Search for long-lived particles decaying to displaced jets at CMS in Run 3

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On behalf of the CMS collaboration

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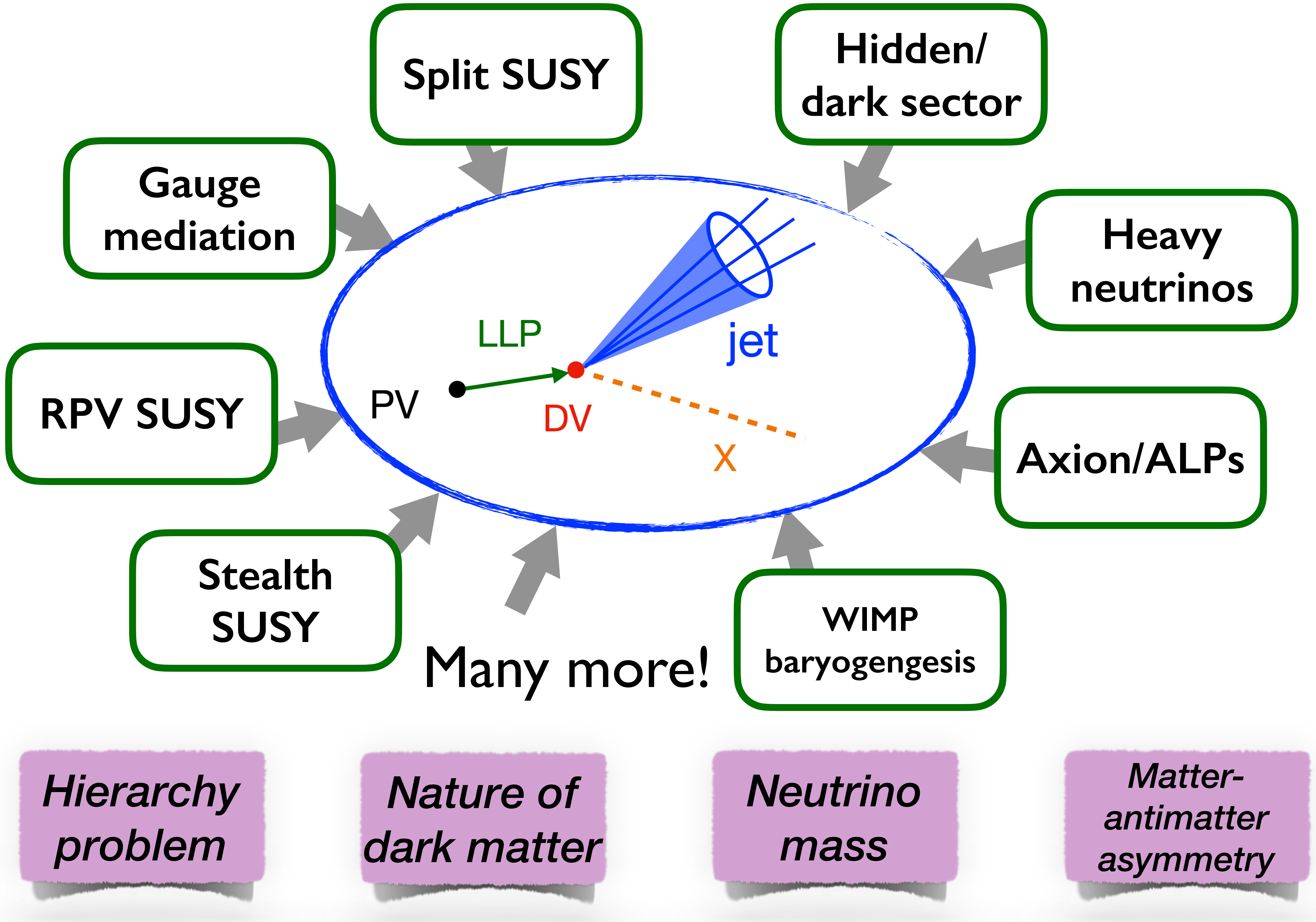
Displaced-jets signatures

- **Displaced-jets signatures:** long-lived particles (LLPs) decaying to hadronic final states

Can naturally appear in many BSM scenarios



- Small coupling
- High-mass mediator
- Compressed spectrum

A powerful tool to address long-standing puzzles in particle physics

Run-2 displaced-jets search

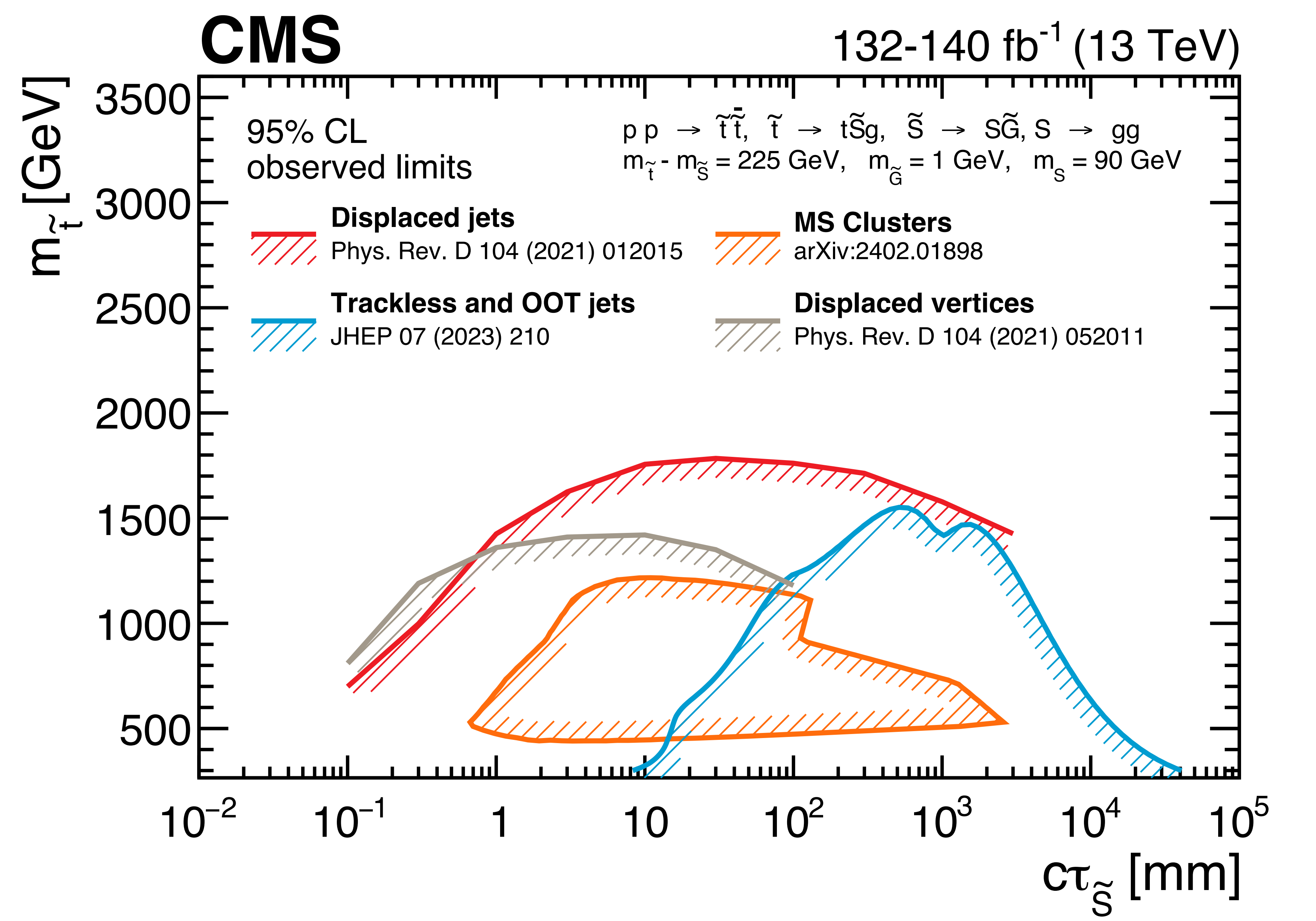
- **Full Run-2 CMS displaced-jets search** [Phys. Rev. D 104 (2021) 012015]

  13 TeV data collected in 2016-2018, $132\ \mathrm{fb}^{-1}$

  - Providing the widest coverage within the LHC-LLP program;
  - World-leading sensitivities to a large variety of LLP models, for LLP masses from ~10GeV to ~3TeV

Many more interpretations can be added

- Example: stealth SUSY reinterpretation (CMS dark-sector review paper)



Many interpretations, the best sensitivities to Split SUSY, gauge-mediated SUSY, RPV SUSY (λ''_{323}, λ'_{x3y}, η''_{3xx},…), exotic Higgs decays,…

Early Run-3 result

- **We also have an early Run-3 result public recently!** [CMS-PAS-EXO-23-013]

Contact: cms-pag-conveners-exotica@cern.ch 2024/03/25

Search for low-mass long-lived particles decaying to displaced jets in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

The CMS Collaboration

Utilizing 13.6 TeV data collected in 2022

$\mathscr{L}$: 34.7 fb^{-1}

- In the early Run-3 analysis, we focus on low-mass hadronically decaying LLPs within ~10-60 GeV
  - Not because it's easy, but because it's hard — calling for innovations and breakthroughs in our experimental techniques;
  - High scientific importance — expected to be a primary physics target over the next decade.

Physics motivations

- **The main physics motivation — Higgs portal hidden sectors**
- **Hidden/dark sector (HS):** a family of particles that are SM gauge singlets

  The hidden sector can communicate with the SM sector through different possible portals:

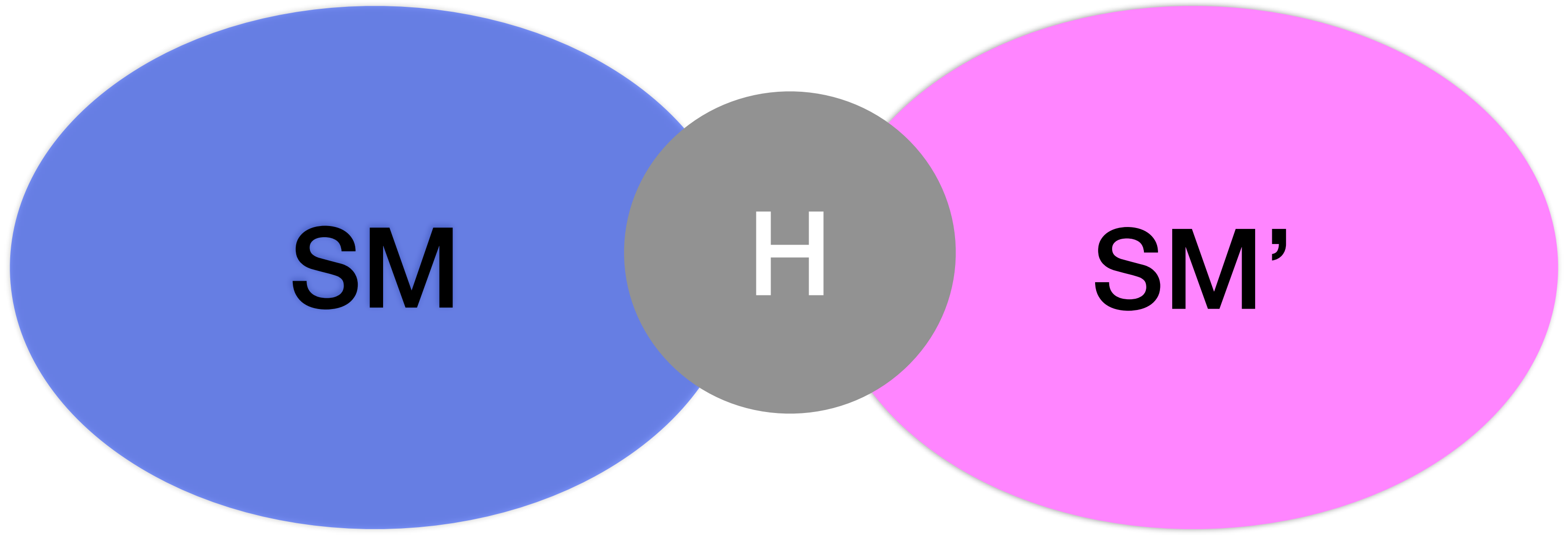
  Higgs boson (scalar), **dark photon** (vector), **heavy neutrino** (fermion), **ALP** (pseudo scalar)

The Higgs portal is possibly the most attractive one

- The Higgs boson has been discovered experimentally;
- The Higgs boson has a unique position in the standard model.

[Brain Patt & Frank Wilczek, 2006]

A well-motivated example: Neutral naturalness



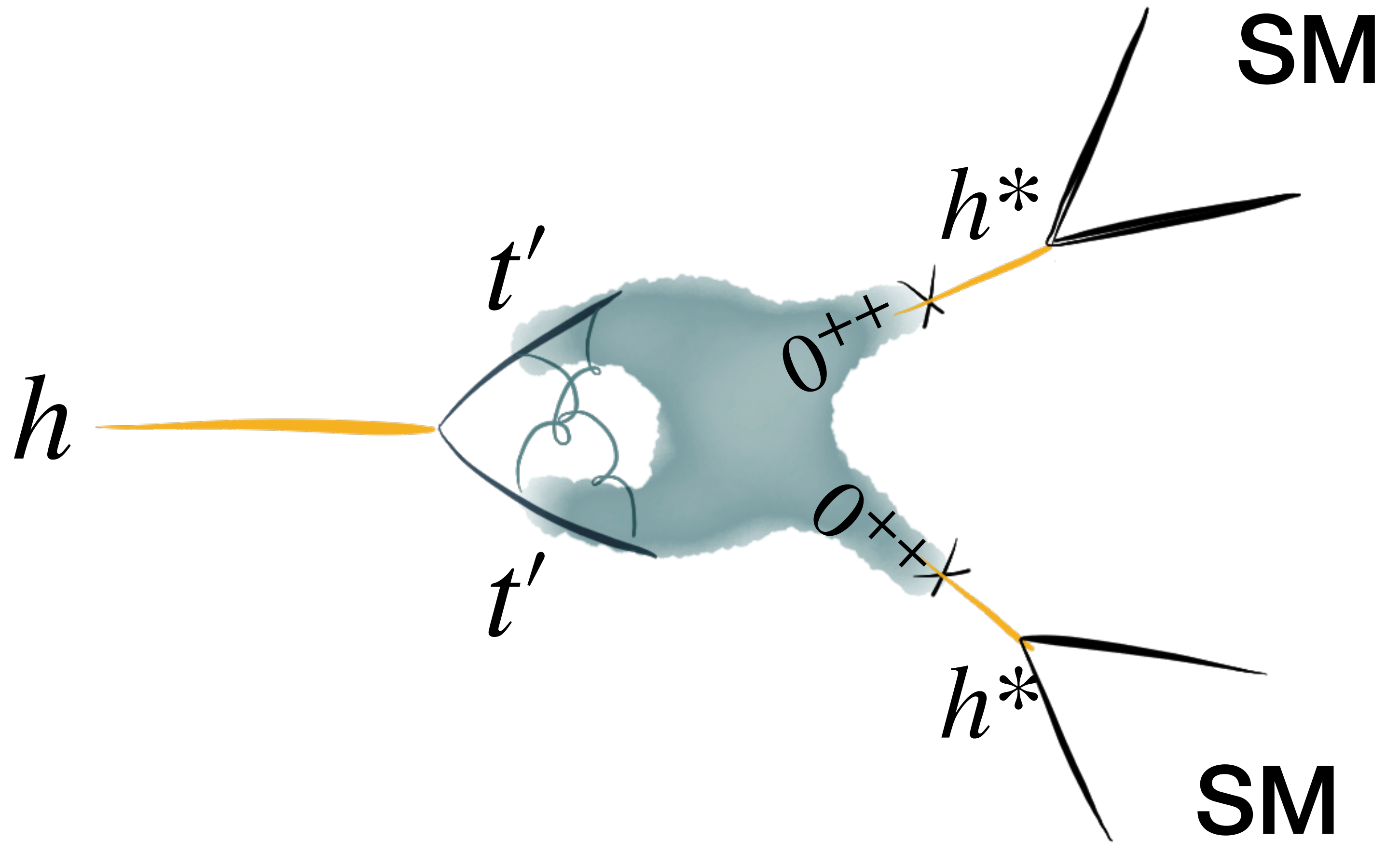
- Higgs mass protected by a global symmetry between the HS and SM;
- Also has many other important implications:
  - Dark matter, early-universe phase transition, baryogenesis, Hubble-constant tension, etc.

Physics motivations

- **Long lifetime is a generic feature in Higgs-portal hidden sectors**

Decays of hidden-sector particles back to SM particles are suppressed by Higgs-portal interactions

Exotic Higgs decay signature: Higgs→LLPs→displaced jets



PC: Nathaniel Craig

[Strassler & Zurek, 2006]

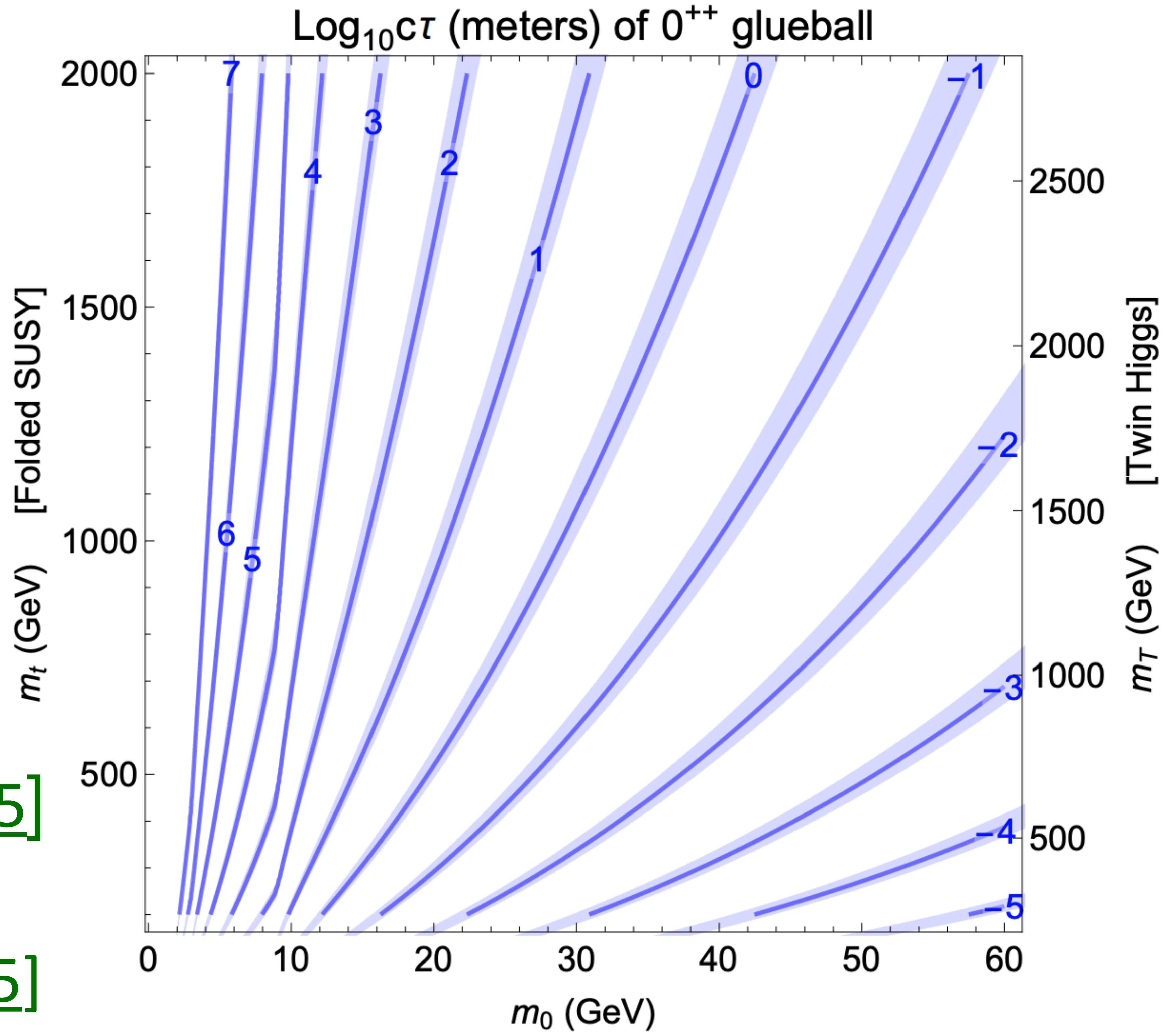
[Strassler & Zurek, 2006]

[Craig, Katz, Strassler, Sundrum, 2015]

[Curtin & Vehaaren, 2015]

[Csaki, Kuflik, Lombardo, Slone, 2015]

CERN LHC Higgs Yellow Report



- LLP → bb decay is usually preferred because of the Higgs-portal interaction;
- Tracker-based searches provide critical coverages for the central region of the related phase space
- The branching ratio of the exotic Higgs decay can easily be made very small
  - **Will remain a primary physics target throughout the HL-LHC and beyond**

Physics motivations

- **Expected to be a primary physics target over the next decade**

> *"Searches for exotic Higgs boson decays remain highly motivated… these new particles could be our only direct window into physics beyond the Standard Model. … Long lifetimes are a generic feature of BSM particles in these cascades, yielding hard to detect but extremely low background signatures. The rate of such decays can be very small, so large samples of Higgs bosons are needed."*
>
> **— 2023 P5 Report**

Experimental challenges

- **Tracker-based searches for $\mathrm{H} \rightarrow \mathrm{LLPs}$ with hadronic final states are extremely challenging**

Especially for ggF production

- ‣ Soft objects (jets, tracks, vertices);
- ‣ Overwhelming QCD background:

Requires a background rejection of $\sim 10^{10}$

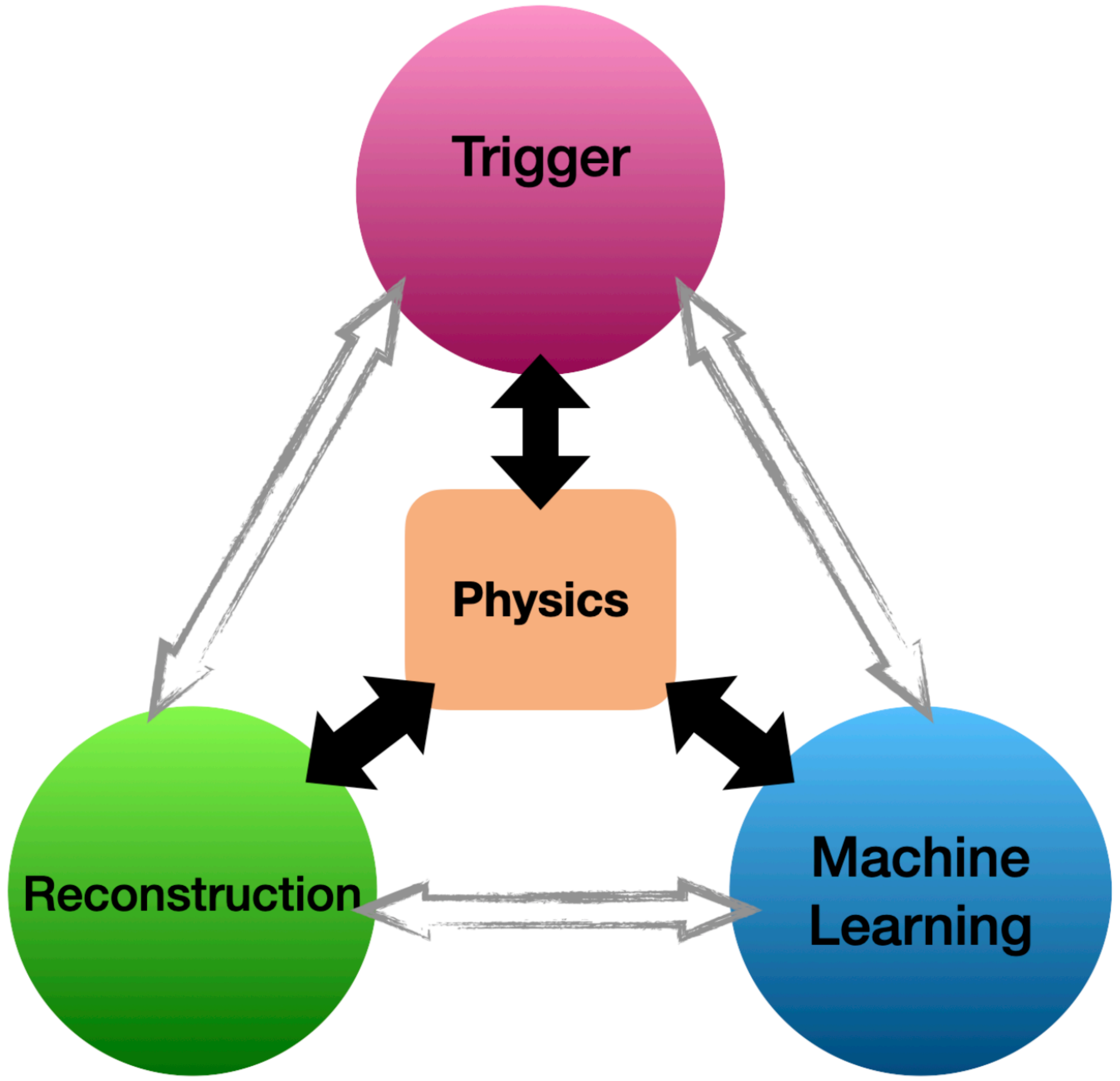
Difficult for trigger;

Difficult for reconstruction;

Difficult for offline selection;

A complete blind spot before April 2020

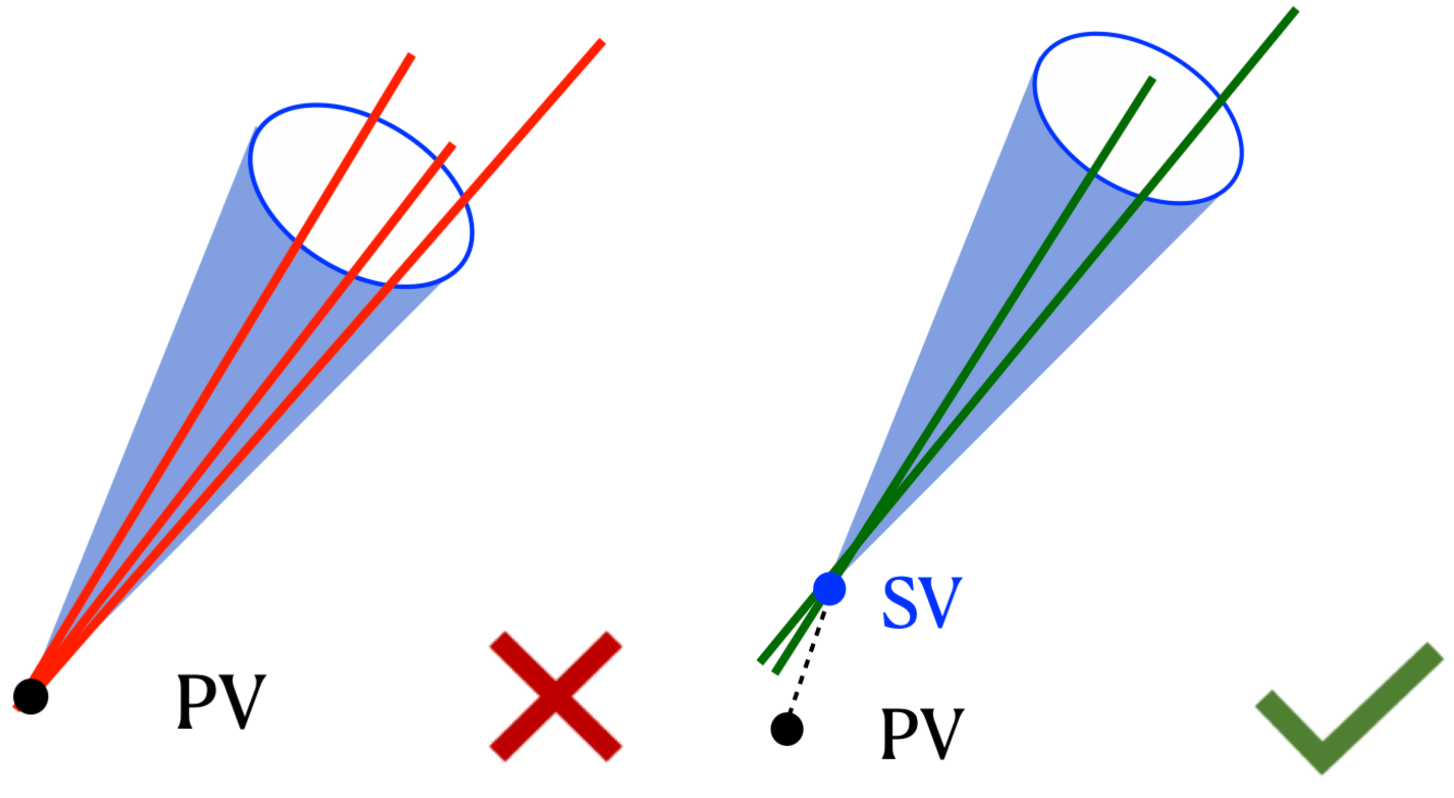
Probed for the first time by our Run-2 displaced-jets search



New techniques in trigger, reconstruction, and machine learning have been developed for the early Run-3 analysis, significantly pushed the boundaries of what we can do at CMS.

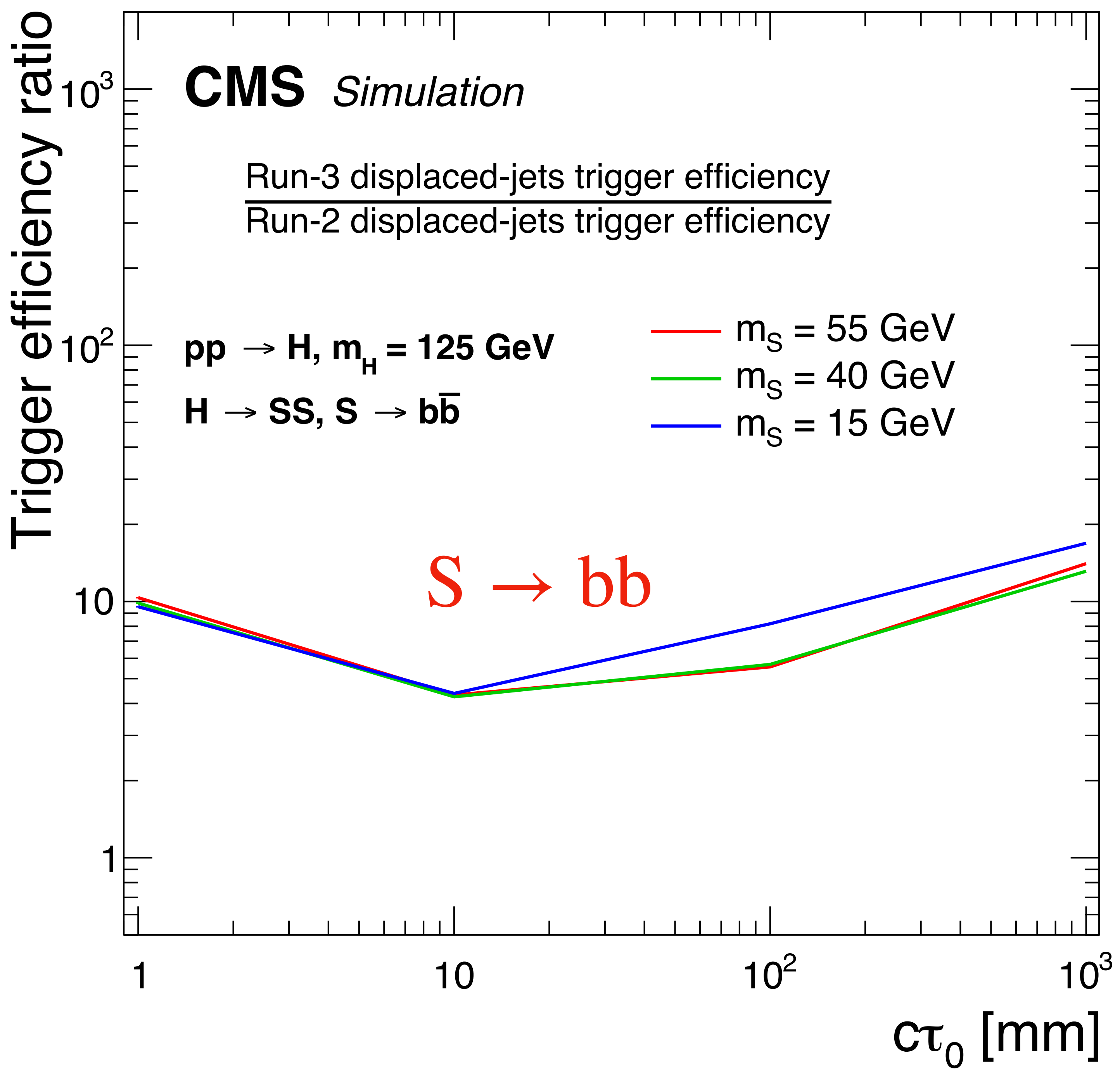
New displaced-jets triggers

- We developed and implemented new displaced-jets triggers in Run 3 to significantly improve the efficiencies for low-mass LLPs:
  - Tracking-based online displaced-jets tagging has been rethought and redesigned;
  - Leading to a factor of ~5-10 gain in efficiencies for $H \to \mathrm{LLPs}$.



Efficiency gains w.r.t. Run 2

[CMS-DP-2023-043]



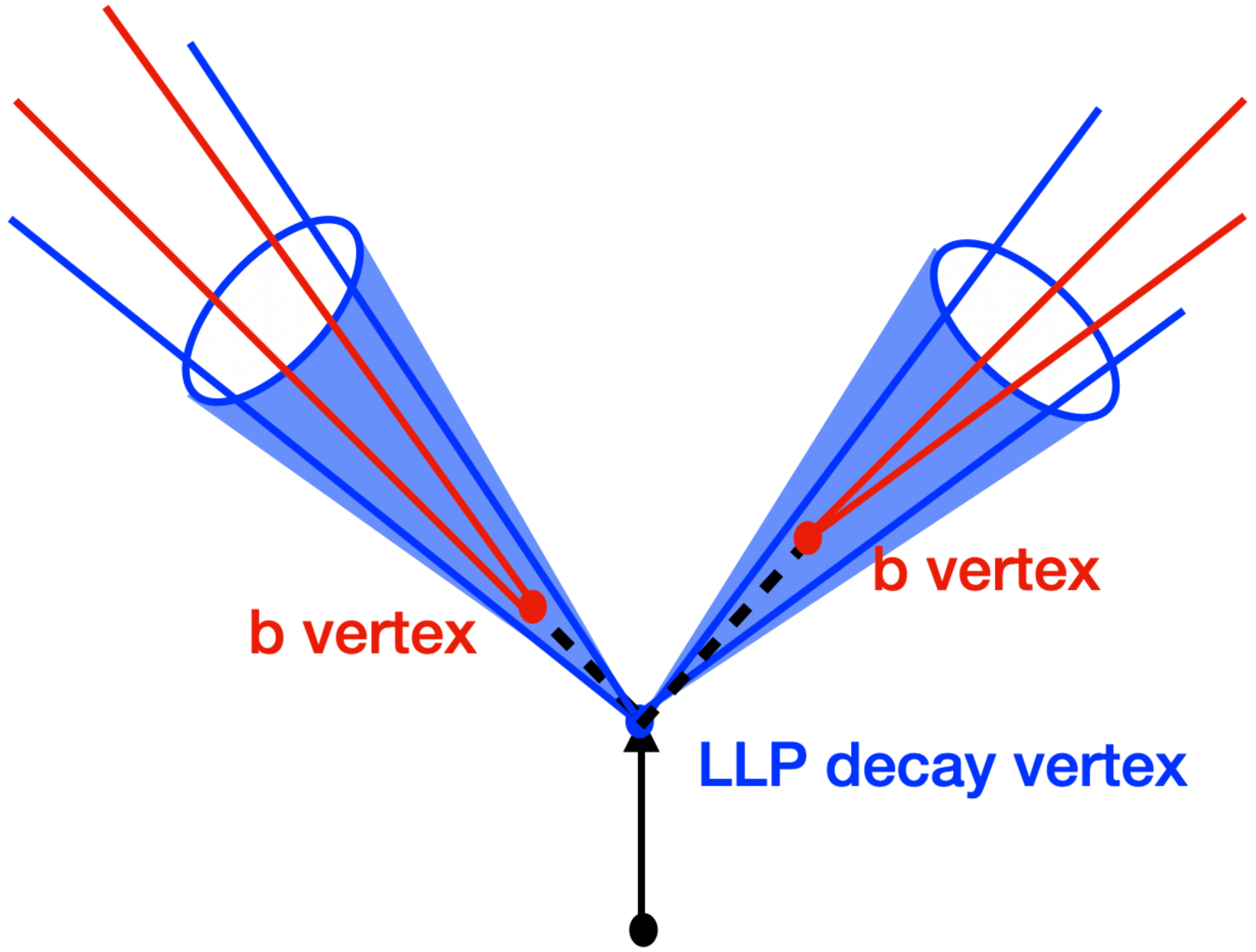
The trigger efficiencies have been further improved in 2023 and beyond, thanks to the **new LLP parking**

(CMS scouting and parking review paper — arXiv:2403.16134)

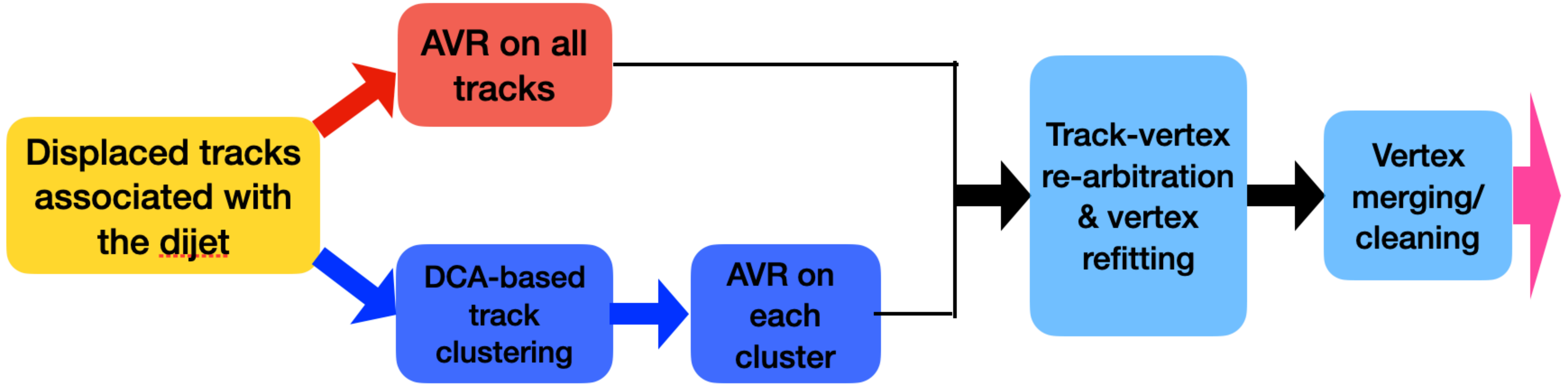
Displaced vertex reconstruction

New displaced vertex reconstruction algorithm has been developed for Run 3

- Strongly driven by the physics consideration on tackling complex LLP decay systems like $S \to bb$;
- Critical for extracting more physics information from LLP decay systems.



Starting with the displaced tracks ($IP_{2D} > 0.5$ mm, $Sig[IP_{2D}] > 5.0$) associated with **two jets**

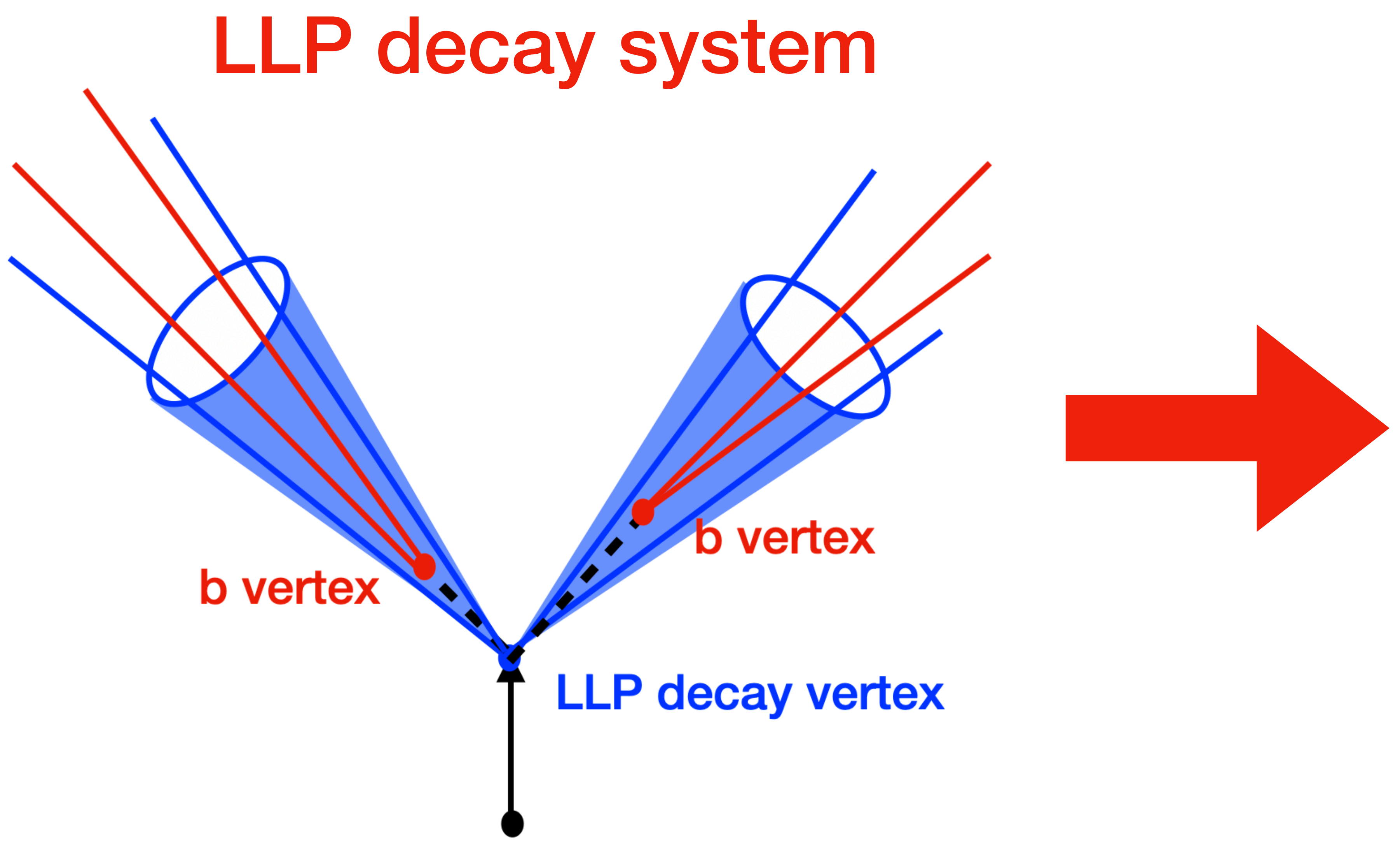


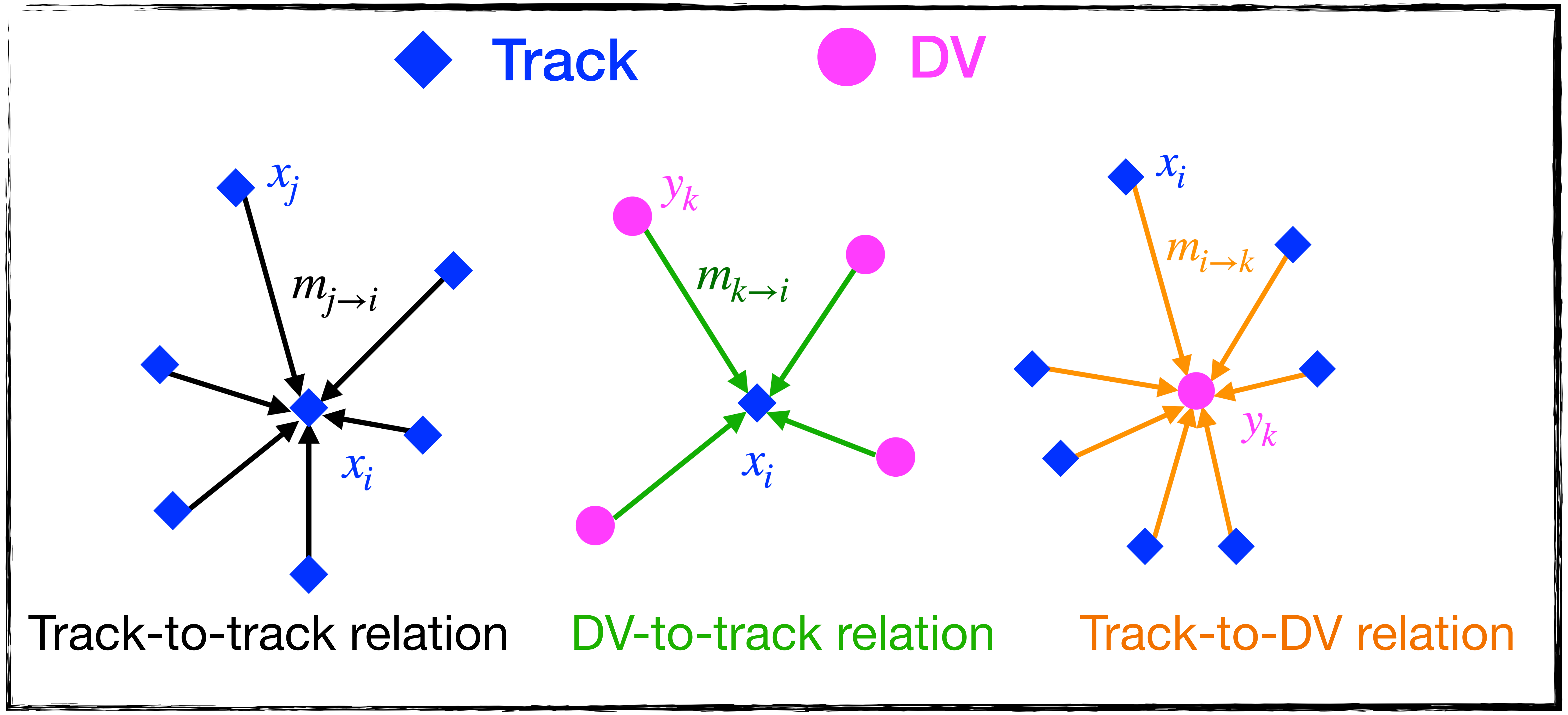
Compared to the Run-2 algorithm, the main difference is the reconstruction of the additional DVs within the dijet, which is crucial for the improvements of sensitivities to $S \to bb$ decays

New GNN-based LLP tagging

- **New Graph Neural Network (GNN) based LLP taggers have been developed in Run 3.**

  Driven by the physics insight that track-to-vertex relations are critical physics information for LLP decays:
  - We chose GNN not because it's fashionable, but because it perfectly fits our physics needs;
  - The design of the ML architecture is driven by and tailored for physics considerations.

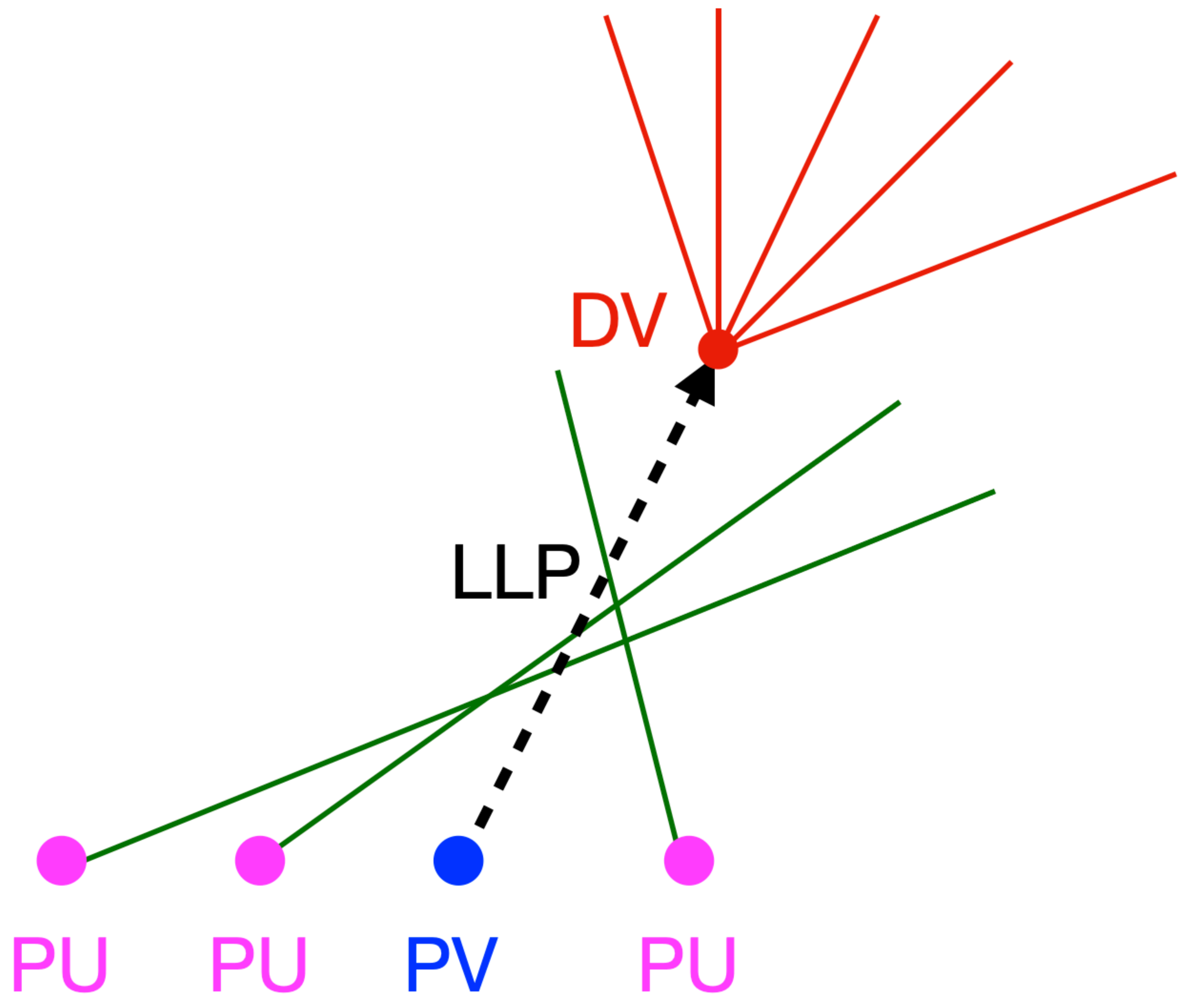


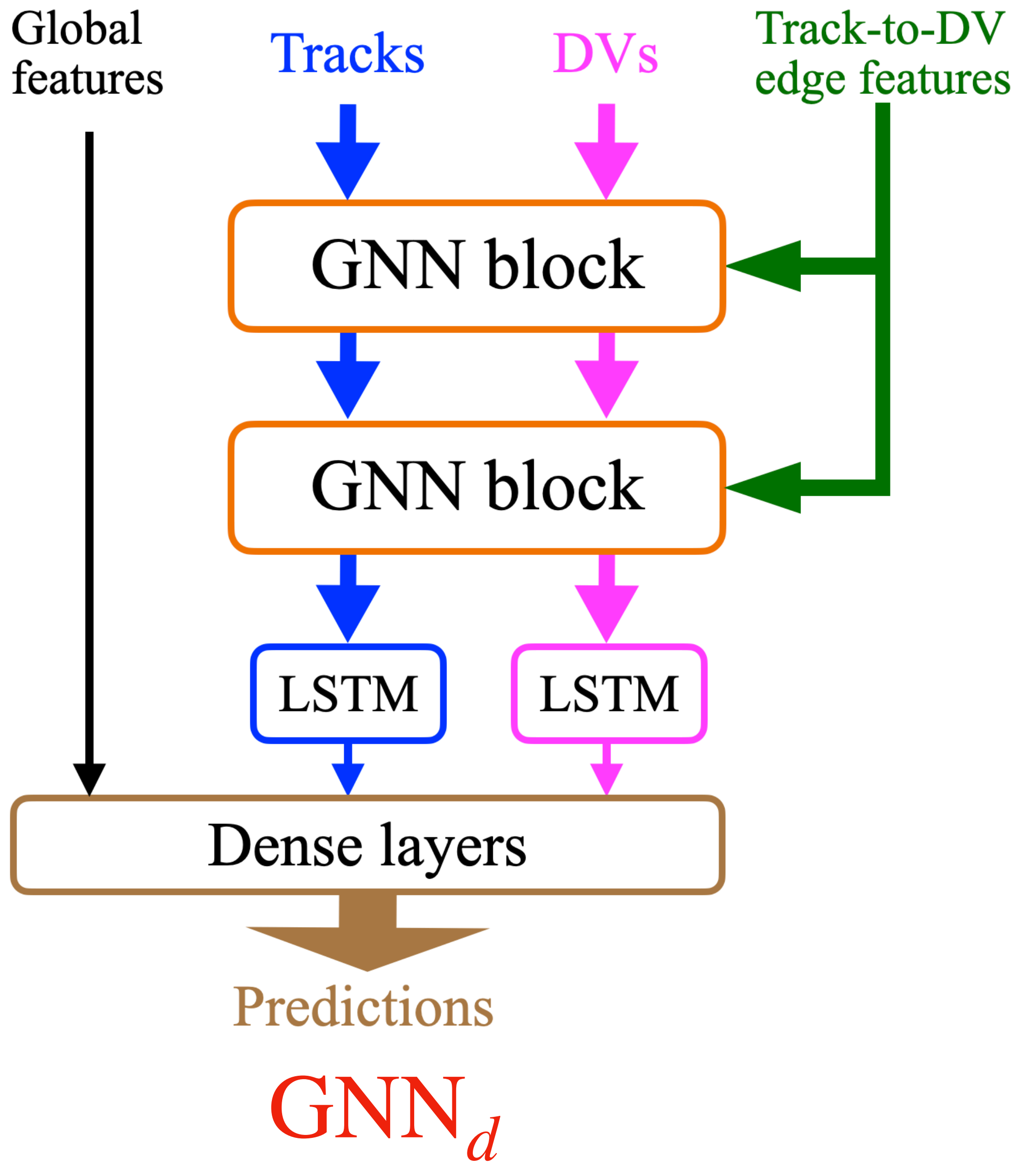


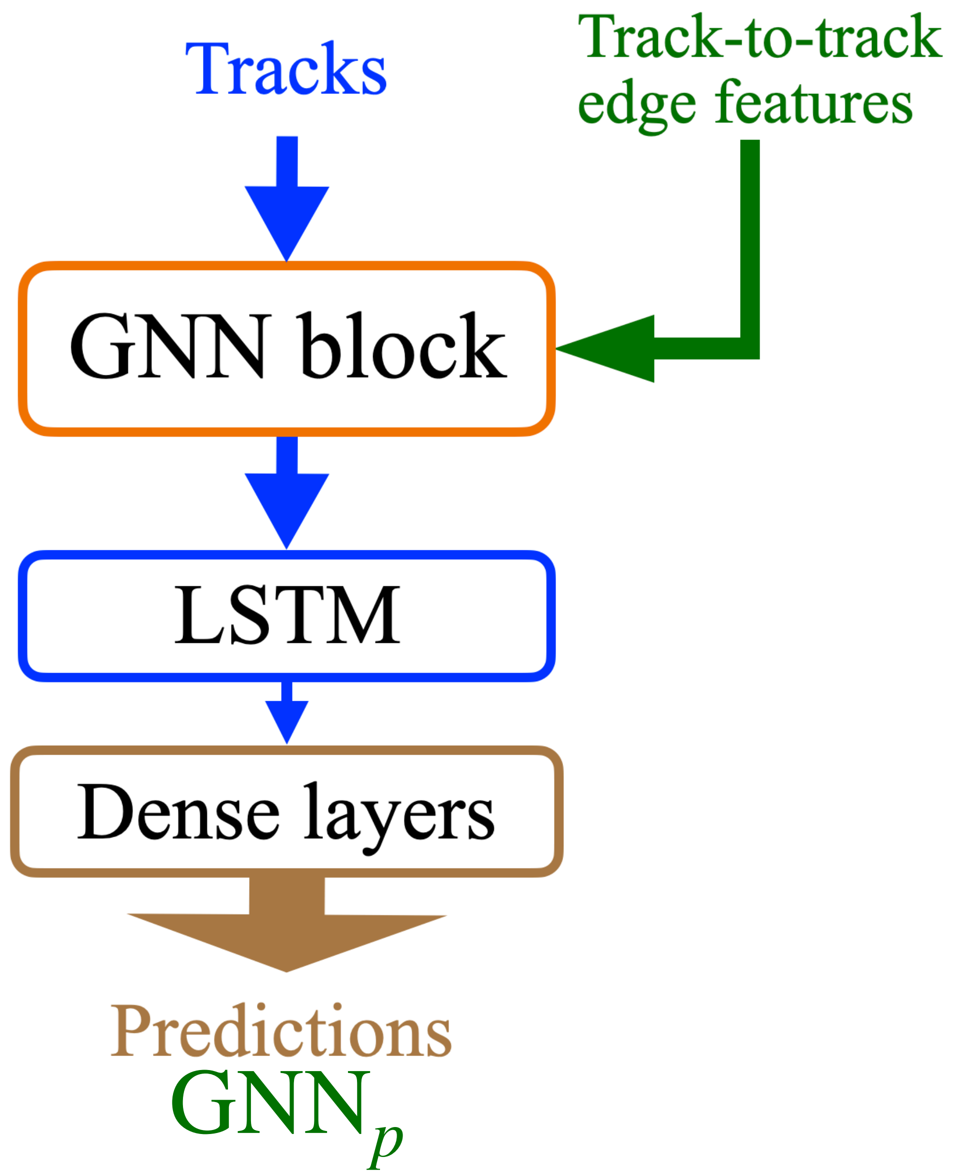
Message-passing formalism

New GNN-based LLP tagging

- **New GNN-based LLP taggers have been developed in Run 3.**
  - We developed and implemented two GNN taggers using the tracks and DVs associated with a given dijet:
    - GNN_d: taking **displaced tracks** and **DVs** as inputs, incorporating track-to-DV edge features like track-to-DV associations;
    - GNN_p: taking **prompt tracks** ($\mathrm{IP_{2D}} < 0.3\ \mathrm{mm}$) as inputs, incorporating track-to-PV/PU association information







The two taggers have small correlations for the background processes, and thus enable data-driven **ABCD method** for the background estimation

Event selection and background estimation

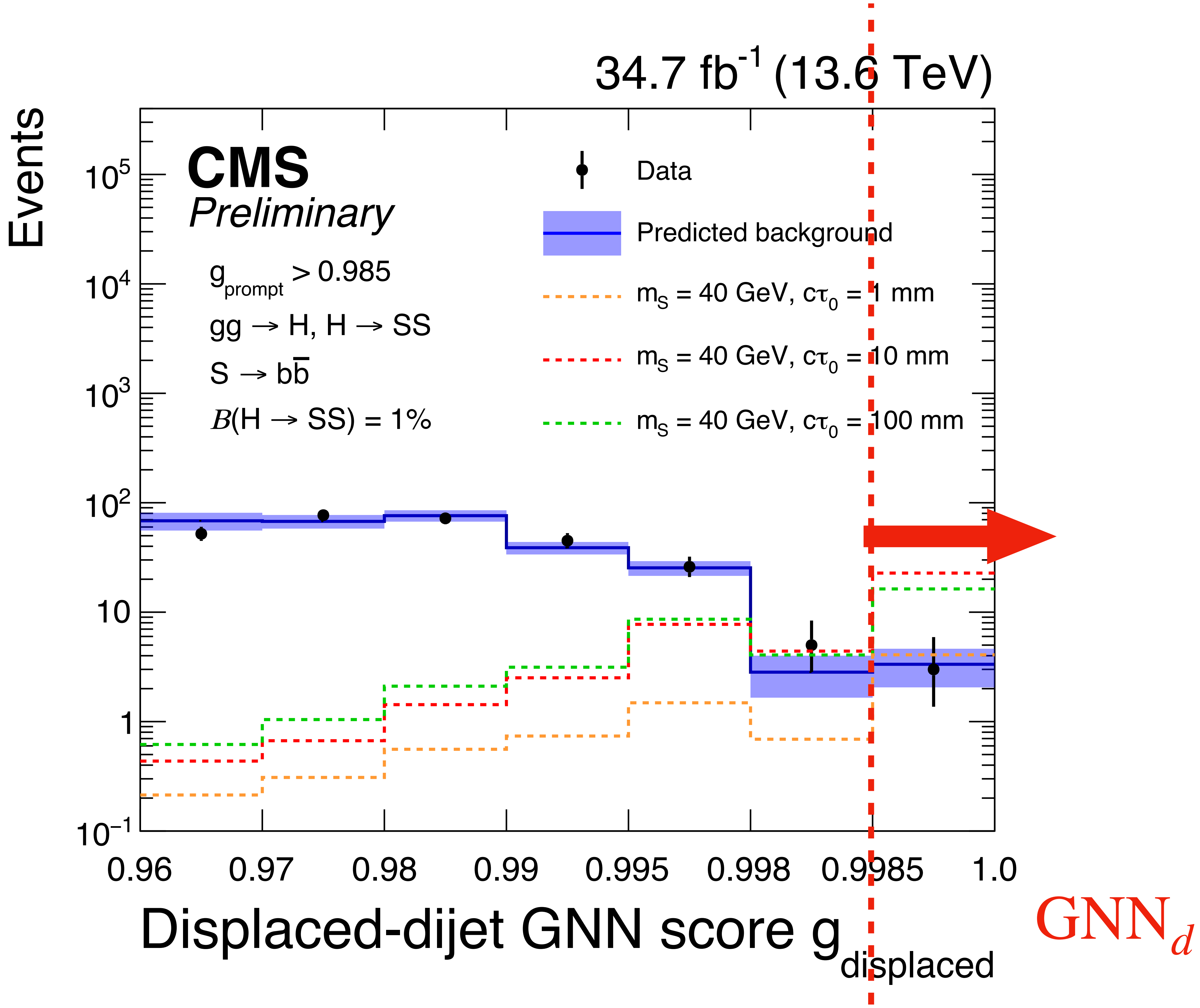
- **In contrast to the dedicated developments in low-level techniques, the high-level event selection is very simple**

  - After the trigger selections, we build and examine all possible dijet candidates using jets satisfying $p_T > 40\text{GeV}, \, |\eta| < 2.0$;

  - We compute $\mathrm{GNN_d}$ and $\mathrm{GNN_p}$ for each dijet and select the dijet having the largest $\mathrm{GNN_p}$ score in a given event;

  - Simple cuts on $\mathrm{GNN_d}$ and $\mathrm{GNN_p}$ to extract signals (ABCD method for background estimation)

The search remains to be highly model independent



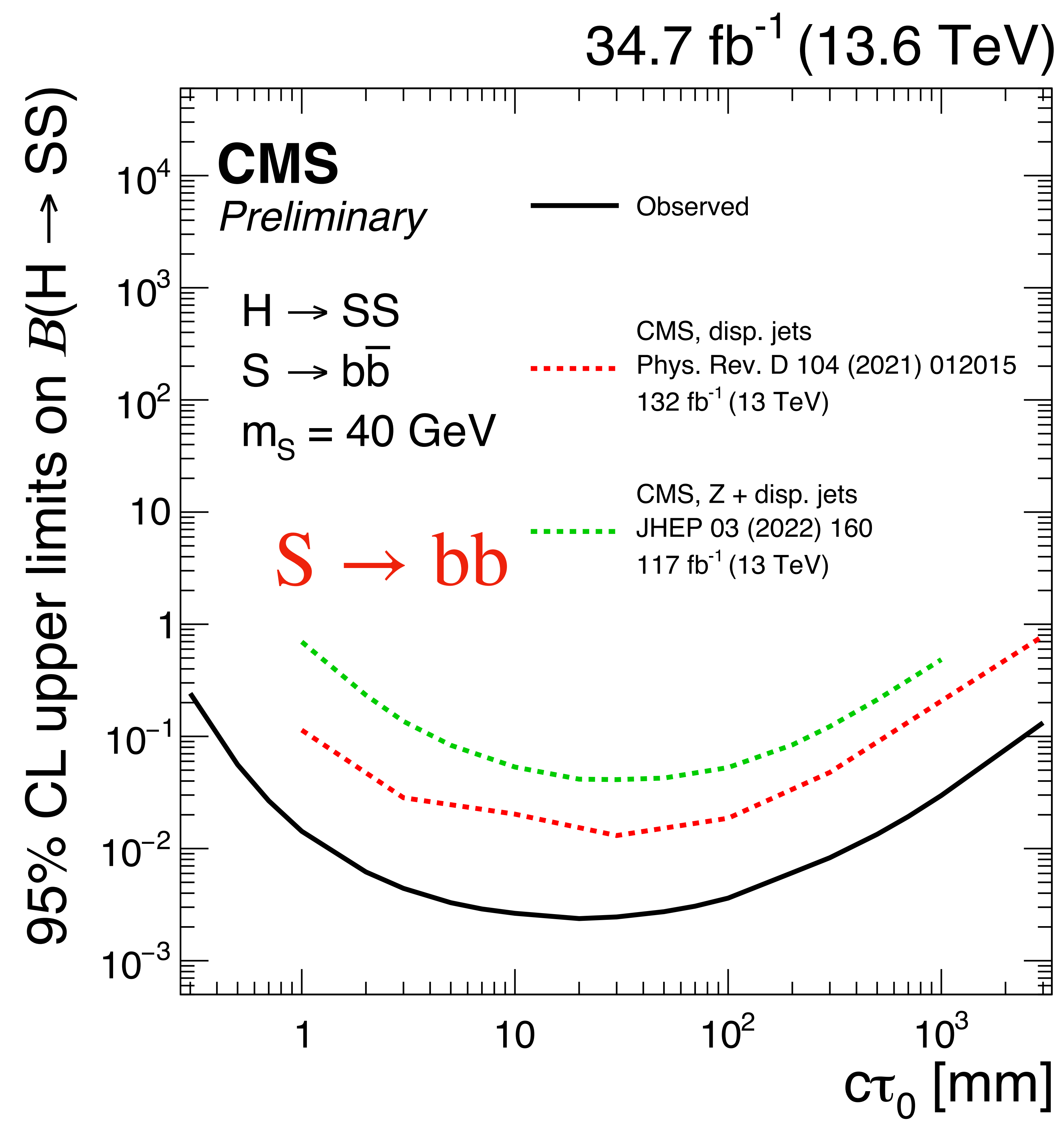
Predicted background yield: 3.34 ± 1.28 **(stat. only)**

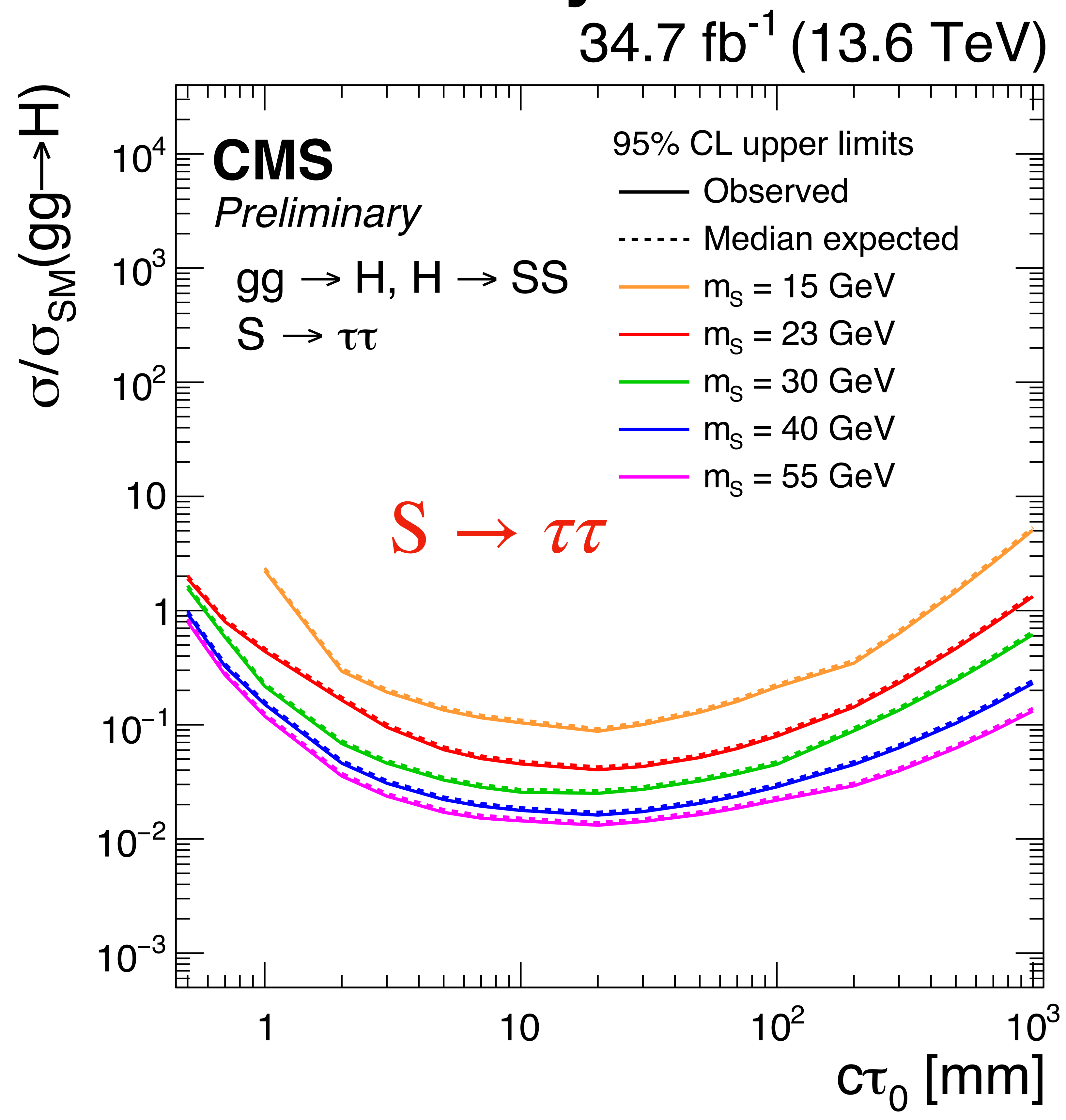
Observation: 3

Results

- Limits are set on the branching fraction for the Higgs boson to decay to LLPs

Much better than any other existing results



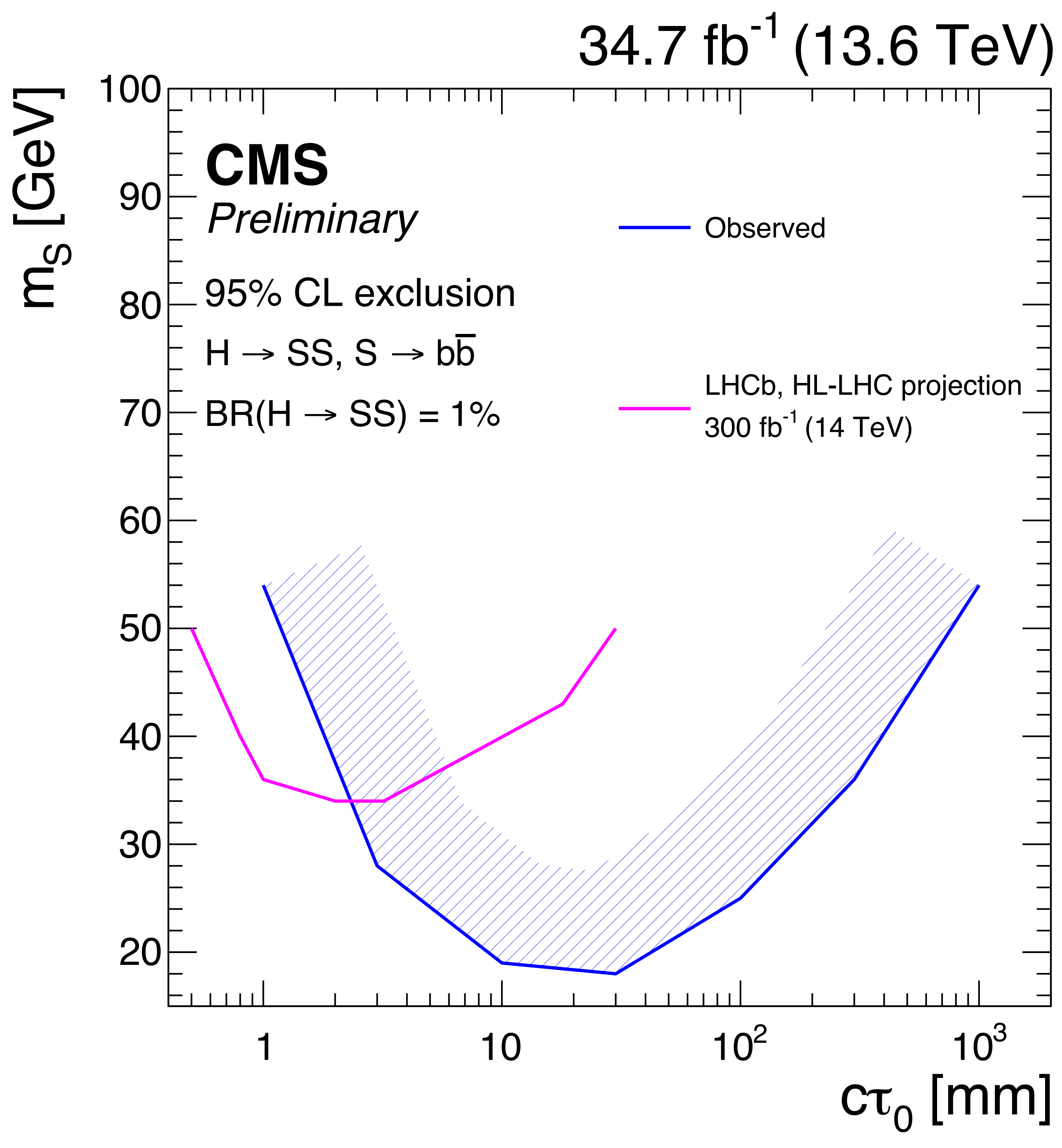


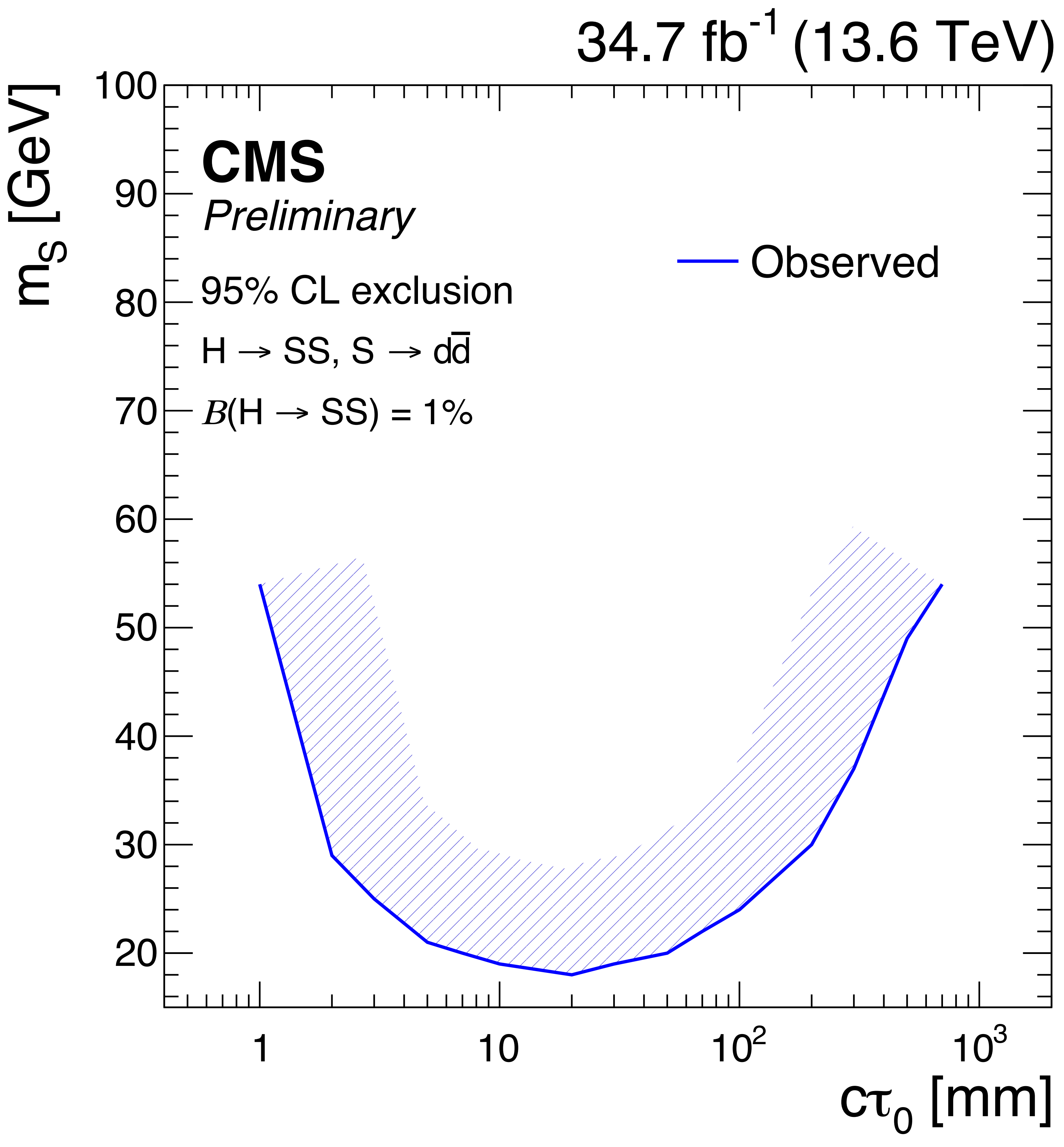
With only 1/4 of the luminosity compared to Run 2, achieved a factor of 10 improvement!

First-ever displaced hadronic tau sensitivities with decay lengths smaller than ≈ 1 m

Results

- BR=1% exclusion on LLP masses as a function of lifetime





$S \rightarrow bb$ and $S \rightarrow dd$ limits are now similar

(not the case in the Run-2 search)

Thanks to the new DV reconstruction and GNN taggers

A full HL-LHC projection of LHCb is shown for comparison [arXiv:2105.12668]

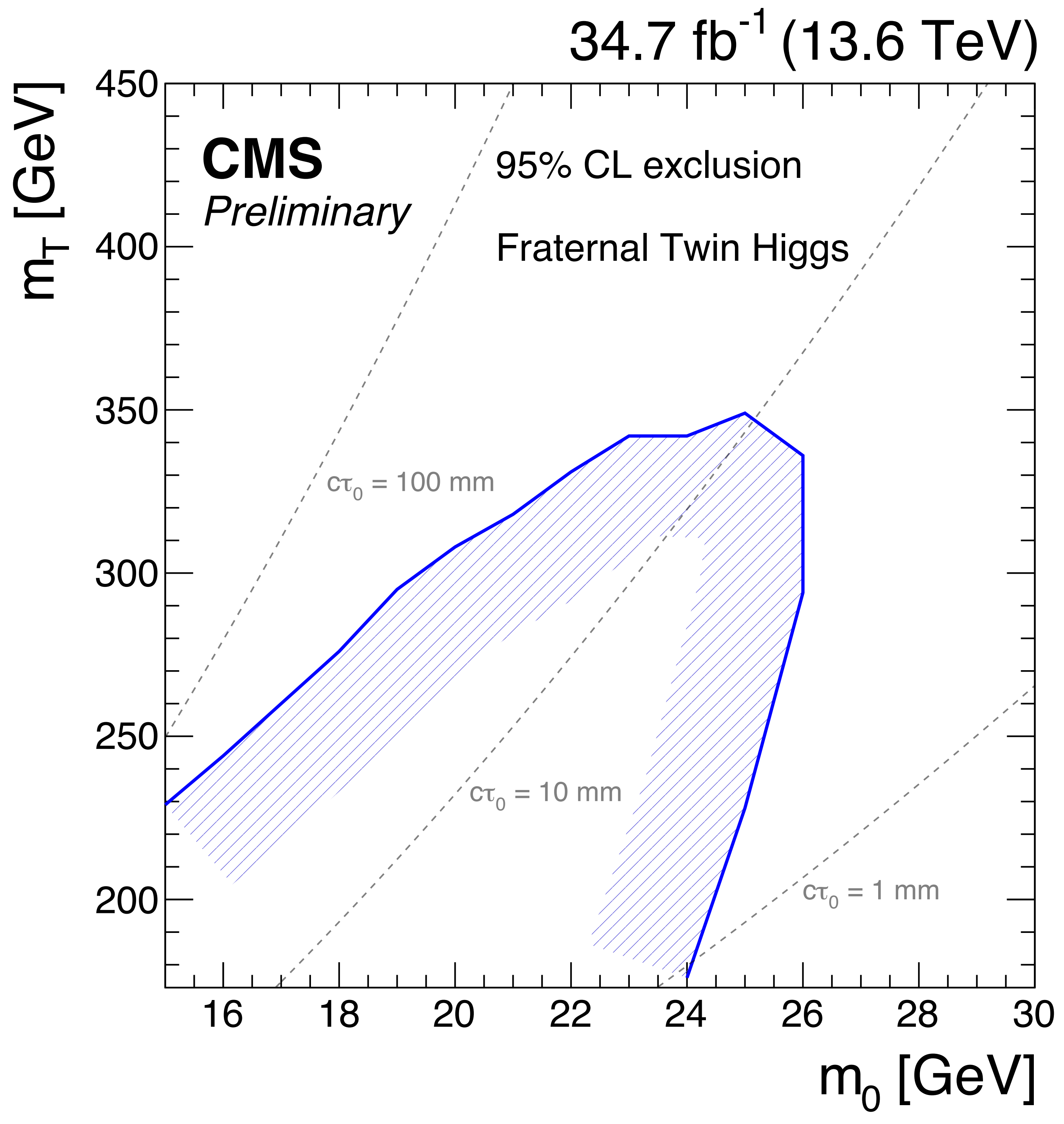
Interpretations for the neutral-naturalness scenario

- Interpretations for the fraternal Twin Higgs and folded SUSY models in the neutral naturalness scenario

Fraternal Twin Higgs

[Craig, Katz, Strassler, Sundrum, 2015]

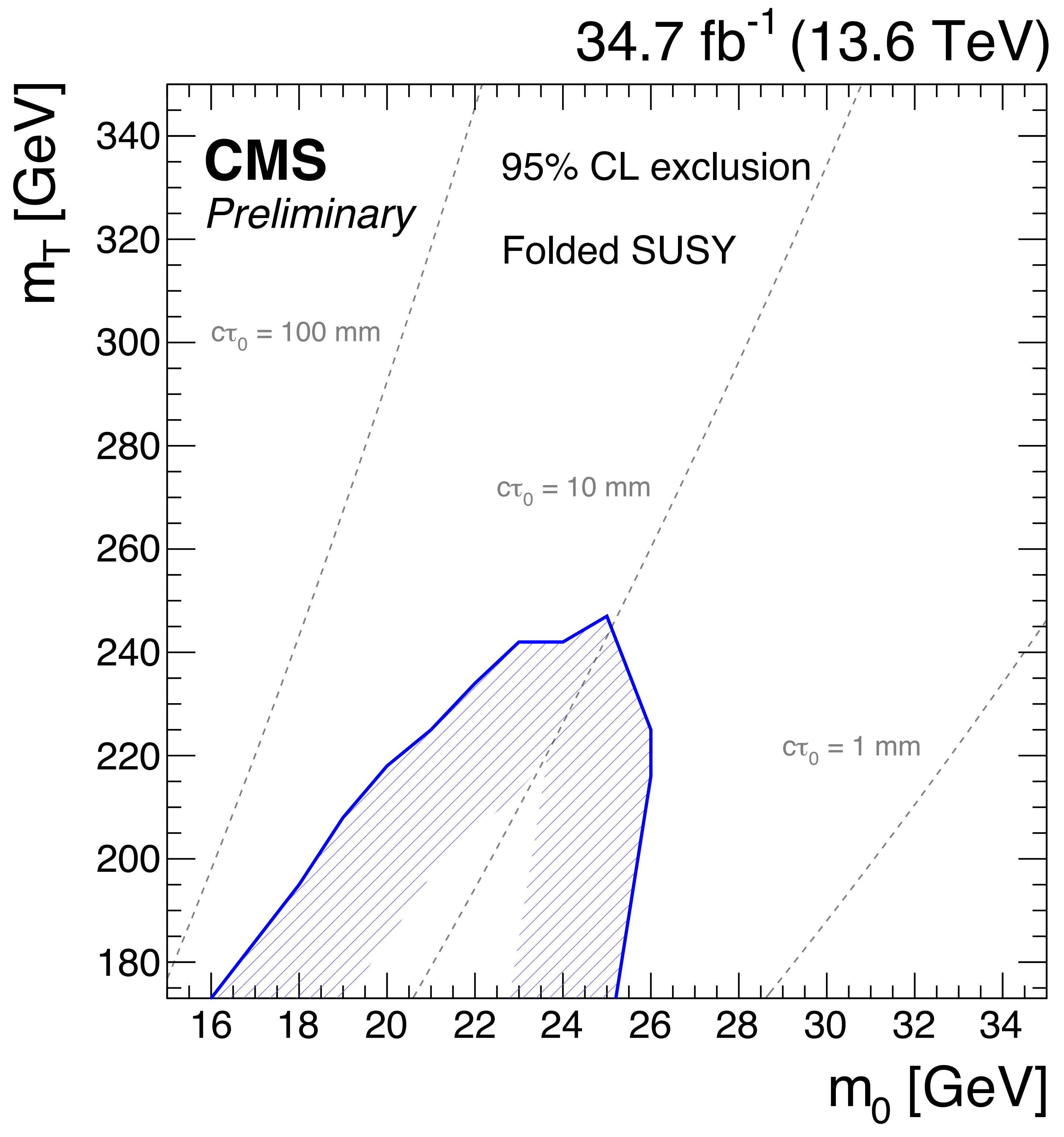
Hidden top mass



Hidden glueball mass

Folded SUSY

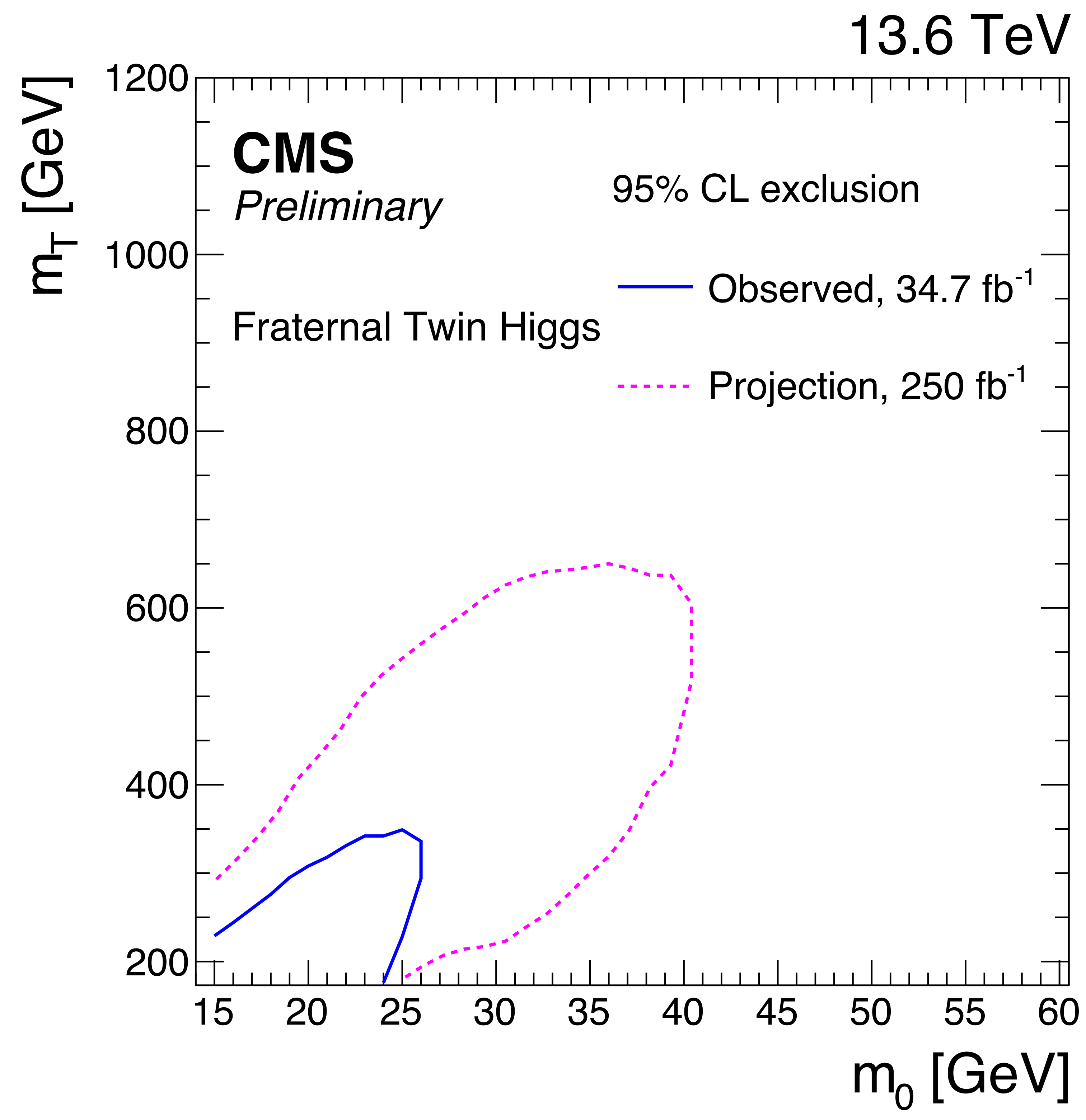
[Burdman, Chacko, Goh, Hrnik, 2006]

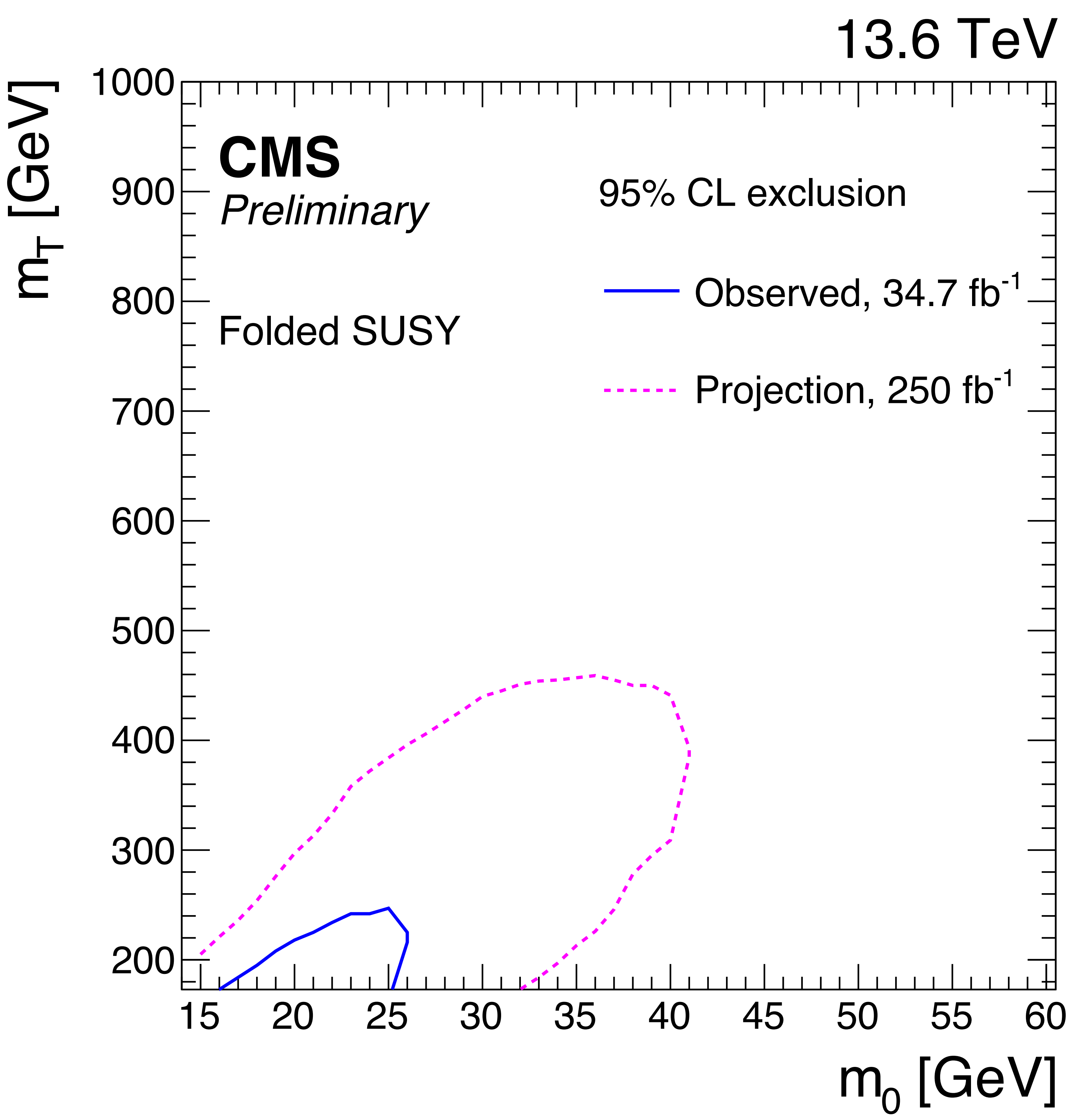


First experimental constraints

Projections with full Run-3 data

- The Run 3 of LHC is ongoing:
  - The data analyzed in this work is just a small fraction of the total data to be taken in Run 3
    - $34.7\ \mathrm{fb}^{-1}$ in 2022 v.s. $\approx 250\ \mathrm{fb}^{-1}$ in 2022—2025





Significant expansions of the coverages are expected by the end of Run 3;

More new techniques are under development, which will further significantly improve the sensitivities;

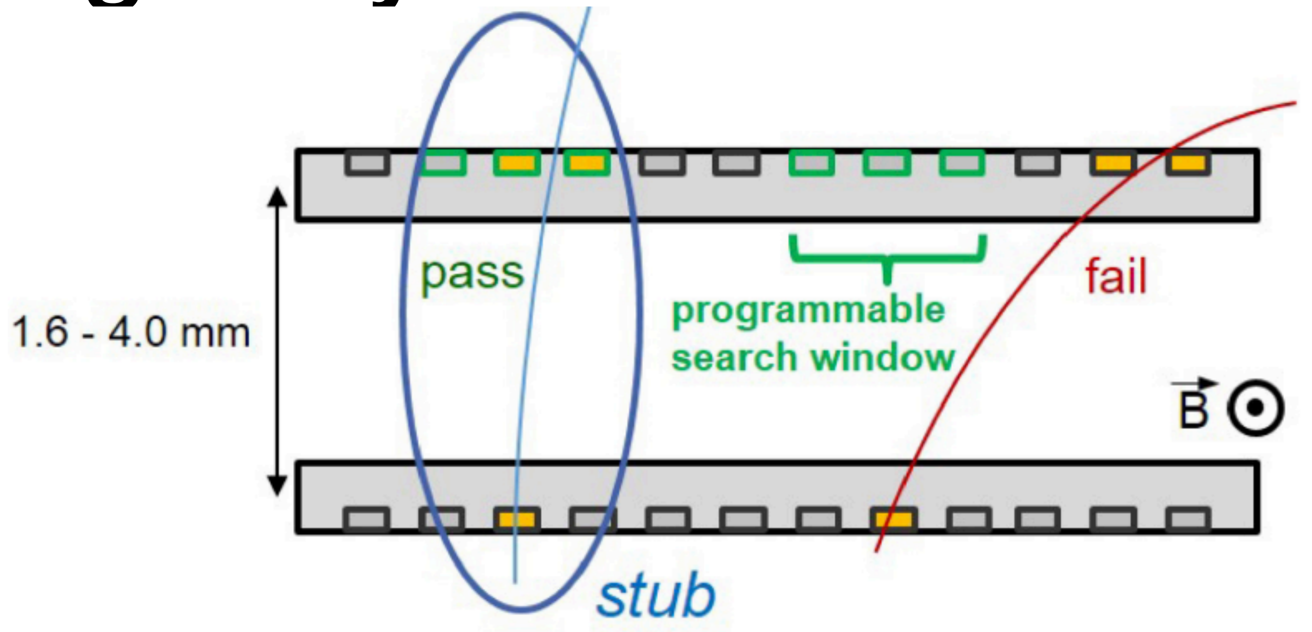
We should be able to reach or even surpass many future collider projections by the end of Run 3.

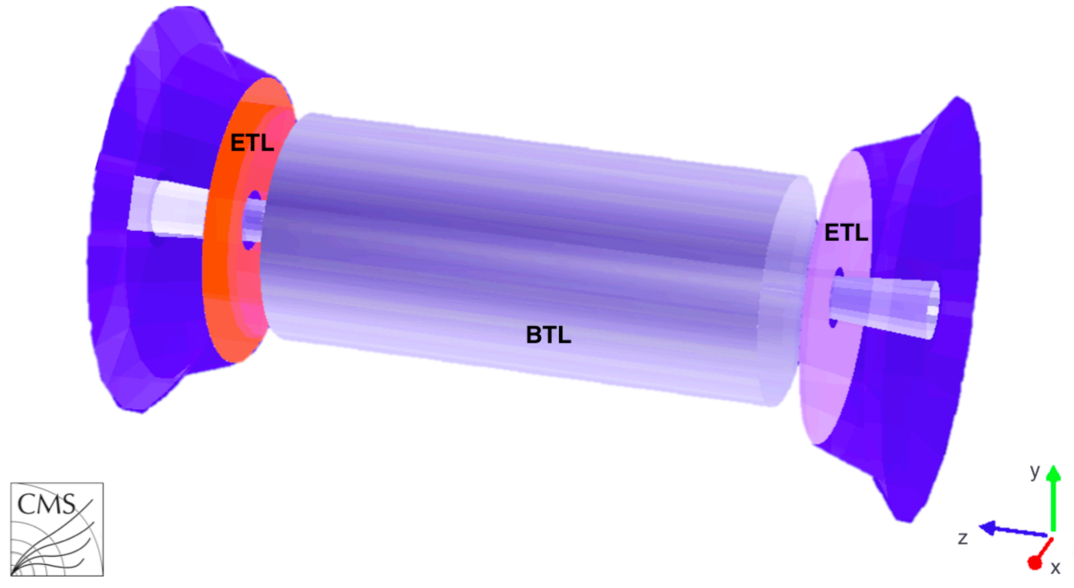
Summary and outlook

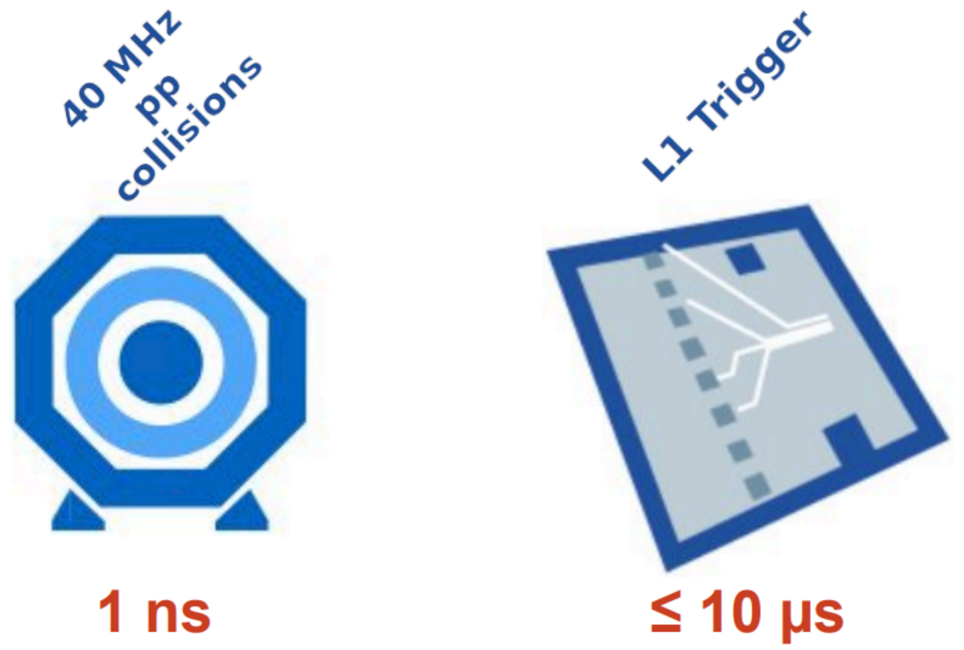
- We present a search for long-lived particles decaying into displaced jets, using the first year (2022) data collected in LHC Run3;
  - Novel techniques in trigger, reconstruction, and machine learning;
  - Up to a factor of 10 improvement over other results despite utilizing a much smaller dataset.

- This is just a new beginning of an exciting journey full of many physics opportunities
  - Much larger dataset to be analyzed by the end of Run 3;
  - More low-level developments — will further significantly improve the sensitivities;
  - The new techniques have great generalizability, many more exciting applications:
    - HNLs, ALP, high-quality axion, dark shower, dedicated displaced tau tagging;

- Will greatly benefit from the HL-LHC upgrades



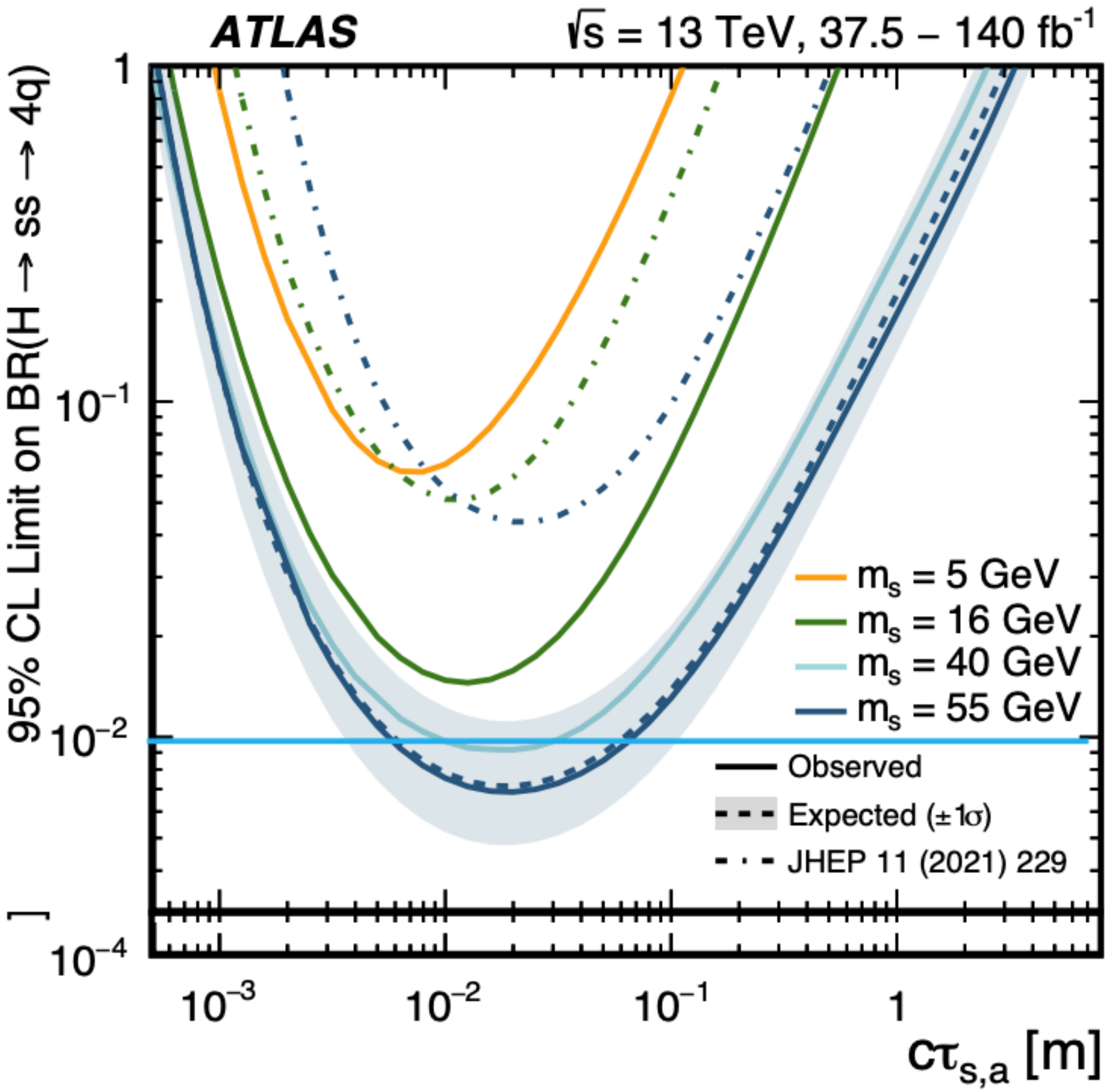


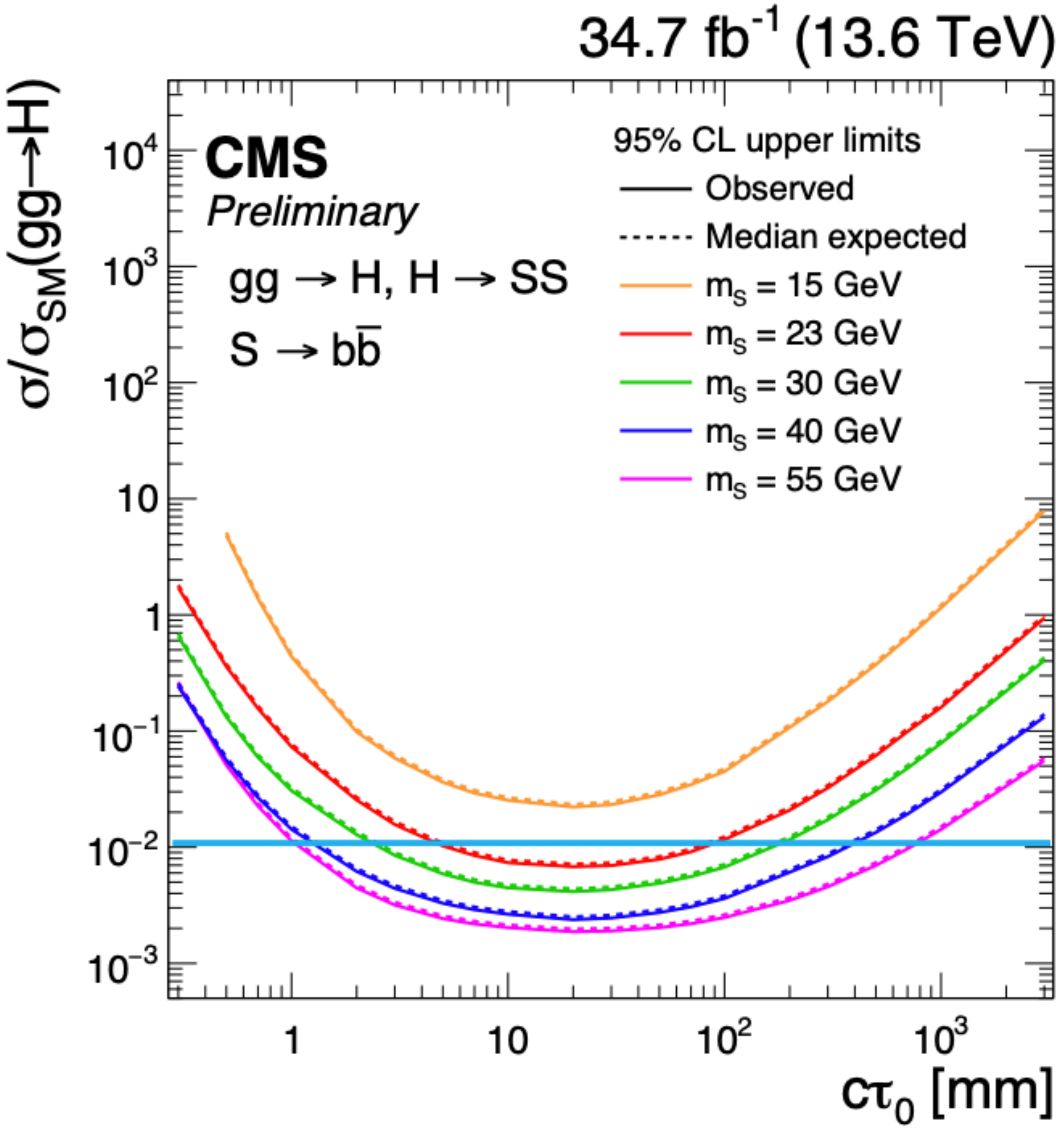


Backup

Comparison with the updated full Run-2 ATLAS results

https://arxiv.org/abs/2403.15332

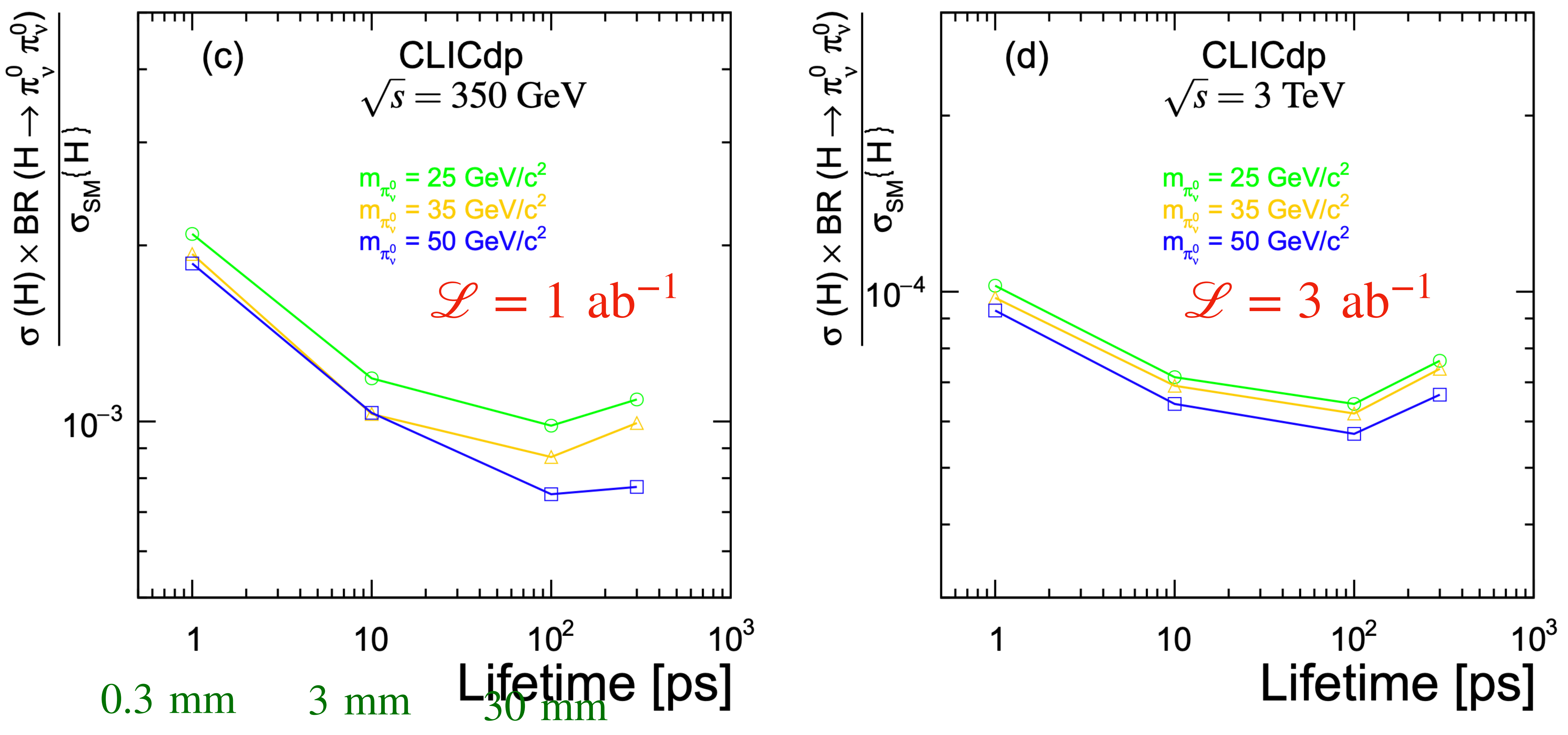




Comparison with future collider projections

- **There are also many projections for future collider experiments**
- We are in fact getting close to these projections even only with the first year data of Run 3.

Example: recent studies for CLIC [JHEP 03(2023)131]



By the end of Run 3, we should be able to reach or even surpass some of these projections from future colliders.