Overview of ATLAS Results

LLP2024: Fourteenth Workshop of the Long-Lived Particle Community

July 1, 2024, Tokyo, Japan

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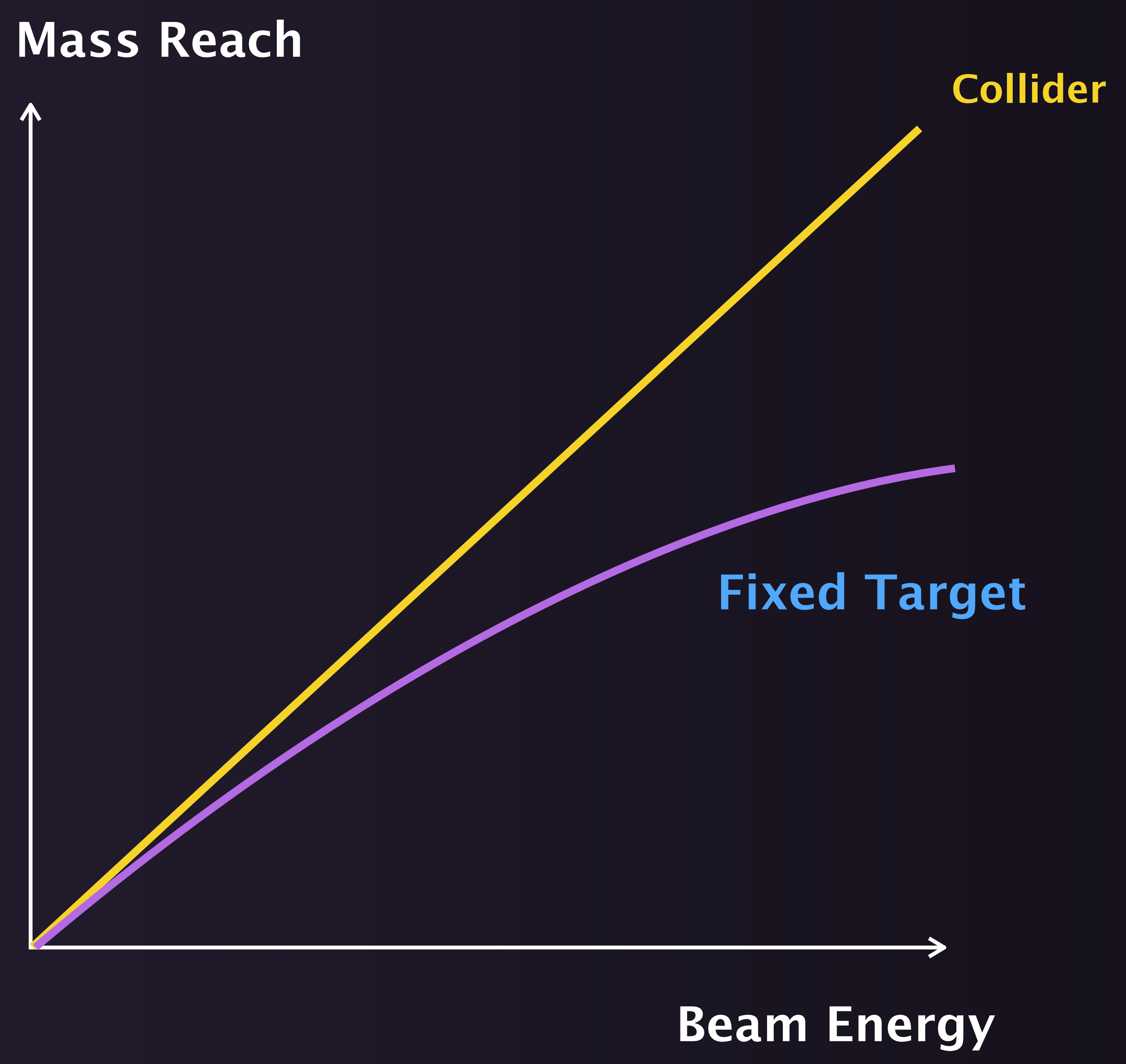
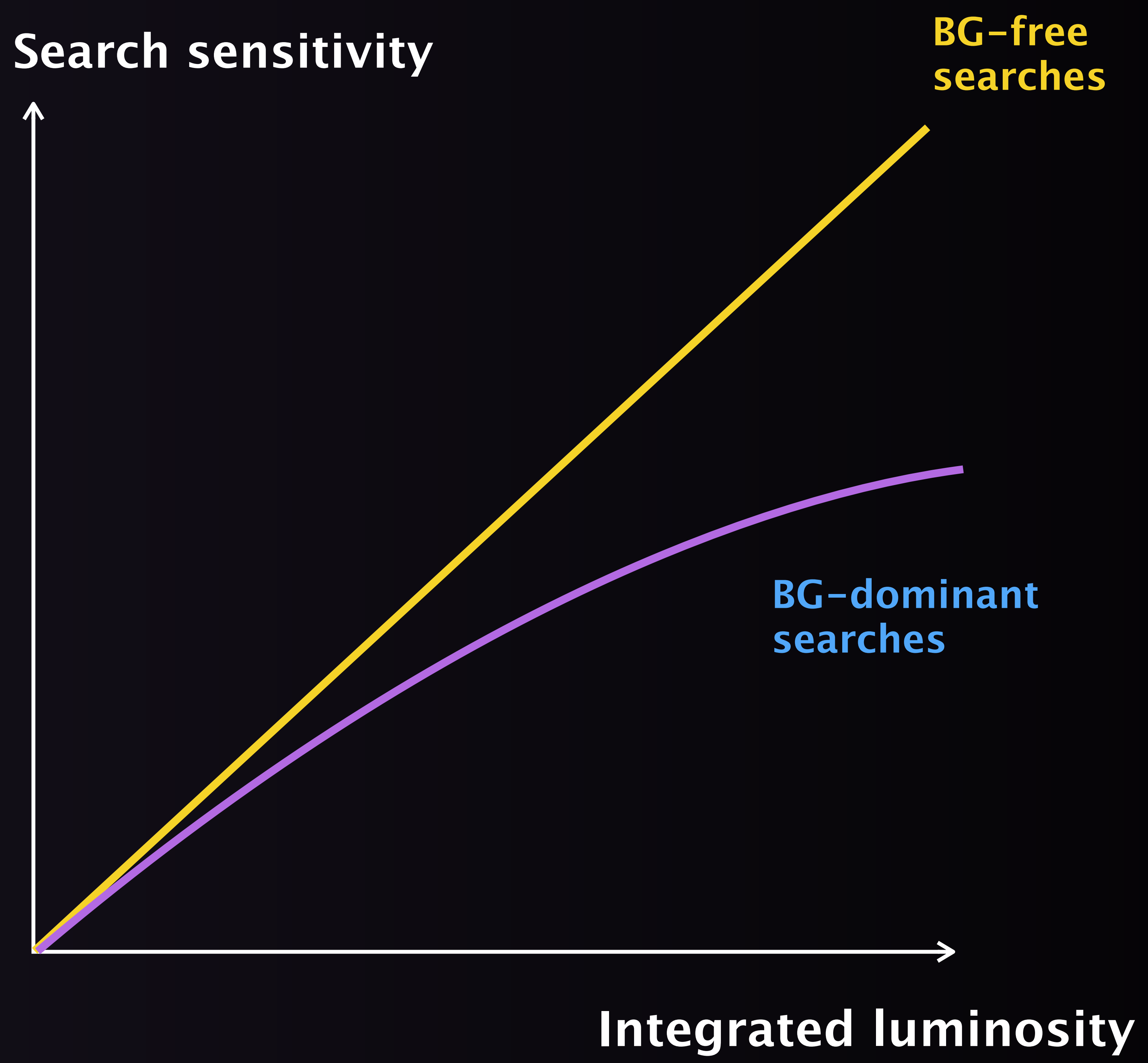
on behalf of the ATLAS Collaboration

Introduction

- Why LLP searches are significant.
  - Distinctive signature → Zero or Low SM Bkg
  - Sensitivity gain promised with accumulating luminosity
  - Unconventional / Dedicated reconstruction + trigger
  - Instrumental backgrounds: Beam-induced backgrounds, Cosmic rays, Fake, etc.





Accelerator LLP searches Landscape

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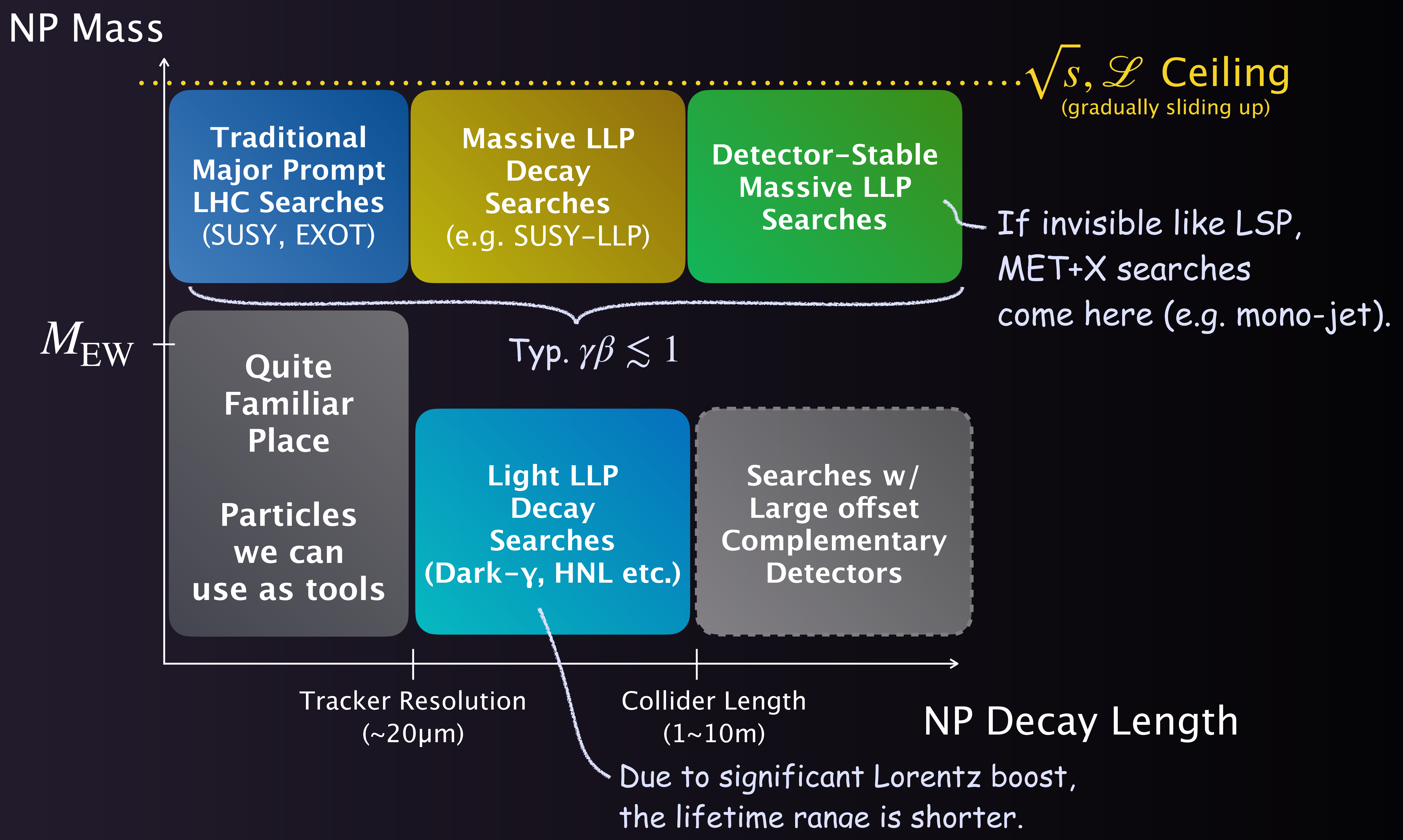

Collider LLP Search Signature Classes

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Prompt Event Topology

Trigger & Basic Event Selection

$$\left(E_{\mathrm{T}}^{\mathrm{miss}} \quad e^{\pm} \quad \text{Jets} \quad \gamma \quad \mu^{\pm} \right) \otimes$$

Long-lived Peculiar Obj's/Feat's

Special Discriminants to Effecitve-Zero SM Background

- Displaced Vertices
- Anomalous Energy Loss
- Slow Time-of-Flight
- Short Track (Decay in Flight)
- Non-prompt Leptons / Photons / Tracks

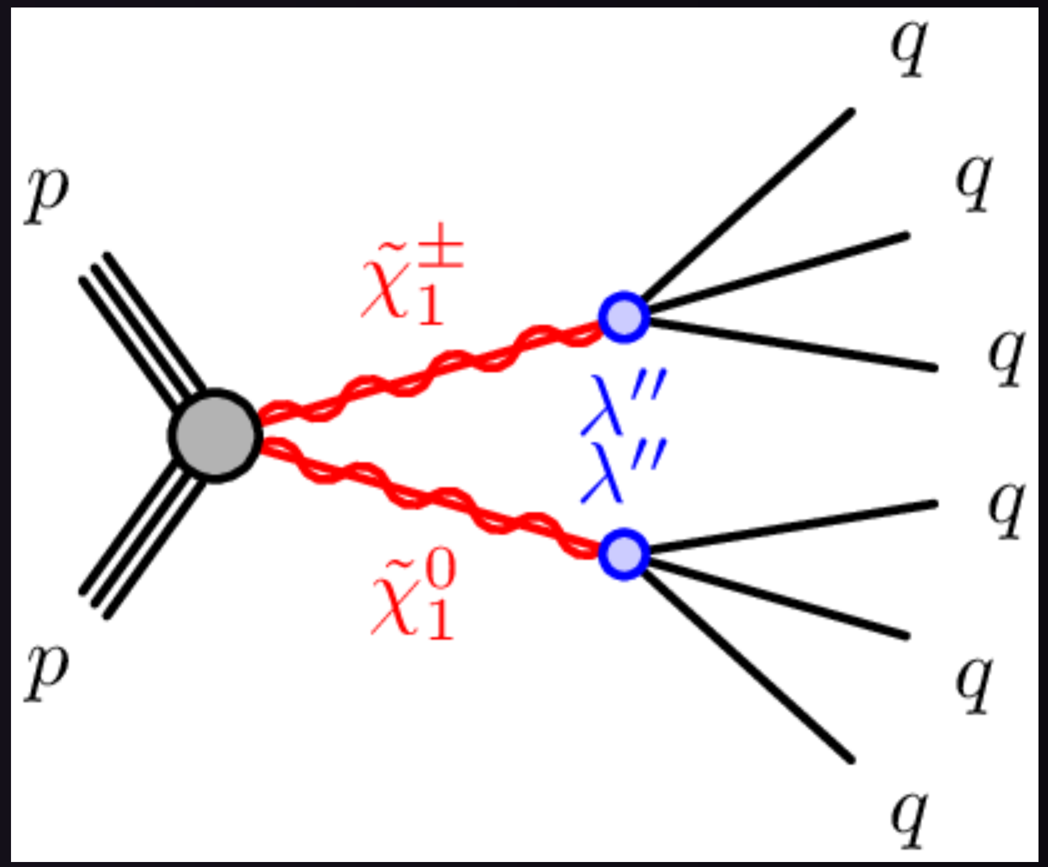
Just roughly speaking: details matter.

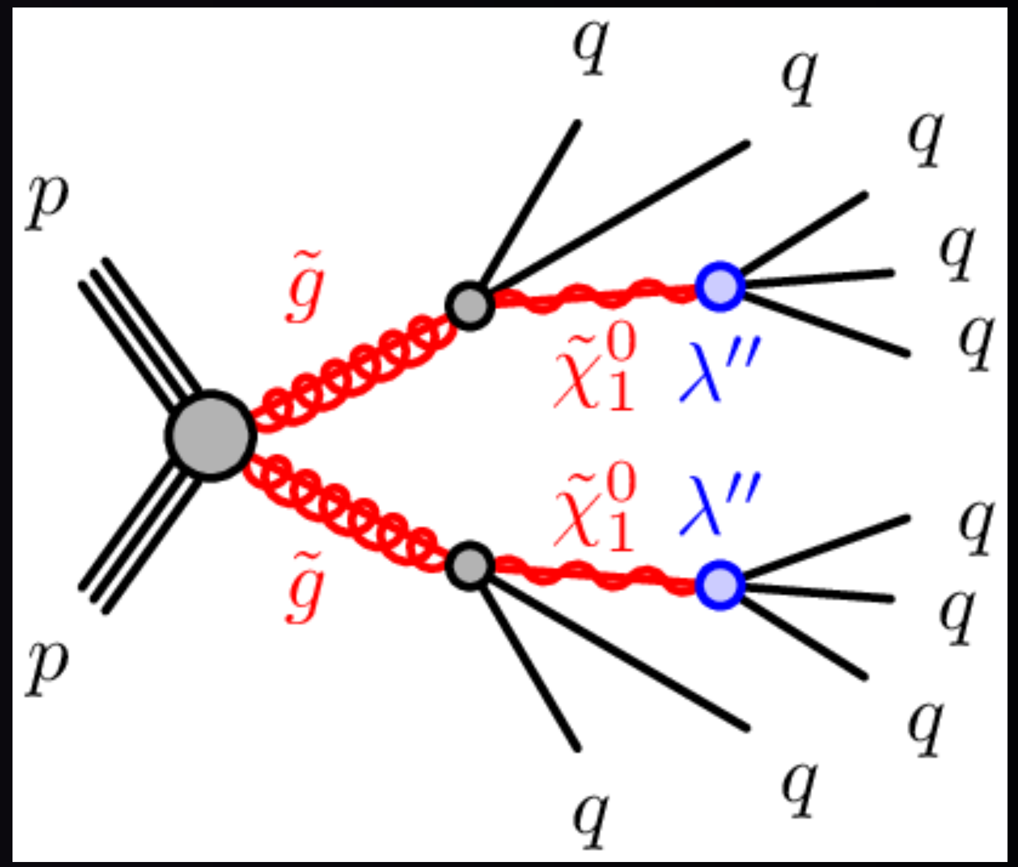
This talk

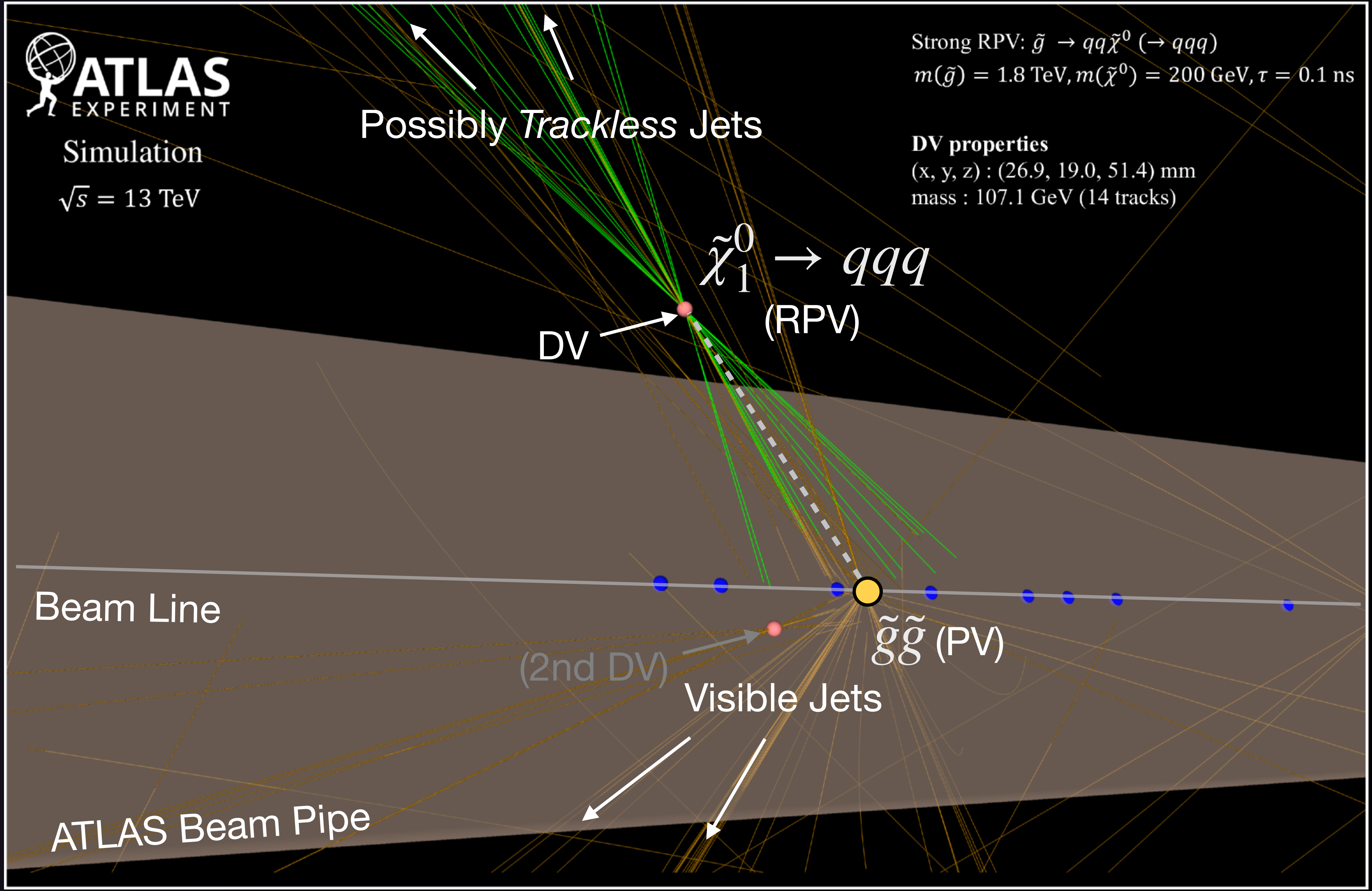
- Attempts to explain selected showcase analyses of ATLAS LLP searches.
- Classic Examples
  - Displaced Vertex + Jets
  - Multi-charged stable particles
- Some Sophistication
  - Displaced Heavy Neutral Leptons
  - Unit-charged massive particles (dE/dx + ToF)
- “Prompt” lifetime frontiers
  - Micro-displaced muons
  - Compressed Higgsino
  - Prompt reinterpretations
- More Developments & Prospects for HL-LHC

Decay Detection Search Example: DV+Jets

- Benchmark: targeting at an UDD R-parity Violating SUSY scenario.
  - Direct EWK: 2x $\tilde\chi_1^\pm / \tilde\chi_1^0 \to qqq$
  - 2-step strong: 2x $\tilde g \to qq\tilde\chi_1^0, \tilde\chi_1^0 \to qqq$
- Signature: No-lepton multijet + DV
  - Event Topology-#1: high-p_{T} multijet ($\geq 4j$)
  - Event Topology-#2: multijet w/ *trackless* jets
- An inclusive secondary vertexing algorithm optimized for high-multiplicity displaced vertices with track post-attachment after vertex finding.
- DV selection: $m_{\mathrm{DV}} > 10\ \mathrm{GeV}$ and $N_{\mathrm{trk}} \geq 5$
  - ATLAS-standard material veto, quality cuts.
  - DV properties“tailored”: attached tracks trimming-out for optimization.



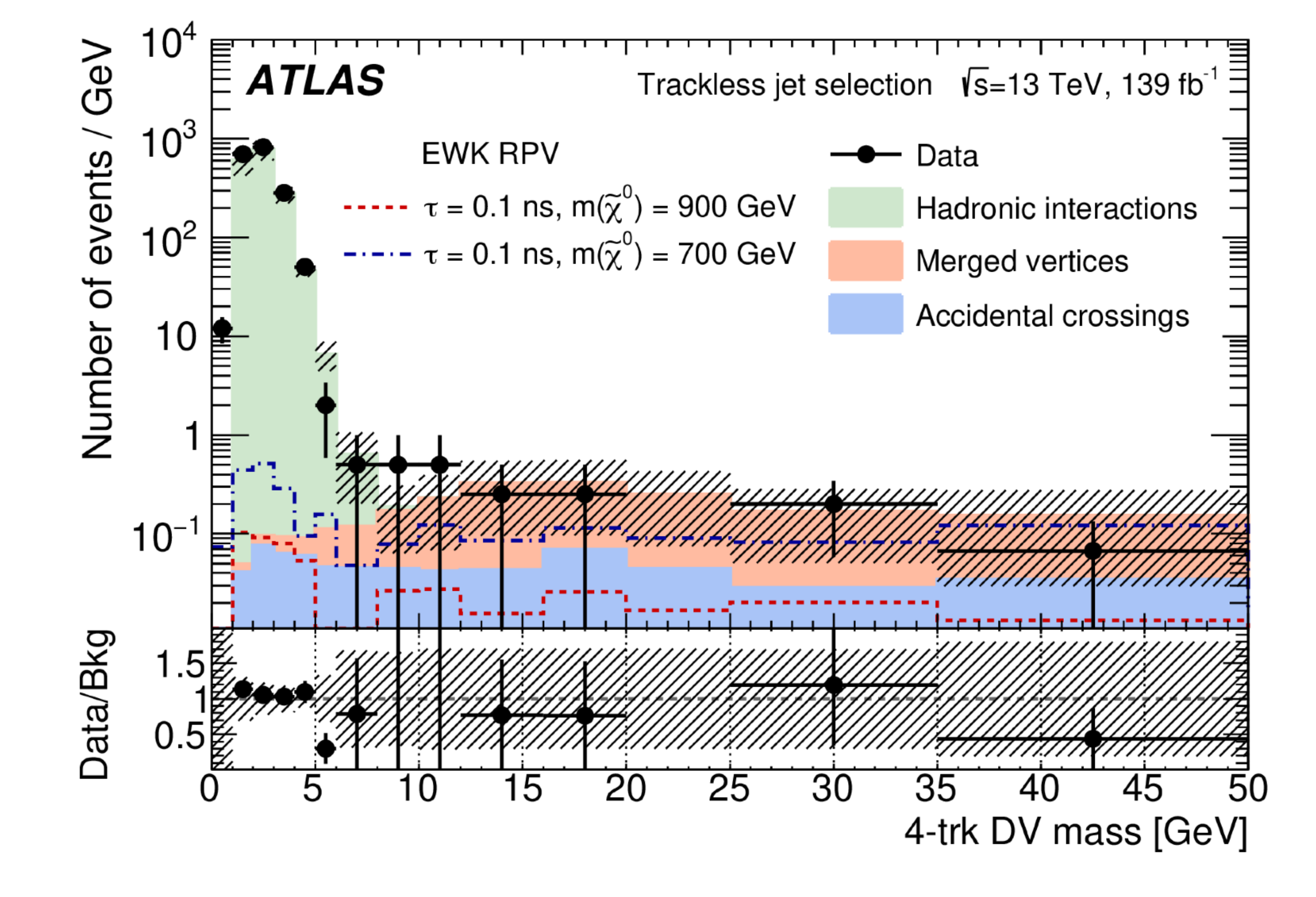




Decay Detection Search Example: DV+Jets

- 3 major sources of background events.
  - Non-vetoed hadronic interactions
  - Merging of near-by vertices
  - Random crossing irrelevant tracks with DV yielding rather high invariant mass (esp. large crossing angle)
- Each background component is individually estimated, while an inclusive background estimation method is devised.
- Inclusive method chosen (smaller uncertainty)
  - Component-based estimation is compatible within uncertainties.

Region	Merged vertices	Hadronic interactions	Accidental crossings	Combined	Inclusive
High-p_T jet SR	0.79 ± 0.66	0.006 ± 0.018	0.28 ± 0.21	1.08 ± 0.69	$0.46^{+0.27}_{-0.30}$
Trackless jet SR	1.5 ± 1.1	0.248 ± 0.077	0.32 ± 0.24	2.1 ± 1.1	$0.83^{+0.51}_{-0.53}$



Decay Detection Search Example: DV+Jets

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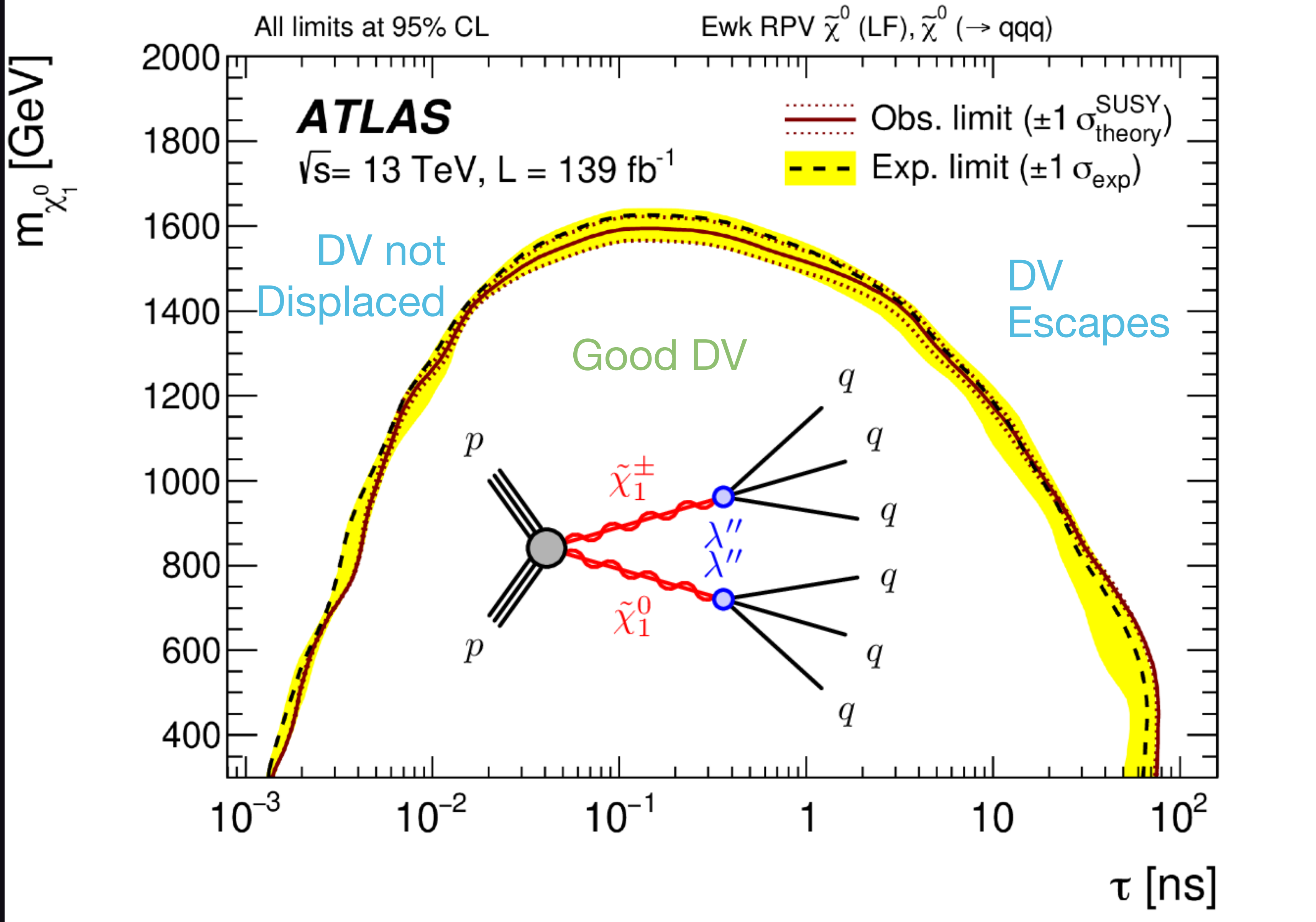
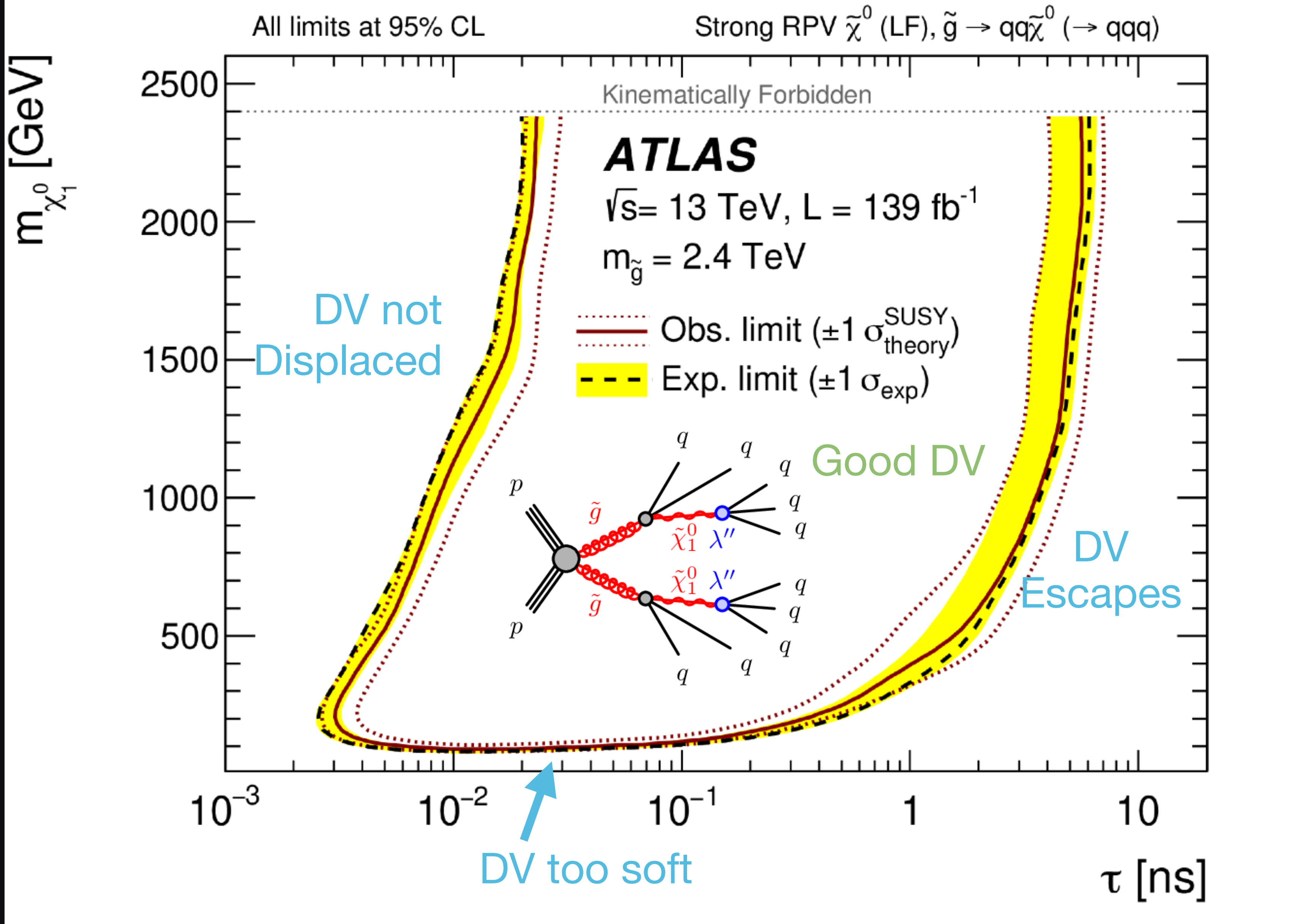
- Good agreement with background in two SRs.

Signal Region	Observed	Expected	S^{95}_{obs}	S^{95}_{exp}	$\langle\sigma_{vis}\rangle^{95}_{obs}$ [fb]
High-p_T jet SR	1	$0.46^{+0.27}_{-0.30}$	3.8	$3.1^{+1.0}_{-0.1}$	0.027
Trackless jet SR	0	$0.83^{+0.51}_{-0.53}$	3.0	$3.4^{+1.3}_{-0.3}$	0.022

- Stringent limits on UDD RPV scenarios.





Direct Detection Example: Multi-Charged Stable Particle

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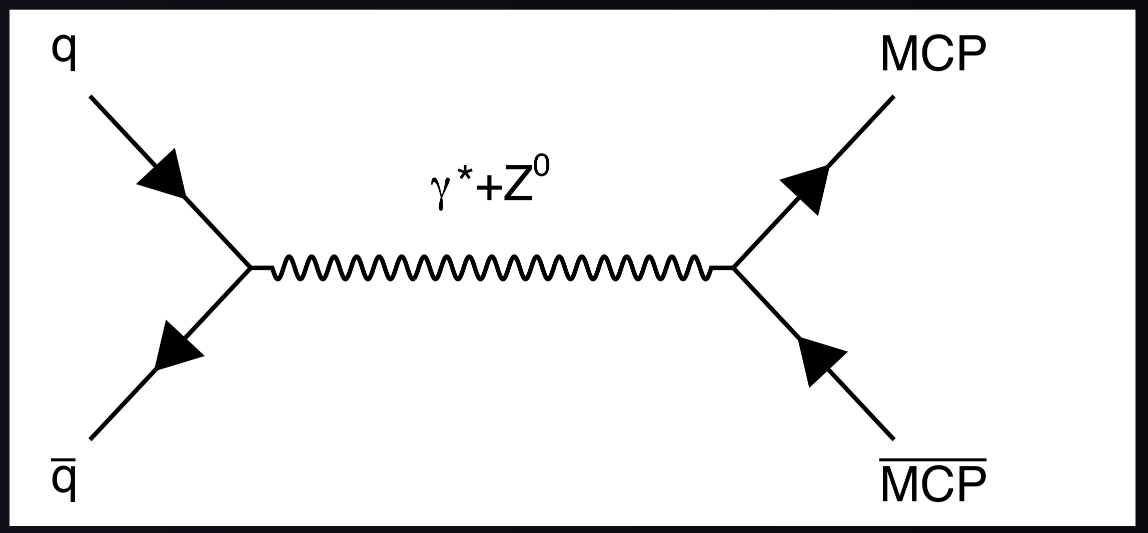
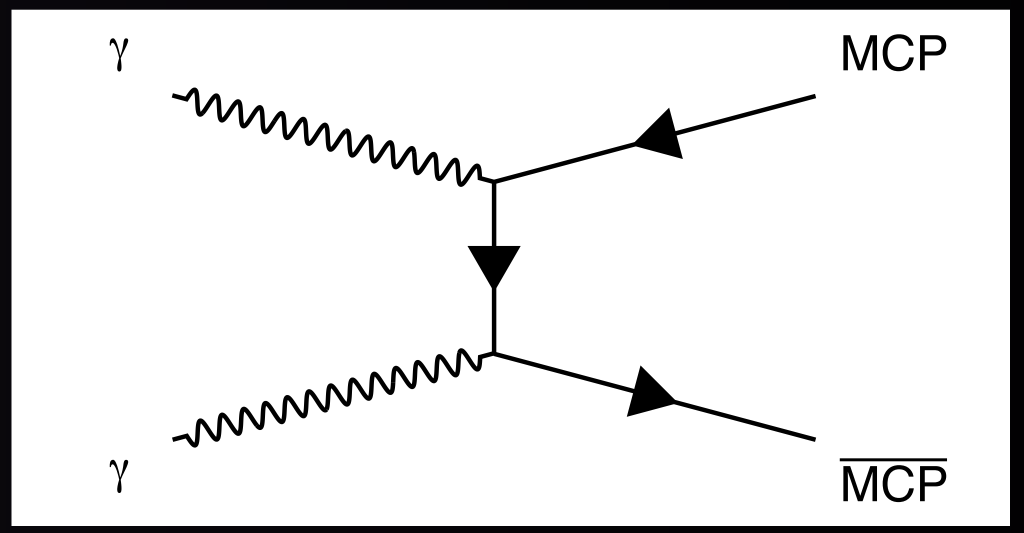
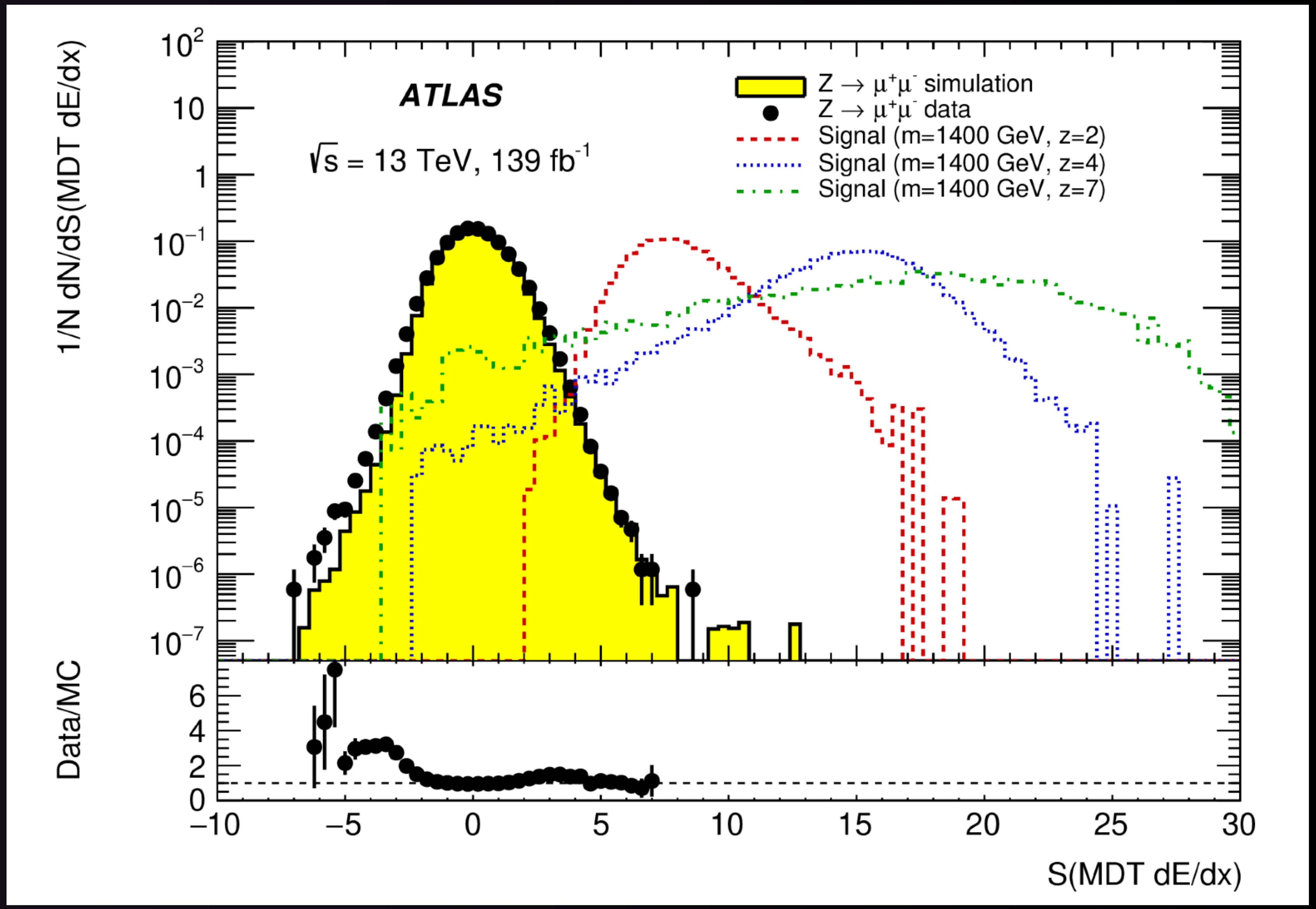
- A generic multi-charged particles (MCP) produced in pairs via Drell-Yan or photon-fusion processes.
- Scope: $z = 2$ and $3 \leq z \leq 7$.
- ingle muon trigger supplemented by the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and the “late muon” trigger.
- Require at least one track with $p_{\mathrm{T}}/z > 50\ \mathrm{GeV}$ in $|\eta| < 2.0$ identified as an isolated muon.
- Require anomalously large $\mathrm{d}E/\mathrm{d}x$ significane, $\mathcal{S}(\mathrm{d}E/\mathrm{d}x)$, in multiple subsystems:
  - $z = 2$: $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{pixel}) > 13.0$, then $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{TRT}) > 2.0$ & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT}) > 4.0$
  - $z > 2$: TRT high-threshold hits fraction (f_{HT}) > 0.7 & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT}) > 7.0$

(*) Pixel dE/dx unused due to saturation and inefficiency.



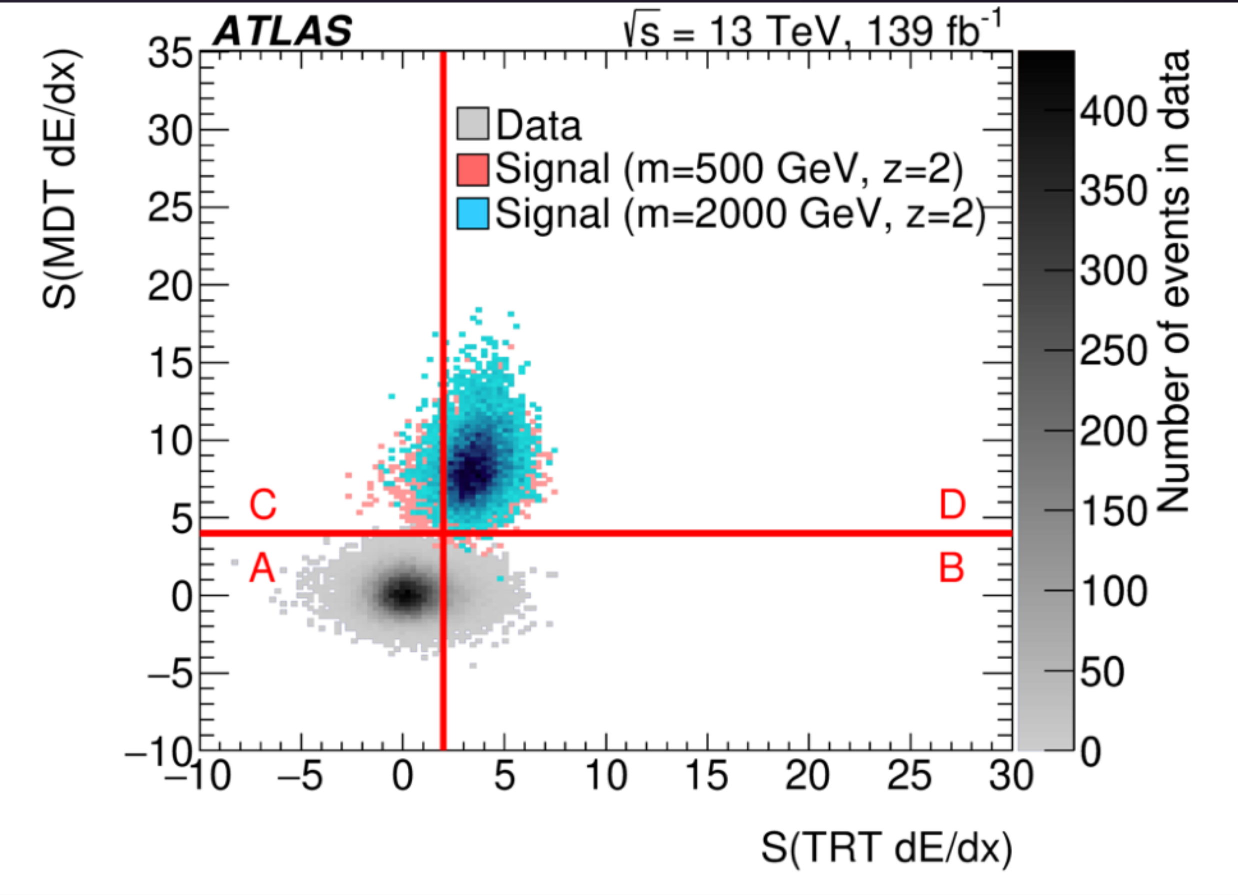


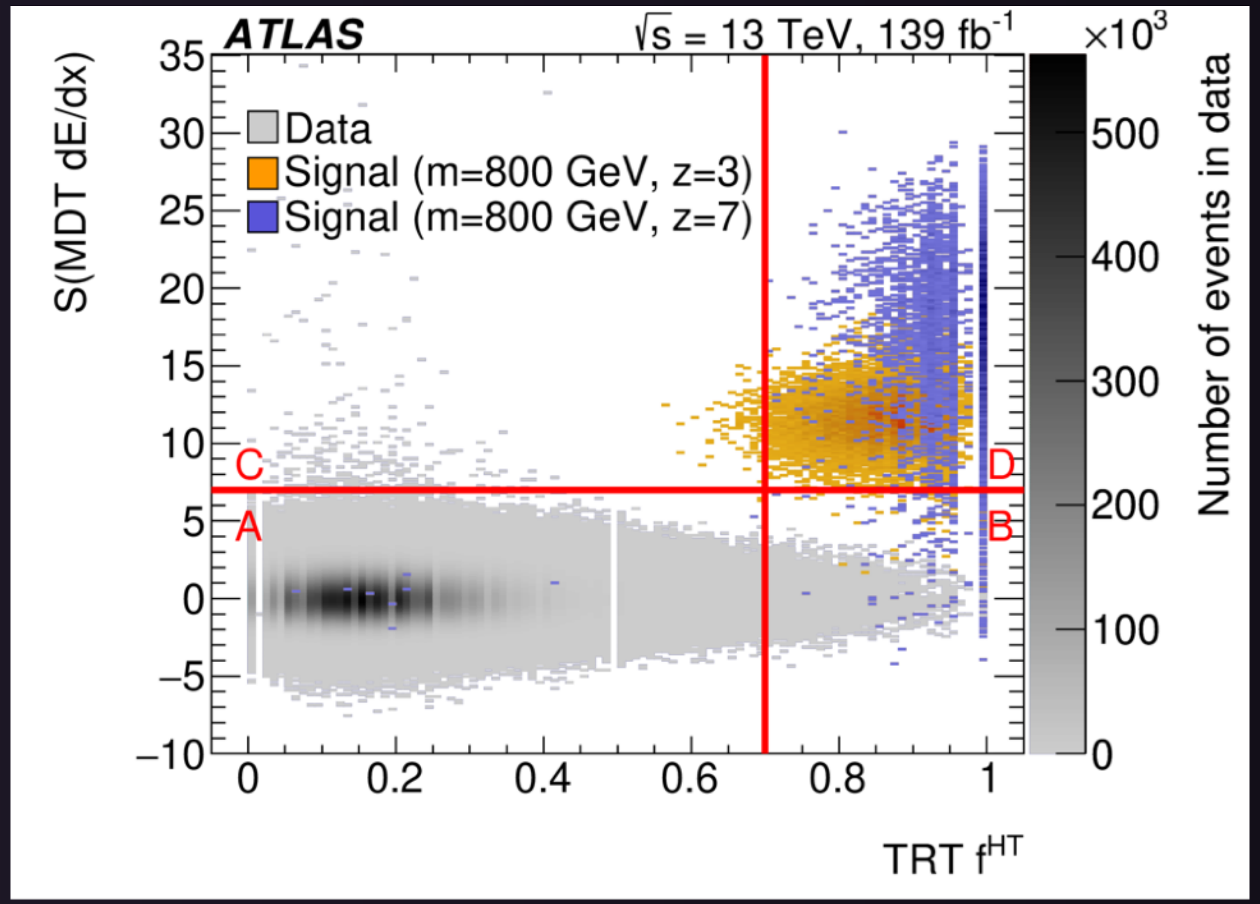


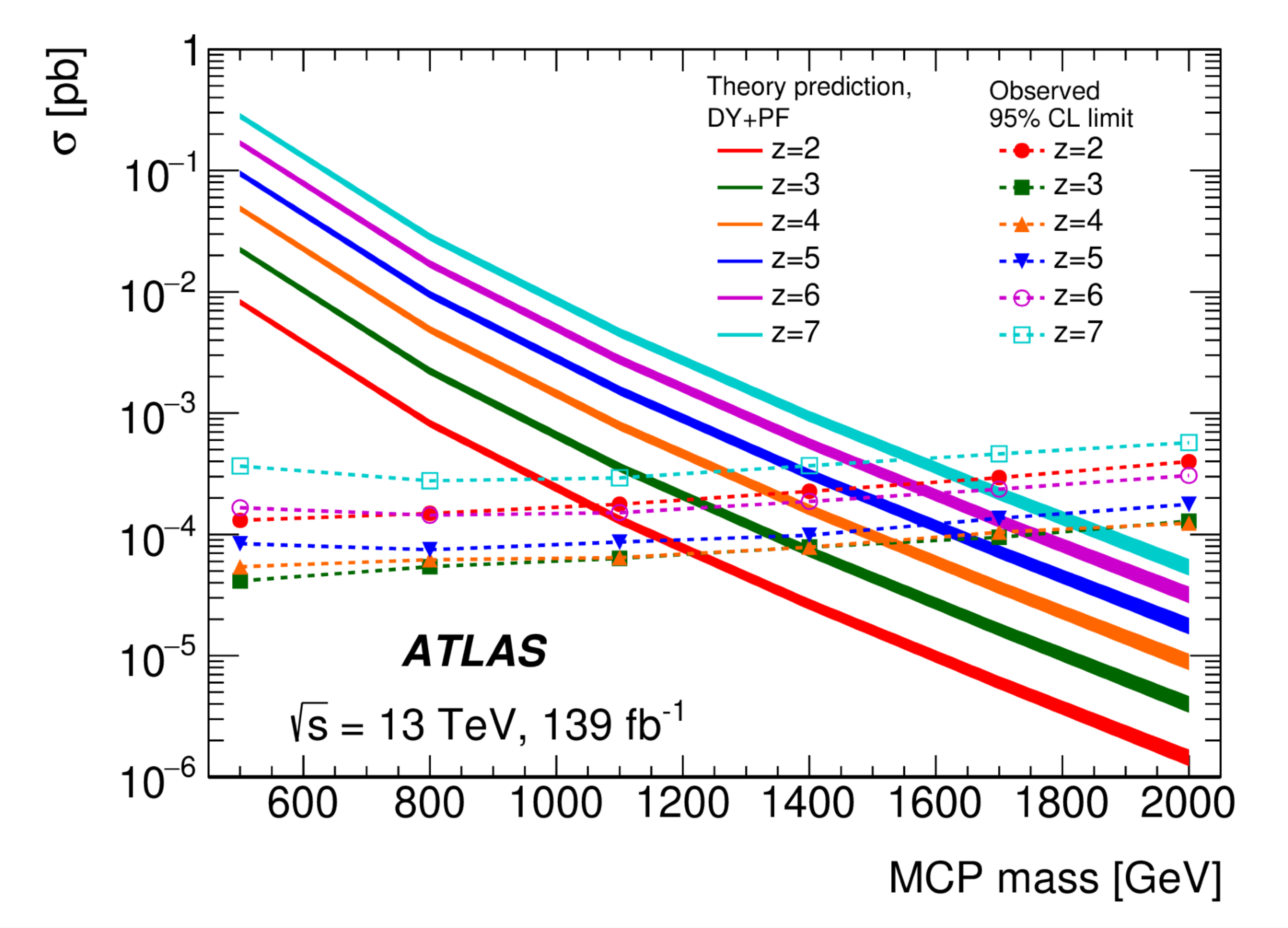
Direct Detection Example: Multi-Charged Stable Particle

[PLB 847 (2023) 138316](#) [EXOT-2018-54](#)

- Backgound estimation: the ABCD method assuming two final discriminants are orthogonal each other.
  - $z = 2$: $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{TRT})$ & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT})$
  - $z > 2$: f_{HT} & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT})$







Search category	$N^{\mathrm{A}\text{ observed}}_{\mathrm{data}}$	$N^{\mathrm{B}\text{ observed}}_{\mathrm{data}}$	$N^{\mathrm{C}\text{ observed}}_{\mathrm{data}}$	$N^{\mathrm{D}\text{ expected}}_{\mathrm{data}}$	$N^{\mathrm{D}\text{ observed}}_{\mathrm{data}}$
$z = 2$	41 674	5024	13	1.6 ± 0.4 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0

- Observed events in SR well consistent with the estimation.
- Put stringent limits to MCPs

Lifetime Frontier Advancement (1): disp.HNL

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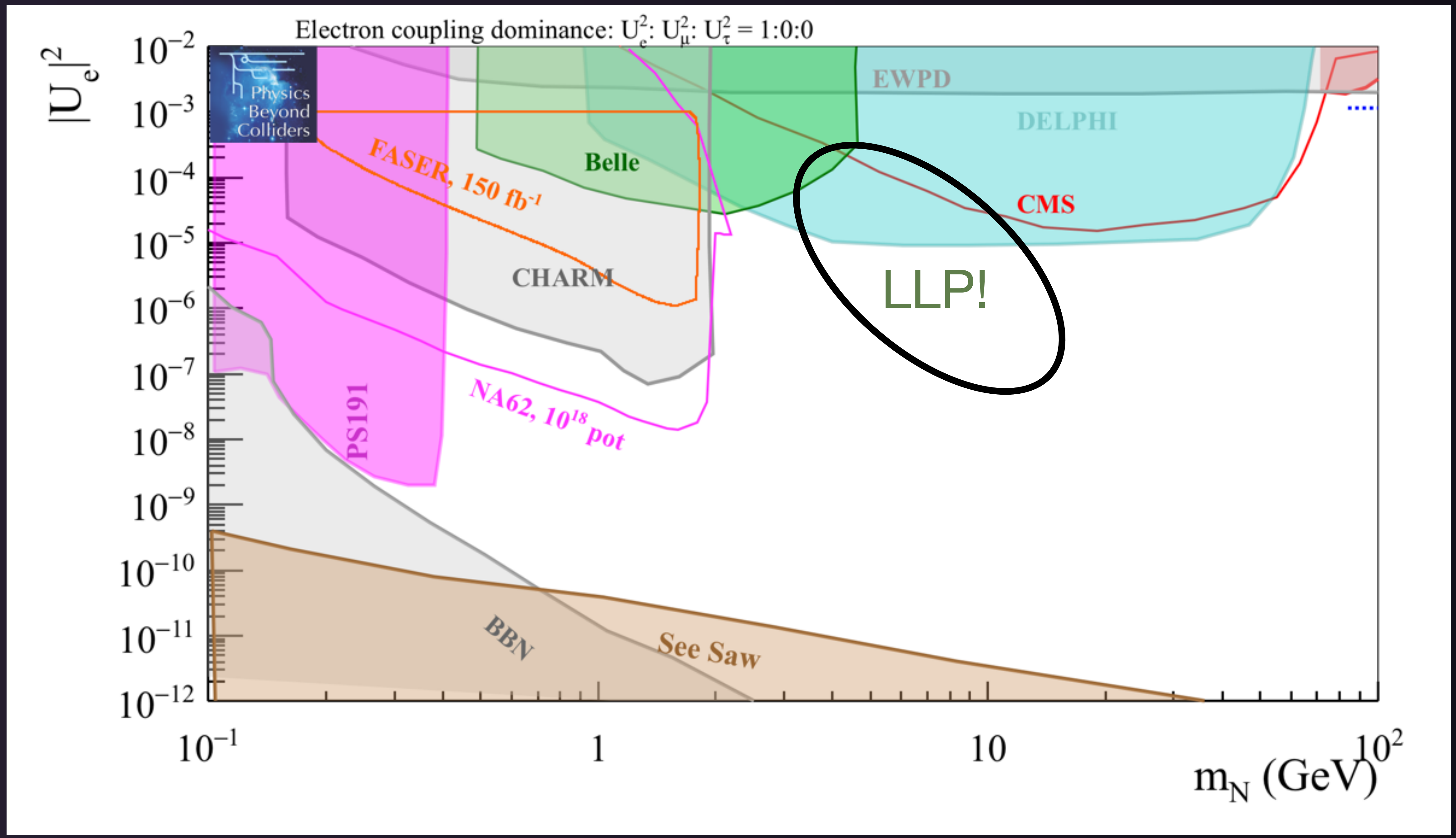
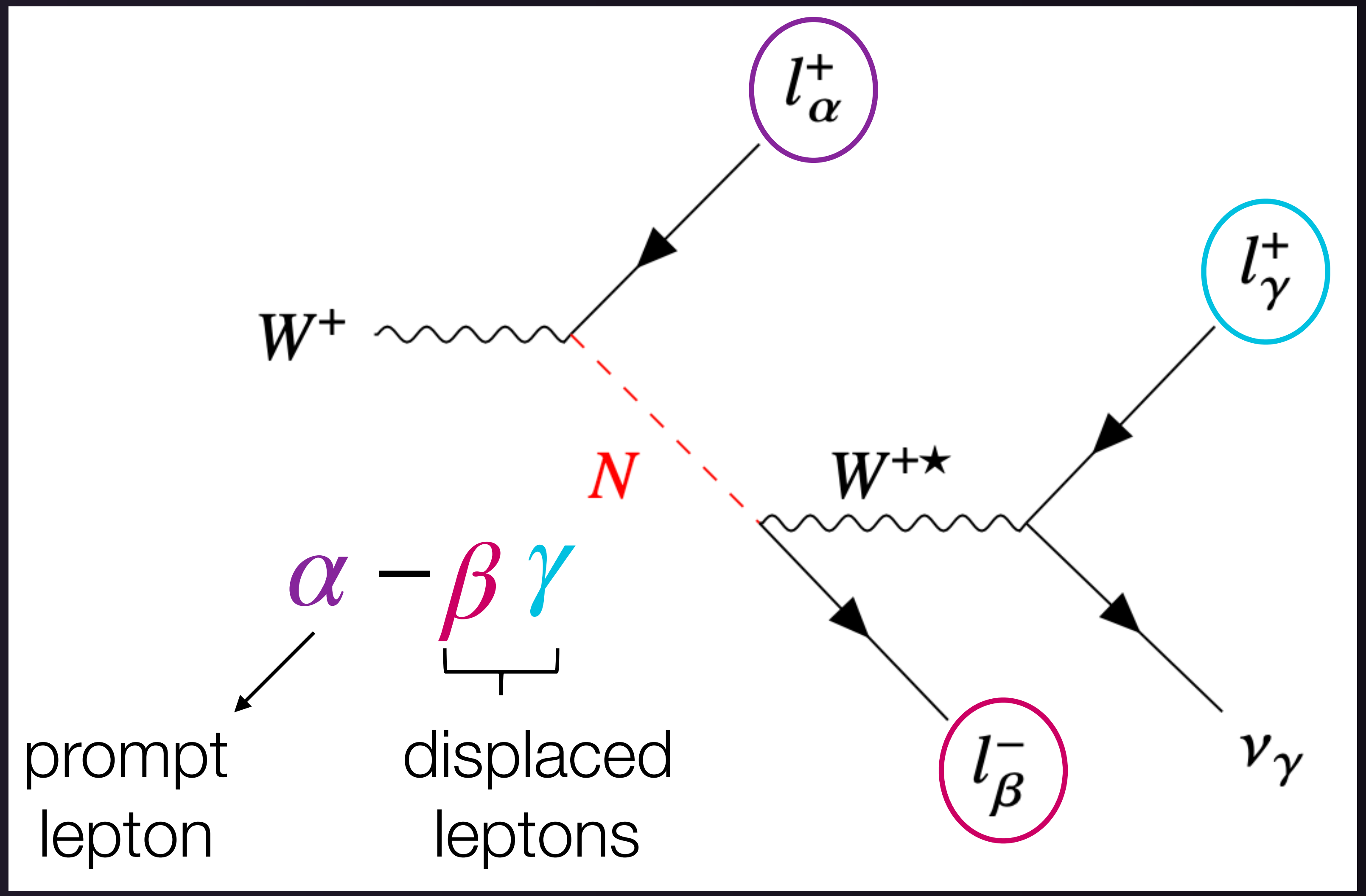




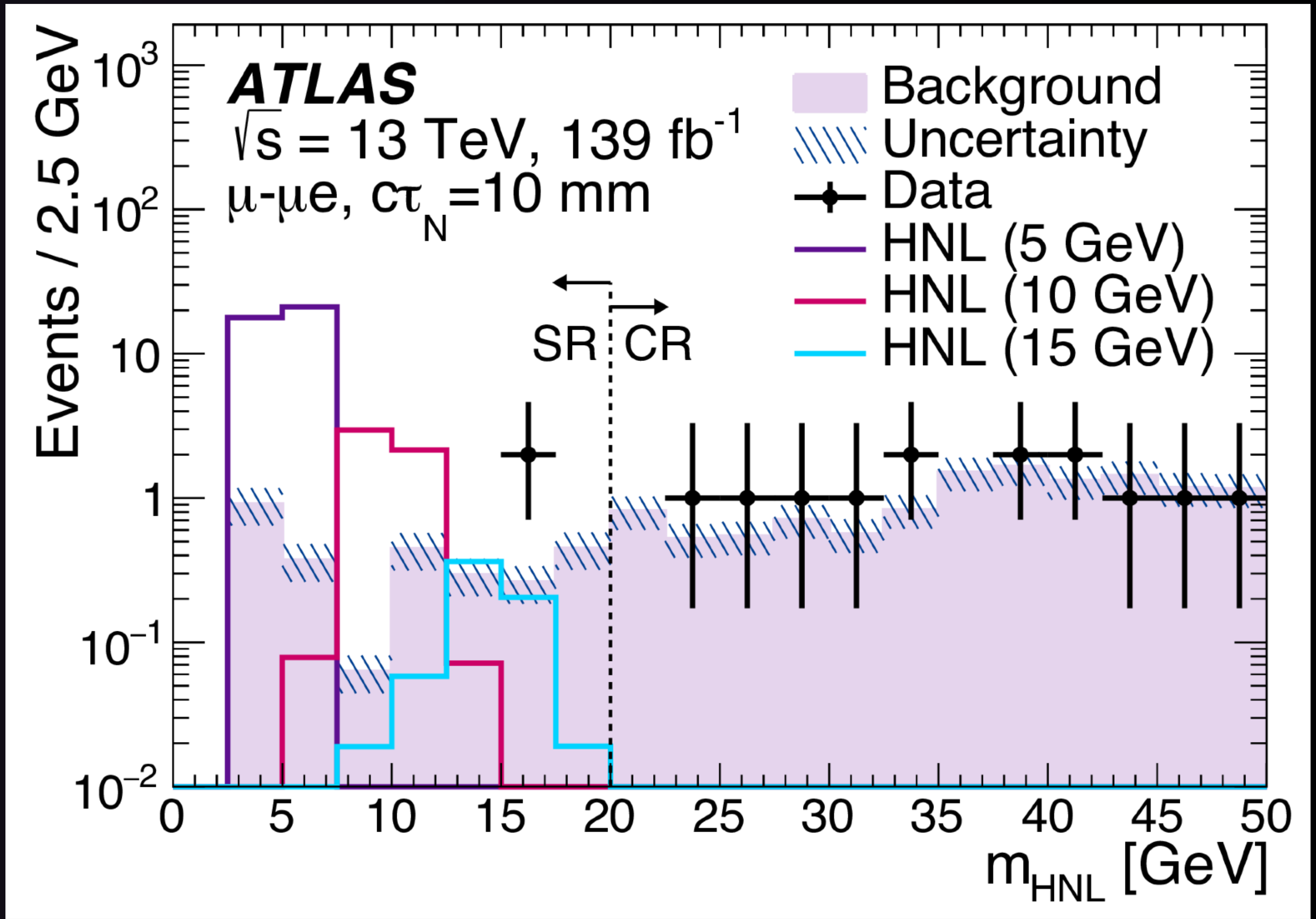
- Heavy Neutral Leptons (HNL) : an intriguing model explaining the neutrino mass with type-I see-saw model.
- The W boson decay can probe a possible mixture of SM neutrino—HNL.
- A specific range of mixing $|U|$ will have a displaced decay of HNL to neutrino + virtual W/Z via $\nu - N - \nu$ mixing: LLP regime.
- Focusing only decays involving (e, μ) → 6 flavor permutations incl. prompt lepton.
- ID displaced vertexing employed lepton-preselected vertexing → clean analysis!
- 4-vectors of 3 leptons can kinematically deduce the HNL mass assuming the mother is W boson: a peculiar discriminant than "just a dilepton DV".

Lifetime Frontier Advancement (1): disp.HNL

ATLAS EXPERIMENT

- Event selection optimized so that the residual background dominated by random crossing of displaced leptons.
  - Assumption validated by comparing SS and OS displaced vertices in no-prompt-lepton DV events.
- Signal region background estimated by randomly pairing “prompt lepton” and “DV” from different event sets.
  - Effectively inflate statistics with a caveat of reusing same objects multiple times in evaluation of the sample statistics impact on the background uncertainty.
- 6 lepton permutations bins simultaneously fit to data: No significant excess wrt. background.

PRL 131 (2023) 061803 EXOT-2019-29



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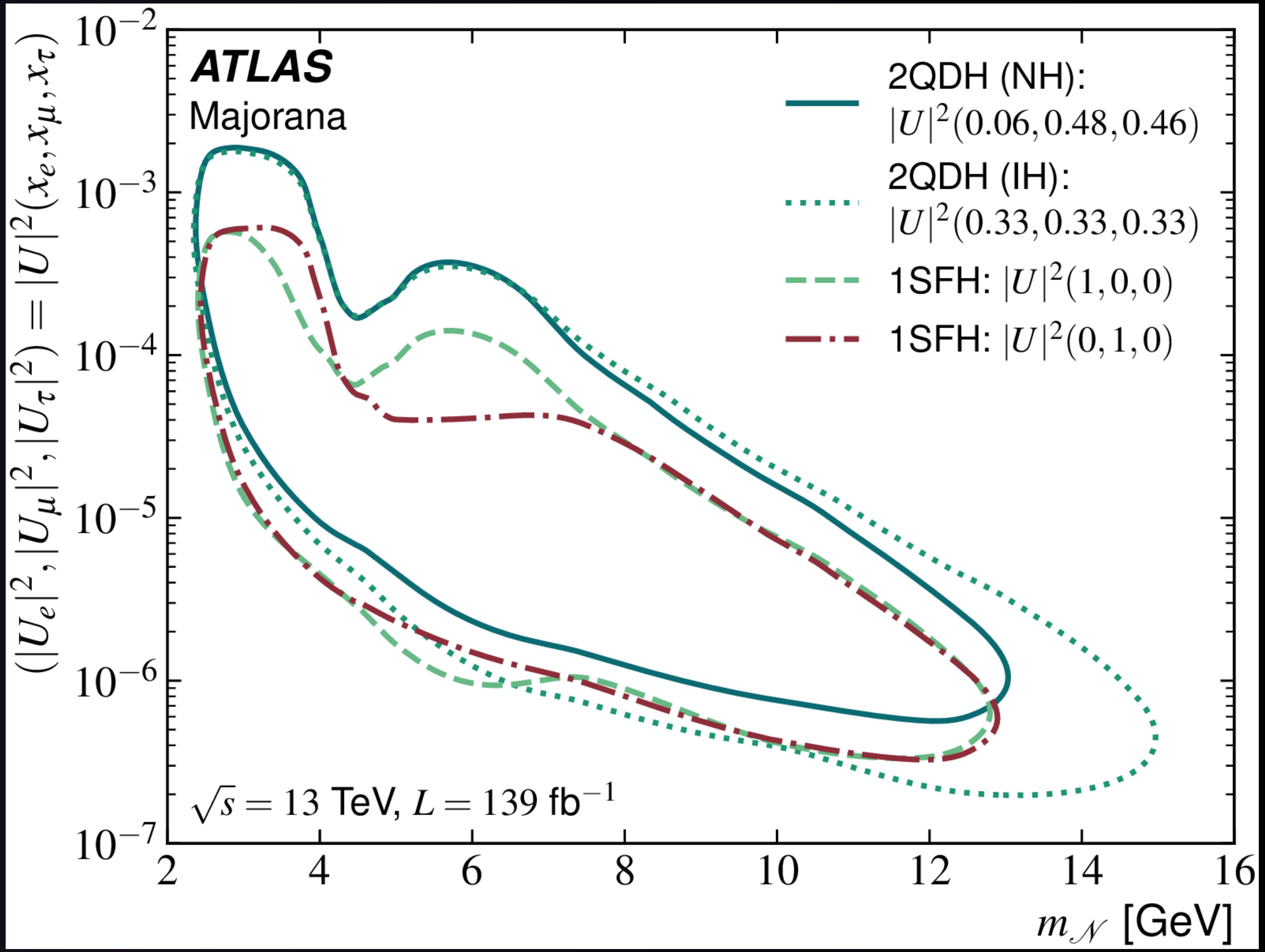
  - Effectively inflate statistics with a caveat of reusing same objects multiple times in evaluation of the sample statistics impact on the background uncertainty.
- 6 lepton permutations bins simultaneously fit to data: No significant excess wrt. background.
- Limits quoted to long-lived HNL with various flavor-mixing senarios and Normal and Inverted neutrino mass hierarchies.

PRL 131 (2023) 061803 EXOT-2019-29



Lifetime Frontier Advancement (2): charged LLP

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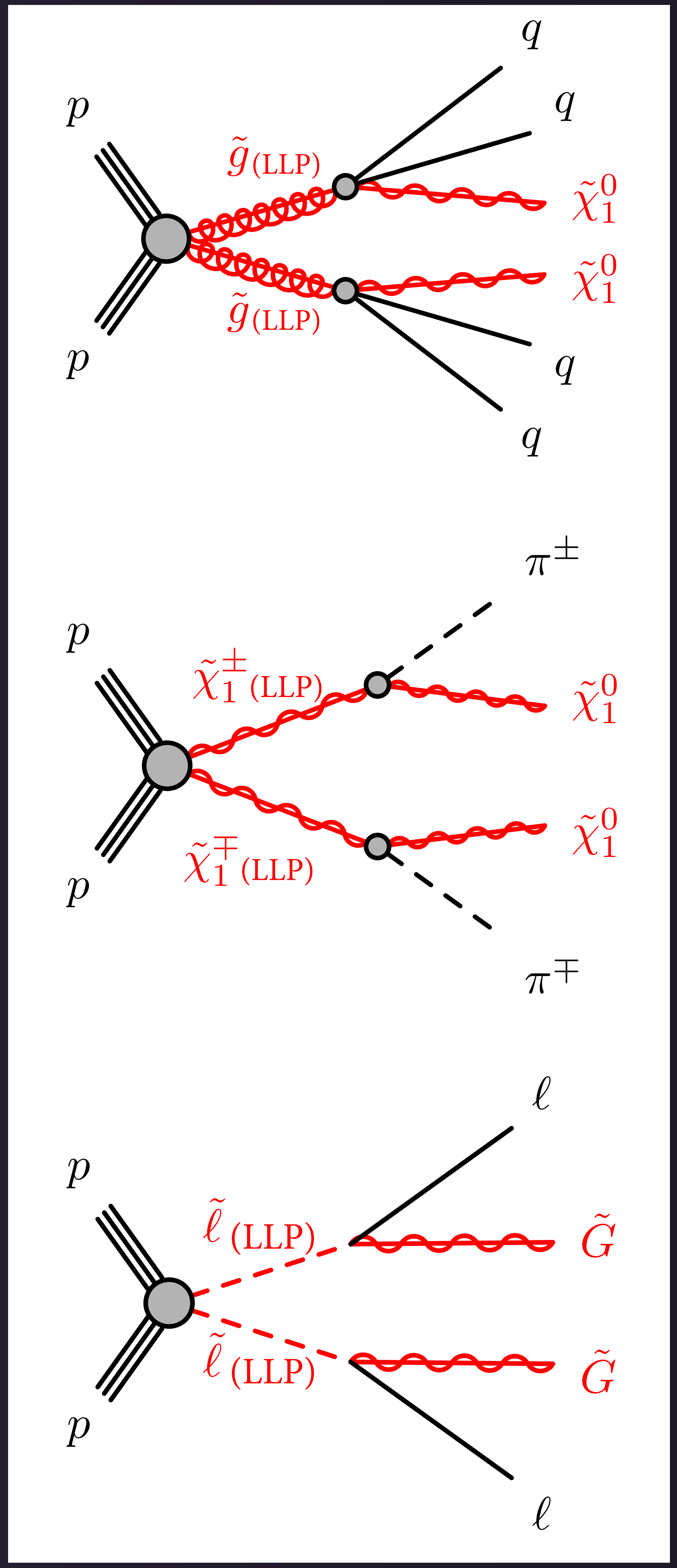
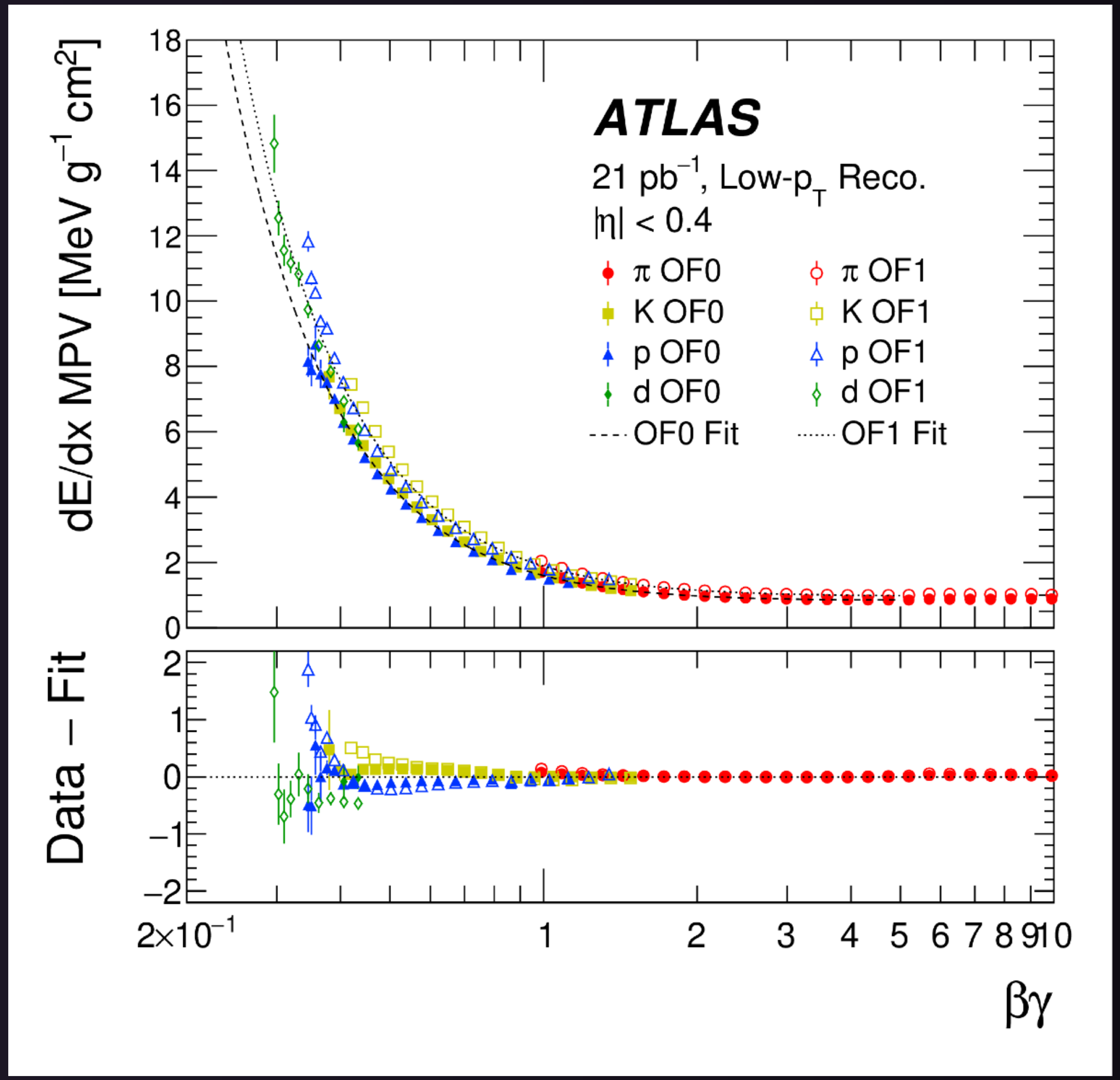
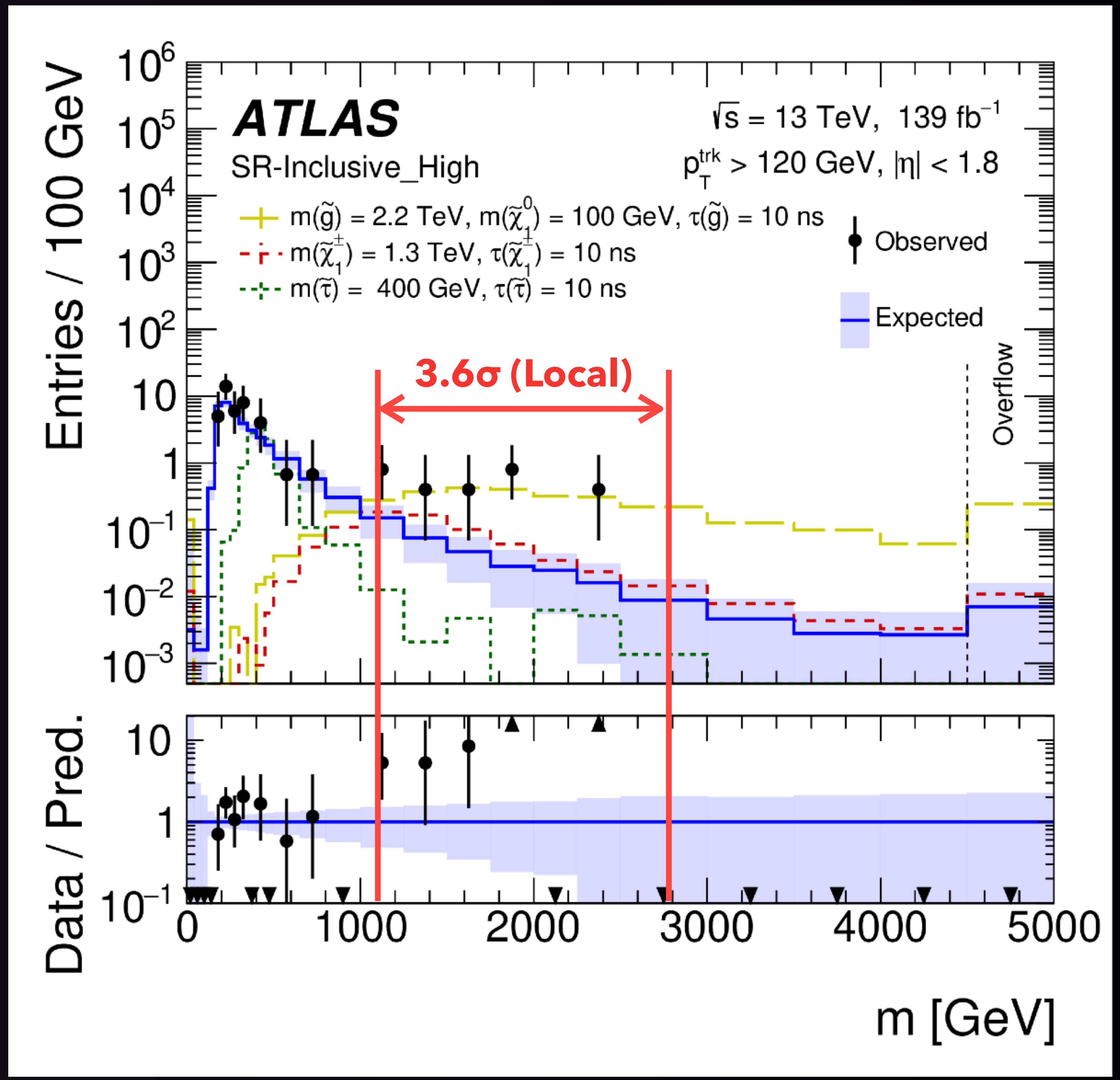






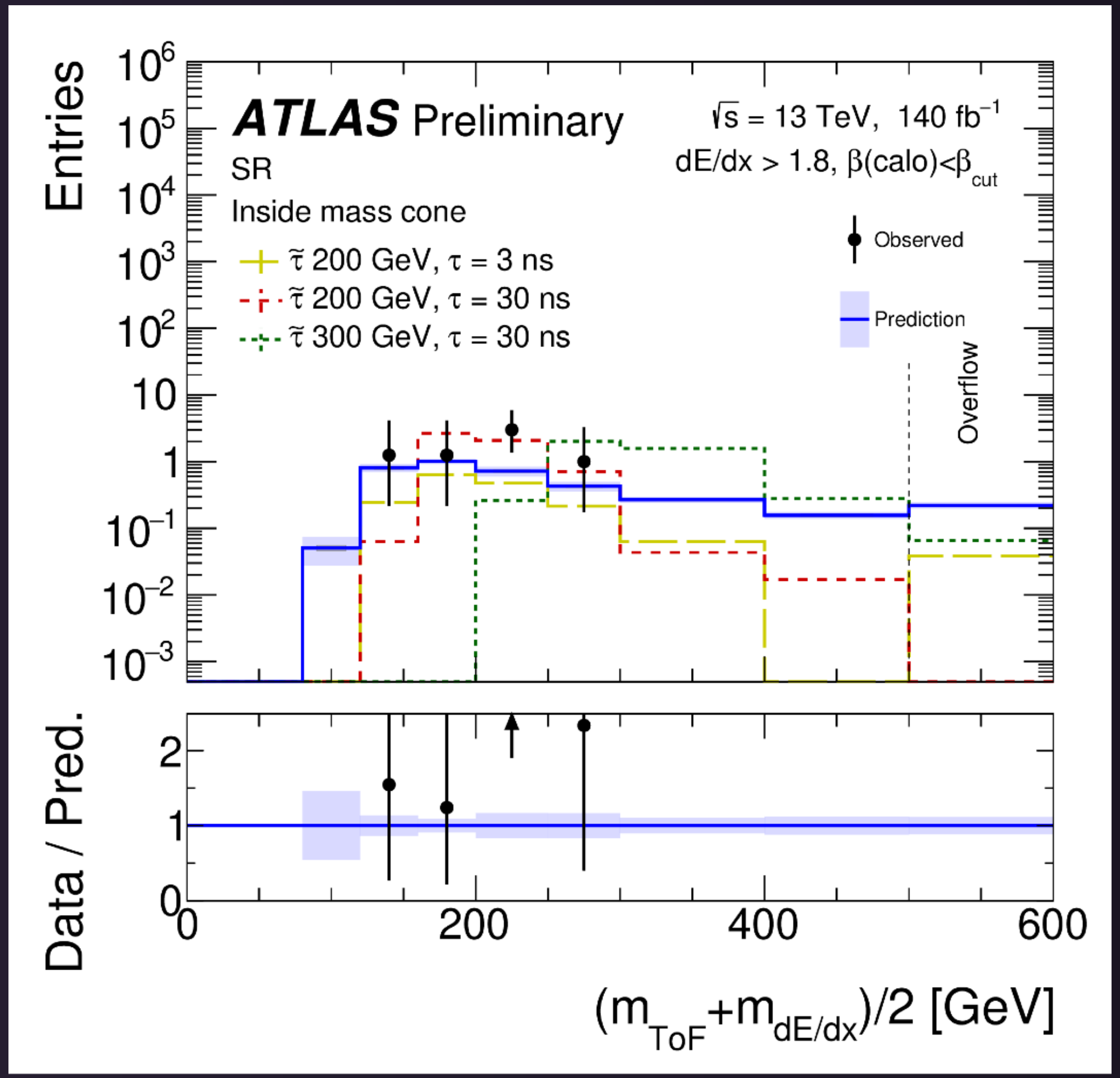
- A high-p_T inner detector track with a significantly large $\mathrm{d}E/\mathrm{d}x$ is a possible BSM particle for various scenarios.
- The pixel detector's charge measurement offers a good $\mathrm{d}E/\mathrm{d}x$ measurement, spanning from a few ns to detector-stable lifetimes.
- The full Run 2 analysis observed a 3.6 sigma (local) events at high mass range with no obvious instrumental pathologies, though a check of ToF did not indicate slowness of candidates.
- A past LLP Workshop had a dedicated discussion session for this result…

Lifetime Frontier Advancement (2): charged LLP

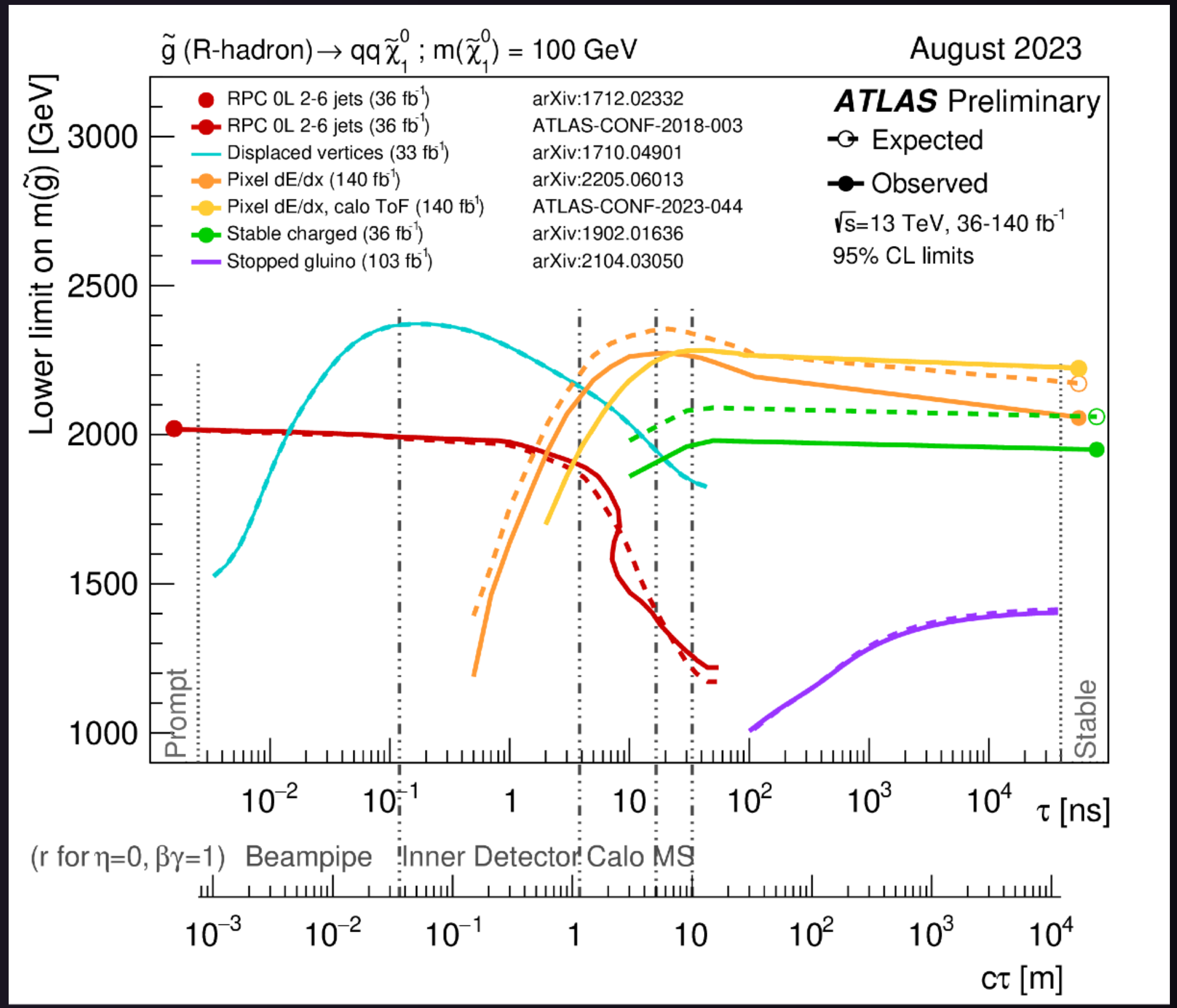
- As a follow-up, the tile-calo ToF is more extensively used on top of pixel $\mathrm{d}E/\mathrm{d}x$, with a slight sacrificing of sensitivity in the short lifetime end, conserving most of event selections $\Longrightarrow$ consistent with Bkg.
- Advantage in estimating the mass using independent observable of $\mathrm{d}E/\mathrm{d}x$ and ToF and much more stringent background rejection.

ATLAS-CONF-2023-044

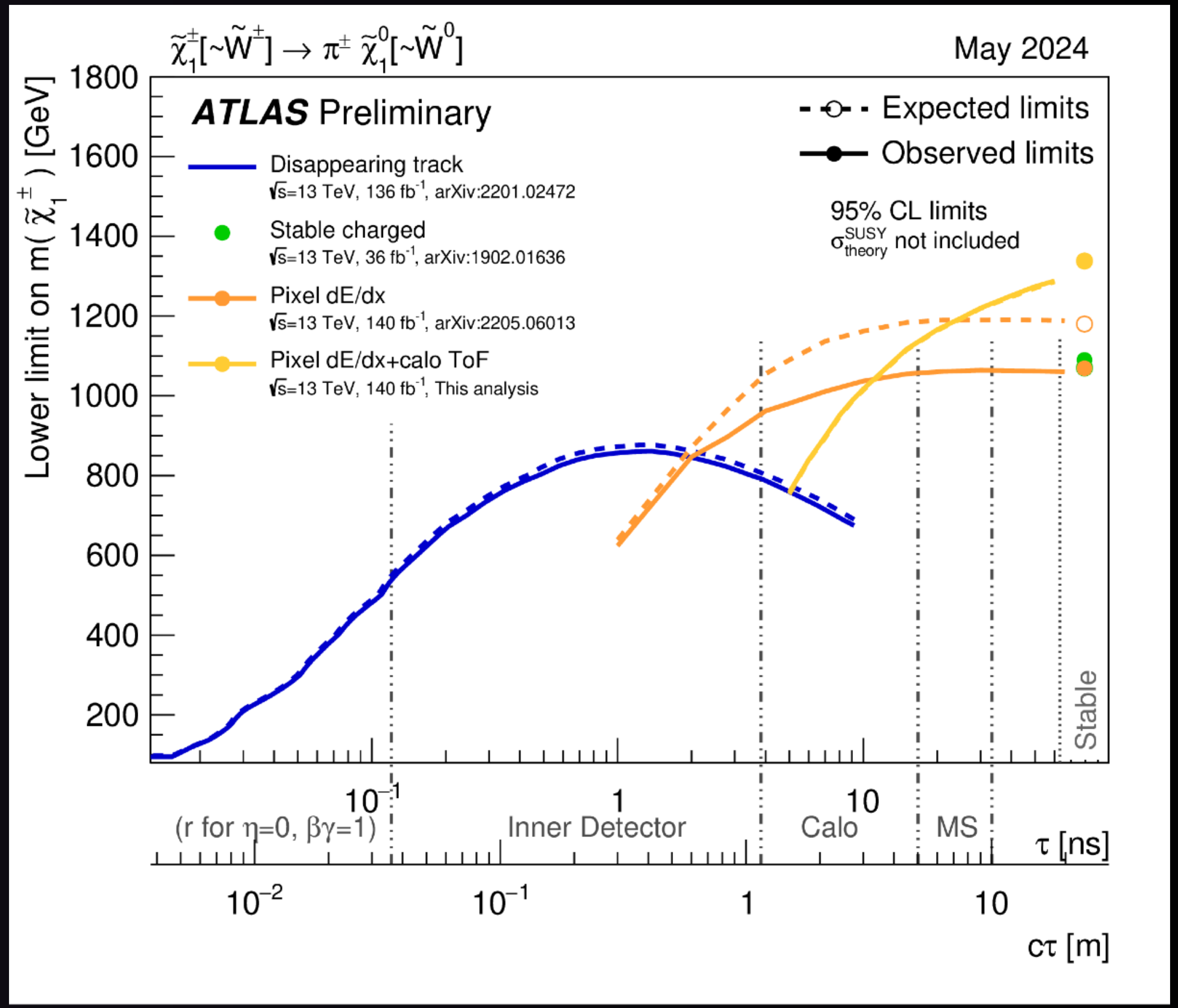
ATLAS-PUB-2024-009



Averaged Mass Distribution



Gluino R-hadron Interpretation

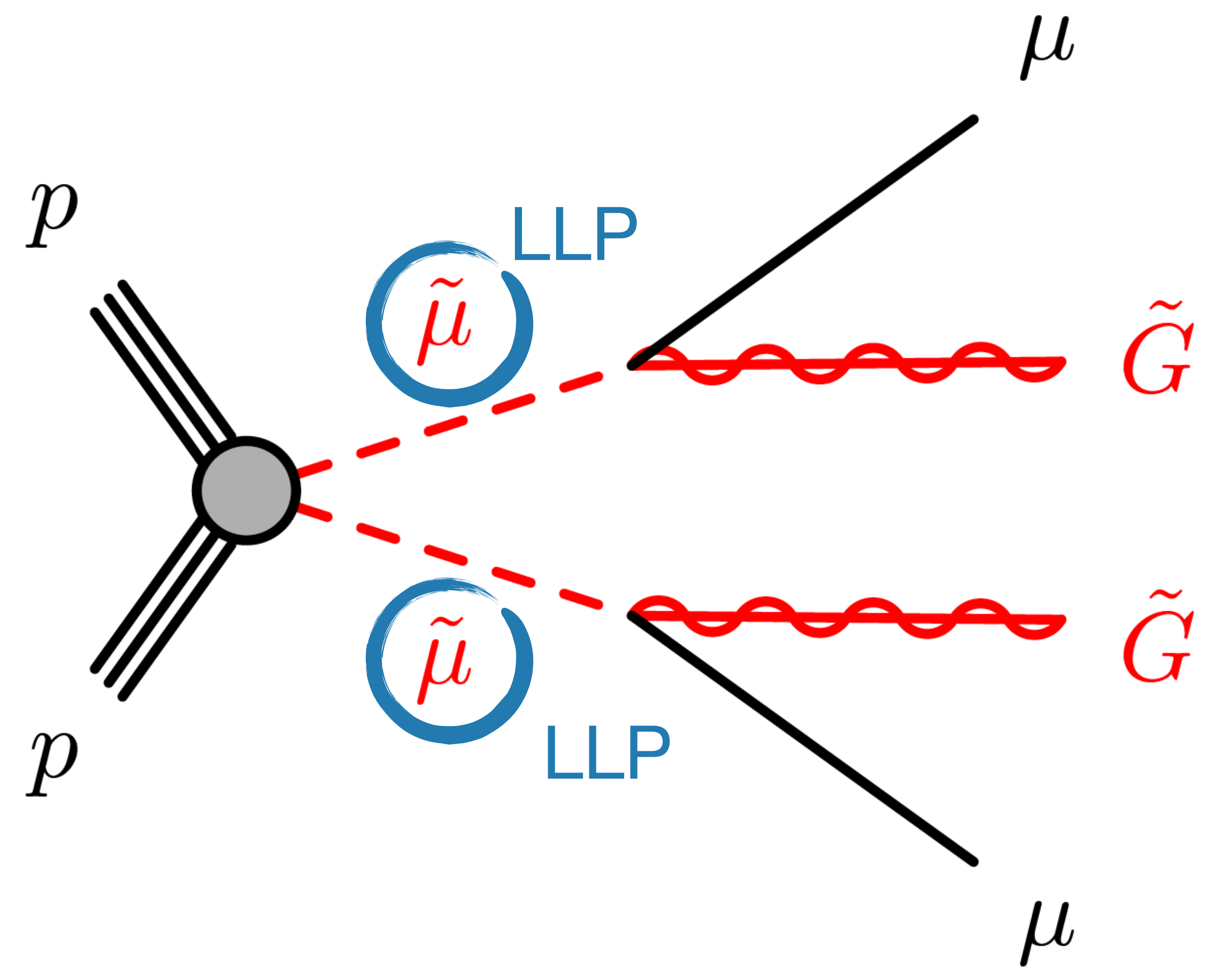


Wino Interpretation

⇒ Dedicated presentation: A. E. Mulski (Wed Morning)

Closing the Near-Prompt Frontier : Case-#1

- Targeting a slight displacement from PV is a hard analysis byte!
- Harsh contamination of SM backgrounds.



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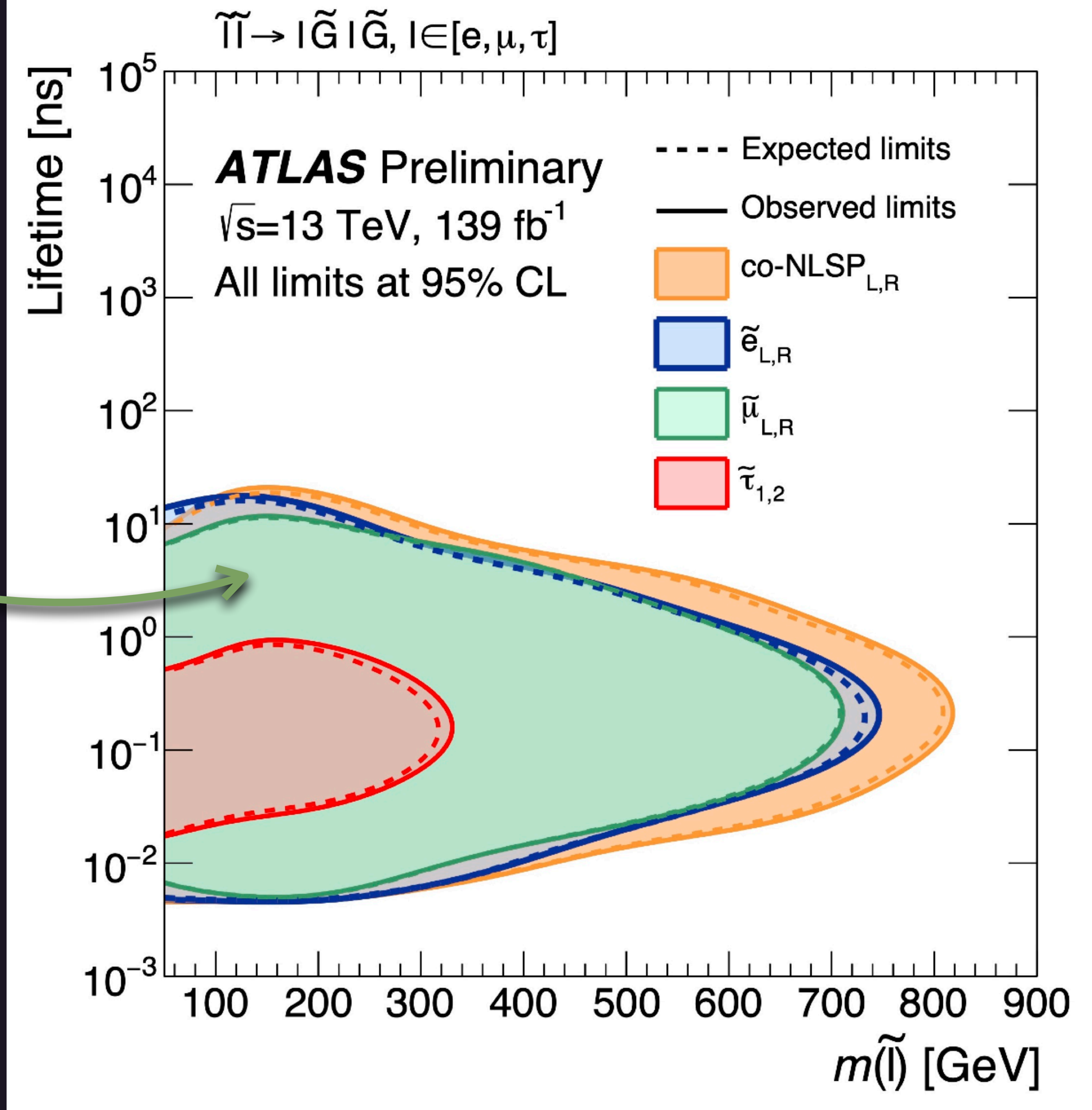
Example: Displaced leptons
$(e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp)$

Run2 round-#1 analysis
$|d_0| \in [3,\ 300]$ mm



Interpretation for $\tilde{e}$, $\tilde{\mu}$
and leptonic decays of $\tilde{\tau}$

Closing the Near-Prompt Frontier : Case-#1

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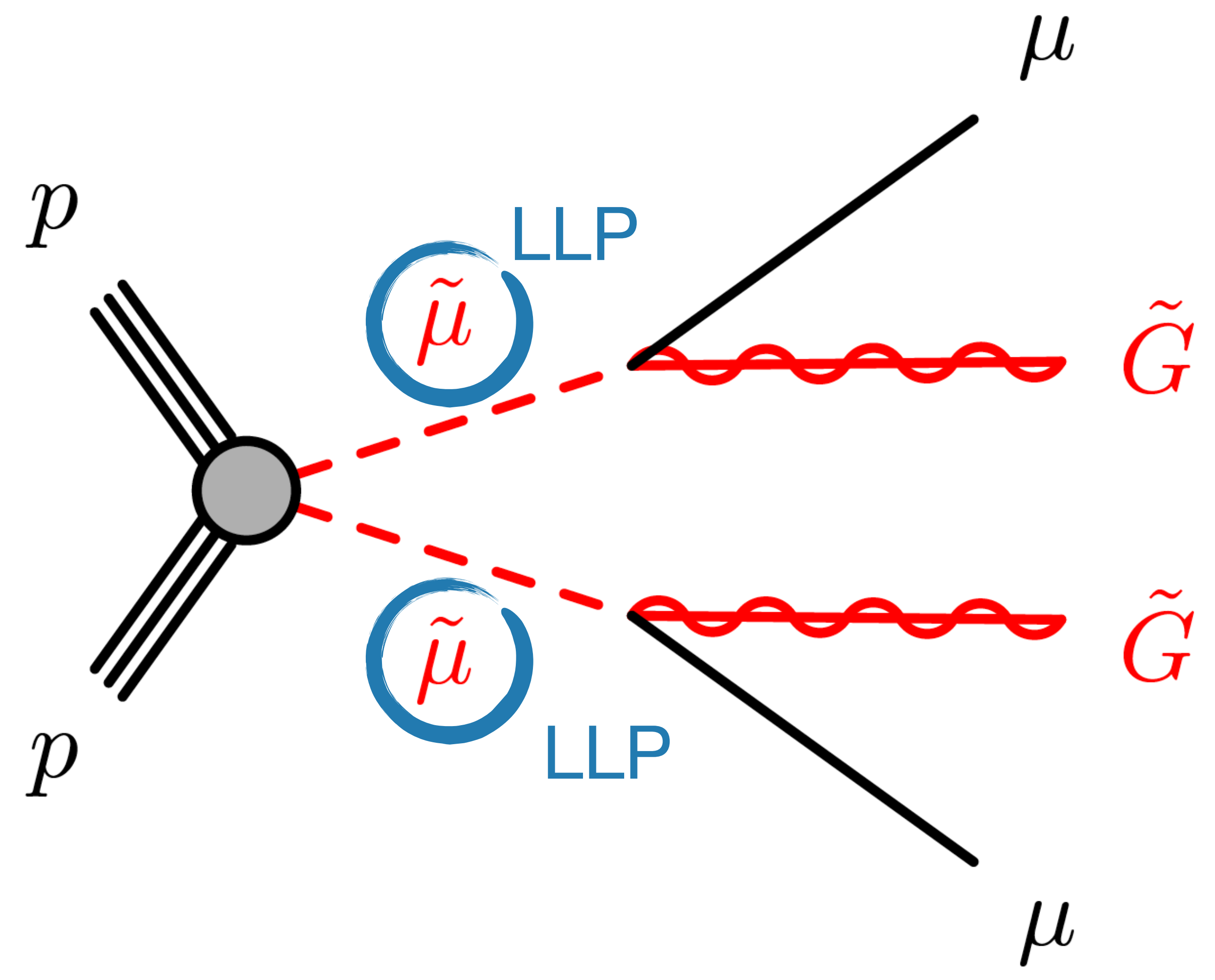

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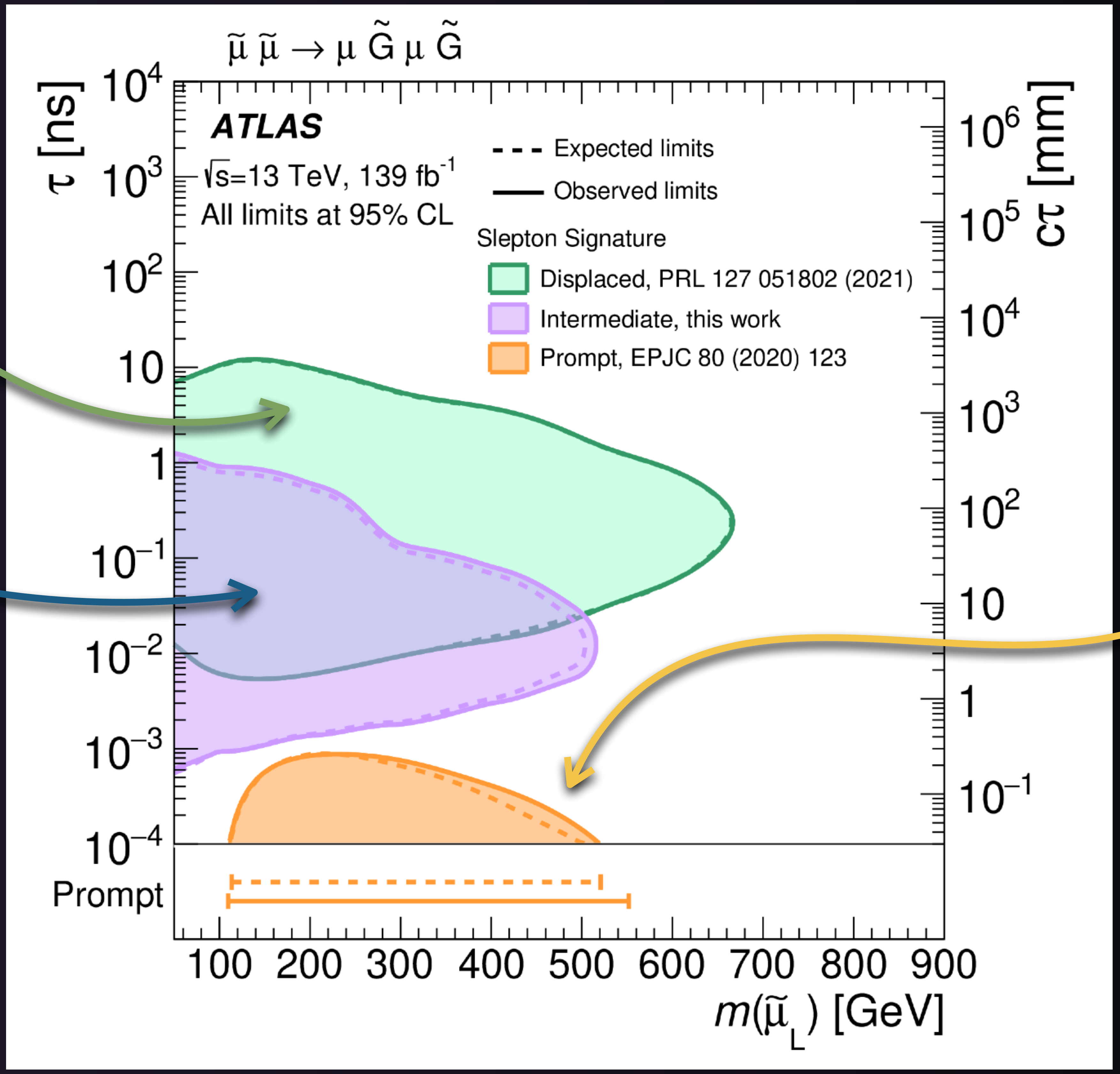
Run2 round-#1 analysis
$|d_0| \in [3, 300]$ mm

Run2 round-#2 analysis
$\mu^+\mu^-$ channel only
$|d_0| \in [0.6, 3]$ mm

Interpretation for $\tilde{\mu}$
(This Figure: $\tilde{\mu}_L$ case)



Extended interpretation
from the prompt slepton (m_{T2}) search

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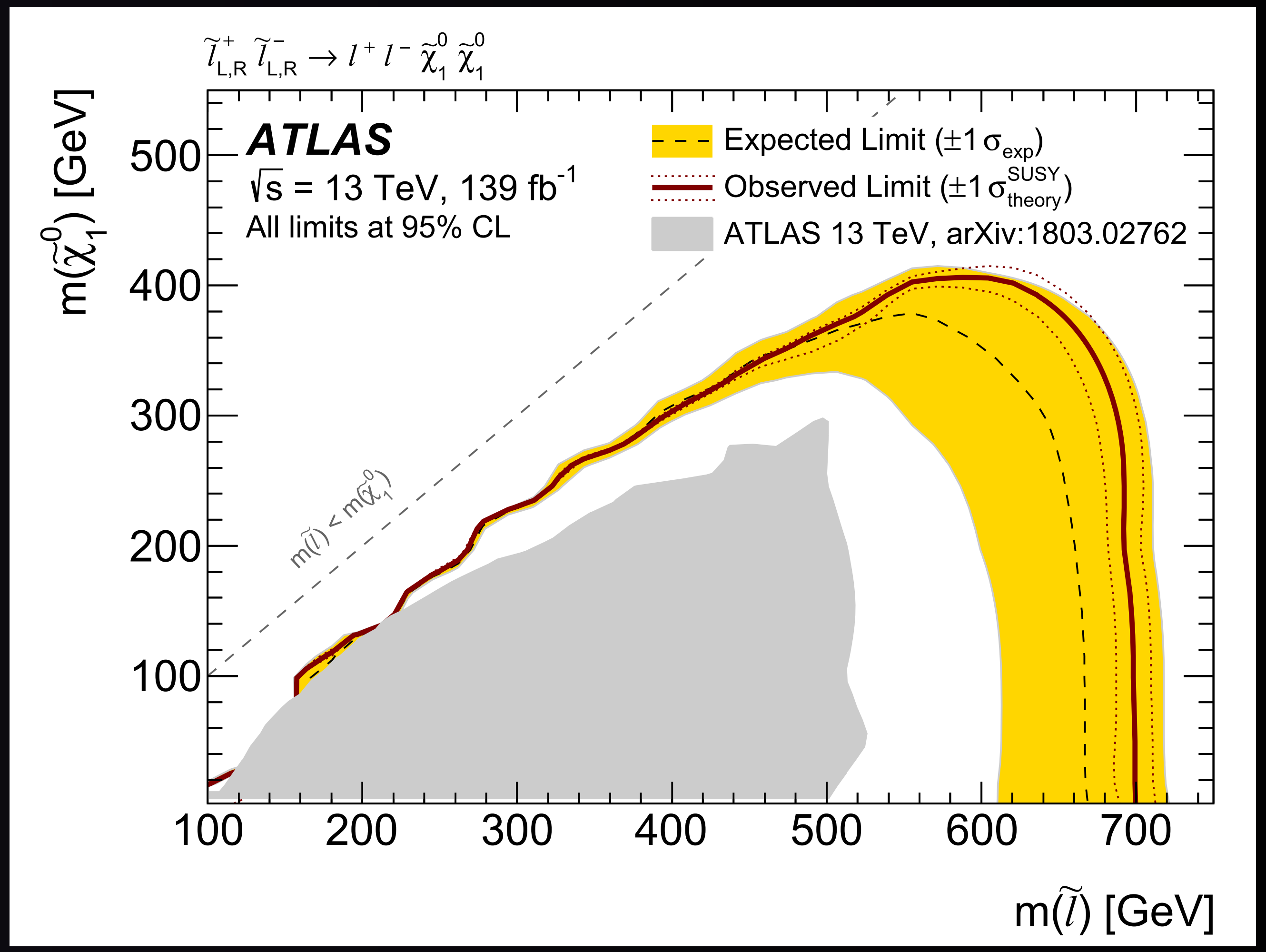
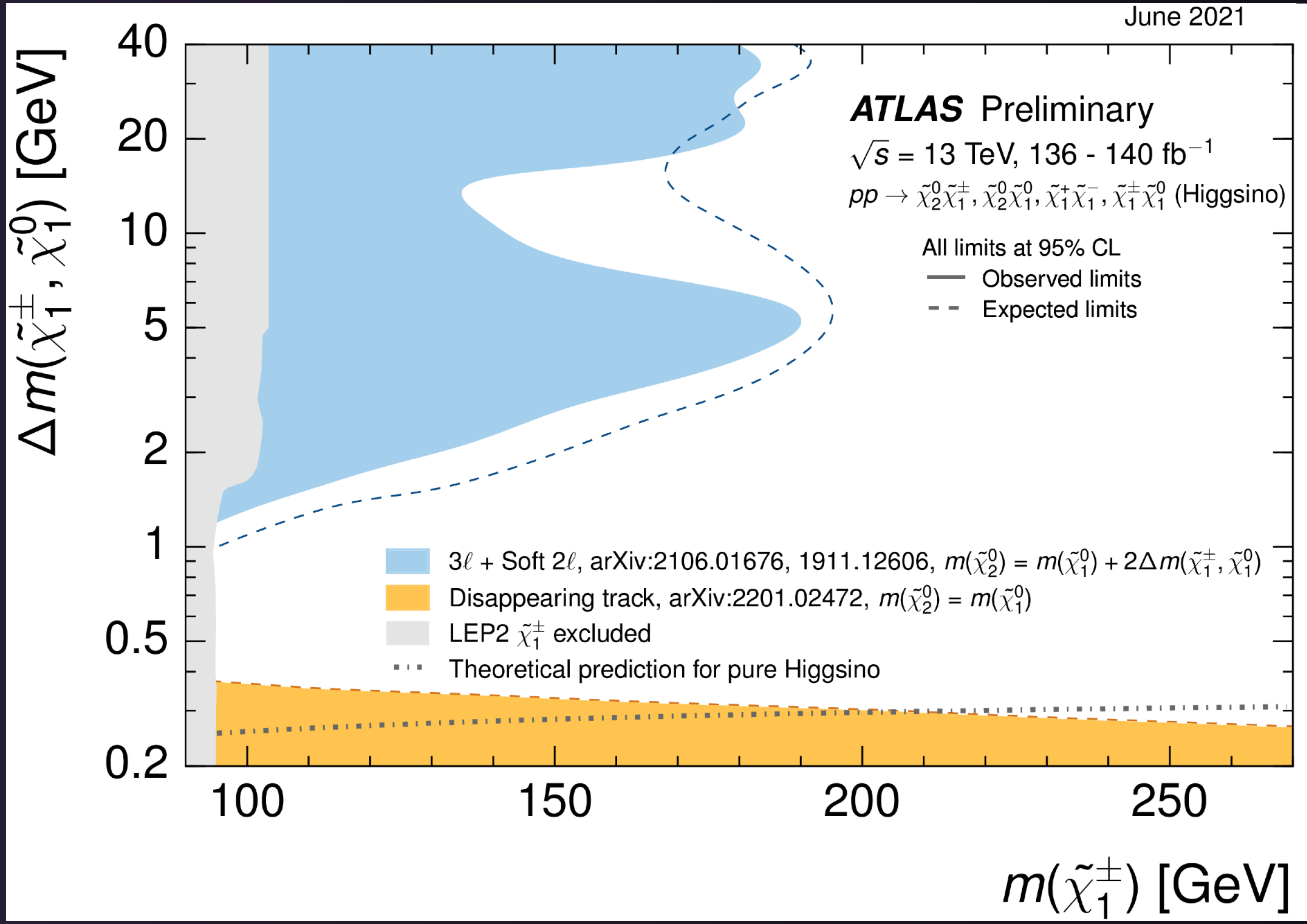
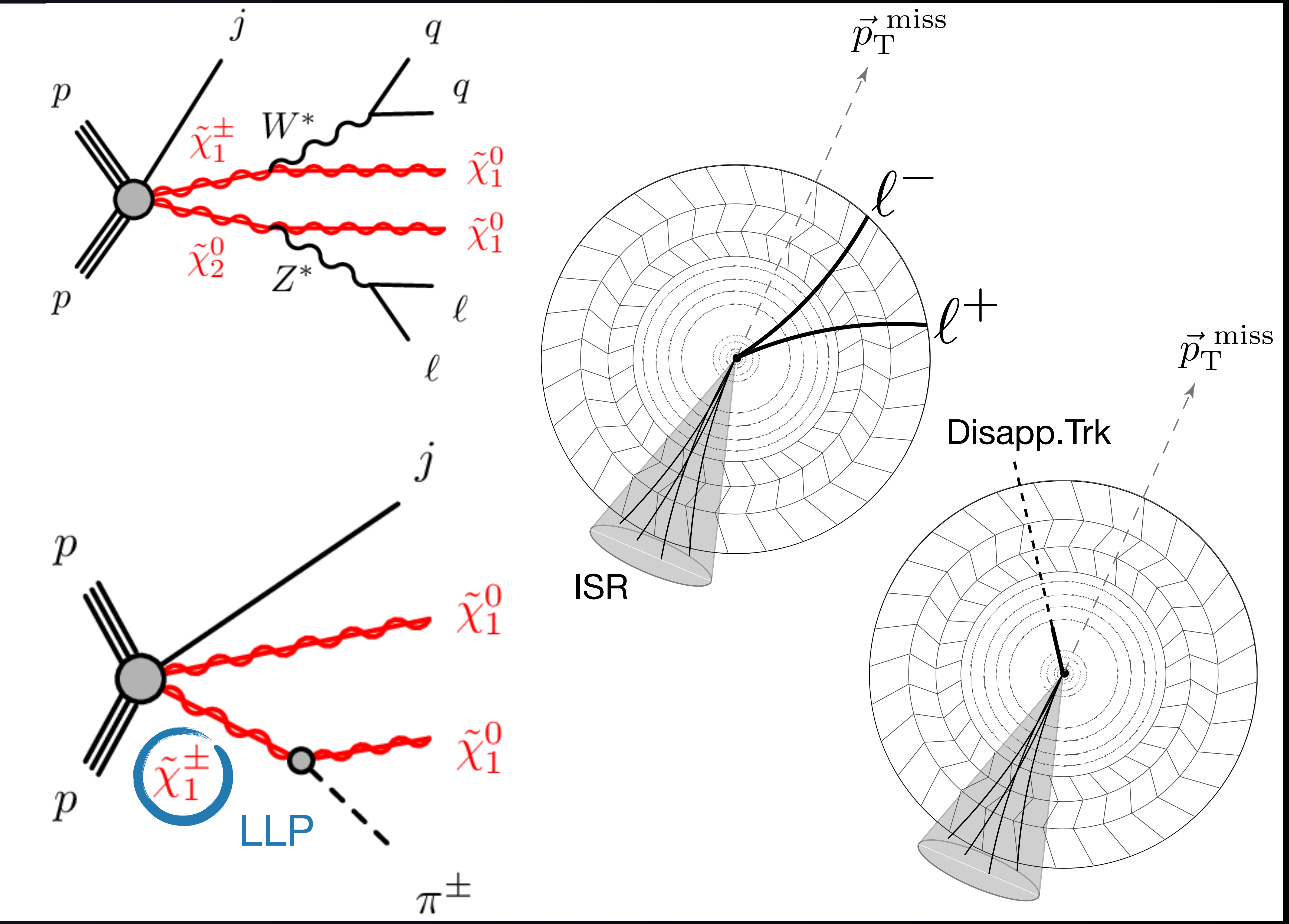
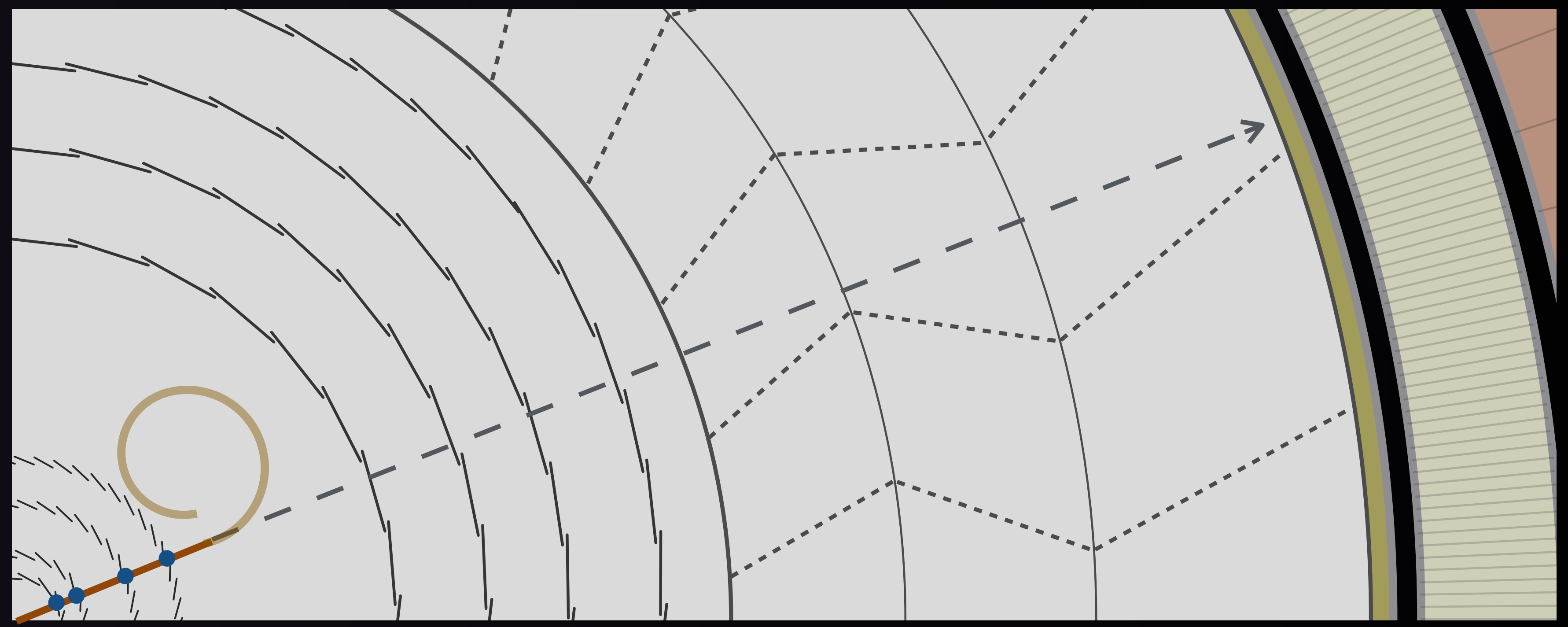


Closing the Near-Prompt Frontier : Case-#2





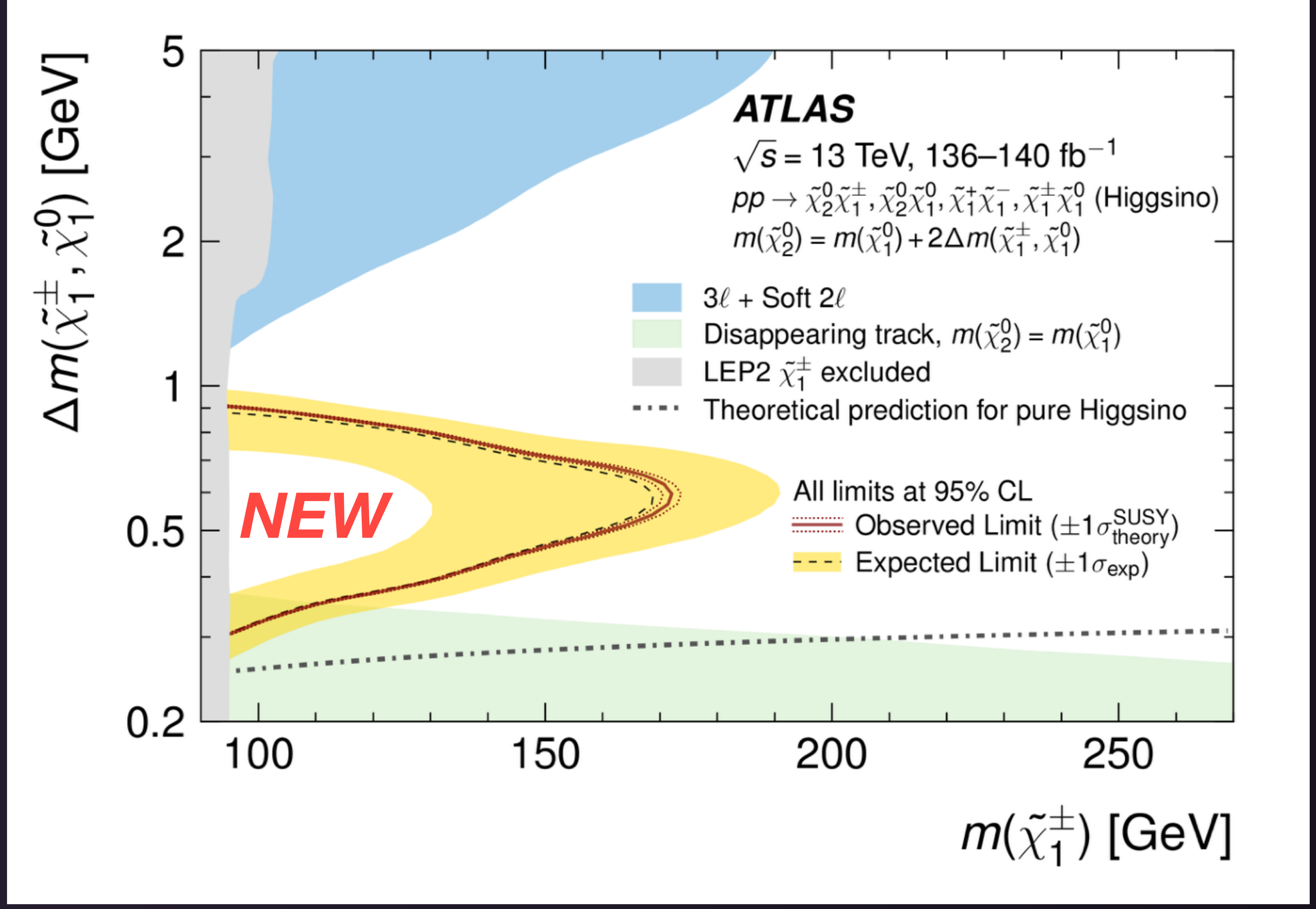
- Mass-degenerated Higgsino is one intriguing DM candidate.
- Basic search strategy: ISR + E_T^{miss} (mono-jet) + “some additional feature”
- So far devised “soft di-lepton” and “disappearing track”
- A gap is present between “prompt” and “long-lived”

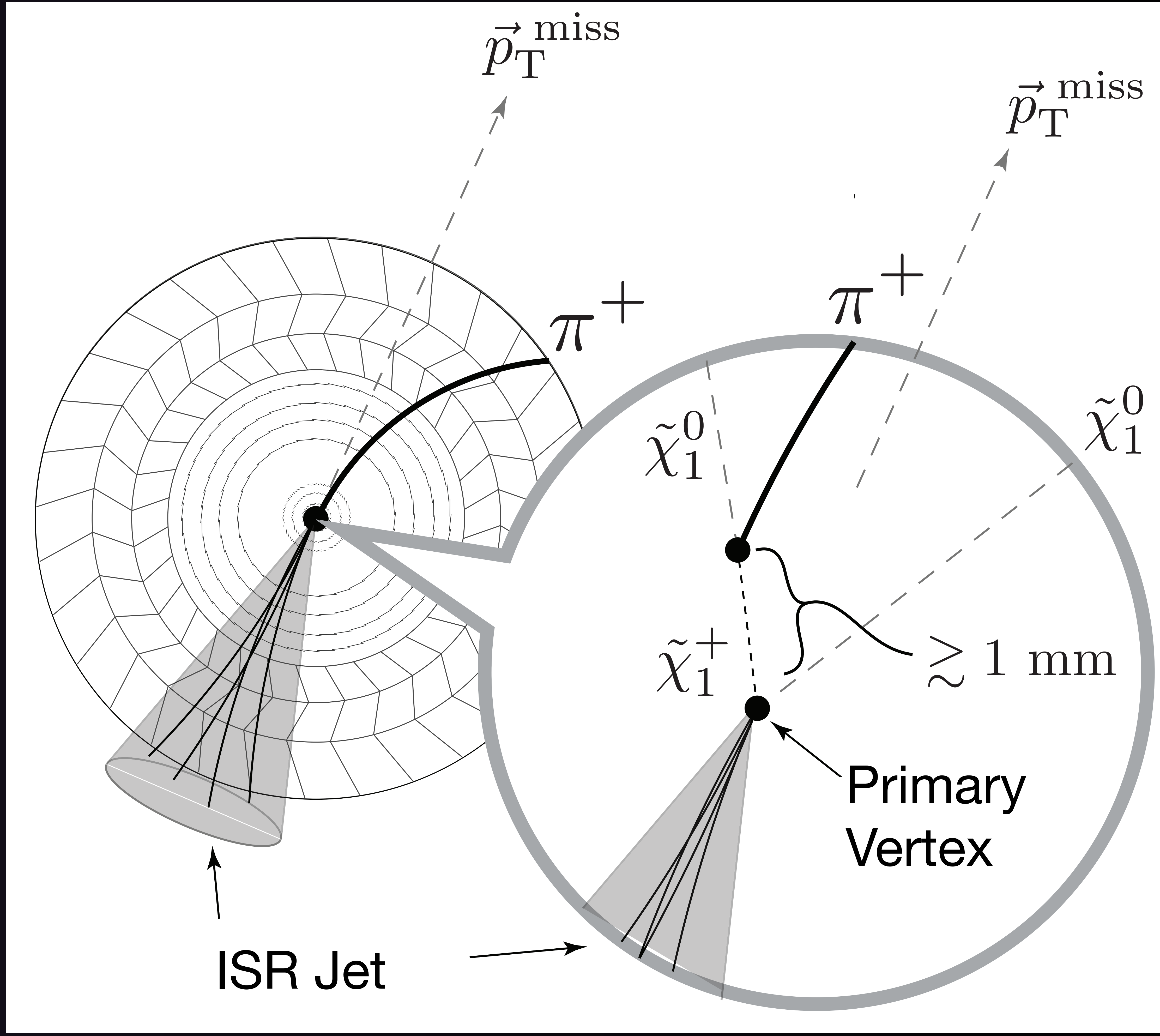


Closing the Near-Prompt Frontier : Case-#2

- A curious phase space is found in the $\Delta m \simeq 1$ GeV range PRL 124 101801 (2020).
- Higgsino emits a track-reconstructible $\pi^{\pm}$ while the mother chargino flies slightly.
- A unique "mildly displaced soft track" signature.
  - Discriminant: combination of soft track ($p_{\mathrm{T}} \leq 5$ GeV) and a pronounced d_0 significance.

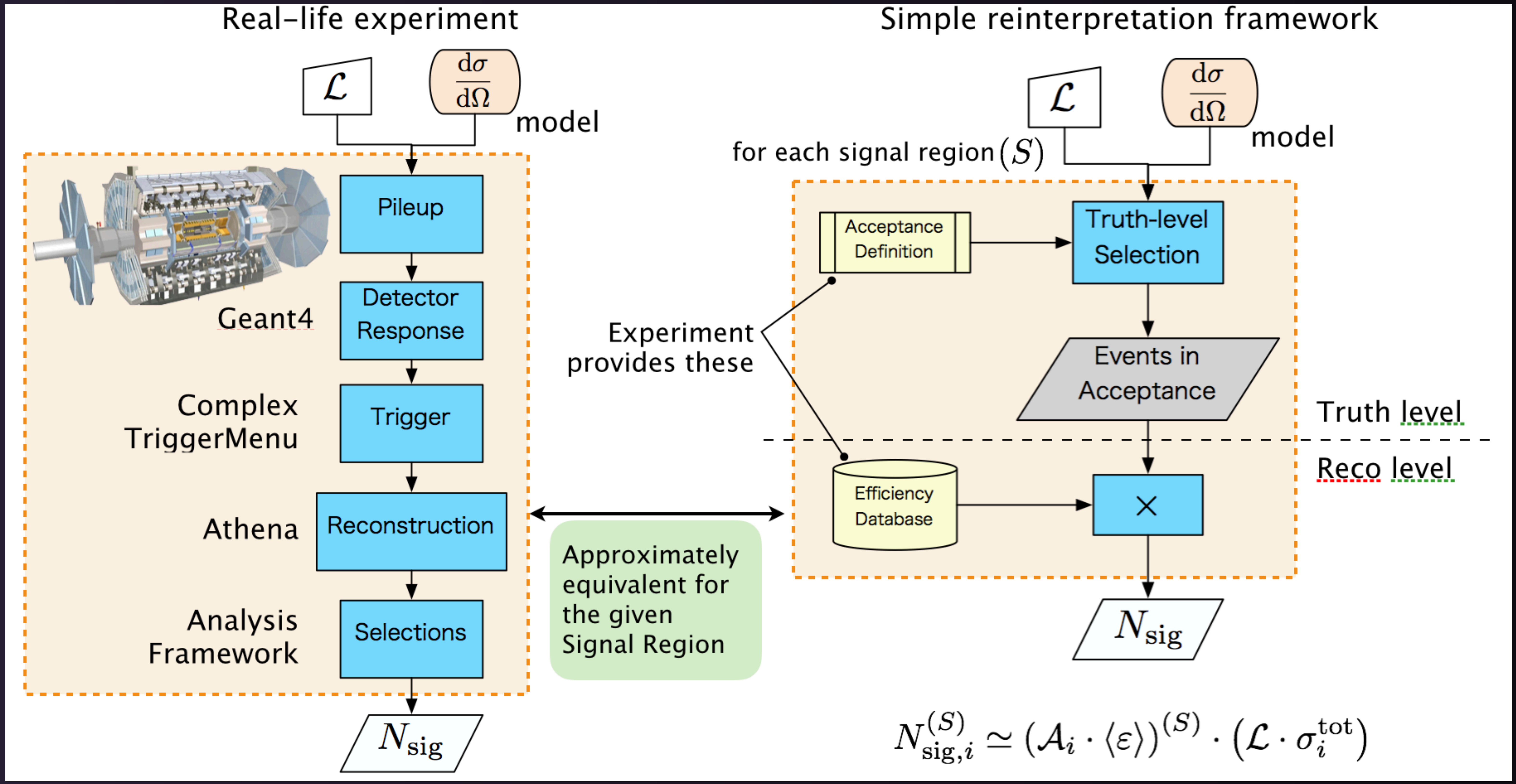
PRL 132 (2024) 221801   SUSY-2020-04

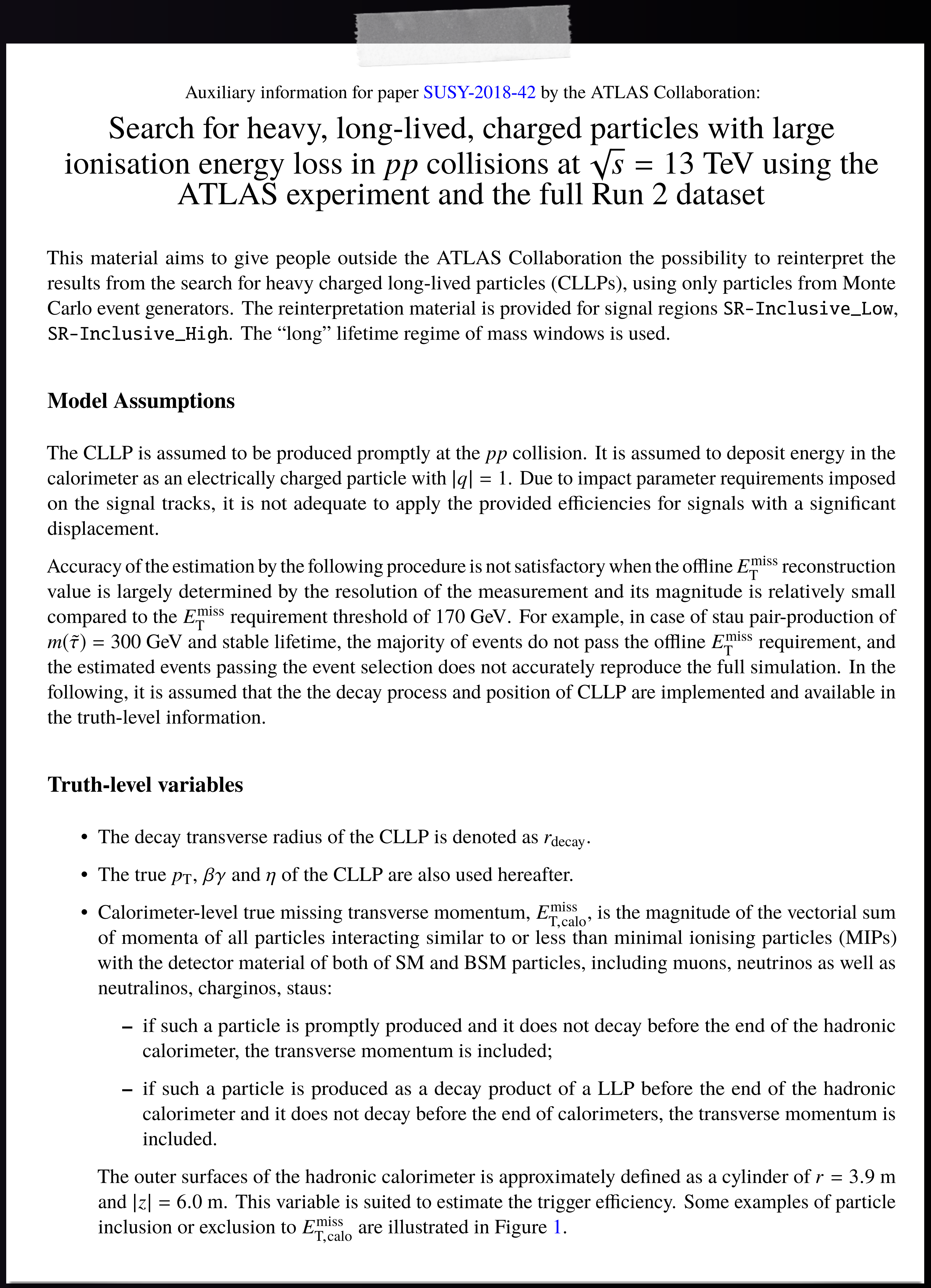




⇒ Dedicated presentation: Y. Mino (Thu Morning)

Re-interpretation Derivarables: Strategy





Auxiliary information for paper SUSY-2018-42 by the ATLAS Collaboration:

Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS experiment and the full Run 2 dataset

This material aims to give people outside the ATLAS Collaboration the possibility to reinterpret the results from the search for heavy charged long-lived particles (CLLPs), using only particles from Monte Carlo event generators. The reinterpretation material is provided for signal regions SR-Inclusive_Low, SR-Inclusive_High. The "long" lifetime regime of mass windows is used.

Model Assumptions

The CLLP is assumed to be produced promptly at the pp collision. It is assumed to deposit energy in the calorimeter as an electrically charged particle with $|q| = 1$. Due to impact parameter requirements imposed on the signal tracks, it is not adequate to apply the provided efficiencies for signals with a significant displacement.

Accuracy of the estimation by the following procedure is not satisfactory when the offline $E_{\text{T}}^{\text{miss}}$ reconstruction value is largely determined by the resolution of the measurement and its magnitude is relatively small compared to the $E_{\text{T}}^{\text{miss}}$ requirement threshold of 170 GeV. For example, in case of stau pair-production of $m(\tilde{\tau})$ = 300 GeV and stable lifetime, the majority of events do not pass the offline $E_{\text{T}}^{\text{miss}}$ requirement, and the estimated events passing the event selection does not accurately reproduce the full simulation. In the following, it is assumed that the the decay process and position of CLLP are implemented and available in the truth-level information.

Truth-level variables

- The decay transverse radius of the CLLP is denoted as r_{decay}.
- The true p_{T}, $\beta\gamma$ and η of the CLLP are also used hereafter.
- Calorimeter-level true missing transverse momentum, $E_{\text{T,calo}}^{\text{miss}}$, is the magnitude of the vectorial sum of momenta of all particles interacting similar to or less than minimal ionising particles (MIPs) with the detector material of both of SM and BSM particles, including muons, neutrinos as well as neutralinos, charginos, staus:
  - if such a particle is promptly produced and it does not decay before the end of the hadronic calorimeter, the transverse momentum is included;
  - if such a particle is produced as a decay product of a LLP before the end of the hadronic calorimeter and it does not decay before the end of calorimeters, the transverse momentum is included.

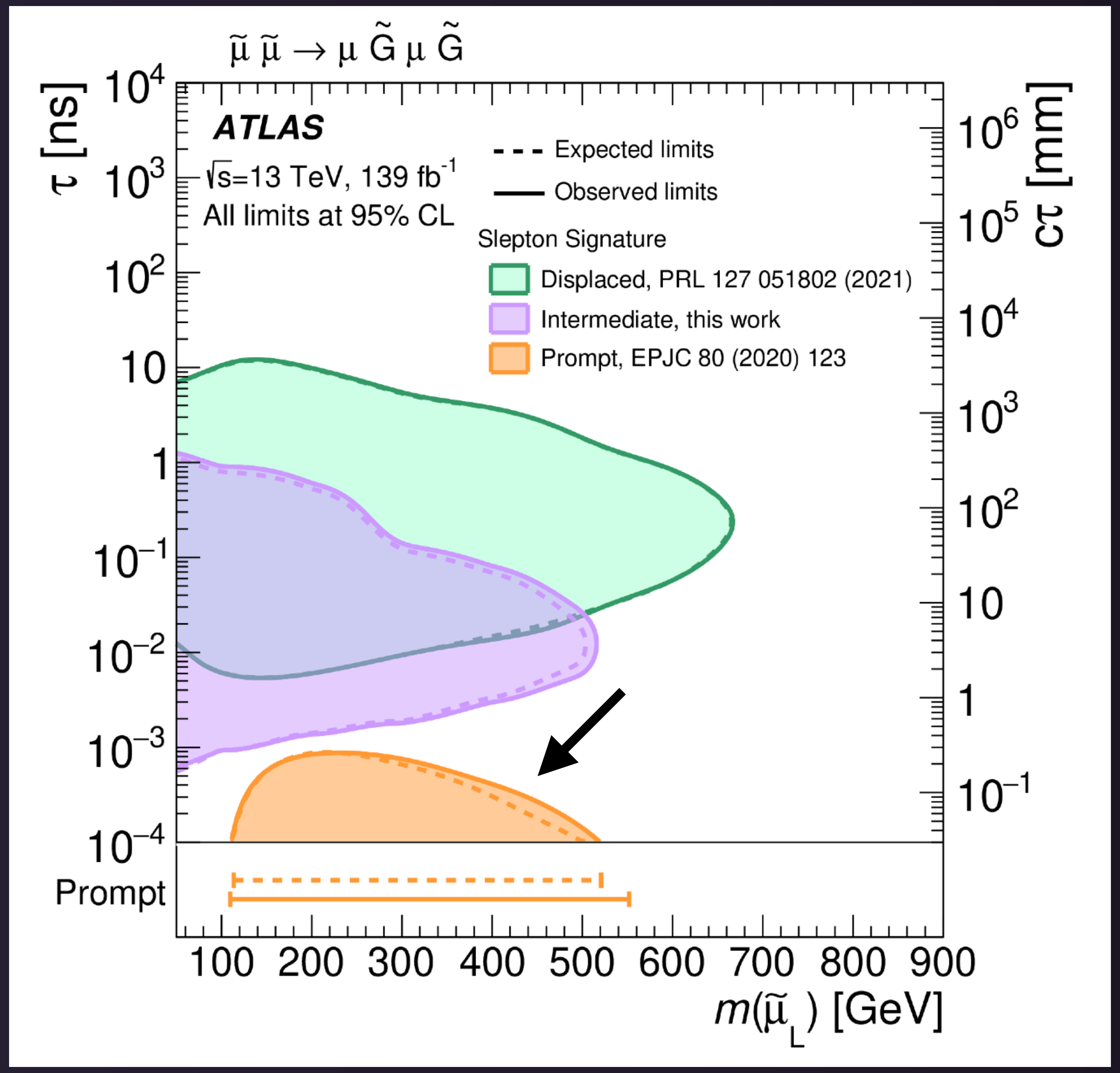
  The outer surfaces of the hadronic calorimeter is approximately defined as a cylinder of r = 3.9 m and $|z|$ = 6.0 m. This variable is suited to estimate the trigger efficiency. Some examples of particle inclusion or exclusion to $E_{\text{T,calo}}^{\text{miss}}$ are illustrated in Figure 1.

- Usage of LLP reinterpretation material published in HepData has basic applicability limitations, provided the signature event phase space would be much broader than benchmark signal samples can effectively probe.
- Non-triviality of such limitations are attempted to be clarified as possible.
- Detailed presentation on this topic in the *2018 LLP workshop*.

Prompt Search Inference to LLPs

ATLAS EXPERIMENT

PLB 846 (2023) 138172 SUSY-2020-09



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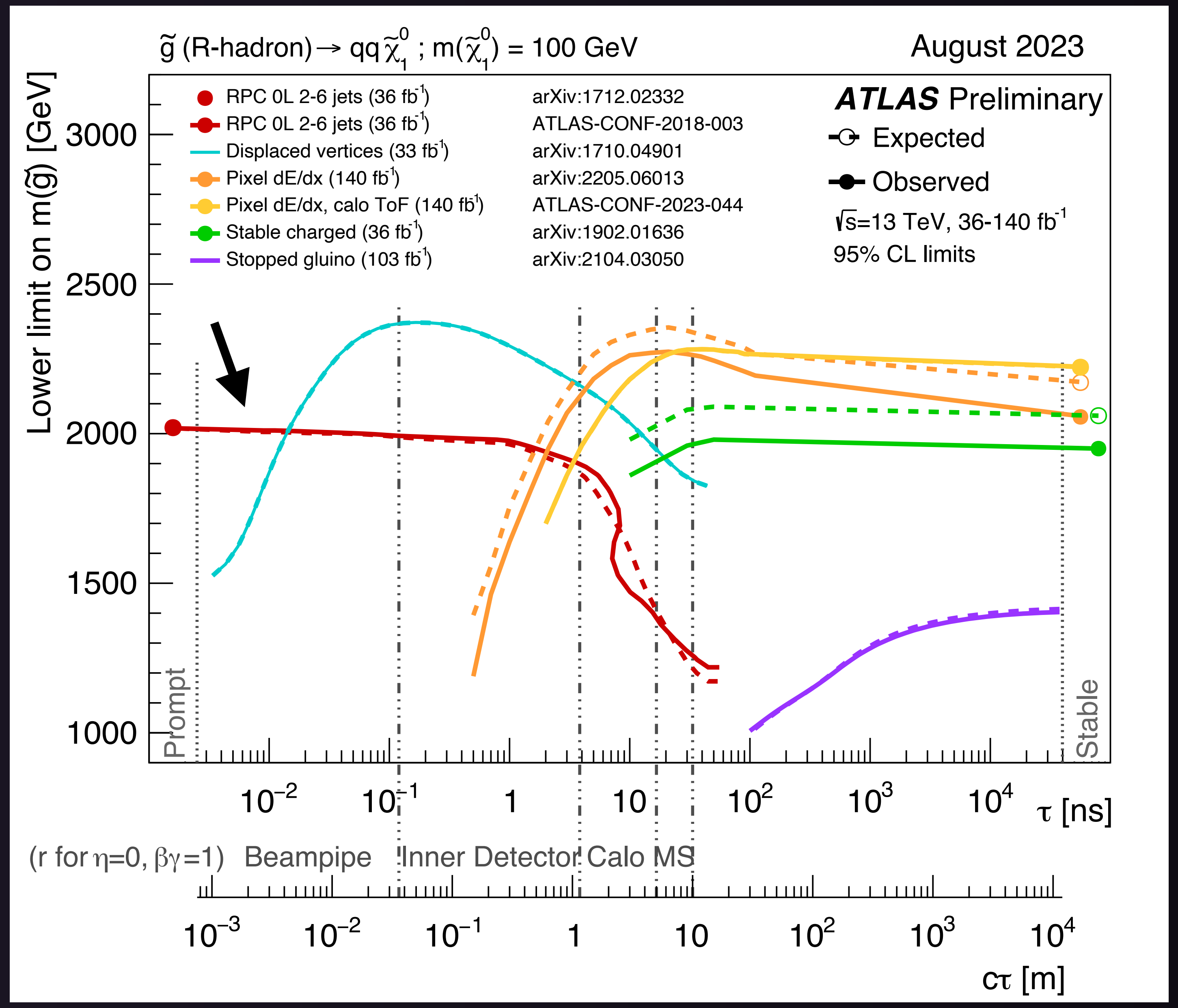

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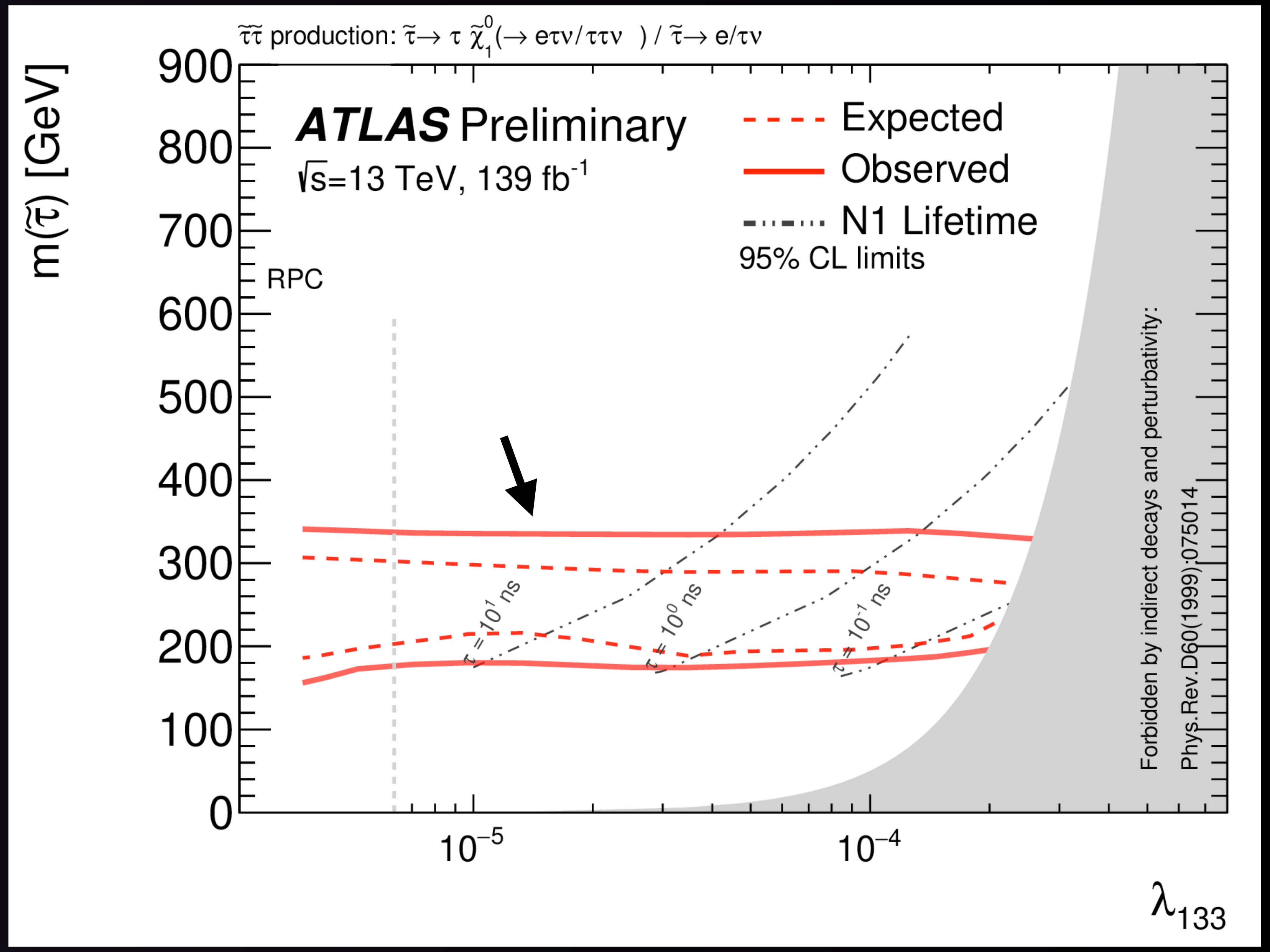

- Prompt searches are "indiscernible limit" of LLP searches!
- Re-interpretation of prompt searches effectively complements LLP searches where LLP techniques hit the "wall" of SM backgrounds.
- Illustrative examples: GMSB sleptons (from m_{T2} search), gluino R-hadrons (from SUSY 0-lepton), R-parity-conserving (RPC) to R-parity violation (RPV) (from EWK di-tau search)

Schematic Data Flow Evolution

- Reconstruction & Data Production workflow have largely changed from Run 1 to Run 3.
- Data flow scheme is largely determined by available computing resources.
- Major impacts on LLP search analysis timeline and available features.

Technical Advancement: Track Reconstruction

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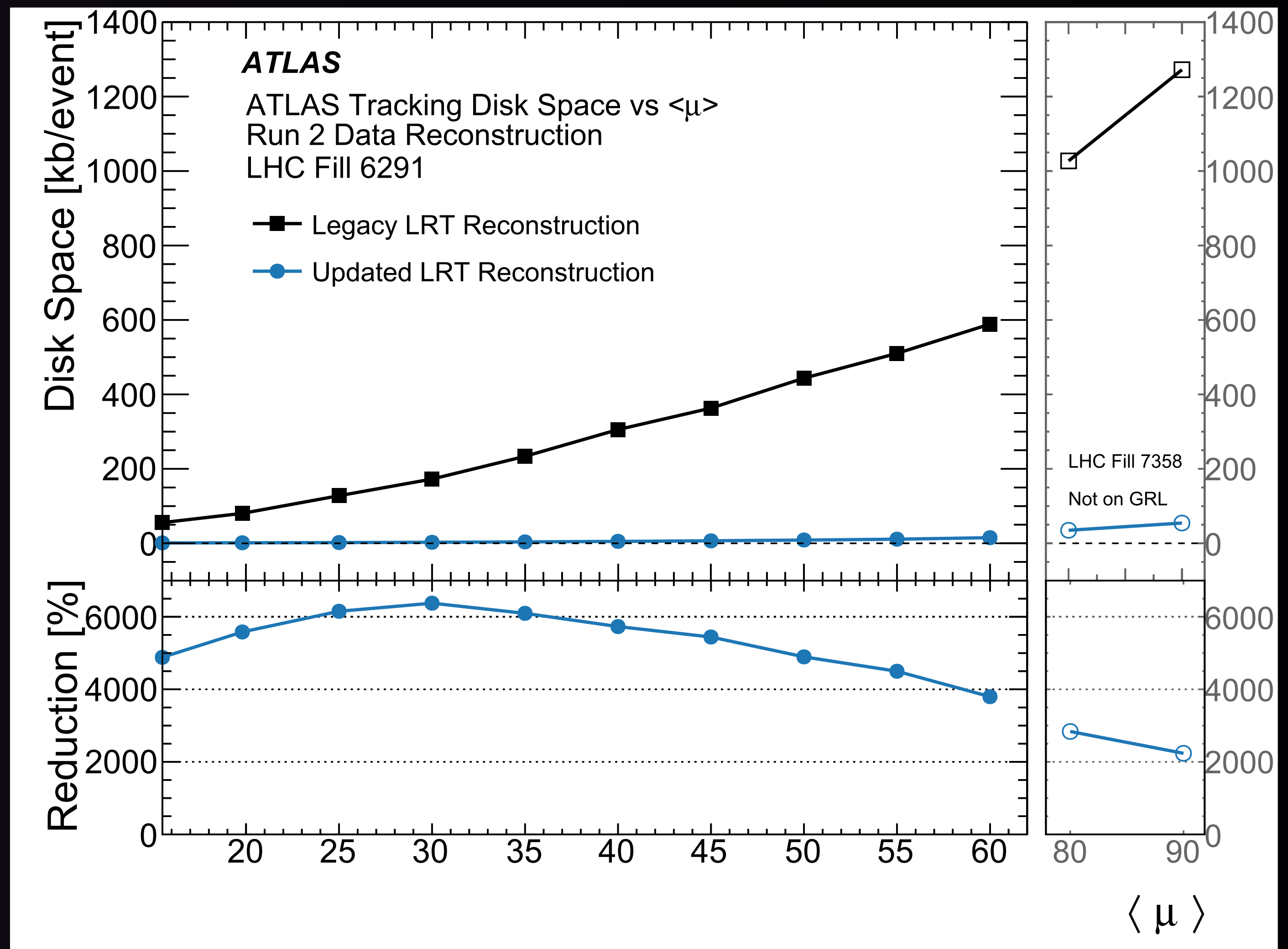
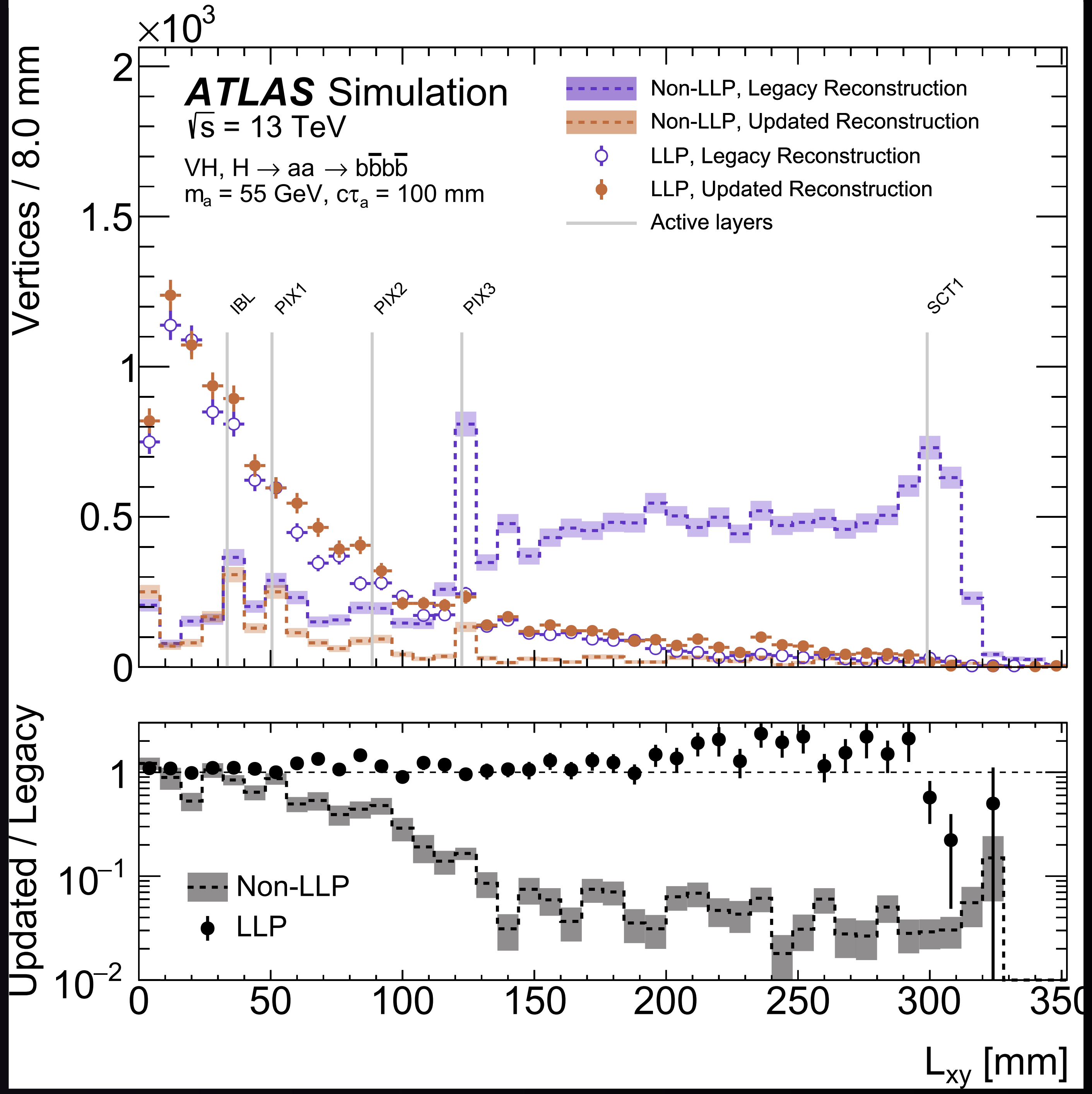
EPJC (2023) 83:1081

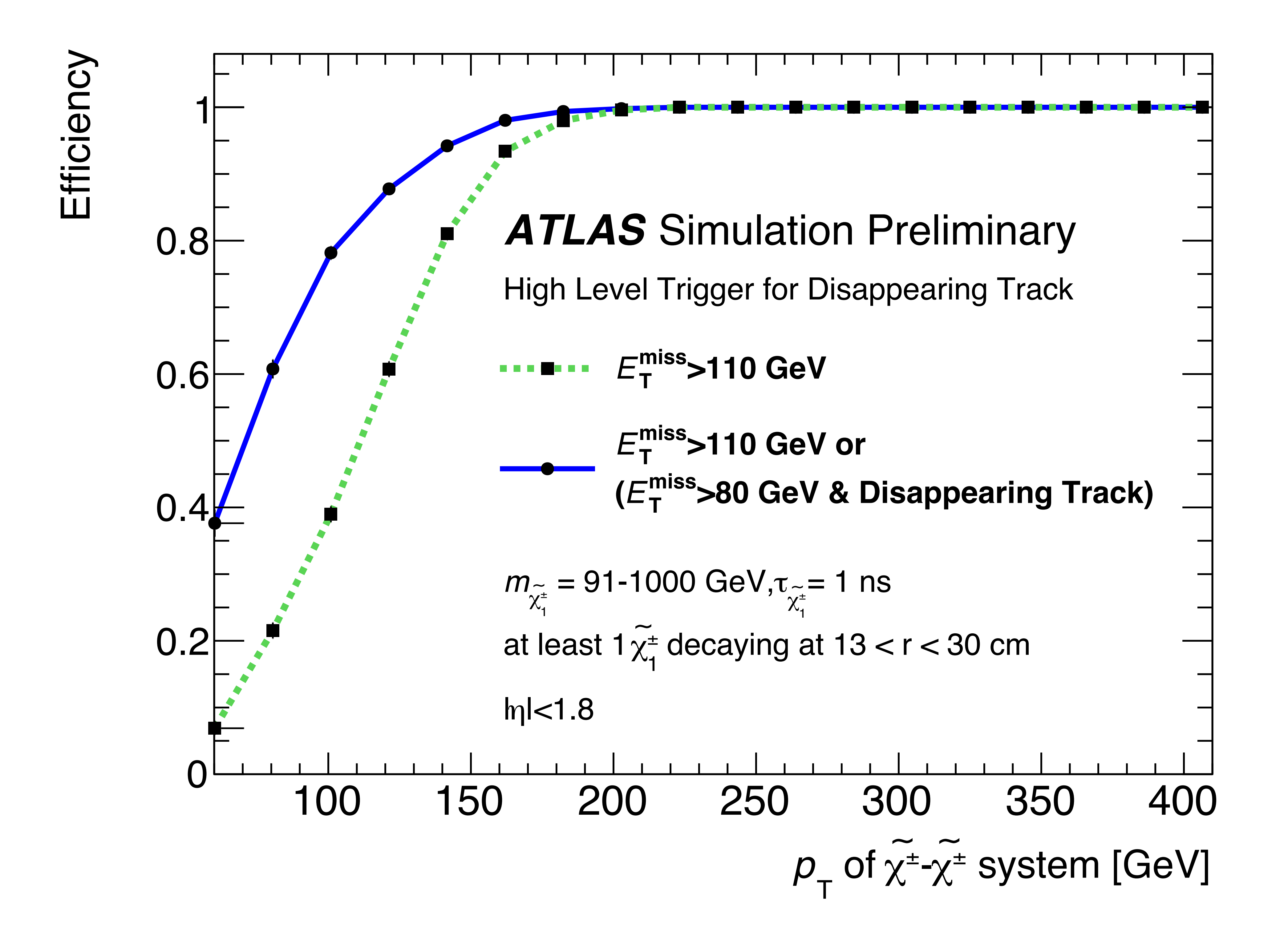
- ❖ LLP-dedicated extended tracking (large-d_0 tracking)
  $\Longrightarrow$ ATLAS Jargon: Large-Radius Rracking (LRT)
  - ▸ An additional track finding only using the left-over hits.
  - ▸ Extending up to $|d_0| < 300\ \mathrm{mm}$ (near the 1st strip layer).
- ❖ LRT in Run 2: specially processed for exclusive RAW data samples reserved for LLP searches.
  - ▸ While efficiency for real particles is high, both the CPU cost and the amount of fake track rate were high.
  - ▸ Acceptable in Run 2, as this "distilled" data sample size is small.
  - ▸ Somewhat vulnerable against pileup: CPU cost and fake rate.
- ❖ Run3: re-optimization of the LRT algorithm.
  - ▸ Strategy-#1: Find & quit seeking the fake tracks as early as possible.
  - ▸ Strategy-#2: Significantly reduce fake tracks by optimizing selections.
- ❖ Significantly robust against pileup.
  - ▸ "Standardizing" LRT as a part of the nominal reconstruction.
  - ▸ Opening up wide opportunities for LLP searches (also for Run 2 data!)

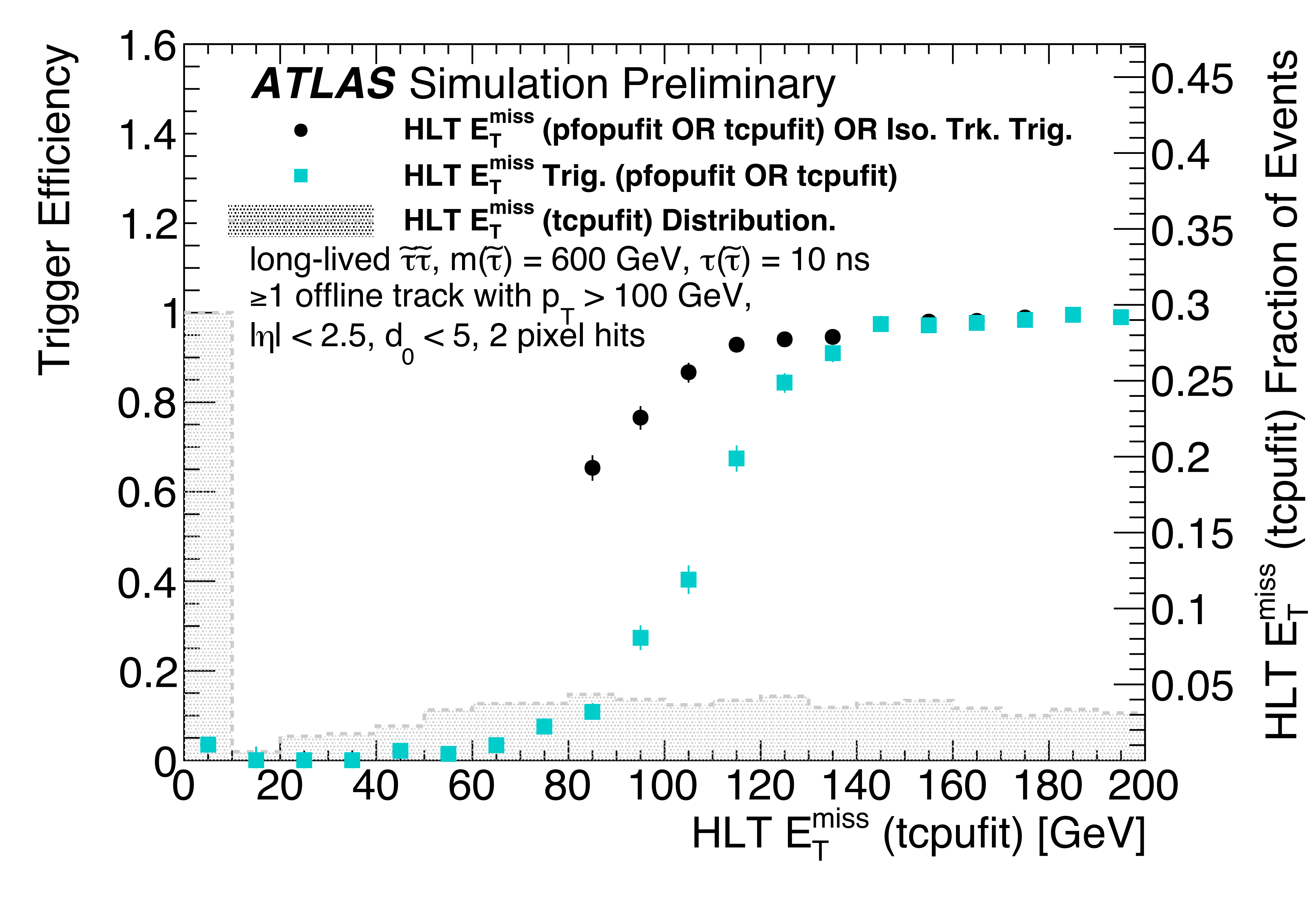




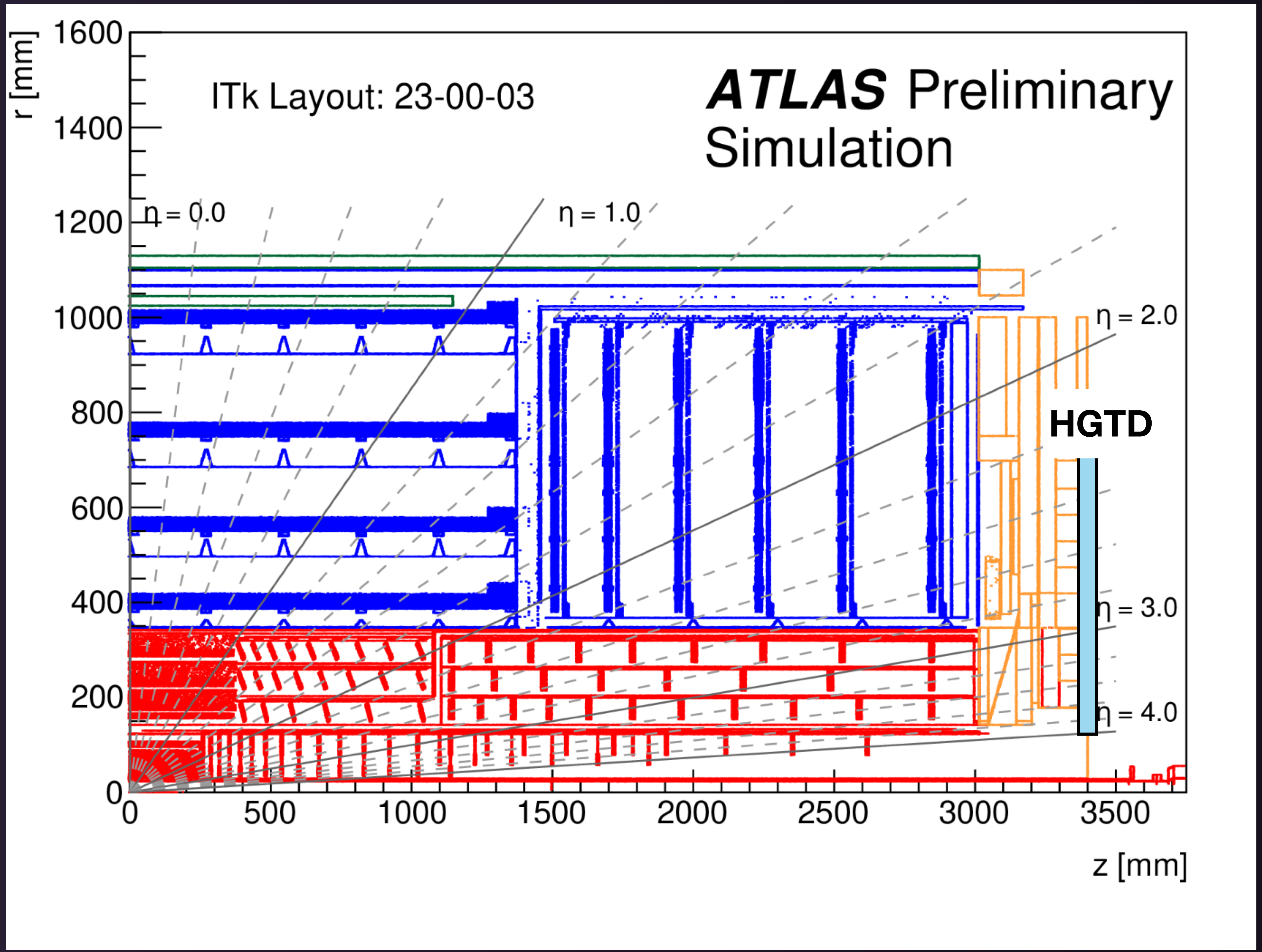
Technical Advancement: Trigger Development

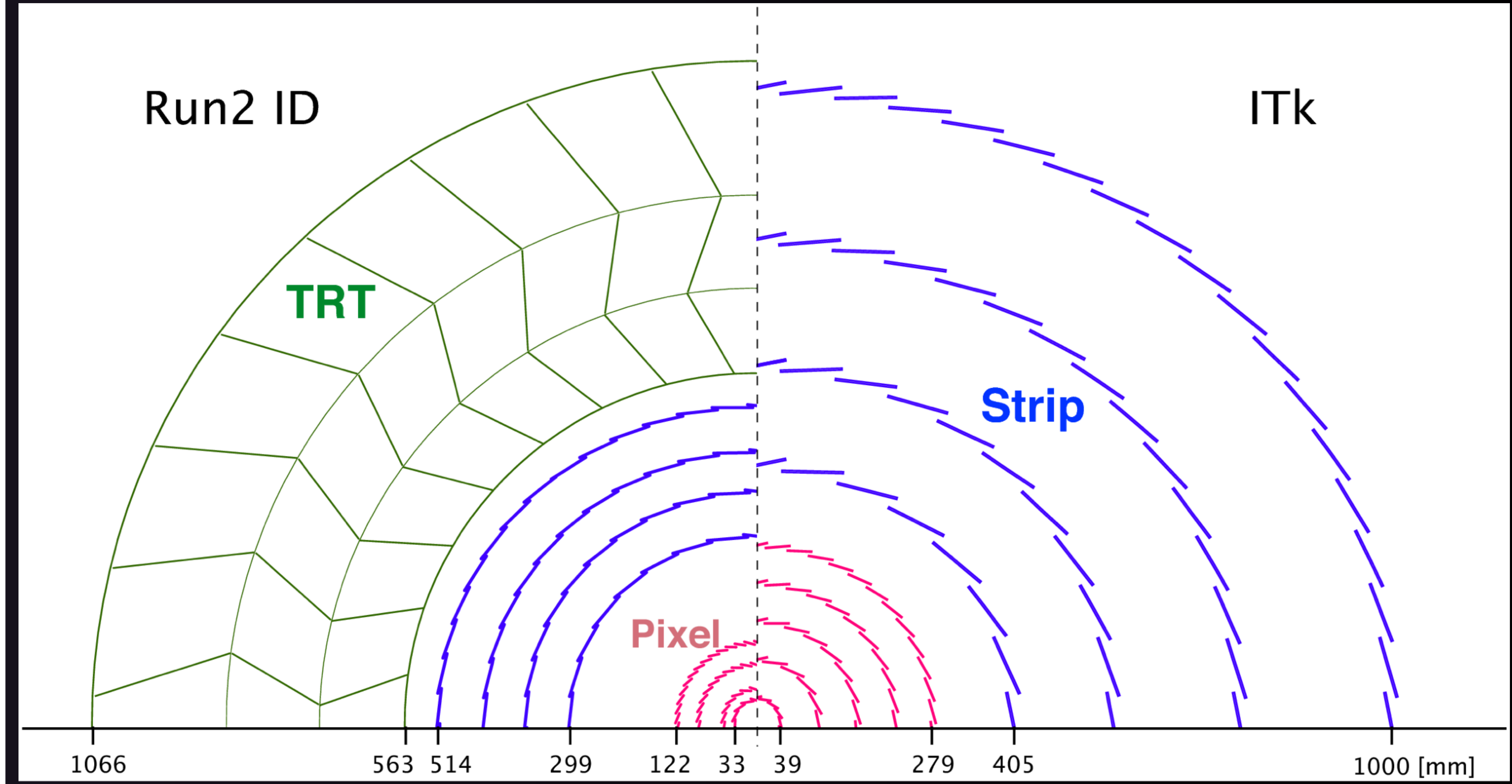
- A number of strong initiatives towards Run 3 for devising LLP-dedicated triggers in High-Level Triggers.
  - Combined with L1, these help to lower thresholds for conventional trigger signatures.
- Much flexibility in implementation of filters for LLP derivation in Run3.





HL-LHC Prospects (Brief)





- Inner Tracker Upgrade will change the game.
  - Layout change: lots of opportunities, but with caveats.
  - Readout change: high data rate acts differently to LLPs than ongoing Inner Detector (e.g. charge measurement)

HL-LHC Prospects (Brief)

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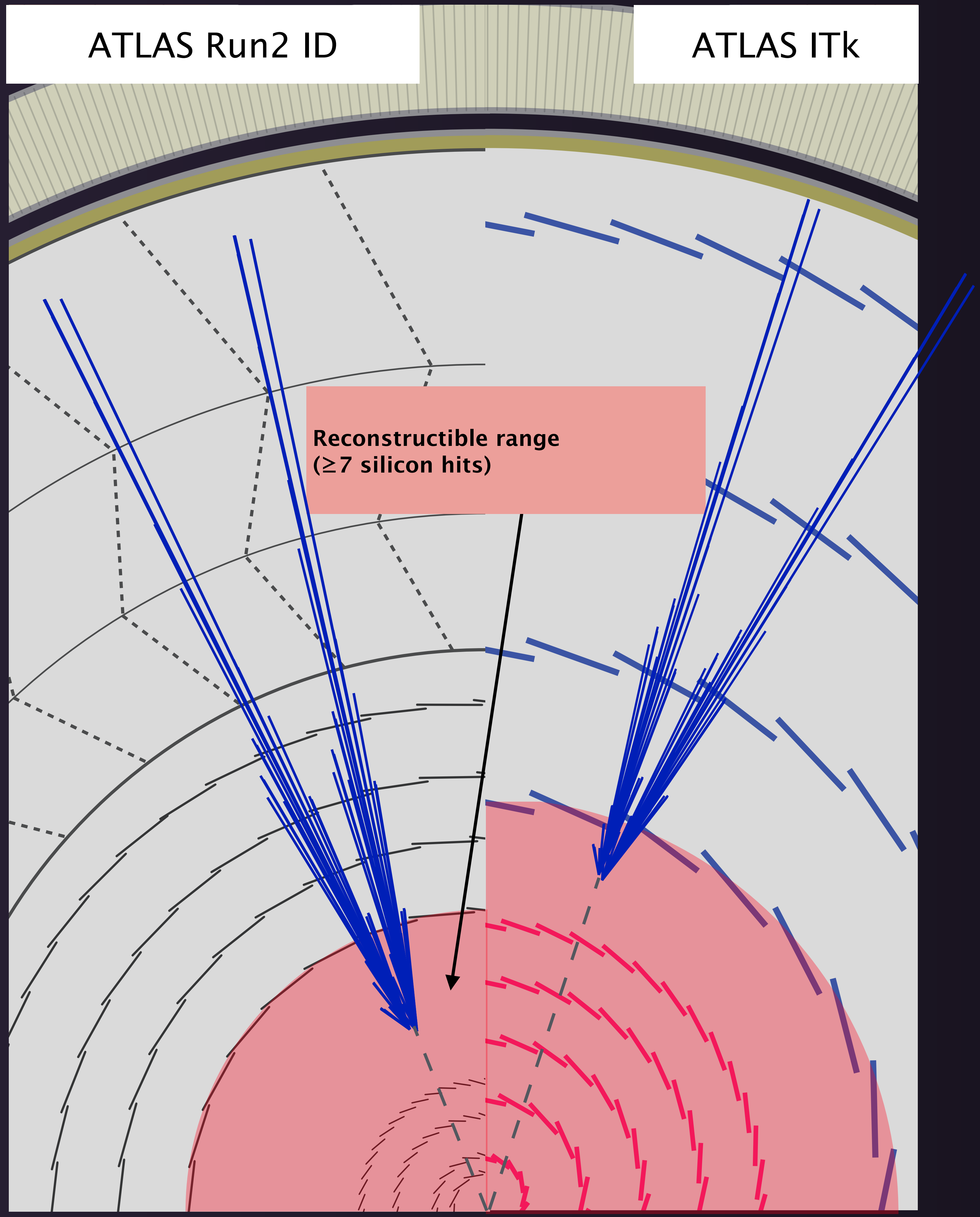
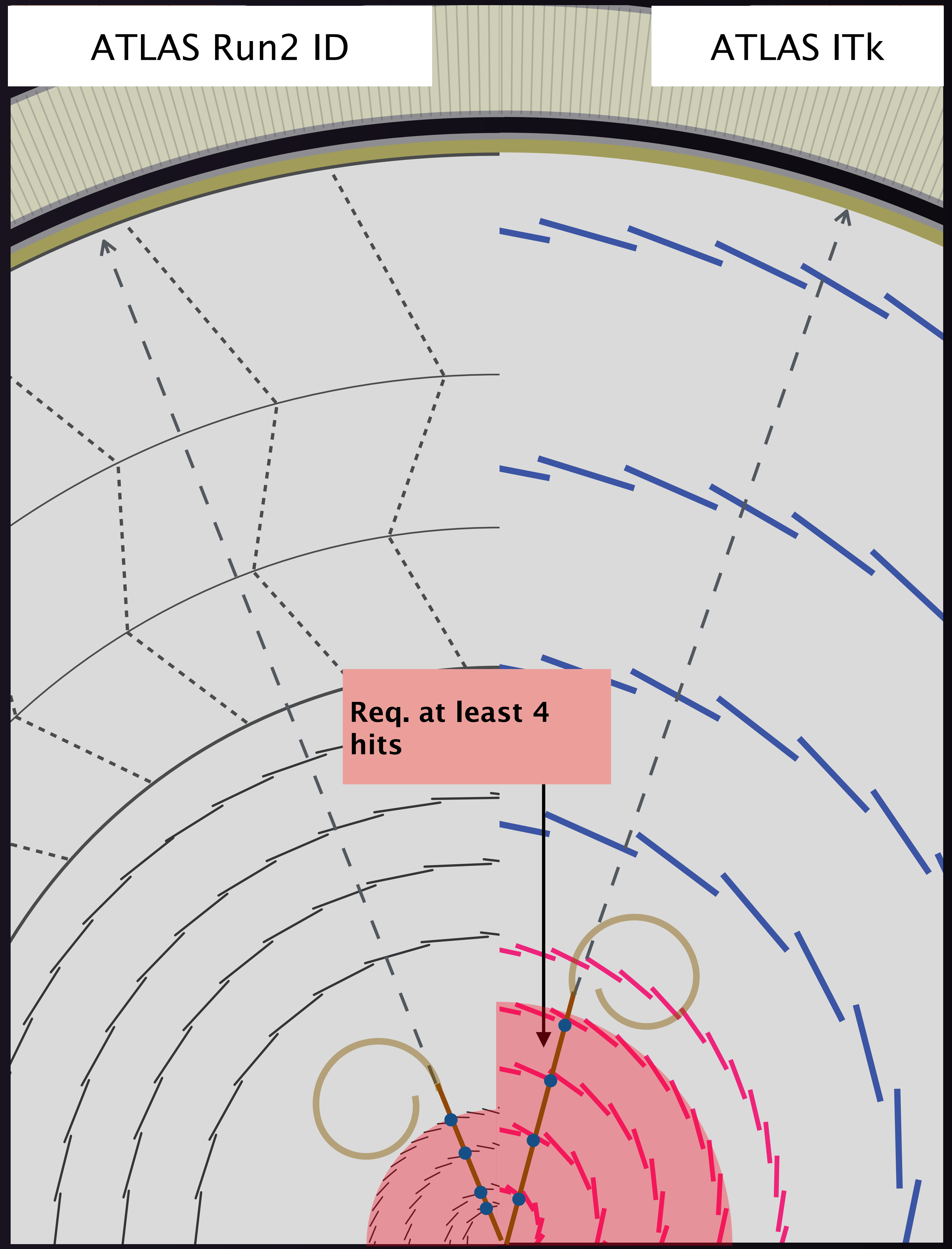
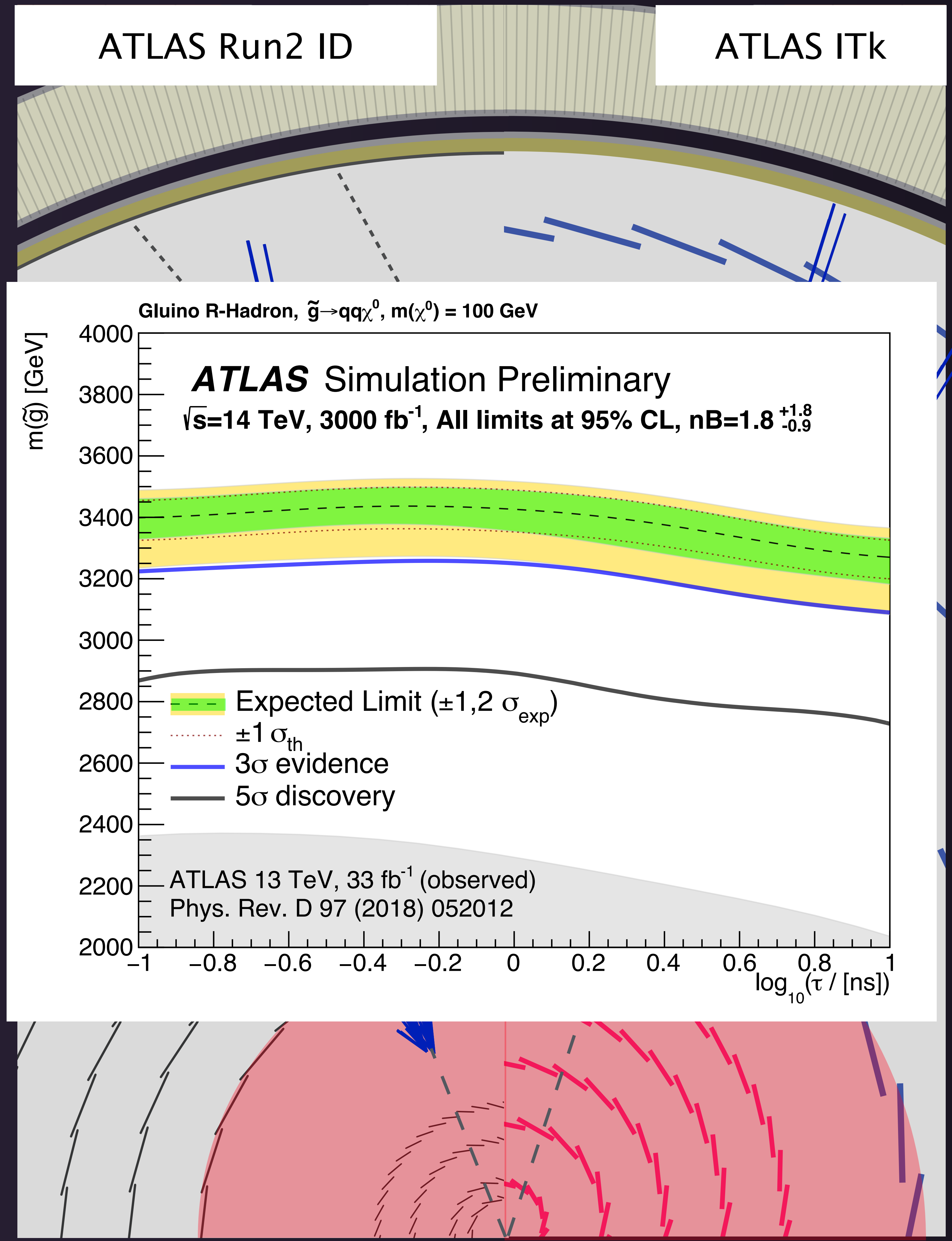
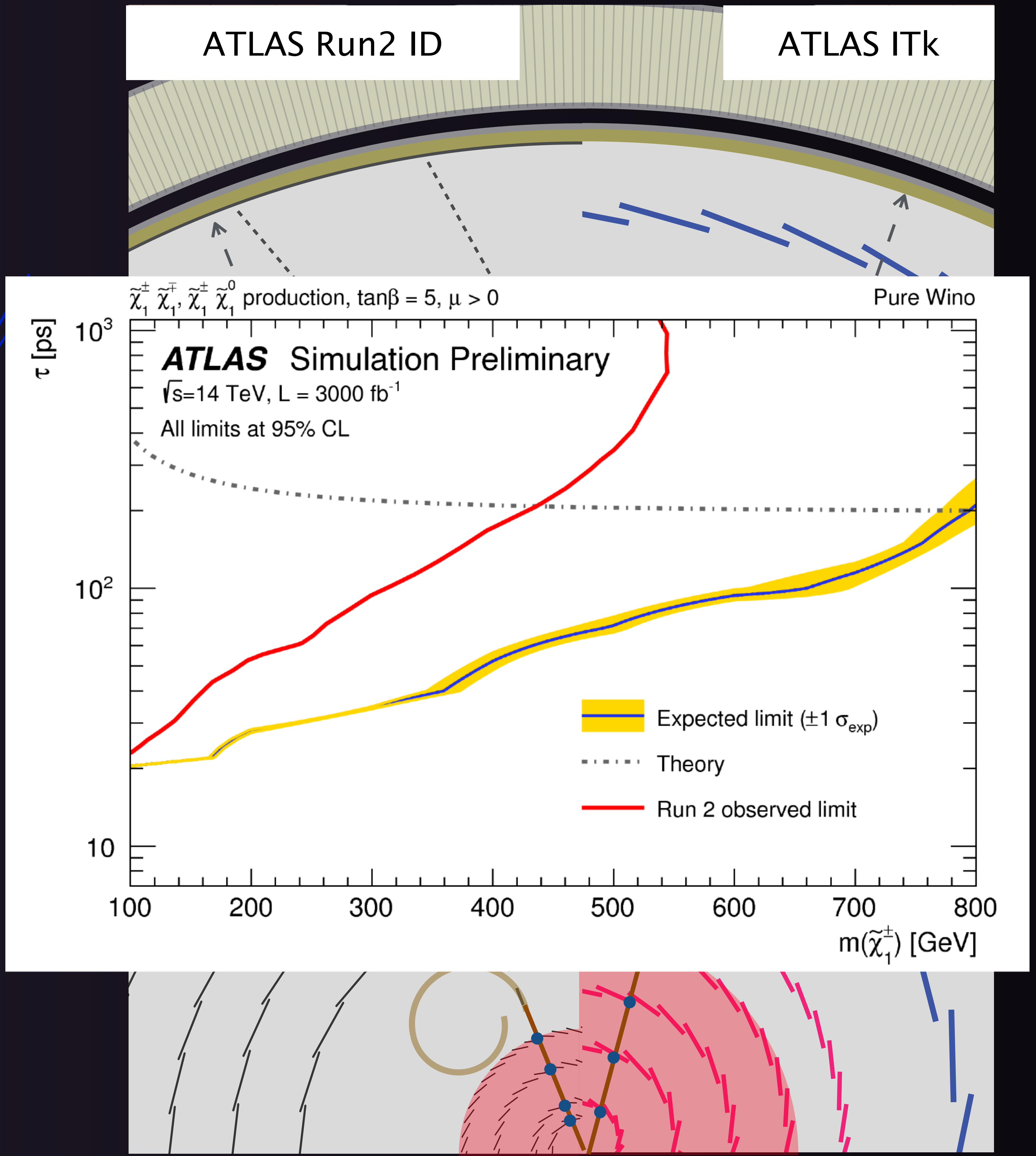




- Inner Tracker Upgrade will change the game.
  - More advantageous for displaced decay tagging.
  - Less acceptance for short lifetime charged LLP searches.
- HGTD timing pads at forward would offer more opportunities than pileup vertices discrimination.

HL-LHC Prospects (Brief)





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Summary

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- ❖ Many LLP searches in ATLAS have bloomed in the middle of Run2.
  - ▸ A number of productive and interesting results have been released.
- ❖ Not just signature-driven!
  - ▸ Can probe many of promising BSM scenarios.
- ❖ Not only riding on growing integrated lumi!
  Continuous evolution and sophistication of search techniques.
  - ▸ Large-radius tracking
  - ▸ Vertexing
  - ▸ Trigger
  - ▸ Reconstruction
  - ▸ Derivation
- ❖ LLP searches will continue to gain search sensitivity in HL-LHC.
  (as this community all aware of) Well anticipated to discover BSM.

We have a rich menu of
Dedicated talks within LLP2024

A.E. Mulski (Wed Morning)	dE/dx + ToF(Calo)
H. Hanif (Thu Morning)	Higgs → DV
Y. Mino (Thu Morning)	Higgsino w/ displaced track
R. González (Thu Afternoon)	Displaced Lepton Jets
A.M. Rodriguez Vera (Thu Afternoon)	HIP/monopole

Backup