Overview of the long-lived particle searches in ATLAS

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Introduction

- A particle has its own lifetime as the inverse of the decay width (the uncertainty principle)
- “Long-lived”: the lifetime ($c\tau$) is macroscopic, and is the same order of magnitude as the size of the instruments.
- Long-lived particles searches: finding resonances from new phyiscs with narrow widths in a specific range matching to the detector scale.

e.g. general 2-body decay

$$\Gamma = \frac{1}{32\pi^2 M} \int \mathrm{d}\Omega \, |\mathcal{M}|^2 \sim \hbar/\tau$$

Mechanisms of long lifetime

Analogous situations may be found in SM…

- Scale
  - e.g. lifetime of $\pi^{\pm}$ is determined by a large off-shellness $$\Gamma \sim g_W^2 \left(\frac{m_\pi}{M_W} \right)^4 m_\pi$$
- Degeneracy
  - e.g. neutron lifetime (~15 min) is related to "accidental" degeneracy of (u, d) quark masses and the gap to the EW scale $$\Gamma \sim g_W^2 \left(\frac{m_n - m_p}{M_W} \right)^4 (m_n - m_p)$$
- Rules
  - Lepton flavor conservation: $\mu \to e\gamma$ almost forbidden in SM → Michel decay only.
  - SUSY R-parity conservation: stable neutralino and proton (in the canonical SUSY)
- Coupling
  - If coupling involved in the decay process is very weak, lifetime gets longer.
- Kinematic phase space
  - e.g. $K_L \to 3\pi$ has longer lifetime than $K_S \to 2\pi$

LLP searches in ATLAS

- Most of the standard set of triggers and obj.reco. are designed for prompt event signatures.
- Dedicated expansion of the experimental capabilities is required.
  - Custom high-level trigger filters
  - Custom data stream for special reconstruction
  - Dedicated performance evaluation and optimization
  - Custom MC simulation codes for LLP generation
- Limited resources (both computing and person power)

<table>
<tr><th rowspan="2">LLP Observables</th><th colspan="3">ID</th><th colspan="2">Calorimeter</th><th rowspan="2">Muon</th></tr>
<tr><th>Pix</th><th>SCT</th><th>TRT</th><th>LAr</th><th>Tile</th></tr>
<tr><td>ToF</td><td></td><td></td><td></td><td colspan="2">✓</td><td>✓</td></tr>
<tr><td>dE/dx</td><td>✓</td><td></td><td>✓</td><td colspan="2"></td><td></td></tr>
<tr><td>displacement</td><td>✓</td><td>✓</td><td>✓</td><td colspan="2">✓</td><td>✓</td></tr>
<tr><td>Causality: (dis)appearance</td><td>✓</td><td>✓</td><td>✓</td><td colspan="2">✓</td><td>✓</td></tr>
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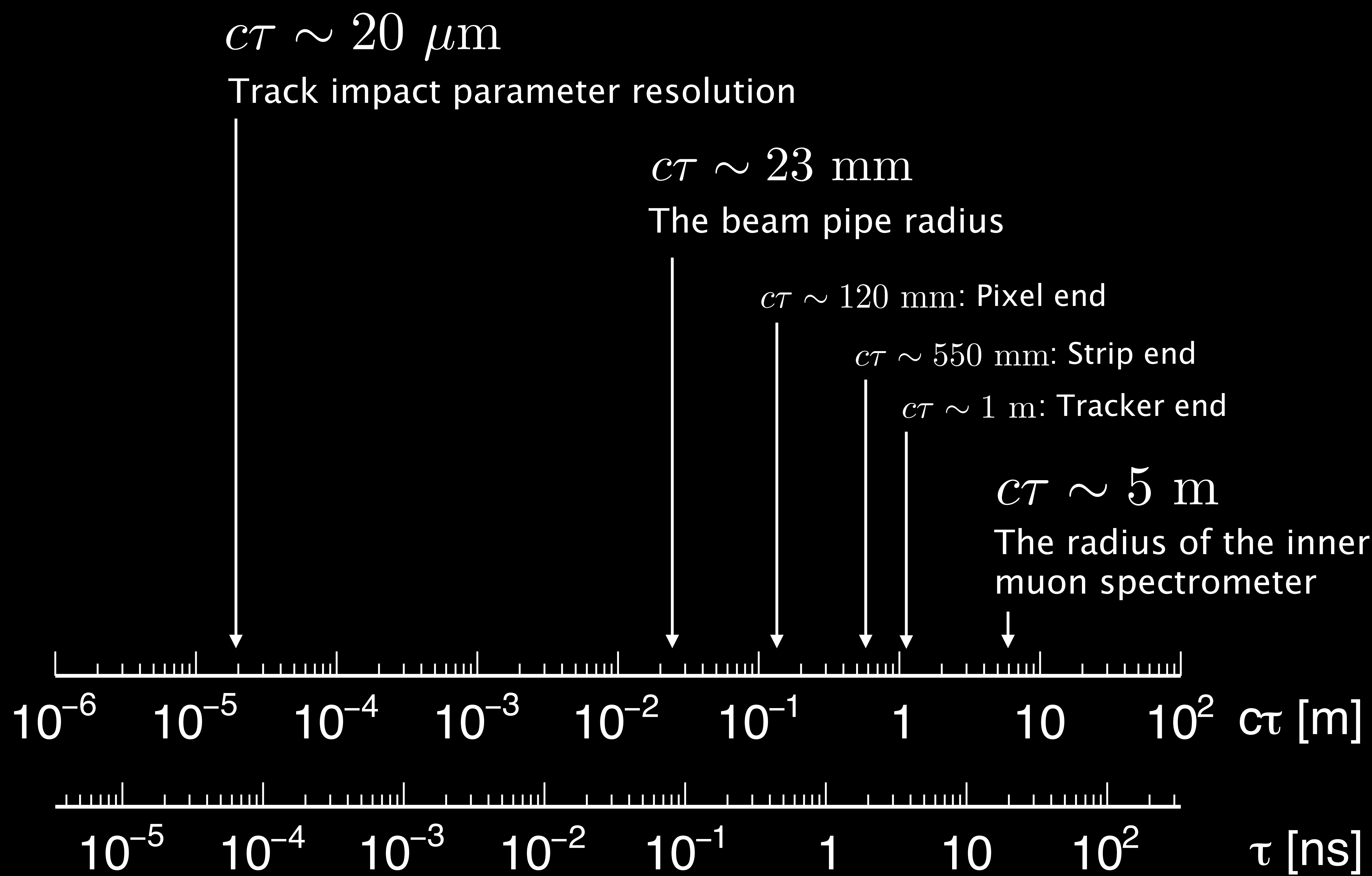
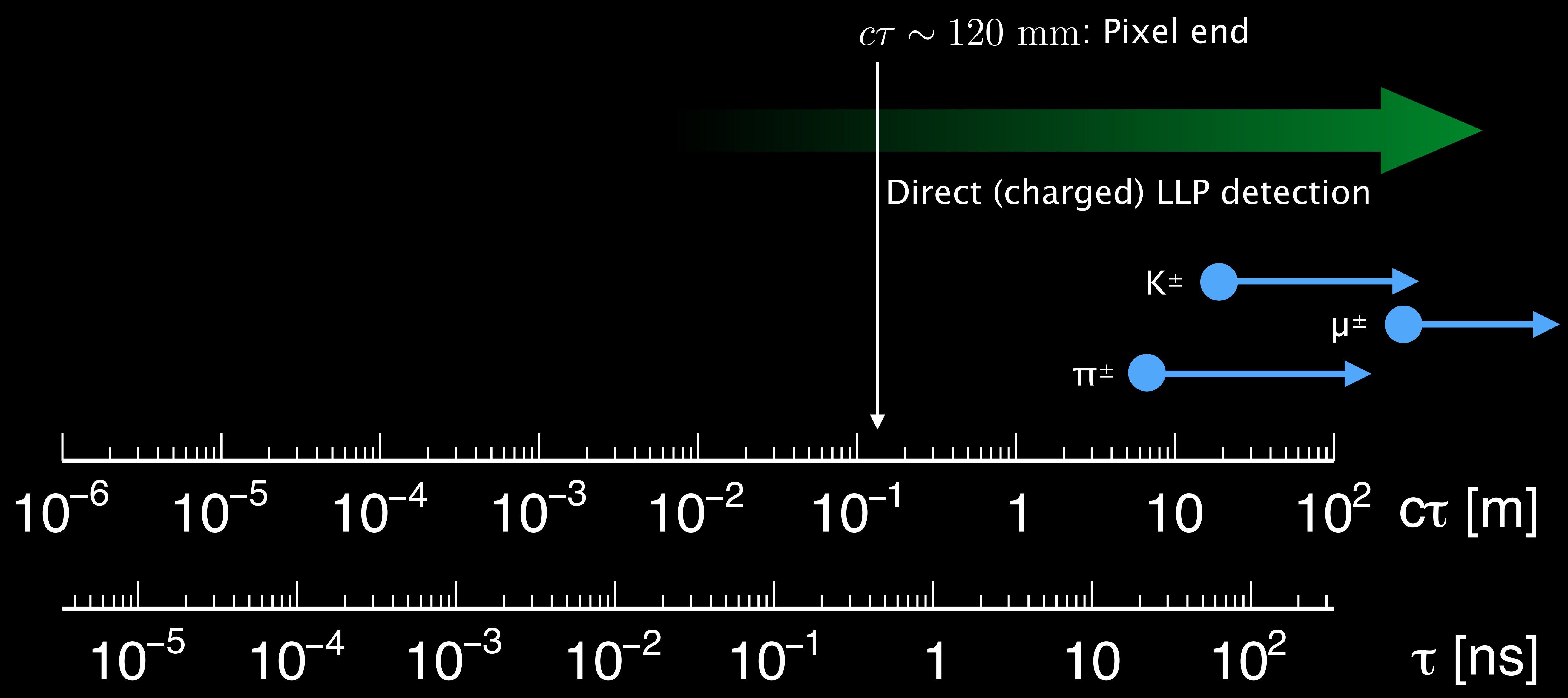
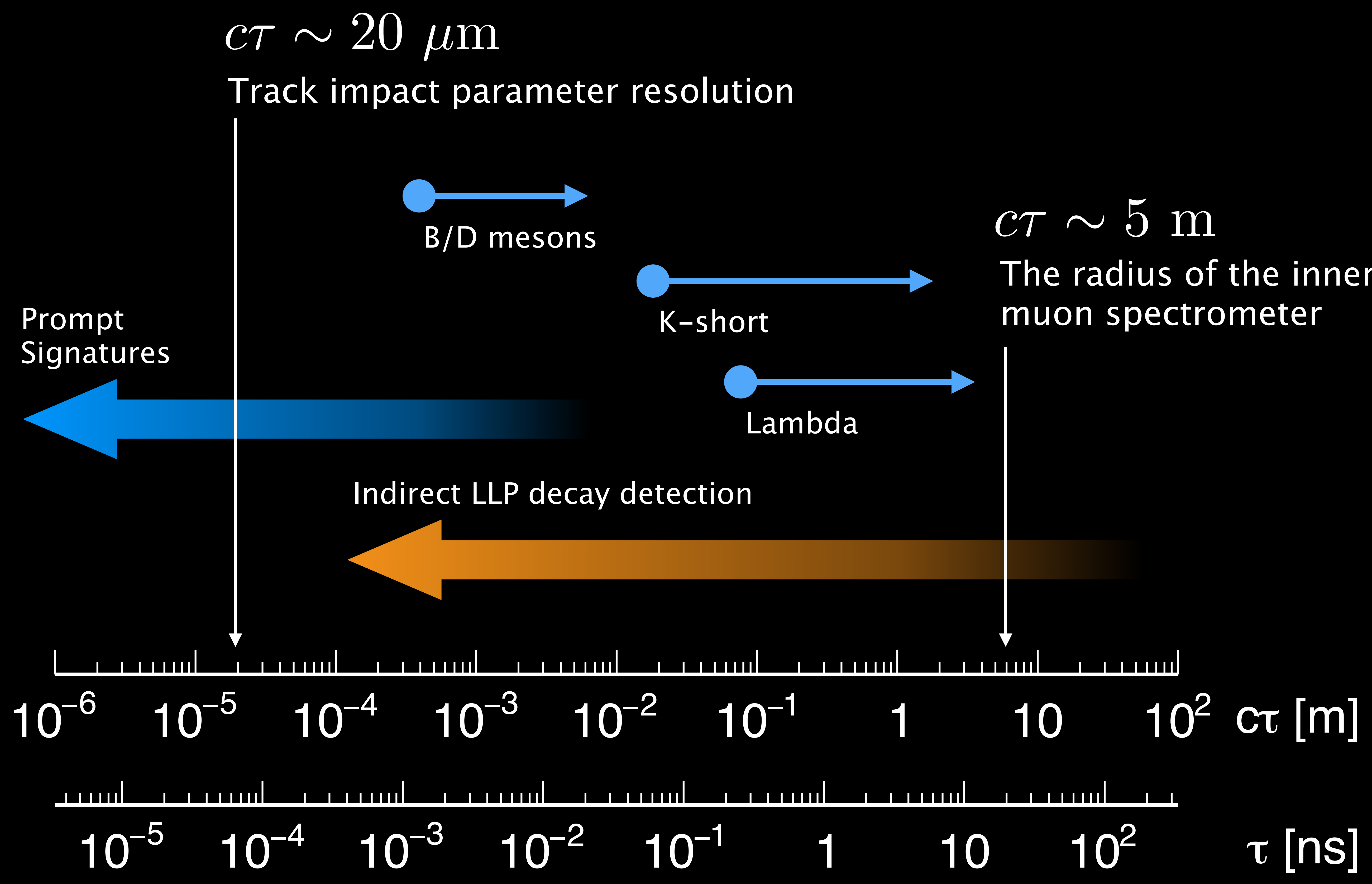
radius [mm]: 33, 125, 500, 1.4×10^3, 2.2×10^3, 3.7×10^3

Geometry and lifetime



Trackers require O(100 mm) of minimum track length for trajectory reconstruction.

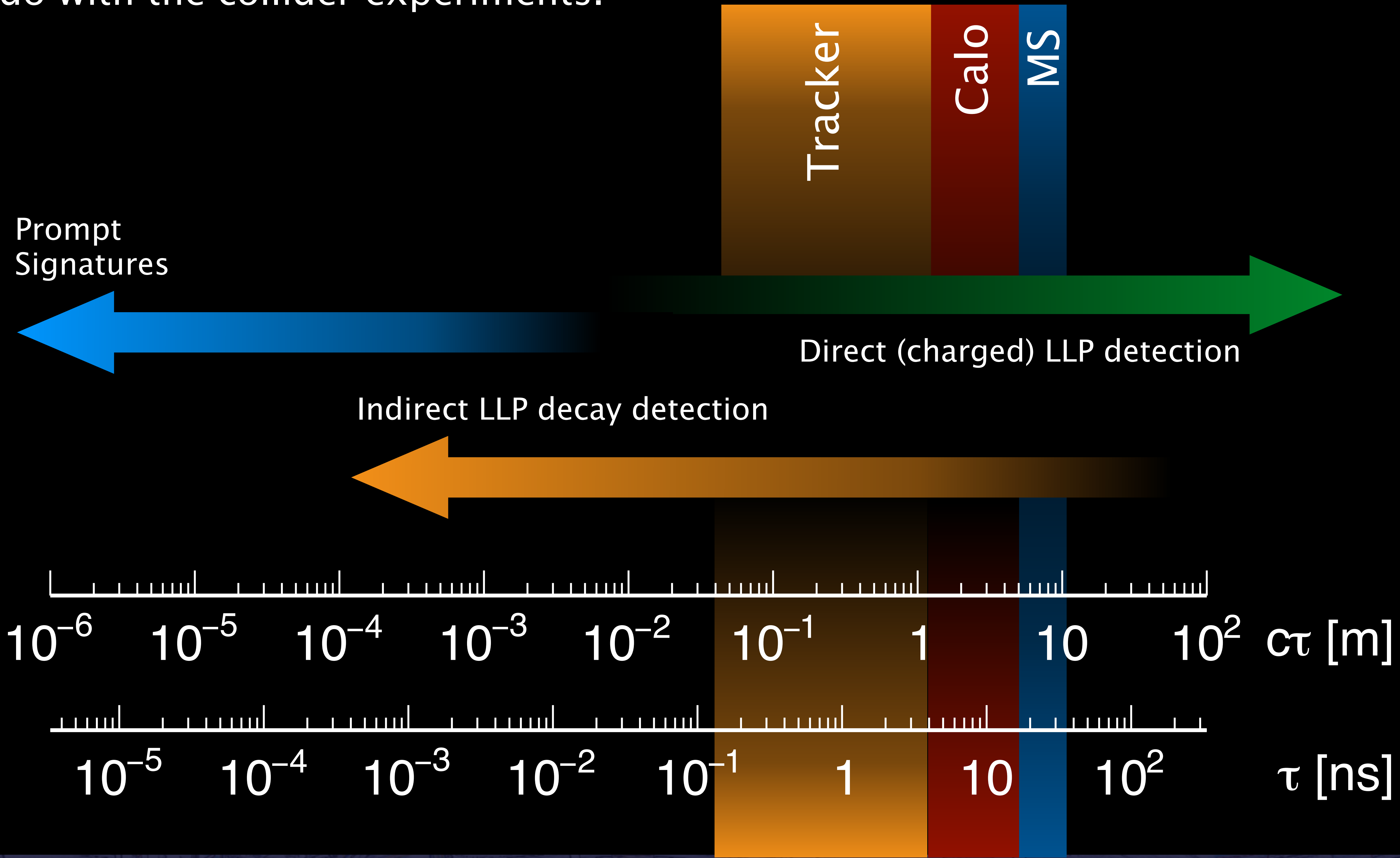




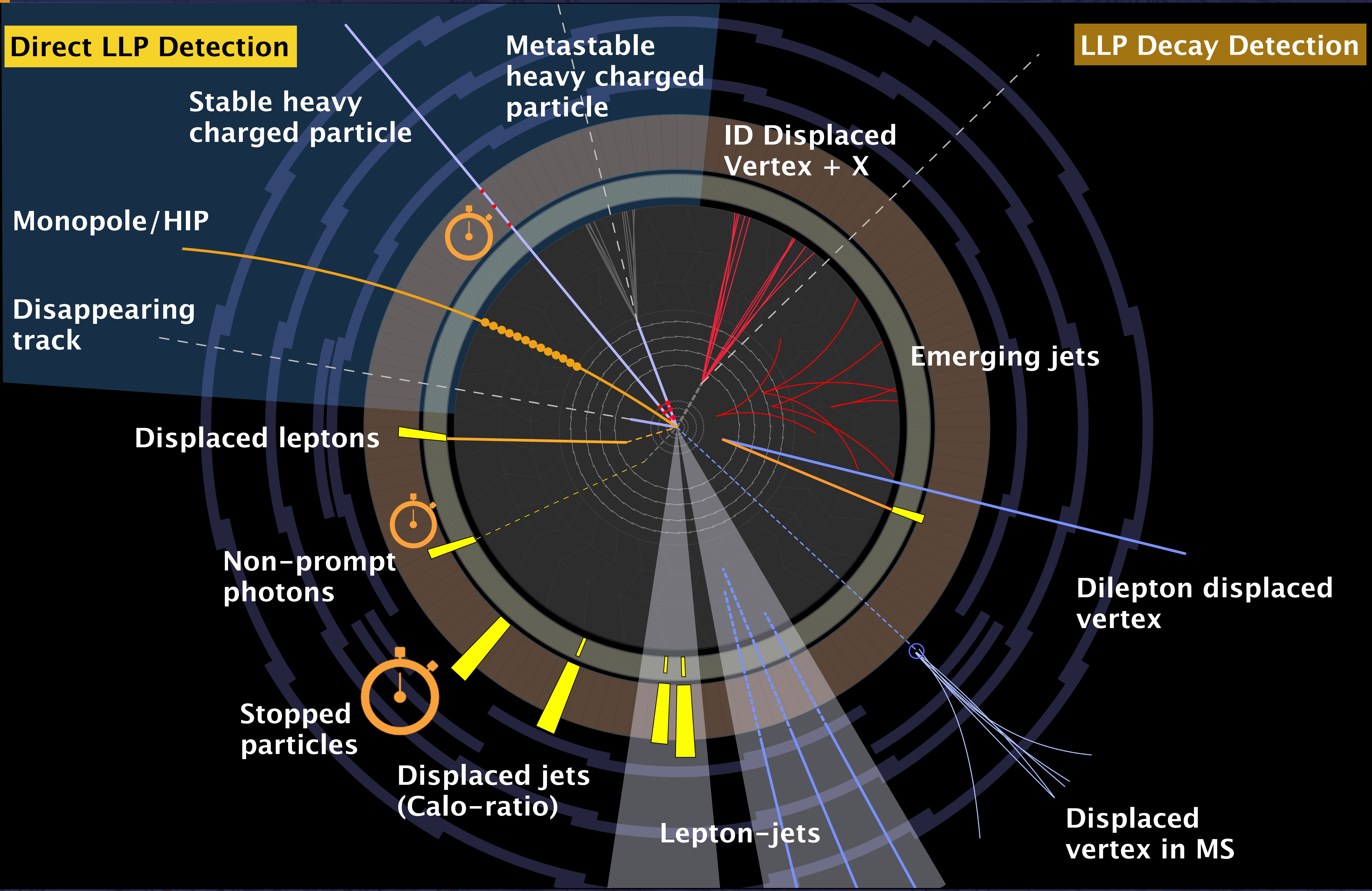
$c\tau \sim 20\ \mu m$
Track impact parameter resolution
B/D mesons
$c\tau \sim 5\ m$
The radius of the inner muon spectrometer
K-short
Prompt Signatures
Lambda
Indirect LLP decay detection
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} $c\tau$ [m]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} τ [ns]

Geometry and lifetime

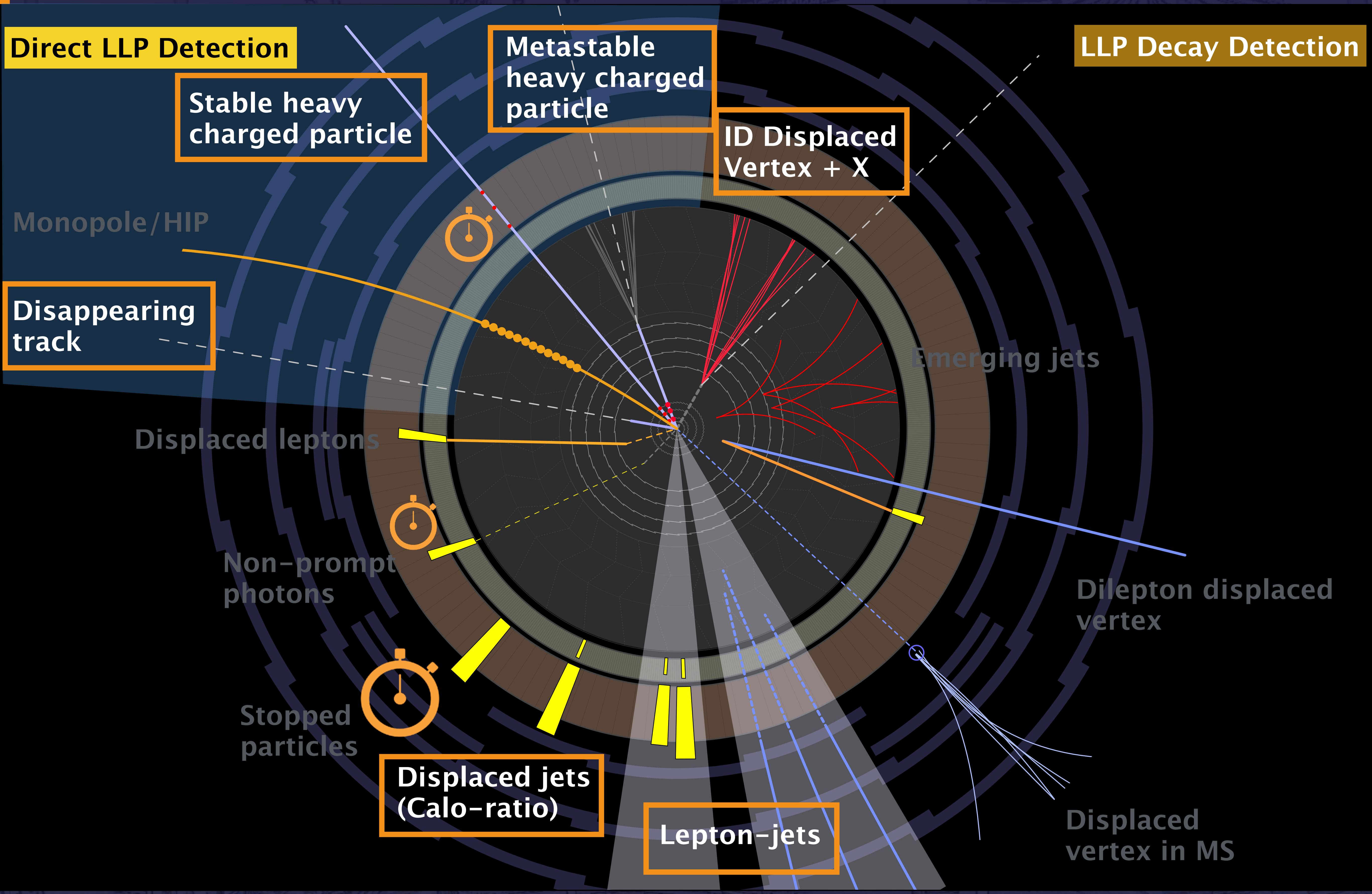
LLP searches complete what we can do with the collider experiments.



LLP Search Classes

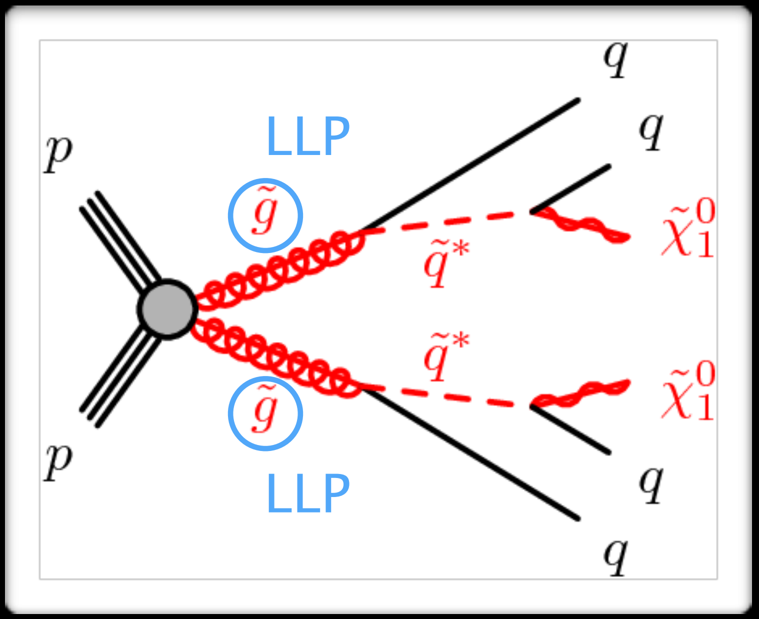


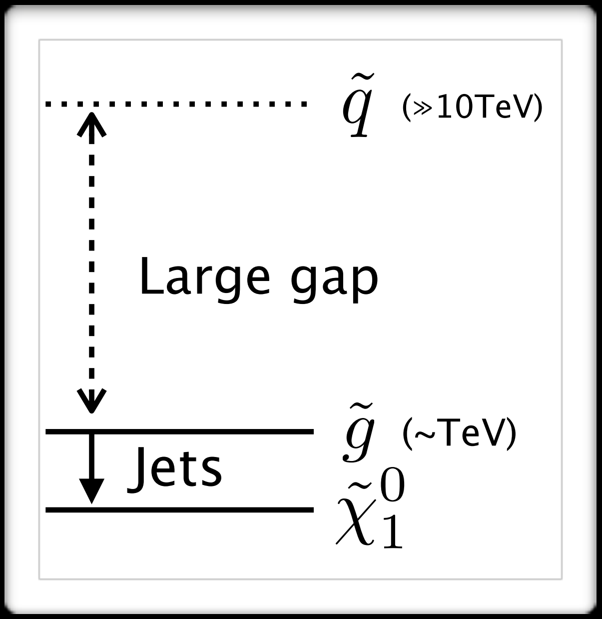
LLP Search Classes



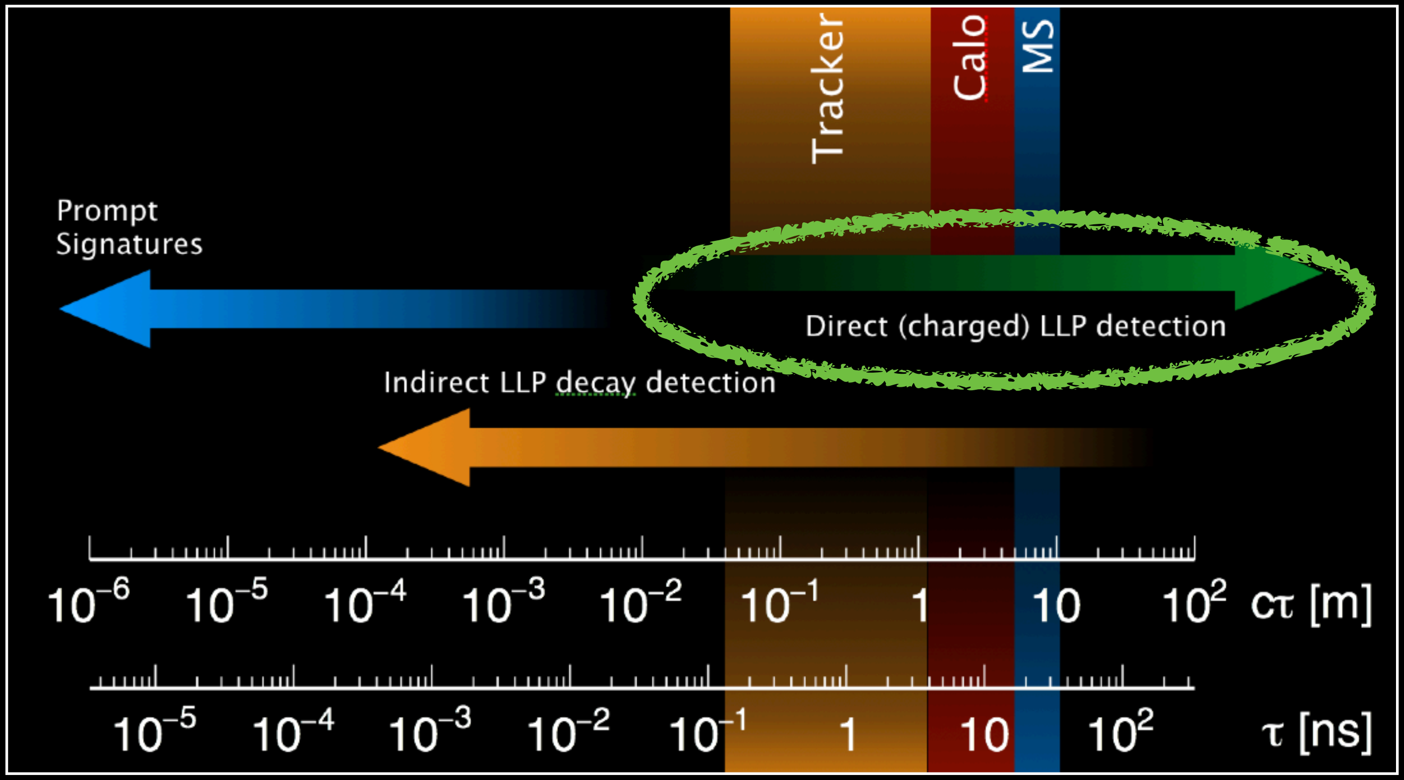
(Meta)stable heavy charged particles: *R*-hadron

- Split-SUSY scenario: thinking of cases of gluino pair production that squark mass scale is much higher than the LHC reach.
- Gluino hadronizes and forms the so-called **R-hadron**, which is either neutral or charged.
- The lifetime is coupled to the squark mass, (somewhat analogous to SM pion decay).





- When an R-hadron is charged, its track can be identified as a high-momentum **slow** particle.
- The track length depends on the lifetime.
- The event may exhibit a significant amount of missing transverse momentum (MET):
  - Decay neutralino inside tracker (LSP) → MET
  - Neutral R-hadron → energy loss at the calorimeter is small.



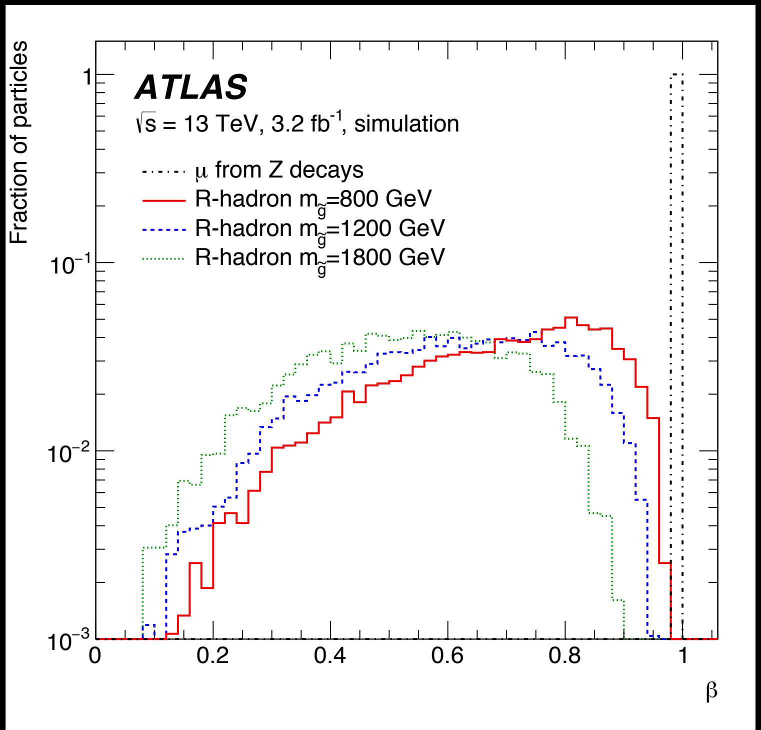
- R-hadrons can be searched directly via a signature of MET + heavy (slow) meta-stable charged particle(s) with a focus of τ ≥ ~1 ns.

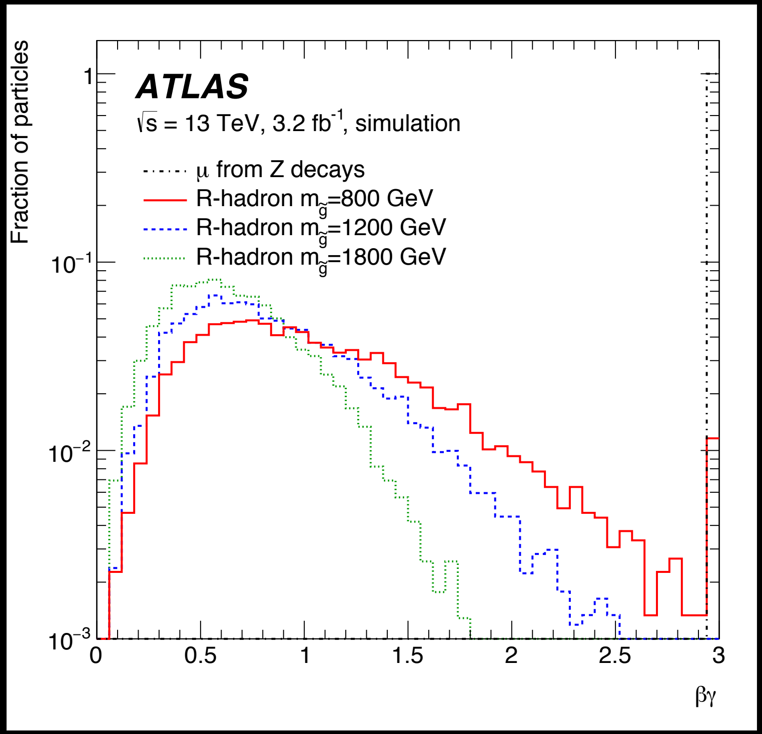
(Meta)stable heavy charged particle: general

- A direct detection of charged LLP.
- Signature: a high-momentum **slow** prompt track + (sth. for trigger)
- Application of techniques often used for particle identifications
  - Time-of-flight: measured at the Tile calorimeter
  - Energy deposit (dE/dx): measured at the Pixel detector

$$\mathrm{ToF}(\beta) \to M = p/\beta\gamma$$

$$\frac{\mathrm{d}E}{\mathrm{d}x}(\beta\gamma) \to M = M(p, \beta\gamma)$$

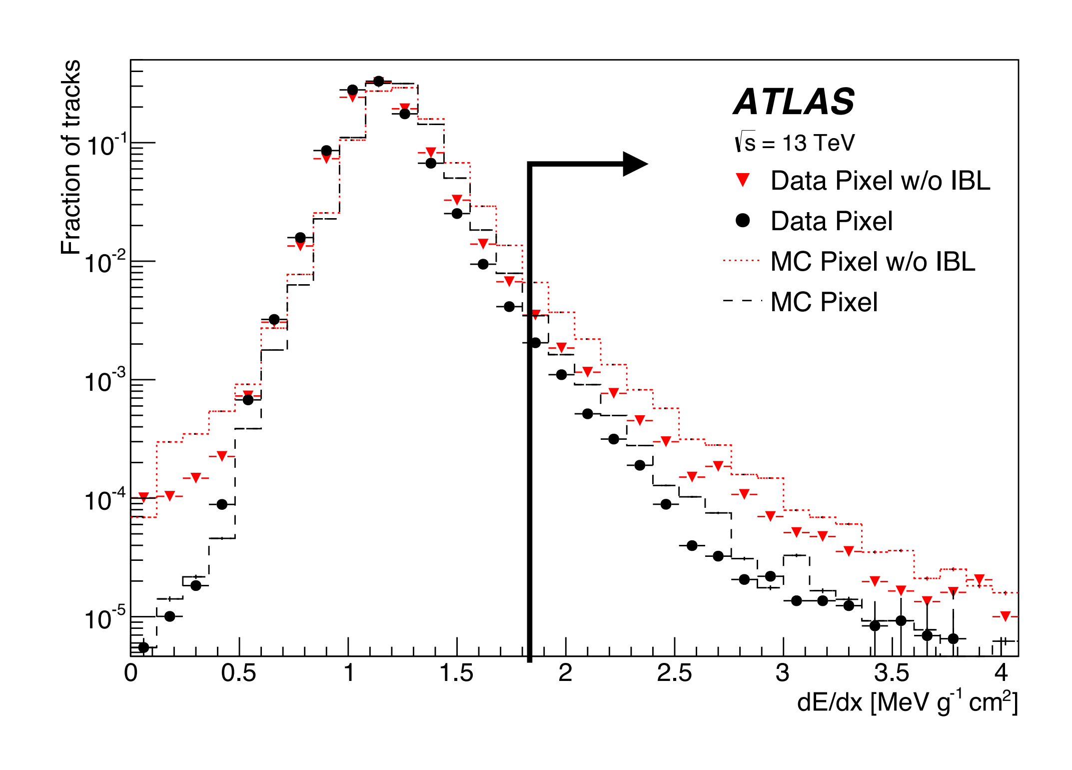


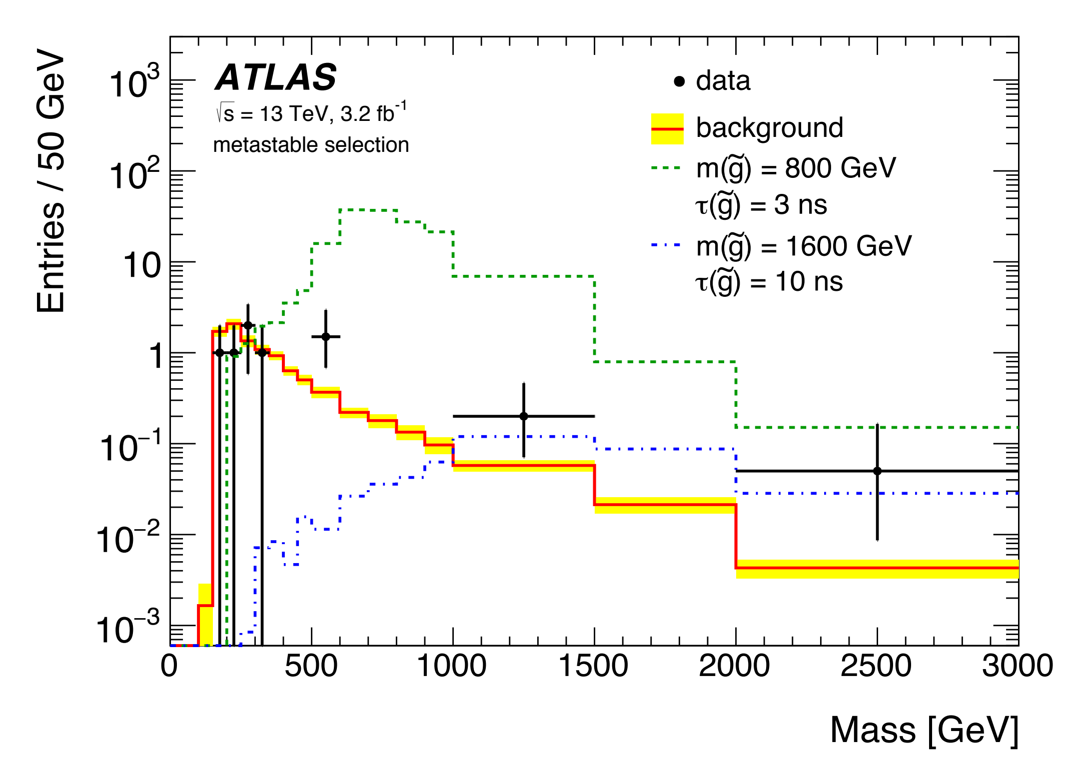


- Two of parallel independent searches
  - Meta-stable and stable cases, using only pixel dE/dx
  - Stable using pixel dE/dx and tile calorimeter ToF

(Meta)stable massive charged particle

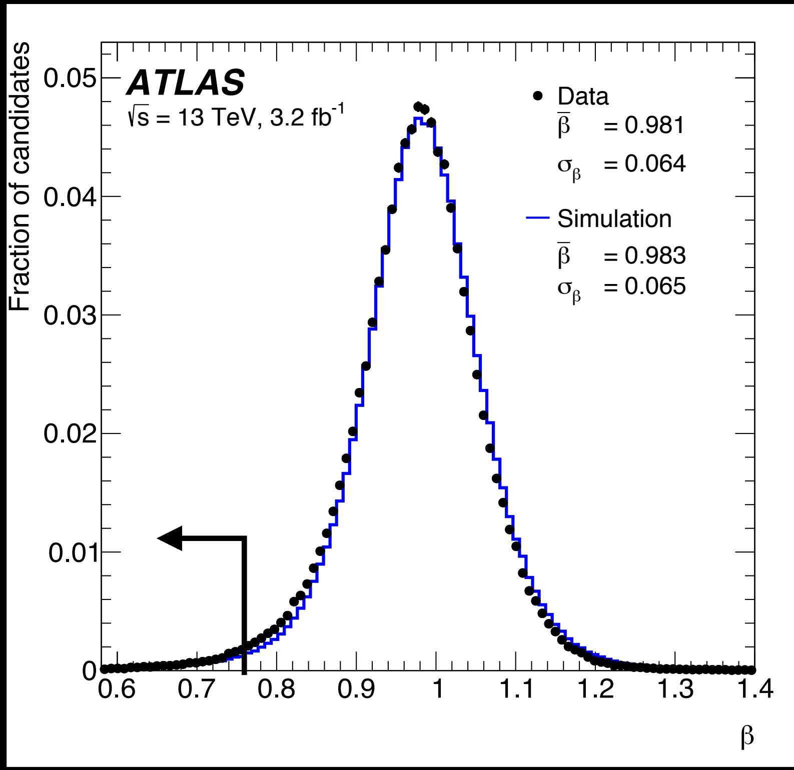
- Trigger: online MET > 70 GeV, offline MET > 130 GeV
- A well-isolated track of $p_T > 50$ GeV
- Leptonic W veto by $m_T > 130$ GeV
- Jets associated to the cand.track must have smaller energy than the track's.
- Meta-stable case: reject muon-matched tracks. Stable case: accept them, but with tighter isolation req.
- η-dependent dE/dx requirement.
- A full data-driven background estimation by templating momentum and dE/dx distributions for estimating the relative rate of random formation of (fake) large invariant mass.

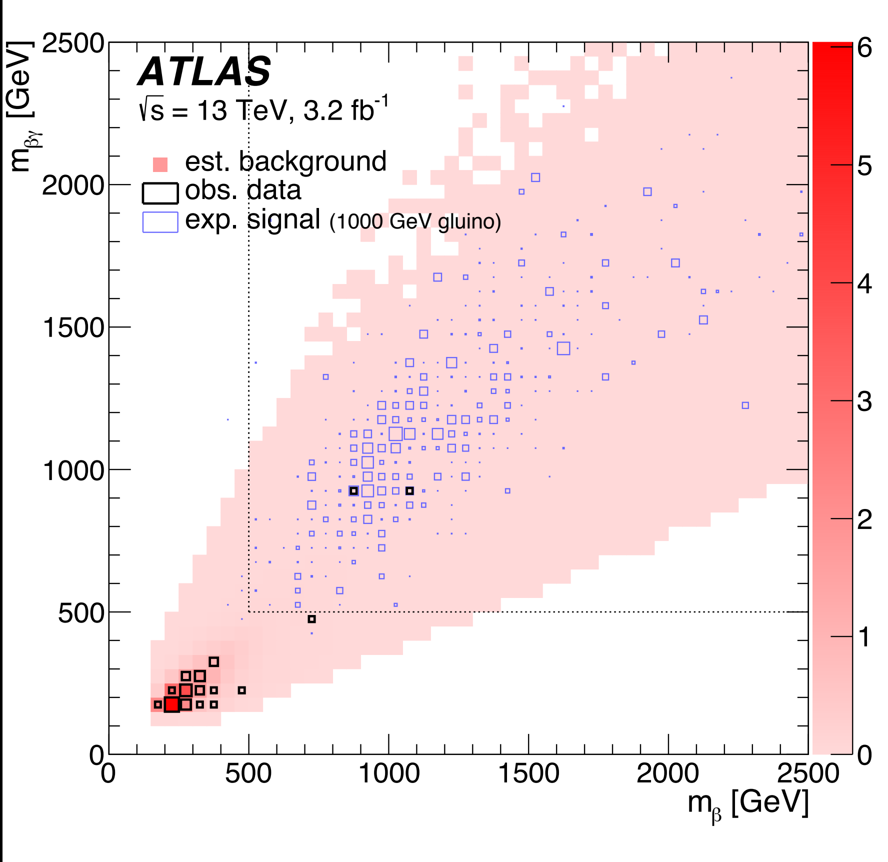




Stable massive charged particle

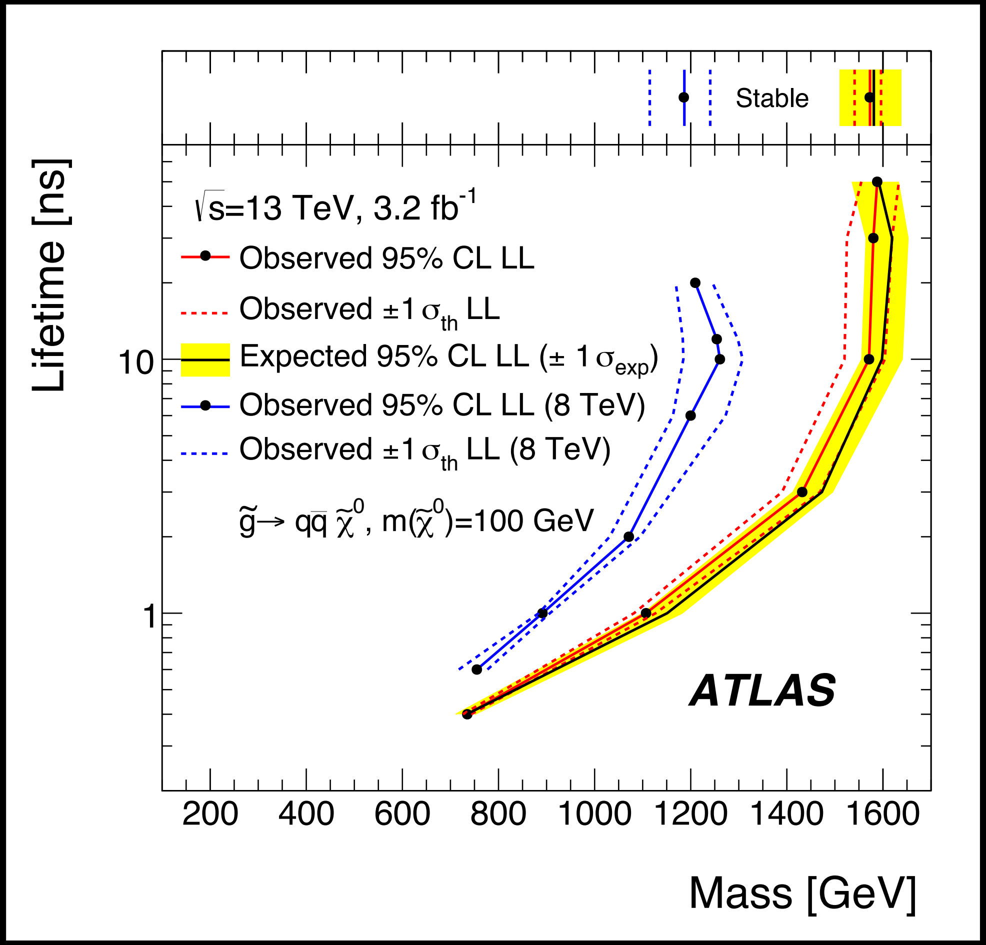
- Dedicated calibration of tile calorimeter ToF.
  - Pixel dE/dx calibration as described previously.
- MET trigger > 70 GeV.
- Candidate track: p_T > 50 GeV, |η| < 1.65
  - "MS-agnostic": does not use MS information for reducing model-dependence of R-hadron interactions with the calorimeter.
  - Good isolation and good association to PV
- Signal region is defined in a 2D manner using 2x independent reconstructed masses: **$m_{dE/dx}$ and m_{ToF}.**
- Background estimation in a full data-driven manner; template momentum, ToF and dE/dx distributions extracted using independent control regions then randomly combined.



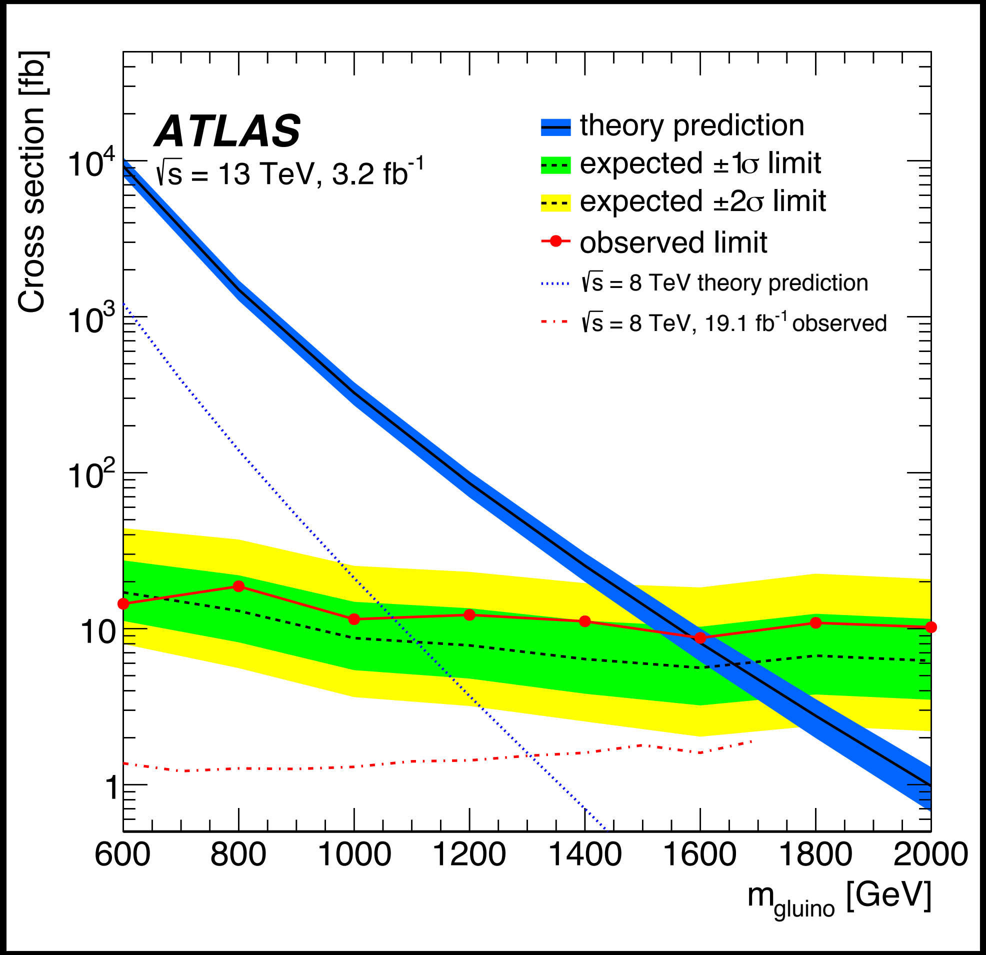


(Meta)stable heavy charged particles: result

Pixel dE/dx

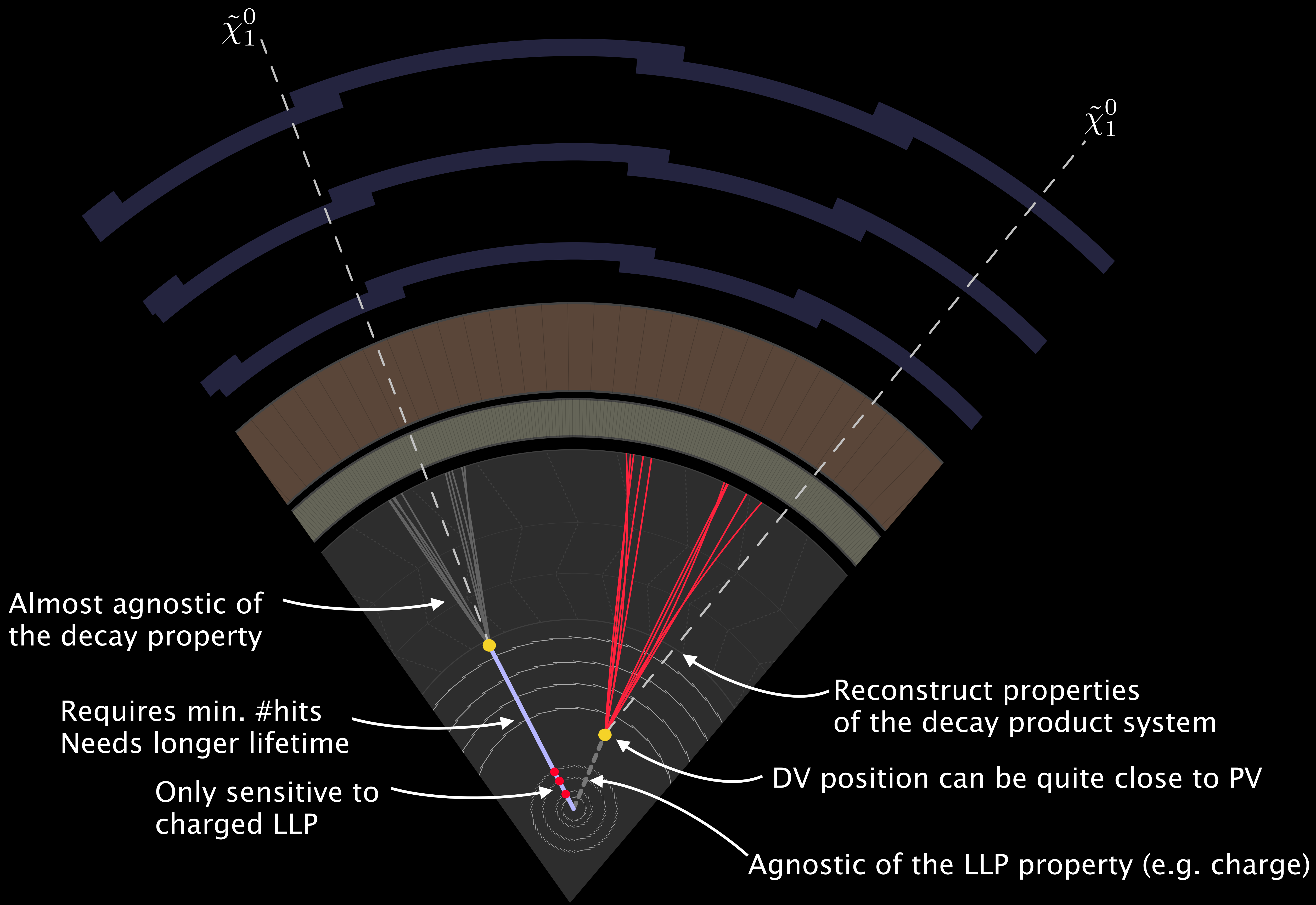


Pixel dE/dx + Tile ToF; Stable

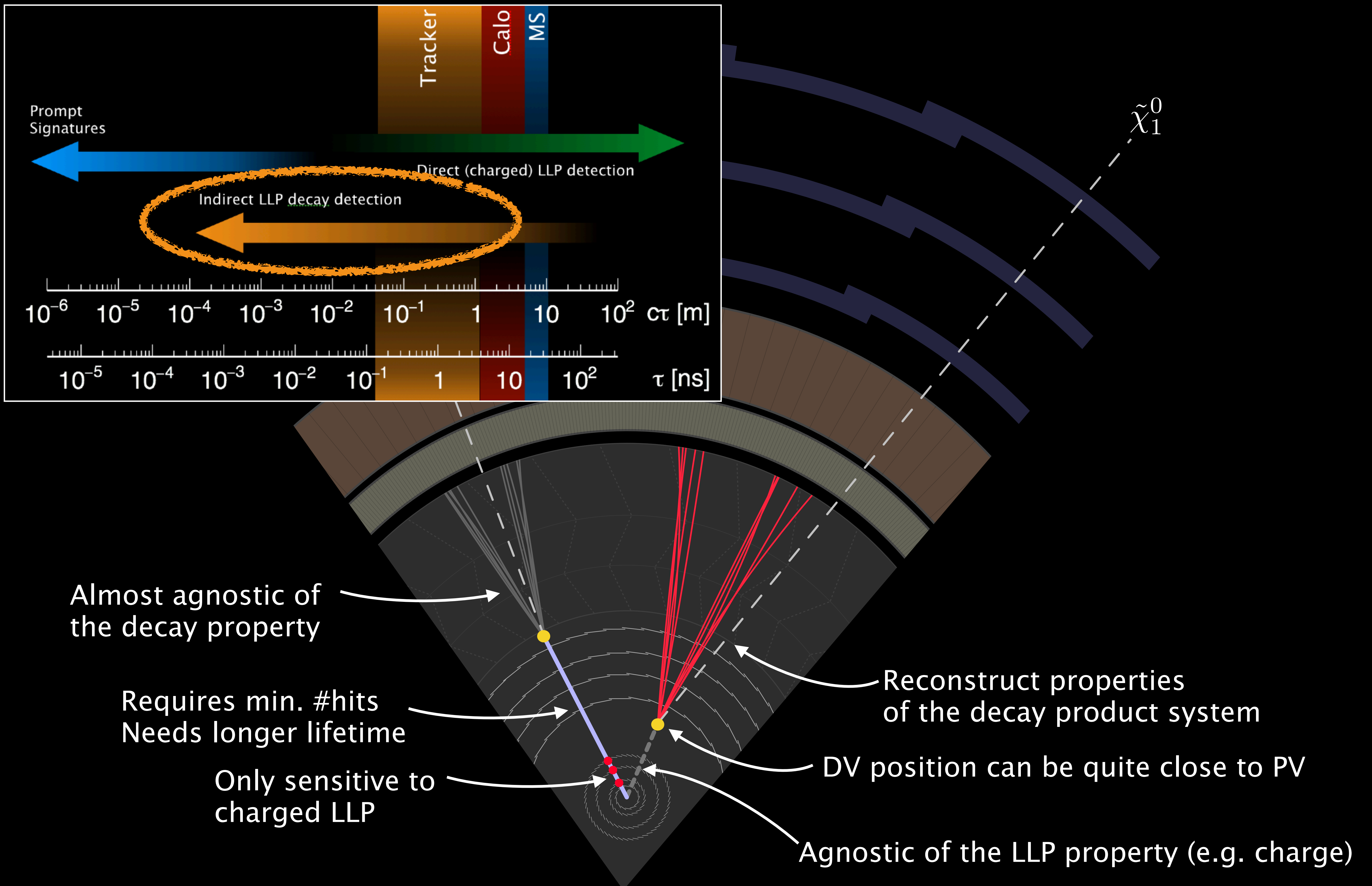


- No significant excesses have been observed.
- Gluino mass of up to ~1.6 TeV was excluded in both analyses.
- Lower sensitivity at shorter lifetime due to acceptance (insufficient track length).

Complementarity in *R*-hadron search

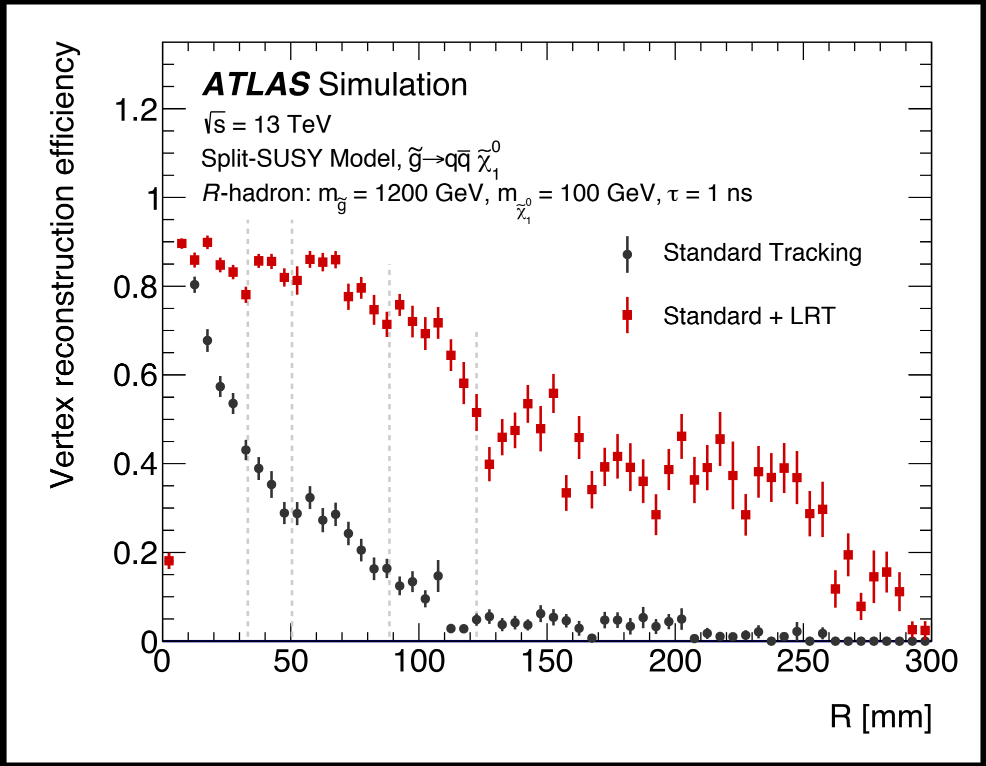


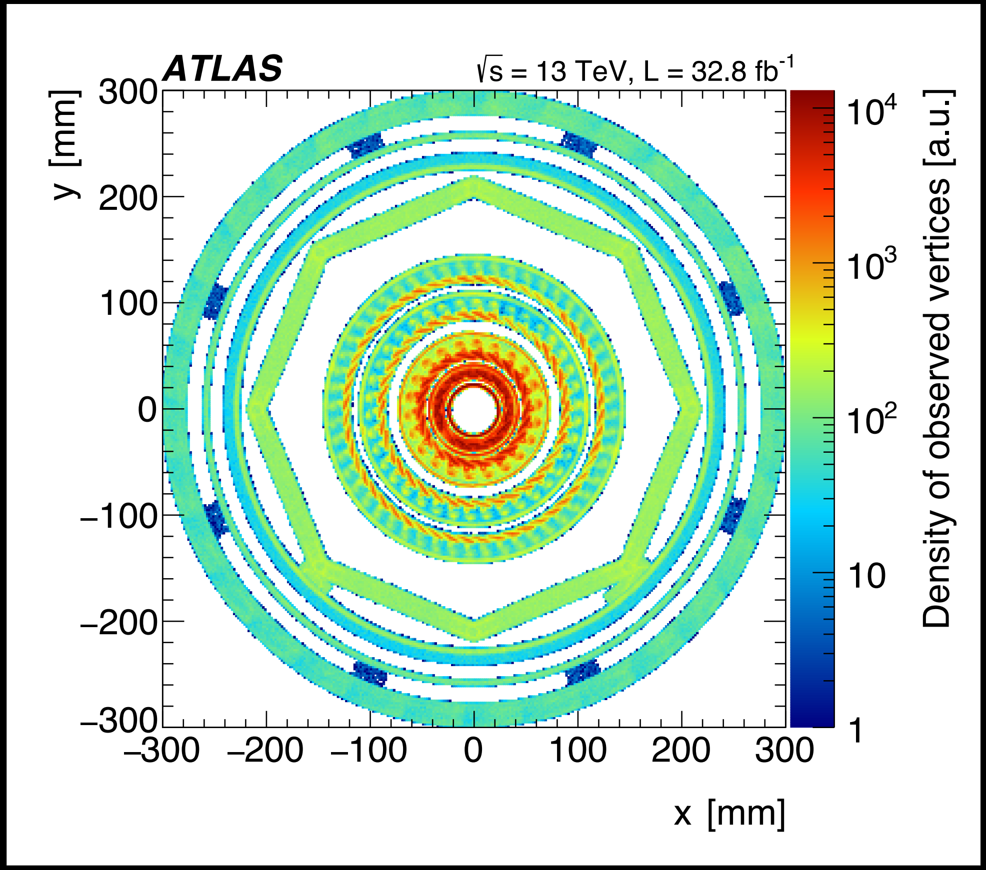
Complementarity in *R*-hadron search



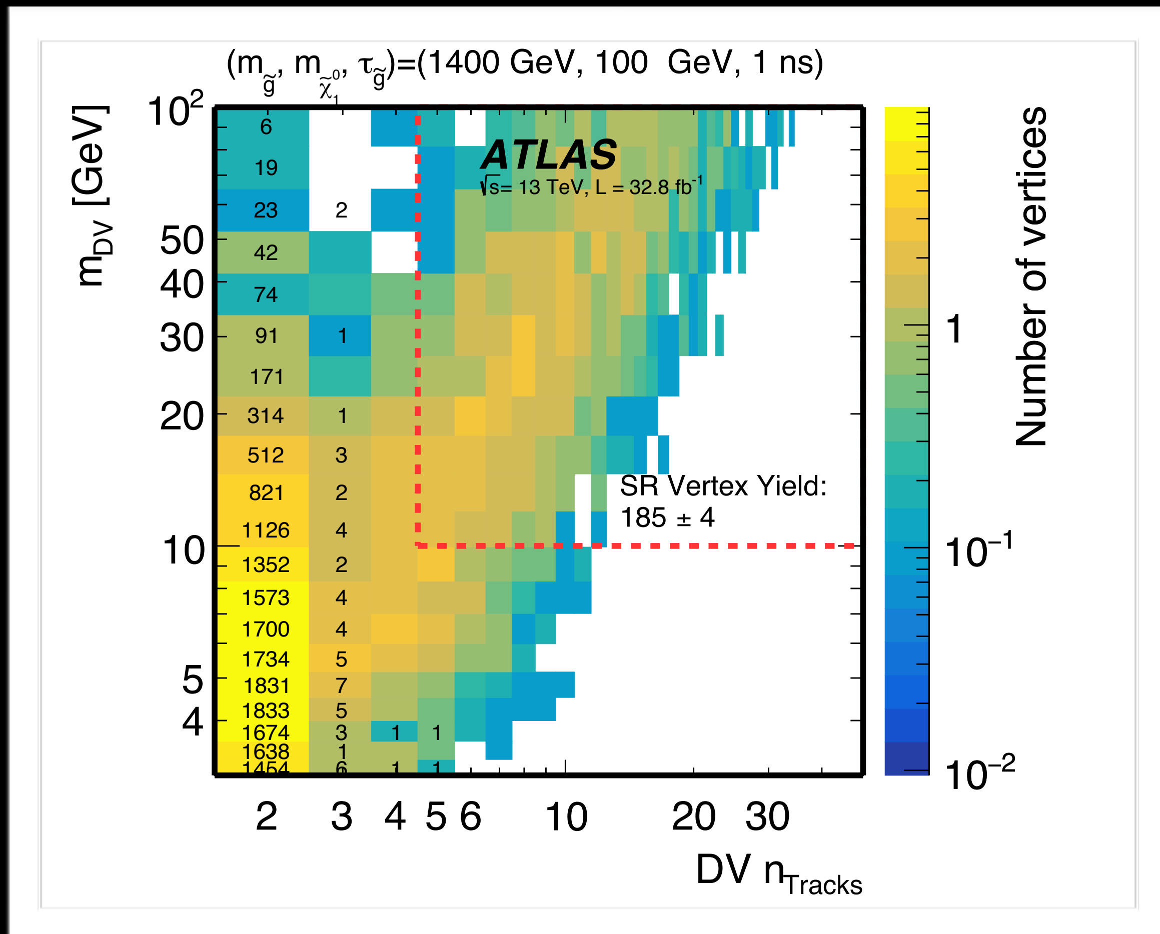
DV+MET

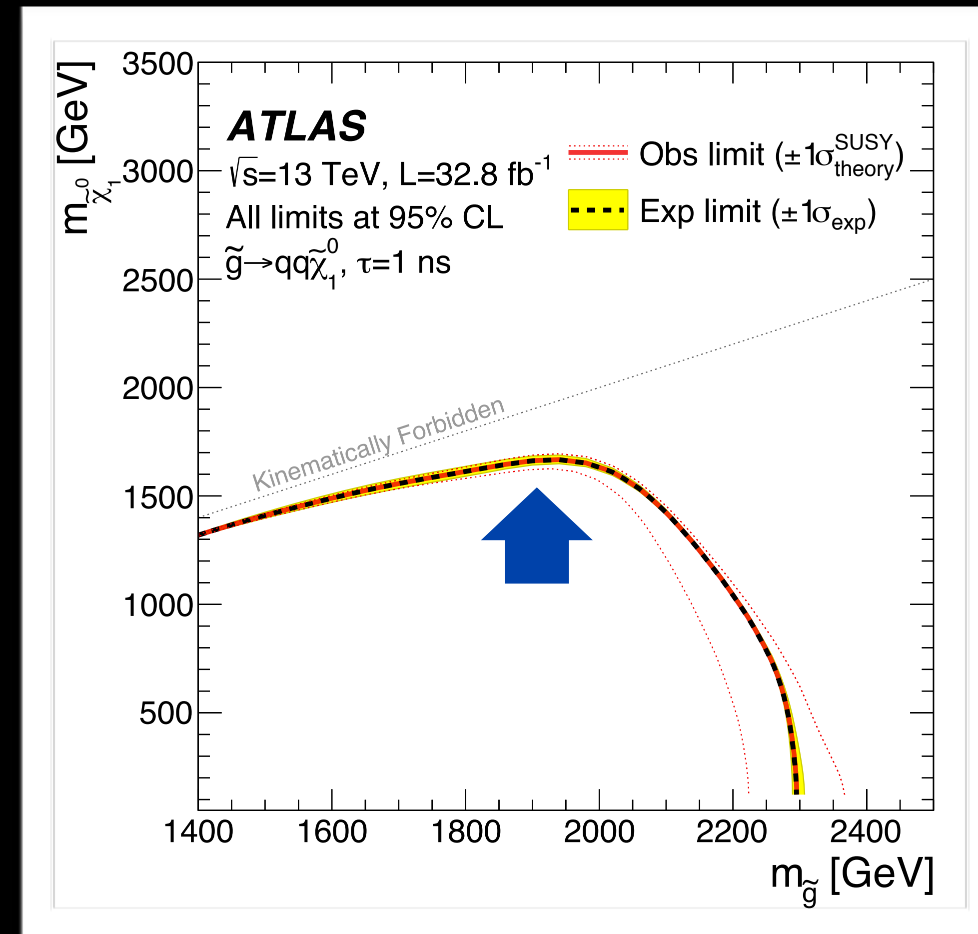
- Reserving a special data stream with the MET trigger.
- Special reconstruction with "large-d_0 tracking"
  - $|d_0| < 300$ mm, $|z_0| < 1500$ mm
  - More detail will be in Shih-Chieh's talk.
- A dedicated displaced vertex reconstruction algorithm.
  - Can reconstruct up to $r < 300$ mm.
  - $|d_0| > 2$ mm, $p_T > 1$ GeV as seed tracks
  - Attempt to find all 2-track vertex pairs then resolve ambiguity and merge.
  - Final merging of nearby vertices within 1 mm to reduce split DVs.
- Requiring offline MET > 250 GeV.
- Detailed tracker material map for vetoing hadronic interactions.
- Signal region: $N_{trk} \geq 5$ and $m_{DV} > 10$ GeV.
- Backgrounds: random-crossing, residual material interactions, accidental merging.
- Full data-driven background yield estimation.





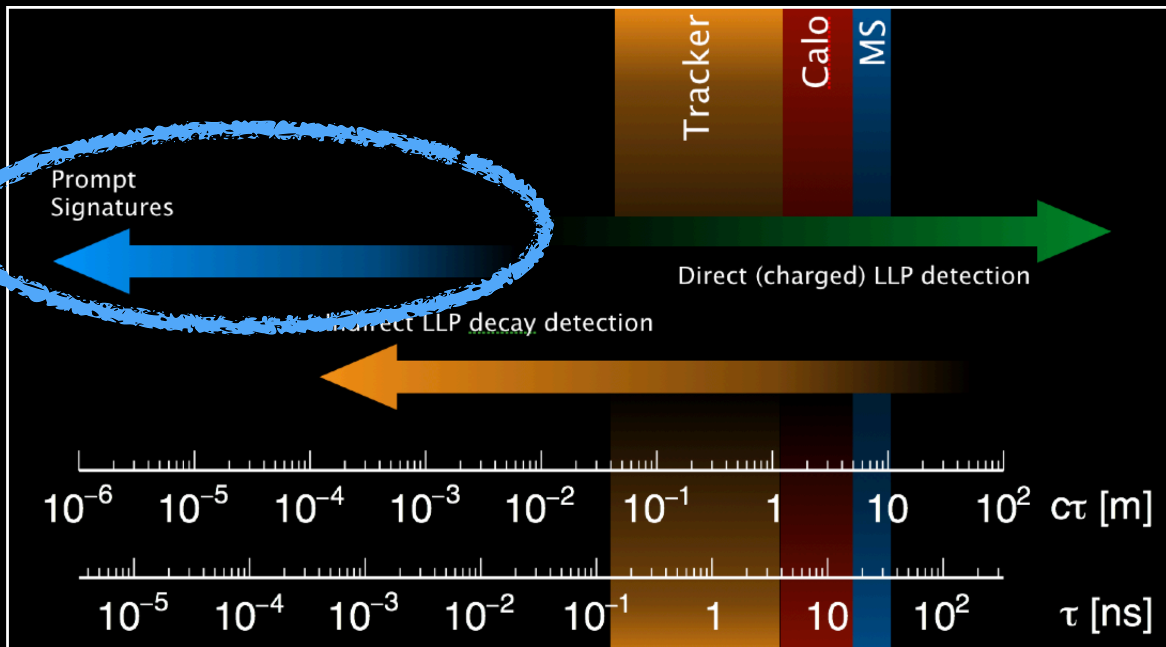
DV+MET



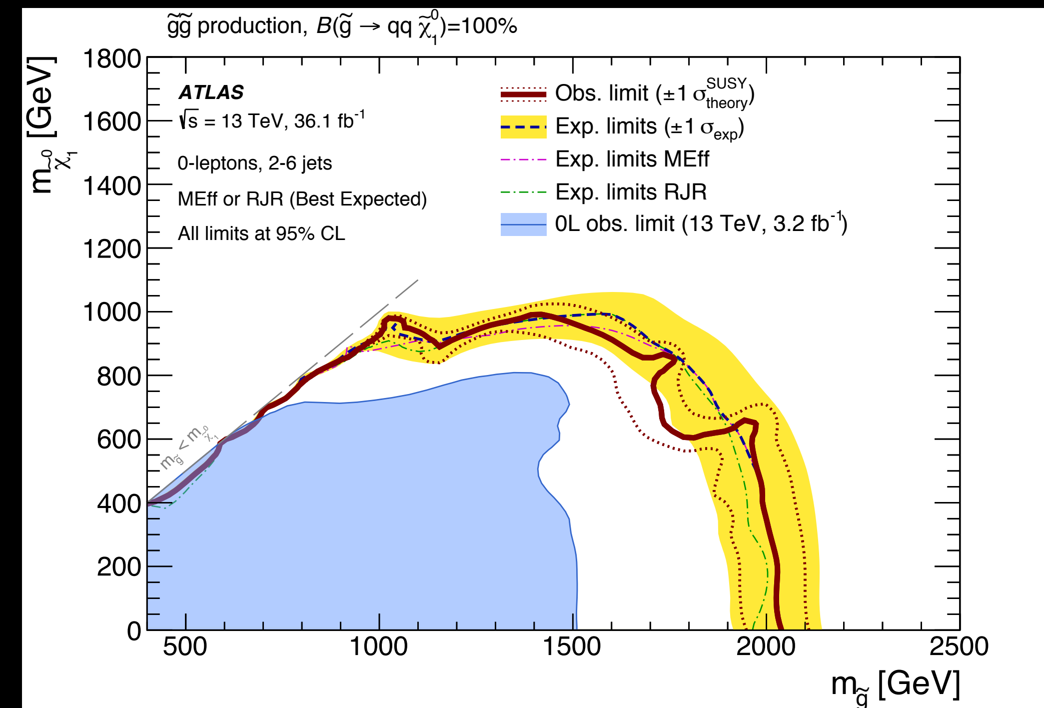


- Observed no events in the signal region while expecting 0.02±0.02 backgrounds.
- Strongest limit to the gluino mass among all SUSY searches at m(N_1) = 100 GeV. (~2.4 TeV at 0.1 ns lifetime)
- A very stringent limit to the compressed regions as well.

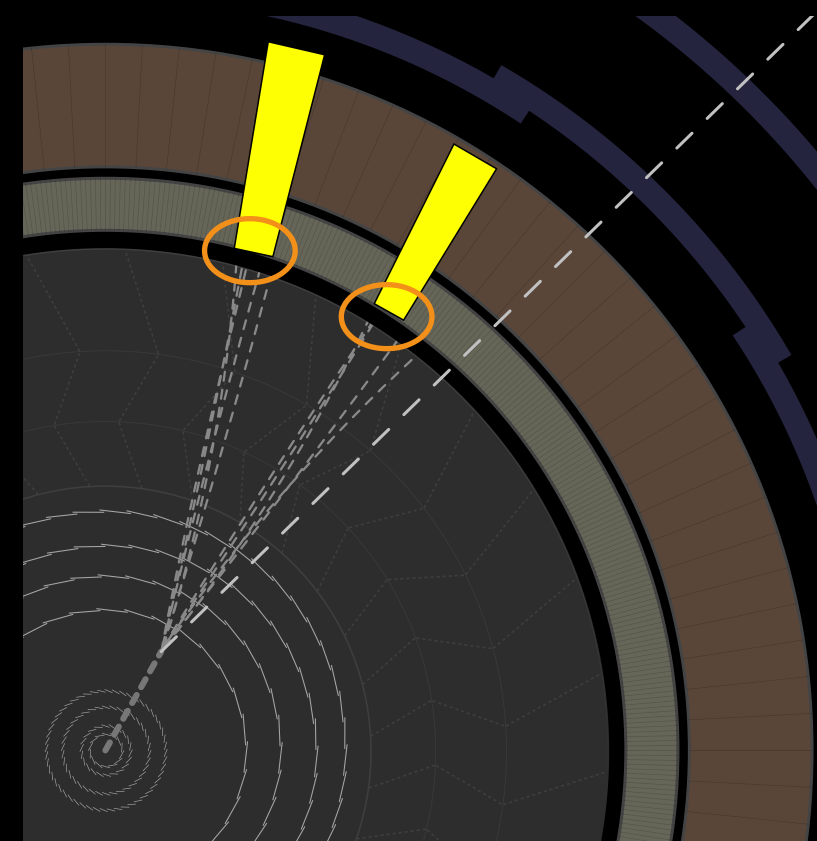
RPC 0-lepton + MET re-interpretation



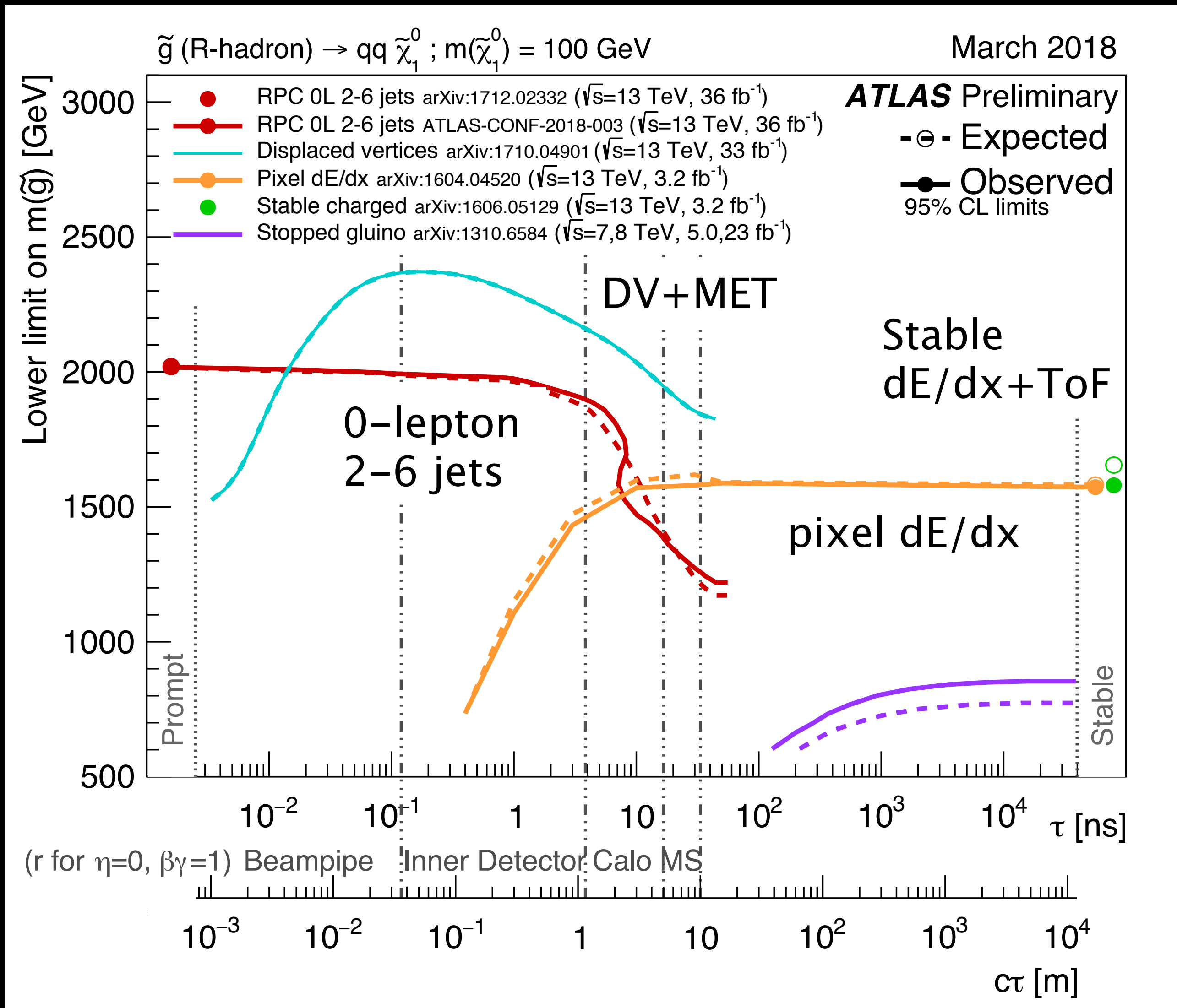
SUSY-2016-25, Phys. Rev. D 97 (2018) 112001

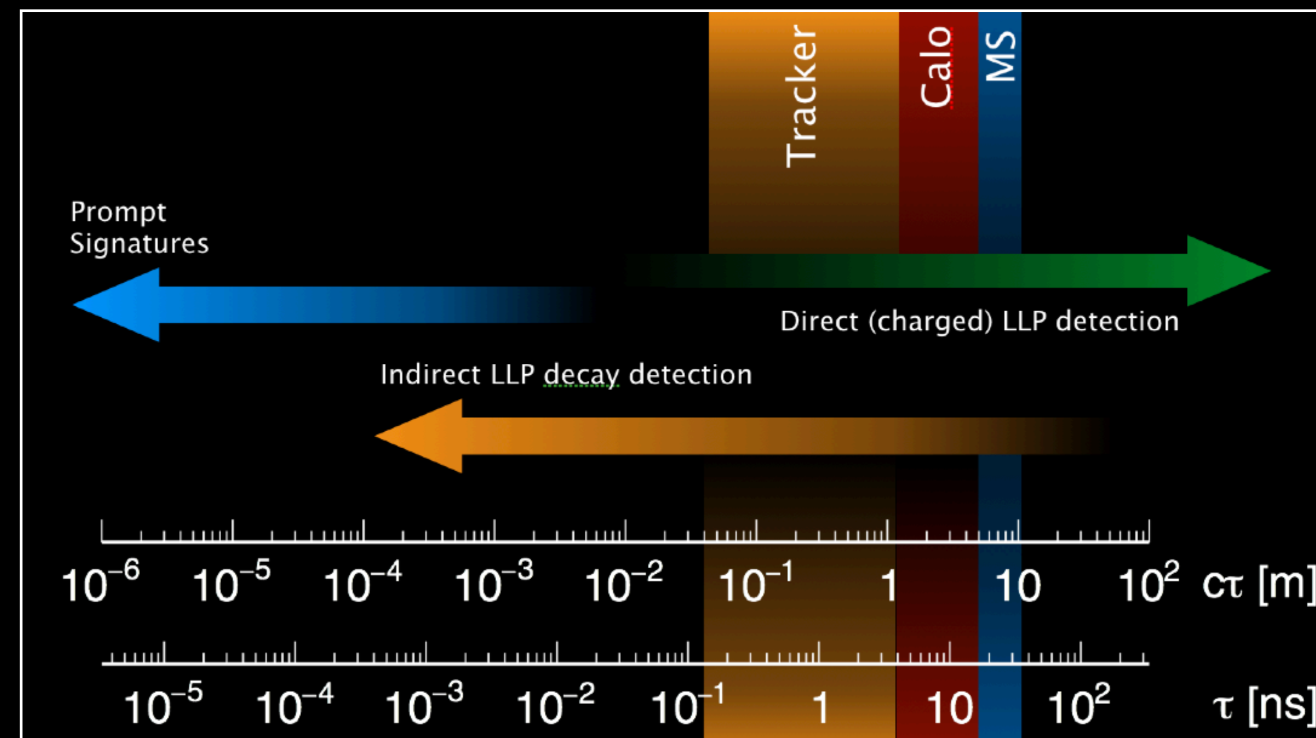


- The inclusive prompt squark/gluino search (0-lepton + MET, 2-6 jets) can be re-interpreted for long-lived gluino scenario (i.e. R-hadron).
- It was found that the original analysis “tight” requirement on jet charged particle fraction imposes a sizable selection inefficiency (displaced jets may have very few associated tracks). Removing this selection has minimal impacts on background estimation.
- The full analysis was re-run and the R-hadron re-interpretation was made.



R-hadron search summary

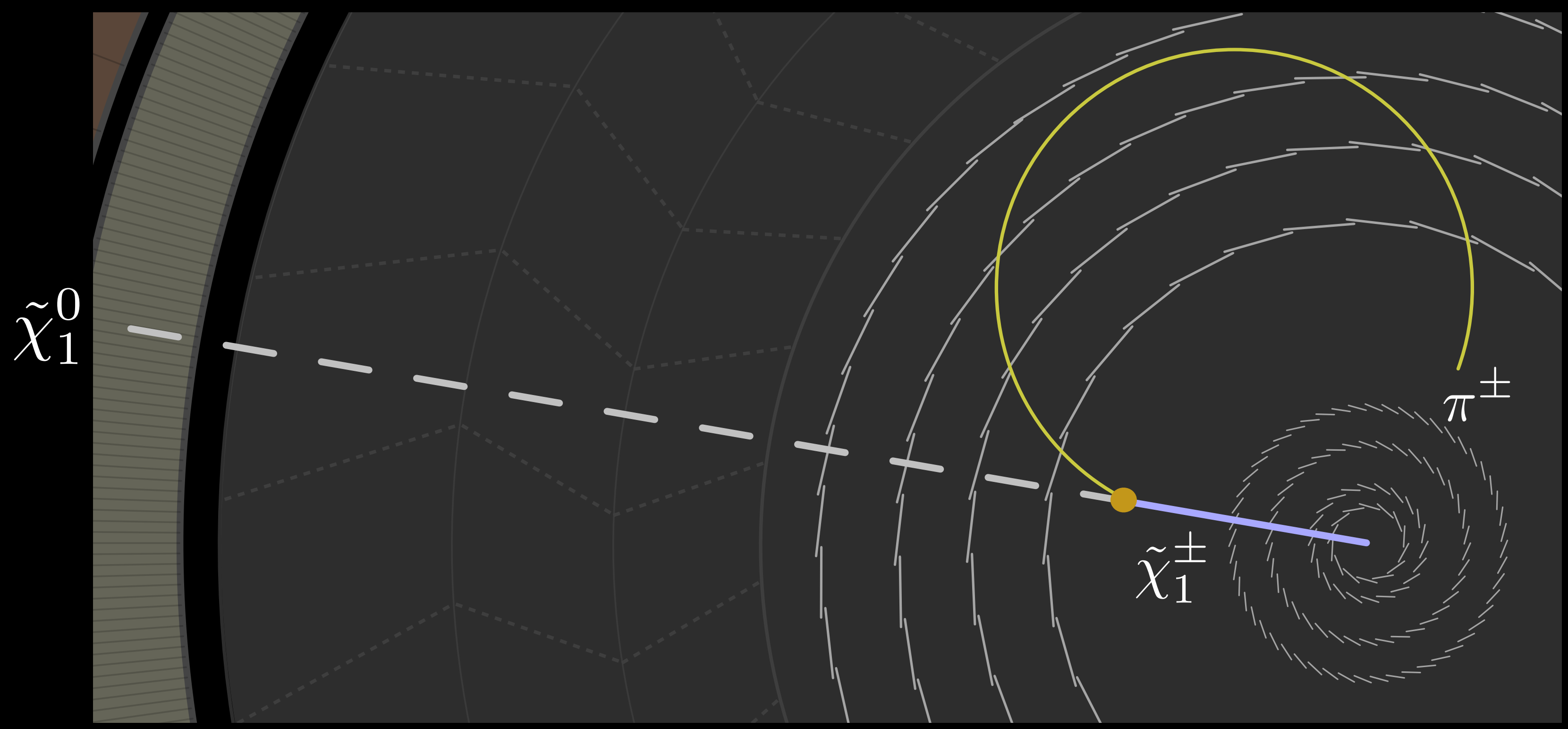


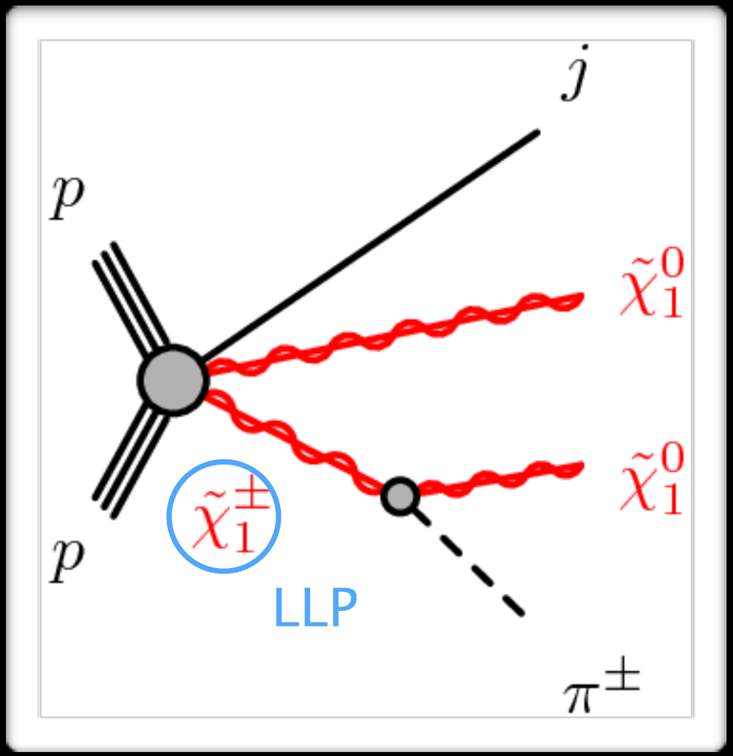


- Each analysis has advantages in different lifetime ranges.
- A very good complementarity over wide lifetime range.

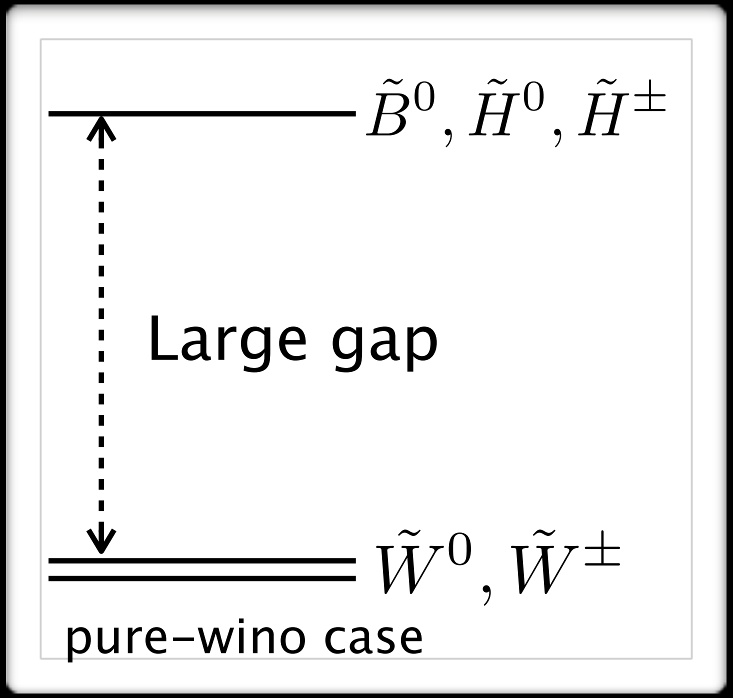
SUSY-2016-06, arXiv:1712.02118
JHEP 06 (2018) 022

Disappearing track

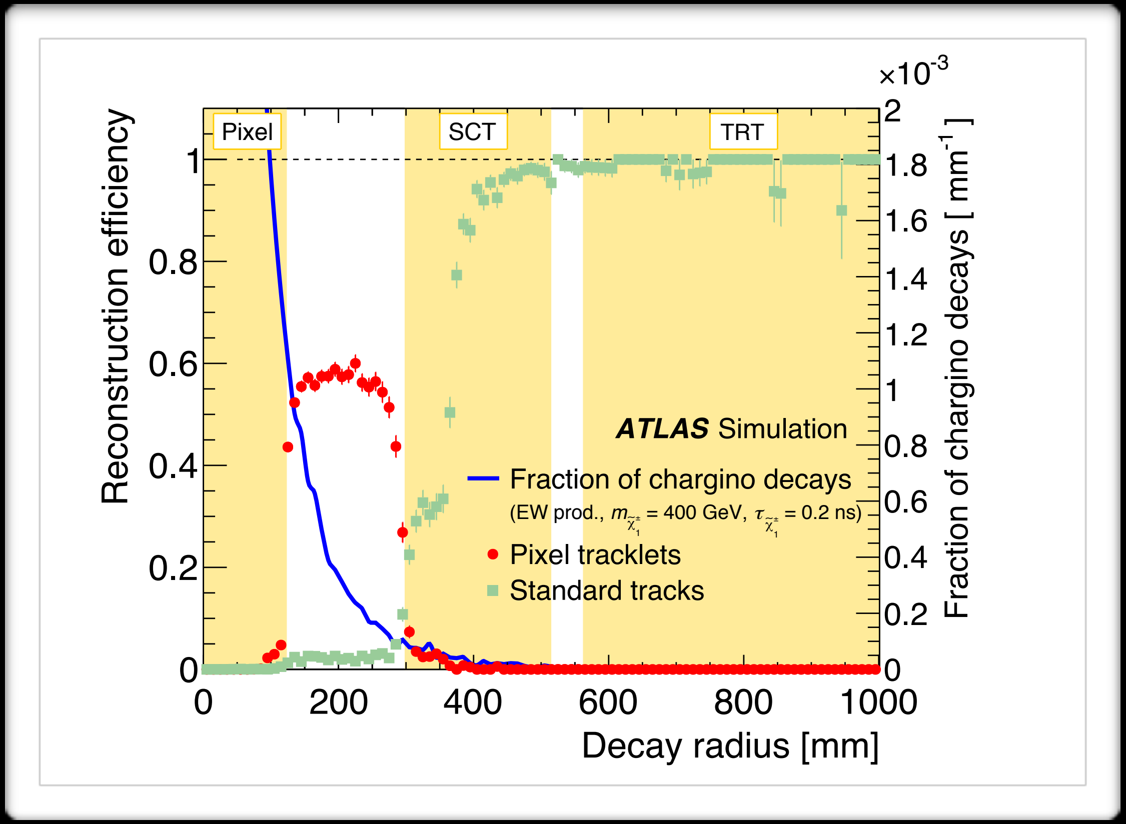


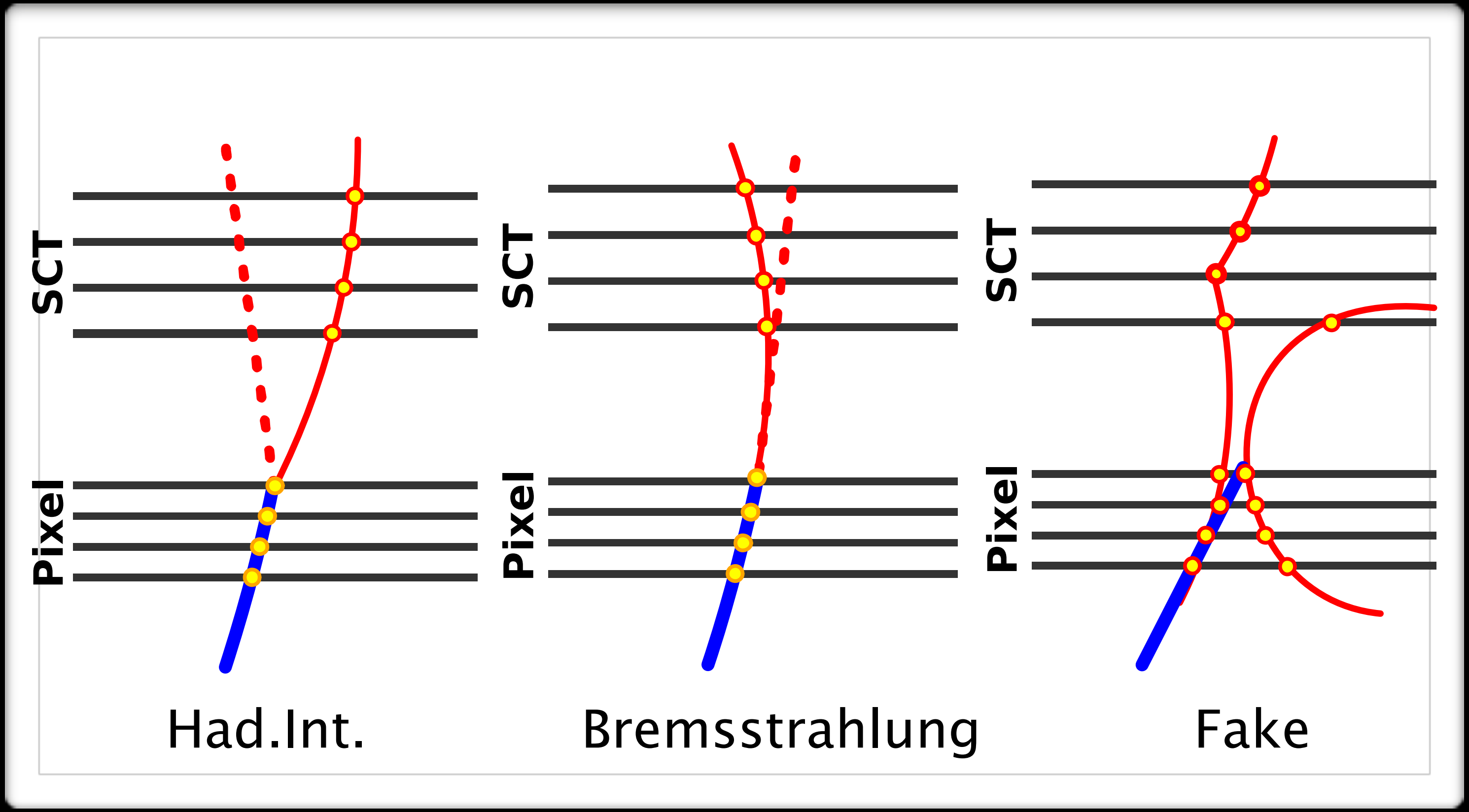


- Degenerate chargino—neutralino mass splitting (AMSB, pure higgsino). → Chargino as LLP.
- Motivated for very short lifetime of O(0.1ns) → pixel-only tracking "tracklet".
- Decay pion is extremely challenging to reconstruct and practically invisible. → the disappearing track signature (a well-isolated tracklet).
- For EW production, requiring ISR for effectively boosting the system to gain the decay length.
- Also looking at the strong production channel as the second SR.



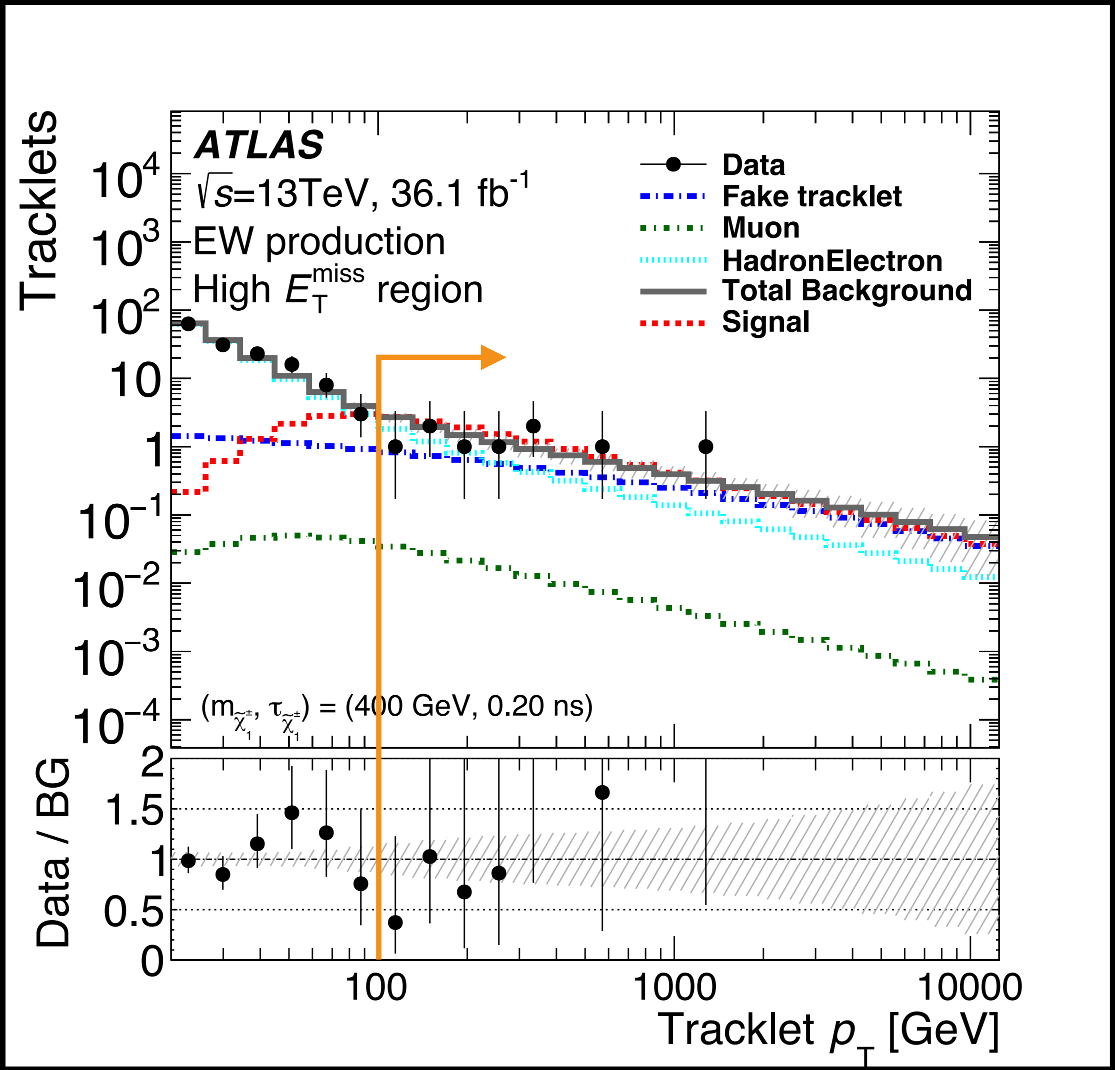
Disappearing track: pixel tracklet

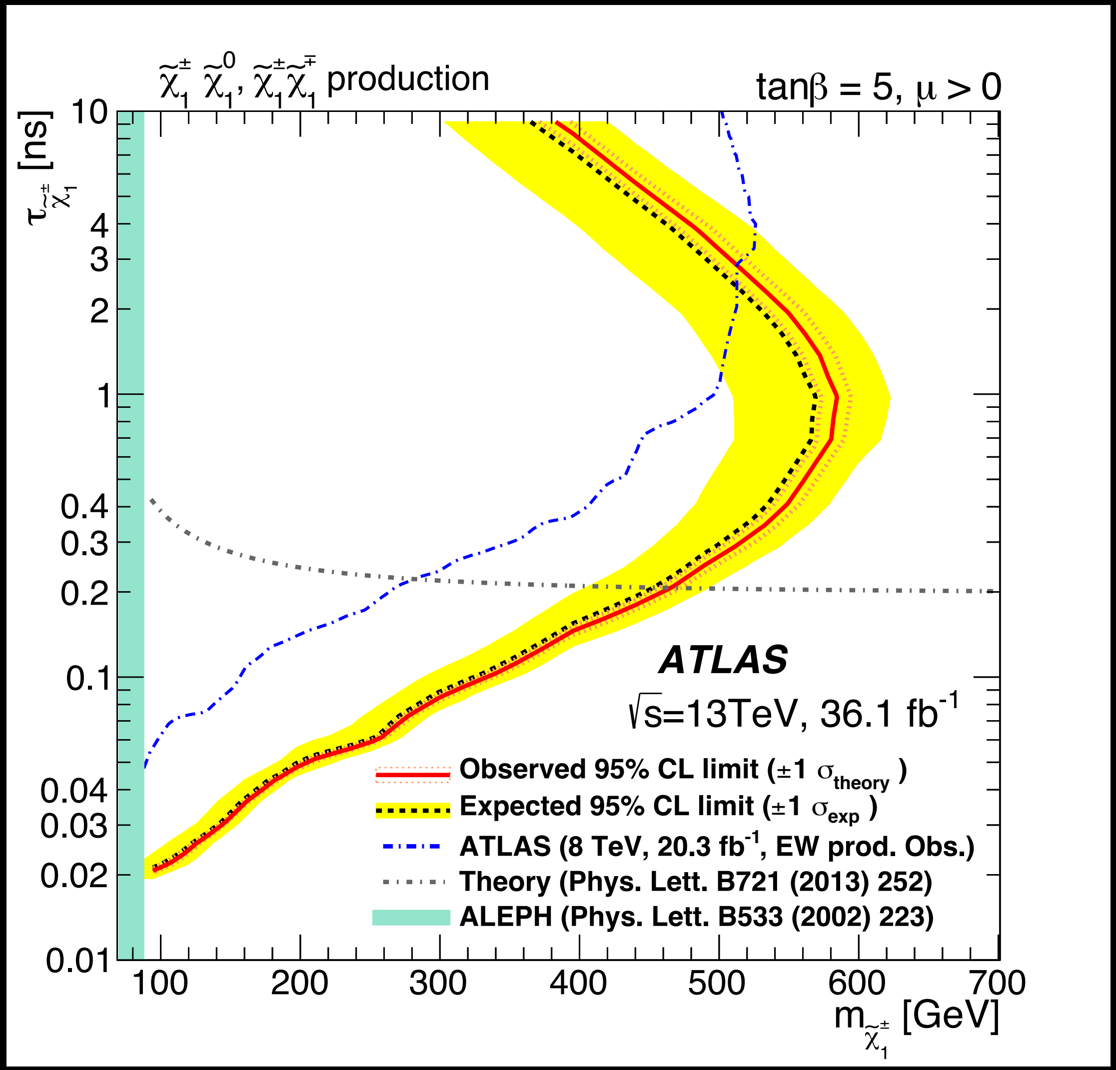




- Installation of the new innermost pixel layer, IBL (r~33 mm) in Run2 consolidates track reconstruction only using Pixel detector.
- Achieving a quite high reconstruction efficiency and access to significantly shorter lifetime.
- Main backgrounds: bremsstrahlung/hadronic interactions, fake tracklets

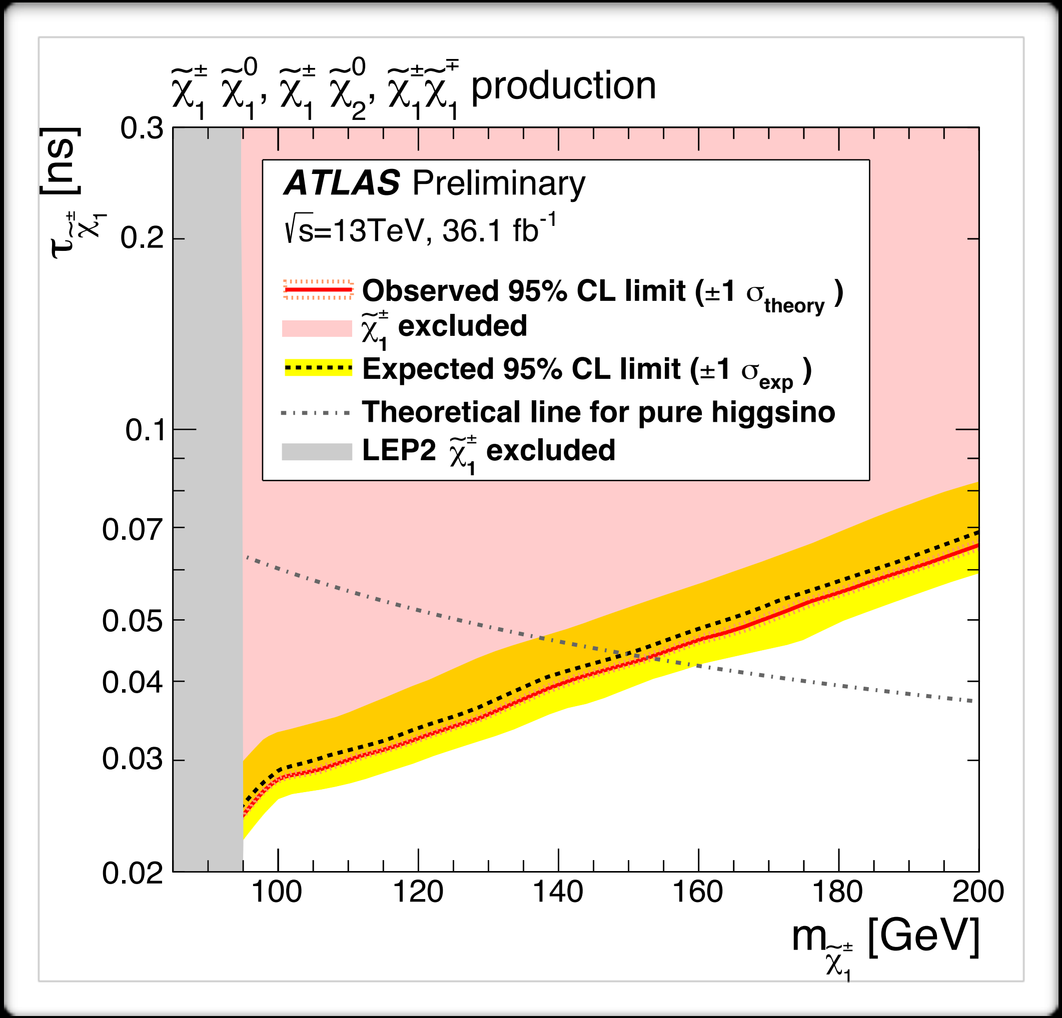
Disappearing track: wino result

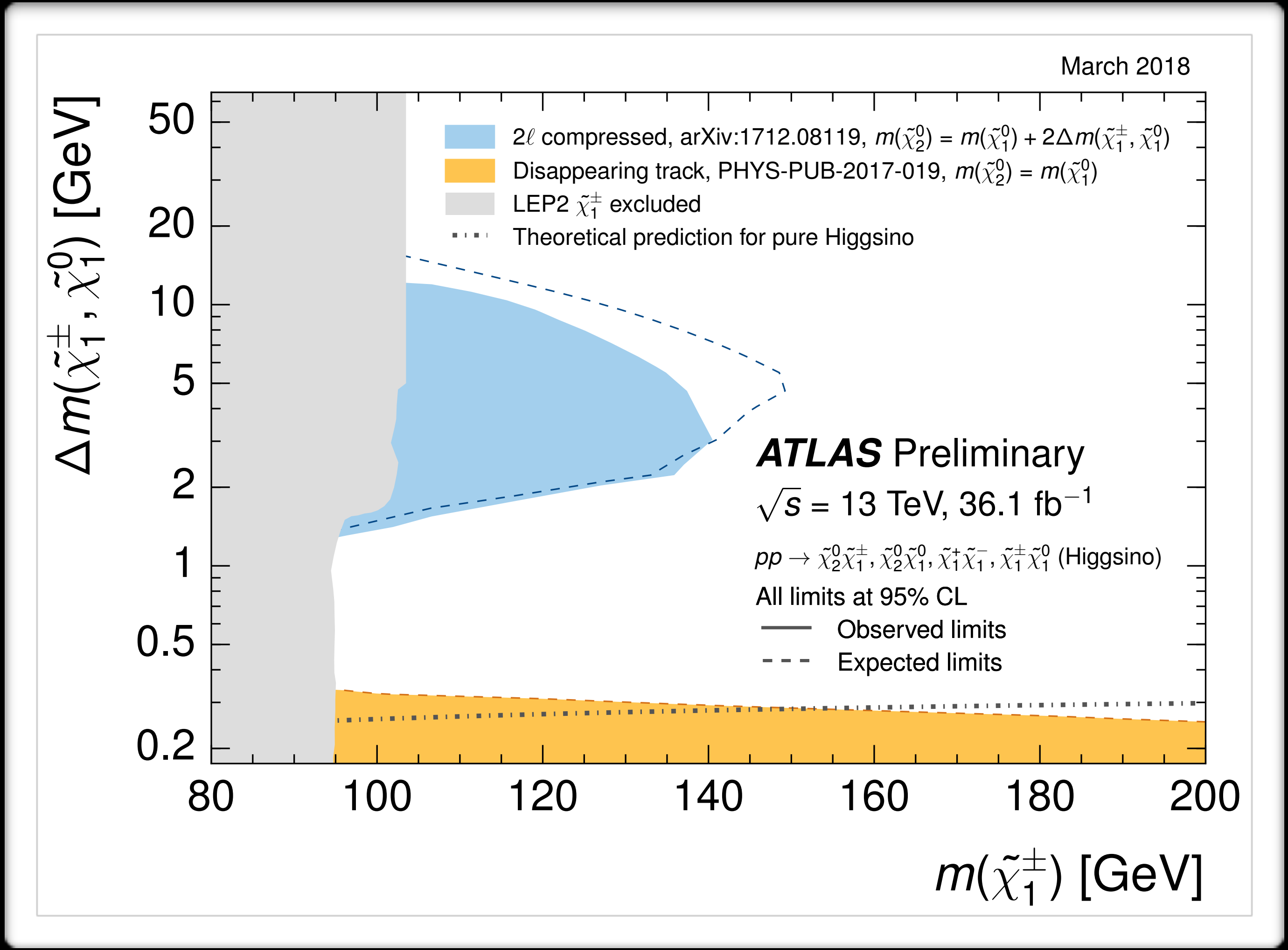




- EW signal region: MET > 140 GeV, ISR pT > 140 GeV.
- Strong signal region: 1 jet pT > 100 GeV, with ≥2 additional jets (pT > 50 GeV), offline MET > 150 GeV.
- Additional "low-MET" region for each EW and strong for validating backgrounds.
- Data-driven background estimation for each component, and likelihood fitting.
- No significant excess in SR → a stringent limit for AMSB-motivated scenario, large gain by pixel tracklet!! (Excluded 460 GeV chargino for EW production)

Disappearing track: higgsino reinterpretation

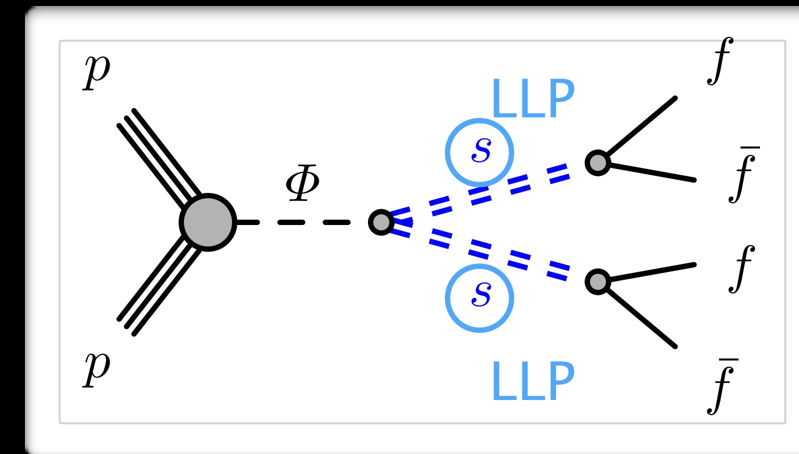


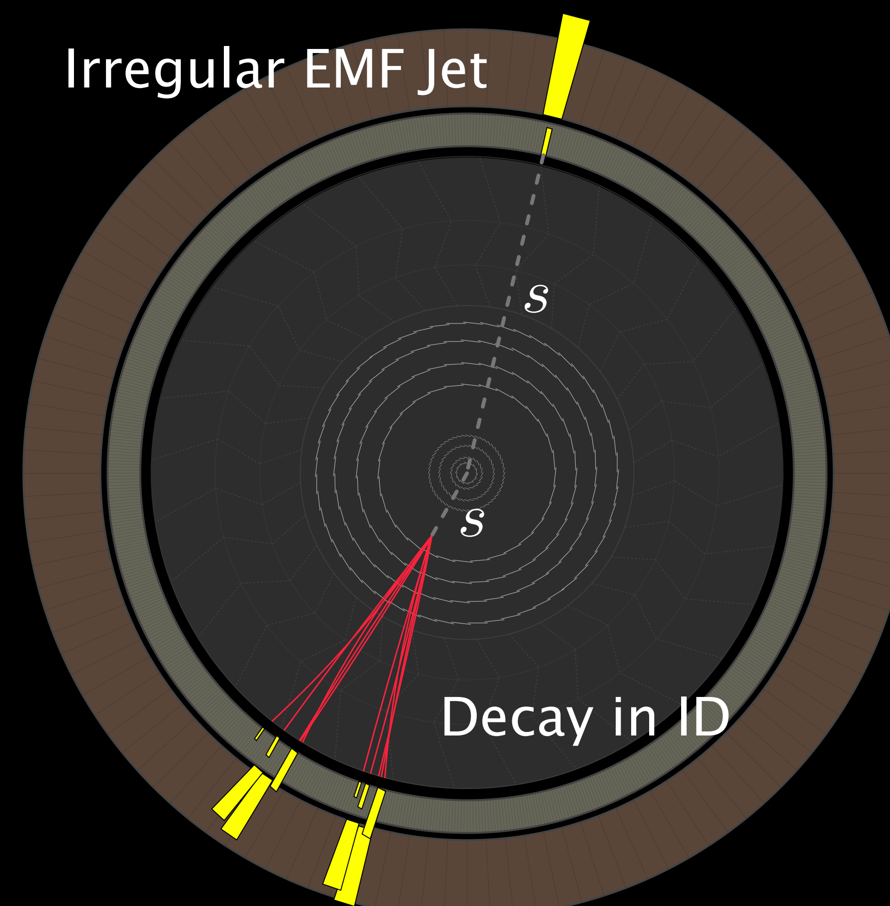


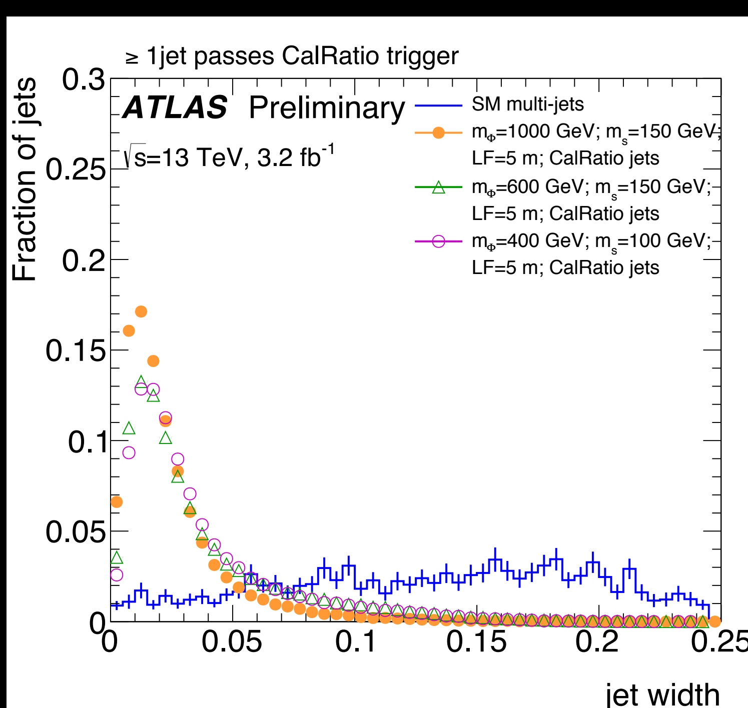
- Pure-higgsino: theoretical lifetime is much smaller than the wino case, quite challenging signature.
- Excluded chargino mass below ~150 GeV.
- Exceeding the LEP limit for the first time for the pure-higgsino scenario.
- Complementary to the prompt higgsino (SFOS dilepton) analysis [SUSY-2016-25].

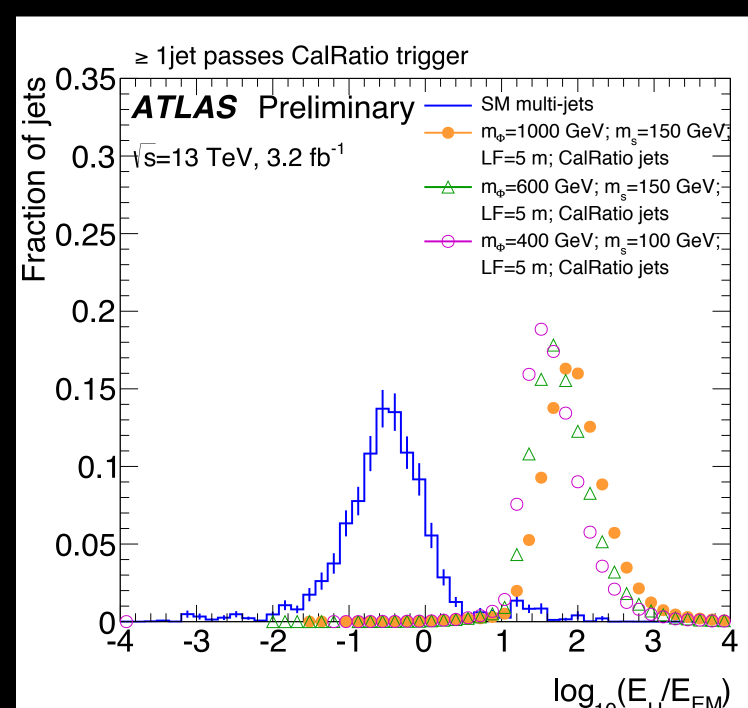
LLP decays in HCal

- A hidden-sector model: pair-produced scalar LLPs decay to fermion pairs (assuming the dominant decay is bb)
- If the decay is inside the tile calorimeter (1.8 < r < 4 m):
  - Energy fraction E_H/E_{EM} is irregularly very large
  - The jet shape is much sharper than SM.
- A dedicated trigger for tagging low EM fraction jets (seeded by L1 tau trigger).
  - $\log 10(E_H/E_{EM}) > 1.2$
  - Trackless jet, but pass beam-induced BG alg.
- Estimated 50—70% trigger eff. for $p_T > 100$ GeV jet.



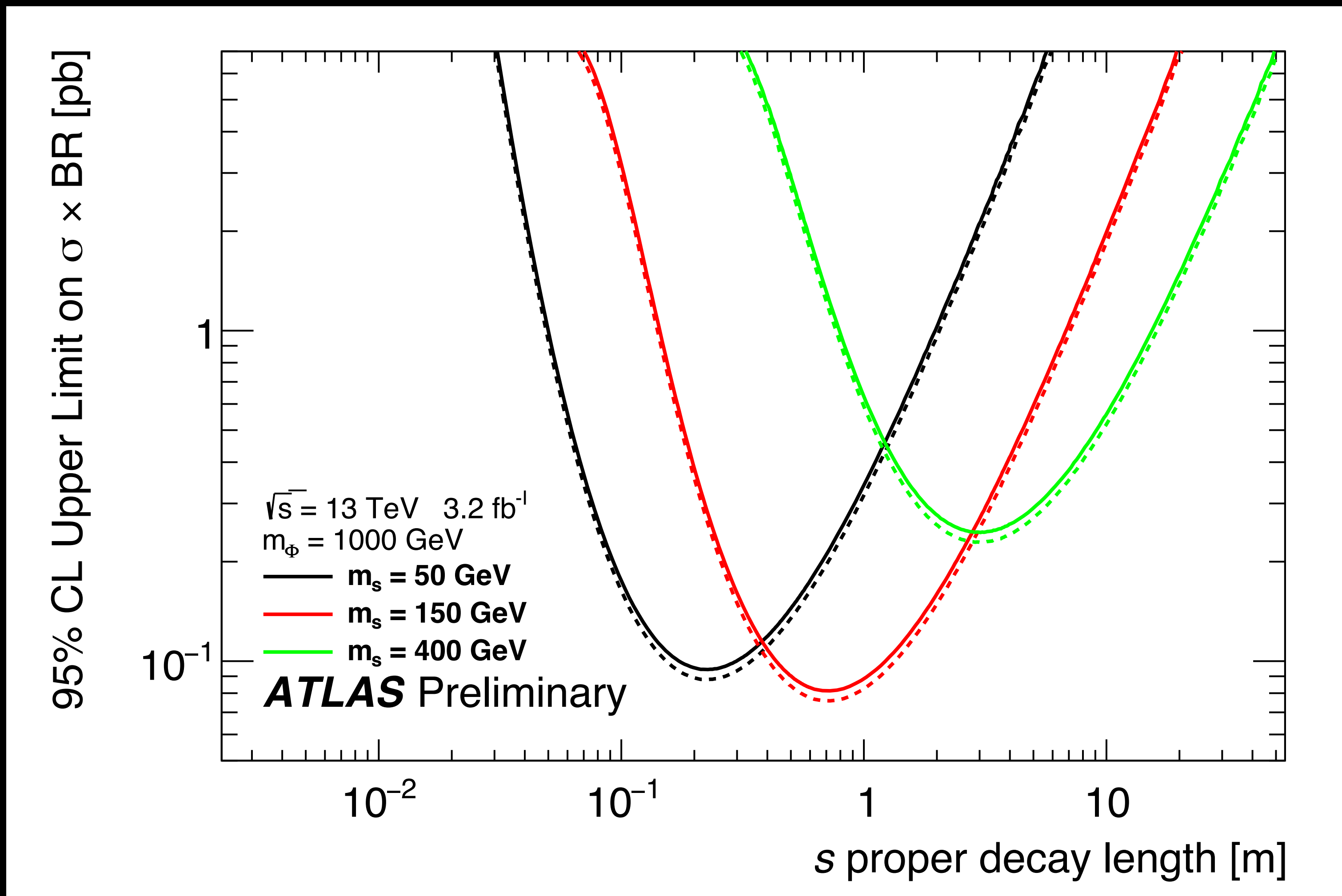


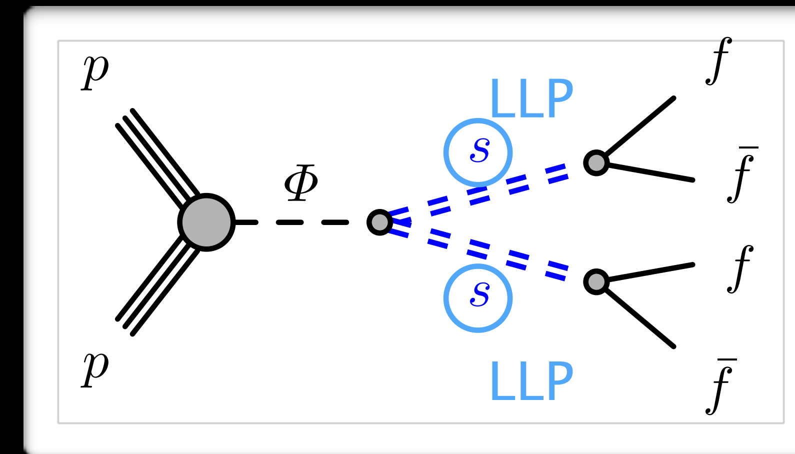




Main backgrounds:
Cosmic, multijets, non-collision beam-induced backgrounds

LLP decays in HCal



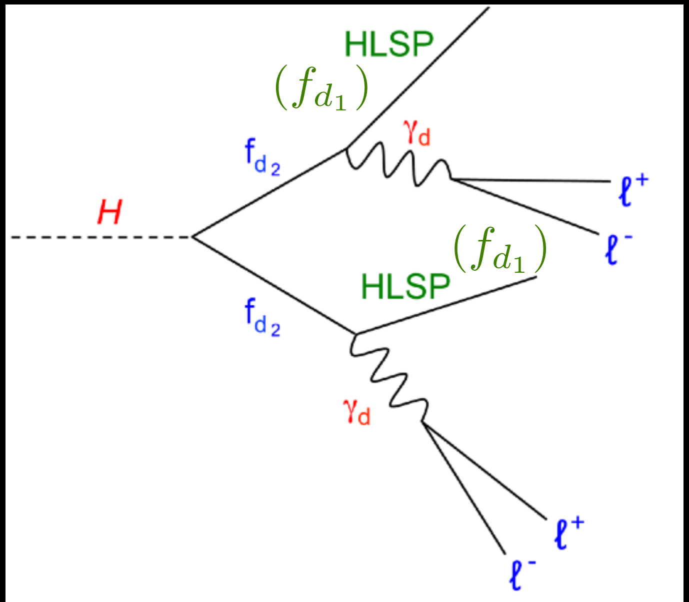


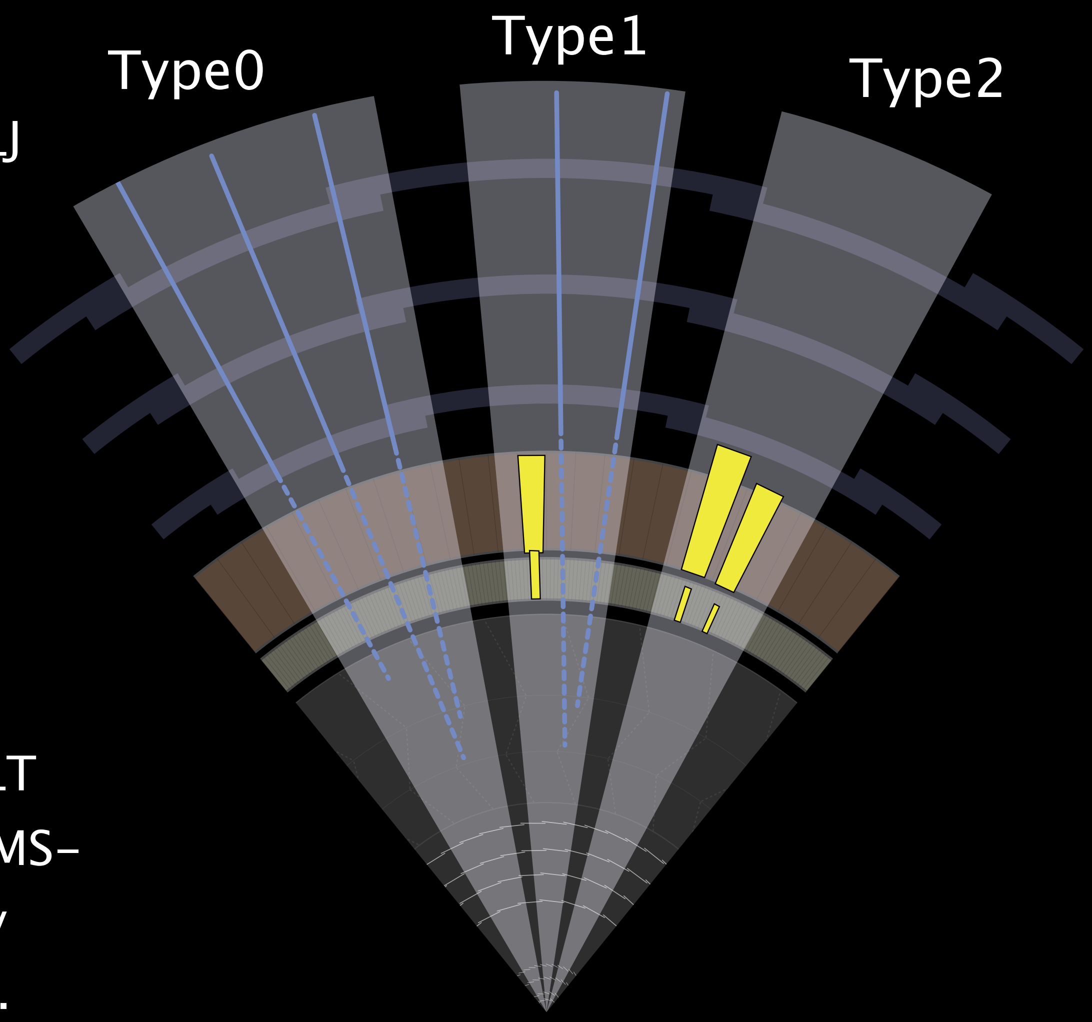
- No significant excess is observed in the SR.
- Interpretation depending on the mass of the mother scalar (Φ) and the LLP (s).
- Peak sensitivity lifetime varies reflecting the boost factor of the LLP (s).
- Cross section upper limit varies reflecting the signal acceptance.

Leptonic LLP decays: displaced lepton-jets

ATLAS-CONF-2016-042

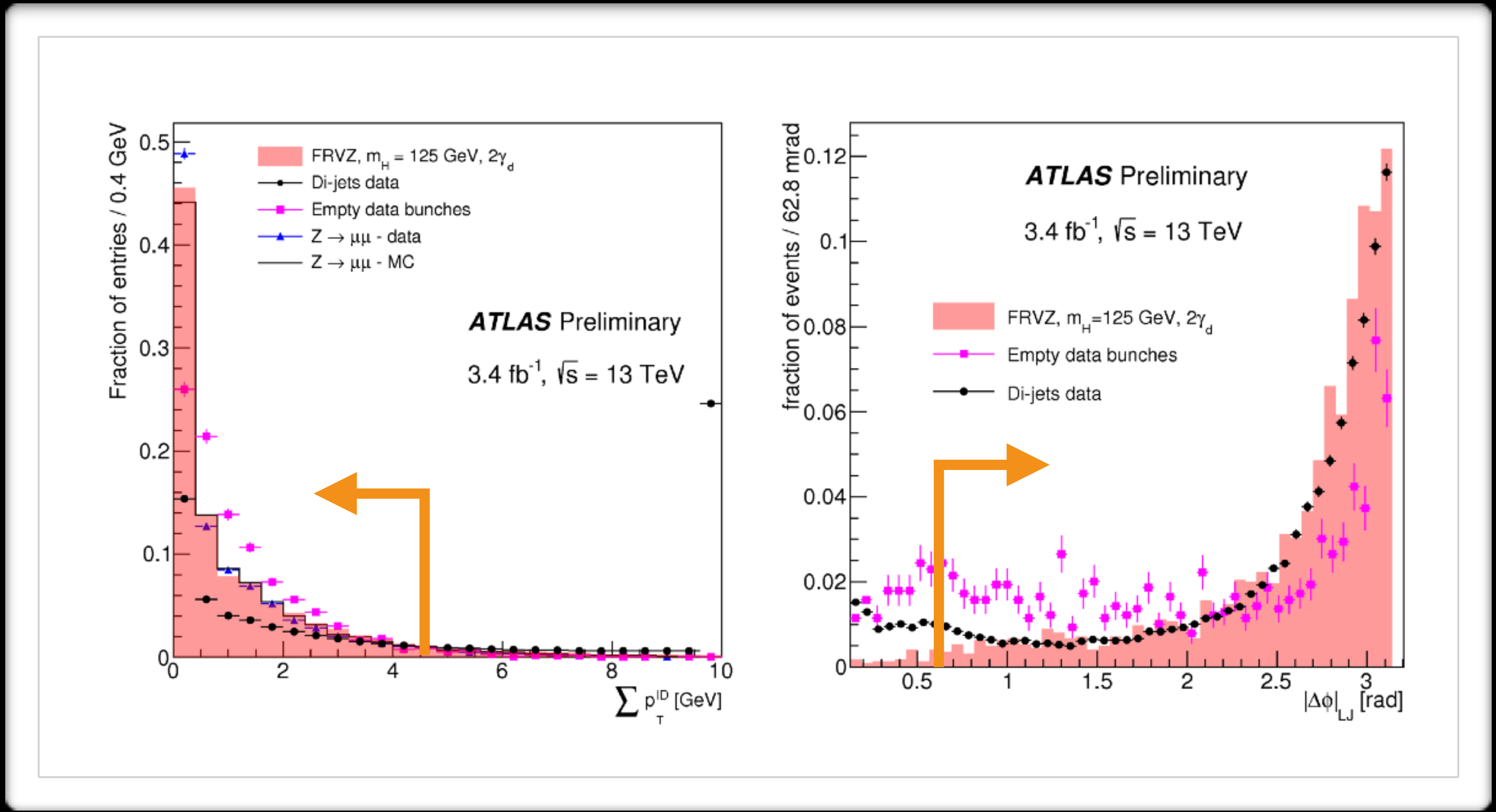
- A light (MeV—GeV) dark photon mixing with SM photon decays to lepton pairs or to light mesons.
- Collimated flow of displaced particles including leptons: displaced lepton-jets (dLJ).
- Benchmark: higgs portal, decaying to dark fermion pairs producing dark photons.
  - Case1: $f_{d2} \rightarrow f_{d1} + \gamma_D$, ($\gamma_D \rightarrow$ dLJ): up to 2μ / dLJ
  - Case2: $f_{d2} \rightarrow s_{d1} + f_{d1}$, $s_{d1} \rightarrow \gamma_D\ \gamma_D$ ($\gamma_D \rightarrow$ dLJ): up to 4μ / dLJ
- Multiple dLJ types:
  - Type0: muonic (clean ≥2 collimated muons)
  - Type1: mixture (collimated muons + 1 jet)
  - Type2: a jet w/o muons, but CaloRatio required.
- Dedicated trigger objects for dLJs
  - 2015 result: muon “narrow scan” trigger: the dedicated HLT for single-dLJ trigger. A 20 GeV L1 muon is confirmed as MS-only at HLT; then ask for the existence of the 2nd MS-only muon of 6—15 GeV in ΔR < 0.5 around the primary muon.



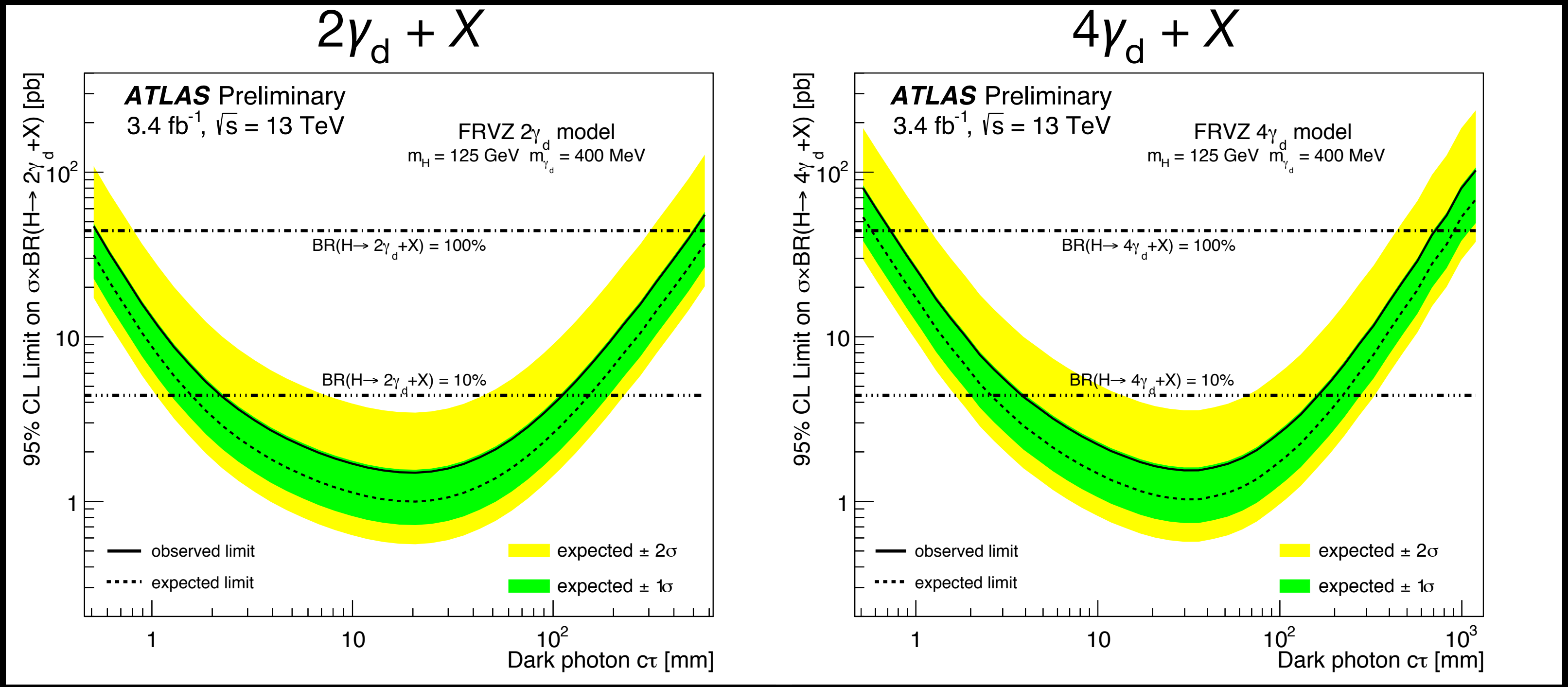


Leptonic LLP decays: displaced lepton-jets

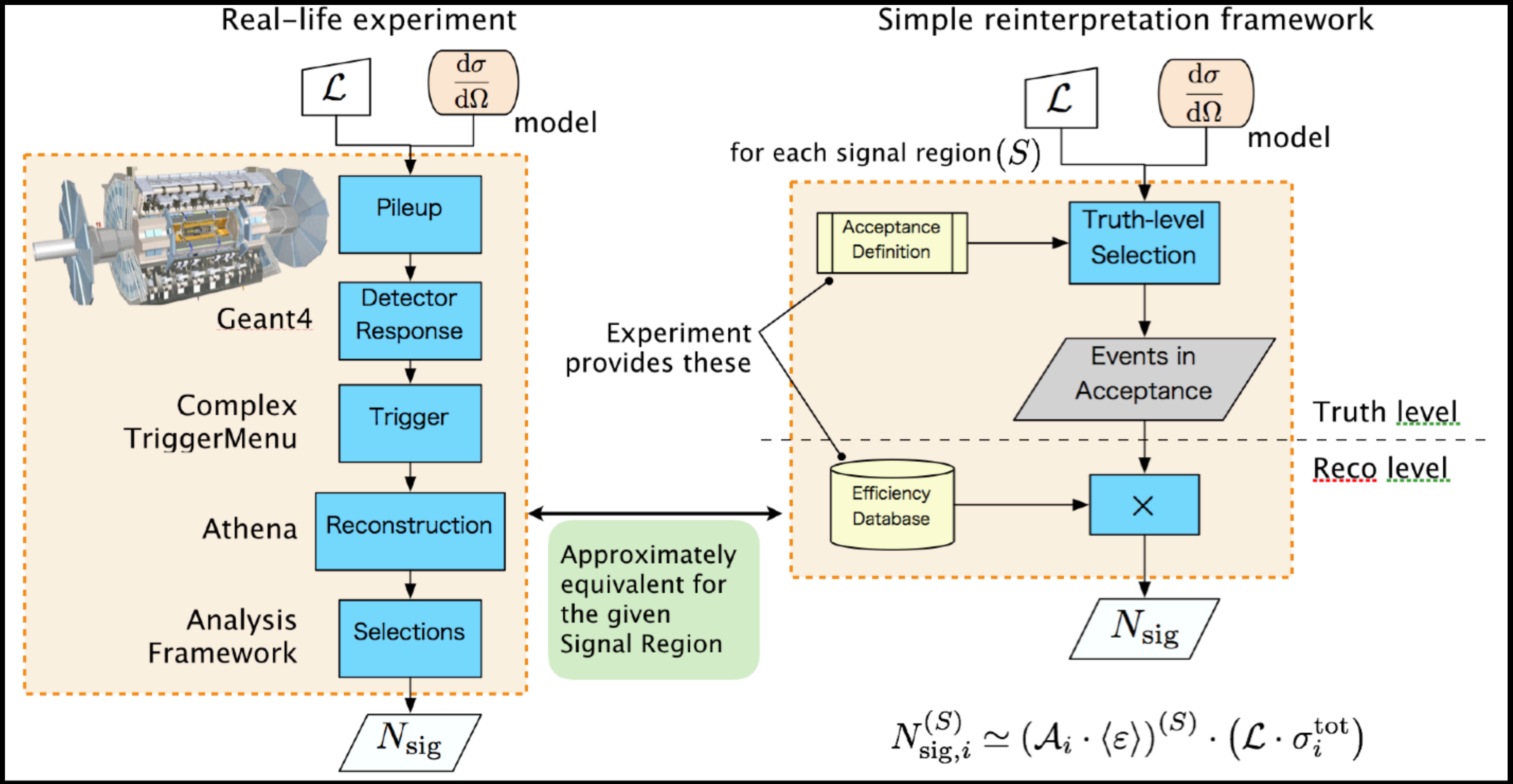
- Requiring 2 LJs in the event.
  - 5 LJ-type combinations used: (T0, T0), (T0, T1), (T0, T2), (T1, T1), (T1, T2).
  - Major backgrounds: cosmic showers and QCD di- and multi-jets.
- No excess observed in 2015 results: upper limit to σ×BR for $h \to 2\gamma_D + X$ and $H \to 4\gamma_D + X$ for m_H = 125 and 800 GeV.
- Comparable sensitivity to the 8 TeV 20 fb^{-1} result, despite ~15% of ∫Ldt, thanks to improvements in trigger and reconstruction efficiency of collinear muons.



125 GeV Higgs ggF



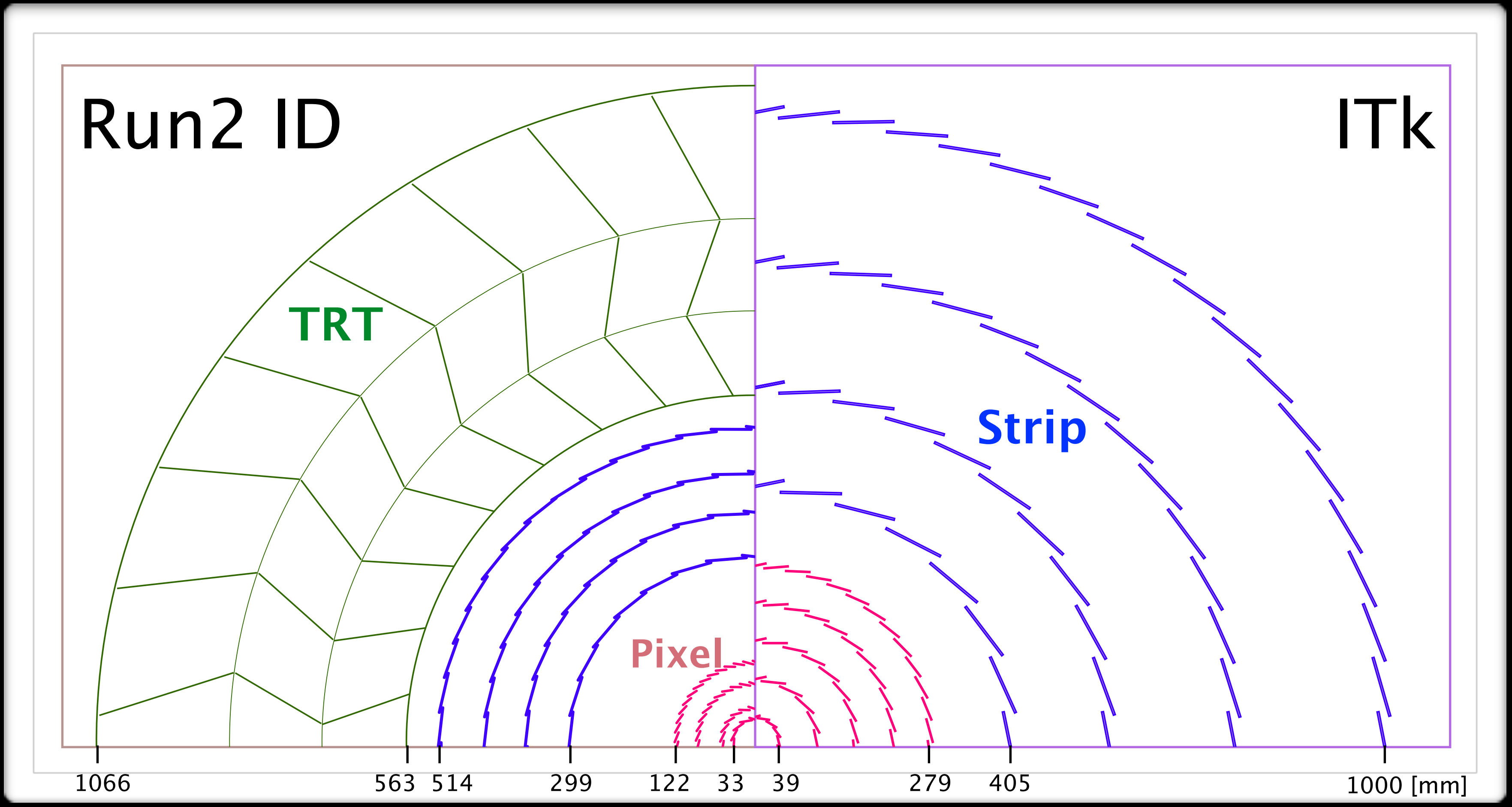
Materials for reinterpretation



- Recent LLP results provide a decent amount of informations for reinterpretation in HepData.
- General: compared to the simplest case, the concept of “acceptance” and “efficiency” needs to be generalized.
- Peculiarity in the LLP searches: often the efficiency could be largely position dependent (e.g. decay radius); detailed parameterization (binning) would be required.
- Recently provided full informations for DV+MET and Disappearing track.
- Detailed explanations in a recent talk in the Reinterpretaiton+LLP workshop (and this backup).
- But also caveat: applicability of the reinterpretation needs to be evaluated carefully!!
  - For example, we have not yet estimated about reconstruction performance when heavy flavors produced from a displaced vertex.

LLP Searches in the HL-LHC

- Replacement of the ATLAS inner tracker to the ongoing ID to ITk has a major implication for LLP searches in the HL-LHC era, primarily due to the geometry change.
- Early studies are ongoing. Details are in recent HL-LHC workshop at Fermilab. (also this backup)



Summary

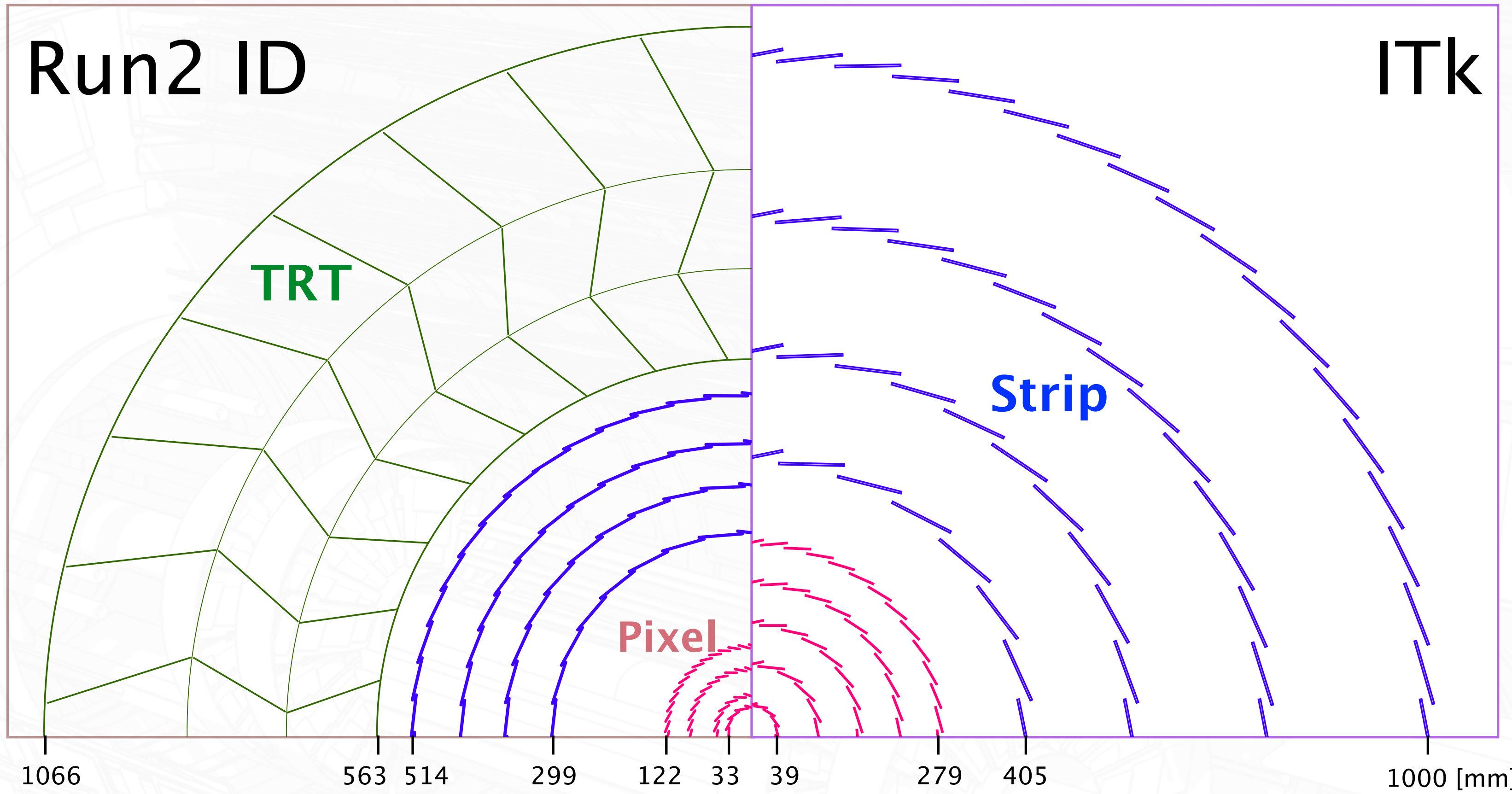
- LLP searches are along the context of full exploitation of the LHC potential for discovery of new physics and new particles.
- Given that no discovery so far and no significant $\sqrt{s}$ increase in the upcoming decades, importance of covering LLP scenarios has been enhanced.
- A creative area of the experiment with relatively small teams.
  - Requires special triggers, reconstructions, computing resources.
  - Dedicated background estimation methods.
- Run2 analyses are middleway.
  More room of ideas and improvements, more of ongoing analyses…
- Stay tuned for upcoming new results (and we may eventually find something new!!)

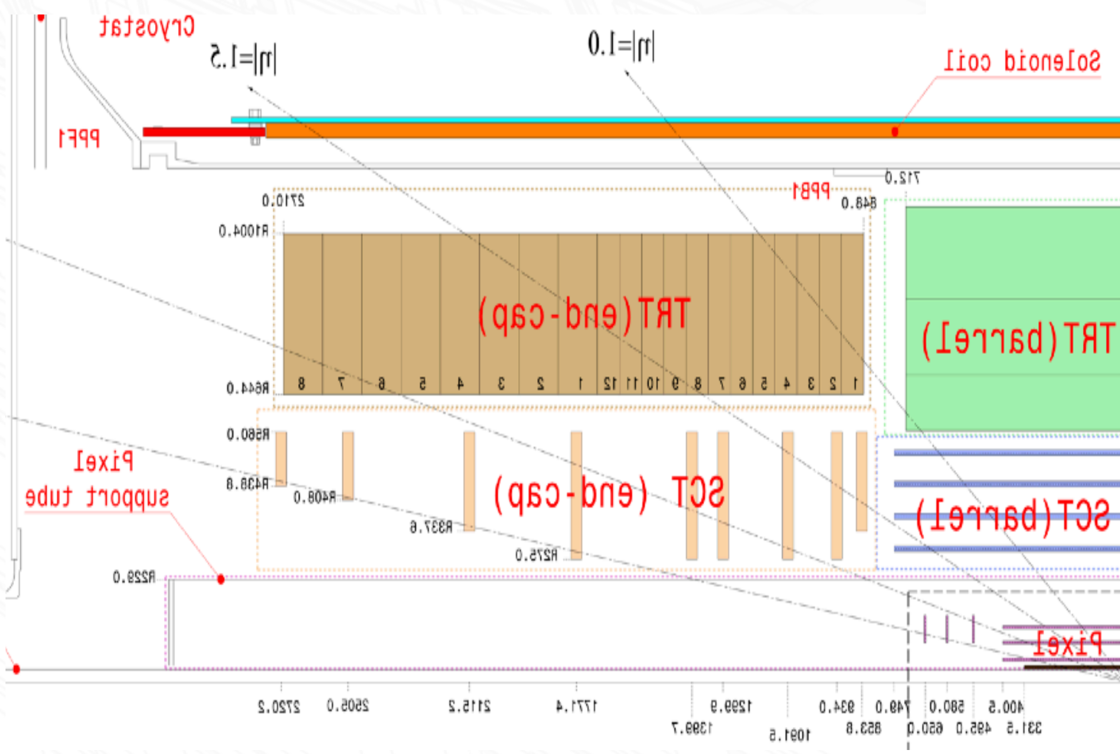
Backup

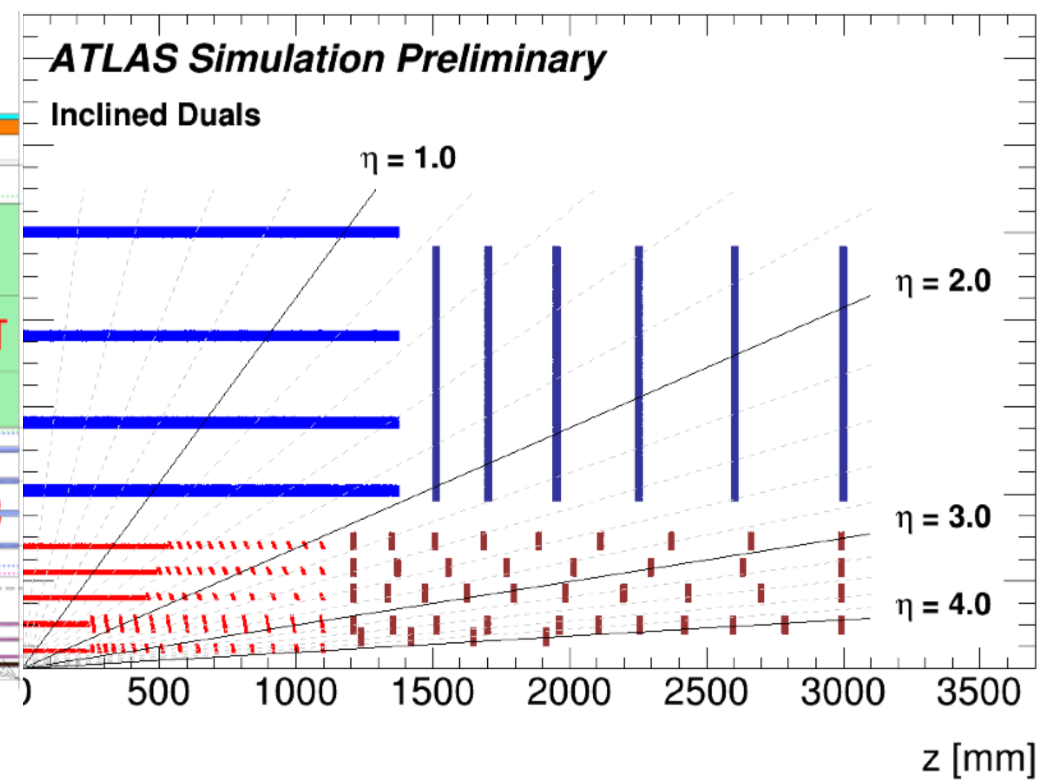
ATLAS LLP Results

	Short title	Ref. numbers	Latest Dataset
Run2	Disappearing Track (Wino)	SUSY-2016-06, JHEP 06 (2018) 022 arXiv:1712.02118	13 TeV, 36 fb^{-1}
	Disappearing Track (Pure Higgsino reint.)	ATL-PHYS-PUB-2017-019	13 TeV, 36 fb^{-1}
	Displaced vertex + MET	SUSY-2016-08, Phys. Rev. D 97 (2018) 052012 arXiv:1710.04901	13 TeV, 32.8 fb^{-1}
	Stable Massive Particle (pixel dE/dx and ToF)	Physics Letters B 760 (2016) 647 arXiv:1606.05129	13 TeV, 3.2 fb^{-1}
	(Meta)stable Massive Particle (pixel dE/dx)	Phys. Rev. D 93, 112015 (2016) arXiv:1604.04520	13 TeV, 3.2 fb^{-1}
	Prompt searches reint. to RPV incl. LLP cases	ATLAS-CONF-2018-003	13 TeV, 36 fb^{-1}
	Displaced jets (calo ratio)	ATLAS-CONF-2016-103	13 TeV, 3.2 fb^{-1}
	Displaced lepton-jets	ATLAS-CONF-2016-042	13 TeV, 3.4 fb^{-1}
Run1	Highly ionizing particle (HIP; TRT dE/dx)	EXOT-2014-16, Phys. Rev. D 93, 052009 (2016) arXiv:1509.08059	8 TeV, 20 fb^{-1}
	Non-prompt photon	SUSY-2013-17, Phys. Rev. D. 90, 112005 (2014) arXiv:1409.5542	8 TeV, 20 fb^{-1}
	Stopped particle	SUSY-2013-03, Phys. Rev. D 88, 112003 (2013) arXiv:1310.6584	8 TeV, 20 fb^{-1}
	Displaced vertex having a lepton or dilepton DV	SUSY-2014-02, Phys. Rev. D 92, 072004 (2015) arXiv:1504.05162	8 TeV, 20 fb^{-1}
	Displaced vertex in ID and MS	EXOT-2013-12, Phys. Rev. D 92, 012010 (2015) arXiv:1504.03634	8 TeV, 20 fb^{-1}
PERF	Large-d_0 tracking	ATL-PHYS-PUB-2017-014	—
	Vertexing in Muon Spectrometer	PERF-2013-01, JINST 9 (2014) P02001 arXiv:1311.7070	—

Phase-II upgrade programs: ATLAS

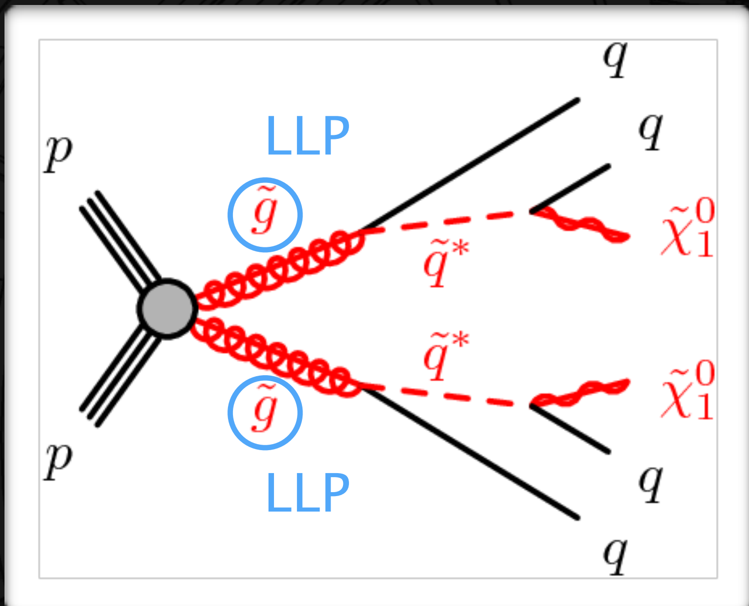


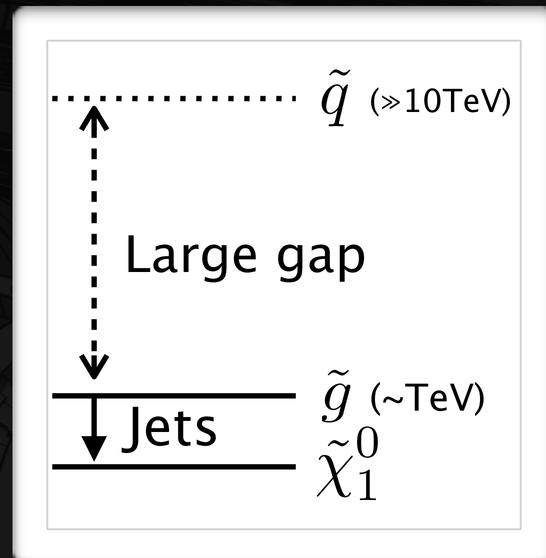




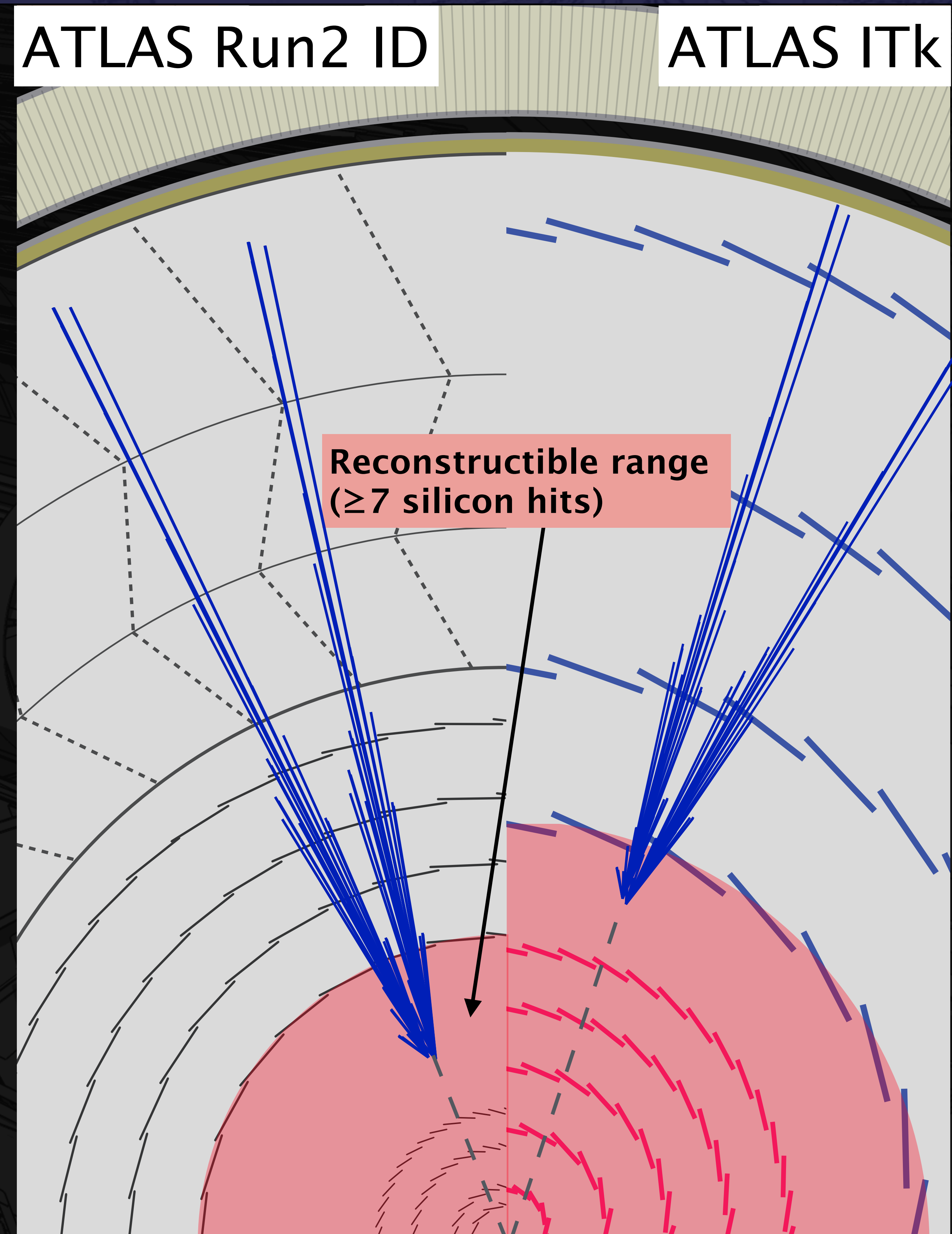
Long-lived signature in the tracker vs. layout (1)

Run2 DV+MET search: Phys. Rev. D 97 (2018) 052012

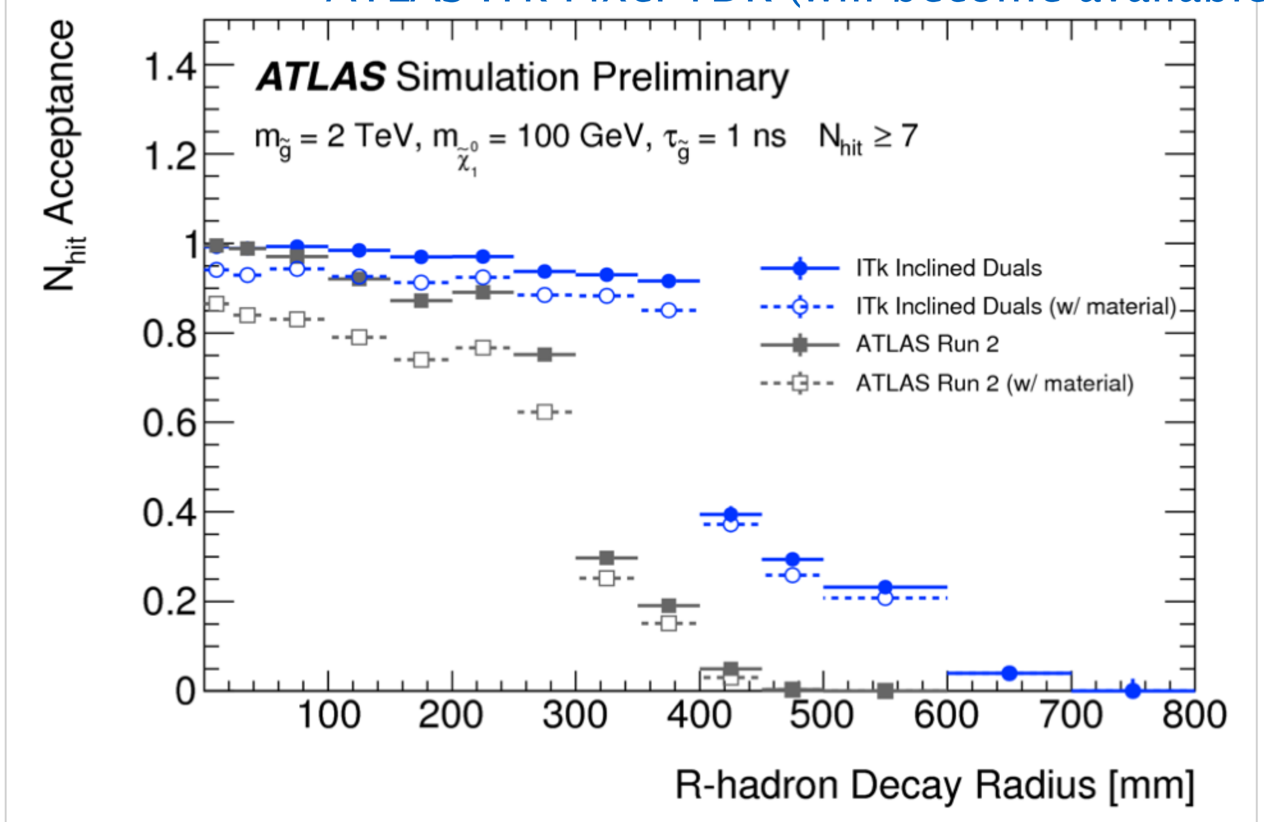


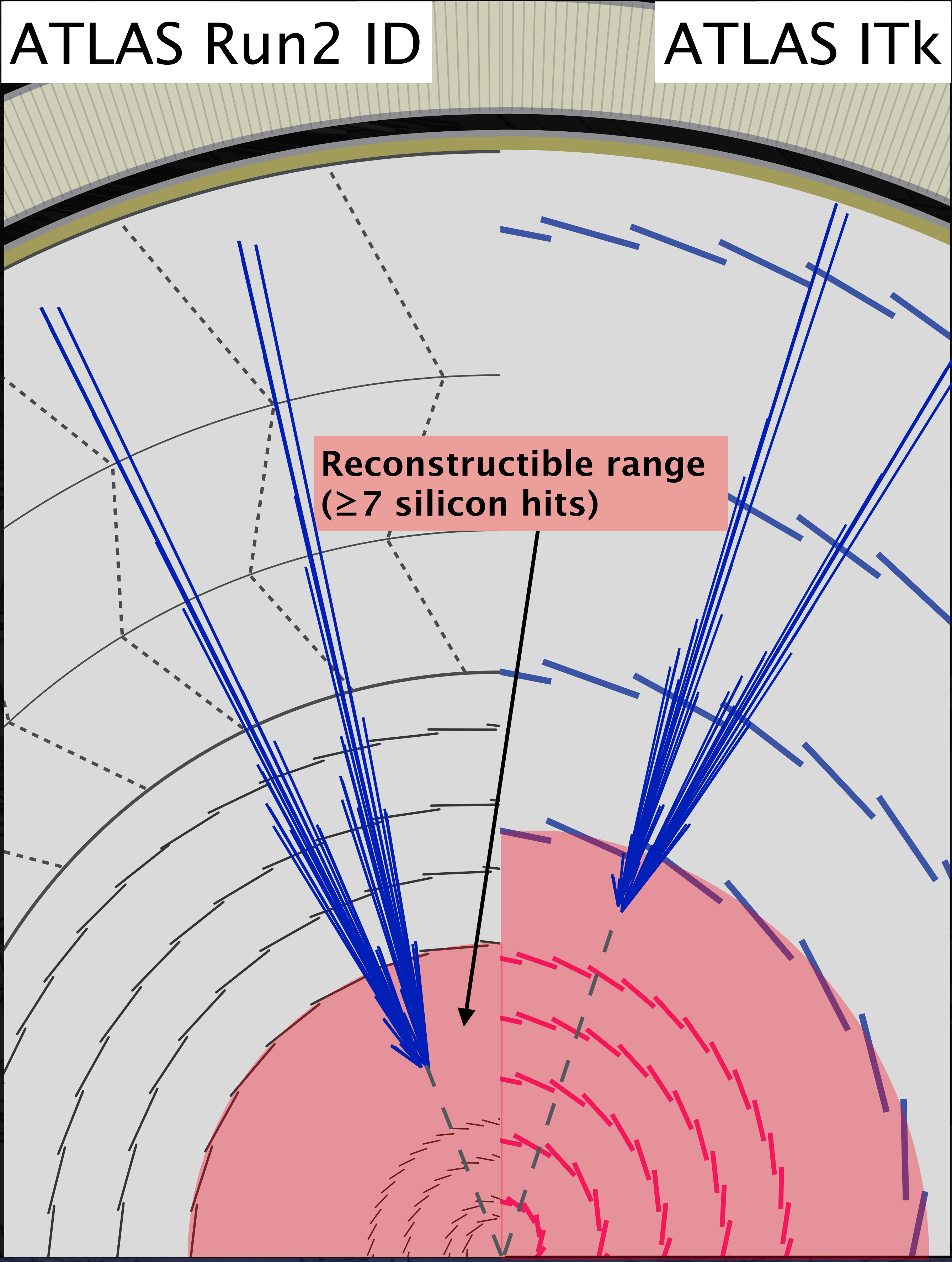


- ATLAS inner tracking detectors have a new layout: different implications depending on the signature.
- Displaced vertices (R–hadron search): need **tracking using outer layers** → increase of acceptance is expected.



ATLAS ITk Pixel TDR (will become available)

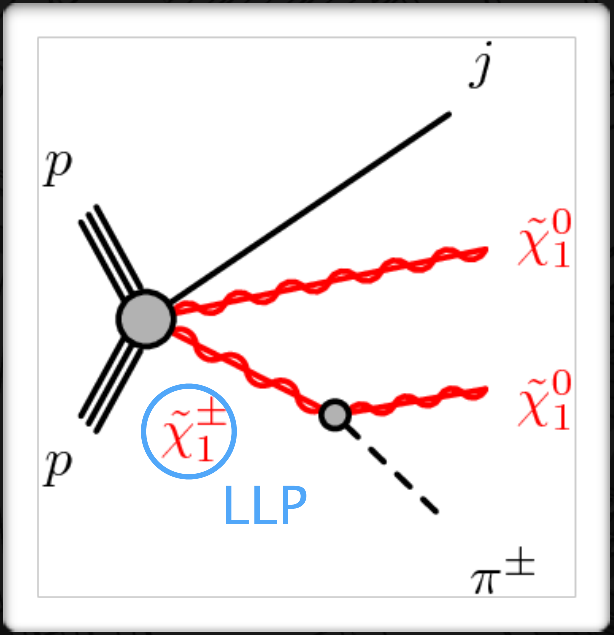


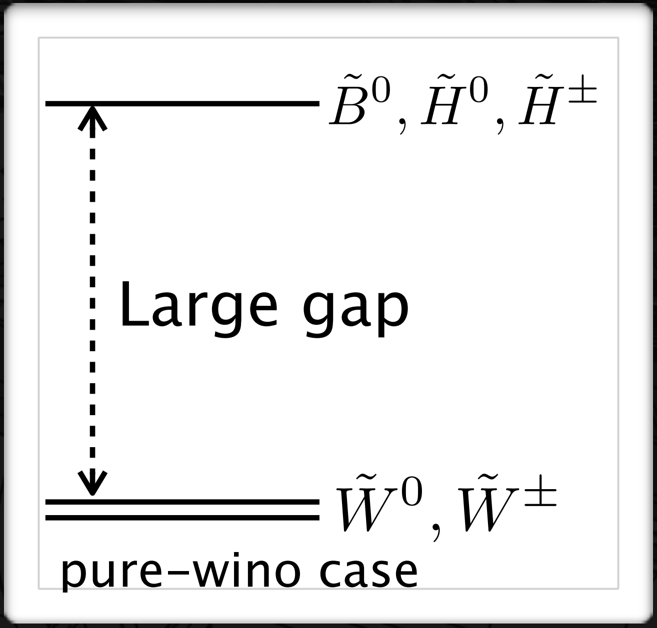


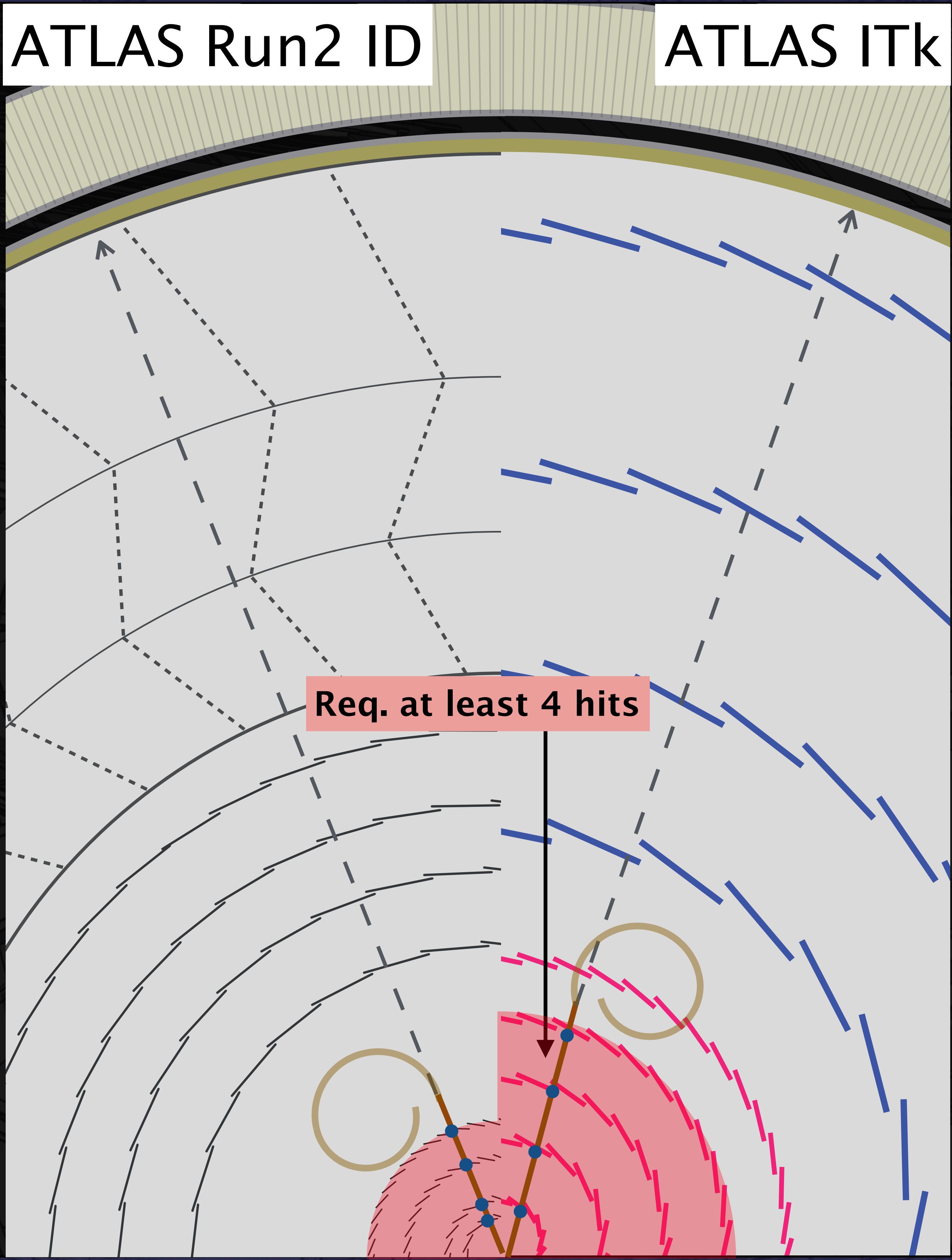
- ATLAS inner tracking detectors have a new layout: different implications depending on the signature.
- Displaced vertices (*R*–hadron search): need **tracking using outer layers** → increase of acceptance is expected.

Long-lived signature in the tracker vs. layout (2)

Detail of Run2 analysis in H. Russel's talk



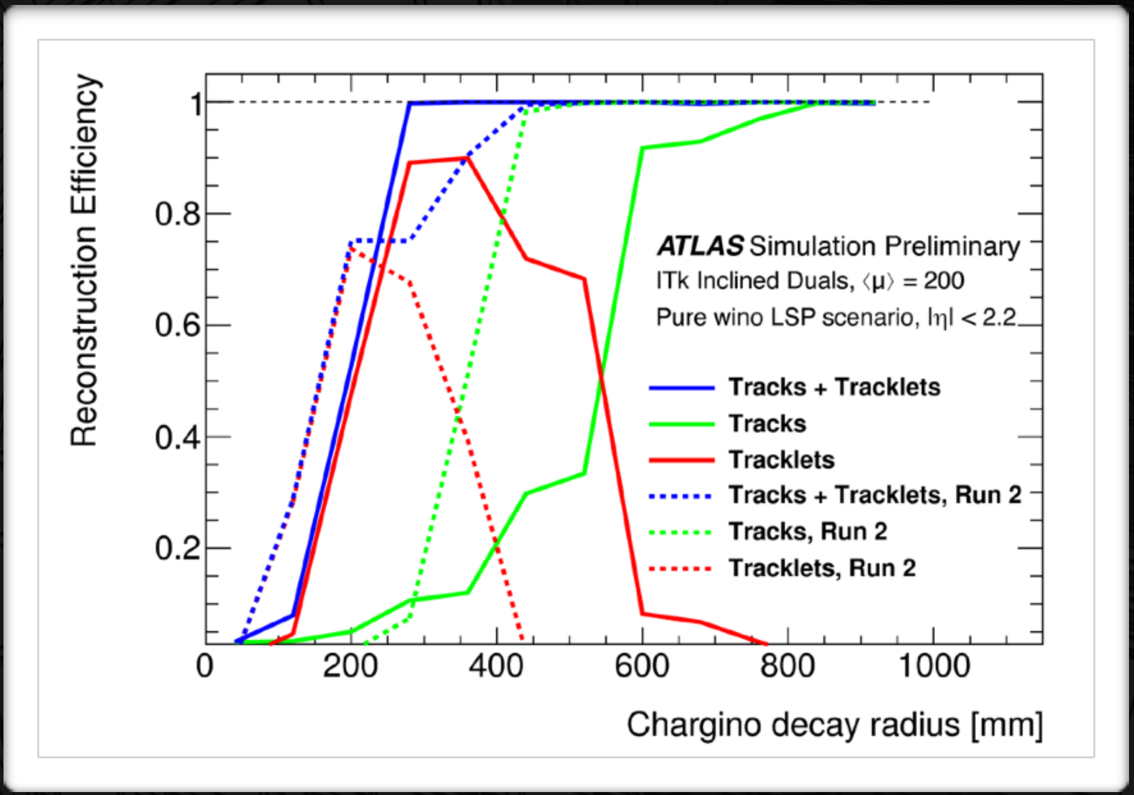


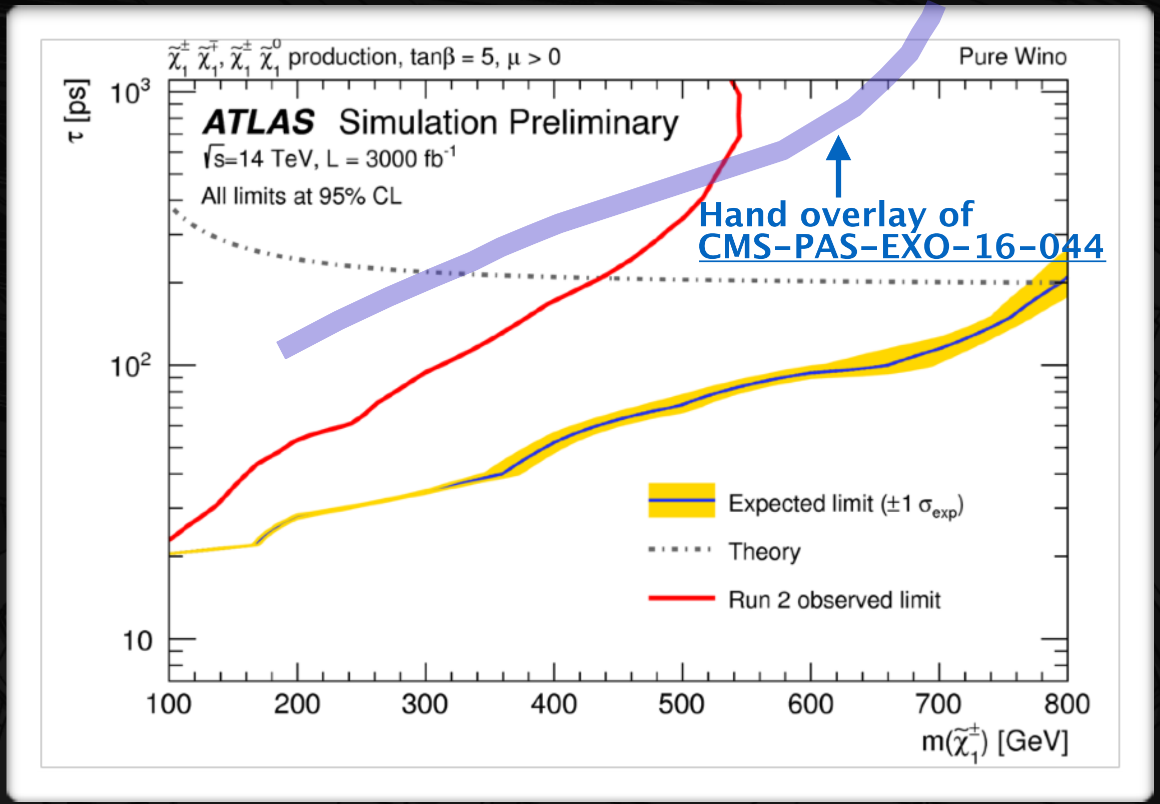


- ATLAS inner tracking detectors have a new layout: different implications depending on the signature.
- Disappearing track (long-lived chargino search): need **tracking using only innermost layers**
  → decrease of acceptance is expected.

Disappearing track prospect

ATLAS ITk Pixel TDR (will become available)





- In the current simulation, observing fake tracks more significant with ATLAS ITk: more kinked tracks than current inner detector
  — but reconstruction algorithm will certainly evolve!
- Expected exclusion with 3000 fb^{-1}:
  - **At least >800 GeV for pure wino, (τ = 0.2 ns)**
  - **Also >250 GeV for pure higgsino scenario (τ = 0.05 ns)**

Math modelling of a search

Truth variables have hat!

Truth-level variable space: $\hat{\Omega} = \{\hat{E}_{\mathrm{T}}^{\mathrm{miss}}, \hat{p}_{\mathrm{T}}^{j}, \cdots\}$

Reco-level variable space: $\Omega = \{E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{j}, \cdots\}$ → Ω space is wider than $\hat{\Omega}$ for reco-level variables

Reconstruction efficiency: $\varepsilon(\hat{\Omega})$

factorization between efficiency and resolution

Reconstruction resolution (smearing): $J(\hat{\Omega}, \Omega) = \dfrac{\partial \Omega}{\partial \hat{\Omega}}, \quad \left(\int \mathrm{d}\hat{\Omega} \, \dfrac{\mathrm{d}f}{\mathrm{d}\hat{\Omega}} = \int \mathrm{d}\hat{\Omega} \, J(\hat{\Omega}, \Omega) \dfrac{\mathrm{d}f}{\mathrm{d}\Omega} = \int \mathrm{d}\Omega \, \dfrac{\mathrm{d}f}{\mathrm{d}\Omega} \right)$

Trigger + Kinematic selection (cut-based):

$$K(\Omega) = \theta(E_{\mathrm{T}}^{\mathrm{miss}}) \cdot \theta(p_{\mathrm{T}}^{j}) \cdots = \prod_{j} \theta(k_j)$$

Truth-level kinematic selection (cut-based):

$$K(\hat{\Omega}) = \theta(\hat{E}_{\mathrm{T}}^{\mathrm{miss}}) \cdot \theta(\hat{p}_{\mathrm{T}}^{j}) \cdots = \prod_{j} \theta(\hat{k}_j)$$

Quality selection (cut-based):

$$Q(\Omega) = \theta(\mathrm{isolation}) \cdot \theta(\cdot) \cdots = \prod_{j} \theta(q_j)$$

No truth-level correspondence!!

Signal region:

$$S(\Omega) = K(\Omega) \cdot Q(\Omega)$$

And usually we have multiple signal regions…

Model-dependent acceptance and efficiency

Number of expected signal events in the signal region:

$$N_i^{(S)} = \mathcal{L} \cdot \int \mathrm{d}\Omega\, \underbrace{S(\Omega)}_{\text{analysis}} \cdot \left\{ \underbrace{J(\hat{\Omega}, \Omega)}_{\text{resolution}} \cdot \underbrace{\varepsilon(\hat{\Omega})}_{\text{trg.reco.}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}\hat{\Omega}} \right\}$$

Acceptance * efficiency: $\langle \mathcal{A} \cdot \varepsilon \rangle_i^{(S)} = \dfrac{N_i^{(S)}}{\sigma_i^{\mathrm{tot}} \cdot \mathcal{L}}$

Acceptance: $\mathcal{A}_i^{(K)} = \dfrac{1}{\sigma_i^{\mathrm{tot}}} \displaystyle\int \mathrm{d}\hat{\Omega}\, K(\hat{\Omega}) \frac{\mathrm{d}\sigma_i}{\mathrm{d}\hat{\Omega}}$

Efficiency: $\langle \varepsilon \rangle_i^{(S)} = \dfrac{\langle \mathcal{A} \cdot \varepsilon \rangle_i^{(S)}}{\mathcal{A}_i^{(K)}} = \dfrac{N_i^{(S)}}{\mathcal{L} \cdot \displaystyle\int \mathrm{d}\hat{\Omega} K(\hat{\Omega}) \frac{\mathrm{d}\sigma_i}{\mathrm{d}\hat{\Omega}}}$

Mathematically, acceptance is only defined within the truth-level variable space (fully model dependent)

Efficiency is also strictly-speaking always model-dependent, as it's dependent on acceptance and the number of expected signal events in SR.

Special case: factorization of efficiency

If the efficiency is not strongly dependent on models and quasi-universally applicable to all models concerned, it can be regarded as approximate model-independent efficiency.

$$\langle \varepsilon \rangle_i^{(S)} \sim \langle \varepsilon \rangle_j^{(S)} \sim \langle \varepsilon \rangle^{(S)}$$ **Model-independent!!**

If the reconstruction resolution is good enough and migration by smearing is sufficiently small,

$$\mathrm{d}\hat{\Omega} \sim \mathrm{d}\Omega$$ (for the sub-space of kinematic/topological variables)

and the trigger+reco efficiency, quality variable distributions are approximately universal:

$$\varepsilon(\hat{\Omega}) \sim \bar{\varepsilon}, \quad J(\boldsymbol{q}, \hat{\Omega}) \sim J(\boldsymbol{q})$$

In this case, the number of expected signal events in the signal region S is approximated as

$$\begin{aligned} N_i^{(S)} &\sim \mathcal{L} \cdot \bar{\varepsilon} \cdot \int \mathrm{d}\boldsymbol{q}\, Q(\boldsymbol{q}) \left\{ \int \mathrm{d}\hat{\Omega}\, J(\boldsymbol{q}, \hat{\Omega})\, K(\hat{\Omega}) \frac{\mathrm{d}\sigma_i}{\mathrm{d}\hat{\Omega}} \right\} \\ &\sim \mathcal{L} \cdot \left(\bar{\varepsilon} \cdot \int \mathrm{d}\boldsymbol{q}\, Q(\boldsymbol{q}) J(\boldsymbol{q}) \right) \cdot \mathcal{A}_i^{(K)} \cdot \sigma_i^{\mathrm{tot}} \\ &= \mathcal{L} \cdot \langle \varepsilon \rangle^{(S)} \cdot \mathcal{A}_i^{(K)} \cdot \sigma_i^{\mathrm{tot}} \end{aligned}$$

In this limit, efficiency can be model-independent.

Model i

$$N_{i}^{(S)} = \mathcal{L} \cdot \sigma_{i}^{\text{tot}} \cdot \mathcal{A}_{i}^{(K)} \cdot \langle \varepsilon \rangle^{(S)}$$

Injected model acceptance

Common

Model j

$$N_{j}^{(S)} = \mathcal{L} \cdot \sigma_{j}^{\text{tot}} \cdot \mathcal{A}_{j}^{(K)} \cdot \langle \varepsilon \rangle^{(S)}$$

Injected model acceptance

In principle, the experiment only needs to provide $\langle \varepsilon \rangle^{(S)}$ and how to define $\mathcal{A}^{(K)}$, and the value of acceptance $\mathcal{A}_{i}^{(K)}$ for the primary model i is only a crosscheck.

If the efficiency is not possible to factorize…

In this case, in order to estimate the number of signal events in SR,
one needs to be able to calculate it based on the original formula:

$$N_i^{(S)} = \mathcal{L} \cdot \int \mathrm{d}\Omega\, S(\Omega) \cdot \left\{ J(\hat{\Omega}, \Omega) \cdot \varepsilon(\hat{\Omega}) \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}\hat{\Omega}} \right\}$$

Experiment needs to provide this part in a differential manner.

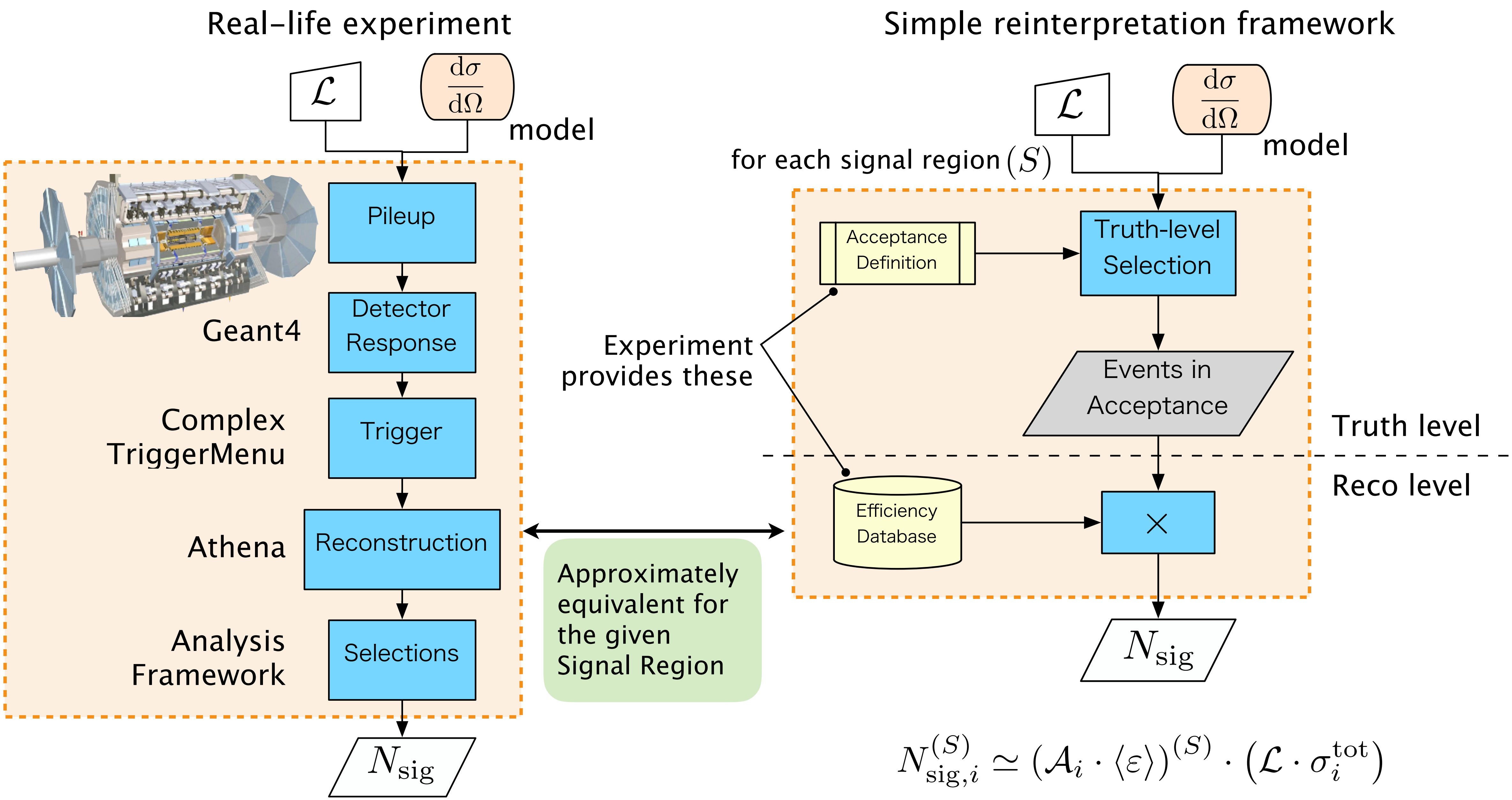
But, **“partial factorization”** may be possible in many cases.
(for example, the resolution of track pseudorapidity, or displaced vertex position are determined with a good precision, and hence possible to integrate-out).
In this case, “factorized acceptance” will be a useful notion.

The “interface” has to be variables available/calculable within the MC truth-level.
The part highlighted by the box can be a “black box”, and in that sense S(Ω) can be **MVA** as well in principle. (analyses also do not need to decompose everything).

Cut-based analysis has a room of more factorization.

But each analysis will need to taylor-out reasonably-simplest amount of informations.

Introduction: reinterpretation in general



$$N_{\mathrm{sig},i}^{(S)} \simeq (\mathcal{A}_i \cdot \langle \varepsilon \rangle)^{(S)} \cdot (\mathcal{L} \cdot \sigma_i^{\mathrm{tot}})$$

- **Efficiency**: a coefficient defined for each SR which is **approximately** applicable to various signal models (model-independent) for the specified acceptance to predict N_{sig}.
- **Acceptance**: The rate of events passing a fiducial selection defined at the **truth level** for each SR. The acceptance is chosen to give as much uniform efficiency as possible, and users need to be able to calculate the acceptance with the specified way for themselves with standard generators.
→ Effectively, this determines the “user interface”

See Iacopo’s talk for the standard reint. case

Reinterpretation with a single efficiency value is rather special

From real experiment: $$\langle \mathcal{A}_i^{(S)} \cdot \varepsilon_i^{(S)} \rangle = \frac{N_{\mathrm{sig},i}^{(S)}}{\mathcal{L} \cdot \sigma_i^{\mathrm{tot}}}$$

(S : reco-level selection to define SR)

Truth-level calculation: $\mathcal{A}_i^{(\hat{K})}$ ($\hat{K}$: truth-level kinematic selection)

Efficiency: $$\langle \varepsilon \rangle_i^{(S,\hat{K})} \equiv \langle \mathcal{A}_i^{(S)} \cdot \varepsilon_i^{(S)} \rangle / \mathcal{A}_i^{(\hat{K})}$$

If the value of the efficiency is approximately similar over different models, **(with an adequate choice of acceptance definition)**, such efficiency can be regarded as the effective model-independent efficiency:

$$\langle \varepsilon \rangle_i^{(S,\hat{K})} \sim \langle \varepsilon \rangle_j^{(S,\hat{K})} \sim \langle \varepsilon \rangle^{(S,\hat{K})}$$

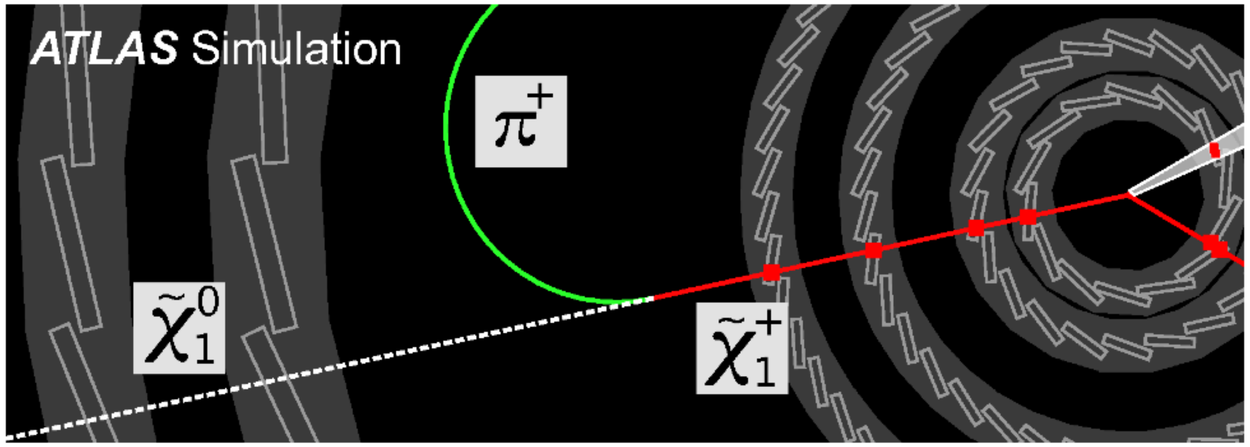
Model-independent!!

Despite such an efficiency can be found in many cases of prompt searches, this is not always fulfilled, and more complex treatment might be required depending on cases. We show such cases in our 2 LLP search reinterpretations.

We check closure of N_{sig} for the main model in the paper.

Disappearing track analysis [arXiv: hep-ex/1712.02118]

Selection requirement	Electroweak channel Observed	Electroweak channel Expected signal
Trigger	434 559 704	1276 (0.20)
Jet cleaning	288 498 579	1181 (0.19)
Lepton veto	275 243 946	1178 (0.19)
E_T^{miss} and jet requirements	2 697 917	579.1 (0.092)
Isolation and p_T requirement	464 524	104.2 (0.017)
Geometrical $\|\eta\|$ acceptance	339 602	83.6 (0.013)
Quality requirement	6134	29.6 (0.0047)
Disappearance condition	154	24.1 (0.0038)



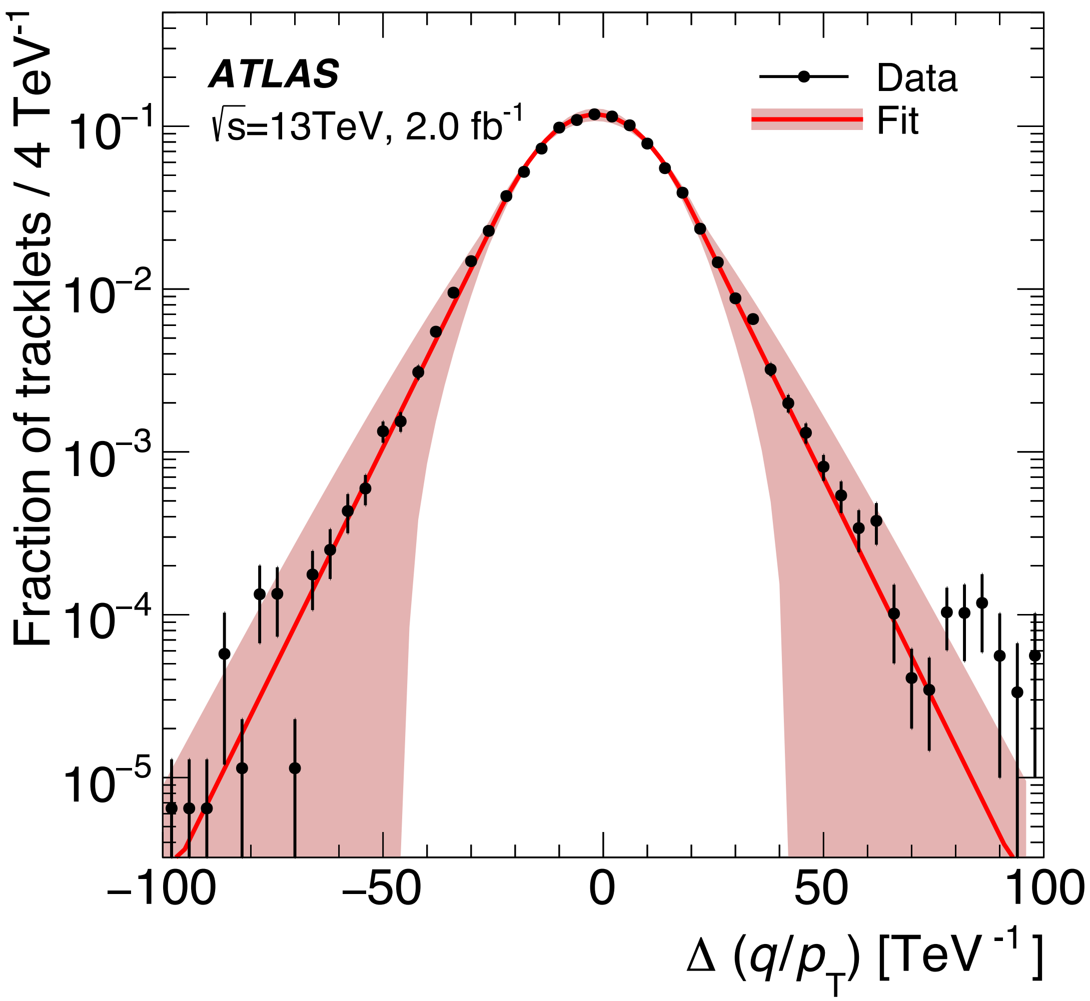
Analysis:

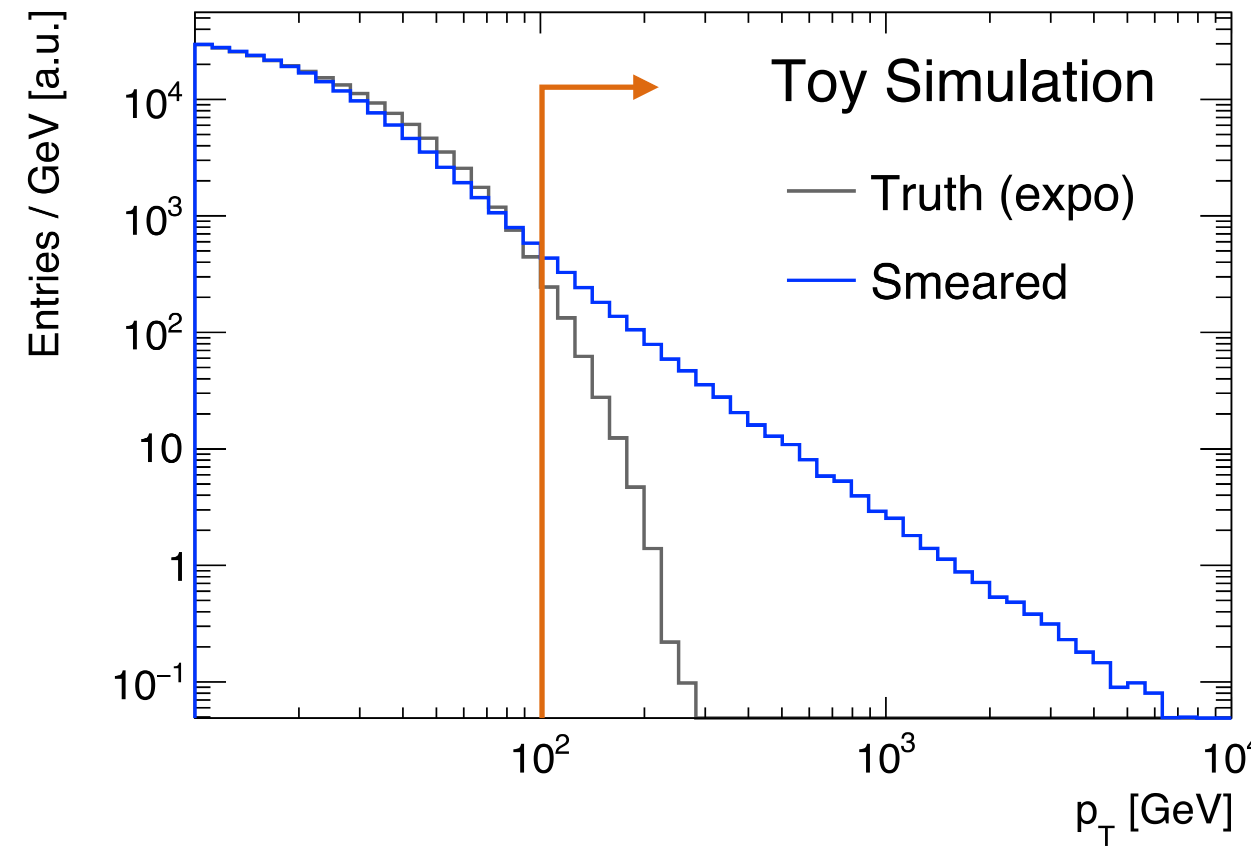
- Well-isolated, high-quality & high-p_T pixel tracklet (p_T^{reco} > 100 GeV)
- MET and ISR jet for boosting the system
- 2 signal regions for Electroweak (single-jet) and strong (multijet) productions

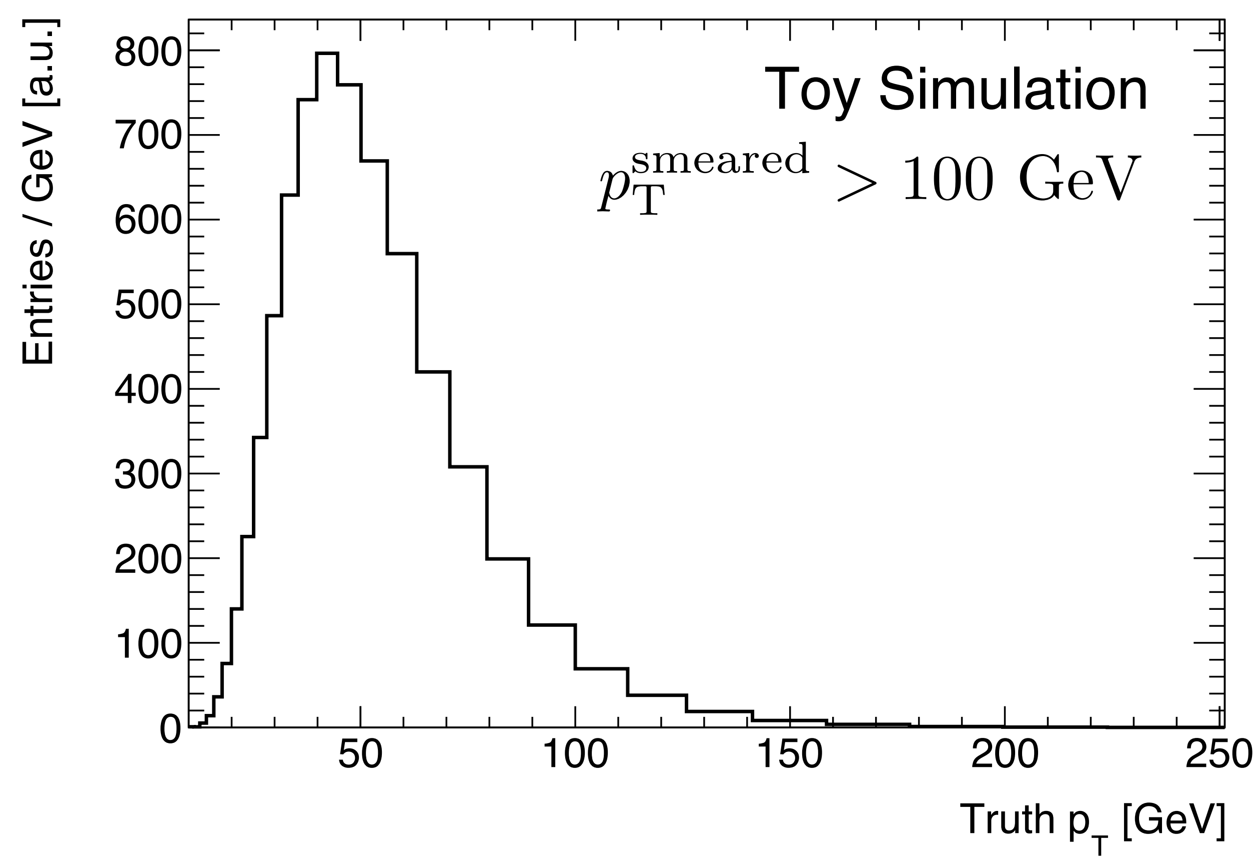
Reinterpretation Strategy:

- factorize the “event-level” topological part of selections and the pixel tracklet part.
- Pixel tracklet has large p_T smearing → provide the smearing function.
- Pixel tracklet (decay radius, η) are not smearing much: reconstruction&selection efficiency can be defined using binning in truth variables.
- Requiring at least 1 pixel tracklet satisfying the quality cut.
- Informations provided for both electroweak SR and strong SR.

Complexity (1): Large smearing

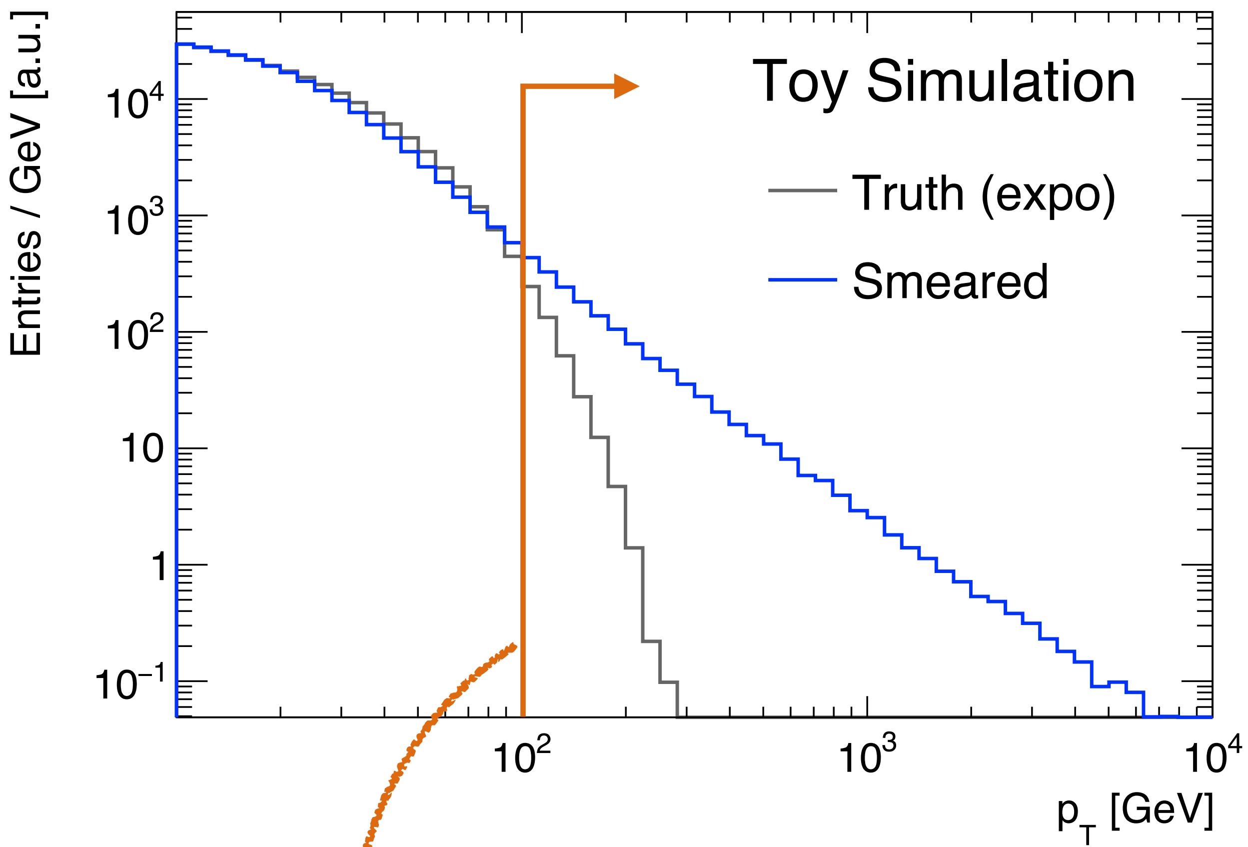


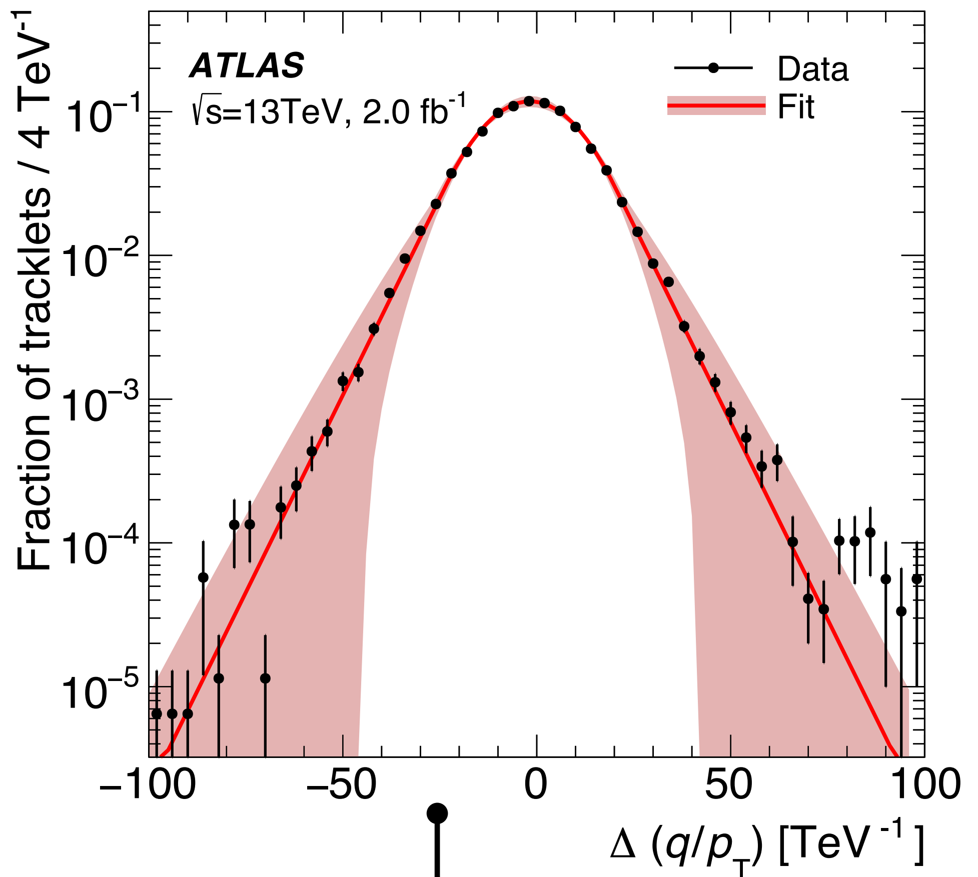




- Signal selection with a certain p_T cut where the resolution is not great.
- Acceptance definition with truth p_T is not very meaningful due to very large migration of events from low-p_T.
- In such cases, detector response functions needed for reinterpretation.
- **LLP Example**: disappearing (short) track

Complexity (1): Large smearing





$$n = \int_{p_T^{\rm thr}}^{\infty} dp_T^{\rm reco}\, J(p_T^{\rm reco}; p_T^{\rm truth}) \cdot \frac{\mathrm{d}n}{\mathrm{d}p_T^{\rm truth}}$$

smearing function

No acceptance here; but the signal yield is calculable by providing the smearing function.

Partial acceptance: factorizing simpler things and the rest

If the analysis selection S is possible to approximately divide into uncorrelated factors:

$$S = S_1 \times S_2$$

the corresponding partial acceptance and efficiency for each sub-selection are possible to be defined:

$$S_1 \Longleftrightarrow \left\{ \mathcal{A}_i^{(S_1)}, \langle \varepsilon \rangle^{(S_1)} \right\}$$

$$S_2 \Longleftrightarrow \left\{ \mathcal{A}_i^{(S_2)}, \langle \varepsilon \rangle^{(S_2)} \right\}$$

$$N_{\mathrm{sig},i}^{(S)} \simeq \left(\mathcal{A}_i \cdot \langle \varepsilon \rangle \right)^{(S)} \cdot \left(\mathcal{L} \cdot \sigma_i^{\mathrm{tot}} \right)$$

⬇

$$N_{\mathrm{sig},i}^{(S)} \simeq \left[\prod_k \left(\mathcal{A}_i \cdot \langle \varepsilon \rangle \right)^{(S_k)} \right] \cdot \left(\mathcal{L} \cdot \sigma_i^{\mathrm{tot}} \right)$$

Factorization is convenient and helpful to integrate-out and encapsulate simpler parts of the analysis.

But whether factorization works or not would depend on cases!

Disappearing track: acceptance and efficiency

Definition in backup; more details including overlap removal are given in code snippet in HepData

Factorized!

Tracklet LLP term: at least 1 tracklet

$$N_{\mathrm{sig},i} = \mathcal{L} \cdot \left[\mathcal{A}_i^{\mathrm{evt}} \cdot \langle\varepsilon\rangle^{\mathrm{evt}}\right] \cdot \left[1 - \prod_k^{\mathrm{LLP}} \left(1 - \mathcal{A}_{\mathrm{trk},i}^k \cdot \varepsilon_{\mathrm{trk}}^k\right)\right] \sigma_i$$

Event term

Tracklet efficiency

$$\varepsilon_{\mathrm{trk}}^k = \left[\int_{p_{\mathrm{T}}^{\mathrm{thr}}} \mathrm{d}p_{\mathrm{T}}^{\mathrm{reco}} J(p_{\mathrm{T}}^{\mathrm{reco}}; \hat{p}_{\mathrm{T}}) \frac{\mathrm{d}}{\mathrm{d}\hat{p}_{\mathrm{T}}} \cdot \int \mathrm{d}\hat{r}_{\mathrm{dec}} \mathrm{d}\hat{\eta}\, \varepsilon_{\mathrm{pix}}^{\mathrm{trk}}(\hat{r}_{\mathrm{dec}}, \hat{\eta}) \cdot \frac{\mathrm{d}^2}{\mathrm{d}\hat{r}_{\mathrm{dec}} \mathrm{d}\hat{\eta}}\right]_k$$

p_T smearing

reco-level pT cut after smearing

Position/angle-dependent reco/selection efficiency

Tracklet acceptance definition: $\mathcal{A}_{\mathrm{trk}}^k$

- $p_T > 20$ GeV
- $0.1 < |\eta| < 1.9$
- 122.5 mm $< r_{decay} <$ 295 mm
- $\Delta R > 0.4$ between tracklet and each of up to 4 leading jets

Symbols with hat: truth variable

[dashed light-blue box] : provided informations

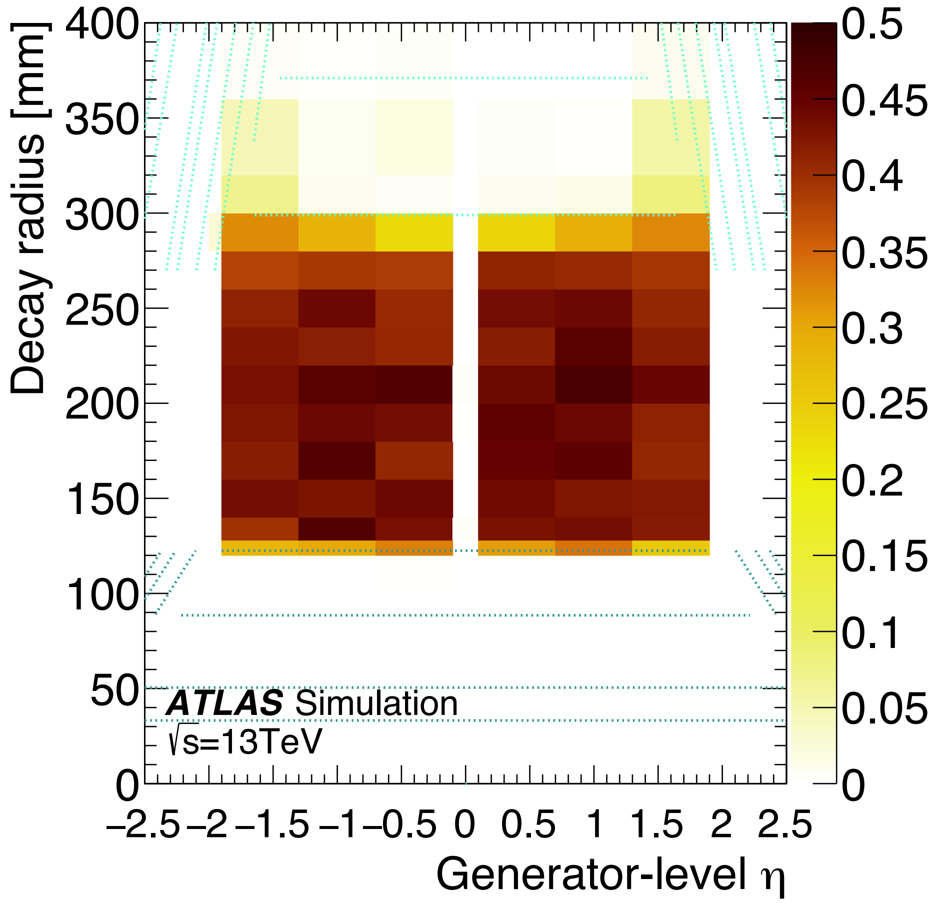
Disappearing track: reinterpretation materials

Signal model		Event		Tracklet		
Mass [GeV]	Lifetime [ns]	Acceptance	Efficiency	Acceptance	Efficiency	P
Electroweak production						
$m_{\tilde{\chi}_1^\pm}$=400	0.2	0.09	1.03	0.07	0.47	0.57
$m_{\tilde{\chi}_1^\pm}$=600	0.2	0.12	1.05	0.05	0.48	0.57
$m_{\tilde{\chi}_1^\pm}$=600	1.0	0.11	1.03	0.20	0.47	0.57
Strong production						
$m_{\tilde{g}}$=1600, $m_{\tilde{\chi}_1^\pm}$=500	0.2	0.71	0.97	0.10	0.38	0.55
$m_{\tilde{g}}$=1000, $m_{\tilde{\chi}_1^\pm}$=900	0.2	0.18	0.93	0.03	0.36	0.55

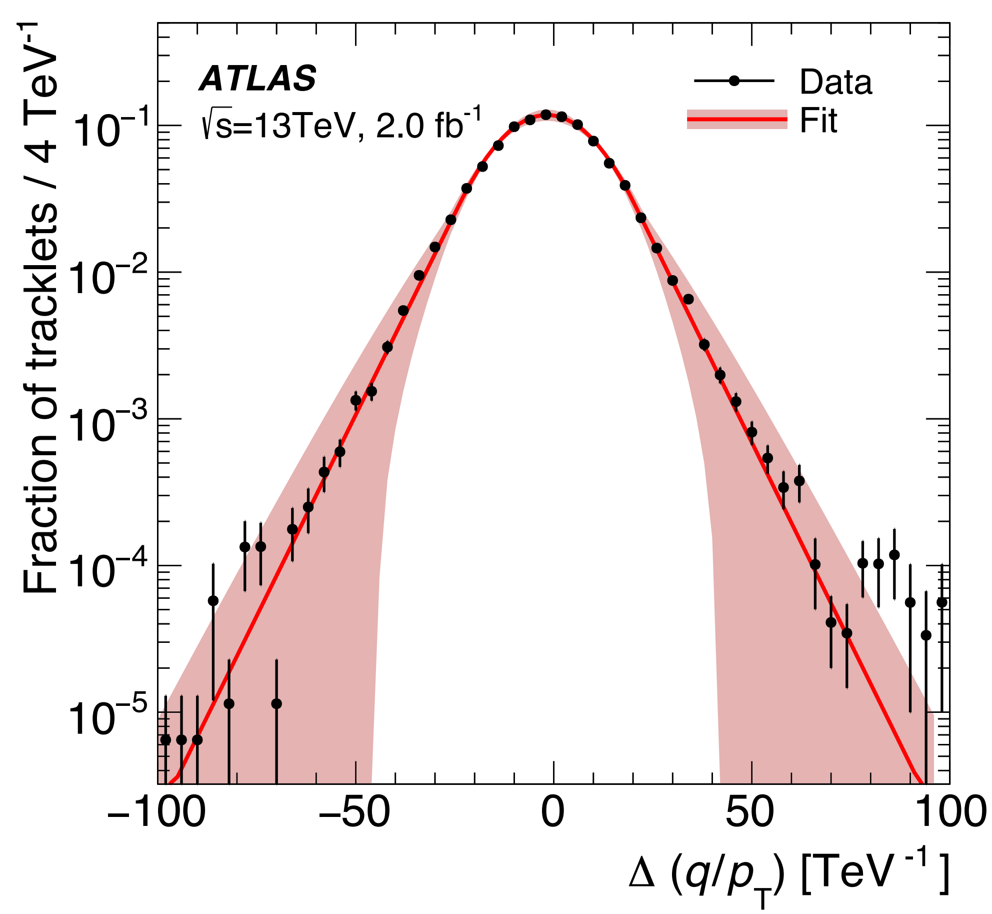
$\langle\varepsilon\rangle^{\mathrm{evt}}$

Tracklet efficiency (EW)

$\left(\mathcal{A}_{\mathrm{trk}} \times \varepsilon^{\mathrm{trk}}_{\mathrm{pix}}(\hat{r}_{\mathrm{dec}}, \hat{\eta})\right)_{\mathrm{EW}-\tilde{\chi}_1^\pm}$

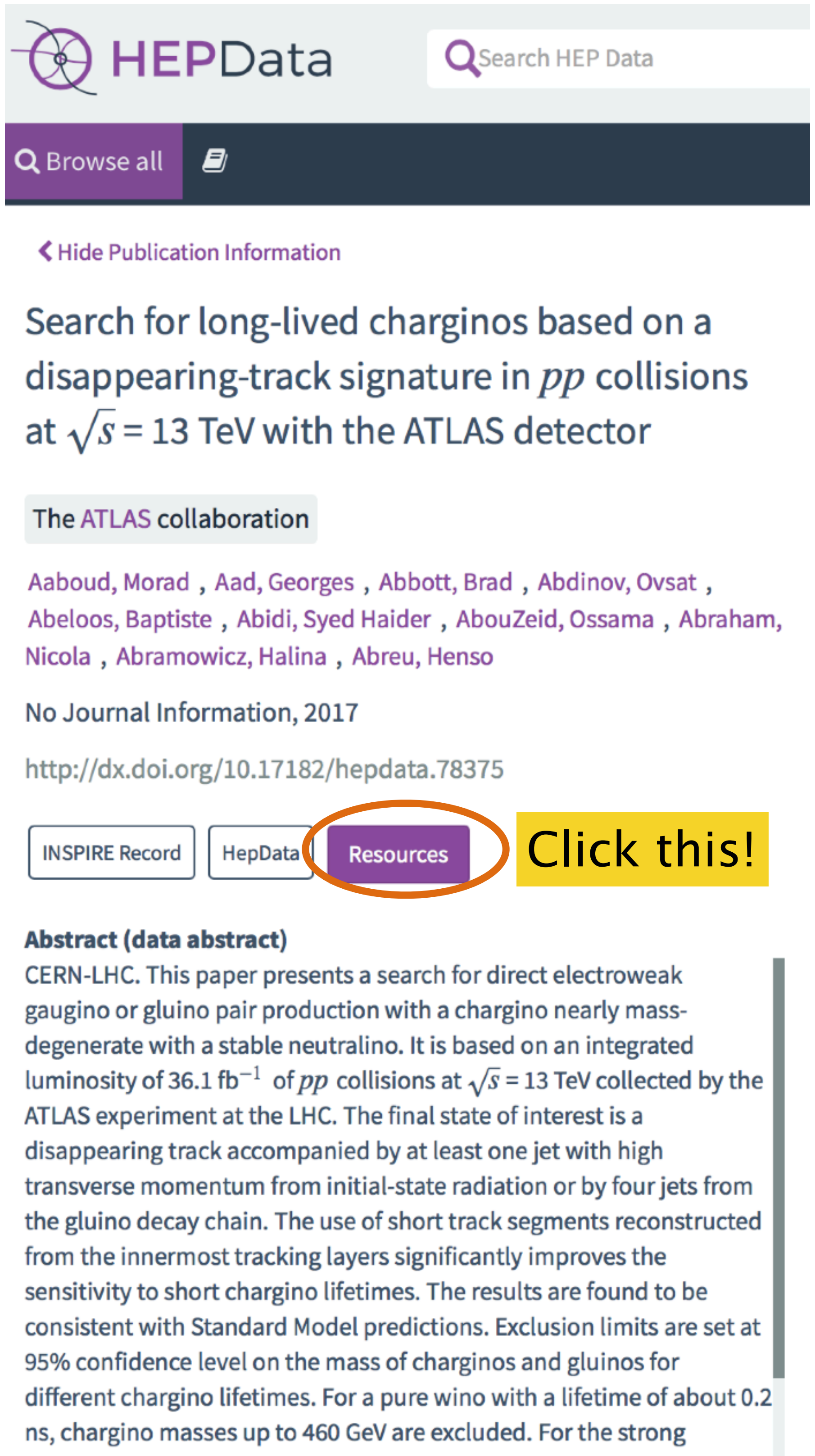


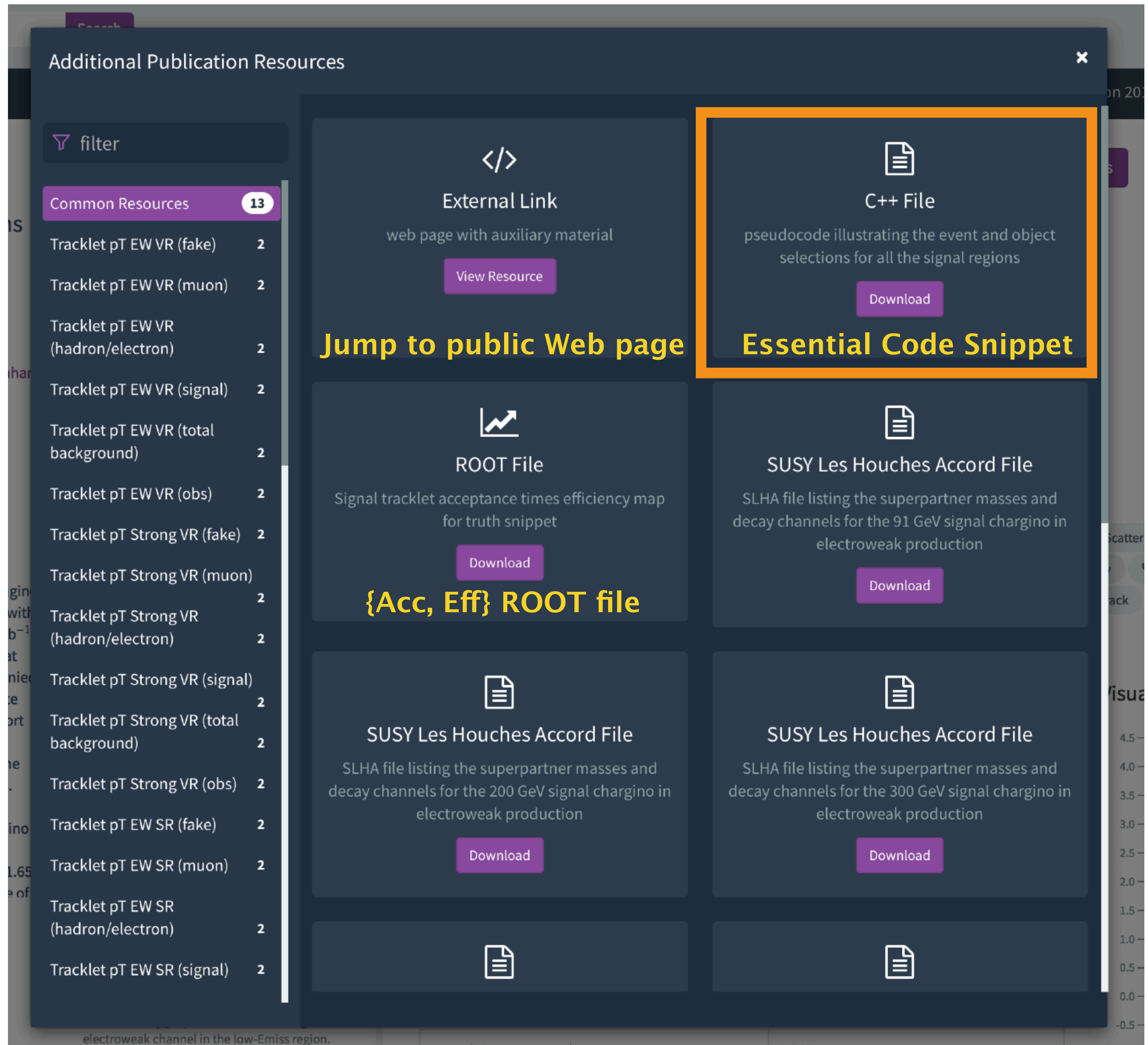
Pixel tracklet pT smearing $J(p_{\mathrm{T}}^{\mathrm{reco}}; p_{\mathrm{T}}^{\mathrm{truth}})$



Disappearing track: HepData information

https://www.hepdata.net/record/78375





Disappearing track: HepData information

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Search for long-lived charginos based on a disappearing-track signature in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

Aaboud, Morad , Aad, Georges , Abbott, Brad , Abdinov, Ovsat , Abeloos, Baptiste , Abidi, Syed Haider , AbouZeid, Ossama , Abraham, Nicola , Abramowicz, Halina , Abreu, Henso

No Journal Information, 2017

http://dx.doi.org/10.17182/hepdata.78375

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Abstract (data abstract)

CERN-LHC. This paper presents a search for direct electroweak gaugino or gluino pair production with a chargino nearly mass-degenerate with a stable neutralino. It is based on an integrated luminosity of 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV collected by the ATLAS experiment at the LHC. The final state of interest is a disappearing track accompanied by at least one jet with high transverse momentum from initial-state radiation or by four jets from the gluino decay chain. The use of short track segments reconstructed from the innermost tracking layers significantly improves the sensitivity to short chargino lifetimes. The results are found to be consistent with Standard Model predictions. Exclusion limits are set at 95% confidence level on the mass of charginos and gluinos for different chargino lifetimes. For a pure wino with a lifetime of about 0.2 ns, chargino masses up to 460 GeV are excluded. For the strong production channel, gluino masses up to 1.65 TeV are excluded

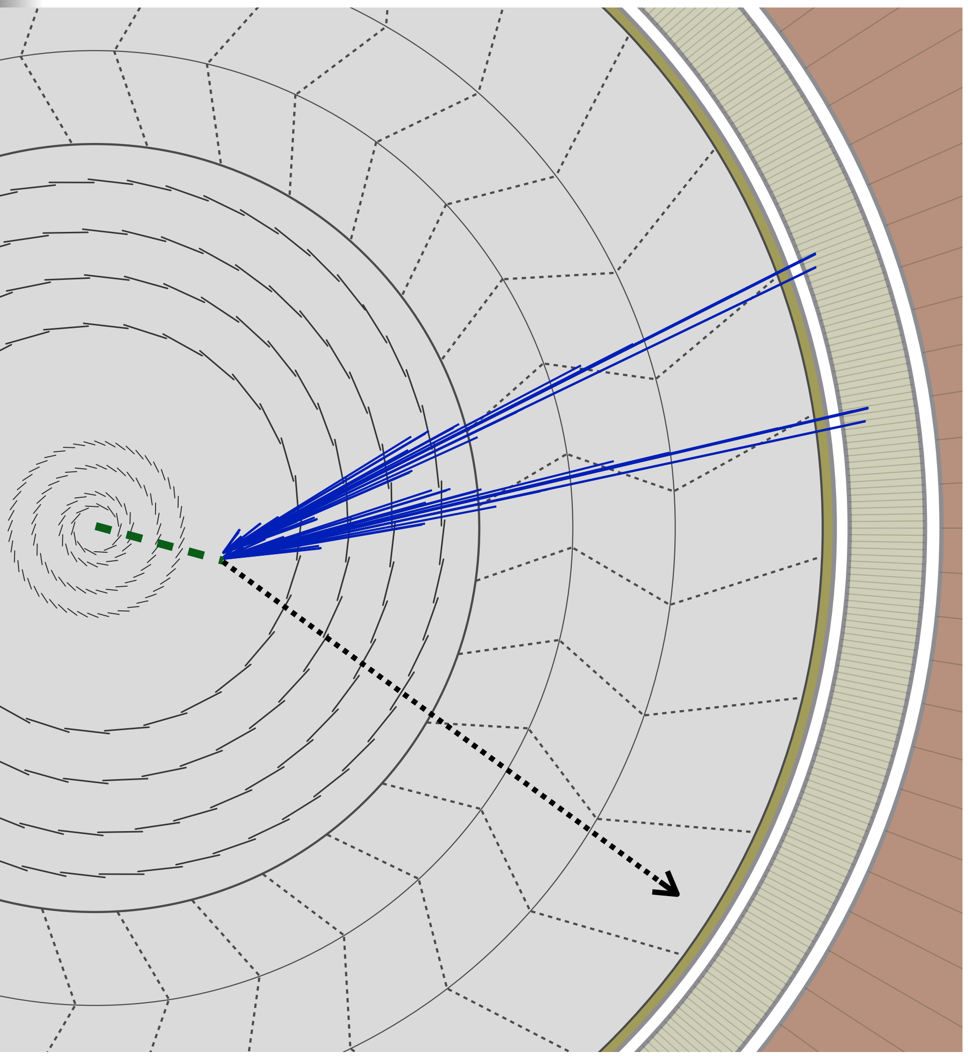
DisappearingTrack2016.cxx

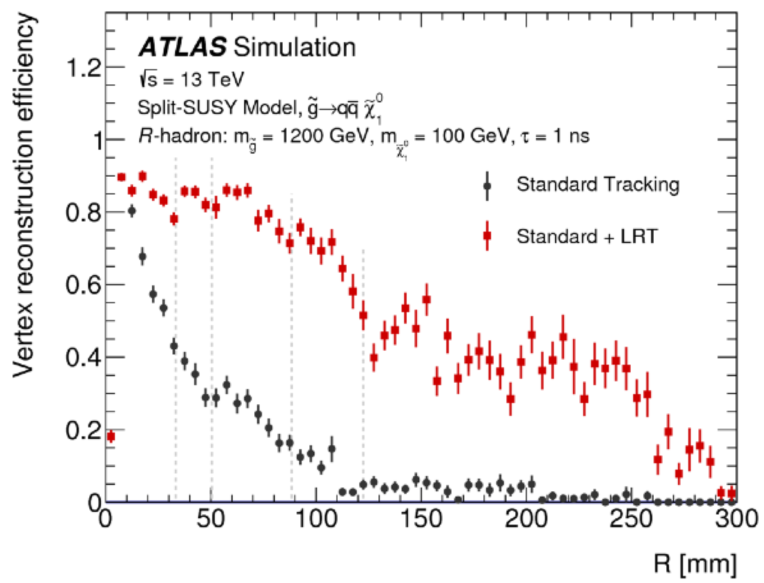
DisappearingTrack2016.cxx 〉 DisappearingTrack2016::ProcessEvent(AnalysisEvent * event)

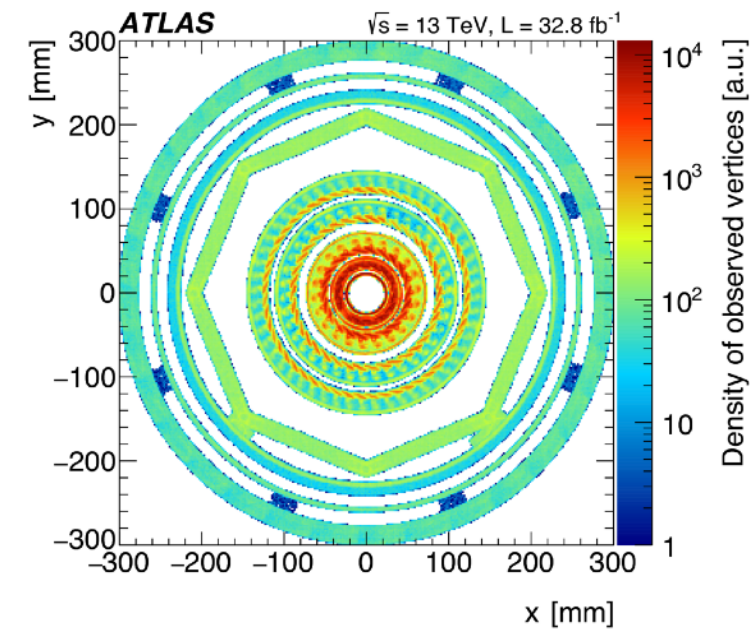
```
#include "SimpleAnalysis/AnalysisClass.h"
#include <TRandom.h>
#include <TFile.h>
#include <TH2.h>
#include <TF1.h>
#include <TMath.h>

DefineAnalysis(DisappearingTrack2016)

namespace
{
    // Efficiency maps depend on the production channel.
    // Strong channel has lower acceptance and efficiency
#if 1
    const std::string production = "electroweak";
#else
    const std::string production = "strong";
#endif
    const char *const acceffmapFilePath         = "SimpleAnalysis/data/DisappearingTrack2016-TrackAcceptanceEfficiency.root";
    const char *const acceffStrongHistName      = "StrongEfficiency";
    const char *const acceffElectroweakHistName = "ElectroweakEfficiency";
    TFile *acceffmapFile                        = 0;
    TH2 *acceffmapHist                          = 0;

    // Lifetime
    const double tau  = 0.2e-9;   // seconds

    // Switch to simulated pT resolution of tracklets
    const bool doPtSmearing = true;

    // Smearing function to simulation pT resolution
    const double smearPar0 = 1;                              // constant
    const double smearPar1 = -1.72142e+00;                   // mean  [/TeV]
    const double smearPar2 = 1.32009e+01 * (1 - 0.0843956); // sigma [/TeV]
    const double smearPar3 = 1.66707e+00 * (1 - 0.0498447); // slope
    double PixelTrackletSmearingFunction(double *x, double *par) {
        double constant = par[0];
        double mean     = par[1];
        double sigma    = par[2];
        double alpha    = par[3];

        // evaluate the crystal ball function
        if (sigma < 0) {
            return 0;
        }
        if (alpha < 0) {
            return 0;
        }
        double z = (x[0] - mean) / sigma;
        alpha = fabs(alpha);
        double norm1 = sigma * sqrt(2 * M_PI) * erf(alpha / sqrt(2));
        double norm2 = sigma * exp(-alpha * alpha / 2) / alpha;
        double norm3 = norm2;
        constant /= (norm1 + norm2 + norm3);
        if (z < -alpha) {
            return constant * std::exp(+alpha * (z + 0.5 * alpha));
        } else if (z > +alpha) {
            return constant * std::exp(-alpha * (z - 0.5 * alpha));
        } else {
            return constant * std::exp(-0.5 * z * z);
        }
    }
}
```

Displaced Vertex (DV) + MET

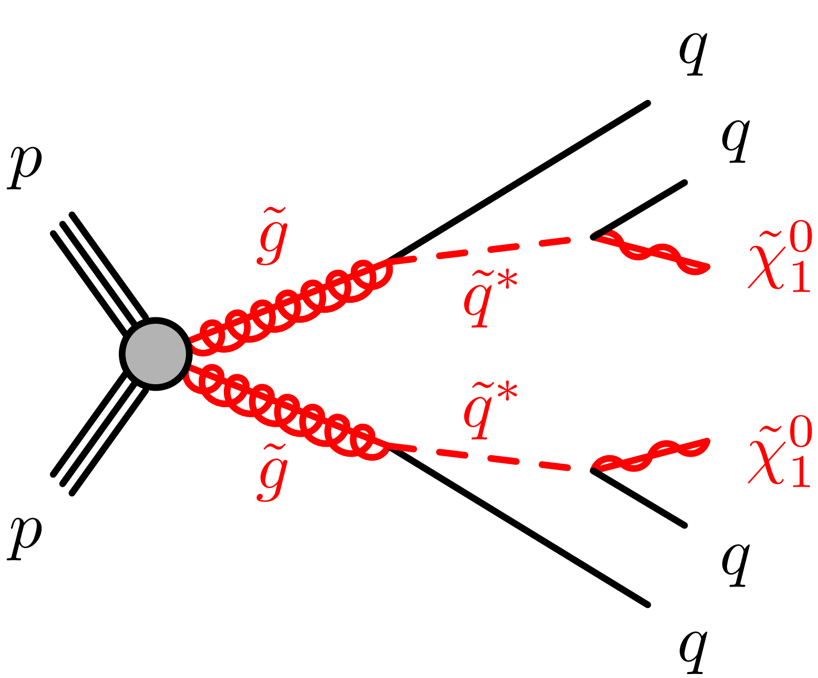
Phys. Rev. D 97 (2018) 052012
arXiv:hep-ex/1710.04901







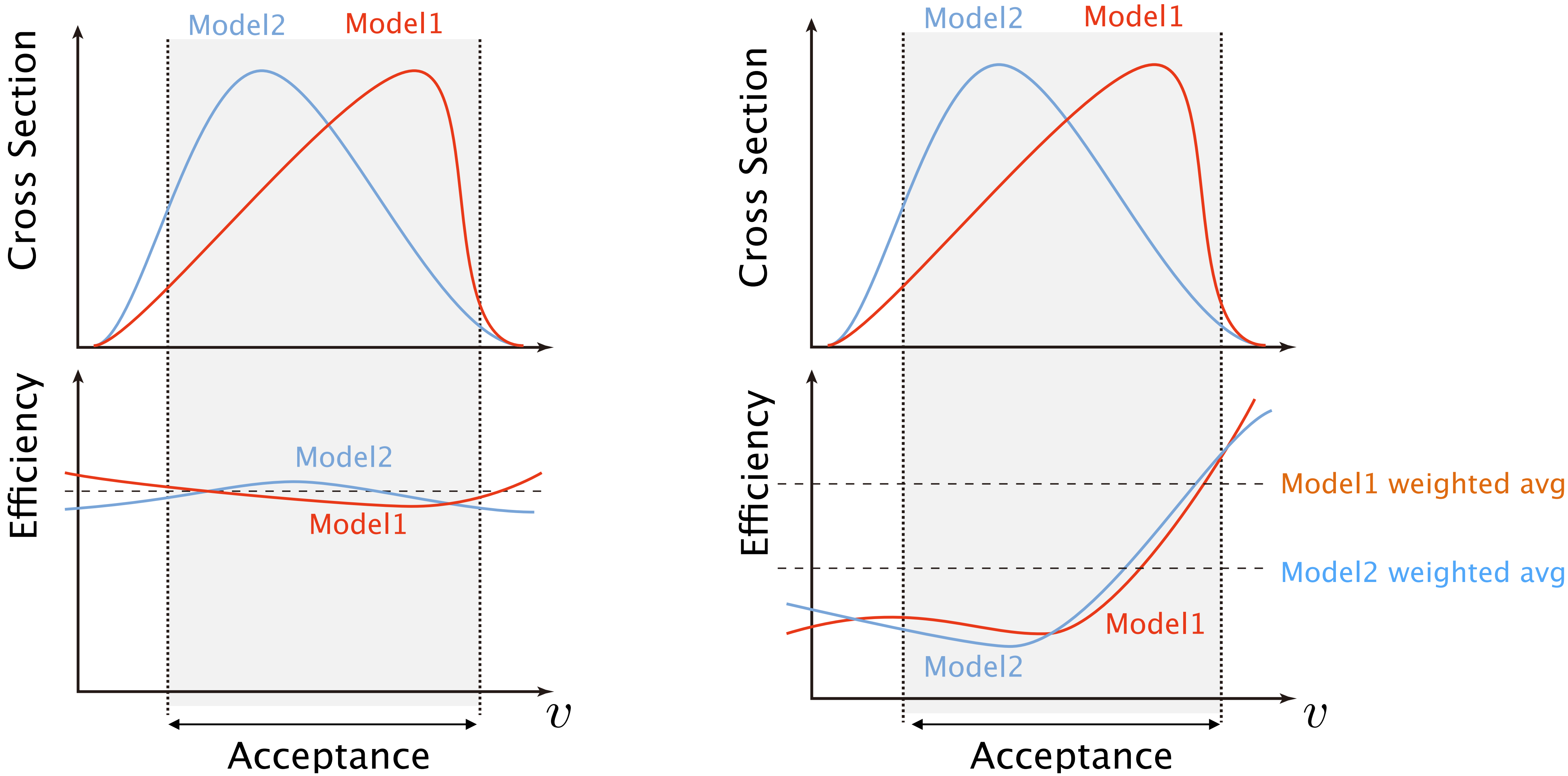
Analysis:
- At least 1 DV with visible m > 10 GeV and $n_{trk} \geq 5$
- Hadronic interaction veto (material veto)
- MET > 250 GeV
- "zero background" (N_{bg} = 0.02 ± 0.02 events)
- Primary interpretation for SUSY R-hadron decays



Reinterpretation Strategy and concerns:
- factorize the "event-level" MET requirement and the DV part.
- Drastic change of the tracking efficiency with $|d_0|$
- Complex material veto structure to be encapsulated.
- Complex vertex kinematic properties, efficiency is very dependent on those.
- Explored as many as possible of kinematic properties, and figured out the most significant 3 properties.

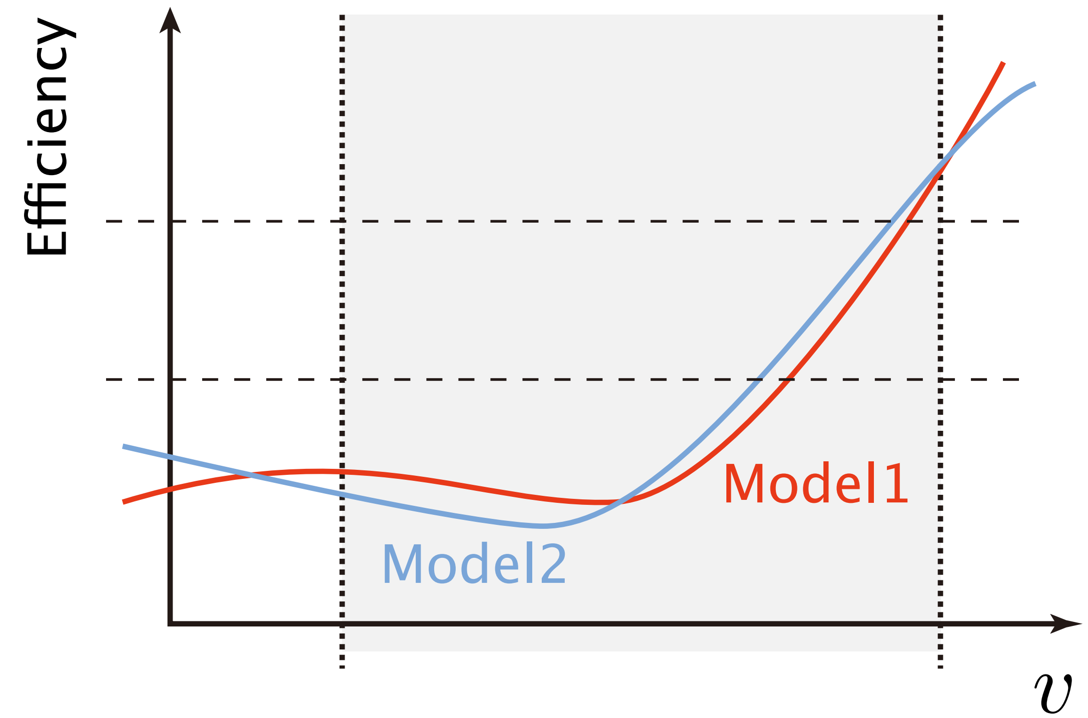
→ Binning in $\{m_{\rm inv}, n_{\rm trk}, r_{\rm decay}\}$

Complexity (2): non-uniform efficiency

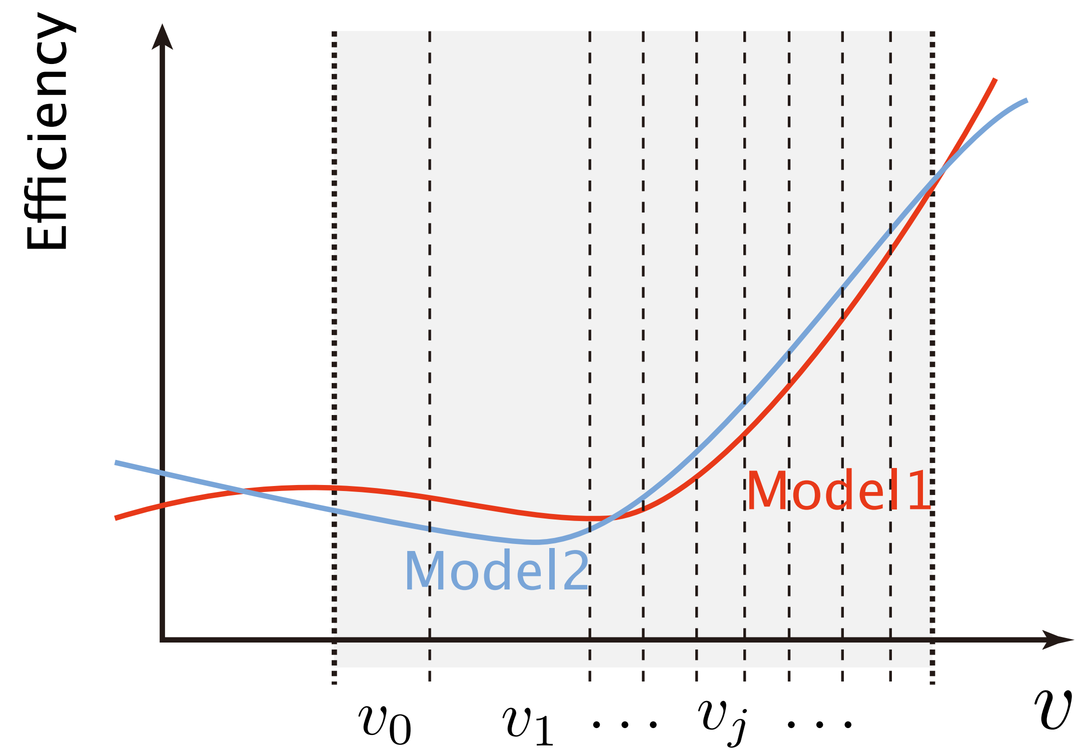


- Single-number efficiency assumes that the efficiency is relatively flat in the corresponding acceptance.
- Approximation is not very good when efficiency largely changes within an acceptance window. → Multi-binned acceptance can be considered as the next step approximation to keep model independency.
- **LLP Example**: radial dependence of efficiency of displaced vertex

$$N_{\mathrm{sig},i}^{(S)} \simeq \left(\mathcal{A}_i \cdot \langle \varepsilon \rangle\right)^{(S)} \cdot \left(\mathcal{L} \cdot \sigma_i^{\mathrm{tot}}\right)$$



$$N_{\mathrm{sig},i}^{(S)} \simeq \sum_j \left(\mathcal{A}_{i,j} \cdot \langle \varepsilon \rangle_j\right)^{(S)} \cdot \left(\mathcal{L} \cdot \sigma_i^{\mathrm{tot}}\right)$$



General trade-off relation between complexity (granularity) and accuracy

DV+MET: acceptance and efficiency

DV term: at least 1 DV

MET Term

$$N_{\mathrm{sig},i} = \mathcal{L} \cdot \langle \mathcal{A}_i^{\mathrm{evt}} \cdot \langle \varepsilon \rangle^{\mathrm{evt}} \rangle \cdot \left[1 - \prod_k^{\mathrm{DV}} \left(1 - \langle \mathcal{A}_{\mathrm{DV},i}^k \cdot \varepsilon_{\mathrm{DV}}^k \rangle \right) \right] \sigma_i$$

Event acc. x eff.

$$\langle \mathcal{A}_i^{\mathrm{evt}} \cdot \varepsilon^{\mathrm{evt}} \rangle = \mathcal{A}_i^{\mathrm{evt}} \cdot \sum_l \varepsilon^{\mathrm{evt}}(E_{\mathrm{T},l}^{\mathrm{miss}}) \cdot \delta(l)$$

Binning in MET and R-hadron max.decay radius

Not counting outside bin

MET acceptance

- MET > 200 GeV

DV acceptance x efficiency

$$\langle \mathcal{A}_{\mathrm{DV},i}^k \cdot \varepsilon_{\mathrm{DV}}^k \rangle = \mathcal{A}_{\mathrm{DV},i}^k \cdot \sum_j \varepsilon_{\mathrm{DV}}^k (m^{\mathrm{sel}}, n_{\mathrm{trk}}^{\mathrm{sel}}, r_{\mathrm{dec}})_j \cdot \delta(j)$$

Binning in mass, multiplicity and decay r

Not counting outside bin

DV common acceptance definition (before binning):

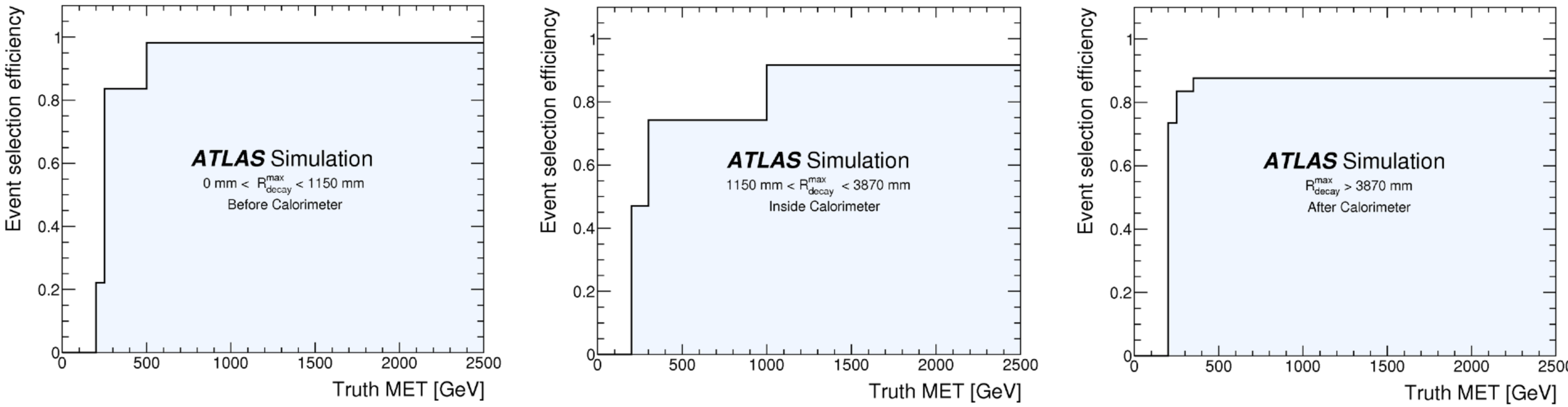
- 4 mm < r_{decay} < 300 mm, |z| < 300 mm
- n_{trk}(sel) ≥ 5
- m(sel) > 10 GeV (visible invariant mass only using selected particles)
- Selected particle: charged, p_T > 1 GeV and pseudo-$|d_0|$ > 2 mm

[dashed cyan box] : provided informations

DV+MET: reinterpretation material

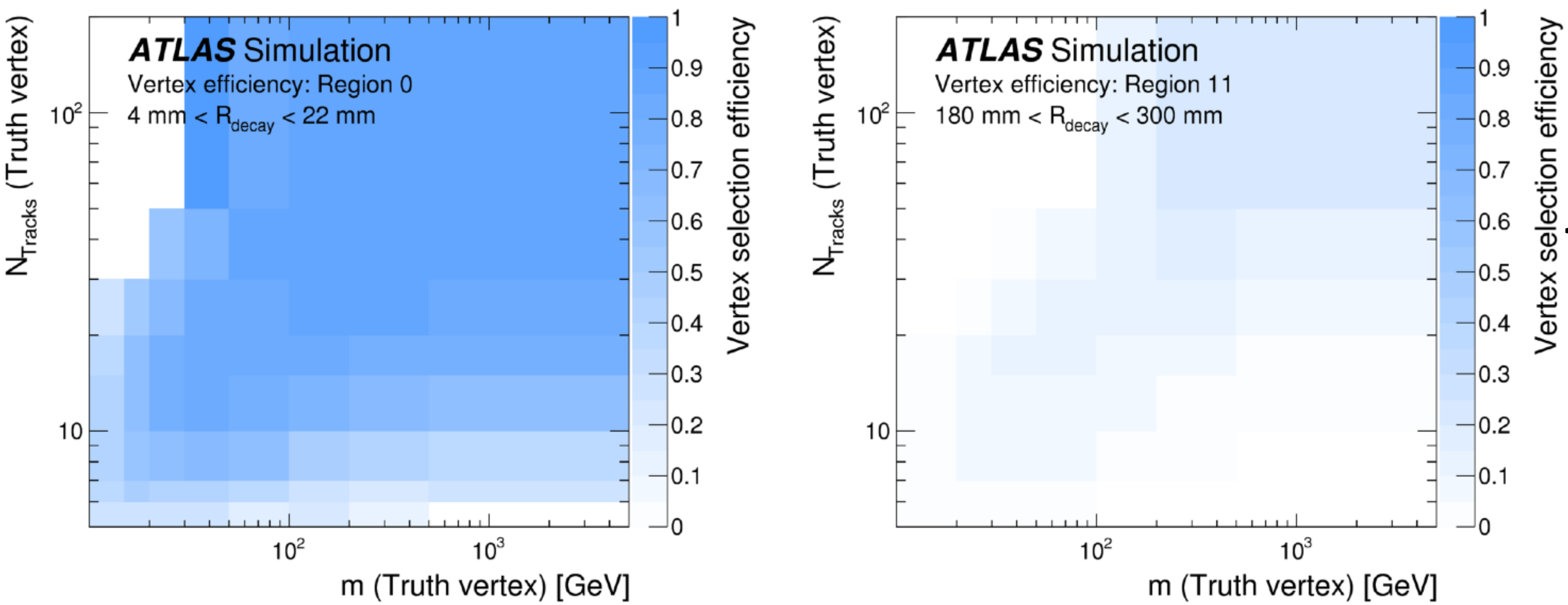
https://www.hepdata.net/record/78697

$\varepsilon^{\mathrm{evt}}(E_{\mathrm{T}}^{\mathrm{miss}})$: different response depending on the R-hadron decay position



Here truth MET is simply adding all stable neutral particles

$\varepsilon_{\mathrm{DV}}(m^{\mathrm{sel}}, n_{\mathrm{trk}}^{\mathrm{sel}}; r_{\mathrm{decay}})$: smaller efficiency for lighter mass, smaller multiplicity and outer radii.



Material veto is also encapsulated within this map.

DV+MET: reinterpretation material cheat sheet

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-08/hepdata_info.pdf

Auxiliary information for paper SUSY-2016-08 by the ATLAS Collaboration:

Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

Parameterized selection efficiencies

To allow those who are not members of the ATLAS Collaboration to reinterpret our results for any model predicting displaced vertices, parameterized efficiencies are provided that allows anyone to calculate expected event yields. The efficiencies can be applied to vertices and events that pass certain particle-level acceptance requirements using the final-state particles in the Monte Carlo truth record.

Definition of acceptances

Model independent selection efficiencies are provided for events passing the event-level acceptance $\mathcal{A}_{\text{event}}$ defined using particle-level requirements on $E_{\text{T,true}}^{\text{miss}}$, jets, and a DV. Events are required to satisfy the following conditions:

- $E_{\text{T,true}}^{\text{miss}} > 200$ GeV, where $E_{\text{T,true}}^{\text{miss}}$ is defined as the magnitude of the transverse component of the vector sum of the momenta of the stable weakly-interacting particles in the final state.
- In order to satisfy the requirements of the post-trigger filters used in the dedicated data processing in the analysis, 75% of the integrated luminosity must require the existence of either
  - one truth jet (with $p_{\text{T}} > 70$ GeV) for which the scalar sum of the charged particle p_{T} does not exceed 5 GeV for those particles with small impact parameter with respect to the PV; or
  - two jets (with $p_{\text{T}} > 25$ GeV) satisfying the same requirement.

  The jets are defined at the stable-particle level, clustered with the anti-k_t clustering algorithm with $R = 0.4$. Note that because of changing filter setups during the data-taking period, 25% of the luminosity need not satisfy these jet requirements, retaining acceptance for signals without large amounts of displaced high-p_{T} jet activity.
- Events must contain at least one DV passing the vertex-level acceptance requirements described below.

The vertex-level acceptance $\mathcal{A}_{\text{vertex}}$ requires displaced decays of massive particles to have the following properties:

- The transverse distance between the IP and the decay position must be greater than 4 mm.
- The decay position must lie within the fiducial volume of $R_{\text{decay}} < 300$ mm and $|z| < 300$ mm.
- The number of *selected decay products* (described below) must be at least 5.
- The invariant mass of the *truth vertex* must be larger than 10 GeV. The *truth vertex* is constructed using the momenta of the *selected decay products* with a charged pion mass assumption to simulate the assumptions in the DV reconstruction used in the analysis.

The *selected decay products* used in the above *truth vertex* construction are those decay products of a given massive particle decay that satisfy the following conditions:

- The particle is charged and stable for timescales required to traverse the tracking volume.
- The particle has a transverse momentum $p_{\text{T}}(|q| = 1) > 1$ GeV. For particles with electric charge $|q| \neq 1$, this requirement should use p_{T} calculated assuming a charge of $|q| = 1$.
- The particle has an approximate transverse impact parameter $d_0 \equiv R_{\text{decay}} \times \sin \Delta\phi > 2$ mm, where R_{decay} is the transverse distance between the interaction point and the massive particle decay and $\Delta\phi$ is the azimuthal angle between the particle momentum at its creation and the vector from the primary vertex to the position of the displaced decay.

Efficiencies

Parameterized efficiencies are provided at the event level and vertex level. Because of the inability of the ATLAS detector to fully measure the energy of jets that are produced within or beyond the calorimeter system, the event selection efficiency $\varepsilon_{\text{event}}$ is provided as a function of the truth $E_{\text{T}}^{\text{miss}}$ described above as well as the transverse distance of the furthest heavy particle decay. These efficiencies can be found in Figure 20.

As part of the event-level efficiency, events entering the SR are required to have at least one selected DV. For each massive particle decay, an efficiency for reconstructing a DV is provided as a function of truth vertex mass, particle multiplicity, and radial detector position. These efficiencies can be found in Figures 21 and 22. The effects of the material and disabled pixel module vetoes are encapsulated in the radial binning of these efficiencies.

Overall, the probability that a particular event will fall into the SR is given symbolically by

$$P = \mathcal{A}_{\text{event}}\, \varepsilon_{\text{event}} \times \left(1 - \prod_{\text{Vertices}} (1 - \mathcal{A}_{\text{vertex}}\, \varepsilon_{\text{vertex}}) \right). \quad (1)$$

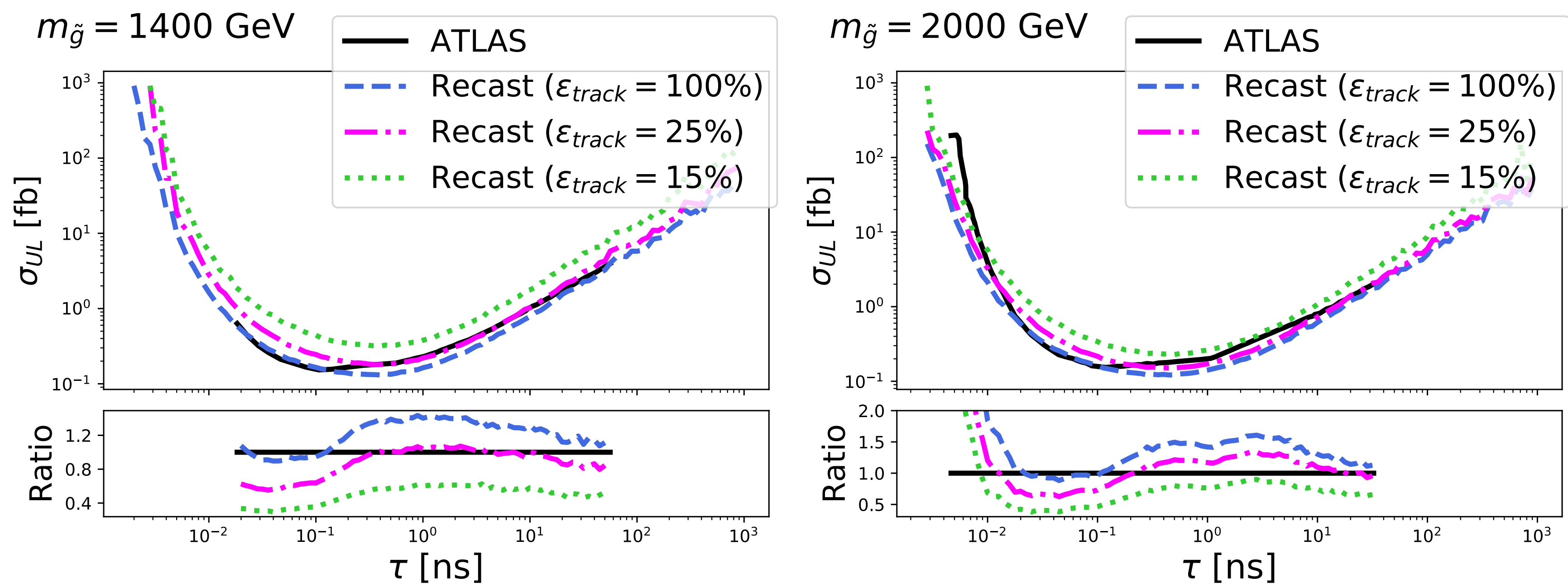
Across the signal models considered in this search, this procedure gives yields that agree with the proper analysis to roughly 10% level or less.

First DV+MET reinterpretation attempt outside ATLAS

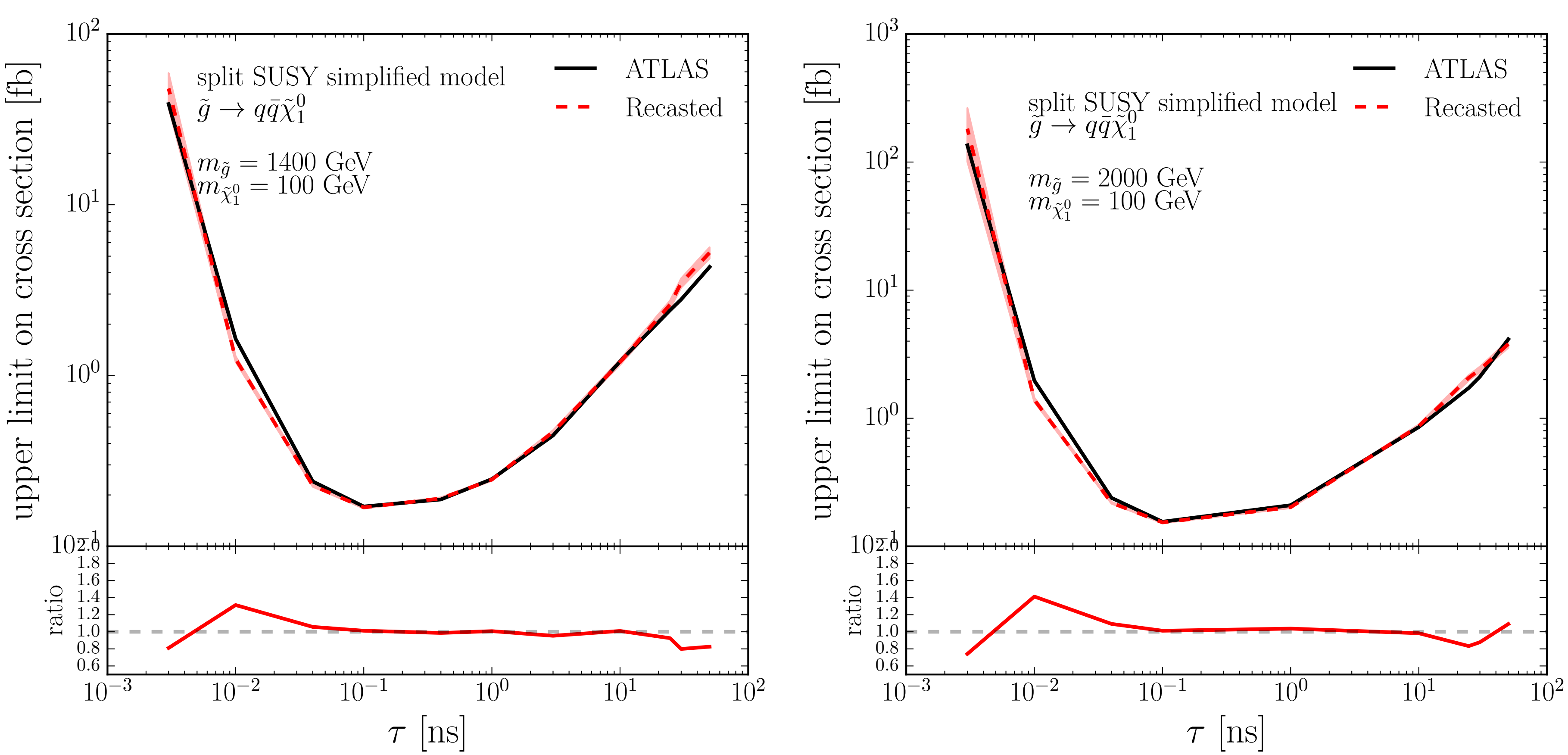
LES HOUCHES 2017: PHYSICS AT TEV COLLIDERS NEW PHYSICS WORKING GROUP REPORT

arXiv: hep-ph/1803.10379 Chapter 22

Closure test of R-hadron DV



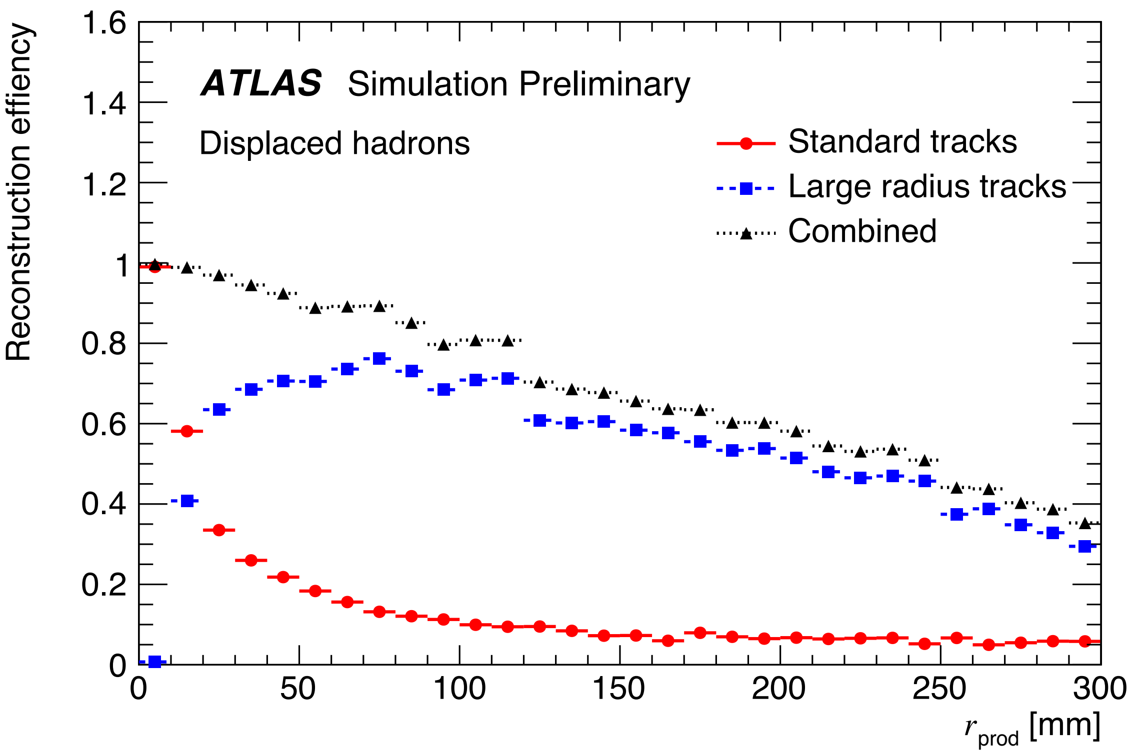
Method 1:
Speculated vertexing efficiency based on paper Figure 1 only. Not a great reproduction especially for short lifetime!



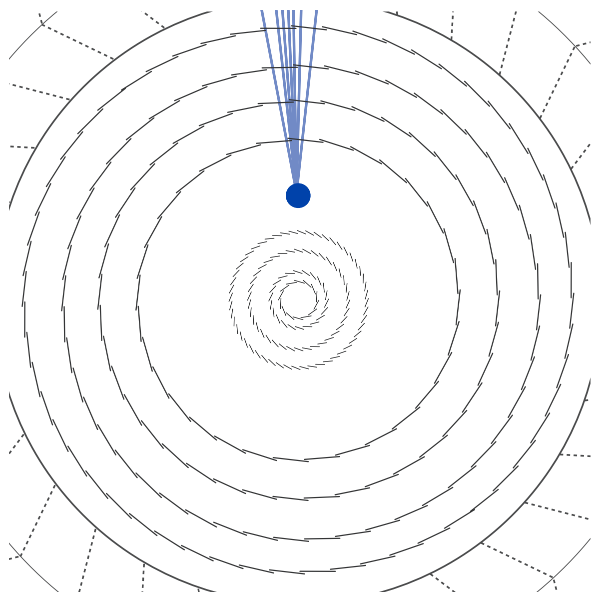
Method 2:
Using ATLAS reinterpretation material reproduces the limit in a quite favorable manner (largest deviation: 40%)

DV+MET Caveats (1)

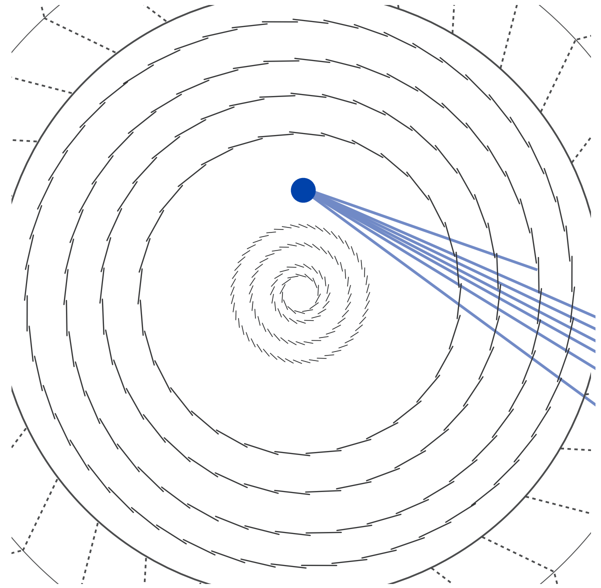
ATL-PHYS-PUB-2017-014



Higher tracking efficiency

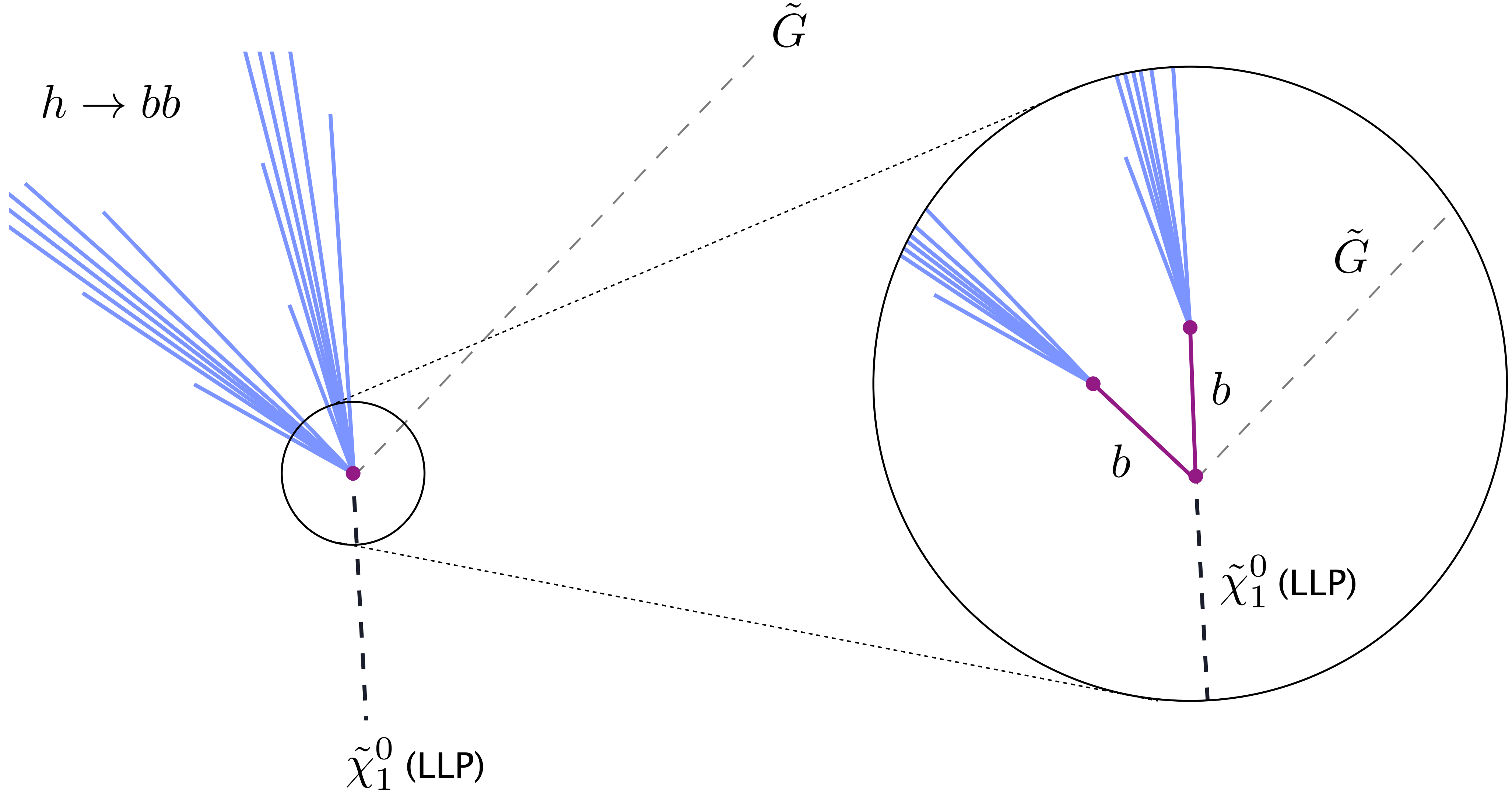


Lower tracking efficiency



- The current way of acceptance binning { m(sel), n_{trk}(sel), r_{decay} } integrates out tracking efficiency dependent on impact parameters and direction.
- If the angular distribution of the decay products is very distinct from the R-hadron decay ($\tilde{g} \to qq N_1$), the closure of the reinterpretation could be potentially worse.

DV+MET Caveats (2)



- The R-hadron decay process (~g → qq N_1) assumes all decay products are prompt from the DV, and applicability when the decay products involves e.g. heavy flavor quarks is tricky.
- e.g. displaced higgs(bb): depending on the flight length of b-hadrons, the DV may involve both b-hadrons as merged DV, or they may be reconstructed as separated vertices.
  - Detail of vertexing algorithm matters; DV+MET analysis employs force-merging of nearby DVs within 1 mm.
- The current reinterpretation material does **not** support this as a use case explicitly.