Searches for New Resonances in CMS

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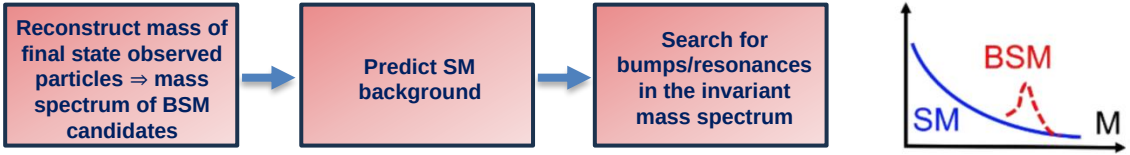
Introduction

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



- A selection of recent, full Run2 (2016 – 2018) CMS results will be discussed in this talk:
  - ✓ "**Search for VBF $Z' \to \tau\tau$ (WW)**" (CMS-EXO-21-015)
  - ✓ "**Search for DY $Z' \to \tau\tau$**" (CMS-EXO-21-016)
  - ✓ "**Search for BFF $Z' \to \mu\mu$ associated with b – jets**" (CMS-EXO-22-006)
  - ✓ "**Search for low mass boosted dijet resonances**" (CMS-EXO-24-007)
  - ✓ "**Search for paired dijet resonances**" (CMS-EXO-21-010)

Dark sector searches with the CMS experiment

Invisible	Visible	Long-lived
Mono-X	**Low-mass resonances**	**Displaced leptons**
Monojet (EXO-20-004)	Boosted dijet (EXO-18-012)	Displaced ee, emu, mumu (EXO-18-003)
Mono-Z (EXO-19-003)	Dijet + photon (EXO-17-027)	Displaced dimuons (EXO-21-006, EXO-23-014)
Monotop (EXO-16-051)	Boosted bbbar (EXO-17-024)	H to aa to 4mu (HIG-18-003)
Monophoton (EXO-16-053)	Dimuon including scouting (EXO-19-018)	Displaced dimuon scouting (EXO-20-014)
Mono-H (EXO-18-011)	Dimuon scouting (EXO-21-005)	**Hadronic LLP decays**
Dark Higgs (WW) + MET (EXO-21-012)	**High-mass resonances**	Displaced jets (EXO-19-021)
H to invisible	Dijet + ISR (EXO-19-004)	Displaced vertices (EXO-19-013)
VBF (HIG-20-003)	Dijet (EXO-19-012)	Emerging jets (EXO-18-001, EXO-22-015)
ttH/VH (HIG-21-007)	Dilepton (EXO-19-019)	Stopped particles (EXO-16-004)
Dark photons: ZH (EXO-20-005), VBF (EXO-19-007)	**Other signatures**	Muon detector showers (EXO-20-015, EXO-21-008)
Hidden Valley	Fractionally charged part. (EXO-19-006)	**LLP + p_T^{miss}**
Semivisible jets (EXO-19-020)	SUEPs, offline (EXO-23-002)	Inelastic DM (EXO-20-010)
	Stealth/RPV stops (SUS-19-004)	Delayed jets (EXO-19-001)
	ALPs in PbPb (FSQ-16-012)	Trackless and OOT jets (EXO-21-014)
	CEP w/ TOTEM (EXO-19-009)	Displaced vertices + MET (EXO-22-020)

CMS-EXO-23-005

- New **review paper on CMS Dark Sector searches** has been submitted recently in Physics Reports.

- The **impact of ~ 40 CMS analyses on the search for dark matter** are being reviewed, including **new results and re-interpretations**.
- **Couplings as low as 10^{-5}** and **mass ranges between ~1 GeV and a few TeV** have been investigated.
  - No signal observed but large regions of the model parameter space excluded.
- Among these **are searches for low and high mass resonances**.

Search for VBF $Z' \to \tau\tau$ (WW)

CMS-EXO-21-015

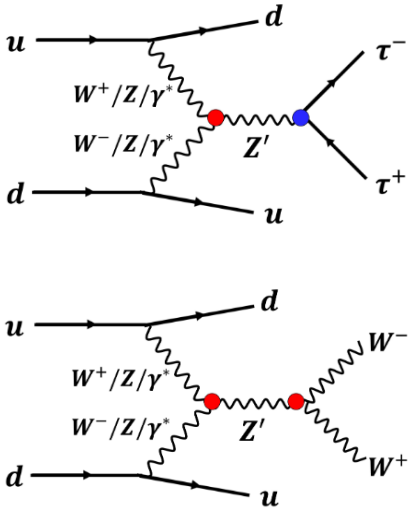
Signal model:

- **Heavy neutral spin-1 gauge boson (Z')** produced via **vector boson fusion** (VBF) processes.
- Two decay modes: $Z' \to \tau\tau$ and $Z' \to WW$
- **Non-universal fermion couplings, favouring higher-generation fermions**.

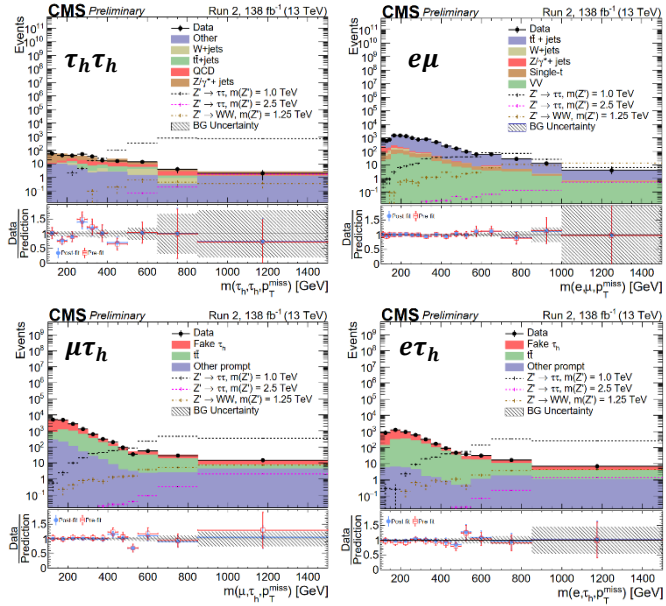
Experimental signature:

- **Four final states** considered: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$
- Two forward jets from **unique VBF topology** → allows significant **background rejection** (QCD)
  - Dijet invariant mass > 500 GeV
  - $\eta_{j1}\eta_{j2} < 0$, $|\Delta\eta(j1, j2)| > 4.2$

First ever search for Z' production through VBF at the LHC



Search for VBF $Z' \to \tau\tau$ (WW)



CMS-EXO-21-015

Bump hunt in $m(\ell_1, \ell_2, p_T^{miss})$ spectrum

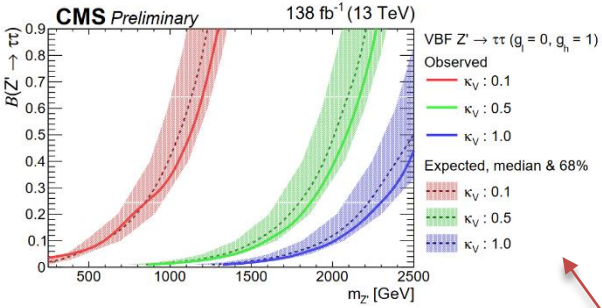
Dominant backgrounds:

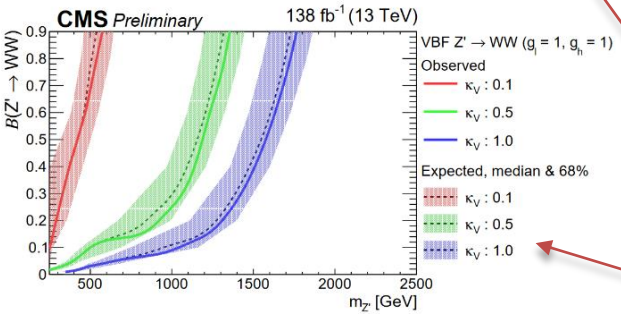
- **Depend on the final state → Jets faking τ_h or genuine τ_h**
  - **W/Z + jets**
  - **$t\bar{t}$ production**
  - **QCD multijets**

Background prediction:

- **Major backgrounds** in each channel are estimated **from data**.
  - Dedicated data CRs
  - ABCD method
- Smaller backgrounds estimated with use of simulation.

Search for VBF $Z' \to \tau\tau$ (WW)





CMS-EXO-21-015

Results:

- **No deviations from SM predictions**.
- **Upper cross section** and **exclusion limits** derived for **different signal scenarios**.
  - Varying **coupling to SM weak bosons** ($g_{Z'VV} = \kappa_V g_{ZVV}$)
  - **Coupling** to **1st and 2nd generation** fermions ($g_{Z'f\bar{f}} = g_l g_{Zf\bar{f}}$)
  - **Coupling** to **3rd generation** fermions ($g_{Z'f\bar{f}} = g_h g_{Zf\bar{f}}$)

Non-universal fermion coupling (NUFM)

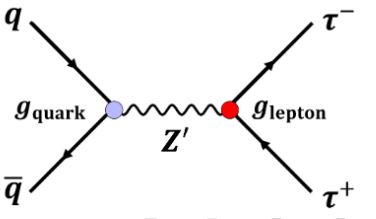
Universal fermion coupling

Search for DY $Z' \to \tau\tau$

Signal model:

- Z' produced via **quark-antiquark fusion** processes.
- Explore models with **non-universal couplings to fermions**, by probing $Z' \to \tau\tau$ decays.

CMS-EXO-21-016



Experimental signature:

- **Three final states** considered: $\tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$

Veto events from VBF processes → complementary and orthogonal to CMS-EXO-21-015

Process	$\tau_\mu\tau_h$ Events	%	$\tau_e\tau_h$ Events	%	$\tau_h\tau_h$ Events	%
W + jets	851 ± 86	24	717 ± 89	30	158 ± 16	10
DY	1315 ± 70	37	661 ± 34	28	920 ± 43	55
$t\bar{t}$	637 ± 21	18	468.1 ± 8.1	20	32.8 ± 1.6	2
Single t	157.4 ± 6.0	5	116.1 ± 5.4	5	5.5 ± 1.2	<1
VV	302.4 ± 7.7	9	247.5 ± 6.0	11	26.8 ± 1.8	2
QCD multijet	251 ± 44	7	135.0 ± 8.0	6	514 ± 27	31
Total background	3514 ± 122	100	2345 ± 96	100	1658 ± 53	100
Data	3737		2269		1549	

Dominant backgrounds:

- Depend on the final state.
- **QCD multijets** → **data-driven** prediction with **ABCD method**.
- **DY, W + jets, VV, $t\bar{t}$, single top** → prediction from **simulation** using SFs from CRs.

Search for DY $Z' \rightarrow \tau\tau$

CMS-EXO-21-016

Analysis strategy:

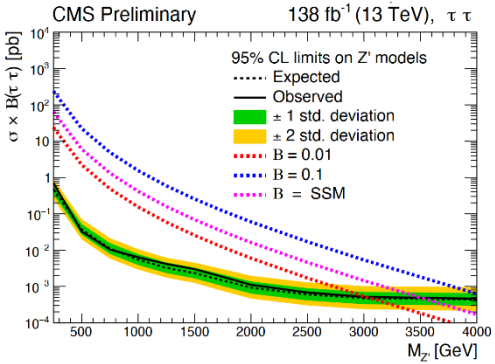
- A **shape-based analysis** is performed using the reconstructed mass of the Z' candidate:

$$m_{rec}(Z') = \sqrt{(E_1^{\tau\,vis} + E_2^{\tau\,vis} + |\boldsymbol{p}^{Z'miss}|)^2 - (\boldsymbol{p}_1^{\tau\,vis} + \boldsymbol{p}_2^{\tau\,vis} + \boldsymbol{p}^{Z'miss})^2}, \quad \boldsymbol{p}^{Z'miss} = (-(\vec{p}_{1T}^{\,\tau\,vis} + \vec{p}_{2T}^{\,\tau\,vis}), 0)$$

- The $\boldsymbol{m_{rec}(Z')}$ **distribution** is used as the **fit discriminant** to determine the likelihood of observing signal in the presence of the predicted background rate.

Results:

- **No deviations from SM** predictions found.
- Set upper cross section limits on $\sigma B(Z' \rightarrow \tau\tau)$ vs $m(Z')$.
- **Exclude a Z' with mass less than 3, 3.5, and 4.1 TeV for BF of 1%, 3.37% (SM), and 10% respectively**.
- These exclusion limits are **the most stringent to date for $Z' \rightarrow \tau\tau$**.



Search for BFF $Z' \to \mu\mu$ associated with b – jets

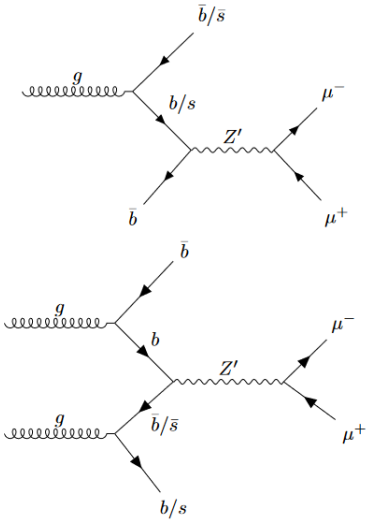
CMS-EXO-22-006

🔥**Brand new results!** 🔥

Signal model:

- **Heavy neutral, spin-1, gauge boson (Z')**
- **Non-universal flavour production** (narrow resonance) via bottom quark (g_b) or bottom-strange quark ($g_b \delta_{sb}$) coupling (**Bottom Fermion Fusion** – BFF).
- **$Z' \to \mu\mu$ only, no couplings to electrons or taus**.

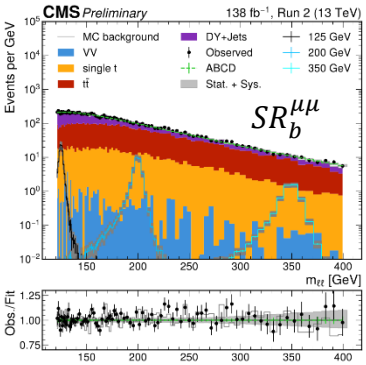
- $m(Z')$ range **between 125 and 350 GeV** probed.
  - Complementary to **CMS-EXO-22-016** that probes masses between 350 GeV and 2 TeV.
  - Complementary to **CMS-EXO-21-015** & **CMS-EXO-21-016** ($\tau\tau/WW$ final states)

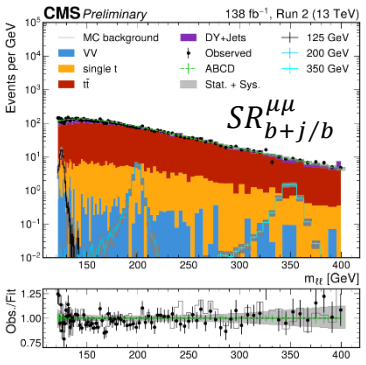


Experimental signature:

- **Di-muon final state associated with at least one b – jet**:
  - $SR_b^{\mu\mu}$ (1-jet category)
  - $SR_{b+j/b}^{\mu\mu}$ (2-jet category)

Search for BFF $Z' \to \mu\mu$ associated with b – jets





CMS-EXO-22-006

🔥**Brand new results!** 🔥

- Mass dependent selection cuts to maximize sensitivity.

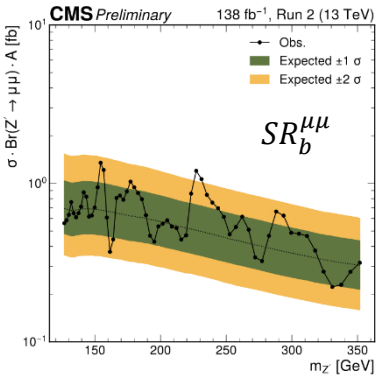
Cut	**1j**
$p_{\mathrm{T}}^{\mathrm{miss}}/m_{\mu\mu}$	$< 223 \cdot (m_{\ell\ell})^{-1.23}$
$H_T - L_T$	$< -0.43 \cdot m_{\ell\ell} + 47$
Cut	**2j**
$p_{\mathrm{T}}^{\mathrm{miss}}/m_{\mu\mu}$	$< 67 \cdot (m_{\ell\ell})^{-1.04}$
$H_T - L_T$	$< -0.56 \cdot m_{\ell\ell} + 124$

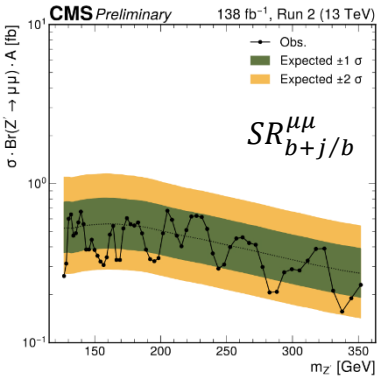
Dominant backgrounds & prediction:

- **DY at lower dilepton masses, $t\bar{t}$ at higher**.
- **Fully data-driven background prediction with ABCD method:**
  - Construct CRs with di-electron and non b – jet final states.
  - Fit the CRs with log-norm function to smoothen the prediction.

N_{b}	$N_{\mathrm{jets}}^{\mathrm{all}}$	$\mu\mu$	ee
≥ 1	2	$SR_{b+j/b}^{\mu\mu}$	$CR_{b+j/b}^{ee}$
0	2	$CR_{j+j}^{\mu\mu}$	CR_{j+j}^{ee}
1	1	$SR_{b}^{\mu\mu}$	CR_{b}^{ee}
0	1	$CR_{j}^{\mu\mu}$	CR_{j}^{ee}

Search for BFF $Z' \to \mu\mu$ associated with b – jets





CMS-EXO-22-006

🔥**Brand new results!** 🔥

Limits between 125 and 200 GeV are the only ones in Run2.

Limits between 200 and 350 GeV are the most stringent on this set of production modes.

Results:

- Simultaneous maximum likelihood fit across data-taking years in both jet multiplicity categories to extract any potential signal contributions.
- **No significant deviation from background expectation**.
- Highest excess at ~230 GeV in $SR_b^{\mu\mu}$ not statistically important (**only 0.3σ global significance)**.
- Set **model independent limits** separately in the two categories.
  - Avoid assumptions on the mix of processes.

Search for low mass boosted dijet resonances

CMS-EXO-24-007

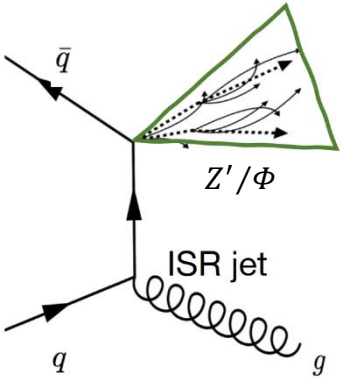
🔥**Brand new results!** 🔥

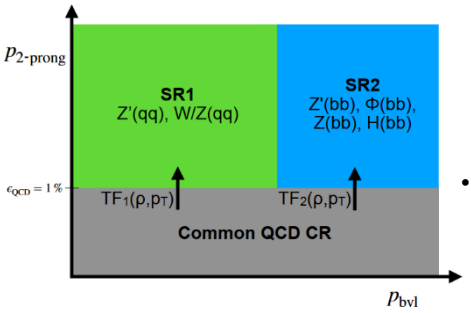
Signal model:

- Low mass **vector (Z')** and **scalar (Φ)** resonances which **couple directly to quark-antiquark pairs**.

Experimental signature:

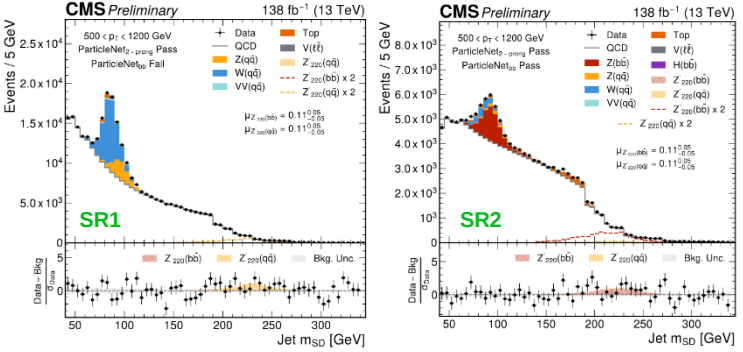
- **Low mass boosted dijet with large ISR**, reconstructed as a **large-radius jet with 2-prong substructure**.
- **High p_T (> 500 GeV) jet** → meet trigger thresholds → probe low masses → **unique sensitivity for $m \leq 300$ GeV**





- Leading **graph-based jet tagger in CMS** (ParticleNET) **identifies 2-prong substructure**.
  - ➢ Further categorization to **light quark (SR1)** and **b −quark (SR2)** decays.

Search for low mass boosted dijet resonances



CMS-EXO-24-007

🔥**Brand new results!** 🔥

Dominant backgrounds & prediction:

- **QCD multijet (~85%)** → **Data-driven** estimation using **differential ABCD method**

Prediction of QCD entering SR in bin *i*

Ratio of QCD in SR/CR (~1%)

Polynomial in (m_{SD},p_T) parametrizing residual data-MC QCD differences *in situ*

$$N_{\mathrm{SR}}^{i} = N_{\mathrm{CR}}^{\mathrm{data},i}\, R_{\mathrm{SR/CR}}^{\mathrm{MC},i}\, TF_{\mathrm{MC}}(p_T^i, \rho^i)\, TF_{\mathrm{res}}(p_T^i, \rho^i)$$

Number of data events in CR in bin *i*

Polynomial in (m_{SD},p_T) parametrizing residual sculpting in QCD MC

$$TF(p_T,\rho) = \sum_{k=0}^{n_\rho}\sum_{l=0}^{n_{p_T}} a_{k,l}\left[b_{k,n_\rho}(\rho) b_{l,n}(p_T)\right] \quad , \; b_{\nu,n}(x) = \binom{n}{\nu} x^\nu (1-x)^{n-\nu}$$

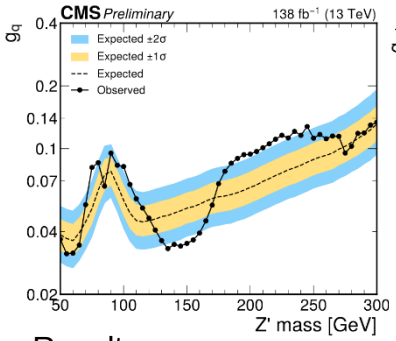
$$\rho = 2log\left(\frac{m_{SD}}{p_T}\right)$$

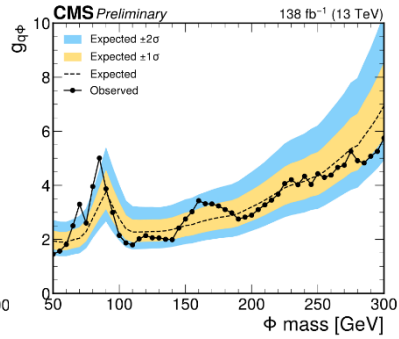
- $W/Z\,(qq)$, $Z(b\bar{b})$ **(~13%)** $t\bar{t}$**, single top (~2%)**
  - Estimated from **MC**.

Analysis strategy:

- Main observable: **jet soft-drop mass (m_{SD})** → invariant mass of the jet constituents after removing soft and wide-angle radiation.
- **Simultaneous fit across 5 p_T bins, quark flavor categories (SR1, SR2) and Run2 years**.

Search for low mass boosted dijet resonances



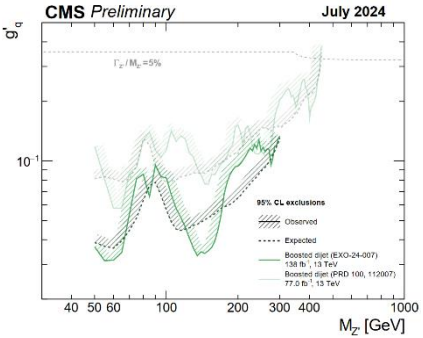


CMS-EXO-24-007

Brand new results!

Set limits on
- Z' coupling to quarks (g_q)
- coupling parameter ($g_{q\Phi}$) of Φ to quarks.

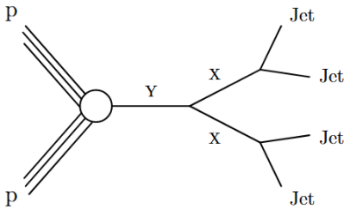
EXO summary plots

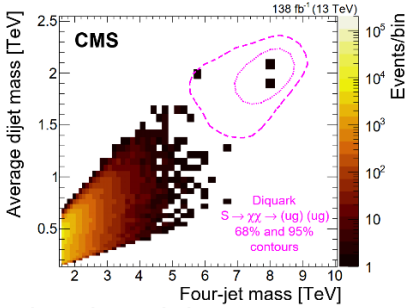


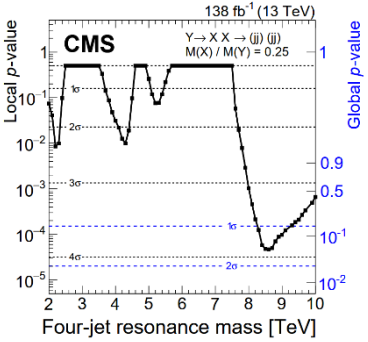
Results:

- **Good agreement with SM expectation** → largest deviation yields $< 3\sigma$ (2σ) local (global) significance.
- **Large improvement** over **CMS-EXO-18-012** **($Z'(qq)$ + jet)** and **CMS-EXO-17-024** **($\Phi(bb)$ + jet)**:
  - Luminosity scaling (full Run2 data)
  - Integration of latest/greatest jet tagger
  - Simultaneous sensitivity to light and heavy decays
- **Leading limits on Z'/Φ in mass range of $50 - 300$ GeV.**

Search for paired dijet resonances







CMS-EXO-21-010

Experimental signature:

- **Four resolved jets, forming two equal mass dijet pairs**.

Dominant background:

- QCD multijet production

Signal model:

- Massive scalar diquark decaying to a pair of vector-like quarks, each decaying to a ug pair.

Background prediction:

- Four-jet mass is fitted simultaneously in bins of $\bar{m}_{jj}/m_{4j}$ with **multiple parametric functions**, utilizing the **discrete profiling method** (envelope).

Results:

- **Largest excess corresponds to the two isolated events at $\sim$ 8 TeV: 3.9σ (1.6σ) local (global) significance.**

Summary

- **Searches for low and high mass resonances** were presented:
  - **No significant deviations from SM** so far, except for an **interesting excess at 8 TeV in the paired dijet analysis** that is being followed up with Run3 data.
  - Try to **maximize the discovery potential** (limits in case of no excess) in each channel (e.g. in different production modes and masses of Z').
  - **Probe previously unexplored regions and new final states**.

- Aim for **maximum sensitivity**:
  - Data driven background predictions wherever possible.
  - New methods, ML techniques (see talks from Javier M. Duarte and Manuel Sommerhalder).

- **Review paper on dark sectors**:
  - Covering Run1 to Run3 analyses.
  - New results, combination of already existing ones and re-interpretations.

- Hopefully, **Run3 data and HL-LHC** will allow us to **fully exploit the discovery potential**.

Thank you for your attention!

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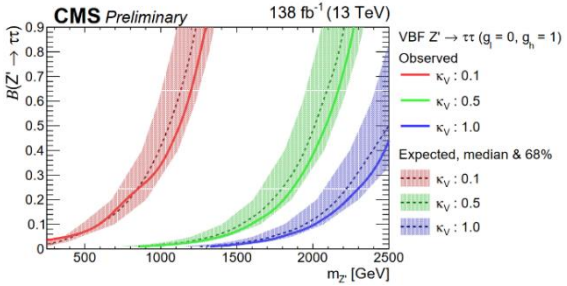
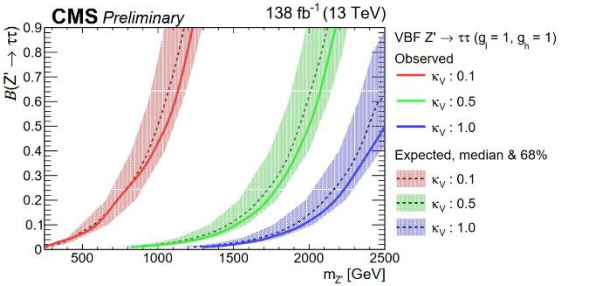
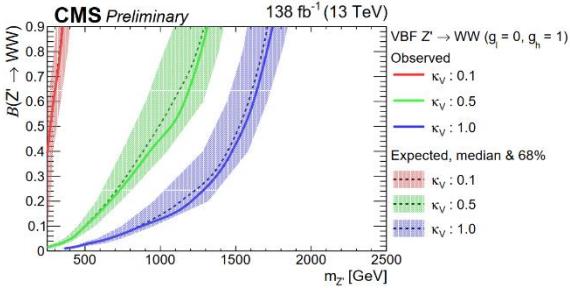
Back up slides

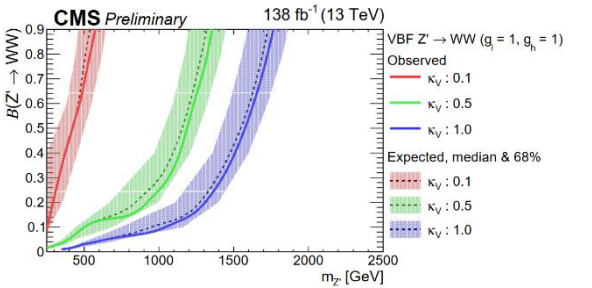
Search for VBF $Z' \to \tau\tau$ (WW)

CMS-EXO-21-015



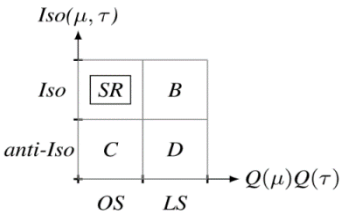




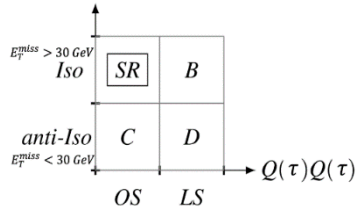


Search for DY $Z' \to \tau\tau$

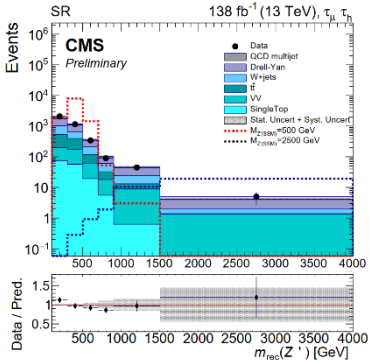
$\tau_\ell\tau_h$ channel

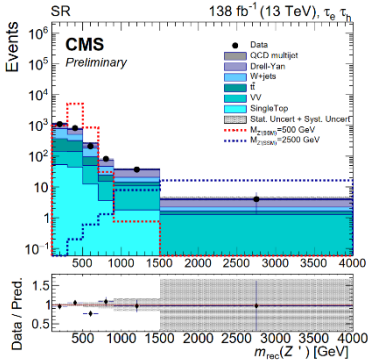


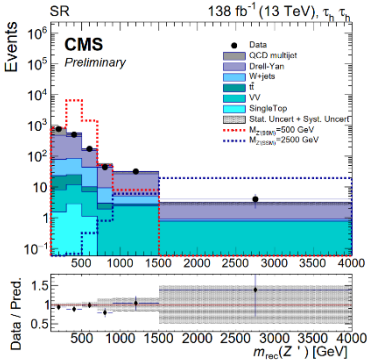
$\tau_h\tau_h$ channel



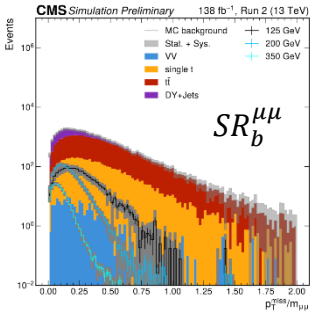
CMS-EXO-21-016

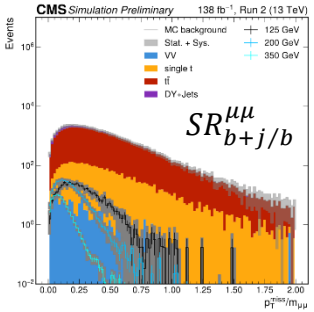


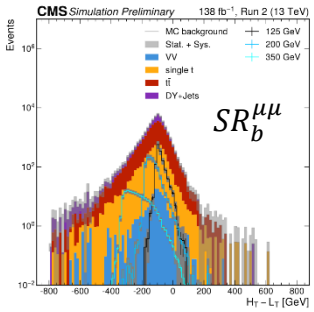


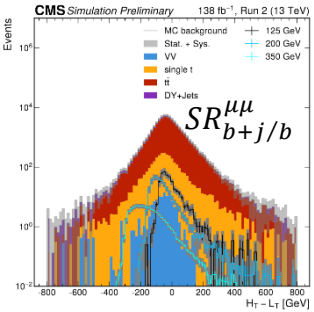


Search for BFF $Z' \to \mu\mu$ associated with b – jets







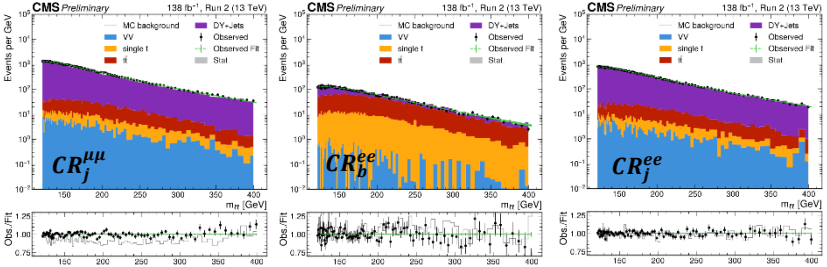


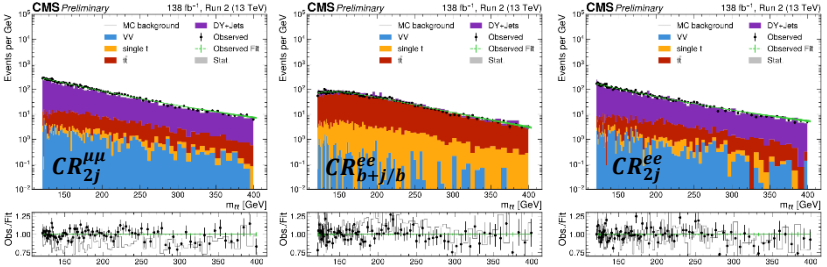
CMS-EXO-22-006

BFF cuts:

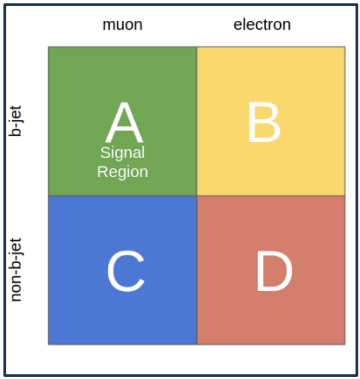
- Signal characterized by low p_T^{miss} and hadronic activity.
- $p_T^{miss}/m_{\mu\mu}$: suppresses $t\bar{t}$ due to real neutrinos
- $H_T - L_T$: Scalar sum of hadronic minus leptonic p_T, SM backgrounds (DY and $t\bar{t}$) prefer balanced types of momenta

Search for BFF $Z' \to \mu\mu$ associated with b – jets





CMS-EXO-22-006



Search for $Z' \to \mu\mu$ associated with b – jets (high mass)

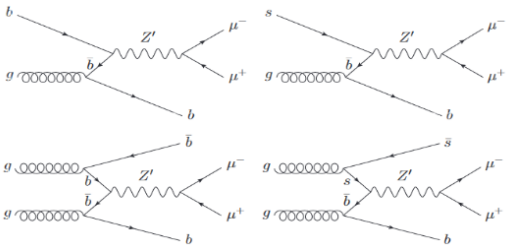
CMS-EXO-22-016

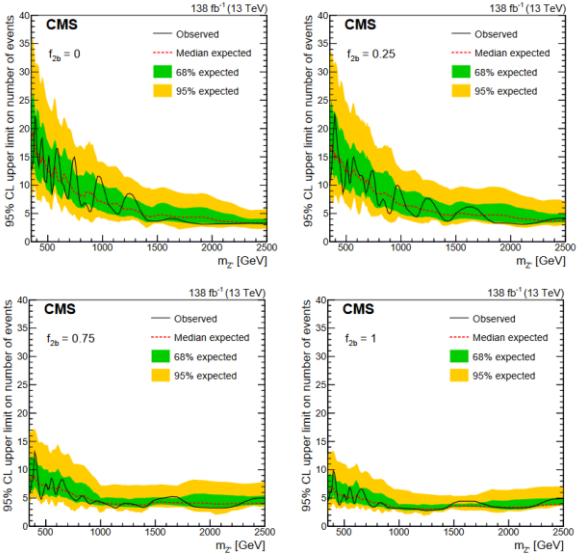
Signal model:

- BSM **neutral vector boson Z'** with $m(Z') \in [0.35, 2.5]$ TeV
- **Z' coupling to b and s**.

Experimental signature:

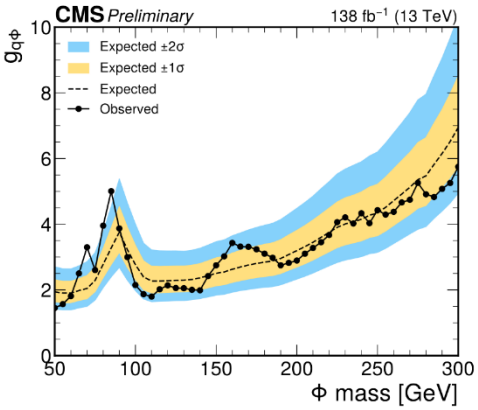
- **High p_T dimuon pair** in the final state with **at least 1 tight b-jet.**
- $N_b = 1, N_b \geq 2$ categories.
- **f_{2b}** = relative fraction of signal events with $N_b \geq 2$

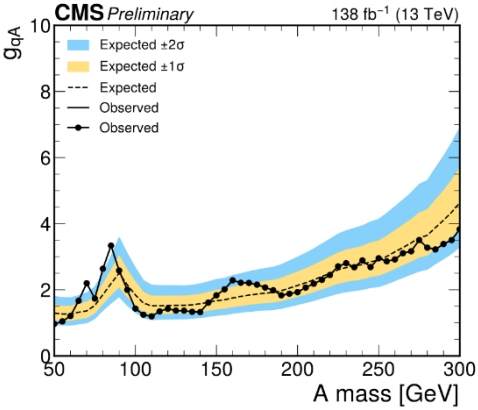




Search for low mass boosted dijet resonances

CMS-EXO-24-007

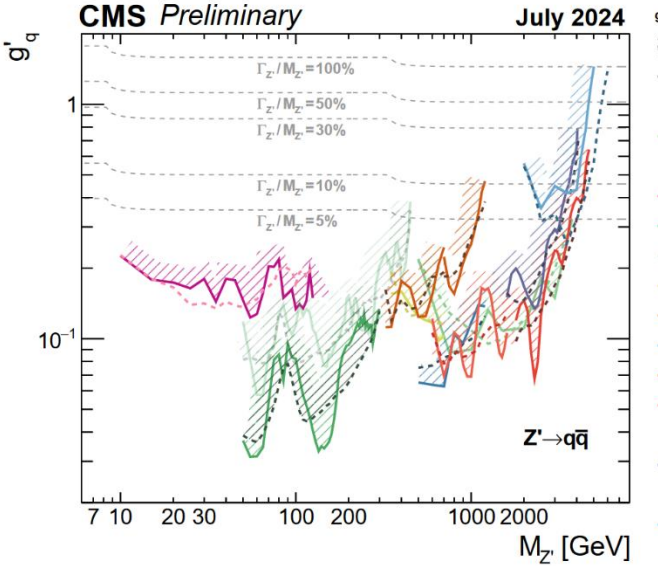


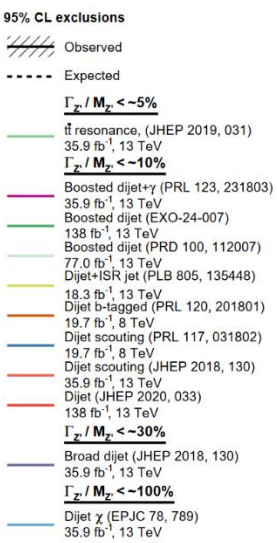


- The scalar (Φ) and pseudoscalar (A) bosons couple to quarks with a coupling given by $g_{q\Phi}$ and g_{qA} times the SM Yukawa couplings, respectively, and decay dominantly to $b\bar{b}$.

Dijet summary plot

EXO summary plots

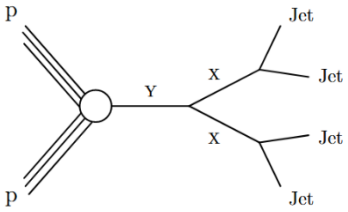


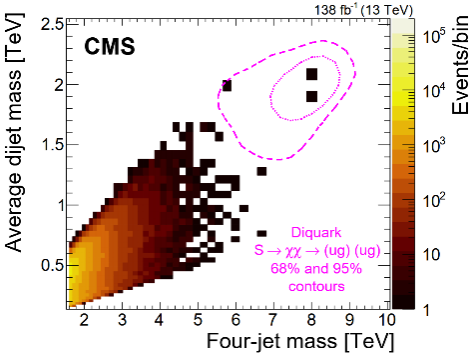


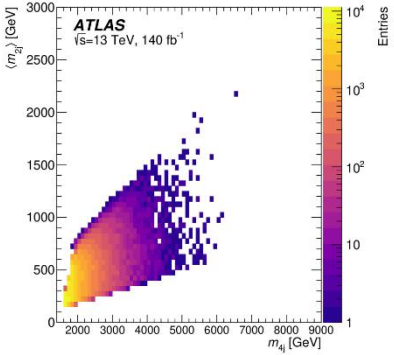
Search for paired dijet resonances

CMS-EXO-21-010

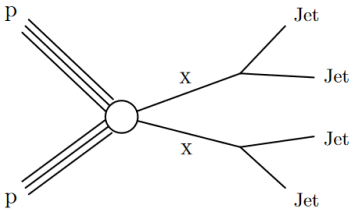
- Currently, **Run3 data are being analyzed**.
- **Interesting isolated event recorded by the ATLAS experiment** (10.1103/PhysRevD.108.112005).
  - Motivated by this ATLAS event, and the 3rd isolated CMS event at ~6 TeV, the analysis is being extended by searching for **broader resonances** as well.

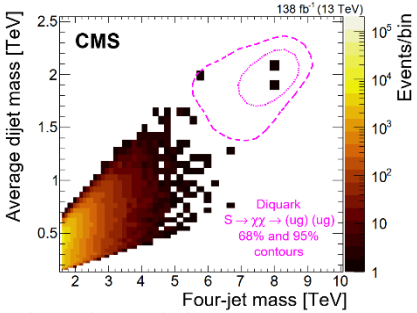


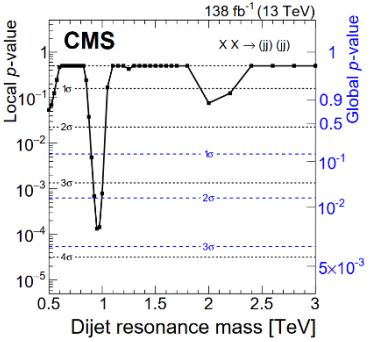




Search for paired dijet resonances (non-resonant part)







CMS-EXO-21-010

Experimental signature:

- **Four resolved jets, forming two equal mass dijet pairs**.
- Non-resonant in four-jet mass but **resonant in average dijet mass**.

Signal model:

- Pair production of RPV top squarks, each decaying to a pair of ds quarks.

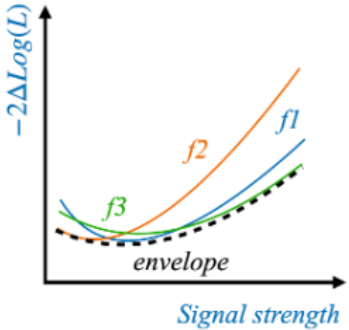
Background prediction:

- Average dijet mass is fitted simultaneously in bins of $\overline{m}_{jj}/m_{4j}$ with **multiple parametric functions**, utilizing the **discrete profiling method** (envelope).

Results:

- **Largest excess corresponds to a resonance mass of 0.95 TeV : 3.6σ (2.5σ) local (global) significance.**

Discrete profiling method



- The envelope method considers the choice of the functional form as a discrete nuisance parameter, which is profiled in an analogous way to continuous nuisance parameters.
- An envelope of the NLL curves is created that considers all different background function forms.
- The NLL minimization can dynamically switch between the (three) possible functional forms as a function of signal strength.