X ATLAS Italia workshop
on Physics and Upgrades

February 10th-12th, 2015
Dipartimento di Fisica dell'Università degli Studi di Milano
and INFN - Sezione di Milano

Long Lived Particles: highly ionizing and neutral decaying hadronically

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Outline

- Long Lived Particles (LLPs): SUSY and exotic models
- Strategy and results from Run1:
    - Heavy charged LLPs
    - Neutral LLPs hadronically decaying in the hadronic calorimeter
    - Neutral LLPs hadronically decaying in the Inner Detector and/or in the Muon Spectrometer
- Lessons from Run1
- Run2 perspective
- Summary

LLPs in SUSY and exotic models

“Long-lived” here means “lived enough to be detected”.

A number of theories and models foresee non-SM LLPs to be produced at LHC, namely: Hidden Sector, SUSY RPV decays, Split-SUSY, GMSB, AMSB… (list far from exhaustive).

The signatures to exploit for the detection depend on the nature of the LLP:

- slow —> TOF measurements
- unusually (usually **highly**) **ionizing —> dE/dx measurements**
  - ***R-hadron (coloured sparticle (squark or gluino) + light SM quark) decays; heavy squarks mediate gluino decay (strong virtuality, e.g. Split-SUSY)***
  - ***lightest chargino only slightly heavier than lightest neutralino (AMSB)***
- charged decaying —> observation of disappearance or detection of unusual tracks
- **neutral decaying —> detection of displaced vertices or jets** or MET measurements
  - ***An hidden sector interacts with the SM sector via (heavy) “communicator” particle(s)***
  - ***Long-lived singlinos decaying in Stealth SUSY.***

Highly Ionising LLPs

Analysis carried out by the Genova ATLAS group: A. Favareto, C. Gemme, E. Guido, S. Passaggio, L. Rossi.

This week ready for circulation in the SUSY group, aiming at Moriond2015.

Supporting note here.

Searching LLPs with a pixel-only approach has some advantages:

- provides a direct (and rather model independent) measurement of the mass of the hypothetical particle;
- signal efficiency not affected by other sub detector (calorimeter or MS) requirements
- Higher geometrical acceptance and good lifetime acceptance

Main issues:

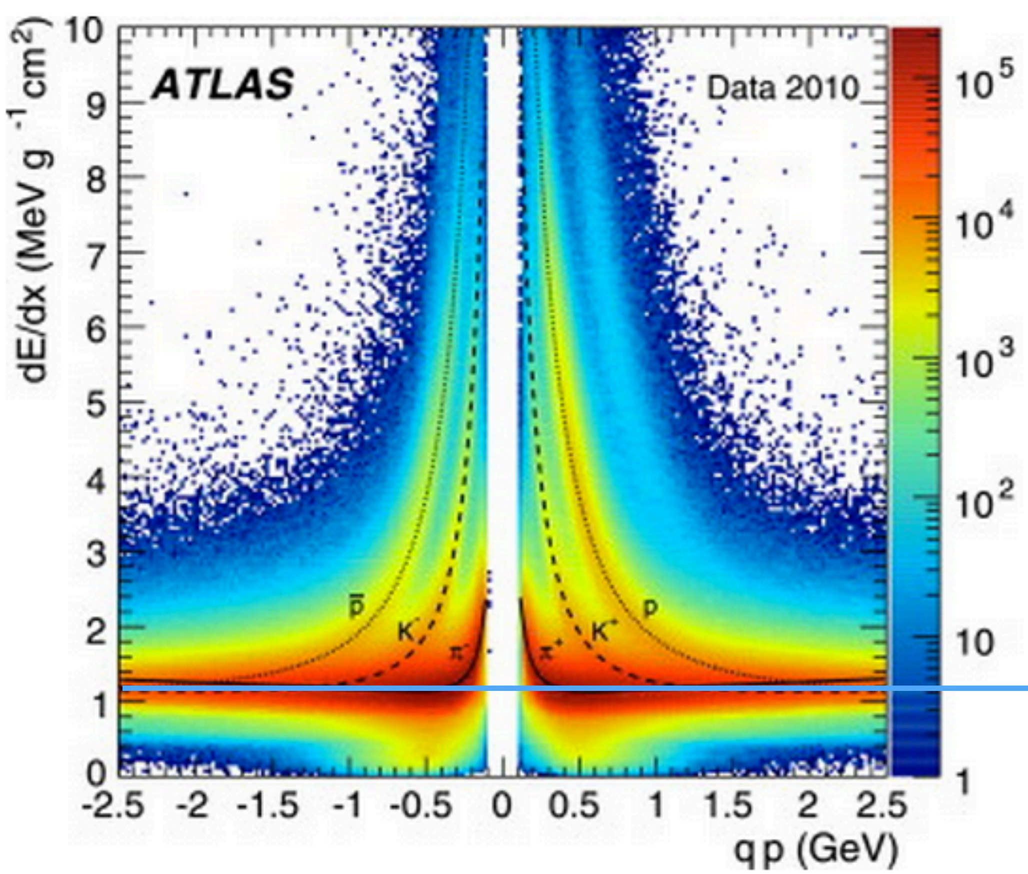
- Background estimation has to be data-driven, properly reproducing dE/dx dependence on p and η.
- Background rejection requires severe high-p_T and isolation cuts;
- Pixel ionization is not available at the trigger level: other signatures (MET!) must be used – efficiency is ~20% for stable particles and 60-90% for metastable.

Stable and LLPs searched for:

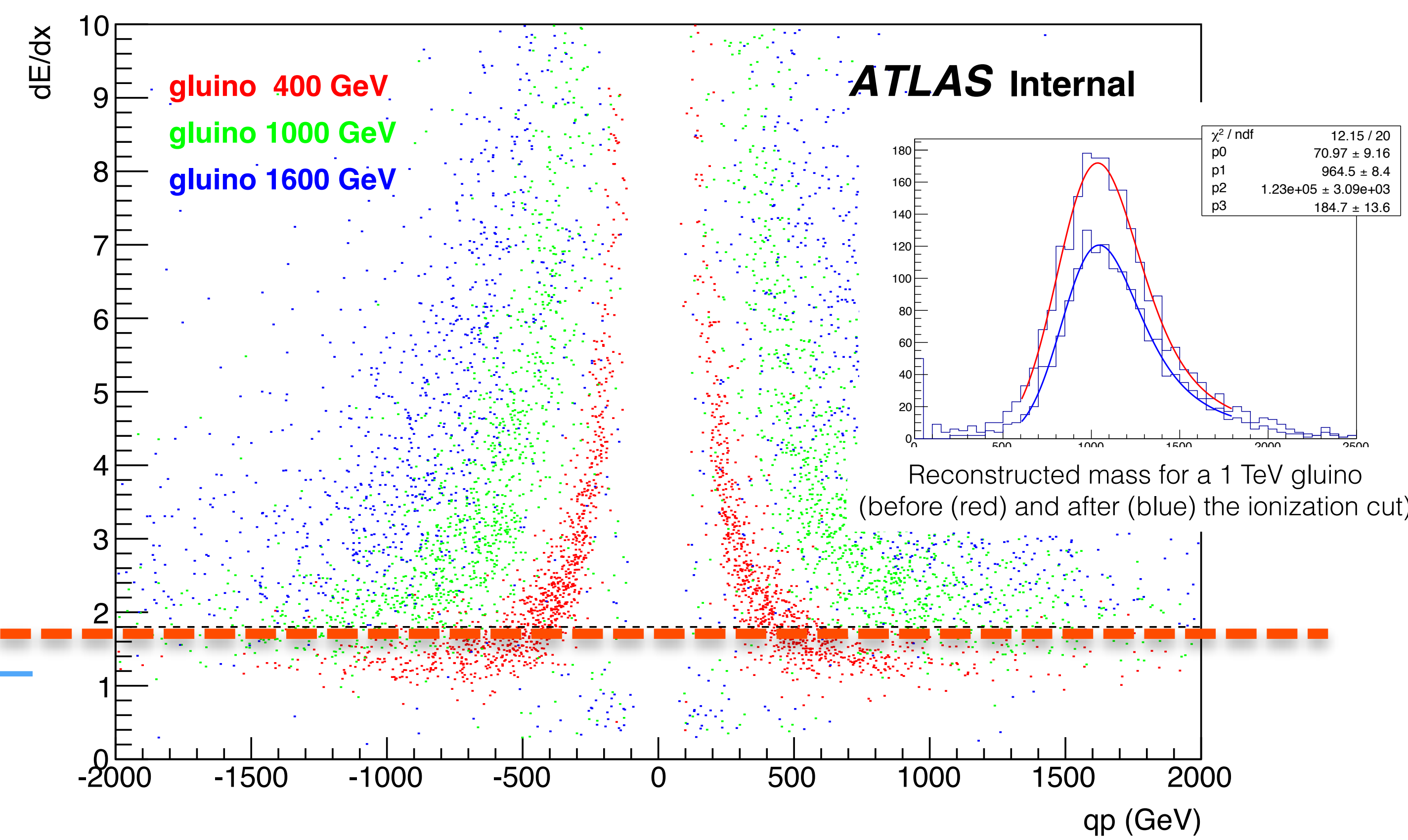
- **Stable charginos** (studied between 100 and 800 GeV)
- **Stable gluino, sbottom and stop R-hadrons** (100-1500 GeV, distributed over generic, Regge and intermediate models)
- **Metastable charginos** (80-600 GeV, $\tau_{chargino}$=0.3/1.0 ns, AMSB parameter from $m_{3/2}$=29 TeV to 212 TeV, decay forced to neutralino+pion ($m_{neutralino}$=$m_{chargino}$-140 MeV))
- **Metastable gluino R-hadrons** (decay to neutralino+gluon or neutralino+qqbar, gluino mass 400-1400 GeV, neutralino 100-1300 GeV in different samples, τ_{gluino}=0.1/1.0/10 ns)

Highly ionizing LLPs - search strategy

- Fit a Bethe-Bloch empirical function of low mass SM particles in special mbias run.
- Check the calibration monitoring the proton mass peak.
- The BB function allows to measure the particle mass from its energy release and momentum measurement (for $0.3<\beta\gamma<1.5$).
- Search for high-pT, isolated particles with high ionization.



MIP release 1.2 [σ(MIP)~0.15]



Cut in the current analysis is 1.8

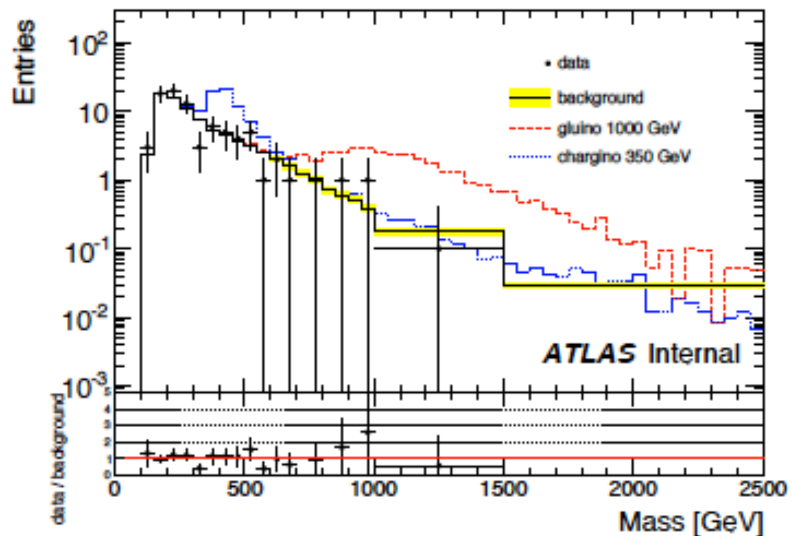
Charged LLPs - cut flow

Cut level	# Events	Cut Eff.	Total Eff.
Offline E_T^{miss}	798001	0.21	0.019
Primary vtx	796772	1.00	0.019
High-p_T	534692	0.67	0.013
Isolation	88431	0.17	2.1E-03
Electron veto	60450	0.68	1.5E-03
High-p	35684	0.59	8.6E-04
High-M_T	6589	0.18	1.6E-04
Ionization	85	0.013	2.1E-06
Muon veto	28	0.33	6.8E-07

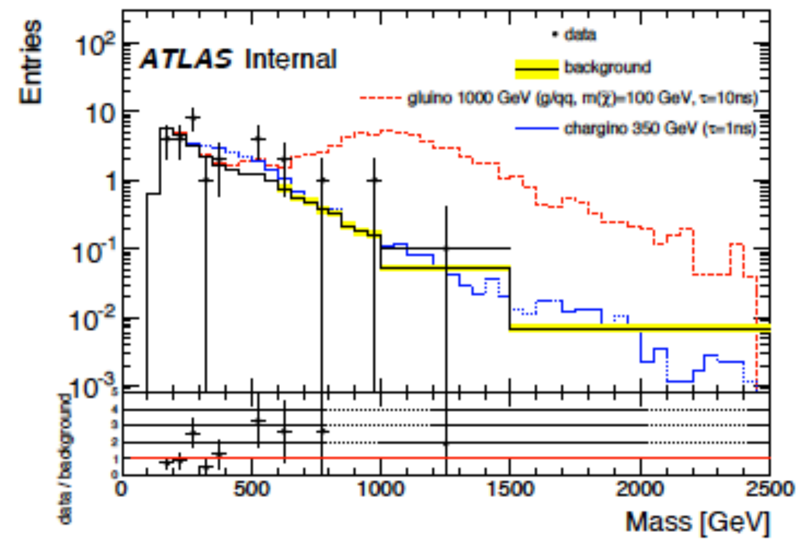
Table 10: Observed event yields at different steps of the selection procedure in the 2012 data sample. The total efficiency is computed with respect to the events that have been selected at Tier0 in the JetTauEtmiss.PhysCont.DESDM_RPVLL stream. *Offline* E_T^{miss} is the requirement on MET_RefFinal > 100 GeV. *Primary vtx* requires a primary vertex with at least five tracks. The following cuts require at least one track in the event with: *High-*p_T corresponds to the request on high p_T, cuts on the impact parameters and Pixel/SCT clusters; *Isolation* refers to the requirement that there is no other primary track with p_T > 1 GeV within a cone of 0.25; *Electron veto* rejects tracks matched with electrons; *High-p* corresponds to the requests on $p > 150$ GeV and $\sigma_p/p < 50\%$; *High-*M_T corresponds to the requests on transverse mass > 130 GeV, *Ionization* is the request on the Pixel dE/dx as explained in the text; finally the *Muon veto* is applied to candidates for the metastable searches.

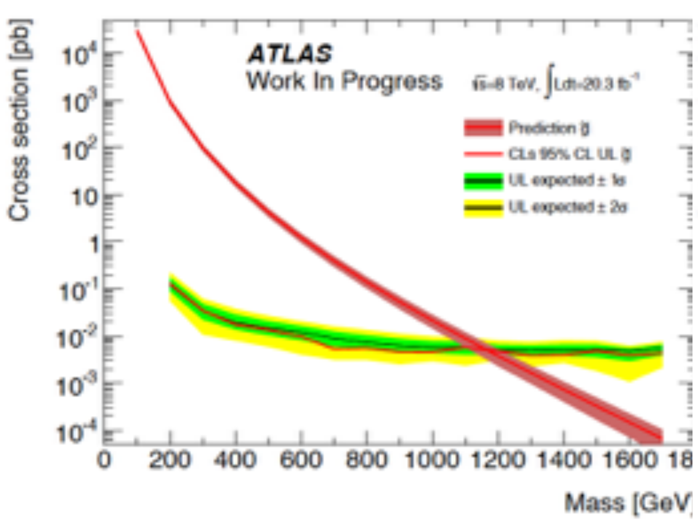
Highly Ionizing LLPs - results

Stable

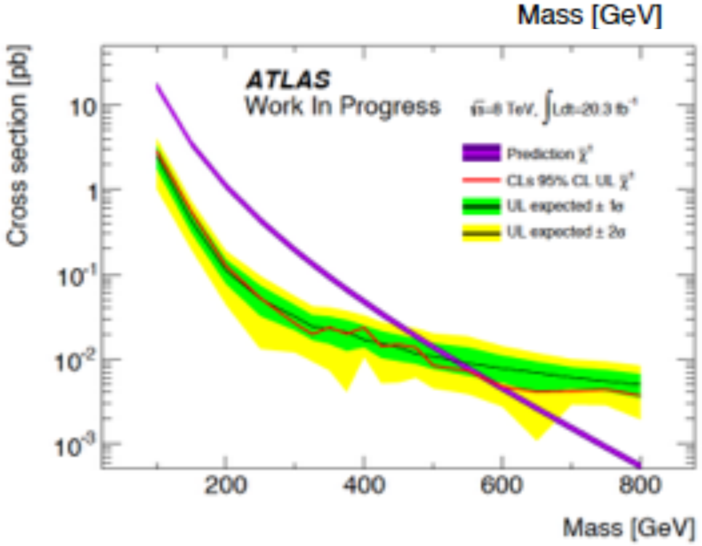


Metastable

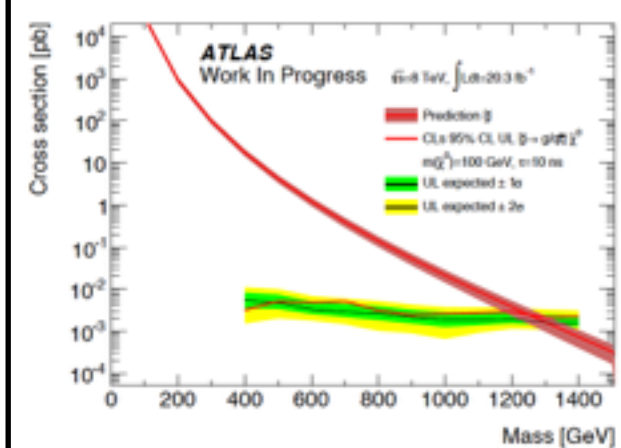


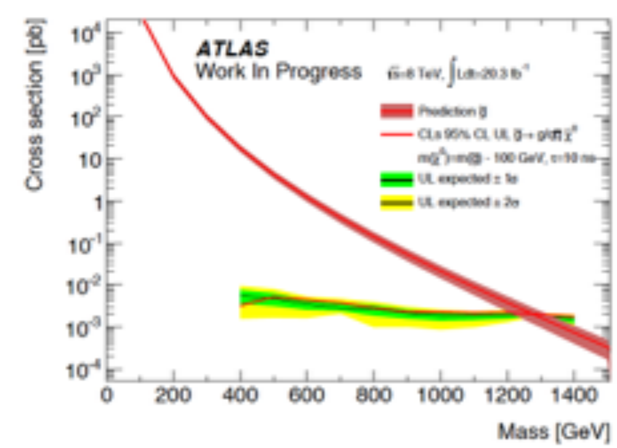


stable gluino R-hadrons

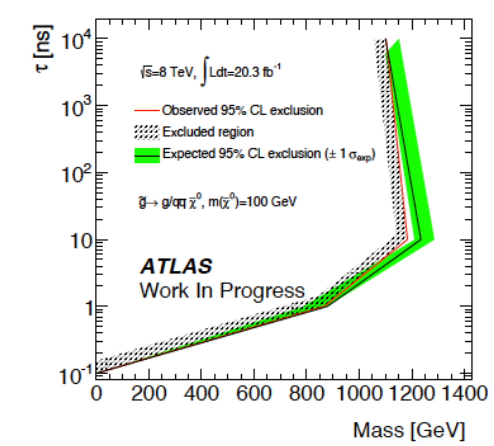


stable chargino





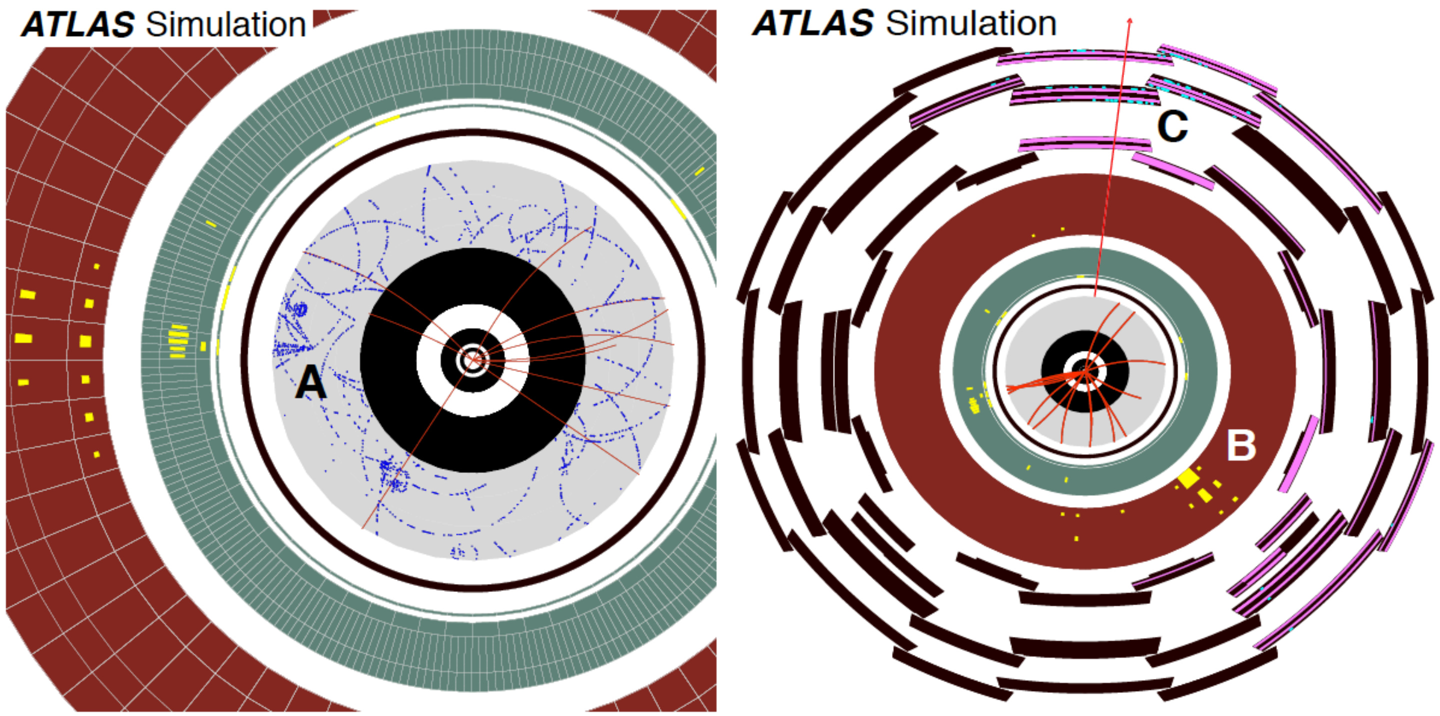
metastable gluino R-hadrons



Particle	Decay mode	$m(\tilde{\chi}_0)$ [GeV]	τ [ns]	$m >$ [GeV]
gluino R-hadron	stable	–	–	1102
sbottom R-hadron	stable	–	–	745
stop R-hadron	stable	–	–	758
chargino	stable	–	–	549
gluino R-hadron	$g/q\bar{q}$	100	10	1183

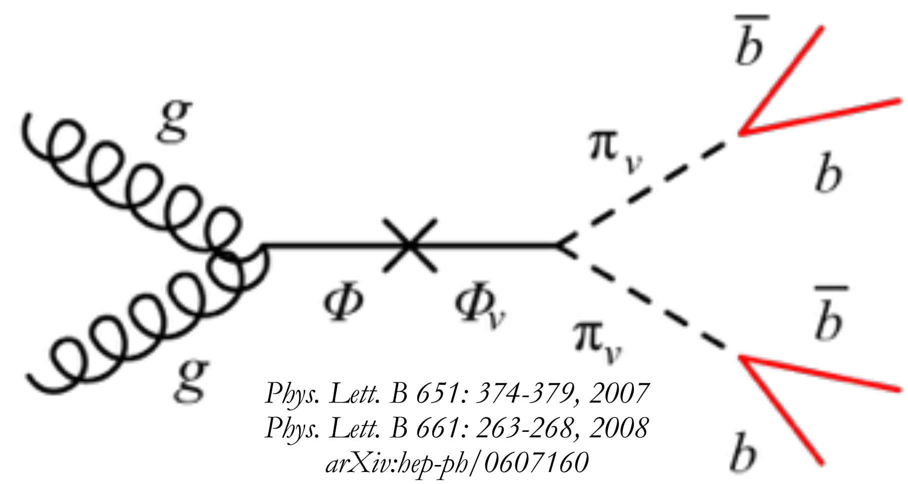
95% C.L. lower limits of masses of LLPs computed

Neutral LLPs: topology



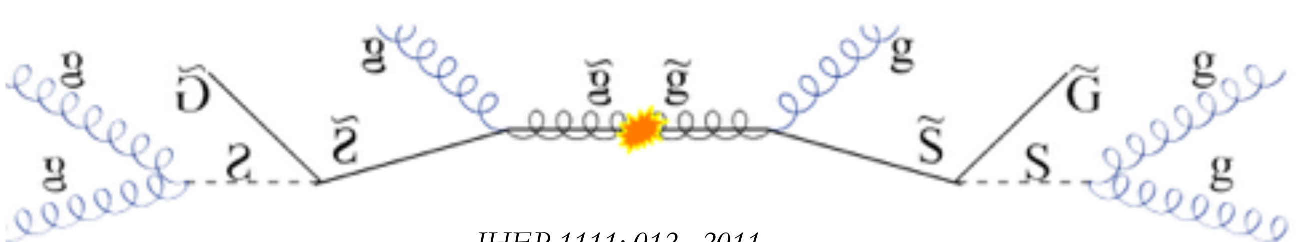
Two events $H \rightarrow \pi_v \pi_v$ with different signatures of decay to hadronic jets. Left: π_v decaying in the inner detector (A). Right: a π_v decaying in the hadronic calorimeter (B) and a second π_v in the muon spectrometer (C).

HV scalar boson (100-900 GeV mass range explored)



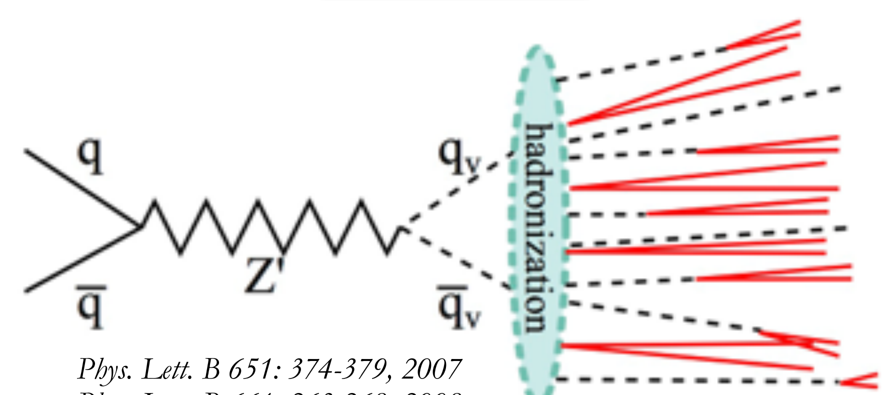
Phys. Lett. B 651: 374-379, 2007
Phys. Lett. B 661: 263-268, 2008
arXiv:hep-ph/0607160

Stealth SUSY



JHEP 1111: 012 , 2011
JHEP 1207: 196, 2012

Z' decay



Phys. Lett. B 651: 374-379, 2007
Phys. Lett. B 661: 263-268, 2008
arXiv:hep-ph/0607160

The CalRatio analysis

Analysis published: arxiv:1501.04020 (submitted to PLB).

Italian Groups involved in the analysis:

- Universita' della Calabria and INFN:
  A. Mastroberardino, D.Salvatore, G. Susinno
- INFN Roma: M. Verducci

The collaboration includes members of the University of Washington (USA)

Scalar boson Φ decays to a pair of neutral, long lived scalars or pseudo-scalars (π_v) which in turn decay to fermion pairs

- several combinations of Φ and π_v masses have been explored

Φ Mass [GeV]	π_v Mass [GeV]
100	10, 25
126	10, 25, 40
140	10, 20, 40
300	50
600	50, 150
900	50, 150

Look for decays in the Hadronic Calorimeter (HCal) – A pair of jets with:

- A narrow radius
- No ID tracks pointing towards the jet
- A large energy deposit in the HCal with little to no energy in the Electromagnetic Calorimeter (ECal)

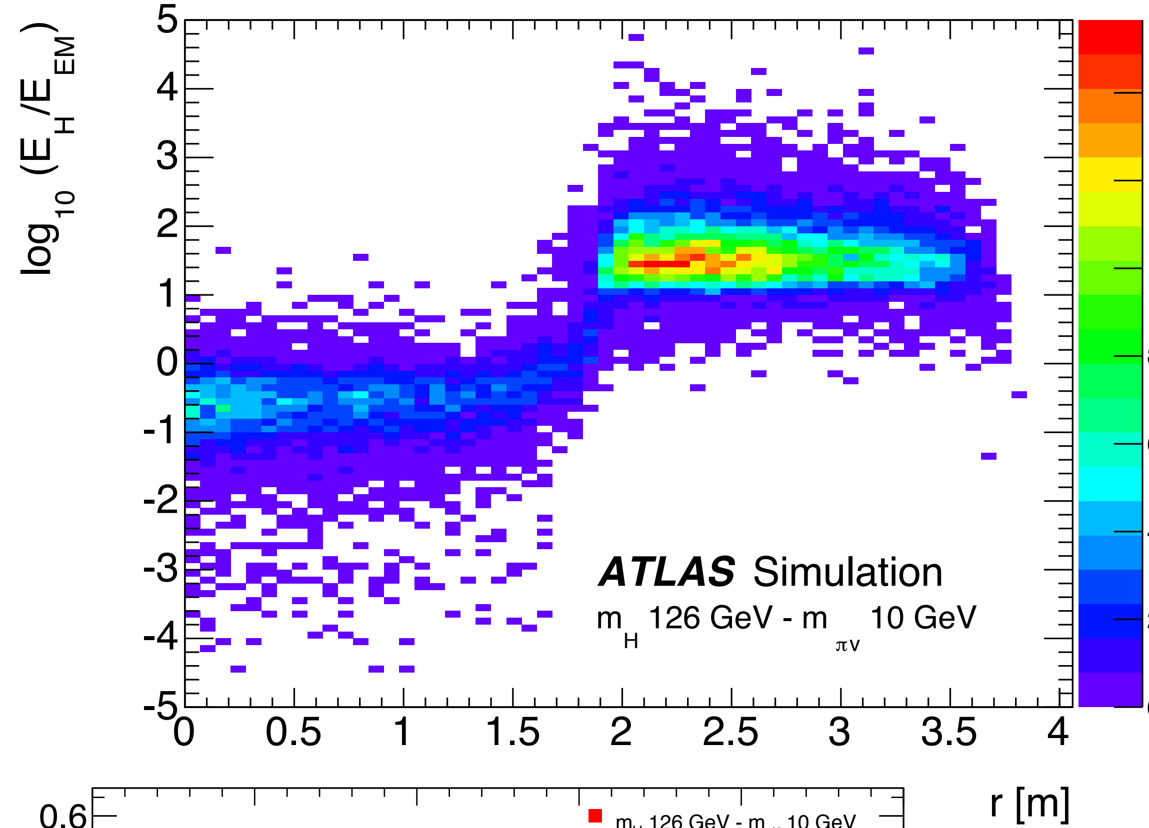
Primary background from SM multijets

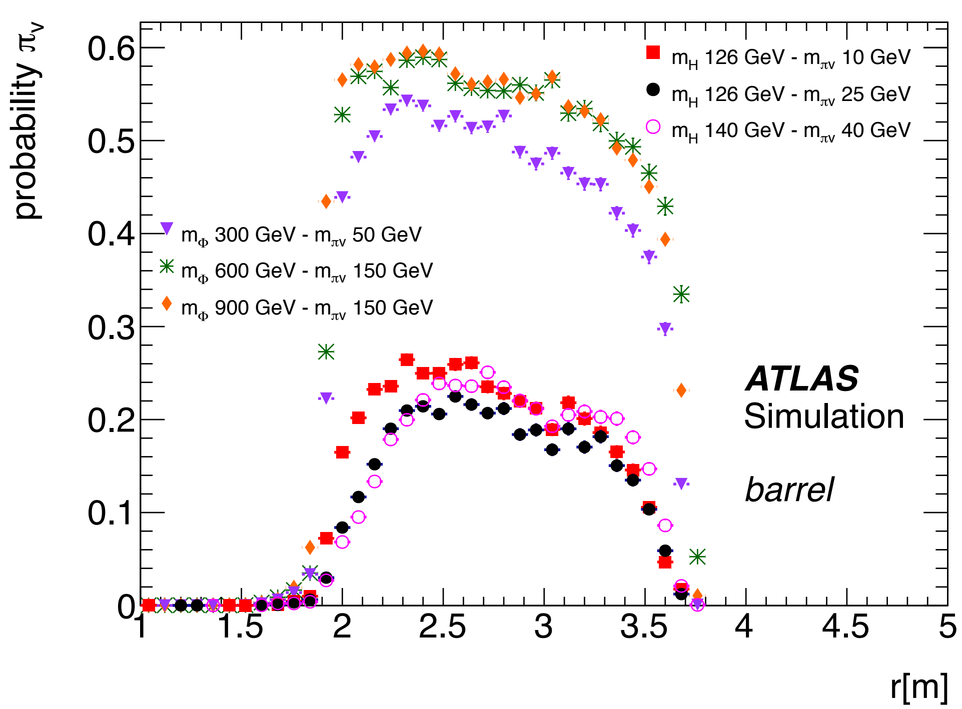
- Small contribution from cosmic ray and beam halo events

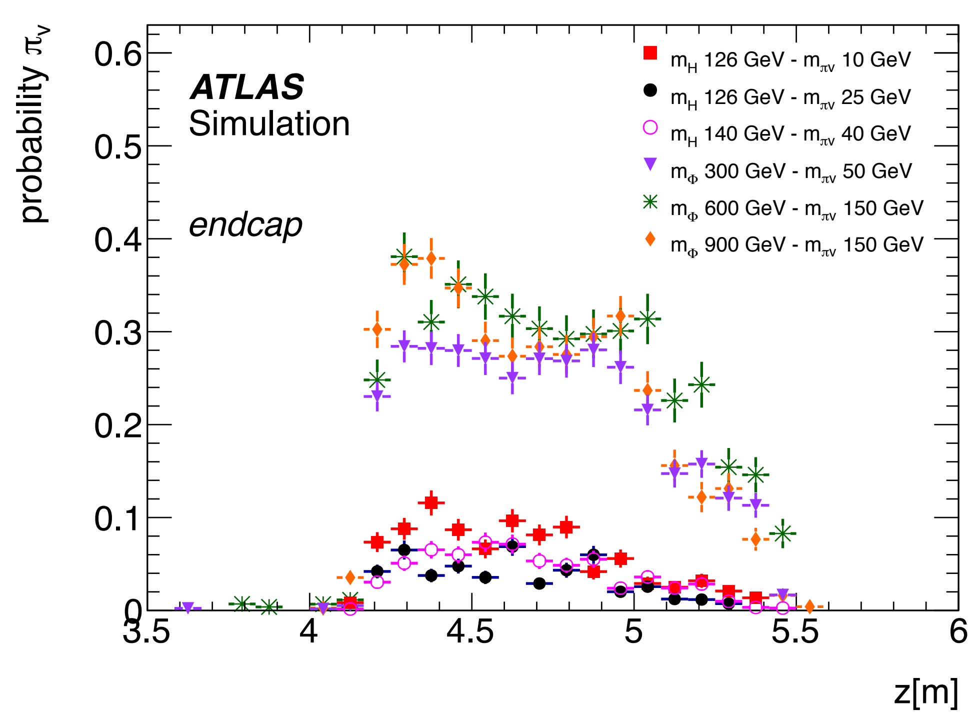
CalRatio trigger

Dedicated CalRatio trigger to select at least one jet (π_V) in the HCal (JINST 8 (2013) P07015):

- $\log_{10}(E_{Had}/E_{Em}) > 1.2$
- |eta| < 2.5
- no ID tracks with p_T > 1 GeV in ΔR=0.2
- E_T > 35 GeV
- Line of Fire jets removal: fake jets by beam-halo muon emitting bremmstrahlung radiation in the HCal





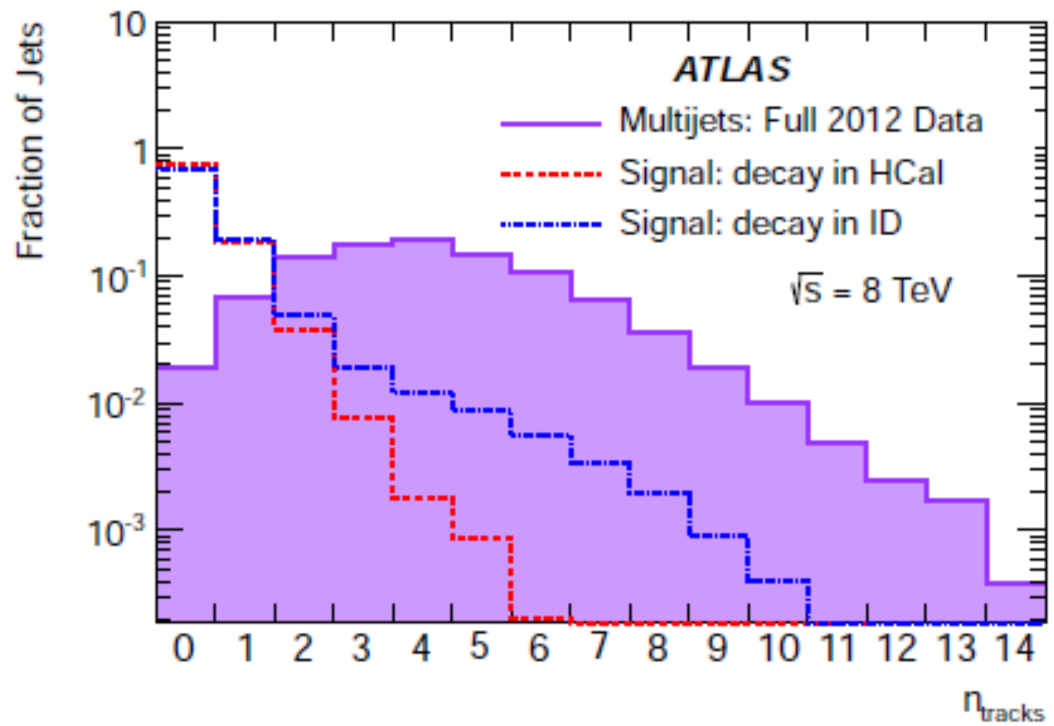


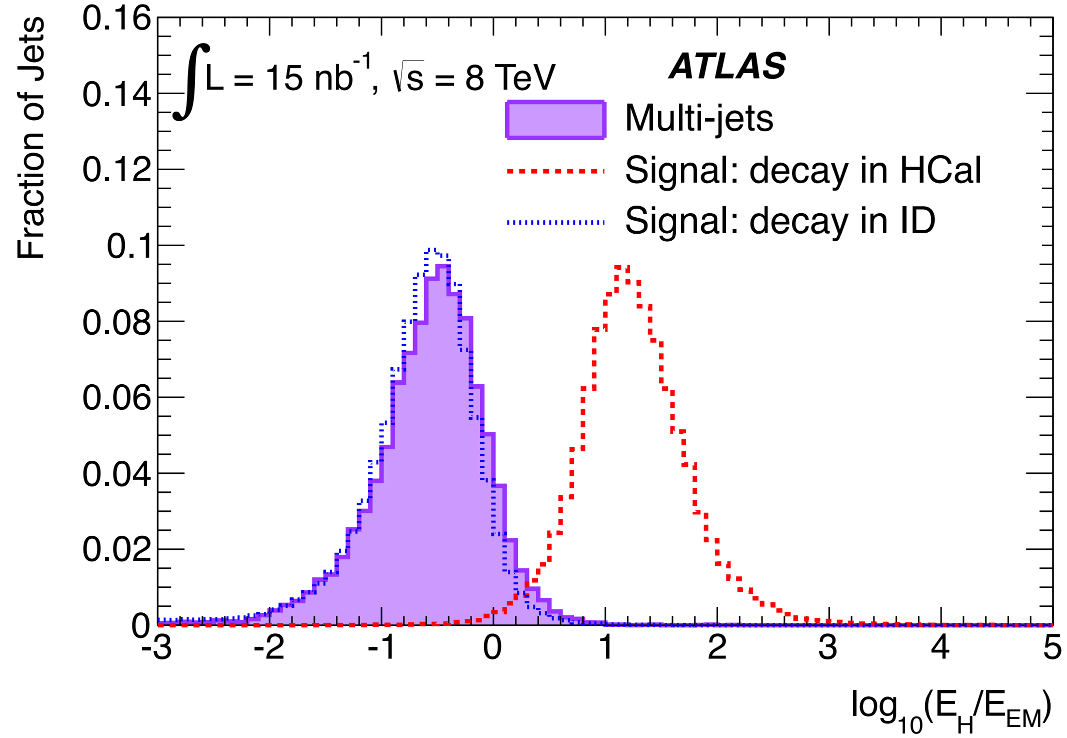
CalRatio analysis cut flow

Considering all ϕ and π_v masses

The same cut-flow has been applied to all the signal samples. Requiring two jets passing all analysis cuts

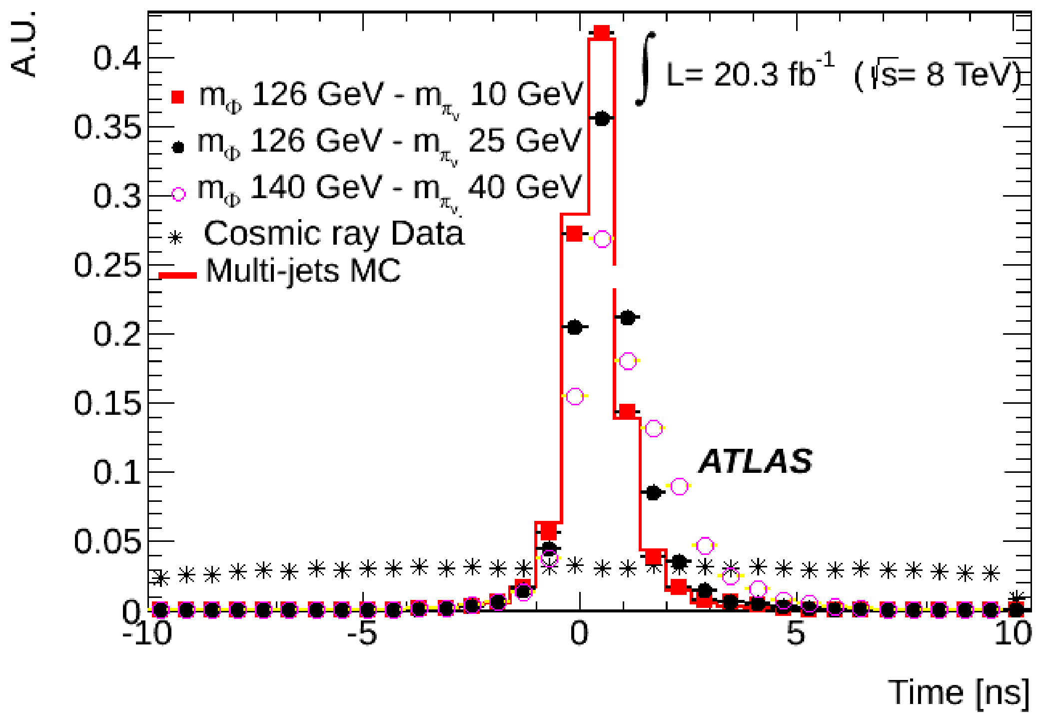
A. Event Level Cuts
B. Event triggered by dedicated CalRatio trigger
C. Data Quality criteria
D. Missing Energy (E_T^{miss}) <50 GeV
E. Require two jets passing:
   1. log10 (Eh/Eem) >1.2
   2. no tracks p_T> 1.0 GeV in a 0.2 cone around the jet
   3. |eta| <2.5 and -1 ns <t< 5 ns
   4. One of the two jets must have fired the trigger and satisfy E_T>60 GeV the other must have E_T >40 GeV





CalRatio background modelling

Three sources of background considered:

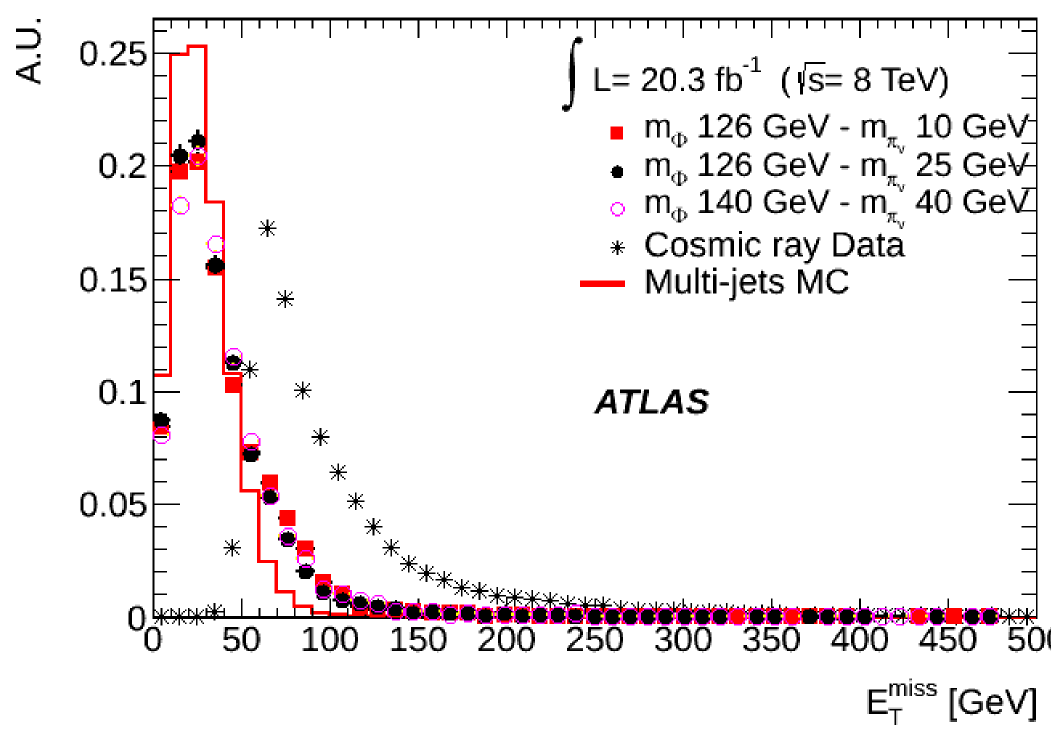


SM multijet events

- Dominant background
- Studied with a tag-and-probe method on an independently triggered dataset

Cosmic ray events

- Small contribution
- Reduced by cuts on ET miss and jet timing



Beam halo events

- Very small
- Reduced by same cuts as in cosmic ray events as well as by dedicated trigger and analysis DQ cuts

CalRatio systematics

Dominant systematic uncertainty comes from the Higgs cross-section

Pile-up and trigger uncertainty evaluated using a direct data vs MC comparison with multijet samples for relevant variables

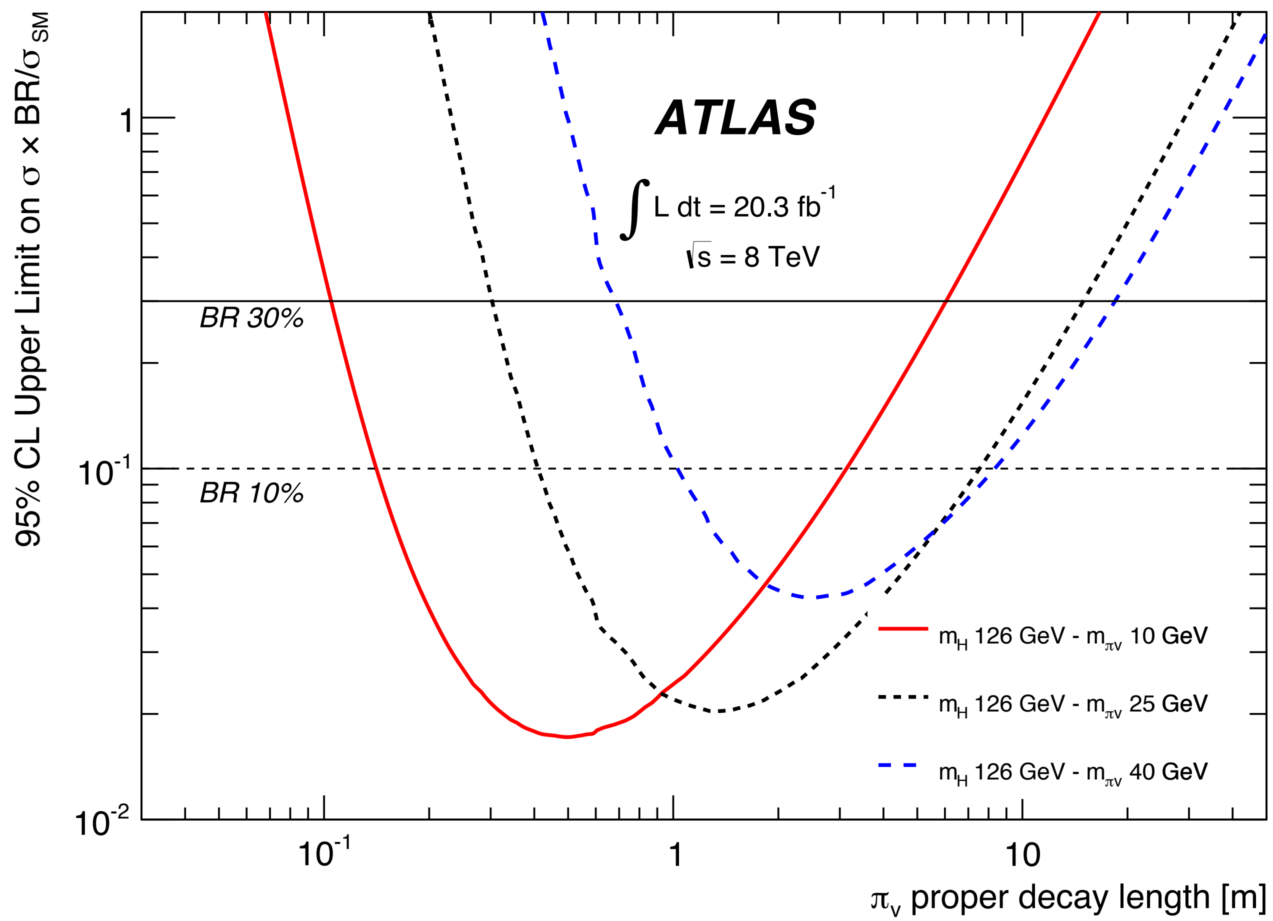
JES uncertainty calculated as a function of EMF and η for low EMF jets by comparing balance in data and MC

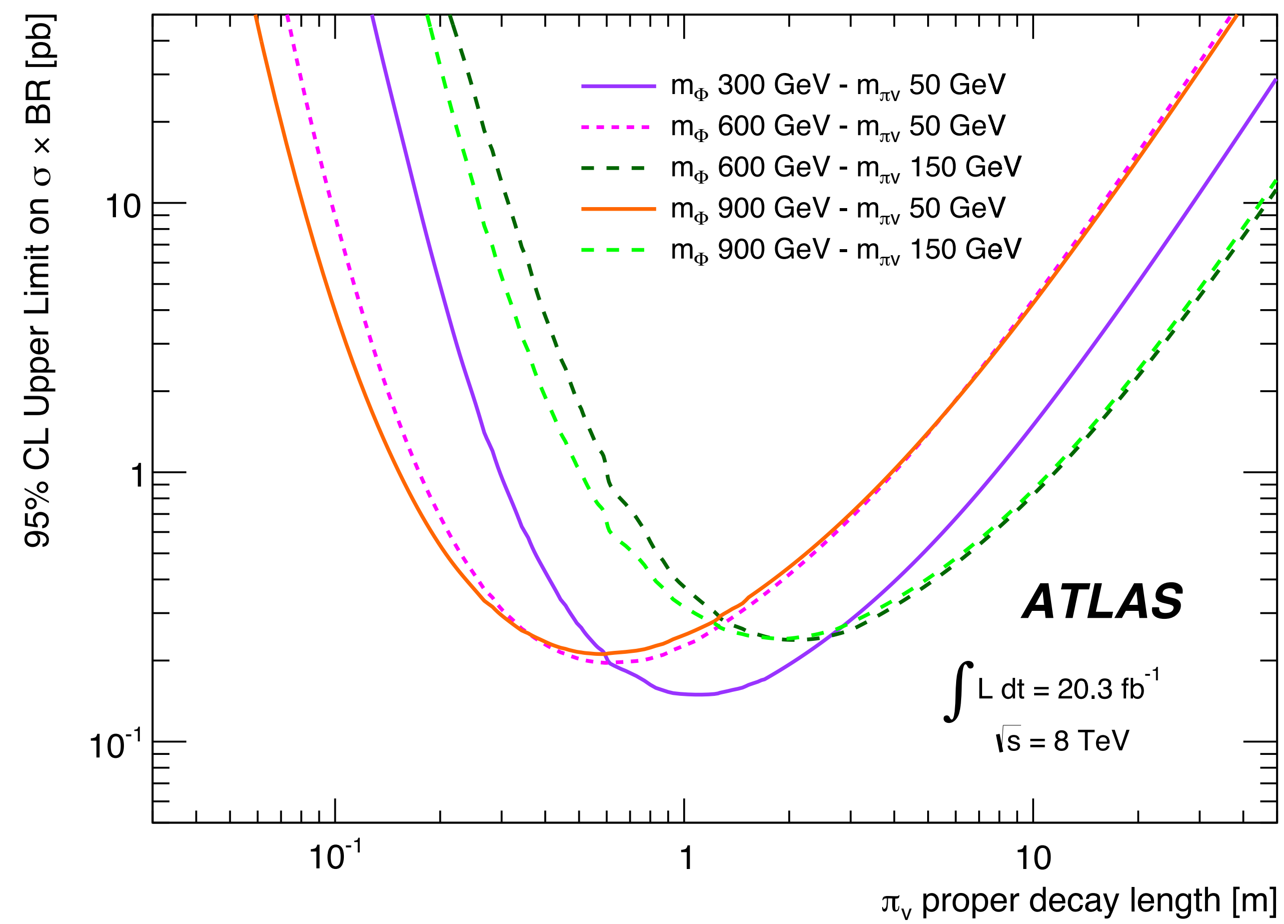
(*) Systematic errors that have common values across samples are not listed (Pile-up at 10%, ISR at (+2.9, -1.2)%, and PDF at 2.1%). The last column reports the overall systematic uncertainty (including the luminosity and common systematic errors).

Sample m_H, m_{π_v} [GeV]	H σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
126, 10	$^{+10.4}_{-10.4}$	$^{+2.2}_{-2.7}$	±1.1	$^{+5.5}_{-2.4}$	$^{+1.6}_{-6.6}$	$^{+16.4}_{-16.7}$
126, 25	$^{+10.4}_{-10.4}$	$^{+1.5}_{-1.6}$	±1.3	$^{+3.1}_{-1.8}$	$^{+0.8}_{-3.3}$	$^{+15.6}_{-15.5}$
126, 40	$^{+10.4}_{-10.4}$	$^{+2.6}_{-6.2}$	±1.1	$^{+7.7}_{-4.6}$	$^{+1.9}_{-5.9}$	$^{+18.2}_{-16.9}$

Sample m_Φ, m_{π_v} [GeV]	Φ σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
100, 10	$^{+11.1}_{-10.6}$	$^{+2.3}_{-4.0}$	±0.1	$^{+4.6}_{-3.4}$	$^{+2.7}_{-9.5}$	$^{+16.7}_{-18.5}$
100, 25	$^{+11.1}_{-10.6}$	$^{+5.5}_{-3.7}$	±1.2	$^{+3.4}_{-2.5}$	$^{+1.7}_{-0.7}$	$^{+17.0}_{-15.8}$
140, 10	$^{+10.1}_{-10.3}$	$^{+0.6}_{-1.1}$	±0.5	$^{+4.0}_{-5.6}$	$^{+1.9}_{-6.6}$	$^{+15.6}_{-17.2}$
140, 20	$^{+10.1}_{-10.3}$	$^{+1.2}_{-1.6}$	±1.0	$^{+4.0}_{-3.9}$	$^{+0.4}_{-5.0}$	$^{+15.5}_{-16.2}$
140, 40	$^{+10.1}_{-10.3}$	$^{+1.3}_{-1.6}$	±1.5	$^{+6.3}_{-4.6}$	$^{+1.8}_{-2.4}$	$^{+16.5}_{-15.8}$
300, 50	$^{+9.6}_{-10.0}$	$^{+0.1}_{-0.3}$	±0.3	$^{+9.0}_{-7.4}$	$^{+0.5}_{-3.0}$	$^{+13.9}_{-13.3}$
600, 50	$^{+11.2}_{-10.1}$	$^{+0.0}_{-0.1}$	±0.2	$^{+11.7}_{-11.3}$	$^{+2.2}_{-4.4}$	$^{+17.0}_{-16.2}$
600, 150	$^{+11.2}_{-10.1}$	$^{+0.2}_{-0.2}$	±0.3	$^{+11.5}_{-10.2}$	$^{+2.7}_{-5.3}$	$^{+17.5}_{-15.1}$
900, 50	$^{+12.8}_{-11.5}$	$^{+0.0}_{-0.1}$	±0.1	$^{+12.6}_{-9.7}$	$^{+1.0}_{-3.7}$	$^{+18.5}_{-15.9}$
900, 150	$^{+12.8}_{-11.5}$	$^{+0.2}_{-0.3}$	±0.2	$^{+11.8}_{-10.9}$	$^{+0.9}_{-2.5}$	$^{+18.1}_{-16.3}$

CalRatio results





MC sample m_H, m_{π_v} [GeV]	Excluded range 30% BR $H \rightarrow \pi_v\pi_v$ [m]	Excluded range 10% BR $H \rightarrow \pi_v\pi_v$ [m]
126, 10	0.10 – 6.08	0.14 – 3.13
126, 25	0.30 – 14.99	0.41 – 7.57
126, 40	0.68 – 18.50	1.03 – 8.32

The MS-ID analysis

Paper draft under revision with the Editorial Board.

Involved groups:

- University of Washington, Seattle, USA,
- University of Massachusetts, Amherst, USA
- University and INFN of Tor Vergata, Rome, Italy (R. Iuppa)

- Simply looking for a pair of Displaced Vertices (DV) in the MS, ID or one in each.
- Benchmark models:
  - Scalar boson Φ decays to a pair of neutral, long lived scalars or pseudo-scalars (π_v) which in turn decay to fermion pairs (several combinations of Φ and π_v mass have been explored). Z' decaying in many π_v
  - Search for two displaced vertices in the MS, ID or one in each.
  - Stealth SUSY with gluing decaying into long lived singlino.
- Dedicated triggers needed (Muon RoI for MS and jet + E_T^{miss} for ID)
- Standalone vertex reconstruction in the MS, as well as in the ID
- Challenging estimation of backgrounds: difficult choice and handling of control regions

Table I. The five different topologies considered in the analysis and the corresponding analysis channels and benchmark samples.

Channel	Applicable topologies	Benchmarks
Muon Cluster	IDVx+MSVx, 2MSVx	Scalar boson Stealth SUSY
Jet+E_T^{miss}	2IDVx, IDVx+MSVx, 2MSVx	Z'

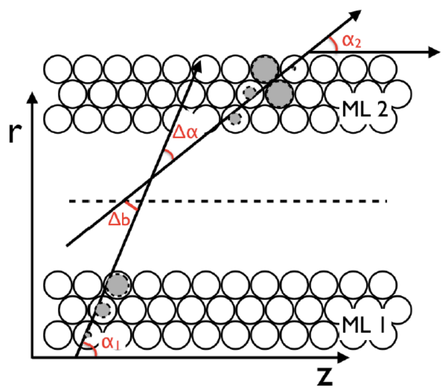
Table II. Mass parameters for the simulated scalar boson, Z' and Stealth SUSY models.

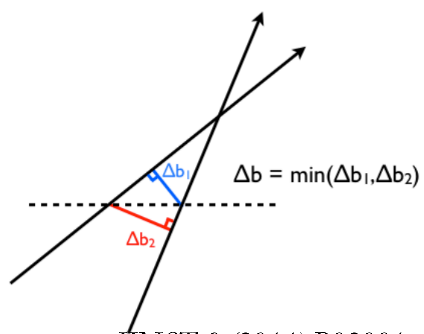
scalar boson mass [GeV]	π_v mass [GeV]
100	10, 25
125	10, 25, 40
140	10, 20, 40
300	50
600	50, 150
900	50, 150
Z' mass [TeV]	**π_v mass [GeV]**
1	50
2	50
2	120
$\tilde{g}$ mass [GeV]	**$\tilde{S}$, S mass [GeV]**
110	100, 90
250	100, 90
500	100, 90
800	100, 90
1200	100, 90

MS-ID vertexing and cut flow

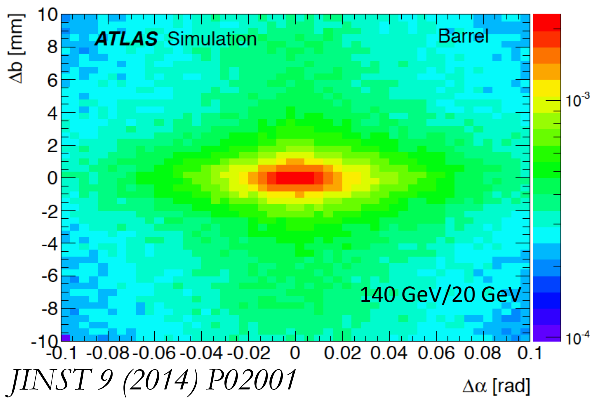
Search and reconstruction algorithm in the MS:

1. Construction of segments in single MultiLayers (ML), via chi2 minimisation, if P>0.05;
2. merging segments (ML1 and ML2) in tracklets on the basis of specific criteria on Δb and Δα (barrel and endcap).





JINST 9 (2014) P02001



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Search and reconstruction in the ID:

Tracking algorithm developed for use in a SUSY search for displaced vertices in the ID. The signatures studied in this analysis will produce many unassociated hits in the default tracking, because the larger impact parameters. Displaced tracks are reconstructed by making a second iteration of track finding using only unassociated hits, with loosened requirements on the track impact parameter and number of hits shared between tracks.

Table V. Summary of good MS vertex criteria requirements in barrel and endcap regions.

Description	Barrel criteria	Endcap criteria
MDT hits	$300 \leq n_{MDT} < 3000$	$300 \leq n_{MDT} < 3000$
RPC/TGC hits	$n_{RPC} \geq 250$	$n_{TGC} \geq 250$
Track isolation	$\Delta R < 0.3$	$\Delta R < 0.6$
Track Σp_T	$\Sigma p_T < 10$ GeV	$\Sigma p_T < 10$ GeV
Jet isolation	$\Delta R < 0.3$	$\Delta R < 0.6$

Table IV. Good vertex criteria for vertices reconstructed in the ID.

Requirement	Scalar boson	Stealth SUSY	Z'
d/σ from material	≥ 6	≥ 6	≥ 6
vertex χ^2 prob.	> 0.001	> 0.001	> 0.001
ΔR(vtx,jet)	< 0.4	< 0.4	< 0.6
nTracks	≥ 5	≥ 5	≥ 7

MS-ID trigger and vertexing efficiency

	MS BARREL	MS ENDCAP	ID

TRIGGER EFF.

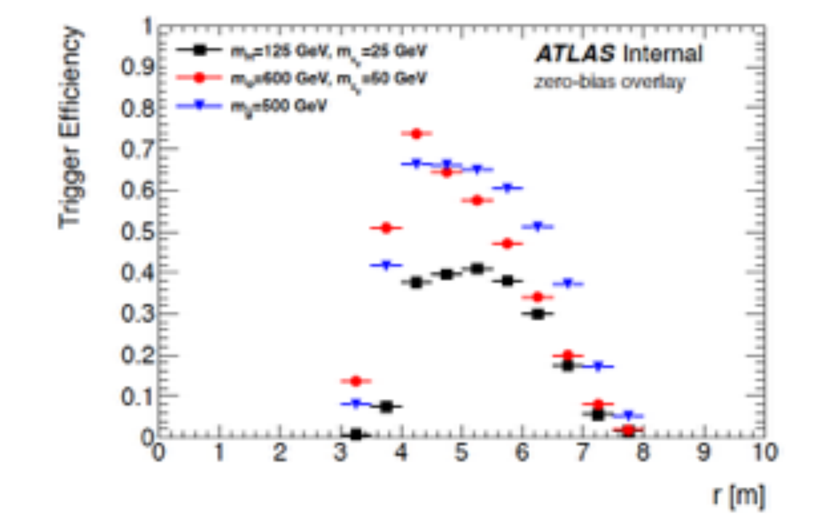


Figure 1. Efficiency for the Muon RoI Cluster trigger as a function of the long-lived particle's decay position for decays in the barrel.

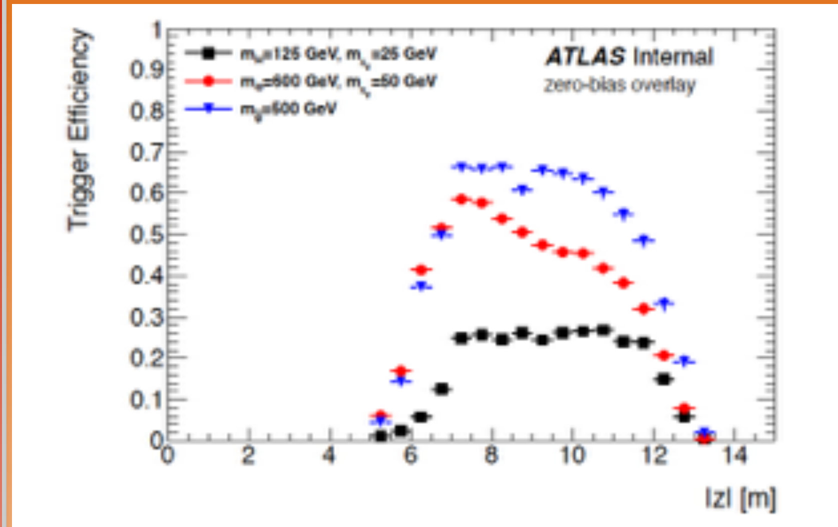


Figure 2. Efficiency for the Muon RoI Cluster trigger as a function of the long-lived particle's decay position for decays in the endcaps.

jet + ETmiss trigger practically 100% efficient

RECO EFF.

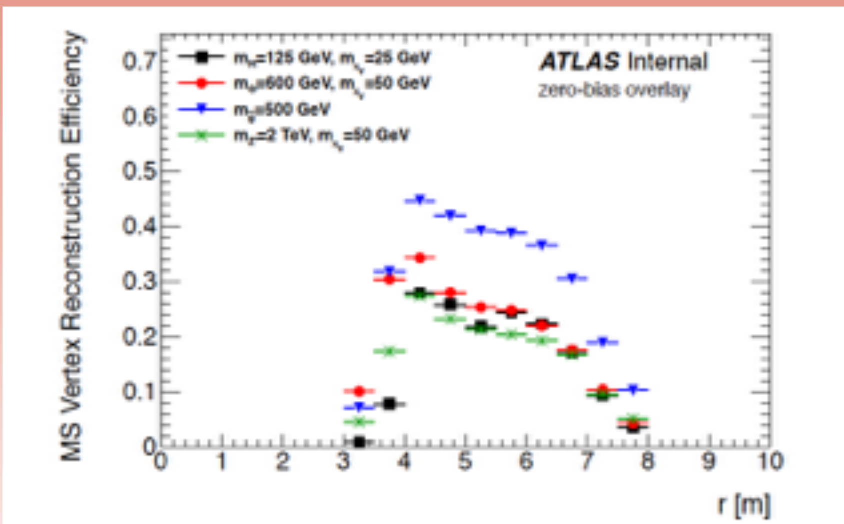


Figure 6. Efficiency for reconstructing a vertex in the MS barrel as a function of the radial position of the long-lived particle decay.

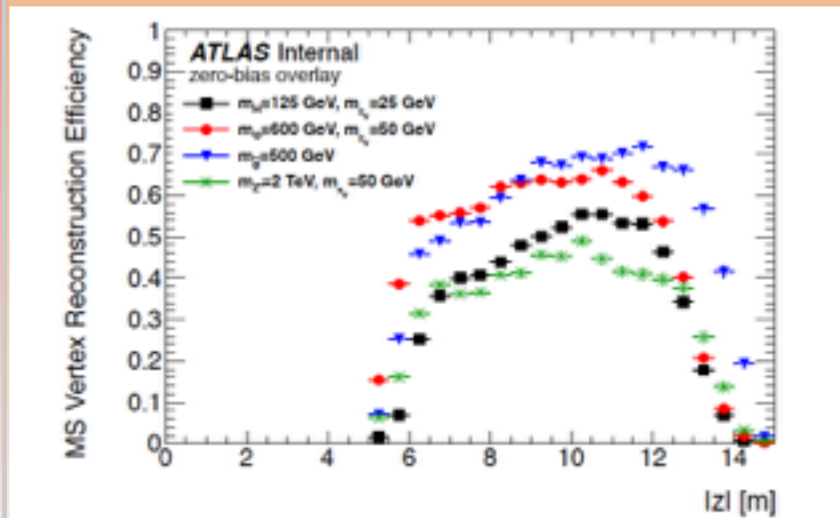


Figure 7. Efficiency for reconstructing a vertex in the MS endcaps as a function of the $|z|$ position of the long-lived particle's decay.

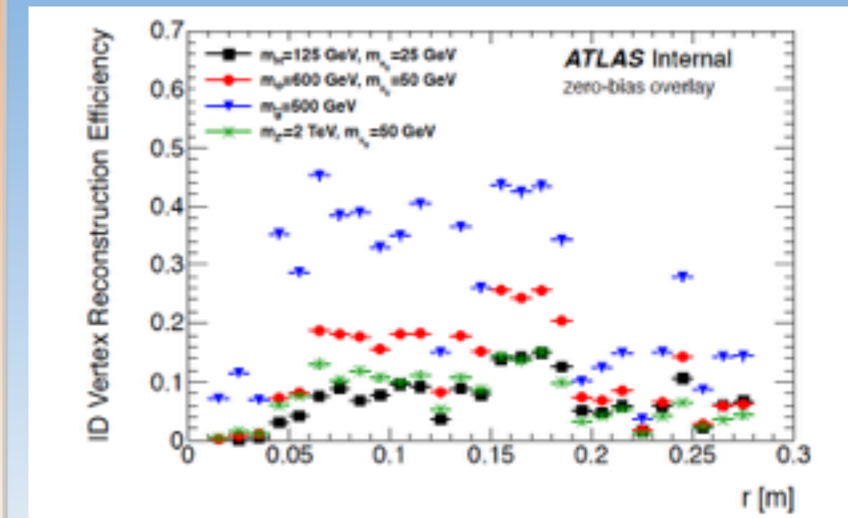


Figure 5. ID Vertex reconstruction efficiency for scalar boson, Stealth SUSY and Z' benchmark samples.

MS-ID systematics and expected background

Table VI. Summary of the systematic uncertainties on displaced vertex reconstruction efficiencies in the ID and MS.

m_Φ [GeV]	m_{π_v} [GeV]	IDVx	MSVx barrel	MSVx endcaps
100	10	2.7%	6.8%	11.2%
100	25	2.1%	6.4%	10.4%
125	10	2.5%	7.0%	9.9%
125	25	2.5%	6.8%	9.7%
125	40	2.4%	6.5%	8.0%
140	10	2.7%	7.0%	9.6%
140	20	2.7%	6.6%	9.6%
140	40	1.6%	6.6%	7.9%
300	50	2.7%	6.9%	6.3%
600	50	2.9%	6.8%	5.4%
600	150	3.1%	6.6%	4.0%
900	50	3.5%	6.6%	5.7%
900	150	3.0%	5.9%	3.8%

$m_{\tilde{g}}$ [GeV]	IDVx	MSVx barrel	MSVx endcaps
110	3.8%	5.6%	4.0%
250	2.3%	5.8%	3.8%
500	2.4%	6.3%	3.8%
800	2.7%	6.5%	3.5%
1200	1.5%	6.6%	3.8%

$m_{Z'}$ [TeV]	m_{π_v} [GeV]	IDVx	MSVx barrel	MSVx endcaps
1	50	2.5%	6.8%	6.3%
2	50	2.6%	7.0%	6.6%
2	120	2.2%	6.6%	5.2%

ID: Systematic uncertainty due to differences in track reconstruction in data and simulation was estimated by studying K_S^0 decays in multi-jet control samples.

MS: Systematic uncertainties due to data-simulation discrepancies were studied using jets that punch through the calorimeter and shower in the MS. Both for trigger and reconstruction.

JES, pileup, PDF and ISR considered.

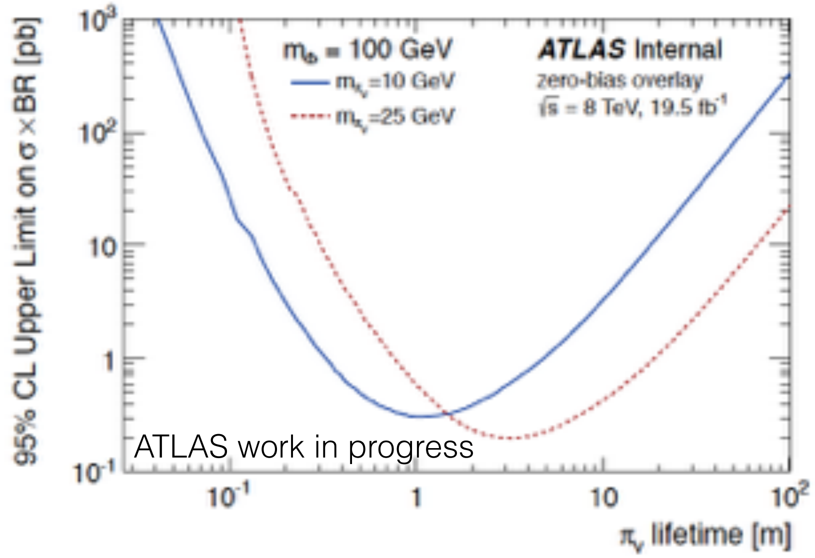
Other possible sources of systematic uncertainty are negligible compared to the uncertainty related to the vertex reconstruction.

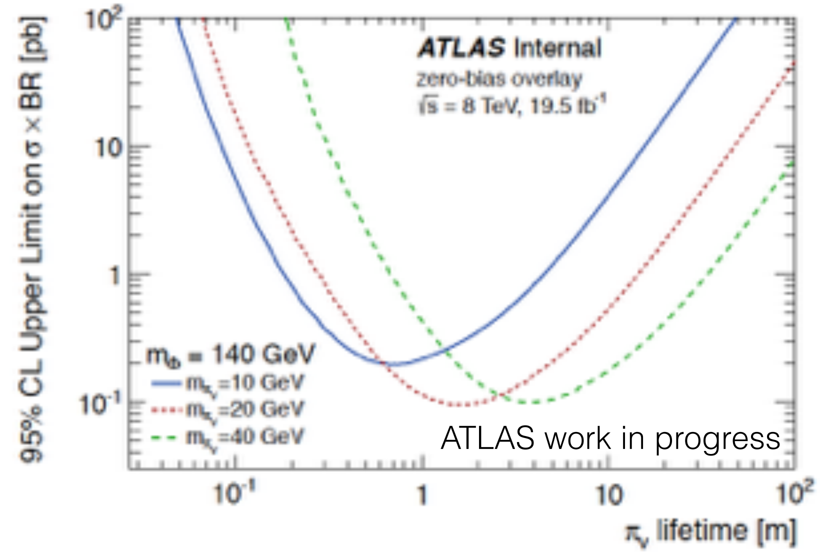
Background events

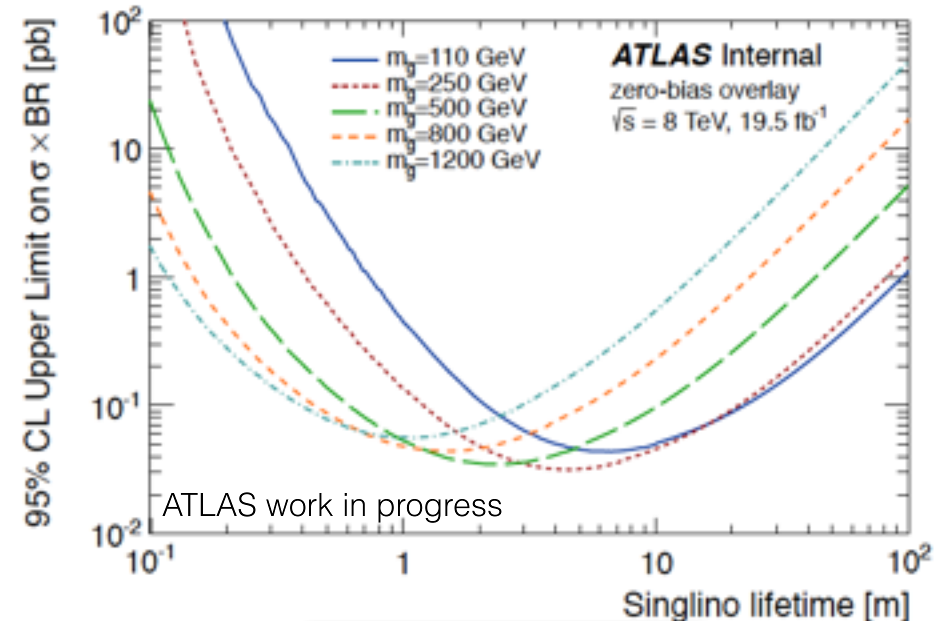
Table VIII. Number of events predicted for different final-state topologies.

Channel	Topology	Predicted
Jet+E_T^{miss}	2IDVx	$(1.8 \pm 0.4) \cdot 10^{-4}$
Jet+E_T^{miss}	IDVx+MSVx	$(5.5 \pm 0.9) \cdot 10^{-4}$
Jet+E_T^{miss}	2MSVx	$(0.0^{+1.4}_{-0.0}) \times 10^{-5}$
Muon Cluster	IDVx+MSVx	2.0 ± 0.4
Muon Cluster	2MSVx	$0.436^{+0.052}_{-0.002}$

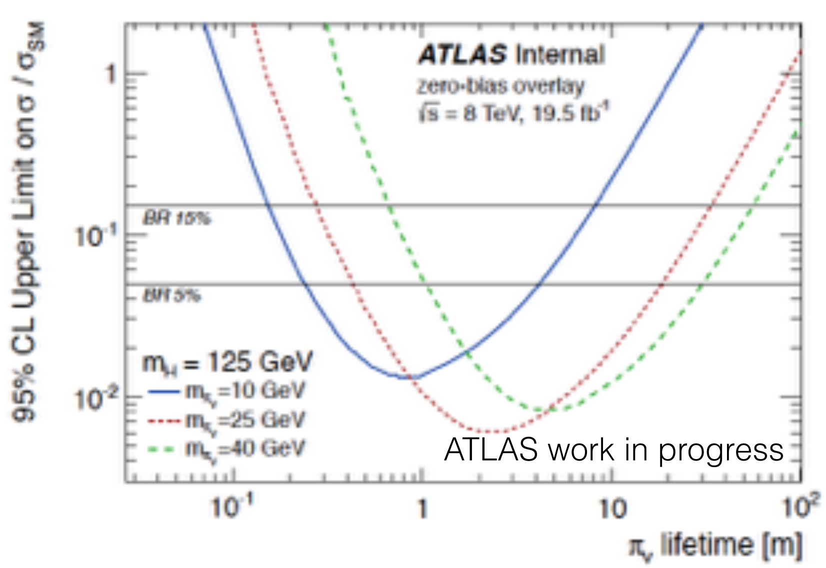
MS-ID results

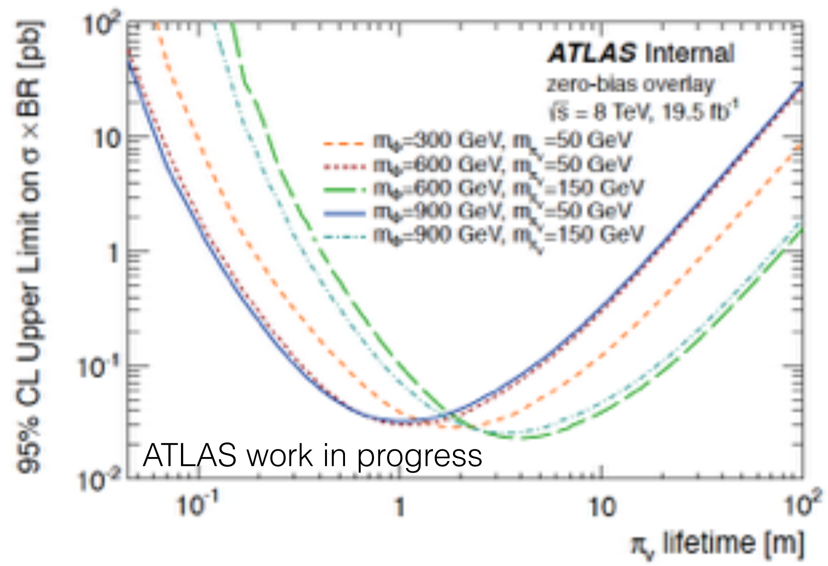






Stealth SUSY



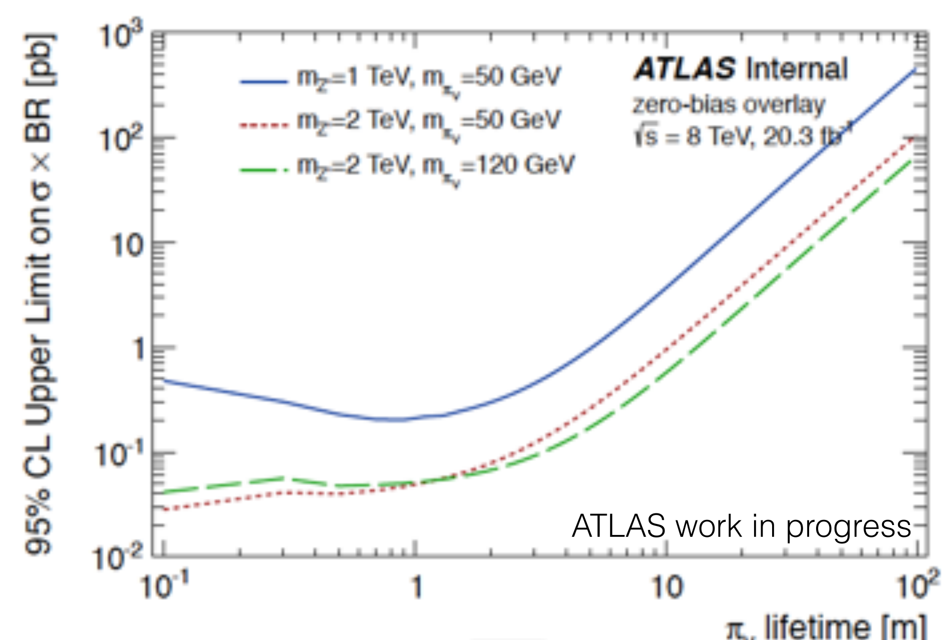


Hidden Valley scalar boson

Table X. Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30%, 15%, or 5% BR for $m_H = 125$ GeV.

m_H [GeV]	m_{π_v} [GeV]	Excluded range [m]		
		5% BR	15% BR	30 % BR
125	10	0.24–4.2	0.16–8.1	0.12–11.8
125	25	0.43–18.6	0.28–33.6	0.21–47.7
125	40	1.02–30.6	0.63–56.0	0.52–79.5

Most stringent limits to-date



Z’

Lessons from Run1

Theories and models:

Incorporating many models can well be complicated, but also reveal the limitations of the analysis (e.g., MC only lists out a maximum of 12 Muon RoIs per event, not an issue for low-mass samples but a problem for higher masses)

Selection cuts:

- Be careful about how internal cuts in algorithms can shape the analysis
- Selection cuts are simple to add, but they make the analysis more model and signature dependent.

Background:

- Estimation of Background can be complicated, e.g.:
  - QCD background: a novel method of calculating the background was developed which relied on determining the probability that a single jet would pass the analysis cuts…BUT, development and implementation of the method were time consuming at every stage including the review
  - Beam Halo was suppressed too well! The background prediction was 0, but the uncertainty was enormous due to the scaling from unpaired iso to collision BCs!
- Standard prescriptions for MC production might not provide all the backgrounds you need (MS-ID suggestion use zero-bias rather than minimum bias overlay).
- Background estimations work better when you have access to a solid control region.

Collaboration:

- Collaborate properly with other groups doing similar analyses: share methods, MC samples and challenges.
- Have a better grasp of the cover (and limitations) of the analysis (e.g.: SUSY DV+jet more sensitive than IDvx+IDvx).
- Develop analyses like you're sharing them with the entire collaboration (make the code modular, readable and usable).

Run2 perspective

H.I.P.

- With IBL, in Run2 we can measure the Pixel dE/dx with 4 points (discrimination power increased, area ionization detectable).
- Running the analysis on xAOD we save for each track dE/dx, good cluster number, IBL in overflow.
- The use of tracklets (p_T>5 GeV, pixelHits>=4, no request on SCT) will increase the lifetime acceptance and lower needs for timing and CPU (not yet established whether include them in xAOD or not).
- New Pixel dE/dx, including IBL, now in Release 20, being validated by Tracking group.
- Few fb should be sufficient to improve the present results.

CalRatio

- Novel methods of background prediction can be extremely time consuming and alternatives should be considered early on.
- A variety of new cuts should be investigated, not just those expected to give a high signal-to- background ratio, to allow for easier calculation of the background and for model-independence or multiple signatures.
- Consider how the signature would evolve with increasing proper lifetime (or whatever parameter you are concerned with).

MS+ID

- try and add a (heavily prescaled) trigger to select events with lots MS activity that fail a jet veto (background estimation)
- migrating the old analysis code to be xAOD compatible (MSvertex default in standard reconstruction). Add new features.
- find better options for the IDvx background
- anticipate needs for background/control-regions before data-taking

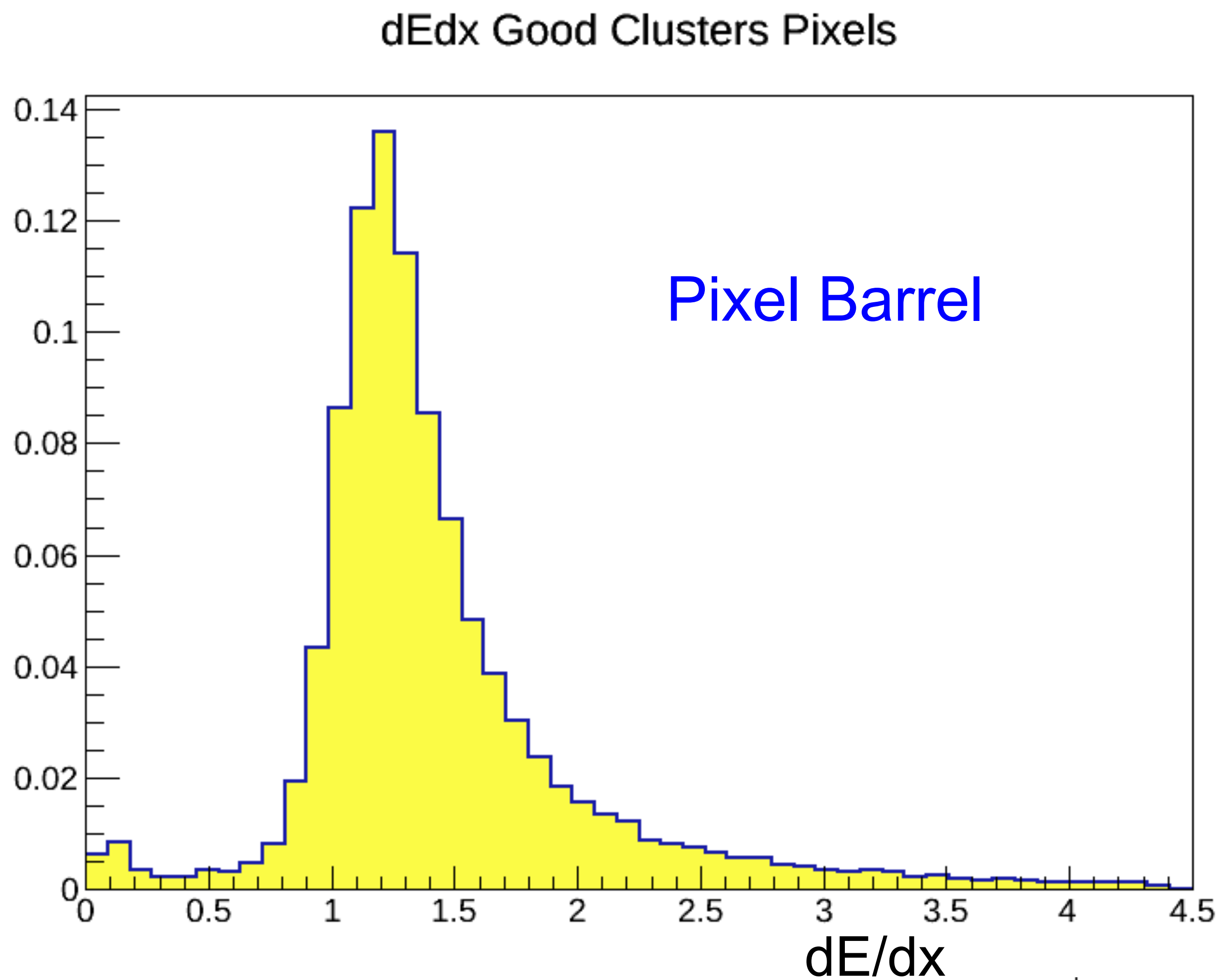
FIND LLP :D

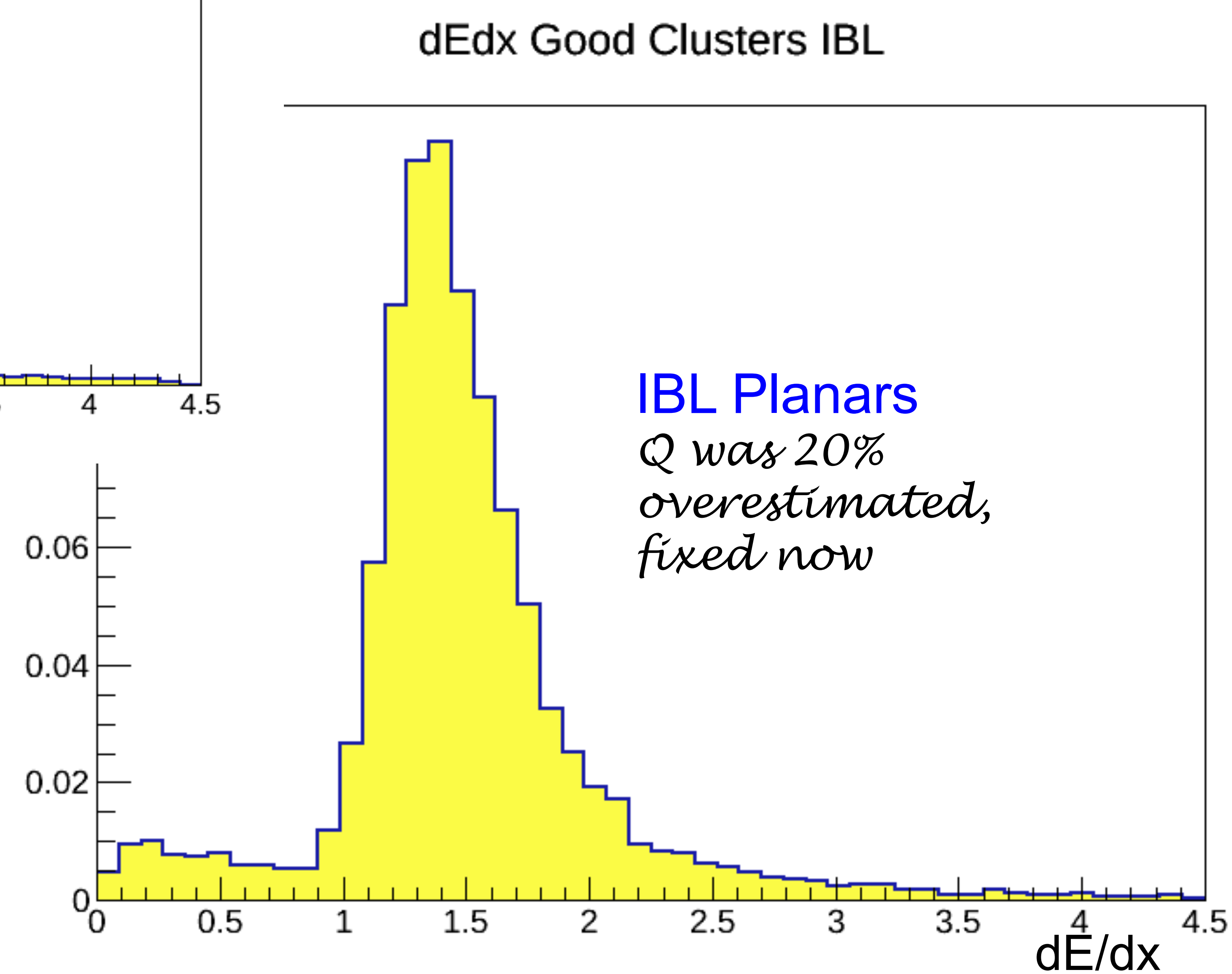
Summary

- Italian groups are deeply involved in searches for Long Lived Particles at LHC with the ATLAS detector.
- The Run1 dataset has been explored looking for Highly Ionising Particles and Displaced Vertices. No indication of New Physics was found and the results have just been or are going to be published.
- The experience of Run1 is the basis for important improvements of the analysis, in terms of approaches, methods and tools.
- All groups contributing to the H.I.P/D.V. Run1 analyses are already at work on the Run2 challenge.

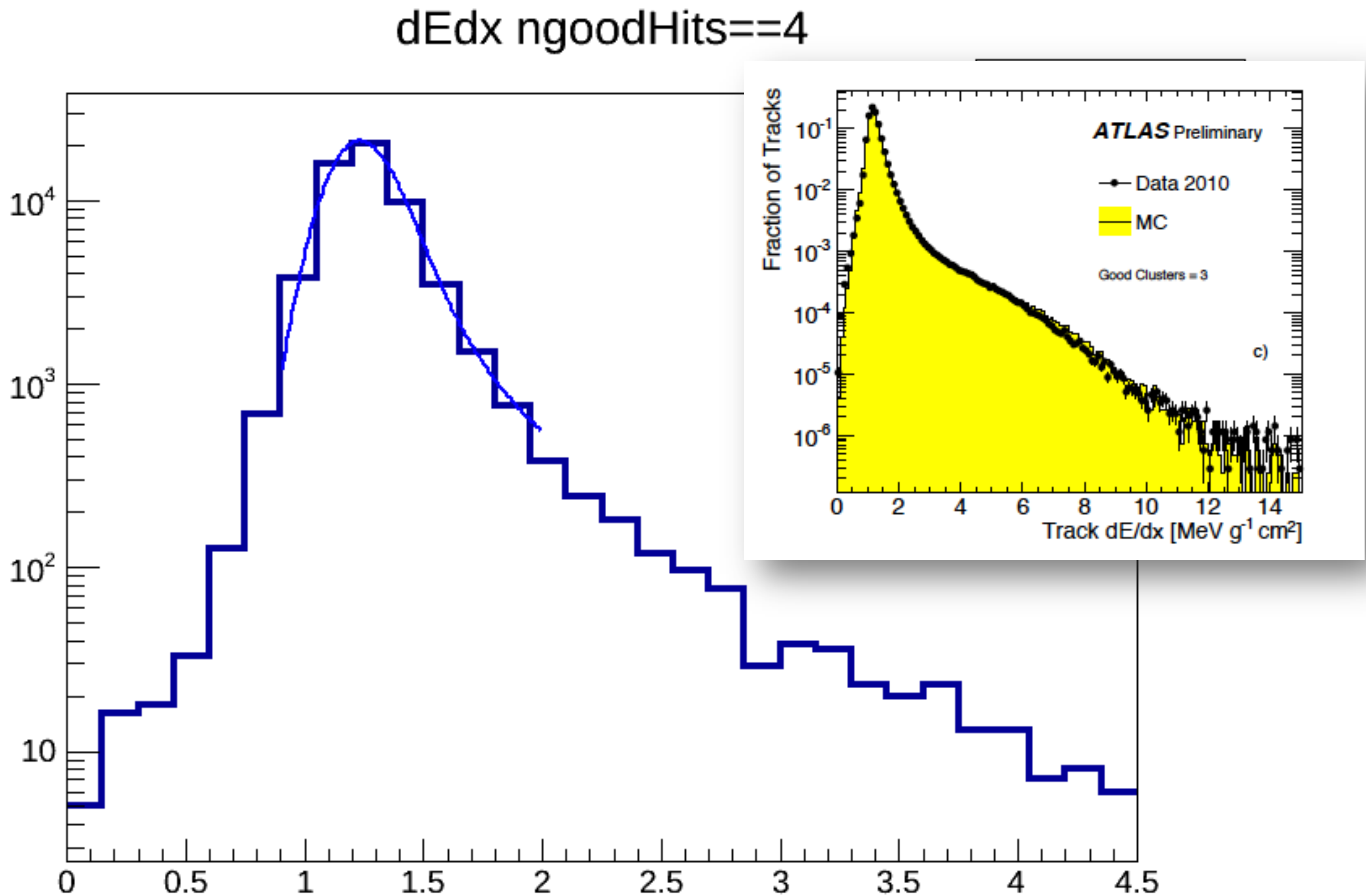
Backup

Good clusters dE/dx – Maybe spare

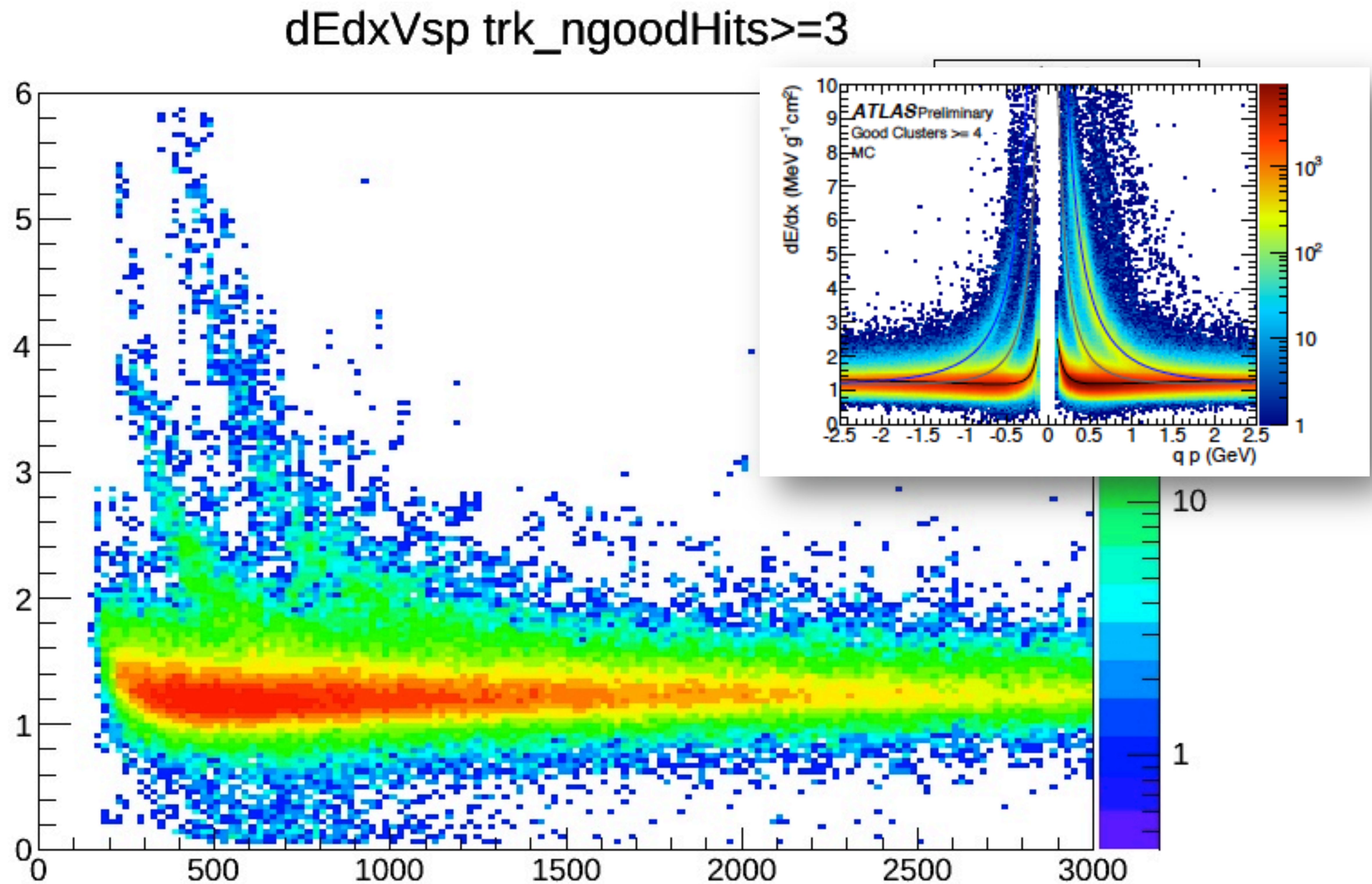




Track dE/dx with IBL – Maybe spare



Track dE/dx with IBL



Selection -Spare

- **Strategy:** search for high-p_T, isolated particles with high ionization. For metastable search, also requiring that candidate is not a muon.
- Event Selection
  - GRL
  - Confirmation of Missing energy (>100 GeV)
  - PV and event cleaning
- Candidate track
  - High pT (>80 GeV)
  - Primary with at least 3 pix hits and 6 SCT hits
  - Isolated in a cone 0.25
  - No electron matching
  - Large momentum (p>150 GeV)
  - Large Transverse mass > 130 GeV
  - Large ionization (>1.8 MeV/g cm-2)
  - (no Muon matching for metastable searches)

Line of Fire Selection: ATL-COM-PHYS-2011-844

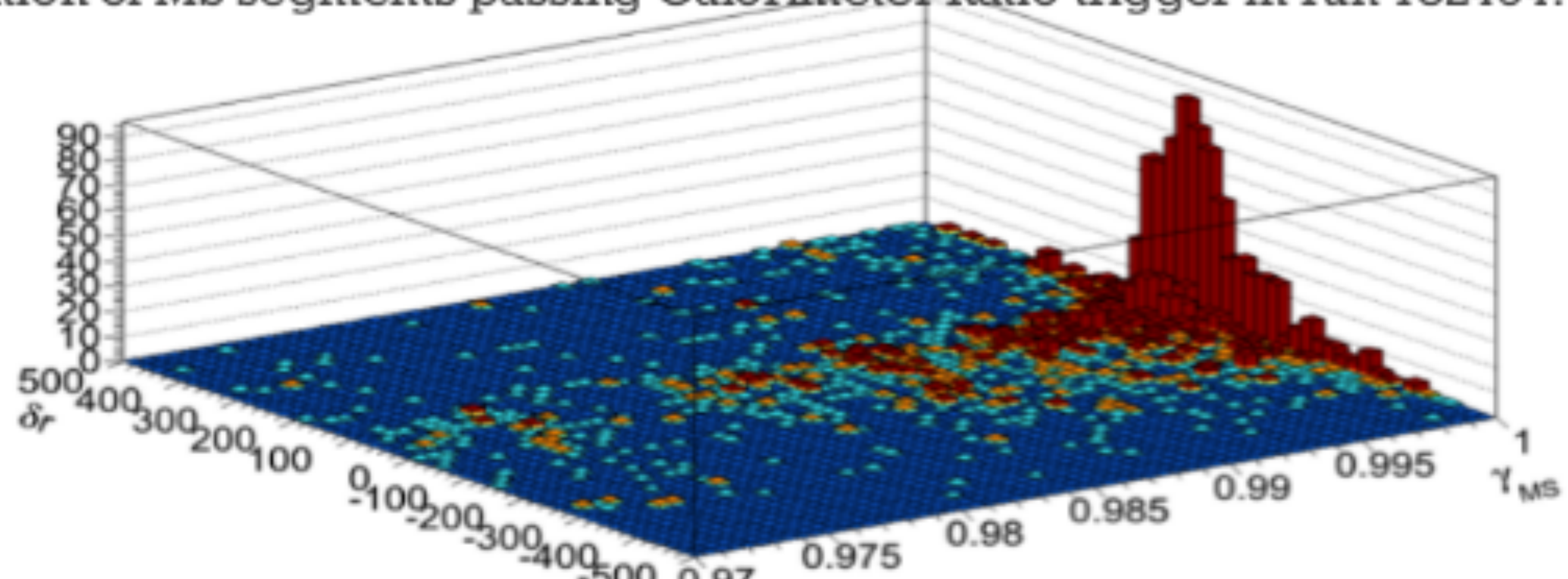
+ Off-line selection criteria, continued.

Uses 3 parameters of MS segments:

- $\delta\phi$, the difference in phi between the trigger jet and Moore segment.
- $\gamma_{MS} = p_{\hat{Moore}} \cdot \hat{z} / |p_{Moore}|$, the directional cosine between the Moore segment and z-axis.
- δr, the difference between the radius of the leading HEC cell in the jet and CSC segment.

	Criteria
End-cap	
	1 MS segment with: $\lvert\delta r\rvert < 120$ mm, $\lvert\delta\phi\rvert < 0.2$, $\lvert\gamma_{MS}\rvert > 0.98$.

Distribution of MS segments passing Calorimeter Ratio trigger in run 182454.



ATL-COM-PHYS-2011-844

Line of Fire Selection: ATL-COM-PHYS-2011-844.

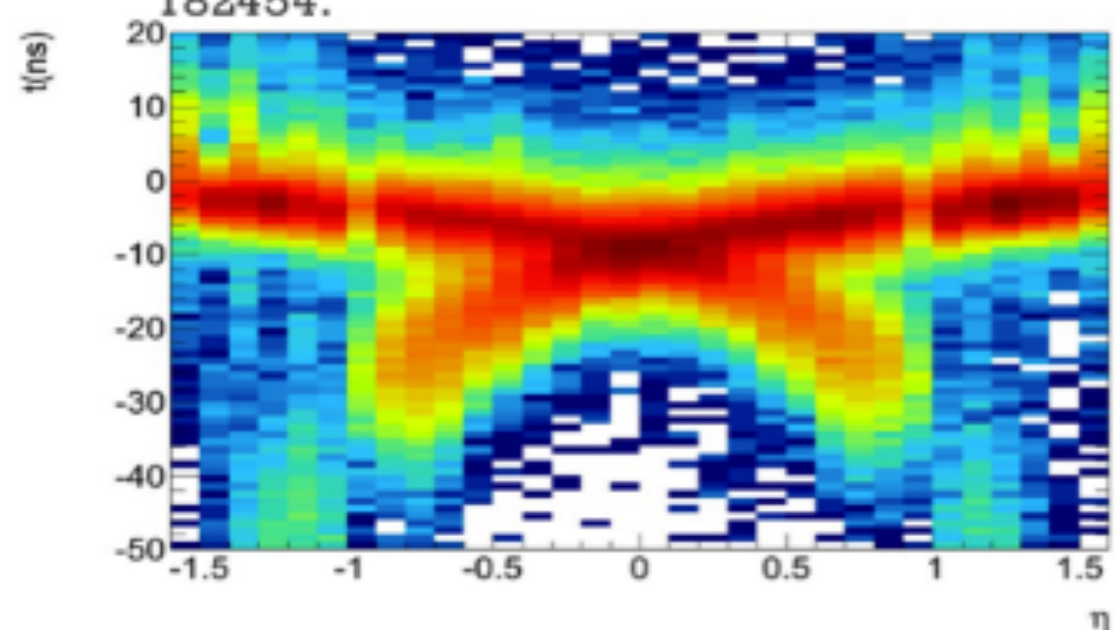
+ On-line selection criteria, continued.

Uses 6 parameters of HCAL cells:

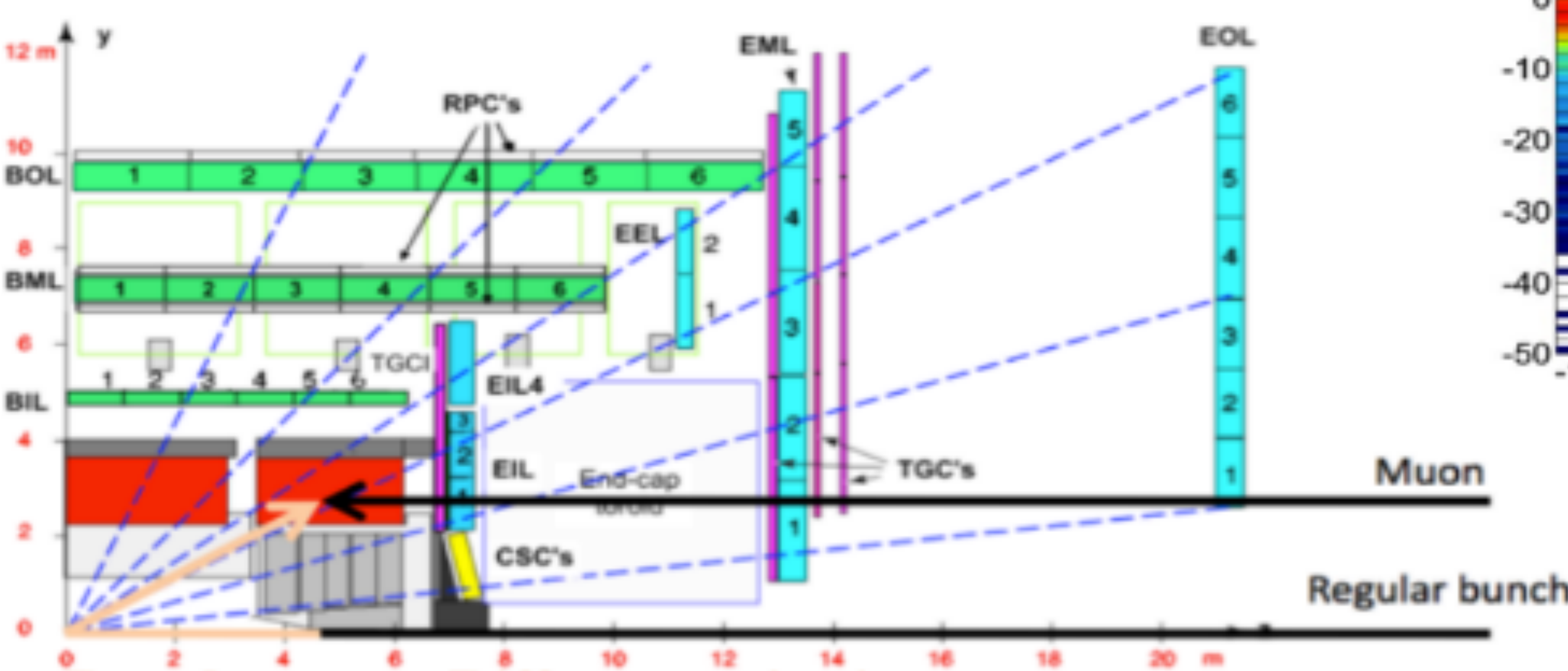
Criteria	
≥ 3 cells in the HCAL such that:	$\lvert\delta\phi\rvert < .2$, $E > 240$ MeV, each lie outside of the triggering jet cone of ΔR of .3, $t < 2.0$ ns, $\lvert t - \delta t\rvert < 5.0$ ns, where $\delta t = \frac{\pm z - \sqrt{z^2 + R^2}}{c}$

- $\delta\phi$, the difference in phi between the trigger jet and HCAL cell.
- Based on the early arrival of beam halo muons.

Distribution of HCAL cells in events passing Calorimeter Ratio trigger in run 182454.

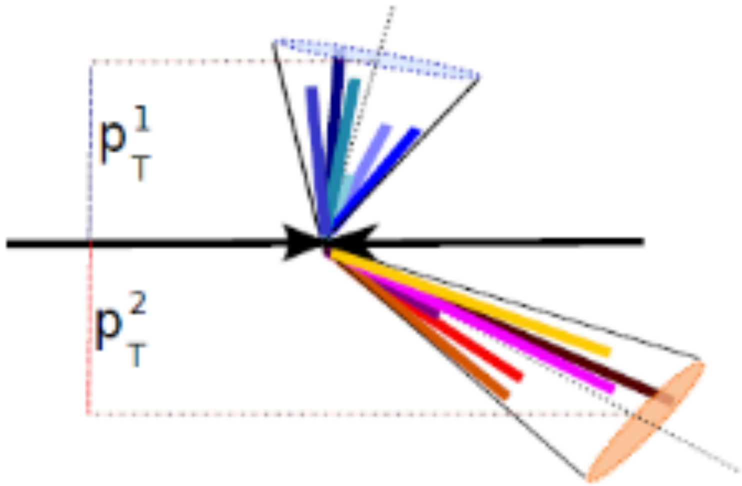


ATL-COM-PHYS-2011-844



Peach arrow: Difference in time

How do we estimate the JES Uncertainty?



- We use the **Dijet Pt Balance Method** (In-situ technique D0: hep-ex/0012046v2)
- This technique uses two jets:
  - a **Reference jet**
  - and a **Probe jet,** back-to-back
- We study the **di-jet pT balance** of the jet energy response in pseudo-rapidity (we added even EMF dependency)
- We study the **Asymmetry** of dijets pt:

$$A = \frac{p_T^{Probe} - p_T^{Ref}}{p_T^{average}}$$

- and the **Response** of the probe jet wrt the reference jet:

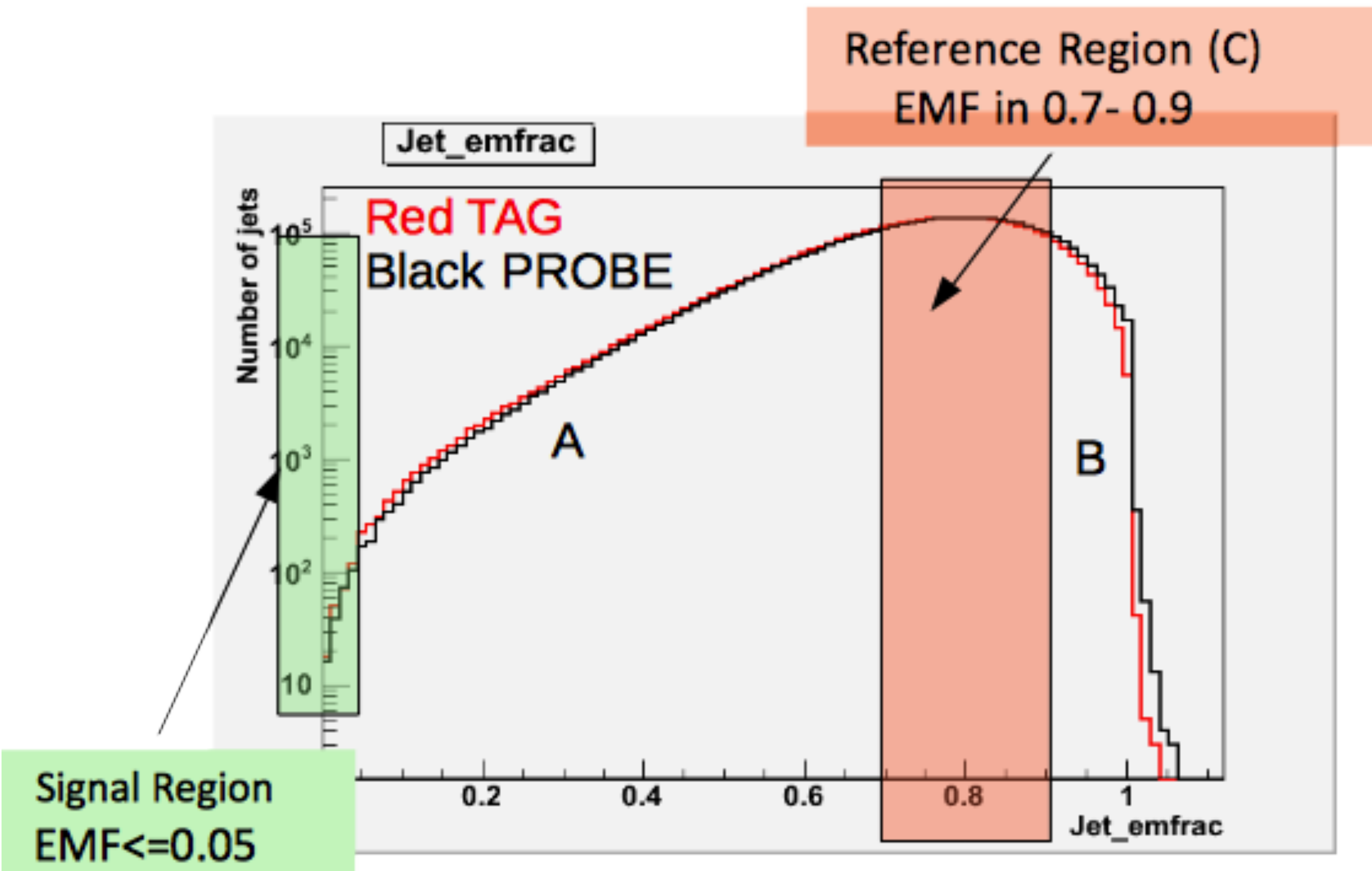
$$R = \frac{2+A}{2-A} = \frac{p_T^{Probe}}{p_T^{Ref}}$$

The inverse of the Response is proportional to the average JES correction

- **The final uncertainty is obtained by comparing DATA / MC Response**

Asymmetry Definition

- We identified a **Reference Region (REF)**:
  - EMF in 0.7- 0.9 range (high statistics and standard EMF jets)

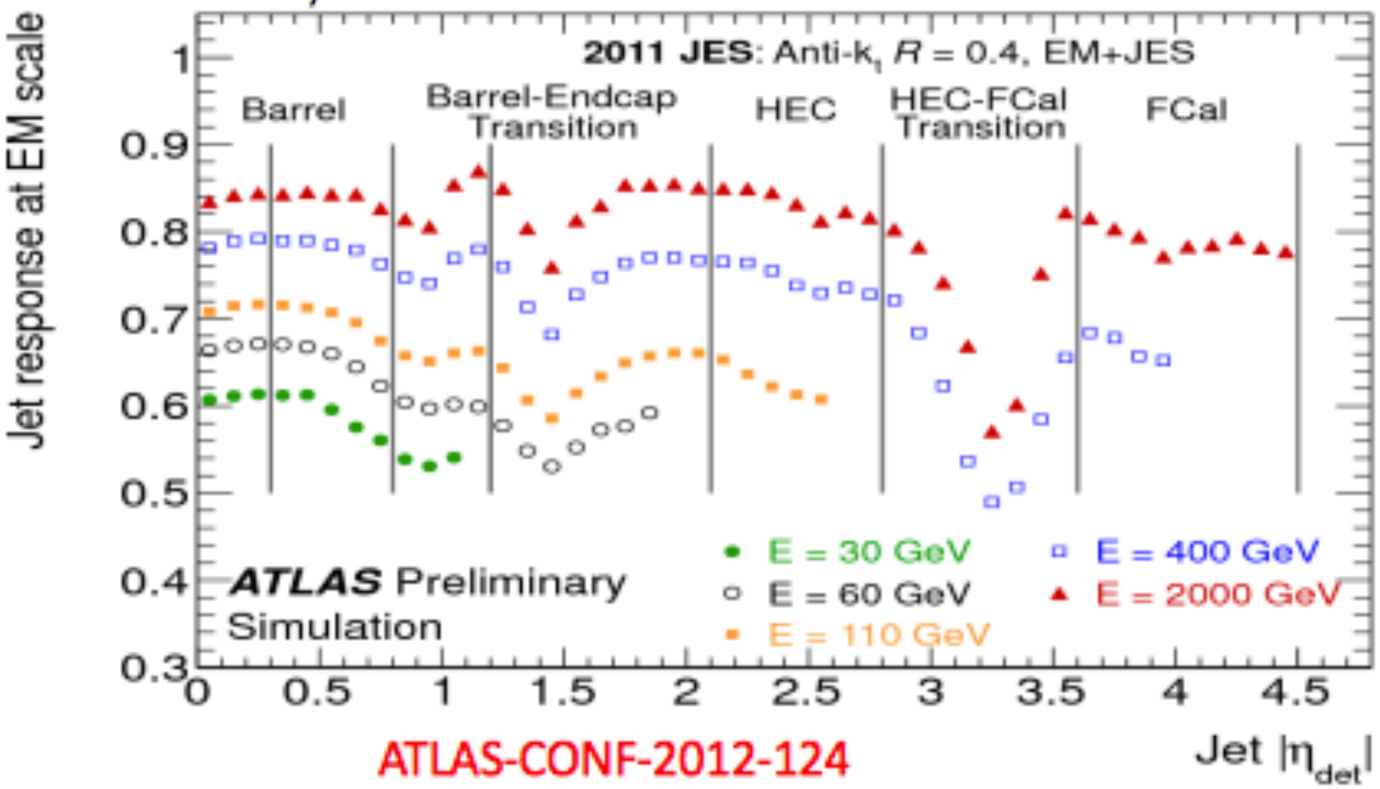


$A = (P_T^{PROBE} - P_T^{REF}) / P_t^{avg}$

- CASE1: one jet in Region A or B, PROBE in C
  - $A = (P_T^{PROBE} - P_T^{REF}) / P_t^{avg}$
- CASE2: one jet in Region C, PROBE in A or B
  - $A = (P_T^{REF} - P_T^{PROBE}) / P_t^{avg}$
- CASE2: one jet in Region C, PROBE in C
  - $A = (P_T^{PROBE} - P_T^{REF}) / P_t^{avg}$
  - $A = (P_T^{REF} - P_T^{PROBE}) / P_t^{avg}$

Dependency on pTavg, EMF and Eta

- We identified a **Reference Region (REF)**:
  - EMF in 0.7- 0.9 range (high statistics and standard EMF jets)
- We divided the analysis in **different pTavg ranges**:
  - Depending on Trigger threshold we have:
    - EF_j55 60 <pTavg < 100
    - EF_j80 85 <pTavg < 125
    - EF_j110 115 <pTavg < 155
    - EF_j145 150 <pTavg < 180
- **Different asymmetries for each EMF bin** (7 bins):
  - 0-0.05, 0.05- 0.20, 0.20-0.40, 0.40-0.60, 0.60-0.70, 0.7-0.9, 0.9-1.0
  - Signal Region EMF<=0.05 (excluded for poor statistics)
- **Four different Eta regions**
  - $|\eta|<0.8$
  - $0.8<|\eta|<1.35$
  - $1.35<|\eta|<1.70$
  - $1.70<|\eta|<2.5$

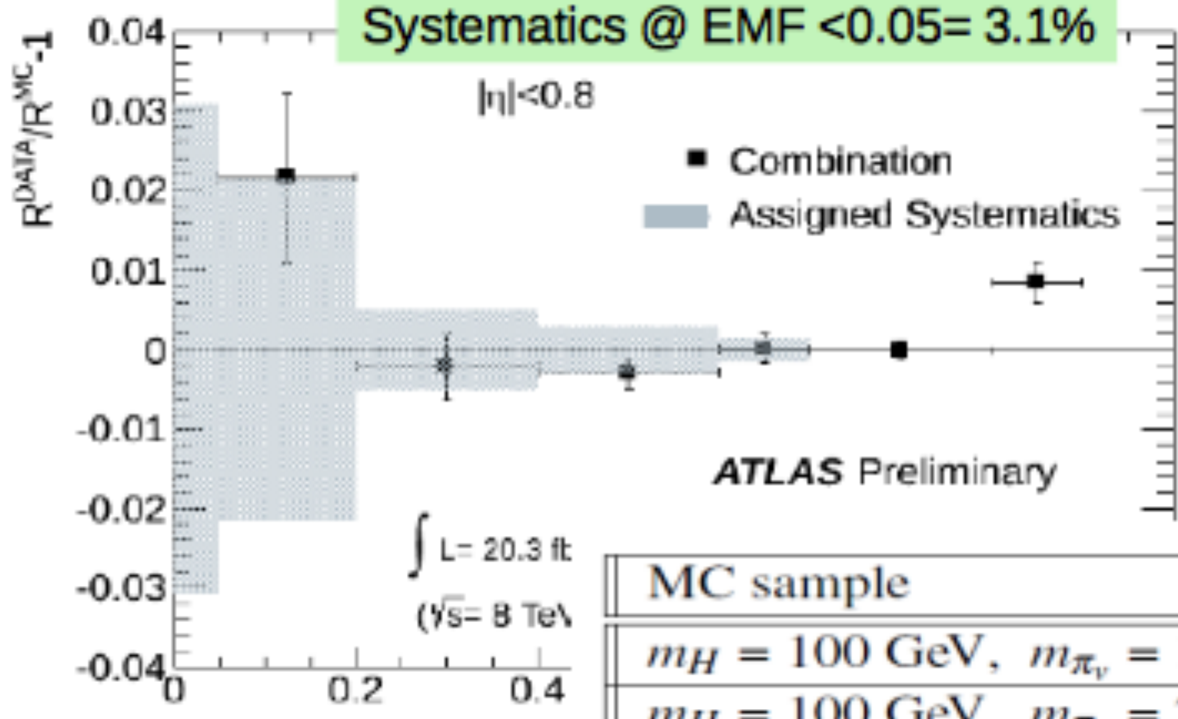


ATLAS-CONF-2012-124

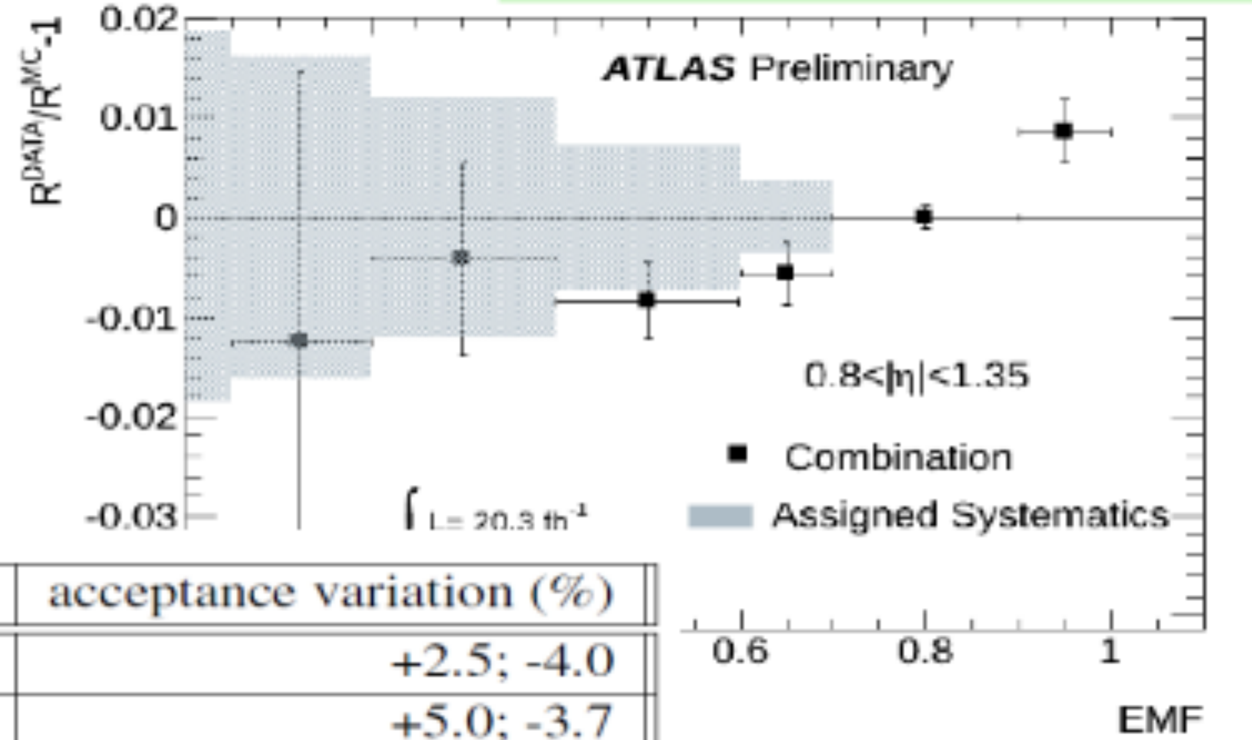
ATLAS-CONF-2014-041

JES Systematics II

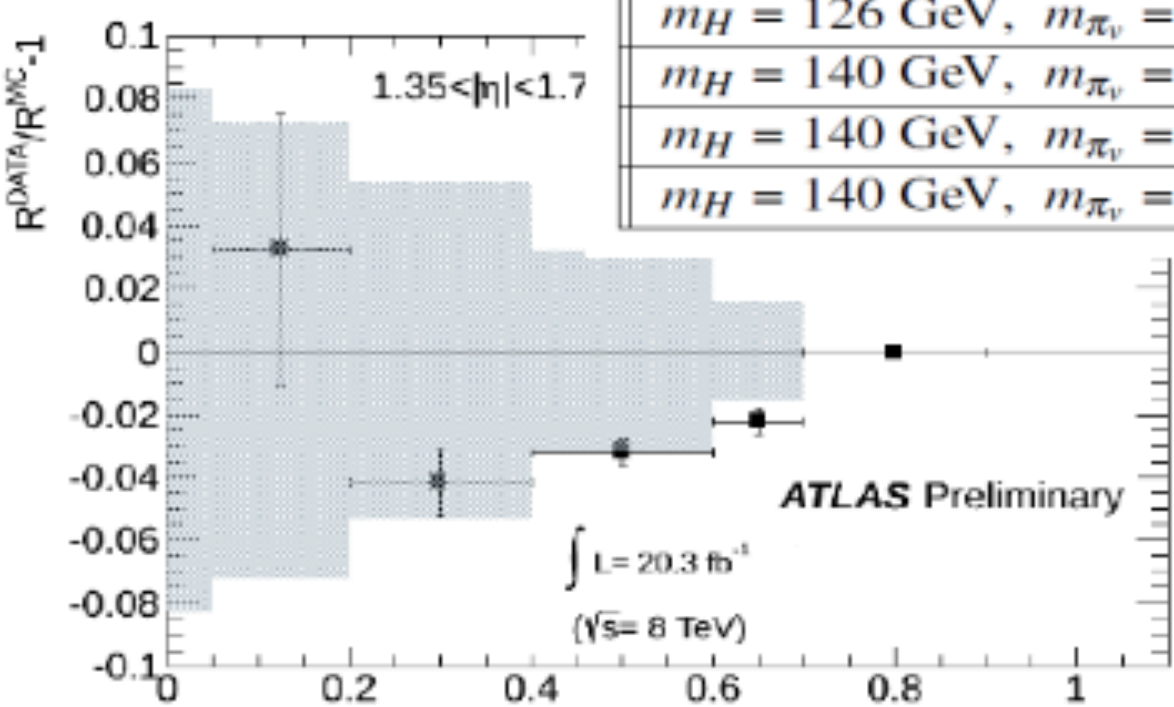
Systematics @ EMF <0.05= 3.1%



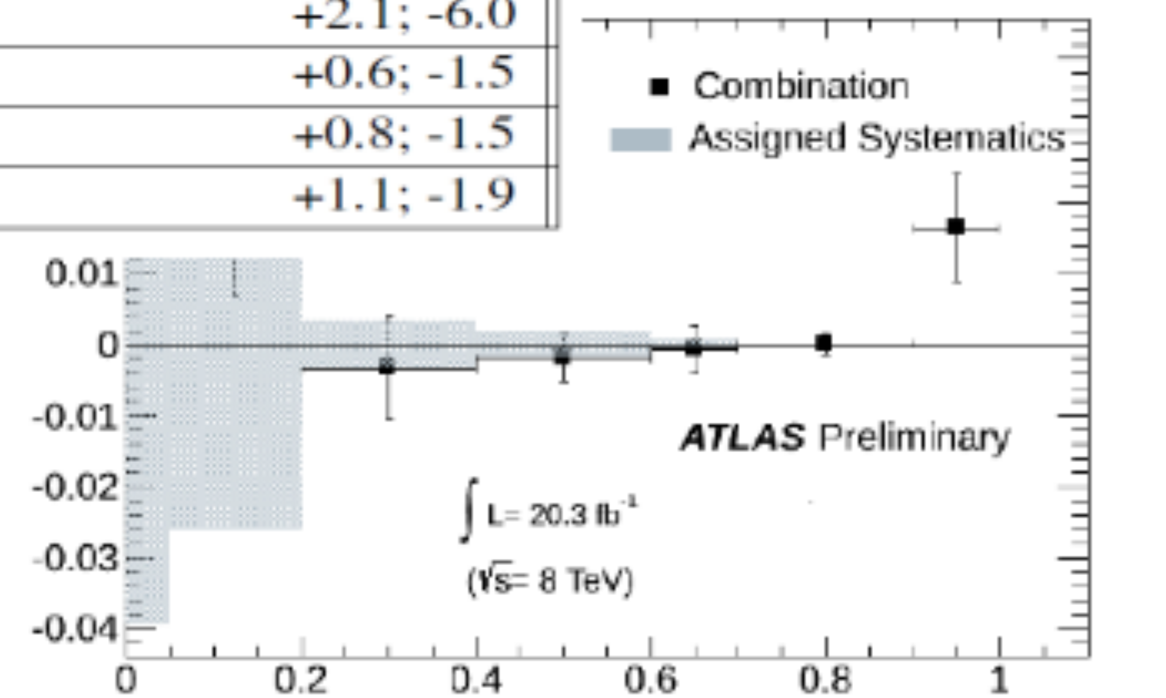
Systematics @ EMF <0.05= 1.9%



MC sample	acceptance variation (%)
m_H = 100 GeV, m_{π_v} = 10 GeV	+2.5; -4.0
m_H = 100 GeV, m_{π_v} = 25 GeV	+5.0; -3.7
m_H = 126 GeV, m_{π_v} = 10 GeV	+2.1; -2.6
m_H = 126 GeV, m_{π_v} = 25 GeV	+1.3; -1.6
m_H = 126 GeV, m_{π_v} = 40 GeV	+2.1; -6.0
m_H = 140 GeV, m_{π_v} = 10 GeV	+0.6; -1.5
m_H = 140 GeV, m_{π_v} = 20 GeV	+0.8; -1.5
m_H = 140 GeV, m_{π_v} = 40 GeV	+1.1; -1.9



Systematics @ EMF <0.05= 8.3%



Systematics @ EMF <0.05= 3.9%

HV Good Medium Jet & Robust Tracks

A Robust Track has: **Pixel_hits >= 2, Pixel_hits+SCT_hits >=9**

A HVGood Medium Jet is : not BadHVMedium and not Ugly

A *BadHVMedium* jet occurs if at least one of the following conditions is satisfied:

- hecf>0.5 and |HECQ| >0.5 (HEC spikes);
- |jetNegET| >60 GeV (HEC spikes);
- |timing| >10 ns (non-collision background and cosmics);
- FMax>0.99 and $|\eta| < 2.0$ (non-collision background and cosmics);
- emf>0.95 and CHf<0.05 and $|\eta| < 2$ (non-collision background and cosmics);
- 1-|HECQ| <hecf (HEC spikes);
- emf>0.9 and |LArQ| >0.8 and $|\eta| < 2.8$ (EM coherent noise).

An *Ugly* jet occurs if BCH_CORR_JET>=0.05 and BCH_CORR_CELL>=0.05.

<table>
<tr><th>Name</th><th>Looser</th><th>Loose</th><th>Medium</th><th>Tight</th></tr>
<tr><td></td><td></td><td>Looser or</td><td>loose or</td><td>medium or</td></tr>
<tr><td>HEC spikes</td><td>HECf>0.5 &&
|HECQ|>0.5
&&LArQmean>0.8,
or
|neg. E| >60 GeV</td><td>HECf>0.5 &&
|HECQ|>0.5</td><td>HECf>1-|HECQ|</td><td></td></tr>
<tr><td>EM coherent noise</td><td>EMf>0.95 &&|LArQ|>0.8
&&LArQmean>0.8 &&
|eta|<2.8</td><td>EMf>0.95
&&|LArQ|>0.8&&
|eta|<2.8</td><td>EMf>0.9 && |LArQ|>0.8
&& |eta|<2.8</td><td>LArQ > 0.95
or
EMf > 0.98 && |LArQ| >
0.05</td></tr>
<tr><td>Non-collision bkg
& cosmics</td><td>EMf<0.05 && Chf
<0.05&& |eta| < 2
or
EMf<0.05 && |eta| >= 2
or
FMax > 0.99 && |eta|<2</td><td>|t|>25 ns</td><td>|t|> 10 ns
or
EMf<0.05 && Chf < 0.1
&& |eta| < 2
or
EMf>0.95 && Chf < 0.05
&& |eta| < 2</td><td>Emf<0.1&&Chf < 0.2 &&
|eta| < 2.5
or
EMf>0.9 && Chf<0.1 &&
|eta| <2.5
Or
Chf < 0.01 && |eta| < 2.5
or
EMf<0.1 && |eta| > 2.5</td></tr>
</table>

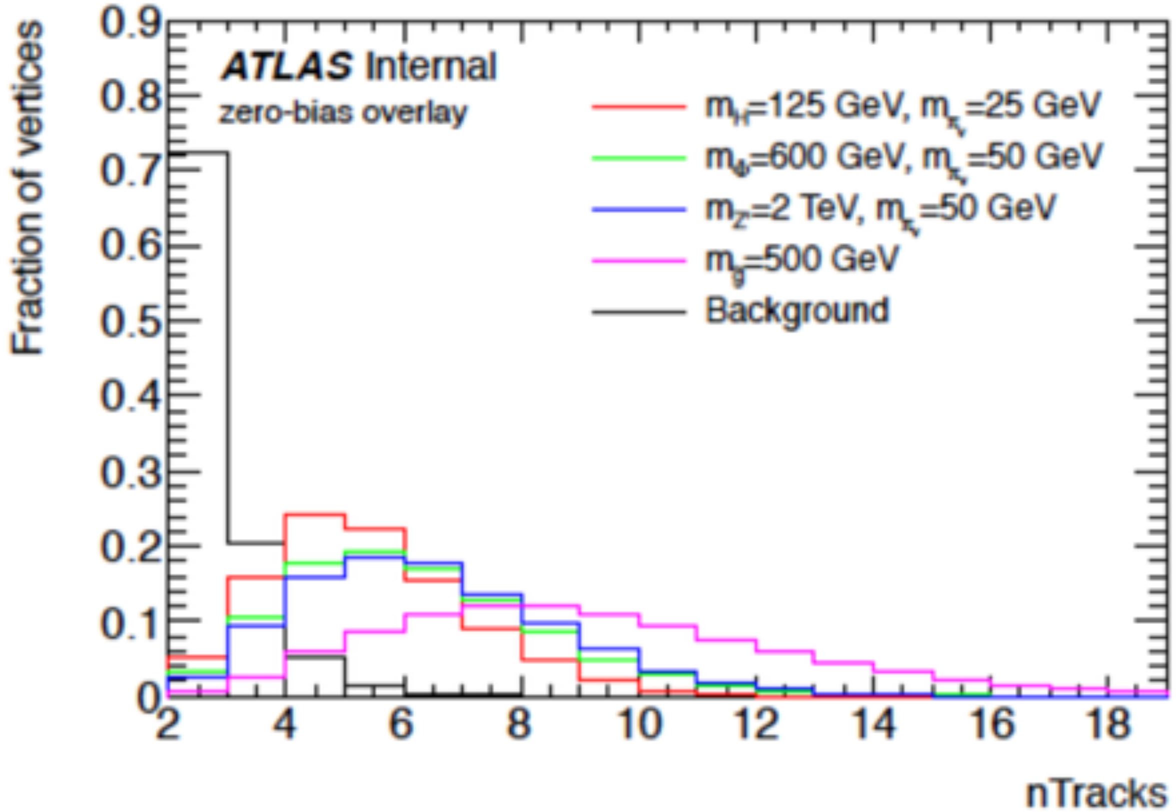


Figure 5. Track multiplicity for vertices obtained from four signal benchmark samples and background multi-jet events.

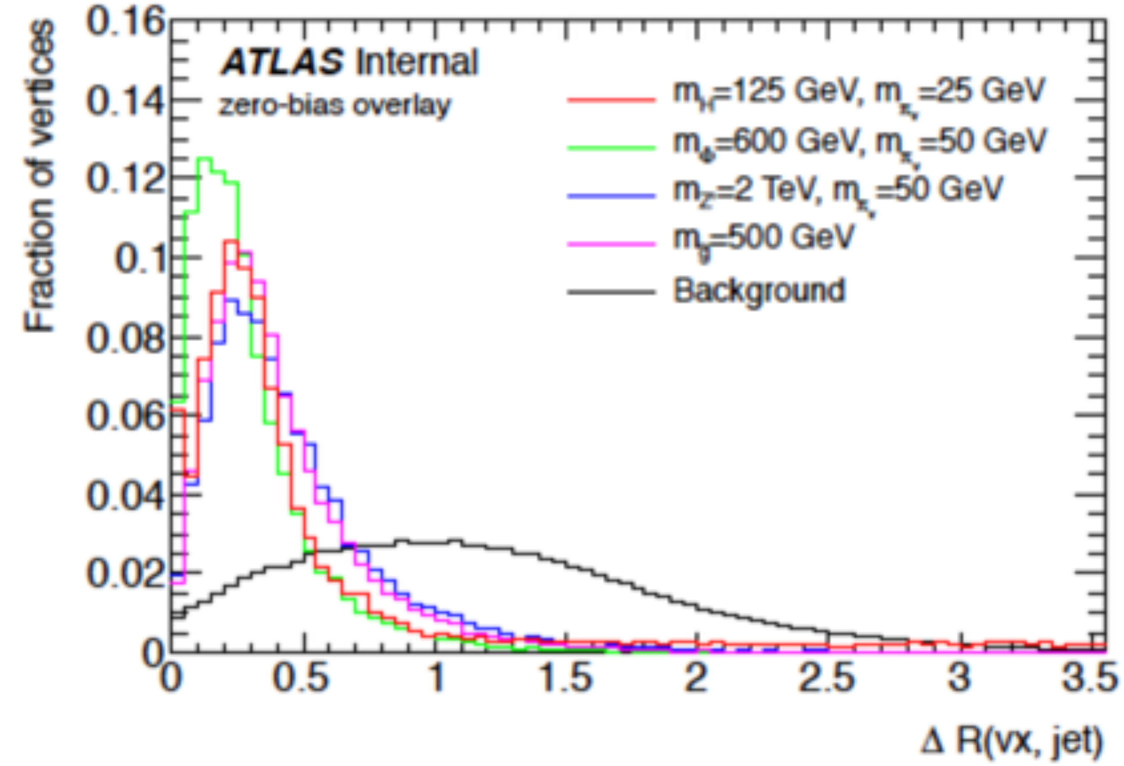


Figure 6. ΔR between the vertex and the center of the nearest jet for vertices from four signal benchmark samples and background multi-jet events.

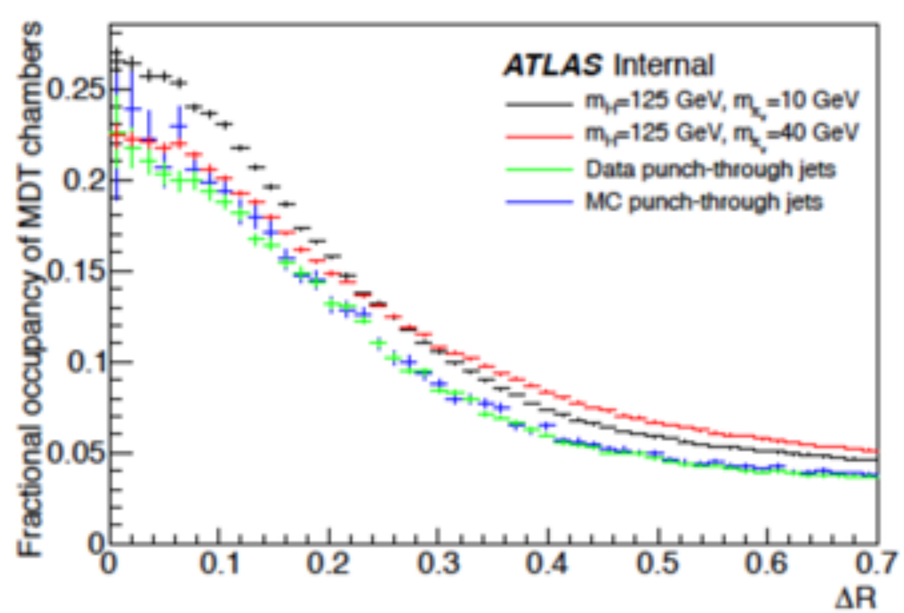


Figure 10. Average fractional occupancy of chambers as a function of ΔR between the center of the MDT chamber and either the punch-through jet's axis for the multi-jet samples or the π_v decay position for signal MC samples. Only punch-through jets with at least 250 MDT hits are included.