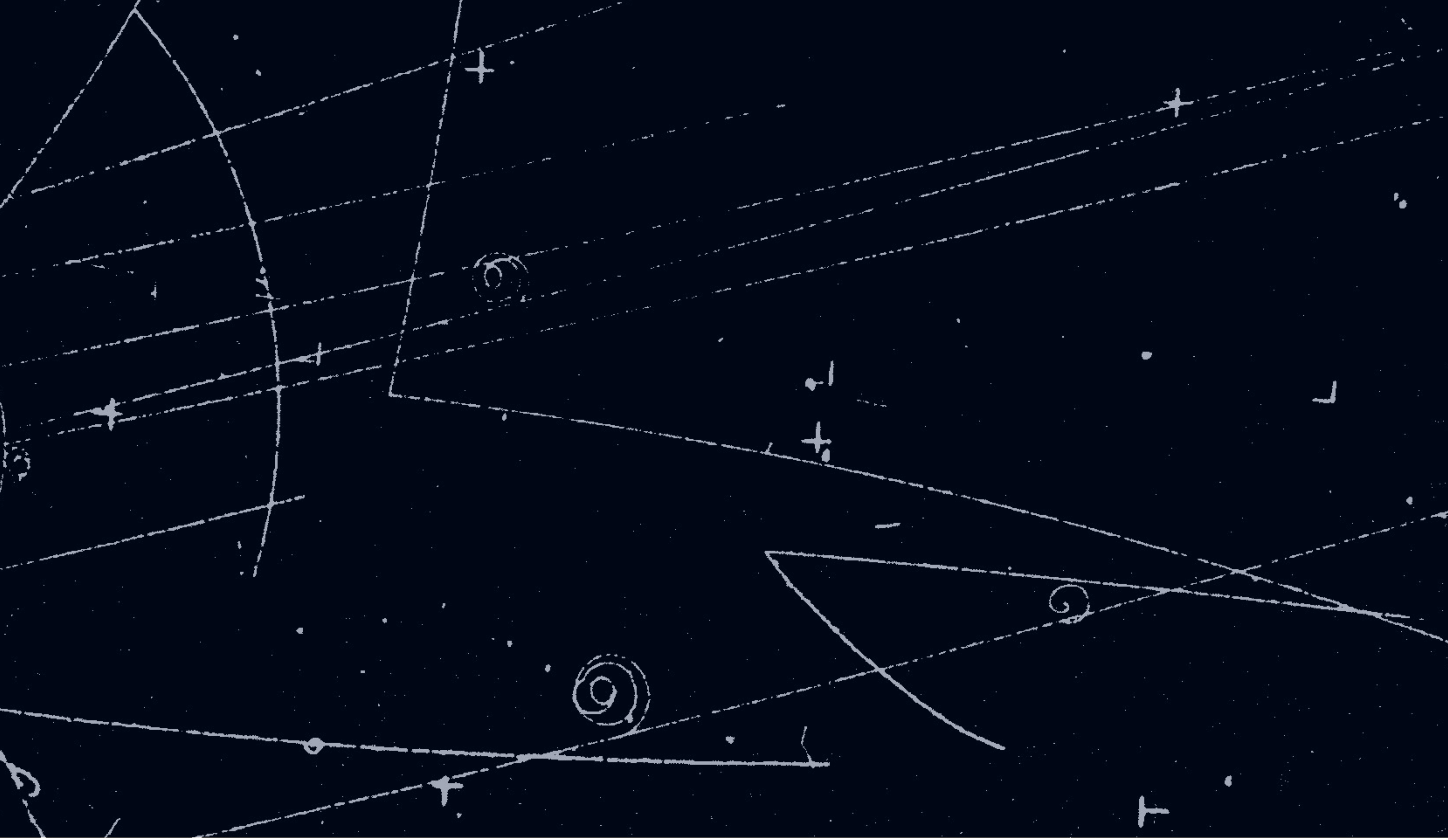
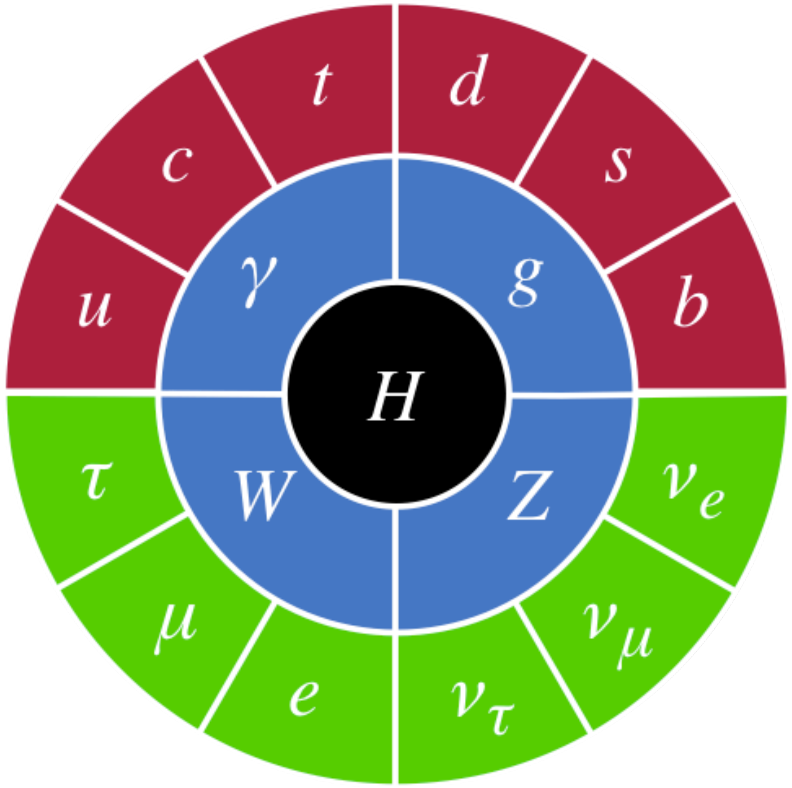


Probing the lifetime frontier with the ATLAS detector

Kate Pachal
Duke University
o.b.o. the ATLAS collaboration

Particle physics check-in: how are we doing?

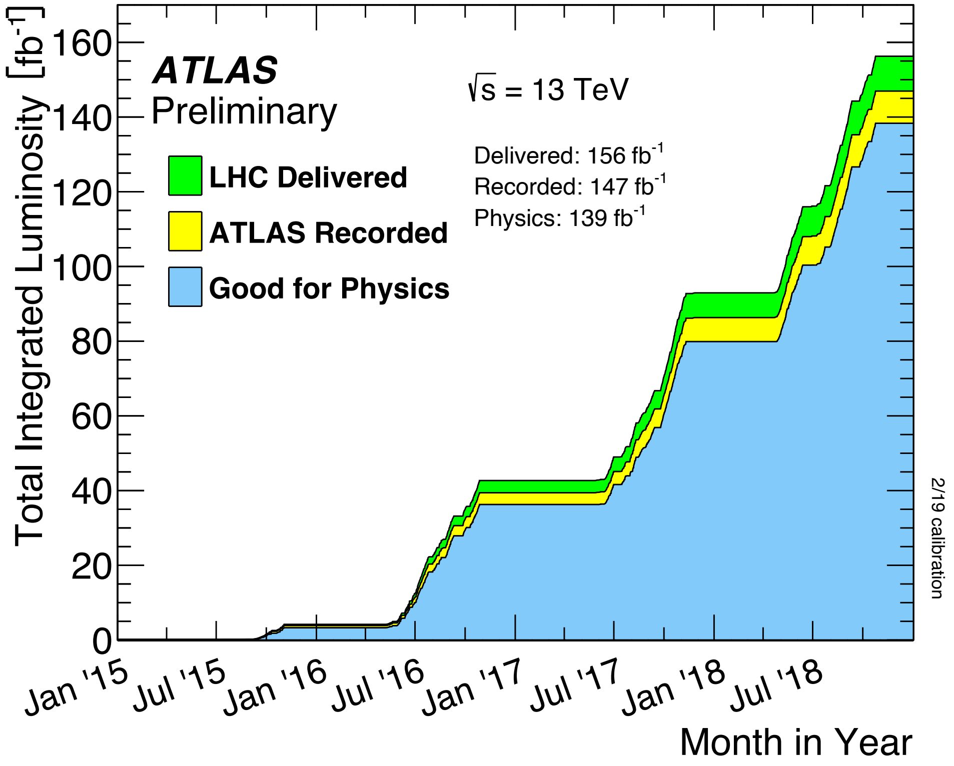
Kyle Cranmer, David Kaplan



Higgs discovery at LHC Run 1 completed our picture of the **Standard Model**

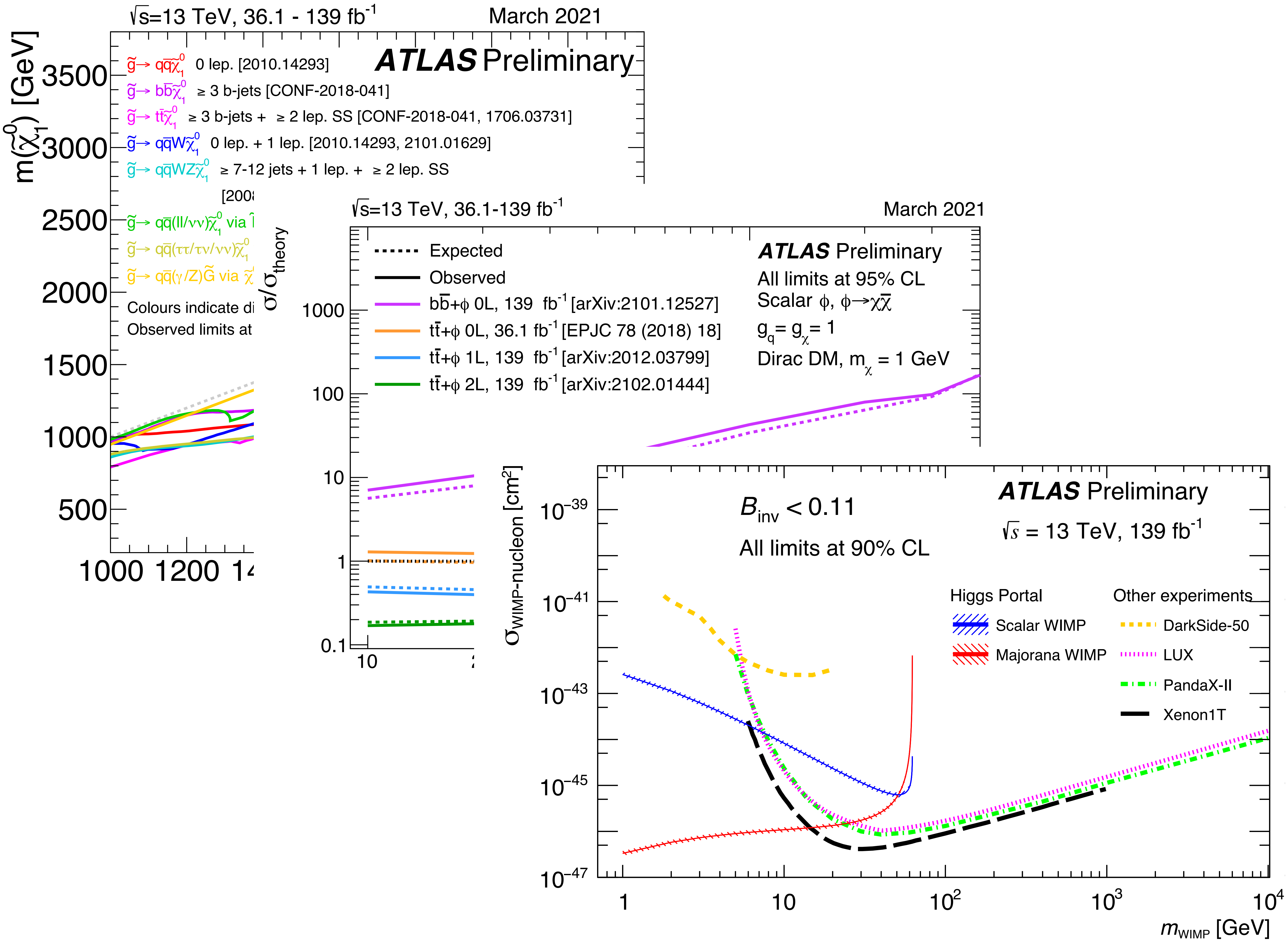
But we believe this picture is **not yet final**: observational and theoretical issues need resolution

Searches for **beyond-Standard-Model physics** a core element of LHC programme



Run 2 provided **139 fb^{-1} of 13 TeV data** for us to analyse

To date, **40 ATLAS papers** on BSM searches with full Run 2 dataset!



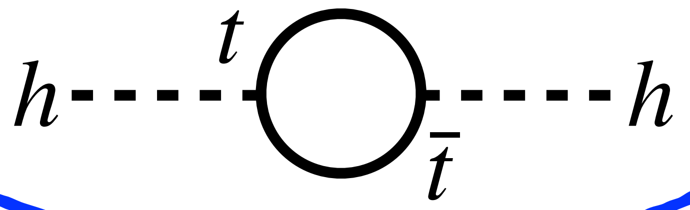
√s=13 TeV, 36.1 - 139 fb^{-1}
March 2021
ATLAS Preliminary
m($\tilde{\chi}_1^0$) [GeV]
3500
3000
2500
2000
1500
1000
500
1000
1200
$\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$ 0 lep. [2010.14293]
$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$ ≥ 3 b-jets [CONF-2018-041]
$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$ ≥ 3 b-jets + ≥ 2 lep. SS [CONF-2018-041, 1706.03731]
$\tilde{g}\rightarrow q\bar{q}W\tilde{\chi}_1^0$ 0 lep. + 1 lep. [2010.14293, 2101.01629]
$\tilde{g}\rightarrow q\bar{q}WZ\tilde{\chi}_1^0$ ≥ 7-12 jets + 1 lep. + ≥ 2 lep. SS
[200
$\tilde{g}\rightarrow q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via
$\tilde{g}\rightarrow q\bar{q}(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$
$\tilde{g}\rightarrow q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}$
Colours indicate di
Observed limits at
√s=13 TeV, 36.1-139 fb^{-1}
March 2021
ATLAS Preliminary
All limits at 95% CL
Scalar ϕ, $\phi\rightarrow\chi\bar{\chi}$
$g_q = g_\chi = 1$
Dirac DM, m_χ = 1 GeV
σ/σ_{theory}
Expected
Observed
$b\bar{b}+\phi$ 0L, 139 fb^{-1} [arXiv:2101.12527]
$t\bar{t}+\phi$ 0L, 36.1 fb^{-1} [EPJC 78 (2018) 18]
$t\bar{t}+\phi$ 1L, 139 fb^{-1} [arXiv:2012.03799]
$t\bar{t}+\phi$ 2L, 139 fb^{-1} [arXiv:2102.01444]
1000
100
10
1
0.1
10
ATLAS Preliminary
$B_{inv} < 0.11$
All limits at 90% CL
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$\sigma_{WIMP-nucleon}$ [cm^2]
10^{-39}
10^{-41}
10^{-43}
10^{-45}
10^{-47}
Higgs Portal
Scalar WIMP
Majorana WIMP
Other experiments
DarkSide-50
LUX
PandaX-II
Xenon1T
1
10
10^2
10^3
10^4
m_{WIMP} [GeV]

Where is the new physics?

We **know** it's out there:

Dark matter?

Higgs mass too light?



Where is all the antimatter?

We still have **as many reasons to expect new physics** as before the LHC turned on

So why haven't we found it yet? A couple possible reasons

1. It is above the scale accessible by the LHC
2. It isn't where we have been looking

What if it is just **very hard to see**?

How we do our searches

Search program follows a common sense approach:

Start simple - low complexity, high reward - and **work our way up**

By end of Run 2, ATLAS is increasingly focusing energy on various well-motivated but **more complicated targets**

Signals with interference

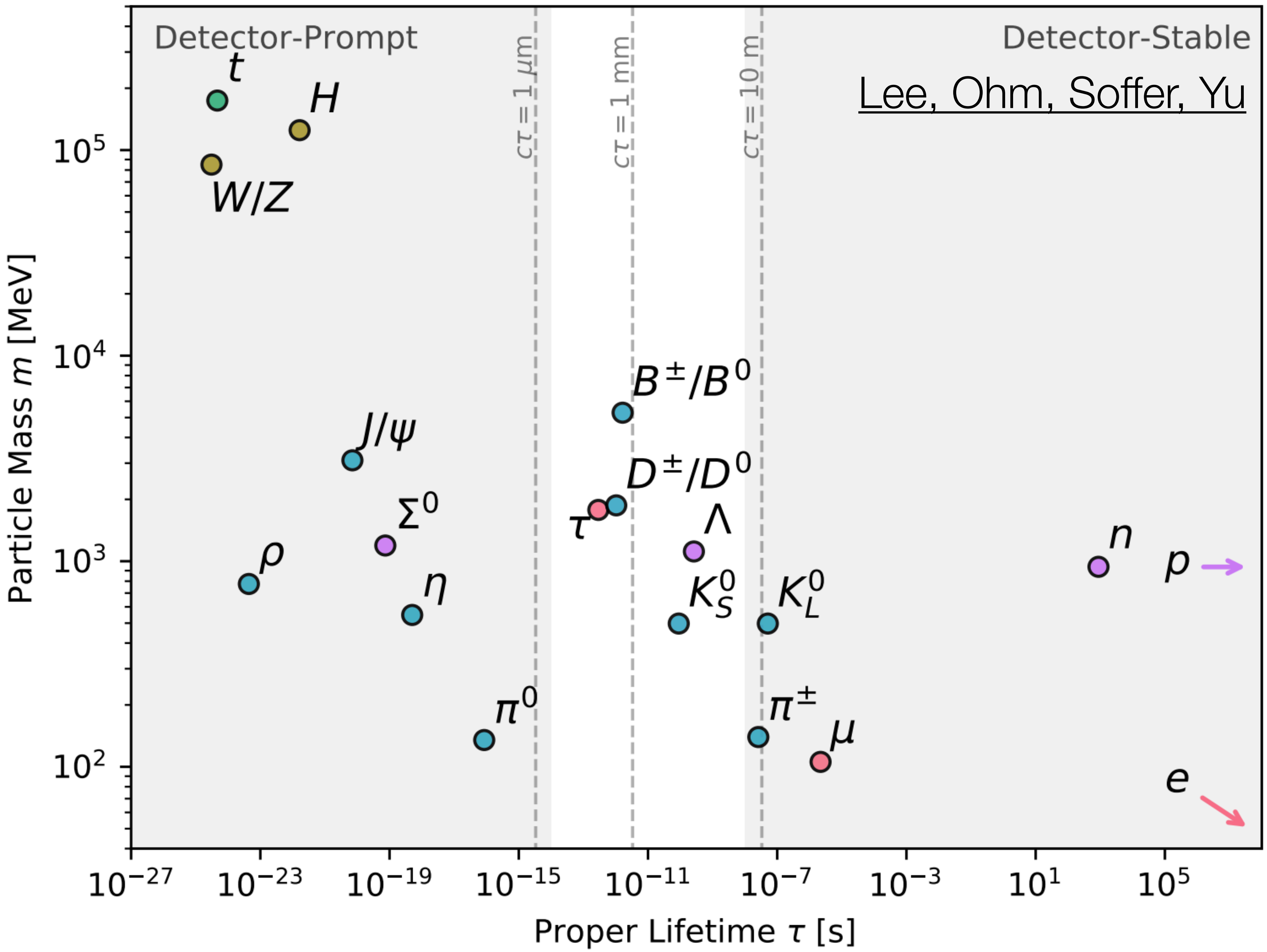
Low-mass, low cross section signals

Very soft final states

Giant backgrounds

Non-prompt decays

Standard Model particles exist over a great range of proper lifetimes



So too can particles beyond the Standard Model!

Origins of long lifetimes

Small couplings

e.g. SM lepton flavour violation

Limited phase space

e.g. K_{short} vs K_{long} lifetimes

Decays via heavy particle

e.g. μ to e via off-shell W

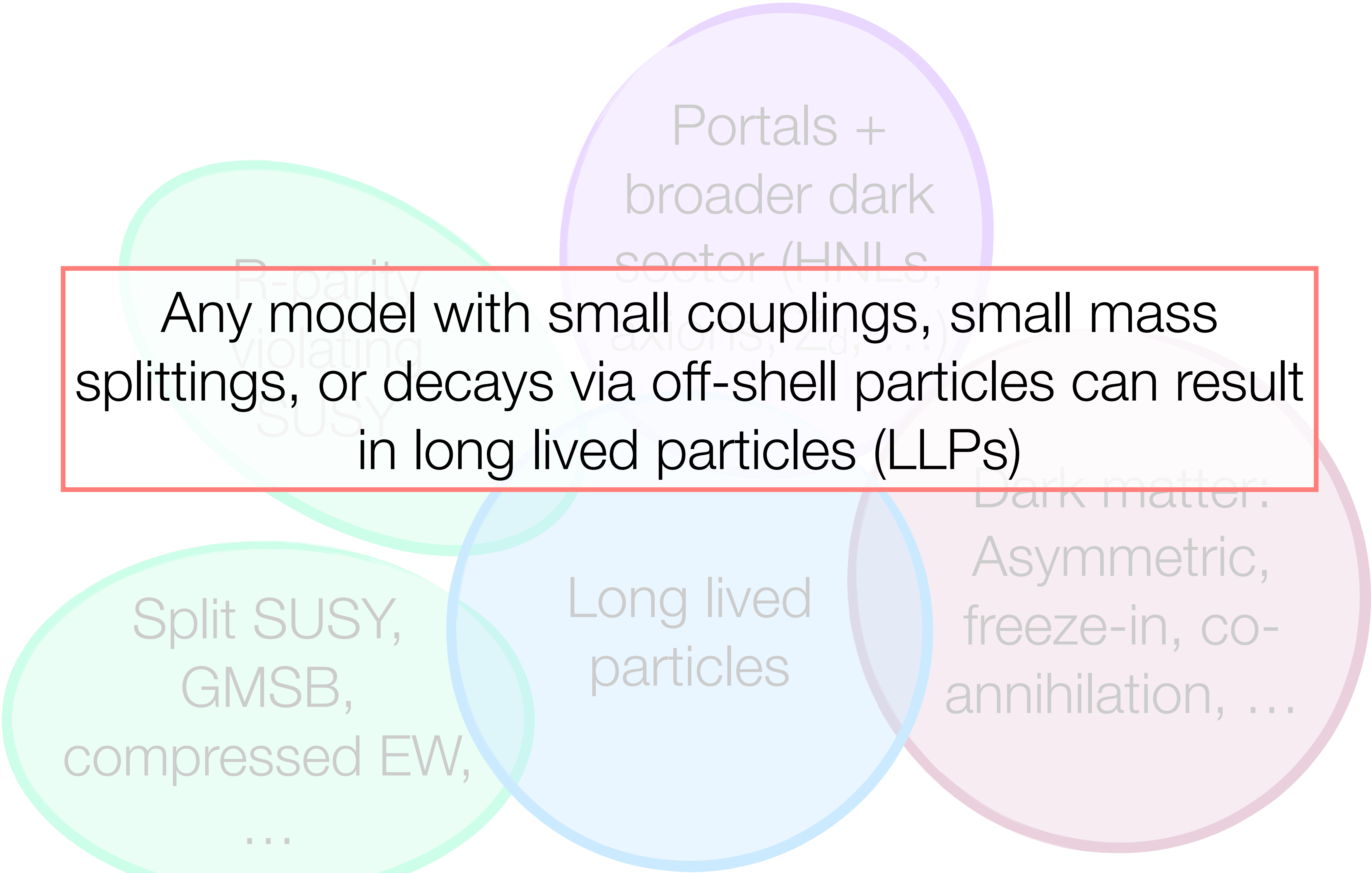
Long lifetimes in the BSM world

Small couplings
e.g. R-parity violating SUSY

Limited phase space
e.g. compressed SUSY scenarios

Decays via heavy particle
e.g. heavy neutrinos

(Parts of) the LLP world



R-parity violating SUSY

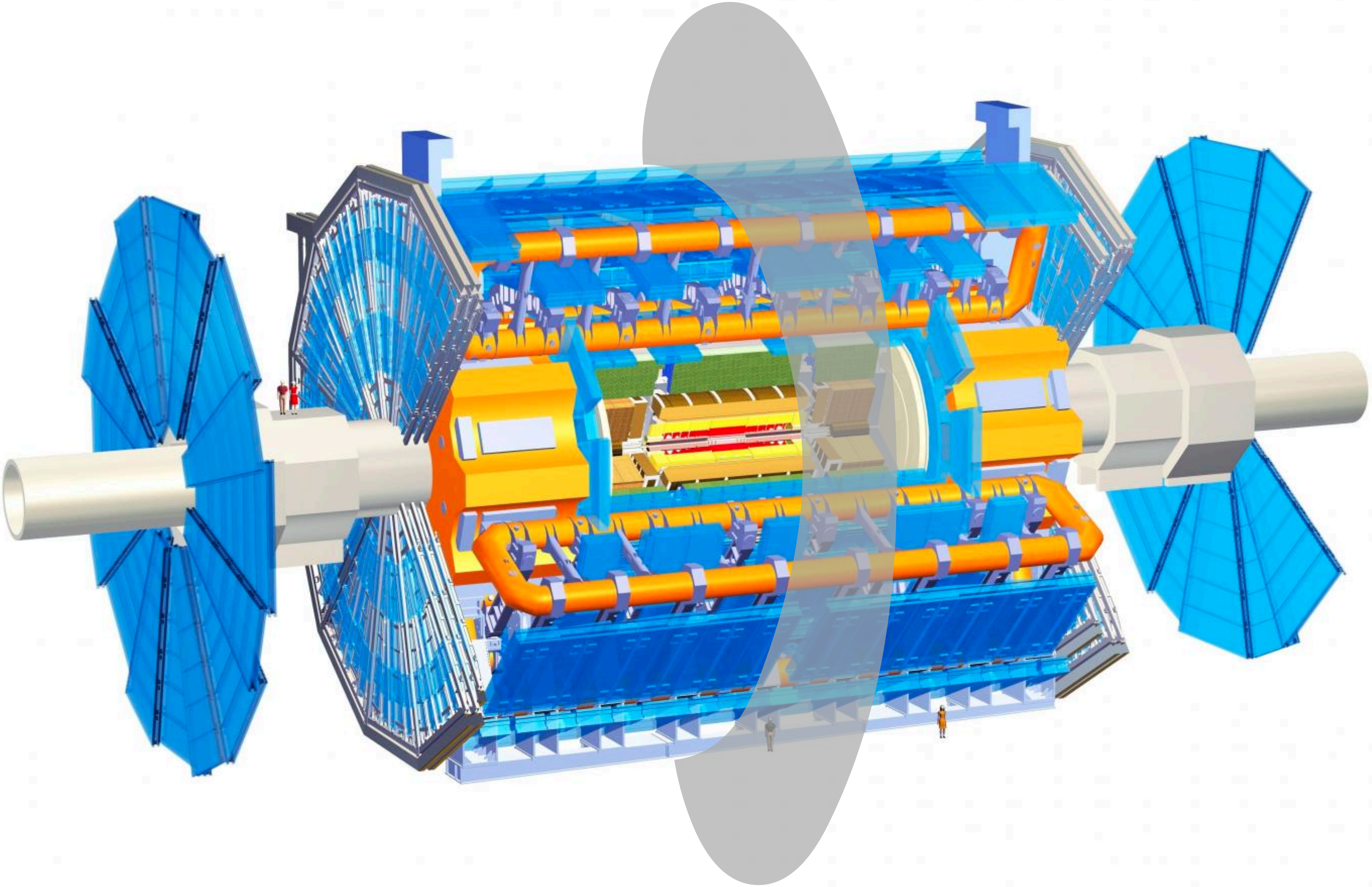
Portals + broader dark sector (HNLs, axions, Z_d, …)

Split SUSY, GMSB, compressed EW, …

Long lived particles

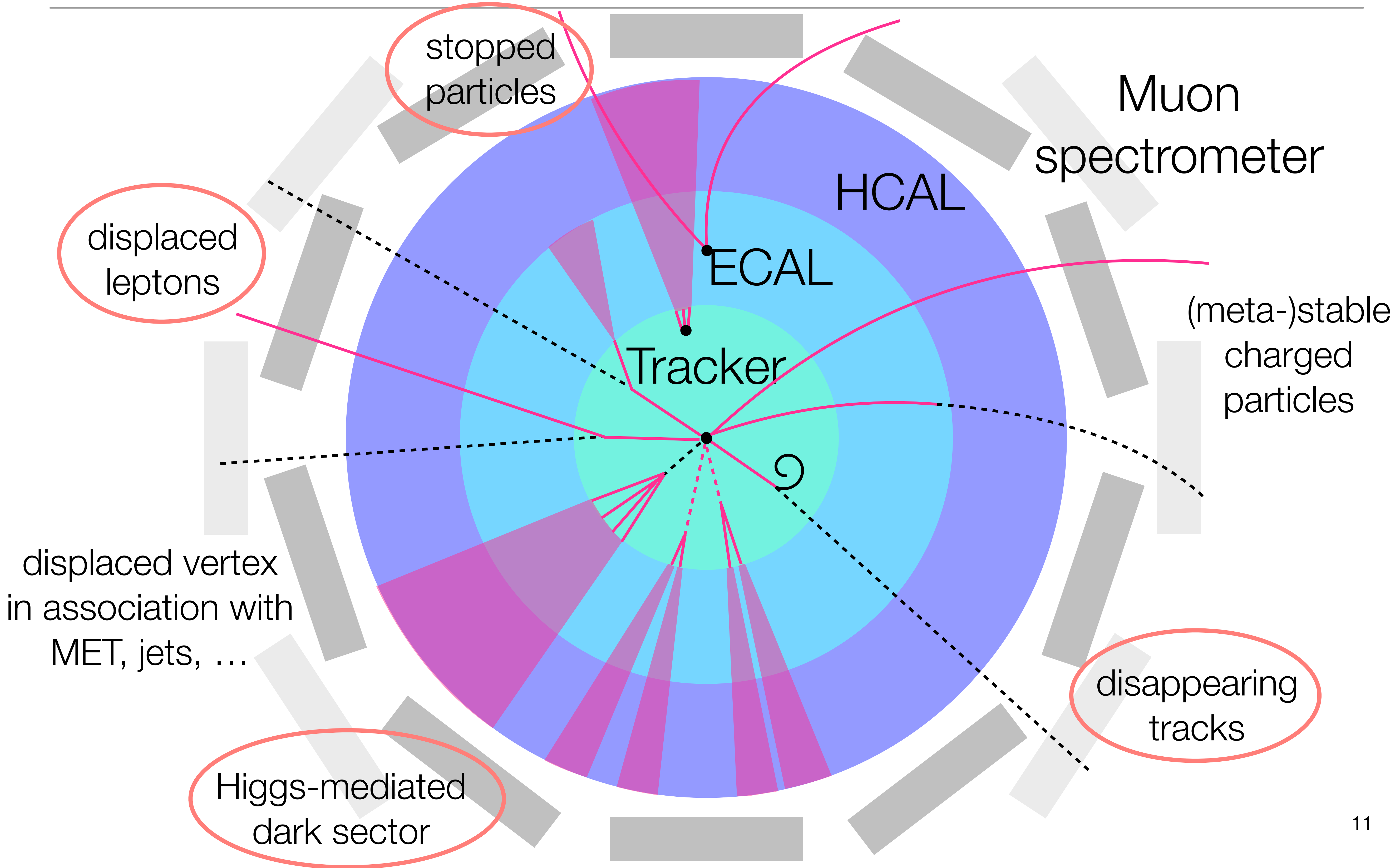
Dark matter: Asymmetric, freeze-in, co-annihilation, …

Any model with small couplings, small mass splittings, or decays via off-shell particles can result in long lived particles (LLPs)

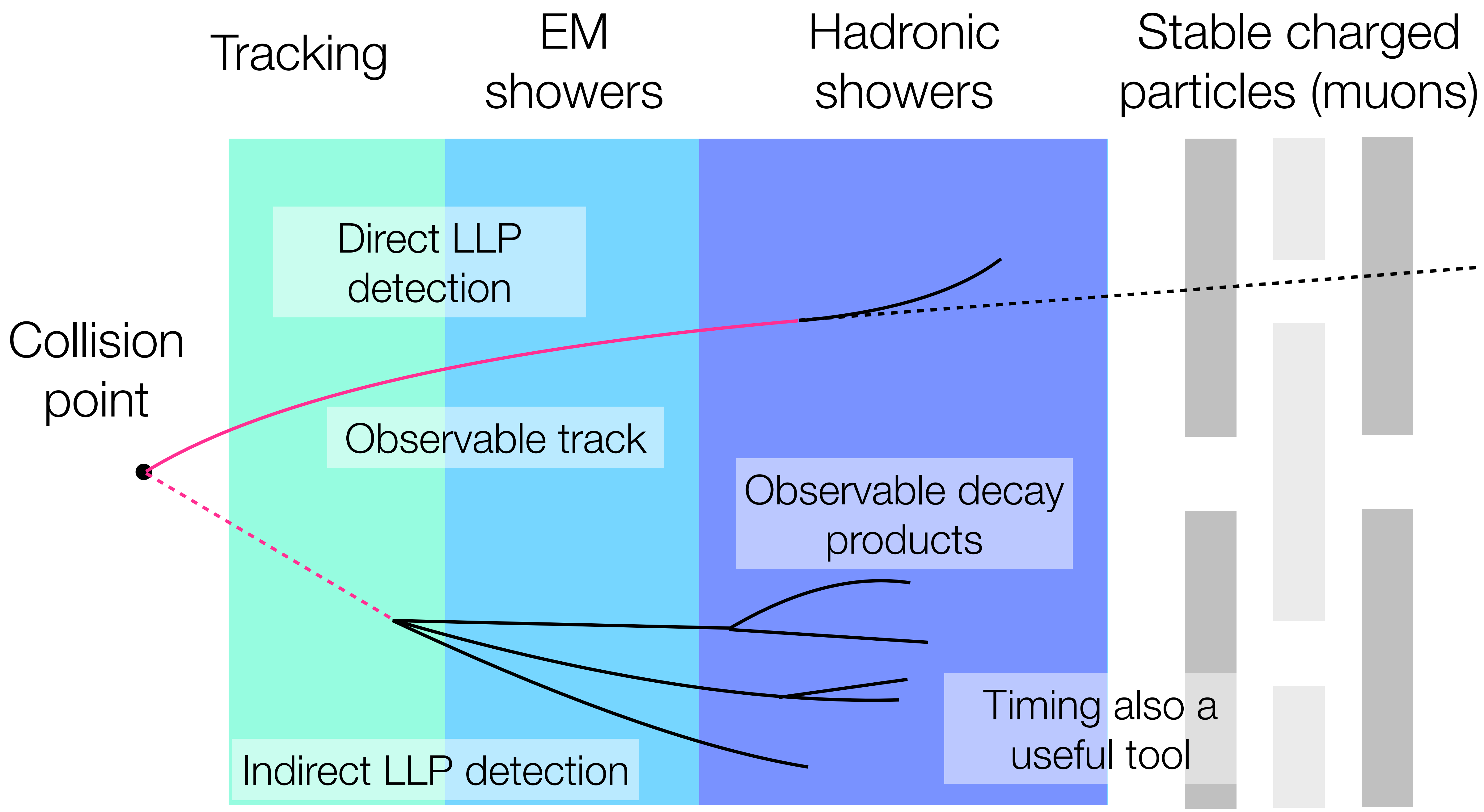


ATLAS Experiment

What would new long-lived physics look like?



How do we use our detectors for these searches?



Tracking

EM showers

Hadronic showers

Stable charged particles (muons)

Collision point

Direct LLP detection

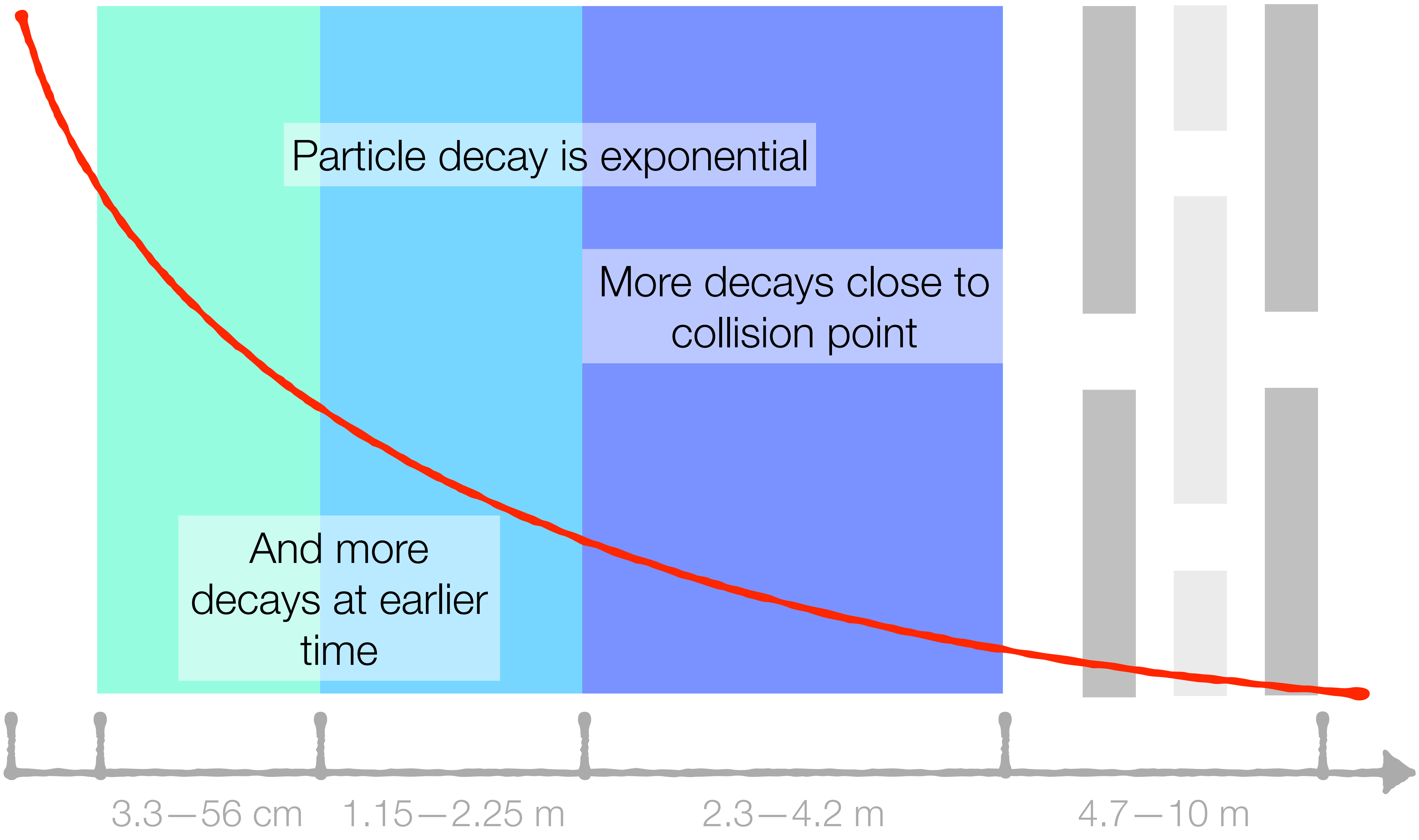
Observable track

Observable decay products

Timing also a useful tool

Indirect LLP detection

Exponential nature of decays



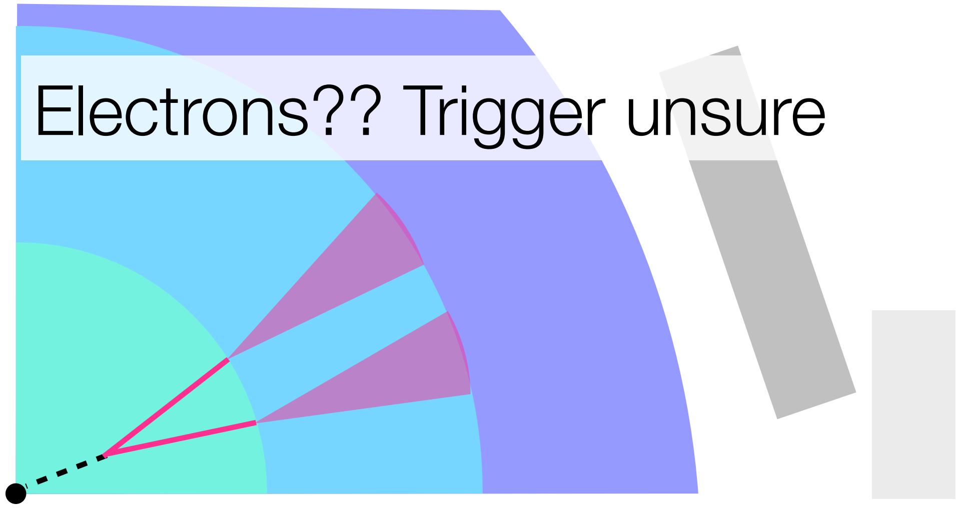
Particle decay is exponential

More decays close to collision point

And more decays at earlier time

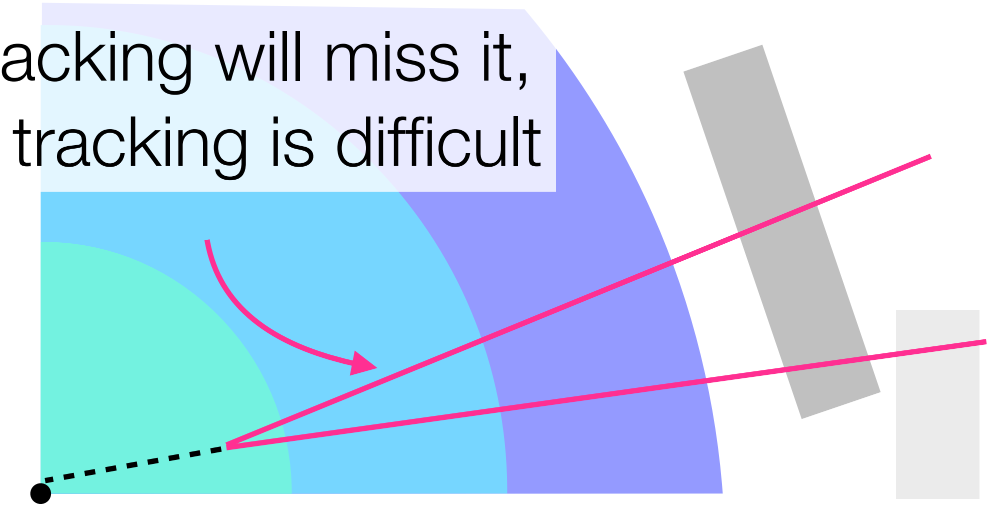
What makes LLPs so hard?

Triggering



Electrons?? Trigger unsure

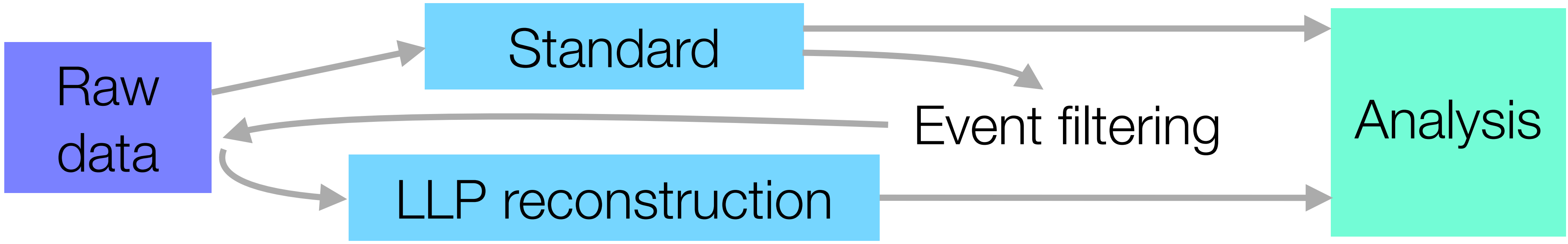
Special reconstruction needs



Standard tracking will miss it, specialised tracking is difficult

Backgrounds: non-standard and non-simulated

Data flow



Raw data

Standard

LLP reconstruction

Event filtering

Analysis

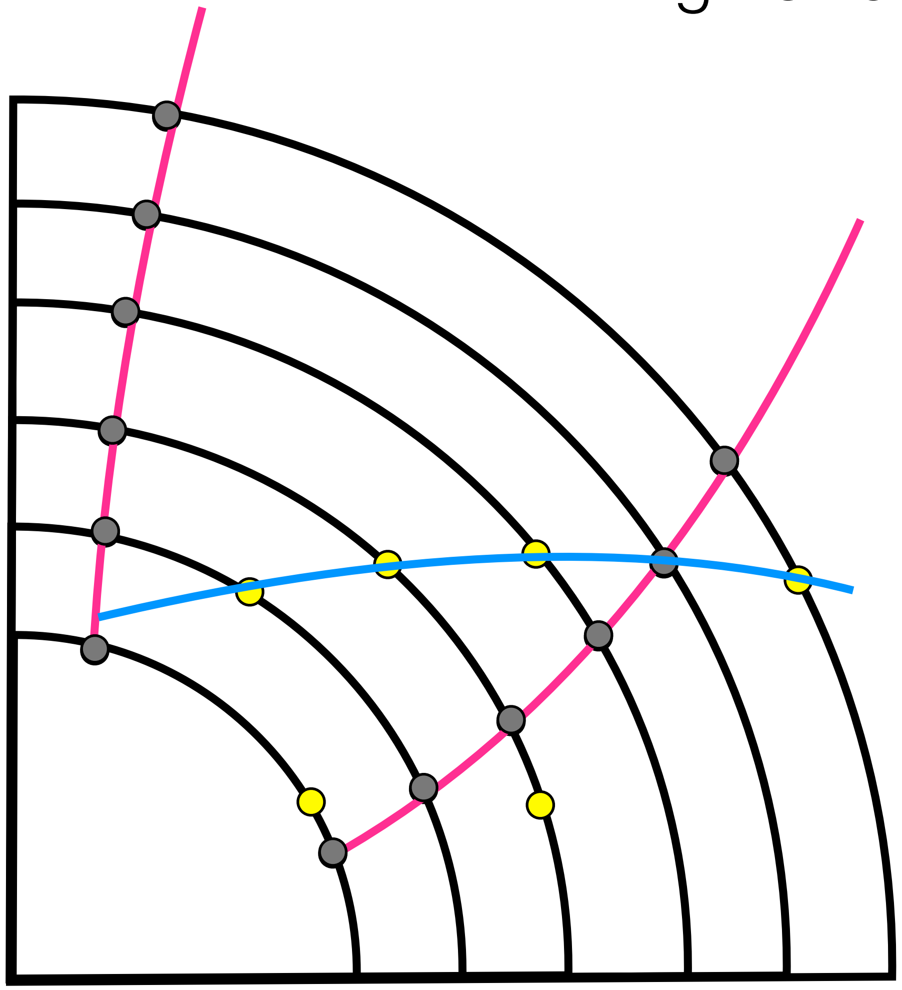
Reconstructing displaced tracks in ATLAS

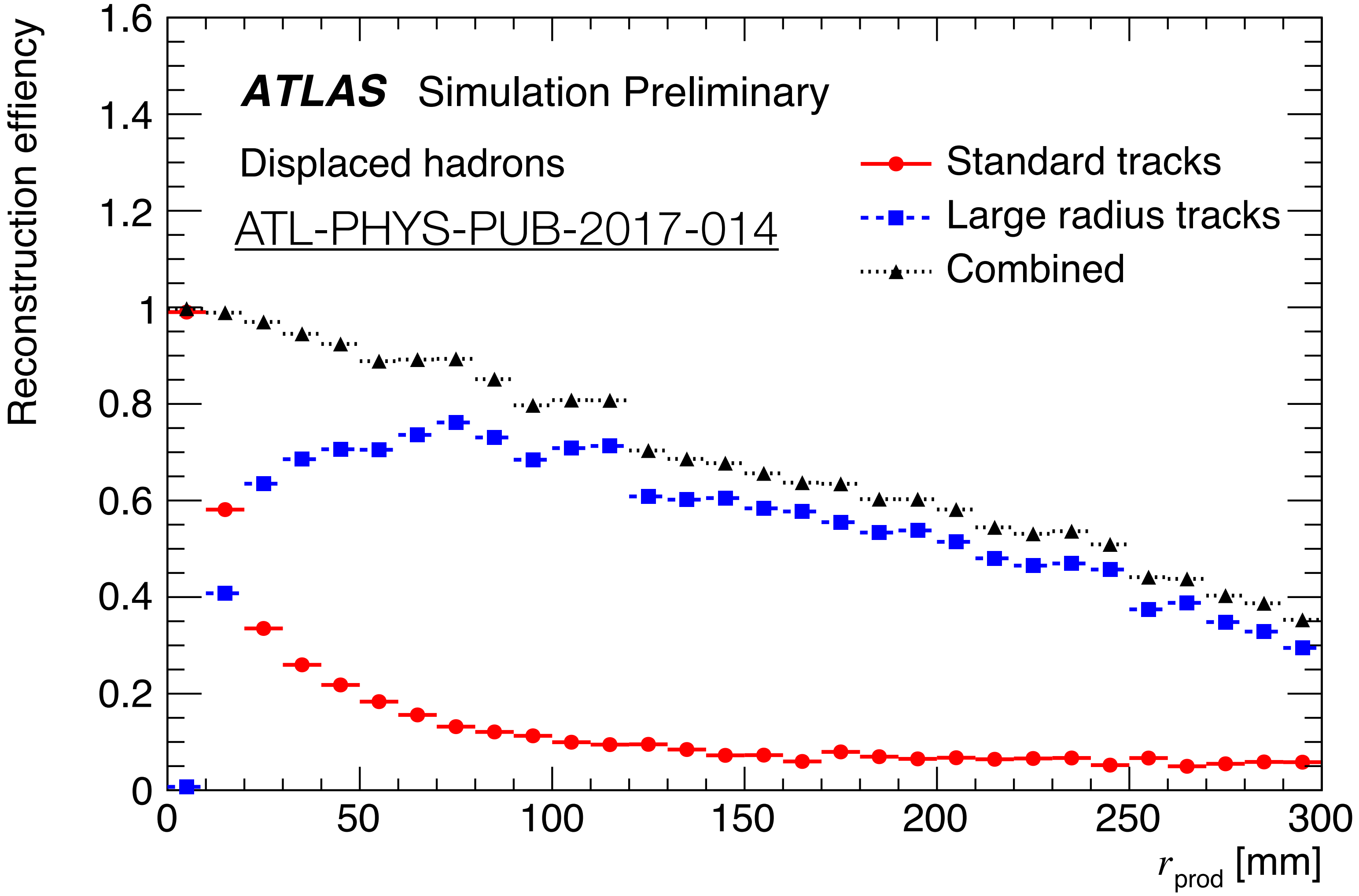
Standard track reconstruction in ATLAS considers only prompt tracks

For selected subset of events, run dedicated “large radius tracking” (LRT)

LRT runs as a second pass on hits not used by prompt tracking

High efficiency and high fake rate in Run 2





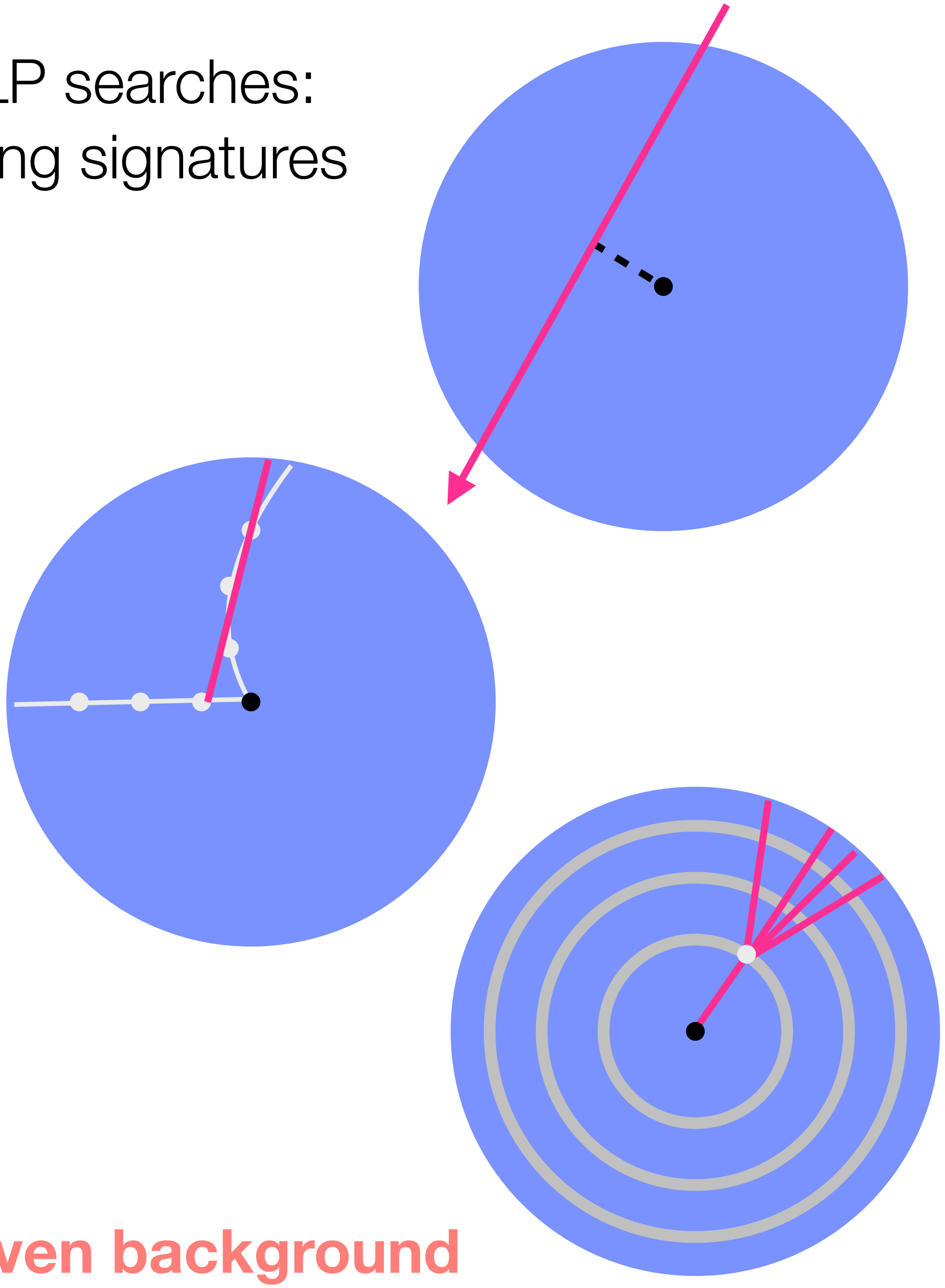
Understanding backgrounds

Small and/or **unusual backgrounds** for LLP searches:
~no simple Standard Model processes imitating signatures

Backgrounds do include:

- Cosmic muons
- Mis-reconstructed SM objects (fake tracks, pileup contamination, …)
- Material interactions in detector components
- Beam-induced backgrounds

For almost all background contributions, no possibility of simulating them well



So you will see **fully data-driven background estimates** for ~all LLP searches!

Today ….

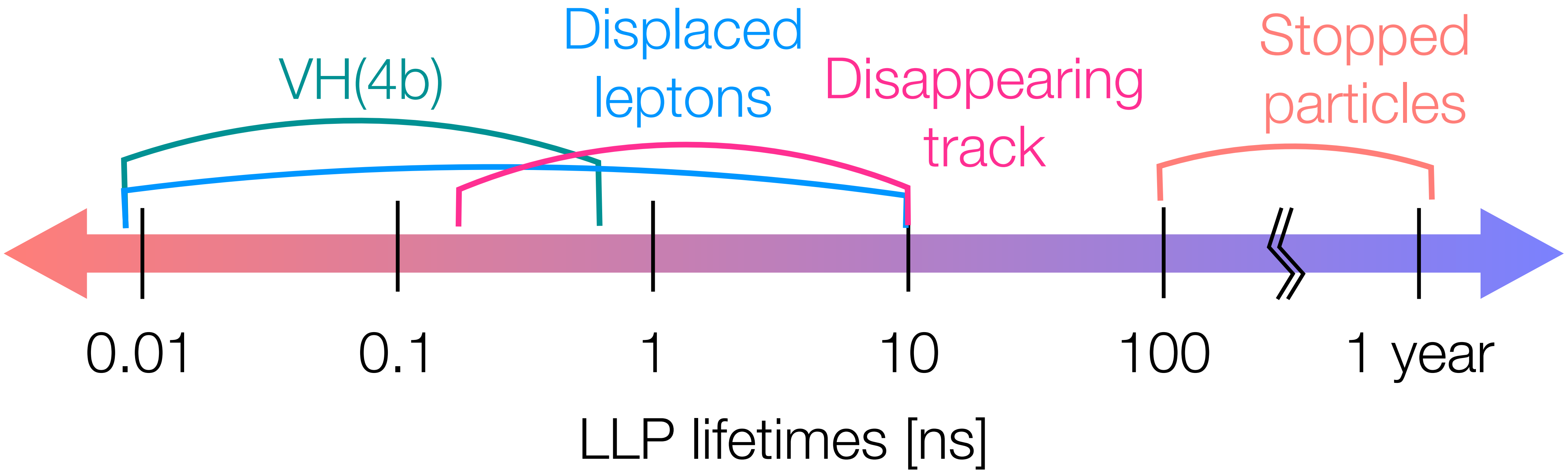
Presenting **four analyses** looking for long-lived particles in ATLAS

Three use **indirect detection**, one uses **direct detection**

Three rely on unusual **track-based signatures**

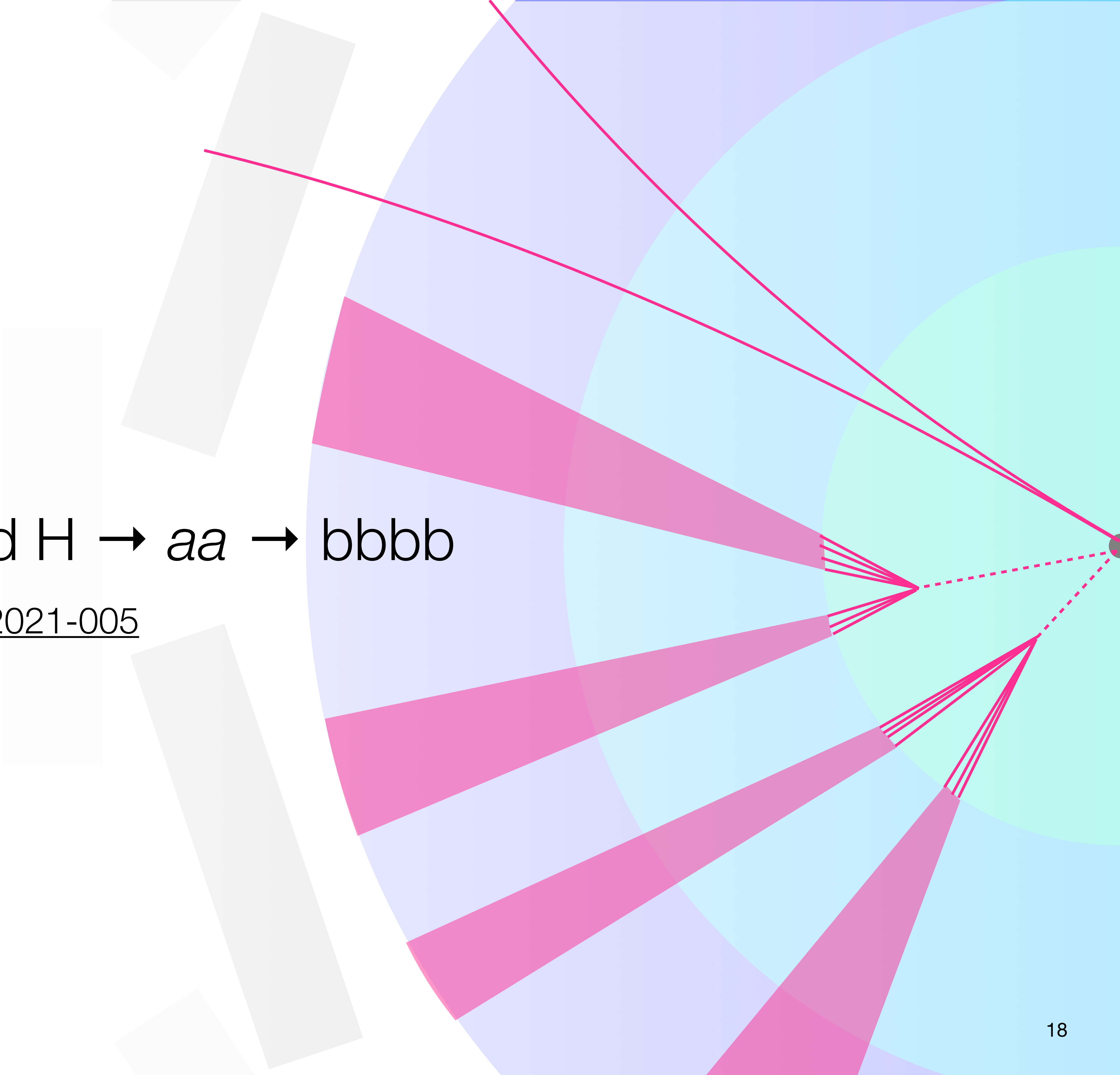
Range of **trigger solutions**, including loose triggers and use of associated production

All four have fully **data driven** background estimates



Long-lived H → *aa* → bbbb

ATLAS-CONF-2021-005

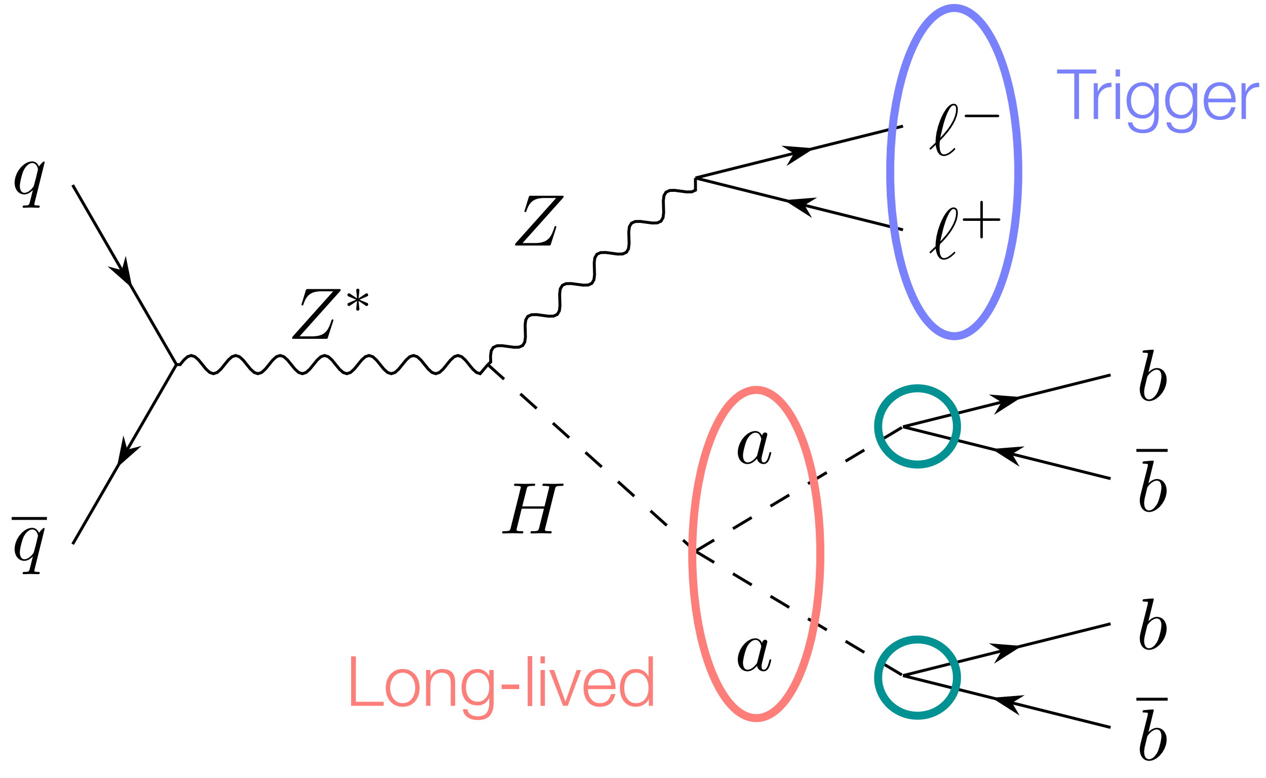


Analysis concept

Motivation: uncoloured + neutral LLPs produced in SM Higgs decay

- Neutral naturalness (signatures e.g. light glueballs)
- scalar/pseudoscalar mediators to a dark sector

When decays proceed via H, expect Higgs-like BR for decay products



Benchmark: **pseudoscalars**,
$15 < m_a < 55$ GeV,
10 mm $< c\tau < 1$ m

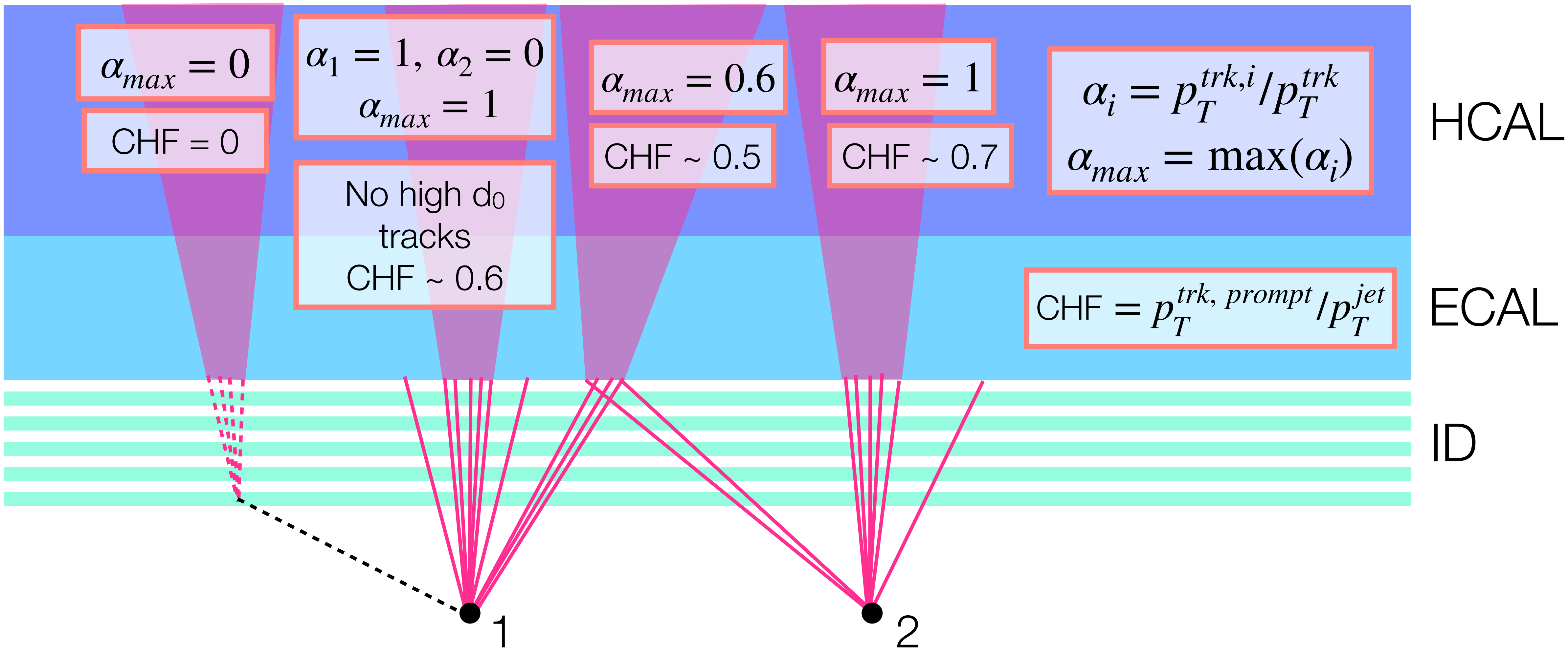
Higgs production mode: ZH allows **single lepton trigger,** two lepton final state minimises QCD backgrounds

Final state jets are **soft, displaced**
Require 2+ displaced vertices

Displaced jets

Jets from pseudoscalar decay will be **displaced**

To identify interesting events in filter, only **prompt tracks** available



$\alpha_{max} = 0$

CHF = 0

$\alpha_1 = 1,\ \alpha_2 = 0$
$\alpha_{max} = 1$

No high d_0 tracks
CHF ~ 0.6

$\alpha_{max} = 0.6$

CHF ~ 0.5

$\alpha_{max} = 1$

CHF ~ 0.7

$$\alpha_i = p_T^{trk,i} / p_T^{trk}$$
$$\alpha_{max} = \max(\alpha_i)$$

CHF $= p_T^{trk,\ prompt} / p_T^{jet}$

Signal jets: low α_{max}, low CHF

They should also have associated displaced **vertices**…

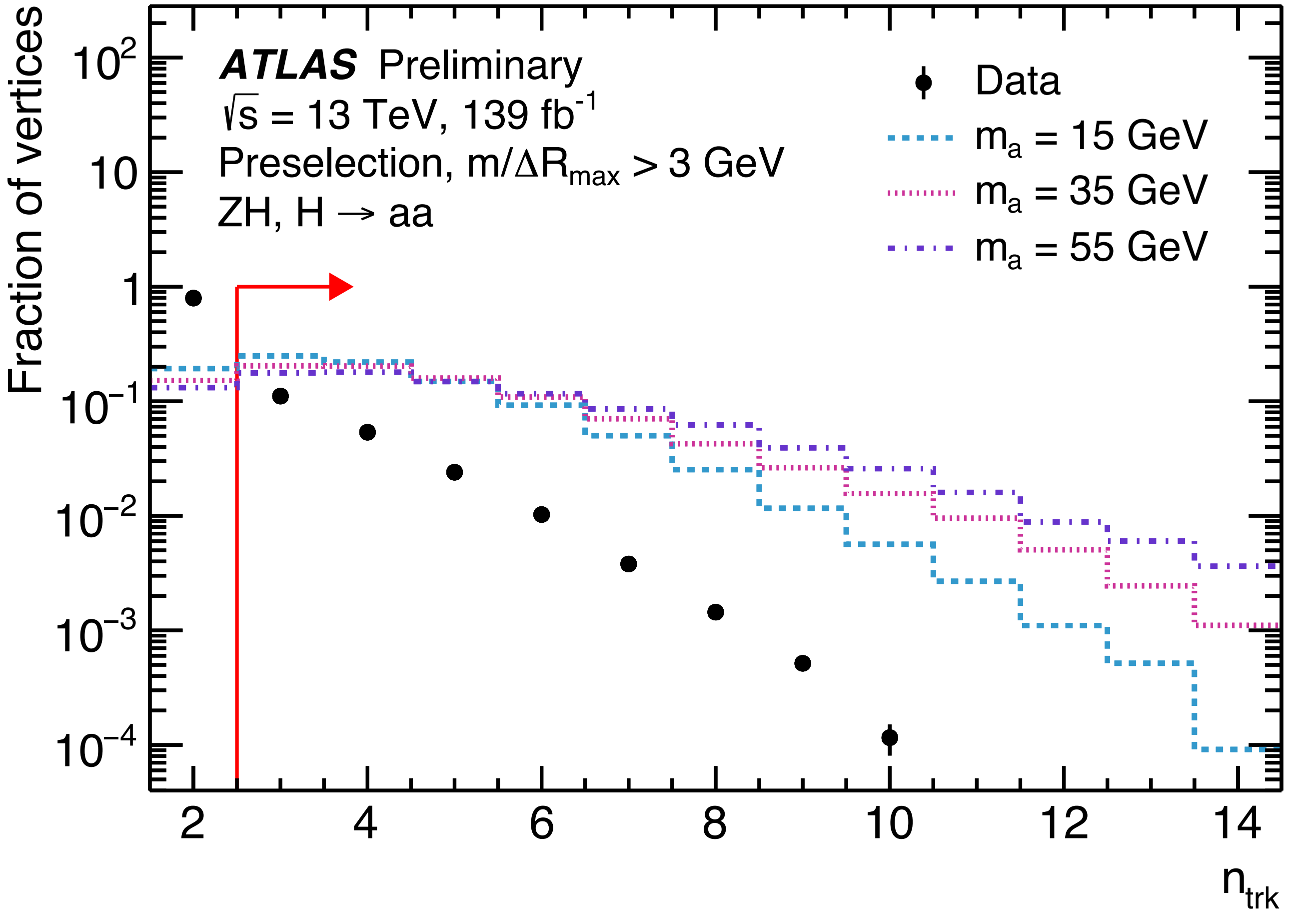
Displaced vertices

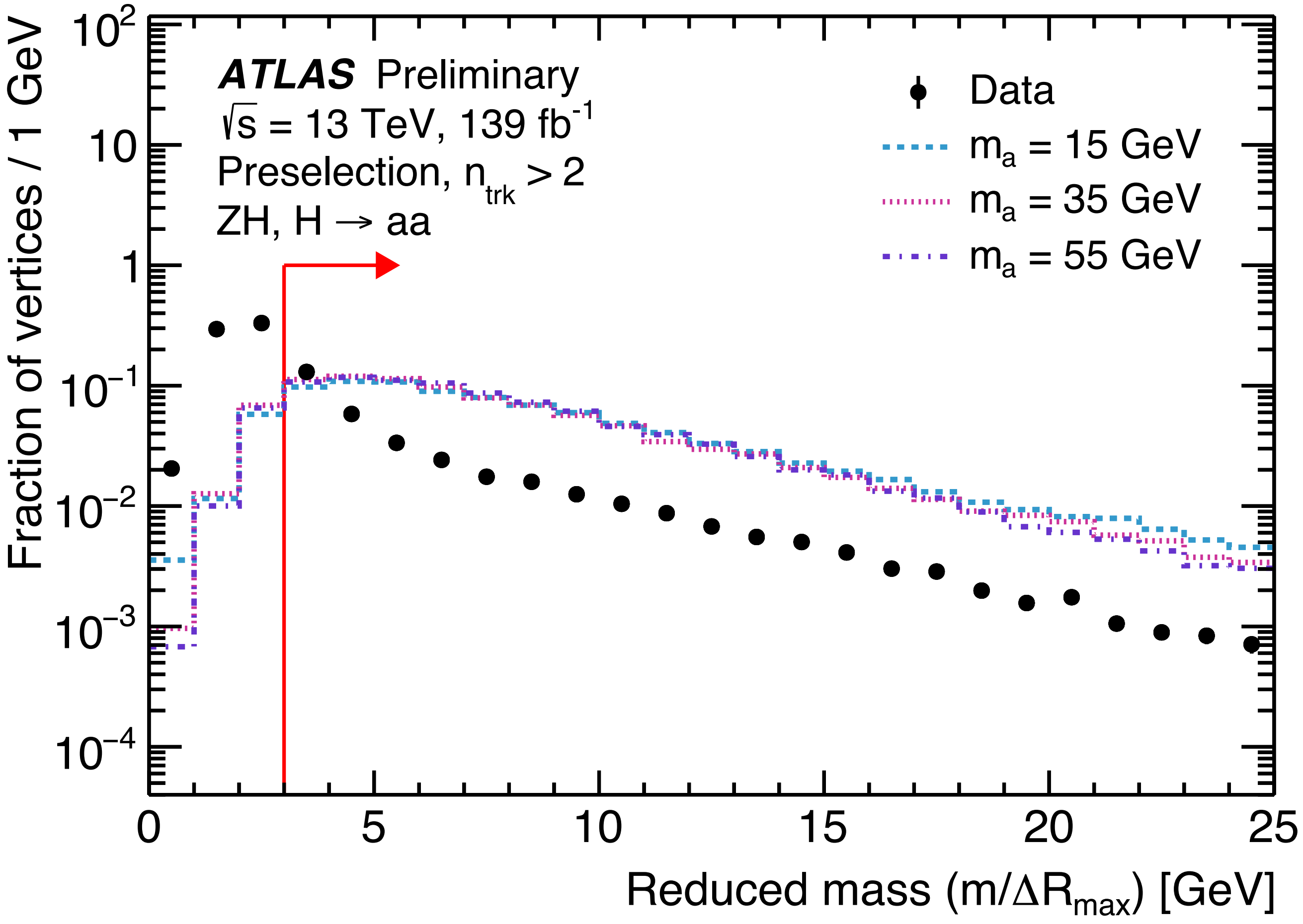
Vertices reconstructed from both standard and large-radius tracks

Reject vertices **in material**

Suppress **SM LLP backgrounds** by requiring vertices with **3+ tracks**

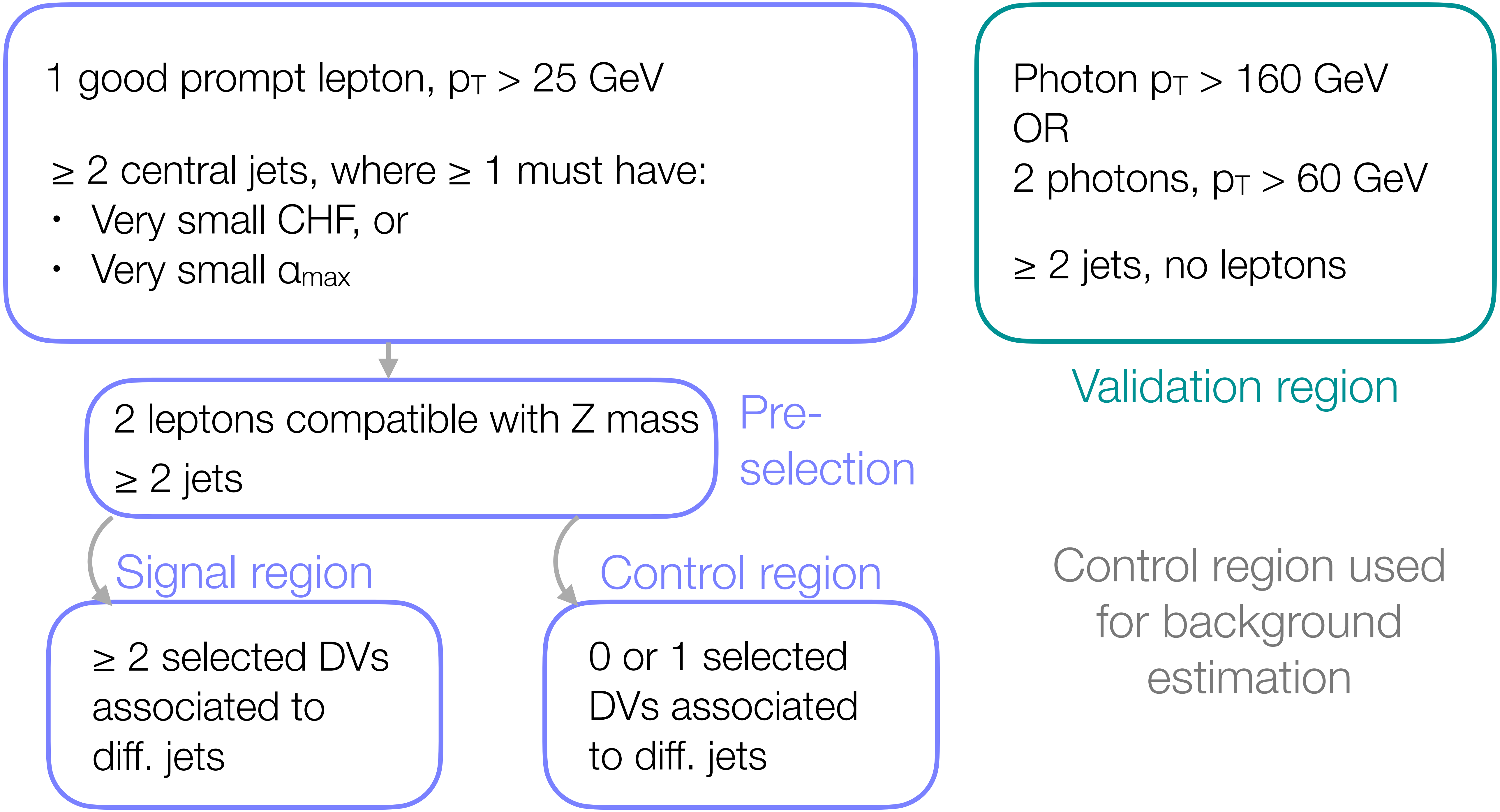
Suppress **accidental crossings** with vertex "reduced mass" > 3 GeV





Analysis selection summary

“Filter” selections for specialised reconstruction



1 good prompt lepton, $p_T > 25$ GeV

≥ 2 central jets, where ≥ 1 must have:
- Very small CHF, or
- Very small α_{max}

2 leptons compatible with Z mass

≥ 2 jets

Pre-selection

Signal region

≥ 2 selected DVs associated to diff. jets

Control region

0 or 1 selected DVs associated to diff. jets

Photon $p_T > 160$ GeV

OR

2 photons, $p_T > 60$ GeV

≥ 2 jets, no leptons

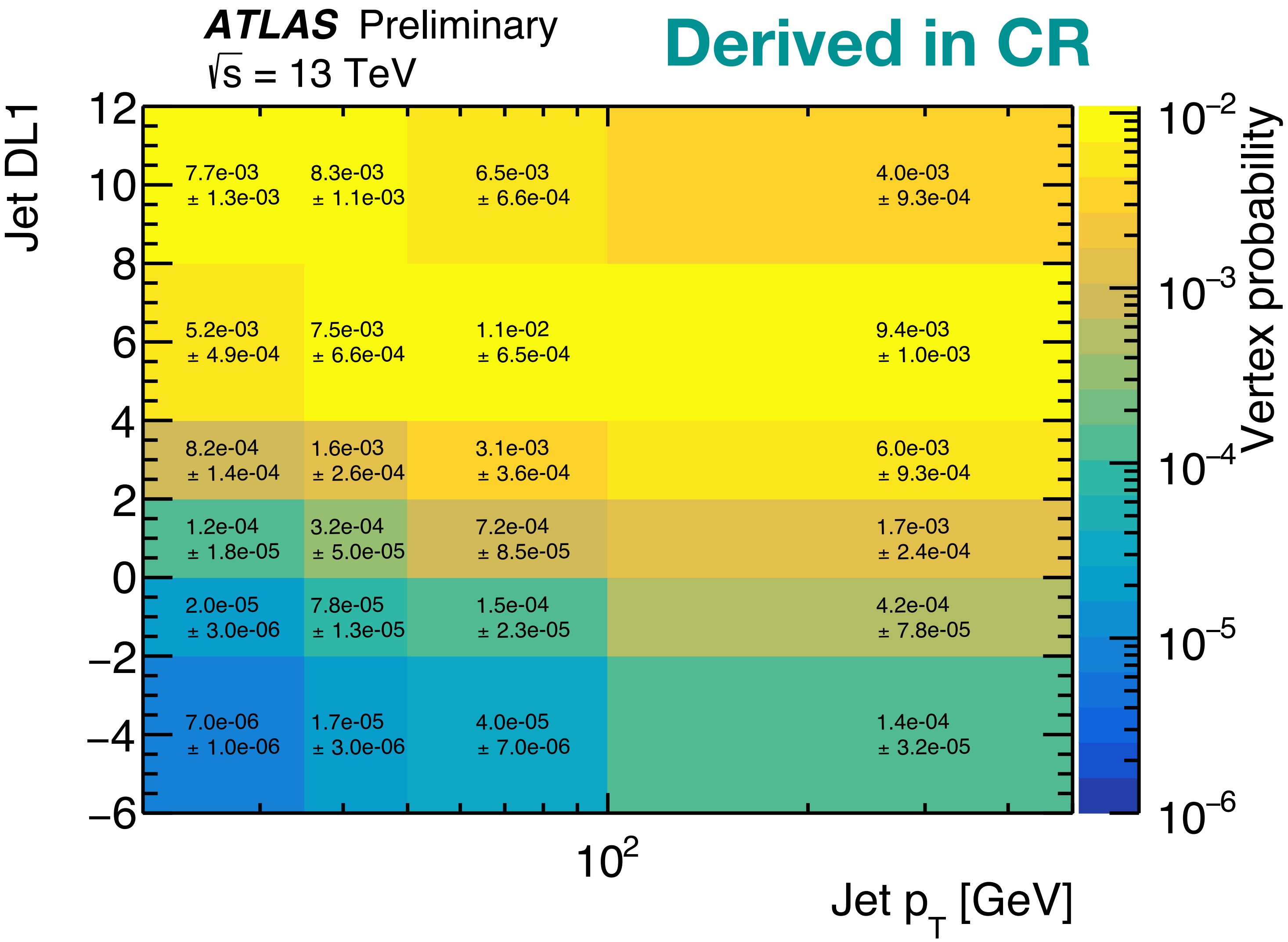
Validation region

Control region used for background estimation

Estimating the backgrounds

Known: probability of jet containing a DV increases with **p_T** and with **heavier flavour**

B-tagger trained on mass, kinematics, lifetime of heavy flavour jets:
Higher b-tag score → higher rate of DVs



Derived in CR

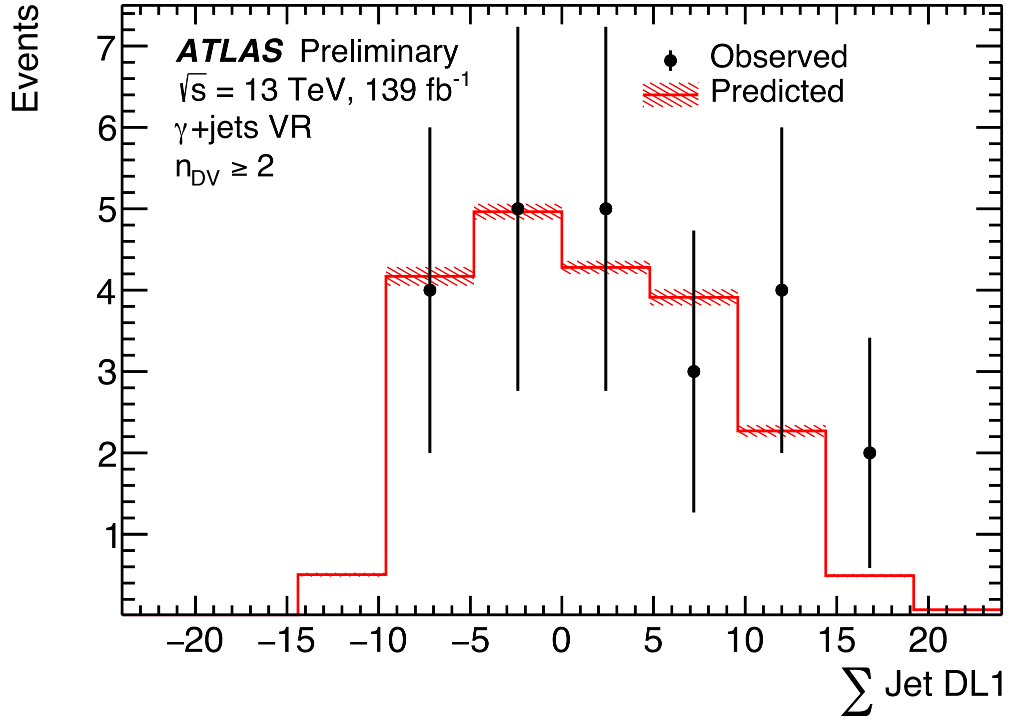
Calculate probability of event containing N DVs based on p_T, DL1 of all jets

All pre-selected events

x

P(nDV) ≥ 2

= background prediction

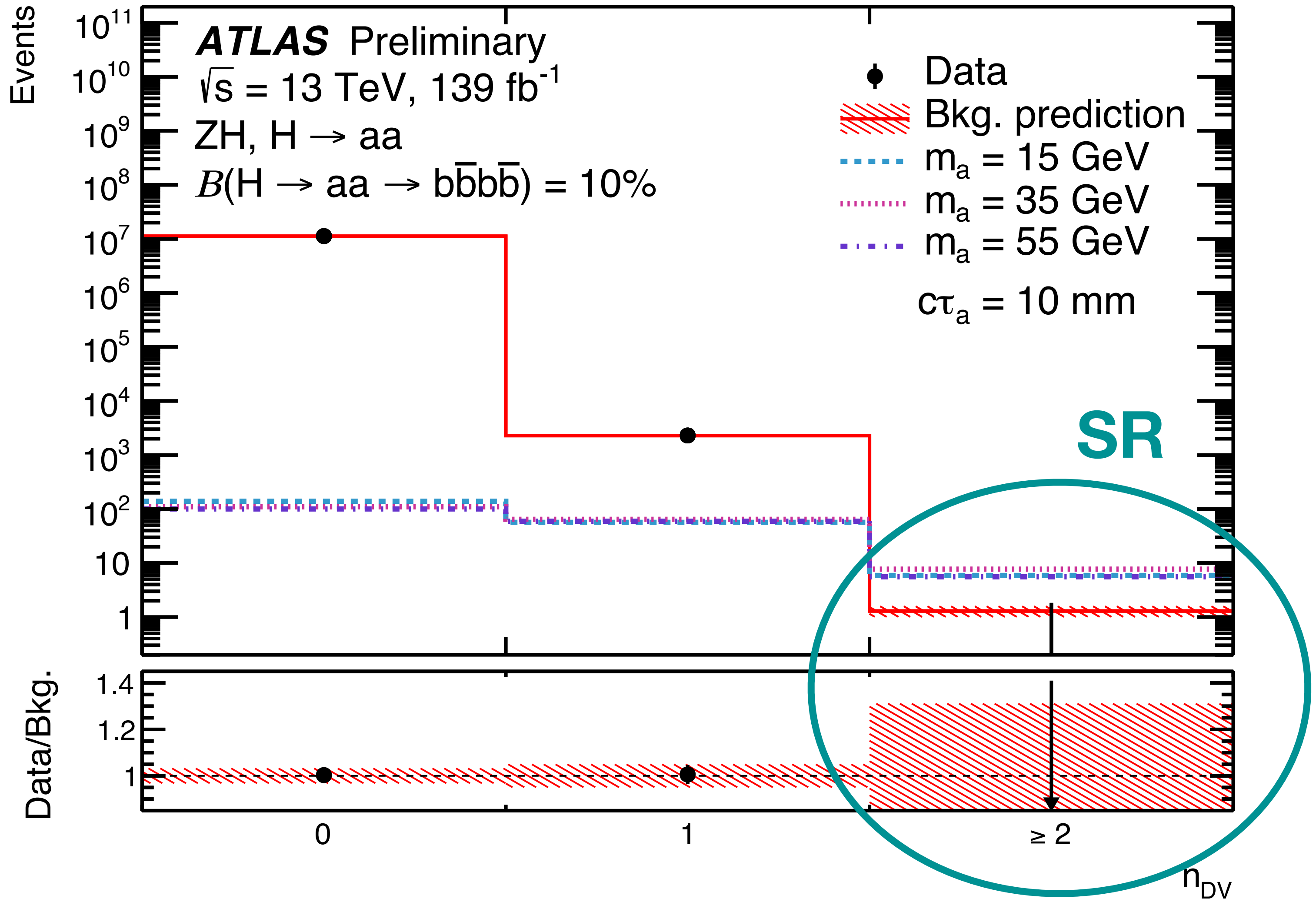


Results

Background prediction: 1.30 events

Stat. uncertainty from pseudoexperiments in p_T, DL1 map: 0.08 events

Syst. uncertainty from validation region closure: 0.27 events



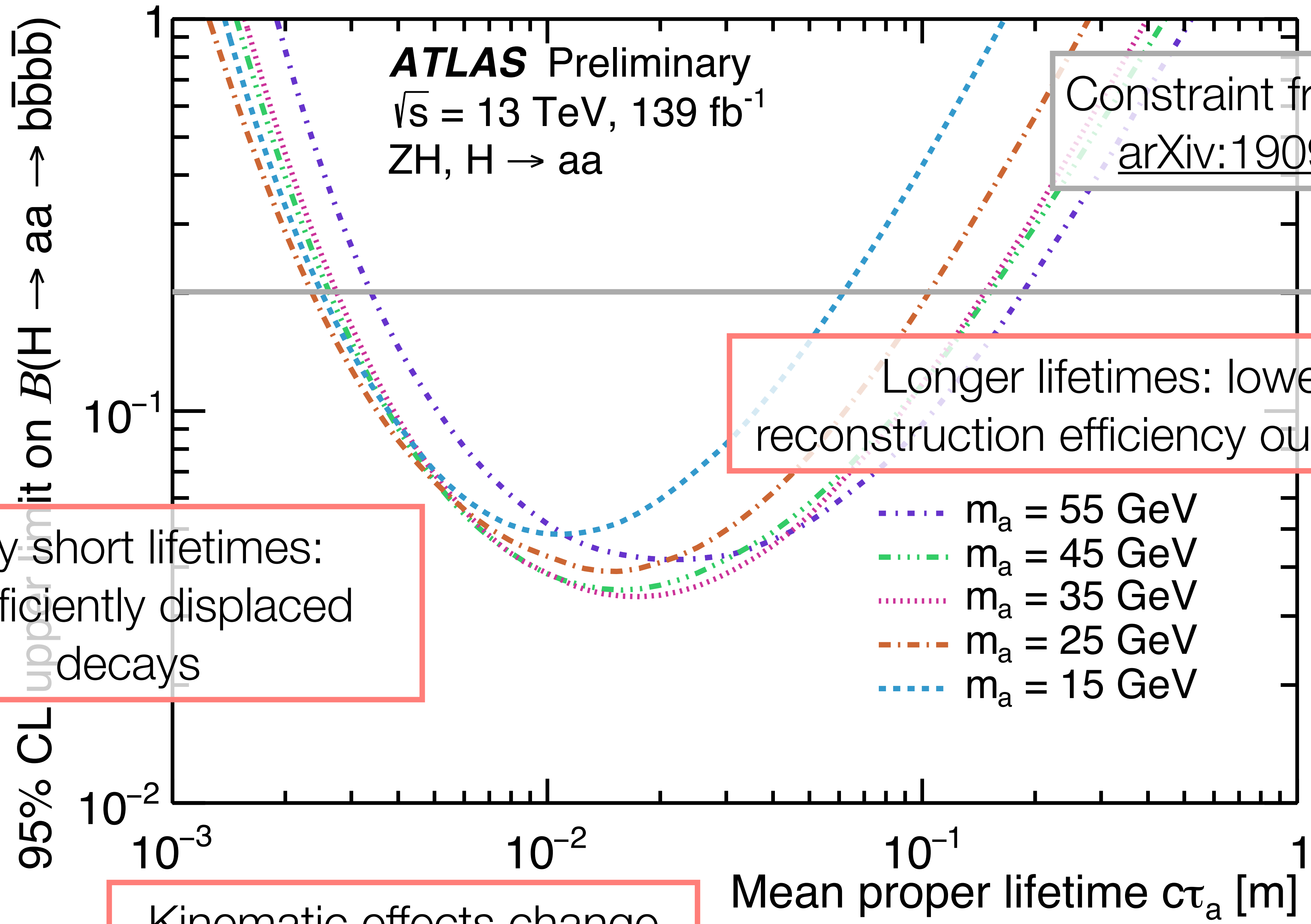
Leading signal uncertainties

Mis-modelling of LRT; its effects on vertexing efficiency

Filter efficiency

Theory

Limits on Standard Model H → aa → bbbb

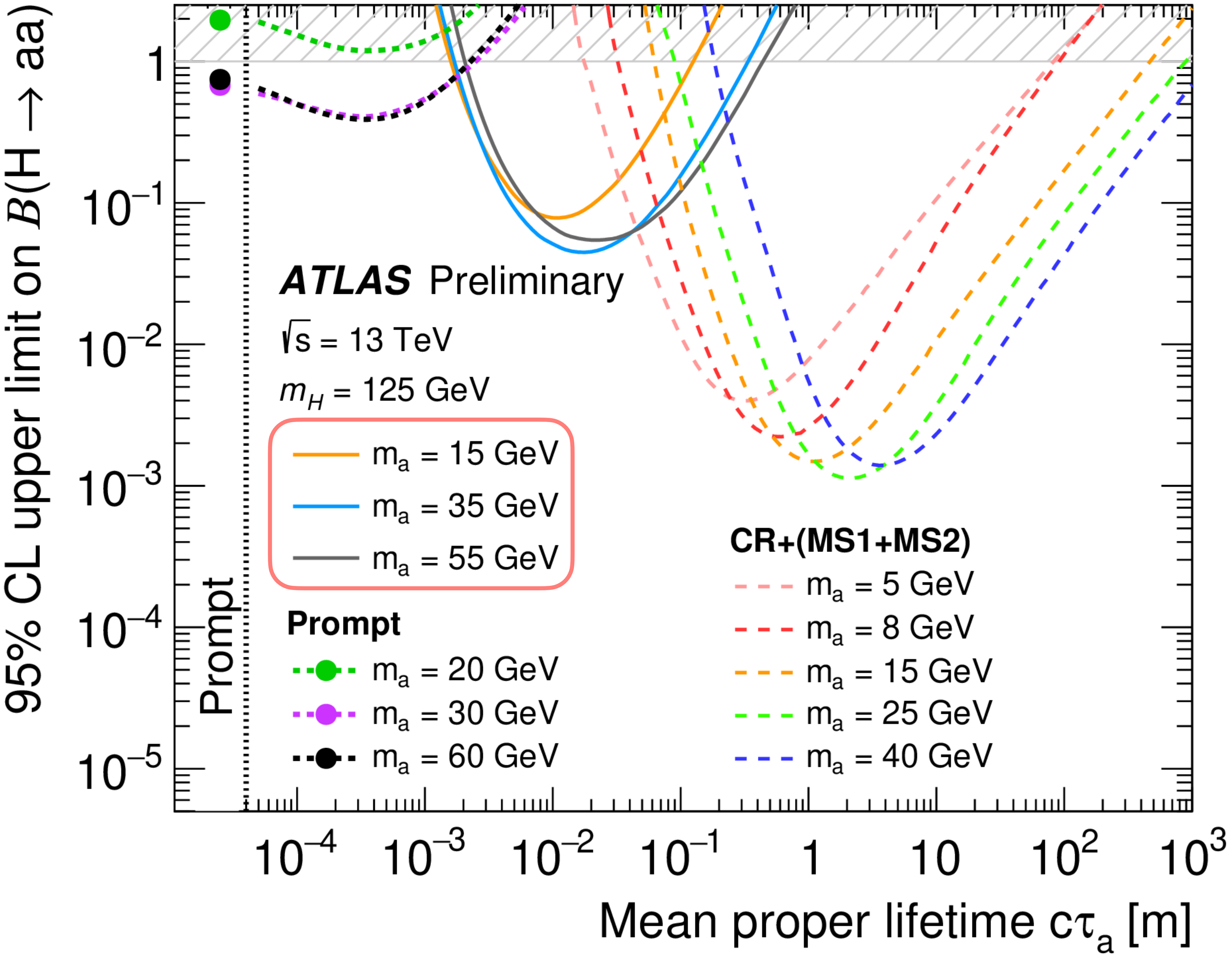


Constraint from ATLAS arXiv:1909.02845

Longer lifetimes: lower DV reconstruction efficiency outside pixels

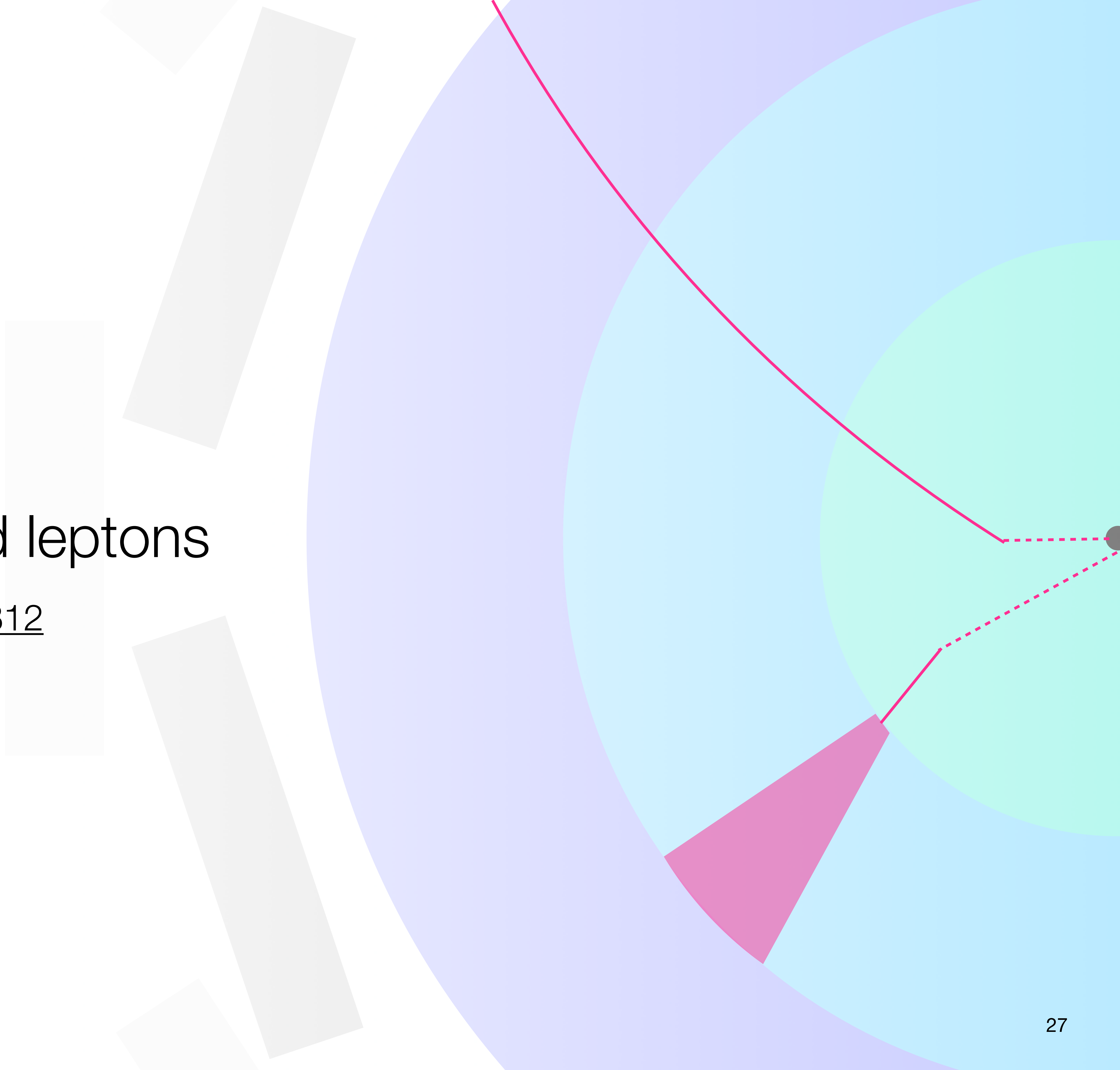
Very short lifetimes: insufficiently displaced decays

Kinematic effects change relative sensitivity between m_a values


95% CL upper limit on $\mathcal{B}(H \to aa)$
Mean proper lifetime $c\tau_a$ [m]
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
m_H = 125 GeV
m_a = 15 GeV
m_a = 35 GeV
m_a = 55 GeV
Prompt
Prompt
m_a = 20 GeV
m_a = 30 GeV
m_a = 60 GeV
CR+(MS1+MS2)
m_a = 5 GeV
m_a = 8 GeV
m_a = 15 GeV
m_a = 25 GeV
m_a = 40 GeV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}

Displaced leptons

arXiv:2011.07812



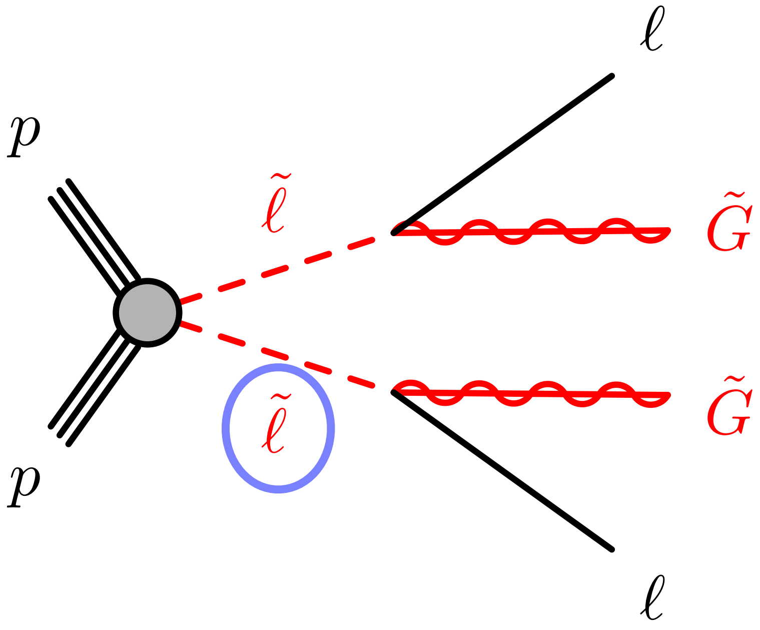
Analysis concept

Quite general search for **two light leptons** that do not point to the primary vertex

No vertex between leptons required

Benchmark model: **sleptons** in GMSB model

Small coupling to gravitino gives $\tilde{l}$ a **long lifetime**



Trigger?

Not MET - keep it general

Use two:

- **Muon spectrometer** signal with no ID track required
- **Single/di-photon (loose)**: again, no requirement placed on matched track

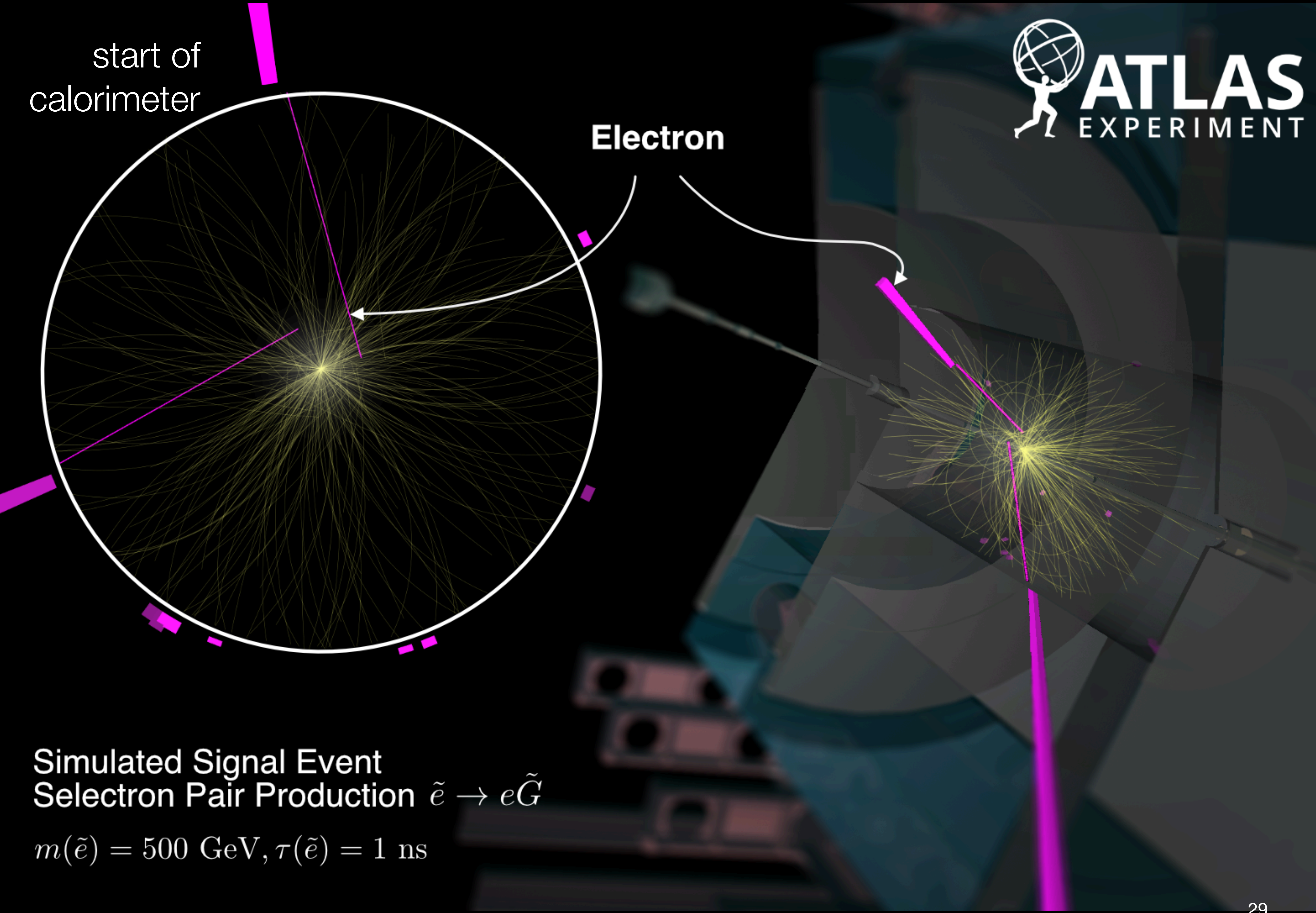
Signal regions

ee	**eμ**	**μμ**

Both leptons $p_T > 65$ GeV

Both leptons $d_0 > 3$ mm

Angle ΔR between leptons > 0.2



Simulated Signal Event
Selectron Pair Production $\tilde{e} \rightarrow e\tilde{G}$

$m(\tilde{e}) = 500\ \mathrm{GeV}, \tau(\tilde{e}) = 1\ \mathrm{ns}$

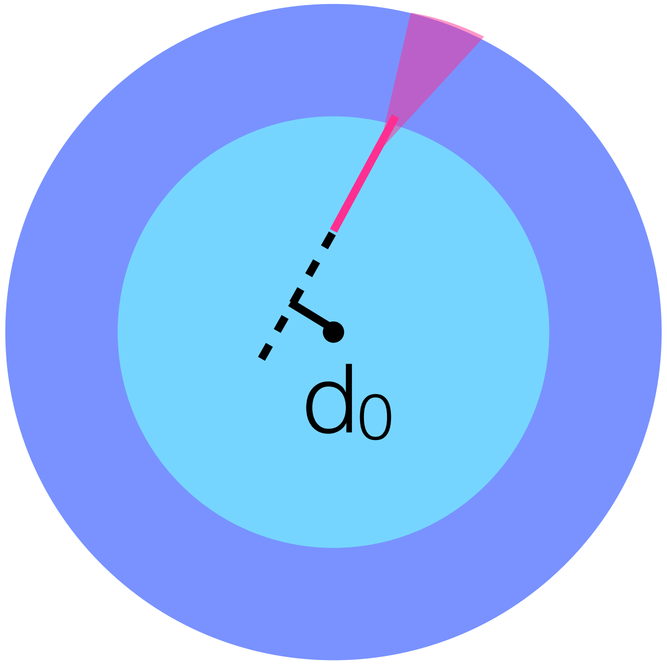
Displaced lepton reconstruction

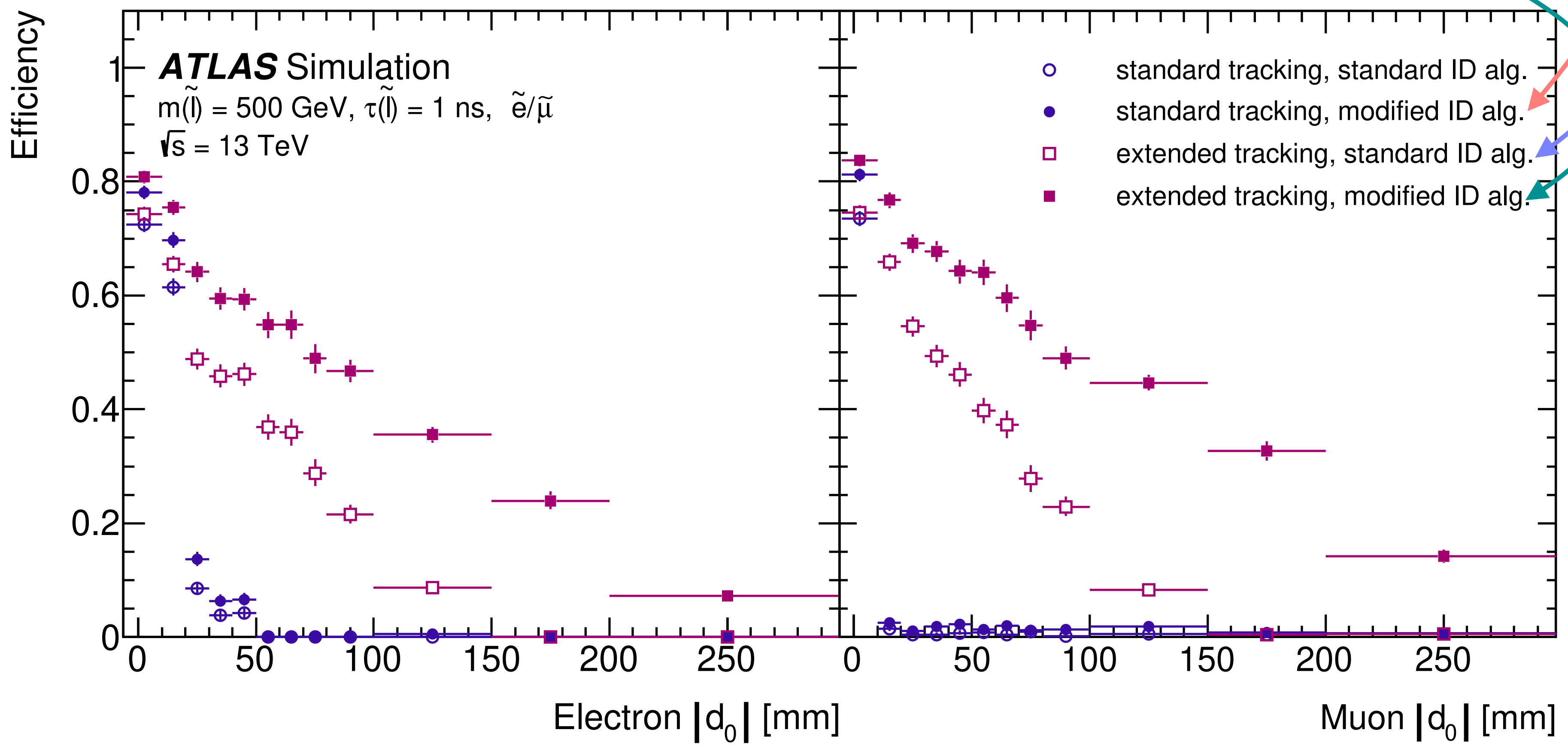
Default lepton reconstruction assumes leptons point to the PV

Very low efficiency for high d_0 leptons

Adding **large-radius tracks** to reconstruction algorithm improves efficiency to ~ 100 mm

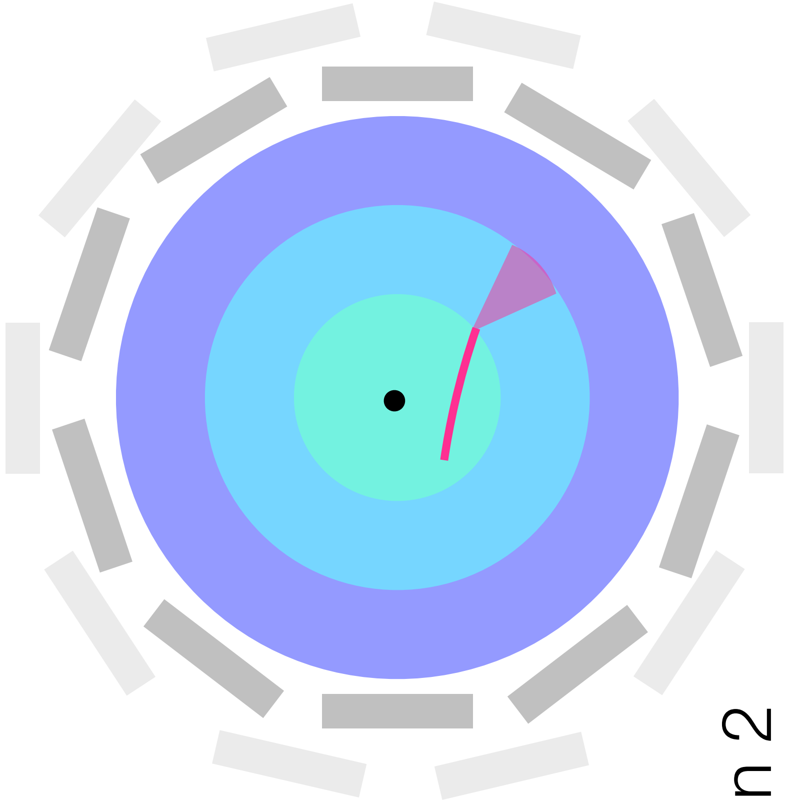
Modified reconstruction algorithms remove requirements on d_0 and number of pixel hits





Fakes & heavy flavour decays

Dominant ee and eμ background: fakes



Large-radius tracks prone to **combinatorial fakes**

Fake track can then be **mis-assigned** to calo energy

Poorer quality: inconsistency between track and cluster p_T estimates

Quality of l_1 and l_2 are **independent**

Use "ABCD" estimate

$N_A = (N_B N_C)/N_D$

Quality lepton 2

(C) L1 poor quality	(A) Both leptons good
(D) Both L's poor quality	(B) L2 poor quality

Quality lepton 1

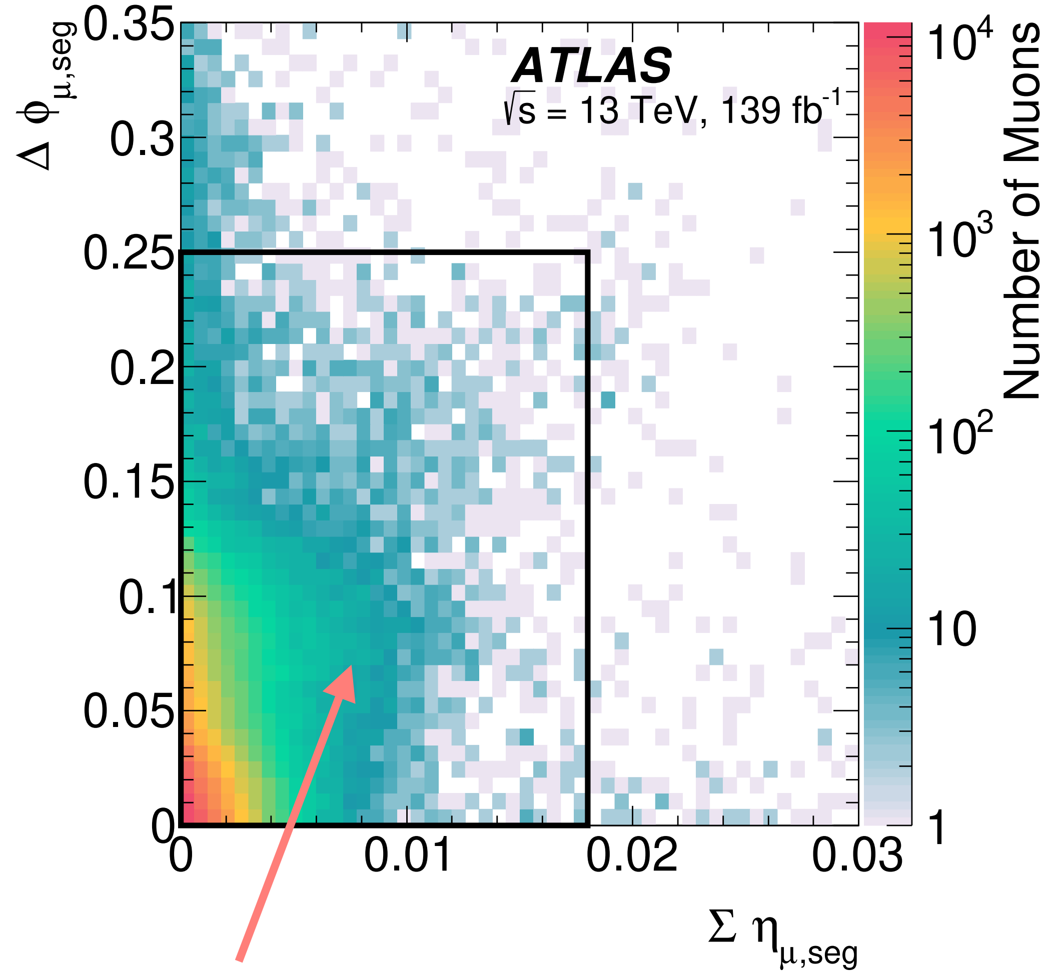
Leptons from **heavy flavour** decay checked separately; negligible

ABCD validated in heavy-flavour-enriched sample

Cosmic muon background

In μμ channel, only significant background is cosmic muons

Reduce:



Tagged cosmic muons

99.5%

Signal region requires zero tagged cosmics

Estimate:

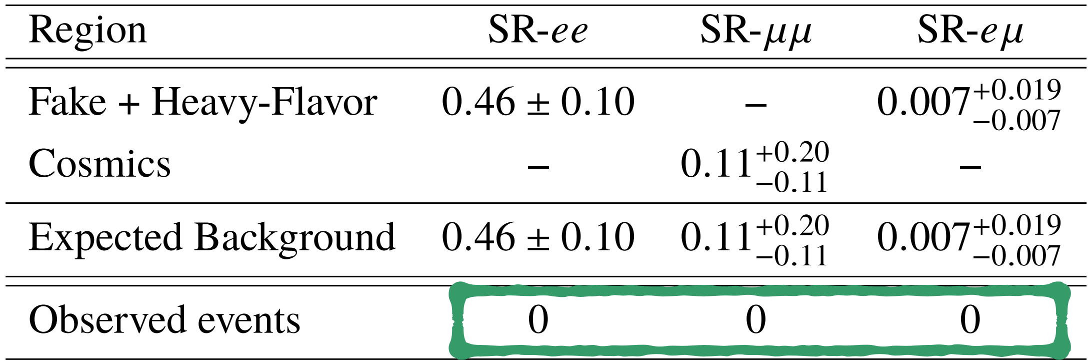
Muon quality **not correlated** with cosmic tag

Instead, cosmic tag depends on quality of the muon **on the other side of the detector**

Use tag and quality info to create **ABCD-like background estimate**, scaling from number of 1-tagged events

Results

* “lightest supersymmetric particle”



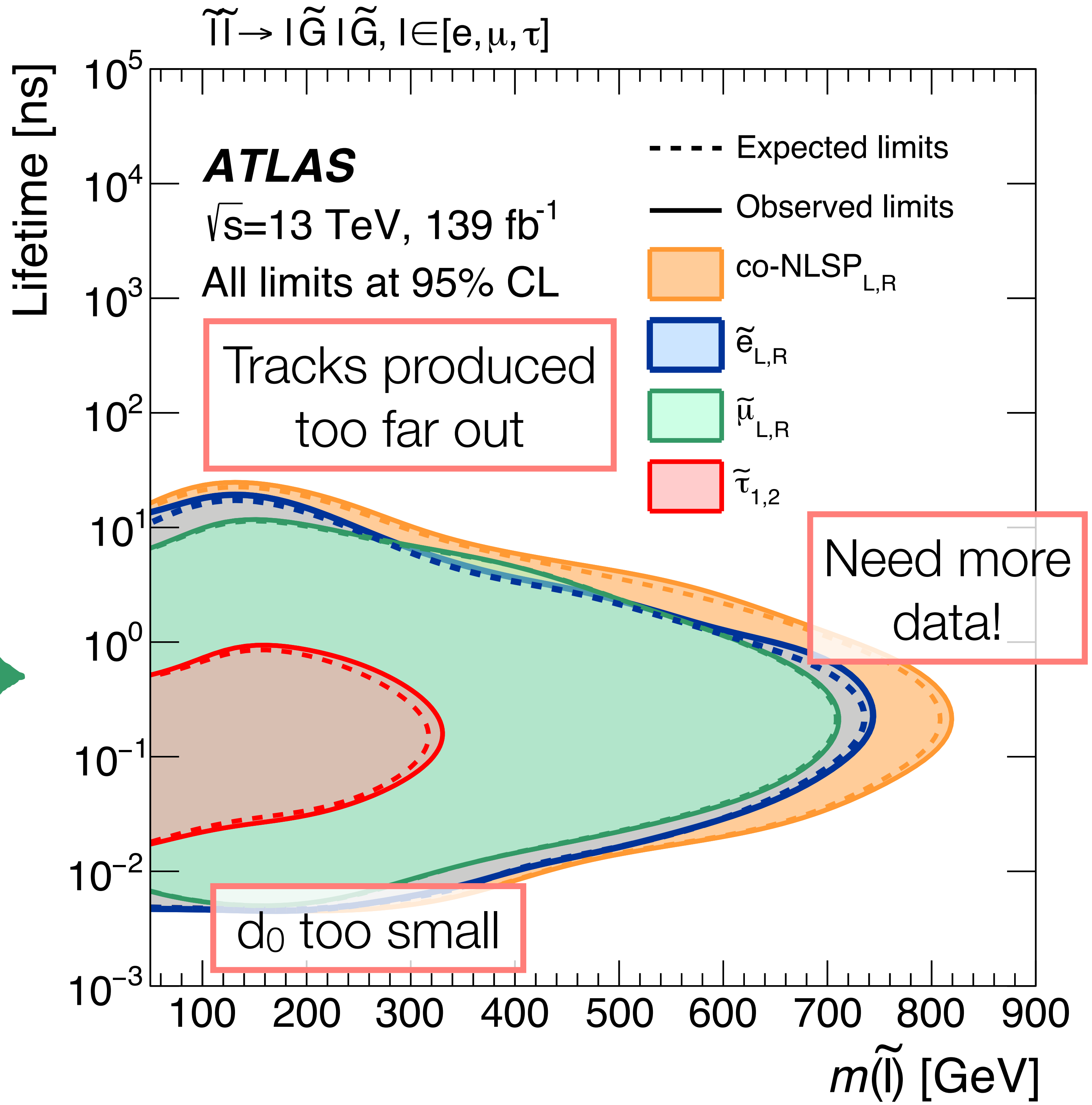
Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + Heavy-Flavor	0.46 ± 0.10	–	$0.007^{+0.019}_{-0.007}$
Cosmics	–	$0.11^{+0.20}_{-0.11}$	–
Expected Background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

Model-independent upper limits: ~3 events

Model-dependent limits: staus and co-NLSP* sleptons

LEP limits (previous best) are up to ~ 65-90 GeV

All new at the LHC!



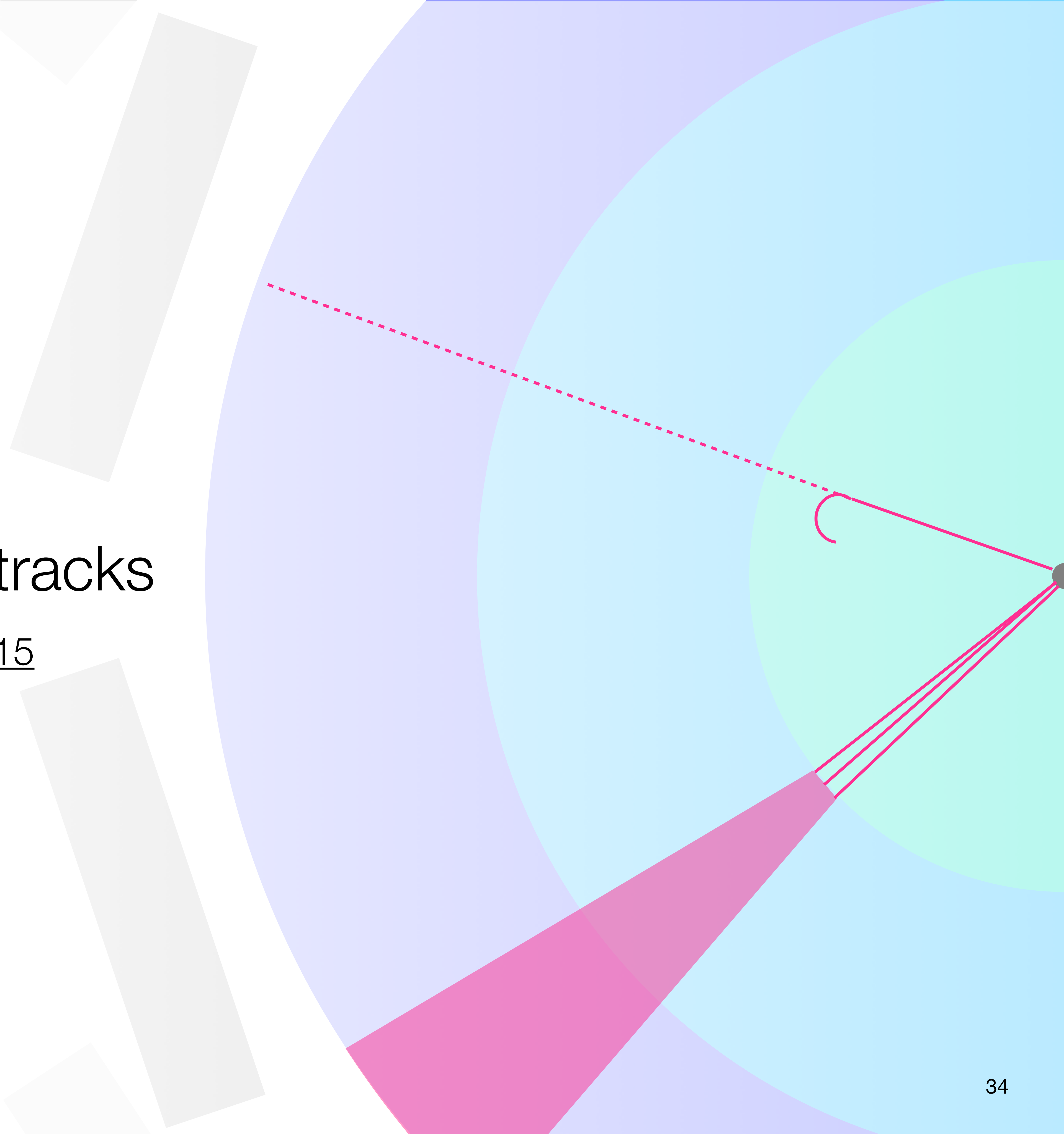
Tracks produced too far out

Need more data!

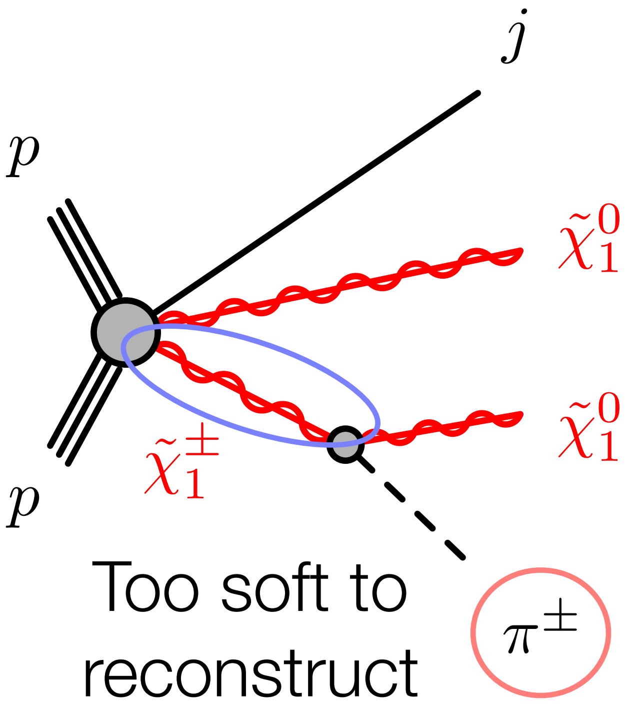
d_0 too small

Disappearing tracks

ATLAS-CONF-2021-015



Analysis concept



Too soft to reconstruct

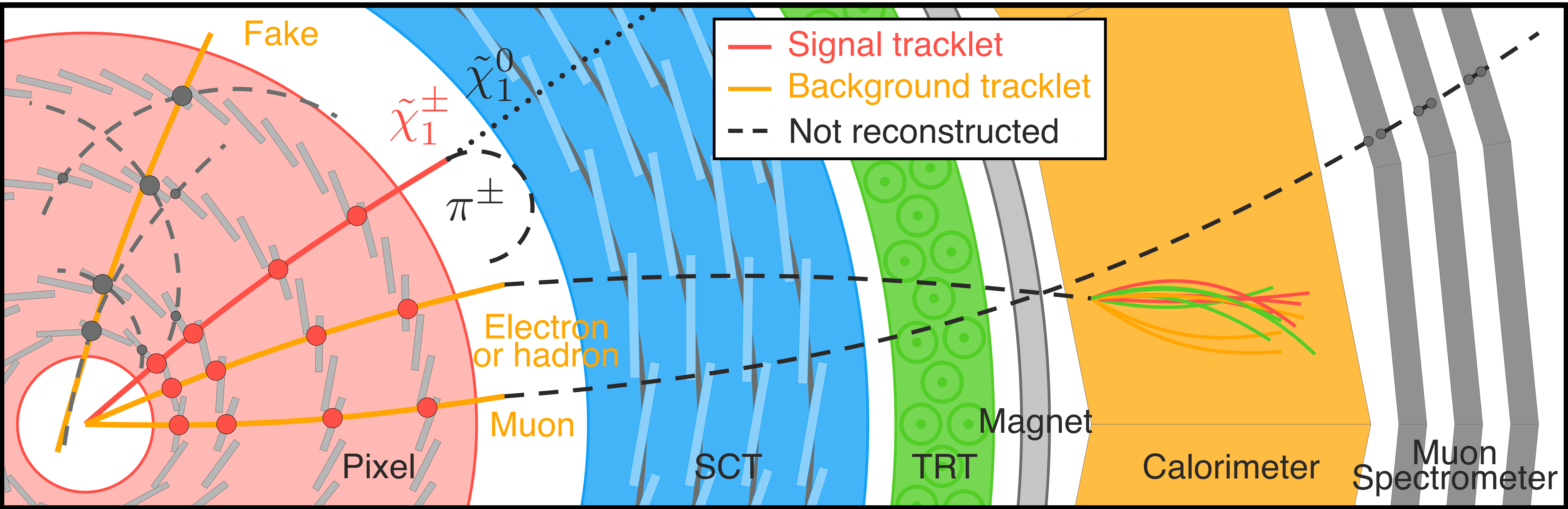
Various SUSY models predict wino or Higgsino LSP

Theoretical prediction of a **very small mass gap** between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$

Small mass splitting → **long lifetime** for $\tilde{\chi}_1^\pm$

Pure wino:
$\tau = 0.2$ ns
$c\tau \sim 6$ cm

Pure higgsino:
$\tau = 0.02 - 0.05$ ns
$c\tau \sim 7 - 14$ mm

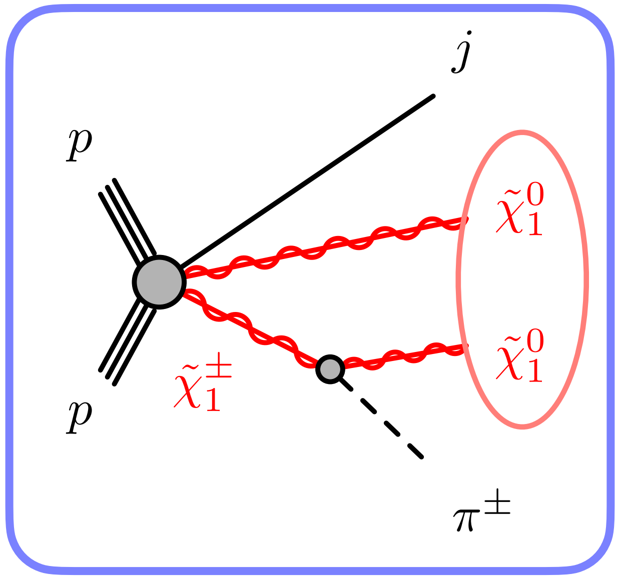


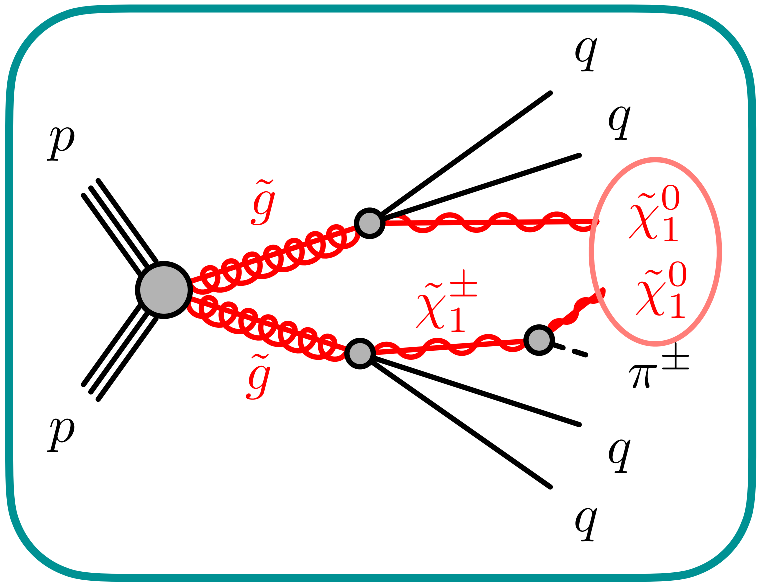
Event selection

Two selections optimised for different production modes (**electroweak**, **strong**)

Missing E_T trigger

Lepton veto





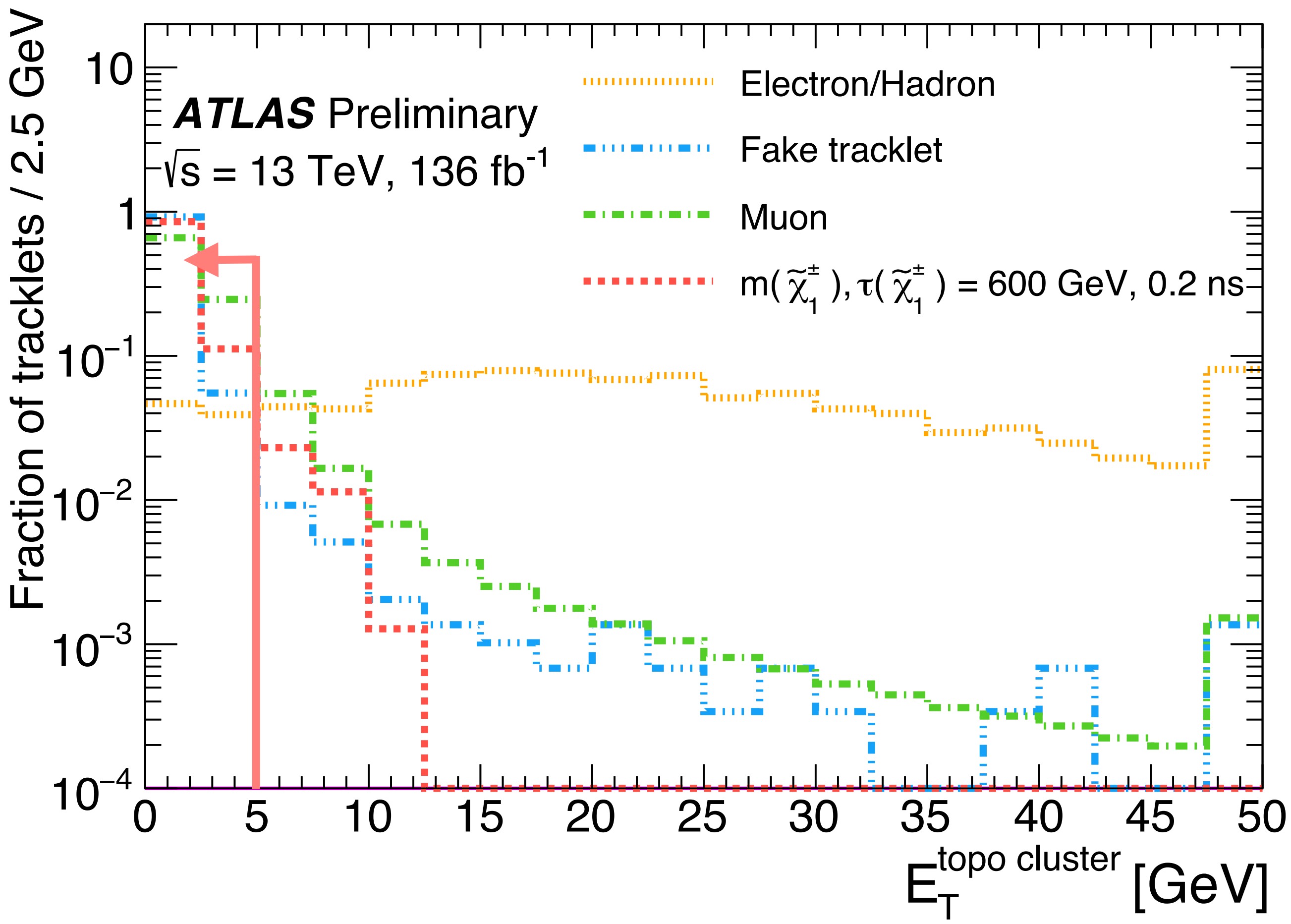
MET > 200 GeV
≥1 jet

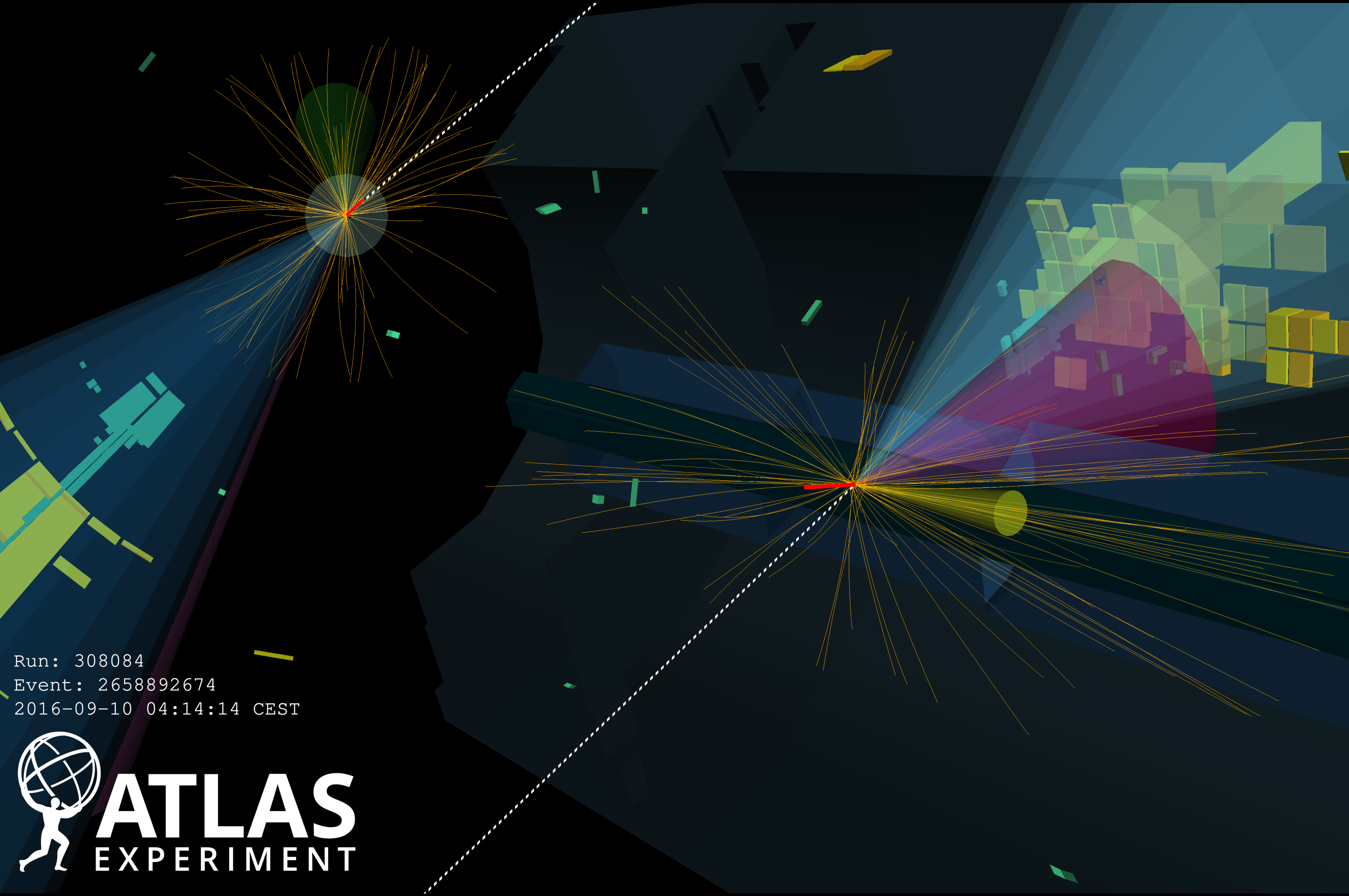
250 GeV
≥ 3 jets

≥ 1 “disappearing” **tracklet**

- 4 pixel layer hits
- No hits in strips
- Good χ2 quality
- Isolated from other tracks
- Isolated from calorimeter energy

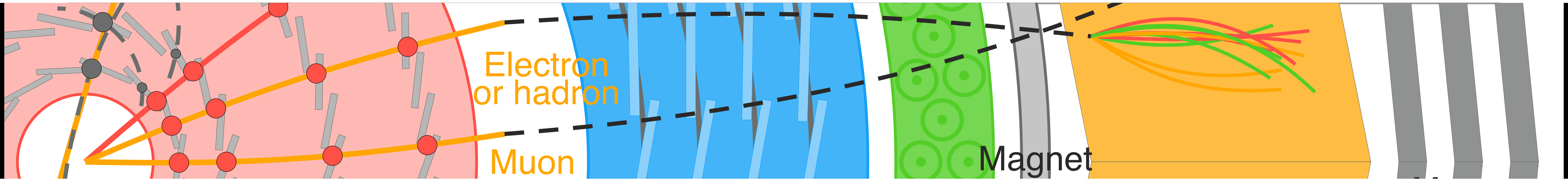
New: calorimeter veto





Run: 308084
Event: 2658892674
2016-09-10 04:14:14 CEST

Charged particle backgrounds



Lepton or hadron scatters in material or emits hard radiation

Take track **p_T templates** from control regions

Electron	Muon	Hadron
Good e	Good μ	Good track
No-e MET	No-μ MET	Standard MET

Make η and (ϕ || p_T) dependent **transfer factors**

Select Z → ll events

$TF_{\text{pixel-only}}$ = fraction of leptons with only tracklet in inner detector

$TF_{\text{no-calo/MS}}$ = fraction of leptons with good track but no other signal

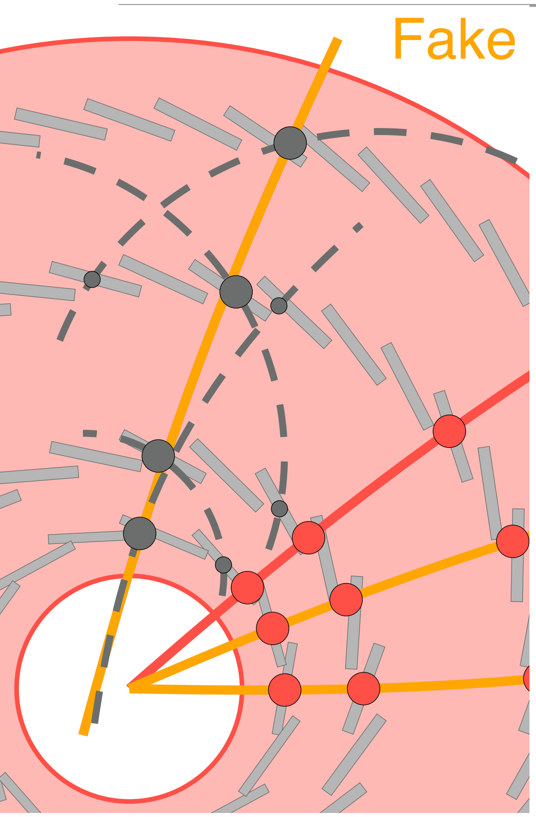
Make p_T resolution **smearing factor**

x TF

x Smearing factor

Full prediction

Fakes and systematics



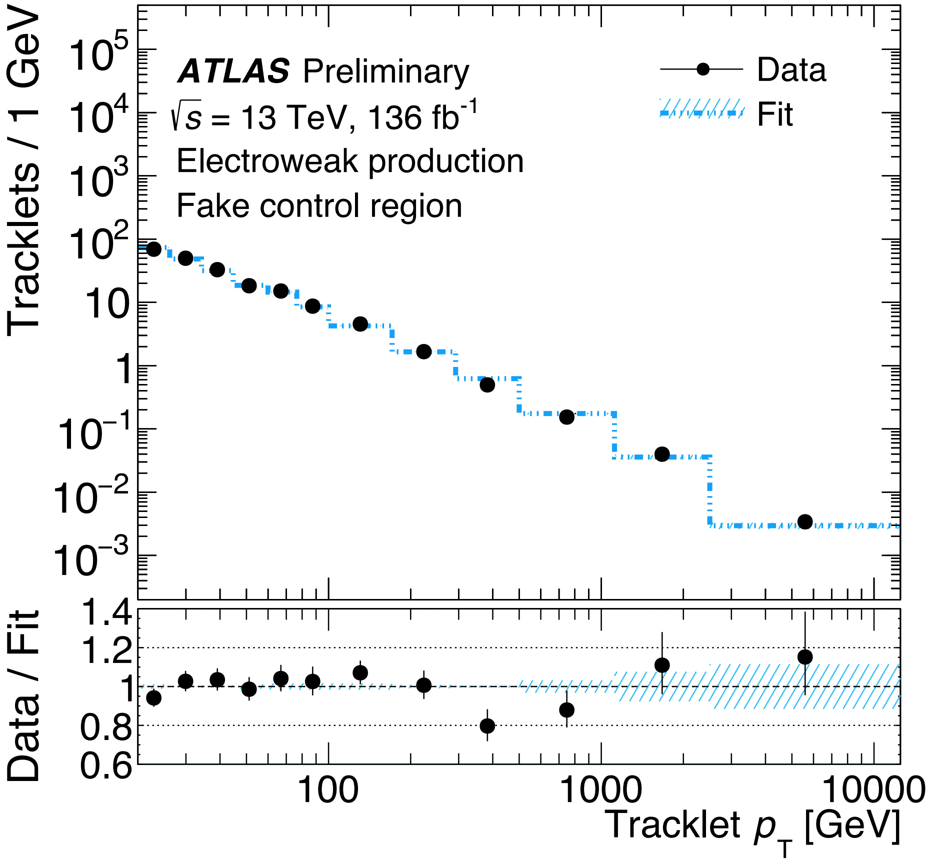
Fake tracks: **random hit combinations**

No need to point to PV

Therefore, **high d_0 tracklets** are fake-enriched control sample

Fit to obtain p_T template

Constrain normalisation with fraction of high-MET events



Background uncertainties

Constraints on fake normalisation

p_T smearing function

Signal uncertainties

Initial/final state radiation

Tracklet reconstruction efficiency

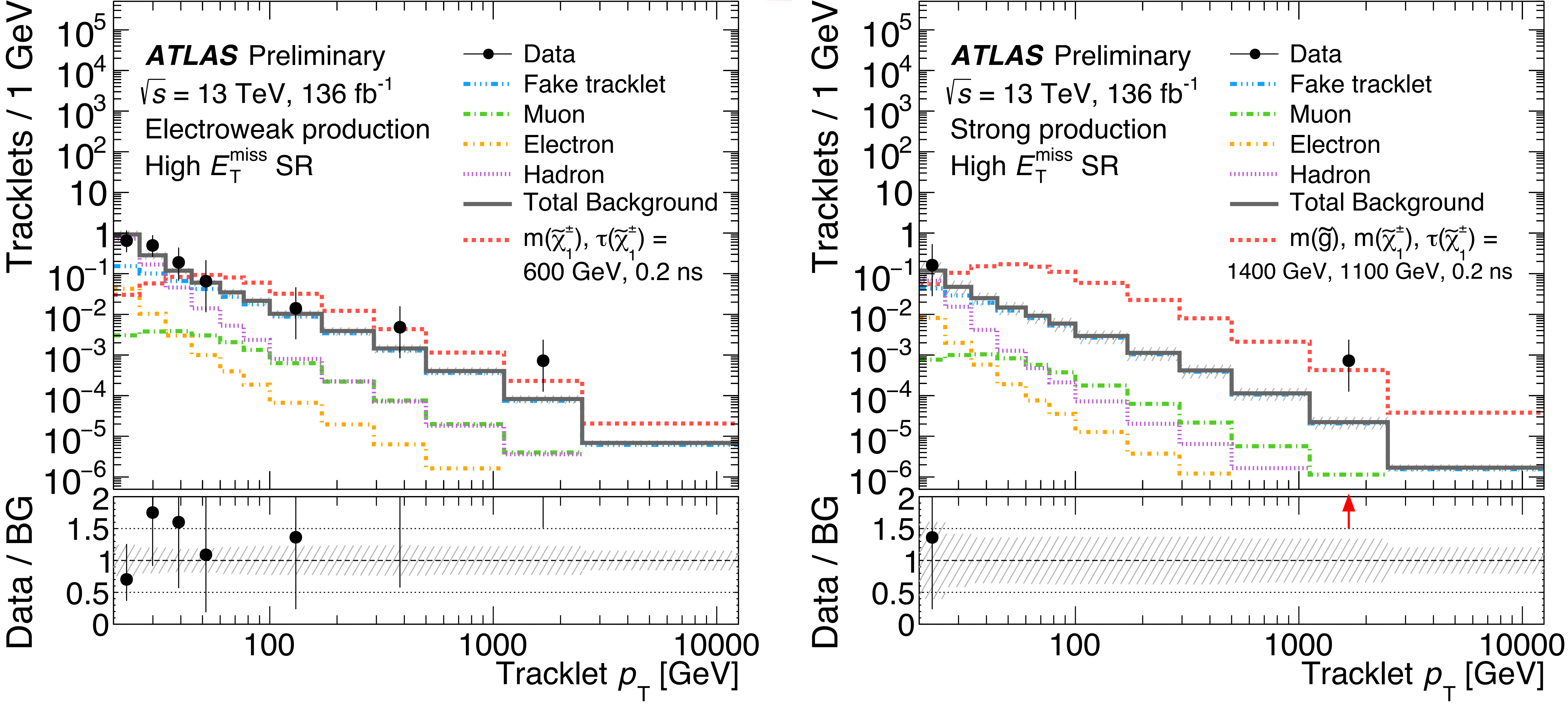
Jet energy scale & resolution

Results

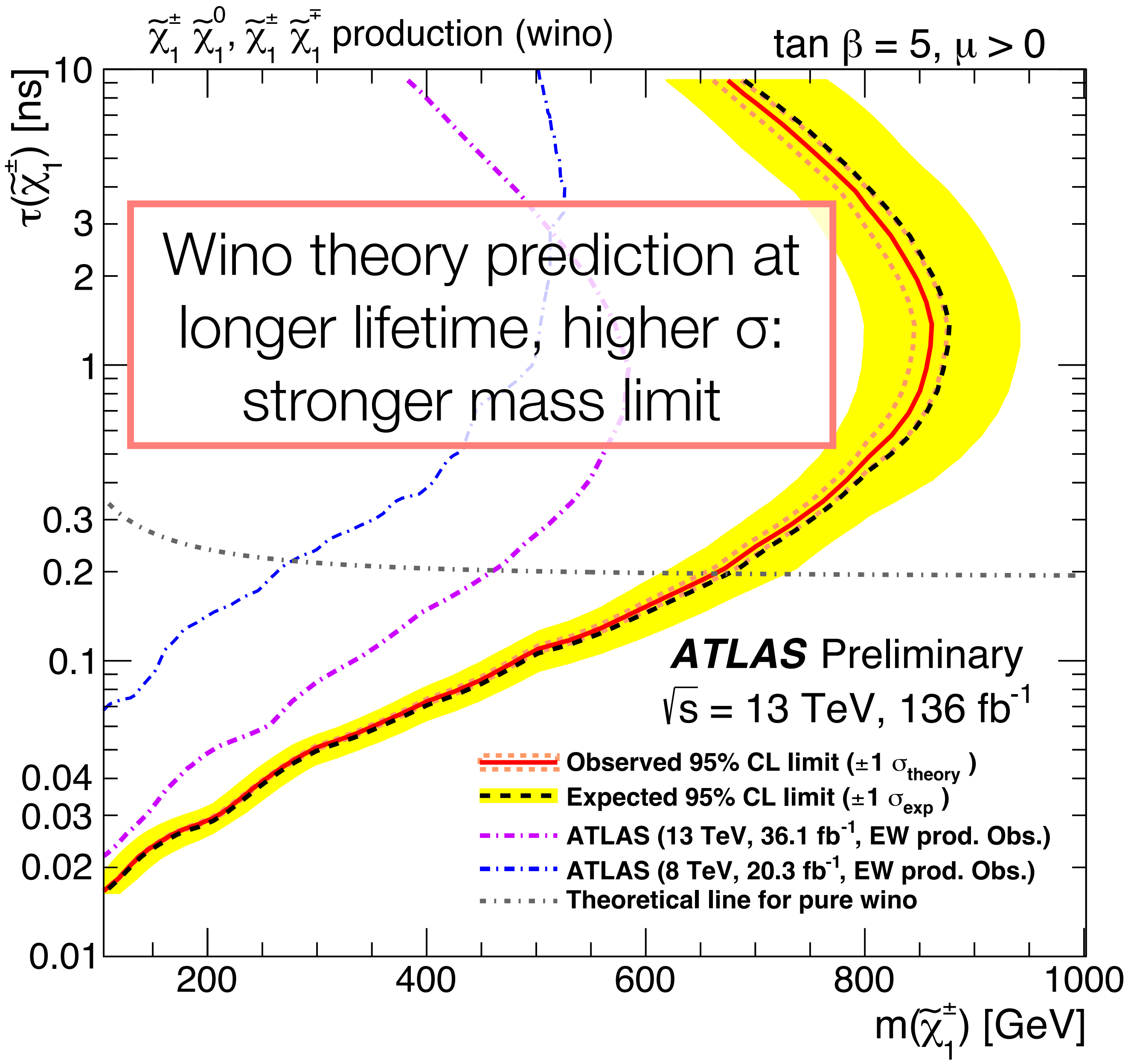
Discovery regions are SRs with tracklet p_T > 60 GeV

	Electroweak channel	Strong channel
	High-E_T^{miss} SR	
Fake	2.6 ± 0.8	0.77 ± 0.33
Hadron	0.26 ± 0.13	0.024 ± 0.031
Electron	0.021 ± 0.023	0.004 ± 0.004
Muon	0.17 ± 0.06	0.049 ± 0.018
Total Expected	3.0 ± 0.7	0.84 ± 0.33
Observed	3	1

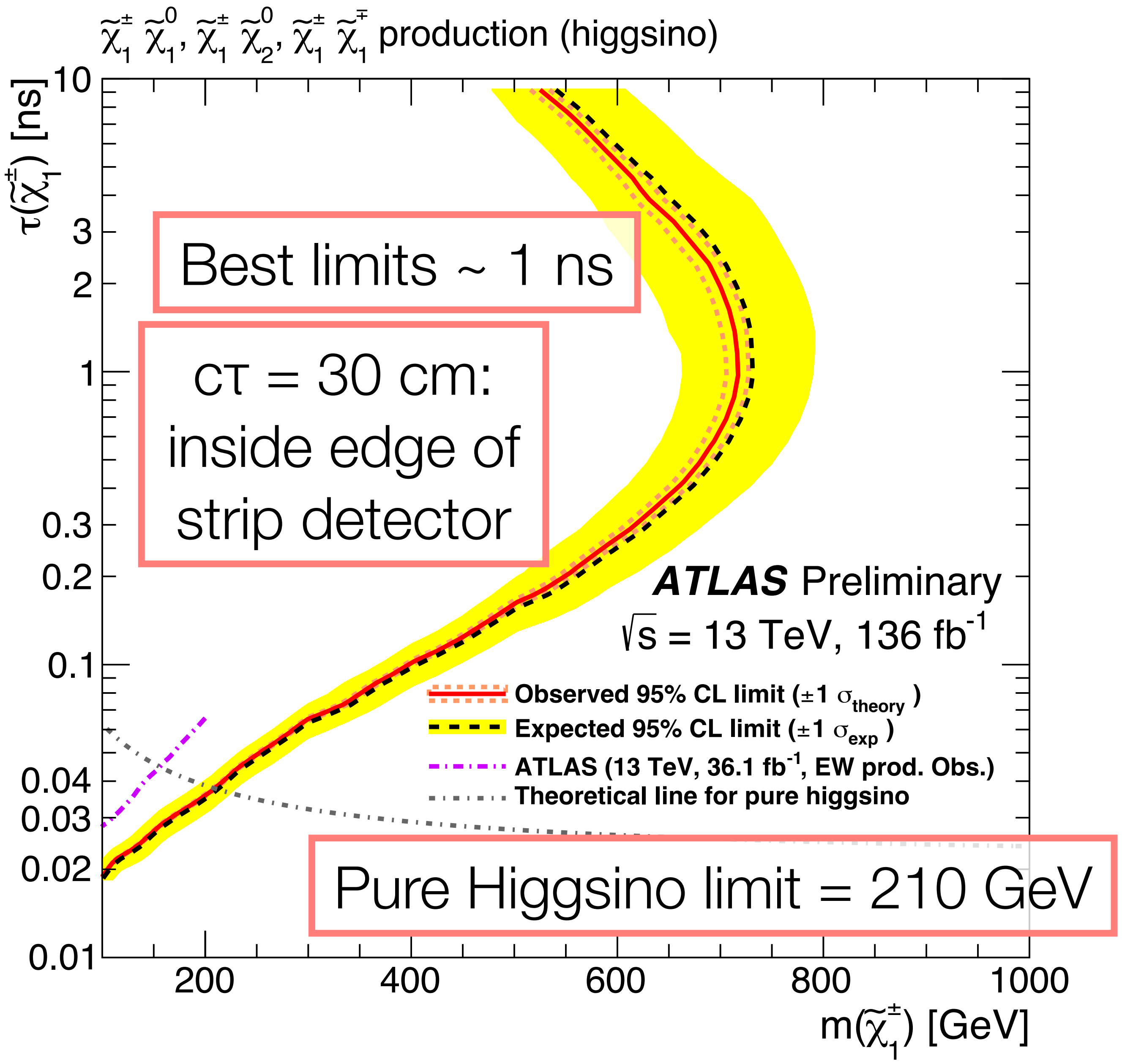
Full signal regions



Limits



Wino theory prediction at longer lifetime, higher σ: stronger mass limit

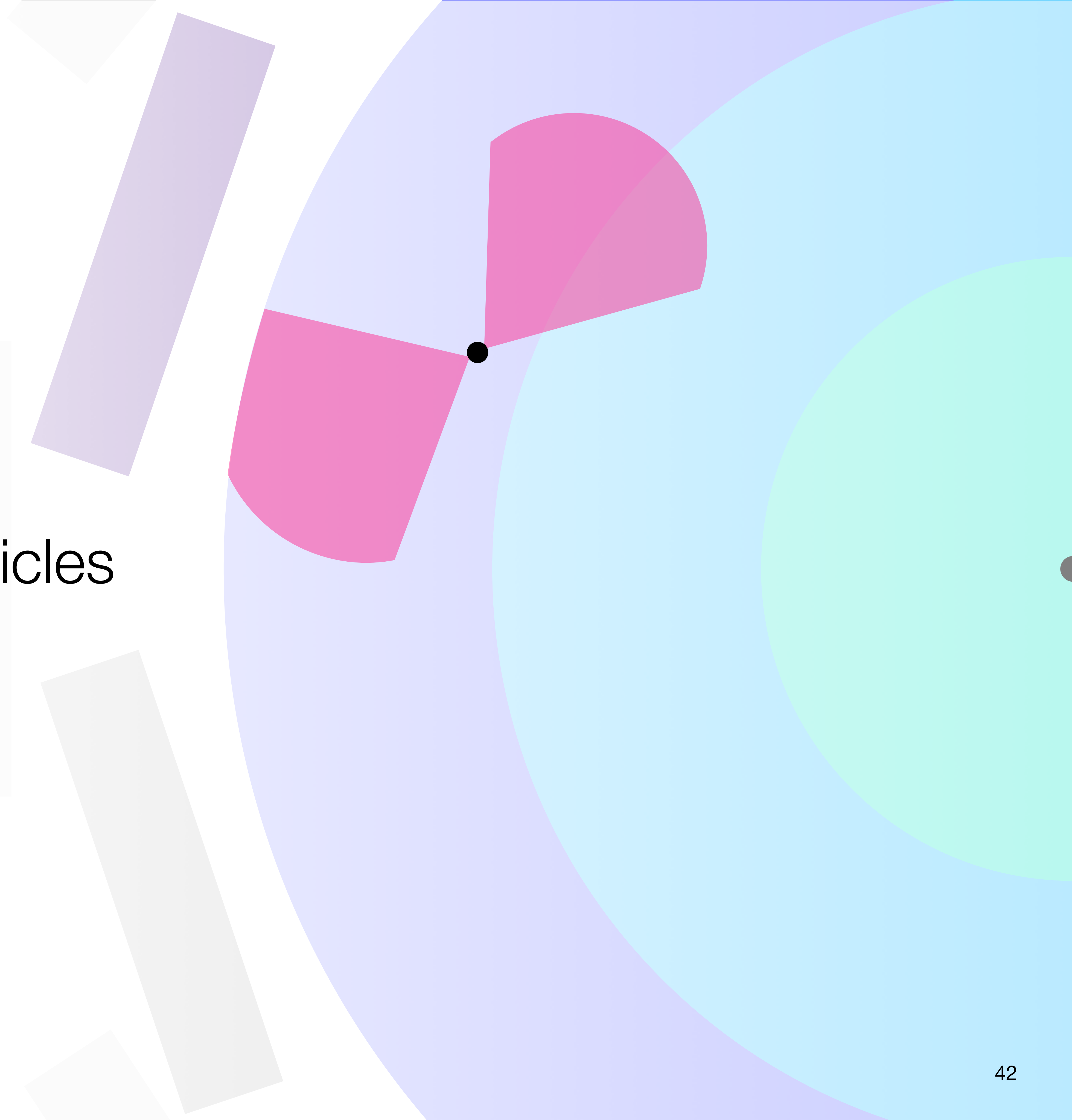


Best limits ~ 1 ns

cτ = 30 cm: inside edge of strip detector

Pure Higgsino limit = 210 GeV

Compelling dark matter models: these limits are a meaningful statement on sub-TeV WIMPs

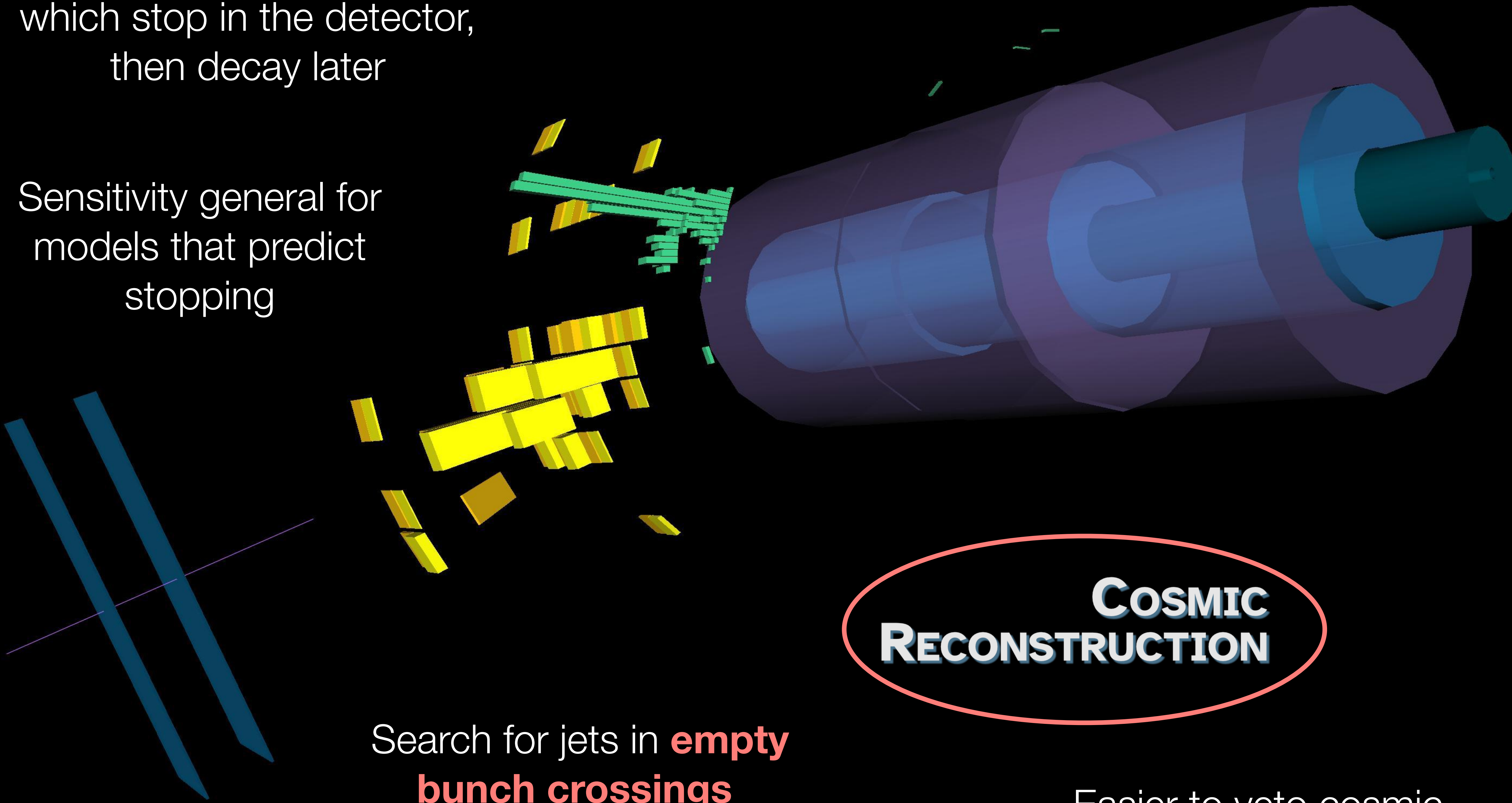


Stopped particles

arXiv:2104.03050

Target: hadronised long-lived SUSY particles (**R-hadrons**) which stop in the detector, then decay later

Sensitivity general for models that predict stopping



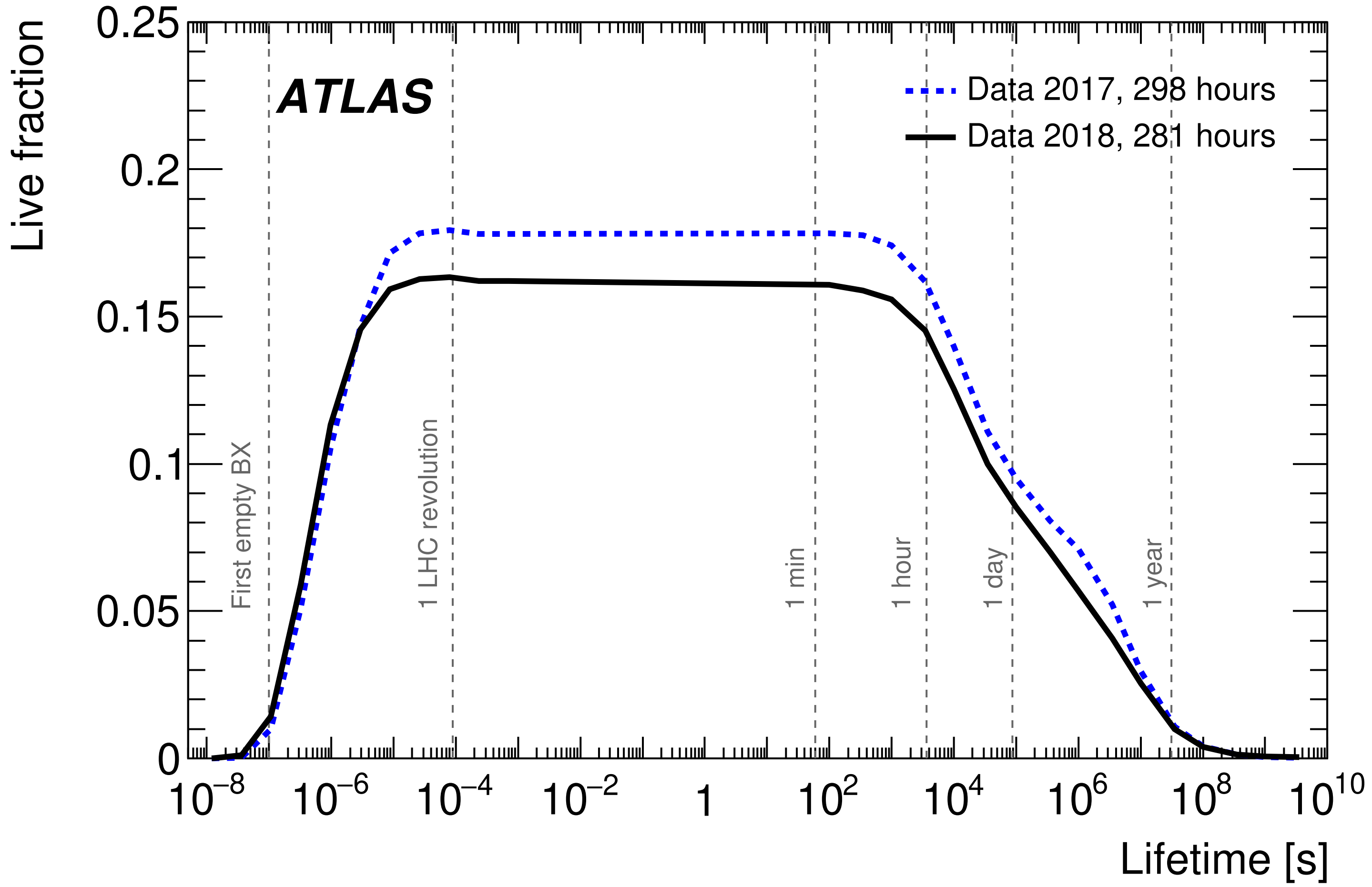
COSMIC RECONSTRUCTION

Search for jets in **empty bunch crossings**

- Low backgrounds
- Low trigger thresholds

Easier to veto cosmic muons

Datasets and regions



Trigger in empty bunch crossings

Signal produced with full bunches; recorded in empty

"**Live time**": trigger-able time during run

Background ∝ live time

Signal ∝ live time * luminosity

2015 and 2016: low luminosity, high live time → do not add sensitivity

Only analyse 2017 and 2018 datasets

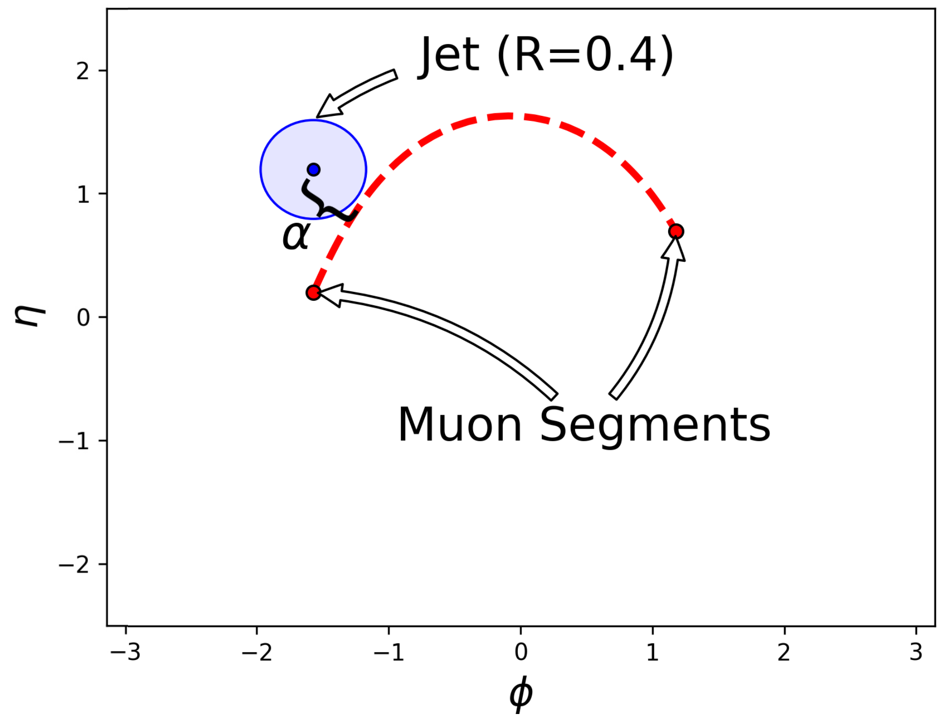
Search dataset	Empty bunches
Cosmic sample	No proton fill
Beam-induced background sample	Unpaired bunches

} Jet $p_T > 90$ GeV, $|\eta| < 2.4$, no PV

Signal regions: jet $p_T > 150$ GeV; inclusive or $|\eta| < 0.8$

Cosmic backgrounds

Path of cosmic muon in η, ϕ geometrically defined

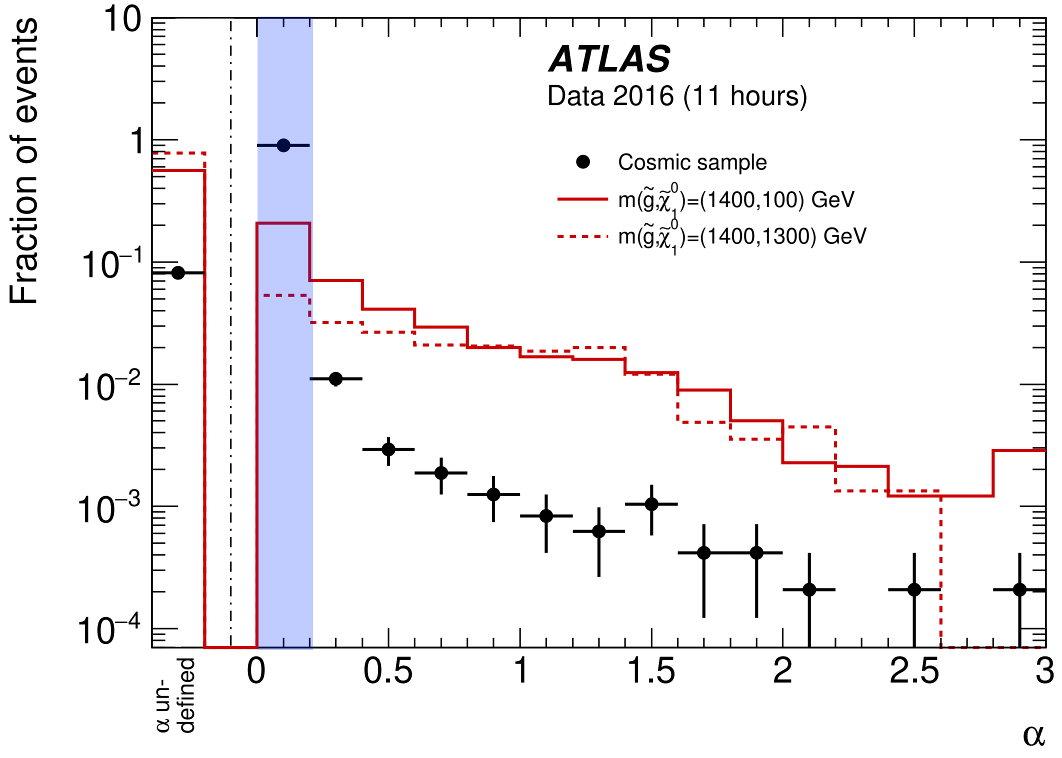


Jet caused by radiating cosmic μ should have **small α**

Reject event:

- If any reconstructed μ
- If α defined and < 0.2

Control region: Search dataset + BIB sample with **α < 0.2**



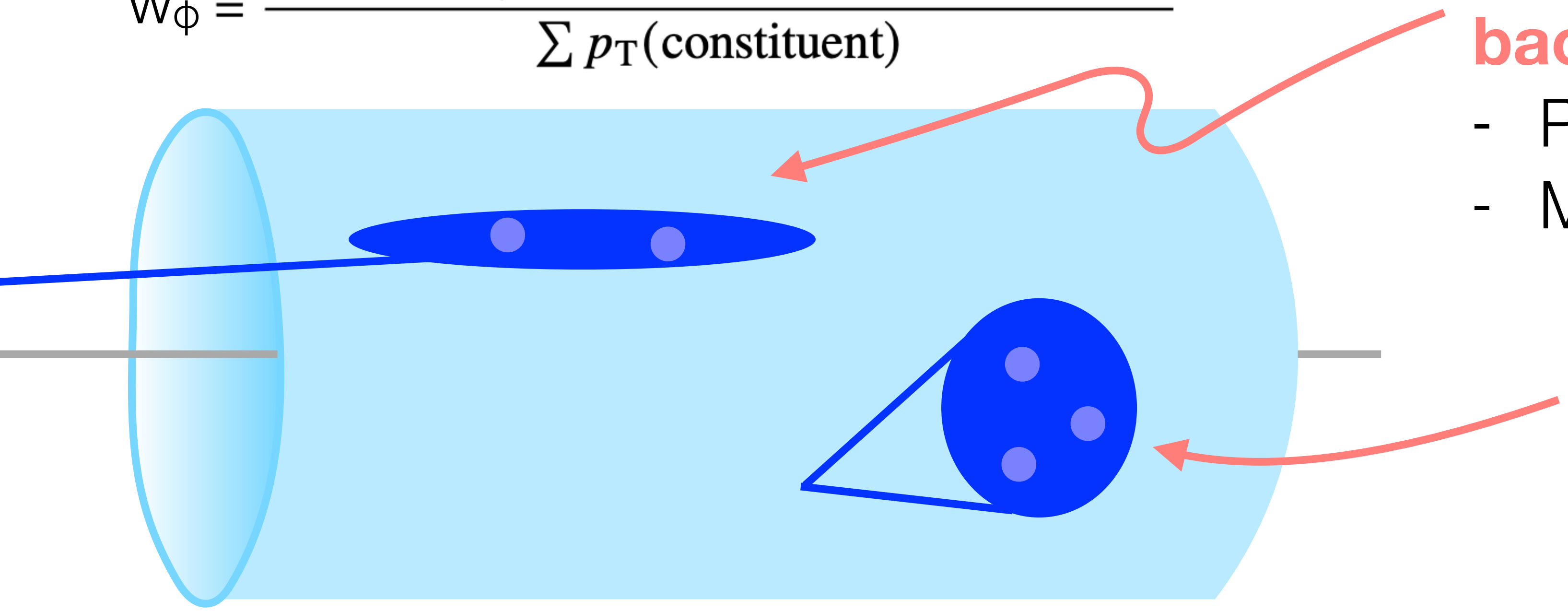
Take jet **p_T spectrum template** from CR; validate in cosmics sample

Normalise with **transfer factor**:

$$F = \frac{N^{\text{cosmics sample}}_{\text{SR-like}}}{N^{\text{cosmics sample}}_{\text{CR-cos-like}}}$$

Beam-induced backgrounds

$$w_\phi = \frac{\sum(\text{abs}(\Delta\phi(\text{jet, constituent}))\,p_{\mathrm{T}}(\text{constituent}))}{\sum p_{\mathrm{T}}(\text{constituent})}$$



Jet from **beam-induced backgrounds (BIB):**

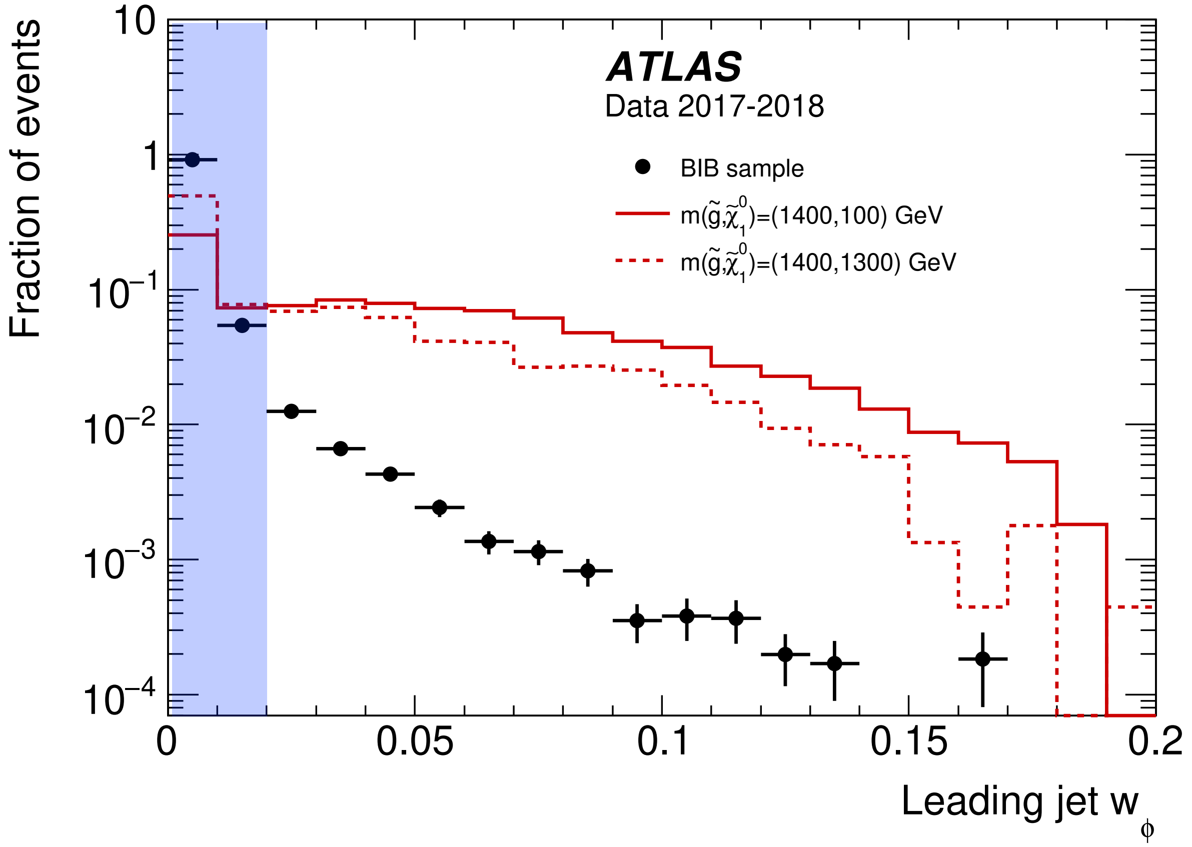
- Primarily electromagnetic
- Momentum along beam axis

→ small w_ϕ

Jet from **signal**:

- Primarily hadronic

→ any w_ϕ



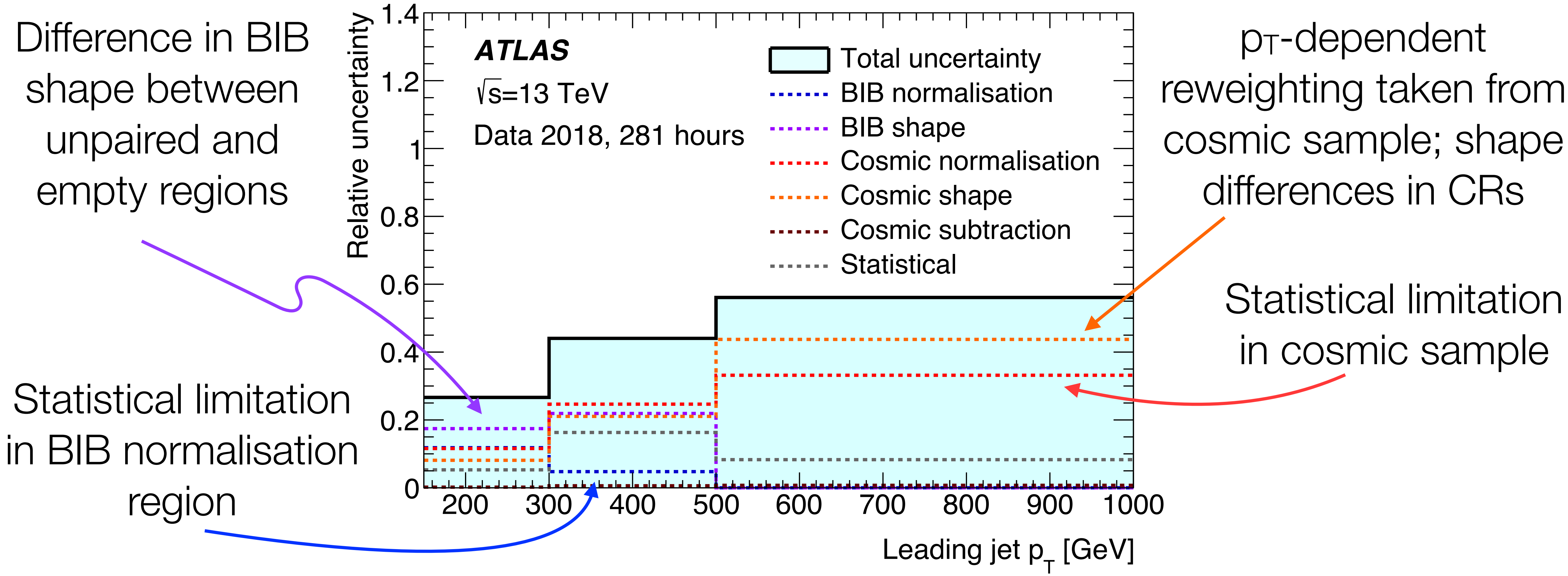
Control region: BIB sample with **w_ϕ > 0.01**, cosmics subtracted

Take jet **p_T spectrum template** from CR

Normalise template in low jet p_T regions

$$90\ \text{GeV} < p_T^{jet} < 150\ \text{GeV}$$

Uncertainties



Difference in BIB shape between unpaired and empty regions

Statistical limitation in BIB normalisation region

p_T-dependent reweighting taken from cosmic sample; shape differences in CRs

Statistical limitation in cosmic sample

Leading signal uncertainties

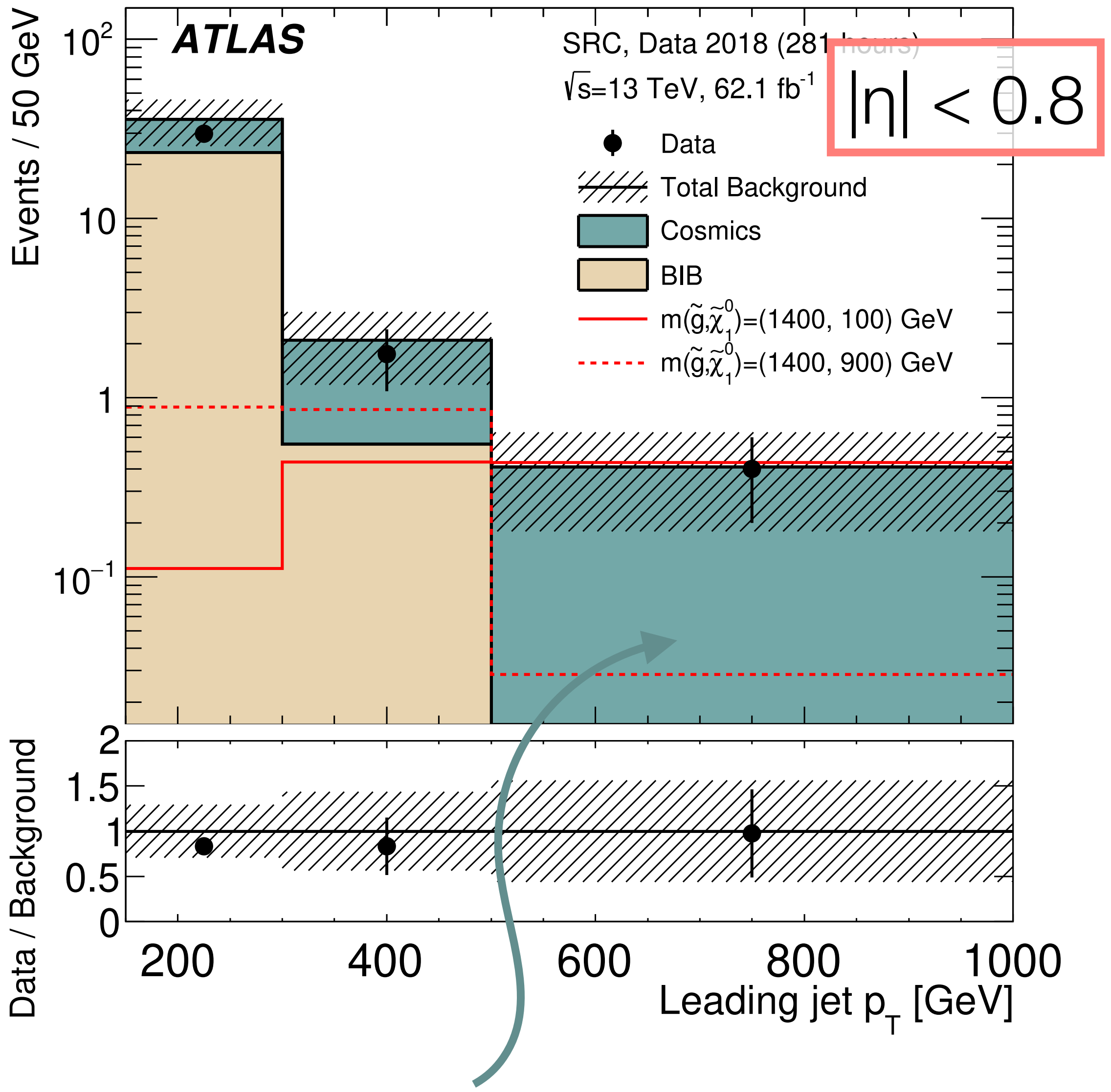
Out-of-time jet occurrences:
5% - 50%

Jet non-projectivity:
12%

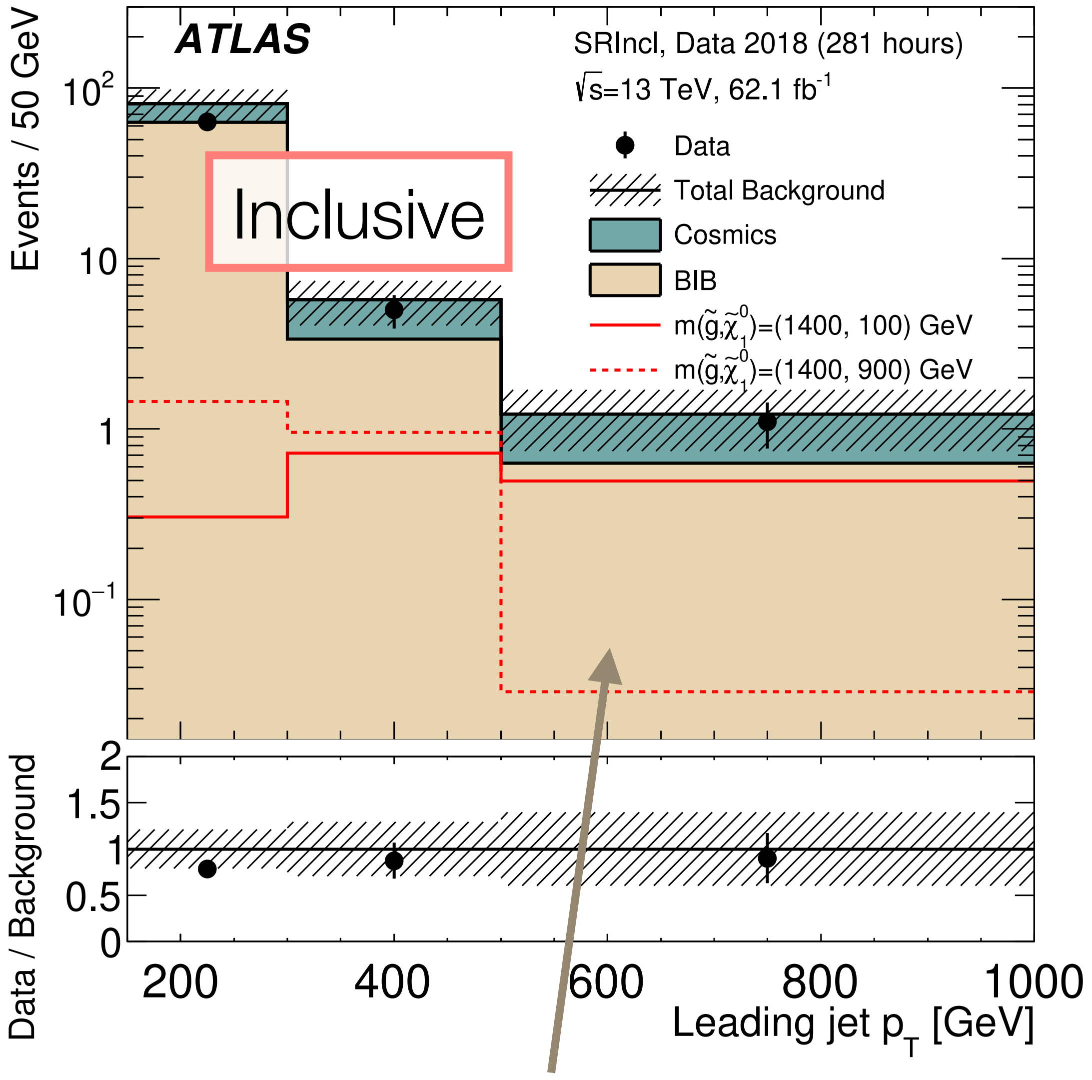
Results

No observed excesses

Great agreement from background estimation



|η| < 0.8

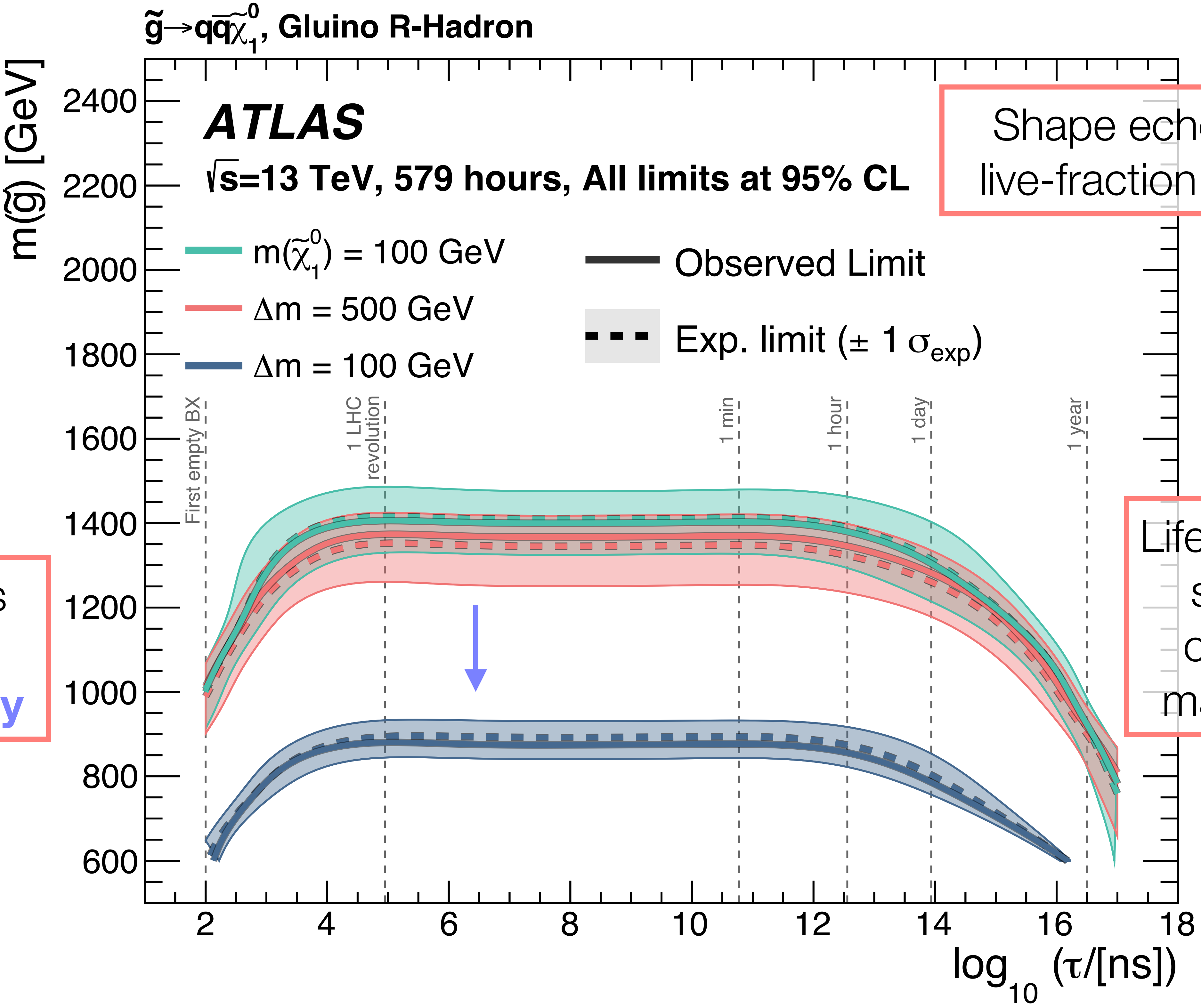


Inclusive

Cosmics dominate central, high p$_T$ jet backgrounds

BIB a greater factor in more forward region

R-hadron limits



Shape echoes live-fraction plot

Smaller mass gap = **less visible energy**

Lifetime limits span 15 orders of magnitude!

Conclusions

Conclusions

Long-lived particles are a well motivated search target at the LHC

They pose **interesting challenges** for reconstruction and performance

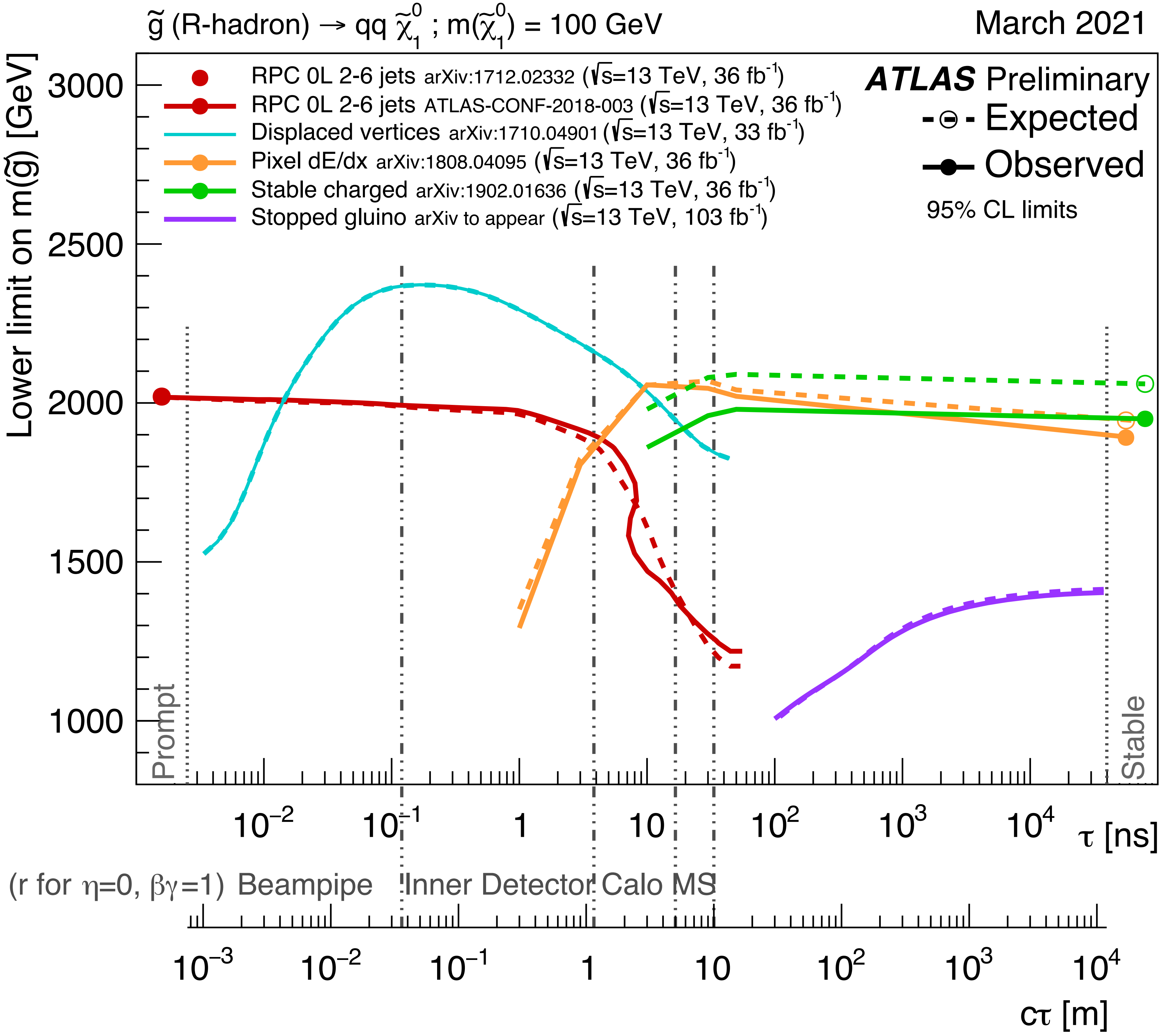
Exciting new results shown today:

- First ever ATLAS searches in **V(H→4b)**, **displaced leptons** signatures
- Significantly improved sensitivity in **disappearing track** signature
- First ATLAS **stopped particle** search in 13 TeV data

More results still to come from Run 2, and
we are looking forward to new LLP opportunities in Run 3!

Backup

Why standard searches don’t suffice



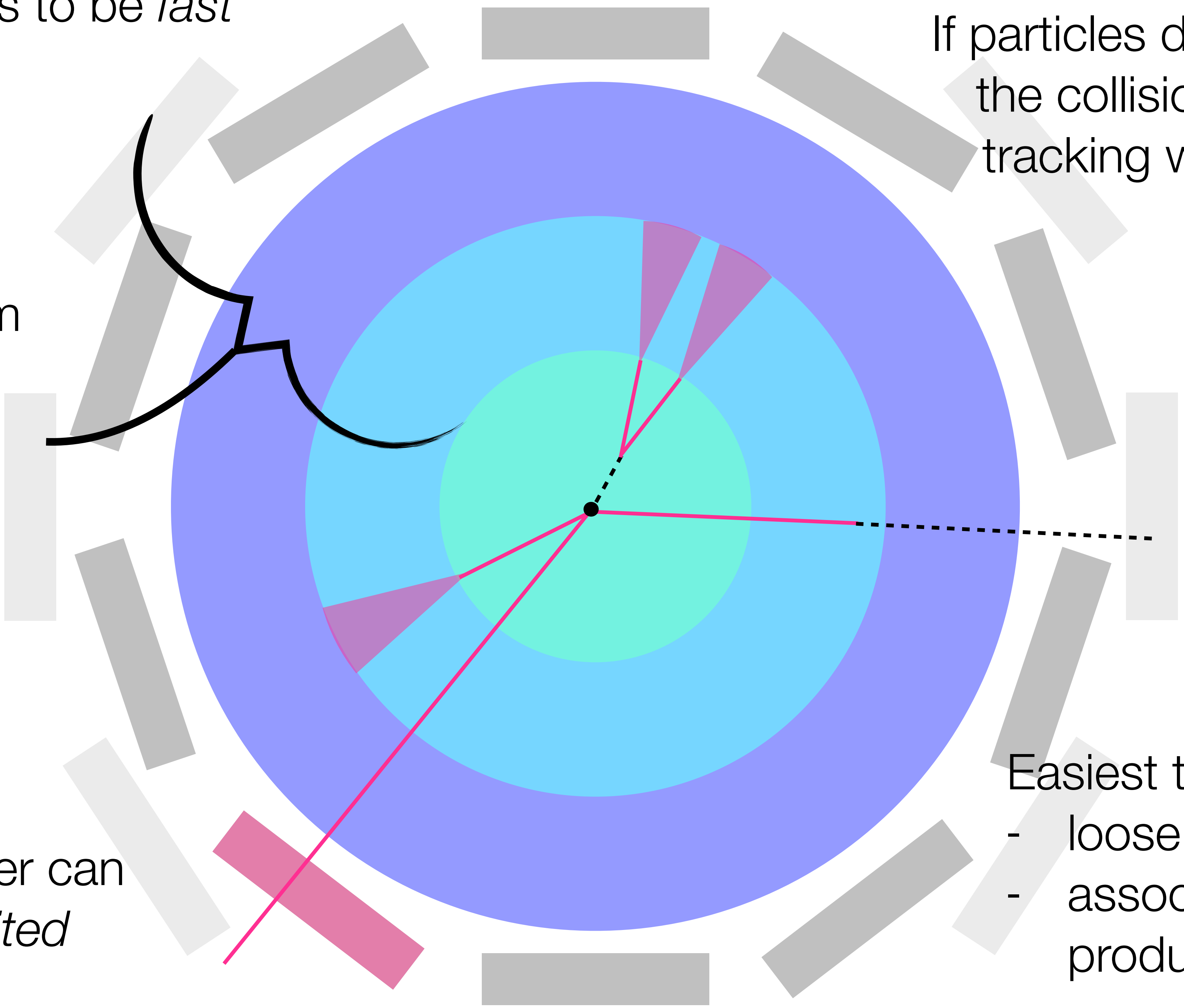
Connecting lifetime to location

Mean distance travelled = $\beta\gamma c\tau$

- $c\tau$ = simple distance metric. Order 30cm for τ = 1 nanosecond
- Lorentz boost $\beta\gamma = p/M$. Ranges from ~ 0.8 or 0.9 for really heavy particles to ~30 for really light ones.
- What distance travelled counts as "displaced" varies with the resolution of the detector system being used!
  - Tracker d0 and z0 resolution ~0.02-0.1 mm while ECal pointing resolution ~50 mm
  - Timing resolution also relevant for some subsystems/searches

Values of $\tau \sim 10^{-13}$ to 10^{-7} seconds are "long-lived particles"

Triggering and long-lived particles



Trigger needs to be *fast*

L1 uses only information from muons and calorimeters: fast to collect and analyse

High level trigger can add very *limited* tracking

If particles don't come from the collision, the limited tracking will miss them

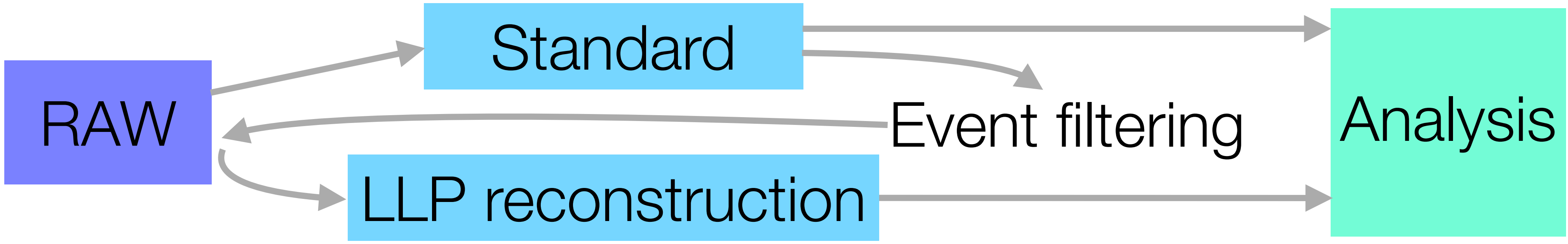
If signature is just a track, out of luck!

Easiest to use:

- loose trigger
- associated production

Data flow in ATLAS

Run 2:

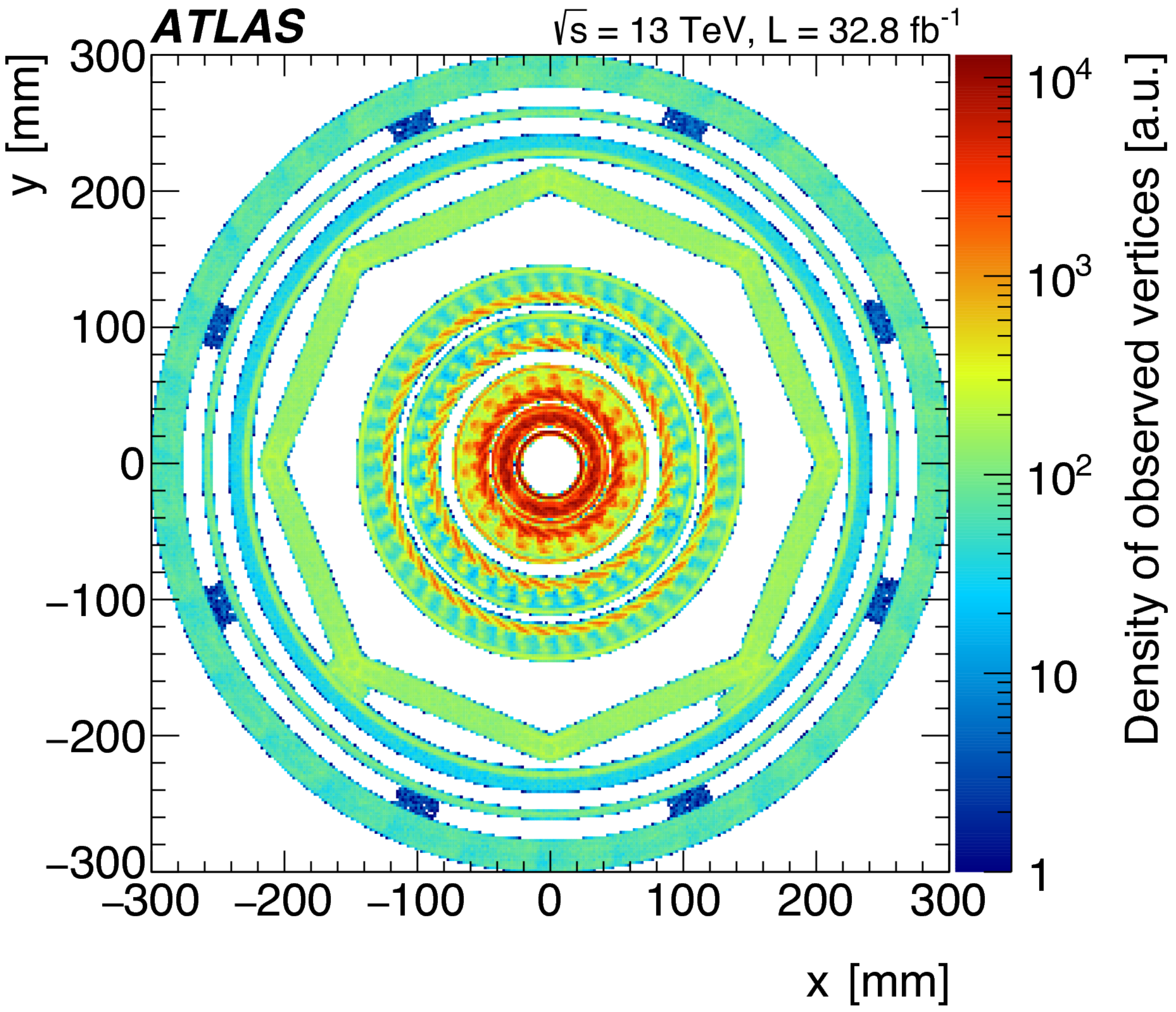


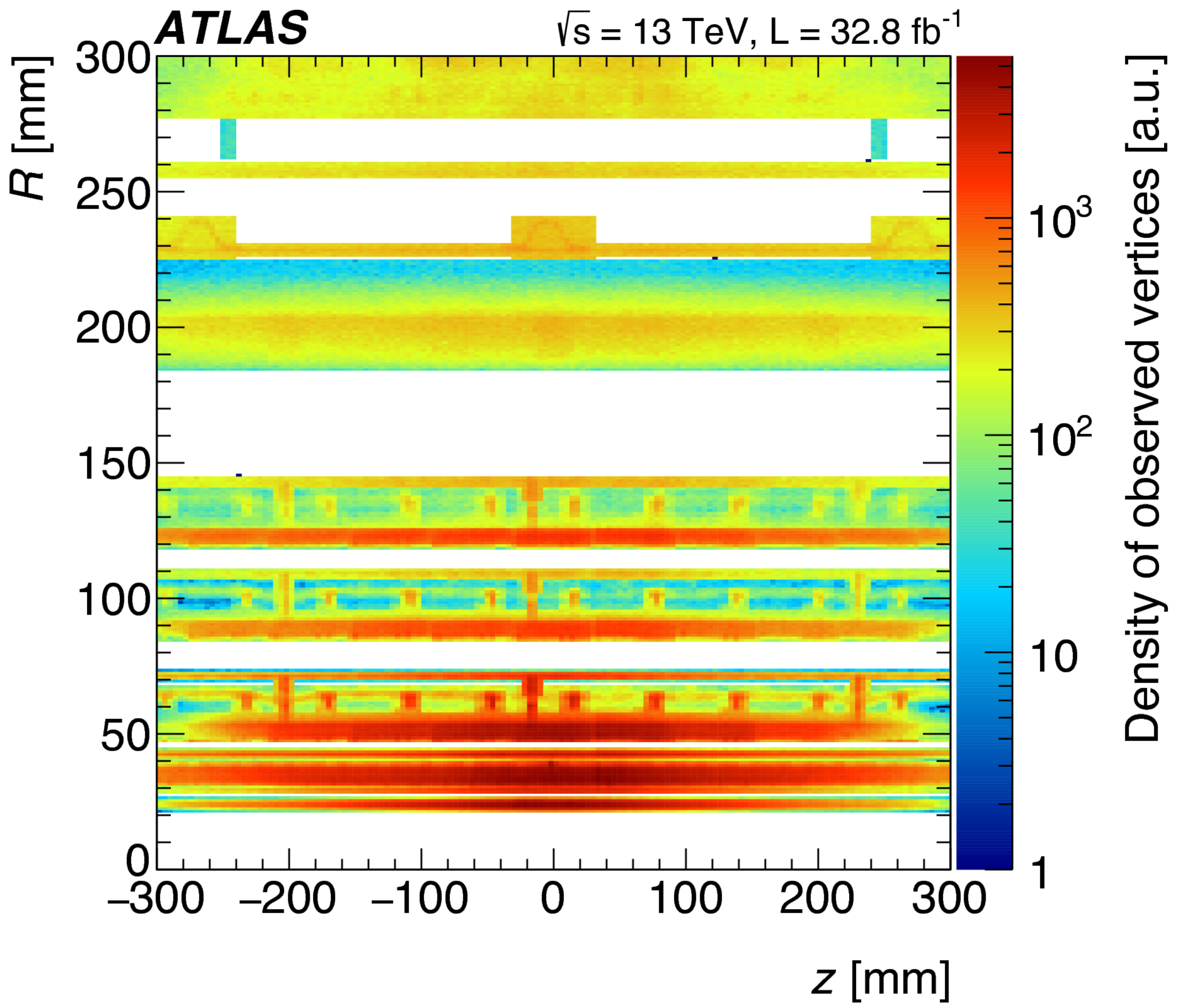
- Due to size of large-radius tracking output, was impossible to run on all events
- Filtering step used information in standard reconstruction to pick events which would be processed with LRT - essentially acts as a second trigger with signal efficiency < 1
- Filter requirements constrain what can be done in LLP analyses at present. Moving to a tidier model for Run 3

Material veto for DVs

VH(4b)

- Material map taken from ATLAS SUSY-2016-08 (displaced vertices)





Muon trigger Displaced leptons

- L1 has an implicit d_0 requirement as hardware was designed to reconstruct muons coming from the PV. No effect until $|d_0| \sim 50$ mm and then it begins to impact efficiency a little, but the effects are quite small

- HLT requirement: not checking for a track, therefore inclusive of having or not having one. No d_0 selection.

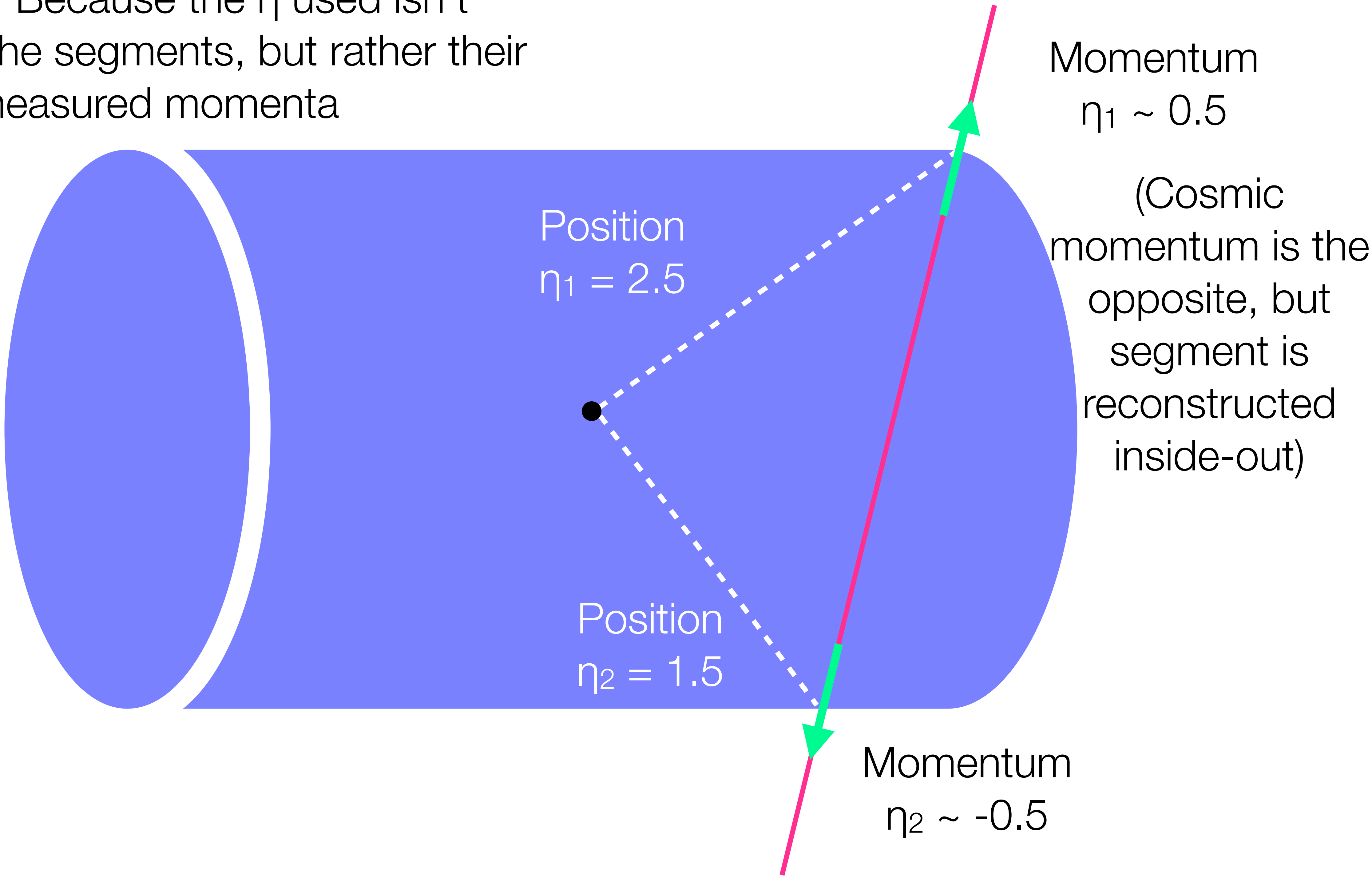
Cosmic veto details

- ~70% of cosmic events in ATLAS reconstructed as two muons. Remainder are missing top half (timing identified as backward-going).
- In these cases, use muon spectrometer hits to check opposite a reconstructed muon
  - Use direction from spectrometer hits to do matching, rather than η/ϕ w.r.t. origin
- Additional veto for cases where incoming muon would have passed through non-instrumented slice at $\eta=0$
- Efficiency for eliminating cosmics = 99.7% as tested in cosmic run

Cosmic veto details

Displaced leptons

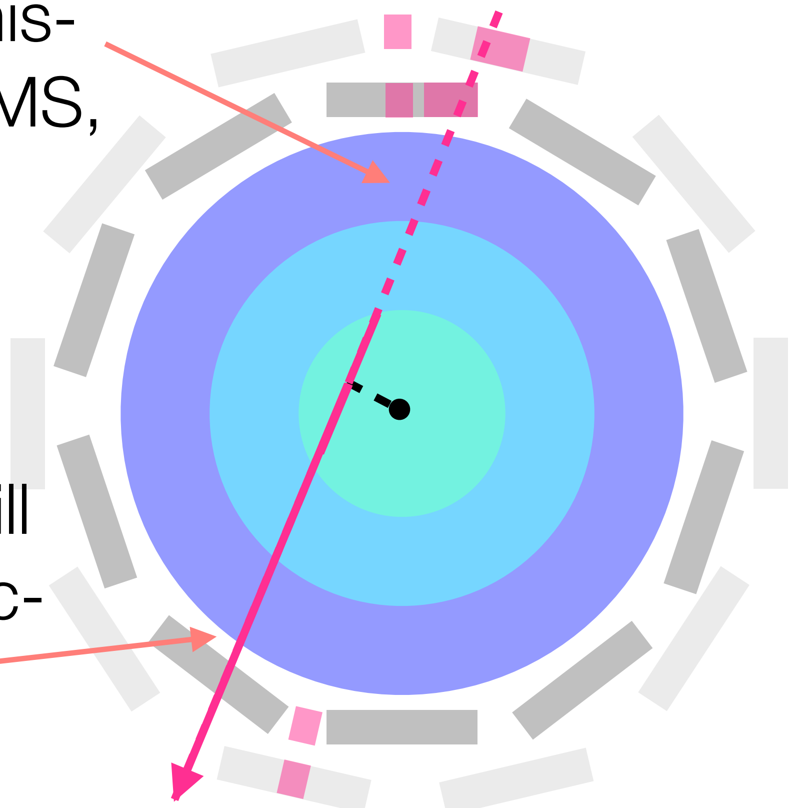
Why Ση? Because the η used isn't position of the segments, but rather their measured momenta



(Cosmic momentum is the opposite, but segment is reconstructed inside-out)

Cosmic estimate details

Displaced leptons



If this muon is sufficiently mis-measured in MS,

This muon will not be cosmic-tagged

If both are mismeasured but of good quality, neither one will be cosmic tagged → enter SR

Muon quality **not correlated** with tag

$$N(SR) = N\,(1\ \text{bad}\ \mu,\ \text{no tag}) * \frac{N(1\ \text{good tagged}\ \mu)}{N(1\ \text{bad tagged}\ \mu)}$$

Systematics

Displaced leptons

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

Validation results: ABCD Displaced leptons

VR-*ee*-fake			
Variable used in the estimate	ID track χ^2/n_{DOF}	number of missing layers	both
Estimate	1372 ± 85	1320 ± 95	1356 ± 49
Observed	1440	1440	1440

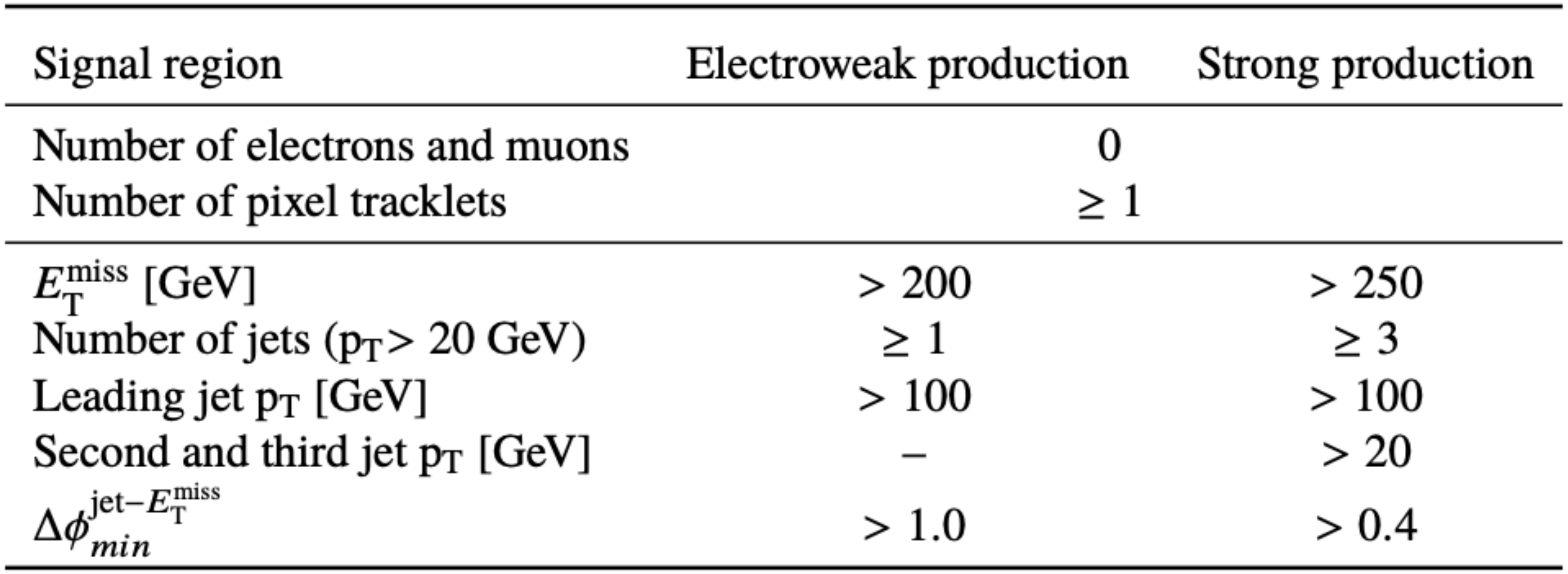
VR-*ee*-heavy flavor		
$(p_{\mathrm{T}}^{\mathrm{track}} - p_{\mathrm{T}}^{e})/p_{\mathrm{T}}^{e}$	> -0.5	> -0.9
Estimate	1.85 ± 0.28	23.5 ± 1.9
Observed	0	26

VR-$e\mu$-fake	
Estimate	$1.9^{+1.8}_{-1.0}$
Observed	2

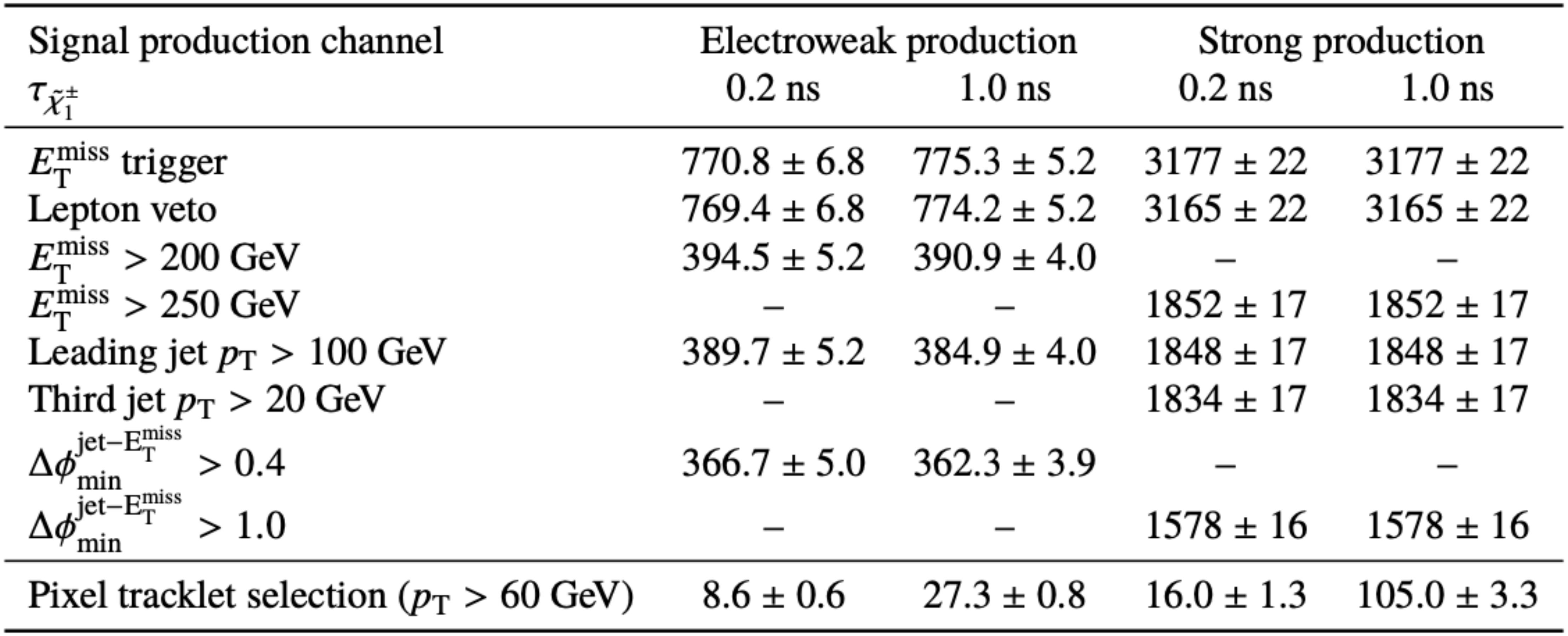
VR-$e\mu$-heavy flavor		
$(p_{\mathrm{T}}^{\mathrm{track}} - p_{\mathrm{T}}^{e})/p_{\mathrm{T}}^{e}$	> -0.5	> -0.9
Estimate	-	$0.38^{+0.37}_{-0.32}$
Observed	0	1

Region definitions

Disappearing track

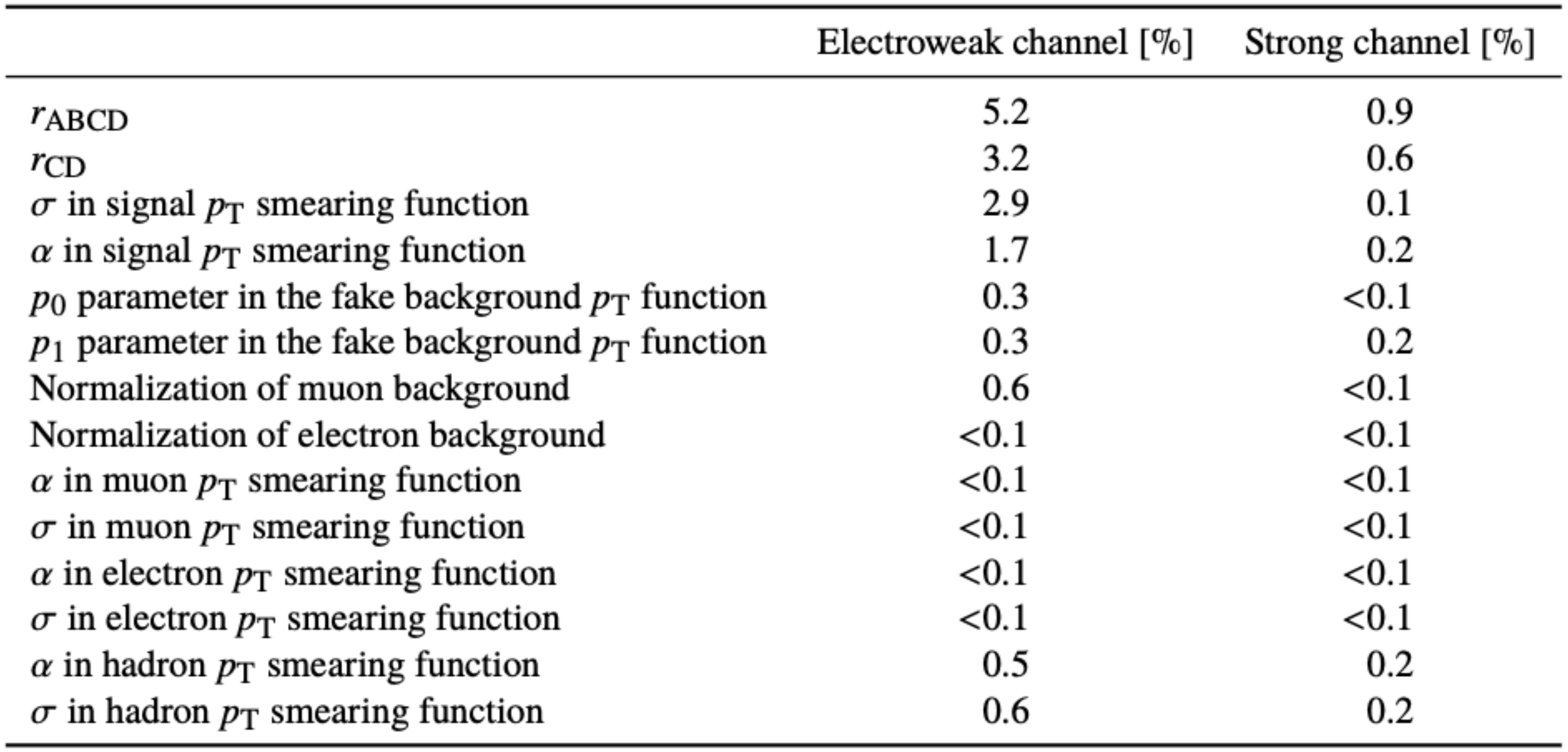


Signal region	Electroweak production	Strong production
Number of electrons and muons	0	
Number of pixel tracklets	≥ 1	
E_T^{miss} [GeV]	> 200	> 250
Number of jets ($p_T > 20$ GeV)	≥ 1	≥ 3
Leading jet p_T [GeV]	> 100	> 100
Second and third jet p_T [GeV]	–	> 20
$\Delta\phi_{min}^{jet-E_T^{miss}}$	> 1.0	> 0.4

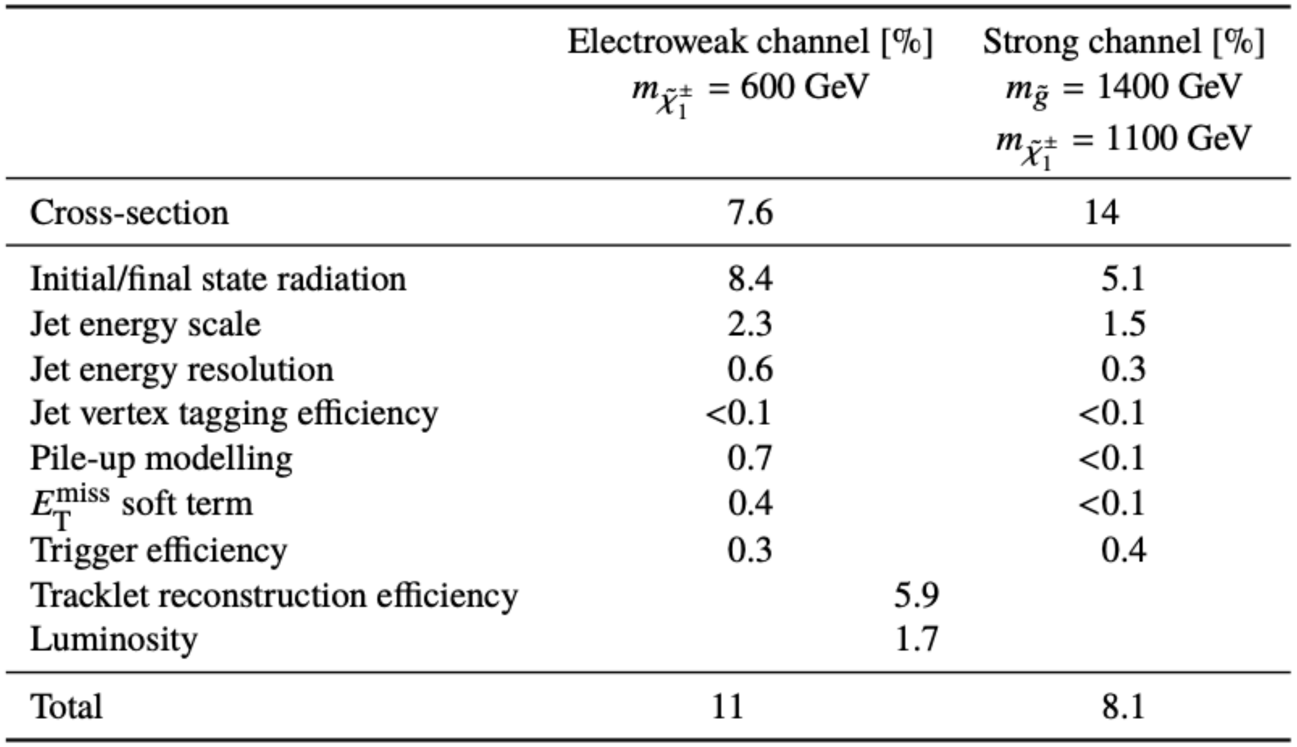


Signal production channel	Electroweak production		Strong production	
$\tau_{\tilde{\chi}_1^\pm}$	0.2 ns	1.0 ns	0.2 ns	1.0 ns
E_T^{miss} trigger	770.8 ± 6.8	775.3 ± 5.2	3177 ± 22	3177 ± 22
Lepton veto	769.4 ± 6.8	774.2 ± 5.2	3165 ± 22	3165 ± 22
$E_T^{miss} > 200$ GeV	394.5 ± 5.2	390.9 ± 4.0	–	–
$E_T^{miss} > 250$ GeV	–	–	1852 ± 17	1852 ± 17
Leading jet $p_T > 100$ GeV	389.7 ± 5.2	384.9 ± 4.0	1848 ± 17	1848 ± 17
Third jet $p_T > 20$ GeV	–	–	1834 ± 17	1834 ± 17
$\Delta\phi_{\mathrm{min}}^{\mathrm{jet-E_T^{miss}}} > 0.4$	366.7 ± 5.0	362.3 ± 3.9	–	–
$\Delta\phi_{\mathrm{min}}^{\mathrm{jet-E_T^{miss}}} > 1.0$	–	–	1578 ± 16	1578 ± 16
Pixel tracklet selection ($p_T > 60$ GeV)	8.6 ± 0.6	27.3 ± 0.8	16.0 ± 1.3	105.0 ± 3.3

Systematic breakdown Disappearing track



	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



	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

Region definitions

Stopped particle

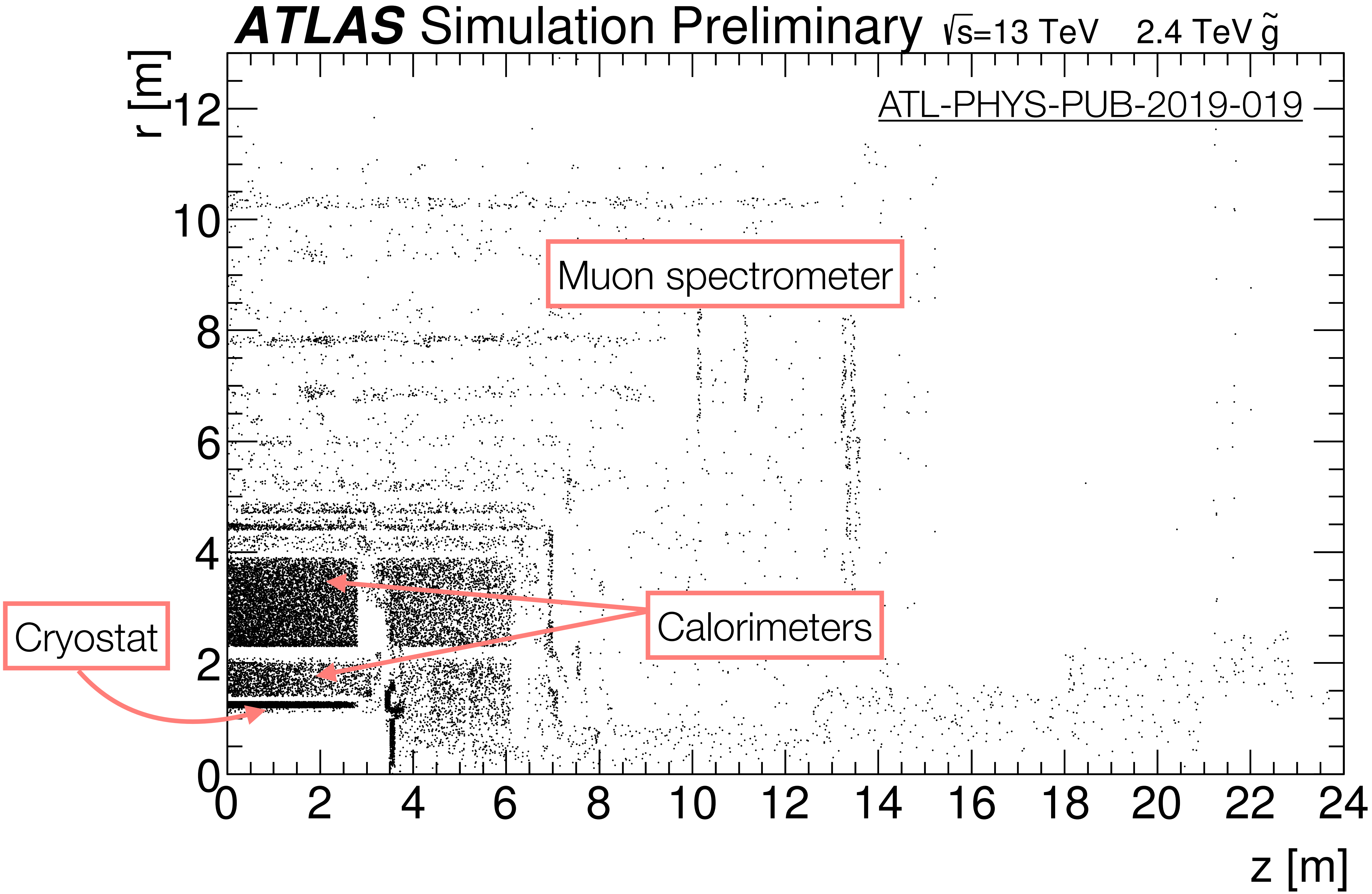
Region	Data sample	Number of muons	Leading jet p_{T} [GeV]	α	Leading jet w_{ϕ}	Leading jet $\lvert\eta\rvert$
Central signal region						
SRC	Search sample	0	150–300 300–500 > 500	> 0.2	> 0.02	< 0.8
Inclusive signal region						
SRIncl	Search sample	0	150–300 300–500 > 500	> 0.2	> 0.02	< 2.4
Central discovery regions						
DRC-150 DRC-300 DRC-500	Search sample (2018 data only)	0	> 150 > 300 > 500	> 0.2	> 0.02	< 0.8
Inclusive discovery regions						
DRIncl-150 DRIncl-300 DRIncl-500	Search sample (2018 data only)	0	> 150 > 300 > 500	> 0.2	> 0.02	< 2.4

Region	Data sample	Number of muons	Leading jet p_{T} [GeV]	α	Leading jet w_{ϕ}	Leading jet $\lvert\eta\rvert$
Central control and normalisation regions						
CRC-cos	Search sample & BIB sample	**≥ 1 ($\lvert\eta\rvert$ < 1.4)**	> 90	**< 0.2**	> 0.02	< 0.8
CRC-bib	**BIB sample**	0	> 90	> 0.2	> 0.01	
NRC-bib	Search sample	0	**90–150**	> 0.2	> 0.02	
Inclusive control and normalisation regions						
CRIncl-cos	Search sample & BIB sample	**≥ 1 ($\lvert\eta\rvert$ < 1.4)**	> 90	**< 0.2**	> 0.02	< 2.4
CRIncl-bib	**BIB sample**	0	> 90	> 0.2	> 0.01	
NRIncl-bib	Search sample	0	**90–150**	> 0.2	> 0.02	

Jet cleaning Stopped particle

- Standard cuts kept
  - LAr noise burst suppression (large fraction of jet energy in cells with poor signal shape quality, most of jet in EM calorimeter)
  - Hadronic endcap spikes (poor quality jets largely in the endcap)
  - Beam halo rejection (jets with large negative energy and large energy fraction in single calorimeter layer)
- Custom cuts
  - HEC noise and beam-induced background: reject jet with too high a fraction of energy in HEC
  - Pre-sampler noise: reject jet if calorimeter layer with highest E is in presampler
  - Isolated LAr activity: majority of energy is in LAr and is in either single layer or single jet constituent

Stopping locations

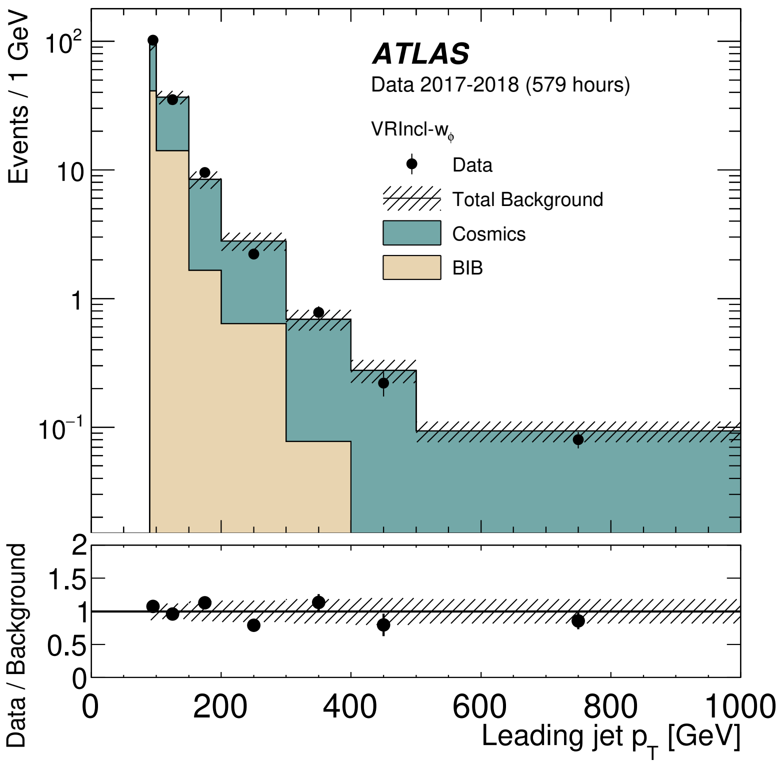


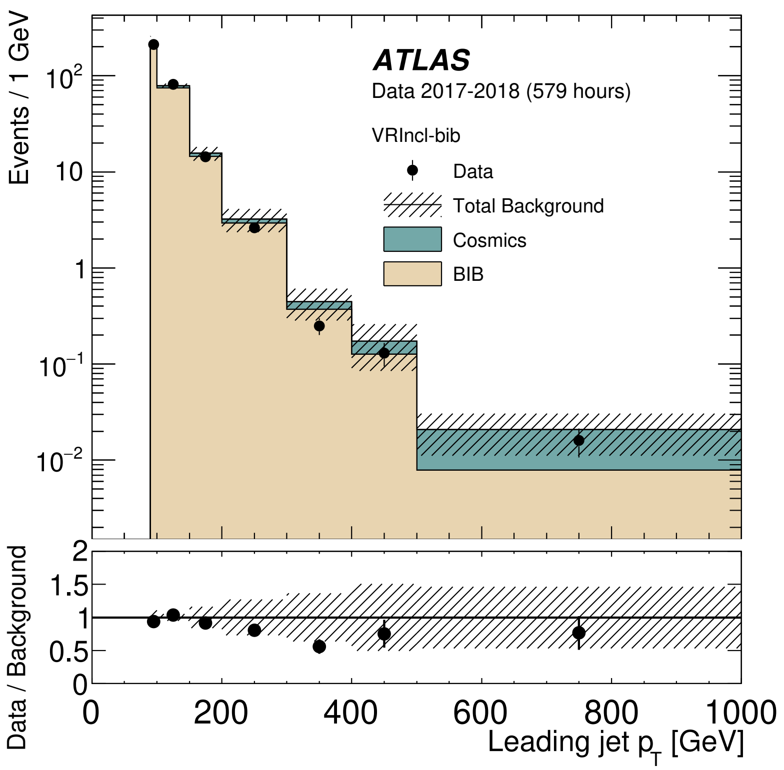
Muon spectrometer

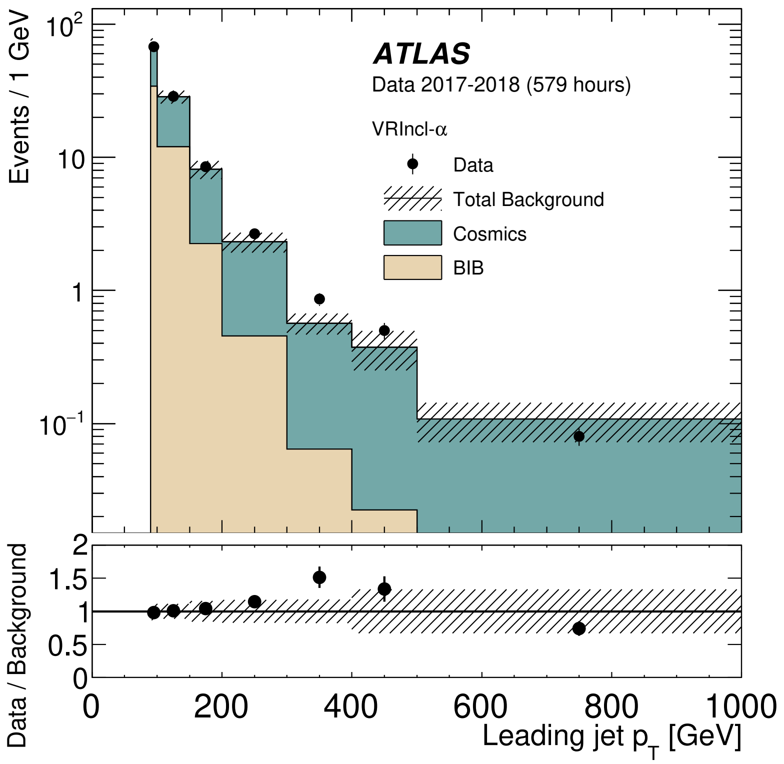
Calorimeters

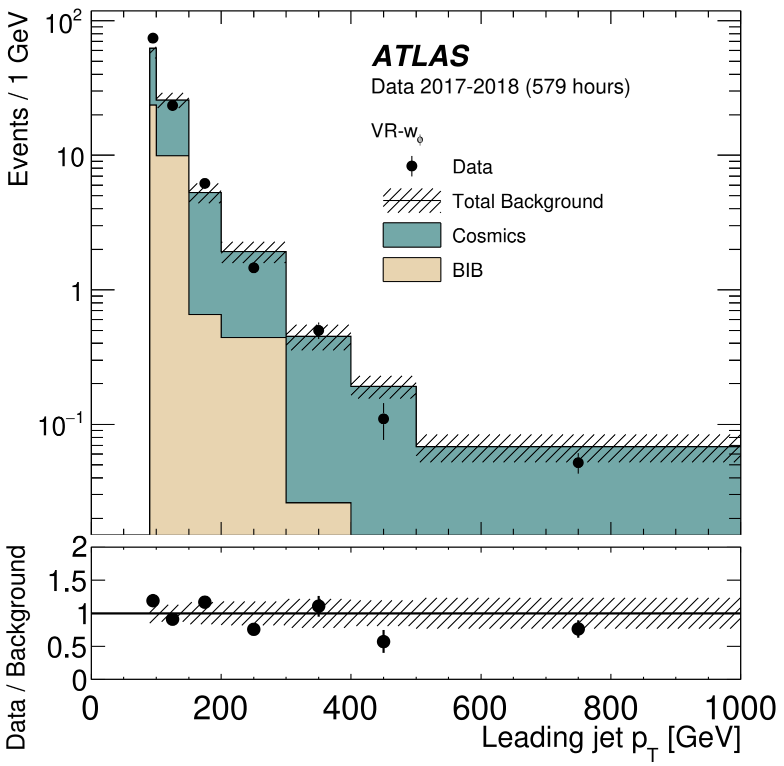
Cryostat

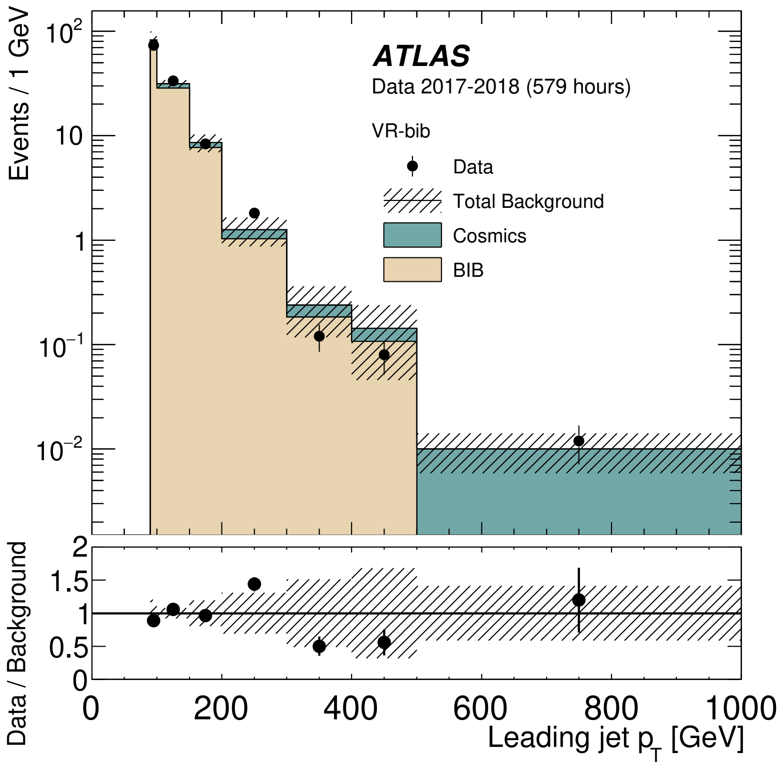
Background validation

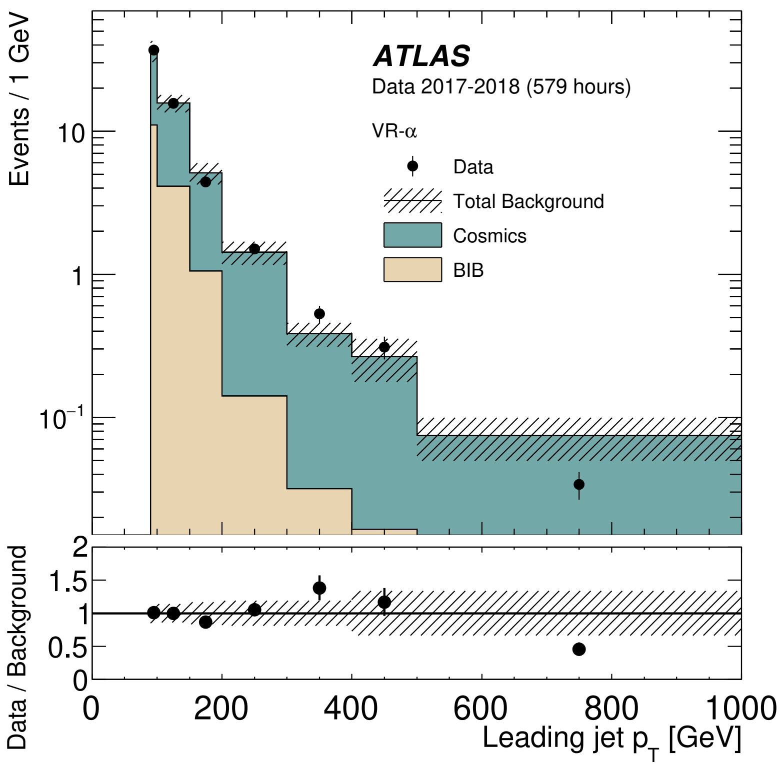




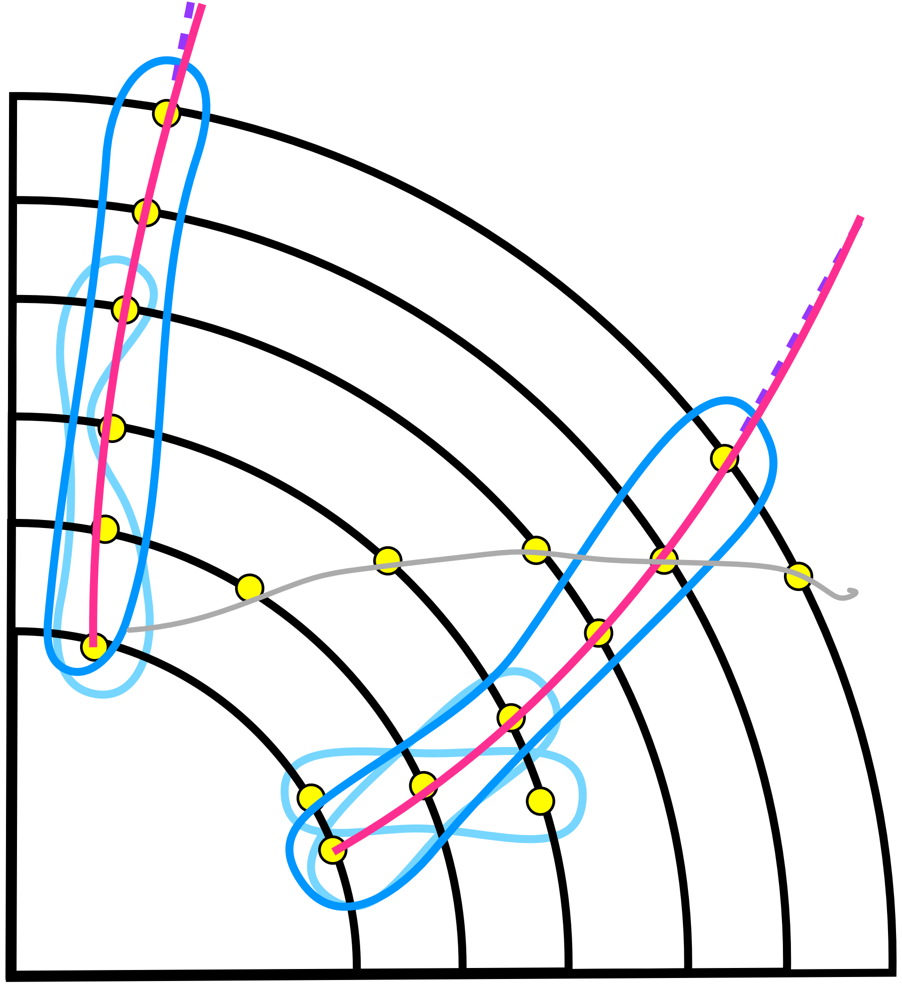








How does track reconstruction work? ATLAS



Pierfrancesco Butti

Next: outside-in starts from TRT seeds and extrapolates backwards. Both restrict candidates to near PV.

- Inside-out tracking (ATLAS primary)
  - Find **seeds** (pixel detector only) using 3-hit groups.
  - **Extend** seeds to strips detector layers with combinatorial Kalman filter
  - Assess track candidates: χ2, number of holes, number of shared hits, etc. Throw away suboptimal ones
  - **Extend to TRT**
  - **Refit with all points** to get best track parameters

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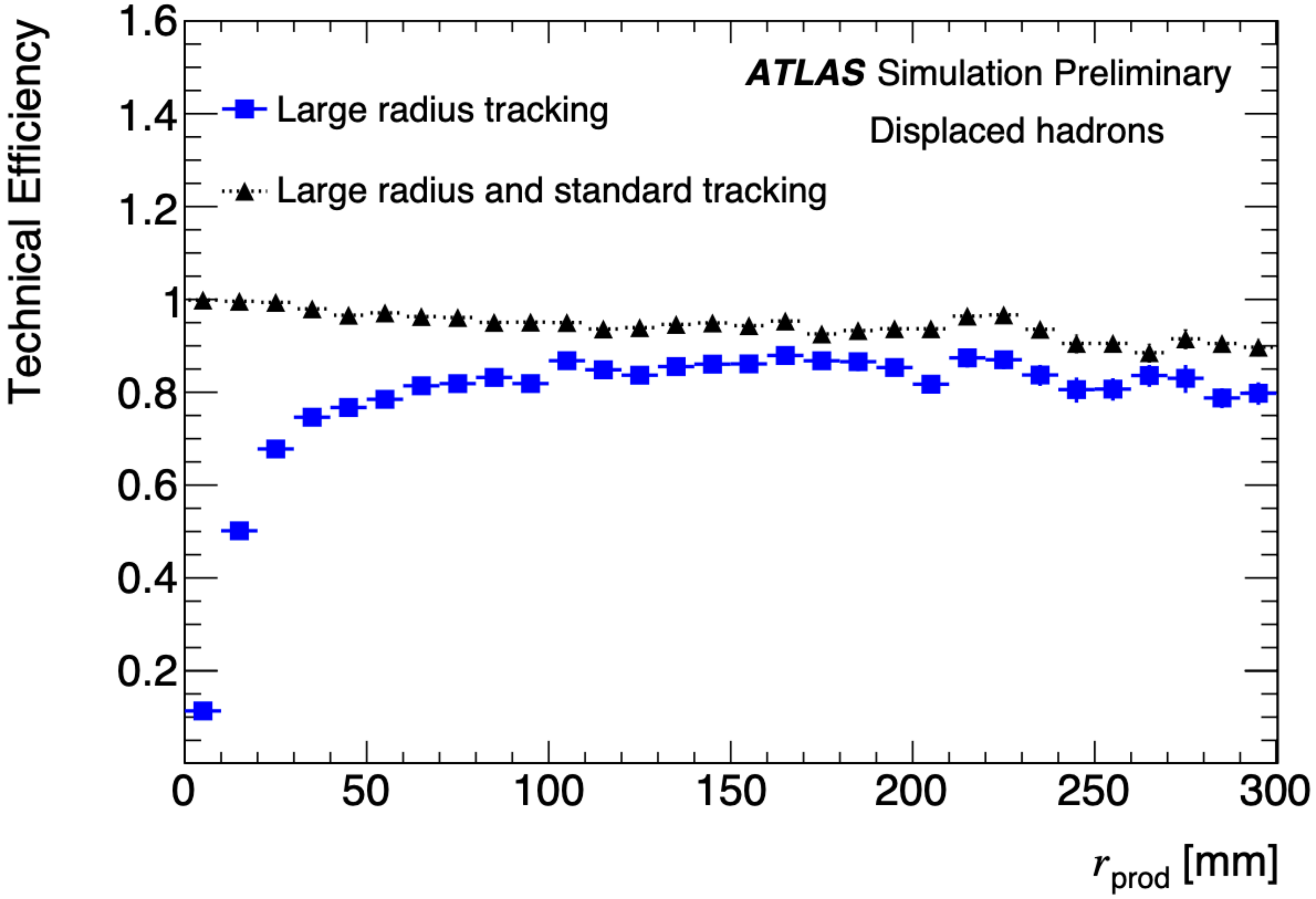
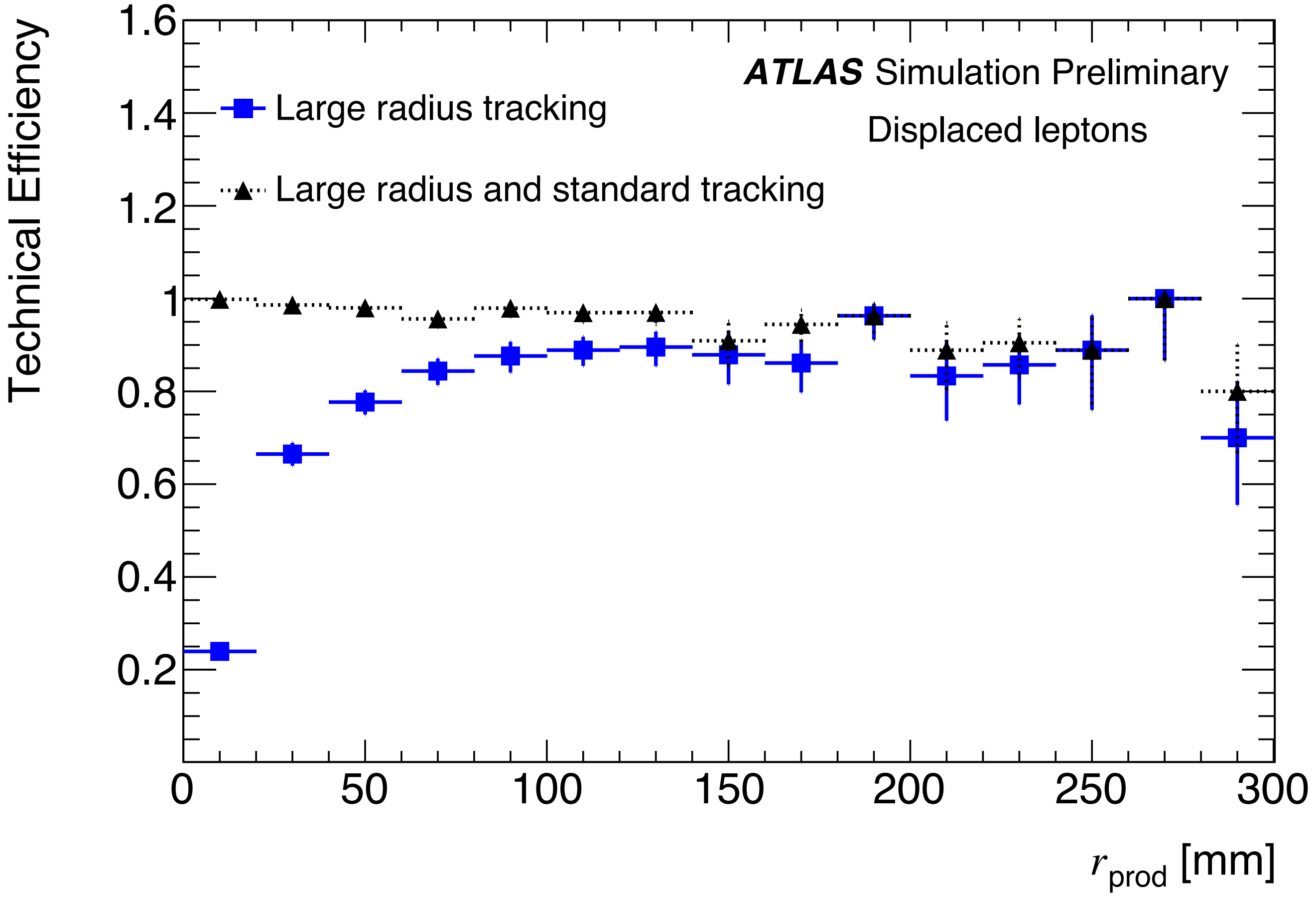
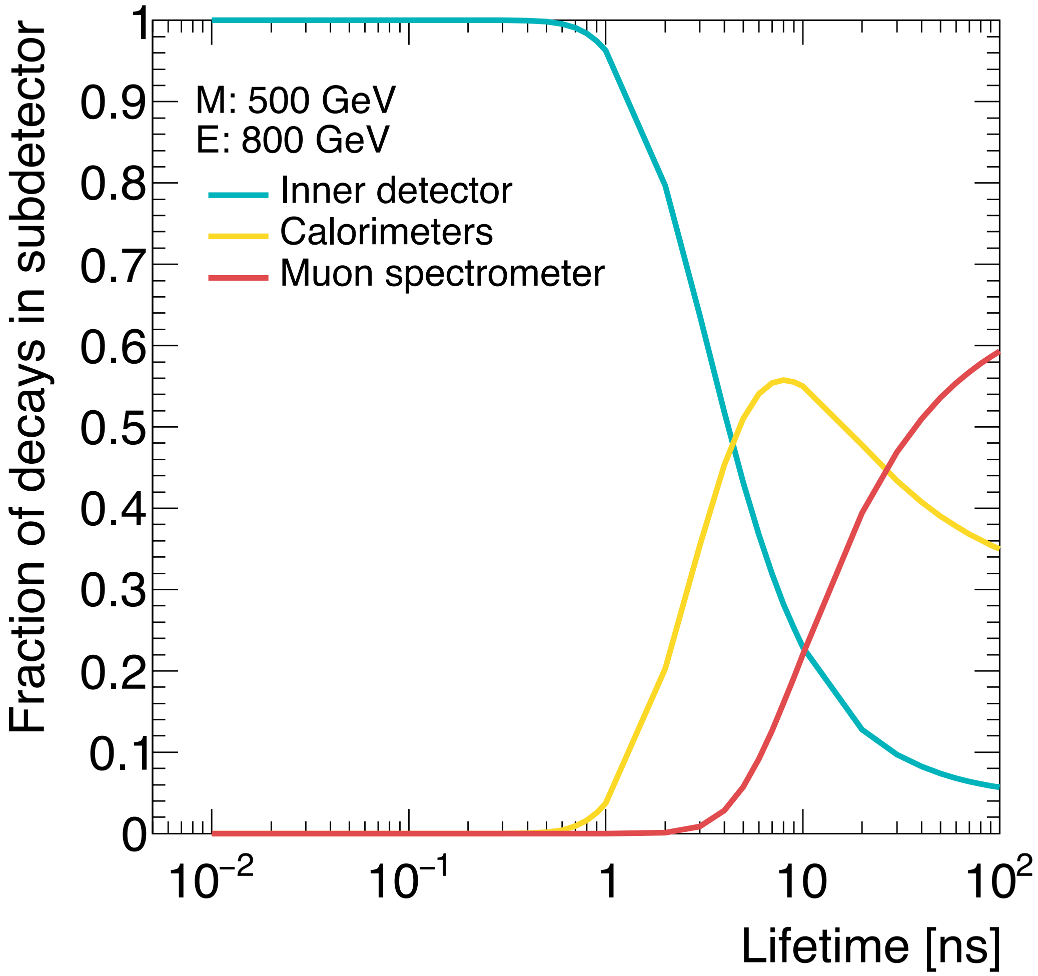
Large-radius tracking performance details

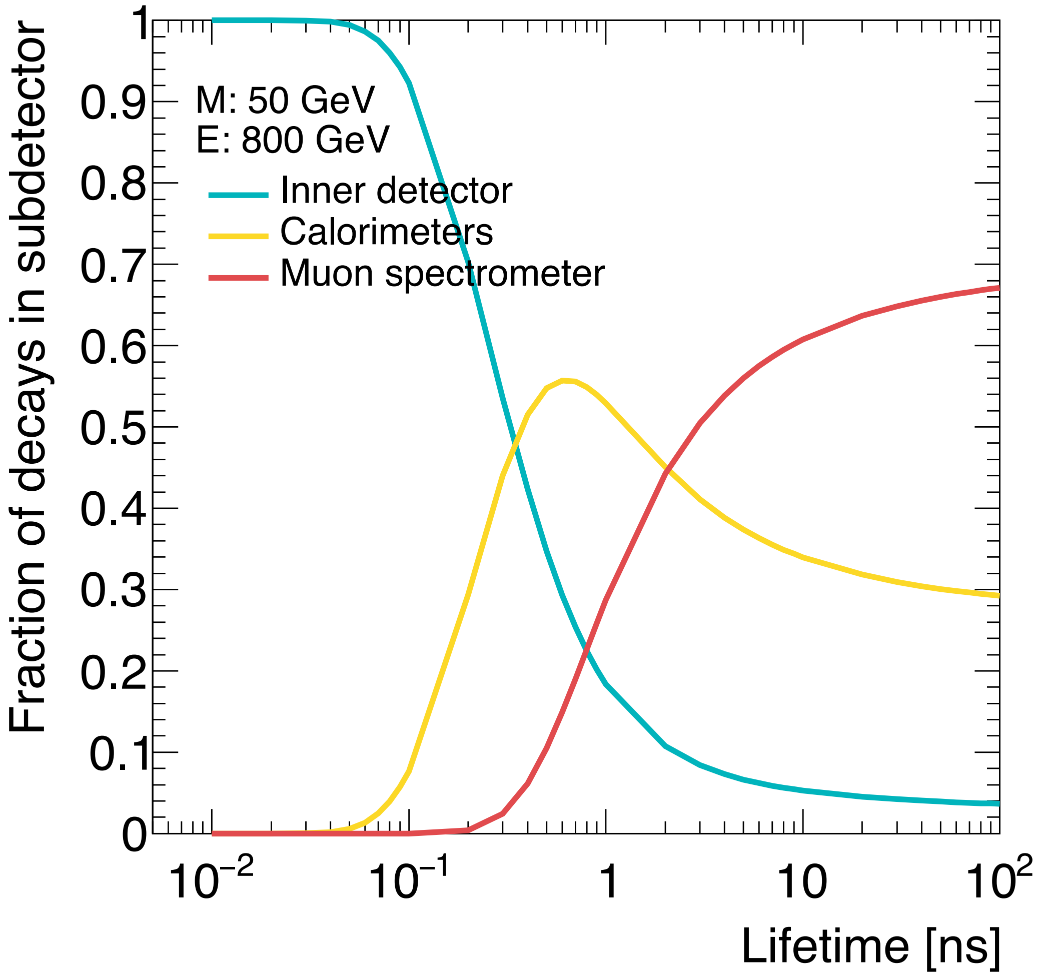




Technical efficiency: efficiency of reconstructing truth particles that leave sufficient hits in the ID that they are expected to be reconstructable

Different detector systems for different targets





- Lighter particles have higher βγ and so travel farther for the same lifetime
- Muon spectrometer becomes useful for many Higgs-portal-style signatures
- For target masses > order 100 GeV and shorter lifetimes, **inner detector is critical**