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Bundesministerium
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CMS

FSP CMS
Erforschung von
Universum und Materie

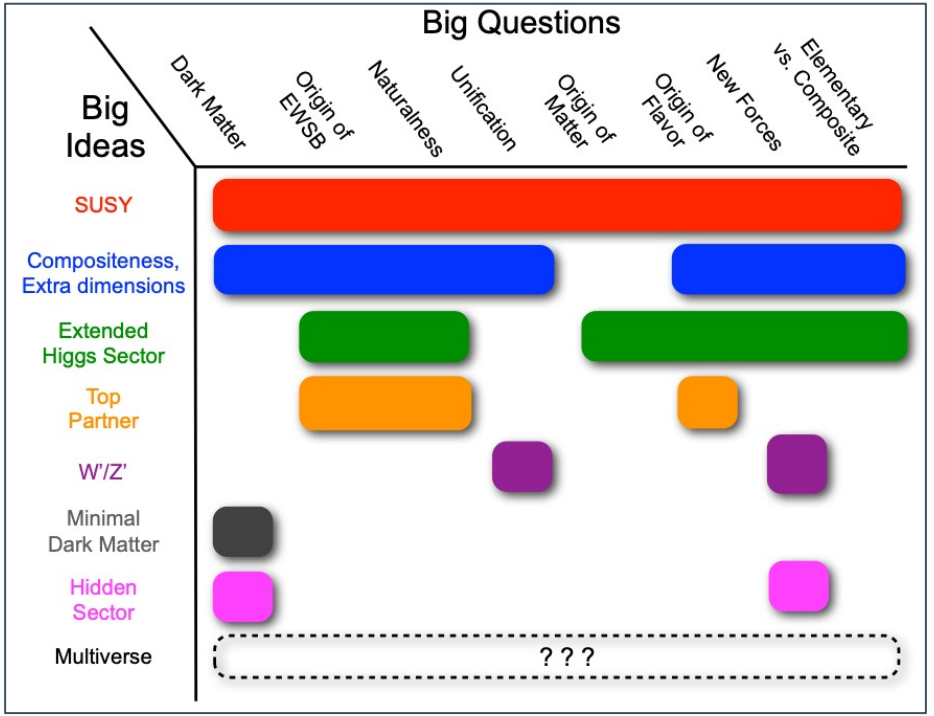
Daniel Hundhausen (Universität Hamburg) on behalf of the **CMS Collaboration**

Searches for Diboson Resonances at CMS

42nd International Conference on High Energy Physics – 20.07.2024

New Physics Likely to Have Diboson Final States

- What physics is there beyond the SM?
  - Work in progress…
- New heavy resonances can decay into pairs of SM gauge bosons
  - heavy Higgs bosons
  - Kaluza-Klein (KK) excitations
  - new gauge bosons (W', Z')
- Very likely: BSM signature includes diboson final states
  - $X \to VV \;/\; VH$



arXiv:1311.0299 **[hep-ex]**

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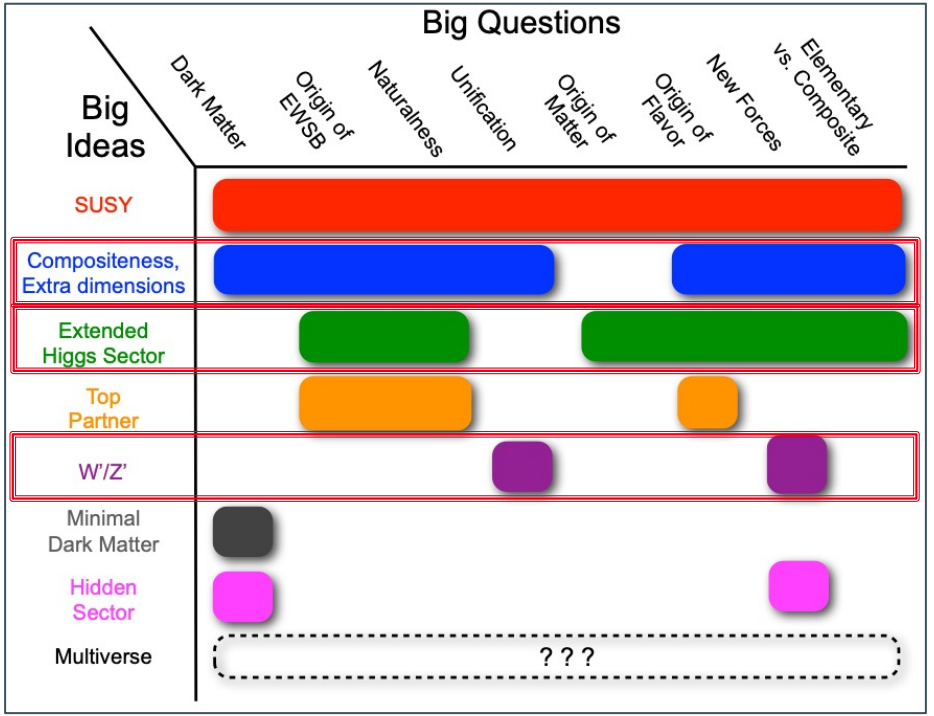
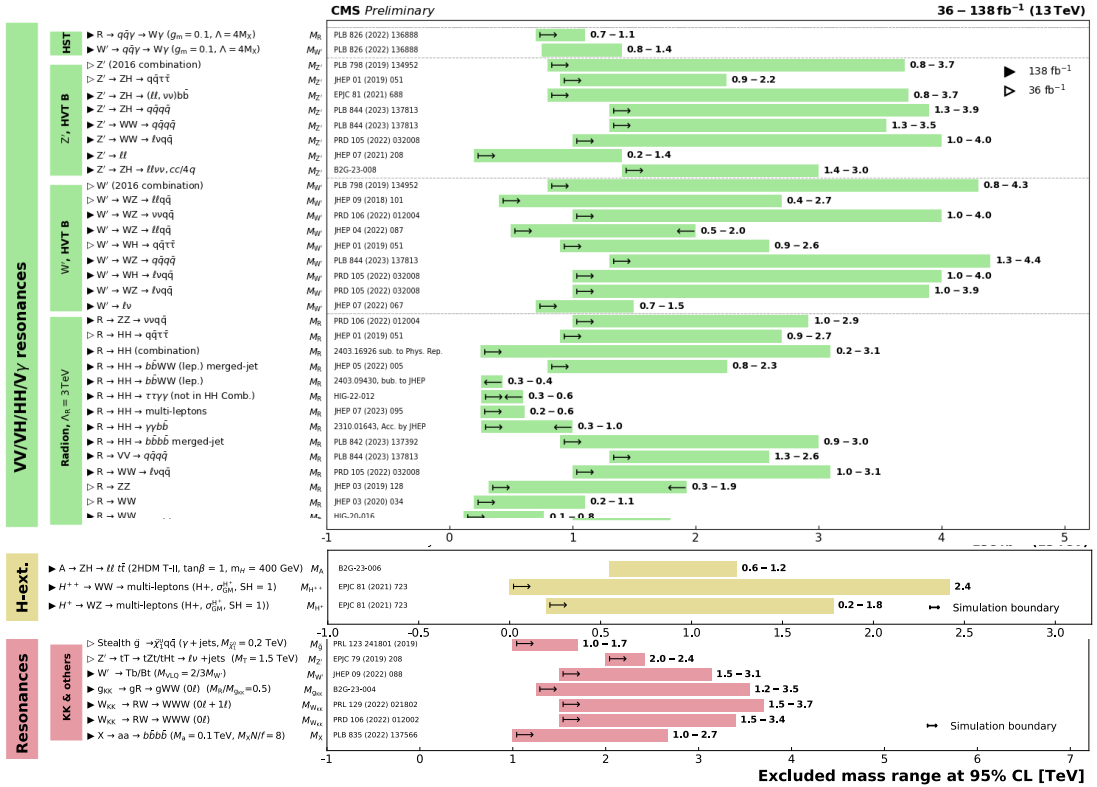


arXiv:1311.0299 **[hep-ex]**

CMS Diboson Searches

- CMS features a rich program of diboson searches
- This talk presents new results in $X \to VV$ / VH
- $X \to HH$ covered in the next talk by Chayanit Asawatangtrakuldee

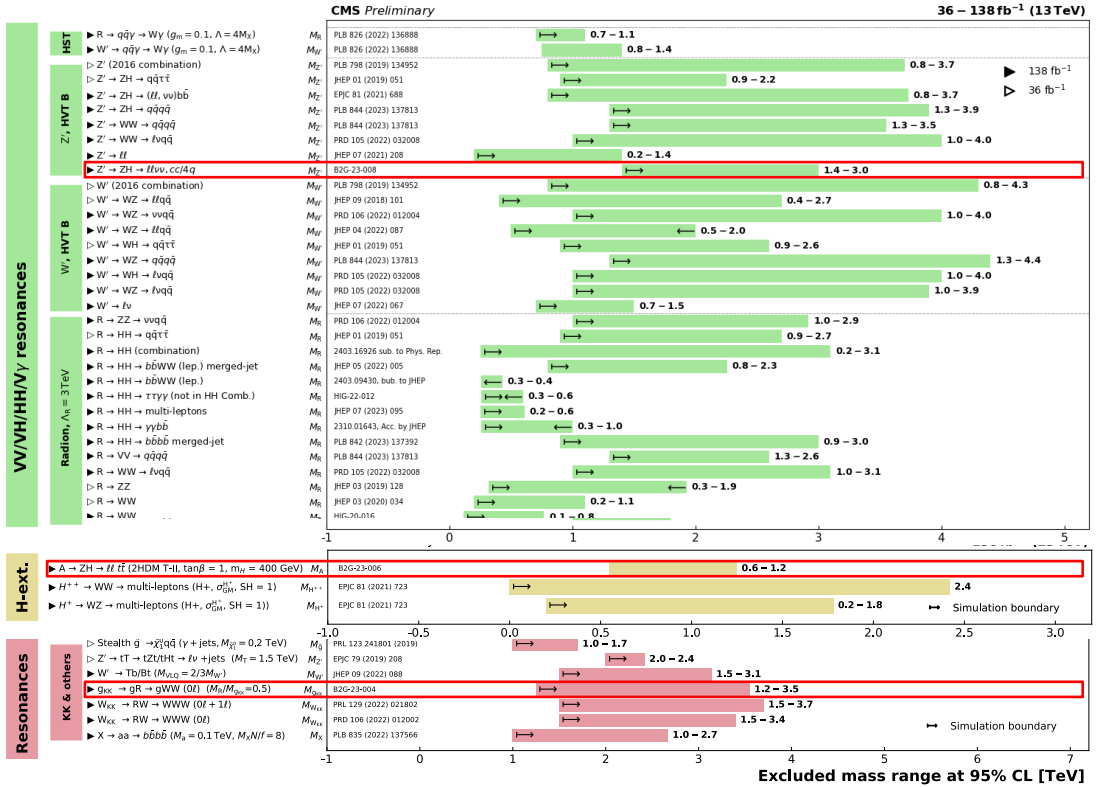


full summary

This Talk

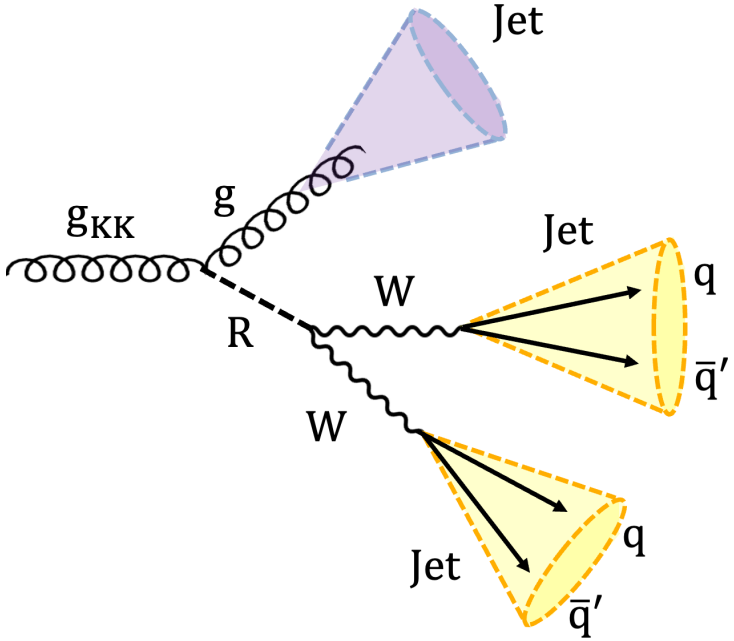
Three recent CMS Run II results

- g_{KK}, R – *extended warped extra-dimensional model*
- Z' – *Heavy Vector Triplet model*
- A, H – *2 Higgs-doublet model*



full summary

May 2024



CMS-PAS-B2G-23-004

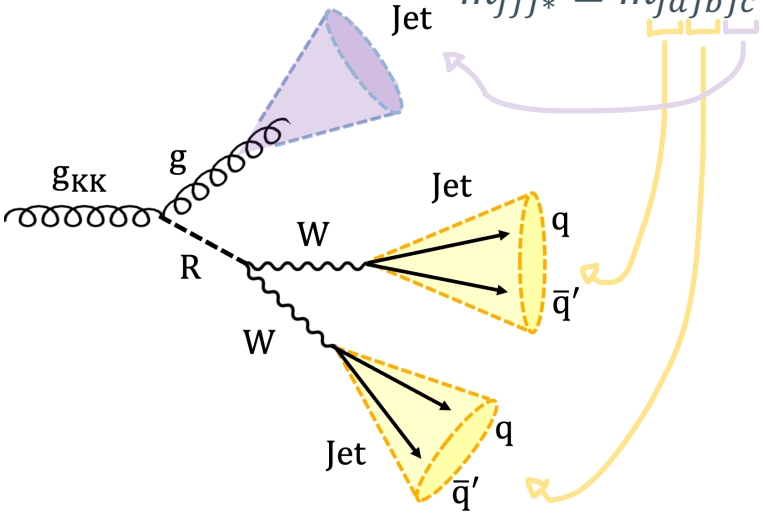
$g_{KK} \rightarrow gR \rightarrow gWW$

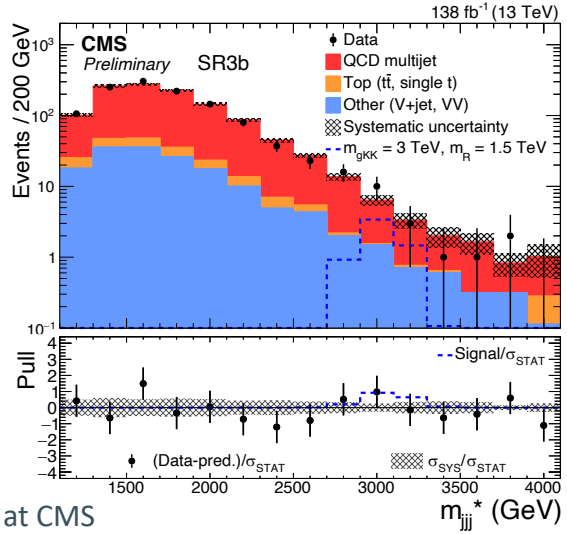
$g_{KK} \rightarrow gR \rightarrow gWW$

- Motivation: extended warped extra-dimensional (EWED) models
- Use of machine learning (ML) based W-tagger
- Modified invariant masses for improved resolution

CMS-PAS-B2G-23-004

$$m_{jjj*} \equiv m_{jajbjc} - m_{ja} - m_{jb} + 2 \times 85\ \text{GeV}$$

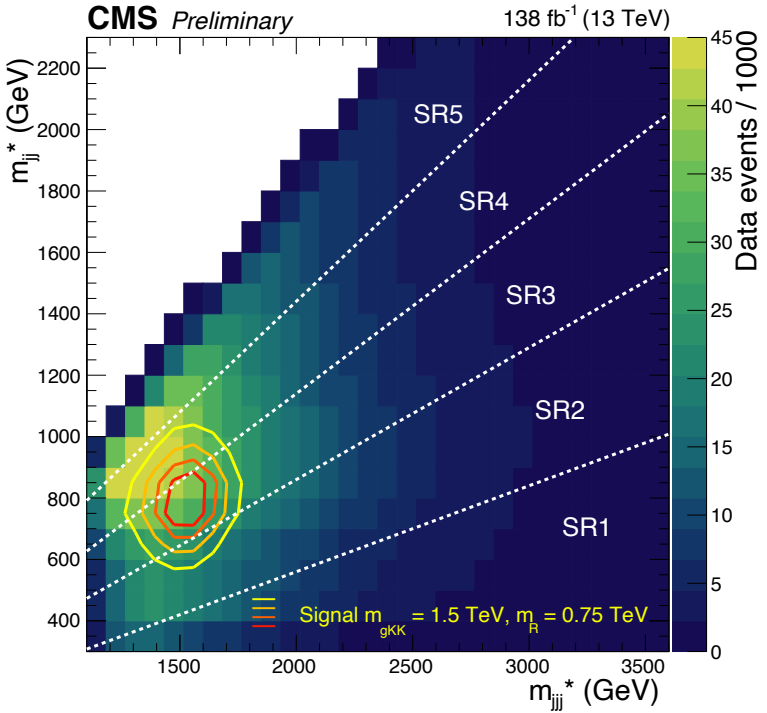




$g_{KK} \rightarrow gR \rightarrow gWW$: Event Categorization

CMS-PAS-B2G-23-004

- Different Signal Regions (SR) by ratio of m_{jj*} to m_{jjj*} to better probe different R masses
- Events with isolated leptons or b-tagged jets are rejected
- The important backgrounds are estimated from data



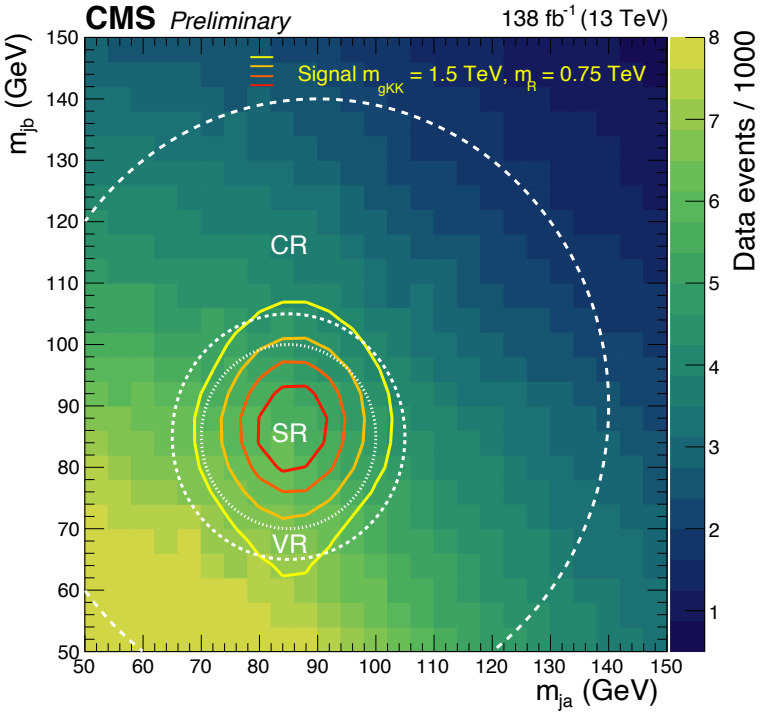
$g_{KK} \rightarrow gR \rightarrow gWW$: QCD Background Estimation

CMS-PAS-B2G-23-004

- Jet masses in SR are required to be around m_W
- CRs consist to about 90% of QCD multijet events

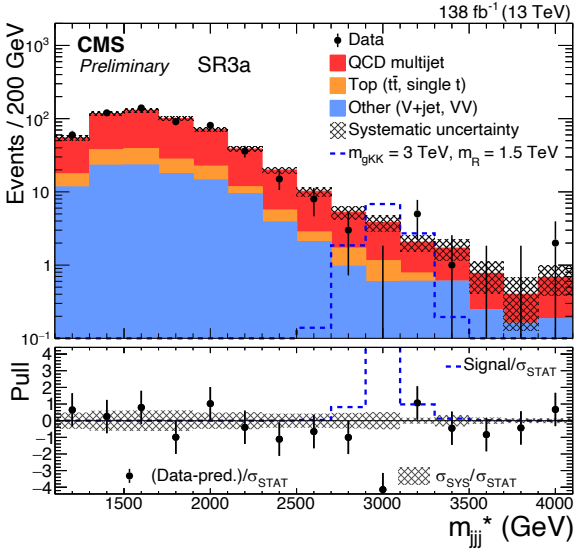
$$\mathrm{QCD_{SR}} = [\mathrm{Data} - \mathrm{Rest}]_{\mathrm{CR}} \times \frac{\mathrm{QCD_{SR}}}{\mathrm{QCD_{CR}}}$$

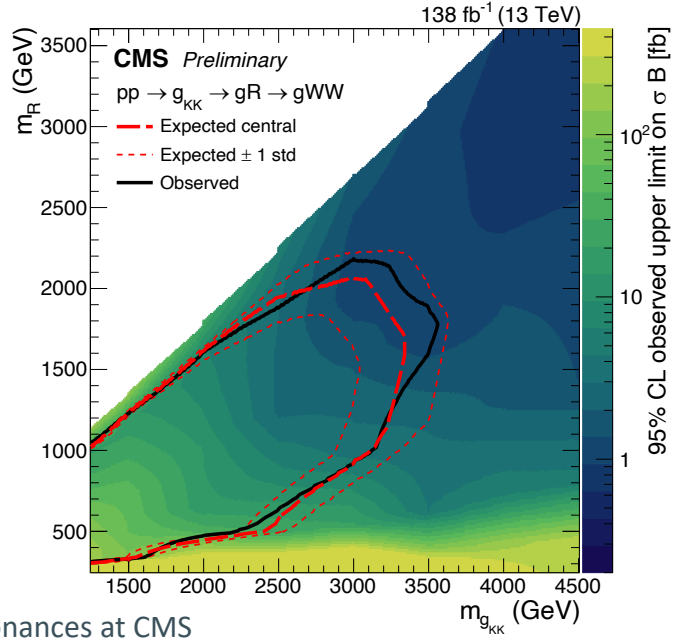
- $1.6 - 1.8$ larger QCD multijet background than in simulation (MadGraph + Pythia)



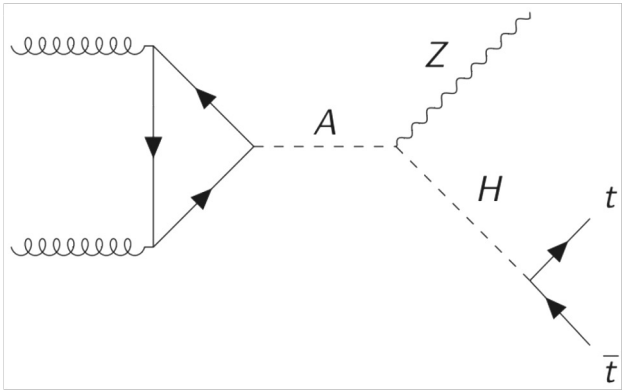
$g_{KK} \rightarrow gR \rightarrow gWW$: Results

- No significant excesses above the SM-only hypothesis observed [CMS-PAS-B2G-23-004]
- Exclude $m_{g_{KK}} \leq 3.55$ TeV and $m_R \leq 2.18$ TeV at 95% CL in an extension of the standard warped extra dimensional model [see Agashe, K. et al. JHEP 2018, 27]





March 2024



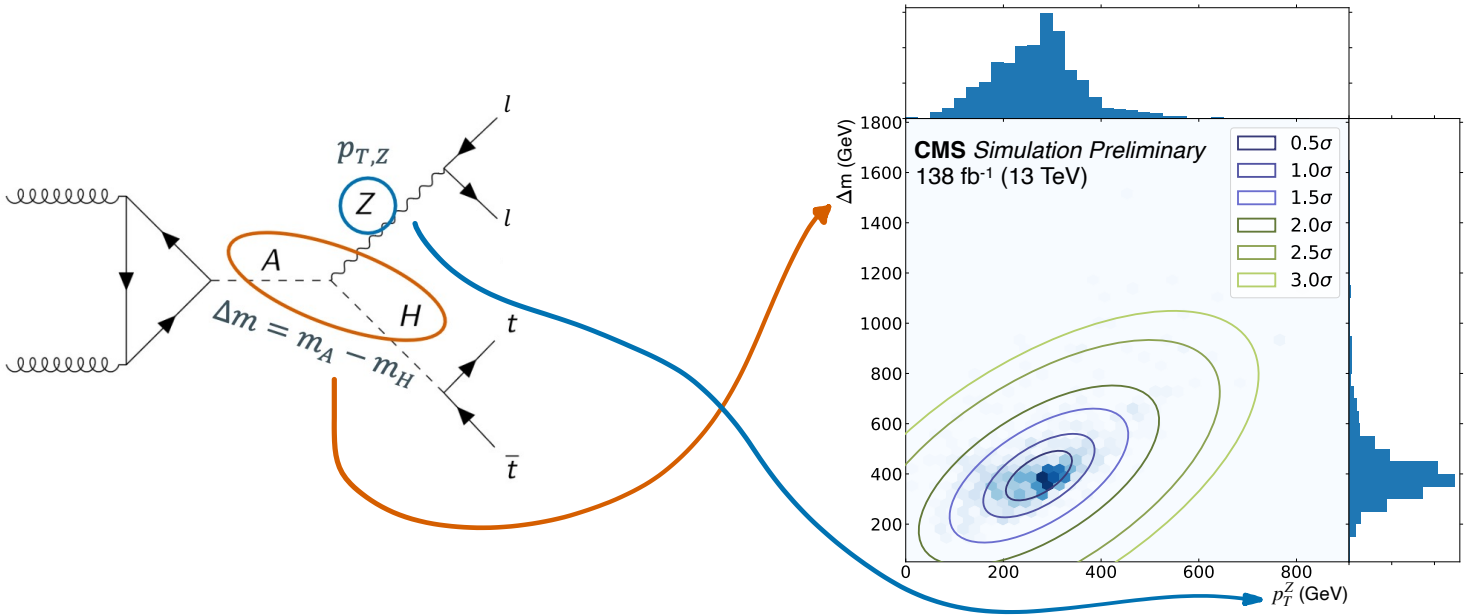
CMS-PAS-B2G-23-006

$A \rightarrow Z(l\bar{l})H(t\bar{t} \rightarrow jets)$

$A \to Z(l\bar{l})H(t\bar{t})$: Analysis Strategy

CMS-PAS-B2G-23-006

- Targeting resonant X→ ZY production with narrow resonances X and Y
- Channel well motivated: FOEWPT in targeted 2HDM parameter space



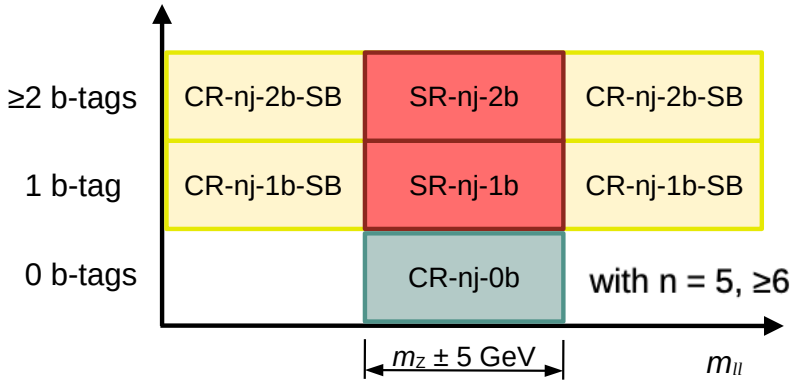
$A \to Z(l\bar{l})H(t\bar{t})$: Event Categorization

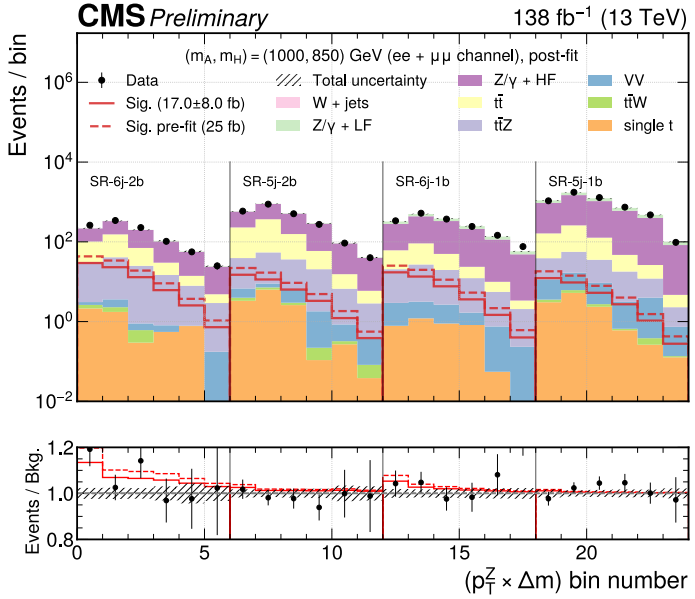
CMS-PAS-B2G-23-006

normalization floating in the fit!

Sidebands ($t\bar{t}$)

0b Region (Z+Jets)



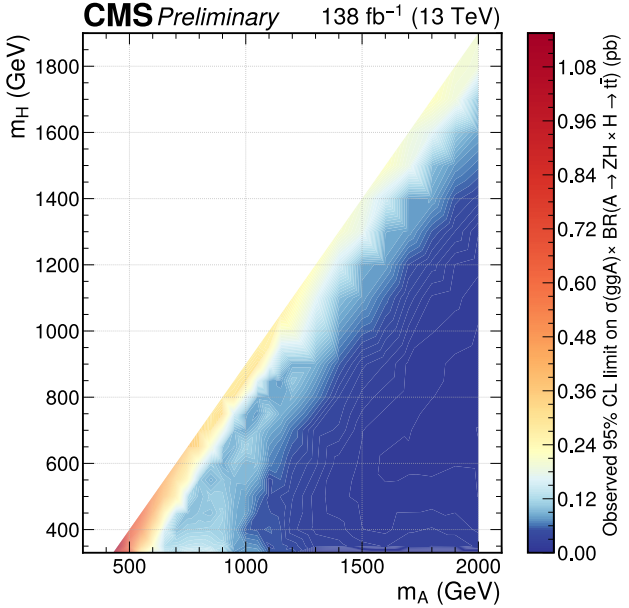


unrolled elliptical bins

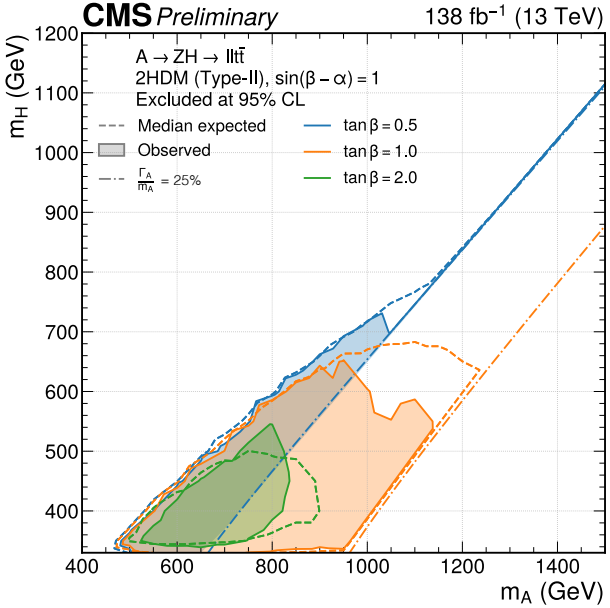
$A \to Z(l\bar{l})H(t\bar{t})$: Results and Interpretation

CMS-PAS-B2G-23-006

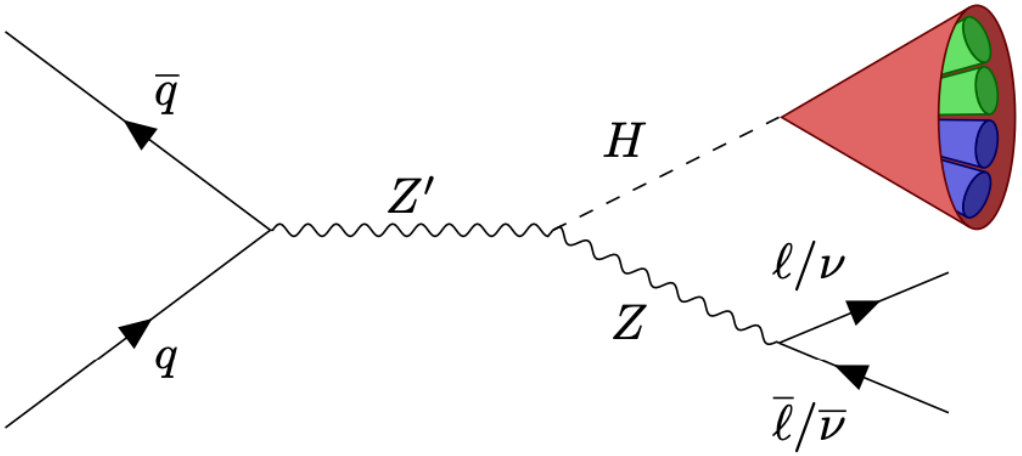
- Model independent upper limits on $\sigma \times BR$ of narrow resonances A and H



- Interpretation in the $m_A - m_H$ mass plane in the 2HDM, excluding large areas of parameter space



March 2024



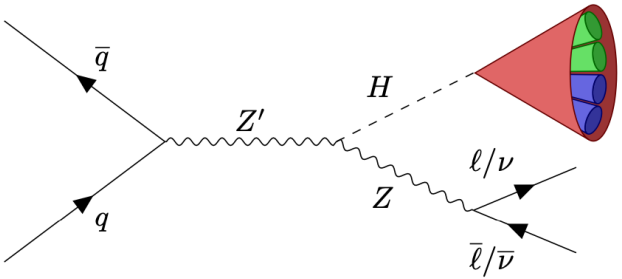
CMS-PAS-B2G-23-008

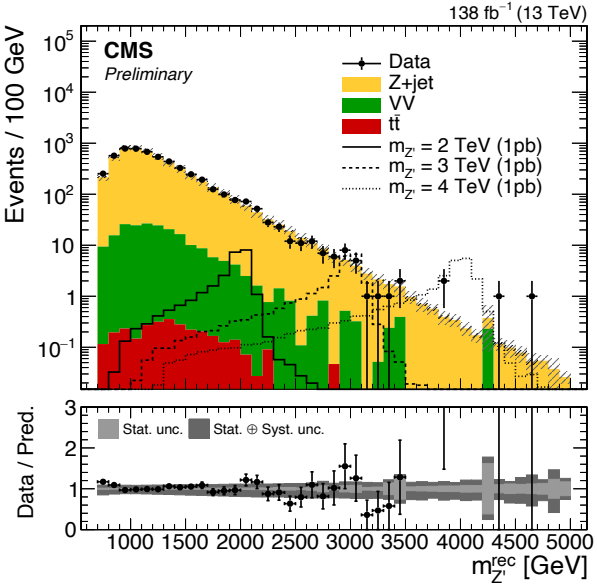
$Z' \rightarrow Z(l\bar{l}/\nu\nu)\ h(c\bar{c}/4q)$

$Z' \rightarrow Zh$: Overview and Event Selection

CMS-PAS-B2G-23-008

- Motivation: Heavy Vector Triplet (HVT) model
  - Describes EW spin-1 resonances
- Search for heavy resonances Z' decaying to Zh
  - $Z \rightarrow e^+e^- / \mu^+\mu^- / \nu\nu$
  - $h \rightarrow c\bar{c} / VV^* \rightarrow$ jets
- h is reconstructed as a single large radius jet requiring an ML-based score

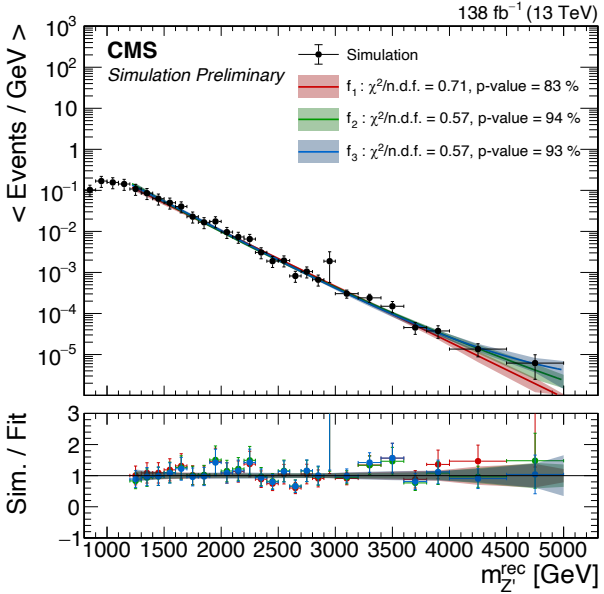




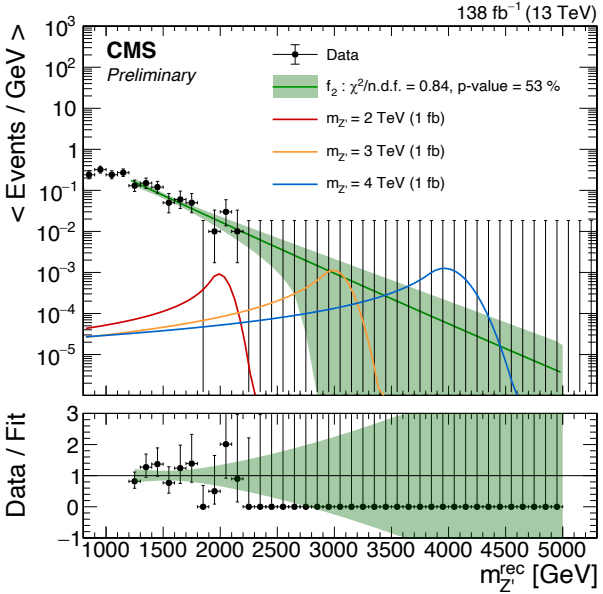
$Z' \rightarrow Zh$: Background Modeling

CMS-PAS-B2G-23-008

- Background modeled by exponential function
- Tested in Validation Region with inverted ML score requirement



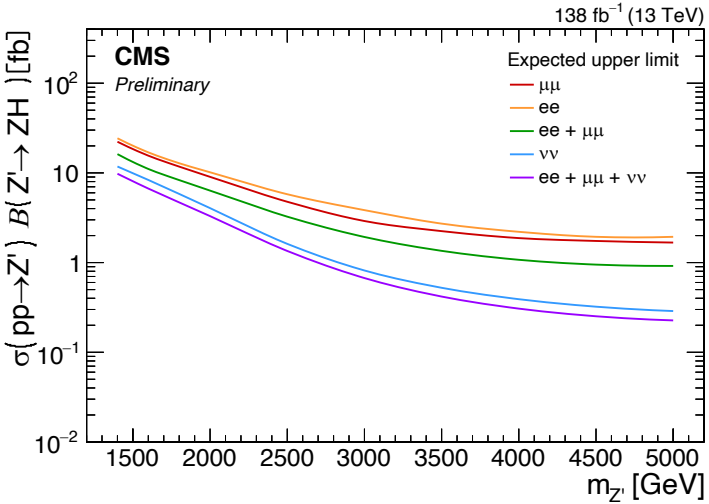
- Signal modeled by Crystal Ball function

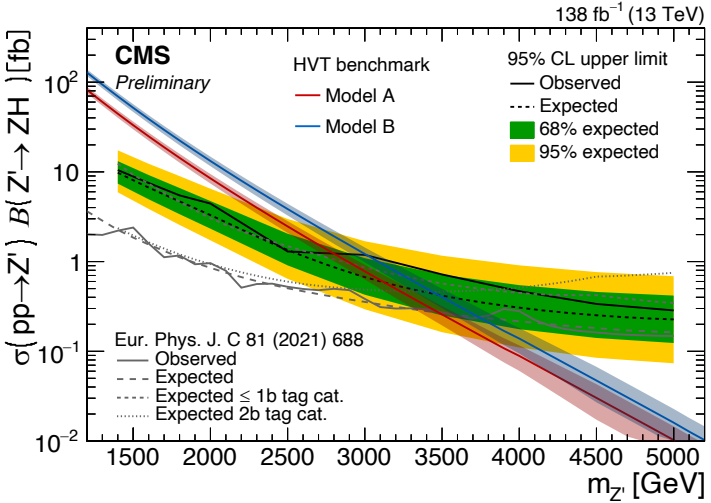


$Z' \rightarrow Zh$: Results

CMS-PAS-B2G-23-008

- Combined limits on $\sigma \times \mathrm{BR}$ in the range of $m_X = 1.4 - 5$ TeV
- Neutrino channel has highest sensitivity due to largest BR
- The new limits exclude the HVT benchmark models up to 2.8 and 3.0 TeV



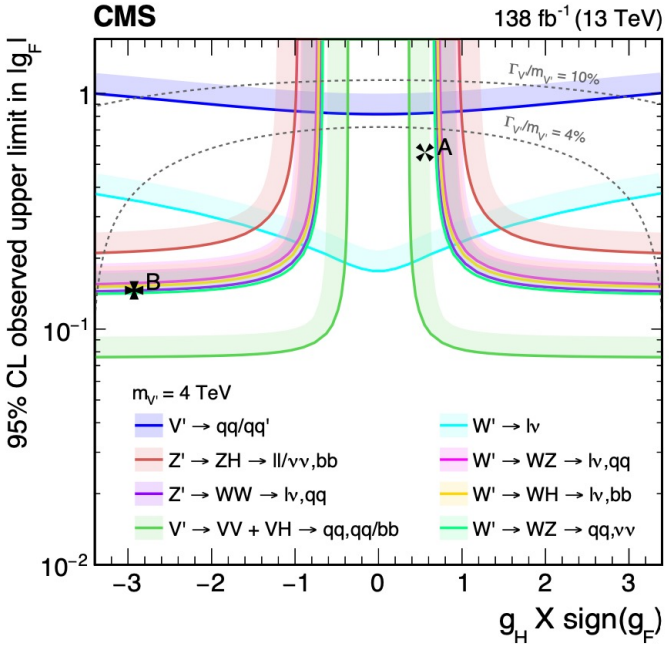


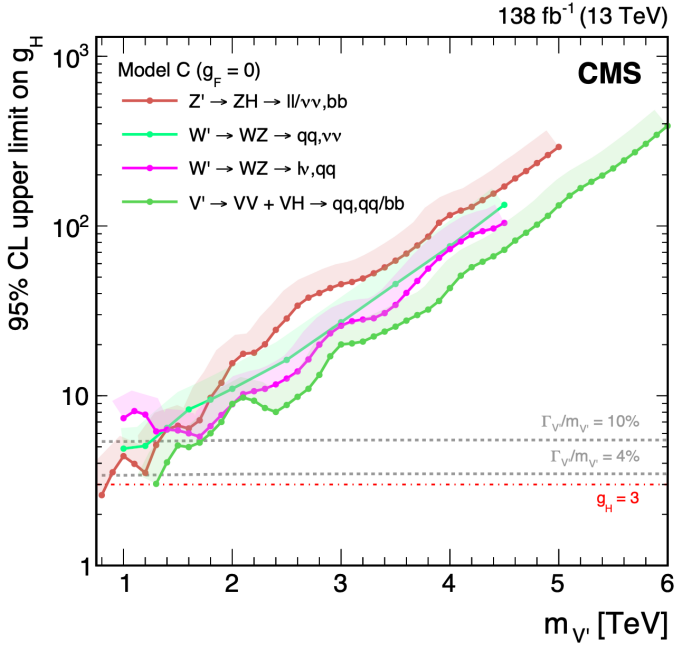
Searches for Higgs boson production through decays of heavy resonances

- Translation σ×BR limits in $X \to VV/VH$ searches to limits on g_F and g_H in HVT model

CMS-PAS-B2G-23-002

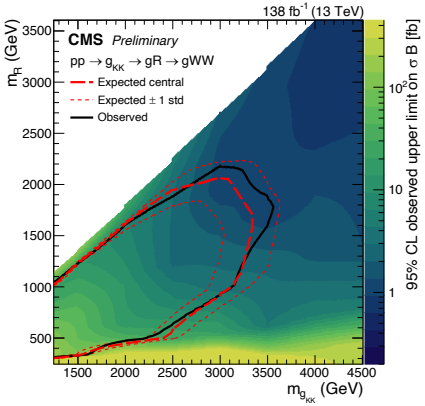
March 2024

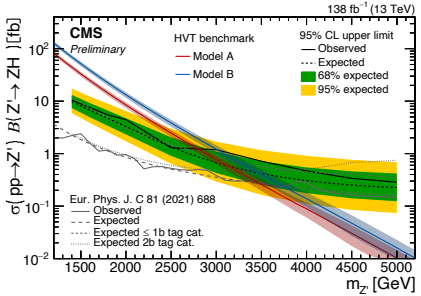


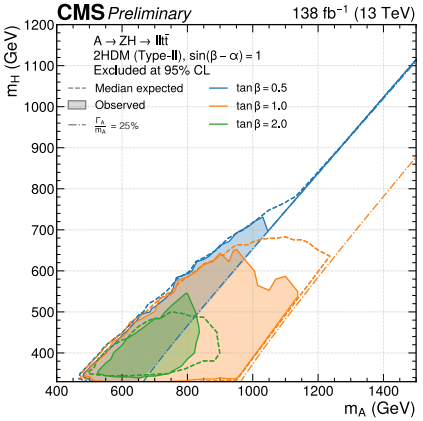


Summary

- Searches for BSM physics in diboson final states are an essential part of the CMS program
- Latest results
  - Search for Kaluza-Klein gluon resonances g_{KK} in a boosted trijet final state
  - Search for heavy resonances decaying to Zh with a single boosted jet
  - First search in the $A \to Z(l\bar{l})H(t\bar{t})$ hadronic channel – FOEWPT smoking gun
- Improved results with run III data in the working







Thank You!

Additional Material

Two-Higgs-doublet Model (2HDM)

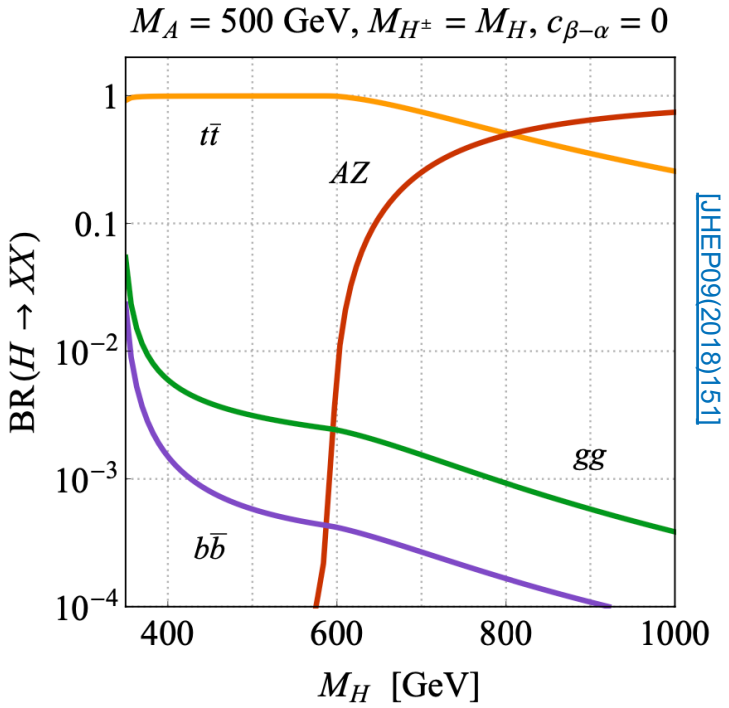
- The 2HDM introduces an additionall Higgs doublet to the SM
- General 2HDM: CP violating, contains FCNCs
    - Commonly constraints are placed on the model to avoid this
- Important free parameters
    - $\tan\beta = \frac{v_2}{v_1}$
    - $\cos(\beta - \alpha) \simeq 0$ (alignment limit)

α : Mixing angle between CP-even Higgses

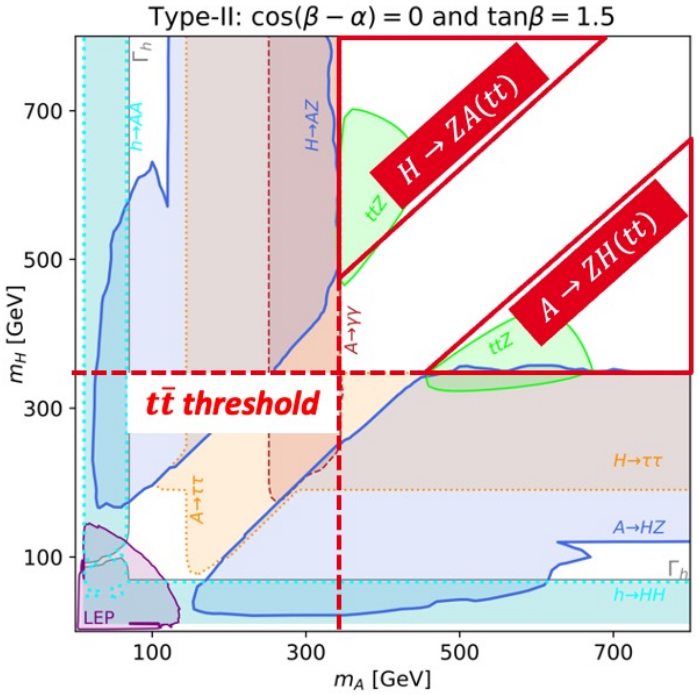
	Charge	*CP*	*Mass*
A	0	odd	?
H	0	even	?
h	0	even	$m_{h,SM} = 125$ GeV
$H^{\pm}$	± 1	-	m_A / m_H

- 4 types of the 2HDM with different fermionic couplings

$A \to Z(l\bar{l})H(t\bar{t})$: Channel



[JHEP09(2018)151]

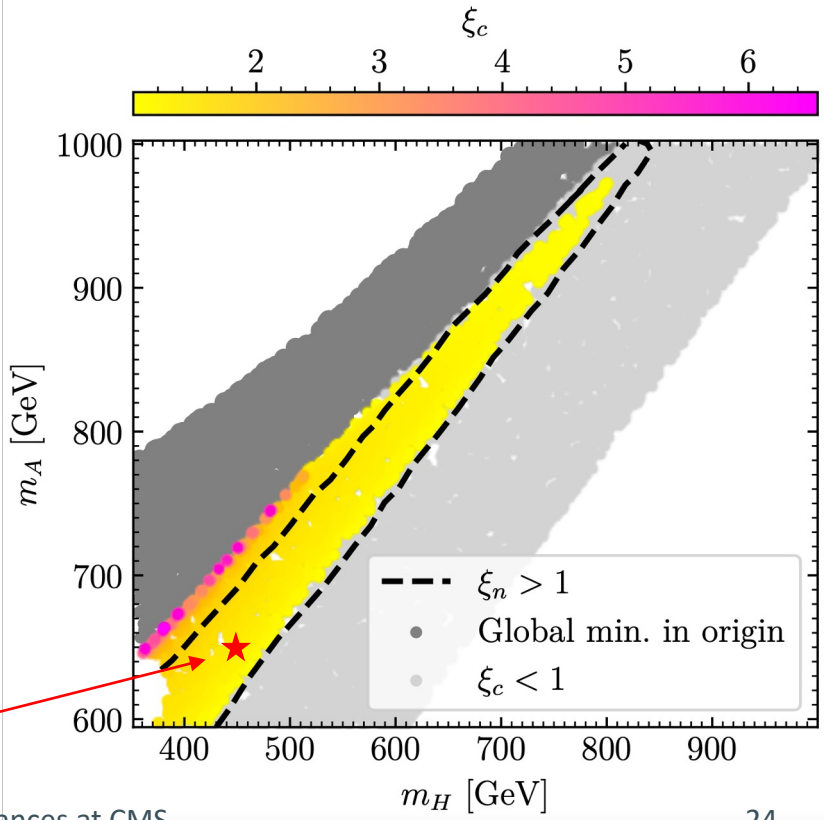


[JHEP06(2020)163]

$A \to Z(l\bar{l})H(t\bar{t})$: Smoking Gun for FOEWPT

- Baryon asymmetry of the Universe not explained by the SM, could arise from EW baryogenesis in the early Universe
- 2HDM configurations that facilitate EW baryogenesis require first order electroweak phase transition (FOEWPT)
- Interesting parameter region targeted in $A \to Z(l\bar{l})H(t\bar{t})$

Thomas Biekötter *et al* JCAP03(2023)031

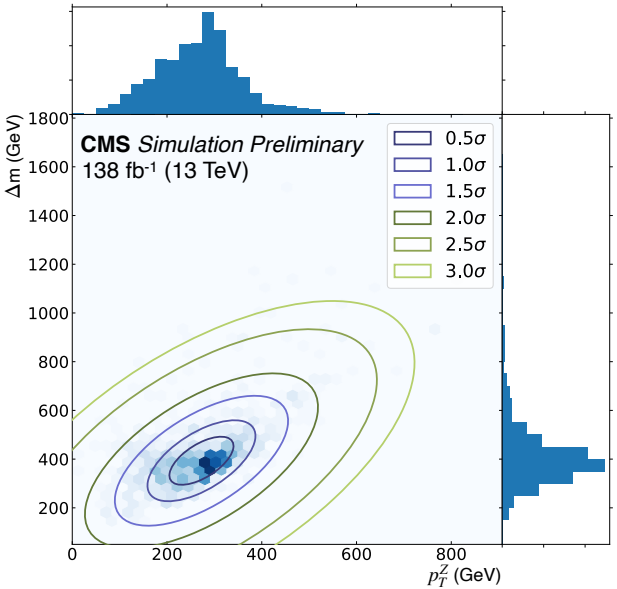


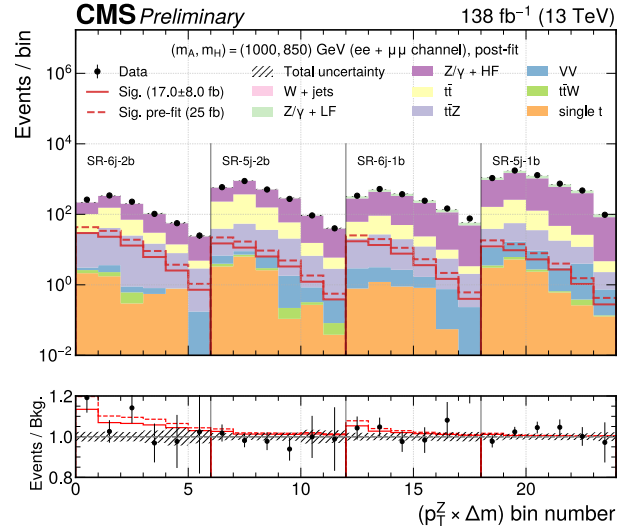
2.85 σ local excess in ATLAS search in multi lepton channel
[ATLAS-CONF-2023-034]

$A \to Z(l\bar{l})H(t\bar{t})$: Binning

CMS-PAS-B2G-23-006

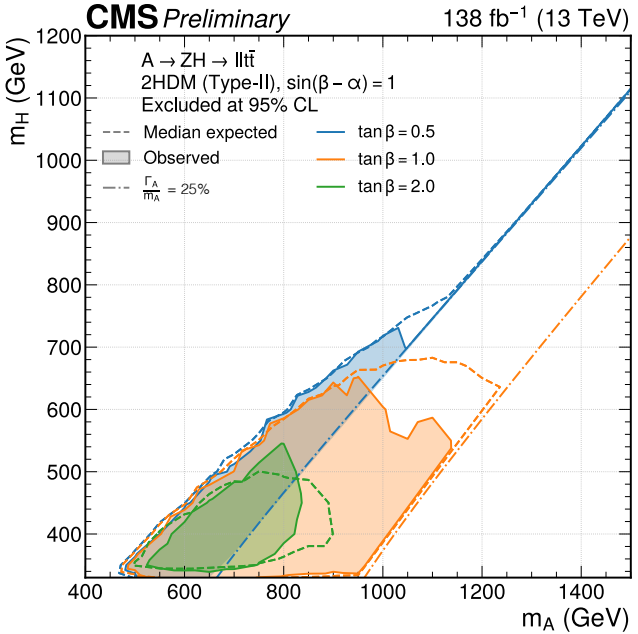
- Statistical analysis via binned maximum likelihood fit
  - *SR binning*: fit ellipses to the signal distribution in the $p_T(Z) \times \Delta m$ plane
  - *CR binning*: fit ellipses to the cumulative background distribution

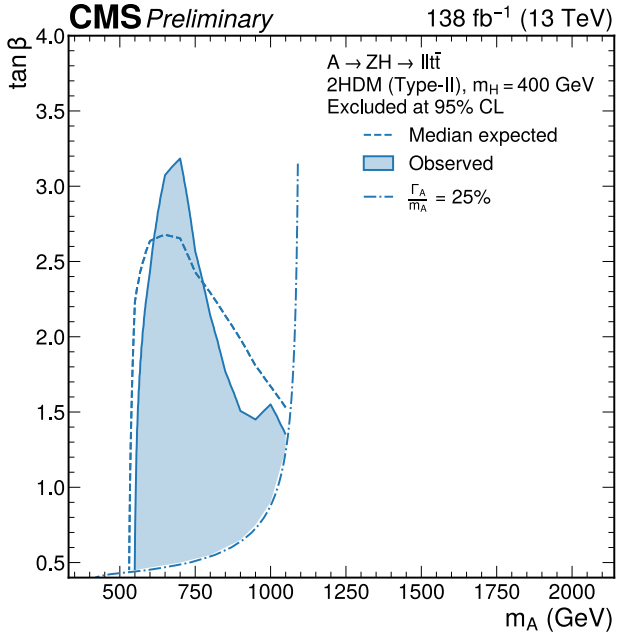


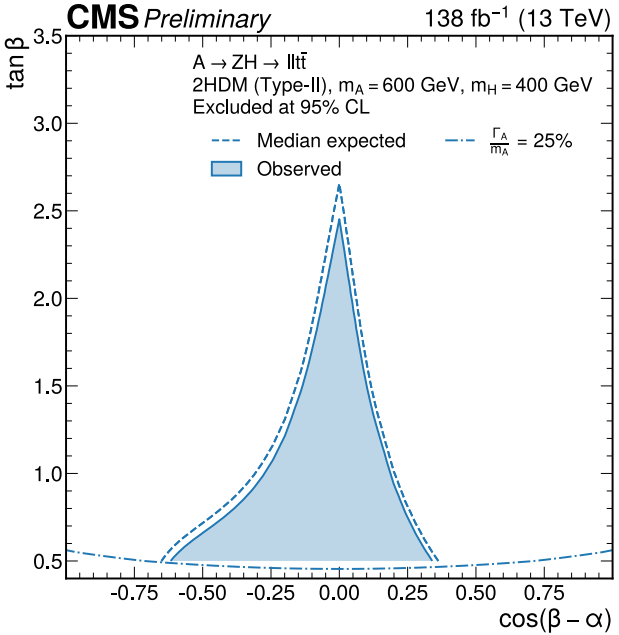


$A \to Z(l\bar{l})H(t\bar{t})$: 2HDM Interpretations

CMS-PAS-B2G-23-006







$g_{KK} \rightarrow gR \rightarrow gWW$: Definitions

CMS-PAS-B2G-23-004

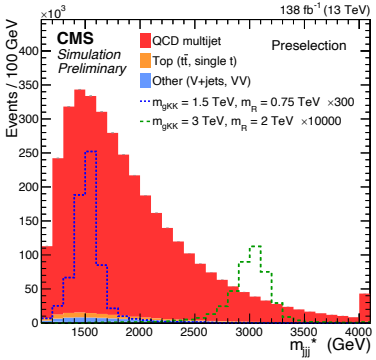
- Measure of compatibility of tagged jets with coming from a W boson

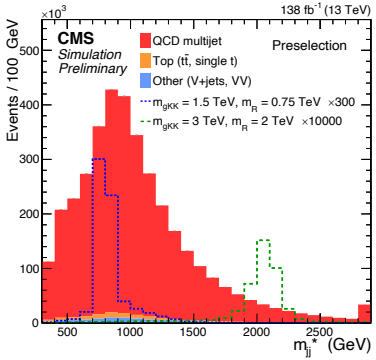
$$m_{85} \equiv \sqrt{(m_{ja} - 85\,\text{GeV})^2 + (m_{jb} - 85\,\text{GeV})^2}$$

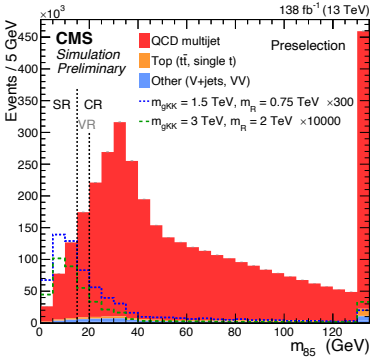
Region	m_{jj*}/m_{jjj*}	s_{jb} (2nd highest W tagger score)
SR1a	< 0.28	≥ 0.9
SR1b		0.8–0.9
SR2a	0.28–0.43	≥ 0.9
SR2b		0.8–0.9
SR3a	0.43–0.57	≥ 0.9
SR3b		0.8–0.9
SR4a	0.57–0.72	≥ 0.9
SR4b		0.8–0.9
SR5a	> 0.72	≥ 0.9
SR5b		0.8–0.9

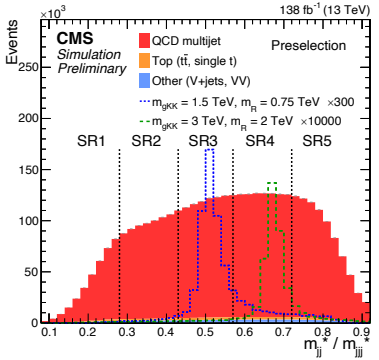
$g_{KK} \rightarrow gR \rightarrow gWW$: Distributions

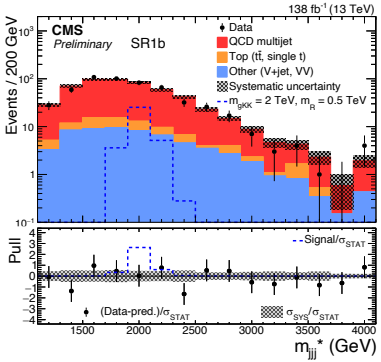
CMS-PAS-B2G-23-004

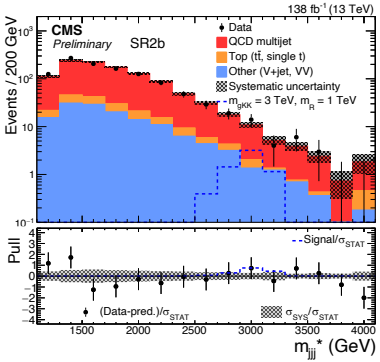


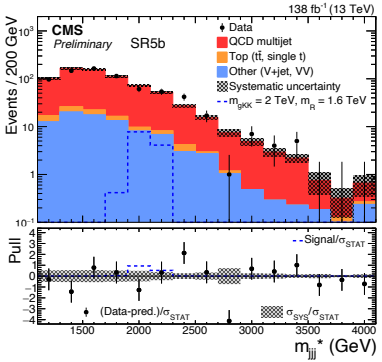












$g_{KK} \rightarrow gR \rightarrow gWW$: Systematic Uncertainties

CMS-PAS-B2G-23-004

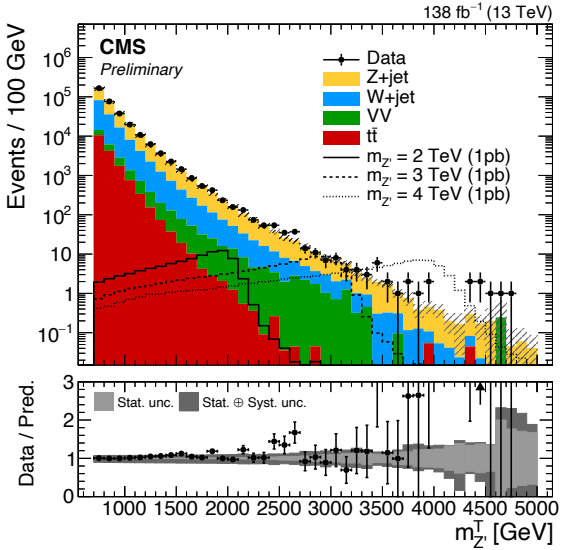
Uncertainty source	S or B	Effect on	Magnitude	Number of NPs & correlations
Normalization QCD	B	Rate	20%	10, uncorr. across SRs
Normalization Top	B	Rate	50%	10, uncorr. across SRs
Normalization Other	B	Rate	30%	10, uncorr. across SRs
QCD shape due to m_{90} usage	B	Shape	$\pm 1\sigma$ templates	10, uncorr. across SRs
QCD shape due to other processes	B	Shape	$\pm 1\sigma$ templates	10, uncorr. across SRs
PU reweight & luminosity	S	Rate	1.7%	1, correlated across all SRs
PDFs	S	Rate	$\leq 10\%$	1, correlated across all SRs *
QCD scales μ_F,μ_R	S	Rate	$< 0.8\%$	1, correlated across all SRs *
PNet selection eff. per jet (event)	S	Rate	6% (12%)	1, correlated across all SRs
JEC	S	Shape	$\pm 1\sigma$ templates	1, correlated across all SRs *
JER	S	Shape	$\pm 1\sigma$ templates	1, correlated across all SRs *

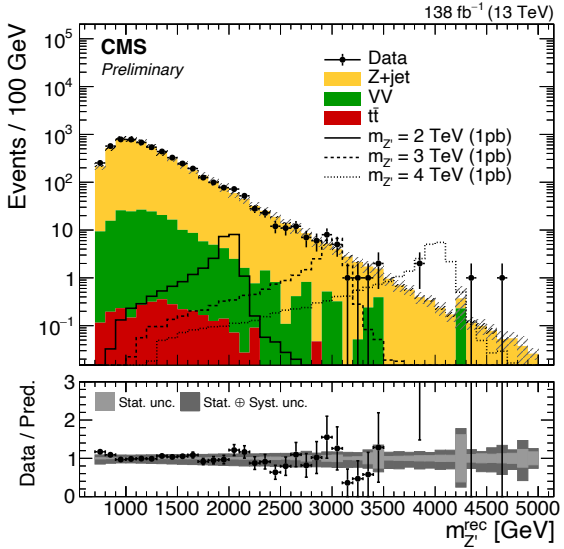
$Z' \rightarrow Zh$: Distributions

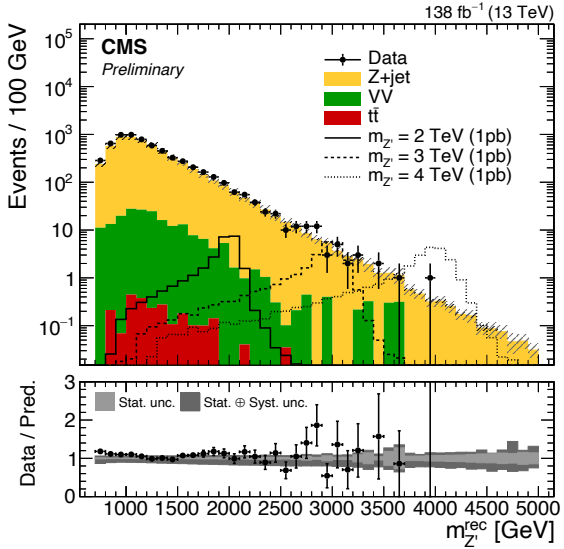
CMS-PAS-B2G-23-008

- Sensitive distribution in the neutrino channel transverse mass

$$m_{Z'}^{T} = \sqrt{2 p_T^H p_T^{miss} (1 - \cos \Delta\phi(H, \vec{p}_T^{miss}))}$$







$Z' \rightarrow Zh$: Systematic Uncertainties

CMS-PAS-B2G-23-008

Table 1: Sources of systematic uncertainties considered in this analysis, and their effect on the signal normalisation. The uncertainty ranges correspond to different signal masses.

Source	uncertainty	Source	uncertainty
H jet identification	2.0–5.0%	Trigger	0.9–1.5%
b tagging veto	0.4–1.0%	Muon identification	0.1–0.3%
Jet energy scale and resolution	0.2–2.0%	Electron identification	5.2–5.9%
Pileup	0.3–1.8%	Lepton reconstruction	0.9–1.7%
Luminosity	1.6%	PDF	0.3–13.4%
Prefiring	0.3–0.8%	QCD scales	6.6–17.2%

$Z' \rightarrow Zh$: HVT Interpretations

CMS-PAS-B2G-23-008

- The upper limits on the cross sections are translated into two-dimensional upper limits on the coupling parameters for fermions, $g_F = g^2 c_F / g_V$, and bosons $g_H = c_H g_V$ in the HVT model, where g is the $SU(2)_L$ gauge coupling.