Challenging searches at the LHC (results and perspectives)

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Introduction

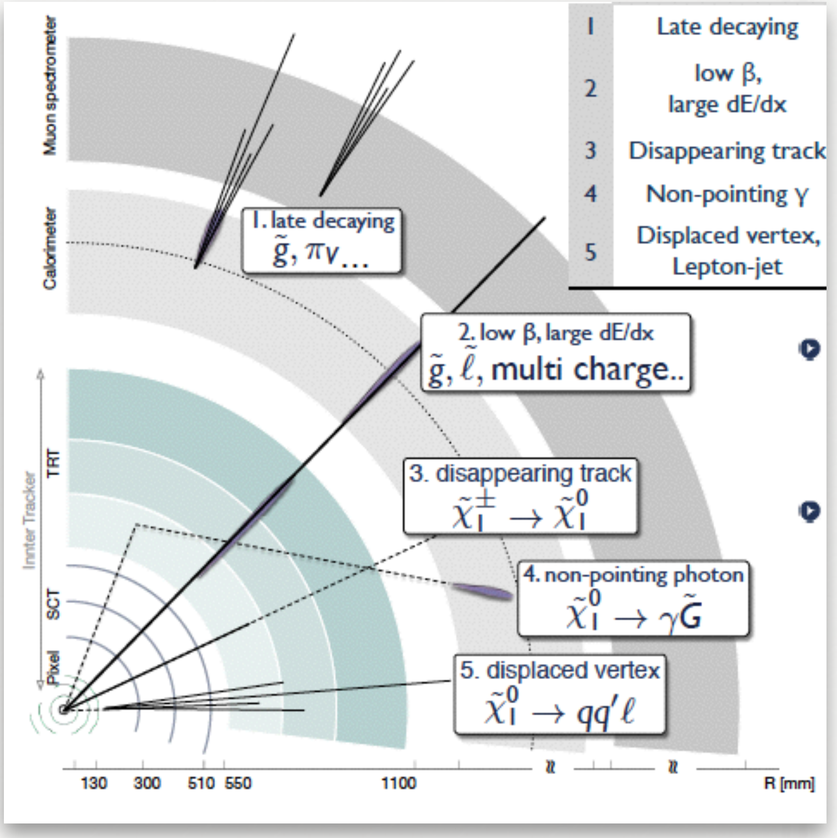
- The experimental results beautiful fit in Standard Model (SM) framework...but some mysteries are still opened and need physics beyond the SM (BSM) to be solved!

- **A wide variety of BSM models** (Hidden Sectors, RPV violating decays, Split-SUSY, AMSB, GMSB, etc.) **predict the existence of Long Lived Particles (LLP),** ***new particle with long life-time*****, enabling direct measurements.**

- **LLP have unusual and interesting signatures, extremely challenging due to the non-standard final topologies.**

  - May be overlooked or misidentified by searches not dedicated to LLP

  - May require customised trigger and selection algorithm



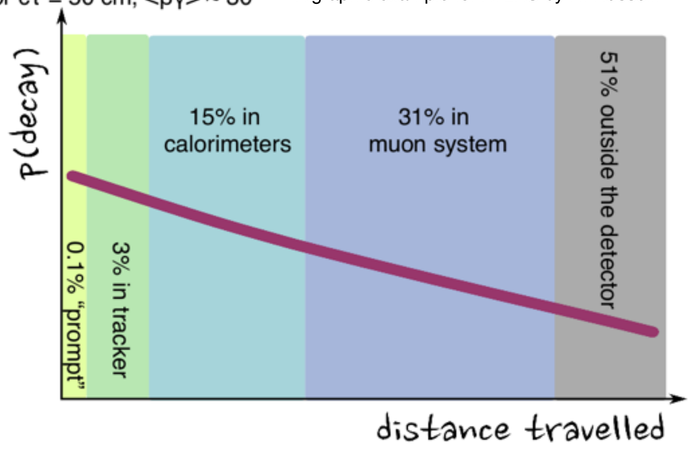
	Signature	Scenario	decay-length sensitivity
1	Late decaying	split SUSY, Hidden Valley	—
2	low β, large dE/dx	GMSB, Split-SUSY, Stealth SUSY, Multi-charged	>1000mm
3	Disappearing track	AMSB (wino-LSP)	O(100-1000)mm
4	Non-pointing γ	GMSB	O(100-1000)mm
5	Displaced vertex, Lepton-jet	RPV, GMSB, Hidden Valley	O(10-100)mm

Searching for LLP...

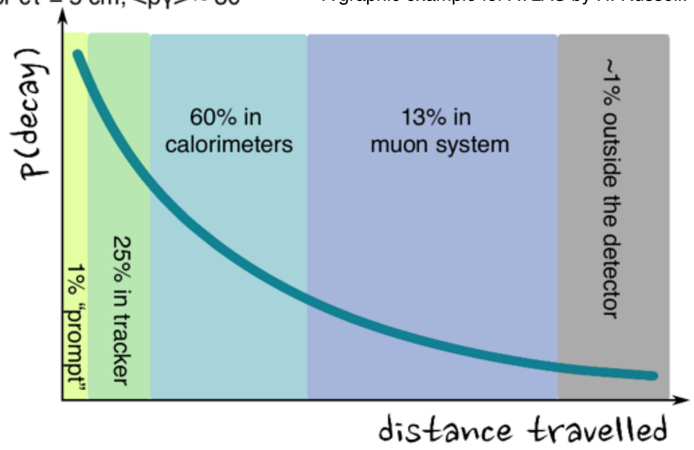
Unconventional signatures require challenging analysis methods

- **Detector-signature based search**
  - Experimentally very diverse, depending on particles' properties (dE/dx, Time-of-flight, kinked or disappearing tracks, displaced vertex)
  - Identification/discriminating variables depends on properties of the LLP. Lifetime? Charge? Decay products? Decay position in detector?
- Standard trigger are not designed for unusual objects
- **Self-made objects reconstruction is required**
- **Requires non-standard analysis strategies and tools**
  - Custom made MC simulation
  - Non-standard background, generally data-driven estimation
- **Claim discovery if statistically significant excess is found or, if not, interpret the result in term of constraints on selected models.**

e.g. for cτ = 50 cm, <βγ> ~ 30 A graphic example for ATLAS by H. Russell:

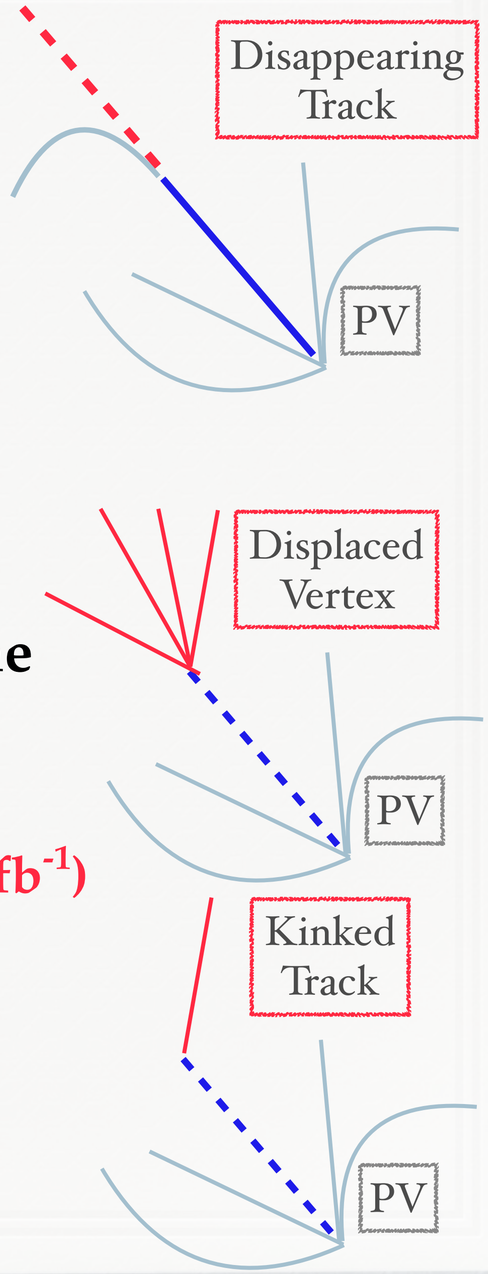


e.g. for cτ = 5 cm, <βγ> ~ 30 A graphic example for ATLAS by H. Russell:



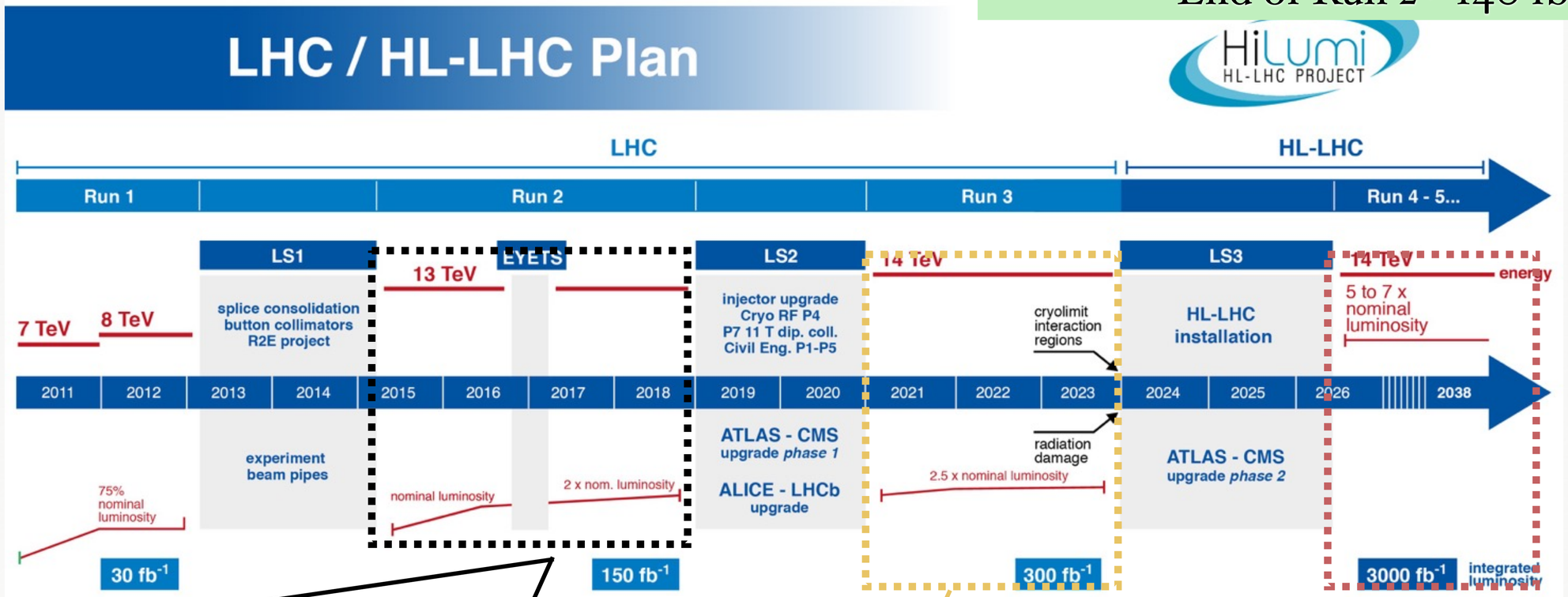
LLP analysis in this talk…

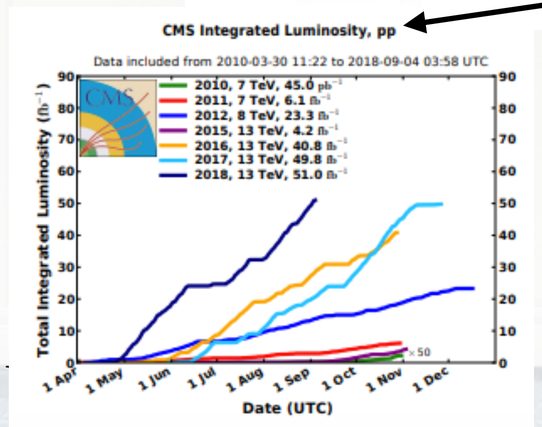
- Highlight Run2 results and their perspectives at HL-LHC for:
  - **Disappearing tracks and displaced vertices**
  - **Displaced Jets**
  - **Large dE/dx**
- **In these analyses, the signal event reconstruction and selection, as the background estimation, use dedicated, unique and very specialised technicalities.**
  - **Run2 results include 2016 and/or 2015 data taking (from few fb^{-1} up to 36 fb^{-1})**
  - **HL-LHC projections are obtained by scaling the signal and background datasets used for the Run 2 analyses (36 fb^{-1}), to the HL-LHC expected integrated luminosity (3000 fb^{-1})** and center-of-mass energy ($\sqrt{s}$ = 13 TeV →$\sqrt{s}$ = 14 TeV). Scale factors are applied to event yields and systematics uncertainties.

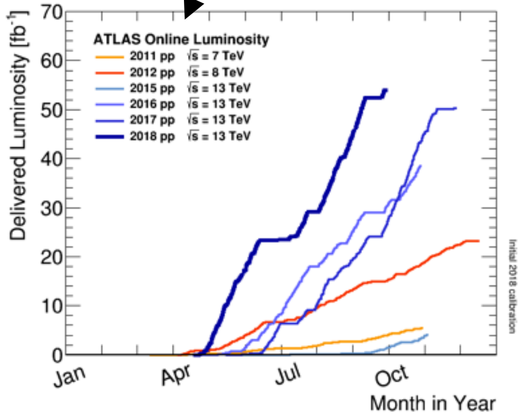


LHC Working Plan

Run 2: Available luminosity: ~ 130 fb-1
- 2016: ~40 fb-1 @ 13 TeV
- 2017: ~45 fb-1 @ 13 TeV
- End of Run 2 ~ 140 fb-1







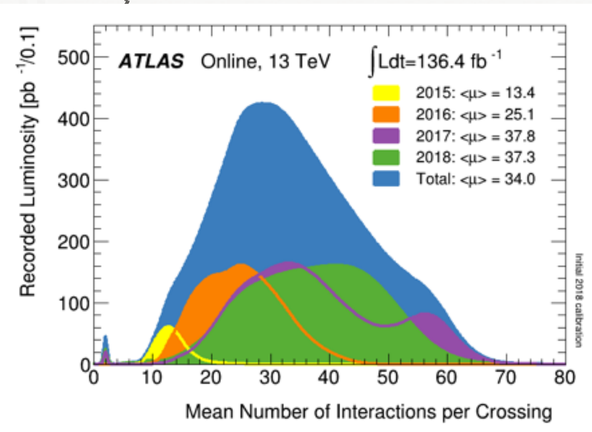
Phase-I upgrades for
$\mathcal{L}$=2–3 x 10^{34} cm^{-2}s^{-1}
- Small changes in the actual detector layout

Phase-II upgrades for
$\mathcal{L}$=5–7.5 x 10^{34} cm^{-2}s^{-1}
being designed & prototyped.

The Challenge of High Luminosity

The **5-7.5 x 10^{34} $cm^{-2}s^{-1}$ instantaneous luminosity** is beyond the capabilities of the current detectors

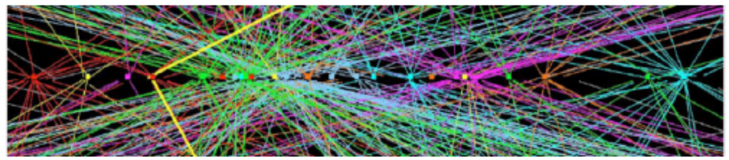
High luminosity means a big number of simultaneous events: <μ> =140-200



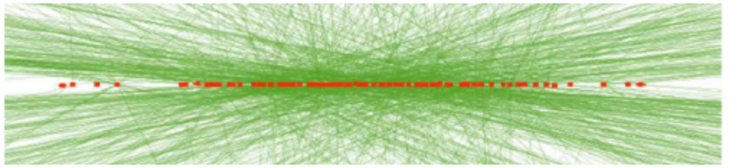
Requires very granular detectors, very good vertex reconstruction capabilities and bunch crossing identification, fast trigger -> **Detector Upgrade**.

Essential to mitigate effects from the pile-up!

LHC with 25 vertices



HL-LHC with 200 vertices

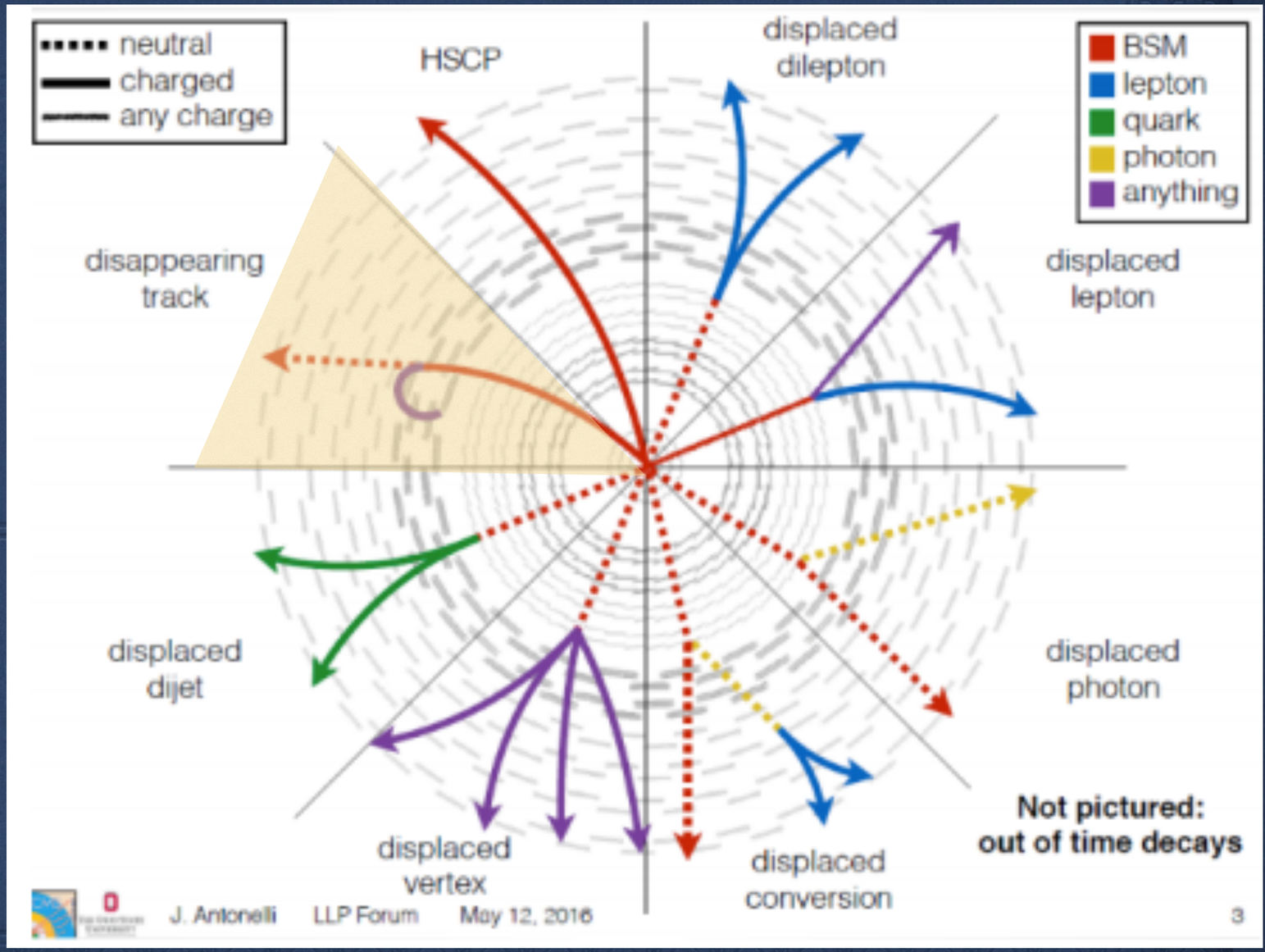


Very High Radiation doses: replace several parts to achieve a robuster, faster, radiation harder and lighter detector. **Detectors ageing** very quickly and having to be replaced/refurbished.

Challenging experimental conditions need to improve **detector performance as trigger and tracking systems crucial for LLP searches.** Upgrade Phase at High Luminosity will increase the physics coverage of all the experiments.

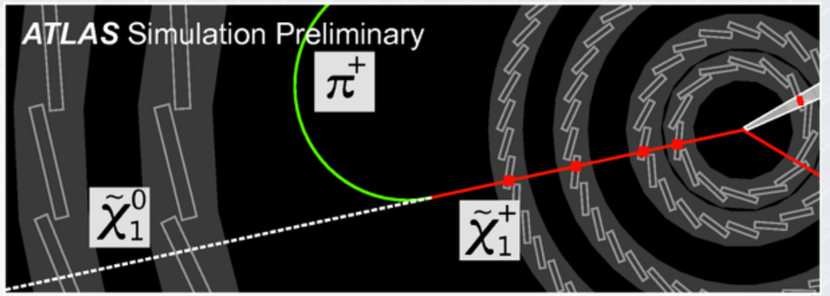
Disappearing Tracks

JHEP 06 (2018) 022
JHEP 08 (2018) 016
CERN-LHCC-2017-021
ATLAS-TDR-030



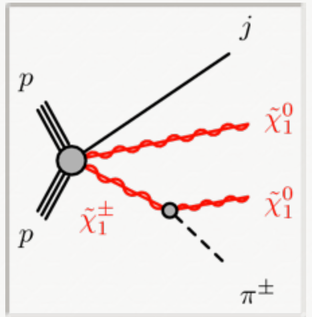
JHEP 06 (2018) 022

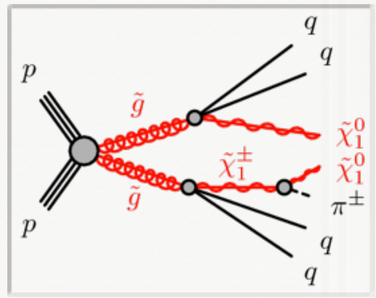
Disappearing tracks



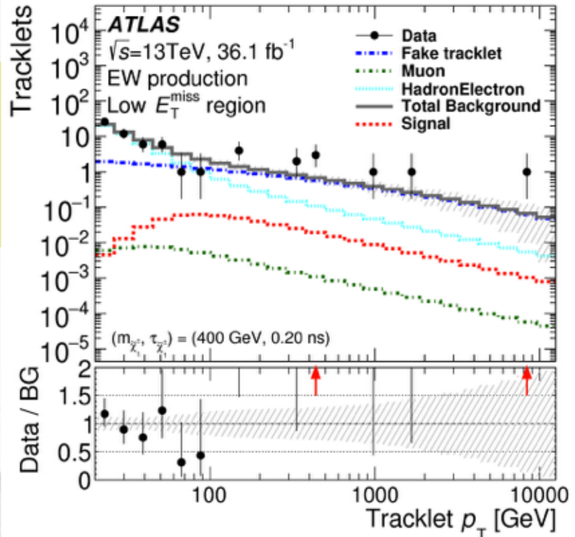
Long-lived charginos in AMSB model

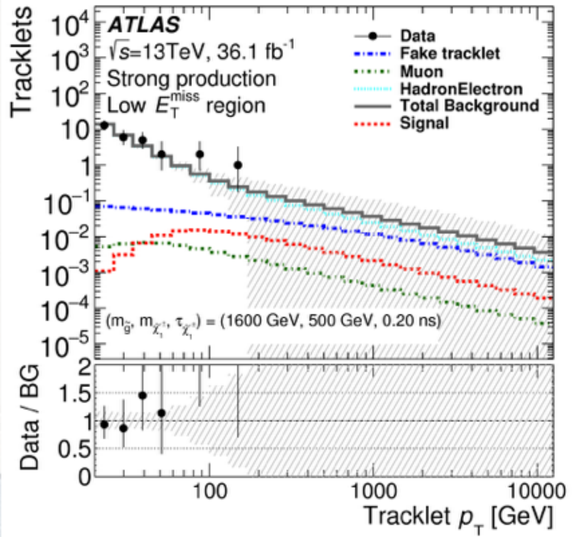
- Search for a disappearing track in the inner detector
  - Chargino and neutralino nearly degenerate, the soft pions are not reconstructed.
  - For Wino LSP generic prediction of ~160 MeV splittings, or lifetimes of ~0.2ns -> 6cm
- **Event Topology: high transverse momentum (p_T), large missing transverse energy (E_T^{miss}), high p_T jets and a short track .**
  - Two selections are defined for weak (direct) and strong (gluino) production.





EW Production
ISR jet
E_T^{miss}





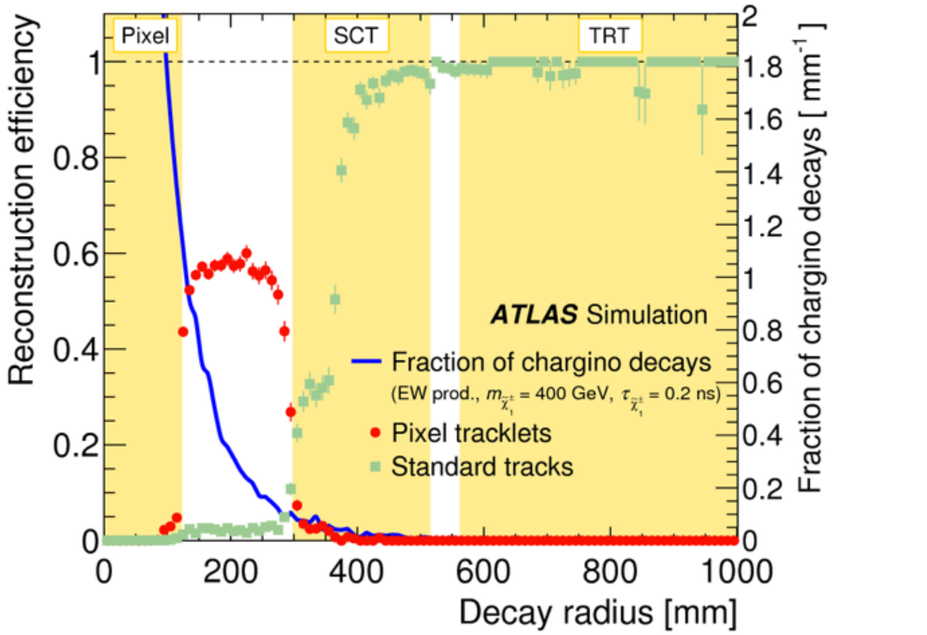
Strong Production
many jets
E_T^{miss}

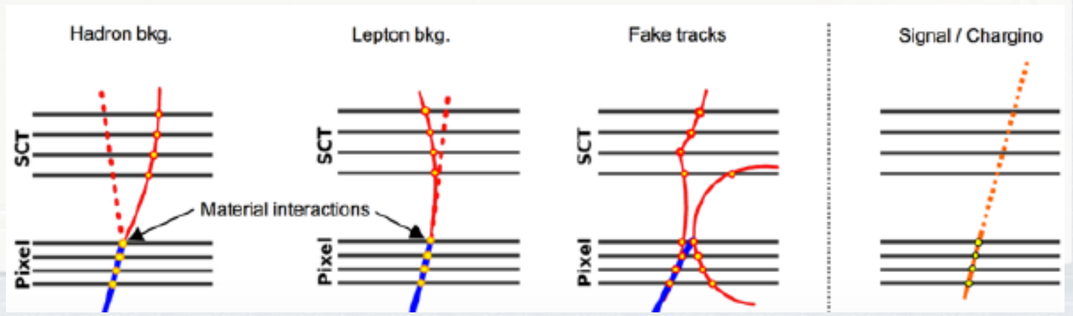
JHEP 06 (2018) 022

Analysis Strategy

Pixel tracklets effectively increase the efficiency at decay radius < 300 mm from near 0% up to 60%
Remaining inefficiency is due to LLP decaying before obtaining 4 pixel hits

- **Challenging identification of disappearing track – reconstruction of short tracks.**
  - Track reconstruction is done in two steps
    - Standard algorithms–e.g. to find mainly the primary tracks
    - Requiring at least seven measurements (hits) in the silicon detector layers
    - A second pass of the tracking is run
    - Only using leftover measurements from the first pass
      - The hit requirement is significantly looser and aimed at short tracks: ***at least four hits in the pixel layers***
- **Backgrounds estimated by a simultaneous fit to the tracklet p_T distribution**
  - p_T templates are built for each background category
  - Typically using Control Region (CR) with standard tracks smeared for a tracklet resolution function



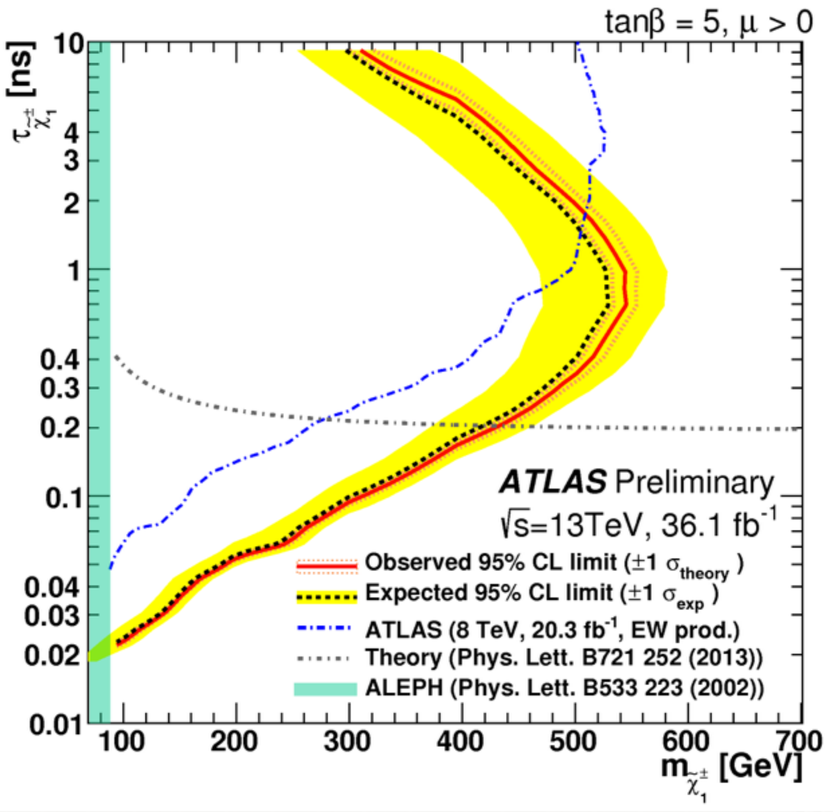


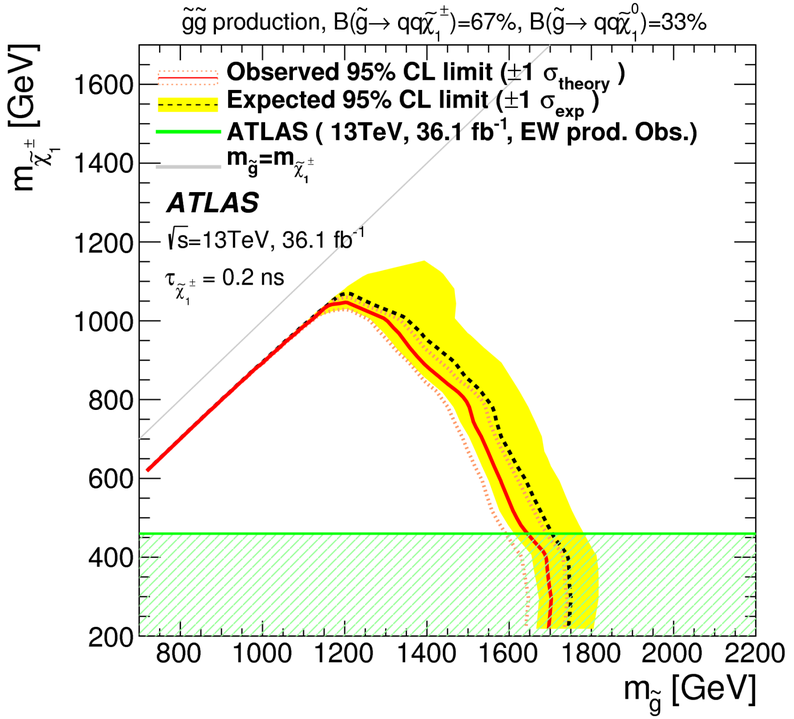
Results

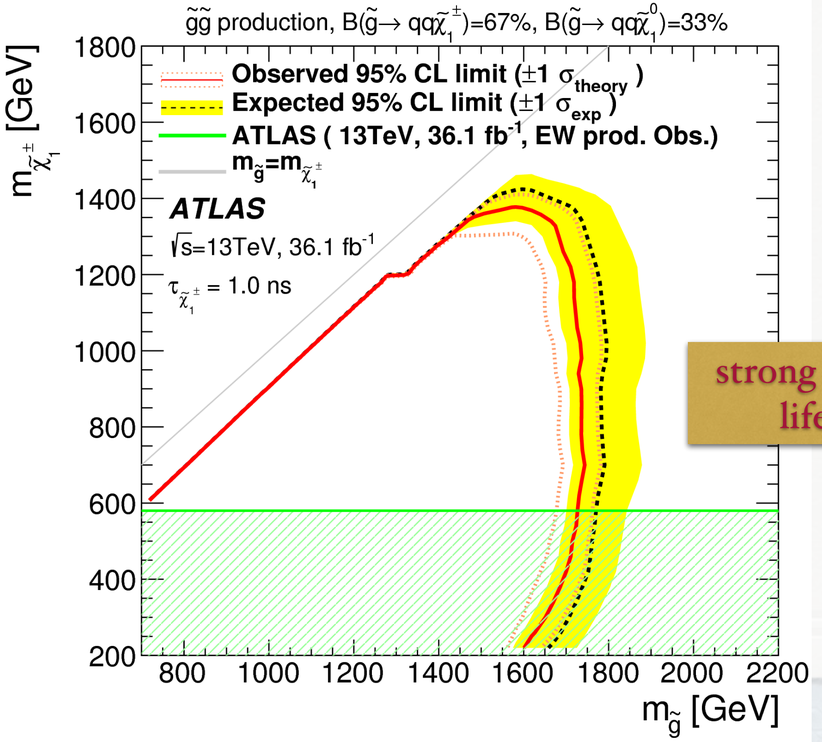
No significant excess is observed in ATLAS

- For electroweak production limits are significantly improved at low lifetimes
- For strong production reaching 1.4 (1.1) TeV in chargino mass for lifetimes of 1.0 (0.2) ns

electroweak production channel in terms of the lifetimes and the masses of chargino







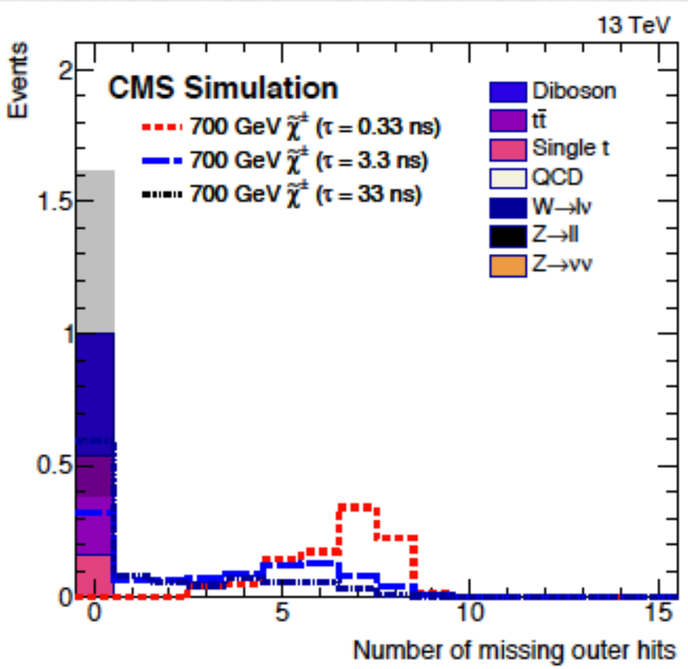
strong production channel in terms of the lifetimes and the masses of gluino

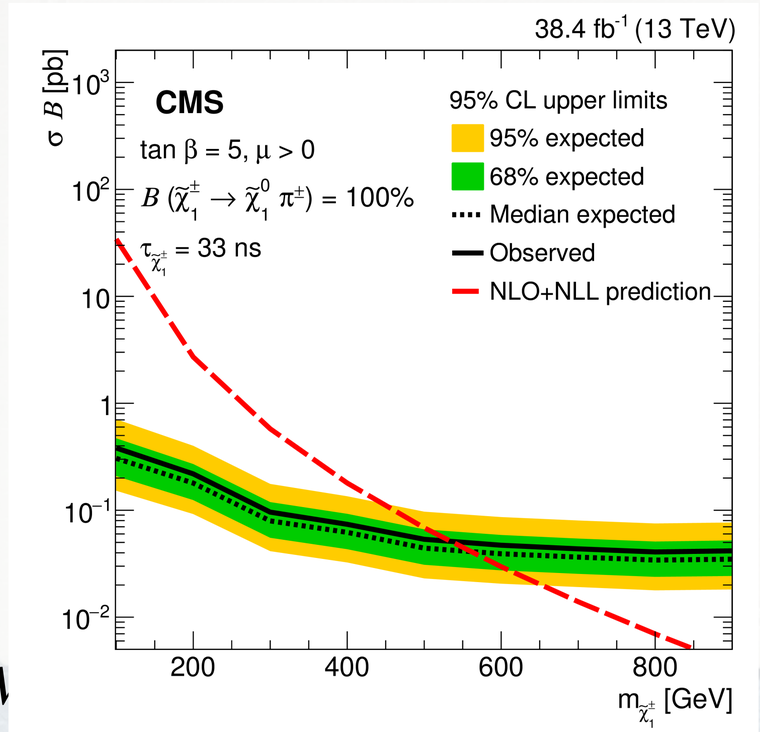
JHEP 08 (2018) 016

Disappearing Tracks in CMS

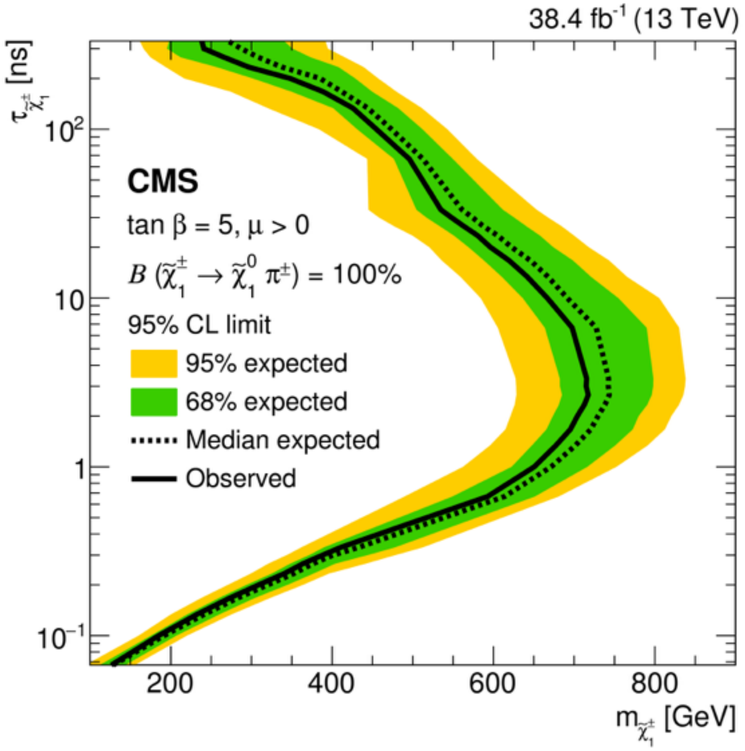
Extended lifetimes (0.1-100 ns), requiring:

- Isolated track with missing ≥3 outer hits
- p_T^{Miss} > 100 GeV
- Lepton veto
- The dominant source of high-p_T, isolated tracks from SM processes arises from charged leptons of W or Z bosons.





CMS Results: Charginos with masses up to 715 (695) GeV for a lifetime of 3 (7) ns are excluded at 95% confidence level, as are charginos with lifetimes from 0.5 to 60 ns for a mass of 505 GeV.



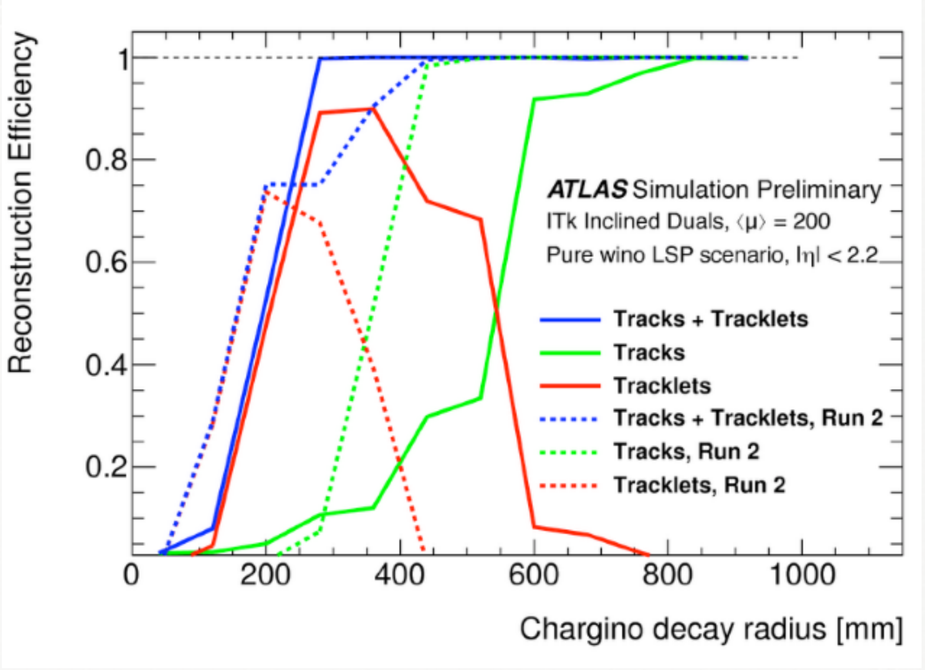
ATLAS HL-LHC

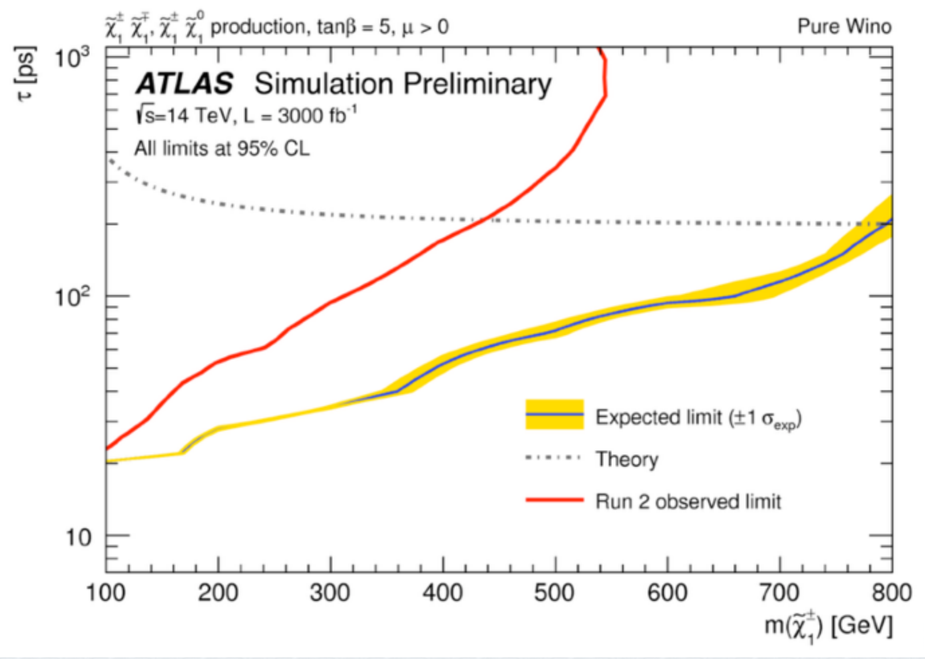
Selection (from Pixel TDR):

- MET > 450 GeV + one jet > 300 GeV.
- Tracklet with 4 pixel hits and pT > 250 GeV disappearing in strips.
- Background is mostly fake tracklets (estimated using Upgrade MC & Run 2 data).

HL-LHC projection for pure wino LSP & tracking efficiency below:

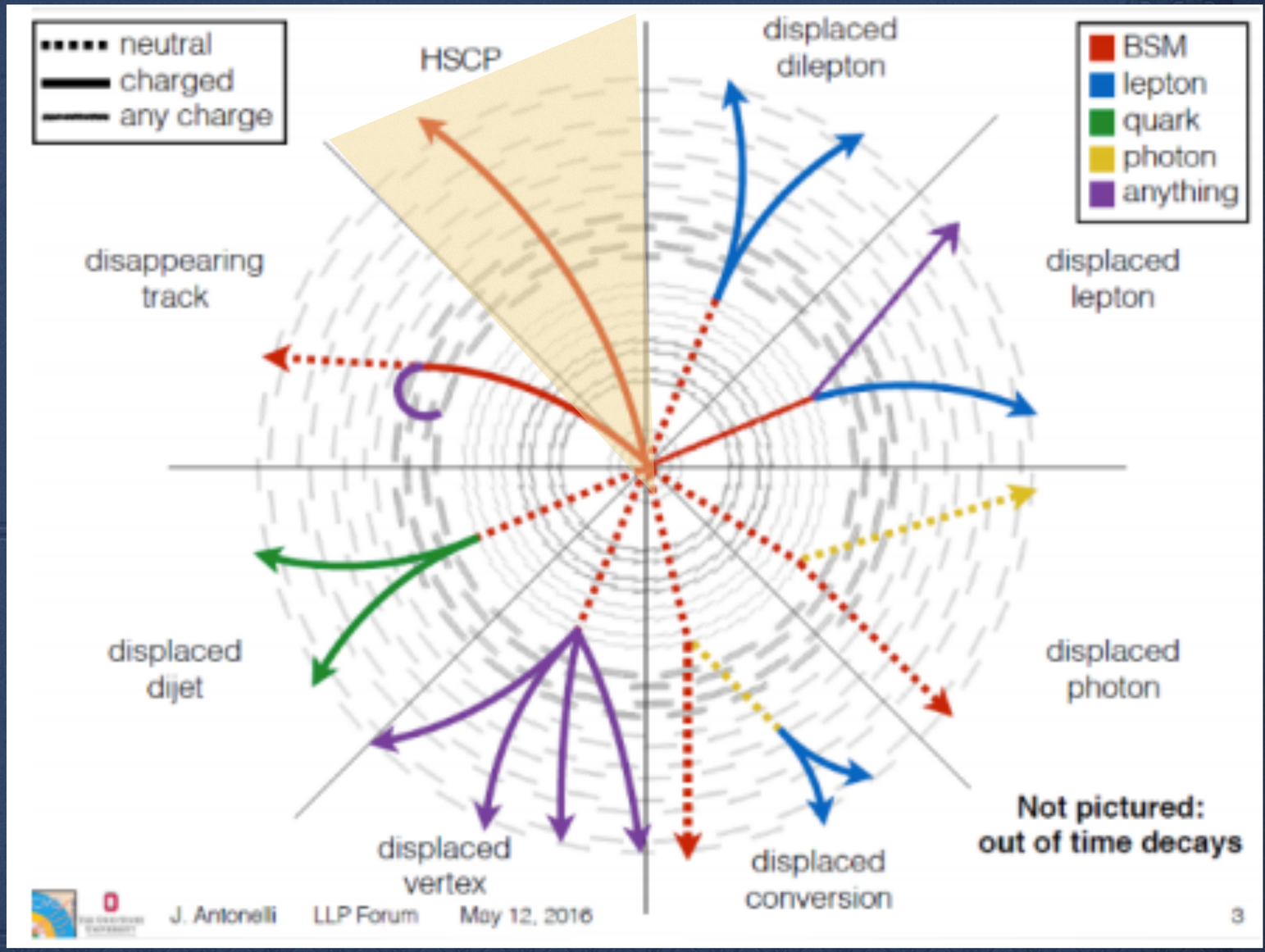
- Standard tracking produces more kinked tracks for pions than current ID. Further optimisation of selection to reject fakes.
- Expect to exclude > 800 GeV (> 250 GeV) for pure wino (higgsino) with 3000 fb-1 data.





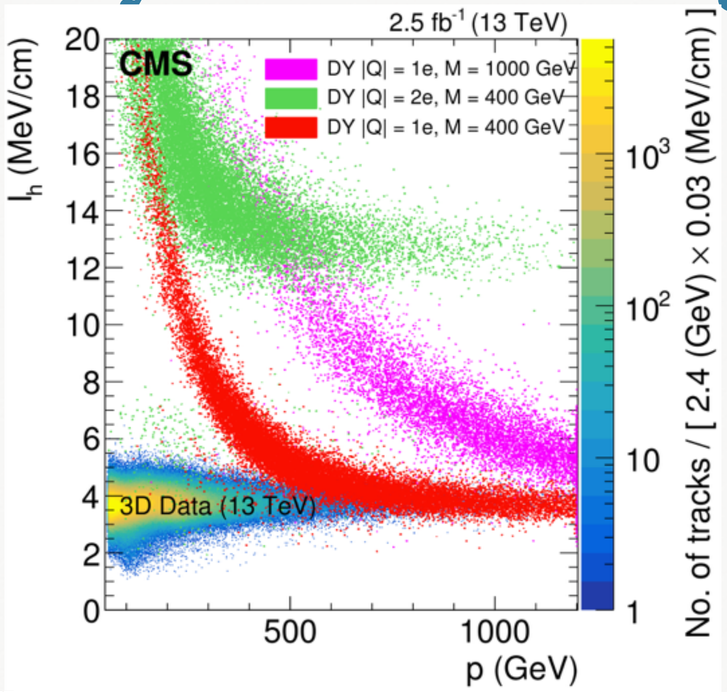
Heavy Stable Charged Particles (HSCP)

CERN-EP/2016-204
CERN-EP-2018-198
[CMS-TDR-17-001] [CMS-TDR-17-003]



CMS-EXO-15-010 ; CERN-EP/2016-204

Heavy Stable Charged Particles (HSCP)



- Massive (M > 100 GeV), Stable (does not decay within detector) or quasi-stable and charged -> large ionisation in detector and long time-of-flight to outer detectors
  - Many models : hidden valleys, RPV SUSY, Split SUSY, magnetic monopoles, Lepton-like, R-hadron models
- Two complementary analyses in CMS were performed: using **only the tracker** and using both the **tracker and the muon system**.

Tracker only
- Sensitive to any HSCP produced prompt
- Uses dE/dX in tracker to separate signal from BKG

Muon Only
- Sensitive to any HSCP crossing muon detector
- Uses TOF to separate signal from BKG

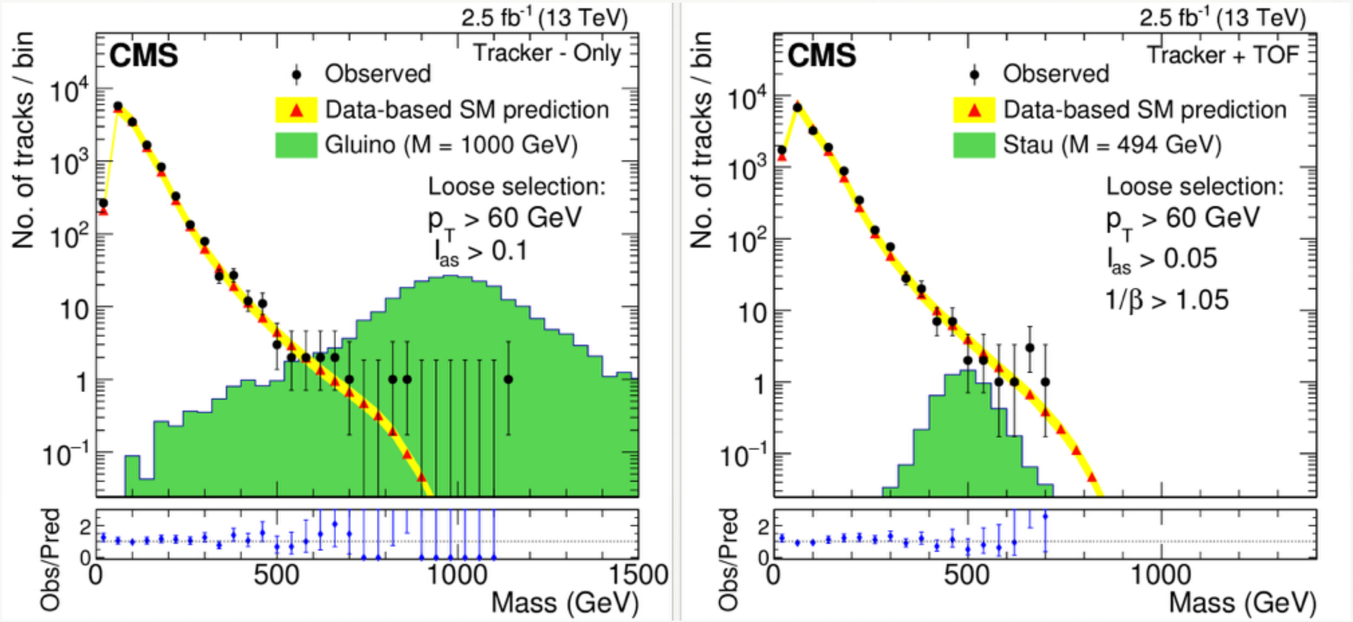
Tracker+TOF
- uses both (for HSCP crossing the detector)

	Selection requirements				Numbers of events $\sqrt{s} = 13$ TeV	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
tracker-only	>65	>0.3	—	>0	28.7 ± 6.0	24
				>100	20.7 ± 4.4	15
				>200	3.8 ± 0.8	2
				>300	0.82 ± 0.18	0
				>400	0.25 ± 0.05	0
tracker+TOF	>65	>0.175	>1.250	>0	18.2 ± 3.7	14
				>100	5.4 ± 1.1	4
				>200	0.90 ± 0.19	0
				>300	0.06 ± 0.04	0

CMS-EXO-15-010 ; CERN-EP/2016-204

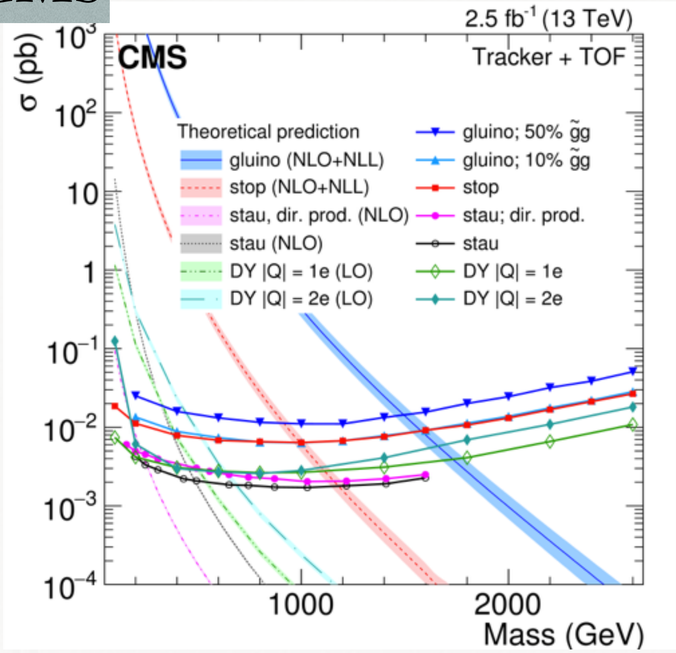
Analysis Selection

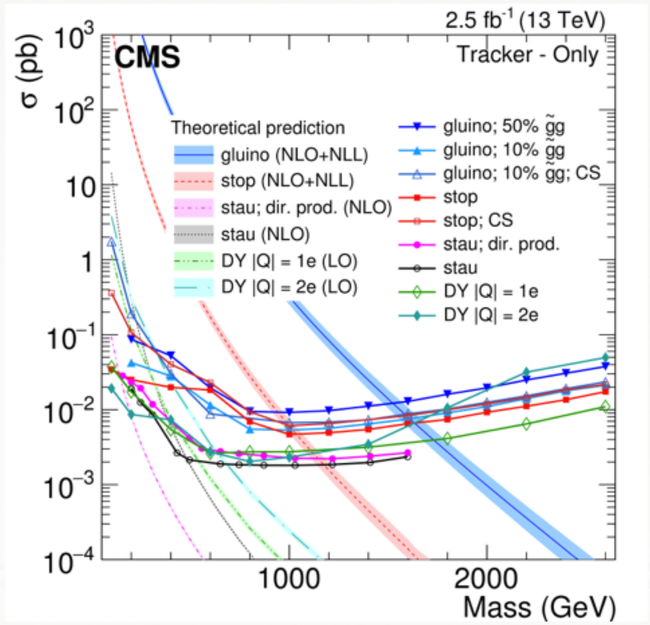
- **Selection**: muon and E_T^{Miss} Trigger.
  - Muon P_T > 50 GeV and E_T^{Miss} >170 GeV)
  - Quality on the tracks to reject SM background



- For the reconstructed track, information about **dE/dx** can be gained from measurements of ionisation deposited in layers of the pixel and silicon tracker.
- **The time of flight to the muon system** can be used to discriminate between particles travelling at near the speed of light and slower candidate.

Source of systematic uncertainty	Relative uncertainty (%)	
Signal acceptance	*tracker-only*	*tracker+TOF*
- Trigger efficiency	13	13
- Track momentum scale	<20	<20
- Track reconstruction	<2	<2
- Ionization energy loss	<15	<15
- HIP background effect	<3	<4
- Time-of-flight	—	<5
- Muon reconstruction	—	2
- Pileup	<1	<1
Tot. uncert. in signal acceptance	<20	<25
Collision background uncert.	20	20
Luminosity uncertainty	2.7	2.7





Results of the HSCP

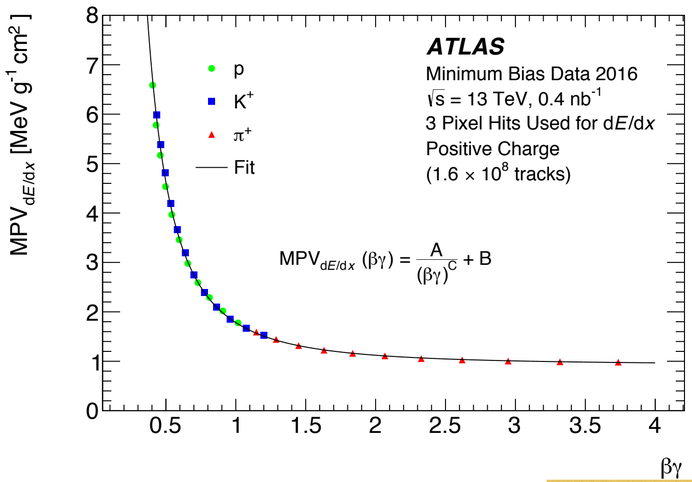
- **Results of the HSCP search as the cross section upper limits at 95% CL for various signal models**
- **Set mass limits for long-lived gluinos, top squarks, tau sleptons, and multiply charged particles**

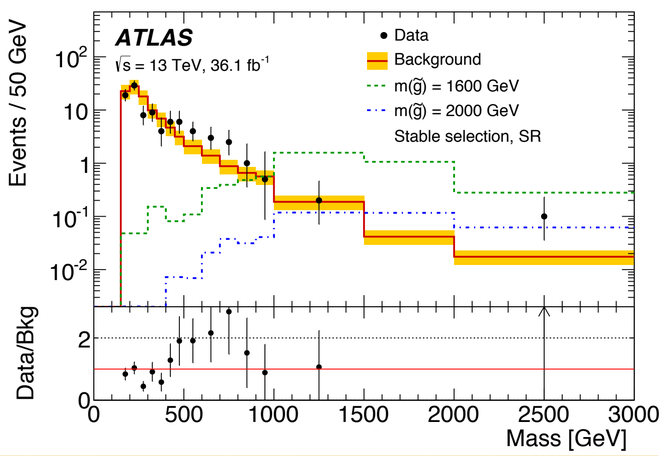
Model	analysis used	$\sqrt{s} = 7 + 8$ TeV	$\sqrt{s} = 13$ TeV
Gluino $f = 0.1$	*tracker-only*	$M > 1320$ GeV	$M > 1610$ GeV
	tracker+TOF	$M > 1290$ GeV	$M > 1580$ GeV
Gluino $f = 0.1$ CS	*tracker-only*	$M > 1230$ GeV	$M > 1580$ GeV
Gluino $f = 0.5$	*tracker-only*	$M > 1250$ GeV	$M > 1520$ GeV
	tracker+TOF	$M > 1220$ GeV	$M > 1490$ GeV
Gluino $f = 0.5$ CS	*tracker-only*	$M > 1150$ GeV	$M > 1540$ GeV
Top squark	*tracker-only*	$M > 930$ GeV	$M > 1040$ GeV
	tracker+TOF	$M > 910$ GeV	$M > 990$ GeV
Top squark CS	*tracker-only*	$M > 810$ GeV	$M > 1000$ GeV
GMSB tau slepton	*tracker+TOF*	$M > 430$ GeV	$M > 490$ GeV
	tracker-only	$M > 389$ GeV	$M > 480$ GeV
Pair prod. tau slepton	*tracker+TOF*	$M > 330$ GeV	$M > 240$ GeV
	tracker-only	$M > 180$ GeV	—
DY $\|Q\| = 1e$	*tracker-only*	$M > 640$ GeV	$M > 510$ GeV
	tracker+TOF	$M > 650$ GeV	$M > 550$ GeV
DY $\|Q\| = 2e$	*multiply charged*	$M > 720$ GeV	—
	tracker-only	$M > 520$ GeV	$M > 680$ GeV
	tracker+TOF	$M > 520$ GeV	$M > 660$ GeV

CERN-EP-2018-198 , arXiv:1808.04095

HSCP in ATLAS

In ATLAS the search for gluinos (R-hadrons) is performed in two separate signal regions: stable and metastable (not be seen in the muon system).

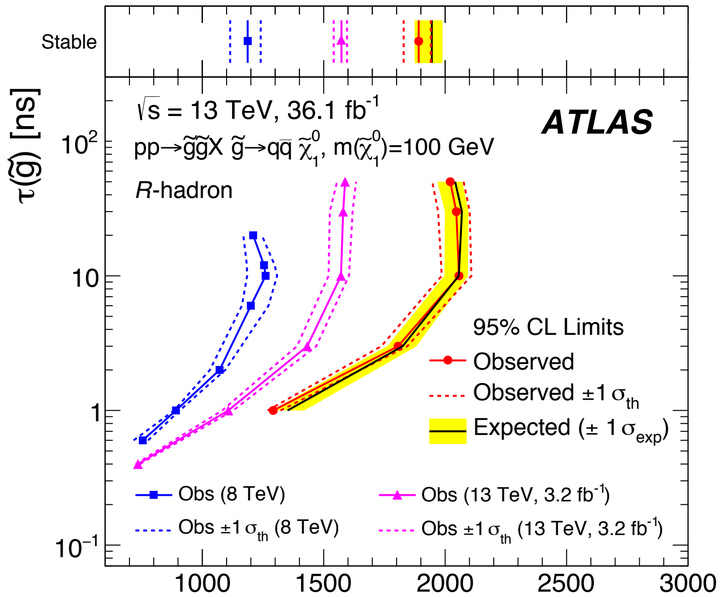




Signal Selection: Heavy gluinos are recognized by their higher specific ionisation in (four) pixel layers of the tracker. The search variable is the mass m=p/(βγ) where βγ is obtained solving the equation shown in the figure numerically.

- **Selection driven by MET trigger** with threshold varied from 70 to 110 GeV.
- **Events are selected by requiring (offline)** MET > 170 GeV. Candidates must have p_T> 50 GeV, p> 150 GeV, |η| < 2 and (most probable value) $MPV_{dE/dx}$> 1.8 MeV cm² /g (which is roughly equivalent to βγ < 0.9)
- The background is fully estimated from data.

Results interpreted for pair production of R-hadrons as composite colourless states of a long-lived gluino and SM partons.



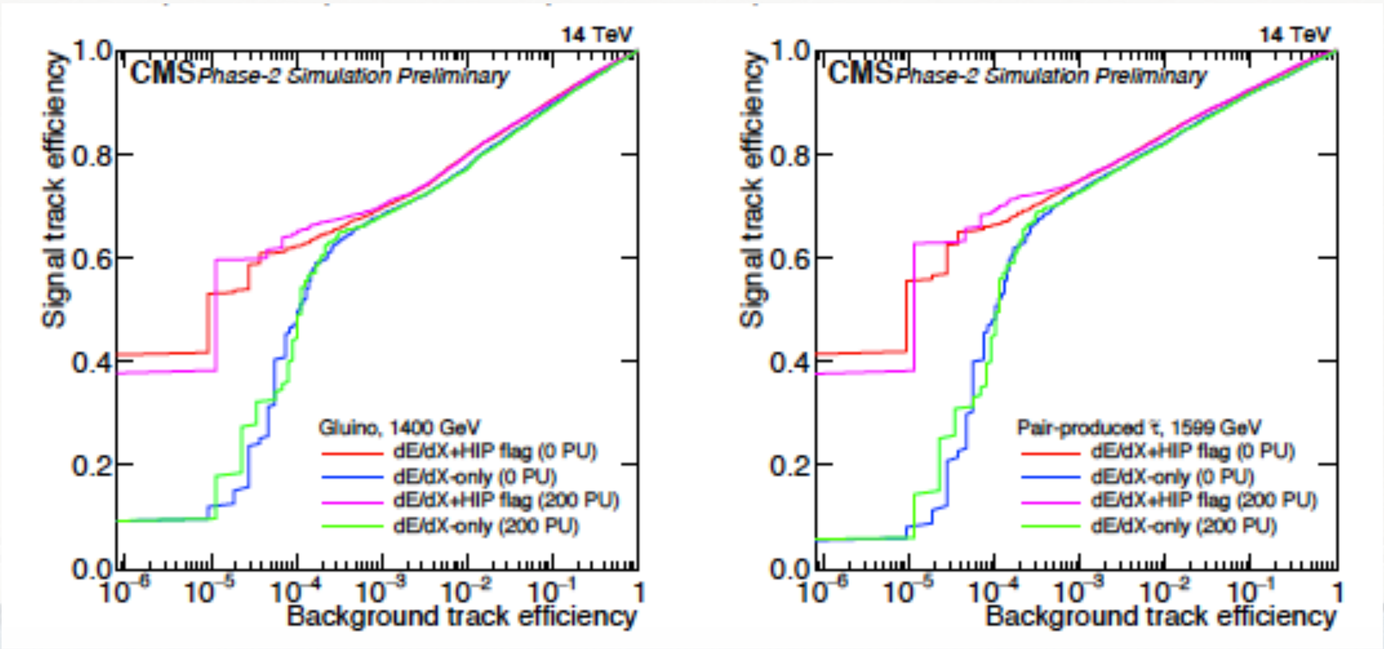
R -hadrons with lifetimes above 1.0 ns are excluded at the 95% confidence level, with lower limits on the gluino mass ranging between 1290 GeV and 2060 GeV. In the case of stable R-hadrons, the lower limit on the gluino mass at the 95% confidence level is 1890 GeV.

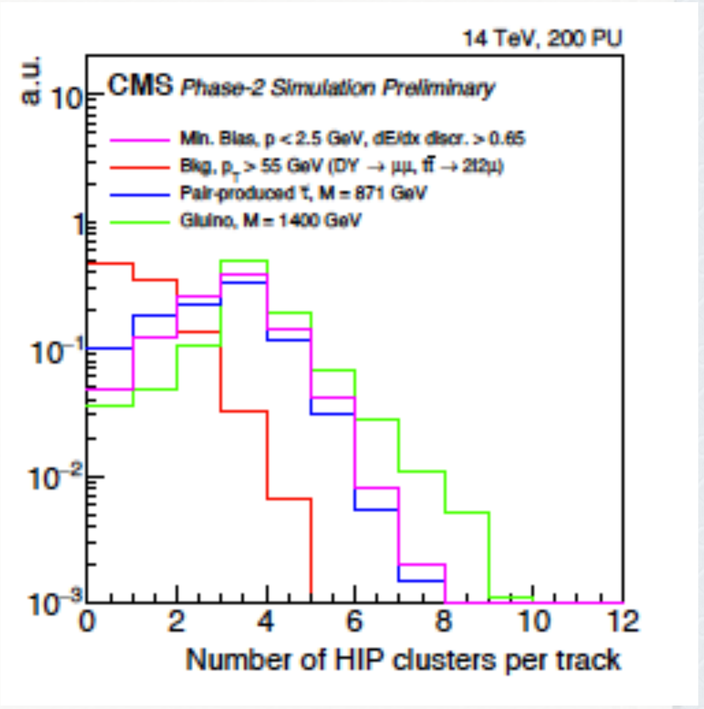
HSCP at HL-LHC

Exploit intrinsic time resolution of the RPC system (trigger chambers) and upgraded tracker:

- HSCPs look like slow muons -> RPC triggers HSCPs with β-0.25.
- Use trackers to identify signal tracks looking for anomalously high energy loss measurements (IT vs. OT) -> **HIP Flag.**
- Improved performance of dE/dx discriminator for Phase 2

- **ROC curve(*) for gluino (1.4 TeV) and stau (1.599 TeV)**

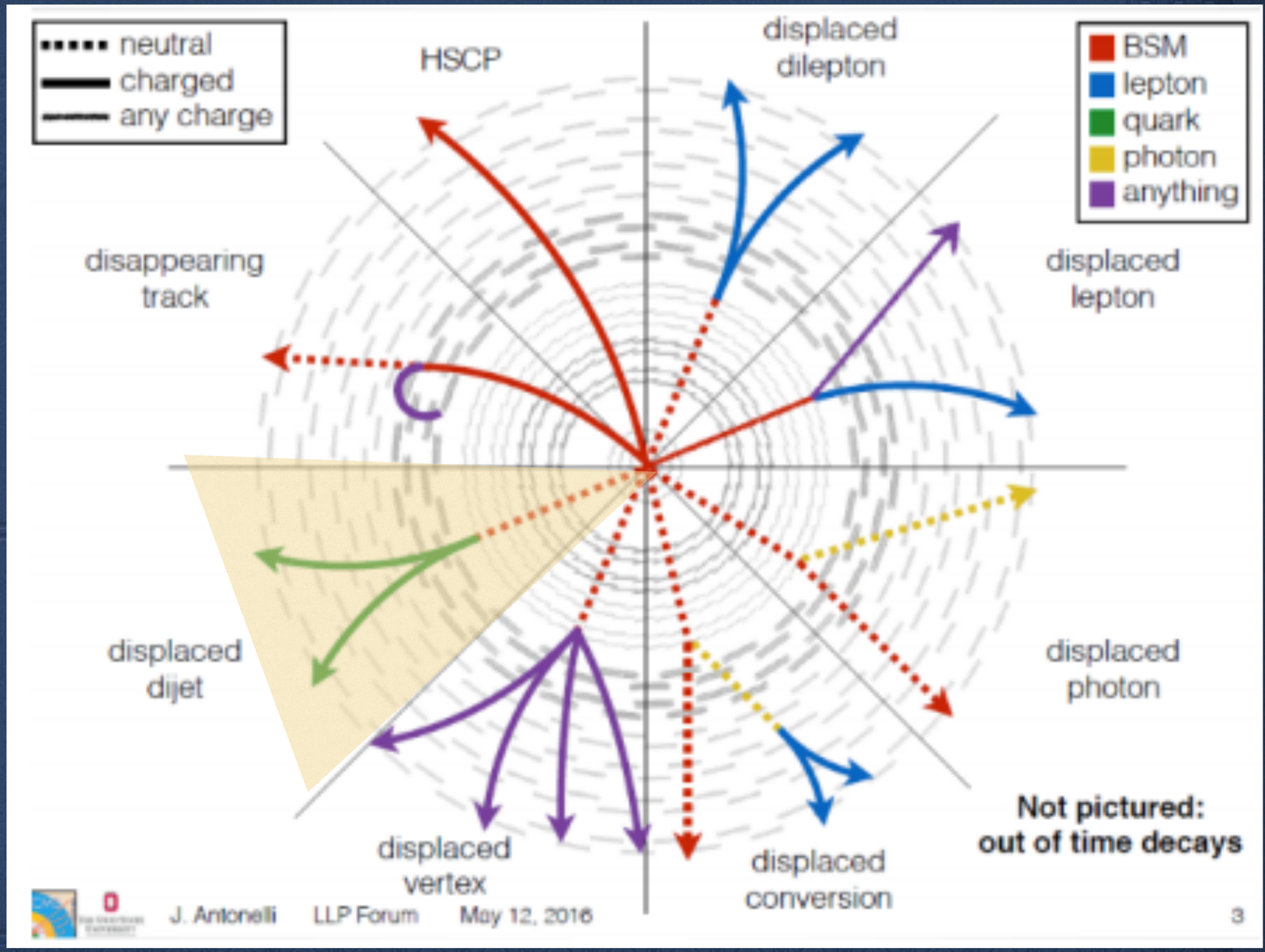




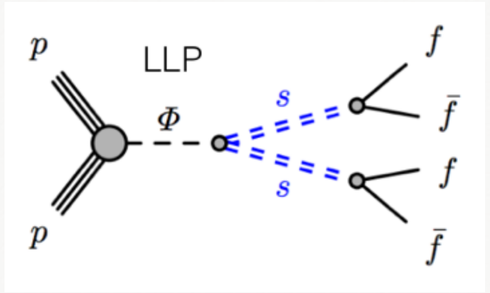
(*) Receiver Operating Characteristic curve, i.e. ROC curve, is a graphical plot that illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied.

Displaced Jets

ATLAS-CONF-2016-103
LHCB-PAPER-2016-065
CERN-LHCC-2017-019
ATLAS-TDR-028



Displaced Jet Topology



Weakly coupled Hidden Sector (HS) may communicate with the via neutral LLP that decays within the ATLAS detector.

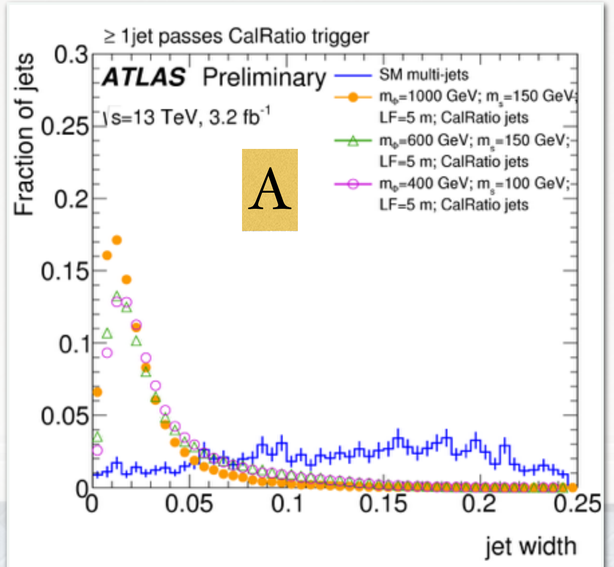
This analysis explores signature, where a neutral LLP decaying in the hadronic calorimeter.

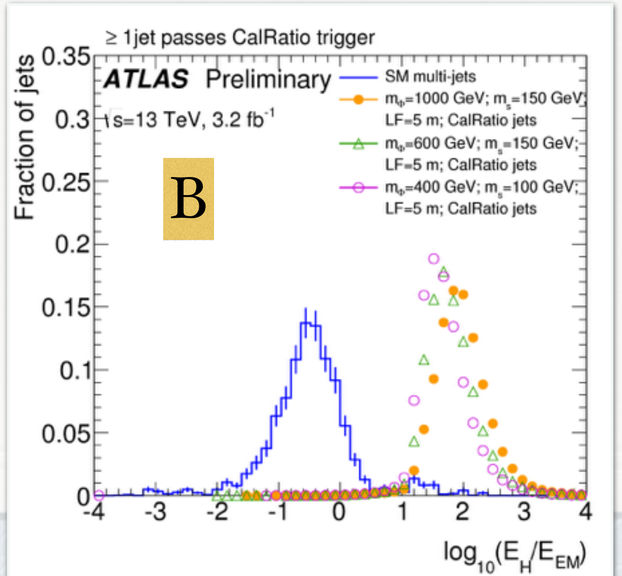
Event Topology: an atypical jet with no tracks in the inner tracker and would deposit no energy in the electromagnetic calorimeter

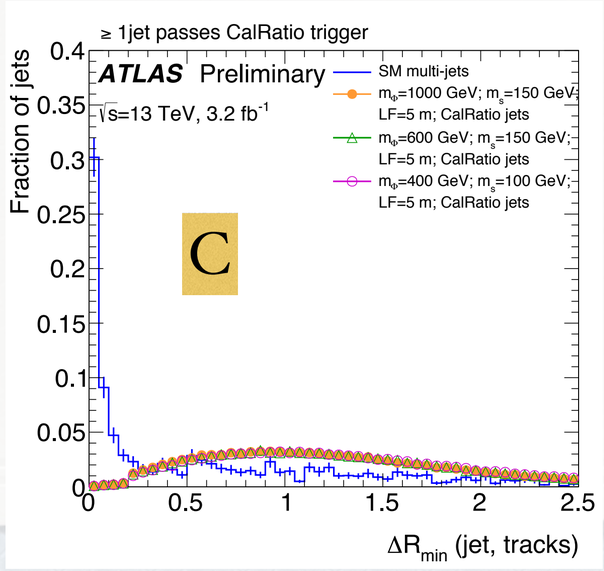
A. Produce narrower cone than typical SM jets originating from the IP

B. Ratio of energy in the HCal (E_{H}) to the energy in the ECal (E_{EM}) is large (large $log(E_{\mathrm{H}}/E_{\mathrm{EM}})$)

C. No associated ID tracks to the jet –large ΔRmin between the jet direction and the tracks



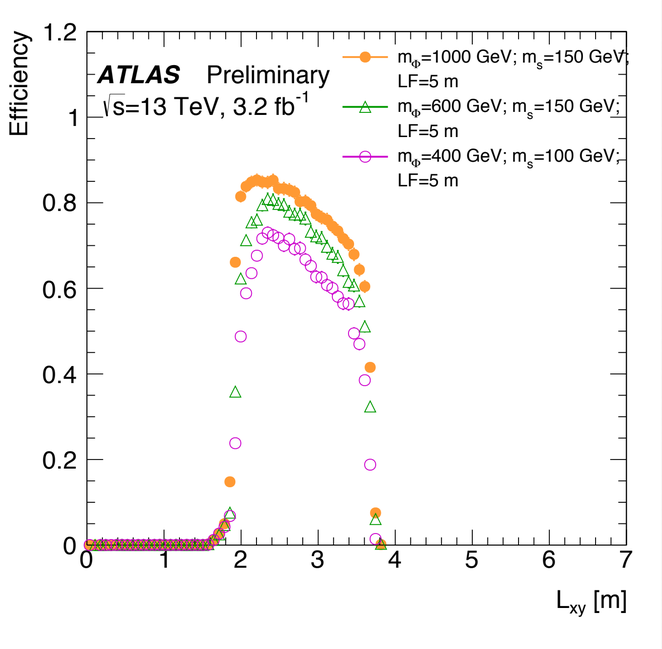


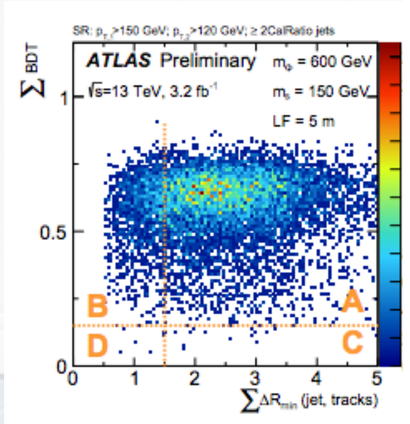


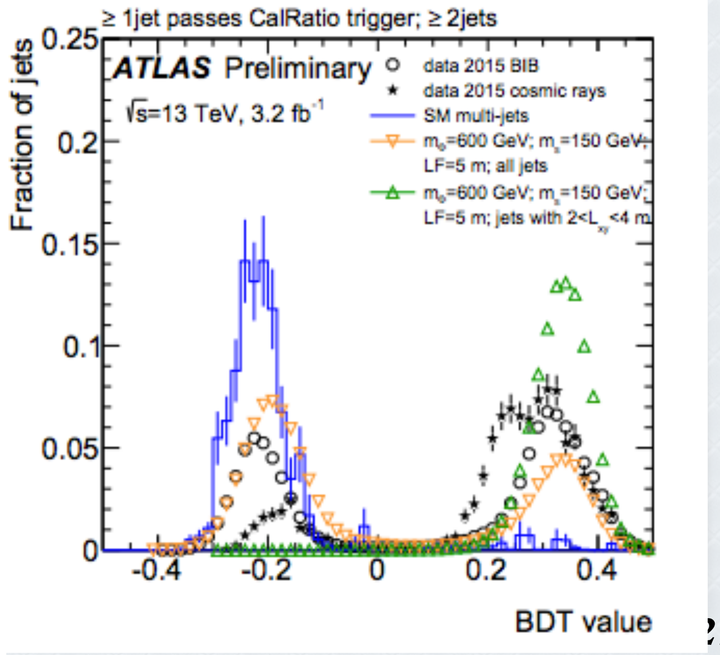
Analysis Strategy

Analysis Selection

- **Dedicated signature-driven trigger: "CalRatio Trigger".**
  - Although the jets from neutral LLP decays pass standard jet triggers, the high prescales of these triggers and the high multijet and other background-process cross-sections required a dedicated trigger selection.
- **Offline Selection: Modifying Jet quality cuts and systematics,** standard jet selection removes the low em-fraction jets and not includes them in the standard Jet systematics estimation.
  - **Boosted Decision tree (BDT) is used to select signal based on kinematics of the jets**
- **Non standard background: cosmics and beam induced background are quite relevant, along with multijets**
  - **Background estimation from ABCD Method**

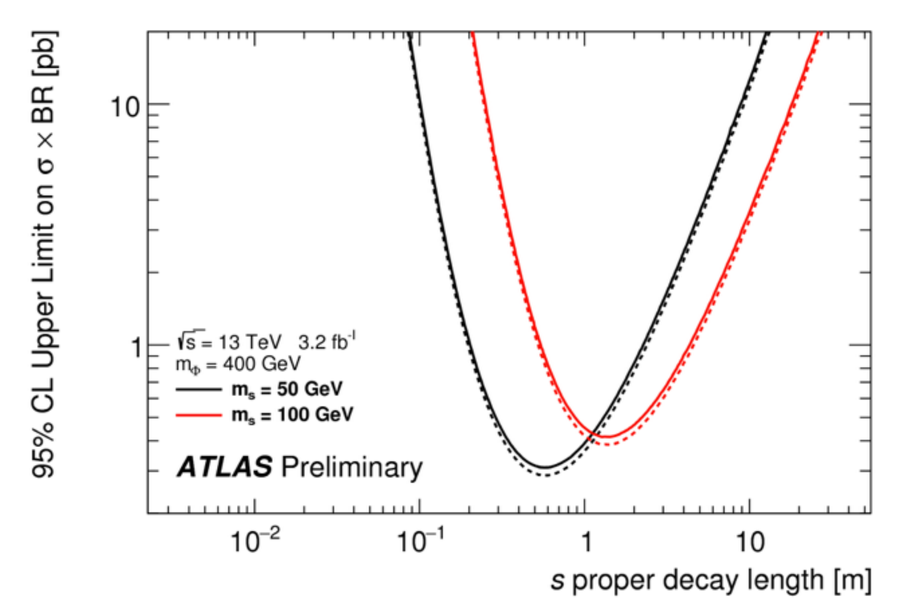


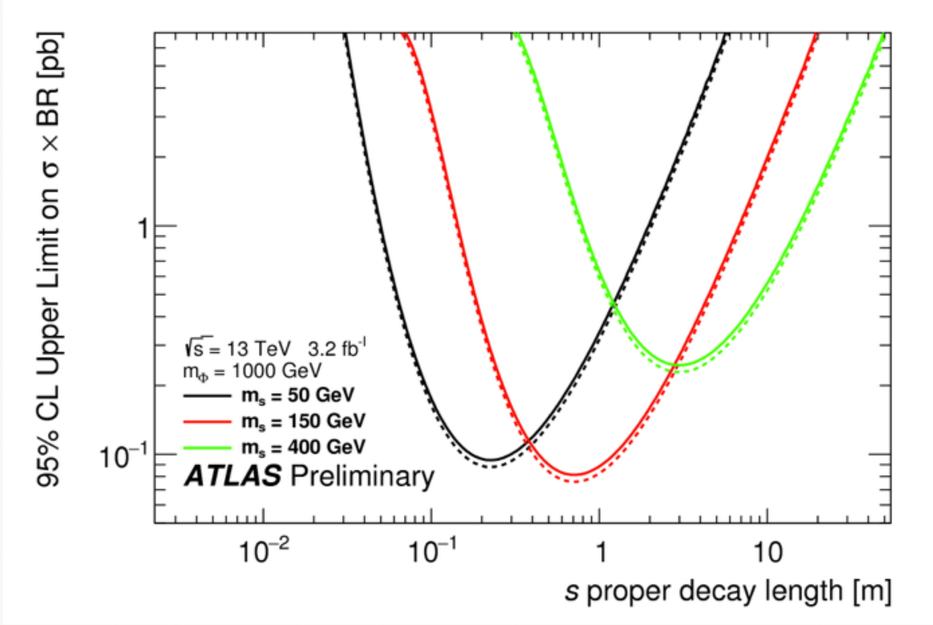




Displaced Jets: Results

The observed 95% CL upper limits on the σ × BR for the signal samples with different ϕ and s masses





	$m_s = 50\ GeV$	$m_s = 100\ GeV$	$m_s = 150\ GeV$	$m_s = 400\ GeV$
	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

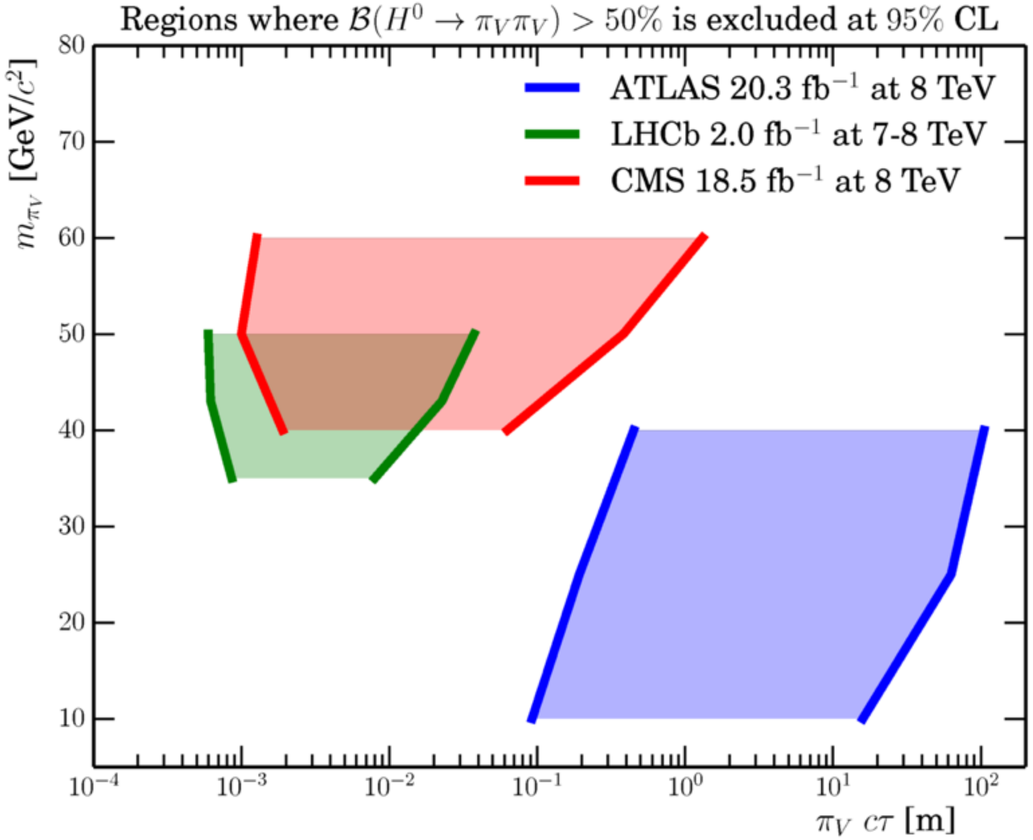
Comparison LHCb, CMS and ATLAS

Keep complementarity between LHCb, ATLAS and CMS:

- Detector acceptance and vertexing capabilities play an important role.
- LHCb can reach lifetime and masses that ATLAS & CMS can not and vice-versa.

An example Run 1 search for pair produced Hidden Valley via SM Higgs decay:

- **CMS 18.5 fb^{-1} [PRD 91 (2015) 012007], recast [PRD 92 (2015) 073008]**
- **ATLAS 20.3 fb^{-1} [PRD 92 (2015) 012010] [PLB 743 (2015) 15-34]**
- **Parameter space BR(H->$\pi_v\pi_v$) >50% is excluded at 95% confidence level**



CERN-LHCC-2017-019 ; ATLAS-TDR-028

Displaced Jets in HL-LHC (ATLAS)

Current Run2 trigger:

- Dedicated L1 trigger based on tau candidates + low EMfrac.

Upgraded (Phase2) trigger ideas:

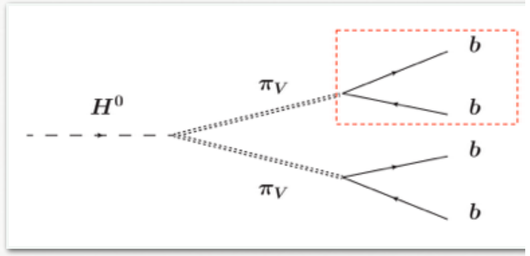
- **Expected high pile-up activity in EM calorimeter: low EMfrac jets will become problematic.**
- **Increased longitudinal L1 granularity in Tile:**
  - Compare energy deposit per layer will reduce sensitivity to pileup.
  - The energy deposit per layer could be use to identify the exact decay point

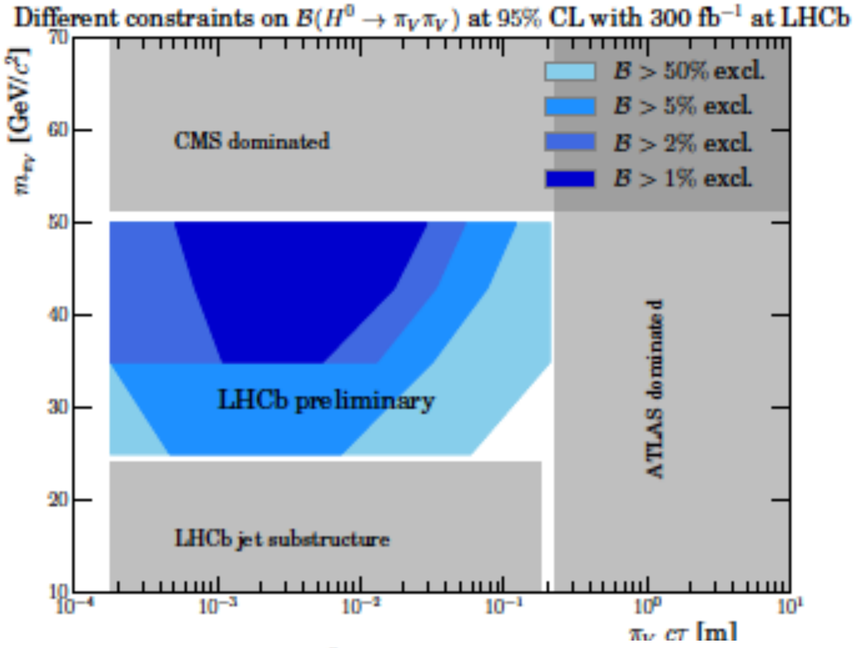
Displaced jets in HL-LHC - (LHCb)

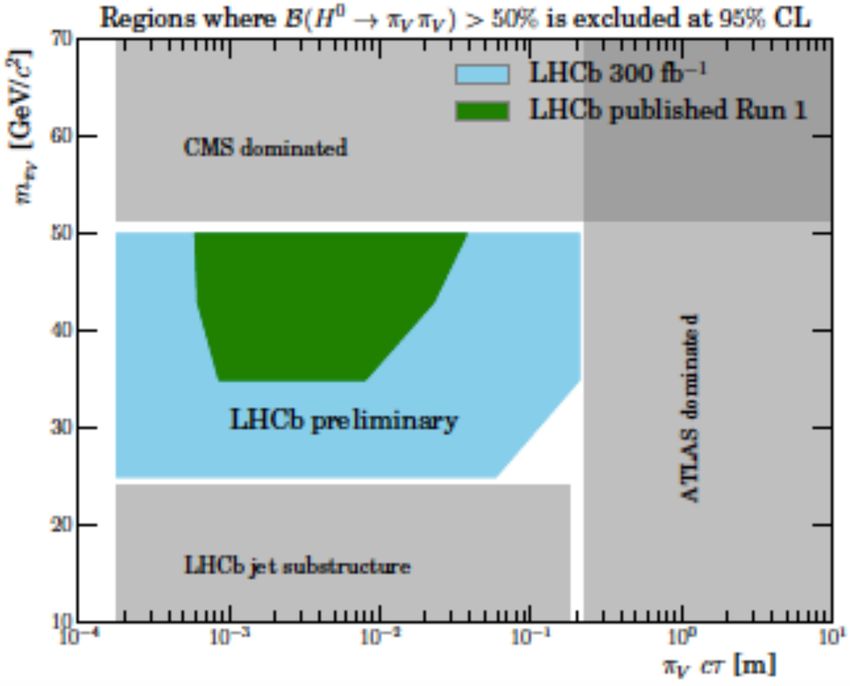
Phase 2 prospects start from Run 1 results [EPJC (2017) 77:812]

- **Signature:** Displaced Vertex with two associated heavy flavour jets
  - **Dedicated trigger lines for displaced jets & jet substructure tools to reach lower masses.**
- Background dominated by bb and material interactions.
- **Sensitive to several benchmark production models, focus on the decay of a Higgs-like particle into two π_v .**

Pile-up in Phase 2 will probably affect jet reconstruction.

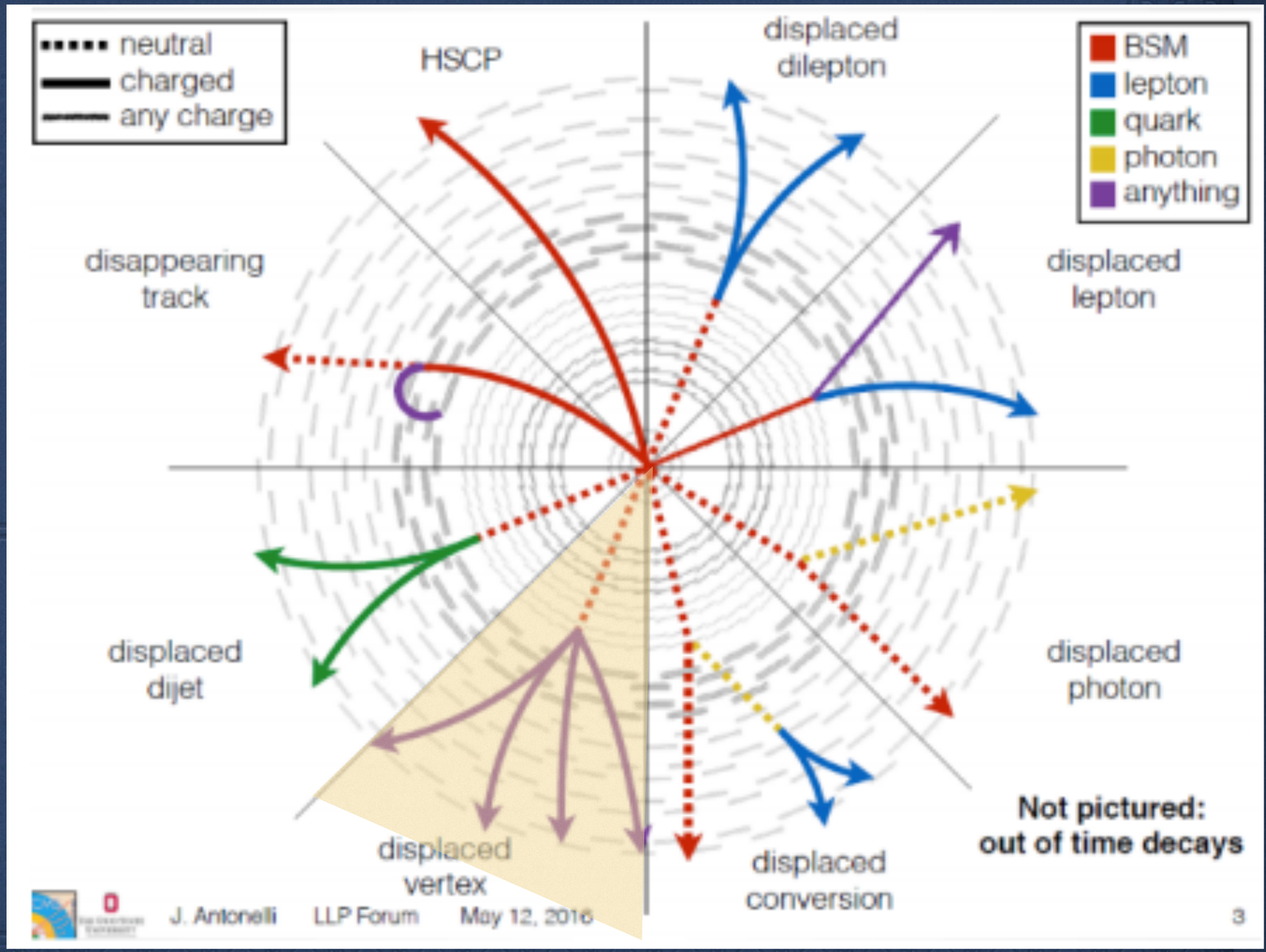






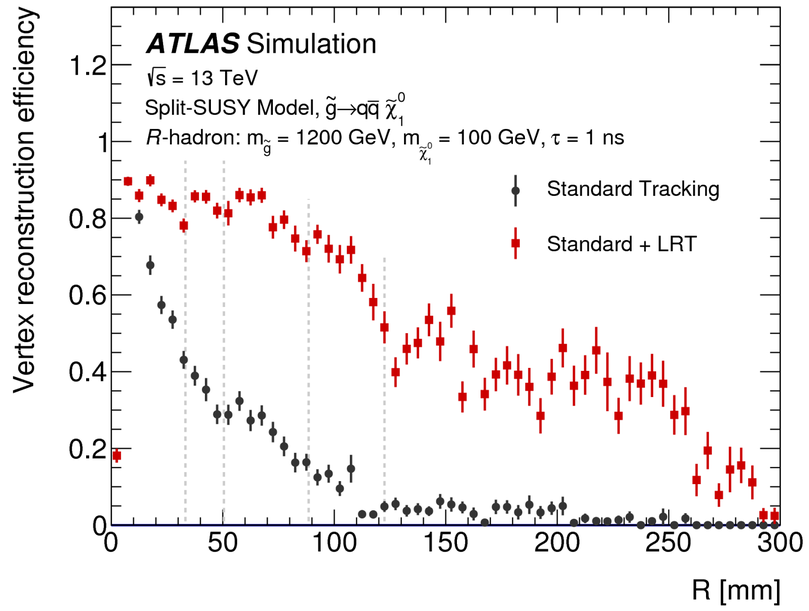
Displaced Vertex

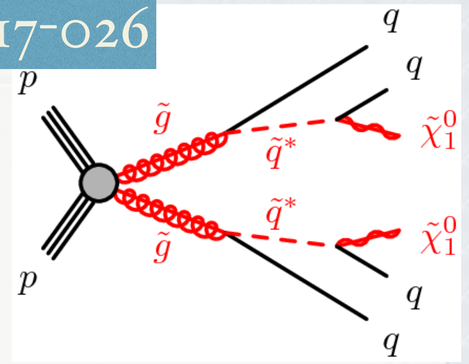
ATLAS-CONF-2017-026
CMS-EXO-17-018
CERN-LHCC-2017-021
arXiv:1808.03057



ATLAS-CONF-2017-026

Displaced Vertices - ATLAS





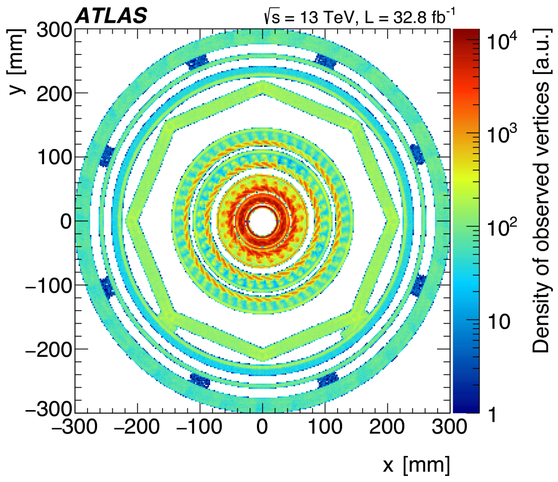
R-hadrons decaying within the ID can be reconstructed as a Displaced Vertex (DV)

- Long-lived Gluinos are present in Mini-split SUSY models
- Analysis sensitive to decay length up to 300 mm
- **Large MET is expected and used for trigger and selection.**

Standard Tracking has low efficiency:

- Standard cuts on transverse (d_0) and longitudinal (z_0) impact parameters with respect to the IP remove displaced decay (large impact parameters)
- **Large radius tracking (LRT).** A dedicated second pass of the tracking is ran on leftover hits from the standard track -much like for the disappearing-track analysis -but with ***looser cut on do and zo*** algorithm.

- Final selection: MET > 250 GeV at least one good DV with mass $\mathbf{m_{DV} > 10\ GeV}$ and number of associated tracks **ntrk ≥ 5**
  - Main background from hadrons interaction with detector material. Create a 3D map of the dense material region of the ID and veto vertices in these regions



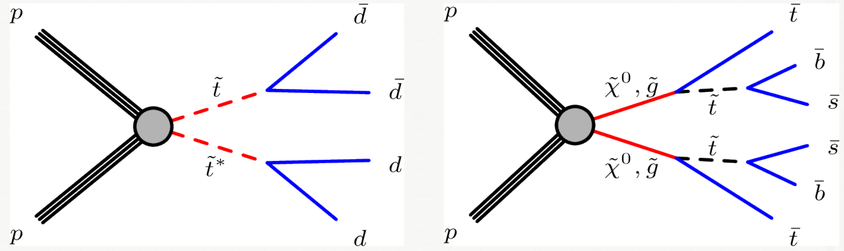
Production of long-lived gluinos with masses up to 2.37 TeV and lifetimes of O(10-2)-O(10) ns in a simplified model inspired by split supersymmetry.

CMS-EXO-17-018 - arXiv:1808.03078

Displaced Vertices in Multijet Events - CMS

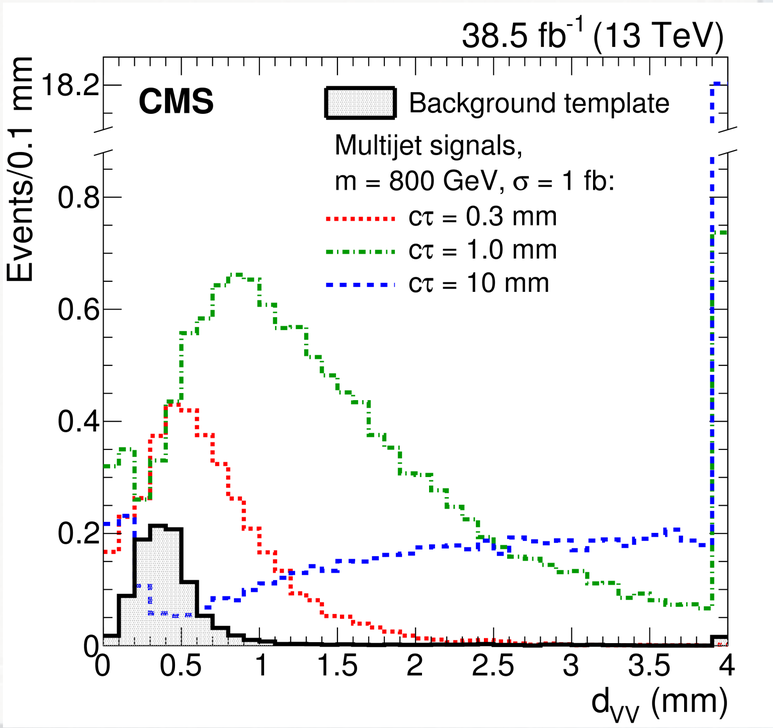
Search for long-lived resonance decaying to a pair of jets (RPV Model):

- Dijet (stop channel)
- Multijet (gluino, neutralino channel)



Analysis Strategy

- No MET but large number of hard jets is expected.
- For trigger (selection) H_T > 800, 900 (1000) GeV
  (H_T is the scalar sum of hard jets transverse momenta)
- Use d_{VV} - distance between pair of vertices.
  Only DV vertices inside beam pipe are considered.
- Fit background (multijets & ttbar) and signal d_{VV} templates



The data exclude cross sections above approximately 0.3 fb for particles with masses between 800 and 2600 GeV and mean proper decay lengths between 1 and 40 mm. For mean proper decay lengths between 0.6 and 80 mm, gluino masses below 2200 GeV and top squark masses below 1400 GeV are excluded.

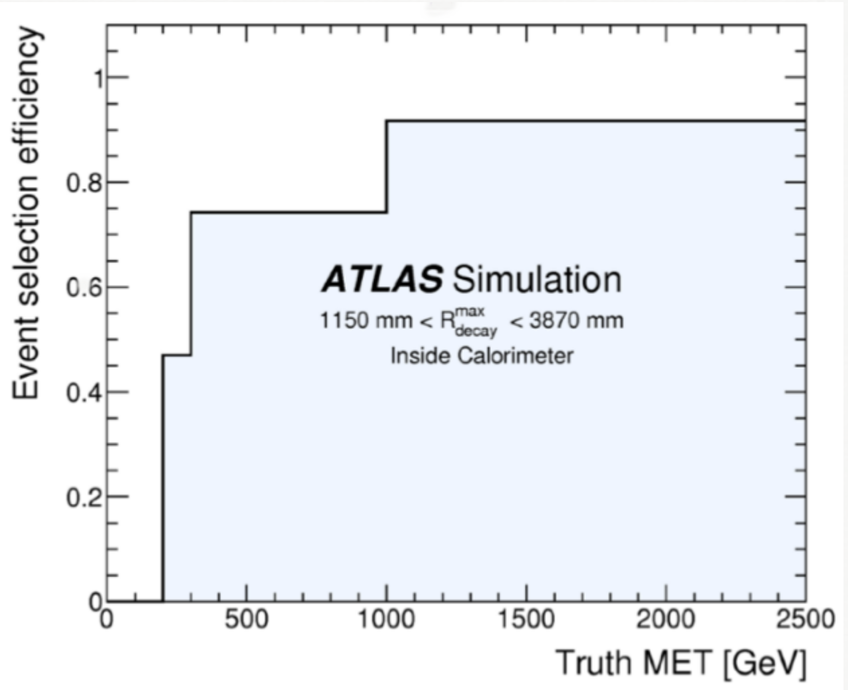
CERN-LHCC-2017-021 ; ATLAS-TDR-030

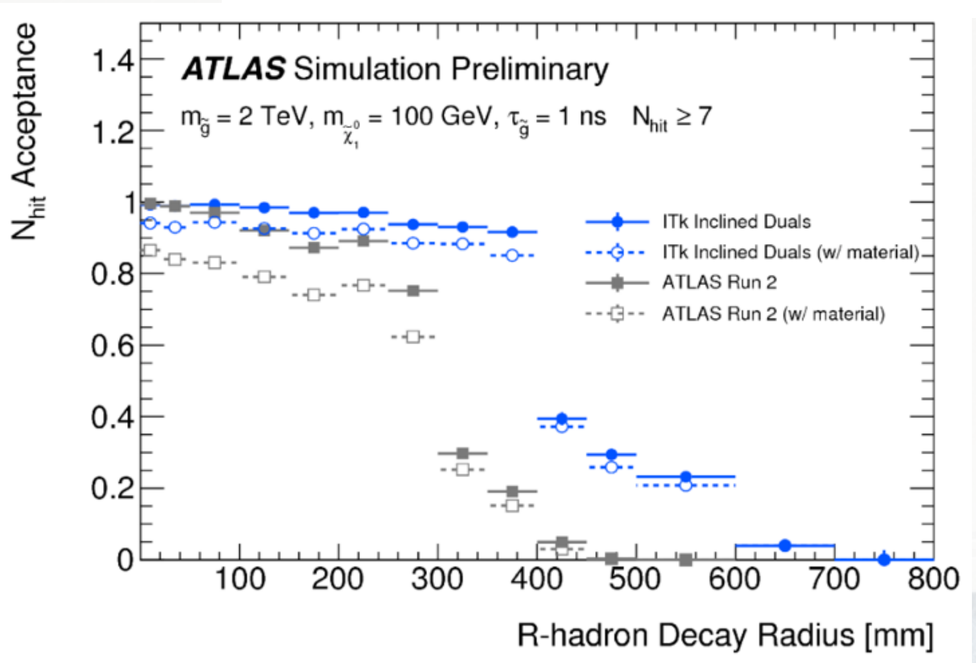
Displaced Vertices in HL-LHC

Selection (taken from Run 2 analysis):

- Relies on reconstructing displaced tracks and displaced vertices from those.
- Veto of vertices in detector material & MET above 200 GeV.
- Requires at least one vertex with at least 5 tracks & DV mass at least of 10 GeV.

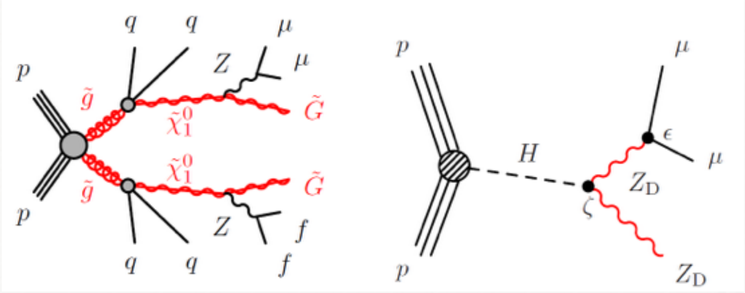
- **Reconstruction efficiency (reach) for displaced tracks increases up to 400 (500) mm.**





arXiv:1808.03057

Displaced Muons



GGM Scenario and Higgs decays Models

Two searches: High mass (Zμμ) and Low mass (Z_Dμμ)

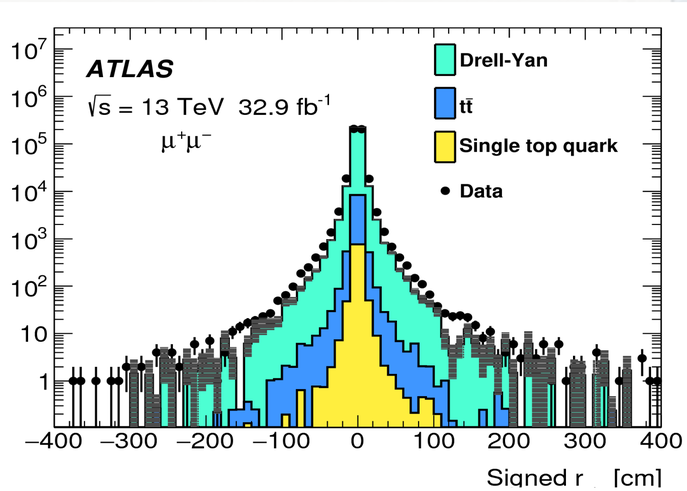
- Opposite-signed muons with vertex up to 4m from interaction point

Trigger: OR of MET, and 1, 2, 3 muon(s).

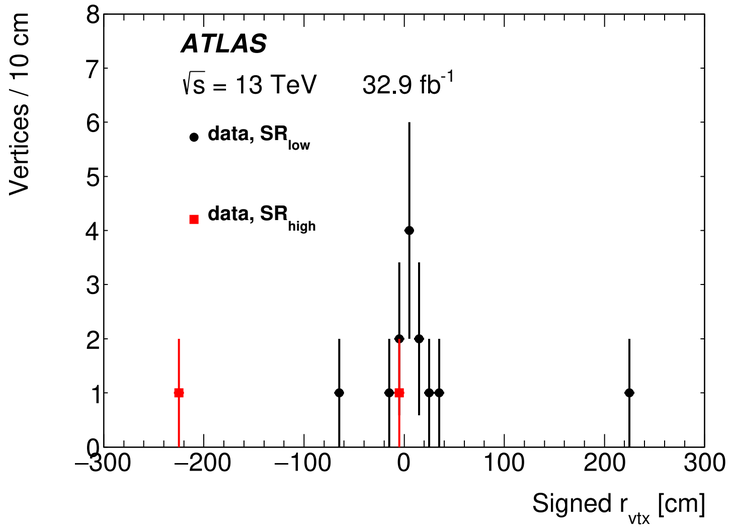
Signal Region-low,high: pair of isolated OS Muon Spectrometer only

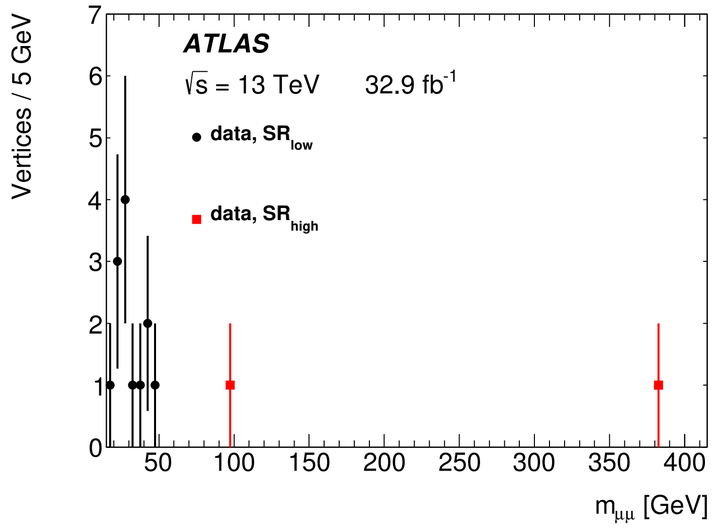
Data Driven Background

- MSonly & MScomb muons
- OS & SS pair of muons - isolated vs non-isolated - pairs.The main background is from accidental pairing, beam-induced background ad Cosmics Ray muons.



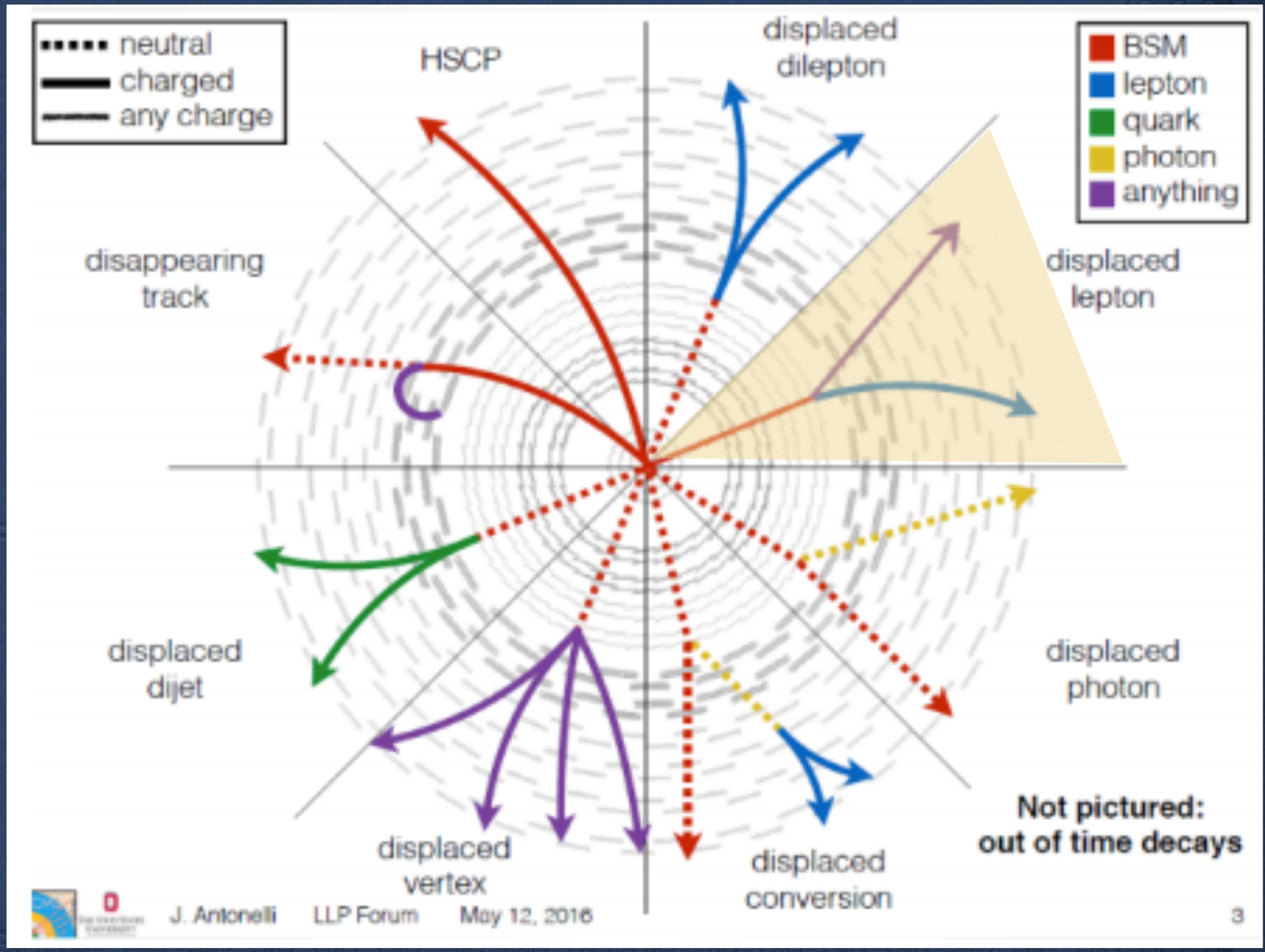
Lifetimes in the range cτ = 1 - 2400 cm are excluded, depending on the parameters of the model.





Displaced leptons

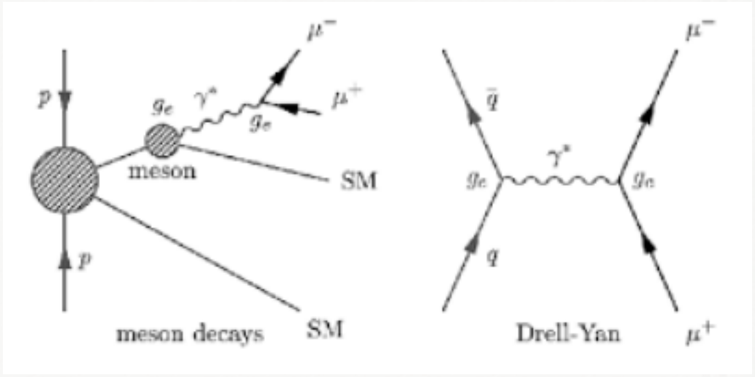
PRL 120 (2018) no.6, 061801

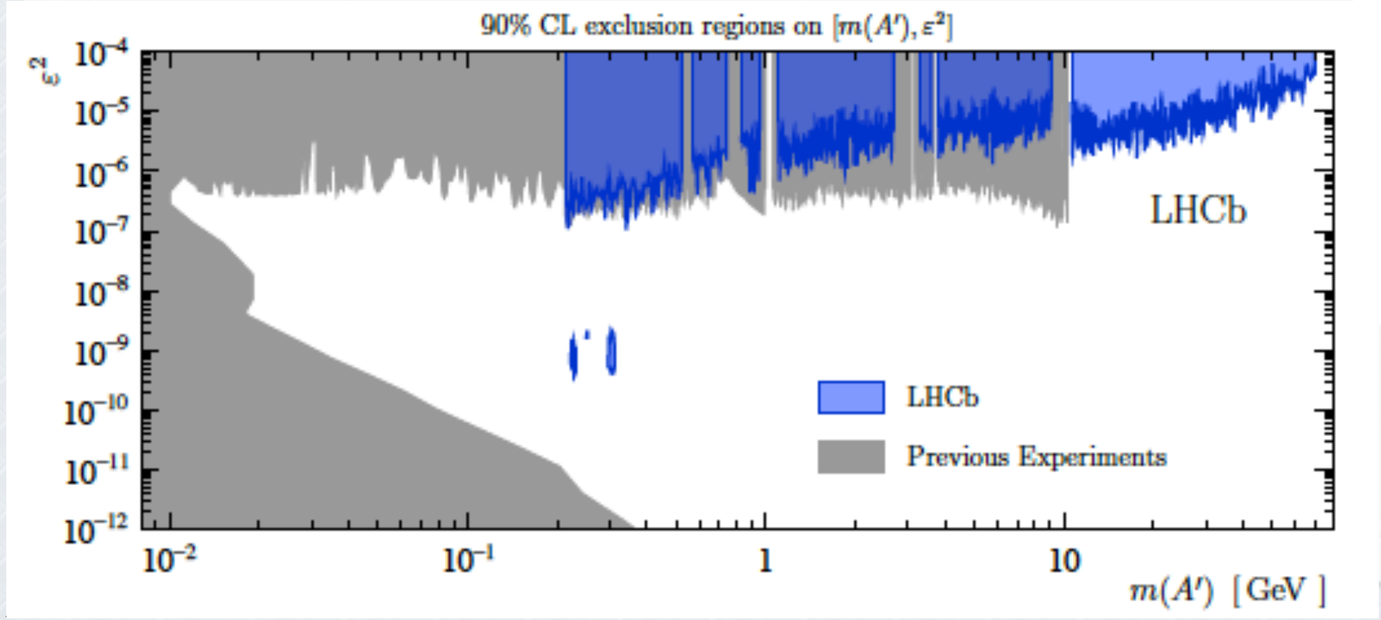


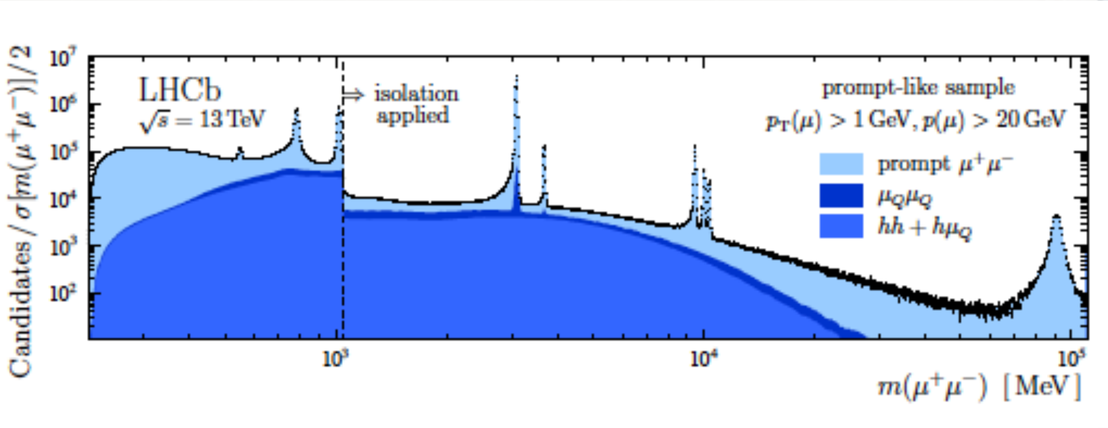
PRL 120 (2018) no.6, 061801

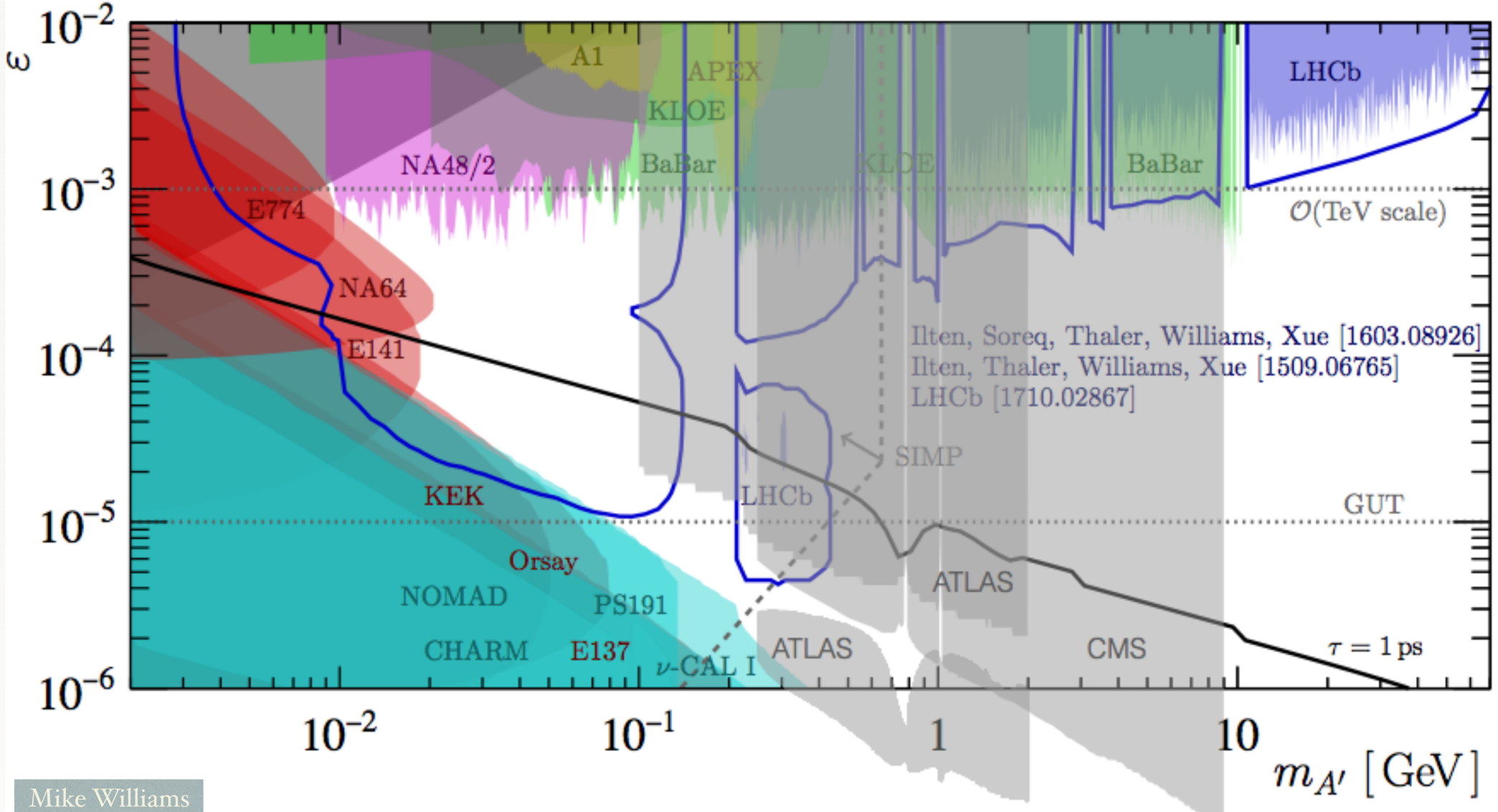
Dark Photons

- **Inclusive search for Dark Photons (A') in $\mu\mu$ only with LHCb 2016 dataset**
  - The model predicts A' light, produced as γ^*
  - Two searches: prompt and displaced muons
- Large fraction in forward region, very soft pT. Online reconstruction of candidates, no pre-scale down to threshold 2mμ. Isolation cut applied above 1 GeV/c.
- Backgrounds from same sign μ, fits to IP χ2









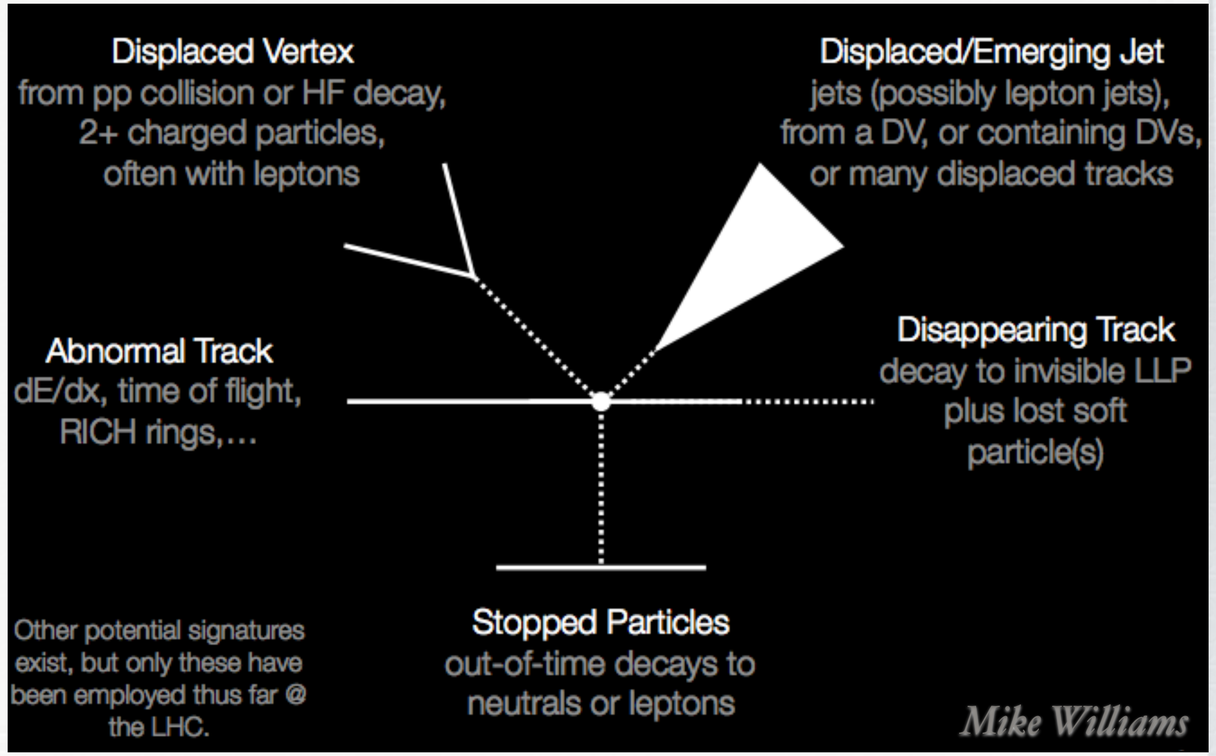
Mike Williams
@ LHCP 2018

ATLAS/CMS limits shown here assume B(H→$f_D f_D$)=10%.

ATLAS [1511.05542] (see also 1505.07645,CONF-2016-042), CMS [PAS-HIG-16-035].

Conclusions

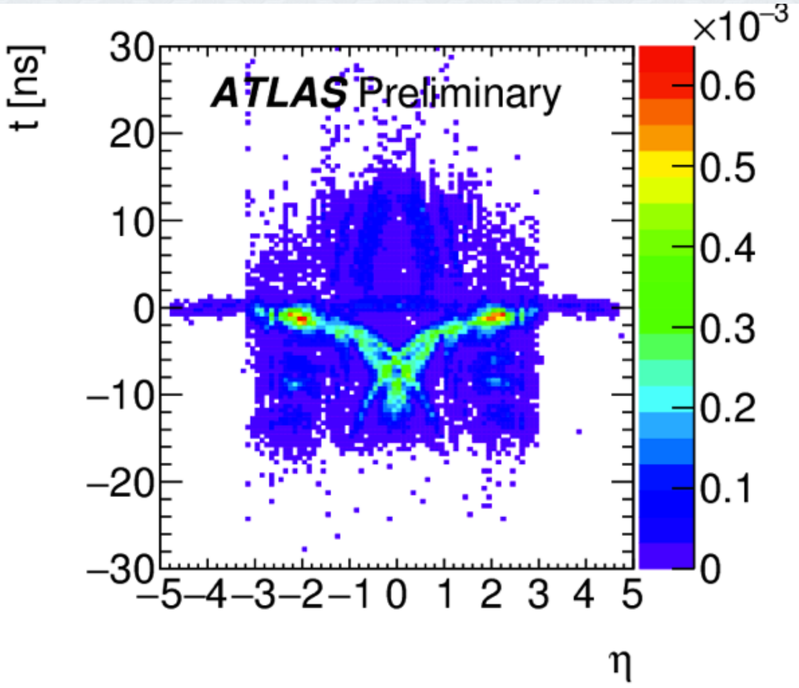
- Many unconventional searches have been reviewed in this talk:
  - **Searches using signatures of Disappearing Track, Displaced Vertex, Displaced Jets, Highly Ionising Particles, Displaced Vertices and Dark Photons**
    - Every analysis used unique technique and methods for the reconstruction and identification of the signal events.
- **The results presented explored Run2 Data Taking and future perspectives from HL-LHC:**
  - Run 2 results achieved a large increase in sensitivity with respect to Run 1 results
    - But no significant deviation observed yet
  - Significant effort to extend our experimental reach and coverage for Phase 2 HL-LHC Projections
    - Exploiting the complementarity of ATLAS, CMS and LHCb

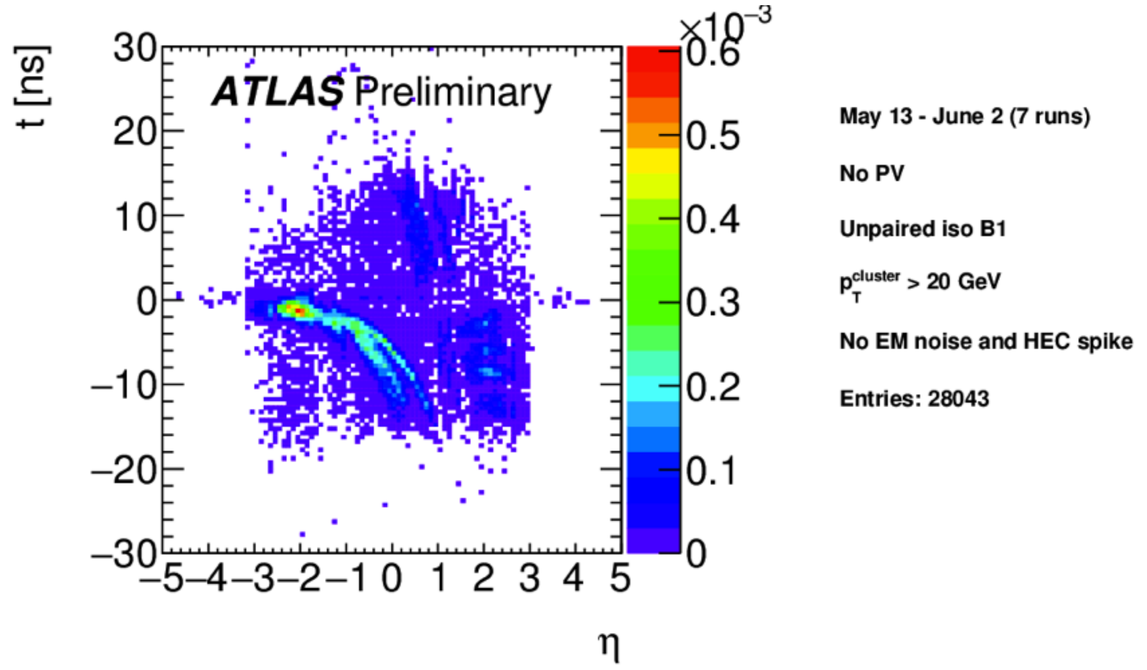


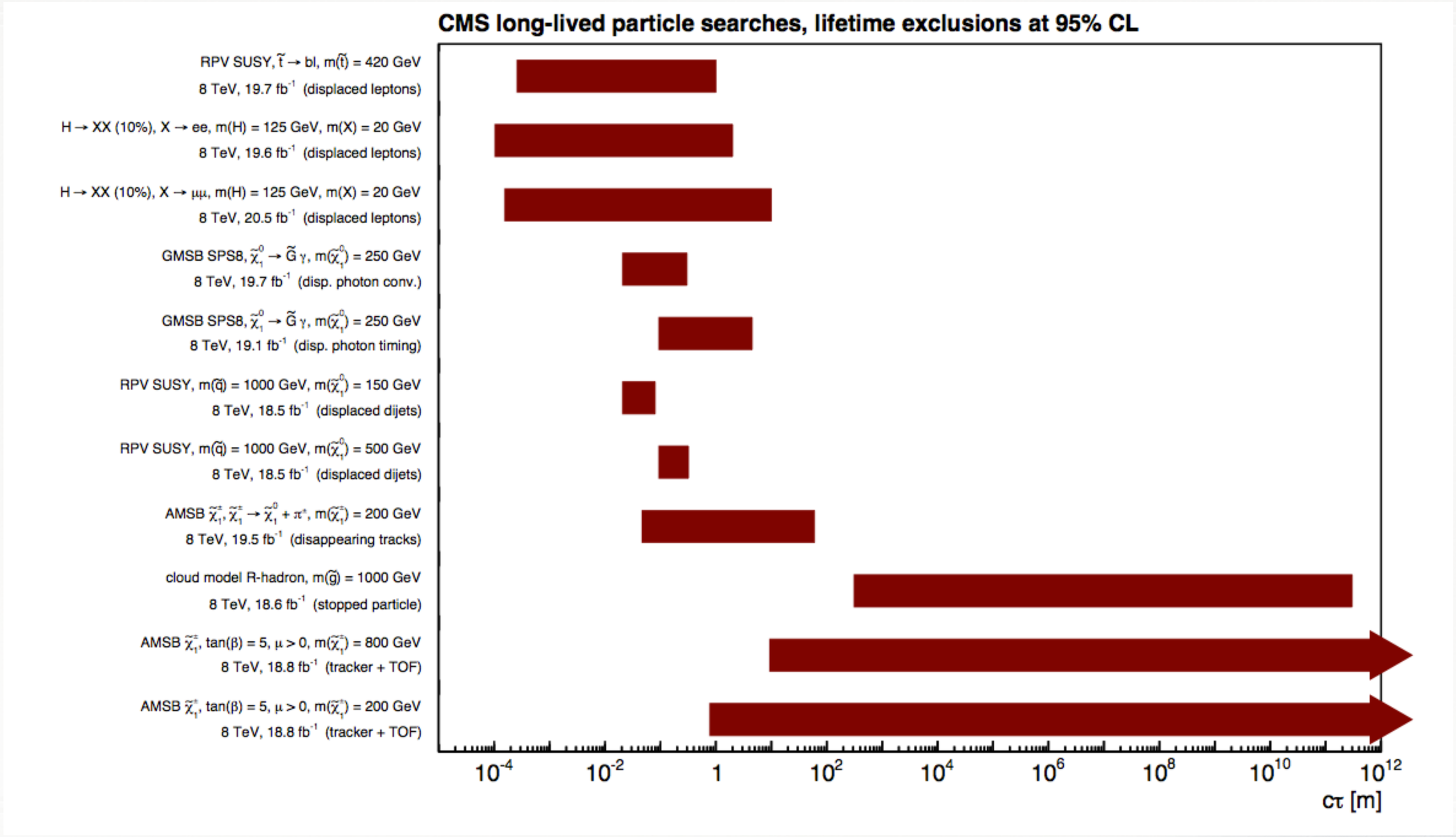
Backup

BIB in ATLAS

Interactions between beam protons and beam collimators upstream of the IP are a source of **high-momentum muons, denoted beam-induced-background (BIB) muons**, that can enter the ATLAS detector nearly parallel to the beam axis. Most MS tracks and jets generated by this process are identified and rejected.





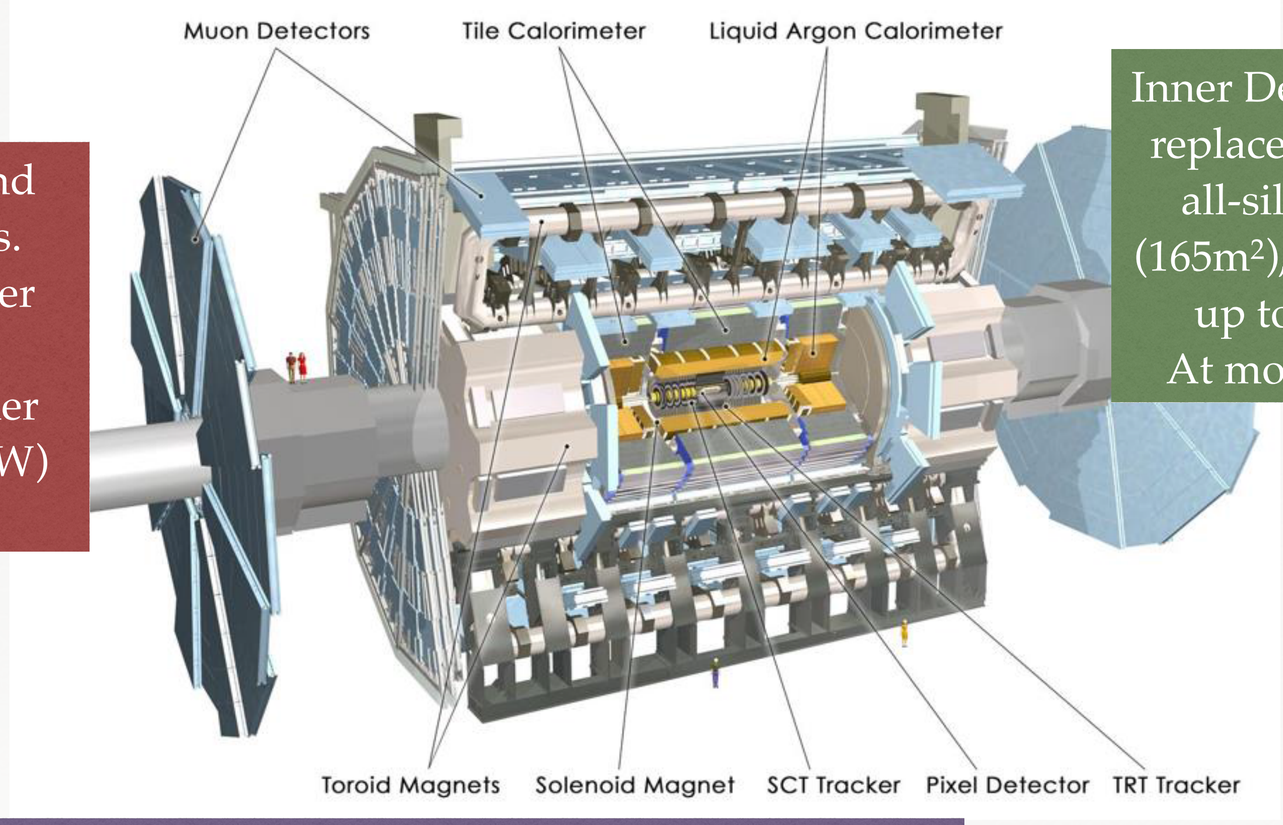

CMS long-lived particle searches, lifetime exclusions at 95% CL
RPV SUSY, $\tilde{t} \to bl$, $m(\tilde{t})$ = 420 GeV
8 TeV, 19.7 fb^{-1} (displaced leptons)
$H \to XX$ (10%), $X \to ee$, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 19.6 fb^{-1} (displaced leptons)
$H \to XX$ (10%), $X \to \mu\mu$, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 20.5 fb^{-1} (displaced leptons)
GMSB SPS8, $\tilde{\chi}_1^0 \to \tilde{G}\,\gamma$, $m(\tilde{\chi}_1^0)$ = 250 GeV
8 TeV, 19.7 fb^{-1} (disp. photon conv.)
GMSB SPS8, $\tilde{\chi}_1^0 \to \tilde{G}\,\gamma$, $m(\tilde{\chi}_1^0)$ = 250 GeV
8 TeV, 19.1 fb^{-1} (disp. photon timing)
RPV SUSY, $m(\tilde{q})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 150 GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
RPV SUSY, $m(\tilde{q})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 500 GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
AMSB $\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \pi^\pm$, $m(\tilde{\chi}_1^\pm)$ = 200 GeV
8 TeV, 19.5 fb^{-1} (disappearing tracks)
cloud model R-hadron, $m(\tilde{g})$ = 1000 GeV
8 TeV, 18.6 fb^{-1} (stopped particle)
AMSB $\tilde{\chi}_1^\pm$, tan(β) = 5, μ > 0, $m(\tilde{\chi}_1^\pm)$ = 800 GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
AMSB $\tilde{\chi}_1^\pm$, tan(β) = 5, μ > 0, $m(\tilde{\chi}_1^\pm)$ = 200 GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
cτ [m]

The ATLAS detector upgrade scenario

TDAQ upgrade

➔Increased latencies and rates

Proposals for adding in forward regions a muon tagger and a timing detector



Muon readout and trigger upgrades.
New Barrel trigger layer.
New end cap inner Muon station (nSW) (Phase I)

Inner Detector: full replacement by a all-silicon one ($165m^2$), extending up to $|\eta|=4$
At most 1.75 X_0

LArg: new FrontEnd and BackEnd electronics for faster readout
Tile Calorimeter : upgrade of electronics and HV distribution

LHCb Upgrade

- Aim for complementarity w.r.t. ATLAS and CMS:
  - Forward acceptance $\rightarrow$ low masses.
  - Excelling vertexing capabilities $\rightarrow$ low lifetimes.

- **Upgraded trigger, tracker and VELO:**
  - Instrumentation studies for Phases 1 and 2.
- **Massive LLPs decaying to μ + jets:**
  - Physics projection studies for yellow report.
- **Massive LLPs decaying to jet pairs:**
  - Physics projection studies for yellow report.
  - Interest in pile-up studies (jet reco efficiencies).
- **Extended reach for LLPs (CODEX-b + LHCb):**
  - New detector to operate interfaced with LHCb.
  - Greatly extend reach for LLP searches.

CMS Upgrade

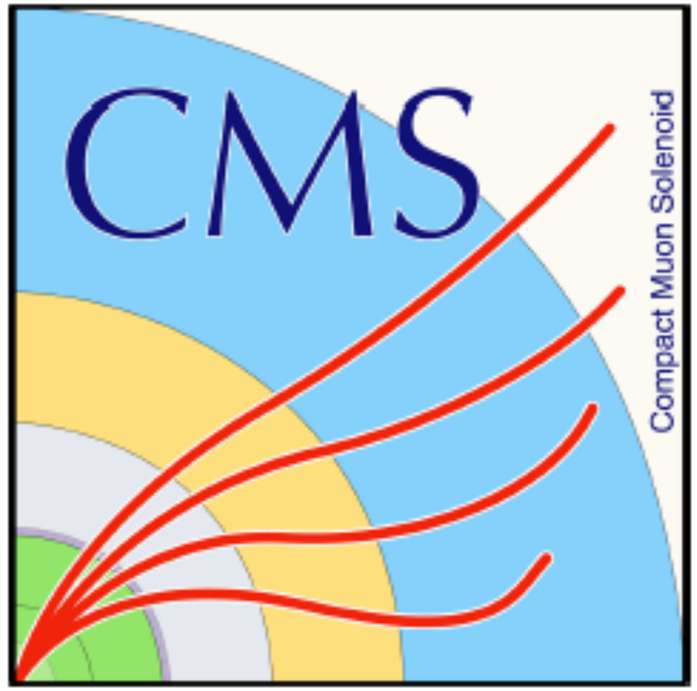
- **Tracker & RPC upgrade for HSCP:**

  [CMS-TDR-17-001] [CMS-TDR-17-003]

  - HSCPs have a distinct signature in the detector.
  - Exploit RPC time resolution & OT capabilities.
- **Displaced muons:**

  [CMS-TDR-17-003]

  - New forward muon detectors to improve trigger.
  - New tracking algorithms for displaced muons.
- **Signatures with delayed photons/Z^0 bosons:**
  - Sensitivity strongly limited by time resolution.
  - New MTD $\rightarrow$ new possibilities for LLP searches.



ATLAS Upgrade

- Interplay between searches and upgraded detector:
  - Performance of ID, ITk, calo and muon triggers.
  - Works towards TDR → go for PUB note before yellow report.

- **Disappearing tracks:**
  - Physics projection studies in Pixel TDR.
- **Multi-track displaced vertices in ID + MET:**
  - Tracking studies in Pixel TDR.
  - Physics projection studies yet to be done.
- **Displaced vertices in muon spectrometer:**
  - Muon trigger studies in TDAQ TDR.
- **Jets in HCAL with low EM fraction:**
  - Calo trigger studies in Tile TDR.
- **High Granularity Timing Detector (HGTD):**
  - Works toward a TDR.
  - Very interesting concept for LLPs.

Simulating Physics channels at HL-LHC

Two possible ways:

CASE 1

1) **Extrapolate from Run1,2 results.** Scale both signal and background to 14TeV and 3000 fb^{-1}
2) **Assume similar detector performances** and apply same analyses

or

CASE 2

1) **Smear event-generator level particles** with parameterised functions
2) Functions are determined from full simulation of the upgraded ATLAS detector and reconstructed assuming pileup of 140 ($5x10^{34}$) or 200 ($7x10^{34}$)
3) **Analyses as for 8 and (or) 13TeV** with some updates for high luminosity

What about systematics? Difficult to predict.

Experimental Systematics: so far , scaled from current knowledge

Theory Systematics : current numbers, half of them, or none.

HL-LHC Systematics Guideline

- **Statistics-driven sources: data → √L, simulation → 0**
  - account for large statistics available
  - assume will overcome limitations in generating large simulations
- **Intrinsic detector limitations stay ~constant**
  - usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
  - detector simulation advances and operational experience may compensate for e.g. detector aging
- **Theory uncertainties tentatively halved**
  - applies to both normalisation (x-sec) and modelling
  - more dedicated discussions with inputs from theorists welcome!
- **Extrapolation based mostly on methods available now**
  - challenges as pile-up compensated by algorithmic improvements

ATLAS HL-LHC analysis techniques

CASE 2

ATLAS HL-LHC studies have to consider:
- upgraded ATLAS detector + trigger systems
- collision energy, $\sqrt{s}$ = 14 TeV
- high pile-up, $<\mu_{PU}>$, of 140 or 200

- We use **generator-level $\sqrt{s}$ = 14 TeV Monte Carlo** samples
  - Overlay with jets from dedicated pile-up library
    - pile-up library contains fully simulated pile-up jets with $<\mu_{PU}>$ = 140 or 200
  - Reconstruct electron, muons, jets, photons and missing-ET from generator+overlay information
- **To simulate the response of the detector:**
  - smear pT and energy of reconstructed physics objects using smearing functions based on fully simulated samples
  - apply reconstruction efficiencies for electrons, muons and jets
- **To emulate triggers: apply trigger efficiency functions**

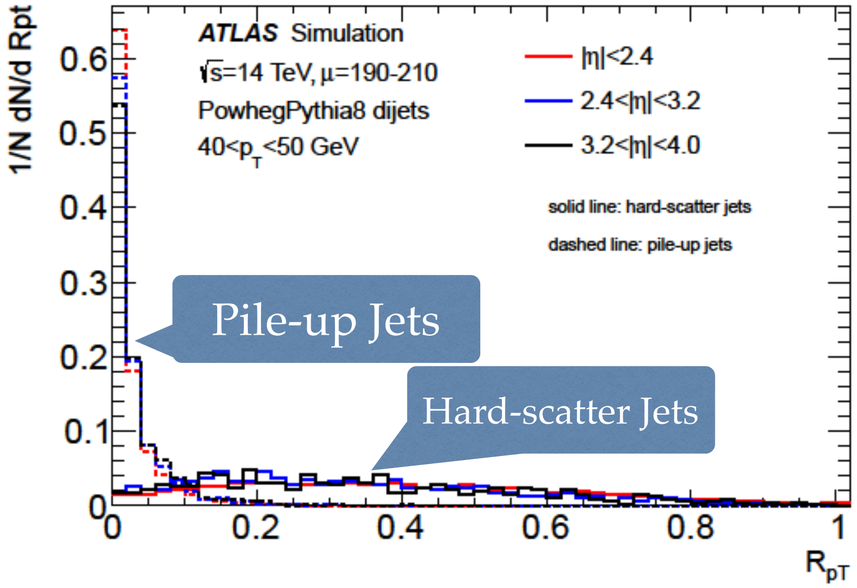
https://twiki.cern.ch/twiki/bin/view/AtlasProtected/UpgradePerformanceFunctions

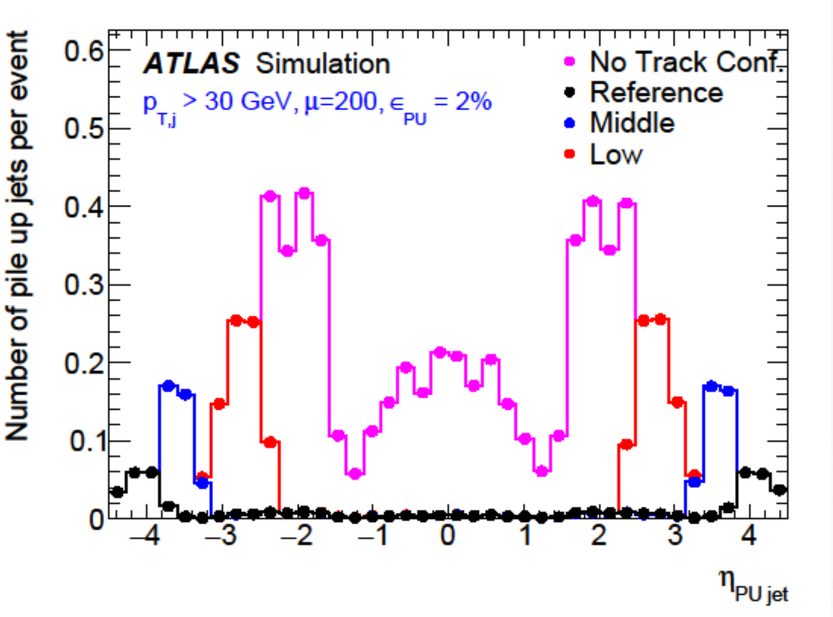
Pile-up Mitigation

- Typical jet selections require p_T(jet) >30 GeV, $|\eta(\text{jet})| < 3.8$
- For $\langle\mu_{PU}\rangle = 200$, expect 4.8 pileup jets with p_T>30 GeV, $|\eta|$<3.8 per event
- **To reduce sensitivity to pile-up in jets we apply a parameterised track-confirmation requirement, based selecting on charged vertex fraction, R_{pT}:**

$$R_{pT} = \frac{\sum_{\text{tracks}} p_T}{p_T(\text{jet})}$$

  - Applied to all non b-tagged jets with pT < 100 GeV and $|\eta|$ <3.8
  - **Reduces pile-up by factor ~ 50 -> 0.2 selected pile-up jets per event.**





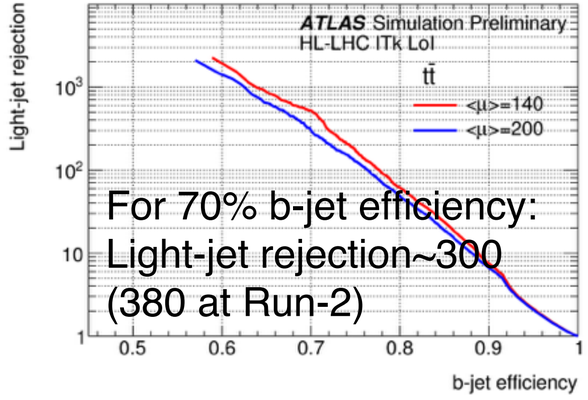
Physics Object Performance

Tracking

The large η extension of the tracker has a significant impact on the identification of physics objects and on pileup mitigation→ most visible contributions are in the area of jets and missing ET performance.
Inclined and Extended Layout as possible options.

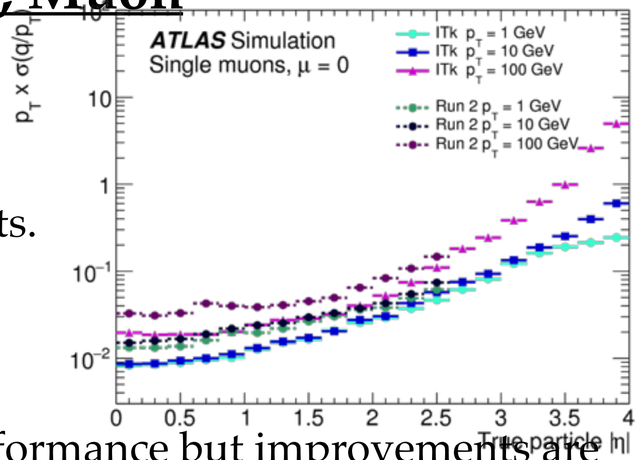
BTagging

The performance is estimated to be similar to the one of the Inner Detector in Run2 conditions.



Electron, Photon, Muon

Electron and Photon performances are in line with Run2 results, room for improvements.
Upgrades of the MS are not expected to change significantly the reconstruction performance but improvements are foreseen in the resolution for combined (ITk+MS) muons and in the large η region.

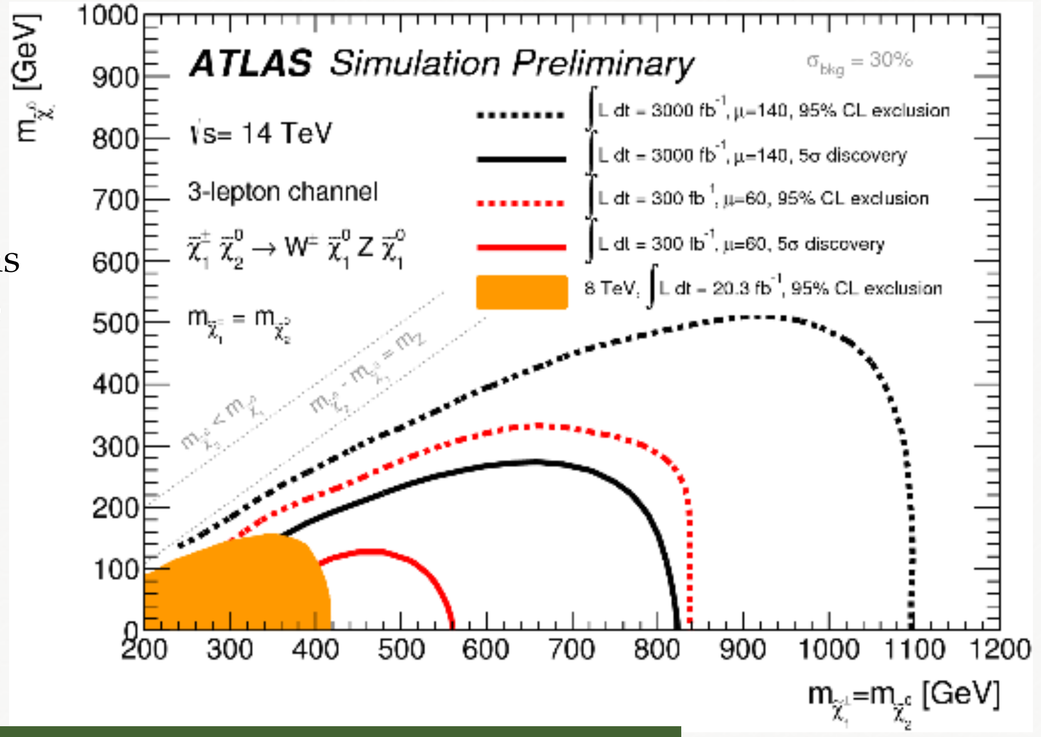


Jet and MET

The tracking extensions improves the resolution of MET. Large impact of pile-up jets in the jets reconstruction. Timing measurements via HGTD.

Motivation for the Upgrades

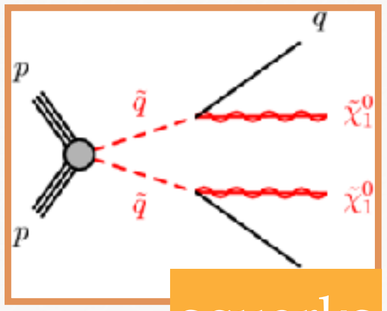
- **Maximise physics perfomance for:**
  - Precision measurements in the 125 GeV Higgs Boson Sector as **Higgs coupling**.
  - Search for **rare Higgs Boson decay** modes as H->μμ or **self-coupling Higgs** from double Higgs events.
  - Study of **low production cross section Standard Model** processes.
  - **New phenomena beyond the Standard Model.**



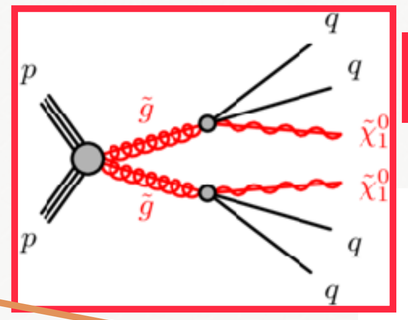
ATLAS projection	gluino mass	squark mass	stop mass	sbottom mass	g_{kk}->tt RS 95% CL	Dark Matter M*
300 fb^{-1}	2.0 TeV	2.6 TeV	1.0 TeV	1.1 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	2.4 TeV	3.1 TeV	1.2 TeV	1.3 TeV	6.7 TeV	2.6 TeV

ATL-PHYS-PUB-2013-003, 2014-007, 2014-010, 2013-011, 2015-0032

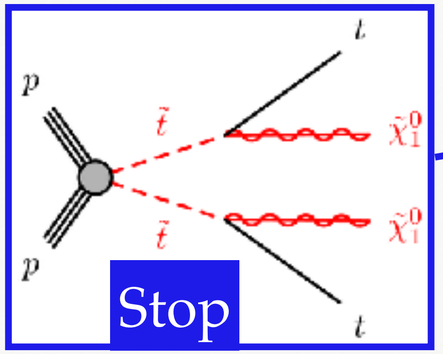
SUSY production at the LHC



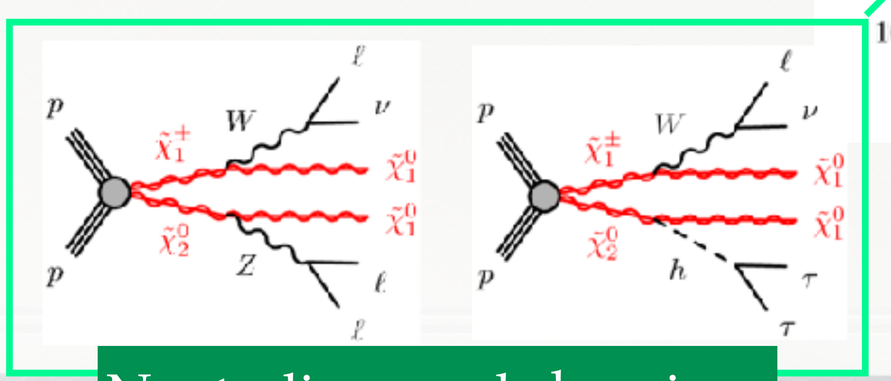
squarks



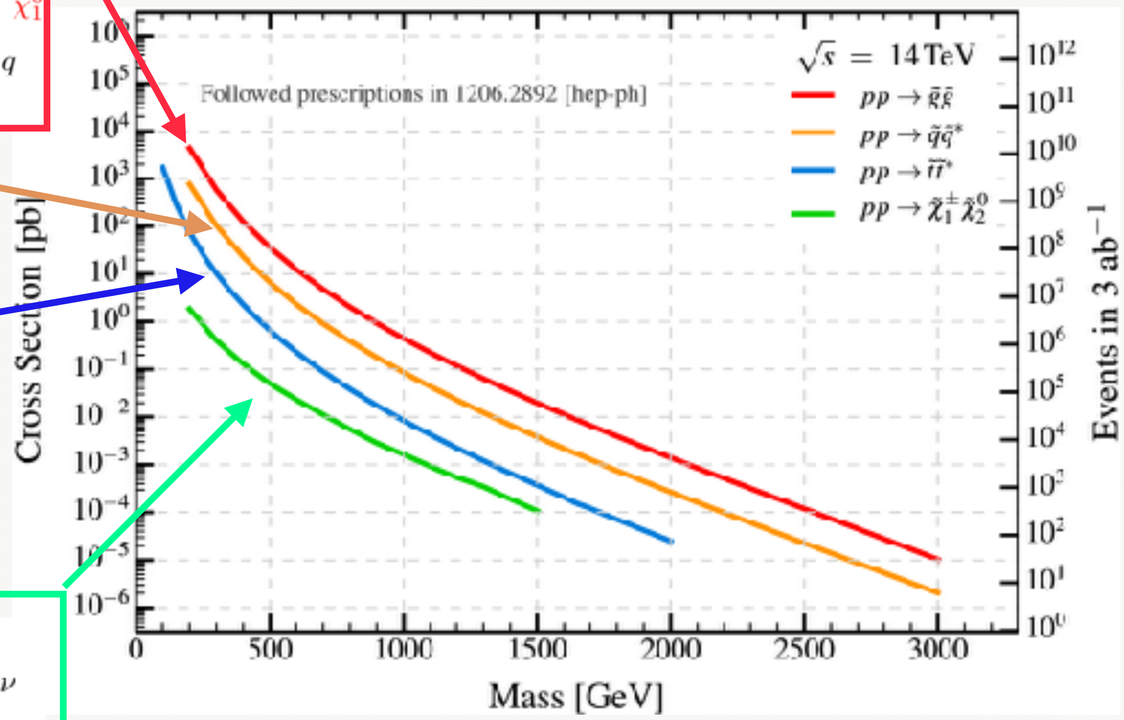
gluinos



Stop



Neutralinos and charginos



The lightest neutralino (LSP) is a candidate to explain dark matter.

Displaced Jet: Cut Flow

Requirement	Data main	SM multi-jets MC	$m_\phi = 600\ GeV$; $m_s = 150\ GeV$	Data BIB	Data cosmic rays
Events passing the trigger	548600 ± 740	404000 ± 27000	25.7%	100%	100%
≥ 2 clean jets	421800 ± 650	197000 ± 19000	22.1%	38.3%	21%
$\text{jet}_{1,2}^{\text{CalRatio}}$ clean	23860 ± 150	900 ± 440	7.21%	6.67%	7.28%
$\Delta\phi > 0.75$	17590 ± 130	600 ± 350	6.85%	0.86%	3.38%
$-3 < \text{time} < 15$	16180 ± 130	600 ± 350	6.84%	0.35%	1.10%
$H_{\text{T}}^{\text{miss}}/H_{\text{T}} < 0.3$	14880 ± 120	600 ± 350	6.09%	0.30%	0.25%
$\sum \Delta\text{R}_{\text{min}} > 0.5$	9500 ± 97	500 ± 330	6.08%	0.14%	0.25%
BDT value($\text{jet}_1^{\text{CalRatio}}$) > 0.2	8190 ± 91	500 ± 330	5.95%	0.09%	0.25%
BDT value($\text{jet}_2^{\text{CalRatio}}$) > -0.2	4890 ± 70	300 ± 260	5.93%	0.06%	0.25%
$p_{\text{T},1} > 150\ GeV$	330 ± 18	0 ± 0	5.31%	0.005%	0%
$p_{\text{T},2} > 120\ GeV$	110 ± 10	0 ± 0	4.27%	0.001%	0%
region A:					
$\sum \Delta\text{R}_{\text{min}} > 1.5$	60 ± 8.0	0 ± 0	3.73%	0%	0%
$\sum \text{BDT} > 0.15$	24 ± 4.9	0 ± 0	3.57%	0%	0%

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