Searches for challenging and long-lived signatures by ATLAS and CMS experiments

Kunihiro Nagano (KEK, Japan)

International Conference on the Physics of the Two Infinities
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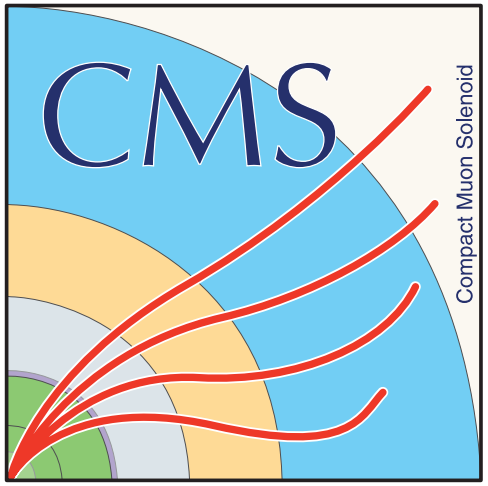
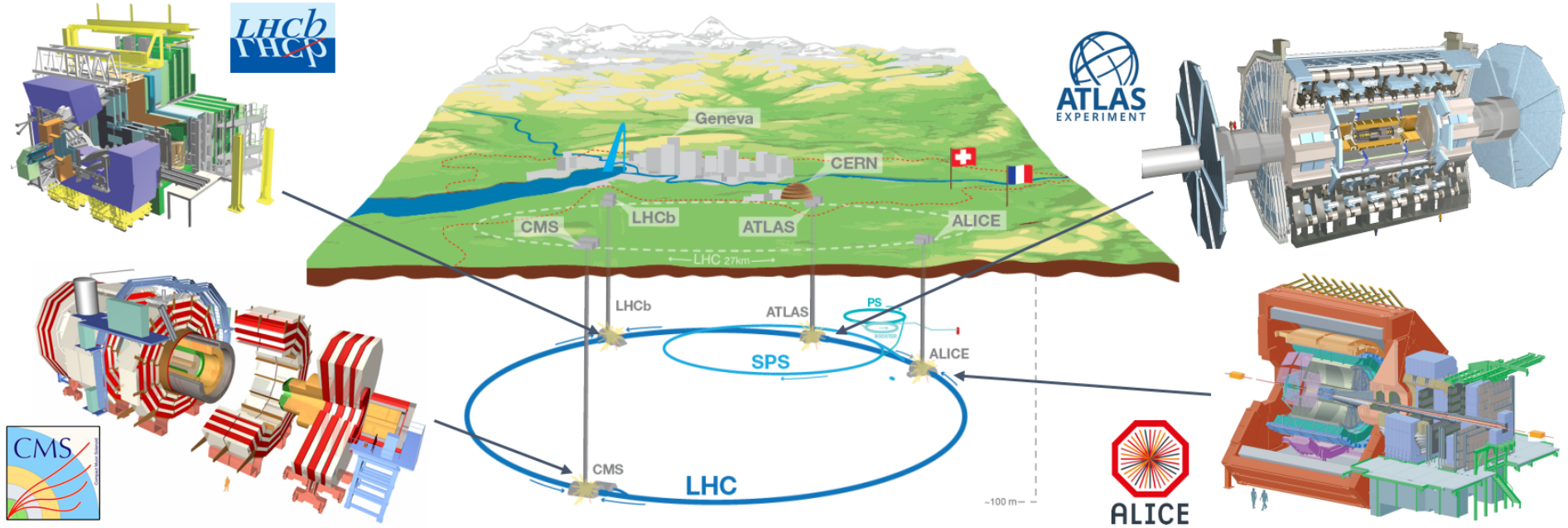


Large Hadron Collider (LHC)

- Proton-proton collider with c.m.s energy → 14 TeV (design)
  -- c.m.s. energy of elementary parton-parton collision: O(1) TeV
  → **The real explorer for "TeV scale" physics, e.g**
    -- Origin of EW symmetry breaking; SM Higgs
    -- New physics search

$$\sqrt{s}_{eff}(q-q) \approx \mathrm{O}(1)\ \mathrm{TeV}$$

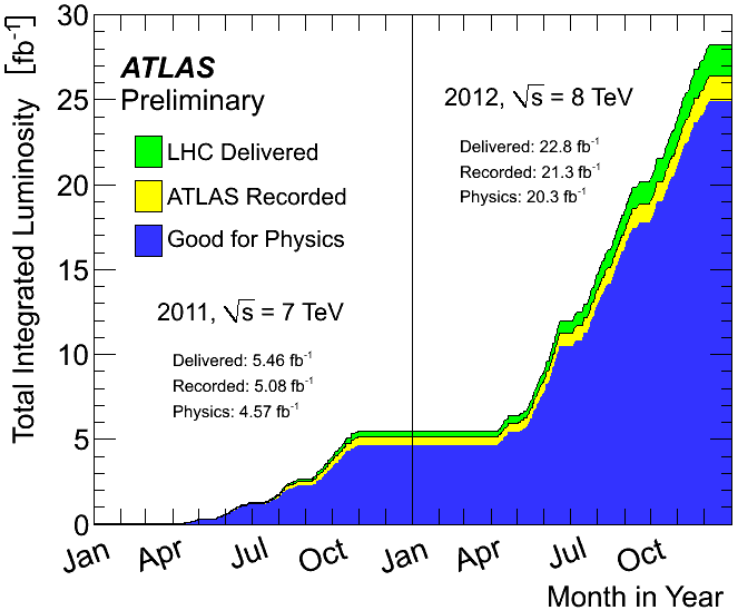
- 2 experiments with general purpose detector, covering ~4π solid angle:
  ATLAS and CMS



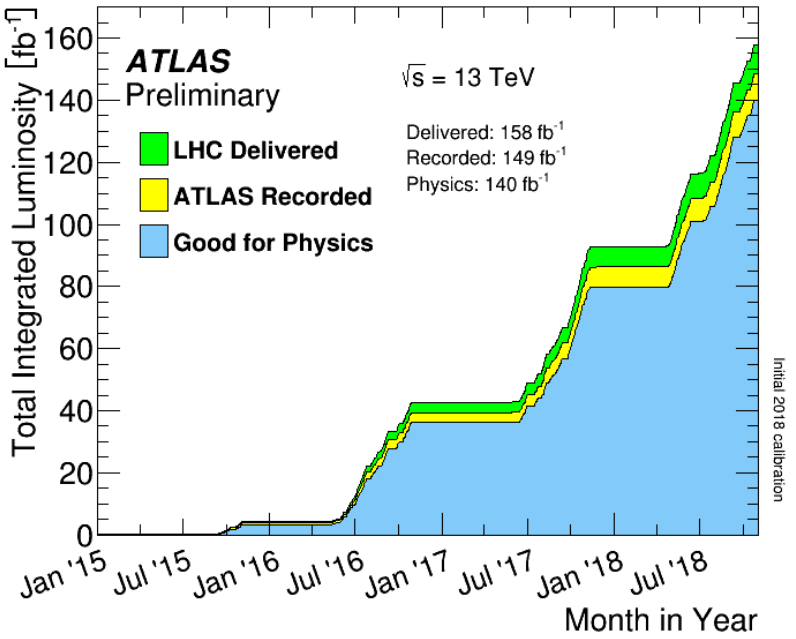
In this talk, searches for new physics (with experimentally challenging signatures) from ATLAS/CMS will be presented

LHC Runs – in a nutshell

- Run-1 (2010-2012)
  - -- 2010-11: $\sqrt{s}$=7 TeV, $\int \mathcal{L}dt$ ~5 /fb
  - -- 2012: $\sqrt{s}$=8 TeV, $\int \mathcal{L}dt$ ~20 /fb



- Run-2 (2015-18)
  - -- $\sqrt{s}$=13 TeV, $\int \mathcal{L}dt$ ~ 140 /fb



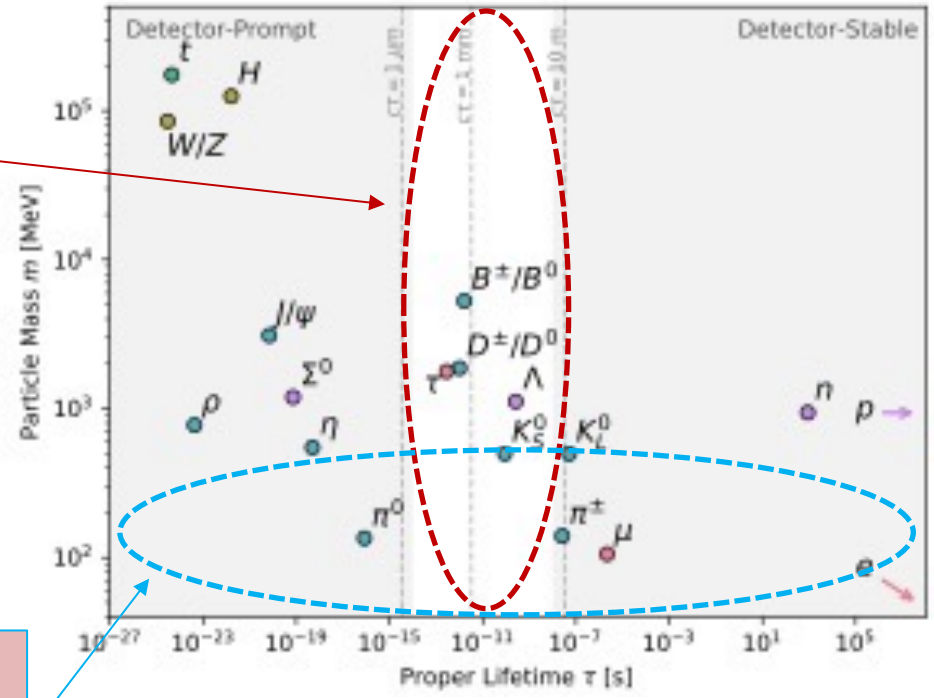
Excellent data taking efficiency and excellent data quality

- Searches for new physics with these high-quality/statistical data
  - → No clear indication yet so far…
  - → Might new physics lie in experimentally challenging signatures?

Challenging and long-lived particles signatures

arXiv:1810.12602

- Long-lived particles (LLP)
  - -- The majority of BSM searches focus on promptly decayed and/or stable new particle
  - -- Such new particles with macroscopic lifetime often result in experimentally challenging signatures (see later)

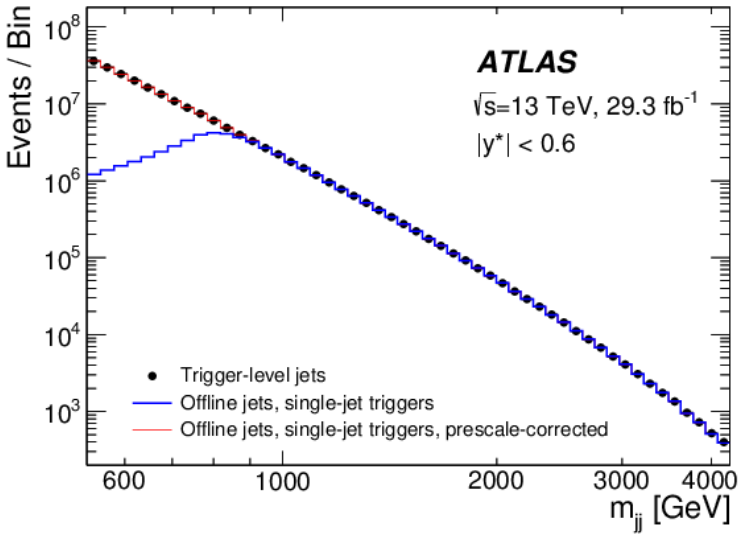


New physics could be hiding here

Phys. Rev. Lett 121.081801

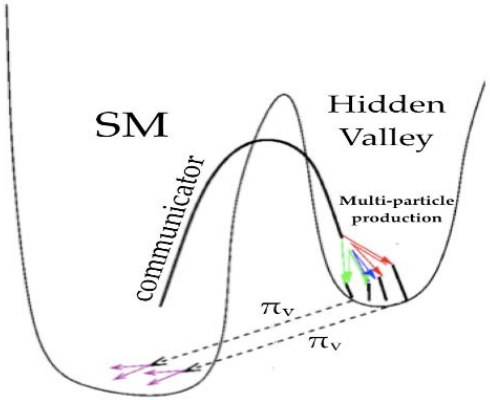
- What else are challenging at LHC?

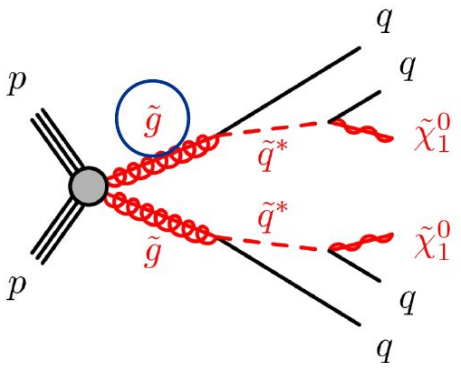
For example, small-mass new particles:
  - -- Difficult to be triggered on, as the background cross section is way too high
    - * Trigger/DAQ system applies usually high energetic signatures to achieve a few/40000 reduction



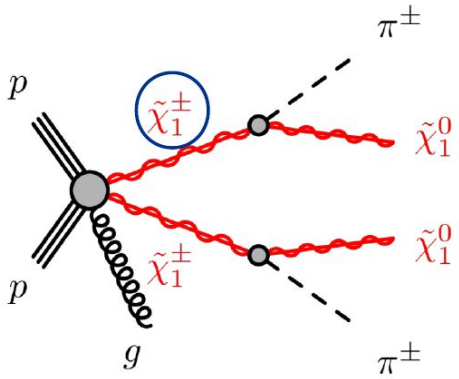
Theoretical motivations for LLP

- Macroscopic lifetime can happen (even in SM) due to various reasons
  - -- Off-shell particles
  - -- Small phase-space
  - -- Small coupling

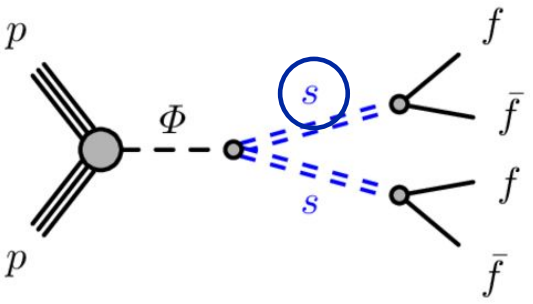




Off-shell decays
-- e.g. split-SUSY with squarks mass > 10 TeV



Small phase-space
-- e.g. small mass splitting AMSB

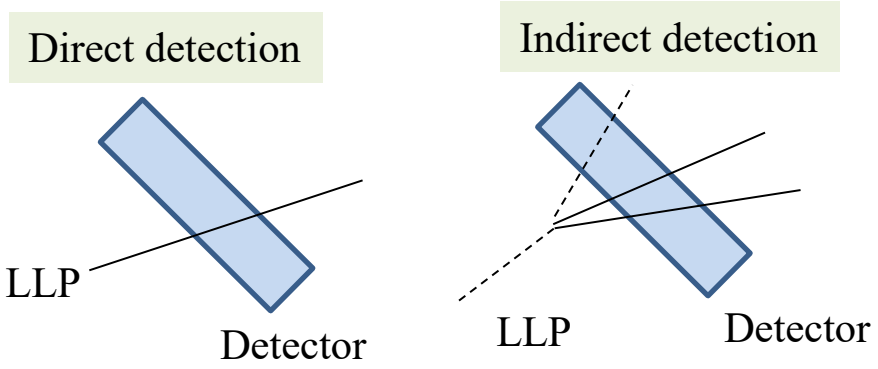


Small couplings
-- e.g. weakly-coupled dark sector, small R-parity violation
…

- Strong interplay between theory and experiments
  - -- Experimental searches based on signatures
    - * Results can be interpreted in different models
  - -- Specific theories can suggest new signatures to look

Experimental signatures of LLP

- **Direct detections**, e.g.
  - -- Electric charge
  - -- Mass and lifetime
  - -- Large ionization (dE/dx)
- **Indirect detections**, e.g:
  - -- Decay vertex
  - -- Displaced objects
    - * Lepton, jets, photons
    - * Pairs, multi-objects
  - -- Disappearing/emerging objects
    - * Tracks, Jets



Various signatures that often require dedicated experimental techniques

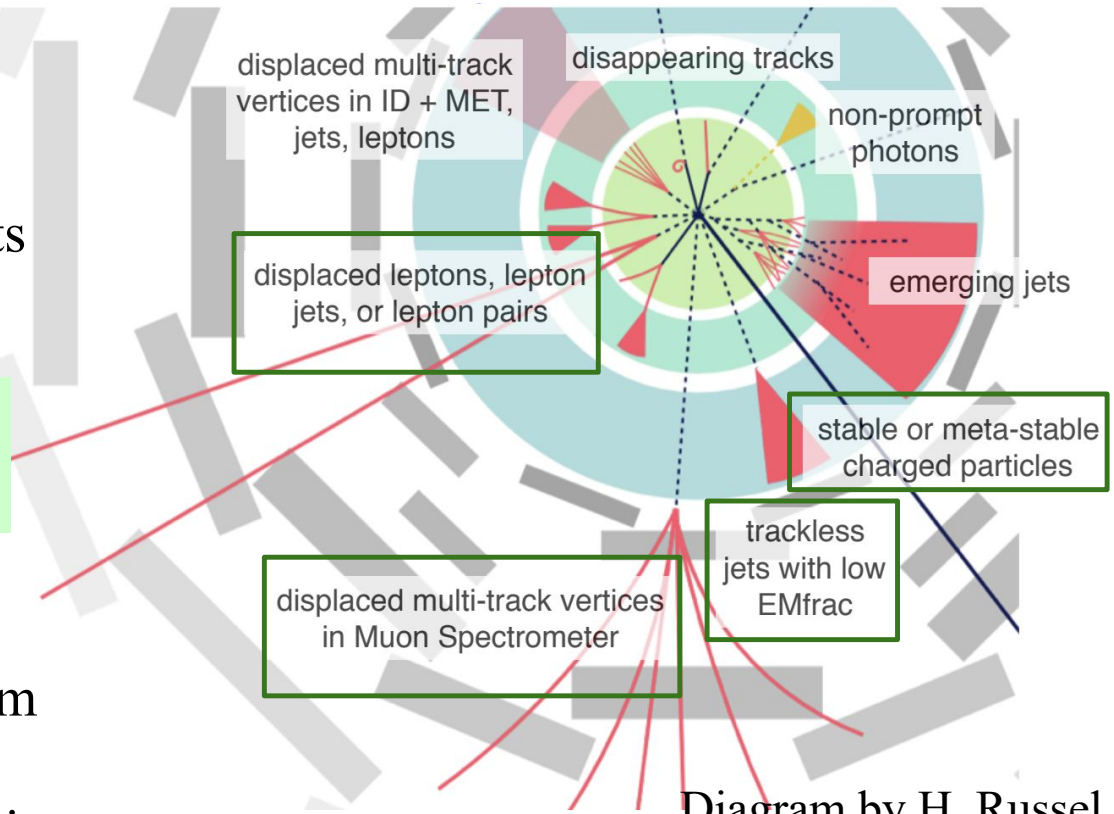
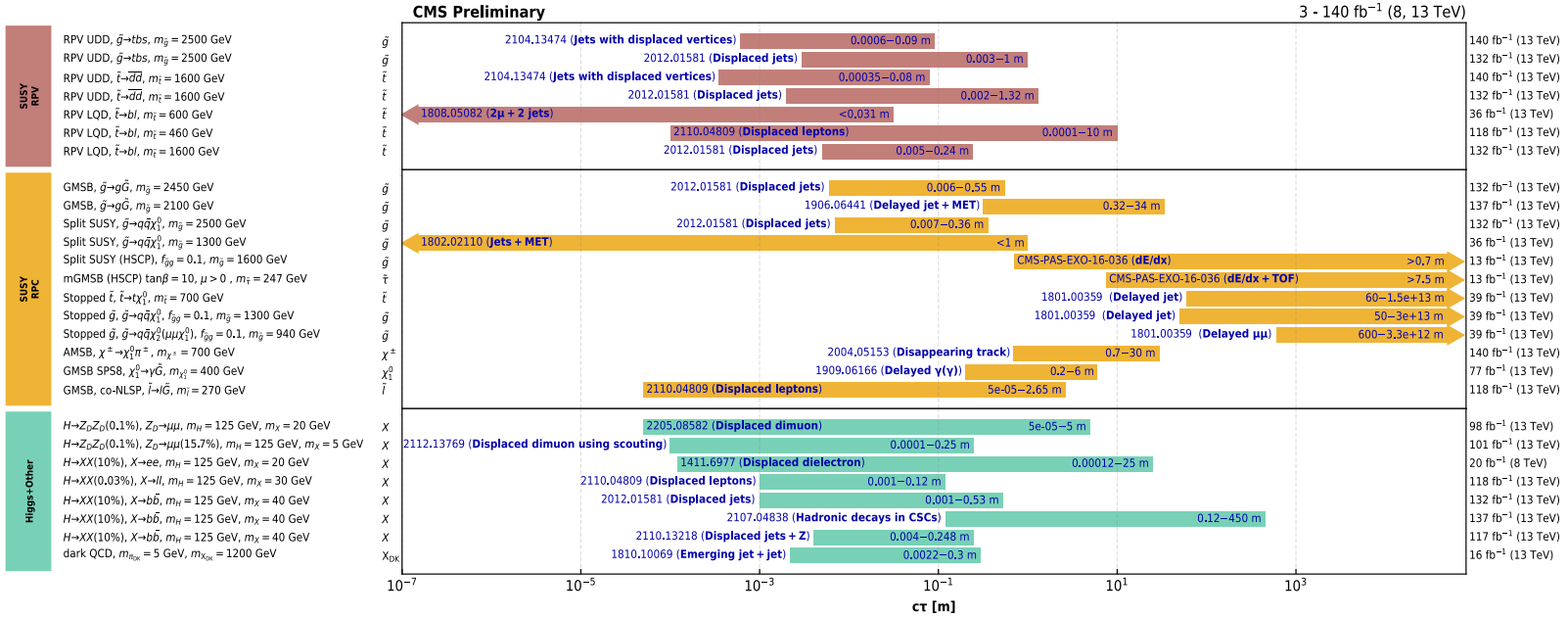


Diagram by H. Russel

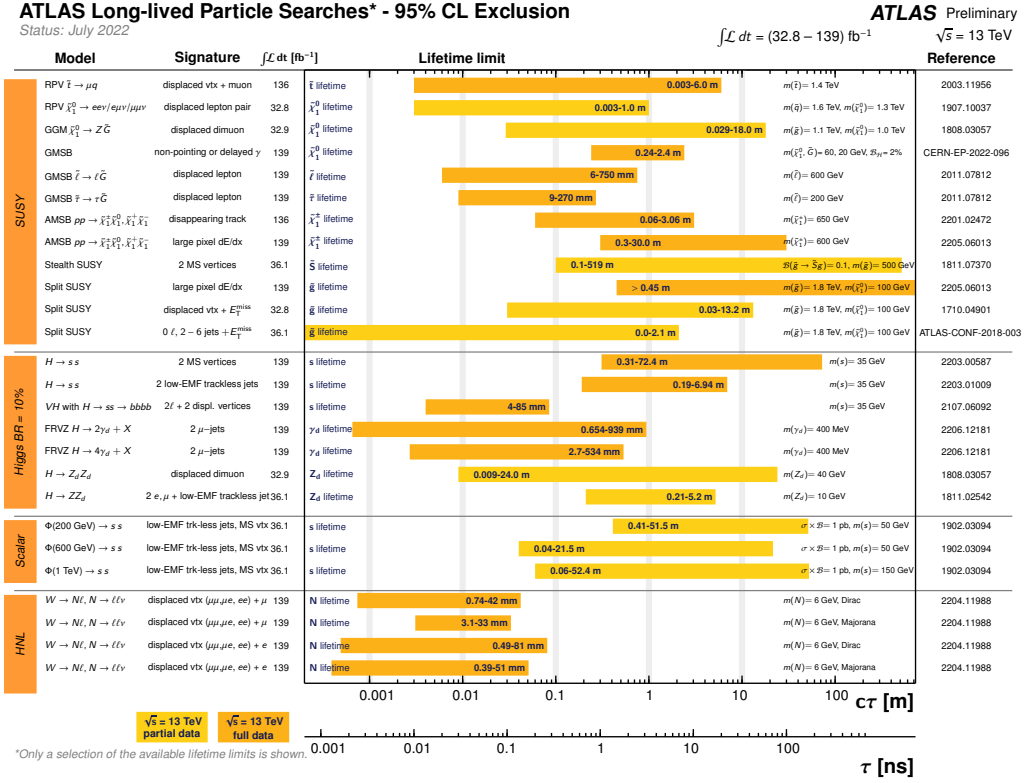
- In addition, backgrounds are often challenging to estimate as they from non-pp collisions, such as
  - -- beam-gas, cosmics, detector noise, etc.

Overview of CMS long-lived particle 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.

ICHEP 2022



[SummaryPlotsEXO13TeV]

[ATL-PHYS-PUB-2022-034]

Extensive searches on many LLP signatures are actively on going.

In this talk, several recent results are picked up to show.

Direct detection searches

- Fractionally-charged particles
- Multiply-charged particles
- Large ionization loss (dE/dx) particles

Public since this winter (last Nov-)

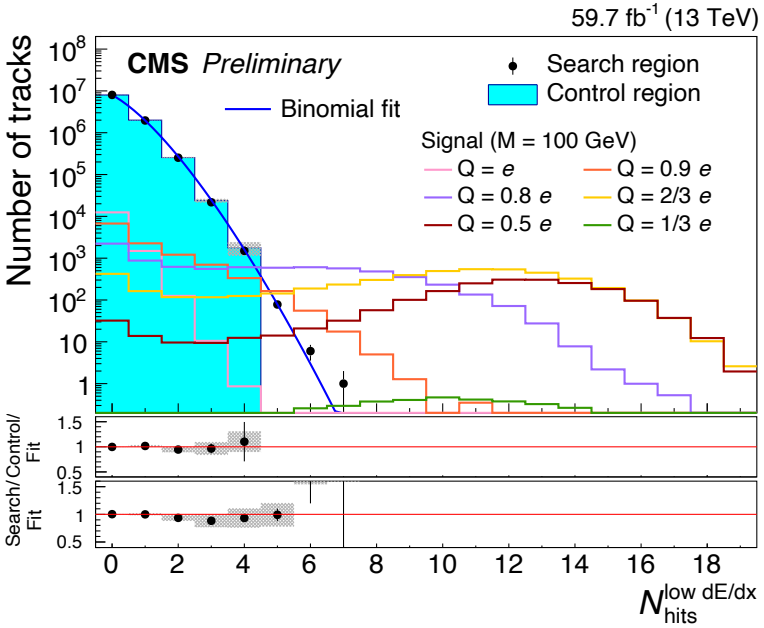
Public since last year

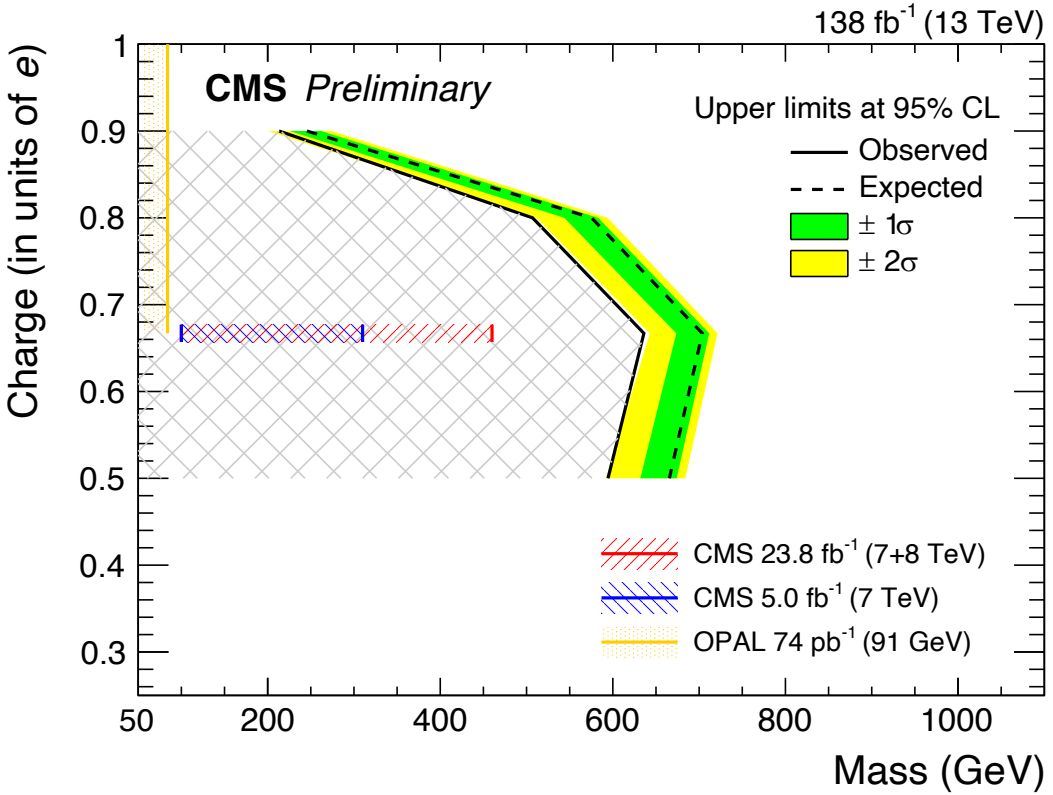
HOT!

CMS-PAS-EXO-19-006

Fractionally-charged particles

- Target: free-propagating fractionally charged (< 1e) particles (FCP)
- Signature
  -- Many hits with low ionization signal (dE/dx) in tracking detectors
  -- Reconstructed as high-p_T muon





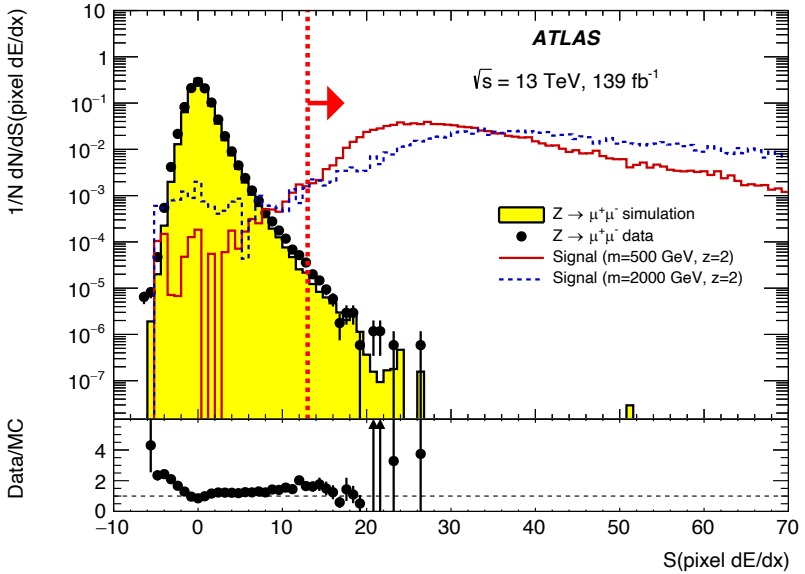
No significant excess of events was observed.
Upper limits on FCP mass vs. charge were derived.

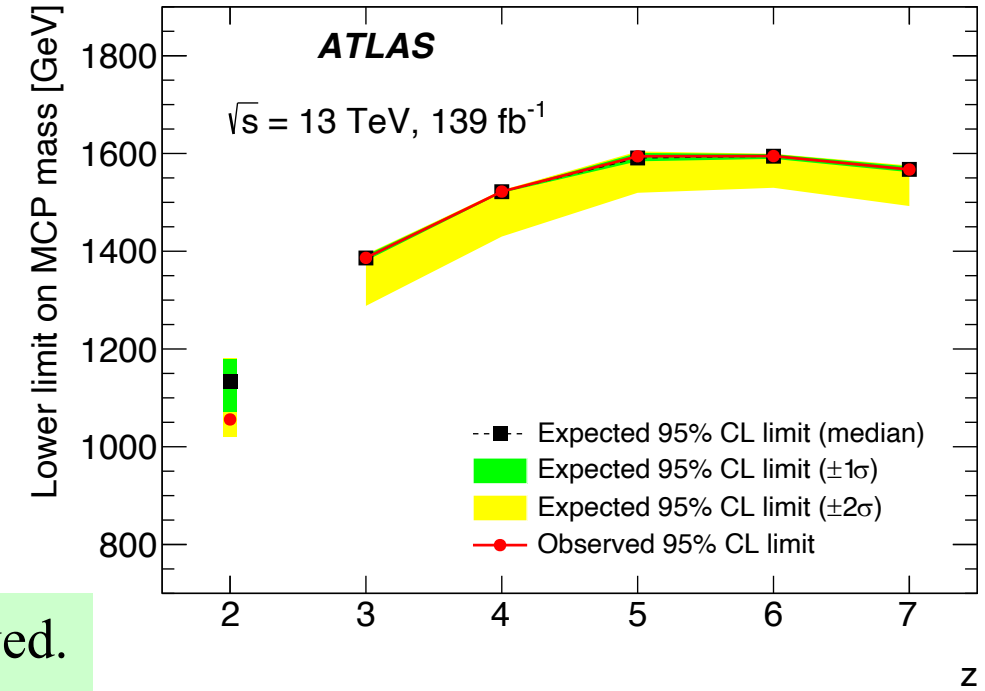
NEW

ATLAS-EXOT-2018-54

Multiply charged particles

- Target: heavy long-lived multi-charged particles (MCP)
- Signature
  -- Large ionization signal (dE/dx) in inner-tracking (Pixel/TRT) and muon (MDT) detectors
  -- Muon-like track in inner-tracking and muon detectors
  -- Trigger with: single-muon, complemented with E_T^{miss}, delayed-muon triggers
  * Single-muon trigger only sensitive for $\beta > 0.65$ due to time window





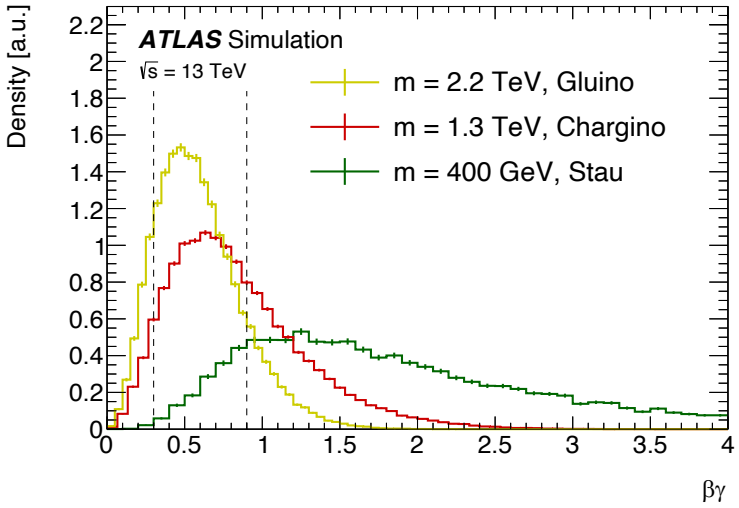
No significant excess of events was observed. Lower limits on MCP mass vs. charge were derived.

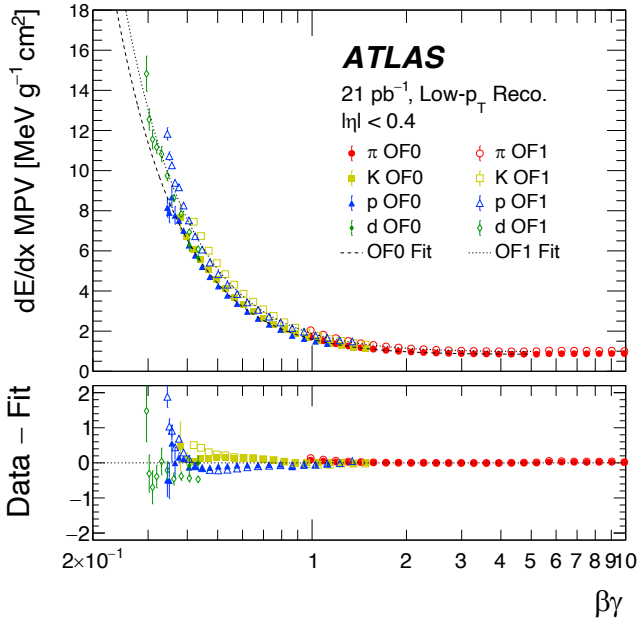
NEW

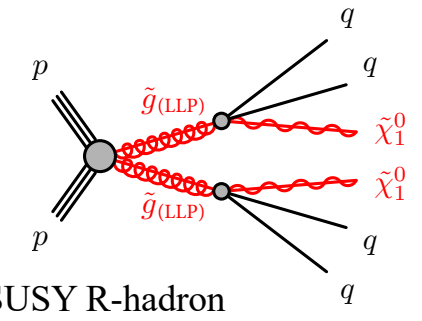
arXiv:2205.06013

Large ionization (dE/dx)

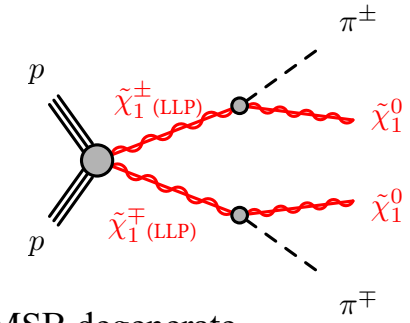
- Target: massive, charged, long-lived particles moving slower than speed of light
- Signature
  -- Large ionization signal (dE/dx) in inner-tracking (Pixel) detector
  -- βγ is with Bethe-Bloch formula with the measured dE/dx
  -- Mass calculated as: $m = \frac{p}{\beta\gamma}$
- Challenges
  -- Fully data-driven background estimation
    * Main backgrounds are due to dE/dx fluctuations



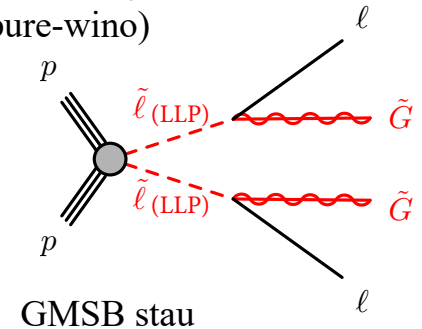




Split SUSY R-hadron



AMSB degenerate (pure-wino)



GMSB stau

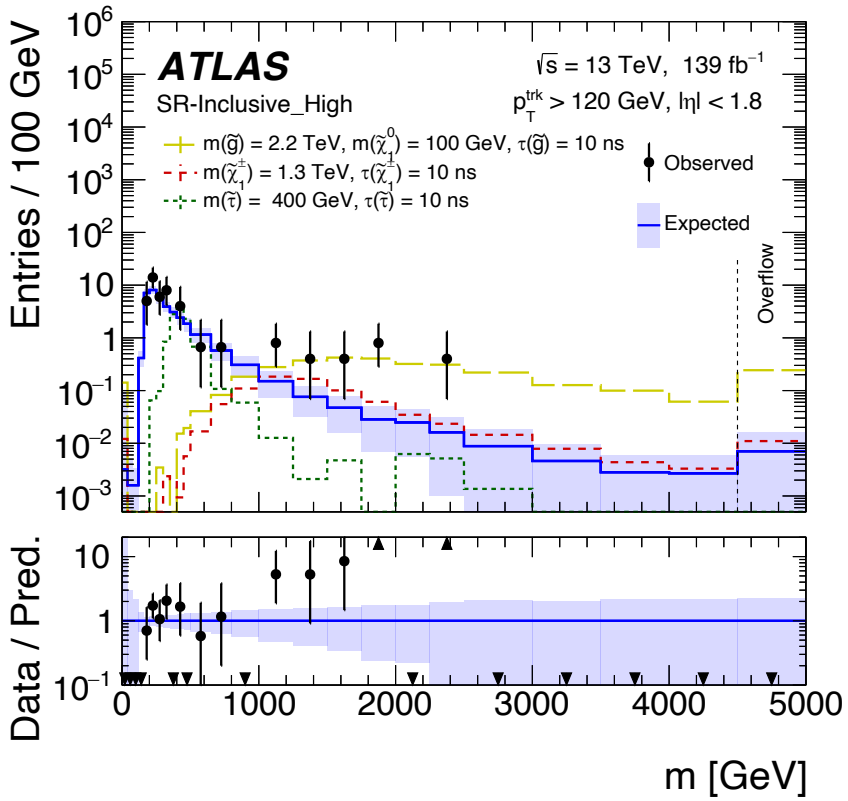
NEW

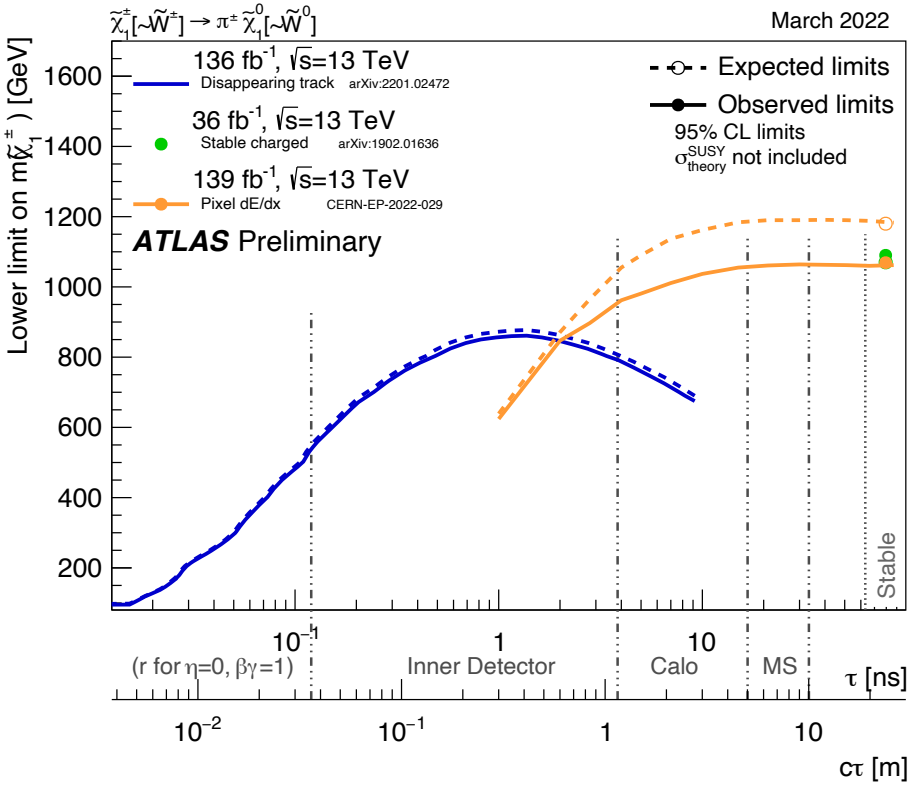
Large ionization (dE/dx) -cont'd-

ATL-PHYS-PUB-2022-013

arXiv:2205.06013

- Results:
  -- 8 signal regions targeting different LLP masses and lifetimes
  -- Agreement with SM prediction except one SR (dE/dx > 2.4 MeV/g/cm)





- 3.3σ global significance deviation at m=1.4 TeV
  -- Cross-check with calorimeter/muon system shows β~1 for these tracks
- Complementary with other ATLAS LLP searches

Indirect detection searches

- Photons
  -- Displaced di-photon vertex
- Hadronic jets
  -- Out-of-time trackless jets
  -- Displaced vertex with jets
- Leptons
  -- Muon pairs with small displacements

Public since this winter (last Nov-)

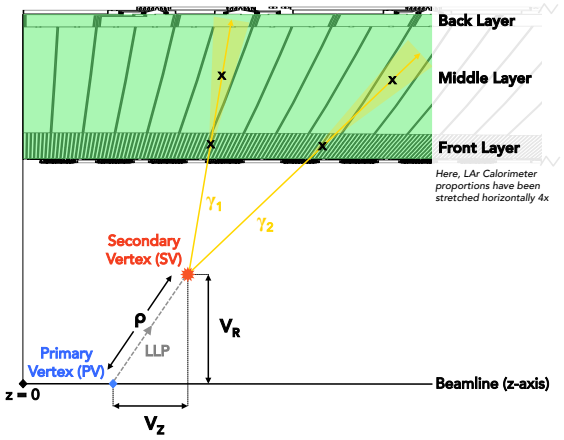
Public since last year

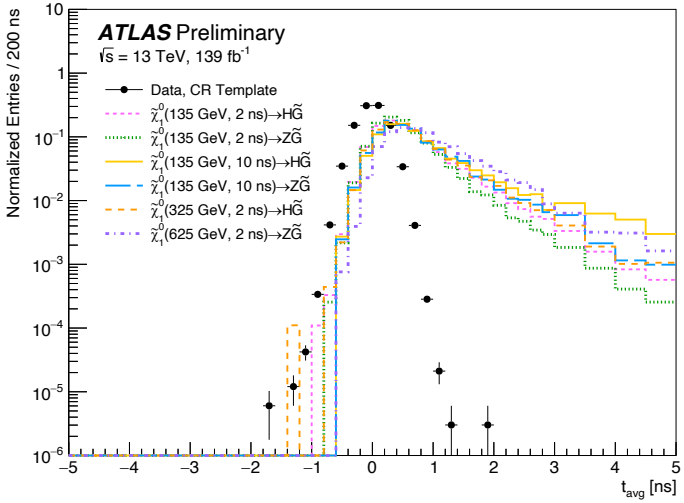
NEW

ATLAS-CONF-2022-051

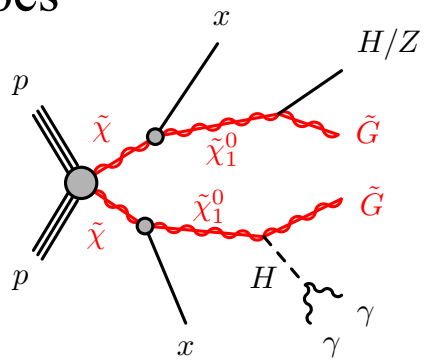
Displaced di-photon vertex

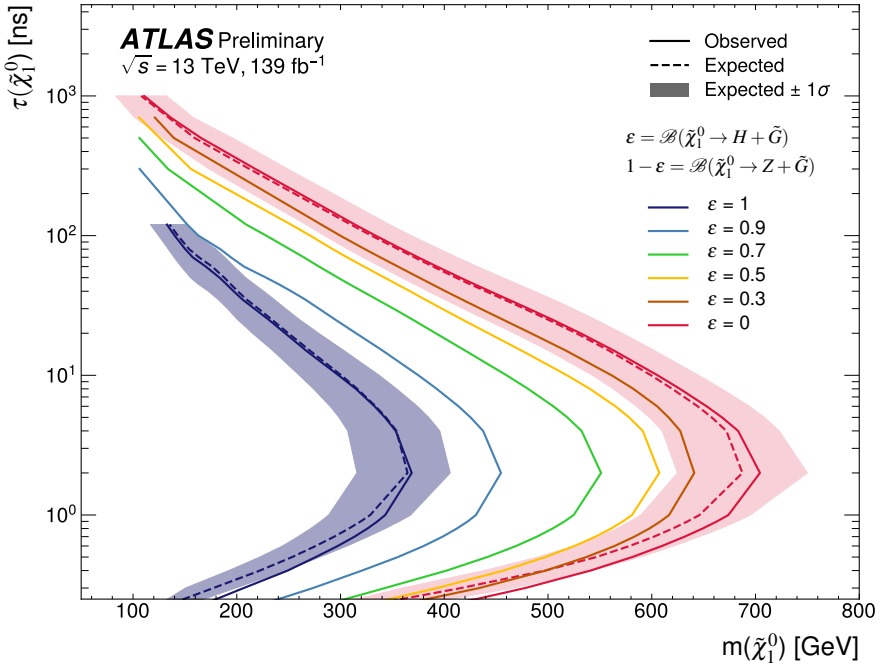
- Target: displaced production of H or Z, originated from neutral LLP
- Signature: displaced vertex of two photons that arrive to the calorimeter delayed. Exploring the ATLAS LAr EM calorimeter capability fully:
  -- Trajectories and vertex reconstruction from EM shower shapes
  -- Calorimeter timing $t_{avg} = (t_1 + t_2)/2$





- Limit on GMSB models with the almost degenerate triplet $\widetilde{\chi^{\pm}}, \widetilde{\chi^{0}}$



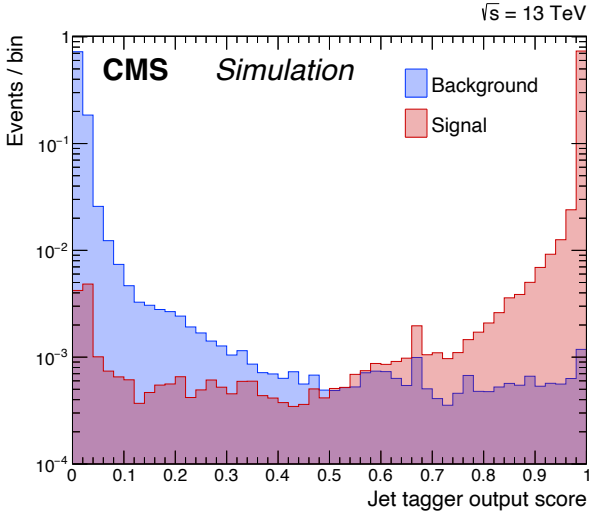


HOT!

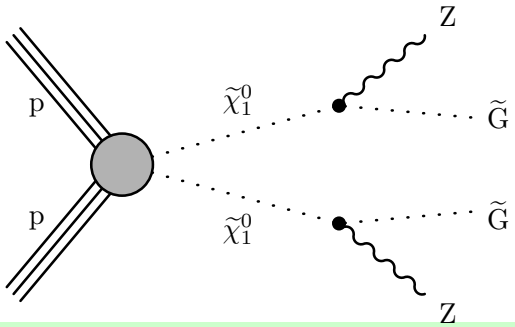
arXiv:2212.06695

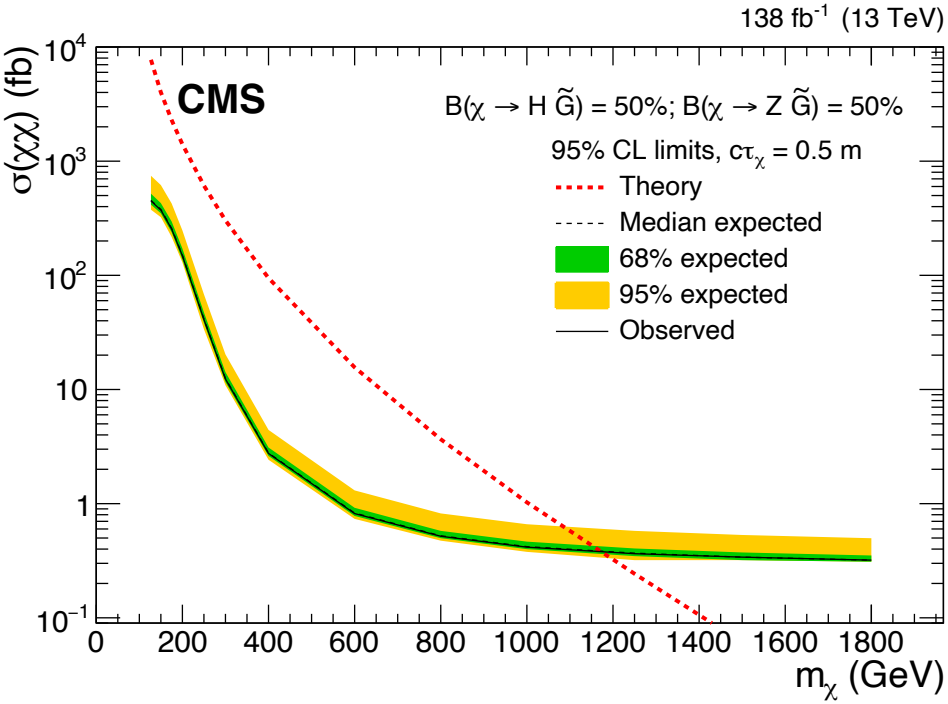
Out-of-time trackless jets

- Target: LLPs decaying in the outer regions of the tracker or within the calorimeter
- Signature: jets that are trackless and out-of-time
- Deep Neural Net (DNN) discriminator, with jet, track, timing information as inputs, was developed



- Results were interpreted using a simplified model of GMSB chargino-neutralino production
  - -- Effective pair production of $\widetilde{\chi_1^0}$ (due to near mass-degeneracy)
  - -- Each $\widetilde{\chi_1^0}$ subsequently decay to (H or Z) and $\tilde{G}$





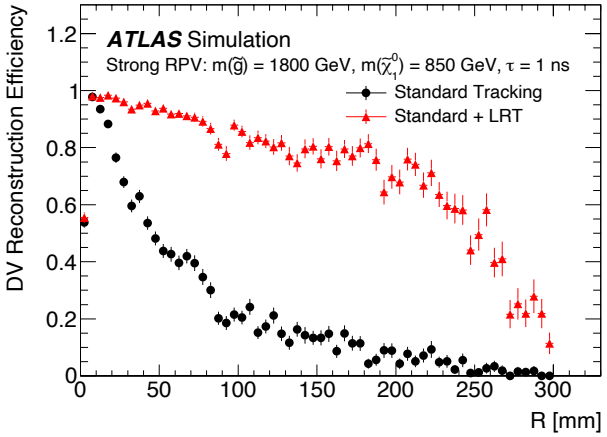
For long-lived χ_1^0 with $c\tau$=0.5m, masses up to 1.18 TeV were excluded

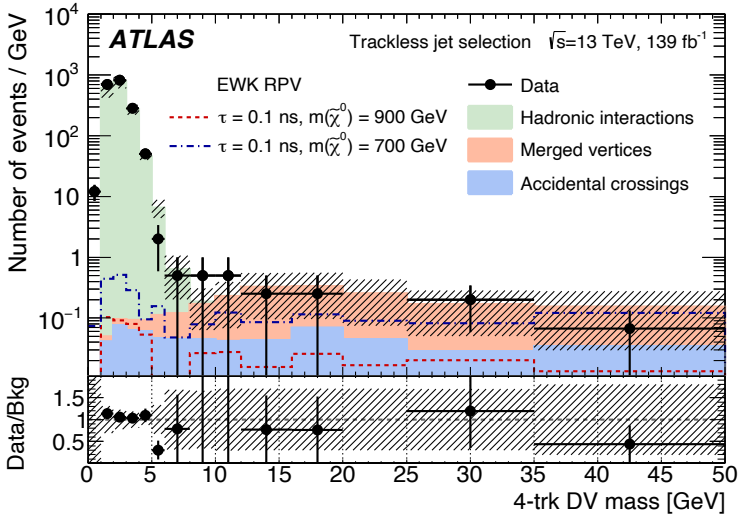
NEW

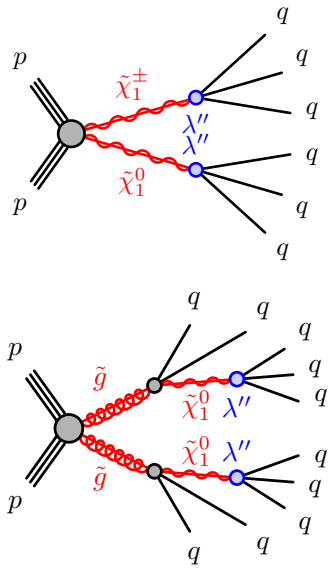
arXiv:2301.13866

Displaced vertex with jets

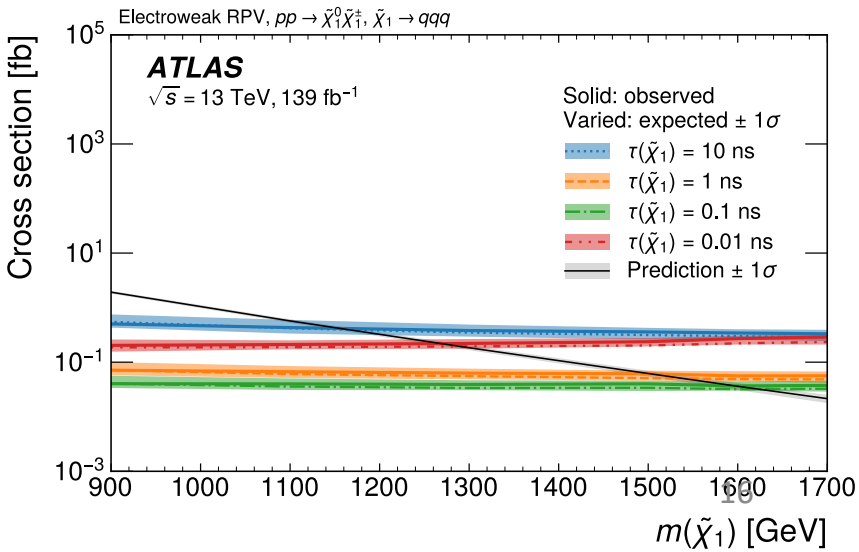
- General search for heavy LLPs decaying into hadrons
- Signature: displaced vertex (large mass, multiple tracks) in multi-jets events
  -- Displaced vertex can be reconstructed up to 300 mm thanks to the large radius tracking (LRT)
- Backgrounds: accidental track crossing, merged close-by vertices etc.







- Limits derived for benchmark models of EW and Strong production of R-parity violating SUSY



For long-lived χ_1^0 with τ=0.1 ns, ewkino masses up to 1.58 TeV were excluded independently of the presence of heavier gluino

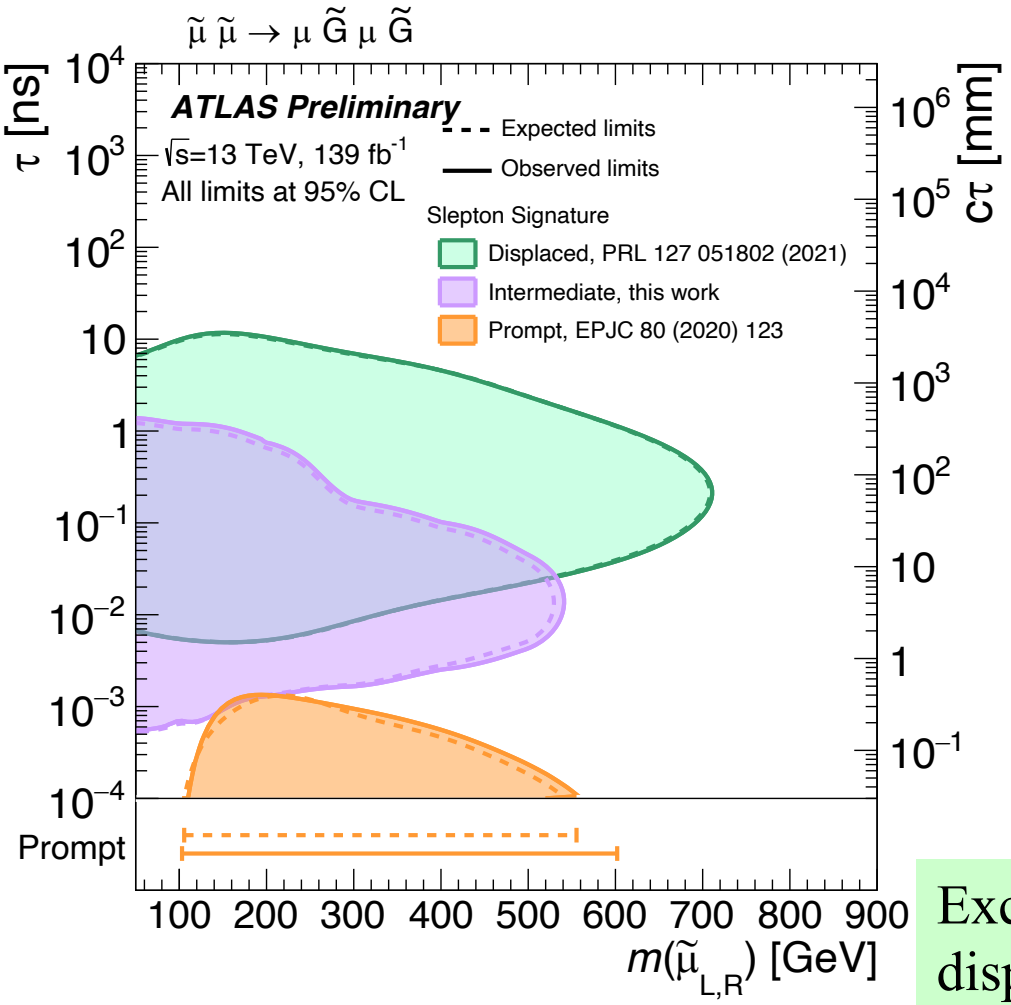
HOT!

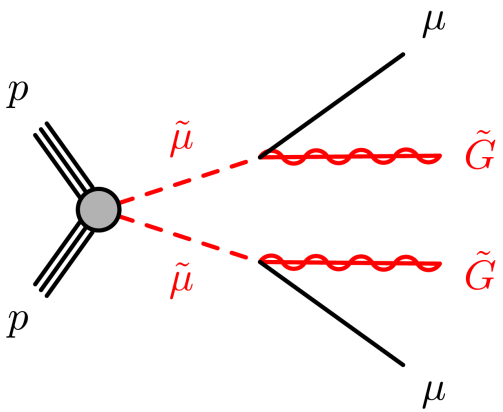
(Prel. on 23 Mar)

ATLAS-CONF-2023-018

Muon pairs with small displacements

- Target: smuon ($\tilde{\mu}$) with a lifetime of $O(1-10)ps$, filling a gap between prompt and displaced $\tilde{\mu}$ searches
- Signature: a pair of opposite-charged muons with impact parameters in mm range
  -- $|d_0| > 0.6\ mm$ for signal region





- The observed number of events in all SRs compatible with background-only expectation
- (In addition to the model-independent cross section limit), the model-dependent 2D exclusion limit for GMSB SUSY is derived

Excluded the gap between the previous displaced and prompt searches

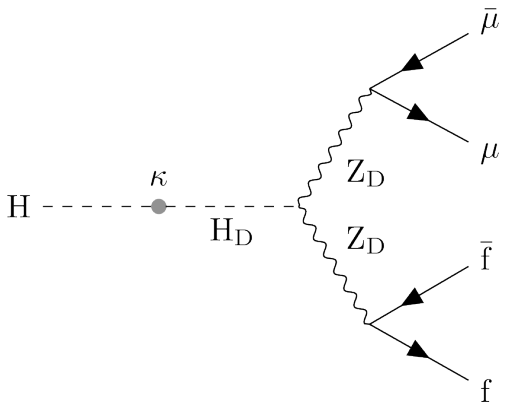
Small masses searches

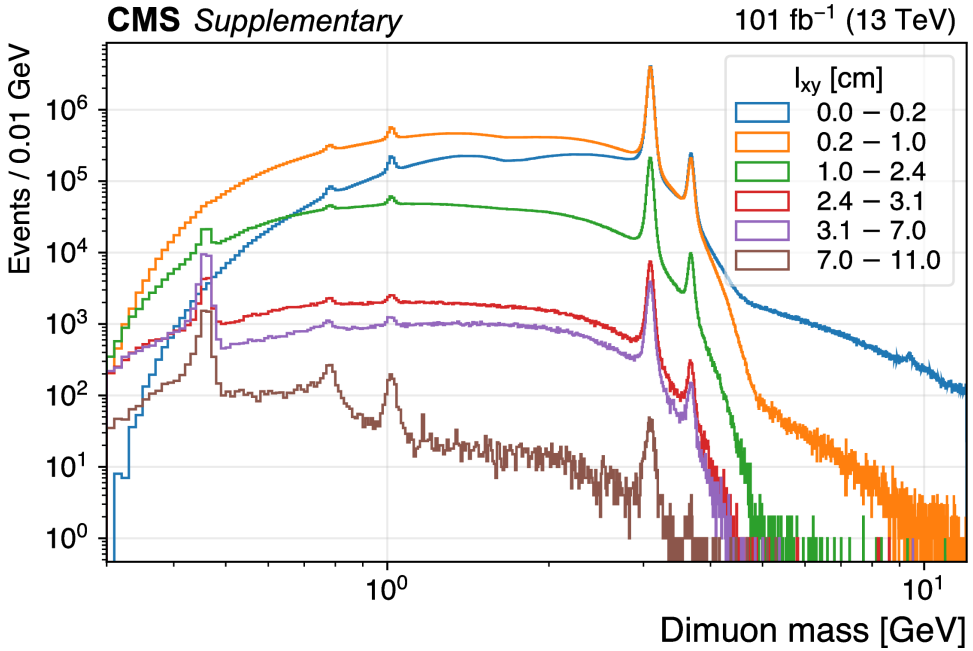
- Small mass di-muon resonance

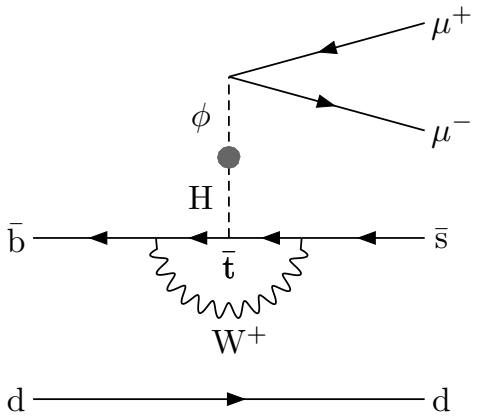
JHEP04 (2022) 062

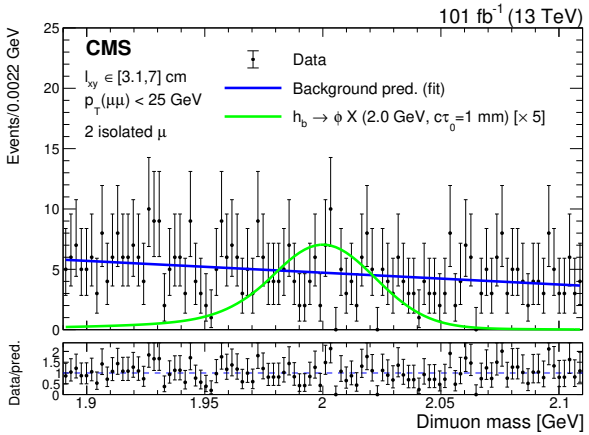
Long-lived small-mass di-muon resonance

- Target: dark photon (Z_D) decaying into di-muon pair
  -- Also, a scalar resonance in decay of b-hadrons
- Nobel experimental technique : ”Data Scouting”
  -- Very high-rate triggers with limited event content
    * to ensure affordable bandwidth usage
  -- Enables to search for di-muon masses > 300 MeV







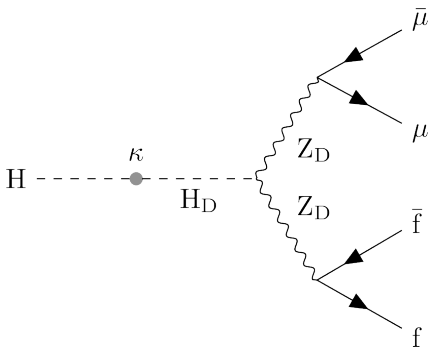


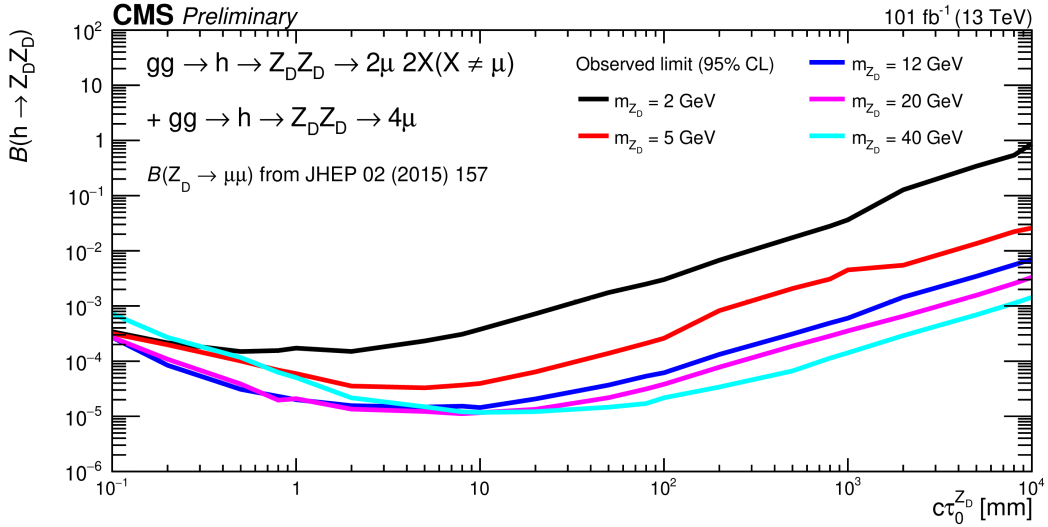
- No significant peak-like structures are observed; upper limits on the branching fraction is set

JHEP04 (2022) 062

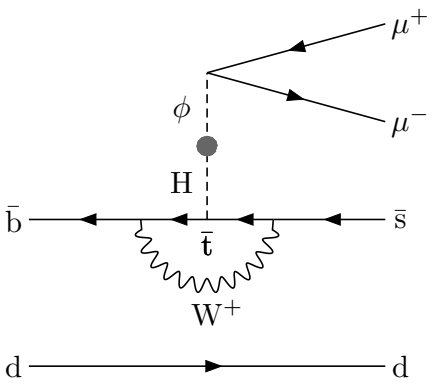
Long-lived small-mass di-muon resonance -cont'd-

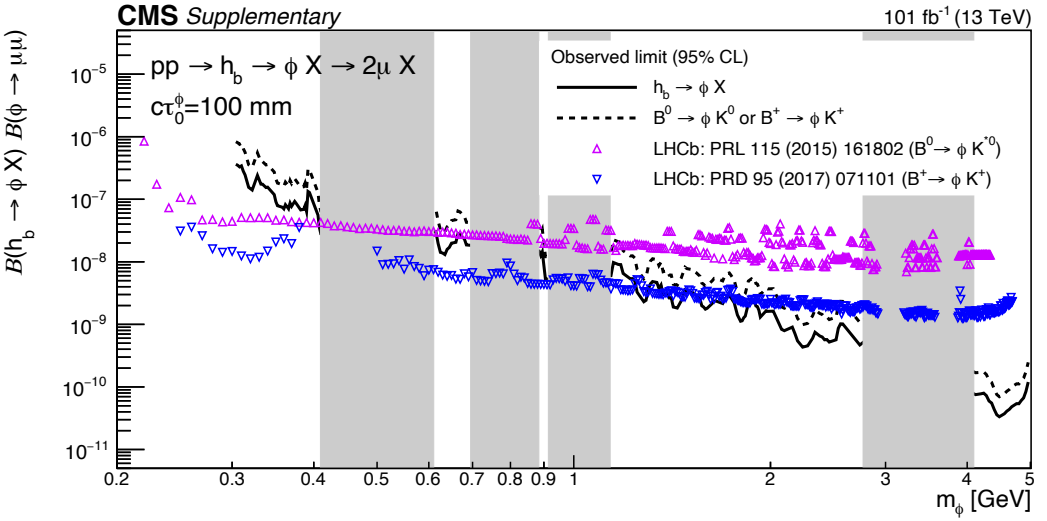
- Limit on branching ratio to dark photon





- Limit on branching ratio to simplified scalar





- The obtained constraints are the most stringent to date for substantial regions of parameter space.
- Competitive with LHCb in higher mass regions.

Summary and Run3 prospects

- In the last few years, ATLAS and CMS have produced a large variety of searches for experimentally challenging signals such as long-lived particles
  -- Various noble and dedicated techniques, calibrations, background handling, trigger, etc. have been invented

- There are still room for further improvements and filling gaps of past searches, and the Run3 has just started since 2022! (already collected ~40 /fb)
  -- New triggers e.g. for unconventional tracking signatures
  -- New dedicated reconstruction and analysis methods
    * For example, large radius tracking (LRT) runs on all events in ATLAS since Run3
  -- Extension to uncovered signatures
  ….