# Searches for Long-lived Particles

**Andrea Coccaro**

on behalf of the ATLAS and CMS Collaborations

DM@LHC Workshop - University of California, Irvine

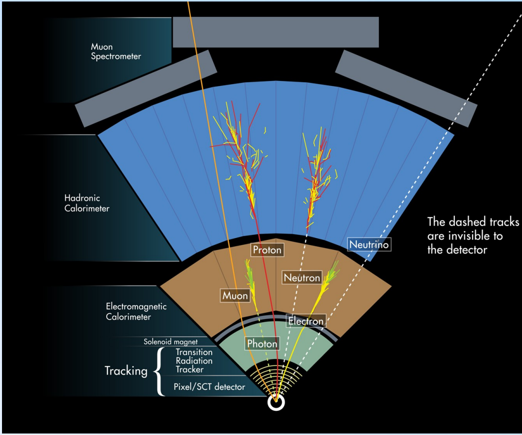
# Looking for unconventional signatures

Prompt physics is built from the few SM particles stable with respect to the detector volume

- still a pletora of searches and measurements

LLP searches are of different kind

- looking for anomalous signatures or more standard signatures in different regions of the detector
- various analysis-dependent challenges related to trigger, reconstruction, access of control region for estimating backgrounds



# Outline / References

LLP public results based on 13-TeV data

1. [CMS] Inclusive displaced jets [CMS-PAS-EXO-16-003]
2. [ATLAS] Displaced jets in the hadronic calorimeter [ATLAS-CONF-2016-103]
3. [CMS] Displaced leptons in the $e\mu$ channel [CMS-PAS-EXO-16-022]
4. [ATLAS] Displaced lepton-jets [ATLAS-CONF-2016-042]
5. [ATLAS] Charged LLP with $dE/dx$ [Phys. Rev. D 93, 112015 (2016)]
6. [CMS] Charged LLP with $dE/dx$ and ToF in MS [CMS-PAS-EXO-16-036]
7. [ATLAS] Charged LLP with $dE/dx$ and ToF in calorimeters [Physics Letters B (2016) 647]
8. [ATLAS] Disappearing tracks [ATLAS-CONF-2017-017]

Tools for unconventional signatures

9. [ATLAS] Triggering on long-lived neutral particles [JINST 8 (2013) P07015]

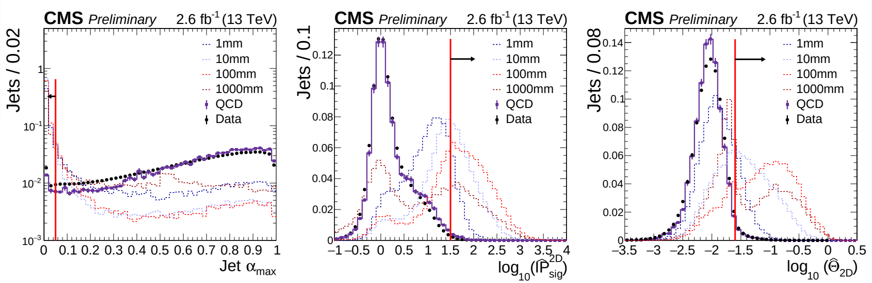
Inclusive displaced jets

[CMS-PAS-EXO-16-003]

# Event selection

- two dedicated triggers based on $H_T$, $p_T$, $\eta$, number of tracks with transverse IP cut
- two signal regions identified by the two triggers
- tagging algorithm to identify displaced jets

1. $\alpha_{jet} = \frac{\sum_{tracks,PV} p_T^{tracks}}{\sum_{tracks} p_T^{tracks}}$
2. median of the significance IP of tracks associated to jets
3. median of the recoil angle of tracks in a jet from the flight direction



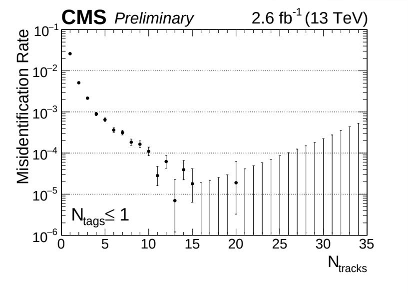
# Background prediction and systematics

Dominant background is QCD multi-jet production

- associated with fake tracks or with displaced tracks from hadronic interactions, photon conversions or weak decay of flavoured hadrons

Likelihood of tagging displaced jets is studied as a function of the number of associated tracks

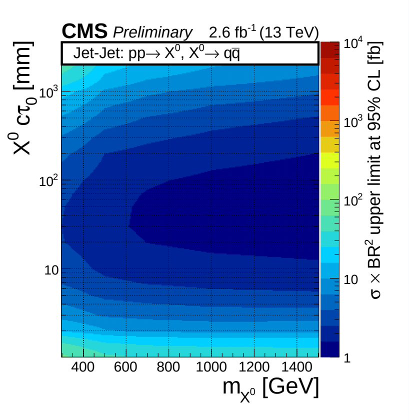
- no signal contamination is assumed



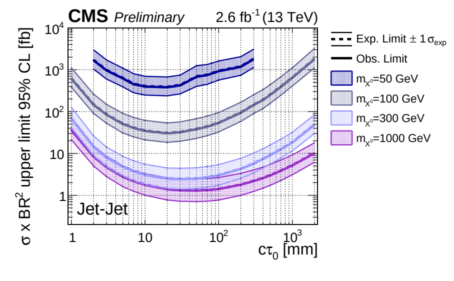

| Signal systematic uncertainty | Effect on yield |
|---|---|
| $H_T$ trigger inefficiency | 5% |
| Jet $p_T$ trigger inefficiency | 5% |
| Trigger online tracking modeling | 1–35% |
| Luminosity | 2.3% |
| Acceptance due to PDF | 1–6% |
| Displaced-jet tag variable modeling | 1–30% |

# Results

Exclusion limits for the jet-jet model (LLP scalar neutral particles decaying to jets), the *B*-lepton model (LLP top squarks in RPV SUSY) and variants of these two



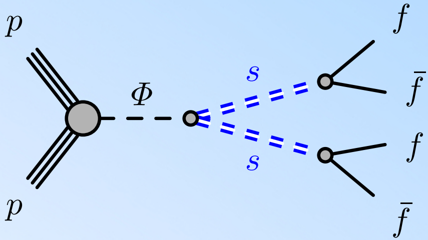

| $N_{tags}$ | Expected | Observed |
|---|---|---|
| 2 | $1.09 \pm 0.16$ | 1 |
| $\geq 3$ | $(4.9 \pm 1.0) \times 10^{-4}$ | 0 |



## Displaced jets in the hadronic calorimeter

[ATLAS-CONF-2016-103]

# Benchmark model



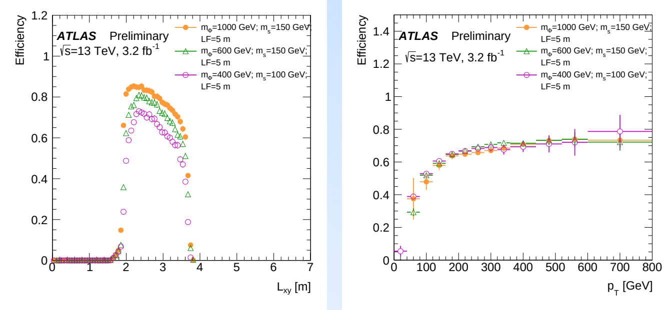

| | lumi [/fb] | $m_\Phi$ [GeV] | $m_s$ [GeV] |
|---|---|---|---|
| 8 TeV result | 20.3 | $100 \div 900$ | $10 \div 150$ |
| 13 TeV result | 3.2 | $400 \div 1000$ | $50 \div 400$ |

Major analysis changes in the 13 TeV analysis

1. BDT for discriminating signal and QCD jets
2. simplified data-driven estimate of QCD jets
3. exotics Higgs channel to be reconsidered at 13 TeV

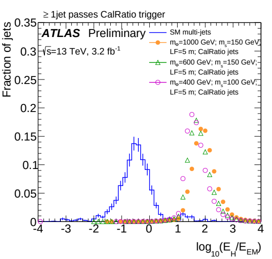
# Calo-ratio trigger

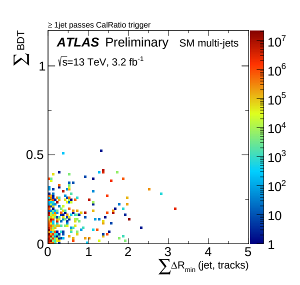
- tau candidate at L1 with at least 60 GeV
- no tracks above 2 GeV in the jet cone
- $\log(E_{HAD}/E_{EM}) > 1.2$
- beam-halo removal using calorimeter cell timing

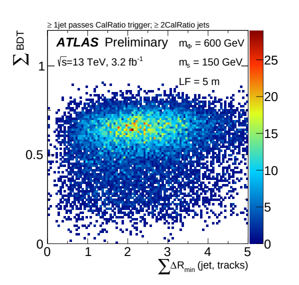


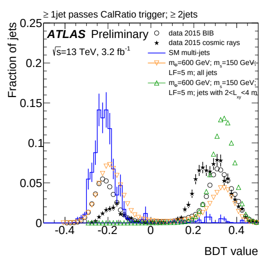
# Analysis ingredients

- two displaced hadronic jets to suppress the QCD multi-jet background
- removal of cosmic rays and non-collision events
- BDT with 13 input variables to discriminate between signal jets and QCD jets
- ABCD for the QCD background
- 24 observed events and $18.4 \pm 6.3(\text{stats}) \pm 6.6(\text{syst})$ predicted

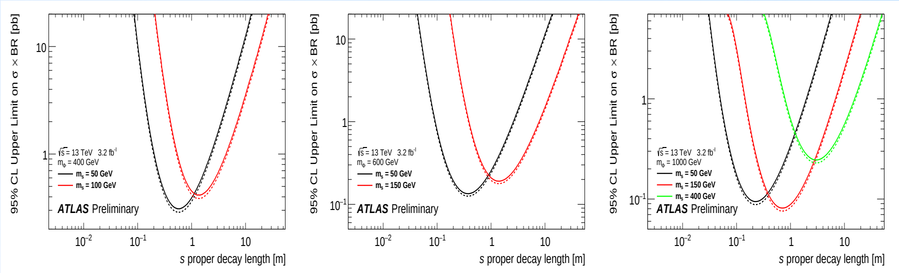


# Results




| | $m_s = 50\ GeV$ | $m_s = 100\ GeV$ | $m_s = 150\ GeV$ | $m_s = 400\ GeV$ |
|---|---|---|---|---|
| | Decay length range excluded at 95% CL for $\sigma\times$ BR = 1 pb | | | |
| $m_\Phi = 400\ GeV$ | (0.20, 2.4) m | (0.52, 4.6) m | – | – |
| $m_\Phi = 600\ GeV$ | (0.09, 2.7) m | – | (0.38, 8.2) m | – |
| $m_\Phi = 1$ TeV | (0.05, 2.0) m | – | (0.14, 7.2) m | (0.78, 16) m |

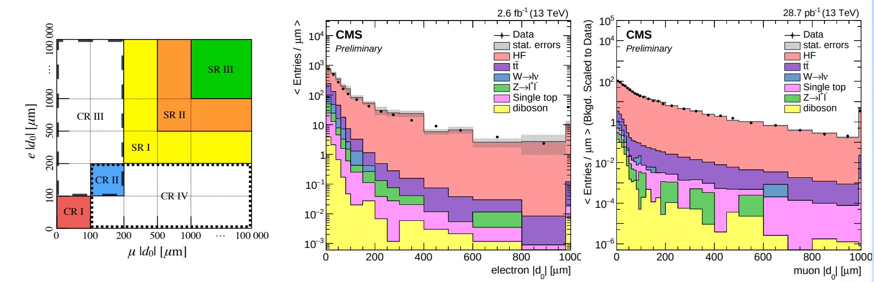
| Mass Point (GeV, GeV) | JES (%) | JES EMF (%) | JER (%) | Trigger (%) | Pile-up (%) | Luminosity (%) |
|---|---|---|---|---|---|---|
| (400,150) | 3.3 | 14 | 0.43 | 2.3 | 4.0 | 2.1 |
| (600,150) | 1.5 | 5.4 | 0.40 | 1.5 | 0.56 | 2.1 |
| (1000,150) | 0.51 | 1.8 | 0.05 | 1.0 | 2.0 | 2.1 |

Displaced leptons

[CMS-PAS-EXO-16-022]

# Event selection

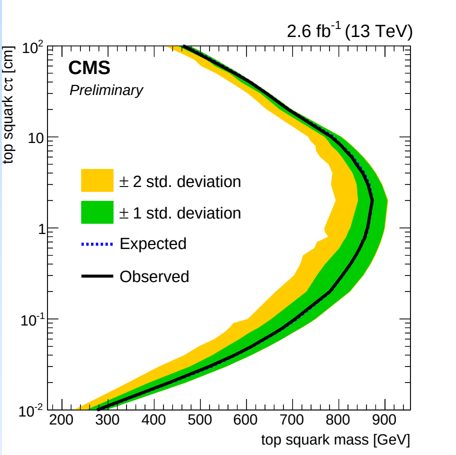
- dedicated di-lepton trigger requiring no impact parameter cut for the muon leg and no track information for the electron leg
- electron and muon with both impact parameter values between 200 $\mu m$ and 10 cm
- leptons to be oppositely charged
- various control regions by reverting the impact parameter cuts



# Systematics and exclusion reach

- systematic uncertainty on the data-driven heavy-flavour background estimation by varying the b-tagging requirement
- displaced track reconstruction studies with cosmic rays
- interpretation in the context of Displaced SUSY, where a RPV vertex induces the top squark decay $\tilde{t} \to bl$

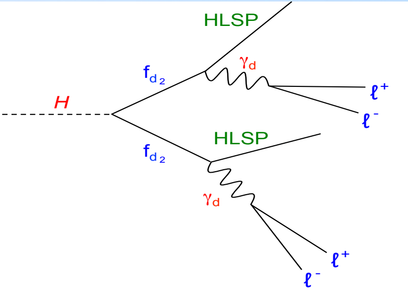
| Dataset | Cross-section | Pileup | $e$ ID/ISO | $\mu$ ID/ISO | Total |
|---|---|---|---|---|---|
| $W \to l\nu$ | 3.8 | 10.2 | 1.9 | 0.29 | 11.1 |
| single top | 4.2 | 0.2 | 2.9 | 0.22 | 5.1 |
| diboson | 2.5 | 0.2 | 2.9 | 0.23 | 3.8 |
| $Z \to ll$ | 3.8 | 1.1 | 2.5 | 0.18 | 4.7 |
| $t\bar{t}$ | 6.1 | 0.9 | 2.9 | 0.22 | 6.8 |
| signal | 13 – 18 | 0.2 – 8.9 | 3.0 – 4.4 | 0.25 – 0.32 | 18 – 24 |

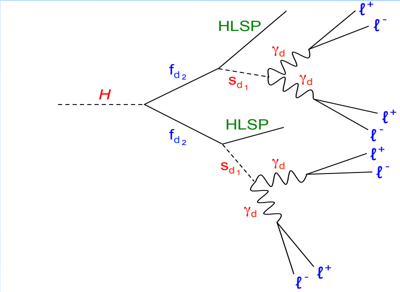


## Displaced lepton-jets

[ATLAS-CONF-2016-042]

# Benchmark model



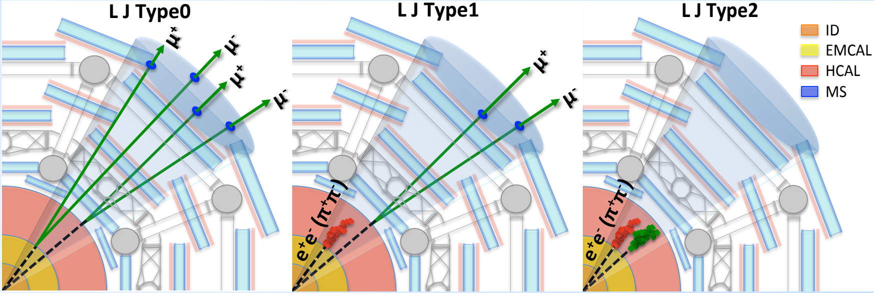




| | lumi [/fb] | $m_H$ [GeV] | $m_{\gamma_d}$ [MeV] |
|---|---|---|---|
| 8 TeV result | 20.3 | 125 | 400 |
| 13 TeV result | 3.4 | 125, 800 | 400 |

Major analysis changes in the 13 TeV analysis

1. dedicated displaced-muon trigger
2. enhancement in the reconstruction of collimated muons

# Lepton-jet definition



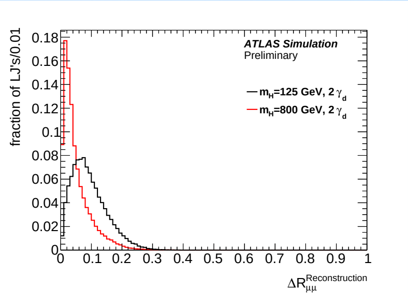

$\gamma_d$ branching ratios at 400 MeV

- $BR(e^+e^-) = 45\%$, $BR(\mu^+\mu^-) = 45\%$, $BR(\pi^+\pi^-) = 10\%$

# Analysis ingredients

New dedicated trigger available since Run II

| Higgs $\to$ $2\gamma_d + X$ | Run2 m=125 GeV | Run1 m=125 GeV | Run2 m=800 GeV |
|---|---|---|---|
| Tri-muons | 2.0 | 2.9 | 2.4 |
| Narrow-scan | 10.6 | N/A | 23.0 |
| Calo-ratio | 0.3 | 2.3 | 9.7 |
| OR of all | 11.9 | 4.6 | 32.0 |
| Higgs $\to$ $4\gamma_d + X$ | Run2 m=125 GeV | Run1 m=125 GeV | Run2 m=800 GeV |
| Tri-muons | 4.9 | 5.8 | 7.8 |
| Narrow-scan | 8.3 | N/A | 38.4 |
| Calo-ratio | 0.1 | 0.5 | 7.4 |
| OR of all | 11.8 | 6.2 | 44.8 |



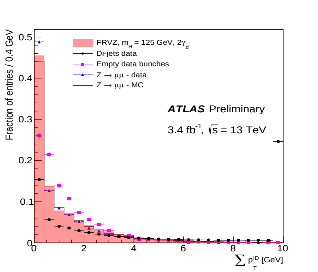

Narrow-scan approach

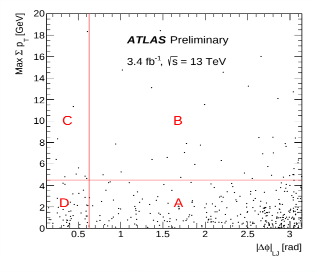
- leading muon seeded by a L1 muon
- sub-leading muon without a L1 seed searched at the HLT in a "narrow" cone by "scanning" the MS detector

# Analysis ingredients

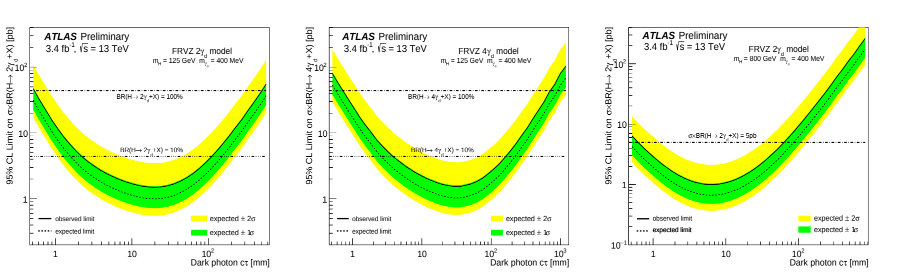
- track isolation implemented for removing multi-jet background and validated in $Z \to \mu\mu$ events
- cosmics background suppressed by looking at distributions on empty bunches
- QCD multi-jet background calculated with ABCD method
- main systematics evaluated using $J/\Psi \to \mu\mu$ events
- 285 observed events and $231 \pm 12$(stats) $\pm 62$(syst) predicted

| Systematic uncertainty | Value |
|---|---|
| Luminosity | 2.1% |
| Trigger: Narrow Scan | 6.0% |
| Trigger: Tri-muon-MS-only | 5.8% |
| Trigger: CalRatio | 11.0% |
| Reconstruction efficiency of single $\gamma_d$ | 15.0% |
| Effect of pile-up on $\Sigma p_T^{ID}$ | 5.1% |
| Reconstruction of the $p_T$ of the $\gamma_d$ | 10.0% |



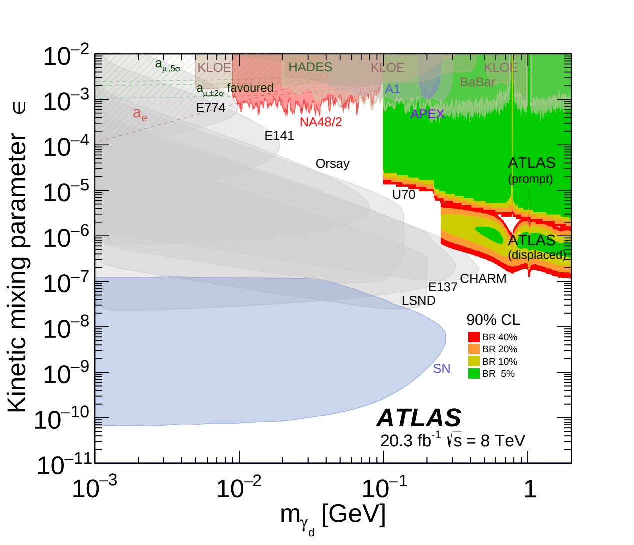



# Results




| FRVZ model | $m_{\mathrm{H}}$ (GeV) | Excluded $c\tau$ [mm] |
|---|---|---|
| Higgs $\rightarrow 2\gamma_{\mathrm{d}} + X$ | 125 | $2.2 \leq c\tau \leq 111.3$ |
| Higgs $\rightarrow 4\gamma_{\mathrm{d}} + X$ | 800 | $3.8 \leq c\tau \leq 163.0$ |
| Higgs $\rightarrow 2\gamma_{\mathrm{d}} + X$ | 125 | $0.6 \leq c\tau \leq 63$ |
| Higgs $\rightarrow 4\gamma_{\mathrm{d}} + X$ | 800 | $0.8 \leq c\tau \leq 186$ |

Hadron-collider experiments entered into the mass vs $\epsilon$ plot of the vector-portal interpretation



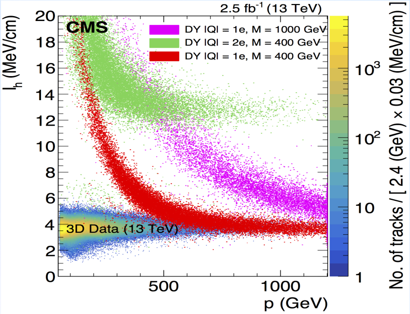
## Charged LLP

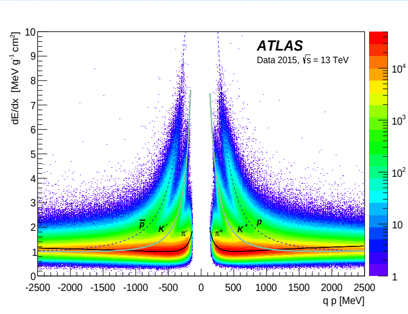
[ATLAS] $dE/dx$ only [Phys. Rev. D 93, 112015 (2016)]
[CMS] $dE/dx$ w/ and w/o time-of-flight in the MS [CMS-PAS-EXO-16-036]
[ATLAS] $dE/dx$ and time-of-flight in the calorimeters [Physics Letters B (2016) 647]

# Ionisation energy loss

Characteristic signature by looking at large ionisation energy loss of charged particles in the pixel detectors.

- measurement starts from the time-over-threshold of the pixel sensors
- in ATLAS improvements compared to Run I driven by the IBL
- only looking at the pixel detector to be sensitive to short lifetimes

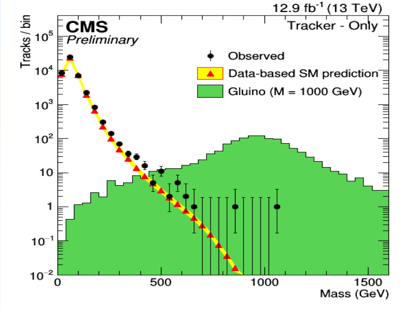


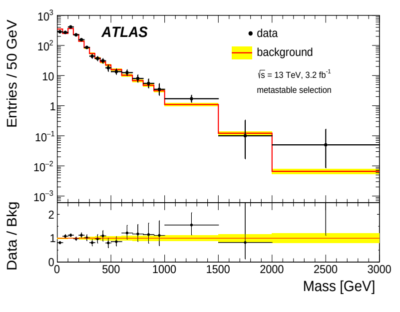



# Analysis ingredients

Similar analyses in ATLAS and CMS

- $E_T^{miss}$ trigger in ATLAS, muon or $E_T^{miss}$ trigger in CMS
- two signal regions in both experiments targeting metastable particles (decaying before the MS) or stable particles (leaving the detector)
- background from SM processes and random overlapping tracks
- interpretation in the context of composite coulorless states of squarks and gluinos with SM quarks or gluons, so-called $R$-hadrons

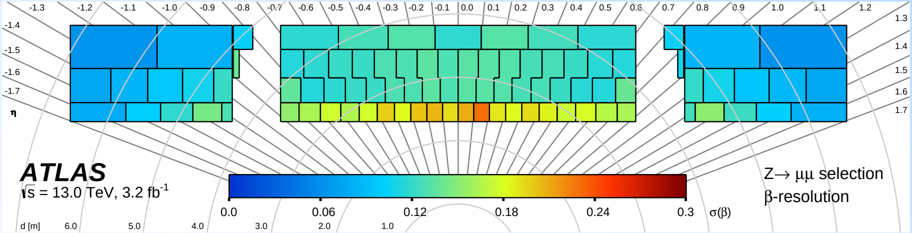


# Timing in the calorimeters

Analysis relying on ionisation energy loss and propagation with velocity lower than $c$ for looking for heavy charged LLP

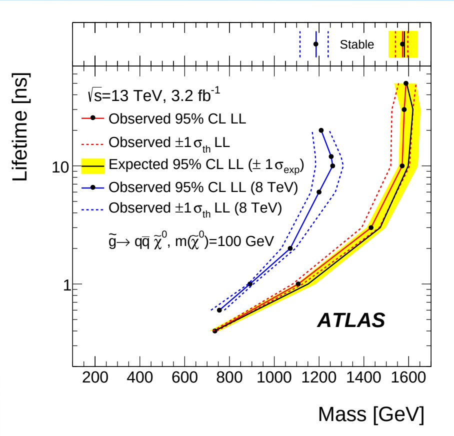
- excellent timing resolution of the calorimeters is crucial
- after calibration routine, cell-time resolution between 0.06 and 0.23 in $\beta$
- validation of simulation in $Z \to \mu\mu$ sample



# Results - ATLAS $dE/dx$ only

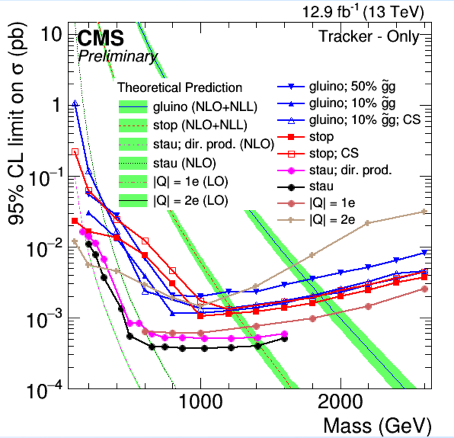
| **Selection region** | **Background exp.** | **Data** |
|---|---|---|
| Metastable $R$-hadron | $11.1 \pm 1.7 \pm 0.7$ | 11 |
| Stable $R$-hadron | $17.2 \pm 2.6 \pm 1.2$ | 16 |

| **Selection** | $\tau$ **[ns]** | $M_{\mathrm{obs}} >$**[GeV]** | $M_{\mathrm{exp}} >$**[GeV]** |
|---|---|---|---|
| Metastable | 0.4 | 740 | 730 |
| " | 1.0 | 1110 | 1150 |
| " | 3.0 | 1430 | 1470 |
| " | 10 | 1570 | 1600 |
| " | 30 | 1580 | 1620 |
| " | 50 | 1540 | 1590 |
| Stable | 50 | 1590 | 1590 |
| " | stable | 1570 | 1580 |



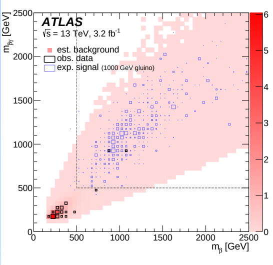
# Results - CMS

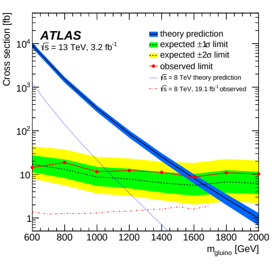
| Model | Analysis | Mass Limits |
|---|---|---|
| Gluino $f = 0.1$ | tracker-only | $M > 1850(1850)$ GeV |
| | tracker+TOF | $M > 1810(1810)$ GeV |
| Gluino $f = 0.1$ CS | tracker-only | $M > 1840(1840)$ GeV |
| Gluino $f = 0.5$ | tracker-only | $M > 1760(1760)$ GeV |
| | tracker+TOF | $M > 1720(1720)$ GeV |
| Gluino $f = 0.5$ CS | tracker-only | $M > 1800(1800)$ GeV |
| Stop | tracker-only | $M > 1250(1250)$ GeV |
| | tracker+TOF | $M > 1200(1200)$ GeV |
| Stop CS | tracker-only | $M > 1220(1220)$ GeV |
| GMSB Stau | tracker-only | $M > 660(660)$ GeV |
| | tracker+TOF | $M > 660(660)$ GeV |
| Pair Prod. Stau | tracker-only | $M > 170(170)$ GeV |
| | tracker+TOF | $M > 360(360)$ GeV |
| DY $Q = 1e$ | tracker-only | $M > 720(720)$ GeV |
| | tracker+TOF | $M > 730(730)$ GeV |
| DY $Q = 2e$ | tracker-only | $M > 670(750)$ GeV |
| | tracker+TOF | $M > 890(890)$ GeV |



# Results - ATLAS $dE/dx$ and ToF

| $R$-hadron | mass [GeV ] | $N_{sig} \pm \sigma_{N_{sig}}$ | eff.$\pm \sigma_{eff}$ | $N_{bkg} \pm \sigma_{N_{bkg}}$ | $N_{obs}$ |
|---|---|---|---|---|---|
| Gluino | 600 | 3340±660 | 0.113±0.022 | 4.5±1.4 | 3 |
| | 800 | 500±110 | 0.105±0.022 | 1.75±0.53 | 3 |
| | 1000 | 143±28 | 0.137±0.027 | 1.23±0.37 | 2 |
| | 1200 | 36.5±6.4 | 0.133±0.023 | 0.77±0.25 | 2 |
| | 1400 | 12.2±2.2 | 0.151±0.028 | 0.54±0.19 | 2 |
| | 1600 | 3.6±0.6 | 0.140±0.023 | 0.185±0.071 | 1 |
| | 1800 | 1.00±0.18 | 0.11±0.02 | 0.138±0.057 | 1 |
| | 2000 | 0.378±0.063 | 0.12±0.02 | 0.126±0.053 | 1 |
| Bottom squark | 600 | 36.1±7.7 | 0.064±0.014 | 4.5±1.4 | 3 |
| | 800 | 6.6±1.5 | 0.073±0.016 | 1.75±0.53 | 3 |
| | 1000 | 1.62±0.33 | 0.082±0.017 | 1.23±0.37 | 2 |
| | 1200 | 0.407±0.077 | 0.079±0.015 | 0.77±0.25 | 2 |
| | 1400 | 0.122±0.024 | 0.082±0.016 | 0.54±0.19 | 2 |
| Top squark | 600 | 47.5±9.5 | 0.085±0.017 | 4.5±1.4 | 3 |
| | 800 | 10.7±2.3 | 0.118±0.025 | 1.75±0.53 | 3 |
| | 1000 | 2.70±0.52 | 0.137±0.026 | 1.23±0.37 | 2 |
| | 1200 | 0.72±0.13 | 0.141±0.025 | 0.77±0.25 | 2 |
| | 1400 | 0.216±0.039 | 0.146±0.027 | 0.54±0.19 | 2 |



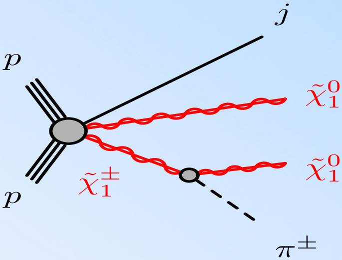



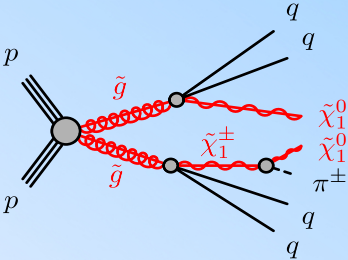

Gluino, bottom and top squarks long-lived R-hadrons are excluded up to 1580 GeV, 805 GeV and 890 GeV, respectively

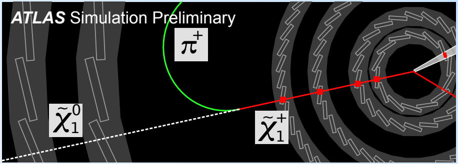
Disappearing tracks

[ATLAS-CONF-2017-017]

# Benchmark model and signature



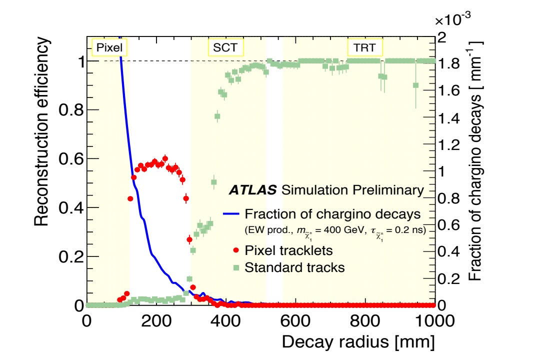




- emitted pion in the $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0$ transition is not reconstructed due its low momentum
- disappearing track between the pixel and SCT detectors

# Analysis ingredients

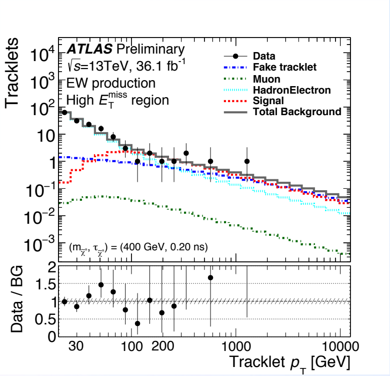
Dedicated track reconstruction algorithm

- second routine using only the unassociated hits left and requiring at least four pixel-detector hits to form so-called *tracklets*
- suppression of fake *tracklets* by requiring isolation and $p_T$ requirements, quality requirements, geometrical acceptance and disappearing condition (no SCT hits associated to the tracklet)

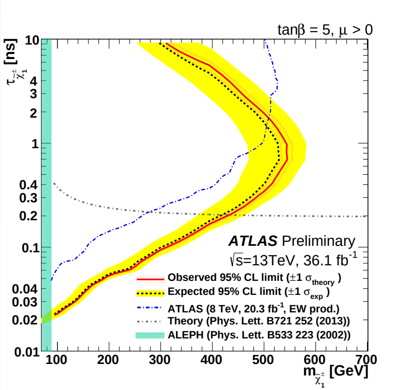


# Background estimation and results

- hadronic interactions, multiple scattering, bremsstrahlung or random combination of hits contributing may fake a possible signal
- background templates extracted in dedicated control regions




- unbinned likelihood fit on the *tracklet* $p_T$ distribution for extracting the signal contribution



# Conclusions

Exciting ongoing program of LLP searches at the LHC

- signature driven
- dedicated efforts will be necessary in HL-LHC for understanding the Higgs sector, the Naturalness problem and obviously for looking for dark matter

Looking for LLP poses various experimental challenges

- detectors are designed for prompt physics
- standard triggers and reconstruction may not be adequate

Preliminary results at 13 TeV

- various improvements compared to Run I despite higher pile-up and harsher conditions
- new signatures being considered for the first time but not yet public
- much more results being planned for the final LHC Run-II dataset