Searches for unconventional signatures and long-lived particles

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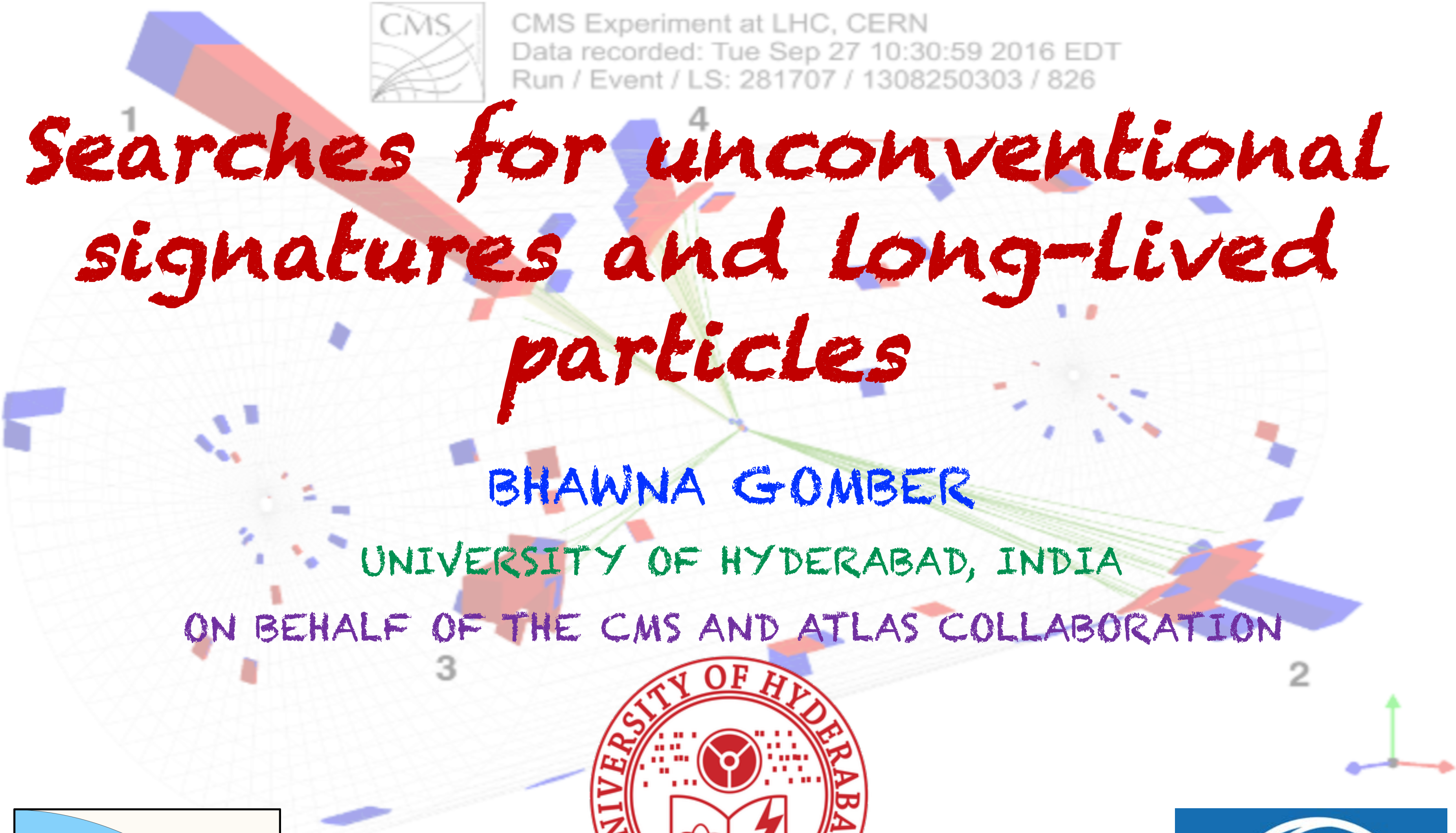
ON BEHALF OF THE CMS AND ATLAS COLLABORATION



LHCP 2020

May 25-30 2020

Searches for long-lived particles

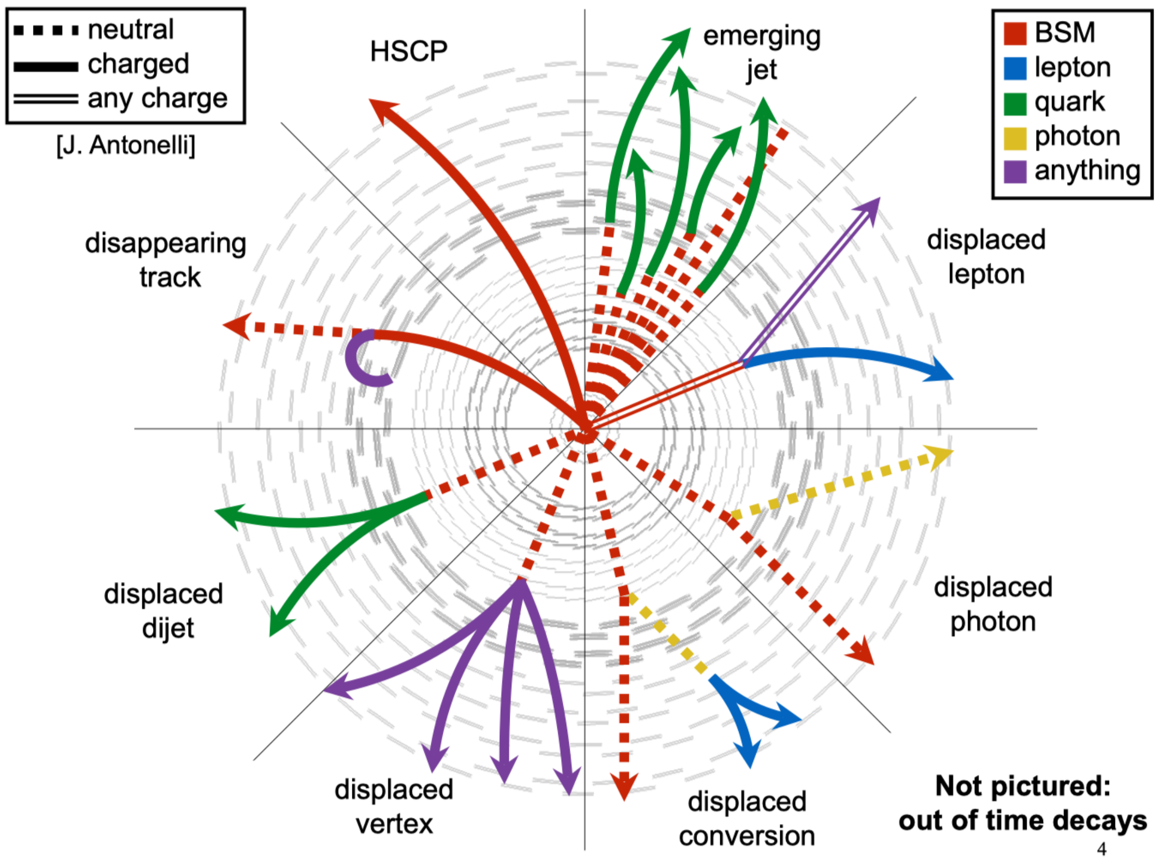
☆ **LLPs** have **unconventional signatures**

☆ **LLPs** signature depend on the **lifetime cτ**

☆ Quasi-stable LLP
Cross the detector

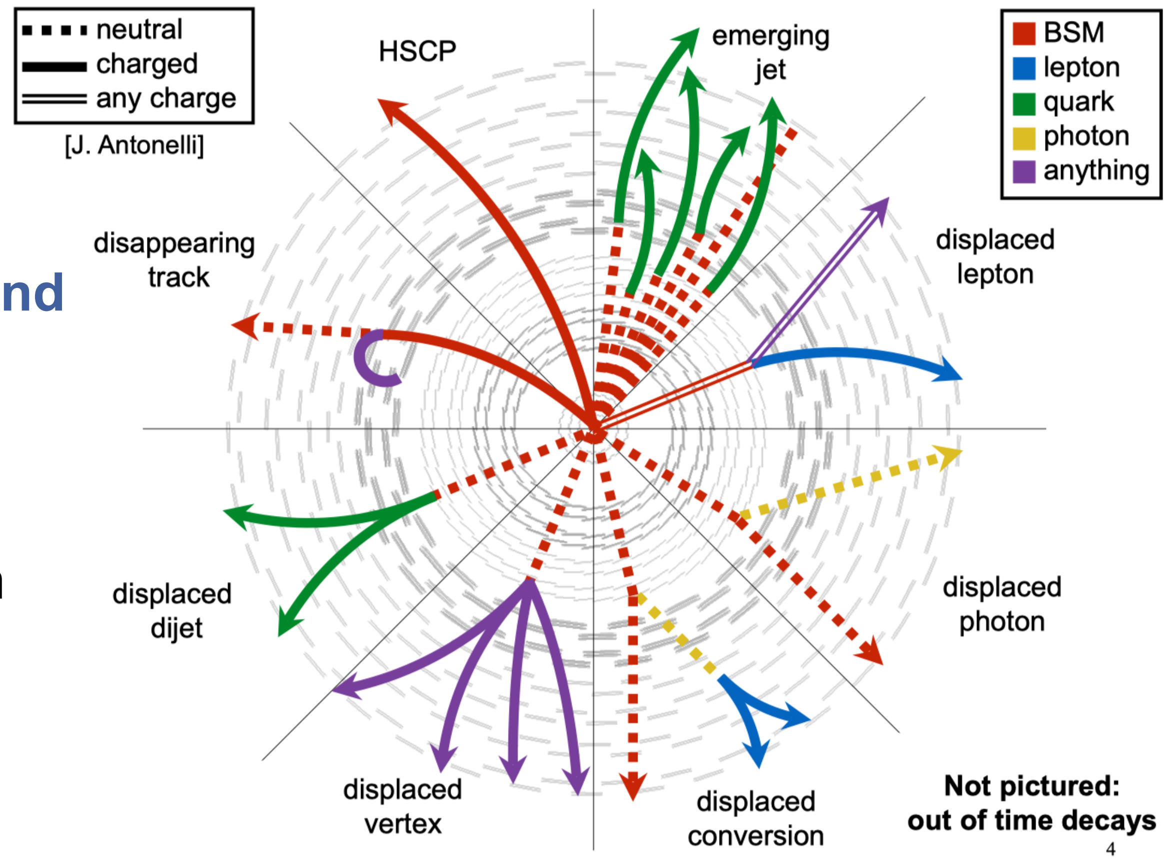
☆ Decay inside the detector

- ☆ Displaced or disappearing objects, stopped particles



Searches for long-lived particles

- ☆ **Challenging** from the **experimental point of view**
  - ☆ Non-standard reconstruction
    - ☆ Displacements, timing and ionization
  - ☆ **Dedicated triggers**



- ☆ **Non-standard background** is a challenge
- ☆ **Detector noise, cosmic rays, reco failures**
- ☆ Should be estimated from **data**

Many Long-lived Searches

Results presented in the talk today

ATLAS	**EXO PublicResults**
Displaced vertex and muon **(136 fb^{-1})**	CERN-EP-2019-219 Full Run2
Displaced Hadronic jets (36 fb^{-1})	EPJC 79 (2019) 481, PRD 101 (2020) 052013
Reinterpretation of Displaced Hadronic jets with RECAST framework (36 fb^{-1})	ATL-PHYS-PUB-2020-007

CMS	**EXO PublicResults**
Displaced jets **(132 fb^{-1})** Full Run2	EXO-19-021
Disappearing tracks **(140 fb^{-1})** Full Run2	arXiv:2004.05153
Neural-network based LLP search (36 fb-1)	EXO-19-011, arXiv:1912.12238

- ☆ **More can be seen in these talks in parallel session:**
  - ☆ Searches for long-lived particles in CMS: Allison Hall
  - ☆ Searches for long-lived particles in ATLAS: Masahiko Saito

Full Run2

LLP SEARCH WITH DISPLACED VERTEX AND MUON WITH LARGE IMPACT PARAMETER

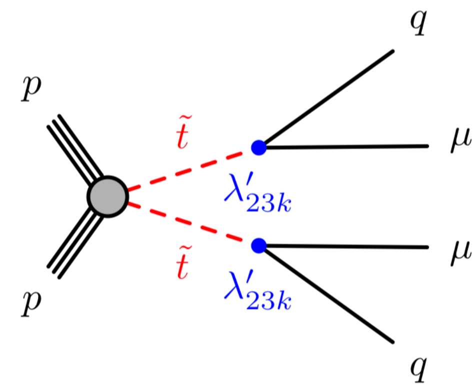
CERN-EP-2019-219, arXiv:2003.11956

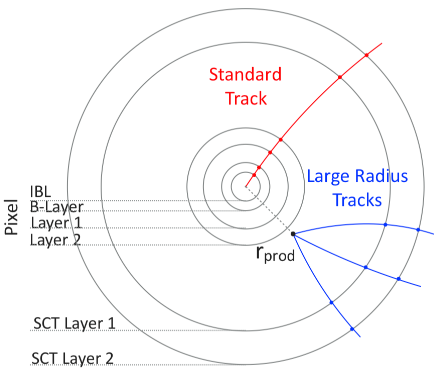
Displaced Vertices and Muon

arXiv:2003.11956

Full Run-II result ! (136 fb^{-1}, 2016-2018)

- Pair production of stop LSP, followed by t~ -> qμ with small λ'_{23k} coupling
- Range of lifetime ~ 0.01 ns to 100 ns





- Large radius tracking: using the leftover hits not already associated to tracks from standard reconstruction by relaxing req. for impact parameter and number of shared hits [ATL-PHYS-PUB-2017-014]
- Displaced secondary vertex algorithm and muons should be non-pointing [ATL-PHYS-PUB-2019-013]

- Main Backgrounds:
  - Cosmic muons
  - Fake muons from random hit combinations (have poor quality of fit)
  - Semi-leptonic decays of SM hadrons

ATLAS

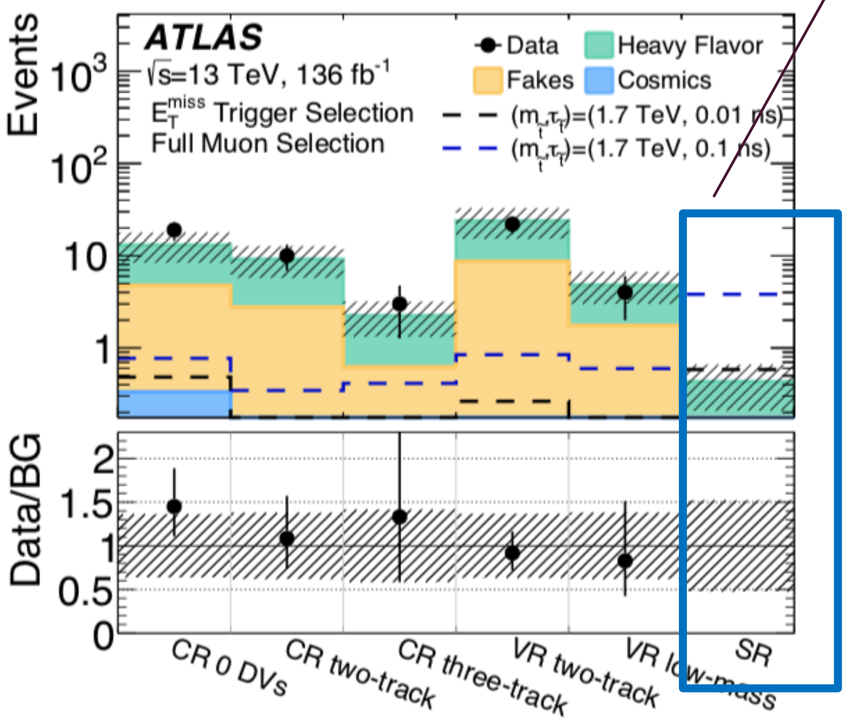
Displaced Vertices and Muon

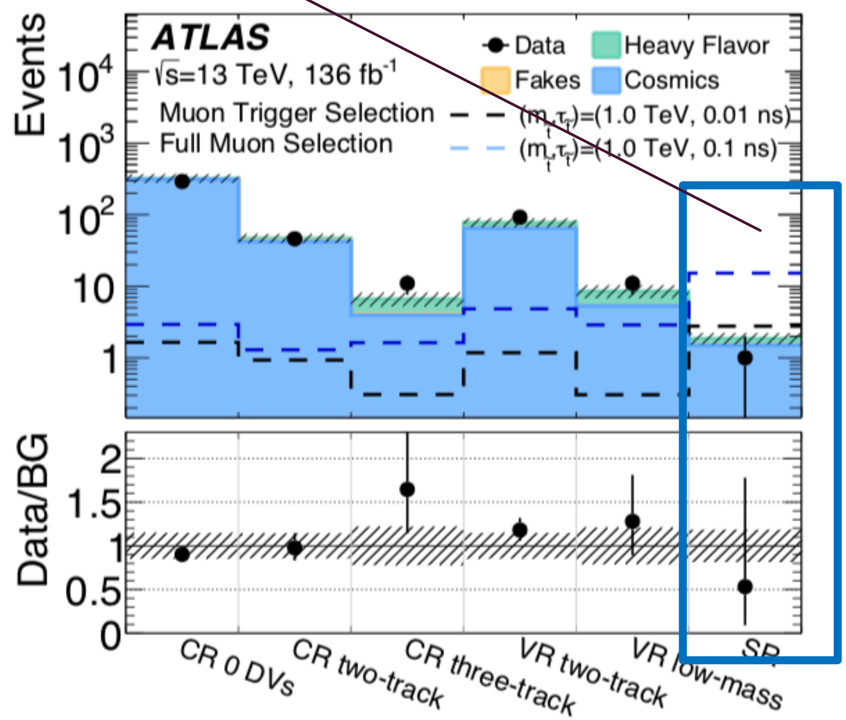
arXiv:2003.11956

- Two Mutually exclusive trigger-based selections
  - missing E_T > 180 GeV
  - muon (p_T^{μ} > 60 GeV, $E_{T,miss}$ < 180 GeV)

- Background estimation comes from transfer factors in region that don't pass the full selection

Signal Region



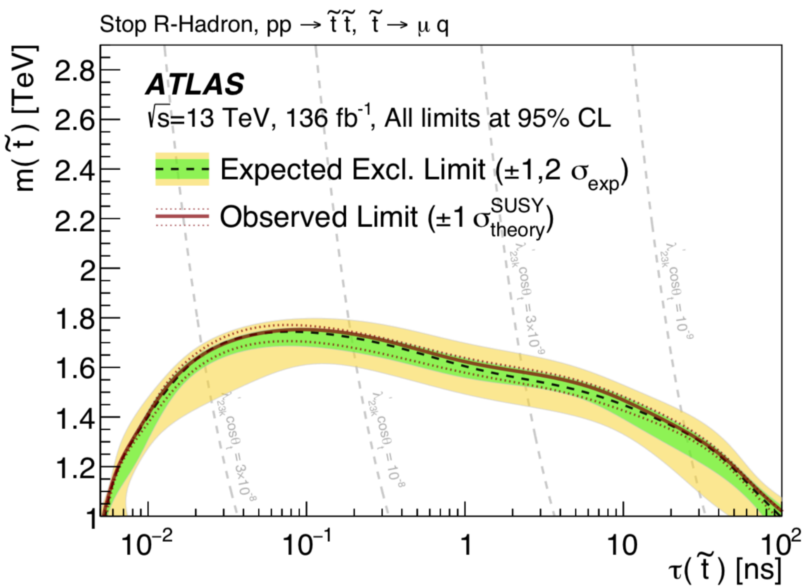


ATLAS

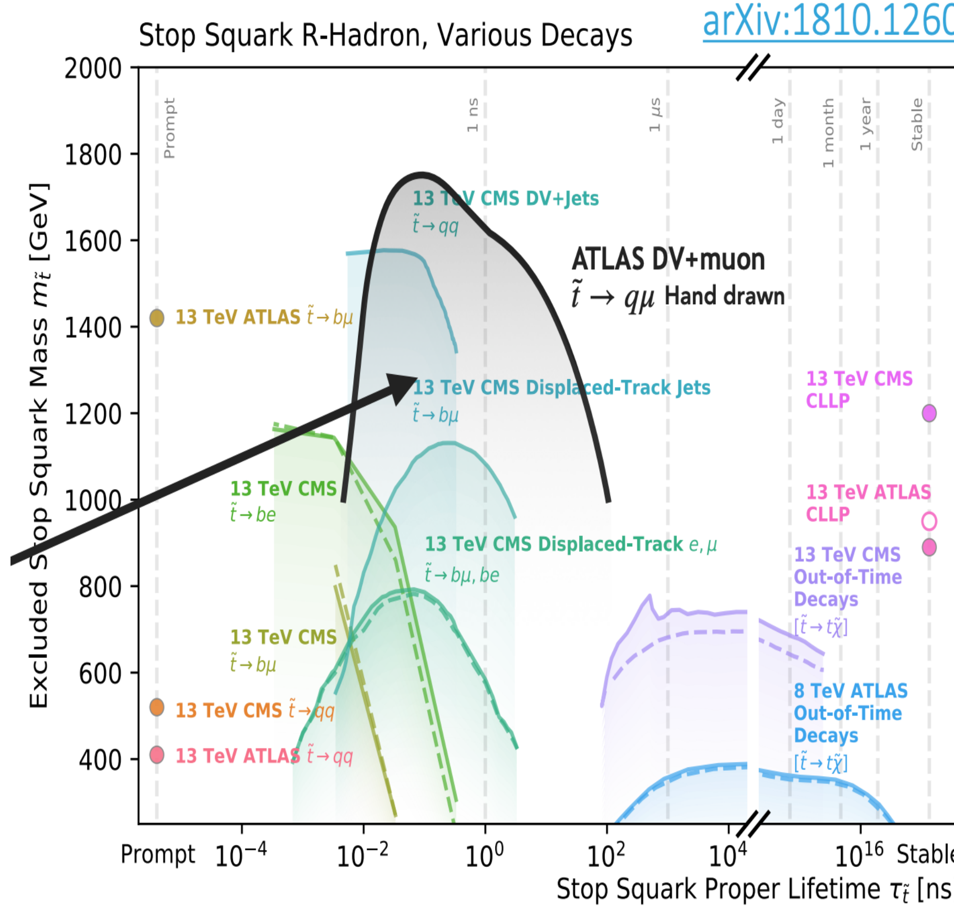
Displaced Vertices and Muon

arXiv:2003.11956

- Limits set for $m_{\tilde{t}}$ as a function of $c\tau$
- *For the mean proper life-time of 0.1 ns, masses below roughly m(t~) = 1.7 TeV are excluded*
- *For wide range of mean life-time of 0.01 ns and 30 ns, mass below 1.3 TeV are excluded*



arXiv:1810.12602



DISPLACED JETS

Full Run2

CMS EXO-19-021

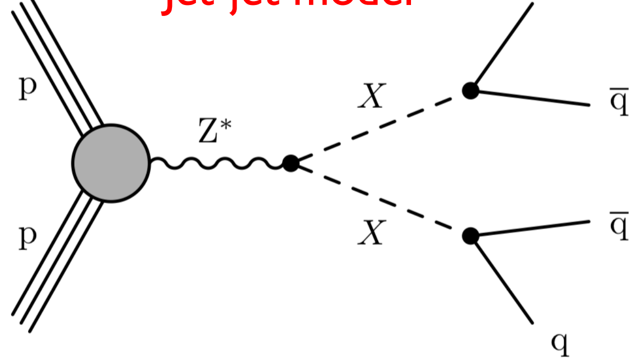
Displaced Jets

EXO-19-021

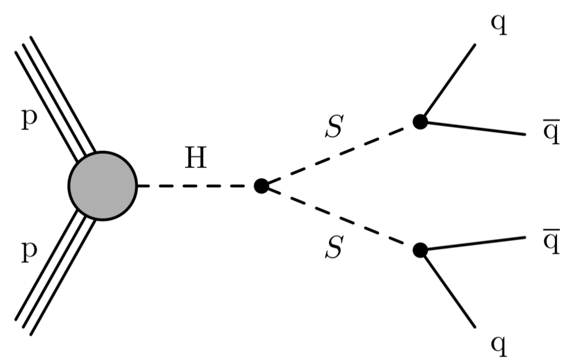
Full RunII result! (132 fb^{-1}, 2016-2018)

- **Distinctive topology** : pair of jets originating at a secondary vertex
- Different **signal models** targeted
- jet-jet Benchmark model :
  - Long-lived scalar neutral particles (X) decaying to quark-antiquark pairs
- Exotic decays of SM Higgs boson
  - gg → H → 2S, S → qq
  - where cτ ~ 1mm to 3m
- Other BSM Models
  - Hidden Valley Higgs, Split SUSY, RPV SUSY, General Gauge Mediated SUSY

Jet-jet model



Exotic Higgs model



Displaced Jets: Pre-selection

EXO-19-021

- **Dedicated triggers : Displaced trigger** and **Inclusive trigger**

  - **A dedicated secondary Vertex reconstruction is performed**

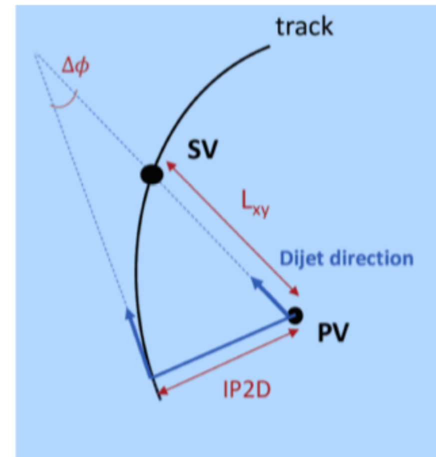
  - **QCD multijet process dominates the background**

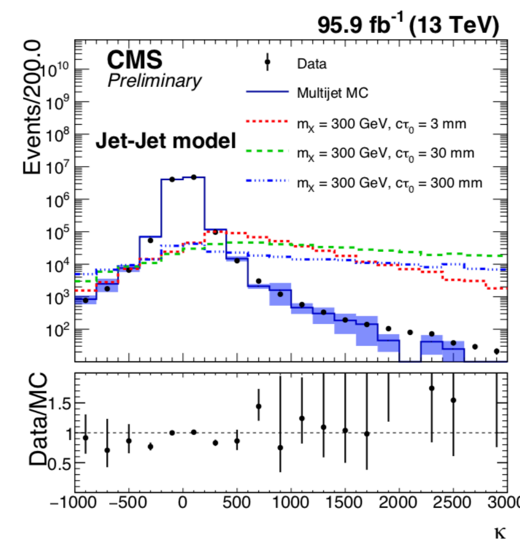
  - **Gradient Boosted decision tree (GBDT)** as the discriminant on four variables
    - Vertex track multiplicity
    - Cluster RMS
    - Vertex Lxy significance
    - |k|

$$\mathrm{RMS}_{\mathrm{cluster}} = \sqrt{1/N_{\mathrm{tracks}} \sum_{i=1}^{N_{\mathrm{tracks}}} \frac{(L_{\mathrm{xy}}^{\mathrm{exp}}(i) - L_{\mathrm{xy}})^2}{L_{\mathrm{xy}}^2}}.$$

$$L_{\mathrm{xy}}^{\mathrm{exp}} = \frac{IP_{2D}^{\mathrm{track}}}{\sin(\phi_{\mathrm{track}} - \phi_{\mathrm{dijet}})} \left(1 - \frac{|IP_{2D}^{\mathrm{track}}|}{R}\right)$$

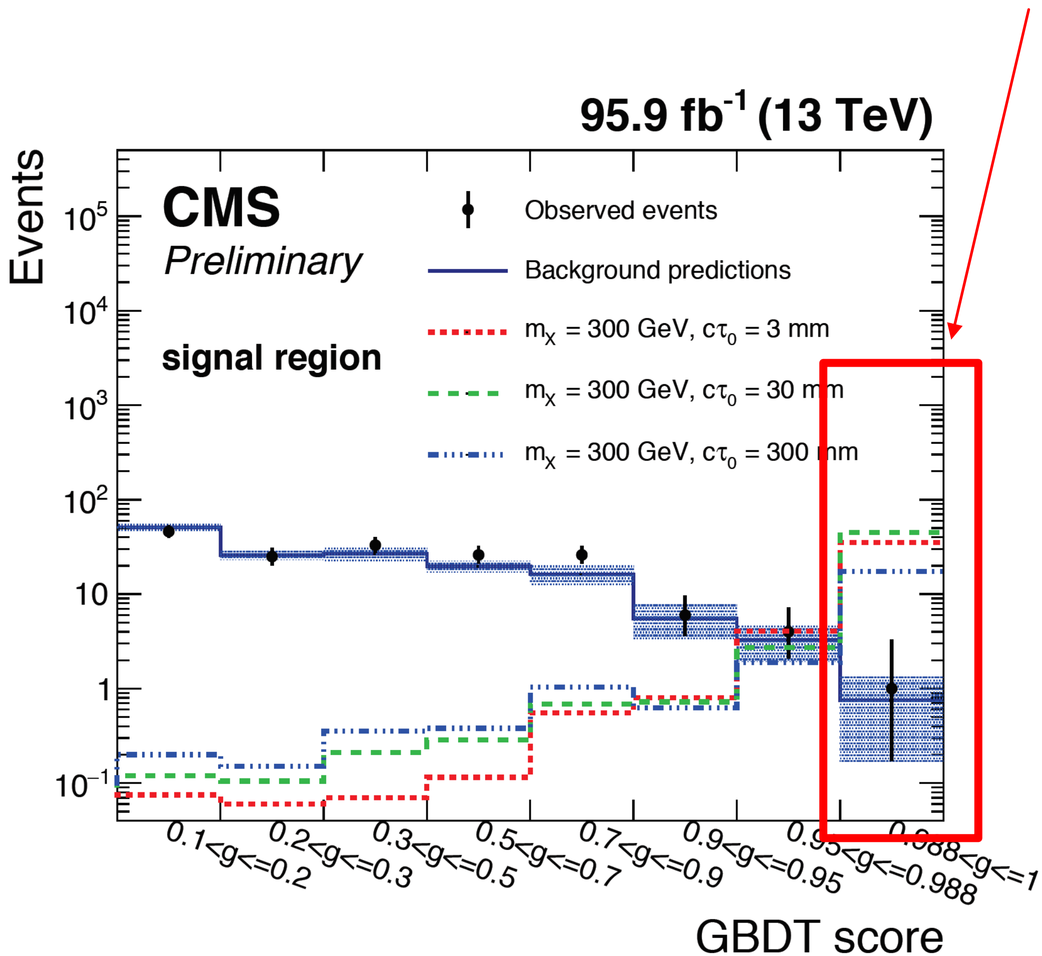
$$\kappa = \sum_{i=1}^{6} \mathrm{Sig}[\mathrm{IP}_{2\mathrm{D}}(\mathrm{track}_i)].$$





Displaced Jets: Backgrounds

EXO-19-021



- Background estimation is purely data-driven
  - Use different control regions
- **Signal region :** GBDT > 0.988

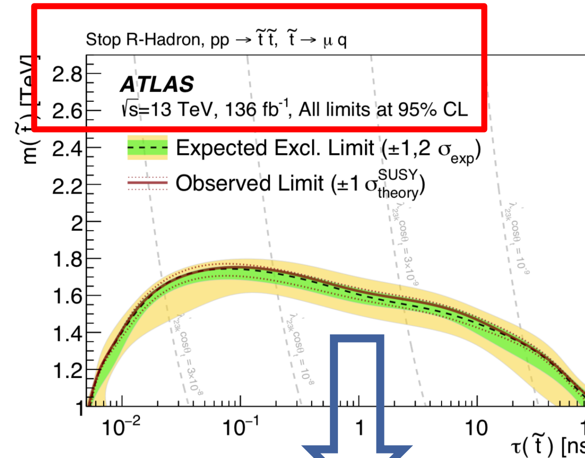
- Predicted background in the final signal region : 0.75 + /- 0.44 (stat) +/- 0.39 (syst)
- Number of observed events : 1 event

CMS

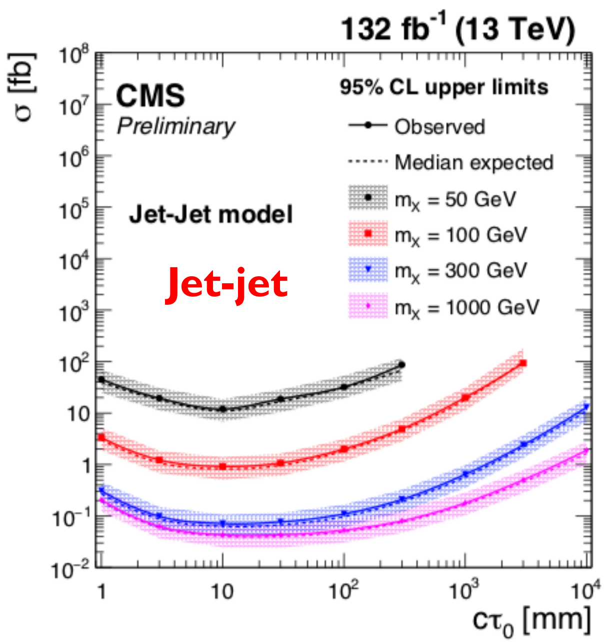
Displaced Jets

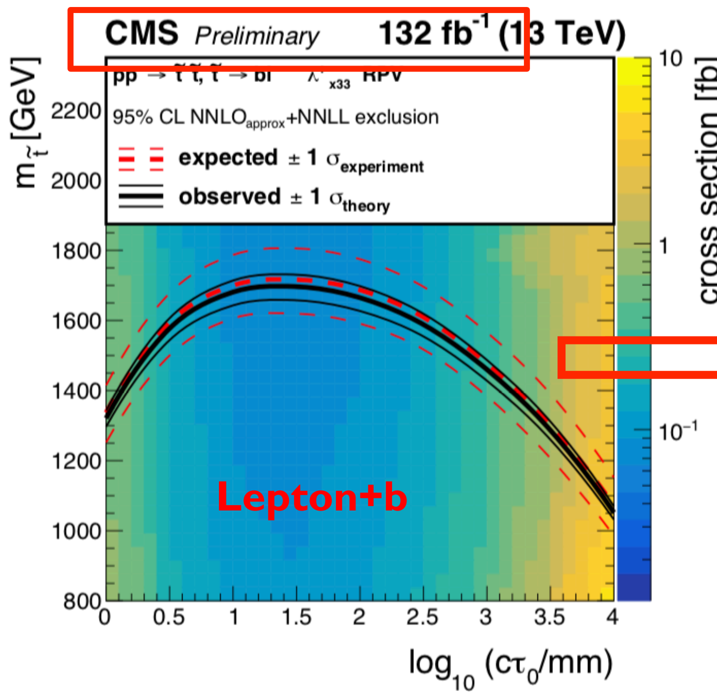
EXO-19-021

- **Combined results for Full Run2 data (2016 + 2017/2018)**
- For Exotic decay of **SM Higgs model**, **branching fractions larger than 1% is excluded** for mean proper decay lengths between 1 mm and 1 m .
- For **GMSB and SUSY RPV** models, the **most restrictive limits are set from CMS**



ATLAS excludes top squark **masses upto 1.4 TeV** for cτ between 0.003 to 6 m





*CMS excludes top squark **masses upto 1.6 TeV** for cτ between 3 and 340 mm*

DISPLACED HADRONIC JETS

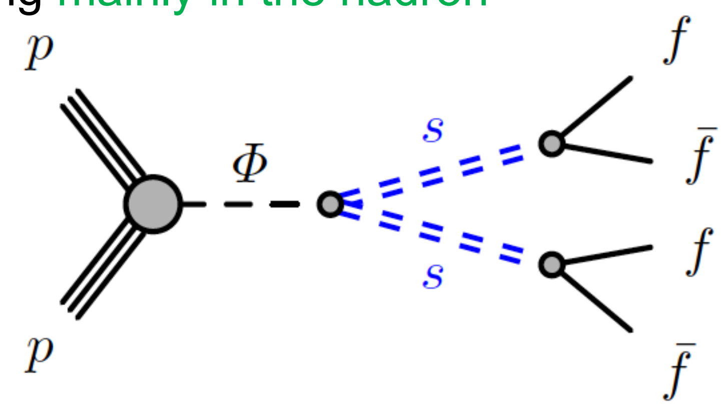
EUR. PHYS. J. C 79 (2019) 481

Displaced Hadronic Jets

Eur. Phys. J. C 79 (2019) 481

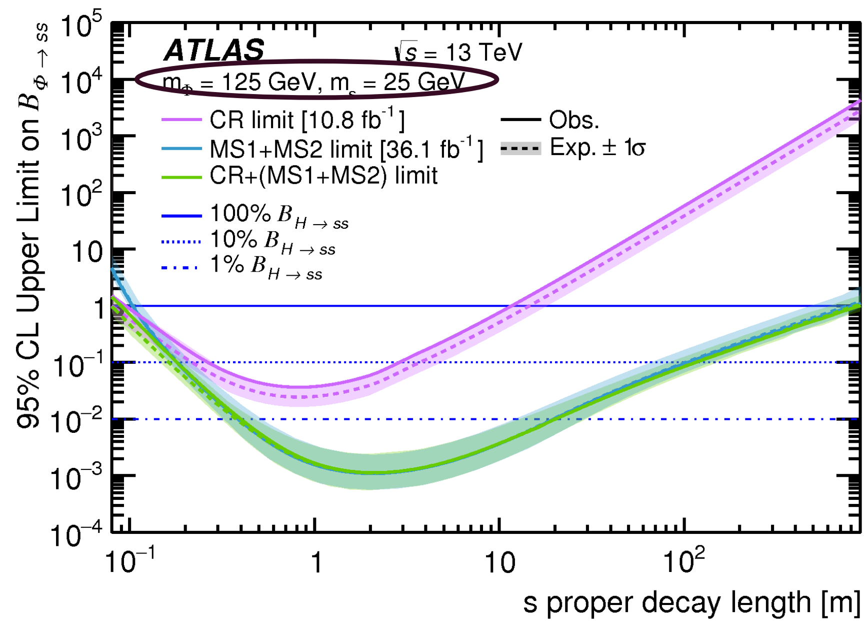
(33 fb^{-1}, 2016)

- **Distinctive topology** : Neutral LLPs decaying mainly in the hadron calorimeter or at the edge of the ECAL



- No associated activity in the tracker
- These jets have a high ratio of E_H/E_E (CalRatio Jets)
- Narrow shower
- 2 CalRatio Jets are required in the analysis

- Two dedicated triggers to target heavy bosons with m_φ > 200 and < 200 GeV topology
  - low-ET trigger (10 fb^{-1})
  - high-ET trigger (33 fb^{-1})
- Offline strategy to use MVA to discriminate between displaced jet, Non-collision background or multi-jet like



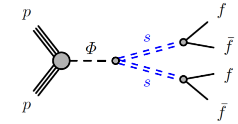
LLP DECAYING TO DISPLACED HADRONIC JETS IN INNER DETECTOR & MUON SPECTROMETER

PRD 101 (2020) 052013

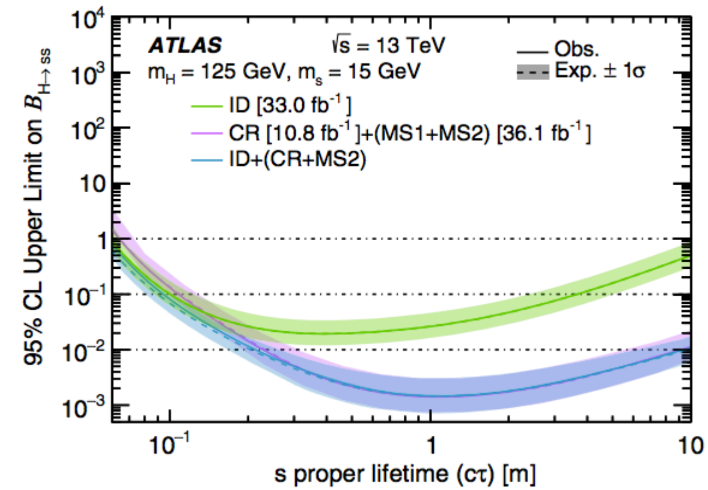
PRD 101 (2020) 052013

Displaced Hadronic Jets in ID + MS

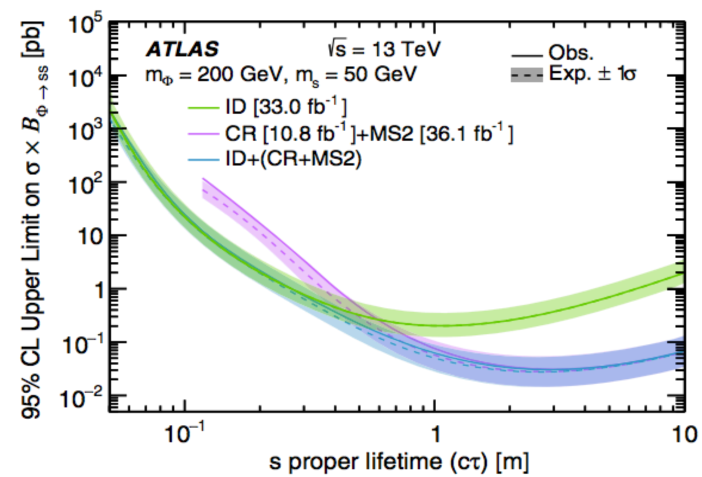
(36.1 fb^{-1}, 2015 + 2016)



- **Distinctive topology** : 2 neutral LLPs produced, with one decaying in the ATLAS inner tracking detector (ID) and the other in the muon spectrometer (MS)
- Sensitivity : cτ from few centimeters to ~meters



- For each event one reconstructed decay vertex is required in the ID in addition to one in MS (JINST 9 (2014) P02001)
  - Specialised tracking and vertex algorithms are used
- Muon Region of Interest (RoI) Cluster trigger
  - L1 trigger search for two RoI in the MS with P_T >10 GeV (JINST 8 (2013) P07015)
  - HLT require atleast 3(4) L1 muons within DR < 0.4 in barrel (endcaps)
- Increases the sensitivity to low-mass scalars with shorter proper lifetimes relative to the combined results of the CR and MS analyses (EPJC 79 (2019) 481)



REINTERPRETATION OF DISPLACED HADRONIC JETS WITH RECAST FRAMEWORK
ATL-PHYS-PUB-2020-007

ATLAS

Displaced Hadronic Jets

RECAST FW

ATL-PHYS-PUB-2020-007

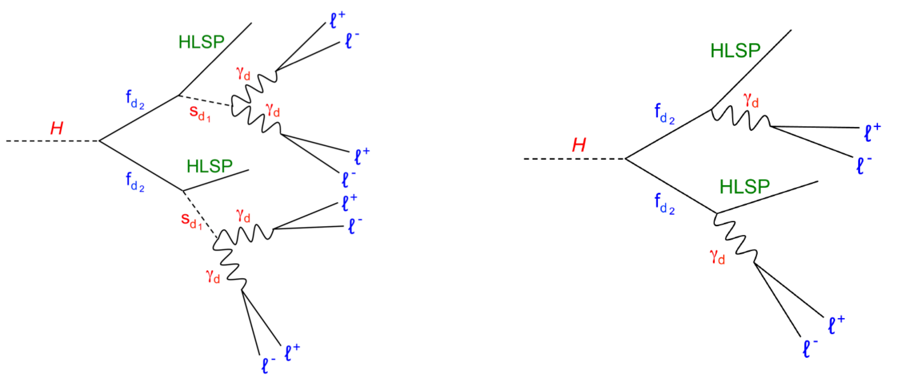
(33 fb^{-1}, 2016)

- **Basics of RECAST Framework**
  - Difficult to construct optimised analyses for the wide range of physics models
  - But analysis optimised for original model offer good sensitivity to other models provided the signature are similar
  - Event selection , background estimate and observed data distributions don't change in the context of re-interpretation
  - ***Only the signal distribution due to a new signal model must be derived***

- RECAST : A framework designed to reuse estimates of backgrounds, systematic uncertainties and observations to test alternative signal hypothesis [arXiv: 1010.2506]

Dark photon model

- Three models recasted
  - Stealth SUSY Model
  - Higgs portal baryogenesis model
  - Dark photon (FRVZ model)



Displaced Hadronic Jets

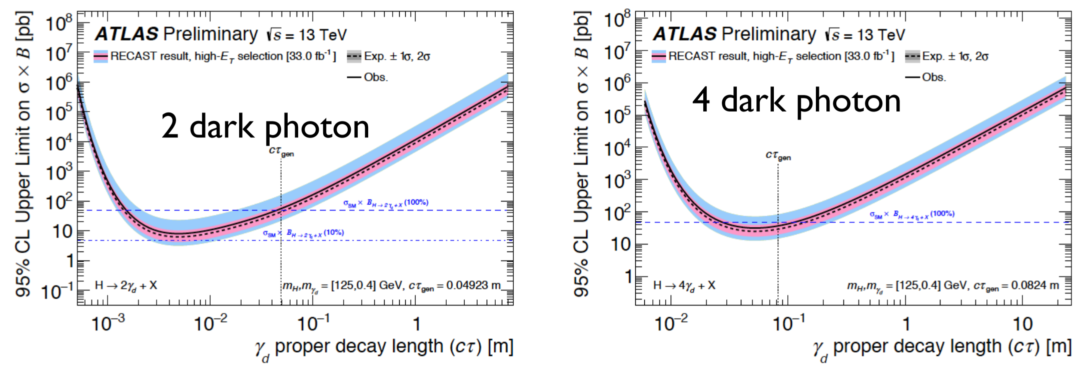
RECAST FW

ATL-PHYS-PUB-2020-007

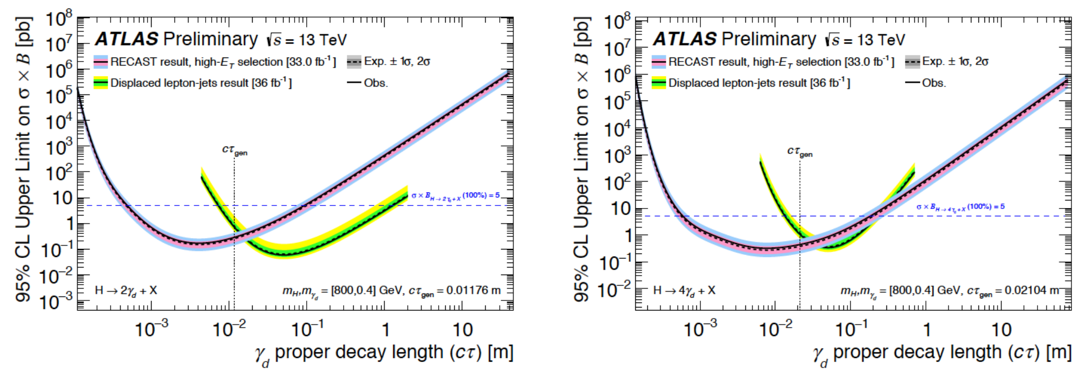
- **95% CL Limits set on the σ_H x $B_{H \rightarrow N\gamma d + X}$ as a function of LLP decay length , where the N can be 2 or 4**
- **Results are compared to previous published ATLAS result (arXiv:1909.01246) of collimated leptons or light hadrons (only considered hDPJ-hDPJ)**

- **First constraints set for h= 125 GeV**

- For h = 800 GeV, limits from this search cover the region complementary to the the existing constraints



(a) m_H = 125 GeV



(b) m_H = 800 GeV

DISAPPEARING TRACKS (ARXIV:2004.05153)

Full Run2

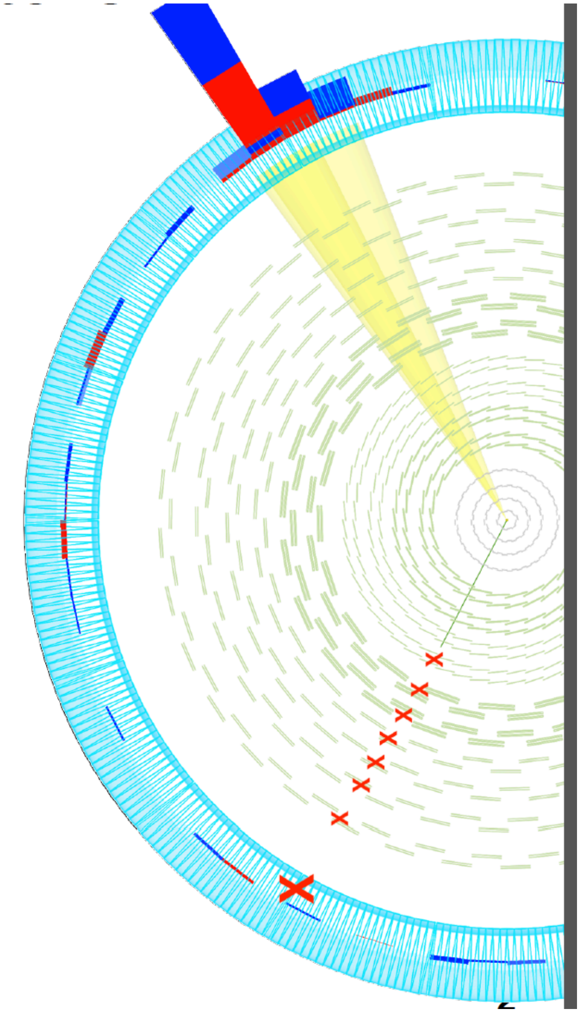
CMS

Disappearing track

arXiv:2004.05153

Full Run-II result! (140 fb^{-1}, 2016-2018)

- A long lived particle decaying within the CMS tracker
- If the decay products are un-detected, the track **"disappears"**
  - Neutral, weakly interacting
  - Too low momentum to be reconstructed



- Canonical Benchmark: anomaly-mediated supersymmetry breaking model (AMSB)
- Small mass splitting between chargino and neutralino
  - Direct electroweak production

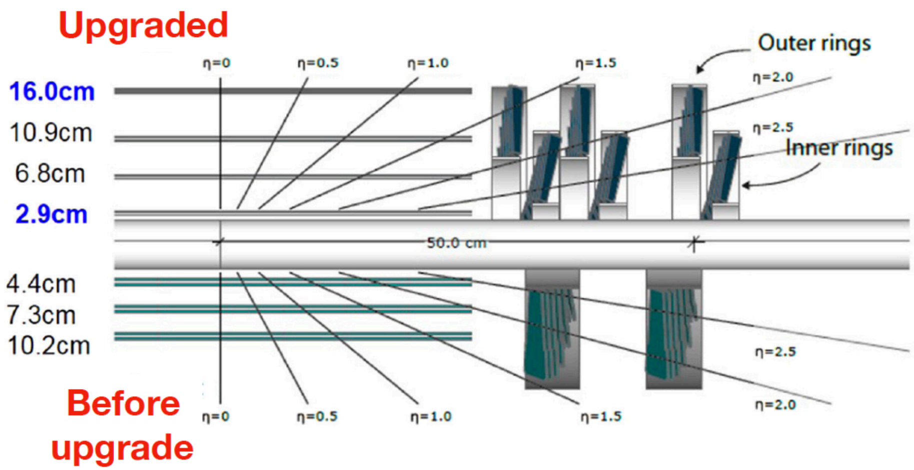
$$pp \to \tilde{\chi}^{\pm}\tilde{\chi}^{\mp},\ \tilde{\chi}^{\pm}\tilde{\chi}^{0}$$

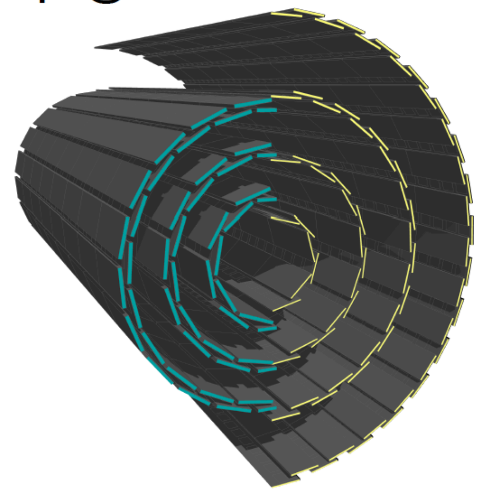
  - $\tilde{\chi}^{\pm} \to \pi^{\pm}\chi^{0}$ with lifetime O(1) ns

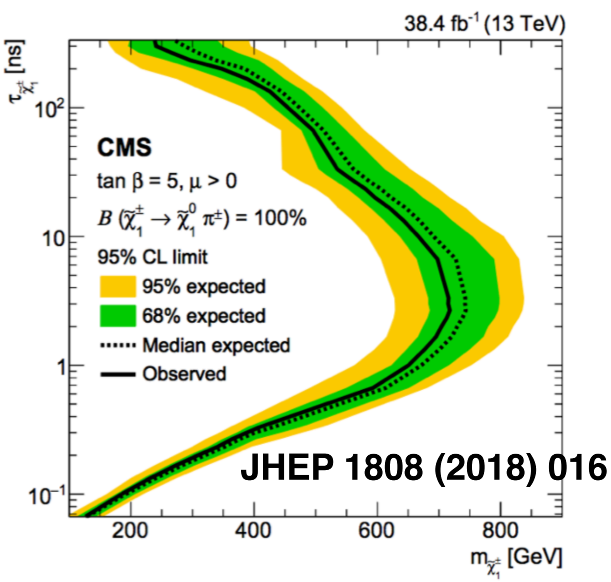
Disappearing track

arXiv:2004.05153

Phase 1 CMS Pixel Upgrade



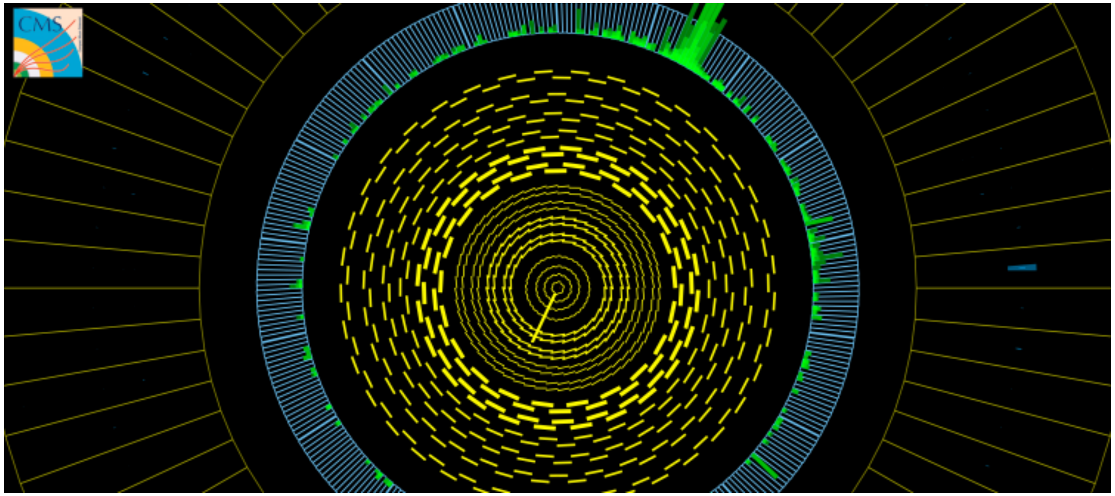




- CMS previously searched for disappearing tracks (@ 8 and 13 TeV) using a 3-layer pixel tracker
  - Limited sensitivity to short tracks (compared to ATLAS' JHEP 1806 (2018) 022)
- Since 2017 CMS now has a 4-layer pixel tracker
- New analysis bins results in the number of layers with measurements:
  - n_{layers} = 4, 5, ≥6
  - **New sensitivity to shorter particle lifetimes**

Disappearing track : Backgrounds

CMS



arXiv:2004.05153

- SM particles don't disappear, however there are rare backgrounds:
  - Charged hadrons can interact with detector material, e.g.

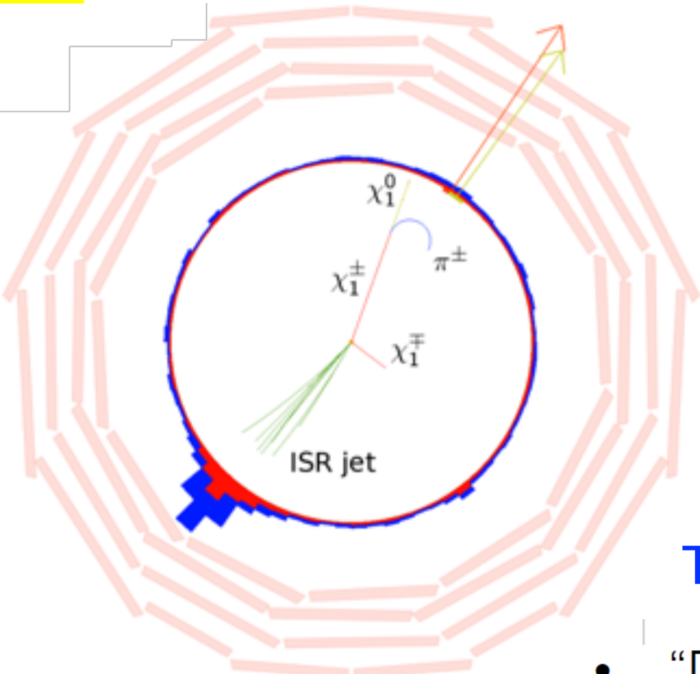
$$\pi^{+} + n \rightarrow \pi^{0} + p$$

  - Leptons can be mis-reconstructed
  - Spurious ("fake") tracks — pattern recognition errors
- Approach to controlling these:
  - Explore and mitigate all possible ways to lose tracker hits
  - Estimate the remaining probability to fall into search region

CMS

Disappearing track : Selection

arXiv:2004.05153



Trigger Selection

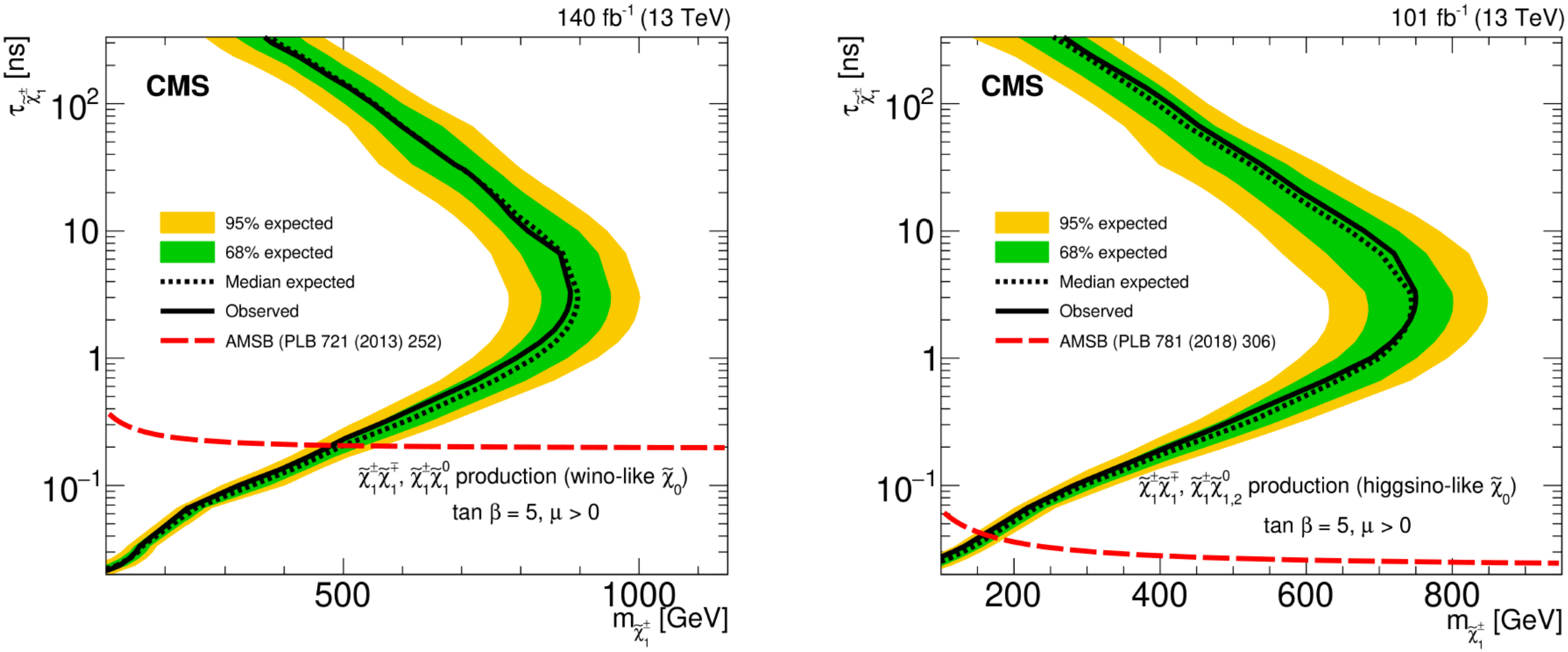
- No tracking information at L1 trigger
    - Trigger on MET from ISR jets at L1
    - At HLT, OR of several MET requirements
        - MET > 105-300 GeV
        - Lowest threshold: MET > 105 GeV and pt > 50 GeV isolated track

Track Selection

- "Disappearing" is defined as:
    - ≥3 missing outer hits — rejects most SM tracks
    - <10 GeV energy deposited within $\Delta R < 0.5$
        - Rejects most electrons and charged hadrons
        - E.g. electrons with significant brem. energy causing a track reconstruction failure

Disappearing track : Results

arXiv:2004.05153



- In the context of AMSB, these results exclude charginos below
  - Wino-like neutralino case – 884 (474) GeV for a lifetime of 3 (0.2) ns
  - Higgsino-like neutralino case – 750 (175) GeV for a lifetime of 3 (0.05) ns
    - ***New interpretation for 2017-2018 data***

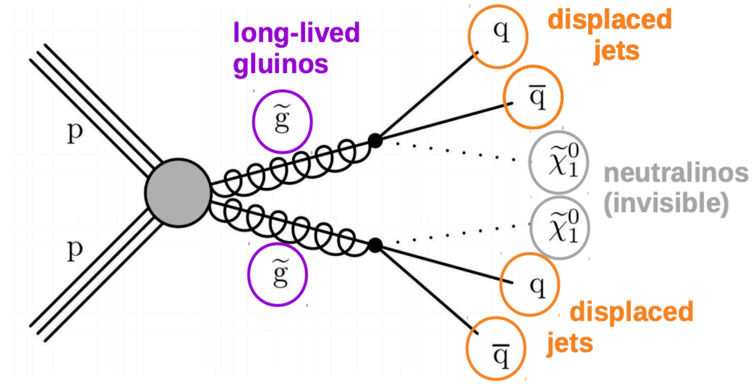
NEURAL NETWORK BASED LLP SEARCH (EXO-19-011, ARXIV:1912.12238)

Neural Network Based LLP Search

EXO-19-011
arXiv:1912.12238

Benchmark model: split SUSY scenario

- Gluons form R-hadrons leading to displaced jets
- Model parameters
  - Masses
  - Proper lifetime

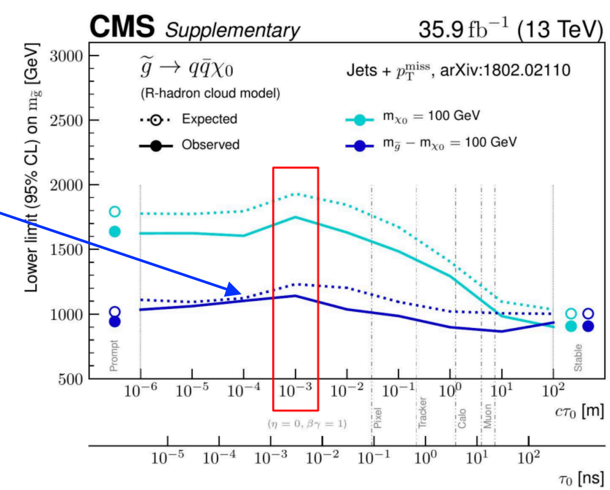


Existing search by **CMS [JHEP 05 (2018) 025]**

- **Sensitivity to LLPs through b-tagging ($c\tau_0$ ~ 1*mm*)**

Enhance sensitivity with generic displaced jet tagger

- Deep Neural Network (DNN) based multiclass classifier (parameterized as per proper decay length) to identify displaced jets

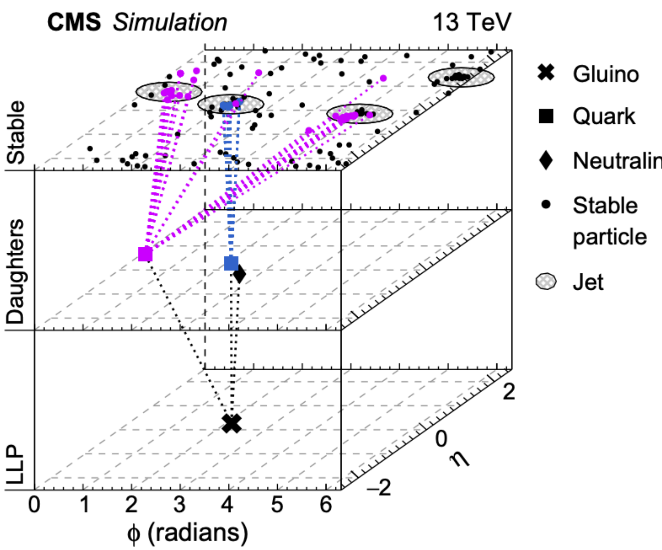


JHEP 05 (2018) 025

EXO-19-011: Labelling "displaced" Jets

EXO-19-011
arXiv:1912.12238

- Initial idea: "ghost" tagging as used for b, c jets
- Strong interactions between displaced quarks at the gluino decay vertex
  - ghost tagging cannot account for non-pointing jets or multiple jets from one parton



Solution:

Define jet momentum fraction of generator-level jet carried by clustered particles j per vertex v

$$f_v(\text{jet}) = \frac{\left(\sum_j \vec{p}_j \middle| j \in \text{vertex } v\right) \cdot \vec{p}_{\text{jet}}}{p_{\text{jet}}^2}, \quad f_v(\text{jet}) \in [0; 1]$$

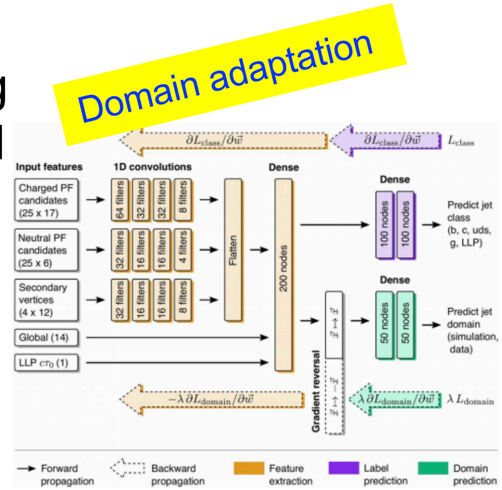
- Label jets 'LLP' where $f_v = max$
- Remaining non-LLP jets can still possess significant fractions of displace particles
  - Ignore in training to avoid confusions

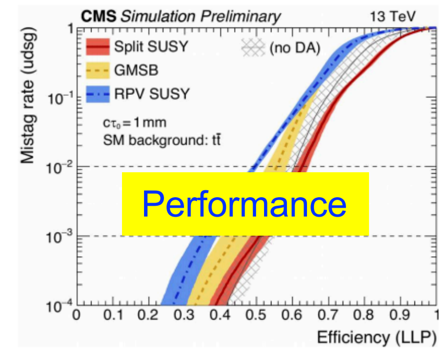
- Neural Network architecture inspired by CMS DeepJet Algo
- Training of NN on simulated events (jets from multijet, tt & split SUSY)
  - *Predict jet class: uds, g, b, c, LLP*

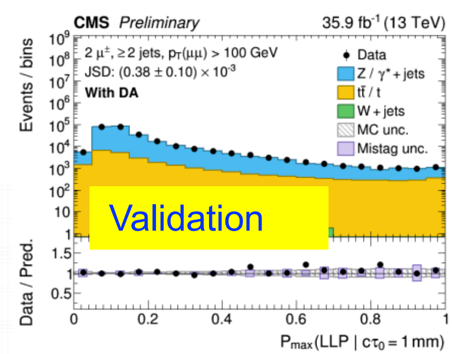
EXO-19-011: Results

EXO-19-011
arXiv:1912.12238

- Domain adaptation by backward propagation to improve signal modelling
- Rejection factor: 10000 for jets from SM
- LLP Jet Tagging Efficiency: 30-80% for gluinos with 1mm ≤ $c\tau_0$ ≤ 10m



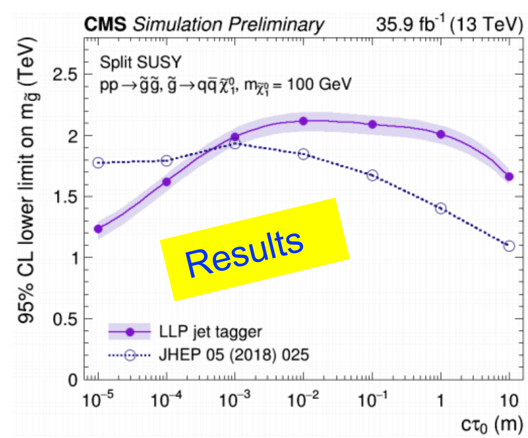


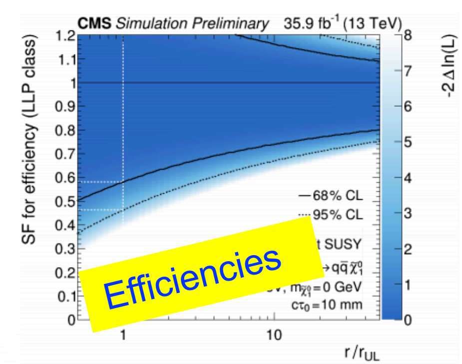


Jet tagger for generic displaced jets:

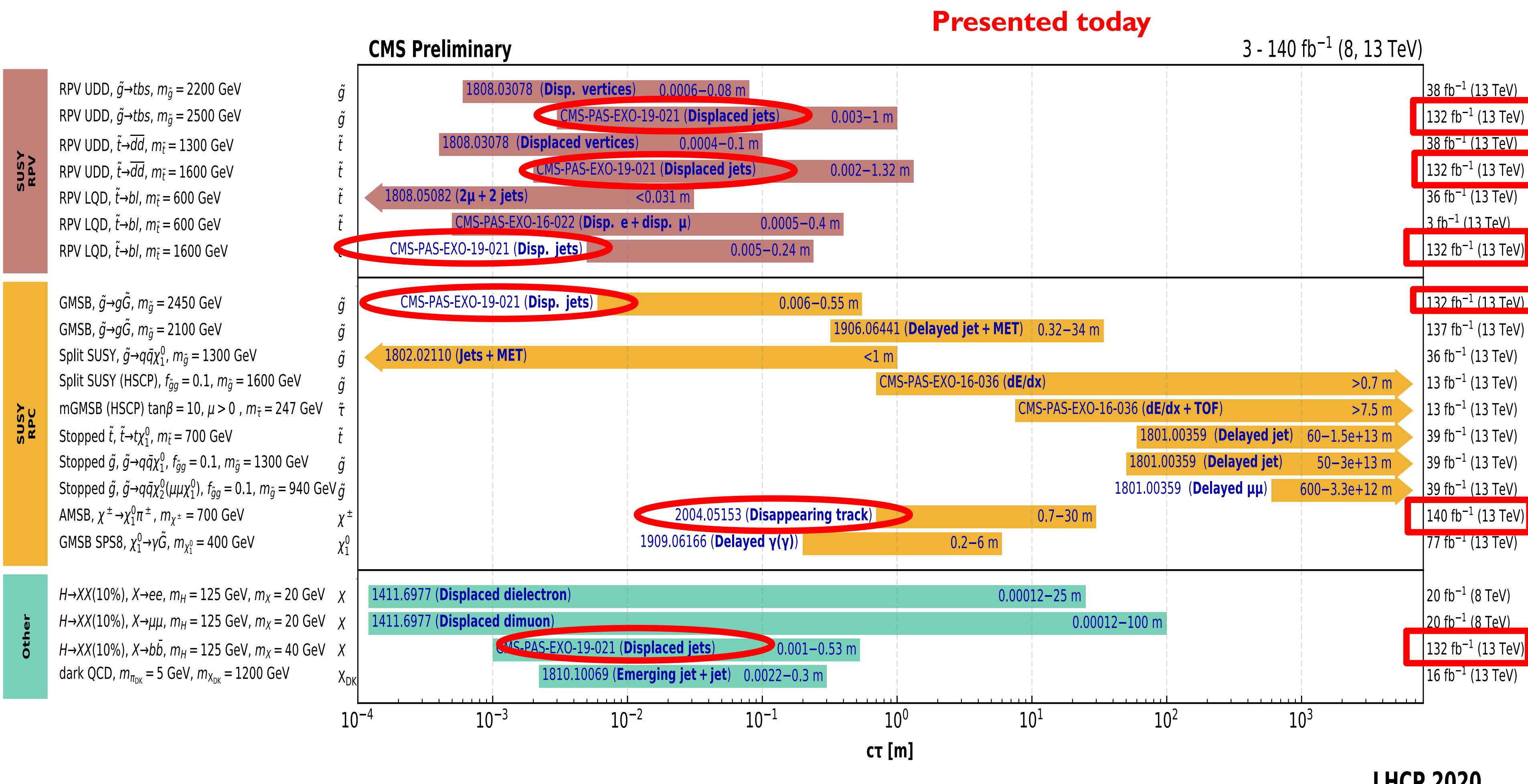
- Parametrized neural network
- Good performance also for models not in training

- Simple event categorization (H_T ,#jets, #jet tags)
- **Competitive expected limits**

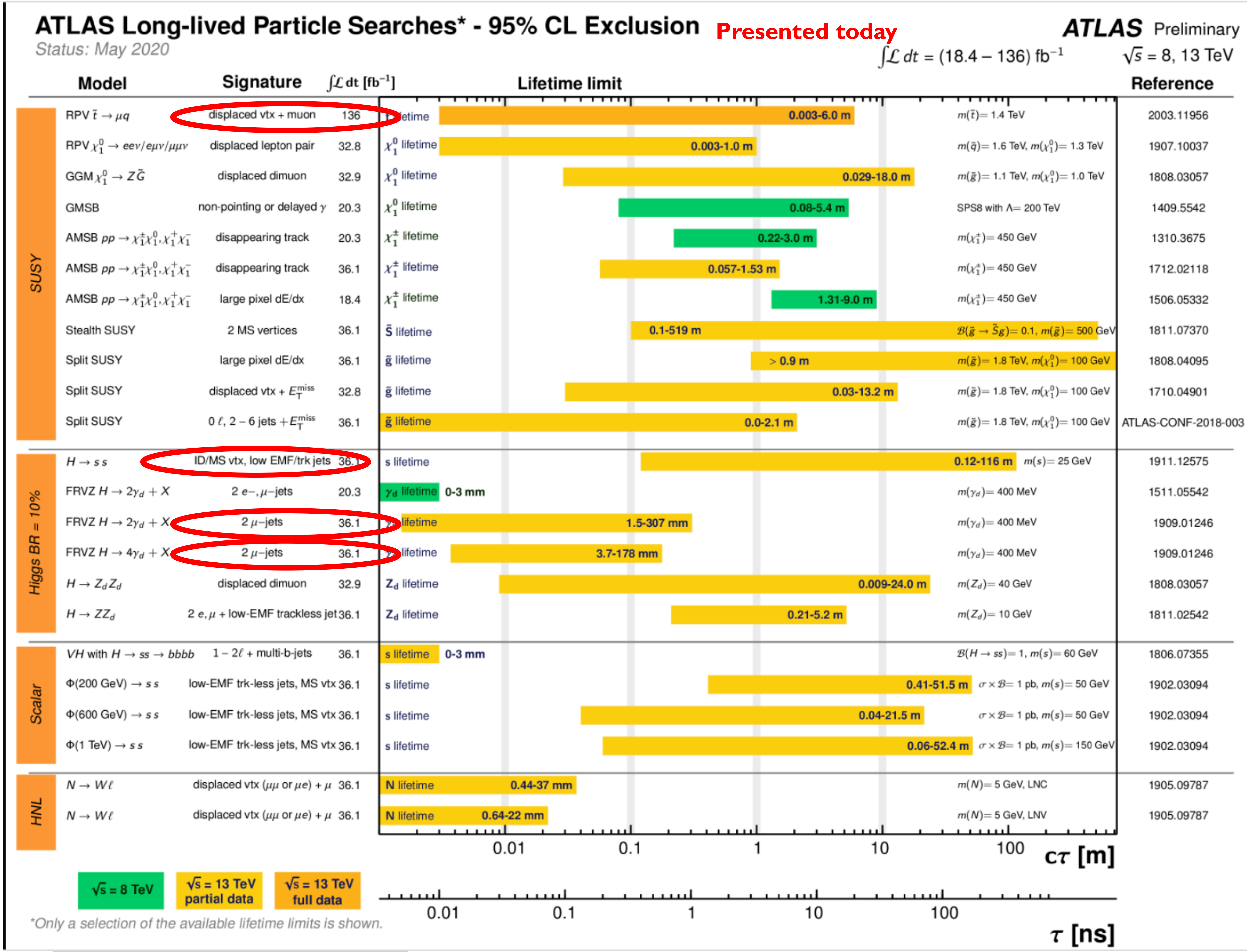




Overview of CMS long-lived particle searches



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.



ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: May 2020
Presented today
ATLAS Preliminary
$\int \mathcal{L}\, dt = (18.4 - 136)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 8, 13$ TeV
Model
Signature
$\int \mathcal{L}\, dt\ [\mathrm{fb}^{-1}]$
Lifetime limit
Reference
SUSY
RPV $\tilde{t} \to \mu q$ | displaced vtx + muon | 136 | $\tilde{t}$ lifetime | 0.003-6.0 m | $m(\tilde{t})$= 1.4 TeV | 2003.11956
RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$ | displaced lepton pair | 32.8 | χ_1^0 lifetime | 0.003-1.0 m | $m(\tilde{q})$= 1.6 TeV, $m(\chi_1^0)$= 1.3 TeV | 1907.10037
GGM $\chi_1^0 \to Z\tilde{G}$ | displaced dimuon | 32.9 | χ_1^0 lifetime | 0.029-18.0 m | $m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV | 1808.03057
GMSB | non-pointing or delayed γ | 20.3 | χ_1^0 lifetime | 0.08-5.4 m | SPS8 with Λ= 200 TeV | 1409.5542
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ | disappearing track | 20.3 | $\chi_1^\pm$ lifetime | 0.22-3.0 m | $m(\chi_1^\pm)$= 450 GeV | 1310.3675
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ | disappearing track | 36.1 | $\chi_1^\pm$ lifetime | 0.057-1.53 m | $m(\chi_1^\pm)$= 450 GeV | 1712.02118
AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$ | large pixel dE/dx | 18.4 | $\chi_1^\pm$ lifetime | 1.31-9.0 m | $m(\chi_1^\pm)$= 450 GeV | 1506.05332
Stealth SUSY | 2 MS vertices | 36.1 | $\tilde{S}$ lifetime | 0.1-519 m | $\mathcal{B}(\tilde{g} \to \tilde{S}g)$= 0.1, $m(\tilde{g})$= 500 GeV | 1811.07370
Split SUSY | large pixel dE/dx | 36.1 | $\tilde{g}$ lifetime | > 0.9 m | $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV | 1808.04095
Split SUSY | displaced vtx + E_T^{miss} | 32.8 | $\tilde{g}$ lifetime | 0.03-13.2 m | $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV | 1710.04901
Split SUSY | $0\ \ell$, $2-6$ jets $+ E_T^{miss}$ | 36.1 | $\tilde{g}$ lifetime | 0.0-2.1 m | $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV | ATLAS-CONF-2018-003
Higgs BR = 10%
$H \to s\,s$ | ID/MS vtx, low EMF/trk jets | 36.1 | s lifetime | 0.12-116 m | $m(s)$= 25 GeV | 1911.12575
FRVZ $H \to 2\gamma_d + X$ | 2 $e-,\mu-$jets | 20.3 | γ_d lifetime | 0-3 mm | $m(\gamma_d)$= 400 MeV | 1511.05542
FRVZ $H \to 2\gamma_d + X$ | 2 $\mu-$jets | 36.1 | γ_d lifetime | 1.5-307 mm | $m(\gamma_d)$= 400 MeV | 1909.01246
FRVZ $H \to 4\gamma_d + X$ | 2 $\mu-$jets | 36.1 | γ_d lifetime | 3.7-178 mm | $m(\gamma_d)$= 400 MeV | 1909.01246
$H \to Z_d Z_d$ | displaced dimuon | 32.9 | Z_d lifetime | 0.009-24.0 m | $m(Z_d)$= 40 GeV | 1808.03057
$H \to ZZ_d$ | 2 e,μ + low-EMF trackless jet | 36.1 | Z_d lifetime | 0.21-5.2 m | $m(Z_d)$= 10 GeV | 1811.02542
Scalar
VH with $H \to ss \to bbbb$ | $1-2\ell$ + multi-b-jets | 36.1 | s lifetime | 0-3 mm | $\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV | 1806.07355
Φ(200 GeV) $\to s\,s$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.41-51.5 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV | 1902.03094
Φ(600 GeV) $\to s\,s$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.04-21.5 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV | 1902.03094
Φ(1 TeV) $\to s\,s$ | low-EMF trk-less jets, MS vtx | 36.1 | s lifetime | 0.06-52.4 m | $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV | 1902.03094
HNL
$N \to W\ell$ | displaced vtx ($\mu\mu$ or μe) + μ | 36.1 | N lifetime | 0.44-37 mm | $m(N)$= 5 GeV, LNC | 1905.09787
$N \to W\ell$ | displaced vtx ($\mu\mu$ or μe) + μ | 36.1 | N lifetime | 0.64-22 mm | $m(N)$= 5 GeV, LNV | 1905.09787
0.01
0.1
1
10
100
$c\tau$ [m]
0.01
0.1
1
10
100
τ [ns]
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
*Only a selection of the available lifetime limits is shown.

Summary

- Highlighted several unconventional signatures and long-lived searches today from full Run-2
  - CMS disappearing track search making use of Phase 1 pixel upgrade to extend sensitivity to lower particle lifetime
    - Added a new higgsino-like neutralino interpretation
  - CMS displaced jet search
    - Added interpretation from Exotic decay of SM Higgs boson
  - ATLAS displaced vertex and muon search

- ATLAS on-going effort to use RECAST framework to reinterpret new results
- CMS neural-network based search to target LLP signatures (requires out-of the box thinking)

Stay tuned for more results!

- Towards run-3
  - *New ideas for trigger, reconstruction techniques and applications of machine learning to expand phase space of long-lived particles*

EXTRA MATERIAL

Systemtic uncertainty for Displaced vertices with muon

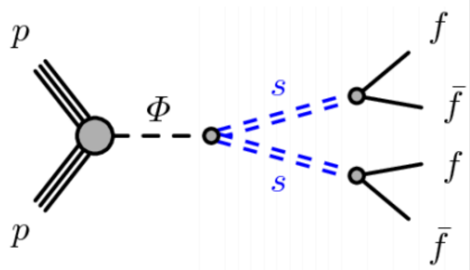
Table 5: Summary of the impact of systematic uncertainties on the event selection efficiency ϵ_{sel} for the signal scenarios with pair-produced long-lived top squarks. These uncertainties apply to both signal region selections used in the search unless otherwise specified.

Source of uncertainty	Relative impact on ϵ_{sel} for signal events [%]
Total	18–20
Tracking and vertex reconstruction	15
Displaced muon efficiency	10–12
Prompt muon efficiency	(0.01–0.7) $\oplus$ (0.9–4.0)
ISR modeling in MC simulation	3
Pileup modeling	0.37–2.2
Hadronic energy scale and resolution (affecting $E_{\text{T}}^{\text{miss}}$)	2.1
Integrated luminosity of dataset	1.7
Trigger efficiency	< 0.2

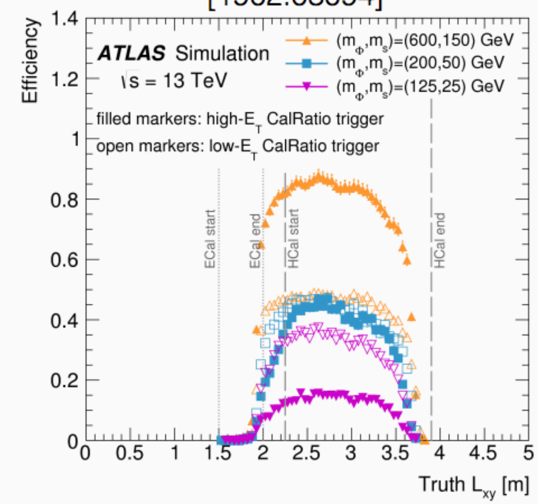
CalRatio Trigger

calRatio: 2015-2016

- Targets LLP decays in HCal
  - High ratio of energy deposited in HCal to energy deposited in the ECal
  - Narrow shower
  - No associated activity in the tracker
- L1
  - High-E_T: 60 GeV τ trigger
  - Low-E_T: 30 GeV τ trigger w/ no ≥3 GeV ECal deposits nearby
    - Exploits L1Topo capabilities - Introduced in mid-2016
- HLT
  - Tracking performed in RoIs around jets with E_T > 30 GeV and E_{EM}/E_H < 0.06
    - Veto presence of tracks with p_T > 2 GeV within ΔR(jet) < 0.2
  - Veto Beam-Induced Background (BIB) via cell timing/ position
- Offline strategy: use MVAs to discriminate against QCD and BIB background



[1902.03094]



RECAST workflow

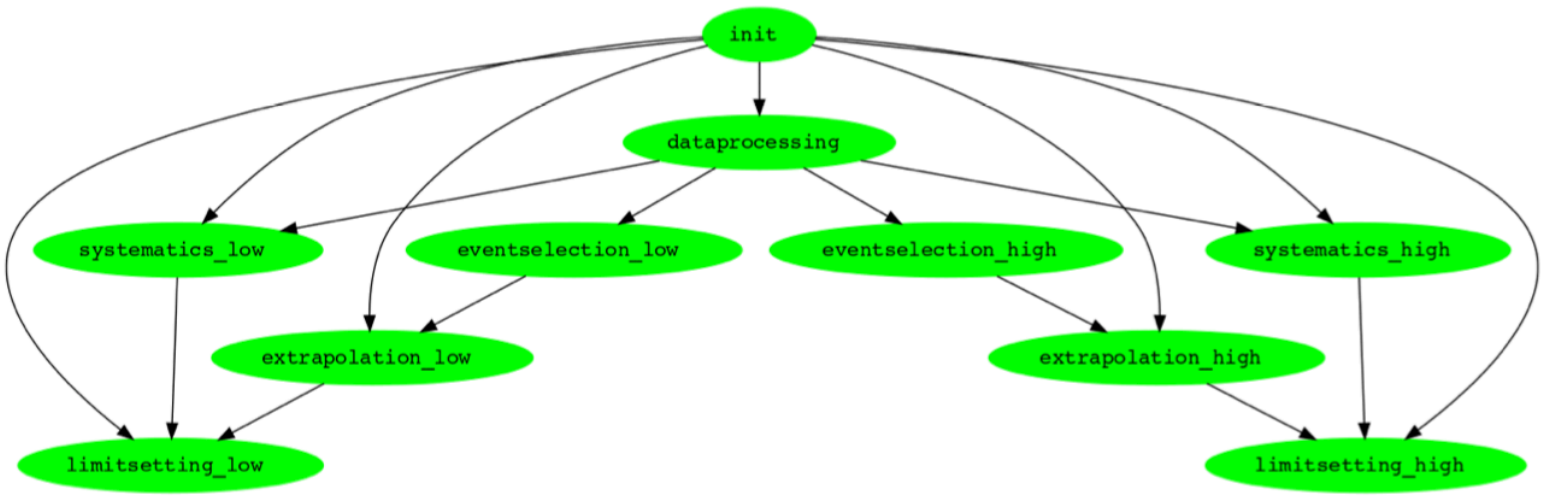


Figure 3: A schematic of the workflow used in the analysis preservation. Individual steps (in green) are defined with dependencies from other steps (indicated by the arrows).

By John Stupak

RECAST workflow

Table 12: Extension of the γ_d proper decay lengths excluded at 95% CL assuming $\sigma_H \times B_{H\rightarrow N\gamma_d+X} = 5$ pb for the FRVZ model with $m_H = 800$ GeV following the reinterpretation of the CalRatio displaced jets search. The existing minimum and maximum decay lengths excluded using the hDPJ-hDPJ selection are denoted by $c\tau^{old}_{min}$ and $c\tau_{max}$. The maximum decay lengths excluded are unchanged following the reinterpretation, but the extended minimum decay lengths are indicated by $c\tau^{new}_{min}$.

Process	$\sigma_H \times B_{H\rightarrow N\gamma_d+X}$ [pb]	$c\tau^{new}_{min}$ [m]	$c\tau^{old}_{min}$ [m]	$c\tau_{max}$ [m]
$H \rightarrow 2\gamma_d + X$	5	0.00046	0.0073	1.298
$H \rightarrow 4\gamma_d + X$	5	0.0006	0.0136	0.231

Displaced ID + MS analysis

TABLE IX. Ranges of proper lifetimes excluded at 95% CL for the $m_H = 125$ GeV benchmark model assuming a 10% branching ratio for $H \to ss$. The $m_s = 55$ GeV exclusion range uses the results of the ID and CR analyses only.

m_s [GeV]	Excluded $c\tau$ range at 95% CL [m]
8	0.06–15
15	0.09–64
25	0.12–116
40	0.26–197
55	0.39–8.1