# NON-CONVENTIONAL FINAL-STATES AT √ 8 TeV and 13 TEV

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ATLAS EXPERIMENT

CMS

# Outline

- Non-conventional-ism:
  - ✓ Definition
  - ✓ Search requirements
- Detailed results:
  - ✓ Metastable scenarios
  - ✓ Long-lived particles
- Summary

# Non-conventional-ism

Non-conventional final-state usually refers to unique detector signatures

- Mostly refers to physics beyond the standard model (BSM)
- Many scenarios include new particles with relatively long life-time, enabling direct measurements
- Final states can include BSM particles
- The new particle interactions with the detector can differ from interactions involving SM particles

• Massive new particles are expected to travel at low velocities ($\beta < 1$)

• If electrically charged, the new particle is expected to be highly ionizing

• Unusual decay products can be produced (L,B numbers violation, multiple jets, etc…)

# Searching for non-conventional final-states

Usually requires non-conventional analysis methods

- Detector-signature driven search
- Standard triggers are not designed for unusual objects
- Self-made object reconstructions is required
- Requires non-standard analysis strategies and tools
- Custom made MC simulations
- Background estimation is usually data driven

# Metastable-ness

## Metastable particles

- Considered as long-lived if their decay occurs inside the detector volume
- The decay location is usually unknown and hence a range of lifetimes will be studied
- In most cases the background sources are cavern/instrumental noise and badly reconstructed objects

## Considered models:

- $\tilde{g}, \tilde{t}$ or $\tilde{b}$ forming R-hadron states together with light SM quarks:
- ✓ Within SplitSUSY - decaying either in the calorimeter or in the Muon system
- ✓ Stopped $\tilde{g}$ - stop within the calorimeter and then decay after a while to $\tilde{\chi}_1^0$+ hadronic jet ($g$ or $\bar{q}q$)
- Disappearing tracks - $\tilde{\chi}_1^{\pm}$ within AMSB model decaying to $\tilde{\chi}_1^0\pi^{\pm}$
- Displaced vertices:
- ✓ Hidden Valley predictions of exotic particles: H/Z decaying to multiple-jets
- ✓ RPV or Stealth SUSY scenarios of either $\tilde{\chi}_1^0$ or $\tilde{g}$ decays
- Prompt and non-prompt Dark photons $\gamma_D$ decays to lepton-jets (LJs)

# ATLAS: Metastable heavy charged particles - 13 TeV

NEW

## Features & search strategy:

The LLP will hadronize together with SM light colored particles into an **R-hadron** bound state

- Massive
- Slow ($\beta < 1$)
- Large ionization ($\frac{dE}{dx} > \frac{dE}{dx}_{MIP}$)

– Mass estimated from $\frac{dE}{dx}$ $(\beta\gamma)$ and $p$ Pixel measurements

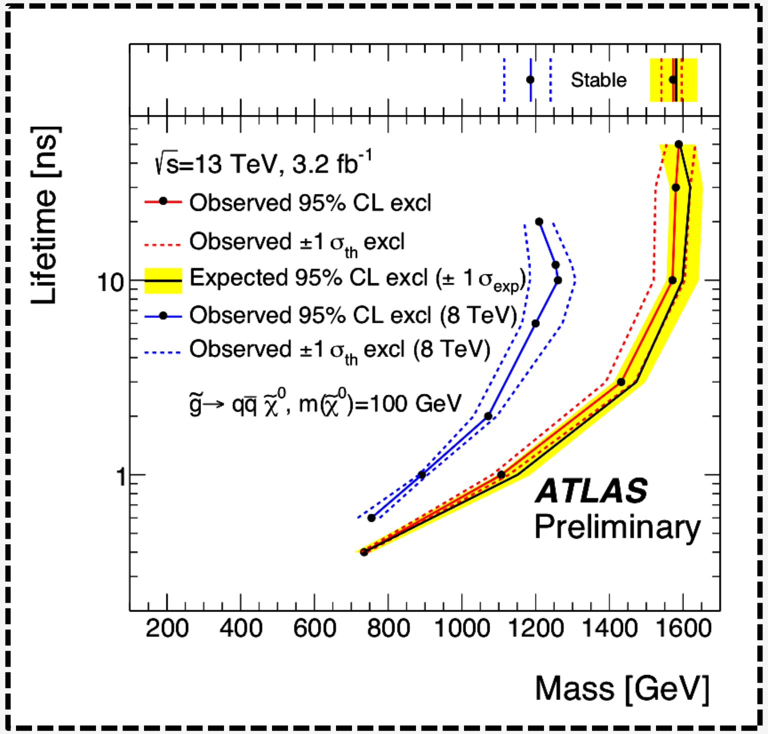
– Background source: badly reconstructed or mis-measured objects

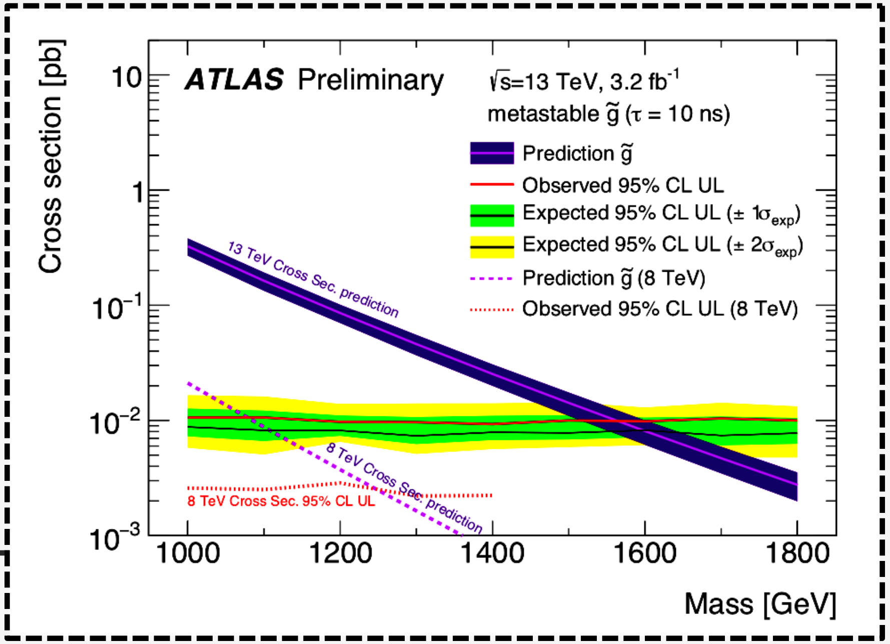
– Background estimation based on control data samples and a randomly generated data sample

## SplitSUSY

- $\tilde{q}$ above the TeV scale
- $\tilde{g}$ as the NSLP
- $\tilde{\chi}_1^0$ as the LSP

– Life-time depend on $\Delta m_{\tilde{g}-\tilde{\chi}_1^0}$



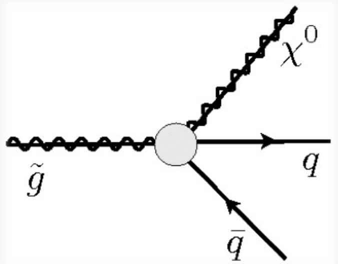

## Limits

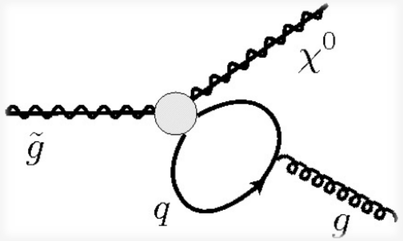
$\tilde{g}$ masses with lifetime $\geq$ 10 ns are excluded at 95% CL up to 1580 GeV

*stable $\tilde{g}$ R-hadron scenarios were considered as well, where $\tilde{g}$ masses up to 1570 GeV are excluded at 95% CL

ATLAS SUSY-2016-03-01
Submitted to Phys. Rev. D

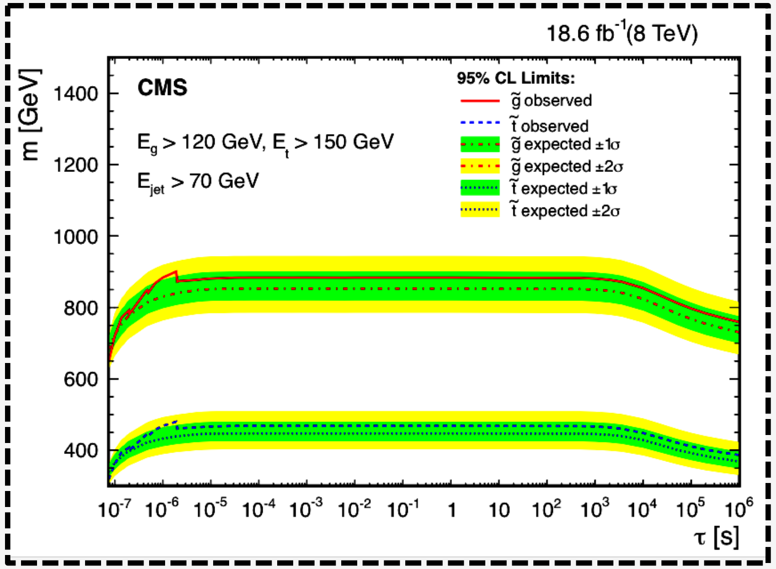
# Stopped $\tilde{g}$ R-hadrons



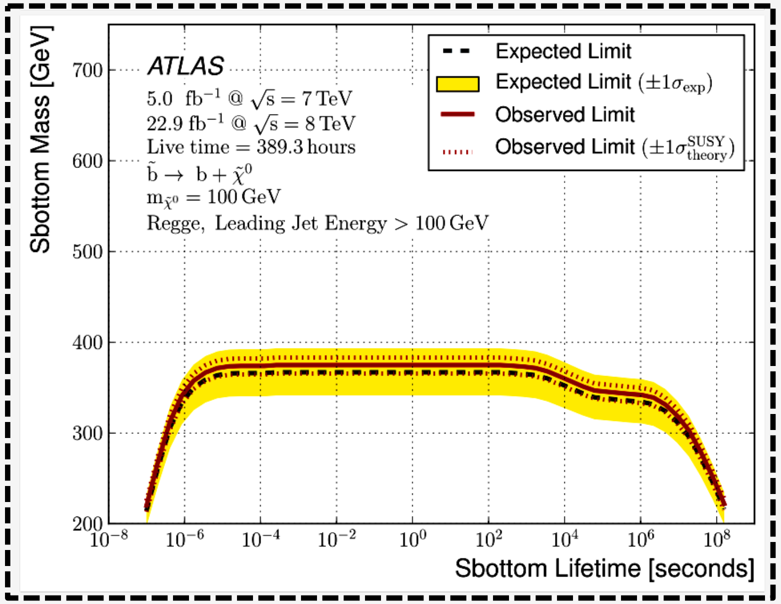

## SplitSUSY

- $\tilde{q}$ above the TeV scale
- $\tilde{g}$ as the NSLP
- $\tilde{\chi}_1^0$ as the LSP
- Life-time depends on $\Delta m_{\tilde{g}-\tilde{\chi}_1^0}$
- Simplified models with either $\tilde{t}$ or $\tilde{b}$ as LLP




## Features & search strategy

- The LLP will hadronize together with SM light colored particles into a R-hadron bound state
- A fraction of the R-hadrons lose all of their momentum and come to rest within the calorimeter ($\beta \leq 0.45c$)
- Search for calorimeter activity during empty collision bunch-crossings (BC) time windows
- Background sources: collision remnants, beam halo, cosmic rays, instrumental noise
- Background estimation using control data samples for the different sources at unpaired & empty collision BC periods




## Limits

Lower limits at 95% CL as a function of LLP life-time between 1 $\mu s$**-1000s:

$m_{\tilde{g}} < 1000$ GeV *

$m_{\tilde{t}} < 525$ GeV *

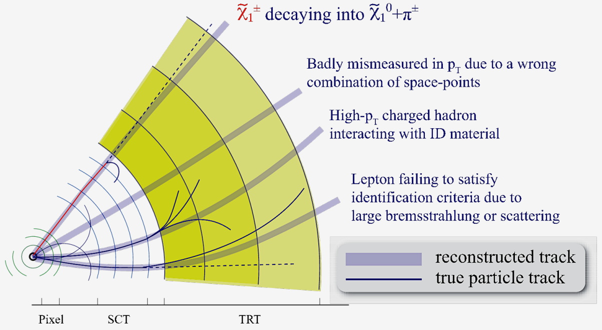
$m_{\tilde{b}} < 344$ GeV

* Increased leading jet energy

** 10 $\mu s$ in the $\tilde{b}$ case

ATLAS arXiv:1310.6584
CMS arXiv:1501.05603

# Disappearing tracks



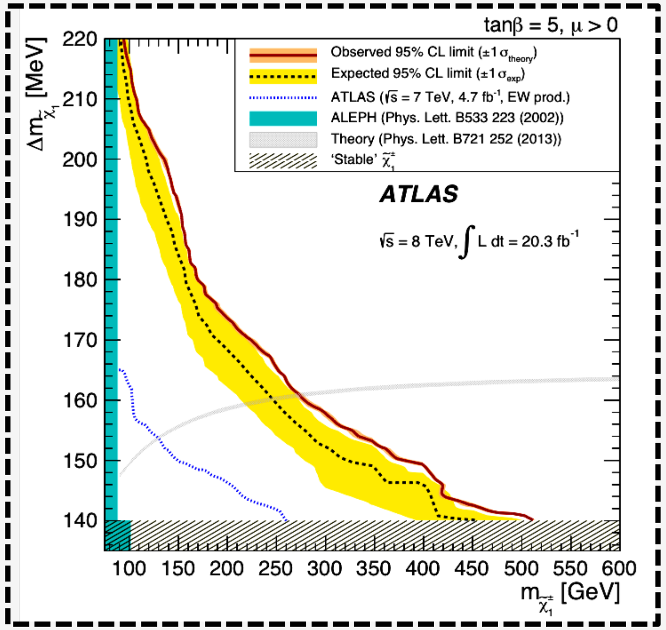

## Search strategy

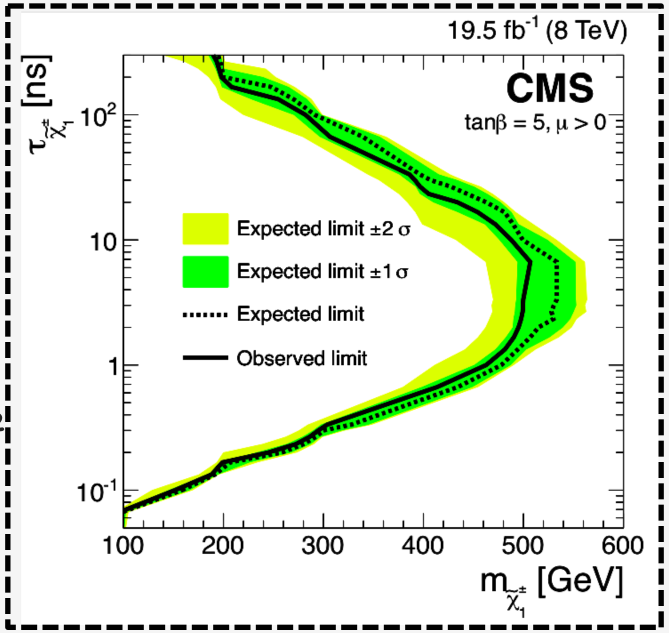
- Charged particle decaying in the tracker
- Detector signature of isolated track with:
  - No hits in the muon detector
  - Little or no calorimeter energy deposits
  - Missing hits in the outer layer of the tracker
- High-$p_T$ ISR jets and $E_T^{miss}$ recoiling against the LLP track
- Background sources:
  - Charged hadrons interacting with the ID material
  - Prompt $e/\mu$ failing identification criteria
  - Fake tracks
- Background estimation based on control data samples for each source and simulation in order to determine the identification inefficiency

ATLAS arXiv:1310.3675
CMS arXiv:1411.6006

## AMSB:

- $\tilde{\chi}_1^0$ as the LSP
- $\tilde{\chi}_1^{\pm}$ as the NLSP
- The typical $\Delta m_{\tilde{\chi}_1^{\pm}-\tilde{\chi}_1^0}$ allows for considerable $\tilde{\chi}_1^{\pm}$ life-time
- $\tilde{\chi}_1^{\pm}$ eventually will decay to $\tilde{\chi}_1^0\pi^{\pm}$
- $\pi^{\pm}$ with too small $p$ to be reconstructed



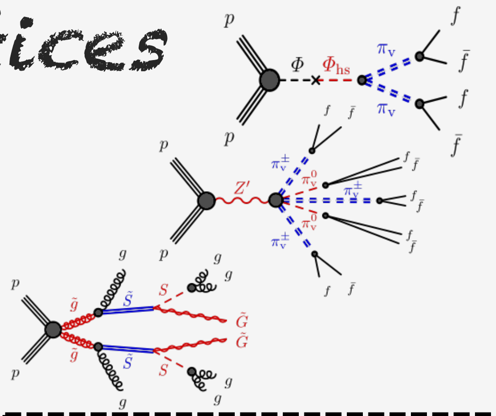



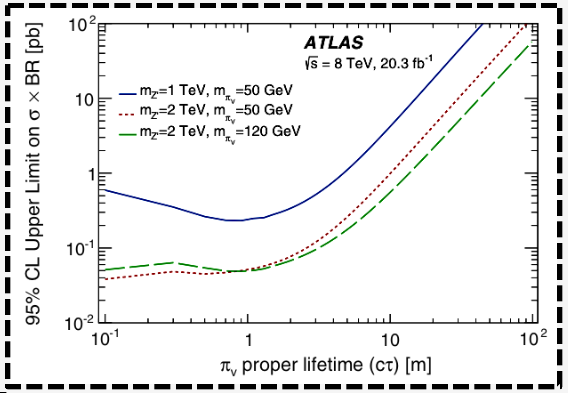

## Limits

At 95% CL excluded masses of:

- AMSB: $m_{\tilde{\chi}_1^{\pm}}$<270 GeV with 0.2 nsec life-time resulted from $\Delta m_{\tilde{\chi}_1^{\pm}-\tilde{\chi}_1^0}$~160 MeV
- DY: $m_{\tilde{\chi}_1^{\pm}}$<505 GeV with 7 nsec life-time

# Displaced vertices



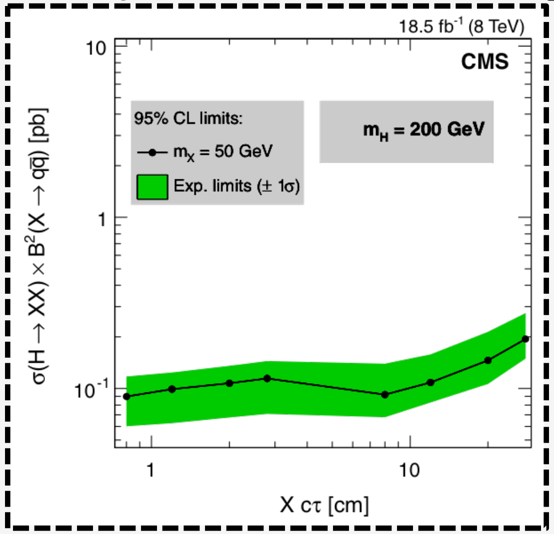


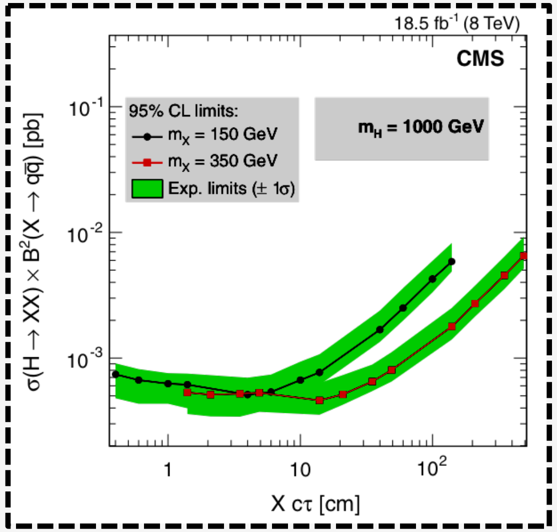

**Hidden-Valley scenarios:**

- BSM H scalar boson decaying to two neutral LLPs X, each decaying into dijet
- Heavy Z′ boson decaying to two neutral LLPs X′, each decaying into hadronic jets

**SUSY scenarios:**

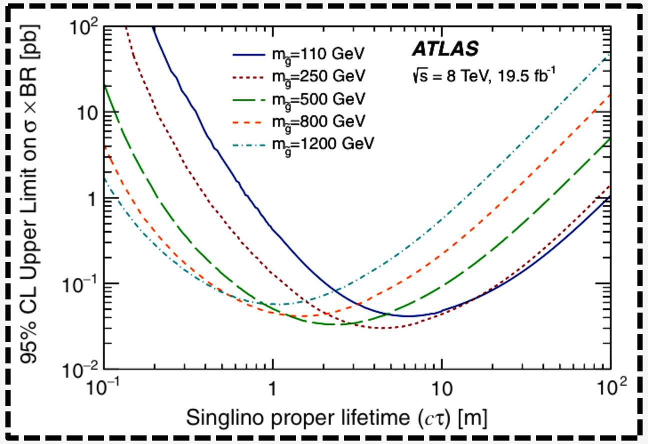
- RPV model of $\tilde{q}$ production decaying into $\tilde{\chi}_1^0$ and then to $q\bar{q}\mu$
- Stealth / Split SUSY predicting production of $\tilde{g}/\tilde{q}$ decaying into $\tilde{G}$+ dijet




**Search strategy**

- Long-lived particles decaying to jets in either the tracker (ID) or Muon (MS) detector stations
- Two secondary (displaced) vertices, located significantly far from the interaction-point in either or both detector stations
- Background source:
  - Jets with high track multiplicity in the ID
  - Cavern background and cosmic rays in the MS
- Data driven methods used for estimation



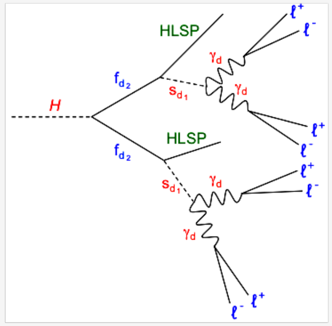

**Limits**

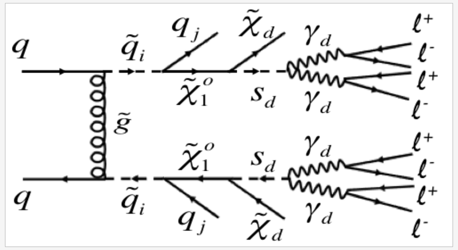
95% CL upper limits on the production Xsec vs decay length:

- $XSec_H$: 0.5-200 fb at decay length of 0.4-200 cm
- $XSec_{\tilde{\chi}_1^0}$: 0.5-3 fb at decay length 2-40 cm

Observed 95% CL limits on σ×BR for Z′ and Stealth SUSY are presented as a function of the particle decay length

ATLAS arXiv:1504.05162,03634
CMS arXiv:1411.6530

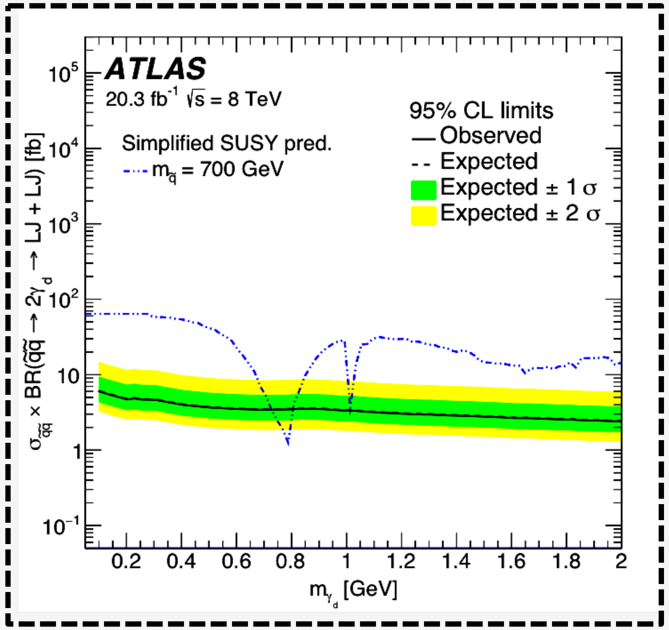




# Lepton-jets

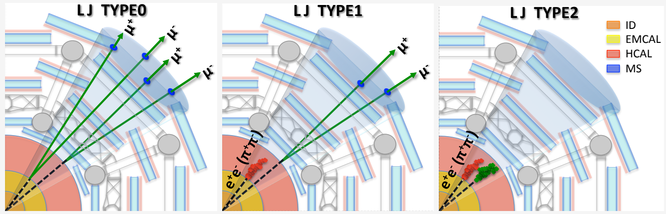
## Dark photon $\gamma_D$

- Light hidden photon $\gamma_D$ mixed kinetically with SM photon
- Expected small mass and hence produced boosted and long-lived
- At its lightest state the $\gamma_D$ will decay to SM particles
- Considered scenarios:
  - Non-SM H decays to hidden fermions $f_D$ / scalars $S_D$ decaying to $\gamma_D$
  - SUSY-portal: $\tilde{q}$ decaying to $\tilde{\chi}_1^0 \to \tilde{\chi}_D$

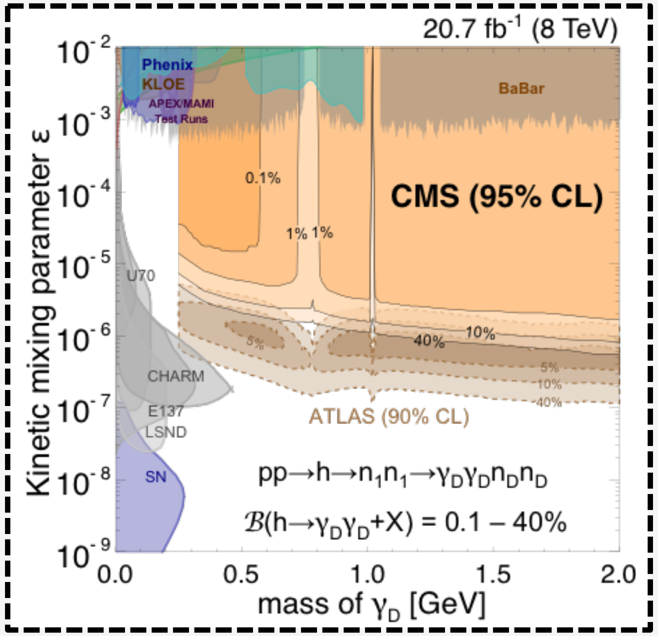



## Search strategy

- The $\gamma_D$ will decay to lepton pairs, reconstructed as LJs
- Model independent search for a detector signature of either prompt or non-prompt decays of LJs




- Background sources: multi-jet production and cosmic-rays
- Estimation of background using control data samples and MC simulations




## Limits

Set on the $\sigma \times BR$ at 95% CL for:

- Prompt LJs scenario based on the SUSY-portal for the possible LJ combinations in the $2\gamma_d + X$ topology at $m_{\gamma_D} = 0.7\ GeV$
- Non-prompt LJs scenario BR lower than 10% for $H$ with $m_H = 125\ GeV$ decaying to $\gamma_d$ with $m_{\gamma_D} = 0.4\ GeV$:
  - $H \to 2\gamma_d + X$ for $\gamma_d$ with (w/o TYPE2) $14mm \le c\tau \le 140mm$
  - $H \to 4\gamma_d + X$ for $\gamma_d$ with (w/o TYPE2) $15mm \le c\tau \le 260mm$
  - $H \to 4\gamma_d + X$ for $\gamma_d$ with (TYPE2 included) $52mm \le c\tau \le 85mm$

ATLAS arXiv:1409.0746, 1511.05542
CMS arXiv:1506.00424

# Long-livedness

Long-lived particles (LLP) - Long enough life-time to be measured by the detector

- Interaction with the detector:

✓ Electrically charged LLPs will leave signal in all detector stations

✓ Strongly interacting LLPs might flip their electric charge while interacting with the detector medium

- LLPs are expected to be massive and hence slower than SM particles ($\beta < 1$)
- Ionization energy loss bigger than a Minimum Ionizing Particle (MIP)

Considered models:

- $\tilde{\tau}_1$ as NLSP within GMSB (Decay product originating from production of $\tilde{g}, \tilde{q}$ or direct production)
- $\tilde{g}$ forming R-hadron within SplitSUSY (simplified models of $\tilde{t}$ as LLP considered as well)
- Multi-charge long-lived heavy particles, with |q| ranging from 2e-8e

NEW

# CMS: Heavy Stable Charged LLPs - 13 TeV

Considered scenarios

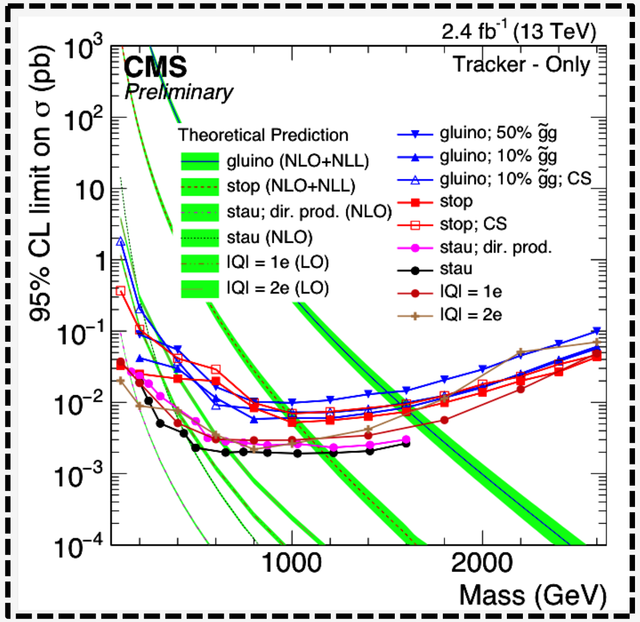
- $\tilde{\tau}_1$ within GMSB or from direct production
- $\tilde{g}$ R-hadrons within SplitSUSY
- Single & doubly charged LLPs

Features different from SM particles:

- Slower ($\beta < 1$)
- Larger ionization ($\frac{dE}{dx} > \frac{dE}{dx}_{MIP}$)
- Massive

Search strategies applied:

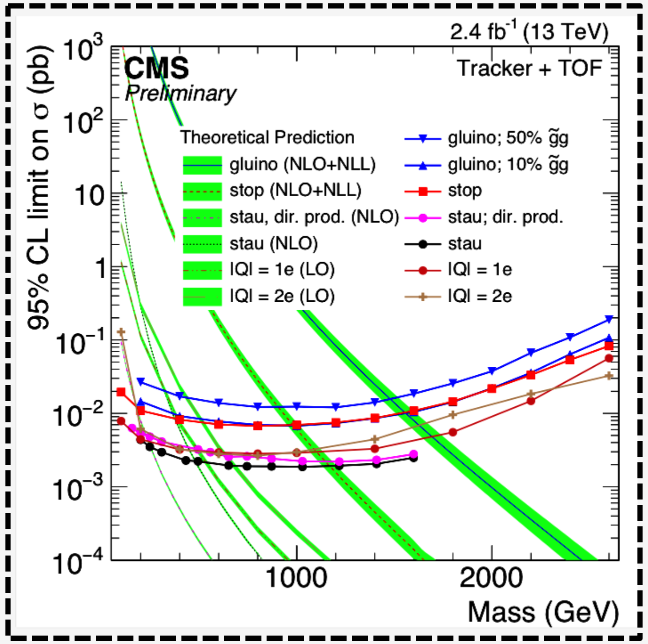
- 'Tracker-only': Mass estimated from the Silicon detector information, via $\frac{dE}{dx}$ and $p$ measurements
- 'Tracker+ToF': Mass is estimated from the Silicon detector information, via $\frac{dE}{dx}$ and $p$ measurements + ToF measured by the Muon detector is used as further selection criteria




'Tracker-Only' Limits

For the R-hadron searches, the highest limits were set based on the 'Tracker-Only' search:

- $m_{\tilde{g}}$<1590 GeV
- $m_{\tilde{t}}$<1020 GeV




'Tracker+ToF' Limits

For the Stau and DY charged HSCP searches, higher limits were set using the 'Tracker+ToF' strategy:

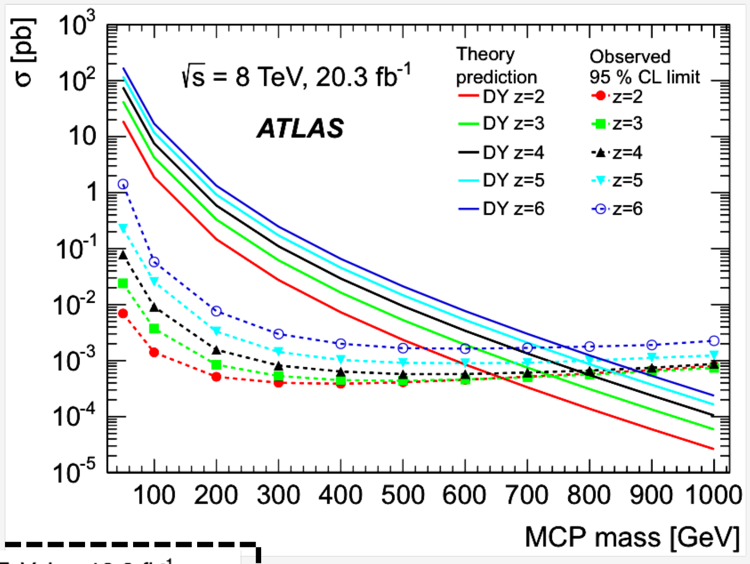
- GMSB $\tilde{\tau}_1$: $m_{\tilde{\tau}_1}$<480 GeV
- DY $\tilde{\tau}_1$: $m_{\tilde{\tau}_1}$<230 GeV
- DY |Q|=1e m<540 GeV
- DY |Q|=2e m<650 GeV

CMS PAS EXO-15-010

# Multi-charge particles

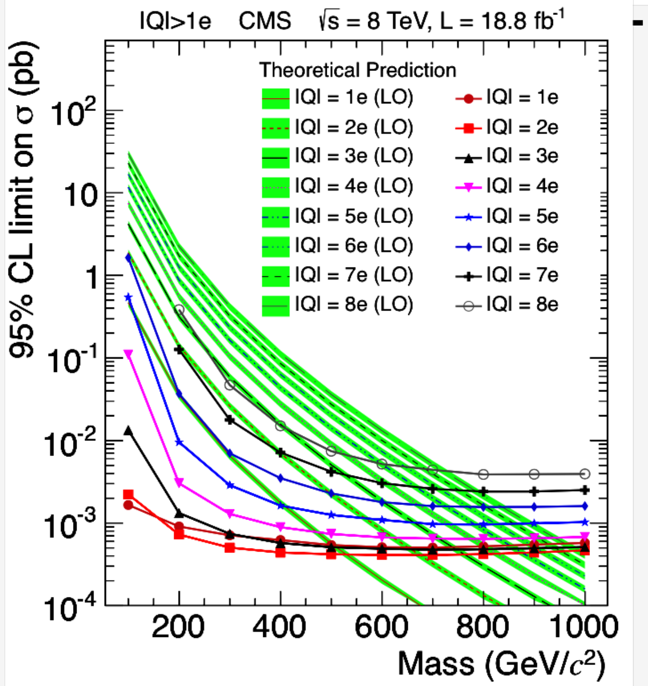
**Scenario**

- Drell-Yan (DY) production of multi-charge particles (MCPs), with only photon exchange included
- Predicted by several DM motivated theories
- Consider |q|: 2e→8e




**Features:**

- Long-lived, slow, massive particles
- Directly produced in DY process
- Highly ionizing, leaving large $\frac{dE}{dx}$ information in all detector layers
- Energy loss in the calorimeter expected to be $q^2$ times of a $\mu$'s (3 GeV)
- $\frac{dE}{dx}$ is used as a discriminating variable between signal and background
- The background is data driven and is estimated using the ABCD method




**Limits**

Observed 95% CL cross-section upper-limits are interpreted as lower mass limits range between 660-796 GeV for charge range between 2e and 8e

ATLAS arXiv:1504.04188
CMS arXiv:1305.0491

# Summary

- Many BSM models predict non-conventional detector signatures
- Custom analysis techniques are designed & used to achieve sensitivity to these important final-states

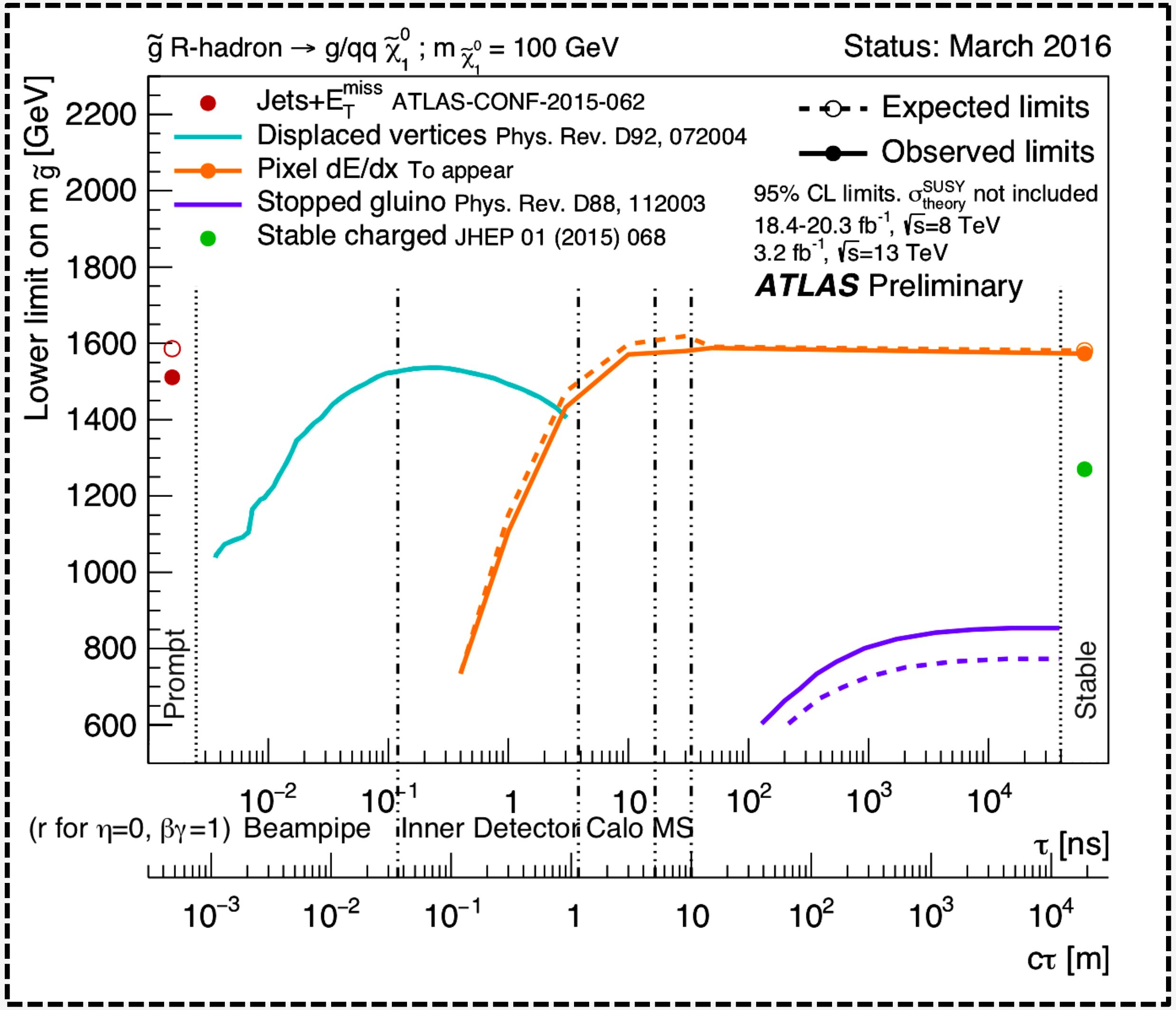
- Presented latest results from searches studied on 8 TeV and 13 TeV datasets
  - ✓ Metastable particles
  - ✓ Long-lived particles

- No evidence for the existence of new physics was found
- Higher limits were set at 95% CL on the new particle mass (and lifetime)

- Increased sensitivity to these searches at 13 TeV due to higher production cross-section
- Work is on-going in analyzing the Run-2 results

# Back-up...

# Metastable & Stable Long-lived particles






ATLAS CERN-PH-EP-2015-049

# CMS: Heavy Stable Charged LLPs - 13 TeV

NEW

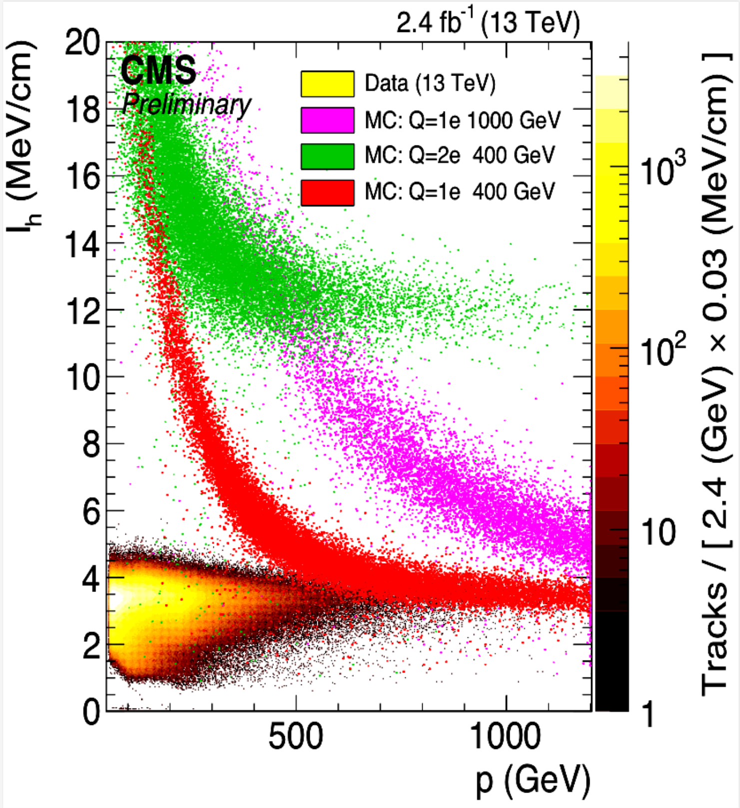
Considered scenarios

- $\tilde{\tau}_1$ within GMSB and from direct production
- $\tilde{g}$ R-hadrons within SplitSUSY
- Single & doubly charged LLPs

Mass estimation based on silicon detector measurements:

$$\frac{dE}{dx} = K\frac{m^2}{p^2} + C$$

K,C — empirical parameters



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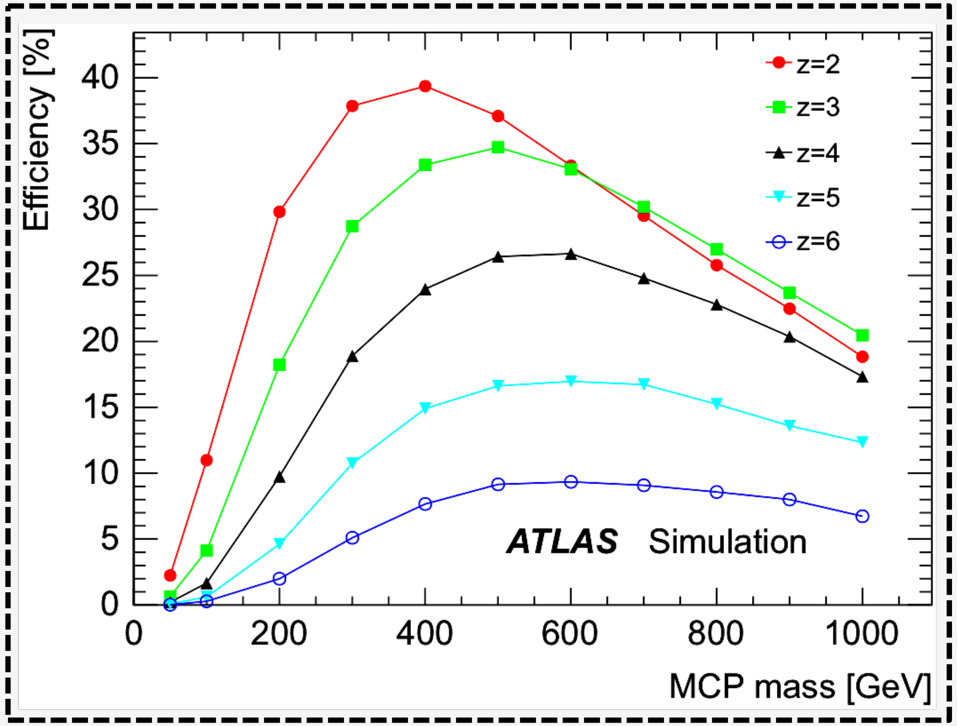
# Multi-charge particles






ATLAS CERN-PH-EP-2015-049