SEARCH FOR LONG-LIVED NEUTRAL PARTICLES PRODUCED IN P P COLLISIONS AT $\sqrt{S}$ = 13 TEV DECAYING INTO DISPLACED HADRONIC JETS IN THE ATLAS INNER DETECTOR AND MUON SPECTROMETER

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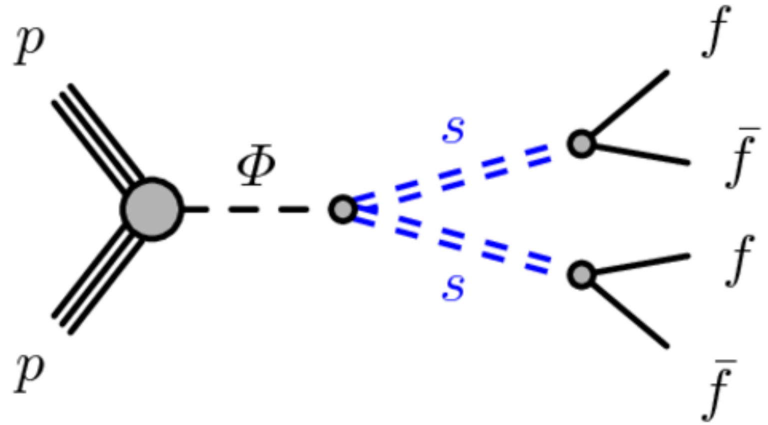
on behalf of

The ATLAS Collaboration

LHC LLP Workshop, Ghent
28 November 2019

LLPs at ATLAS



- New Results!
  - Coming soon on the arXiv
  - CERN preprint: CERN-EP-2019-240
  - Figures and tables: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2018-61 !!
- H/Φ → s s → $f\bar{f}f\bar{f}$
  - Search for pairs of displaced hadronic jets
  - One decay in the ATLAS inner detector (ID)
  - One decay in the ATLAS muon spectrometer (MS)
- Uses specialized trigger and specialized reconstruction algorithms for the displaced tracks, vertices in the ID and MS
- Complementary to searches for LLPs in the MS only (MS analysis) and the hadronic calorimeter (HCal) (CR analysis)

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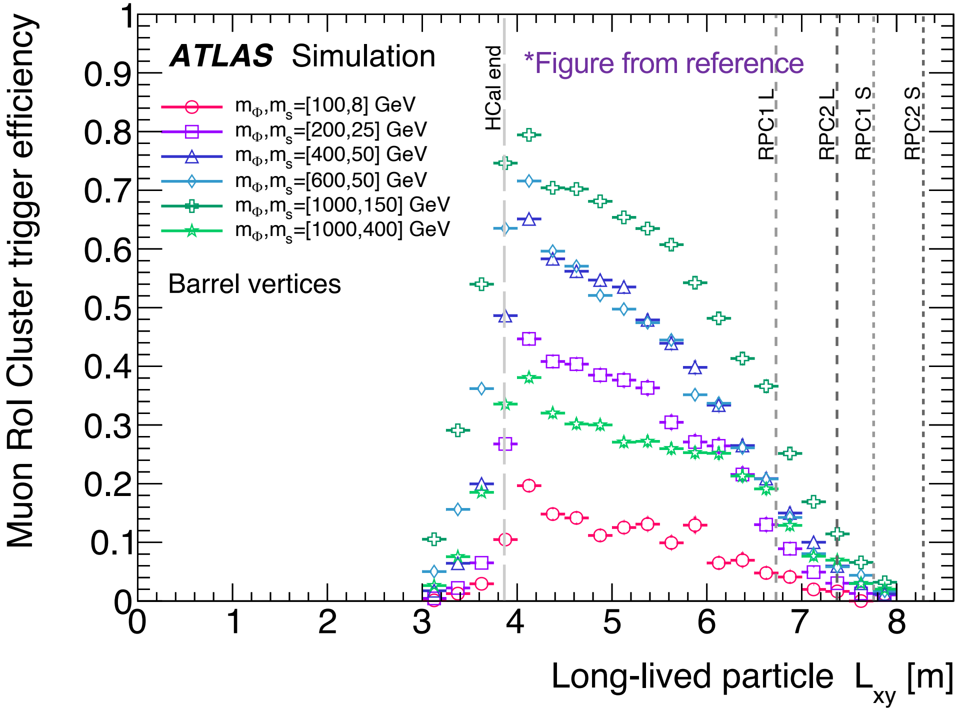
Analysis flow

- Search uses special subset of data which undergoes displaced reconstruction
- Events are collected by Muon RoI Cluster trigger
- Events are required to include an MS vertex (MSVx) which is matched to the trigger cluster
- Events are required to include an ID vertex (IDVx) which is isolated from the MSVx
- Data driven background estimation
- Results ☺

Muon RoI Cluster trigger (also see John's talk)

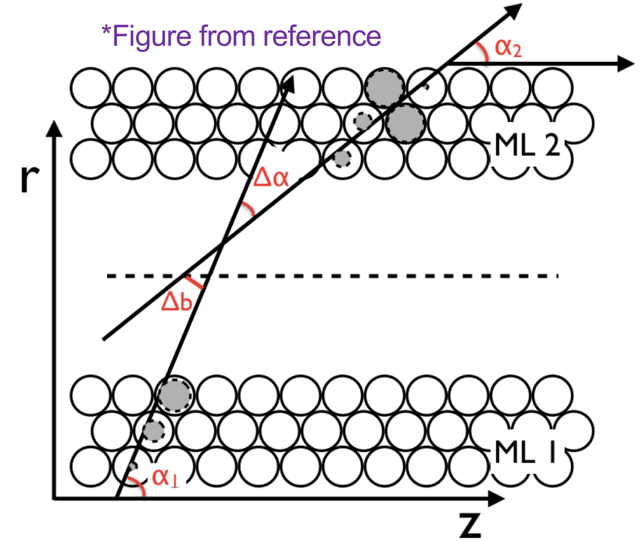
- LLPs decaying at or after the end of the HCal leave clusters of hits in the MS around LLP path
- L1 trigger searches for 2 muon RoIs with $p_T \geq 10$ GeV
- At HLT, the trigger requires clusters of 3 (4) muon RoIs in $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.4$ cone in MS barrel (endcaps)
- High dependence on LLP decay position
- Data/MC scale factors
  - Data/MC – 1.13 ± 0.01 in the barrel and 1.04 ± 0.02 in the endcaps



*MS analysis: https://arxiv.org/pdf/1811.07370.pdf
LLP triggers: https://arxiv.org/pdf/1305.2284.pdf

MSVx reconstruction and selection

- Specialized MSVx reconstruction
  - Dense environment with lower p_T particles
  - Uses MDT chamber structure to form tracklets
  - Tracklets used to reconstruct vertices
  - Slightly different algorithms in barrel, endcaps



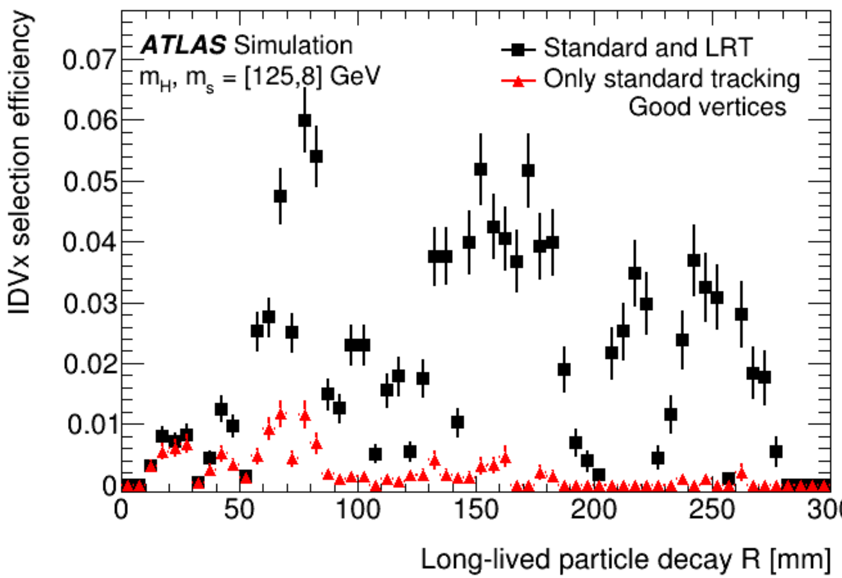
Selection	Barrel	Endcaps
MSVx $\|\eta\|$	< 0.7	> 1.3
Matching to trigger cluster	$\Delta R < 0.4$	$\Delta R < 0.4$
Precision chamber hits	$300 < n_{MDT}$ hits < 3000	
Trigger chamber hits	n_{RPC} hits > 250	n_{TGC} hits > 250
Isolation from > 5 GeV tracks	$\Delta R > 0.3$	$\Delta R > 0.6$
Max Σp_T in $\Delta R = 0.2$ cone	< 10 GeV	< 10 GeV
Isolation from p_T > 30 GeV jets	$\Delta R > 0.3$	$\Delta R > 0.6$

MS analysis: https://arxiv.org/pdf/1811.07370.pdf
*MSVx Reco: https://arxiv.org/pdf/1311.7070.pdf

IDVx reconstruction

- Many tracks from displaced decays in the ID aren't reconstructed with standard tracking (ST)
- Large-radius tracking (LRT)
  - Silicon-seeded tracking
  - Relaxed requirements on track parameters to increase efficiency
  - Drastically improves sensitivity to decays at R > 100 mm
- Secondary vertex reconstruction
  - Uses both ST and LRT with $d_0 > 2$ mm and $p_T > 1$ GeV
  - Seed vertices formed – pairs of tracks
  - Seed vertices merged
    - Poorly fitting tracks dropped

	ST	LRT
$\lvert d_0 \rvert$ [mm]	≤ 10	≤ 300
$\lvert z_0 \rvert$ [mm]	≤ 250	≤ 1500
Si hits	≥ 7	≥ 7
Unshared Si hits	≥ 6	≥ 5
Track p_T [MeV]	> 400	> 500



LRT Reco: https://cds.cern.ch/record/2275635

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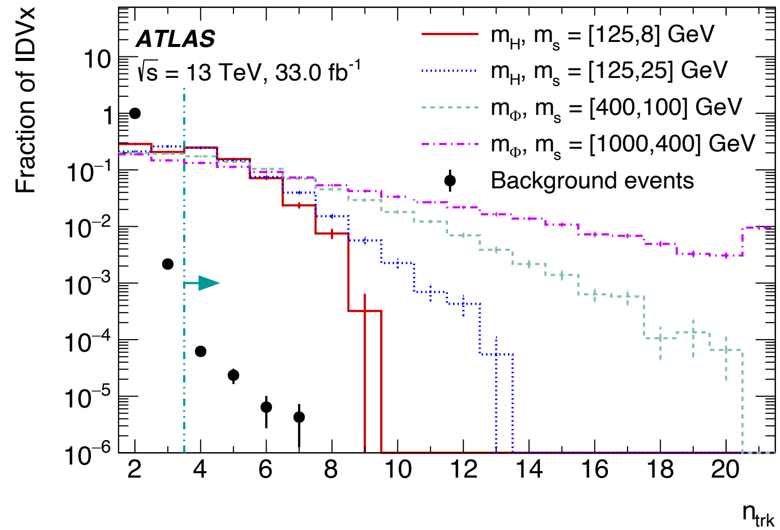
IDVx selection requirements

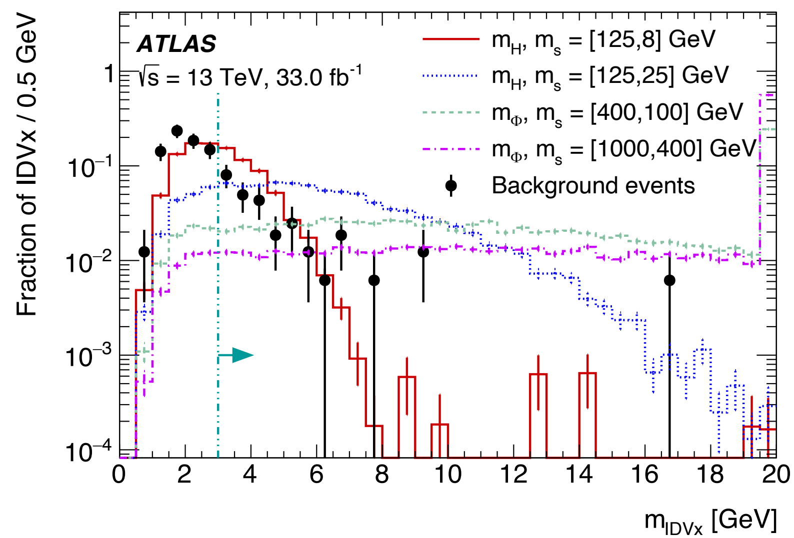
IDVx R, |z| [mm]	< 300
IDVx χ^2/n_{DoF}	< 5
Radial distance from PV [mm]	> 4
Pass material veto and disabled module veto	
IDVx n_{trk}	≥ 4
m_{IDVx} [GeV]	> 3
IDVx be isolated ΔR > 0.4 from good MSVx	

- Fiducial volume and vertex quality requirements
- Remove vertices from material interactions
- Isolation from MDVx to reduce chance of one high energy jet causing both an IDVx and an MSVx

IDVx selection – n_{trk}, m_{IDVx}

- Comparison of IDVx distributions in signal MC samples and background data samples
  - Signal MC IDVx required to be matched to generated LLP decays
- IDVx n_{trk} distribution in data dominated by $n_{trk} = 2$
  - Signal MC distribution much broader
- Selection: IDVx $n_{trk} \geq 4$
- Selection $m_{IDVx} > 3$ GeV
  - Removes ~4% - ~50% of signal MC vertices passing other selections
  - Removes ~70% of data background vertices passing other selections

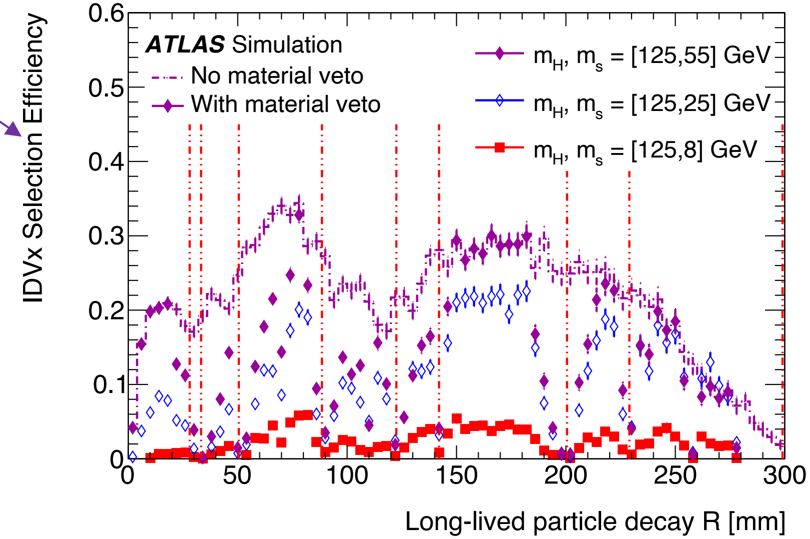


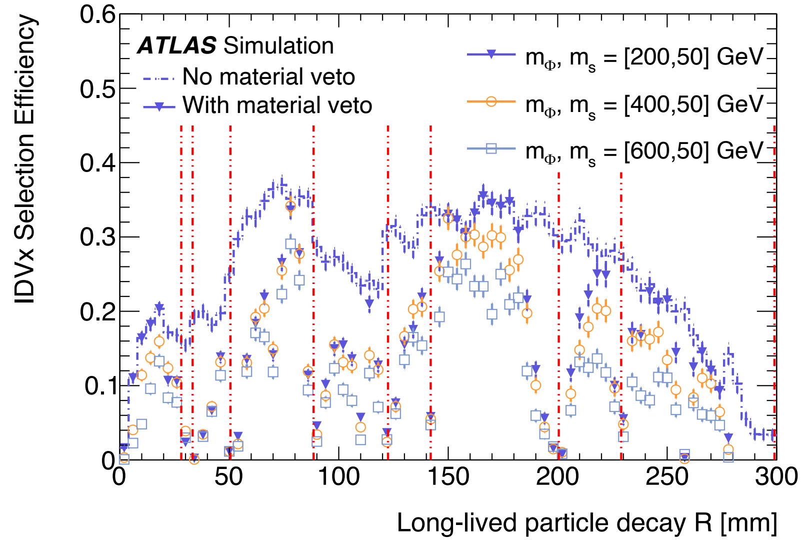


IDVx selection efficiency

- IDVx selection efficiency depends strongly on decay position
- Selection efficiency also impacted by the mass of the LLP and the relative masses of the LLP and the Φ
  - Particle momenta impacts vertex opening angle
- Unique structure of the efficiency vs LLP decay R due to material veto

constant m_H





constant m_s

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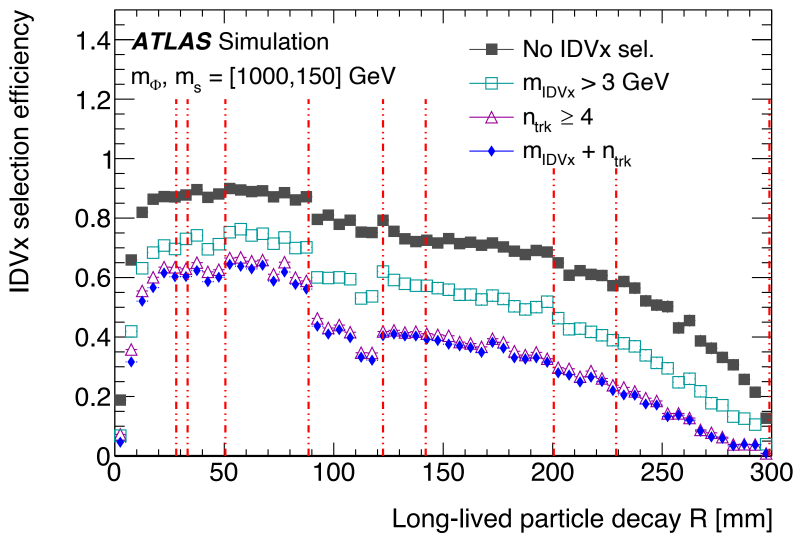
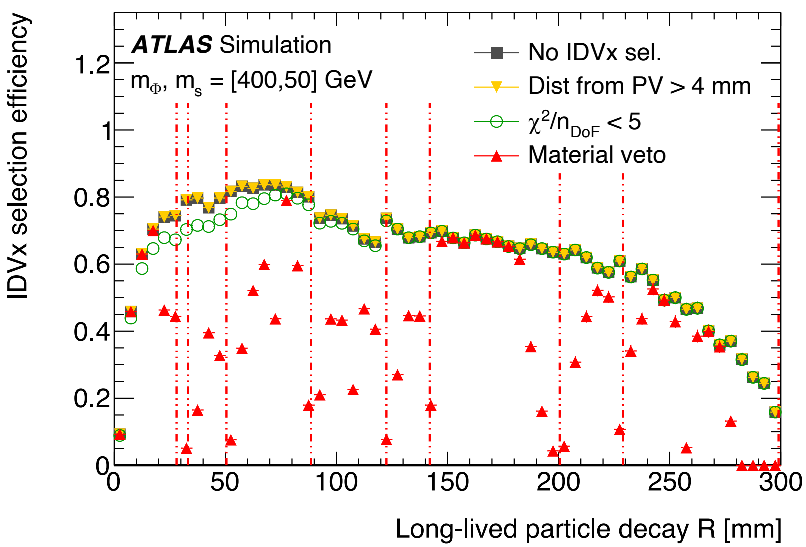
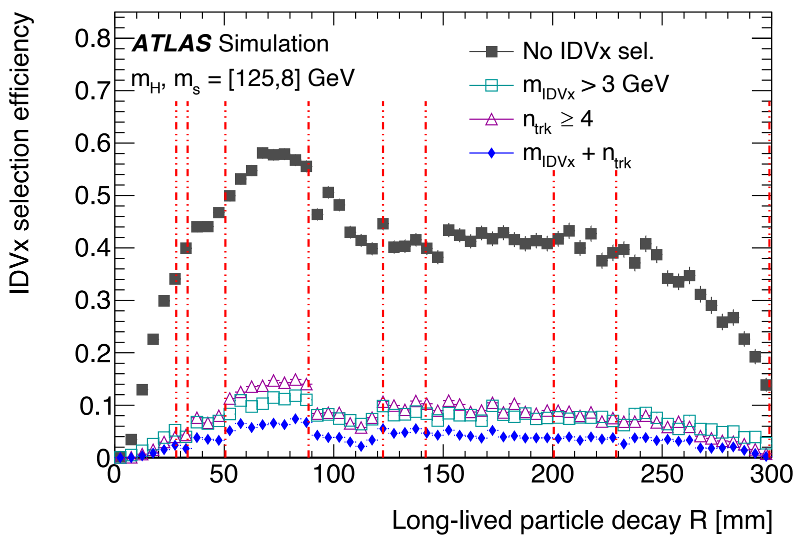
IDVx selection efficiency

- Impact on selection efficiency of each selection requirement
- Structure vs R most impacted by material veto
- Relative impact of n_{trk} and m_{IDVx} requirements has strong dependence on LLP mass



Higher mass





Lower mass

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Data driven background estimation

	Background events		Muon RoI cluster trigger events with good MSVx
Has IDVx passing full selection	*Bkg+IDVx*		*Sig*
	÷		=
Agnostic to IDVx	*Bkg*	×	*Sig – IDVx*

- Background events selected to minimize signal contamination
- Use single muon trigger plus isolated muon requirements based on $Z \rightarrow \mu\mu$ event selection
- Very little overlap with signal MC samples
- Develop factor $F = {}^{N_{Bkg+IDVx}}/_{N_{Bkg}}$
- Estimate $N_{Sig}^{pred.} = N_{Sig\,-IDVx} \times F = N_{Sig\,-IDVx} \times {}^{N_{Bkg+IDVx}}/_{N_{Bkg}}$
- Estimate - 1.16 ± 0.18 (stat.)

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ATLAS EXPERIMENT

Data driven background validation

	Background events	Muon RoI cluster agnostic to MSVx	Muon RoI cluster with good MSVx
Has IDVx, $n_{\mathrm{trk}} \geq 4$, $m_{\mathrm{IDVx}} > 3$ GeV	*Bkg+IDVx*		*Sig*
Has IDVx, $n_{\mathrm{trk}} = 3$, $1 < m_{\mathrm{IDVx}} < 3$ GeV	*Bkg, 3-trk*	*Trig, 3-trk*	
Has IDVx, $n_{\mathrm{trk}} = 2$, $m_{\mathrm{IDVx}} > 3$ GeV	*Bkg, 2-trk*		*Val, 2-trk*
Agnostic to IDVx	*Bkg*	*Trig*	*Sig – IDVx*

- Use 2-track and 3-track vertices for the validation
- Reduce signal contamination for 3-track region, remove MSVx requirement
- Develop same factors to estimate number of events in *Sig*-like regions
- Good agreement found in predicted vs observed numbers
- 25% uncertainty applied to background estimate
- Background estimate: 1.16 ± 0.18 (stat.) ± 0.29 (syst.)

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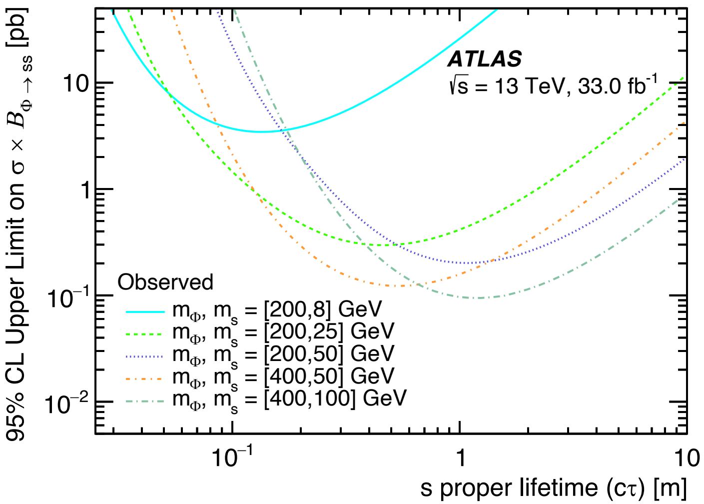
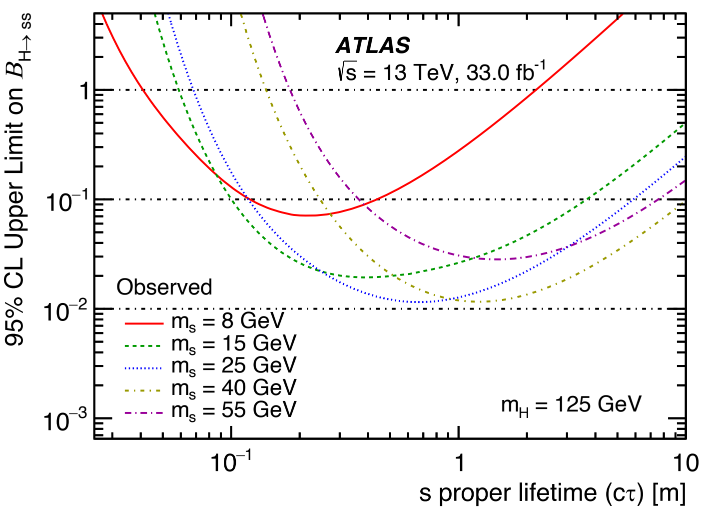
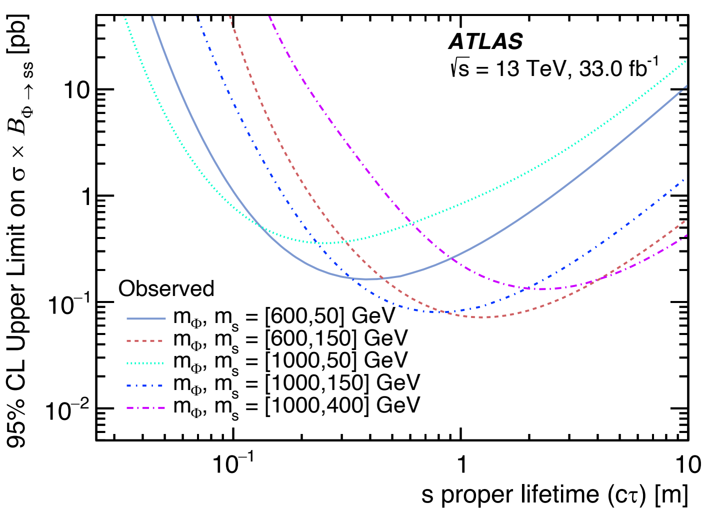
Results

- One observed event – no excess above background ☹
- Set limits using CL_S
- Limits from this analysis only







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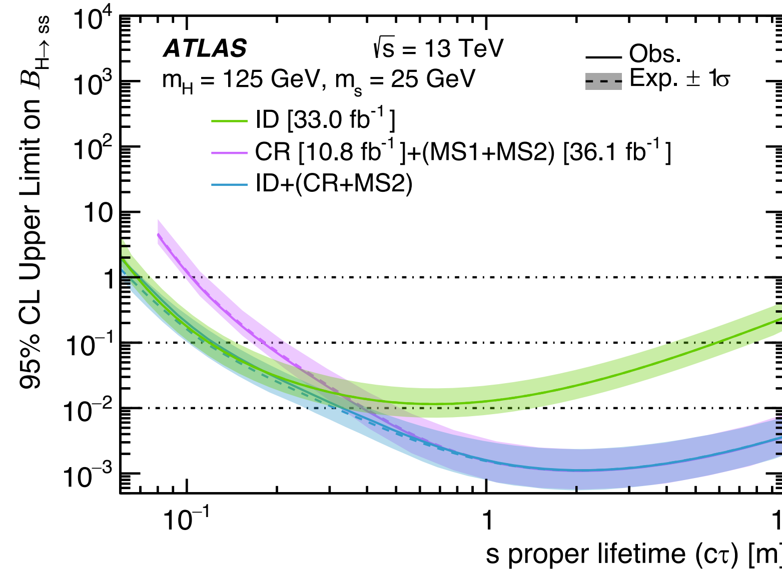
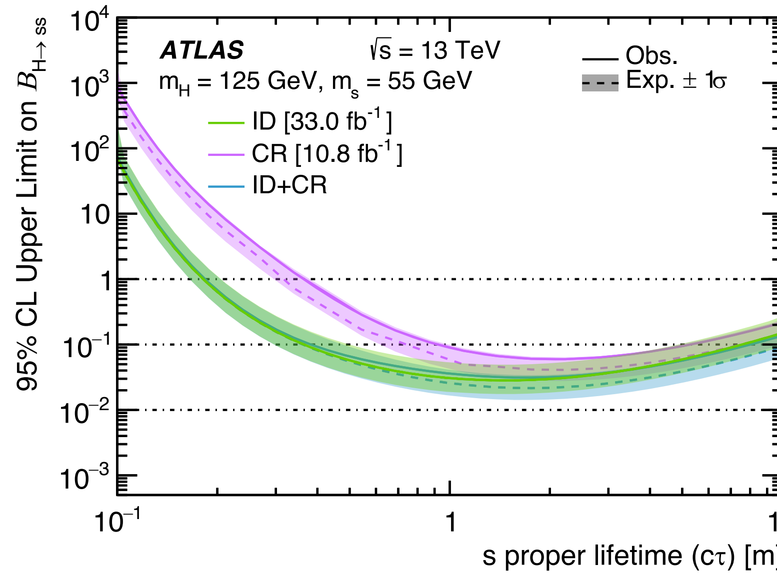
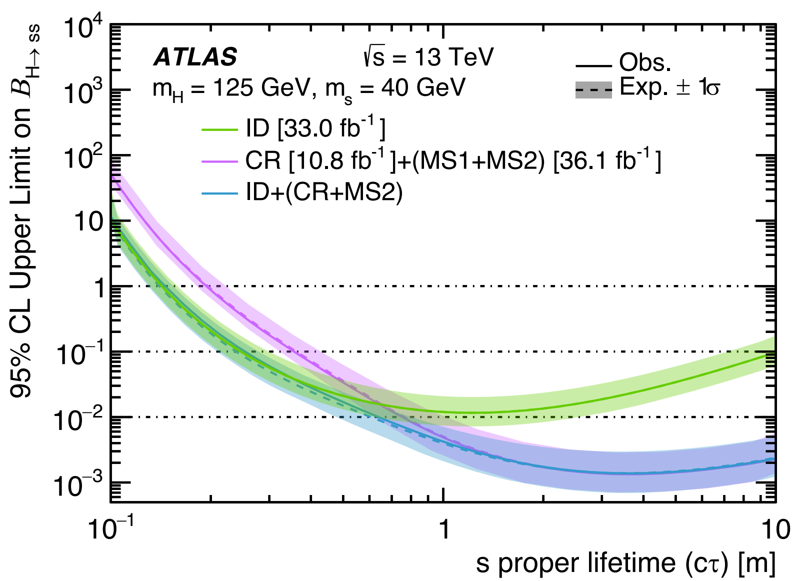
Results

- Limits combined with CR- and MS-analysis limits
- Limits on branching ratio for a SM Higgs → HS
- Extension of limits at low cτ

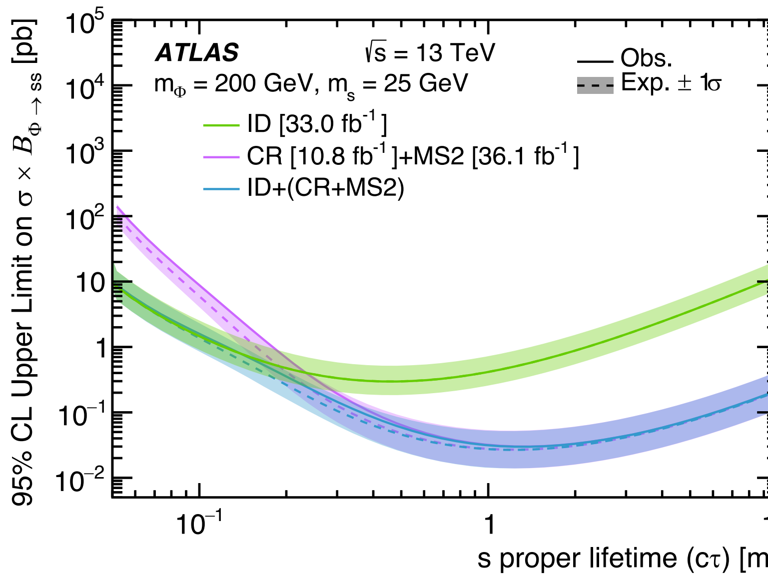


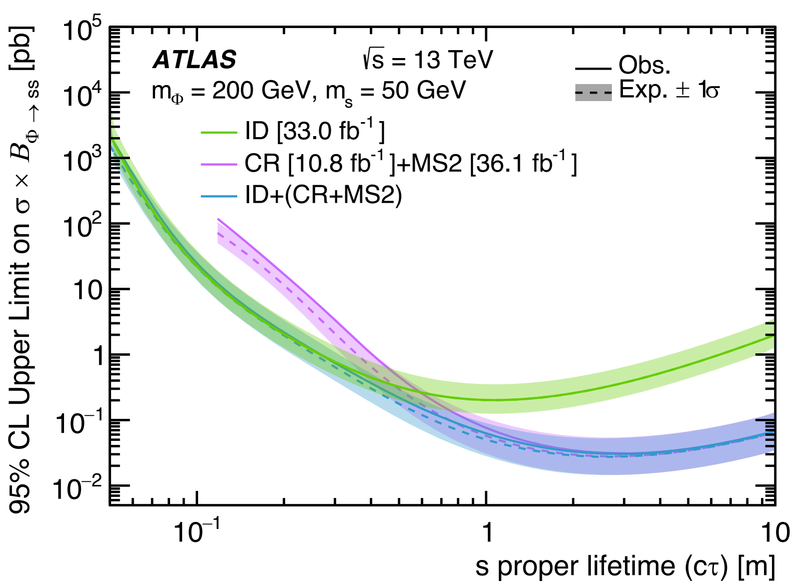




Results

- Limits combined with CR- and MS-analysis limits
- Limits on production cross section of Φ x branching ratio to *ss*
- Extension of limits at low cτ
- Limits for higher mass Φ do not surpass those set by the CR+MS analyses





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Results

- Addition of IDVx to displaced dijet searches allows for higher sensitivity at low cτ, particularly for Higgs or lower mass Φ as a mediator
- Extension to lower cτ would benefit from specialized LLP trigger in the ID which would remove need for decay in the MS (or HCal) without relying on associated production
- LLP search program at ATLAS continues to be exciting
  - Looking forward to full Run 2 results and for potential gains in Run 3

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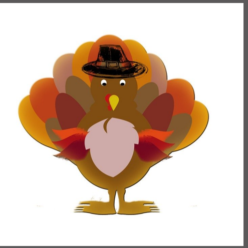
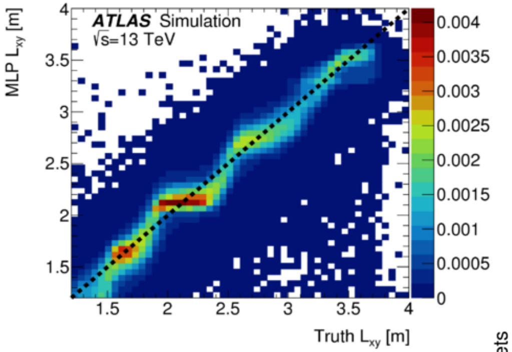
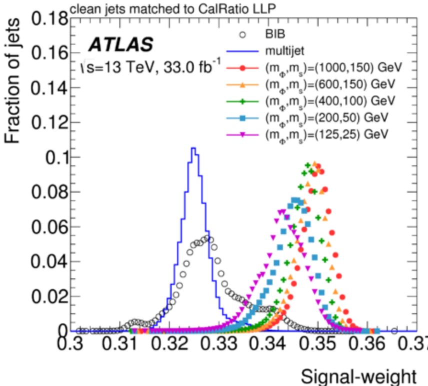
BACKUP

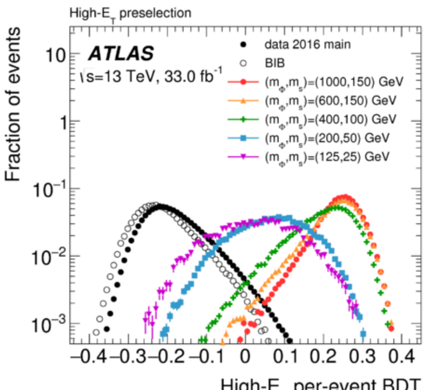


Displaced jets in the HCal – H/Φ → s s → $f\bar{f}f\bar{f}$

- Custom trigger
  - Relies on calRatio, trackless jet features of displaced jets
  - Two triggers for low and high E_T regions
- Multilayer perceptron (MLP)
  - TMVA trained on signal MC samples
  - Used to predict displaced jet decay position
- Per-jet BDT
  - Inputs – MLP, track, jet properties
  - Trained on signal MC, multi-jet MC, BIB data
  - Assigns BIB-, multijet-, signal- weights to jets
- Per-event BDTs
  - Inputs – per-event BDT, event level variables
  - Trained on signal MC, BIB data
  - Separates BIB events from signal events
  - Event cleaning including BDT output – removes BIB
- Data driven ABCD method
  - Use per-event BDT and $\sum \Delta R_{min}(jet, tracks)$







https://arxiv.org/abs/1902.03094

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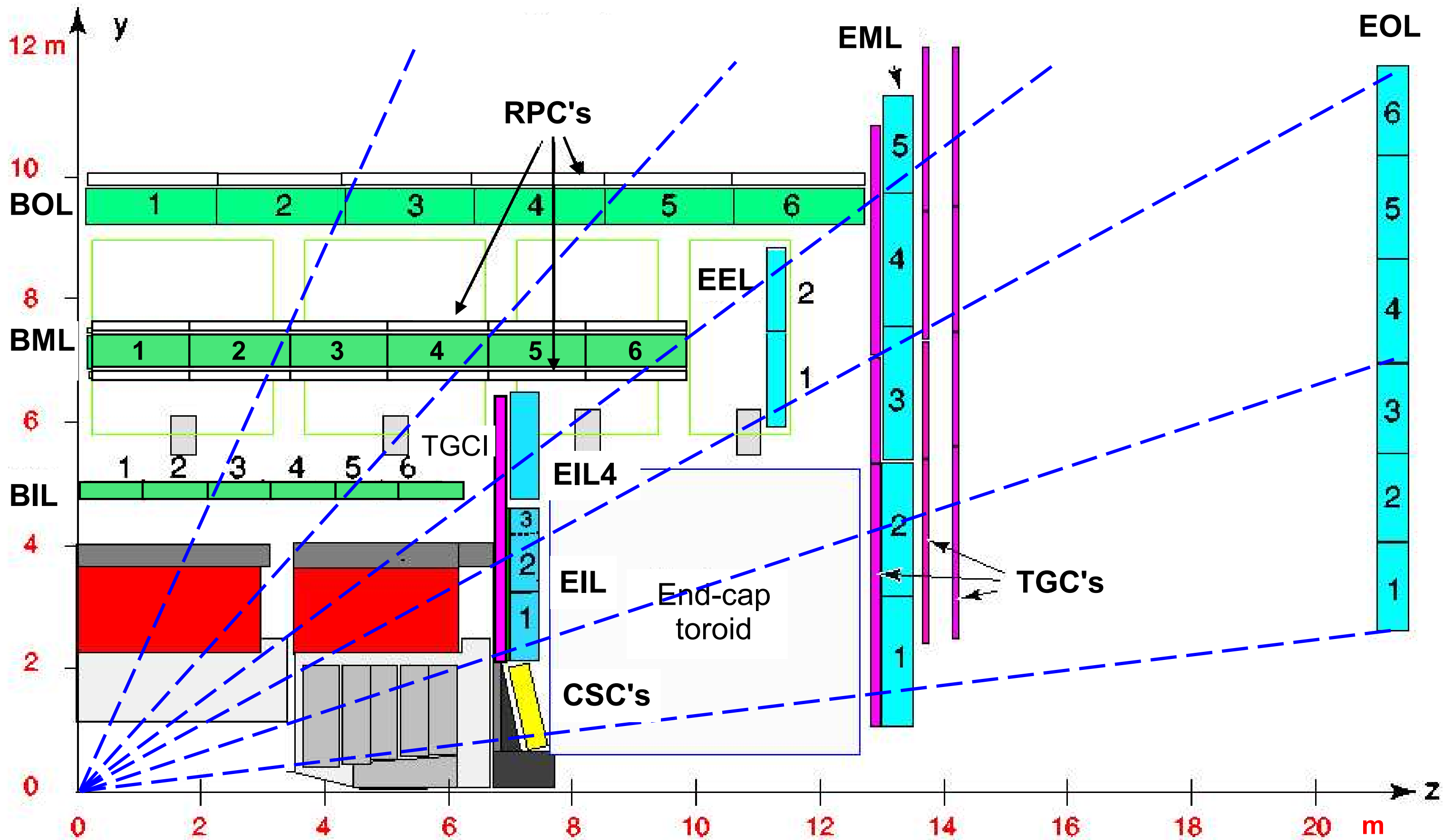
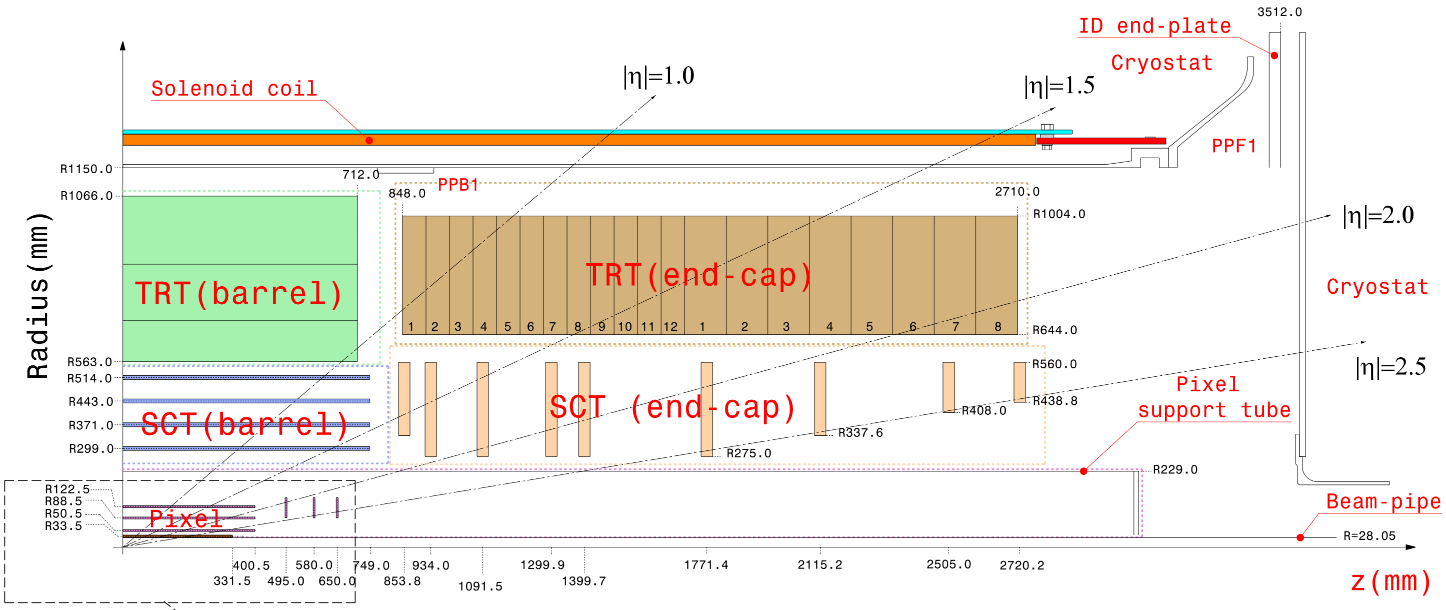
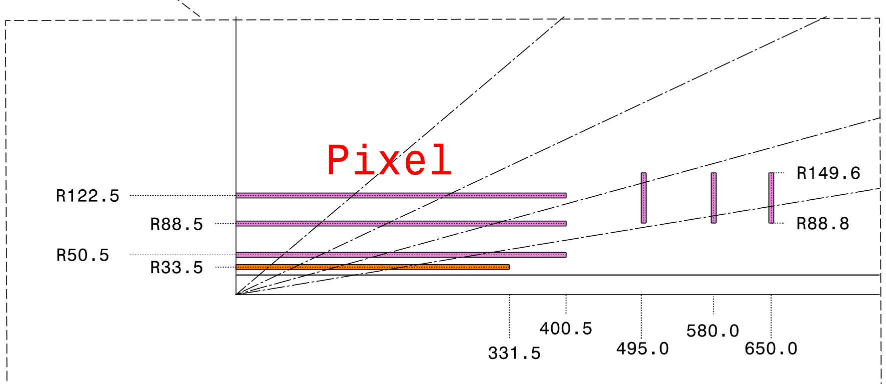
ATLAS muon spectrometer



https://arxiv.org/pdf/1311.7070.pdf

ATLAS inner detector





Envelopes

Pixel		31<R<242 (mm)
SCT barrel		255<R<549 (mm)
SCT end-cap		251<R<610 (mm)
TRT barrel		554<R<1082 (mm)
TRT end-cap		617<R<1106 (mm)

https://arxiv.org/pdf/1707.02826.pdf

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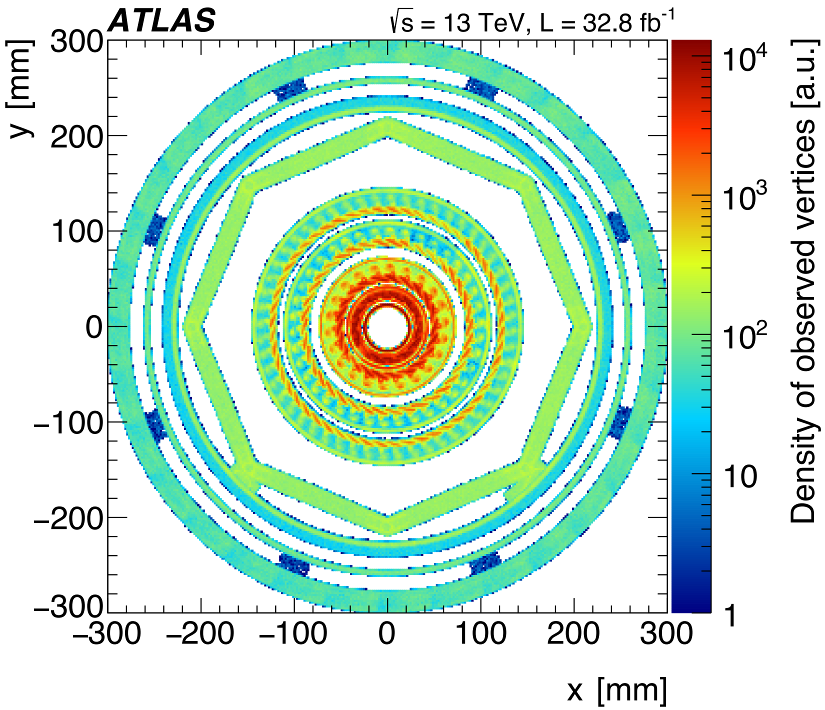
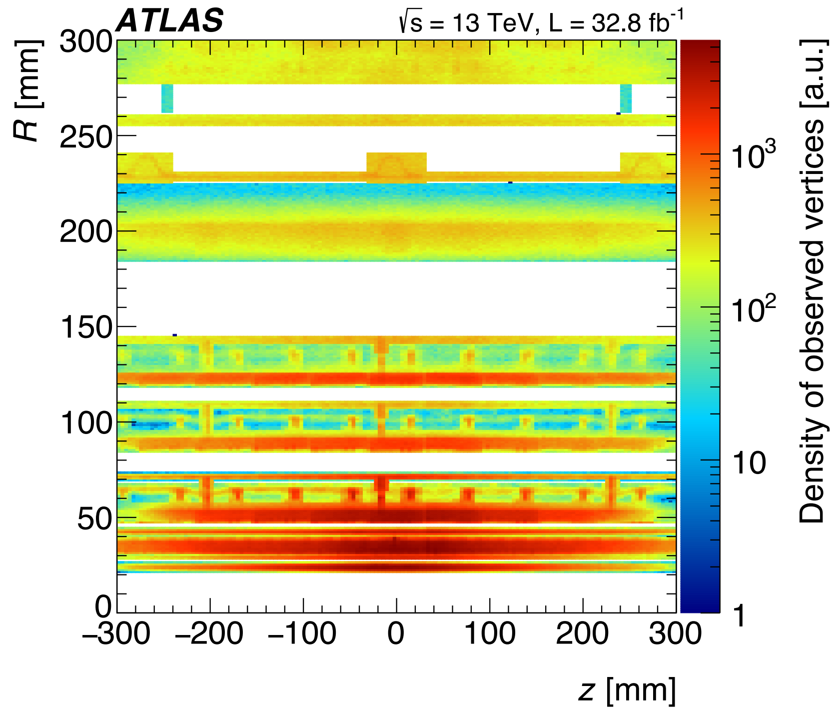
Material in the inner detector





https://arxiv.org/pdf/1710.04901.pdf

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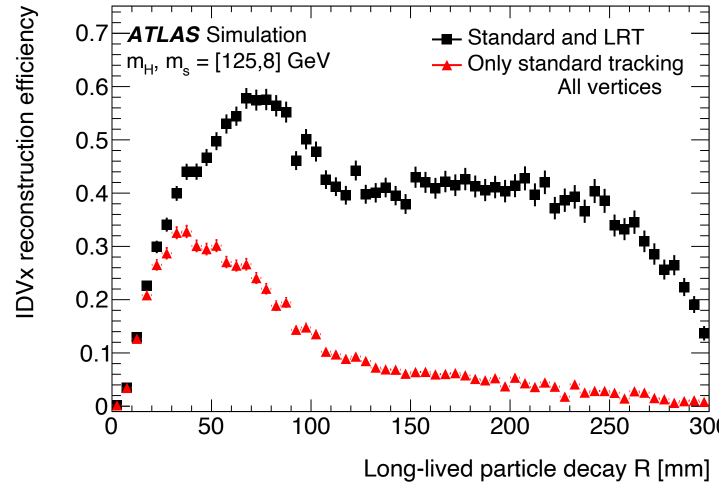
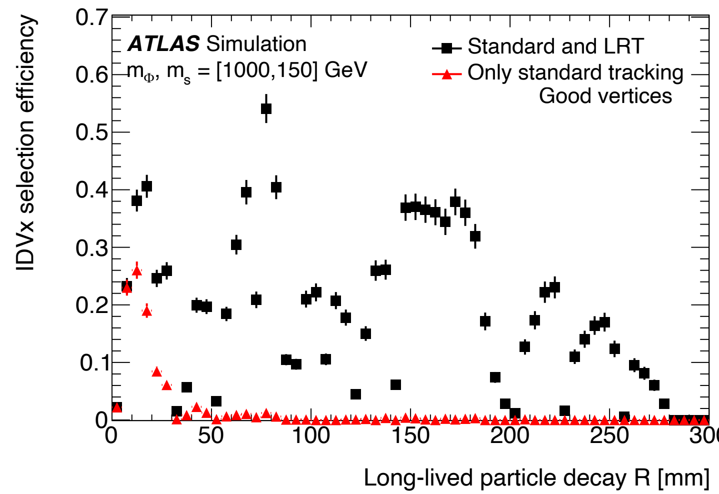
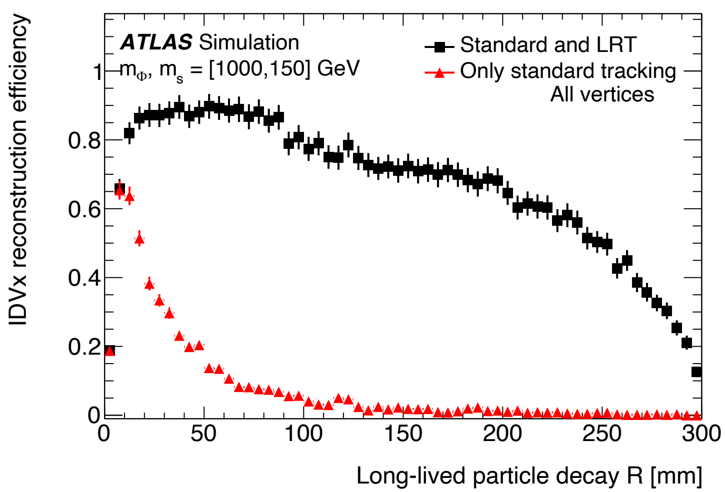
IDVx reconstruction

Track parameter	Requirement
Track $\lvert d_0 \rvert$	2 mm < $\lvert d_0 \rvert$ < 300 mm
Track $\lvert z_0 \rvert$	< 1500 mm
Track p_T	> 1 GeV
Number of SCT hits	≥ 2
Number of pixel and TRT hits	$n_{\text{pixel}} \geq 2$ or $n_{\text{TRT}} > 0$

No hits on track may be present before the vertex
Hits on track must be present in the layer following the vertex



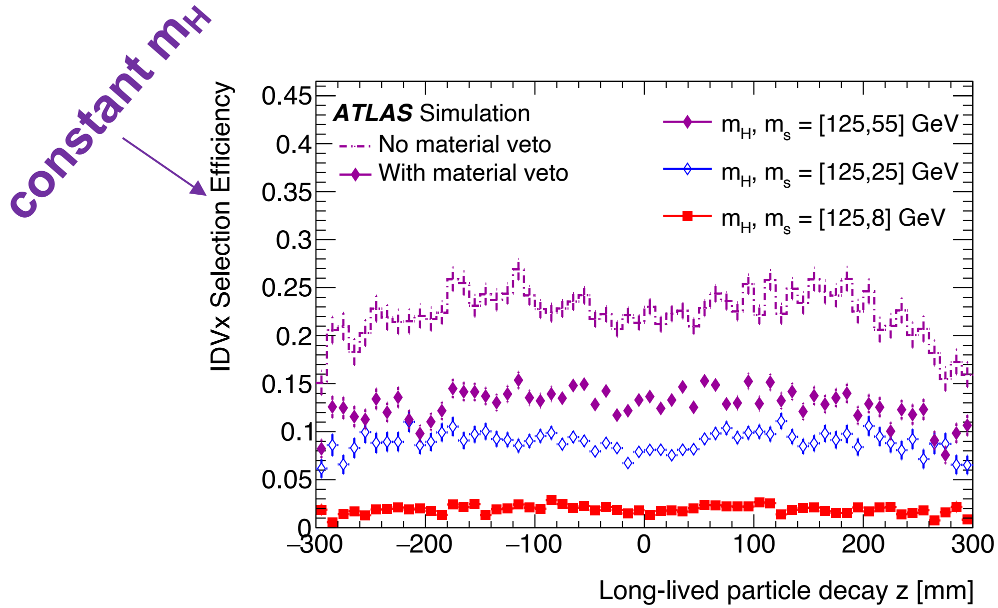


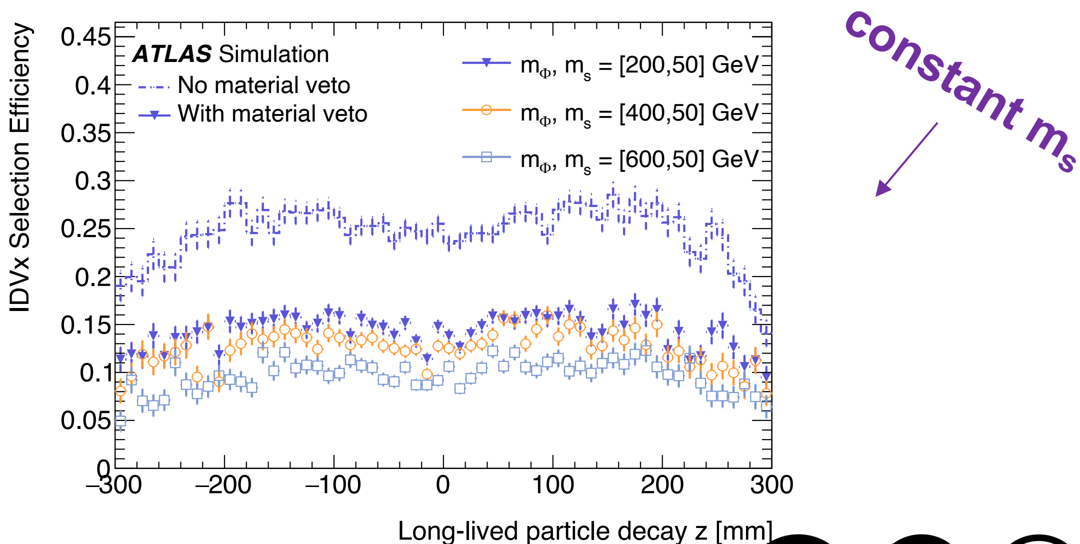


IDVx selection efficiency

- IDVx selection efficiency depends on decay position

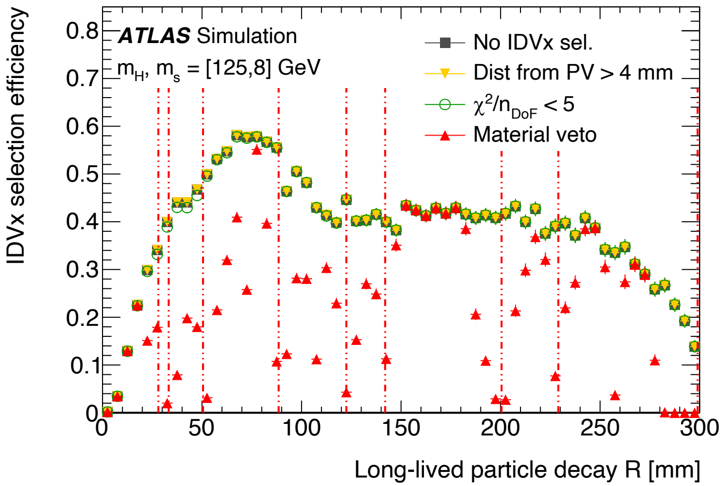
- Selection efficiency also impacted by the mass of the LLP and the relative masses of the LLP and the Φ
  - Particle momenta impacts vertex opening angle

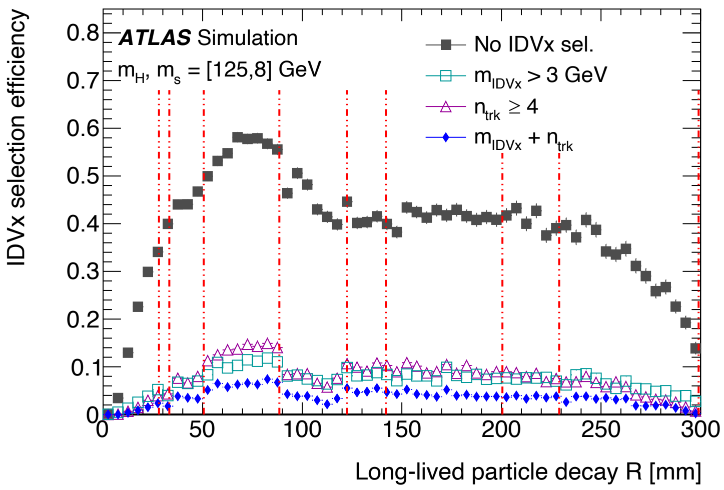


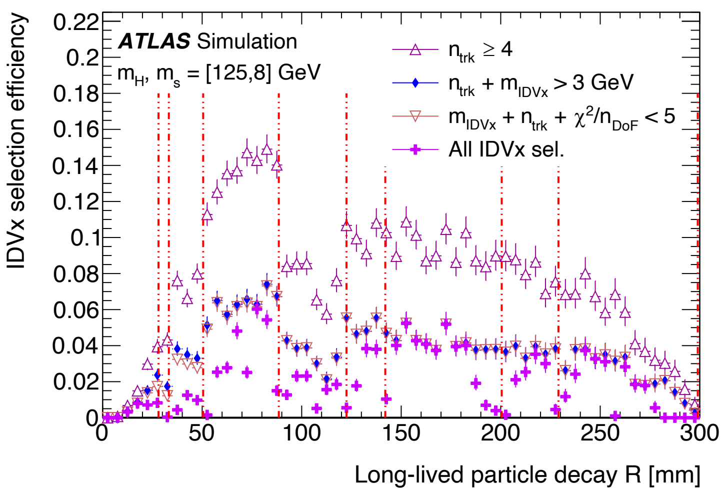


IDVx selection efficiency

- Impact on selection efficiency of each selection requirement
- Structure vs R most impacted by material veto
- Relative impact of n_{trk} and m_{IDVx} requirements has strong dependence on LLP mass







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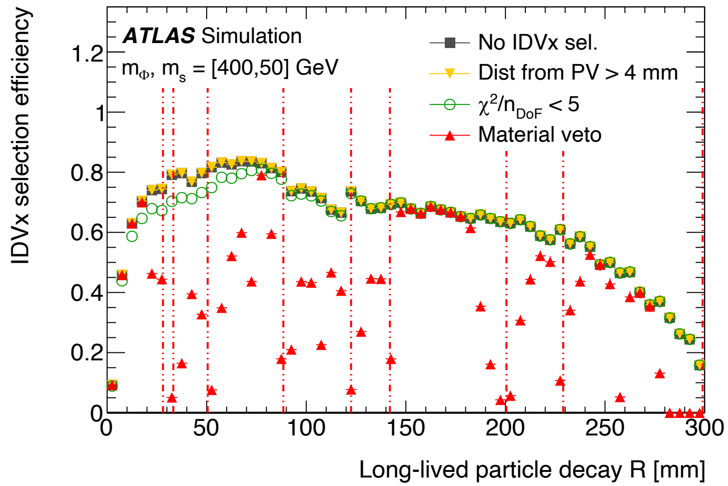

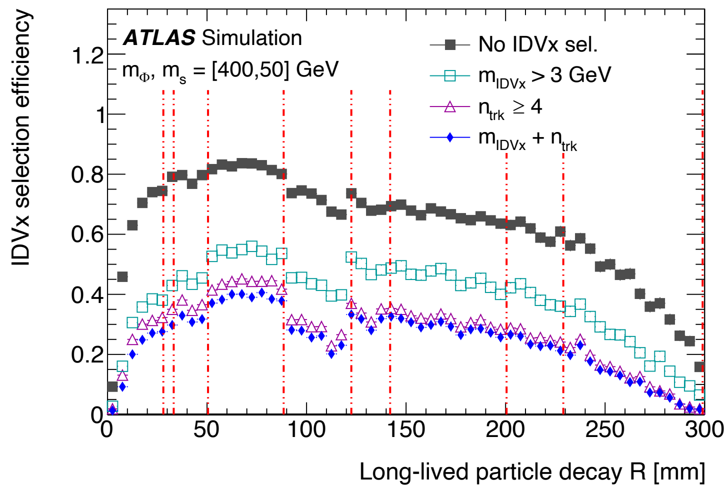

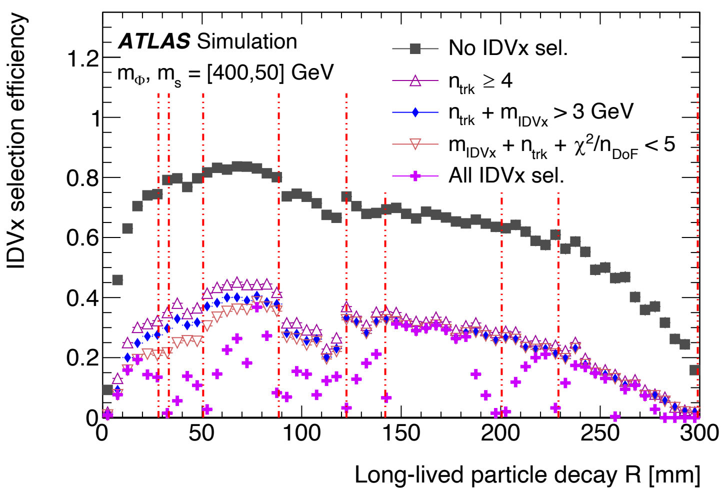

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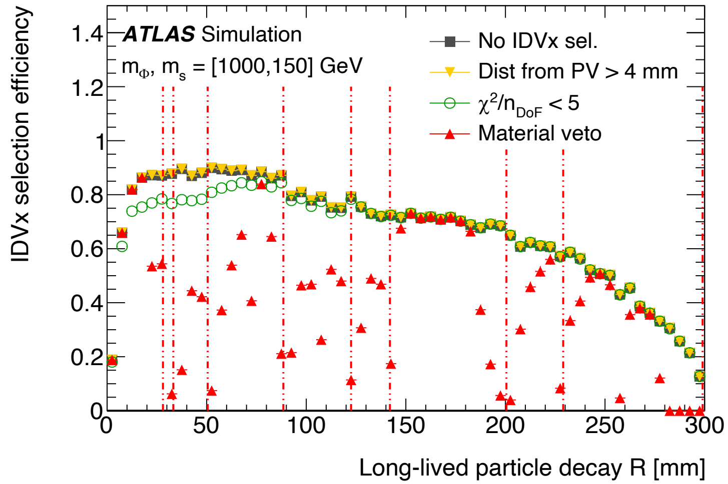

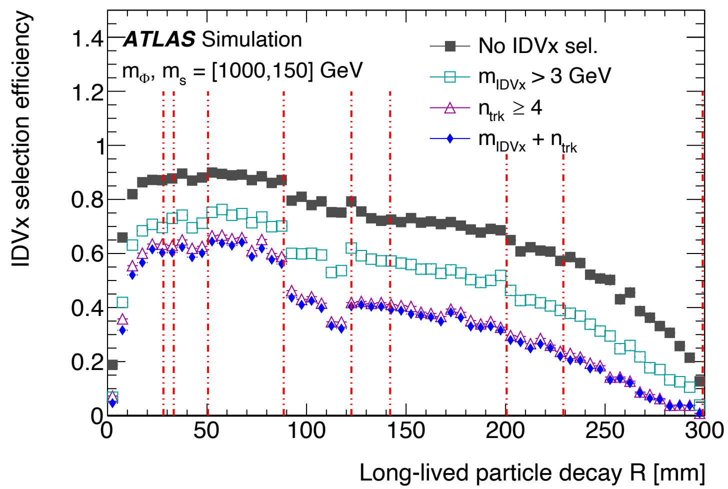

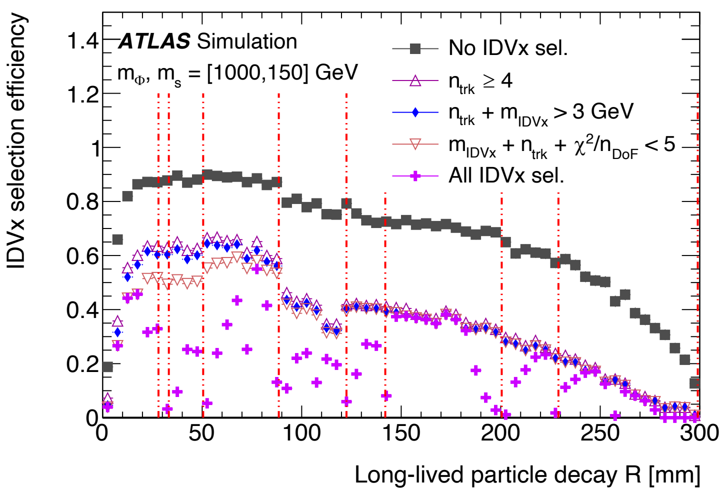

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Overall selection efficiency

Selection requirements Mass point [GeV]	$c\tau$ [m]	Efficiency	Pass trigger	Good MSVx	IDVx	$n_{\mathrm{trk}} \geq 4$	$m_{\mathrm{IDVx}} > 3$ GeV
$m_H, m_s = [125, 8]$	0.200	Total	2.71%	1.07%	0.13%	0.005%	0.003%
		Relative	2.71%	39.3%	12.5%	3.61%	63.2%
$m_H, m_s = [125, 25]$	0.760	Total	5.13%	2.23%	0.30%	0.03%	0.02%
		Relative	5.13%	43.5%	13.3%	9.15%	81.1%
$m_H, m_s = [125, 55]$	1.540	Total	1.98%	0.75%	0.11%	0.01%	0.01%
		Relative	1.98%	37.9%	14.2%	10.1%	85.4%
$m_\Phi, m_s = [200, 50]$	1.070	Total	7.06%	3.05%	0.47%	0.07%	0.06%
		Relative	7.06%	43.2%	15.3%	15.0%	83.9%
$m_\Phi, m_s = [400, 50]$	0.700	Total	13.7%	5.02%	0.73%	0.10%	0.09%
		Relative	13.7%	36.5%	14.5%	14.3%	83.5%
$m_\Phi, m_s = [600, 50]$	0.520	Total	16.4%	4.77%	0.69%	0.08%	0.07%
		Relative	16.4%	29.0%	14.5%	12.2%	78.4%

Data driven background, validation

	n_{obs}	
Region *Bkg*	6,099,660	
Region *Bkg+IDVx*	45	
Region *Sig–IDVx*	156,805	
	n_{pred}	n_{obs}
Region *Val*, 2-*trk*	11,269 ± 46 (stat.)	11,470
Region *Trig*, 3-*trk*	1750 ± 64 (stat.)	2132
Region *Sig*	1.16 ± 0.18 (stat.) ± 0.29 (syst.)	1

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ATLAS EXPERIMENT

Data driven background, validation

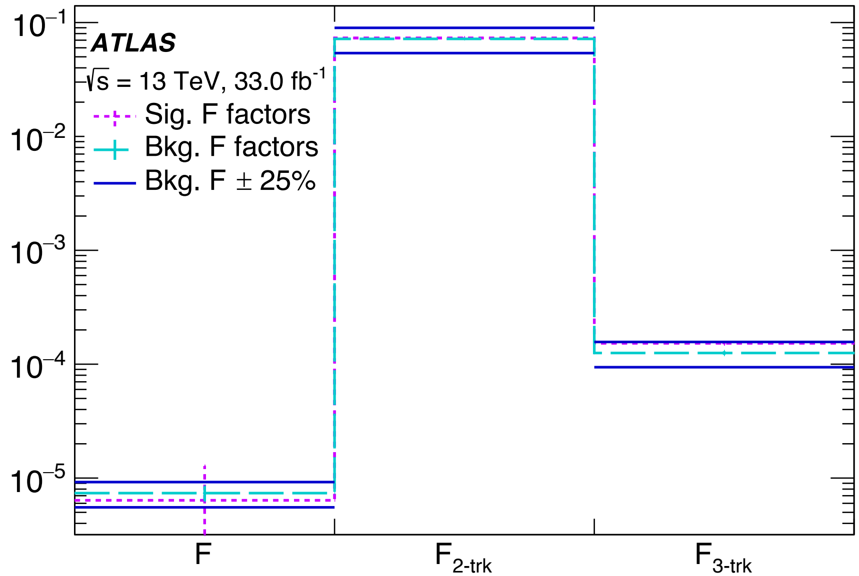
The factors used in the background estimation and the validation regions.

$F_{2\text{-}trk}$, and $F_{3\text{-}trk}$ factors are the *F* factors used to predict the number of events in the 2- and 3- track validation regions.

The F_* factors are compared using the background events, as in $F_{Bkg.} = N_{Bkg,2\text{-}trk}/N_{Bkg}$, or signal-like events, as in $F_{Sig.} = N_{Val,2\text{-trk}}/N_{Sig-IDVx}$.

F_*, ±25% shown in solid blue lines
- All variations, not considering statistical uncertainties, fall within 25%.

(Error bars are the stat only)



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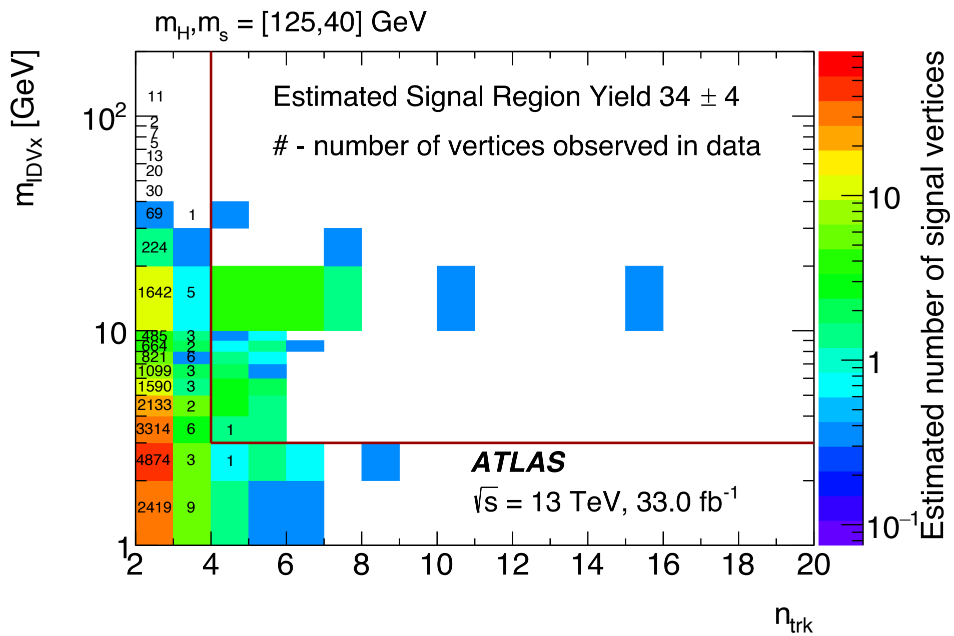
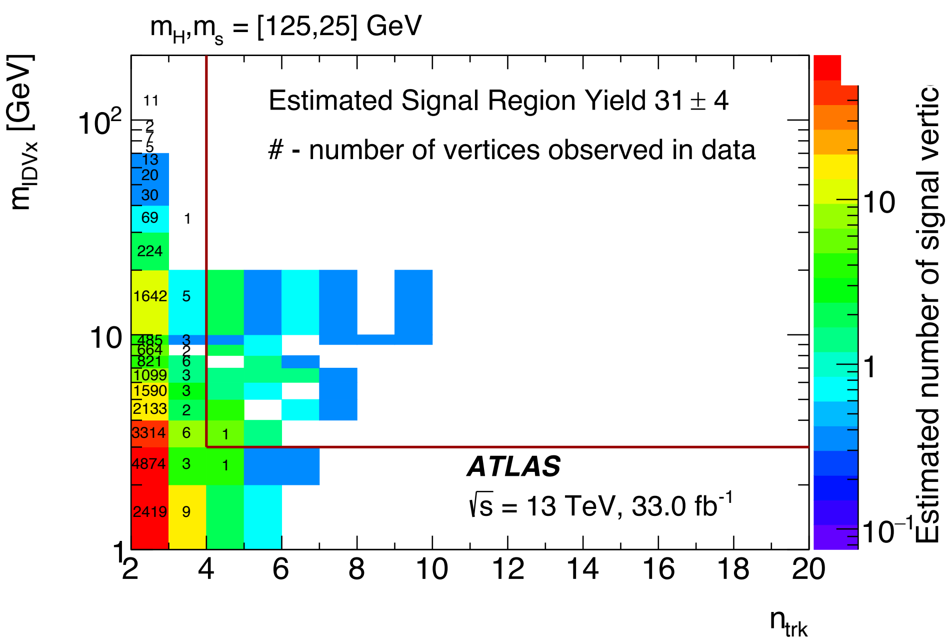
Background vs signal

Two dimensional distributions of m_{IDVx} vs IDVx n_{trk}
-all signal selection criteria other than the requirements on the IDVx *n*trk and *m*IDVx.
-vertices in data are displayed as numbers
-vertices in signal MC as 2D distribution
-final signal region denoted red lines.



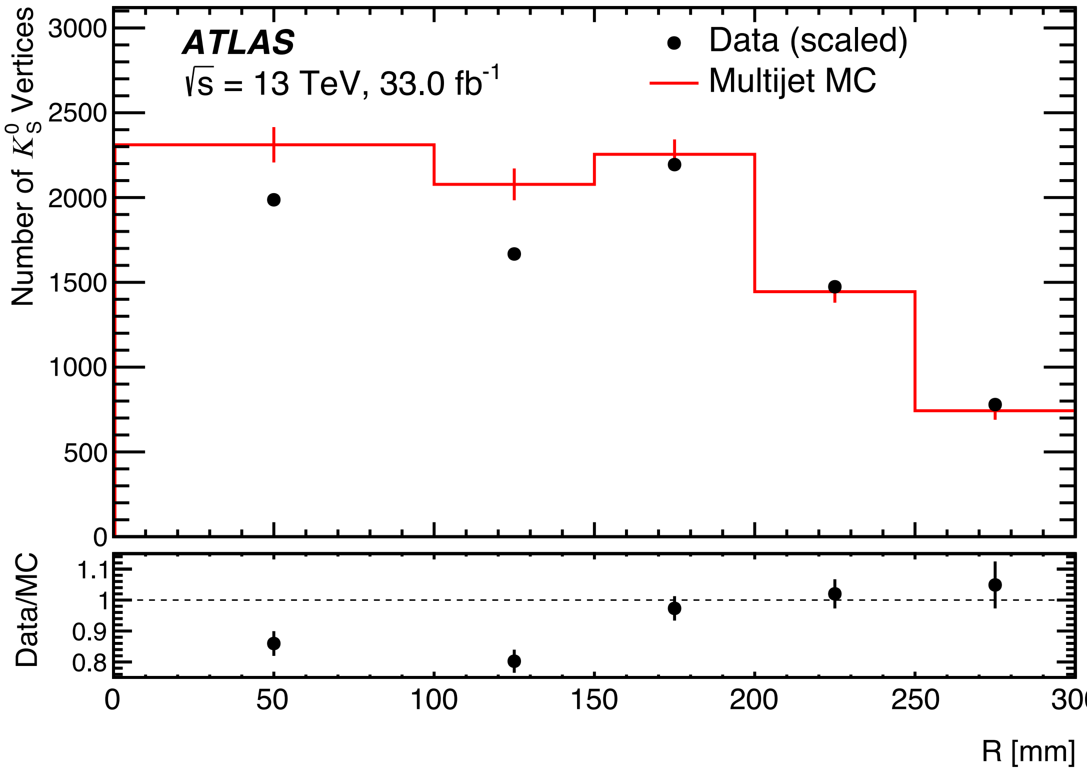


1 event in data (also 1 IDVx in data) consistent with

Estimated yield in the signal region for MC samples assuming ggF production of the Higgs boson and a 10% BR for the Higgs boson decay to the hidden sector.

Systematic Uncertainties – displaced track/vertex in ID

- Data/MC systematic uncertainty
  - Study performed using K_S^0 vertices reconstructed using ST and LRT in multijet MC and in data
  - Good agreement found in kinematic distributions
  - Distributions of data and MC LRT-only vertices binned in R
  - Distributions normalized by ST-only K_S^0 vertices
  - Largest difference in radial bins taken as uncertainty
  - Dominant syst uncertainty in this analysis



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Other systematic Uncertainties

- Data/MC scale factor impact on trigger efficiency uncertainty
  - Scale factors varied up and down by uncertainty on their fit, resulting trigger eff evaluated
  - Flat vs decay position. Uncertainties developed for barrel, endcap, per mass sample
- Pileup uncertainty
  - Impact trigger eff and MSVx reco eff
  - Pileup reweighting varied up and down by uncertainty, resulting effs compared to nominal
  - Flat vs decay position, uncertainties developed for barrel, endcap, per mass point
- PDF uncertainty
  - PDF value comes from 100 fits
  - Trigger, MSVx reco eff compared for each PDF fit vs central value
  - Flat vs decay position, uncertainties developed for barrel, endcap, per mass point
- Combination of all these, at most ~5.5% per mass sample in barrel or endcap on MSVx reco eff, and ~4.8 on trigger eff

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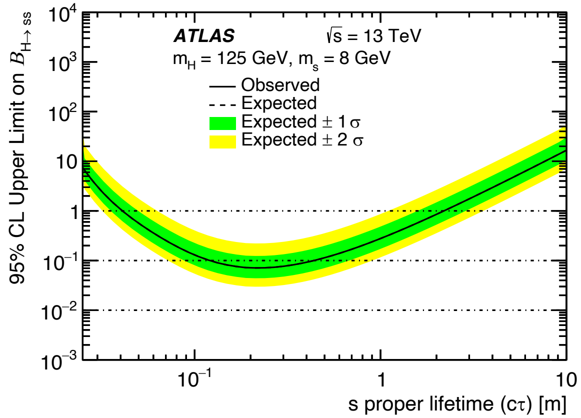
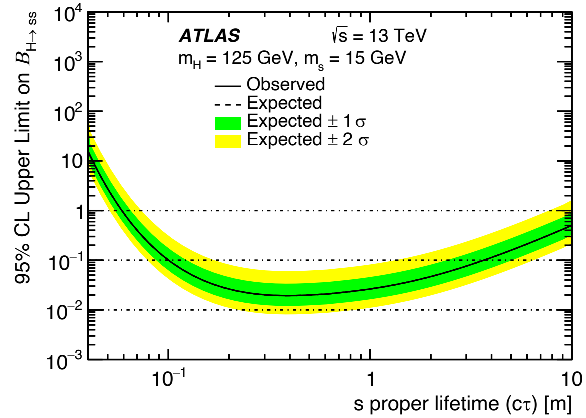
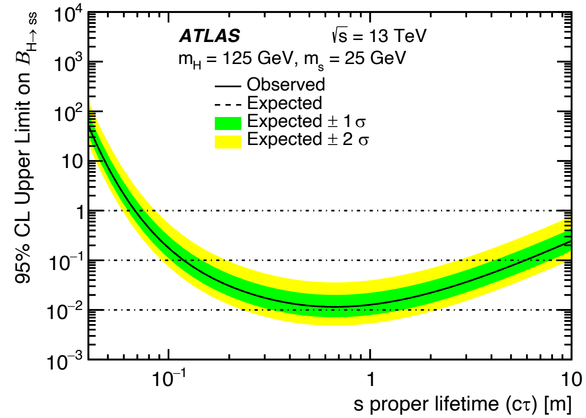
Results

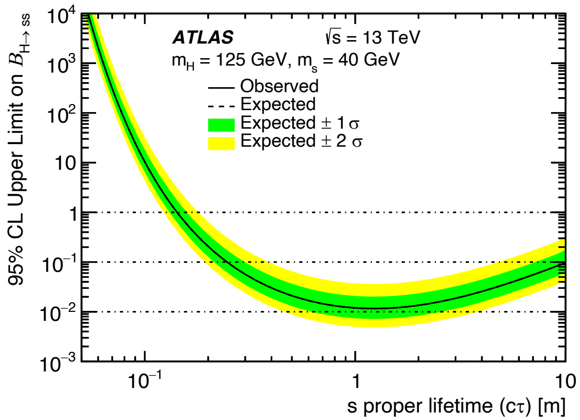
- More limits

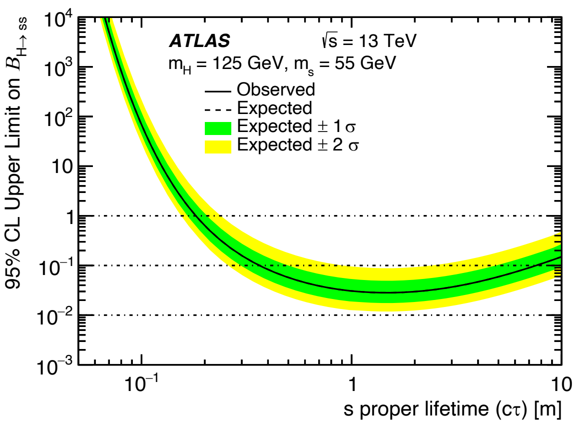




Brazil plots for each mass sample

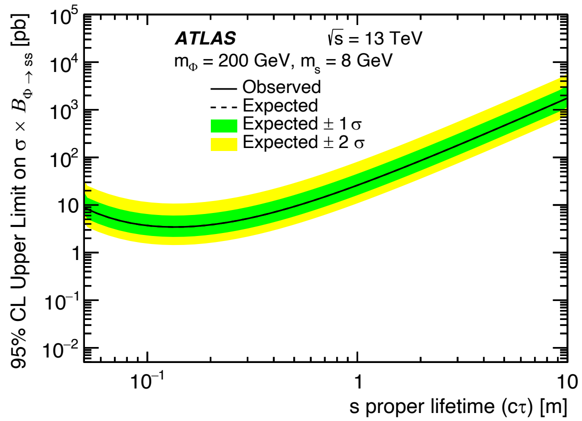


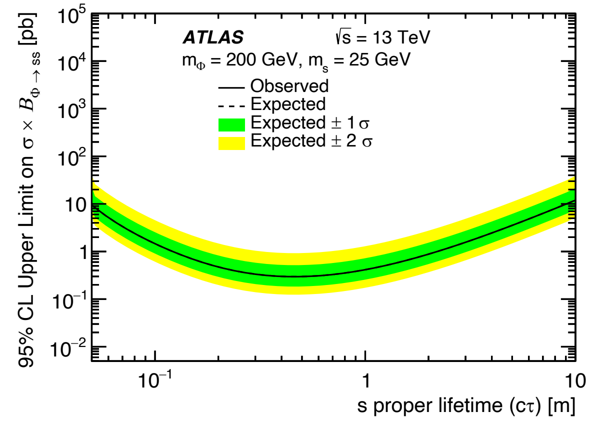


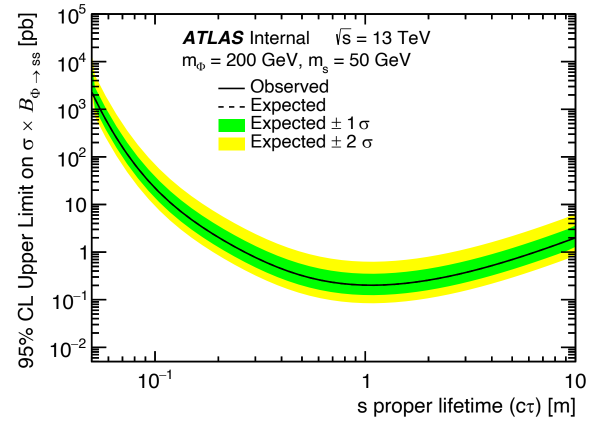


Results

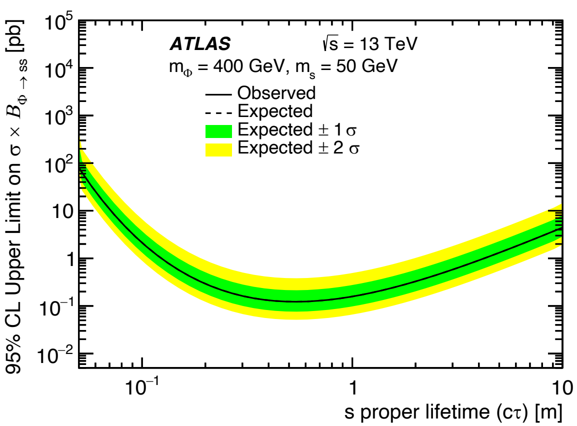
- More limits

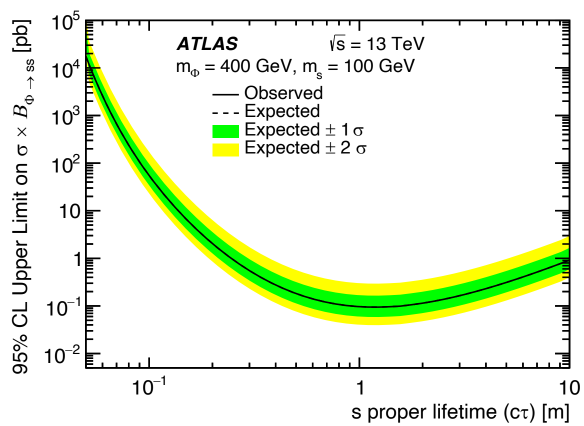






Brazil plots for each mass sample





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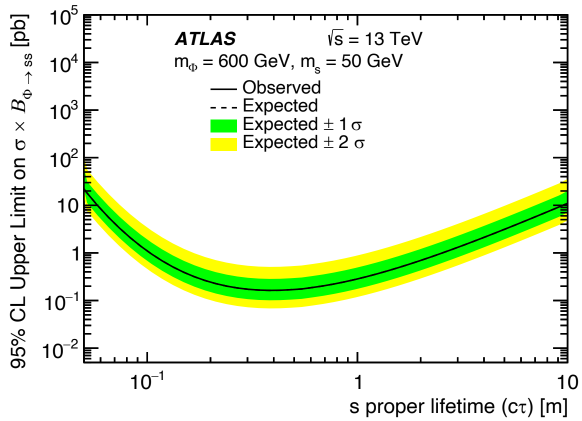
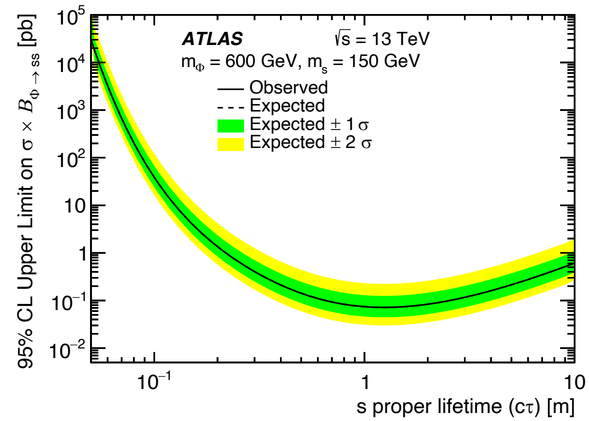
Results

- More limits





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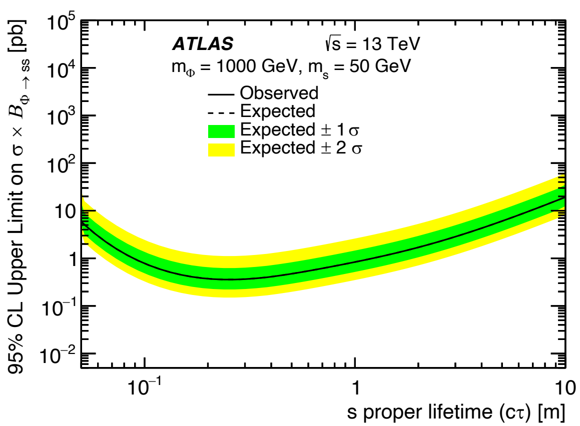
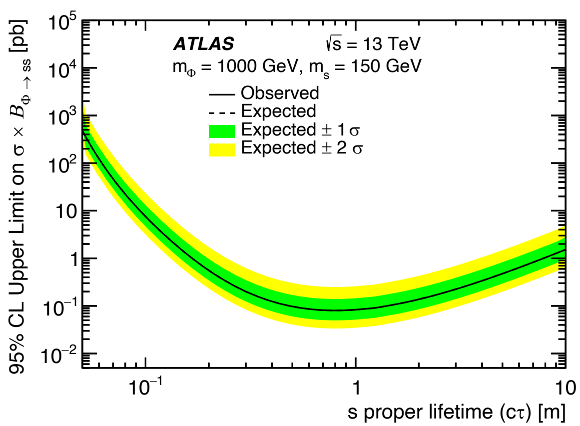
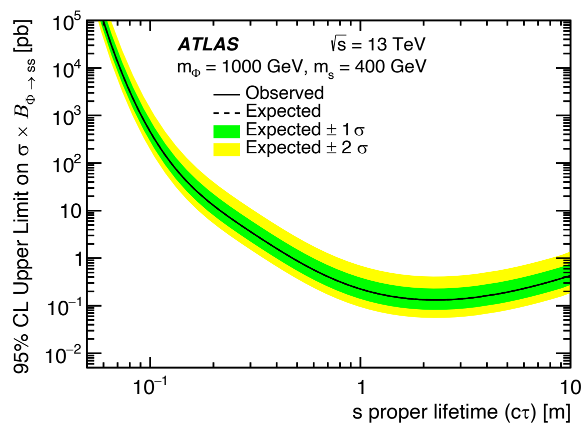
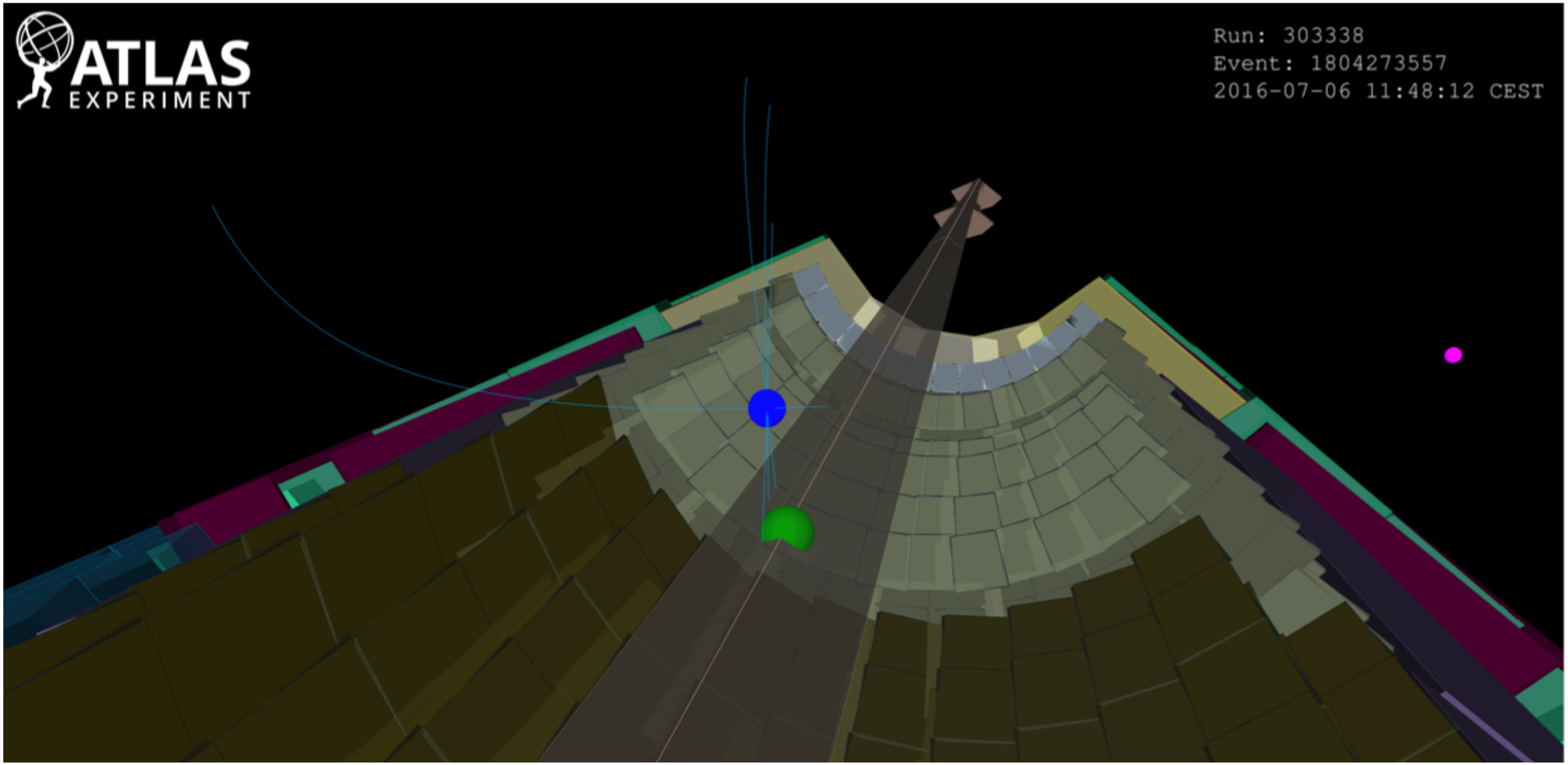






Event in data



Event in data