BSM Physics at CMS, status and perspectives

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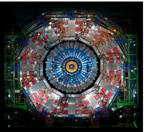
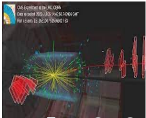
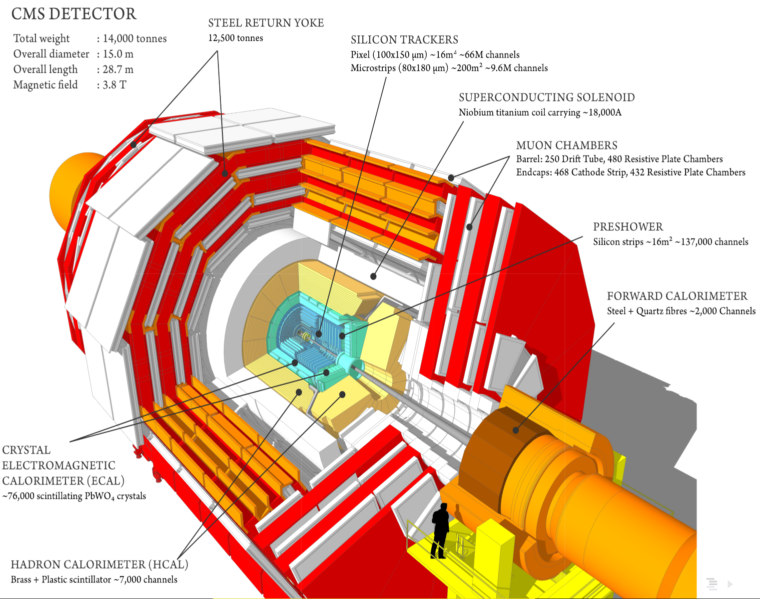
On Behalf of the CMS Collaboration





The CMS Detector



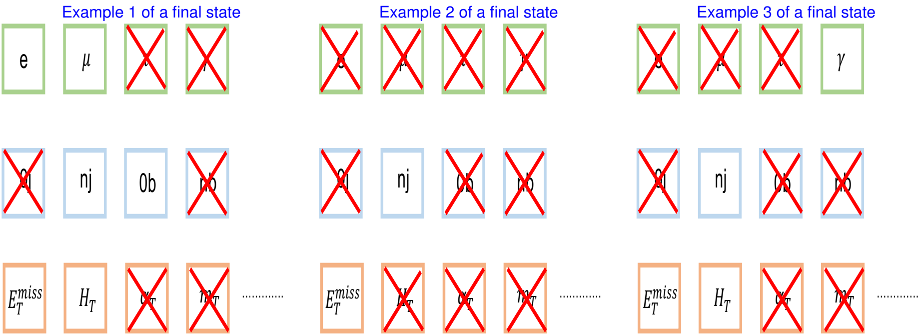
What do we search for?

- Depending on the signal model, we search for different combinations of leptons, photons, jets and, b-jets.
- We also use characteristics of each event to discriminate possible signals from SM processes: displaced vertices, missing transverse momentum (energy) E_T^{miss}, etc.
- In addition, we reconstruct observables based on the topology of the signal process under study: H_T, m_T, α_T etc.

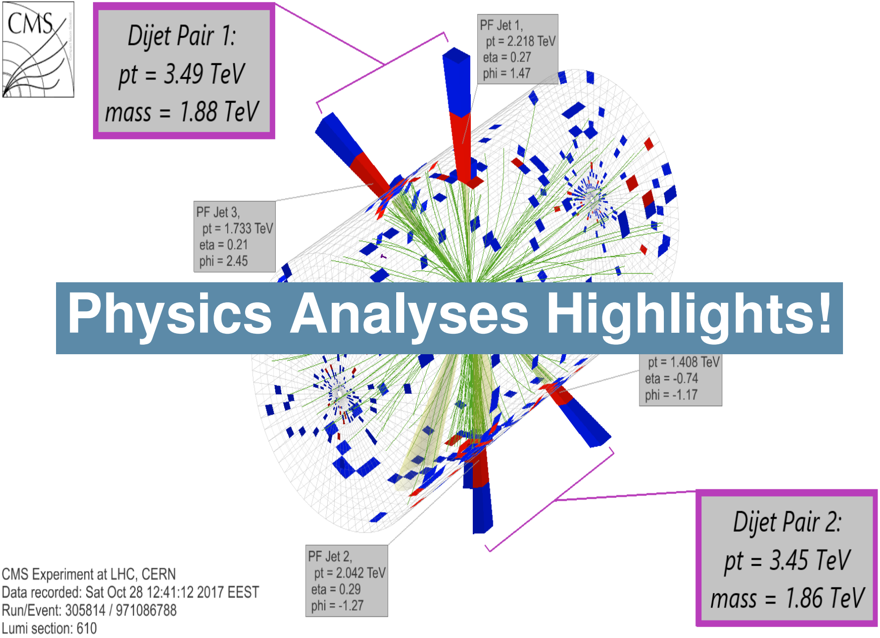
X number of leptons and or photons	e	μ	τ	γ	
Veto jets (j) and/or b-jets (b) and/or select nj or nb jets	0j	nj	0b	nb	
Use some observables based on the topology of the event	E_T^{miss}	H_T	α_T	m_T	....

What do we search for?

- As a general rule of thumb, we search for an enhancement of events with respect to the expected background processes from the SM.
- If there is agreement between the background expectation and the observed data, limits are set at 95% CL on the production cross section of such models.



Physics Analyses Highlights!

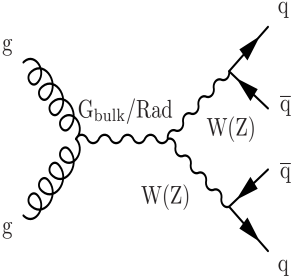


Resonant and Non-Resonant Production of New Particles

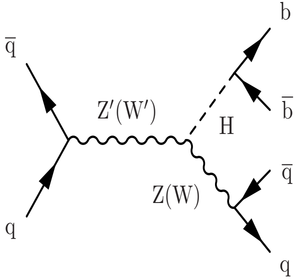
Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH pairs in all-jets final states - Submitted to Phys. Lett. B

Resonances decaying to a VV or VH boson pair with masses above 1.3 TeV, using 138 fb^{-1} of luminosity and $\sqrt{s} = 13\ \mathrm{TeV}$

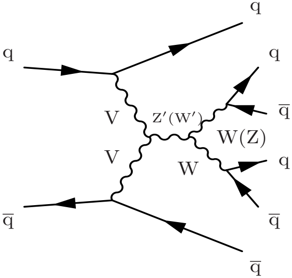
gg produced graviton or radion decaying to WW or ZZ



$\mathrm{q\bar{q}}$ produced $\mathrm{Z'}$ decaying to HZ

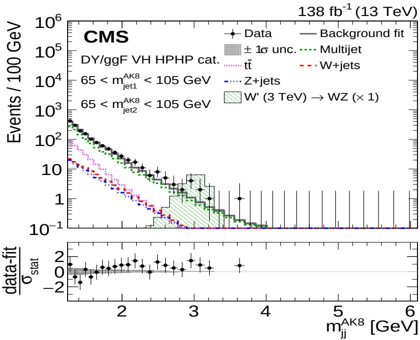


VBF produced $\mathrm{Z'}$ and $\mathrm{W'}$ decaying to WW and WZ



Analysis details

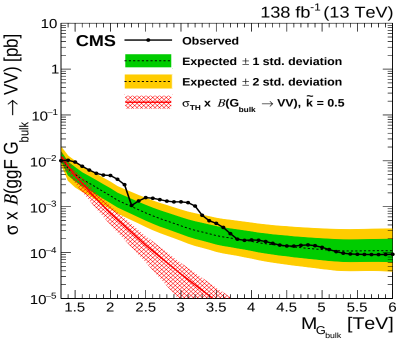
- Each boson decay is clustered as a single large-radius jet.
- We search for two large-radius jets (R = 0.8) with $p_T > 200$ GeV and $|\eta| < 2.5$. For VBF production two additional jets (R = 0.4) are considered ($p_T > 30$ GeV, $|\eta| < 5.0$, and $|\Delta\eta^{AK4}| > 4.5$).



- *DY*/ggF VH: Excess of data events in the 1.7–3.2 TeV range.
- *DY*/ggF VV: Excess of data events in the 2.0–3.0 TeV range.

95% CL upper limits

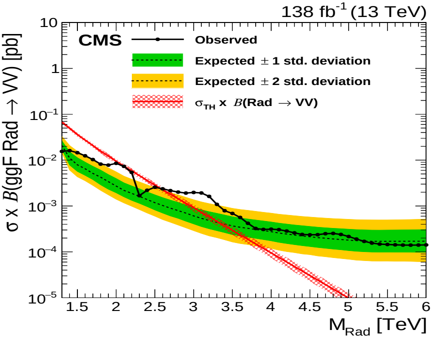
- A maximum local significance of 3.6 σ is observed at masses of 2.1 and 2.9 TeV under the $\mathrm{W}' \rightarrow \mathrm{WZ}$ hypothesis.
- The excess remains above 2σ when increasing the V+jets and $\mathrm{t\bar{t}}$ BKG uncertainties or using a looser (10%) $\mathrm{q\bar{q}}$ tagger.
- With the look-elsewhere effect, the global significance is 2.3σ.



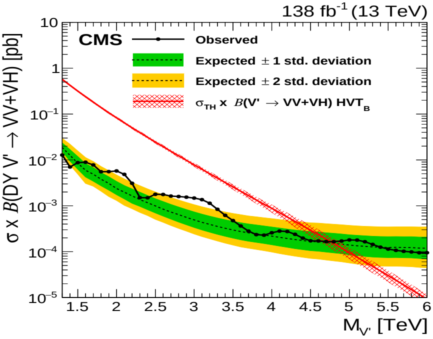
- **Kaluza–Klein bulk graviton:**
  1. Spin-2 boson.
  2. $\tilde{k} = k\frac{8\pi}{M_{pl}}$
- k is the unknown curvature scale of the extra dimension.
- We use $\tilde{k} = 0.5$ (resonance width smaller than detector resolution).

95% CL upper limits

- **Radion model:** r_c, compactification radius, and λ_R, ultraviolet cutoff.
- We consider: $k\pi r_c = 35$ and $\lambda_R = 3\ \mathrm{TeV}$.

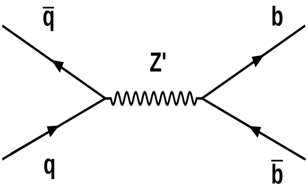


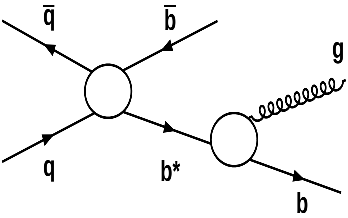
- **HVT model:** heavy vector triplet.
  1. $g_{\rm V} = 3$, $c_{\rm H} = 0.98$, and $c_{\rm F} = 1.02$.
  2. $g_{\rm V} = 1$, $c_{\rm H} = 1 - 3$, and $c_{\rm F} = 0$.



Search for narrow resonances in the b-tagged dijet mass spectrum - Accepted in Phys. Rev. D

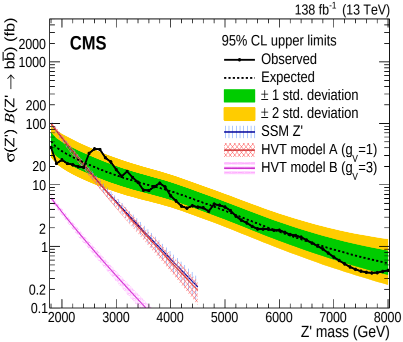
- Two benchmark scenarios (narrow resonances):
  1. Z': $q\bar{q} \to Z' \to b\bar{b}$
  2. Excited b (b^*): Single b^* and contact interaction $q\bar{q} \to b^*b$
- Events divided into categories:
  1. b^*: At least one b jet is required.
  2. Z': 3 categories: 2b, 1b, & μ.
- μ category: Neither jet passes the b tag selection, but at least one jet contains a μ. This enriches heavy-flavor jets, mitigating the loss of signal due to b tagging efficiency.

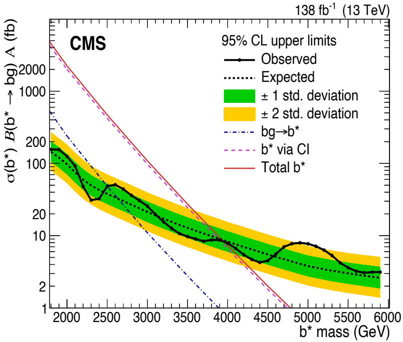




95% CL upper limits

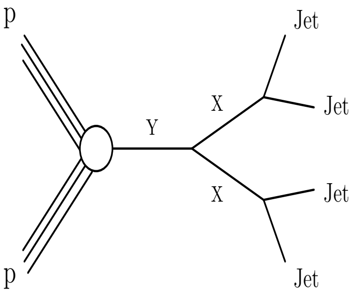
- Limits on $\sigma \times \mathcal{B}$ (left) and for different coupling strengths (right).
  1. **Model A (HVT):** Coupling strengths of the HV bosons to SM bosons and fermions are of the same order.
  2. **Model B (HVT):** Couplings to fermions are suppressed with respect to the couplings to bosons.

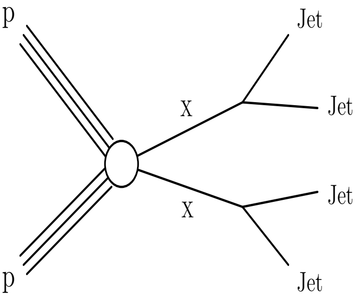




Search for resonant and nonresonant production of pairs of dijet resonances - Accepted in JHEP

- We search for a pair of jets coming from the decay of a new particle, X.
- Resonant and non-resonant production is explored.

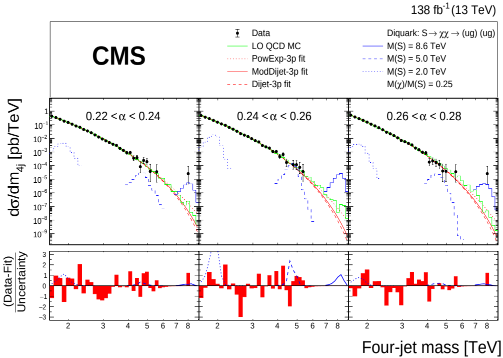




- **We consider pairs of resolved dijet resonances, X, where both jets within each dijet resonance are individually reconstructed.**
- The analysis is sensitive to high resonance masses.

Analysis strategy

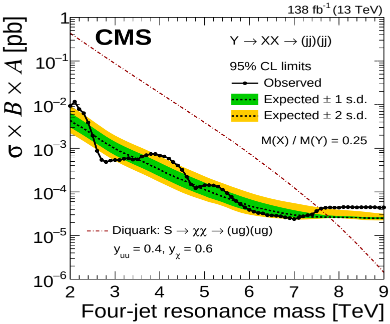
- We use as production benchmark models:
  1. Resonant: $\mathrm{uu} \to \mathrm{S} \to \mathrm{XX} \to (\mathrm{ug})(\mathrm{ug})$ ($\mathrm{S} \to$ scalar diquark).
  2. Nonresonant: $\mathrm{pp} \to \tilde{t}\tilde{t}^{*} \to (\bar{\mathrm{d}}\bar{\mathrm{s}})(\mathrm{ds})$ (RPV SUSY model, $\mathcal{B}(ds) = 1$).
- Use jet trigger that plateaus at $H_{\mathrm{T}} > 1050\ \mathrm{GeV}$.
- The four jets with the largest p_{T} are used to construct jet pairs.
- Additionally we require: $(\frac{|m_1 - m_2|}{m_1 + m_2}) < 0.1$

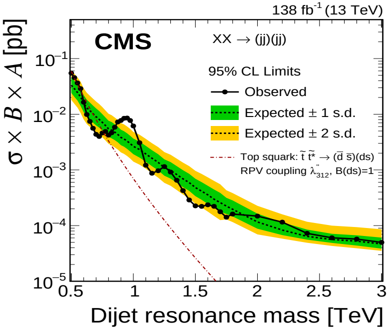


- $\alpha = \bar{m}_{jj} / m_{4j}$
- $d\sigma/dm = p_0 \exp^{p_1 \mathrm{x}} / \mathrm{x}^{p_2}$
- $d\sigma/dm = p_0 (1 - \mathrm{x}^{1/3})^{p_1} / \mathrm{x}^{p_2}$
- $d\sigma/dm = p_0 (1 - \mathrm{x})^{p_1} / \mathrm{x}^{p_2}$
- $\mathrm{x} = m/\sqrt{s}$

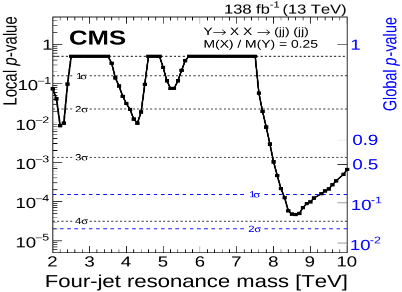
95% CL upper limits

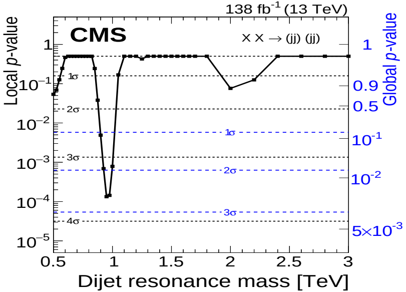
- For the resonant case, we use the m_{4j} distribution in 13 bins of α.
- For the nonresonant scenario, we use the $\bar{m}_{jj}$ distributiuon in 3 bins of α.
- The fit is done simultaneously for all the bins of α.

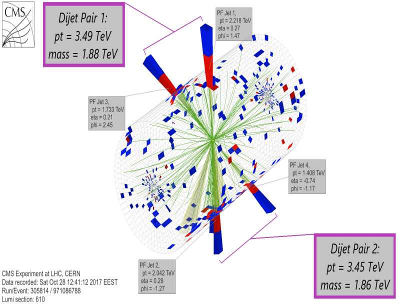


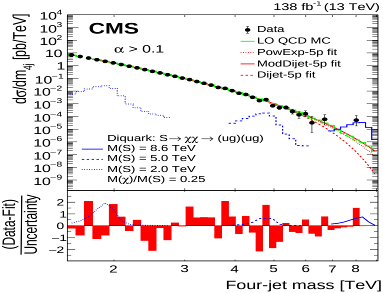


Local *p*-values and event displays



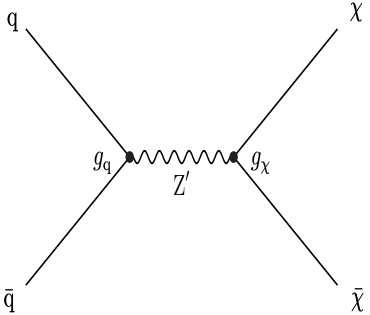






Search for resonant production of strongly coupled dark matter -Published in JHEP, 06/2022

- We consider resonant production of dark matter: $q\bar{q} \rightarrow Z' \rightarrow \chi\bar{\chi}$



- Leptophobic Z' mediator from a $U(1)$ broken symmetry.
- g_q (g_χ) coupling to SM (dark) quarks.
- Dark quarks form bound states called dark hadrons (DHs), which may be either stable or unstable.

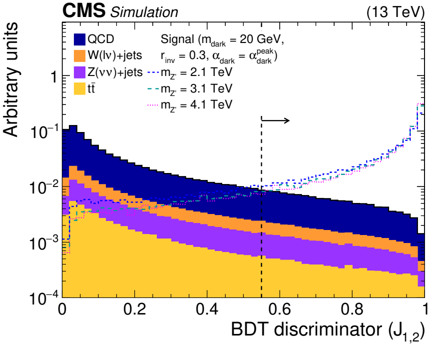
- Unstable DHs decay to SM quarks while stable DHs are DM candidates.
- This leads to collimated mixtures of visible and invisible particles ("semivisible" jets (SVJ)).
- We search for two jets and p_T^{miss}, aligned with one of the jets.

Analysis strategy

- We pre-select events with at least two high p_T ($p_\mathrm{T} > 200$ GeV) central jets ($|\eta| < 2.4$), with $m_\mathrm{T} > 1.5$ TeV, $R_\mathrm{T} = (p_\mathrm{T}^{miss}/m_\mathrm{T}) > 1.5$ TeV, $\Delta\eta(J_1, J_2) < 1.5$, among other criteria.

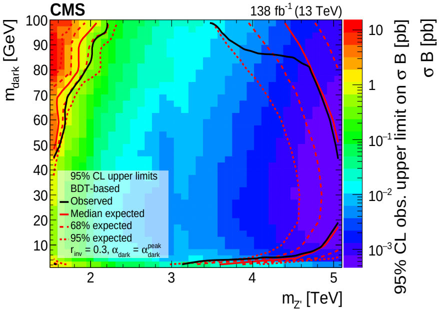
$$m_\mathrm{T}^2 = m_{JJ} + 2p_T^{miss}[\sqrt{m_{\mathrm{JJ}}^2 + p_{\mathrm{T,JJ}}^2} - p_{\mathrm{T,JJ}} cos(\Delta\phi_{\mathrm{JJ},miss})]$$

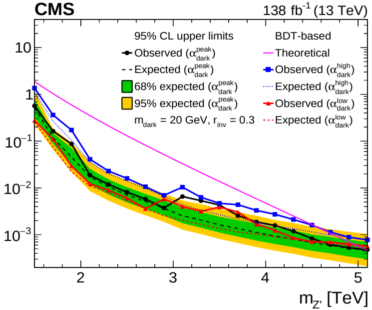
- In addition, we use a BDT to improve signal-BKG rejection.



- QCD is the dominant BKG.
- $\mathrm{t\bar{t}}$, W+jets and W+jets are subdominant BKGs.
- We divide the phase-space for the search in a low and high R_T SR.
- The m_T distribution is the main observable to search for signal.

95% CL upper limits



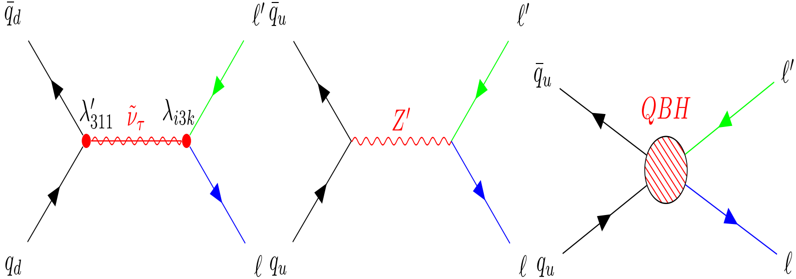


- We are able to exclude $1.5 < \mathrm{Z}' < 5.1\ \mathrm{TeV}$, depending on the signal parameters.
- α_{dark}: coupling strength of the dark QCD force:

$$\alpha_{dark}(\Lambda_{dark}) = \pi/(b_0 ln(Q_{dark}/\Lambda_{dark})), b_0 = (11N_c^{dark} - 2N_f^{dark})/6$$

$$N_c^{dark} = 2,\ N_f^{dark} = 2,\ Q_{dark} = 1.0\,\mathrm{TeV}$$

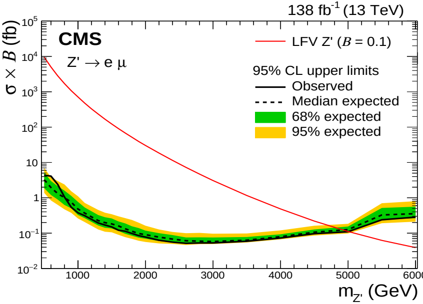
Search for heavy resonances and quantum black holes in $e\mu$, $e\tau$, and $\mu\tau$ final states - Submitted to JHEP

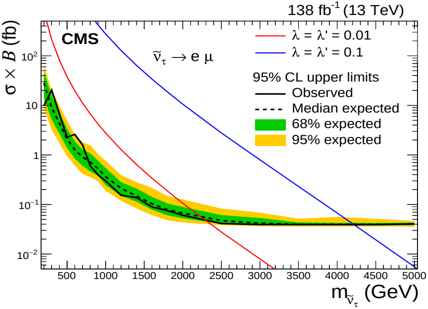


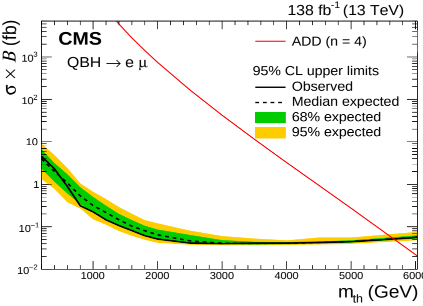
- In this search we probe lepton flavor violation (LFV), using $e\mu$, $e\tau$, and $\mu\tau$ final states.
- Results are interpreted using three different scenarios:
  1. $\tilde{\nu}_\tau$ in RPV SUSY: $W_{RPV} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \frac{1}{2}\lambda'_{ijk}L_iQ_j\bar{D}_k$
  2. Heavy gauge Z' bosons: SSM couplings.
  3. Quantum black holes (QBHs): Spin-0, colorless and neutral.

95% CL upper limits

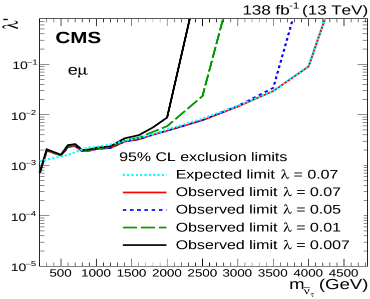
- The $\tilde{\nu}_\tau$, Z', and QBH samples are generated at LO, using the *calcHEP*, *PYTHIA*, and *QBH* 3.0 MC.
- The width of the Z' is taken as 3% of its mass. LVF decays are assumed to account for 10% of the total BF.

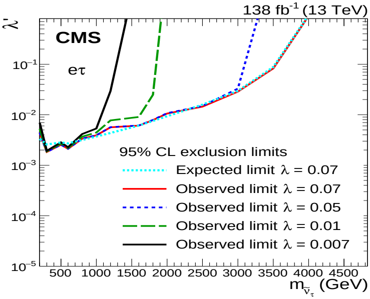


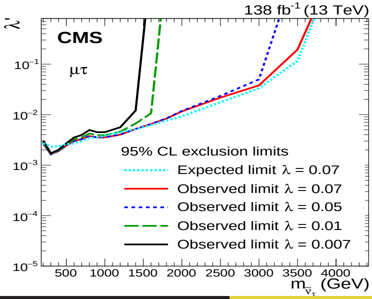


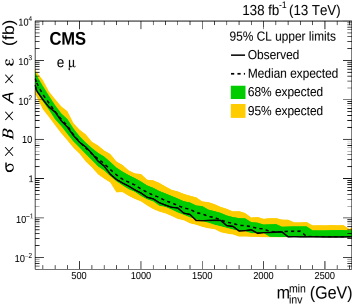


95% CL upper limits

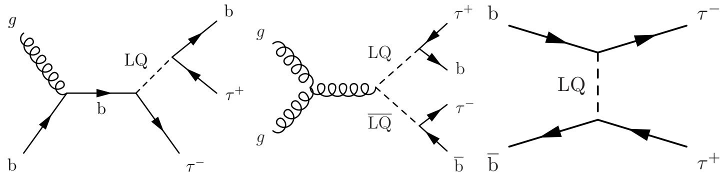






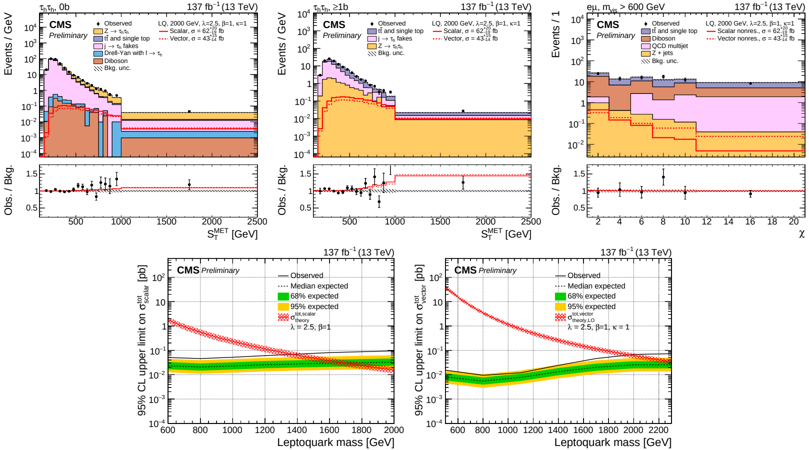


Search for a third-generation leptoquark coupling to a τ lepton and a b quark through single, pair and nonresonant production - CMS PAS



- Signal samples are generated such that the LQ couples to b quark and τ lepton with a coupling strength λ.
- Benchmark models with scalar and vector LQs are considered.
- For resonant production we use the $S_{\mathrm{T}}^{MET} = p_{\mathrm{T}}^{1} + p_{\mathrm{T}}^{2} + p_{\mathrm{T}}^{j} + p_{\mathrm{T}}^{miss}$
- For non-resonant production we use $\chi = \exp(2y*)$, where $y* = \frac{1}{2}|y_1 - y_2|$.

Results

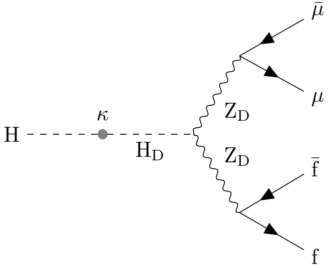


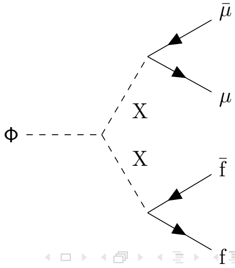
- The data agree with the SM expectation within 2 s.t.d for $\lambda = 1.5$.
- For a LQ mass of 2 TeV and a $\lambda = 2.5$, an excess with a significance of 3.4 s.t.d is observed.

Long-Lived Particles

Search for long-lived particles decaying to a pair of muons - Accepted in JHEP

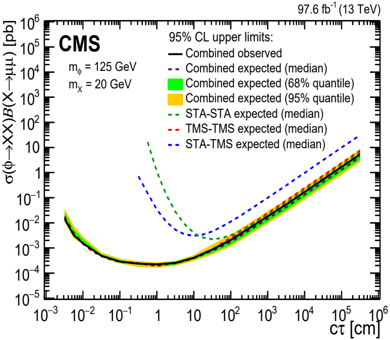
- We search for an exotic massive LLP decaying to a pair of **oppositely charged muons**, referred to as a "displaced dimuon".
- Two signal models are used as benchmarks:
  1. Hidden Abelian Higgs model (HAHM): Include additional $U(1)_D$ symmetry, broken by dark Higgs (H_D), with hypothetical dark photons (Z_D) as mediators. For small values of $\mathrm{Z}-\mathrm{Z}_\mathrm{D}$ kinematic mixing, the Z_D is long-lived.
  2. Simplified model, in which a non-SM Higgs boson decays to a pair of long-lived exotic heavy neutral scalar bosons.

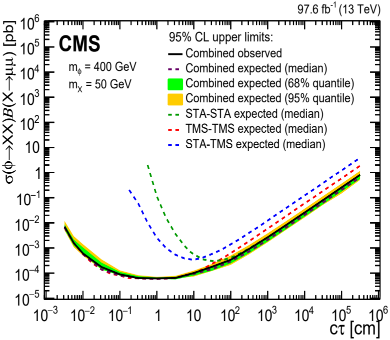




95% CL upper limits

- We set upper limits on the production cross section, $\sigma(\Phi \to \mathrm{XX})$, times BF, $B(\mathrm{X} \to \mu\bar{\mu})$, as function of the decay length ($c\tau$).
- The limits are set for different ranges of masses: $m(\Phi)[125\,\mathrm{GeV} \to 1\,\mathrm{TeV}]$ and $m(\mathrm{X})[20 \to 350\,\mathrm{GeV}]$.

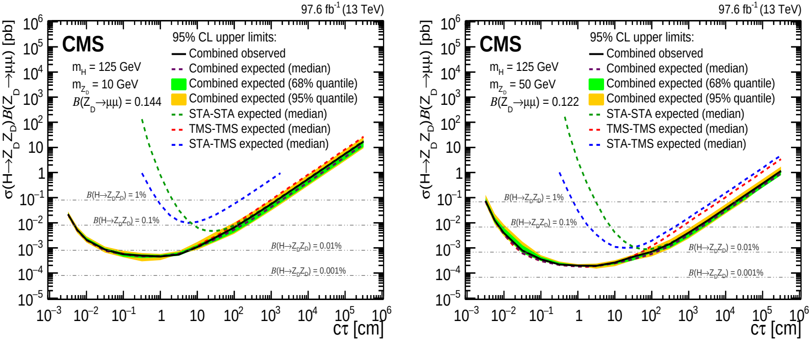




- **The search is sensitive to a broad range of $c\tau$ ($30\,\mu\mathrm{m} \to 1\,\mathrm{km}$).**
- Most restrictive limits for $c\tau$ between $0.1\,\mathrm{mm}$ and 10–$100\,\mathrm{m}$, excluding $\sigma(\Phi \to \mathrm{XX})\mathcal{B}(\mathrm{X} \to \mu\bar{\mu})$ smaller than $1\,\mathrm{fb}$.

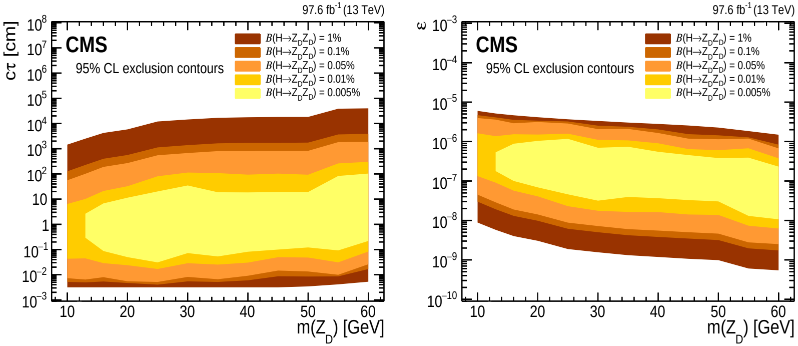
95% CL upper limits

- The signal samples are produced considering small values of $\mathrm{Z} - \mathrm{Z}_D$ kinematic mixing: $\epsilon\,(2 \times 10^{-9} \rightarrow 10^{-6})$.
- The limits are set for different Z_D masses: $m(\mathrm{Z}_D)[10 \rightarrow 60\,\mathrm{GeV}]$.



95% CL upper limits

- Our previous results can be translated into limits on the kinetic mixing ϵ.

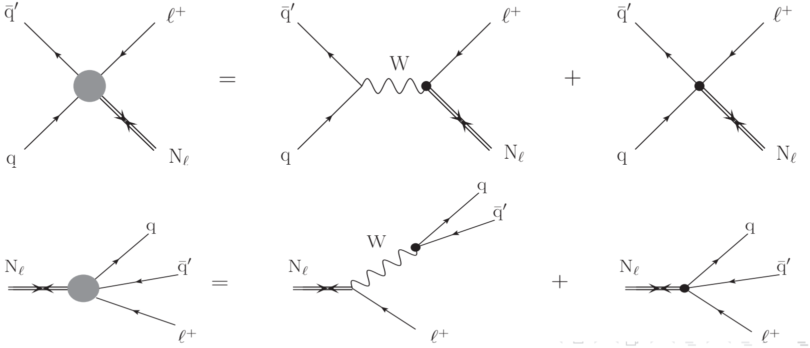


- Our analysis excludes a wide range of ϵ values, between 9×10^{-9} and 6×10^{-6} at $m(\mathrm{Z}_D) = 10\,\mathrm{GeV}$ and between 5×10^{-10} and 1.5×10^{-6} at $m(\mathrm{Z}_D) = 60\,\mathrm{GeV}$ for $B(\mathrm{H} \to \mathrm{Z}_D\mathrm{Z}_D) = 1\%$.

Briefing on additional BSM Searches

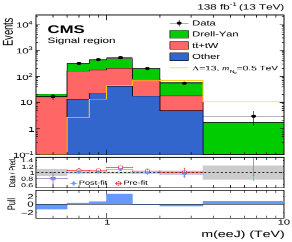
Search for a heavy composite Majorana neutrino in events with dilepton signatures from proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ - Submitted to PLB

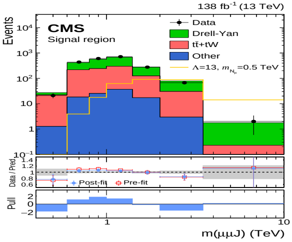
- We consider the composite neutrino model:
  $\mathcal{L}_{GI} = \frac{gf}{\sqrt{2}}\bar{\mathrm{N}}\sigma^{\mu\nu}(\partial_\mu \mathrm{W}_\nu)P_L^\ell + h.c$, $\mathcal{L}_{CI} = \frac{g_*^2\eta}{2}\bar{q}'\gamma^\mu P_L q\bar{\mathrm{N}}\gamma_\mu\ell + h.c$
- The fermion interaction is the sum of the gauge and contact contributions.

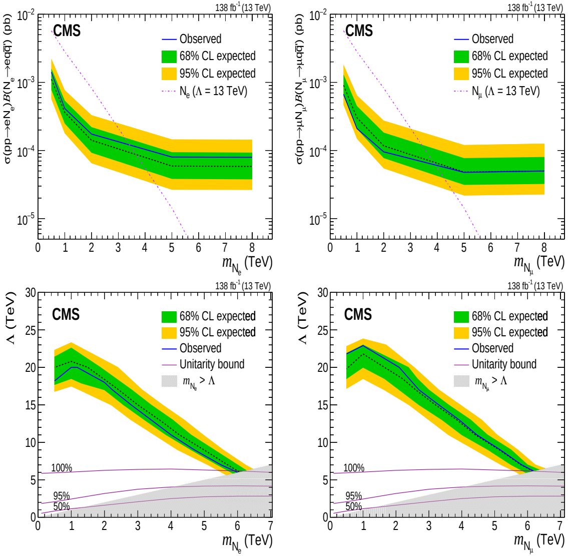


Analysis strategy and 95% C.L limits

We focus on $\mathrm{e\bar{e}q\bar{q}}$ and $\mu\bar{\mu}\mathrm{q\bar{q}}$ final states.

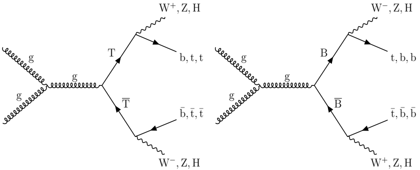






The gray shading indicates the region where $m_{N_\ell} > \Lambda$, and the 3 magenta lines represent the fraction of the signal that satisfies the unitarity condition in the EFT.

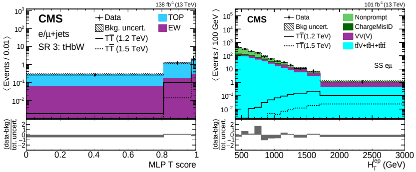
Search for pair production of vector-like quarks in leptonic final states -Submitted to JHEP

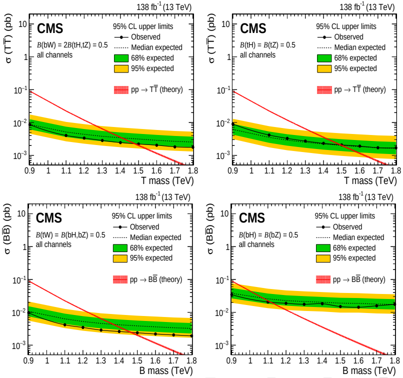


- VLQs are hypothetical fermions whose left- and right-handed components transform identically under the SM electroweak gauge group $SU(2)_L \otimes U(1)_Y$.
- This chiral symmetry allows a mass term in the $\mathcal{L}$.
- VLQs could cancel out m_{H} quantum loop corrections.
- We search for final states with e's or μ's.

Channel	Event selection: Overall	CR	SR
1ℓ	1 tight ℓ	—	—
	$p_{\mathrm{T}}(\ell) > 55\,\mathrm{GeV}$	—	—
	0 other loose ℓ, $p_{\mathrm{T}} > 10\,\mathrm{GeV}$	—	—
	$p_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$	—	—
	≥ 3 large-radius jets	—	—
	—	max MLP not VLQ	max MLP is VLQ
	—		2 VLQ candidates
SS 2ℓ	2 tight SS ℓ	—	—
	$p_{\mathrm{T}}(\ell) > 40\,\mathrm{GeV}, 30\,\mathrm{GeV}$	—	—
	≥ 4 small-radius jets	—	—
	$M(\ell\ell) > 20\,\mathrm{GeV}$	—	—
	$M(\mathrm{ee})$ outside 76–106 GeV	—	—
	—	$H_{\mathrm{T}}^{\mathrm{lep}} < 1000\,\mathrm{GeV}$	$H_{\mathrm{T}}^{\mathrm{lep}} > 1000\,\mathrm{GeV}$
3ℓ	$p_{\mathrm{T}}(\ell) > 30\,\mathrm{GeV}$	—	—
	$M(\mathrm{OSSF}\ \ell\ell) > 20\,\mathrm{GeV}$	—	—
	≥ 1 b-tagged jet	—	—
	$p_{\mathrm{T}}(\mathrm{b\ jet}) > 45\,\mathrm{GeV}$	—	—
	—	3 loose ℓ	≥ 3 tight ℓ GeV
	—	2 small-radius jets	$\geq$ small-radius jets

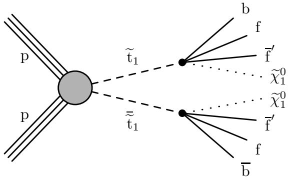
Use a multi-layer perceptron (MLP) for 1ℓ channels

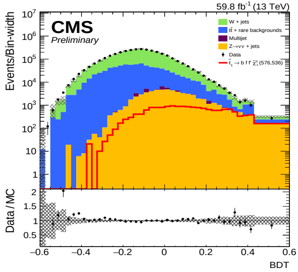


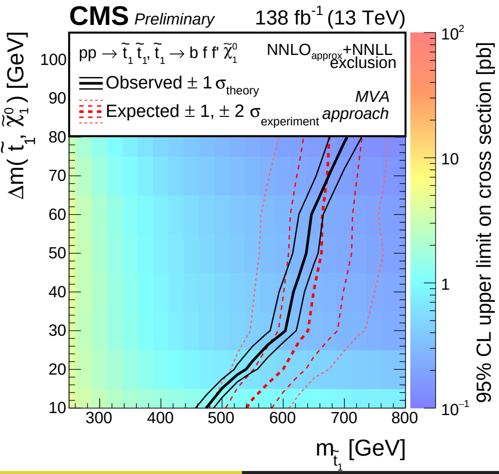


Search for top squarks decaying via the four-body mode in single-lepton final states - CMS PAS

- Target 4-body $\tilde{t}_1$ decays, allowed when $m(\tilde{t}_1) - m(\tilde{\chi}^0_1) < m(\mathrm{W})$: Select events with exactly one e or μ, p_{T}^{miss}, and jets (use BDT).







Probing B Meson Anomalies

Measurement of $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ decay - CMS PAS

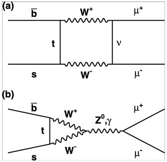


Figure from PLB article-CLICK

- In the SM the BFs ($\mathcal{B}$) for these decays are very small:
  $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
- We use $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi\phi$ events as standard candles, to extract the signal $\mathcal{B}$s:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}} \frac{f_u}{f_s},$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to J/\psi\phi) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B_s^0 \to J/\psi\phi}} \frac{\varepsilon_{B_s^0 \to J/\psi\phi}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0 \to \mu^+\mu^-}} \frac{f_u}{f_d},$$

f_u, f_s and f_d are the B hadron production fractions

- We find the $\mathcal{B}$s to be:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

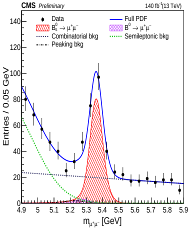
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\,(\text{stat})\,^{+0.08}_{-0.09}\,(\text{syst})\right] \times 10^{-10}.$$

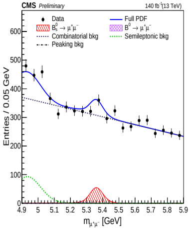
- Where we have used (from PDG and LHCb):

$$\mathcal{B}(B^+ \to J/\psi K^+) = (1.020 \pm 0.019) \times 10^{-3},$$

$$\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033) \times 10^{-2}, \text{ and}$$

$$f_s/f_u = 0.231 \pm 0.008.$$

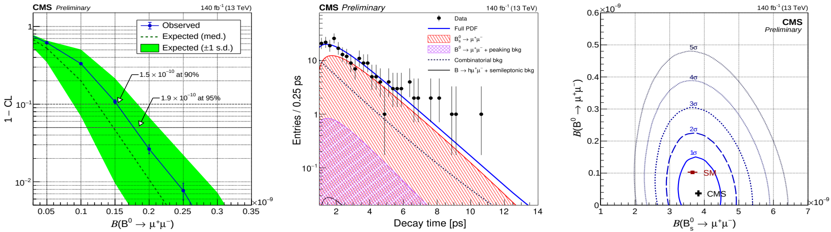




Results

- We also estimate the branching fractions using the $\mathrm{B}_s^0 \to \mathrm{J}/\psi\phi$ decays for the normalization.
- Using $\mathcal{B}(\mathrm{B}_s^0 \to \mathrm{J}/\psi\phi) = (1.018 \pm 0.050) \times 10^{-3}$ from LHCb:

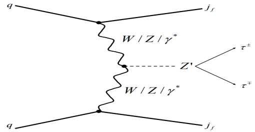
$$\mathcal{B}(\mathrm{B}_s^0 \to \mu^+\mu^-) = [3.95^{+0.39}_{-0.37}(stat)^{+0.27}_{0.22}(syst)^{+0.21}_{0.19}(BF)] \times 10^{-9}$$

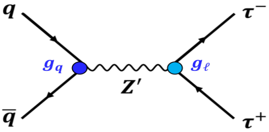


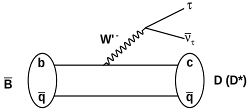
- Comparing LHCb, $\mathcal{B}(\mathrm{B}_s^0 \to \mu^+\mu^-) = [3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}] \times 10^{-9}$, our result is about 1.2 s.t.d higher, more consistent with the SM.

Some of our short term goals and plans

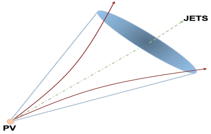
- Several more new results with Run2 data are just around the corner!

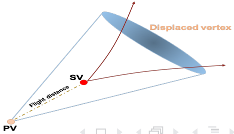






- **For Run-3 data: new triggers deployed, scouting (high rate trigger-objects analysis) and parking (opportunistic reco).**
- Over one billion fully-simulated events produced every week (from GEN to RECO).
- Increasing applications of machine learning techniques in reconstruction and identification of particles and in several different analyses.





Summary

- CMS has produced many interesting results on a very broad set of searches probing BSM physics.
- **There are many interesting results with Run2 data that are on their way to be released (stay tuned!).**
- We have observed several 2-3σ deviations of data w.r.t to SM BKG predictions that we need to further investigate/understand: real signs of new physics? Statistical fluctuations? Bad BKG predictions?
- We are preparing for the HL-LHC and I personally believe that the best of CMS and the LHC is yet to come: we only need to be patient, collect more data, and keep working hard.

THANK YOU
GRACIAS
OBRIGADO