Searches for New Resonances in CMS

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on behalf of the CMS collaboration

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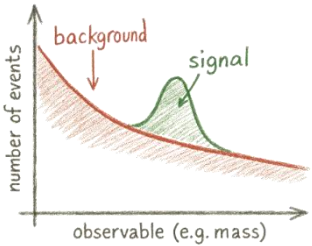
Introduction

- Despite being our most successful theory of particle physics, **the Standard Model is incomplete**.
- Myriad of theoretical models involve Beyond the Standard Model **(BSM) resonances that decay to massive bosons, photons, leptons or jets**.
- **The CMS Experiment has a rich program of hunting for such resonances:**
  CMS EXO public results, CMS B2G public results

Reconstruct the mass of final state observed particles ⇒ mass spectrum of BSM candidates → **Simulate signals + Model the background from Standard Model processes** → **Search for bumps/resonances in the invariant mass spectrum**



- **A selection of the most recent CMS results will be discussed in this talk:**
  - "Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states", CMS-PAS-B2G-23-007
  - "Search for heavy $H(b\bar{b})\gamma$ and $Z(b\bar{b})\gamma$ resonances", CMS-PAS-B2G-24-007
  - "Search for top-philic heavy resonance (Z') in $t\bar{t}Z'$ $(Z' \to t\bar{t})$", CMS-PAS-B2G-24-009
  - "Search for dijet resonances $(X \to jj)$ with data scouting", CMS-PAS-EXO-23-004
  - "Broad resonance reinterpretation of high-mass $Y \to XX \to (jj)(jj)$", CMS-PAS-EXO-24-038

All are Run-2 results at $\sqrt{s} = 13$ TeV

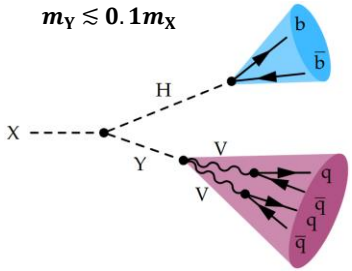
Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states

Brand-new CMS-PAS-B2G-23-007

Signal models & Experimental signature

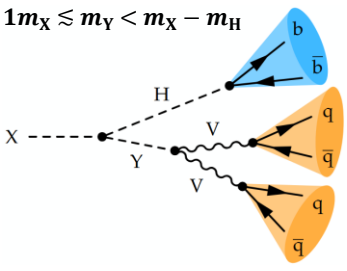
Fully Merged (FM) mode

$m_Y \lesssim 0.1 m_X$



Semi Merged (SM) mode

$0.1 m_X \lesssim m_Y < m_X - m_H$



First search at the LHC for a scalar resonance (X) in all-hadronic $b\bar{b}VV$ final state

H, V: Standard Model bosons

X and Y: BSM scalar resonances

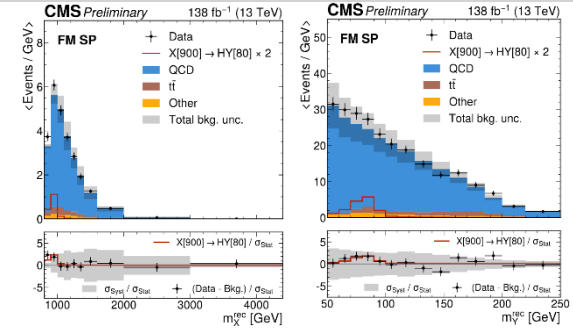
$m_X \in [900, 4000]$ GeV

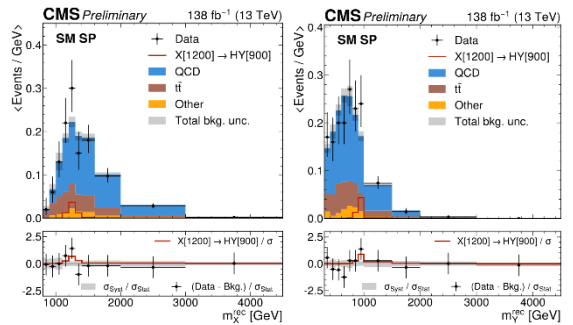
$m_Y \in [60, 2800]$ GeV

The analysis exploits **state-of-the-art substructure techniques and taggers to identify boosted final states**:

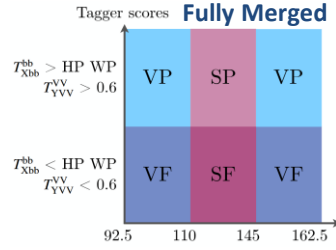
- ✓ **ParticleNET jet tagger for $H \to b\bar{b}$ and $V \to q\bar{q}$: the leading graph-based tagger in CMS** [PhysRevD.101.056019]
- ✓ **ParT jet tagger for $Y \to VV \to 4q$: novel attention-based "particle transformer"** [arXiv:2202.03772]

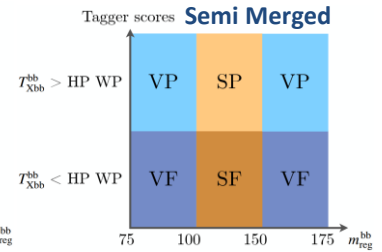
Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states





Brand-new [CMS-PAS-B2G-23-007]



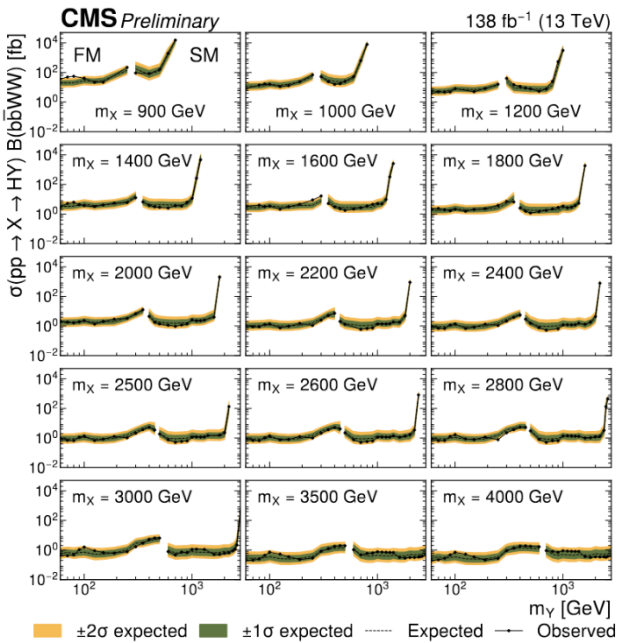


Dominant background is QCD multijet → data-driven prediction
(Much) smaller backgrounds: t or V + jets → prediction from MC

Data-driven background prediction:

- **Signal (SP, SF) and Validation (VP, VF)** regions are defined**,** with **Pass and Fail Modes** to predict background in a data-driven way.
- **[QCD prediction in SP] = [Data in SF]** $\times \mathbf{R}(m_X, m_Y)$
  - $\mathrm{R}(m_X, m_Y)$ parametrized as 2D Bernstein polynomials

Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states

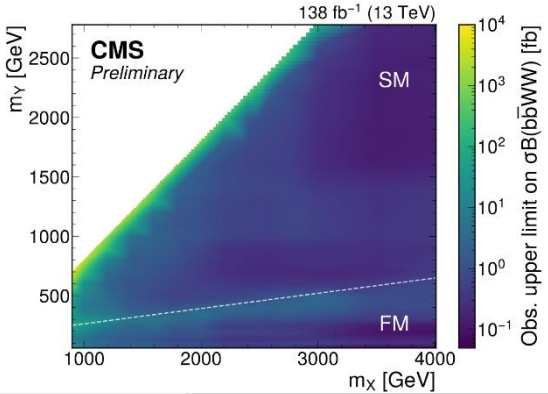


A 2D maximum likelihood fit is performed in m_X^{rec} and m_Y^{rec}, simultaneously in SP and SF.

CMS-PAS-B2G-23-007

Brand-new

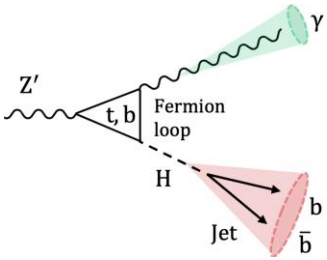
No significant deviation from Standard Model observed. Largest one occurs for $m_X = 900$ GeV and $m_Y = 80$ GeV: 3.3σ (<1.0σ) local (global) significance



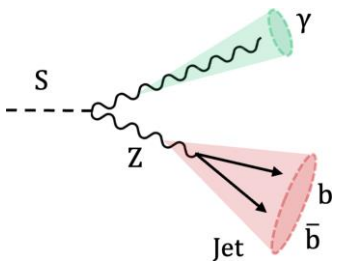
Search for heavy $H(b\bar{b})\gamma$ and $Z(b\bar{b})\gamma$ resonances

Signal models

CMS-PAS-B2G-24-007

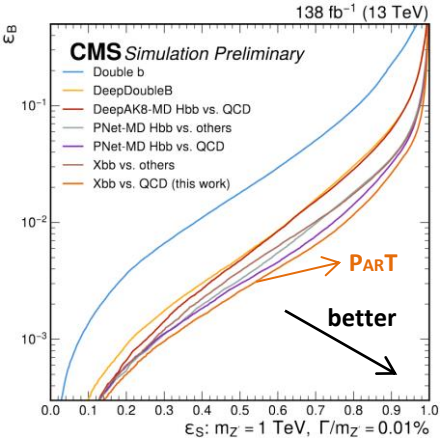


Spin-1 heavy resonance Z'
$Z' \to H\gamma \to b\bar{b}\gamma$
Narrow width: $\Gamma/M_{Z'} = 0.1\%$
$700 < M_{Z'} < 3500$ GeV



Spin-0 heavy resonance S
$S \to Z\gamma \to b\bar{b}\gamma$
Widths: $\Gamma/M_S = 0.014\%, 5.6\%, 10\%$
$700 < M_S < 3500$ GeV

ParT tagger for $H/Z \to b\bar{b}$ (X_{bb})
Best performance compared to previous taggers

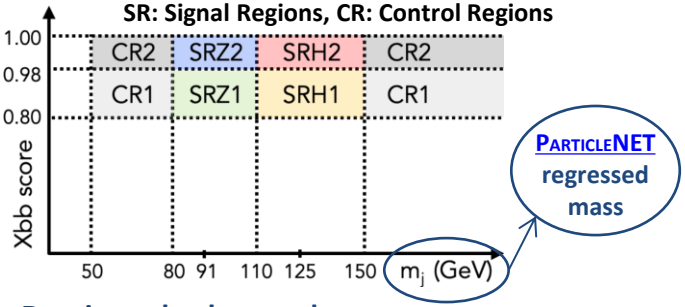


Experimental signature:

- Photon with $p_T^\gamma > 225$ GeV, $|\eta^\gamma| < 1.444$
- Large-radius (AK8), boosted, 2-prong jet with $p_T^j > 250$ GeV, $|\eta^j| < 2.4$

Search for heavy $H(b\bar{b})\gamma$ and $Z(b\bar{b})\gamma$ resonances

CMS-PAS-B2G-24-007



Dominant backgrounds

SRZ1, SRZ2:

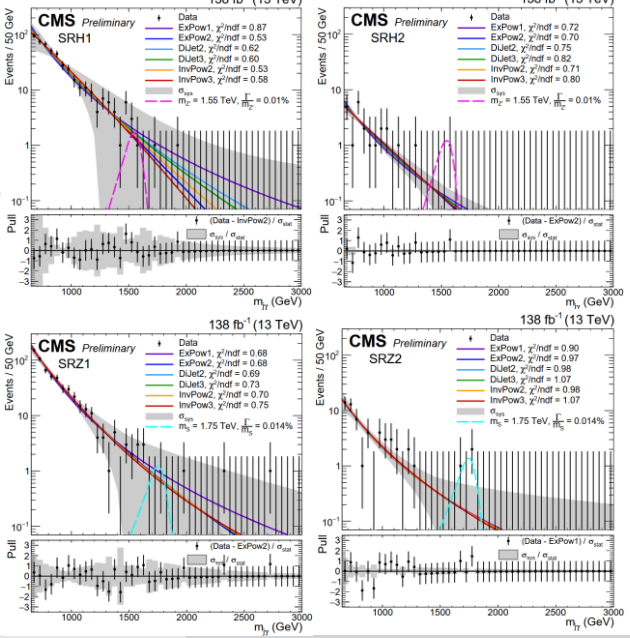
- $\mathbf{QCD + \gamma, Z + \gamma}$ (96%)
- $t\bar{t} + \gamma$, $t + \gamma$, $W + \gamma$ (4%)

SRH1, SRH2:

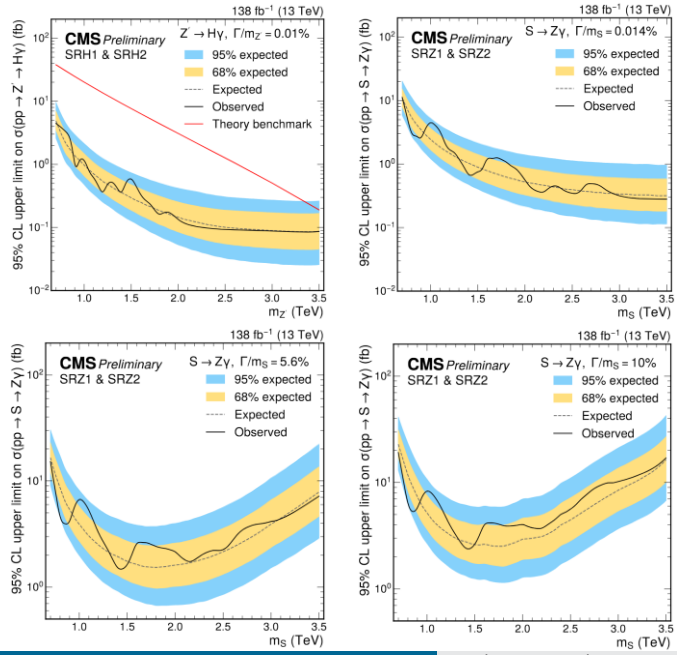
- $\mathbf{QCD + \gamma}$ (84%)
- $\mathbf{Z + \gamma}$ (10%), other (6%)

Data-driven background prediction

- **Fit the $m_{j\gamma}$ spectrum in each SR with 6 different, physics-inspired functions**, using the discrete profiling method.
- **Validation of the functions performed in CRs.**



Search for heavy $H(b\bar{b})\gamma$ and $Z(b\bar{b})\gamma$ resonances



CMS-PAS-B2G-24-007

An unbinned maximum likelihood fit to the $m_{j\gamma}$ across all SRs is conducted

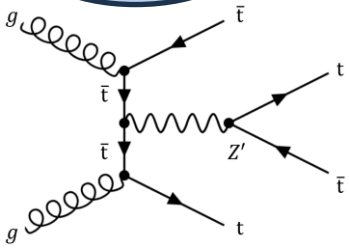
Results

- **No deviation from Standard Model observed.**
- **Exclude $Z' \to H\gamma$ across the entire mass range.**
- **Cross section limits** are the **strongest to date**
  - for the **entire mass range of Z' probed**
  - for $m_S > 1.1$ **TeV**
- **Improvement by factors of ~6 – 10 compared to previous CMS results (**CMS-EXO-17-019, CMS-EXO-17-005**)**
  - Larger dataset (2016 → Run-2) and, more importantly, **more advanced taggers**.

Search for top-philic heavy resonance (Z') in $t\bar{t}Z'$ ($Z' \to t\bar{t}$)

CMS-PAS-B2G-24-009

First search of its kind at CMS



Signal model

Z' couples exclusively to top

$0.5 < m_{Z'} < 3$ TeV

$\Gamma/m_{Z'} = 4\%, 10\%, 20\%, 50\%$

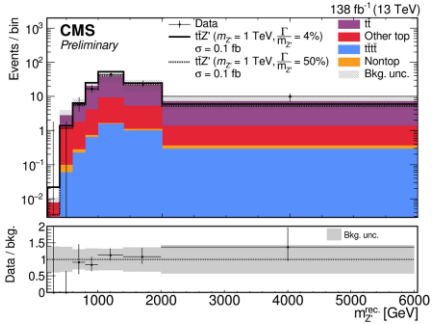
PhysRevD.94.035023

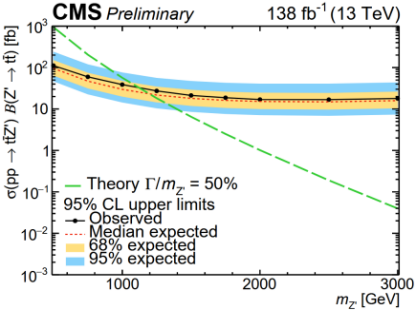
Experimental signature

- $Z' \to t\bar{t} \to$ **2 boosted large-radius (AK8) jets**, tagged with **ParticleNET**.
- **Associated with single-lepton $t\bar{t}$** (μ and e channels).

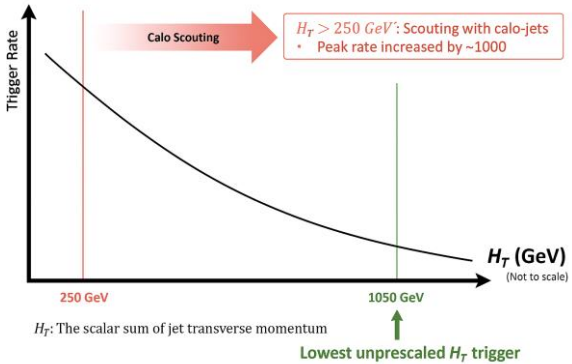
Results

- **No evidence for BSM physics.**
- Imposes the **most stringent mass limits on $Z'(\to t\bar{t})$ at the LHC:**
  - ✓ $500 < m_{Z'} < 564$ GeV (10% width)
  - ✓ $500 < m_{Z'} < 849$ GeV (20% width)
  - ✓ $500 < m_{Z'} < 1125$ GeV (50% width)





Search for dijet resonances ($X \rightarrow jj$) with data scouting



Data scouting

(10.1016/j.physrep.2024.09.006)

Dijets reconstructed online at the High Level Trigger (HLT) from calorimeter information (CALO jets)

Smaller event size → larger event rate → lower trigger thresholds

CMS-PAS-EXO-23-004

Search for generic narrow dijet resonances in qq, qg and gg final states

Experimental signature

A **dijet**, formed by two **wide-jets**.

Wide-jet reconstruction: The two leading (in p_T) AK4 jets are used as seeds. Spatially close ($\Delta R < 1.1$) jets are combined into a wide jet.

Benchmark signal models

Randal-Sundrum graviton:

$q\bar{q} \rightarrow G \rightarrow q\bar{q}$

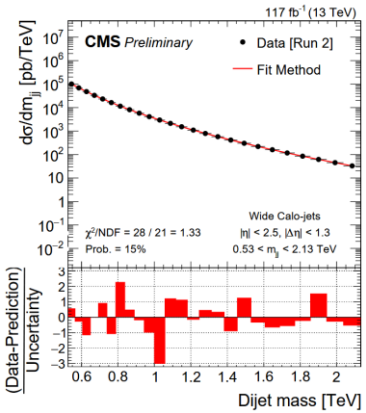
$gg \rightarrow G \rightarrow gg$

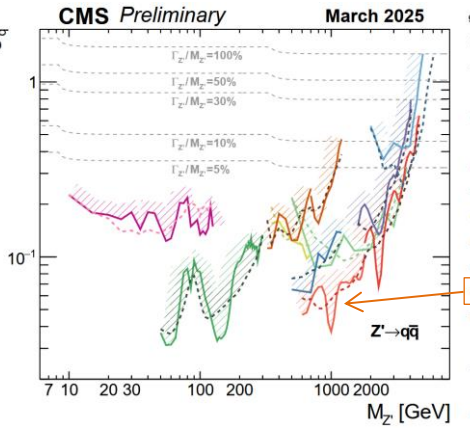
Excited quark:

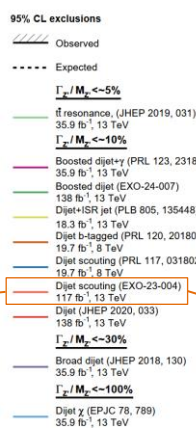
$qg \rightarrow q^* \rightarrow qg$

Enables us to probe dijet resonance masses between 600 and 1800 GeV, previously inaccessible with common datasets

Search for dijet resonances ($X \rightarrow jj$) with data scouting







CMS-PAS-EXO-23-004

Best limits on $g_{q'}$ in the probed mass range

Dominant background

QCD multijets

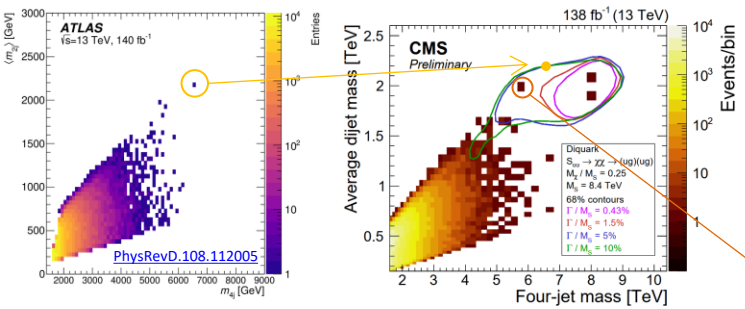
Data-driven prediction

Model QCD by fitting data directly with a background function

Signal extraction: Due to **large dataset** and to **avoid correlations between signal strength** and **background nuisance parameters** → **fit Run-2 sub-datasets simultaneously** → **Robust results**

Use of **4-parameter function** instead of 5-parameter used in 2016 publication → **improved sensitivity (more than lumi scaling)**

Broad resonance reinterpretation of high-mass $\mathbf{Y \to XX \to (jj)(jj)}$



- **Reinterpretation of** JHEP07(2023)161, **motivated by CMS and ATLAS Run-2 data with $\bar{m}_{2j} \sim 2$ TeV and a wide spread in m_{4j}.**
- Searching here for a **broad mediator, Y**, decaying into a pair of **narrow dijet resonances, X**.

Dominant Background

QCD multijet production

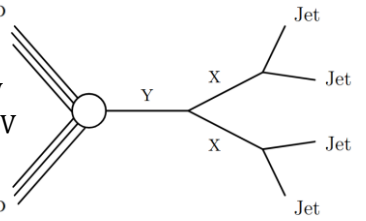
Data-driven background prediction

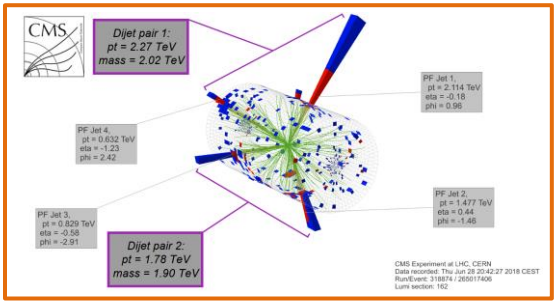
Four-jet mass is fitted simultaneously in bins of $\alpha = \bar{m}_{2j}/m_{4j}$ with 3 parametric functions using the discrete profiling method

JHEP07(2023)161:
$\Gamma/M_Y < 0.5\%$
This analysis:
$\Gamma/M_Y = 1.5\%, 5\%, 10\%$

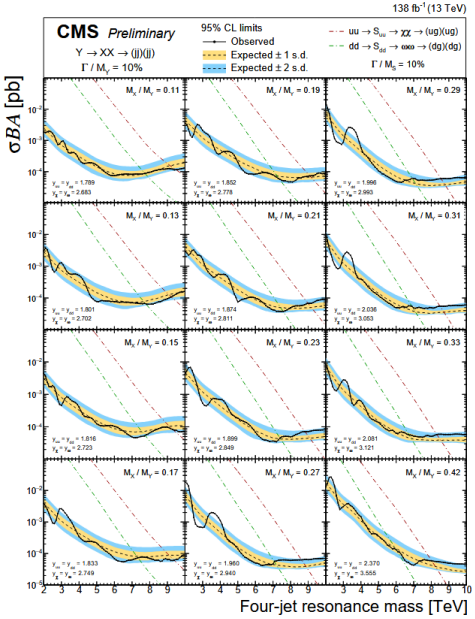
CMS-PAS-EXO-24-038

$M_Y \in [2, 10]$ TeV
$M_X \in [0.2, 4.2]$ TeV



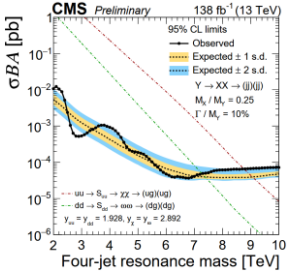


Broad resonance reinterpretation of high-mass $Y \to XX \to (jj)(jj)$



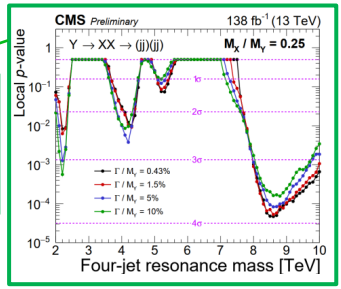
- Set **model-independent** cross section limits for **various Y and X masses, and Y widths up to 10%.**
- **Mass limits on diquarks S_{uu} and S_{dd} decaying into vector-like quarks.**

arXiv:1810.09429

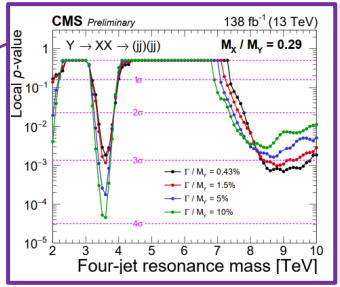


CMS-PAS-EXO-24-038

A broad resonance is an equally valid interpretation of the $M_Y = 8.6$ TeV excess.



A second effect is reported at $M_Y = 3.6$ TeV, $M_X = 1.0$ TeV and $\Gamma/M_Y = 10\%$: 3.9σ (2.2σ) local (global) significance.



Summary

- **Strive for maximizing the discovery potential or limit setting through novel techniques and Machine Learning (ML) methods** (see talks by Louis, Donato and Raffaella)**.**
  - **New taggers for boosted topologies** ($X \to b\bar{b}$, $Y \to 4q$ etc.) with **improved performance**.
    - **ParticleNET** [PhysRevD.101.056019]**, PaRT** [arXiv:2202.03772]
  - **Data scouting** [10.1016/j.physrep.2024.09.006] **and other dedicated data streams** which allow us to **probe previously inaccessible parts of the phase space** (see talk by Celia).

- **We are actively exploring many new channels, final states and signal models** (see talks by Abhirami and Di).
  - **Rich program of $X \to HY$ searches**, looking for various final states (stay tuned for more results of this kind).
  - **Explore extreme scenarios** such as Z' coupling exclusively to top quarks.
  - **Focus on previous excesses and expand these searches**.

- **While we are finalizing Run-2 analyses, we are moving ahead full speed with the Run-3 ones, so..**
  Stay tuned!

Thank you for your attention!

The research project was co-funded by the Stavros Niarchos Foundation (SNF) and the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the 5th Call of "Science and Society" Action Always strive for excellence – Theodoros Papazoglou" (Project Number 20996).

Back up slides

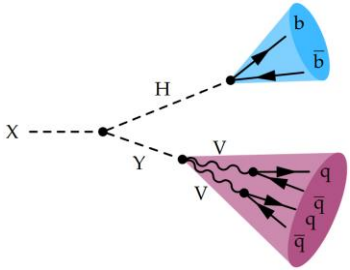
$X \to YH$ resonance searches in CMS

Final state	Publication
$X \to Y(b\bar{b})H(b\bar{b})$ resolved $X \to Y(b\bar{b})H(b\bar{b})$ boosted	CMS-PAS-HIG-20-012 CMS-B2G-21-003
$X \to Y(b\bar{b})H(\tau\tau)$	CMS-HIG-20-014
$X \to Y(b\bar{b})H(\gamma\gamma)$ resolved	CMS-HIG-21-011
$X \to Y(\gamma\gamma)H(b\bar{b})$ resolved	CMS-PAS-B2G-24-001
$X \to Y(VV \to 4q)H(b\bar{b})$ boosted	CMS-PAS-B2G-23-007
$X \to Y(\text{anomalous})H(b\bar{b})$ boosted	CMS-PAS-B2G-24-015
Searches for Higgs boson production through decays of heavy resonances	CMS-B2G-23-002

Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states

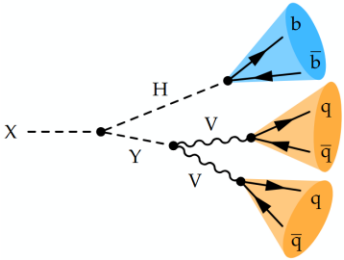
Brand-new CMS-PAS-B2G-23-007

Fully Merged (FM)



- ParticleNET tagger for $H \to b\bar{b}$
  40% signal eff. @ 0.1% bkg eff.
- ParT tagger for $Y \to 4q$
  60% signal eff. @ 1% bkg eff.

Semi Merged (SM)



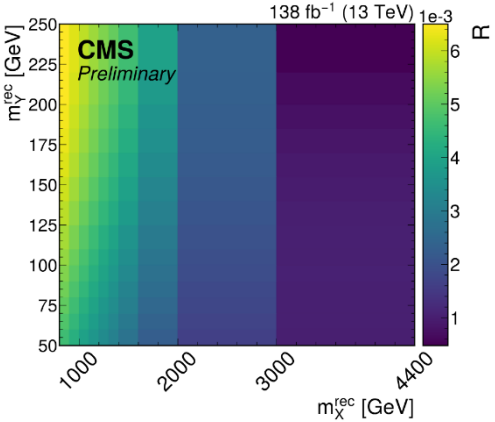
- ParticleNET tagger for $H \to b\bar{b}$
  40% signal eff. @ 0.1% bkg eff.
- ParticleNET tagger for $V \to q\bar{q}$
  60% signal eff. @ 0.06% bkg eff.

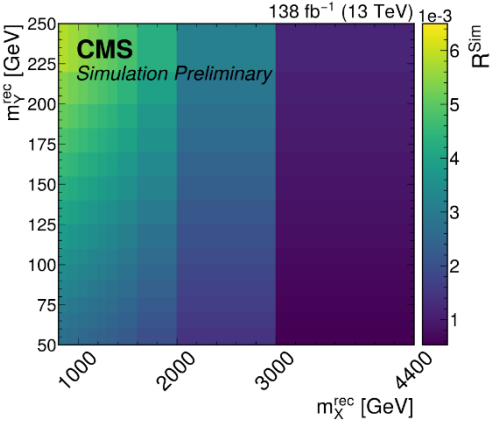
Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states

Brand-new CMS-PAS-B2G-23-007

Data-driven background prediction for QCD:

- **Transfer factor $R(m_X, m_Y)$, parametrized as 2D Bernstein polynomials.** Fisher test to determine order of polynomials
- **In the Semi Merged category** it is a constant number (ParticleNET fully MD and the shape of m_X, m_Y not affected).
- **In the Fully Merged category**: $R(m_X, m_Y) = R^{\mathrm{Sim}}(m_X, m_Y) R^{\mathrm{Data}}(m_X, m_Y)$
  - ParT is MD but may affect the shape of m_Y

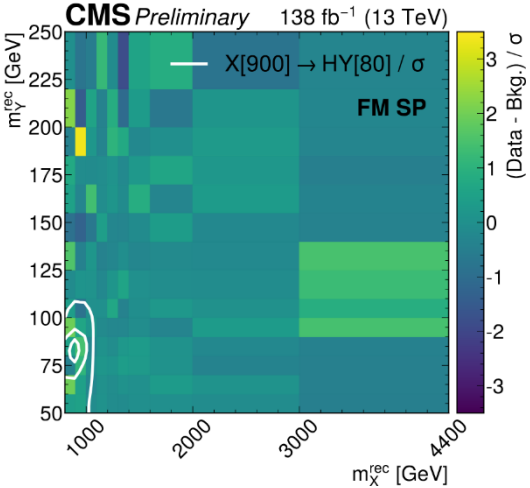


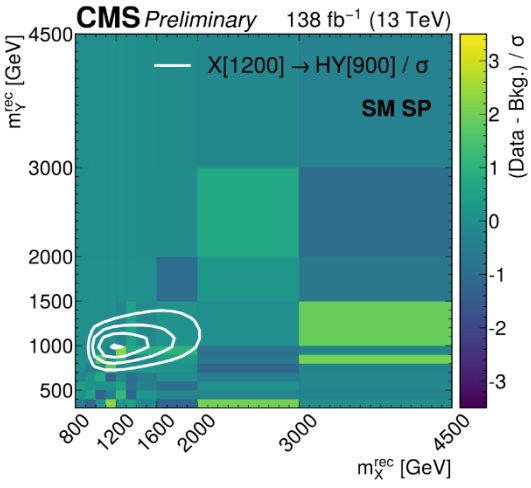


Search for $X \to H(b\bar{b})Y(4q)$ resonances in boosted final states

Brand-new CMS-PAS-B2G-23-007

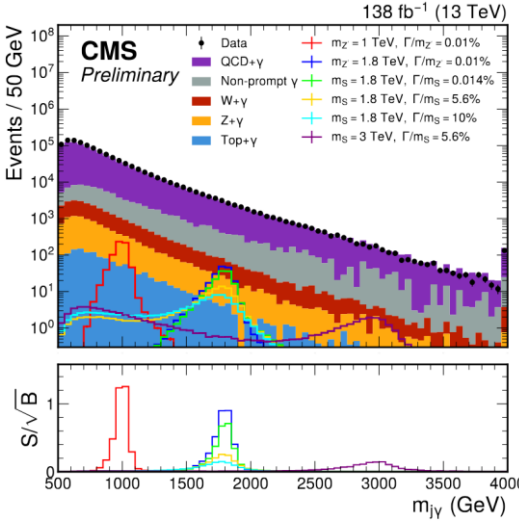
2D pulls

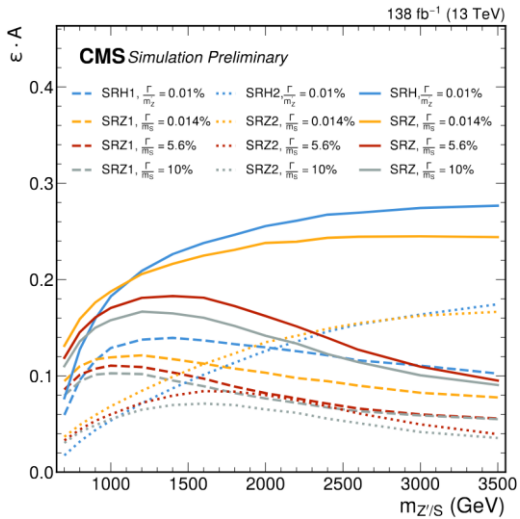




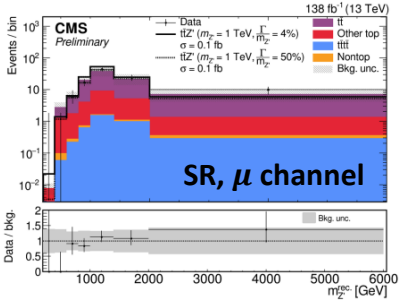
Search for heavy $H(b\bar{b})\gamma$ and $Z(b\bar{b})\gamma$ resonances

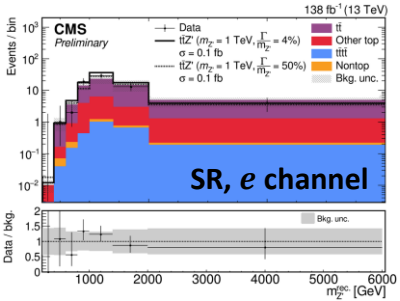
CMS-PAS-B2G-24-007

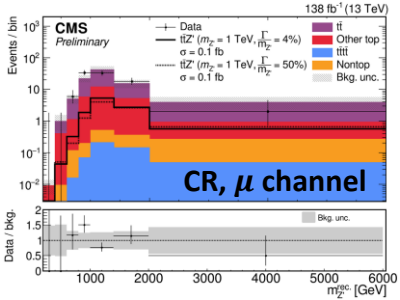


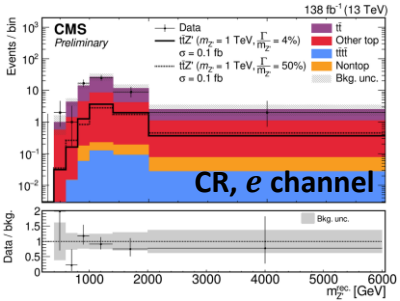


Search for top-philic heavy resonance (Z') in $t\bar{t}Z'$ $(Z' \to t\bar{t})$









CMS-PAS-B2G-24-009

Dominant backgrounds

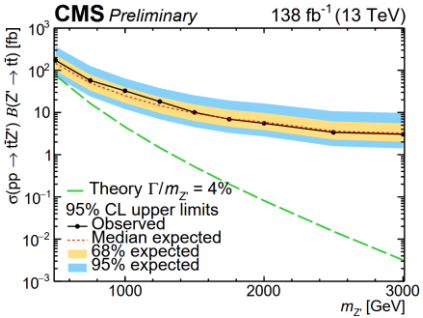
- $t\bar{t} + \mathbf{jets}$ (75%)
- $t\bar{t} + V, t + V/VV, tZq$ (20%)
- $t\bar{t}t\bar{t}$ (4%)
- Non-top $(< 1\%)$

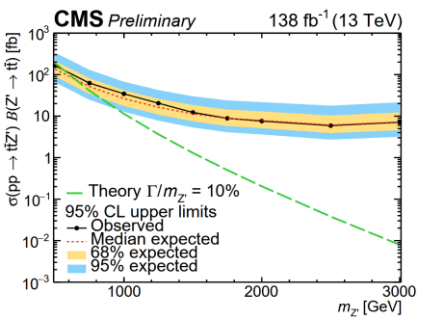
Background estimation & signal extraction

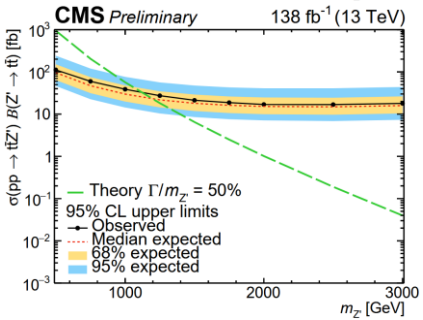
- **Background shape in SR is modeled from MC.**
- Normalization is corrected via a free parameter fitted using SR and CR simultaneously.
- **Maximum likelihood fit extracts both background normalization correction and signal normalization.**

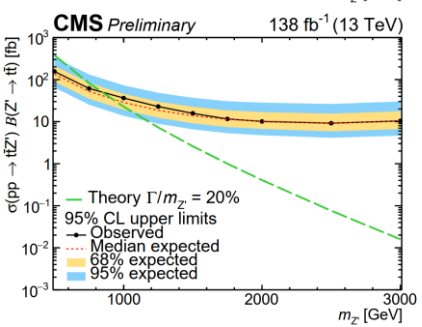
Search for top-philic heavy resonance (Z') in $t\bar{t}Z'$ ($Z' \to t\bar{t}$)

CMS-PAS-B2G-24-009



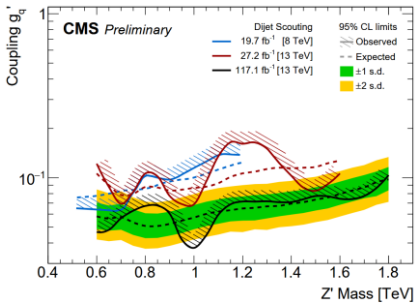


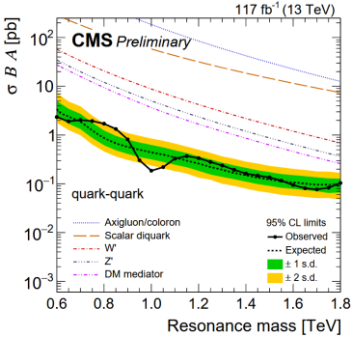


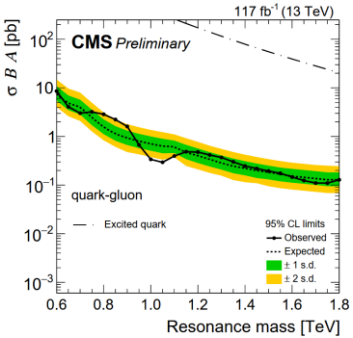


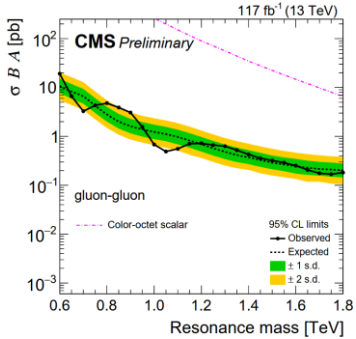
Search for dijet resonances $(X \rightarrow jj)$ with data scouting

CMS-PAS-EXO-23-004



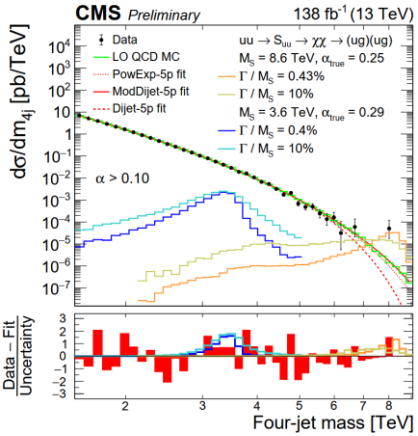


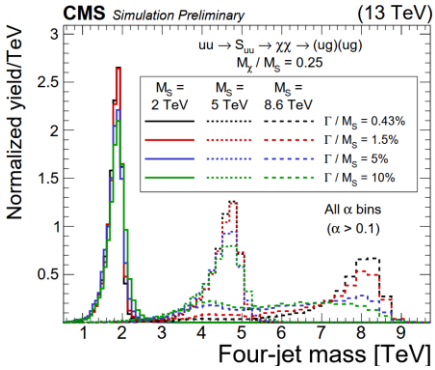


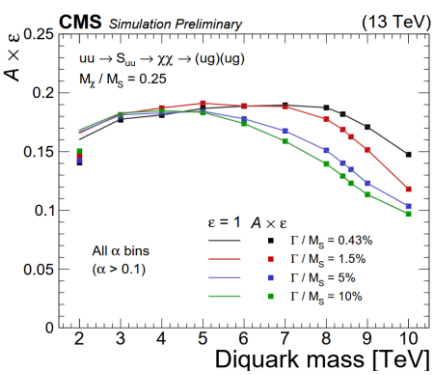


Broad resonance reinterpretation of high-mass $Y \to XX \to (jj)(jj)$

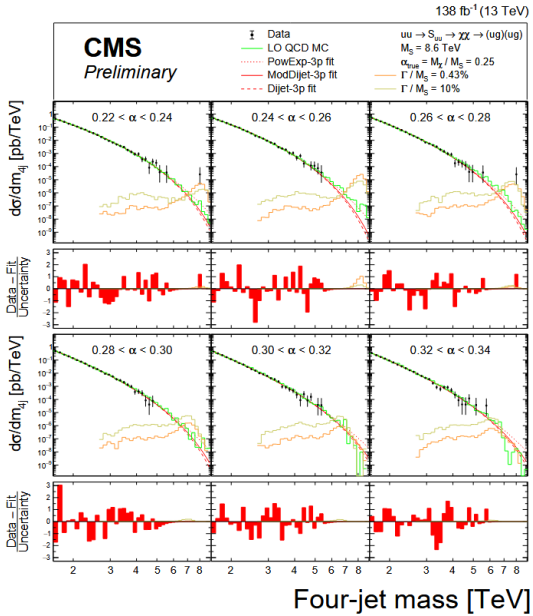
CMS-PAS-EXO-24-038

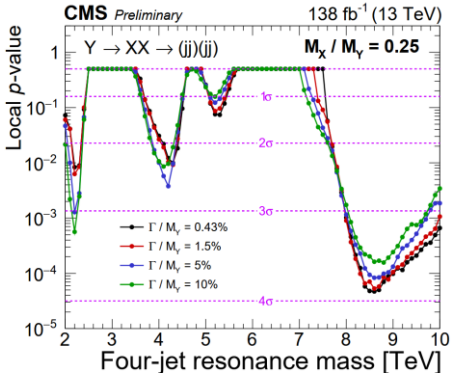






Broad resonance reinterpretation of high-mass $Y \to XX \to (jj)(jj)$



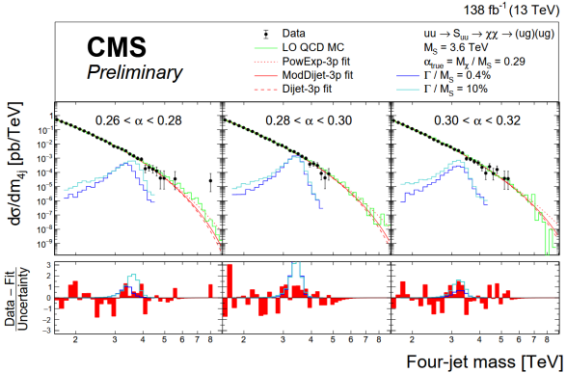


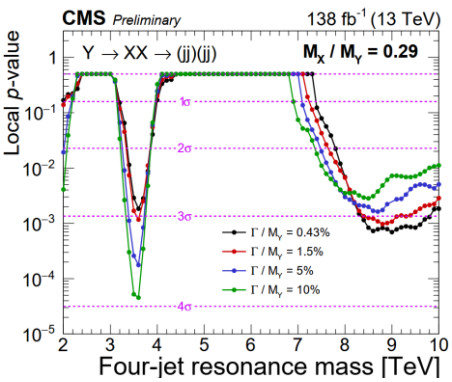
CMS-PAS-EXO-24-038

High-mass excess

- Broad resonances of 10% width can result in signal events both at the resonance mass but also at lower four-jet masses.
- A broad resonance is an equally valid interpretation of the high-mass excess: the local (global) significance ranges from 3.9 to 3.6σ (1.6 to 1.4σ) as the resonance width is increased from 0.4% to 10%

Broad resonance reinterpretation of high-mass $Y \to XX \to (jj)(jj)$





CMS-PAS-EXO-24-038

Lower-mass excess

- We report the reinterpretation of a second effect, at a four-jet resonance mass of 3.6 TeV, which also has a local significance of up to 3.9σ (global up to 2.2σ).
- This excess points to a wide structure in data, apparent in the three α bins shown.
- Was also reported by the search for nonresonant production of pairs of dijet resonances ($pp \to XX \to (jj)(jj)$) with a magnitude of $3.6(2.5)\sigma$ local (global) significance.