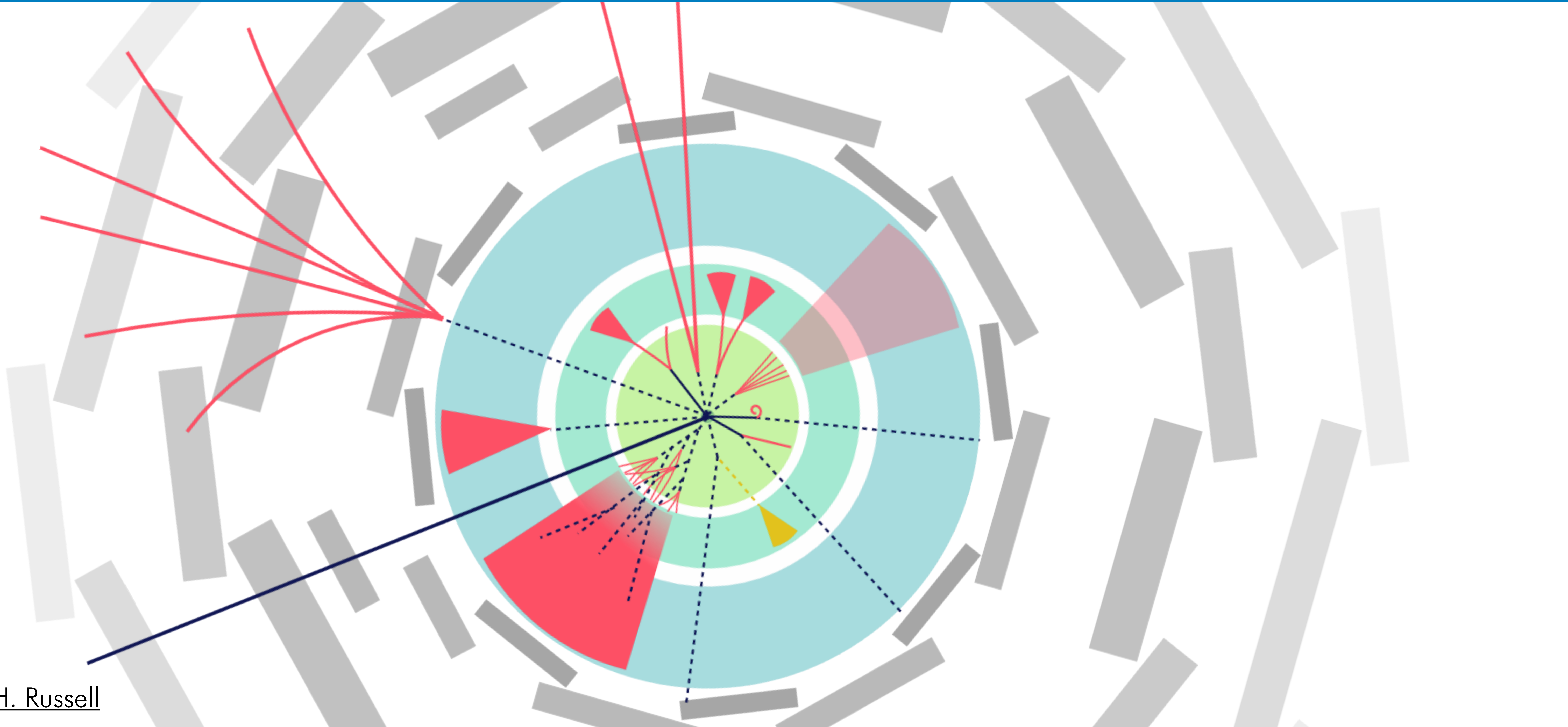
Searches for New Long-lived Particles with the ATLAS detector

ATLAS EXPERIMENT
UMassAmherst

Jackson Burzynski, on behalf of the ATLAS Collaboration | **PHENO 2021**

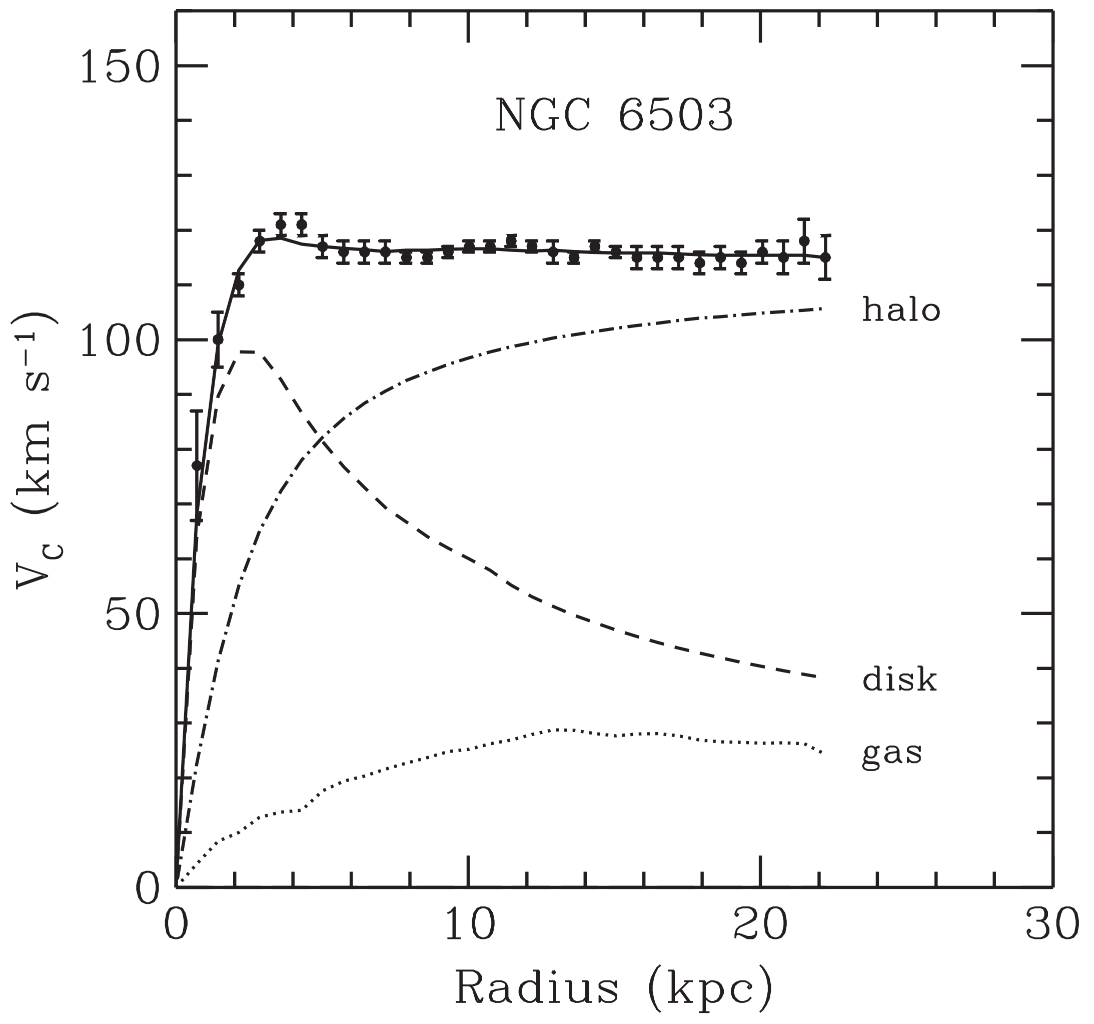


Graphics by H. Russell

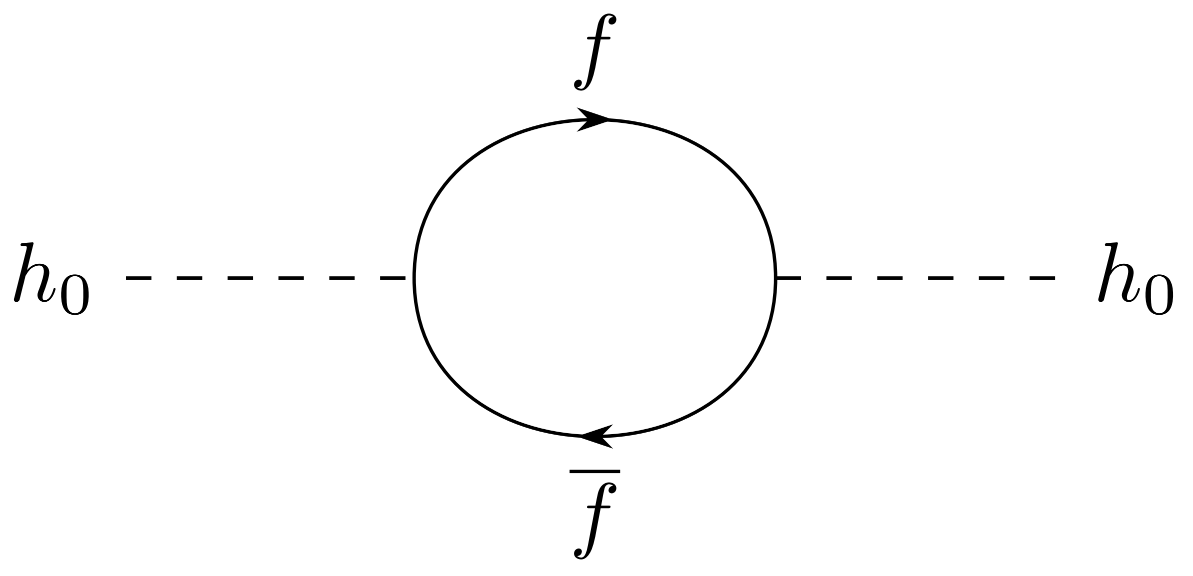
Why long-lived particles?

Elephant in the *Zoom*: **where is the new physics?**

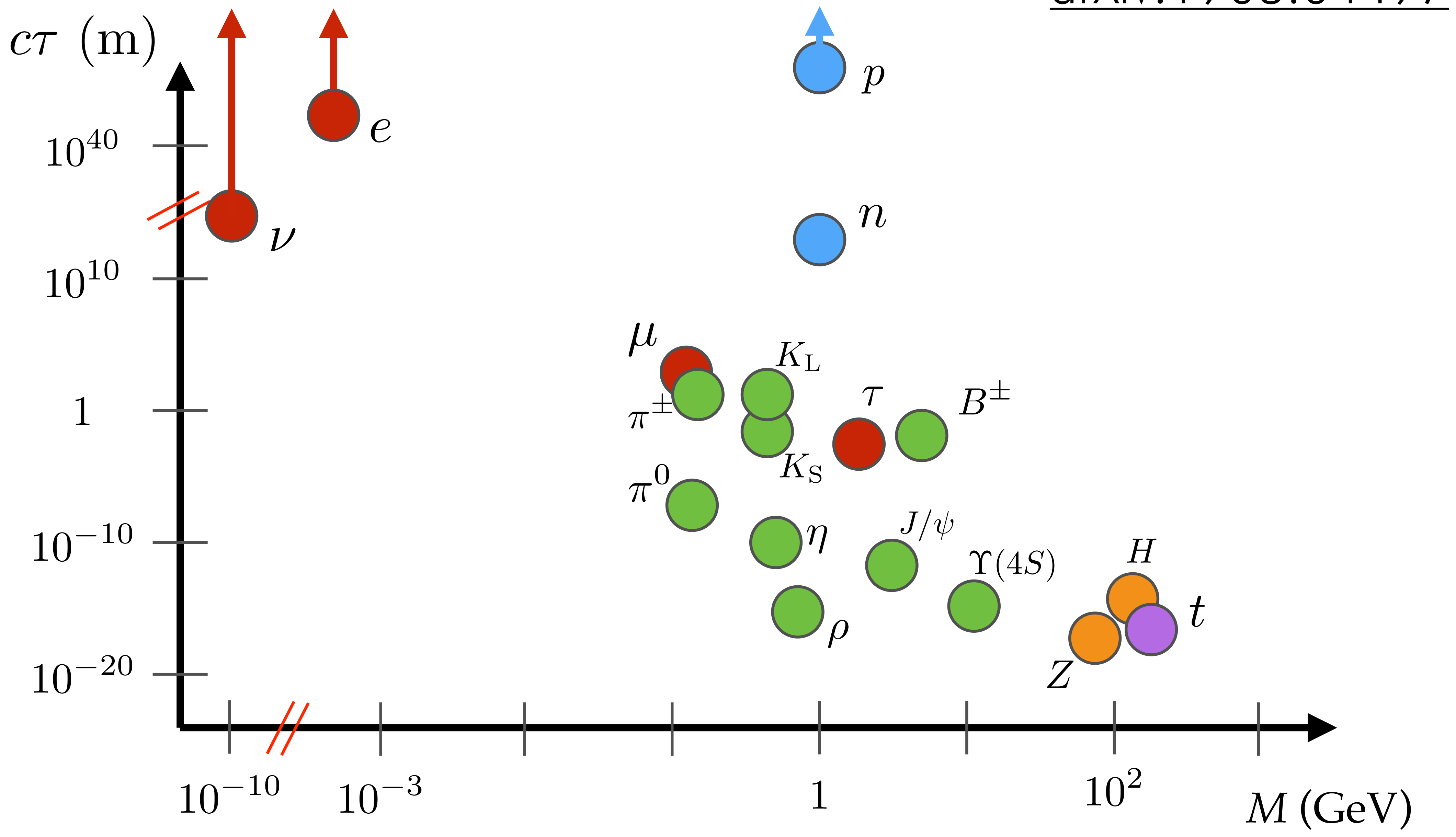
dark matter



hierarchy problem



arXiv:1903.04497



plenty of LLPs in the SM!

Absence of new physics at TeV scale motivates increasing focus on searches for **weakly-coupled** new particles and **exotic signatures**

- Particle lifetime remains an **underexplored** parameter of phase space
- **Long-lived particles (LLPs)** can elude the majority of BSM searches and provide striking detector signatures

Searching for LLPs

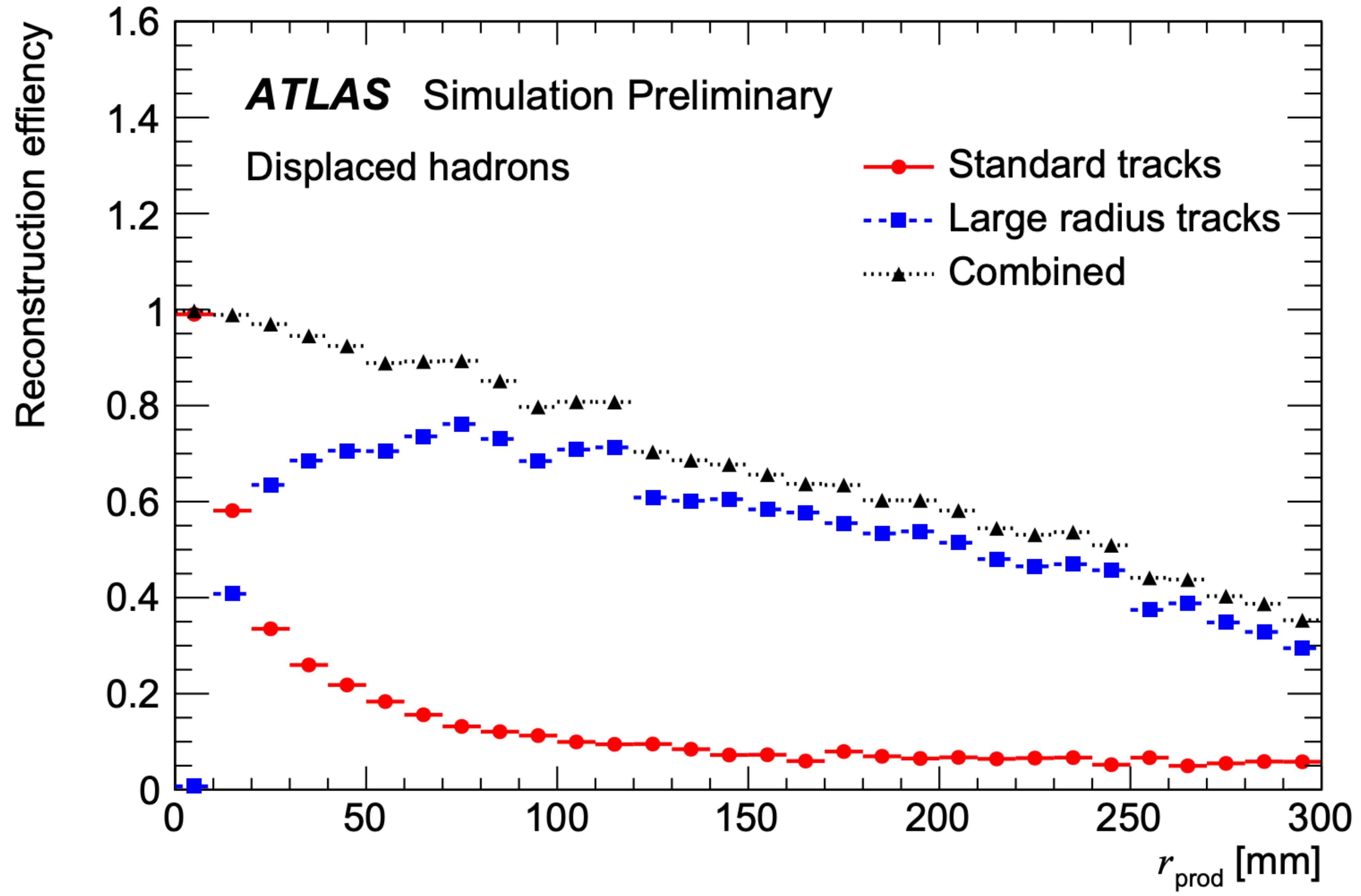
ATLAS has a **growing program** of LLP searches:

- Displaced leptons
- Disappearing tracks
- Stopped particles
- Exotic Higgs decays

today's talk

- Many more! (SUSY, Exotics)

ATL-PHYS-PUB-2017-014



Common themes:

- trigger challenges → dedicated triggers or **associated production**
- small, unconventional backgrounds → **data driven** background estimates
- specialized reconstruction methods → dedicated "**large radius tracking**" (LRT); secondary vertex reconstruction

Displaced Leptons

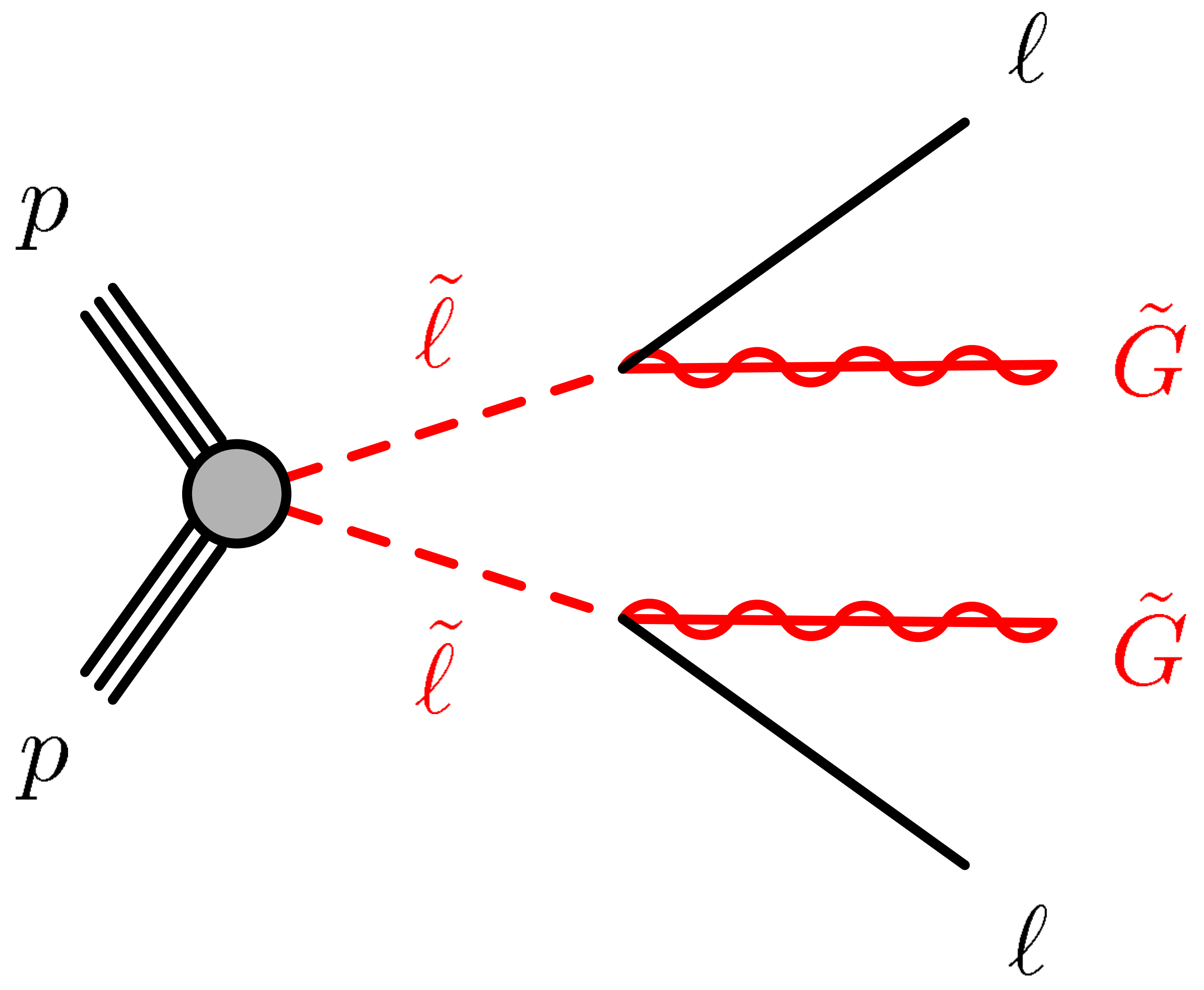
arXiv:2011.07812

General search for pairs of **large-|d_0| leptons**

- Aims to address a **gap in coverage** left by searches that require displaced leptons to originate from common vertex

Benchmark model: **Gauge-mediated SUSY breaking (GMSB)**

- Lightest SUSY particle (LSP) is the nearly massless gravitino
- Next-to-lightest SUSY particle (NLSP) is the slepton (smuon, selectron, stau)
- slepton **long-lived** due to small gravitational coupling to LSP



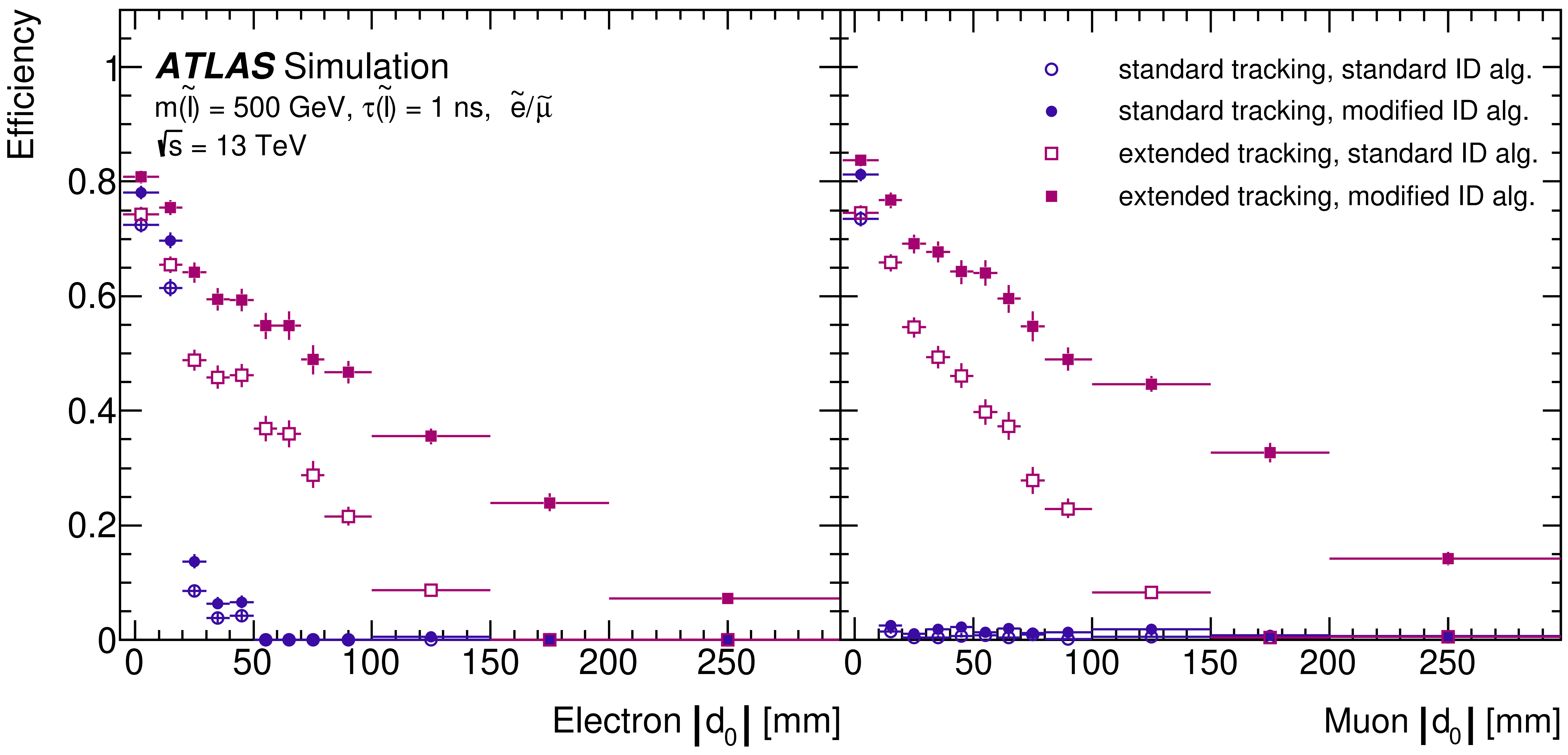
Unprobed at LHC!

- LEP limits (previous best) constrain masses below ~ 65-90 GeV

Analysis Strategy

Displaced lepton reconstruction

- Large radius tracking recovers efficiency up to 100mm
- Standard lepton identification algorithms modified by removing requirements on $|d_0|$ and number of hits matched to track



Use triggers without track requirements

- Muon trigger with no ID track requirement
- Single/di-photon triggers

Signal regions: ee | eμ | μμ

All leptons required to satisfy:

- pT > 65 GeV
- ΔR between leptons > 0.2
- **$|d_0|$ > 3 mm**
- **isolated from activity in ID and calorimeter**

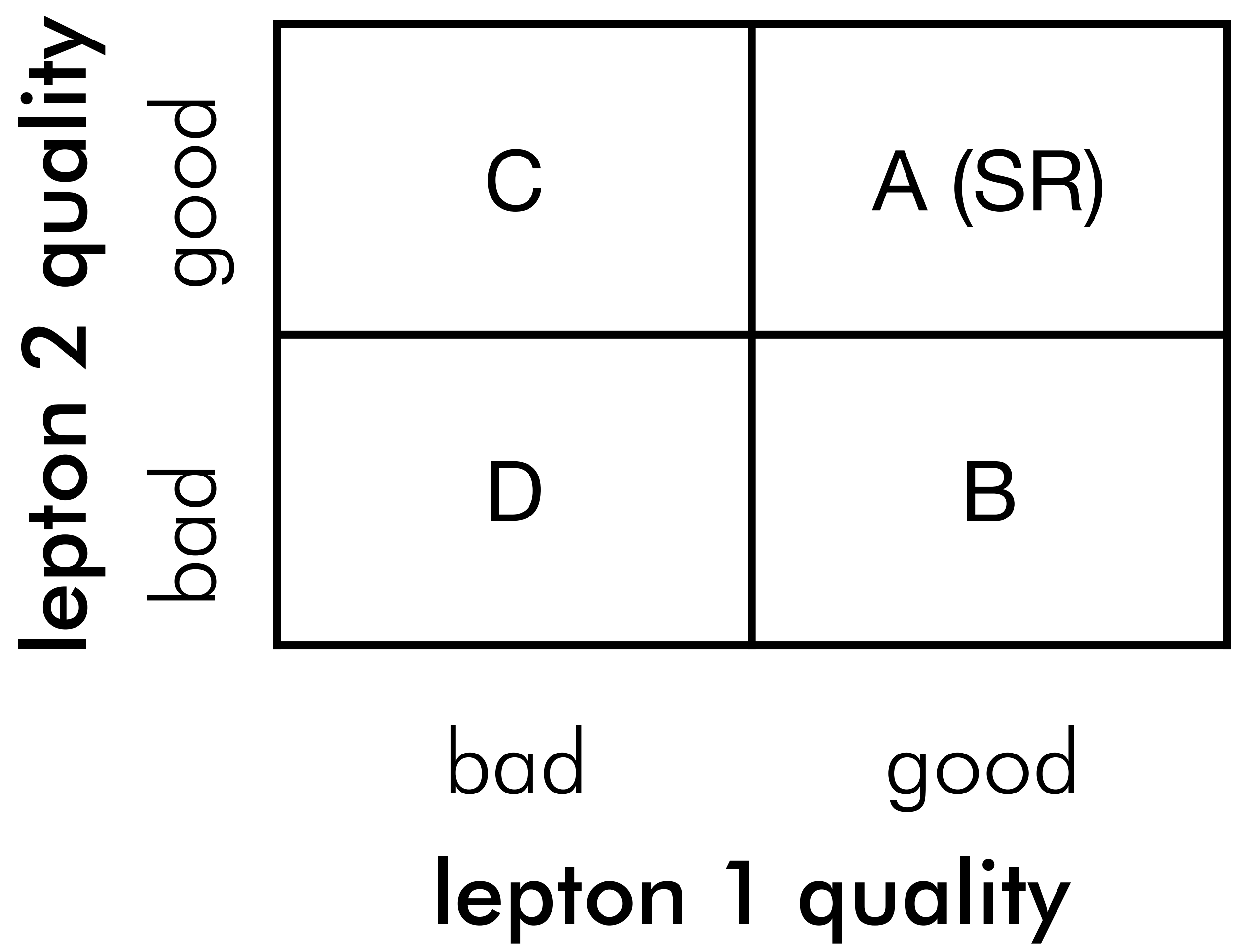
Additional requirements placed on muons to reject **cosmics**

Background estimate

SR-ee/SR-eμ: dominant backgrounds are **fake leptons** and **heavy flavor decays**

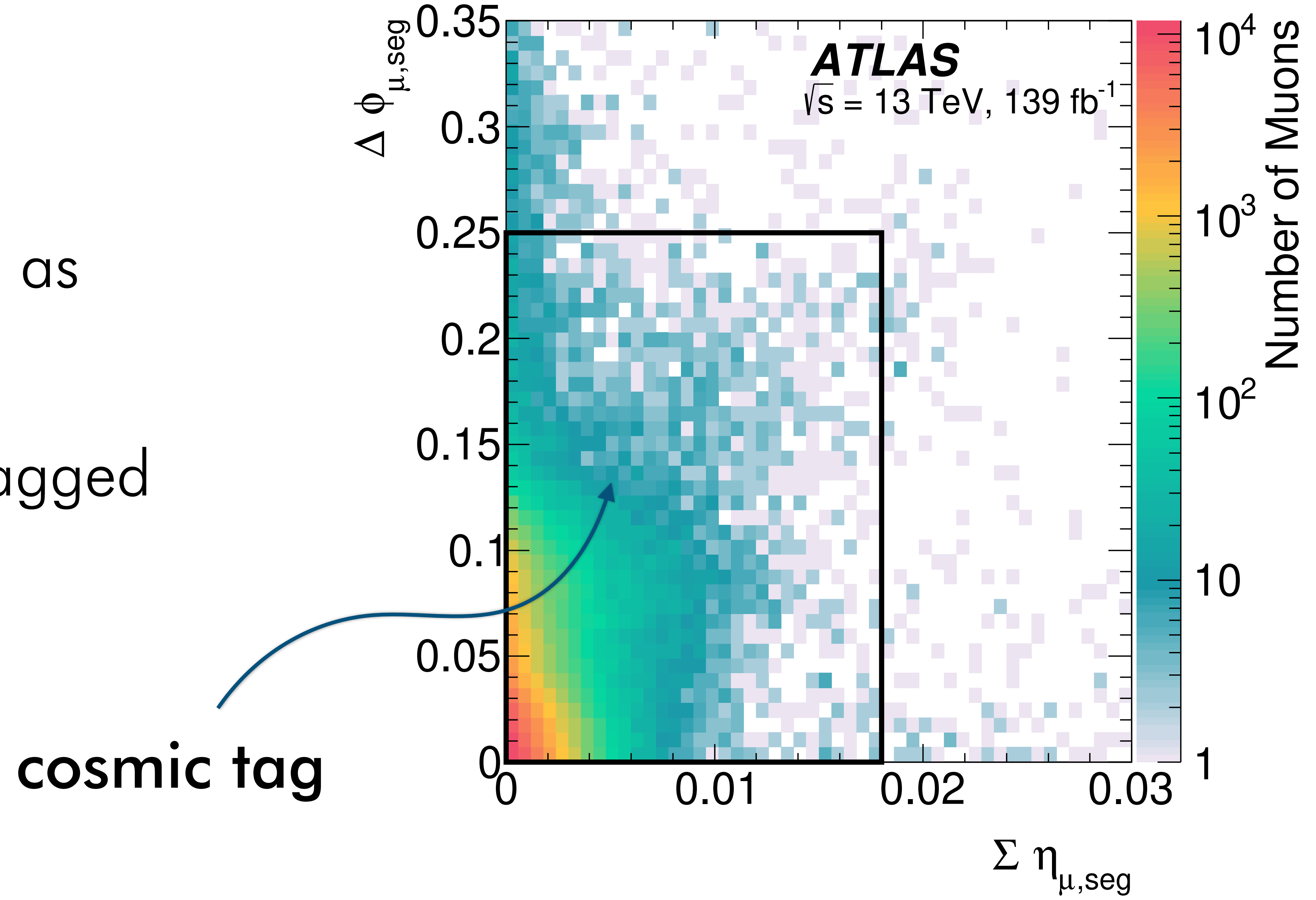
- Data driven **ABCD method** used to predict background: $N_A = N_C*(N_B/N_D)$
- Validated by inverting isolation and track quality requirements

	VR-ee-fake	VR-ee-heavy-flavor	VR-$e\mu$-fake	VR-$e\mu$-heavy-flavor
Estimate	1356 ± 49	23.5 ± 1.9	$1.9^{+1.8}_{-1.0}$	$0.38^{+0.37}_{-0.32}$
Observed	1440	26	2	1



SR-μμ: dominant background is **cosmic muons**

- ABCD-like method with ratio of good to bad cosmic-tagged muons used as transfer factor
- Validated by modifying the cosmic tag window to leave more muons untagged



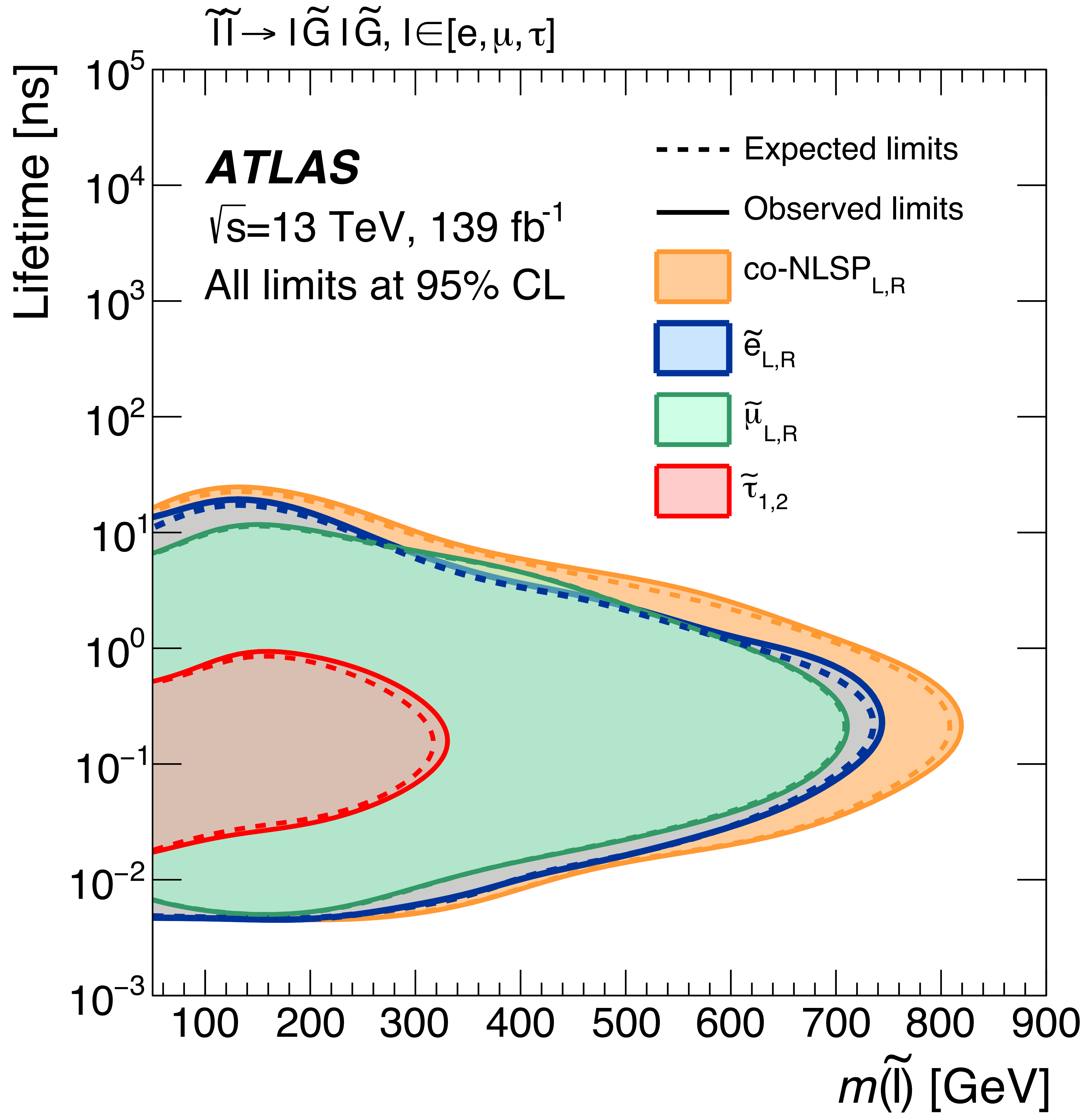
Results

Zero events observed in all signal regions

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + heavy-flavor	0.46 ± 0.10	$< 10^{-4}$	$0.007^{+0.019}_{-0.007}$
Cosmic-ray muons	–	$0.11^{+0.20}_{-0.11}$	–
Expected background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

Limits set on slepton masses and lifetimes

- For lifetimes of 0.1 ns, selectron, smuon and stau masses up to **720 GeV**, **680 GeV**, and **340 GeV** are excluded
- First results from LHC provide significant improvement over LEP



This **model-independent** result is applicable to any BSM model with high-p_T displaced leptons!

Disappearing tracks

ATLAS-CONF-2021-015

Several SUSY models predict **pure wino** or **pure higgsino** LSPs

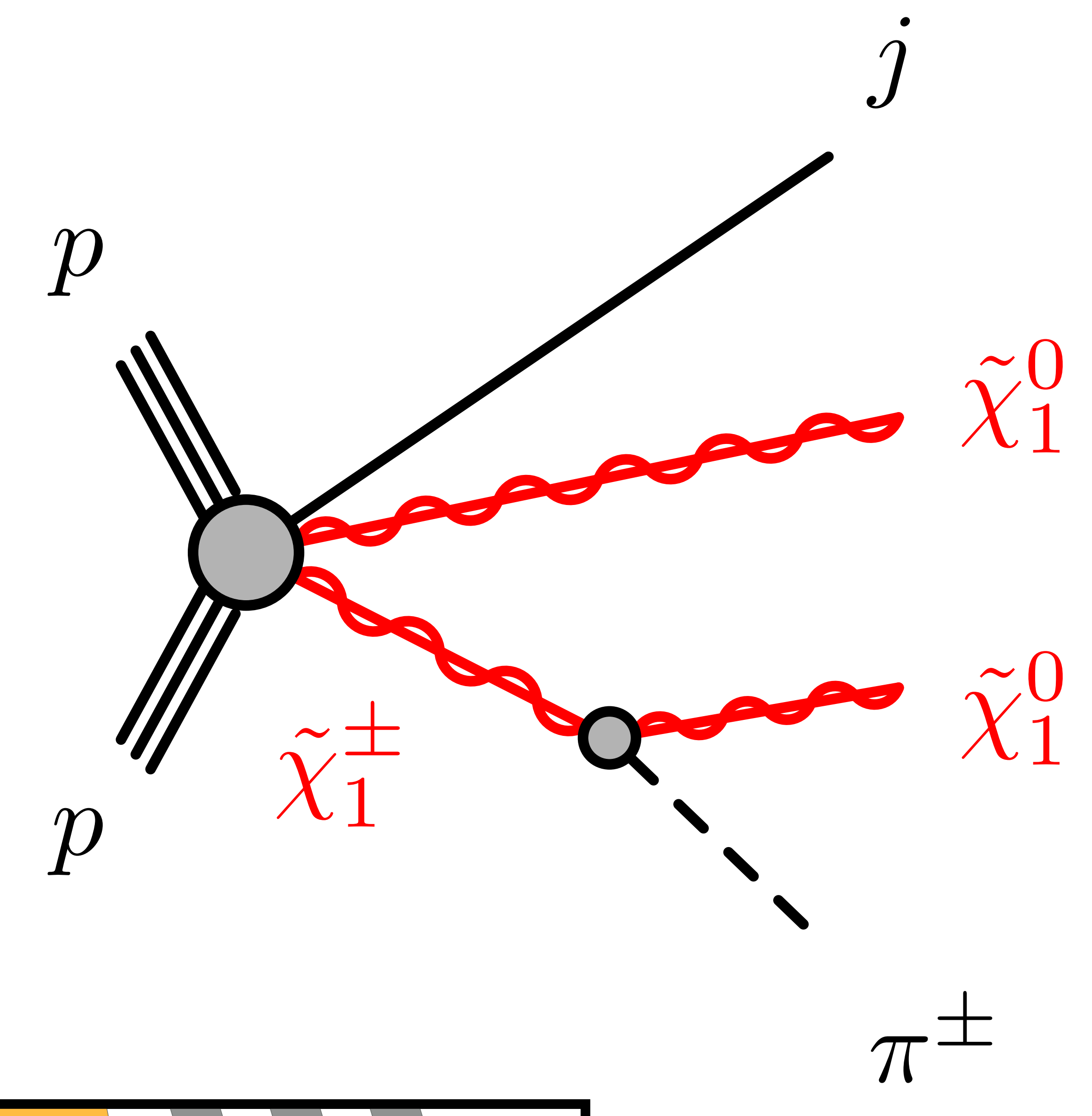
- Well motivated by dark matter and naturalness arguments

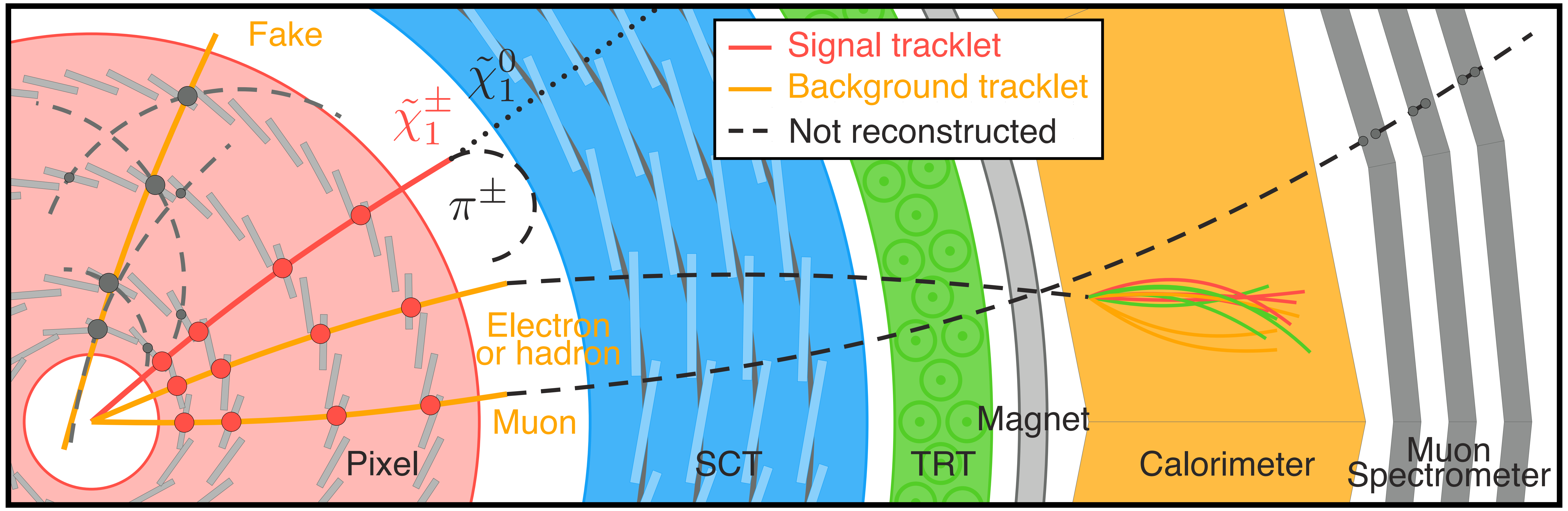
Small mass splitting between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ makes $\tilde{\chi}_1^{\pm}$ **long-lived**

- natural lifetimes ranging from **0.02 ns** (higgsino) to **0.2 ns** (wino)

Chargino decays to **soft pion** (not reconstructed) and **LSP** (MET)

- Gives rise to unique signature of a **disappearing track**





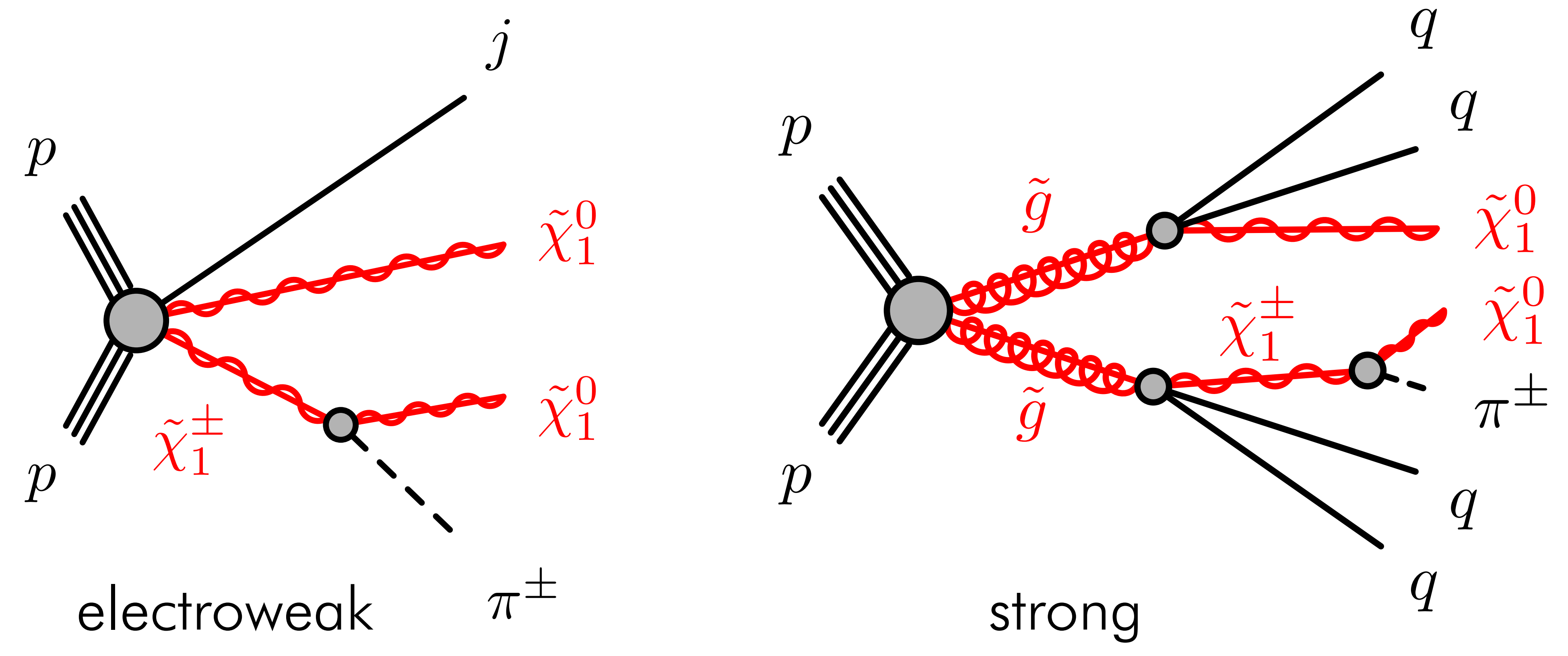
Analysis Strategy

Trigger on MET from LSP; **veto leptons**

Two channels targeting **electroweak** and **strong** production modes

MET > 200 GeV
≥ 1 jet

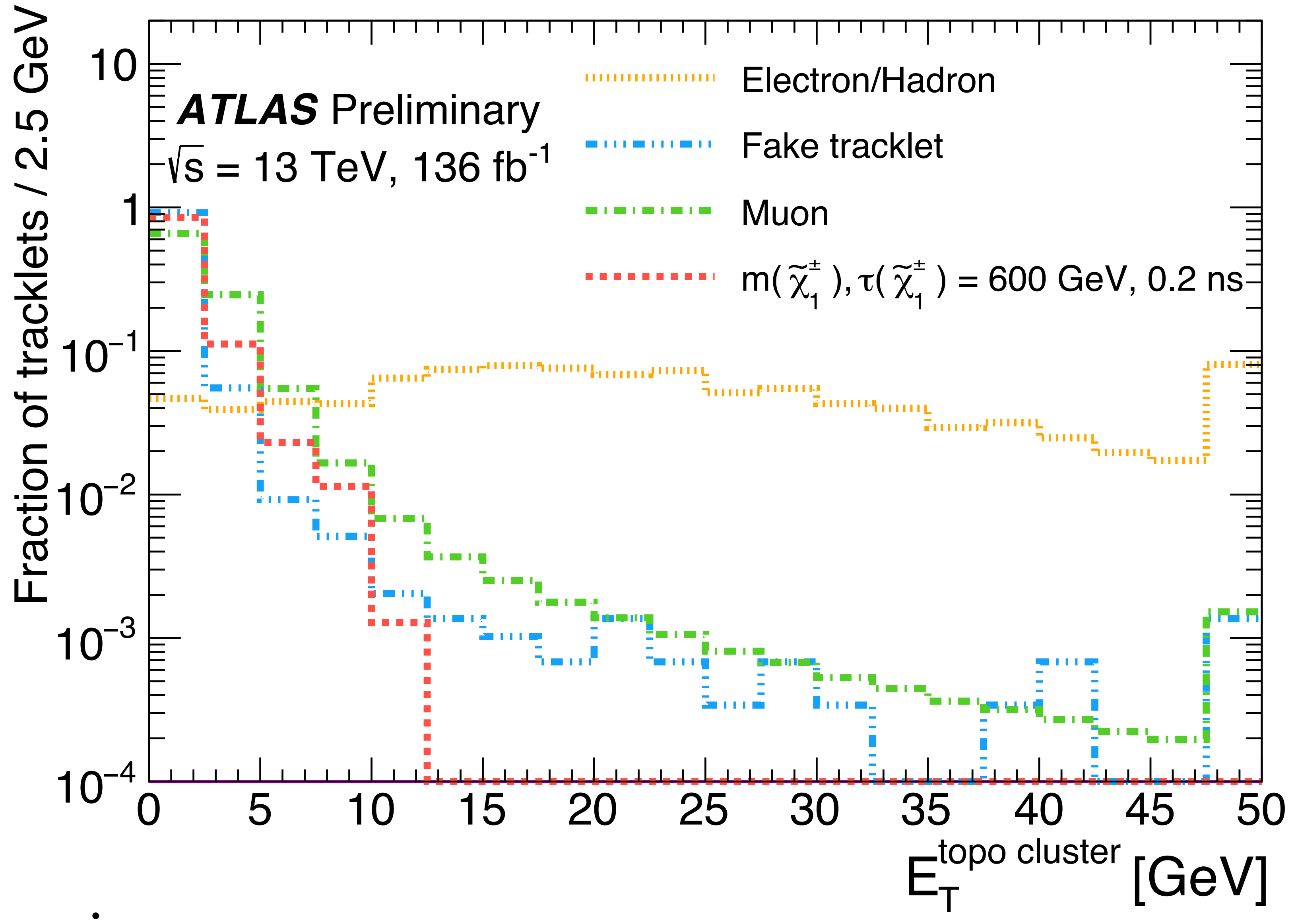
MET > 250 GeV
≥ 3 jets



Dedicated **tracklet** reconstruction run on unassociated hits from standard tracking

Tracklets required to satisfy:

- 4 pixel hits; 0 SCT hits (**disappearing criteria**)
- PV consistency
- isolated from other tracks in the event
- isolated from calorimeter deposits (****new****)



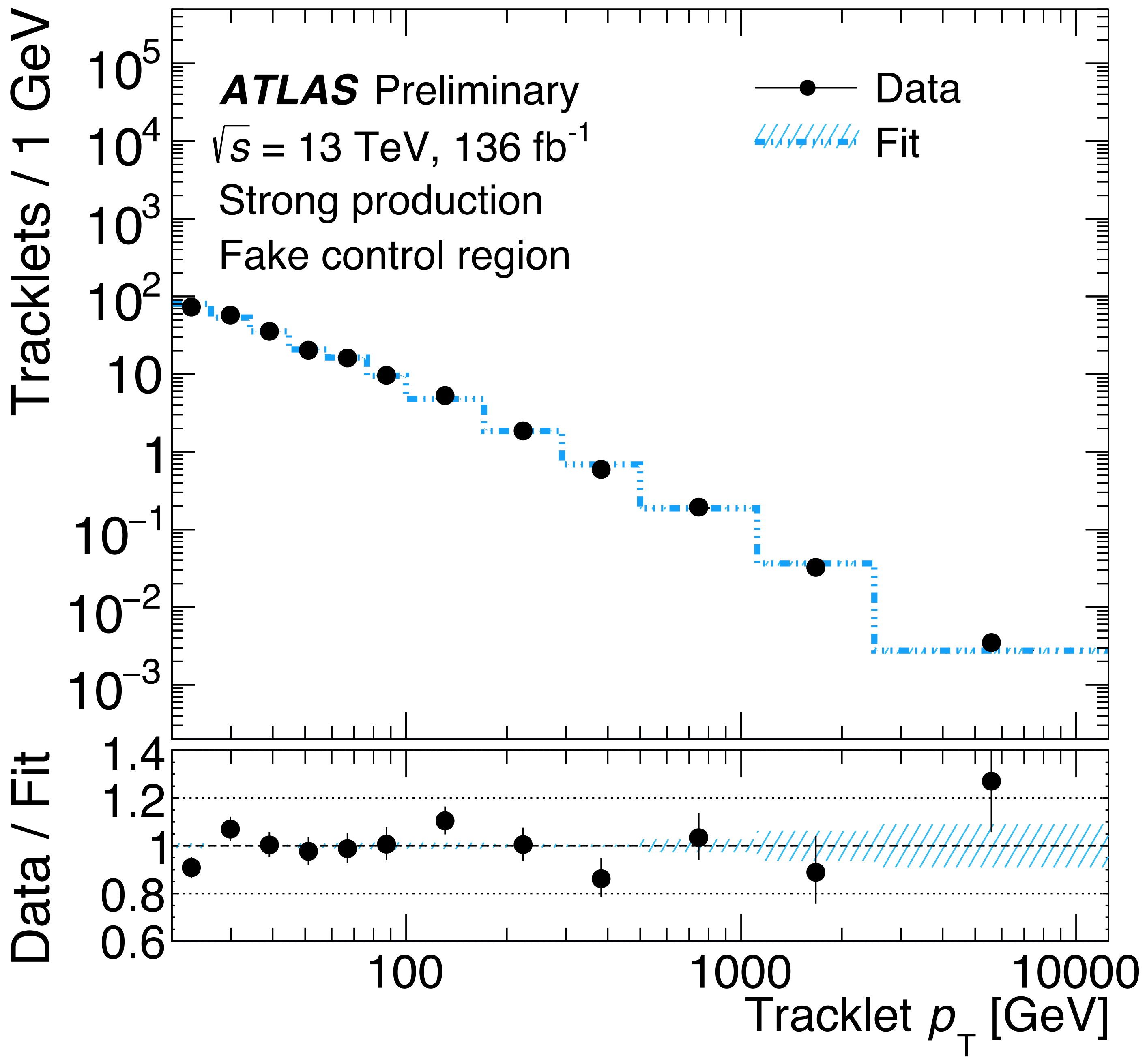
Results extracted from **simultaneous fit** of **tracklet p_T spectrum** in signal and control regions

Background estimate

Two sources of background: **combinatorial fakes** and **charged particle scattering**

p_T template measured in **fake enriched** CR

- defined by inverting cut on tracklet $|d_0|$
- fit tracklet p_T distribution to determine shape

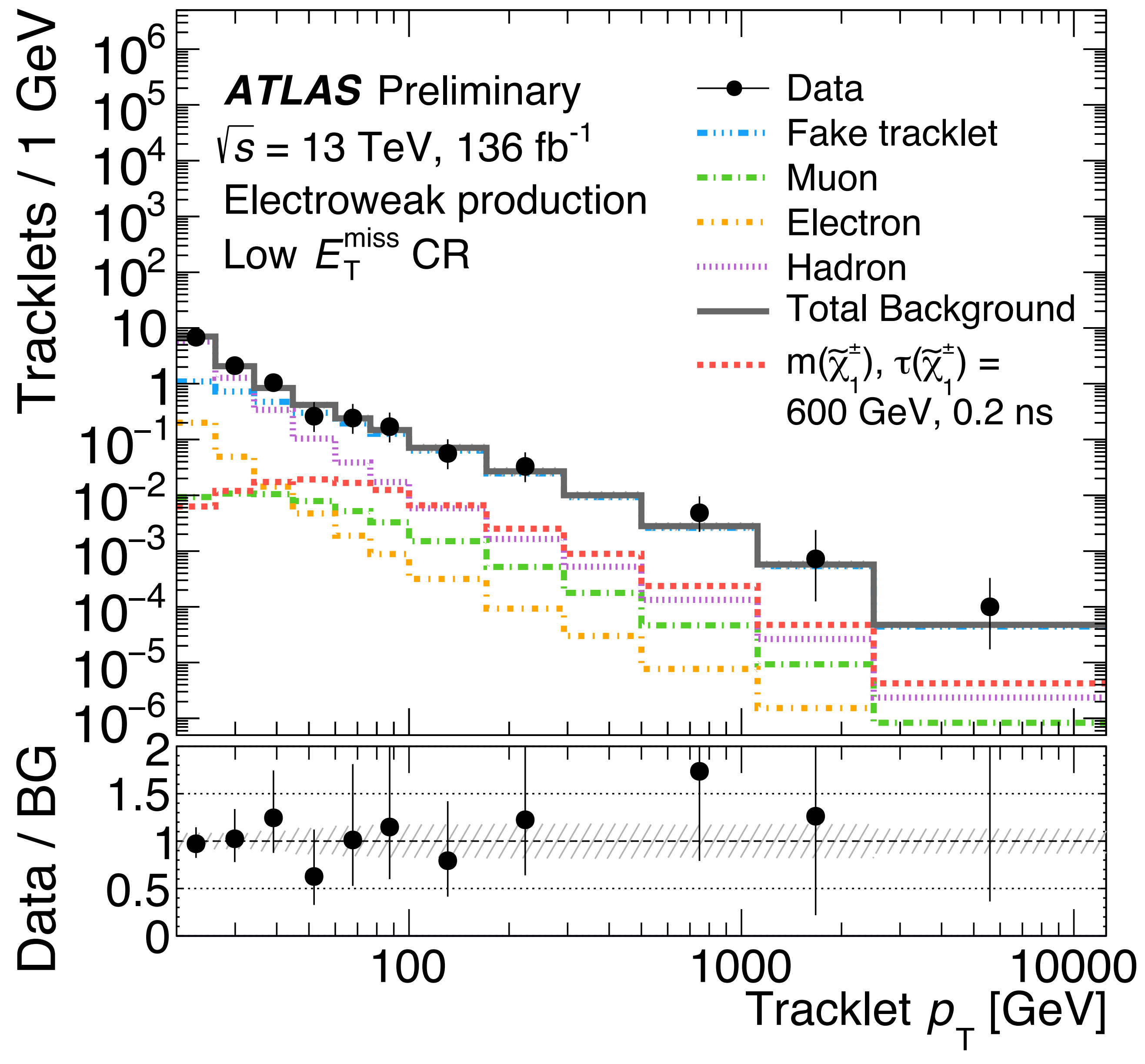


p_T templates measured in **single charged particle** CRs

electron	muon	hadron
good e	good μ	good track
no-e MET	no-μ MET	standard MET

- **measure** probability that lepton is mis-identified as a pixel tracklet using $Z \rightarrow \ell\ell$ tag-and-probe
- **apply** to track distribution in single electron/muon/hadron CR
- **smear** track p_T to match pixel tracklet momentum resolution

relative contributions constrained via **likelihood fit** in low MET CR

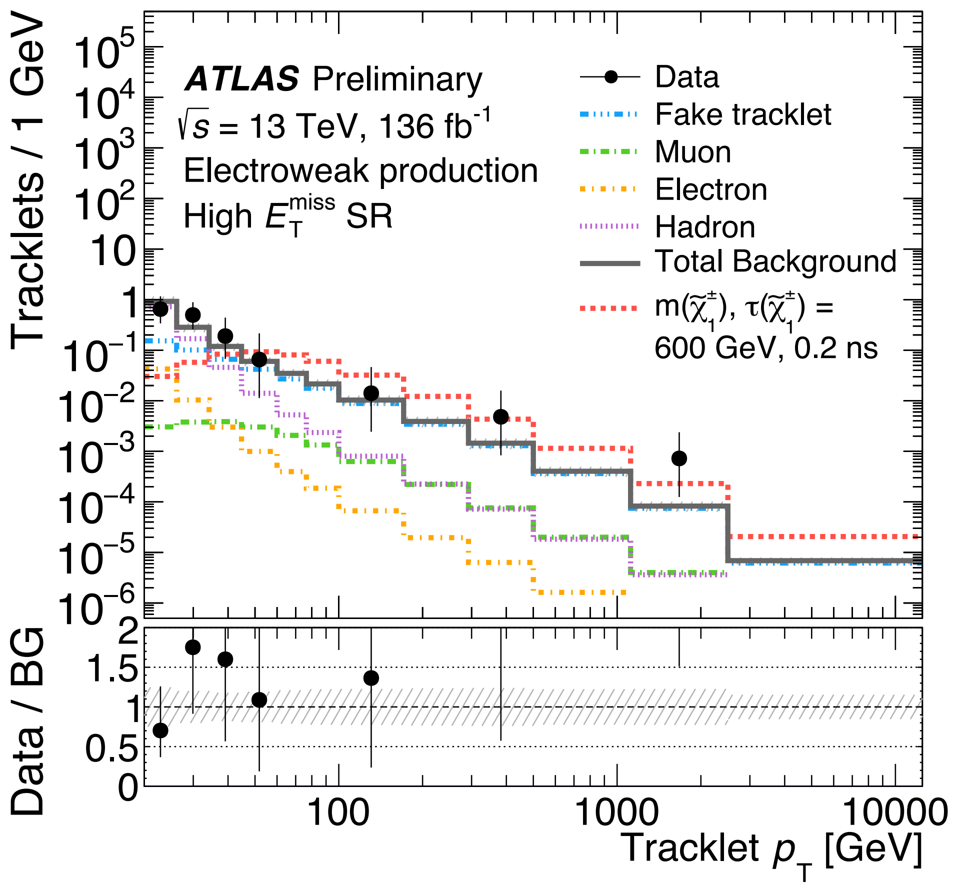


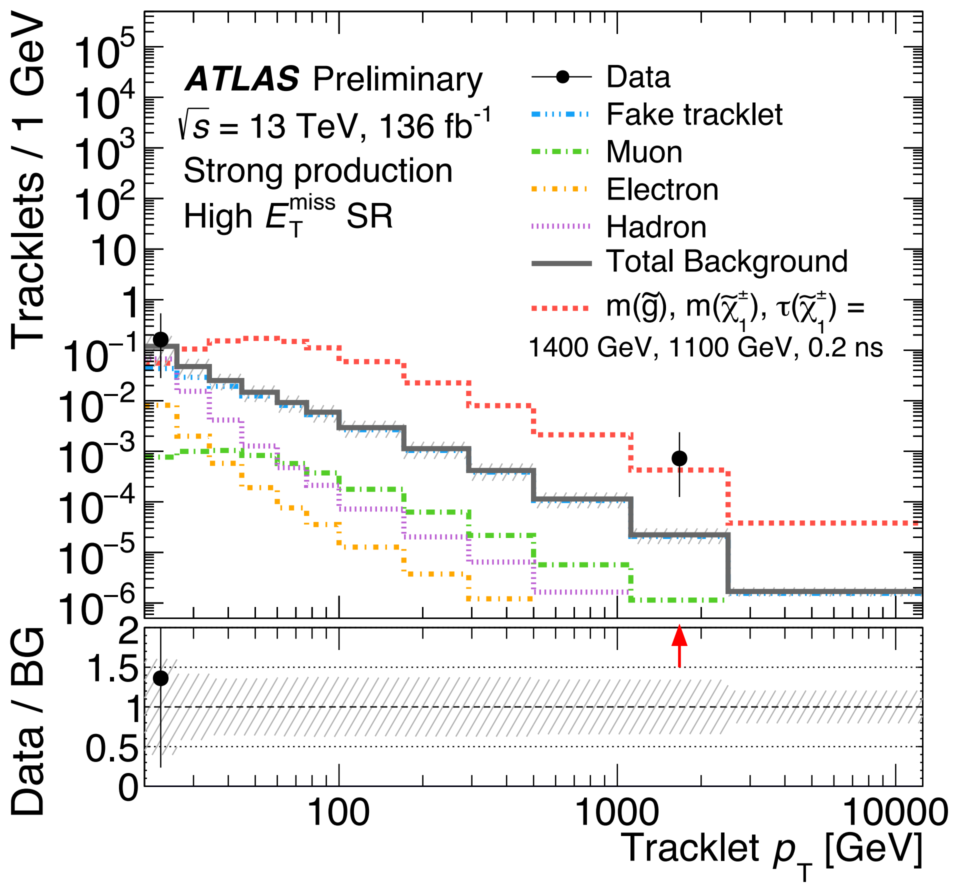
Estimate validated in **sidebands** of calorimeter isolation and **low tracklet p_T** region

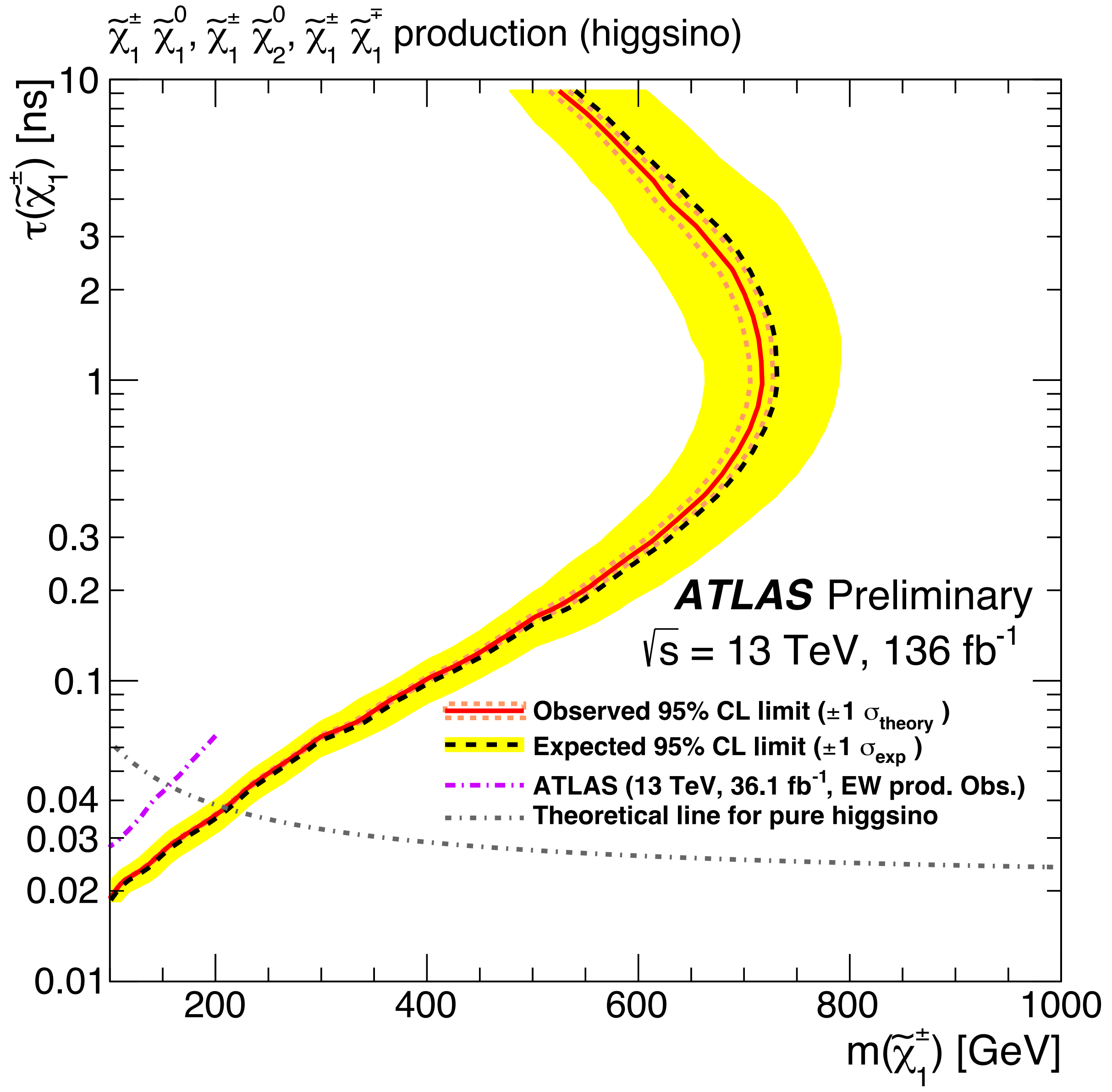
Signal region requires 1 tracklet with **p_T > 60 GeV**

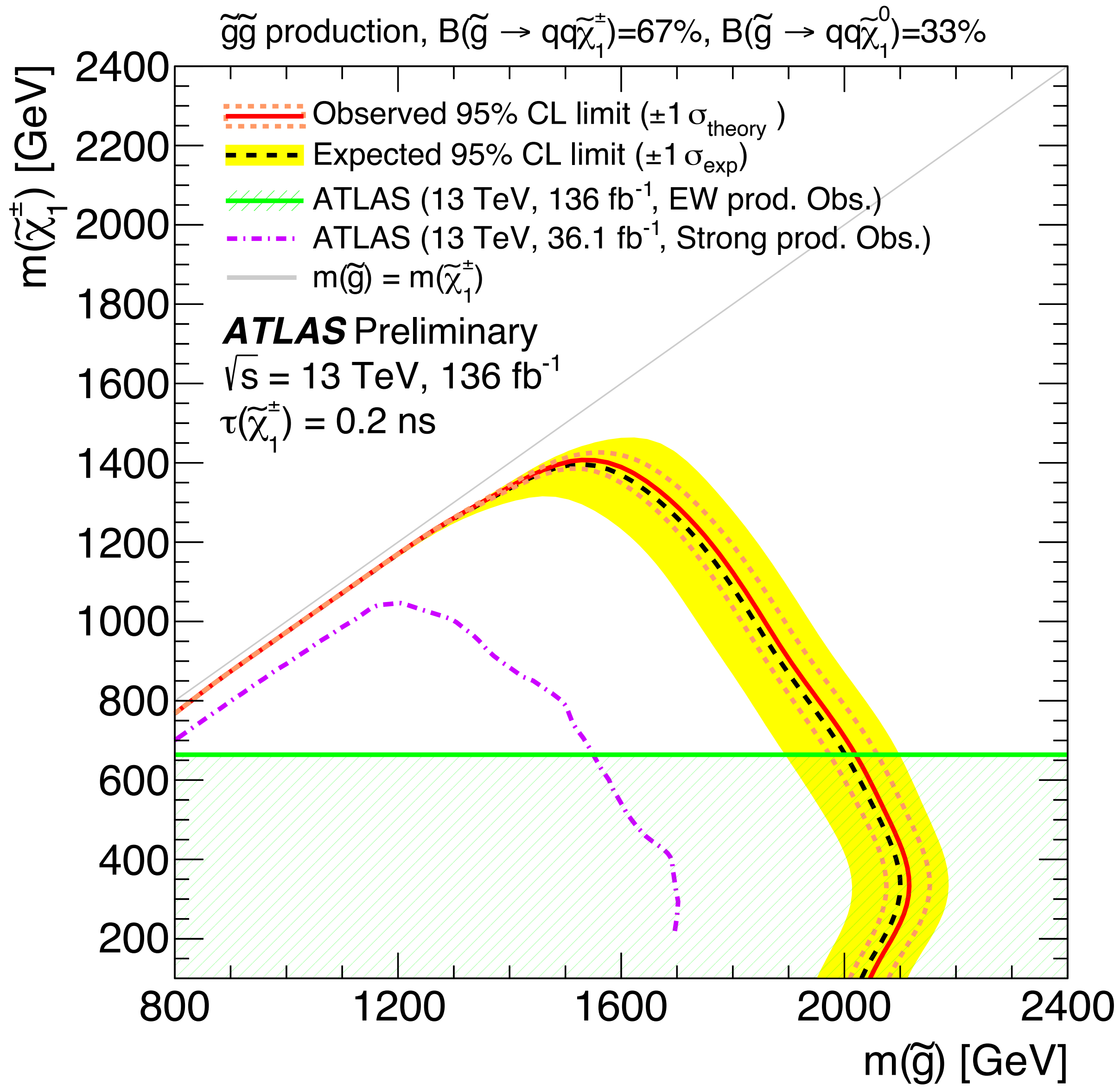
Results

No excess observed above SM backgrounds









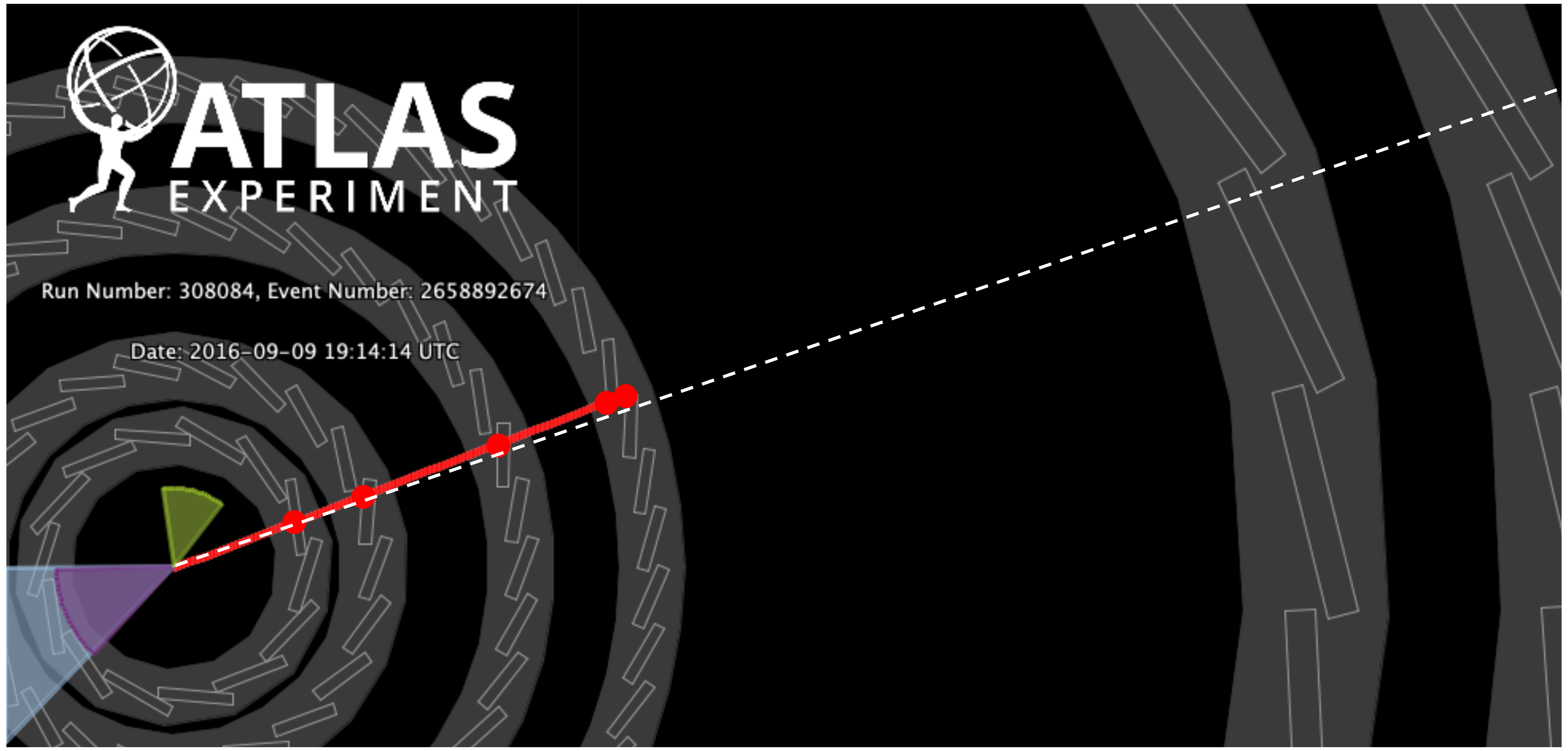
electroweak:

- chargino masses up to 660 (210) GeV excluded for pure wino (higgsino) models

strong:

- gluino masses below 2.1 TeV are excluded for a chargino mass of 300 GeV

most stringent limits to date for natural lifetimes

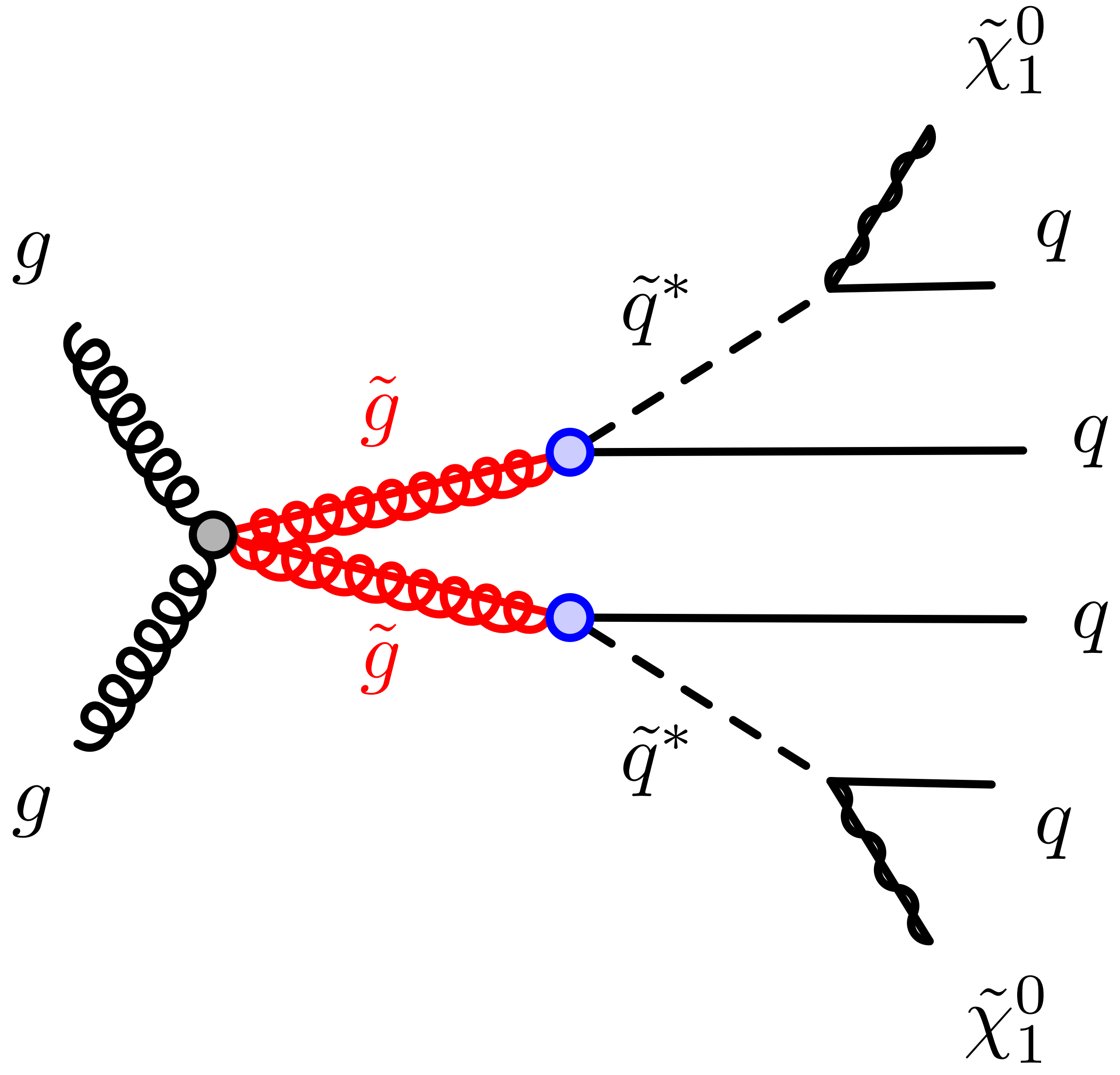


Stopped particles

arXiv:2104.03050

Search for particles which **come to rest** within the ATLAS calorimeters and decay in **empty bunch crossings**

- First ATLAS search for stopped particles at 13 TeV!

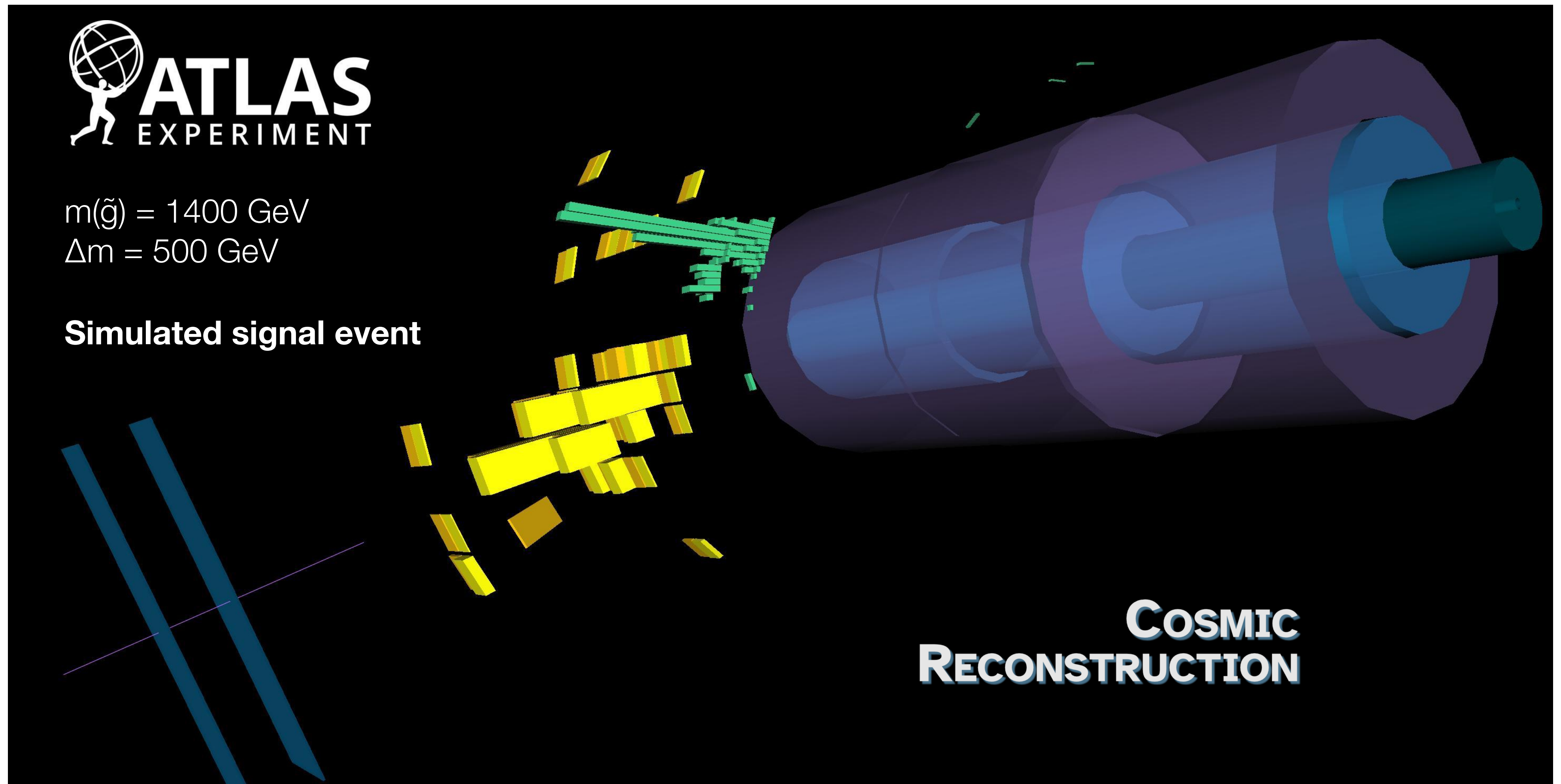


Benchmark model: **SUSY R-hadrons**

- If squarks are sufficiently heavy, gluino can be **long-lived**
- composite states (R-hadrons) may be **slow-moving** and come to rest
- stopped gluino could decay **significantly later** than the bunch crossing in which it was produced

sensitivity to gluino lifetimes across **several orders of magnitude**

- 10^{-7} to 10^{7} s



Analysis Strategy

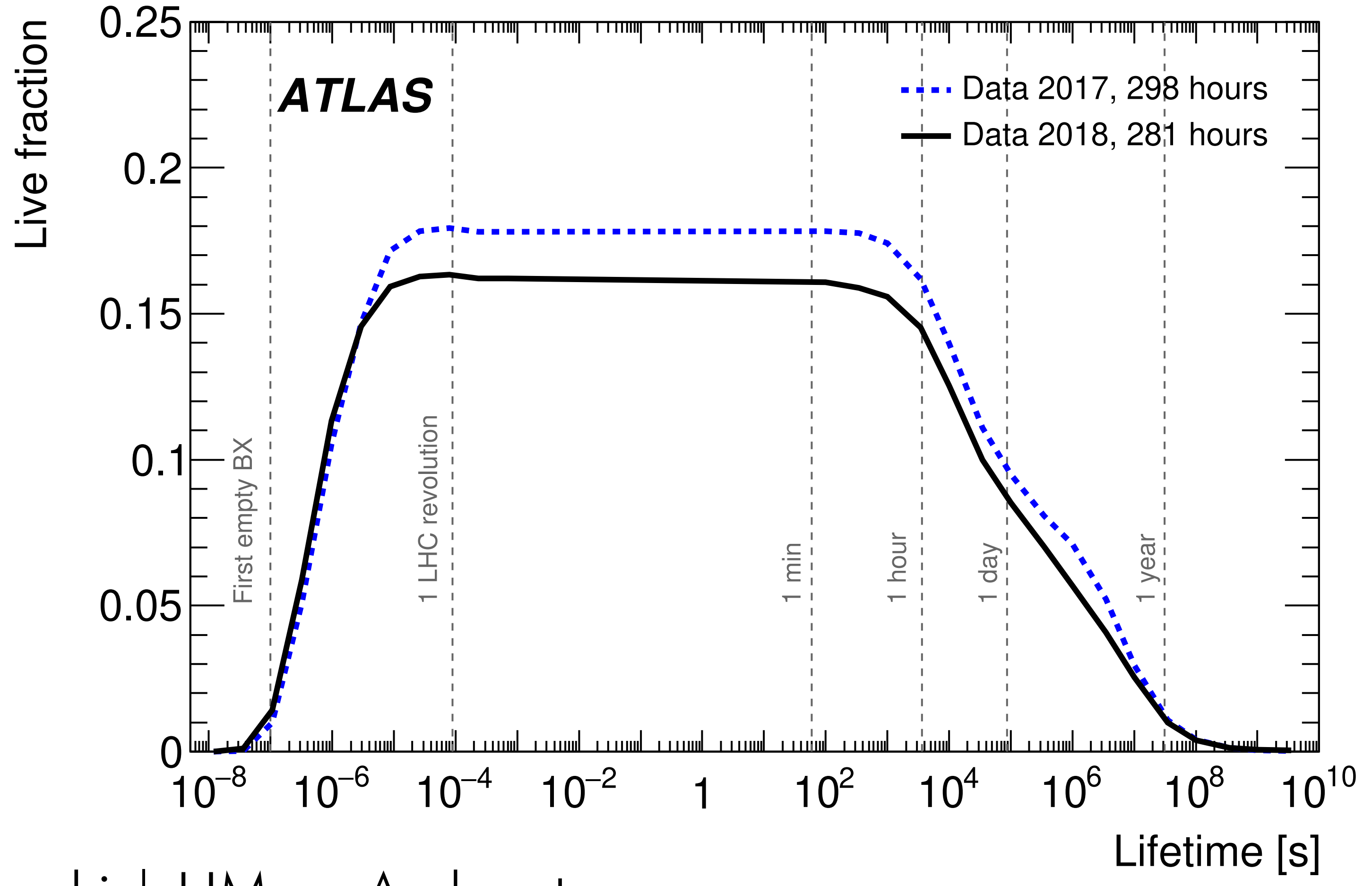
Trigger on jets in **empty bunch crossings**

- MET > 50 GeV, jet p_T > 55 GeV

Two signal regions:

- leading jet p_T > 150 GeV
- PV veto, muon veto
- jet $|\eta|$ < 0.8 (**SRC**), jet $|\eta|$ < 2.4 (**SRInc**)

Signal proportional to **luminosity** and total amount of trigger-able time during run **(live time)**

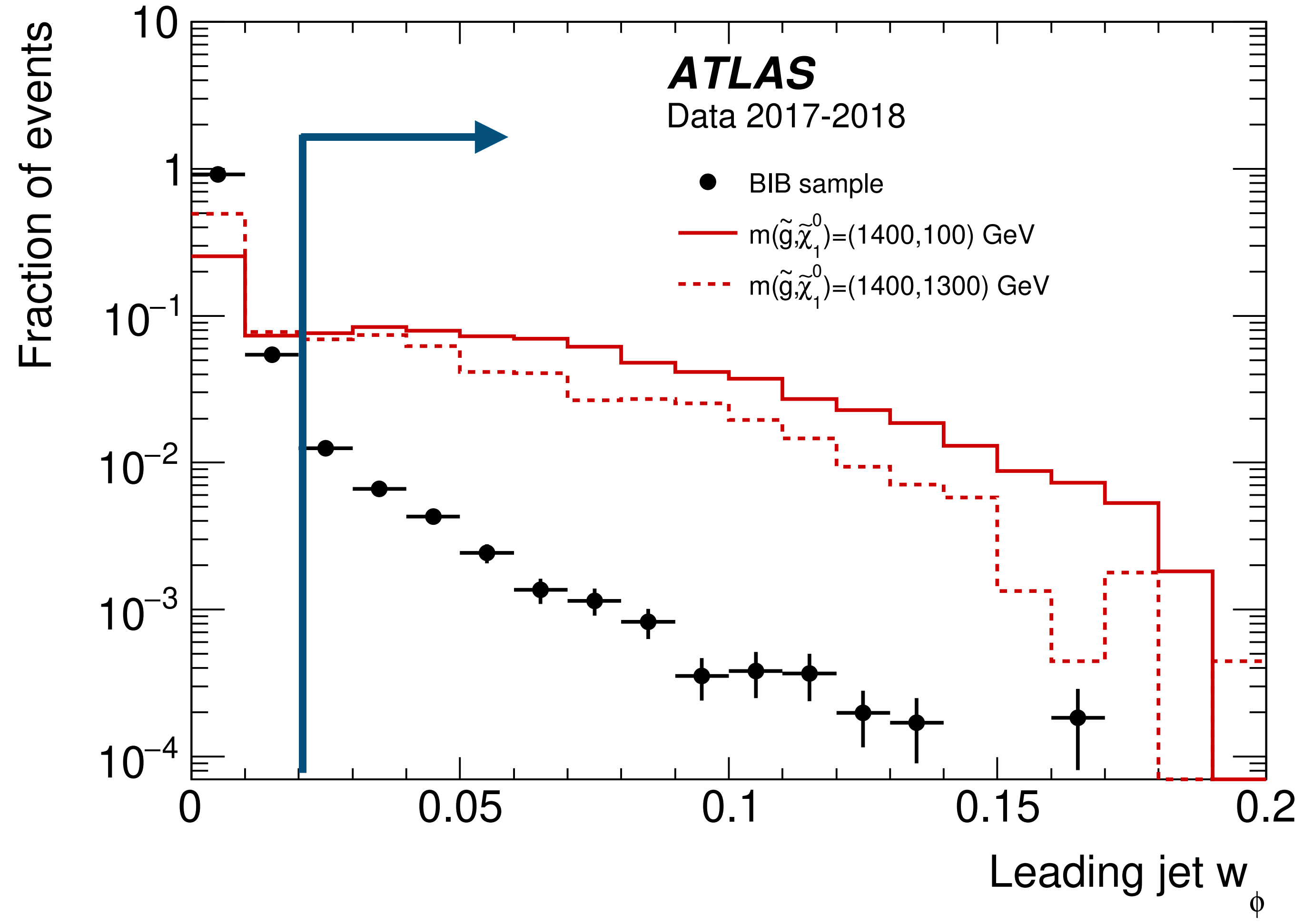


Dominant backgrounds: **beam induced (BIB)** and **cosmics**

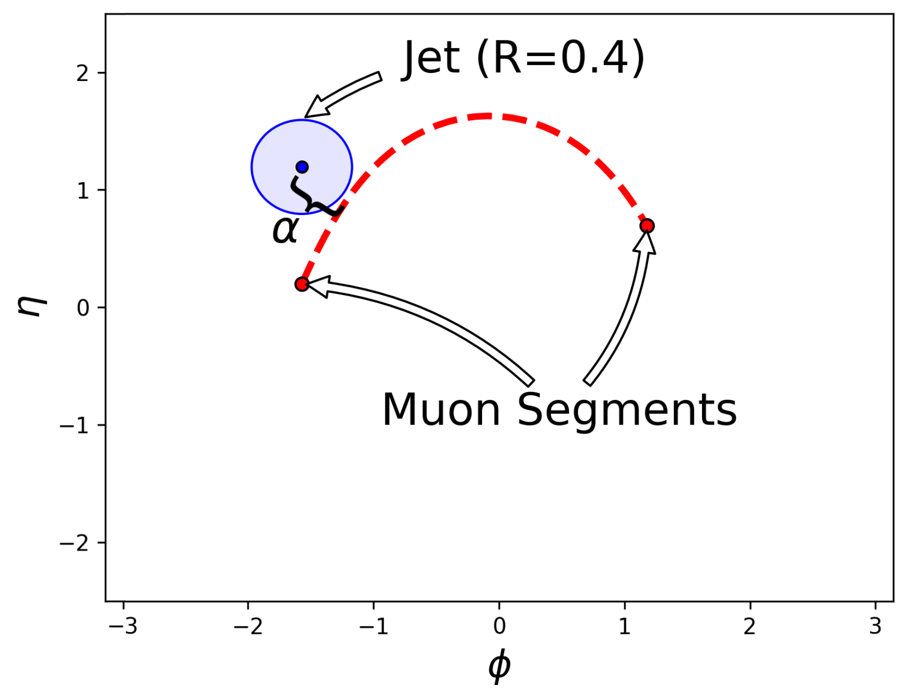
- proportional to **live time only**

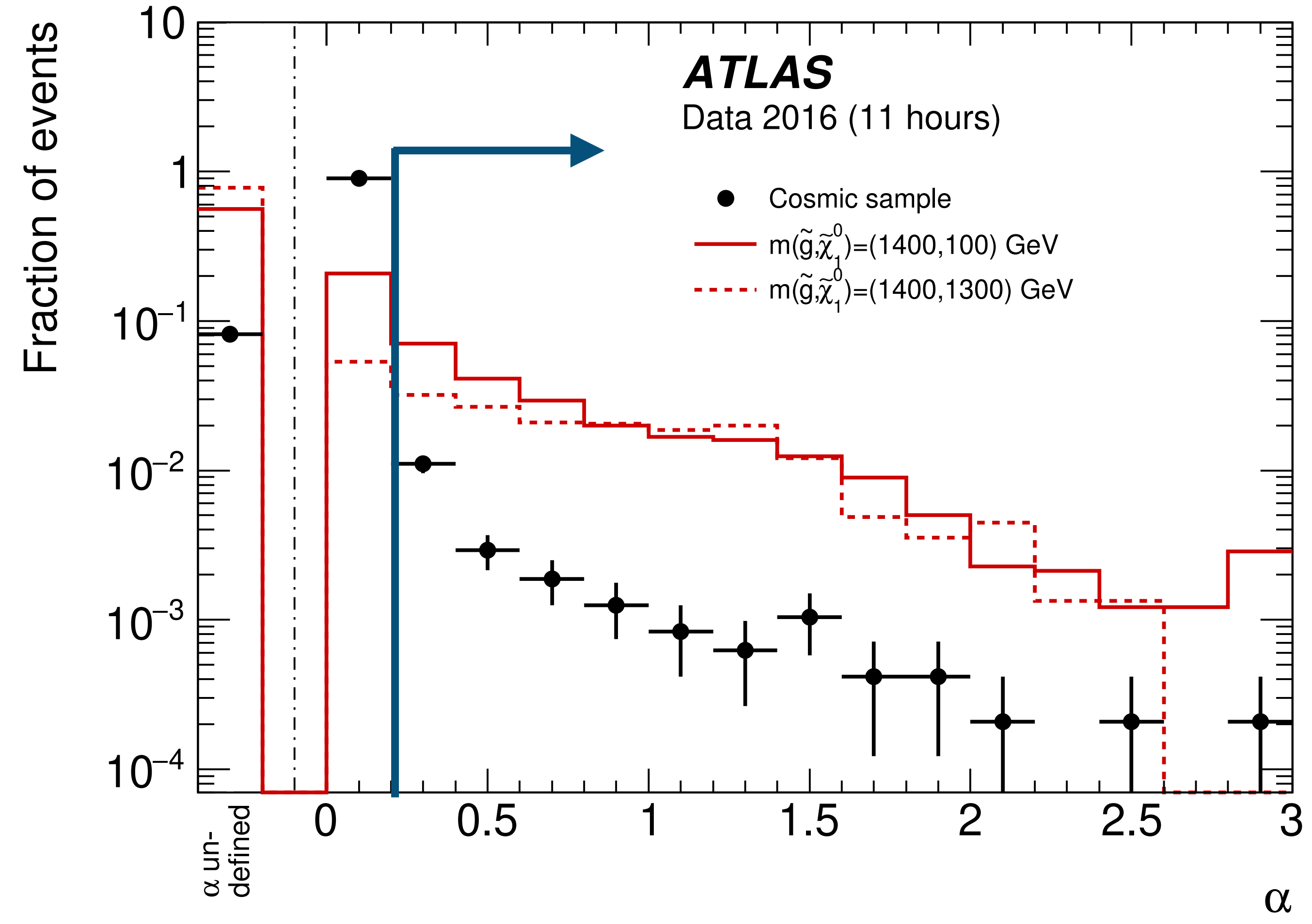
reject events with $\mathbf{w_\phi < 0.02}$

$$w_\phi = \frac{\sum_i p_T(i) \cdot |\Delta\phi(\text{jet}, i)|}{\sum_i p_T(i)}$$



reject events with $\boldsymbol{\alpha < 0.2}$





Background estimate

Jet p_T templates extracted for cosmics and BIB in dedicated control regions

BIB

CR: BIB sample with **w_ϕ > 0.01**

- **measure** jet p_T spectrum template in CR
- **normalize** template in low jet p_T region: $90 < p_T < 150$ GeV

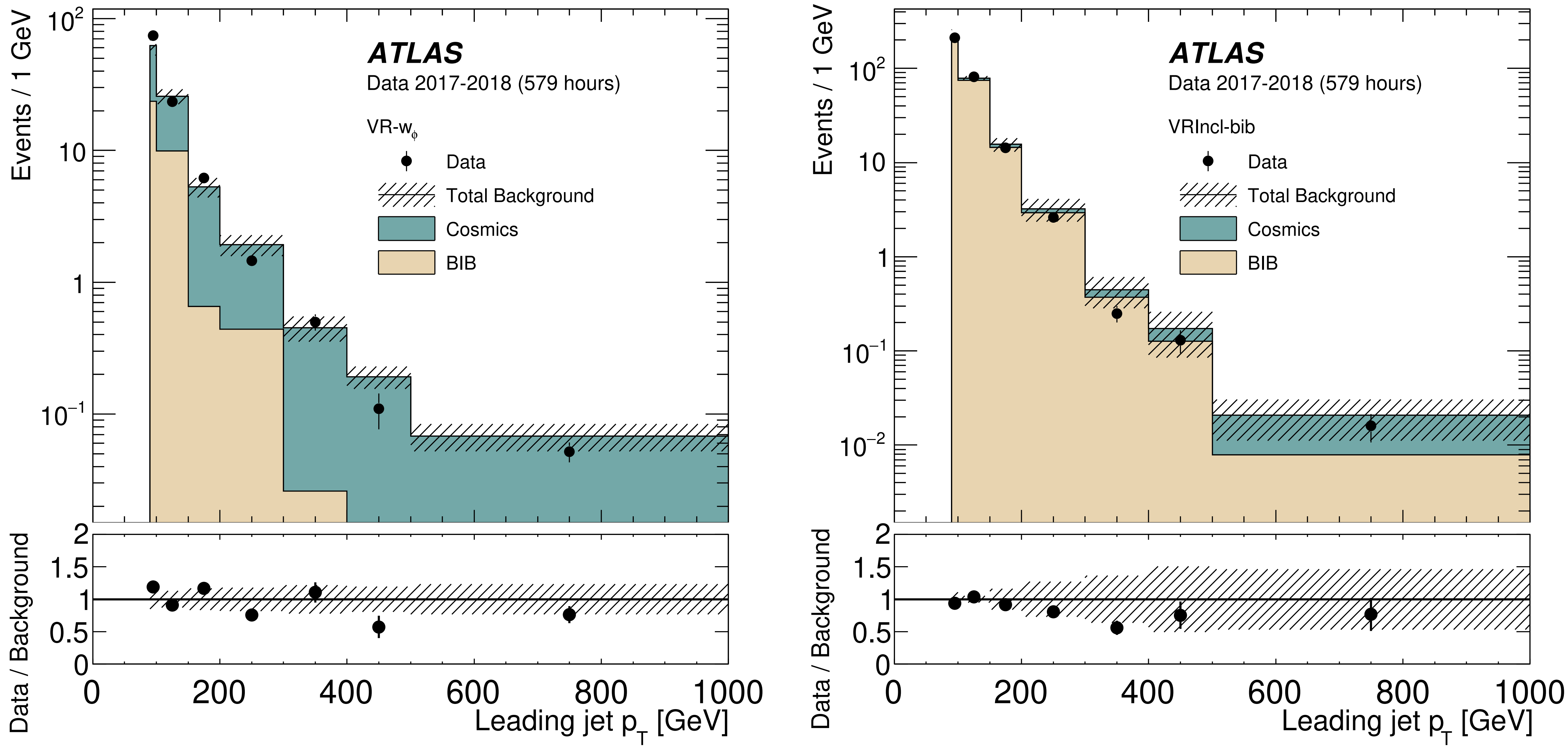
cosmics

CR: search sample + BIB sample with **α < 0.2**

- **measure** jet p_T spectrum template in CR
- **normalize** with transfer factor computed from cosmic run with no proton fill

$$TF = \frac{N^{cosmic-sample}_{SR-like}}{N^{cosmic-sample}_{CR-like}}$$

validation regions defined by loosening or inverting cuts on α and w_ϕ



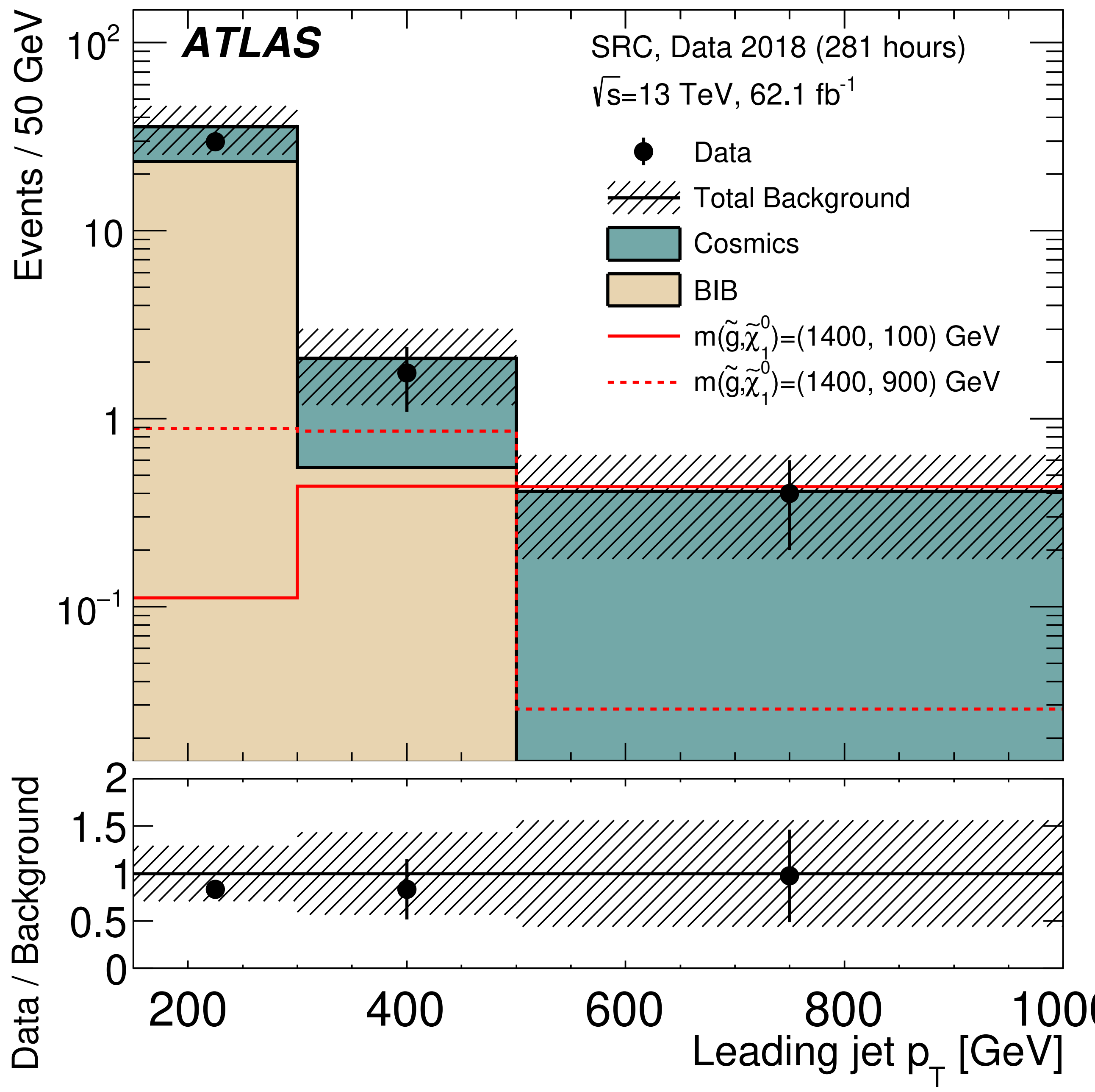
Results

No excess observed above SM backgrounds

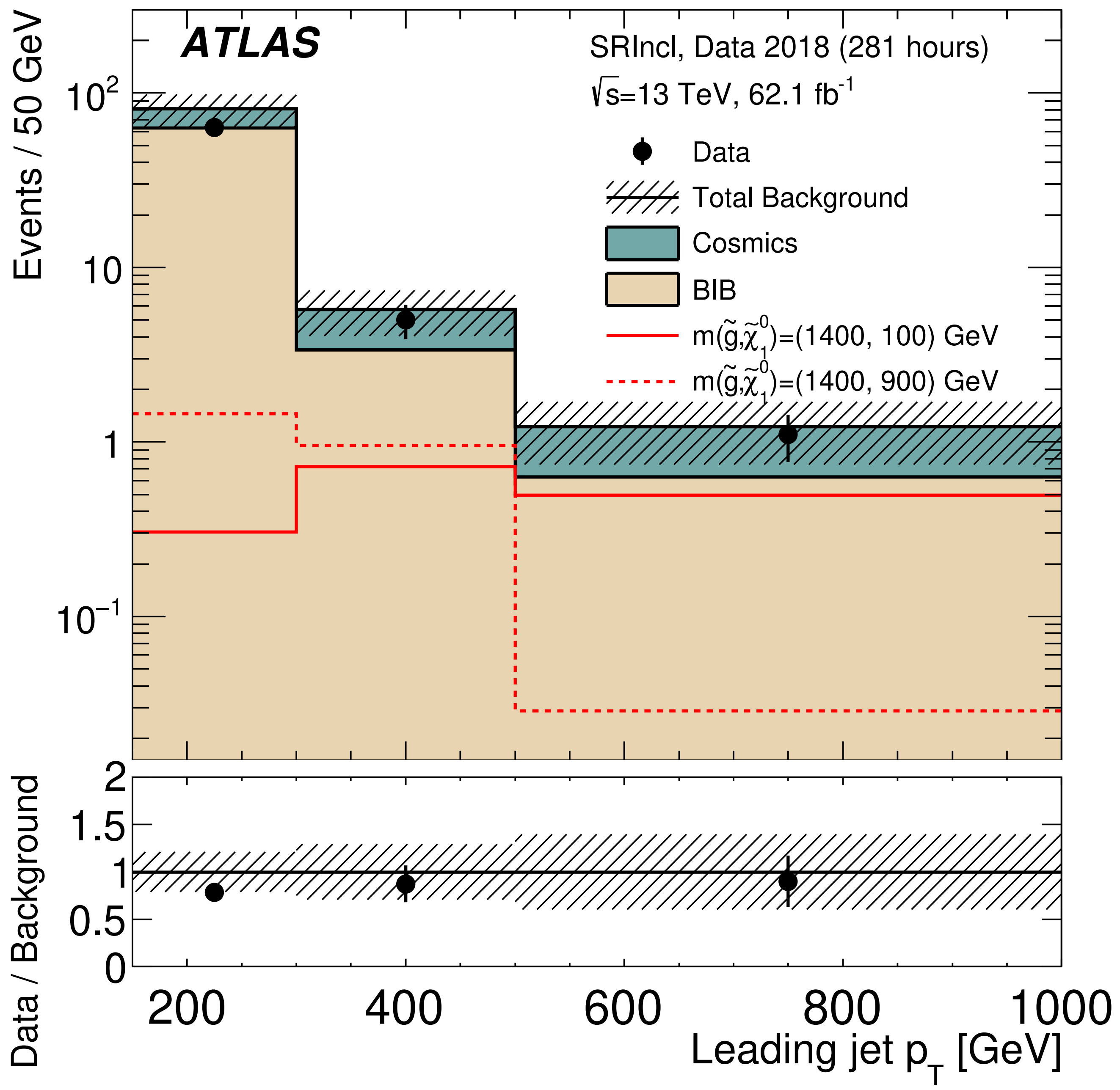
limits set on gluino R-hadron benchmark

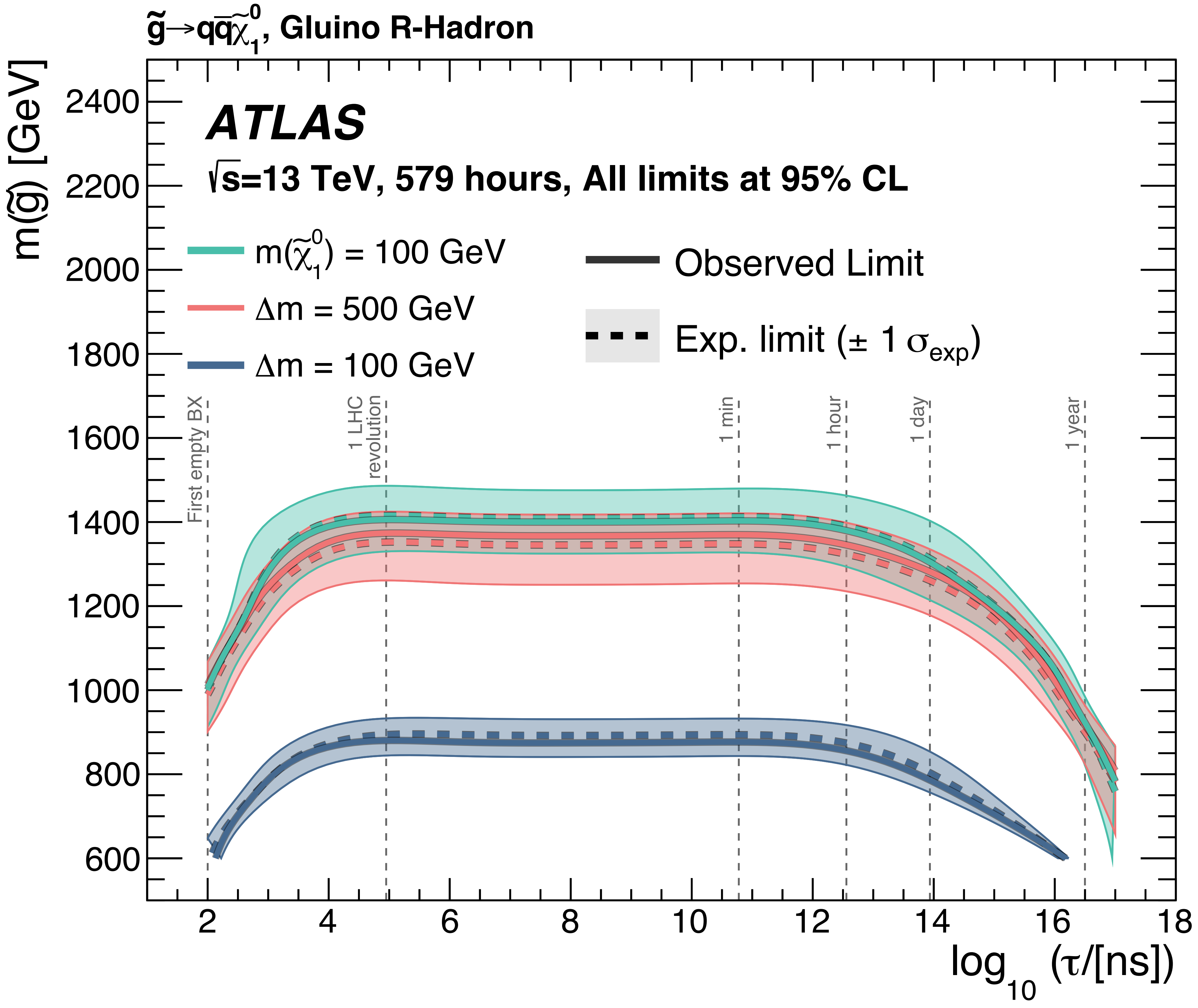
- span **15 orders of magnitude!**

SRC: $|\eta| < 0.8$



SRInc: $|\eta| < 2.4$





significant improvement over Run 1 results

Exotic Higgs decays in the ID

ATLAS-CONF-2021-005

Many BSM models predict **exotic Higgs decays**

- **Top down:** Neutral naturalness
- **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)**

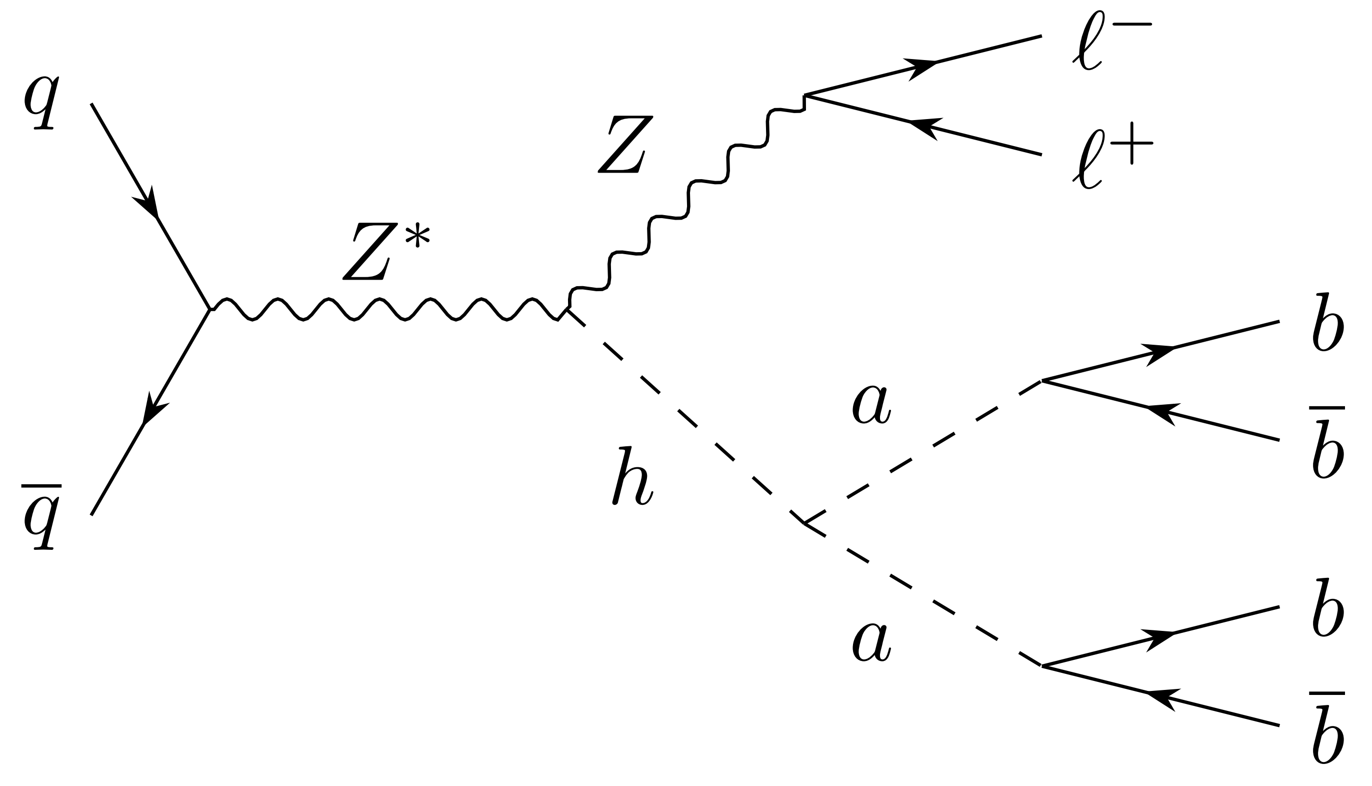
- $15 < m_a < 55$ GeV
- $10\text{mm} < c\tau_a < 1\text{m}$

Yukawa-like branching ratios:

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

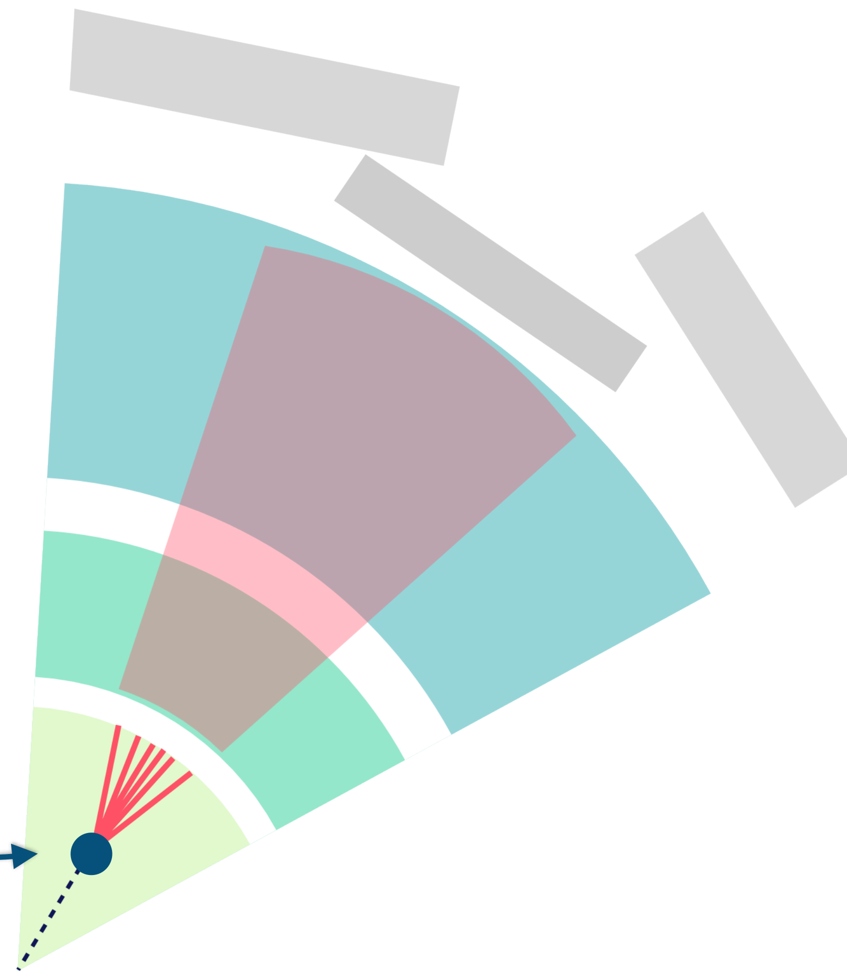
Difficult to trigger, so focus on **associated production**

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



Signature of interest:

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



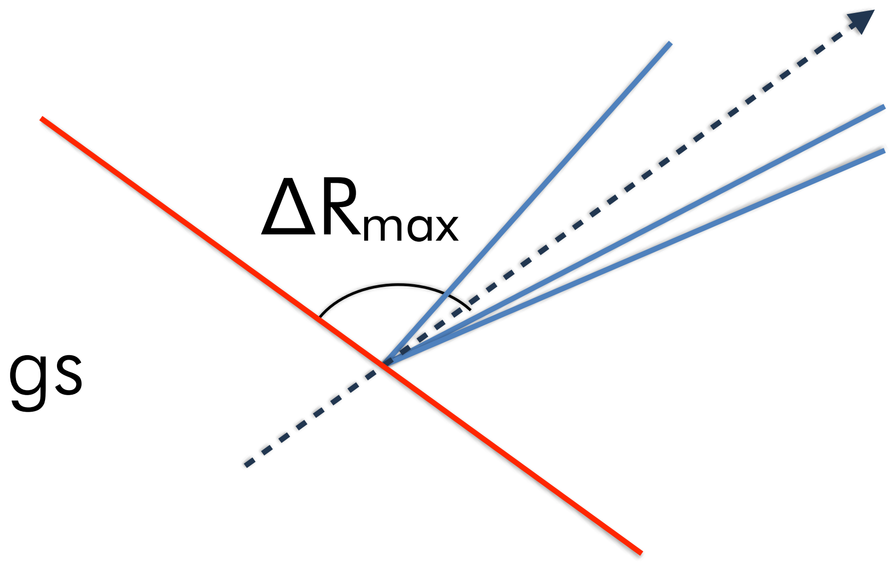
Analysis Strategy

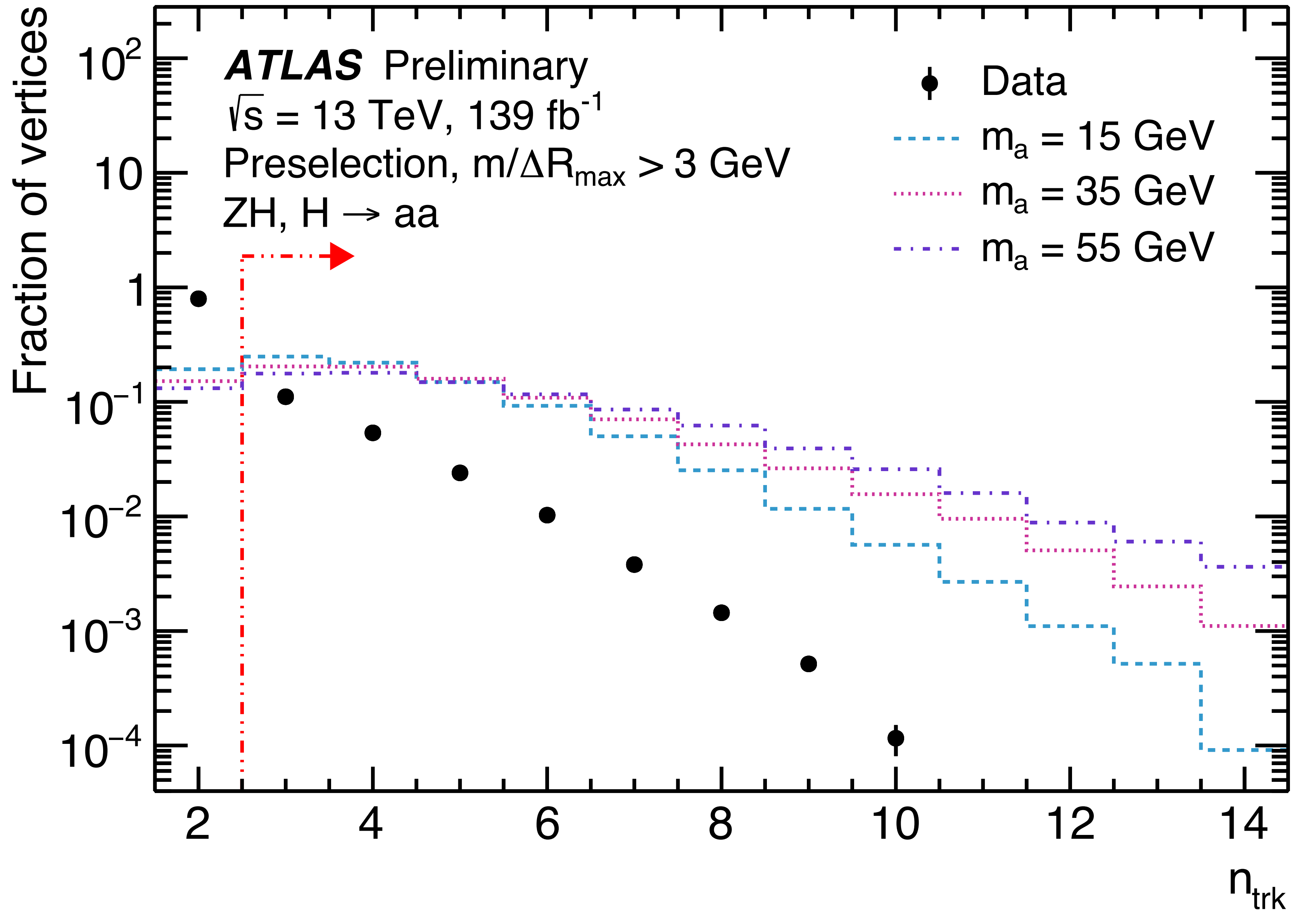
Trigger on prompt leptons from Z decay

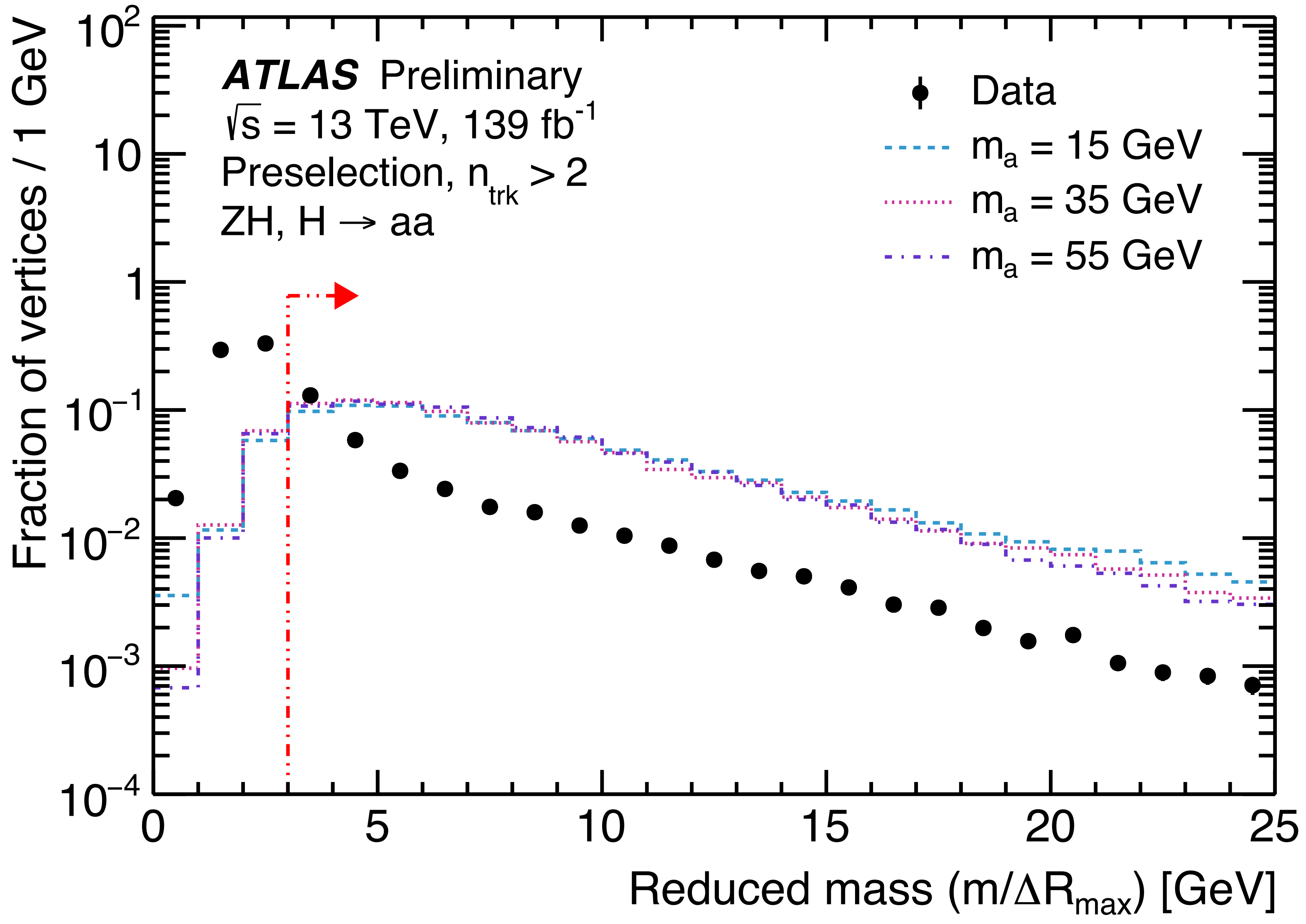
Offline, require
- Two same flavor opposite sign leptons
- $66 < m_{ll} < 116$ GeV
- At least two jets with $p_T > 20$ GeV

Displaced vertices are required to satisfy:

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







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

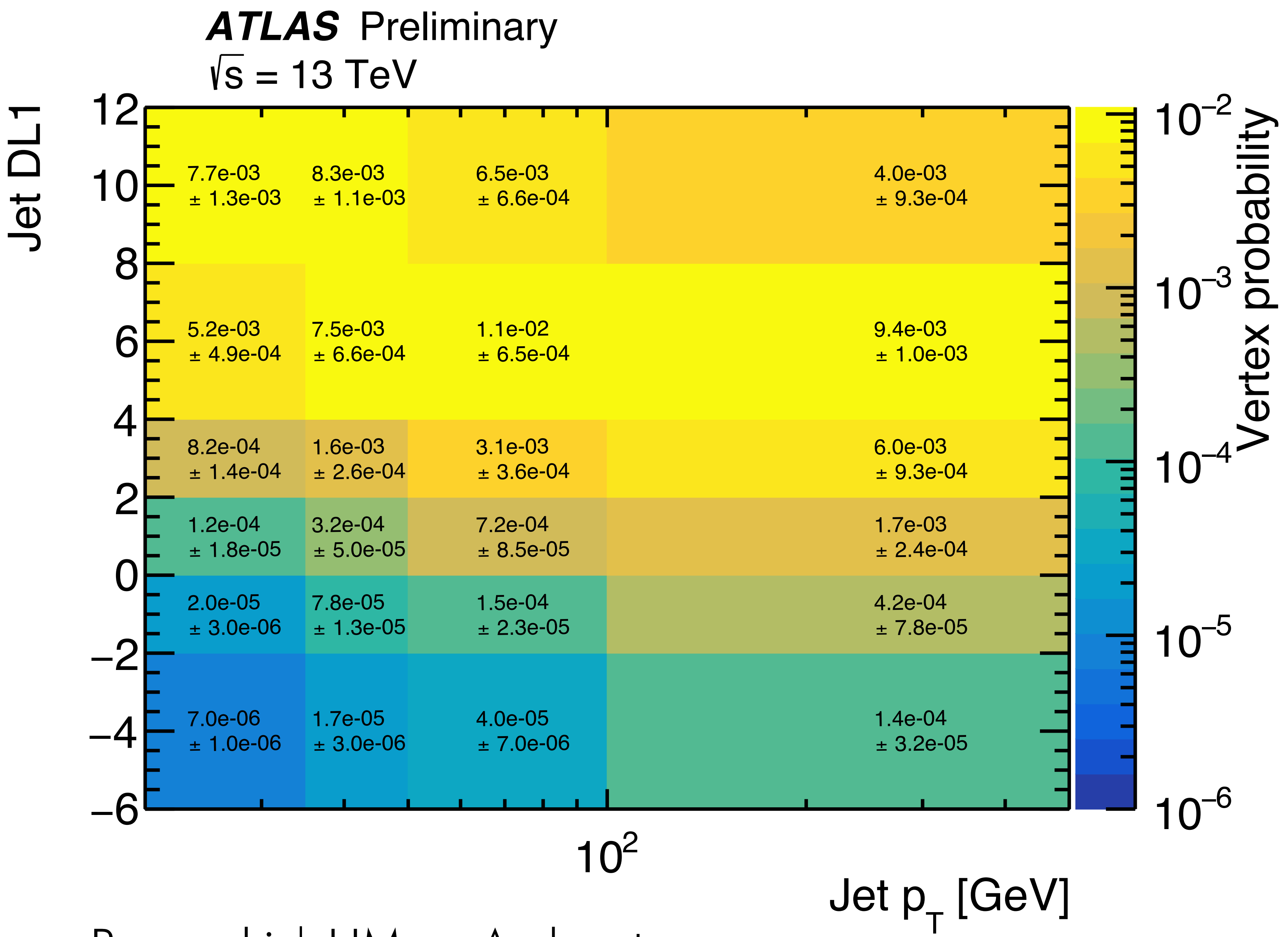
Probability for a jet to contain a DV increases with **p_T** and **b-tag score (DL1)**

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

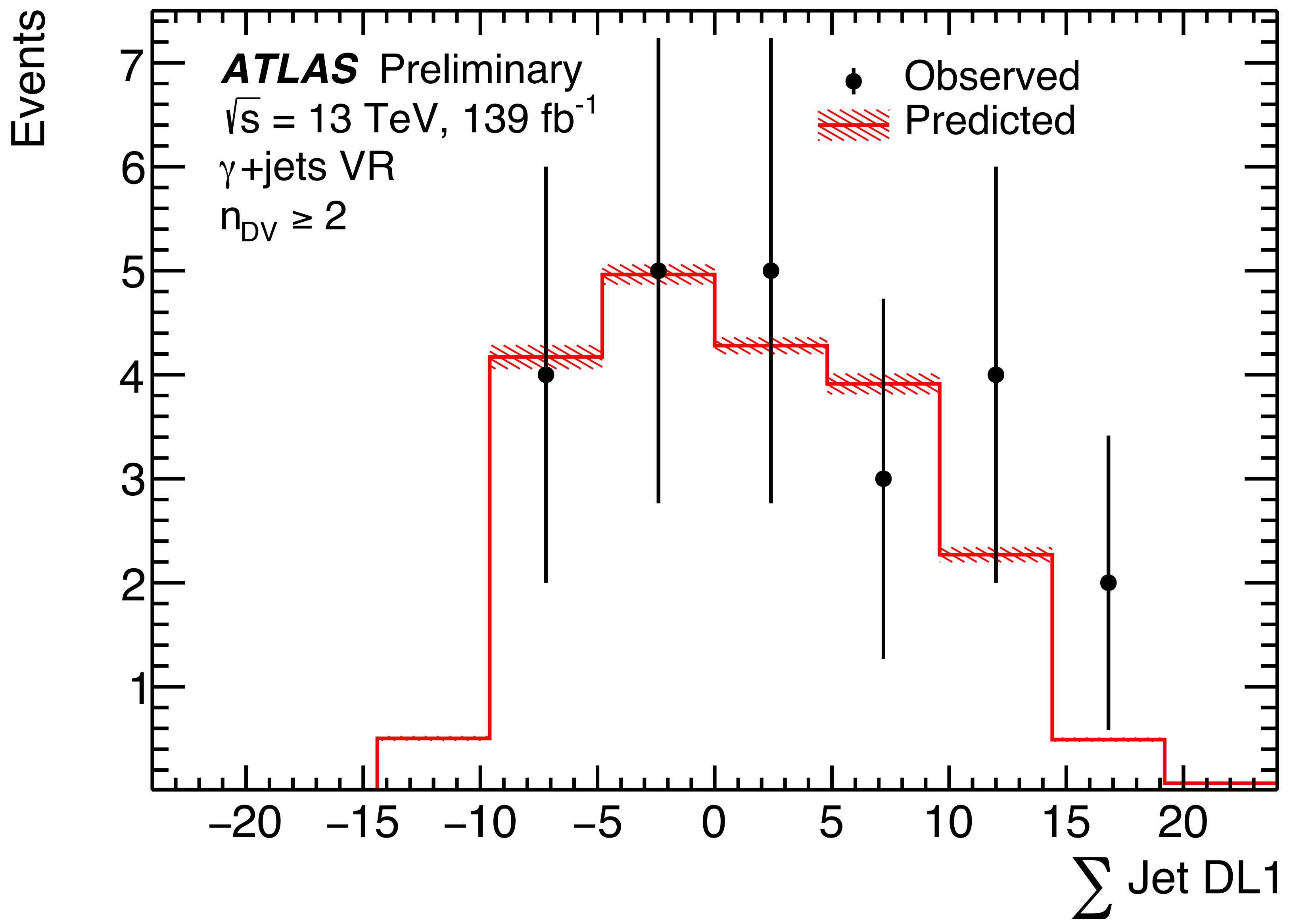
Compute probability that an event contains ≥ 2 DVs from the jets in the event

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

Measure per-jet vertex probability in CR



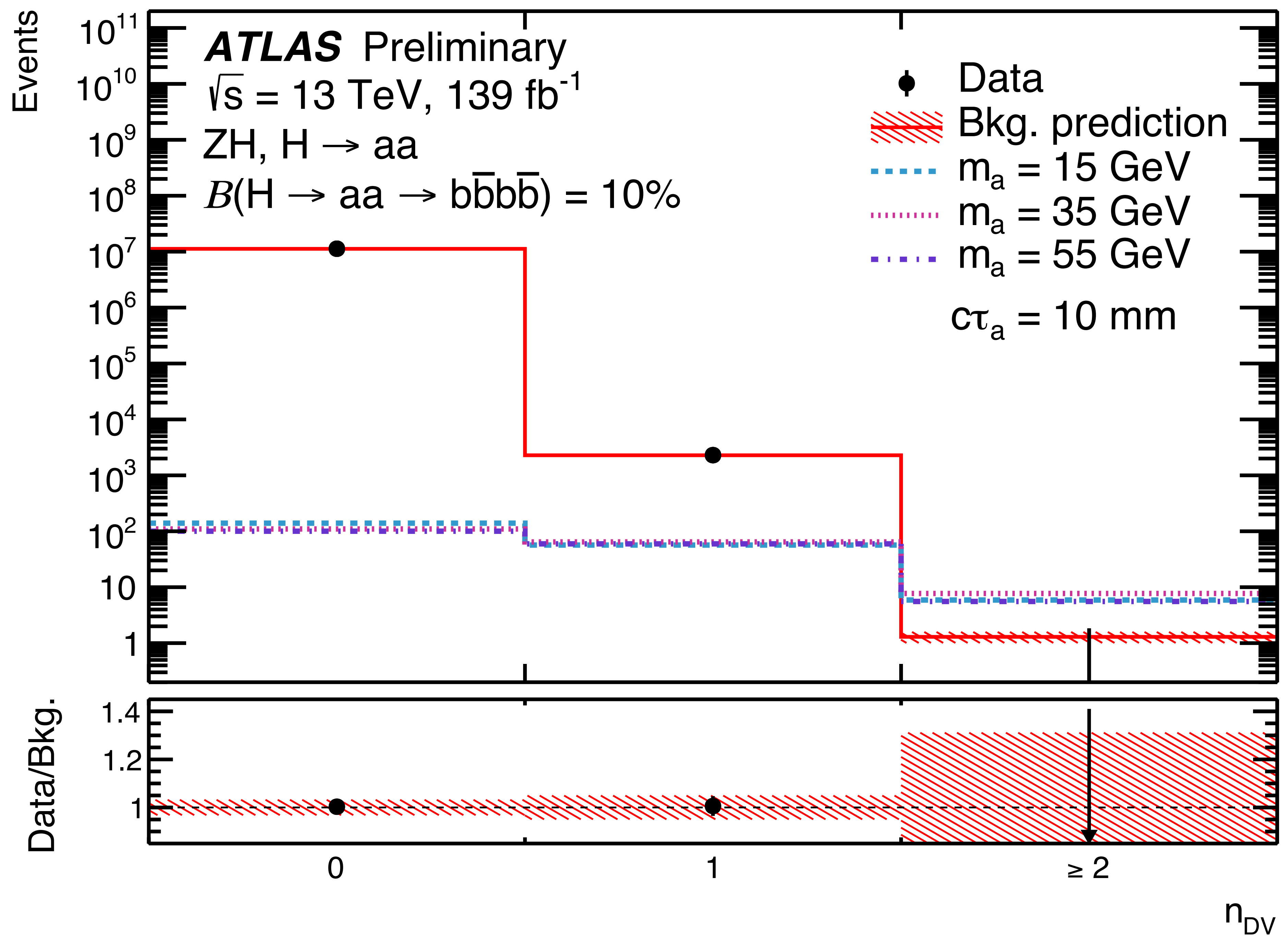
Validate in γ+jets validation region



Results

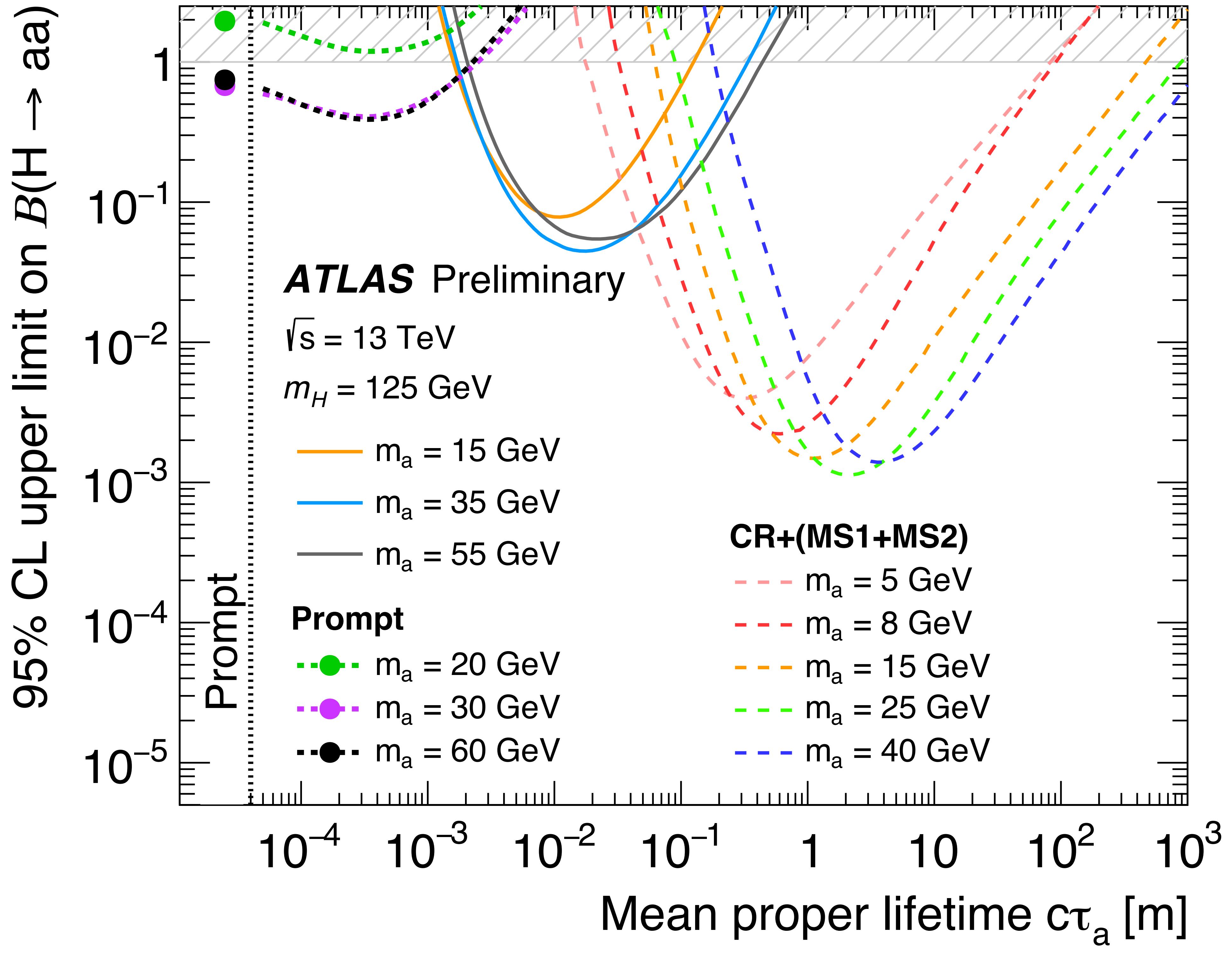
Zero events observed in signal region

- Good agreement with background prediction



Limits set on BR(H → aa → bbbb)

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



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

Conclusions

Long-lived particle signatures are **highly-motivated** yet **underexplored** at the LHC

ATLAS has a robust and growing program of LLP searches

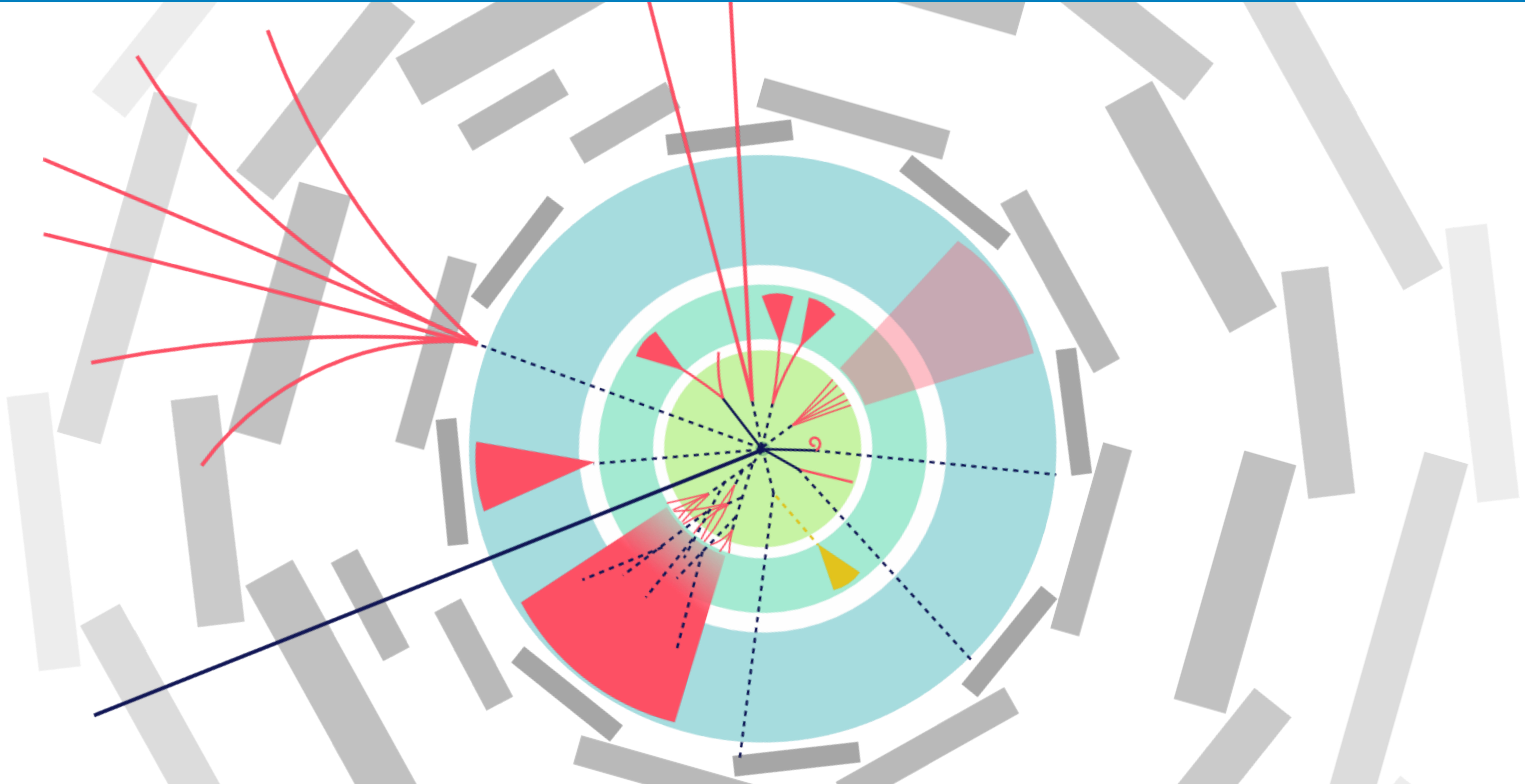
- **Displaced leptons** → first search at LHC, significant improvements over LEP limits
- **Disappearing tracks** → most stringent limits for higgsinos and winos with their natural lifetimes
- **Stopped particles** → first ATLAS search using 13 TeV data
- **Exotic Higgs decays to LLPs in ID** → first dedicated search at LHC, most stringent limits to date for low mass LLPs

With new techniques and more data, we are delving deeper into the **lifetime frontier** 🤠

More Run 2 LLP results from ATLAS coming soon, and exciting prospects on the horizon for Run 3!

- LRT included in **standard reconstruction**! (ATL-PHYS-PUB-2021-012)

Backup

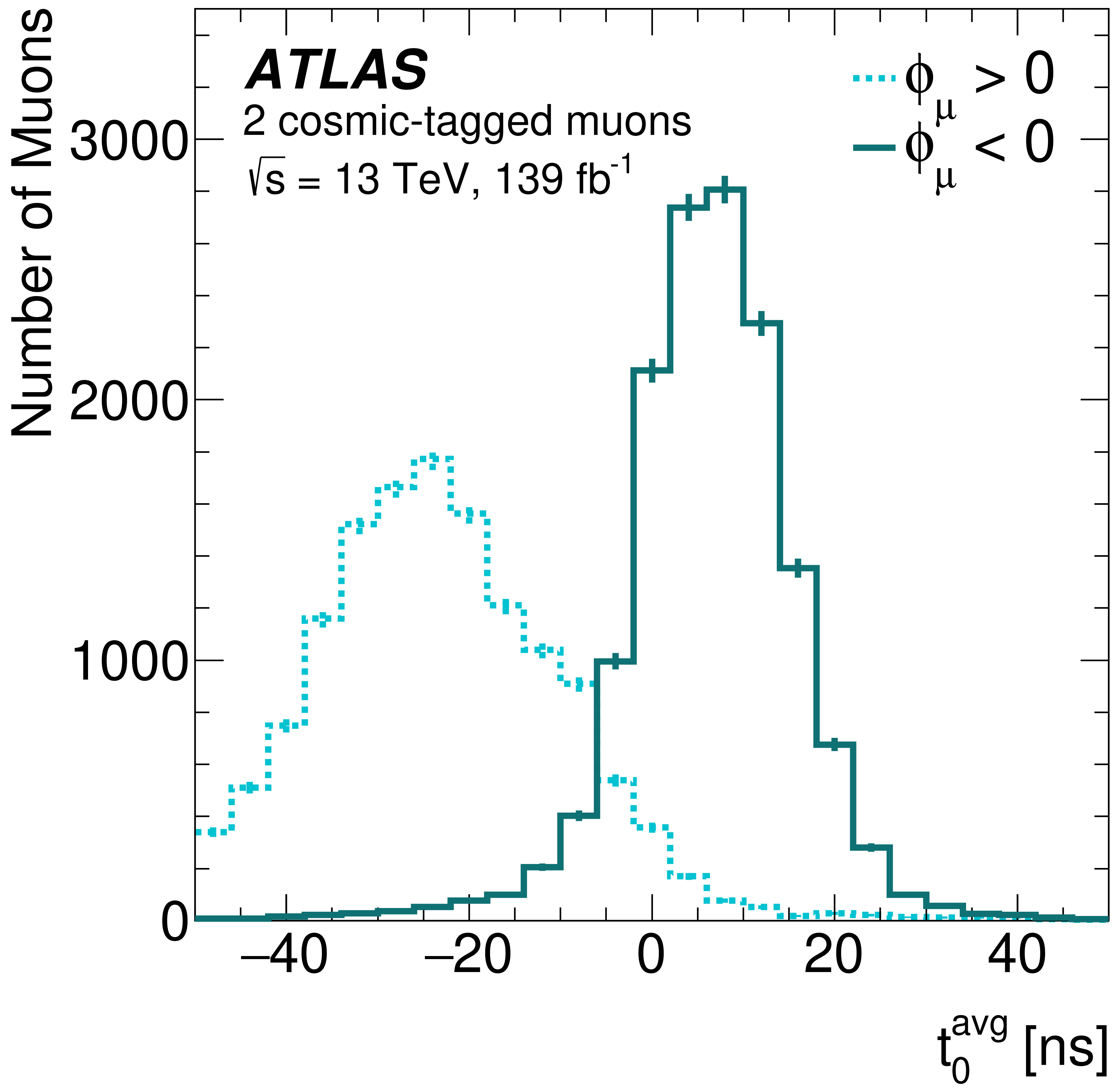


arXiv:2011.07812

Cosmic veto

t_0^{avg}: average time measured by the muon's MS track segments

- $|t_0^{avg}| < 30$ ns



Displaced Leptons

arXiv:2011.07812

Systematics

Background	Uncertainty	Value [%]
ee: fakes and heavy-flavor	statistical	18
	isolation non-closure	11
	fakes non-closure	6
	total	22
$e\mu$: fakes and heavy-flavor	statistical	+257 / −129
	isolation non-closure	92
	fakes non-closure	8
	total	+273 / −159
$\mu\mu$: cosmic muons	statistical	+180 / −95
	R_{good} $\lvert d_0 \rvert$ dependence	38
	estimate variable	16.5
	R_{good} definition muon	13
	total	+185 / −104

Disappearing tracks

ATLAS-CONF-2021-015

Systematics

Background

	Electroweak channel [%]	Strong channel [%]
r_{ABCD}	5.2	0.9
r_{CD}	3.2	0.6
σ in signal p_{T} smearing function	2.9	0.1
α in signal p_{T} smearing function	1.7	0.2
p_0 parameter in the fake background p_{T} function	0.3	<0.1
p_1 parameter in the fake background p_{T} function	0.3	0.2
Normalization of muon background	0.6	<0.1
Normalization of electron background	<0.1	<0.1
α in muon p_{T} smearing function	<0.1	<0.1
σ in muon p_{T} smearing function	<0.1	<0.1
α in electron p_{T} smearing function	<0.1	<0.1
σ in electron p_{T} smearing function	<0.1	<0.1
α in hadron p_{T} smearing function	0.5	0.2
σ in hadron p_{T} smearing function	0.6	0.2

Signal

	Electroweak channel [%] $m_{\tilde{\chi}_1^\pm} = 600$ GeV	Strong channel [%] $m_{\tilde{g}} = 1400$ GeV $m_{\tilde{\chi}_1^\pm} = 1100$ GeV
Cross-section	7.6	14
Initial/final state radiation	8.4	5.1
Jet energy scale	2.3	1.5
Jet energy resolution	0.6	0.3
Jet vertex tagging efficiency	<0.1	<0.1
Pile-up modelling	0.7	<0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term	0.4	<0.1
Trigger efficiency	0.3	0.4
Tracklet reconstruction efficiency	5.9	
Luminosity	1.7	
Total	11	8.1

Disappearing tracks

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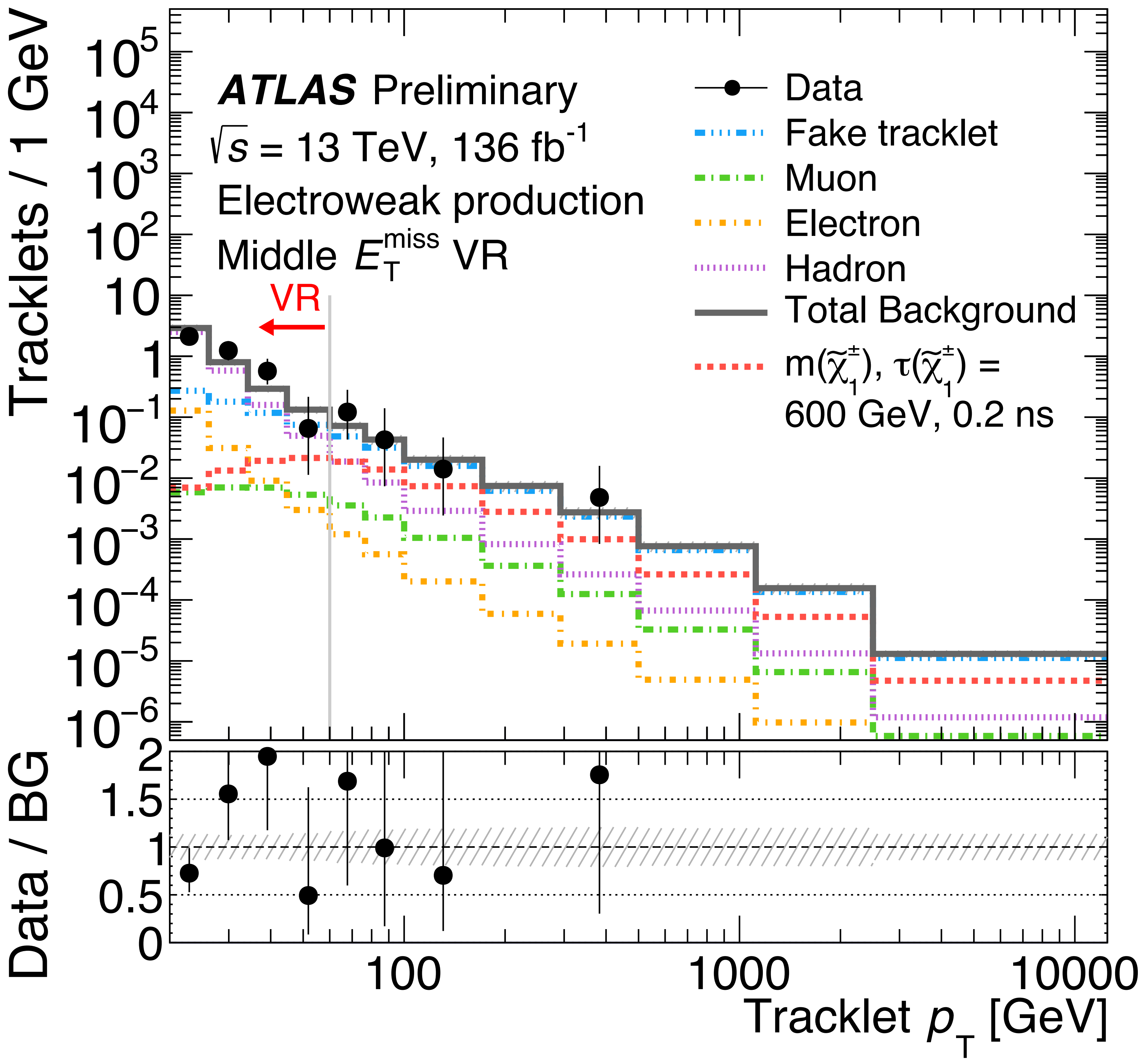
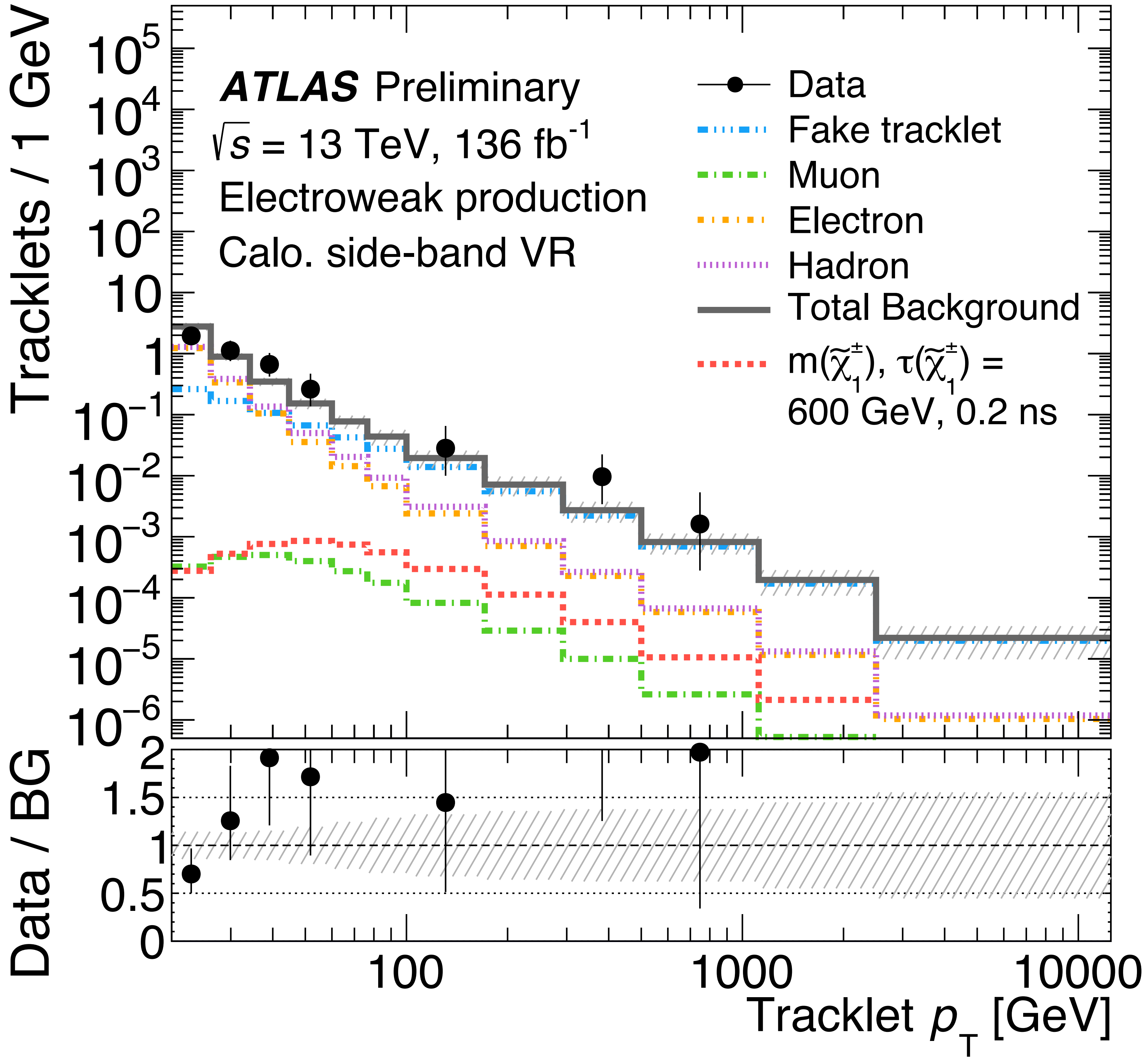
Validation

low MET, low tracklet pT



sidebands of calorimeter isolation



Disappearing tracks

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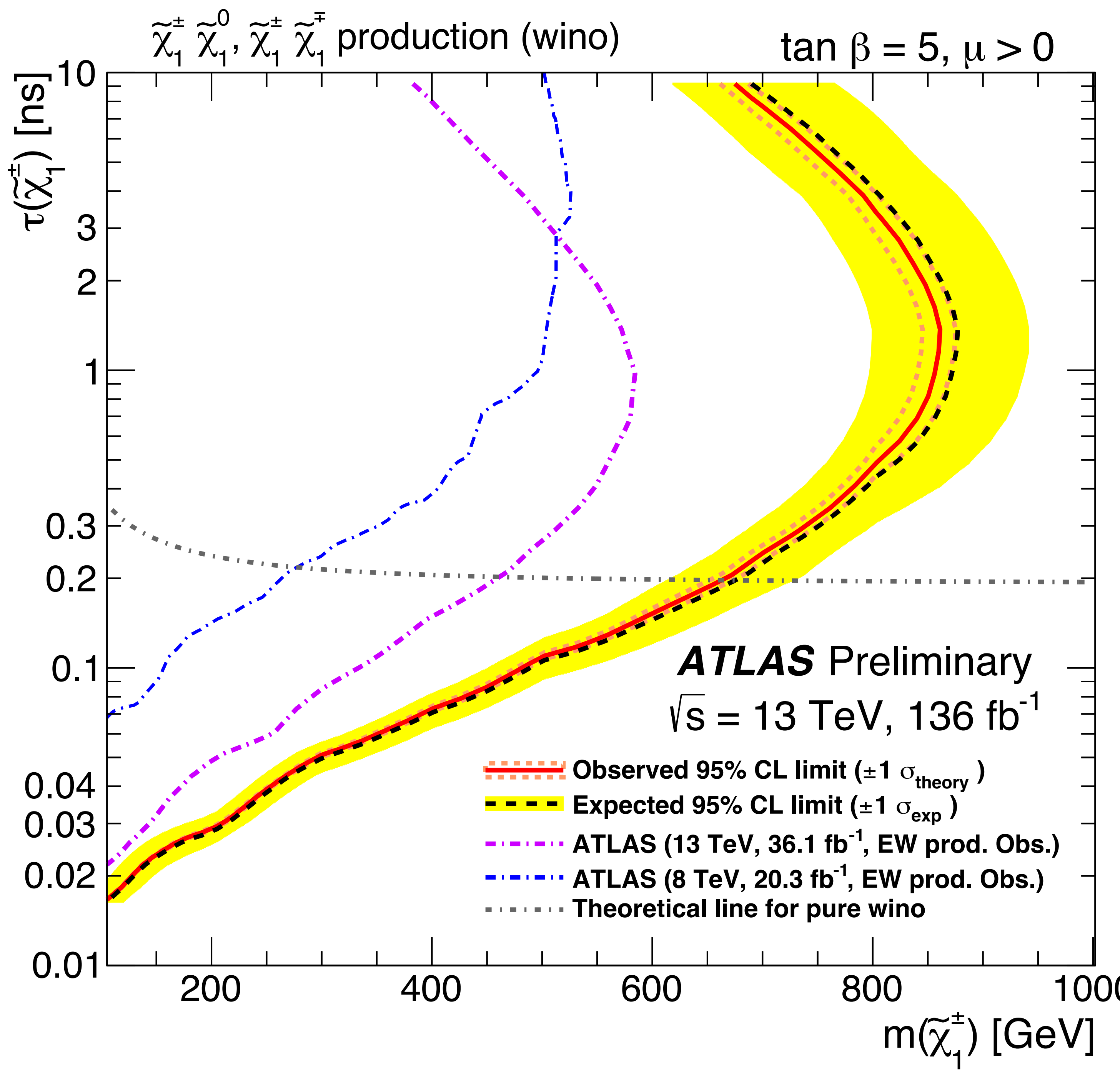
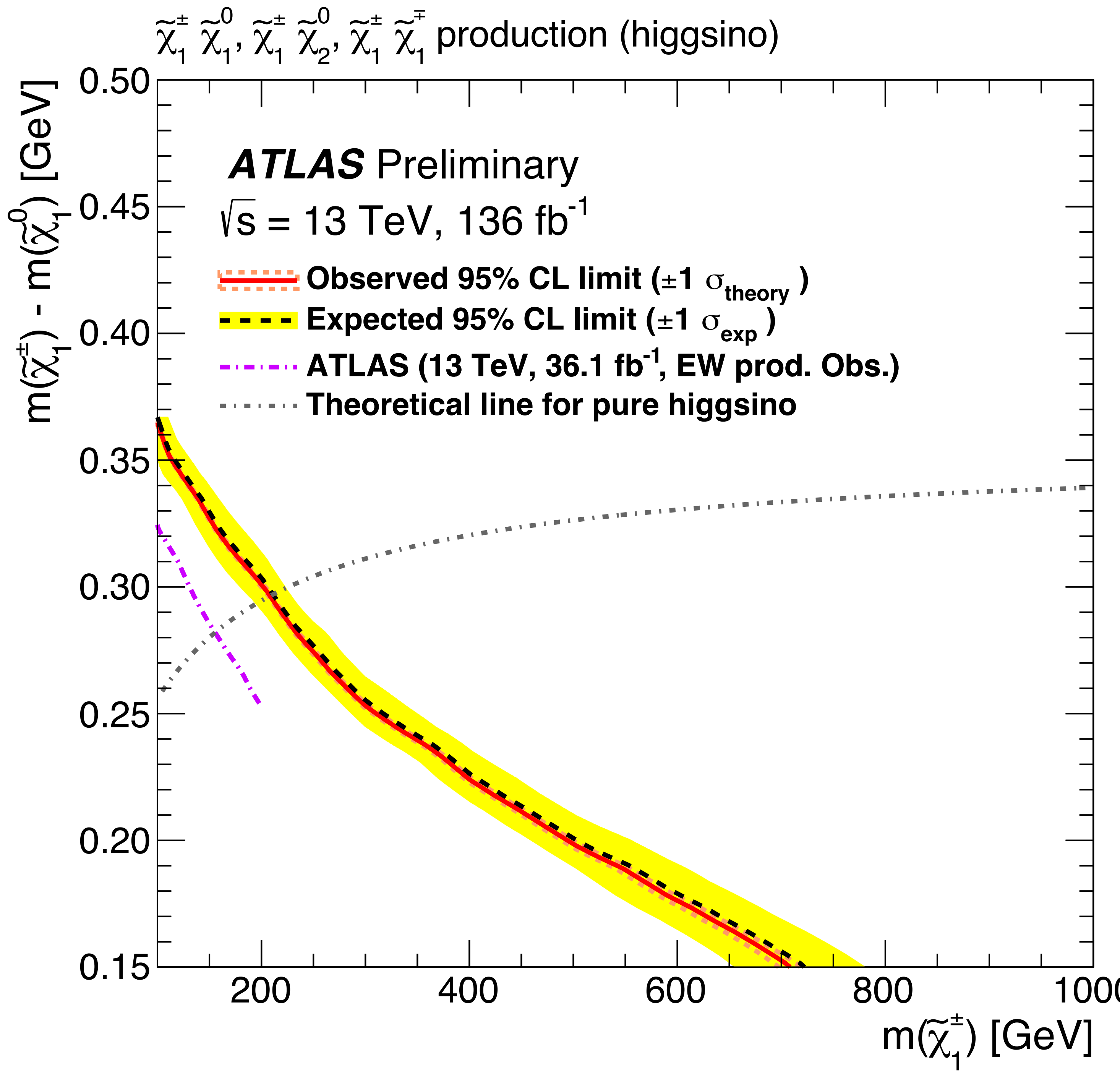
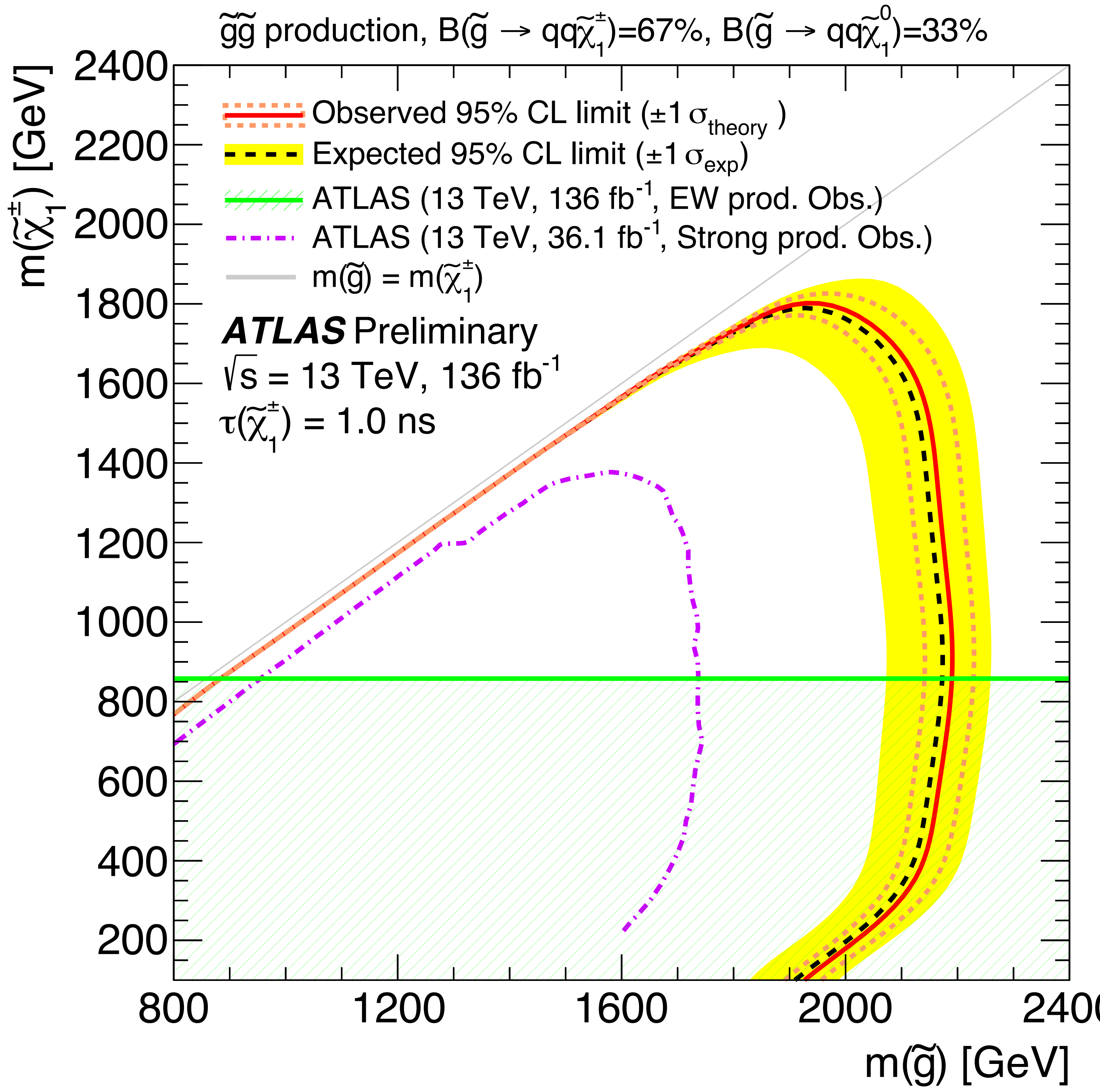
Limits

Electroweak





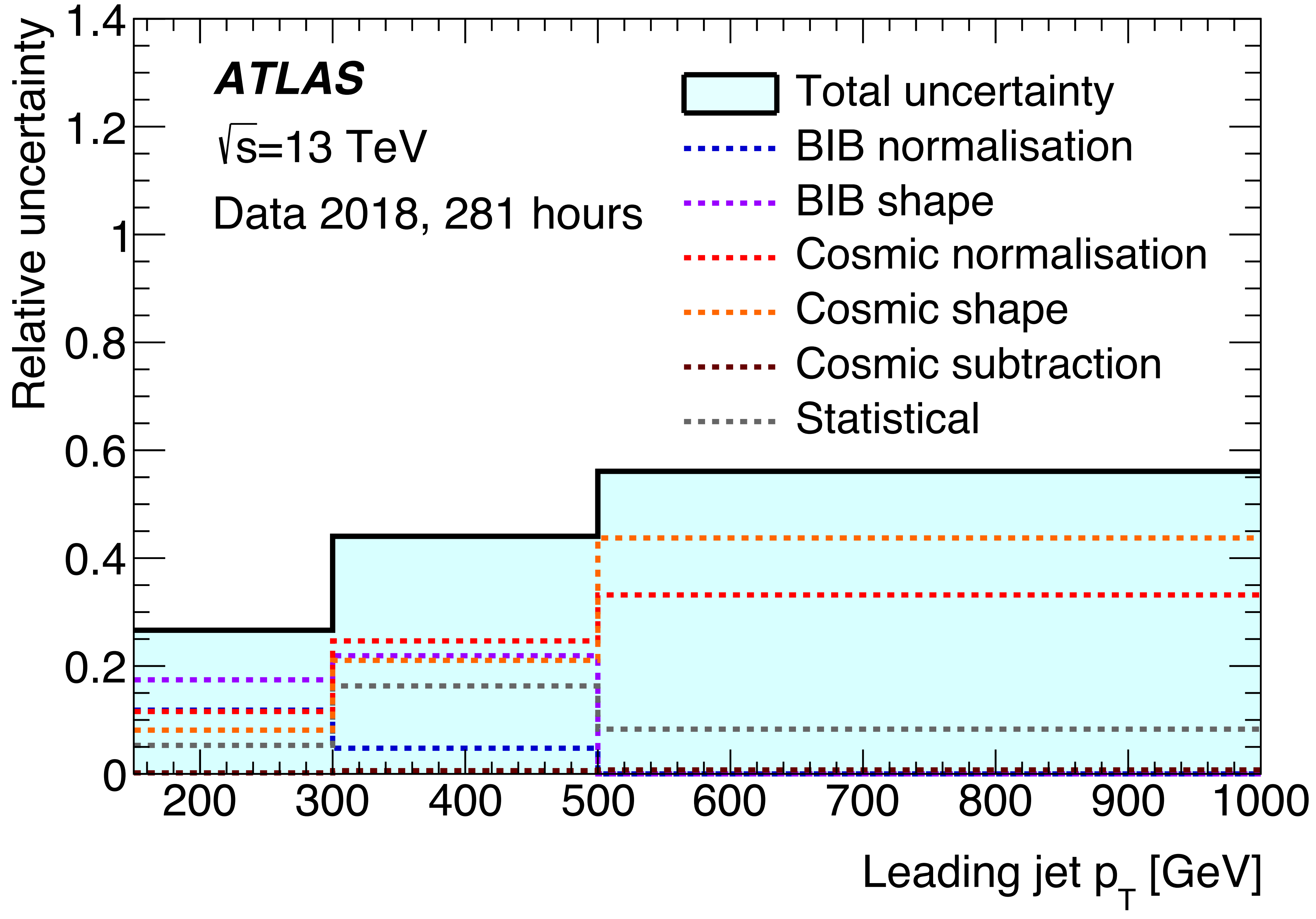
Strong

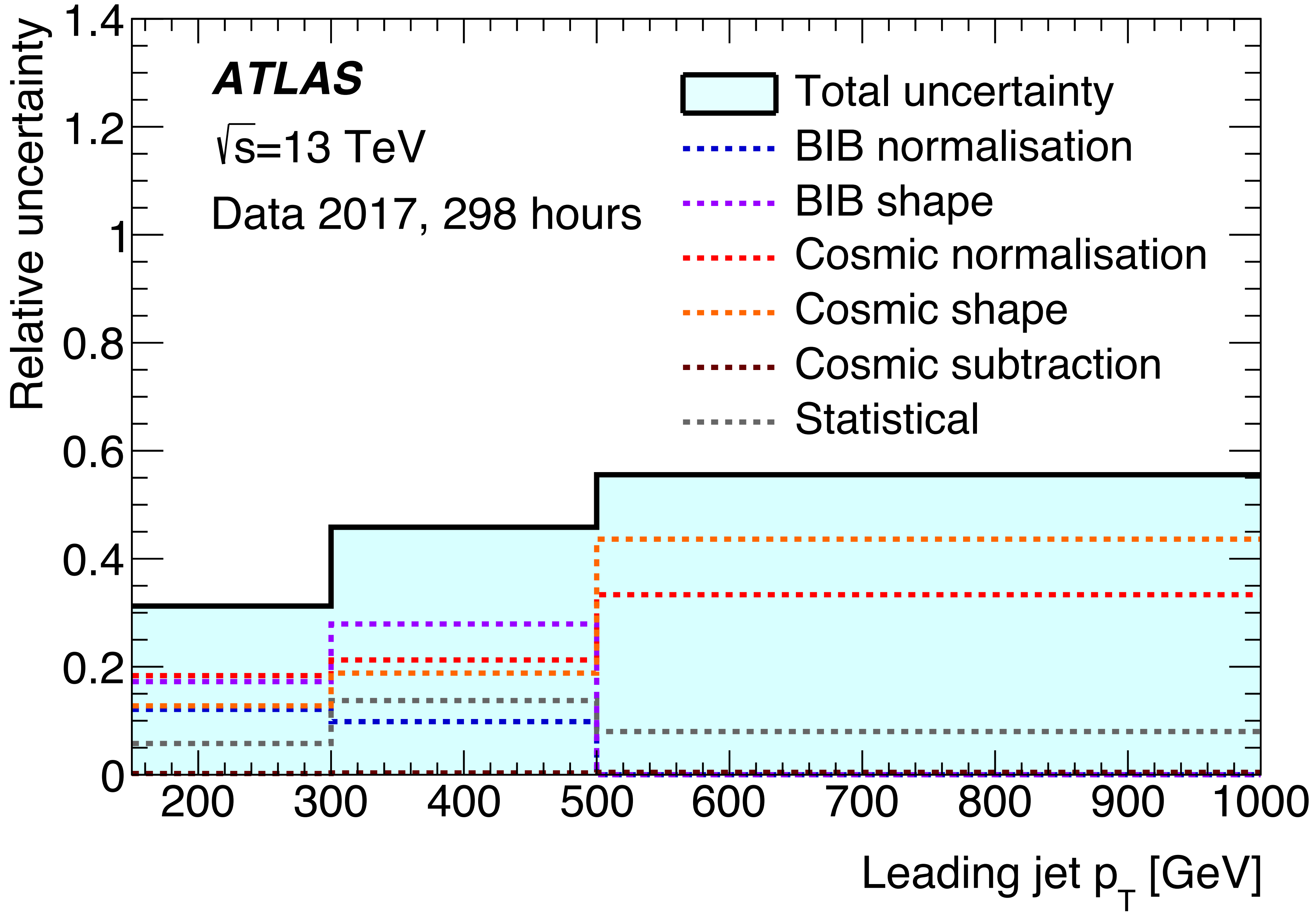


Stopped particles

arXiv:2104.03050

Systematics





Stopped particles

arXiv:2104.03050

Yields

Central signal regions	SRC (2017 data)	SRC (2018 data)
Observed events	92	100
Total expected background events	88 ± 28	119 ± 32
Beam-induced background events	37 ± 23	72 ± 29
Cosmic-ray-induced background events	51 ± 21	47 ± 19
$m(\tilde{g}, \tilde{\chi}_1^0) = (1400, 100)$ GeV	5	6
$m(\tilde{g}, \tilde{\chi}_1^0) = (1400, 900)$ GeV	5	6

Inclusive signal regions	SRIncl (2017 data)	SRIncl (2018 data)
Observed events	239	221
Total expected background events	167 ± 48	208 ± 50
Beam-induced background events	93 ± 42	139 ± 45
Cosmic-ray-induced background events	74 ± 30	69 ± 28
$m(\tilde{g}, \tilde{\chi}_1^0) = (1400, 100)$ GeV	7	9
$m(\tilde{g}, \tilde{\chi}_1^0) = (1400, 900)$ GeV	7	8

Exotic Higgs decays

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Vertex selection

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

Exotic Higgs decays

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Filter

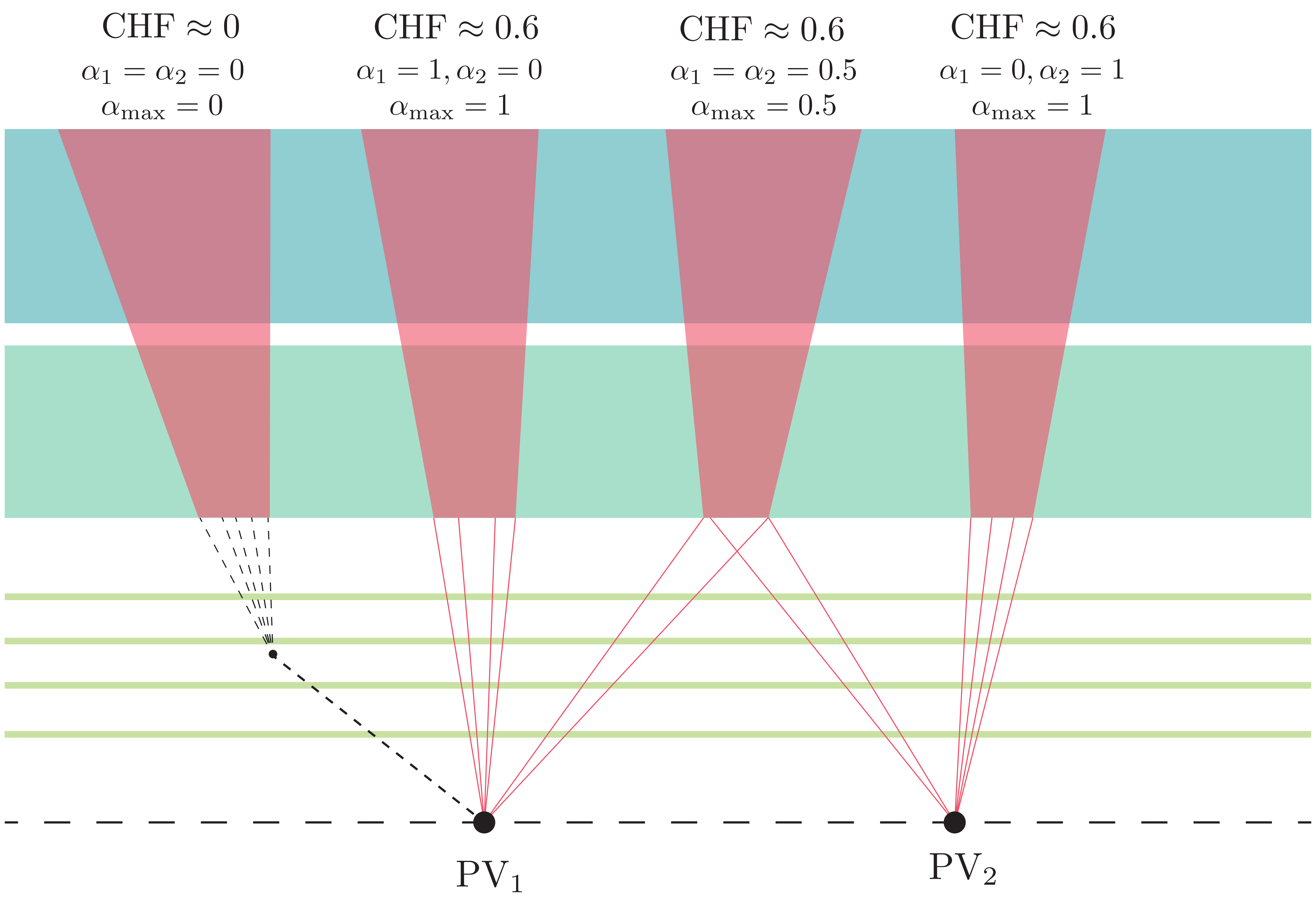

Diagram inspired by Kate Pachal's LHC seminar

Exotic Higgs decays

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Systematics

Dominant uncertainty from LRT

- Measure by comparing yields of **K-short vertices** in data and MC

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