(Other) Exotic Searches by CMS

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On behalf of the CMS Collaboration

Moriond/EW2024 - March 26, 2024 (afternoon session)

Overview

- Direct searches for BSM physics remains a key part of the CMS physics program

- Searches cover wide range of experimental signatures
  - I'll present CMS highlights
  - focus on recent results, avoid overlaps

- Current search strategy
  - follow up on excesses in data
  - explore new final states
  - trigger and analysis developments

Other talks on searches (ATLAS+CMS):

- *"SUSY and dark matter"* Tommaso Lari
- *"VLQs, heavy ν, long-lived particles"* Sergio Grancagnolo
- *"Search for anomaly detection"* Jennifer Ngadiuba
- *"DiHiggs searches (HH, XH)"* Louis D'Eramo
- *"Search for EFT"* Mark Andrew Owen

Dataset (pp)	Years	Int. Lumi.	$\sqrt{s}$
Run 2	2016-2018	~140 fb^{-1}	13 TeV
Run 3	2022-2023	~65 fb^{-1}	13.6 TeV

NEW **Several new results (including Run 3)**

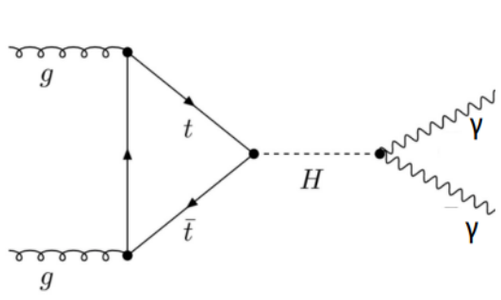
NEW

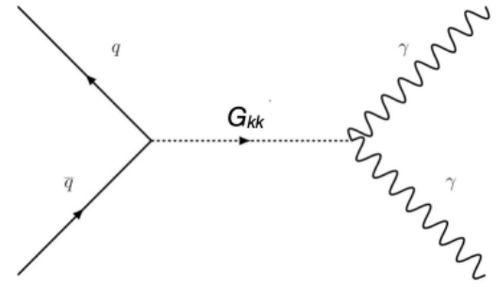
Diphoton resonances

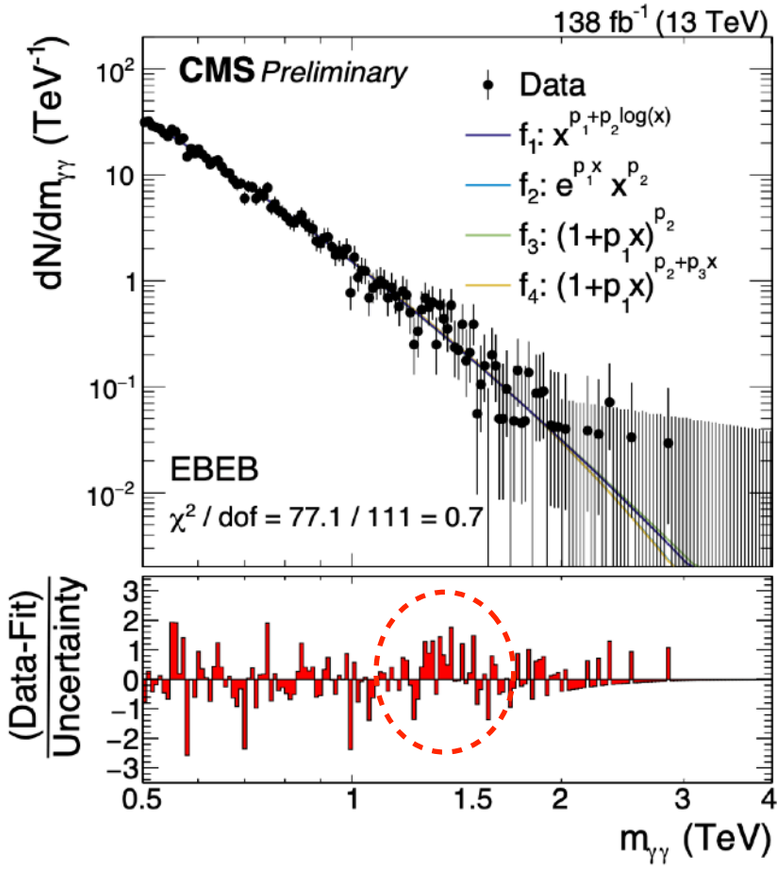
EXO-22-024

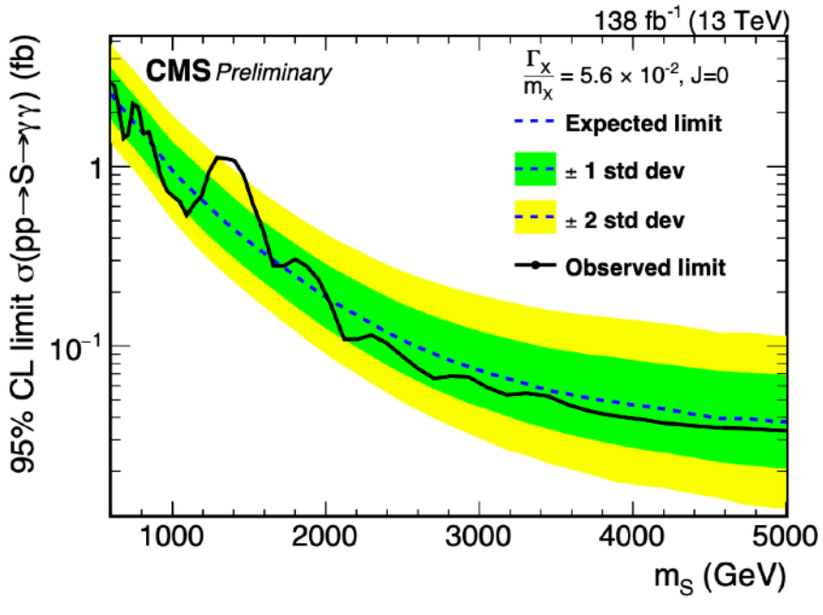
- Bump search in the diphoton mass spectrum
  - spin0 (heavy Higgs) and spin-2 (RS graviton)
  - scan resonance width (10^{-4}, 1%, 5%)
- Largest local excess of 2.6σ at ~1.3 TeV for the broad resonance model
  - global significance 0.8σ
  - no excess observed by ATLAS analysis (arXiv:2102.13405)

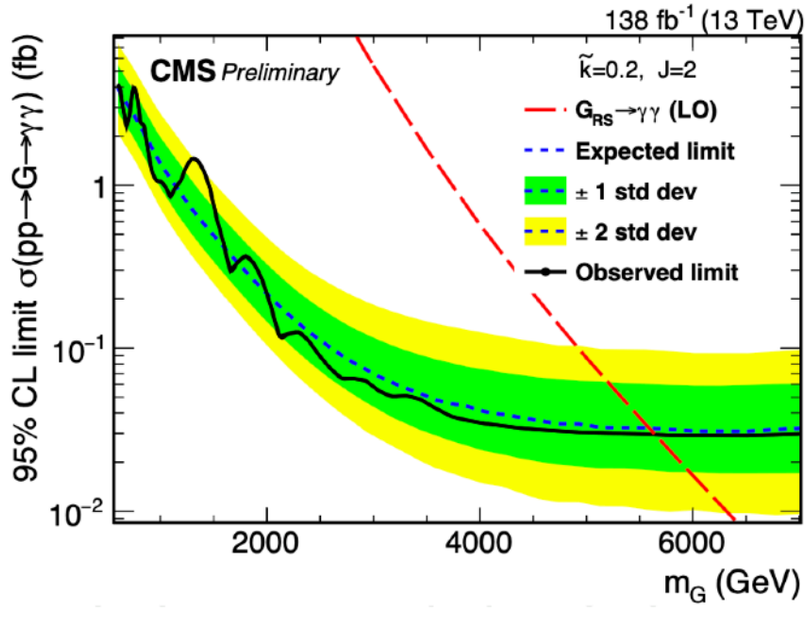
RS Graviton, k=0.1	
	Mass Limit [GeV]
ATLAS	4500
CMS	4850









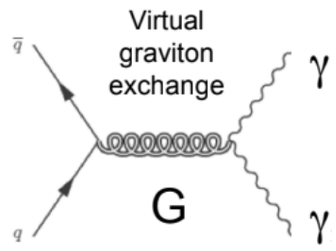


NEW

Non-resonant diphoton

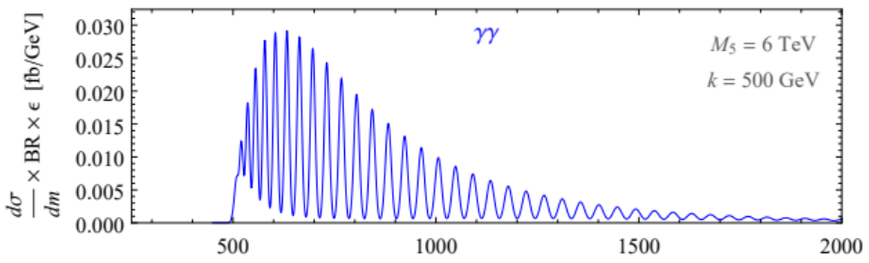
EXO-22-024

Large Extra Dimensions (ADD)

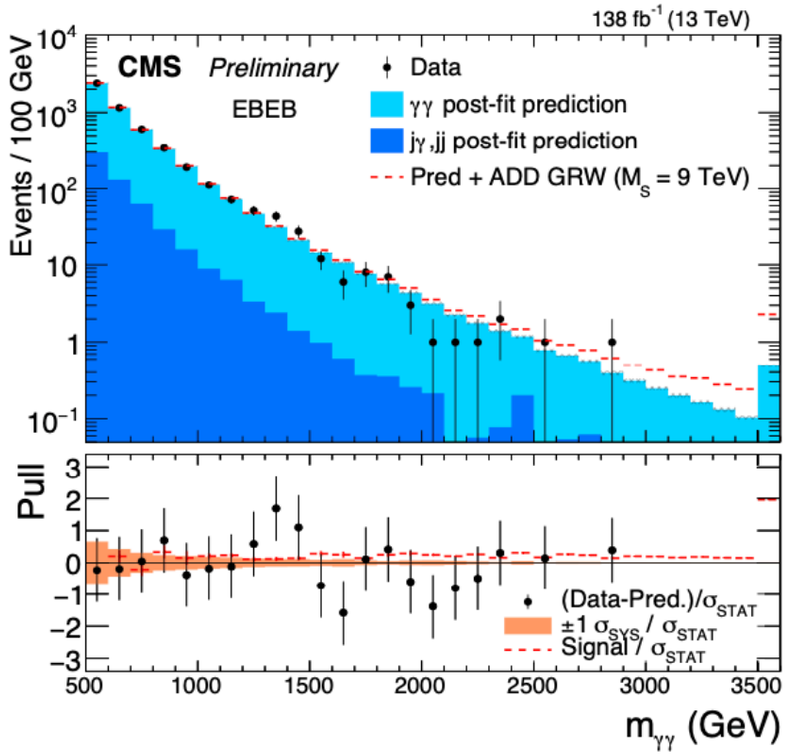


Theory Parameters:
M_S = UV cutoff in σ
n = number of ED

Clockwork (CW) model

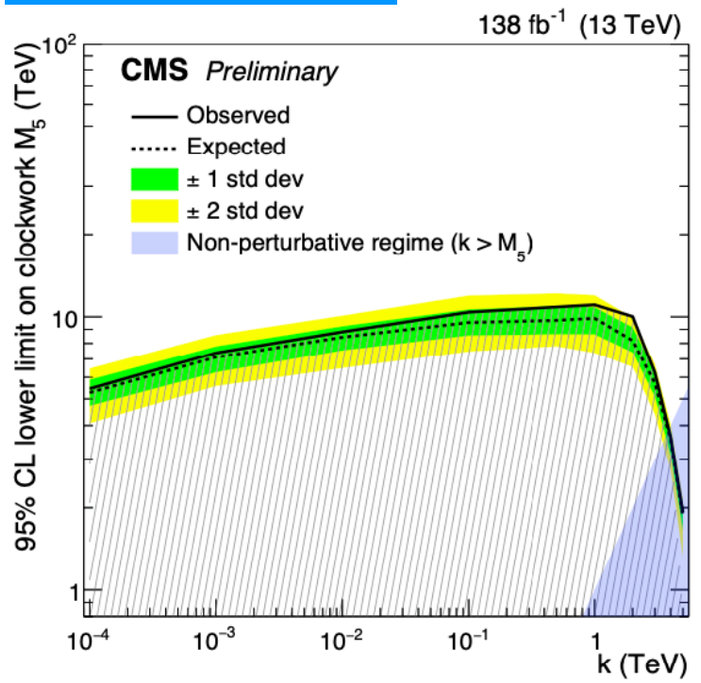


Theory Parameters:
M_5 = 5D Planck scale
k = sets inverse size of ED
(no signal for $m_{\gamma\gamma}$ < k)



- Look for excess at high mass in γγ spectrum
  - γγ SM background from SHERPA + NNLO k factor from MCFM
- No event observed with $M_{\gamma\gamma}$ > 3 TeV
  - in the most sensitive ECAL barrel category
- Set limits in ADD and clockwork model
  - comparable sensitivity with ATLAS (arXiv:2305.10894) for CW model

CW model exclusion



ADD lower limits on M_S [TeV]

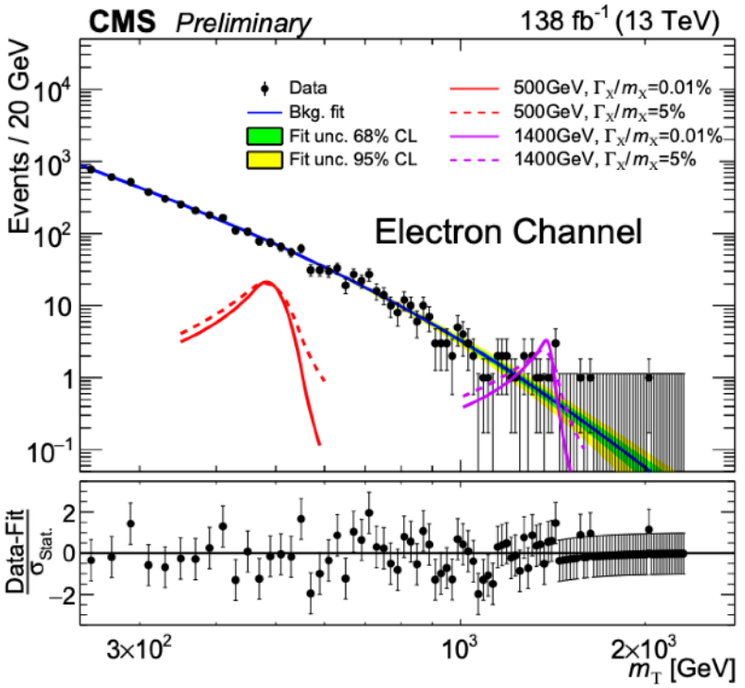
Signal:	GRW	Hewett		HLZ				
		negative	positive	n_{ED}=3	n_{ED}=4	n_{ED}=5	n_{ED}=6	n_{ED}=7
Expected:	$8.7^{+0.7}_{-0.6}$	$7.3^{+0.3}_{-0.3}$	$7.8^{+0.6}_{-0.5}$	$10.3^{+0.8}_{-0.7}$	$8.7^{+0.7}_{-0.6}$	$7.9^{+0.6}_{-0.5}$	$7.3^{+0.6}_{-0.5}$	$6.9^{+0.6}_{-0.5}$
Observed:	9.3	7.1	8.3	11.1	9.3	8.4	7.8	7.4

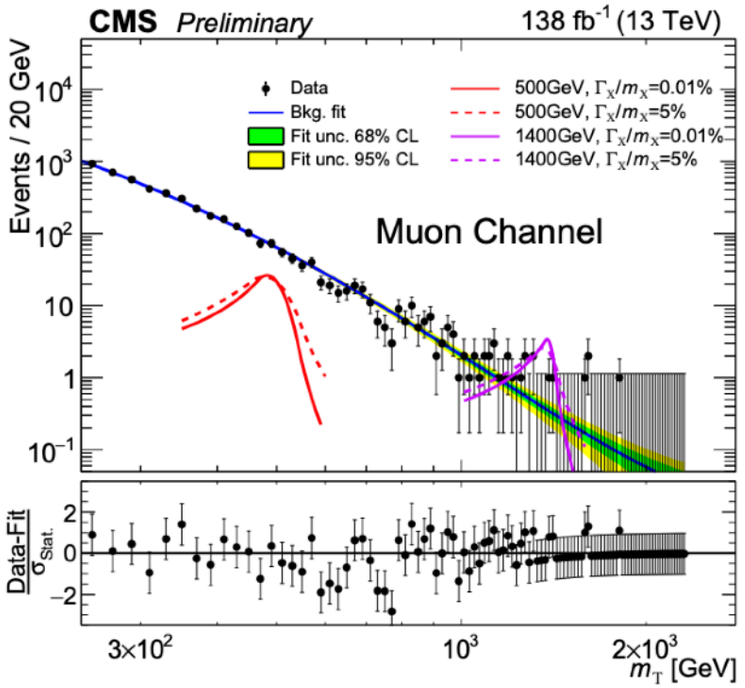
NEW

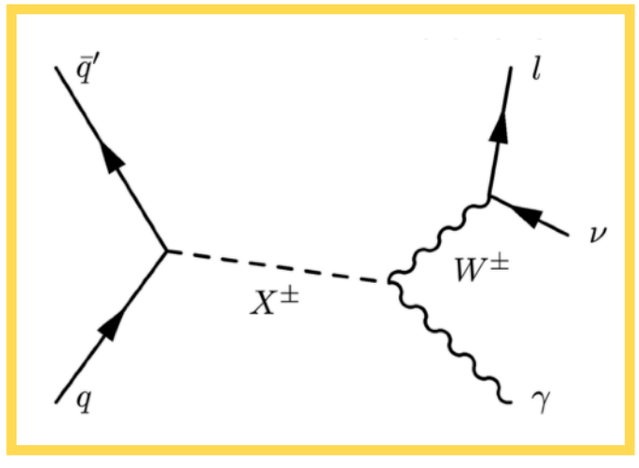
Wγ resonances

EXO-21-017

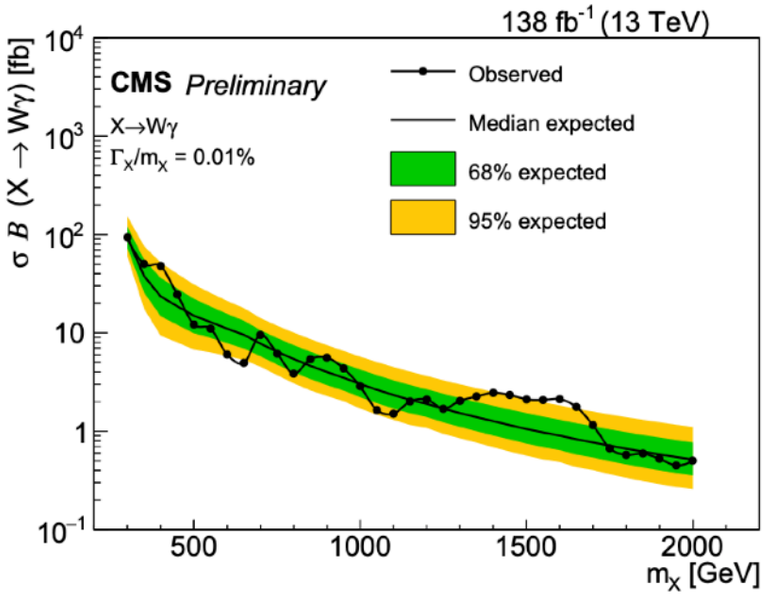
- W leptonic decays (e/μ)
- Bump search in the transverse mass (m_T) spectrum
  - narrow (0.01%) and broad (5%) resonances
  - no significant excess in data
- Results combined with hadronic channel (EXO-20-001)
  - largest local excess reduced to 2.7σ (2.5σ) at resonance mass ~1.6 TeV for narrow (broad) scenario
- Most stringent limits to date in the 0.3-2 TeV mass range



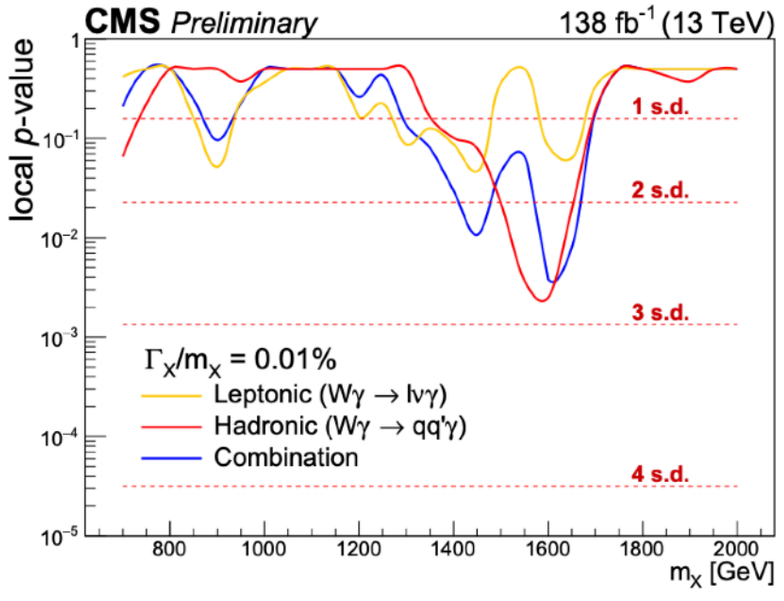




Limits (leptonic + hadronic)



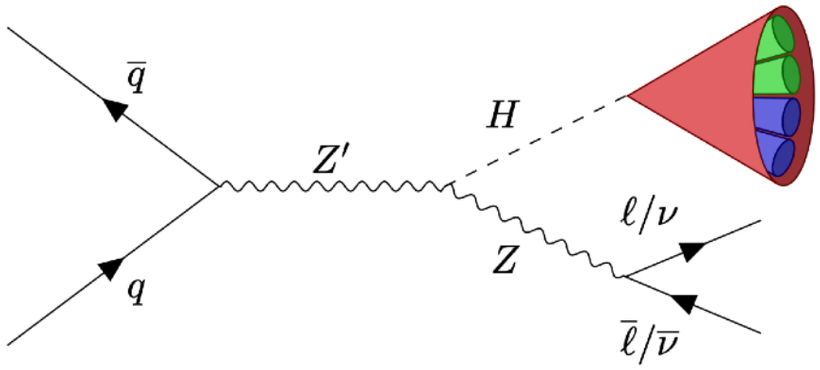
Signal significance



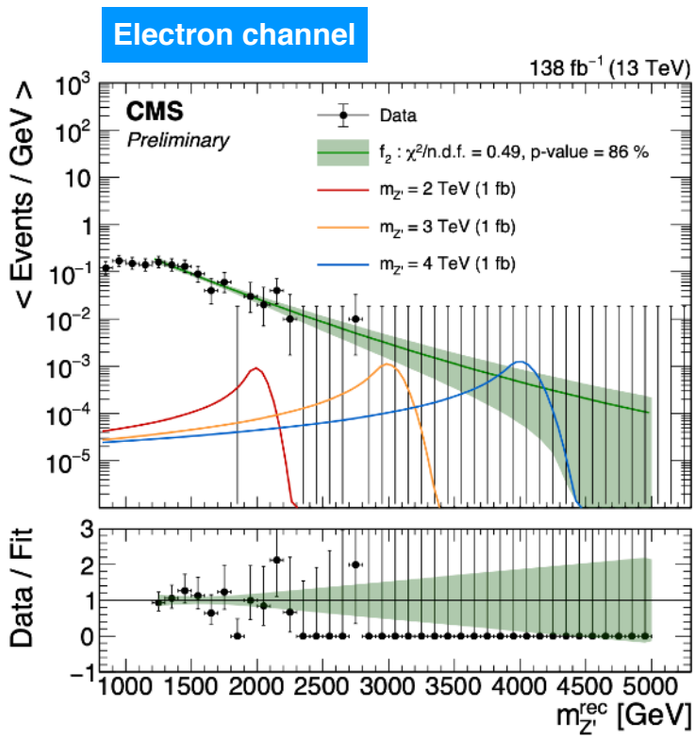
NEW

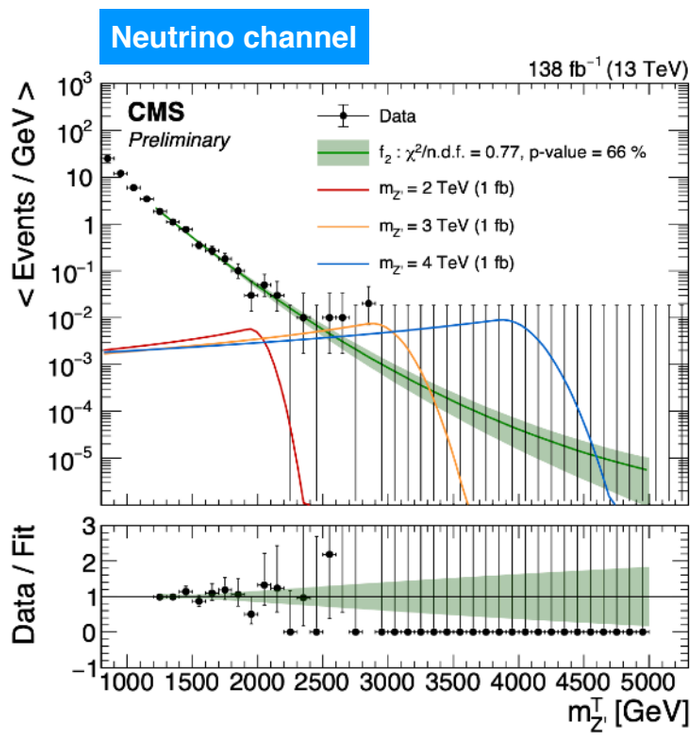
ZH resonances

B2G-23-008



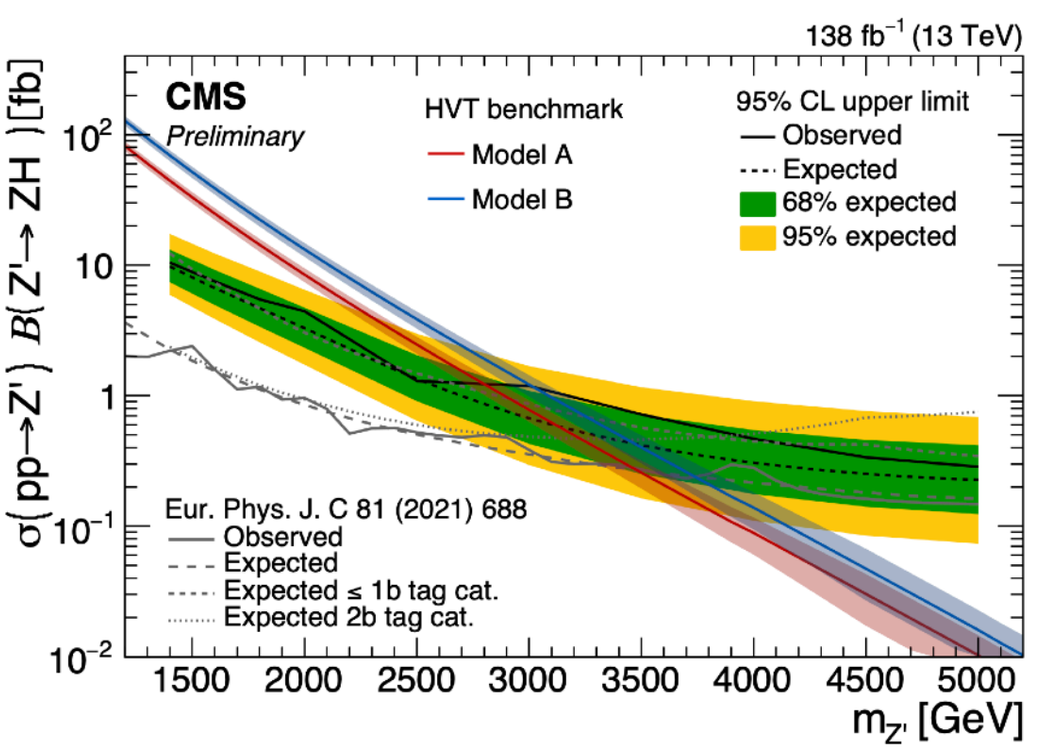
- $Z \rightarrow ee / \mu\mu / \nu\nu$
- $H \rightarrow cc / WW, ZZ \rightarrow 4q$
  - boosted Higgs → jet substructure
  - use deep neural network for classification





- Bump search in reconstructed mass or transverse mass spectrum
  - no significant excess in data

- Complementary with B2G-19-006 (H → jets using b-tag categories)
  - best limits from future combination

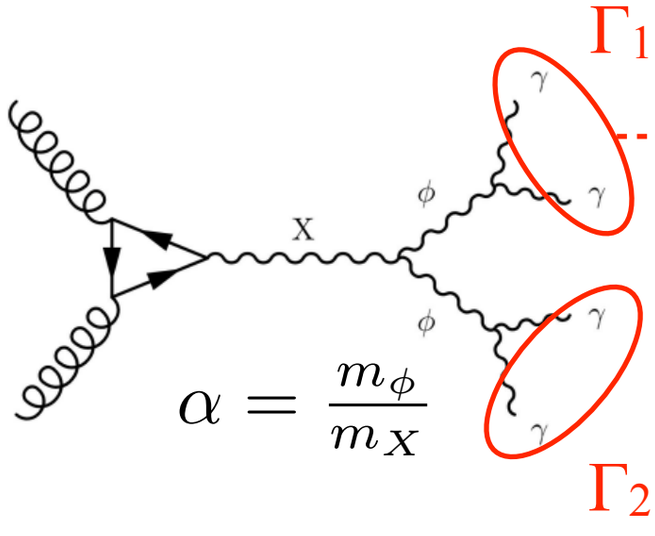


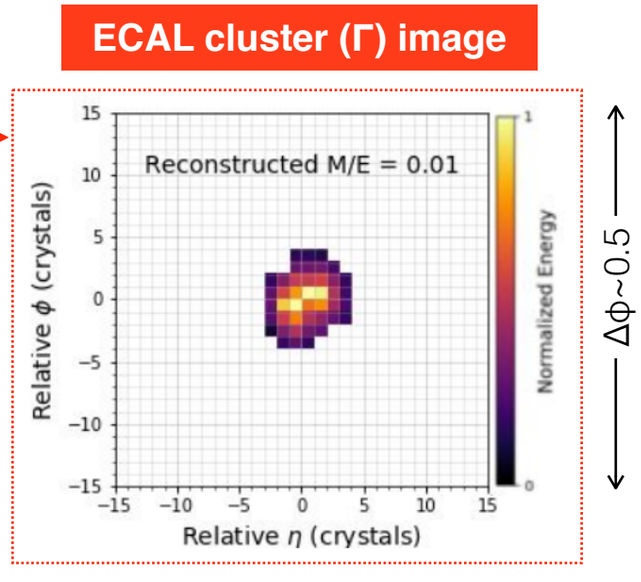
NEW

Boosted diphotons

EXO-22-022
+ CERN seminar

- Benchmark signal: X→φφ→(γγ)(γγ)
  - extended Higgs sector with two new spin-0 particles (X and φ)
  - photons merge in ECAL for α < 2-3%
  - standard photon reconstruction fails

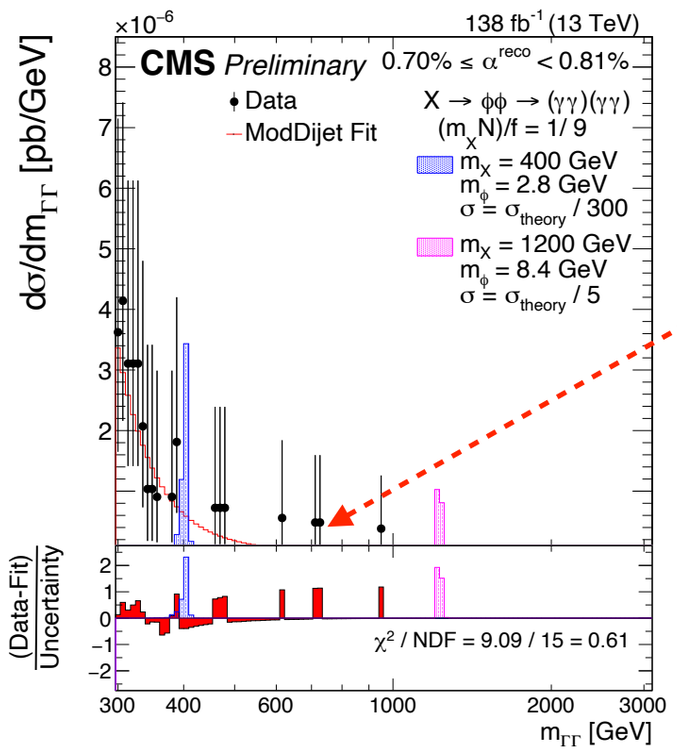


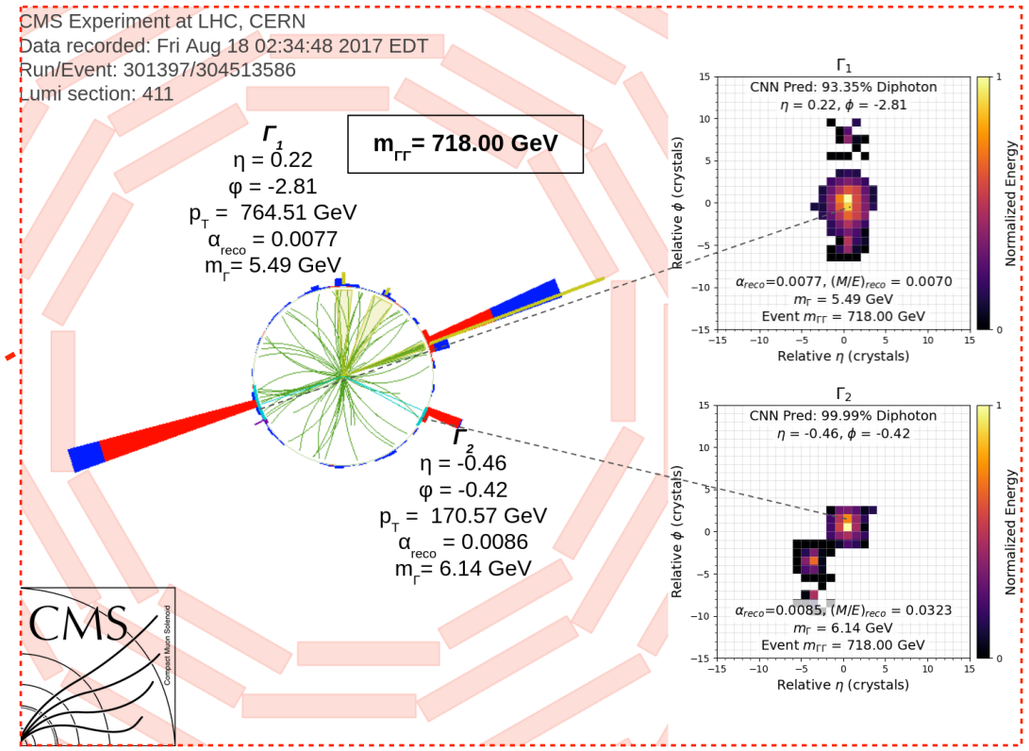


- Convolutional Neural Networks (CNNs) based on ECAL cluster images
  - NN_1: classify merged γγ clusters
  - NN_2: predicts γγ cluster mass (m_Γ)

- Bump search in $m_{\Gamma\Gamma}$ spectrum using empirical background function
  - largest excess of 3.6σ (~1σ) local (global) at m_X~720 GeV and m_φ~6 GeV

- Most sensitive search at the LHC in this final state





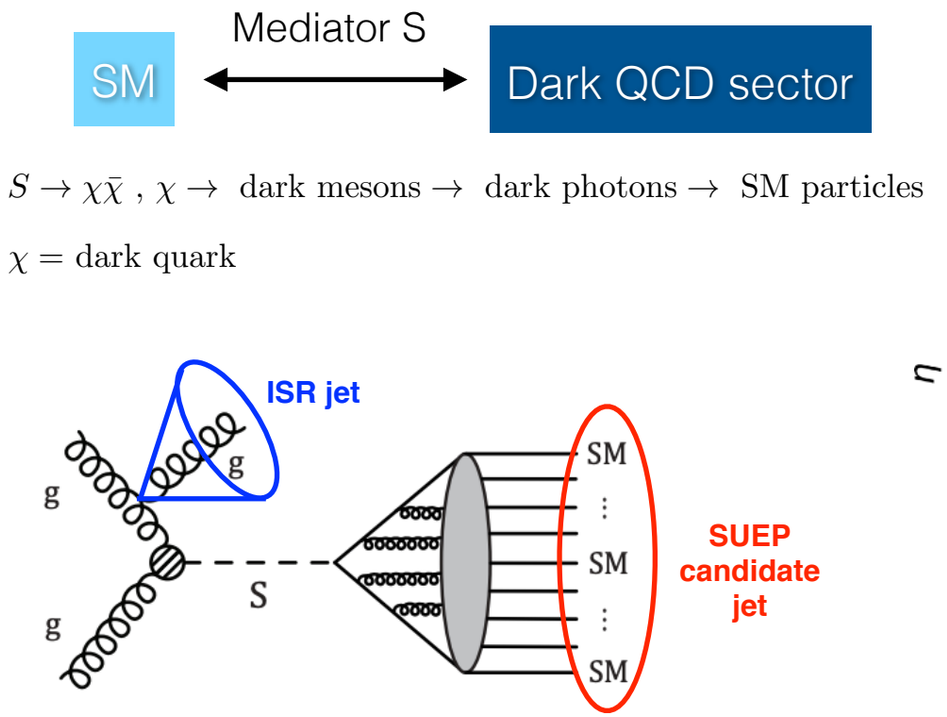
NEW

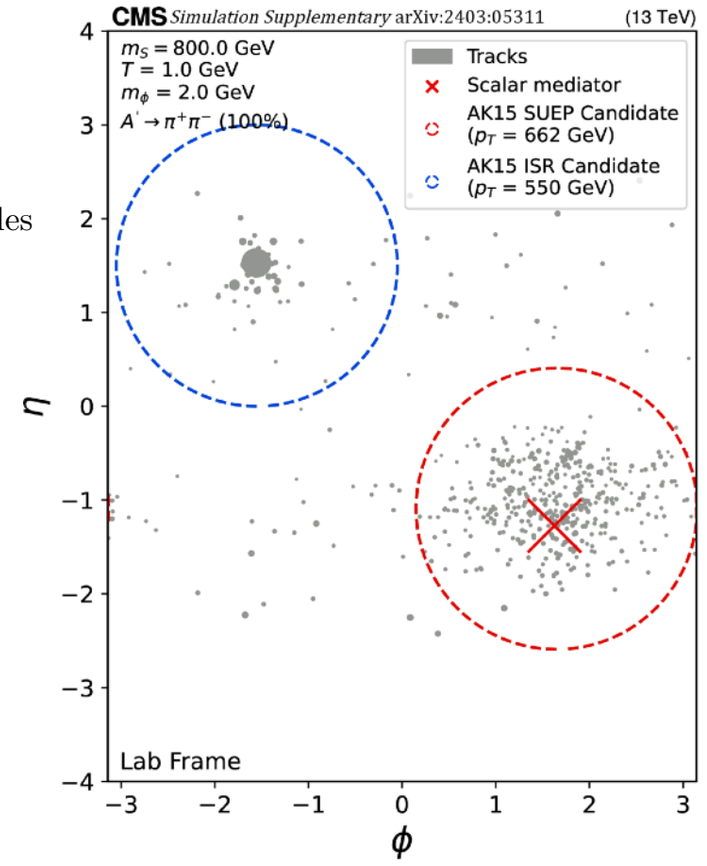
Soft Unclustered Energy Patterns (SUEPs) EXO-23-002

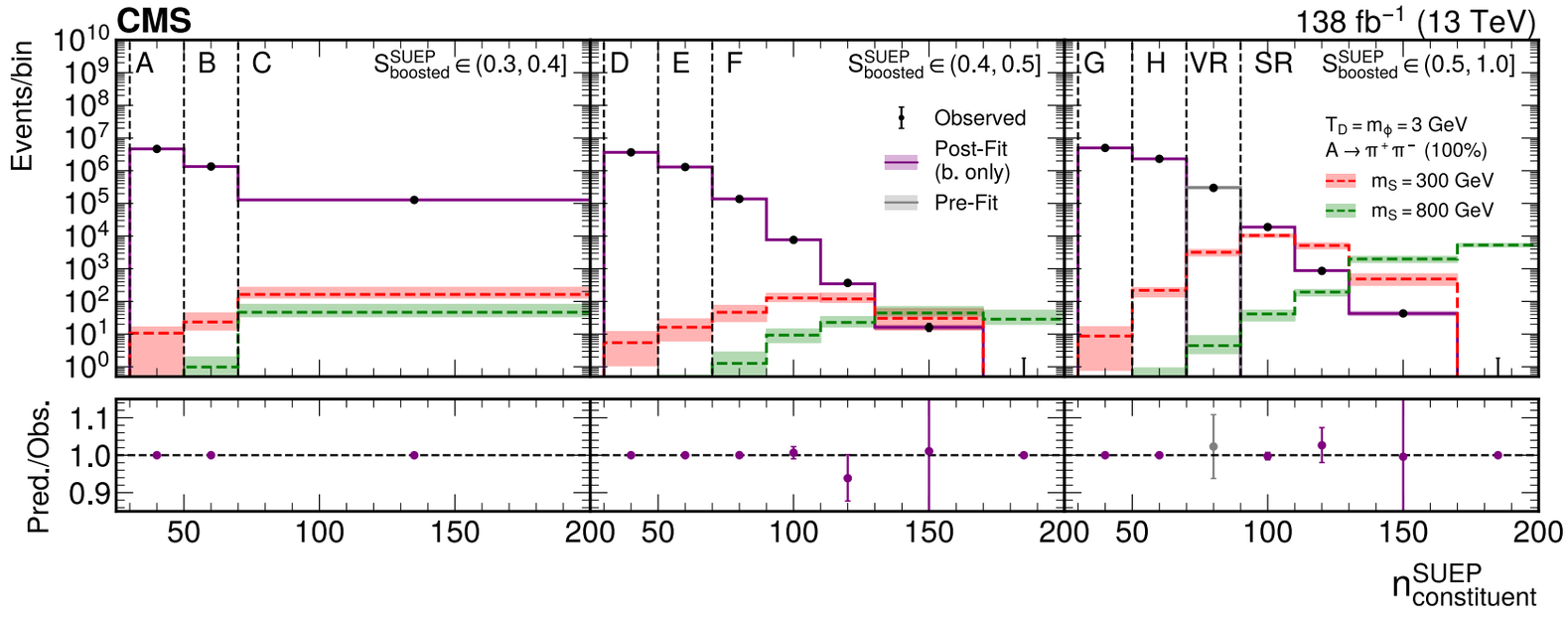
- Dark QCD showers can produce final states with many, isotropically-distributed, low p_T tracks
  - focus on boosted scenario ⇒ mediator S recoils against ISR jet ⇒ dijet system

- SUEP-jet experimental signature
  - high multiplicity of tracks (n^{SUEP})
  - high "Sphericity" (S^{SUEP})

- No excess in data
  - first dedicated search for SUEPs at LHC
  - results interpretable in various models (eg. Hidden Valleys, instantons, microscopic black holes)







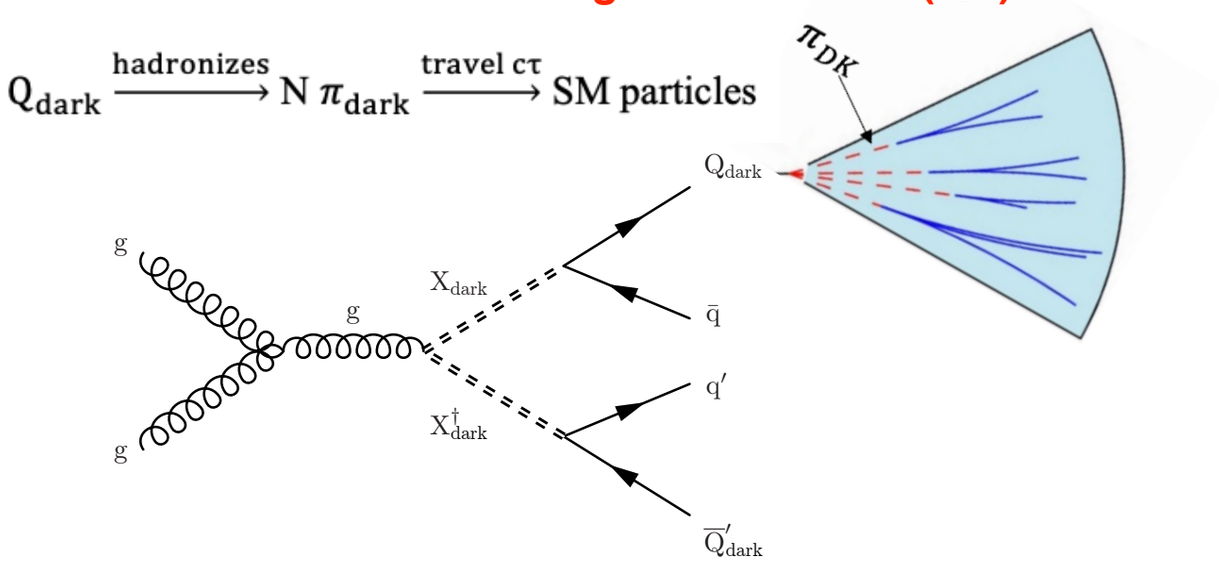
NEW

Emerging Jets (EJ)

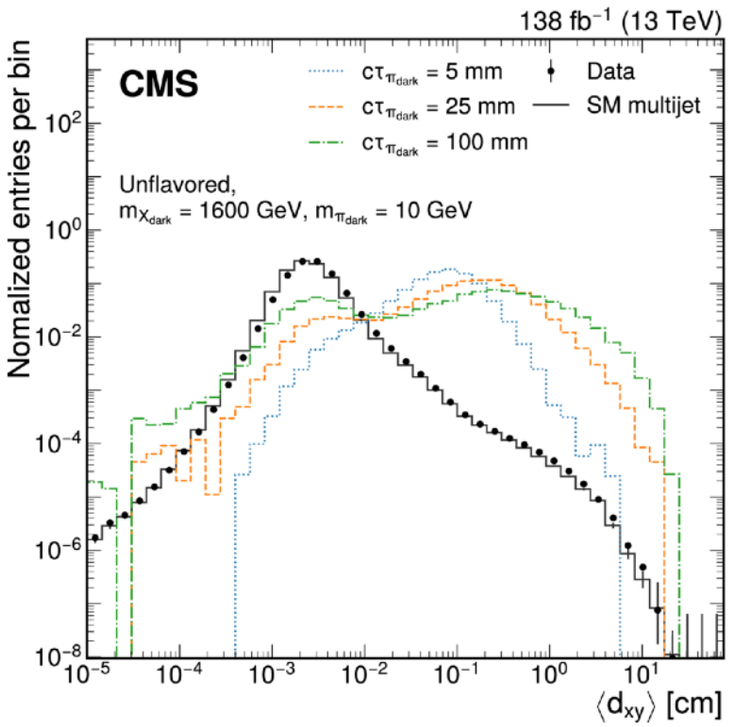
EXO-22-015

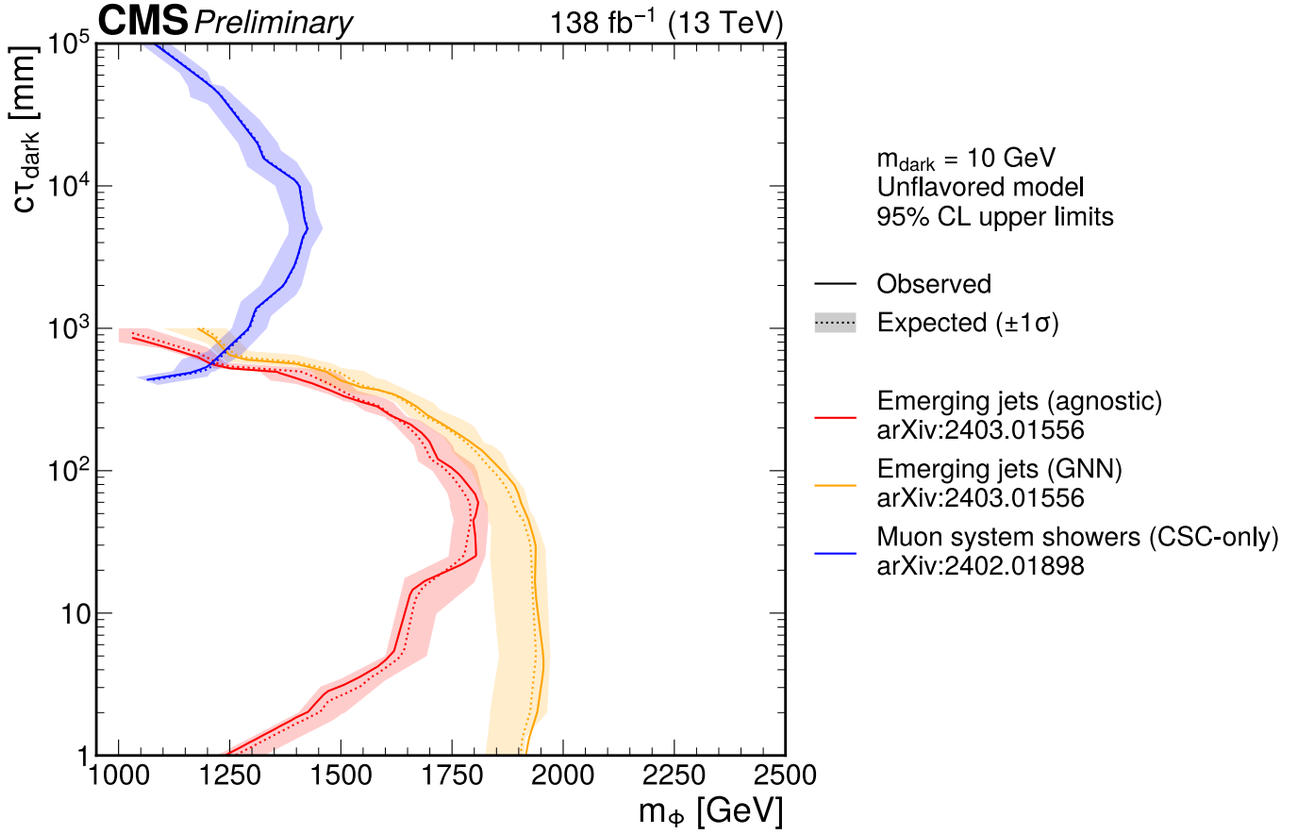
- Another possible dark-QCD signature in jets
  - multiple displaced vertices from decays of dark mesons
  - graph neural network discriminates EJ vs QCD jets
- No excess in data (counting experiment)
  - set most stringent limits to date
  - first limits on “flavour-aligned" scenario (many b quarks)
- CMS covers wide range of cτ (from 1 mm to 10^2 m)
  - complementarity with search based on muon detector showers

Long Lived Particle (π_{DK})



Median of transverse impact parameter (d_{XY}) of tracks in a jet





NEW

Data Scouting

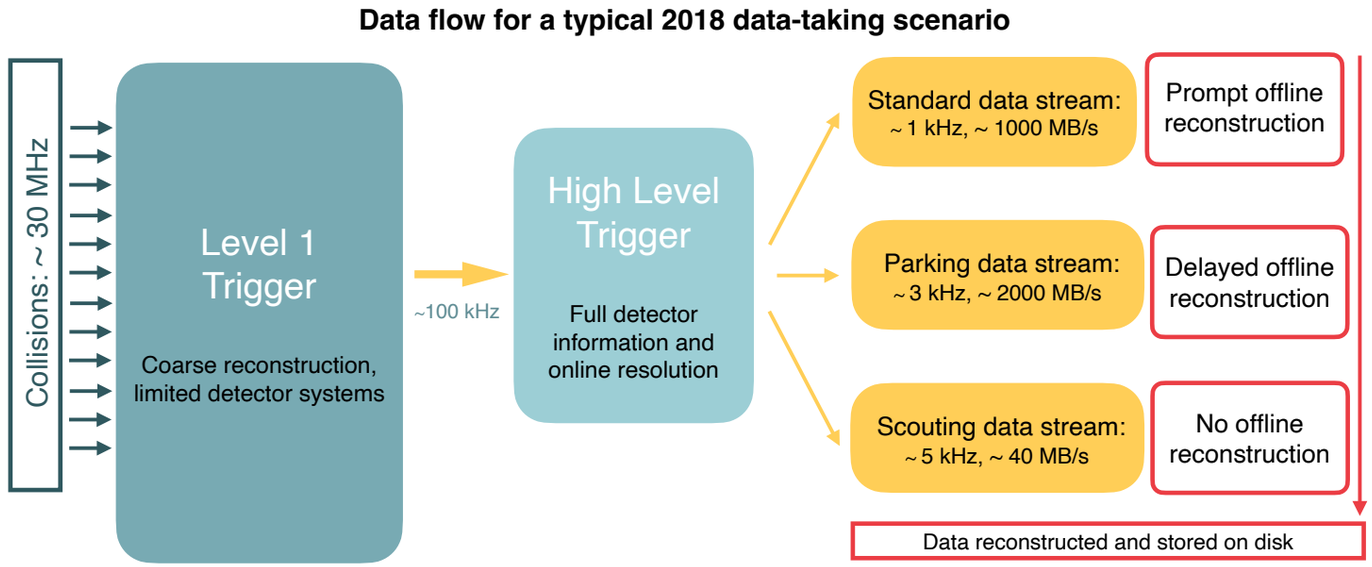
EXO-23-007

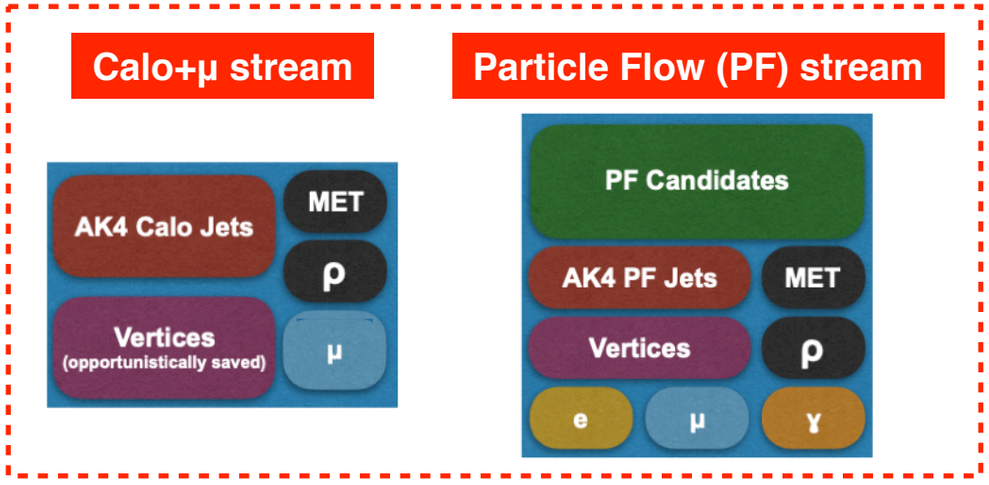
- BSM scenarios often leads to light particles with feeble couplings
  - eg. FIPs workshops (arXiv:2102.12143, arXiv:2305.01715)
  - large SM backgrounds
  - events may be discarded due to high energy thresholds in standard triggers

- Novel data scouting paradigm introduced in 2011 at CMS
  - low trigger thresholds + reduced event content → small impact on bandwidth
  - data analysis with trigger level objects

- Sensitivity greatly expanded at low mass
  - dijets/multijets ($50 < m_X < 1500$ GeV)
  - dimuons ($2m_\mu < m_X < 40$ GeV)

- CMS released a review paper on the topic
  - data scouting and data parking from Run 1 to Run 3





Comparison of typical trigger thresholds

Trigger selection	Standard	Scouting
Jet $H_T = \sum p_T^{jets}$	>1000 GeV	>300 GeV
2 muons: $p_T^1(p_T^2)$	>17(8)	>3(3) GeV

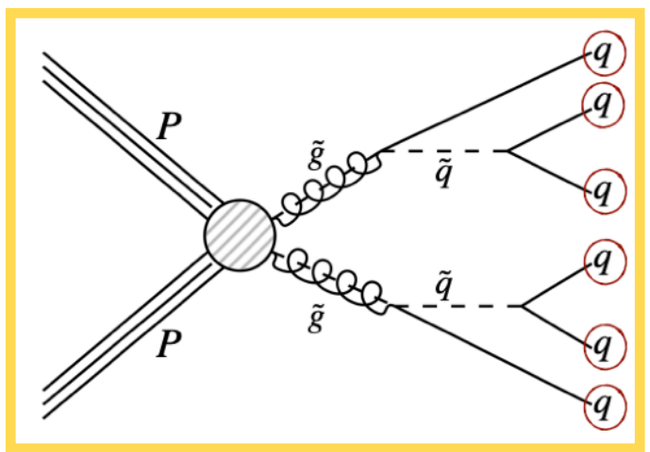
Multijet resonances with scouting

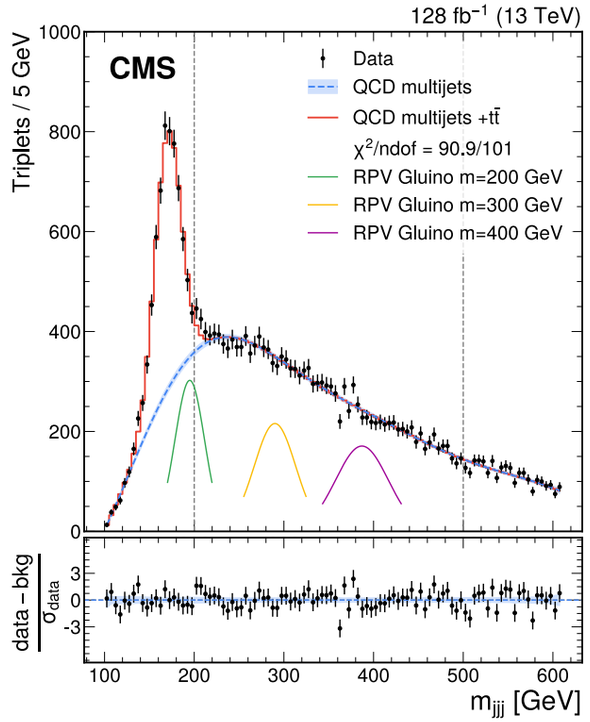
[EXO-21-004](#)

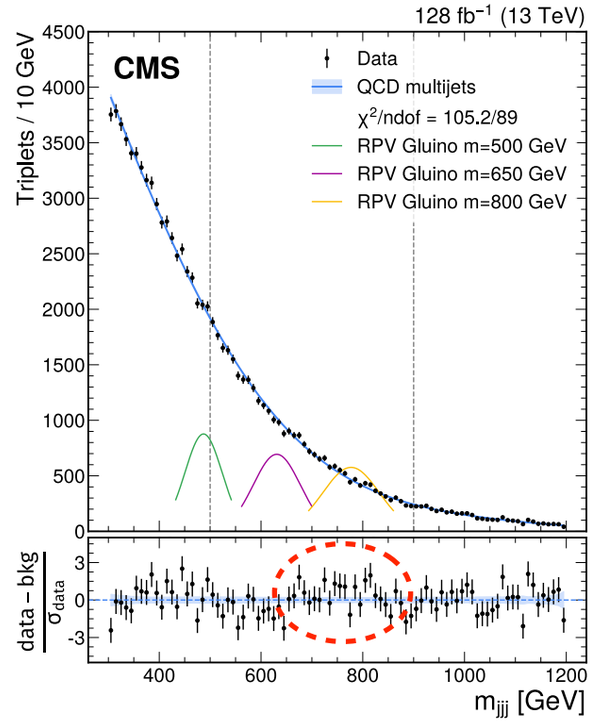
Paper to be released soon

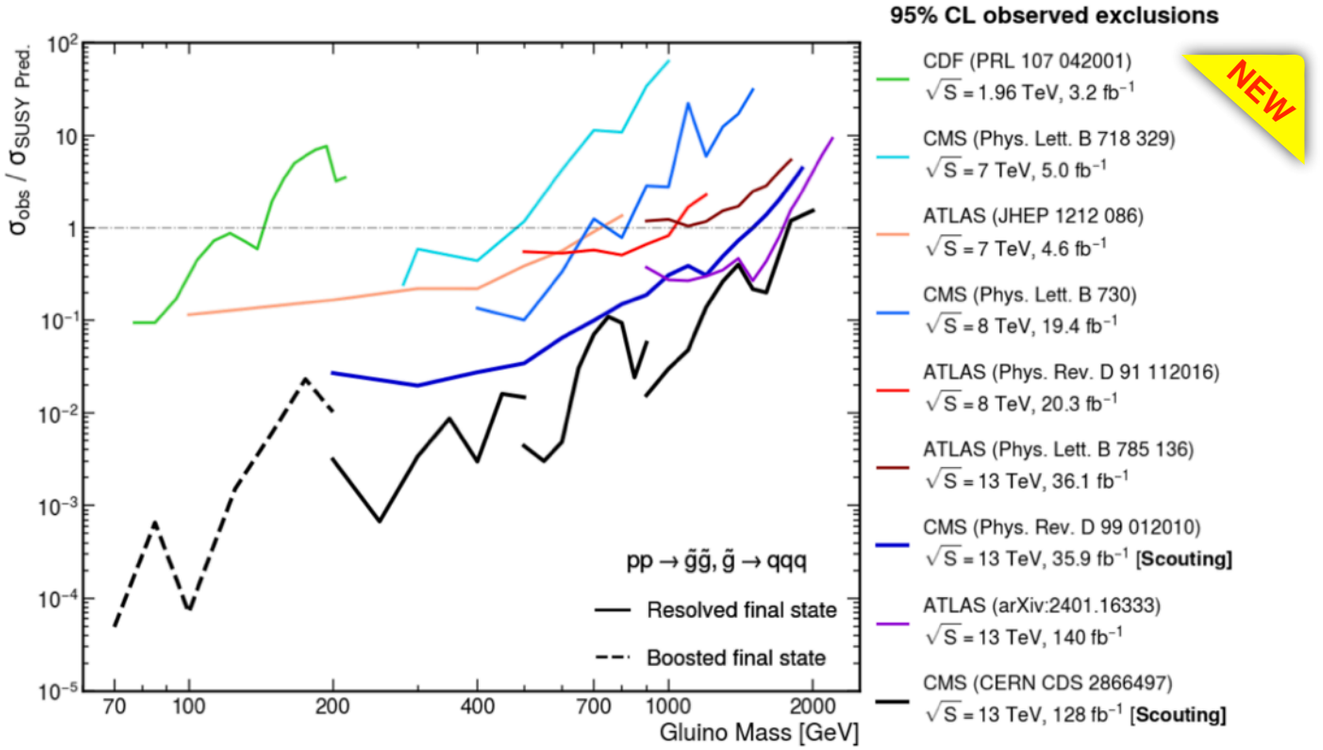
- Comprehensive search for pair produced boosted dijet and trijet, and resolved trijets
  - here focus on resolved 6-jet final state
- Bump search in m_{jjj} spectrum
  - top mass peak clearly visible
  - largest local excess of 2.6σ at mass ~770 GeV
- Large increase in sensitivity thanks to scouting
  - upper limits on cross section are 10-100 times more stringent than other experiments in sub-TeV region
  - extend down to 70 GeV in mass (jet substructure)

RPV gluinos









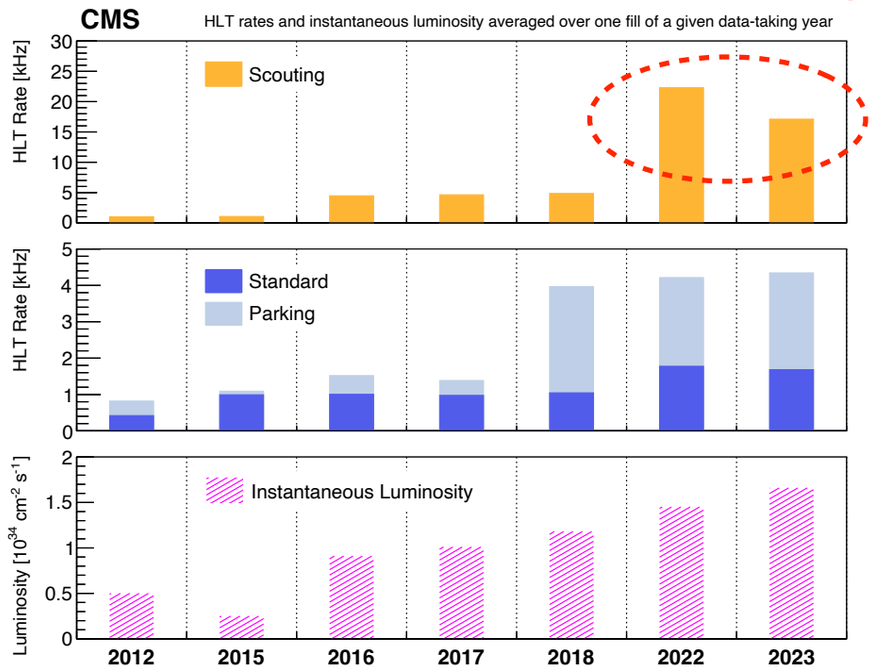
NEW

Data scouting in Run 3

EXO-23-007

- Factor 4 increase in scouting HLT rate (max. ~30 kHz) vs Run 2
  - fast tracking based on pixel-detector only (arxiv:2008.1346) + GPUs at HLT
- Single data-scouting stream with Particle Flow (PF) event record
  - inclusive triggers: jets, muons, electrons/photons
- Rich event content
  - PF candidates, jets, muons, electrons, photons, tracks, vertices
  - excellent quality of HLT reconstruction
- Scouting puts CMS in excellent position to probe low-mass region

Run 3



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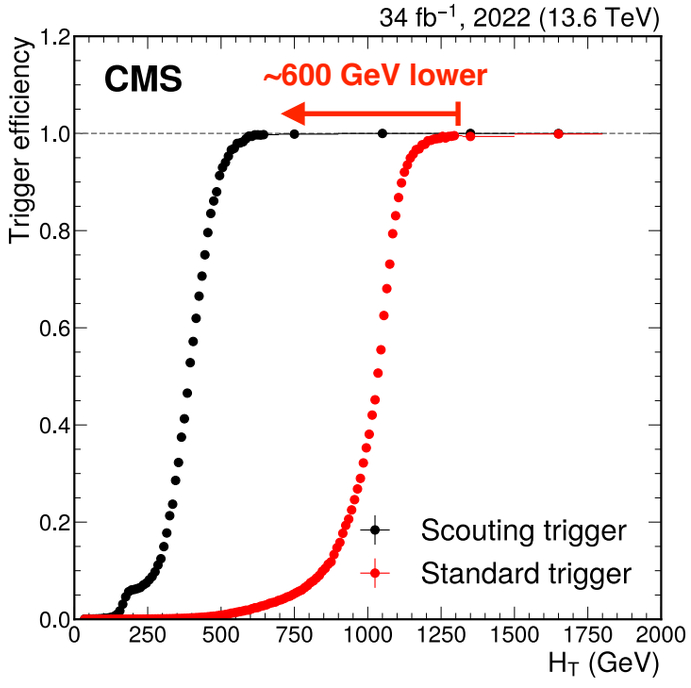
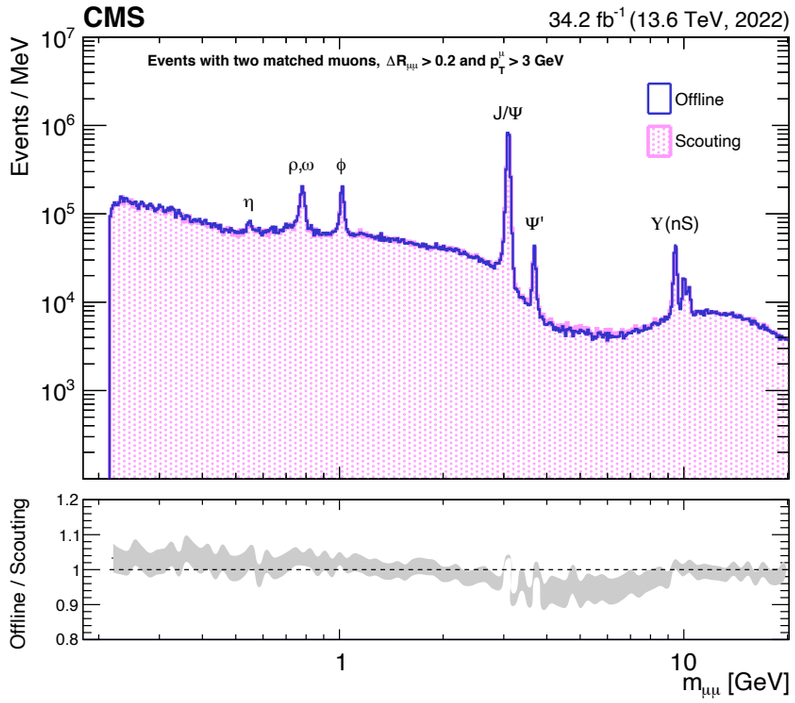
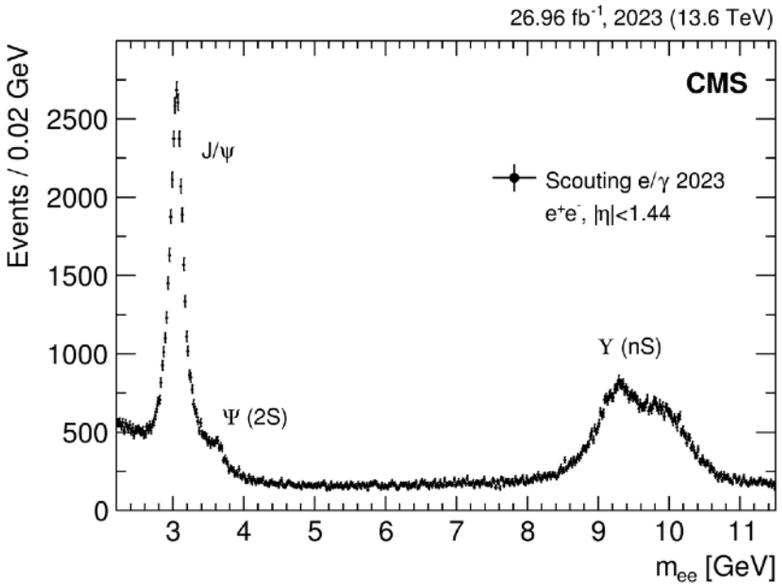
Jets



Muons



Electrons



NEW

Displaced jets with Run 3 data

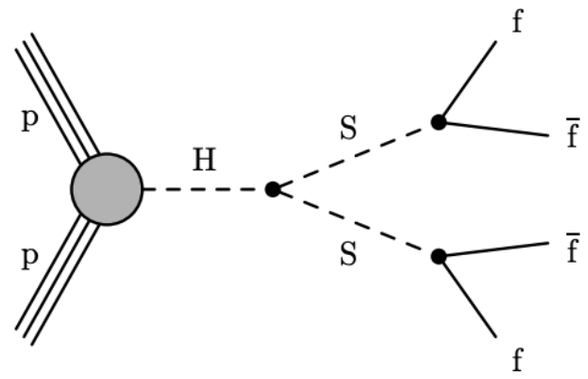
EXO-23-013

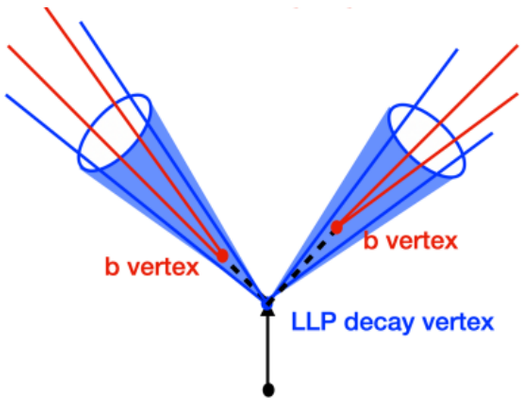
- Higgs boson decays to LLPs
  - displaced vertices in inner CMS tracker, inside jets
  - low mass is challenging

H = 125 GeV Higgs

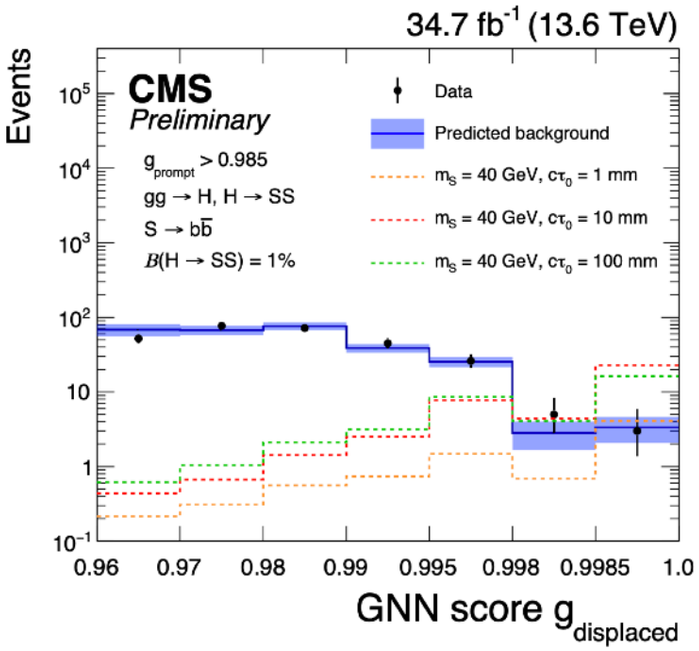
S = **L**ong **L**ived **P**article (**LLP**) with mass m_S

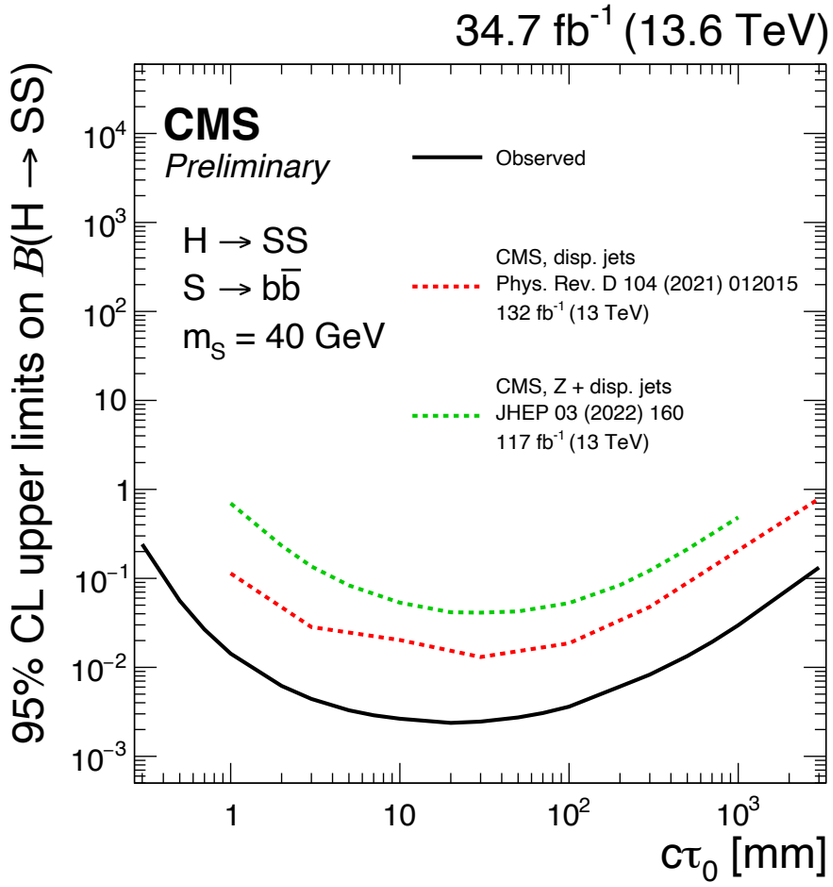
f = fermion = q / b / τ





- Major improvements
  - new triggers (acceptance 10 times higher than Run 2) DP-2023-043
  - new reconstruction for displaced secondary and tertiary vertices
  - new LLP tagging based on graph neural networks (GNN)





factor 10 lower limits

- No excess in data (2022)
  - best limits to date for LLPs in the 15-55 GeV mass range and cτ < 1m, despite smaller dataset
  - first limits for S→ττ decay

Additional gain (+40-100% signal) with 2023 data parking triggers

EXO-23-007

Outlook

- Search for exotic physics is a very active field in CMS
  - wide range of experimental signatures and model interpretations
  - https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html
  - https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

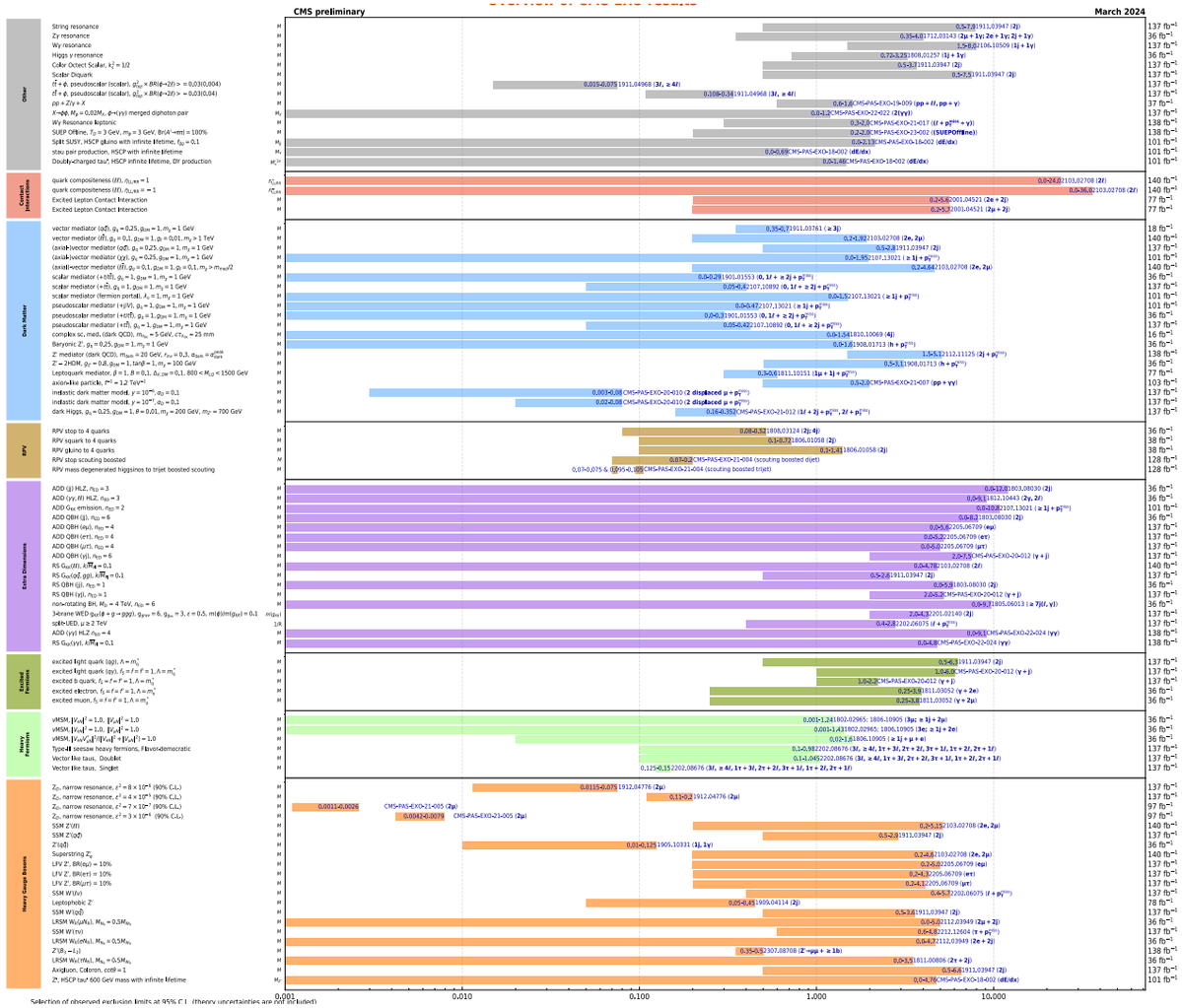
- EXO-23-007 is the first of a series of review papers that we are going to release soon
  - CMS searches from Run 1 to Run 3
  - new interpretations and combinations of results

- **More results coming**
  - **new final states**
  - **check excesses with new data**
  - **trigger improvements (eg. scouting, long-lived particles)**
  - **Run 3 analyses ongoing**

Recent results with **early Run 3 data**

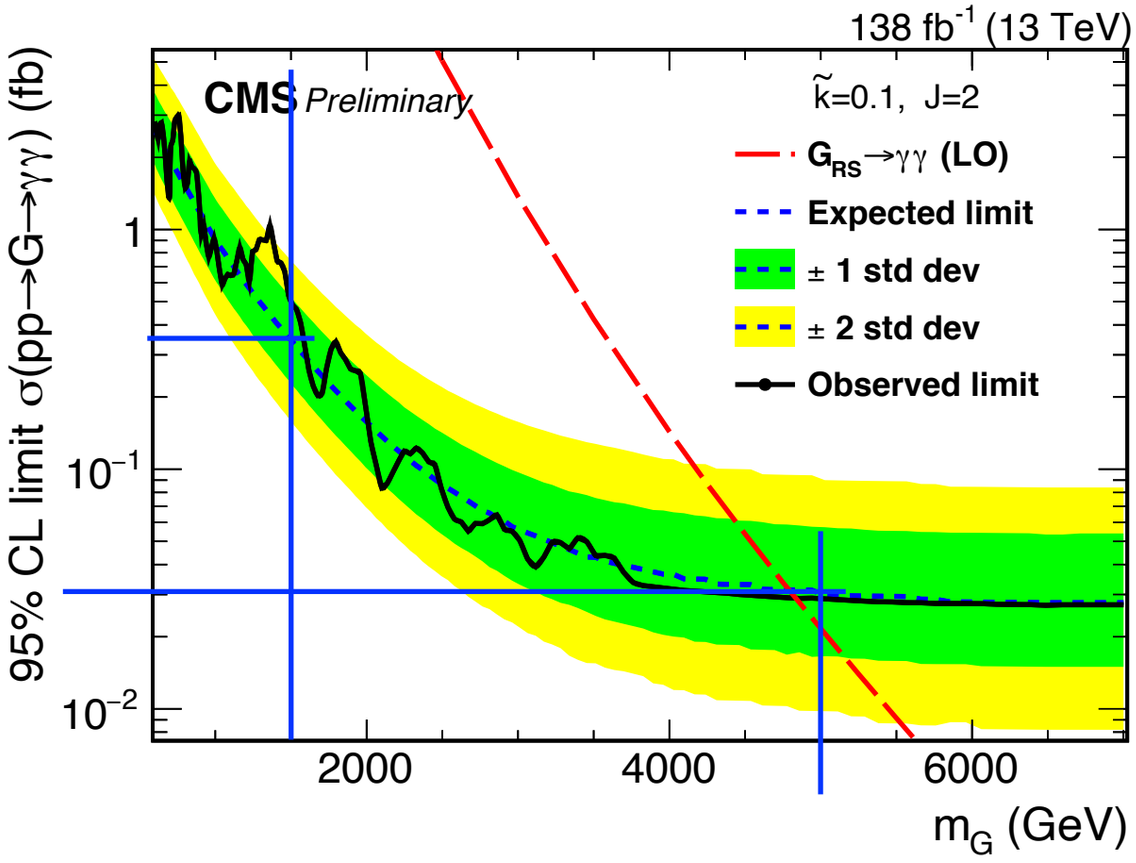
- EXO-23-007: Data parking and data scouting
- EXO-23-013: Displaced jets
- EXO-23-014: Displaced dimuons

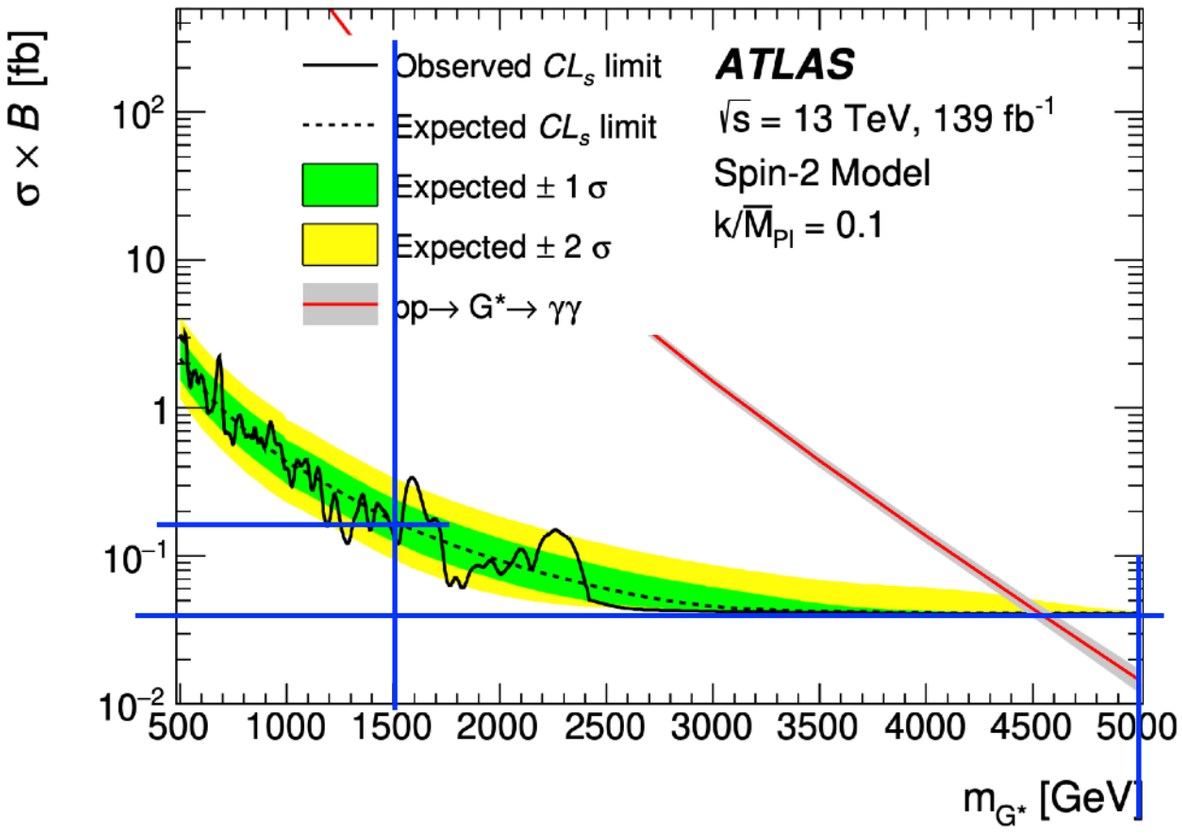
EXO Summary Plot (clickable version)



Backup

Diphoton resonances: CMS vs ATLAS

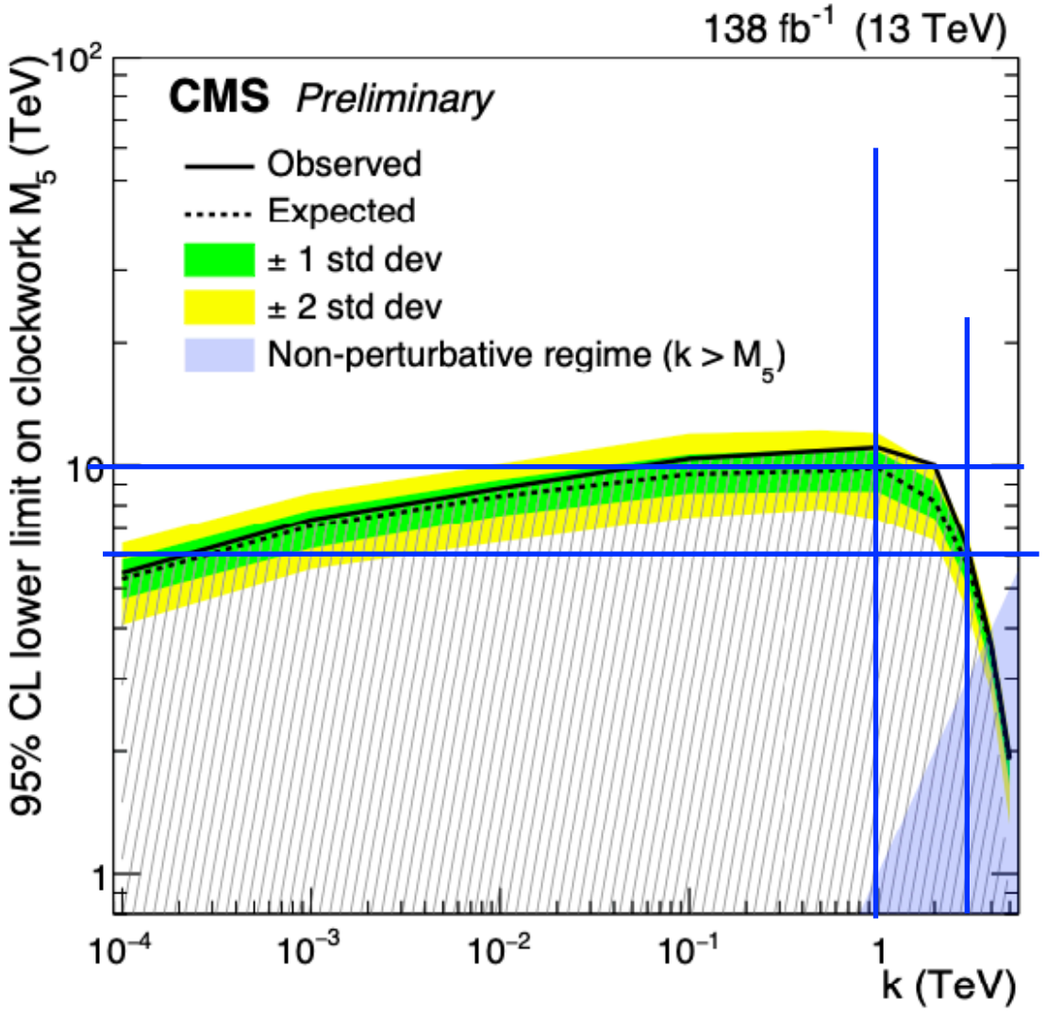




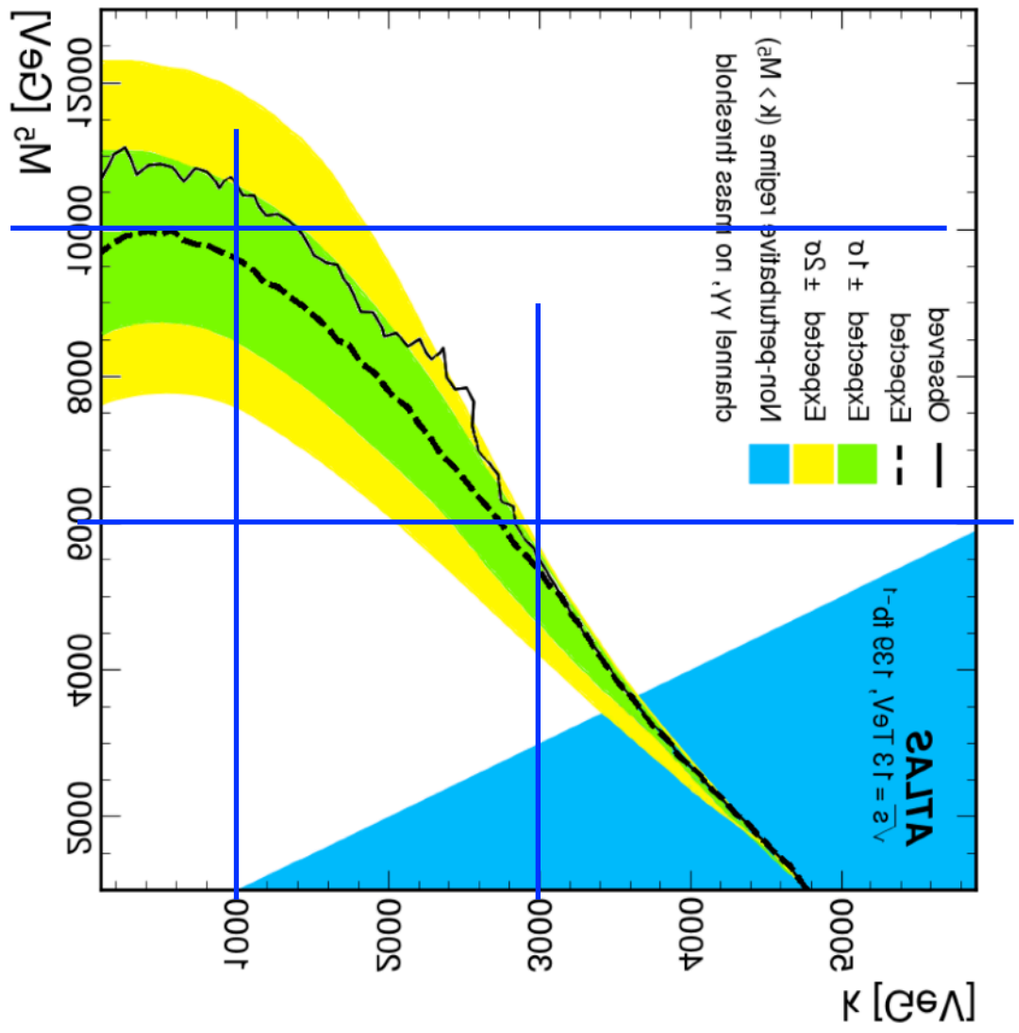
Diphoton non-resonant: CMS vs ATLAS

- Clockwork signals generated from ADD signals after rescaling
  - from arXiv:1711.08437

$$\theta(m_{\gamma\gamma}-k)\frac{30\Lambda_T^8}{283\pi M_5^3}\sqrt{1-\frac{k^2}{m_{\gamma\gamma}^2}}\frac{1}{m_{\gamma\gamma}^5}\left[1+\frac{2975}{283\cdot 2^8}\left(1-\frac{k}{m_{\gamma\gamma}}\right)^9\sqrt{\frac{m_{\gamma\gamma}}{k}}\right]^{-1},$$



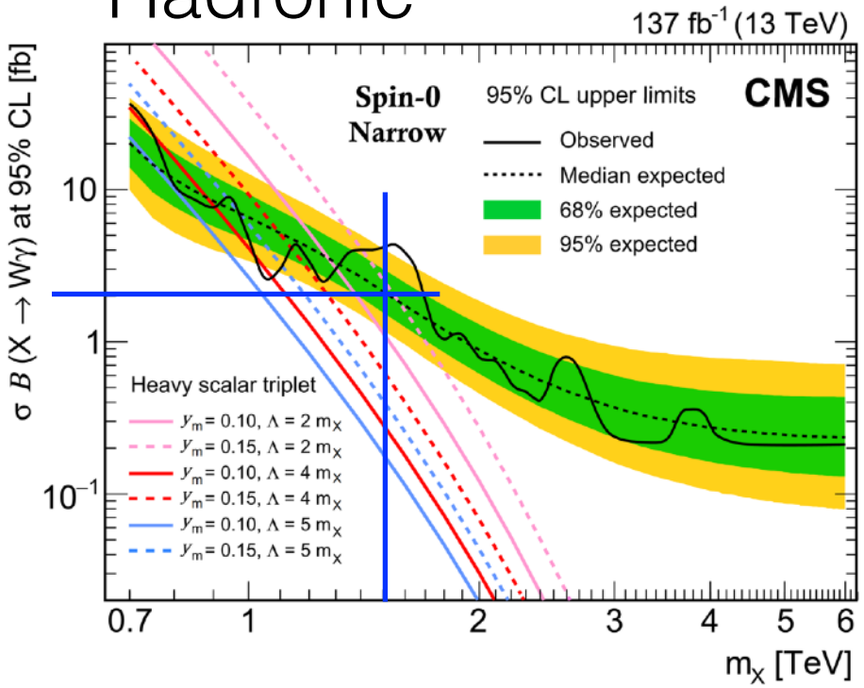
ATLAS plot rotated for comparison



Wγ resonances: CMS vs ATLAS

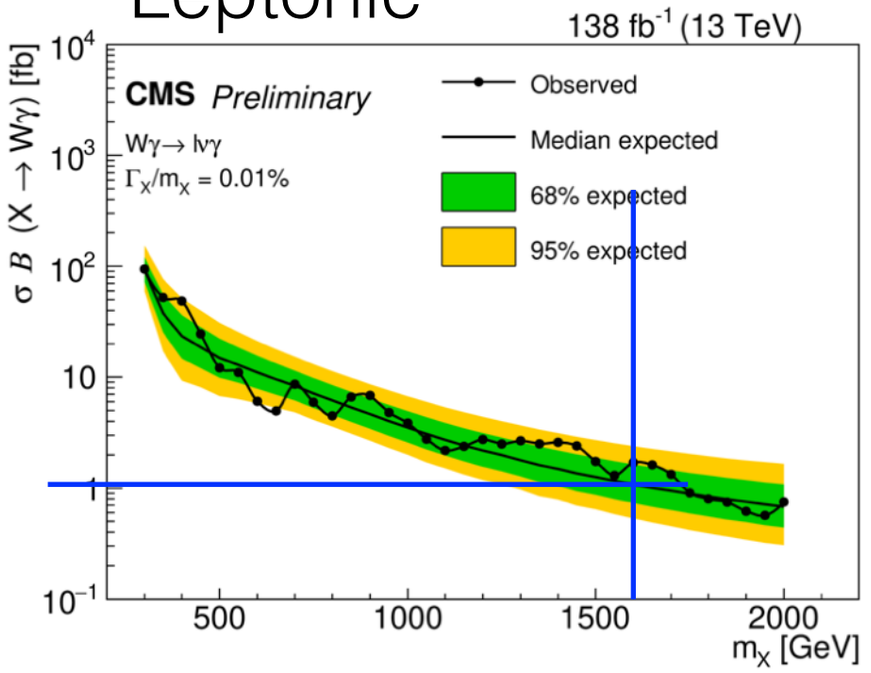
Spin-1 acceptance ~ 30% higher than Spin-0

Hadronic



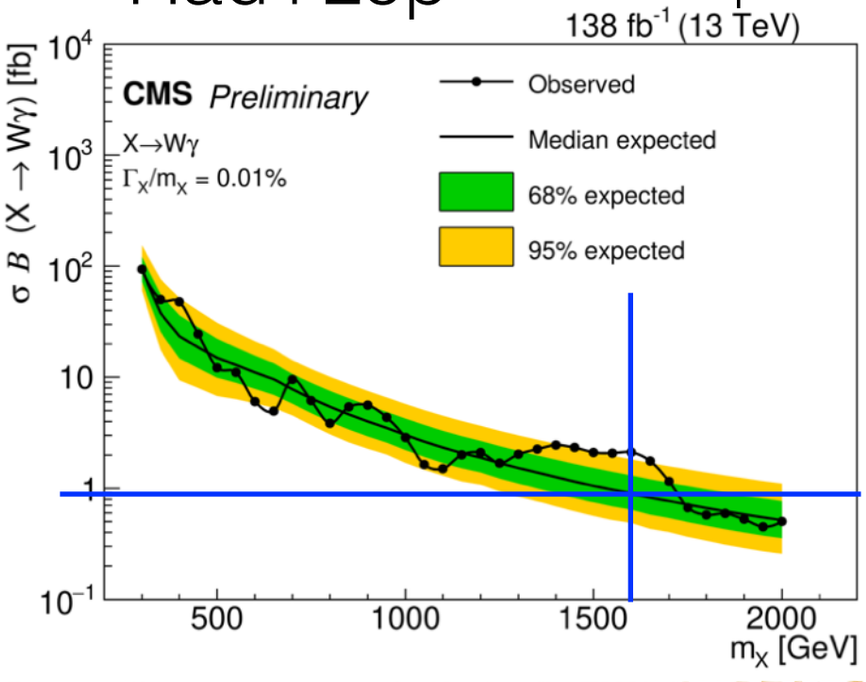
Leptonic

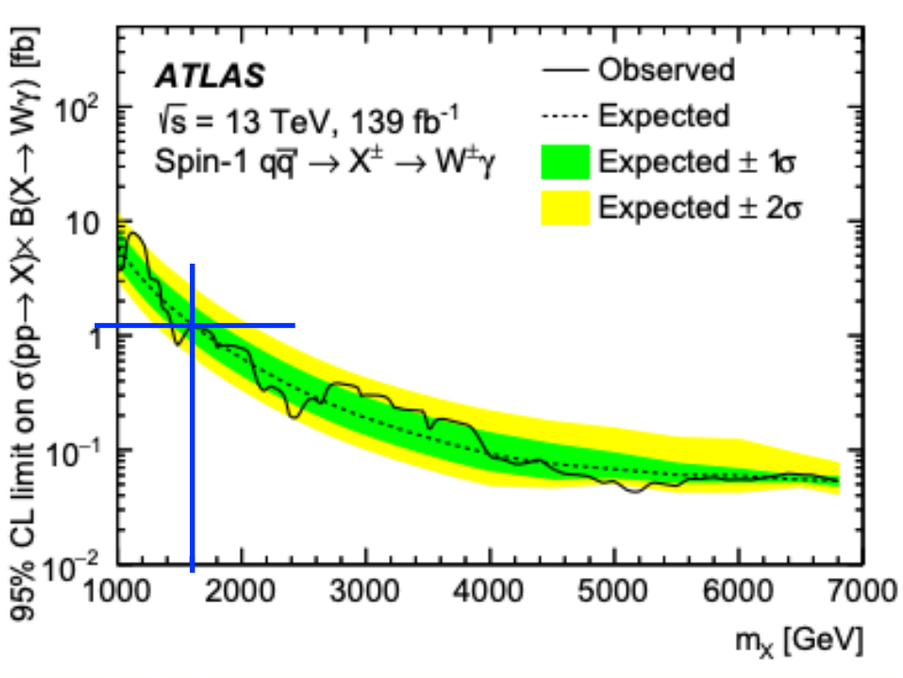
Spin-0



Had+Lep

Spin-0

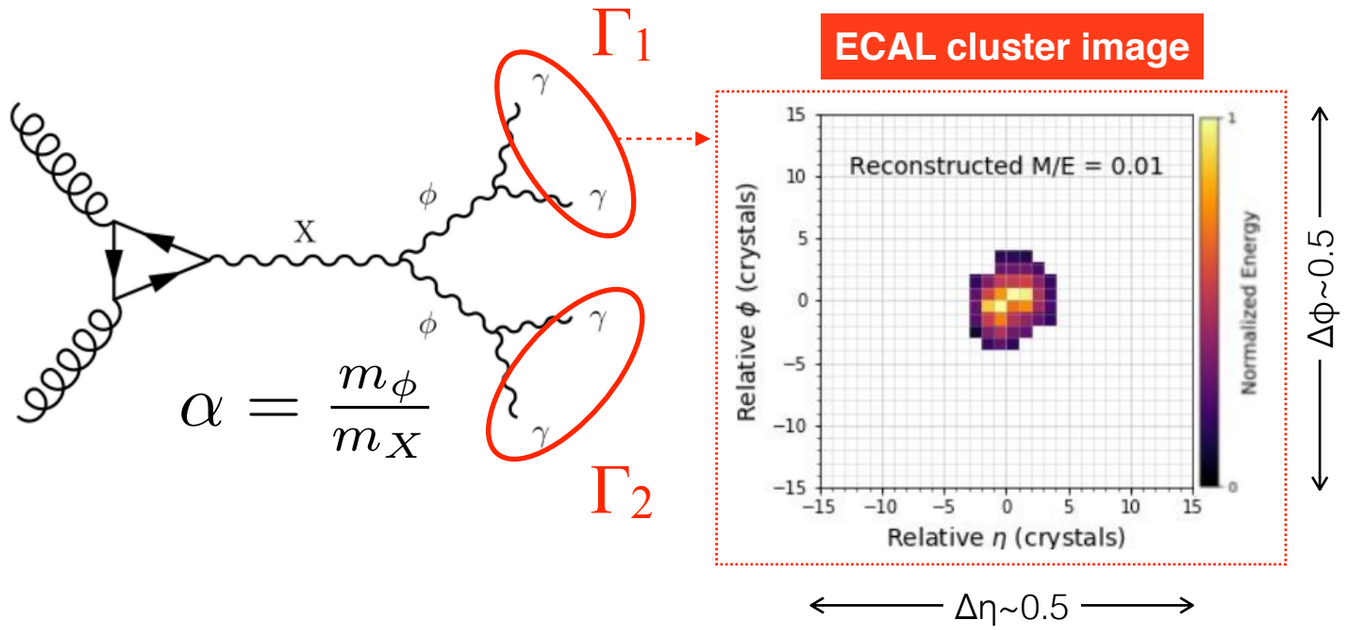




NEW

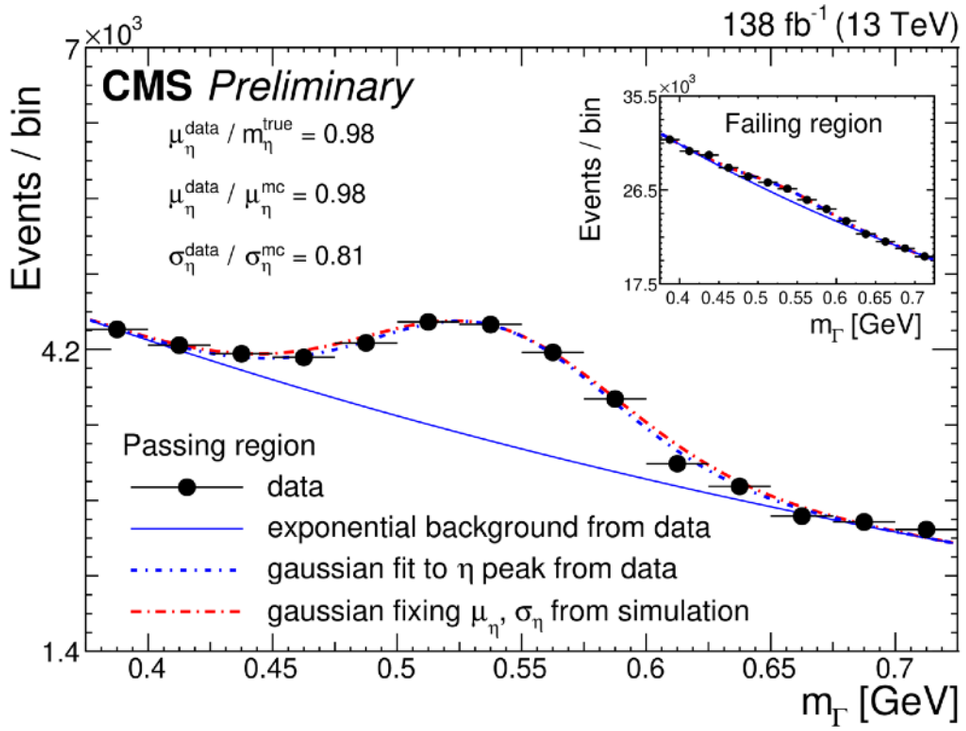
Boosted diphotons

- Benchmark signal: X→φφ→(γγ)(γγ)
  - extended Higgs sector with two new spin-0 particles (X and φ)
  - two photons merge in ECAL for α < 2-3%
  - standard photon reconstruction fails



- Convolutional Neural Networks (CNNs) based on ECAL cluster images
  - NN_1: classify merged γγ clusters
  - NN_2: predicts γγ cluster mass (m_Γ)

- Method validated in data using boosted η→γγ decays within jets
  - good agreement between data and simulation



Boosted diphotons: results

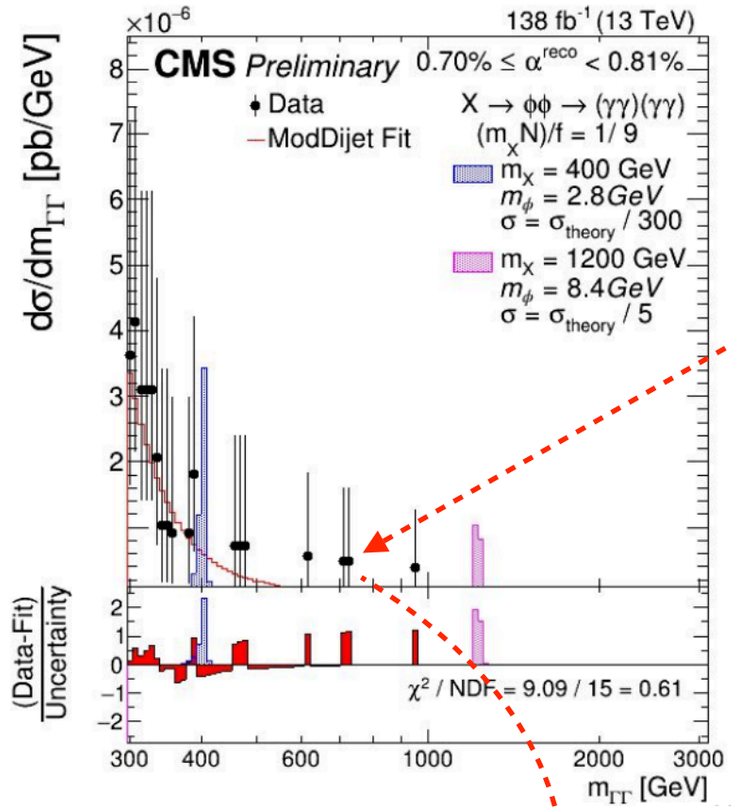
- Select events with two diphoton clusters (Γ_1,Γ_2)
  - reject events with large cluster mass asymmetry

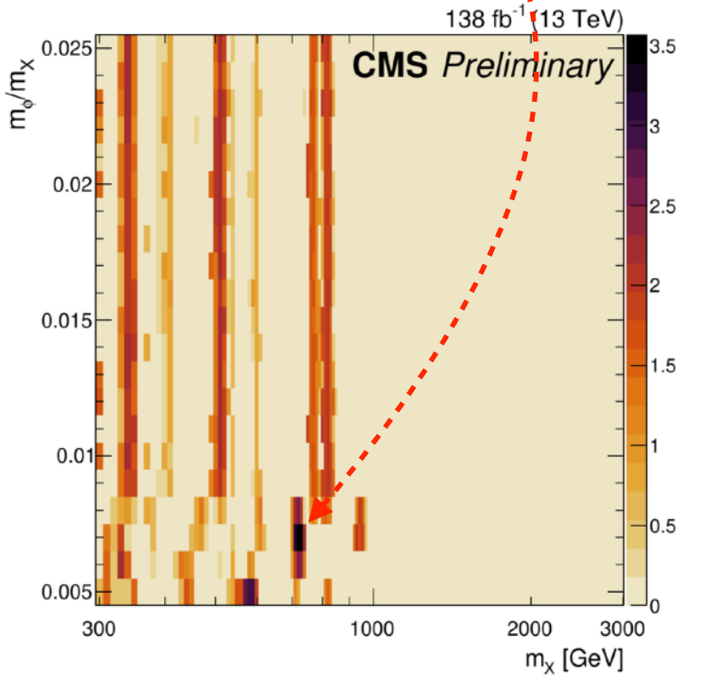
$$\frac{|M_{\Gamma_1} - M_{\Gamma_2}|}{M_{\Gamma_1} + M_{\Gamma_2}} < 0.25$$

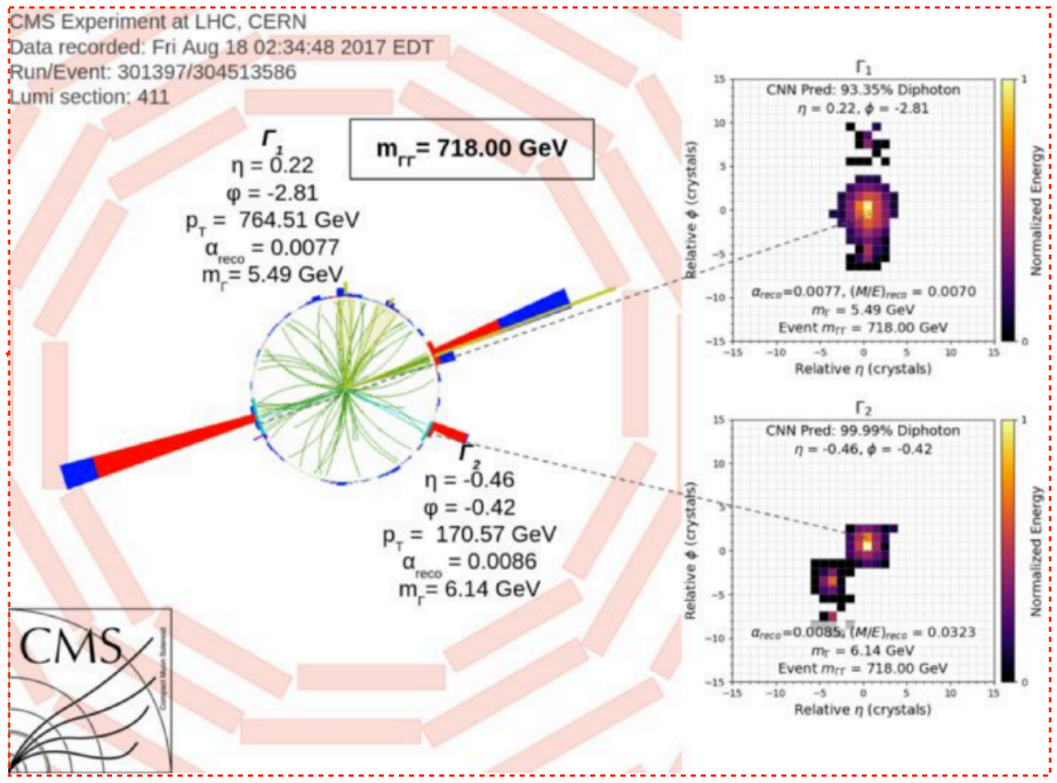
- Bump search in $m_{\Gamma\Gamma}$ spectrum using empirical background function
  - data divided in 9 bins of mass ratio α^{reco}

$$\alpha^{reco} = \frac{<m_\Gamma>}{m_{\Gamma\Gamma}}$$

- 2D scan of resonance masses
  - a given signal contributes to different α^{reco} event categories
  - simultaneous fit to all $m_{\Gamma\Gamma}$ spectra







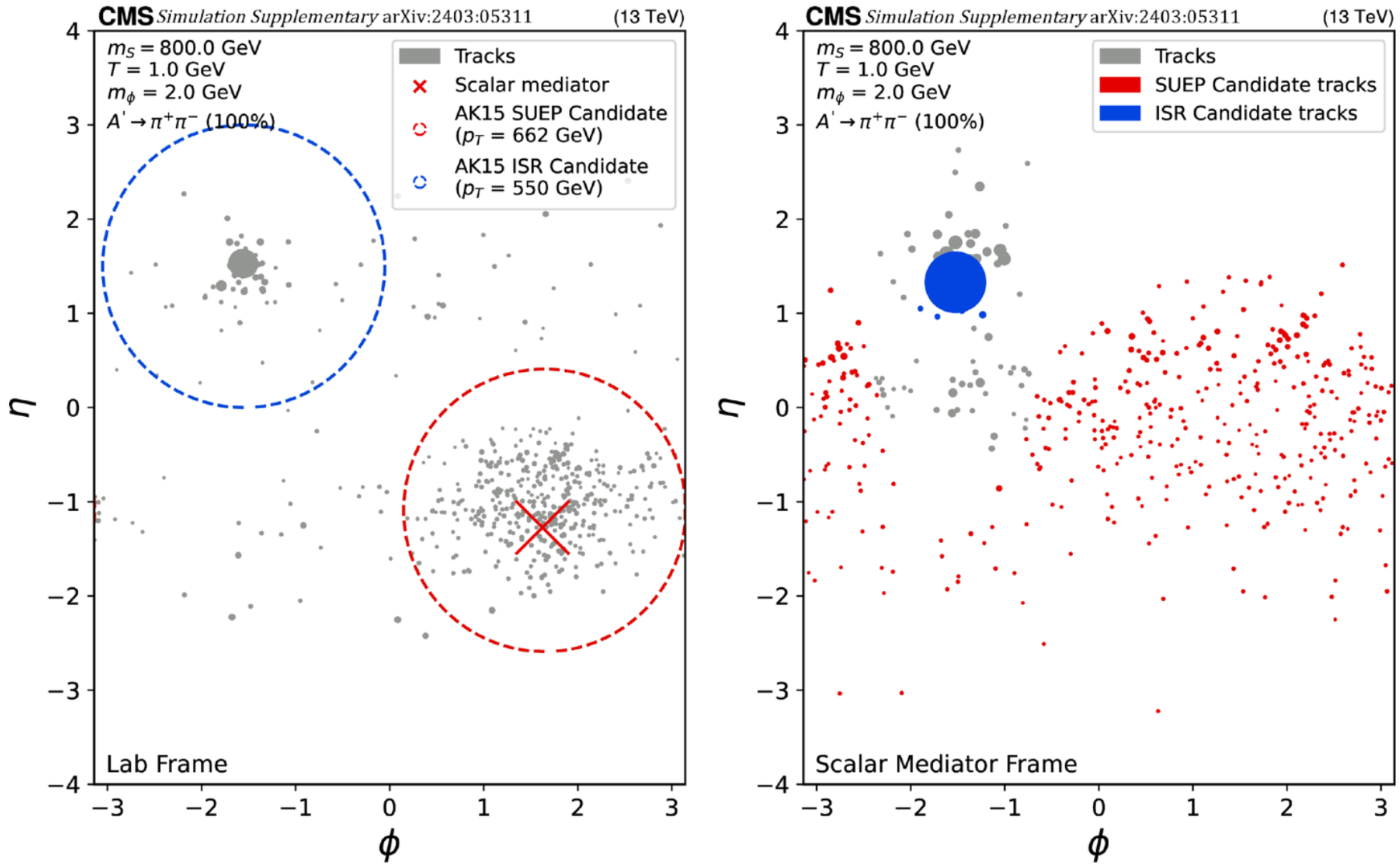
- Largest excess of 3.6σ (~1σ) local (global) at m_X~720 GeV and m_ϕ~6 GeV
- Upper limits on cross section range from 0.03–1.06 fb, depending on m_X and m_ϕ
- Most sensitive search at the LHC in this final state

SUEP event

Trigger:
Jet H_T >~1 TeV

$$H_T = \sum p_T^{jets}$$

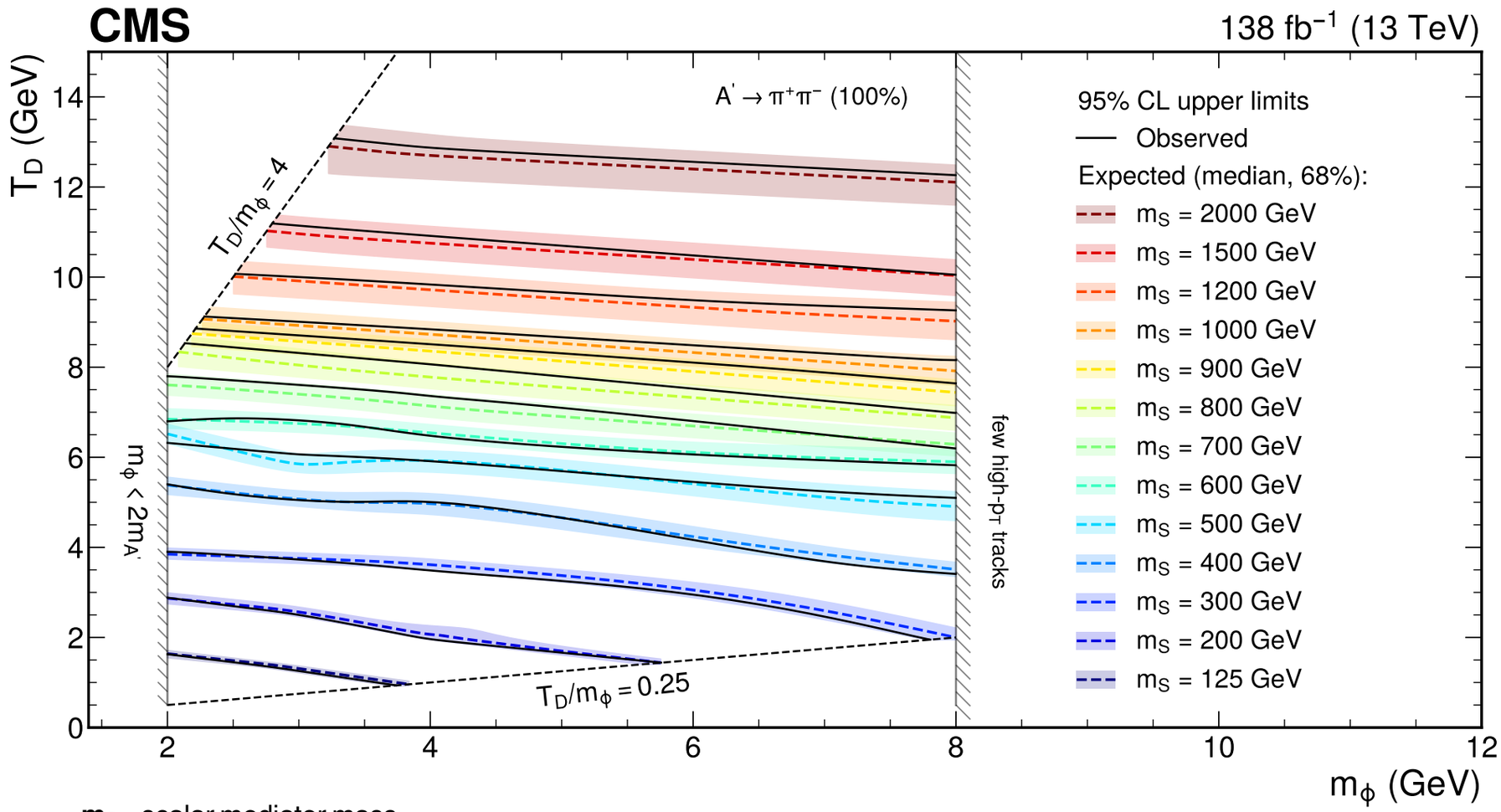
Lab. frame → Lorentz boost → Mediator (S) frame



- High multiplicity of tracks (n^{SUEP}) in SUEP jet
- High "Sphericity" (S^{SUEP}) in SUEP rest frame

SUEPs: limits

- Lose sensitivity at high T_D and m_φ (less tracks) and at low m_S (trigger requirements)



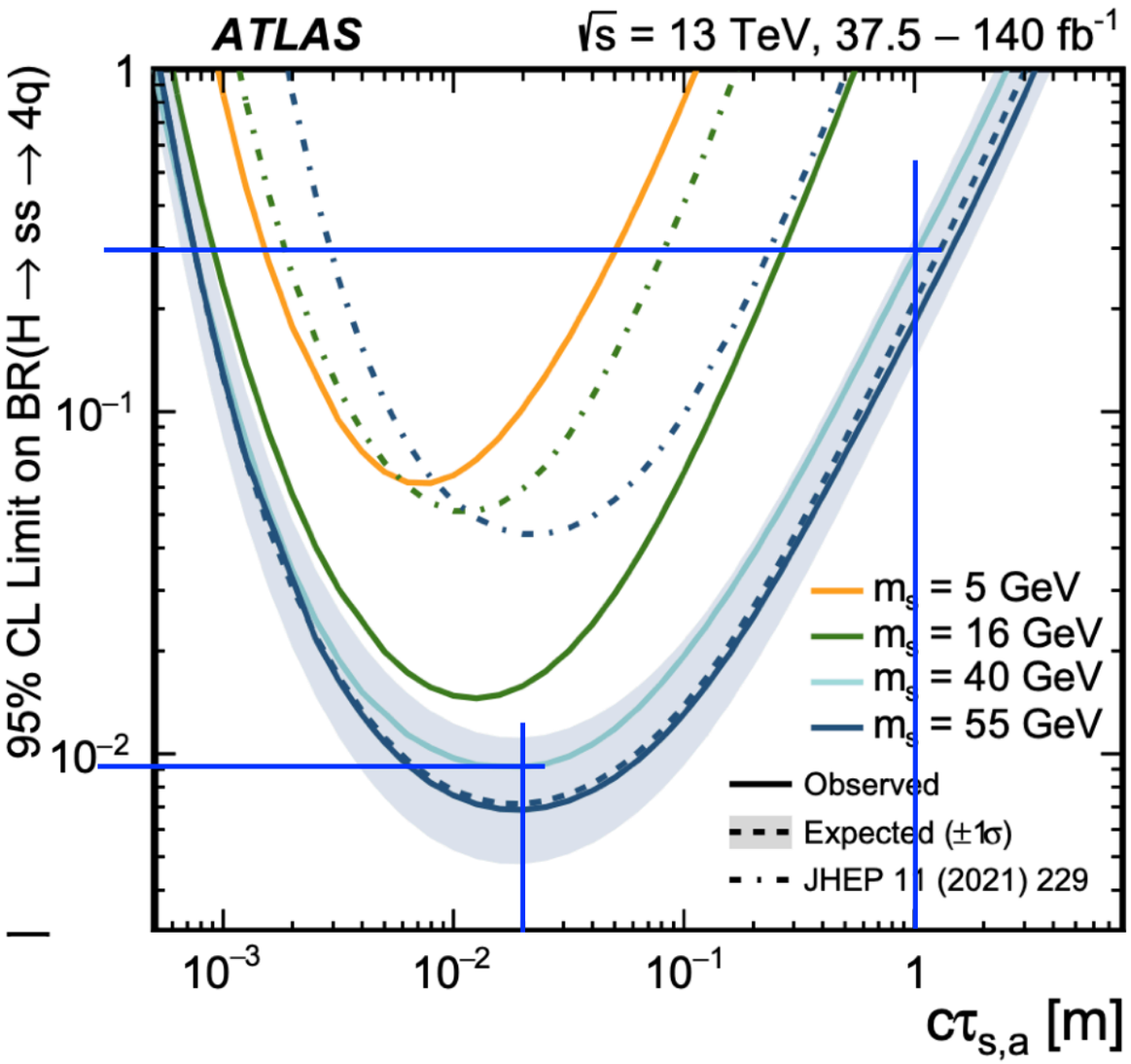
m_S = scalar mediator mass

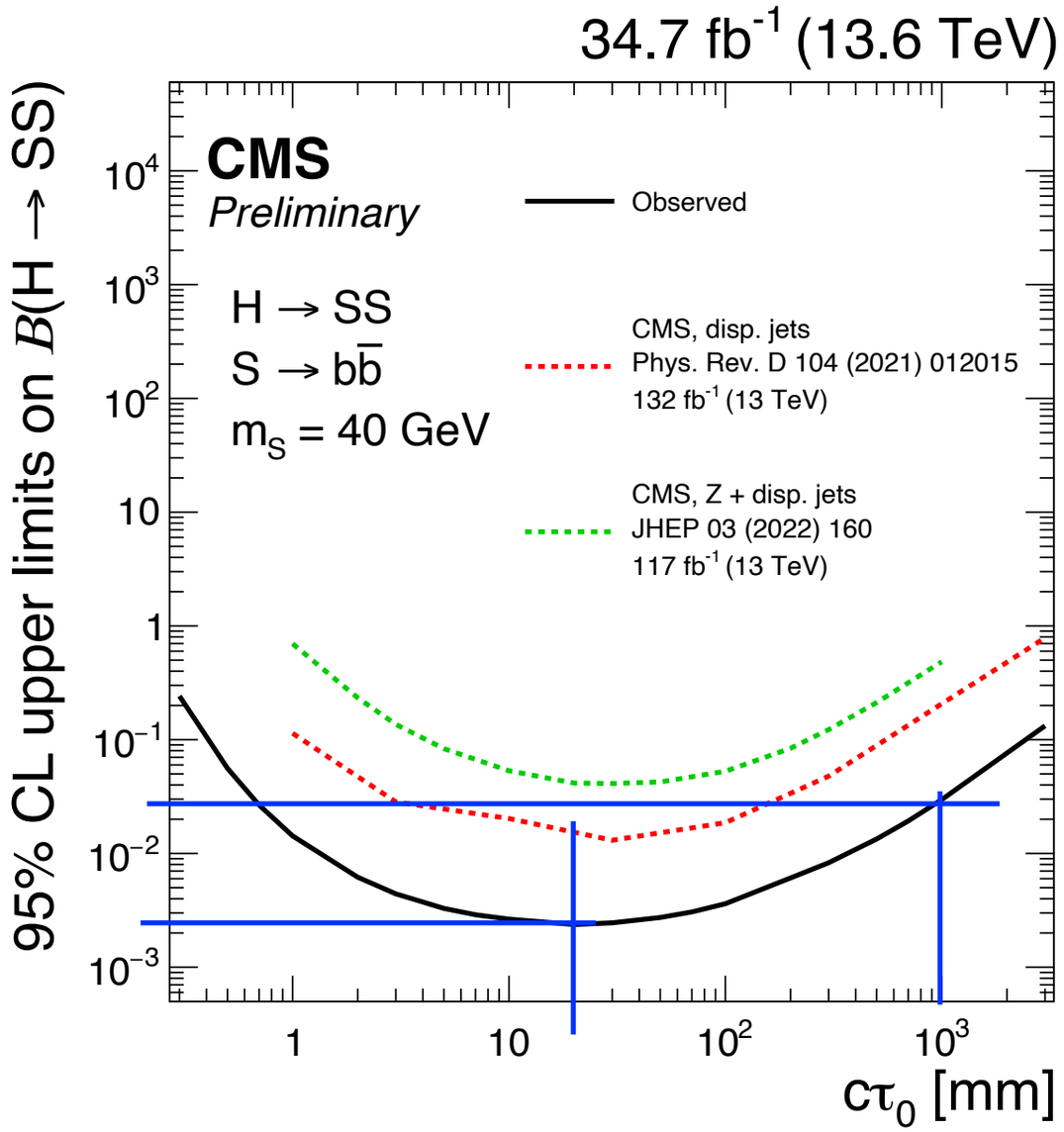
m_ϕ= dark meson mass

$m_{A'}$ = dark photon mass = 1 GeV

T_D = temperature parameter of Boltzmann distribution describing the ϕ pT spectrum

Displaced jets: CMS vs ATLAS [EXO-23-013]





https://arxiv.org/pdf/2403.15332.pdf