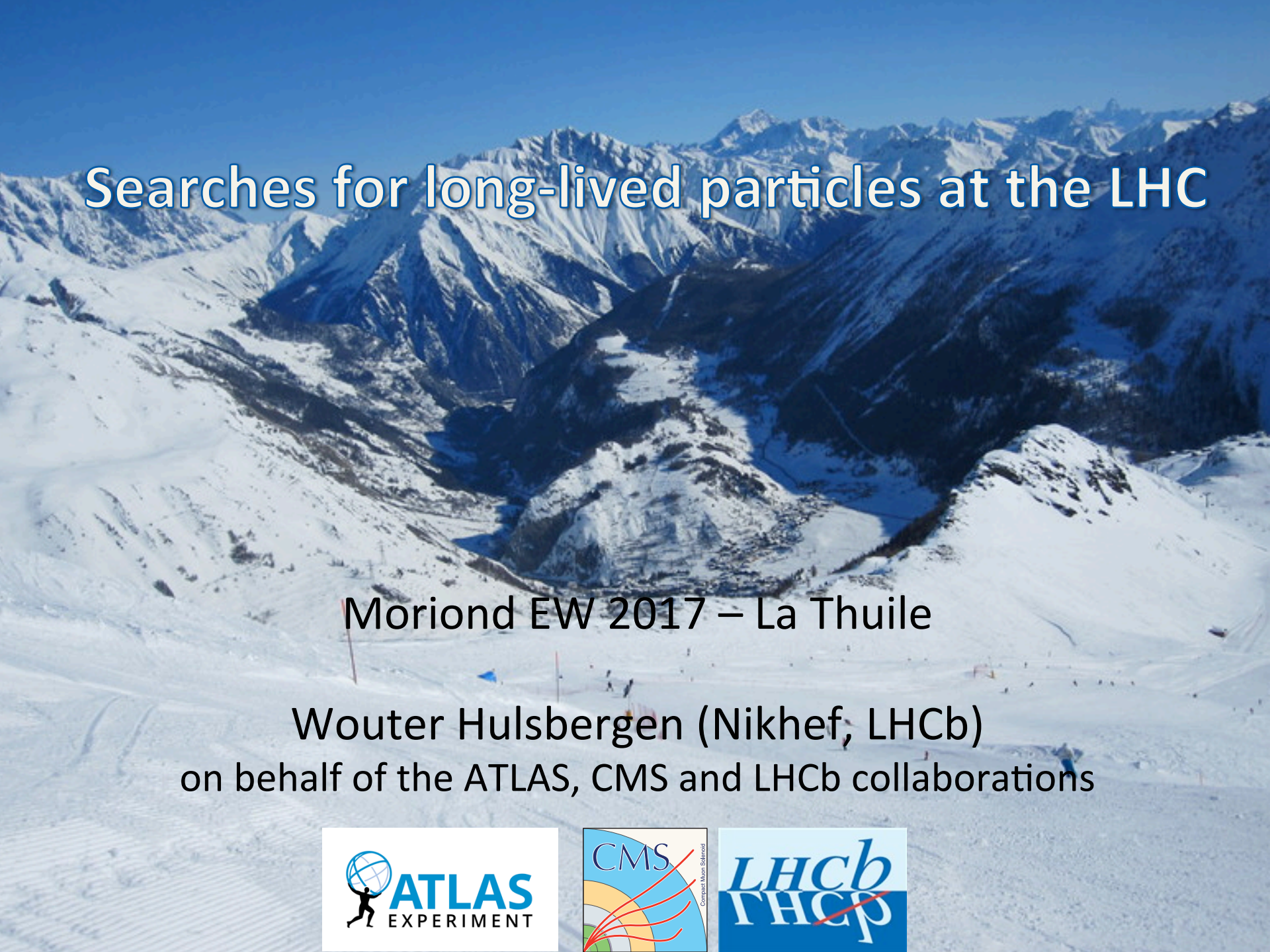


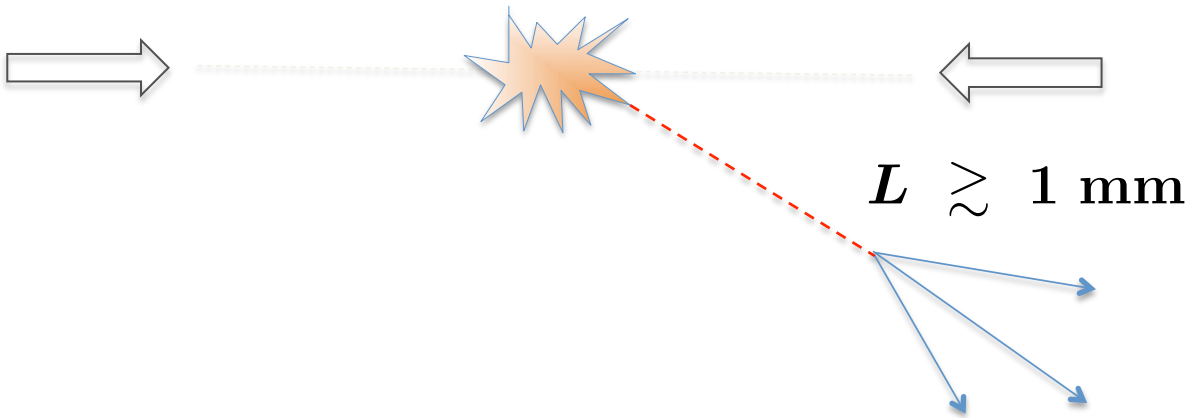
# Searches for long-lived particles at the LHC

Moriond EW 2017 – La Thuile

Wouter Hulsbergen (Nikhef, LHCb)
on behalf of the ATLAS, CMS and LHCb collaborations

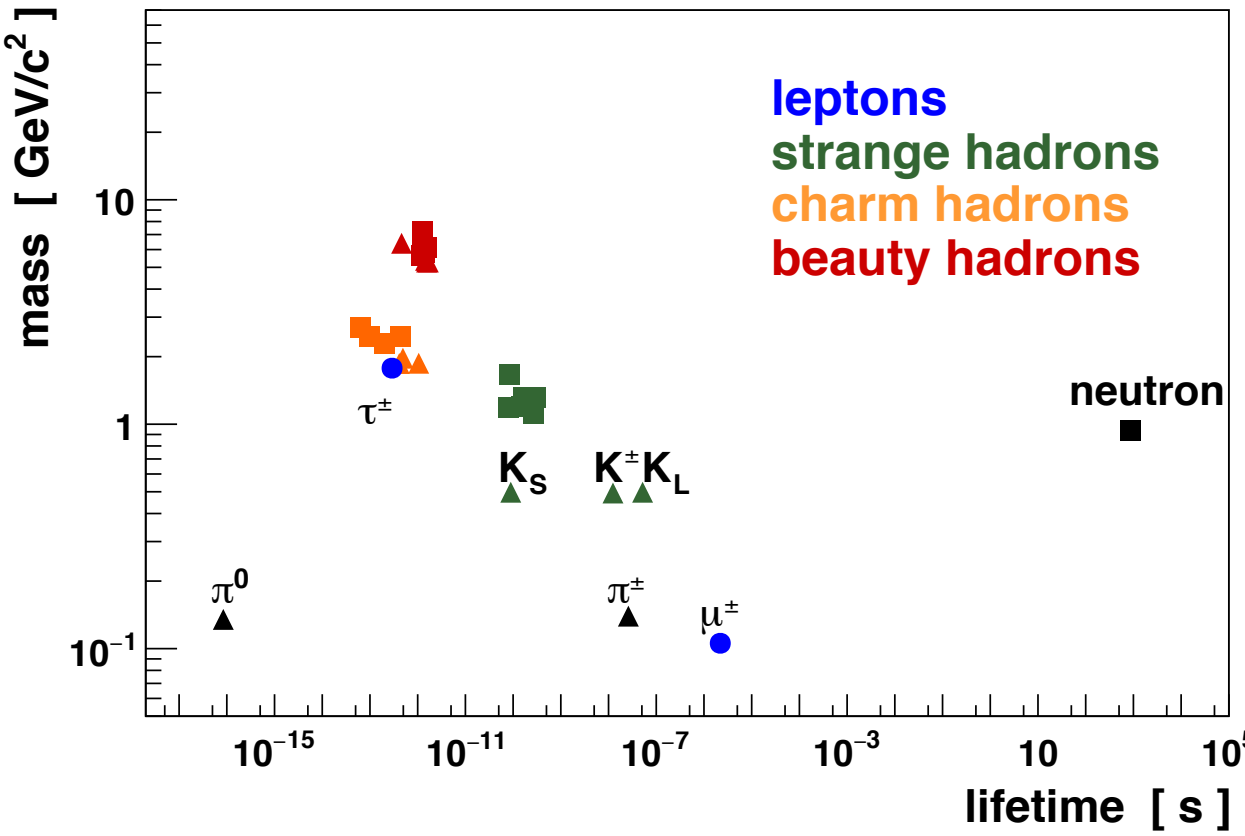
# Long-lived particles at the LHC

- long-lived particles (LLPs): resonances that live long enough to …
  - … escape the detector
  - … decay in the detector, but far enough from the interaction point that the decay length can be measured




- LLPs at the LHC necessarily have lifetime $\tau > \sim 1\mathrm{ps}$
  - characteristic of weak decays
  - narrow resonances (as $\Gamma = \hbar/\tau$)

# Long-lived particles in the Standard Model




- weak decays are backgrounds for LLP searches
- LHC experiments look for particles that do not fit this picture

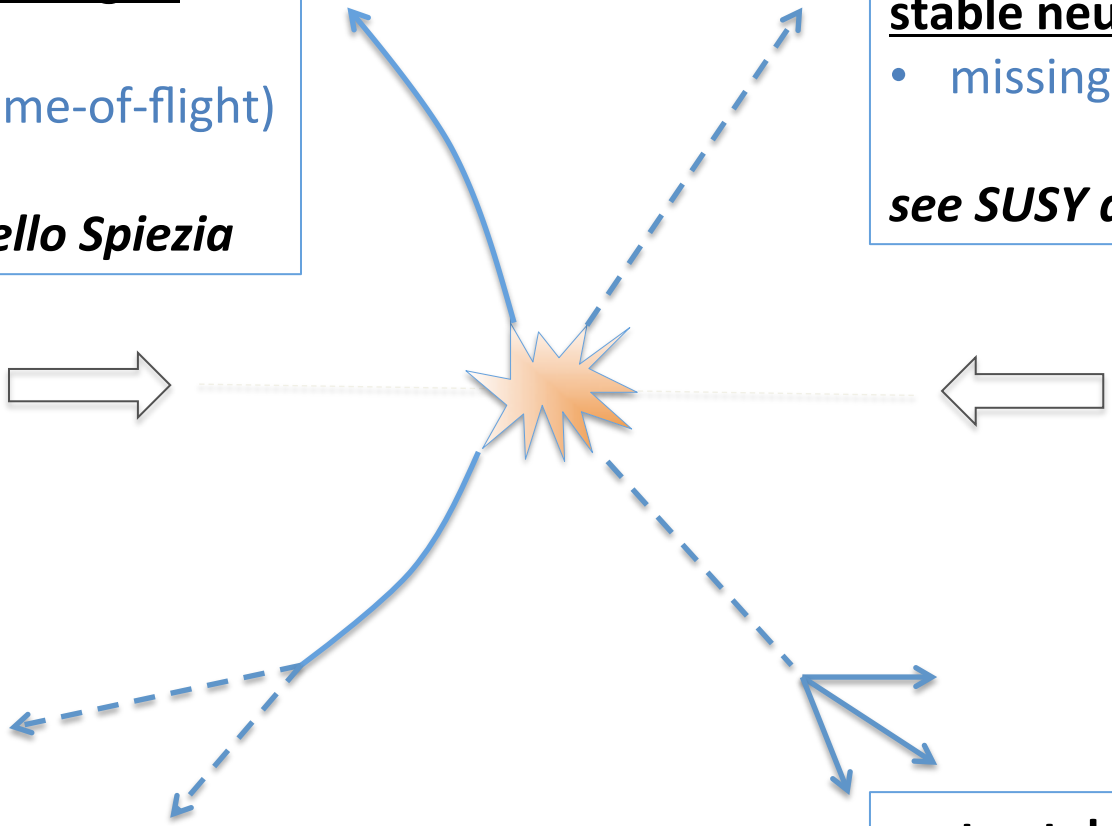
# Detection signatures at the LHC

**stable massive charged**
- large dE/dx
- slow (large time-of-flight)

***see talk by Aniello Spiezia***

**stable neutral**
- missing energy

***see SUSY and LHC DM talks***



**meta-stable charged**
- disappearing track

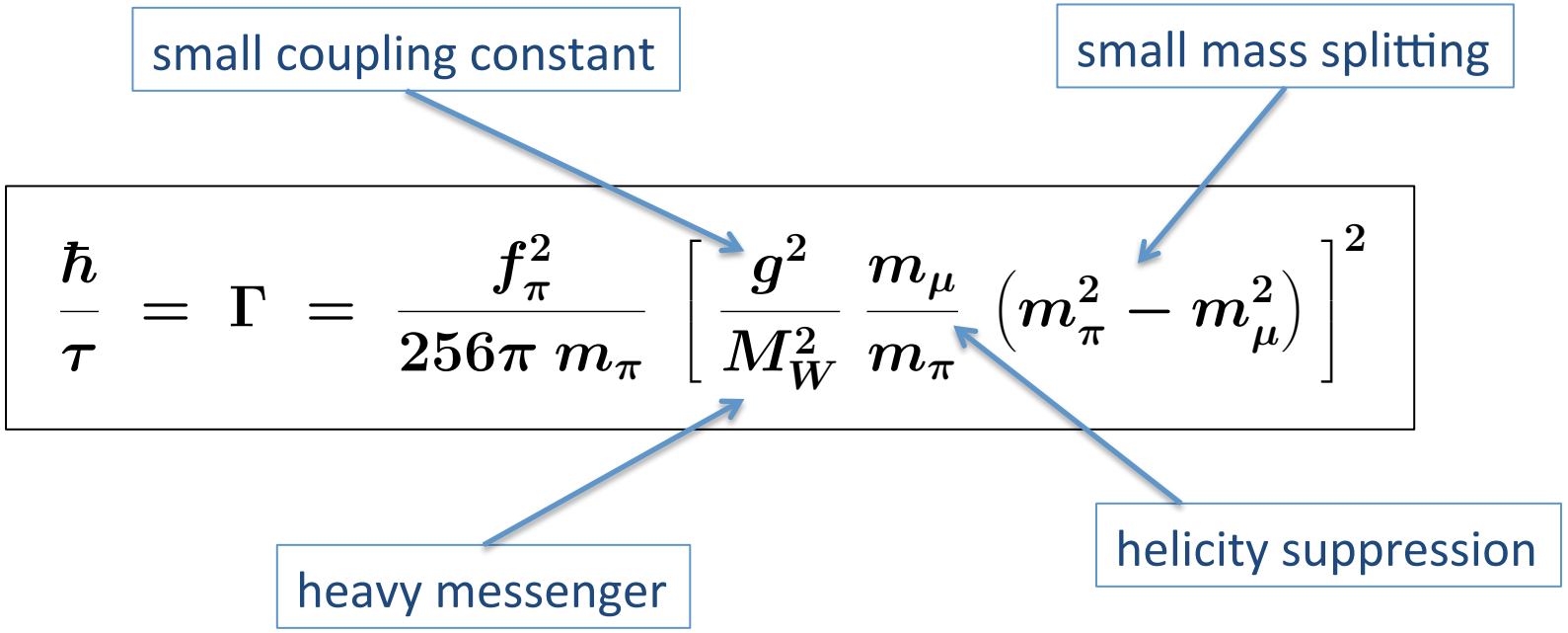
***see talk by Toshiaki Kaji***

**meta-stable neutral**
- displaced vertex/tracks
- jets without tracks

***main subject of this talk***

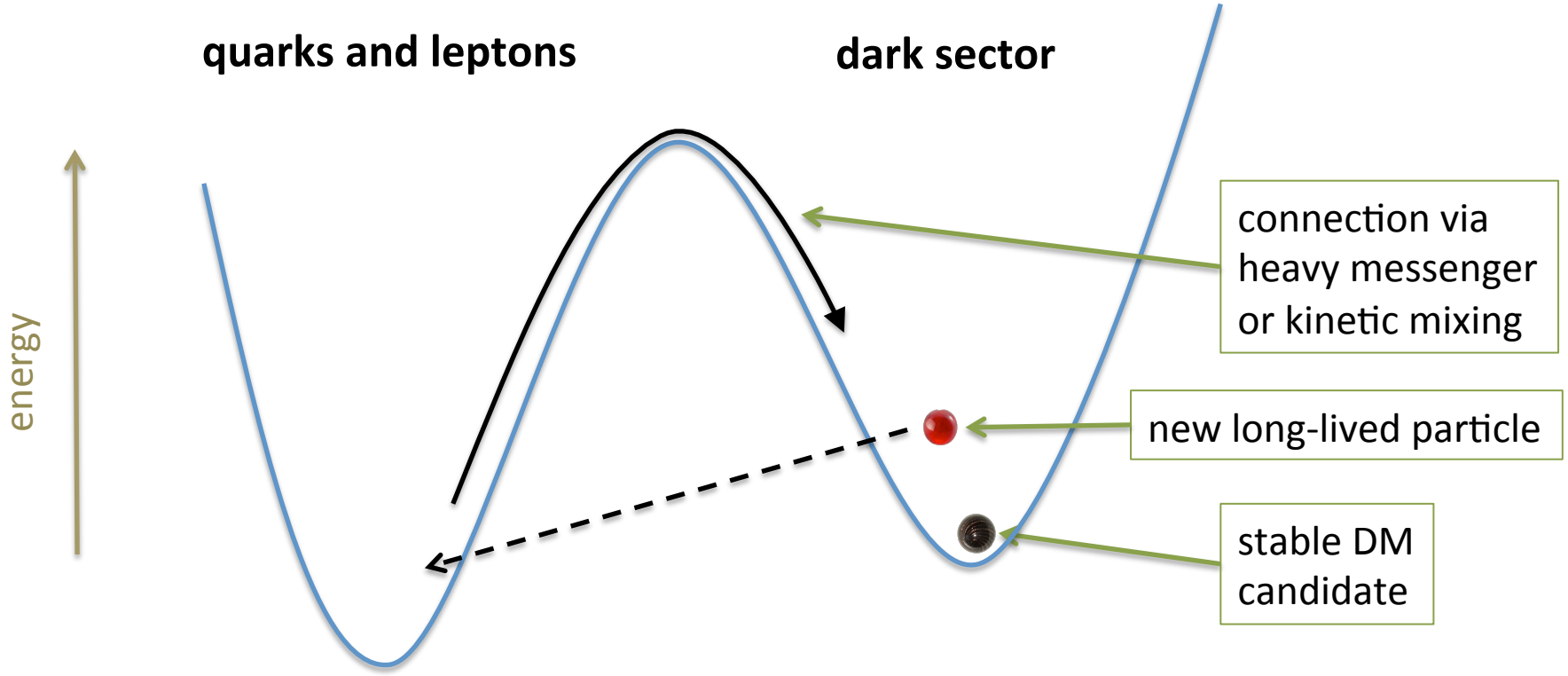
# What makes a particle long-lived?

- textbook formula for lifetime of the charged pion:




- many examples in SUSY:
  - small couplings: R-parity violating couplings, graviton LSP
  - small mass splitting: “Next-to-Lightest-SP”
  - heavy messenger: heavy squarks, Z-prime

# One popular scenario: Hidden Valley

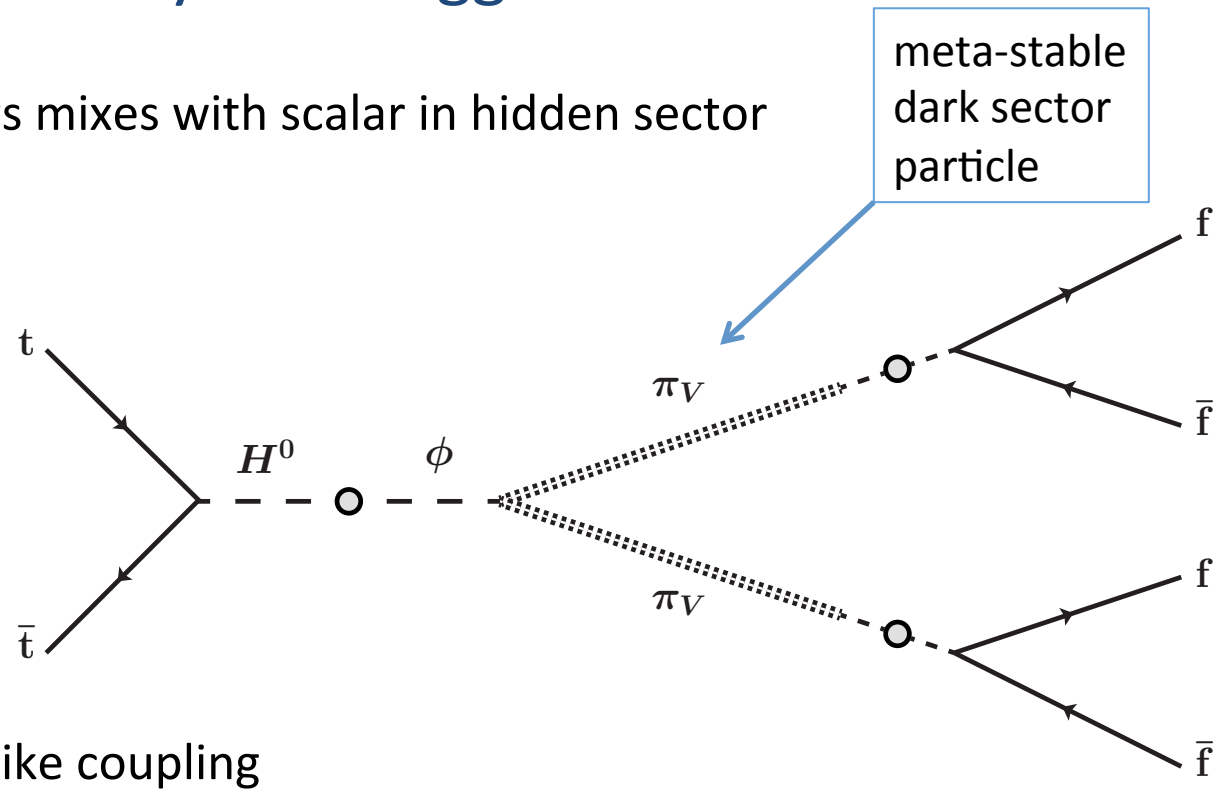



- scenario got renewed interest because of "neutral/uncolored naturalness"
  - top partner 'coloured' under a different SU(3) gauge group
  - dark sector has its own hadronization/confinement
  - Higgs mixes with dark sector scalar and decays to dark sector particles

(see e.g. Curtin and Verhaaren, arXiv:1506.06141; Craig e.a., arXiv:1501.05310v2,

# Hidden Valley via a Higgs Portal

- SM Higgs mixes with scalar in hidden sector

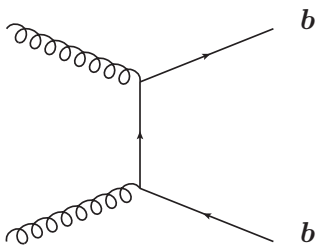



- Higgs-like coupling
  - kinematics known (e.g. SM Higgs production)
  - LLP decays preferentially to heavy fermions (b,c,τ)
- three parameters: m(H), m($\pi_v$), τ($\pi_v$)
- signature
  - most studied: displaced jets
  - alternative: fragmentation in hidden sector → "emerging jets"

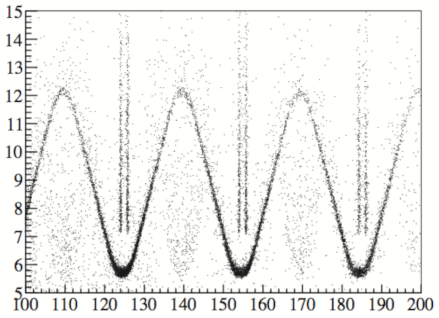
# LLP searches at the LHC

- wide program: see e.g. program of LHC LLP workshops
- ATLAS and CMS are well suited:
  - large luminosity, efficient triggers, excellent tracking/calorimetry
  - new in run-2: 'topological triggers'
- LHCb collects less luminosity, but is more efficient at low mass and lifetime
  - modest $p_T$ requirements; vertex triggers at very high rate
- common experimental issues, e.g. backgrounds:

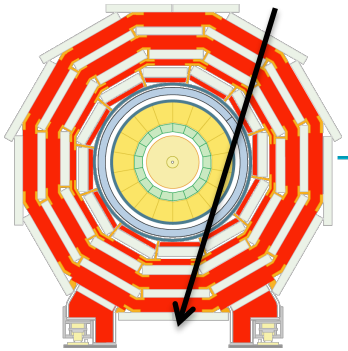
weak decays of heavy flavour



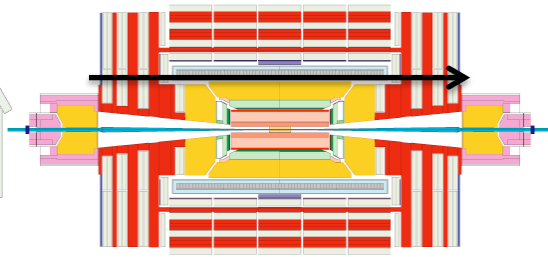

material interactions




cosmic muons

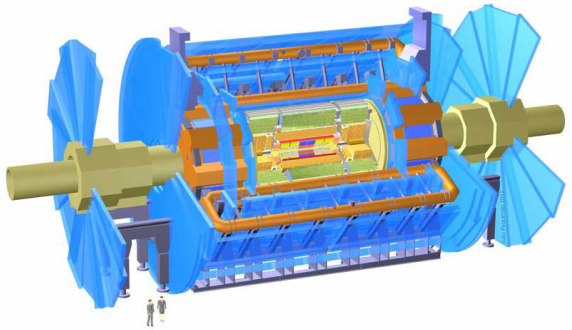


beam halo muons

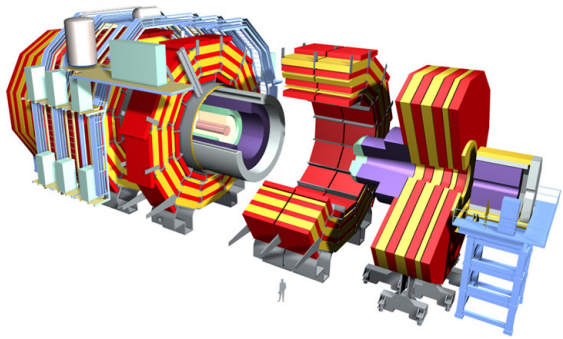


# Selected results

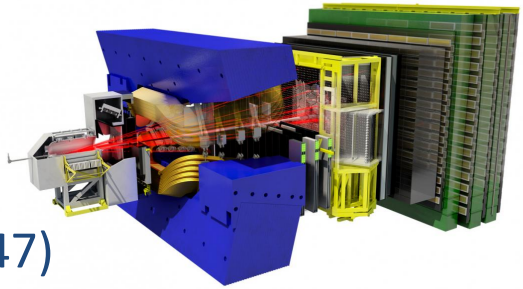
- ATLAS at 13 TeV:
  - neutral LLP in calo (ATLAS-CONF-2016-103)
  - displaced lepton jets (ATLAS-CONF-2016-042)



- CMS at 13 TeV, 2.6/fb:
  - displaced e-mu pairs (CMS PAS-EXO-2016-022)
  - inclusive displaced jets (CMS PAS-EXO-2016-003)



- LHCb at 7/8 TeV:
  - displaced vertex with muon (LHCb-PAPER-2016-047)
  - hidden valley pions decaying to di-jets (LHCb-PAPER-2016-065)
  - scalar resonances in $B \longrightarrow K\mu\mu$ (LHCb-PAPER-2016-52)

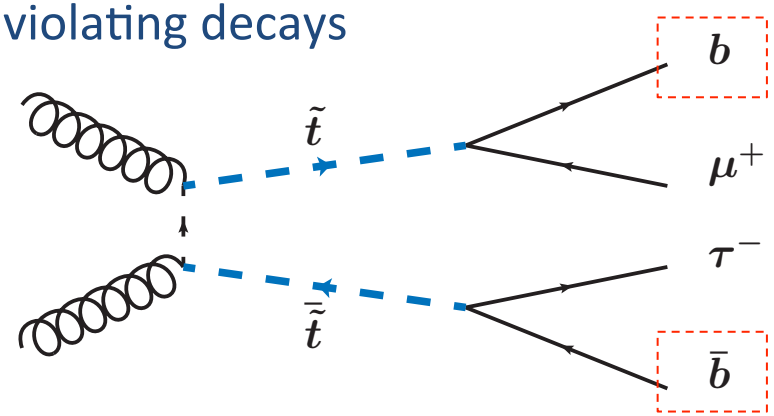


# Inclusive displaced jets at 13 TeV at CMS

- two models:
  - "Jet-Jet": $H \longrightarrow \pi_V\pi_V \longrightarrow$ 4 quarks
  - "B-lepton": top squark pair production with lepton number violating decays

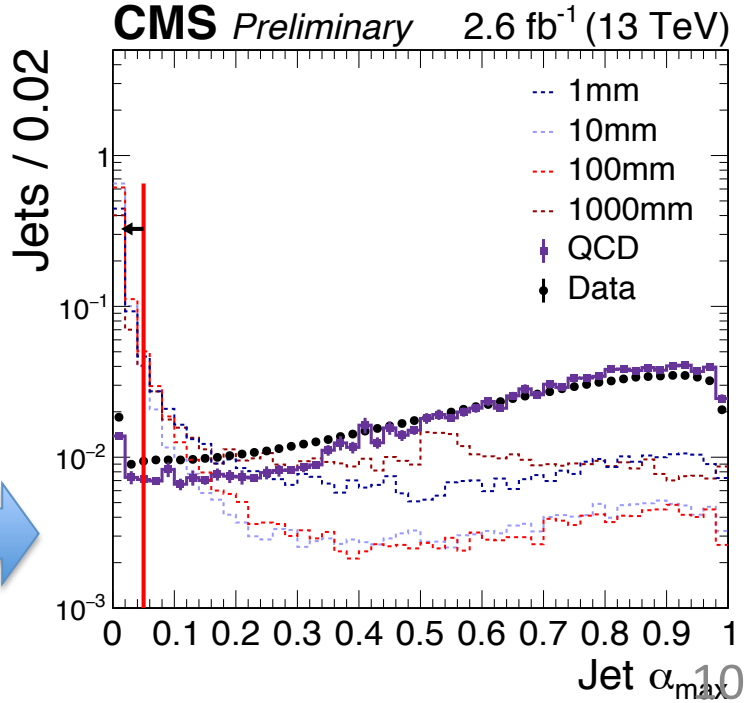
signature:

- 4 displaced hadronic jets
- 2 displaced hadronic jets + evt. tau jets



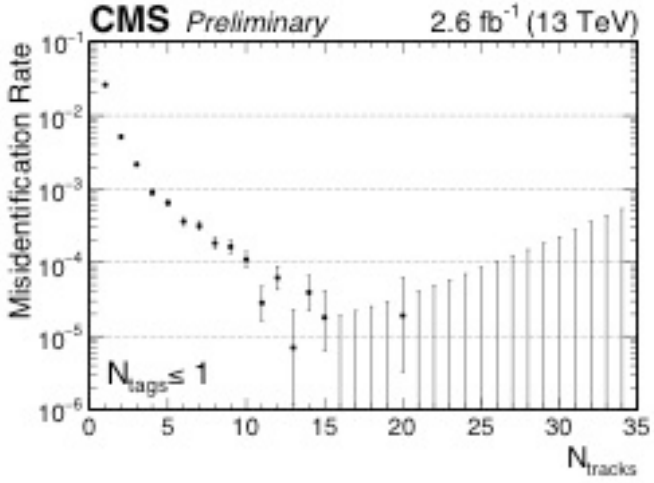

- analysis exploits "topological triggers": high-$p_T$ jets with ≤2 tracks compatible with beam-line

- off-line selection uses several observables to enhance fraction of displaced jets, e.g.
  - max of sum $p_T$ associated to single PV



# Inclusive displaced jets at 13 TeV at CMS

- events with 1 'tagged jet' used to estimate mistag probability as function of #tracks
  → allows to estimate per-event background

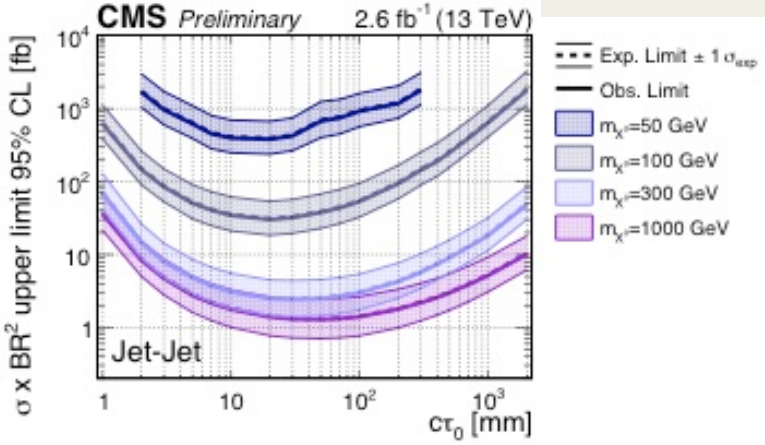



- yield in signal region in 2.6/fb at 13 TeV:

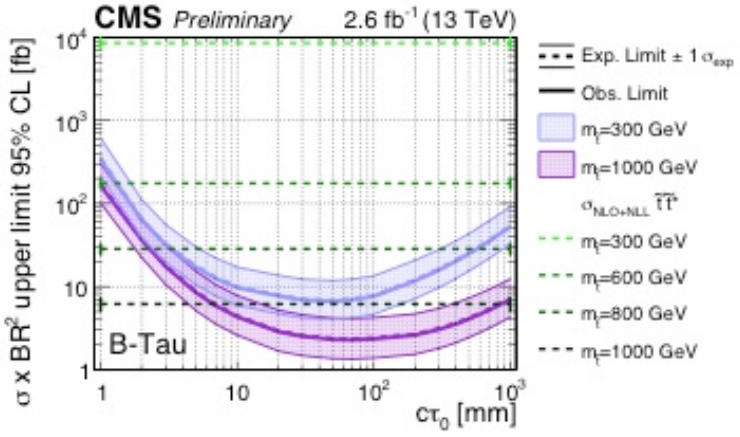
| $N_{\text{tags}}$ | observed | expected |
|---|---|---|
| 2 | 1 | $1.09 \pm 0.16$ |
| $\geq 3$ | 0 | $(4.9 \pm 1.0) \cdot 10^{-4}$ |

- interpretation in models:

*Jet-Jet model*



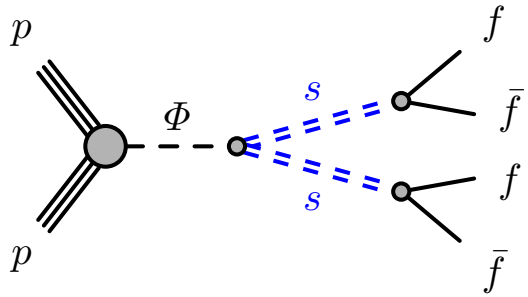

*B-tau model (top squark)*

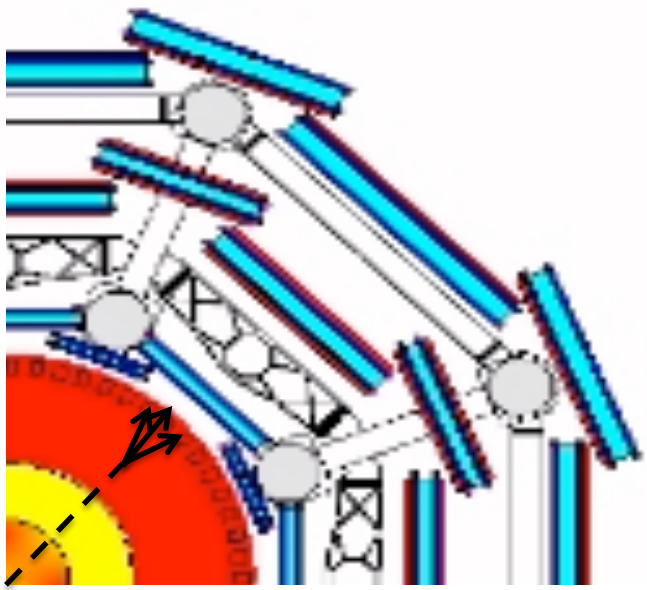



- top squark results are most constraining for long-lived stops to date

# Heavy Higgs decays to track-less jets at ATLAS

- model: heavy Higgs mixing with dark sector scalar
- signature: events with ≥2 hadronic jets without tracks



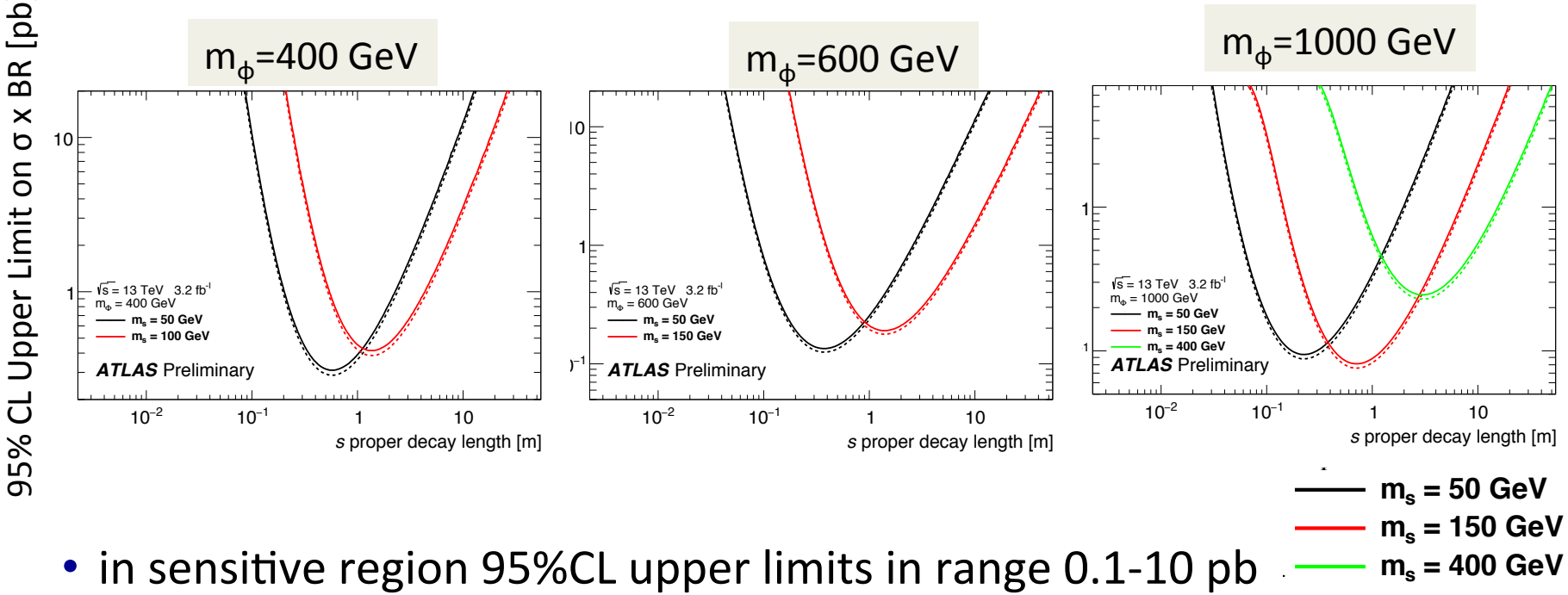
- finite region in decay length:
  - barrel: $2.0 < R_{xy} < 3.6$ m
  - end-cap: $4.2 < R_z < 5.4$ m
- search tuned for LLPs with mass 100-150 GeV, pair produced in the decay of a scalar of 400-1000 GeV

- main backgrounds
  - multi-jet background
  - cosmics
  - beam-halo muons

- main discriminants
  - fraction of hadronic energy ('CalRatio')
  - jet width
  - proximity of high-PT tracks to jet axis
  - calo cluster time

# Heavy Higgs decays to track-less jets at ATLAS

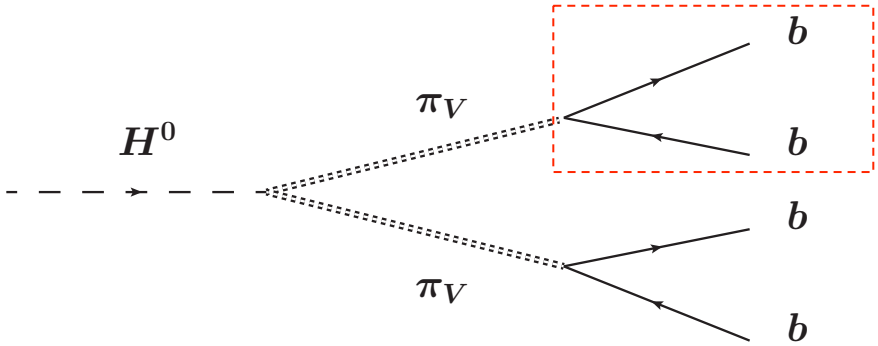
- event yield in **3.2/fb at 13 TeV**:
  - **24** observed
  - **18.0 ± 6.3** expected background
- limits as function of lifetime for different values of $m_\phi$ and $m_S$




- in sensitive region 95%CL upper limits in range 0.1-10 pb
- best sensitivity obtained for lifetimes in range 0.5-5 ns

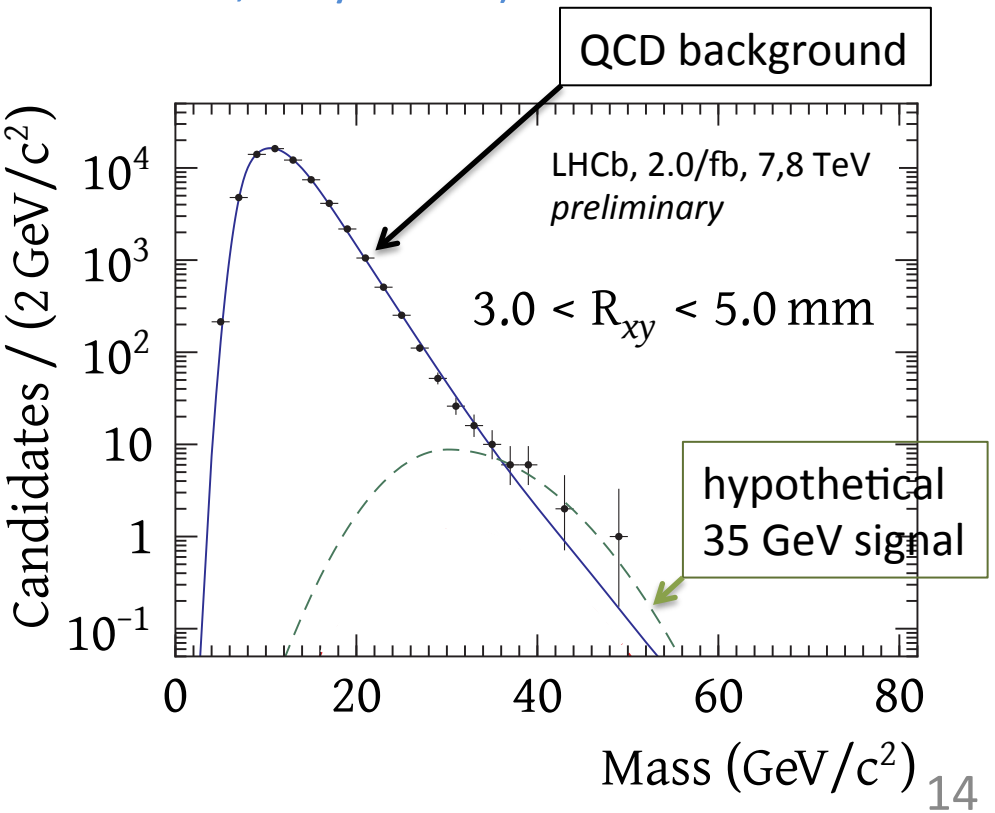
# Hidden Valley v-pions decaying to jet pairs at LHCb

- model: Higgs decay to two LLPs each decaying to two fermions



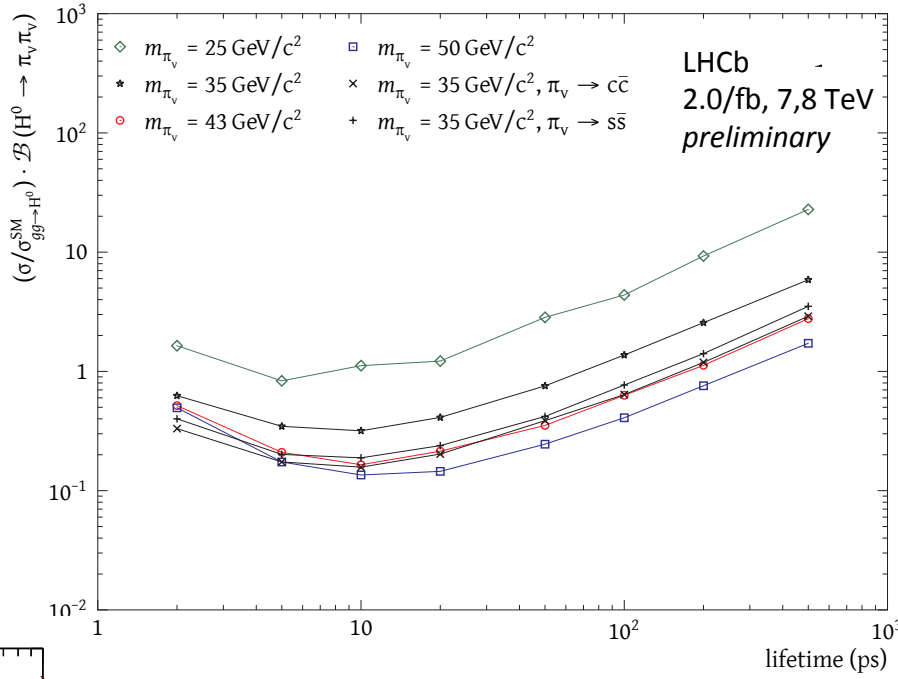

- LHCb signature: single displaced vertex with two associated jets (LHCb acceptance for all 4 jets is small, only few %)

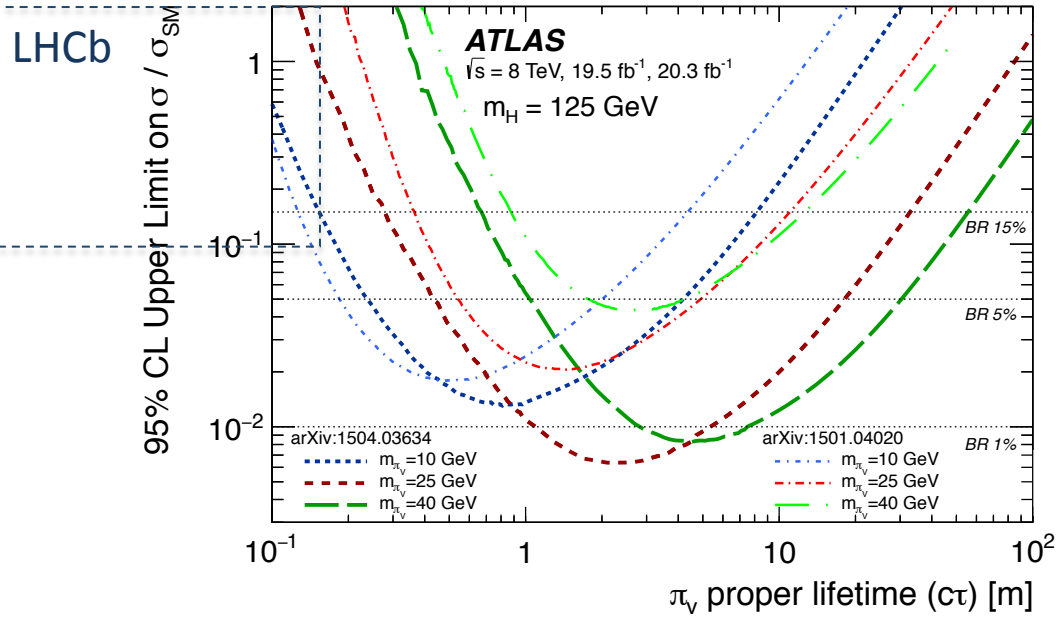
- analysis strategy
  - trigger on displaced vertex
  - find two associated jets
  - extract signal from fit to di-jet mass in bins of distance to beam axis ($R_{xy}$)



# Hidden Valley v-pions decaying to jet pairs at LHCb

- no excess above background in 2.0/fb of 7/8 TeV data
- place 95% CL upper limits on BR( $H^0(125) \longrightarrow \pi_V\pi_V$, $\pi_V \longrightarrow bb$ ) for $25 < m < 50$ GeV and $2 < \tau < 500$ ps
- most sensitive point (m=50 GeV, t=10 ps) exclude BR > 10 %



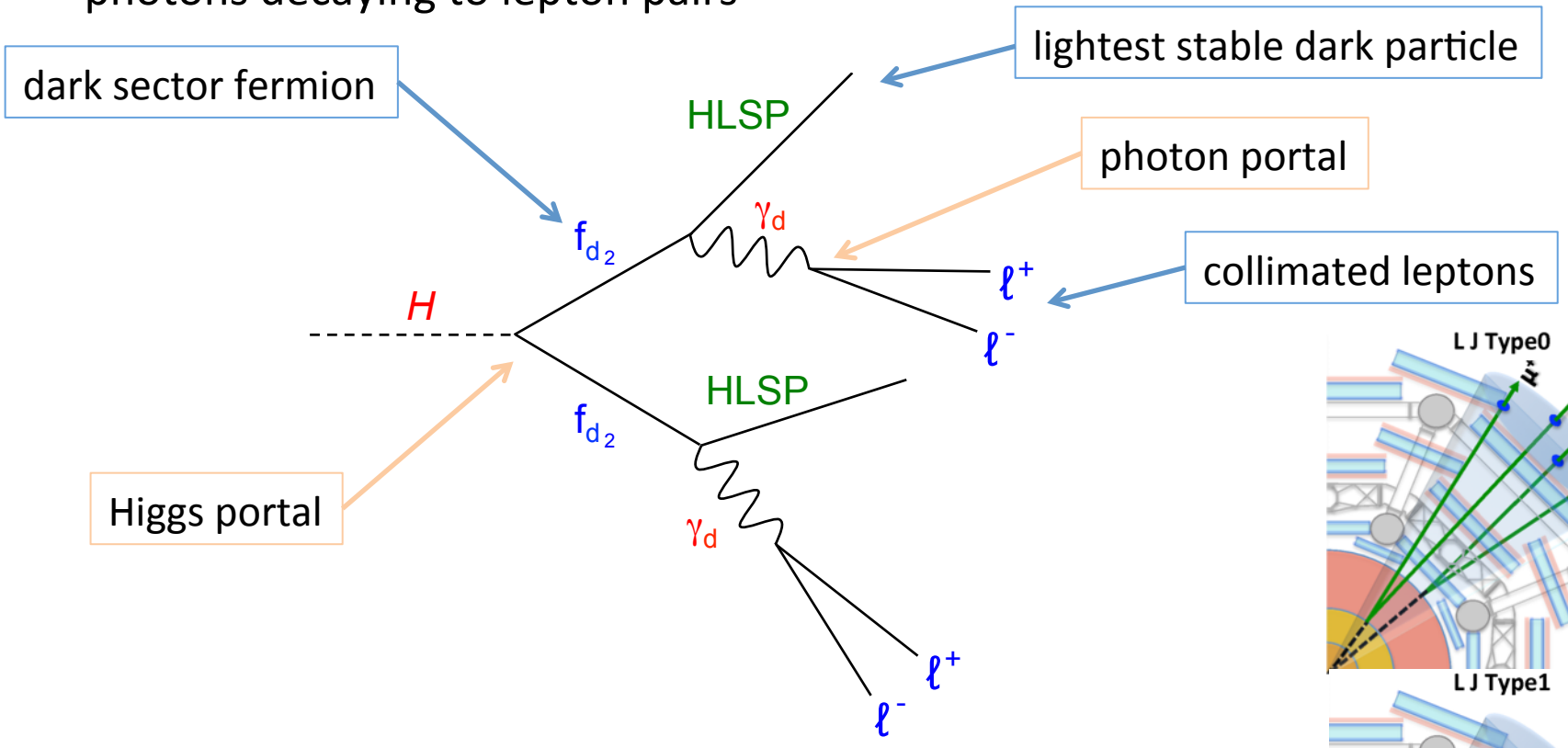



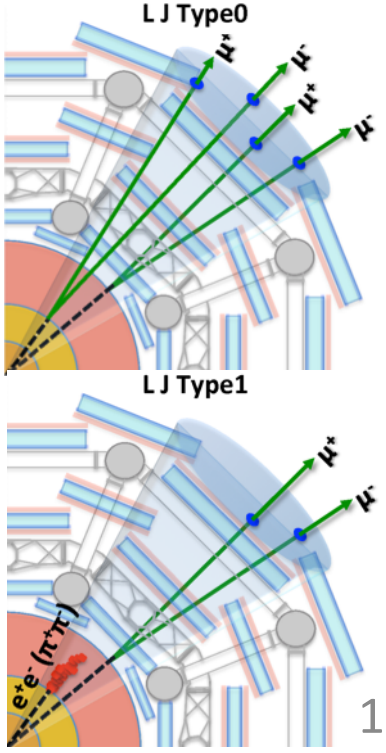

compared to similar analyses from ATLAS (left) and CMS, LHCb is more sensitive in region with small mass and lifetime

# Displaced lepton jets at 13 TeV at ATLAS

(see also V. Martinez Outschoorn in Sunday session!)

- FRVZ(*) model: Higgs decays to dark sector fermions, that radiate dark photons decaying to lepton pairs




- search strategy: look for events with 2 or 4 jets consisting of **pairs of muons, electrons or pions without tracks**

(*) Falkowski-Ruerman-Volansky-Zupan, JHEP05(2010)077, PRL105(2010)241801

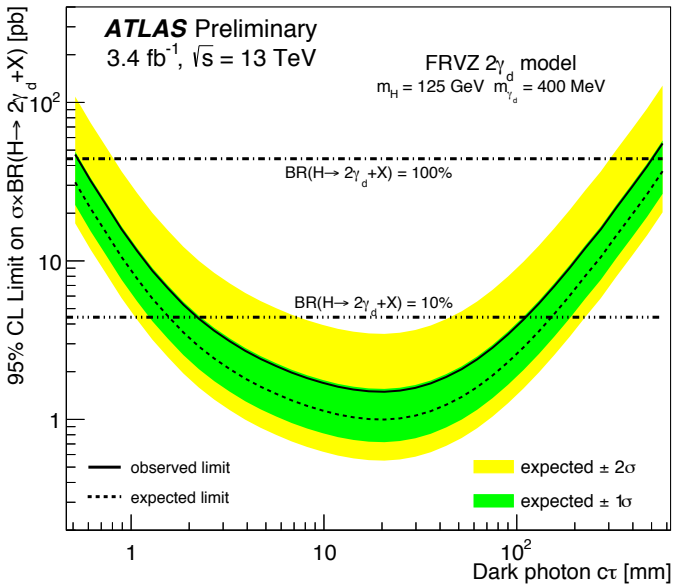
# Displaced lepton jets at 13 TeV at ATLAS

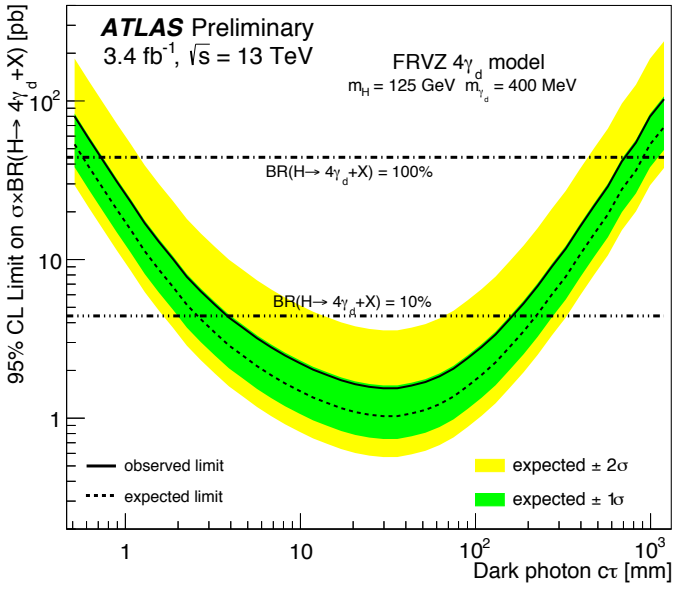
- observed event yields in 3.4/fb compatible with background

| observed | exp.bkg. |
|---|---|
| **46** | **32 ± 9** |

| $H(125) \longrightarrow 2\ \gamma_d + X$ | $H(125) \longrightarrow 4\ \gamma_d + X$ | RFVZ |
|---|---|---|
| 111 ± 2 | 96 ± 2 | |

- results interpreted in FRVZ model with dark photon mass of 400 MeV:



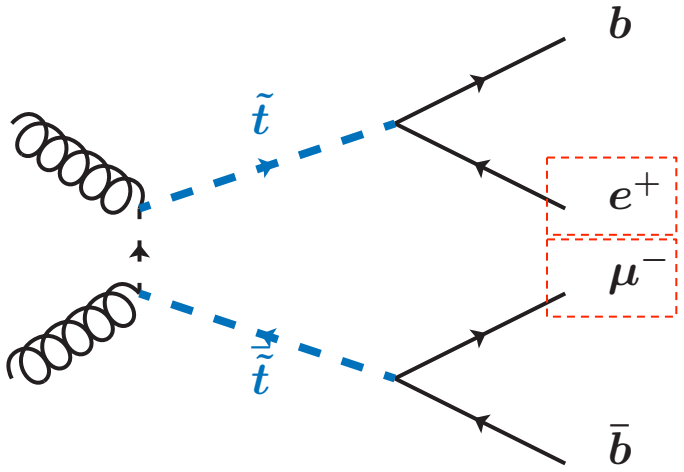




*95%CL limit on BR(H⟶ 2(4) $\gamma_d$+X) versus dark photon lifetime*

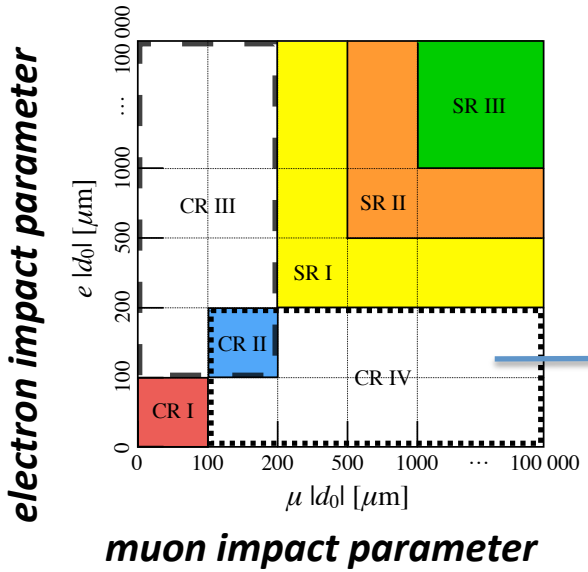
- Higgs branching fraction larger than 10% excluded for $2 < c\tau < 111$ mm
- see paper for limits on model with Higgs of 800 GeV

# Displaced e-mu pairs at 13 TeV at CMS

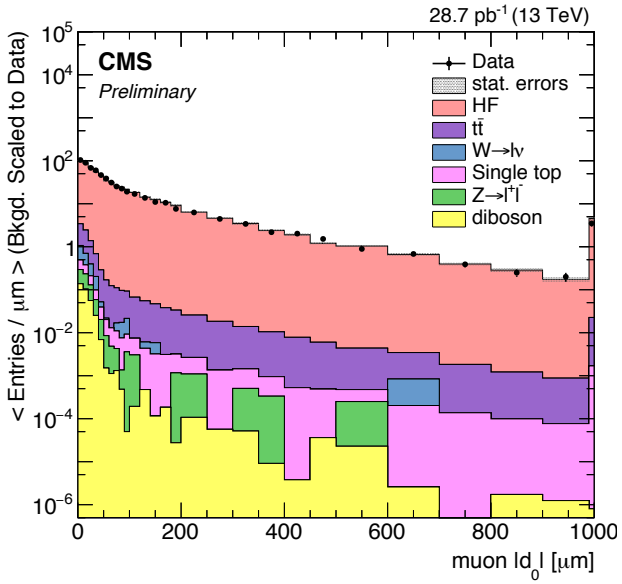
- model: top squark pair production with lepton number violating R-parity violation
- signature: displaced, non-vertexed muon-electron pairs




- main background: semileptonic b and c decays
  - shape estimated using B-tagged tag-and-probe method
  - yield estimated with ABCD method

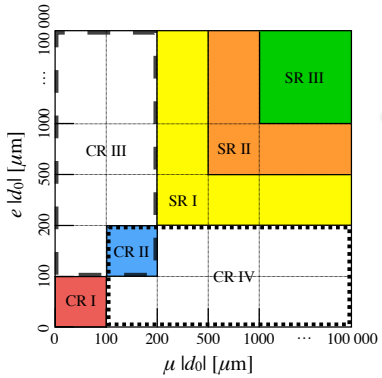



control region (electron replaced with B-tagged jet)



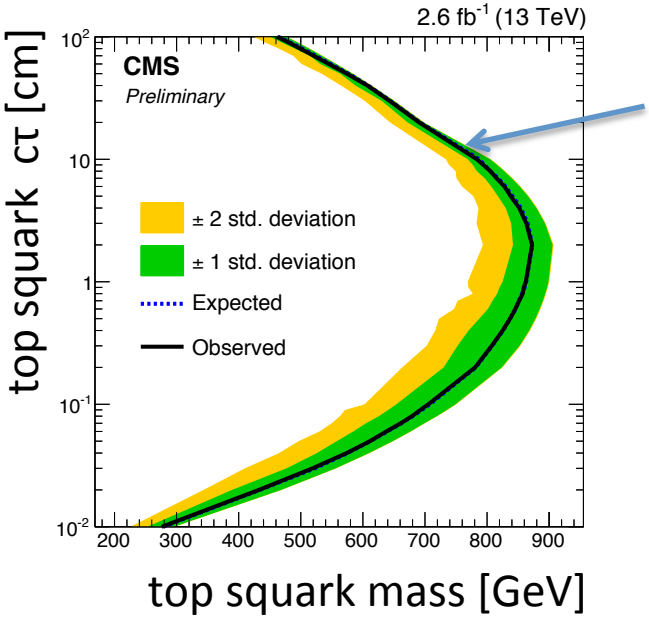
# Displaced e-mu pairs at 13 TeV at CMS

- event yield in different signal regions in 2.6 $fb^{-1}$ at 13 TeV




| SR | estimated background | **observed** | expected stop (1cm,700 GeV) |
|---|---|---|---|
| III | < 0.020 | **0** | 7.0 ± 0.3 |
| II | < 0.50 | **0** | 4.1 ± 0.3 |
| I | < 3.2 | **1** | 5.2 ± 0.4 |

- interpretation in context of stop pair production, for simplified model with decoupled squarks and gluinos:




exclusion limit at 95% CL

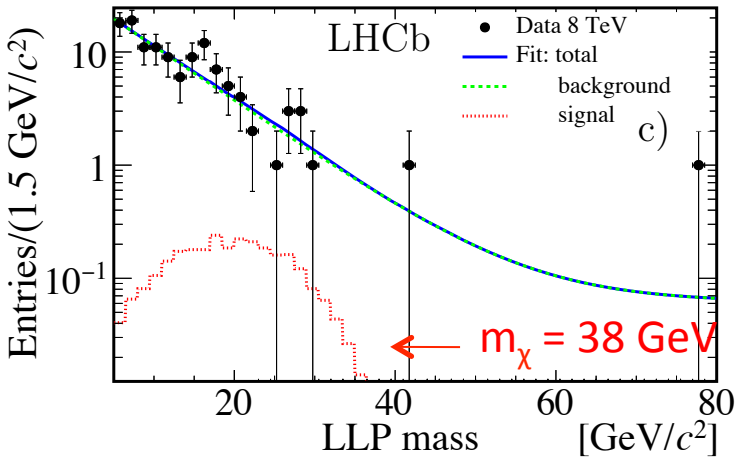
- similar displaced di-lepton analyses in RUN-1 data:

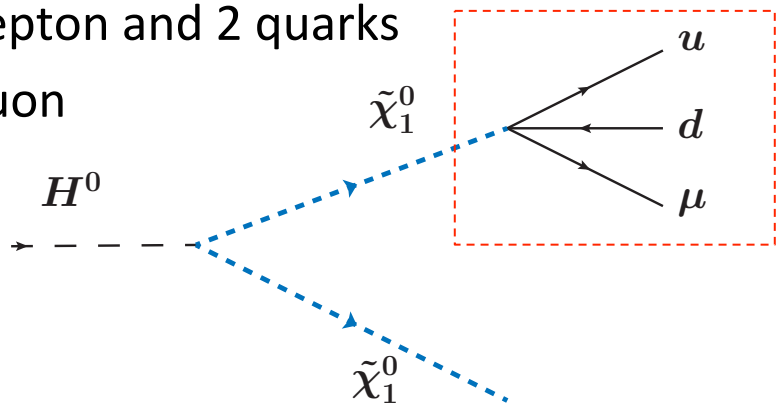
  CMS, PRL114(215)061801

  ATLAS,PRD92(2015)072004

# Semi-leptonic LLP decays at LHCb at 7 and 8 TeV

- model: mSUGRA neutralino decaying to a lepton and 2 quarks
- signature: single displaced vertex with 1 muon



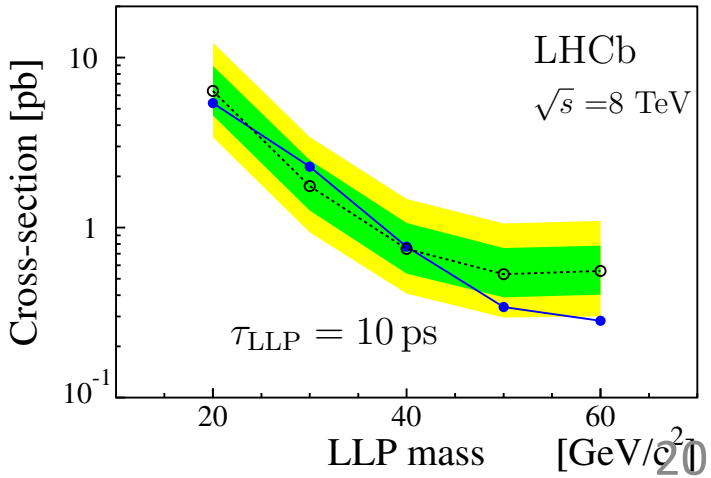




signal yield extracted from fit to vertex invariant mass

- result: no excess above background, at 7 and 8 TeV
- interpretation in various models, a.o.
  - non-resonant neutralino production
  - production in squark decays
  - production in Higgs decays (see right)

  as function of χ mass and lifetime

one example of H(125)⟶χχ limit

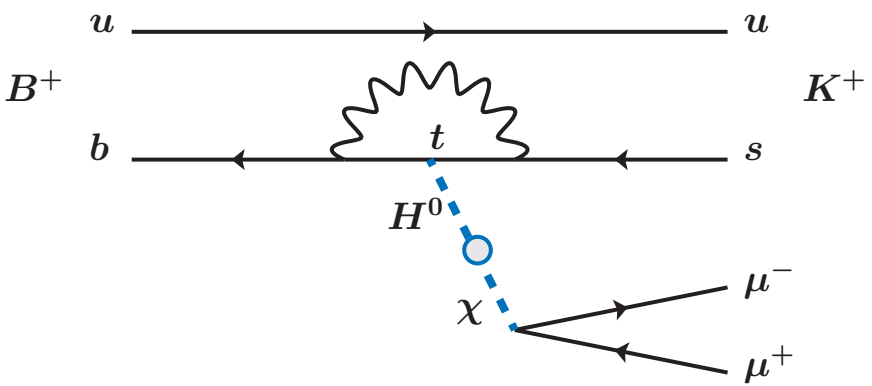


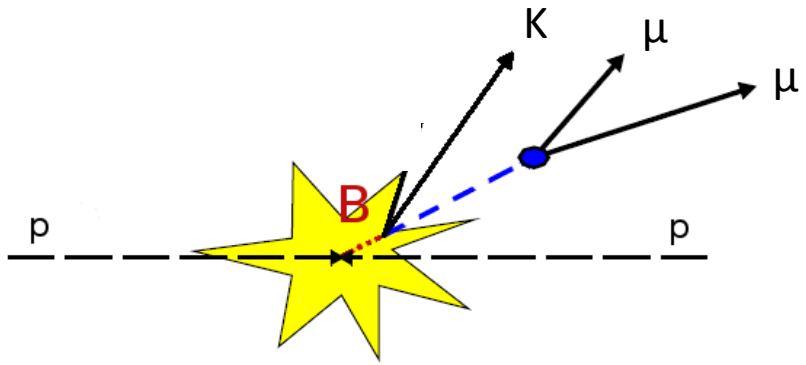

- at most sensitive point (~50GeV, ~10ps) reject BR(H⟶χχ) > 1%

# Hidden sector $\chi \longrightarrow \mu^+\mu^-$ in $B^+ \longrightarrow K^+\mu^+\mu^-$ at LHCb

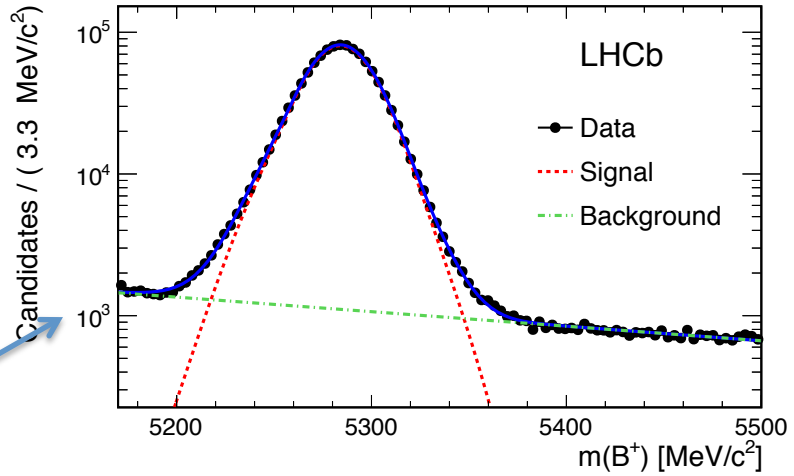
- b⟶s quark transitions give access to new light narrow scalar resonances
  - (prompt) axion (e.g. Freytsis, Ligeti and Thaler, arXiv:0911.5355)
  - (long-lived) inflaton (e.g. Bezrukov and Gorbunov, arXiv:0912.0390)

  via mixing with SM Higgs



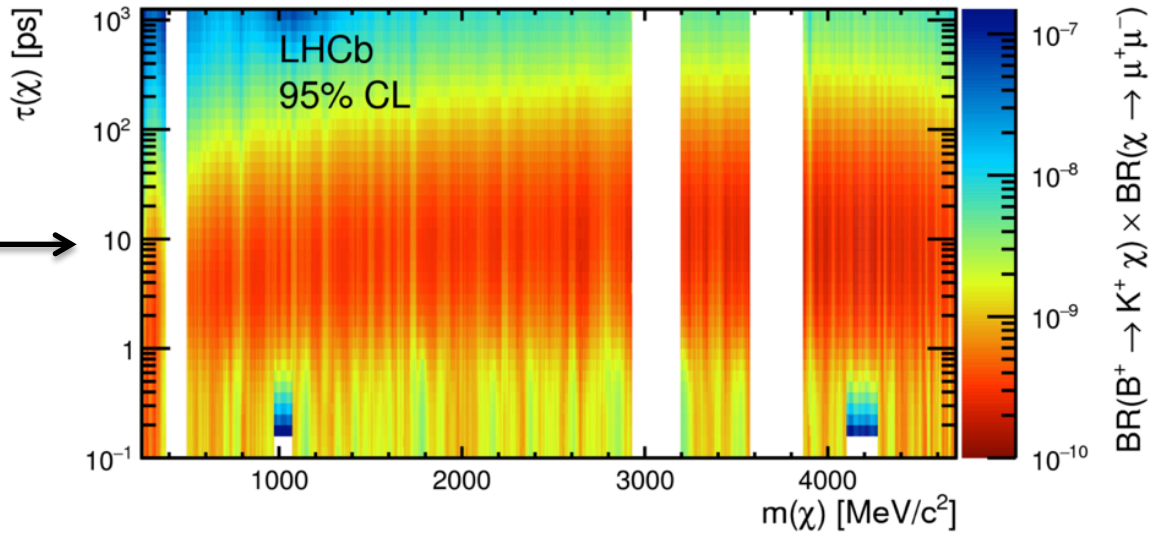

- experimental method:
  - search for narrow peak in μμ invariant mass in B⟶Kμμ decays, in 3 different μμ lifetime bins
  - normalize to $10^6$ B⟶J/ψ K decays

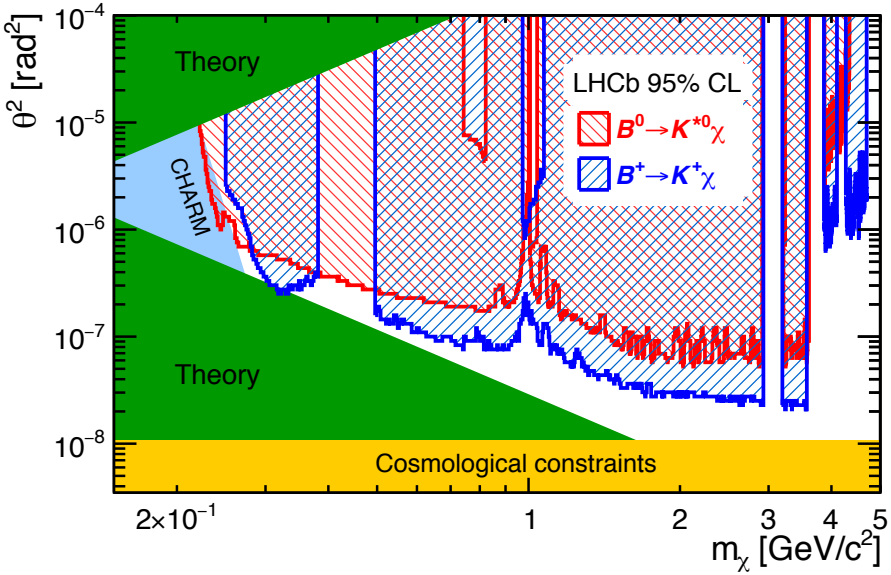


# Hidden sector $\chi \longrightarrow \mu^+\mu^-$ in $B^+ \longrightarrow K^+\mu^+\mu^-$ at LHCb

- no signal above background in 3.0/fb of 7/8 TeV data
- obtained 95% CL on branching fraction as function of $m_\chi$ and $\tau_\chi$

  white areas excluded because of backgrounds from Ks, $\phi(1040)$, $J/\psi$, $\psi(2S)$ and $\psi(4160)$




- interpretation in inflaton model:

$$\mathcal{B}(B^+ \to K^+\chi) \propto \theta^2 \qquad \tau(\chi) \propto 1/\theta^2$$

Higgs-inflaton mixing

→ most of parameter space excluded

- similar searches for LLPs in B decays:

  $\chi \longrightarrow \mu\mu$ in $B \longrightarrow K^*\mu\mu$ (PRL 115, 161802 (2015))

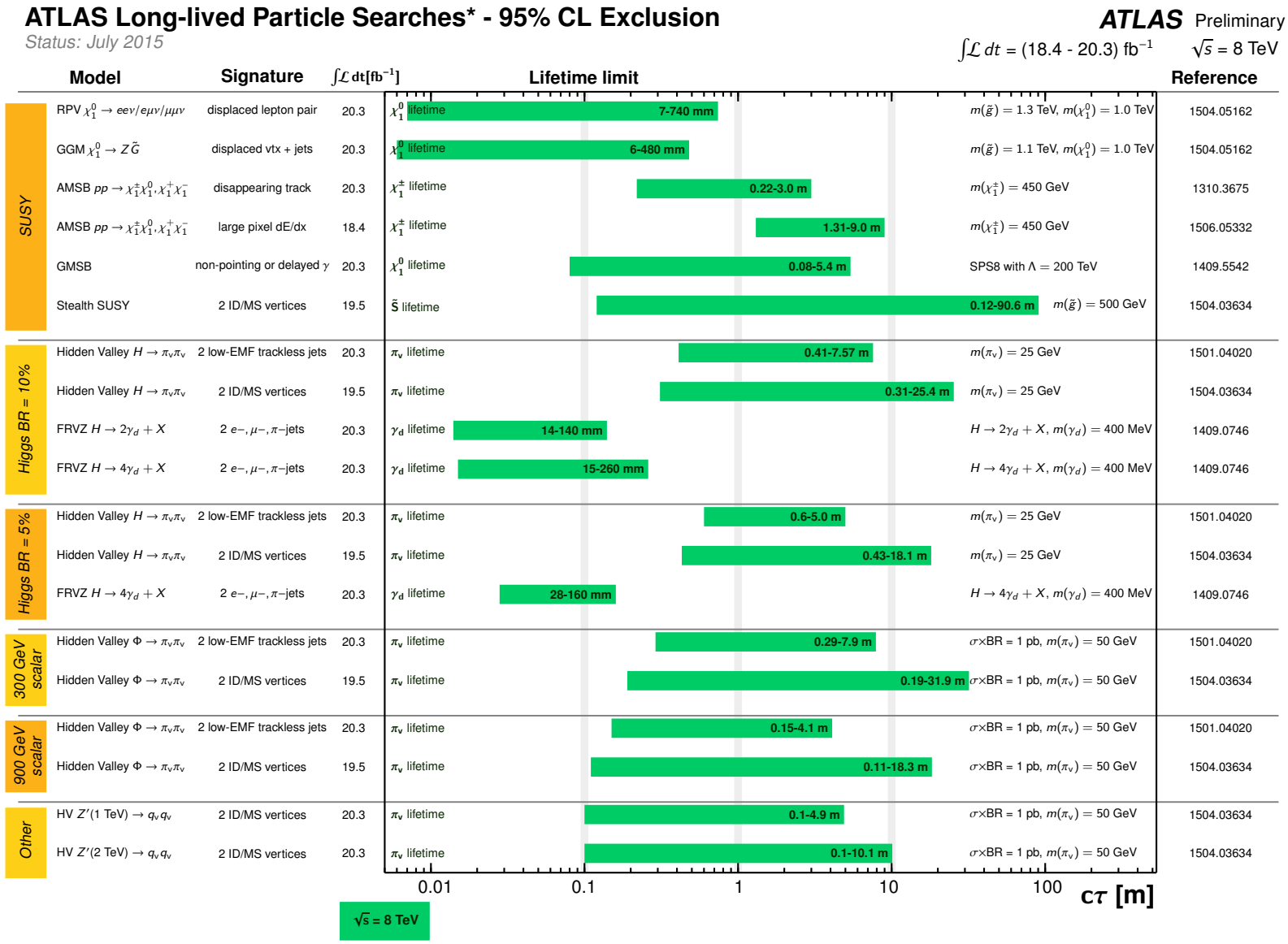
  $N \longrightarrow \mu\pi$ in $B \longrightarrow \pi\mu\mu$ (PRL 112,131802 (2014))

# Summary

- long-lived particle signature is well-motivated and gaining in popularity
  - R-parity violating SUSY, sterile neutrinos, hidden valleys …
- wide variety of searches
  - this talk: new results on signatures with a ‘displaced vertex’
  - for other signatures, see talks by Spiezia and Kaji
- no discovery so far … but we keep looking!
- next LHC LLP workshop (CERN, 24-26 April 2017)

  https://indico.cern.ch/event/607314/
  - missing signatures
  - triggers
  - recasting
  - …

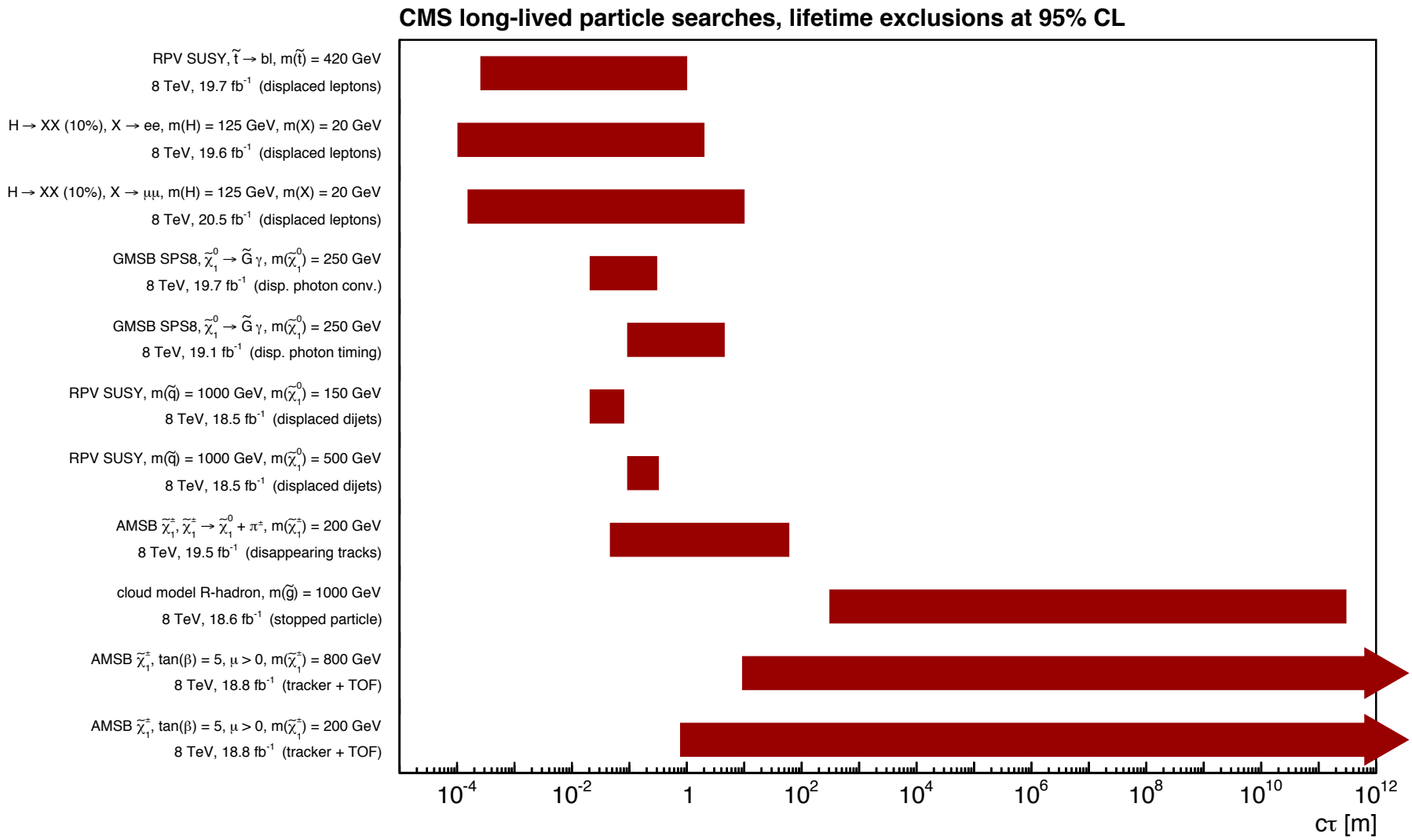
# BACKUP




*Only a selection of the available lifetime limits on new states is shown.

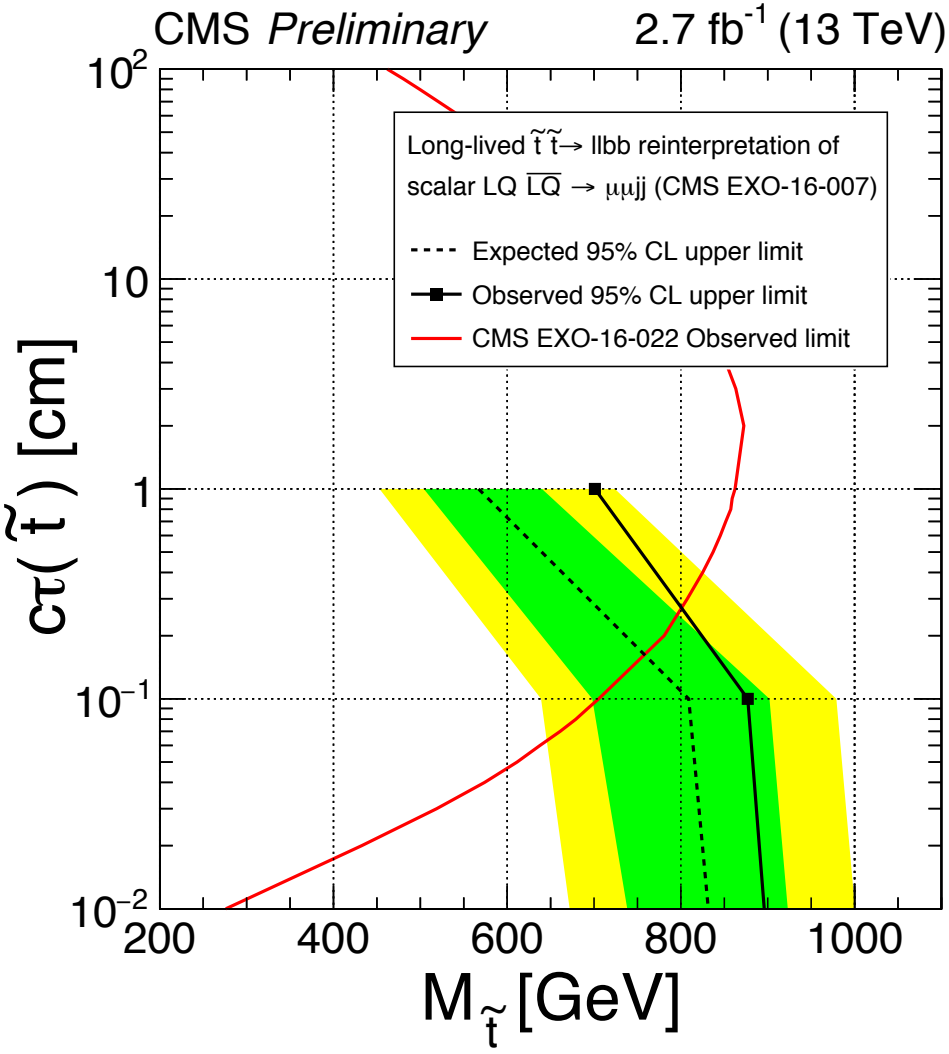
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

CMS-PAS-EXO-16-007




Example of reinterpretation in CMS: constraints on long-lived stop pair production from a lepto-quark analysis