Searches for long lived particles at CMS

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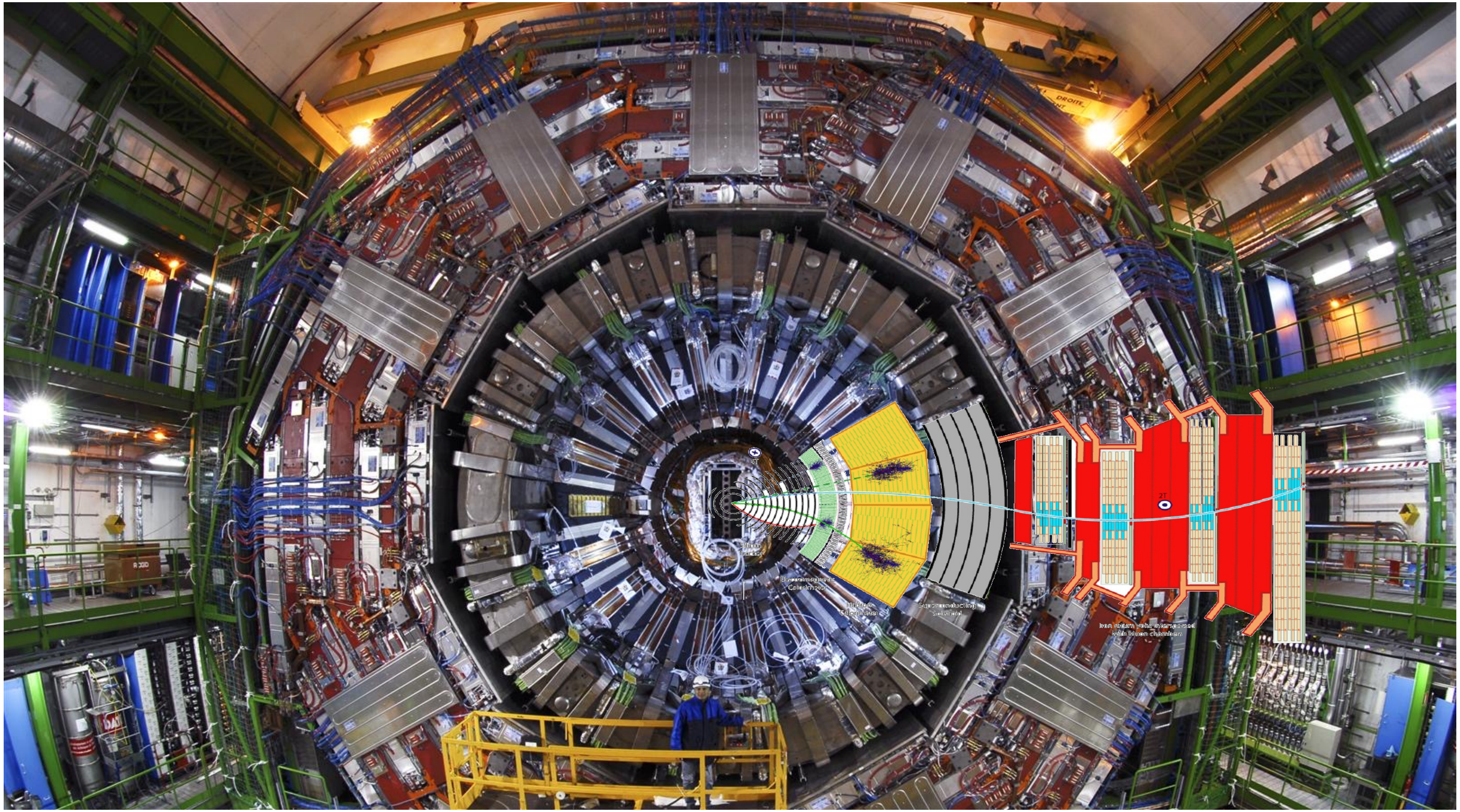
IRN Terascale
13-15 November 2024, Lyon

Long lived particles (LLP)

- Particles with a macroscopic lifetime, $c\tau \geq 1$ mm.
- Theoretical ingredients:
  - small couplings,
  - compressed phase space, or
  - heavy off-shell mediators
- Predicted in many BSM models.
- Searched therefore by many experiments…

→ I will focus only on CMS searches

Particle signatures in CMS



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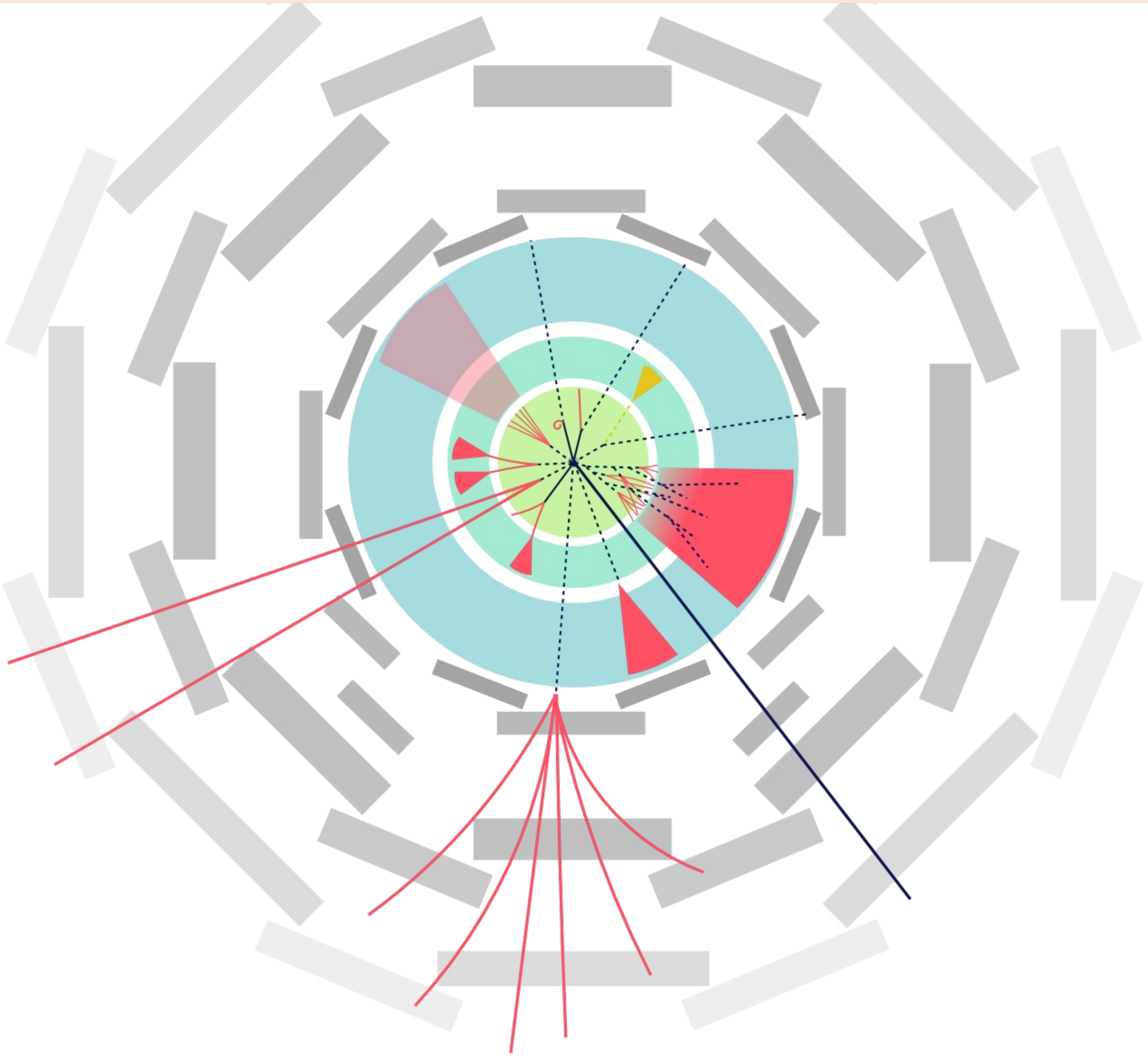
Long lived particle signatures in CMS

Very rich LLP
search program !



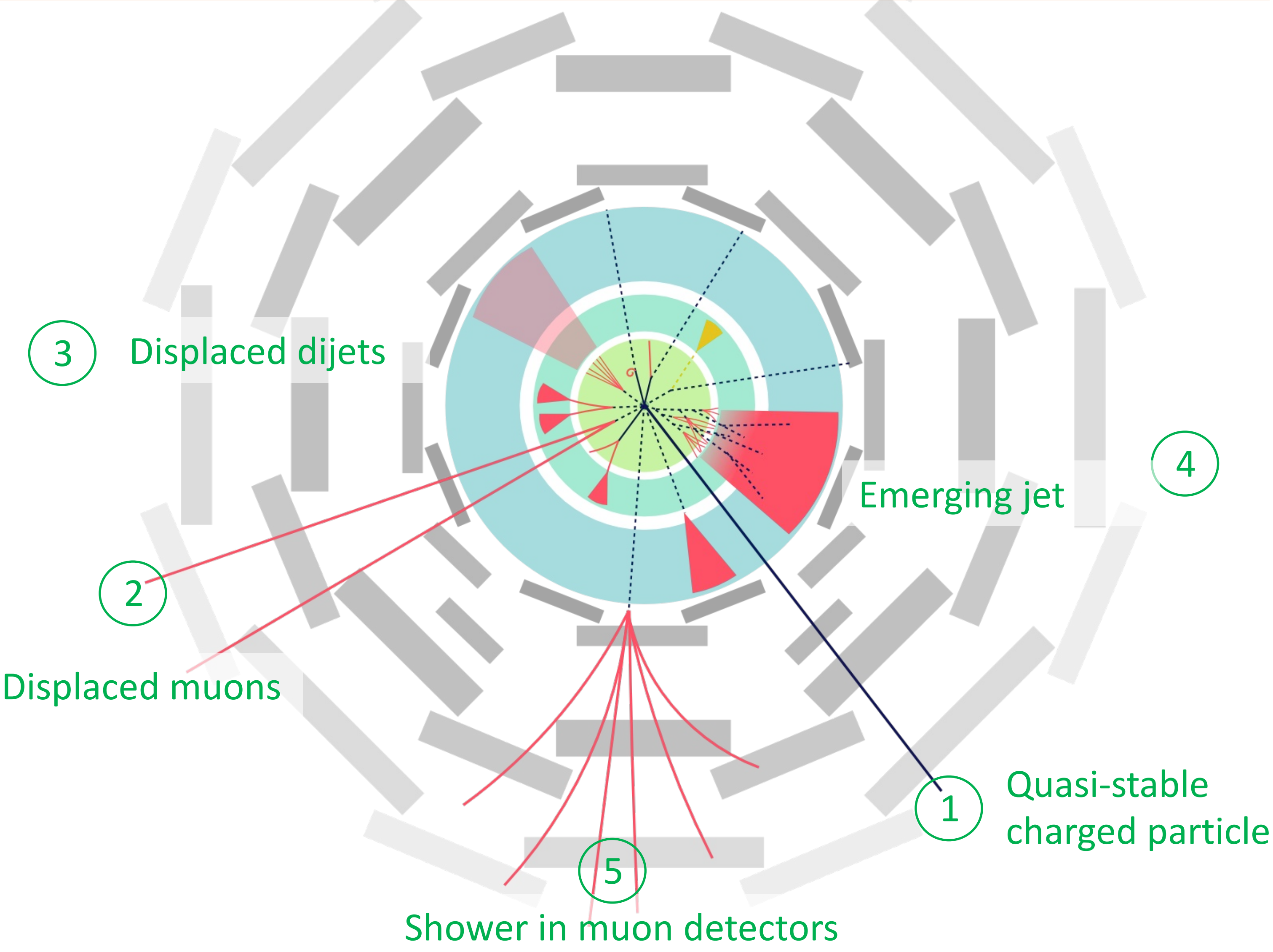
Rather unusual signatures…
→ Experimental challenges:

- Trigger and reconstruction
- Background estimate

Outline of the talk

1) Heavy charged LLP

2) Displaced muons
3) Displaced dijets
4) Emerging jets
5) Showers in Muon detectors



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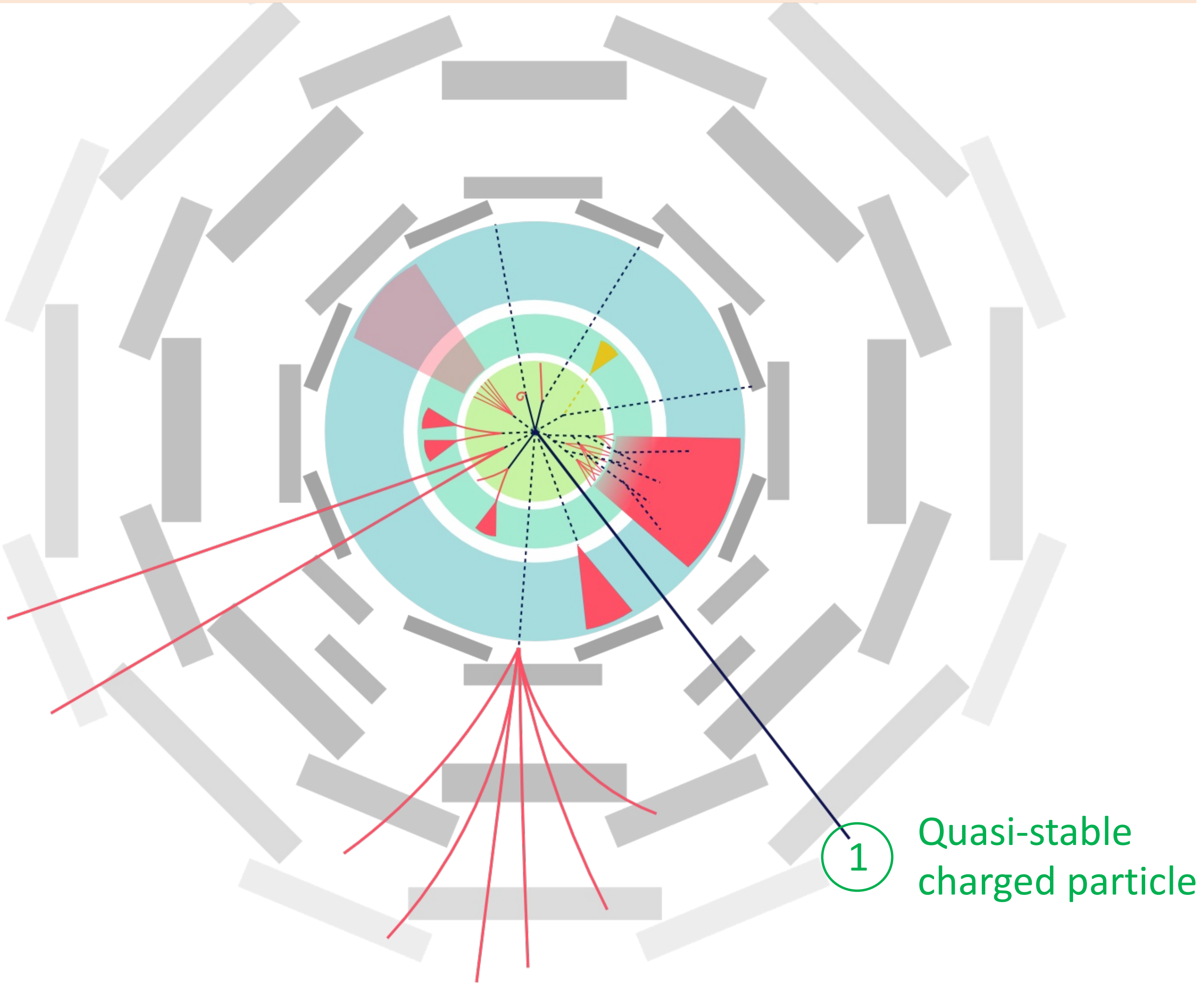
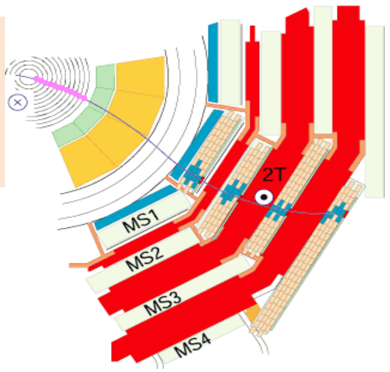
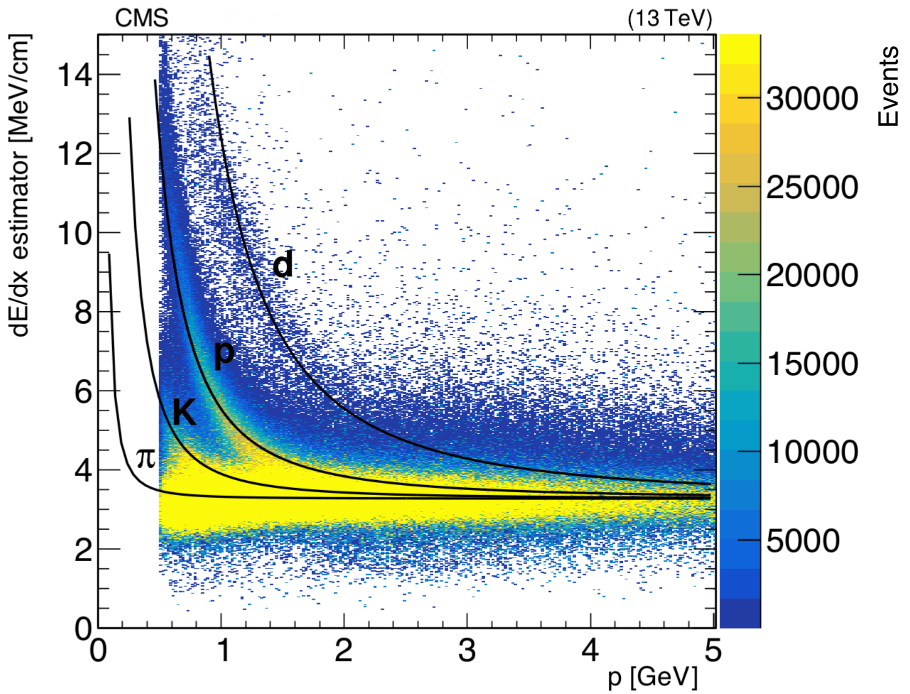


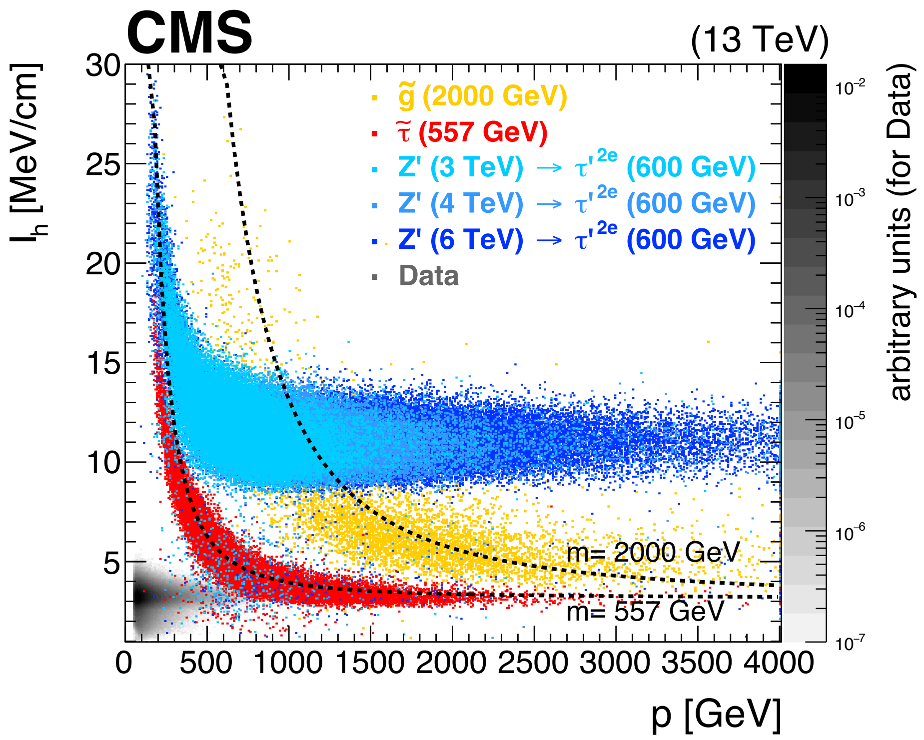
Heavy charged LLP



- Typical signature associated to a charged particle: an isolated track of high pT
- How to separate it from background ?
  - Larger ionization deposit in the tracker: dE/dx information

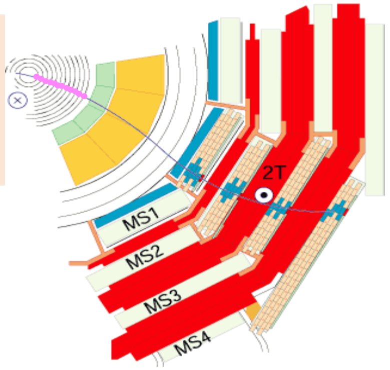


[2405.13778]



[2410.09164]

Heavy charged LLP

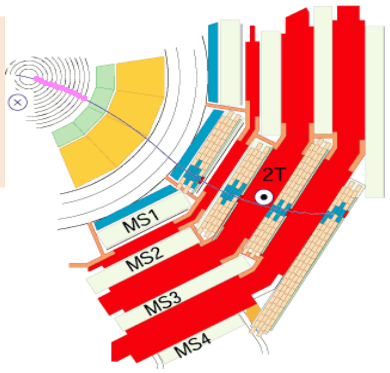


- Typical signature associated to a charged particle: an isolated track of high pT
- How to separte it from background ?
  - Larger ionization deposit in the tracker: dE/dx information
  - Longer time of flight: β information in the muon chambers (or in calorimeter)
  - If small $c\tau$, short track with missing hits at the end.

HSCP

→ Disappearing track

Heavy charged LLP



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HSCP

→ Disappearing track

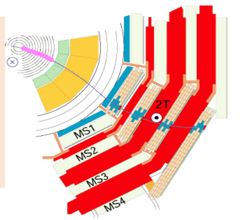
Recent results on the Heavy Stable Charged Particle search:

[2410.09164]

Work performed at IPHC Strasbourg ☺

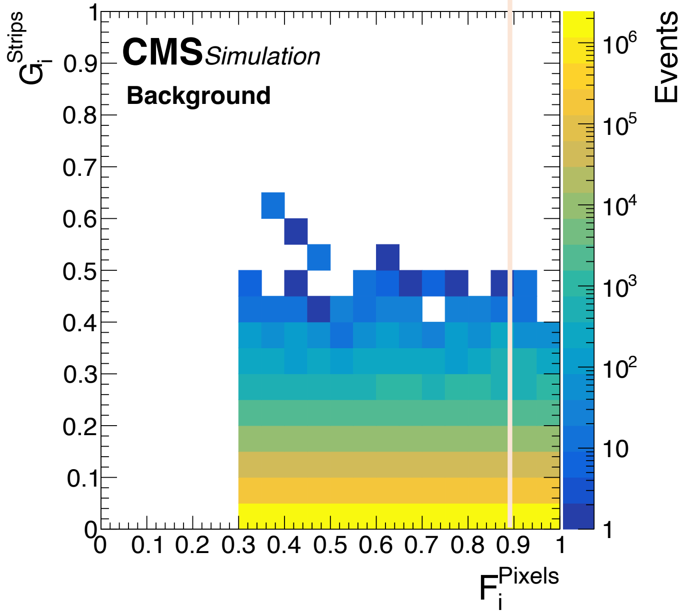
- Signature: An isolated track of high p_T (p_T>55 GeV, $|\eta|$<1) with large dE/dx deposits in the tracker, selected in 2017-2018 data (101 fb^{-1}) with a muon trigger
- Two approaches with data-driven background estimate
- Interpretations for many stable signals, considering |Q|=1e or 2e

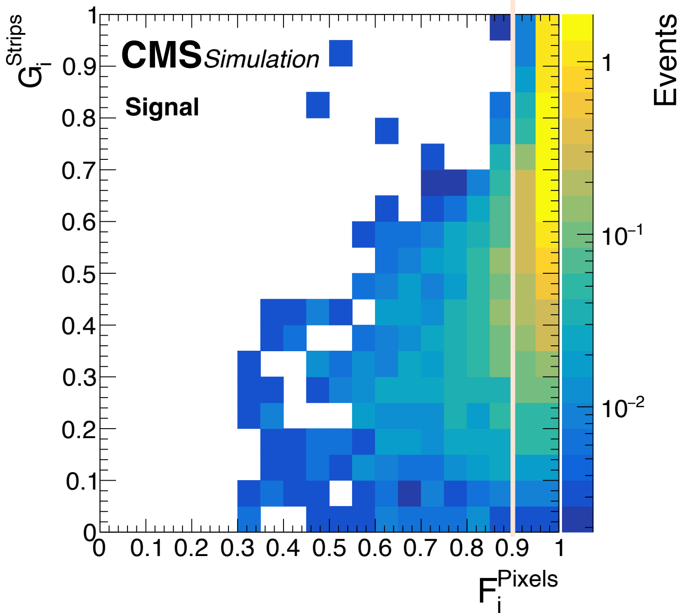
HSCP

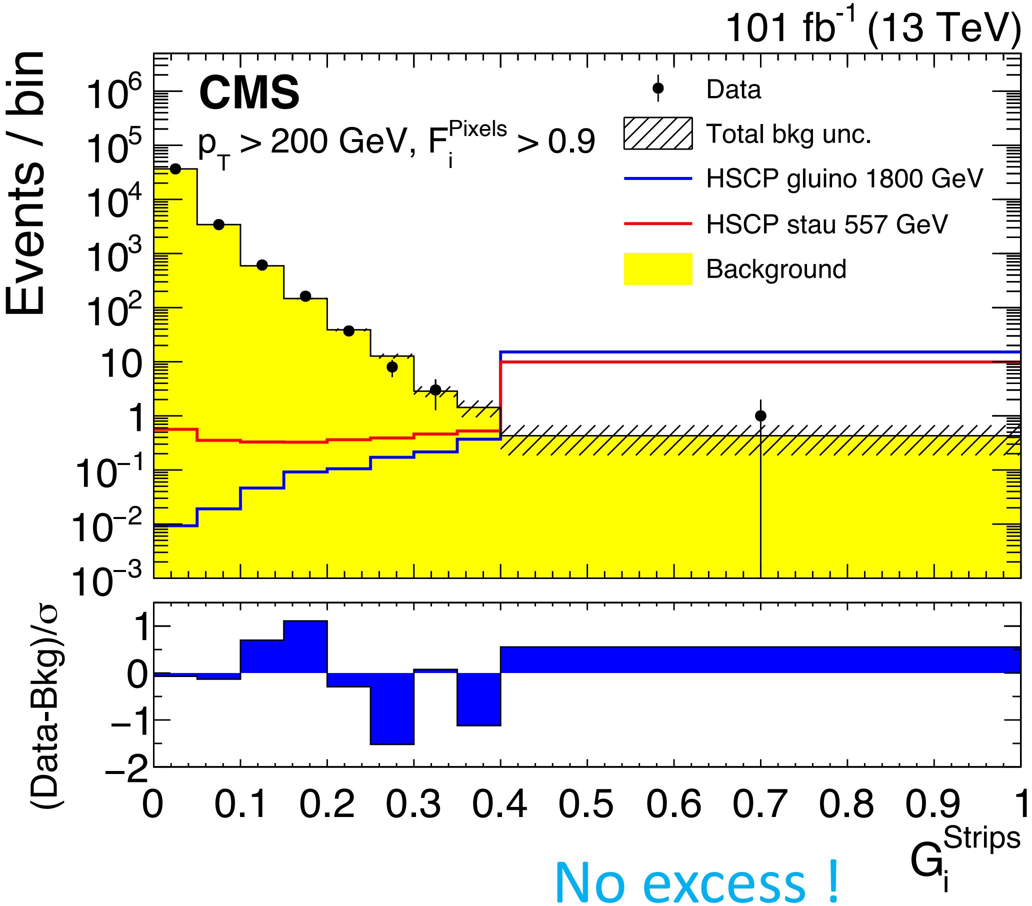


[2410.09164]

Approach 1: Independence of dE/dx in Pixel and Strip tracker for background

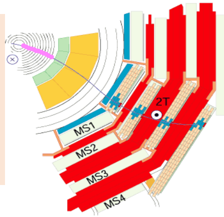






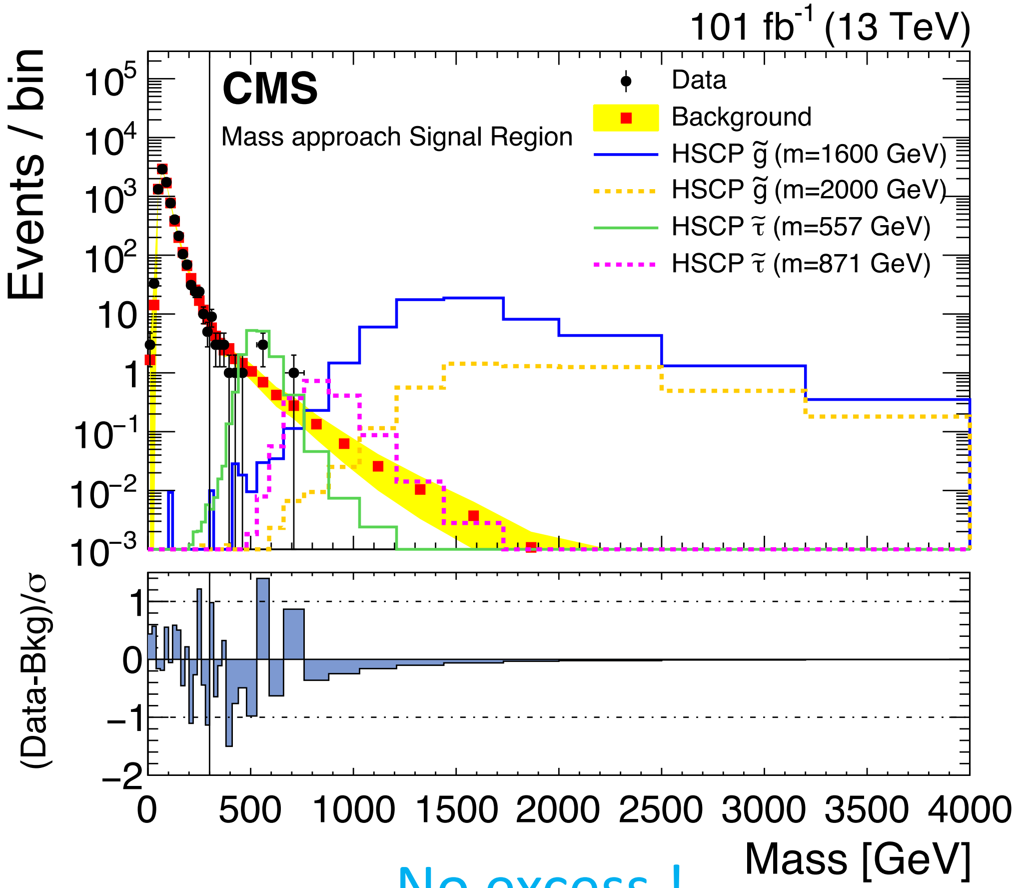
No excess !

HSCP

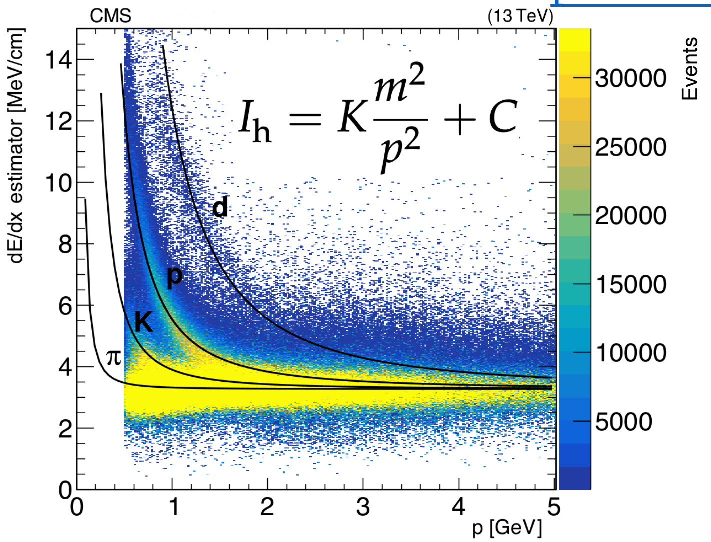


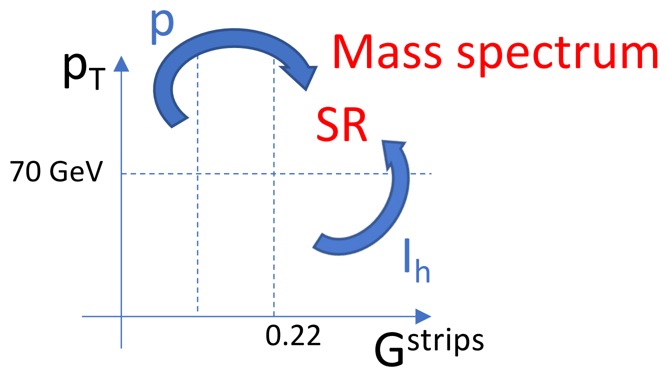
Approach 2: Mass spectrum

[2410.09164]

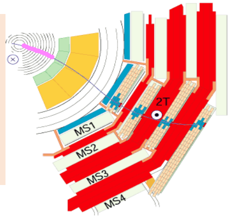


No excess !



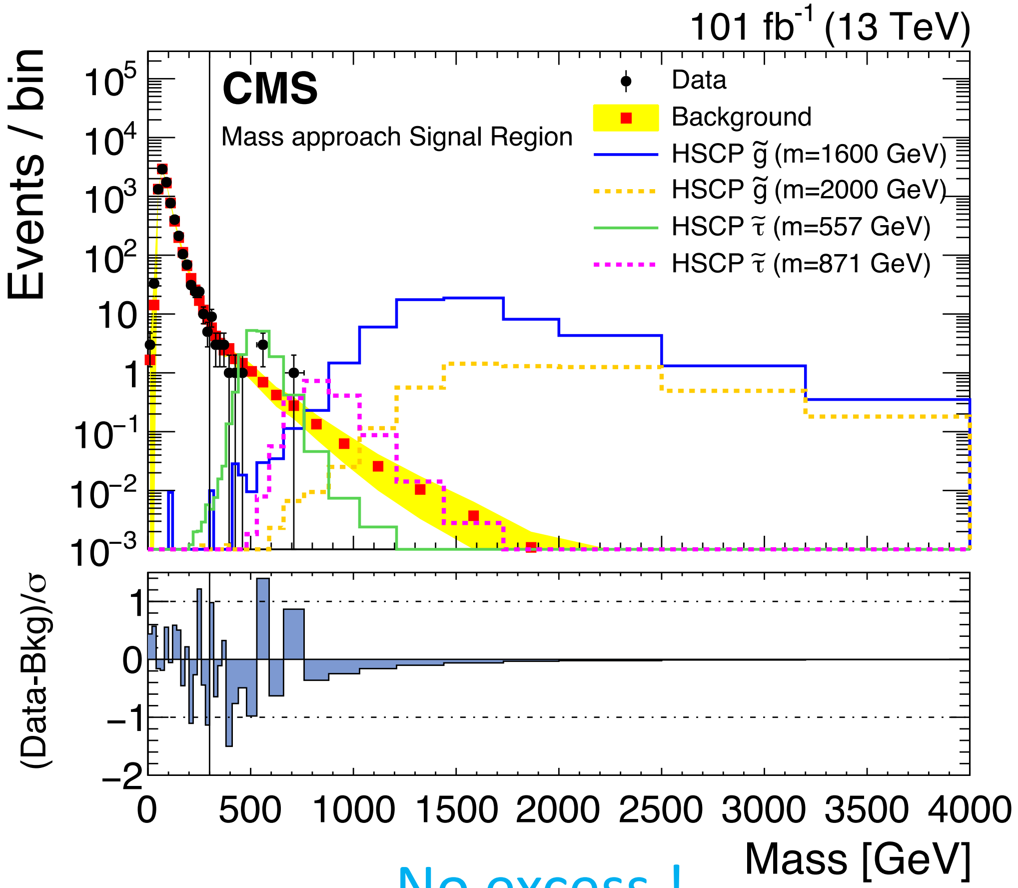


HSCP



Approach 2: Mass spectrum

[2410.09164]



No excess !

⚠ 3.3σ global excess observed by ATLAS

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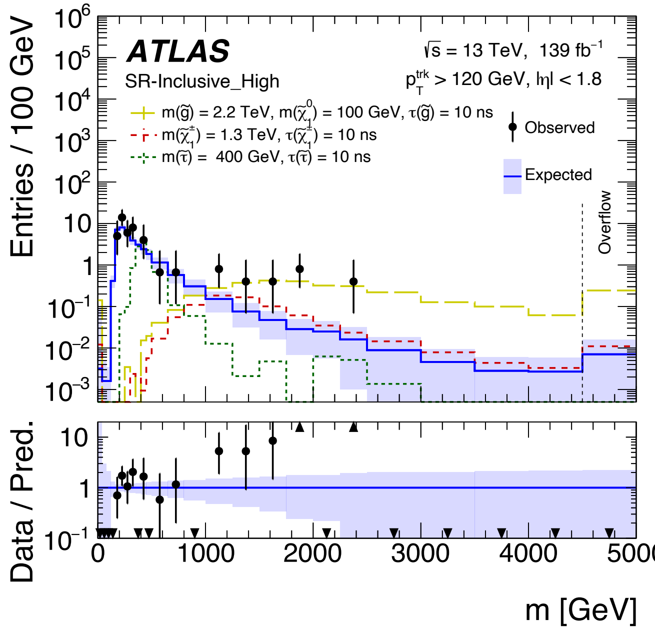
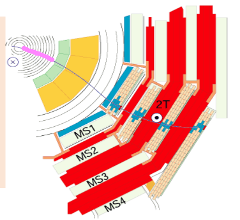


But non confirmed by ATLAS-CONF-2023-044

HSCP

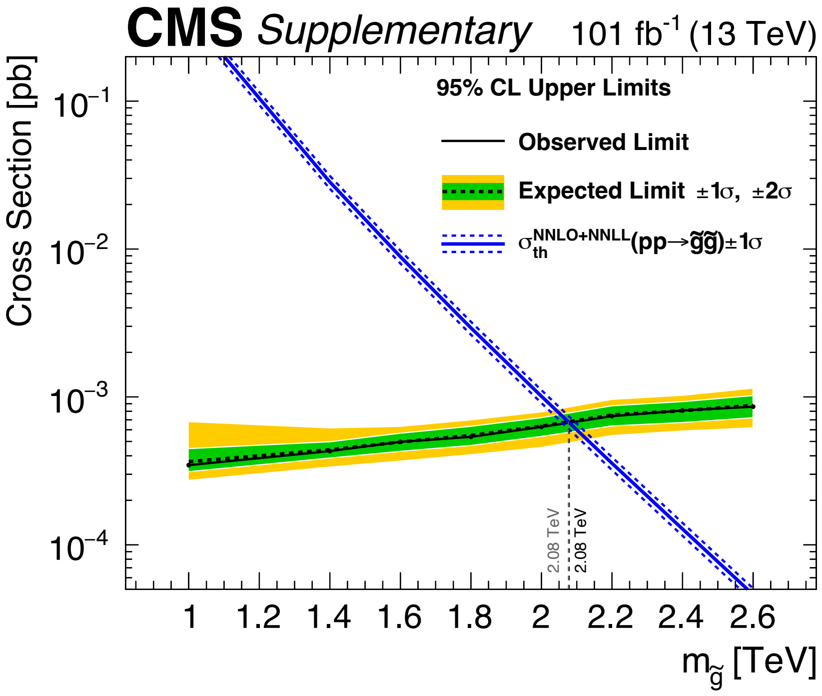


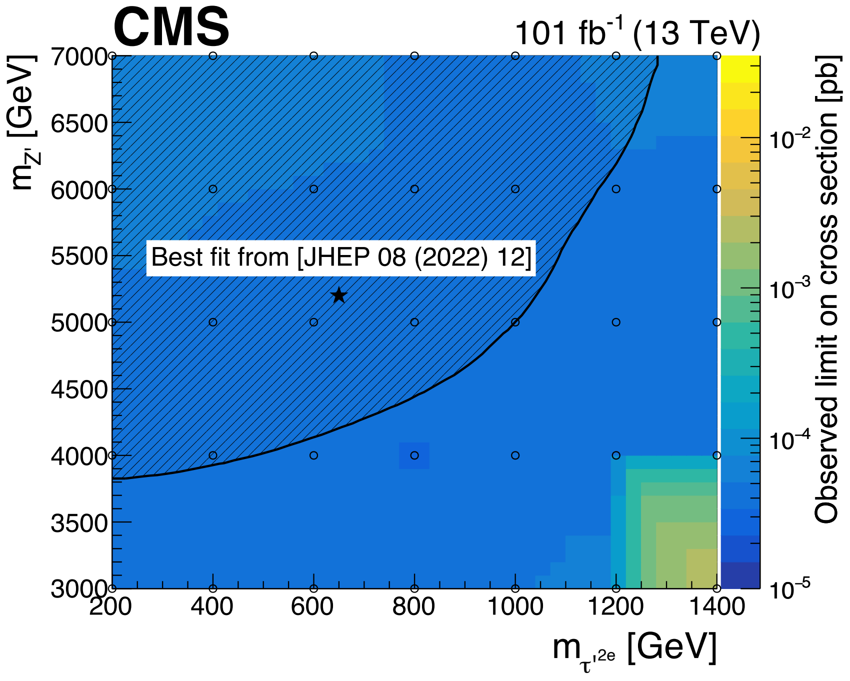
[2410.09164]

Can we say something about the ATLAS excess ? Using [HEPData], $\sigma^{ATLAS} = 0.0453$ fb/($A\varepsilon$)

1) pp→$\tilde{g}\tilde{g}$ with m($\tilde{g}$)= 1.4 TeV ? **No !**
σ^{ATLAS} = 0.59 fb >< 95%CL upper σ^{CMS} = 0.43 fb

2) pp → Z' → $\tau'^{(2e)}\ \tau'^{(2e)}$ with for m(Z') = 5 TeV and m(τ')=0.6 TeV [*JHEP* 08 (2022) 012]? **No**
if $A\varepsilon$ < 95%, as 95% CL upper σ^{CMS} = 0.047 fb





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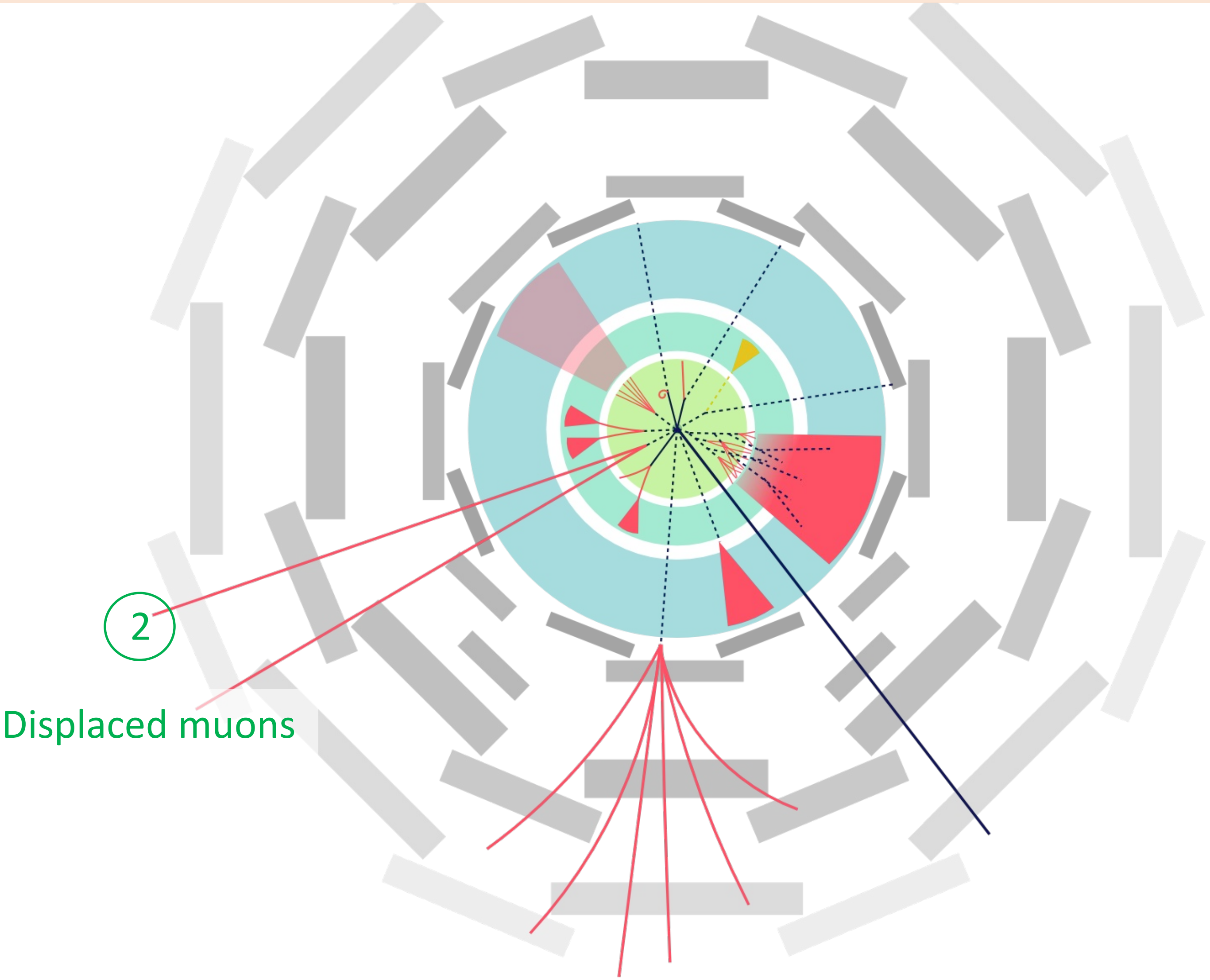
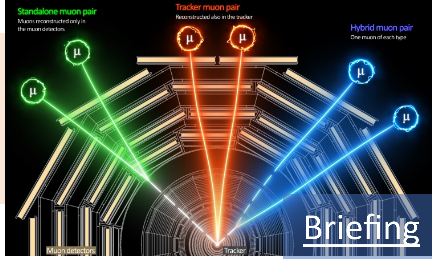
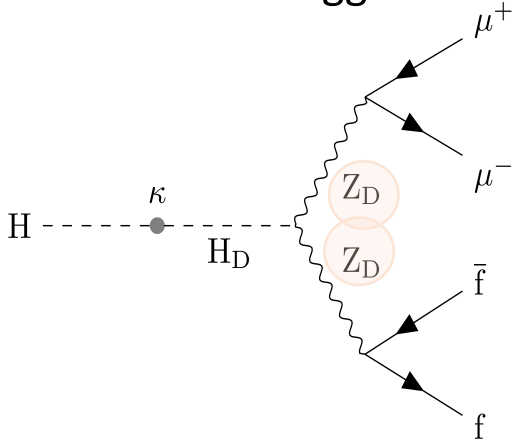


Displaced muons

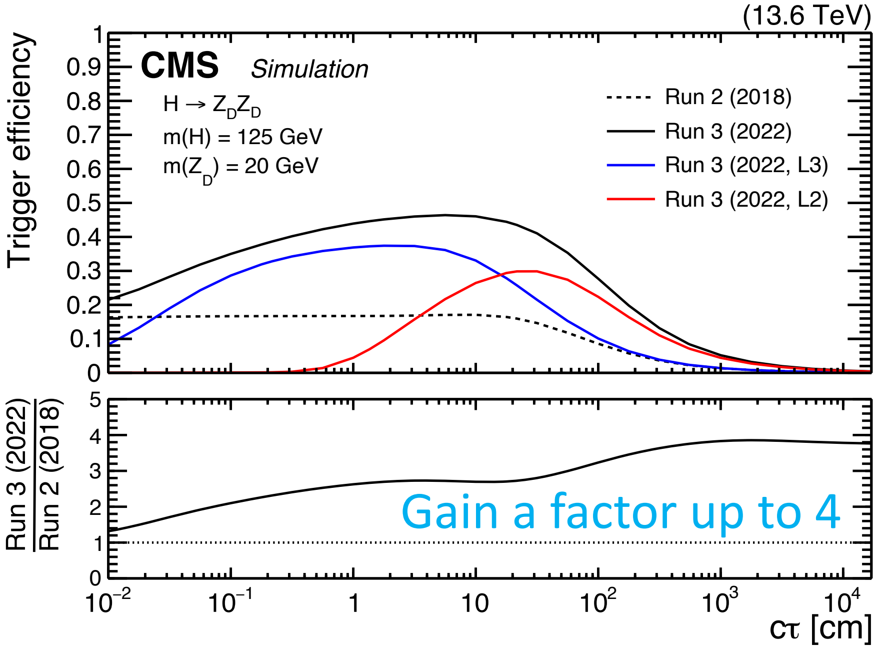


[JHEP 05 (2024) 047]

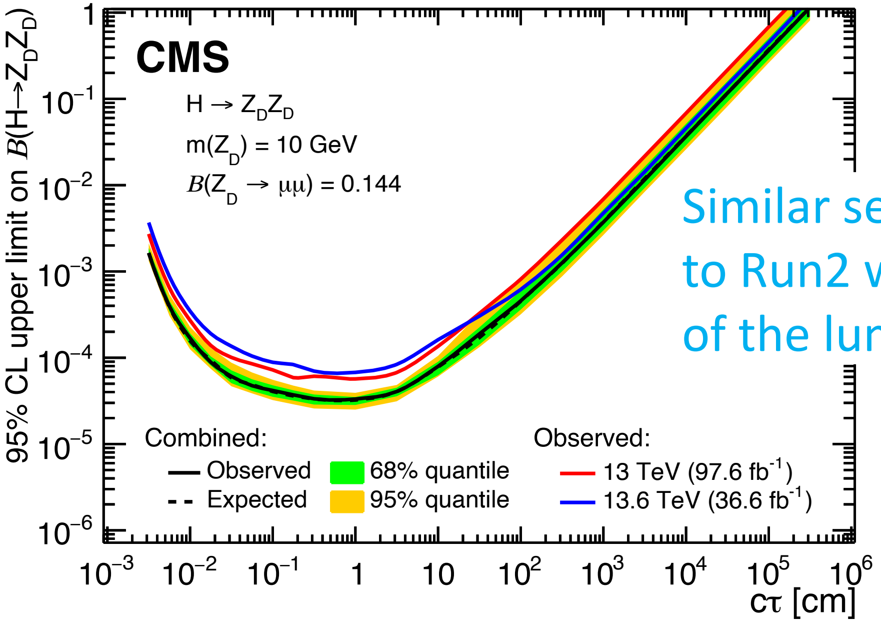
Hidden Abelian Higgs model



- Signature: ≥1 dimuon pair (global or standalone muons, p_T> 10 GeV), selected in **2022 data** (36.6 fb^{-1})
  → First Run3 CMS search !
- New triggers for displaced dimuons developed for Run 3



Gain a factor up to 4



Similar sensitivity to Run2 with only 1/3 of the luminosity !

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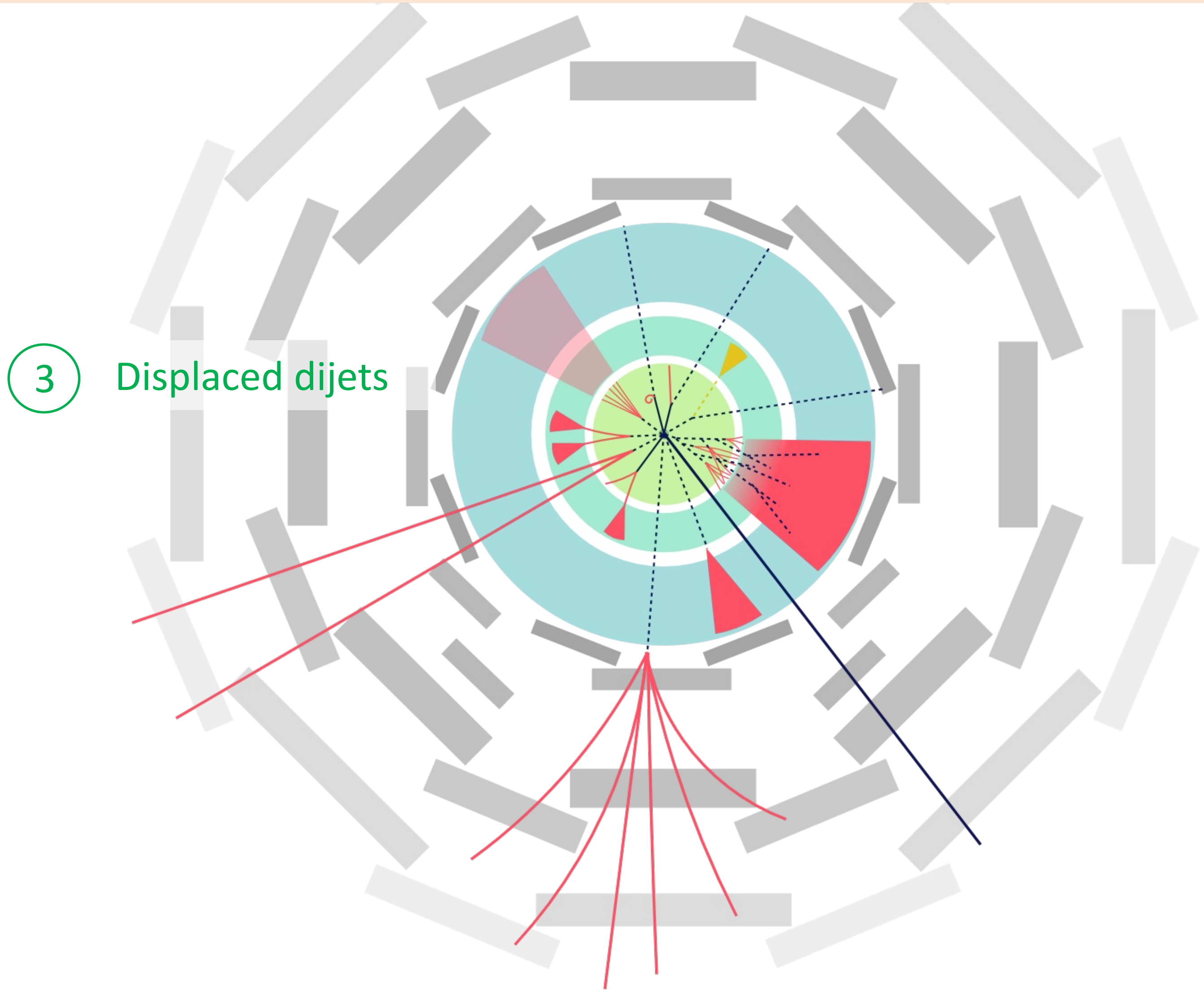
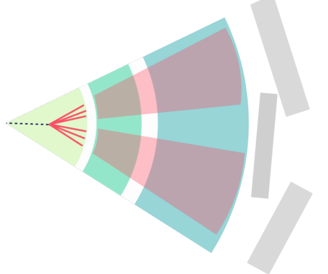
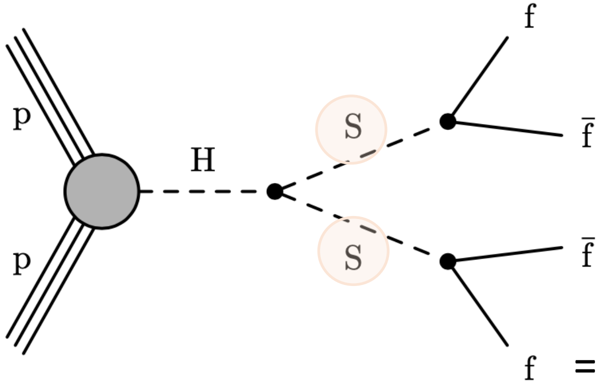


Displaced dijets



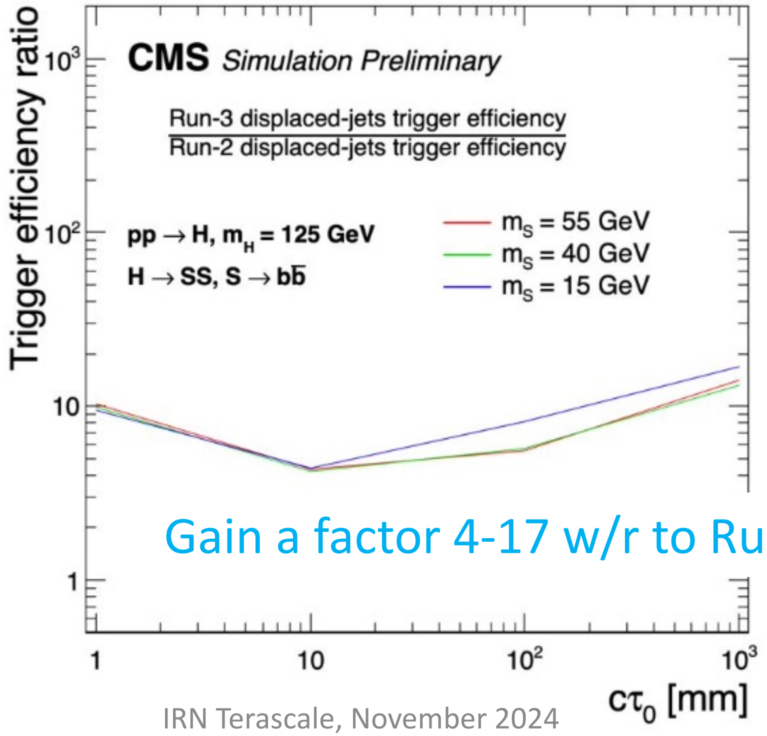
[2409.10806]

- Signature: ≥1 displaced dijet candidate (jets p_T> 40 GeV, $|\eta|$<2), selected in **2022 data** (34.7 fb^{-1})



f = b, d, τ

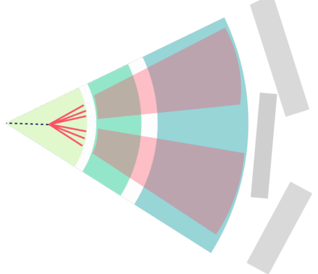
- New displaced jet triggers at Run 3



Gain a factor 4-17 w/r to Run2

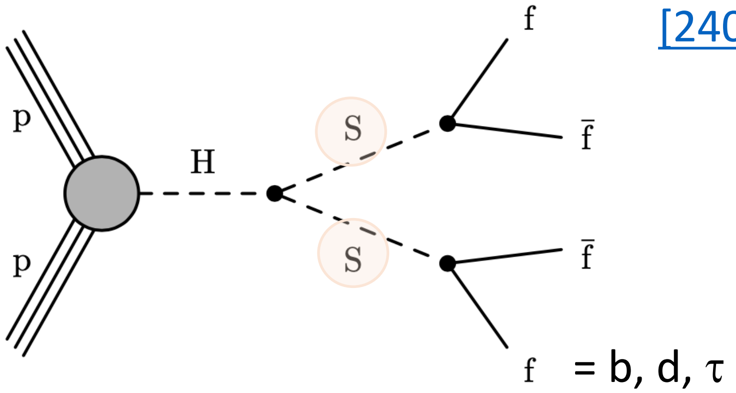
CMS-DP-2023-043

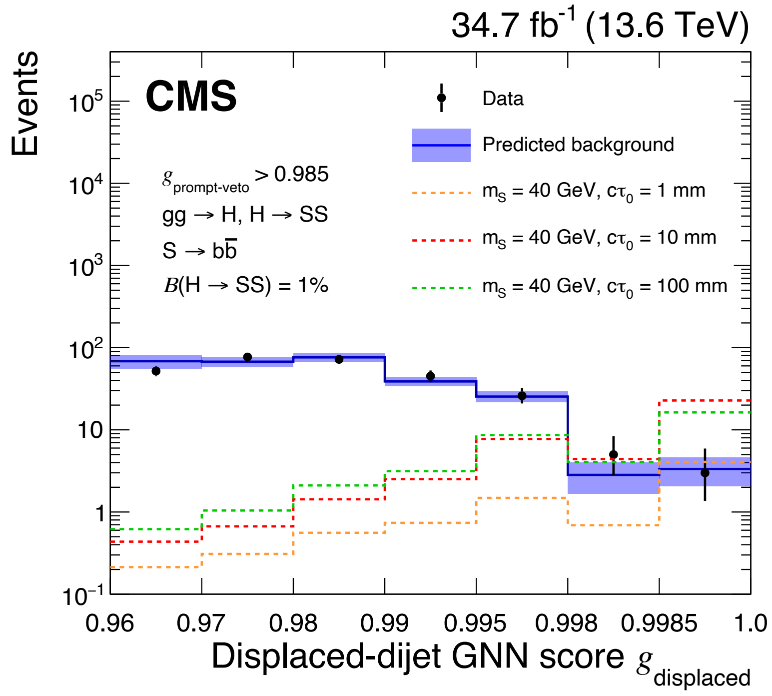
Displaced dijets



[2409.10806]

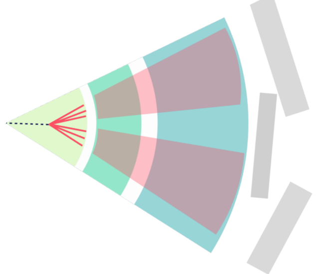
- Improved vertex reconstruction
- Better Signal/background discrimination thanks to 2 GNN-based LLP taggers:
  - $g_{displaced}$: displaced activities during the LLP decay
  - $g_{prompt\text{-}veto}$: lack of prompt activities during the LLP production
- Data-driven background estimate based on uncorrelation of the 2 taggers (ABCD)





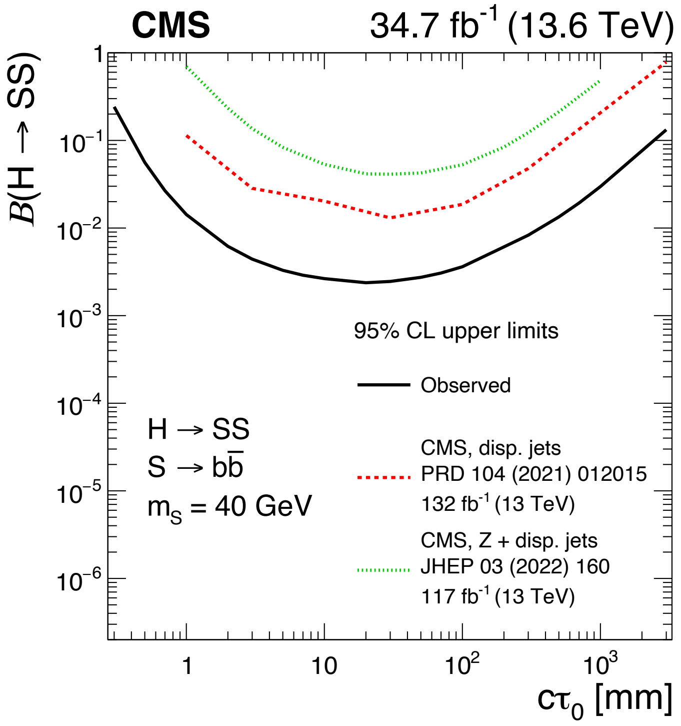
No excess

Displaced dijets



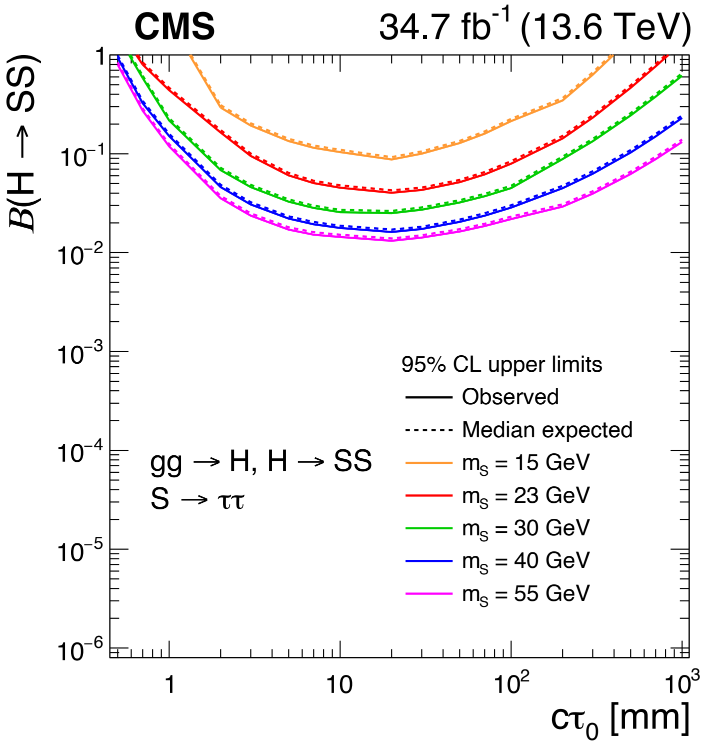
[2409.10806]

$H \rightarrow SS \rightarrow 4b$



Outperforming previous results !

$H \rightarrow SS \rightarrow 4\tau$



First tracker-based displaced hadronic τ result @LHC

Best limits to date to B(H → SS) for m(S) between 20 and 55 GeV and 0.1 mm $\lesssim c\tau \lesssim$ 1 m

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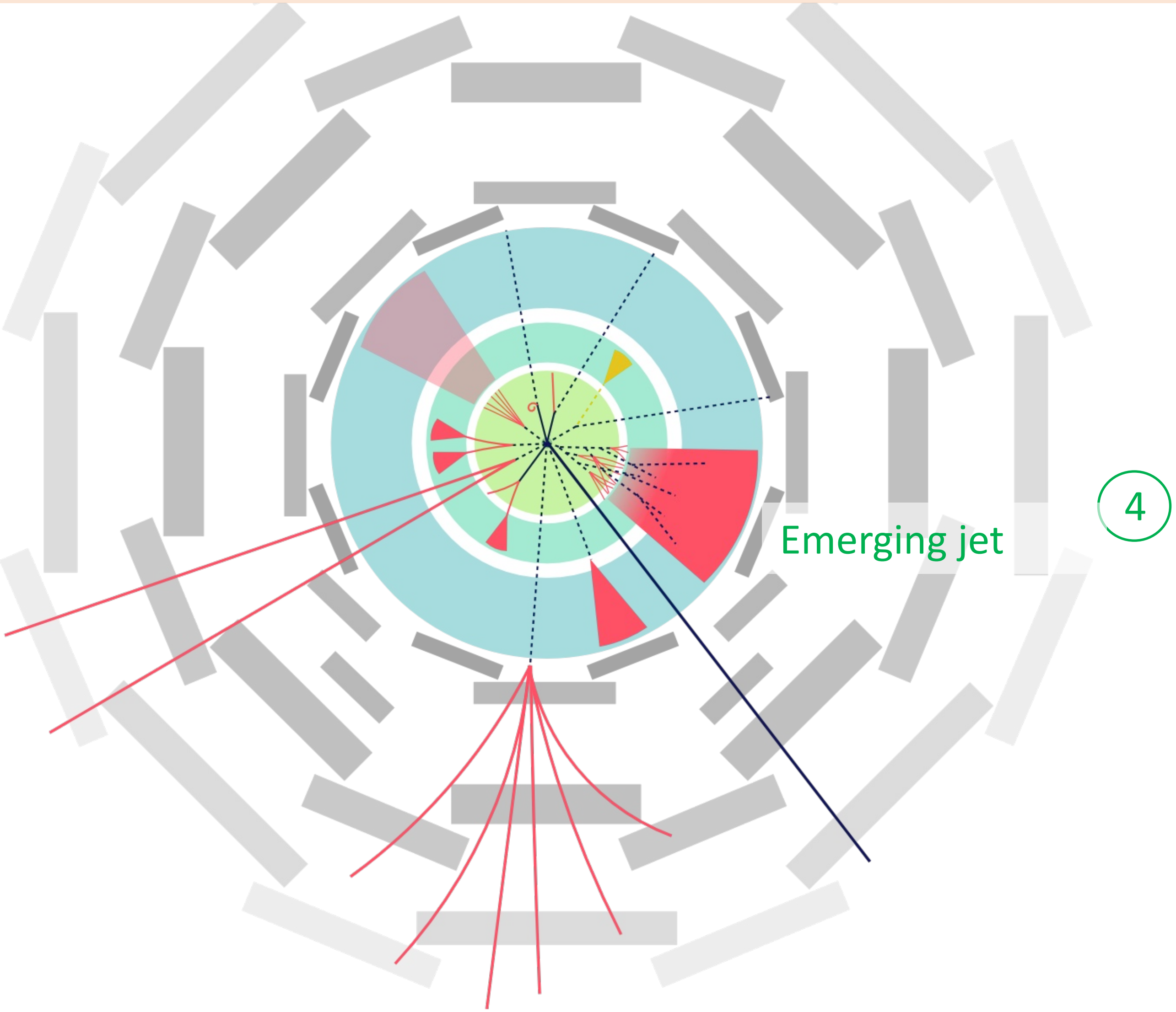
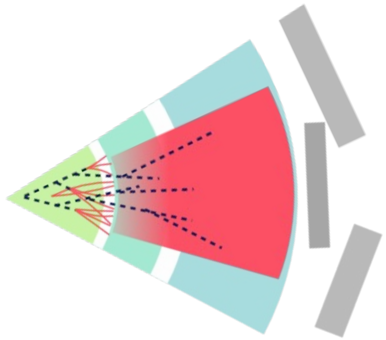
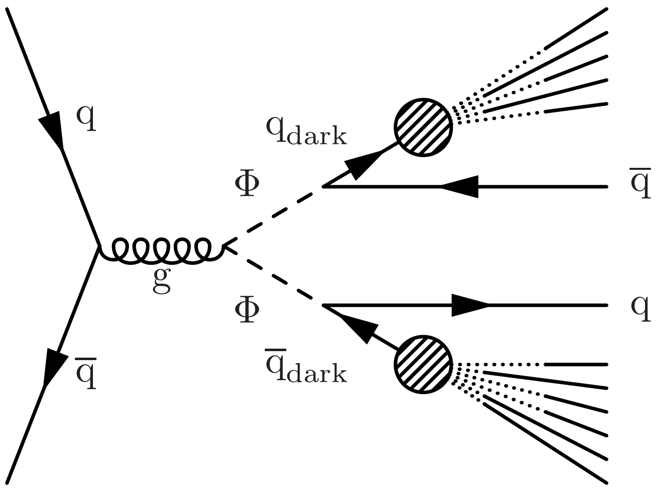


Emerging jets



[JHEP 07 (2024) 142]

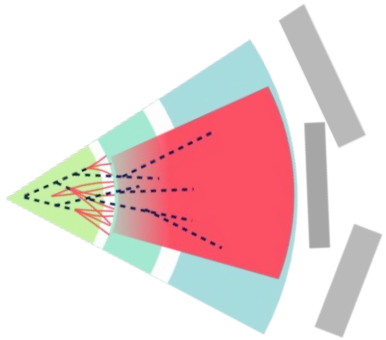
Dark QCD model



During hadronization, the q_{dark} produces LL dark mesons π_{dark} which then decay to SM particles

- Signature: 2 emerging jets (EJ) and 2 SM jets, all jets with p_T>100 GeV, $|\eta|$<2, selected in 2016-2018 data (138 fb^{-1}) with jet and H_T triggers

Emerging jets



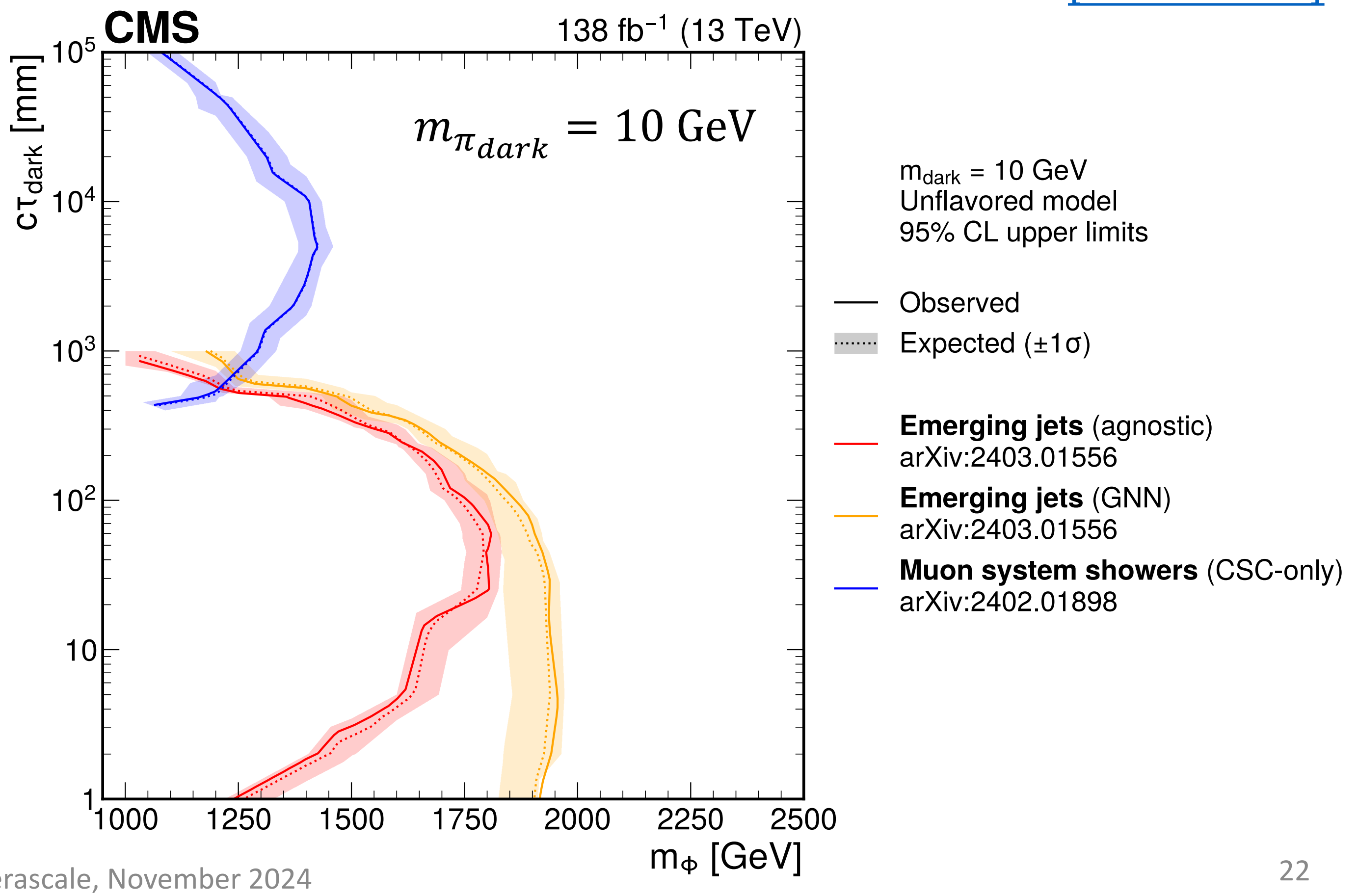
[JHEP 07 (2024) 142]

[2405.13778]

- Two approaches for EJ taggers using track displacements and jet constituents:
  - model-independent cut-based (agnostic)
  - model-specific ML-tagger (GNN)

- Two models :
  - unflavour: Dark Sector coupling to d
  - flavor-aligned: Dark Sector coupling to d, b, s

- GNN significantly improves the sensitivity at low $c\tau_{\pi_{dark}}$ ($\lesssim$ 100 mm)



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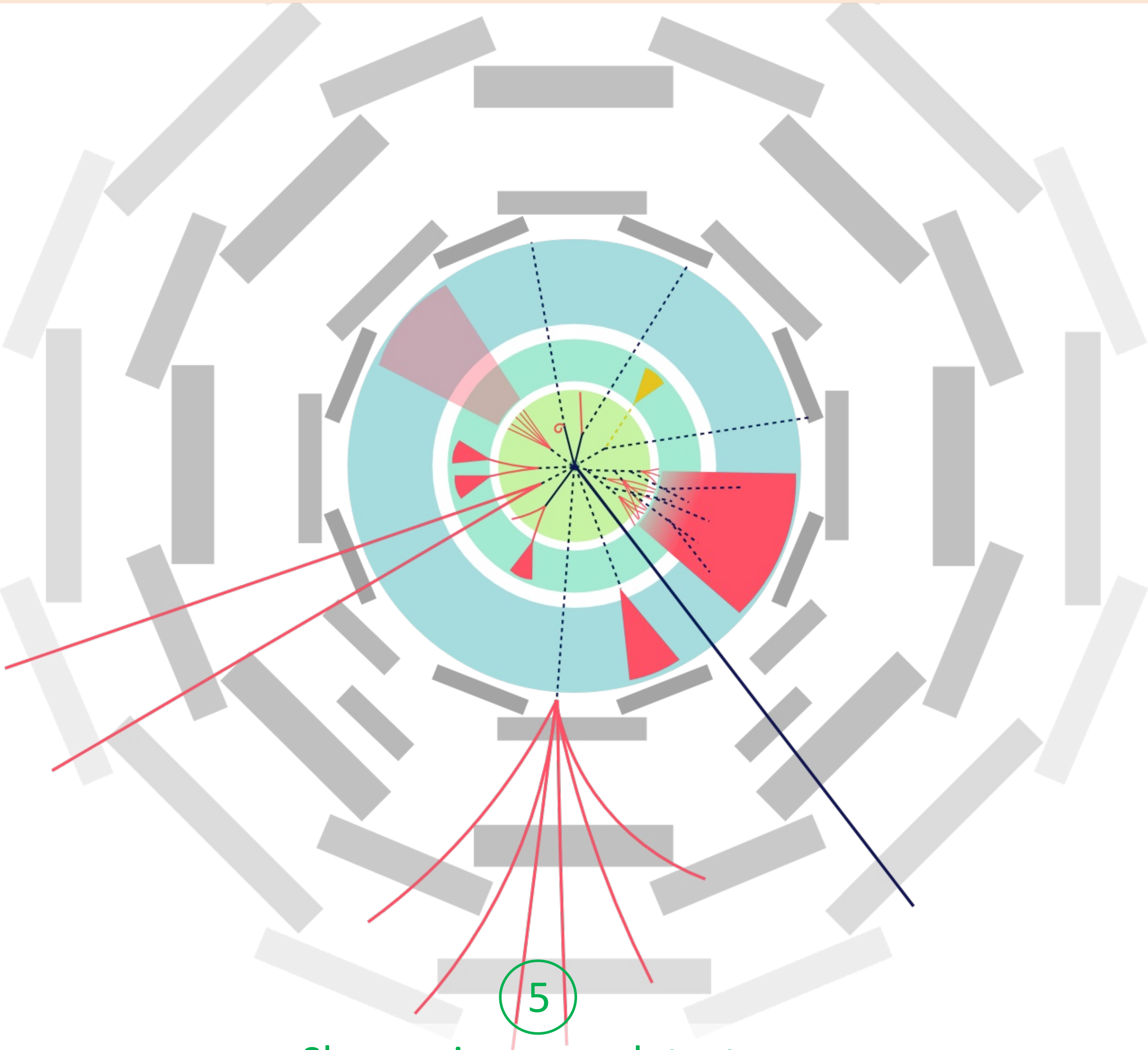
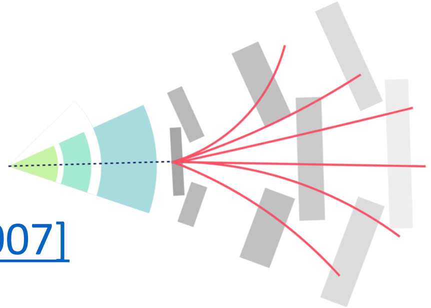


Showers in muon detector

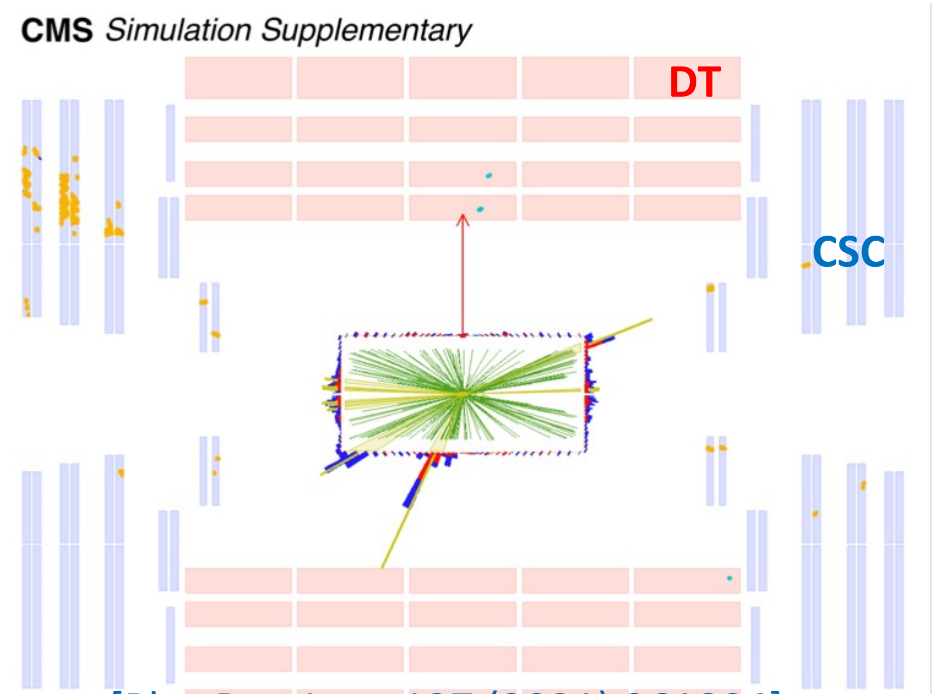


[Phys. Rev. D 110 (2024) 032007]

- The muon system = a sampling calorimeter, thanks to the steel of the magnet flux-return yoke.
- Sensitive to any LLP decay (producing EM or hadronic showers, so except muons) at large cτ
- Muon Detector Shower = high multiplicity of hits (>50 hits) with no association to a muon or a jet.

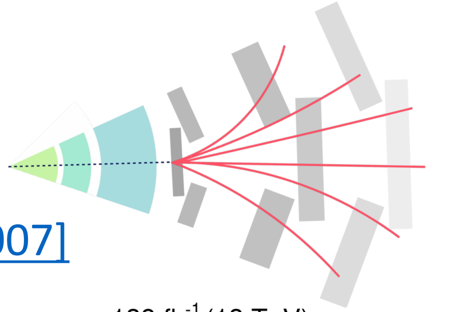
- Signature: 1 or 2 MDS, at least 1 jet (p_T>30 GeV), selected in 2016-2018 data (138 fb^{-1}) with a MET trigger. [+ Run 3 dedicated triggers for Run3 analysis]

- Excellent background suppression from shielding material, and additional veto in inner chambers.



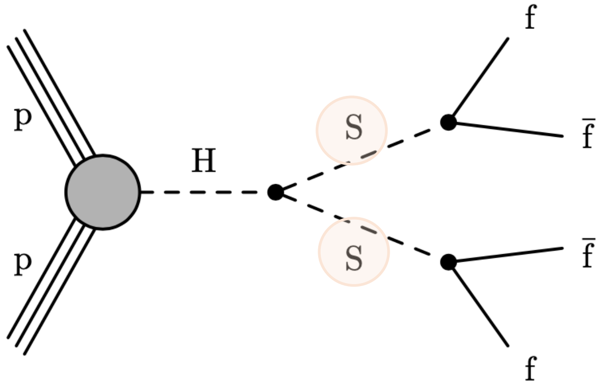
[Phy. Rev. Lett. 127 (2021) 261804]

Showers in muon detector

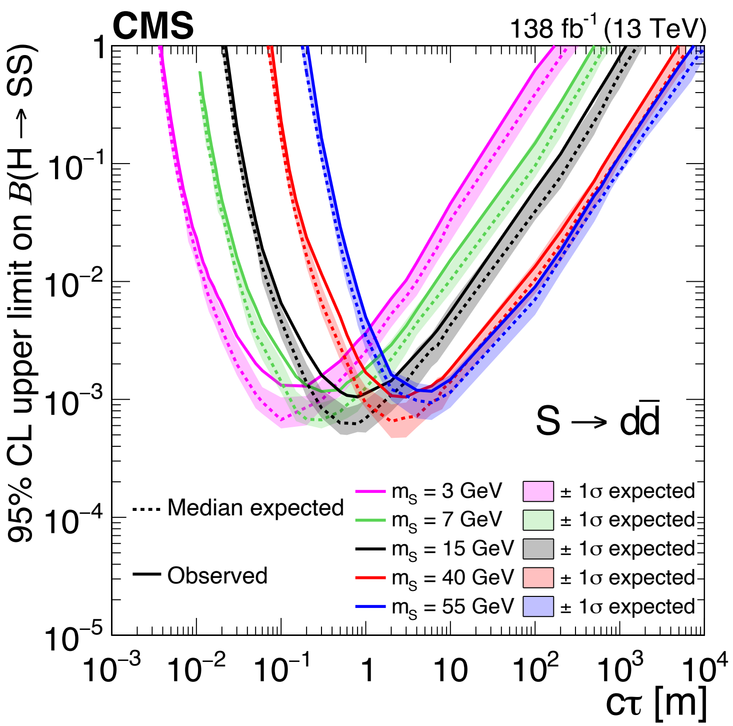


[Phys. Rev. D 110 (2024) 032007]

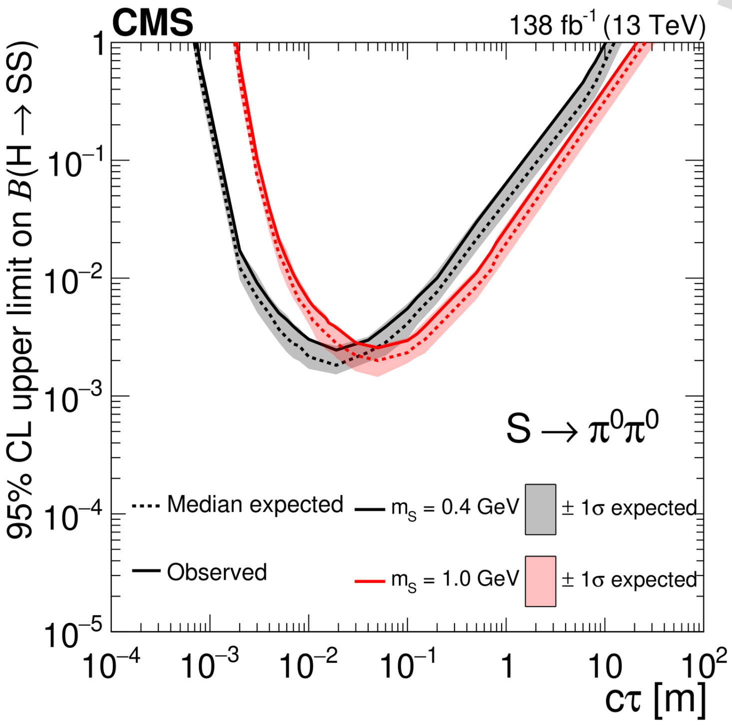
H→SS→4f



9 decay modes with hadronic shower (bb, dd, K^+K^-, K^0K^0, $\pi^+\pi^-$), EM ($\pi^0\pi^0$, $\gamma\gamma$, e^+e^-), or both ($\tau^+\tau^-$)

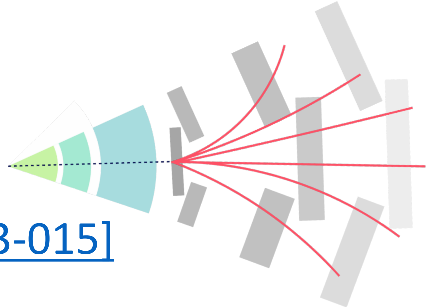


Same sensitivity for same shower type independent of masses



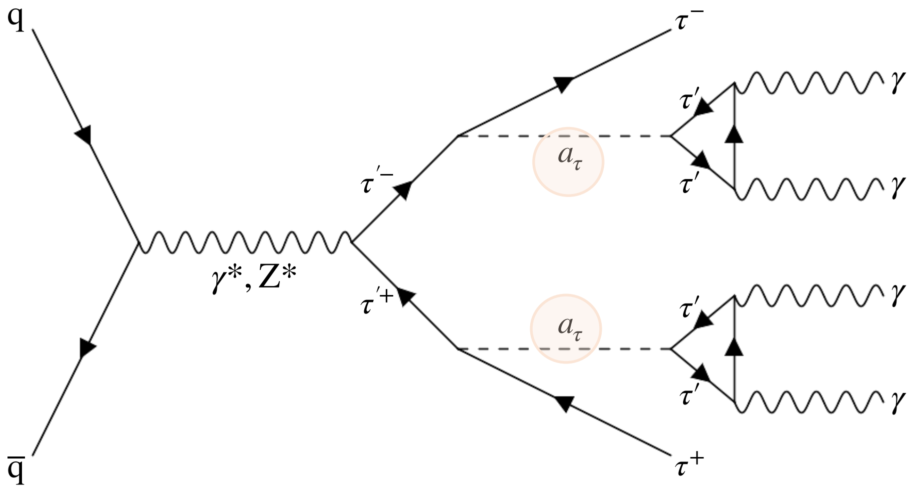
First sensitivity to sub-GeV mass LLPs at BR of a few per mil

Showers in muon detector

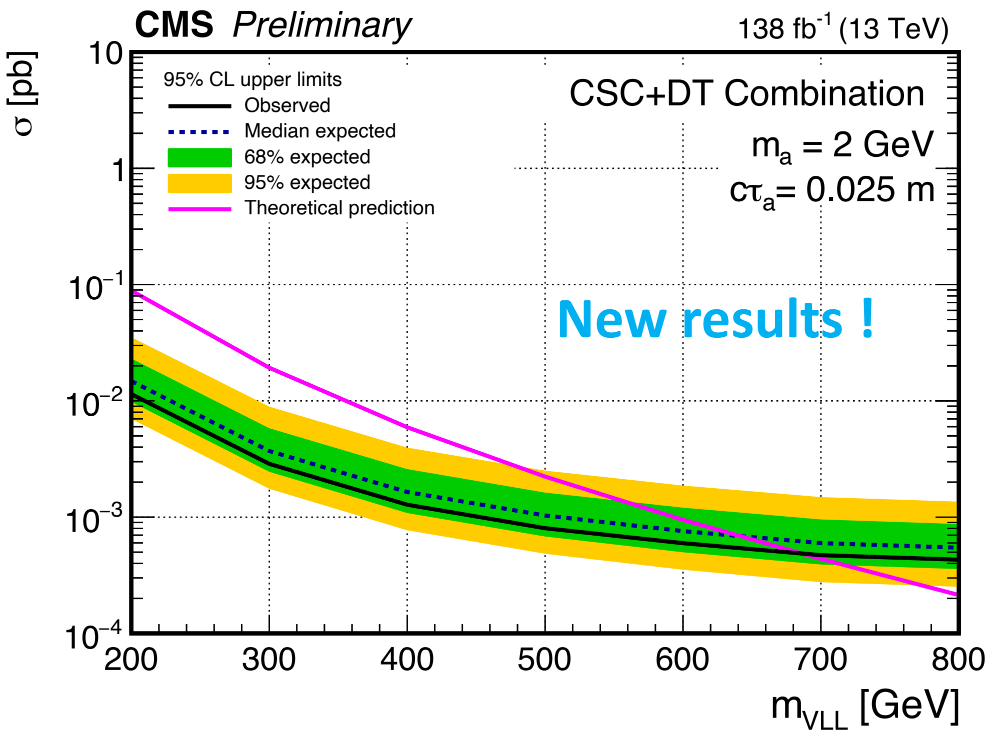


[CMS PAS EXO-23-015]

- Search for Vector-like lepton (VLL) $\tau' \rightarrow \tau\, a_\tau$



a_τ is a light long-lived pseudoscalar ($m(a_\tau)$= 2 GeV), which produces a EM shower as MDS



- Signature: 1 MDS and at least 1 prompt τ_h jet (p_T>30 GeV, $|\eta|$<2.3), selected in 2016-2018 data (138 fb^{-1}) with a MET trigger.

Summary

- The LLP program at LHC is a very active and dynamic field of research,
- highlighting the diversity in how to use the signals recorded by the CMS detector,
  - with the use of new triggers,
  - improved reco algorithms,
  - machine learning taggers,
  - different analysis strategies/techniques, …
- all based on new ideas and high dedicated commitment, already exploiting Run3 data

- And much more to come… ☺

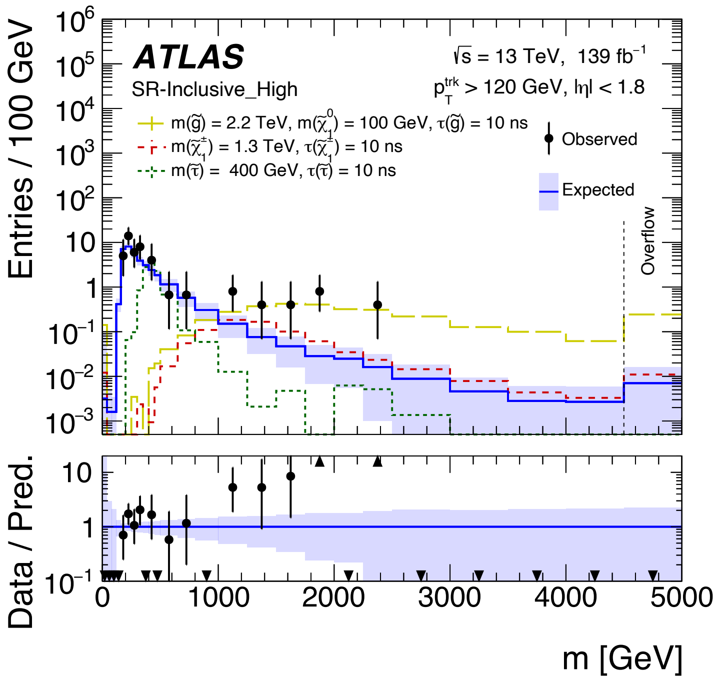
More information ?

Search for massive long lived charged particles

ATLAS analysis with large ionization (dE/dX) in Pixel

[JHEP 06 (2023) 158](#)

- Signature: An isolated track of high p_T (p_T>180 GeV, $|\eta|$<1.8) with large dE/dx deposits in the Pixel, and E_T^{miss} > 170 GeV, selected in 2015-2018 data (139 fb^{-1}) with E_T^{miss} trigger.



3.3σ global (3.6σ local) excess for the target mass of 1.4 TeV: 7 events observed for 0.7 $\pm$ 0.4 predicted in the mass window [1100, 2800] GeV.

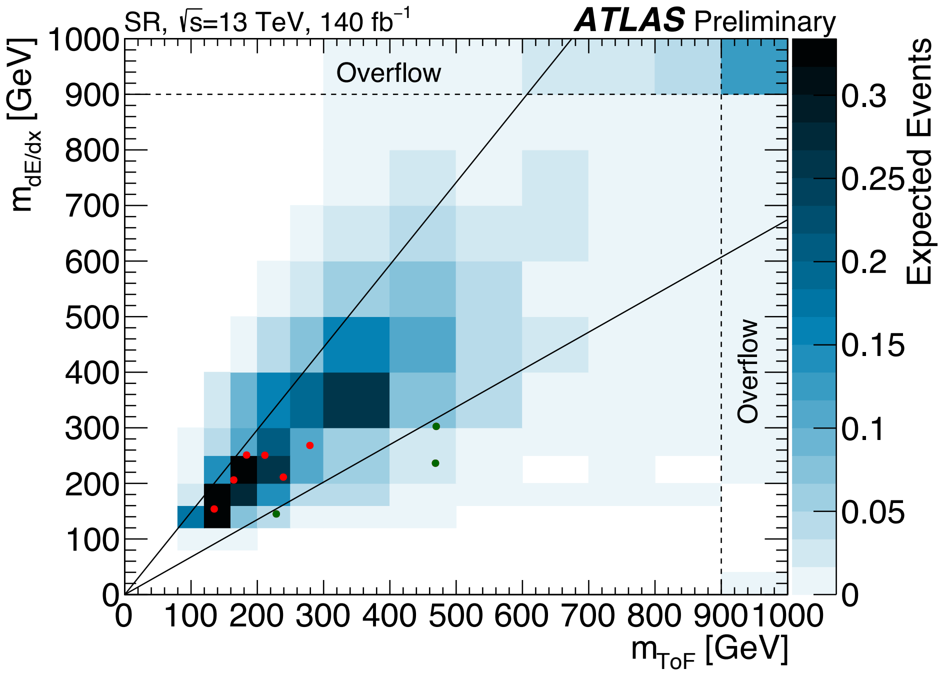
The time-of-flight measured (in calorimeter or muon chambers) for these events is compatible with β=1.

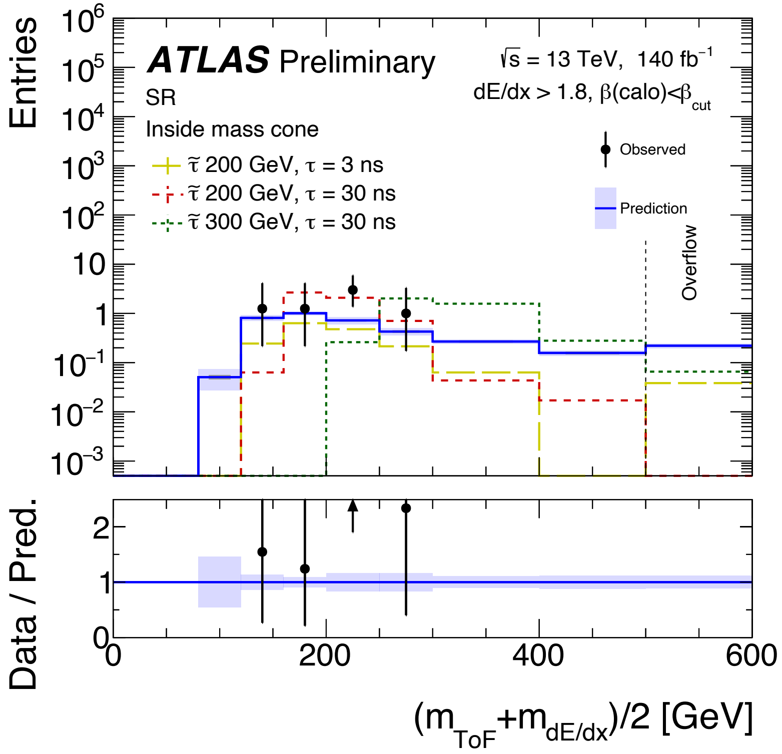
Search for massive long lived charged particles

ATLAS-CONF-2023-044

ATLAS analysis with large ionization (dE/dX) in Pixel and low β in the calorimeter

- Signature: An isolated track of high p_T (p_T>120 GeV, $|\eta|$<1.6) with large dE/dx deposits in the Pixel and low β_{TOF} in hadronic calorimeter, and E_T^{miss} > 170 GeV, selected in 2015-2018 data (140 fb^{-1}) with E_T^{miss} trigger
- Data-driven background estimate, normalization and shape predicted using dedicated Control Regions





Search for massive LL multi-charged particles

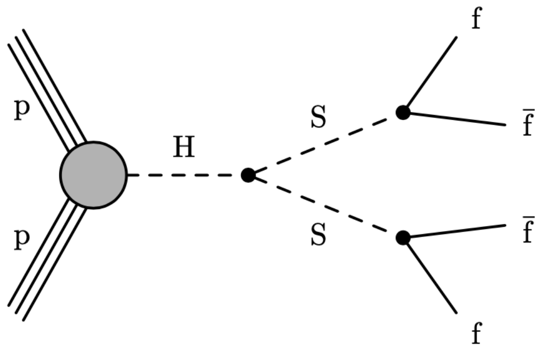
ATLAS analysis targeting |Q|=2e to 7e

Phys. Lett. B 847 (2023) 138316

- Signature: An isolated track of high p_T (p_T^{μ}/z > 50GeV, $|\eta|$<2) with large ionization measured in the Pixel, Transition Radiation Tracker and Monitored-Drift-Tube chambers, selected in 2015-2018 data (139 fb^{-1}) with a mix of Muon, late Muon and E_T^{miss} triggers.

Recently, an excess of events in a signal region in the ATLAS search for heavy long-lived $z = 1$ particles identifiable by their unusually large pixel dE/dx values [18] was observed. Two of these observed events feature candidates with pixel dE/dx values compatible with those satisfying the $z = 2$ tight-selection requirement in the current analysis, but not ending up in the corresponding signal region. A dedicated check was performed to understand the reason for this. It was demonstrated that neither of the two candidates have high enough ionization loss in TRT or MDT to make it into the signal region – in fact, both of them belong to the A control region (see Figure 4(a)).

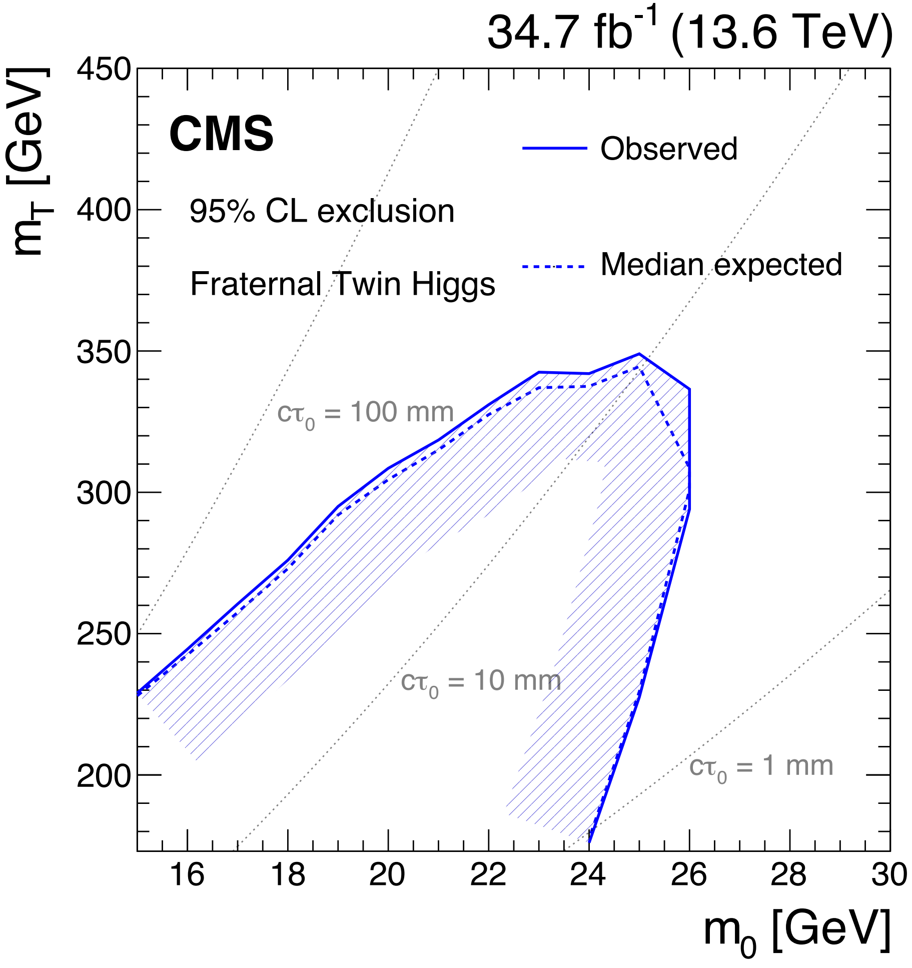
Displaced Dijets



[2409.10806]

Limits for the Fraternal Twin Higgs model in the neutral-naturalness scenario

- The scalar S = the lowest-mass glueball G_0 in the hidden sector.
- The branching fraction $B(H \to G_0G_0)$ and the $c\tau_0$ of G_0 can be estimated according to the glueball mass m_0 and the top-partner mass m_T in the hidden sector. The dependencies of $B(H \to G_0G_0)$ and $c\tau_0(G_0)$ on m_0 and m_T are taken from arXiv:1610.07922, assuming $B(H \to G_0G_0)$ is the same as the branching fraction for the Higgs boson to decay to hidden gluons multiplied by a phase space factor $\sqrt{1 - 4\, m_0^2/m_H^2}$.
- For simplicity, it assumes a $B(G_0 \to b\bar{b})$=100%



Emerging jets

[JHEP 07 (2024) 142]

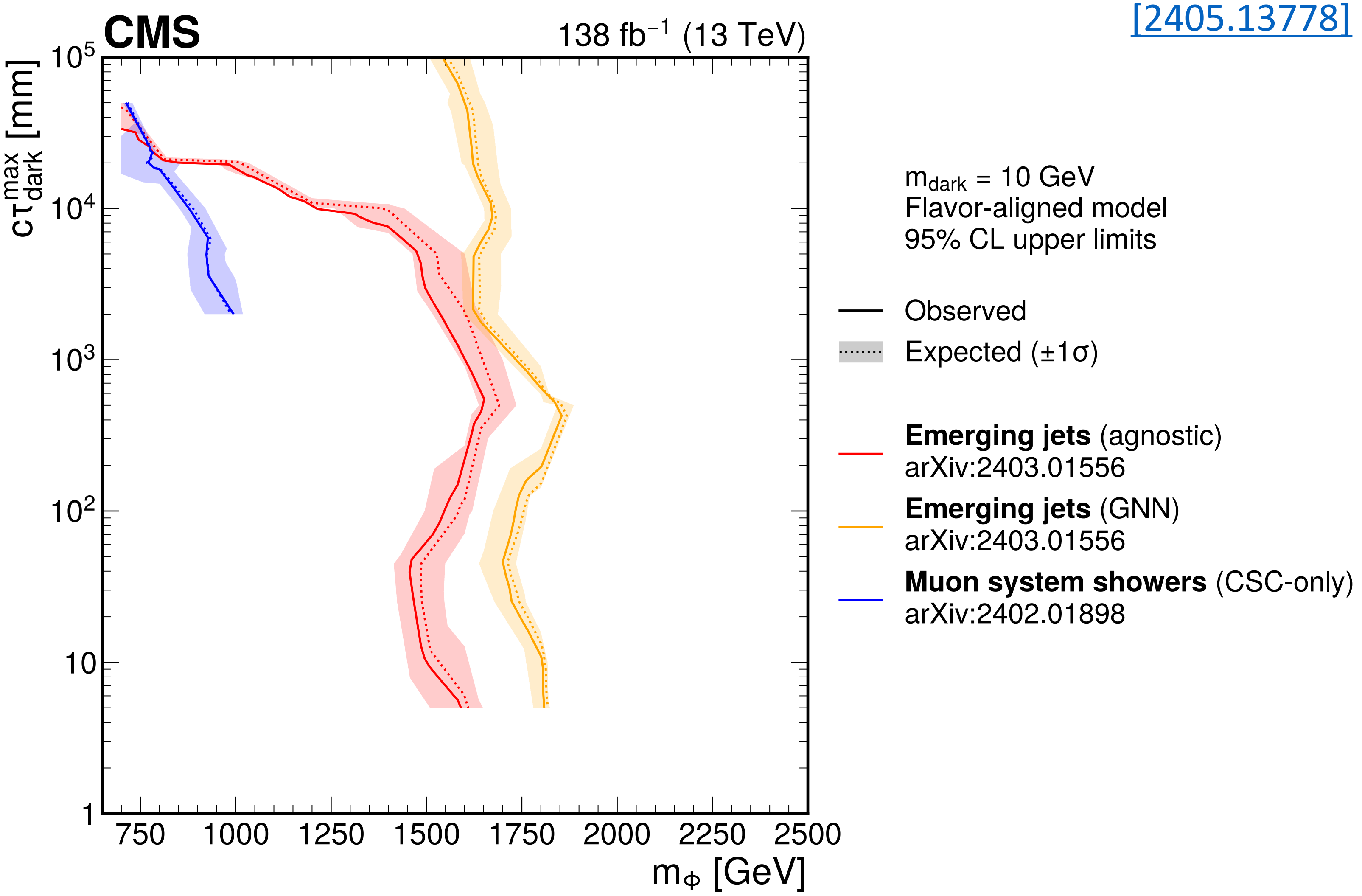
[2405.13778]

Limits for the flavor-aligned model

Three dark quark flavors that couple to the SM down-type quarks (d, s, b)

Dark hadron decays to heavier SM particles are favored, typically resulting in a large number of b quarks in the decays when kinematically allowed.

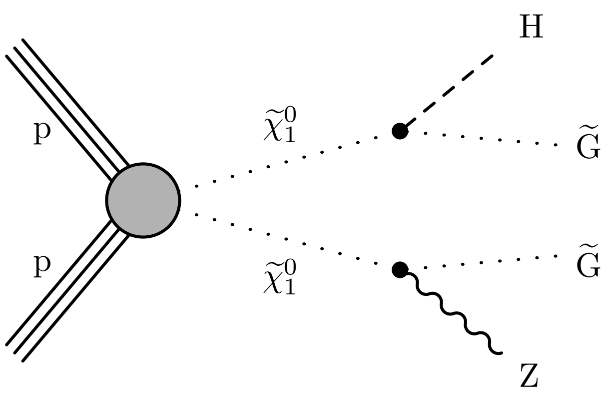
$c\tau_{\pi_{dark}}^{max}$ = maximum lifetime for any dark pion

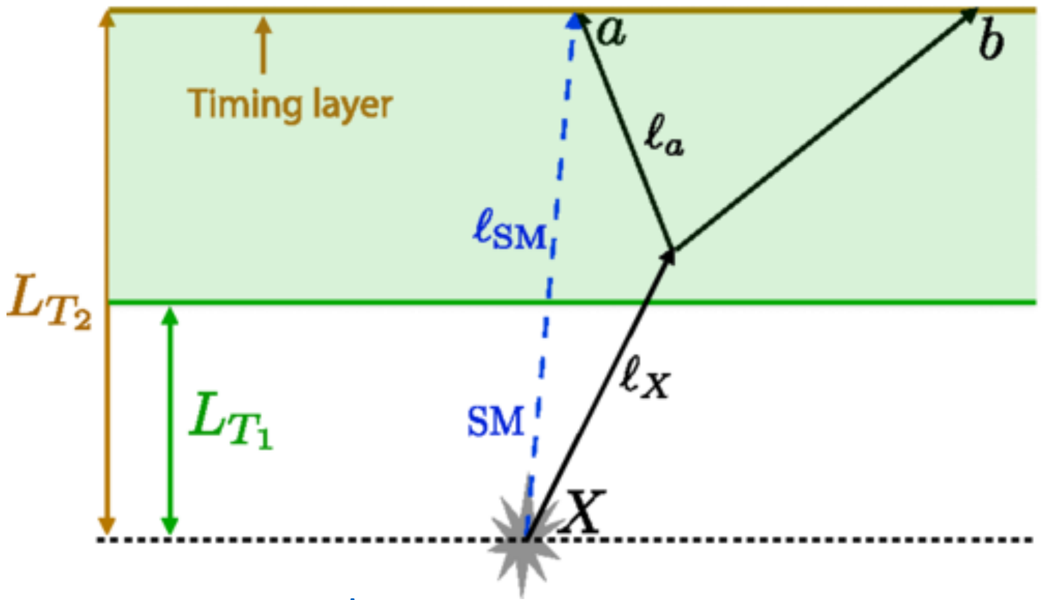


Search for LLP using out-of-time trackless jets

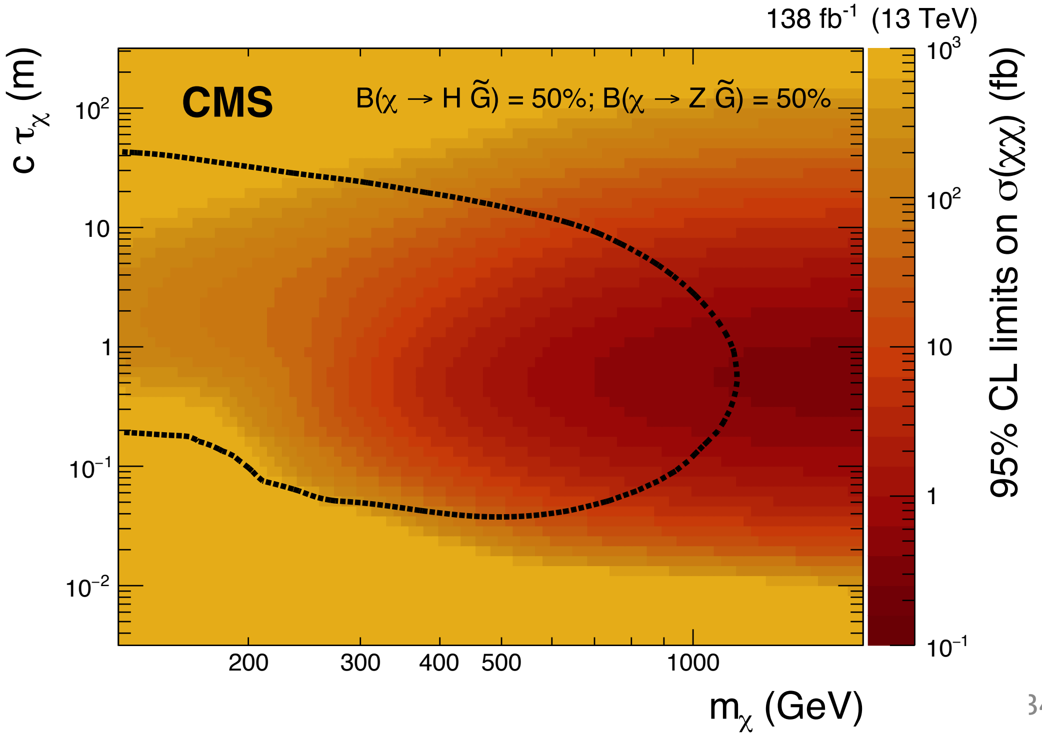
JHEP 07 (2023) 210

- Analysis targeting cτ ~ 1 m (outer tracker / electromagnetic calorimeter ECAL)
- Tracking efficiency decreases with displacement → jets appears as trackless
- Slow-moving LLPs and/or path length increase due to displacement → jets are delayed wrt p-p collision!



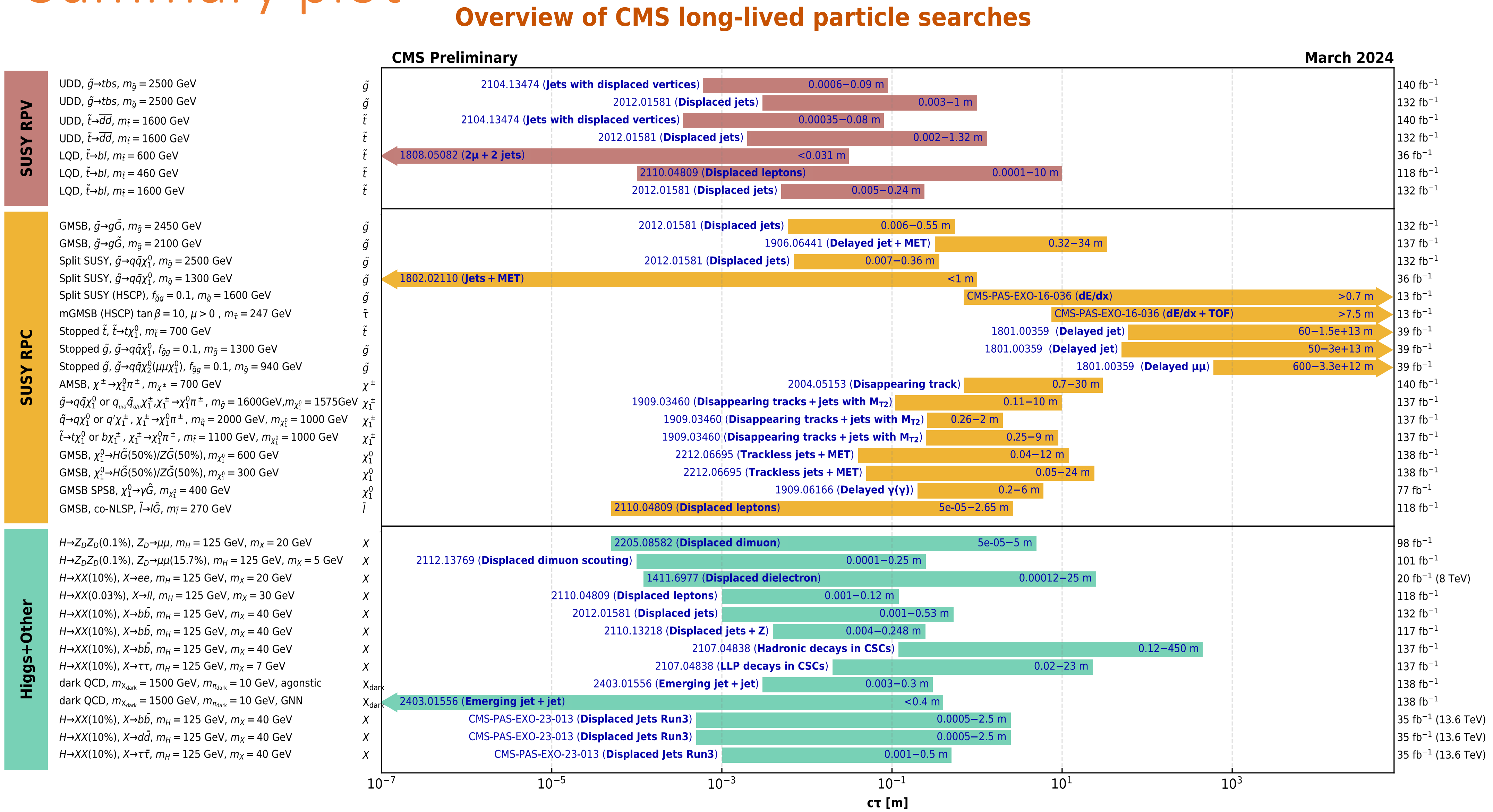


Phys Rev Lett 122 131801



LLP Summary plot

EXO Summary Plots



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

HNL Summary plot

EXO Summary Plots