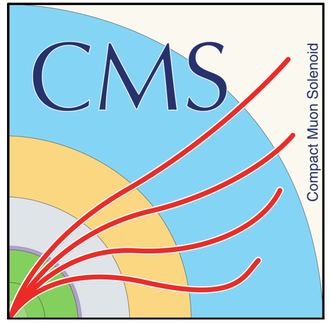


BROWN

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

Jingyu Luo

Brown University

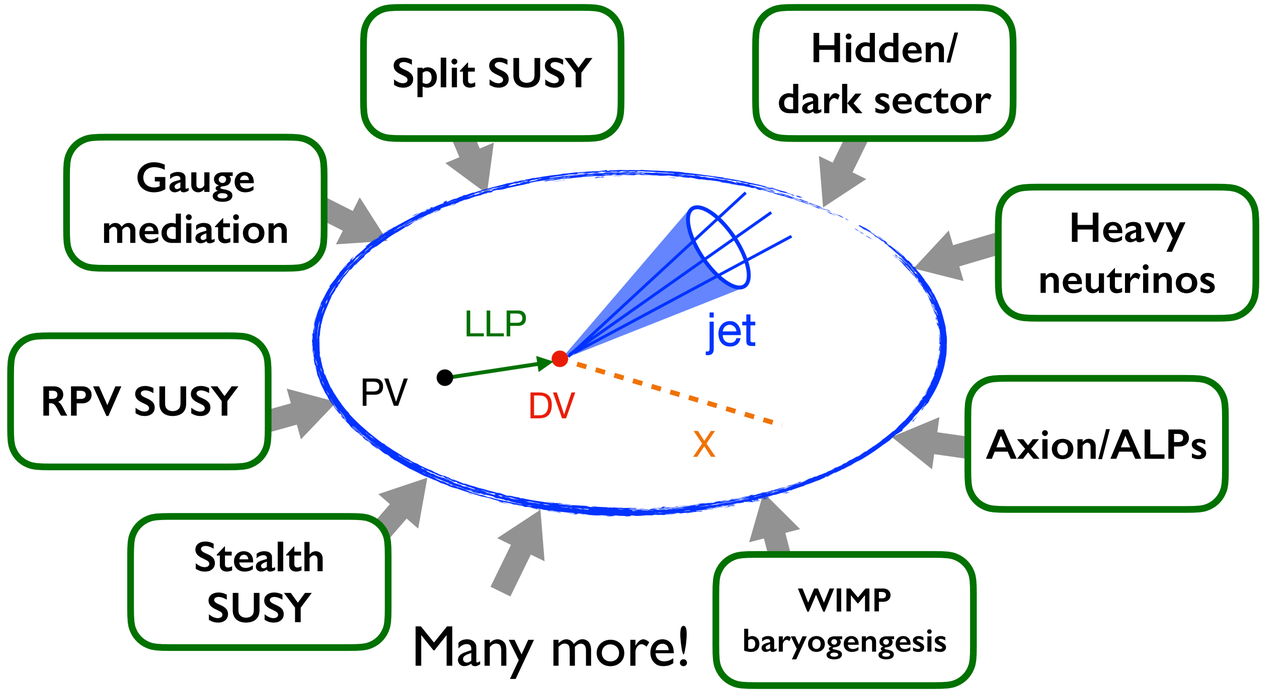
On behalf of the CMS collaboration

14th LHC LLP workshop, July 4, 2024

Displaced-jets signatures

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

Can naturally appear in many BSM scenarios



Hierarchy problem | *Nature of dark matter* | *Neutrino mass* | *Matter-antimatter asymmetry*

- 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, $132\ \text{fb}^{-1}$

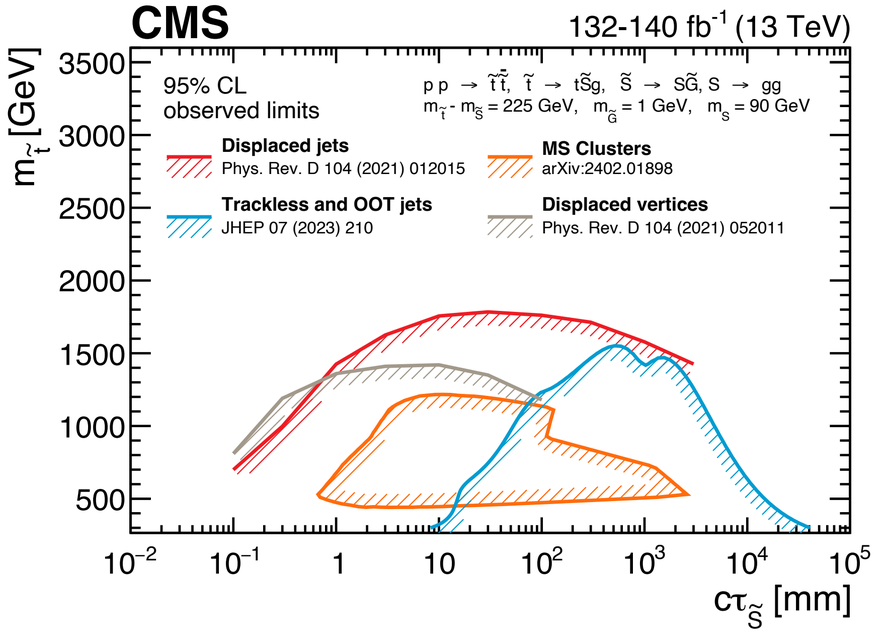
  - **World-leading sensitivities to a large variety of LLP models, for LLP masses from ~10GeV to ~3TeV**

  Many interpretations, the best sensitivities to date to

  Split SUSY, gauge-mediated SUSY, RPV SUSY (λ''_{323}, λ'_{x3y}, η''_{3xx},…), exotic Higgs decays,…

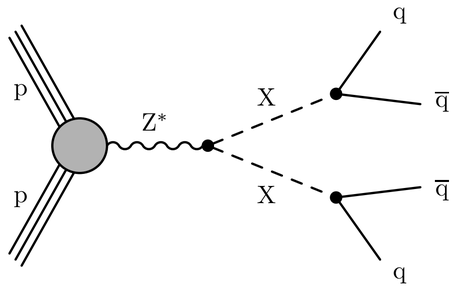
Many more interpretations can be added

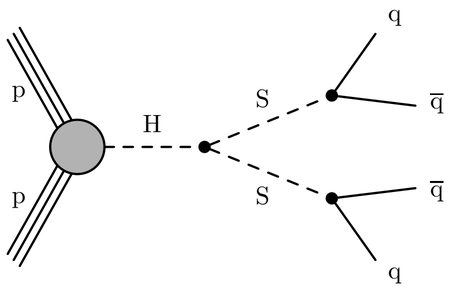
- **Example:** stealth SUSY reinterpretation (CMS dark-sector review paper)

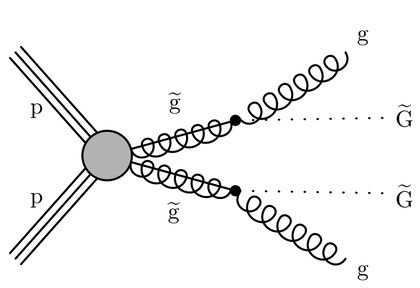


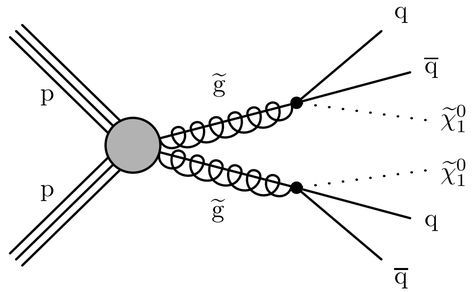
Run-2 displaced-jets search

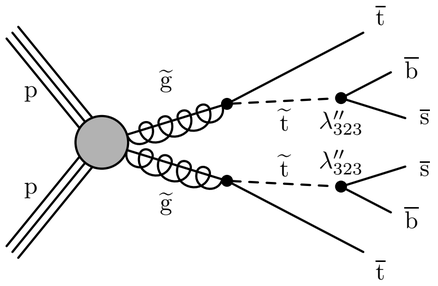
- **Interpretations**

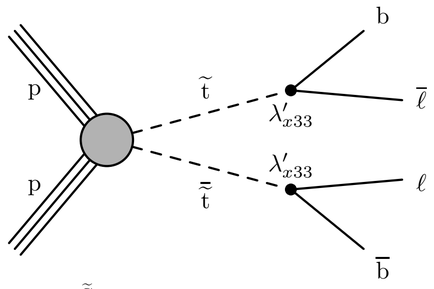


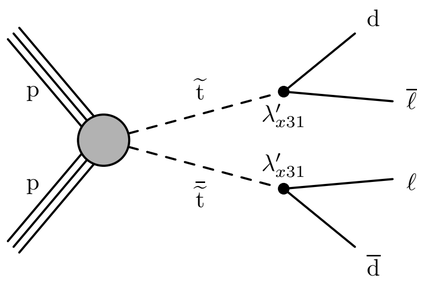


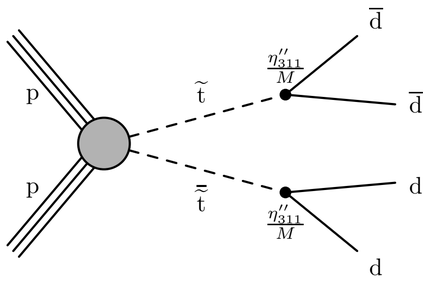


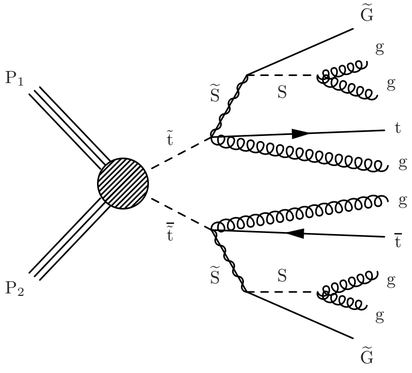


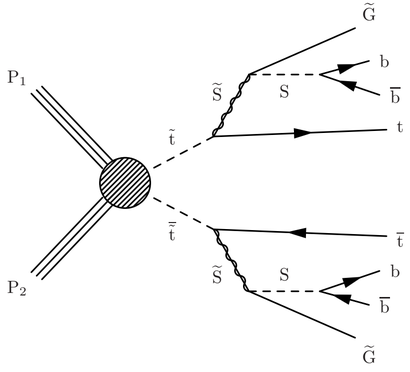












Extremely inclusive and powerful

Run-2 displaced-jets search

- **Directions of improvements**

4 years ago, at the 7th LHC-LLP workshop

❖ **Many new opportunities/directions can be pursued:** (some personal thoughts)

- *Novel L1/HLT algorithms to expand the coverage;*
- *Combine with the info in other sub-detectors to expand the coverage;*
- *Tertiary vertex reconstruction to reconstruct the full decay chain for heavy-flavor decays of LLPs;*
- *More sophisticated reconstruction/discrimination techniques with advanced ML tools.*

Comments/suggestions/new-ideas are welcome!

05/27/20 Jingyu Luo (jingyu.luo@cern.ch) 17

The visions conceived then become realities now → new Run-3 search

Early Run-3 result

- **We 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
  - High importance from the physics point of view

Physics motivation

- **The main physics motivation — Higgs portal hidden/dark sectors**

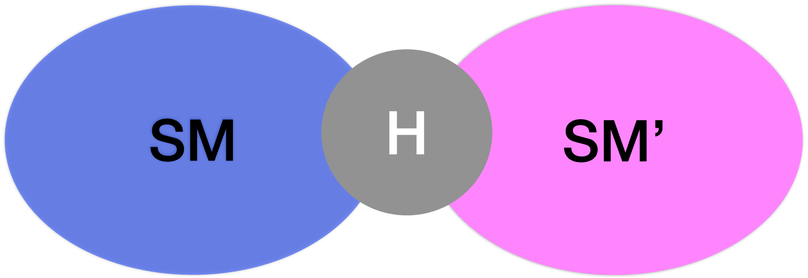
  hidden sectors can communicate with the SM sector through different possible portals

  The Higgs portal is possibly the most attractive one, due to various physics reasons

  [Brain Patt & Frank Wilczek, 2006]

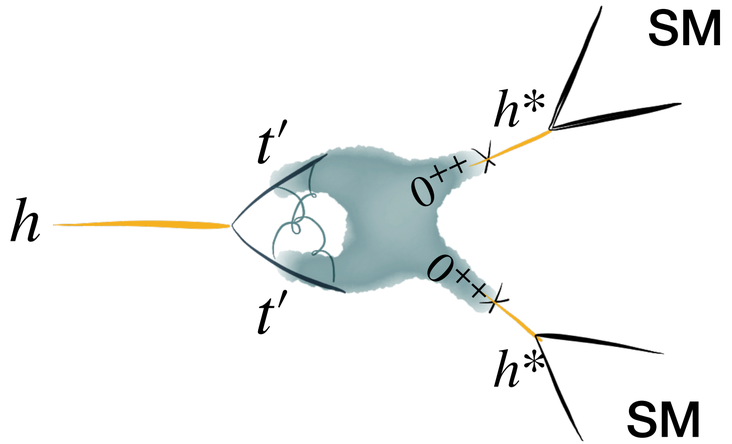
  Long lifetime is a generic feature due to typically weak interactions between the SM sector and hidden/dark sectors

A well-motivated example: Neutral naturalness



Provides novel solutions to hierarchy problem and other critical puzzles in particle physics

Higgs→LLPs→displaced jets



PC: Nathaniel Craig

Experimental challenges

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

Especially for ggF production

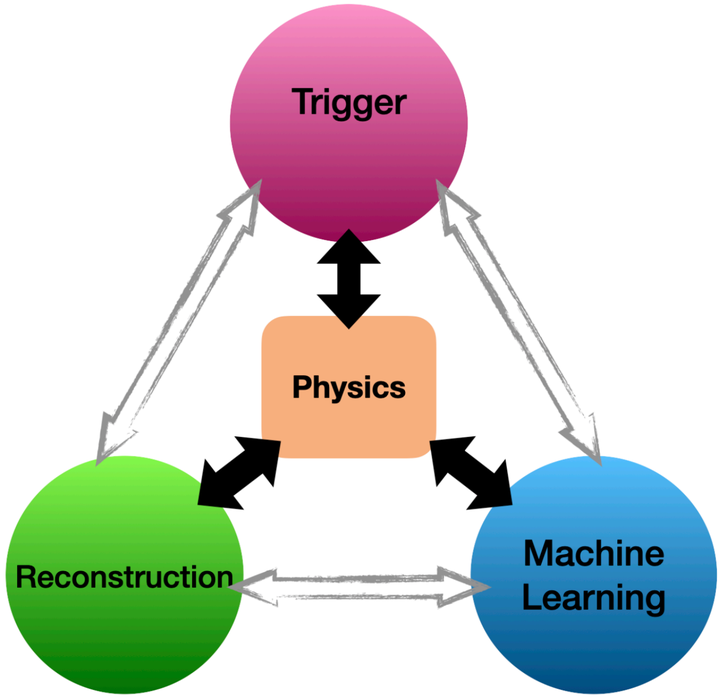
- Soft objects (jets, tracks, vertices);
- Overwhelming QCD background:

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

Difficult for trigger;

Difficult for reconstruction;

Difficult for offline selection;



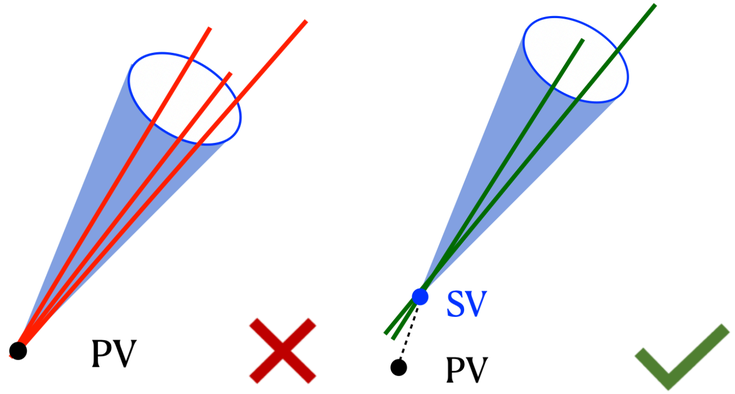
A complete blind spot before April 2020

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.

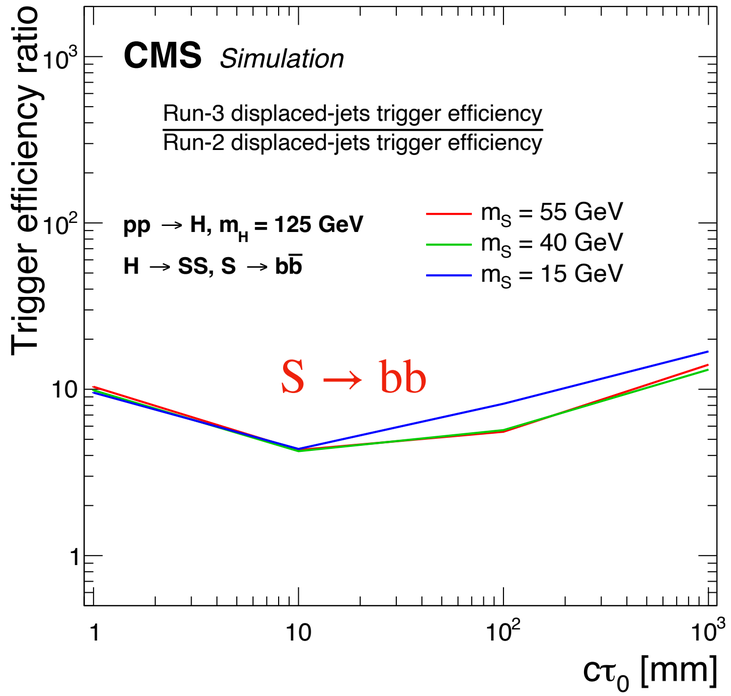
New displaced-jets triggers

- 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 $H \rightarrow LLPs$.



Efficiency gains w.r.t. Run 2

[CMS-DP-2023-043]



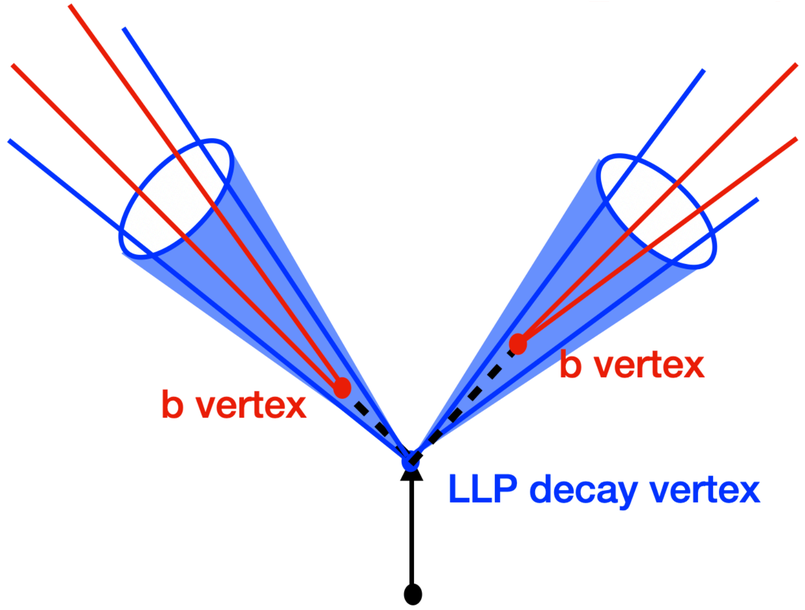
The trigger efficiencies have been further improved in 2023 and beyond, thanks to the **new LLP parking**

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

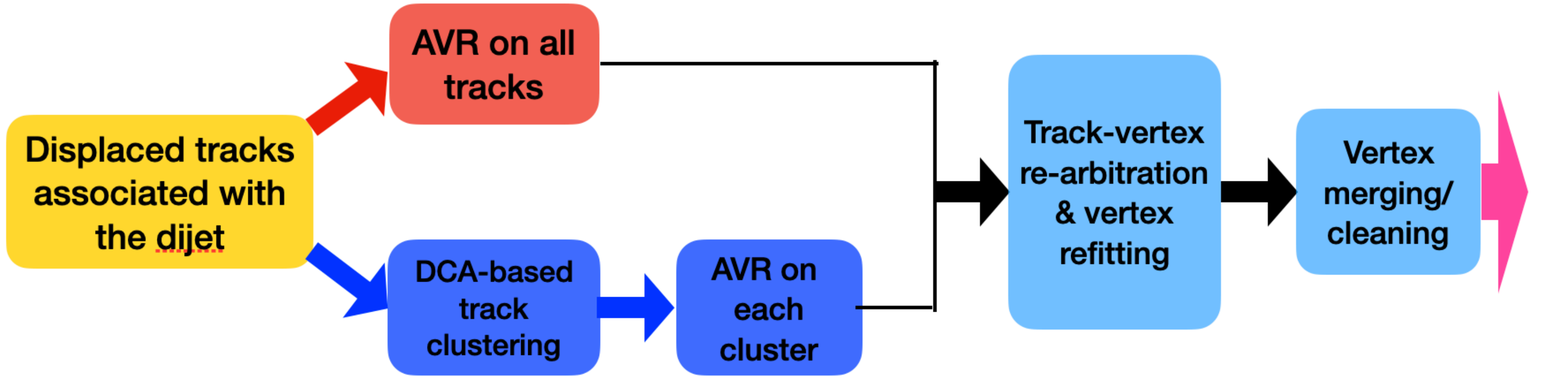
Displaced vertex reconstruction

New displaced vertex reconstruction algorithm has been developed for Run 3

- Strongly driven by the physics consideration on tackling complex LLP decay systems like $S \rightarrow bb$;
- 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 $S \rightarrow bb$ decays

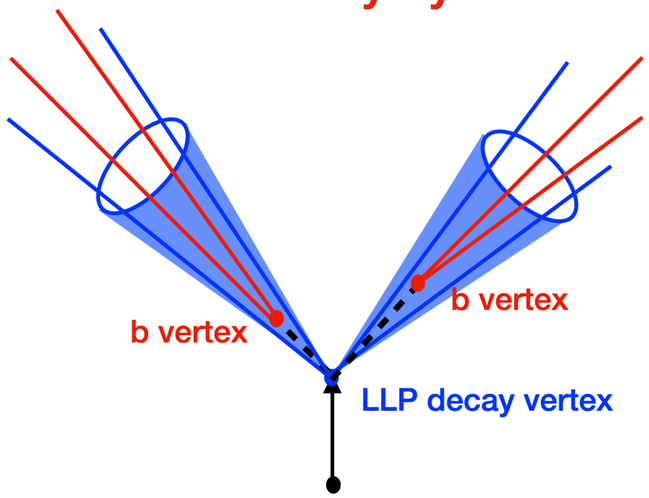
New GNN-based LLP tagging

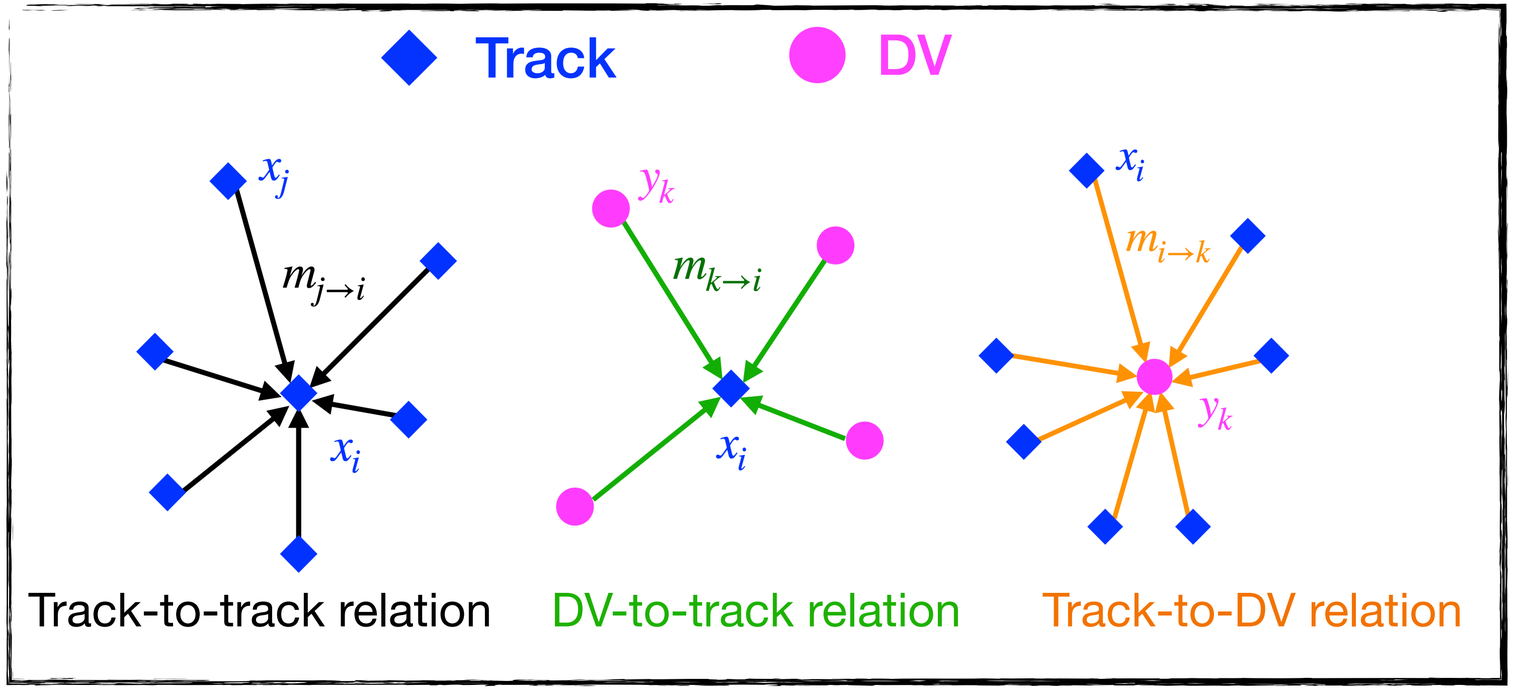
- **New Graph Neural Network (GNN) based LLP taggers have been developed in Run 3.**

Driven by the physics insight that track-to-vertex relations are important physics information:

- 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.

LLP decay system

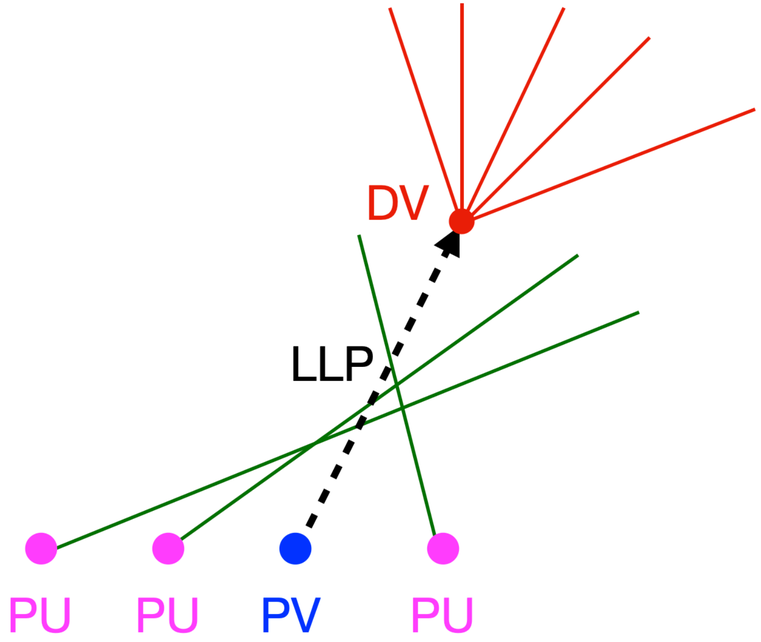


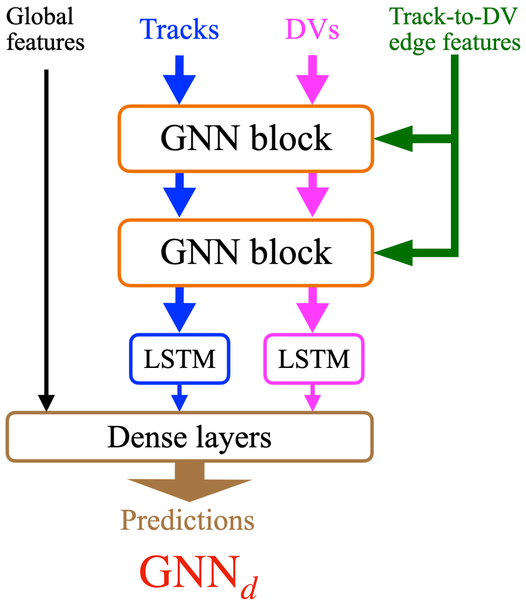


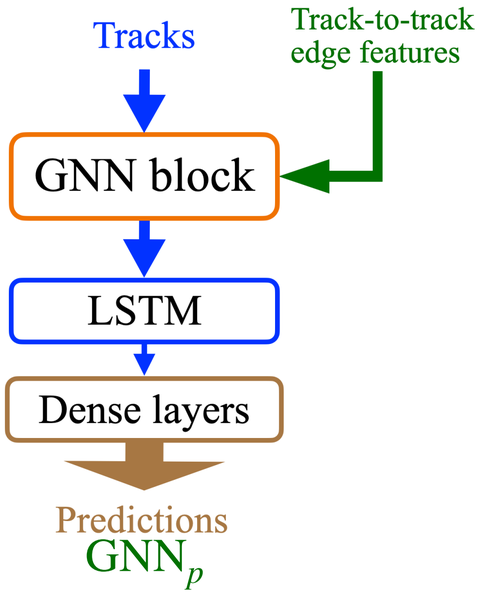
Message-passing formalism

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 ($\mathrm{IP}_{2D} < 0.3$ mm) as inputs, incorporating track-to-PV/PU association information







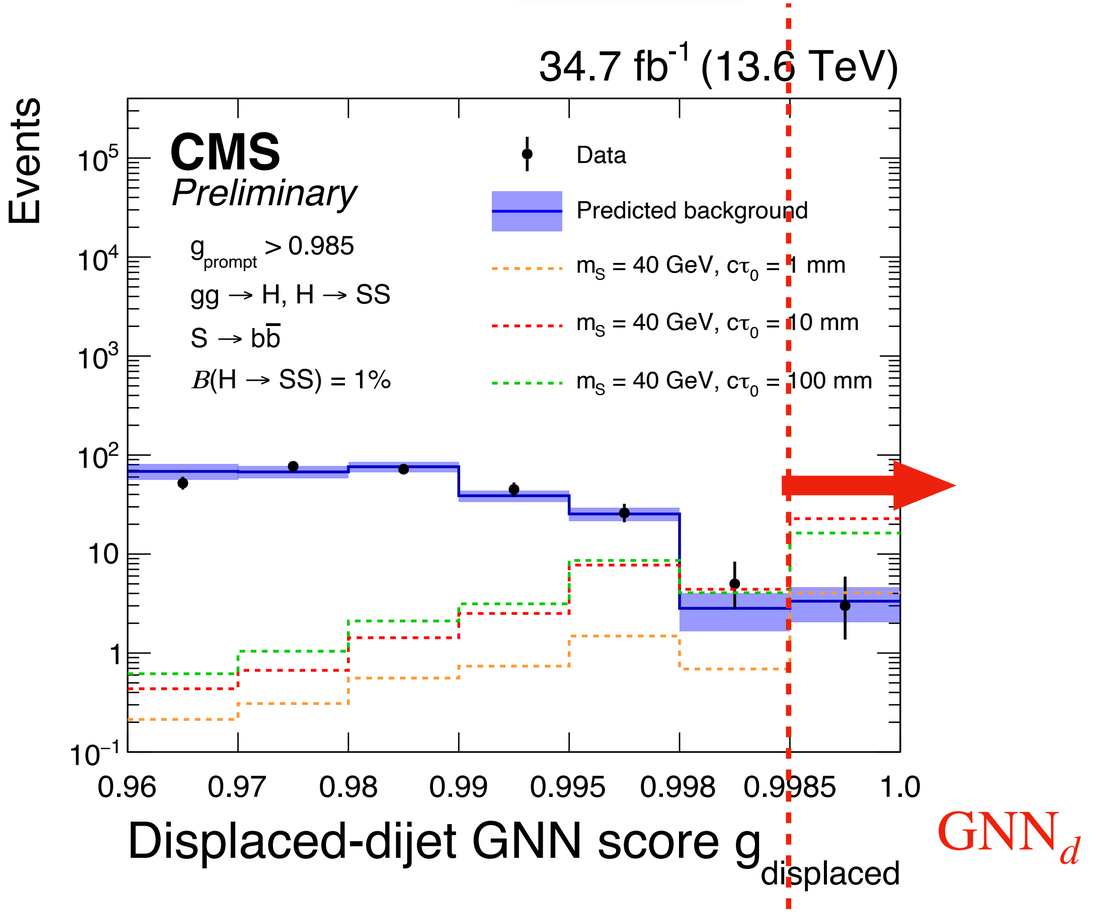
The two taggers have small correlations for the background processes, and thus enable data-driven ABCD method for the background estimation

Event selection and background estimation

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

  - Examine all possible dijet candidates with jets satisfying $p_{\mathrm{T}} > 40\mathrm{GeV},\ |\eta| < 2.0$;
  - We compute $\mathrm{GNN_d}$ and $\mathrm{GNN_p}$ for each dijet
  - 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

The search remains to be highly model independent



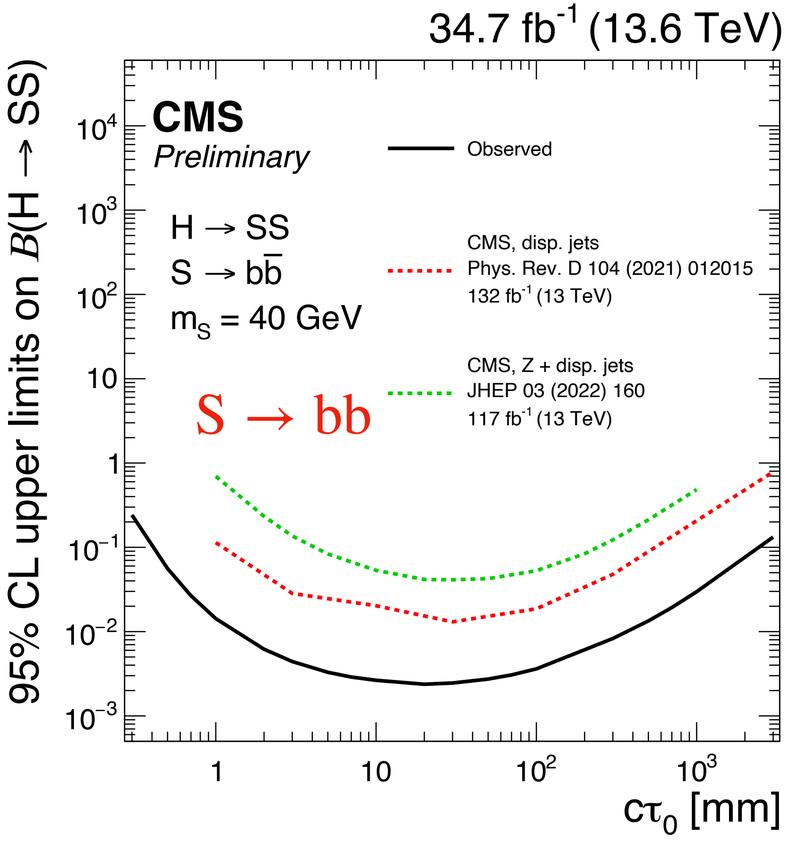
Predicted background yield: 3.34 ± 1.28 **(stat. only)**

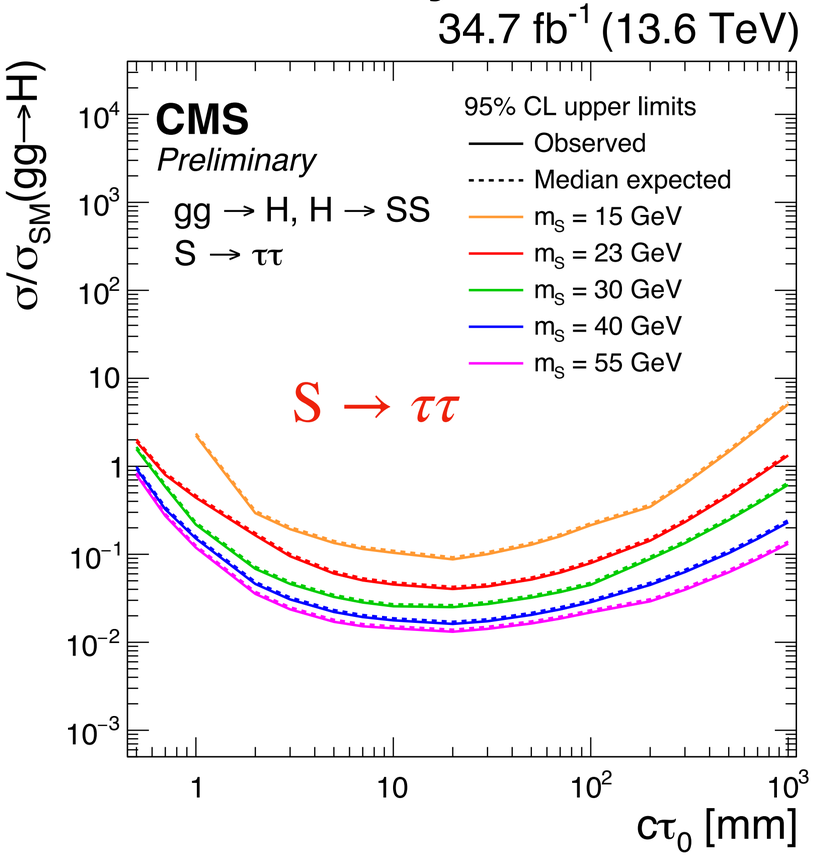
Observation: 3

Results

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

Much better than any other existing results



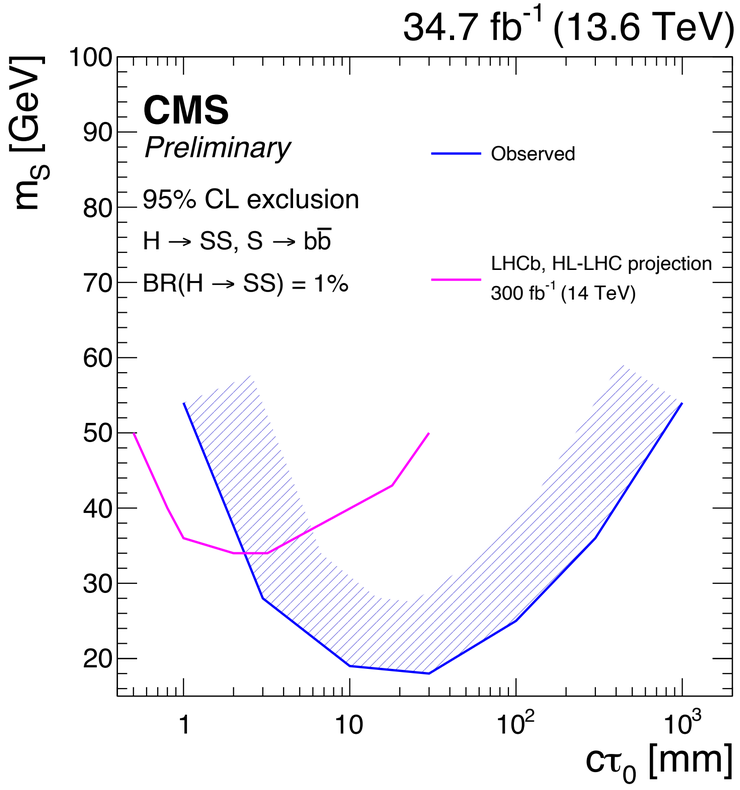


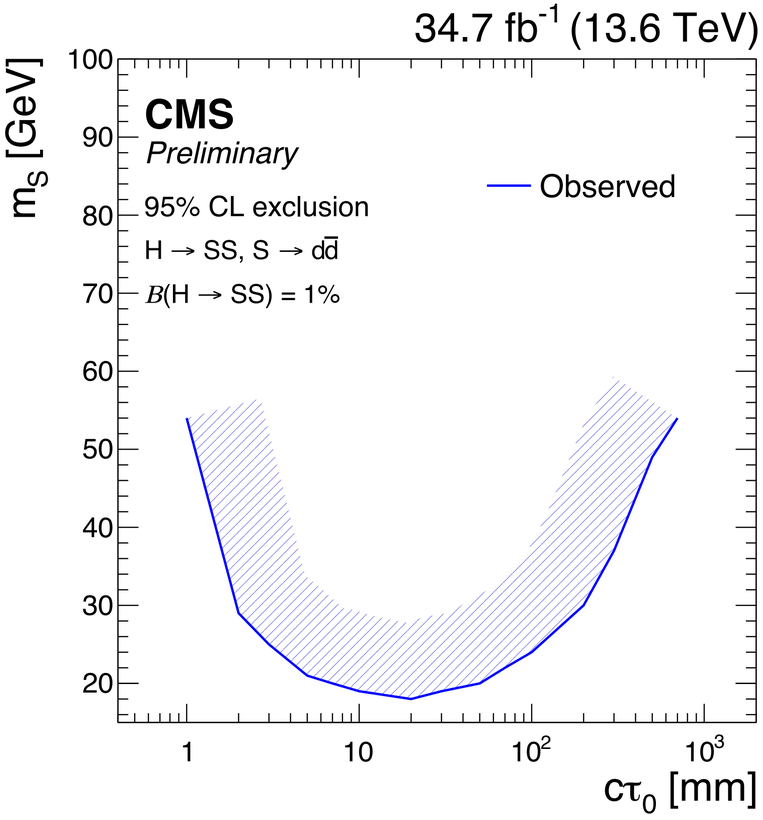
With only 1/4 of the luminosity compared to Run 2, achieved a factor of 10 improvement!

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





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

(not the case in the Run-2 search)

Thanks to the new DV reconstruction and GNN taggers

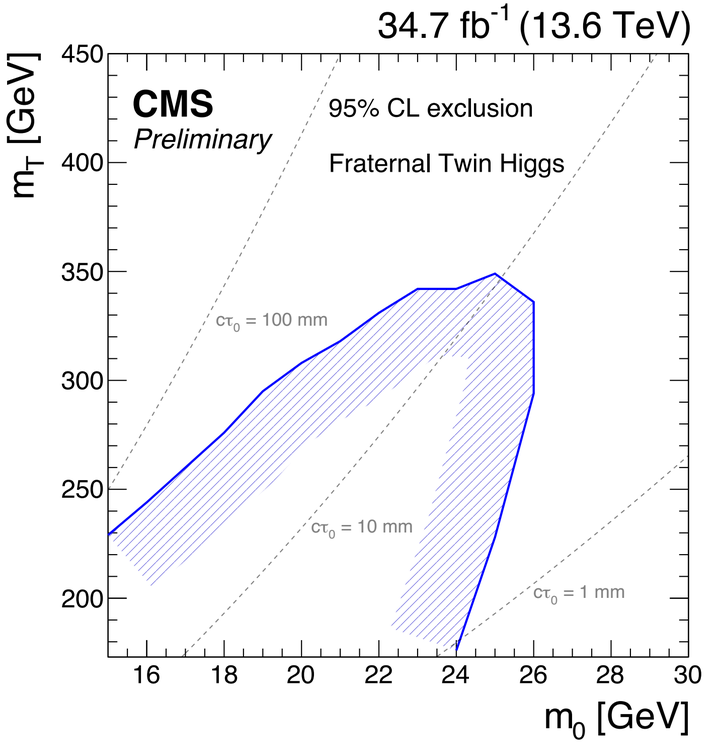
A full HL-LHC projection of LHCb is shown for comparison [arXiv:2105.12668]

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]

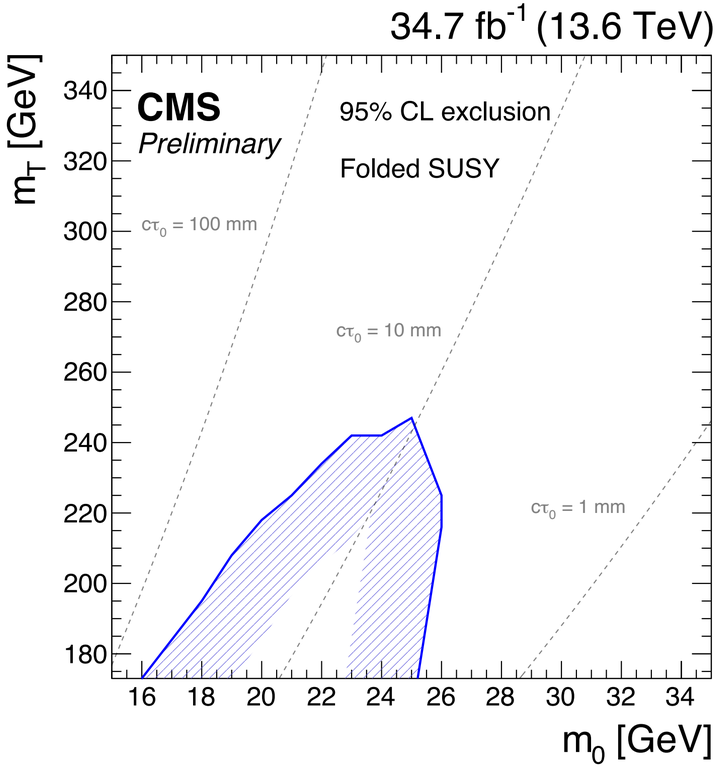


Hidden top mass

Hidden glueball mass

Folded SUSY

[Burdman, Chacko, Goh, Hrnik, 2006]



First experimental constraints

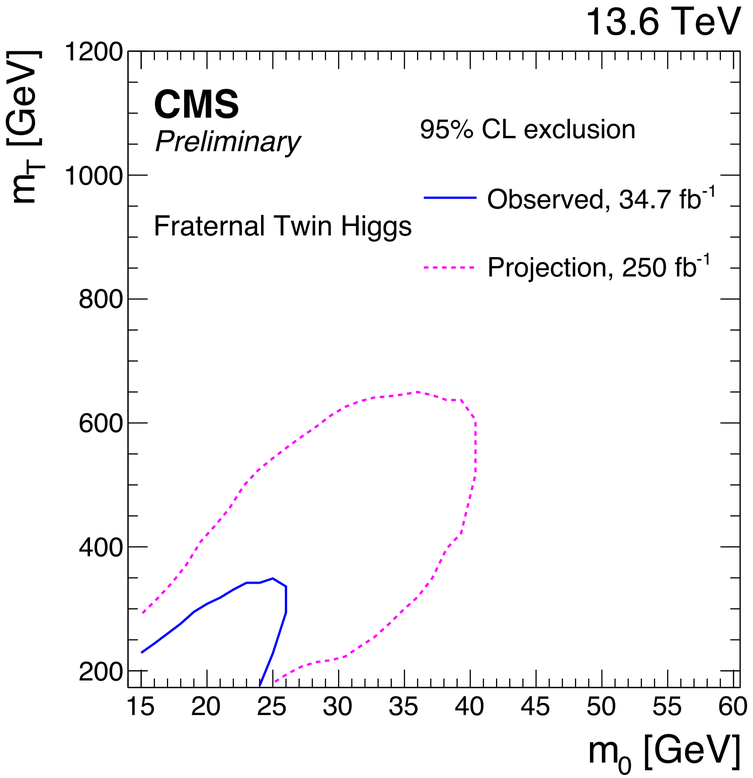
Based on $H \to G_0 G_0 \to 4f$ assumption

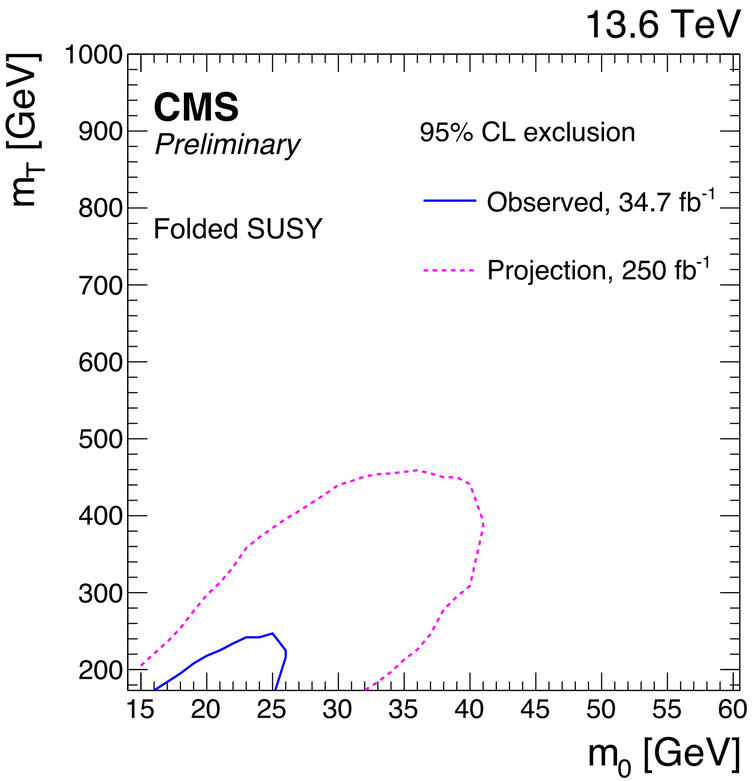
In future iterations of the analysis, plan to incorporate recent developments from theory community in hidden/ dark glueball hadronization.

arXiv: 2310:13731

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
    - $34.7\ \text{fb}^{-1}$ in 2022 v.s. $\approx 250\ \text{fb}^{-1}$ in 2022—2025





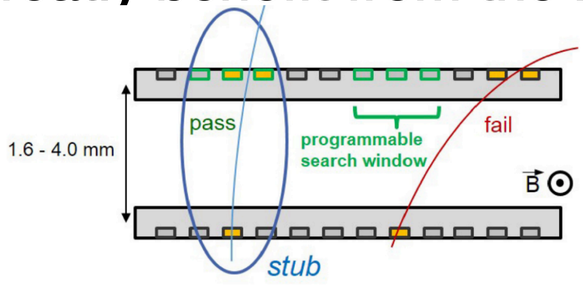
Significant expansions of the coverages are expected by the end of Run 3;

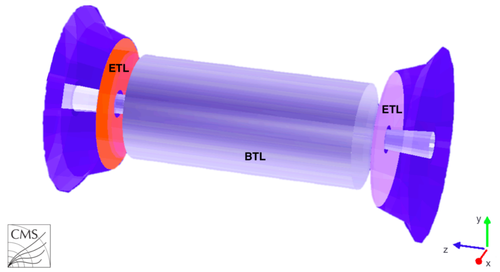
More new techniques are under development, which will further significantly improve the sensitivities;

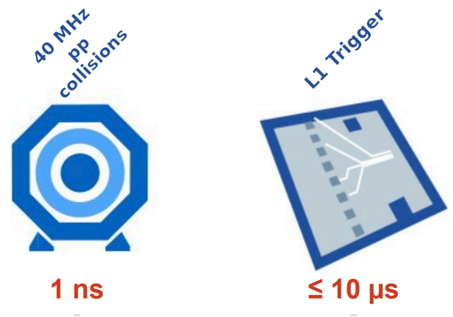
We should be able to reach or even surpass some future collider projections by the end of Run 3.

Outlook

- **This search just represents the new beginning of an exciting journey:**
  - Much larger dataset to be analyzed by the end of Run 3;
  - More low-level developments — will further significantly improve the sensitivities;
    - A deeper understanding of our experimental techniques and underlying physics pictures is the key.
  - The new techniques have great generalizabilities, many more exciting applications:
    - HNLs, ALP, soft displaced jets from DM scenarios, high-quality axion, dark shower, dedicated displaced tau tagging, etc.
- **Will greatly benefit from the HL-LHC upgrades**



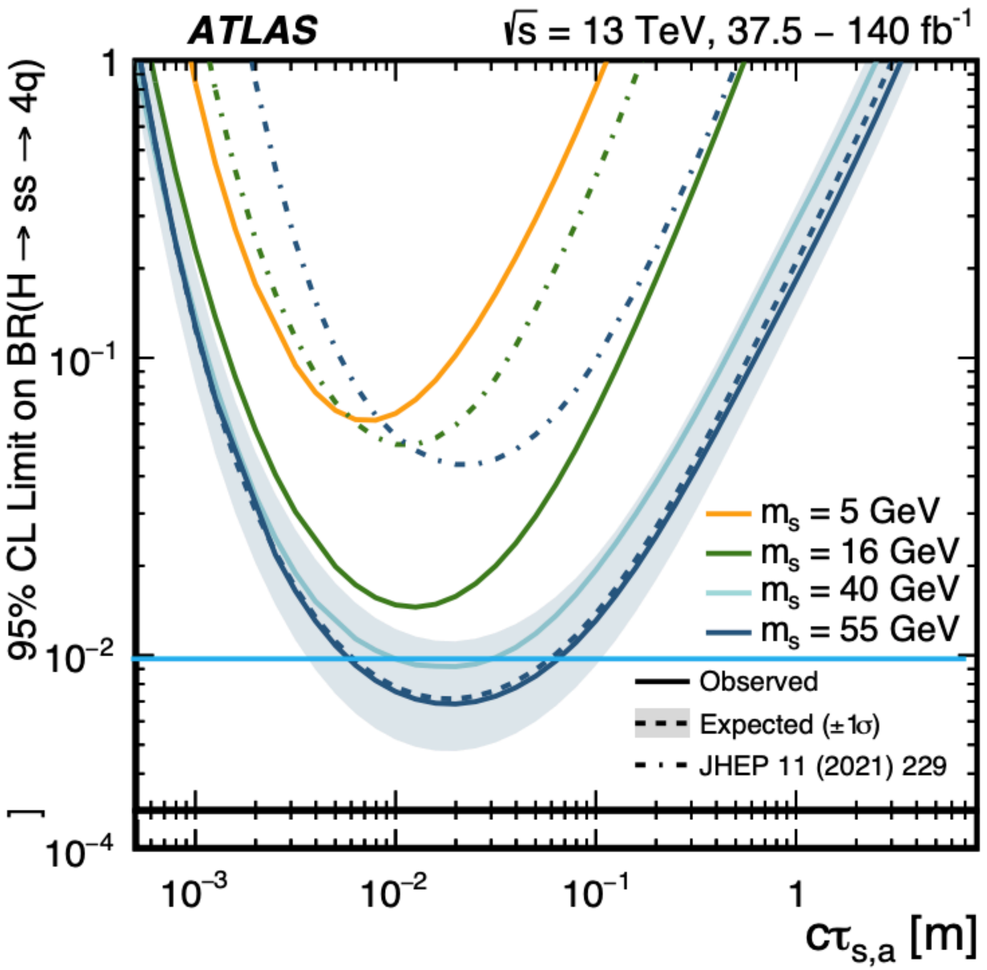


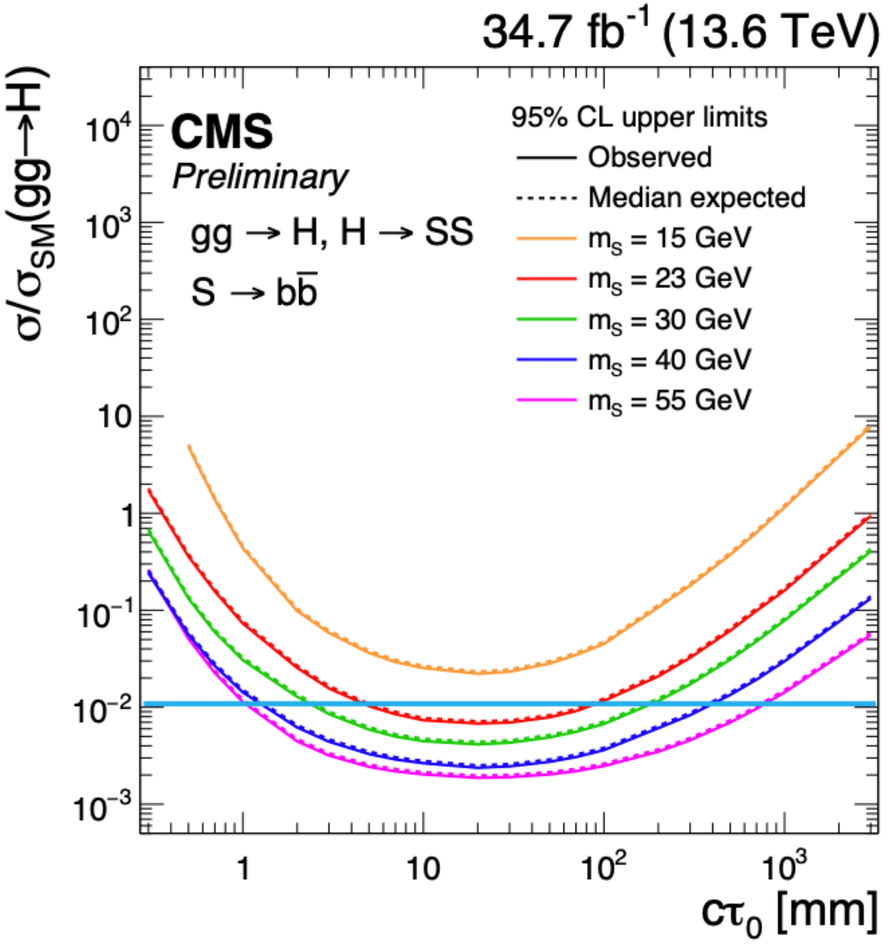


Backup

Comparison with the updated full Run-2 ATLAS results

https://arxiv.org/abs/2403.15332

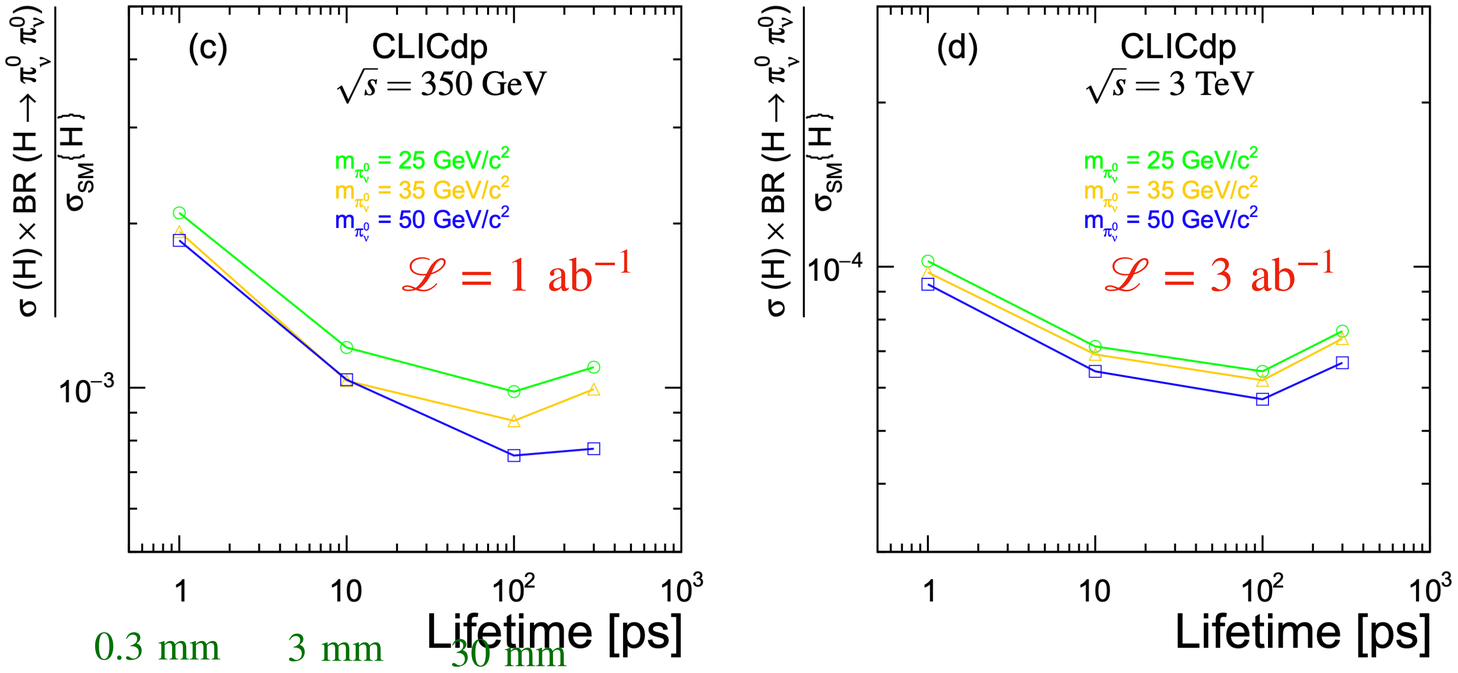




Comparison with future collider projections

- **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.