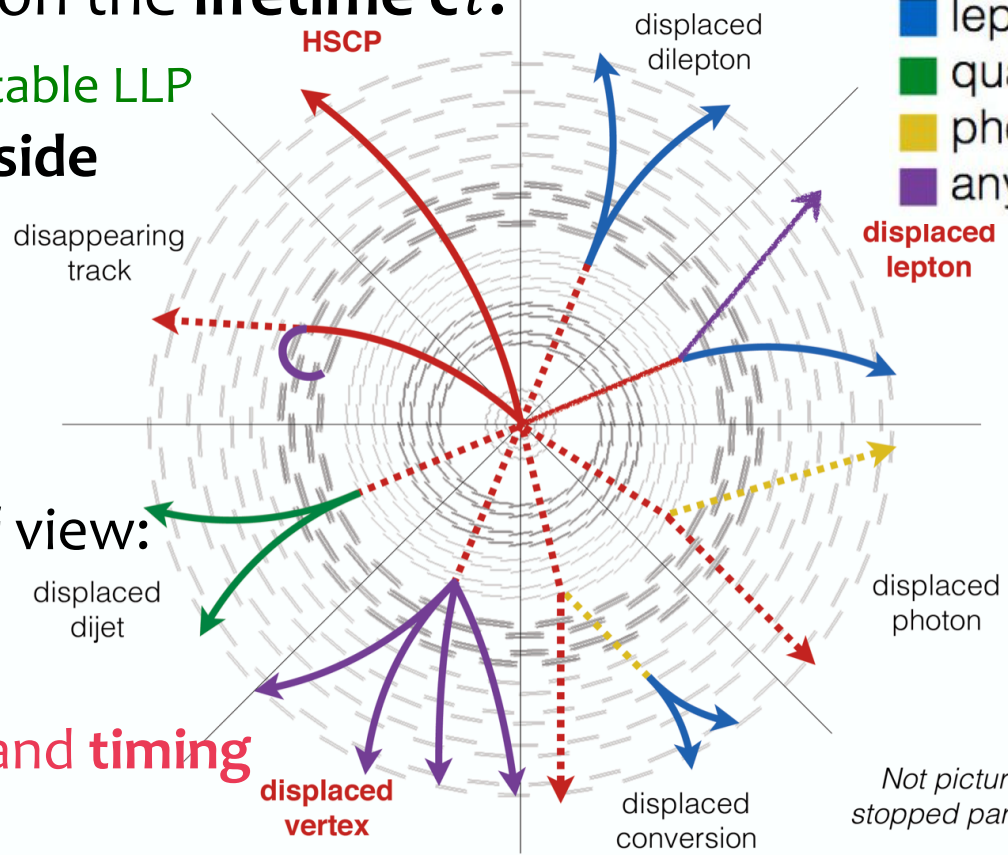
■ Often difficult triggering

■ Non-standard reco:

Displacements, ionization and timing

■ No much SM background, no such objects in SM, mostly detector noise, cosmic rays, reco failures – can be estimated from data

- neutral
- charged
- BSM
- lepton
- quark
- photon
- anything

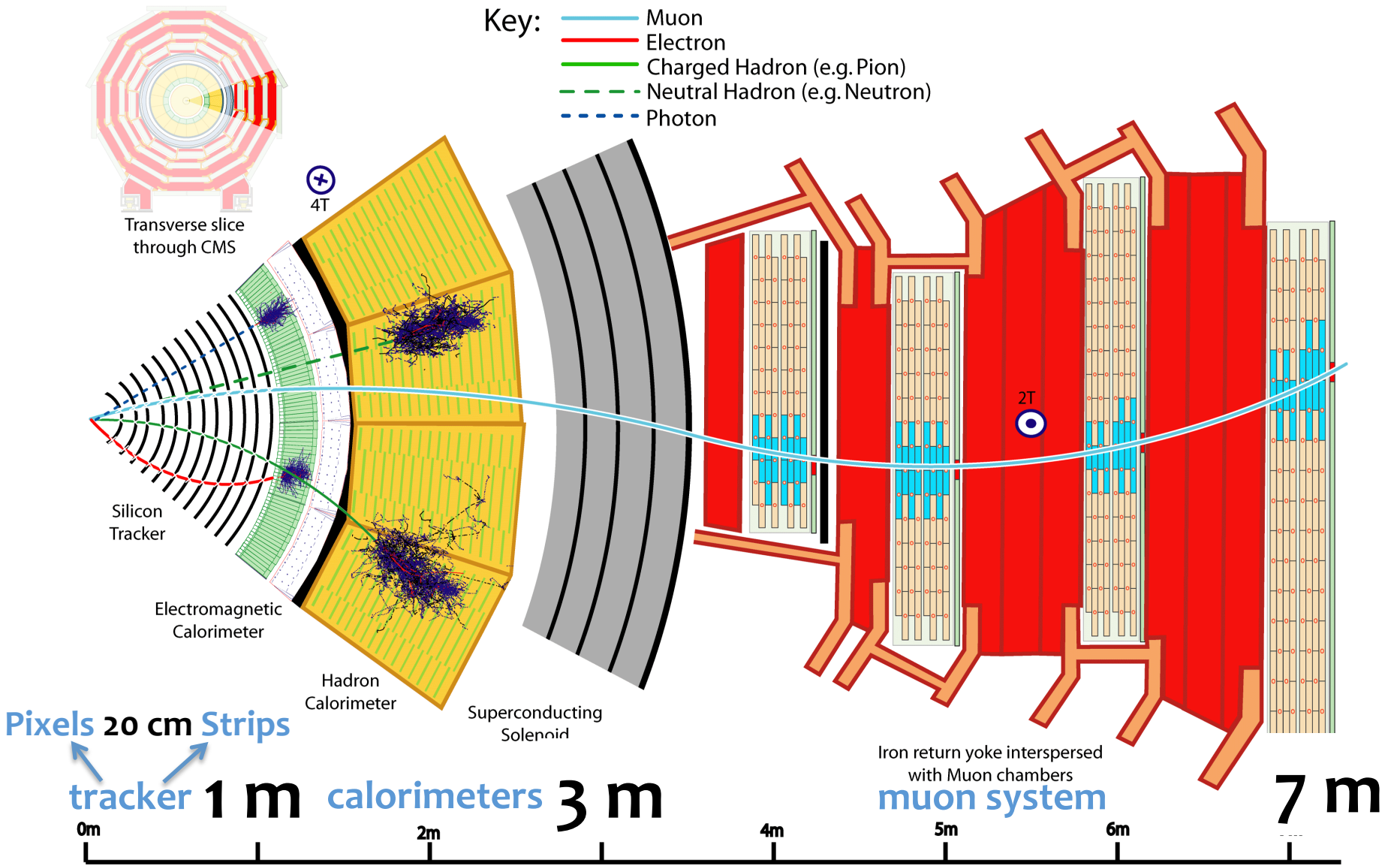


Not pictured: stopped particles

From J. Antonelli



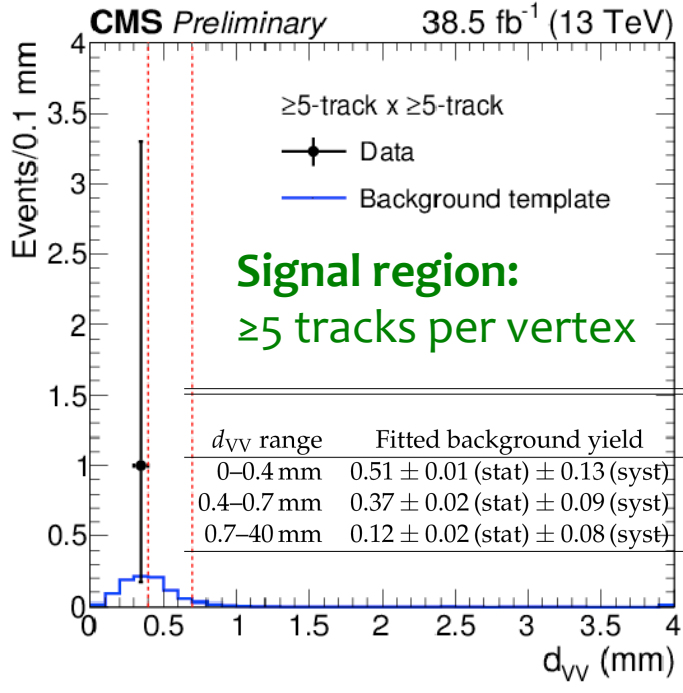
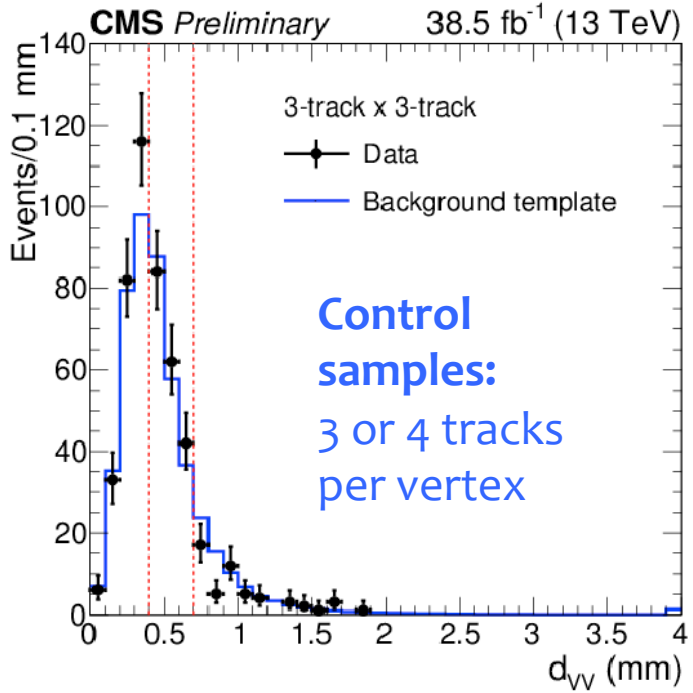
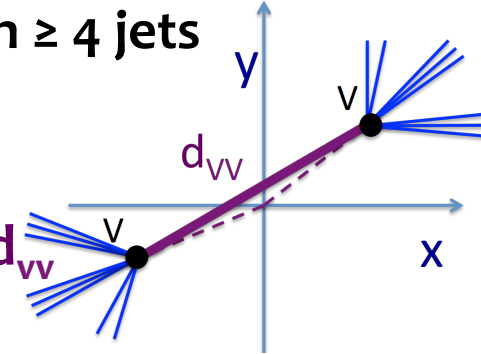
Regions of LLP decay/production in CMS





Displaced vertices in multijet events

- Pair produced long-lived **neutralinos/gluinos** or **stops** in **RPV SUSY**
- **Signature:** displaced vertices from tracks in a event with ≥ 4 jets
- **SM bkg:** vertices in SM prompt multijet events
- **Strategy:** (focus on $0.1 \text{ mm} < c\tau < 10 \text{ cm}$)
- Distinguish signal in **2-vertex events** with discriminate d_{VV}
- **Trigger:** $HT = \sum^{N_{\text{jets}}} E_T > 800 \text{ GeV}$



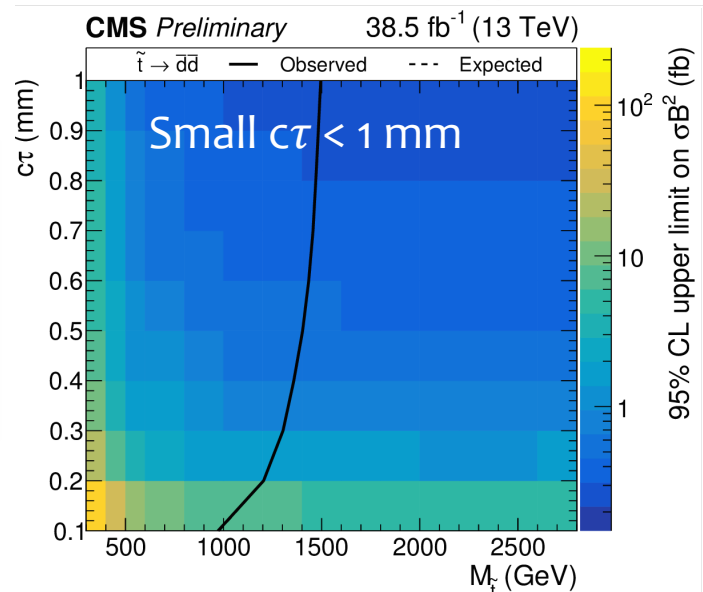
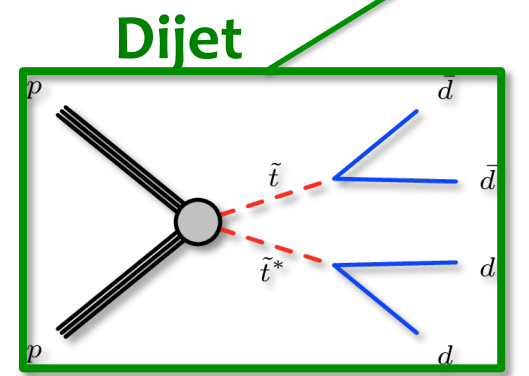
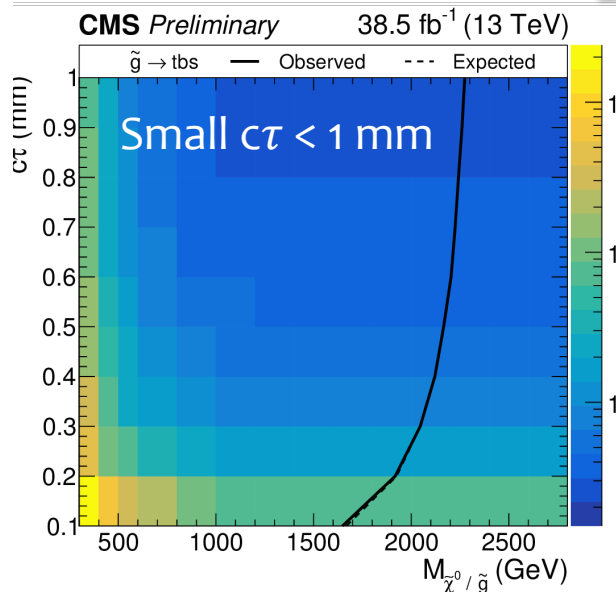
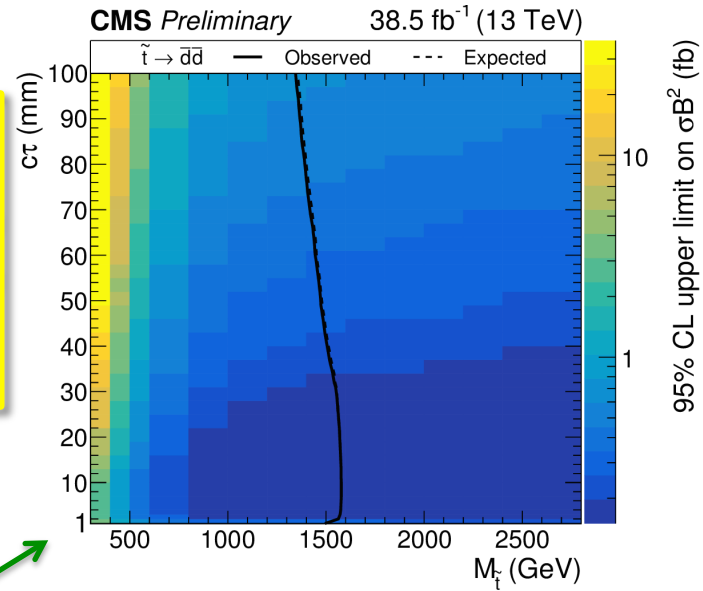
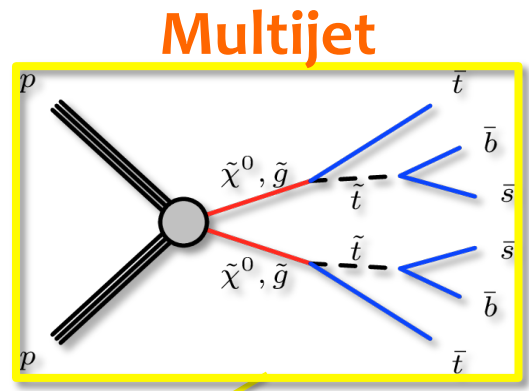
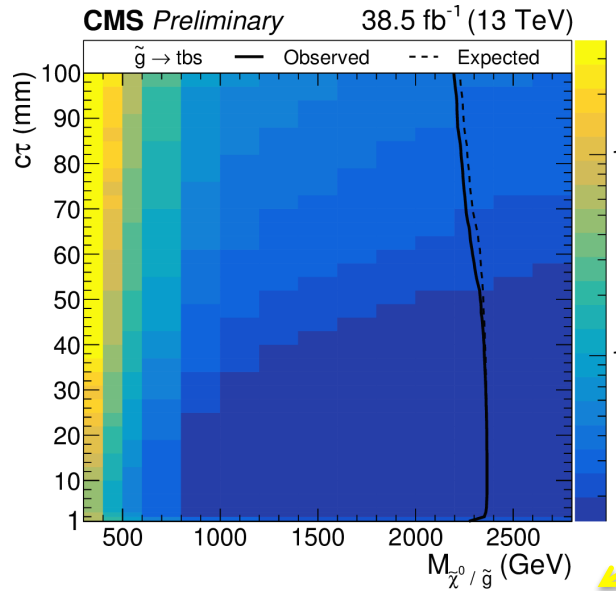
2015+2016: 38.5/fb

1 event observed
with $d_{VV} = 396 \mu\text{m}$

| Observed | Predicted signal yields | | |
|----------|-------------------------|---------------|---------------|
| | 0.3 mm | 1 mm | 10 mm |
| 1 | 2.8 ± 0.7 | 3.5 ± 0.8 | 1.0 ± 0.2 |
| 0 | 2.0 ± 0.5 | 3.7 ± 0.9 | 0.5 ± 0.1 |
| 0 | 1.1 ± 0.3 | 11 ± 3 | 31 ± 7 |



Displaced vertices in multijet events

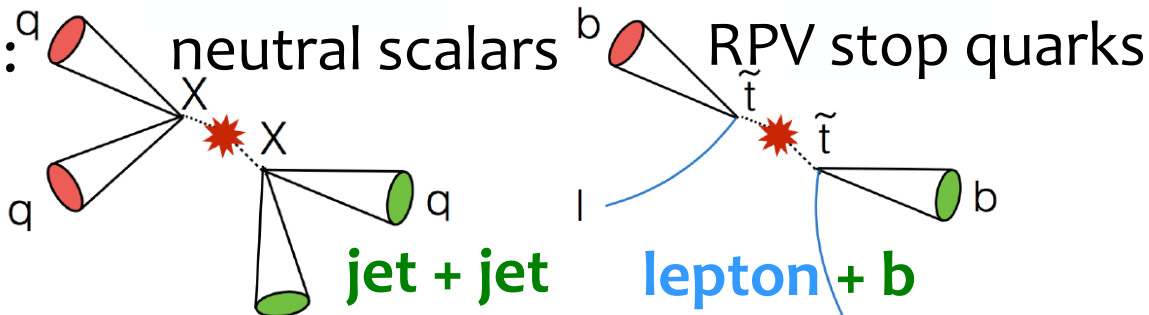


2015+2016: 38.5/fb

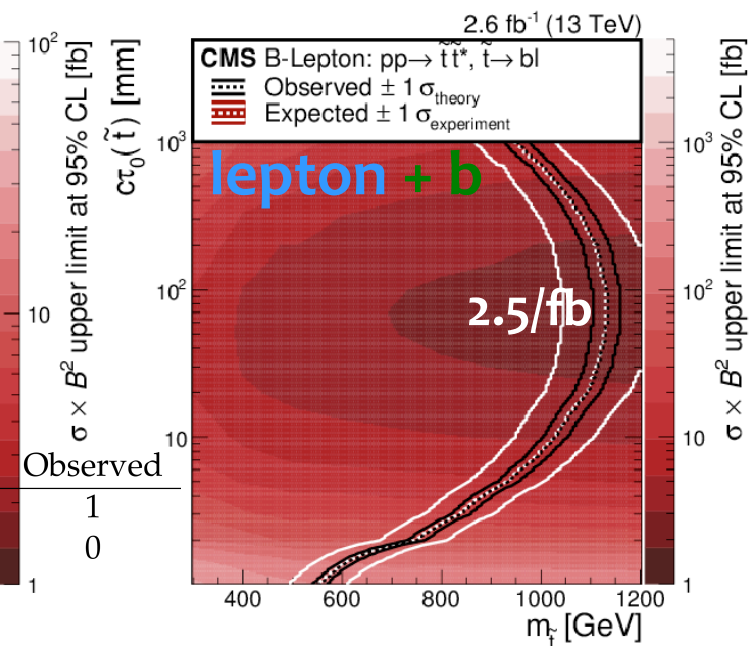
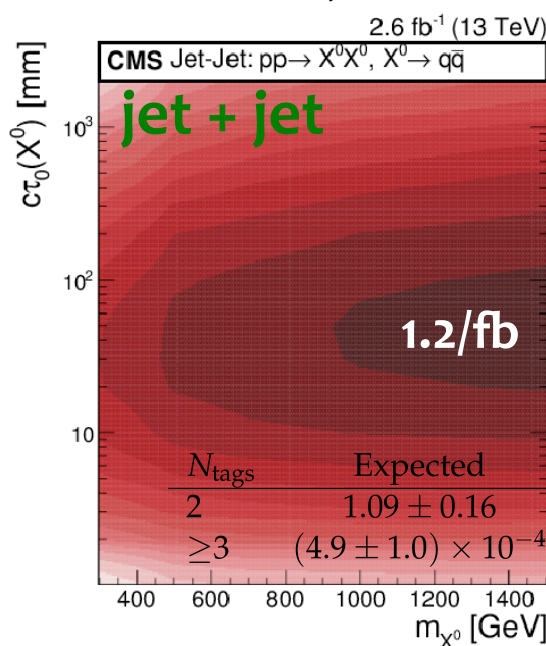
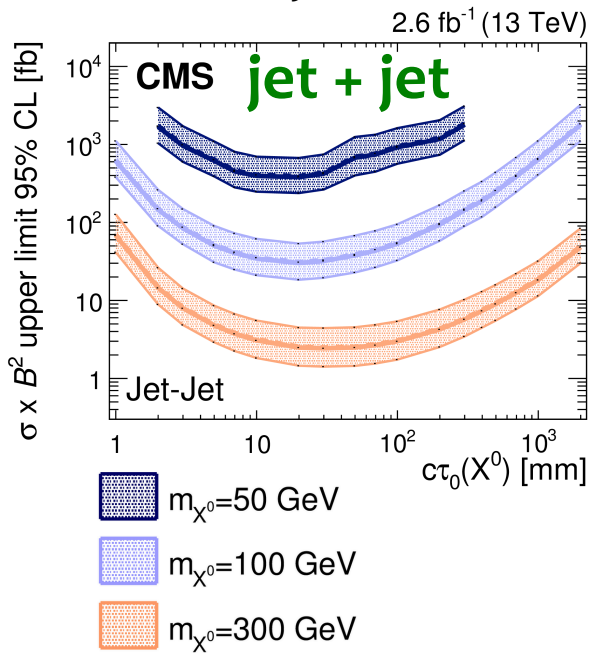


Inclusive displaced jets

- Pair produced long-lived: X decaying to jets and leptons which are displaced



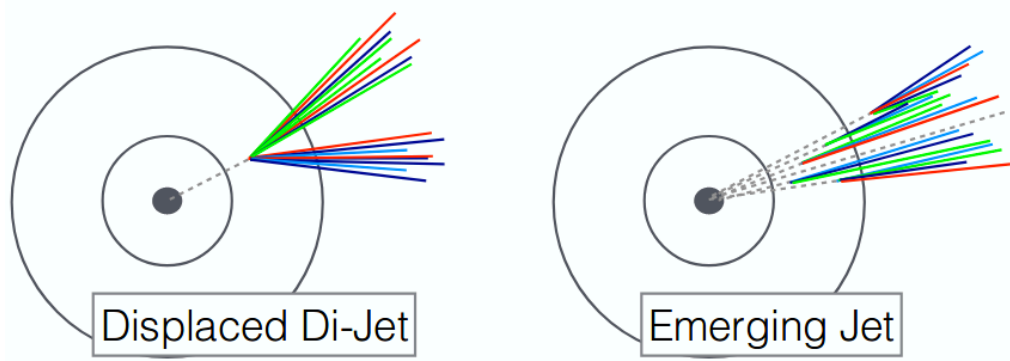
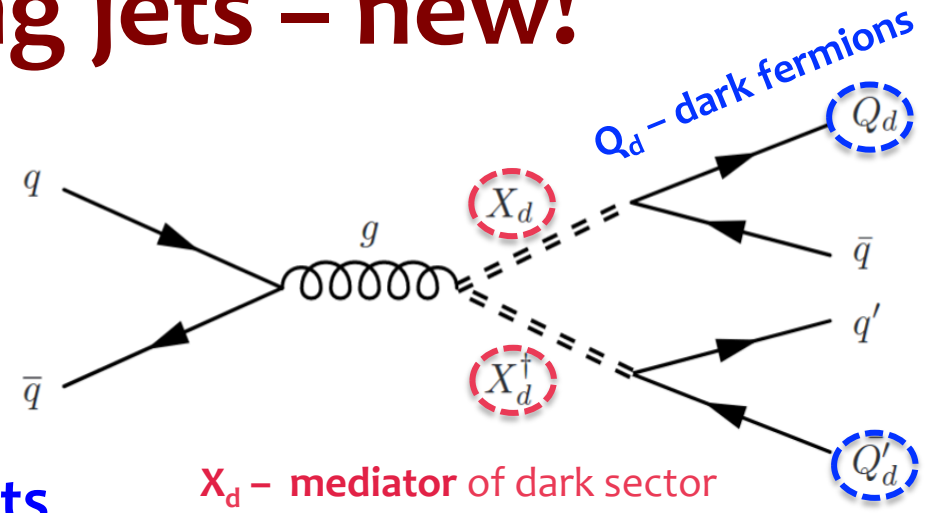
- Dedicated trigger** and offline algo for **jet displacement tagging** tag on primary vertex compatibility, displacement significance and emission angle
- Secondary vertex not required, but a single reconstructed track per decay inclusively for electrons, muon, taus and jets





Emerging jets – new!

- The **Dark QCD** model with
- Q_d – long-lived dark-pions, π_d which can decay to SM particles
- **Signal:**
2 prompt jets and **2 emerging jets**



Emerging jets are produced in the hadronization of Q_d to dark hadrons (π_d) 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_d} [GeV] | 400, 600, 800, 1000, 1250, 1500, 2000 |
| Dark pion mass m_{π_d} [GeV] | 1, 2, 5, 10 |
| Dark pion decay length τ_{π_d} [mm] | 1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000 |

focus on lifetimes of **1 mm < cτ < 1 m**
336 signal hypotheses

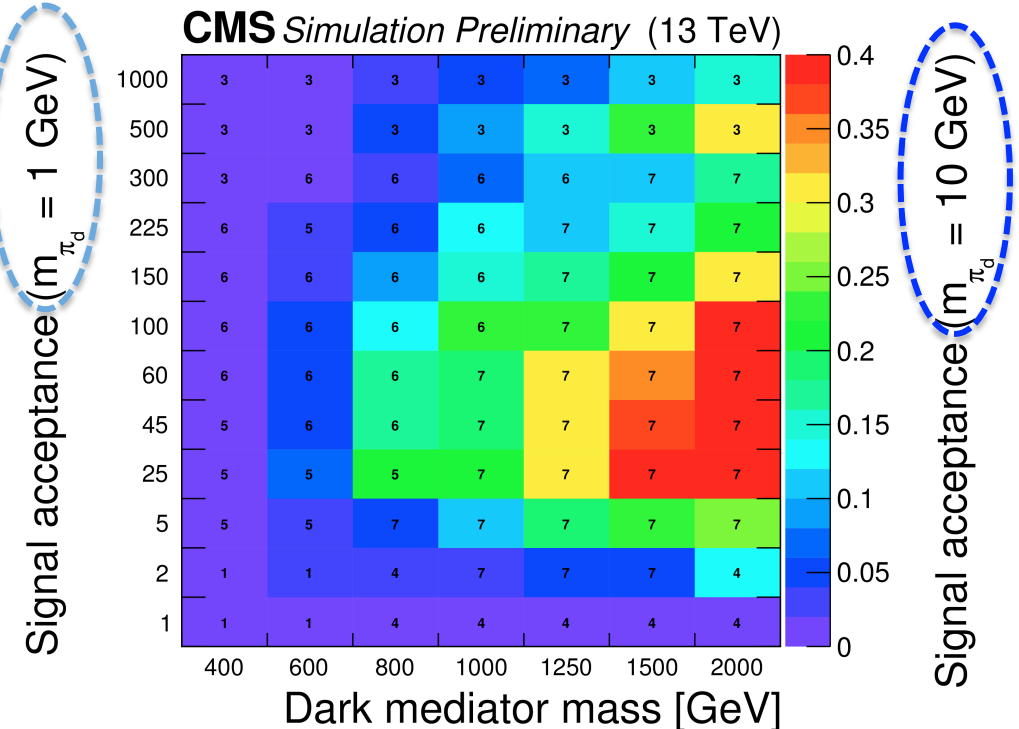
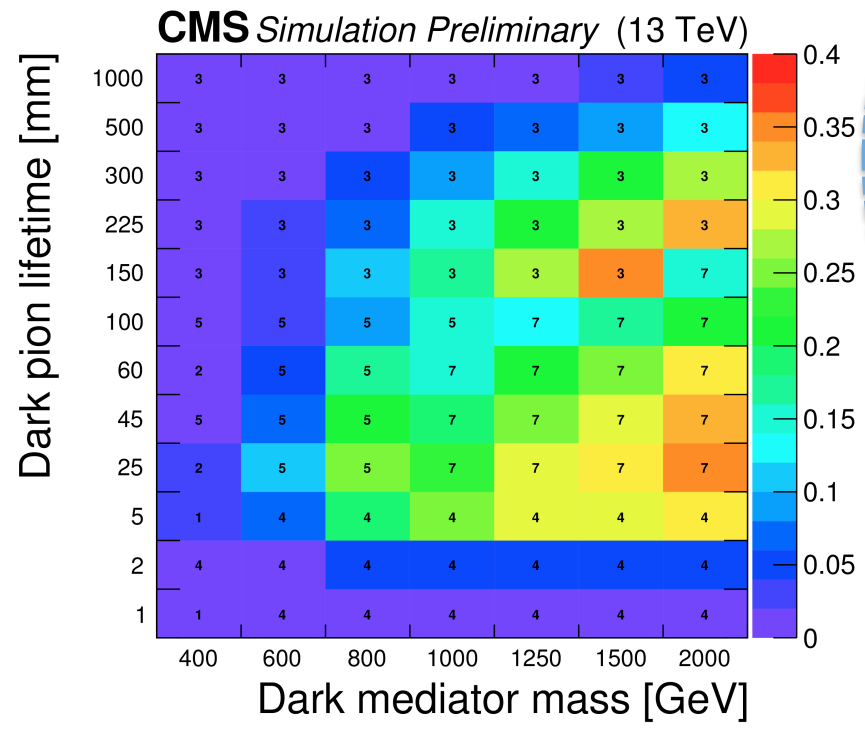


Emerging jets

- **Trigger:** $HT > 900$ GeV

Strategy:

- **Extension** of the displaced jet search and tagger to emerging jets
- **7 Different selections sets** (indicated by numbers below) are used with:
 - optimized kinematic cuts on HT, p_T of jets, MET
 - optimized emerging jet tag cuts



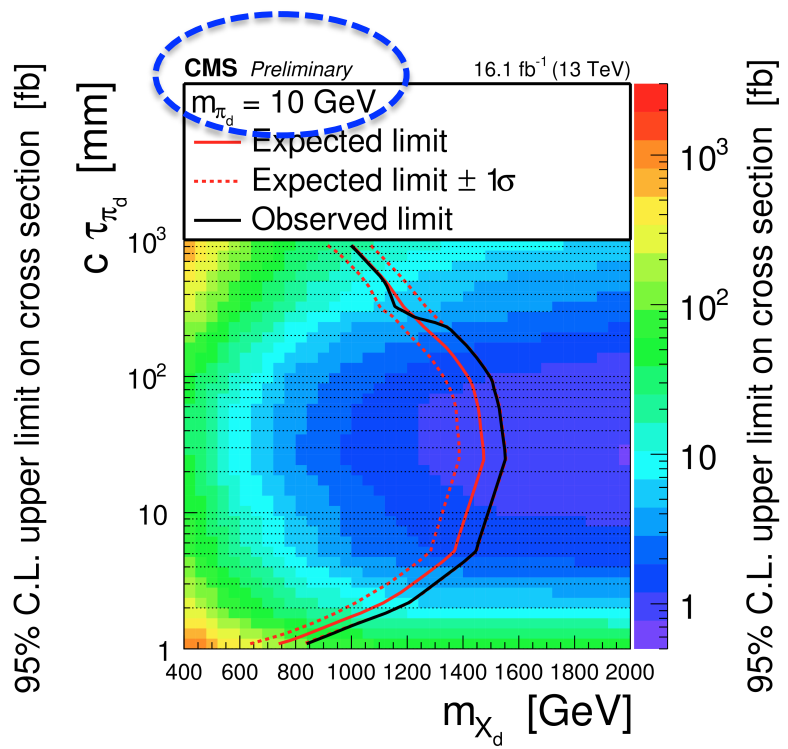
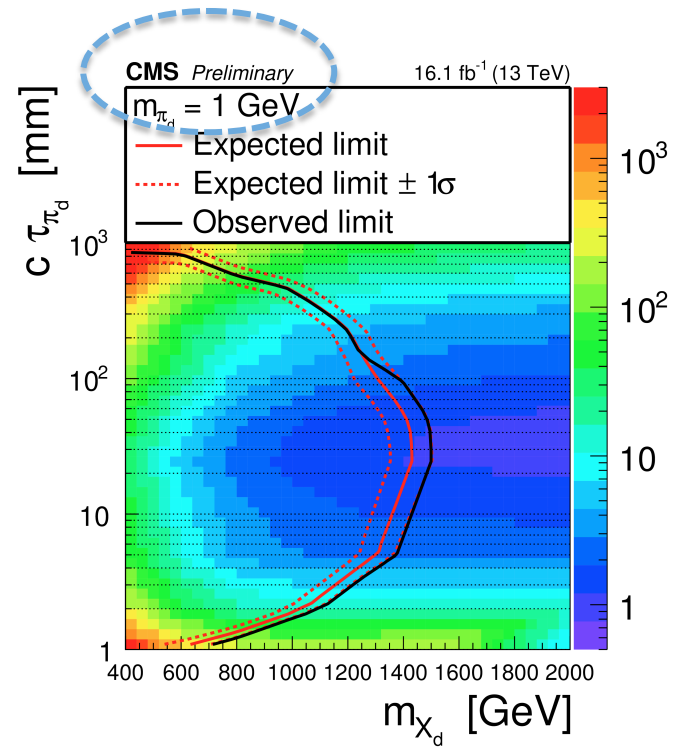


Emerging jets

Results:

- Observed events agree with background expectation in all 7 selection sets
- First Dark QCD limits from CMS!**

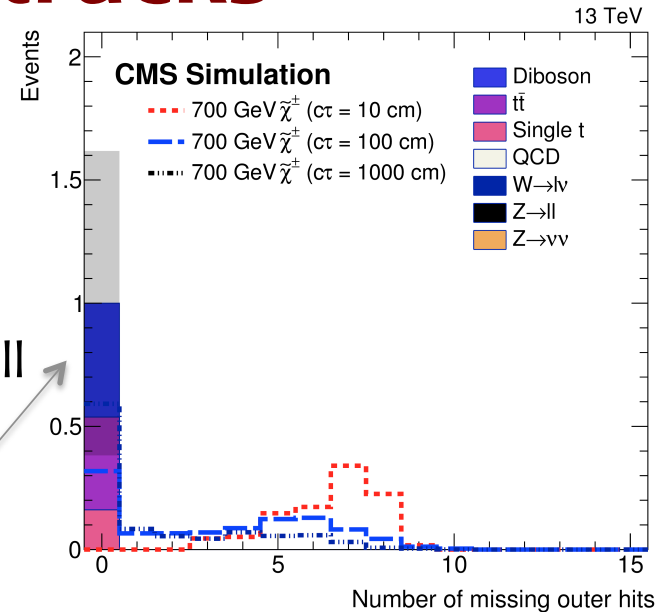
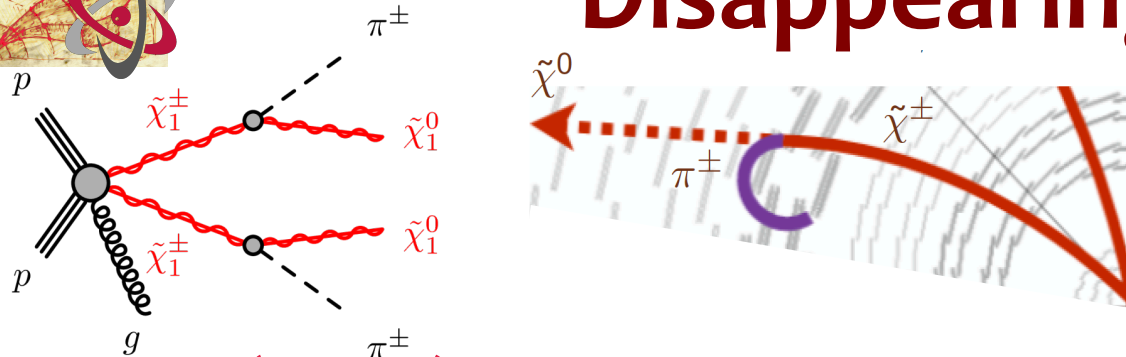
| | Set number | Expected | Observed |
|----------------|------------|--|----------|
| Signal Regions | 1 | 168 ± 15 (syst ₁) ± 5 (syst ₂) | 131 |
| | 2 | 31.8 ± 5.0 (syst ₁) ± 1.4 (syst ₂) | 47 |
| | 3 | 19.4 ± 7.0 (syst ₁) ± 5.5 (syst ₂) | 20 |
| | 4 | 22.5 ± 2.5 (syst ₁) ± 1.5 (syst ₂) | 16 |
| | 5 | 13.9 ± 1.9 (syst ₁) ± 0.6 (syst ₂) | 14 |
| | 6 | 9.4 ± 2.0 (syst ₁) ± 0.3 (syst ₂) | 11 |
| | 7 | 4.40 ± 0.84 (syst ₁) ± 0.28 (syst ₂) | 2 |



Weaker constraints for $c\tau \geq 10 \text{ cm}$ due more decays outside pixel tracker



Disappearing tracks



- **Signal (AMSB): Long-lived charginos** due to small mass splitting with the LSP neutralino

$$m_\pi < \Delta m \approx 200 \text{ MeV} \quad \Delta m = m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$$

→ Pions are too soft to be reconstructed

- **Signature of disappearing track:**

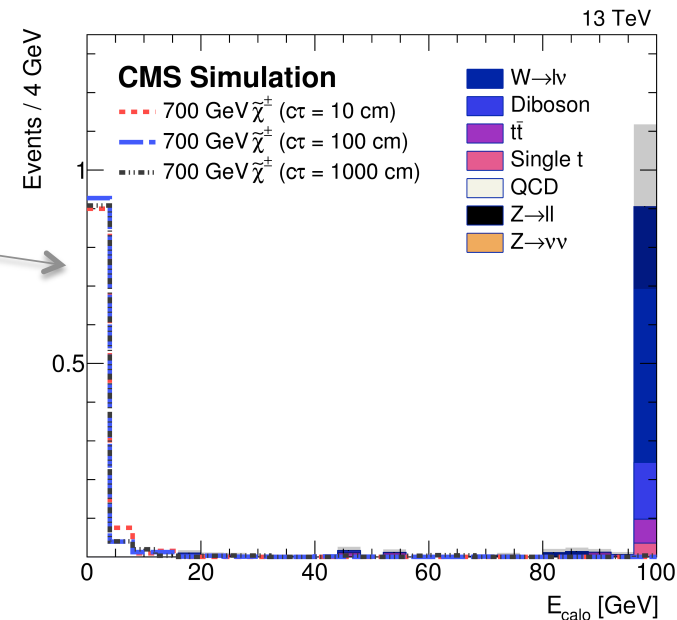
Isolated prompt track with:

- Missing hits in outer layers of tracker
- Small/no energy deposits in calorimeters
- No associated hits in the muon system

- **Trigger:** MET > 75 GeV + p_T -track > 50 GeV recoil against ISR jet

- **Background:**

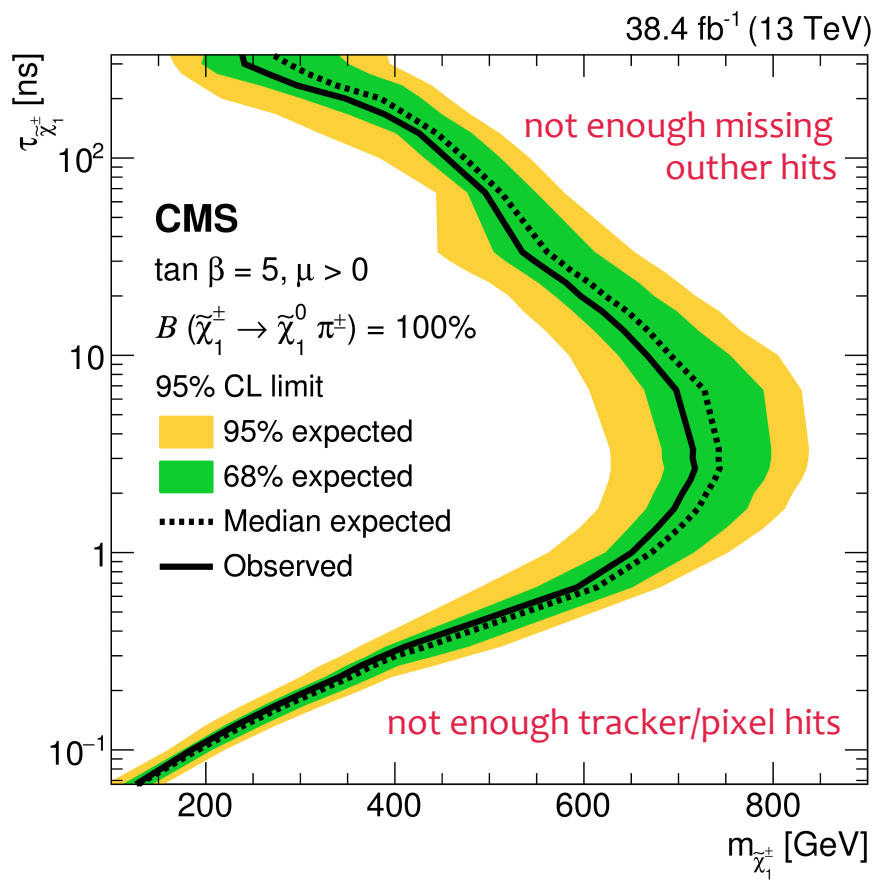
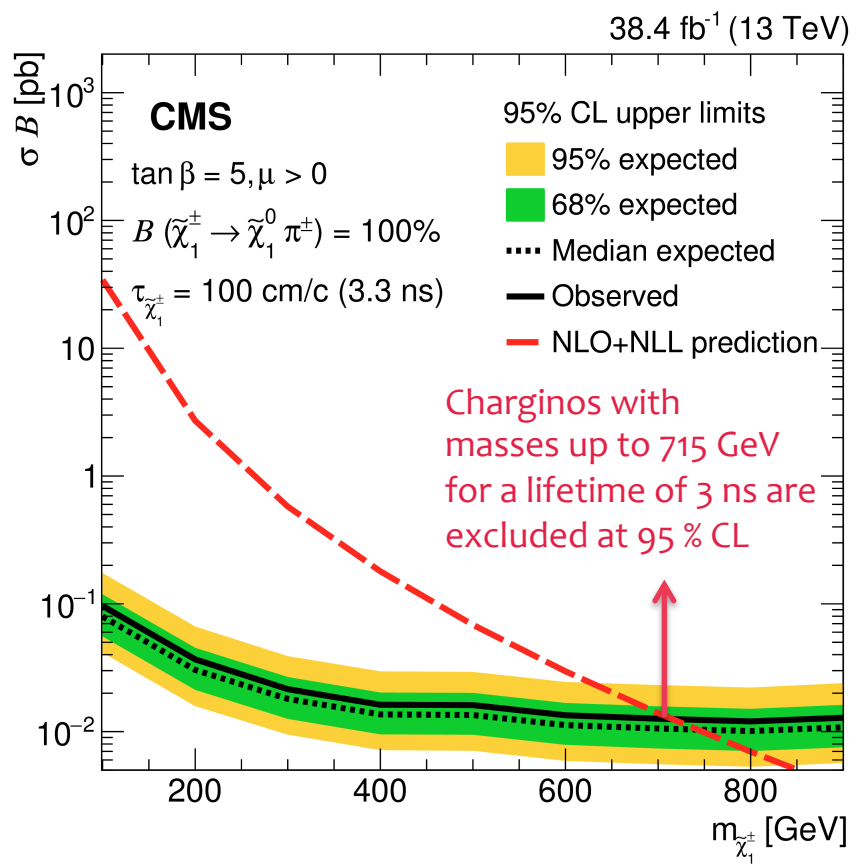
- Data-driven estimation for main backgrounds: fake tracks and charged leptons





Disappearing tracks

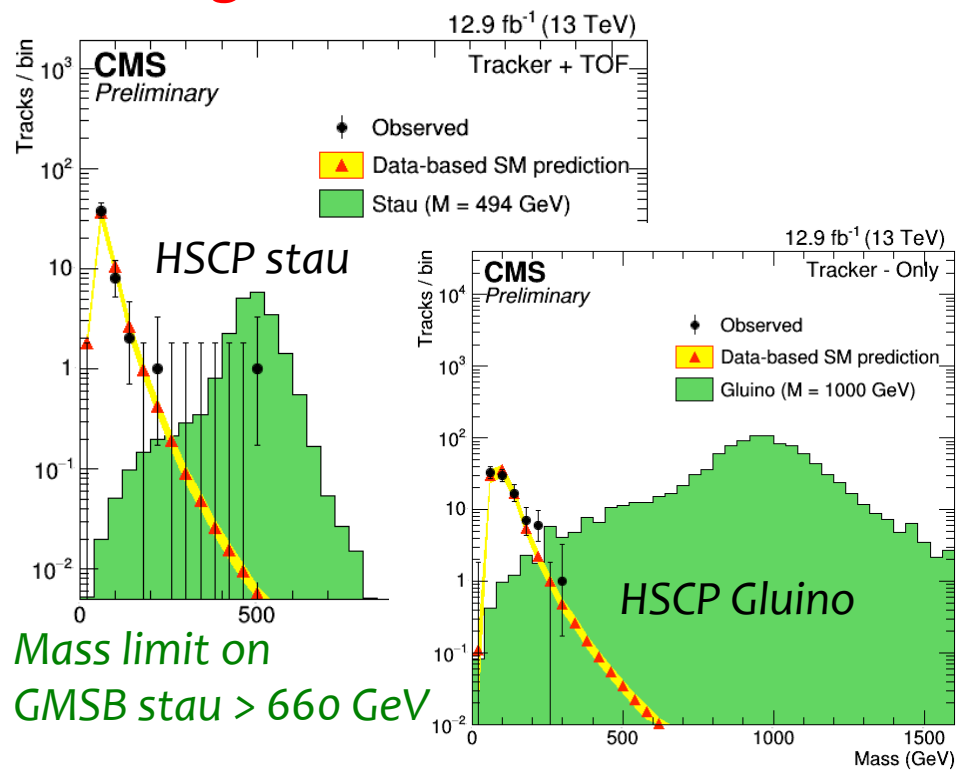
| Run period | Estimated number of background events | | | Observed events |
|------------|---------------------------------------|-----------------------|-----------------------|-----------------|
| | Leptons | Spurious tracks | Total | |
| 2015 | 0.1 ± 0.1 | $0_{-0}^{+0.1}$ | 0.1 ± 0.1 | 1 |
| 2016A | $2.0 \pm 0.4 \pm 0.1$ | $0.4 \pm 0.2 \pm 0.4$ | $2.4 \pm 0.5 \pm 0.4$ | 2 |
| 2016B | $3.1 \pm 0.6 \pm 0.2$ | $0.9 \pm 0.4 \pm 0.9$ | $4.0 \pm 0.7 \pm 0.9$ | 4 |
| Total | $5.2 \pm 0.8 \pm 0.3$ | $1.3 \pm 0.4 \pm 1.0$ | $6.5 \pm 0.9 \pm 1.0$ | 7 |



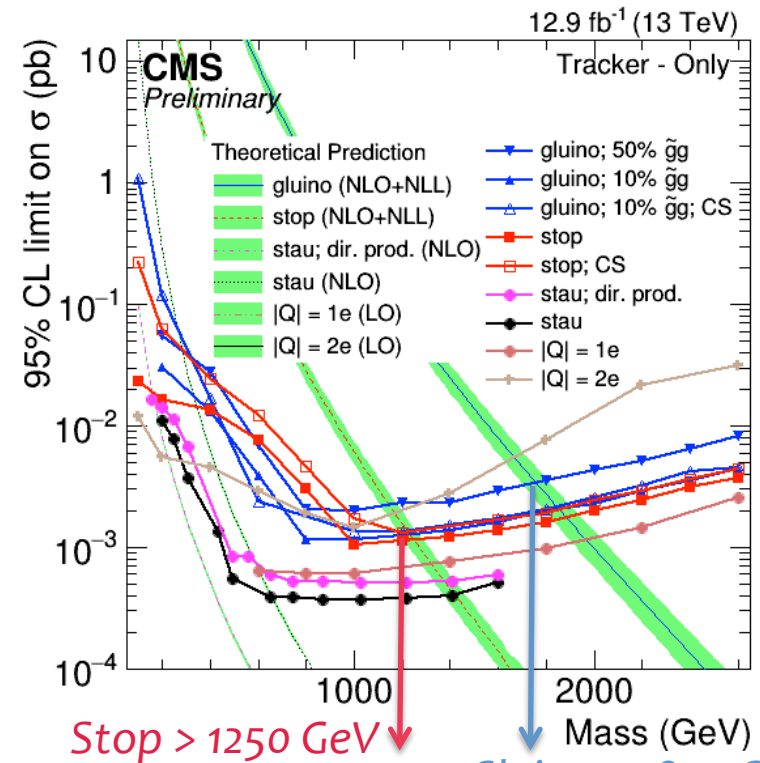


Heavy quasi-stable charged particles

- 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: $1/\beta$ measured)
→ mass measurement from dE/dx
- **Trigger:** MET (>170 GeV) or single muon ($p_T > 50$ GeV)
- **Background** estimated from data using p_T , dE/dx discriminator, $1/\beta$



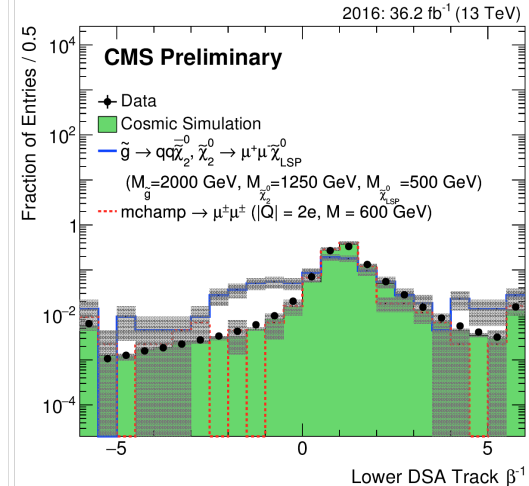
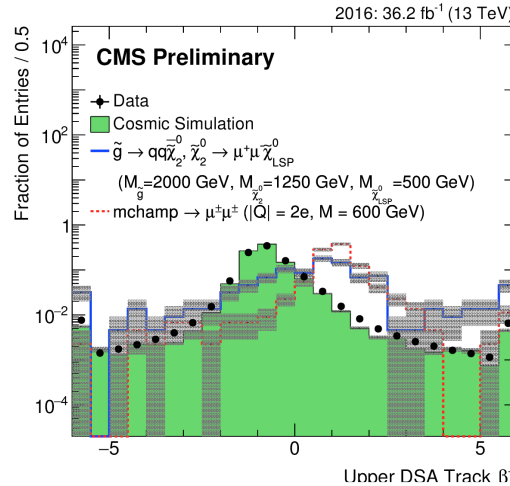
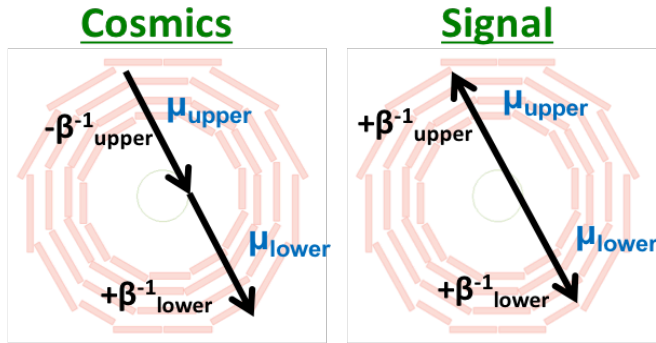
Mass limit on
GMSB stau > 660 GeV



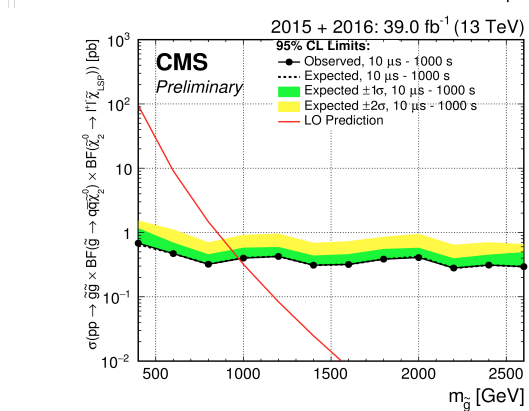
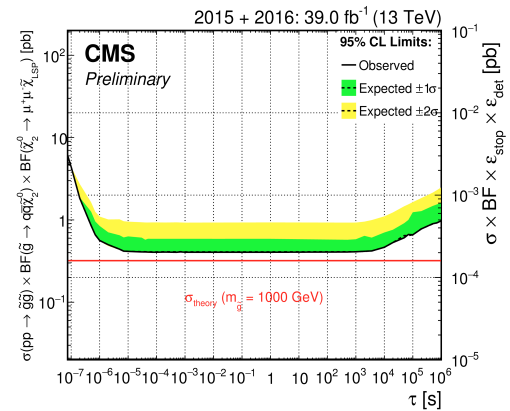


Stopped particles

- R-hadrons from Split SUSY (gluino or $|Q|=2e$) is stopped inside the detector and decay to muons or jets from rest after unknown time (sensitivity to lifetimes between $0.1 \mu\text{s}$ and 10^6s)
- Events recorded out-of-time with collisions with the custom trigger



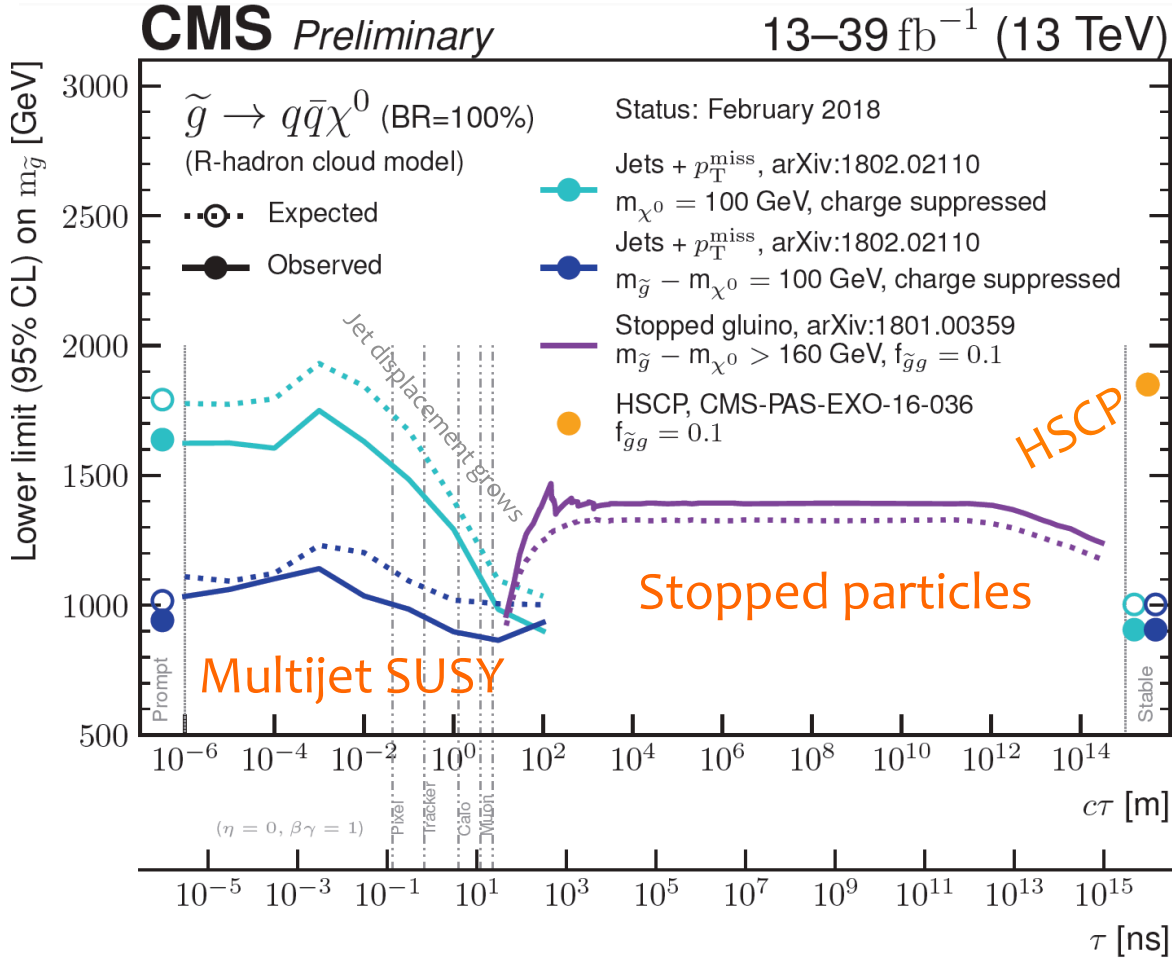
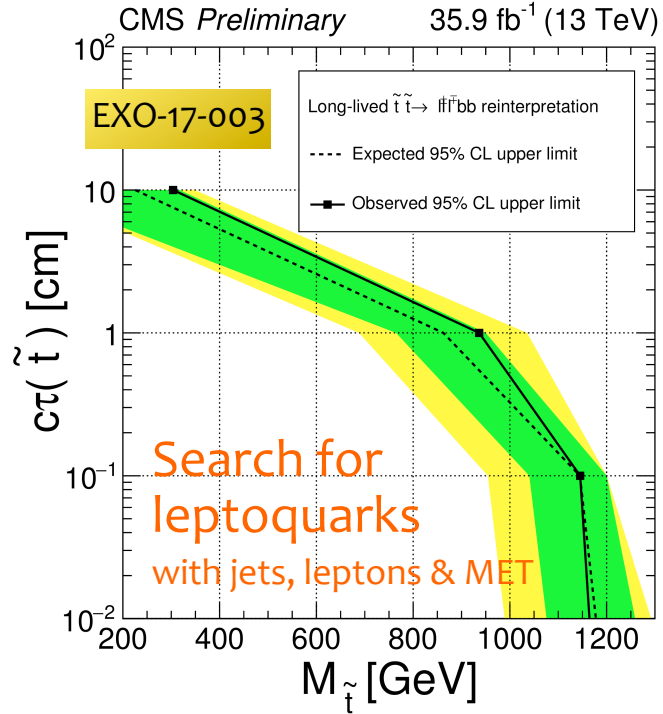
- No events observed
- 13 orders of magnitude of the lifetime tested
- Excluded gluinos with mass between 400 and 970 GeV, assuming 100% BF to muons





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
- Around $c\tau \sim 1$ cm, prompt searches relying on tracking start losing sensitivity





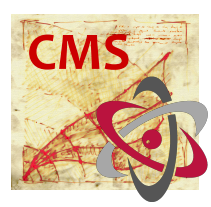
LLP at CMS summary

- **No LLP particle has been observed... yet**
- Any detected signal of LLP would be a clear indication of a new physics
- **CMS has an extensive search program** for different LLP in a model independent way
- **Improvements** on sensitivity to LLP is expected with
 - **Advanced techniques of reconstruction**
displacement, timing and ionization and triggering
 - **New topologies** to be included
 - **Complementary prompt searches**
 - Increasing luminosity – Run II dataset (**~150/fb** in total) soon
- **Future** HL-LHC phase, CMS upgrade to precision timing detector
 - Reject spurious secondary vertices and reduce beamspot uncertainty
 - Measure precisely photon time of flight in calorimeter
- 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

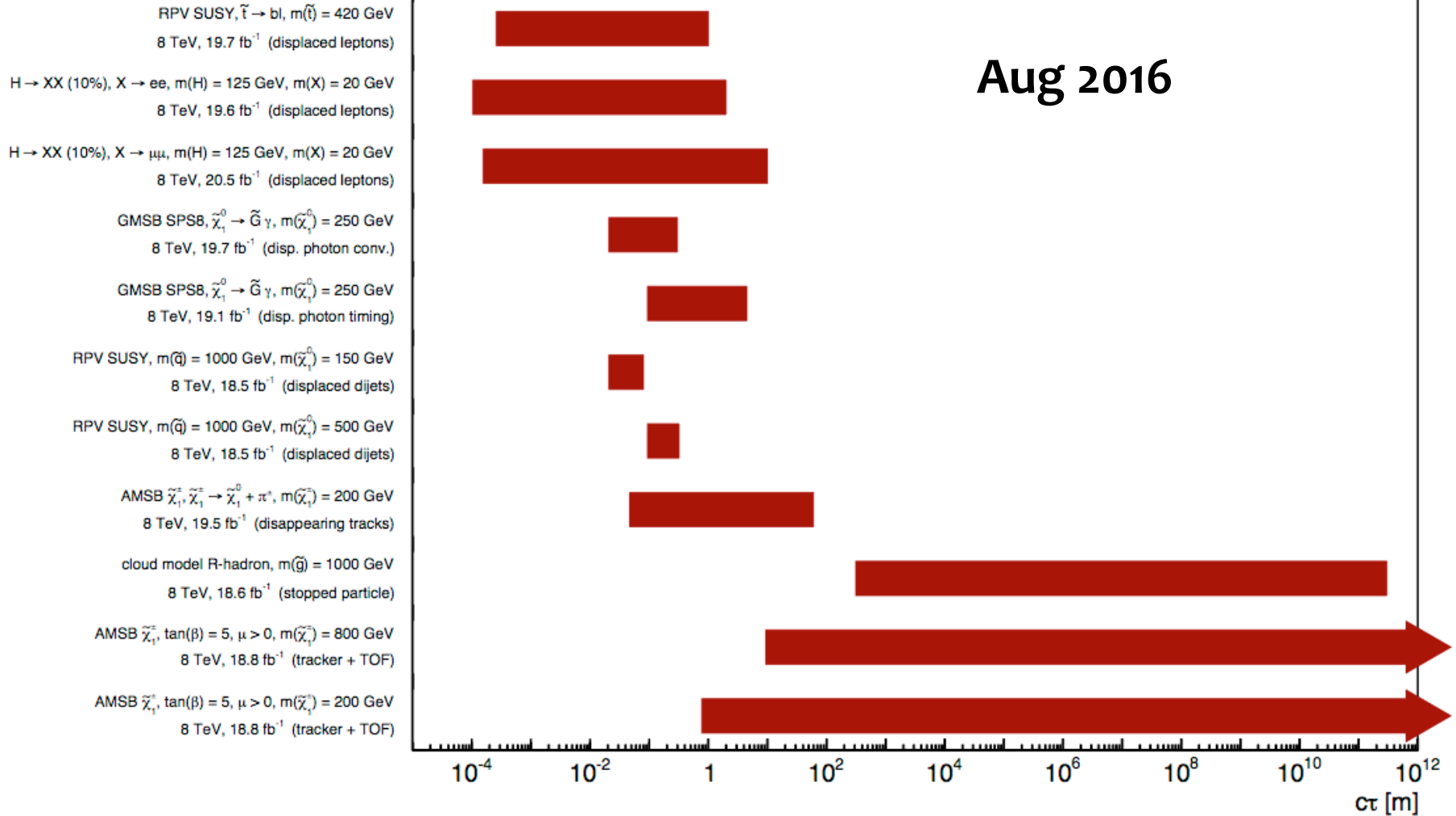


BACKUP



LLP limits

CMS long-lived particle searches, lifetime exclusions at 95% CL





LLP limits

LLP results not covered in this talk:

Displaced jet pairs:

[Phys. Rev. D 91 \(2015\) 012007](#)

Displaced photons with conversions:

[CMS-PAS-EXO-14-017](#)

Displaced photons with timing:

[CMS-PAS-EXO-12-035](#)

Fractionally charged particles:

[Phys. Rev. D 87 \(2013\) 092008](#)