Searches for long-lived particles with ATLAS

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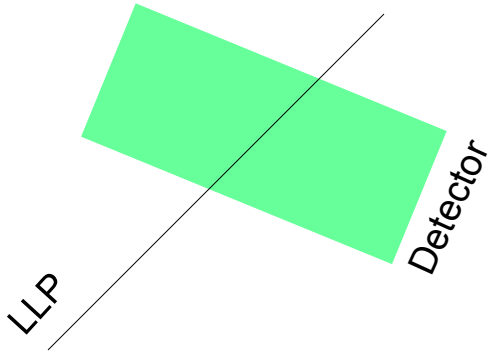
Introduction & Outline

- Signature-based review of BSM long-lived particles (LLP) searches in ATLAS
- Based on $\sqrt{s}$=8 TeV results (~all published, references therein)
  - Some earlier results may still be relevant(?), but not covered here
- Highlight experimental challenges and strengths of the detector
- No attempt to give details for each specific analysis
  - Especially if covered by a dedicated talk later in the workshop
  - List examples of benchmark models used, but won't be comprehensive
  - Highlight (attempt of) model-independence when possible
- Ending with a quick look at the future

Hunting LLP

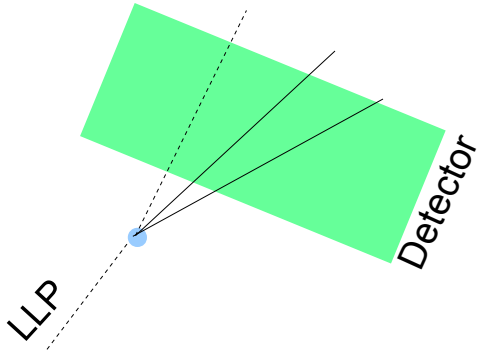
Direct detection

- Through direct interaction with detector
- Energy loss, TOF, special track properties, …
- Mostly fit charged LLP



Indirect detection

- Through SM or invisible decay products
- "Isolated" activity inconsistent with prompt or expected instrumental / SM
- Natural fit for neutral LLP, but also sensitive to charged ones

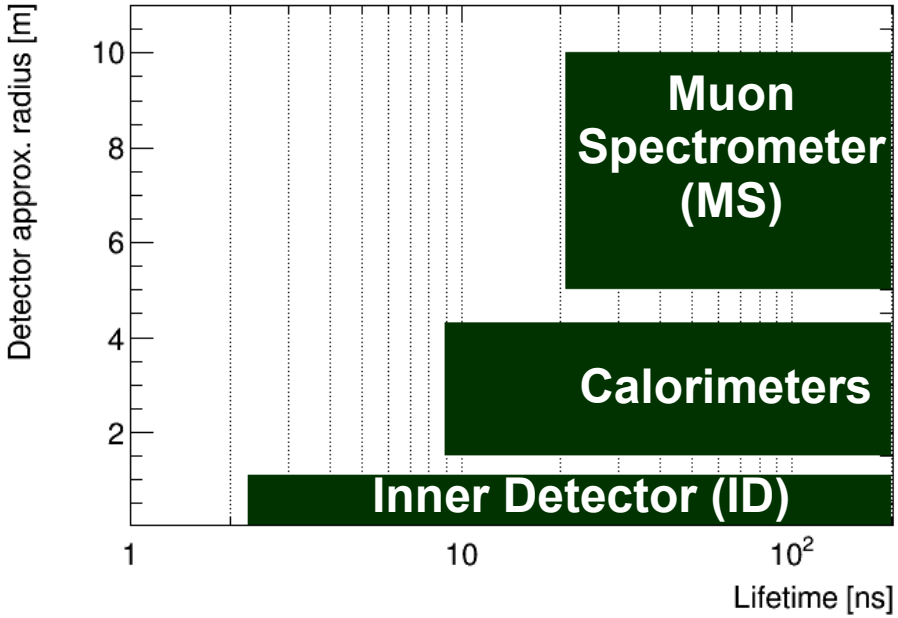


- Various sub-detectors are sensitive to different life-time ranges

Hunting LLP

Direct detection

- Plot: lifetimes for which 20% decays <u>after the outer radius</u> of the sub-detector



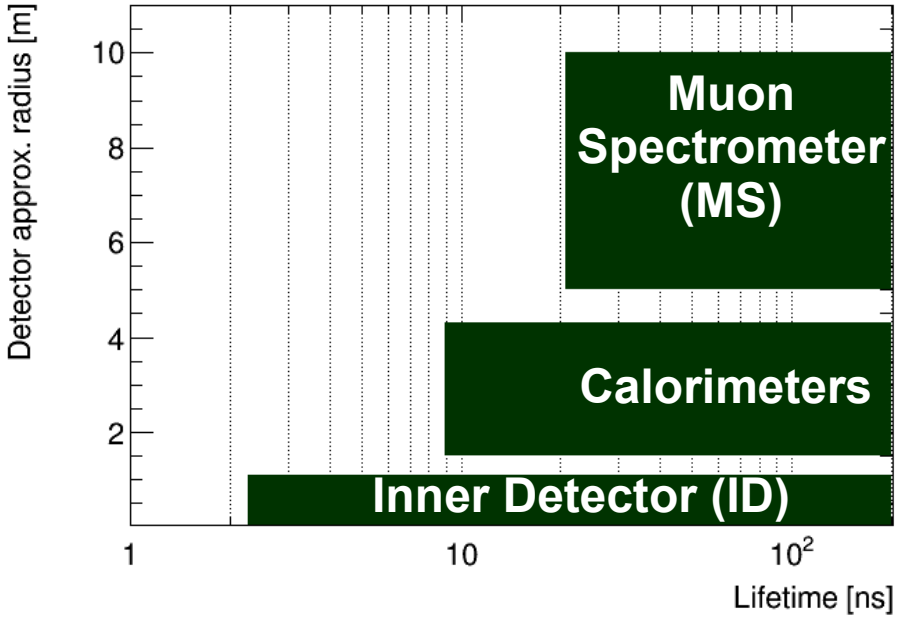
Hunting LLP

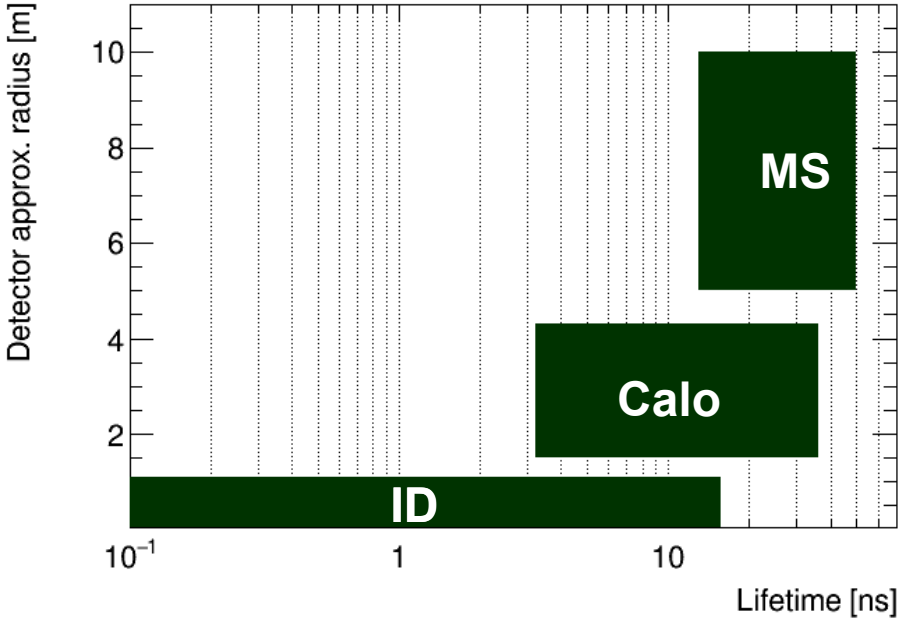
Direct detection

- Plot: lifetimes for which 20% decays <u>after the outer radius</u> of the sub-detector

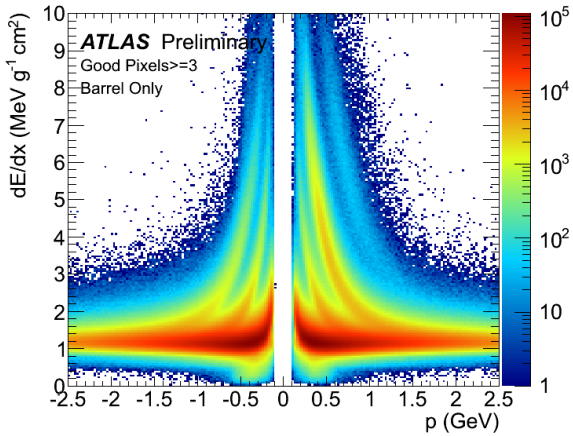
Indirect detection

- Plot: lifetimes for which 20% of decays <u>within the inner/outer radius range</u> of the sub-detector

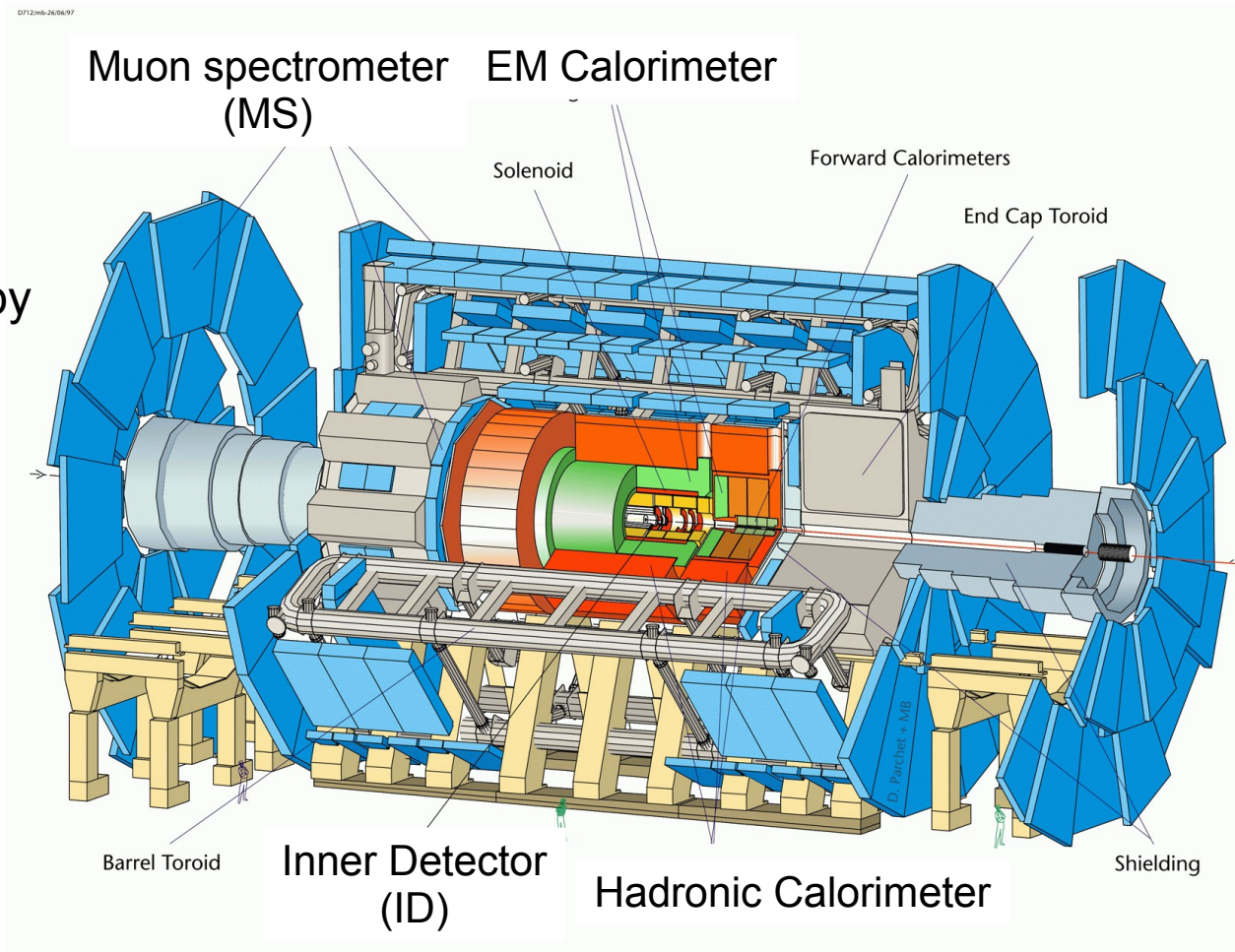




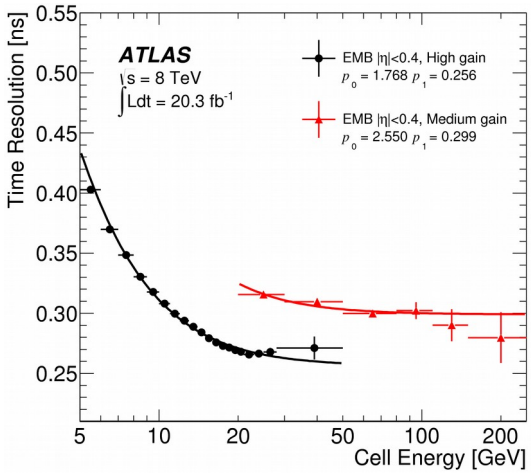
The (non-obvious) ATLAS detector



Ionization loss: charge measured by:
- Pixel system
- Transition-Radiation Tracker (TRT)
- Monitored drift-tubes (MDT) in the muon system



Time of flight: time of arrival by
- Electromagnetic (EM) and Hadronic Calorimeters
- Muon system



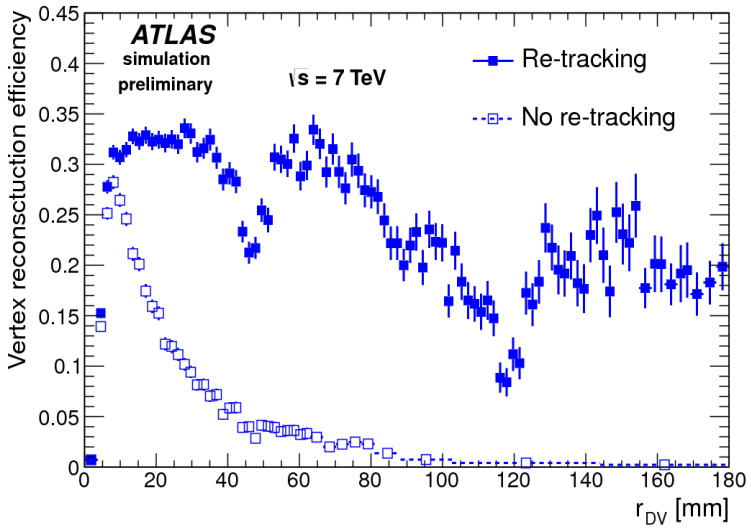
Outline of ATLAS searches

	Primary measurement			
	ID	Calo	MS	
Disappearing Track	✓	☐	☐	Direct detection
Large ionization deposits	✓	☐	✓	Direct detection
Time-of-flight measurements	☐	✓	✓	Direct detection
Prompt analysis (jets+E_T)	✓	✓	☐	Indirect detection
Displaced vertices	✓	☐	✓	Indirect detection
Non-prompt/delayed photons	☐	✓	☐	Indirect detection
“Isolated” jets	☐	✓	☐	Indirect detection
Collimated lepton-jets	☐	✓	✓	Indirect detection

Experimental challenges

- Some signatures can't be exploited at trigger-level directly
  - Need rely on “collateral” features of the event (e.g. ISR, $\not{E}_T$, ..)
  - Develop dedicated trigger chains

- Many analyses targeting LLP require “non-standard” techniques
  - Detailed (low-level) detector information
  - Specific tracking setup to reconstruct highly displaced tracks
  - Custom vertexing algorithms for very displaced vertices
  - Careful balance of CPU timing and disk-space required



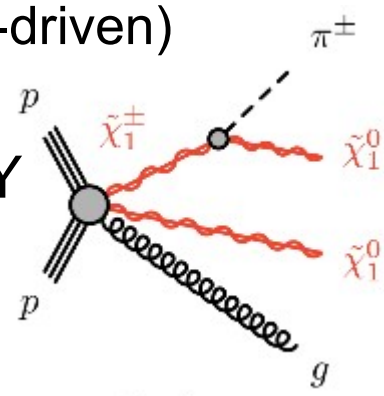
- Detector efficiency model-dependent
  - Limit by careful choice of fiducial region
  - What benchmark to provide
  - How to allow re-interpretation / boundaries?

PR D90 055031 (2014)

Disappearing track

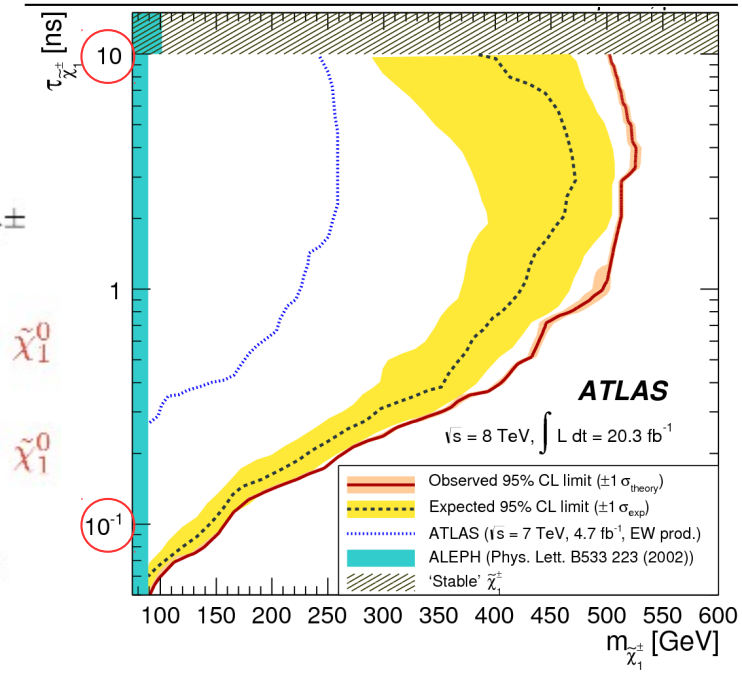
- Charged particle decaying within the ID into un-detected products
  - Manifest as "short" track
- Requires hard ISR to trigger: $\not{E}_T$+jet
- Isolated high-p_T (> 75 GeV) track with at most few hits in the TRT
  - Dedicated tracking setup required
- Results by fitting p_T spectrum
  - Main background at high-p_T: mis-measured tracks (data-driven)
- Signal model: AMSB SUSY

$$pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- + jet$$
$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0 + jet$$



- 2-tracks signal region investigated

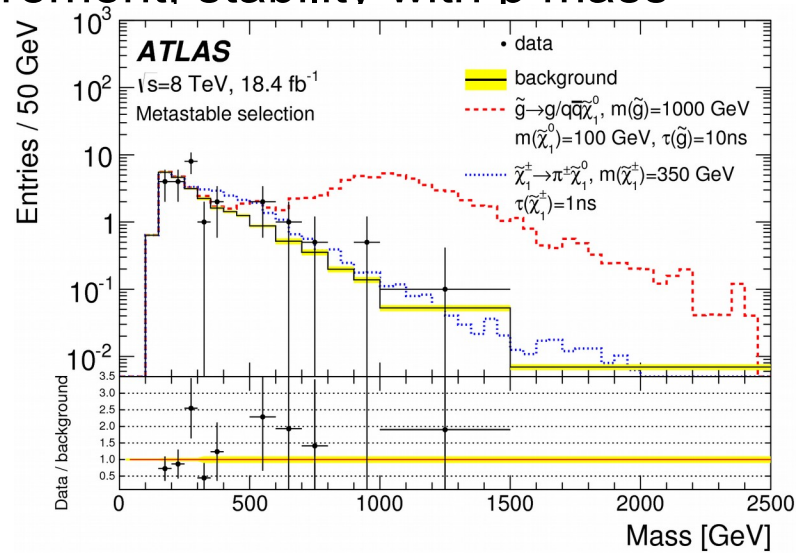
Selection requirement	Observed events	Expected signal MC events (efficiency [%])
Quality requirements and trigger	20479553	1873 (8.8)
Jet cleaning	18627508	1867 (8.8)
Lepton veto	12485944	1827 (8.6)
Leading jet $p_T > 90$ GeV	10308840	1571 (7.4)
$E_T^{miss} > 90$ GeV	6113773	1484 (7.0)
$\Delta\phi_{min}^{jet\text{-}E_T^{miss}} > 1.5$	5604087	1444 (6.8)
High-p_T isolated track selection	34379	21.9 (0.10)
Disappearing-track selection	3256	18.4 (0.087)

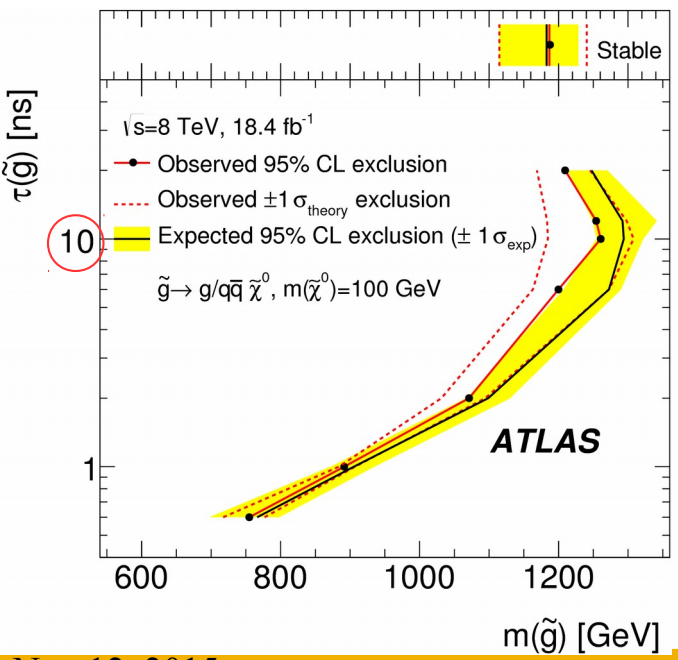


EPJ C75 407 (2015)

Large ionization tracks

- Heavy (→ slow) charged particles produce large ionization loss
  - Pixel detector provides accurate measurement: stability with p mass
- Trigger through calorimeter $\not{E}_T$
- Isolated high-p_T (>80 GeV) track with large energy loss (dE/dx)
  - Background from hadrons and leptons in the tails of dE/dx (data-driven)





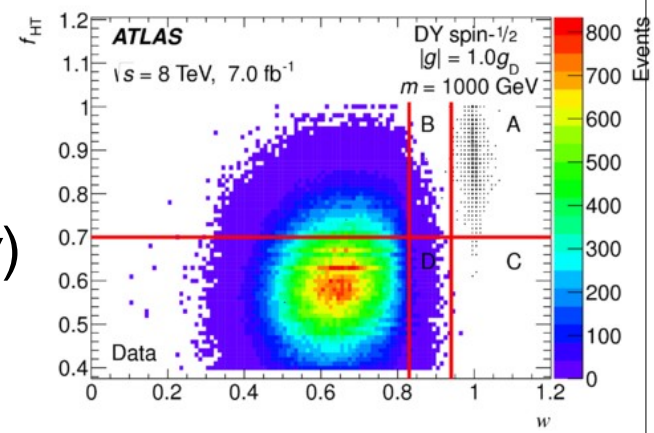
- Limits set for benchmark scenarios:
  - $\tilde{g}/\tilde{b}/\tilde{t}$ Stable R-hadrons, "stable" $\tilde{\chi}^{\pm}$
  - $\tilde{g}$ R-hadrons varying lifetime/mass/decay
    - Decay hypothesis vary limits to some extent
  - $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0}\pi^{\pm}$ (same as disappearing tracks)
- σ vs mass, mass vs lifetime

EPJ C75 362 (2015)
ArXiv:1509.08059 (PRD)

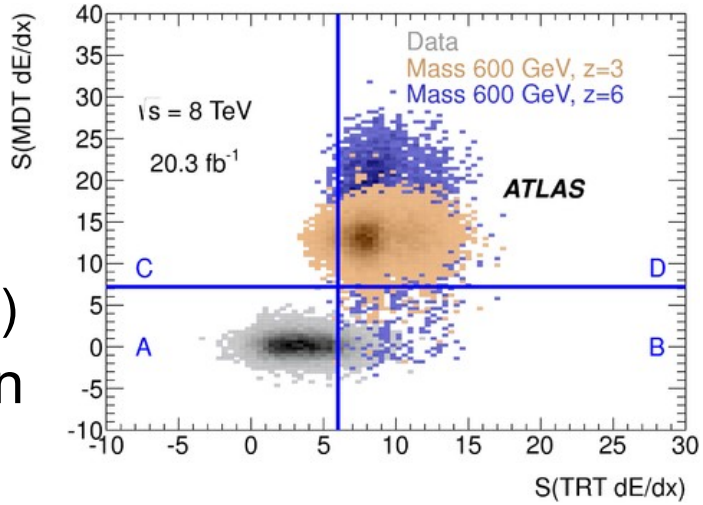
Large ionization tracks

- Multiply charged particles also produce larger ionization loss

- Search for **monopoles**
  - stop in EM calorimeter (special trigger)
- Analysis based on TRT high-threshold hits, no energy in calorimeter past first layers (*w*)
- Fiducial phase space defined to have uniform and > 90% efficiency
  - depends on material traversed



- Search for **multiply-charged particles**
  - Stable within ATLAS detector
- Combine Pixel, TRT and muon dE/dx measurements, depending on charge
  - Note: energy loss in calorimeter μ z^2 (q=ze)
- Benchmark: Drell-Yan like pair production
  - σ vs mass limits; q=z*e, z=2-6;

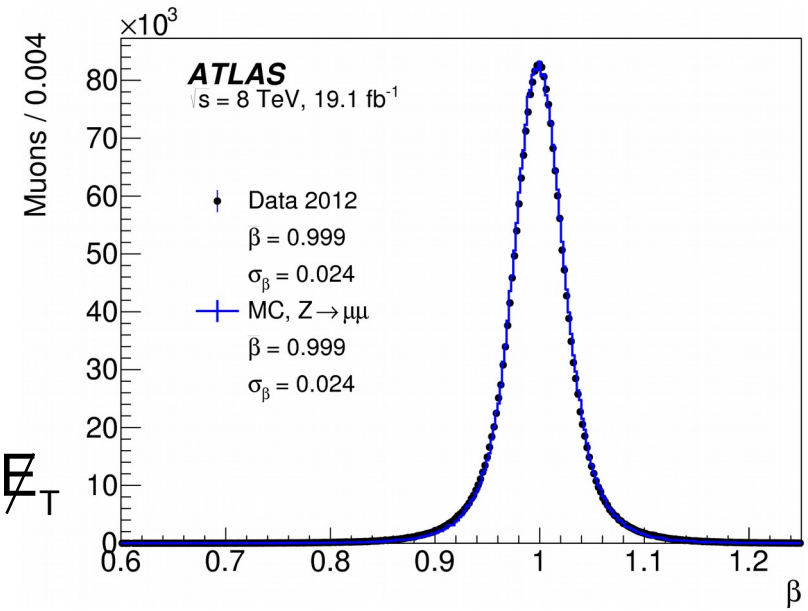


JHEP 01 068 (2015)

Time-Of-Flight

- Heavy charged particles travel with $\beta = v/c < 1 \rightarrow$ detect with TOF
  - Combine with information on ionization loss (dE/dx from pixel detector) $\rightarrow \beta\gamma$
- Average time measurements from calorimeter and muon system
  - Calibrated using $Z \rightarrow \mu\mu$, ad-hoc tracking setup to correctly associate hits in cased where $\beta << 1$

$$m = p/\beta\gamma$$



- Trigger on single-muon or calorimeter $\not{E}_T$
- Background mainly from muons with mis-measured β or high dE/dx
  - Mostly rejected requiring consistency among independent detectors
  - Residual background estimated from random combination from the β and momentum distributions measured in suitable regions

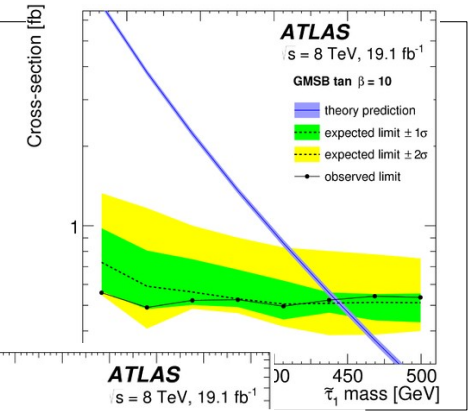
JHEP 01 068 (2015)

Time-Of-Flight

- Three sets of signal regions, selections targeted for each one

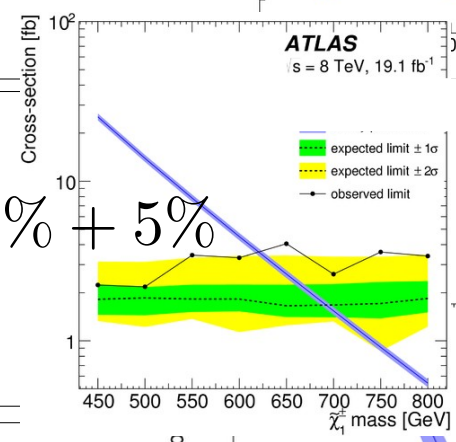
- Sleptons in GMSB ($\tilde{\tau}_1$ NLSP) or LeptoSUSY simplified model ($\tilde{\ell}$ degenerate, $\tilde{\chi}^0$ LSP)
  - Investigate 1 and 2-tracks signal in both ID and muon system

$\epsilon \sim 20\% + 30\%$



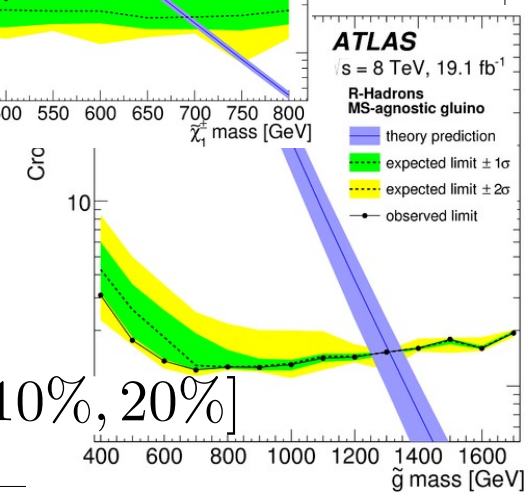
- Charginos nearly mass degenerate with LSP (almost pure neutral wino)
  - Investigate 1 and 2-tracks signal; expect significant $\not{E}_T$ when $\chi^{\pm}\chi^0$ production

$\epsilon \sim 15\% + 5\%$



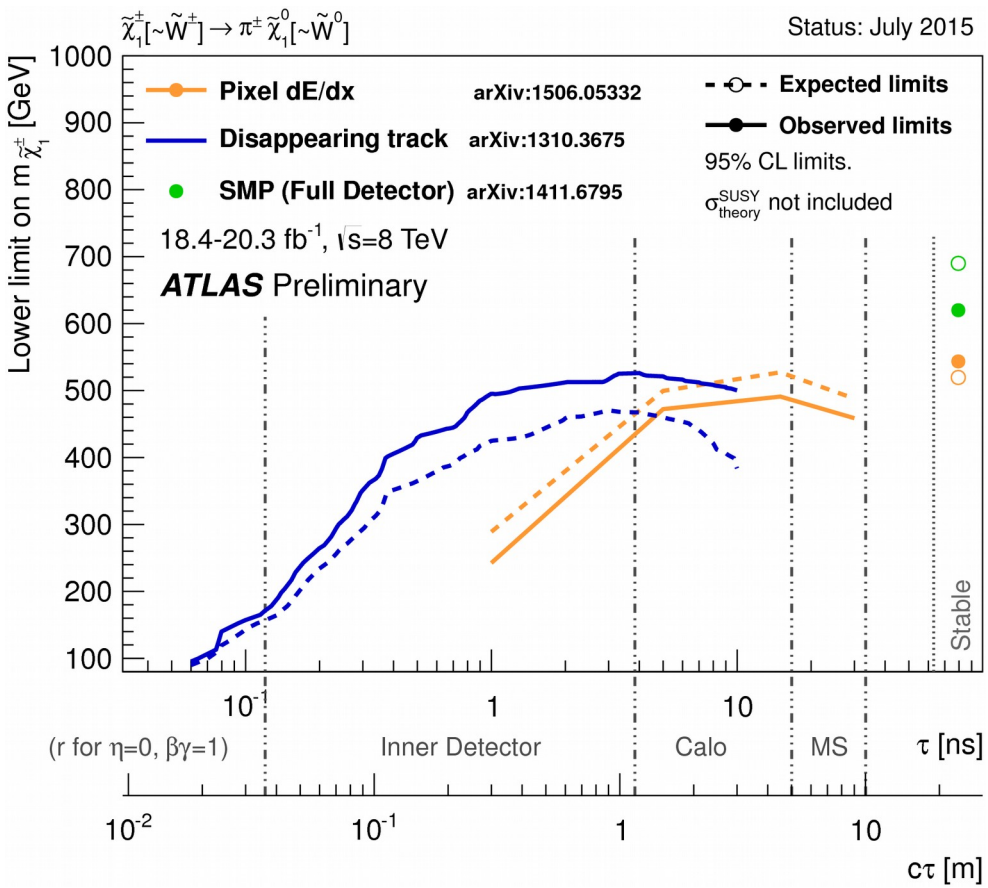
- Squarks and gluinos forming R-hadrons
  - Use full detector or ignore muon system (charge → neutral interacting with calorimeter)
  - Optimized separately for gluino/stop/sbottom

$\epsilon \sim [10\%, 20\%]$



Summary plots

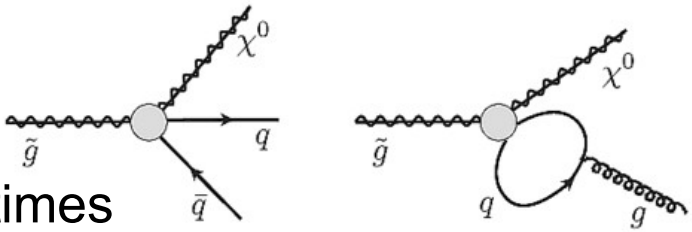
- Example of summary plot for a specific (SUSY) benchmark model
- Useful for us for a quick overview, but need consistent benchmarks

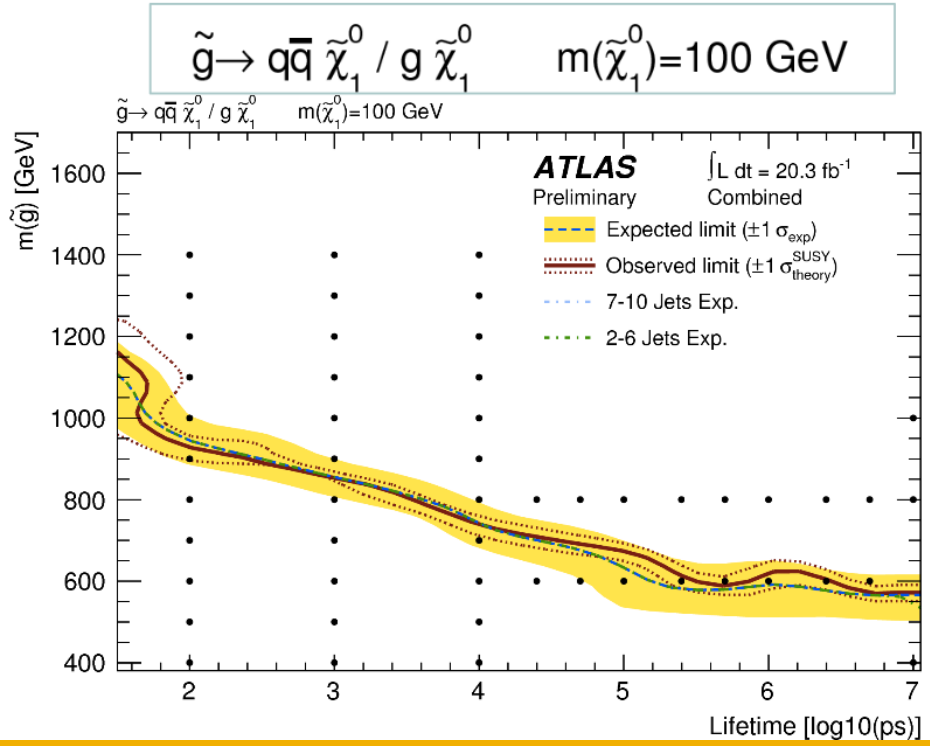


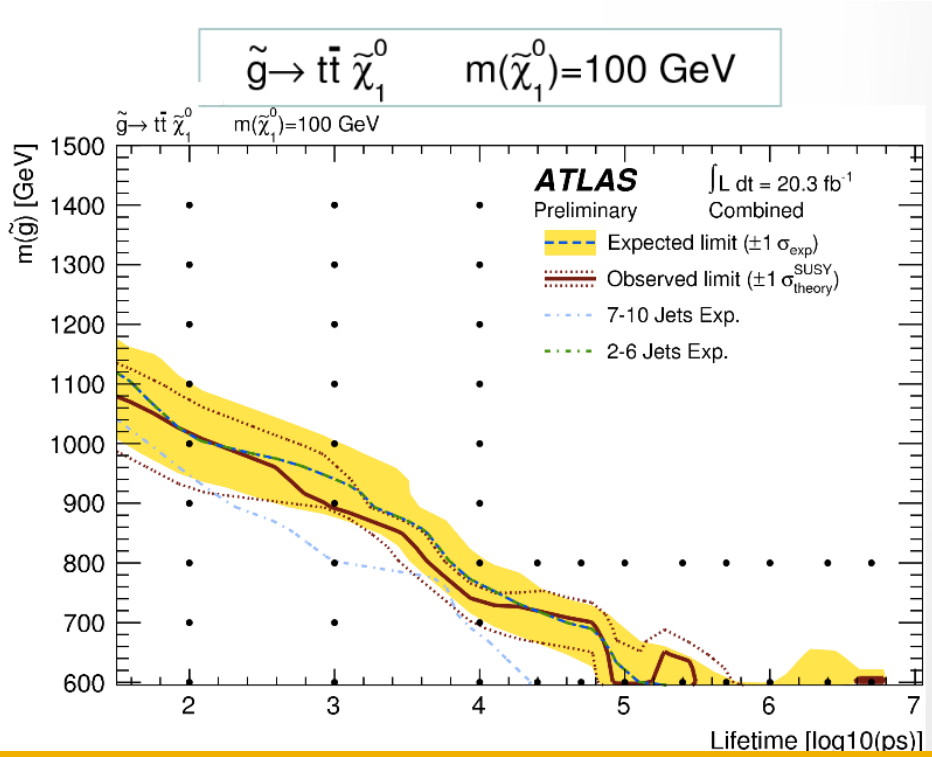
ATLAS-CONF-2014-037

Prompt-analyses re-interpretation

- Re-interpret prompt analyses to target gluinos with ~short lifetime (~ < 1ns)
  - Actual sensitivity extends also for longer lifetimes
- Standard jets+$\not{E}_T$ analysis provides significant constraints
- Lepton and b-jet identification non-optimal for displaced decay







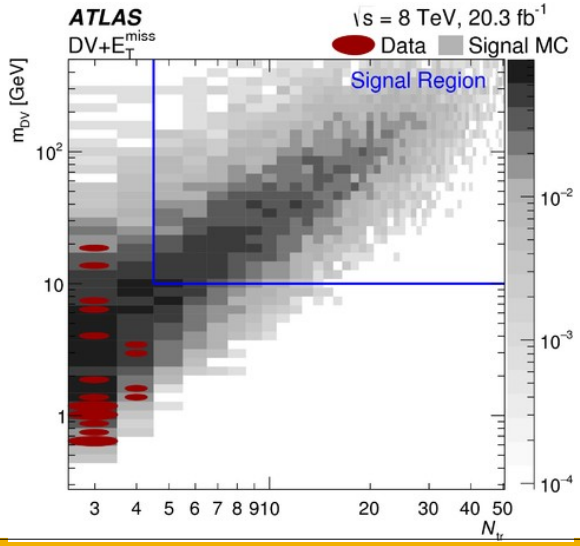
PR D92 072004 (2015)
PR D92 012020 (2015)

Displaced vertices

- Aim to reconstruct explicitly displaced decays of LLPs
  - Ad-hoc tracking (large d_0 tracks), veto known material (had. interactions)
  - Background: accidental crossing, merged vertices, jets punch-through

Inner-Detector analysis

- Multi-track: displaced vertex with either one e,μ, $\not{E}_T$ or jets
- Di-lepton: displaced vertex from opposite charge ee, μμ



Inner-Detector + Muon system analysis

- Dedicated muon-trigger for displaced vertices in the MS
  - Also using jet+E_T trigger
- Two-vertices signal region
  - Aim for large efficiency

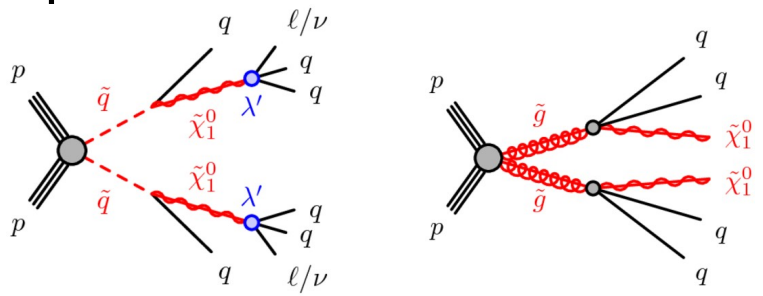
Trigger	Applicable topologies
Muon RoI Cluster	IDVx+MSVx, 2MSVx
Jet+E_T^{miss}	2IDVx, IDVx+MSVx, 2MSVx

PR D92 072004 (2015)
PR D92 012020 (2015)

Displaced vertices

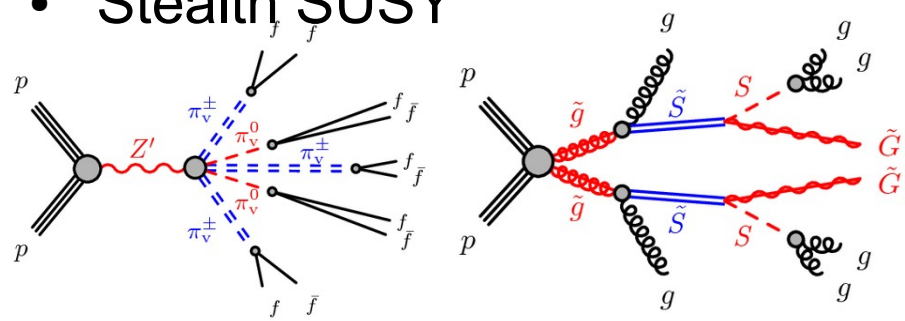
Inner-Detector analysis

- RPV, GMSB: $\tilde{\chi}^0$(N)LSP long-lived
- Split-SUSY: $\tilde{g}$ into R-hadron

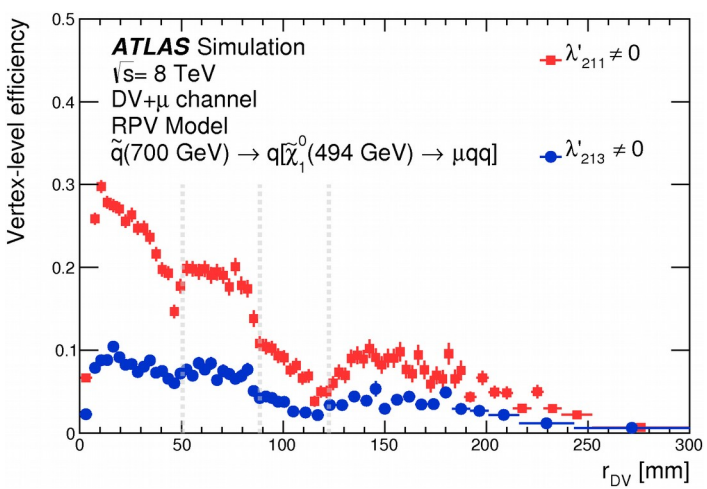


Inner-Detector + Muon system analysis

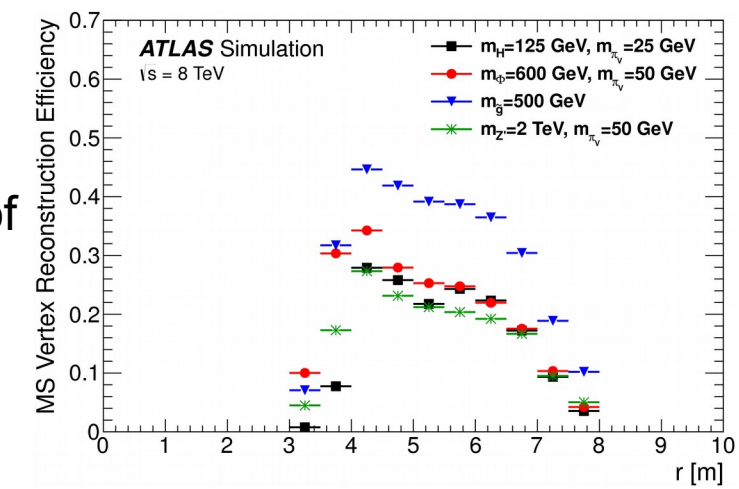
- Hidden Valley, Φ or Z' mediator
- Stealth SUSY



- Non-trivial efficiency dependence on mass, boost, multiplicity, …
  - Weak dependence on originating particle given the above

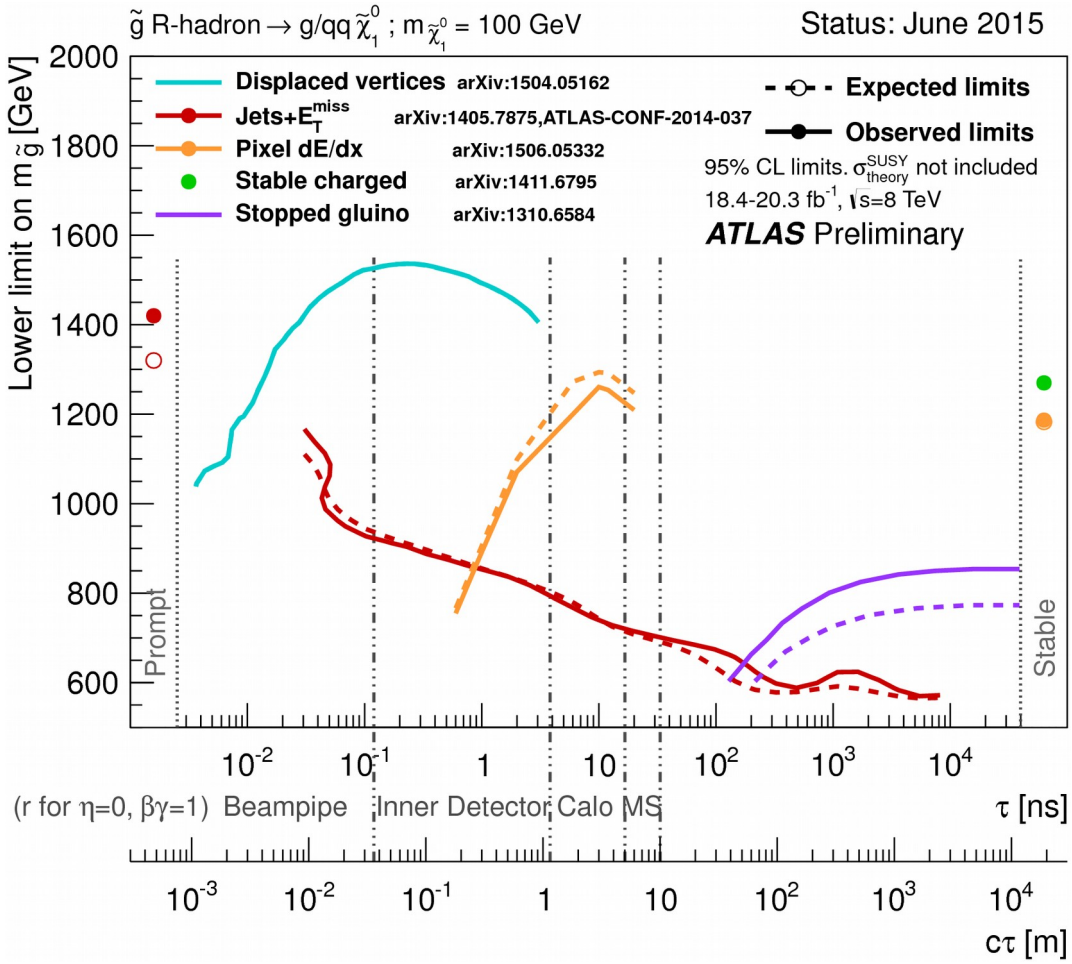


Results presented for benchmark models as function of
- lifetime
- mass spectrum
- final state



Summary plot

- Nice complementarity of analyses shown in example SUSY benchmark summary plot (gluino R-hadron)



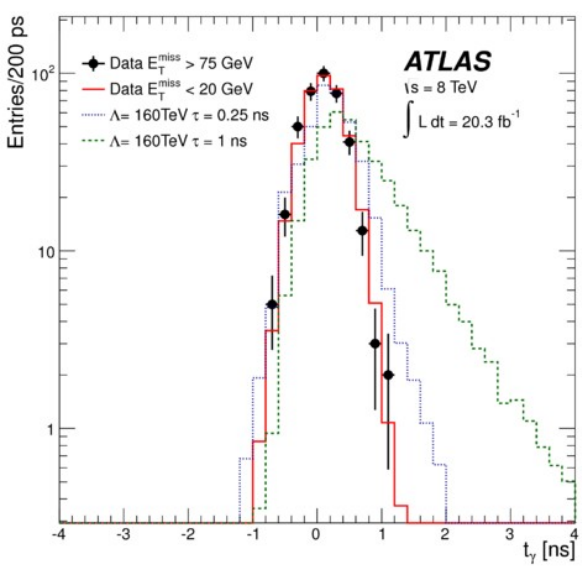
JHEP 11 088 (2014)

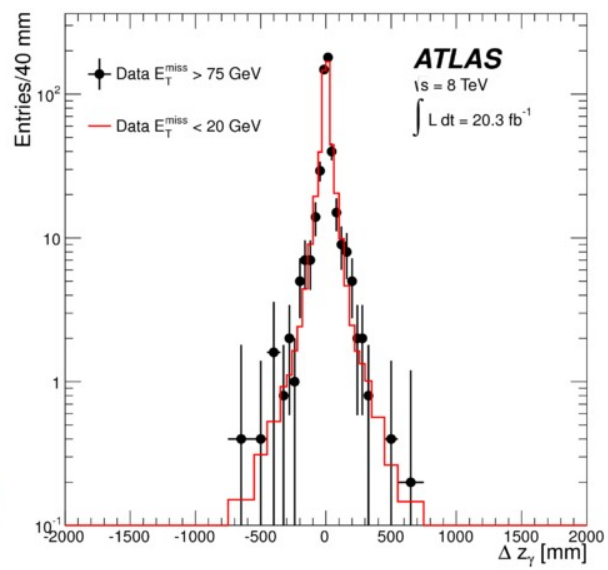
Non-prompt photons

- 2 photons pointing away from interaction and delayed in time
  - Additionally require $\not{E}_T$ (>75 GeV), low $\not{E}_T$ region as control region
- Main background from prompt γ,jets
- Use calorimeter timing (t_γ) and pointing from shower profile (z_{DCA})

Exponential due to acceptance of decay before calorimeter

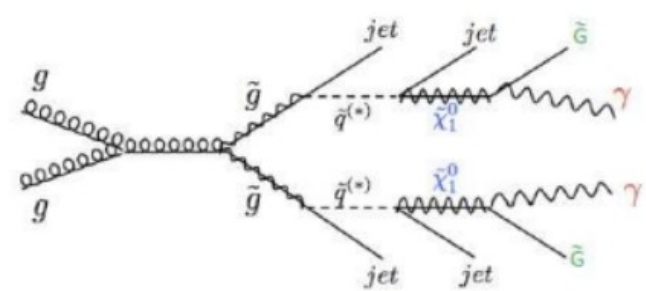
τ	Signal acceptance times efficiency [%]		
[ns]	$\Lambda = 80$ TeV	$\Lambda = 160$ TeV	$\Lambda = 320$ TeV
0.5	8.4 ± 0.6	30 ± 1	46 ± 2
2	5.1 ± 0.3	21 ± 0.2	33.0 ± 0.3
6	1.7 ± 0.1	7.3 ± 0.1	12.5 ± 0.2
10	0.86 ± 0.03	3.71 ± 0.06	6.45 ± 0.09
40	0.089 ± 0.004	0.38 ± 0.01	0.70 ± 0.02
100	0.016 ± 0.001	0.070 ± 0.002	0.129 ± 0.004





Smaller E_T^γ, $\not{E}_T$

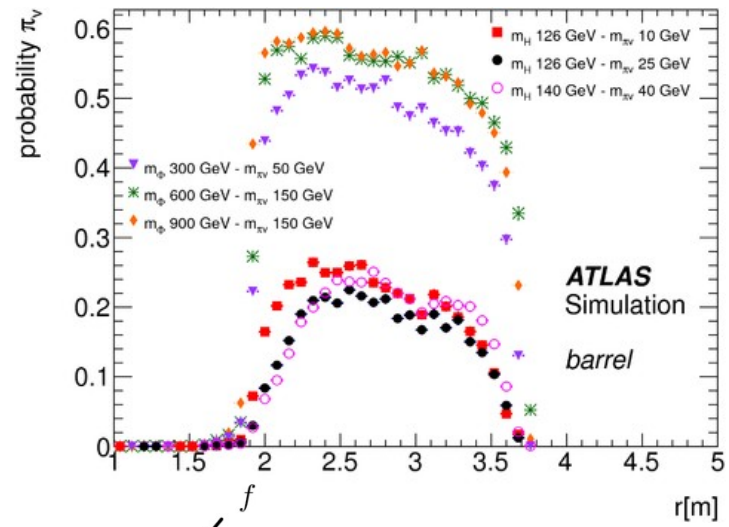
- GMSB(SPS8), $\tilde{\chi}^0$ NLSP
- Limits on #events, σ

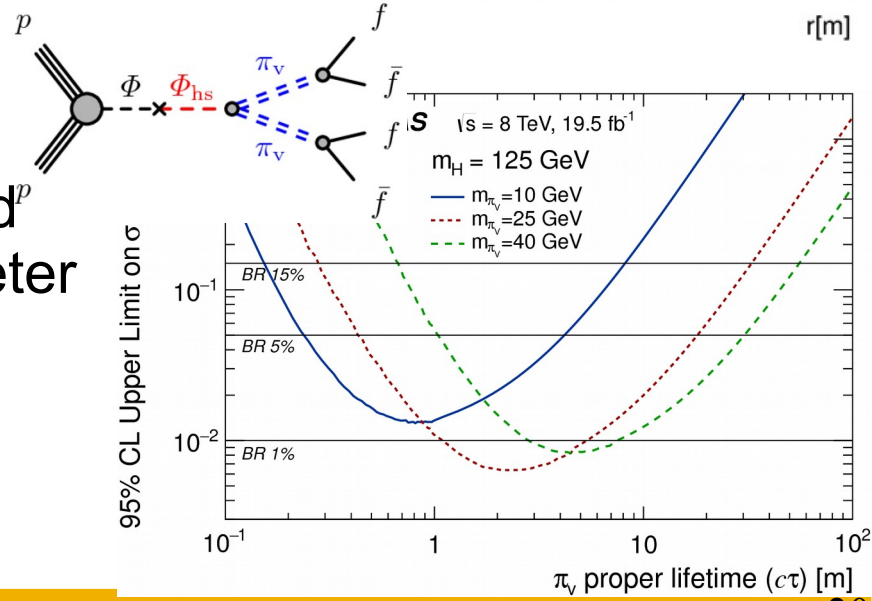


PL B743 15 (2015)

Jets in hadronic calorimeter

- Narrow jets in hadronic calorimeter with no activity before (EM+ID)
  - Well fit neutral LLPs, complements direct vertex reconstruction
- Dedicated trigger: narrow ($\Delta R=0.2$) jets with large E_{HAD}/E_{EM} and no activity in ID
- >= 2 jets required offline, low $\not{E}_T$
  - Loose timing requirement limits acceptance in β (OK, for benchmark)
- Hidden Valley benchmark model with scalar communicator
- Acceptance 0.07%-0.6%, dominated by requiring both decays in calorimeter
- Limits on $\sigma(\Phi)$xBR($\Phi \rightarrow \pi_v\pi_v$) for m_Φ, $m(\pi_v)$, $\tau(\pi_v)$ hypotheses
  - Efficiency map vs π_v boost

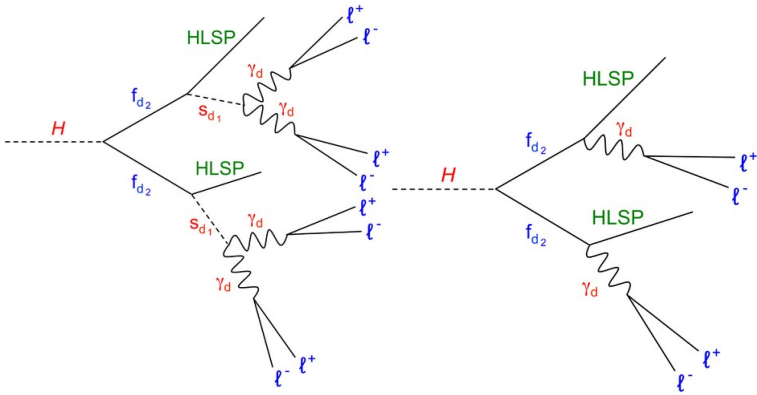




JHEP 11 088 (2014)

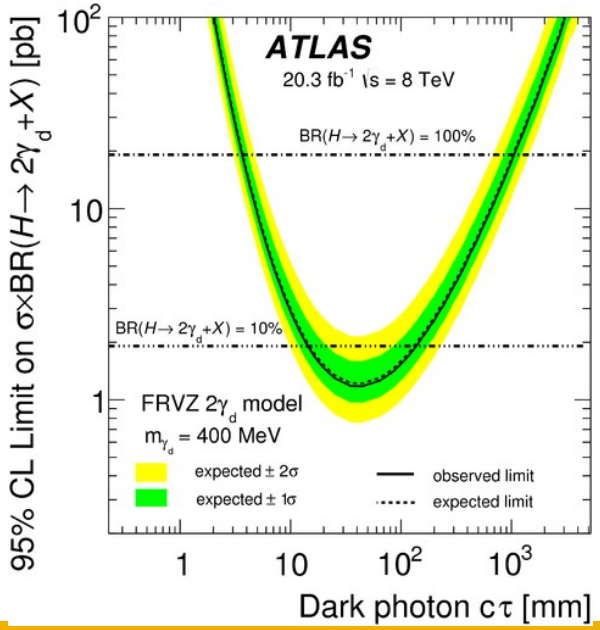
"Lepton"-jets

- Collimated cluster of μ/e/π (="jets")
  - Trigger: multi-μ or jets in had. calorimeter
  - "Lepton"-jet types: 4μ, 2μ + 2 "jets", 4 "jets
- e/π "jets" ~as previous slide
  - Sensitive to decays in had. calorimeter



- Muons reconstructed in MS only for high efficiency when displaced
- Multi-jet and cosmic rays backgrounds data-driven

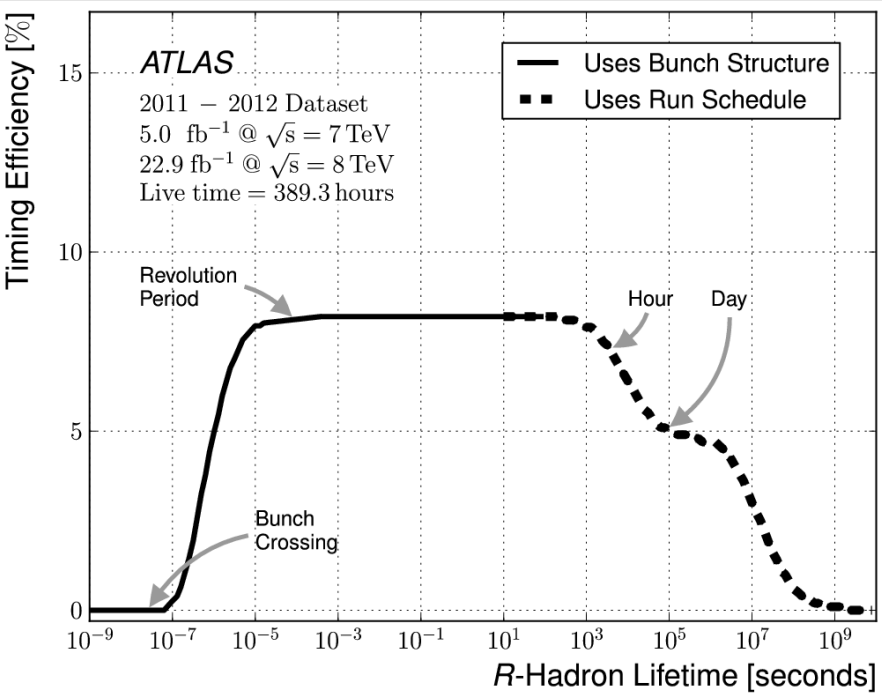
- Benchmark model: Higgs decaying to hidden sector, displaced decay of a light dark-photon (γ_D)
  - $H \rightarrow 2\gamma_D + X$, $H \rightarrow 4\gamma_D + X$
  - Efficiency depends strongly on number of γ_D, decay length and angular distribution

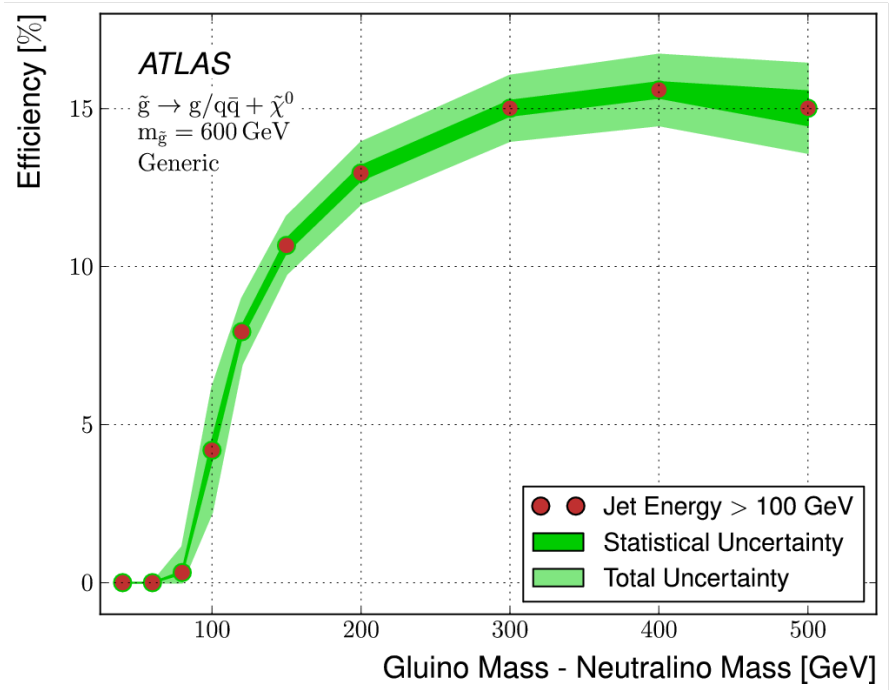


PR D88 112003 (2013)

Very-long lived R-hadrons

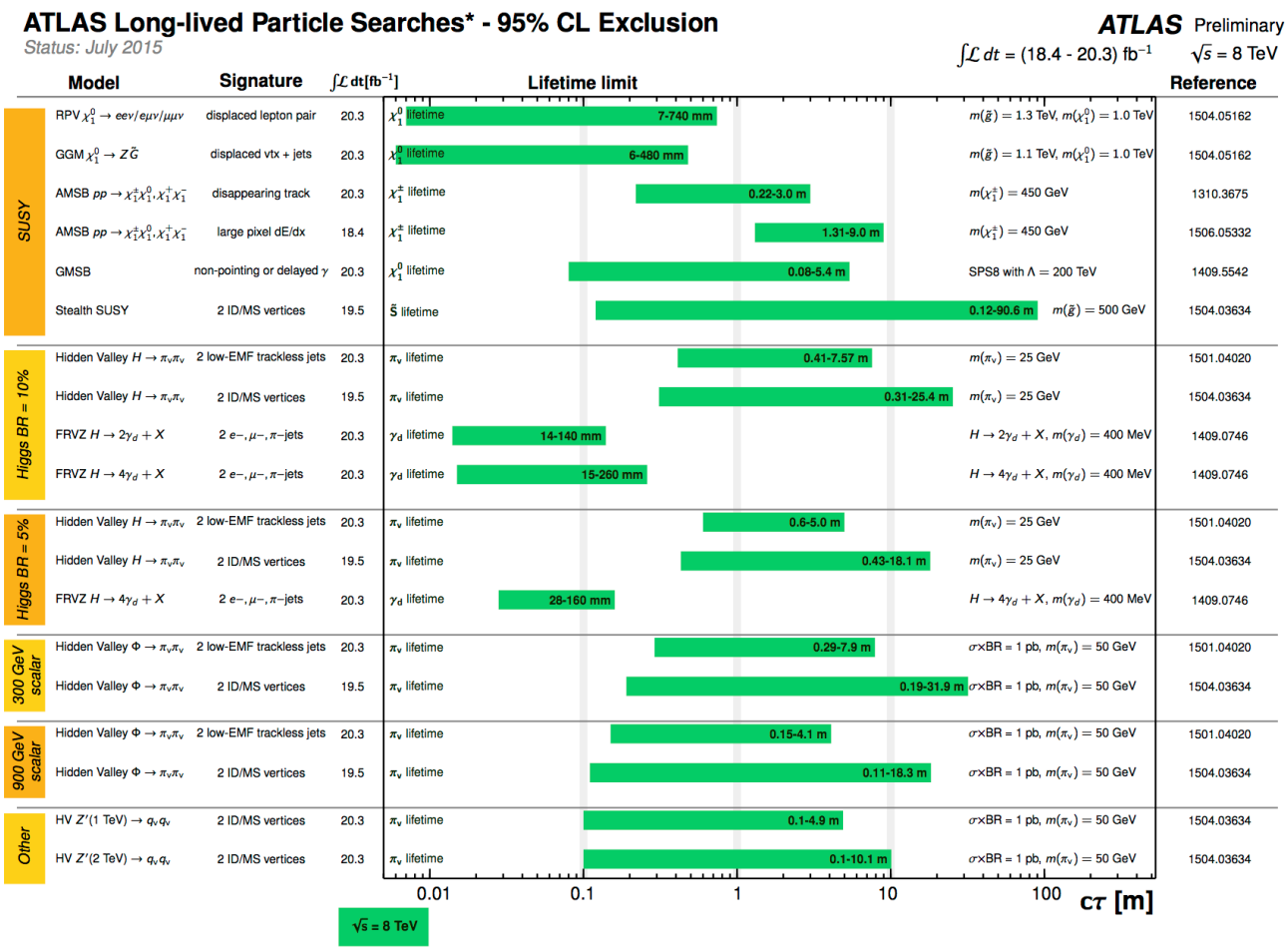
- Use bunch-structure of LHC: R-hadrons that decay in the calorimeter after a "long" time (jet+E_T from $\tilde{\chi}^0$)
- Dedicated trigger; >= 1 calorimeter jet (but <=5), no MS activity
  - Additionally, $\not{E}_T$ and loose jet shape requirements
- Main backgrounds: cosmic rays, beam halo
- Different models of R-hadrons and gluino-neutralino ΔM probed





(Last) summary plot

- Very broad overview of lifetime sensitivity ranges

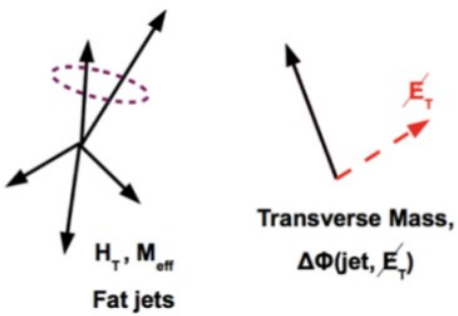


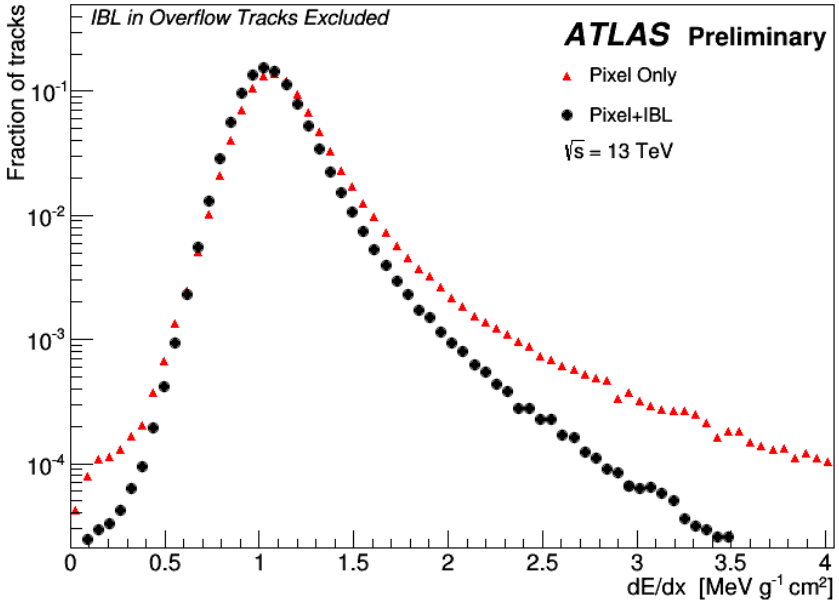
A brief look at the future

- Obvious: 7 TeV → 13 TeV :-)
- Key upgrades can help in LLPs searches

✔ New pixel layer: IBL
  - E.g. better dE/dx measurement

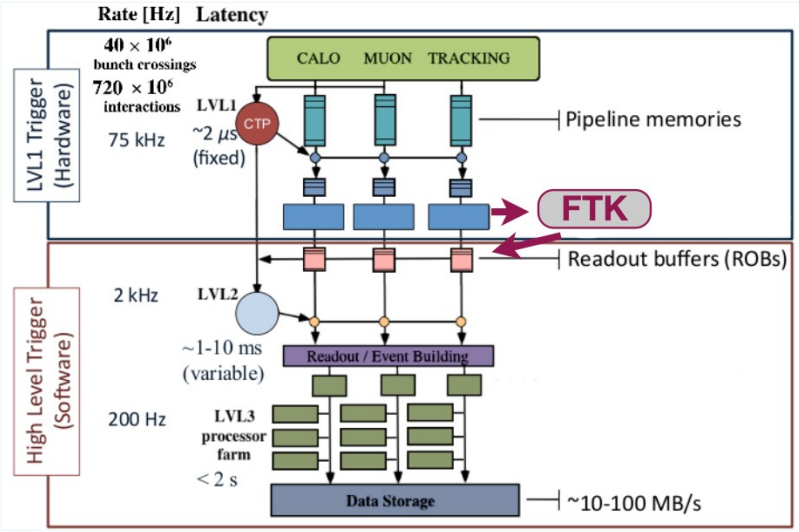
✔ L1 Topological trigger
→ correlation of L1 trigger primitives

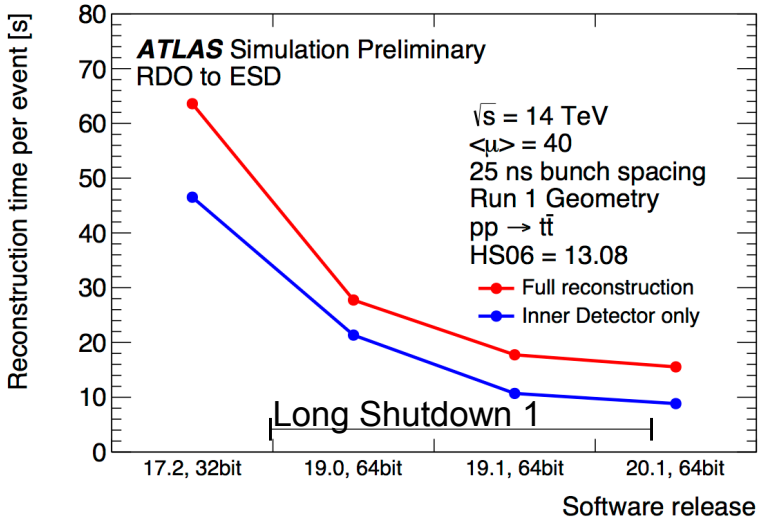




A brief look at the future

- Obvious: 7 TeV → 13 TeV :-)
- Key upgrades can help in LLPs searcl
  - ✔ New pixel layer: IBL
  - ✔ L1 Topological trigger
  - FTK to be commissioned during Run-2 → full-tracking in-between L1 and HLT
    - but tracks reconstructed tightly pointing to interaction region
  - Software and tracking algorithms speed-up a factor of 4, re-invest part of the gain



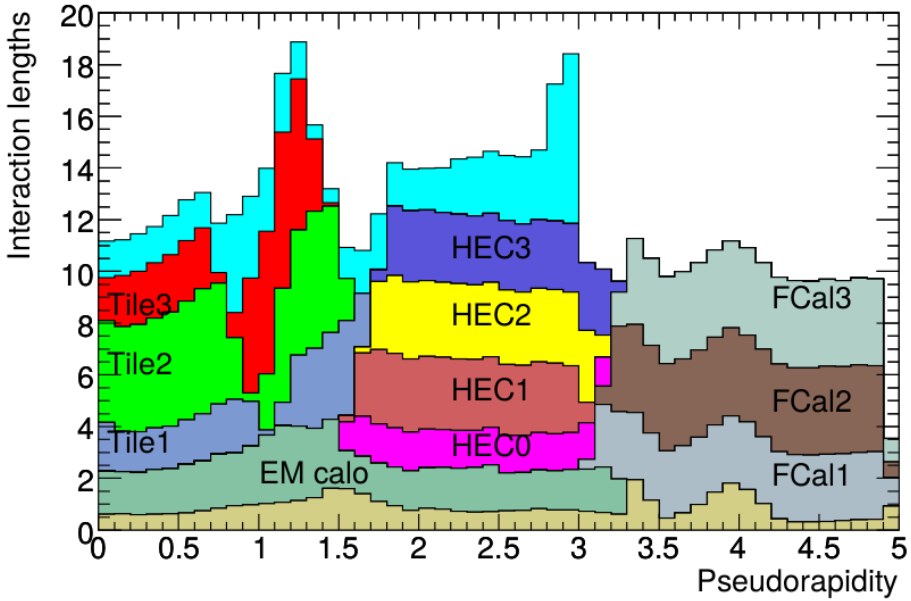


Conclusions (/Opening)

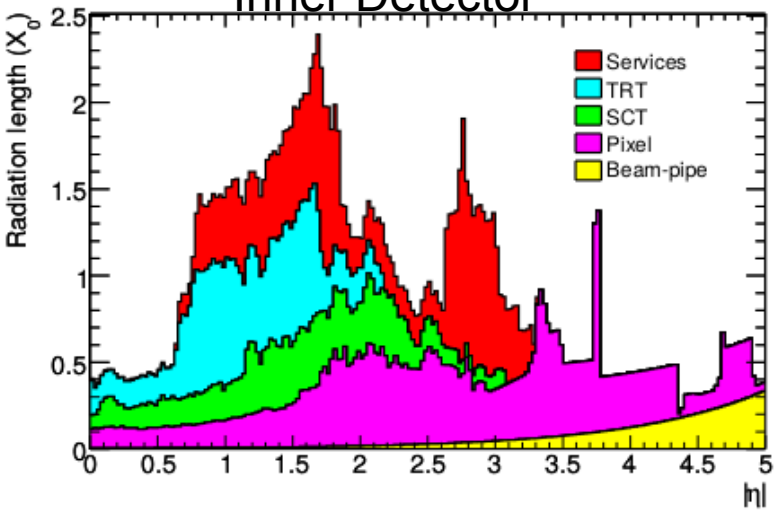
- A variety of complementary methods used in run-1 to hunt for LLPs
- Many of these analyses used the ATLAS detector in unique ways
  - Always looking for new innovative ways to hunt signatures that are theoretically well motivated and presently not fully covered
- Already towards end of Run-1, more systematic attempt to provide efficiency maps with results in simplified/benchmark models
  - However, very large model dependences are often found
  - How to specify “boundaries”?
- Looking forward to a fruitful workshop!

Backup

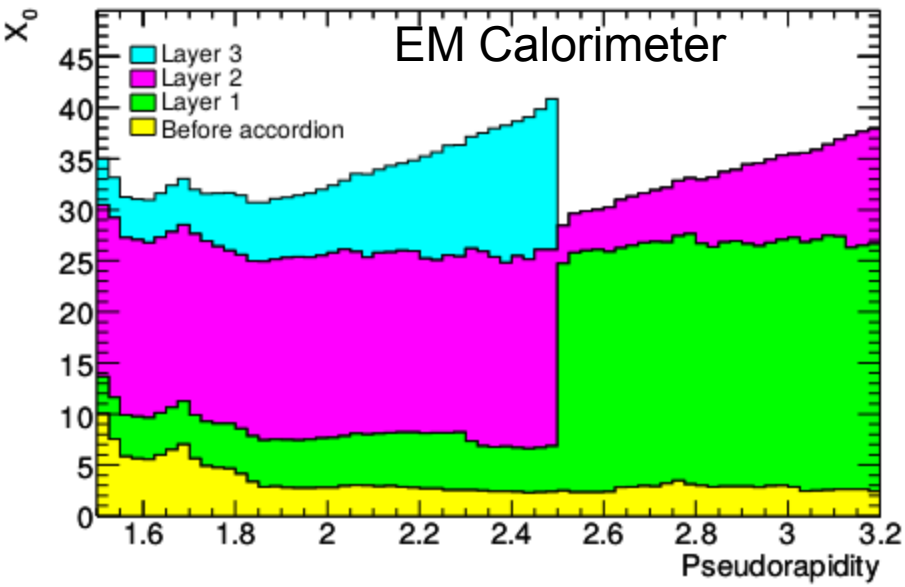
Hadronic calorimeter

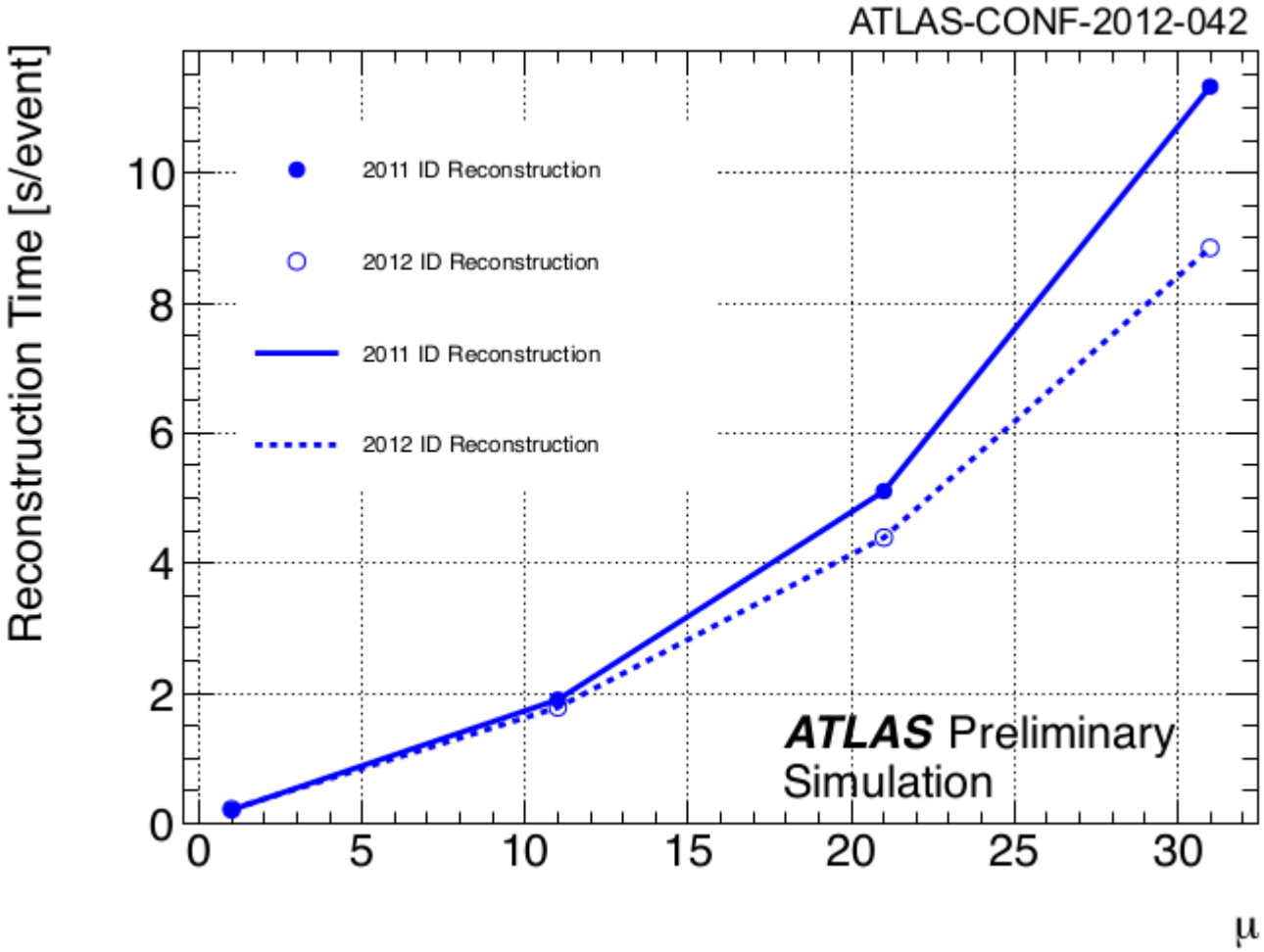


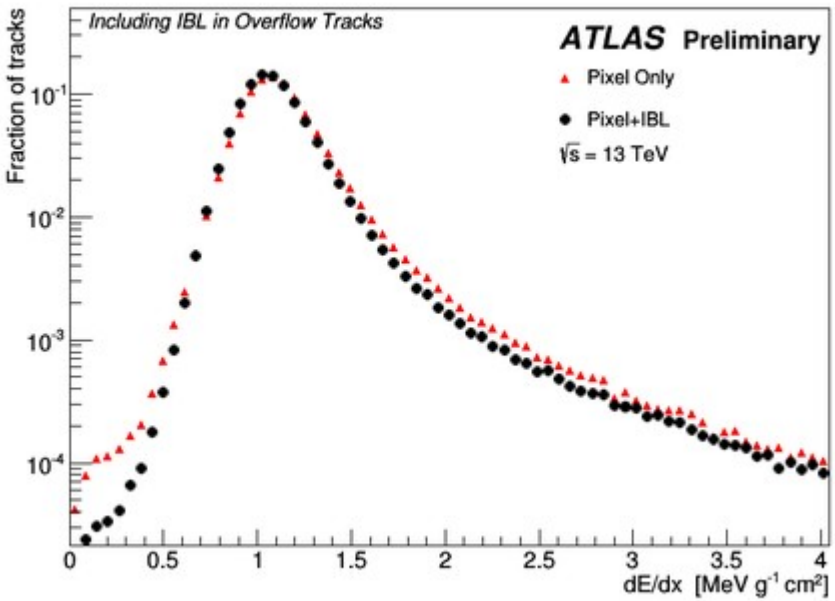
Inner Detector



EM Calorimeter




ATLAS-CONF-2012-042
Reconstruction Time [s/event]
2011 ID Reconstruction
2012 ID Reconstruction
2011 ID Reconstruction
2012 ID Reconstruction
ATLAS Preliminary
Simulation
0
2
4
6
8
10
0
5
10
15
20
25
30
μ


Including IBL in Overflow Tracks
ATLAS Preliminary
Pixel Only
Pixel+IBL
√s = 13 TeV
Fraction of tracks
10^-1
10^-2
10^-3
10^-4
0
0.5
1
1.5
2
2.5
3
3.5
4
dE/dx [MeV g^-1 cm^2]