Searches for Long-lived Particles in ATLAS

Sandbox Studio/Symmetry Magazine

SIMON FRASER UNIVERSITY

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Dark Interactions 2024

17 October 2024

ATLAS EXPERIMENT

Long-lived particles

Many Beyond Standard Model theories predict **long-lived particles (LLPs)**

- Dark sectors, neutral naturalness, SUSY, …

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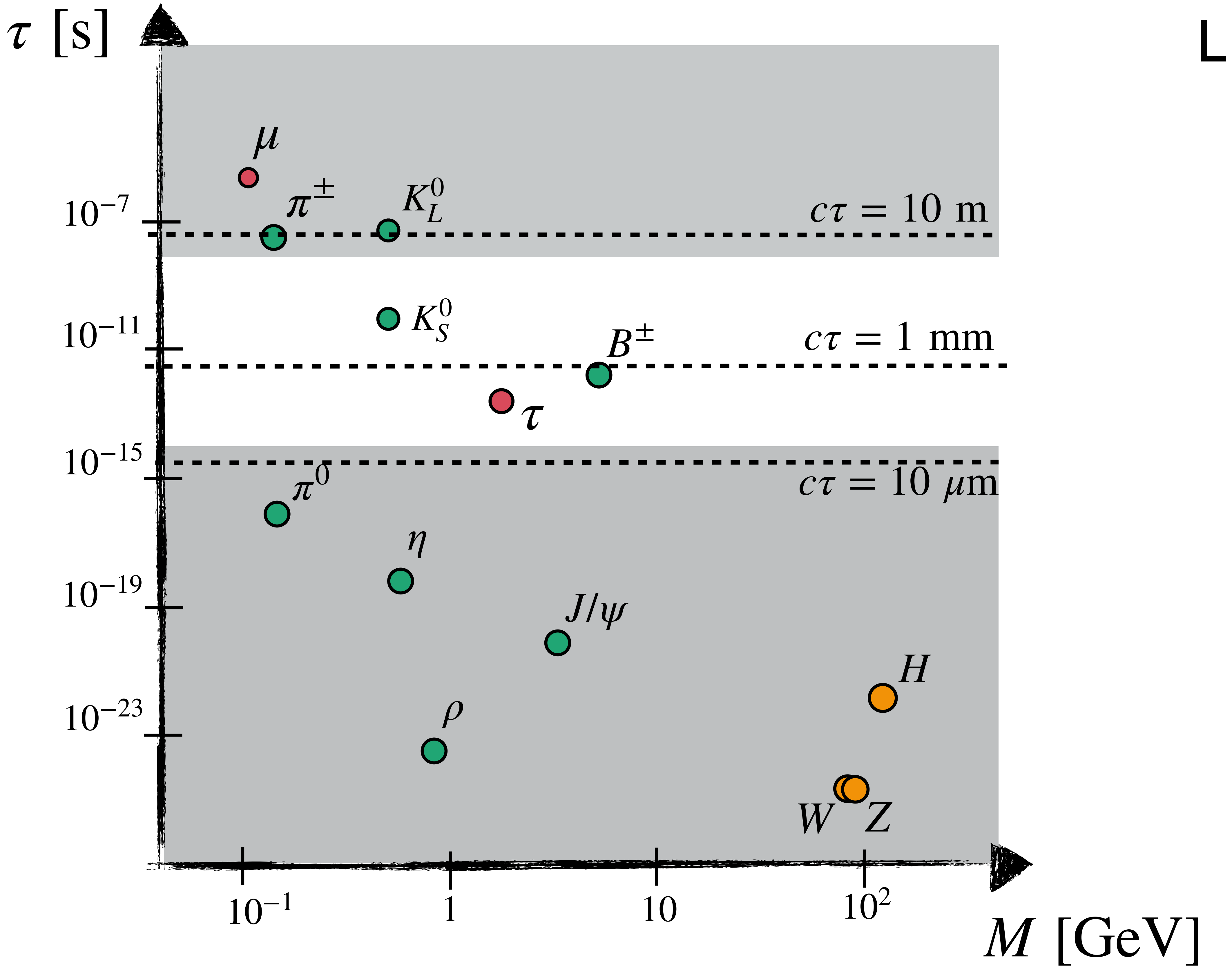

Figure adapted from <u>arxiv:1810.12602</u>

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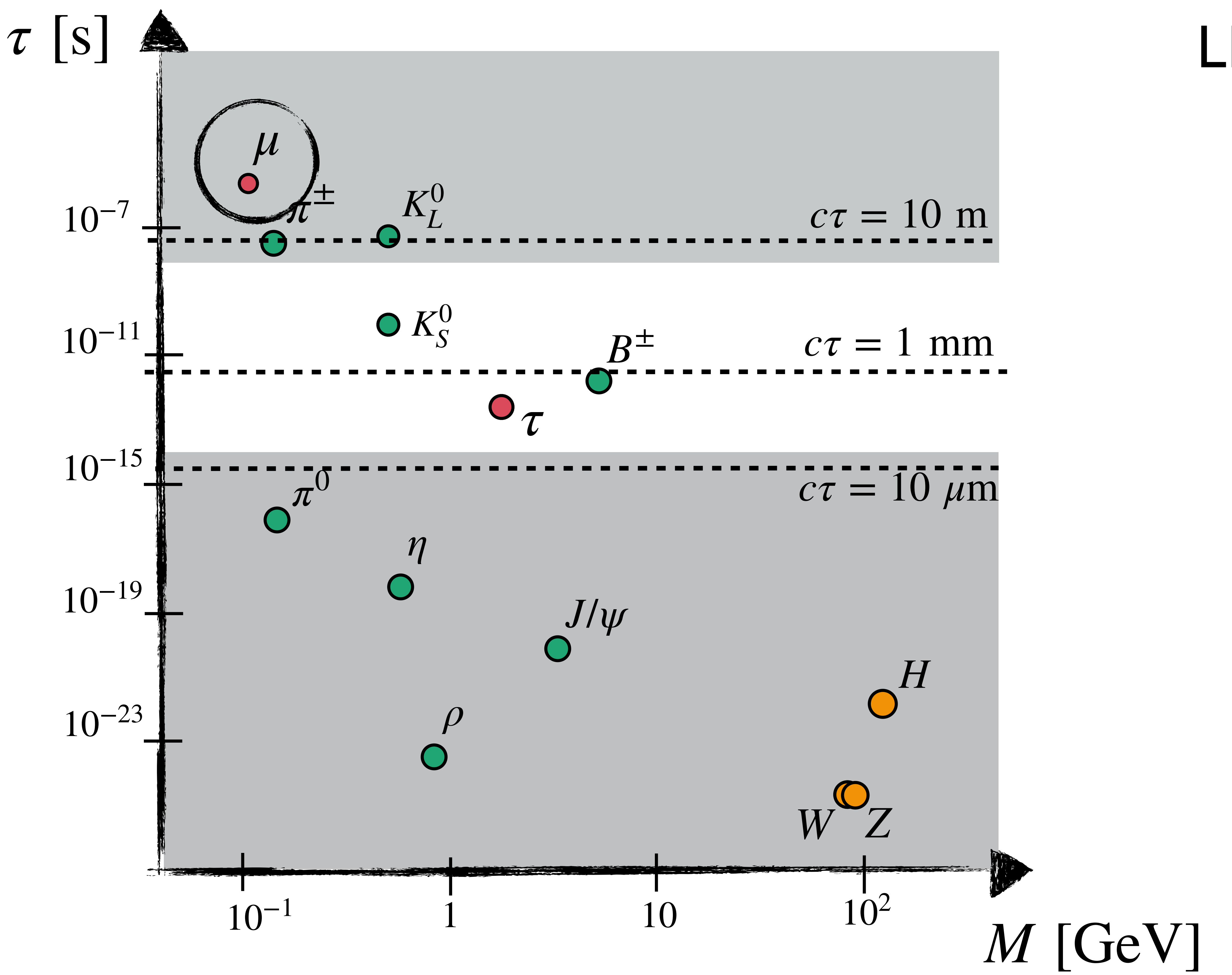

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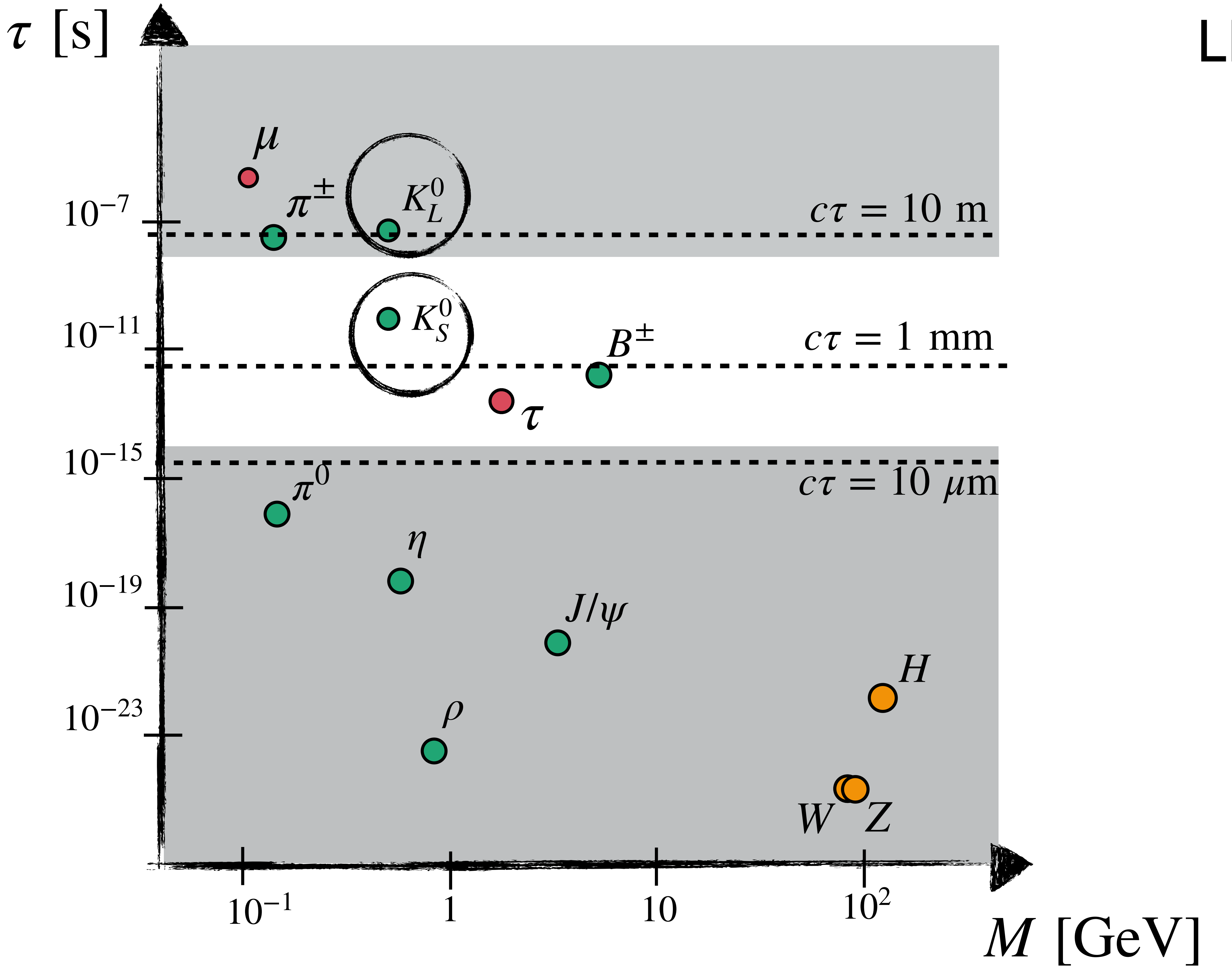

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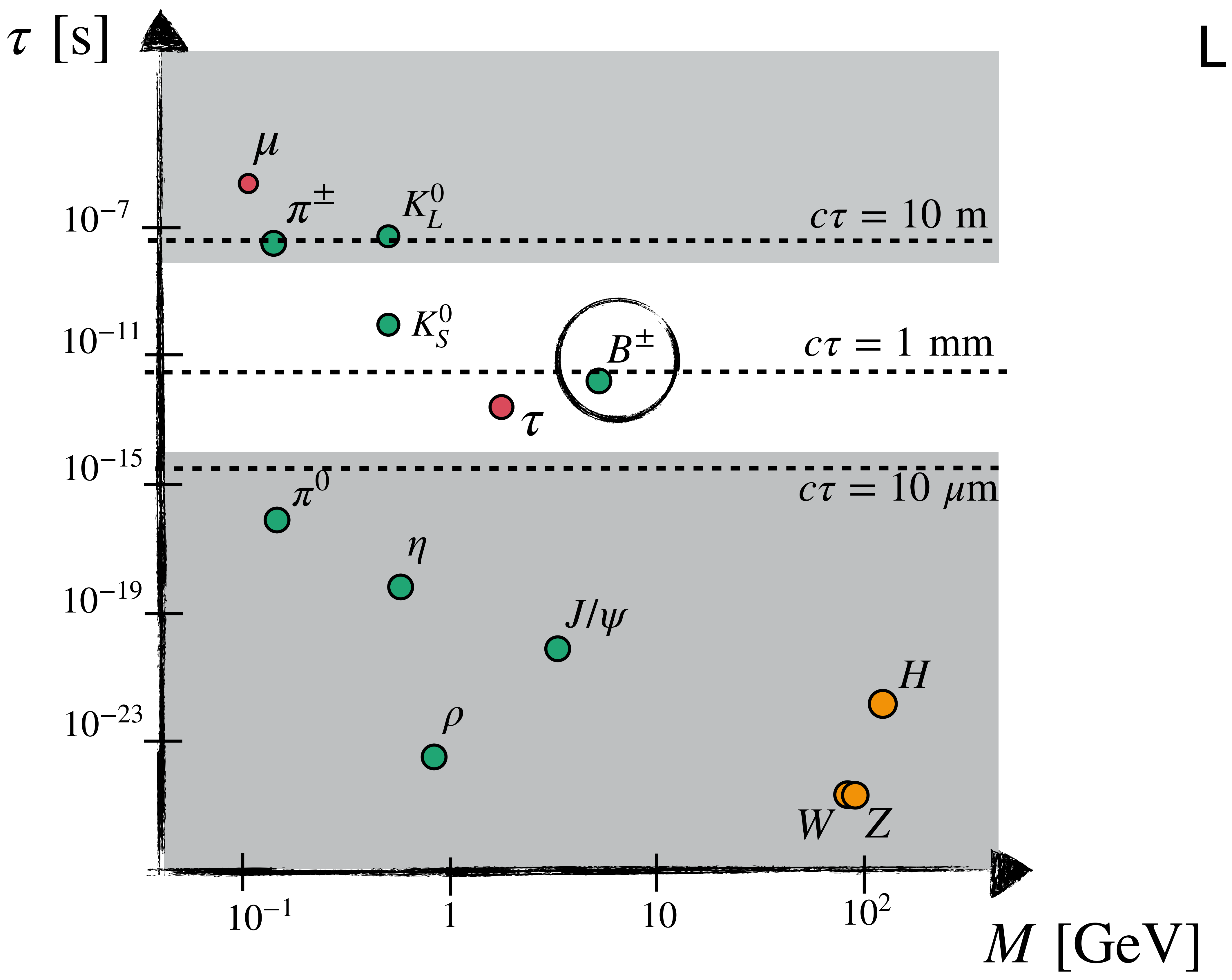

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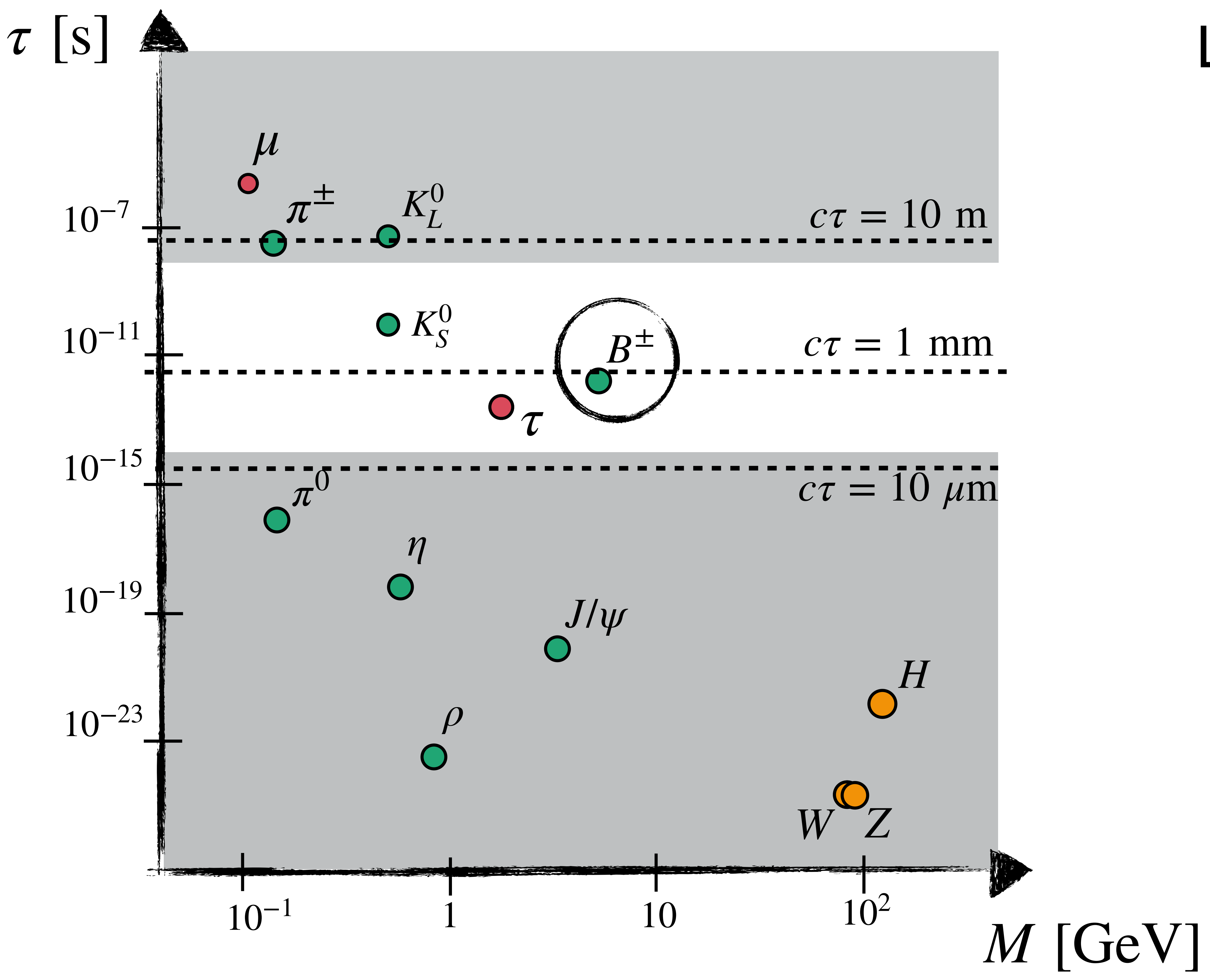

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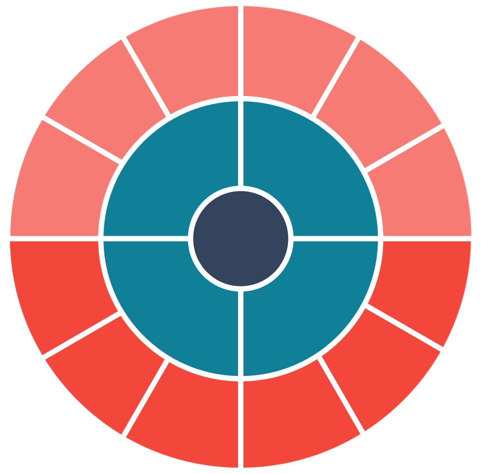
No reason to expect all BSM physics to be prompt!

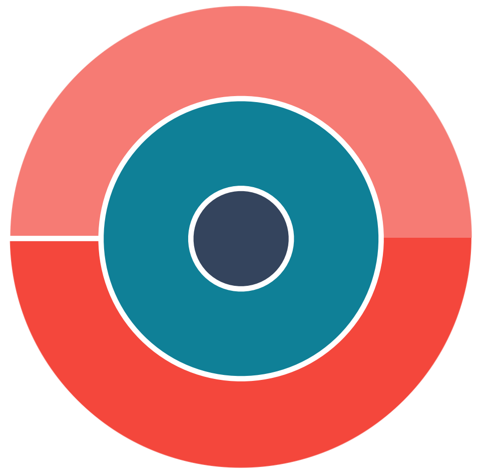
- Any model with small couplings, small mass splittings, or decays via off-shell particles can result in LLPs

LLPs and Dark Sectors

Consider a generic dark sector scenario:

Visible sector





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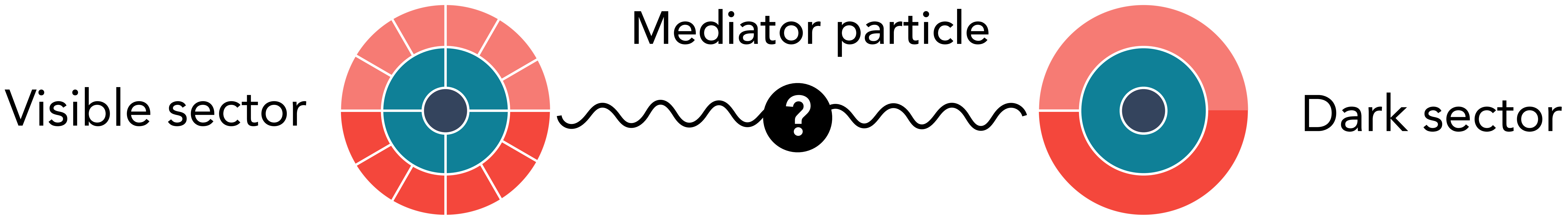

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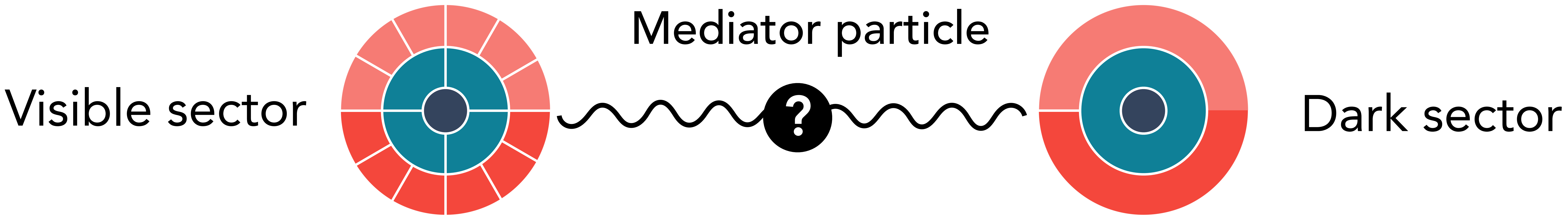
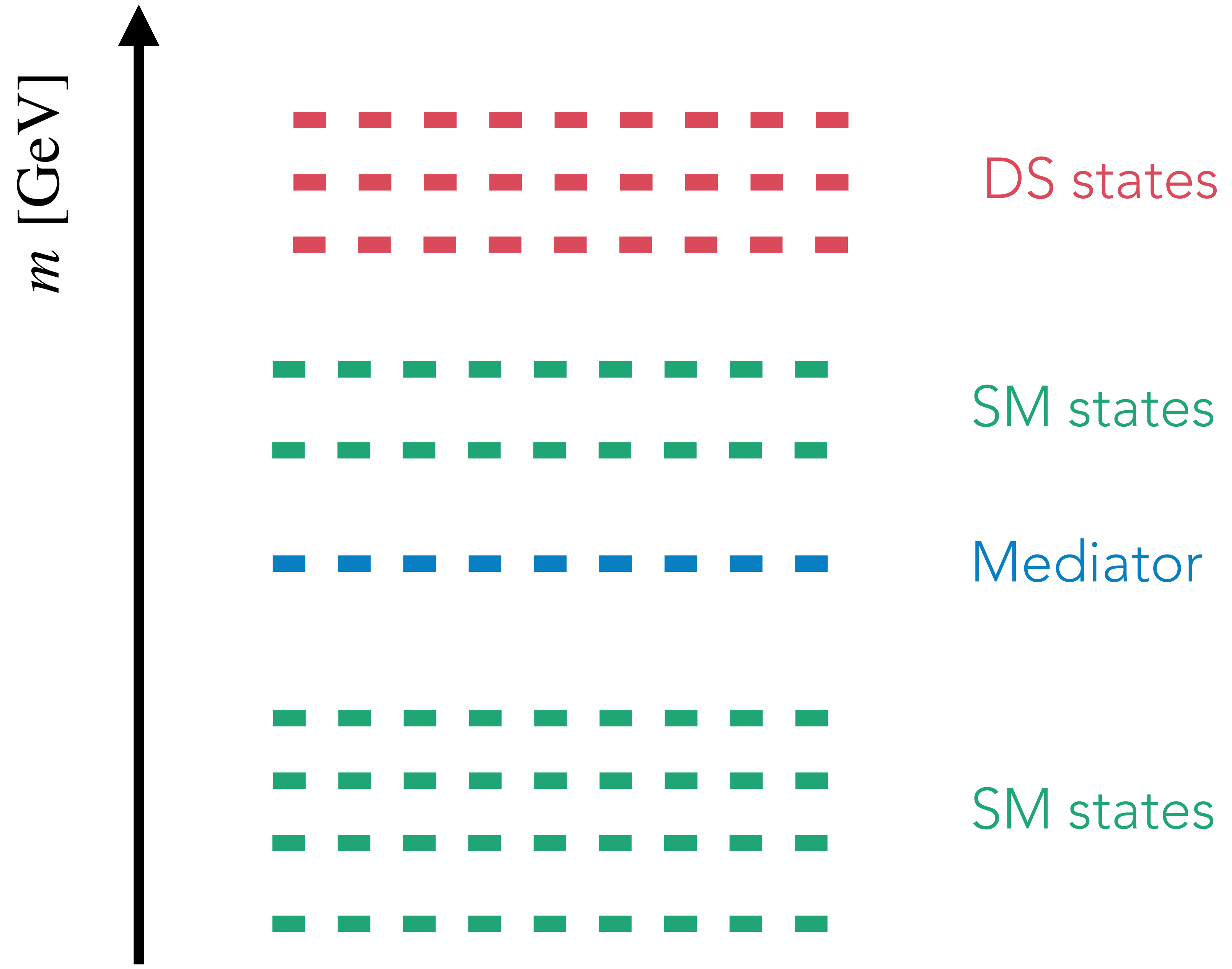


If the the lightest DS state is heavier than $m_{\text{med.}}/2$, decays to DS states will be kinematically forbidden



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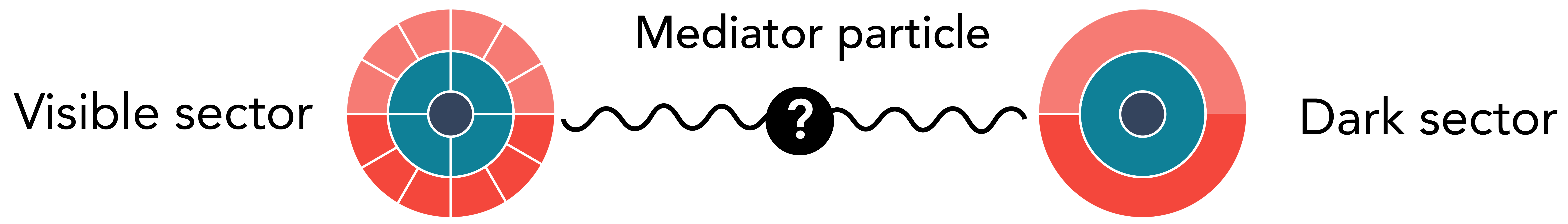

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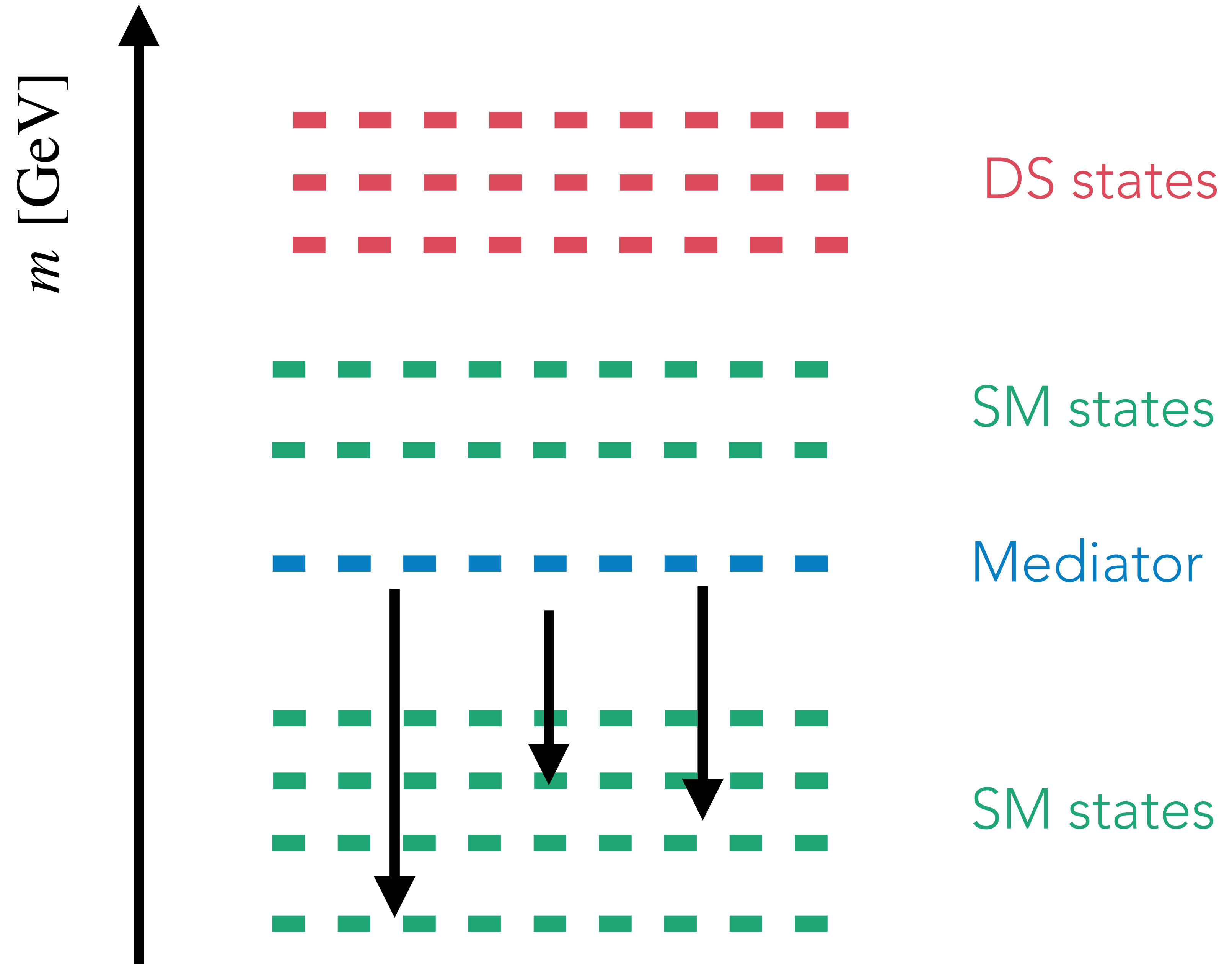

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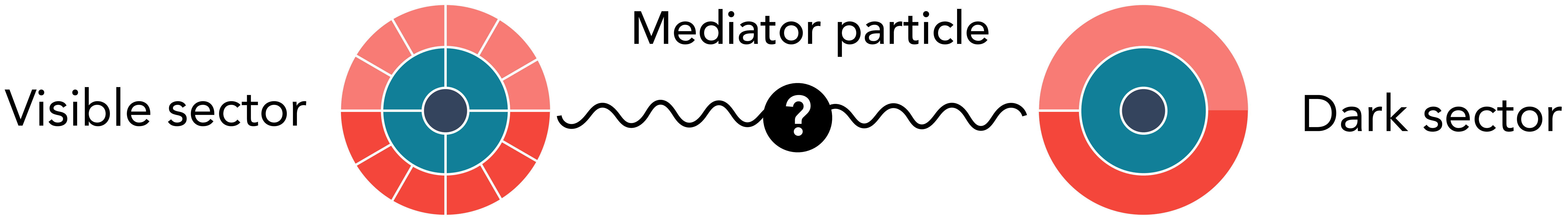

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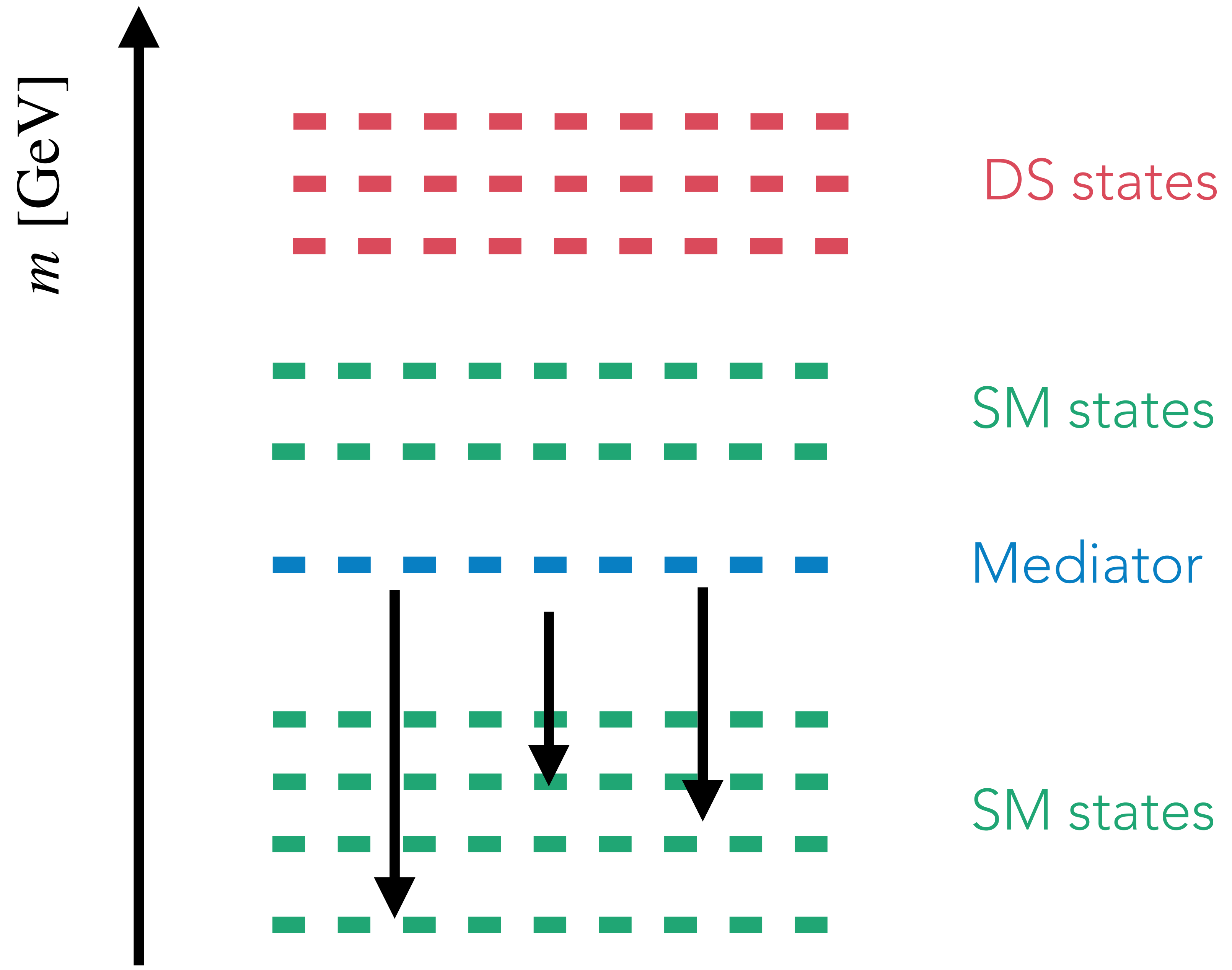
For a weakly coupled dark sector, small coupling between mediator and SM will suppress the decay leading to **long-lived mediator**



Portals between sectors

There are three **renormalizable** portal interactions that guide dark sector phenomenology

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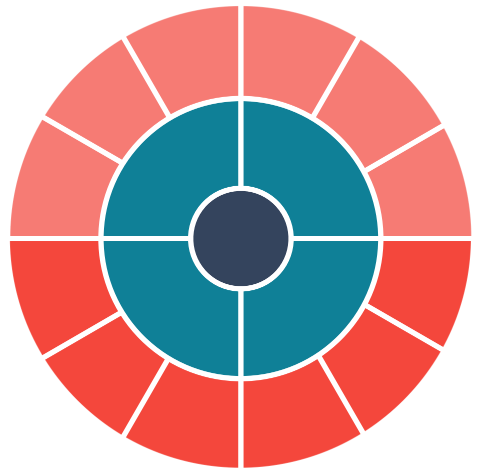
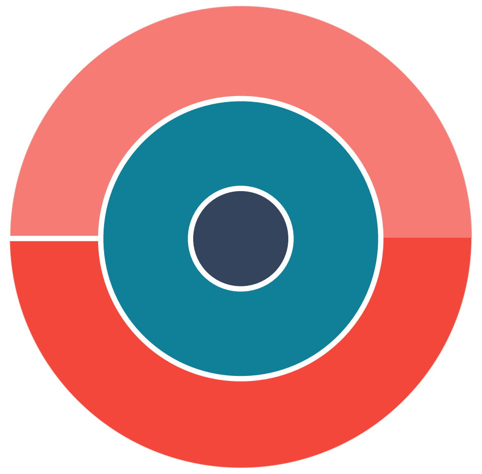


"Scalar portal"

$$h^\dagger h \phi_D^\dagger \phi_D$$

Dark sector



A dark Higgs boson?

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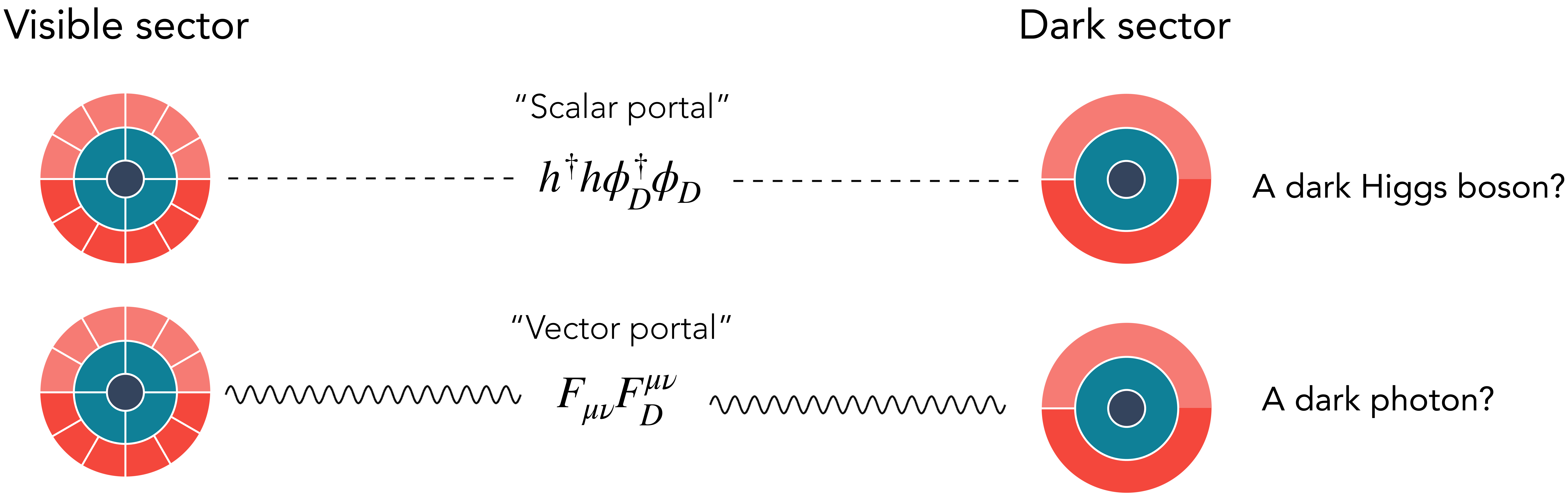

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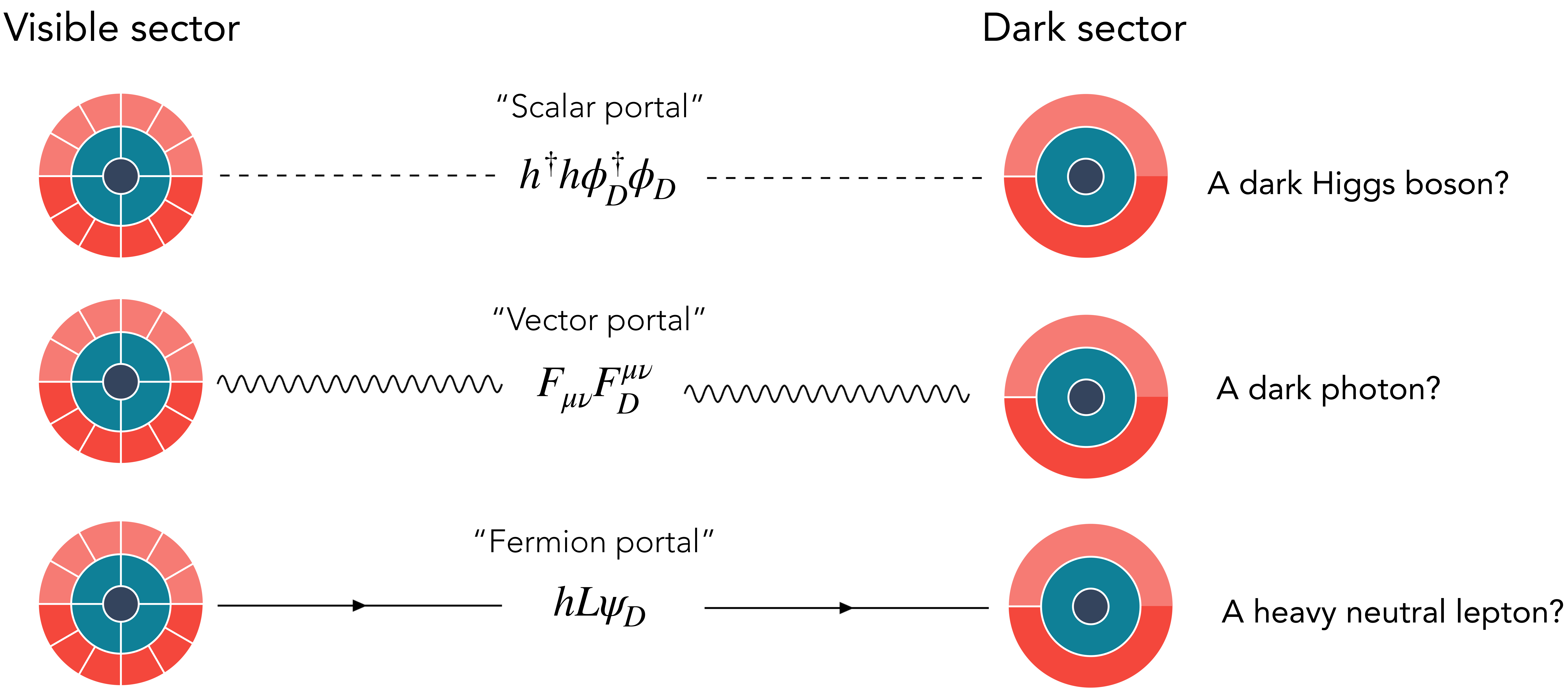

Portals between sectors

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- Very different final states and detector signatures

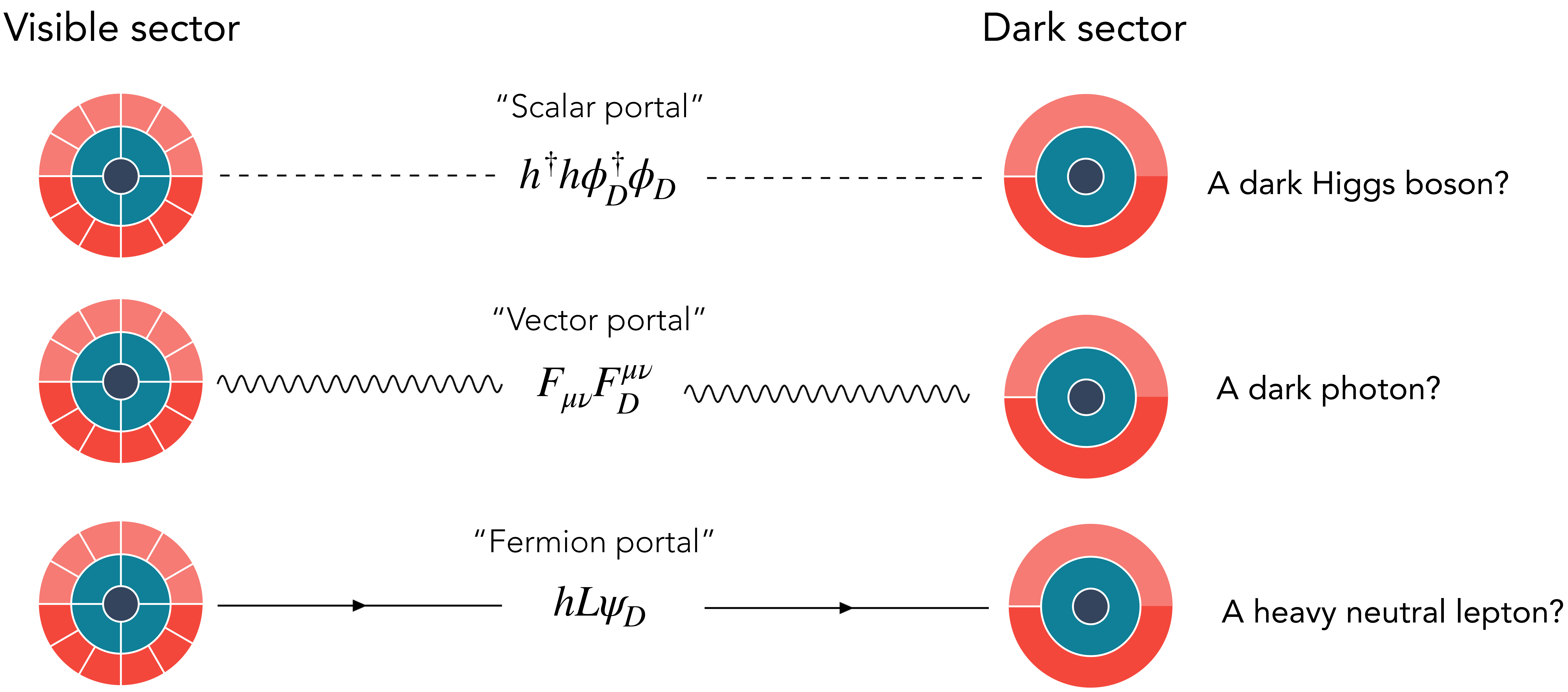

Diagram inspired by Jonathan Feng

Axion-like particles

Beyond renormalizable portals, we can also have **higher-dimensional operators** between SM fields and the mediator

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Axion-like particles (ALPs) are generic pseudo-Nambu-Goldstone bosons associated with the breaking of global $U(1)$ symmetries

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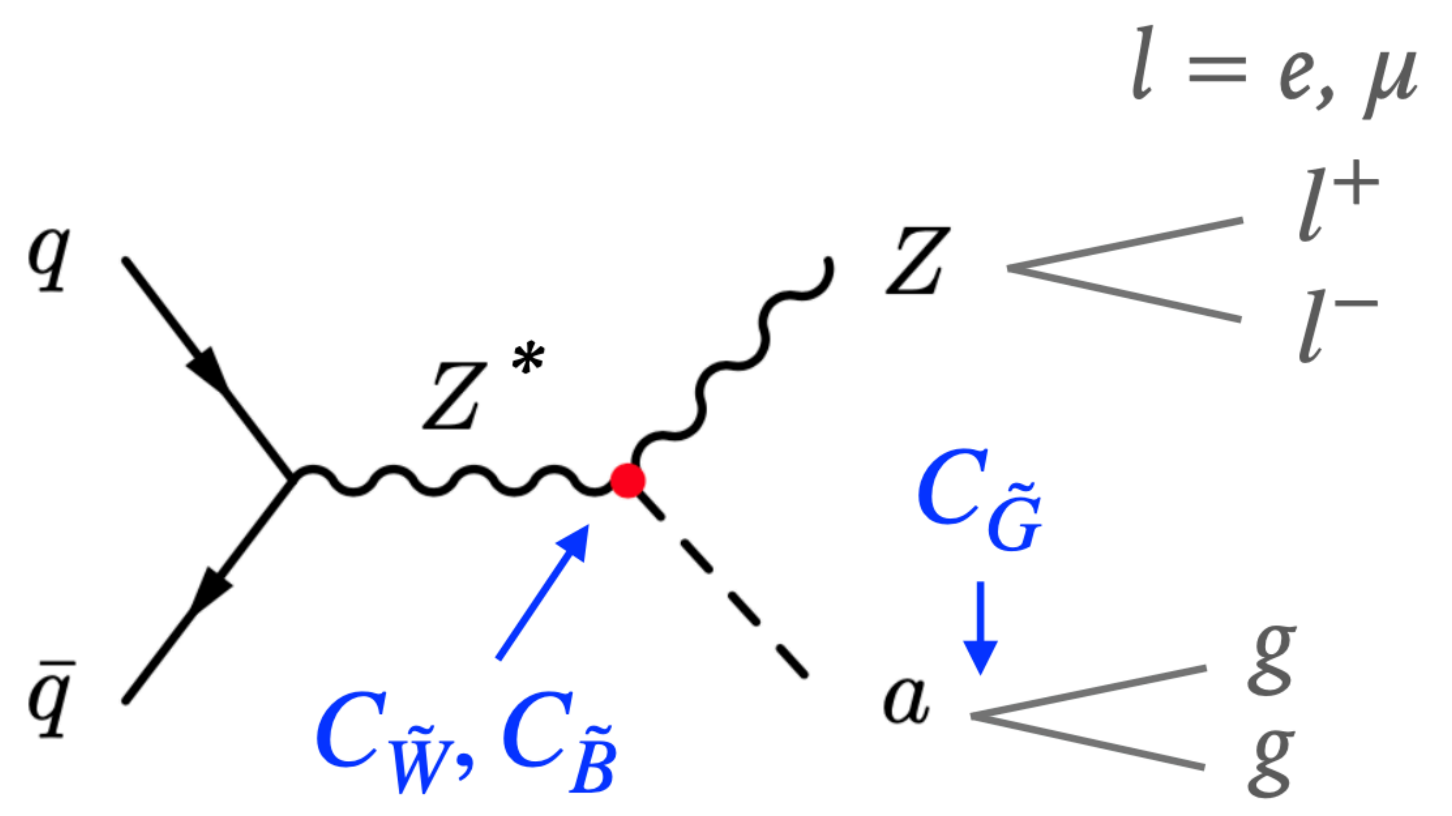
Allows for ALP production in association with vector bosons, and decays to photons and/or gluons

- ALP scale suppresses decays leading to naturally long-lived ALPs

$$\tau_a \propto \frac{f_a^2}{m_a^3}$$



Long-lived SUSY

LLPs are also ubiquitous in various SUSY scenarios:

R-parity violating:

$$\mathscr{W}_{\mathrm{RPV}} = \mu_i \ell_i h_u + \lambda_{ijk} \ell_i \ell_j \bar{e}_k + \lambda'_{ijk} \ell_i q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

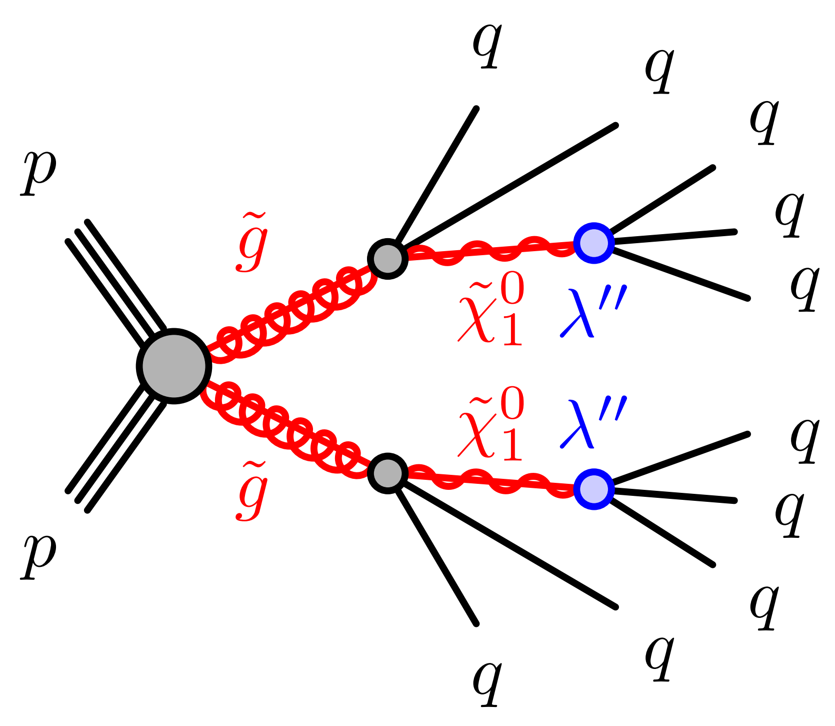
Small λ values suppress decays of SUSY particles leading to long lifetimes

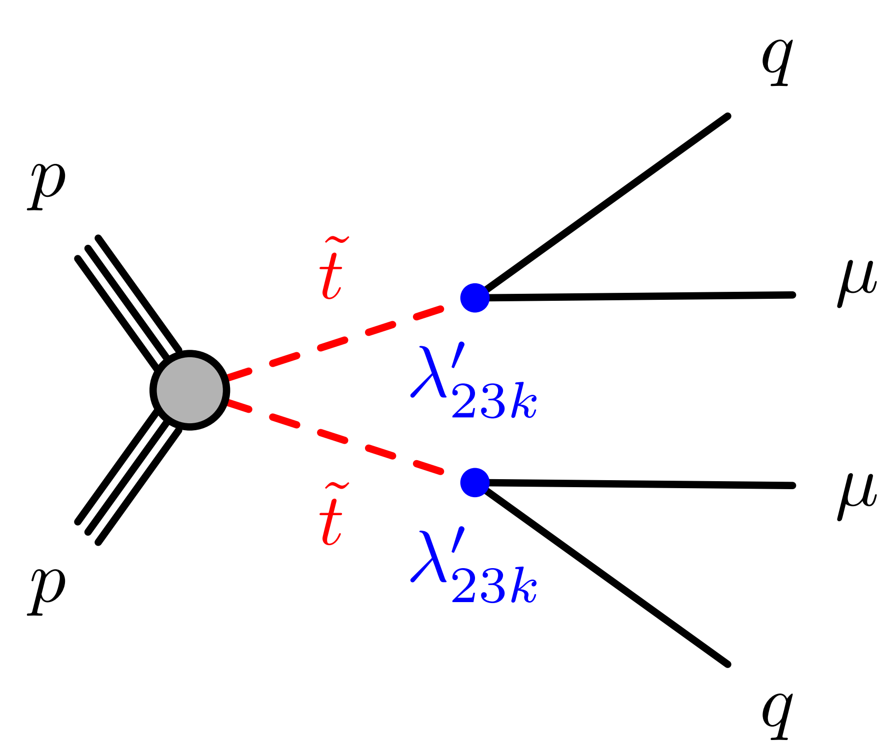
R-parity conserving:

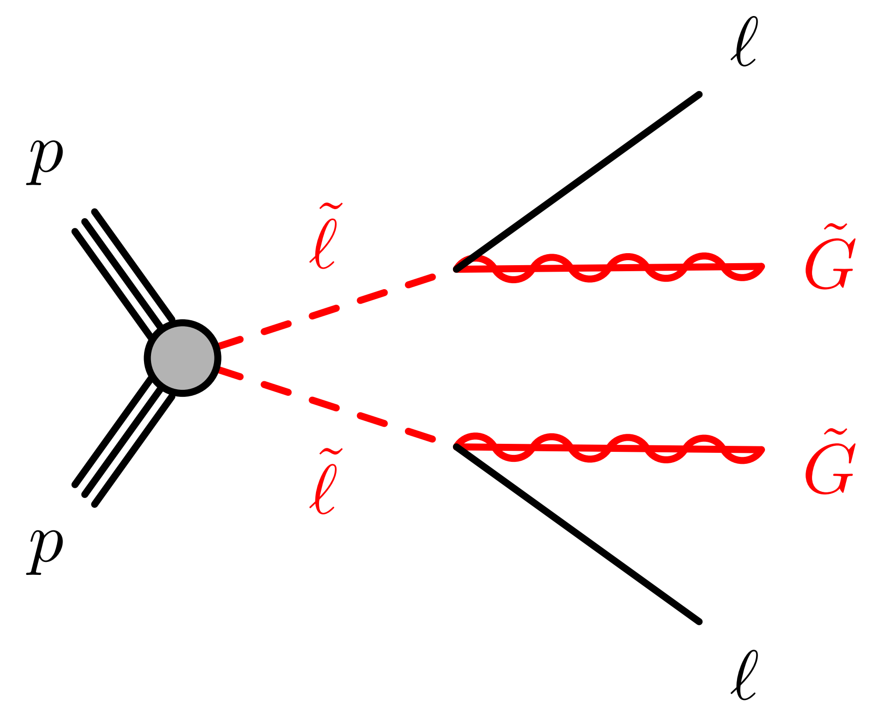
GMSB: weak coupling between NLSP and LSP

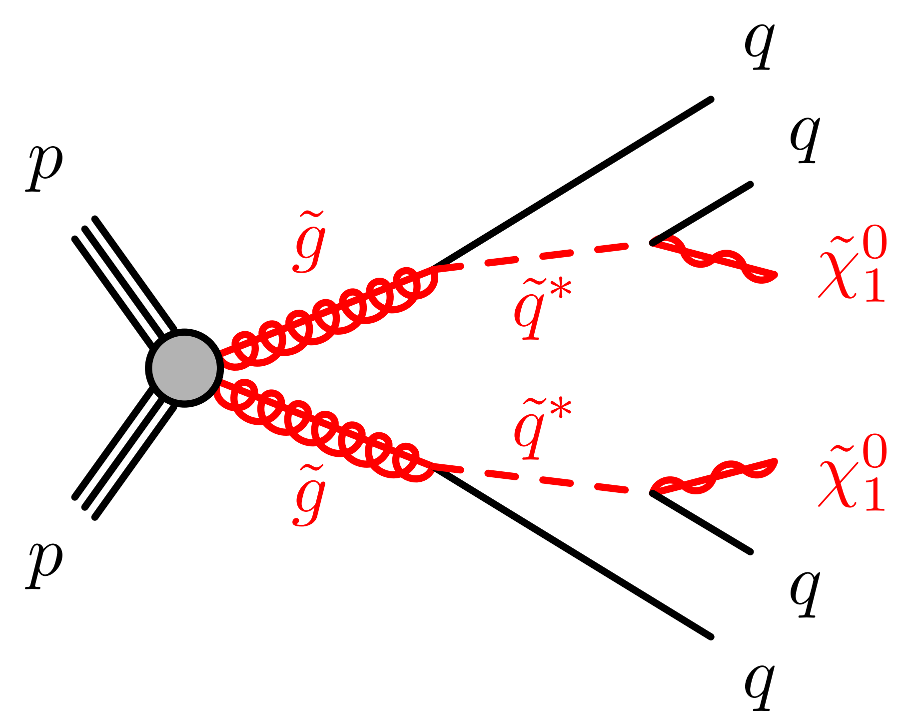
Split SUSY: heavy intermediate particles

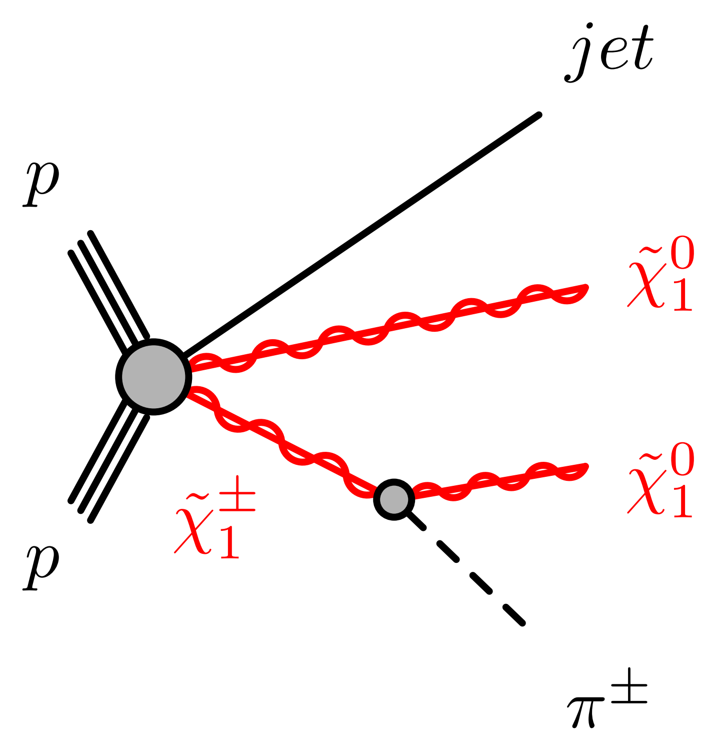
Compressed SUSY: small phase space





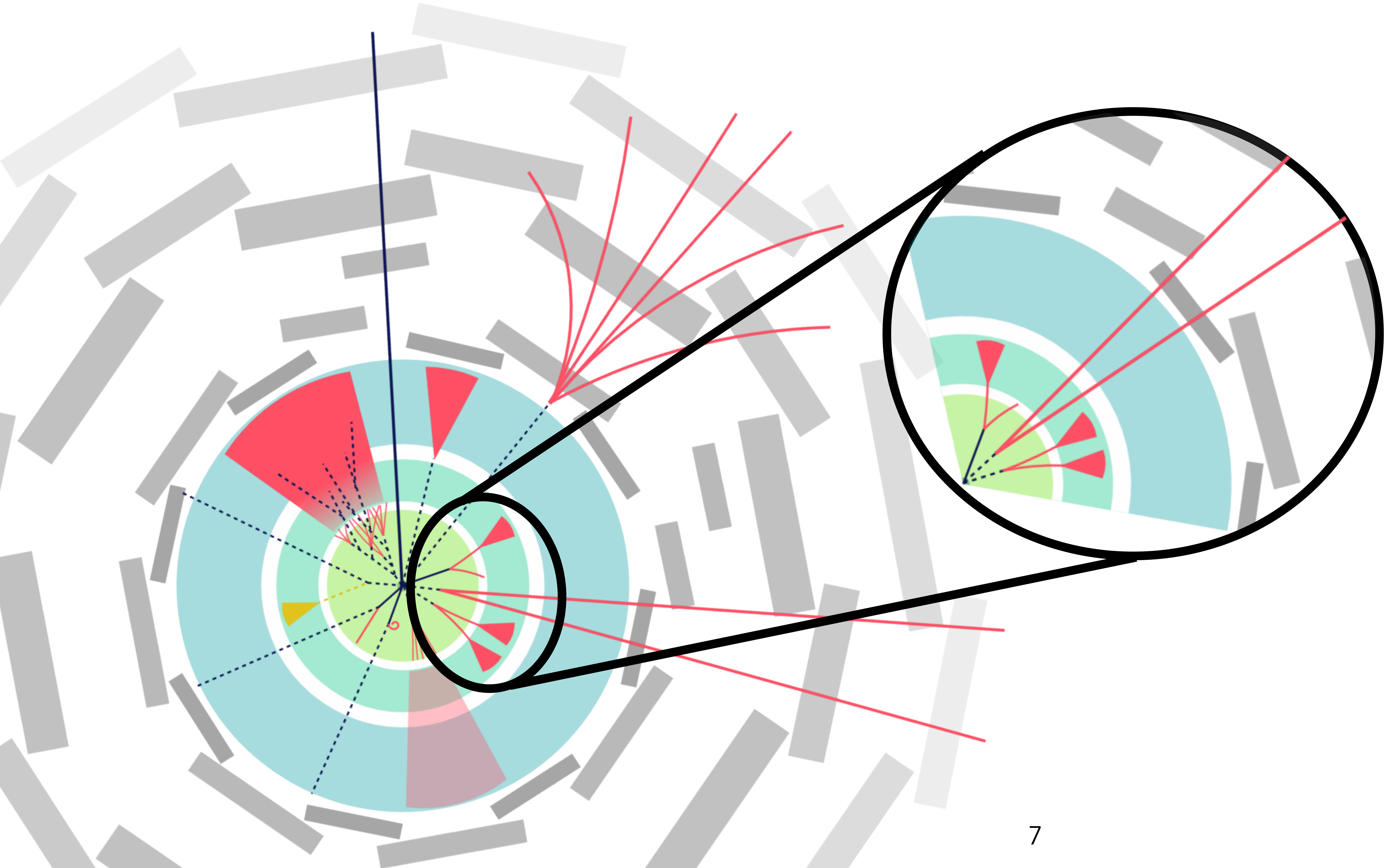






LLP Signatures

Depending on LLP properties, expect a wide range of **<u>unconventional detector signatures</u>**



Displaced leptonic vertices

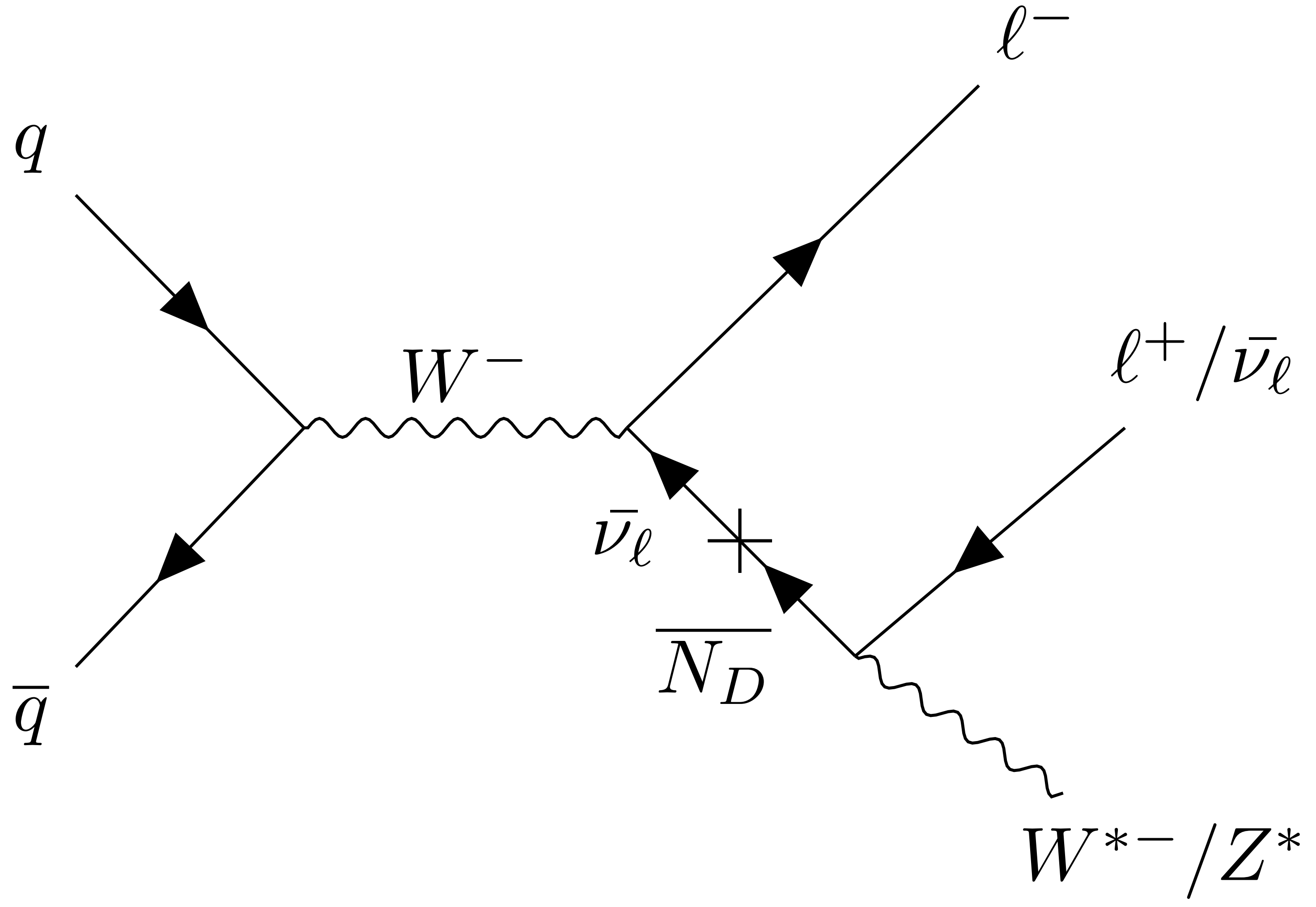


Image credit: <u>Heather Russell</u>

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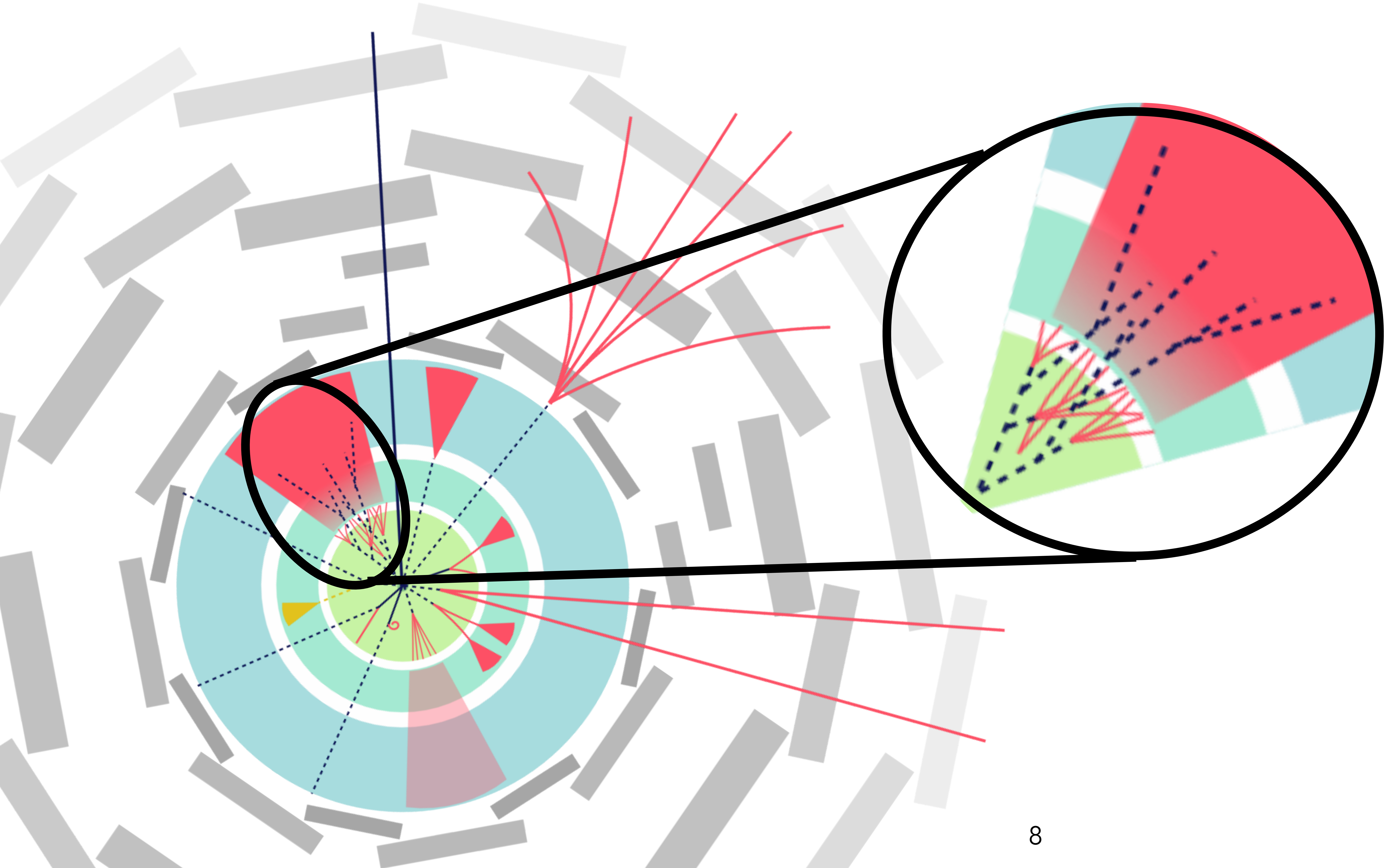
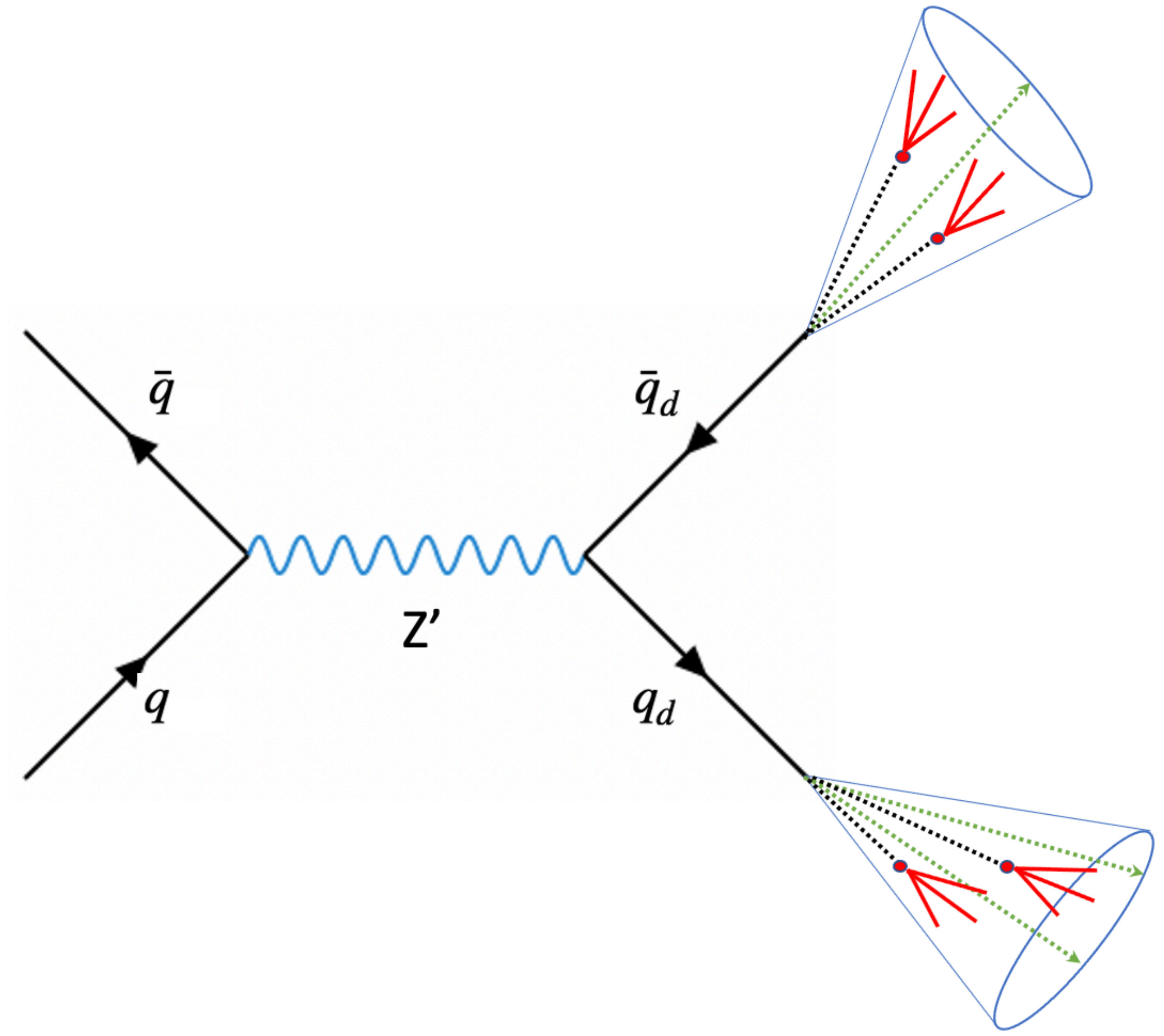


Emerging jets



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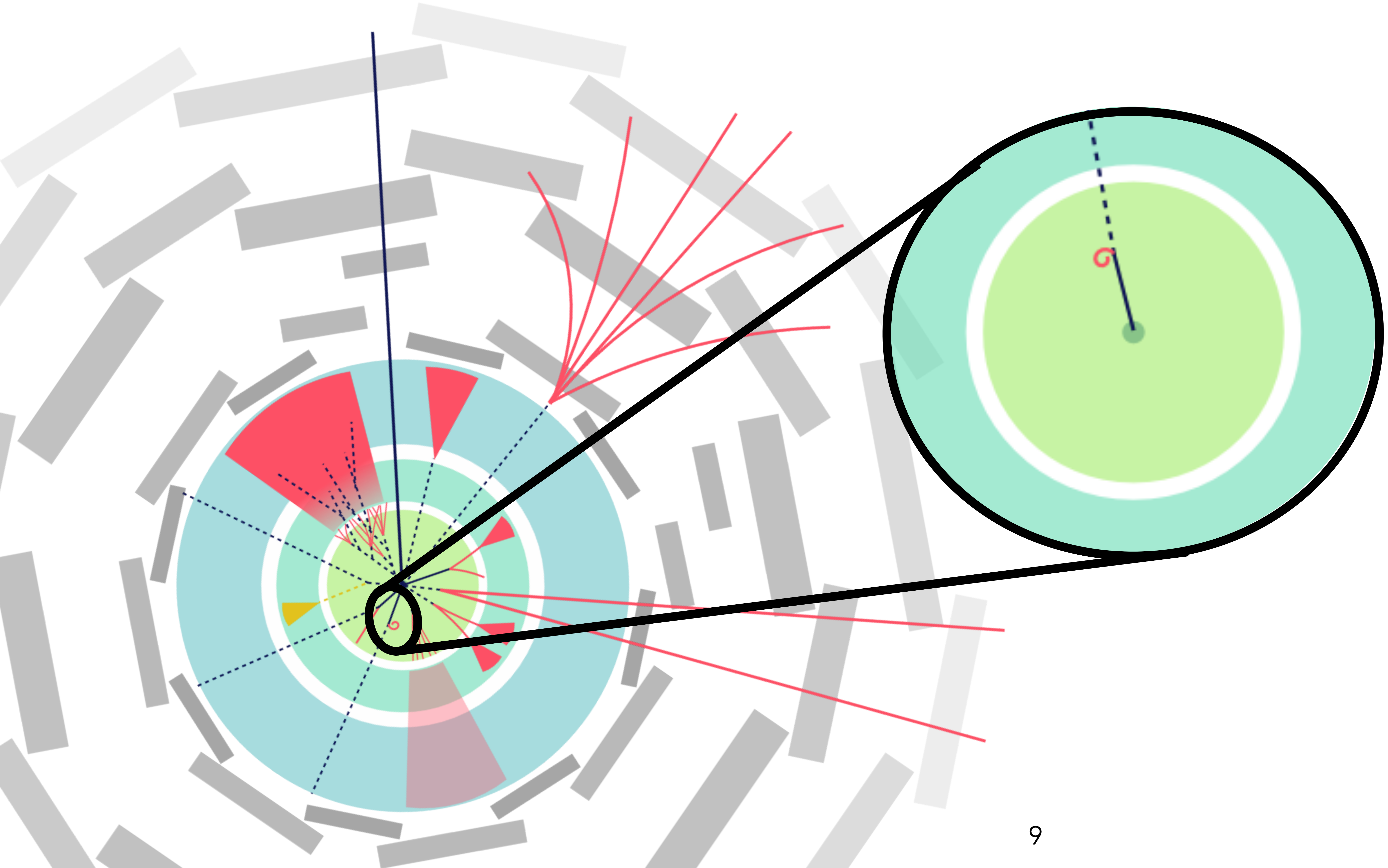
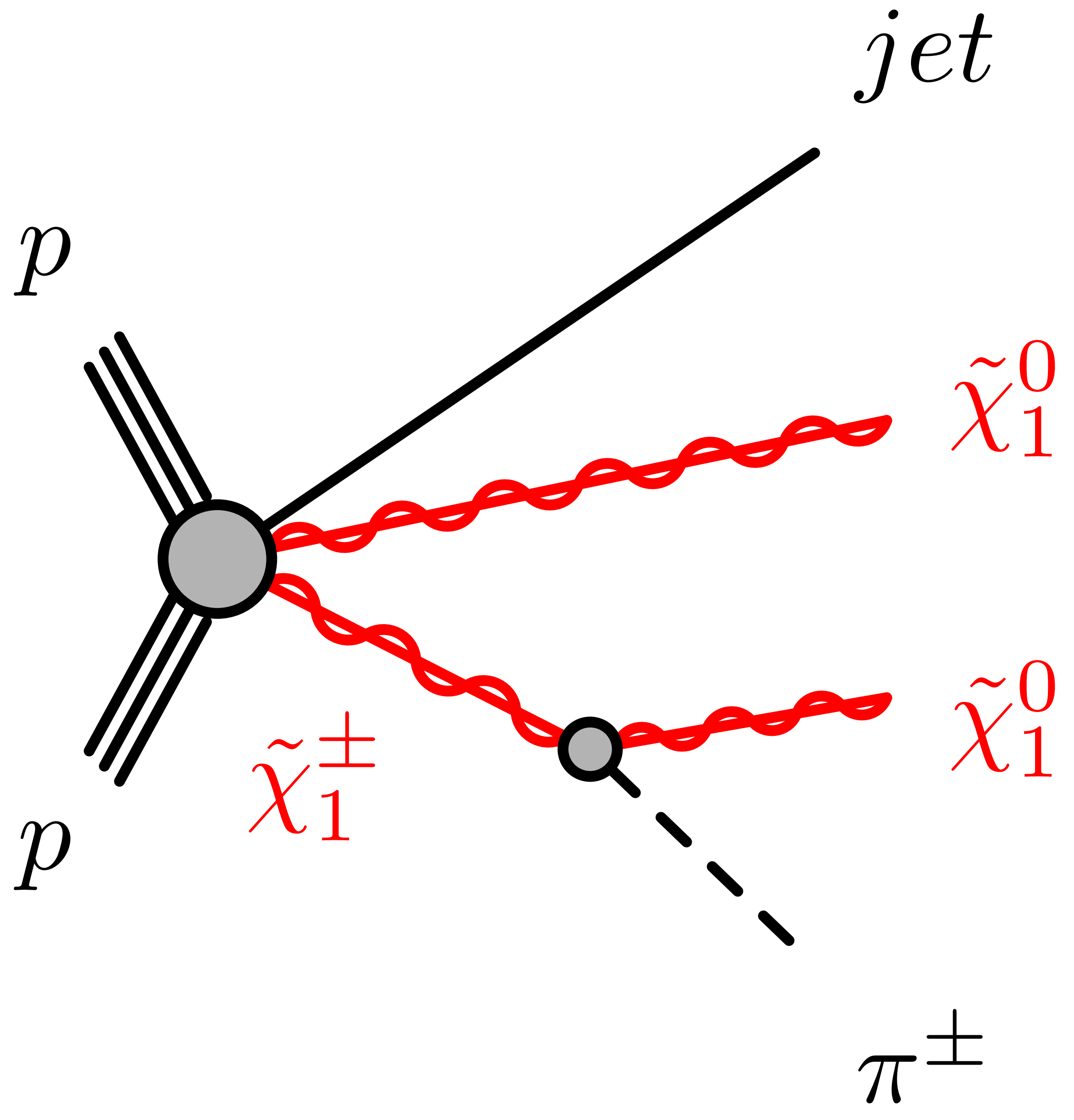


Disappearing tracks



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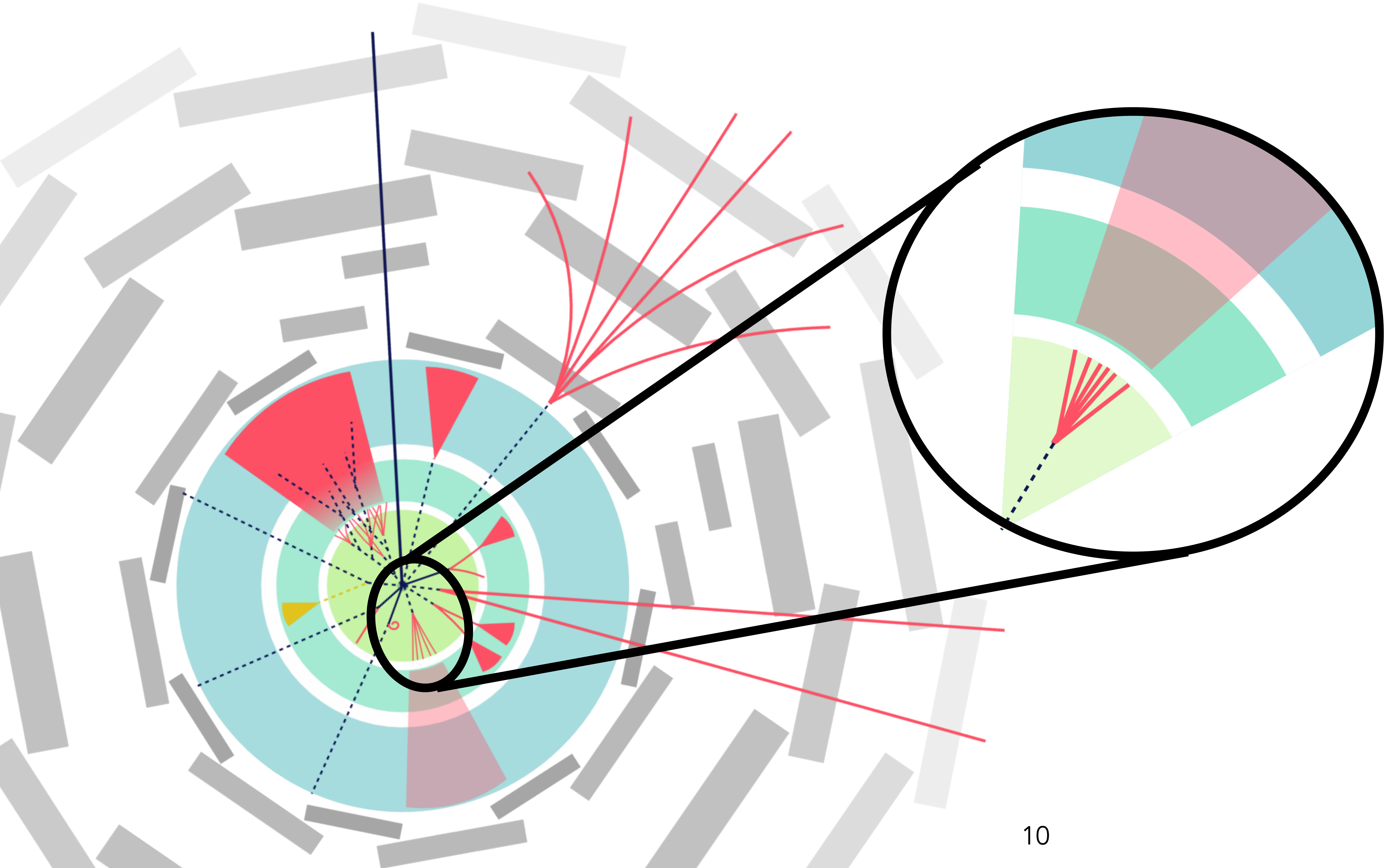
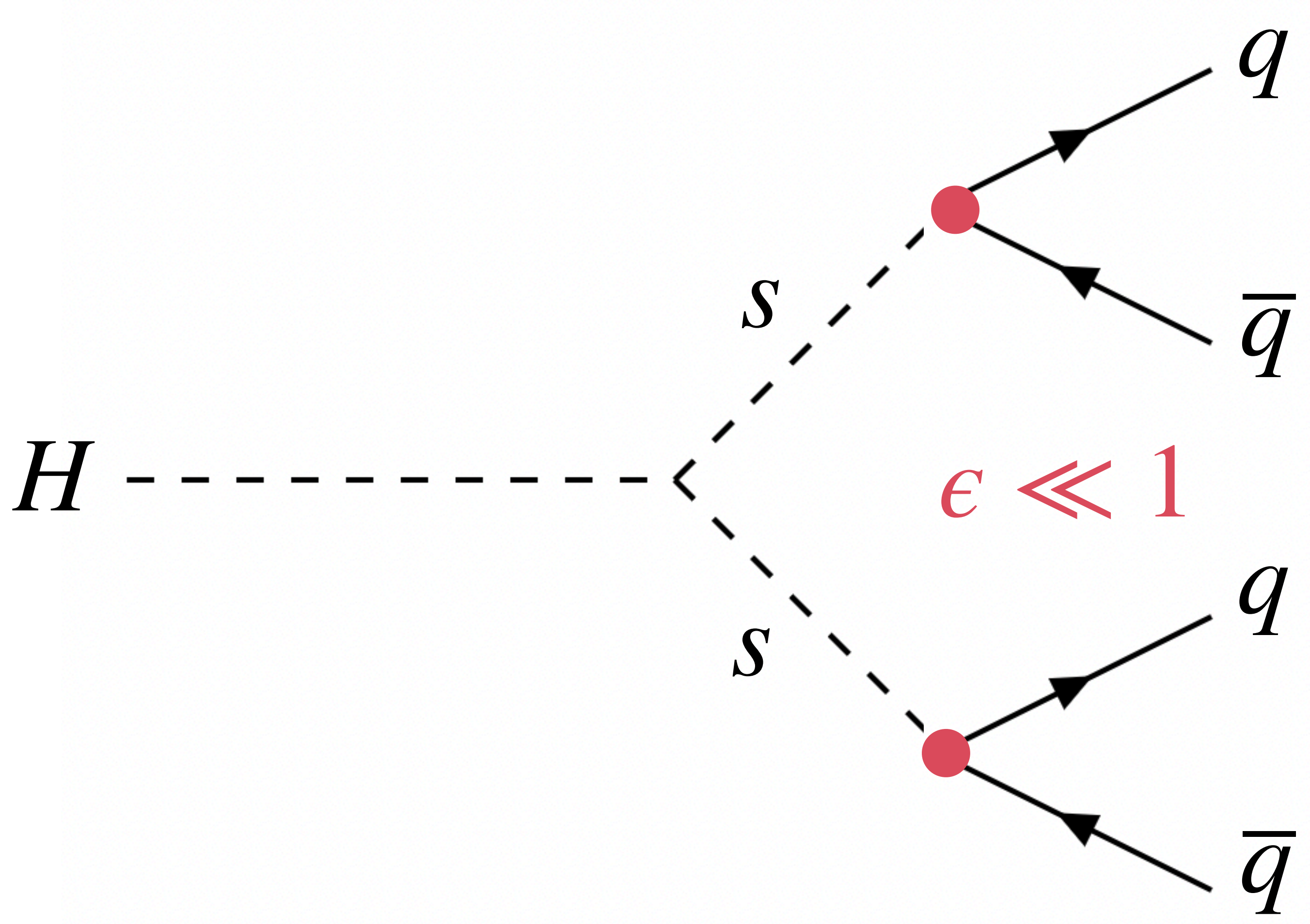


Displaced hadronic jets



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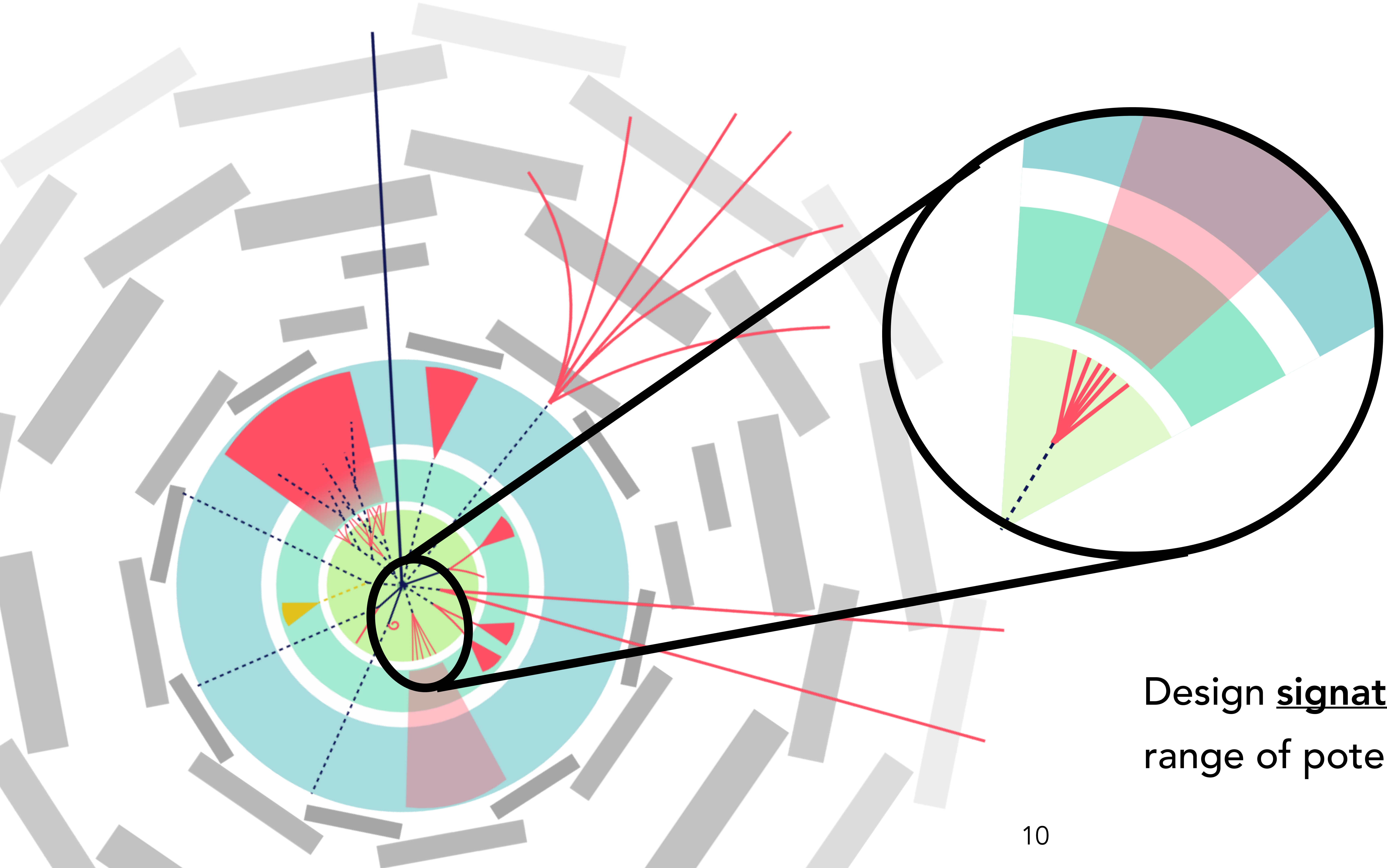

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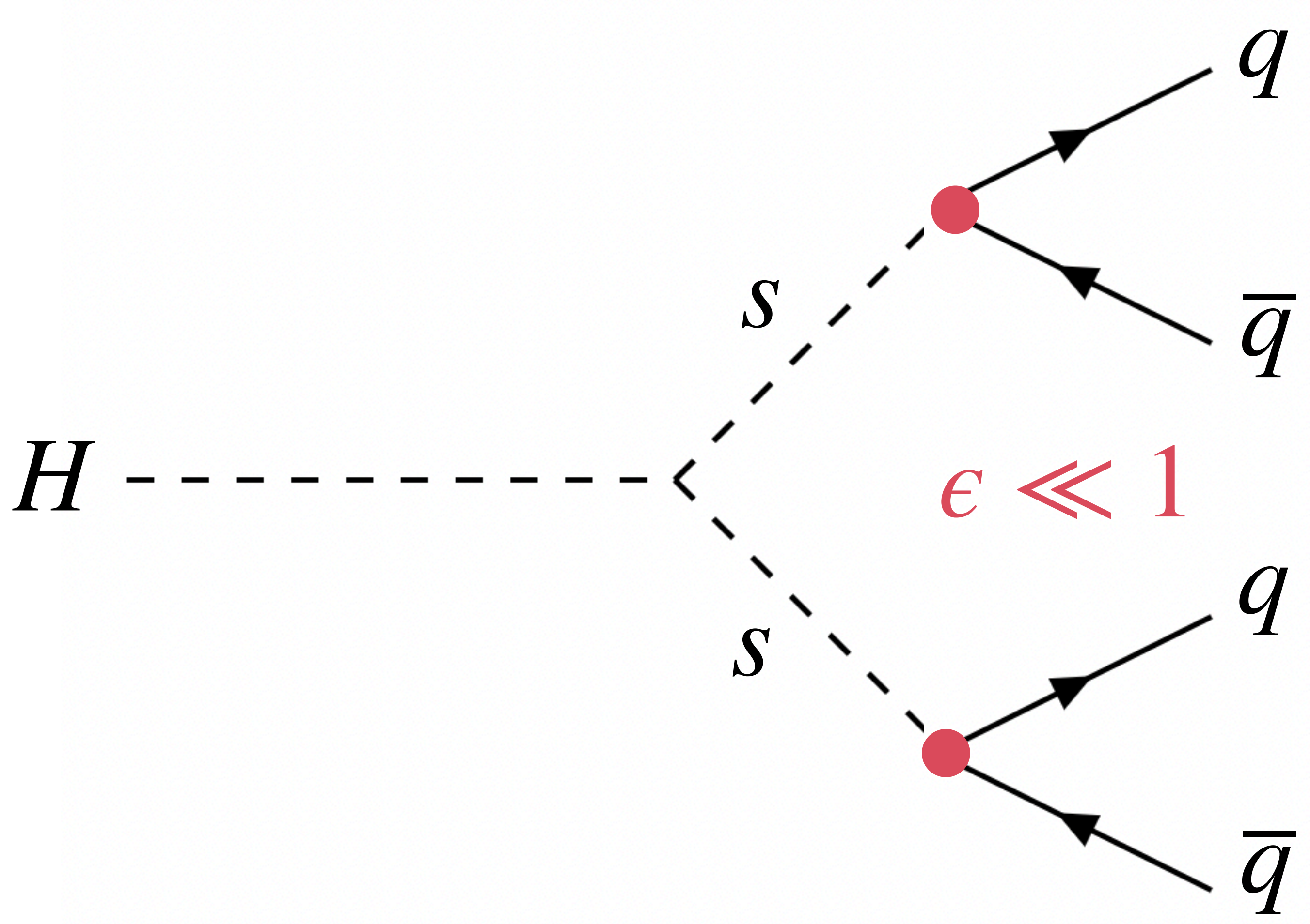

Design **signature driven** searches to maximize range of potential sensitivity to new physics

Image credit: Heather Russell

Where to search for LLPs?

Depending on the lifetime of the LLP, each detector system will contribute differently to sensitivity

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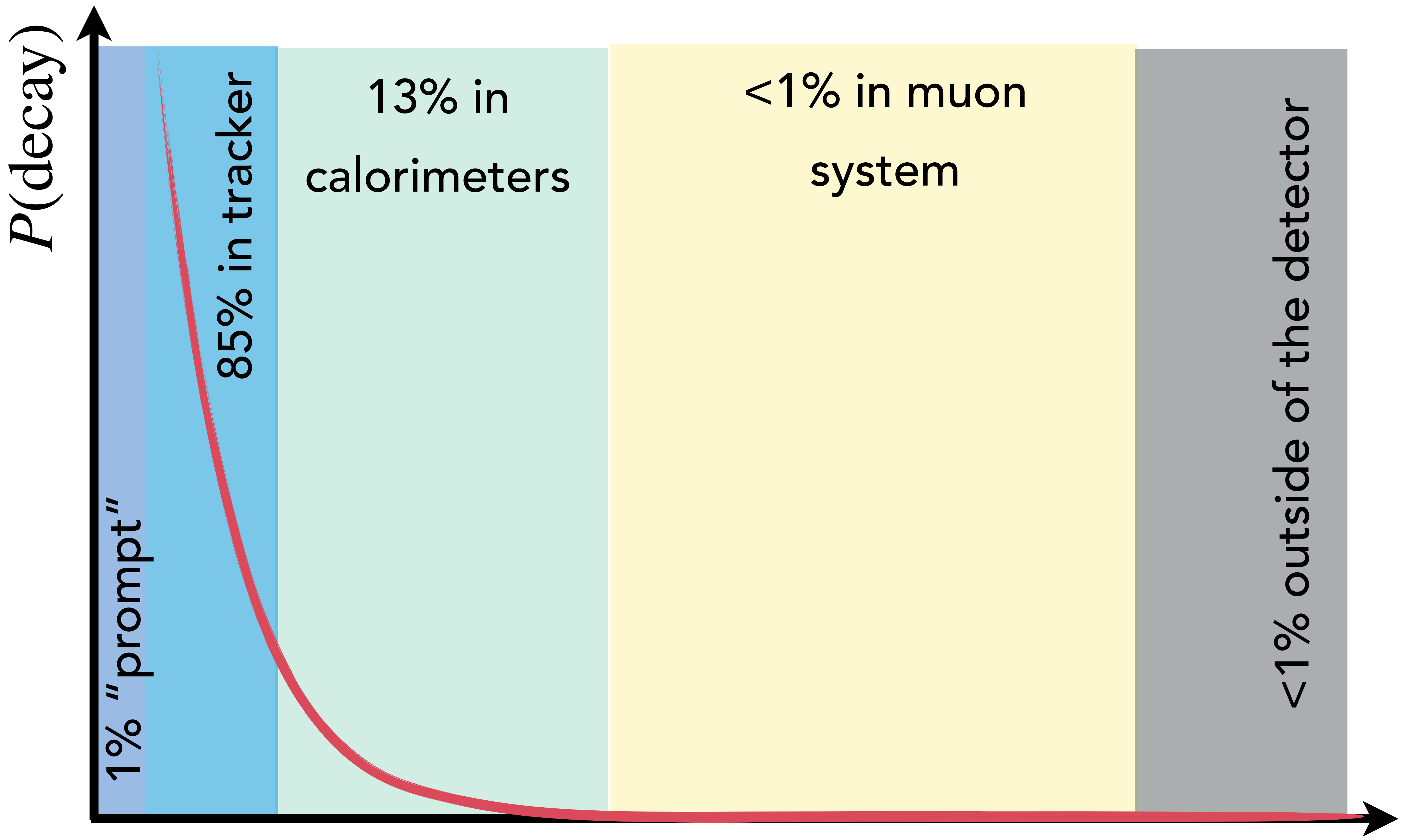

e.g. for $c\tau = 100$ mm, $\beta\gamma \sim 5$

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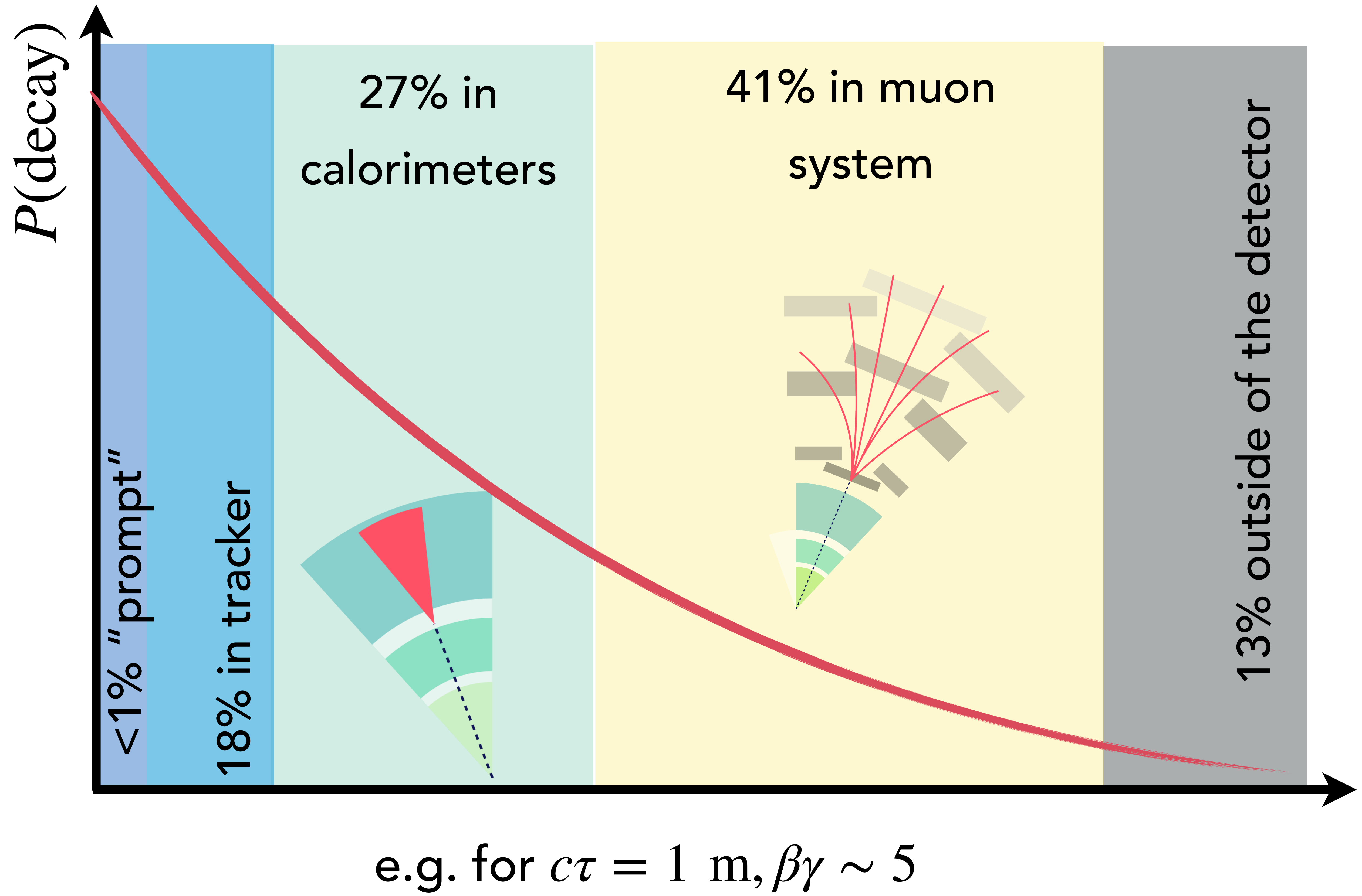
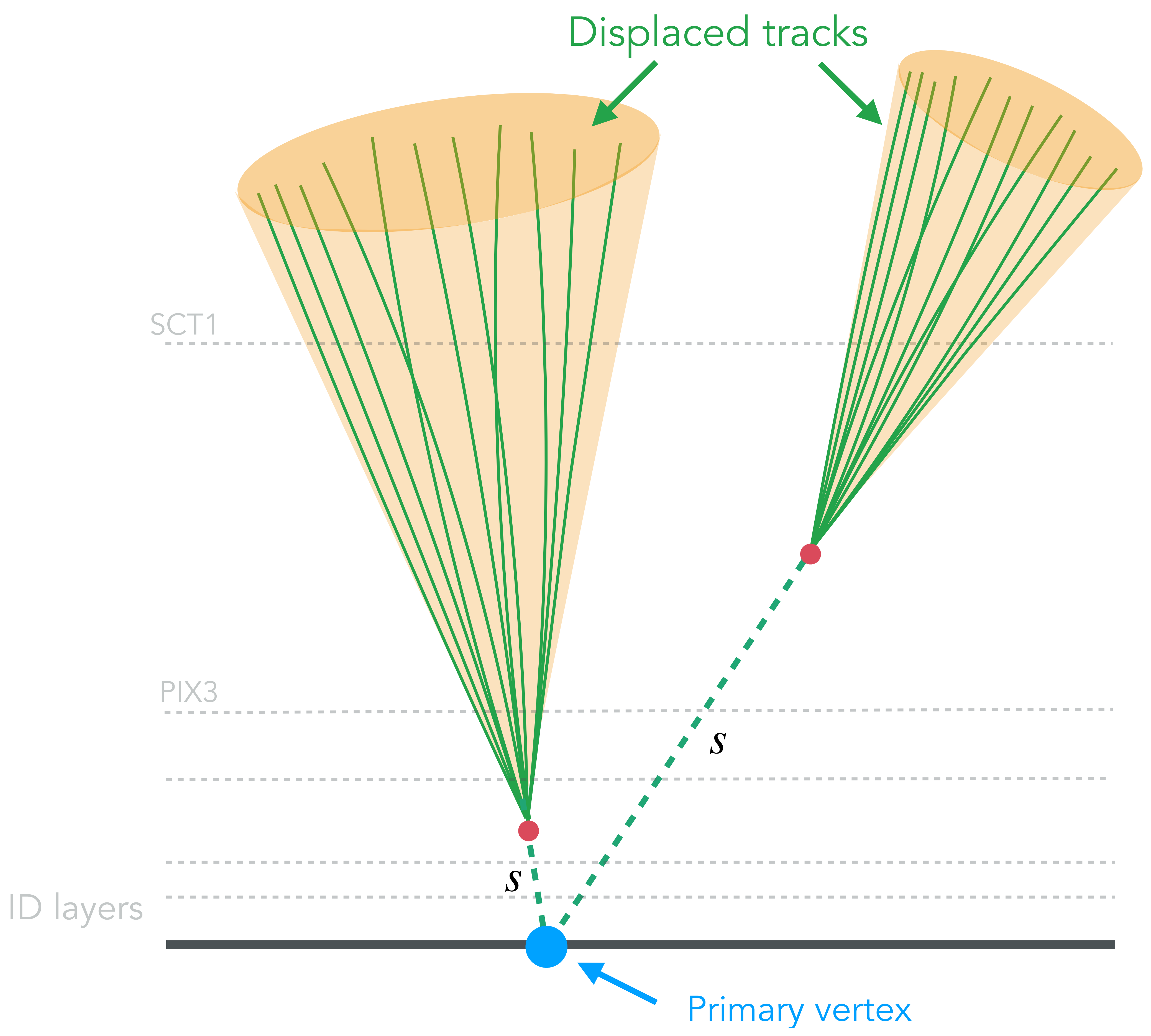
- ATLAS has a robust search program for LLP decays in each subsystem



Hadronic signatures

Inner detector searches

To reconstruct hadronic LLP decays in the inner detector, need to reconstruct displaced tracks and vertices



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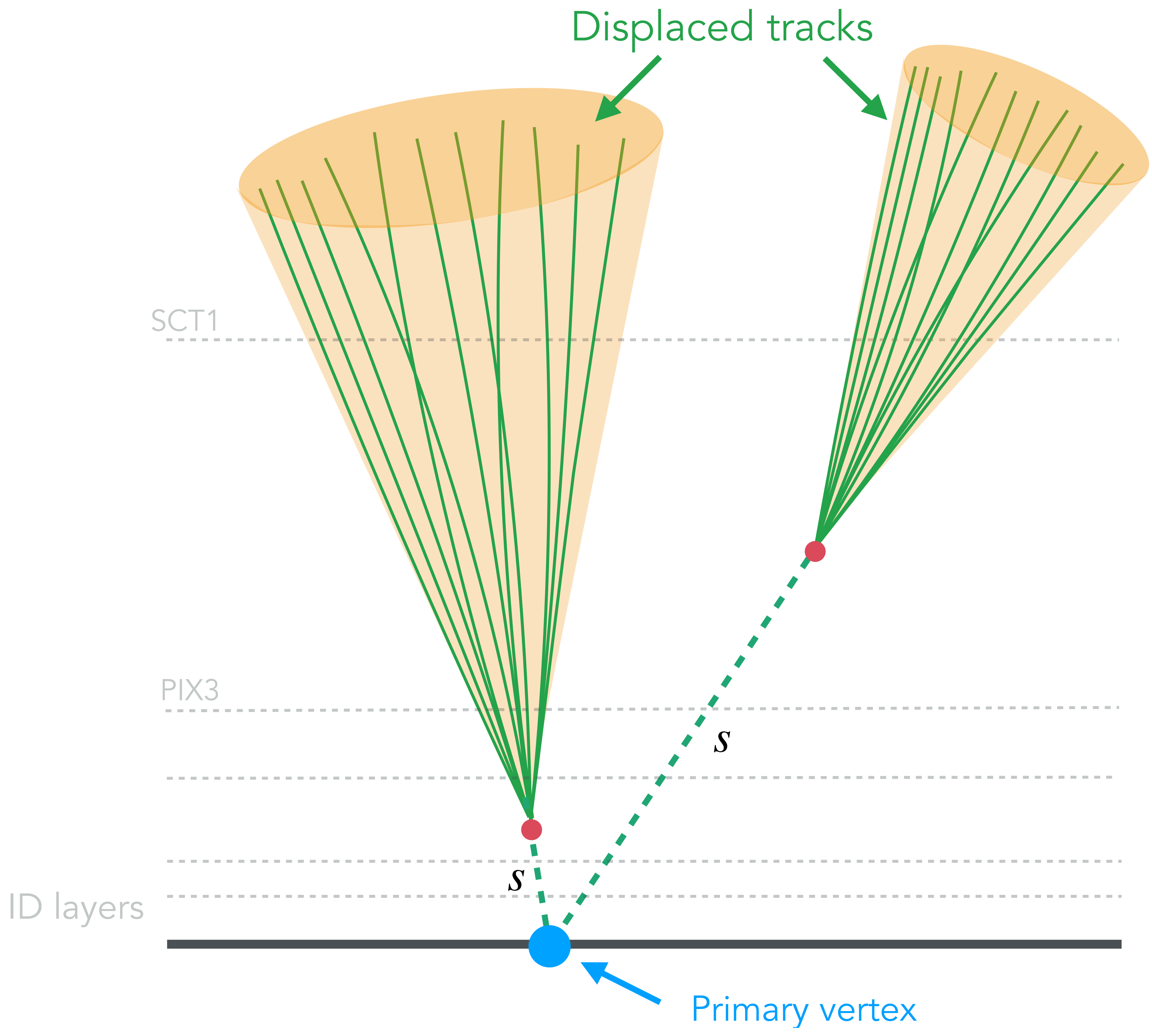
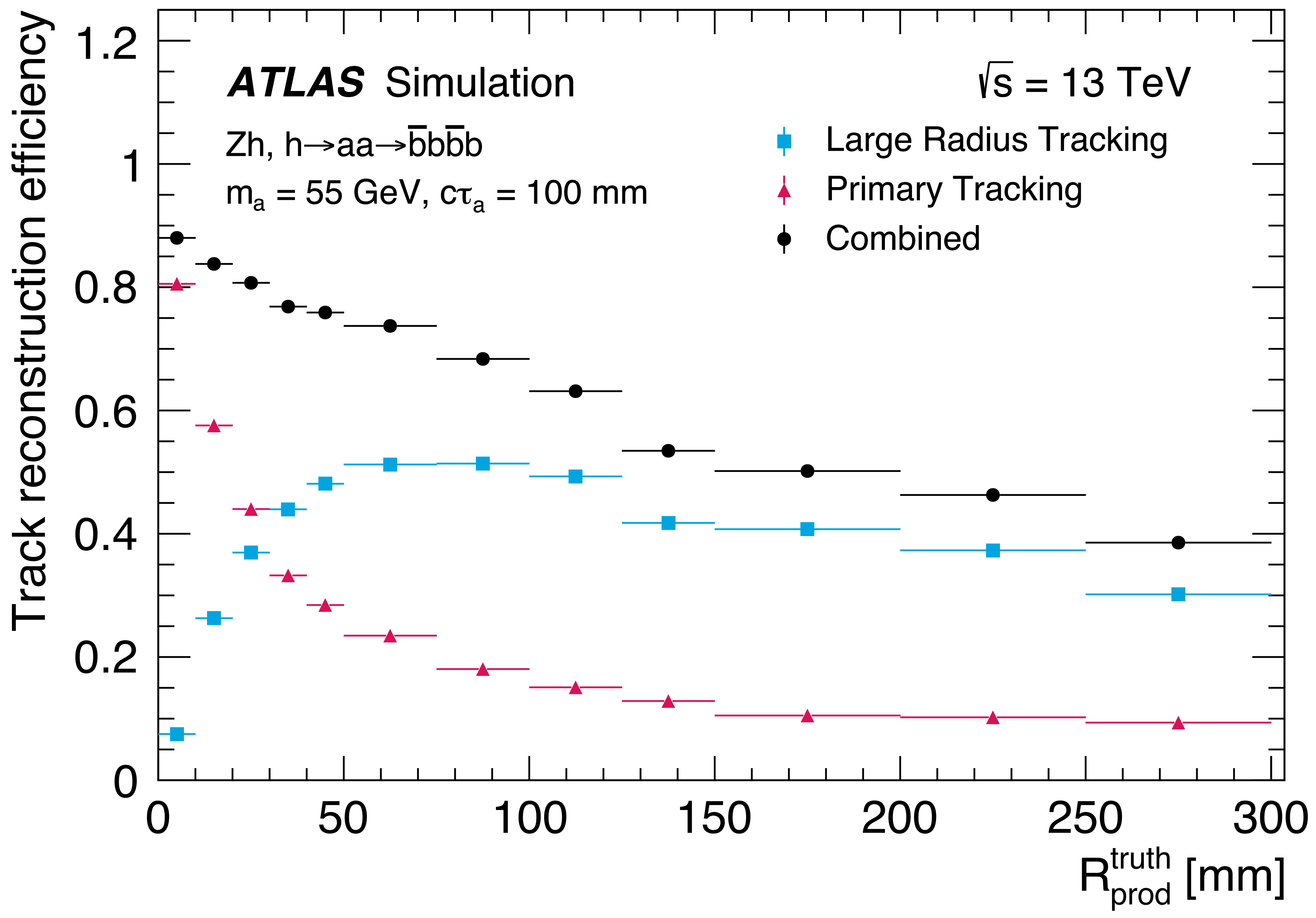


Dedicated "large radius tracking" iteration to recover tracking efficiency for displaced decays



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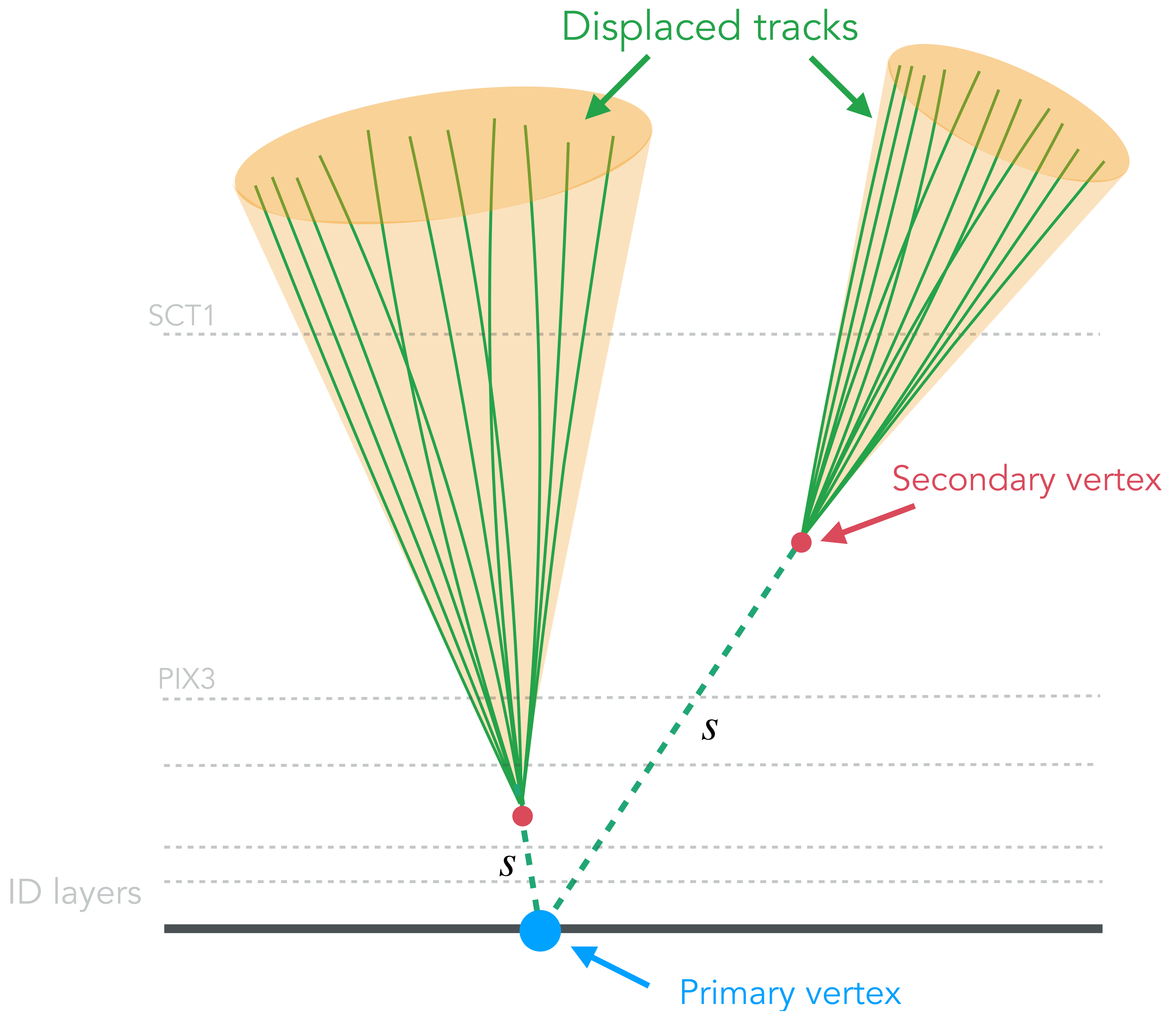
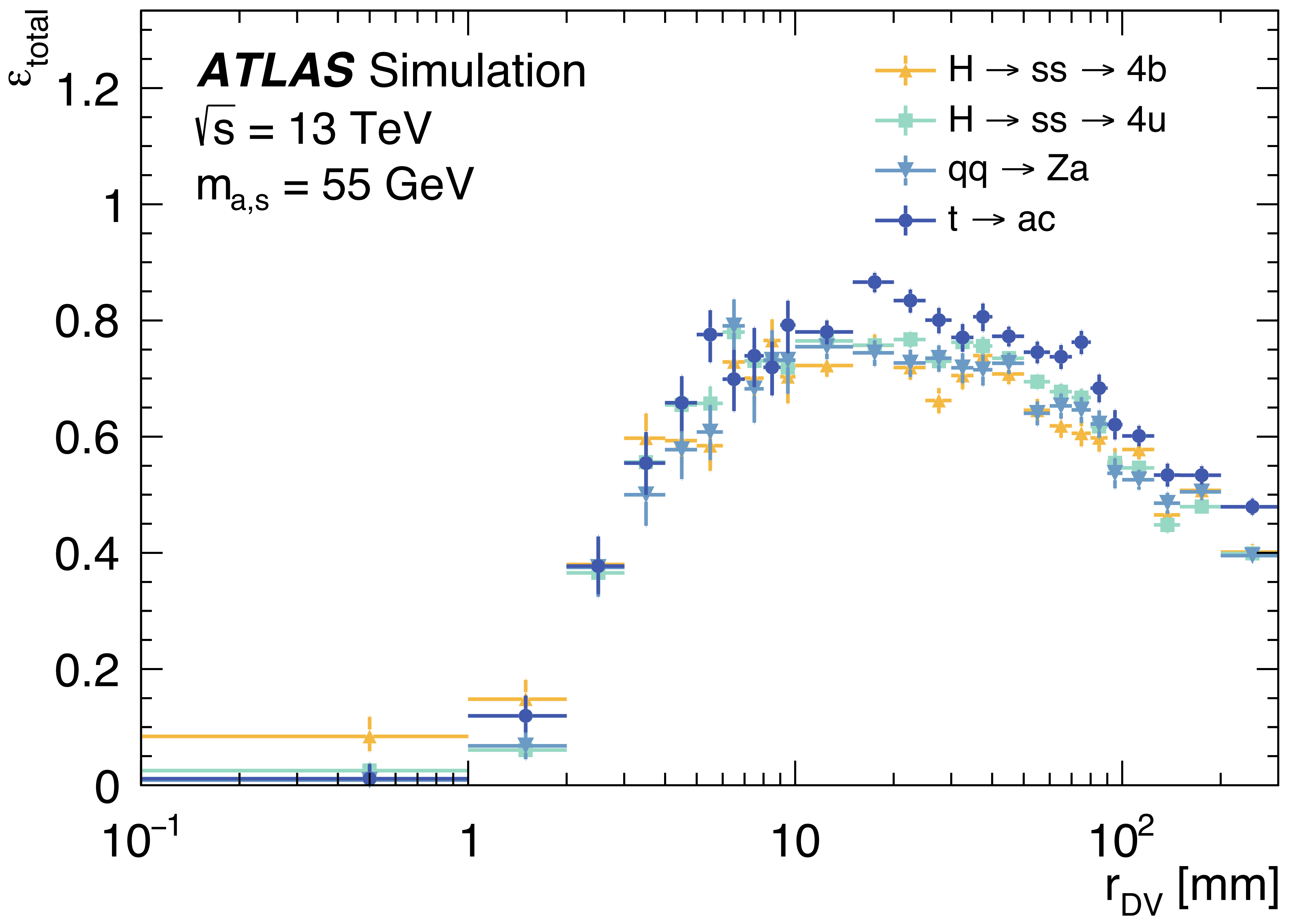


Dedicated secondary vertex reconstruction algorithm to reconstruct LLP decay position and kinematics from displaced tracks



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IDTR-2021-03

For Run 3, displaced track reconstruction was completely overhauled:

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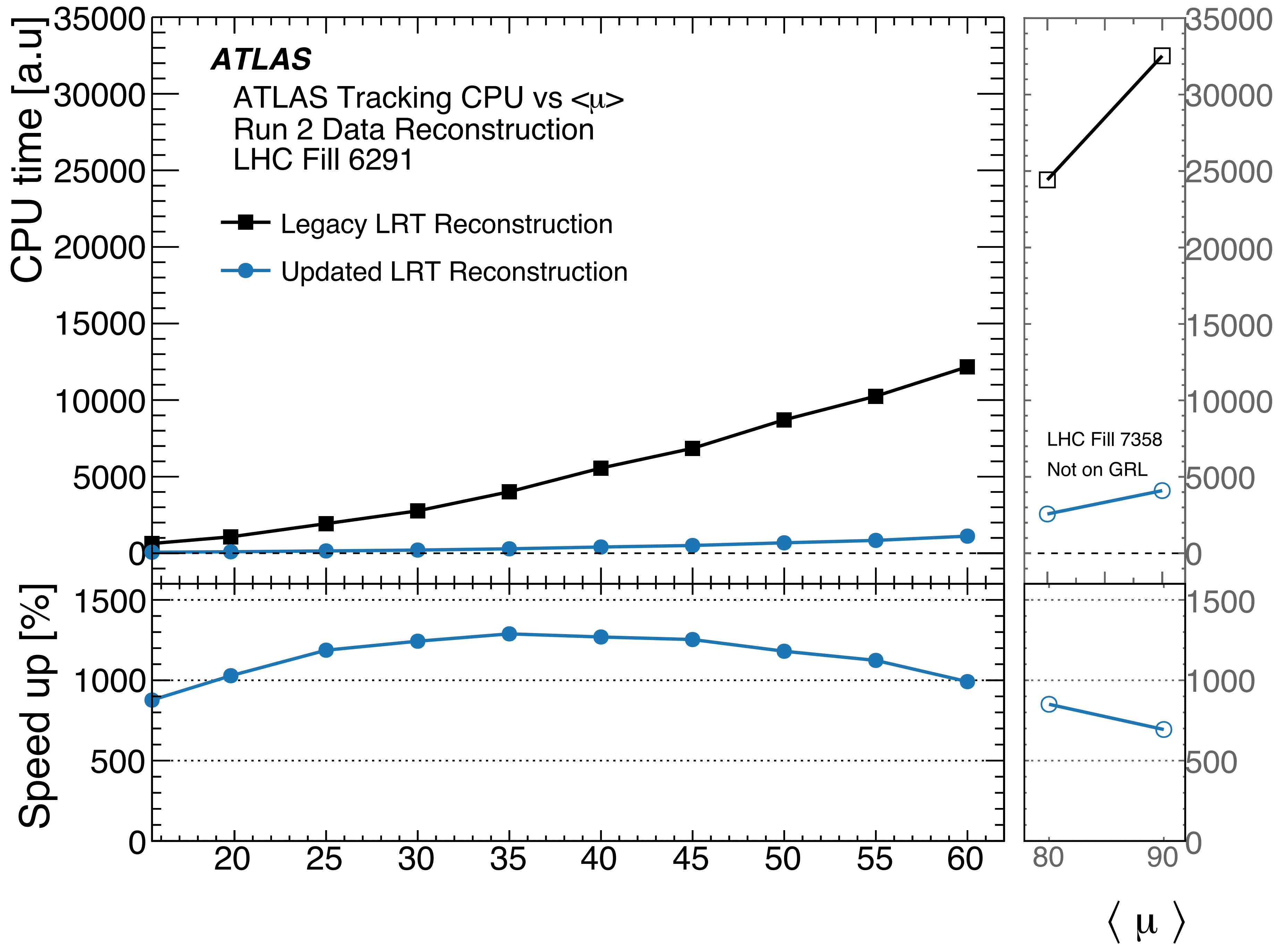
Processing time sped up by over 1000%



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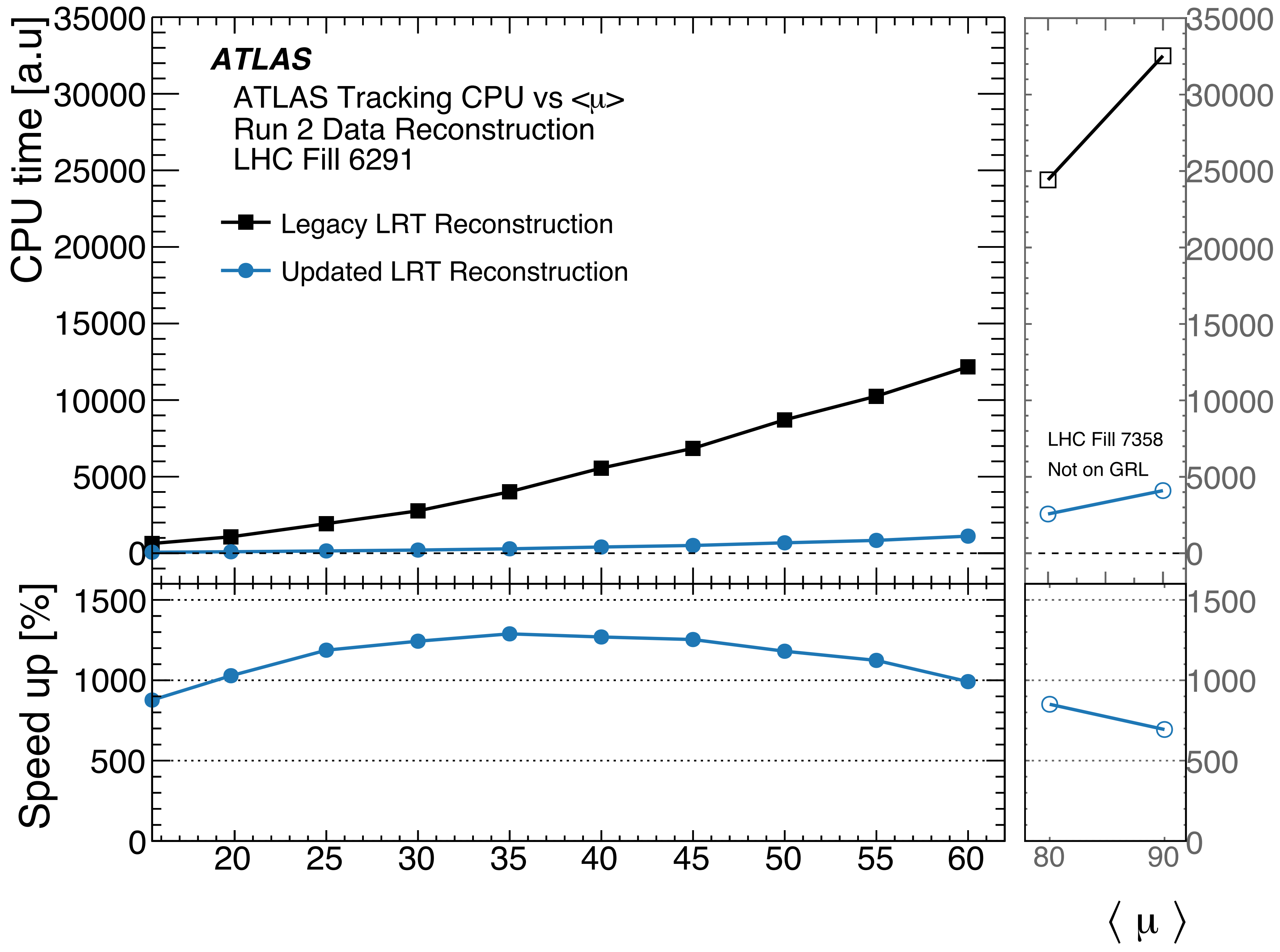
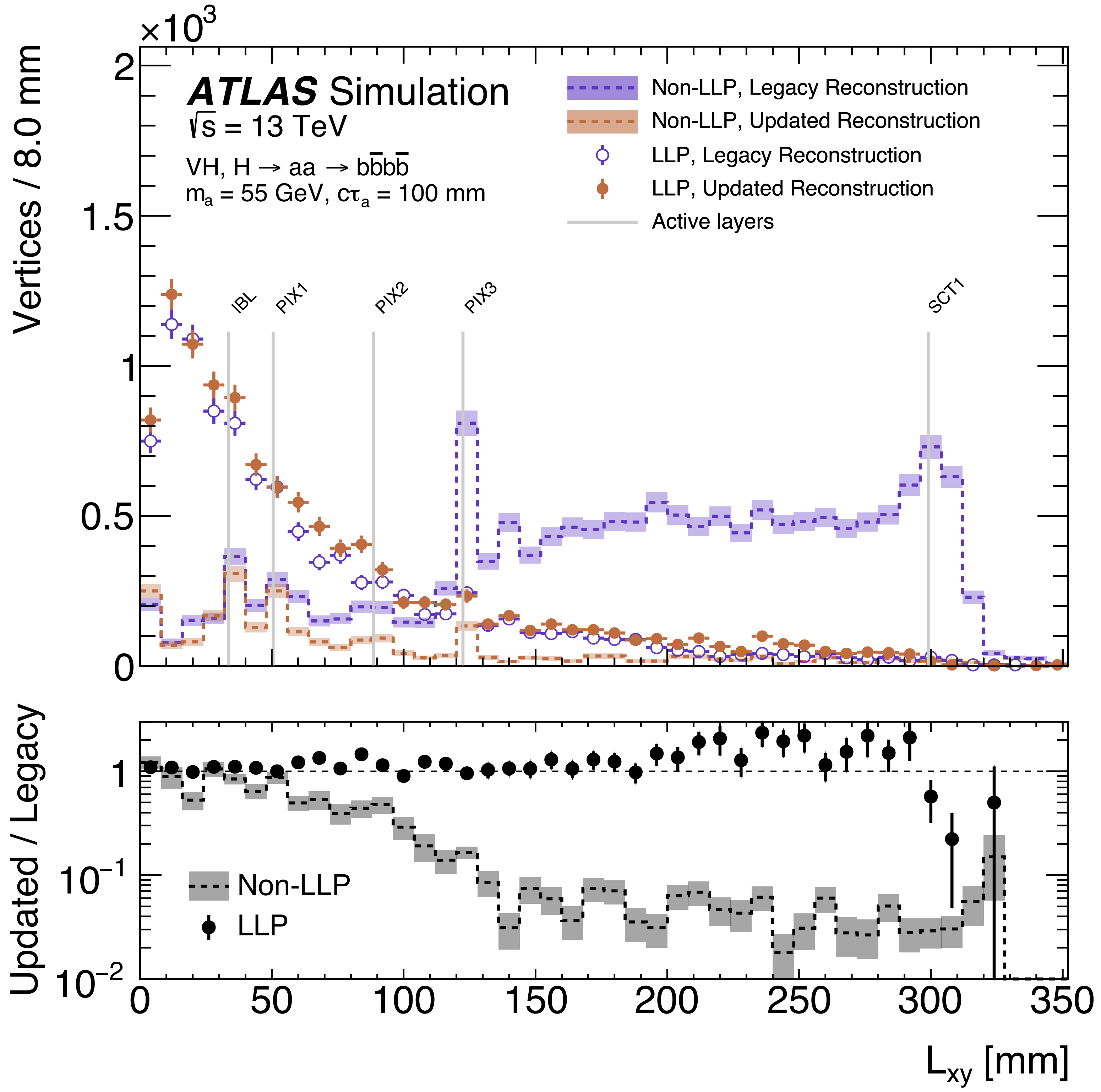


> 10x reduction in fakes for same signal efficiency



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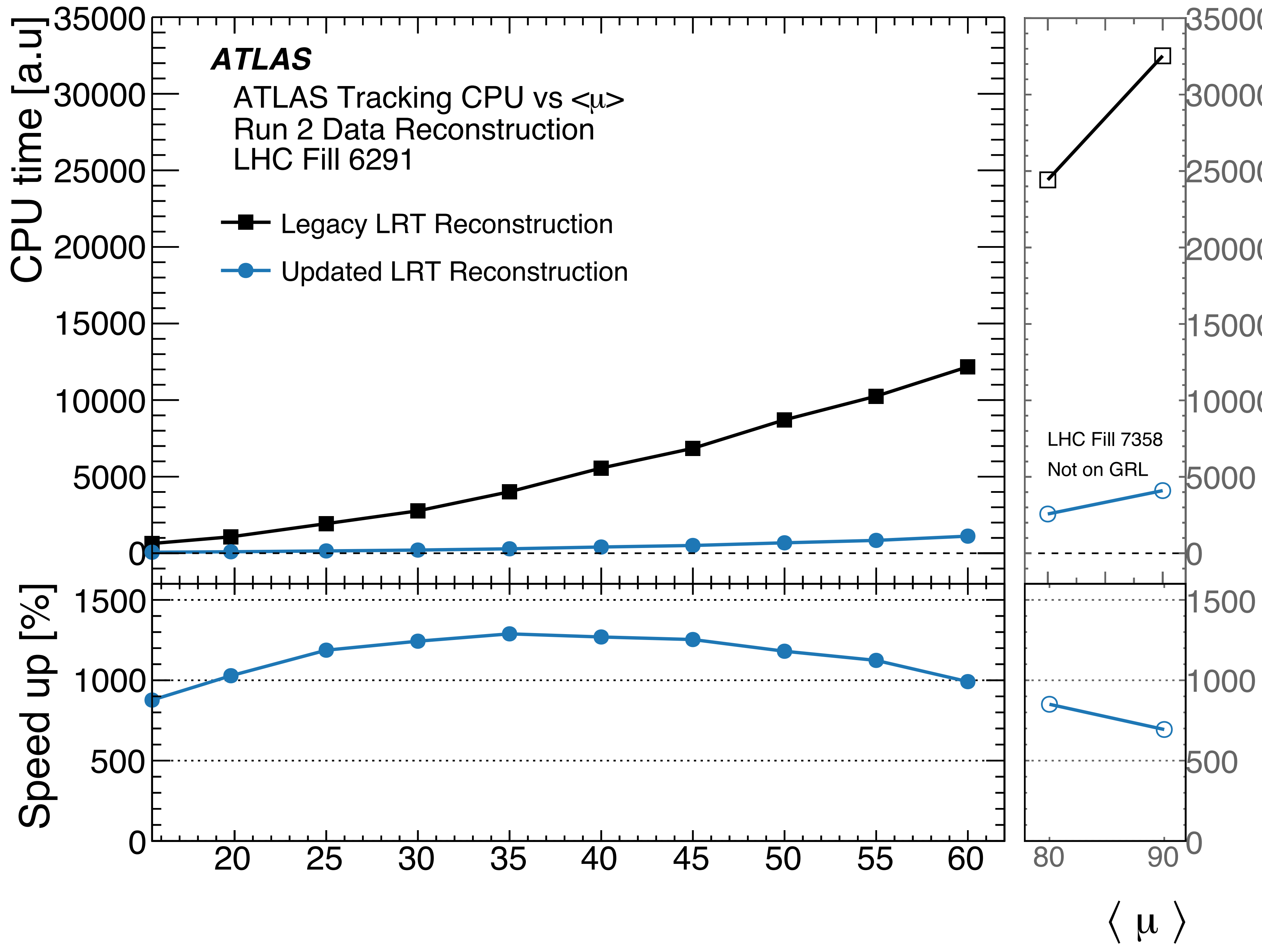

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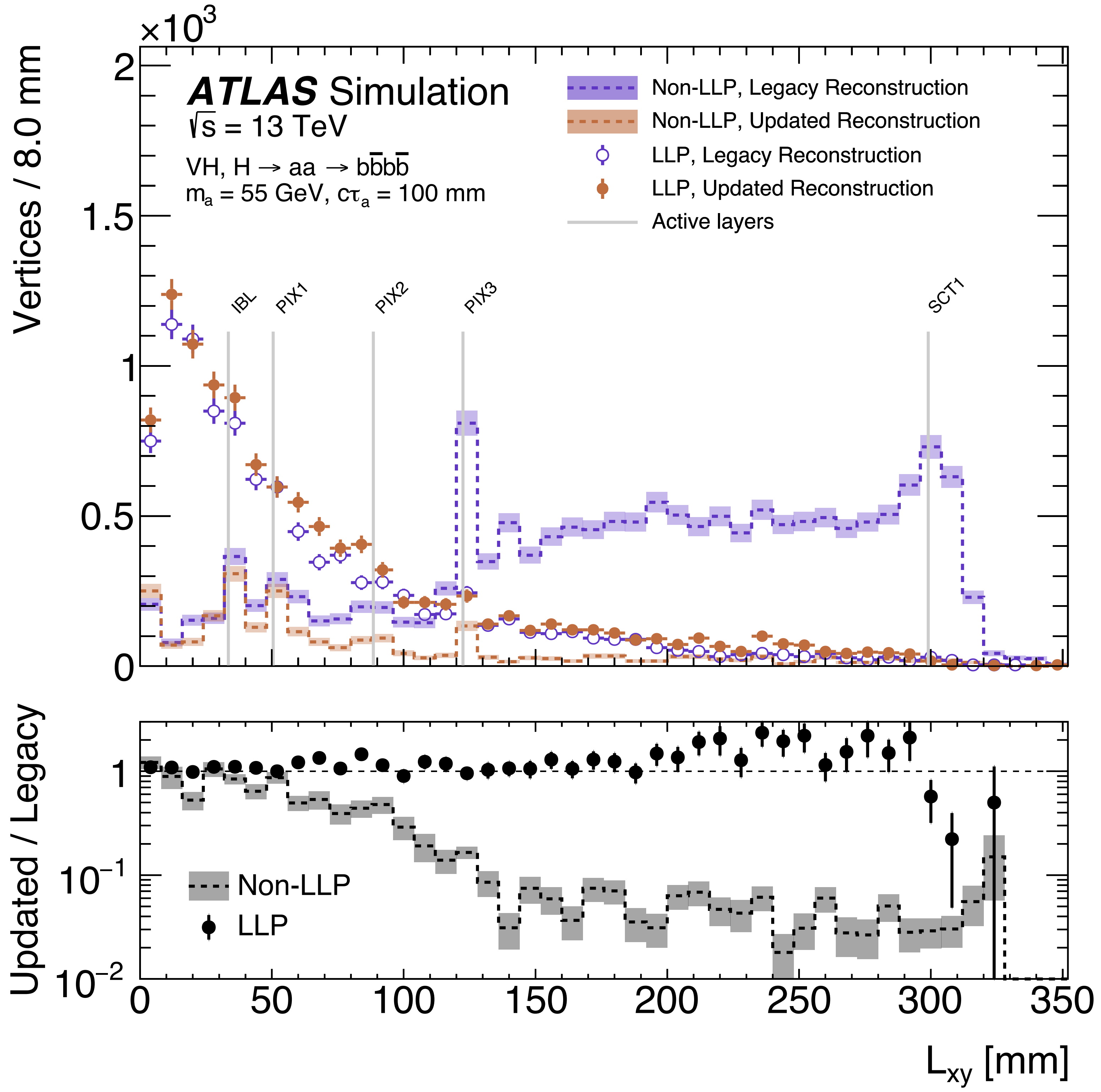

Allowed for integration into standard ATLAS reconstruction for the first time

- Significantly improves ATLAS LLP search program for ID signatures

Inner detector searches

EXOT-2021-32

New ATLAS results using Run 2 data

- First result to use new displaced track reconstruction
- Probe ZH, WH, and VBF production modes
  - Include interpretations in models with ALPs

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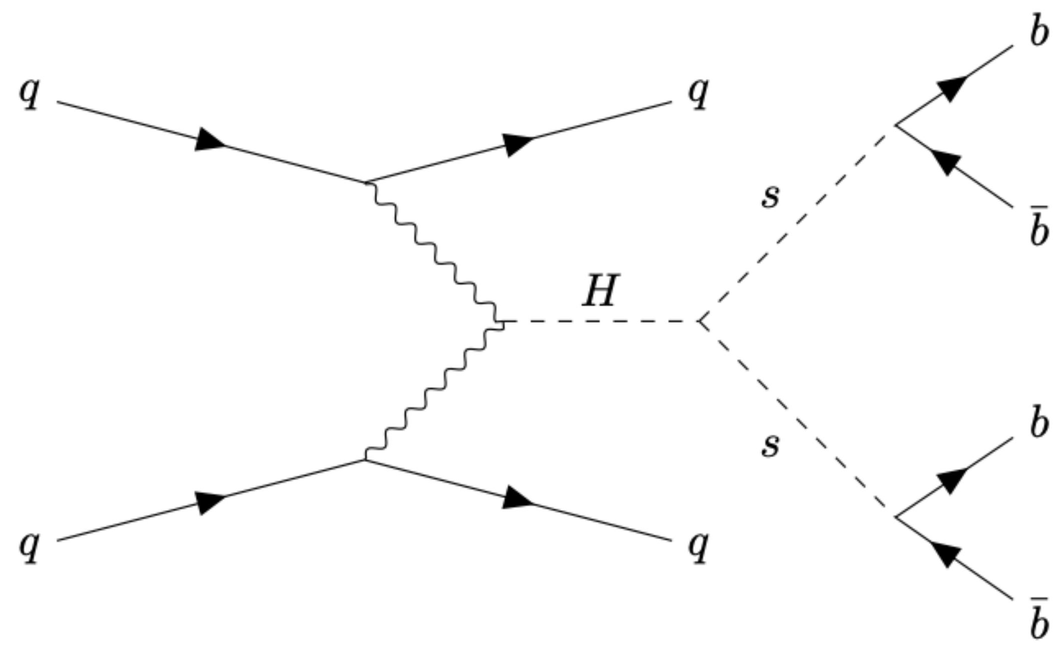

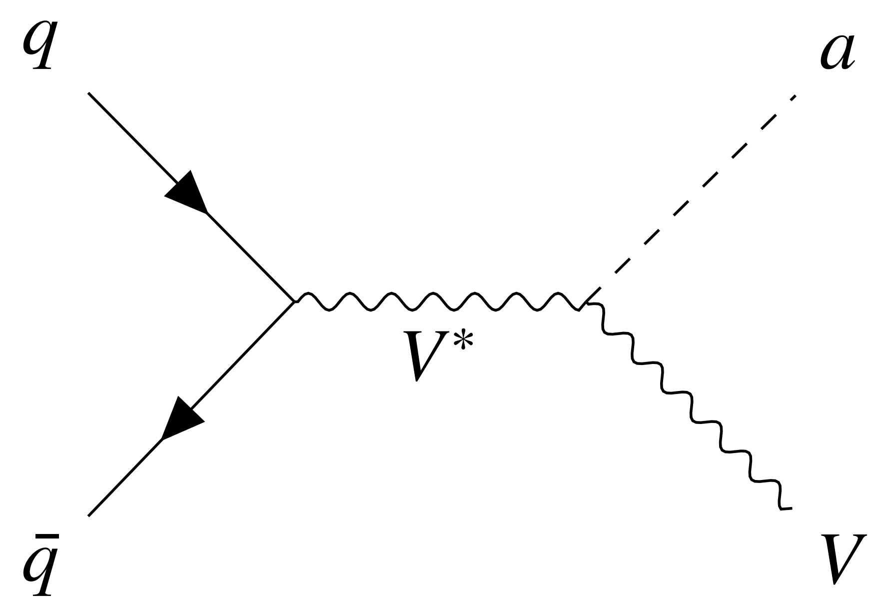

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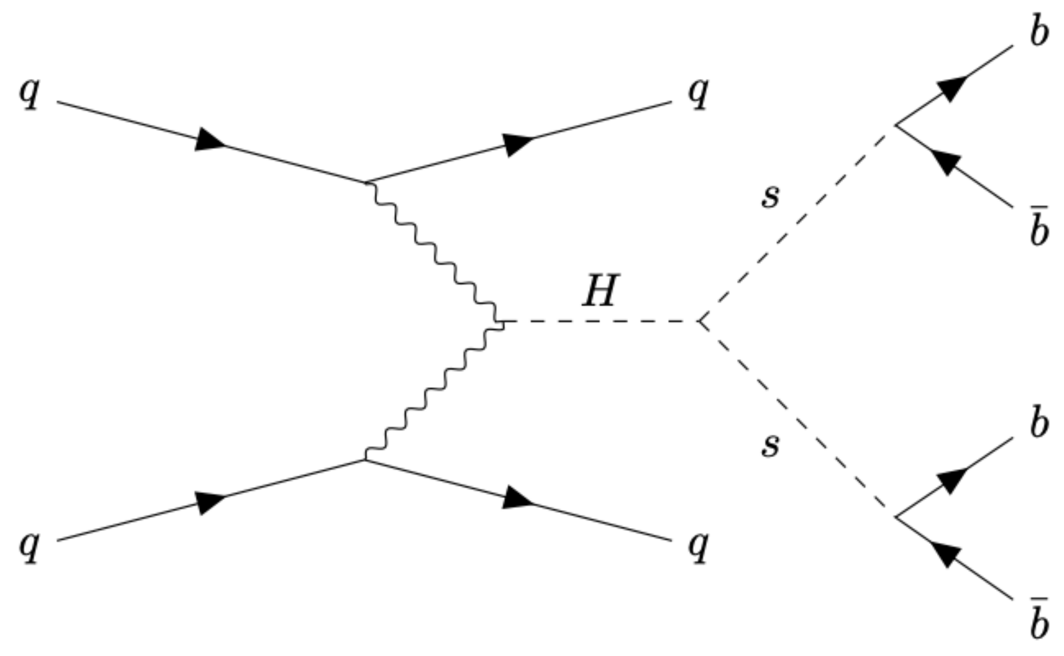
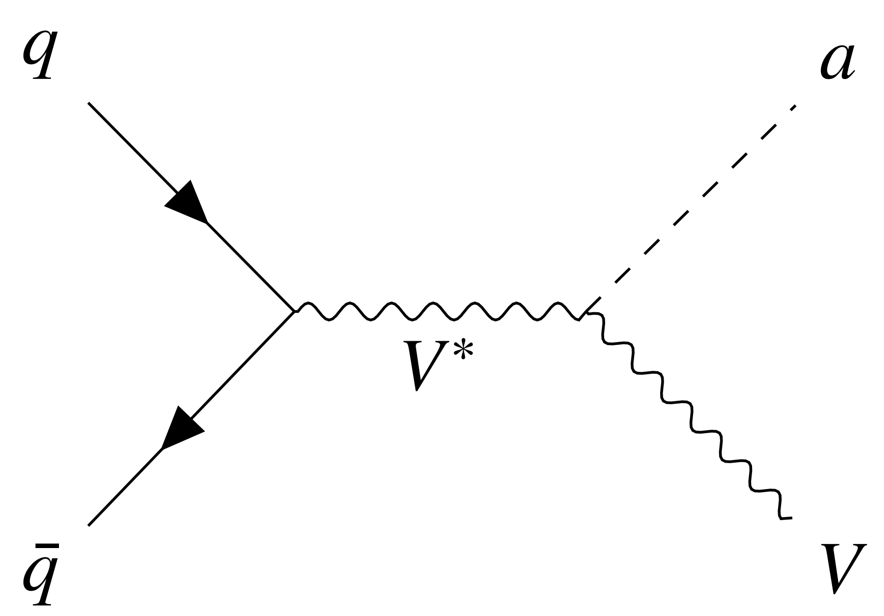
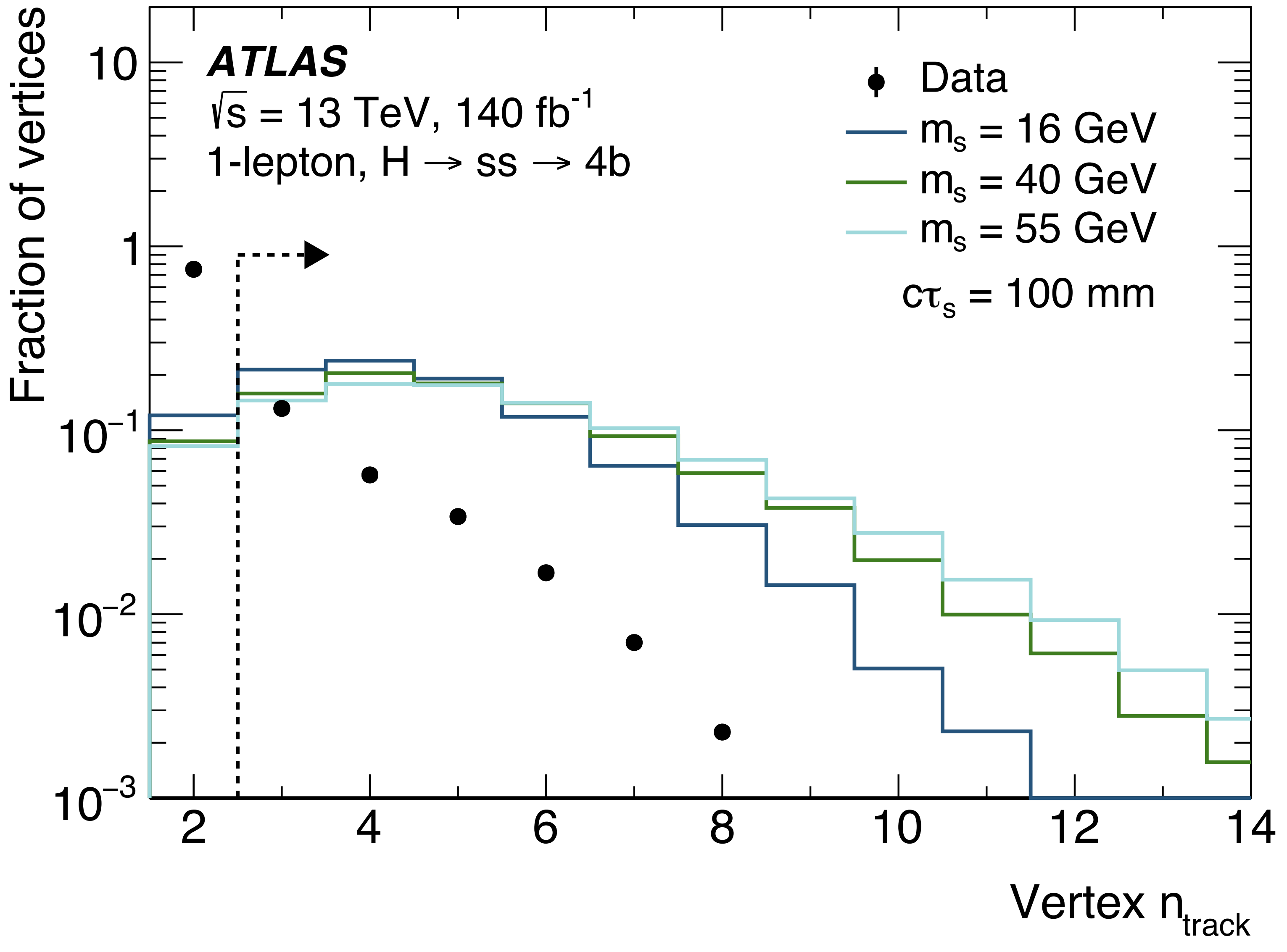




Reconstruct secondary vertices and identify displaced jets using boosted decision tree



Inner detector searches

EXOT-2021-32

New ATLAS results using Run 2 data

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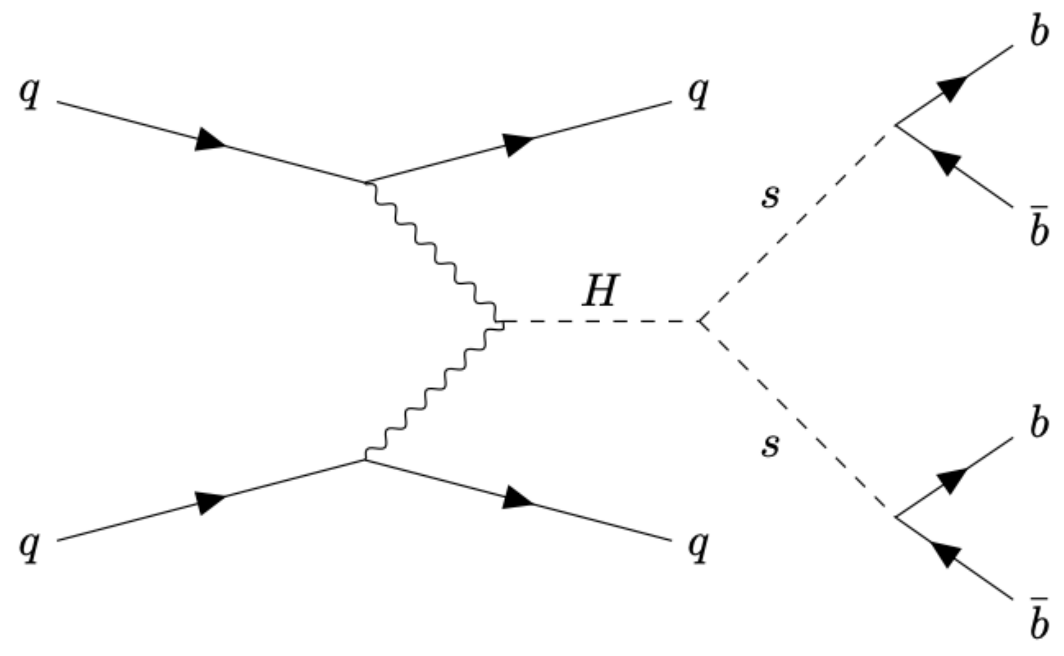

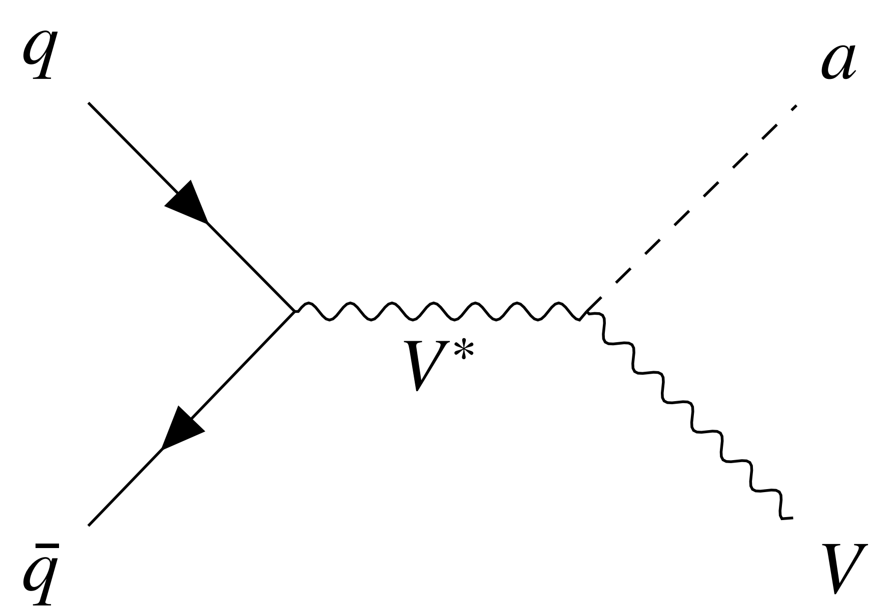

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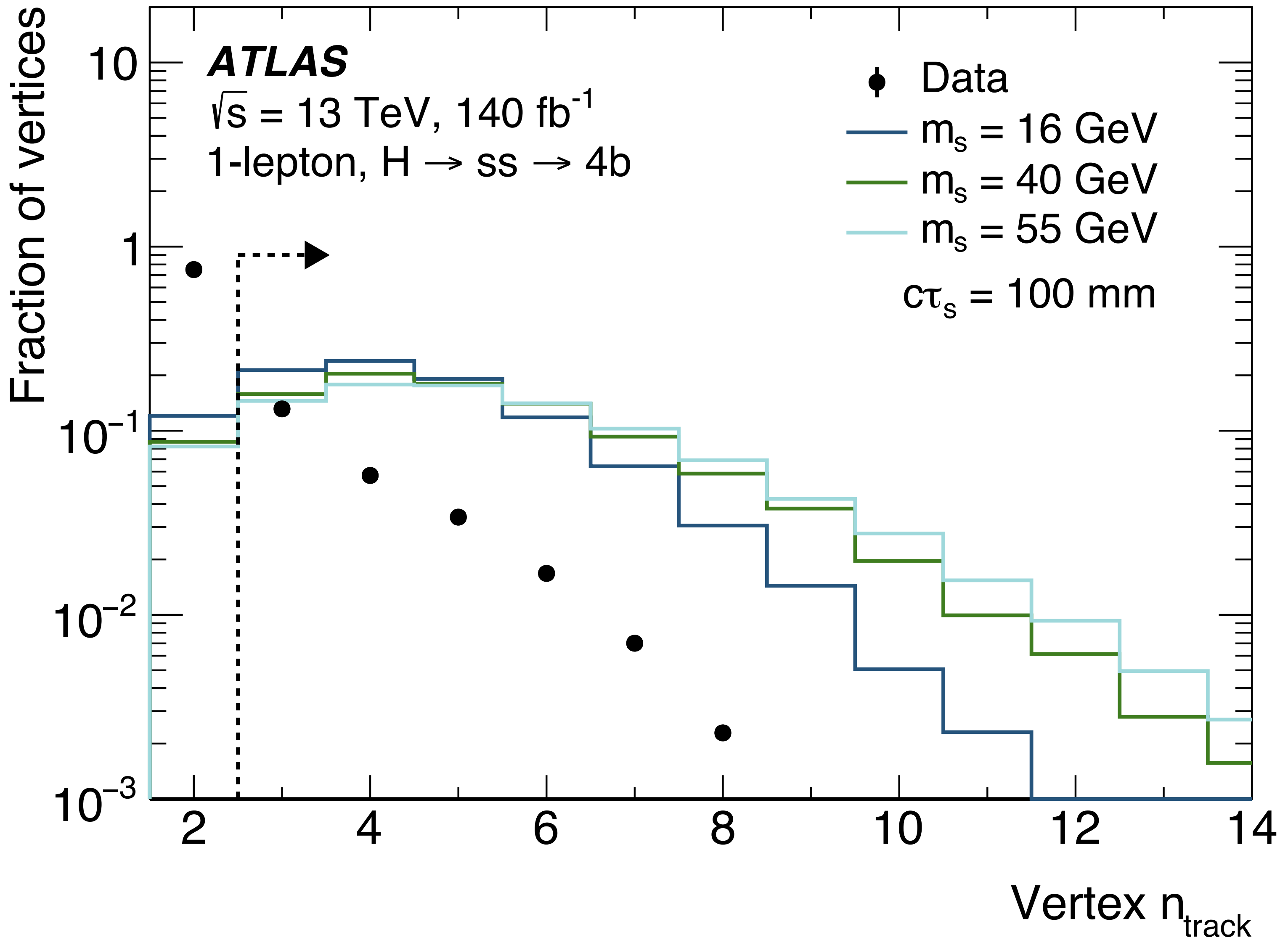

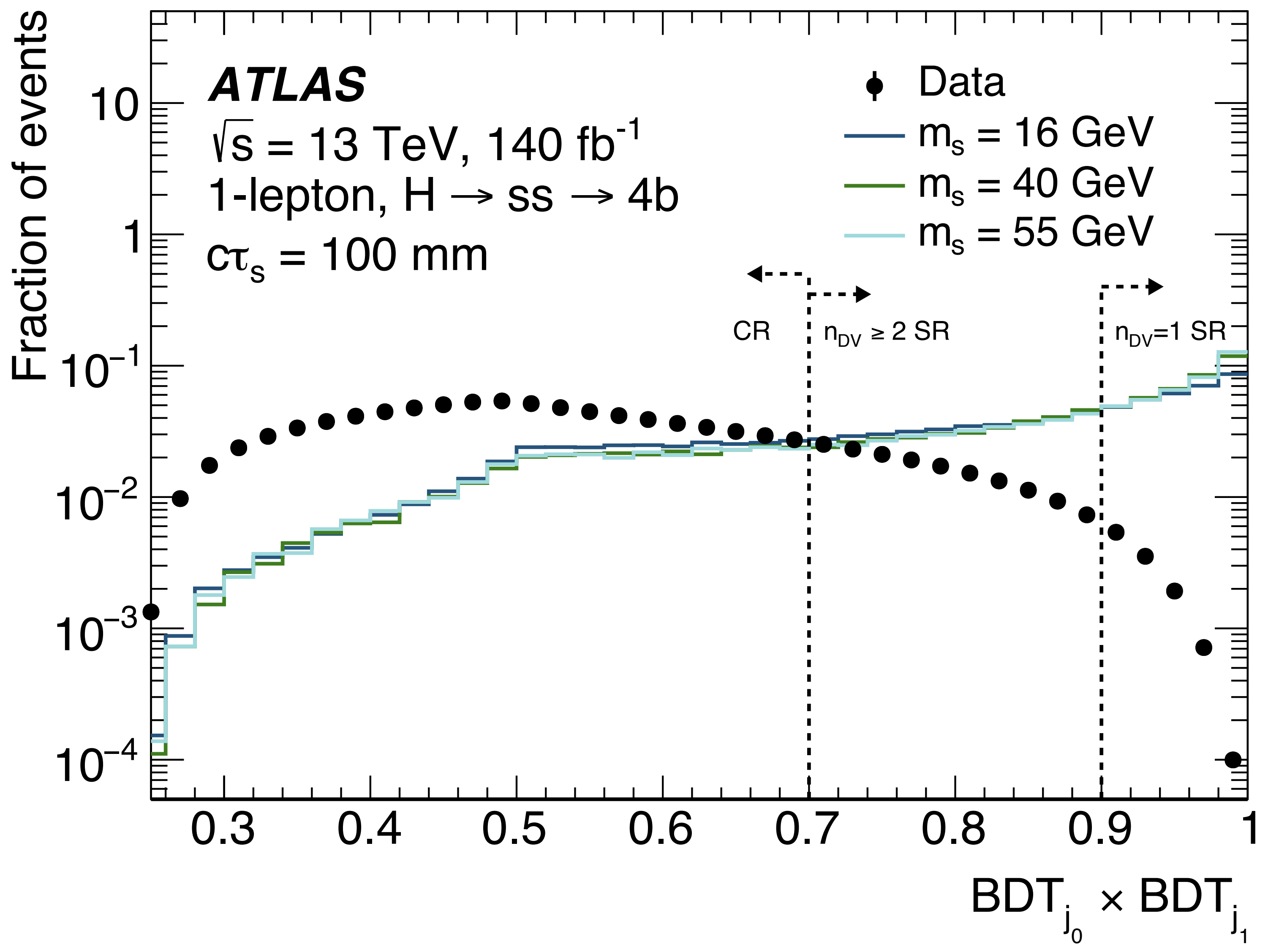

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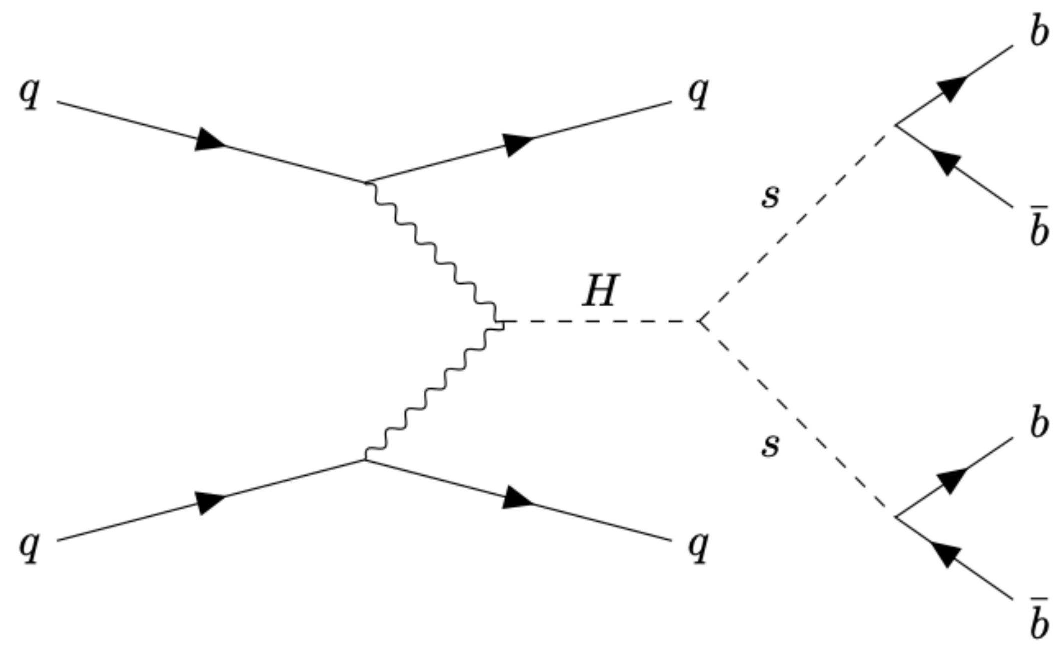

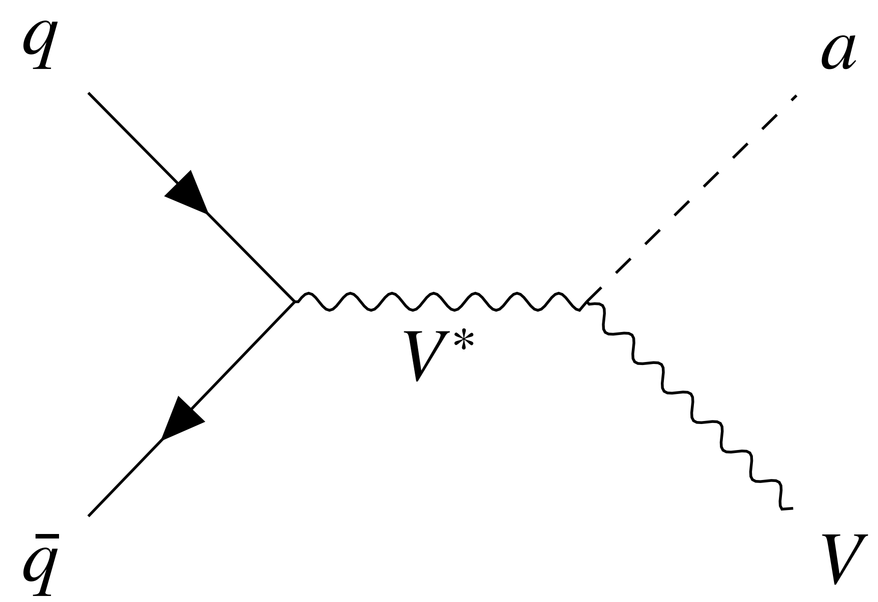

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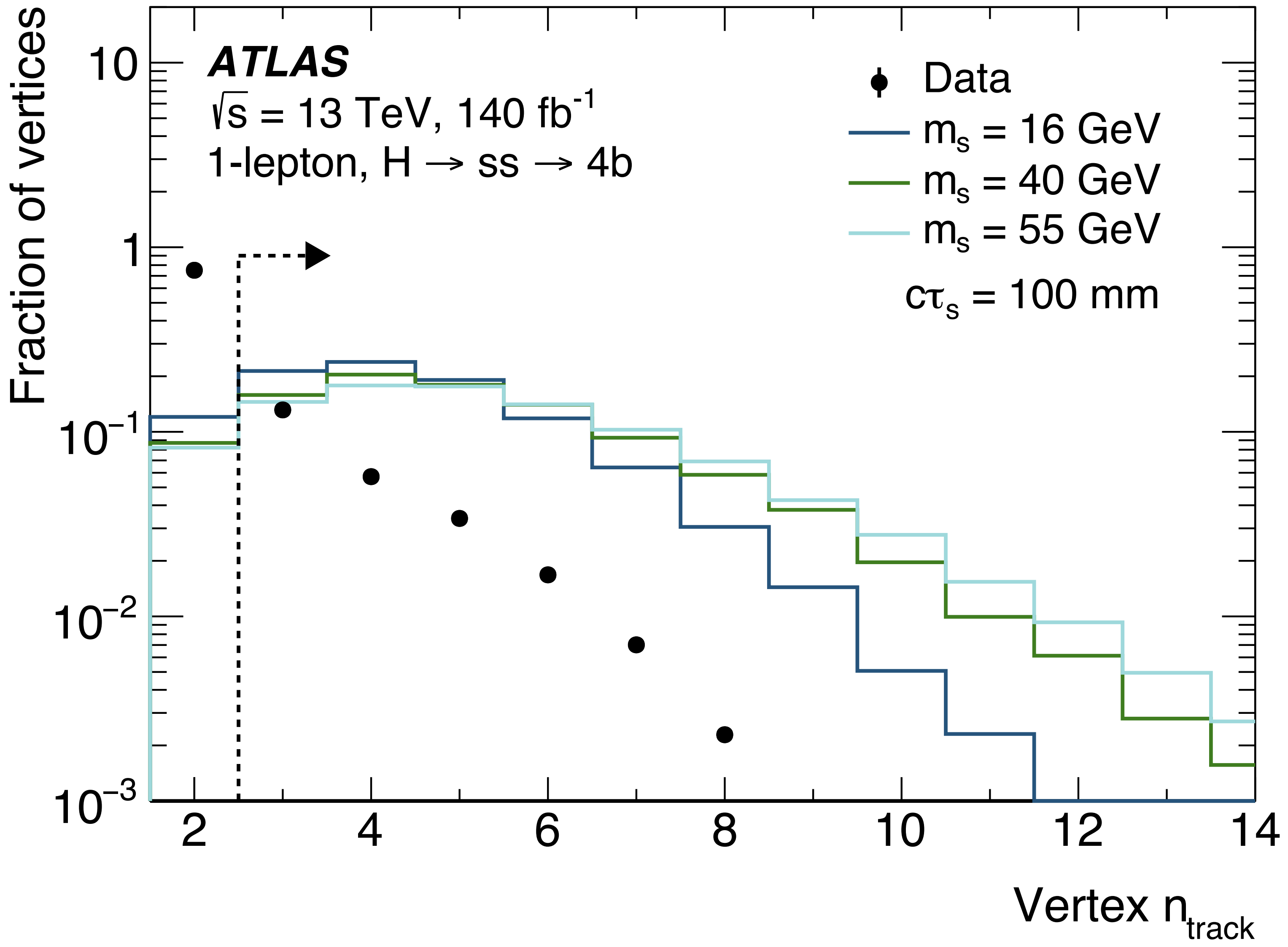
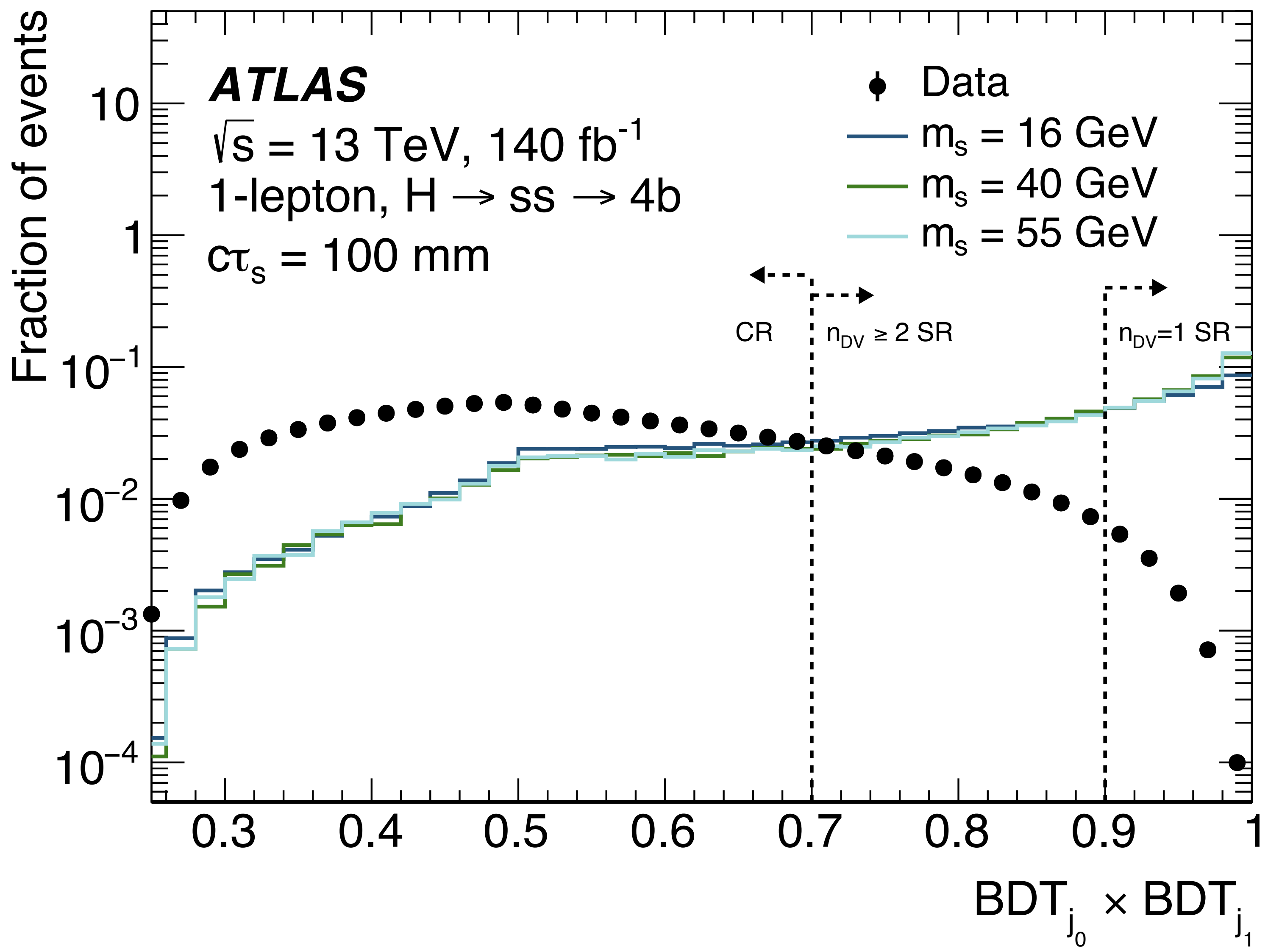
Data-driven background estimate derived by parameterizing per-jet vertex match probability in control region

- Used to estimate distribution of event-level discriminant in events with $n_{\mathrm{DV}} = 1$ and $n_{\mathrm{DV}} \geq 2$



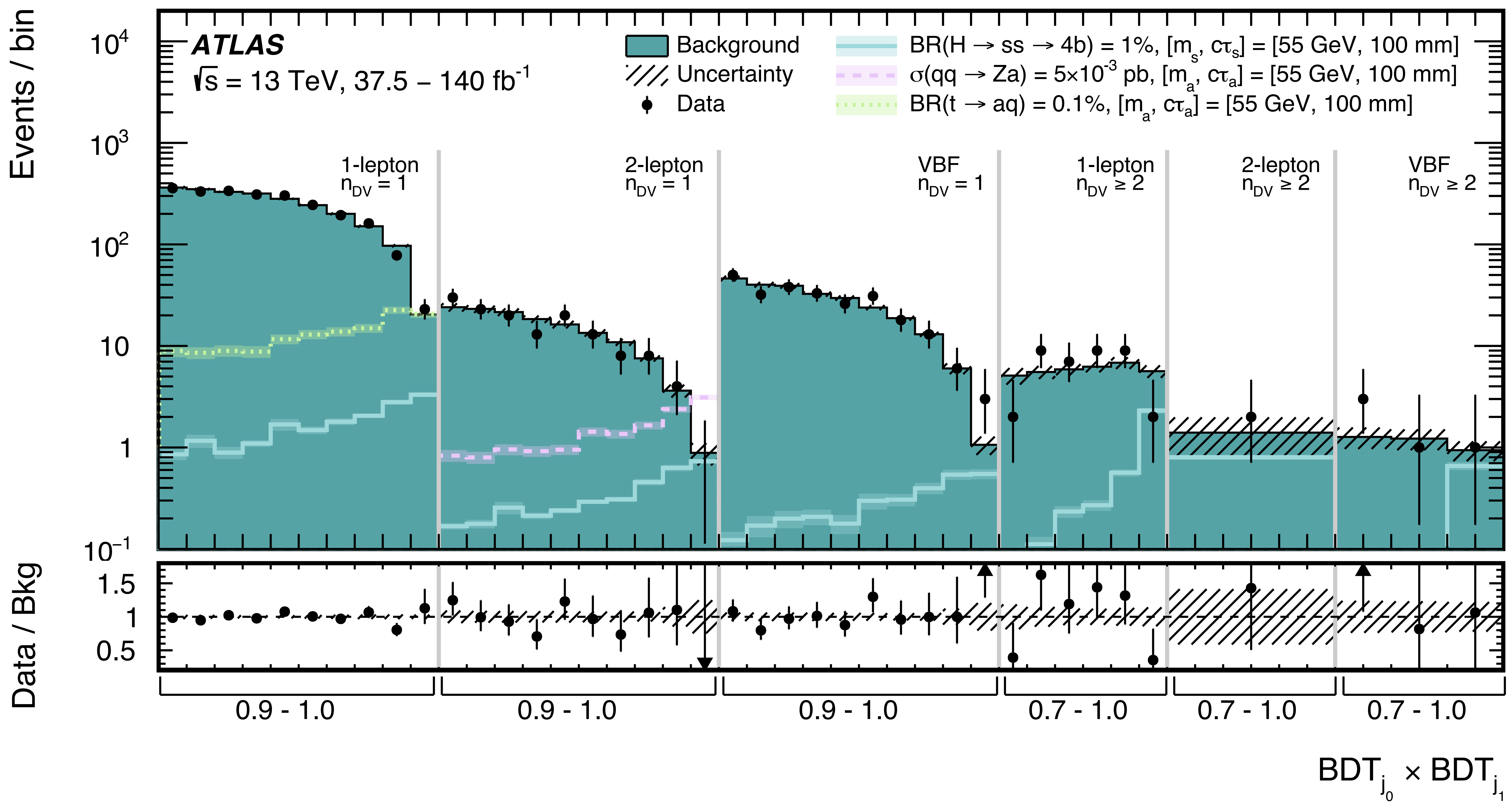


Inner detector searches

EXOT-2021-32

Six signal regions based on Higgs production mode and vertex multiplicity

- Binned in event-level discriminant formed from jet-level BDT scores



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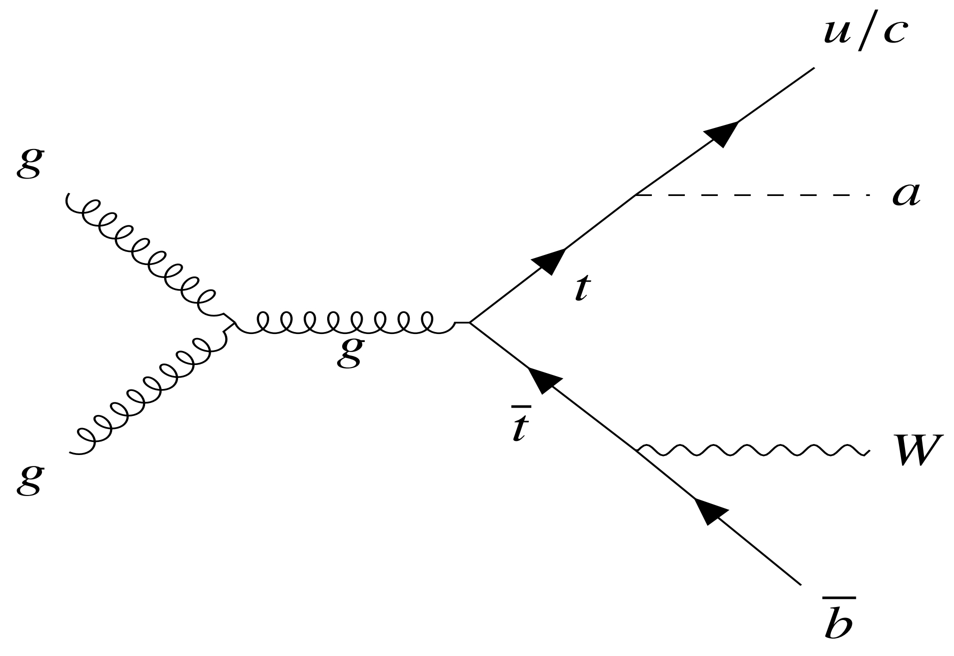
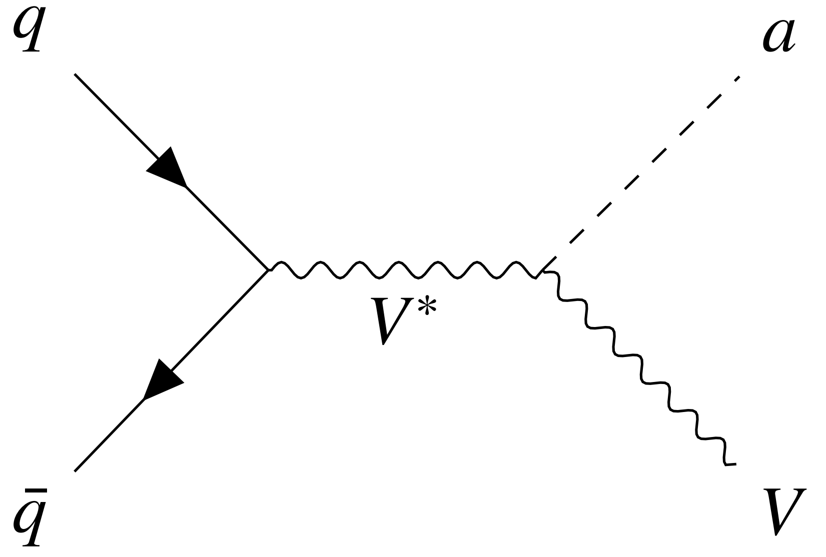
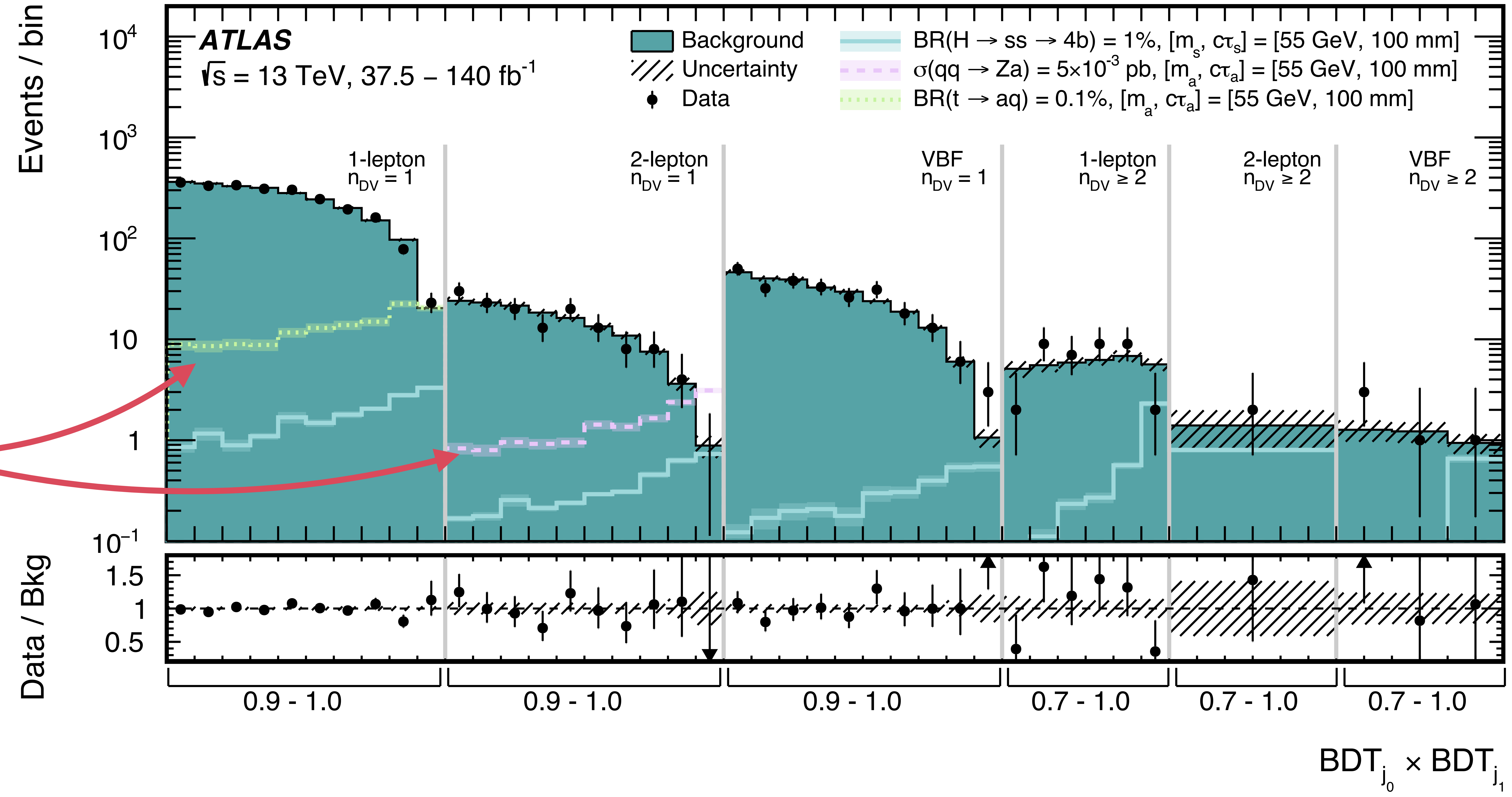


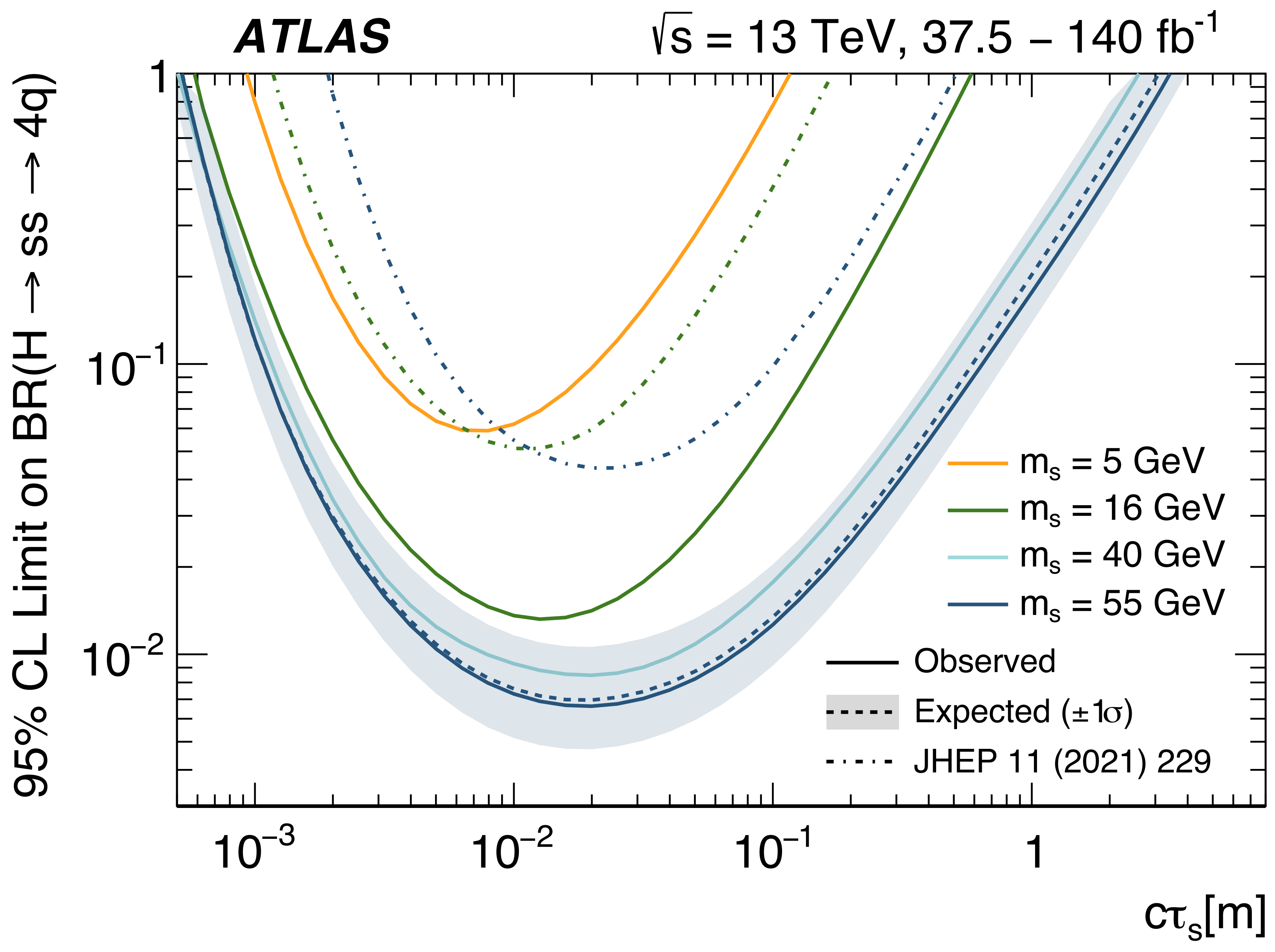
Sensitivity also to axion-like particles from top decays and vector boson couplings

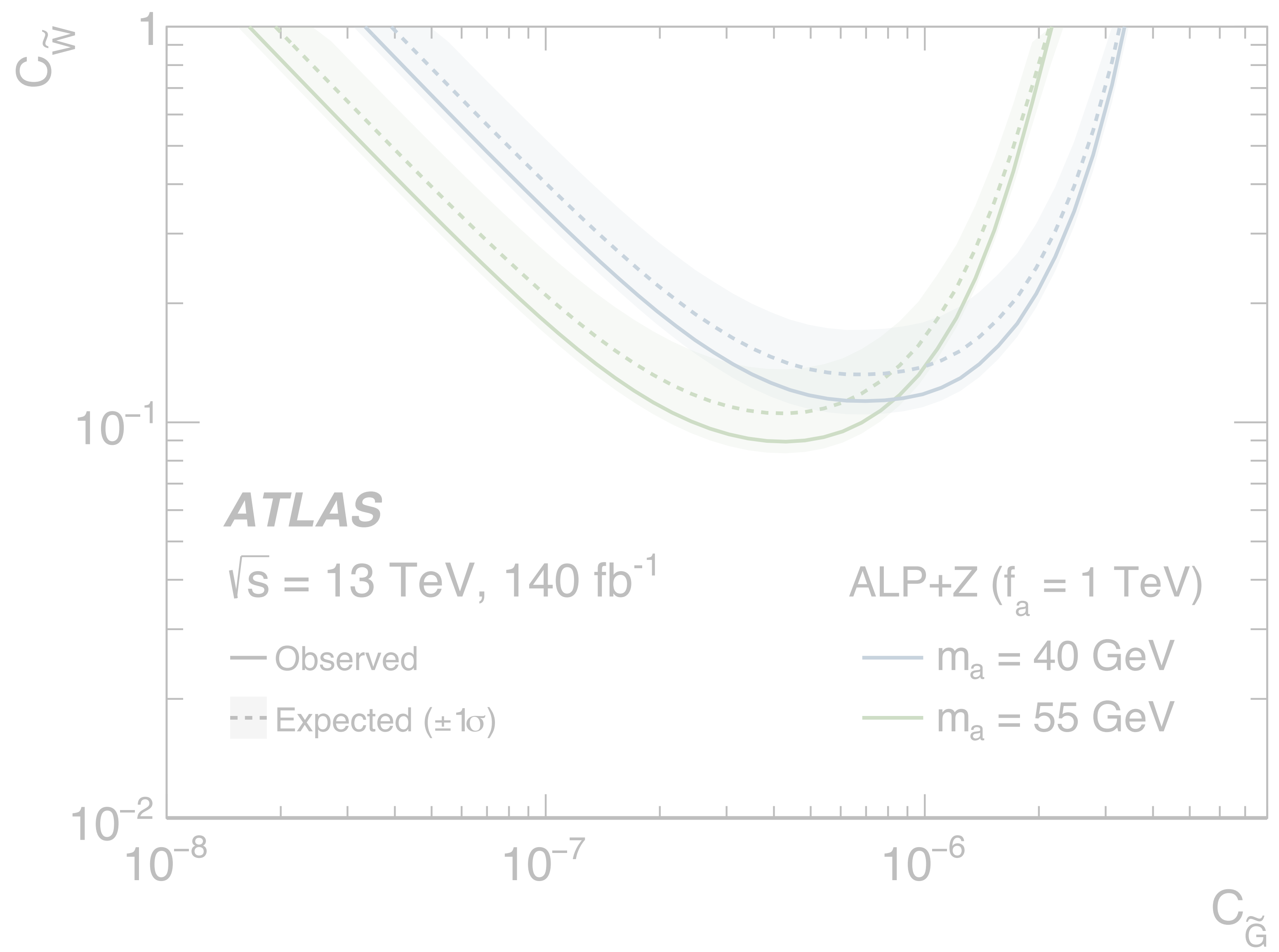


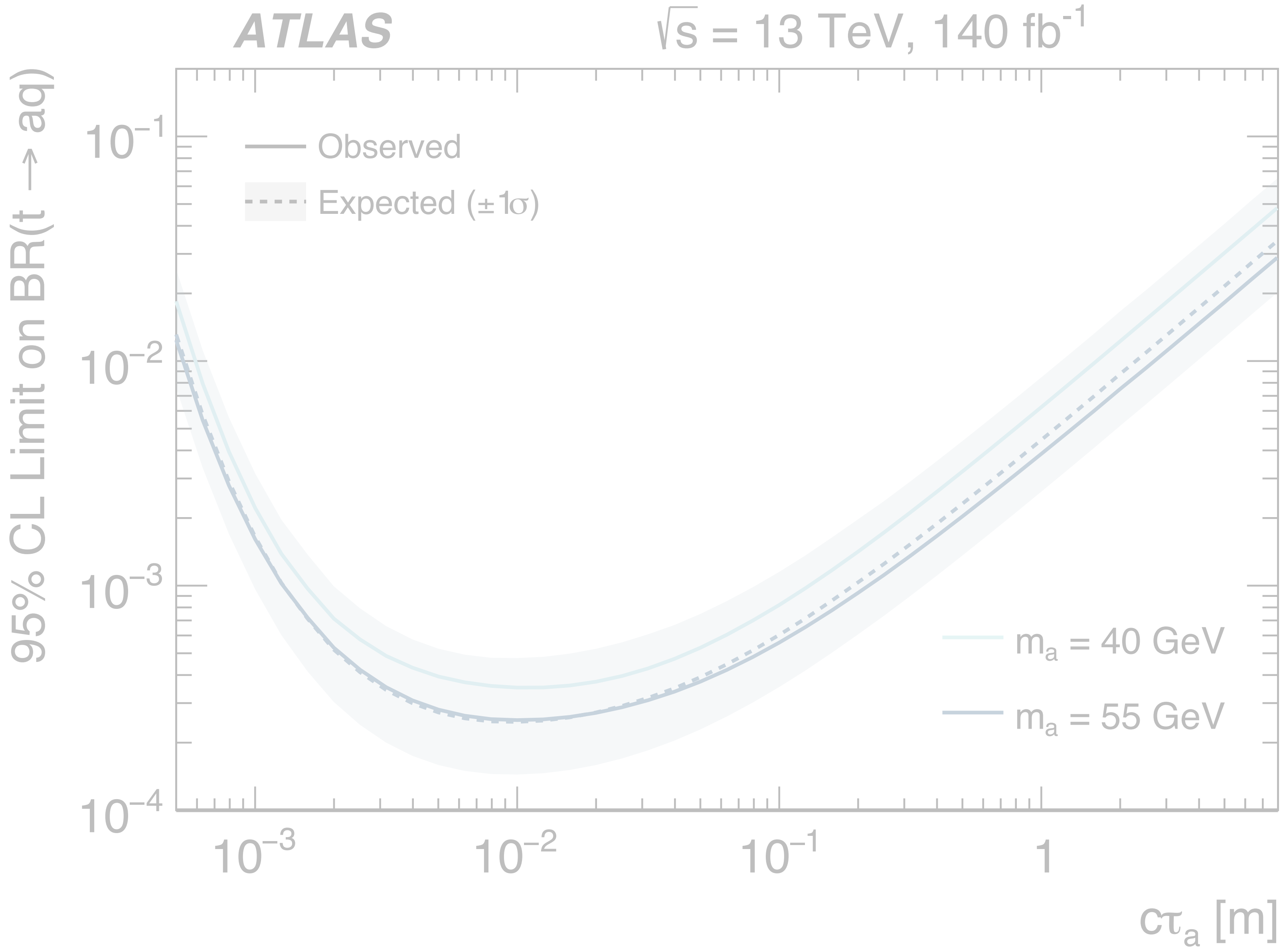


Inner detector searches

EXOT-2021-32







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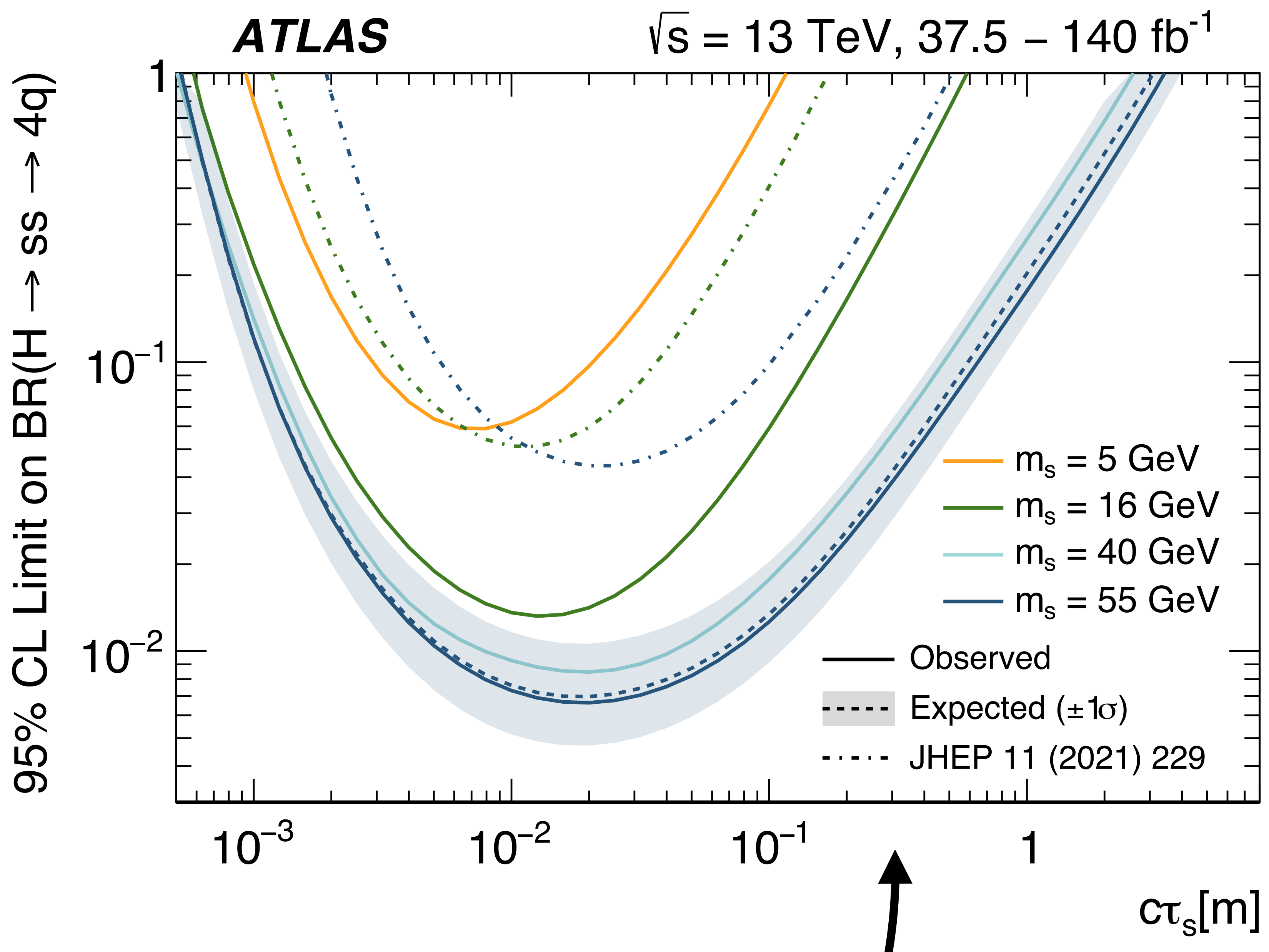
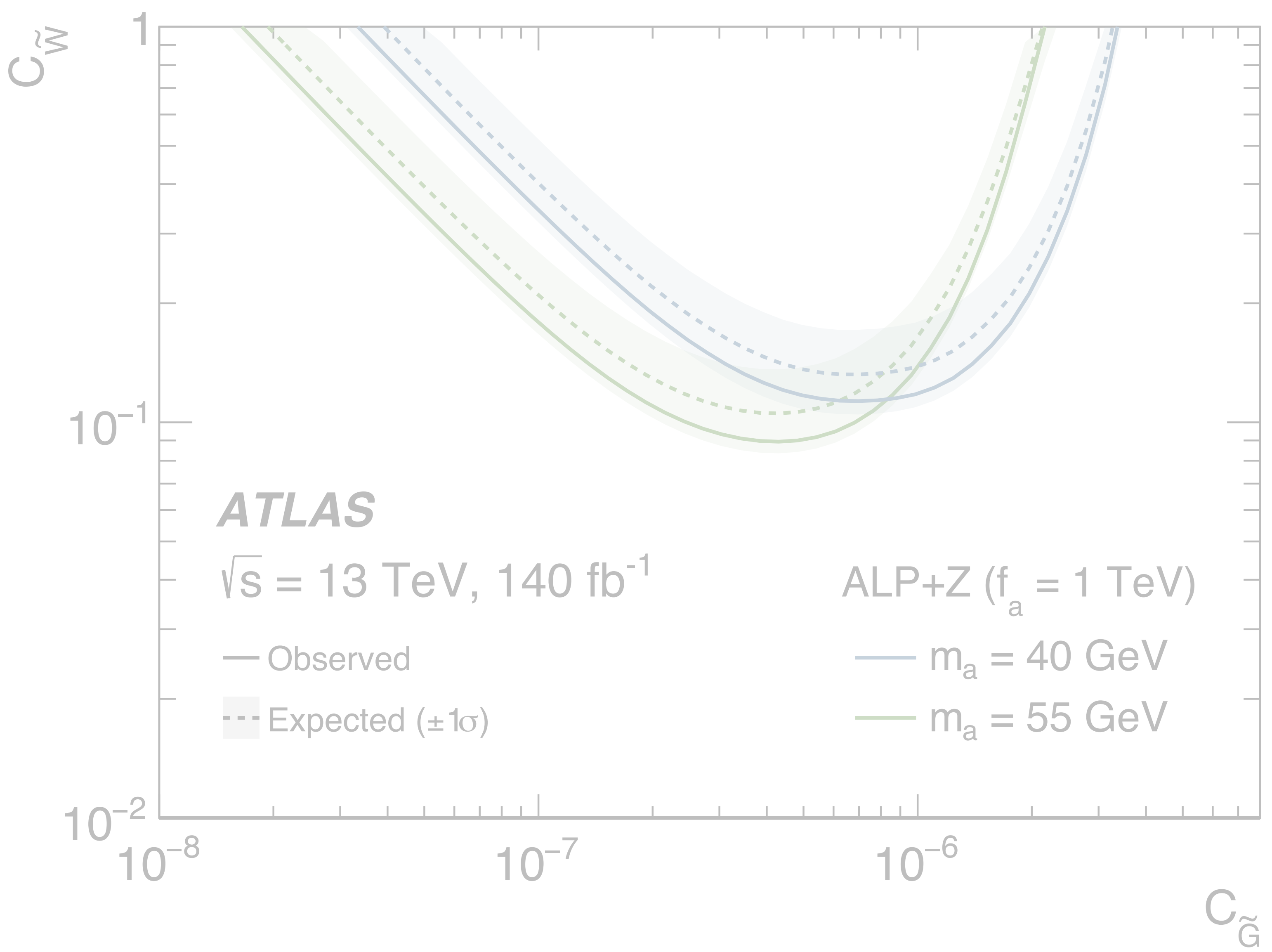
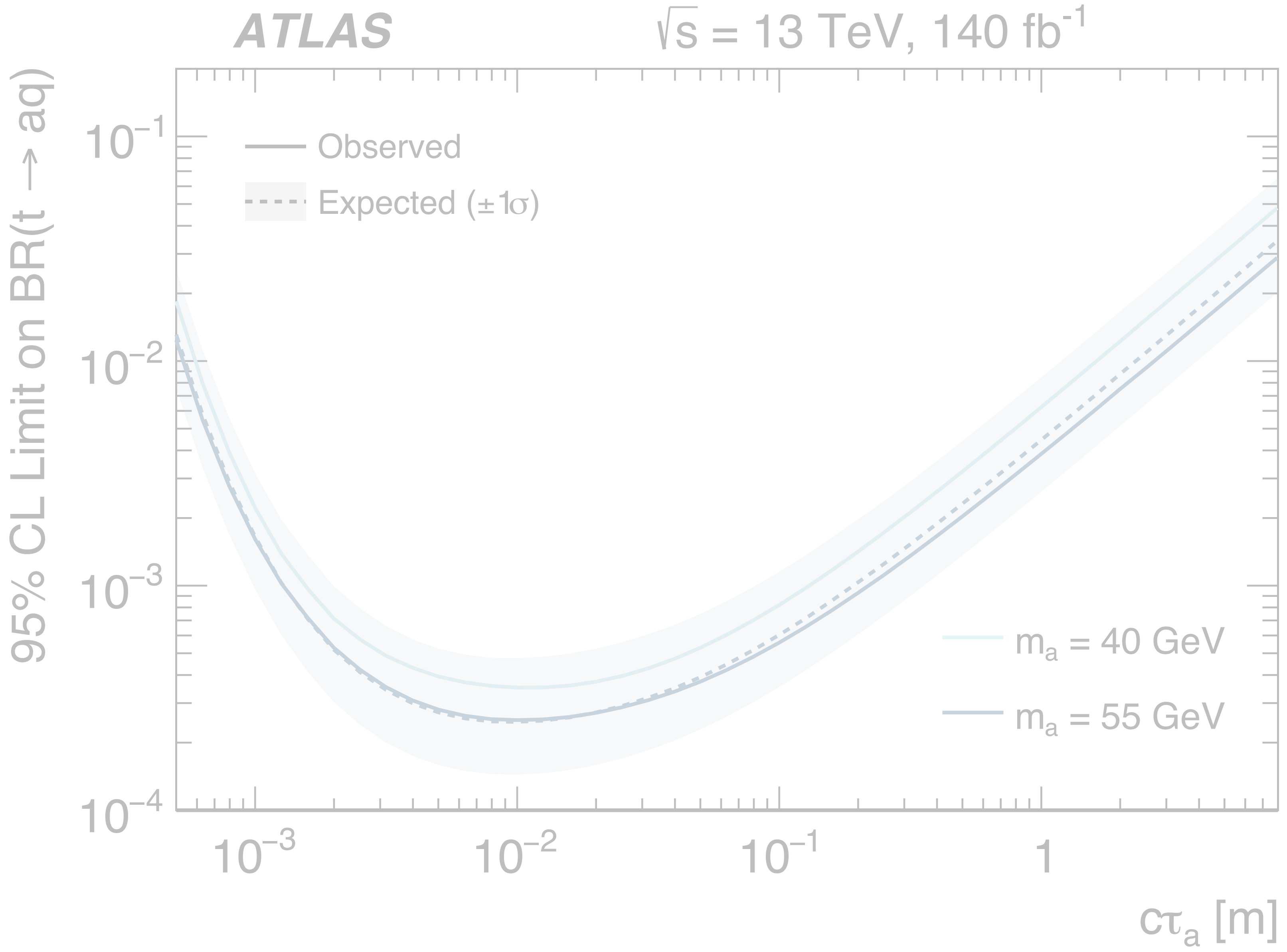






Order of magnitude improvement w.r.t previous ATLAS results

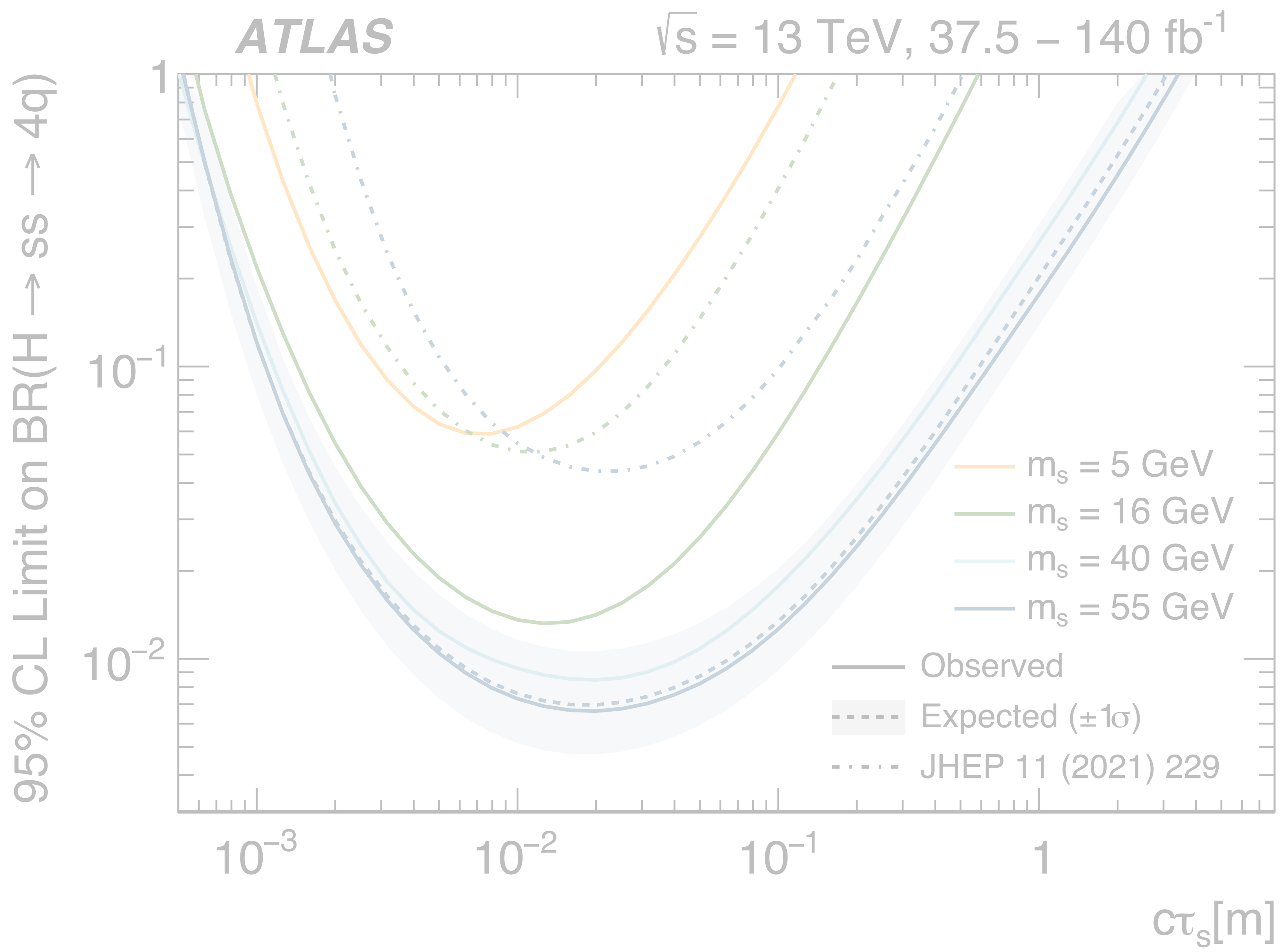
Inner detector searches

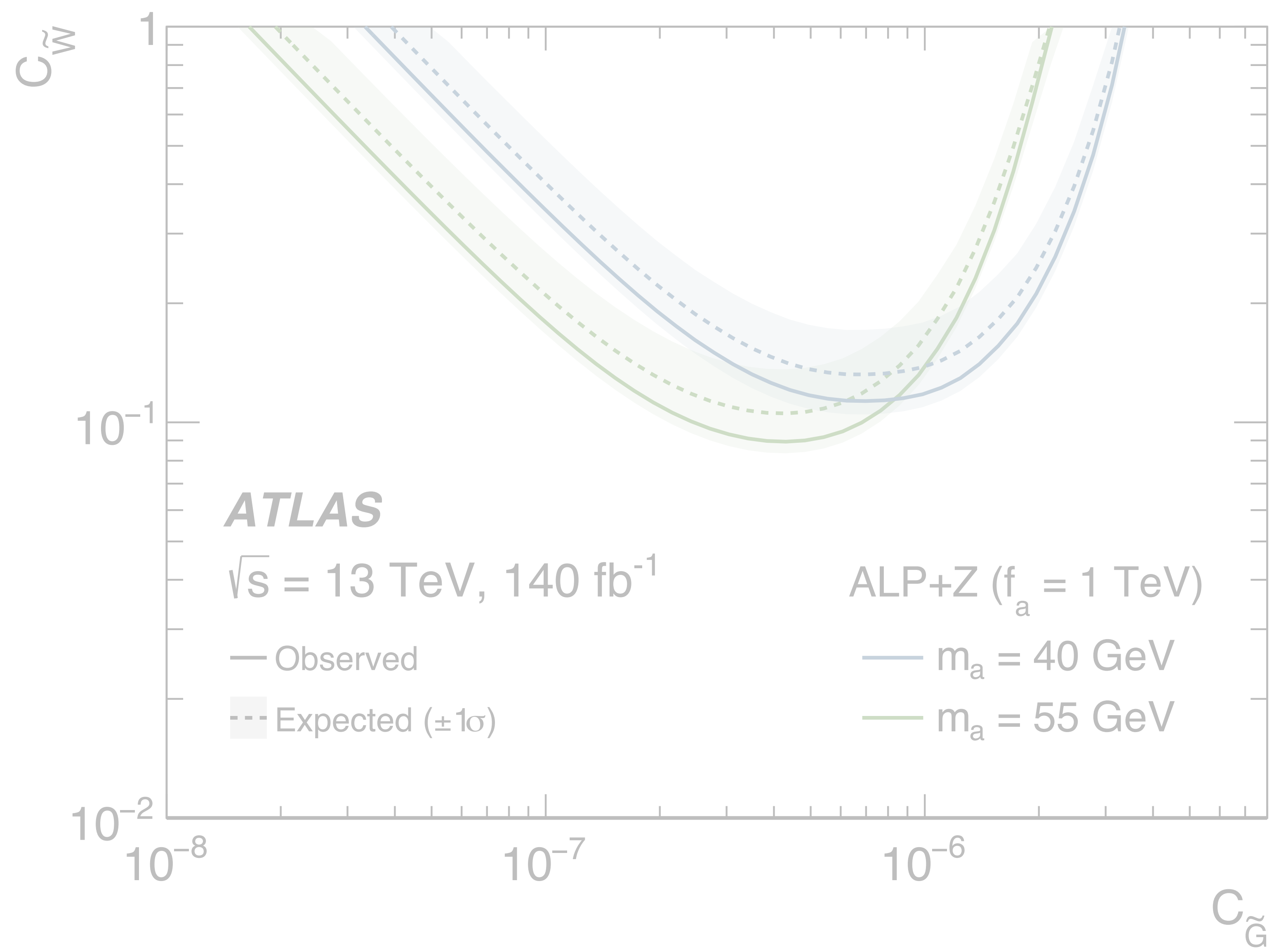
EXOT-2021-32

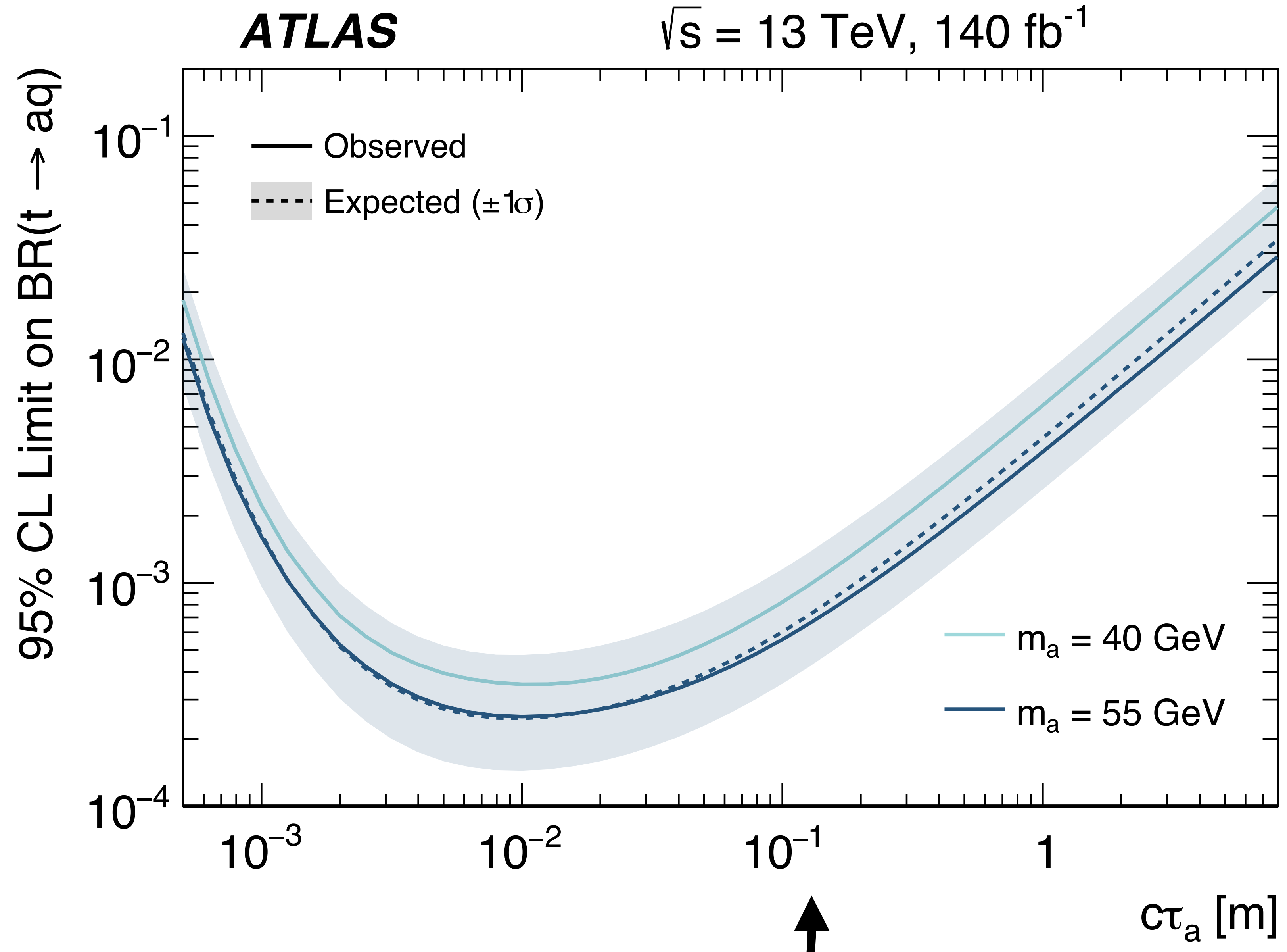
First limits on photophobic ALP decays produced in association with vector bosons

Inner detector searches

EXOT-2021-32

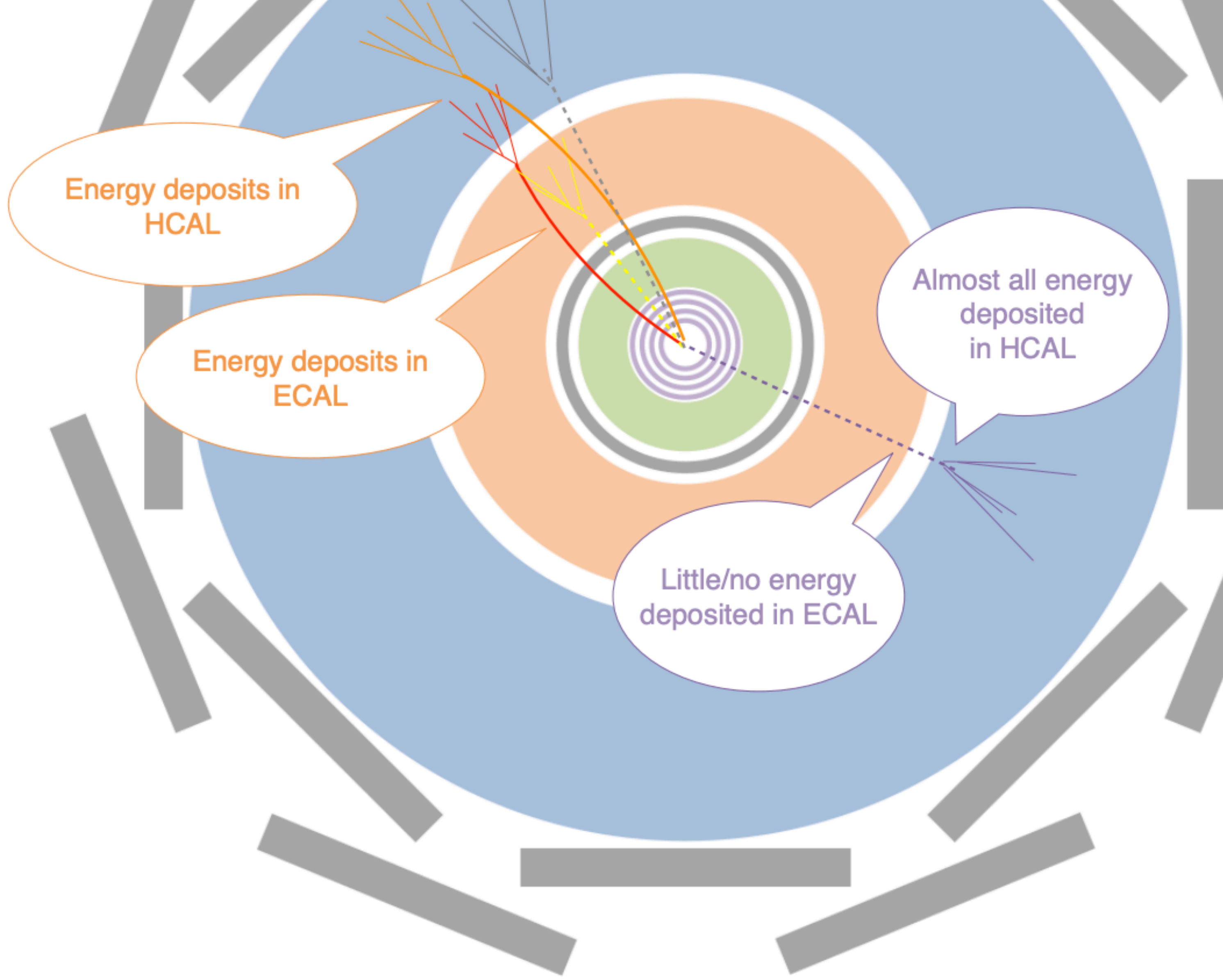






First limits on exotic top decays to ALPs

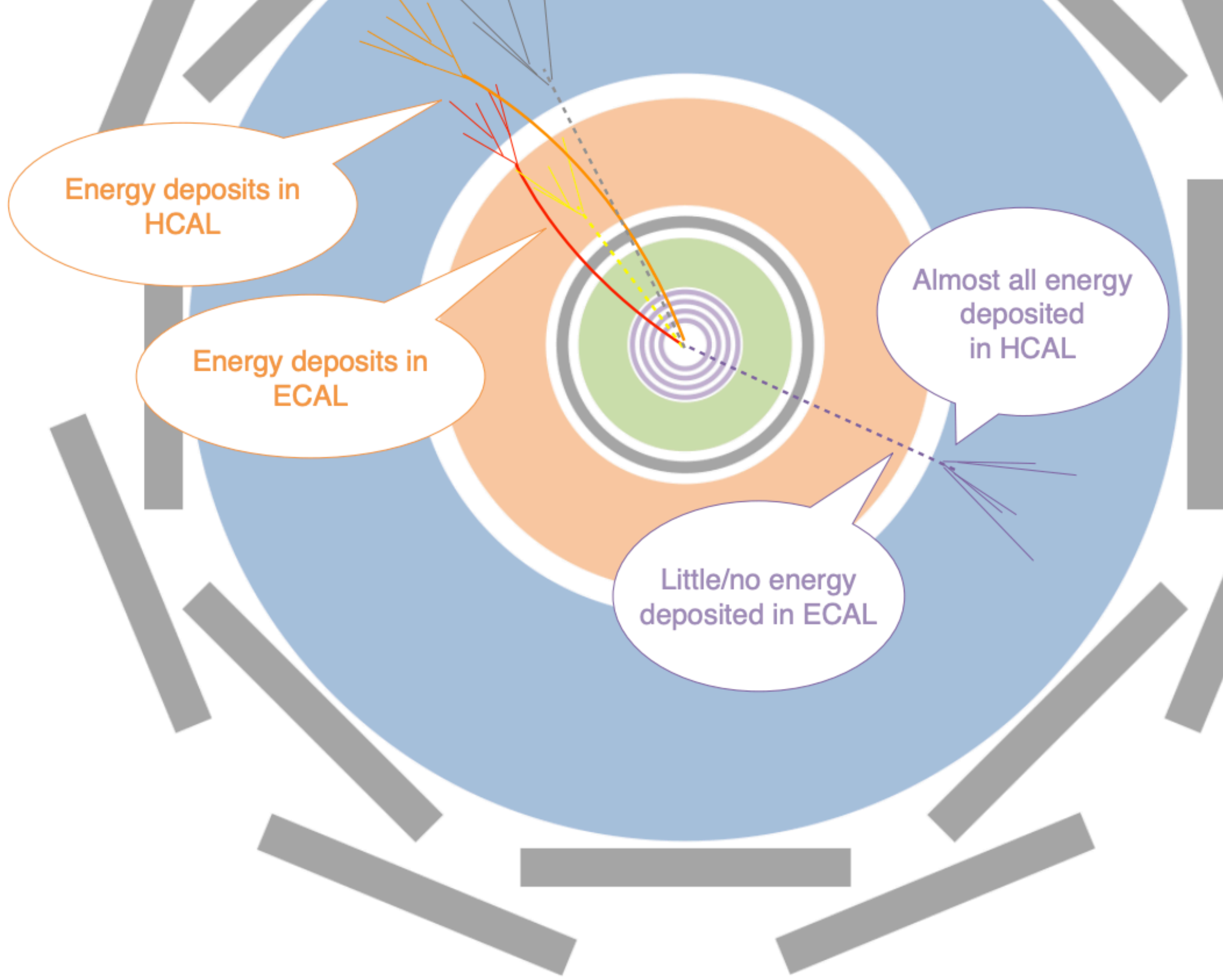
Calorimeter searches



For longer lifetimes, LLPs will decay outside of the ID and inside of the calorimeter

- Rely on anomalous ratio of energy deposits in HCAL vs ECAL ("CalRatio")

Calorimeter searches



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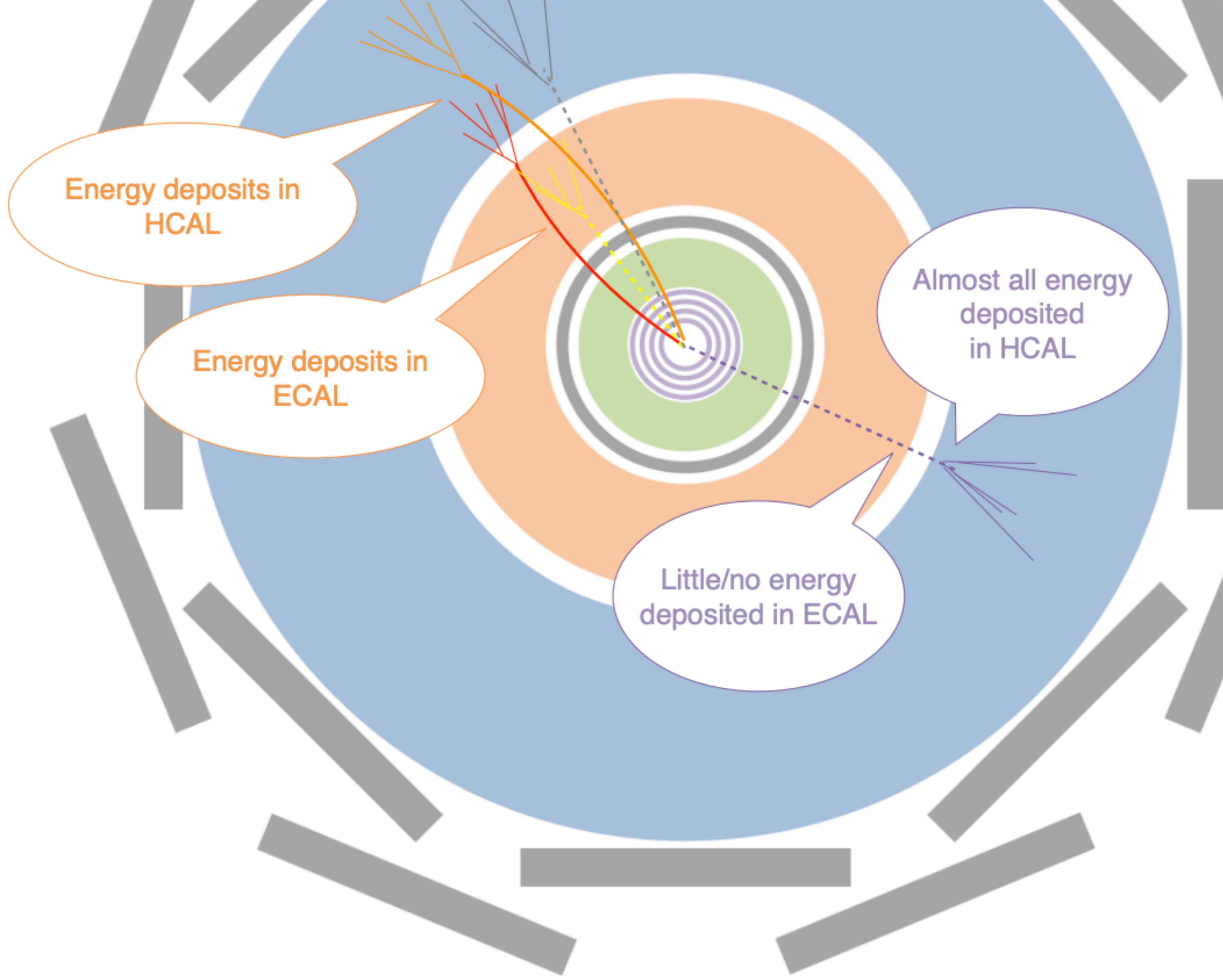

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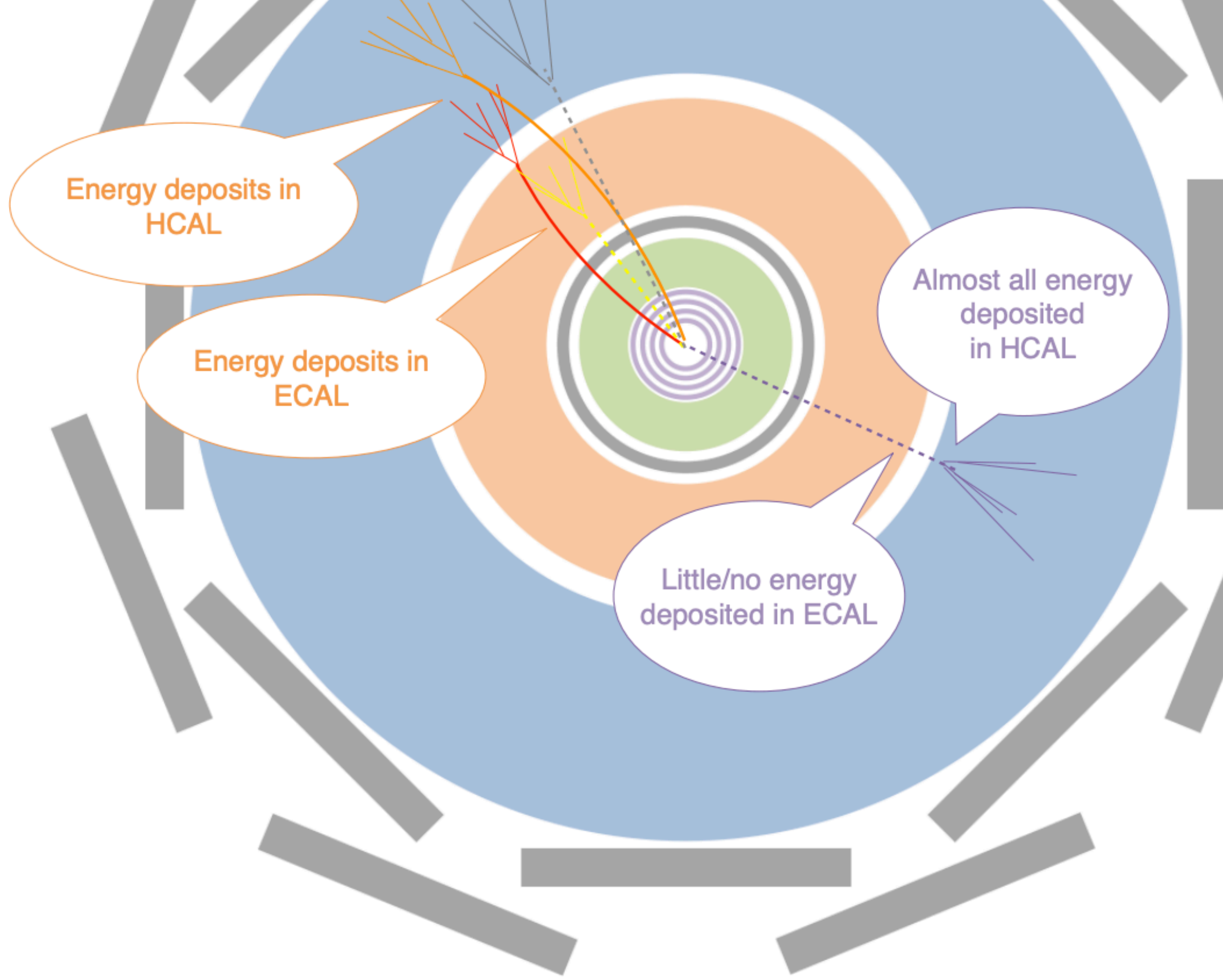

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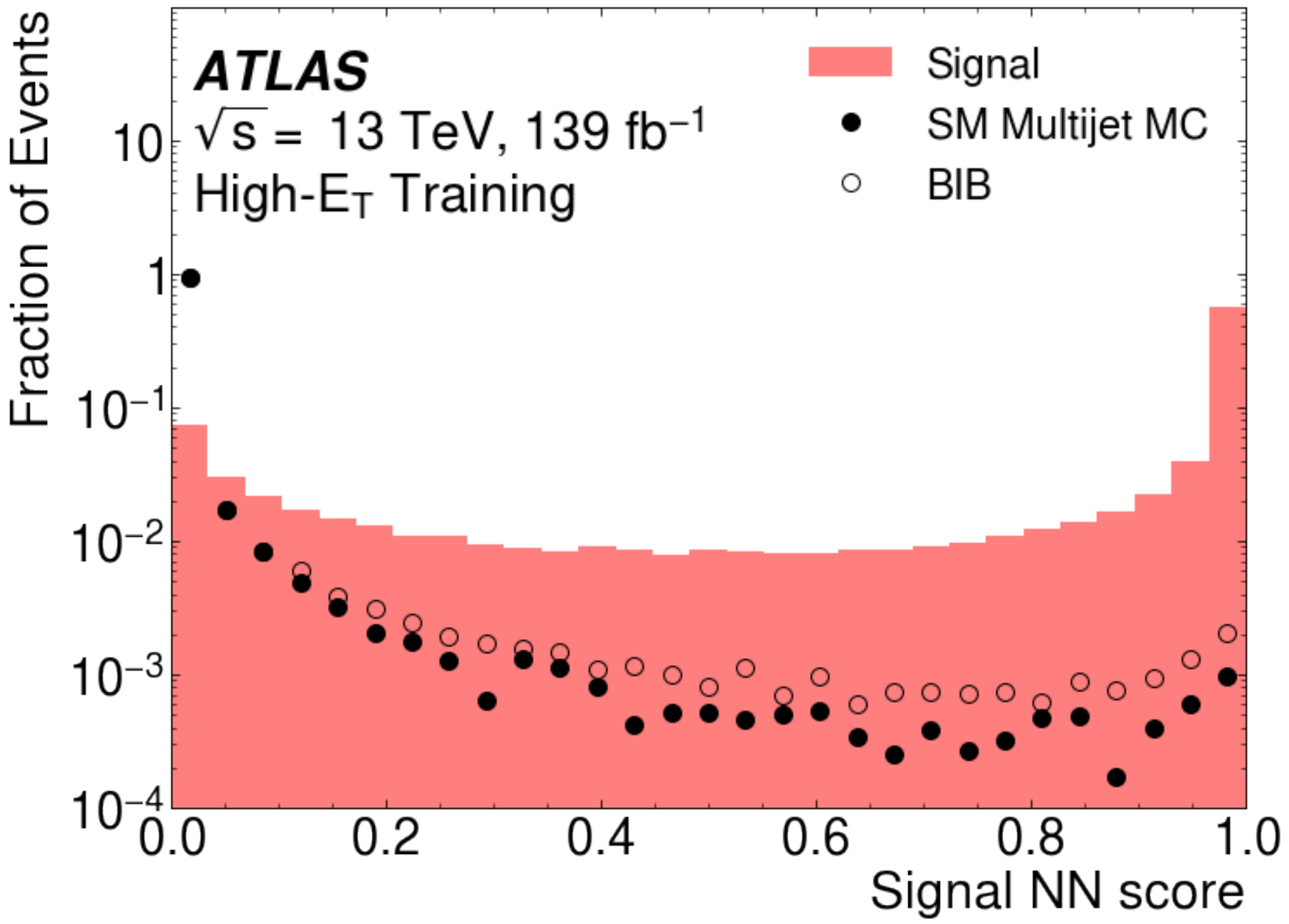
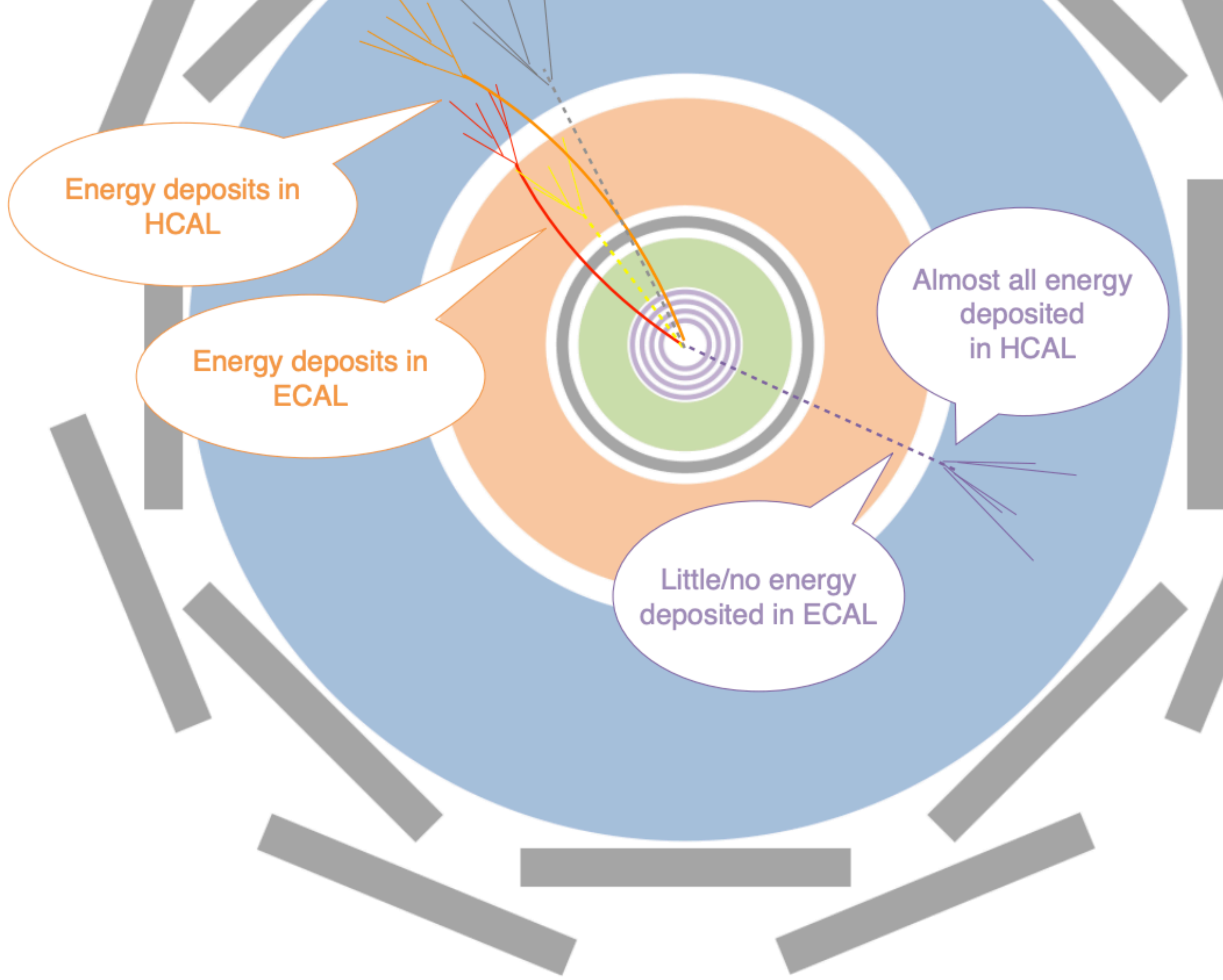


Calorimeter searches



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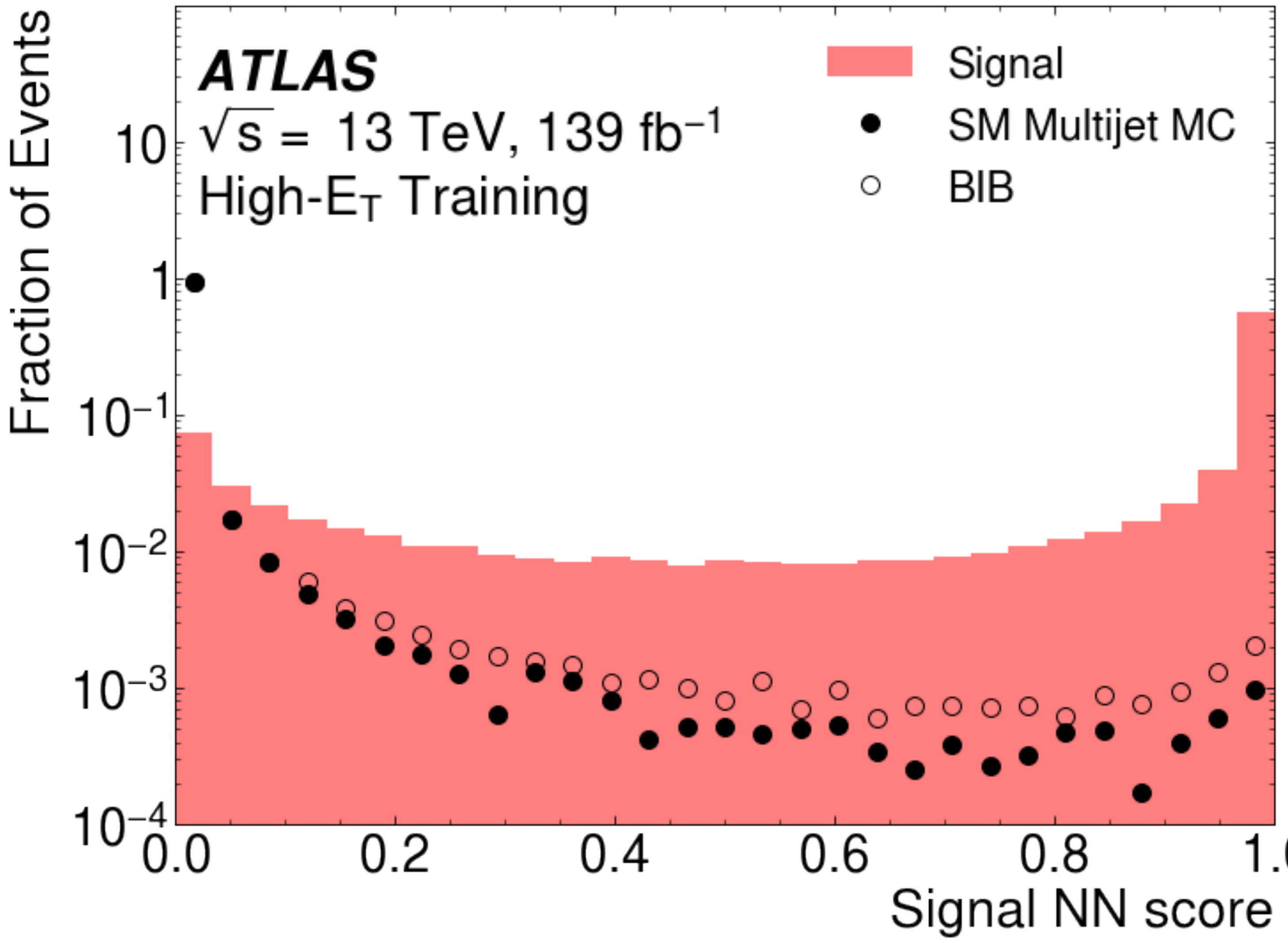
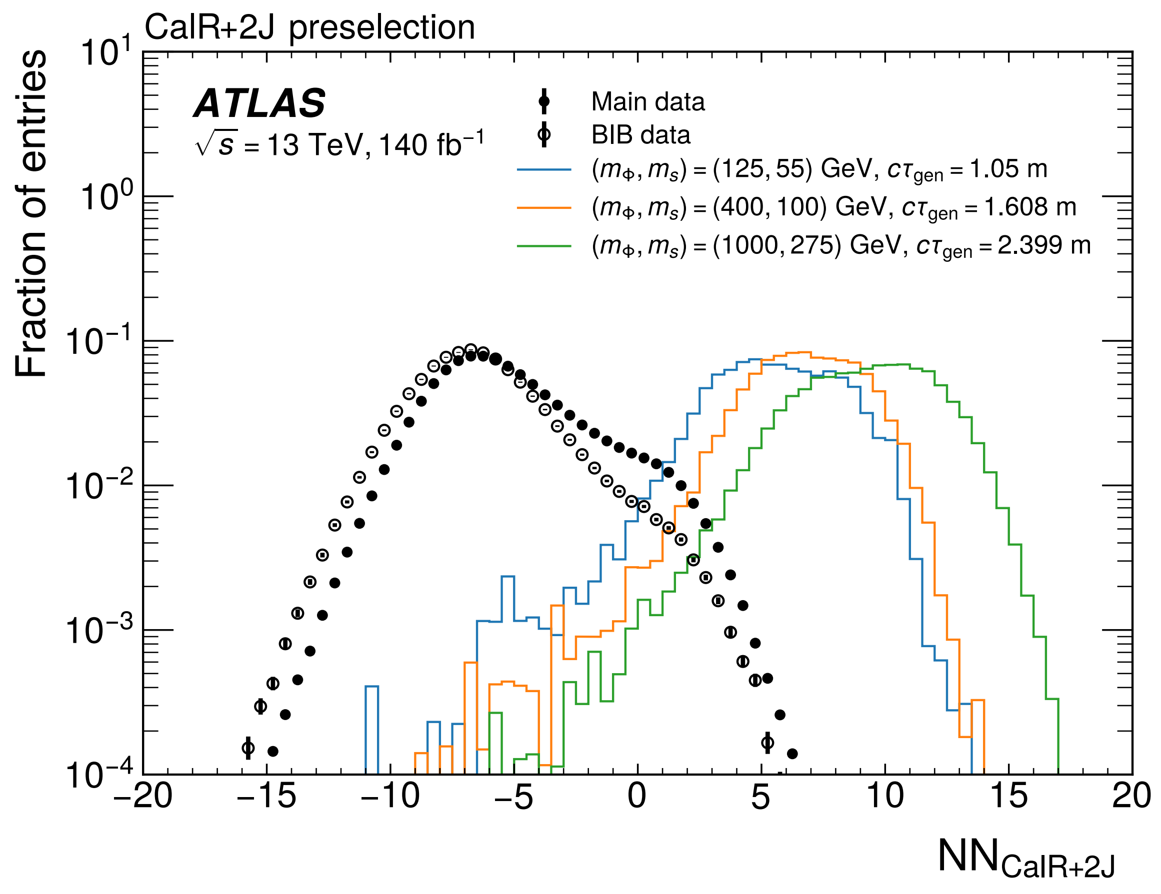
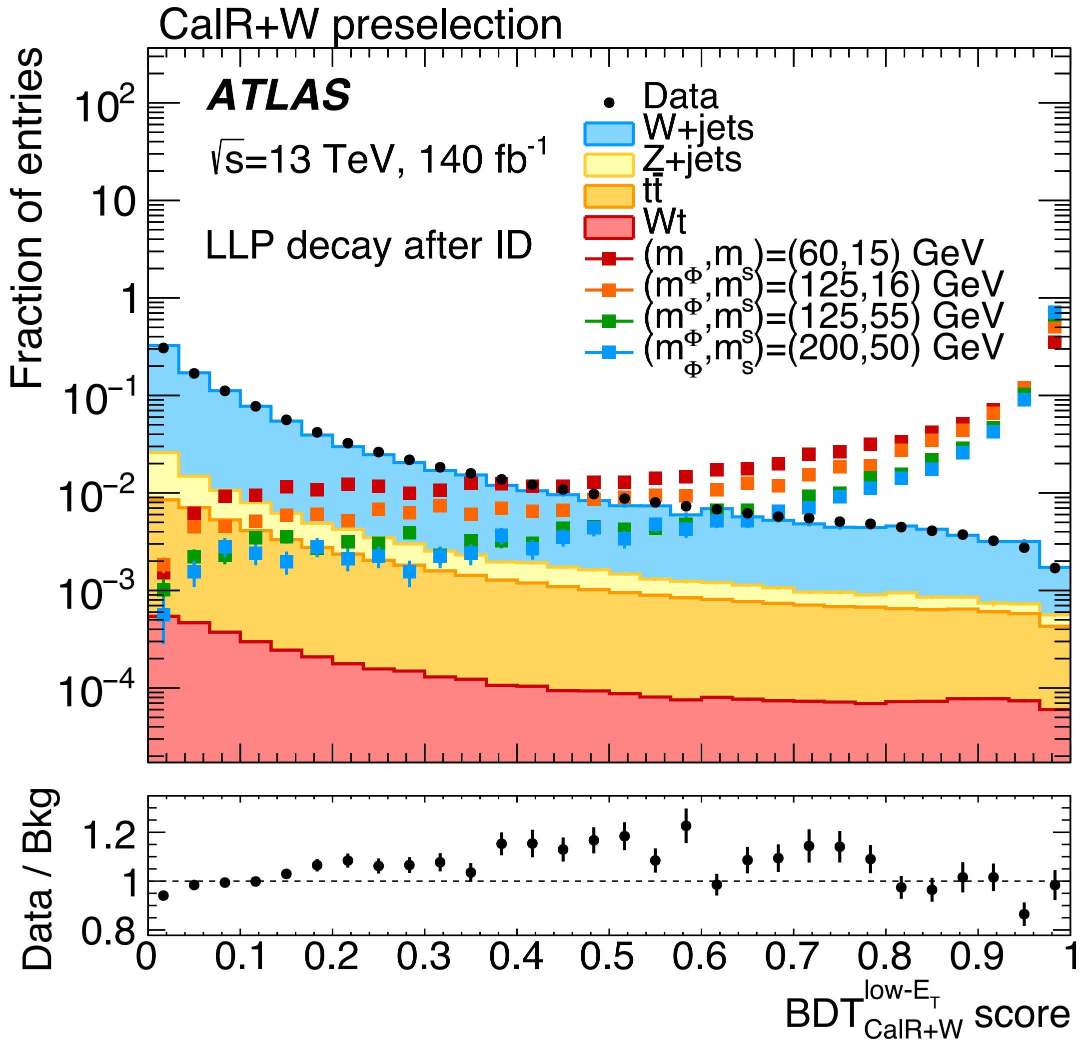


Input into analysis-specific per-event classifiers





Calorimeter searches

EXOT-2022-04

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Background estimated using data-driven ABCD planes

- “DisCo” method used to decorrelate axes in CalRatio+2j channel

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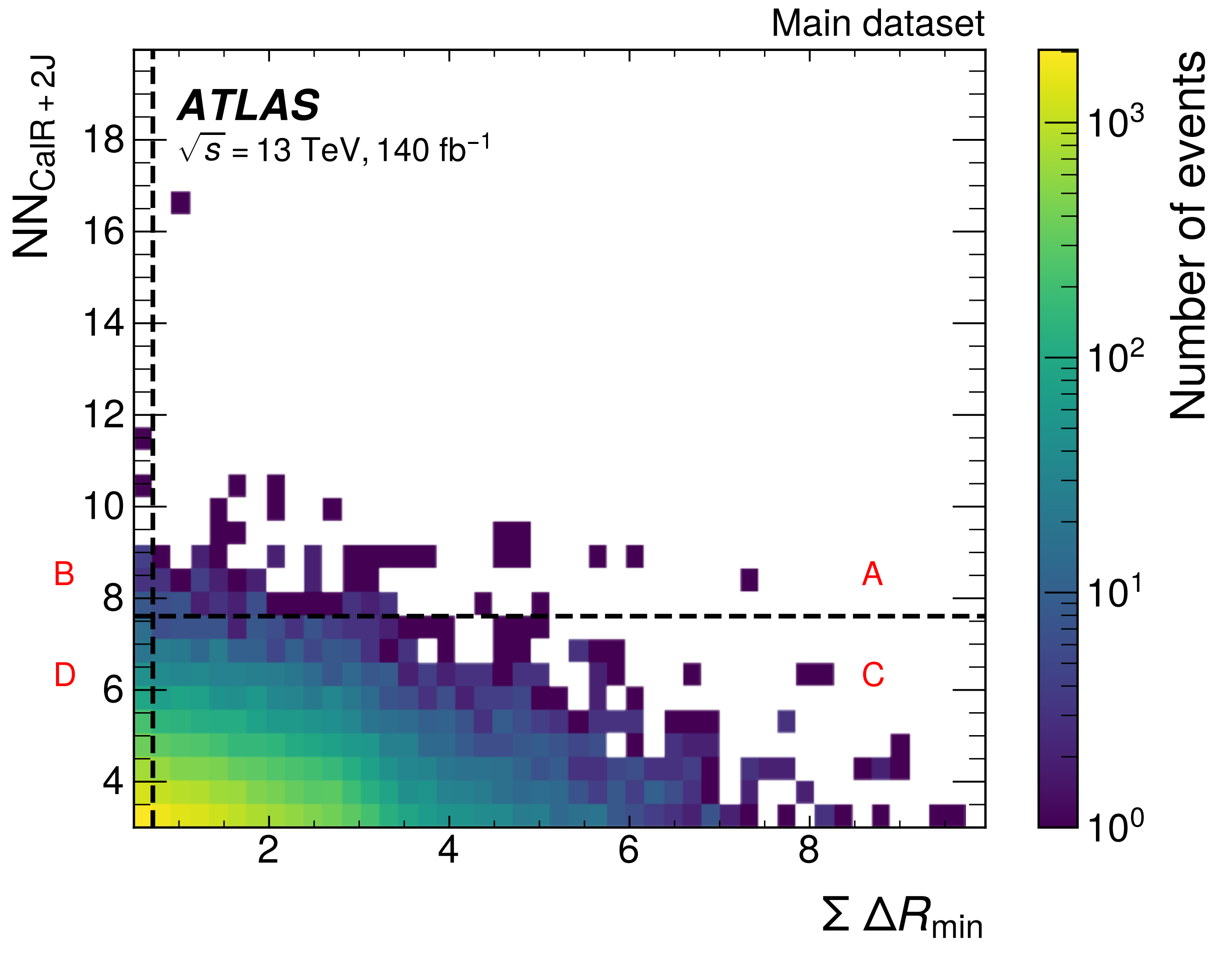

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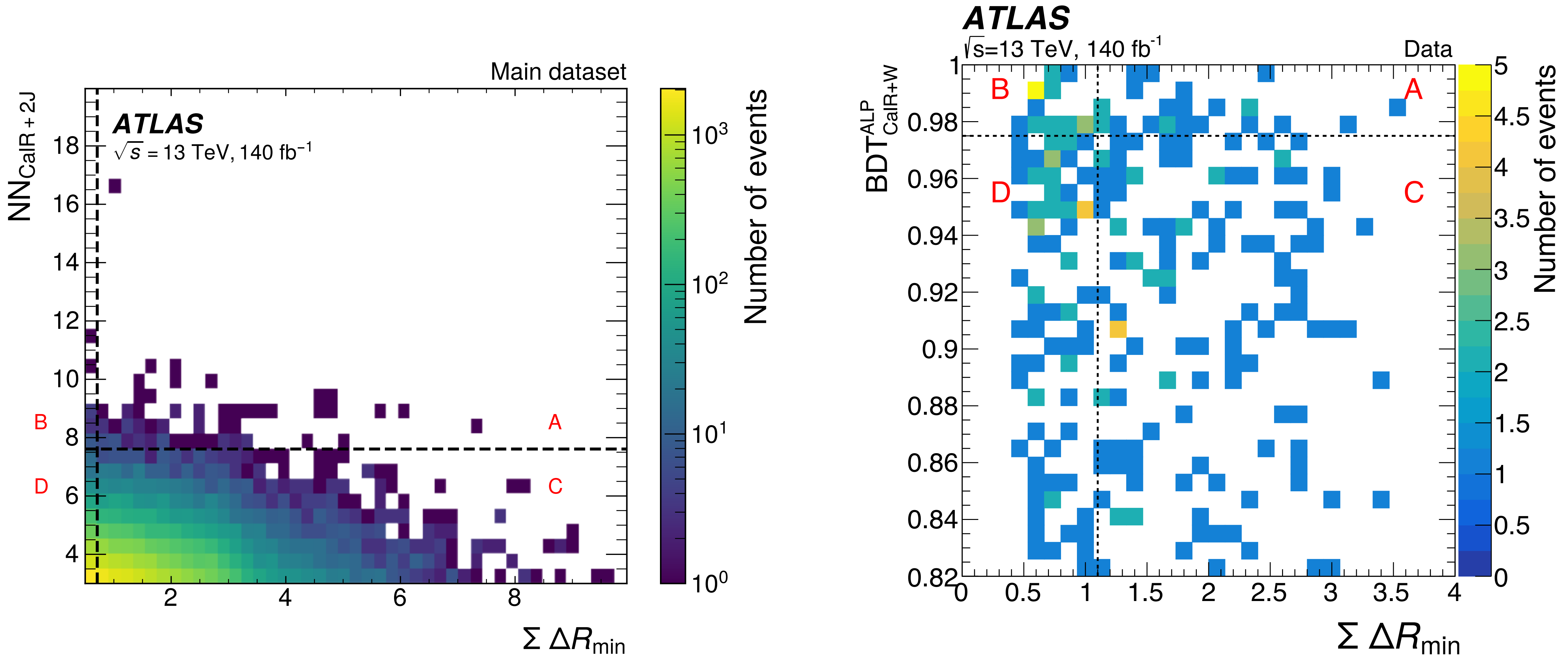

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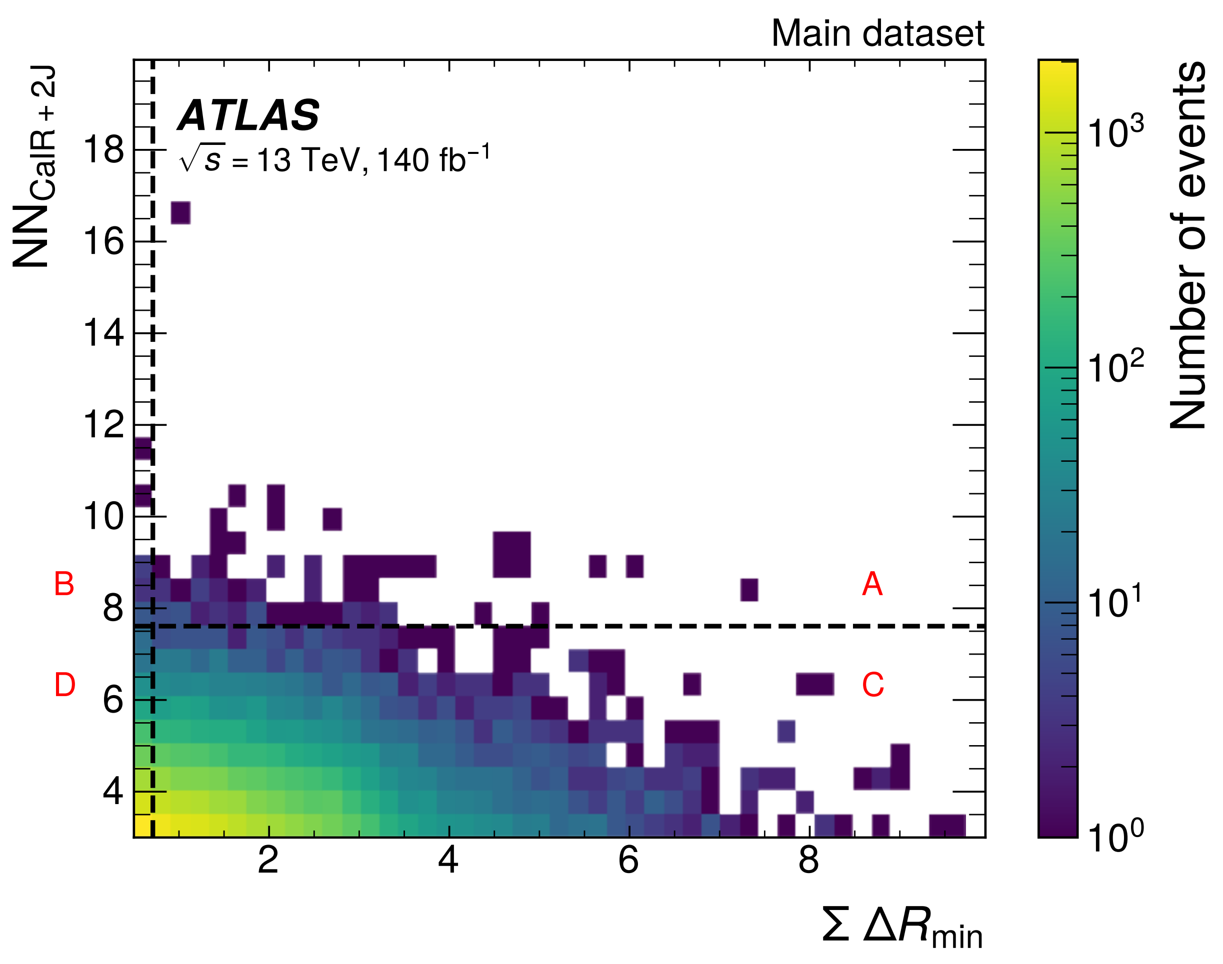

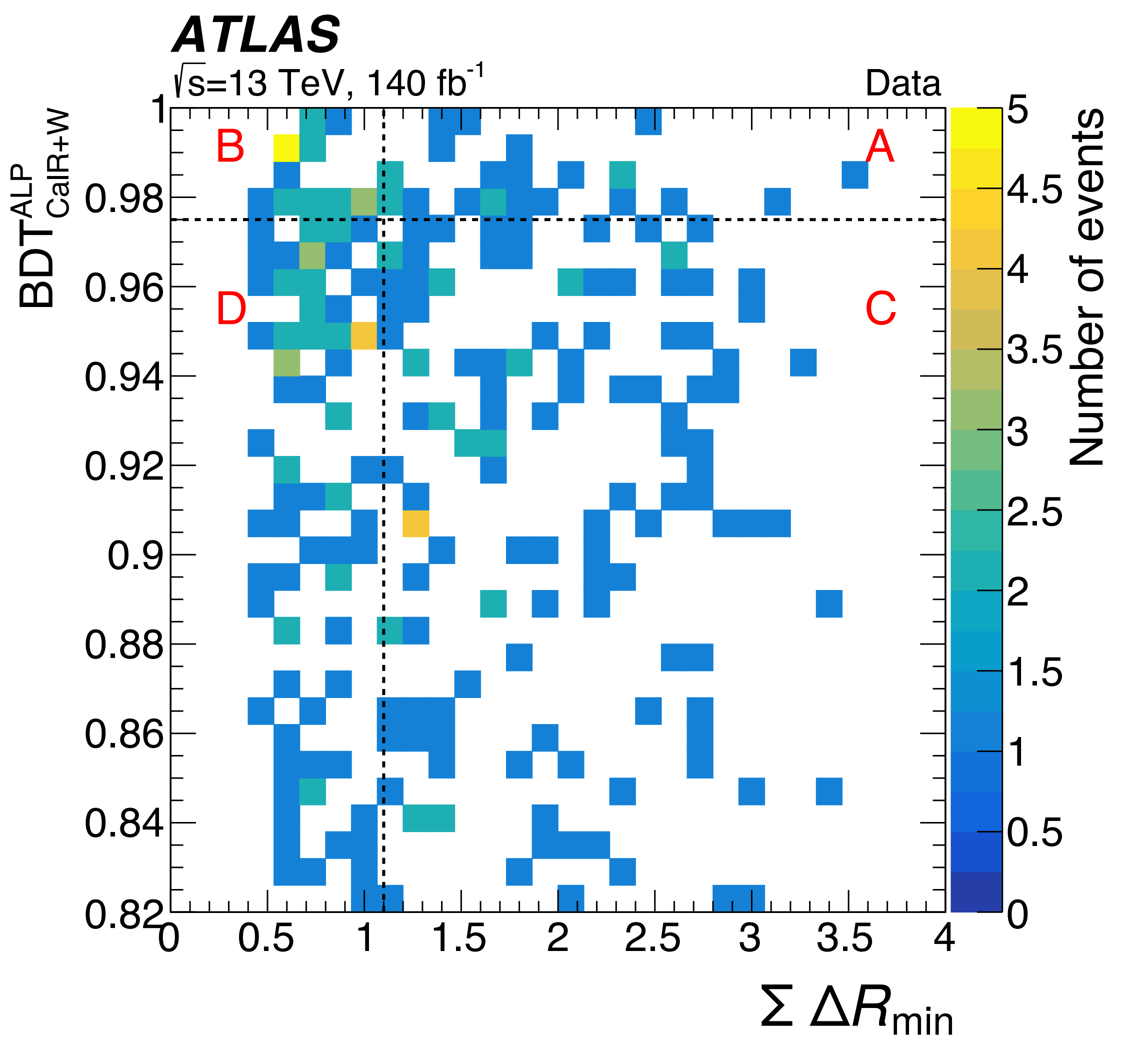

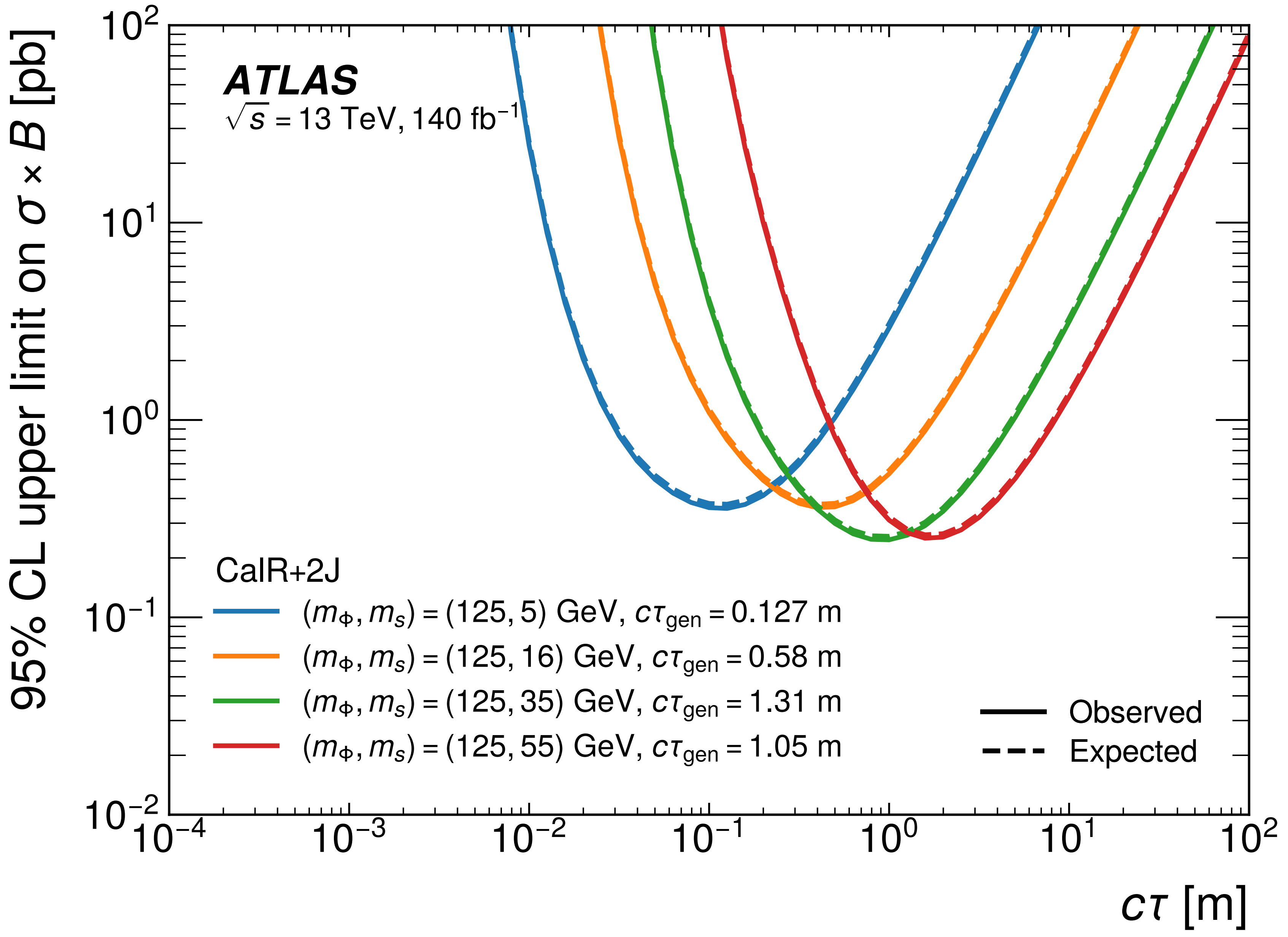

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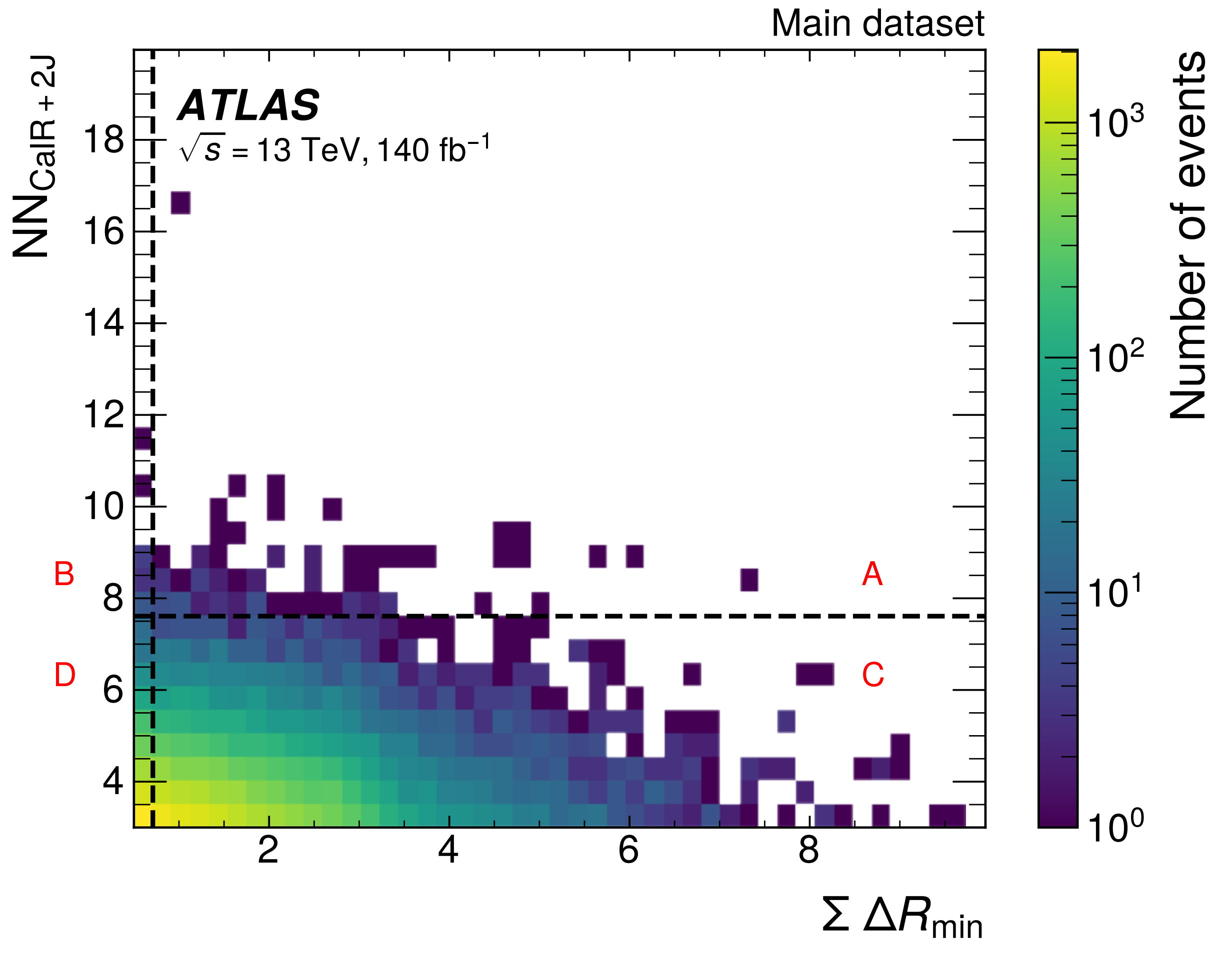

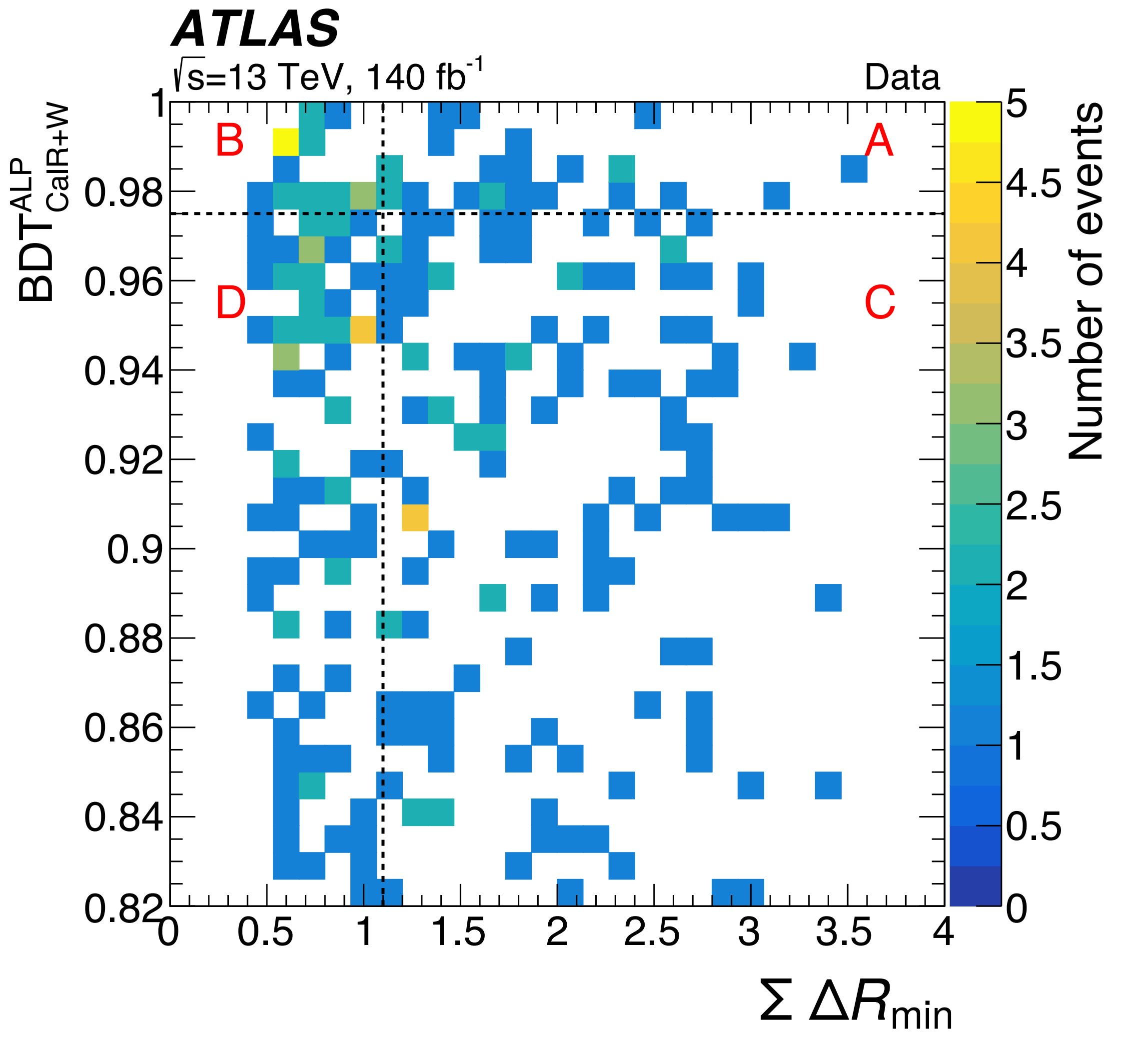

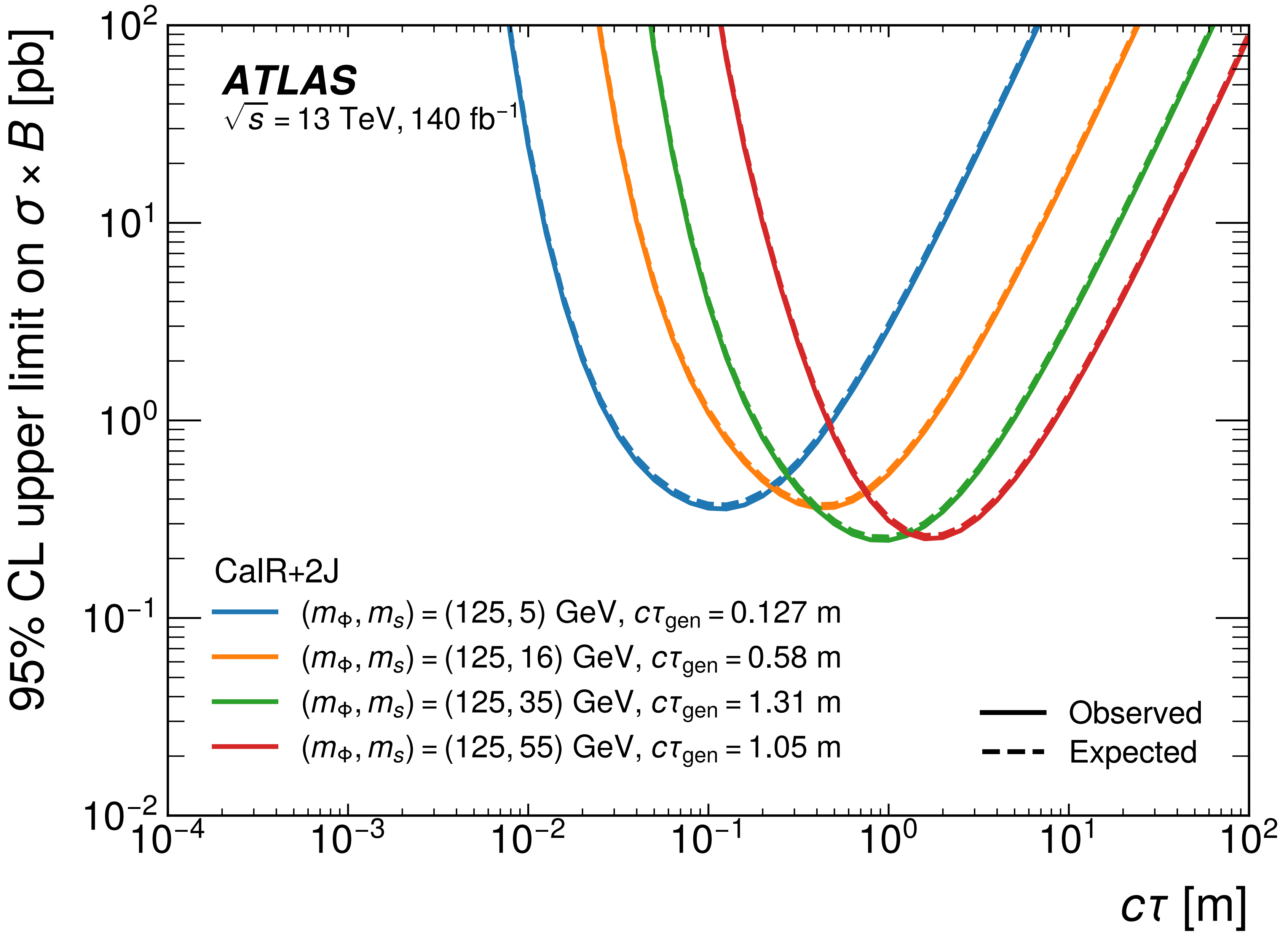

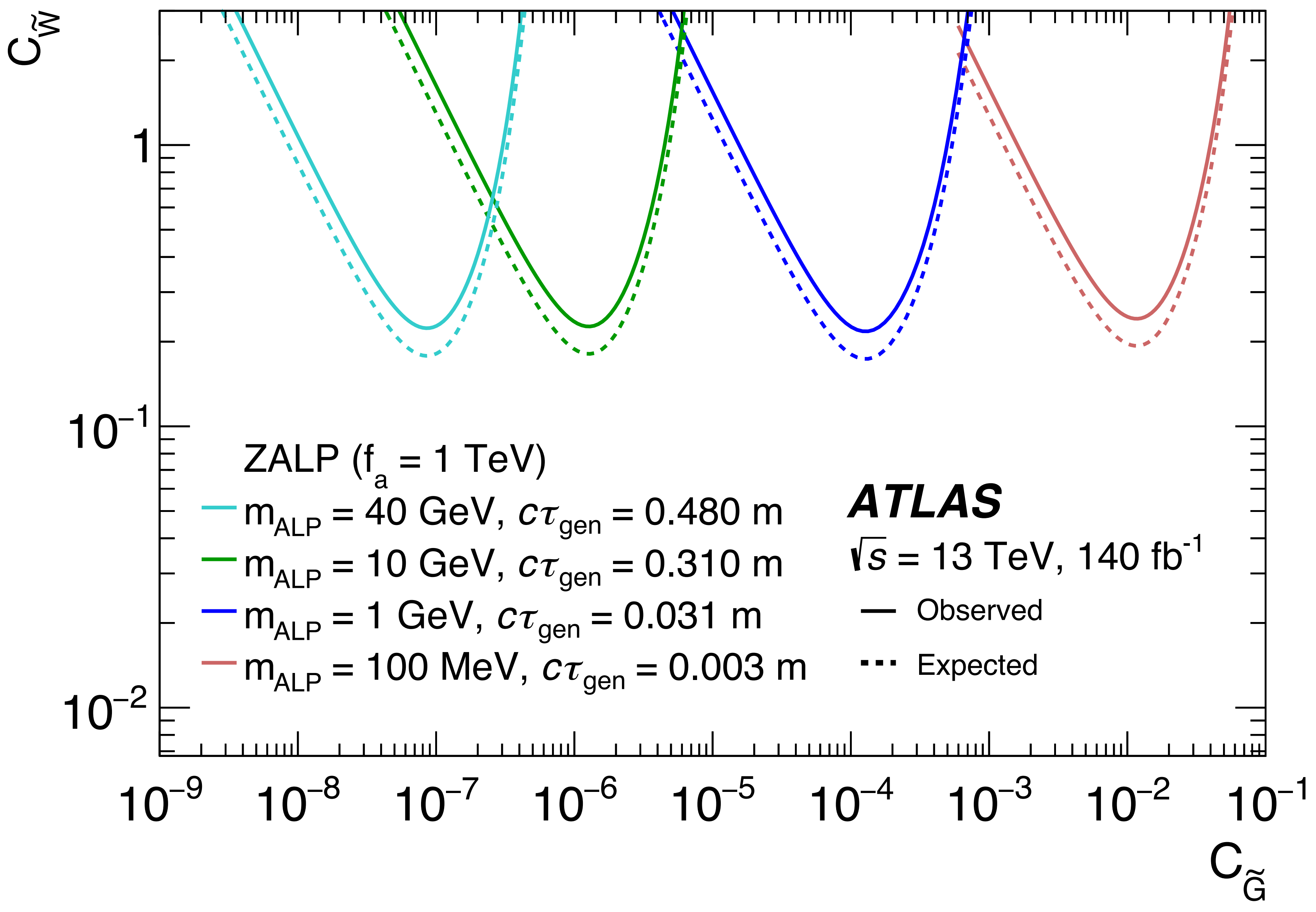

Muon Spectrometer Searches

EXOT-2019-24

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For even longer lifetimes, decays in the Muon system become dominant

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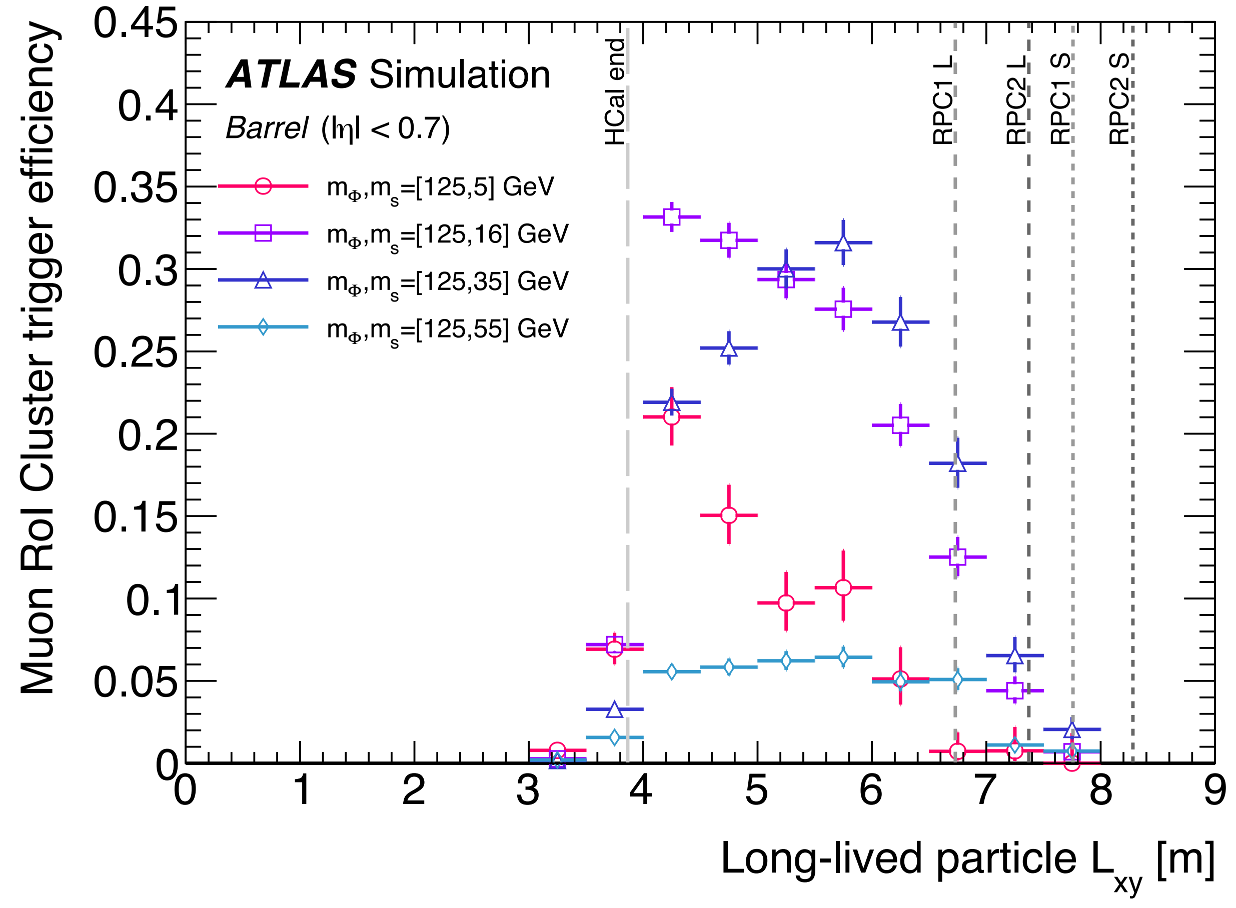

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EXOT-2019-24

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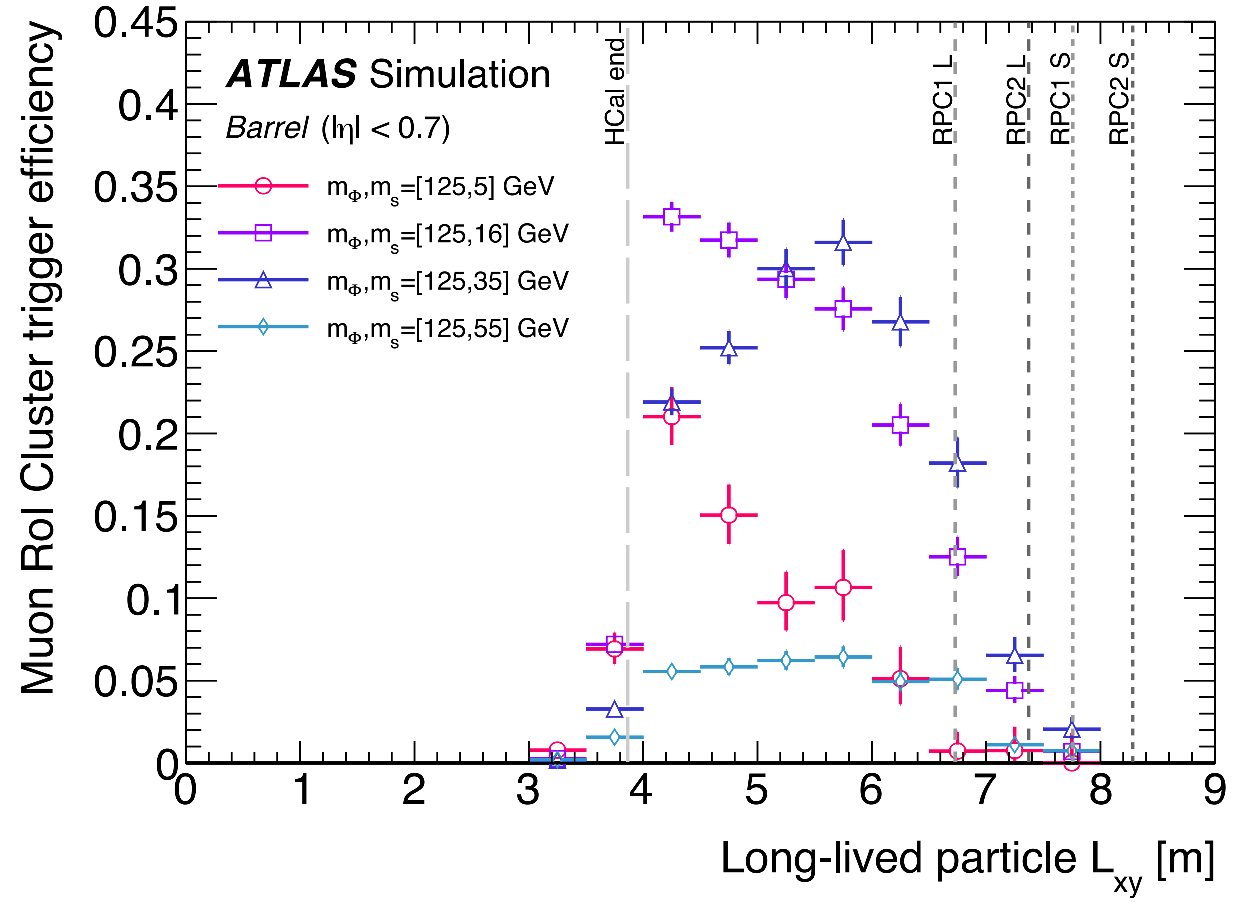
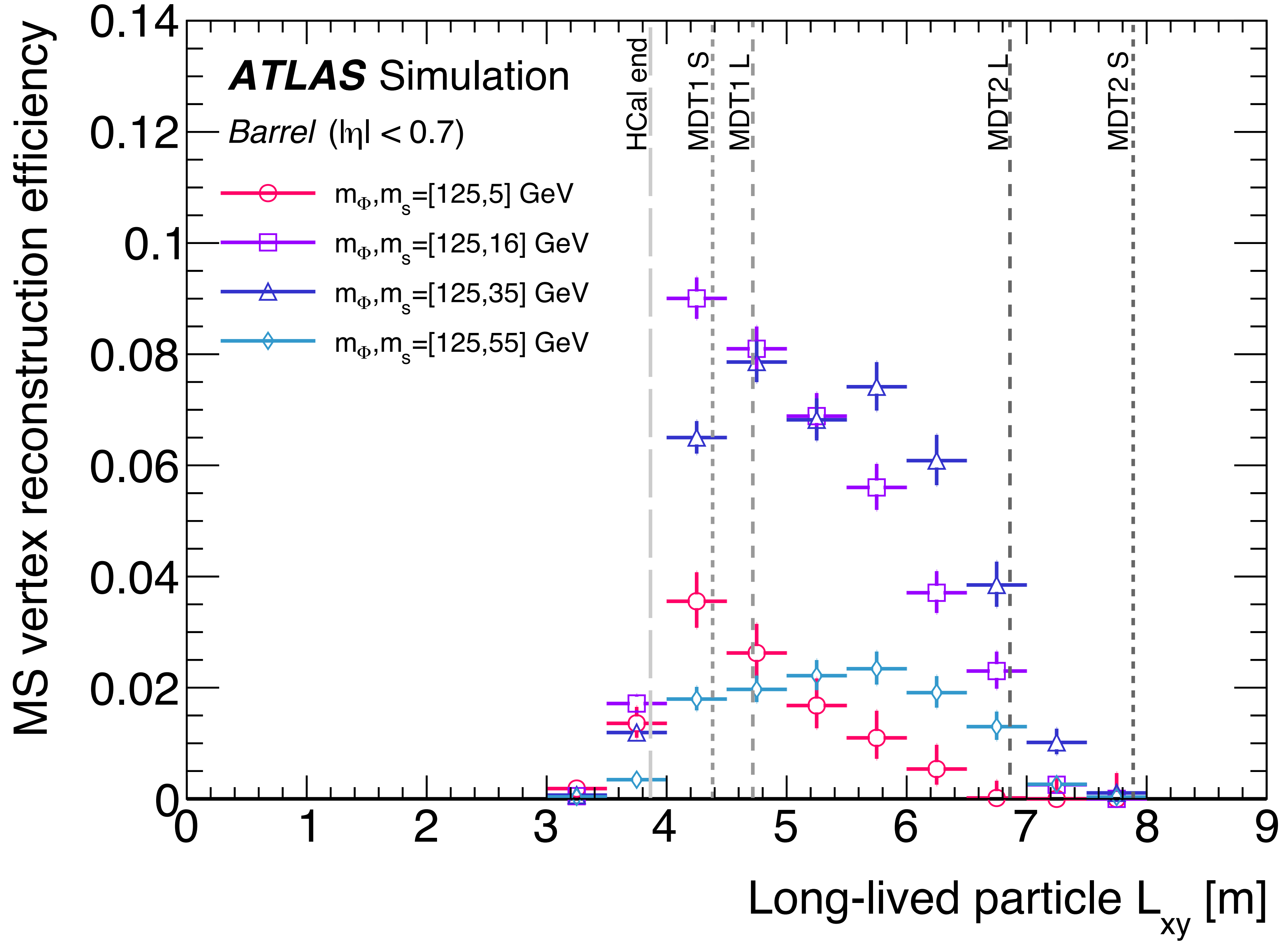
Main background: “punch through jets”

- Custom vertex reconstruction algorithm to reconstruct LLP decay vertices and reject background





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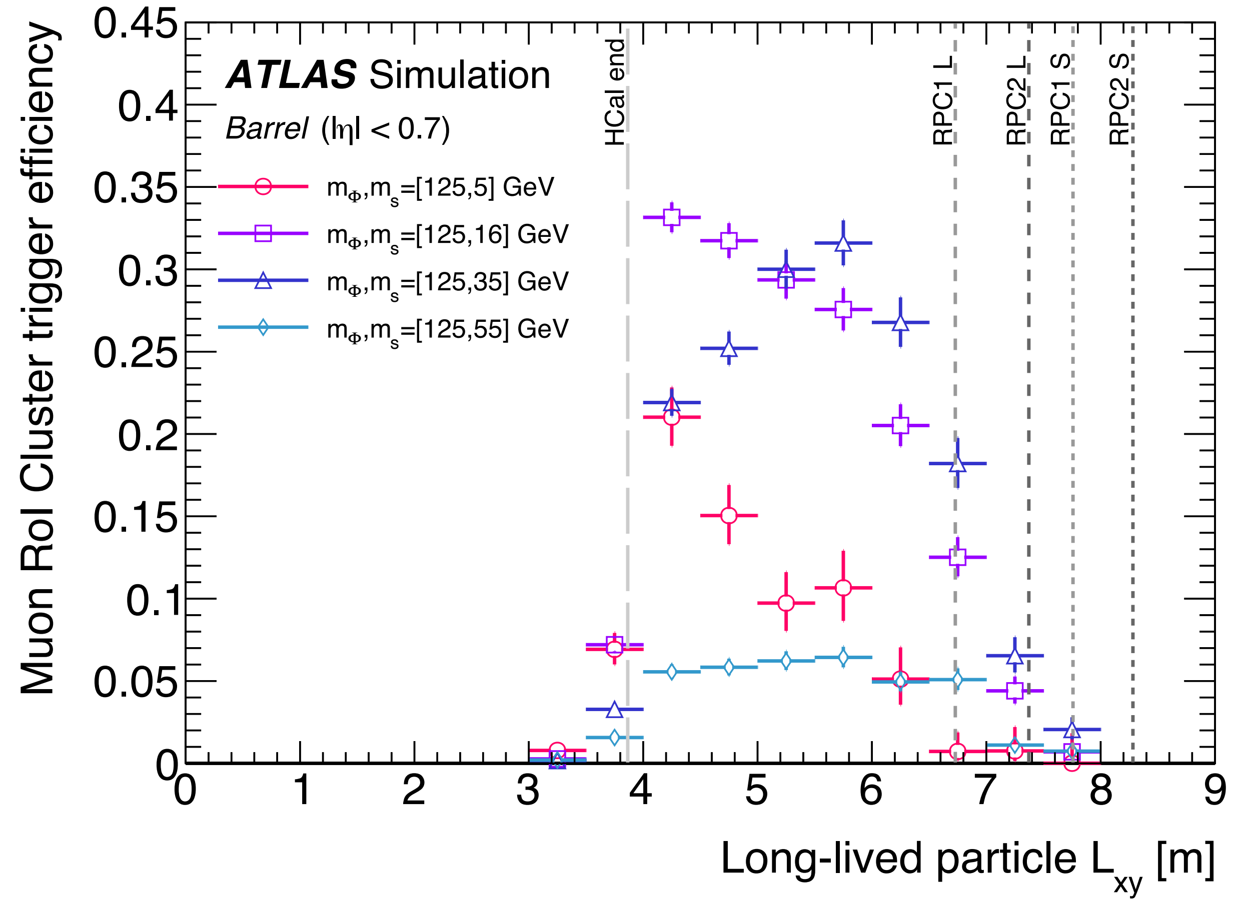

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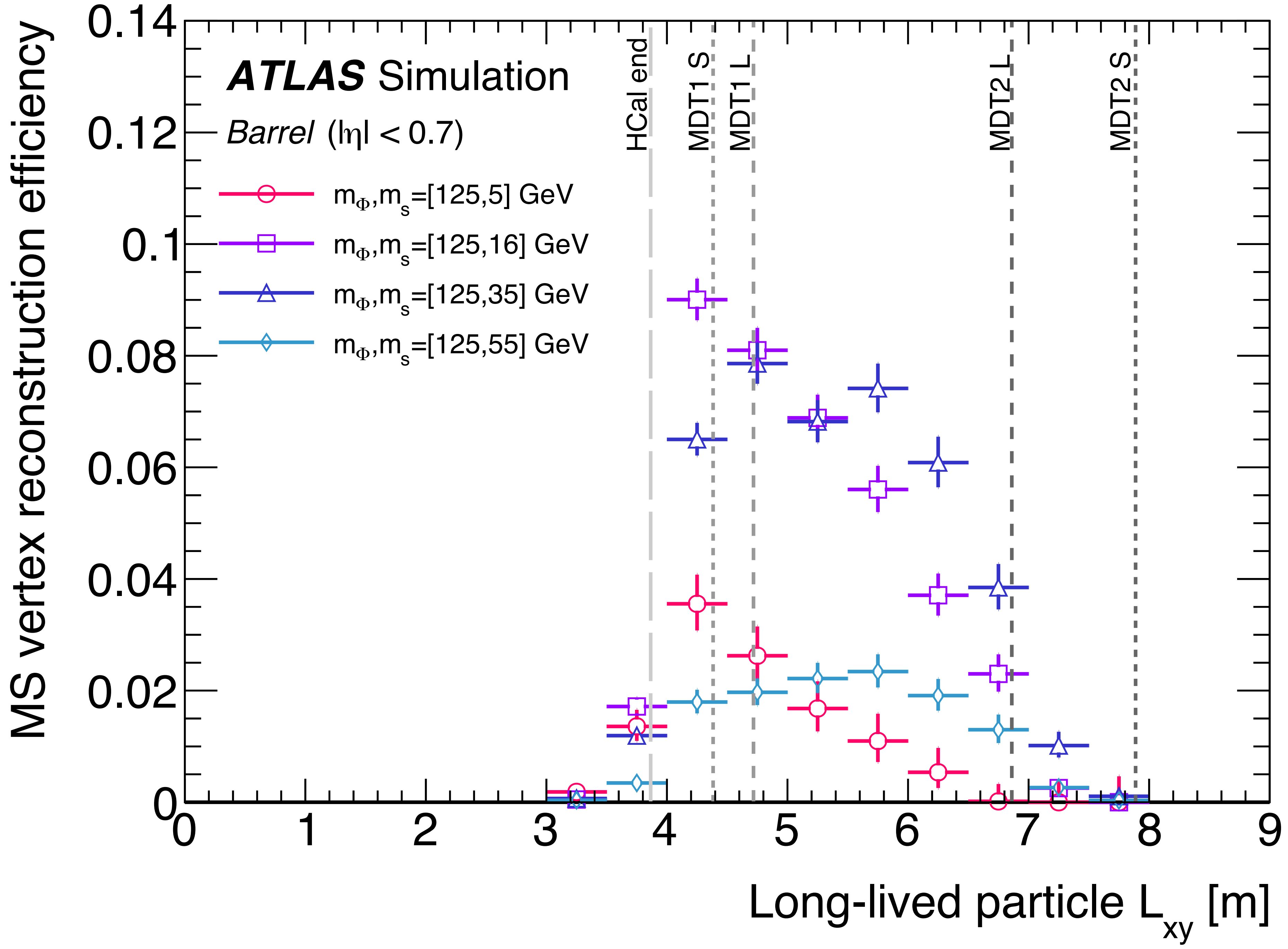
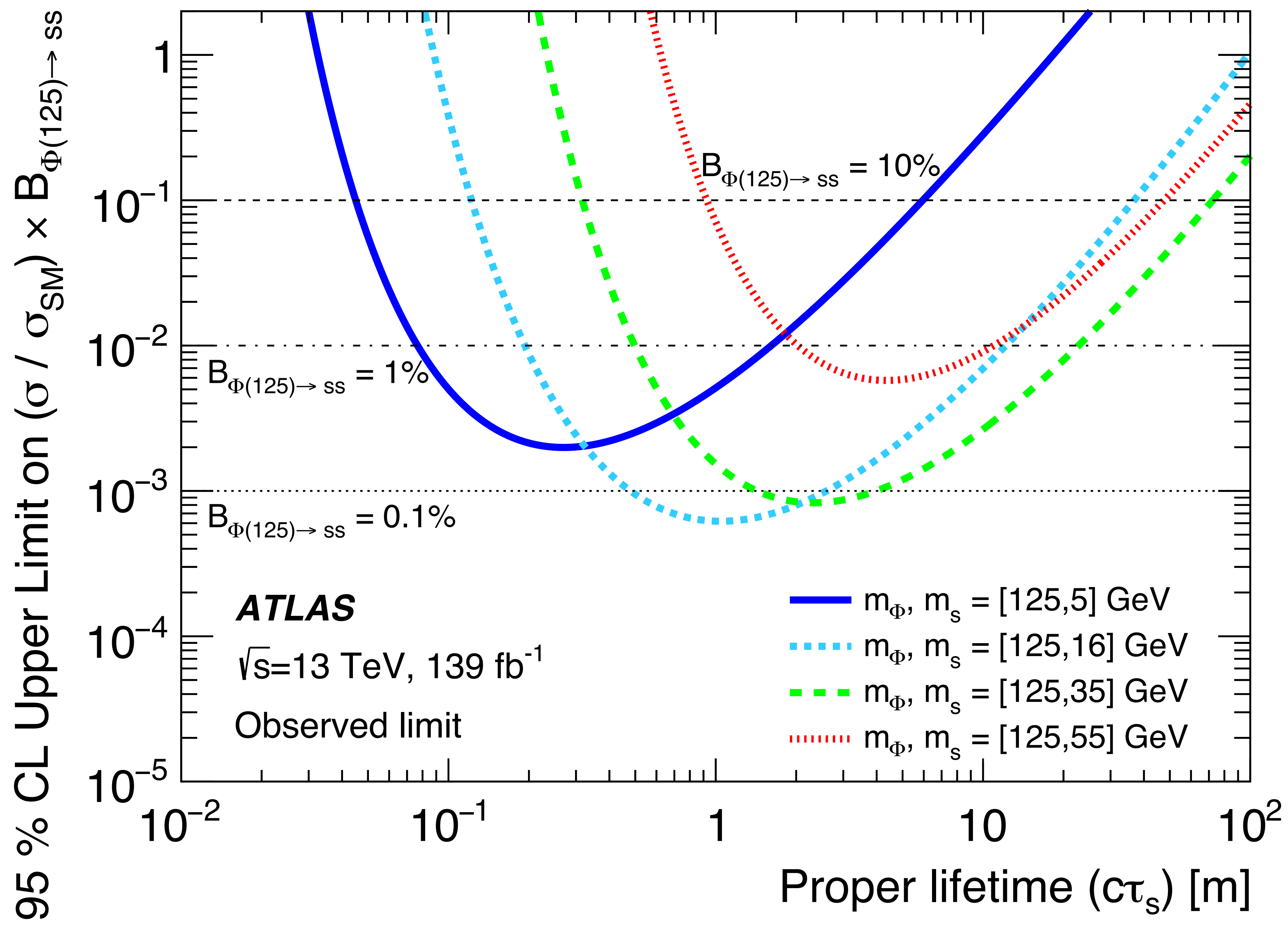
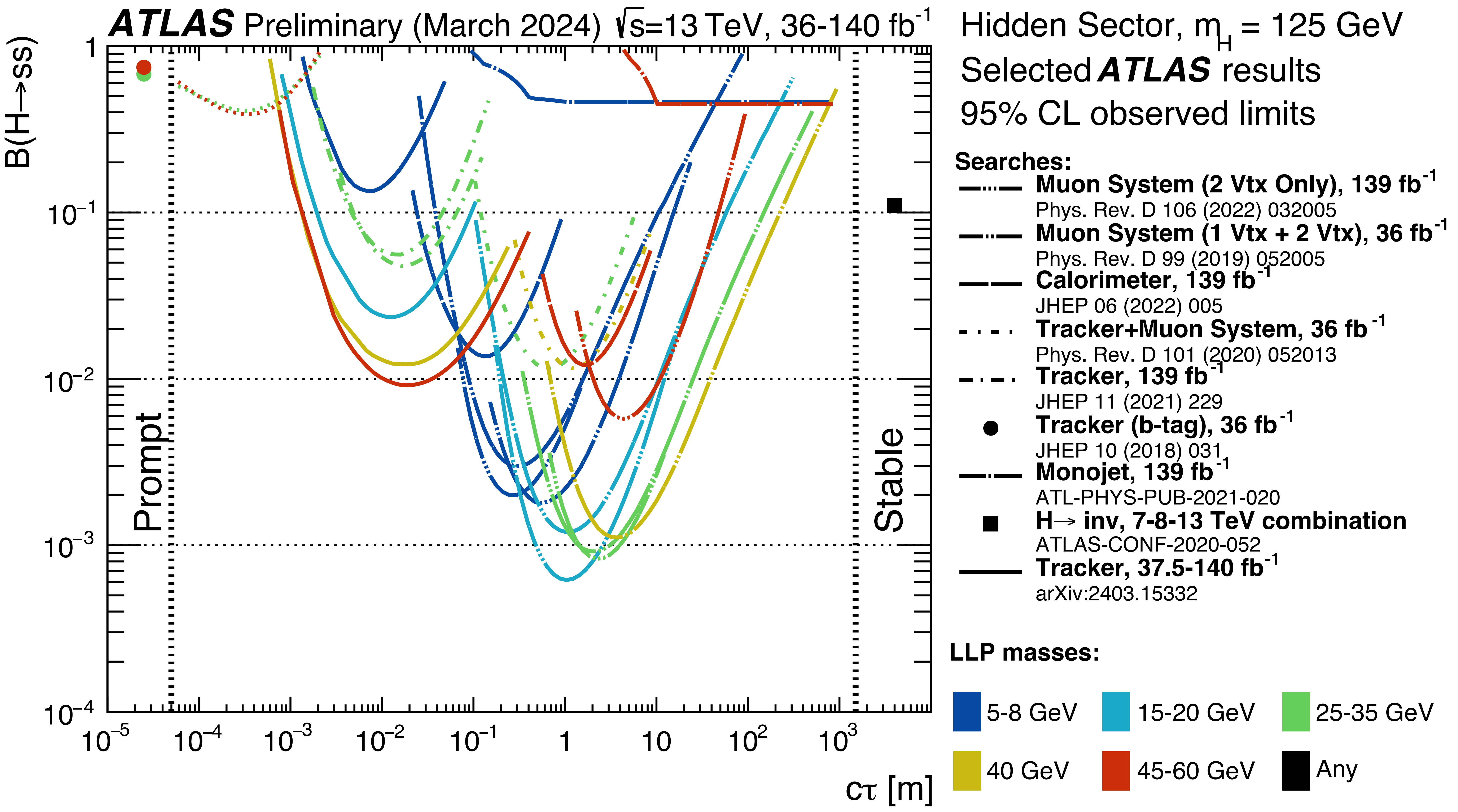


Sensitive to $\mathrm{Br}(H \to ss)$ as small as 0.1%



Scalar portal exclusion

Combined, searches in all three subsystems provide excellent coverage for LLP lifetimes between 1mm and 10m



Leptonic signatures

Dark photons

EXOT-2019-05 EXOT-2022-15

ATLAS probes long-lived dark photons via collimated displaced leptons/hadrons: "**dark photon jets**" (DPJs)

- Searches in ggF, WH, and VBF Higgs production modes

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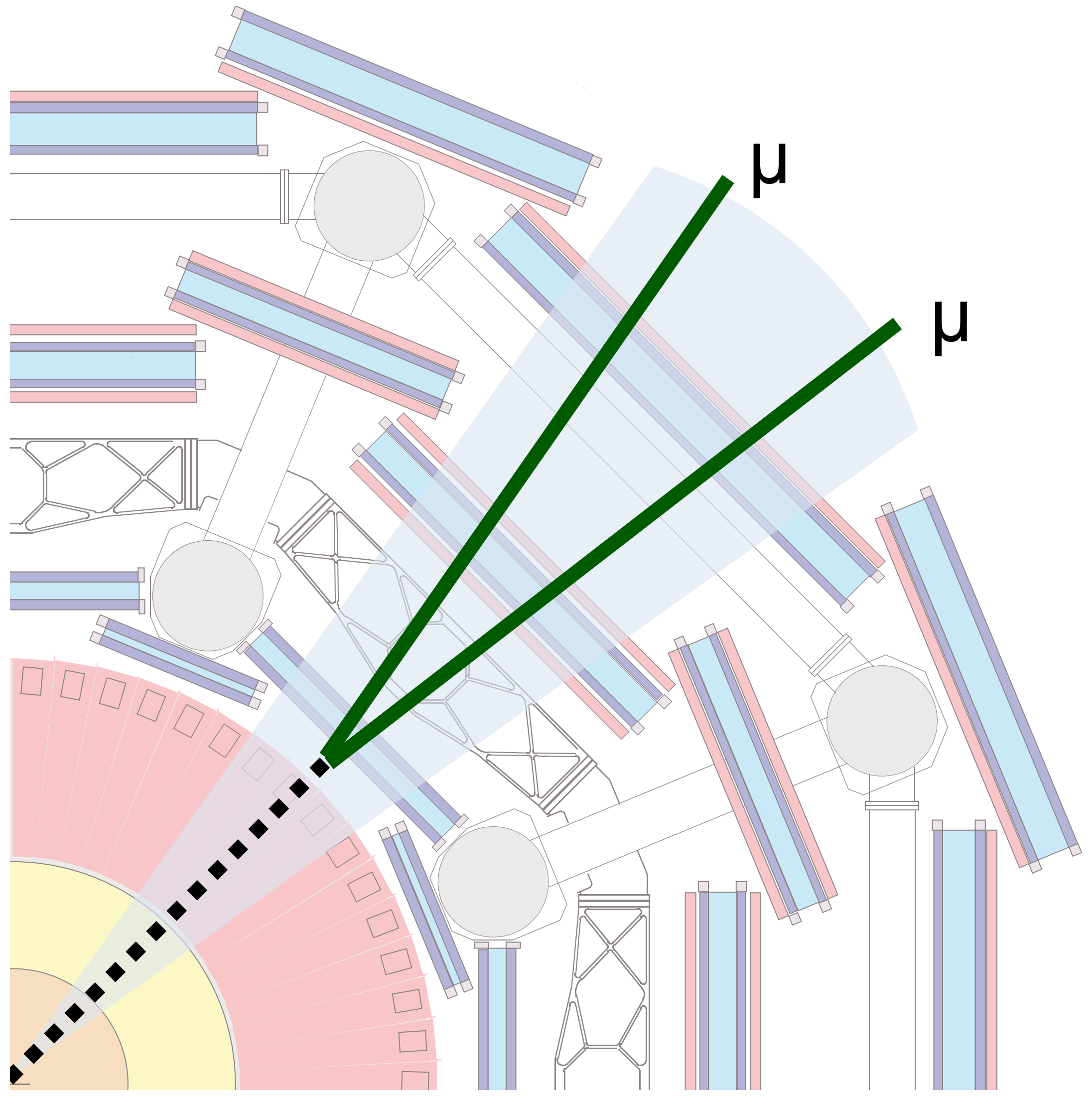
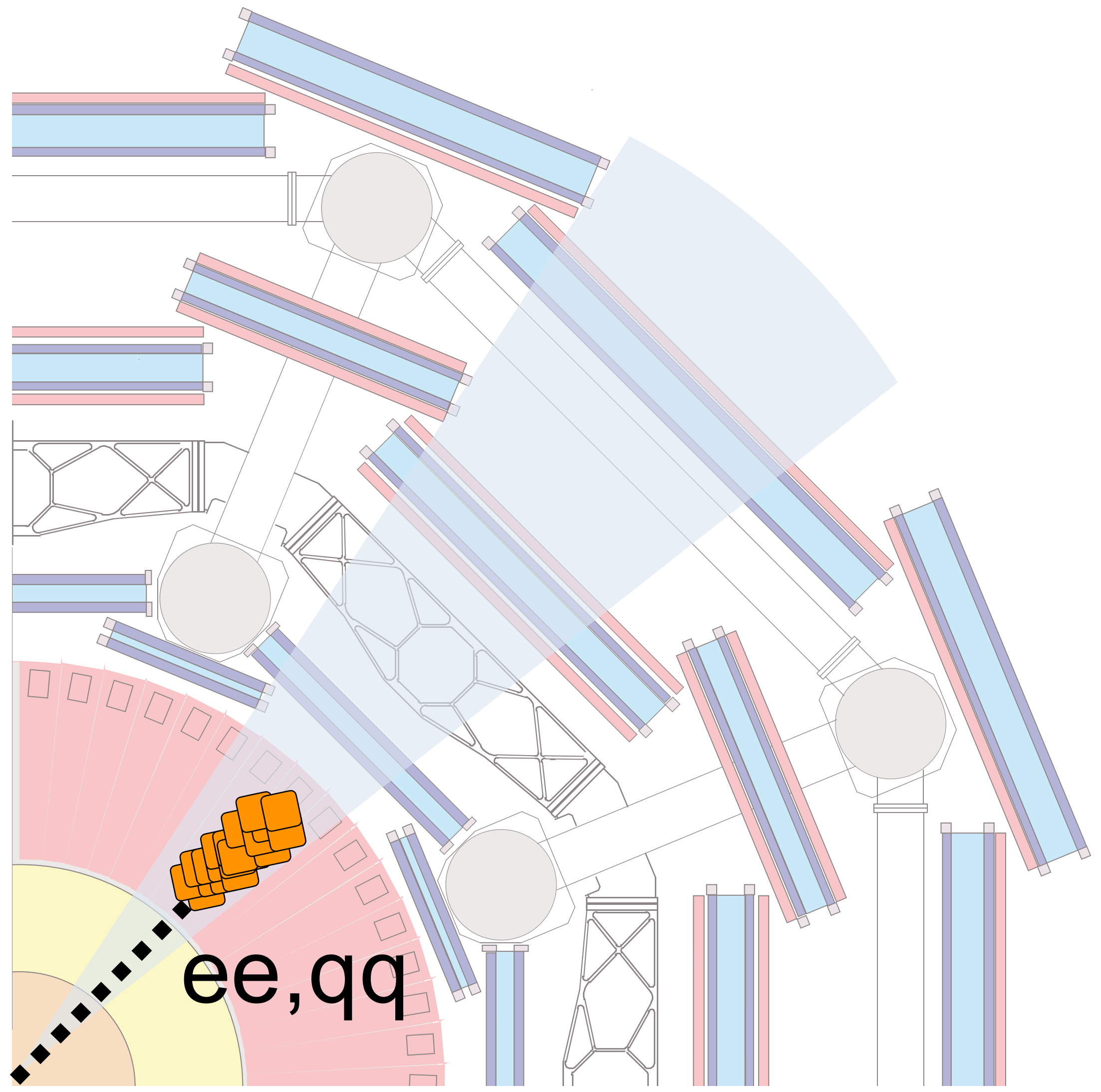


muonic DPJ



calorimeter DPJ

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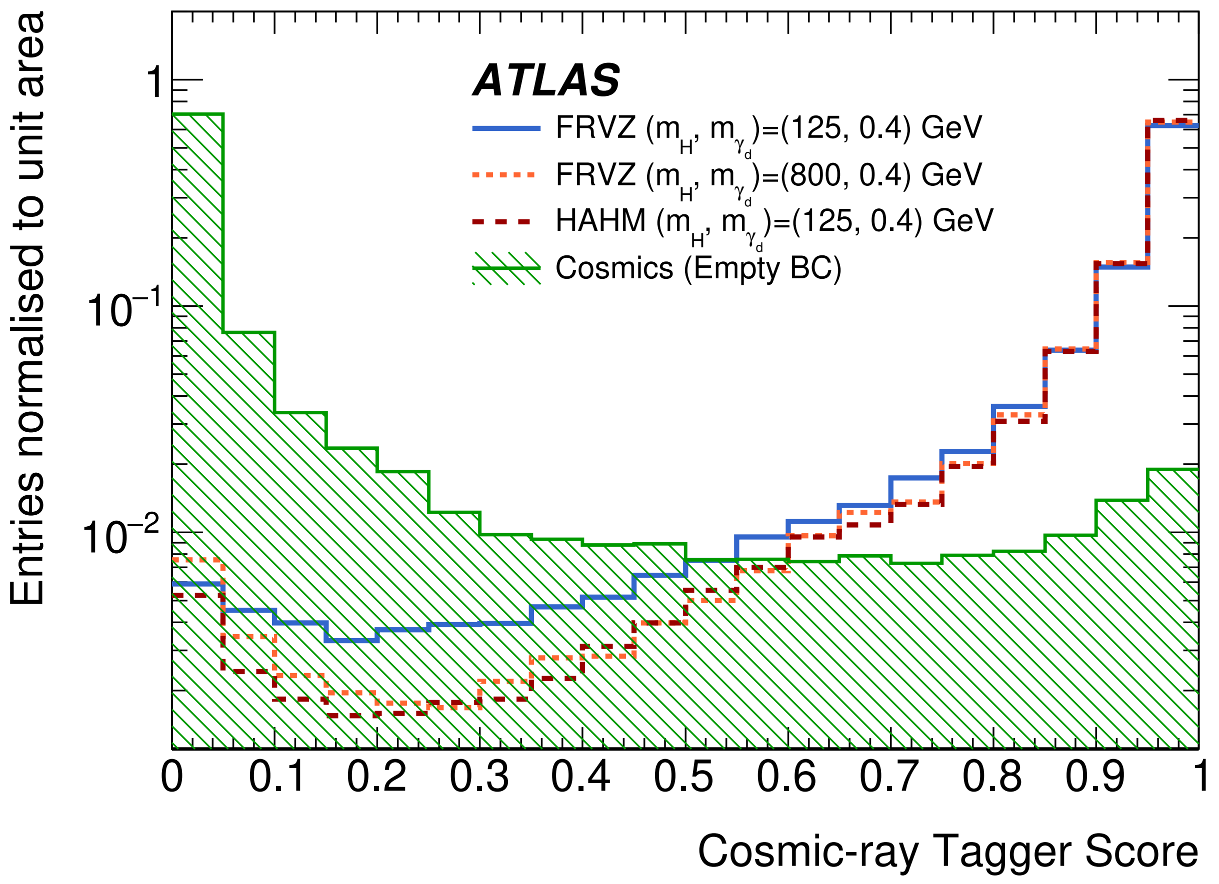
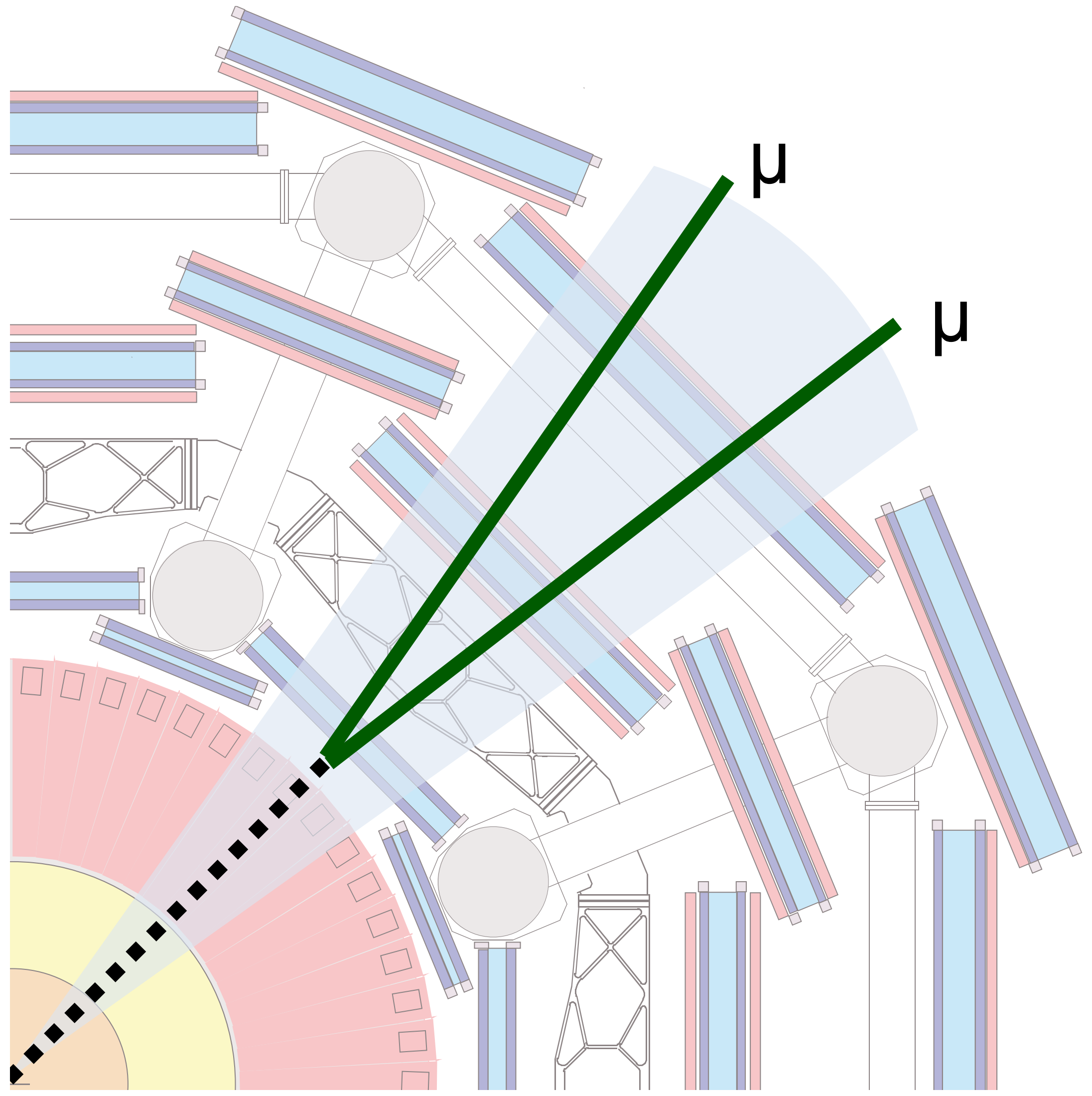
Muonic DPJs

Cosmic ray muons main source of background





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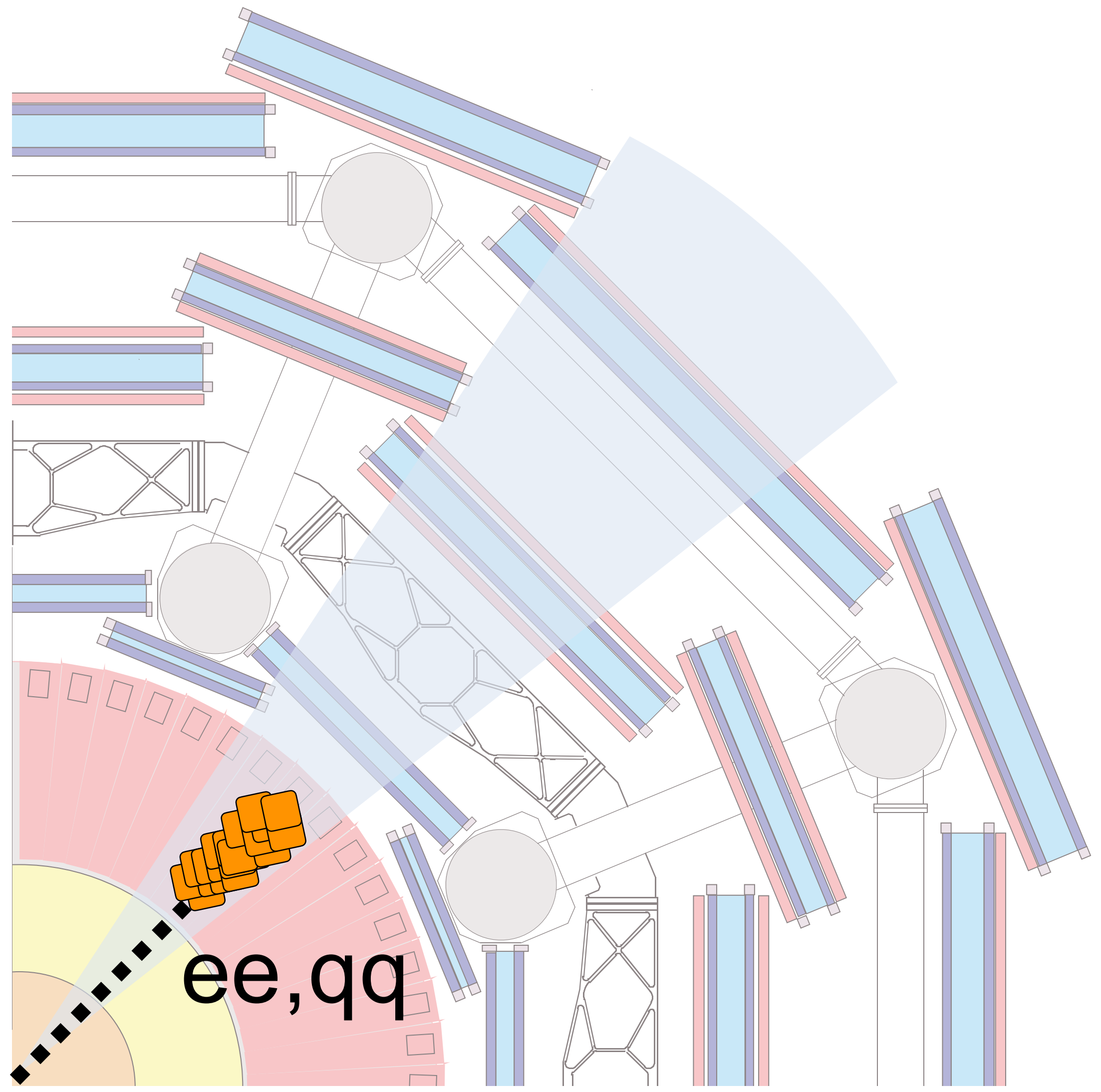

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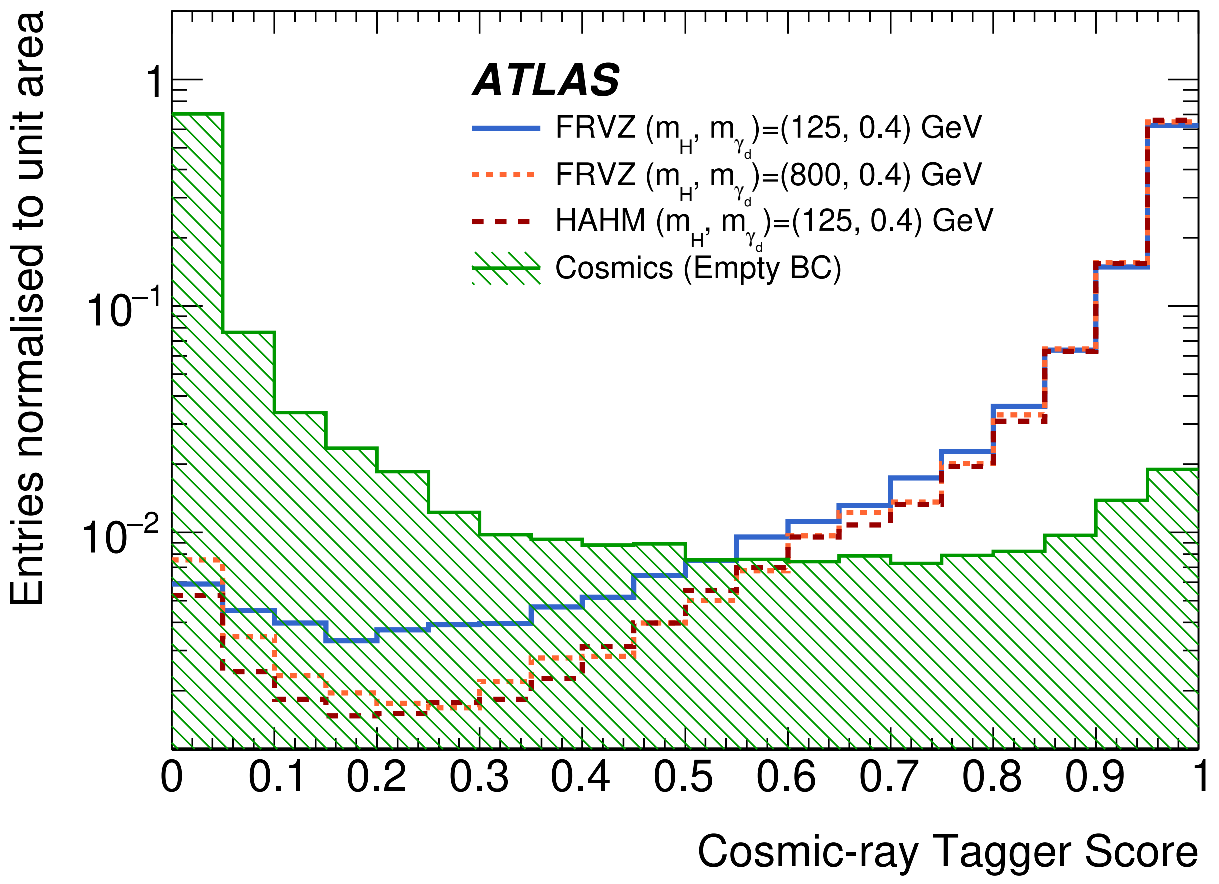

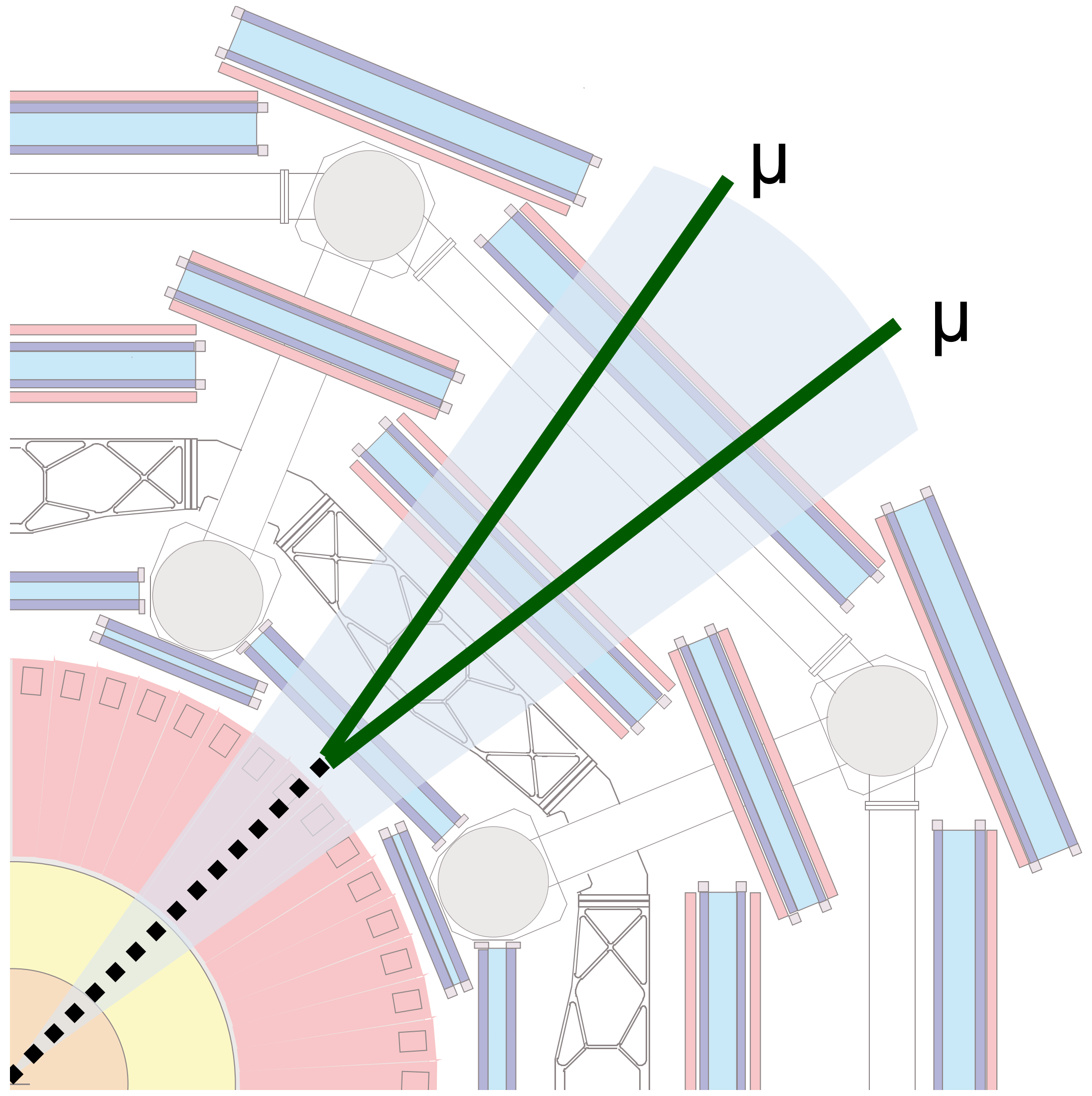

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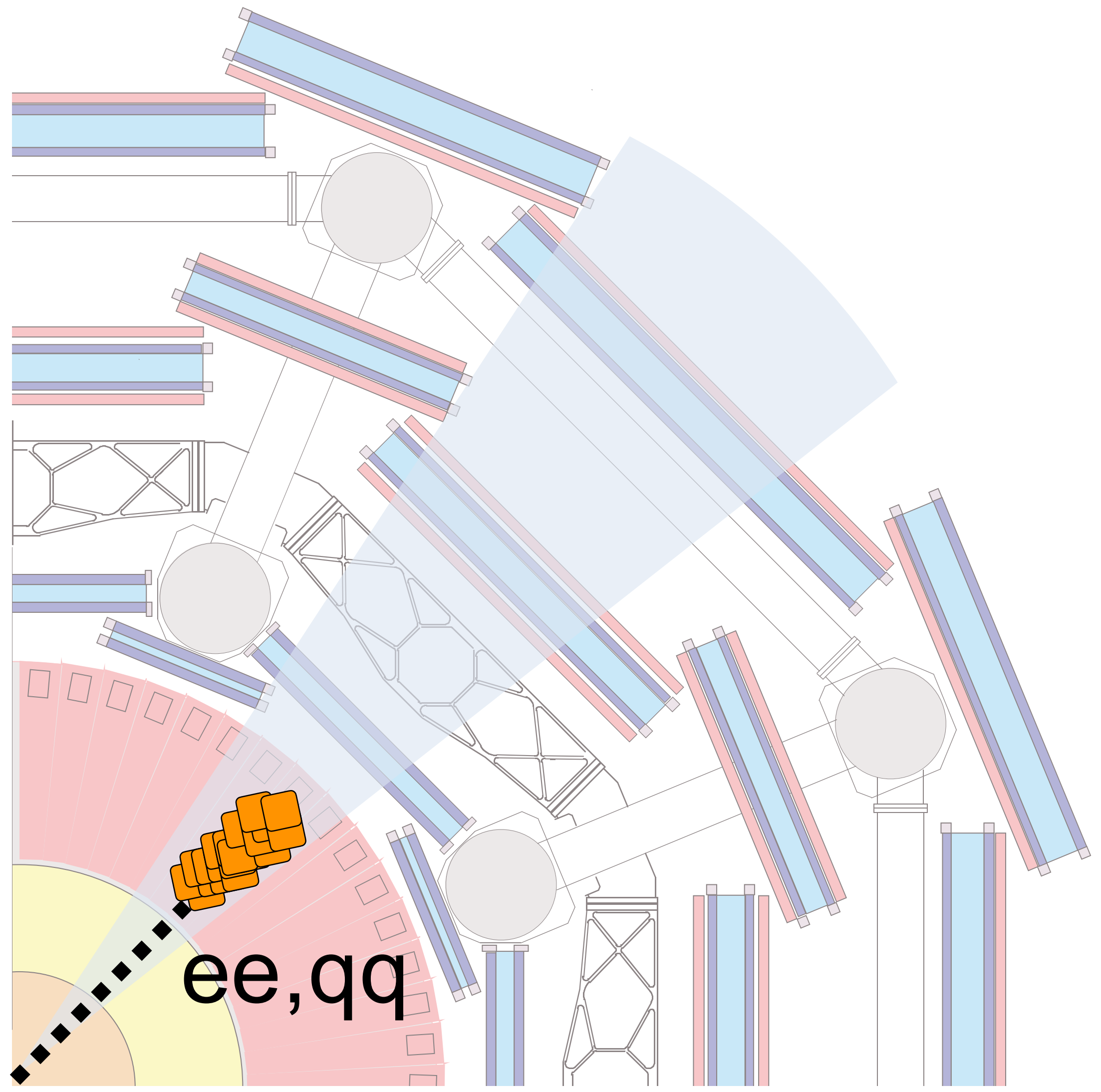
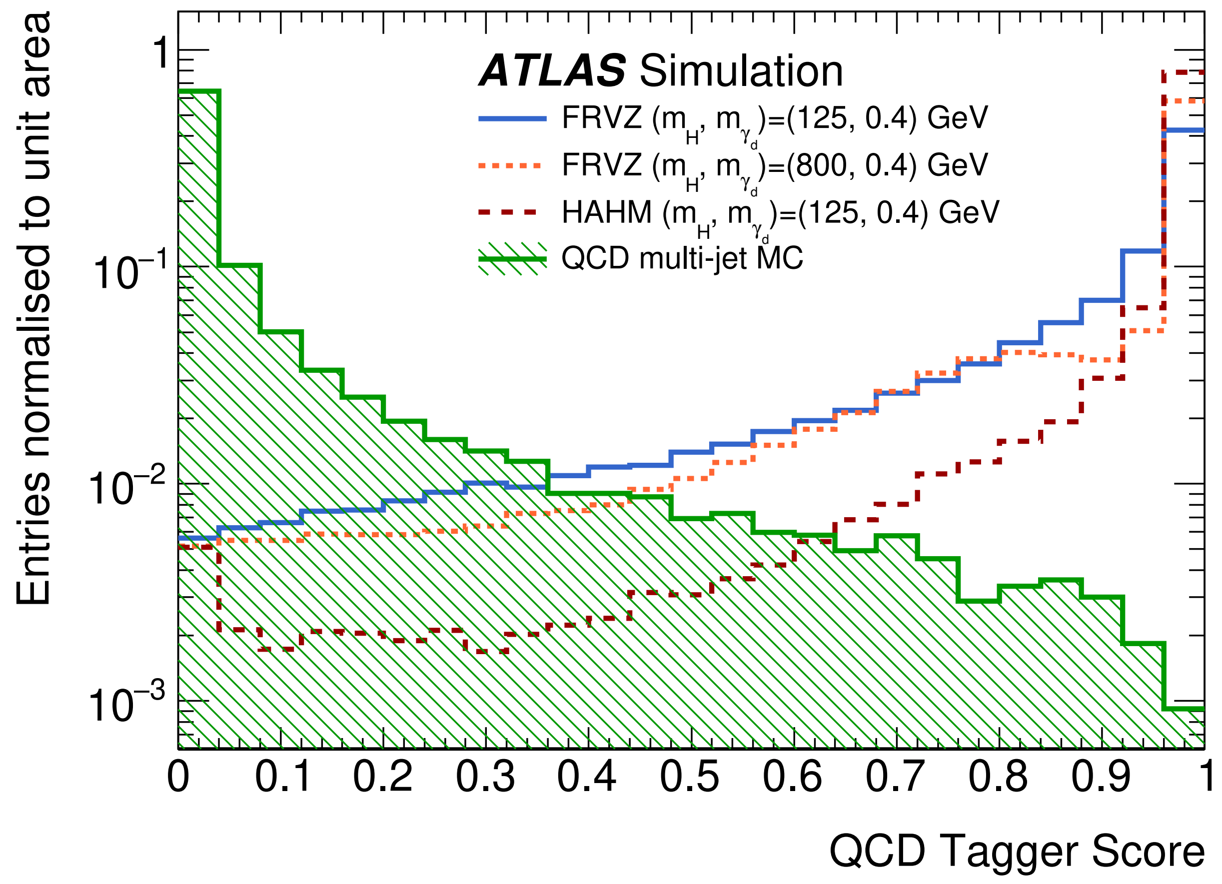


calorimeter DPJ

Calorimeter DPJs

QCD/BIB are main sources of background



Dark photons

EXOT-2019-05 EXOT-2022-15

ATLAS probes long-lived dark photons via collimated displaced leptons/hadrons: "**dark photon jets**" (DPJs)

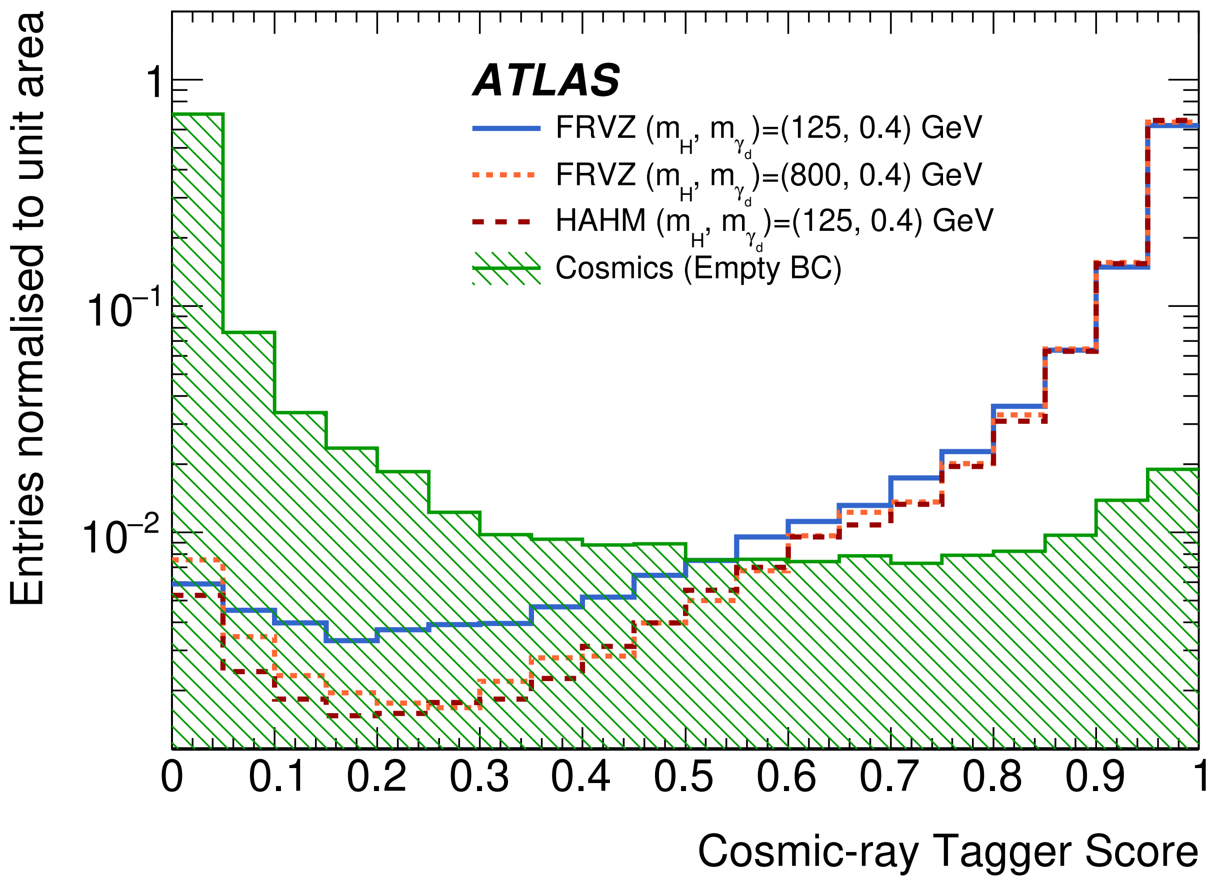
- Searches in ggF, WH, and VBF Higgs production modes

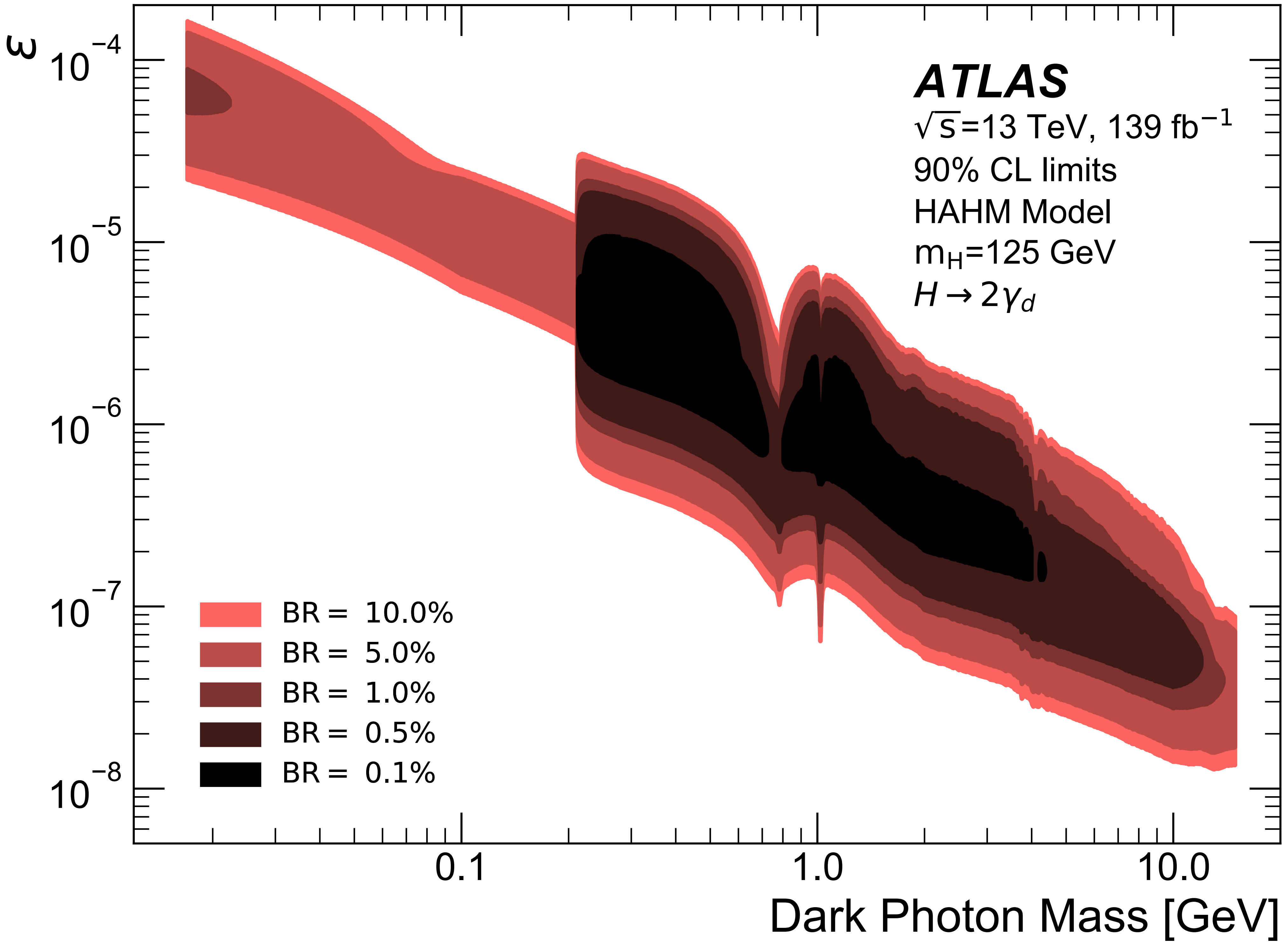
Separate reconstruction algorithms and neural networks to identify muonic and calorimeter DPJs

- ABCD background estimate using tagger score and ID-track isolation

Muonic DPJs

Cosmic ray muons main source of background





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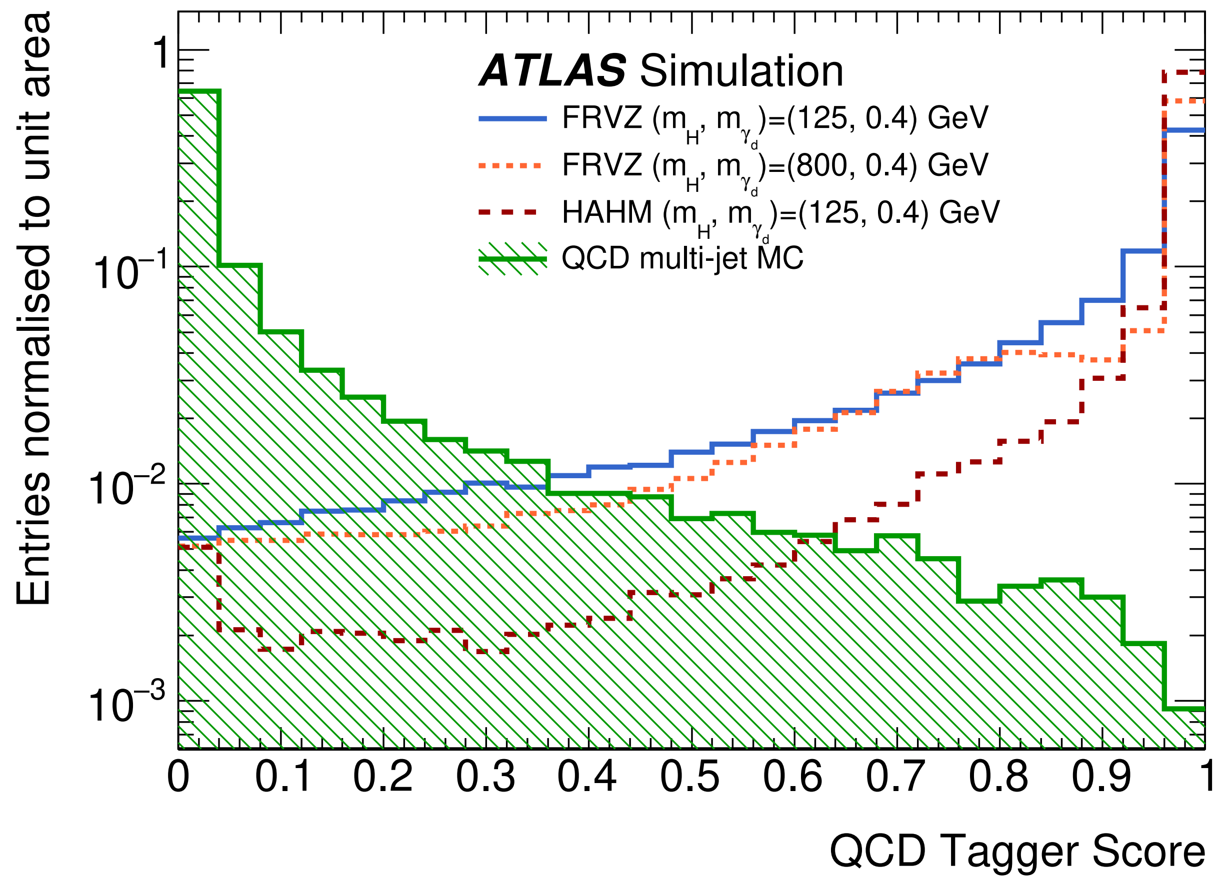

Dark photons

EXOT-2018-55

For shorter lifetimes, lepton jets are formed from electrons & muons with ID-tracks

- Search for pairs of lepton jets: μLJ-μLJ, μLJ-eLJ, eLJ-eLJ

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Muon channel: fit performed to the μLJ mass distribution

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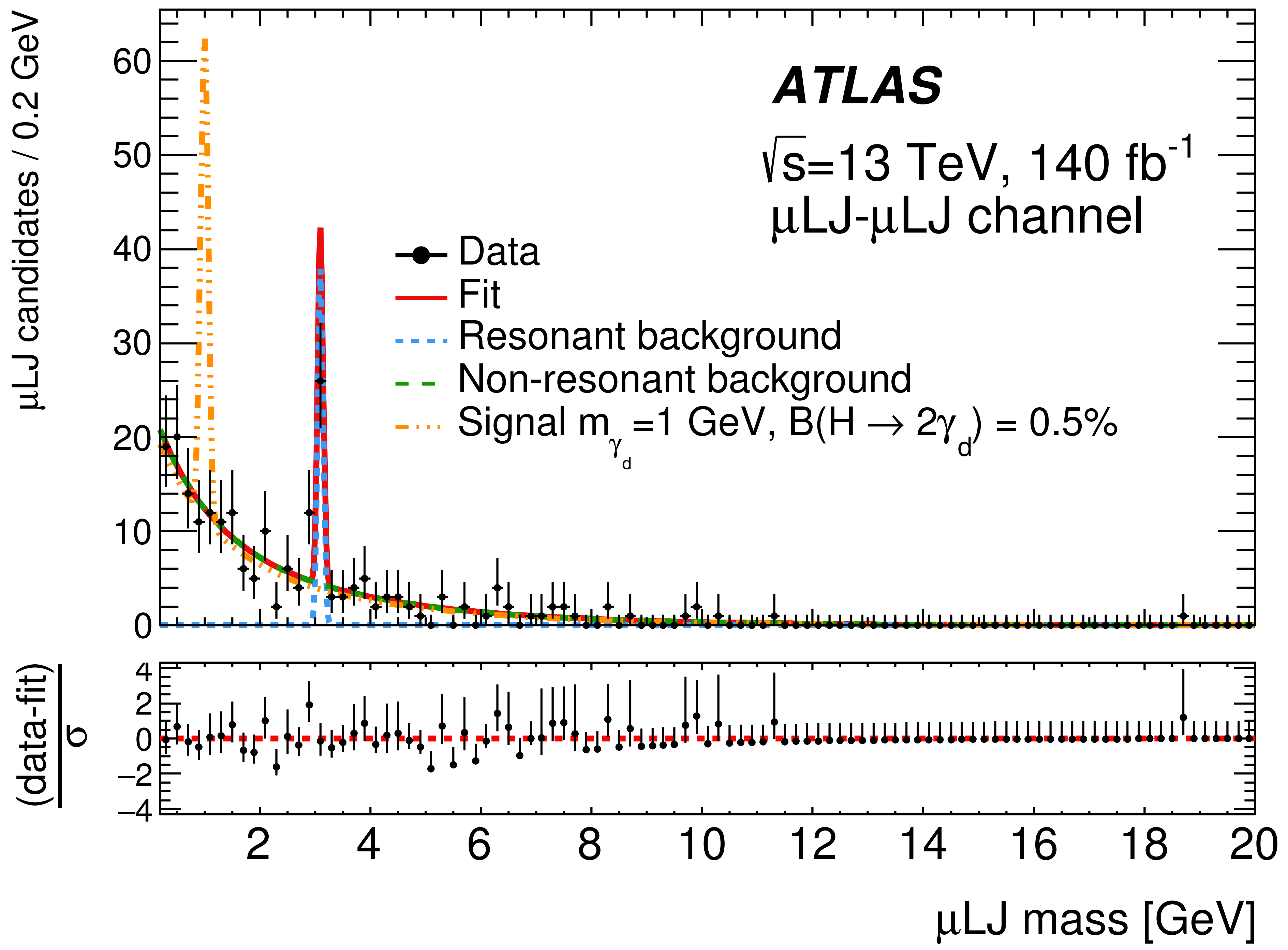

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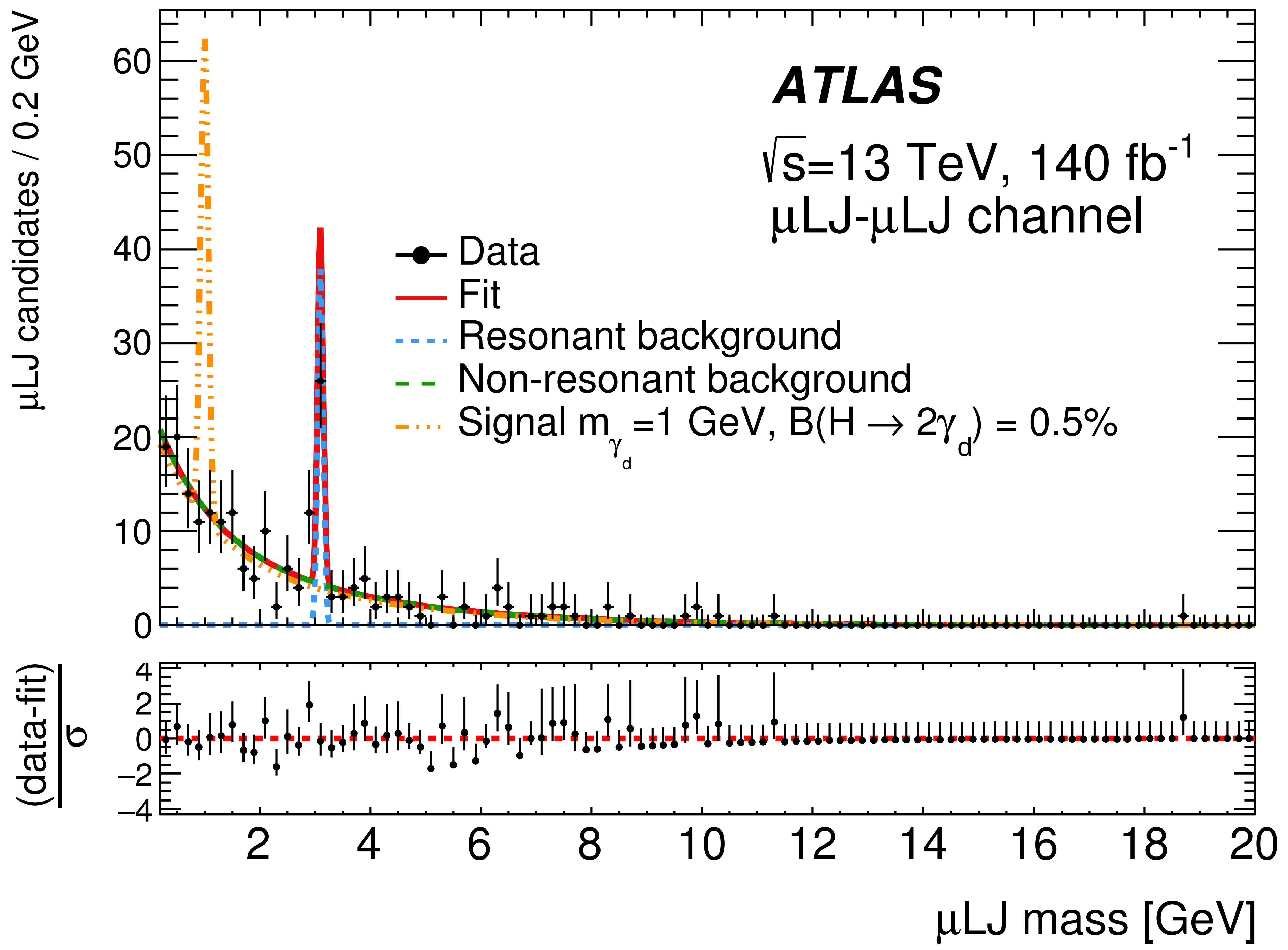

Electron channel: ABCD background estimate

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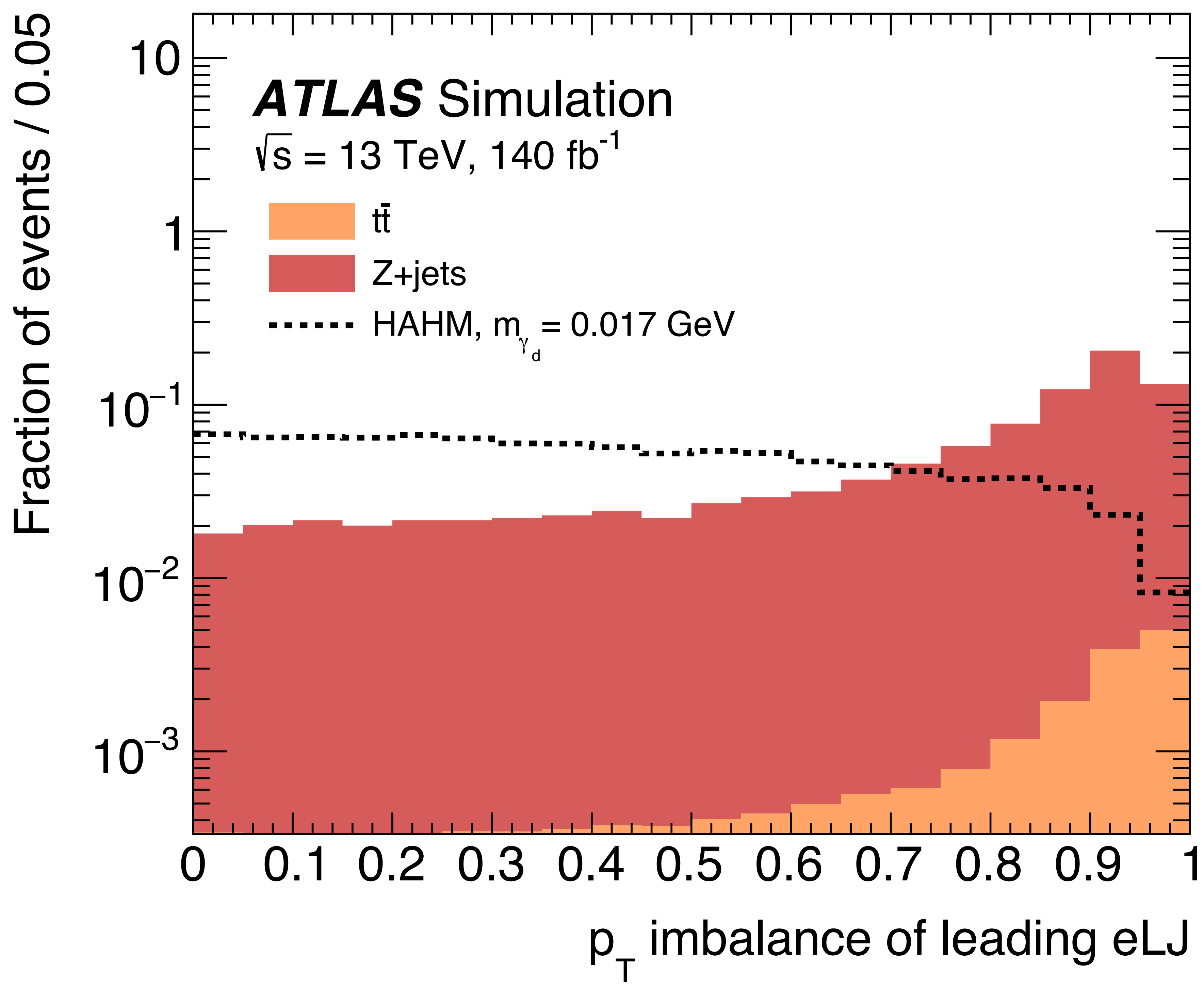

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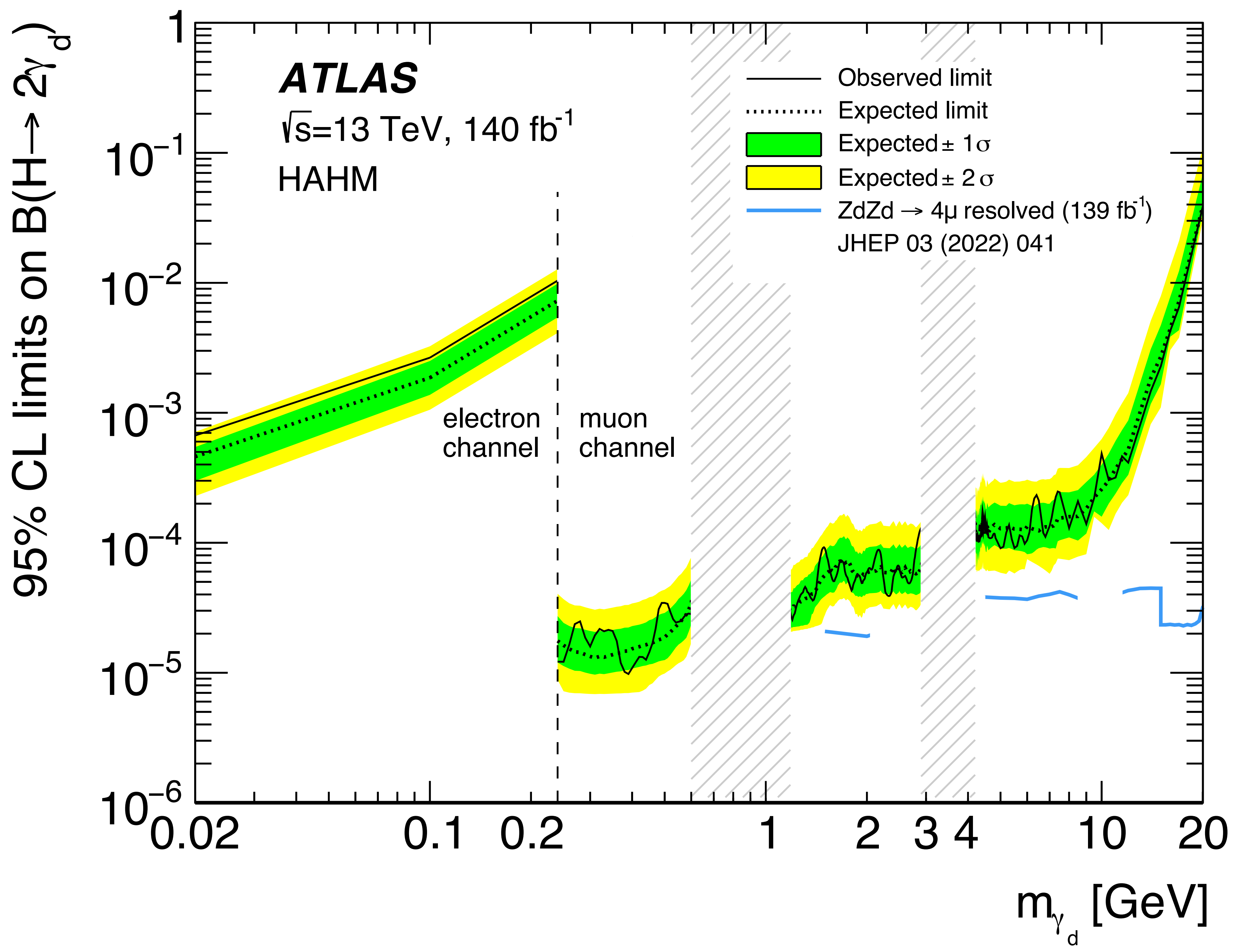

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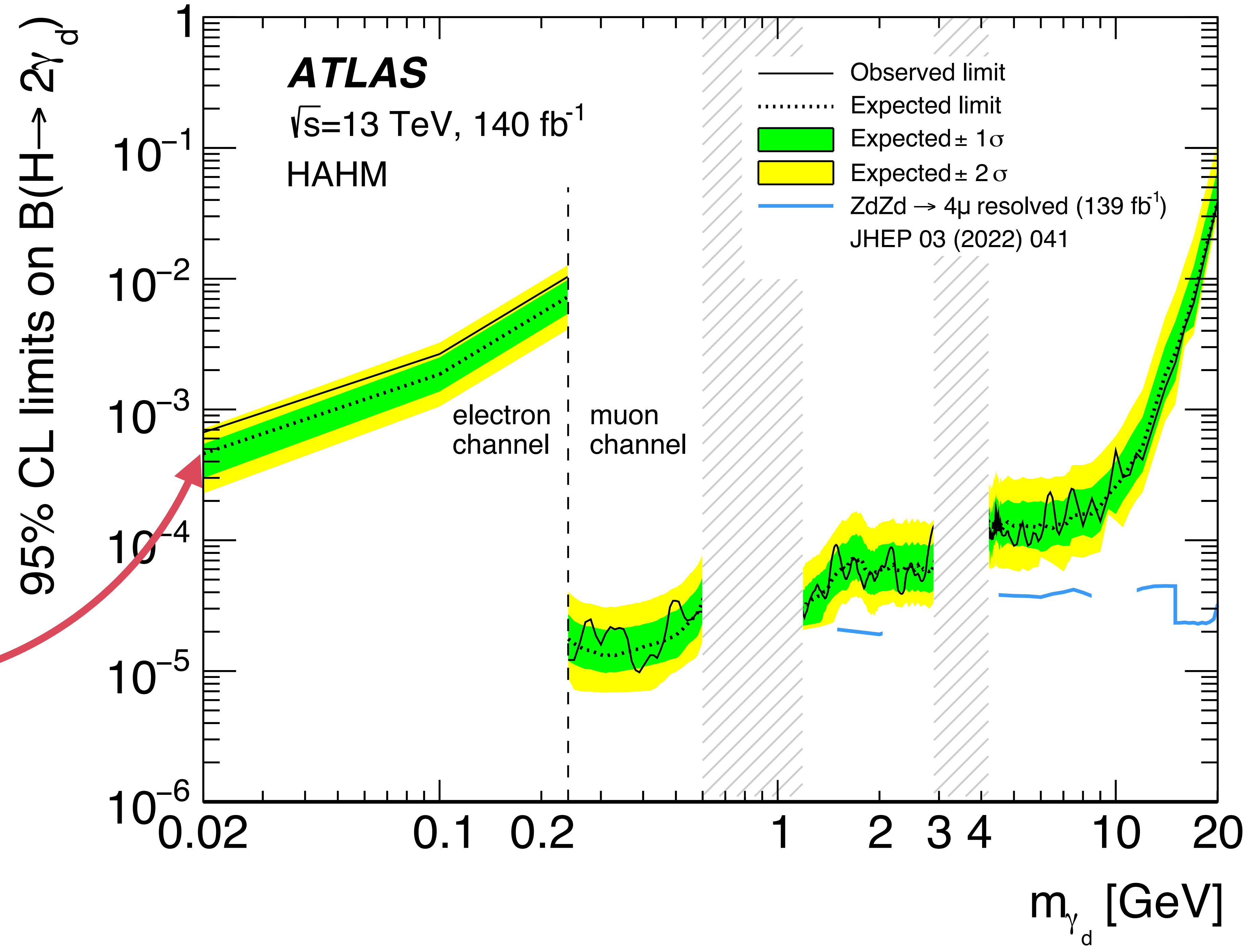


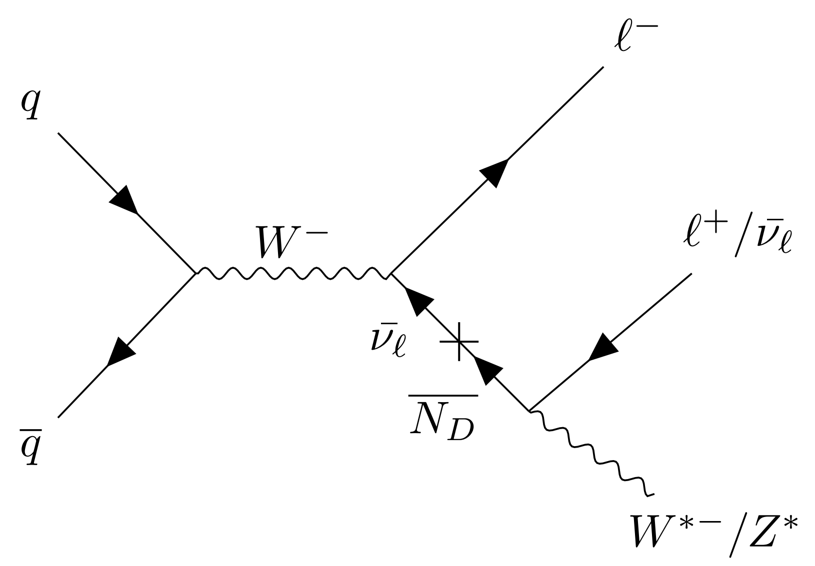
Probe masses down to 17 MeV

Heavy Neutral Leptons

EXOT-2019-29

Extension of SM with right-handed neutrinos can simultaneously explain neutrino masses, baryon asymmetry, and dark matter

- Naturally long-lived due to off-shell W decay



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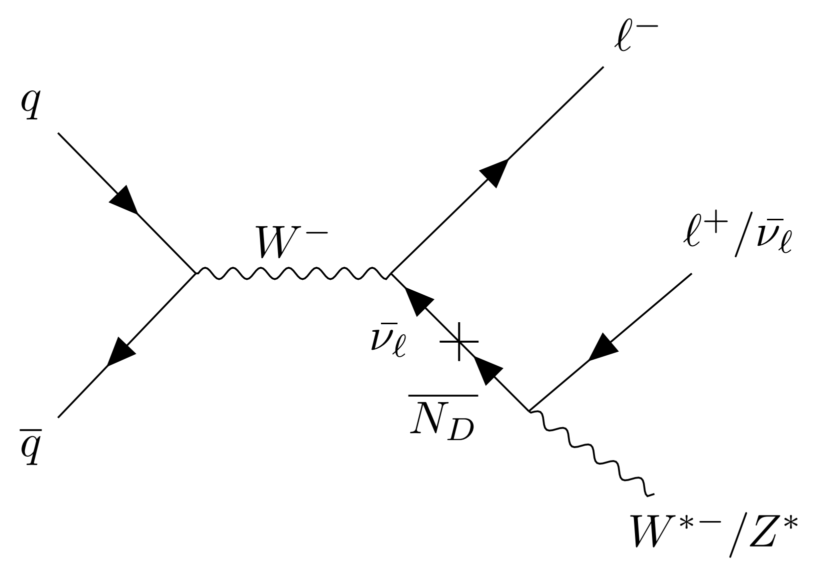

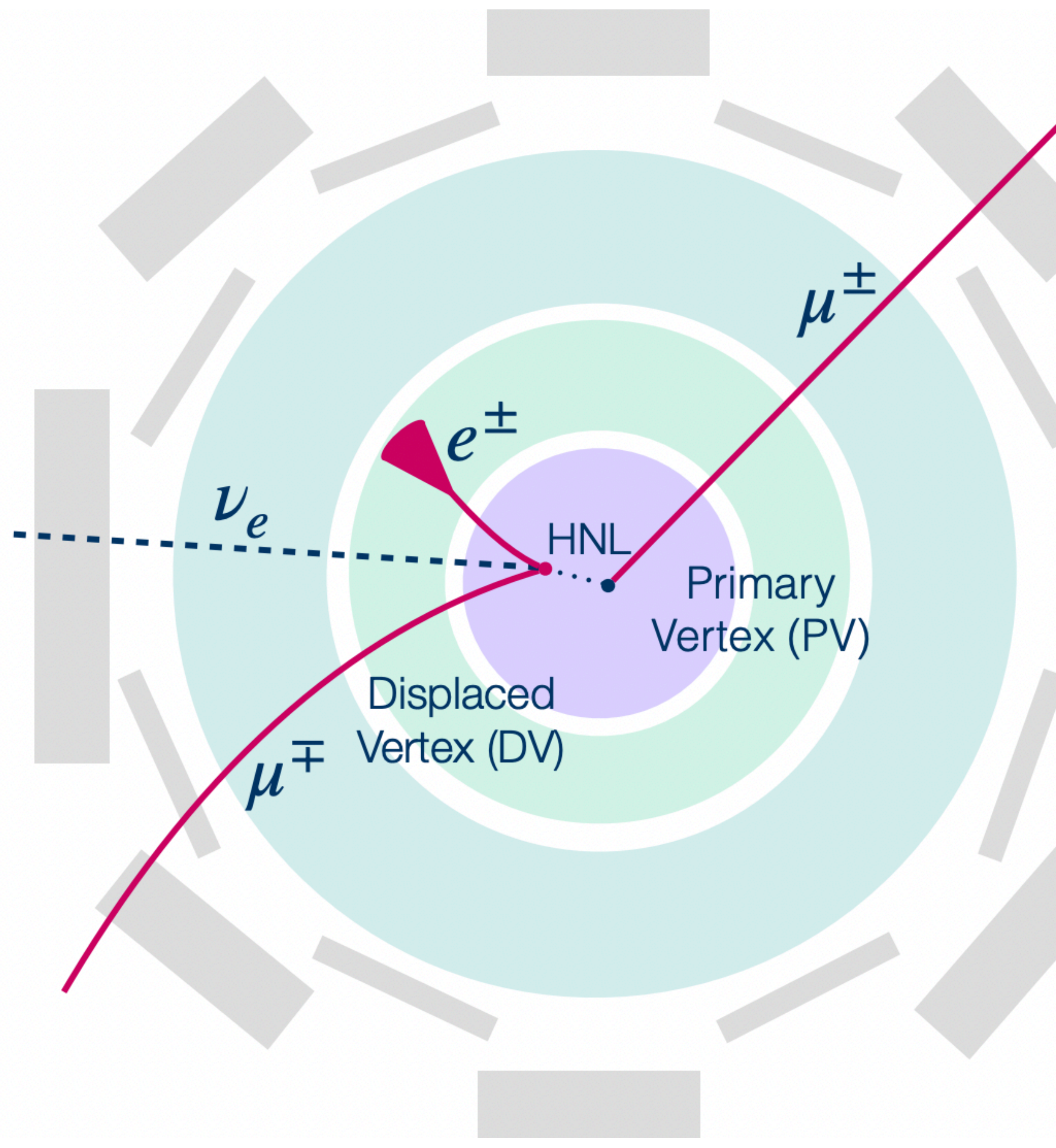

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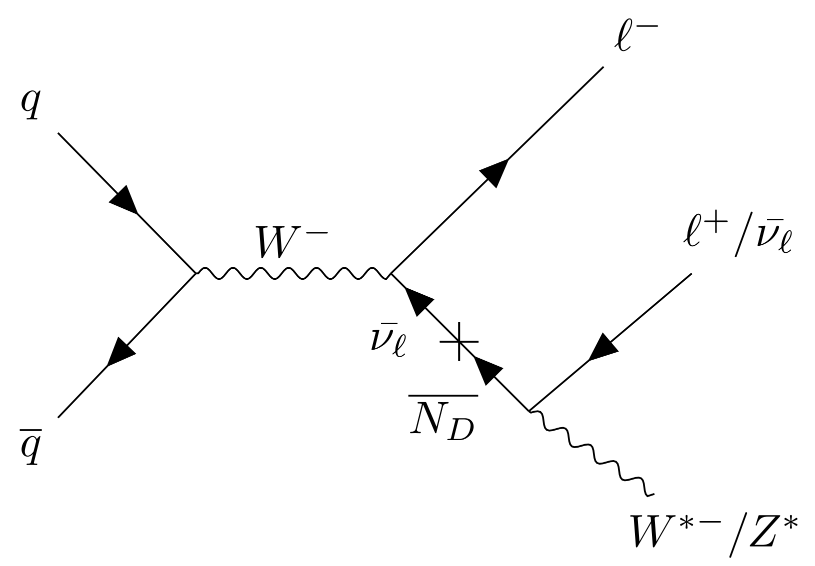

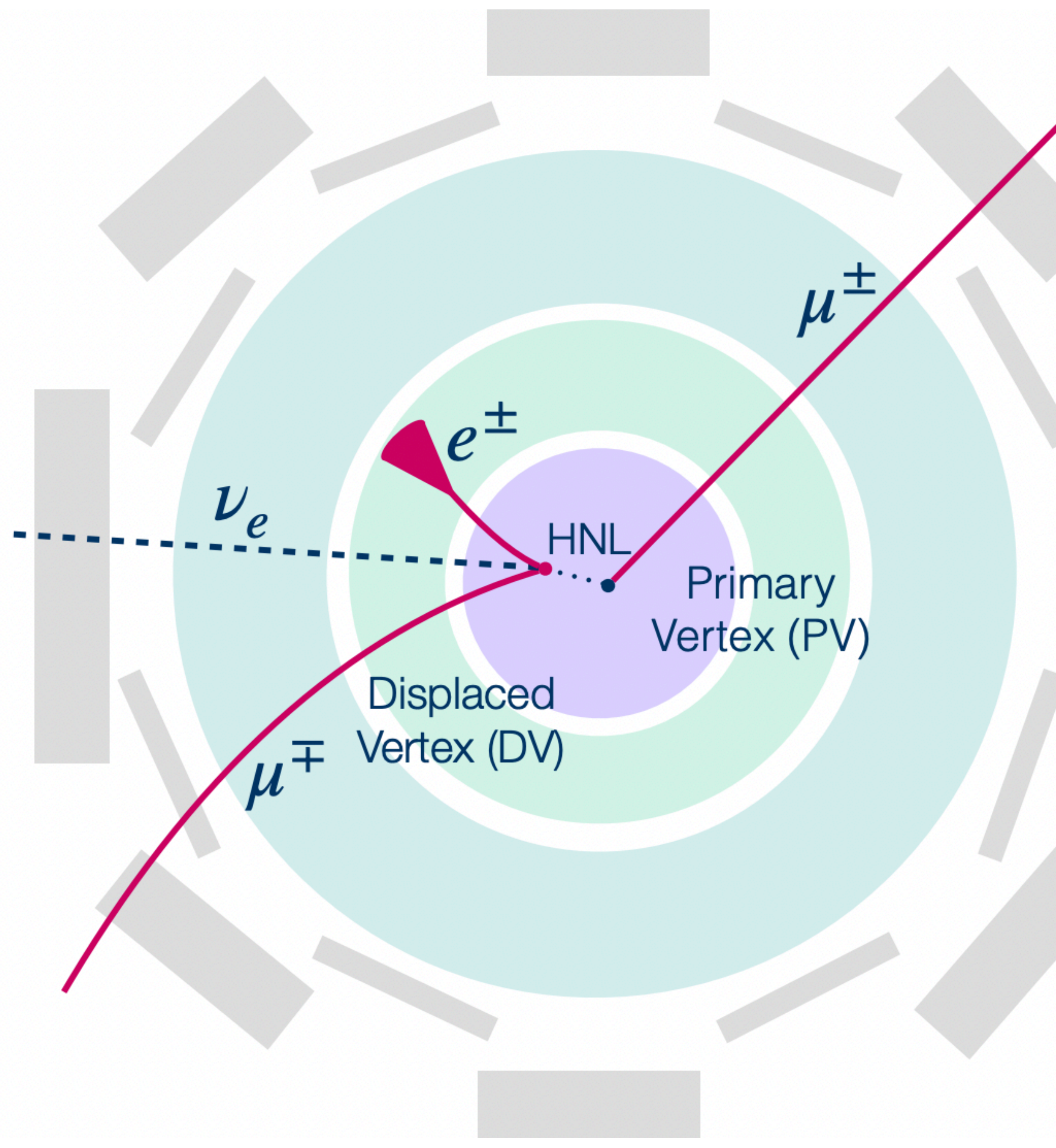

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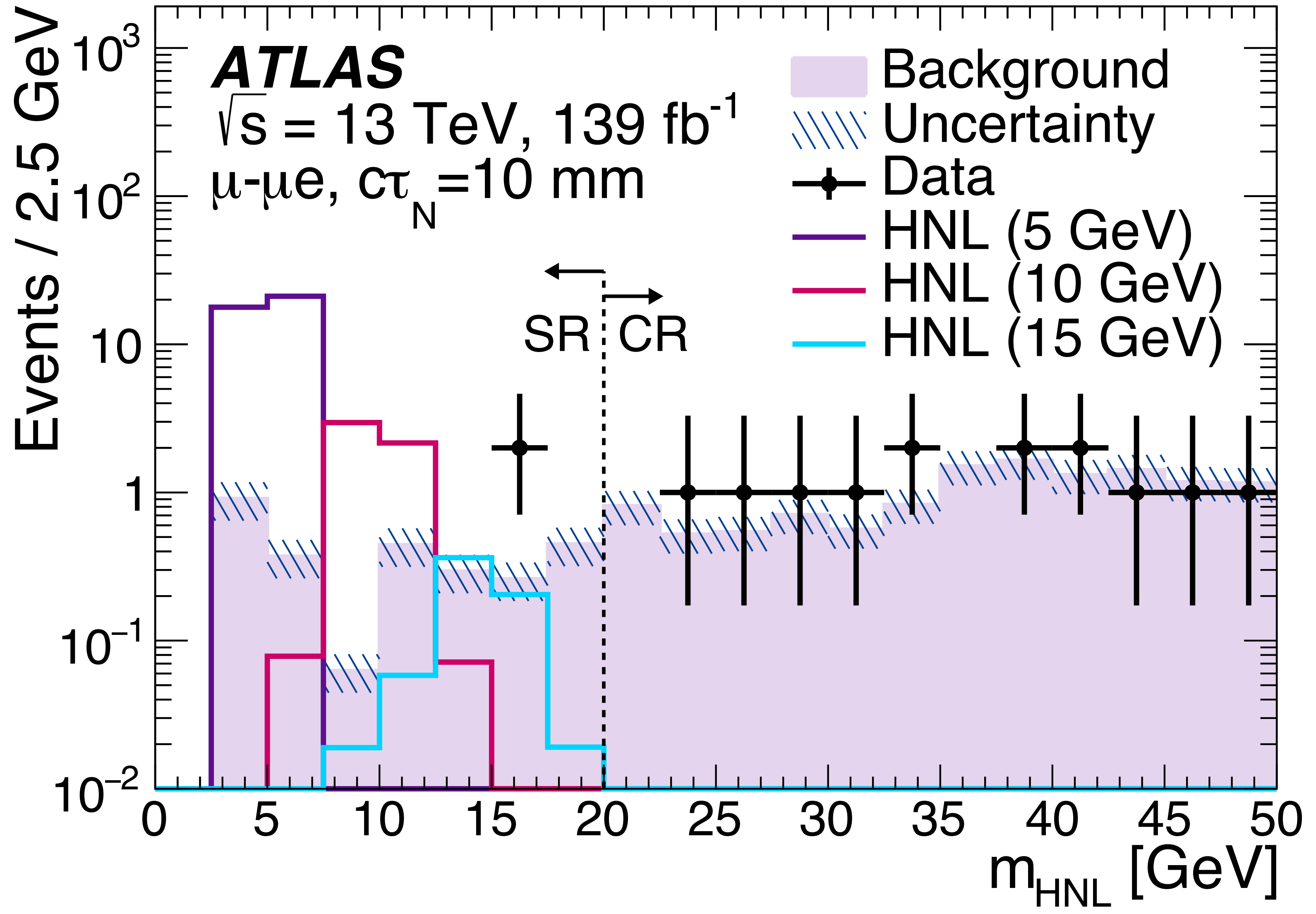

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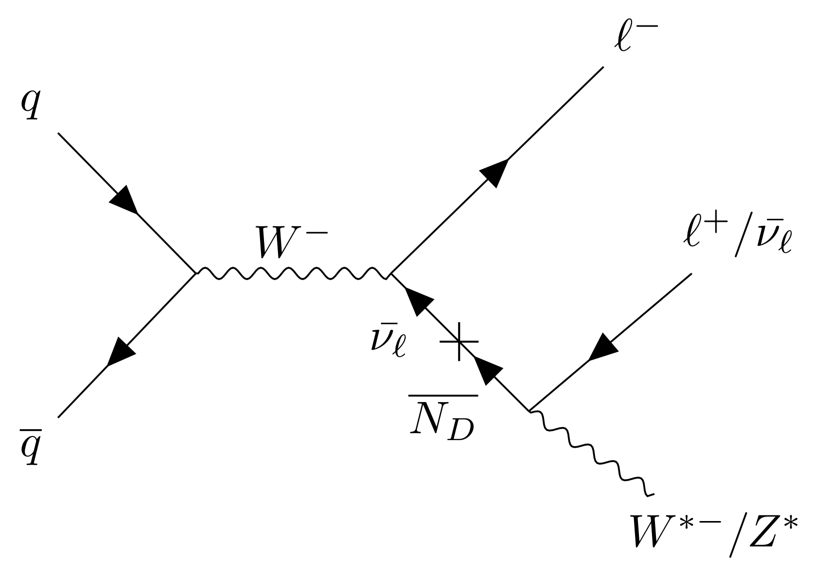

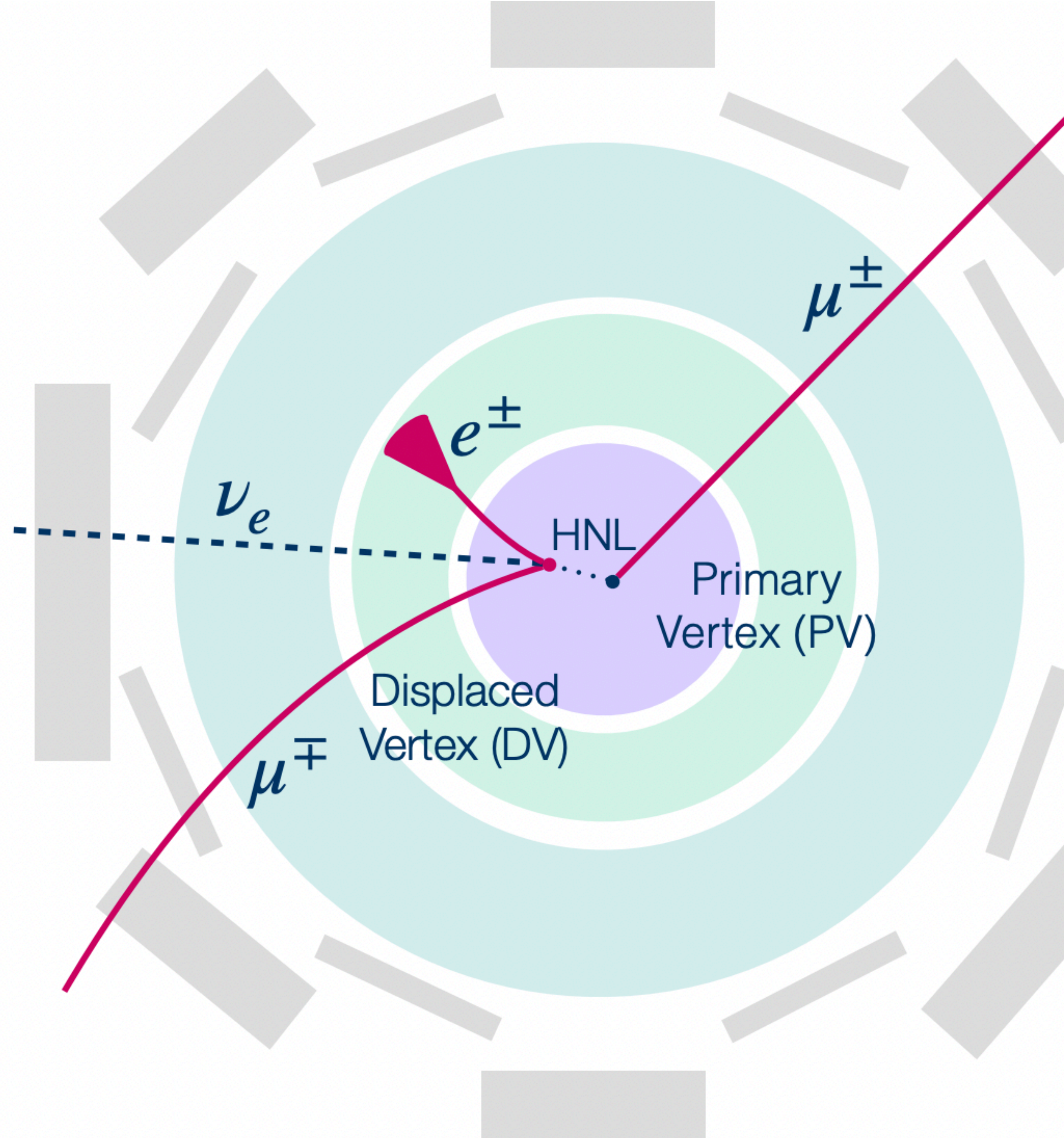

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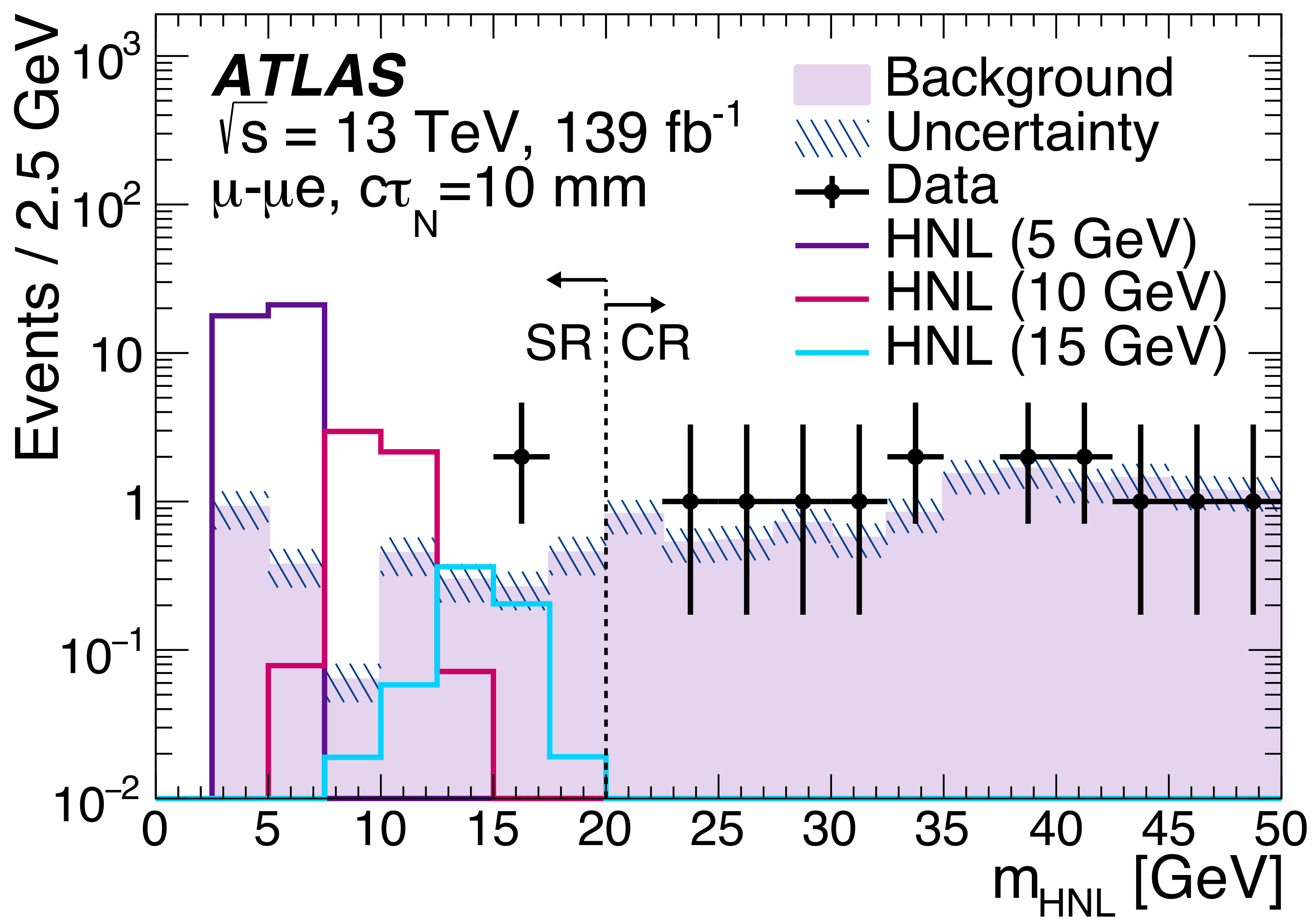
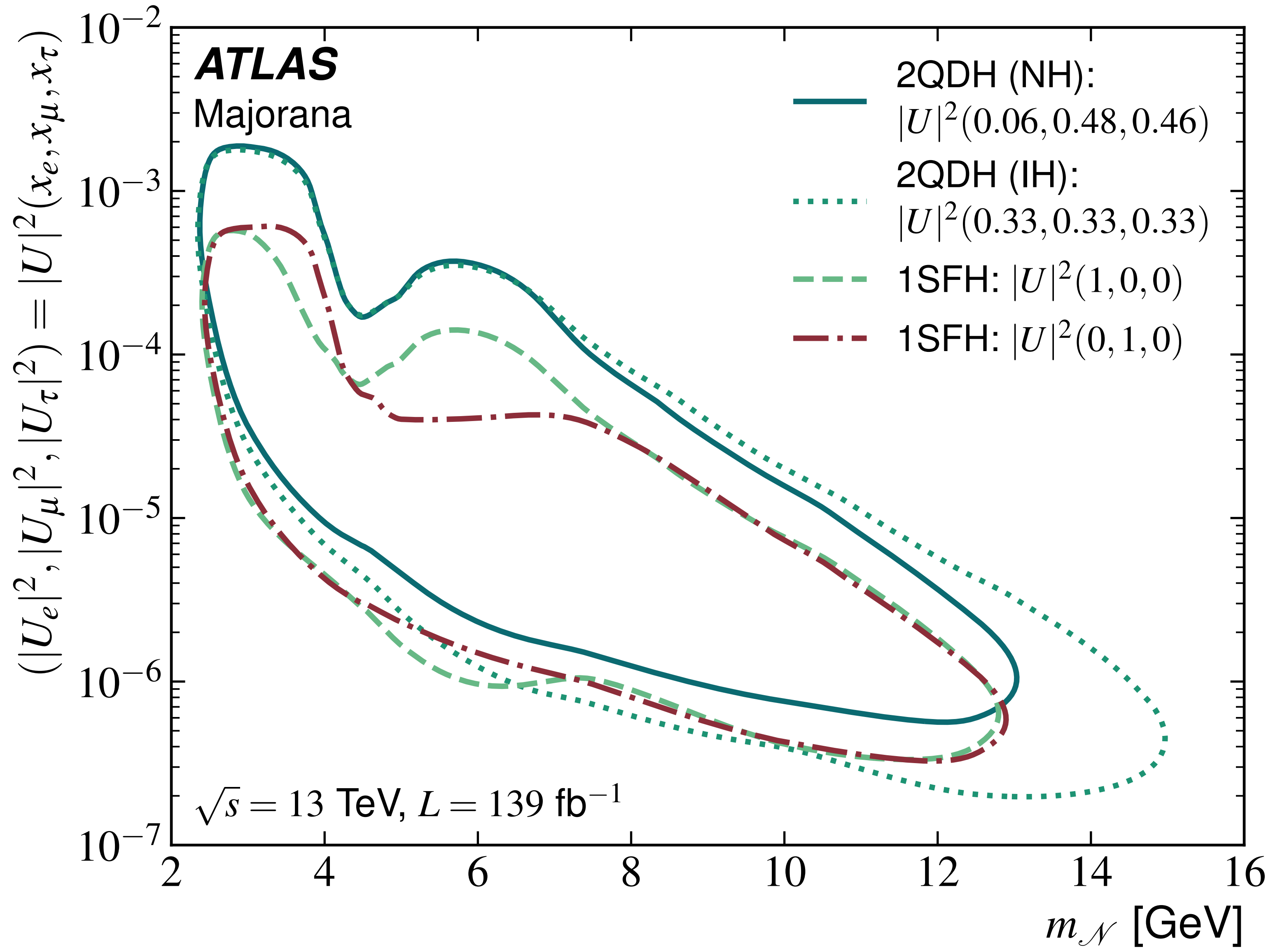
First search to target models with two quasi-degenerate HNLs (2QDH) with multi-flavour mixing





Displaced lepton triggers

TRIG-2022-01

New for Run 3: dedicated triggers for displaced leptons

- Make use of improved displaced track reconstruction ported to the trigger

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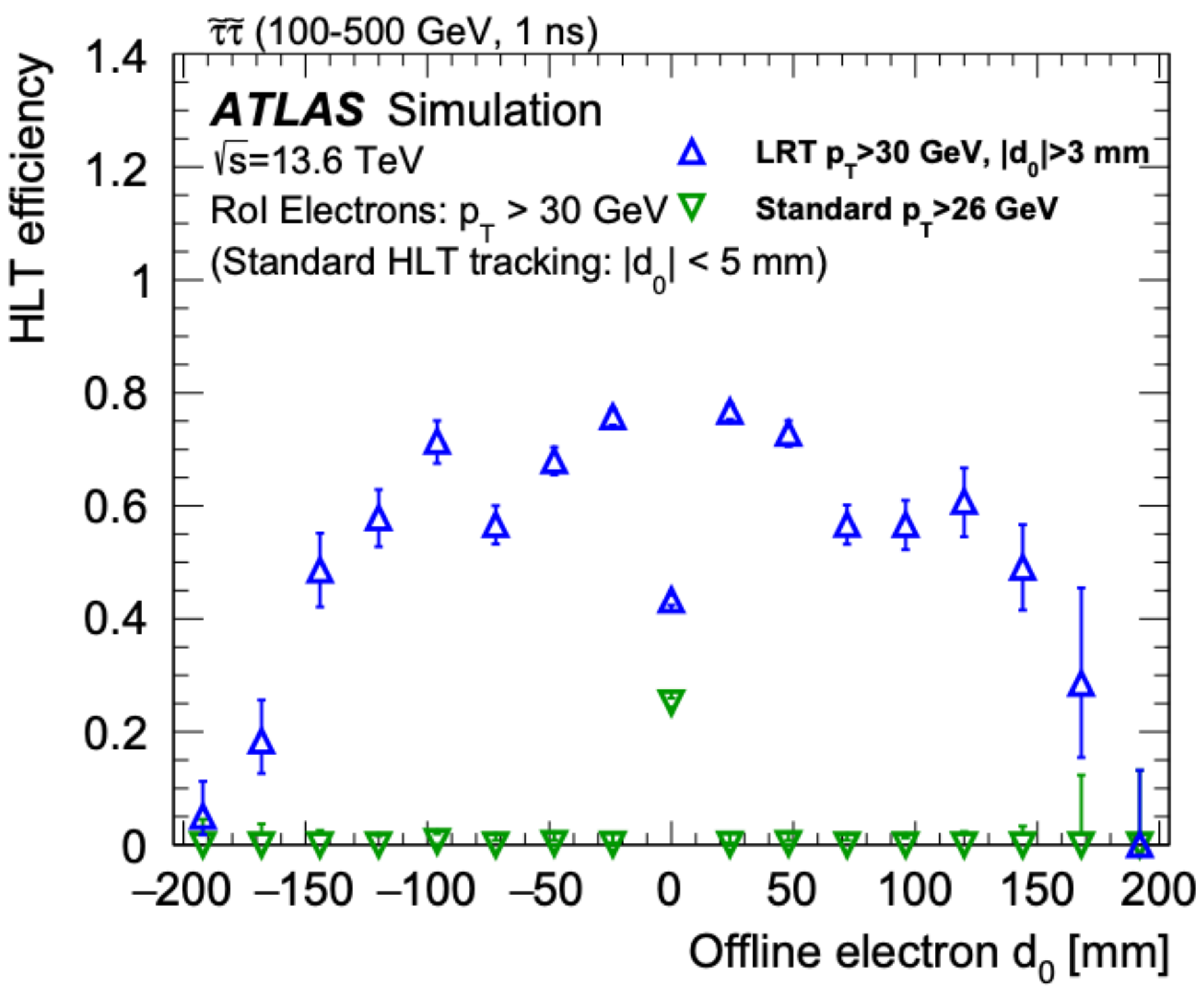

Displaced single-electron trigger runs
LRT in RoI around calo candidate
$p_T > 30$ GeV, $|d_0| > 3$ mm

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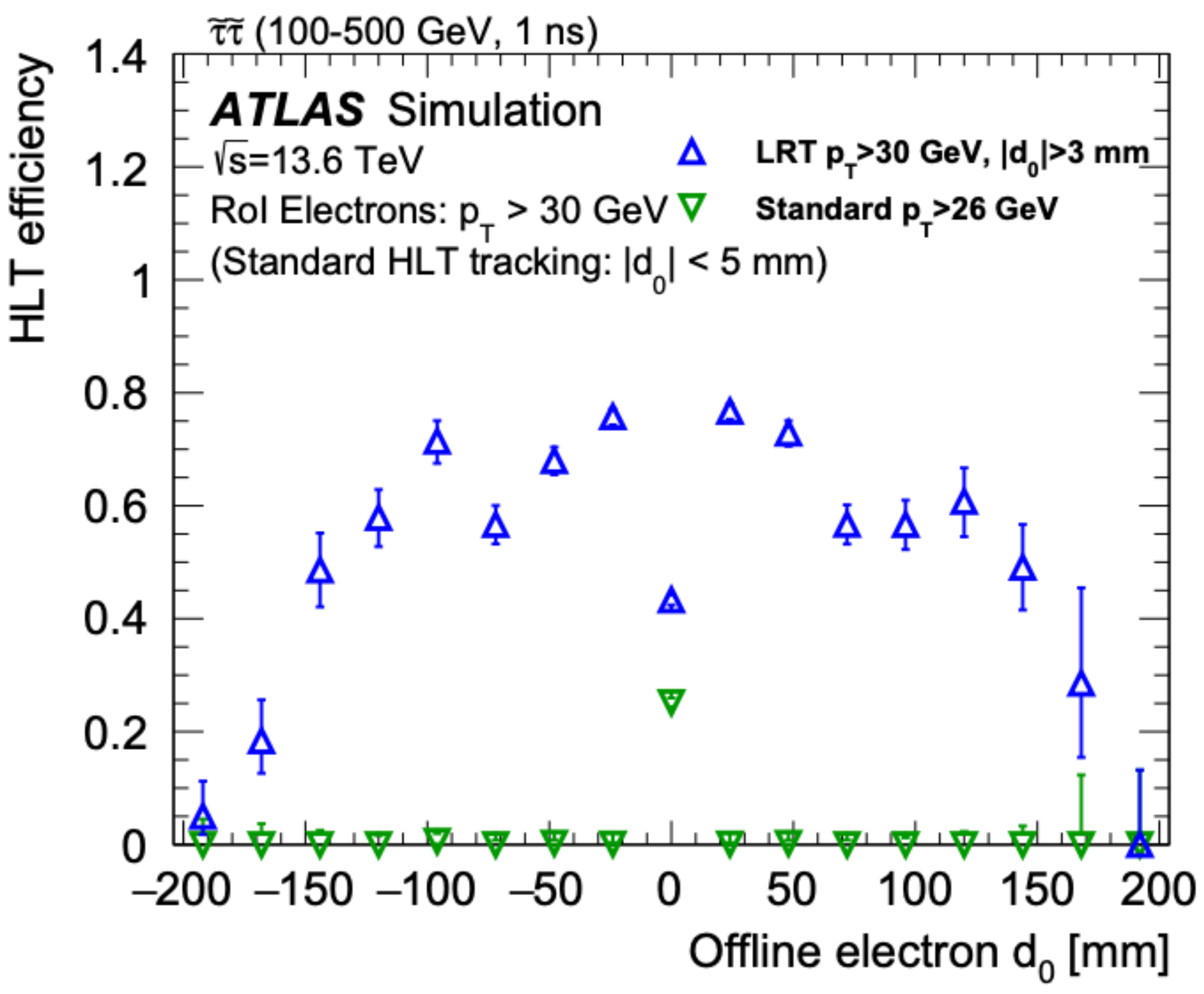

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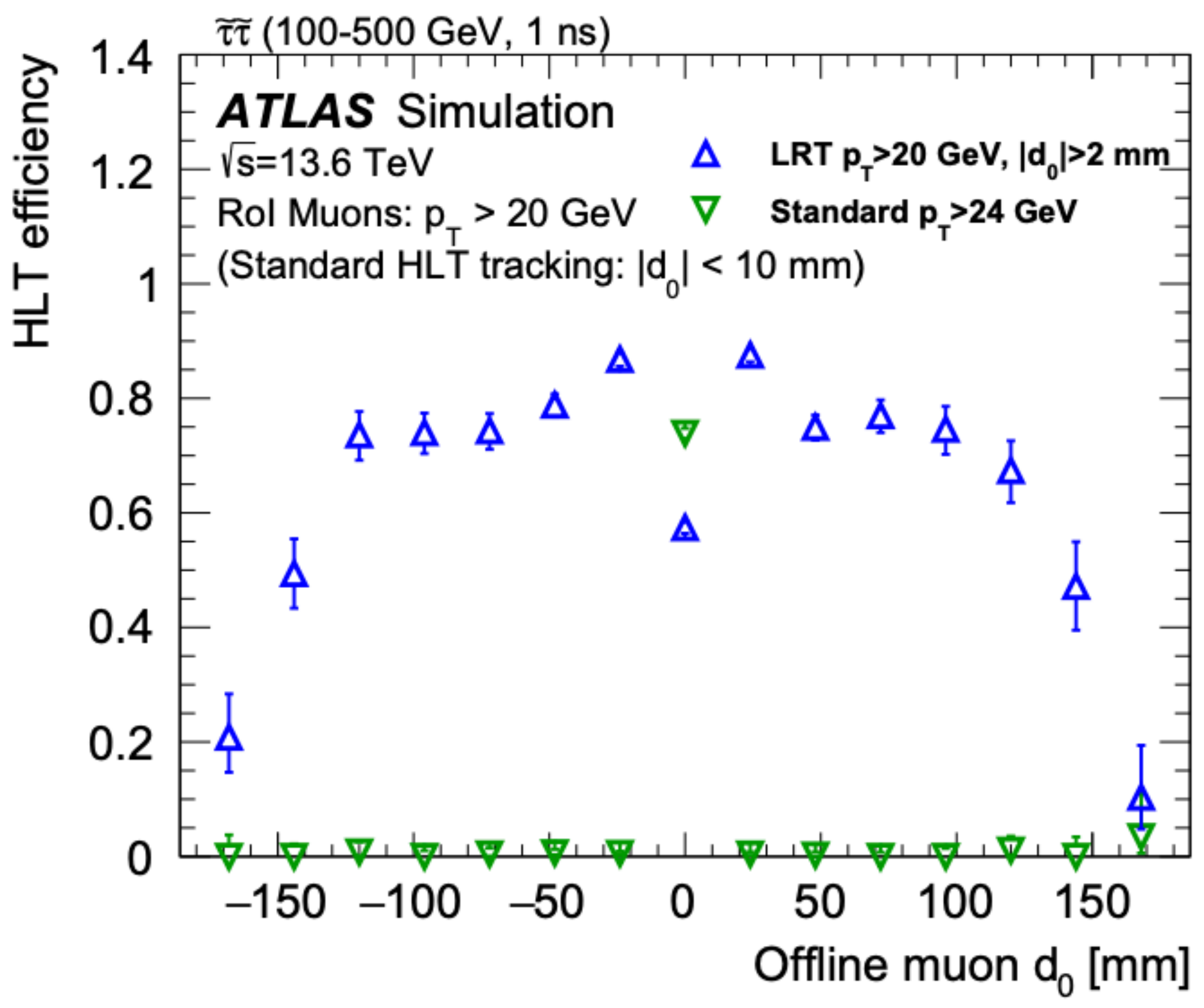

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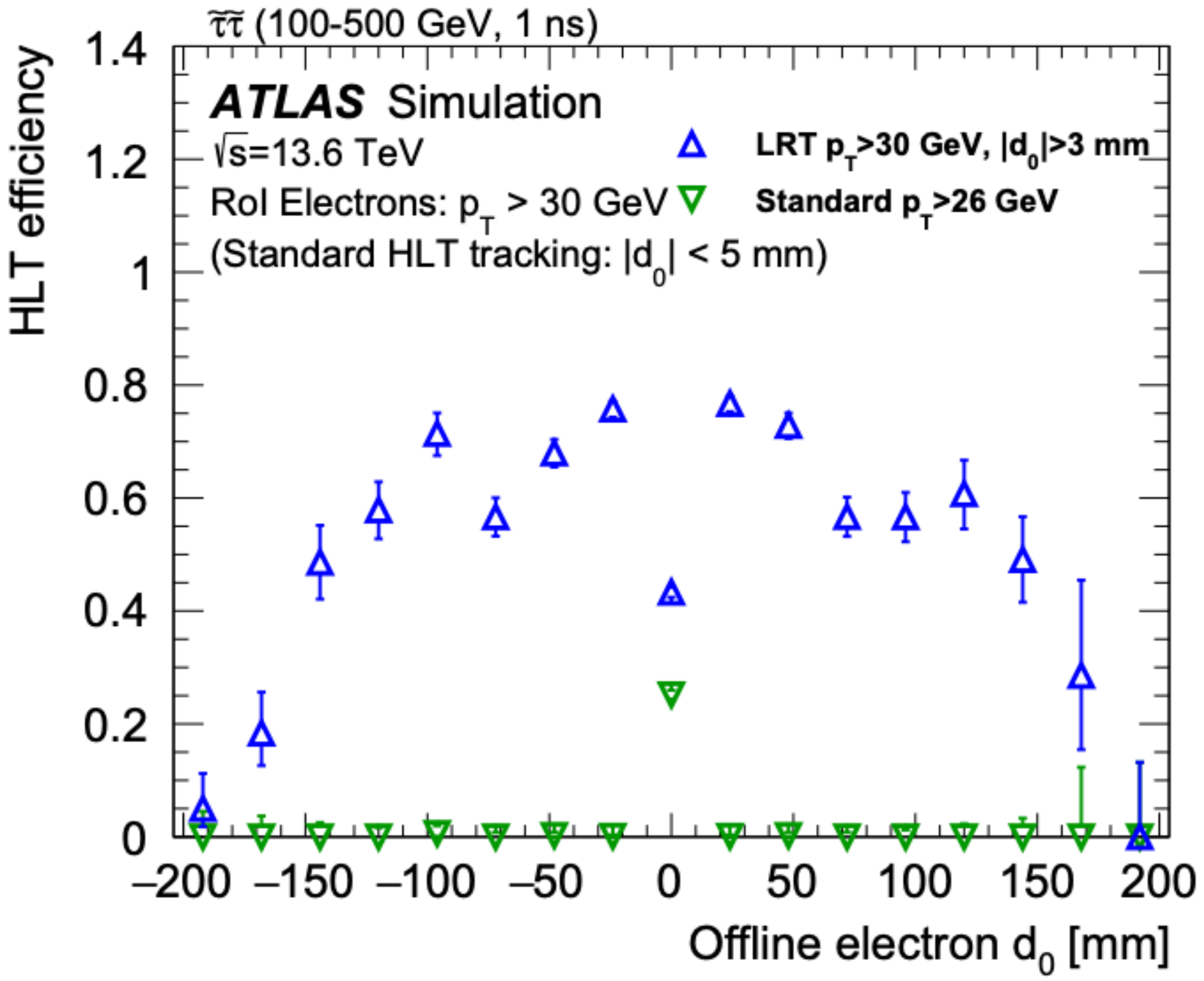

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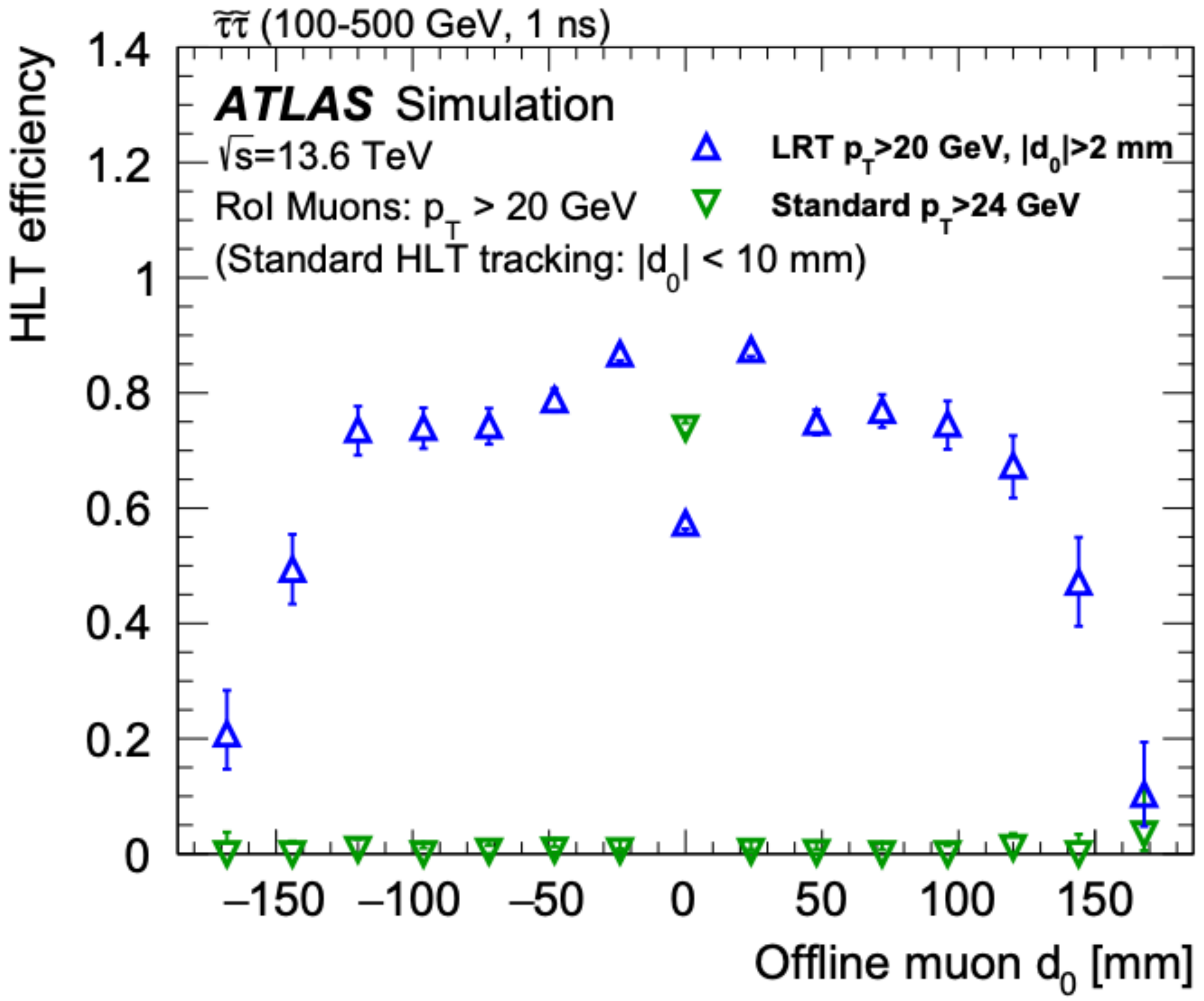

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Allows for significantly lower momentum thresholds than photon/MS-only triggers used in Run 2

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ATLAS-CONF-2024-011

Search for long-lived sleptons in GMSB model

- First ATLAS Run 3 search results! Combined with Run 2 data

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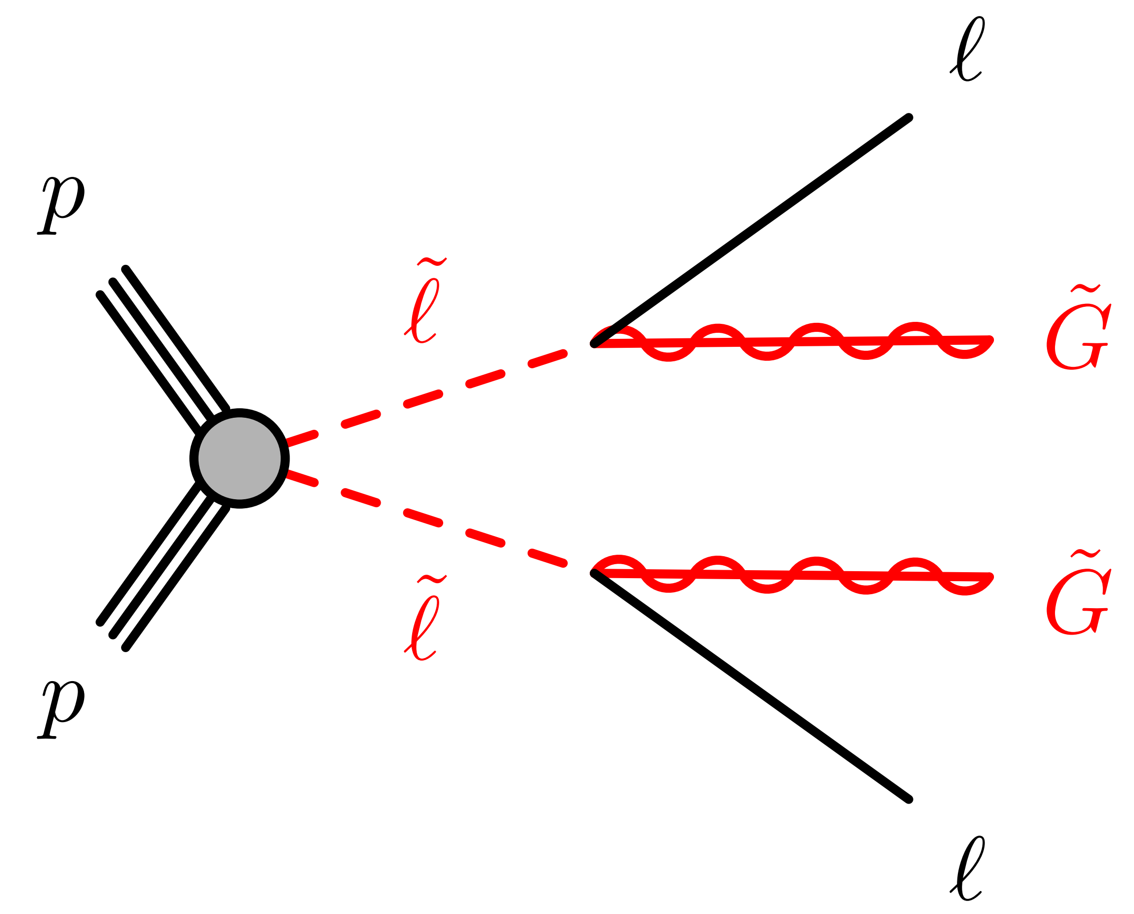

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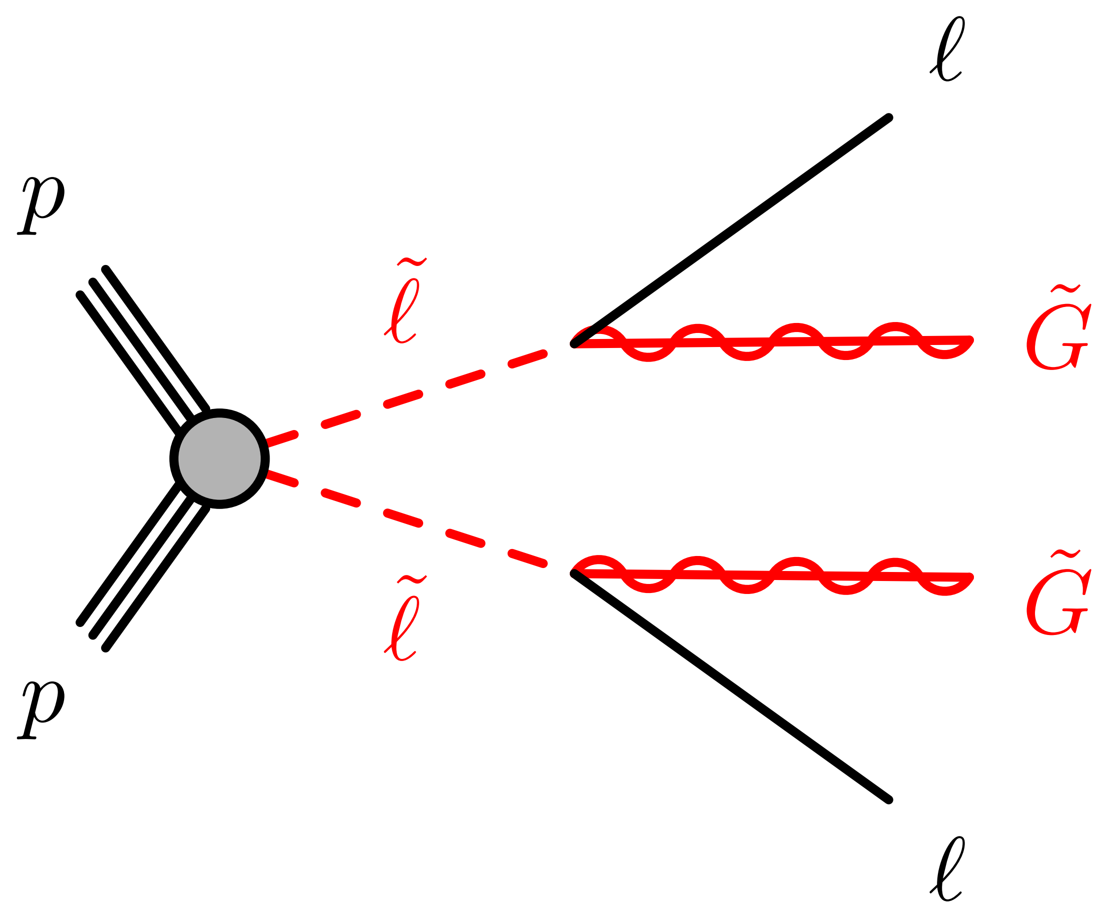

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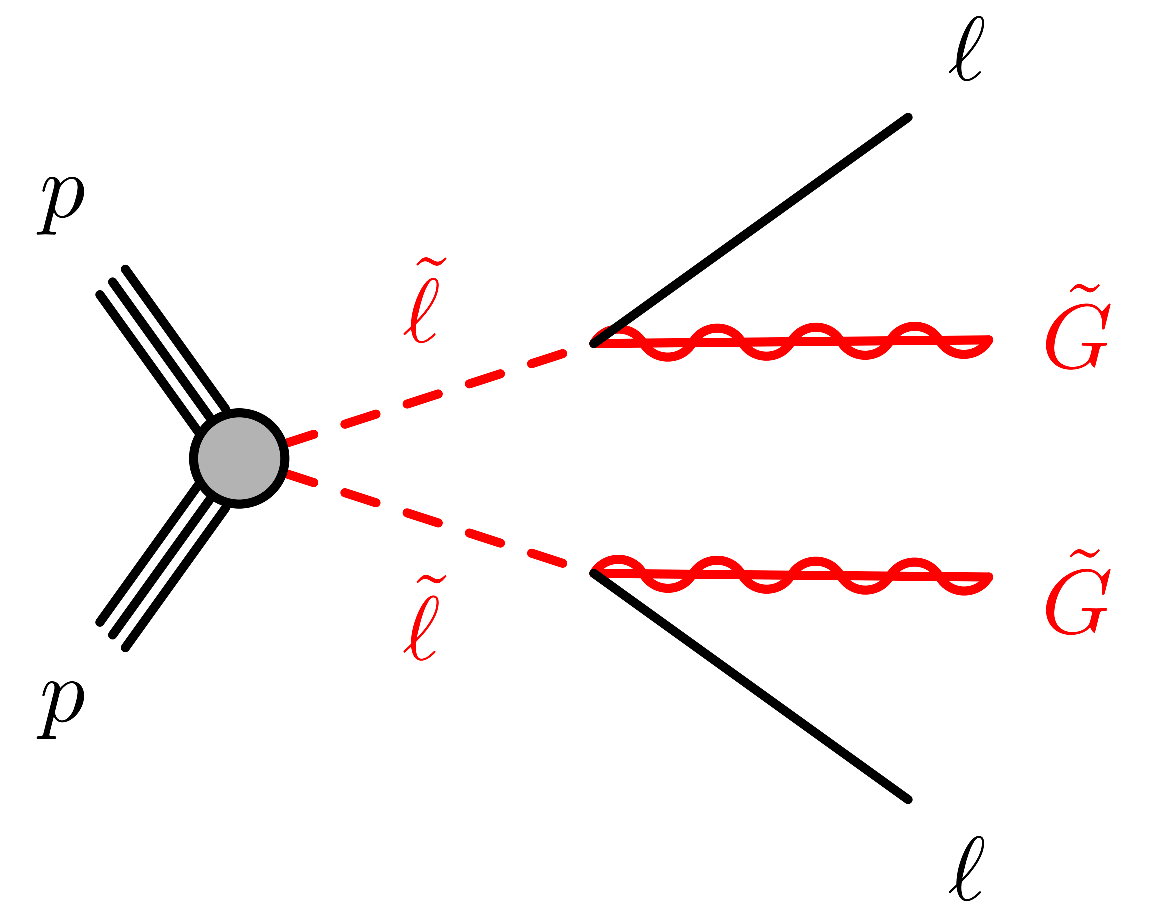

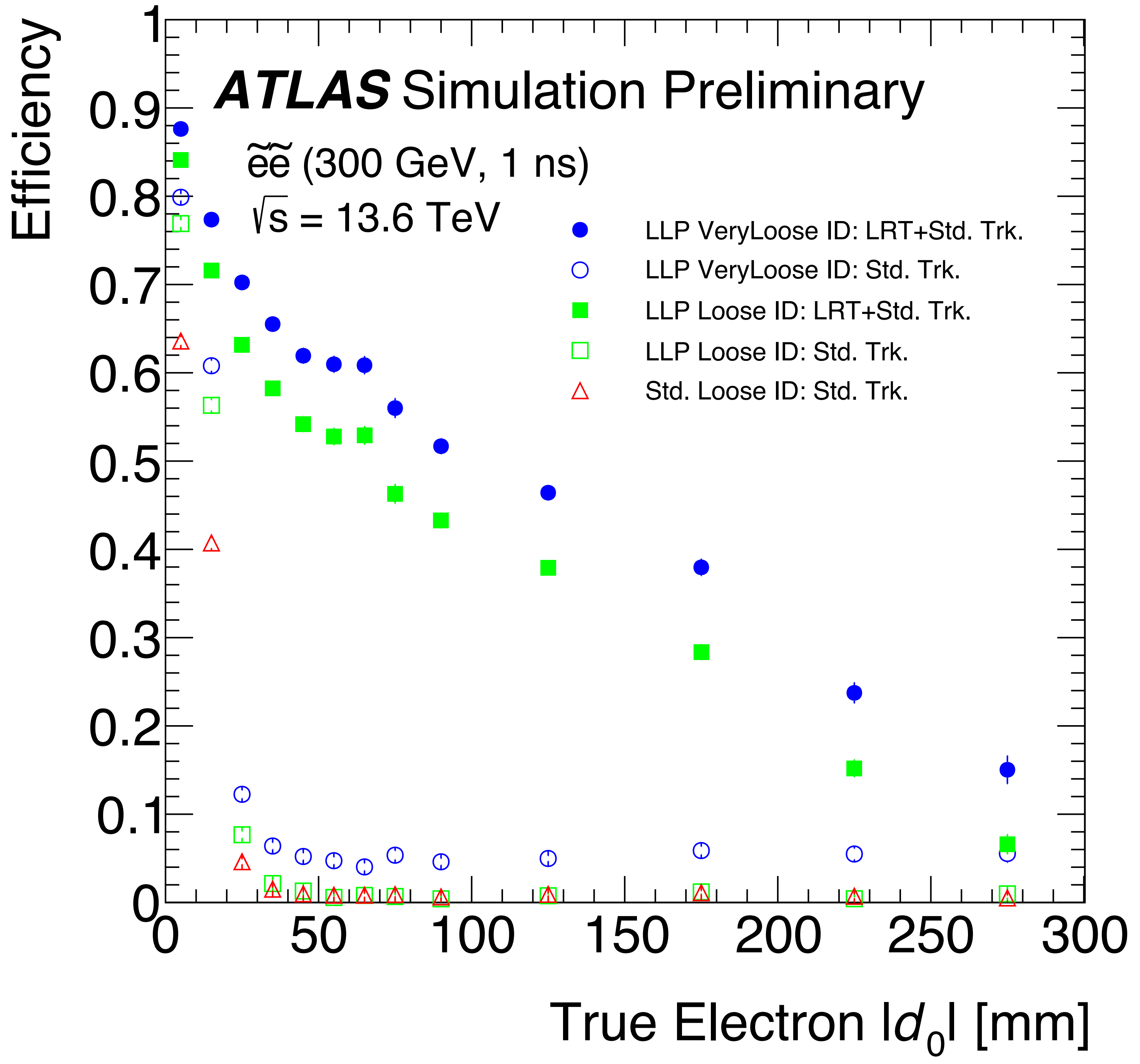

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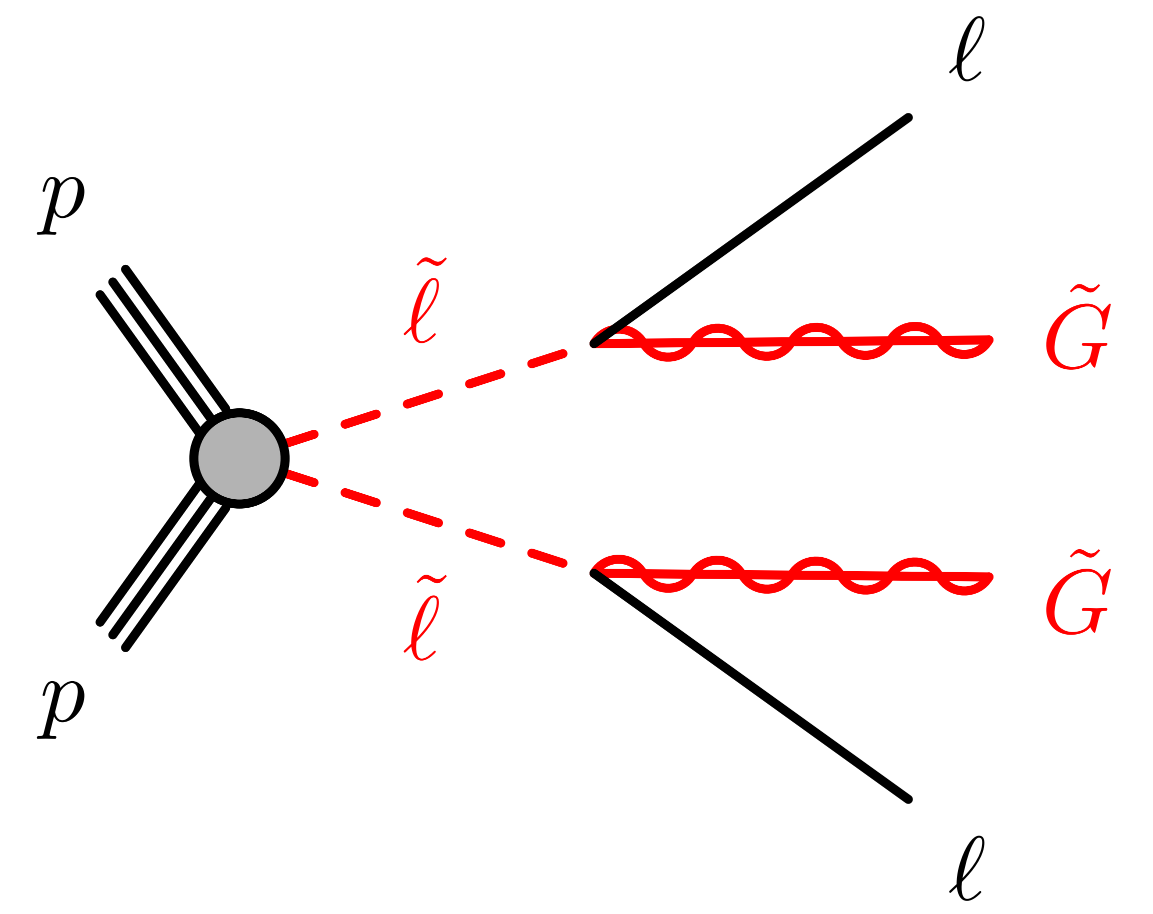

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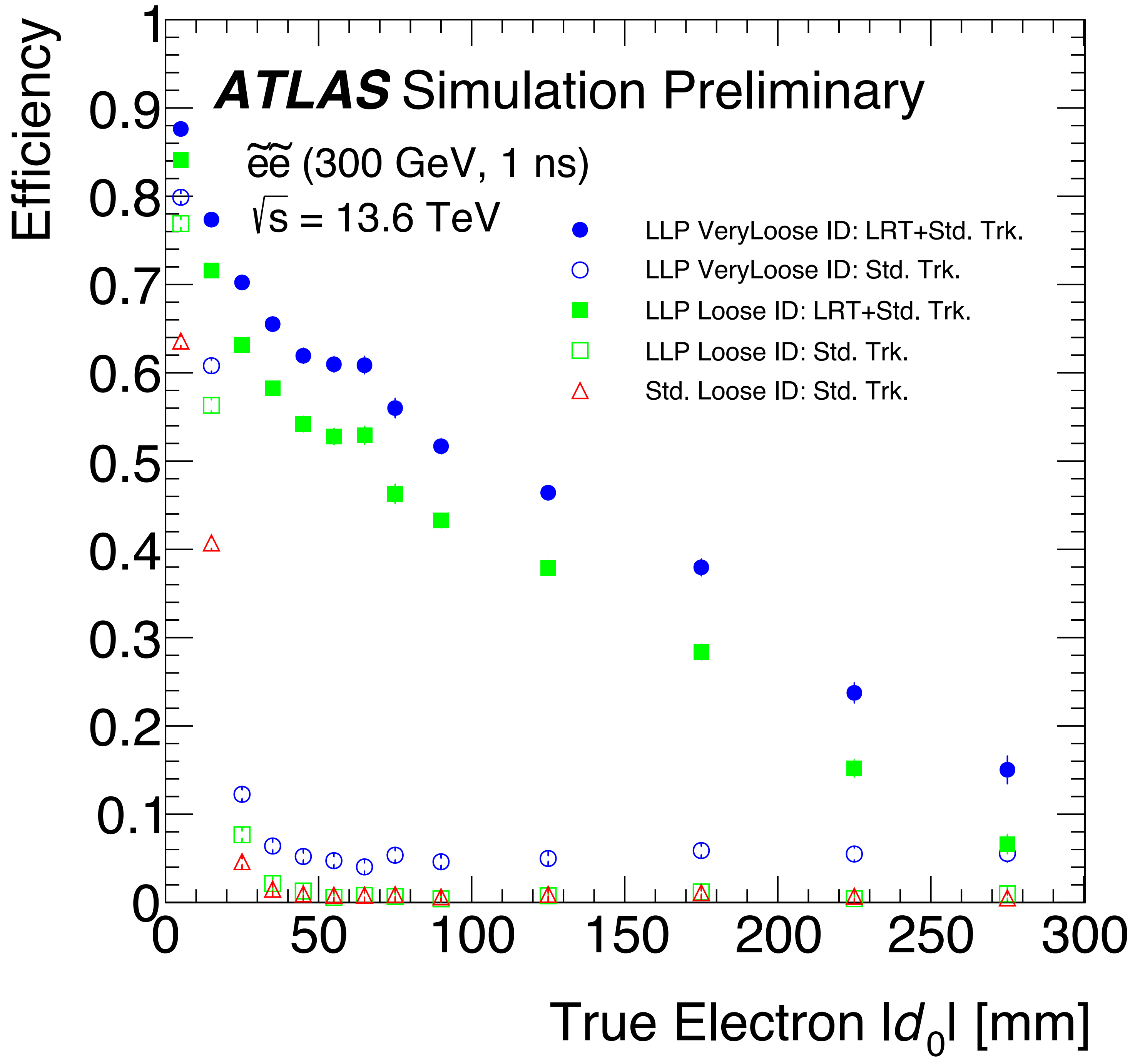

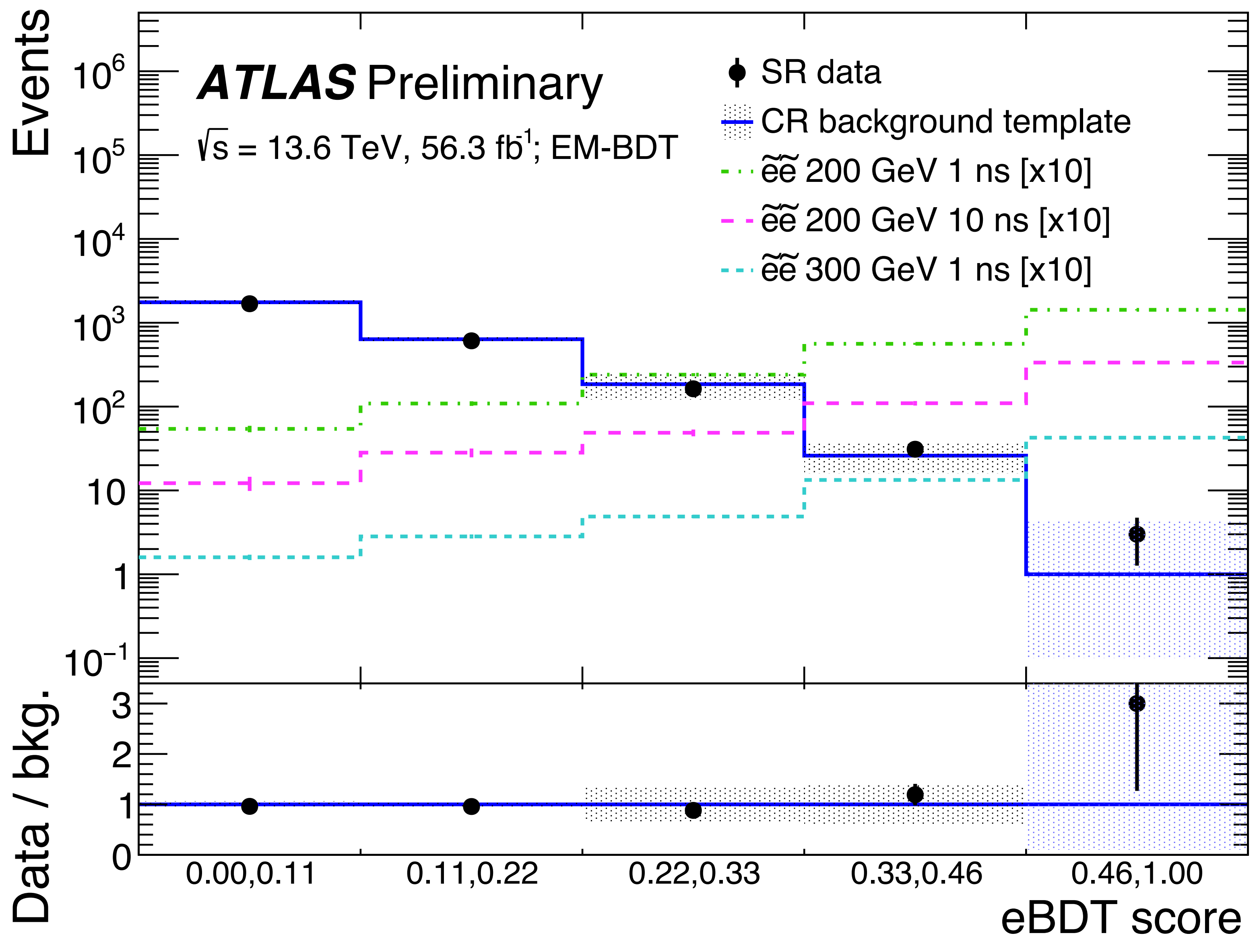

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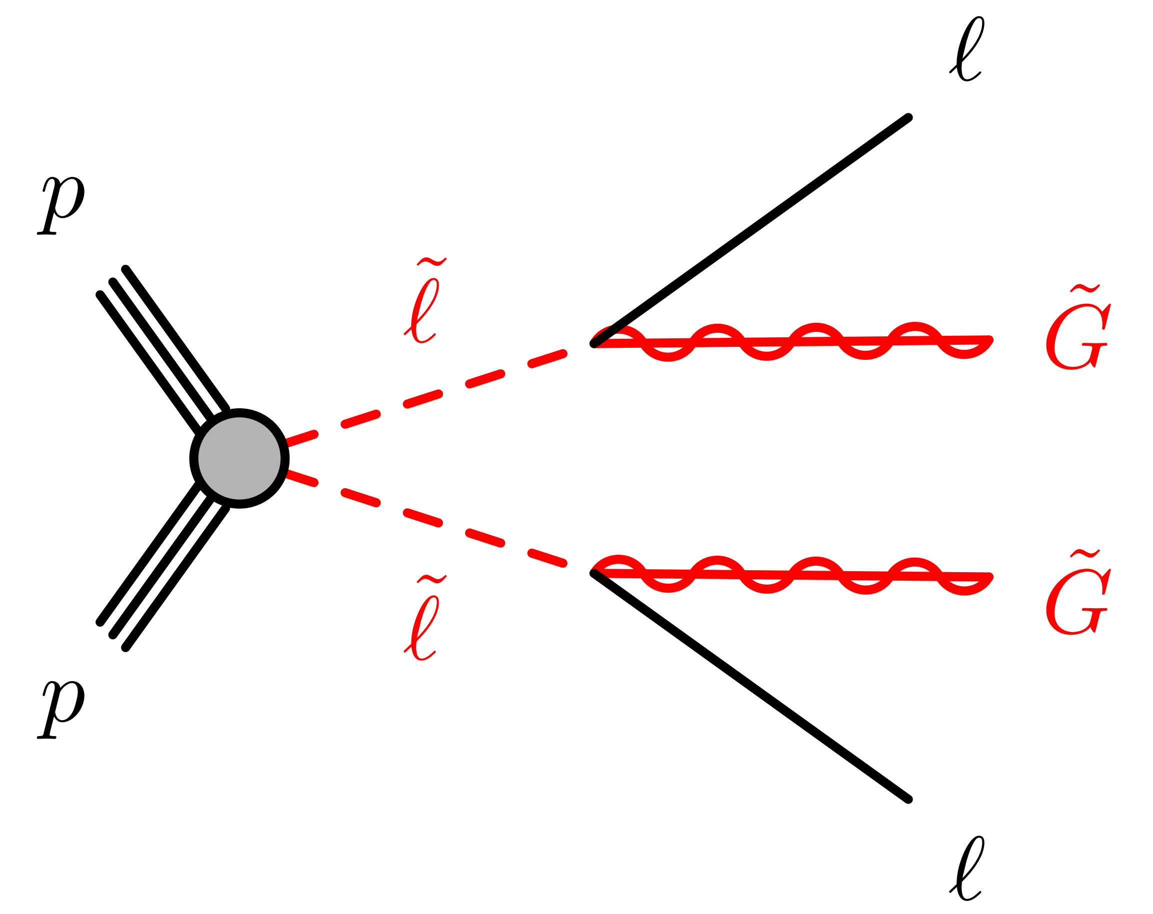

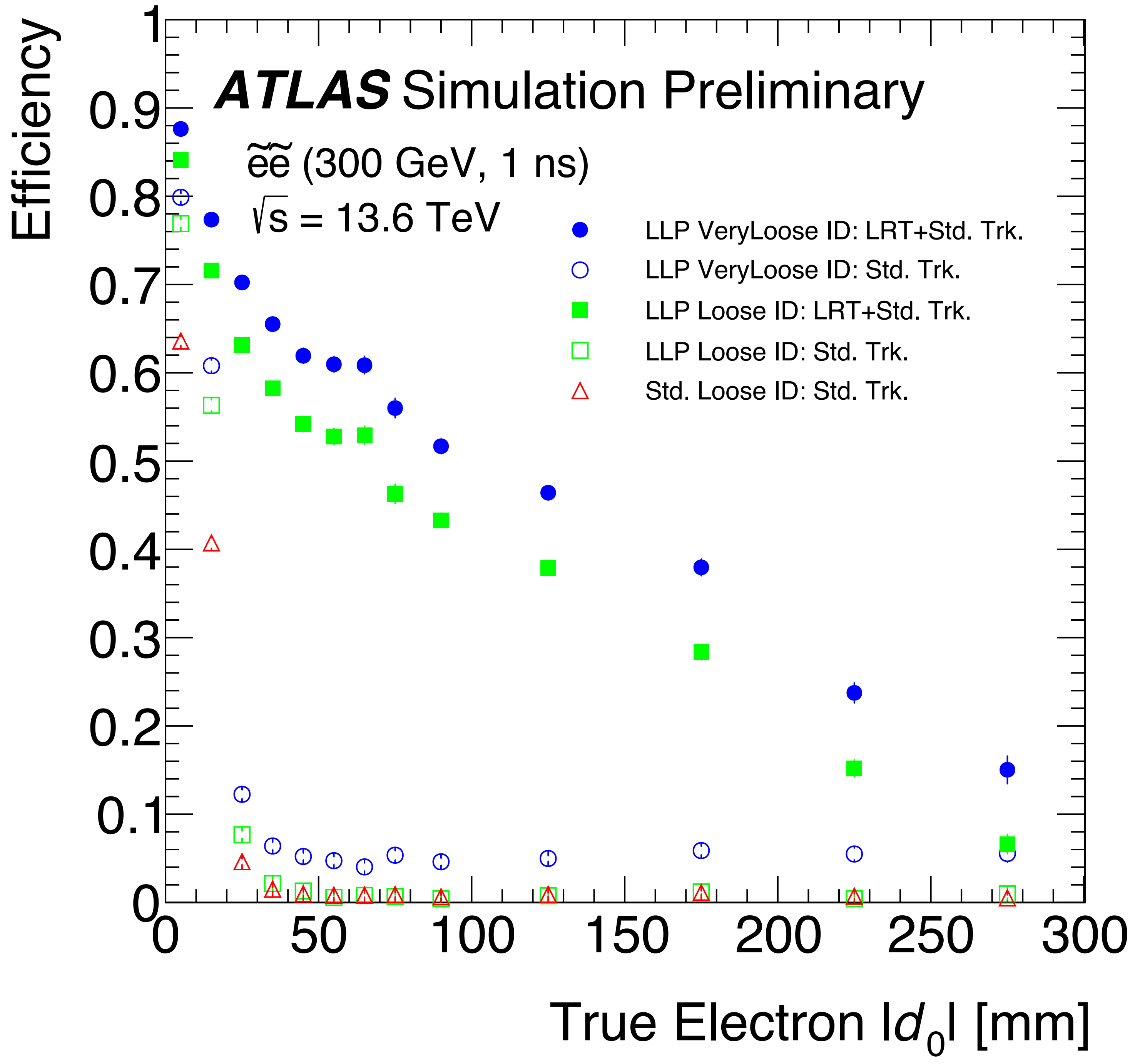

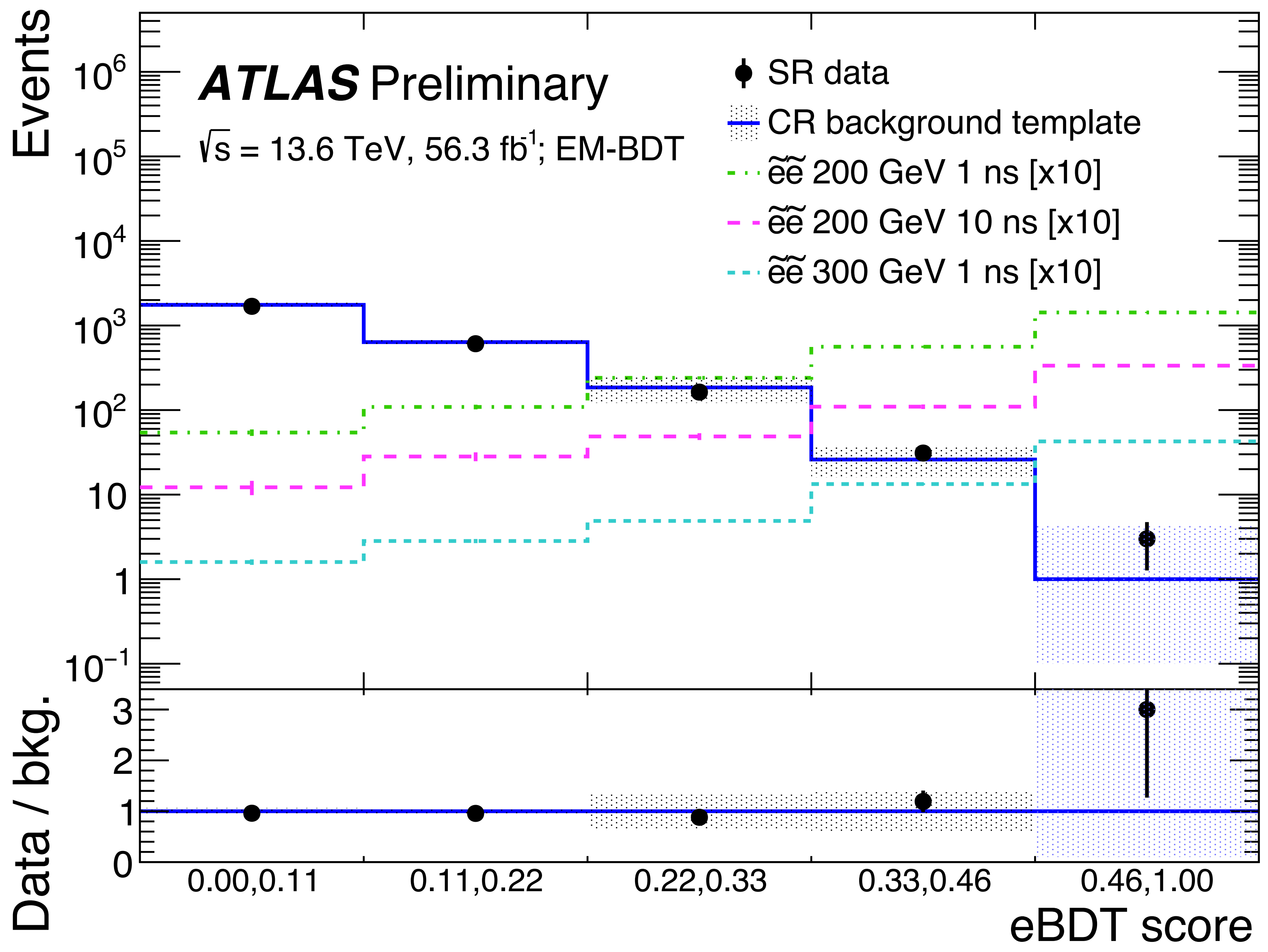

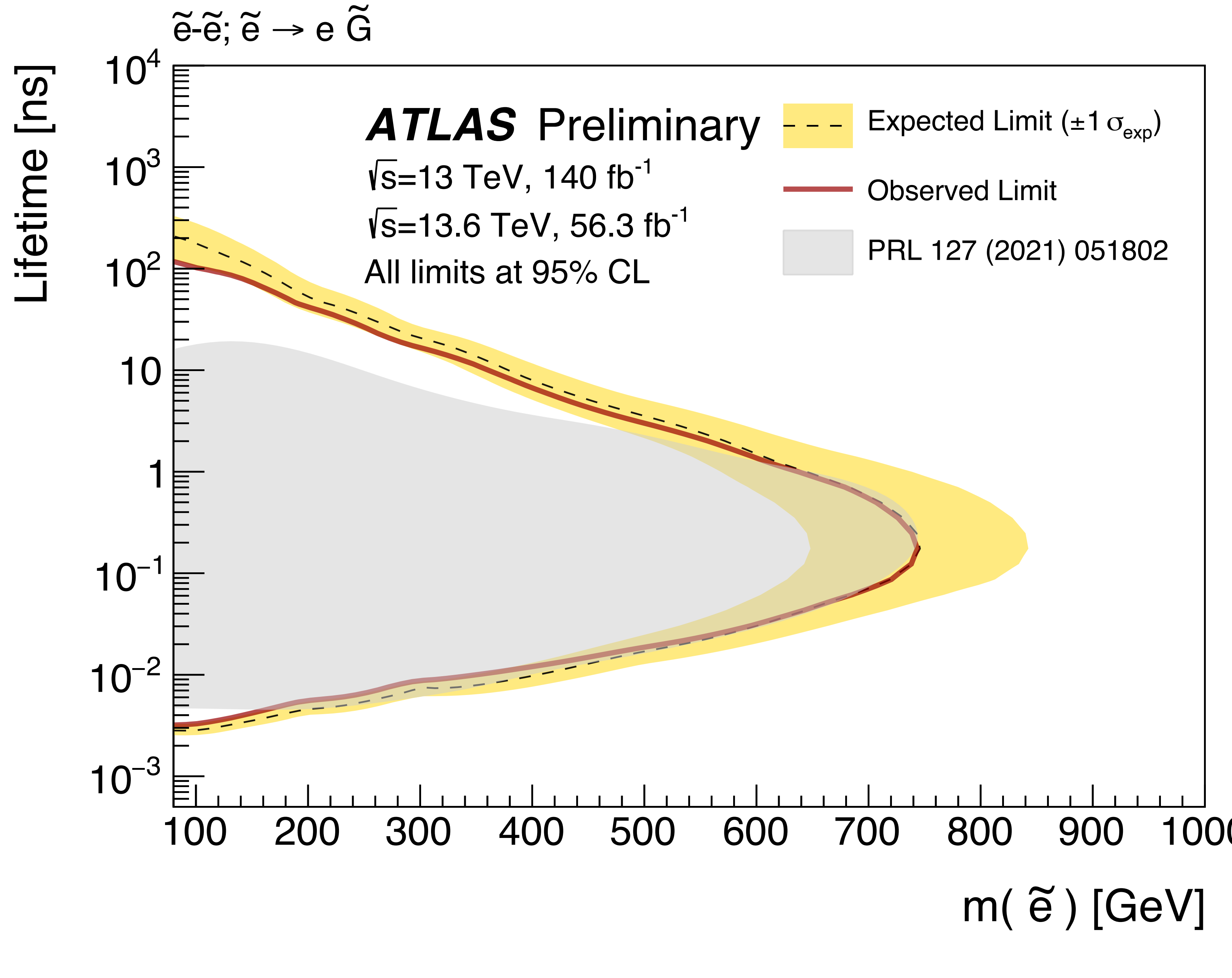

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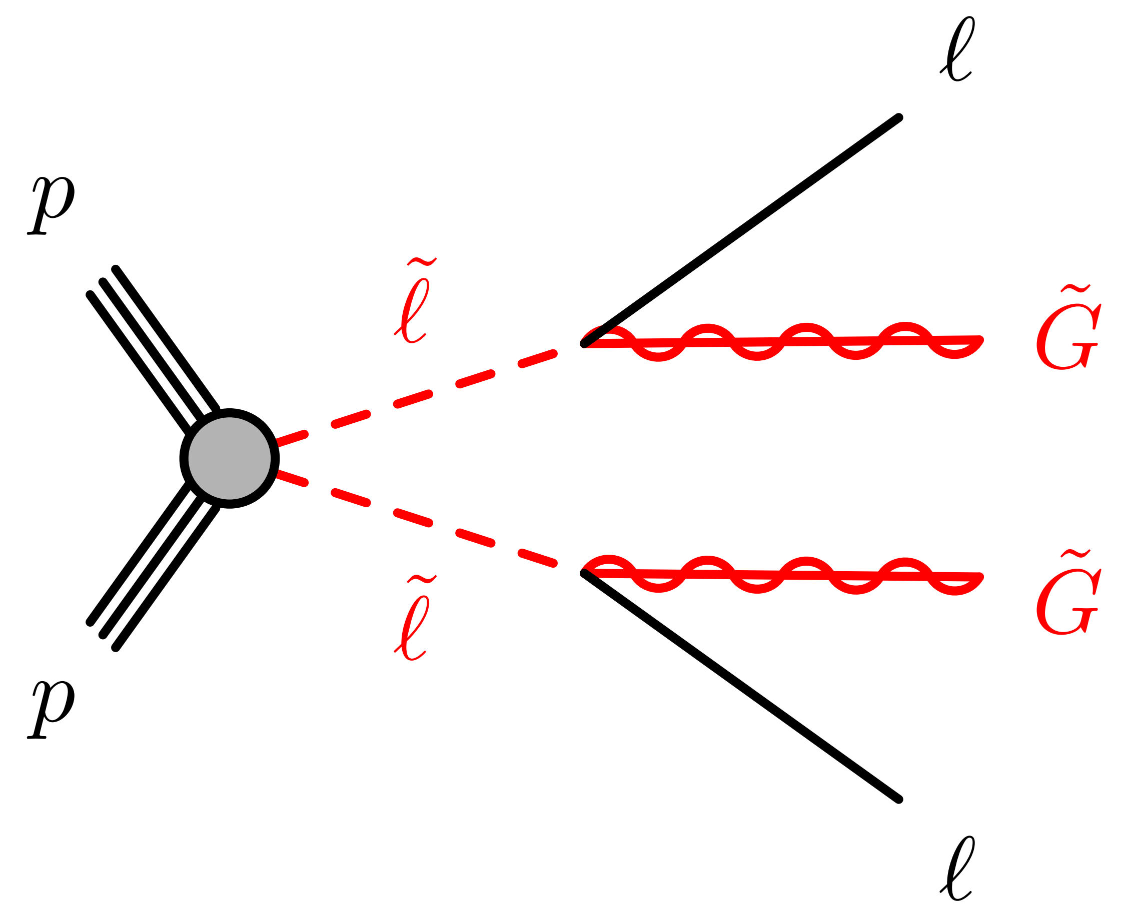

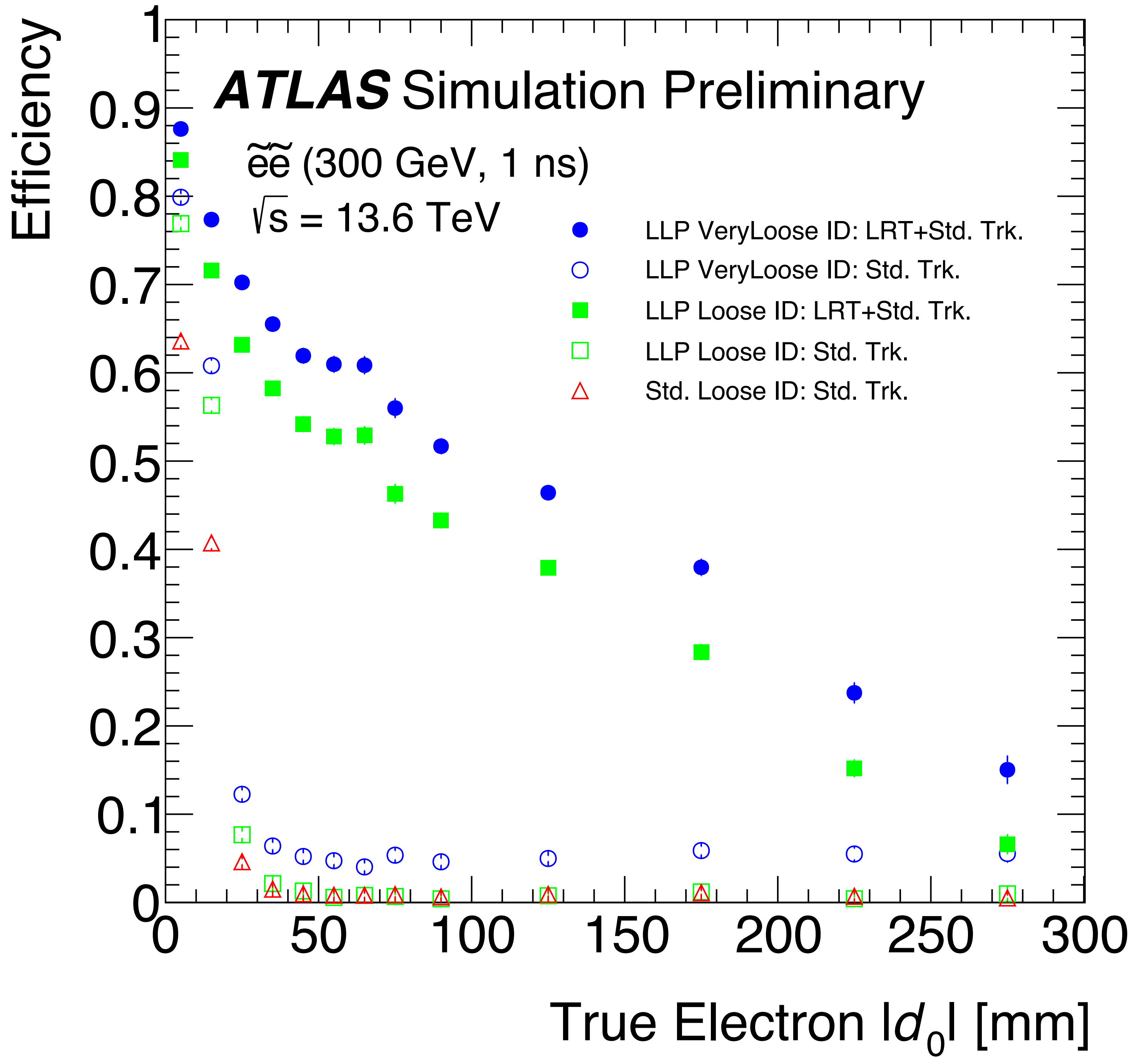

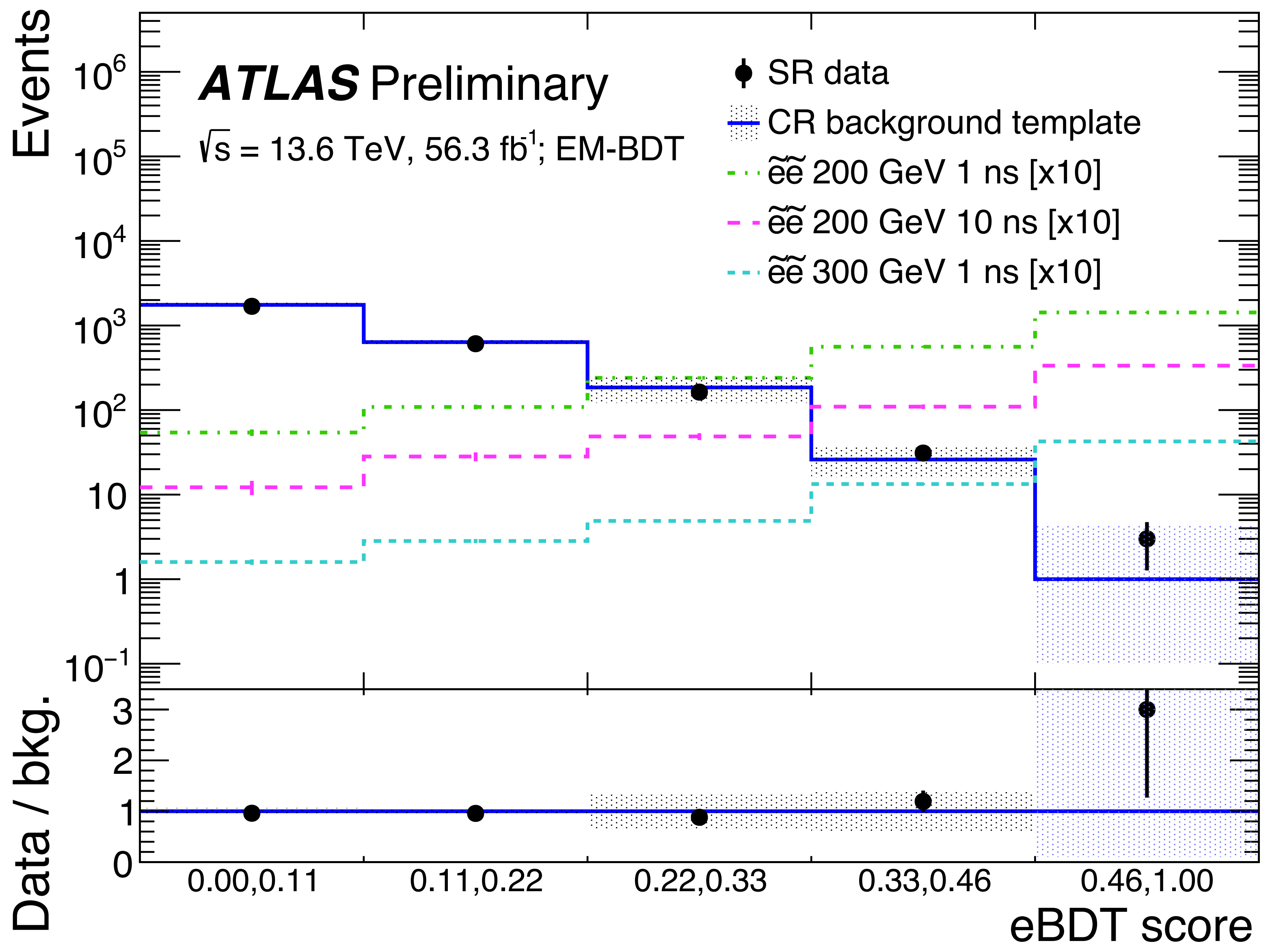

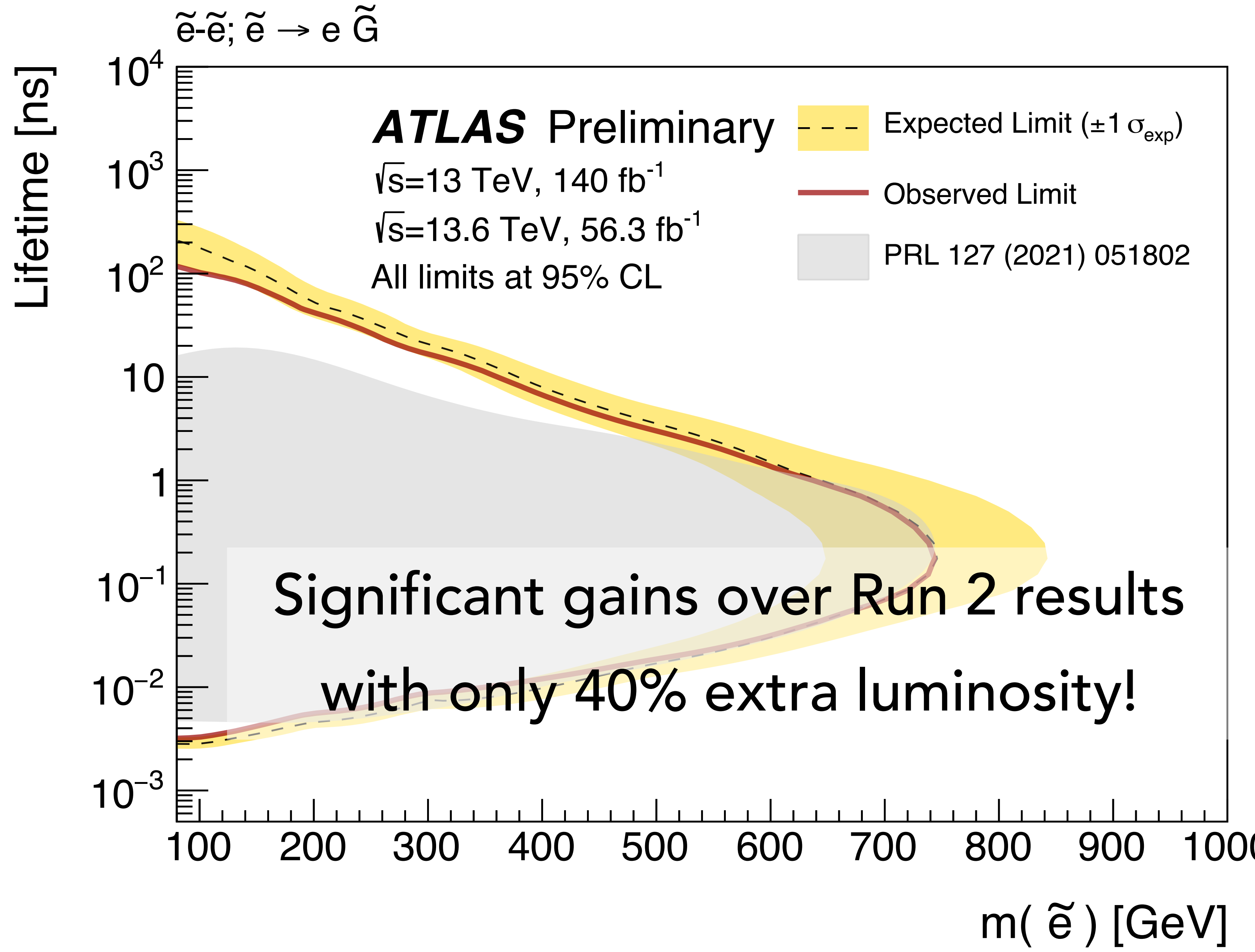

Photon signatures

Axion-like particles

HDBS-2019-19

Search for both prompt and long-lived $h \to aa \to \gamma\gamma\gamma\gamma$

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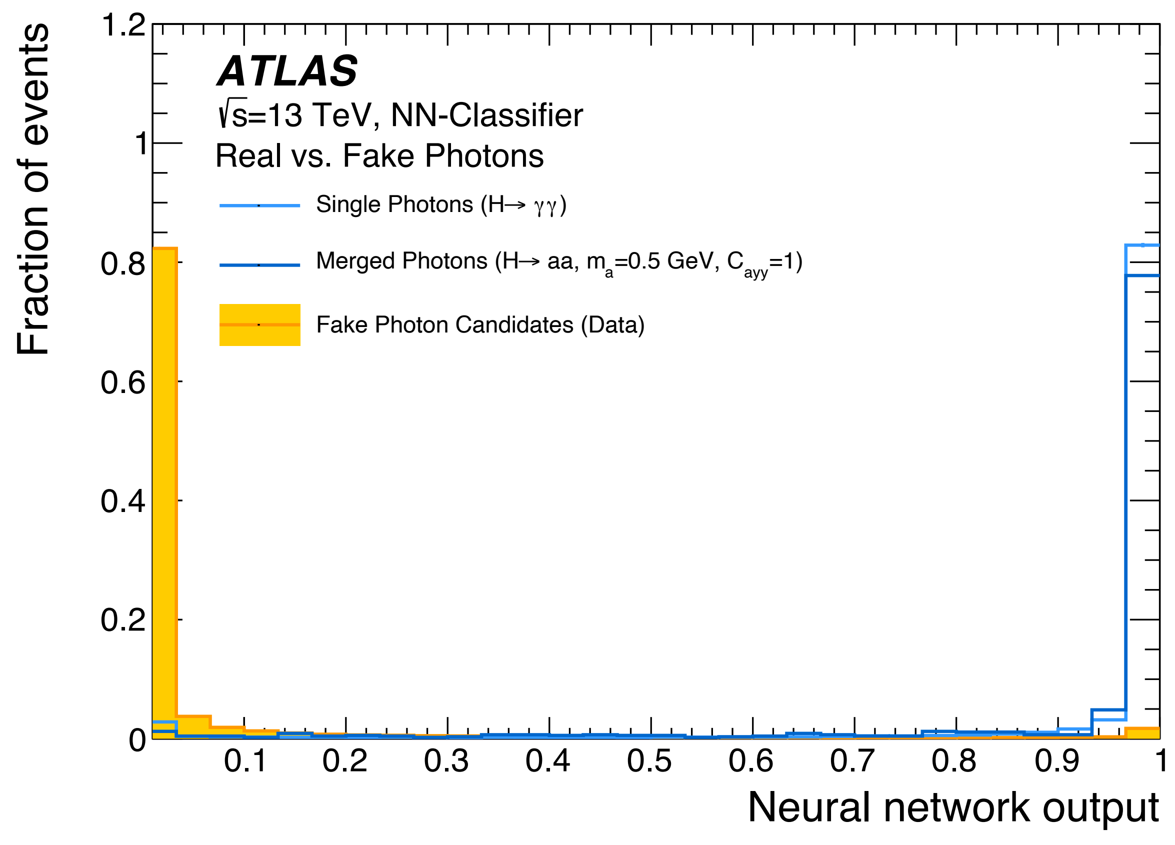

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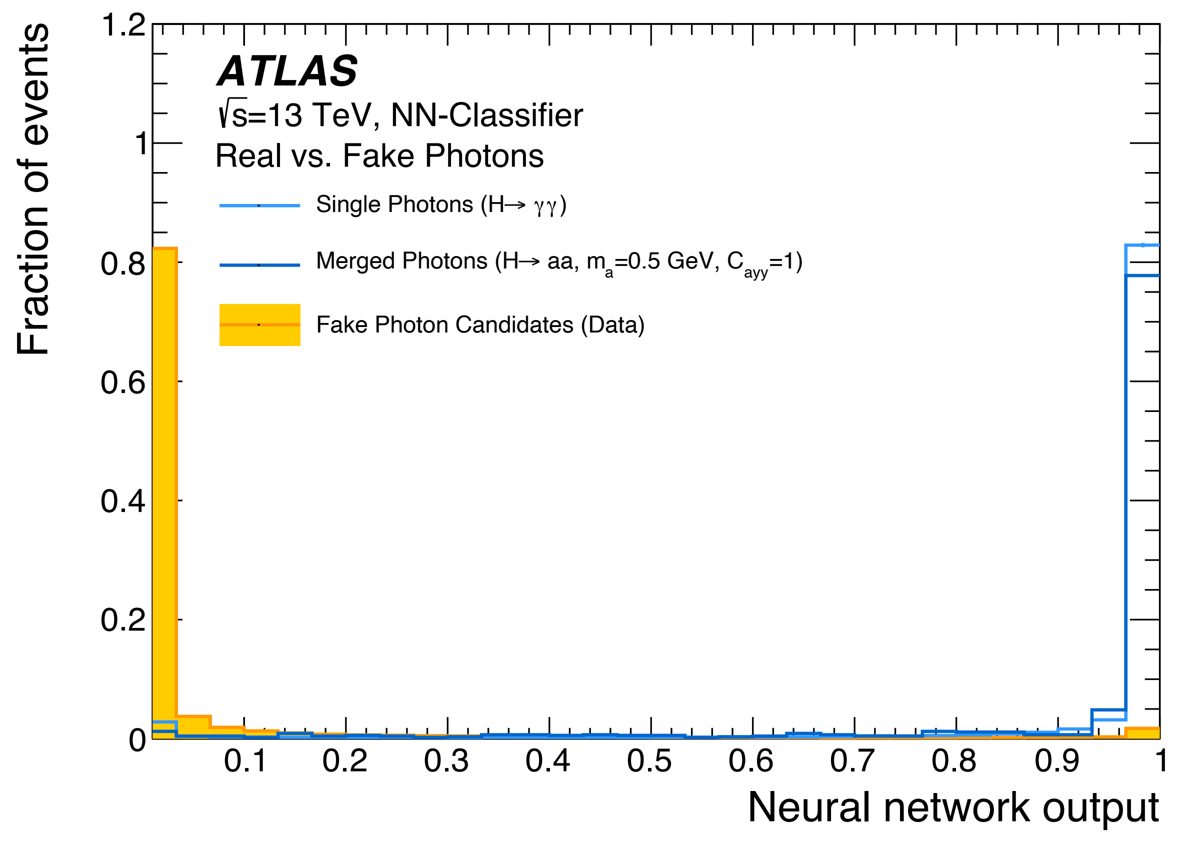

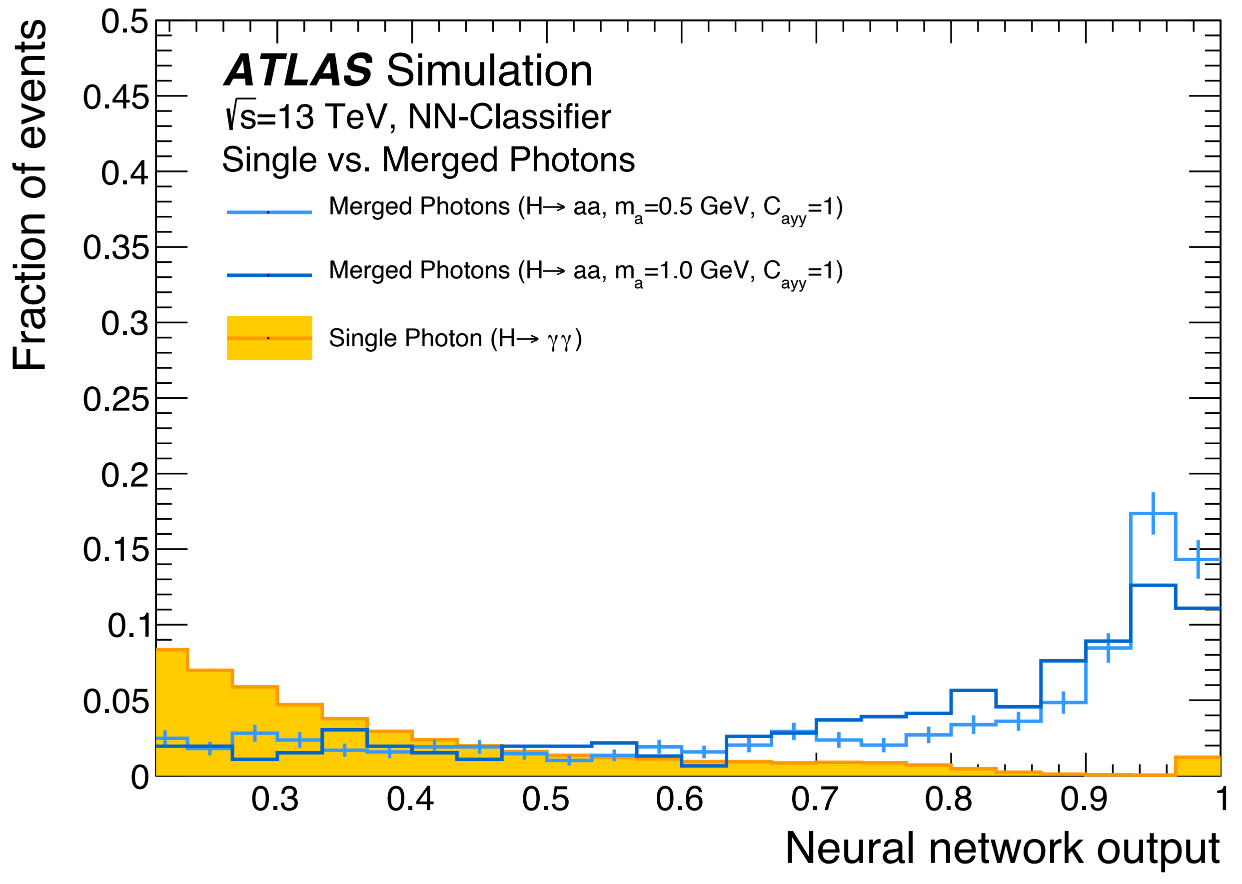

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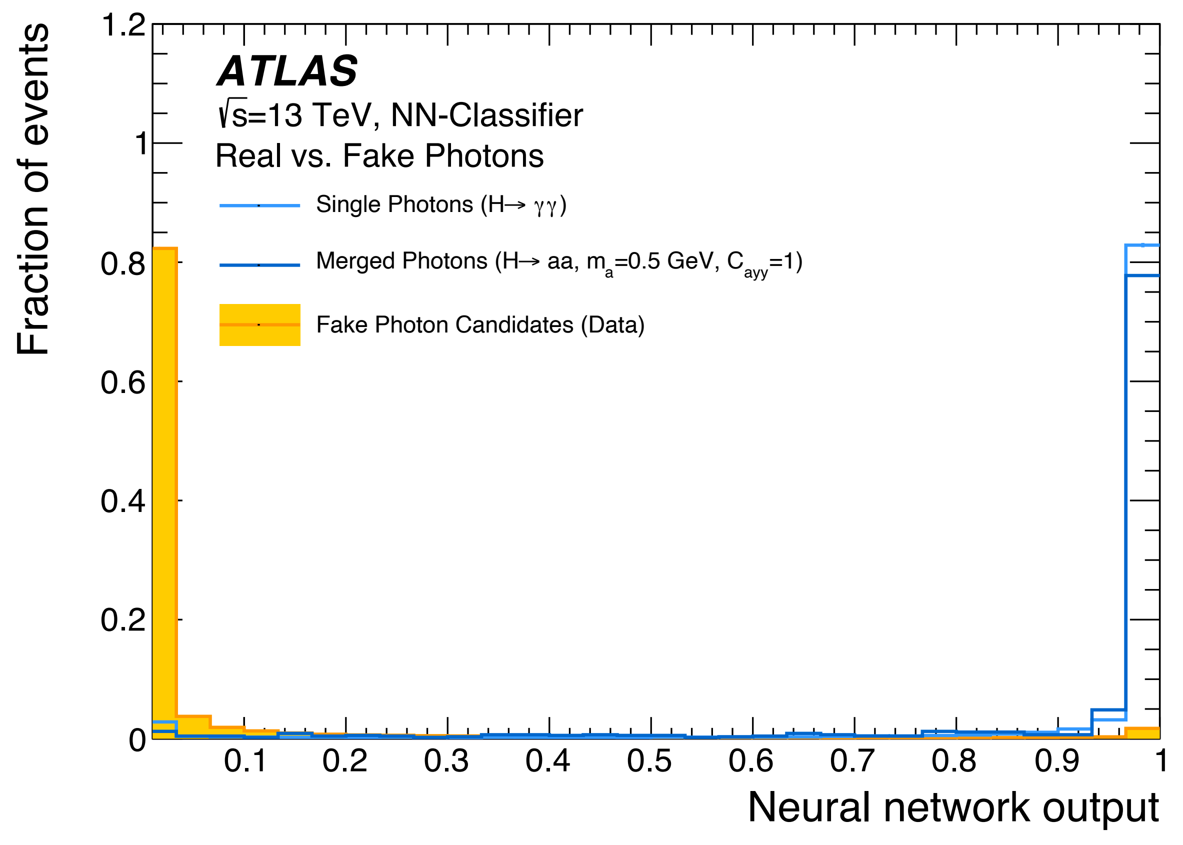

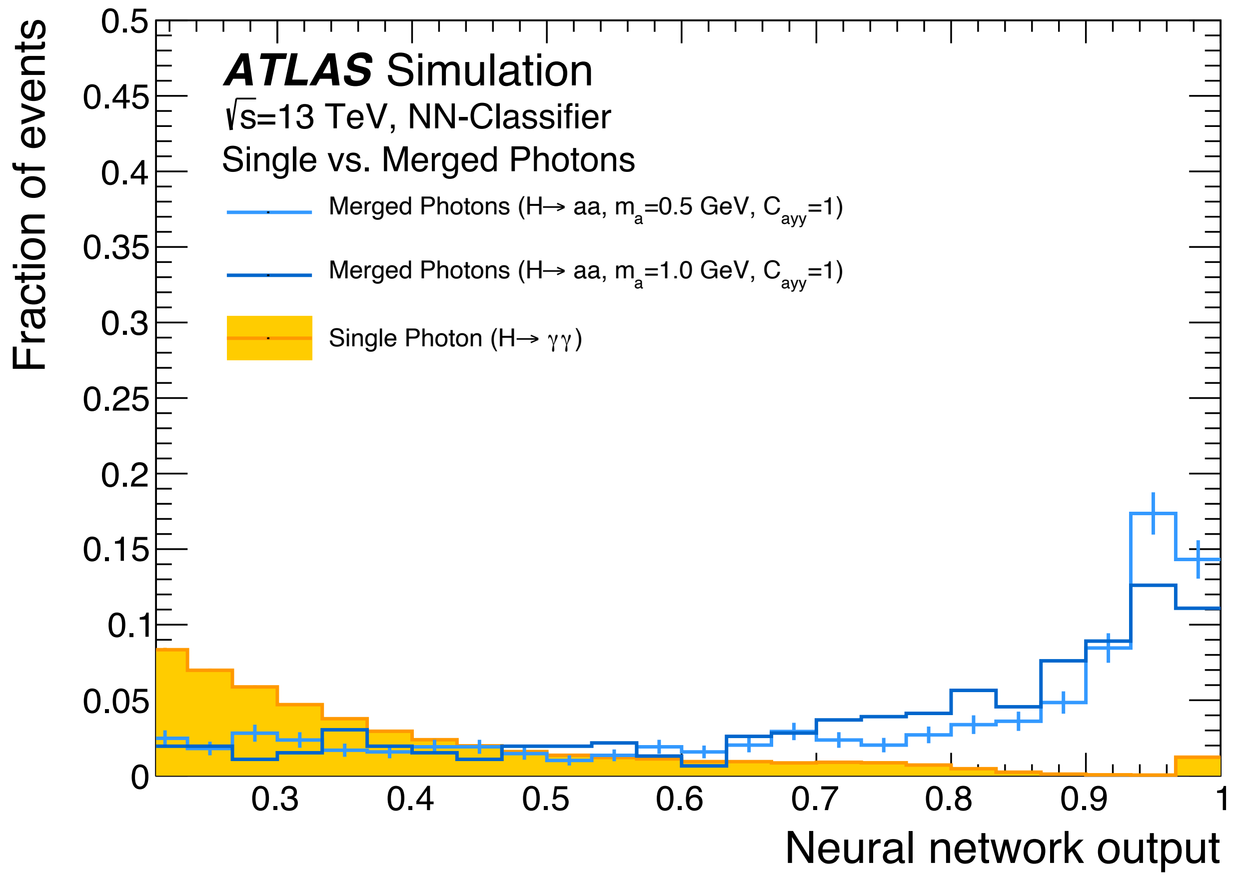

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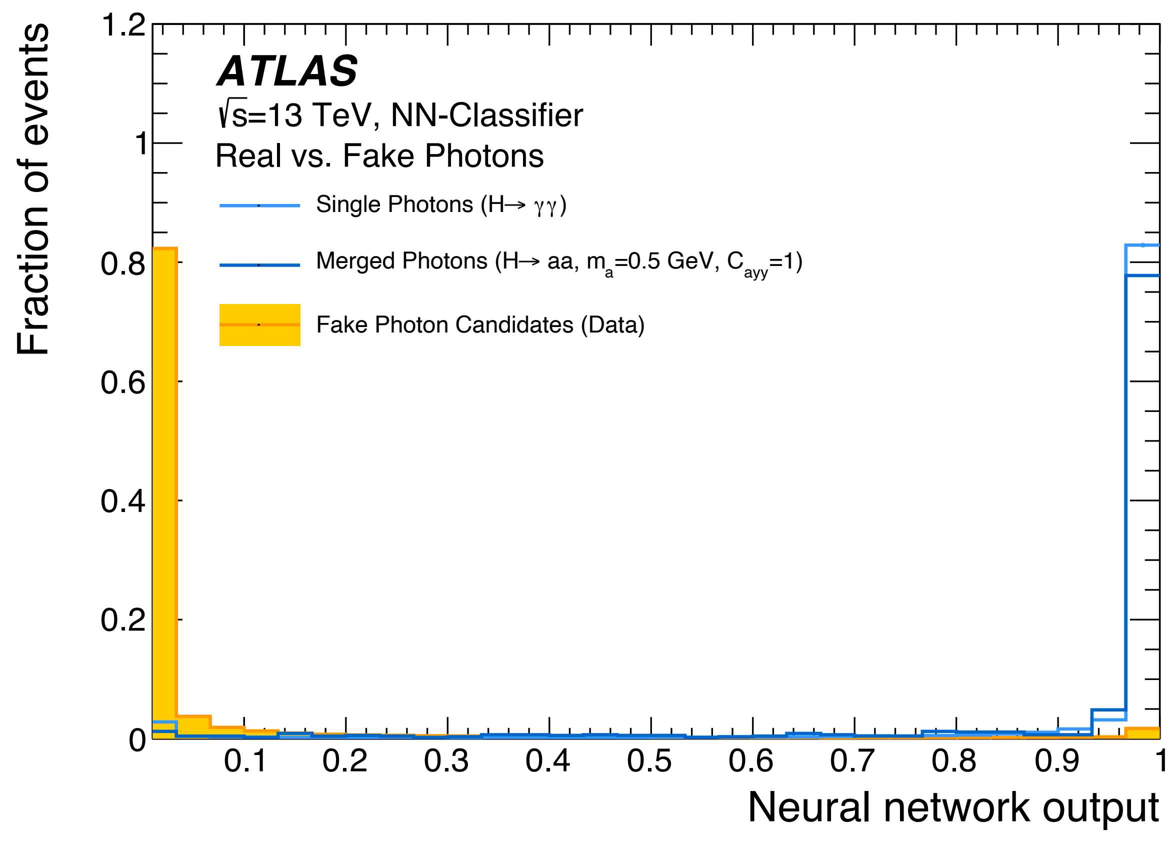

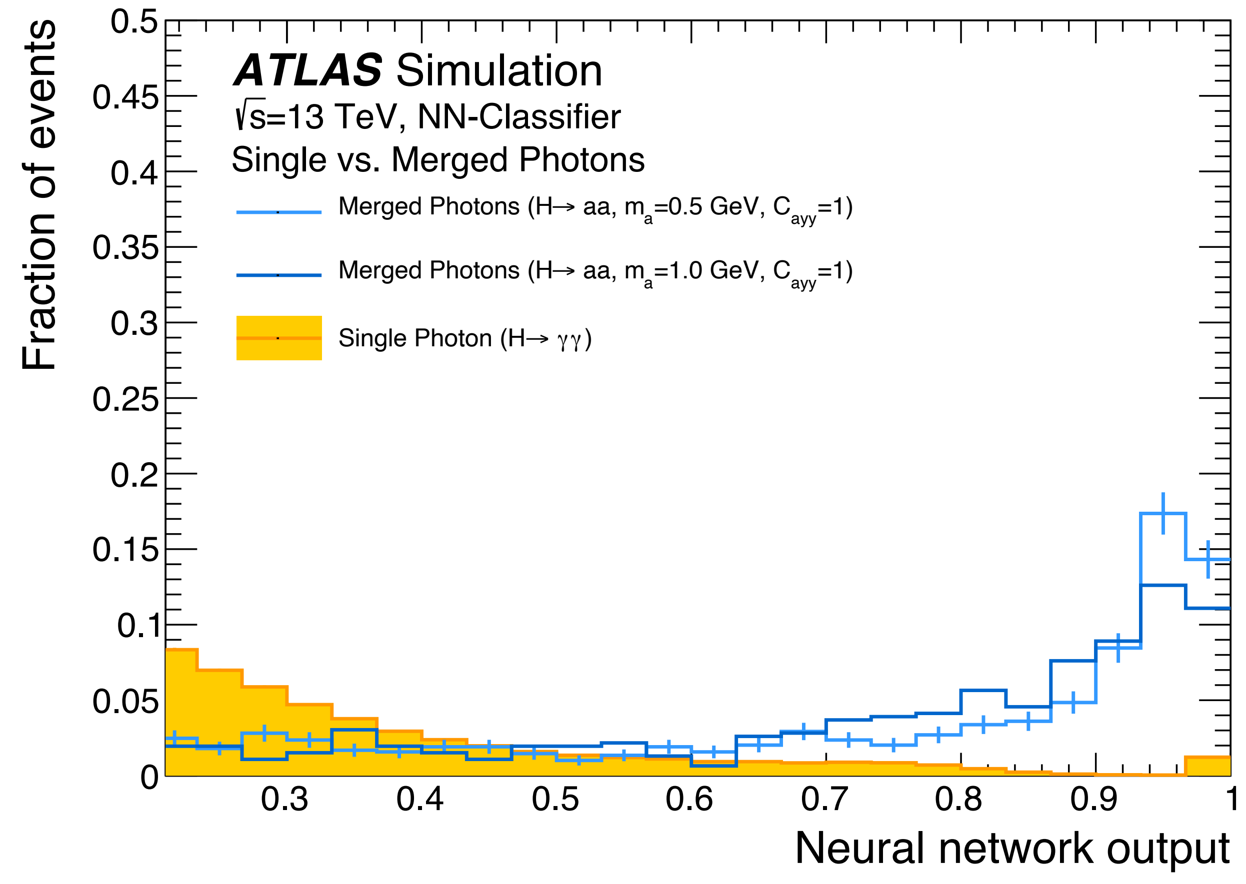

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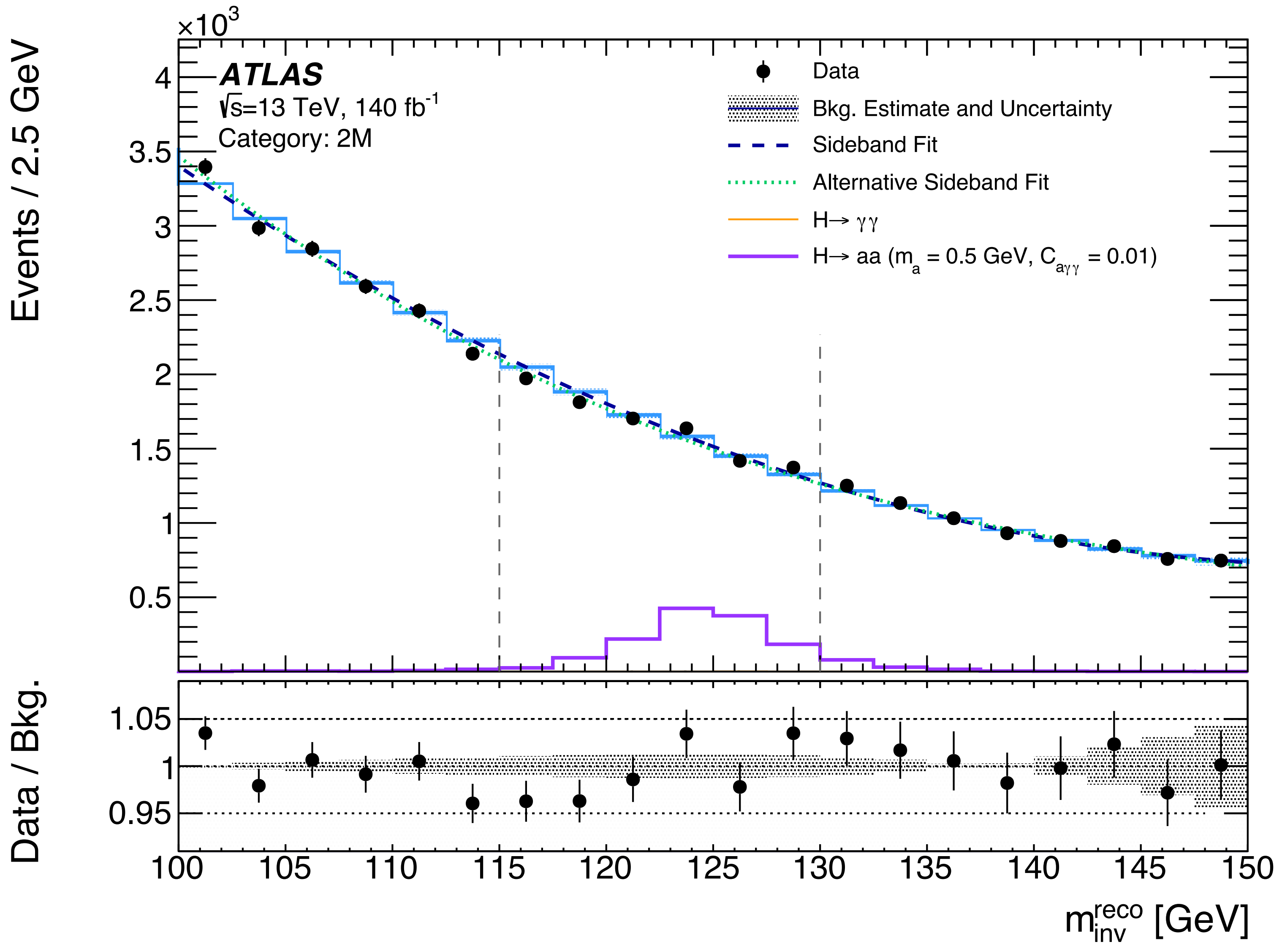

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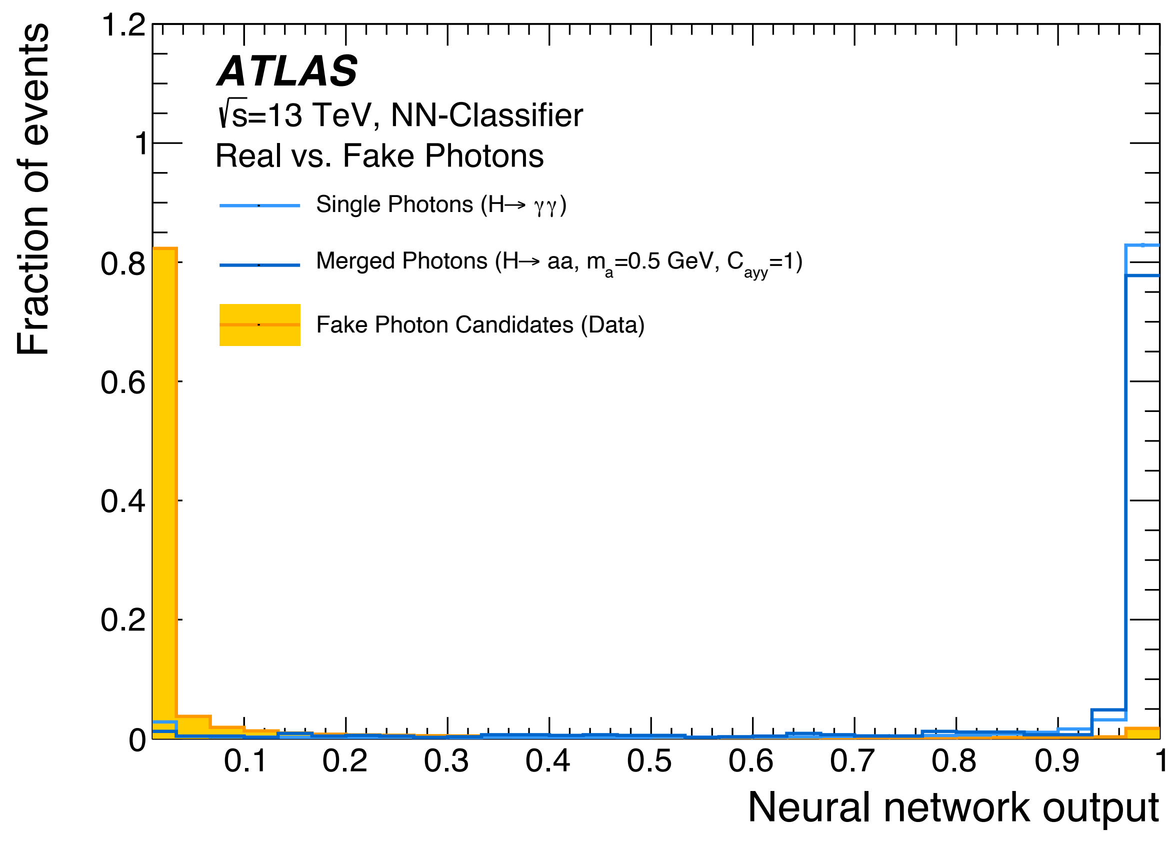

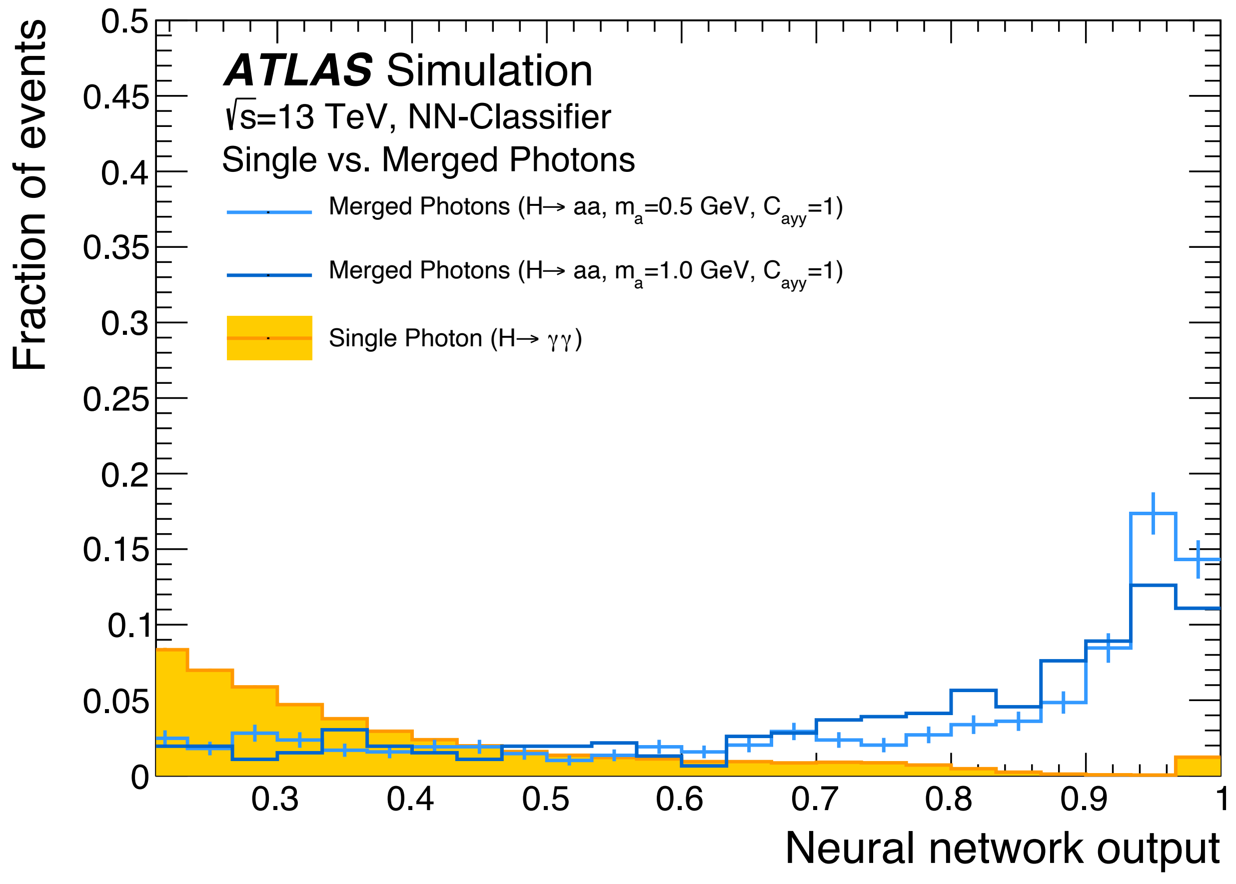

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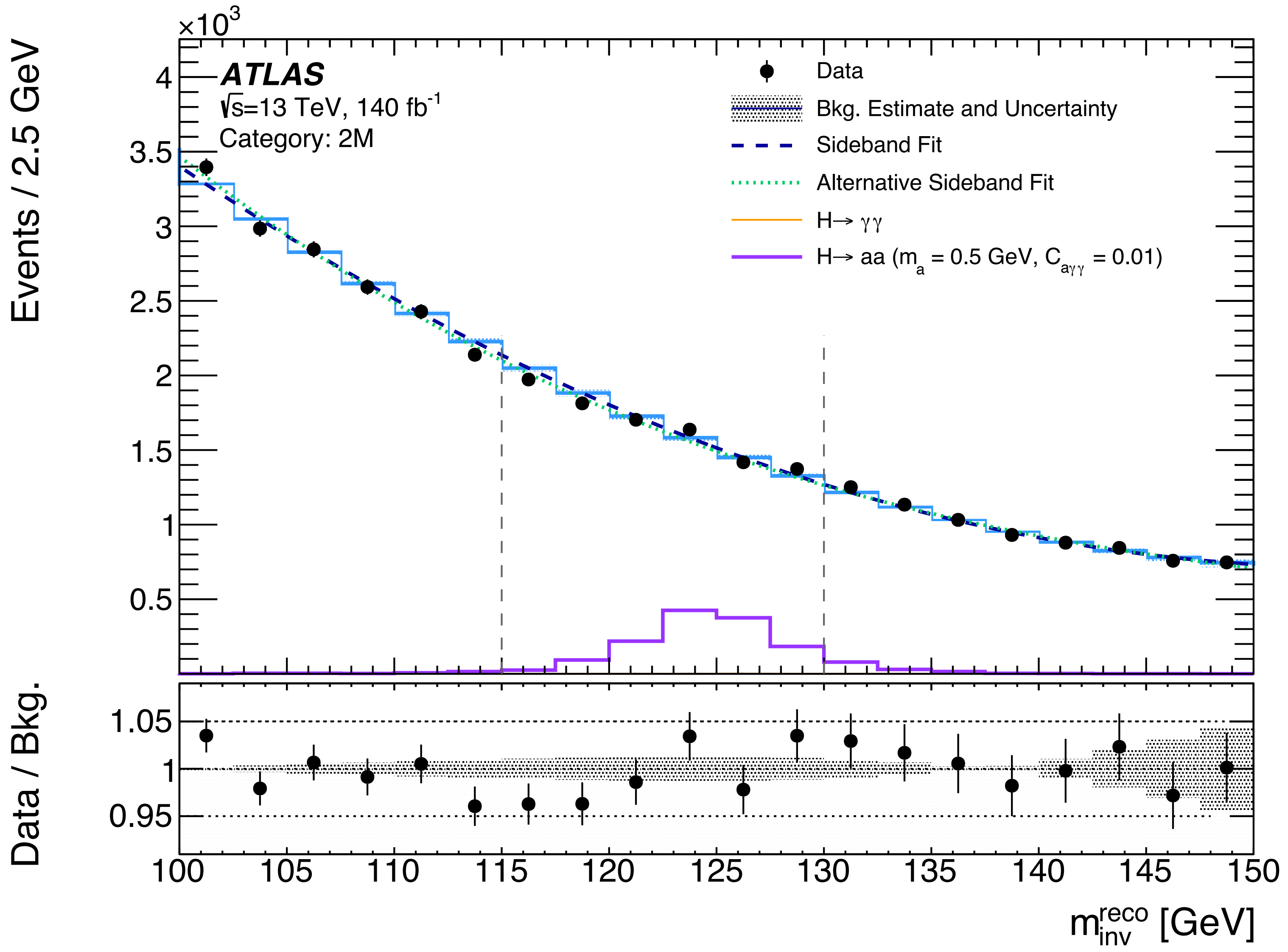
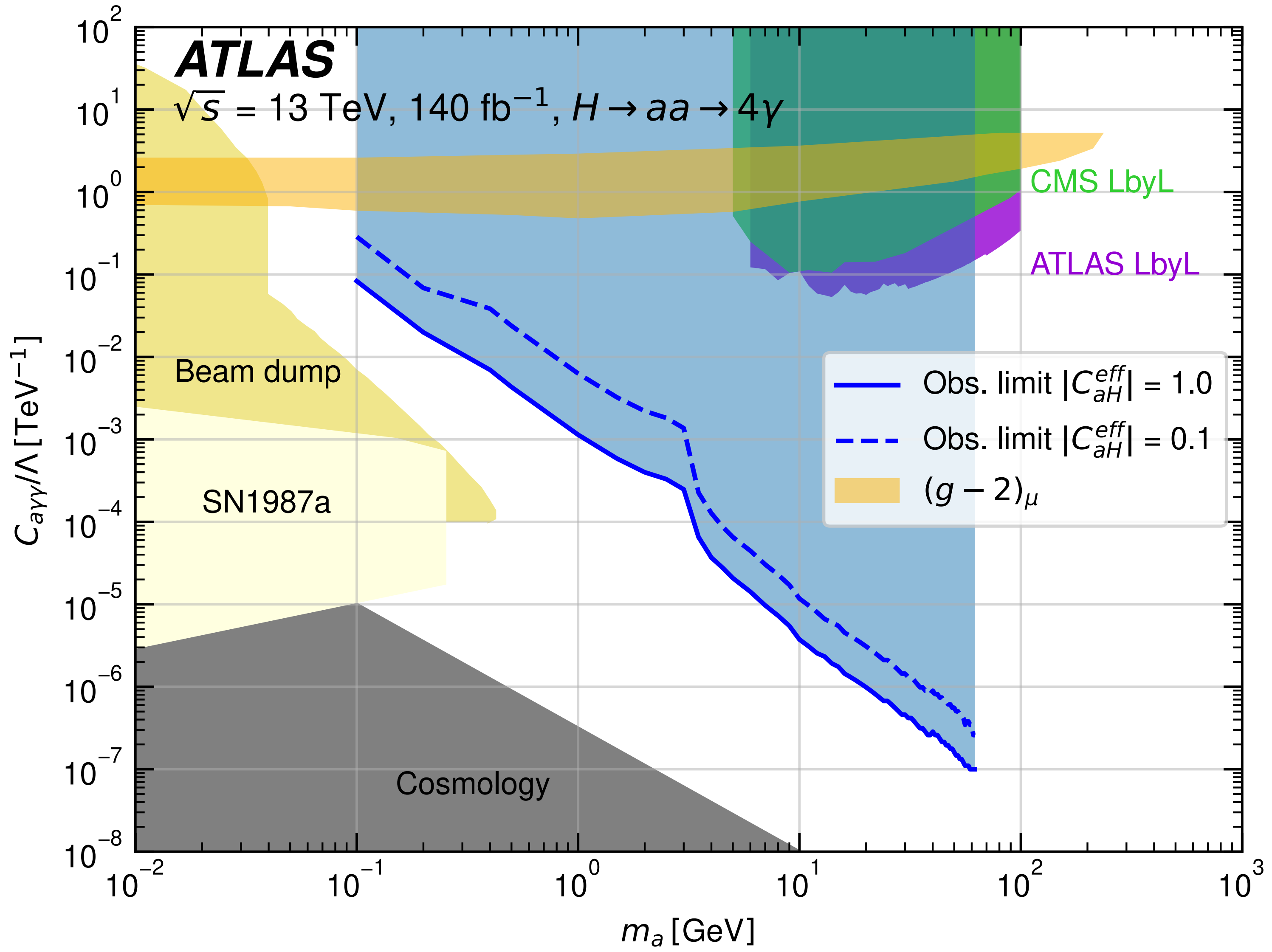


Sensitive to ALPs between 100 MeV and 60 GeV



Displaced photons

SUSY-2020-28 SUSY-2019-14

Displaced photon signatures are common in GMSB SUSY

- Search for **di-photon vertices** and **non-pointing photons** using timing and calorimeter pointing information

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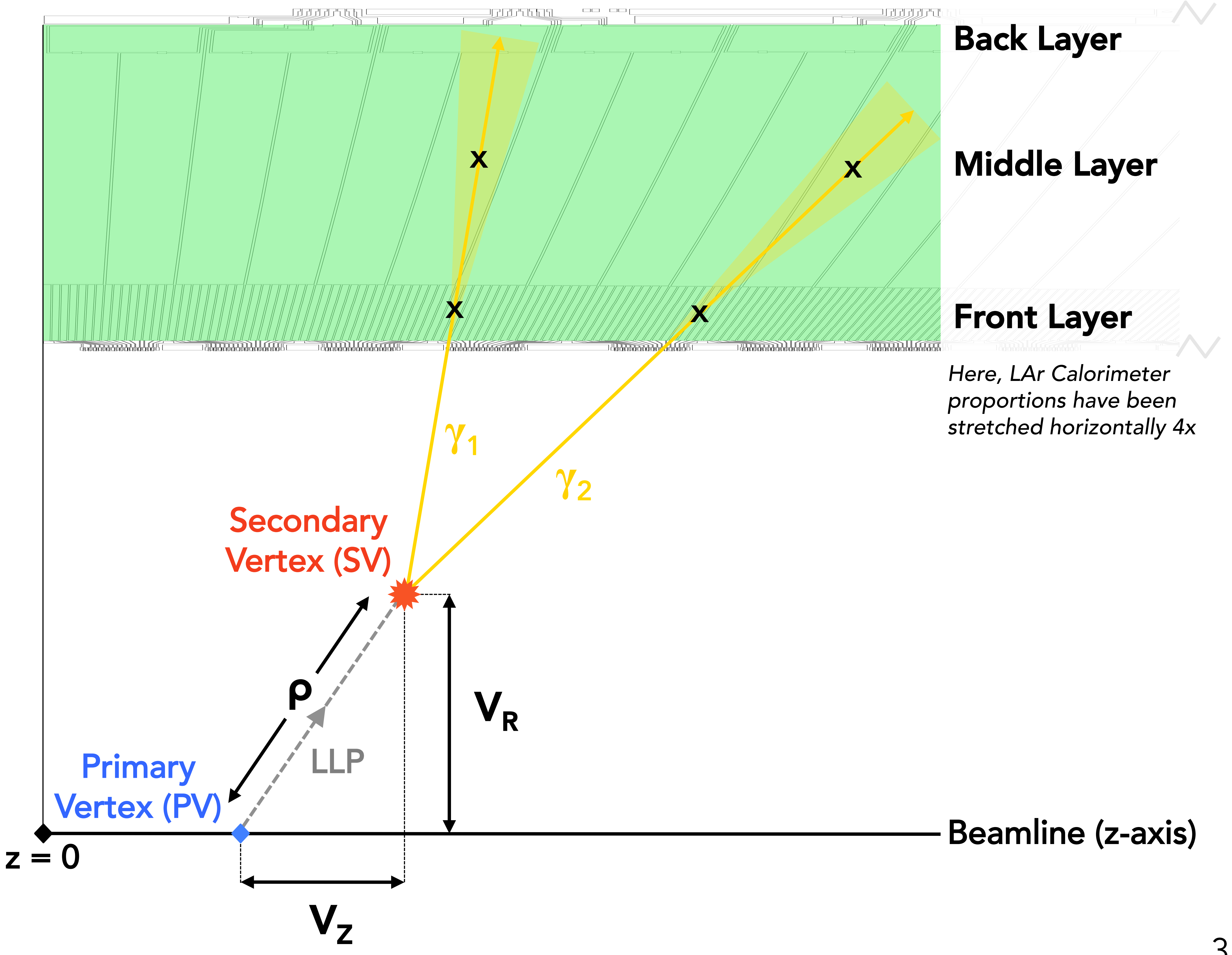

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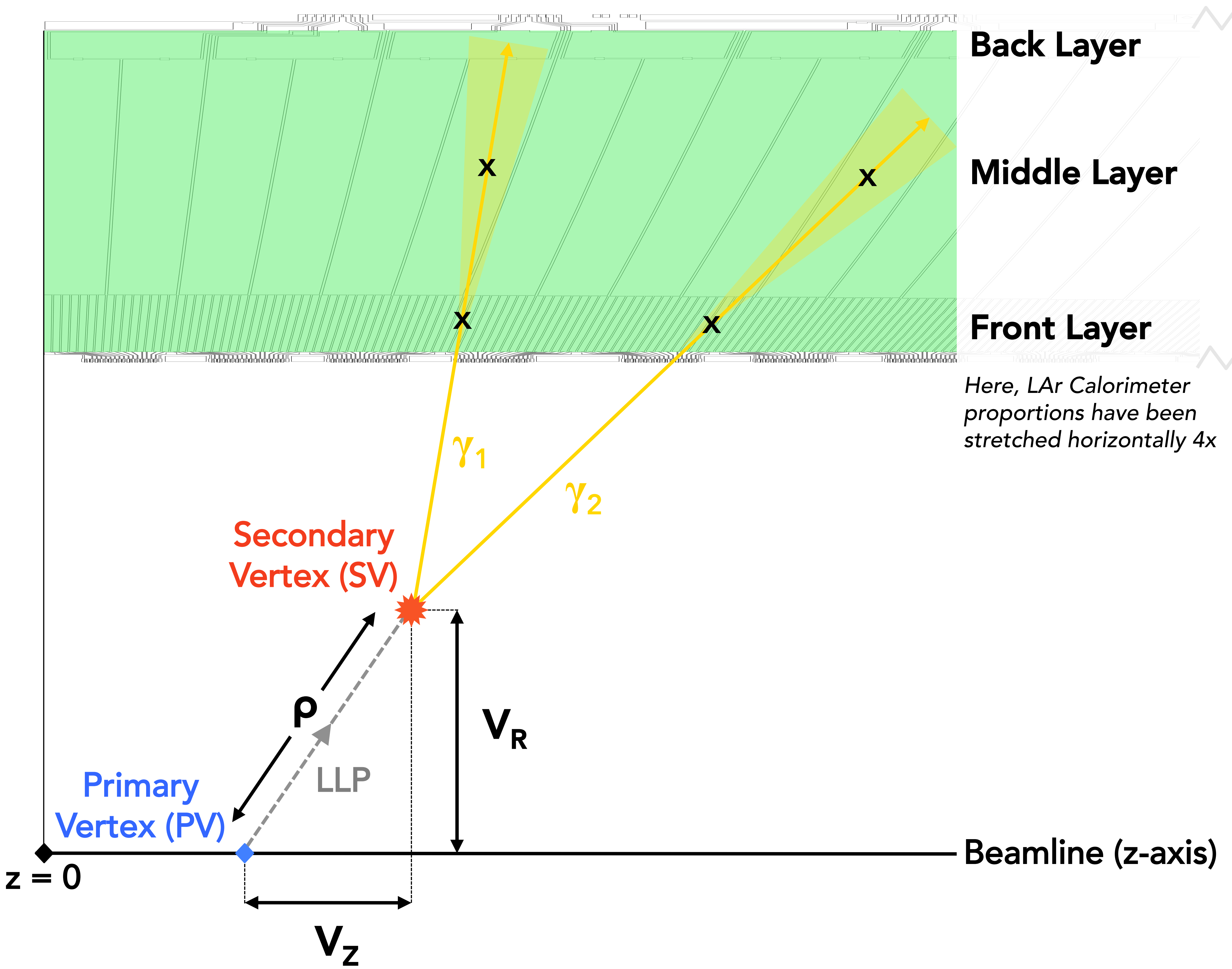
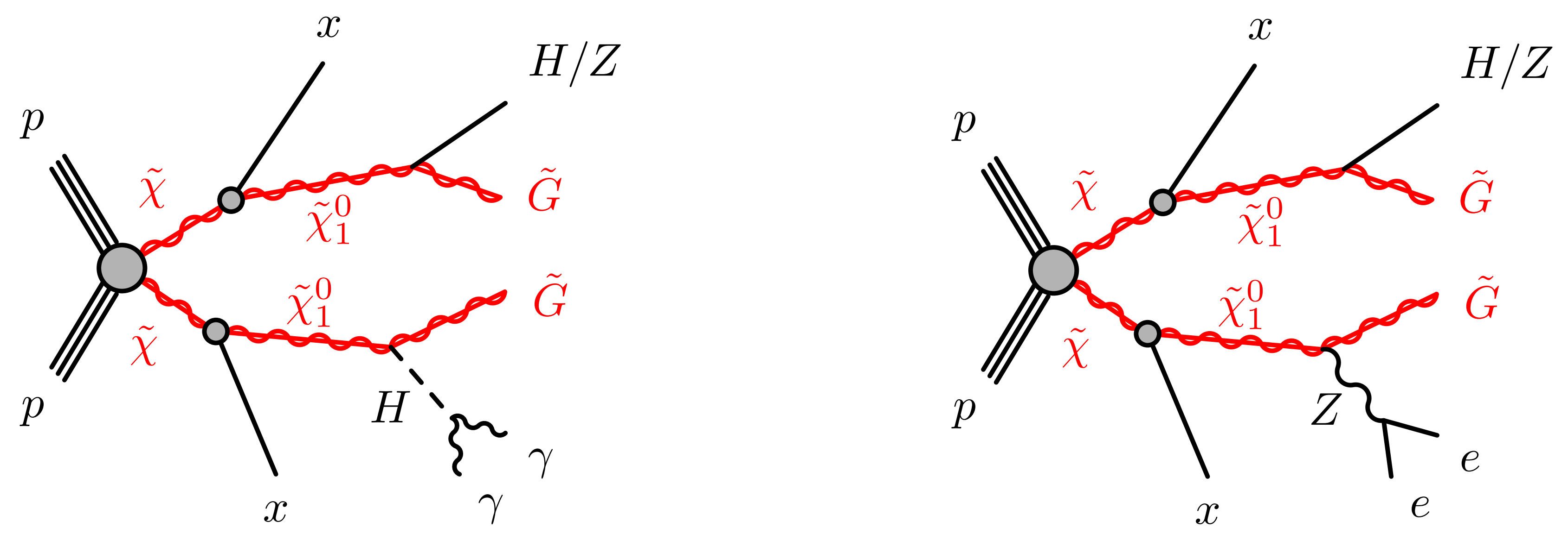
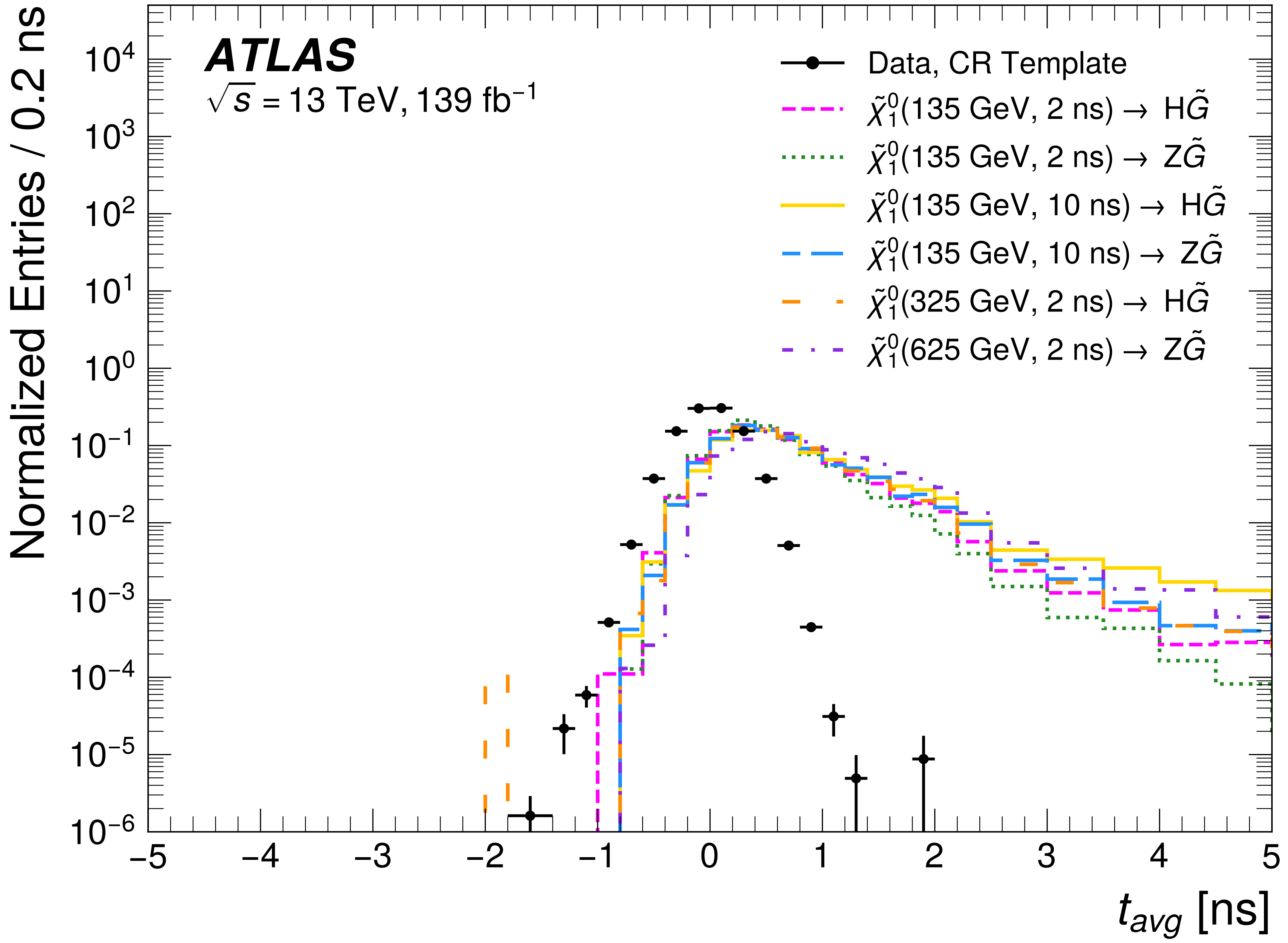




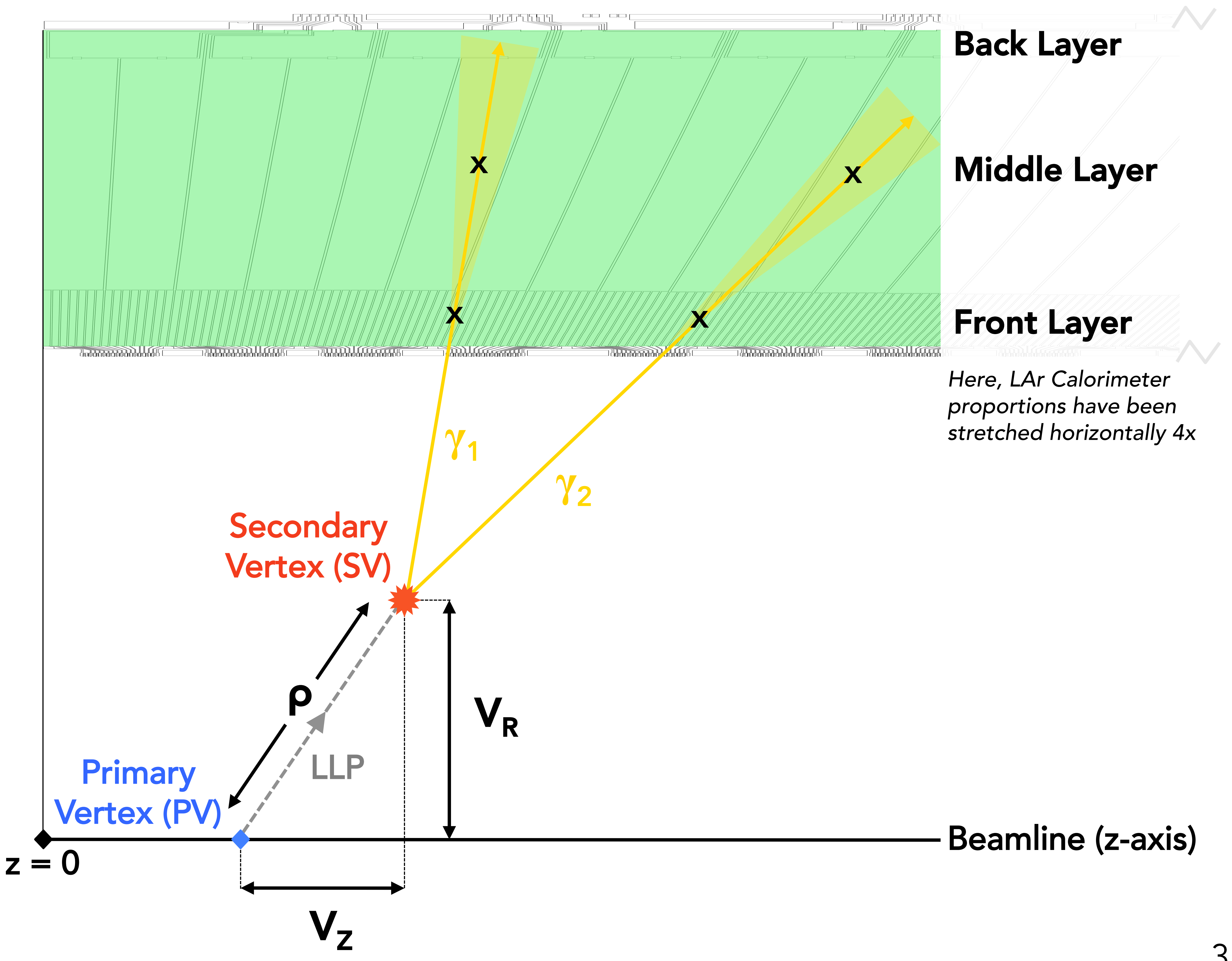


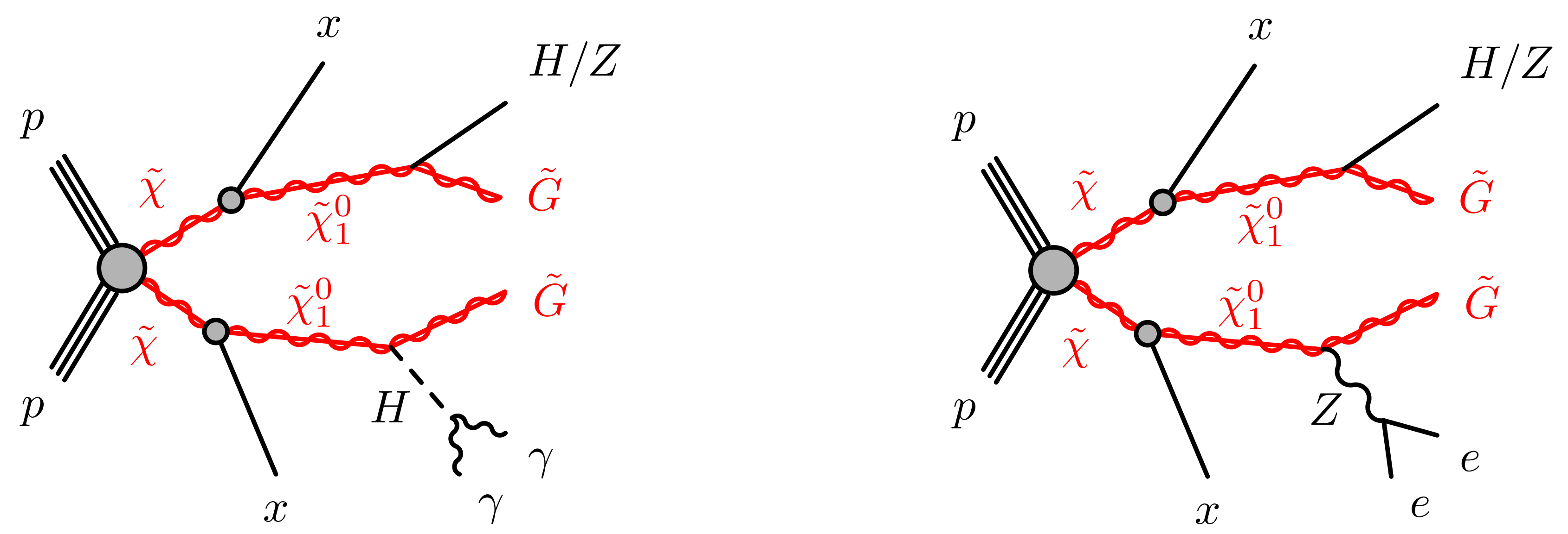
Displaced photons

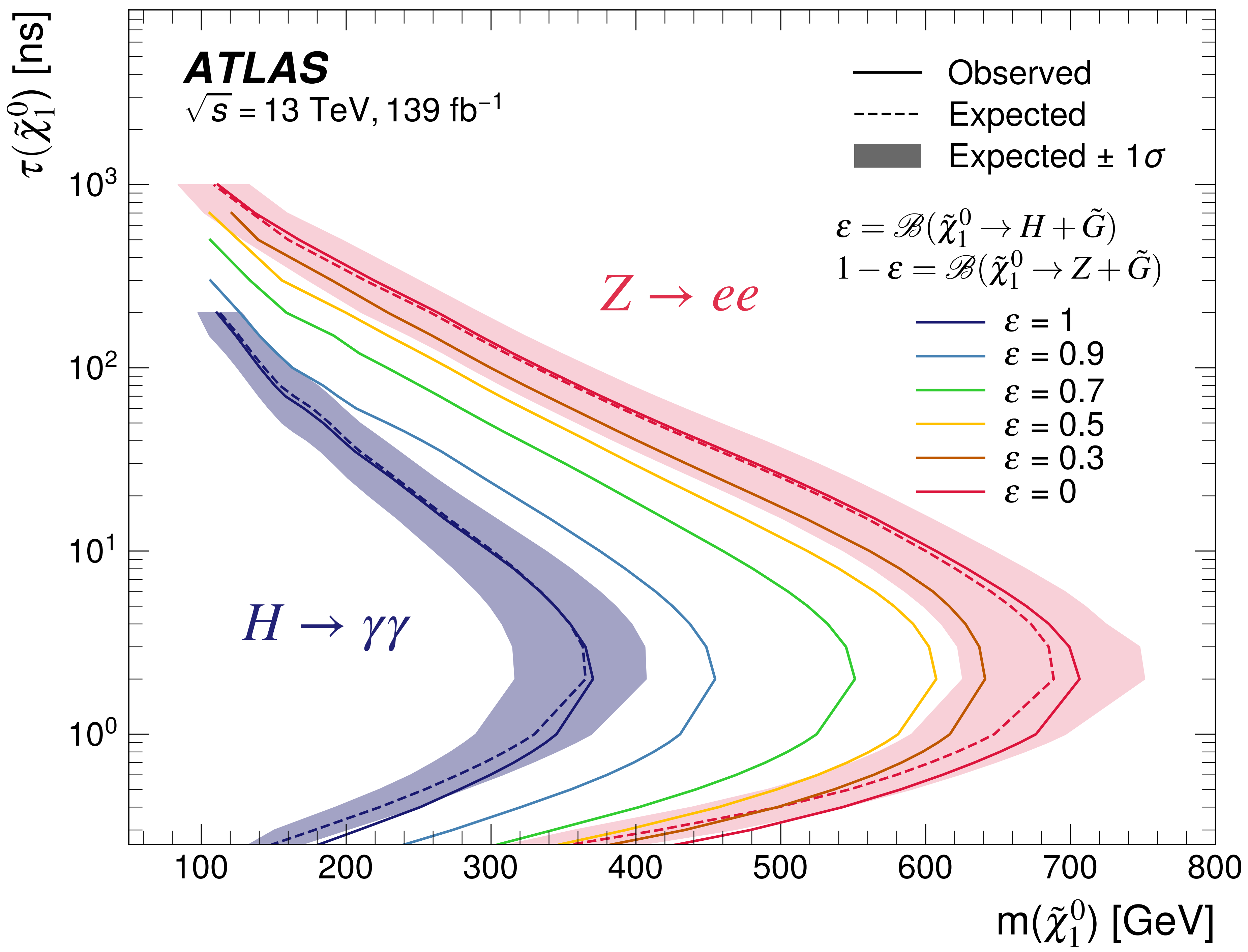
SUSY-2020-28 SUSY-2019-14

Displaced photon signatures are common in GMSB SUSY

- Search for **di-photon vertices** and **non-pointing photons** using timing and calorimeter pointing information







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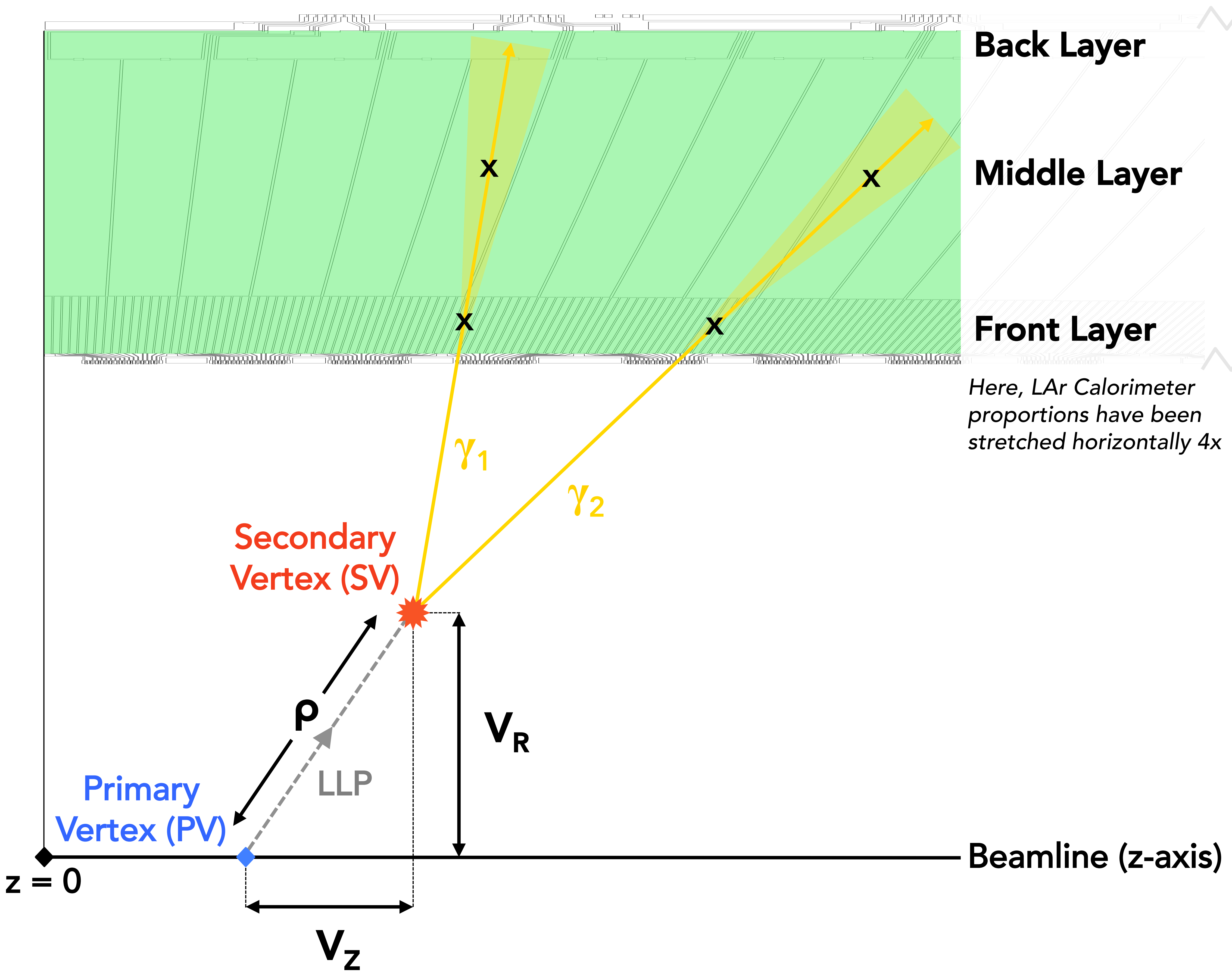

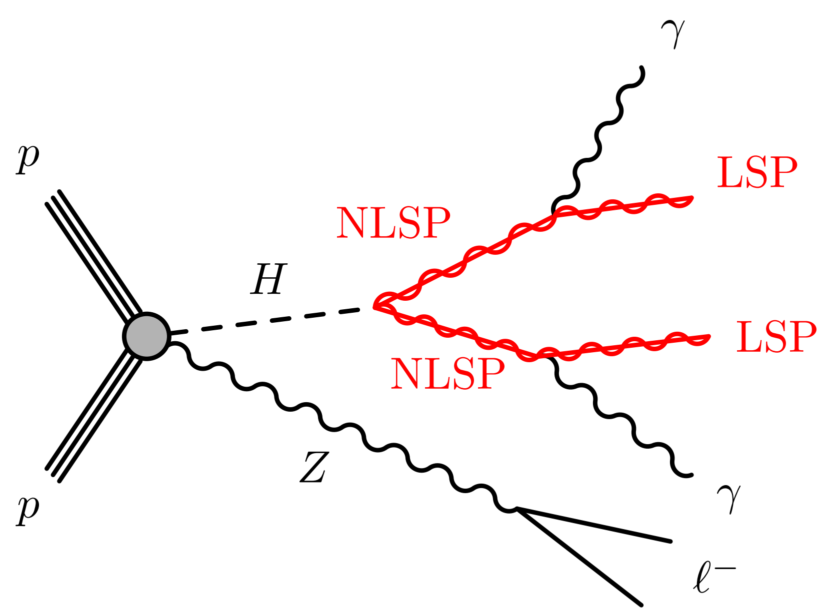

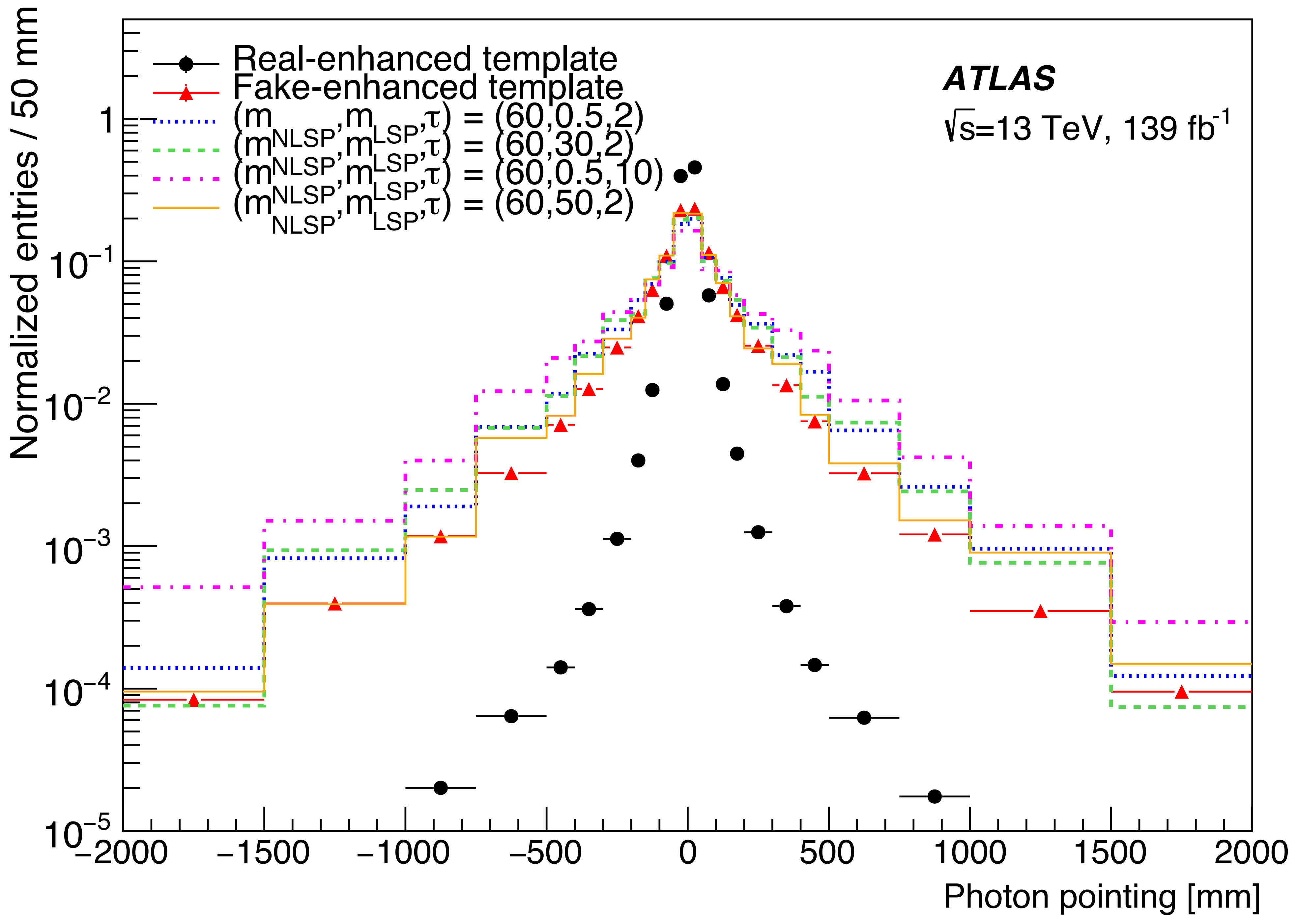

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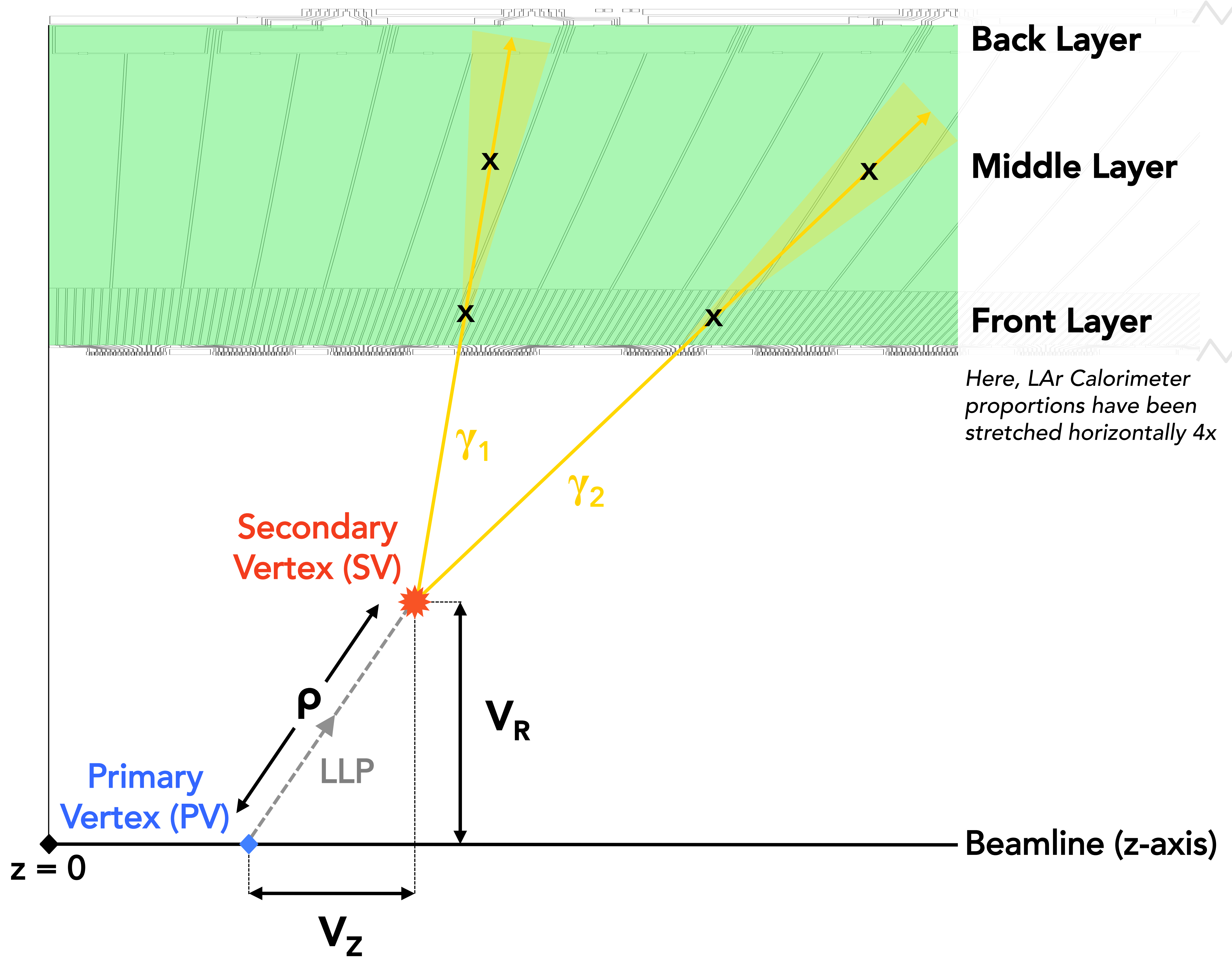

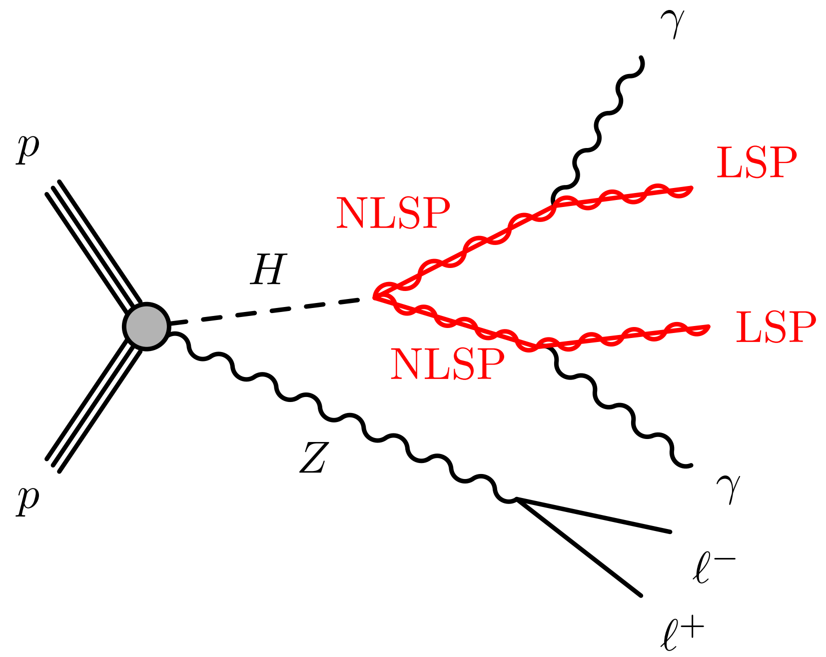

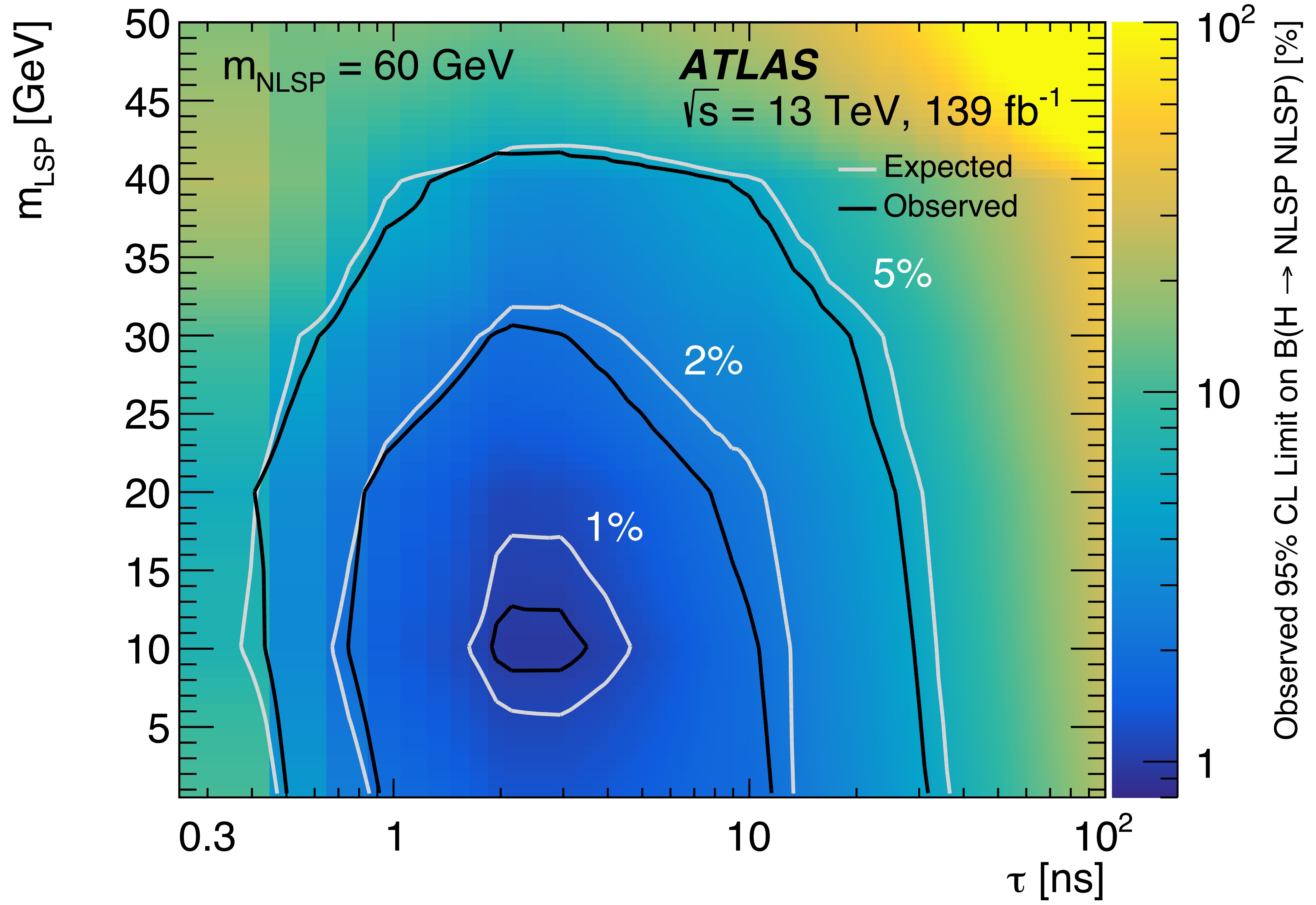

Future prospects for LLPs

Run 3 prospects

TRIG-2022-01

Many new LLP triggers added for Run 3 that open up new search channels

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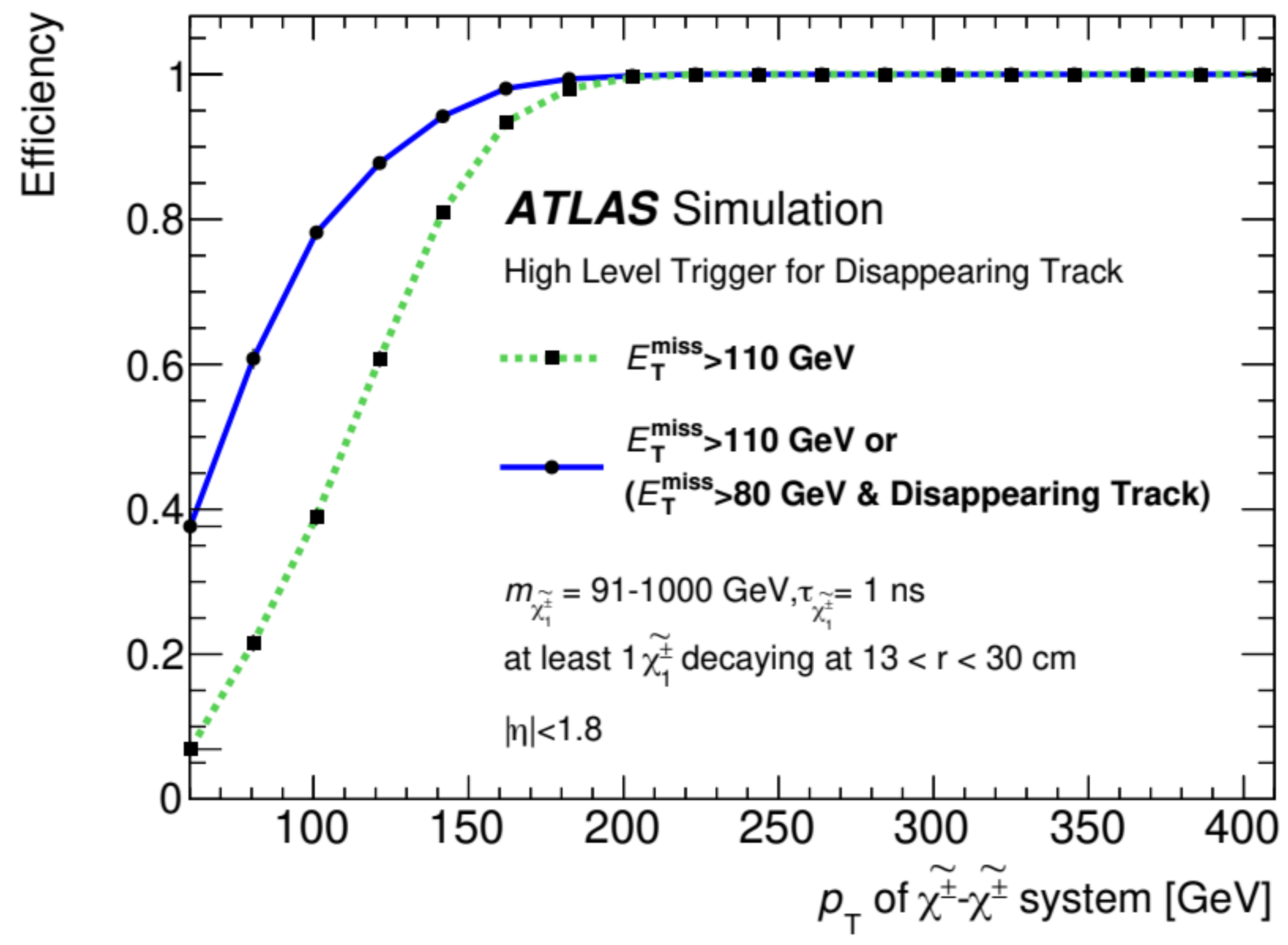

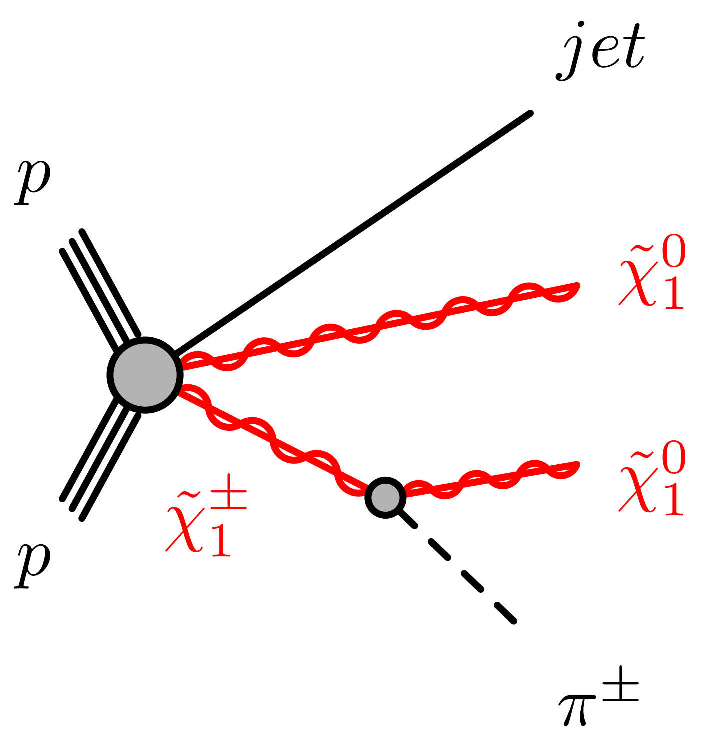

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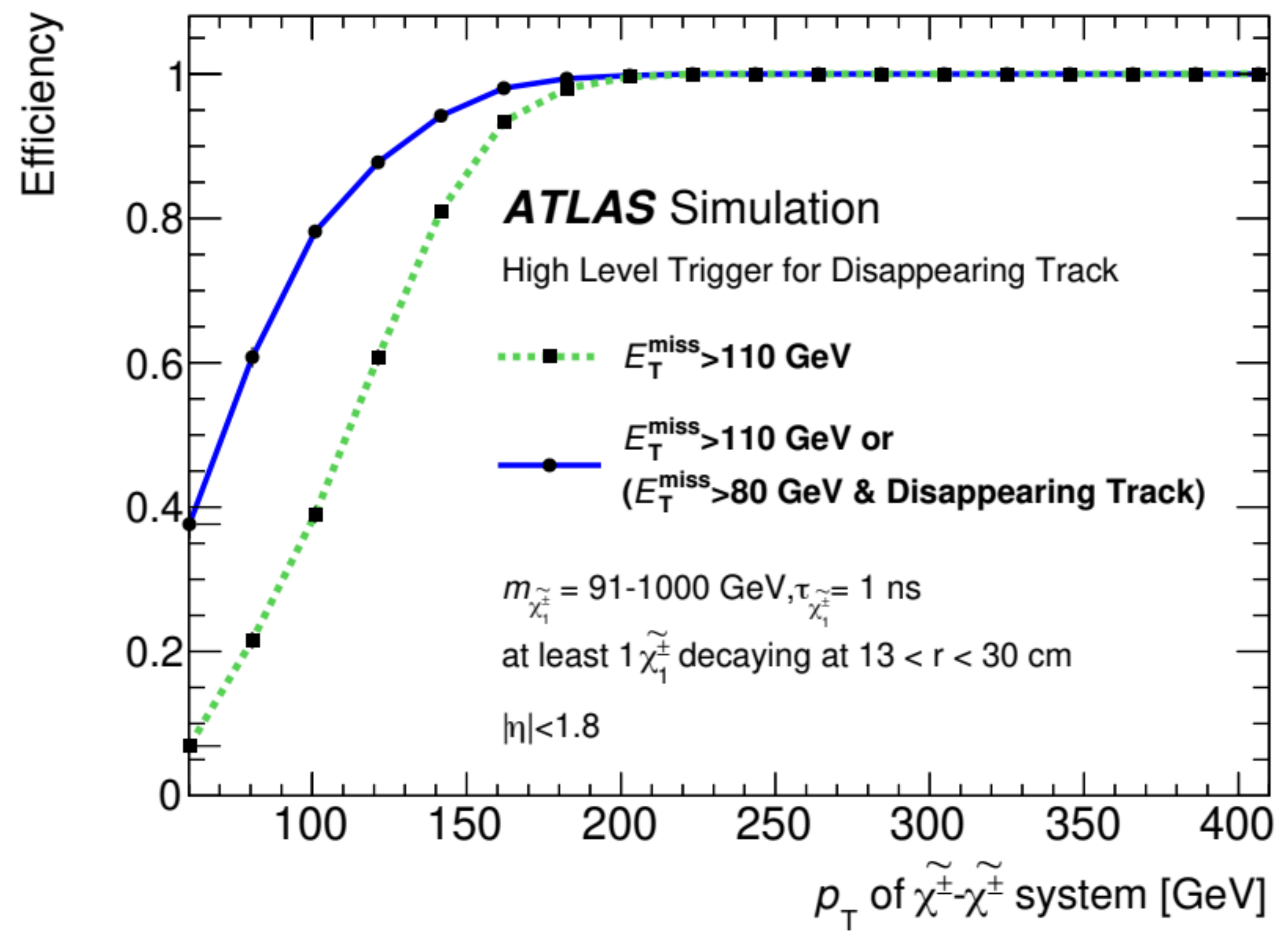
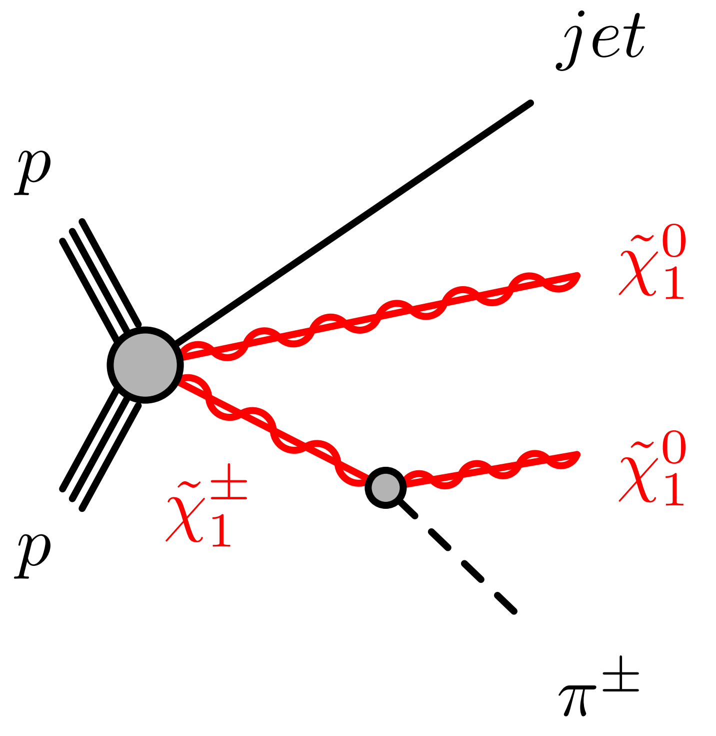
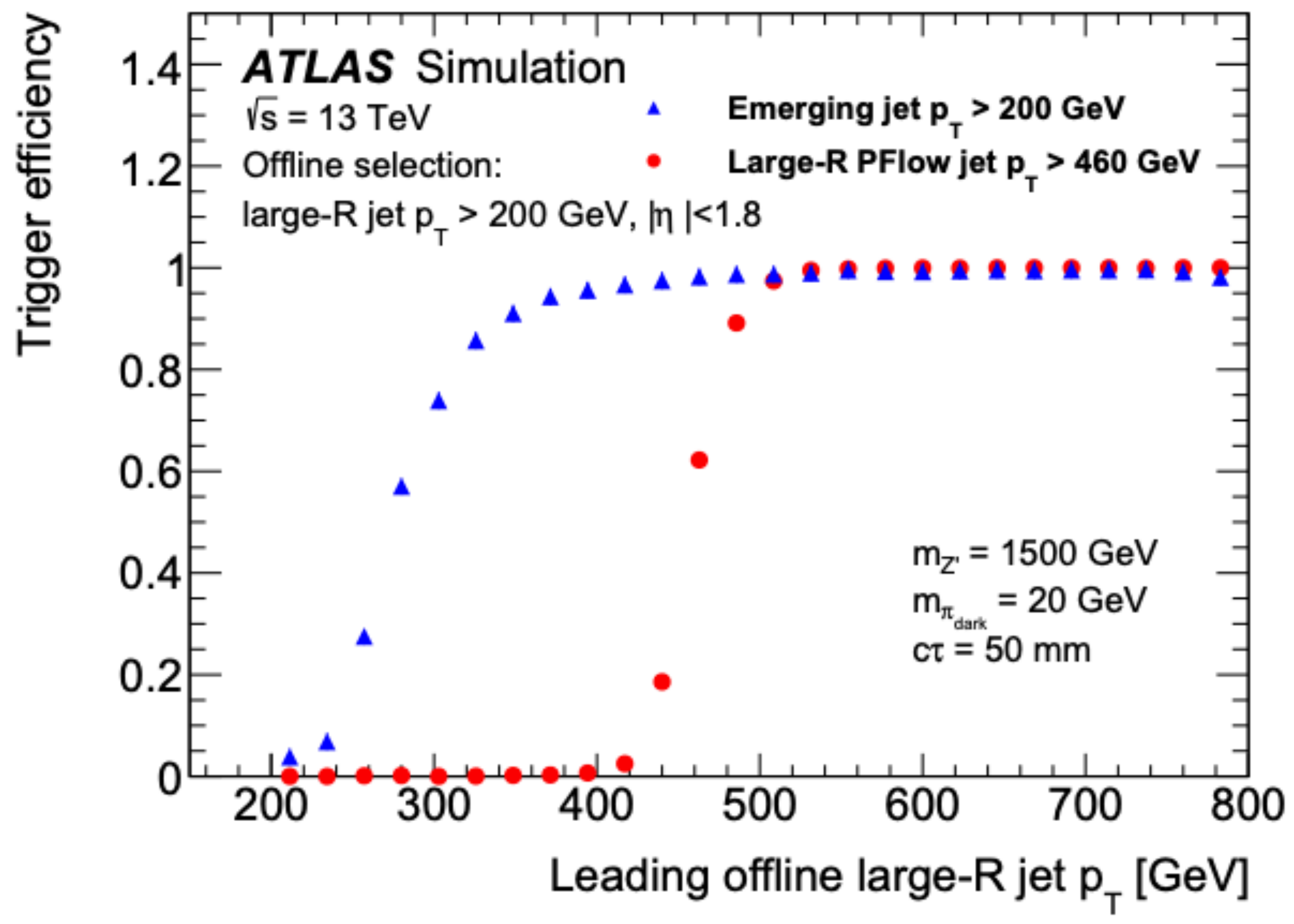
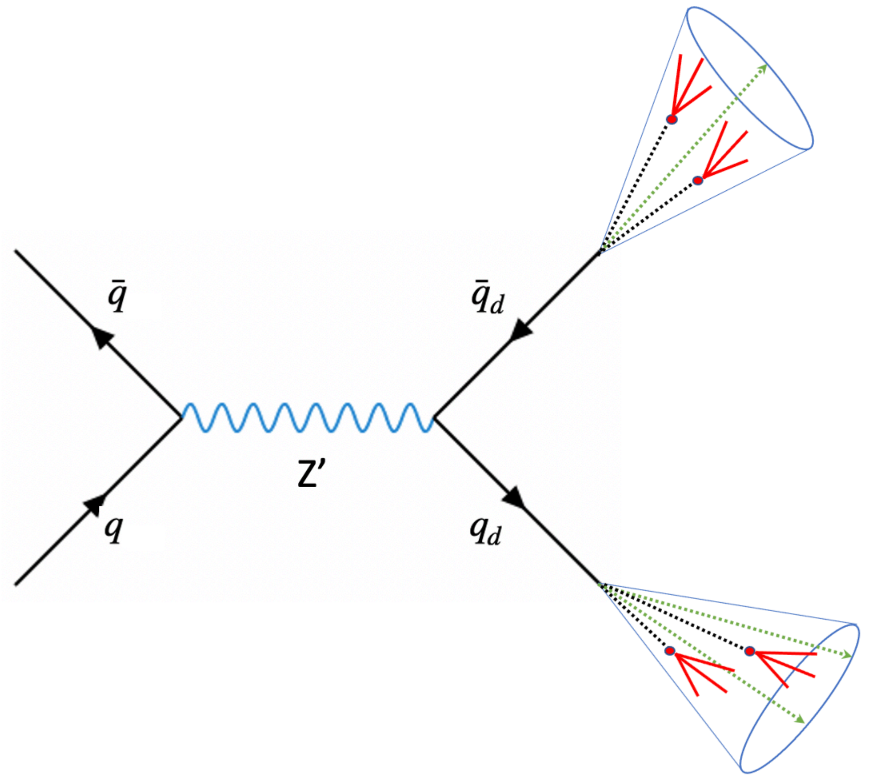




emerging jets





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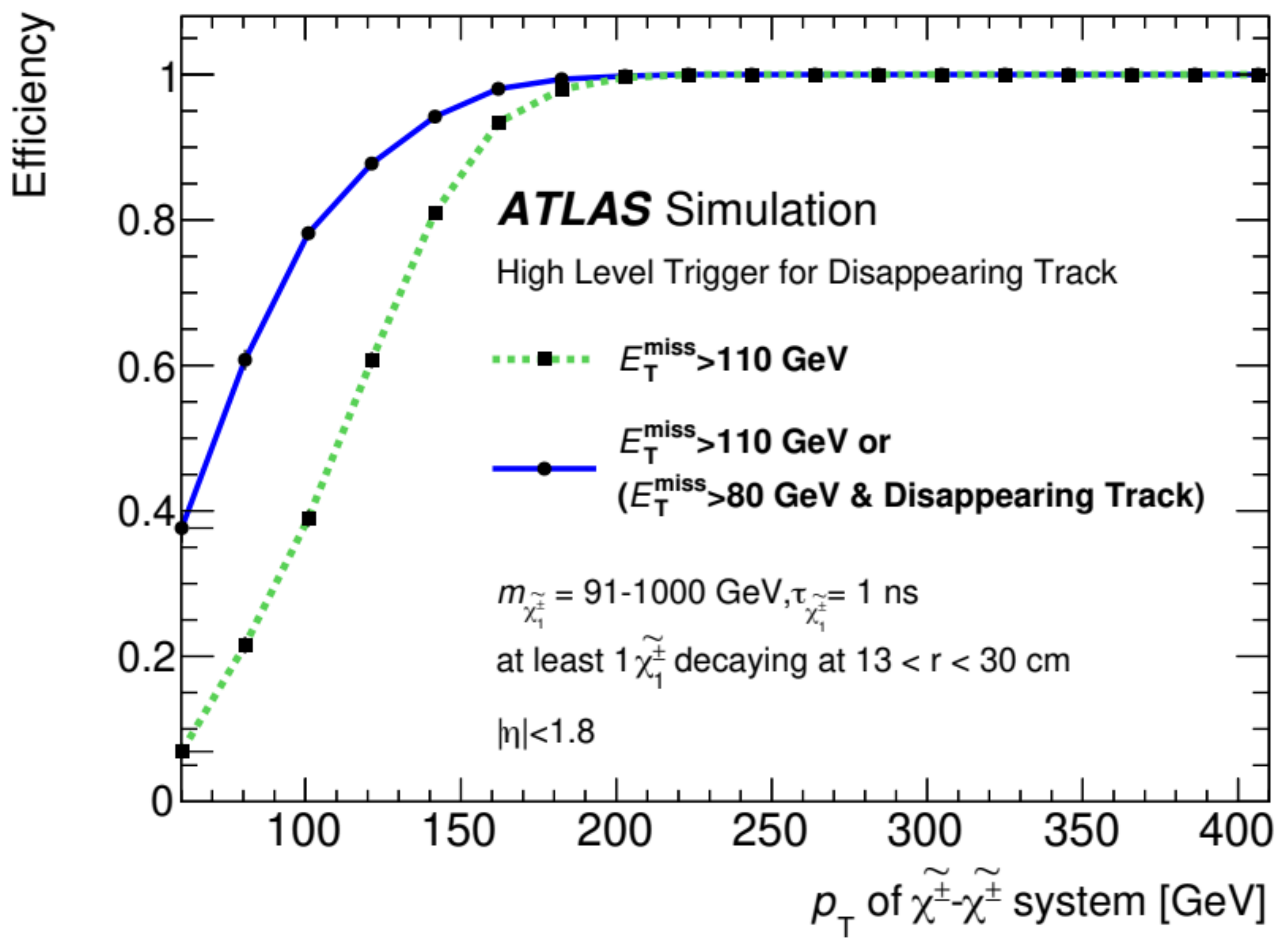

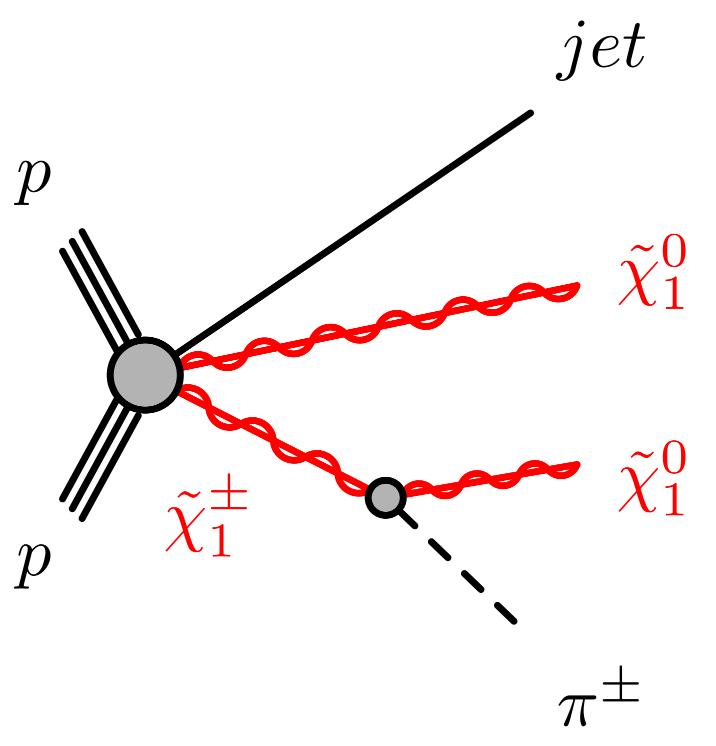

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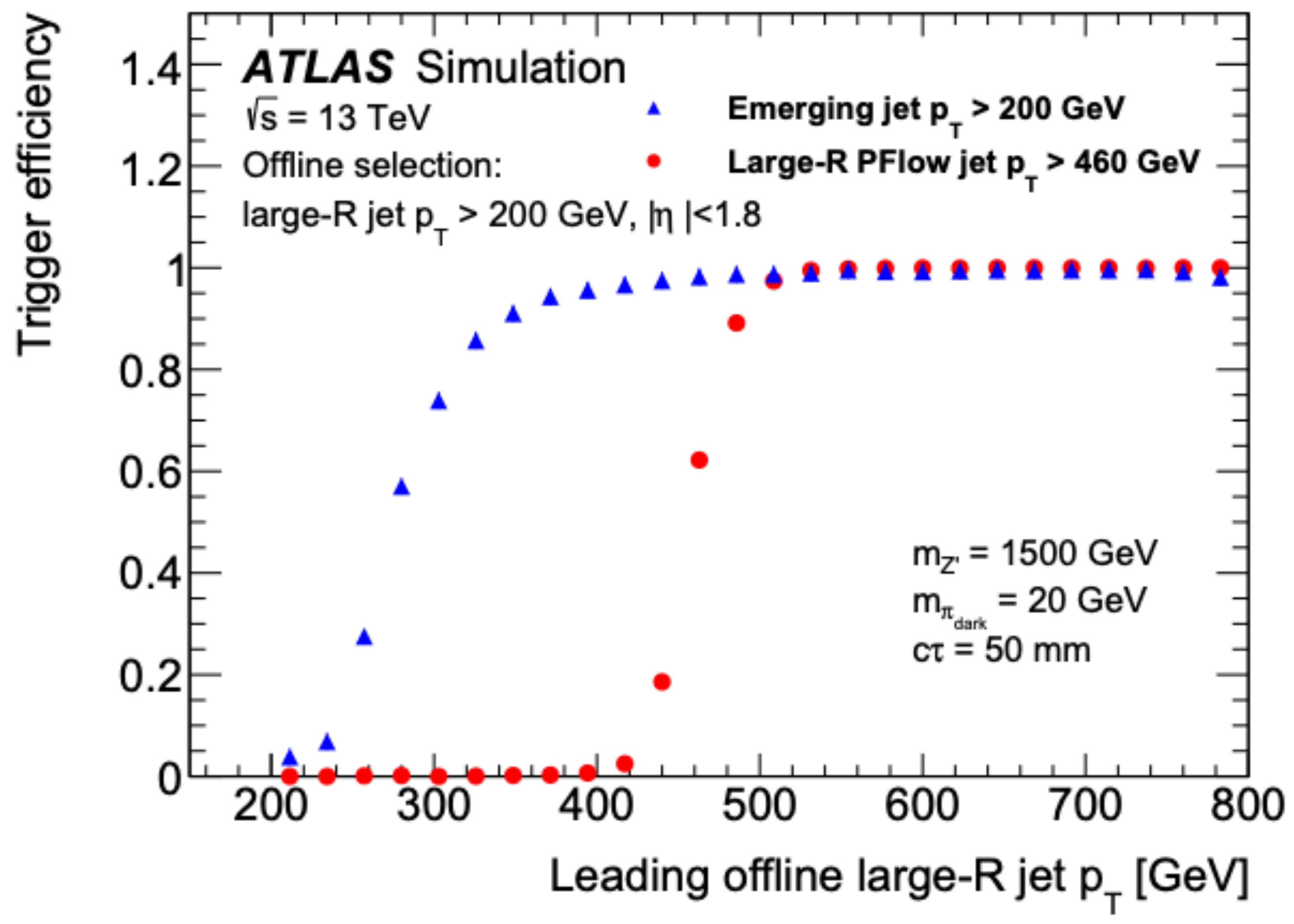
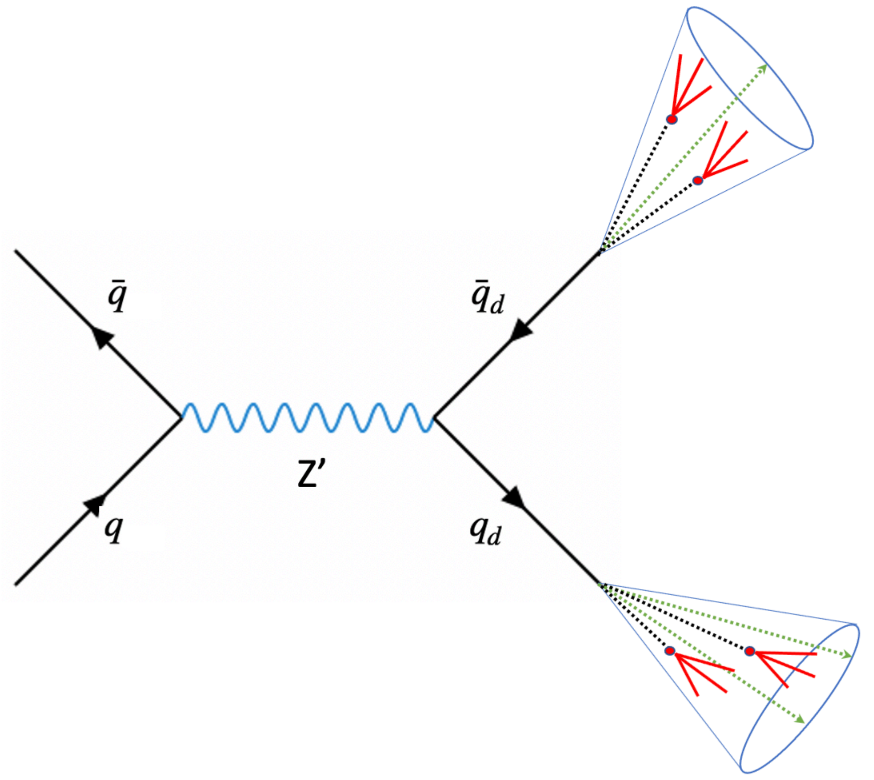
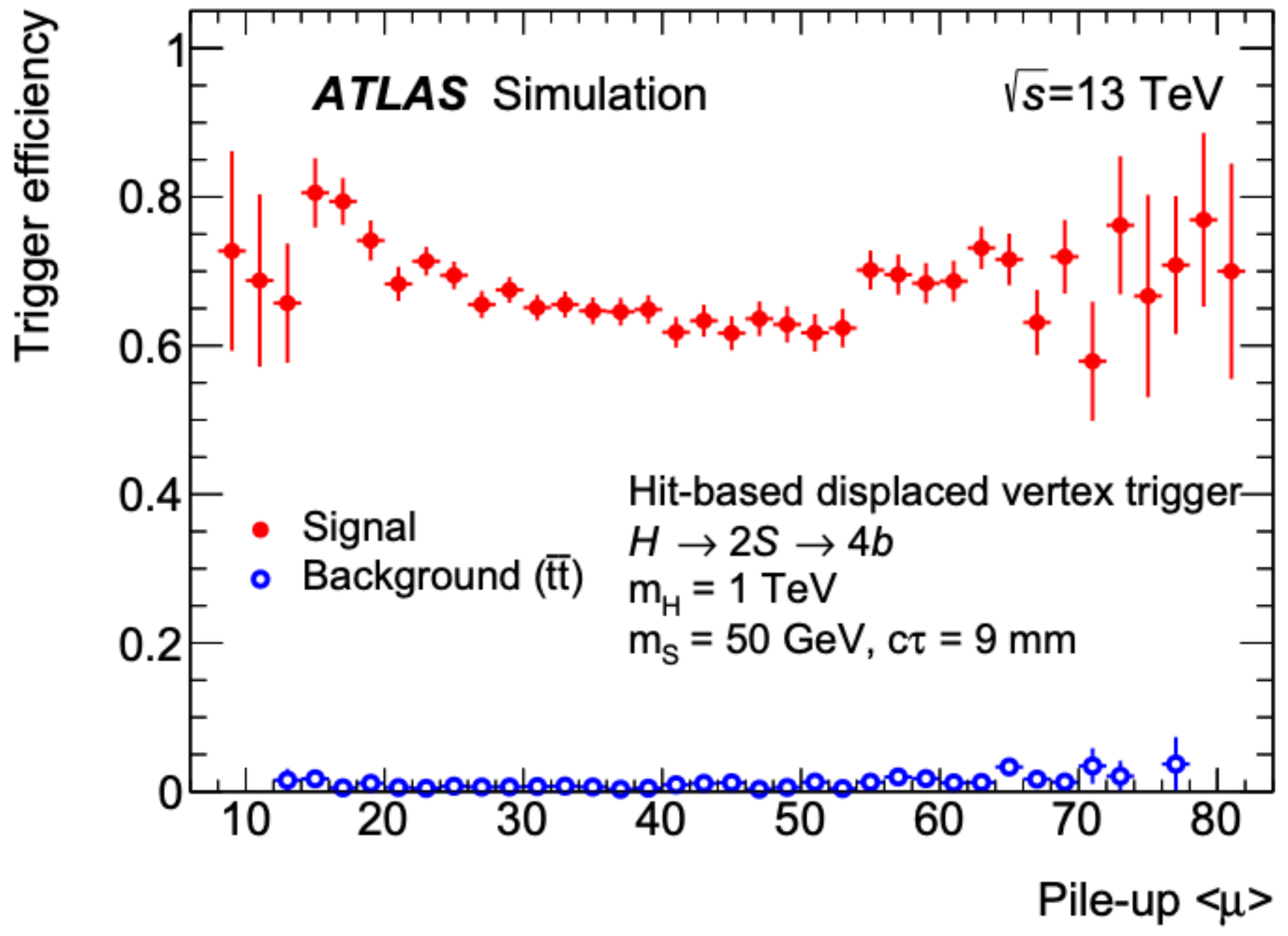
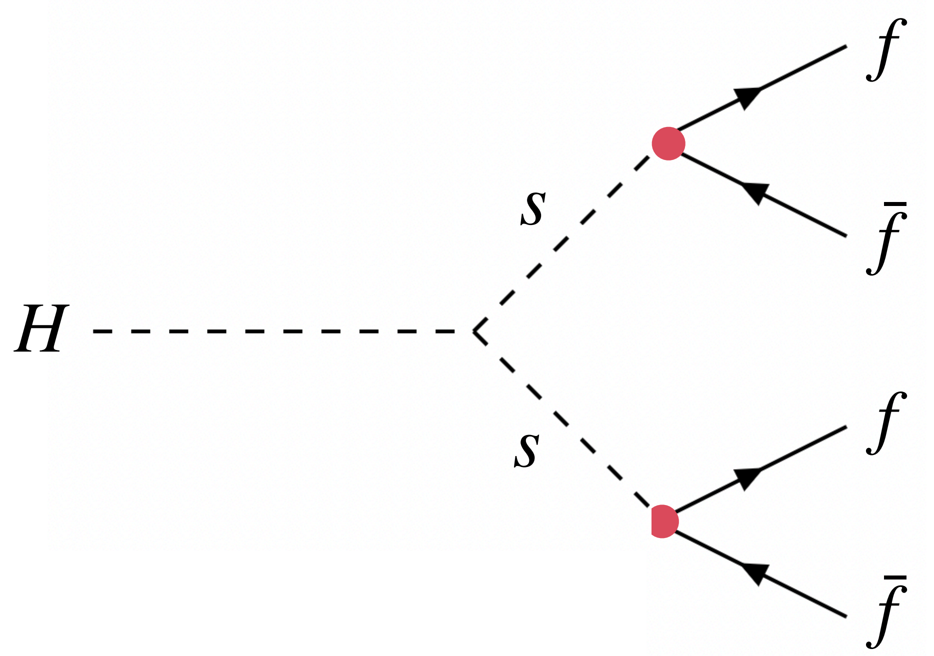




displaced ID vertices

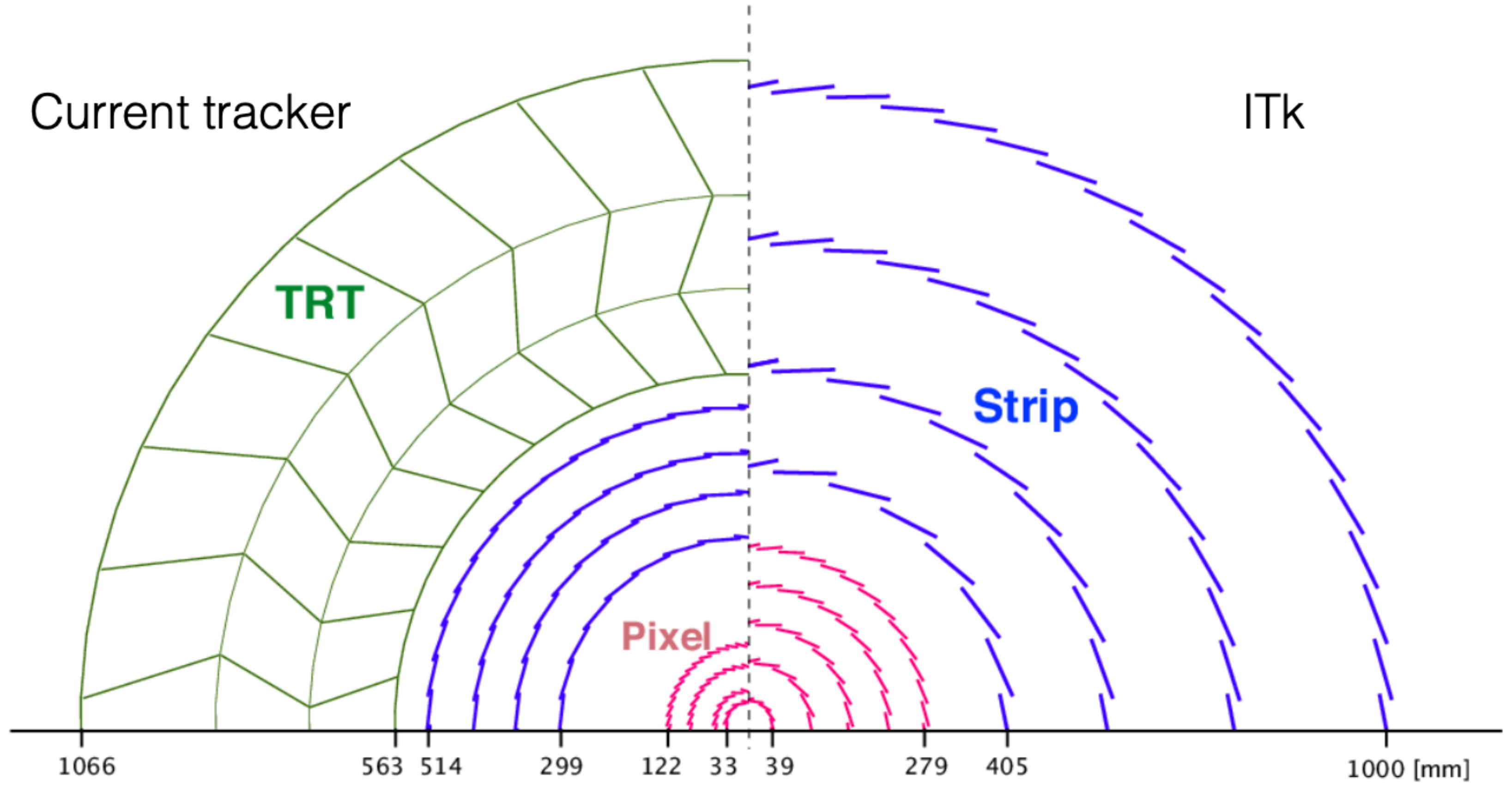




HL-LHC prospects

ITk upgrade will translate to improved LLP acceptance in tracker

- improved geometry
- larger silicon volume
- lower material budget



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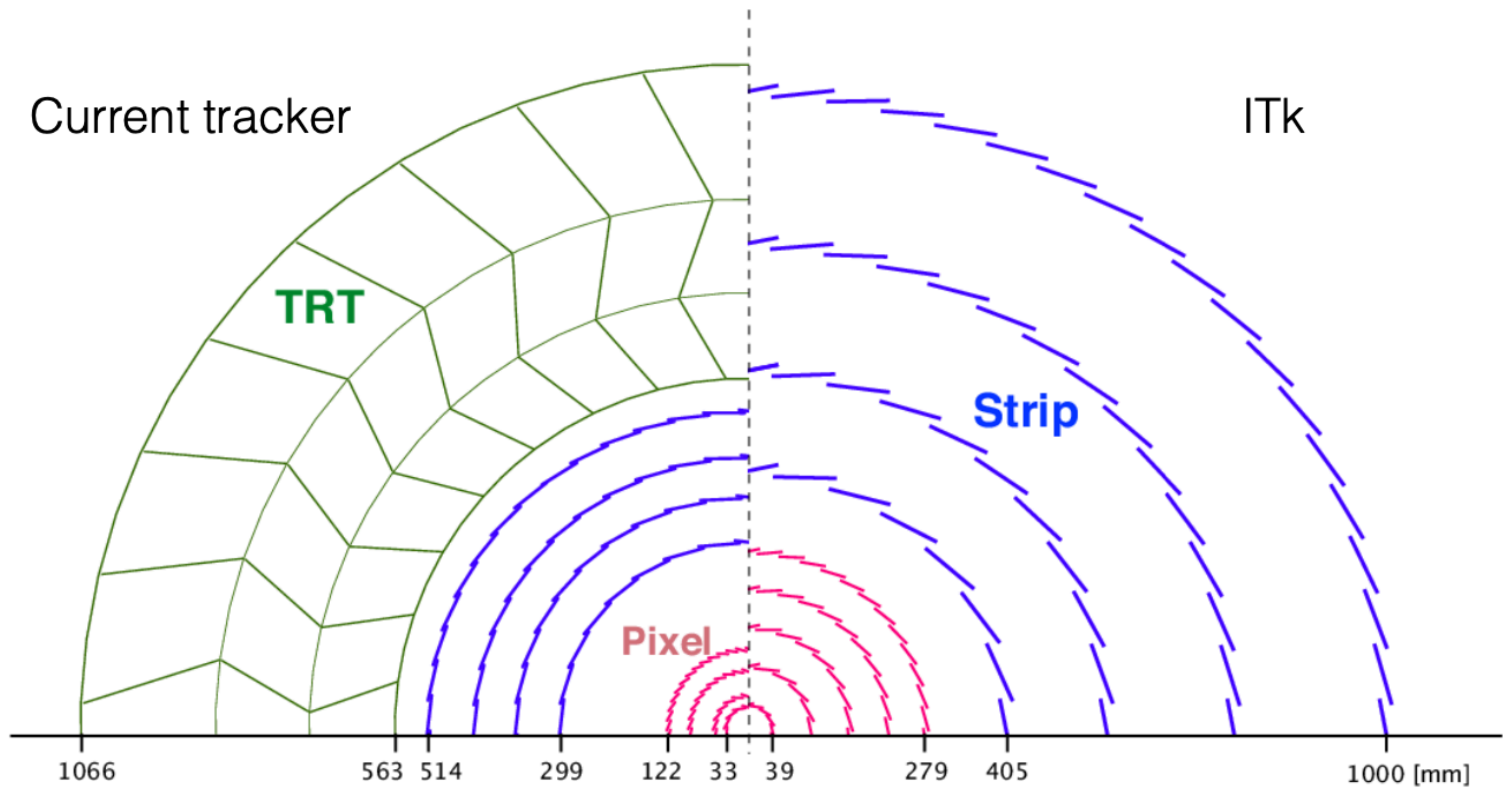
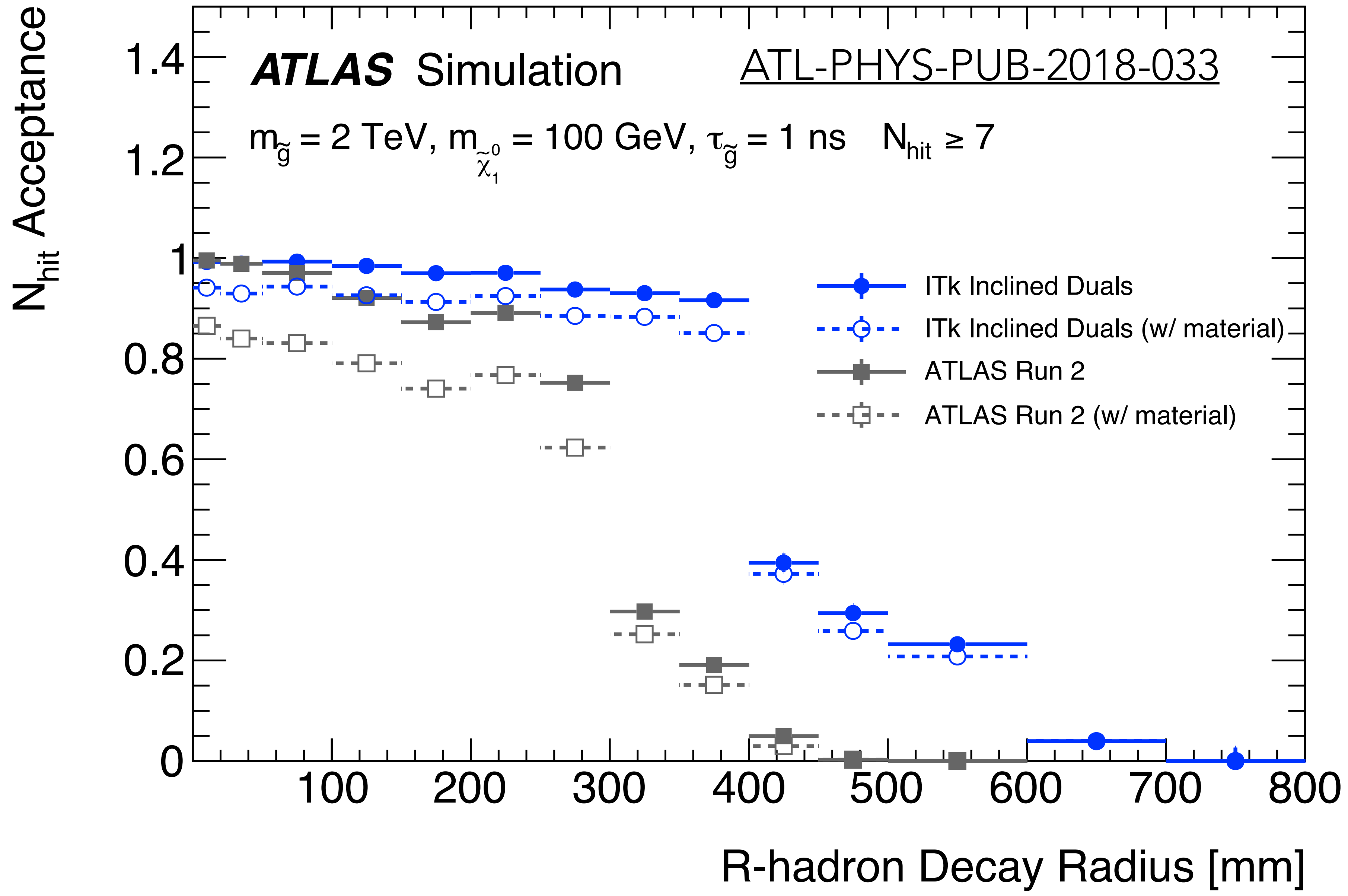


Improved efficiency for displaced vertex signatures



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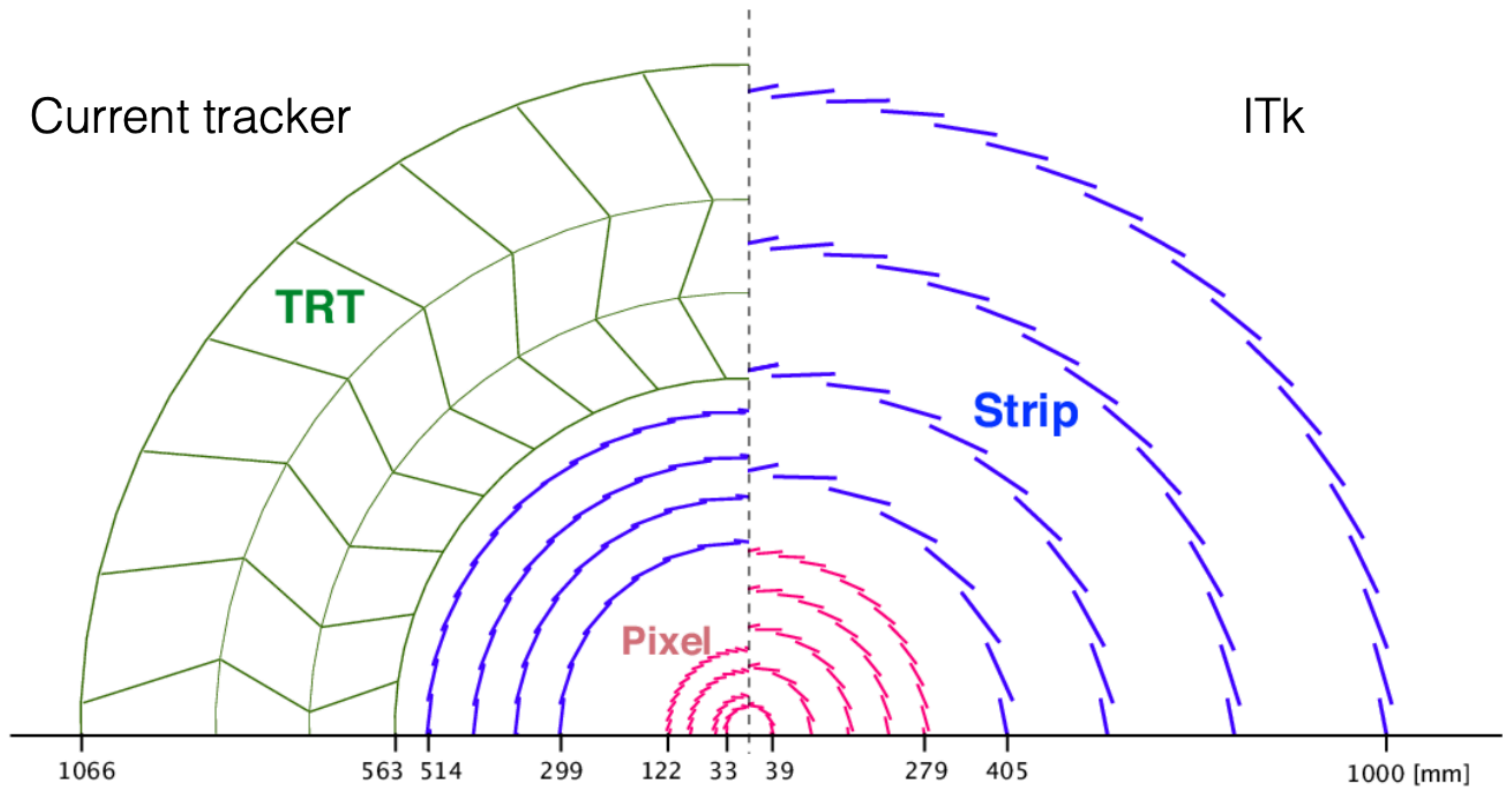

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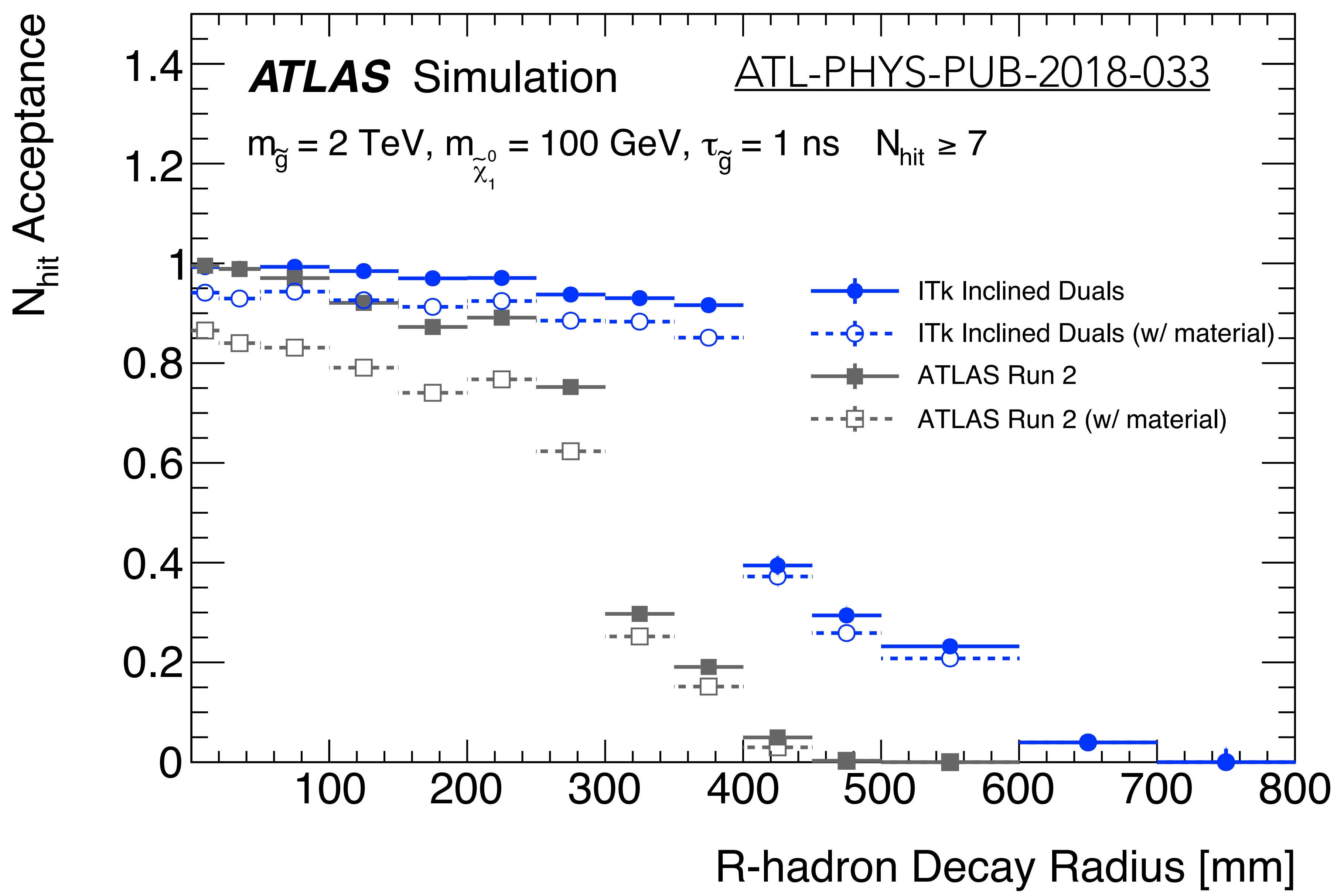
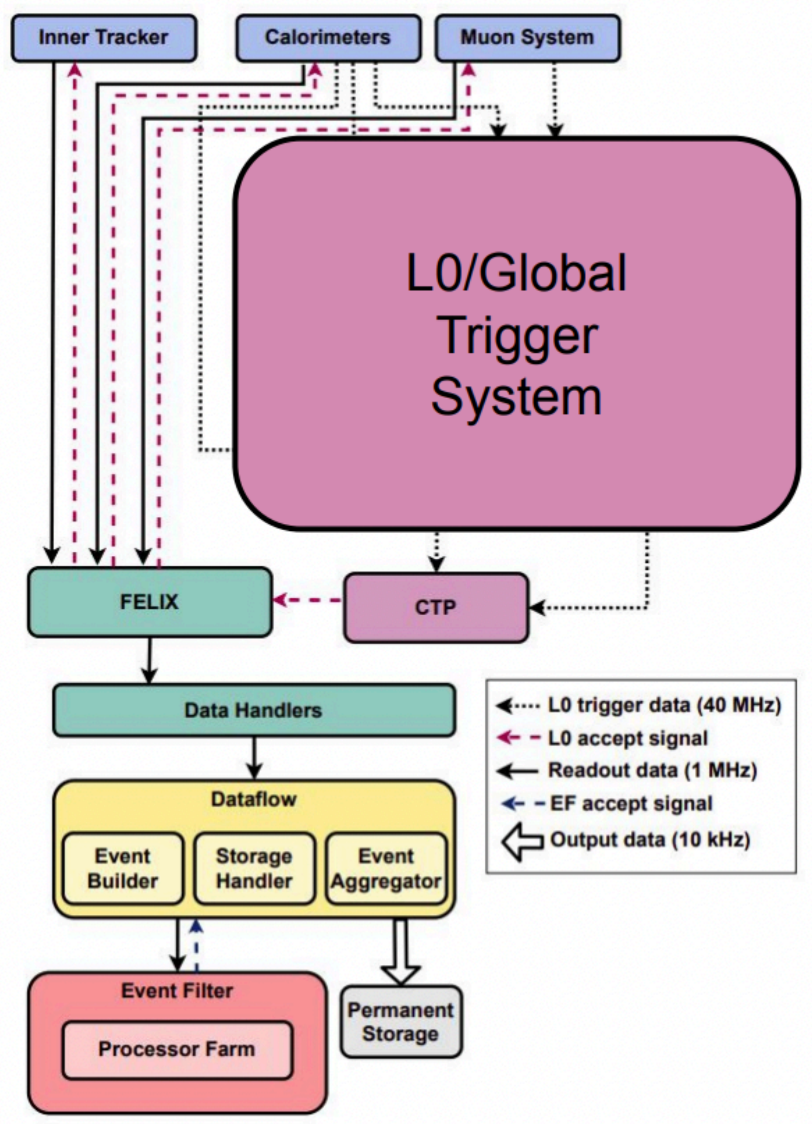


Upgraded TDAQ system brings opportunities for new LLP trigger algorithms

- global tracking @100kHz
  → improved triggers for ID signatures
- New Global Trigger in L0 system will execute "offline-like" processing and allow low p_T thresholds and trigger rates
  → improved sensitivity for low-mass signals



Summary

LLP searches are a crucial aspect of the ATLAS search program

- Strong motivation to search for LLPs from both bottom-up and top-down perspectives
- Lots of fun challenges to overcome in terms of reconstruction, triggering, and analysis strategy

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There is an exciting future ahead at the **lifetime frontier!**

Thank you for your attention! Questions?

Sandbox Studio/Symmetry Magazine

Backup

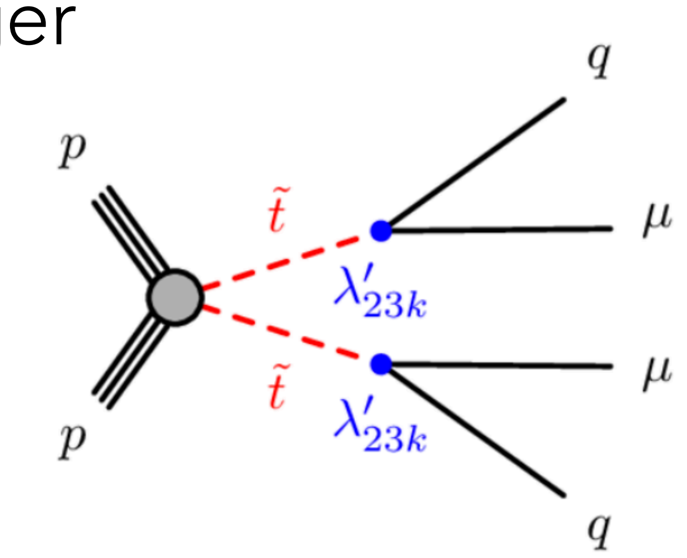
Sandbox Studio/Symmetry Magazine

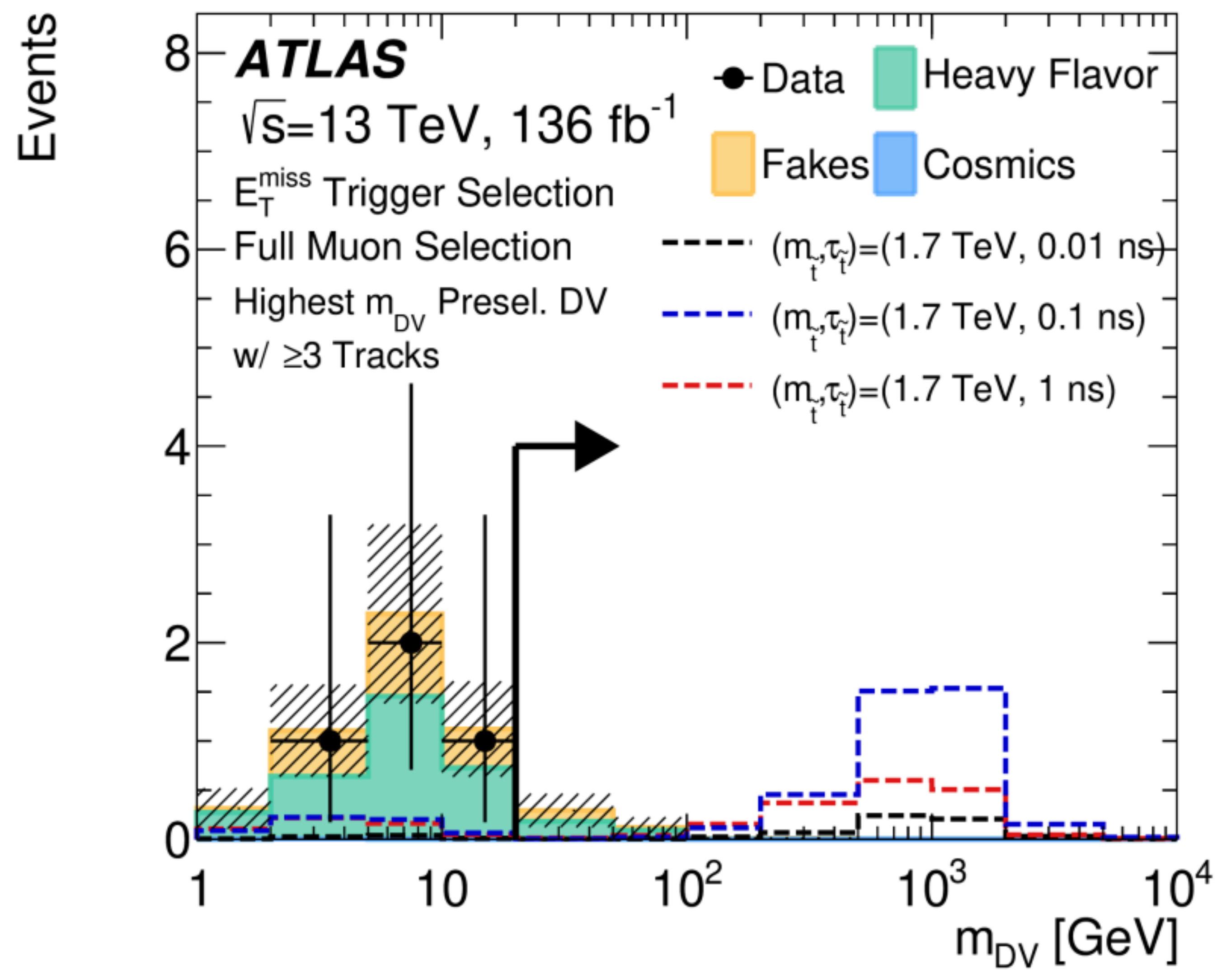
Displaced vertices in SUSY

Multiple searches targeting different final state signatures:

DV+muon: SUSY-2018-33

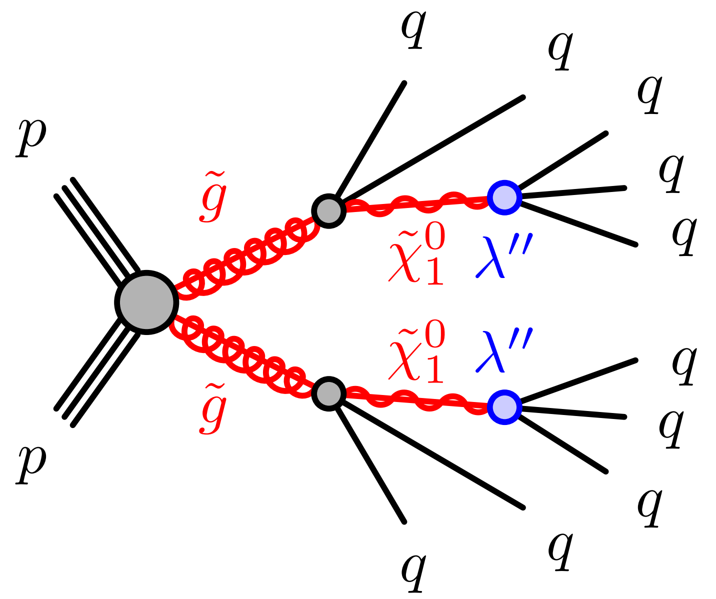
- Targeting λ' RPV coupling
- MS-only muon trigger

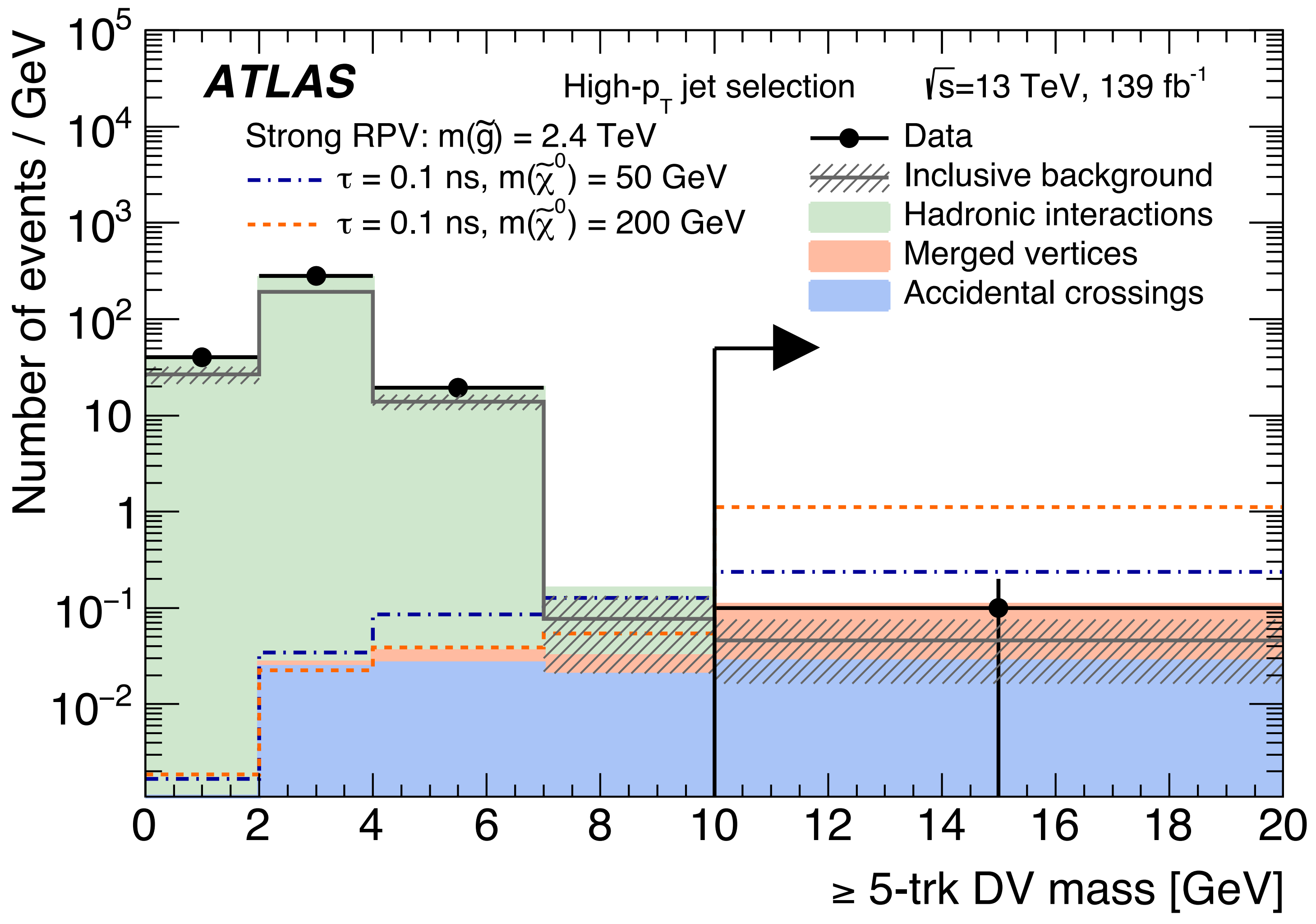




DV+jets: SUSY-2018-13

- Targeting λ'' RPV coupling
- Multi-jet trigger





Common signature: heavy, multitrack DV

- Reduce background to ~0 events through tight cuts on $n_{\rm trk}$ and $m_{\rm vtx}$

LLPs interacting with the detector

A massive, charged, LLP will have $\beta\gamma < 1$ and anomalously large **specific ionisation loss** (dE/dx) in the detector

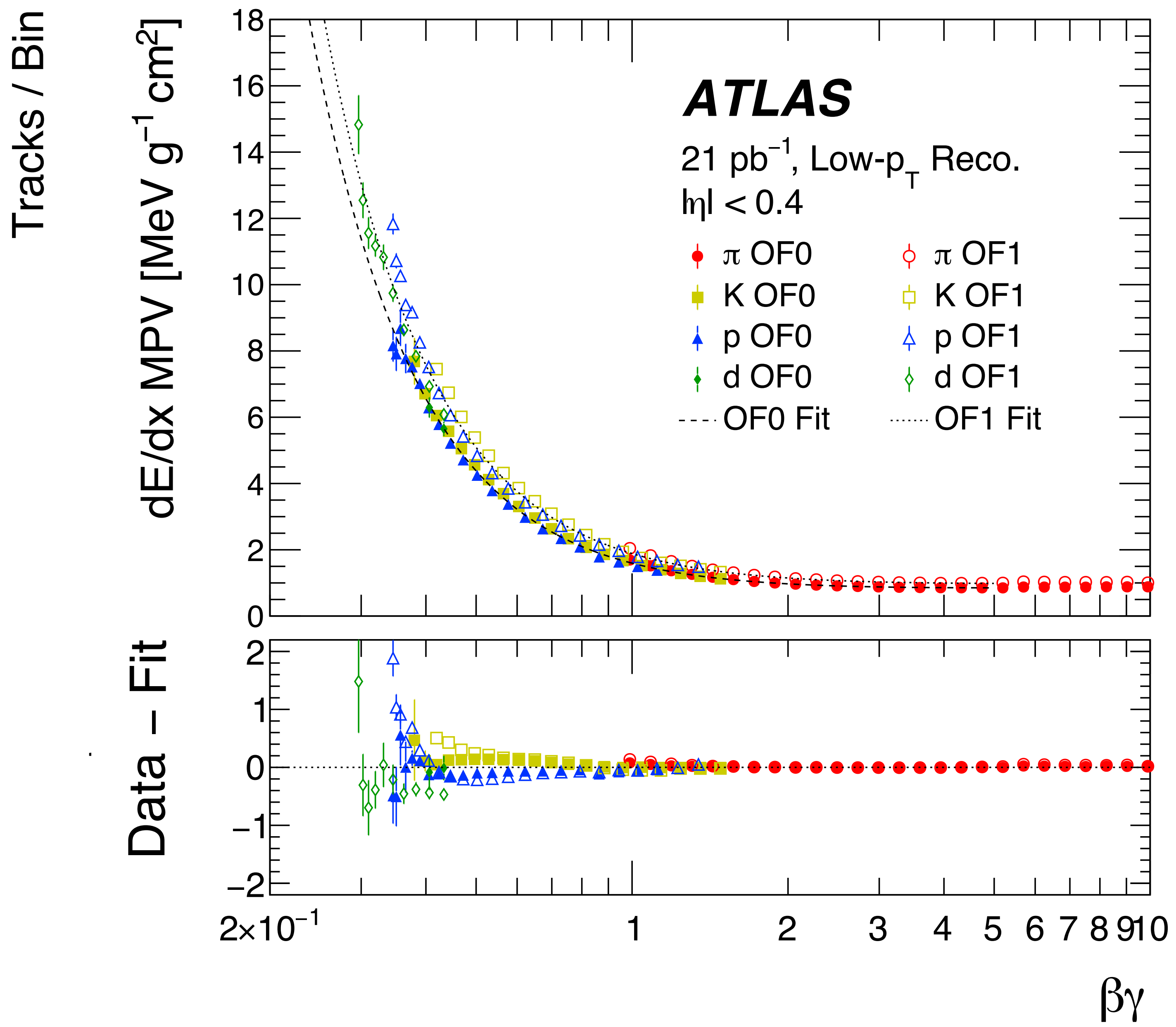
The ATLAS detector subsystems are able to provide a precise measurement of dE/dx

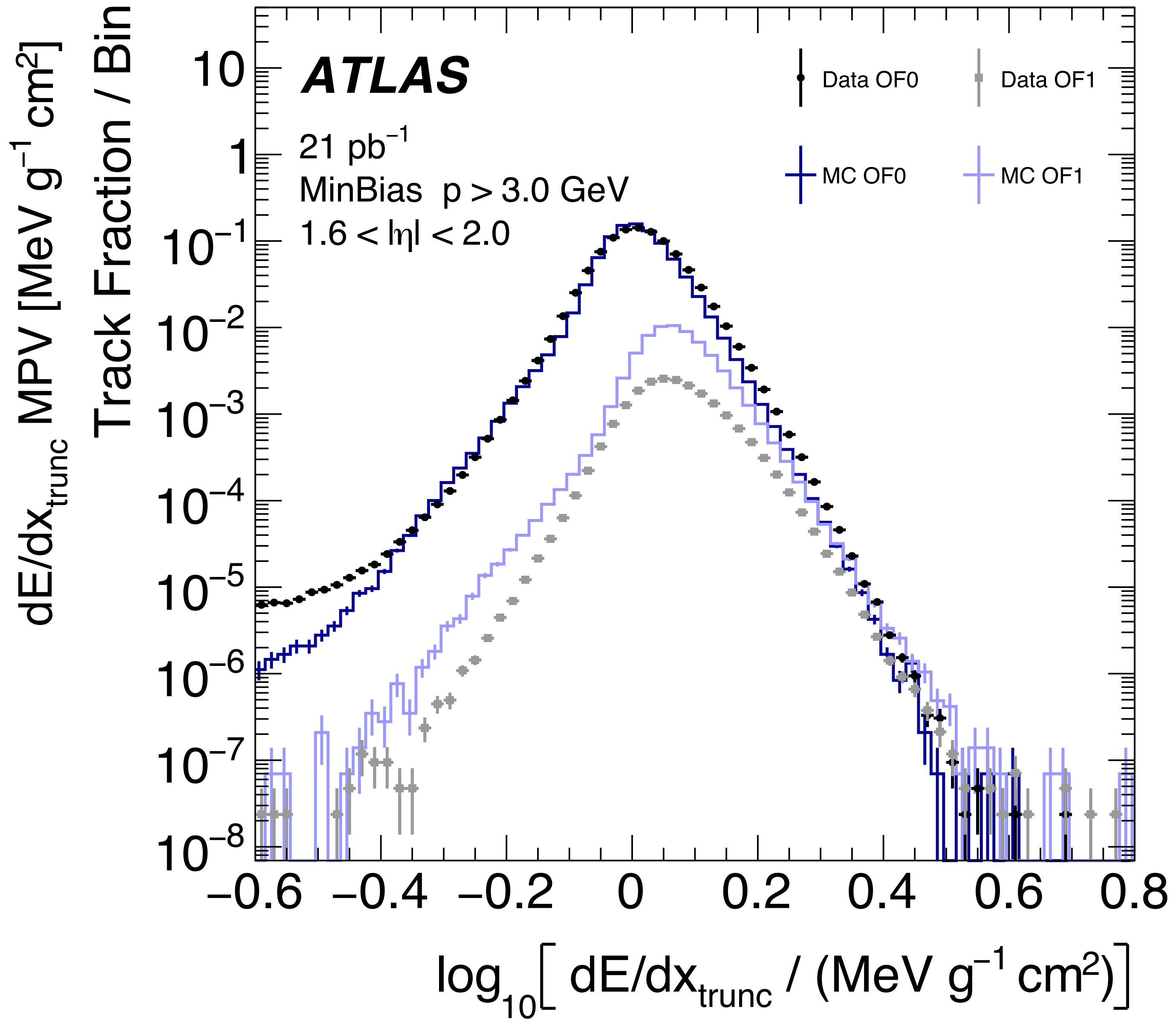
- **Bethe-Bloch relation** can then be used to calculate $\beta\gamma$

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_A r_e^2 m_e c^2 \frac{Z}{A}\frac{z^2}{\beta^2}\left\{ln\left(\frac{2m_e c^2\beta^2\gamma^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right\}$$

Using dE/dx requires significant analysis work to:

- Correct for radiation damage and detector operation effects
- Estimate data-driven dE/dx background template



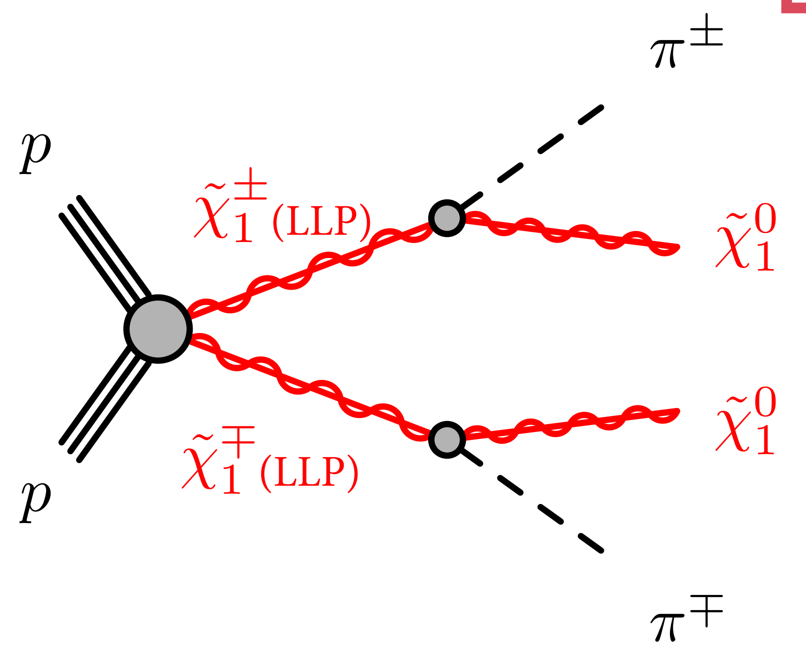


Pixel dE/dx

SUSY-2018-42 ATLAS-CONF-2023-044 **Physics Briefing!**

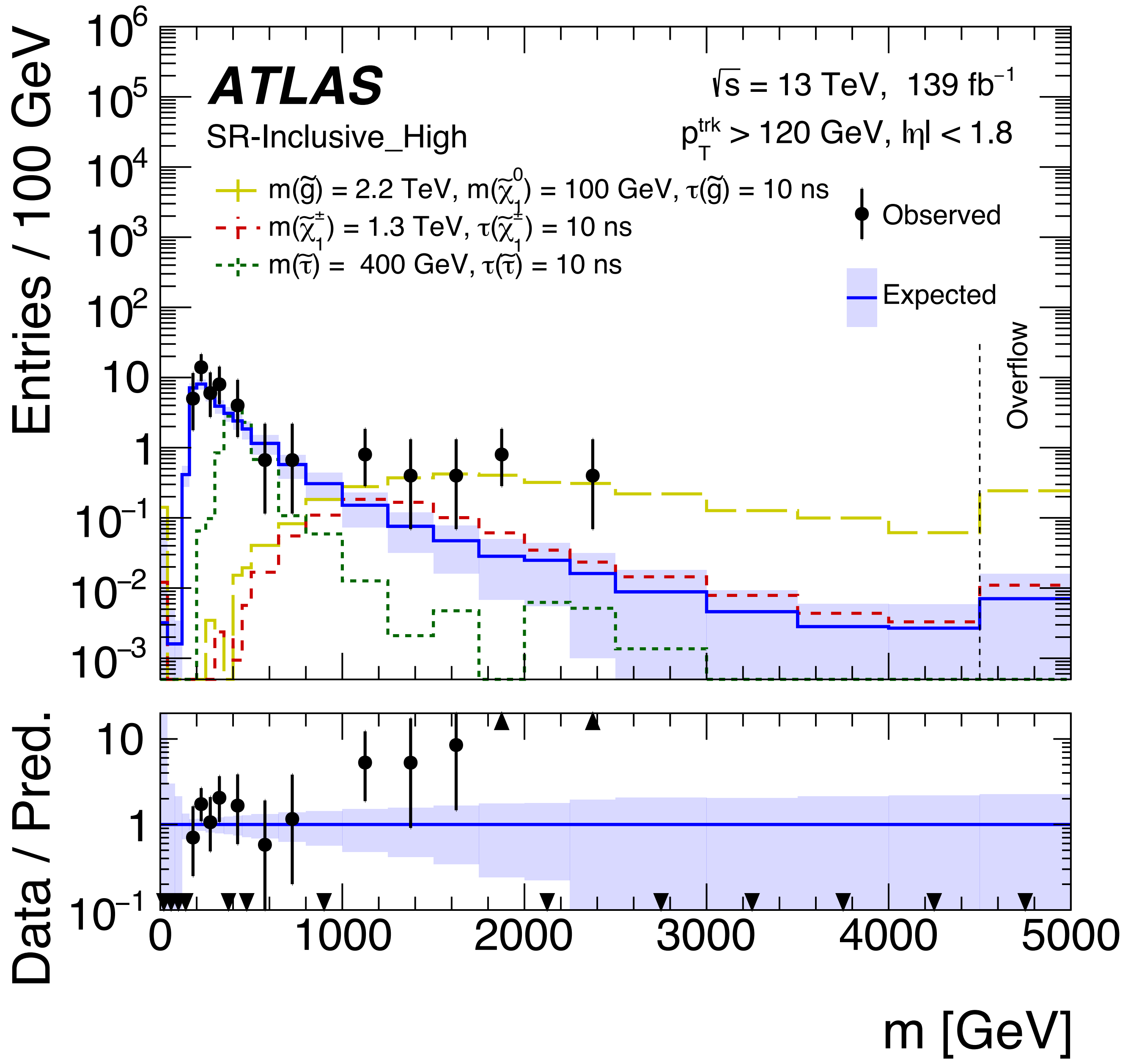
Long-lived charginos will leave anomalous energy deposits in the detector

- Measure dE/dx in silicon tracker based on charge collected
- Determine β, and combine w/ track momentum to determine mass



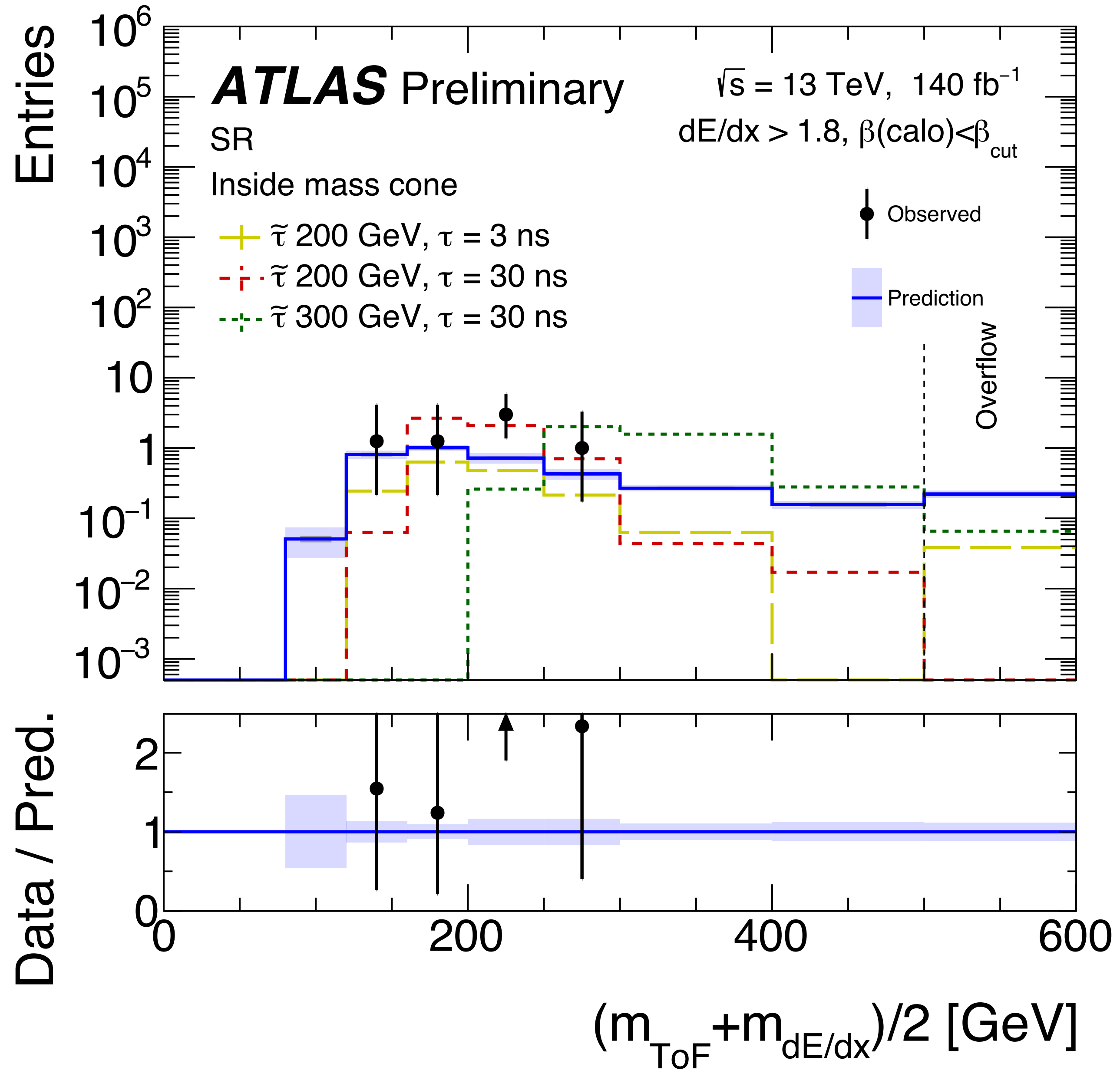
3.3σ global excess observed in first-wave Run 2 analysis

- Consistent with $\beta = 1$ from calo & MS ToF → does not match expectation of a slow-moving heavy particle



Follow-up includes calorimeter time of flight (ToF) information

- Allows for independent determination of $\beta\gamma$ from both dE/dx and calo ToF



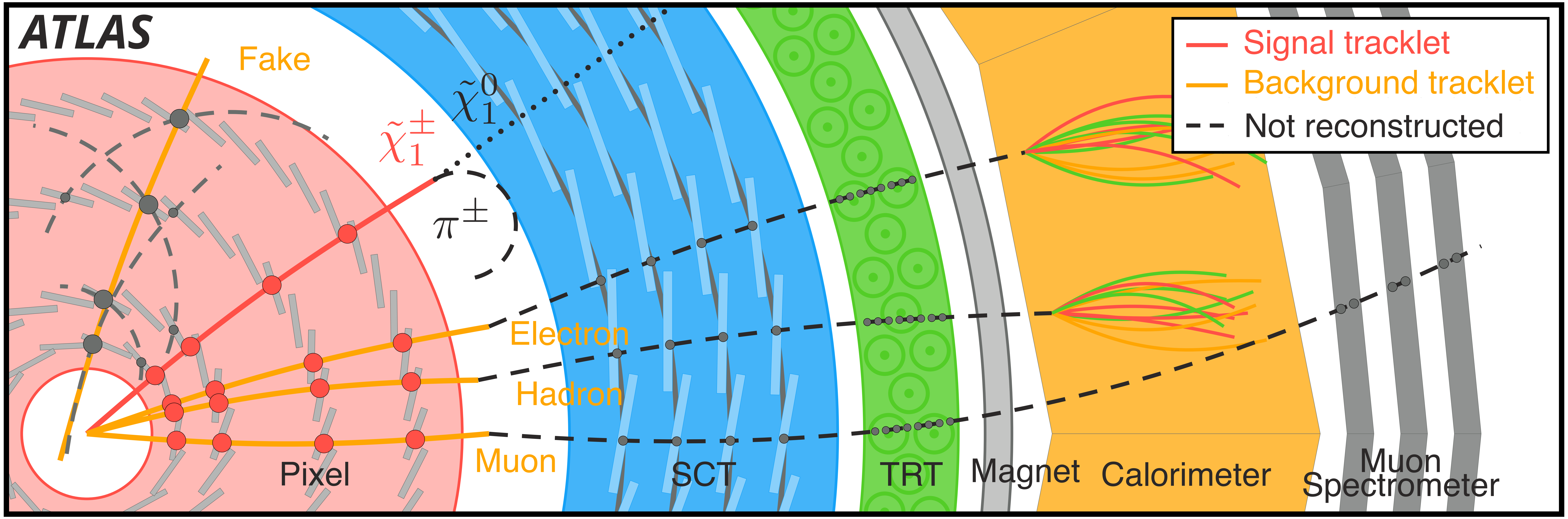
Excess not confirmed

Disappearing tracks

SUSY-2018-19

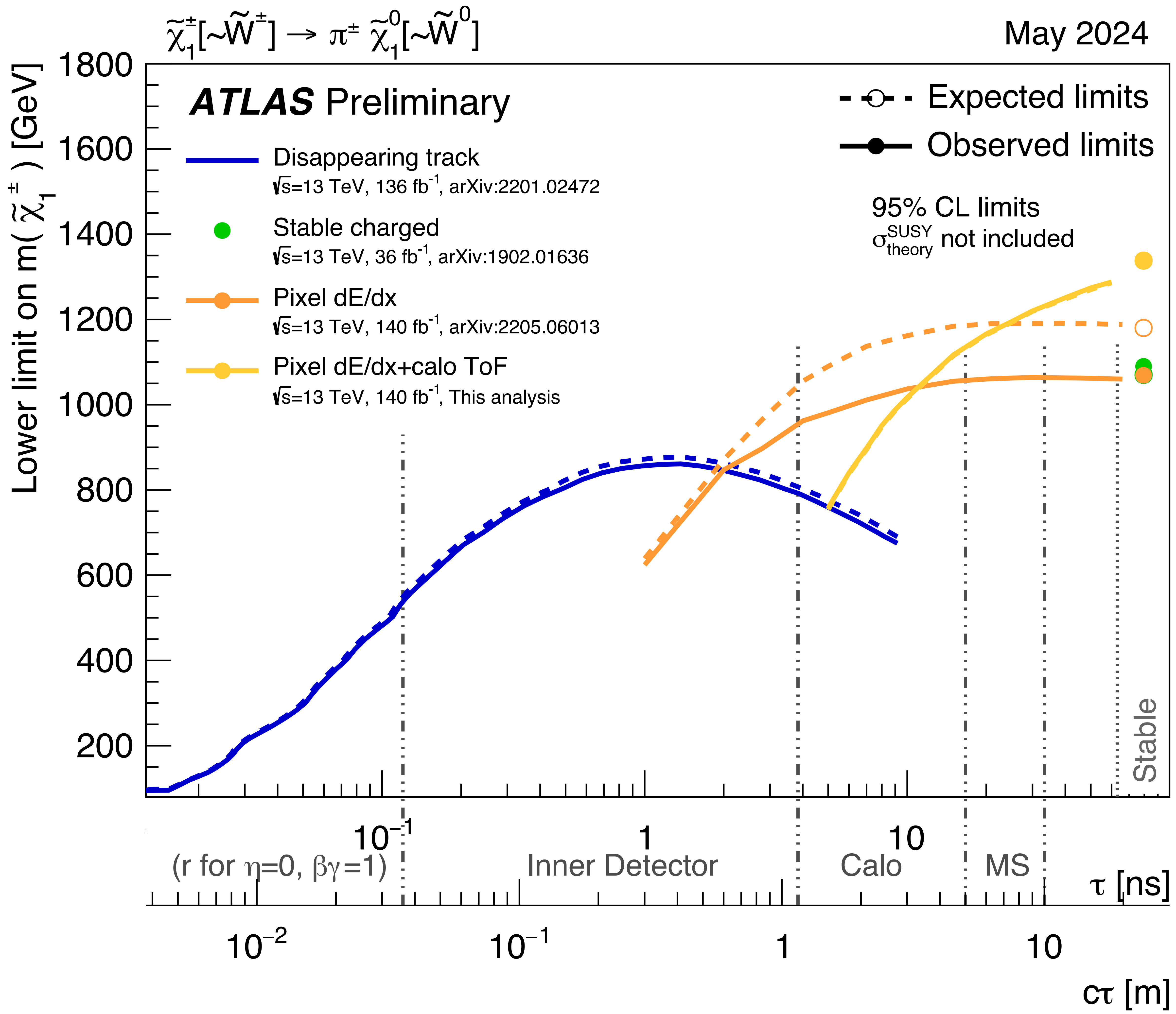
Shorter-lived charginos may interact directly with the pixel detector, but decay before reaching SCT

- Leaves a distinct "disappearing track" signature



Use dedicated **tracklet** reconstruction run on unassociated hits from standard tracking

Chargino exclusion



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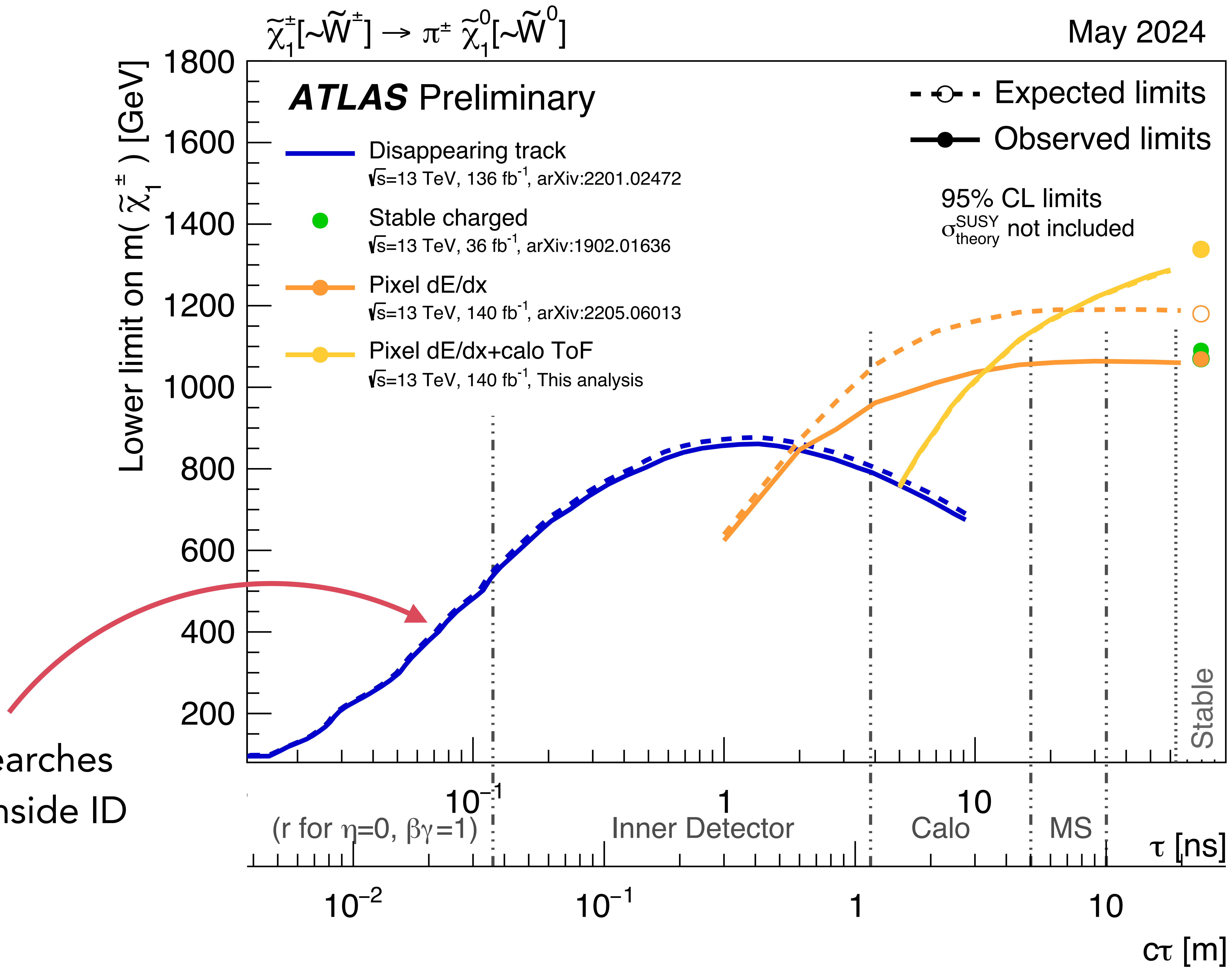

Disappearing track searches dominate for decays inside ID

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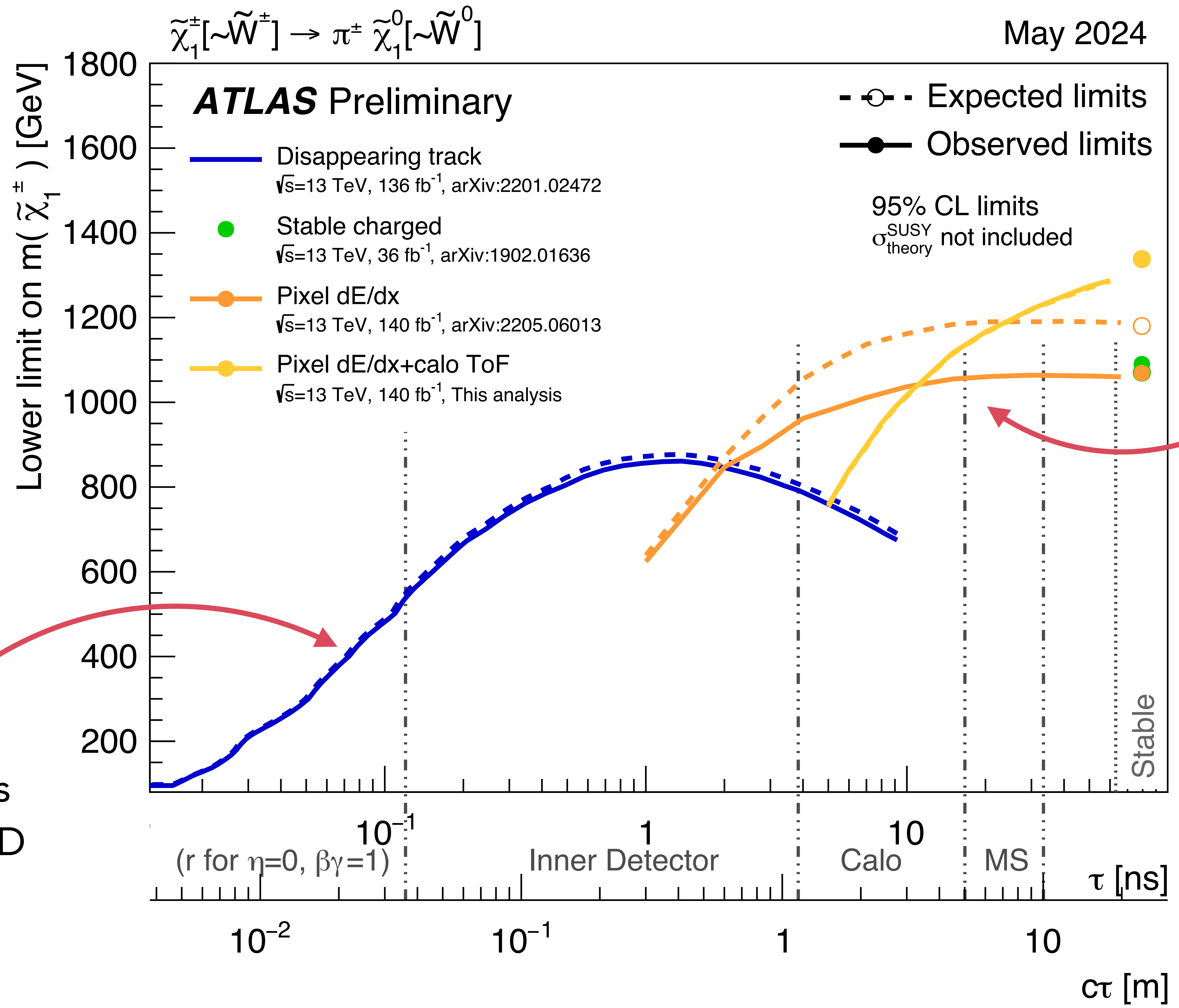


dE/dx searches dominate for decays outside of the ID

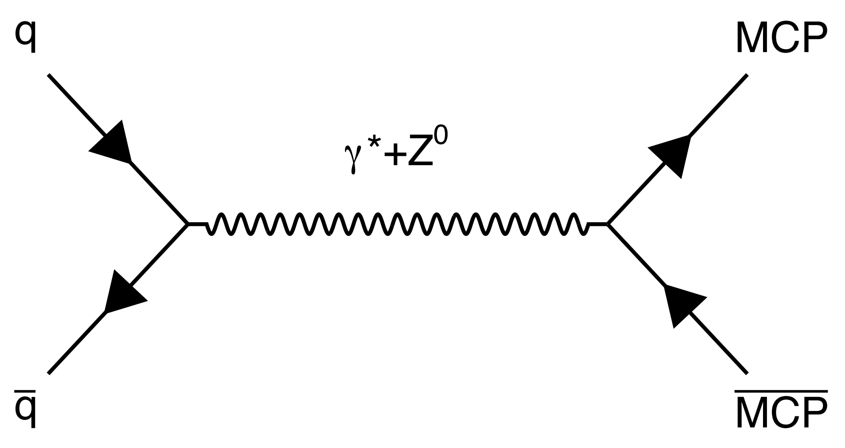
Disappearing track searches dominate for decays inside ID

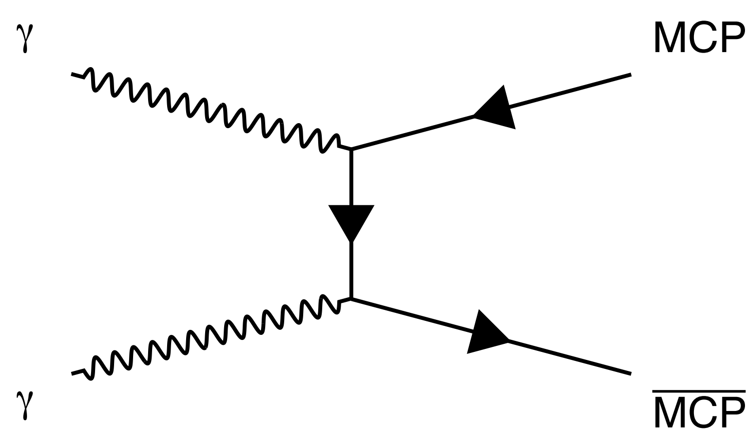
Multi-charged particles

EXOT-2018-54

General search for heavy, long-lived, multi-charged particles (MCPs) with $2 \leq z \leq 7$ ($z = |q|/e$)

Drell-Yan (DY)



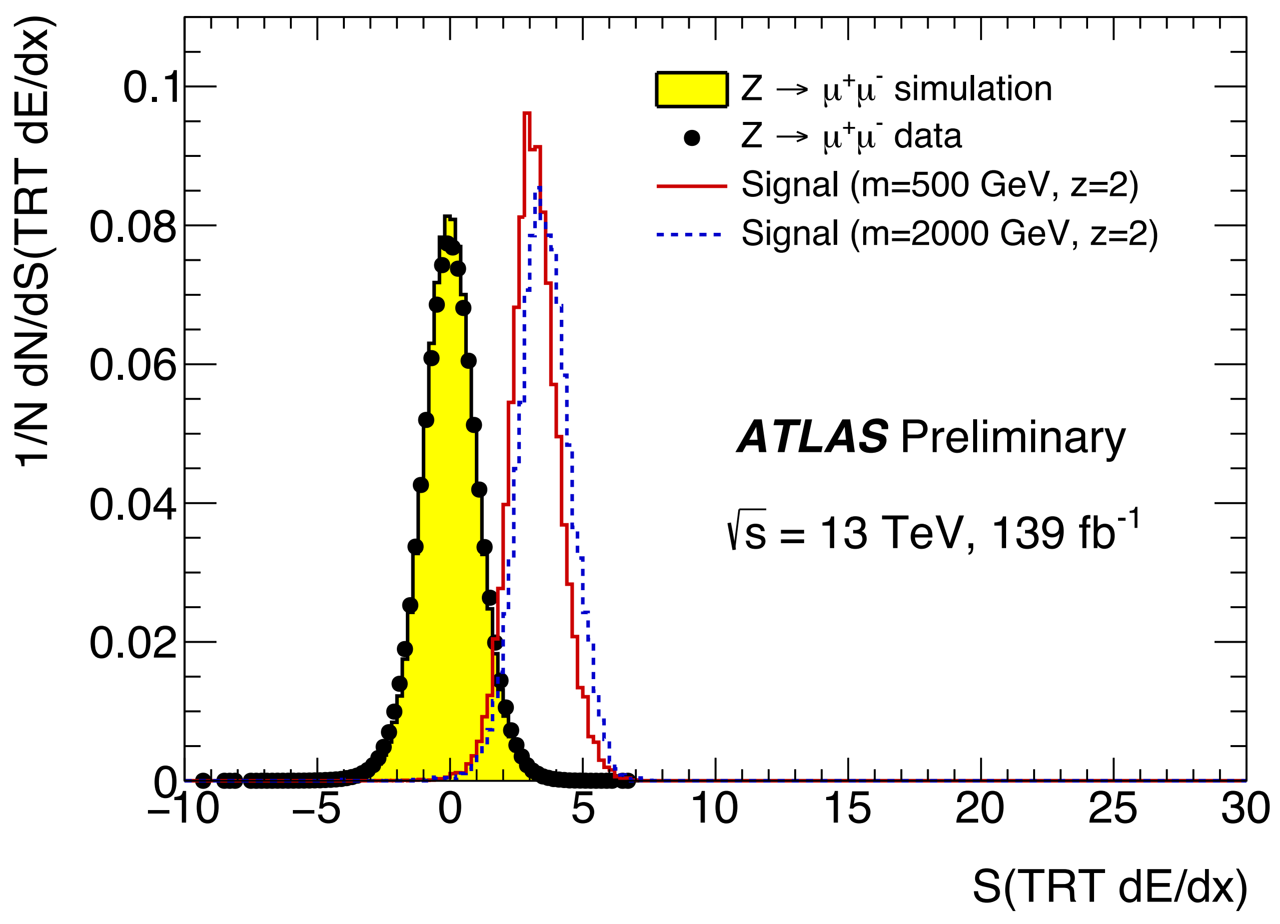


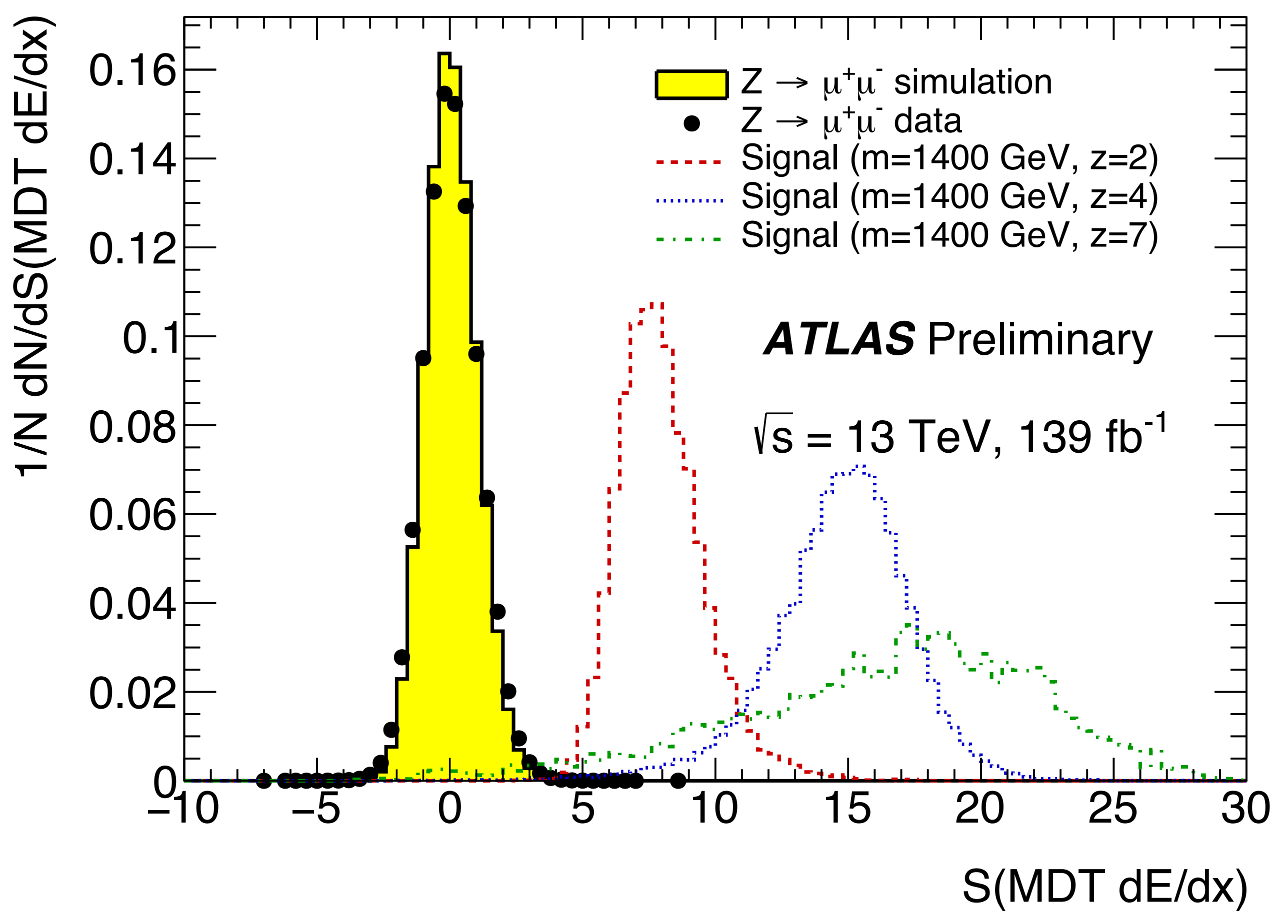
Photon Fusion (PF)

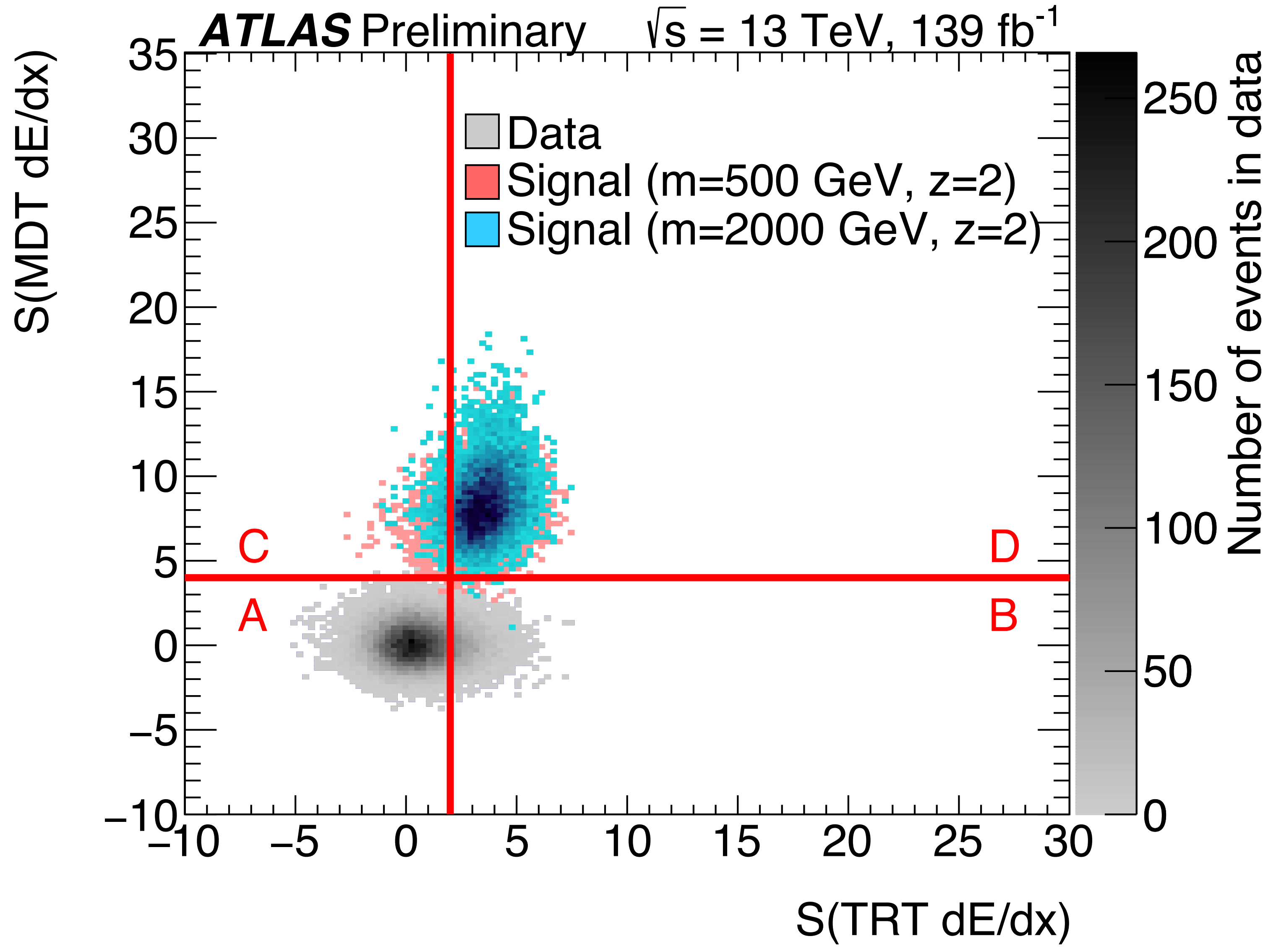
MCPs are highly ionizing, and thus generate abnormally large ionization signals

$$S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}$$

- Analysis searches for muon-like tracks with high dE/dx values in several detector subsystems
- ABCD estimate using $S(dE/dx)$







Magnetic monopoles

EXOT-2019-33

Physics Briefing!

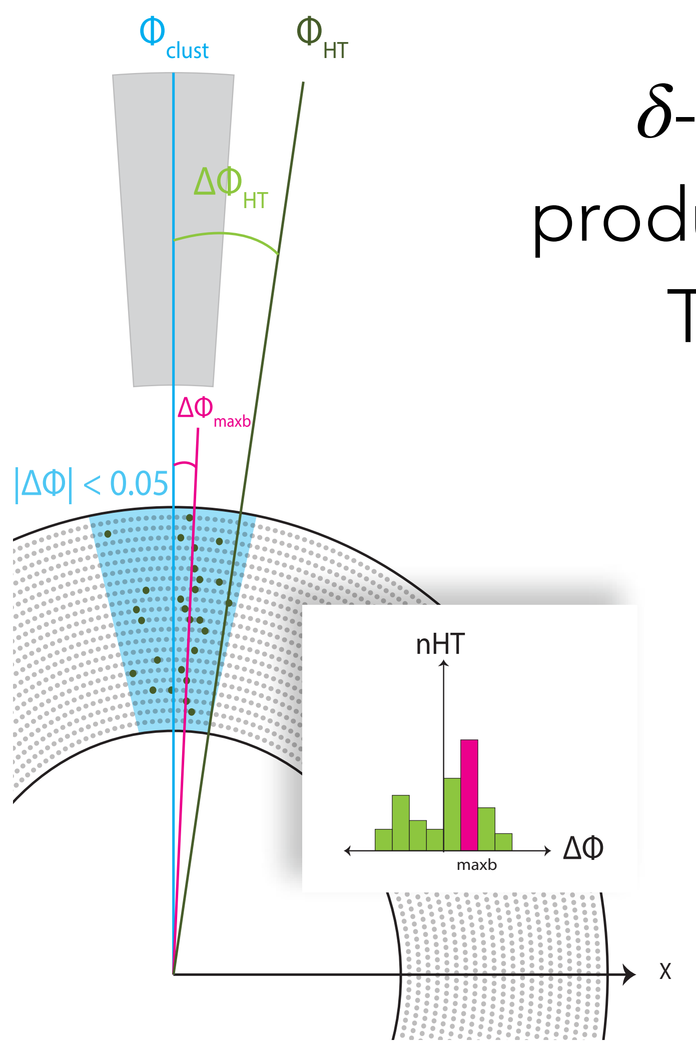
Search for magnetic monopoles and stable particles with high electric charge $(20 < |z| < 100)$

- Target both DY and PF production

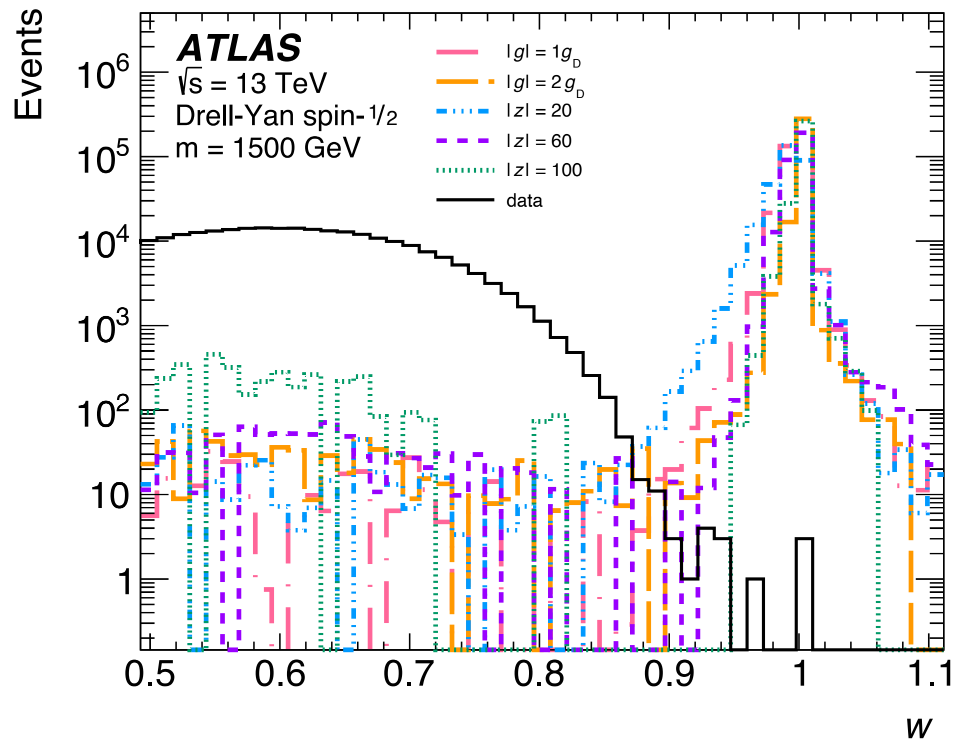
Produce TRT tracks with δ-rays → many high threshold TRT hits (HT)

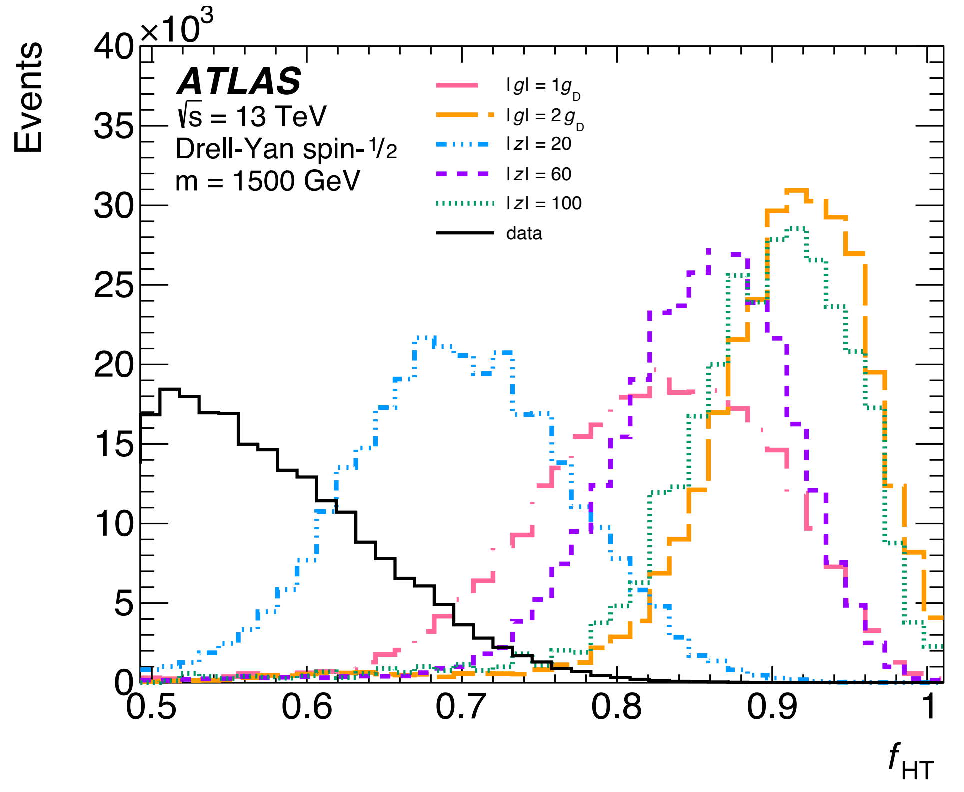
Too massive to produce shower in EM calo → low lateral dispersion (w)

Dedicated trigger

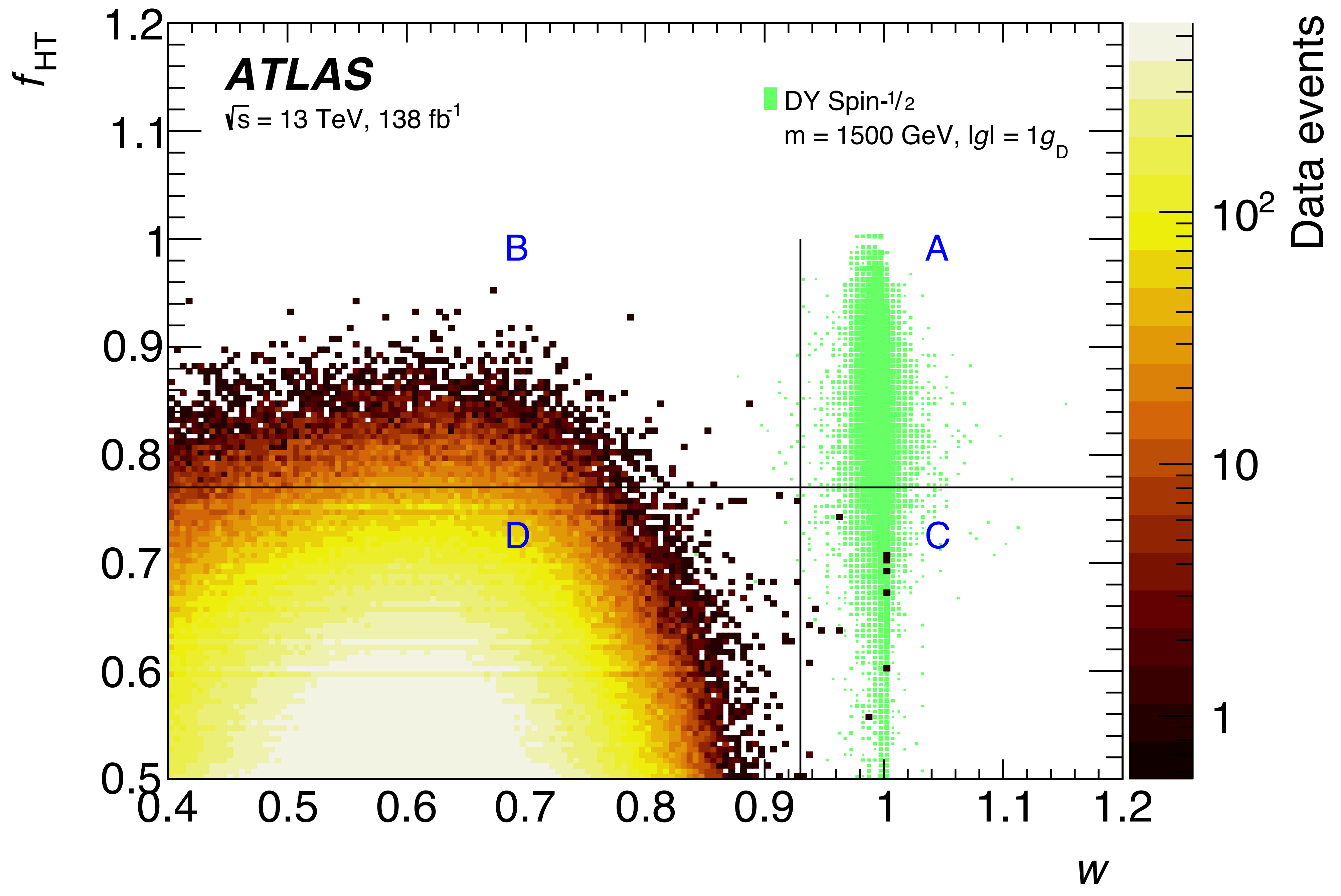


δ-rays produced in TRT



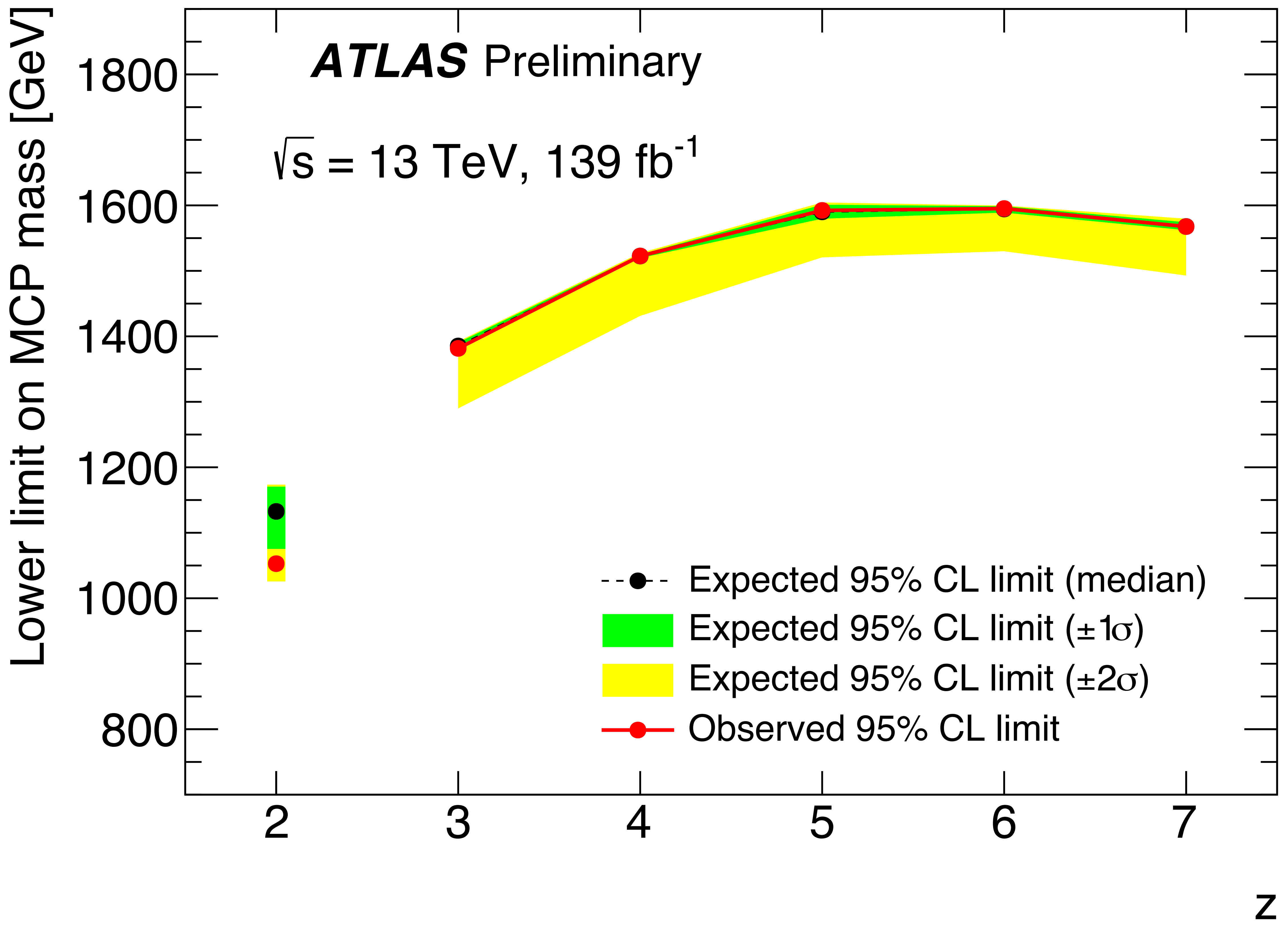


Data-driven ABCD plane



MCP/Monopole exclusion

Multi-charged particles



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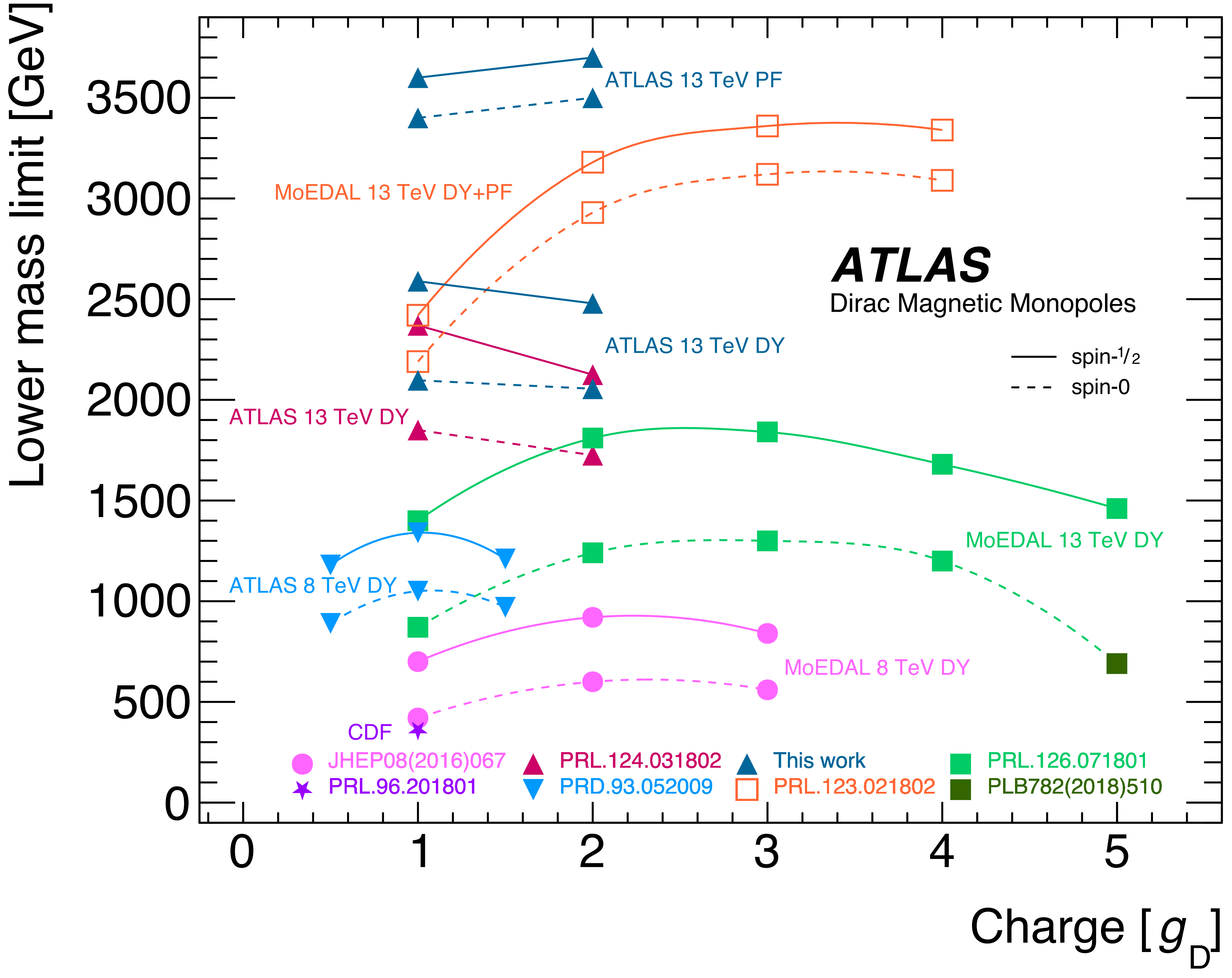
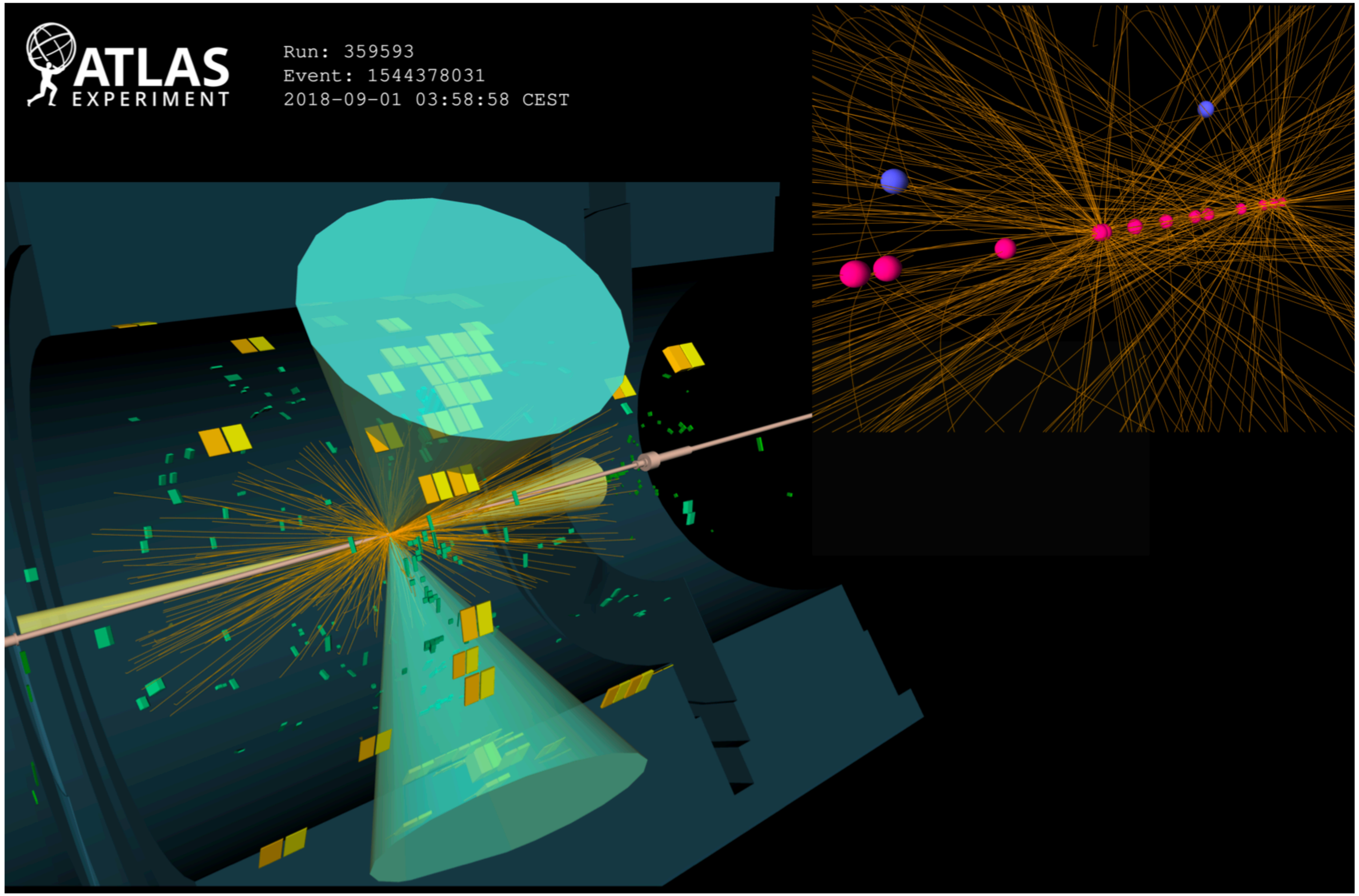


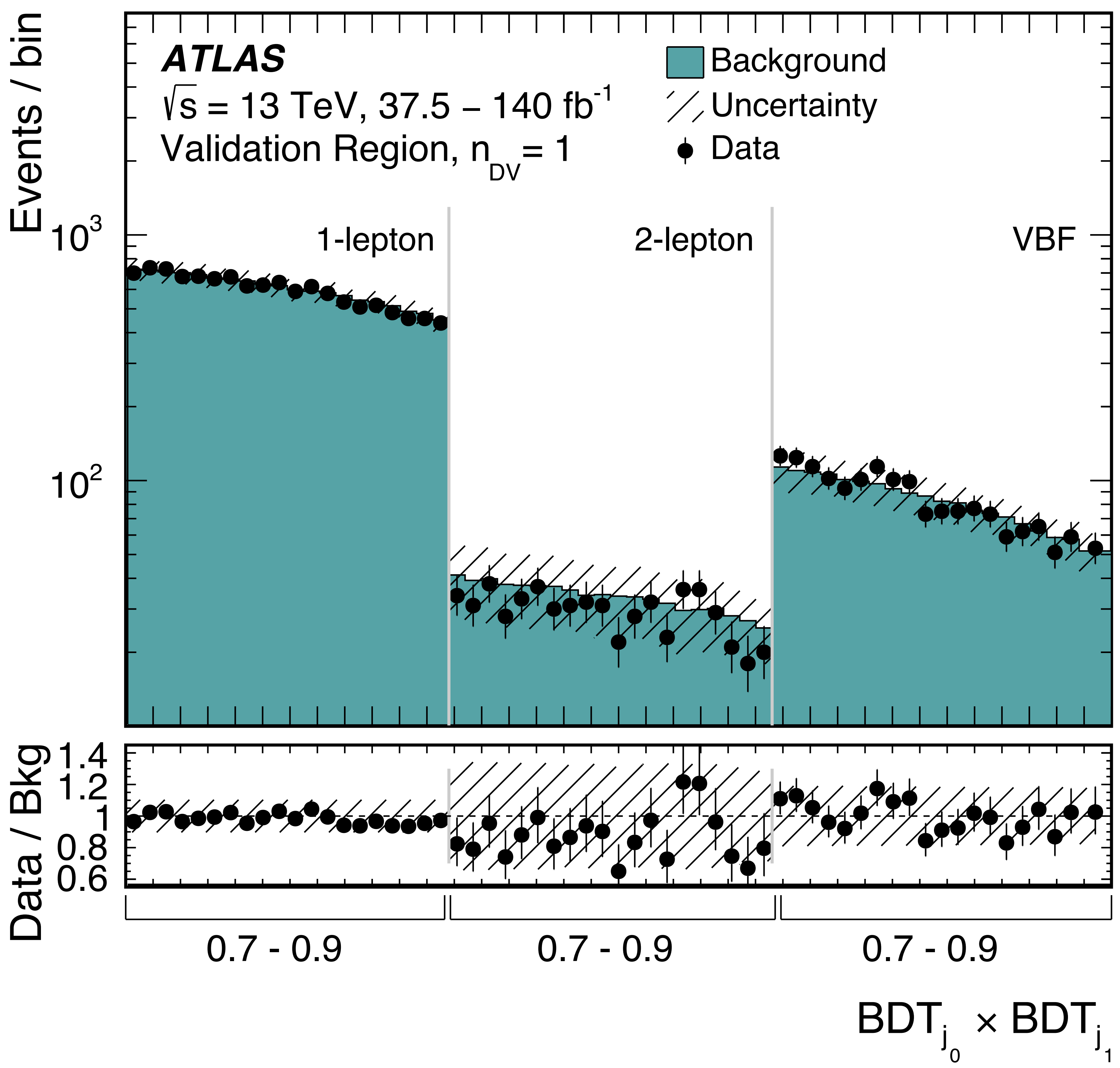
Scalar Portal: ID searches

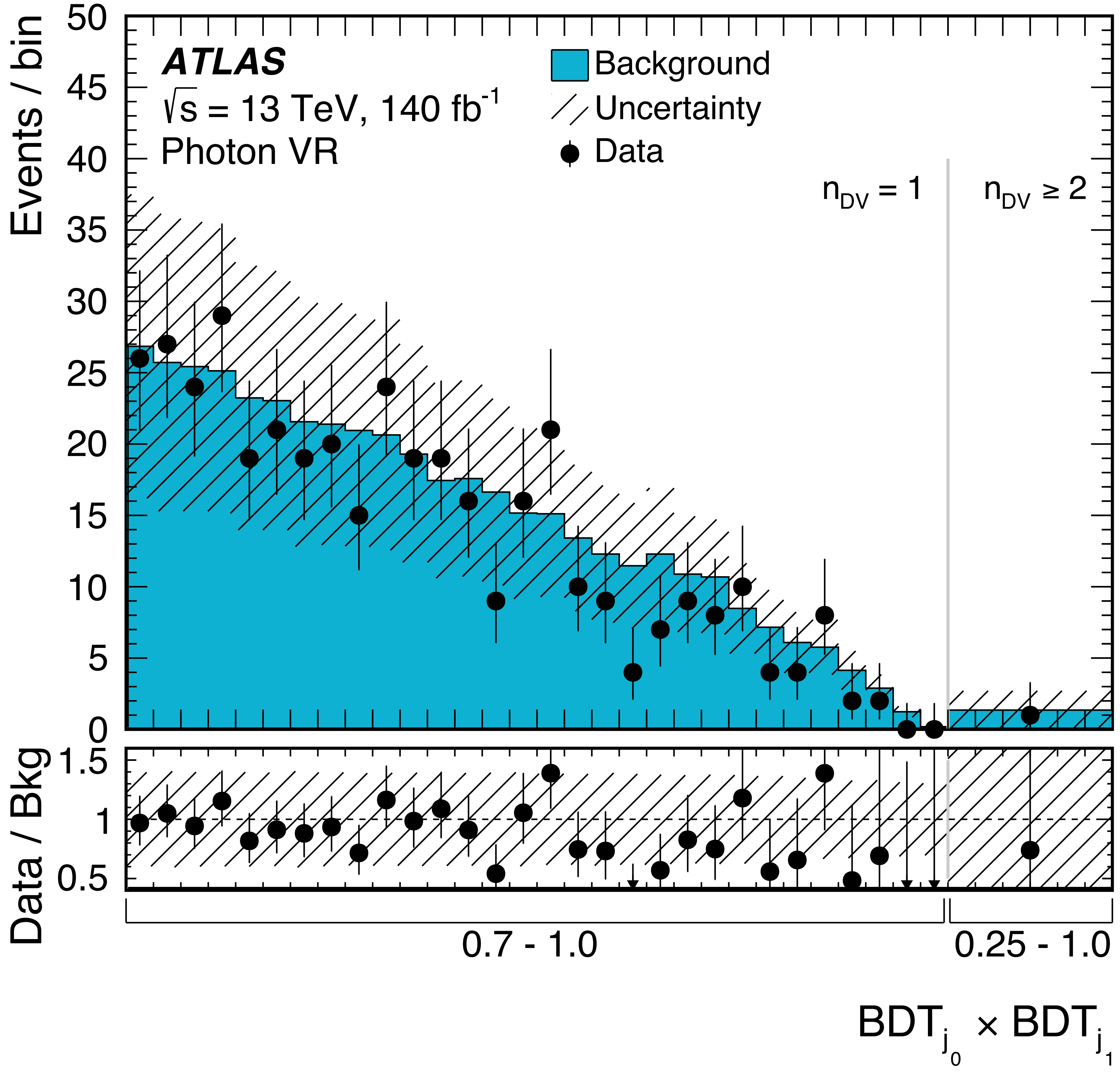
Example $n_{\mathrm{DV}} \geq 2$ event in VBF region:



Scalar Portal: ID searches

Background estimate validated in CRs with intermediate event-level discriminant values and dedicated γ+jets region





Summary of SUSY exclusion