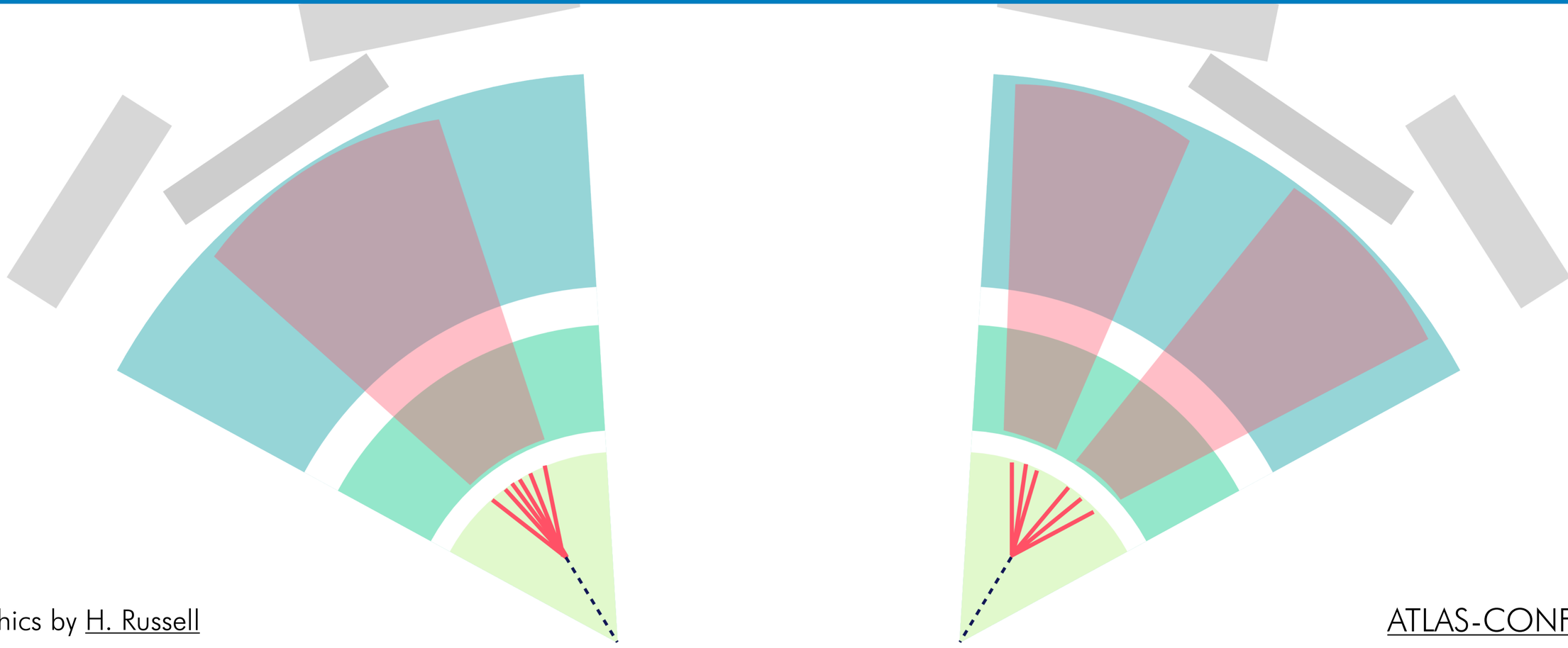
Search for exotic decays of the Higgs boson to long-lived particles using displaced vertices in the ATLAS inner detector

ATLAS EXPERIMENT UMassAmherst

Jackson Burzynski, on behalf of the ATLAS Collaboration | **LHCLLP9**



Graphics by H. Russell

ATLAS-CONF-2021-005

Analysis Overview

Many BSM models predict **exotic Higgs decays**

- **Top down:** Neutral naturalness (mirror glueballs)
- **Bottom up:** Dark sectors, SM+scalar

Decays back to SM via **off-shell Higgs** or **small Higgs mixing**

- long lifetimes
- higgs-like BRs

Benchmark model: **pseudoscalar boson (a)**

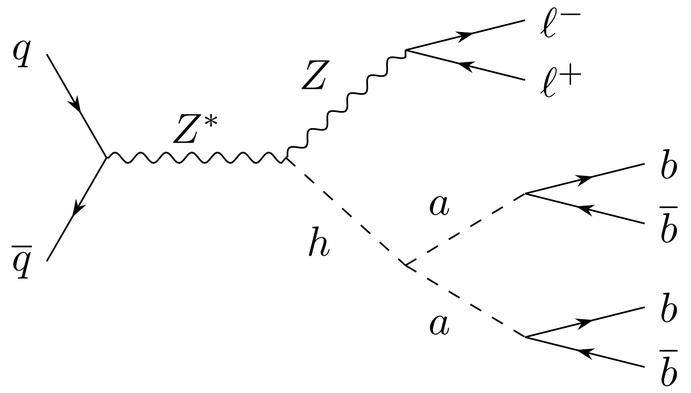
- $15 < m_a < 55$ GeV
- $10\text{mm} < c\tau_a < 1\text{m}$

Yukawa-like branching ratios:

$\Rightarrow$ assume $Br(a \rightarrow bb) = 100\%$

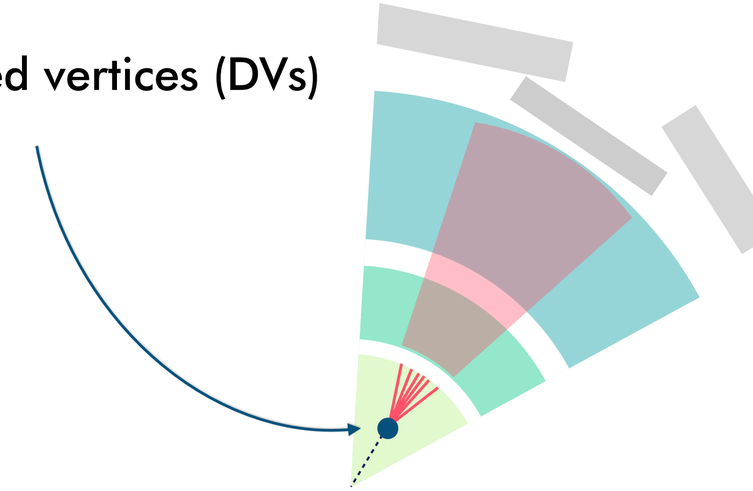
Difficult to trigger, so focus on **associated production**

- **ZH mode** provides a very clean signature



Signature of interest:

two leptons, and two **displaced vertices (DVs)** in the inner detector

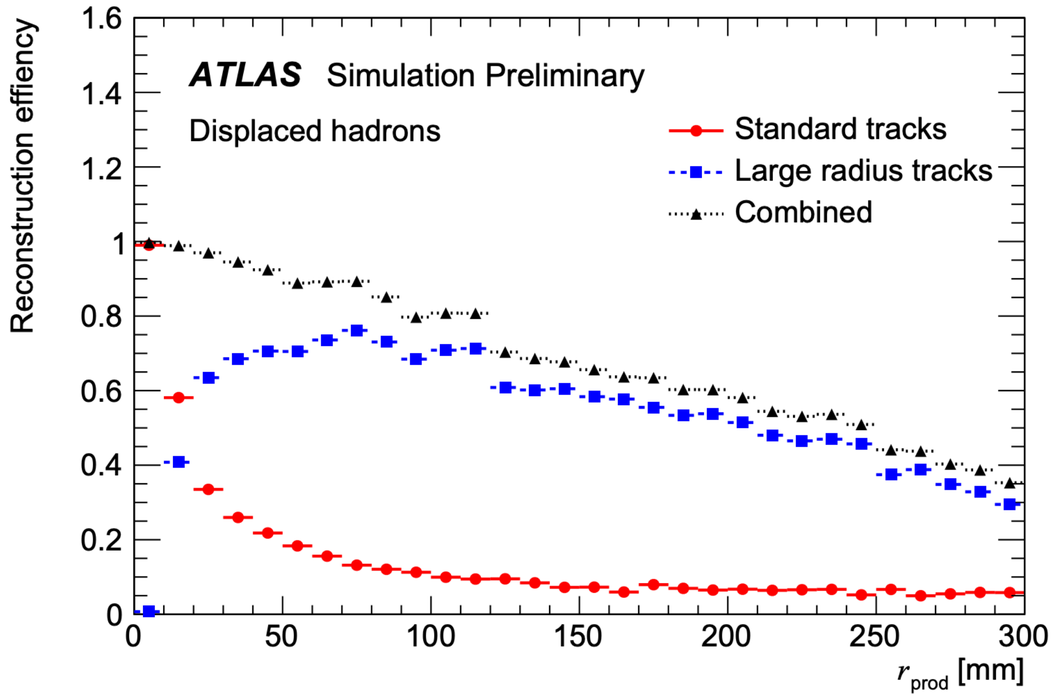


Reconstruction

Dedicated **"large radius tracking" (LRT)**

- secondary tracking pass run on leftover hits
- loosened requirements on hits, d_0, z_0
- high efficiency, higher CPU cost!

ATL-PHYS-PUB-2017-014



Inclusive **secondary vertex reconstruction**

- use combined collection of standard and large radius tracks
- optimized for LLP decays

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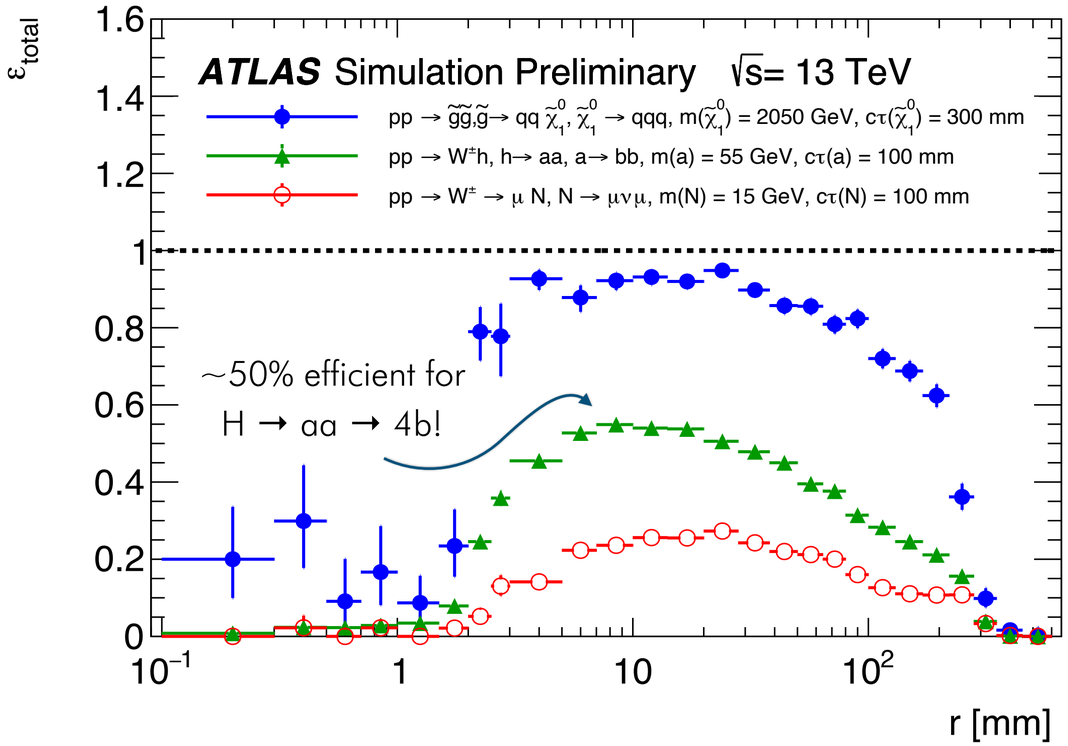


Analysis Strategy

Trigger on **prompt leptons** from Z decay

- require one electron/muon with $p_T > 26$ GeV

Filter on **displaced jets** to preselect events for LRT reconstruction

- use two jet-level observables to identify interesting events
- necessary to reduce rate due to high LRT CPU consumption

Offline, require

- Two same flavor opposite sign leptons
- $66 < m_{ll} < 116$ GeV
- At least two jets with $p_T > 20$ GeV

Charged hadron fraction (CHF)

- fraction of jet p_T from prompt tracks

$$\mathrm{CHF} = p_{\mathrm{T}}^{\mathrm{trk,prompt}} / p_{\mathrm{T}}^{\mathrm{jet}}$$

"alpha max"

- for each PV, define α_i as the fraction of track p_T matched to vertex

$$\alpha_i = p_{\mathrm{T}}^{\mathrm{trk} \in i} / p_{\mathrm{T}}^{\mathrm{trk}}$$

- α_{max} is the max value of α_i among all PVs

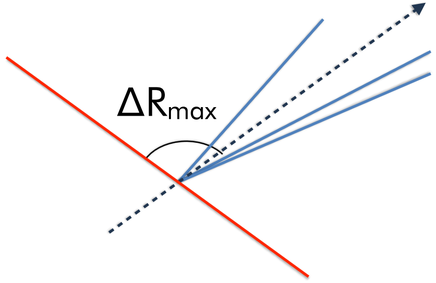
$$\alpha_{\mathrm{max}} = \max\{\alpha_i\}$$

Require: CHF < 0.05 OR $\alpha_{max} < 0.045$

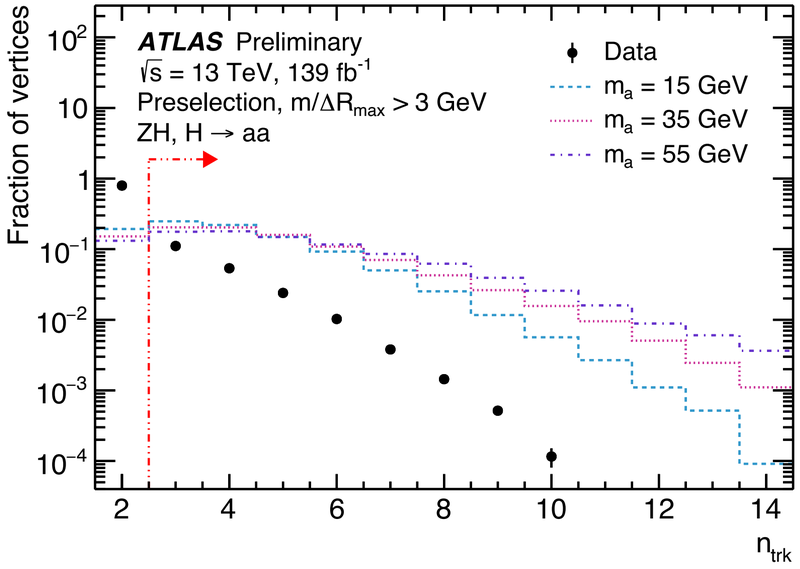
Analysis Strategy

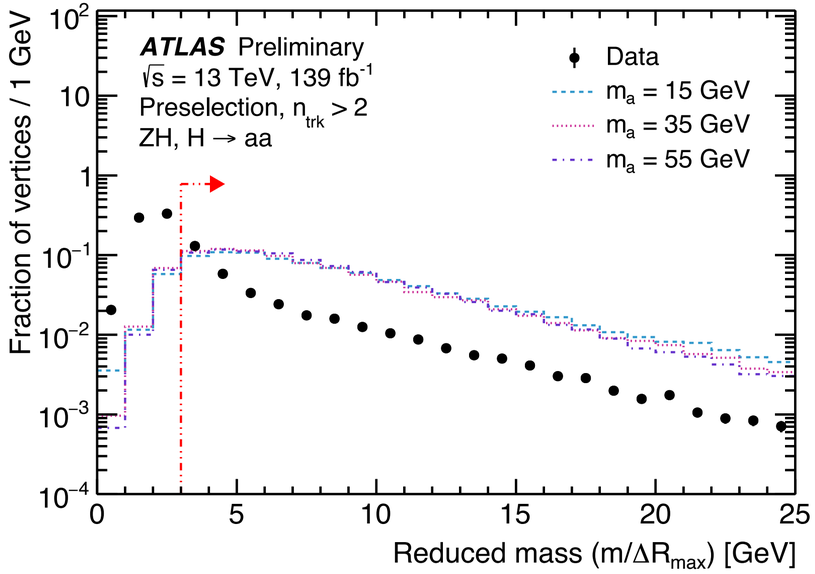
Displaced vertices are required to satisfy:

- material veto → removes hadronic interactions
- $n_{trk} \geq 3$ → removes metastable SM resonances
- $m/\Delta R_{max} > 3$ GeV → removes vertices from random crossings
- $\Delta R(vtx,jet) < 0.6$ → facilitates background modeling



Selection type	Requirement
Track pruning	$\lvert d_0^{DV}\rvert < 0.8$ mm $\lvert z_0^{DV}\rvert < 1.2$ mm $\sigma(d_0^{DV}) < 0.1$ mm $\sigma(z_0^{DV}) < 0.2$ mm
Vertex preselection	$\chi^2/n_{DoF} < 5$ $r < 300$ mm $\lvert z\rvert < 300$ mm pass material veto
Vertex selection	$n_{trk} > 2$ $m/\Delta R_{max} > 3$ GeV $r/\sigma(r) > 100$ $\max(\lvert d_0\rvert) > 3$ mm $\Delta R_{jet} < 0.6$





Events classified based on the **number of displaced vertices** matched to jets:

$n_{DV} < 2$ → **Control region**

$n_{DV} \geq 2$ → **Signal region**

Background estimate

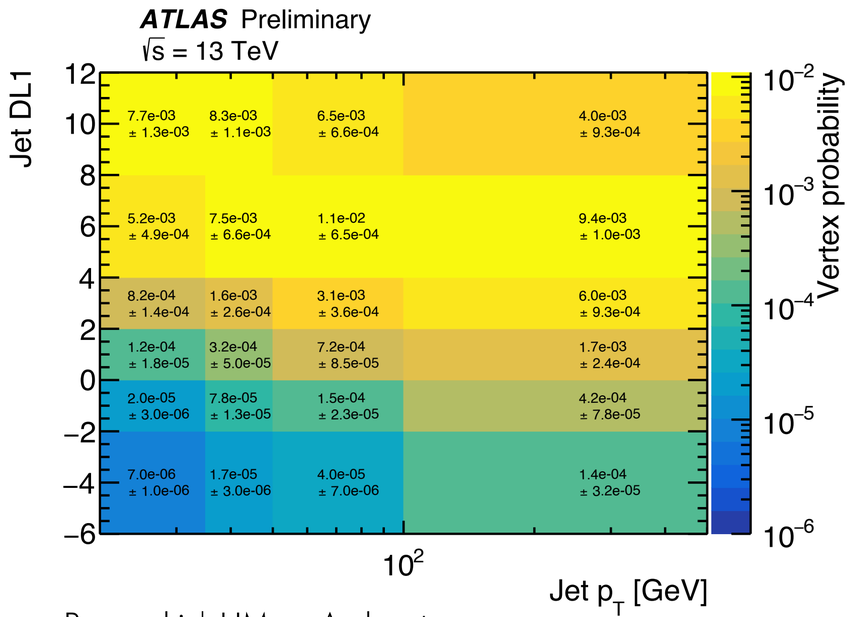
Probability for a jet to contain a DV increases with p_T and **b-tag score (DL1)**

parameterize background using **per-jet probability map** based on these observables

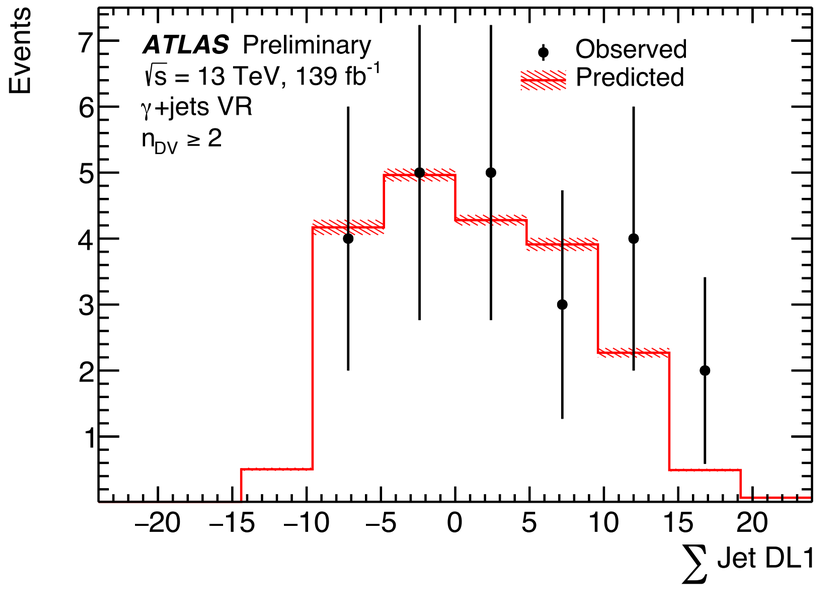
Compute probability that an event contains ≥ 2 DVs from the jets in the event

$$P_{\text{event}}(n_{\text{DV}} = 1|j_{1-4}) = \sum_{i=1}^{4} P_{\text{jet}}(n_{\text{DV}} = 1|j_i) \times \prod_{k \neq i} \left(1 - P_{\text{jet}}(n_{\text{DV}} = 1|j_k)\right)$$

Measure per-jet vertex probability in CR



Validate in γ+jets validation region

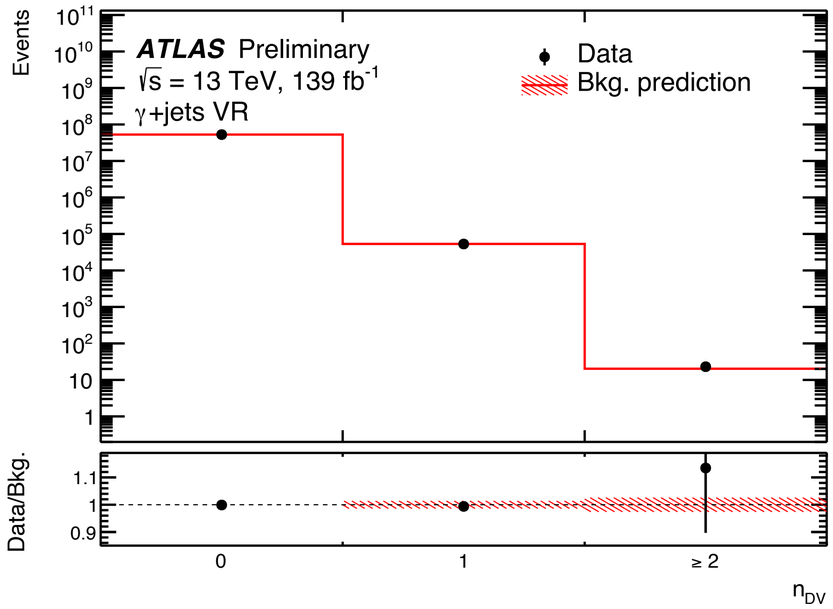


Uncertainties

Background

- Statistical uncertainty derived from **pseudoexperiments** using statistically varied per-jet maps
- Systematic uncertainty derived from **21% statistical uncertainty** on observed number of events in VR

Final estimate: **1.30 ± 0.08 (stat.) ± 0.27 (syst.)**



Signal

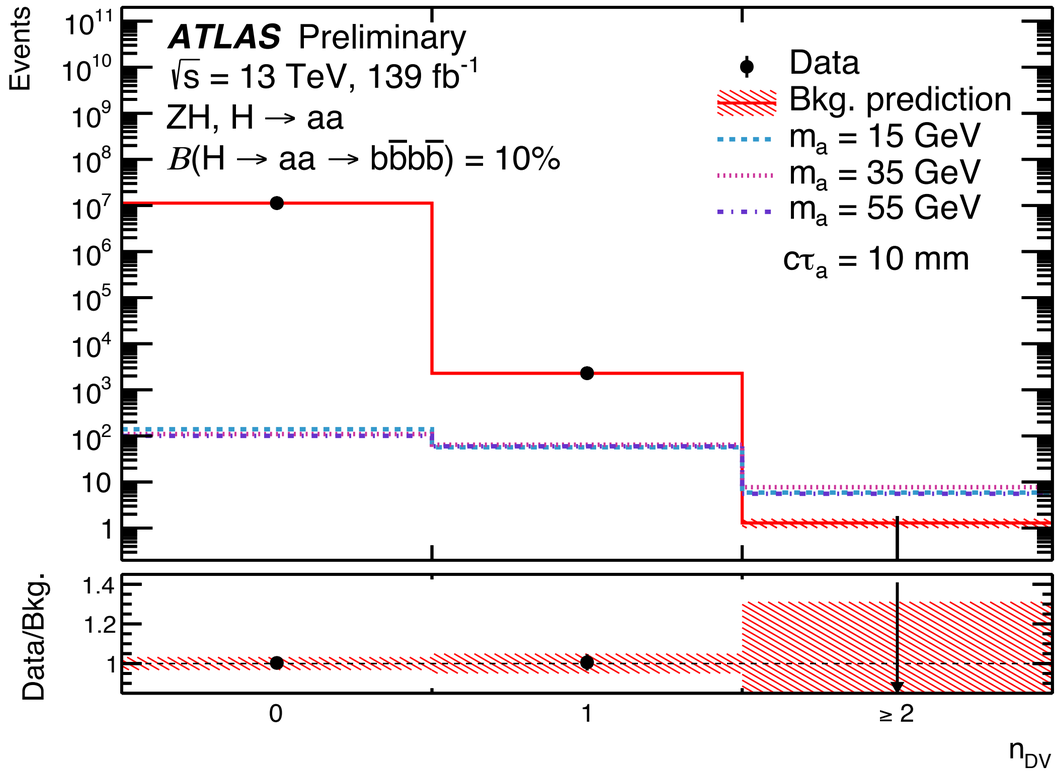
Dominant uncertainty from LRT

- Measure by comparing yields of **K-short vertices** in data and MC
- Propagate to vertices by **randomly removing tracks** and recomputing signal yield

Source	Uncertainty (%)
Theory	4.7
Luminosity	1.7
Pileup reweighting	2.6
Electron identification	1.6
Electron calibration	0.4
Muon reconstruction	0.9
Muon calibration	0.4
Electron trigger	0.7
Muon trigger	1.3
Jet energy scale	1.4
Jet energy resolution	1.3
Filter	2.8-3.8
LRT	2.4-12
Total	7.4-14

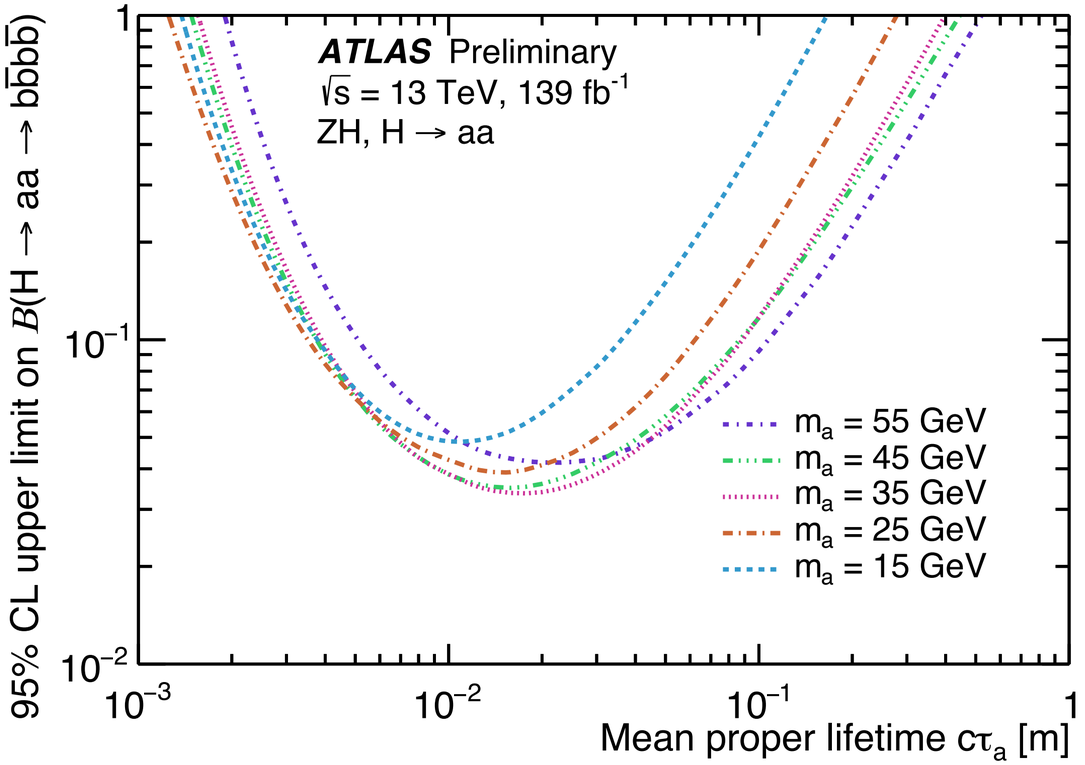
Results

Zero events observed in signal region



Good agreement with background prediction

Limits set on BR(H → aa → bbbb)

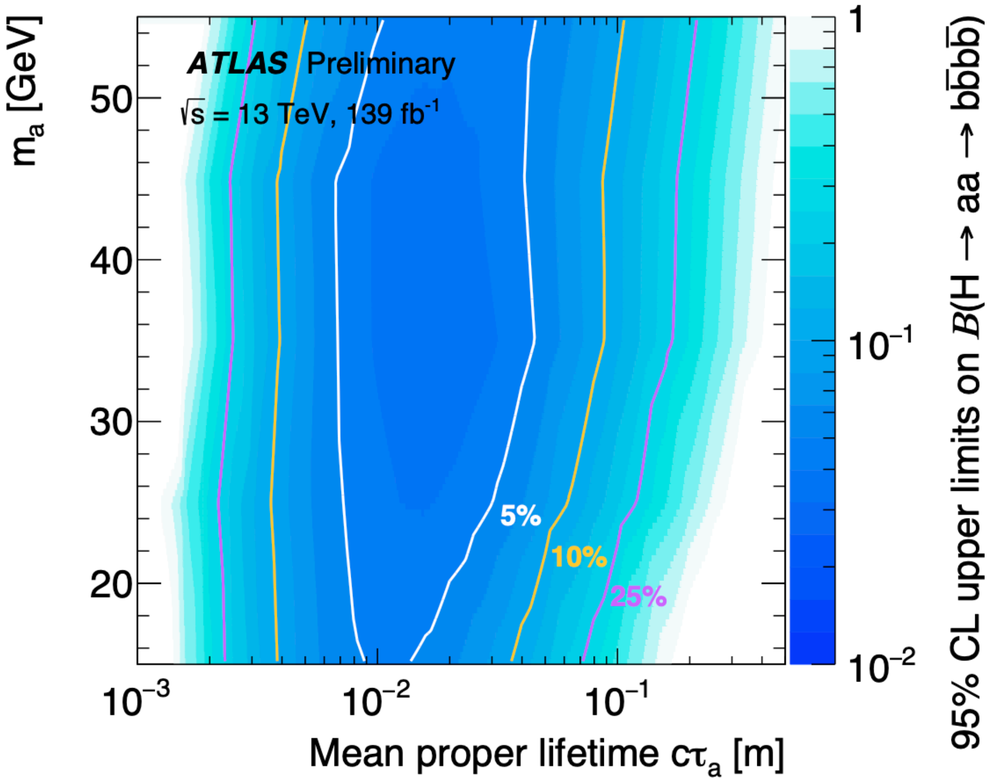


Probe branching ratios of **3-5%**

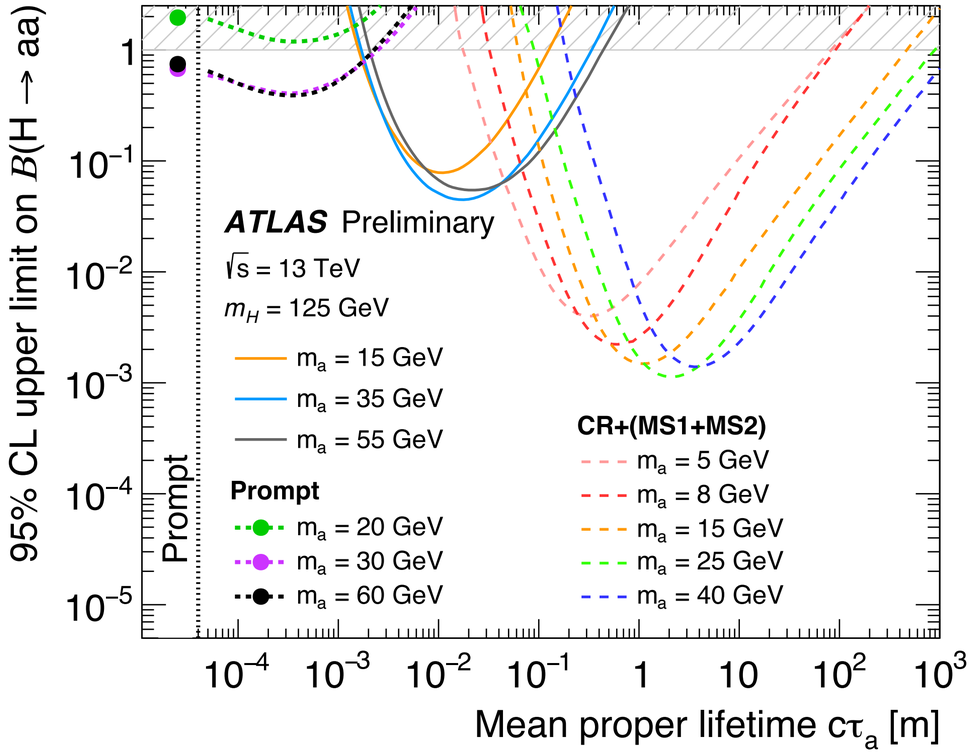
Summary

Limits set on BR(H → aa → bbbb)

10% branching ratios excluded between **~5 and ~100 mm**



Fills a **gap in coverage** left by previous ATLAS analyses



For $m_a < 40$ GeV, these are the **most stringent** limits to date in this lifetime regime!

Future Prospects

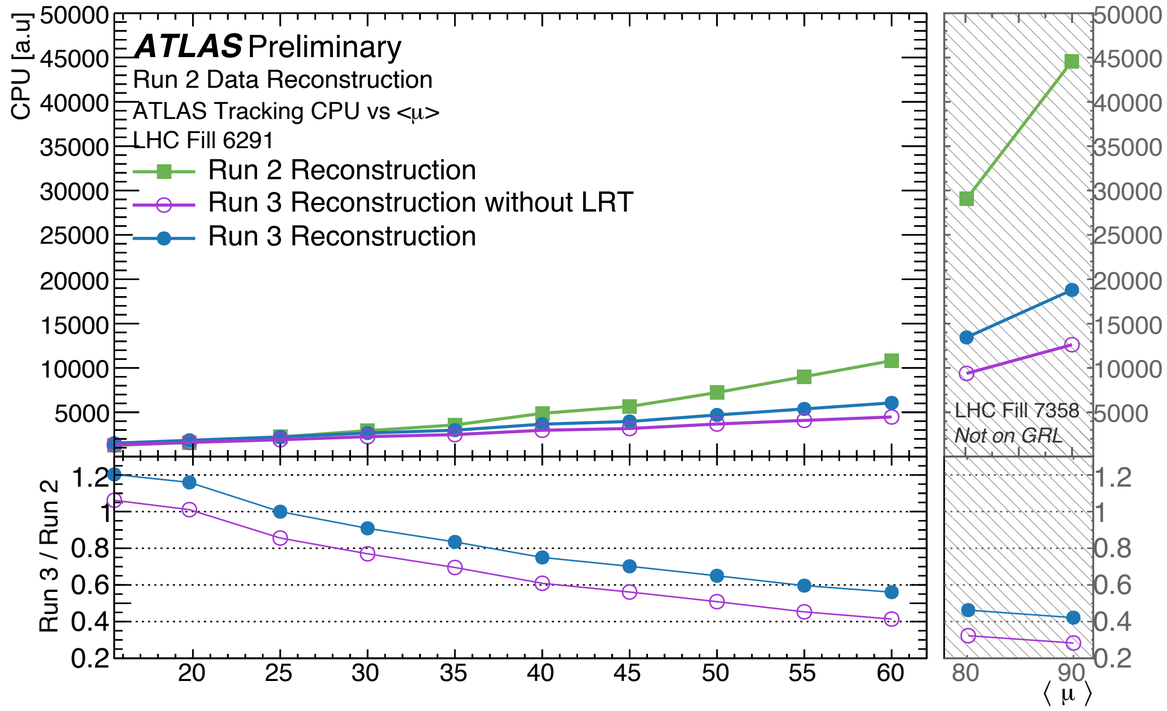
LRT to be included in **standard reconstruction** in Run 3! (ATL-PHYS-PUB-2021-012)

- Eliminates need for custom filters, **greatly simplifies LLP workflow**
- Opens up many possibilities for new ideas and analysis strategies

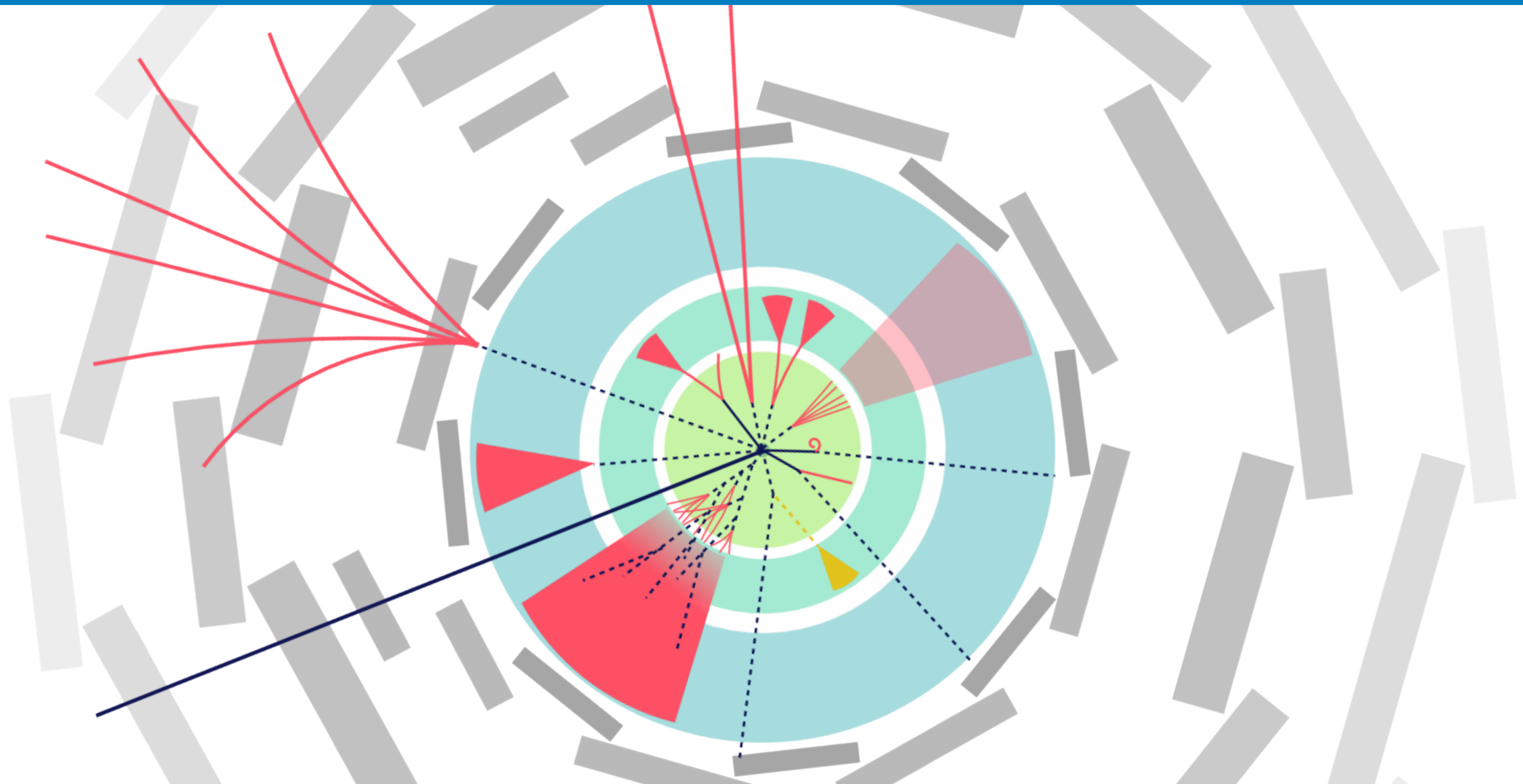
Will allow for **new channels** with different Higgs production modes and **increased sensitivity**

- i.e VBF, ggF

Exciting prospects on the horizon in the search for exotic Higgs decays to LLPs, **stay tuned!**



Backup



Filter

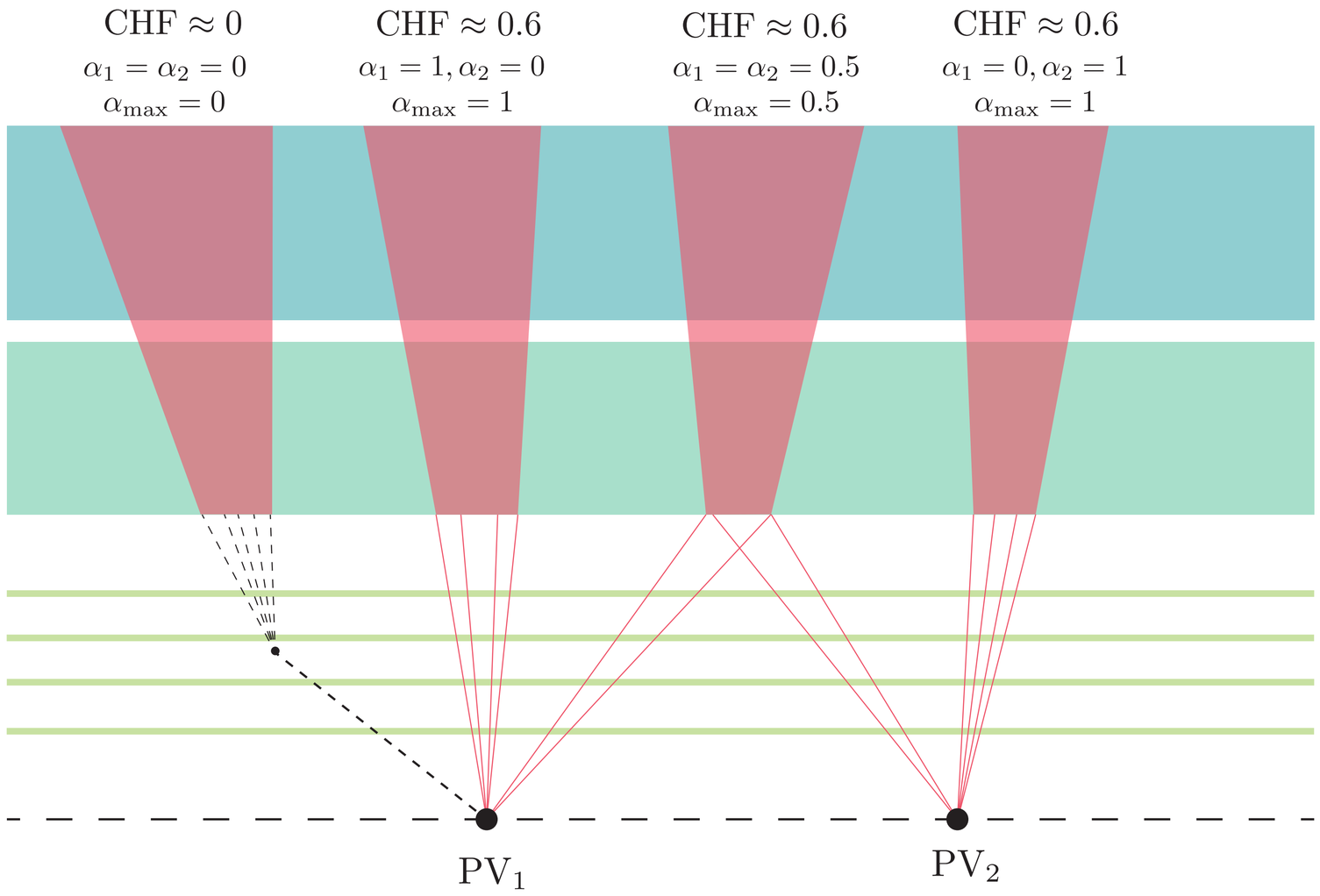
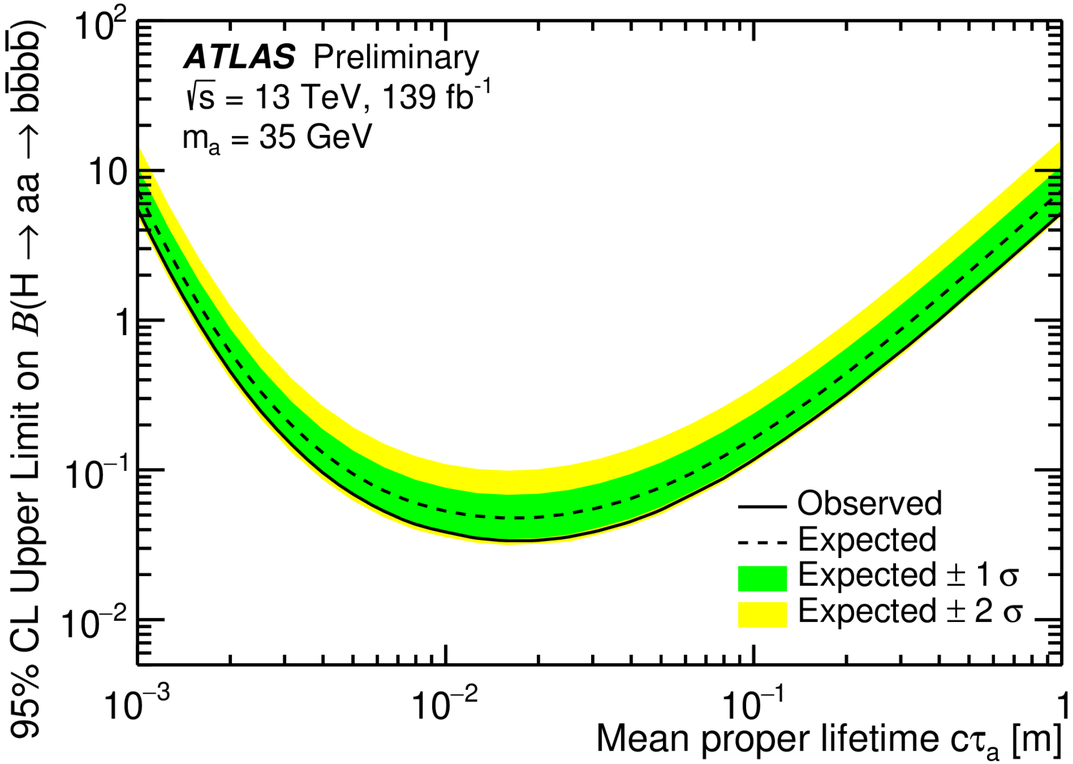
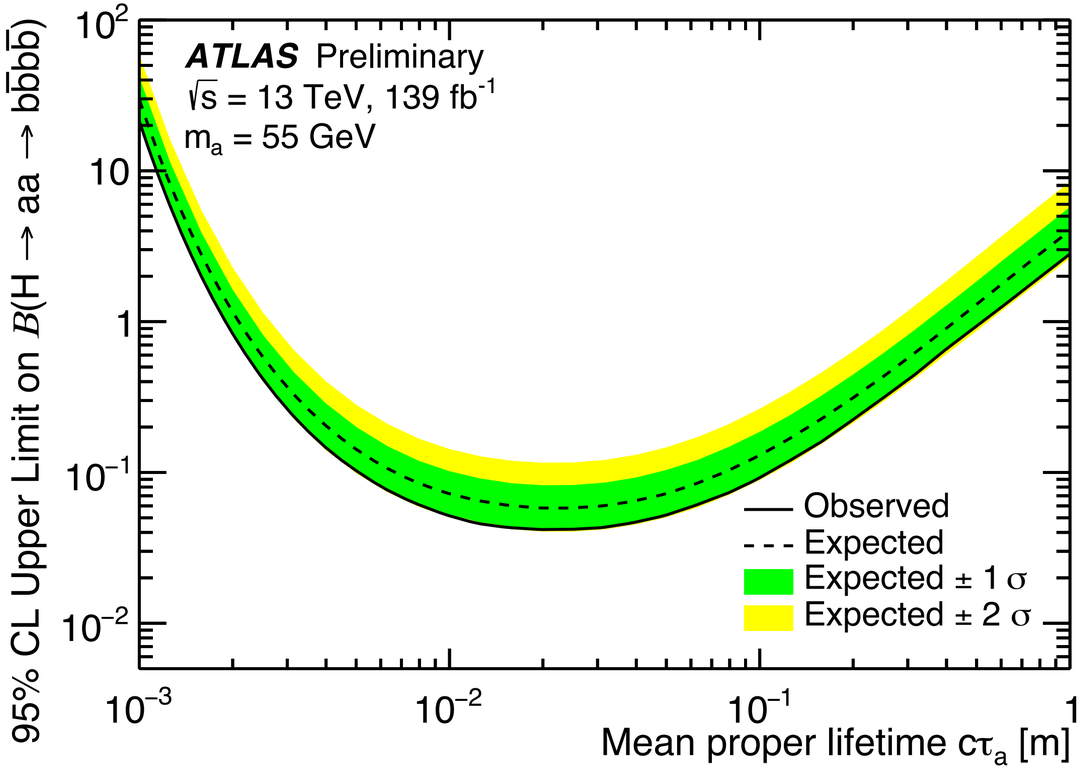


Diagram inspired by Kate Pachal's LHC seminar

Limits


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
ma = 35 GeV
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
95% CL Upper Limit on B(H → aa → bb̄bb̄)
Mean proper lifetime cτa [m]


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
ma = 55 GeV
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
95% CL Upper Limit on B(H → aa → bb̄bb̄)
Mean proper lifetime cτa [m]