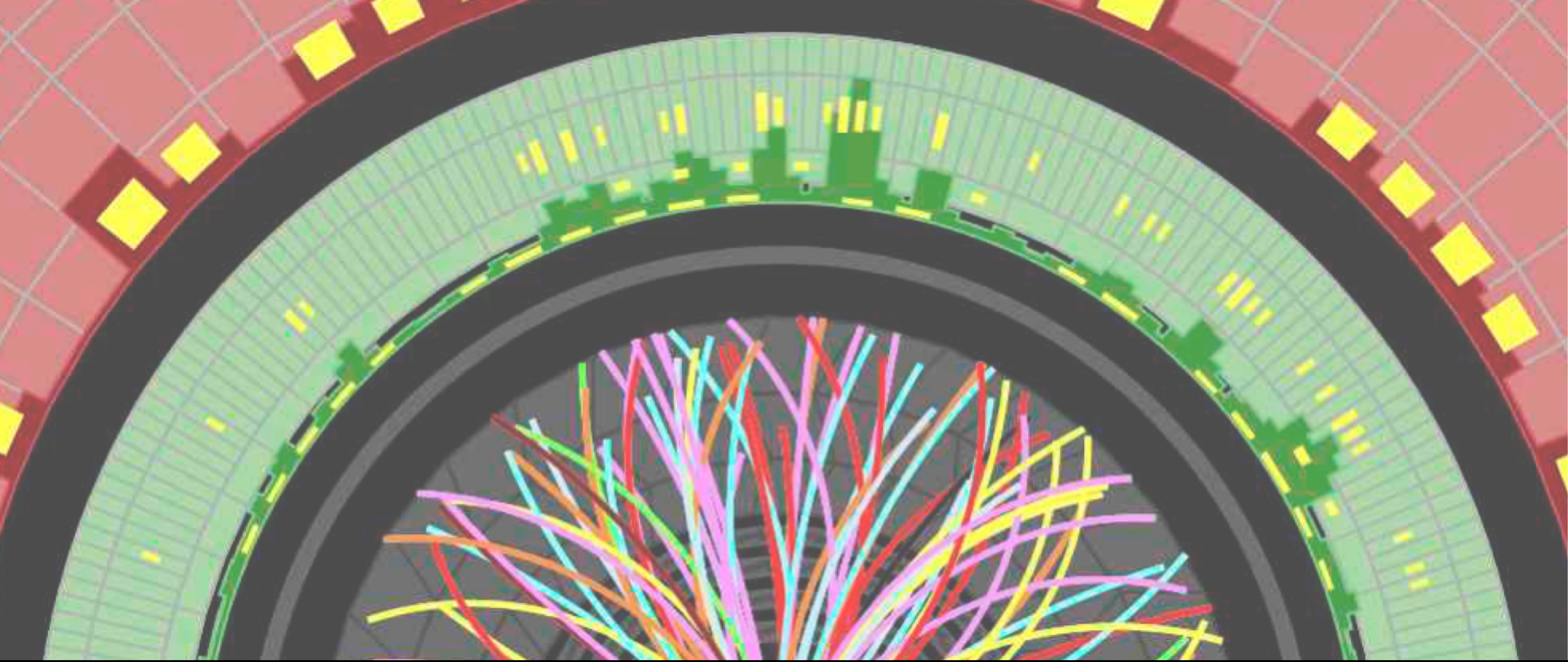


The quest for long-lived particles: searching for displaced vertices and tracking in the trigger

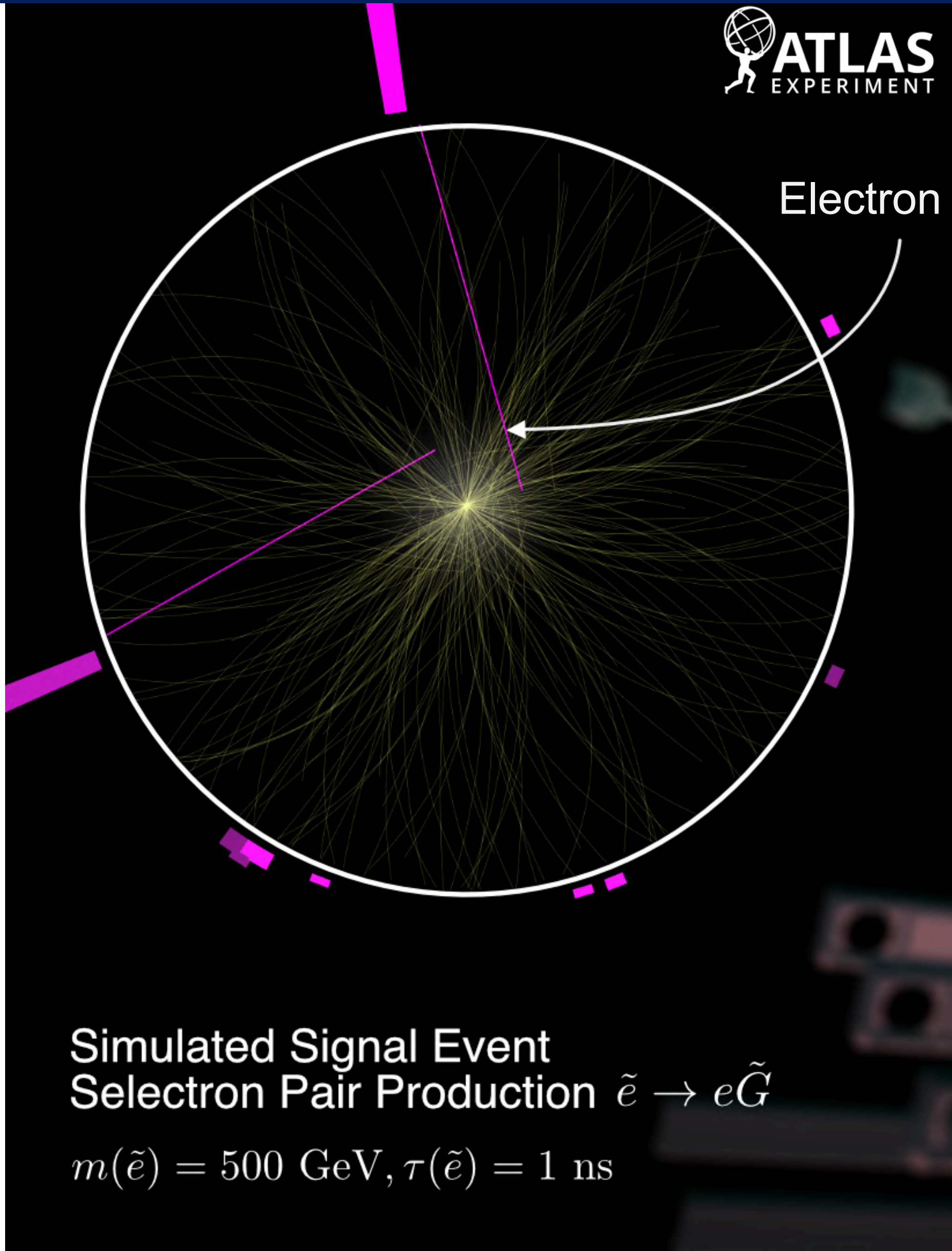
SLAC seminar | Emily A. Thompson | Jan. 11, 2022

Outline

1. Long-lived particles
    - Why are they interesting?
    - How do we search for them?

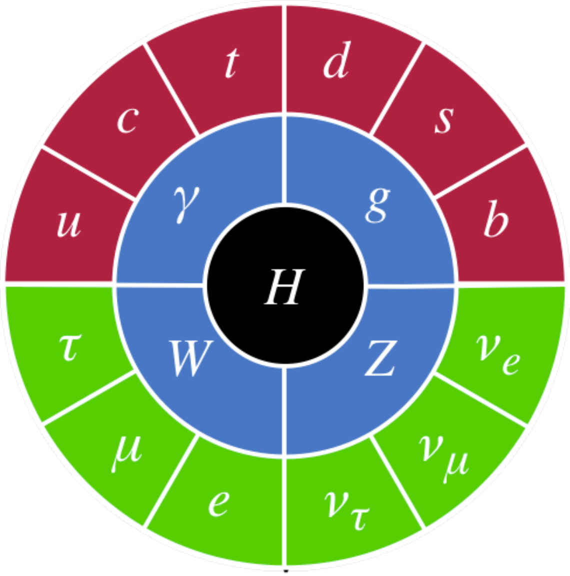
2. Searches for displaced vertices with the ATLAS detector
    - DV + muon (Phys. Rev. D 102, 032006 (2020))
    - DV + jets (work in progress)

3. The ATLAS FastTracKer system
    - Key concepts for speedy & efficient track-finding
    - Applications to long-lived particle searches



The Standard Model is an impressive theory which has been put under intense scrutiny at the Large Hadron Collider (LHC)

quarks
leptons
gauge bosons
higgs boson



David Kaplan, Kyle Cranmer

Proton-proton collisions at $\sqrt{s}$ = 13 TeV

The Standard Model

The Standard Model is an impressive theory which has been put under intense scrutiny at the Large Hadron Collider (LHC)

quarks
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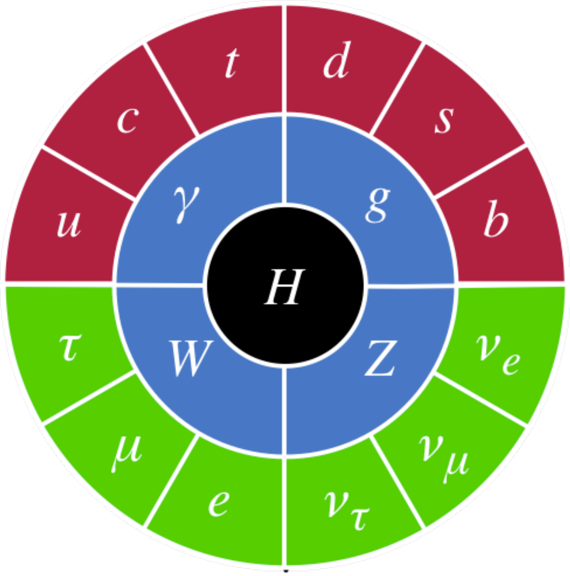
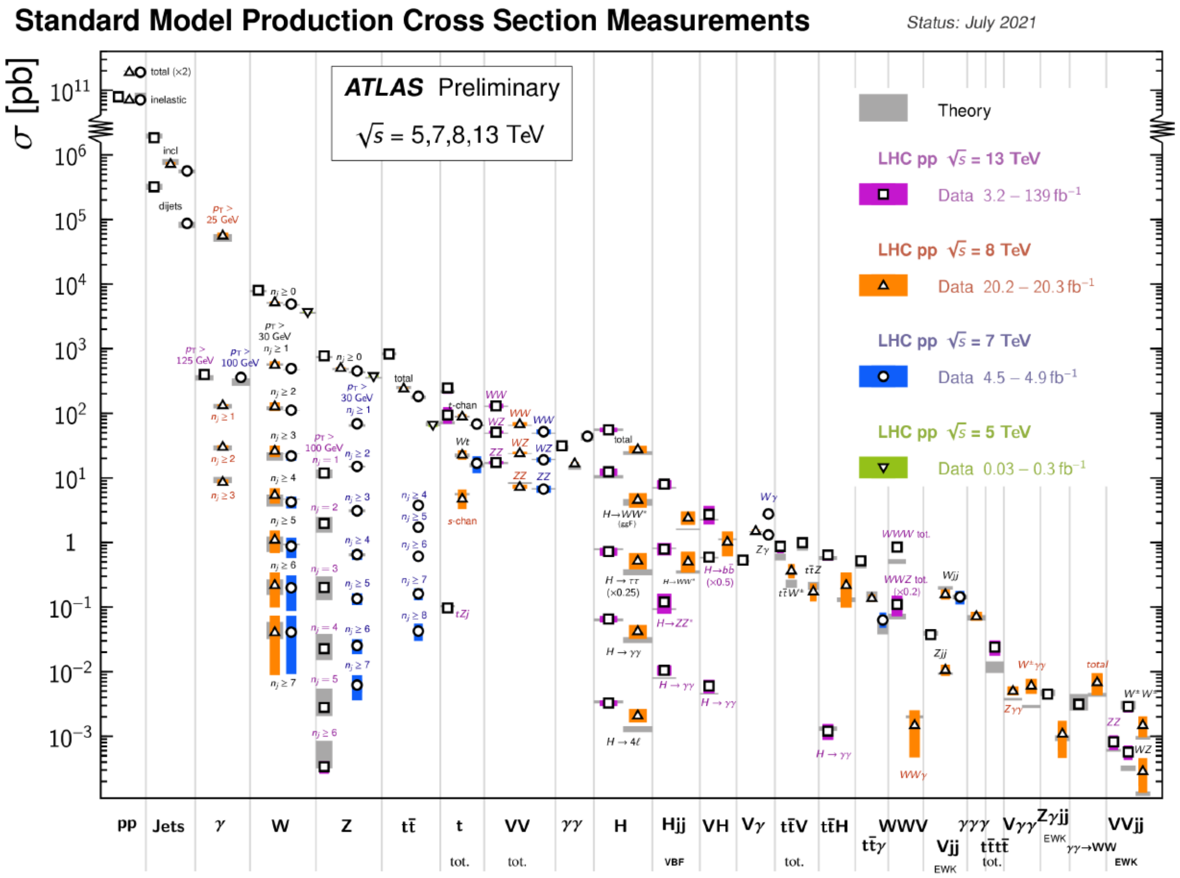


David Kaplan, Kyle Cranmer

It works!

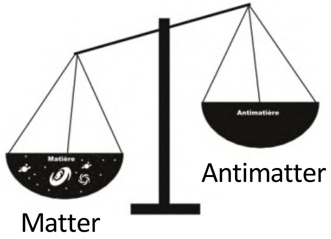


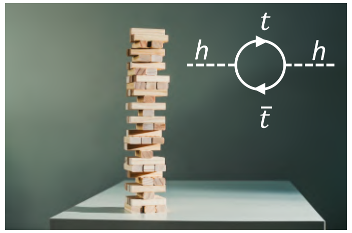
ATL-PHYS-PUB-2021-032

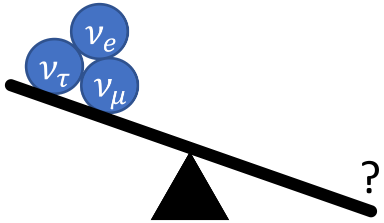
The Standard Model has so far been able to describe ATLAS data remarkably well. Are we done? No!

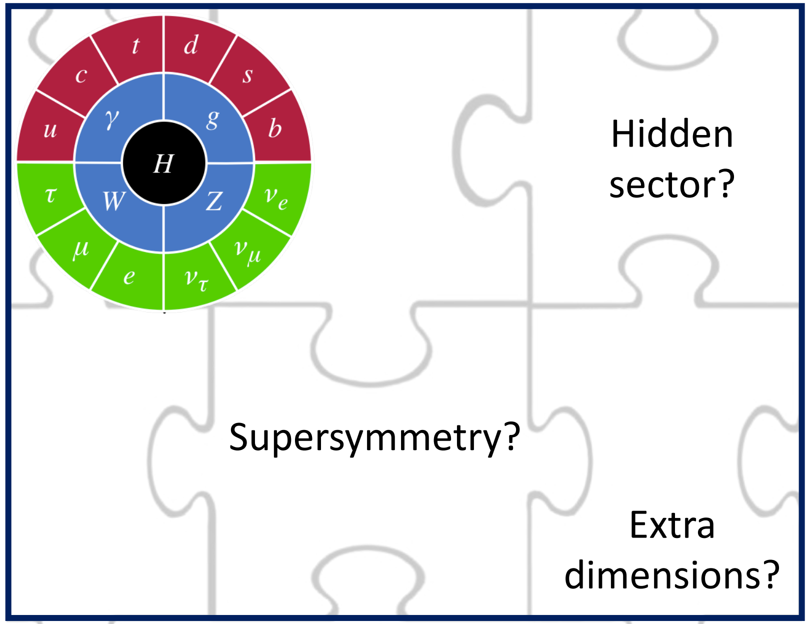
Beyond the Standard Model

We **know** there must be physics beyond the Standard Model.









But so far, there have been **no obvious signs of new physics** at the LHC

→ is new physics is 'hiding' in the data?   i.e. with a long lifetime?

What makes a particle long-lived, and why search for them?

- Long-lived particles (LLPs) arise if: $d\Gamma \sim \frac{1}{M}|\mathcal{M}|^2 d\Pi$

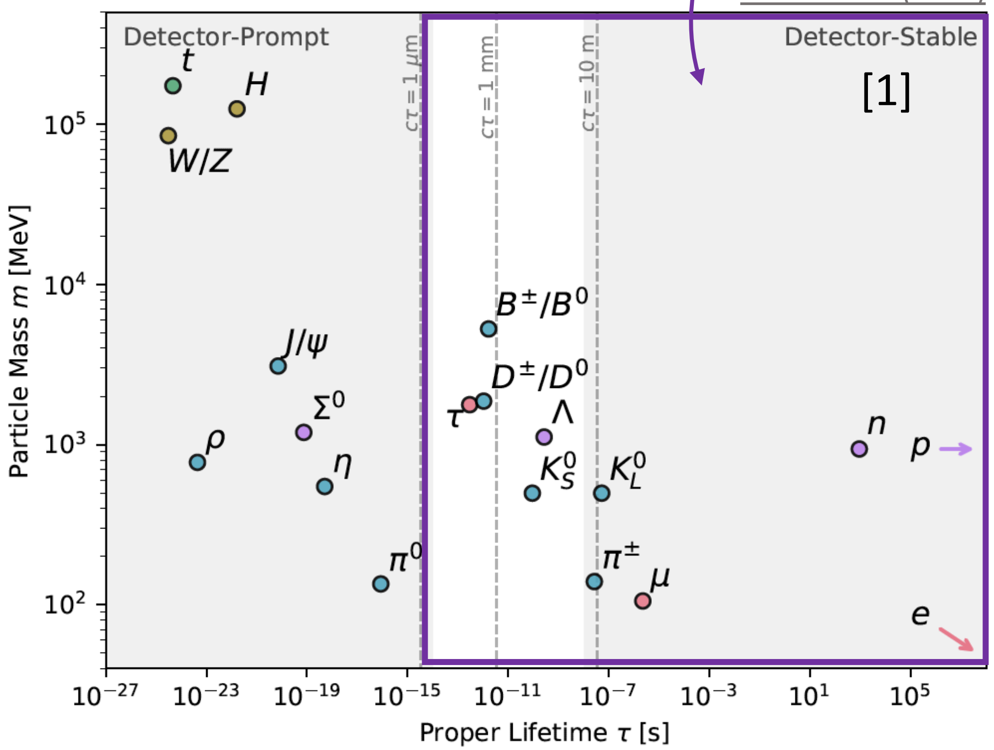
Small matrix element

~ or ~

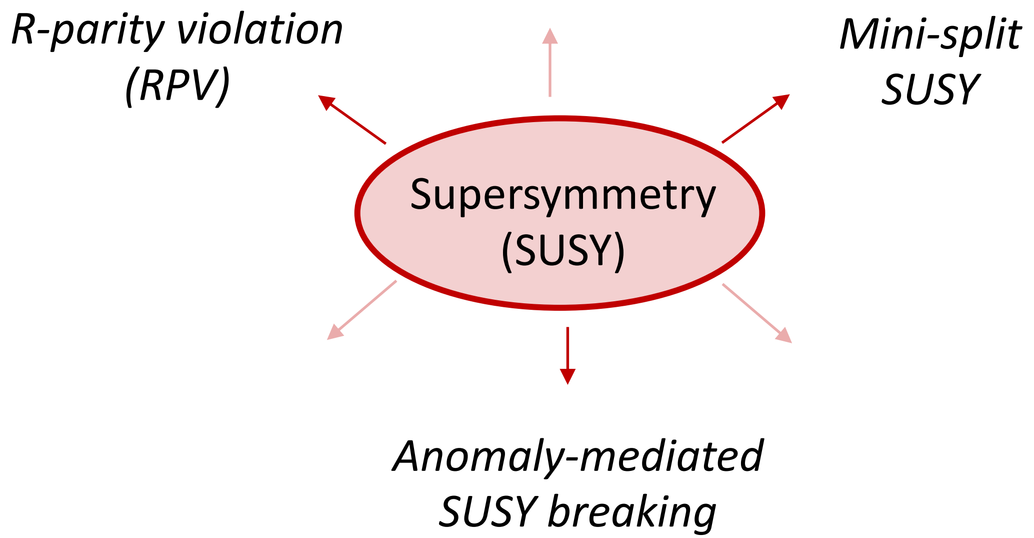
Small phase space

- LLPs are **abundant in the Standard Model** and **arise naturally** in many BSM theories too

JPPNP 3695 (2019)



Any model with a small coupling, small mass splitting, or decays via off-shell particles.



Signatures of long-lived particles in the ATLAS detector

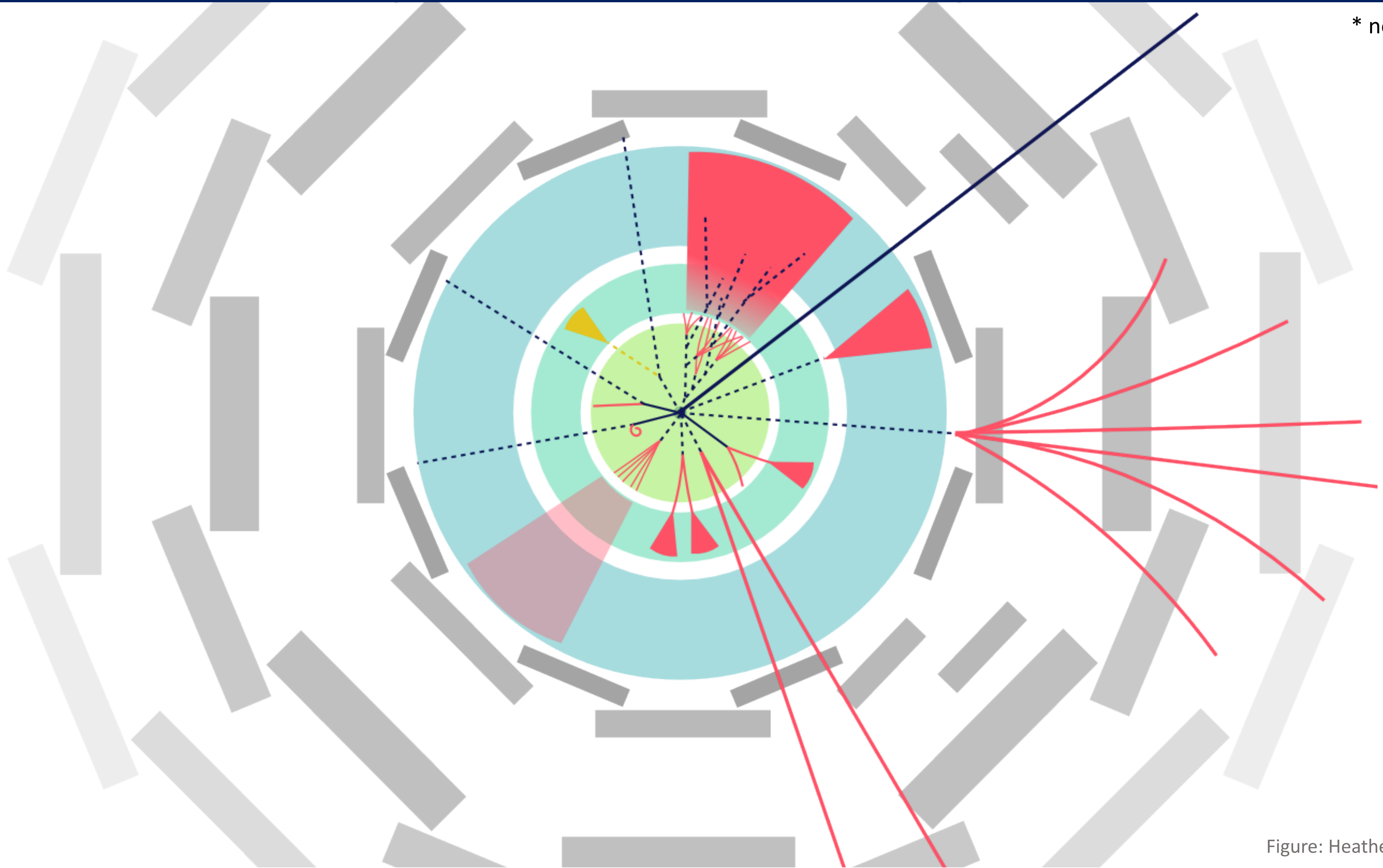
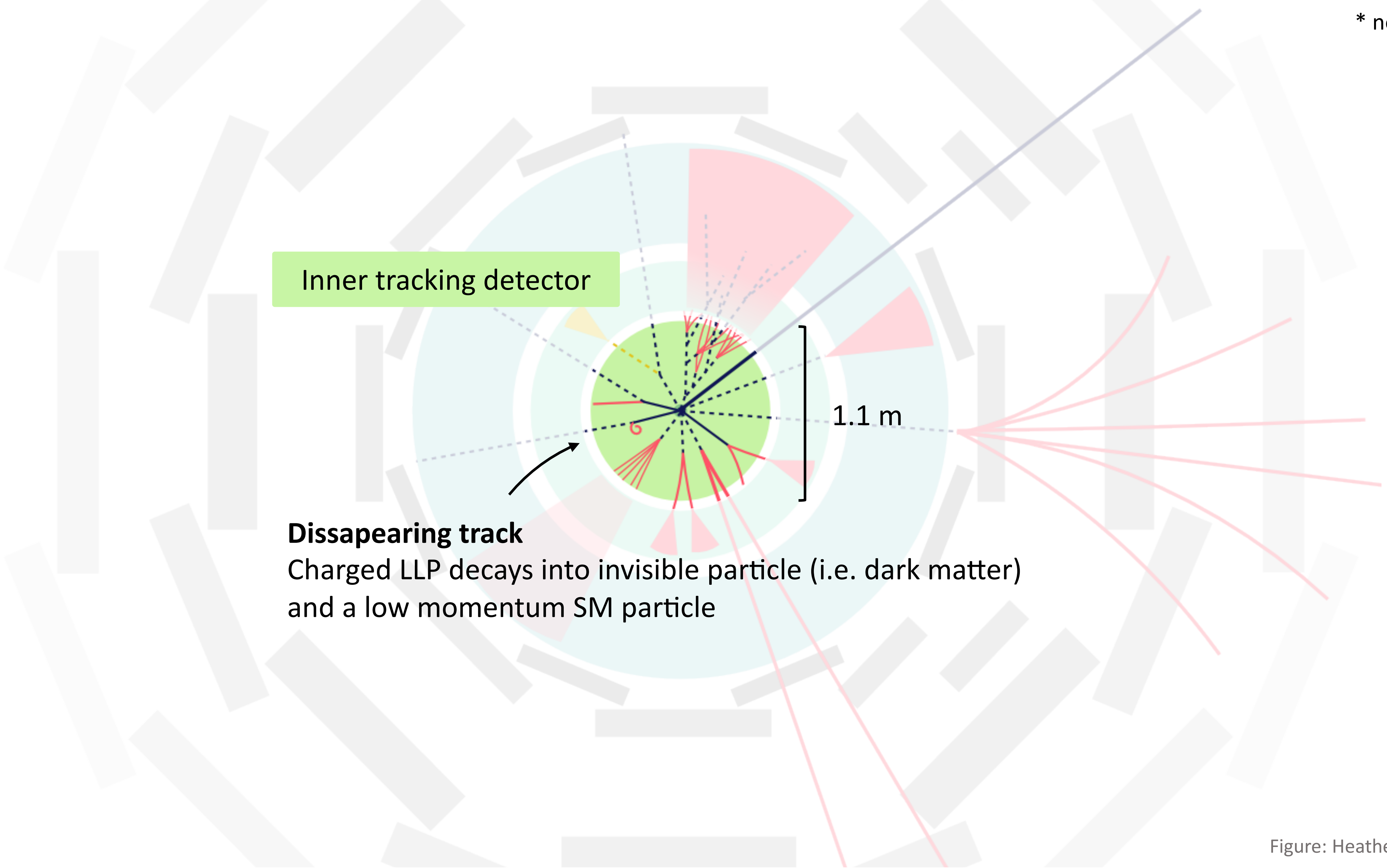


Figure: Heather Russell

Signatures of long-lived particles in the ATLAS detector

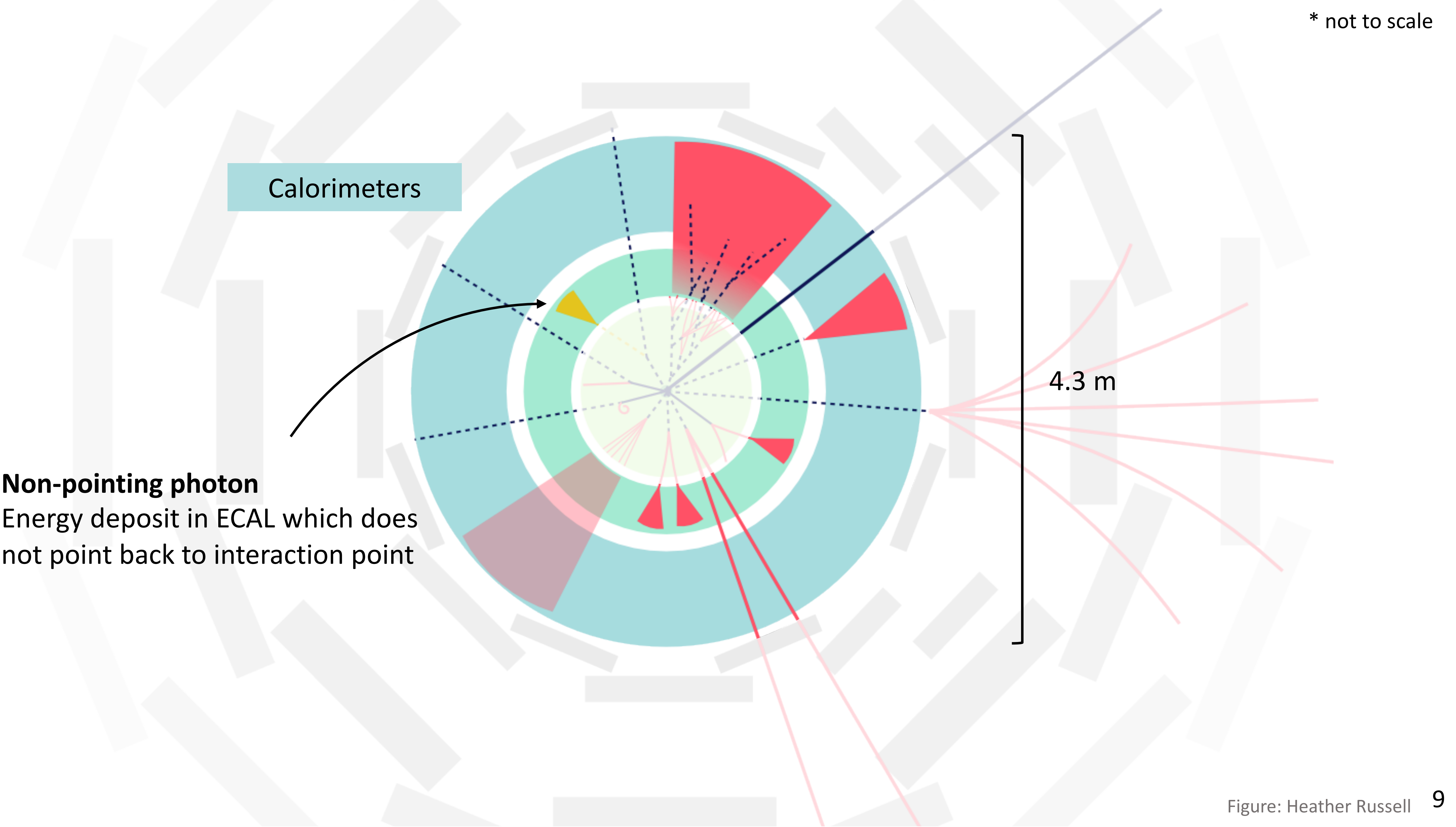
* not to scale



Dissapearing track
Charged LLP decays into invisible particle (i.e. dark matter) and a low momentum SM particle

Figure: Heather Russell

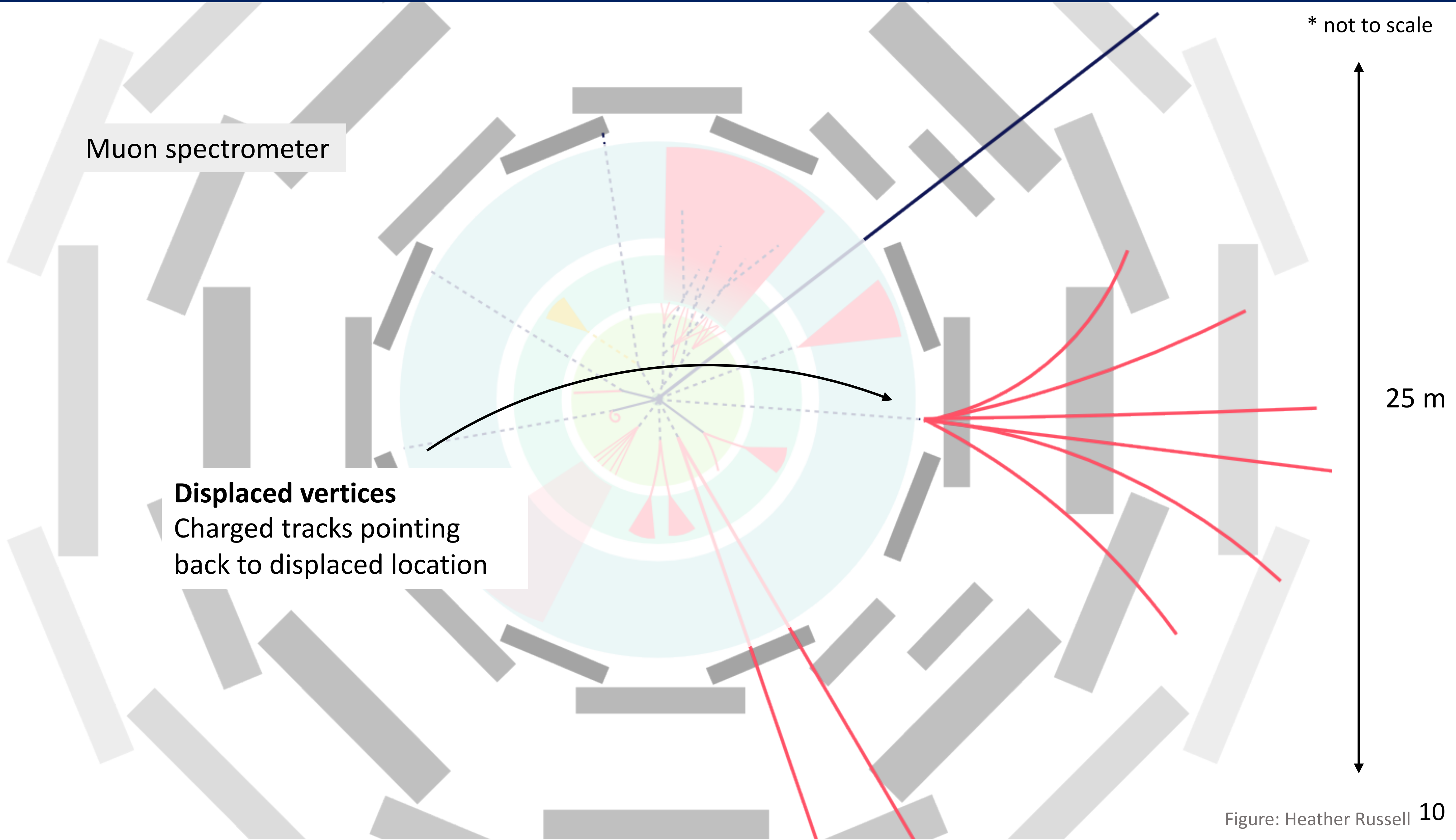
Signatures of long-lived particles in the ATLAS detector



Non-pointing photon
Energy deposit in ECAL which does not point back to interaction point

Figure: Heather Russell

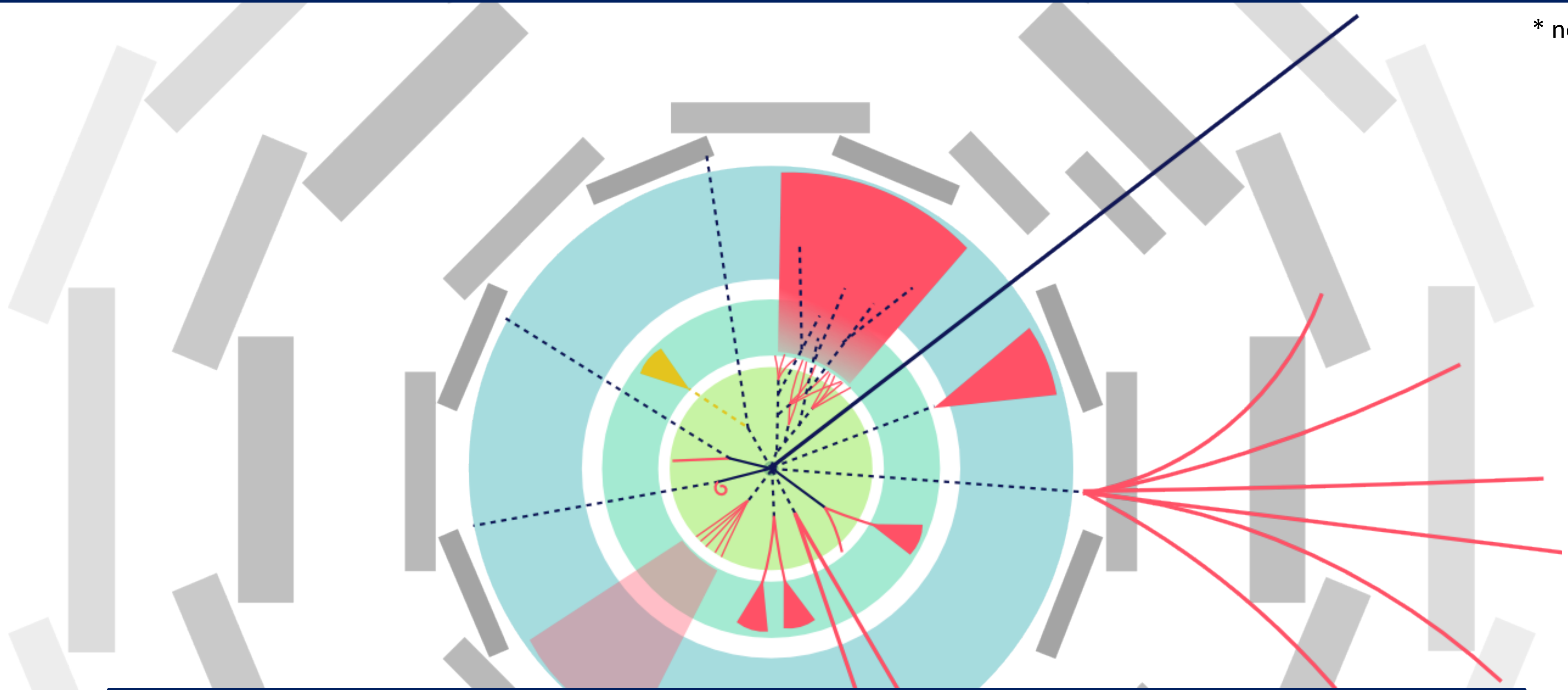
Signatures of long-lived particles in the ATLAS detector



Displaced vertices
Charged tracks pointing back to displaced location

Figure: Heather Russell

Signatures of long-lived particles in the ATLAS detector



LLP signatures are…

1. varied → Depend on the LLP lifetime, mass, charge, and decay products
2. unconventional
   - → Could be missed by traditional new physics searches
   - → Low background from Standard Model processes

Figure: Heather Russell

Ingredients for a long-lived particle (LLP) search

1.

2.

3.

4.

5.

Ingredients for a long-lived particle (LLP) search

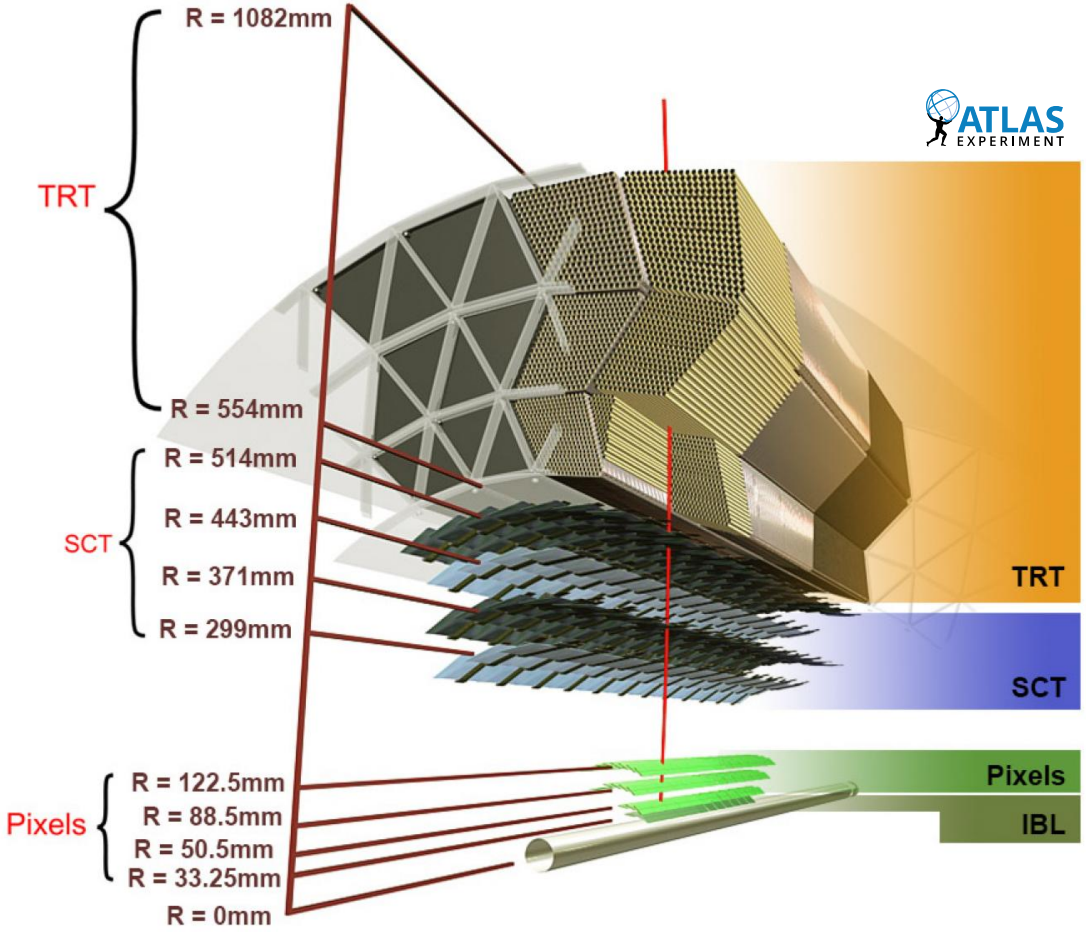
1. **Pick a signature**
    - Displaced vertices in the inner detector

2.

3.

4.

5.



Eur. Phys. J. C 80 (2020) 1194

Ingredients for a long-lived particle (LLP) search

1. **Pick a signature**
   - Displaced vertices in the inner detector
2. **Pick a trigger**
   - Require "triggerable" object in the event

3.

4.

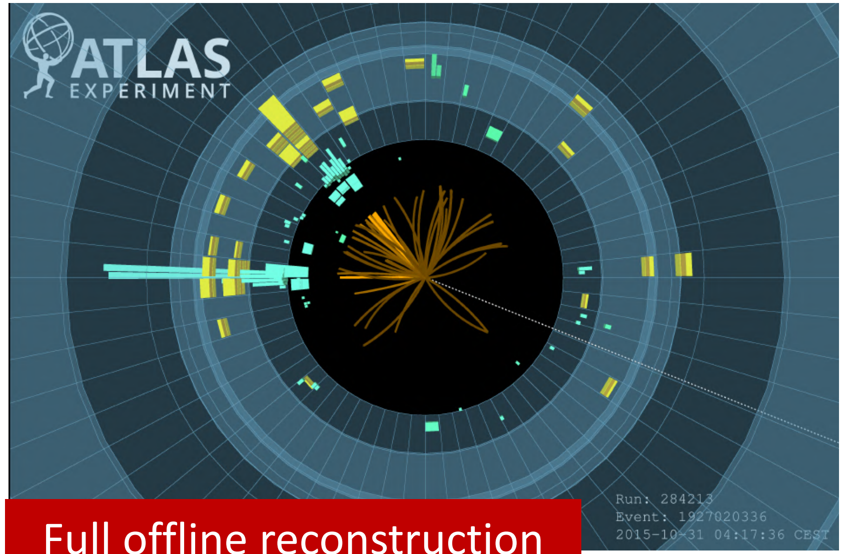
5.

The ATLAS Trigger System

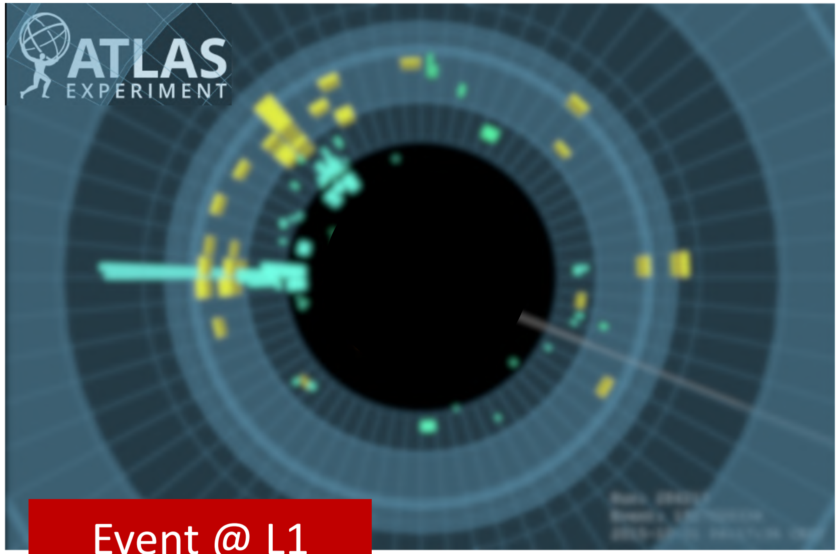
- The **trigger system** aims to reduce the event rate from 40 MHz to 1 kHz, **selecting the most interesting events**

- ATLAS has a two-level trigger system:
  1. Level-1 (L1): hardware based → calo energy deposits, muon segments, but **no tracks**
  2. High Level Trigger (HLT): software based → **tracking limited** to regions of interest

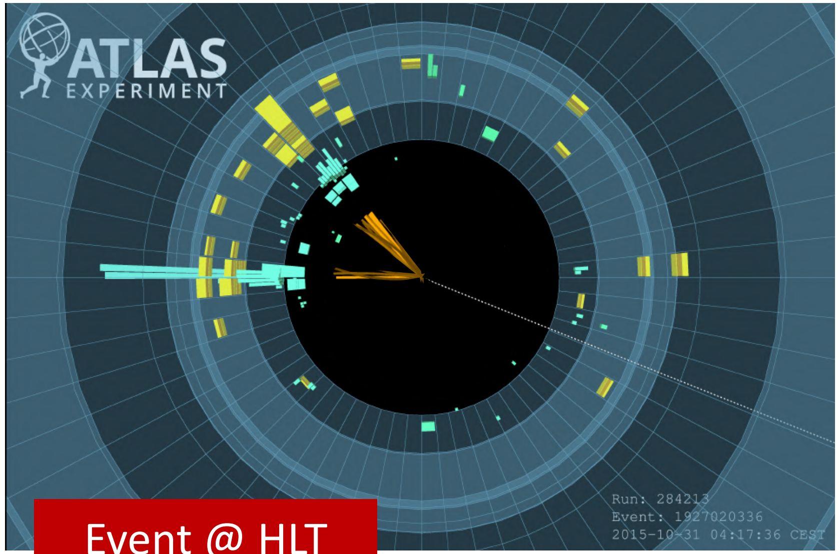
- Searches for displaced vertices must require "triggerable objects" in the event (i.e. jets, leptons, ...)



Full offline reconstruction



Event @ L1



Event @ HLT

Ingredients for a long-lived particle (LLP) search

1. **Pick a signature**
   - Displaced vertices in the inner detector
2. **Pick a trigger**
   - Require "triggerable" object in the event
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4.
5.

Ingredients for a long-lived particle (LLP) search

1. **Pick a signature**
   - Displaced vertices in the inner detector
2. **Pick a trigger**
   - Require "triggerable" object in the event
3. **Utilize special object reconstruction**
   - Displaced track and vertex finding
4.
5.

Reconstructing displaced tracks

Charged particle tracks from LLP decays do not necessarily point back to interaction point.

Standard tracking (ST):

- Tight selection on impact parameters of tracks

Large radius tracking (LRT)

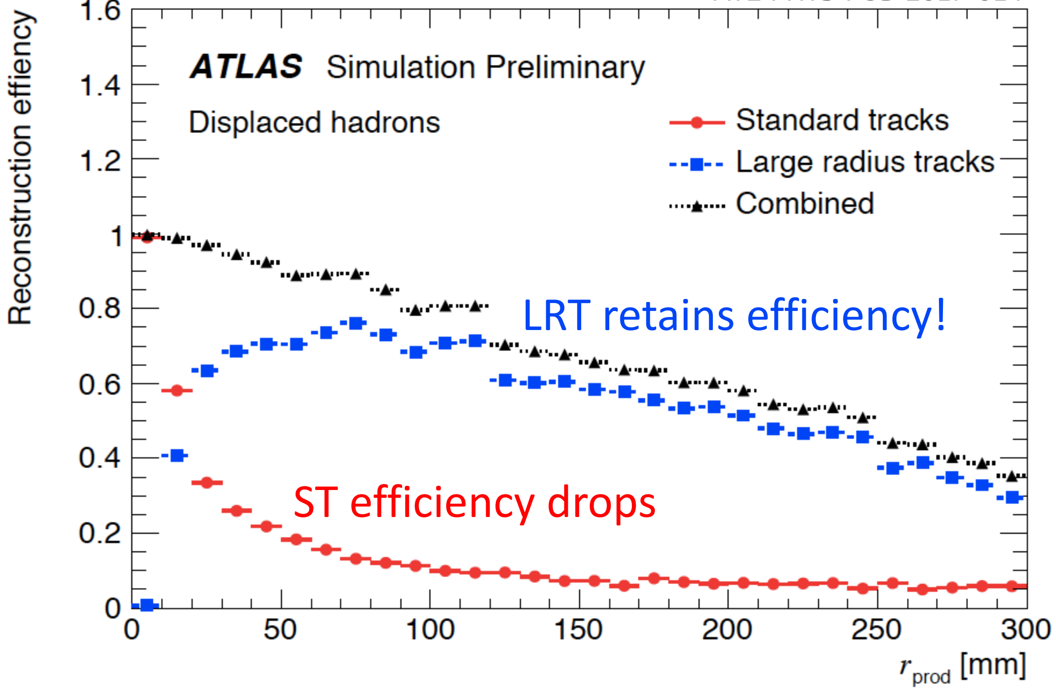
- Uses unused hits after standard tracking
- Loosens selection on impact parameters
- Only subset of data

Distance of closest approach to interaction point

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential

Coming soon: new & improved LRT, run on all data!

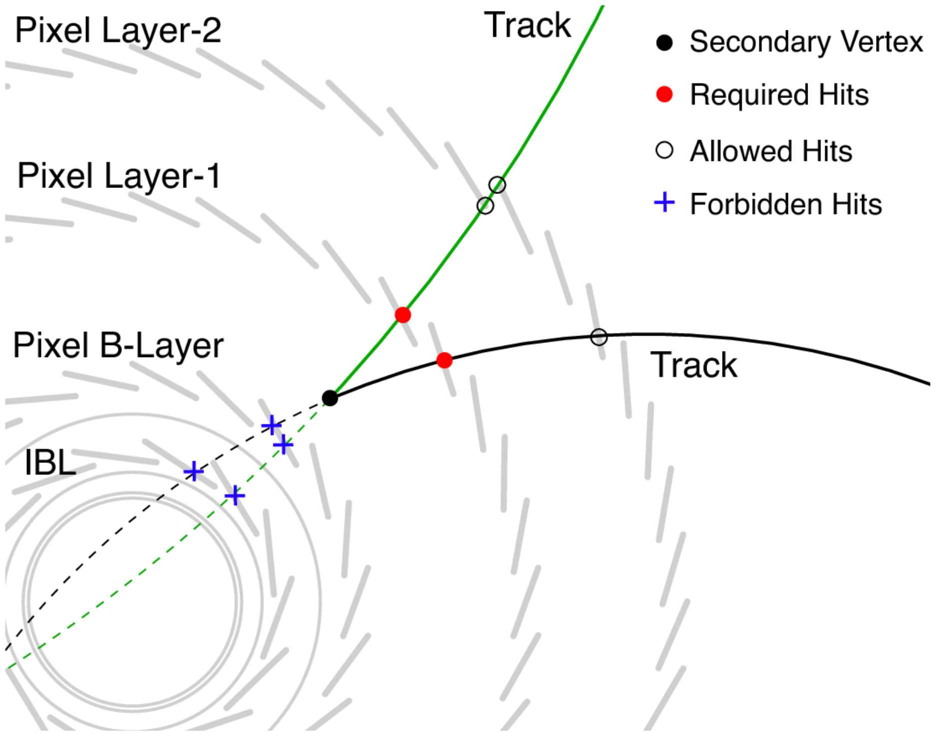
ATL-PHYS-PUB-2017-014



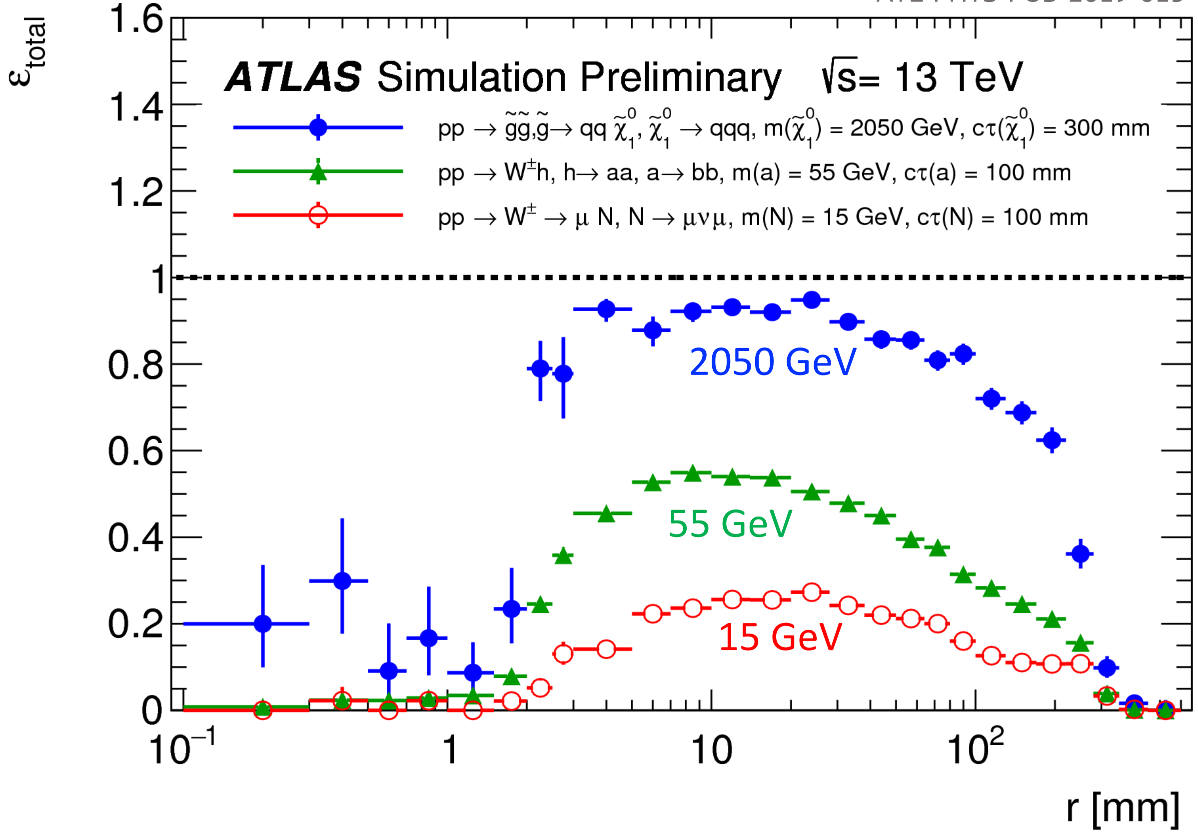
Reconstructing displaced vertices

Find **displaced vertices** from standard and large radius tracks:

1. Form 2-track seed vertices from high-quality tracks; hit-pattern requirements
2. Merge vertices together to form N-track vertices
3. Attach lower quality tracks to vertex



ATL-PHYS-PUB-2019-013



Ingredients for a long-lived particle (LLP) search

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   - Displaced track and vertex finding
4. **Derive background estimate from data**
   - Backgrounds are often difficult to model
5.

Ingredients for a long-lived particle (LLP) search

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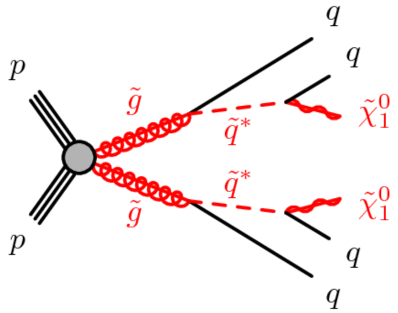
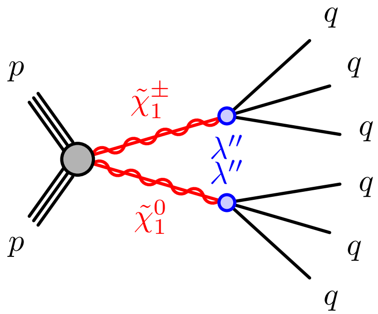
   - Displaced vertices in the inner detector
2. **Pick a trigger**
   - Require “triggerable” object in the event
3. **Utilize special object reconstruction**
   - Displaced track and vertex finding
4. **Derive background estimate from data**
   - Backgrounds are often difficult to model
5. **Choose level of model-independence** – a matter of taste!

Benchmark model



Reinterpret: what do results say about another model?



Search for events with displaced vertex and displaced muon

Using full Run-2 dataset: Phys. Rev. D 102, 032006 (2020)

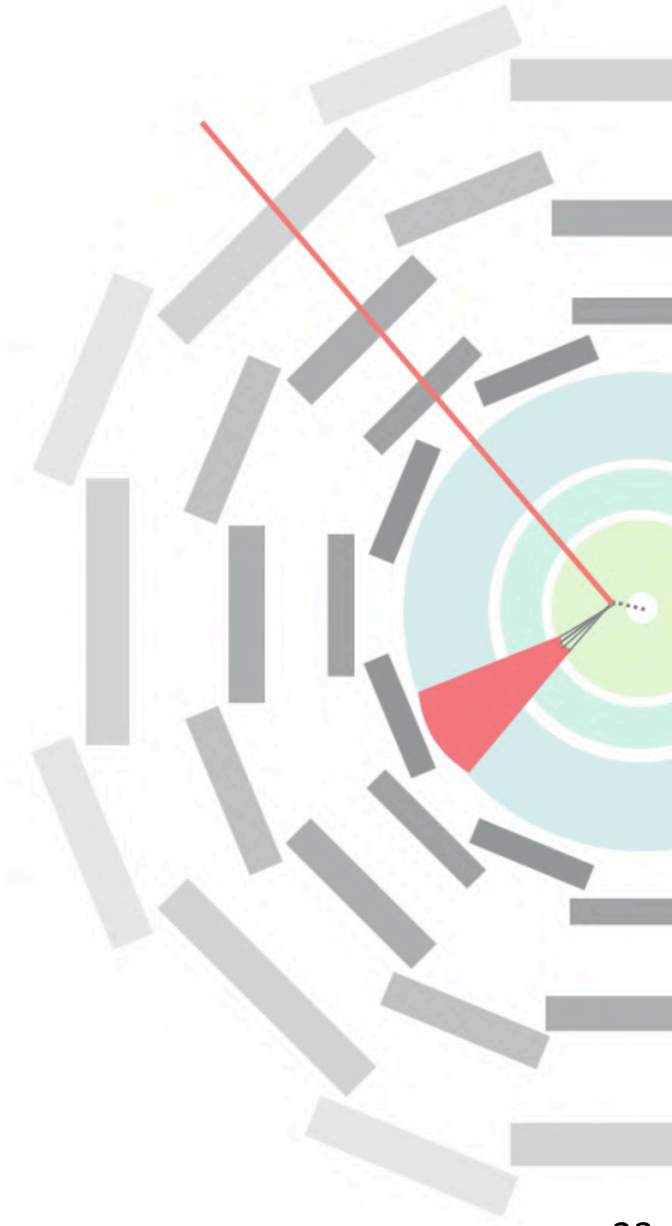
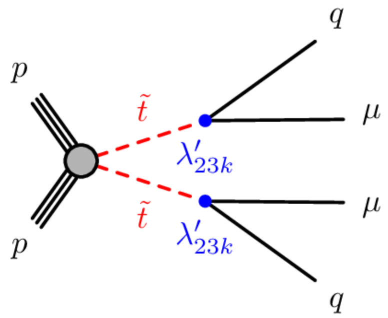


Figure: Karri Dipetrillo

Phys. Rev. D 102, 032006 (2020)

Benchmark model

- Stop pair production; small R-parity violating coupling



Strategy

- Trigger on **muons** or $\mathbf{E_T^{miss}}$

muon spectrometer info only — *calorimeter-based in trigger (muons invisible)*

- Require two displaced objects in the event:

Selection level	Muon selection	Displaced vertex selection
Preselection	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$, $2\text{ mm} < \lvert d_0\rvert < 300$ mm, $\lvert z_0\rvert < 500$ mm	$r_{DV} < 300$ mm, $\lvert z_{DV}\rvert < 300$ mm, $\min(\lvert\vec{r}_{DV} - \vec{r}_{PV}\rvert) > 4$ mm, $\chi^2/N_{DoF} < 5$, Pass material map veto

Muon displacement:

$|d_0| > 2$ mm

Vertex displacement:

R (DV-PV) > 4 mm

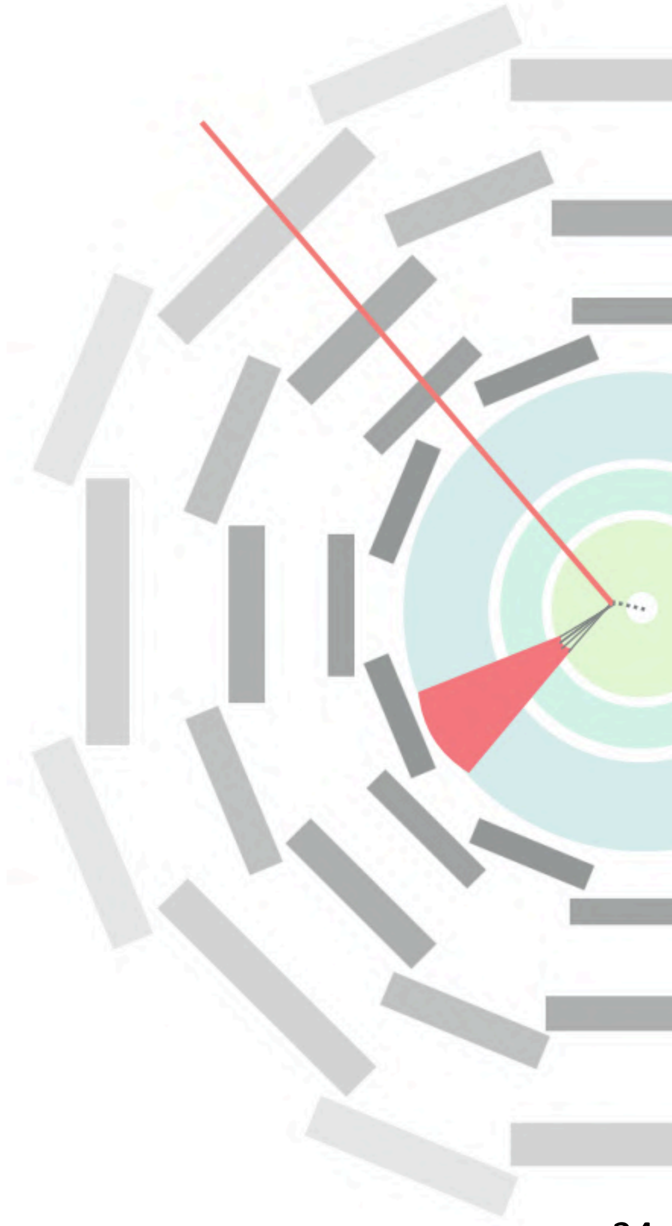


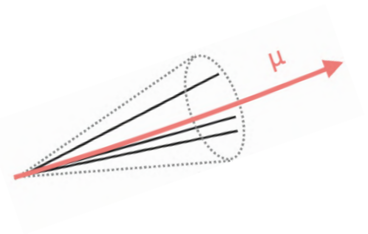
Figure: Karri Dipetrillo

Phys. Rev. D 102, 032006 (2020)

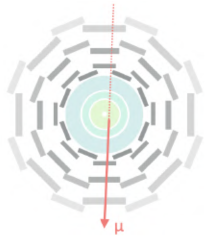
Sources of backgrounds

Sources of background **displaced muons:**

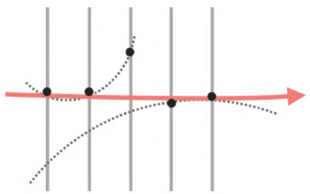
Heavy flavor decays



Cosmics



Algorithm fakes



Sources of background **displaced vertices:**

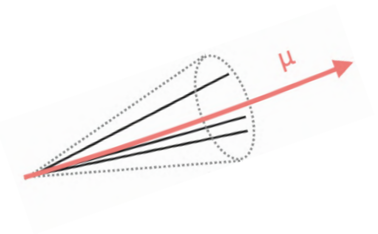
Rejection strategy:

- Heavy-flavor veto → isolation
- Cosmic-muon veto → geometry considerations
- Fake-muon veto → quality

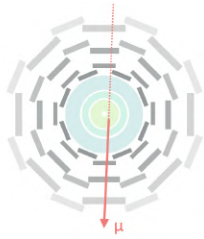
Sources of backgrounds

Sources of background **displaced muons:**

Heavy flavor decays



Cosmics



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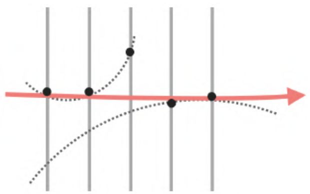
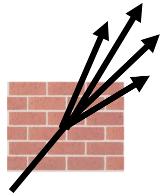
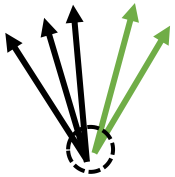


Sources of background **displaced vertices:**

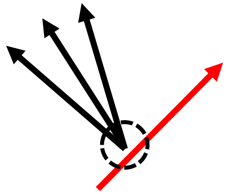
Hadronic interactions



Merged vertices



Accidental crossings

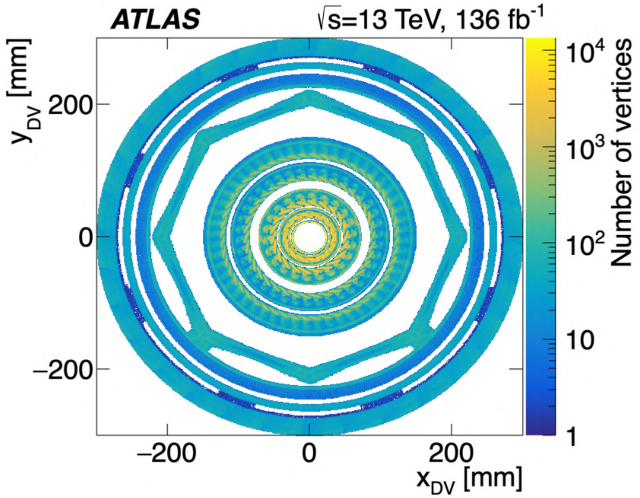


Rejection strategy:

- Heavy-flavor veto → isolation
- Cosmic-muon veto → geometry considerations
- Fake-muon veto → quality

Rejection strategy:

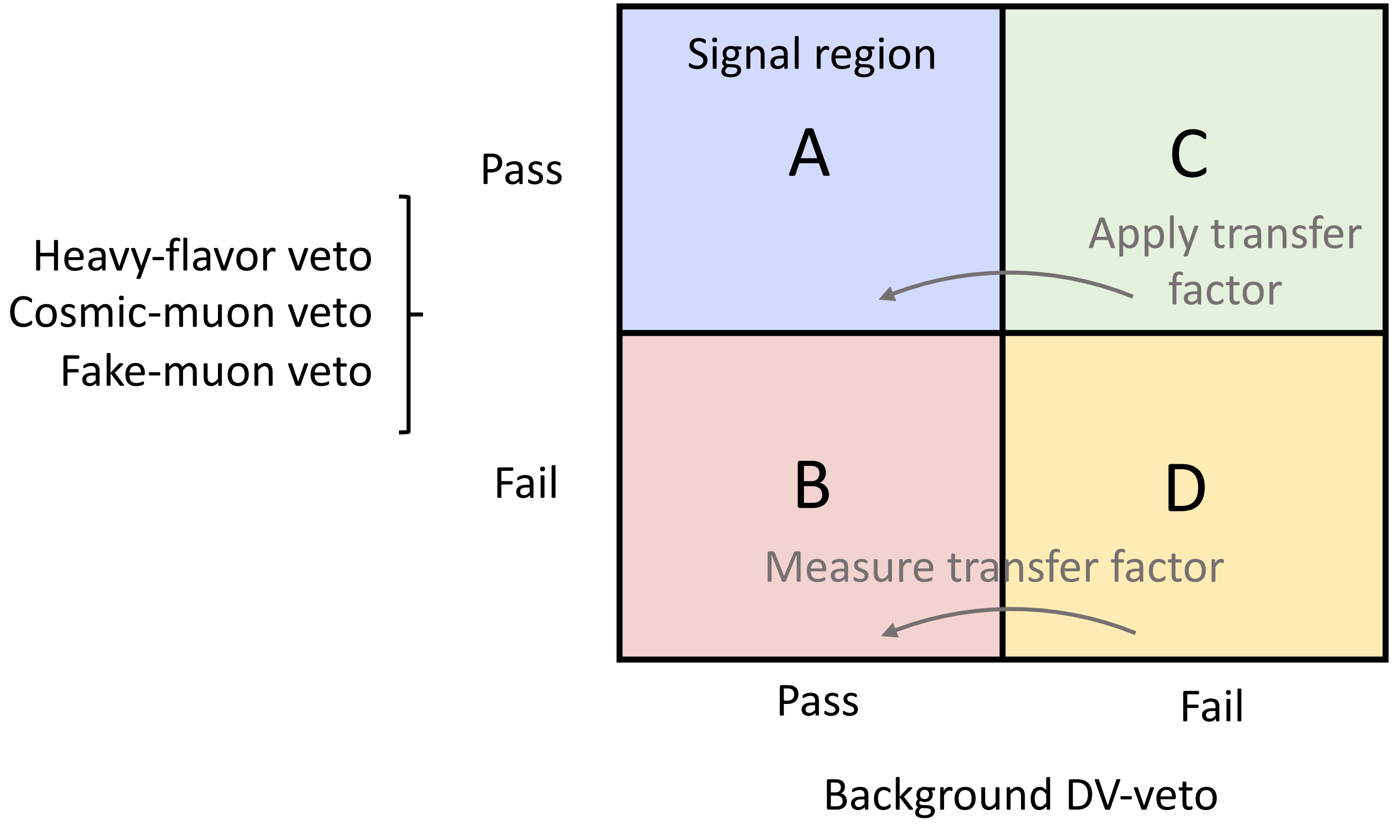
- Require $N_{trk} \geq 3$
- Require m > 20 GeV
- Veto DVs inside material



Data-driven background estimation

Sources of displaced muon background estimated **separately;** displaced vertex background estimated **inclusively**

- Variables used to reject background displaced muons are **uncorrelated** from variables used to reject background DVs
  → use ABCD method:



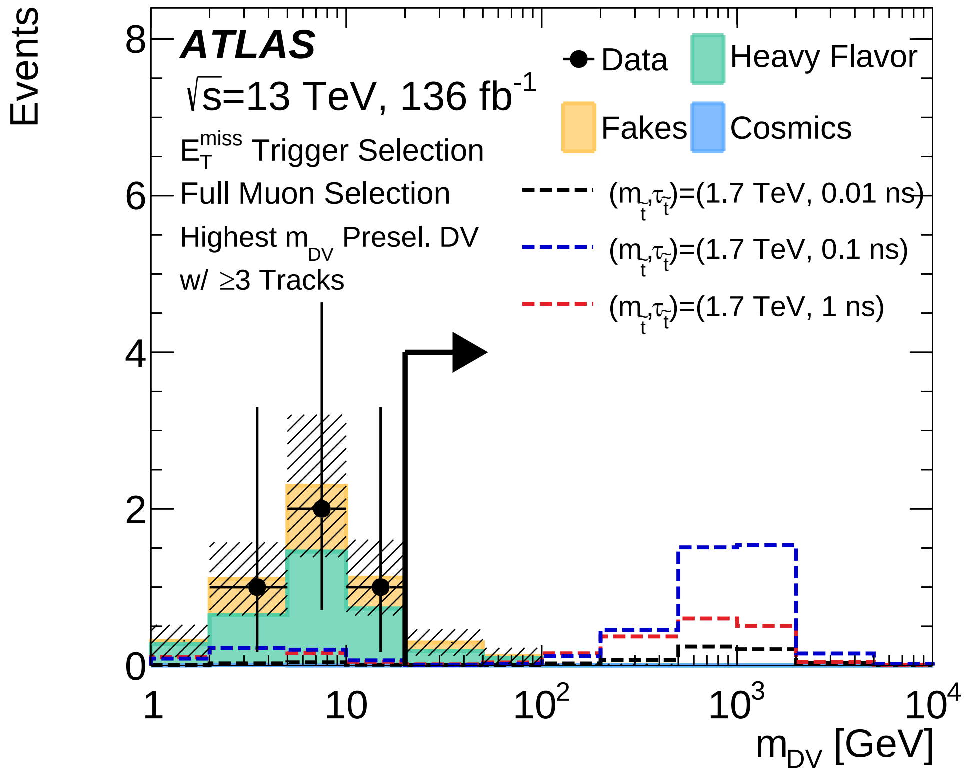
$$N_A^{\text{predicted}} = \frac{N_B \times N_C}{N_D}$$

 Phys. Rev. D 102, 032006 (2020)

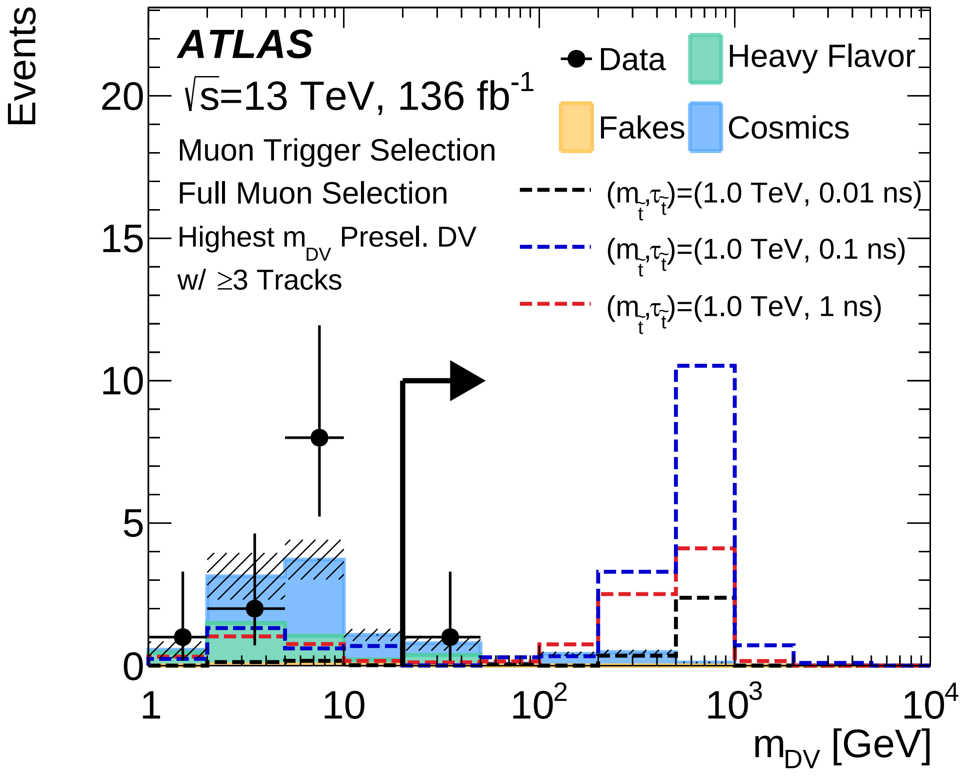
Results

First search for displaced vertices using full Run-2 dataset with ATLAS!

E_T^{miss} -triggered events:



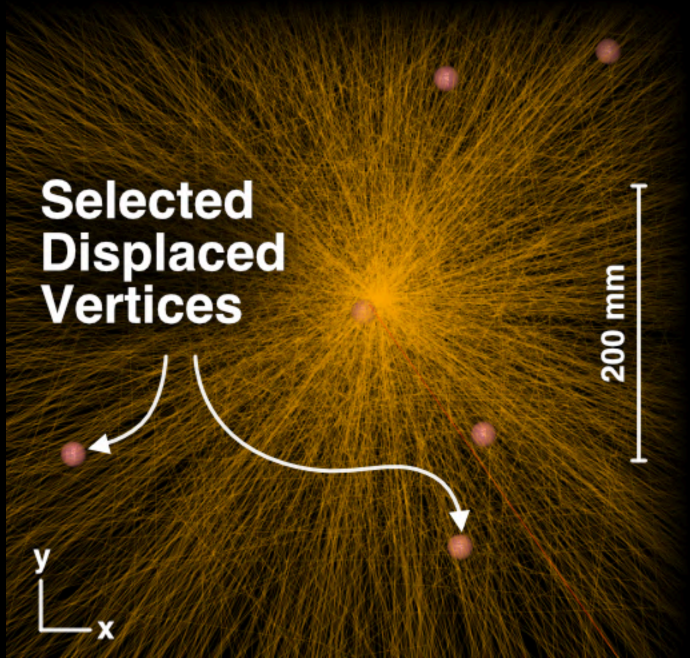
Muon-triggered events:

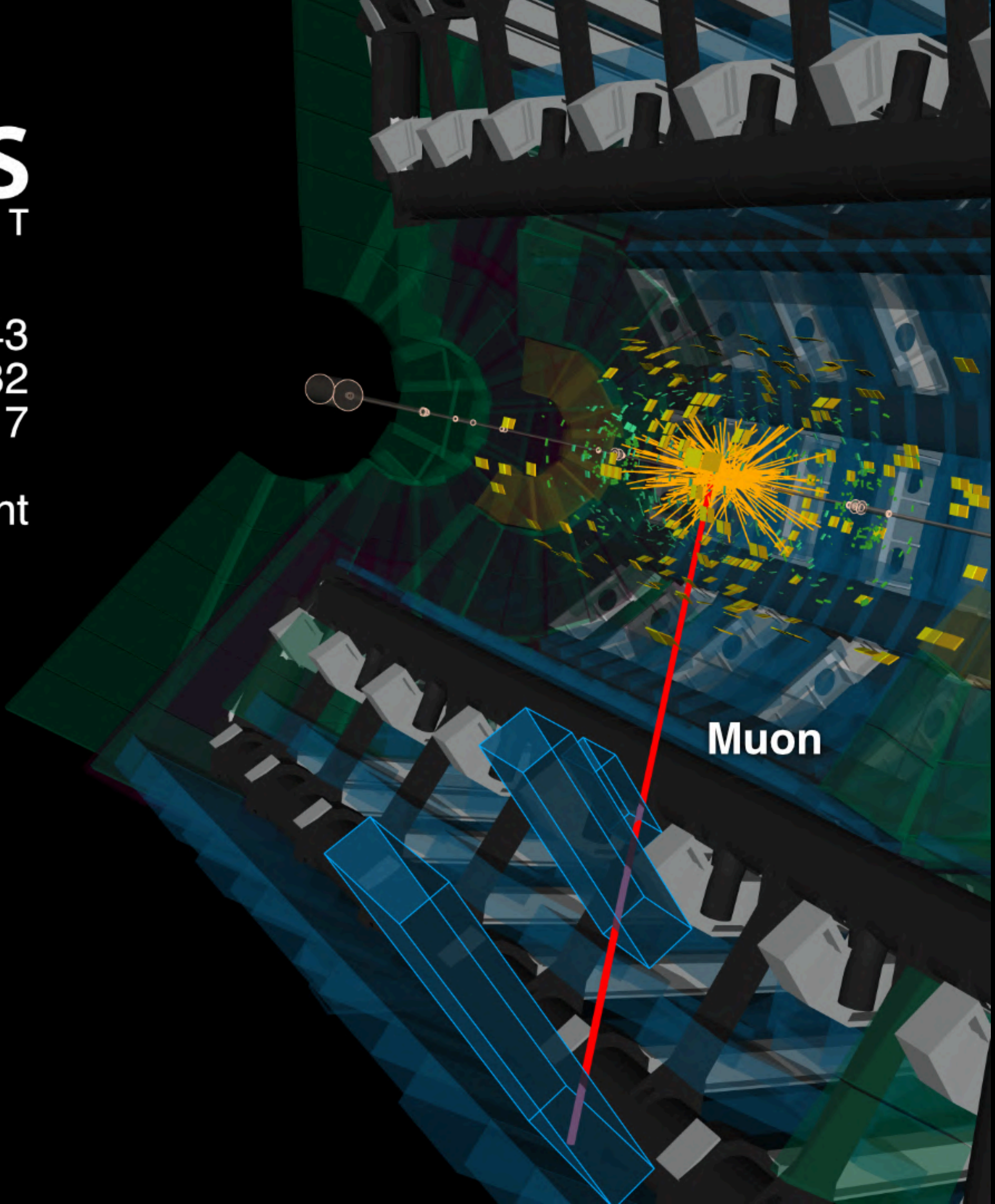


Observed data is consistent with background predictions

Run 350013, LB 243
Event 842252132
Recorded 2018/5/10 23:47:17

Muon Stream Event

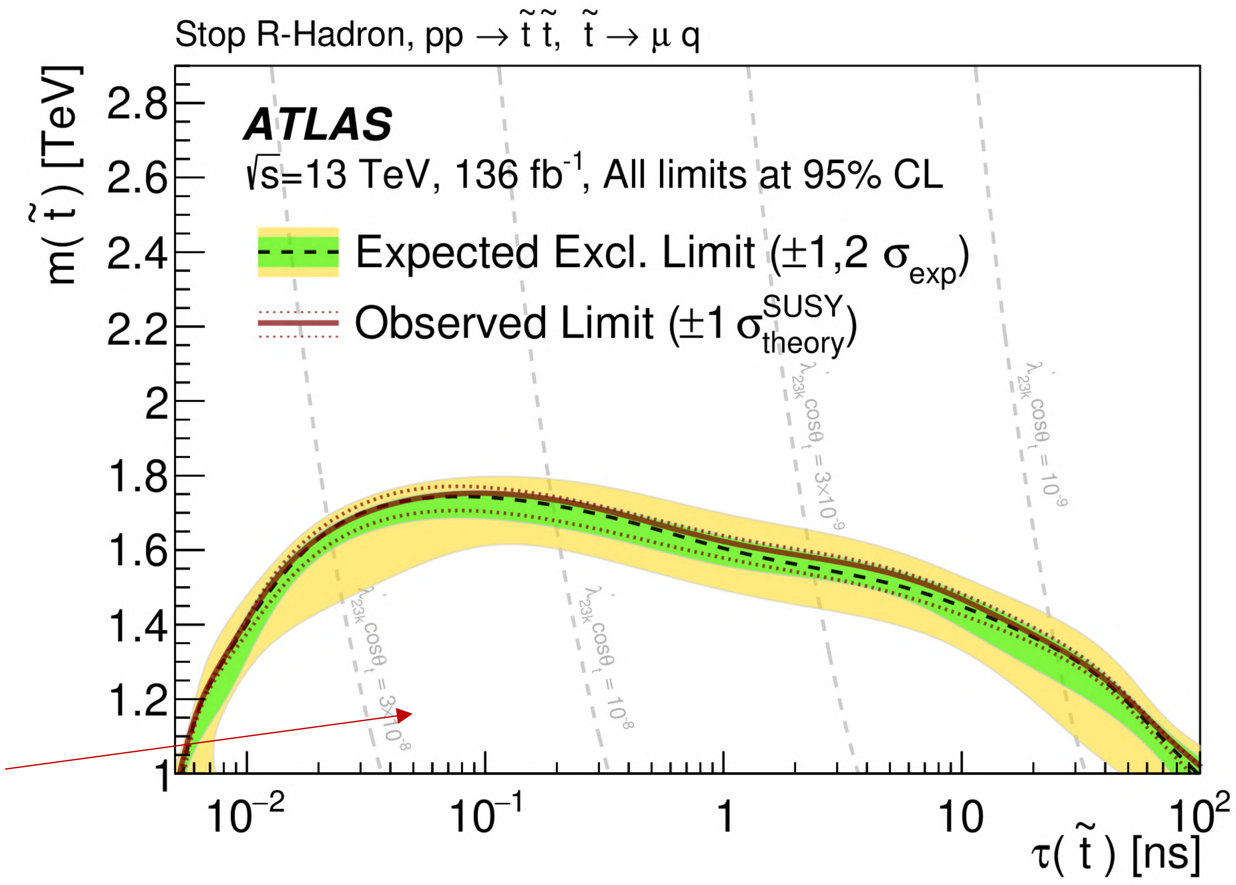




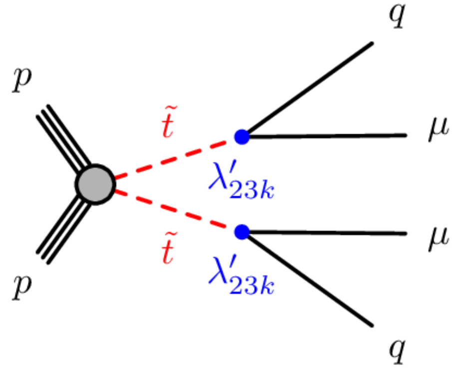
Phys. Rev. D 102, 032006 (2020)

Results

Exclude $\tilde{t}$ with mass below 1.7 TeV and a lifetime of 0.1 ns

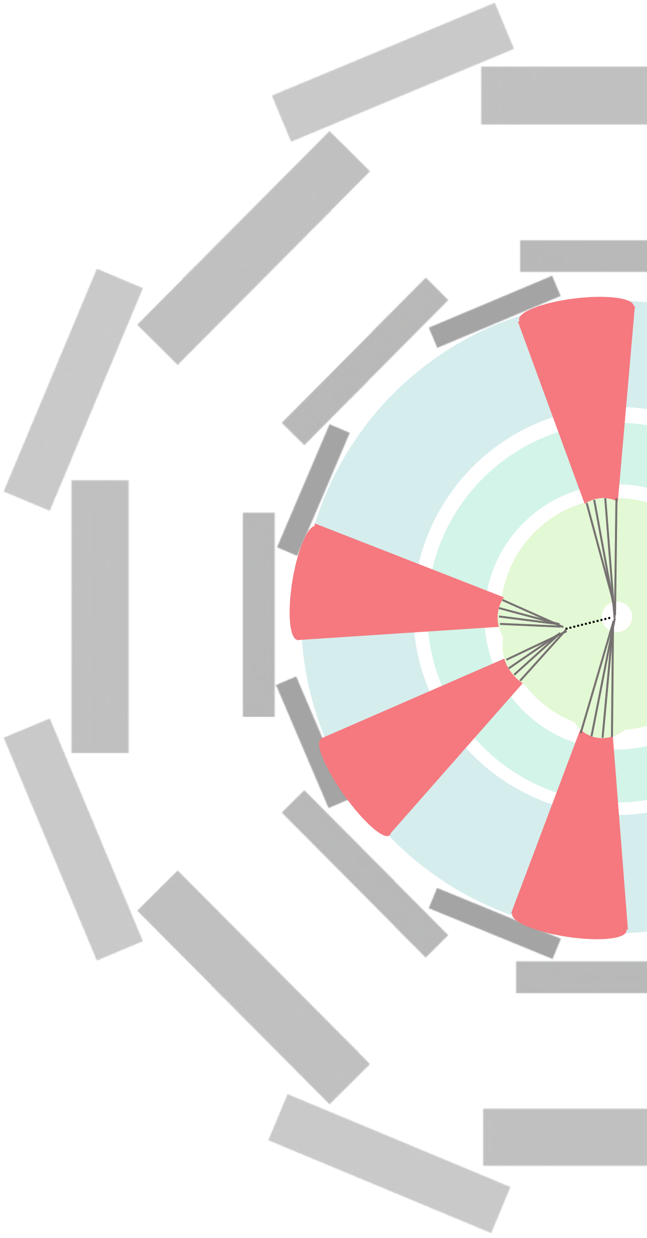


Excluded region



Search for displaced vertices in multijet events

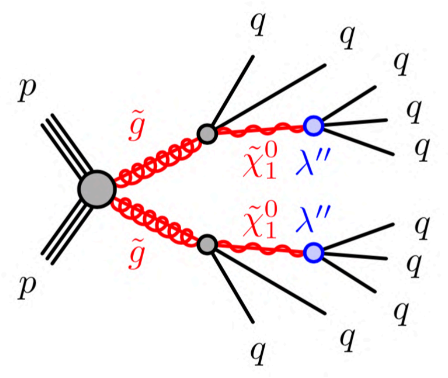
Using full Run-2 dataset: work in progress



Search for DV produced in association with jets

Benchmark model

- Gluino pair production; small R-parity violating coupling



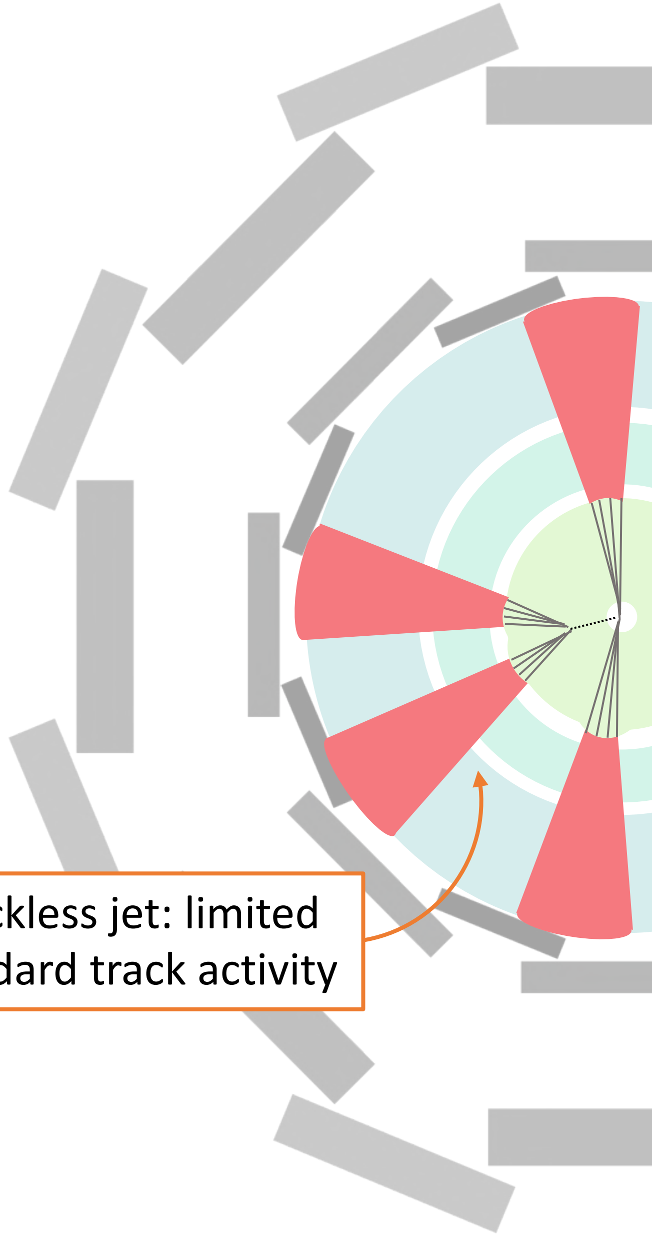
Strategy

- Trigger on **multiple jets** → *3-7 jets at 45-200 GeV*

- Require that events contain:

    1) high multiplicity of **high-pt jets** or **trackless jets**
    2) at least **one displaced vertex**:

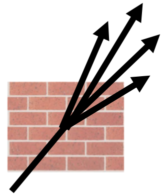
Displaced vertex selection
$r_{DV} < 300$ mm, $\lvert z_{DV} \rvert < 300$ mm
$r_{DV-PV} > 4$ mm
$\chi^2/N_{\mathrm{DoF}} < 5$
Pass material map veto
$N_{\mathrm{trk}} \geq 5$, $m_{DV} > 10$ GeV



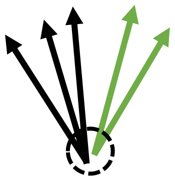
Challenges of the search: background estimation

Background DV sources are the same as in DV+muon, but simple ABCD method is not possible

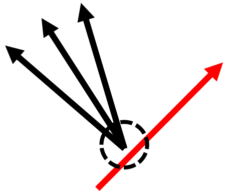
Hadronic interactions

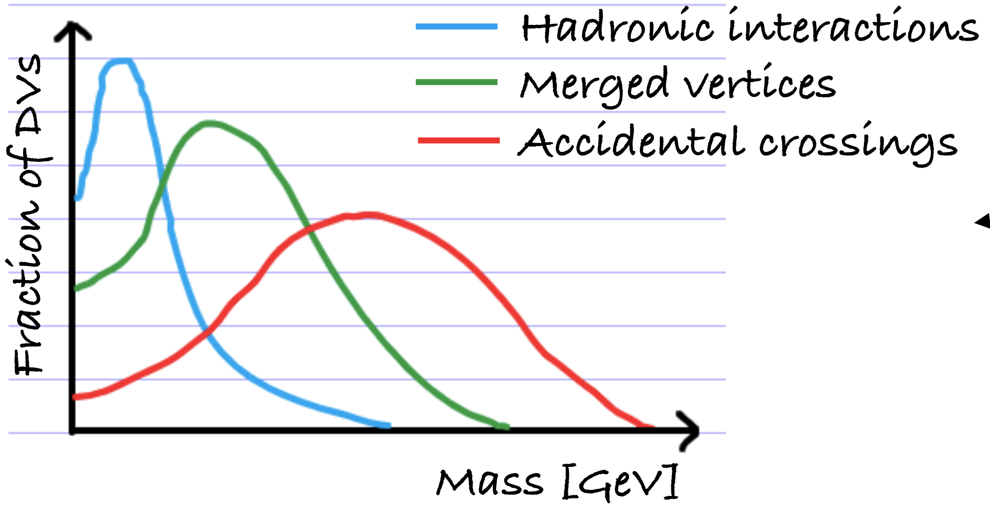


Merged vertices



Accidental crossings





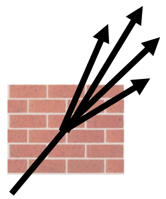
Data-driven background estimation strategy:

1. Estimate each source **individually**
   - Build & normalise mass templates for each
2. Estimate all backgrounds **inclusively**
   - Measure correlations between jets and DV

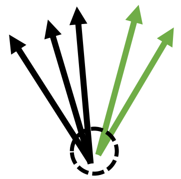
Challenges of the search: background estimation

Background DV sources are the same as in DV+muon, but simple ABCD method is not possible

Hadronic interactions



Merged vertices



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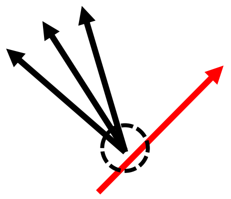


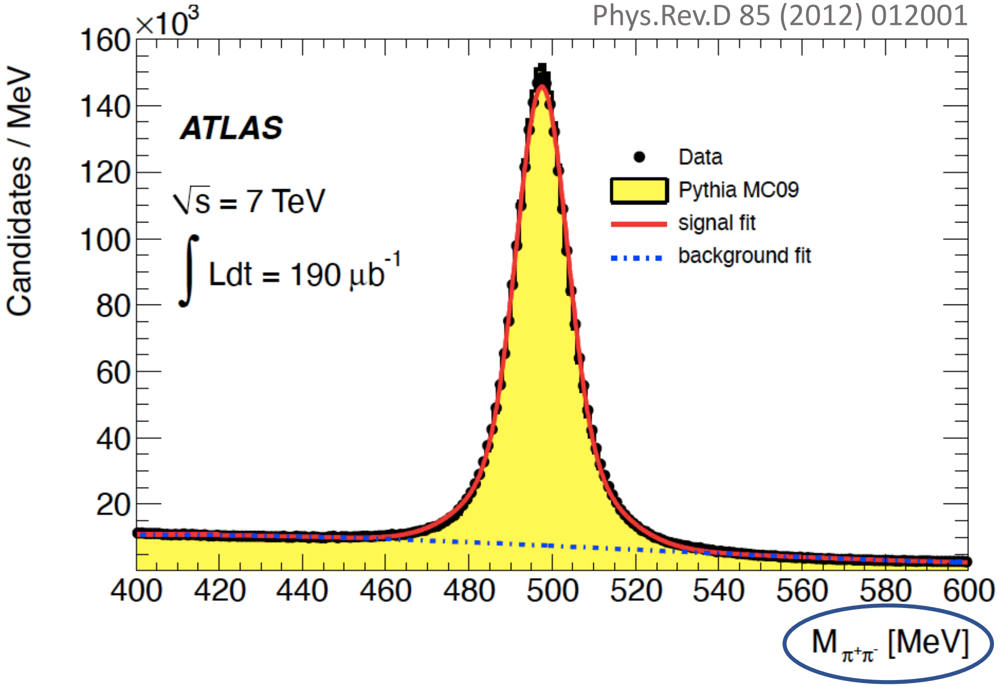
How do we estimate **accidental crossings** from data?

Estimating accidental crossings DV background from data

Use LLPs from the Standard Model to study accidental crossings (AX) in data!

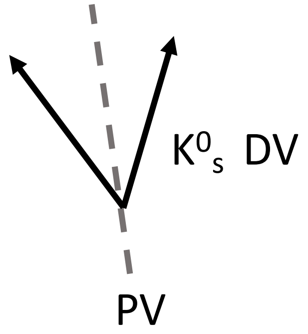
SM LLP	Mass [GeV]	Lifetime [ns]	Target decay	BR
K_s^0	0.498	0.090	$\to \pi^+\pi^-$	69 %
Λ^0	1.12	0.263	$\to p\ \pi^-$	64 %

✓ Long lifetime
✓ High BR to fully reconstructable decays



2-trk mass

- K^0_s DVs **without** an accidental crossing are identified with 2-trk DVs



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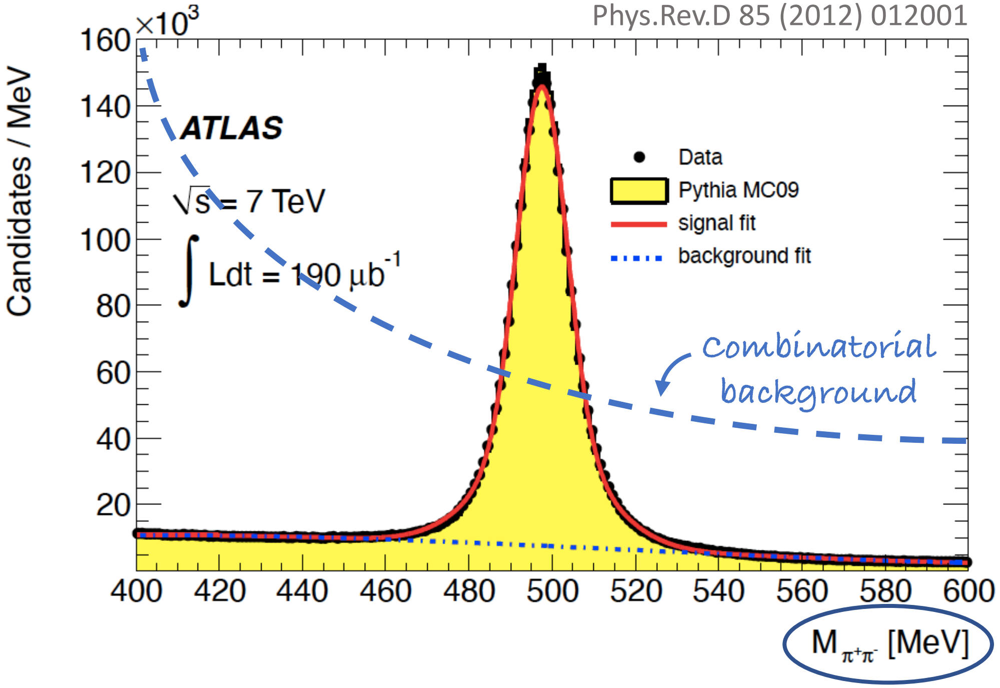
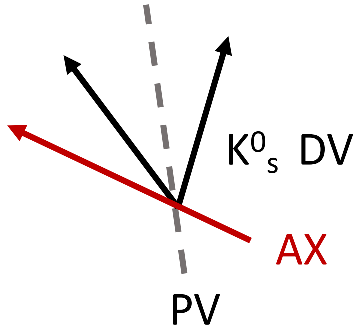


2-trk mass permutations

- K^0_s DVs **without** an accidental crossing are identified with 2-trk DVs
- K^0_s DVs **with** an accidental crossing are identified with 3-trk DVs



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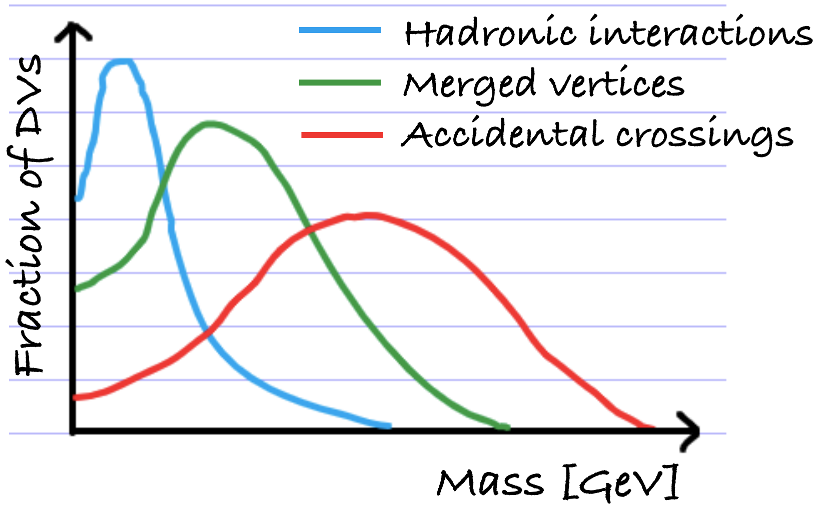

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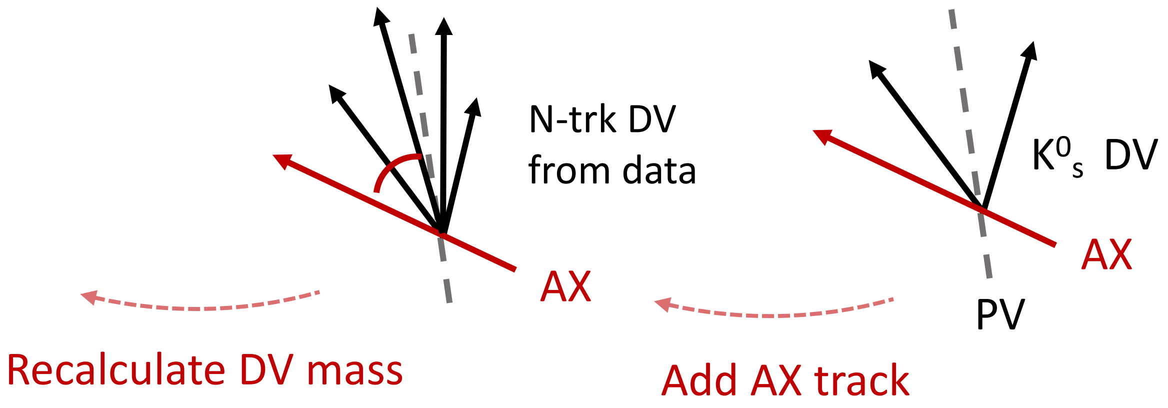

Use LLPs from the Standard Model to study accidental crossings (AX) in data!

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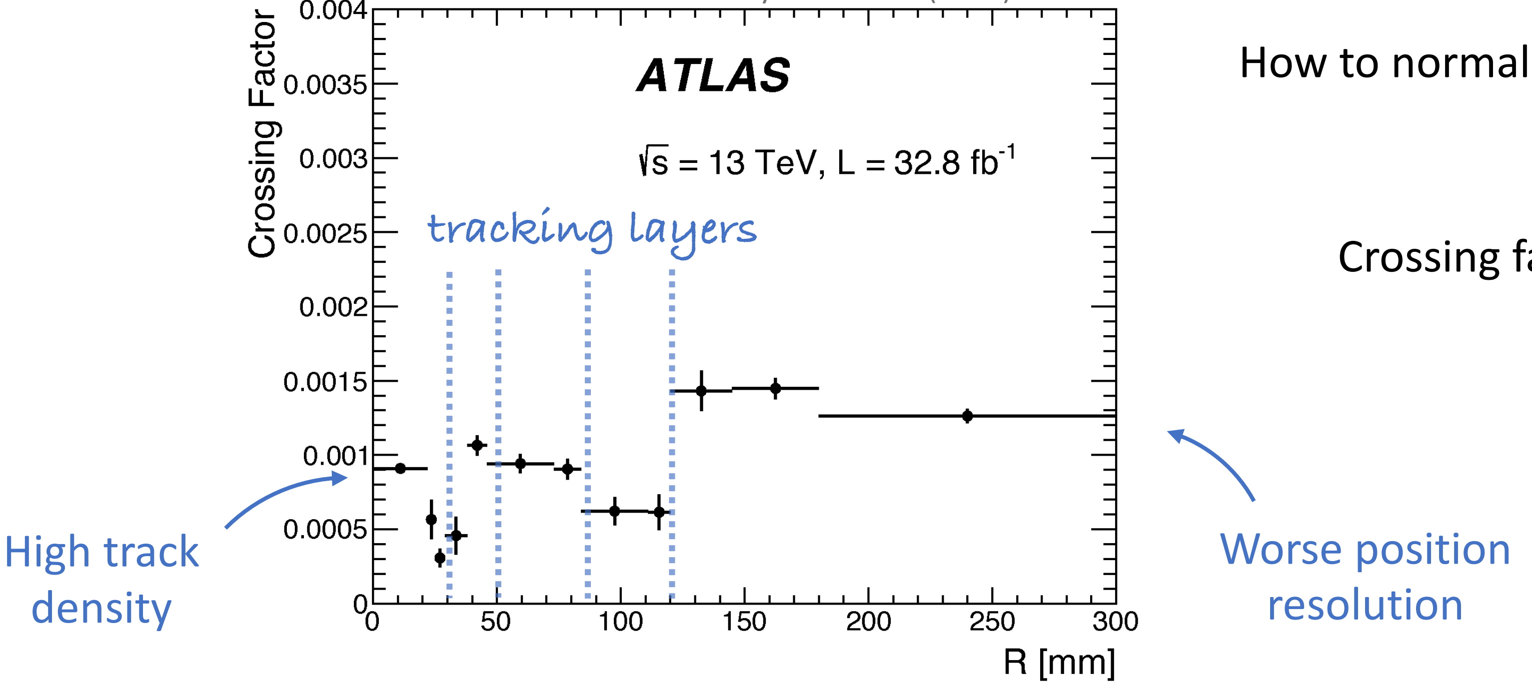


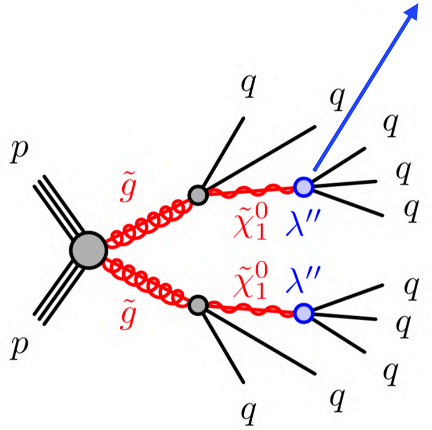
How to normalise AX mass template?

$$\text{Crossing factor} = \frac{\#\, K_S^0 \text{ with AX track}}{\#\, K_S^0 \text{ with or without AX}}$$

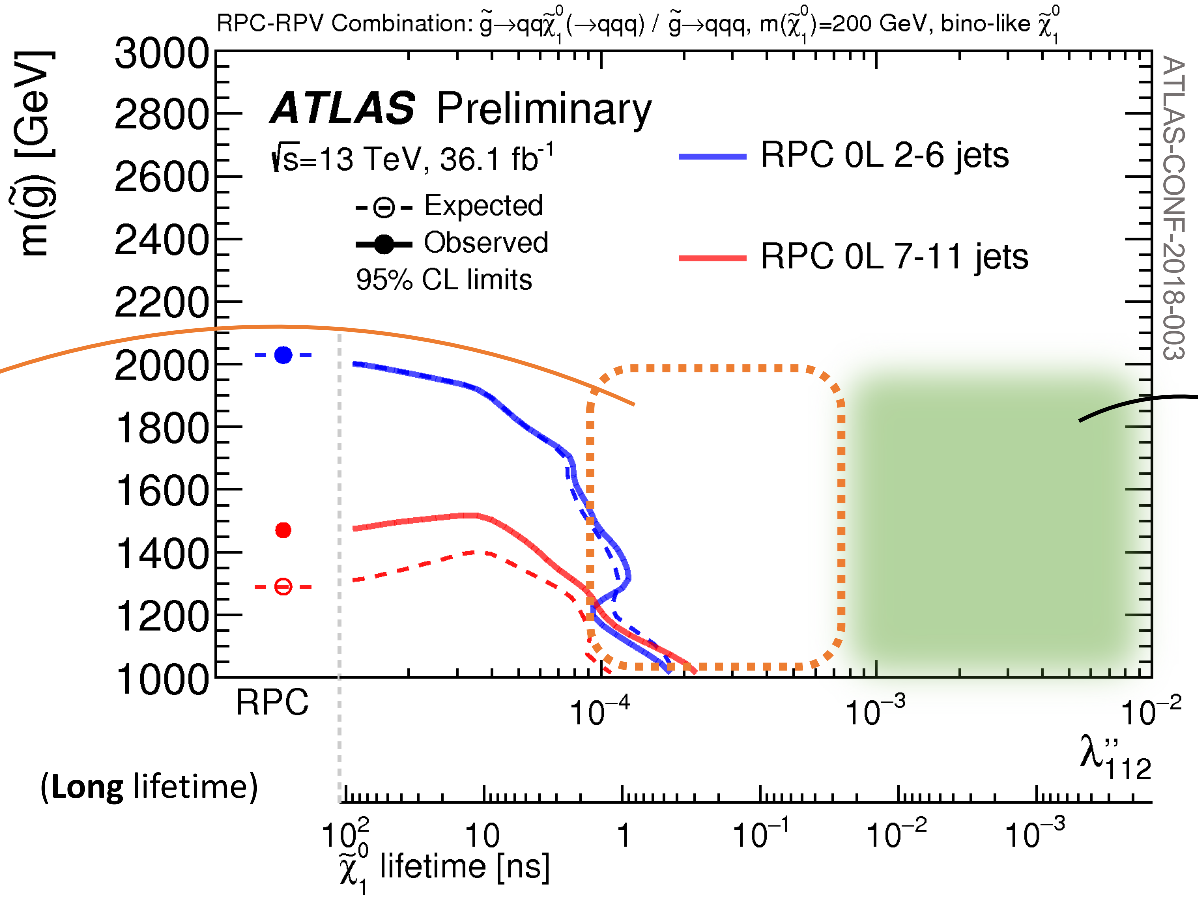
Expected sensitivity of DV+jets search

- Our benchmark model includes small but non-zero RPV coupling λ''
- Partial Run-2 summary paper revealed large area uncovered by existing ATLAS searches:

$$d\Gamma \sim \frac{1}{M}|\mathcal{M}|^2 d\Pi$$



DV + jets search will explore this region!



(**Long** lifetime)

Covered by prompt RPV (multijet) search

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(**Short** lifetime)

Ingredients for a long-lived particle (LLP) search

1. **Pick a signature**
   - Displaced vertices in the inner detector
2. **Pick a trigger**
   - Require "triggerable" object in the event
3. **Utilize special object reconstruction**
   - Displaced track and vertex finding
4. **Derive background estimate from data**
   - Backgrounds are often difficult to model
5. **Choose level of model-independence** – a matter of taste!

Ingredients for a long-lived particle (LLP) search

1. **Pick a signature**
   - Displaced vertices in the inner detector
2. **Pick a trigger**
   - Require "triggerable" object in the event

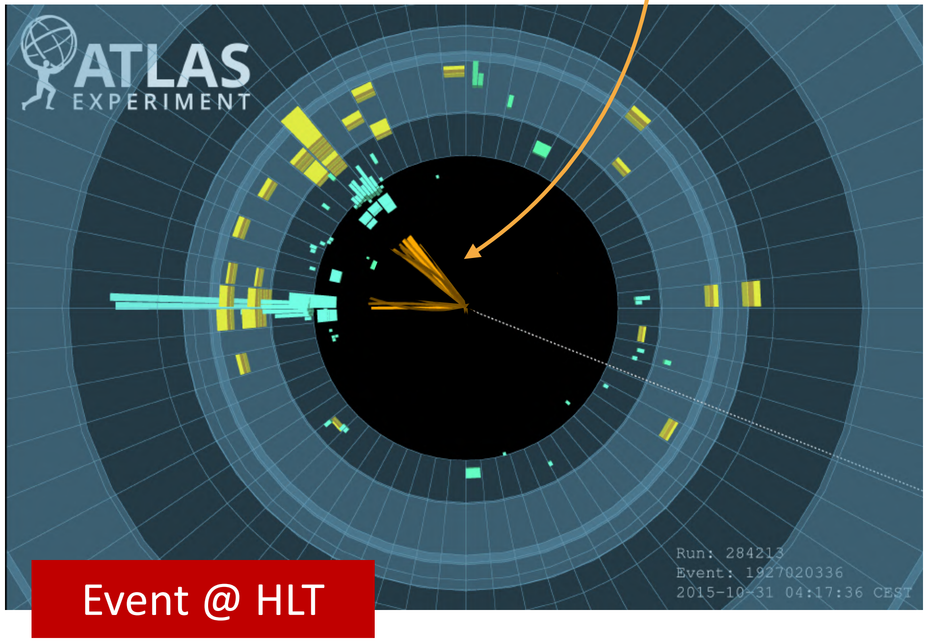
This is a limitation of DV + X searches

Including more **tracking information in the trigger** would open up possibilities to trigger directly on LLP signatures with displaced tracks...

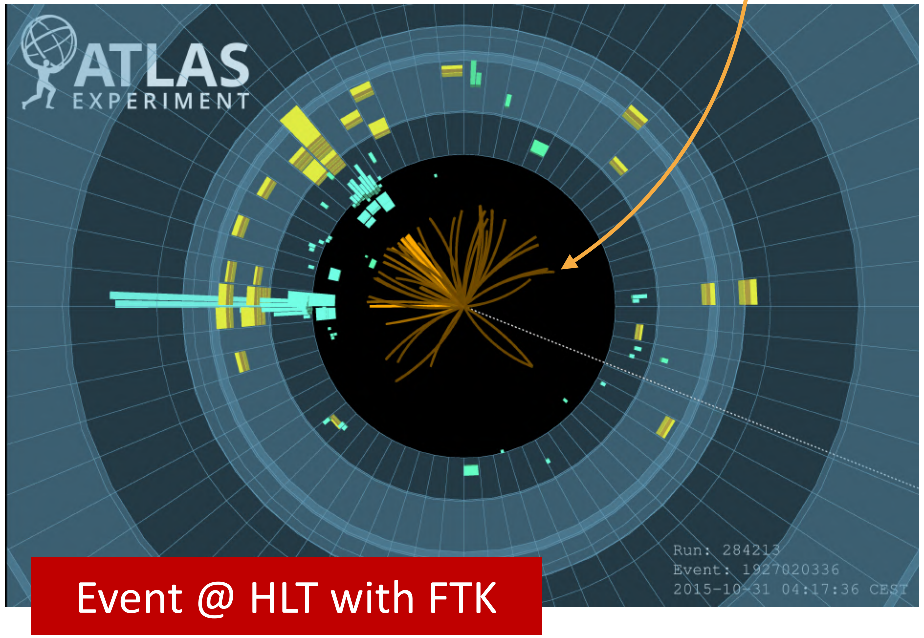
ATLAS FastTracKer (FTK):

a hardware-based track finder designed to provide HLT with **all tracks** ($p_T > 1$ GeV) for every L1-accepted event

Tracking limited to regions-of-interest:



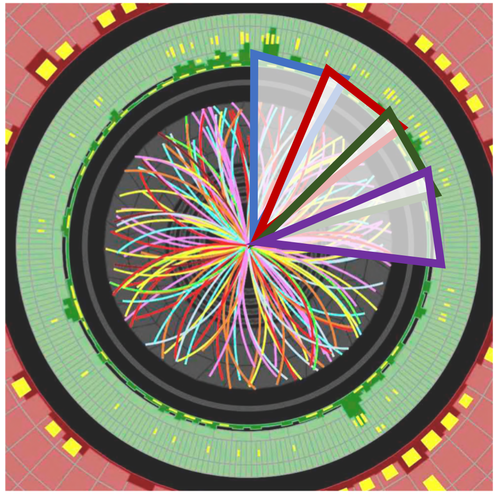
FTK removes region-of-interest limitation:

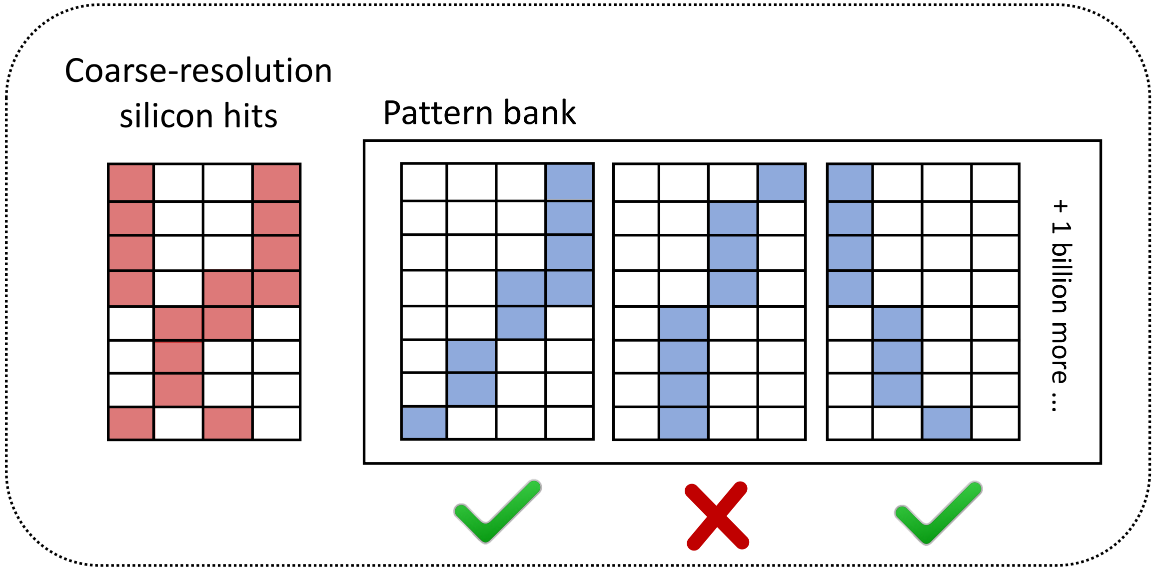


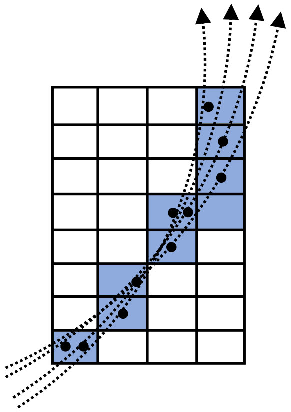
How does FTK perform track-finding fast?

Key concepts:

1. Parallelize 16 (ϕ) x 4 (η) = 64 overlapping towers
2. Utilize information only from silicon tracking layers
3. Pattern matching on Associative Memory chips
4. Linearized track fit on FPGAs (no minimization!)







⚠ One fit for every combination of hits from each layer

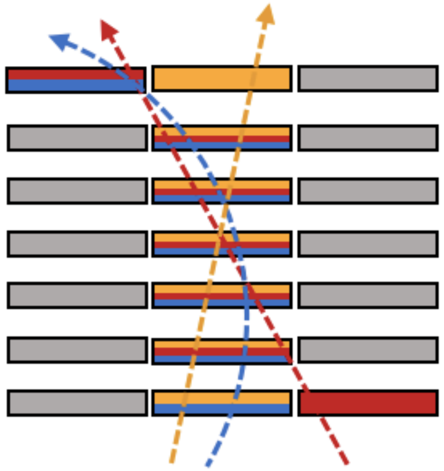
Optimization of FTK pattern bank

- The heart of the FTK system is the pattern bank
- More patterns = higher efficiency. But we are limited by hardware capacity (~ 1 billion pattern addresses available)
- FTK utilizes **variable-width patterns** to increase track-finding efficiency
    - o Maximum pattern width is optimized separately for patterns in barrel and endcap region

Pattern

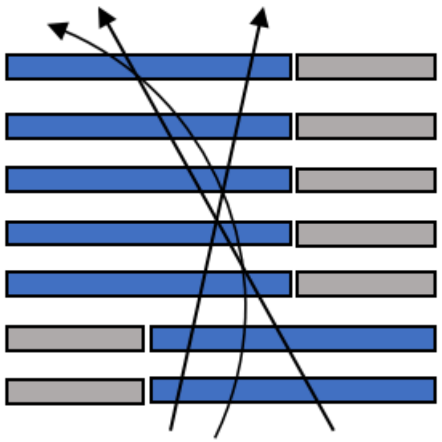
Combination of 8 coarse resolution hits from different silicon layers

Fine resolution patterns:



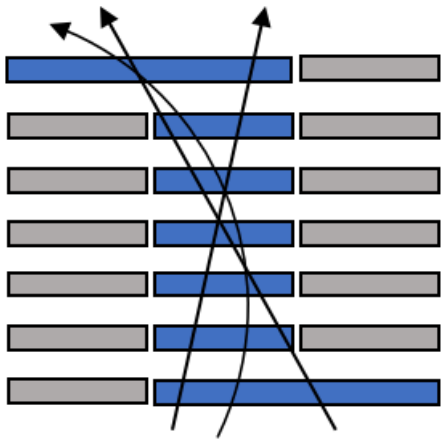
Too many patterns!

Wide patterns:



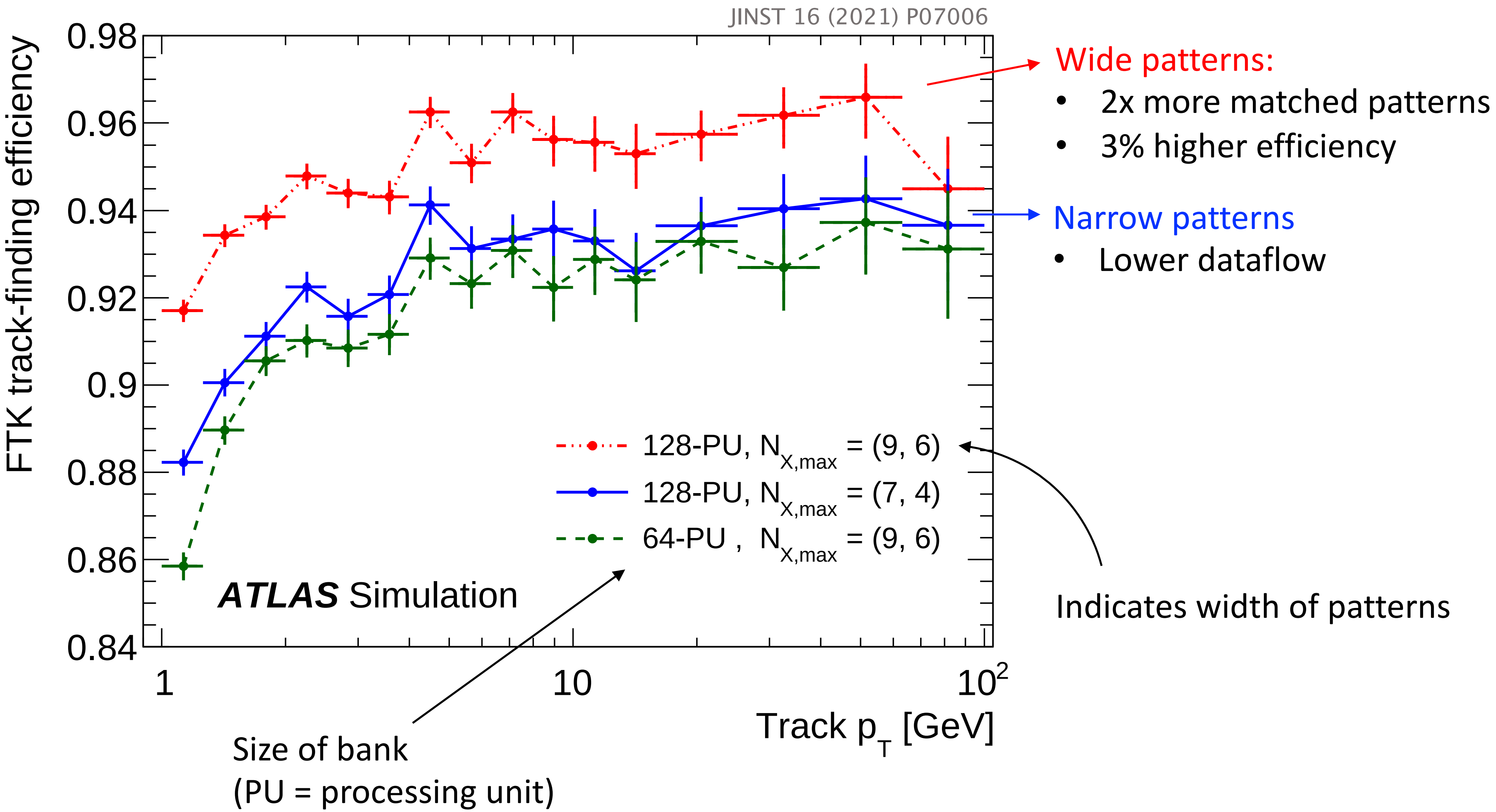
Too many track fits!

Variable-width patterns:



Optimization of FTK pattern bank

Impact of variable-width pattern size on FTK track-finding efficiency:



How can the FTK be used to trigger on displaced tracks?

- The gains in track-finding efficiency decrease with additional patterns:

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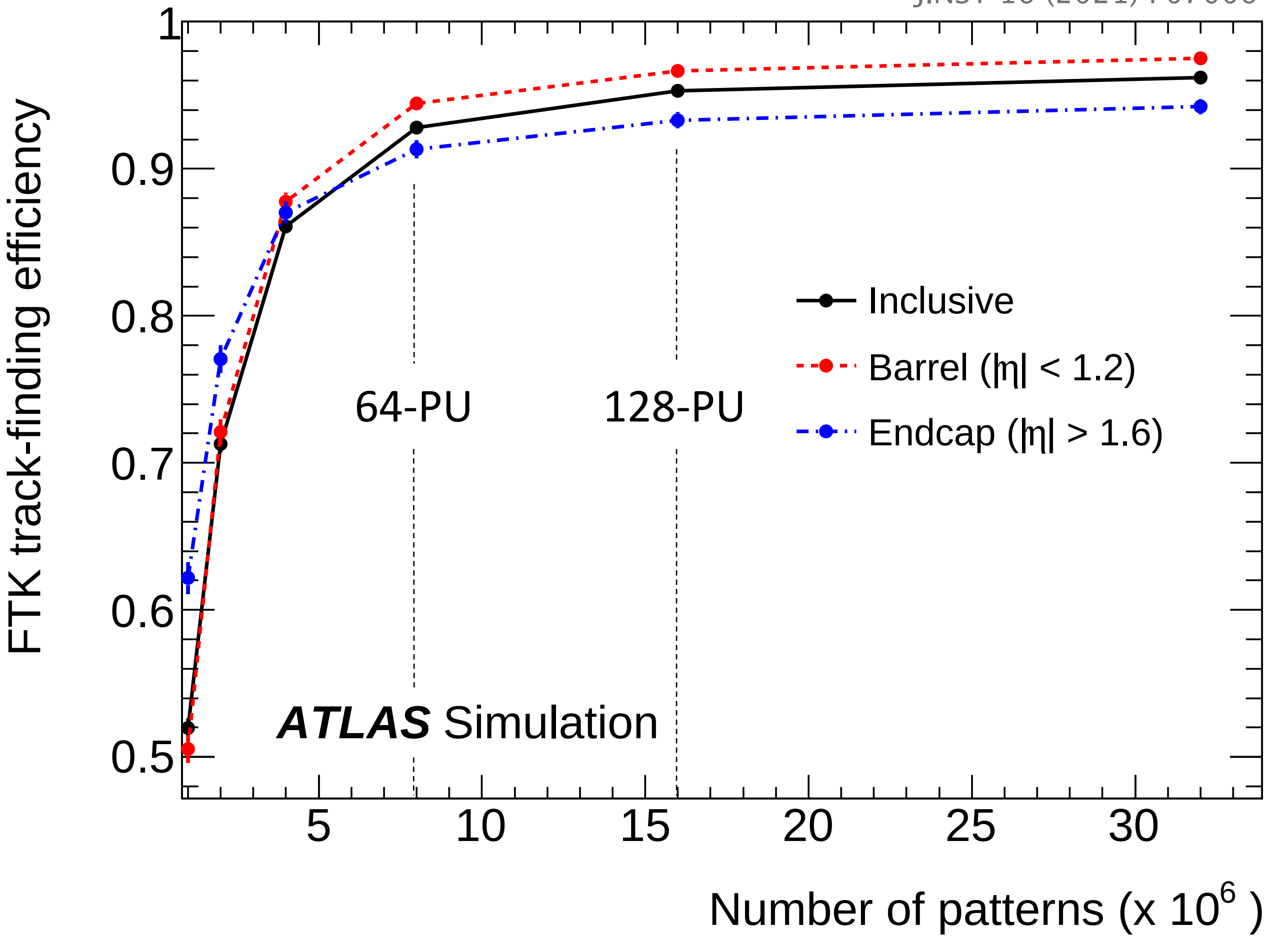


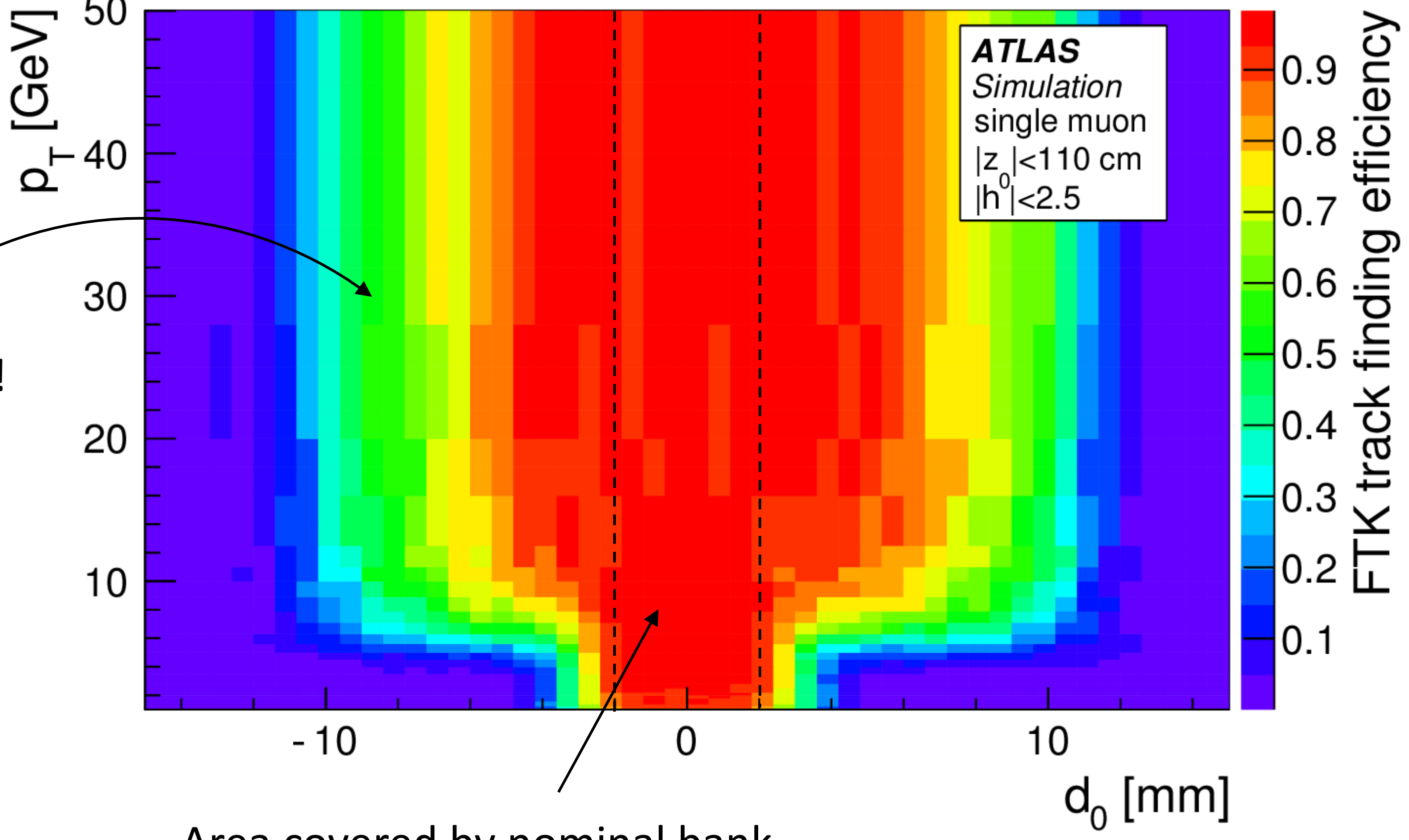
What if we allocate some of these patterns for displaced tracks instead?

How could the pattern bank be used to trigger on LLPs?

- Nominal pattern bank is trained with tracks satisfying: $|d_0| < 2$ mm, $p_T > 1$ GeV
- Allocate 30% of patterns in bank to high-d_0 tracks: $|d_0| < 10$ mm
  - Require $p_T > 5$ GeV for high-d_0 patterns

JINST 16 (2021) P07006

High-d_0 bank is able to identify displaced tracks!



Area covered by nominal bank

How could the pattern bank be used to trigger on LLPs?

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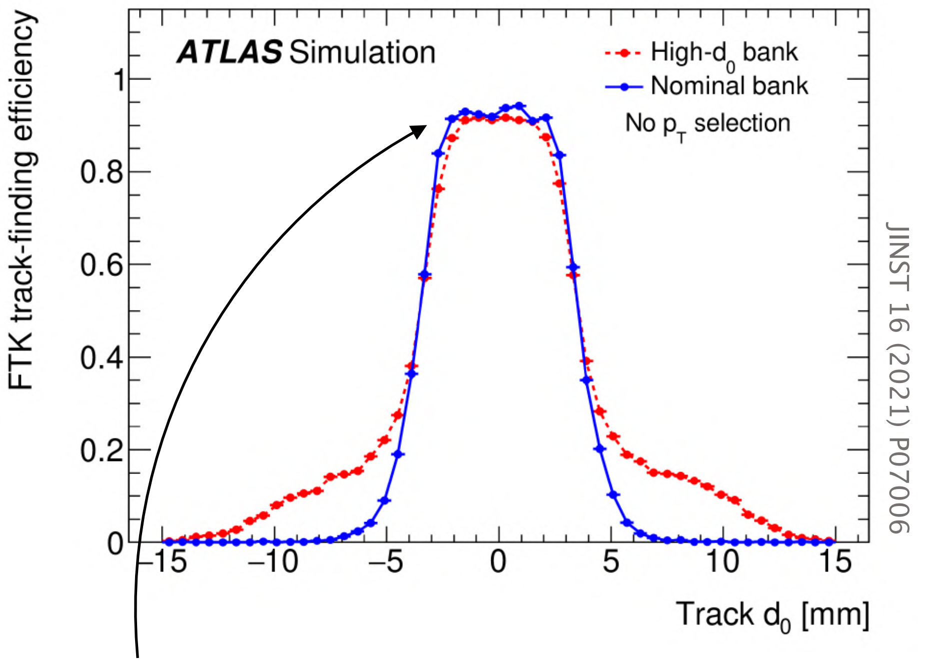
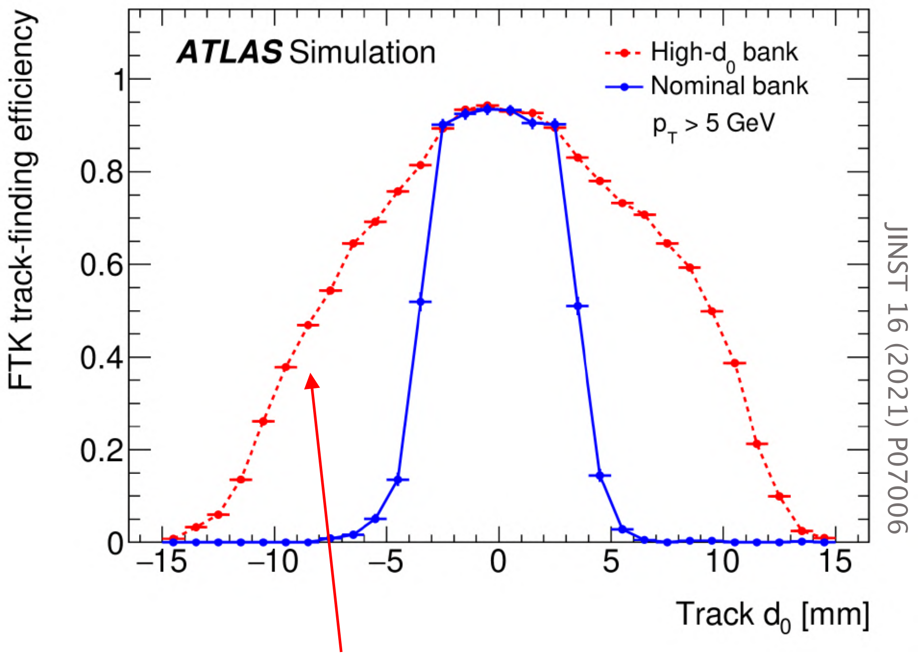
Track-finding efficiency of **all tracks**:



Efficiency loss < 2% in in $|d_0| < 2$ mm region

Track-finding efficiency of $\mathbf{p_T > 5}$ **GeV** tracks:



Displaced tracks in trigger!

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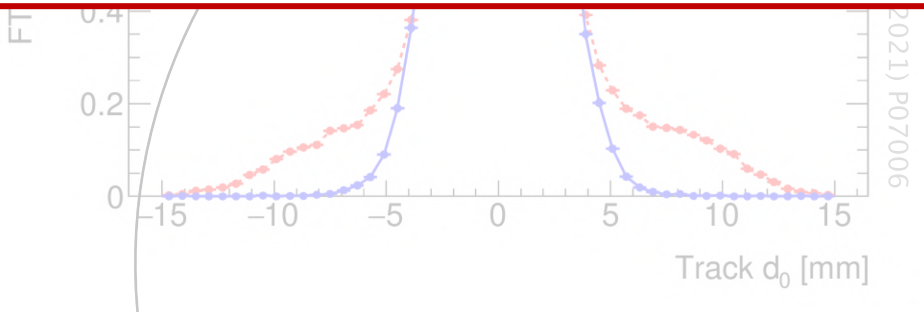
  - o

In Run-3, ATLAS will **not** install full FTK system.

Instead, we plan to perform more full-scan tracking in the HLT for jet / E_T^{miss} signatures.

Good news for LLP searches: new LLP triggering capabilities in Run-3!

i.e. trigger directly on displaced vertices
- Counting unassociated hits
- With large-radius tracks



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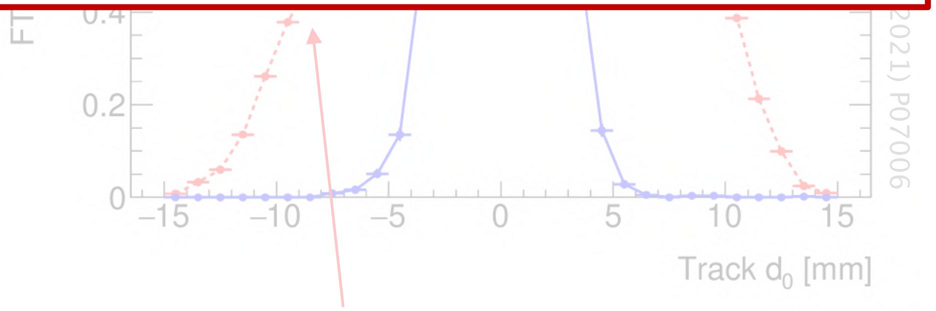
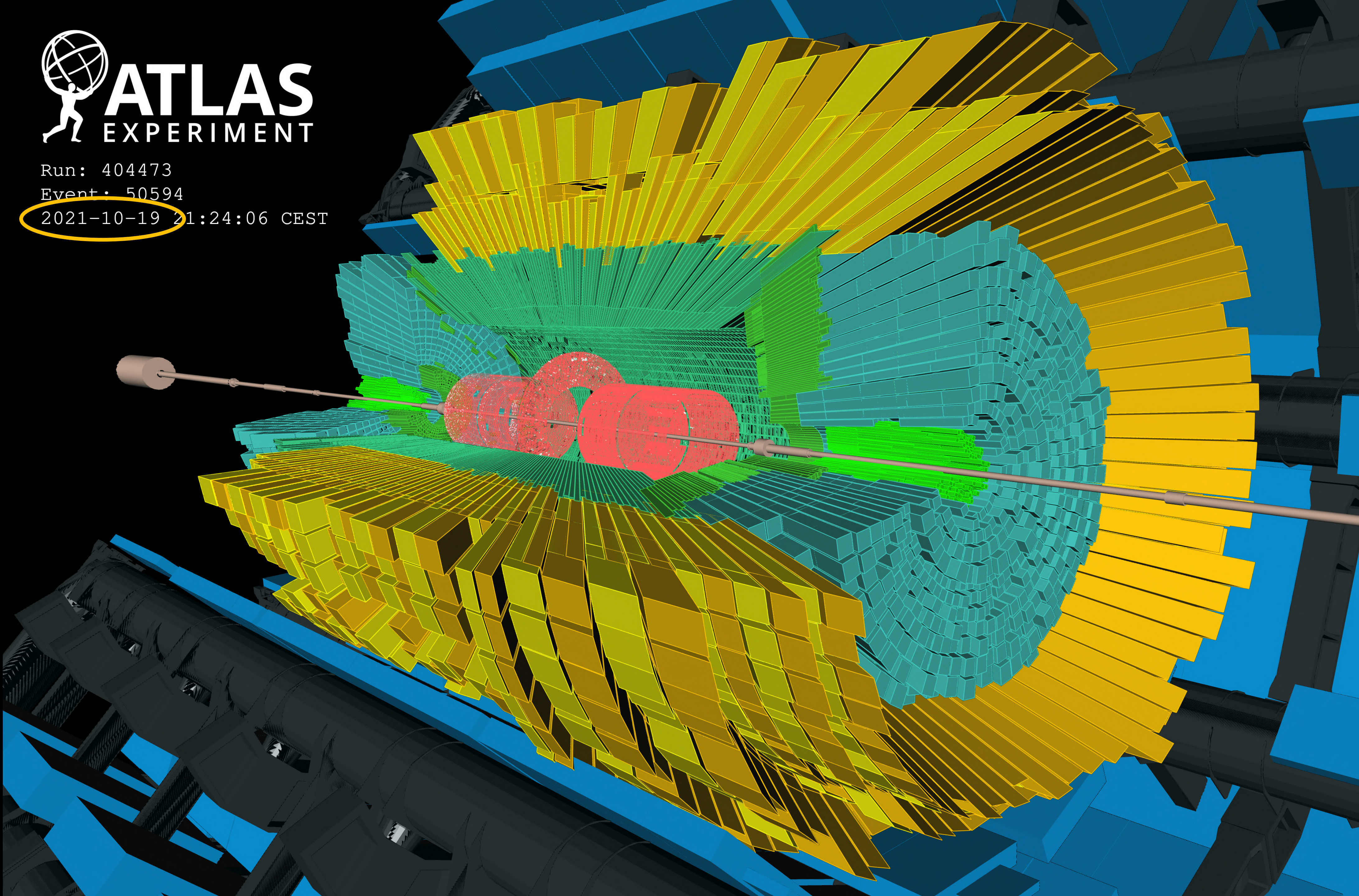


Displaced tracks in trigger!

The search for long-lived particles continues!

Run 3 coming soon…

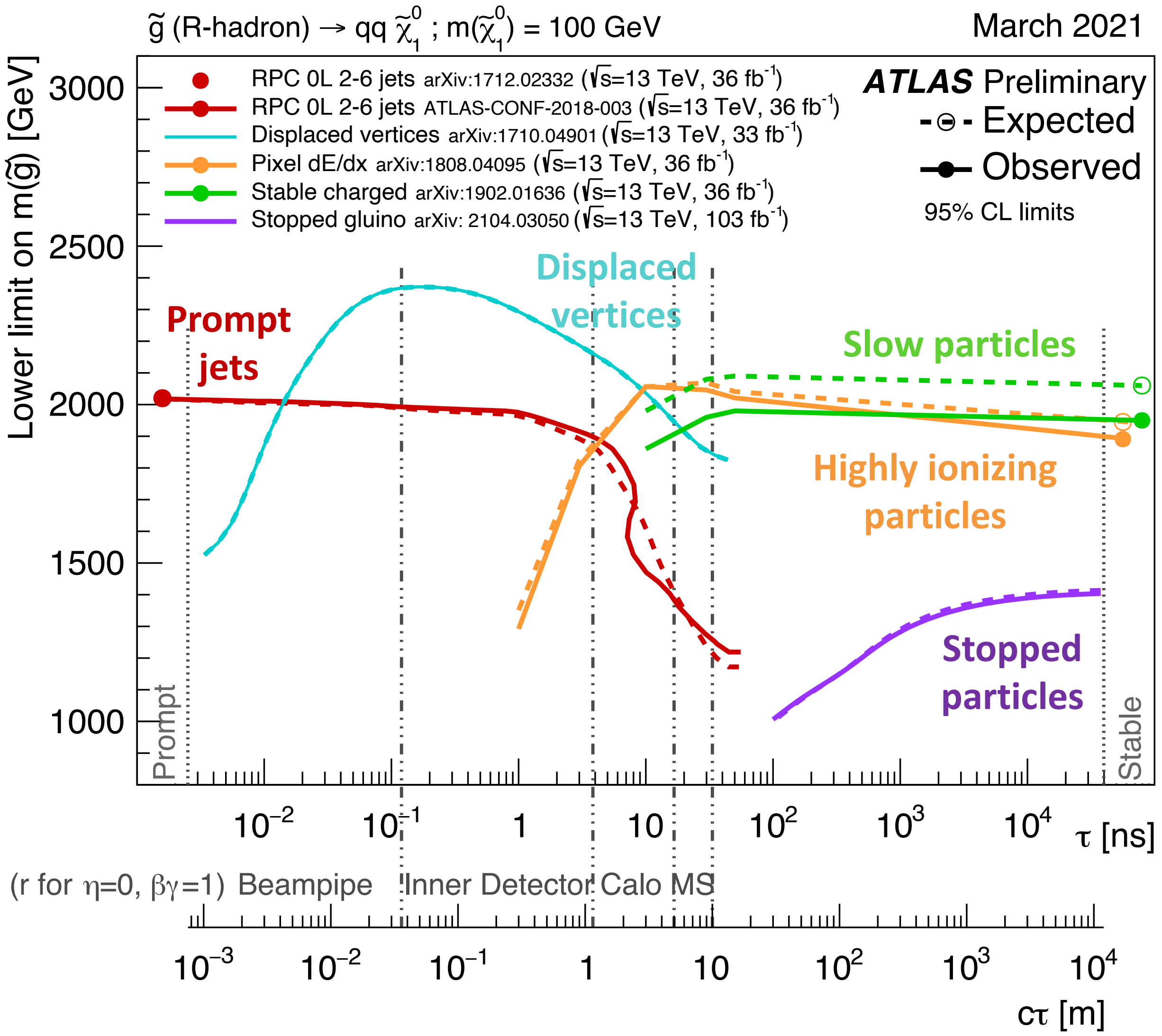


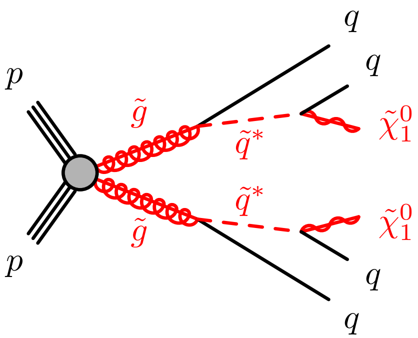
Run-3 event displays

Backup

Signatures of long-lived particles in the ATLAS detector

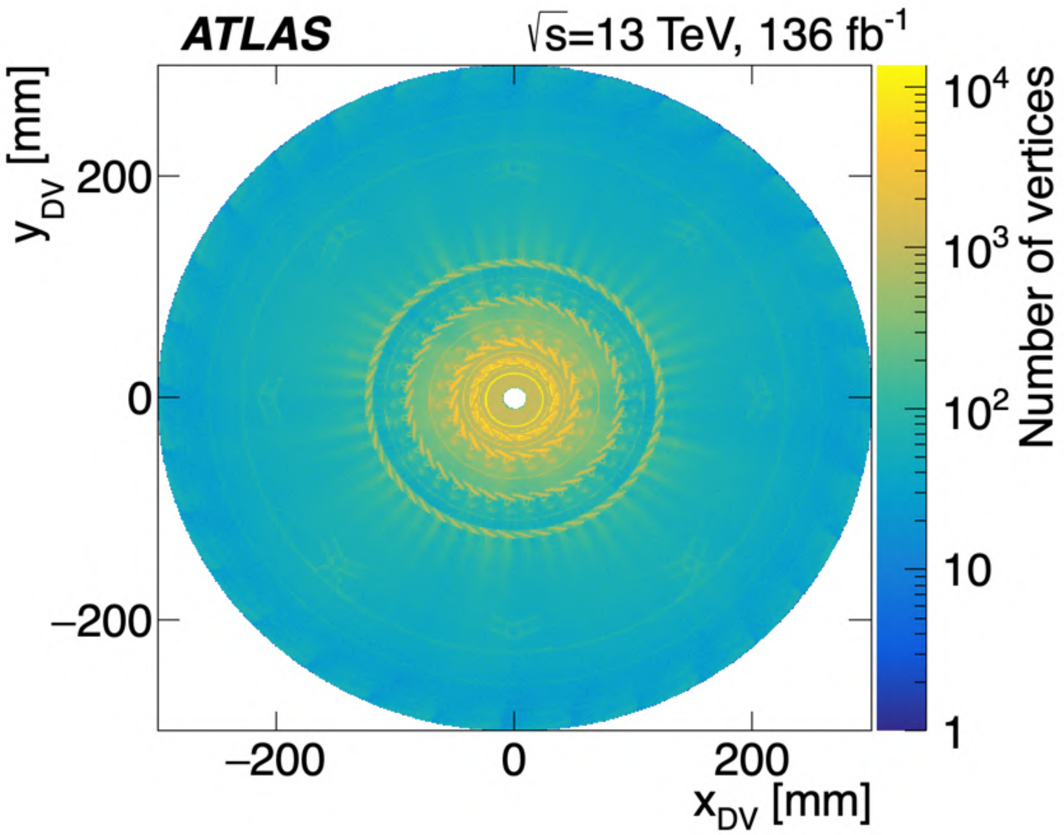
Searching for multiple LLP signatures is critical for covering a wide lifetime range

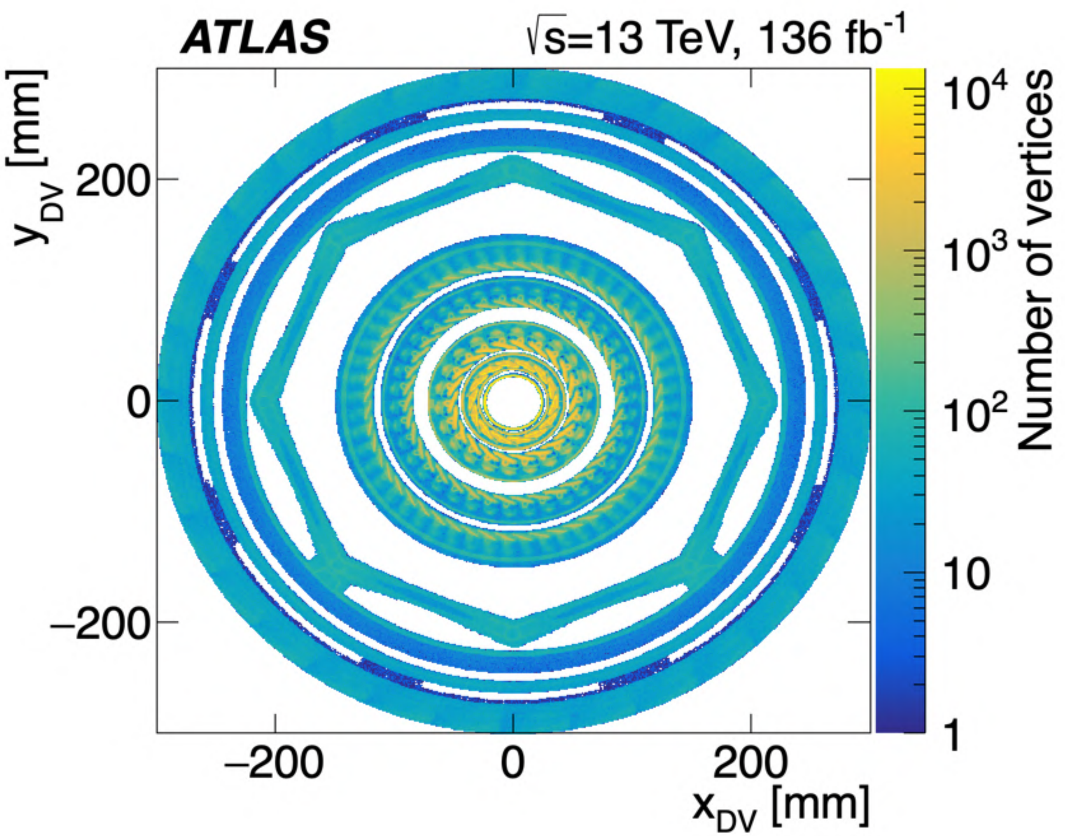




Material map

- Constructed from low mass DVs in data
- Beam pipe and support tubes added by hand
- Removes 42% of fiducial volume





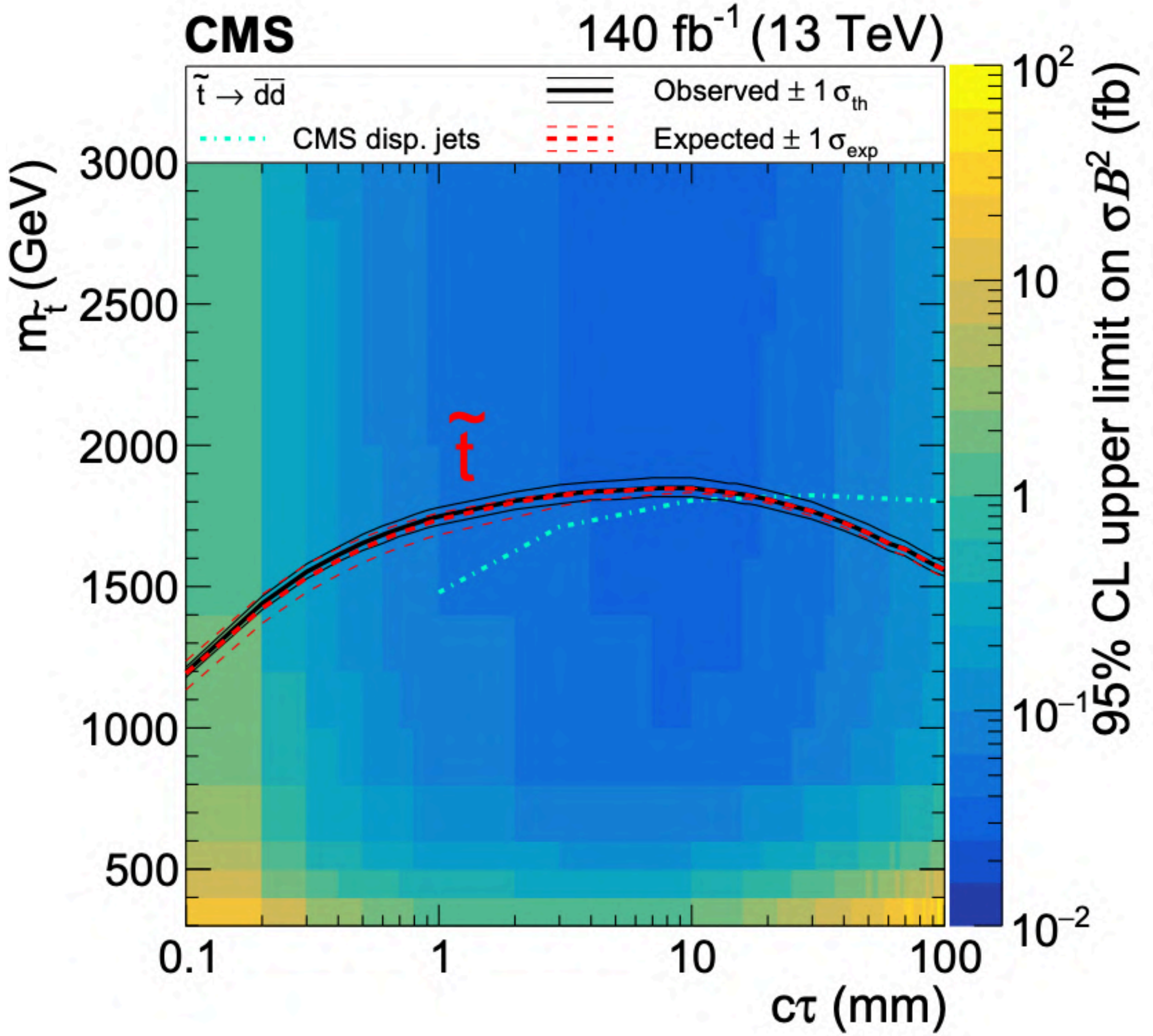
DV + muon uncertainties

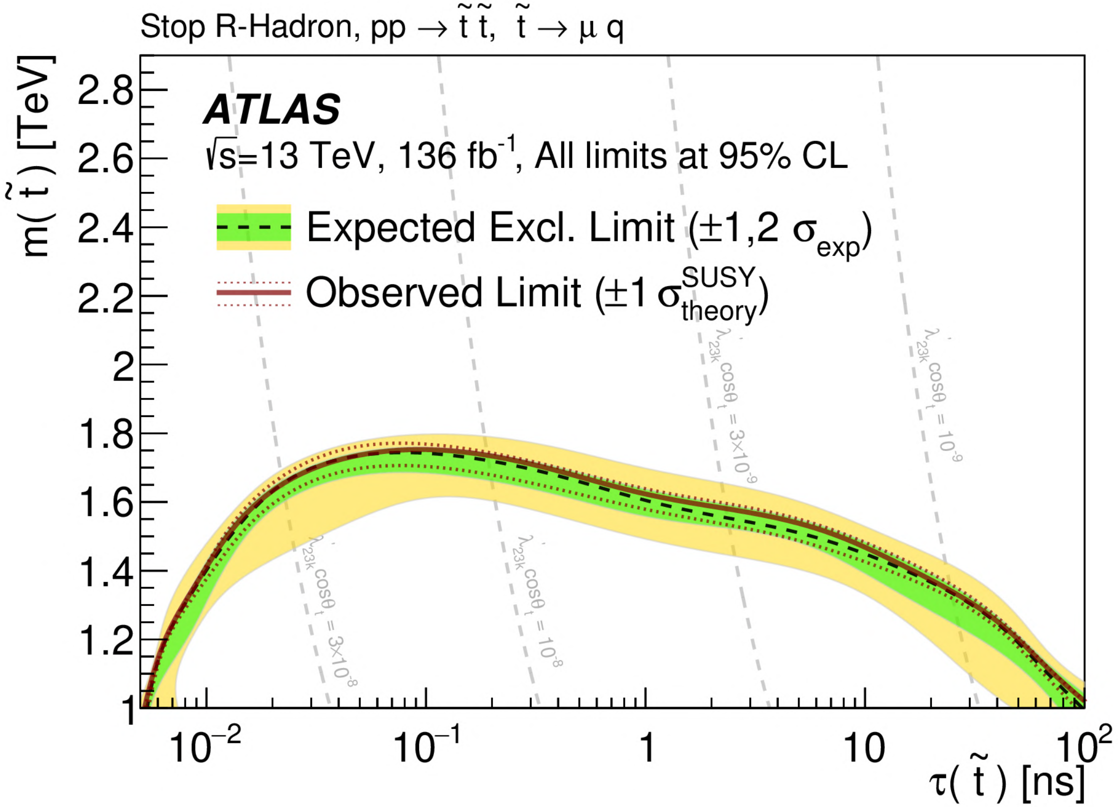
- Uncertainty on background estimates:
  - DV uncertainties evaluated in sub-regions with different DV track multiplicity
  - Muon uncertainties evaluated by varying d_0 requirements
- Signal uncertainties:

Source of uncertainty	Relative impact on ϵ_{sel} for signal events [%]
Total	18–20
Tracking and vertex reconstruction	15
Displaced muon efficiency	10–12
Prompt muon efficiency	$(0.01–0.7) \oplus (0.9–4.0)$
ISR modeling in MC simulation	3
Pileup modeling	0.37–2.2
Hadronic energy scale and resolution (affecting E_T^{miss})	2.1
Integrated luminosity of dataset	1.7
Trigger efficiency	< 0.2

CMS

Phys. Rev. D 104, 052011 (2021)

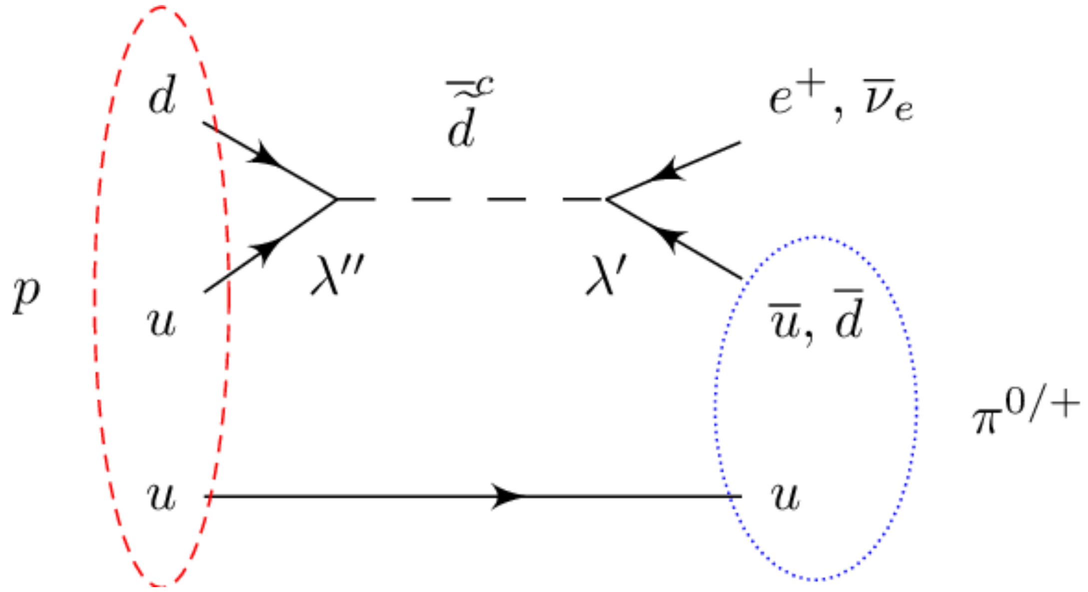


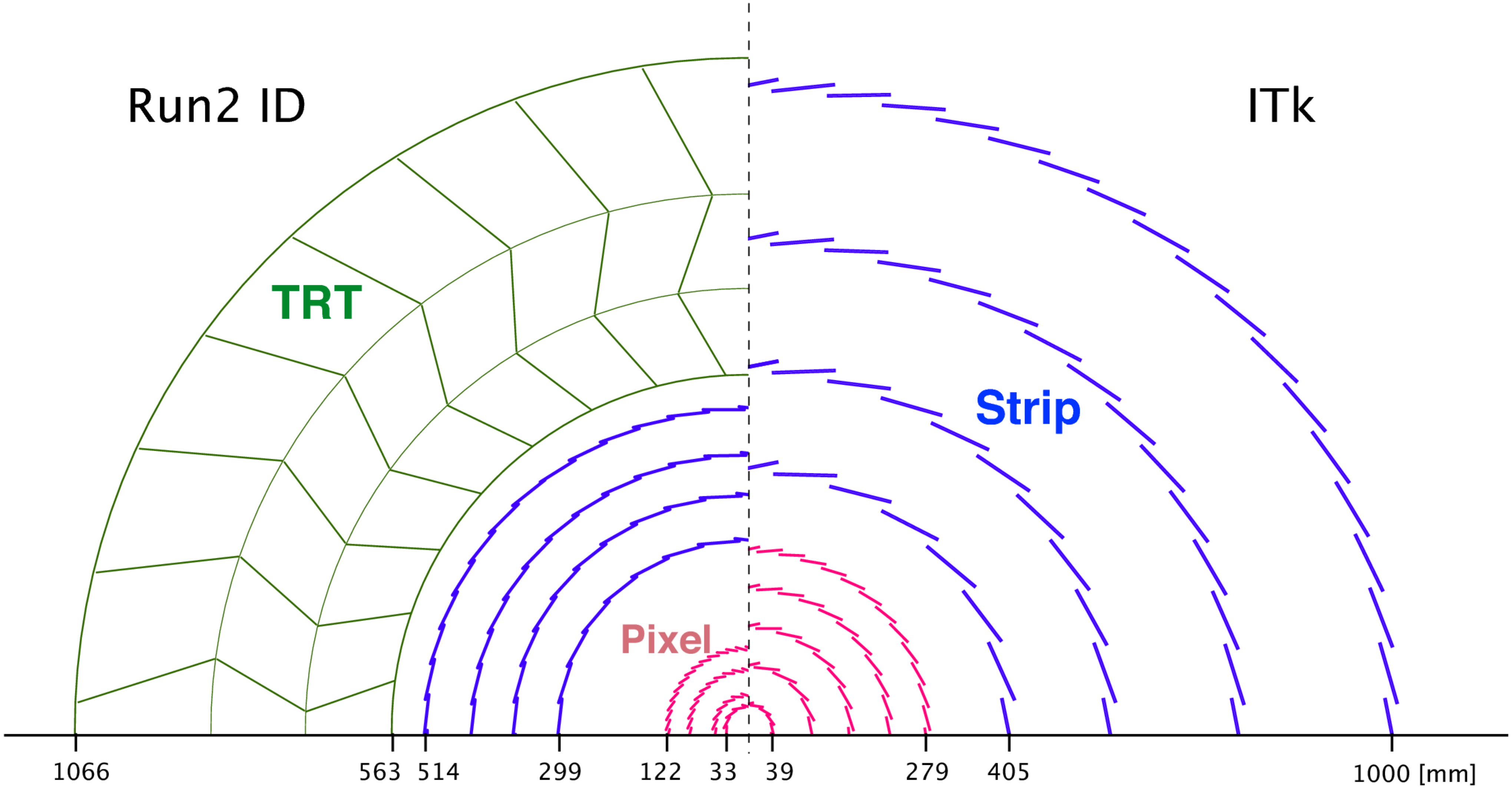


SUSY with R-parity violation

$$\mathcal{W}_{\text{RPV}} = \mu_i l_i h_u + \lambda_{ijk} l_i l_j \bar{e}_k + \lambda'_{ijk} l_i q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

$$P_R = (-1)^{3(B-L)+2s}$$

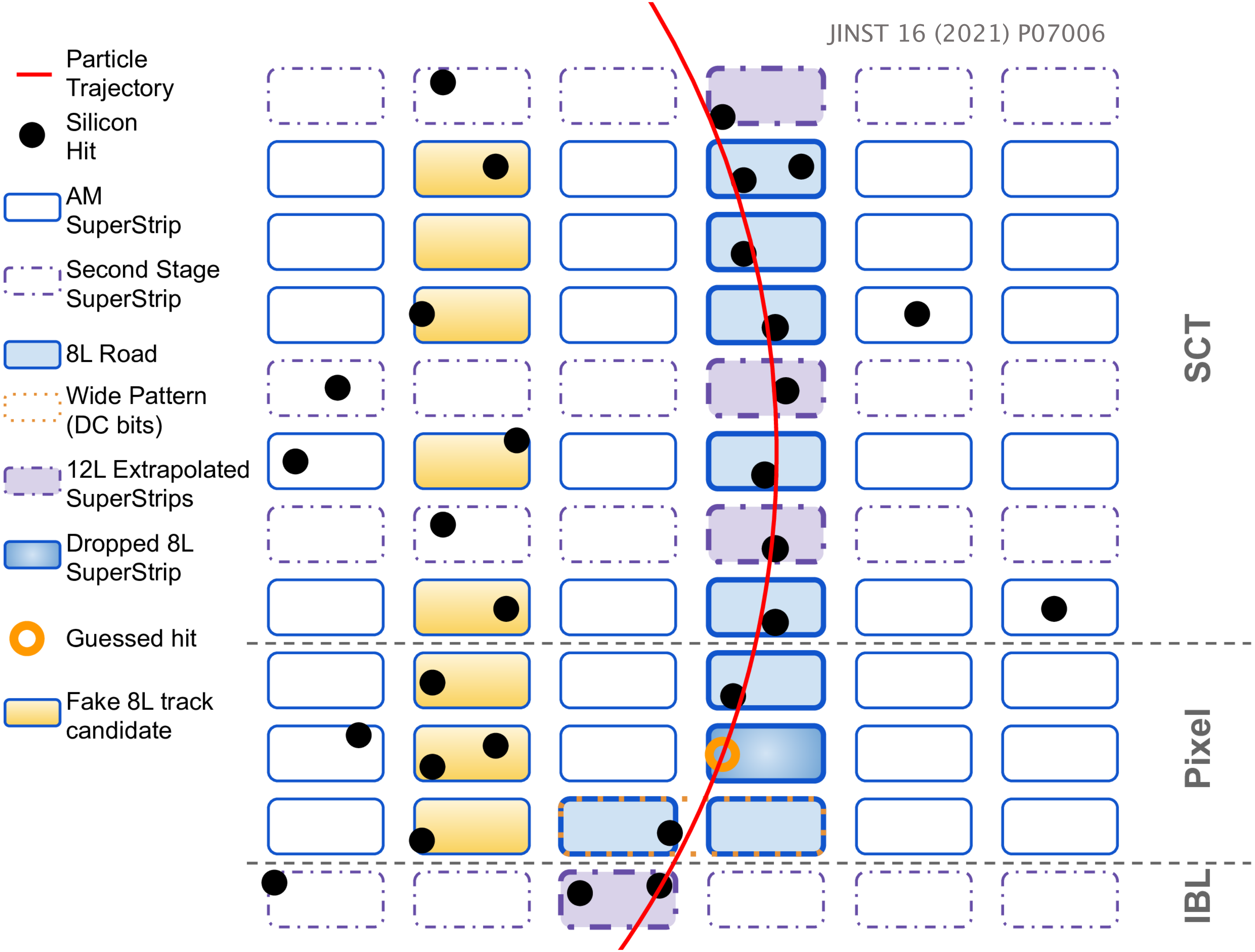



Run2 ID
ITk
TRT
Strip
Pixel
1066
563
514
299
122
33
39
279
405
1000 [mm]

FTK hardware

	Module	Function	Type	Number
IM	Input Mezzanine	Cluster silicon pixel (Pixel) and silicon microstrip (SCT) hits, format module data	Mezzanine	128
DF	Data Formatter	Transport and duplicate module hit data to η–ϕ towers	ATCA	32
AUX	Auxiliary Card	Transport coarse-resolution 8-layer hit data to AMB	VME	128
AMB	AM Board	Transport hit data to AM	VME	128
AM	Associative Memory	Match hits to patterns	ASIC	8192
AUX	Auxiliary Card	Evaluate track candidates in matched patterns	VME	128
SSB	Second Stage Board	Add remaining hits to 8-layer tracks, fit, remove overlaps	VME	32
FLIC	HLT Interface Board	Interface to ATLAS readout	ATCA	2

FTK details


JINST 16 (2021) P07006
Particle Trajectory
Silicon Hit
AM SuperStrip
Second Stage SuperStrip
8L Road
Wide Pattern (DC bits)
12L Extrapolated SuperStrips
Dropped 8L SuperStrip
Guessed hit
Fake 8L track candidate
SCT
Pixel
IBL

Production of FTK constants and sectors

Constants

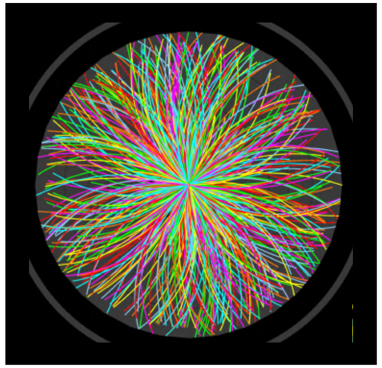
Used to estimate track parameters from hit coordinates

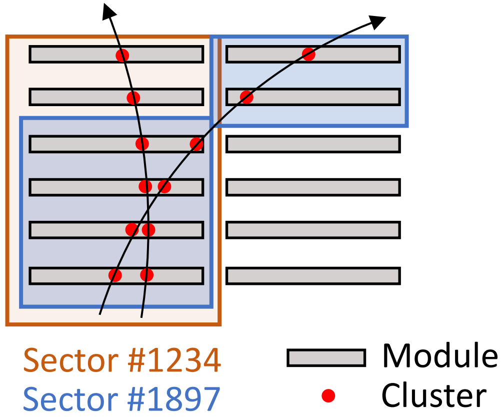
Sector

Combination of 12 silicon modules from different detector layers

1 set of constants per sector

300 million simulated single muon events → **Compile sector list** → **Calculate constants**





fit constants

$$\tilde{p}_i = \sum_{l=1}^{16} C_{il} x_l + q_i$$

track params

hits

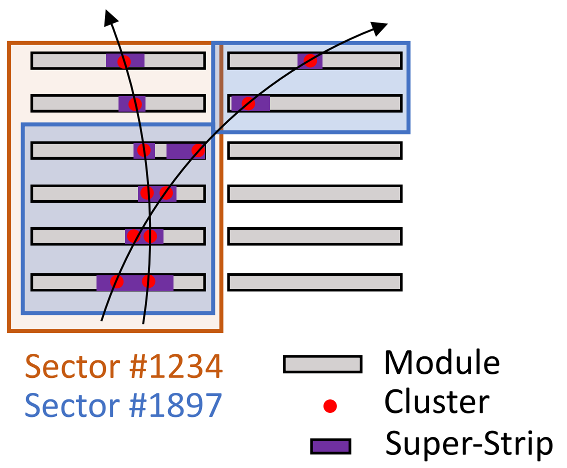
Produces ≈ 1 million sectors … Takes several weeks!

(Sensitive to detector alignment, beamspot position)

Production of FTK constants and sectors

Pattern

Combination of 8 Super-Strips from different detector layers



400 billion muon tracks needed! → ~~Full ATLAS simulation~~

1) Generate random track params.
2) Determine hit coordinates with:

$$\tilde{p}_i = \sum_{l=1}^{N} C_{il}\, x_l + q_i$$

Already calculated

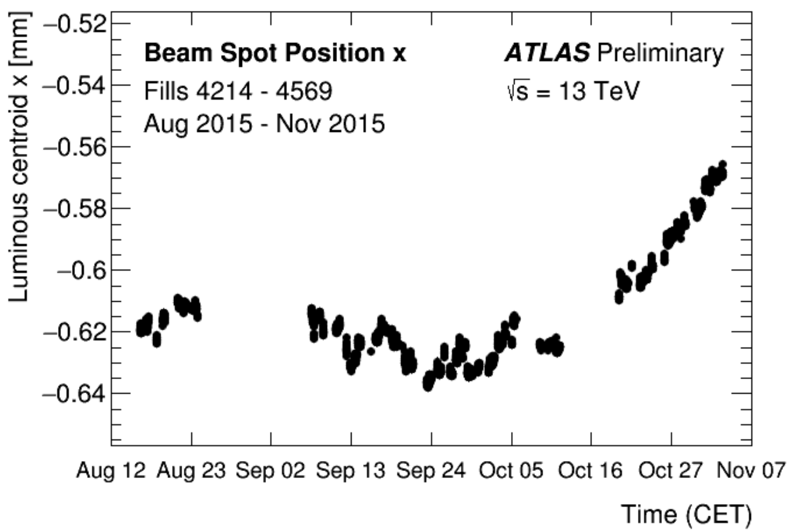
40 billion patterns generated, 1 billion patterns in hardware… Takes ≈ 1 week

(Also sensitive to detector alignment, beamspot position)

Adaptability of FTK system: beamspot position

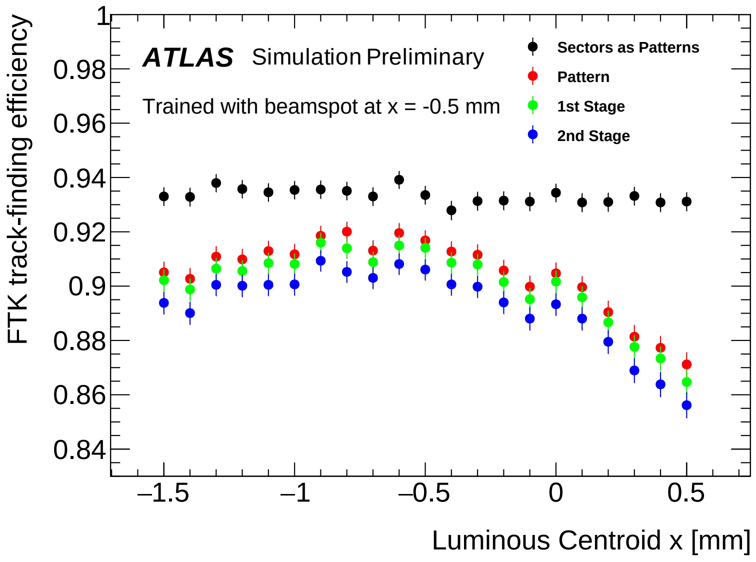
Stability of beamspot:

ATLAS beamspot plots



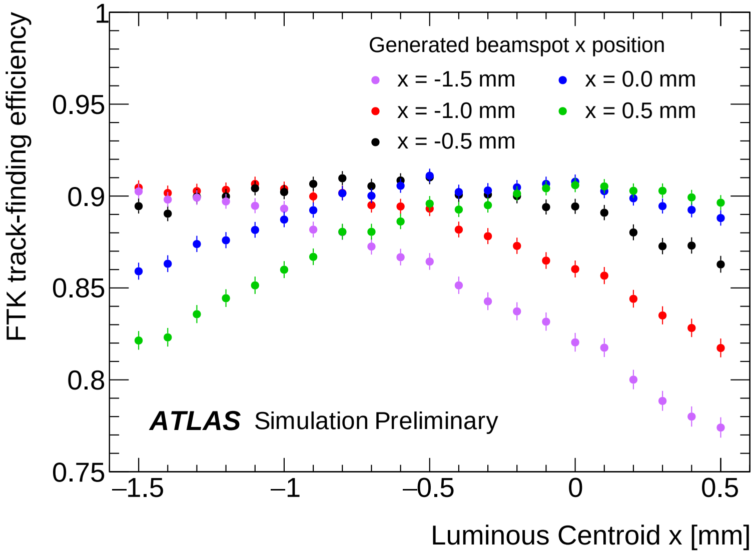
Impact on performance of FTK:

FTK public results

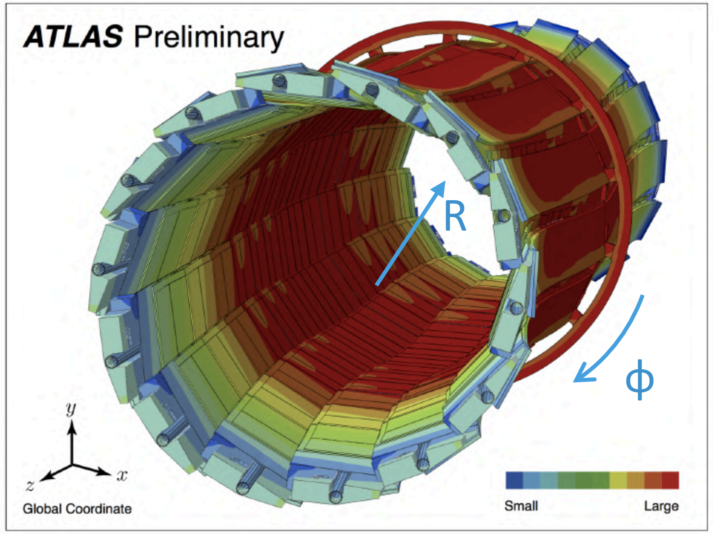


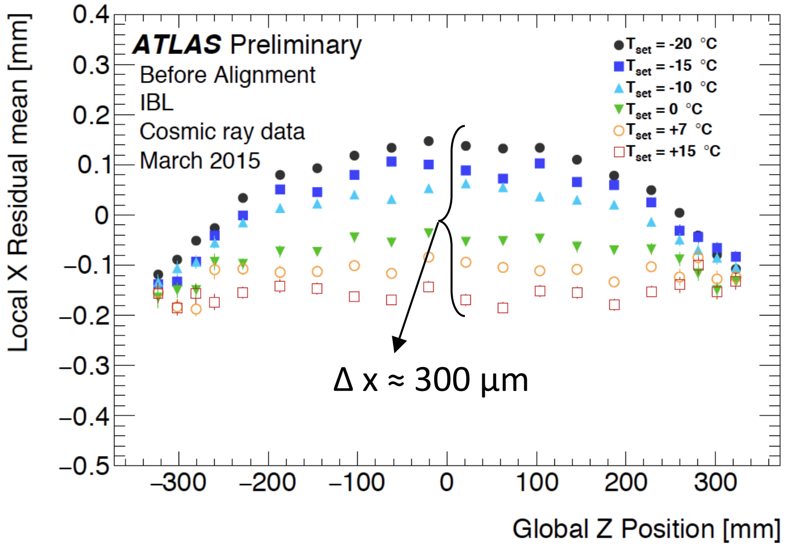
Solution:

FTK public results



Adaptability of FTK system: inner detector module positions





[2]

$$\tilde{p}_i = \sum_{l=1}^{N} C_{il}\, x_l + q_i$$

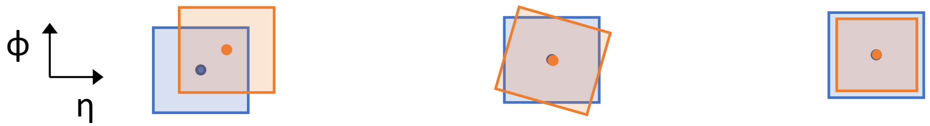
$$\tilde{p}_i = \sum_{l=1}^{N} C_{il}\, (x'_l + \Delta_l) + q_i$$

$$= \sum_{l=1}^{N} C_{il}\, x'_l + \underbrace{\left(\sum_{l=1}^{N} C_{il}\, \Delta_l + q_i\right)}_{q'_i}$$

C_{il}, q_i : fit constants

x_l: hit coordinates

$\tilde{p}_i$: track parameters



Δη, Δϕ of module center ✓

Rotations ✗

Radius from detector origin ✗

FTK vs. offline tracks