Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

Louie Corpe (CERN), for the ATLAS collaboration

EPS-HEP 2021

Why look for long-lived particles?

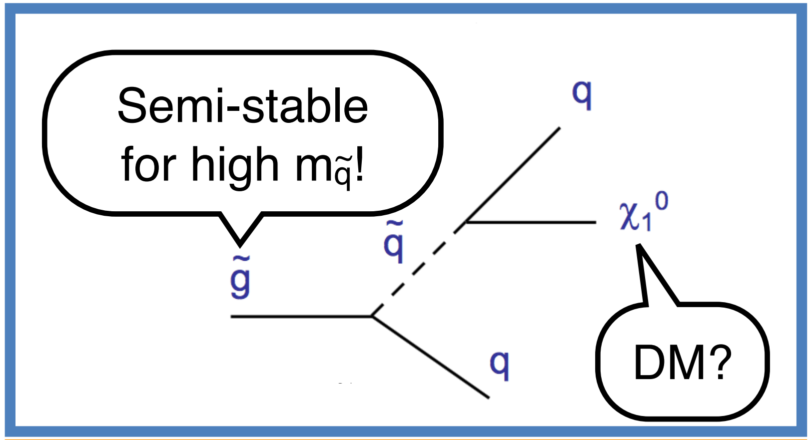
- **Semi-stable particles** everywhere in the SM!
- LLPs occur when **decay suppressed**
- Suppressed decays **are predicted in many extensions to SM,** leading to LLPs:

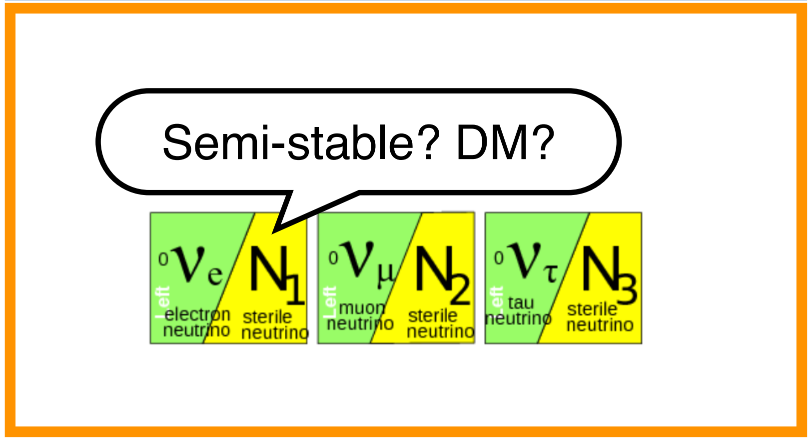
→ SUSY

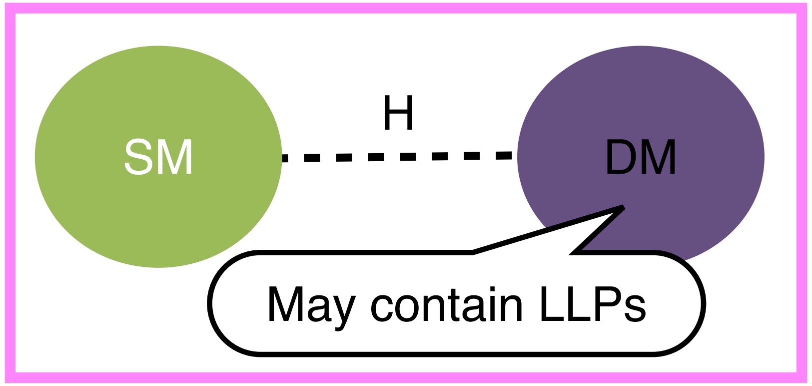
→ Heavy Neutral Leptons

→ Hidden / Dark Sector

→ …

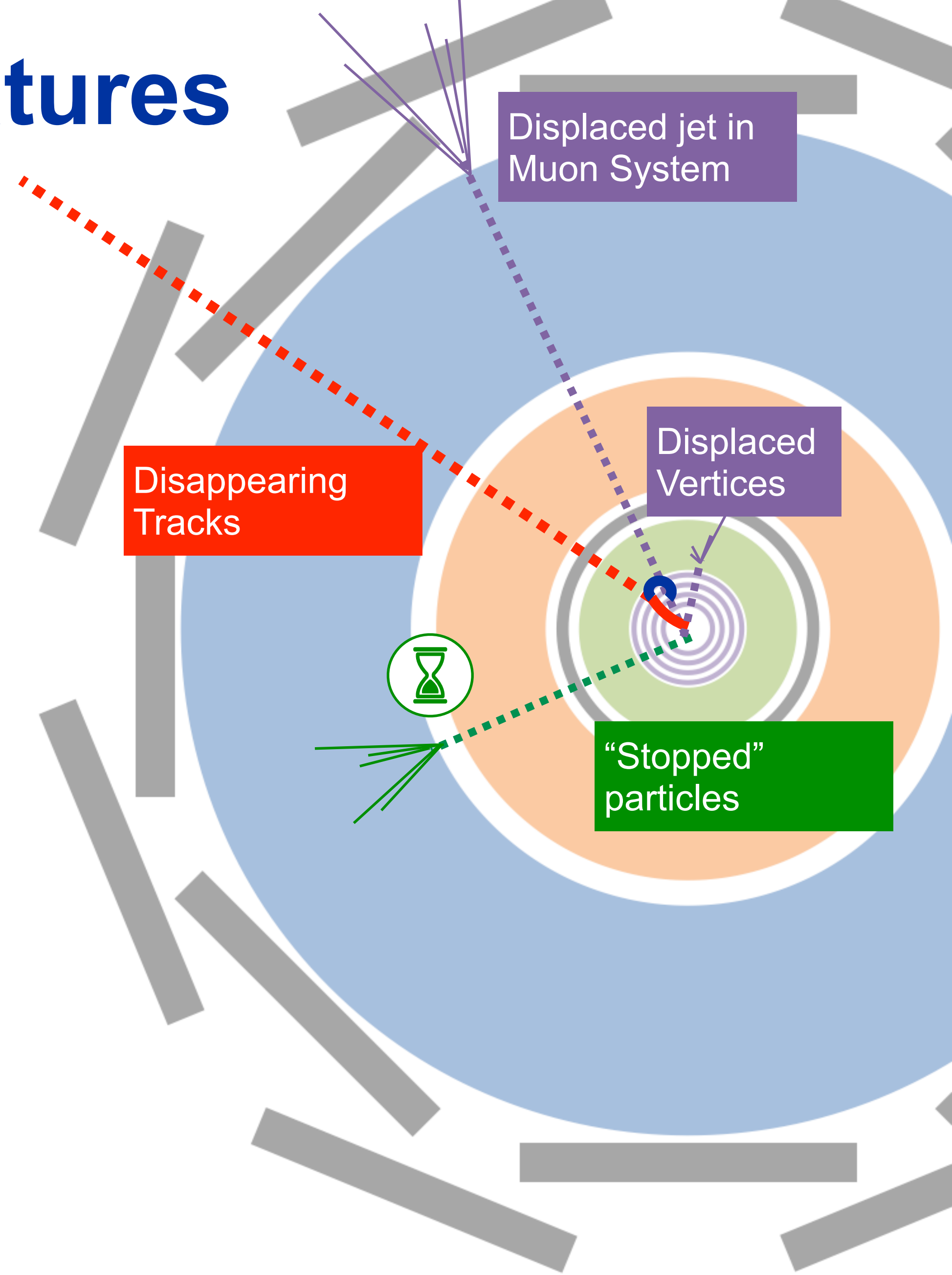






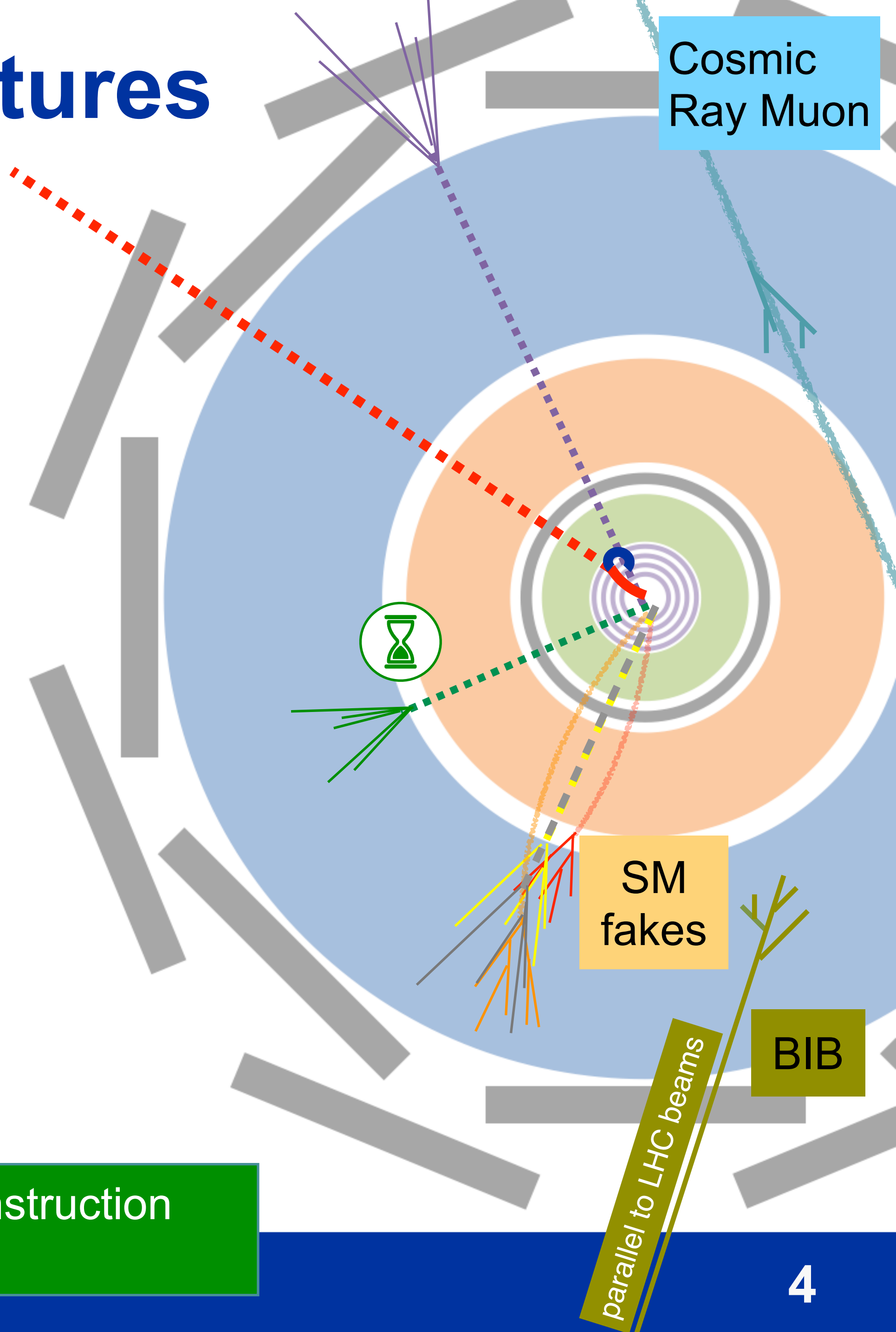
…but these are challenging signatures

- **LLPs** could lead to a plethora of unusual signatures, depending on…
  - LLP lifetime / decay length
  - Charge of LLP and decay products
  - Interaction of LLP with detector



…but these are challenging signatures

- **LLPs** could lead to a plethora of unusual signatures, depending on…
  - LLP lifetime / decay length
  - Charge of LLP and decay products
  - Interaction of LLP with detector
- Unusual signatures = **unusual backgrounds**
  - Beam-induced background (BIB)
  - Cosmic Rays
  - Improbable-but-not-impossible SM fakes

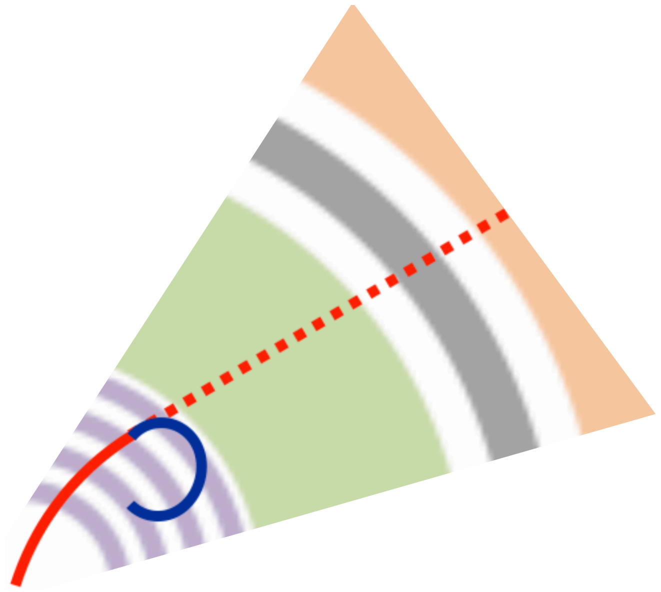


ATLAS was not designed for LLP searches: custom reconstruction and techniques needed for these unusual signatures!

Search for disappearing tracks

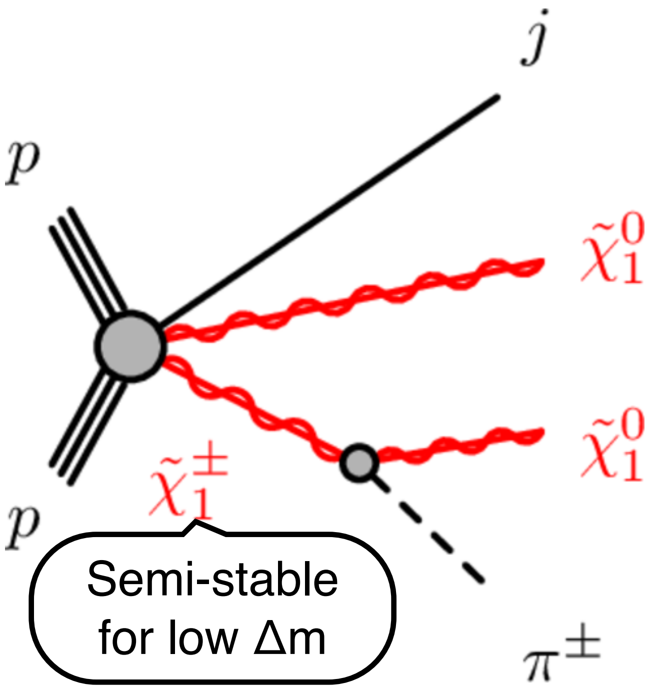
At 13 TeV with the ATLAS detector

http://cdsweb.cern.ch/record/2759676



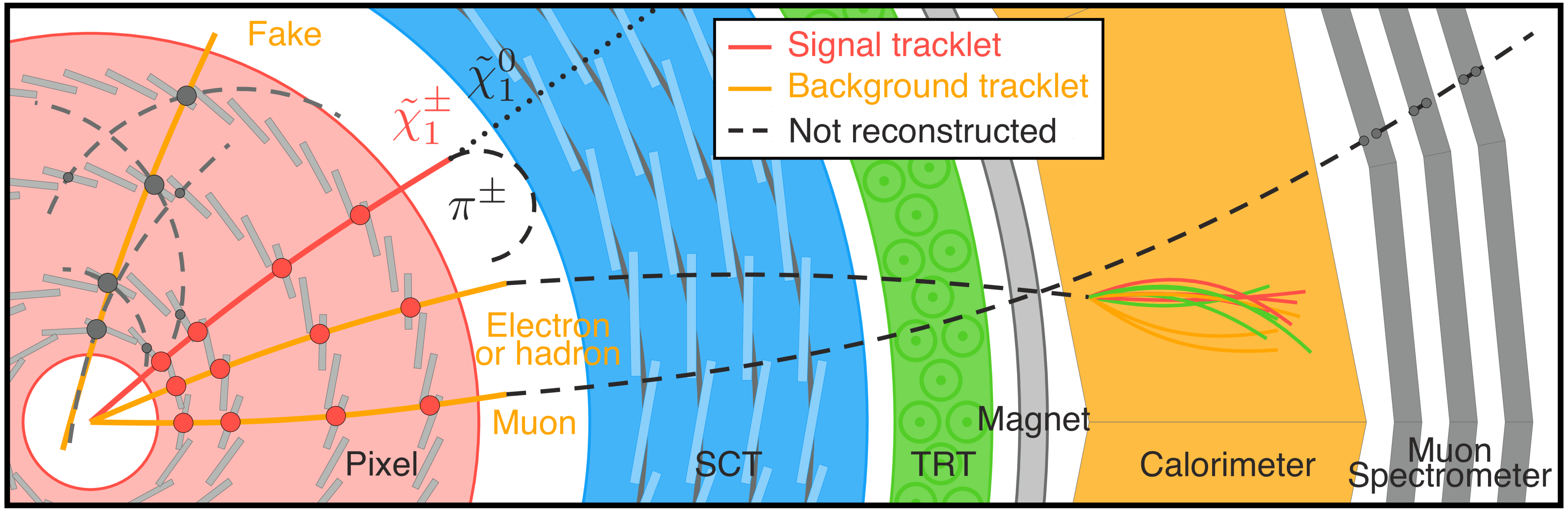
Disappearing tracks: motivation

- What if **LLP is charged**, but **decay products are neutral**?
  - "Disappearing track" signature!
  - Occurs for example in SUSY models where mass difference between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{0}$ is small -> suppressed decay / long-lived $\tilde{\chi}_1^{\pm}$ with $\tau \sim 0.2$ ns
  - Example: models with pure winos or higgsinos, natural +large part of pMSSM parameter space
  - Benchmark model also motivated for Dark Matter



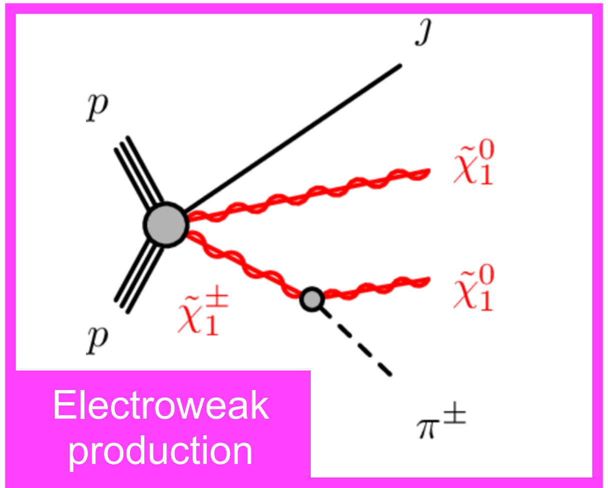
New ATLAS search using full-run-2 dataset with 136/fb at 13 TeV.

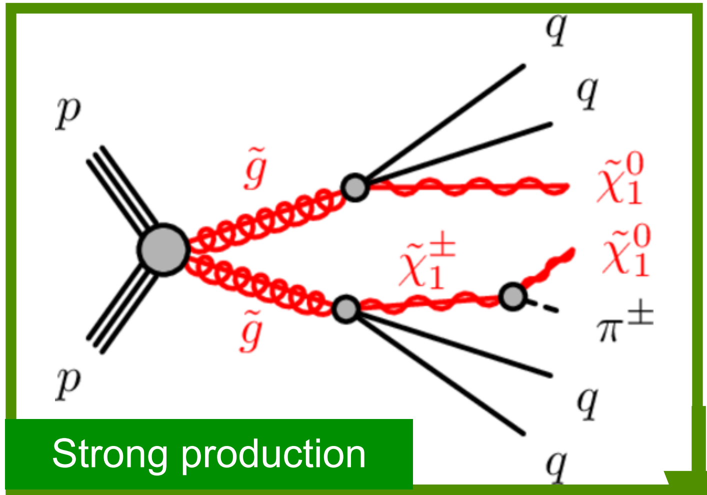
Uses E_T^{Miss} triggers, and veto data with inactive SCT elements (2.7/fb)



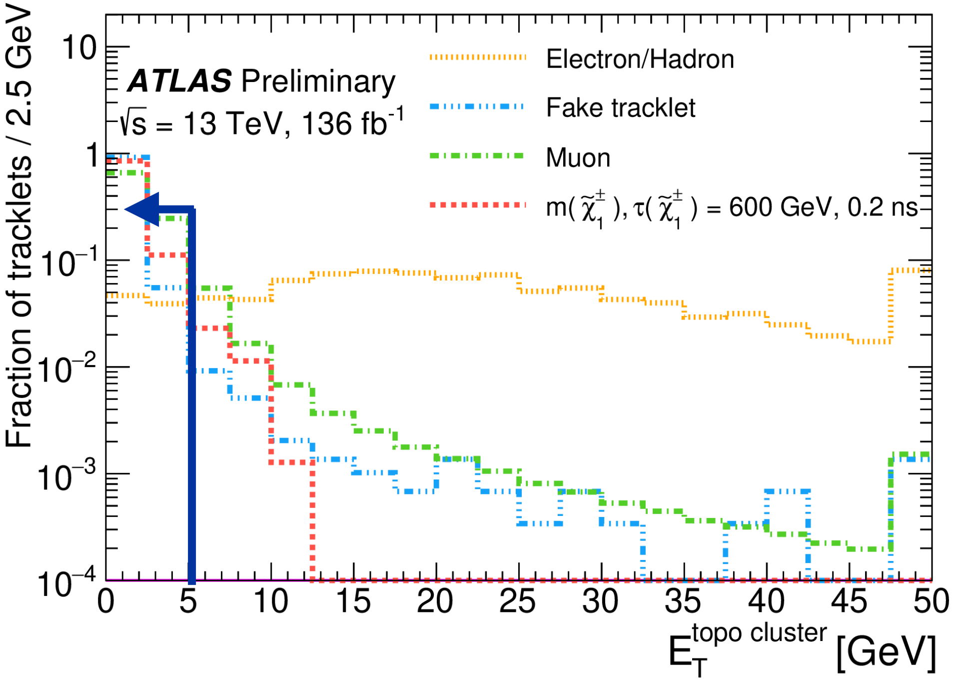
Selecting disappearing tracks

Pixel Tracklets:
- 4 hits in consecutive Pixel detector layers, including innermost
- p_T > 20 GeV, 0.1 < |η| < 1.9
- Isolated + associated to Primary Vertex
- **Veto on upstream SCT hits**
- **Cut on upstream calorimeter activity** New !





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

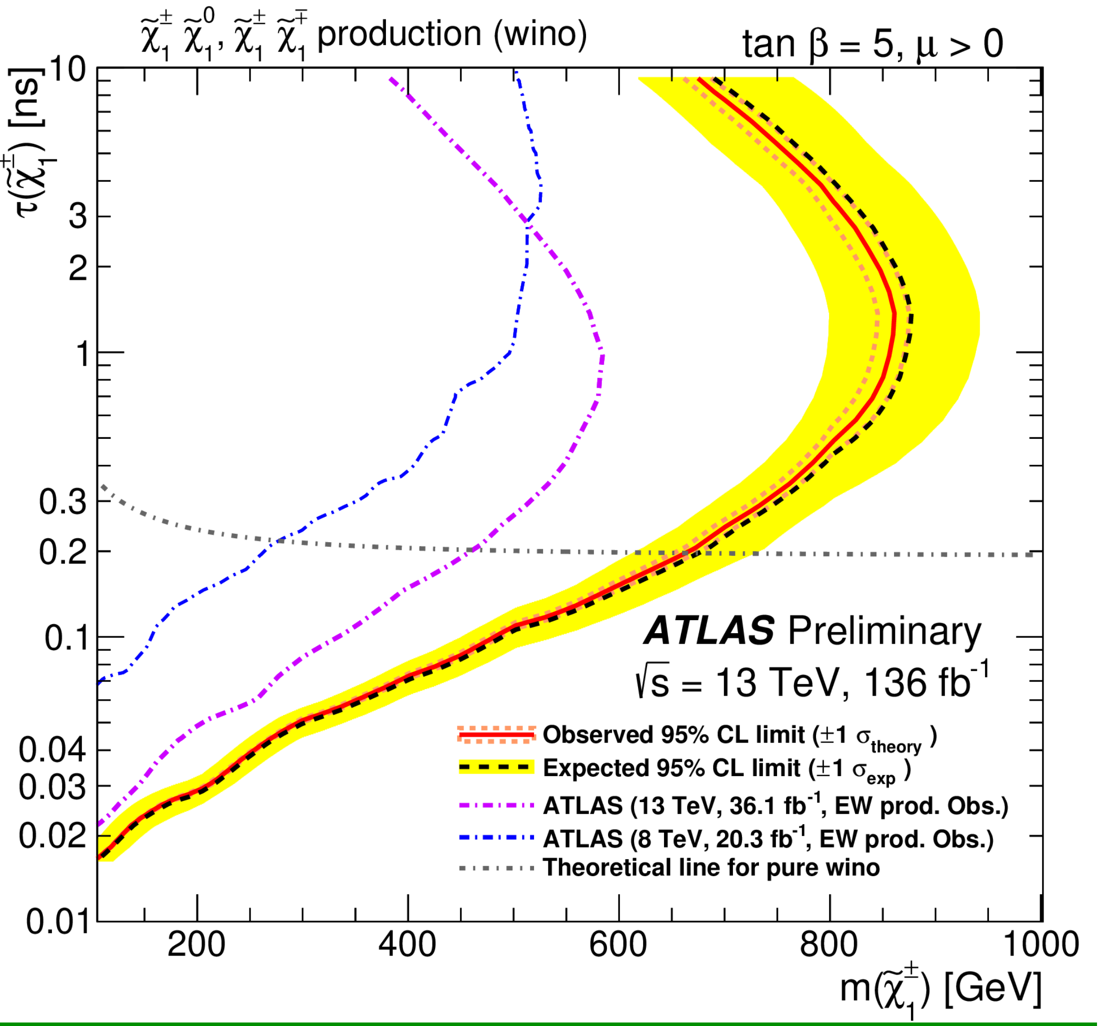


Results

- Data-driven background estimates: templates derived in dedicated control regions, and normalised using likelihood fit to tracklet p_T spectrum
- Uncertainties: bkgd O(1-7%), sig O (15%)

	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
p_0 (Z)	0.5 (0)	0.38 (0.30)
Observed $\sigma_{vis^{95\%}}$ [fb]	0.037	0.028
Expected $\sigma_{vis^{95\%}}$ [fb]	$0.038\ ^{+0.014}_{-0.009}$	$0.024\ ^{+0.009}_{-0.003}$

No excess observed



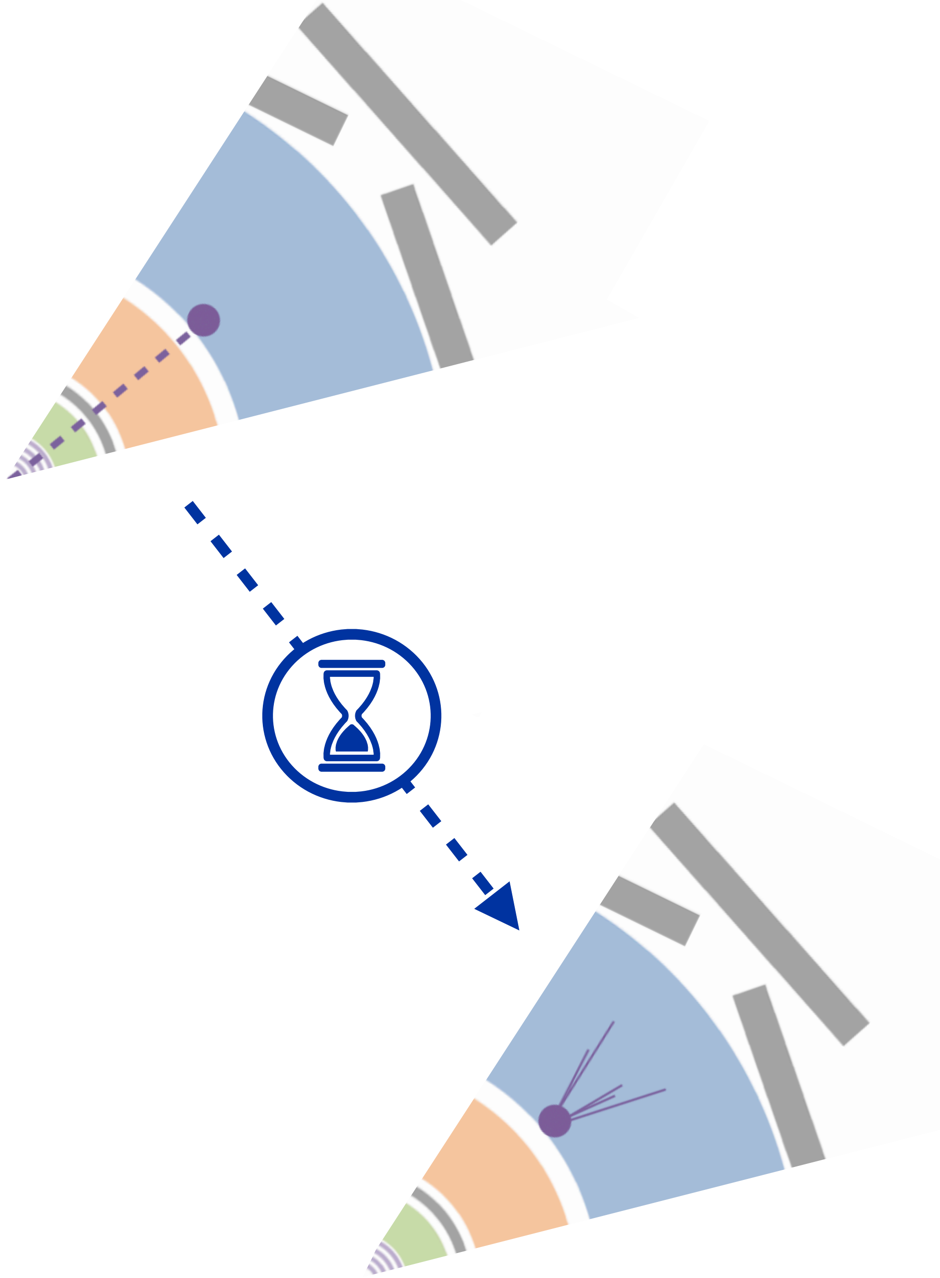
Strong improvement in constraints driven by additional luminosity and new tracklet E^{topo} cut

Most stringent limits on pure winos or higgsinos so far

Search for stopped long-lived particles

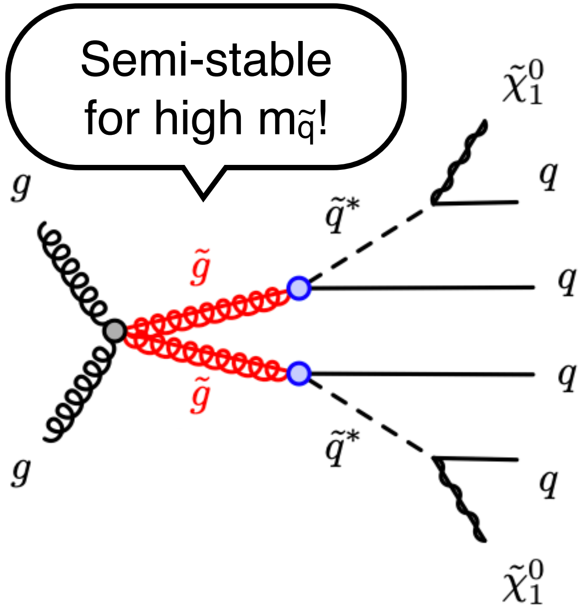
At 13 TeV with the ATLAS detector

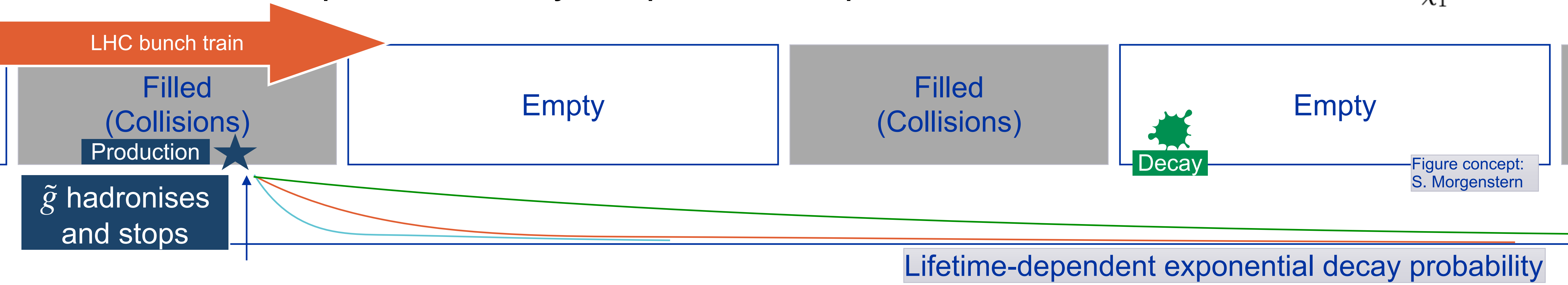
https://arxiv.org/pdf/2104.03050.pdf



Stopped particles: motivation

- If LLP is slow moving and loses momentum though interactions with detector, there is a probability it can be stopped, then decay at a later time:
  - Example: split SUSY: long-lived gluinos
- Strategy: use **empty bunch crossings (BXs)** from LHC bunch train to pick out decays of particles in previous BXs

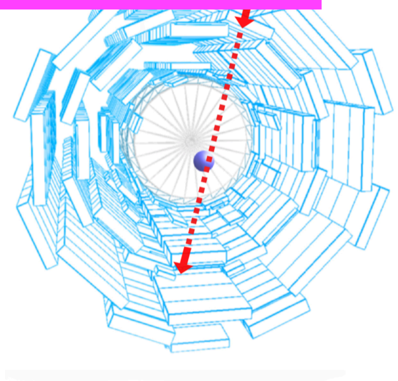


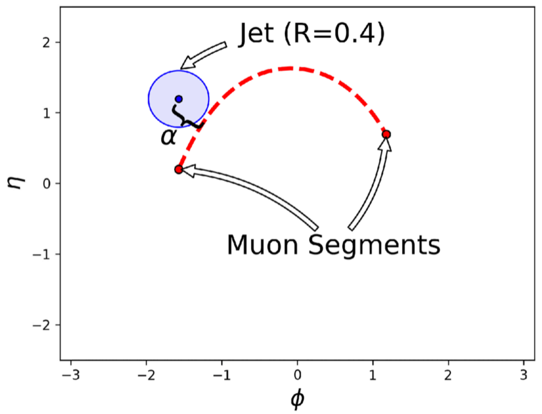


- 2017 dataset: 49.0/fb filled BXs, 298h empty BXs
- 2018 dataset: 62.1/fb filled BXs, 281h empty BXs (different bunch train configuration)

Stopped particles: backgrounds

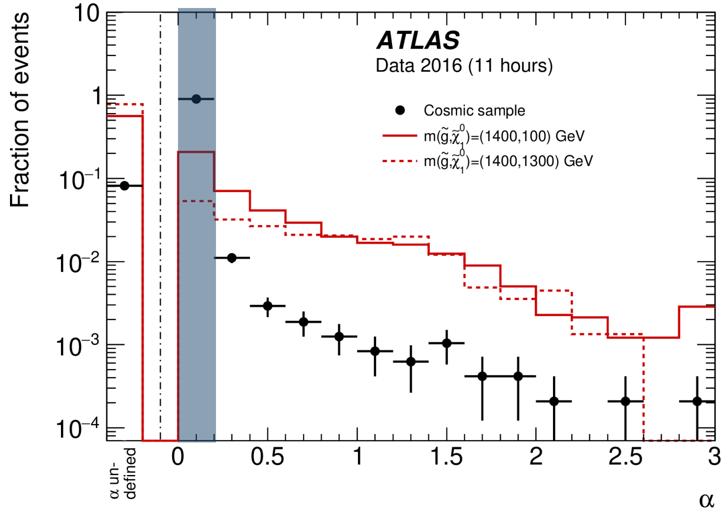
Cosmics





Dedicated cosmic run in 2016:
data taken with no beams

α represents geometrical distance between leading jet and candidate cosmic track: veto small values

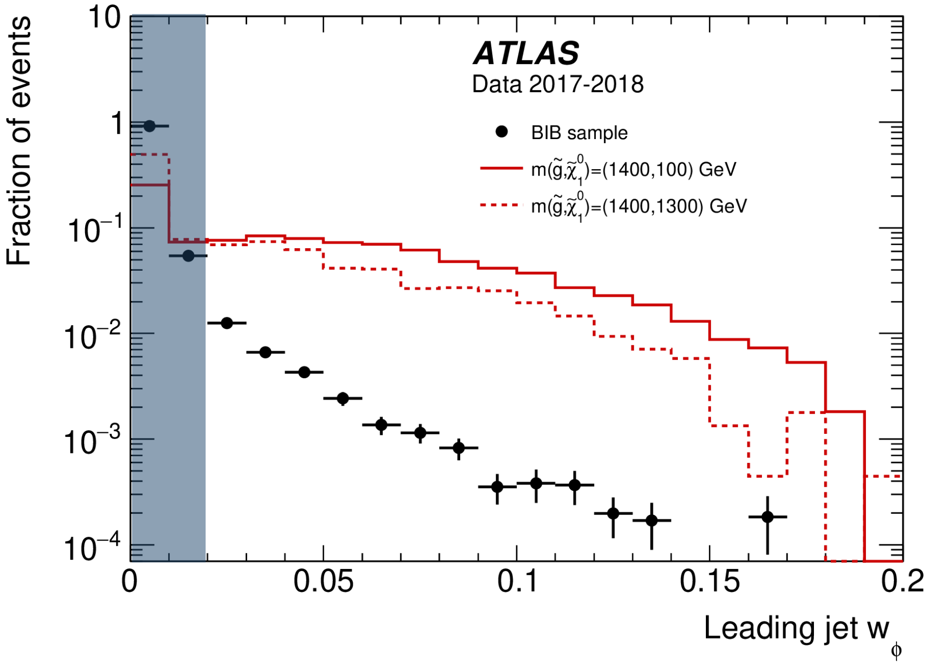


BIB

Data from “unpaired” BXs (beam on one side only)

w_Φ represents width of jet in Φ (p_T-weighted average ΔΦ between jet axis and each cluster)
>> Veto small values

$$w_\phi = \frac{\sum_i p_\mathrm{T}(i) \cdot |\Delta\phi(\mathrm{jet}, i)|}{\sum_i p_\mathrm{T}(i)}$$



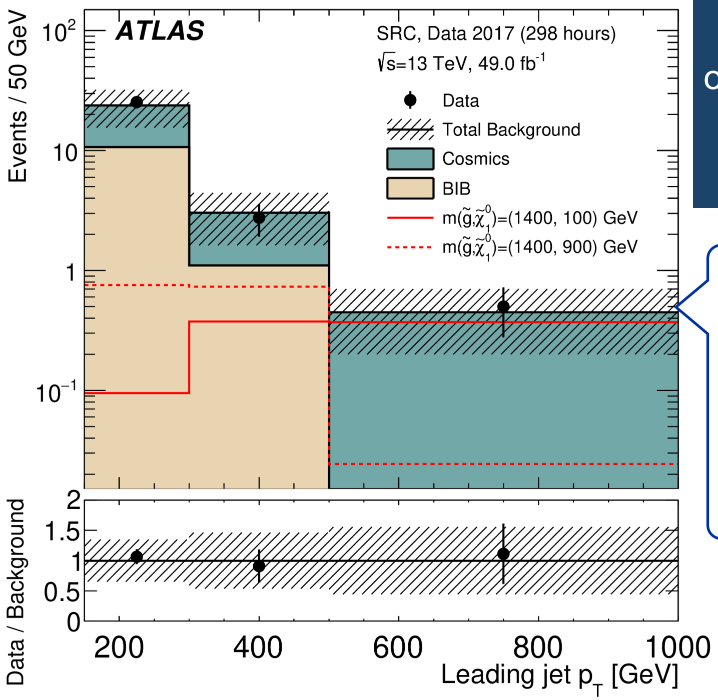
Residual BIB/Cosmics bkgs estimated in Control Regions with transfer factors to main search regions

Stopped particles: Results

Target SUSY models where decays happen centrally

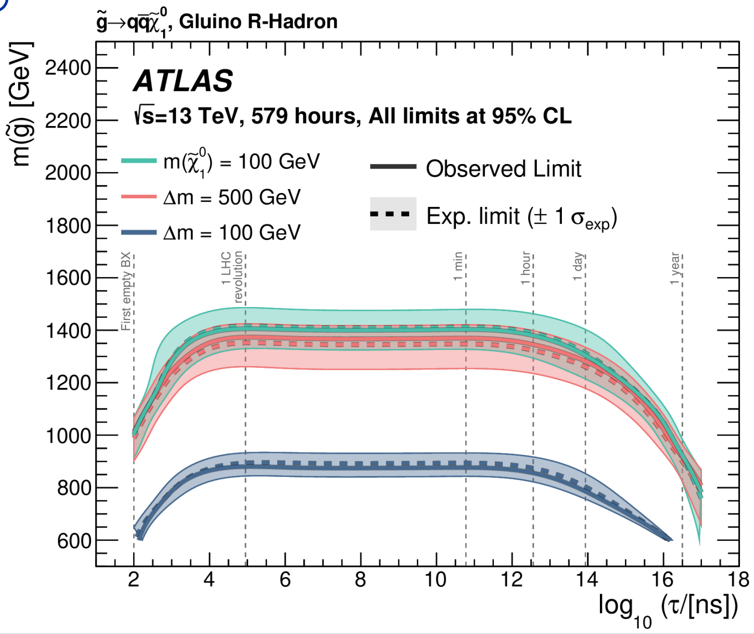
More general region where decays need not be central

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



No excess observed (similar 2018 and SRIncl)

Uncertainties dominated by background normalisation and shape, O(20-50%)



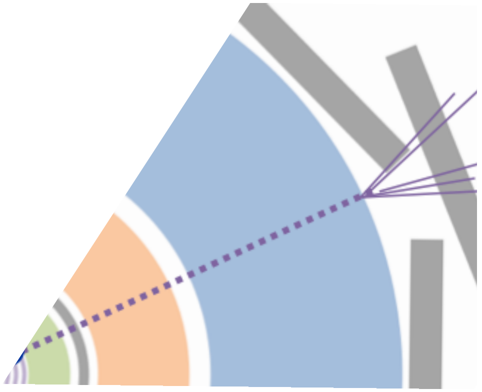
- Limits extracted using multi-bin fit in Search Regions and extrapolated using calculated live time as a function of lifetime
- Gluinos masses up to 1.4 TeV excluded for lifetimes from 10µs to 1 day

New for EPS-HEP21!

Search for displaced vertices in the Muon Spectrometer

At 13 TeV with the ATLAS detector

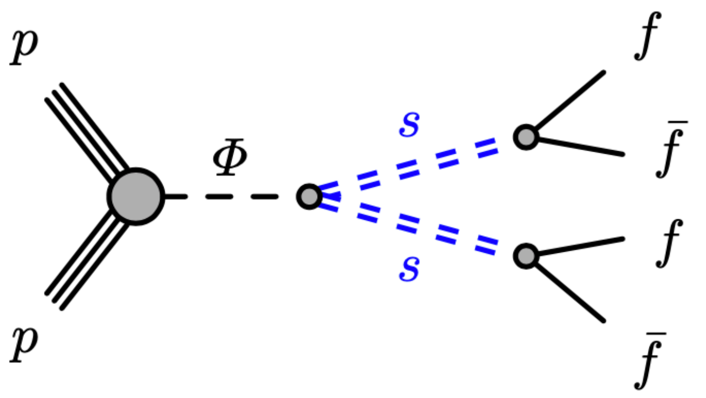
Xxx (to be completed when CONF note appears)



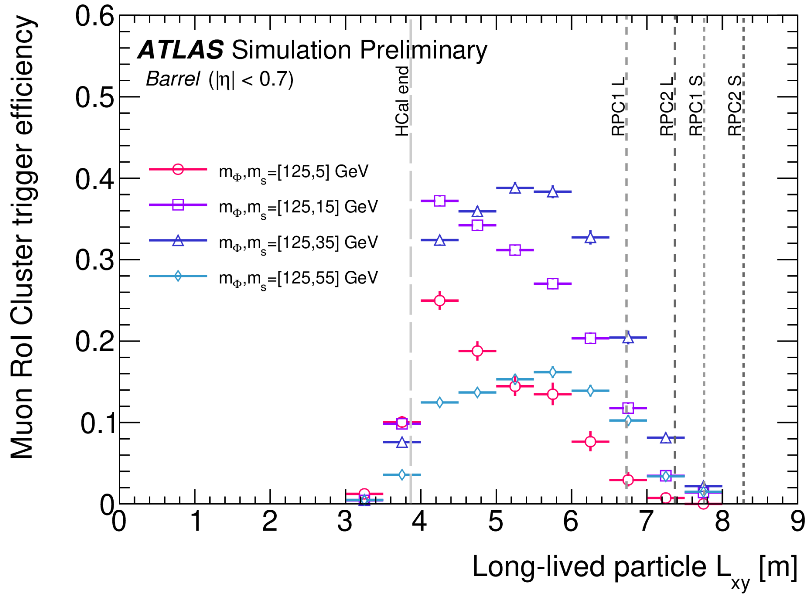
Why displaced MS vertices?

New for EPS-HEP21!

- Neutral LLPs travel through ATLAS undetected until they decay: **signature depends on decay position**
- Example: **Hidden Valley models**, where LLPs produced via Higgs-like mediator Φ. Scalars ***s* are long lived due to weak coupling** to SM.



- This search: **pairs of displaced vertices (DVs)** in MS, using 139/fb of 13 TeV data.
  - ATLAS Muon Spectrometer has good acceptance for a broad range of LLP lifetimes: **O(mm) - O(km)**
  - Require **2xDVs to severely reduce background**
  - *Dedicated HLT trigger*: JINST 8 (2013) P07015
    MS cluster with at least 3 (4) L1 muons within 0.4 of seed in barrel (endcaps)
  - *Dedicated vertexing algorithms* JINST 9 (2014) P02001
    (for barrel/endcaps with different magnetic fields)



MS vertex: selection, backgrounds, results

New for EPS-HEP21!

- Two isolated MS vertices. Exclude DVs in MS/HCal Barrel-Endcap transition regions
- MS vertices matched to triggering cluster(s), and vertices separated by $\Delta R > 1$

- Main background = punch-through QCD jets.

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

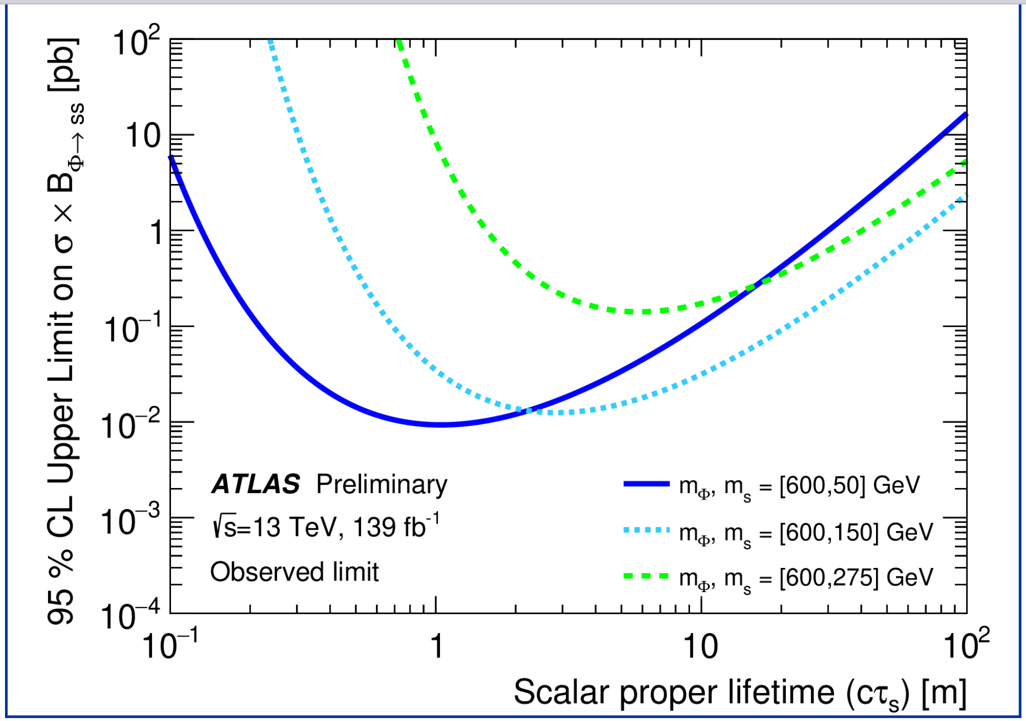
674775 4.6 x 10^{-7} 3 3.2 x 10^{-3} 0 3.53 x 10^{-2}

= 0.32 ± 0.05 (statistical errors)

0 events observed in data

- Main uncertainties:
  lifetime extrapolation O(0-30%),
  modelling of trigger efficiency O(20-25%),
  vertex reconstruction efficiency O(10-15%)

Limits set on a wide range of Hidden-Sector models for mediator masses between 60 GeV and 1 TeV and scalar LLP masses between 5 and 475 GeV



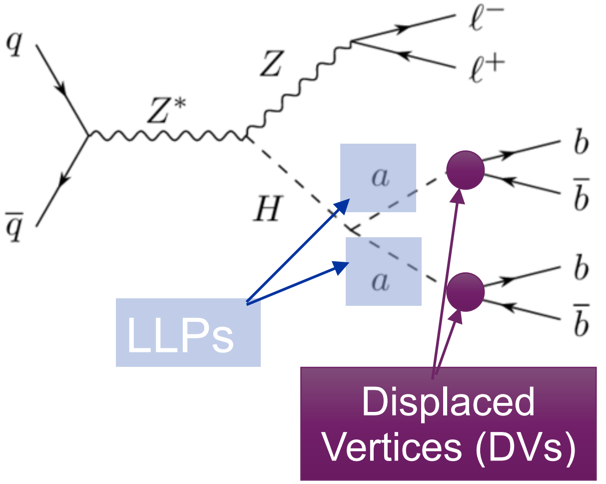
Search Exotic Higgs decays to LLPs

At 13 TeV with the ATLAS detector

https://arxiv.org/abs/2107.06092

Exotic Higgs to 4b

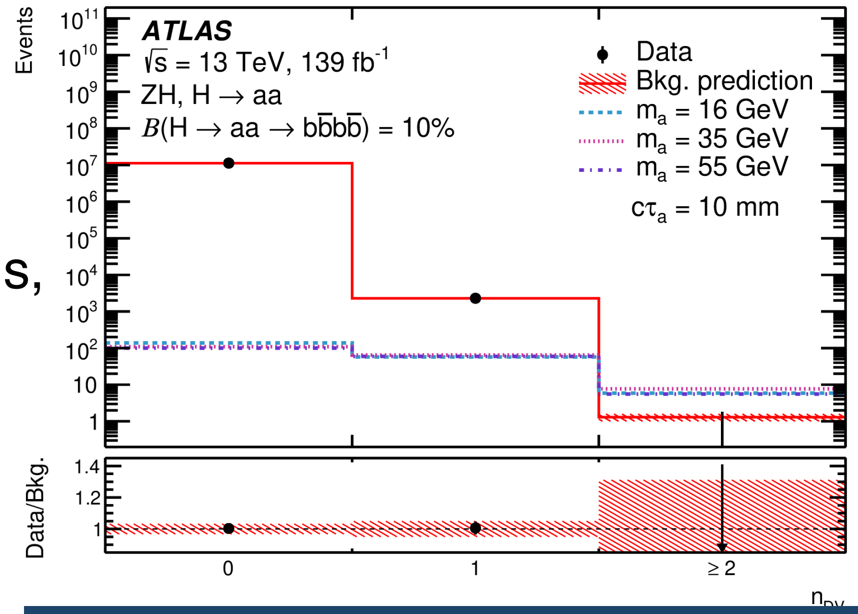
- Mediator in hidden valley models can be Higgs Boson itself
- O(cm) decay lengths difficult to cover due to background + triggering
- Exploit ZH production: trigger on leptons, benefit from large BR to b-quarks



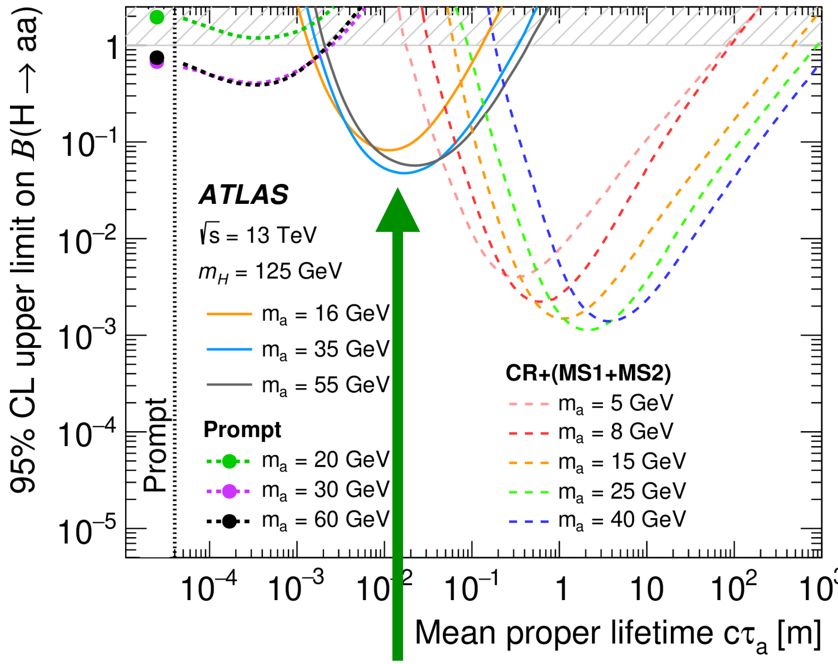
- Use “large-radius tracking” (with looser track-to-vtx association requirements) to reconstruct displaced vertices (DVs)
- Require ≥ 2 jets, leading 4 b-jets matched to DVs

- Data-driven bkg estimate based on DV probability as function of p_T & b-tagging (measured in low-DV regions, validated in y+jet region)

- Main systs: non-standard tracking vertexing (2-12%), theory uncertainties (~5%)



Predicted events: 1.30 ± 0.08 (stat.) ± 0.27 (syst.)
Observed events: 0



Fills gap in coverage at O(cm) decay lengths

Summary

- Direct searches for long-lived and unusual signatures are an important part of the LHC programme, as these signatures could have been missed or thrown away as noise: Important to check all our blind spots!

- Many different mechanisms can lead to LLPs, and they pop up in many extensions to the Standard Model

- Presented results of three recent searches using the ATLAS full Run-2 dataset, with different assumptions on how the LLPs and associated particles are charged and interact with the detector

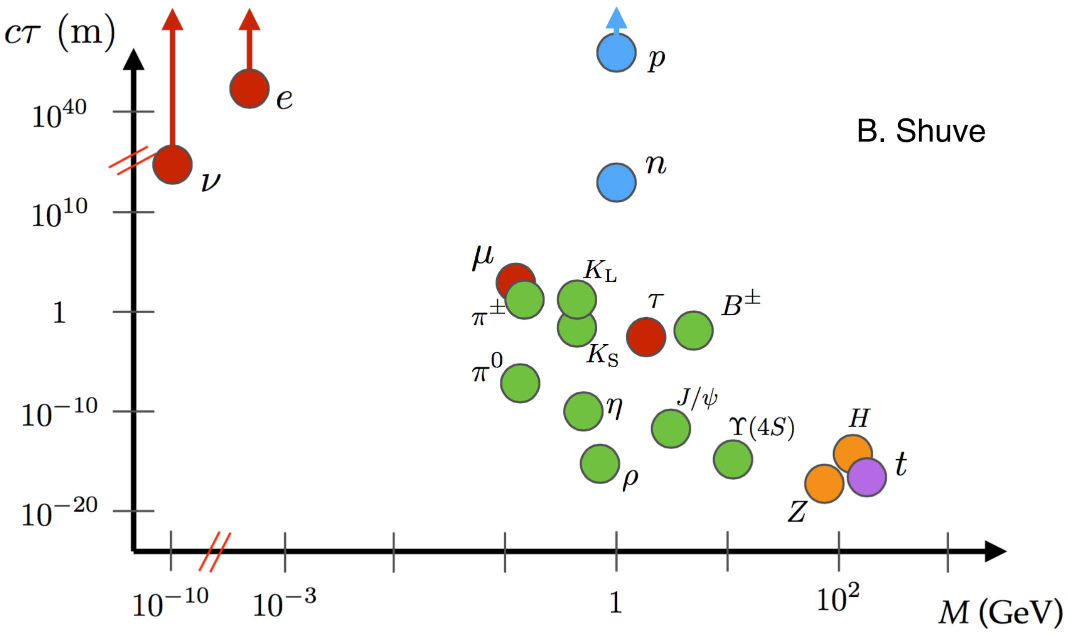
- More searches in complementary channels are in preparation: watch this space

Thank you

Any questions?

Why look for long-lived particles?

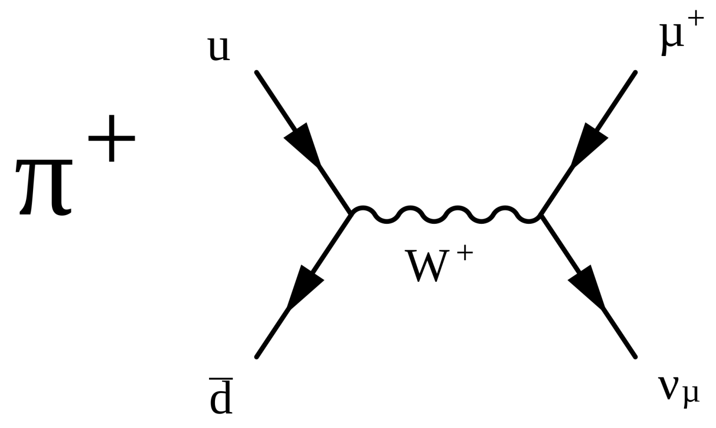
- **Semi-stable particles** everywhere in the SM!
  - *Long-lived particles* (LLPs) := **do not decay instantly** (eg Higgs, W/Z, t, etc)

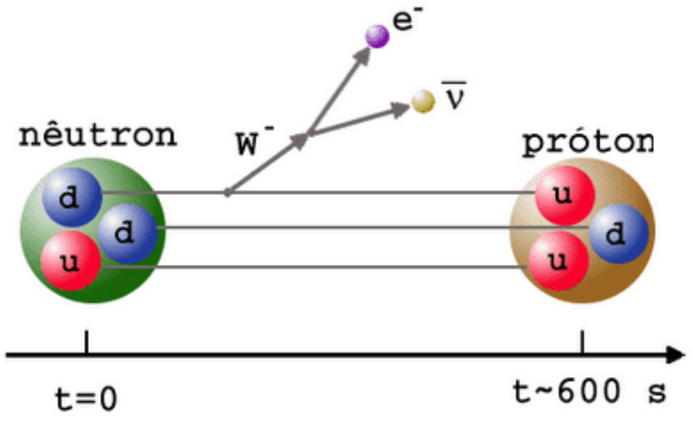


B. Shuve

Why look for long-lived particles?

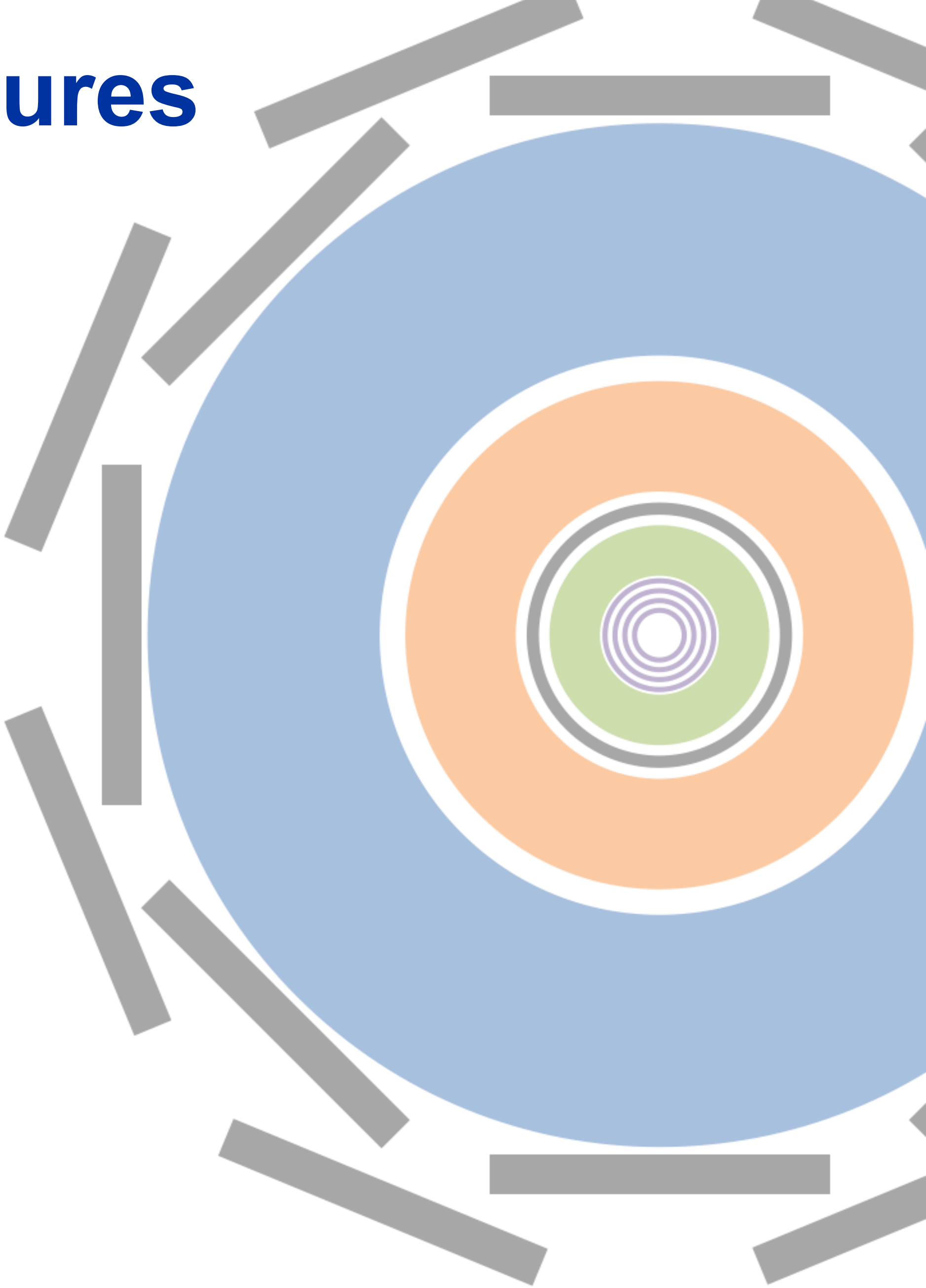
- **Semi-stable particles** everywhere in the SM!
- LLPs occur when **decay suppressed**:
  - Decay interaction **very weak /** mediator particle **very heavy**
  - Density of final states **very low /** Particles **very close** in mass





…but these are challenging signatures

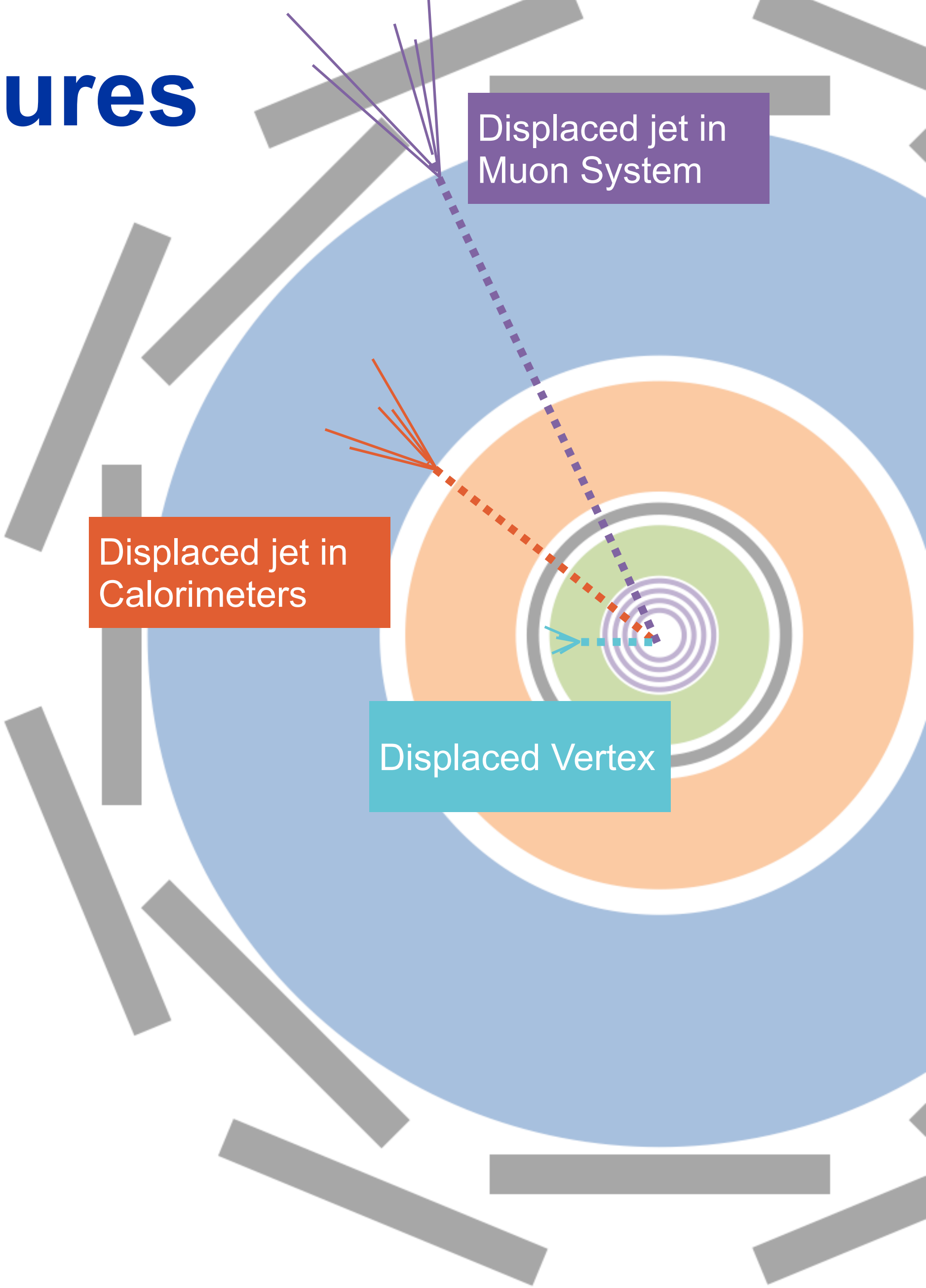
- **LLPs** could lead to a plethora of unusual signatures, depending on…



…but these are challenging signatures

- **LLPs** could lead to a plethora of unusual signatures, depending on…

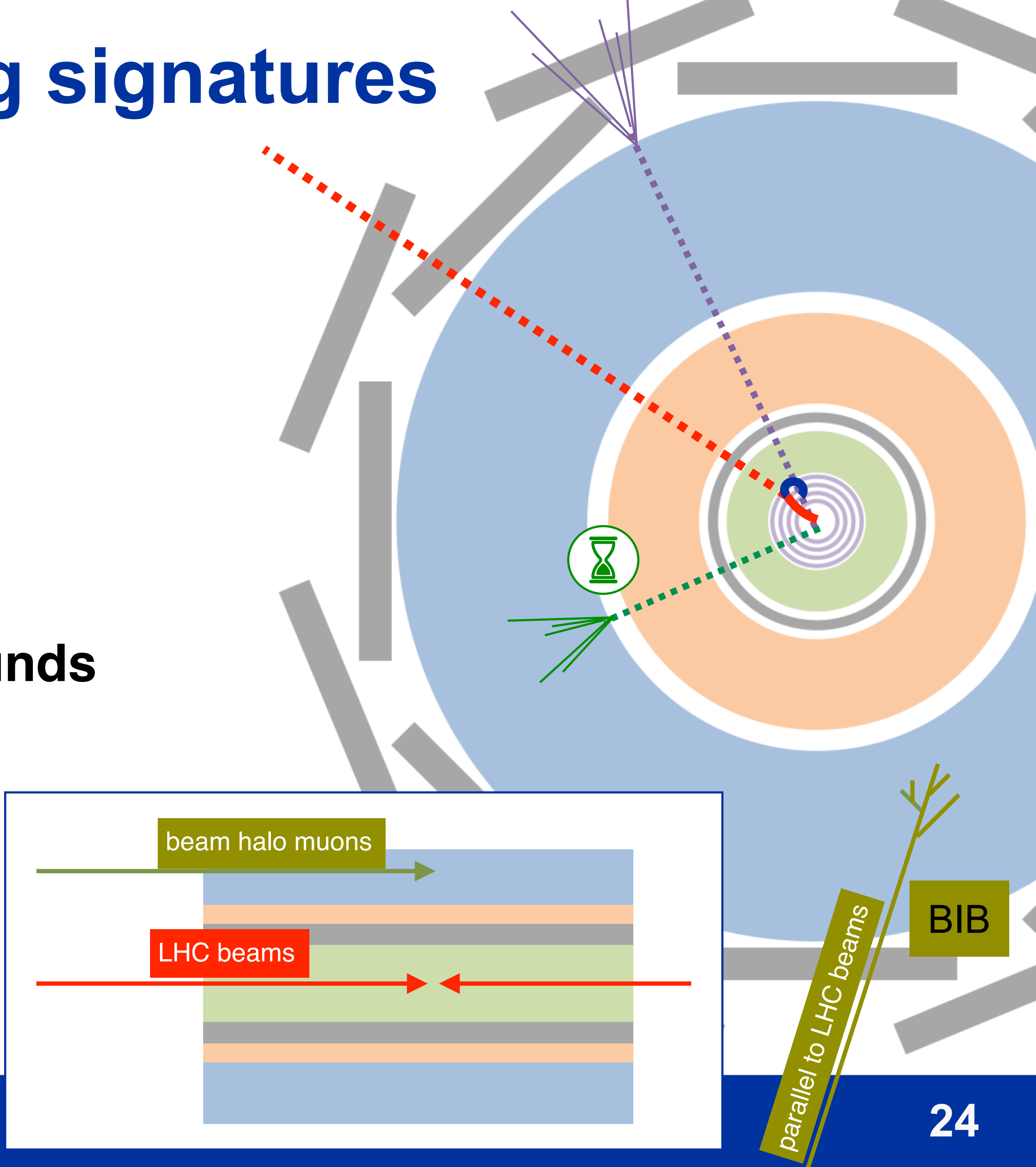
  - LLP **lifetime** / decay length



…but these are challenging signatures

- **LLPs** could lead to a plethora of unusual signatures, depending on…
  - LLP lifetime / decay length
  - Charge of LLP and decay products
  - Interaction of LLP with detector

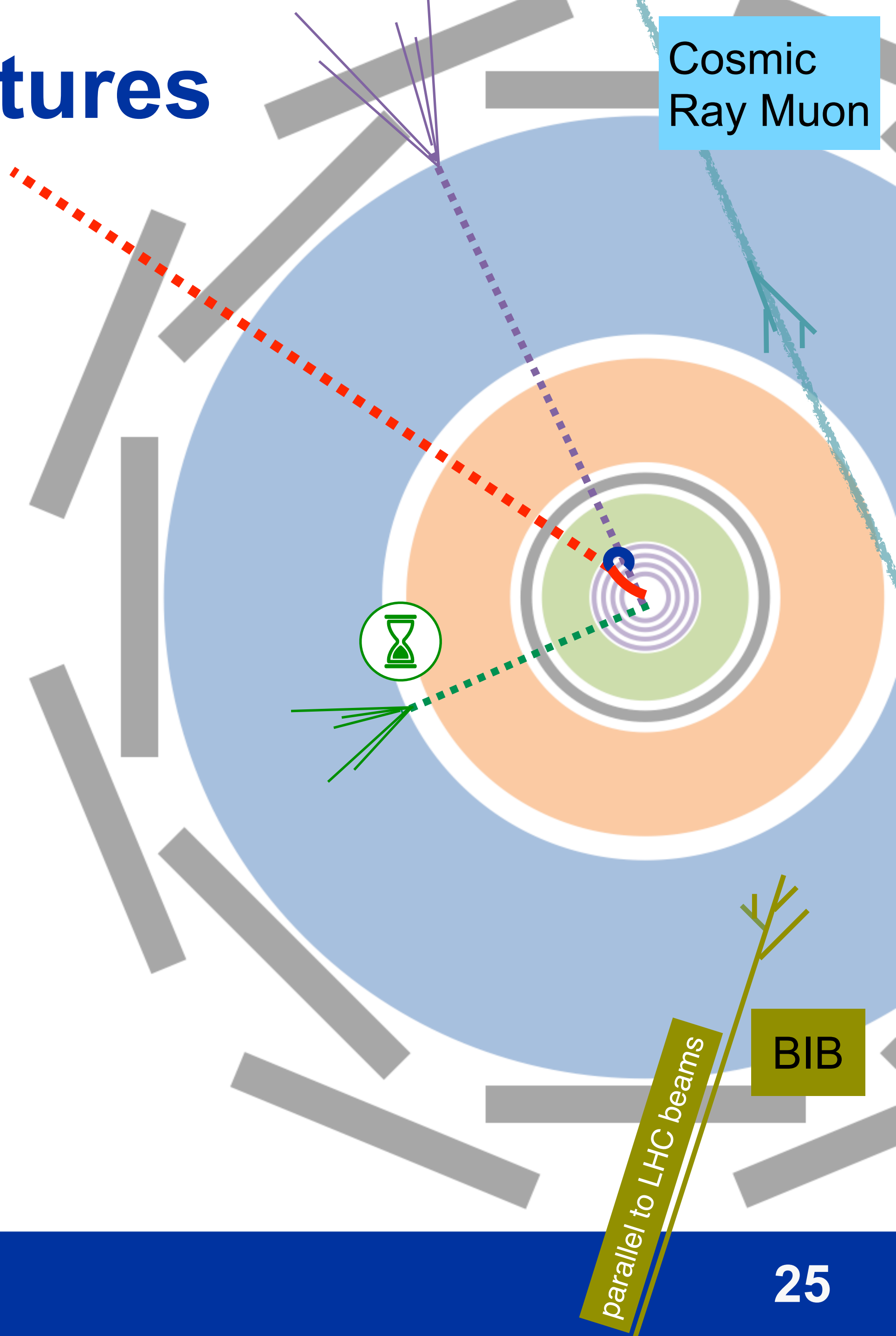
- Unusual signatures = **unusual backgrounds**
  - Beam-induced background (BIB):
    - Beam-halo muons
    - Interactions with gas and upstream collimators



…but these are challenging signatures

- **LLPs** could lead to a plethora of unusual signatures, depending on…
  - LLP lifetime / decay length
  - Charge of LLP and decay products
  - Interaction of LLP with detector

- Unusual signatures = **unusual backgrounds**
  - Beam-induced background (BIB)
  - Cosmic Rays
    - From access shafts to experimental caverns



MS vertex: selection and backgrounds

- Selection:
  - Two MS vertices
  - Both vertices isolated from tracks or jets

Isolation requirements	Barrel	Endcaps
High-p_T track isolation (p_T > 5 GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Low-p_T track isolation ($\Sigma p_T(\Delta R < 0.2)$)	$\Sigma p_T < 10$ GeV	$\Sigma p_T < 10$ GeV
Jet isolation	$\Delta R > 0.3$	$\Delta R > 0.6$

  - Exclude MS and HCal transition regions ($|\eta| \notin$ ([0.7, 1.2] || [0.8, 1.3])
  - MS vertices matched to triggering cluster(s), and vertices separated by ΔR > 1

- Main background: punch-through QCD jets. Data-driven estimate in events passing either the MS DV trigger or a zero-bias trigger:

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

674775 3 0

Number of events selected by trigger containing only one MS DV (N^{1cl})
Number of events selected by trigger containing 2 MS DVs, one cluster of which is unmatched in the Barrel (N^{2cl}_{1UMBcl}) or Endcaps (N^{2cl}_{1UMEcl})

MS vertex: selection and backgrounds

- Selection:
  - Two MS vertices
  - Both vertices isolated from tracks or jets
  - Exclude MS and HCal transition regions ($|\eta| \notin ([0.7, 1.2] \| [0.8, 1.3])$
  - MS vertices matched to triggering cluster(s), and vertices separated by $\Delta R > 1$

Isolation requirements	Barrel	Endcaps
High-p_{T} track isolation ($p_T > 5$ GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Low-p_{T} track isolation ($\Sigma p_{\mathrm{T}}(\Delta R < 0.2)$)	$\Sigma p_{\mathrm{T}} < 10$ GeV	$\Sigma p_{\mathrm{T}} < 10$ GeV
Jet isolation	$\Delta R > 0.3$	$\Delta R > 0.6$

- Main background: punch-through QCD jets. Data-driven estimate in events passing either the MS DV trigger or a zero-bias trigger:

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

674775 4.6×10^{-7} 3   0

Probability of finding a vertex in zero-bias trigger events:
53 events with an isolated DV, in 115,709,381 zero-bias events

MS vertex: selection and backgrounds

- Selection:
  - Two MS vertices
  - Both vertices isolated from tracks or jets

Isolation requirements	Barrel	Endcaps
High-p_T track isolation (p_T > 5 GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Low-p_T track isolation ($\Sigma p_T(\Delta R < 0.2)$)	$\Sigma p_T < 10$ GeV	$\Sigma p_T < 10$ GeV
Jet isolation	$\Delta R > 0.3$	$\Delta R > 0.6$

  - Exclude MS and HCal transition regions ($|\eta| \notin$ ([0.7, 1.2] || [0.8, 1.3])
  - MS vertices matched to triggering cluster(s), and vertices separated by $\Delta R > 1$

- Main background: punch-through QCD jets. Data-driven estimate in events passing either the MS DV trigger or a zero-bias trigger:

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

674775 | 4.6×10^{-7} | 3 | 3.2×10^{-3} | 0 | 3.53×10^{-2}

Probability of finding a vertex the Barrel (Endcaps) given a trigger cluster there:
124,648 (550,127) vertices matched to a cluster found in the barrel (endcaps) in 38,509,130 (15,598,939) data events in the barrel (endcaps)

MS vertex: selection and backgrounds

- Selection:
  - Two MS vertices
  - Both vertices isolated from tracks or jets
  - Exclude MS and HCal transition regions (|η| ∉ ([0.7, 1.2] || [0.8, 1.3])
  - MS vertices matched to triggering cluster(s), and vertices separated by ΔR > 1

Isolation requirements	Barrel	Endcaps
High-p_T track isolation (p_T > 5 GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Low-p_T track isolation ($\Sigma p_T(\Delta R < 0.2)$)	$\Sigma p_T < 10$ GeV	$\Sigma p_T < 10$ GeV
Jet isolation	$\Delta R > 0.3$	$\Delta R > 0.6$

- Main background: punch-through QCD jets. Data-driven estimate in events passing either the MS DV trigger or a zero-bias trigger:

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

674775 | 4.6×10^{-7} | 3 | 3.2×10^{-3} | 0 | 3.53×10^{-2}

= 0.32 ± 0.05 (statistical errors)

… 0 events observed in data

Estimate validated in dedicated Validation region where isolation requirement was inverted

CERN

MS vertex: Results