ATLAS Searches with Unconventional Signatures

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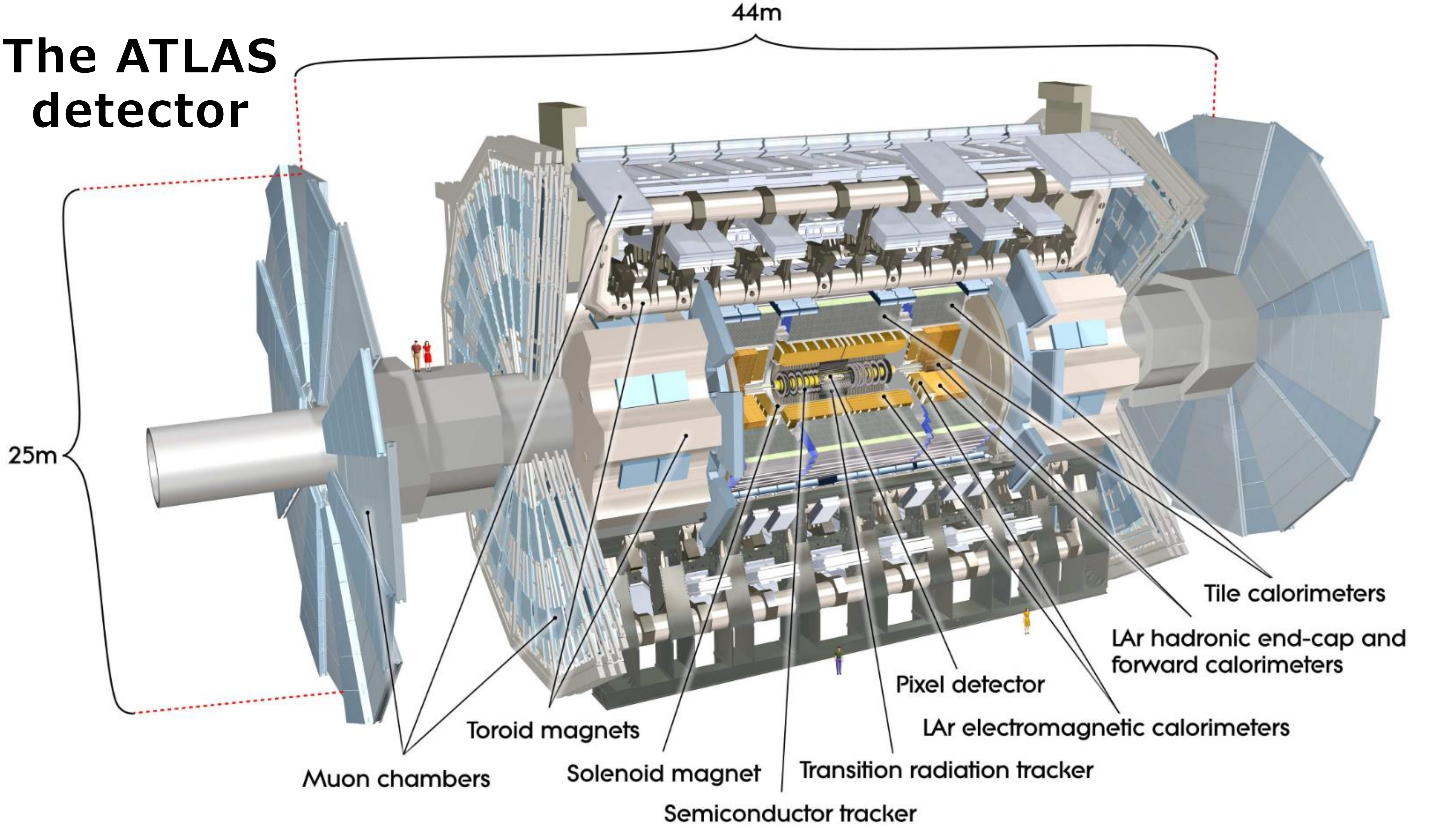
on behalf of the ATLAS Collaboration

DIS2024

Grenoble, 8-12 April 2024

The ATLAS detector



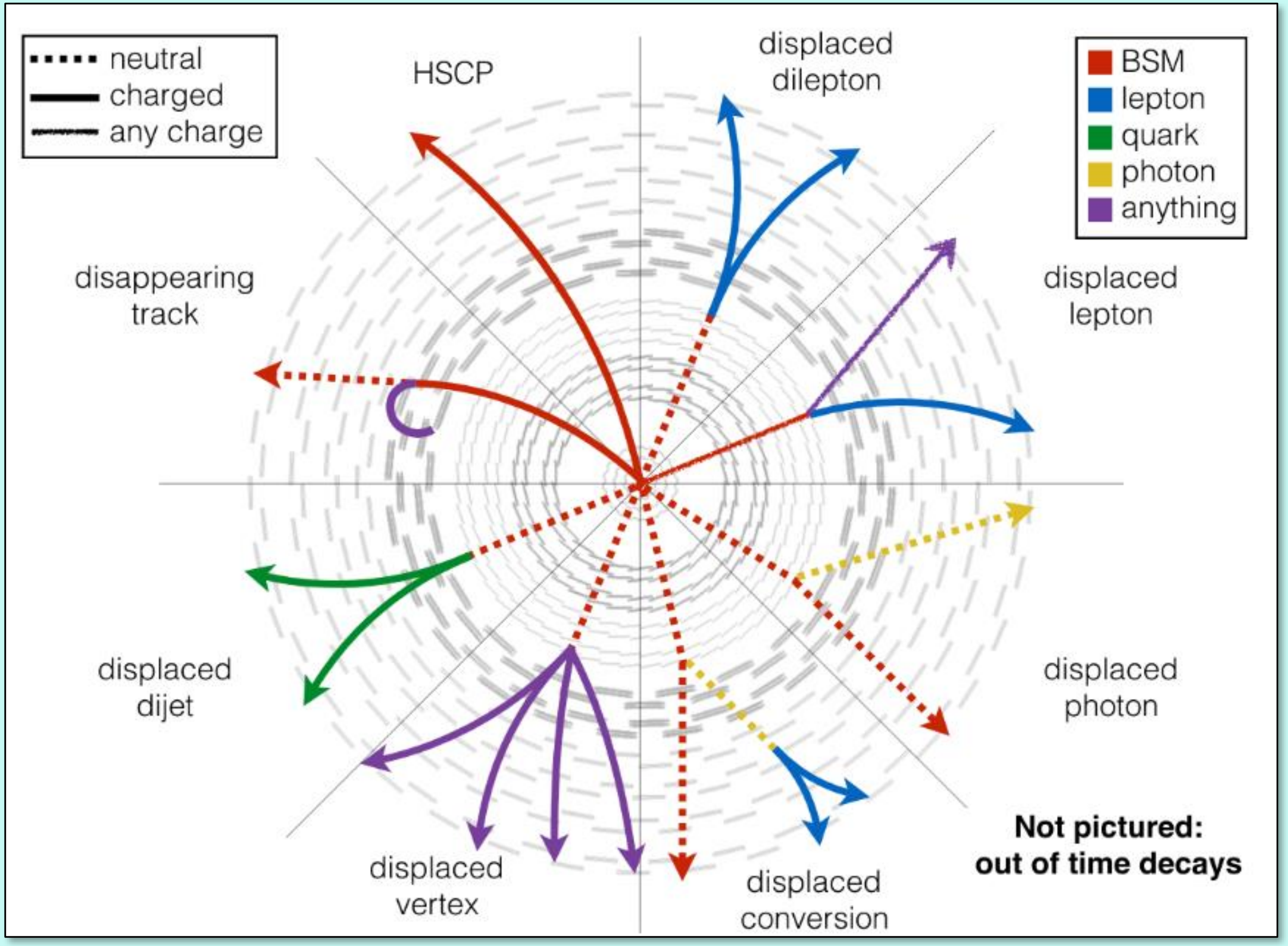
Unconventional Signatures

Unconventional signatures used in searches exploiting lots of models:

- Supersymmetric (SUSY) models and Hidden Sector
- Multi-Higgs models
- Dark matter sector
- Flavour anomalies
- Heavy resonances
- etc.

Non-standard reconstruction methods:

- May be based on specific detectors
- May use specific triggers
- May use special reconstruction algorithms
- May have unusual background

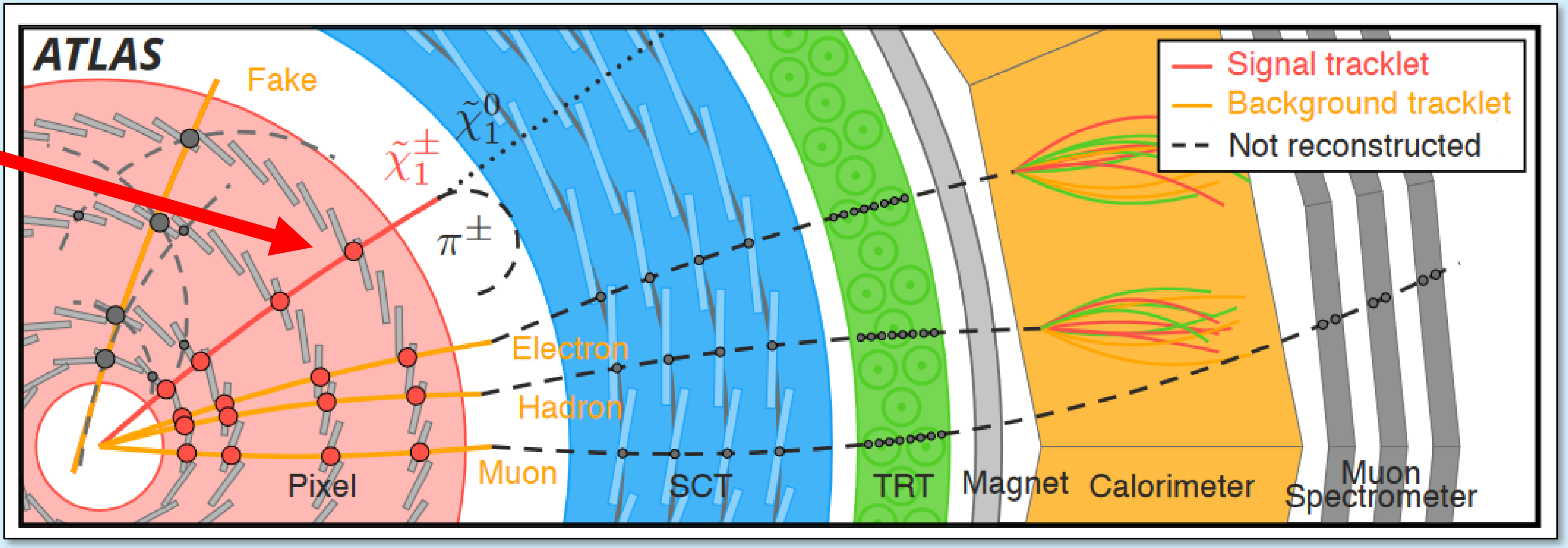


Credits: J. Antonelli

ID: Disappearing track signature

- **Disappearing tracks: charged** long-lived particles (LLPs, e.g. sleptons, charginos) produced in pp collisions or from prompt decays of unstable particles (e.g. gluinos) with lifetime ~0.1−10 ns, decaying **to stable neutral particles or low p** charged particles → **track of charged particle in ID up to its decay point, no tracks outgoing**
  - There is also activity to reconstruct decay products with a dedicated technique
  - Low p charged decay products → inefficient reconstruction with standard algorithm → no tracks

Signal disappearing track

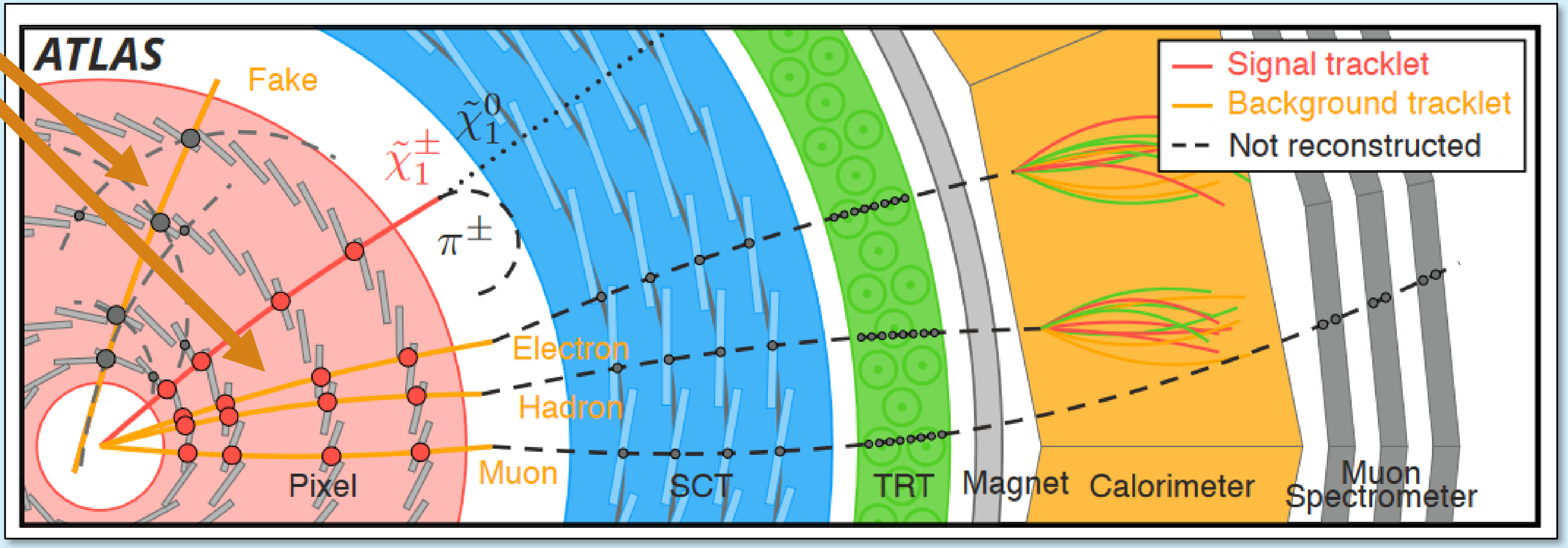


Not to scale (for illustration only)

ID: Disappearing track signature

- **Background**: from badly measured tracks, leptons with large bremsstrahlung or scattering, high-momentum charged hadrons interacting with ID material
  - usually **estimated** using data with tracks in control regions
- Additional objects usually selected to **improve sensitivity** (e.g. large MET)

Background



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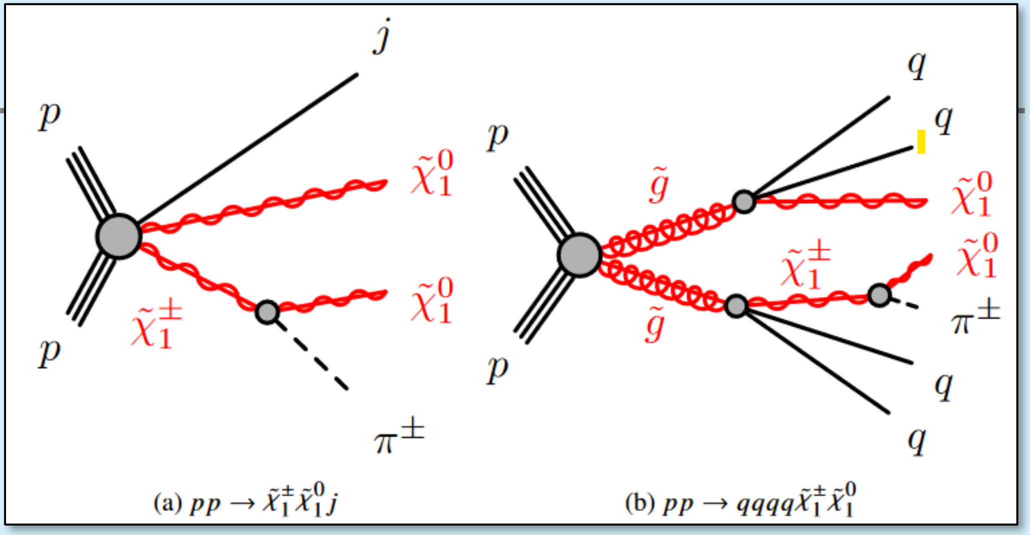
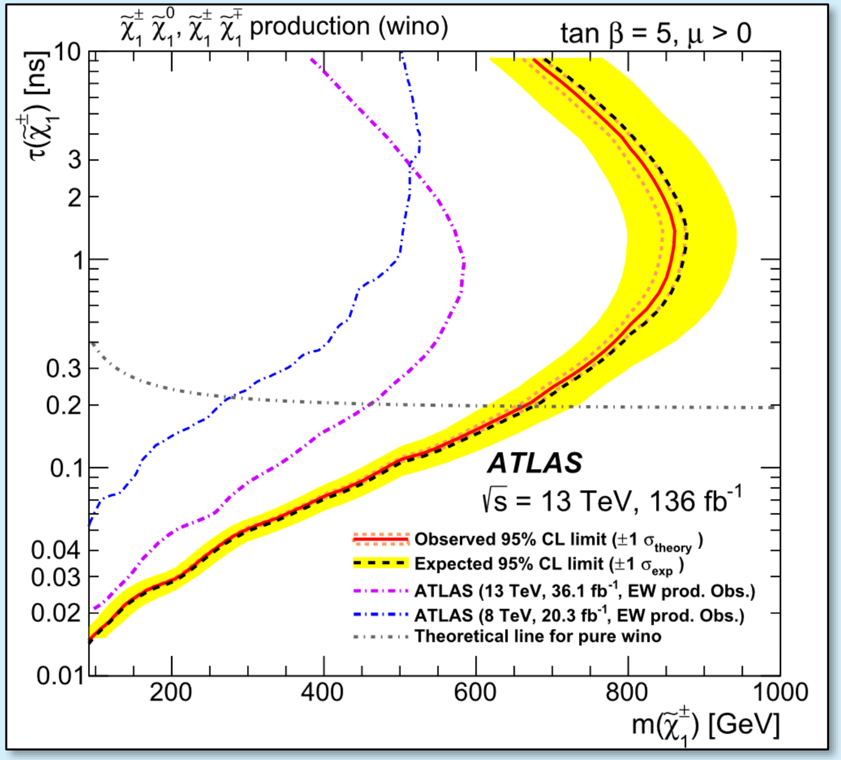
Disappearing tracks analyses

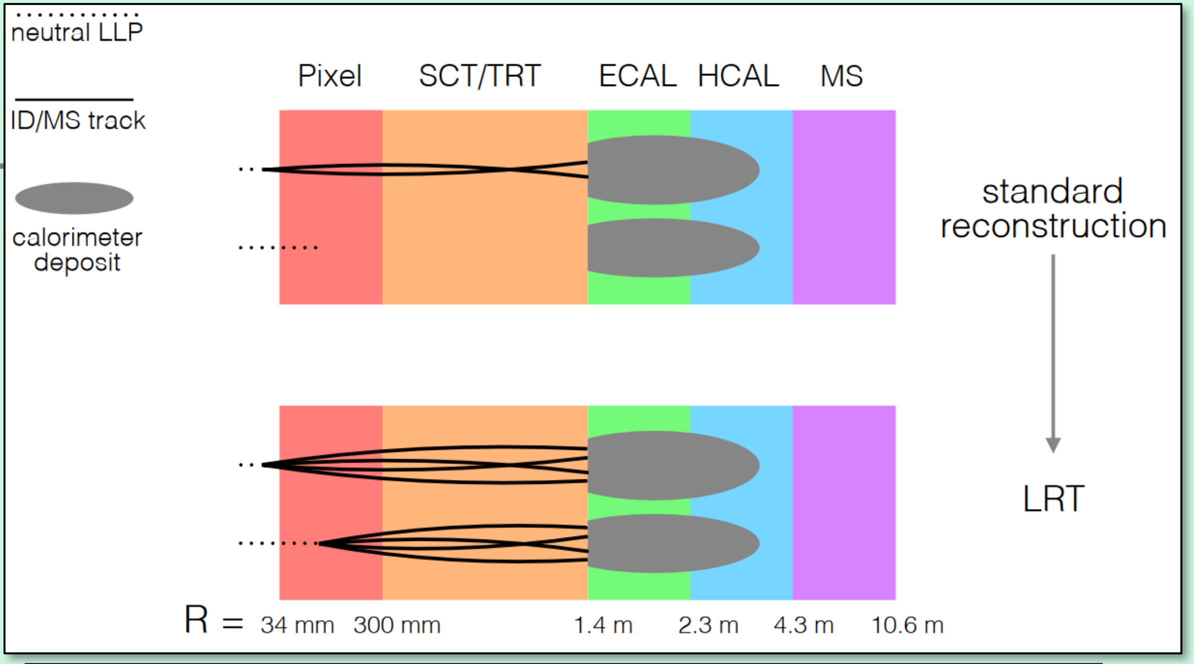
- *Long-lived **charginos** produced directly or in cascade decay of heavy prompt gluino states* [Eur. Phys. J. C 82 (2022) 606]
  - short track **with ≥4 hits in pixel** detector, no points in strip detector, no associated energy in calorimeter
  - final state with large **missing-pT for triggering, ≥1 high-pT jet**
  - No excess observed → excludes pure-wino charginos with masses up to ~850 GeV for lifetimes of about 1 ns

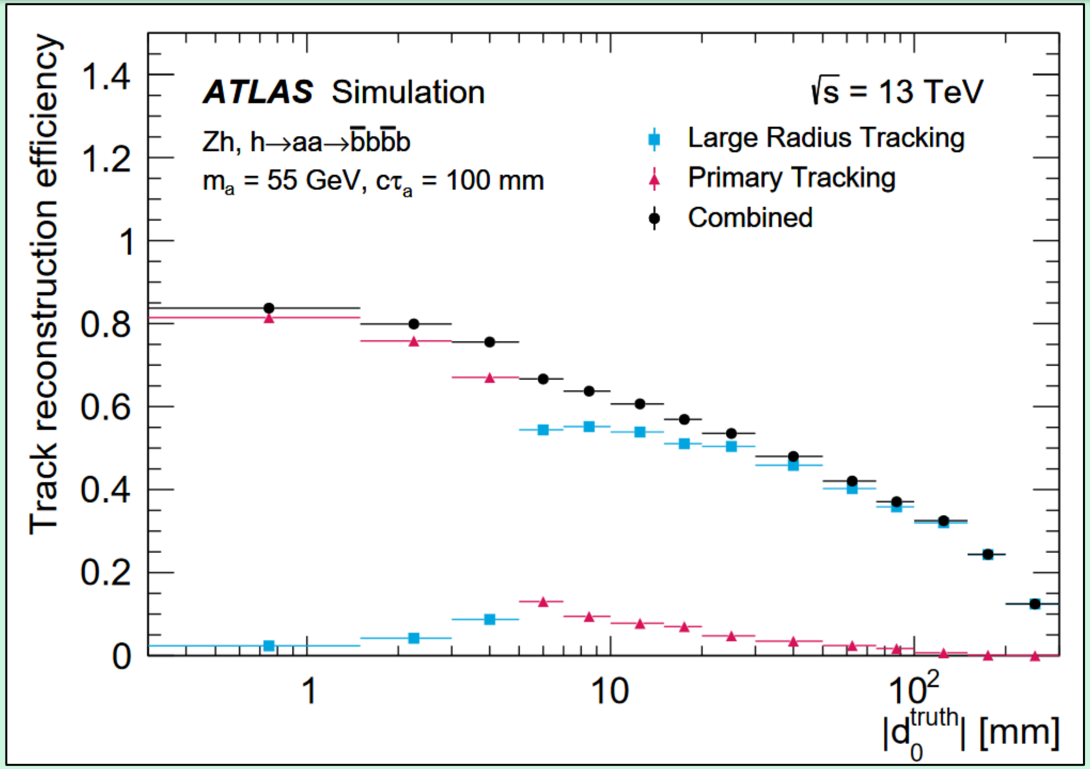




ID: Large Radius Tracking

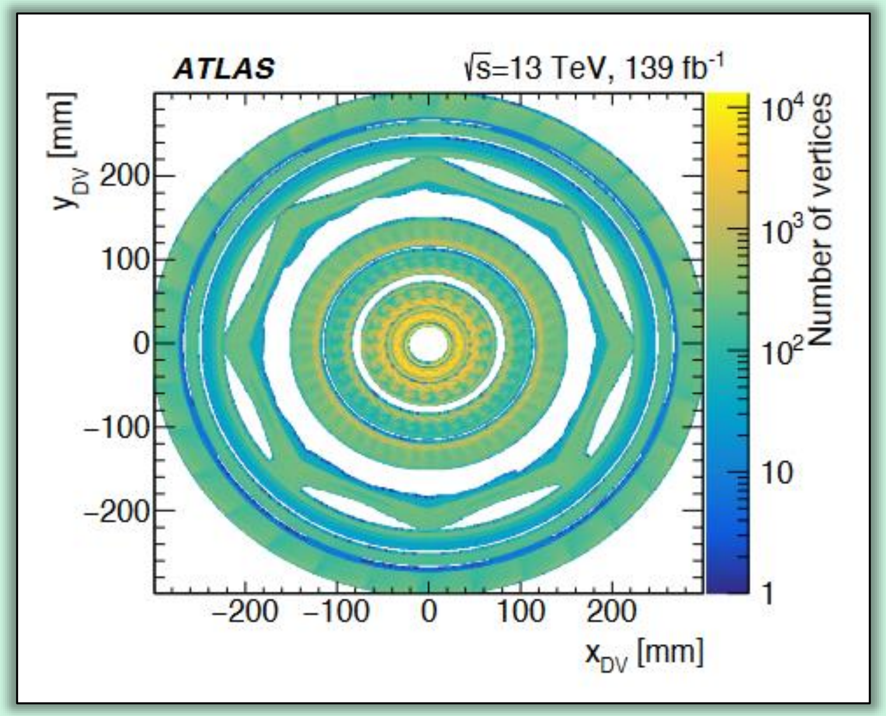
- **Large radius tracking (LRT):** specialised track reconstruction algorithm for tracks with **large impact parameter d_0** → improve the efficiency of DV reconstruction
  - reconstructs charged particles with approx. **10 mm<|d_0|<300 mm**, run on hits not used by standard tracking
  - initially run on O(1%) of data samples [ATL-PHYS-PUB-2017-014], later re-run on **entire Run2** data sample (improved processing time 10x, disk space usage) [arxiv:2304.12867]
  - very efficient for **decays within the pixel detector and out to the first SCT layer** with enough detector hits





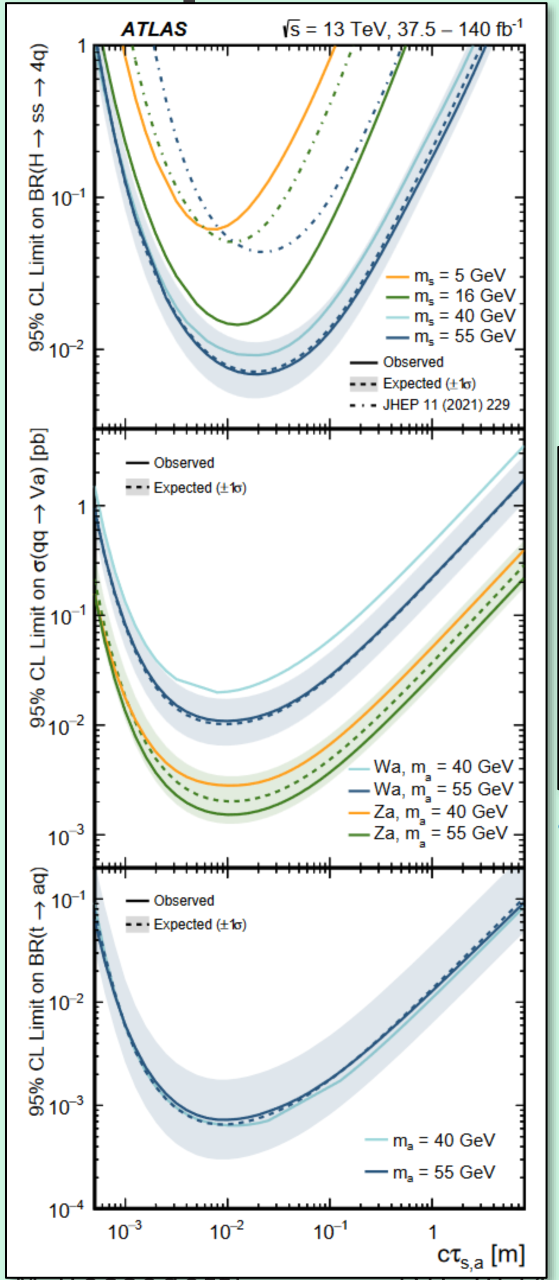
ID: Displaced Vertex signature

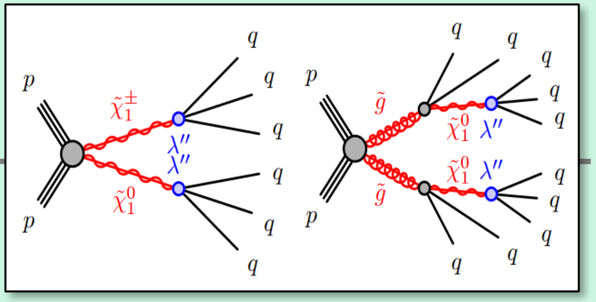
- **Displaced Vertex (DV): neutral particle decay** in inner detector (ID) to charged/neutral particles
  → **tracks pointing (back) to a common DV** far from the interaction point (IP)
  - products from SUSY decays **large invariant mass → easily distinguishable** from SM decays
  - Used for long lived particles (LLPs) → **τ sensitivity complementary to prompt-decay** (see slide 19)



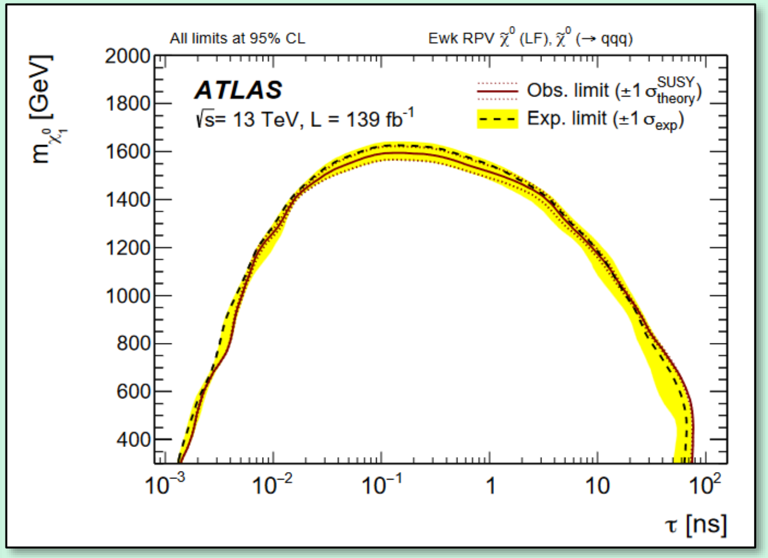
- **Background:**
  - (dominant) random track combinations and merged vertices mimicking high-mass DV
  - (smaller component) hadronic interactions with detector material → **high matter density regions** vetoed

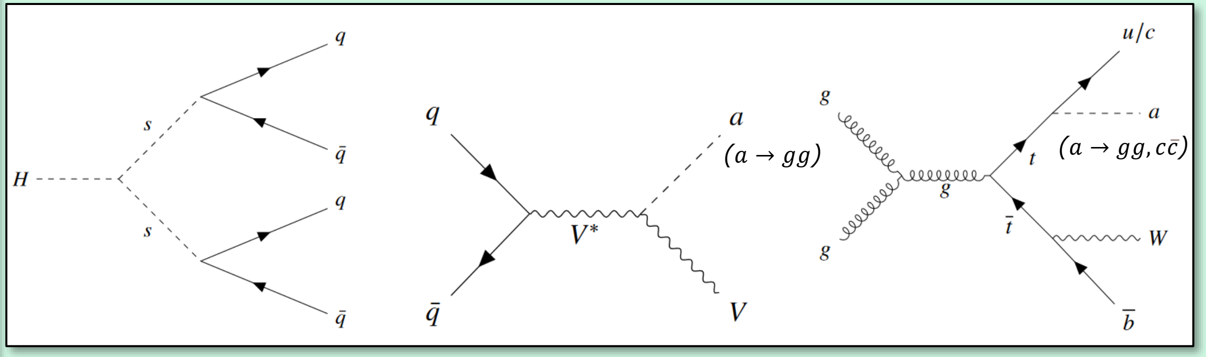
Displaced Vertex analyses





- *Search for long-lived, massive particles in events with* ***displaced vertices and multiple jets*** [JHEP 06 (2023) 200]
  - Signature: **massive DV** with **multiple tracks and multiple jets**
  - Strategy: targets zero background (only 1 background event!)

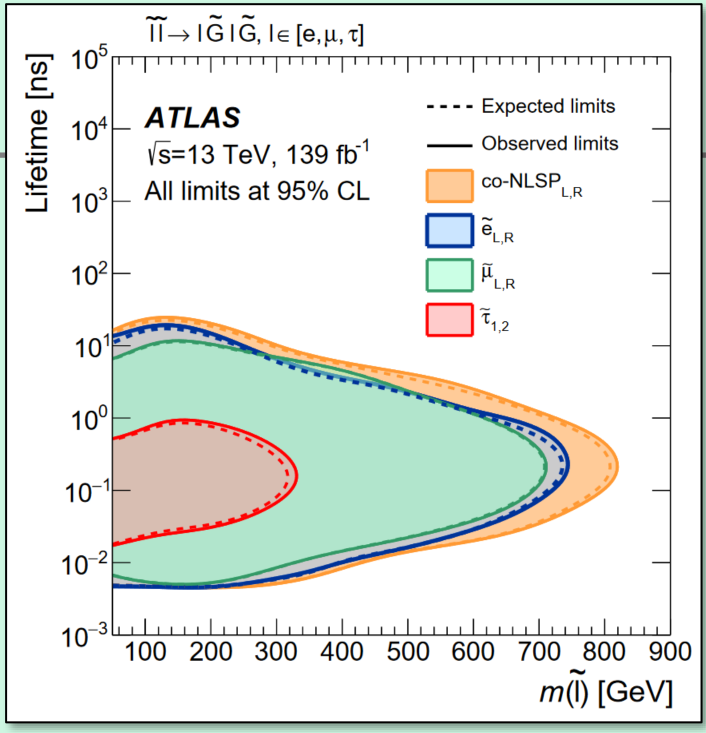




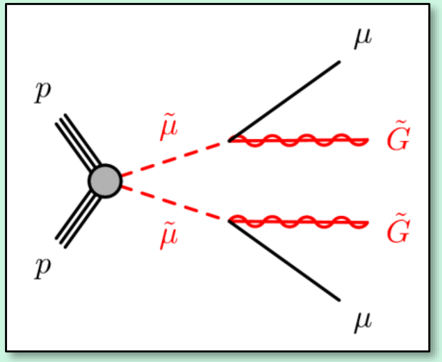
- *Search for light long-lived particles using displaced vertices* [CERN-EP-2024-086]
  - **Target: LLPs** with mass **between 5-55 GeV that decay hadronically** in the ID
  - Considers **3 benchmark models:** $H \to ss \to 4q$ **Higgs exotic decay**, **ALP** a production in association with W/Z and from top exotic decay $t \to ac/au$
  - **Signature: one or more hadronic jets** from a vertex significantly **displaced** from the interaction point
  - Boosted Dectision Tree (BDT) to distinguish displaced/prompt jets, DV reconstruction algorithm to reconstruct their vertex

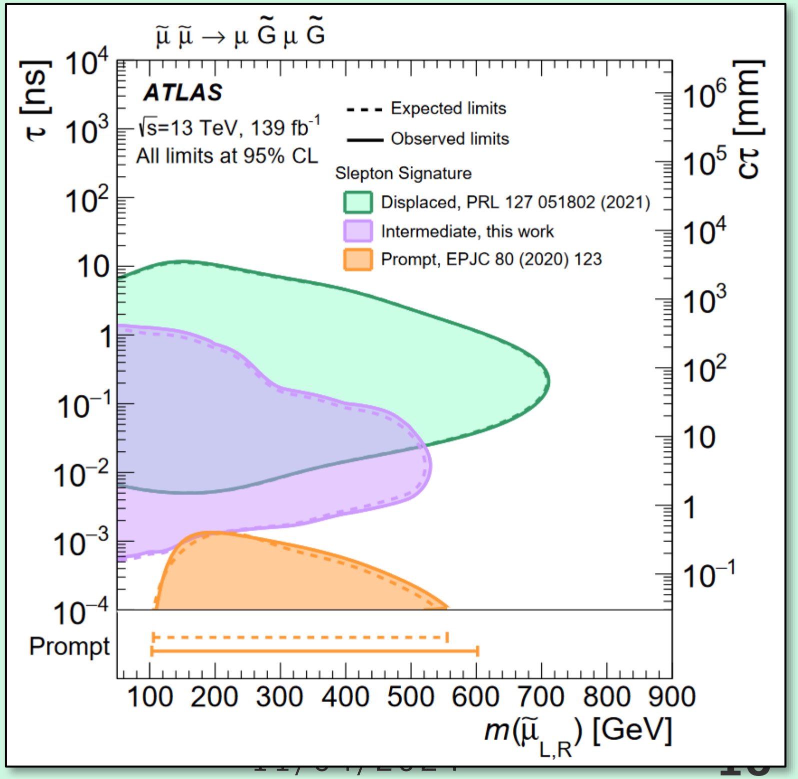
Large d_0 analyses

- *Search for **displaced leptons*** [Phys.Rev.Lett. 127 (2021) 051802]
  - **Signature:** two **displaced leptons** (no visible decay vertex) with large impact parameter ($|d_0|>3$ mm) from **decay of slepton pair**



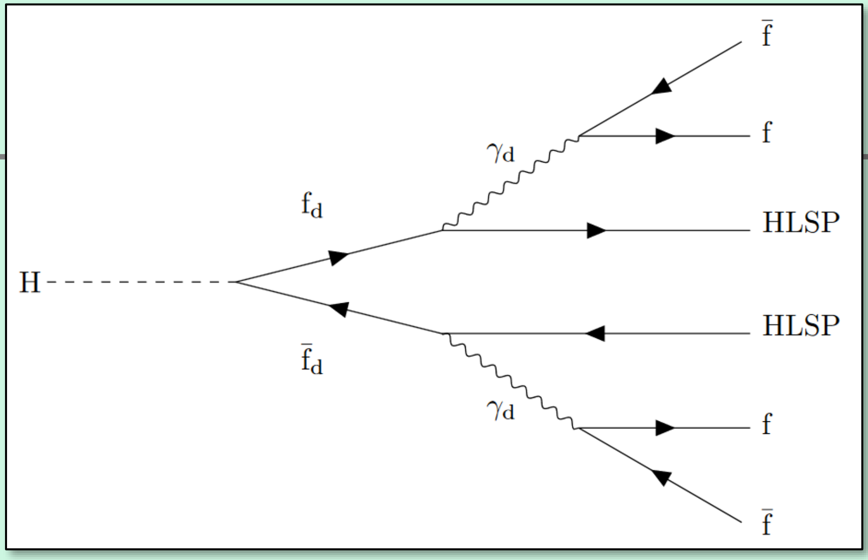
- *Search for **pairs of muons with small displacements*** [Phys.Lett.B 846 (2023) 138172]
  - **Signature:** pair of ***micro-displaced*** leptons with $0.1\text{mm}<|d_0|<3\text{mm}$ and high-invariant mass of the two mouns, uses **standard tracking** algorithms
  - targets sensitivity between long-lived and promptly decaying **sleptons** (smoun $\tau\sim 10^{-3}$-10^{-2} ns)



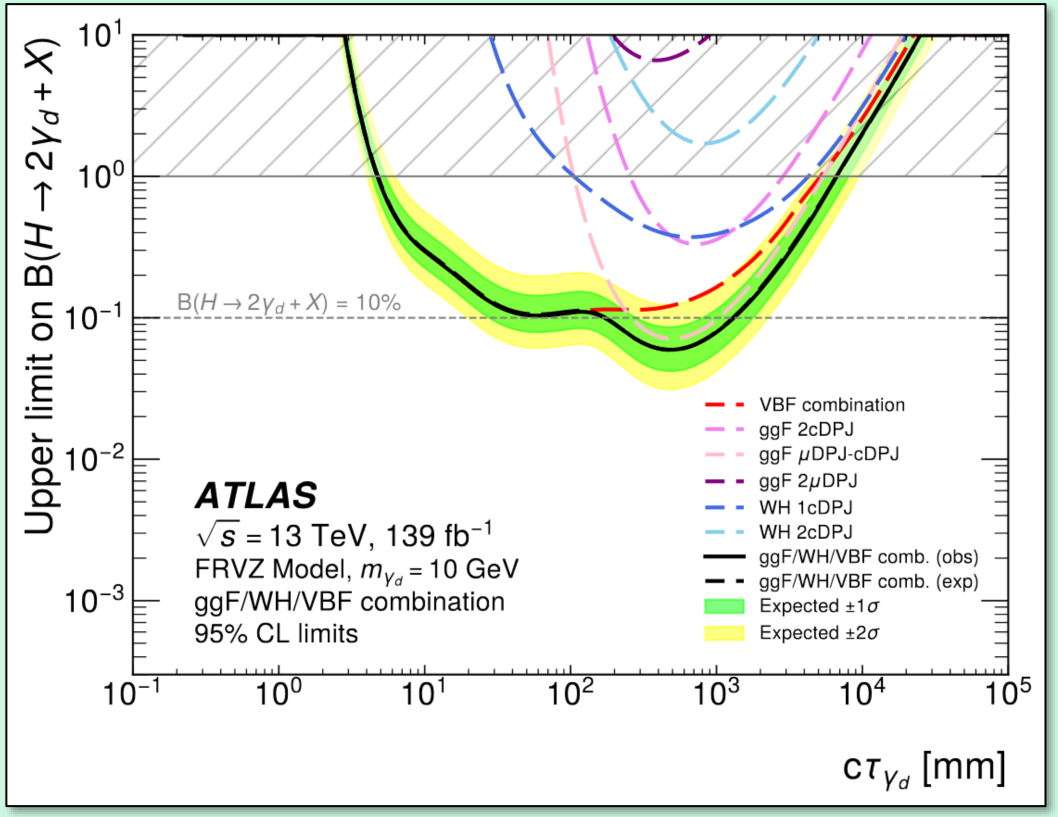


Dark Photon Jets (DPJs)

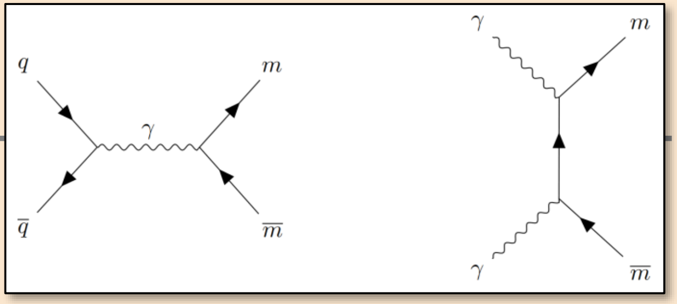
Dark photon jets (DPJs): displaced **collimated group of SM** fermions reconstructed in the **calorimeter or muon spectrometer** with **structure similar to a jet**



- *Search for light long-lived neutral particles from Higgs boson decays via VBF production* [CERN-EP-2023-226]
  - **Target**: **long-lived dark photons** (mass 0.1-15 GeV) from H exotic decays produced via VBF, that decay to DPJs
  - **Signature**: **DPJs** in calorimeter or muon spectrometer (uses standard tracking)
  - Higgs from **VBF for background reduction** (pair of high-energy quark jets, with large Δη, m_{jj}, E^T_{miss})
    → **search for 1 dark photon feasible**
    → extended sensitivity to shorter and longer τ

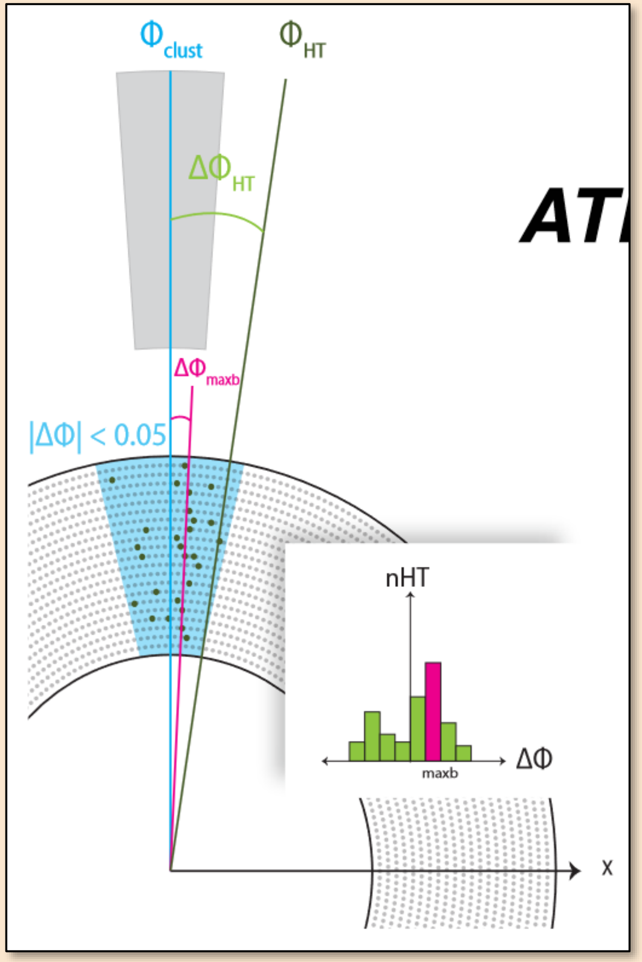


Calorimeter and TRT: HIPs and HECO

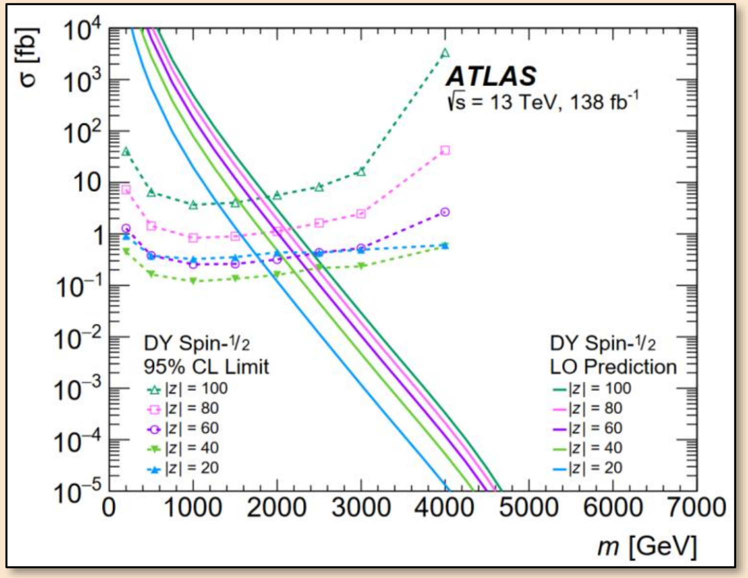


Search for magnetic monopoles and stable particles with high electric charges [JHEP 11 (2023) 112]

- **Target:** spin-0 and spin-½ **magnetic monopoles** (magnetic charges $1g_D$,$2g_D$) **and High-Electric-Charge Objects** (**HECO**, up to $|z|$~100) produced via the Drell-Yan and photon-fusion mechanisms
- **Interaction in matter: Highly Ionizing Particles (HIPs)** (radiation losses <5% of energy loss), **large number of δ-rays**
- HIP signal: High Threshold (HT) hits in TRT, narrow deposit in LAr EM calorimeter (not a shower), most HIPS stopped in EM calo
- Electrons signal: in TRT HT hit probability 50% lower in Ar than in Xe

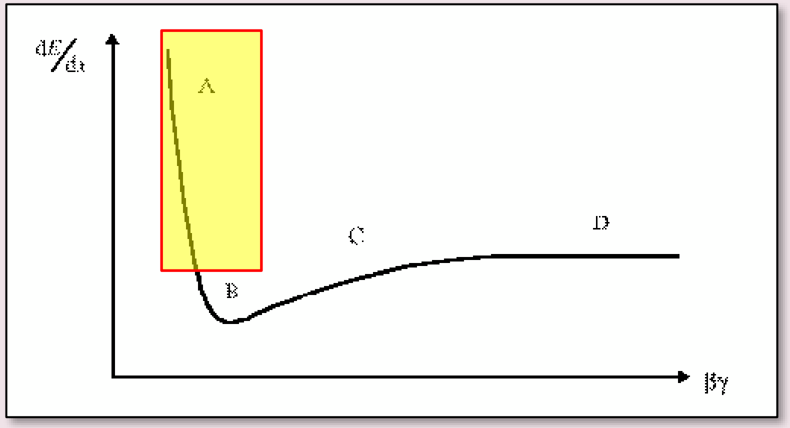


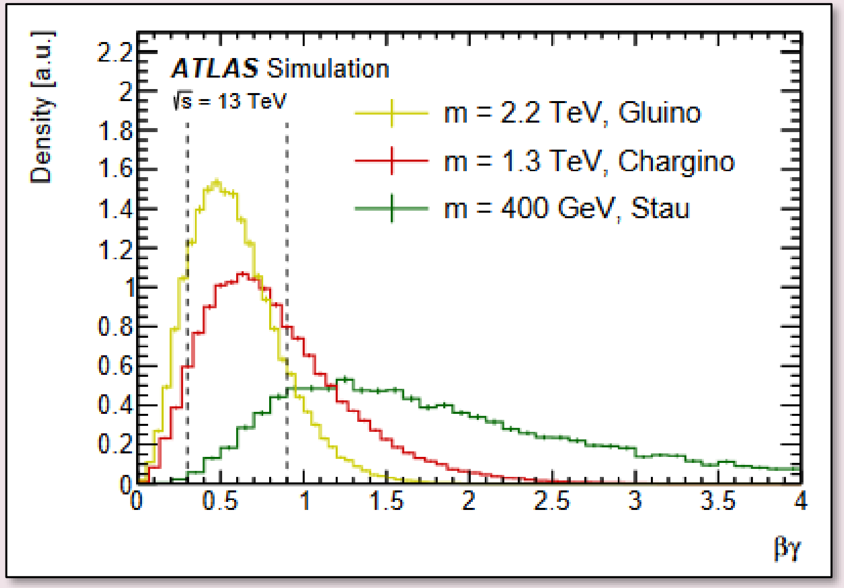
- **Signature**: **many TRT High Threshold (HT) hits** in a region **aligned with a narrow high-energy deposit** in the LAr EM calorimeter
- **Background**: random combinations of rare processes (e.g. overlapping charged particles in multijet events, high-energy electrons superpositions) → data-driven ABCD estimation



Pixel detector: High dE/dx signature

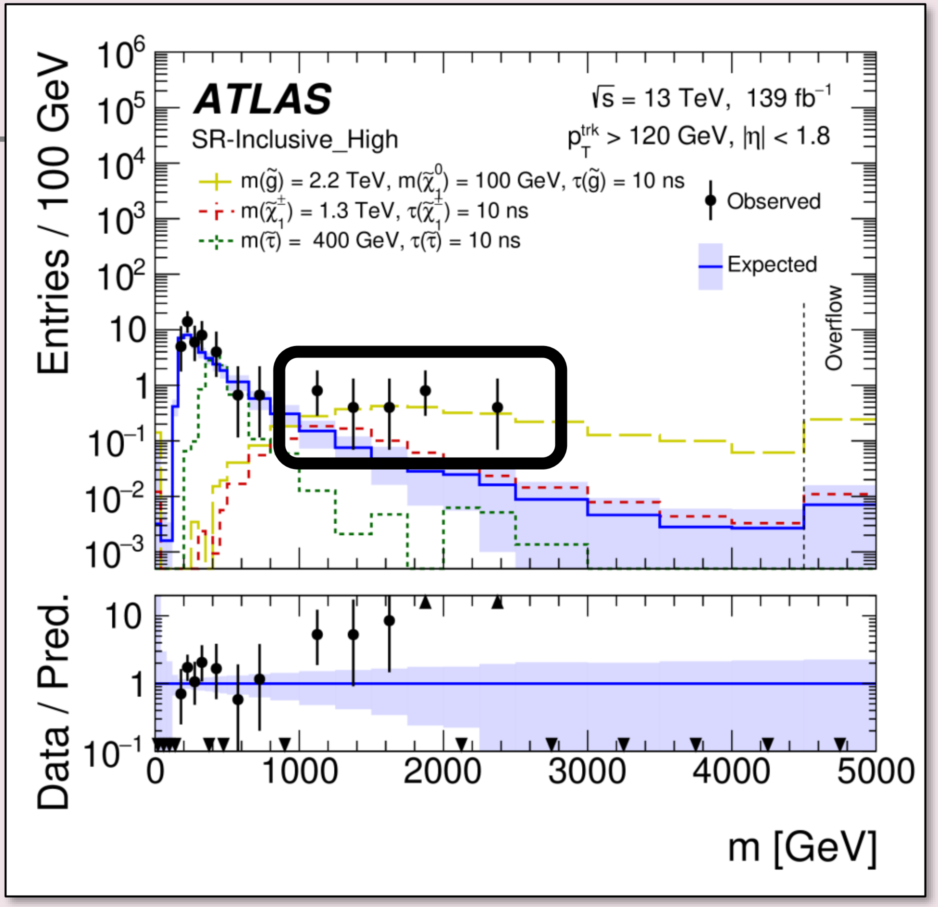
- **High dE/dx**: charged, massive LLPs must be slow ($m = \frac{p}{\beta\gamma}$ → β<1) → high dE/dx due to Bethe-Bloch relation **measured in inner detector** (ID)
- LLP can also decay beyond the inner detector
  → sensitive to lifetimes τ ~**0.3 ns to stable**
  → sensitivity **complementary to disappearing-track and DV**
- **Background:** mostly large dE/dx randomly produced from the Landau distribution for MIPs → estimated with **data-driven** techniques

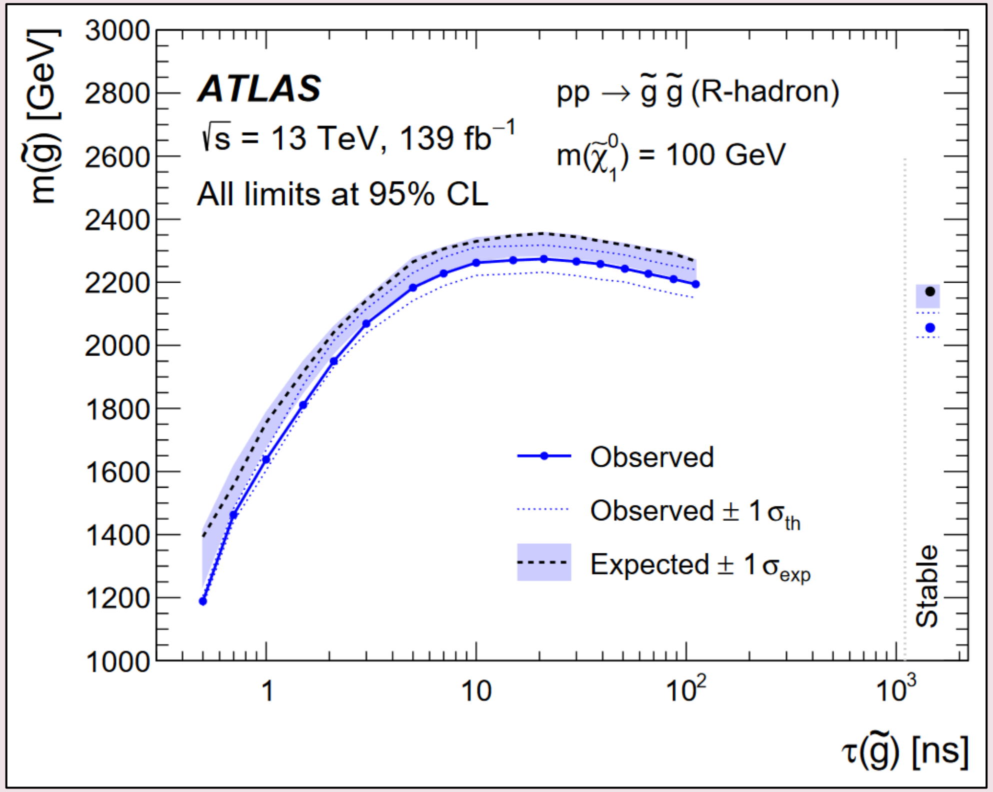




High dE/dx analyses

- *Search for heavy, long-lived, charged particles with large ionisation energy loss* [JHEP 06 (2023) 158]
  - sensitive to **τ~O(1)ns to stable** with m~100 GeV to 3 TeV (complementary to other searches)
  - **Model independent** → results interpreted for pair-production of R-hadrons, charginos and staus

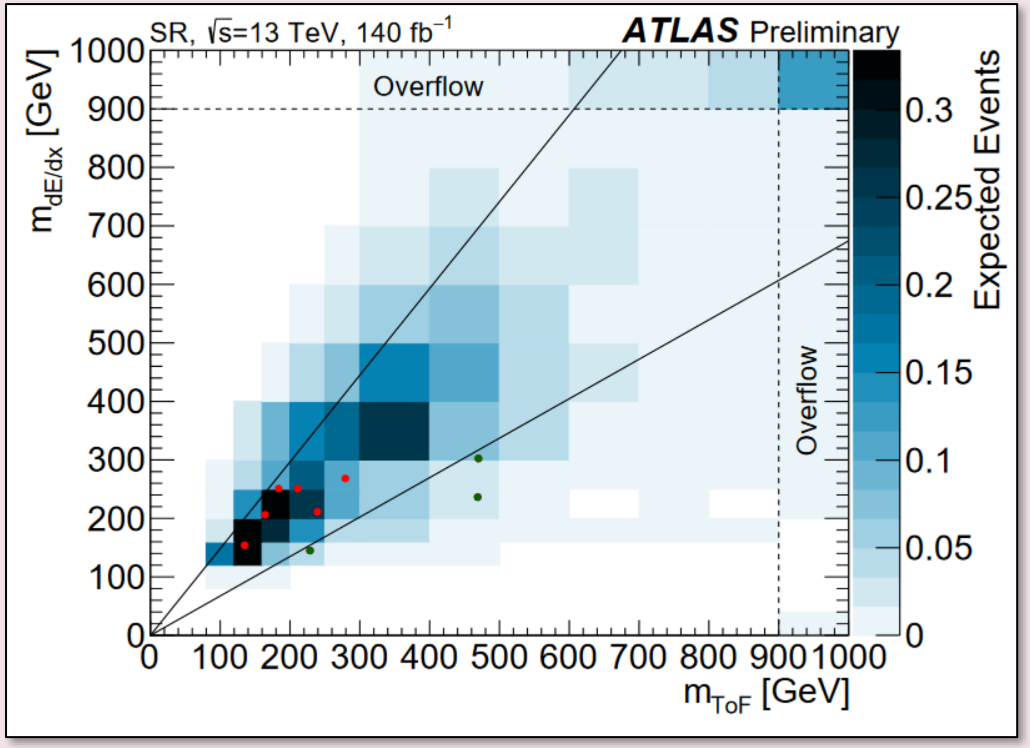


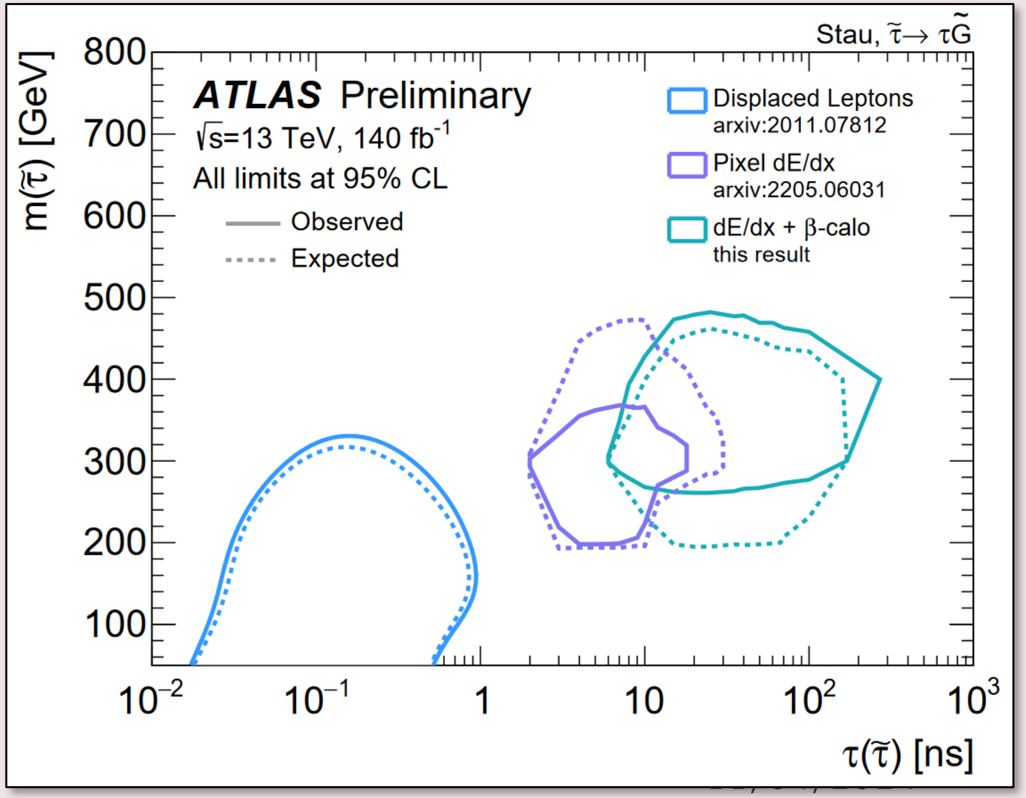


- **3.3σ excess** observed (7 observed, 0.7±0.4 expected) in mass window **[1.1,2.8] TeV**
  - But low β not confirmed by calorimeter and MS (consistent with β=1)

High dE/dx analyses

- *Search for heavy, long lived charged particles with large specific ionisation and low-beta* [ATLAS-CONF-2023-044]
  - New version of the analysis **using also βγ from ToF** measured with the **hadronic calorimeter**
    - mass measurement with pixel and calo required to be compatible → **background reduction**
    - Sensitivity down to τ>3ns
    - found compatibility with the background prediction

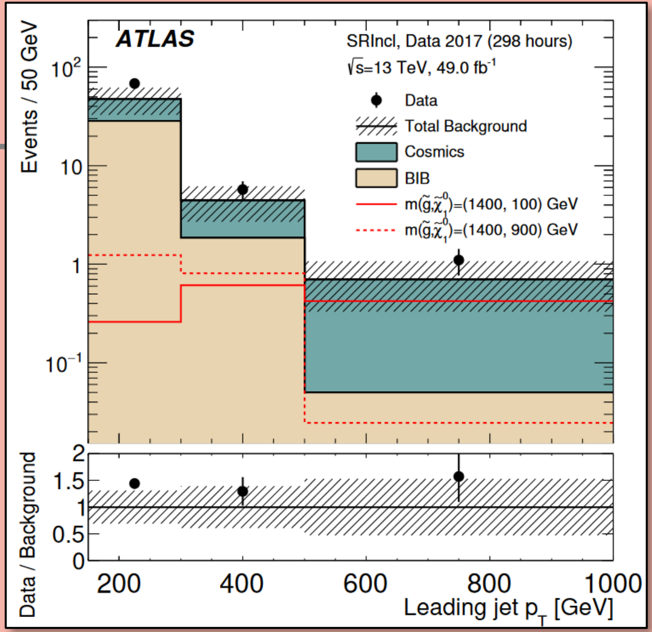


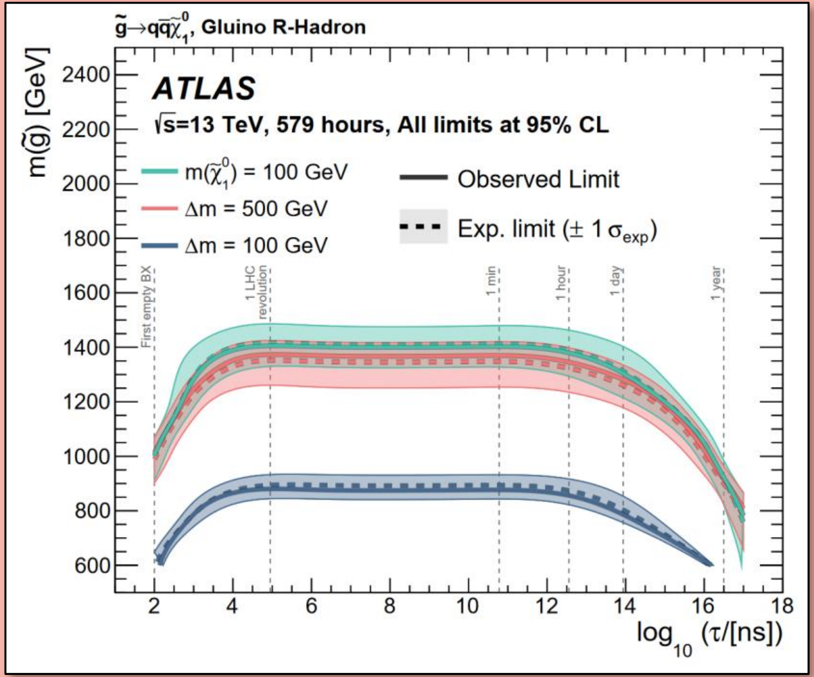


Calorimeter: Out-of-time energy deposits

- **Out-of-time (OOT) energy deposits: hadronic activity** in calorimeter **in absence of collisions** (LLPs that stop in the calorimeter and may decay at a much later time)

- Analysis: *Search for the decays of stopped long-lived particles* [JHEP 07 (2021) 173]
  - Targets **R-hadrons** (long-lived gluino and SM quarks and gluons) stopped in calorimeter (due to ionisation energy losses + nuclear scattering) → **decays 100 ns to one year later!** (depending on $\tau(\tilde{g})$)
  - Sensitivity: several orders of magnitude (10^{-5} to 10^{3} s)
  - Dataset: total 579 hours of **empty bunch crossings** (2017-18) → very clean environment
  - Background: cosmic muons, beam induced background (BIB=protons interactions with collimators, beam pipe, residual gas in pipe)

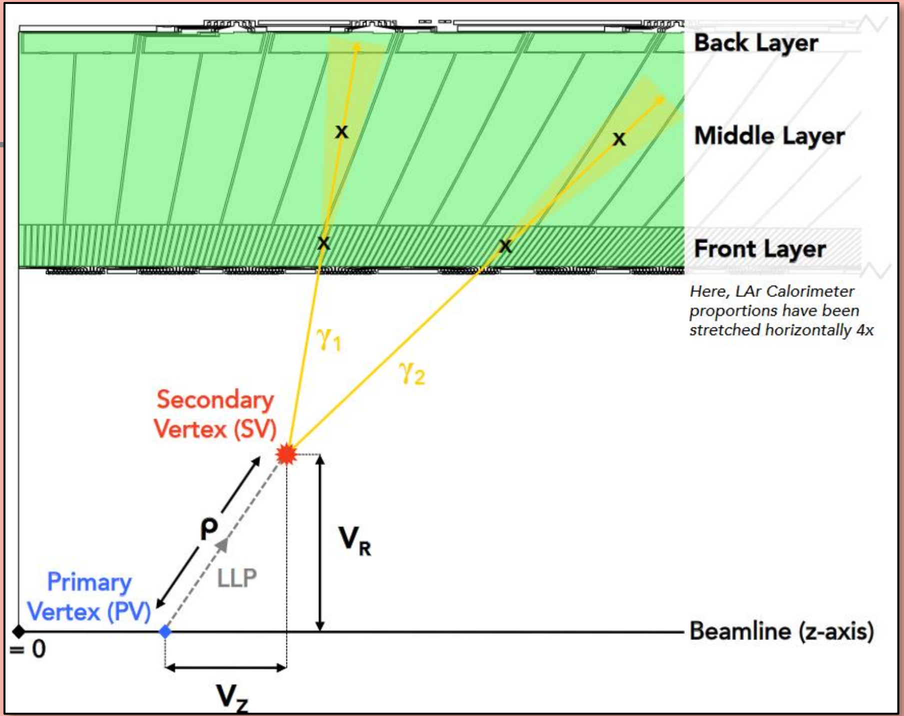


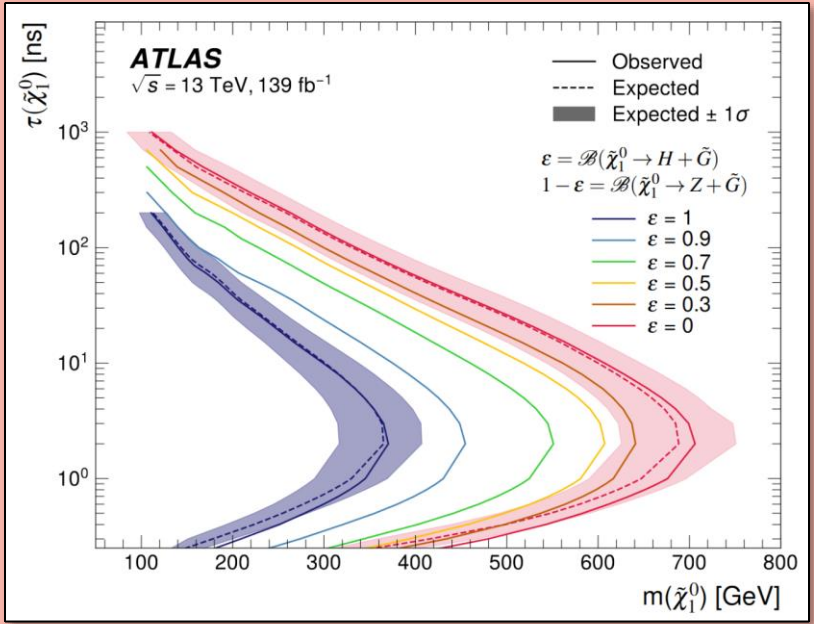


Calorimeter: Non-pointing photons

- **“Non-pointing” photons:** photons detected in **liquid-argon EM calorimeter** not pointing back to the original IP → without tracking information, **longitudinal shape** of shower used to trace back the DV and **delayed timing**

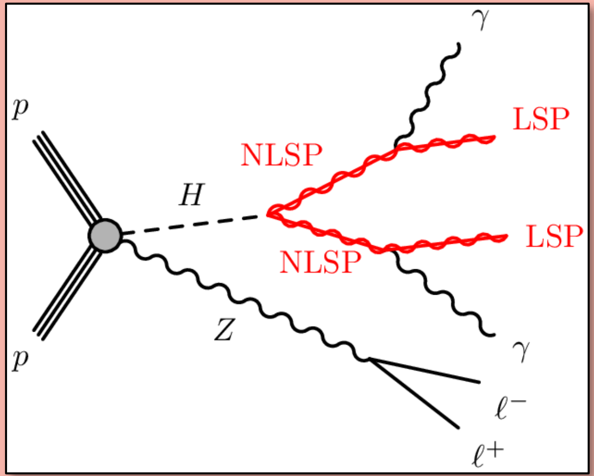
- Analysis: *Search in **diphoton and dielectron** final states for displaced production of Higgs or Z bosons* [Phys. Rev. D 108 (2023) 012012]
  - Target: **neutral LLP displaced decays into H,Z**, reconstructed decay modes **H→γγ, Z→ee**
  - Signature: **two non-pointing photons** forming a high-mass DV (LLP decay to photons)

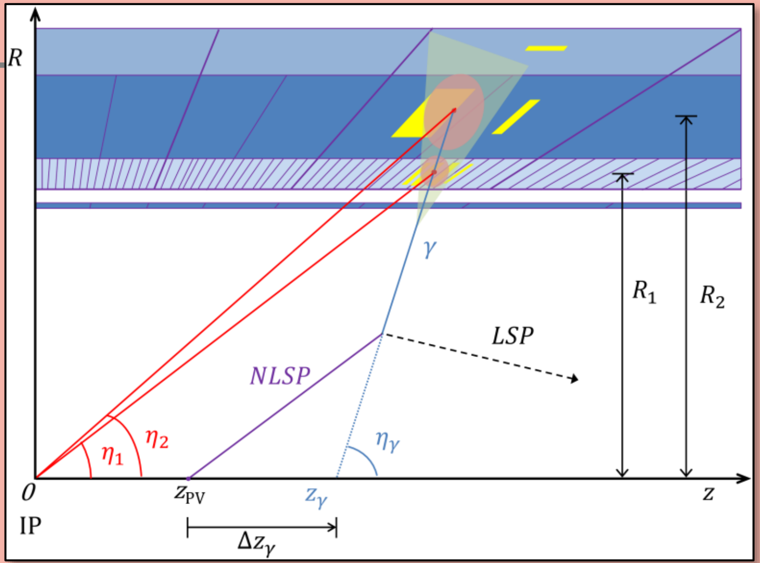


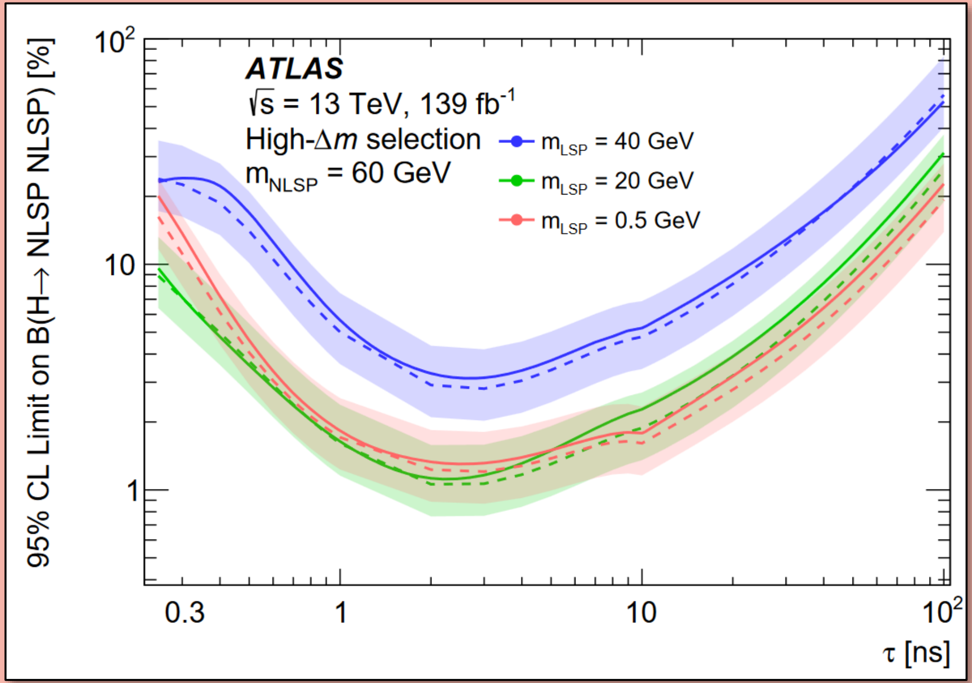


Calorimeter: Non-pointing photons

- Analysis: *Search for displaced photons produced in **exotic decays of the Higgs boson*** [Phys. Rev. D 108 (2023) 032016]
  - **Target**: **neutral LLPs** (NLSP) pair-produced in **H exotic decays**, each **decaying into a photon** and a particle that escapes direct detection (E^{T}_{miss})
  - **Signature**: **delayed** (due to ToF of massive NLSP) and **non-pointing photons** (from displaced decay NLSP)
  - Set **limits on B(H→NLSP+NLSP)** (assuming B(NLSP→LSP+γ)=100%) for τ(NLSP)=0.25 to 100 ns for mass values m_{NLSP}=30 to 60 GeV







Sensitivity to lifetimes

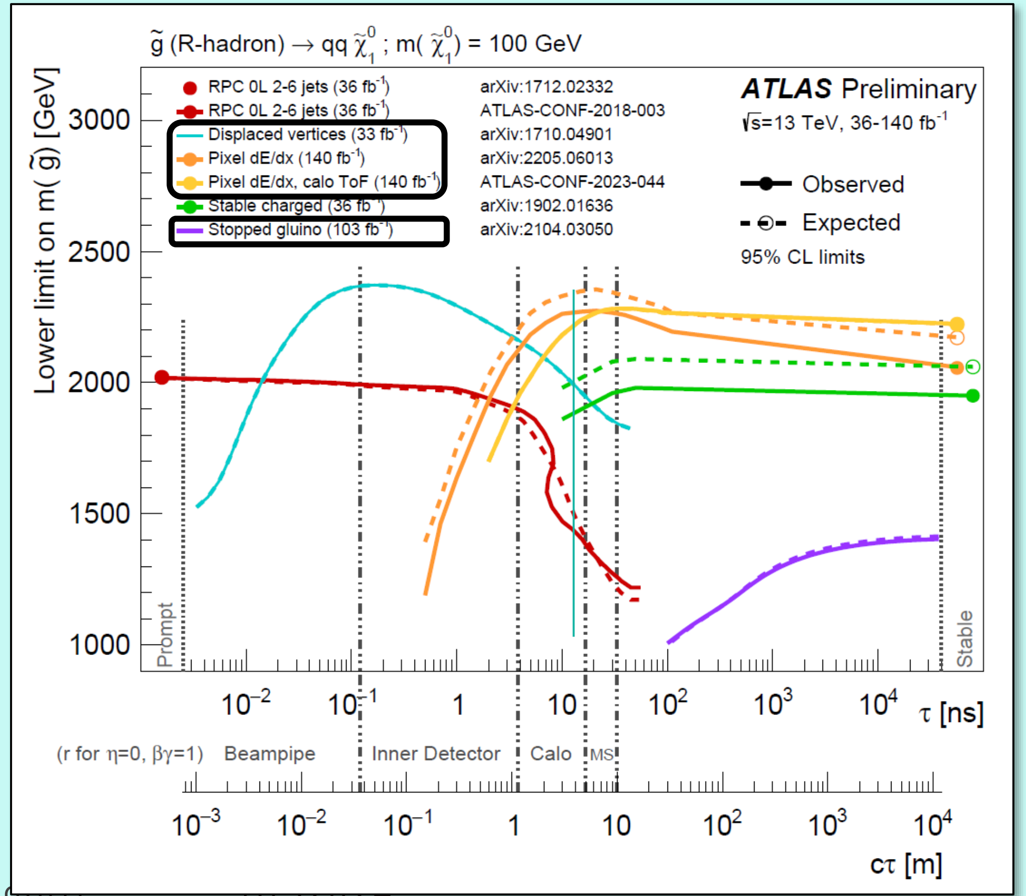
- Signatures have sensitivity to different LLP lifetimes in complementary ranges

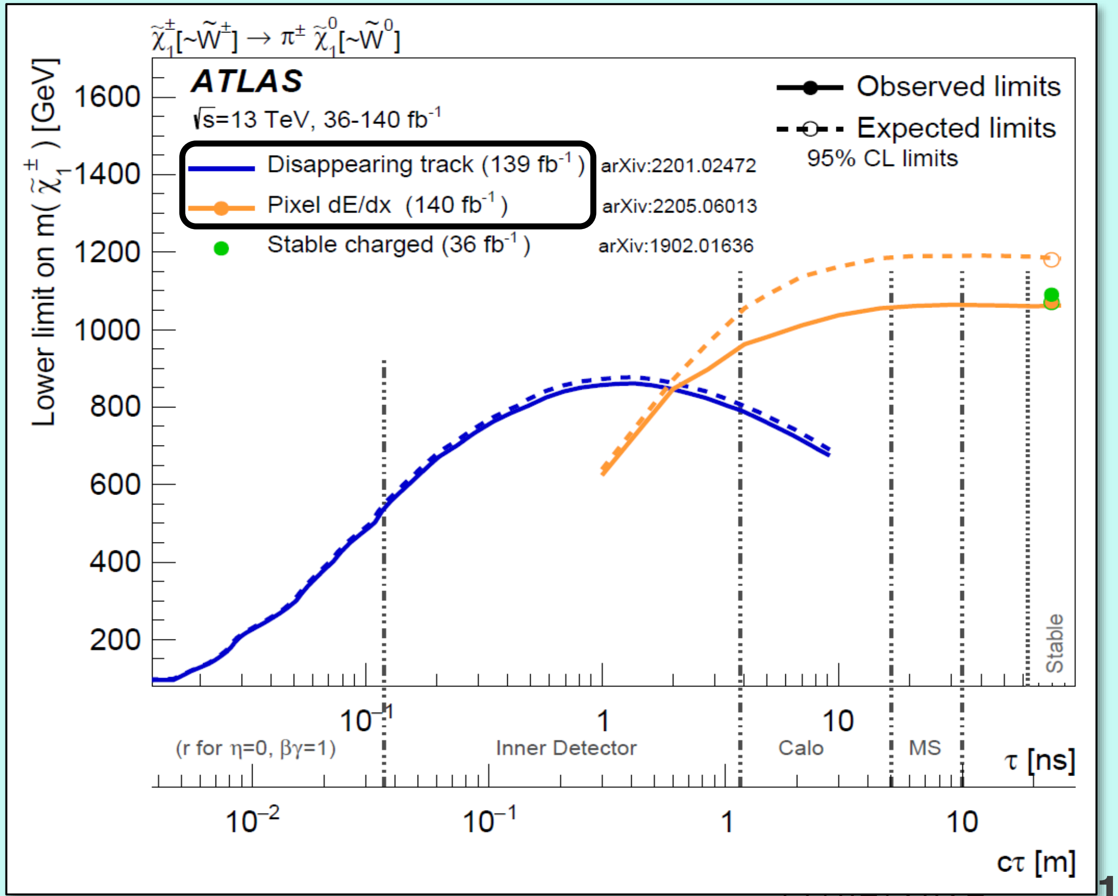
e.g. gluino:

- **Displaced vertices:** 0.02 ns to 40 ns
- **pixel dE/dx (+calo ToF):** >0.5 (2) ns
- **Stopped gluino (OOT):** 100 ns – 11 hours

e.g. chargino:

- **disappearing-track:** <10 ns
- **pixel dE/dx:** >1 ns





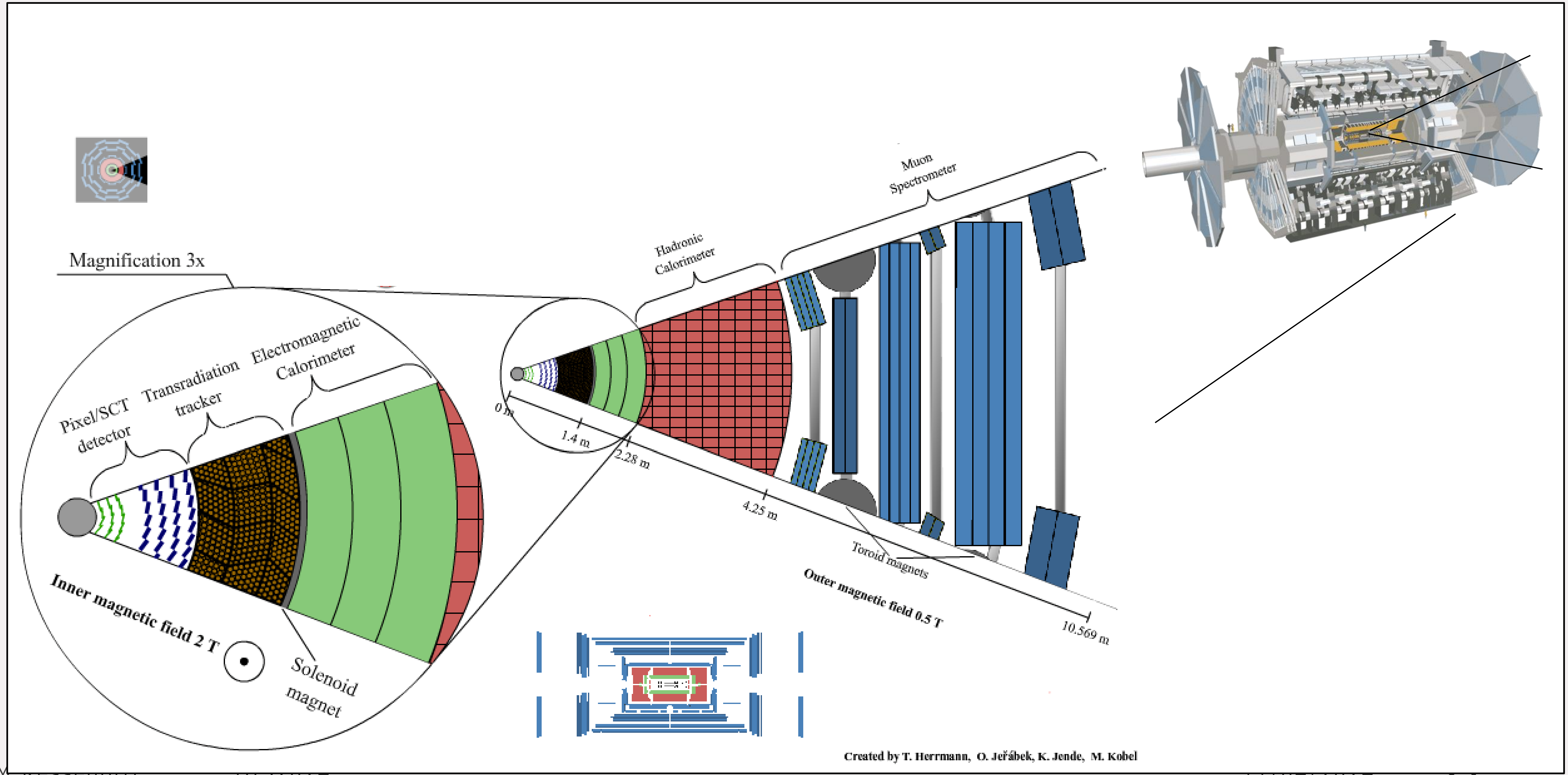
Summary

- Unconventional signatures used in searches exploiting **lots of models**
- Searches can be based on **specific detectors**...
  - Based on inner detector: disappearing tracks, displaced vertices
  - Based on calorimeter (and TRT): Highly Ionizing Particles (HIPs), Out-of-time energy deposits, non-pointing photons
  - Based on pixel detector: high ionization energy loss (dE/dx)
- ...or use **dedicated reconstruction algorithms and triggers**
  - Large Radius Tracking (LRT)
- Several recent searches with the ATLAS detector based on different unconventional signatures have been presented.

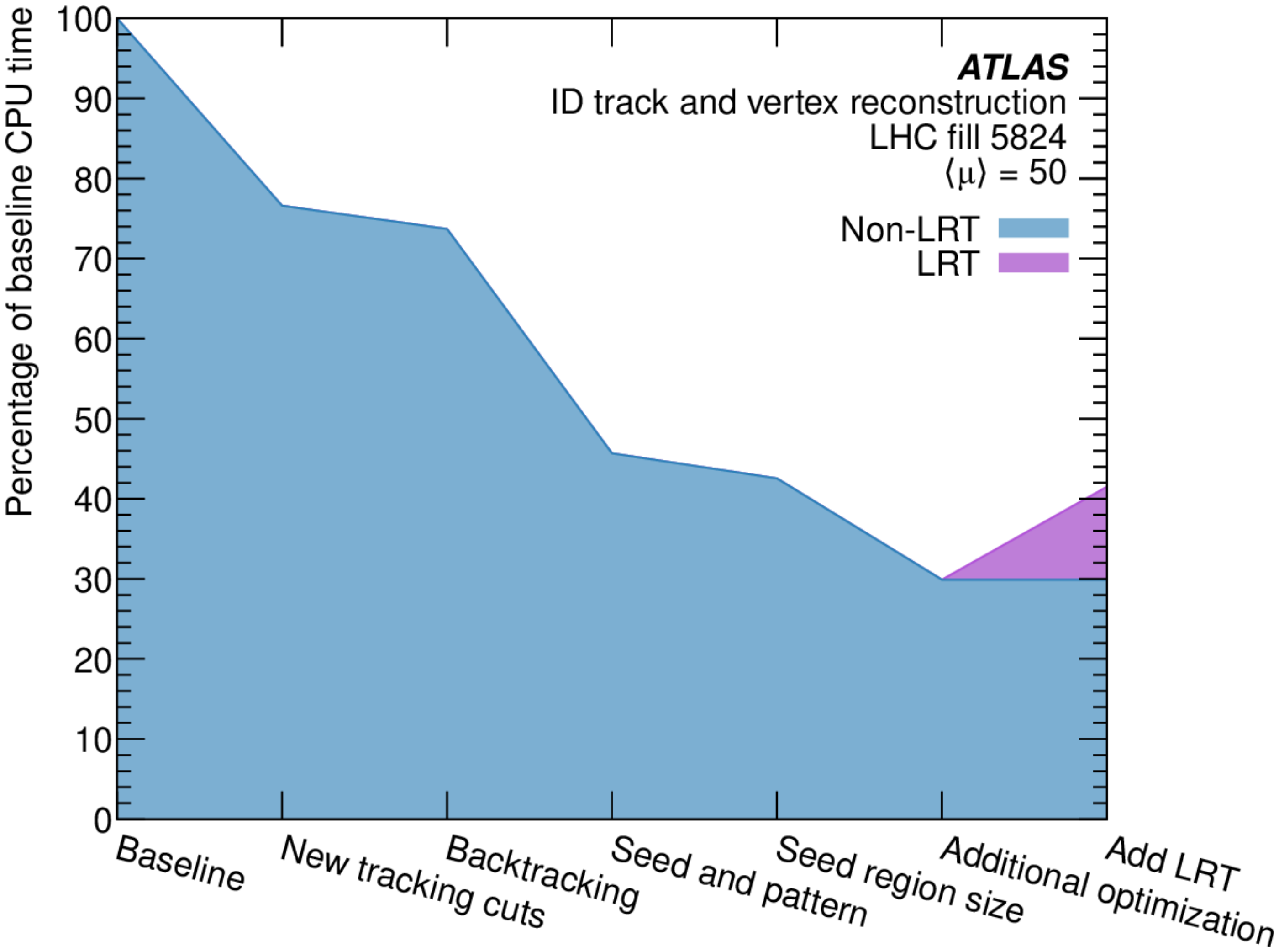
Thanks!

Backup

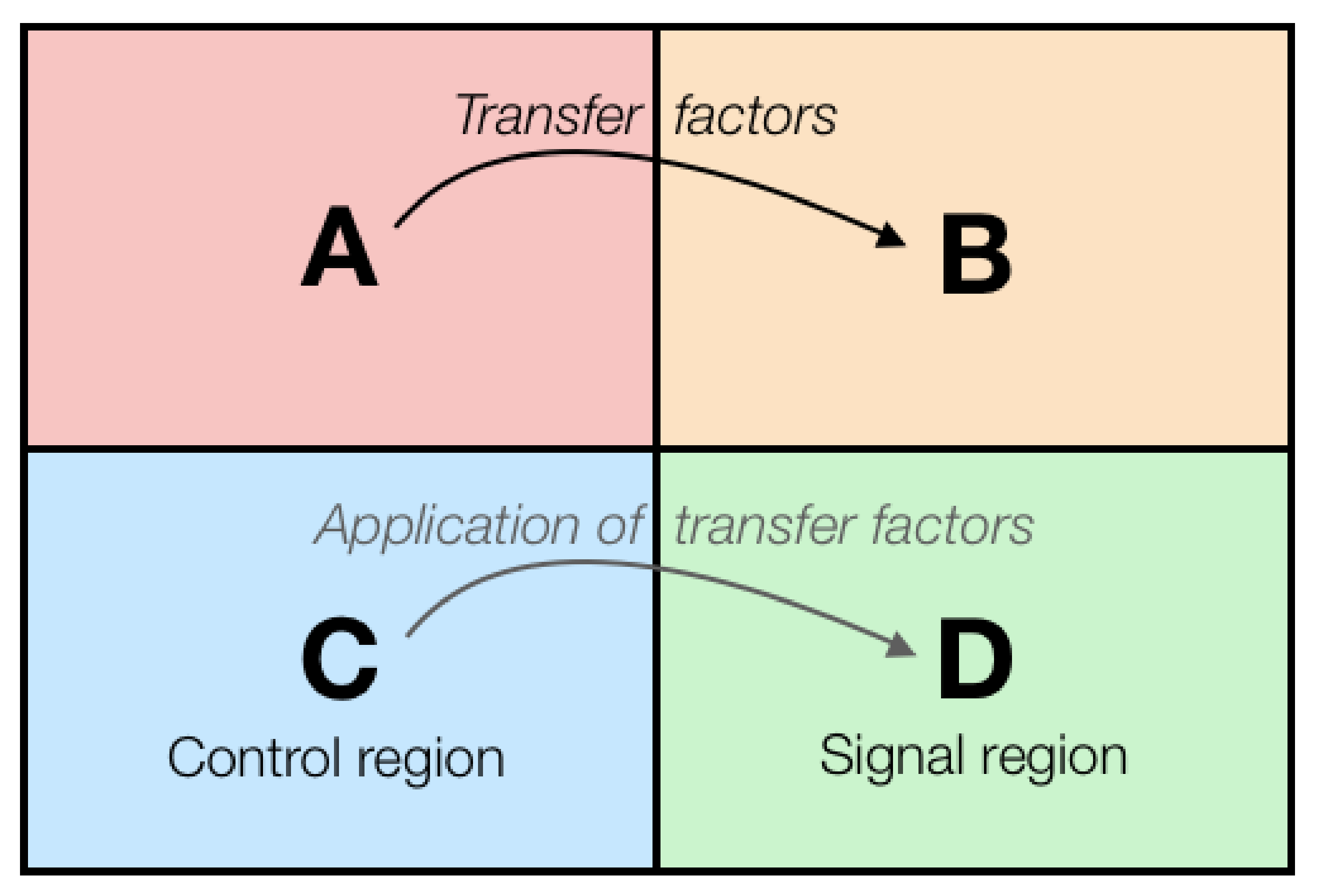
The ATLAS detector



Large radius tracking



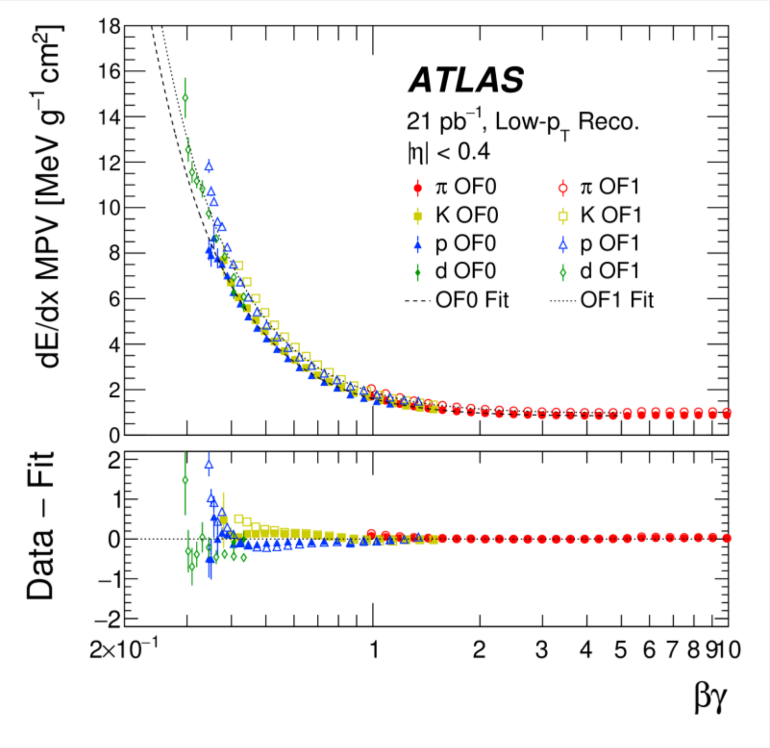
ABCD method

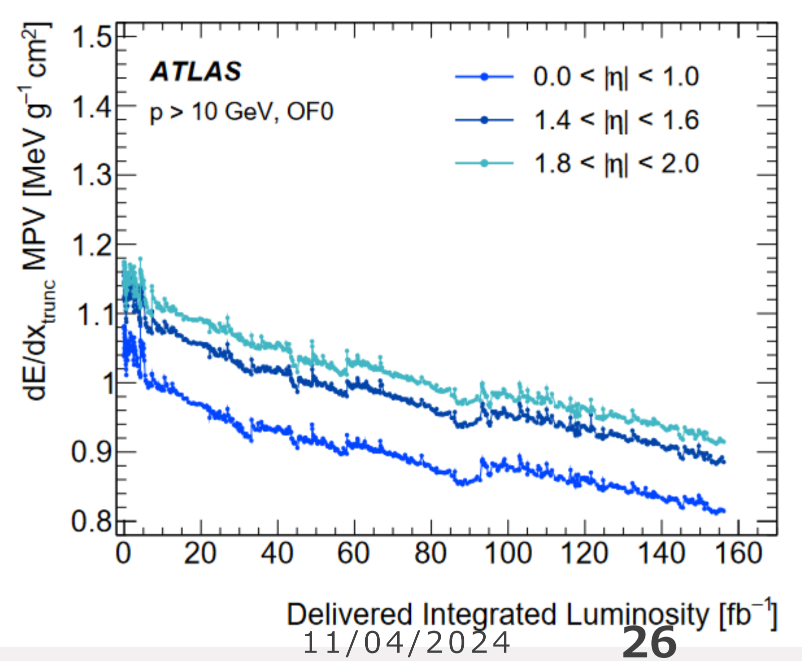


Transfer factors correct for the different selection efficiencies between regions C and D.

Pixel detector: High dE/dx signature

- **Calibration:**
  - Bethe-Bloch reconstructed from measurement of most probable value (MPV) of dE/dx distributions of low-pT pions, kaons, protons and deuterons of pions, kaons, protons and deuterons in momentum slices
  - Radiation damage → dE/dx response changes with position and time → corrections dependent on run and |η| based on data





High dE/dx analyses

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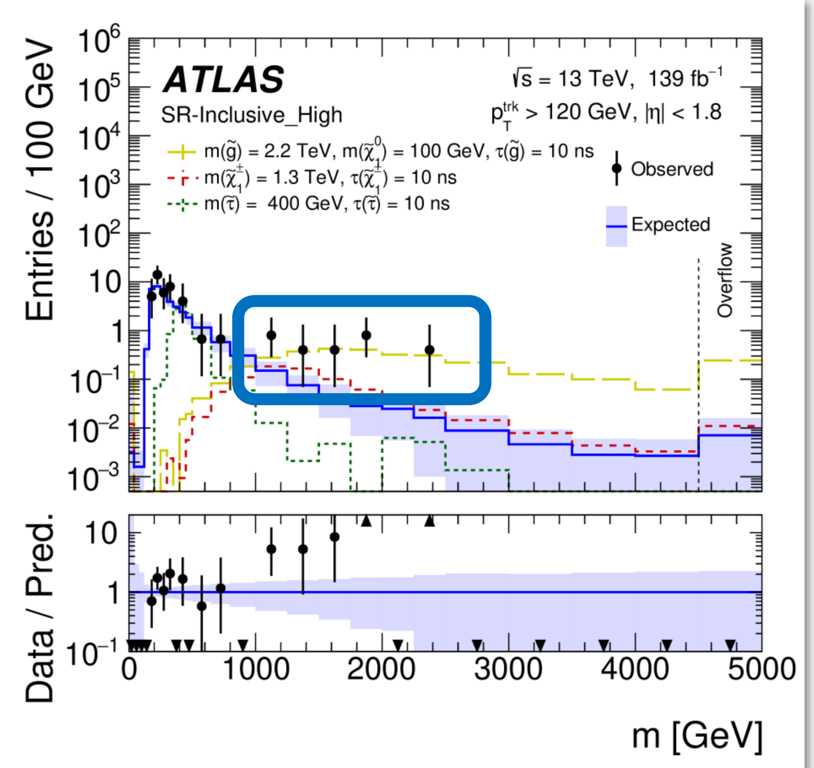
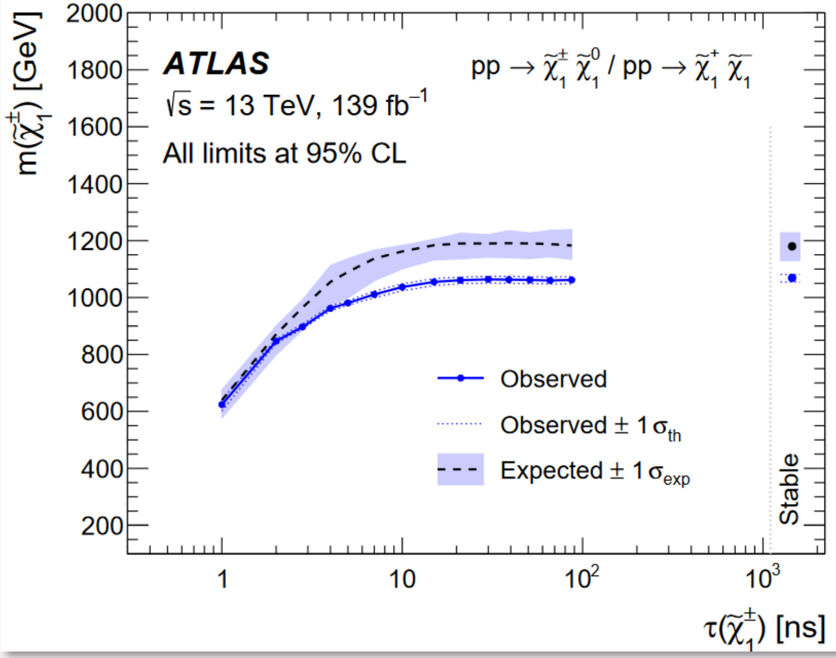
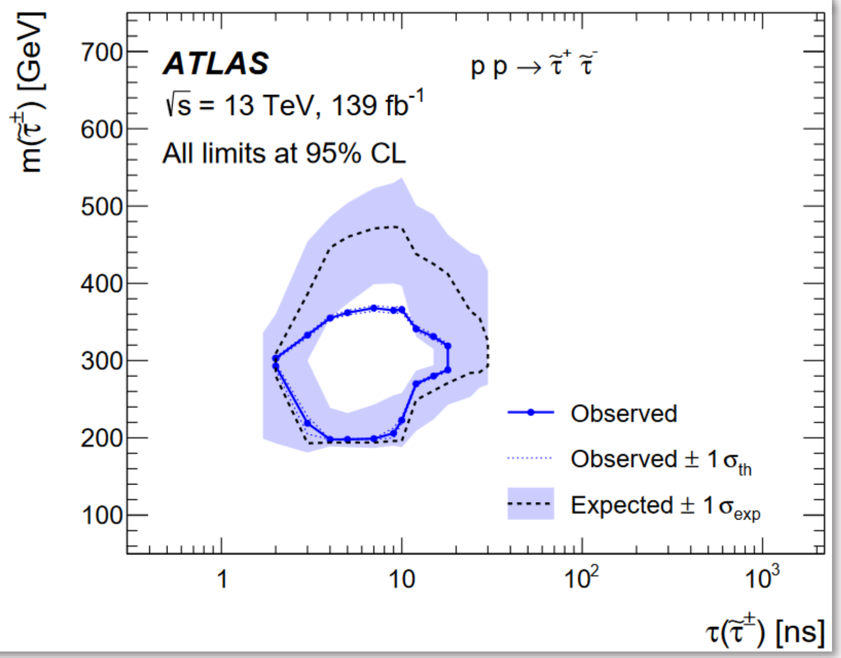
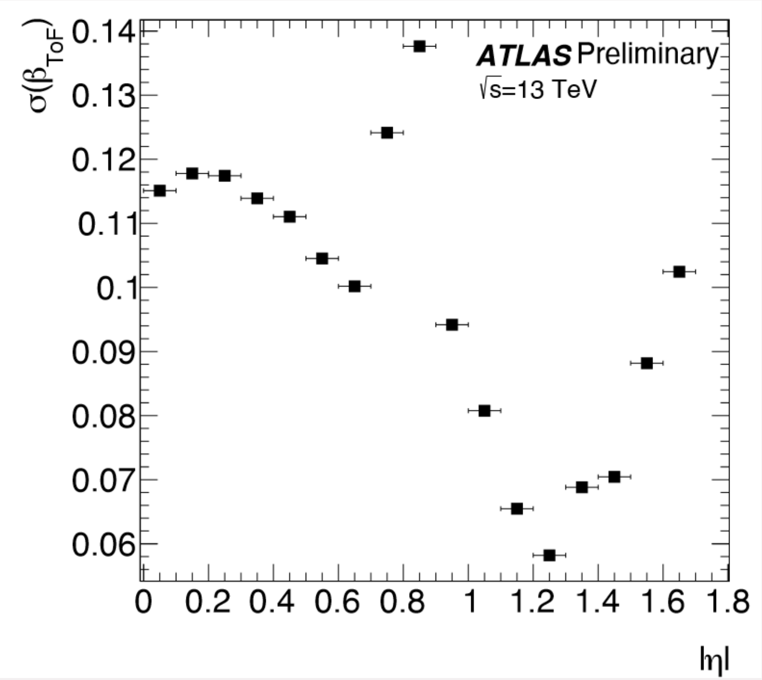
  - **Model independent** → results interpreted for pair-production of R-hadrons, charginos and staus
  - 3.3σ excess observed (7 observed, 0.7±0.4 expected) in mass window [1.1,2.8] TeV
  - But low β not confirmed by calorimeter and MS (consistent with β=1)





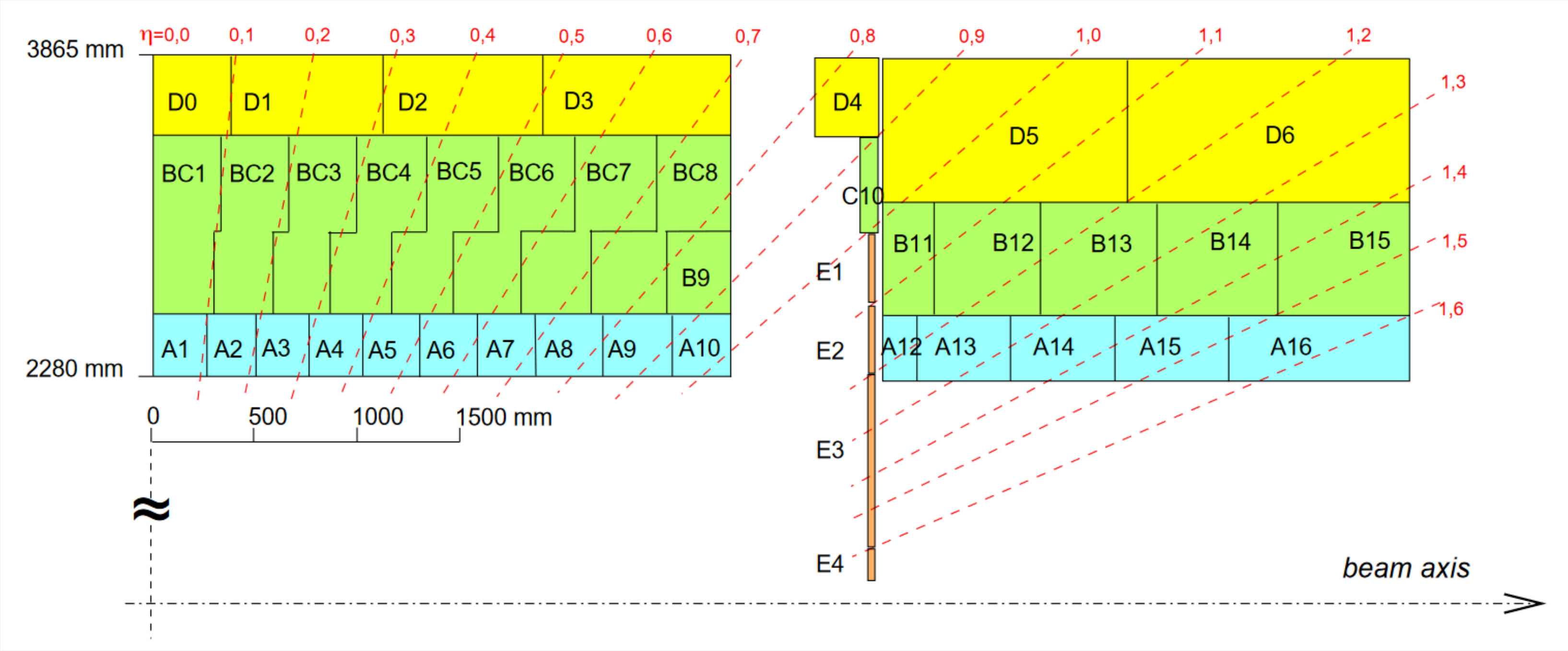


Pixel dE/dx + beta calo: β_{ToF} resolution



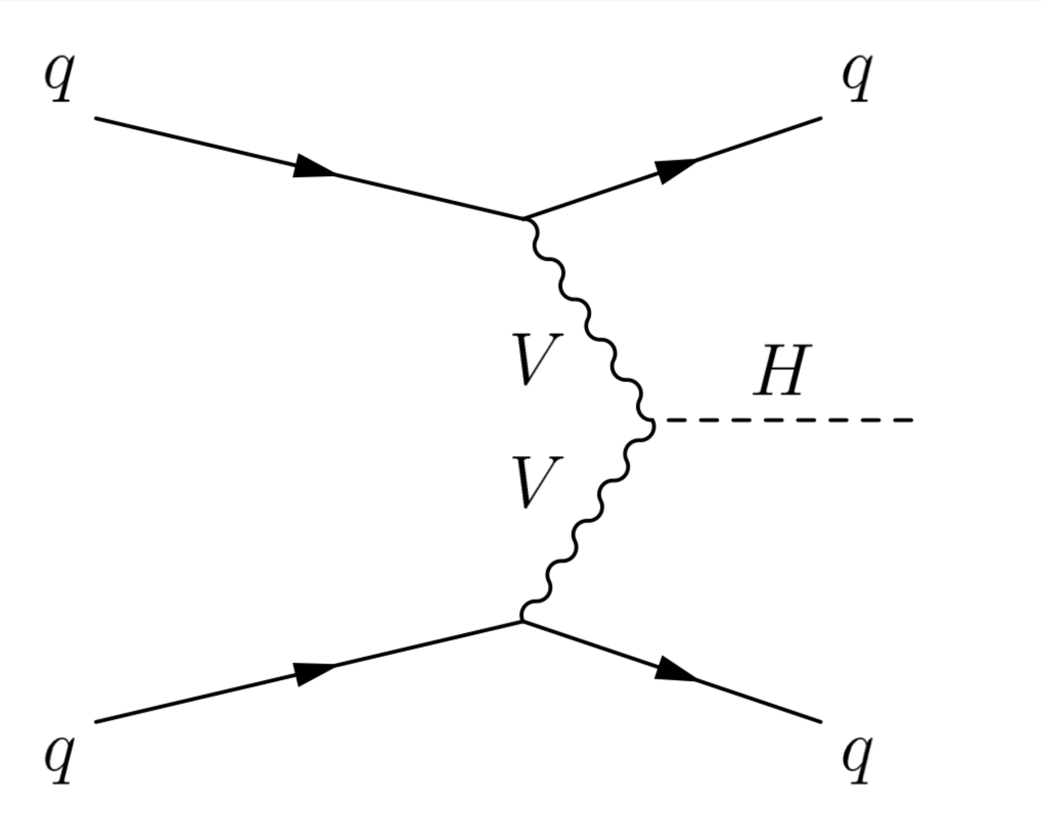
Dependence of resolution on pseudorapidity (2018 isolated muons from $Z \rightarrow \mu\mu$)

- larger $|\eta|$ → longer track path → better β_{ToF} resolution
- barrel-endcap transition and very high $|\eta|$ → fewer calorimeter cells contribute to the ToF measurement → worse β_{ToF} resolution



TileCal cell layout and $|\eta|$ acceptance

Higgs VBF



Long Lived Particles and Unconventional signatures

- Long-lived particles (LLPs) may be long-lived and travel a significant distance before decaying
  - weak couplings to decay products
  - decays through heavy mediator particles
  - small mass differences between the particle and decay products
- → LLP can have unconventional signatures depending on where and how the particle decay
  - can travel from interaction point (IP) through the inner-detector (ID), the calorimeters, even through the muon spectrometer or decay at any point along this way
  - leaving different signatures along its path depending on its properties.

Long Lived Particles and Unconventional signatures

Based on ID:

- **Disappearing (or kinked) track**: charged particle decays in the ID to a nearly degenerate stable neutral particle
- **Displaced vertex (DV):** neutral particle decays in the ID to charged and neutral particles appears as tracks pointing (back) to a DV

Based on calorimeters:

- **"Non-pointing" photons:** photons detected in calorimeter not pointing back to the original IP

Based on muon spectrometer or more ATLAS subdetectors:

- **"Muon-like" or Heavy Stable Charged Particles (HSCP):** if charged and very long-lived, the signature is similar to that of a muon but with high mass
- **Missing transverse momentum**: neutral, weakly interacting LLPs (traverses the ATLAS detector not being detected)