LHCP 2023

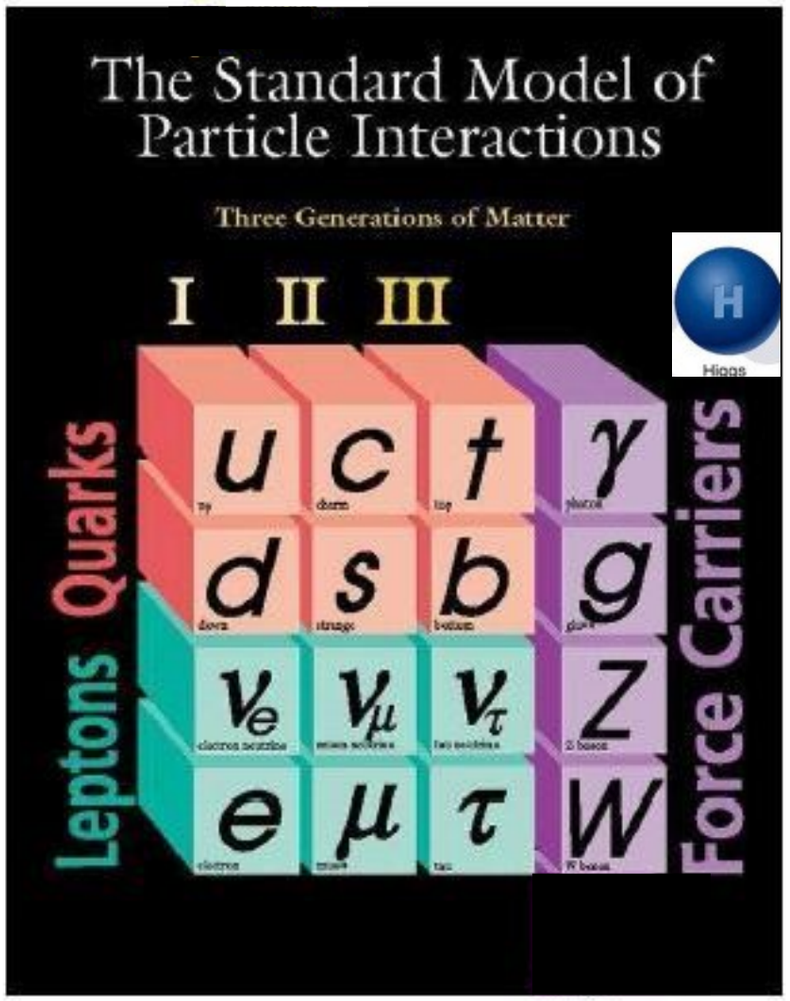
11th Large Hadron Collider Physics Conference

CMS Highlights on Searches for New Physics in Final States with Jets

Emmanouil (Manos) Vourliotis
on behalf of the CMS Collaboration

Introduction

- Standard Model (SM) of Particle Physics:
  - So beautiful...
  - ...yet incomplete...



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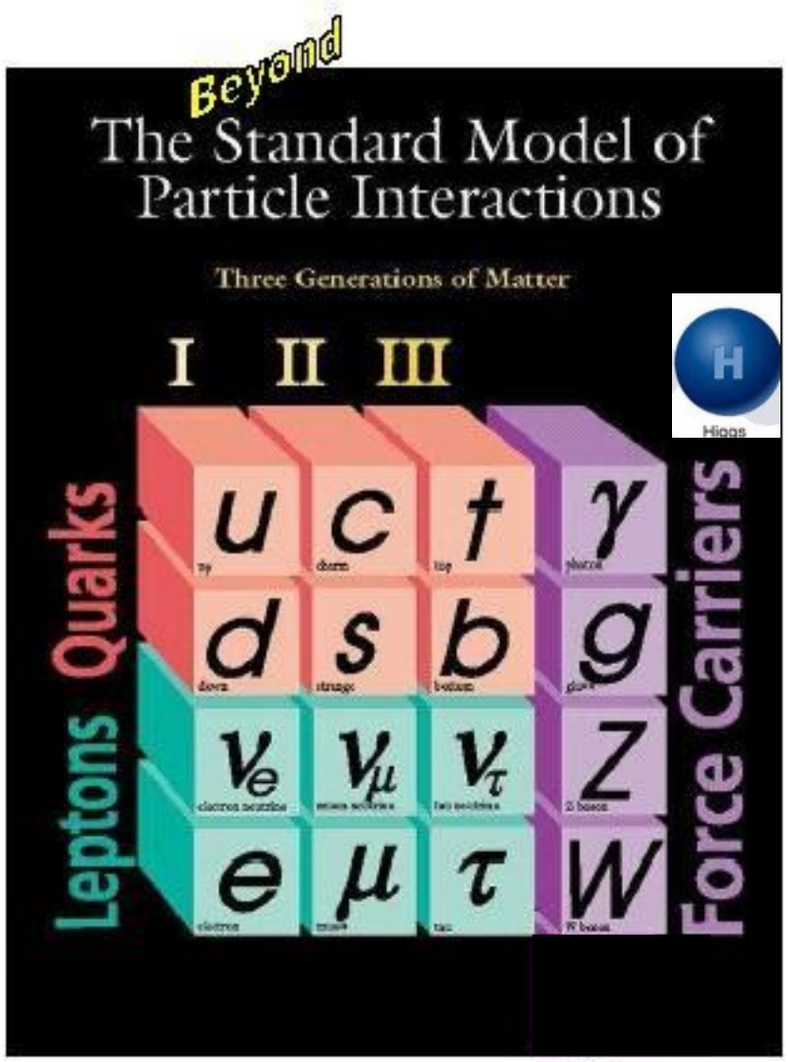

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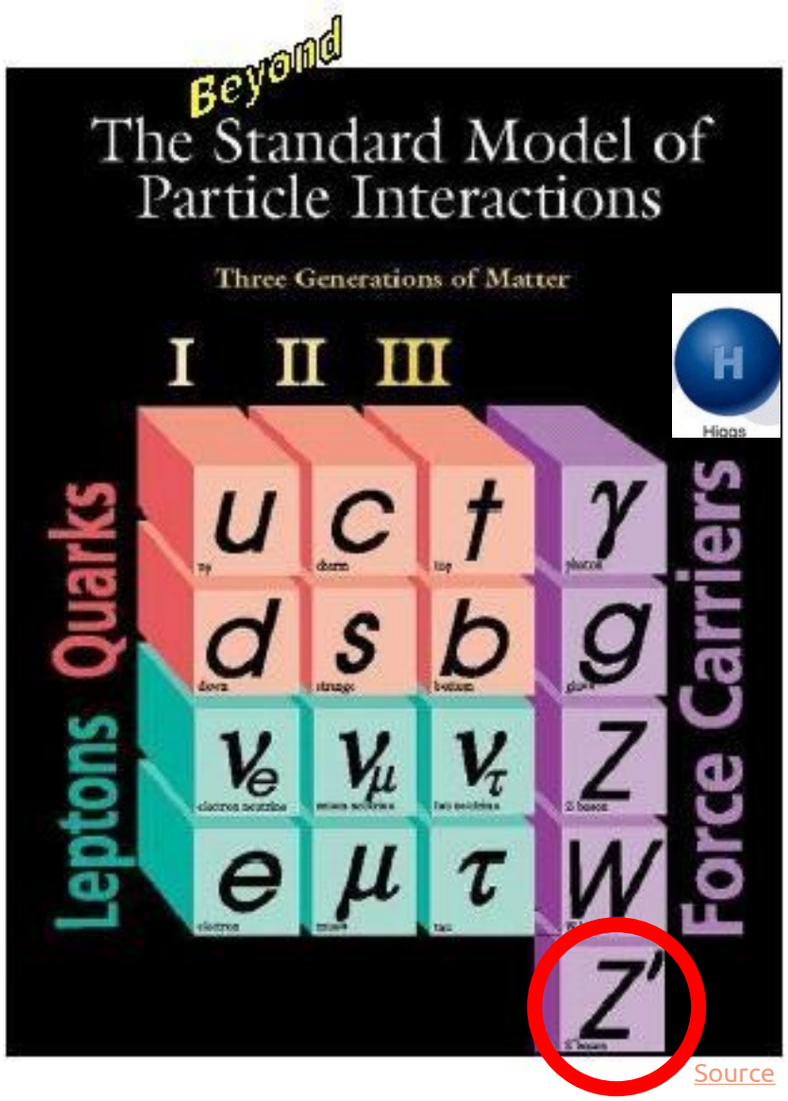

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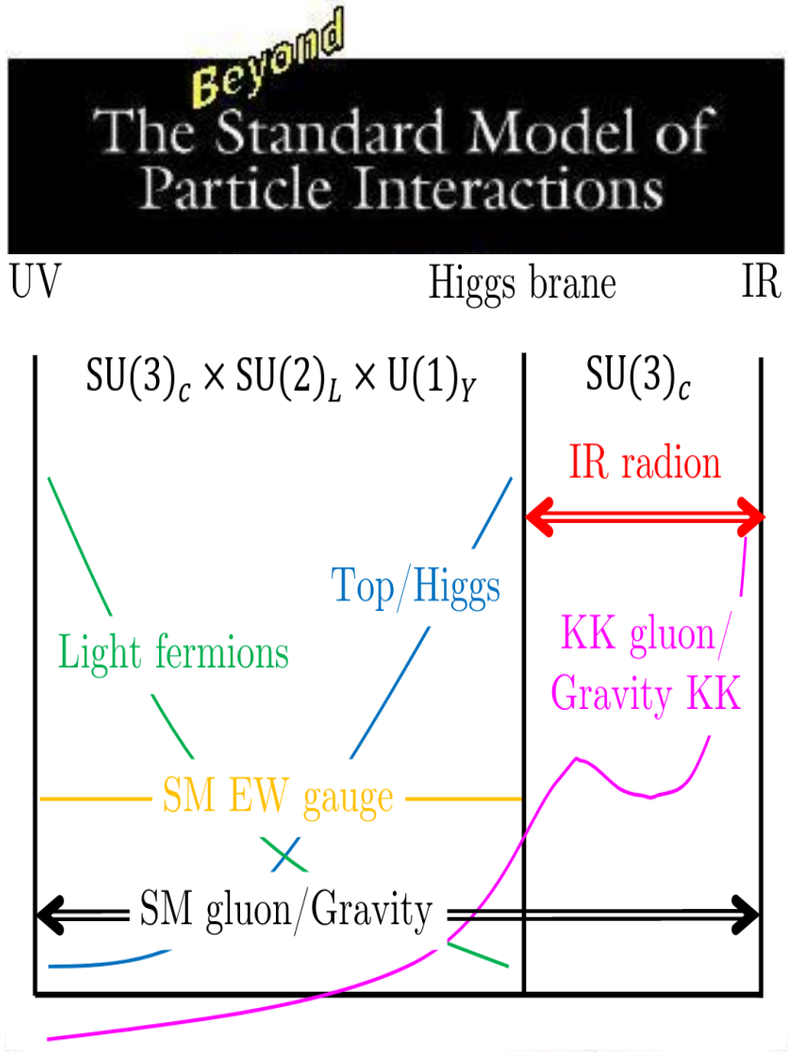

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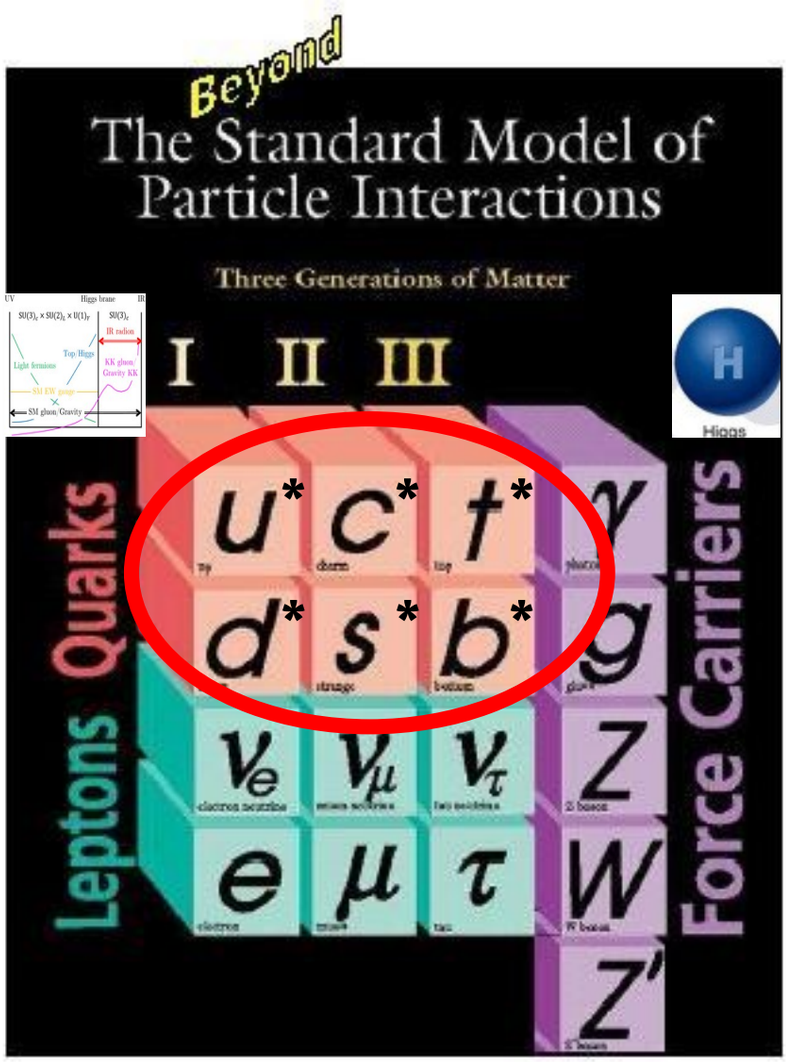

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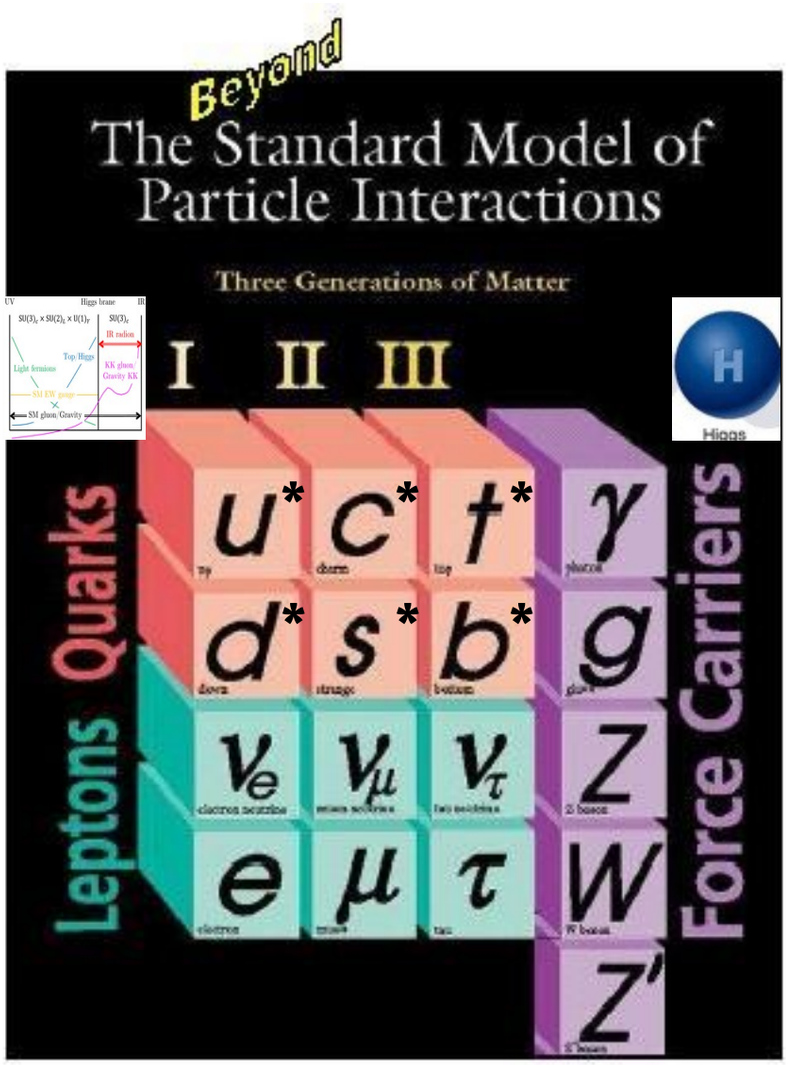
Many more...!!!

- New, simple or elaborate ideas to probe even more beyond the SM.
  - New ways of using common experimental objects



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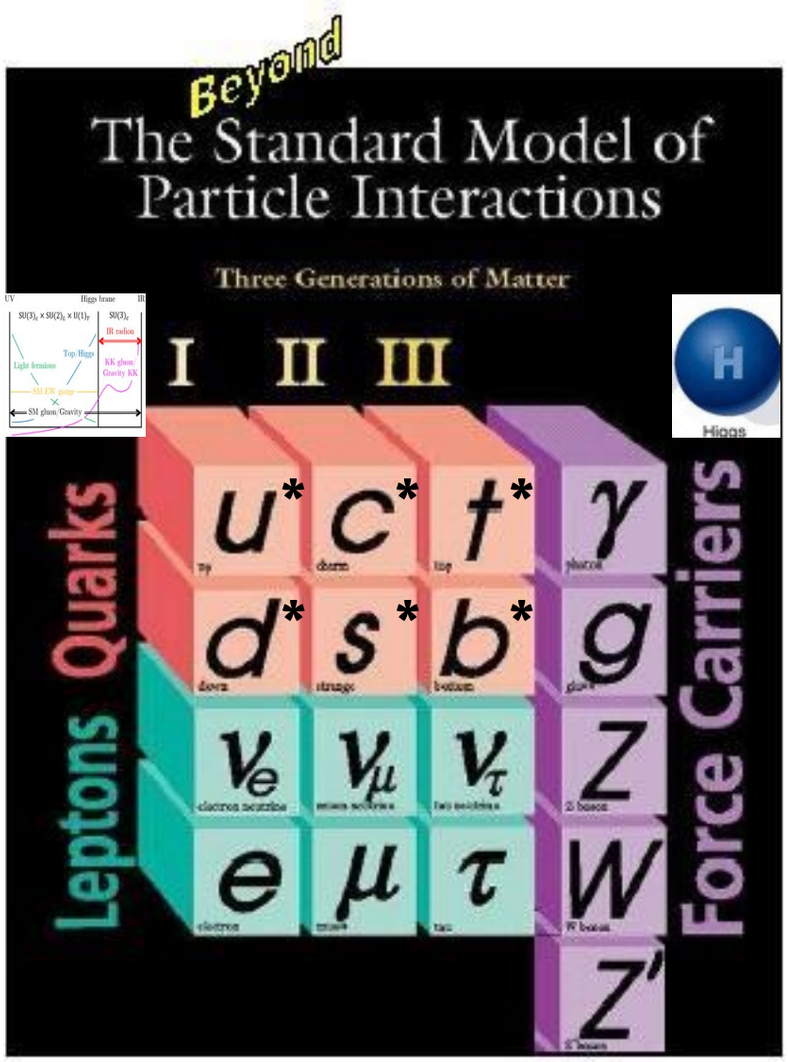
- New, simple or elaborate **ideas to probe** even more **beyond the SM**.
  - New ways of using common experimental objects: **Jets**.

Novel analyses at CMS



Source

Search for a high mass dimuon resonance associated with b quark jets at √s = 13 TeV

CMS-PAS-EXO-22-016

New!

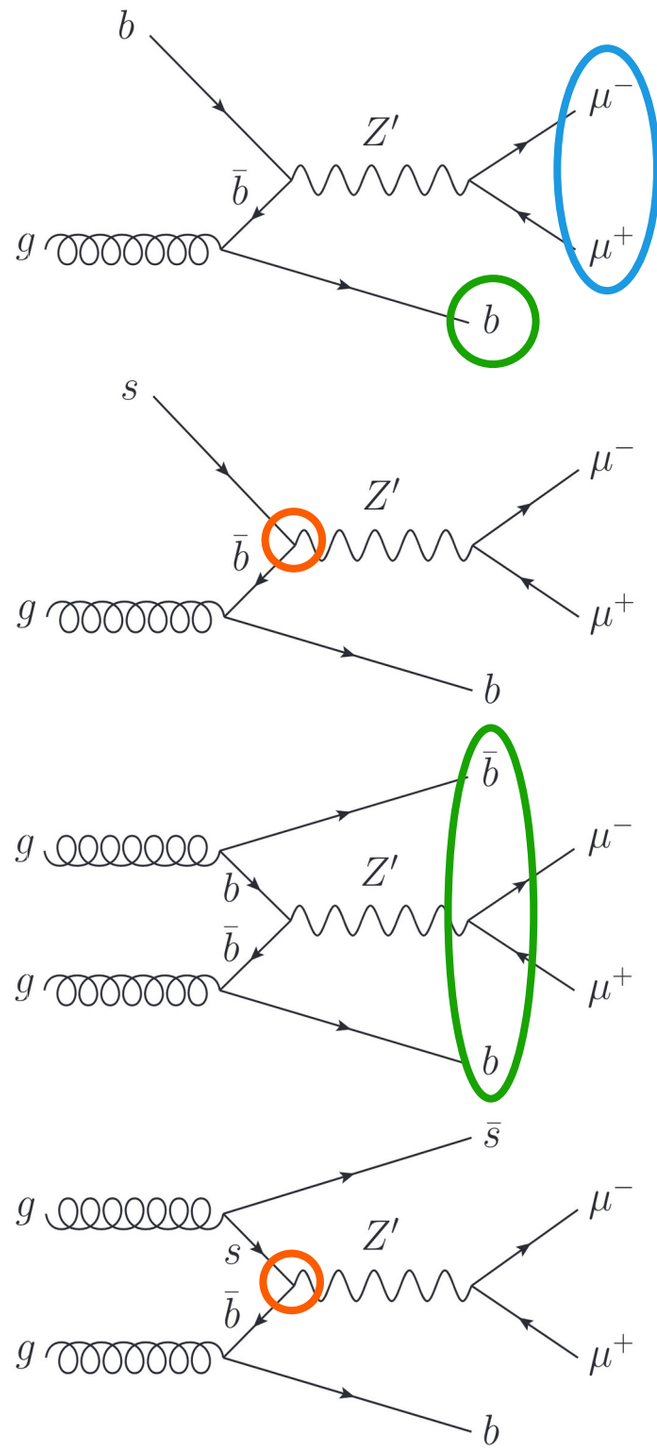
New!

Analysis Motivation

- Search for new neutral vector boson **Z' → μμ** in association with **≥ 1 b-jet**.
  - 350 GeV ≤ $m_{Z'}$ ≤ 2.5 TeV
  - **Z' coupling to b & s** quarks ⇒ Implications to **low energy b→sℓℓ observables**[1].
- Simplified lepton flavor-universal lagrangian[2]:

$$\mathcal{L}_{\mathrm{BSM}} = Z'_\eta \left(g_\ell \sum_{f=e,\mu,\tau} \bar{f}\gamma^\eta P_L f + g_\nu \sum_{f=\nu_e,\nu_\mu,\nu_\tau} \bar{f}\gamma^\eta P_L f + g_\mathrm{b} \left[\bar{\mathrm{b}}\gamma^\eta P_L \mathrm{b} + \delta_{\mathrm{bs}} \left(\bar{\mathrm{s}}\gamma^\eta P_L \mathrm{b} + \mathrm{h.c.} \right) \right] \right)$$

- Full Run 2 CMS data set in a different light → **Enhanced sensitivity** by:
  - Explicit event **categories based on N_b**.
  - $t\bar{t}$ **killer veto**: Suppress the dominant SM background.



[1]: JHEP 04 (2023) 033
[2]: PTEP 2022 (2022) 083C01

New!

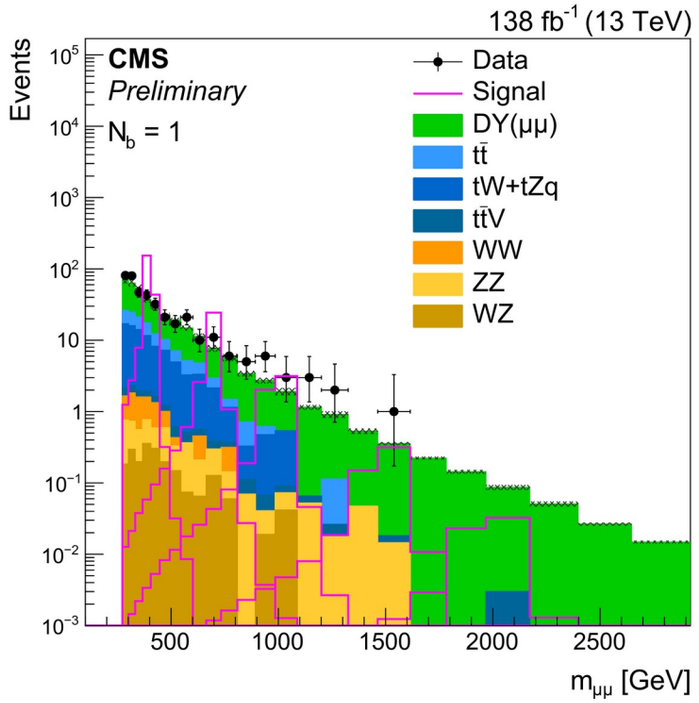
Optimizing Selection & Categorization

- Select high-p_T dimuon pair:
  - Muons with $p_T(\mu) > 53$ GeV & $|\eta(\mu)| < 2.4$.
  - Global high-p_T muon ID.
  - Tight tracker isolation & impact parameter requirements.
- Select ≥1 tight b-tagged jet:
  - $p_T > 20$ GeV, $|\eta| < 2.5$
  - Medium b-tagging WP for other b-tagged jets.

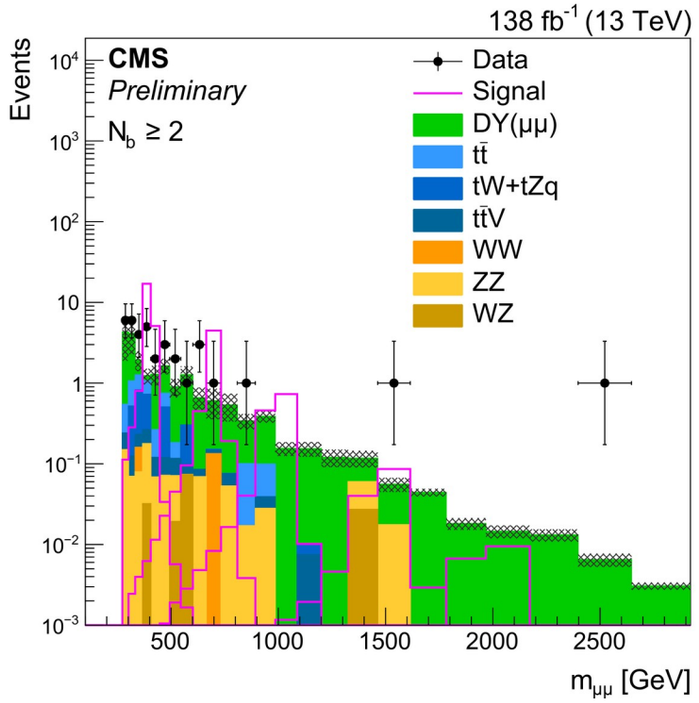
$\min(m_{\mu b}) > 175$ GeV

$\downarrow$

$t\bar{t}$ rejection by > **300×**



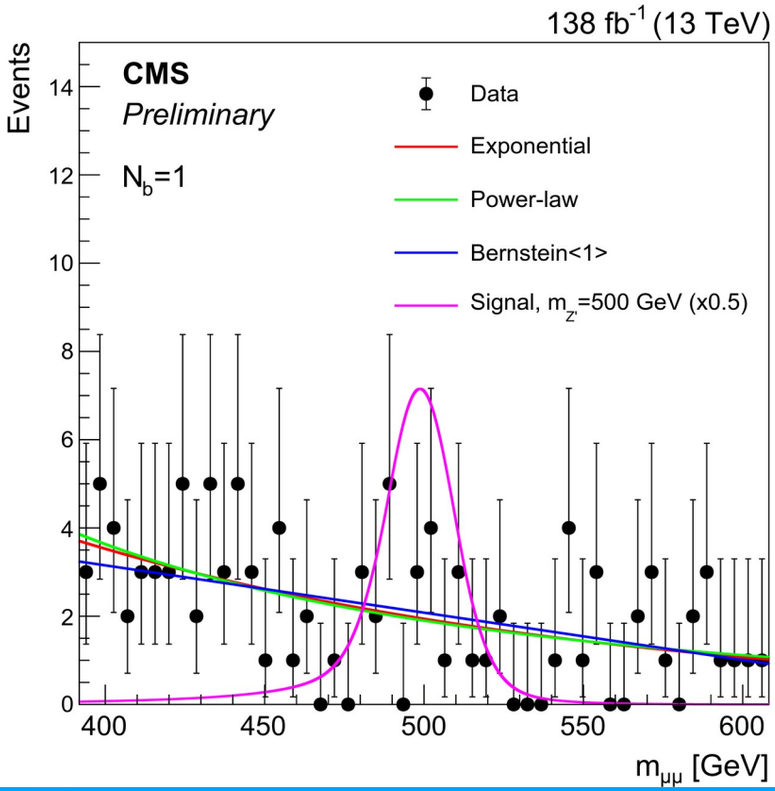
- Veto events with:
  - Cosmics → 3D angle btw. muons < π – 0.02.
  - Extra leptons (e & μ) & isolated tracks (τ leptons).
  - Significant muon or b-jet mismeasurements, i.e.: MET > 250 GeV && ($|\Delta\Phi_{MET,\mu/b}| < 0.3$ || $|\Delta\Phi_{MET,\mu/b}| > \pi - 0.3$)
- Categorize selected events:
  - $N_b = 1$
  - $N_b \geq 2$

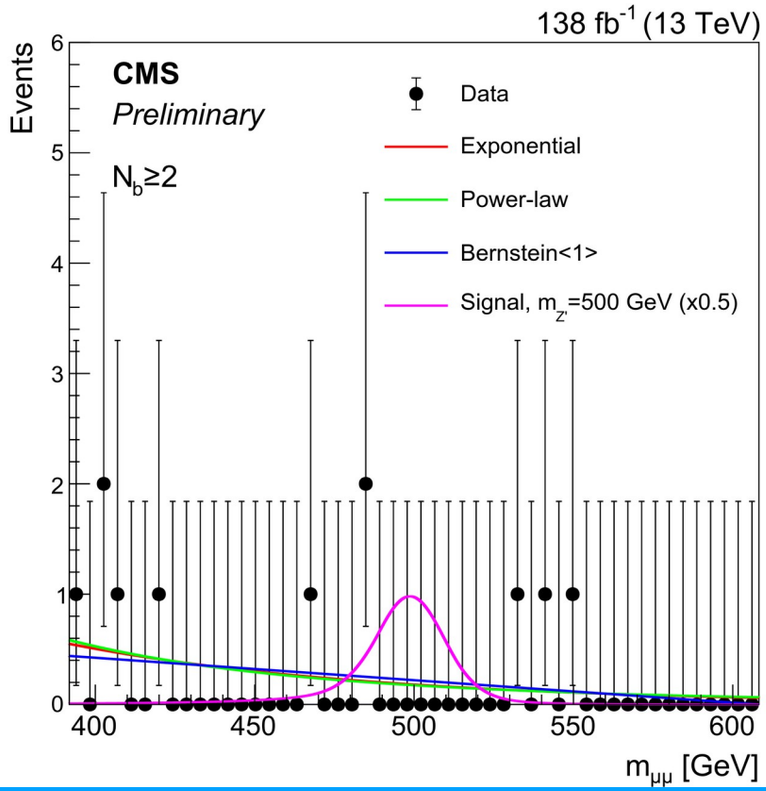


New!

Going Fully Data-Driven

- **Background parametrization:**
  PDF envelope of exponential, power law & bernstein polynomial **functions.**
  - Fit $m_{\mu\mu}$ within $m_{Z'} \pm 10\ \sigma_{mass}$.
  - Unbinned likelihood **fits directly in data** ⇒ **No dependence on SM simulation**.
- **Signal parametrization:**
  Double-sided Crystal Ball + Gaussian.
  - Signal shape **parameters from simulation** → **Dependence vs. $m_{Z'}$**.

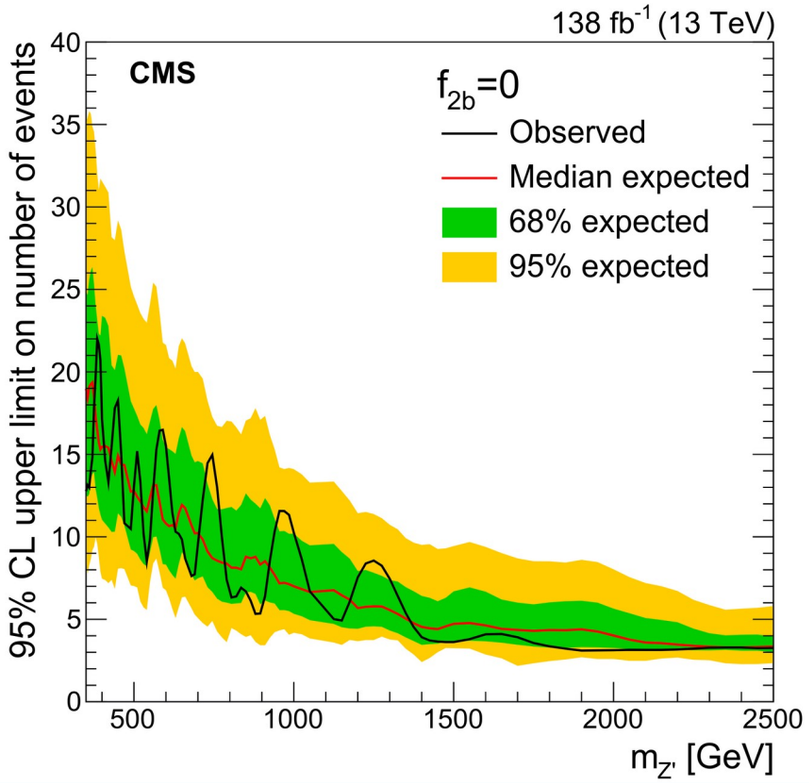


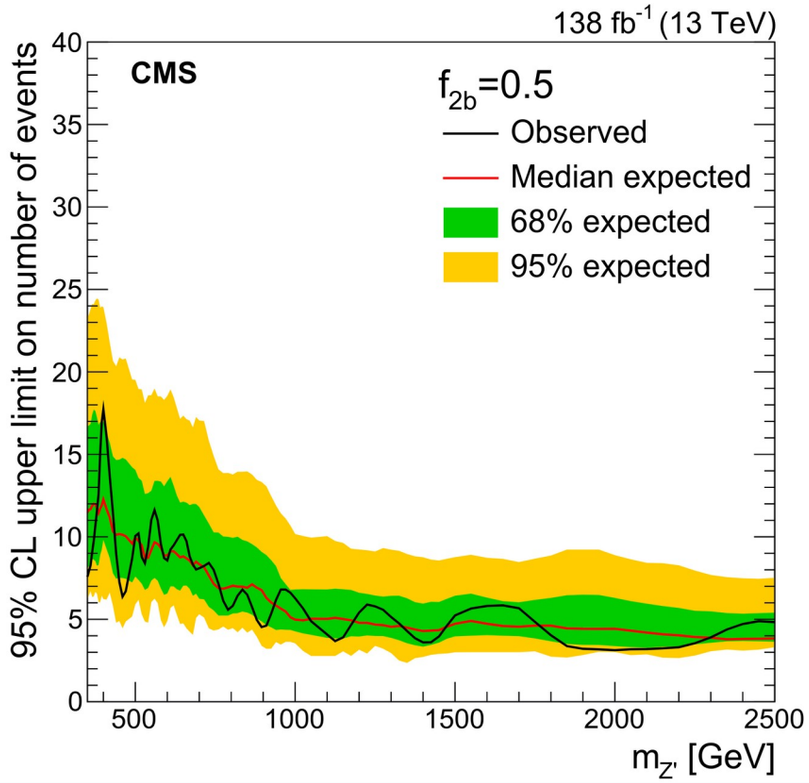


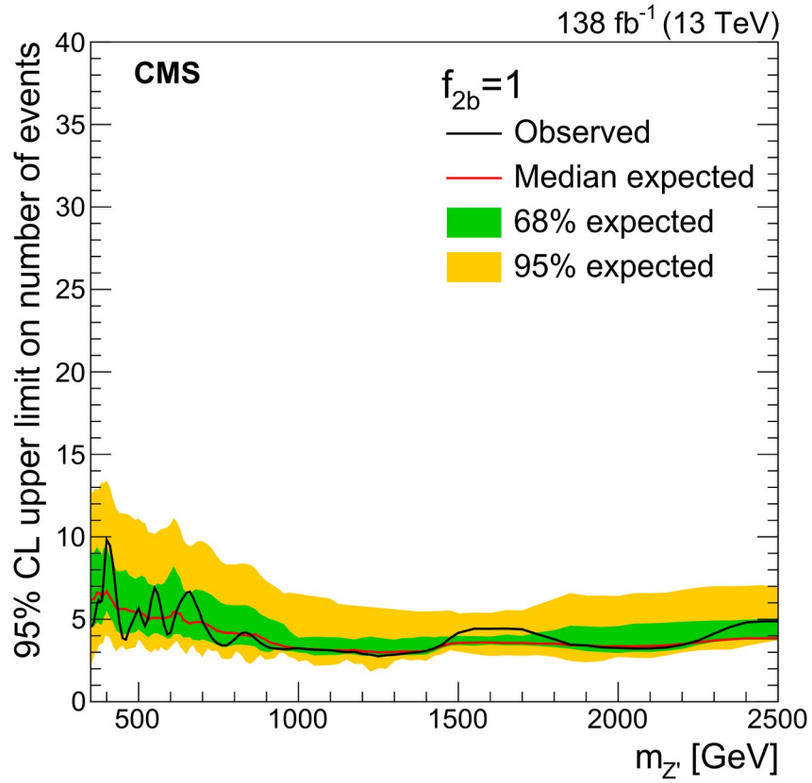
New!

Results

- No significant excess.
- **Model independent limits** on number of signal events with $N_b \geq 1$.
  - Easily reinterpretable for any neutral resonance model!
  - Vary relative fraction of events in $N_b \geq 2$ category, $\mathbf{f_{2b}} \Rightarrow$ Probe different signal hypotheses.
  - Dimishing background for increasing masses and/or $f_{2b} \Rightarrow$ More strigent limits.





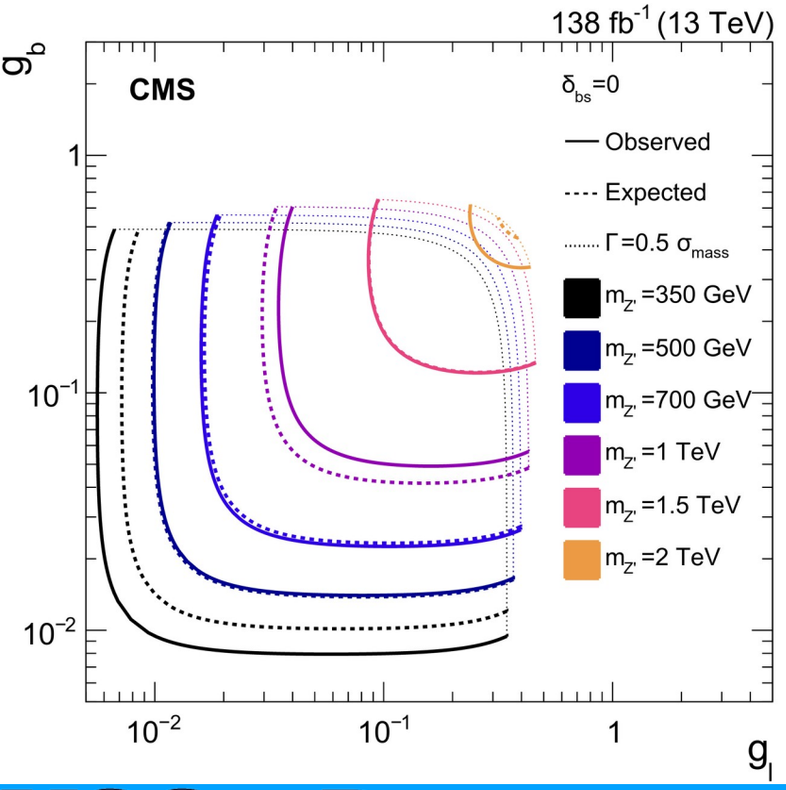


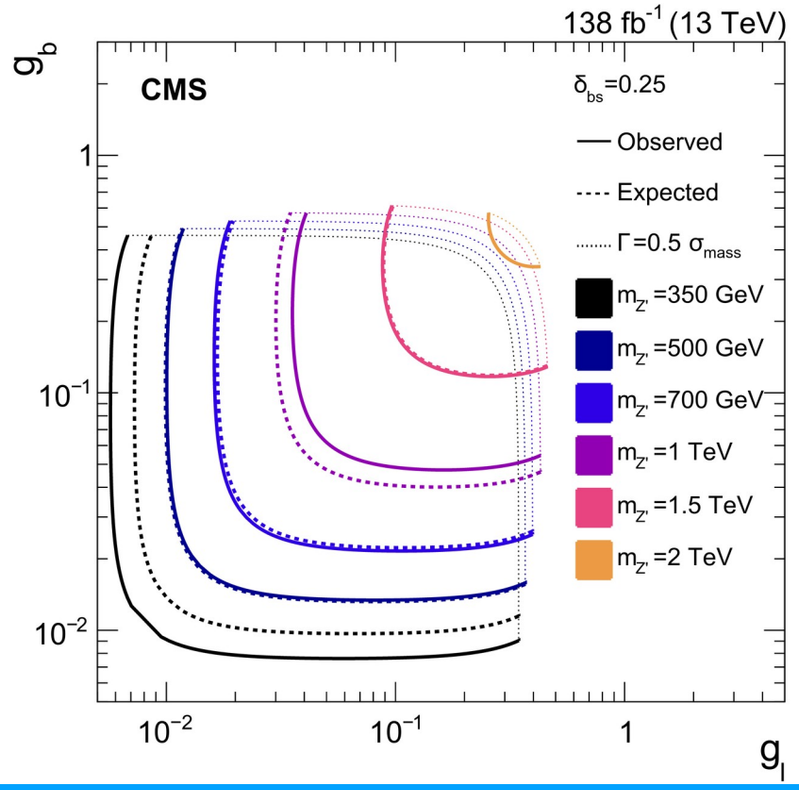
New!

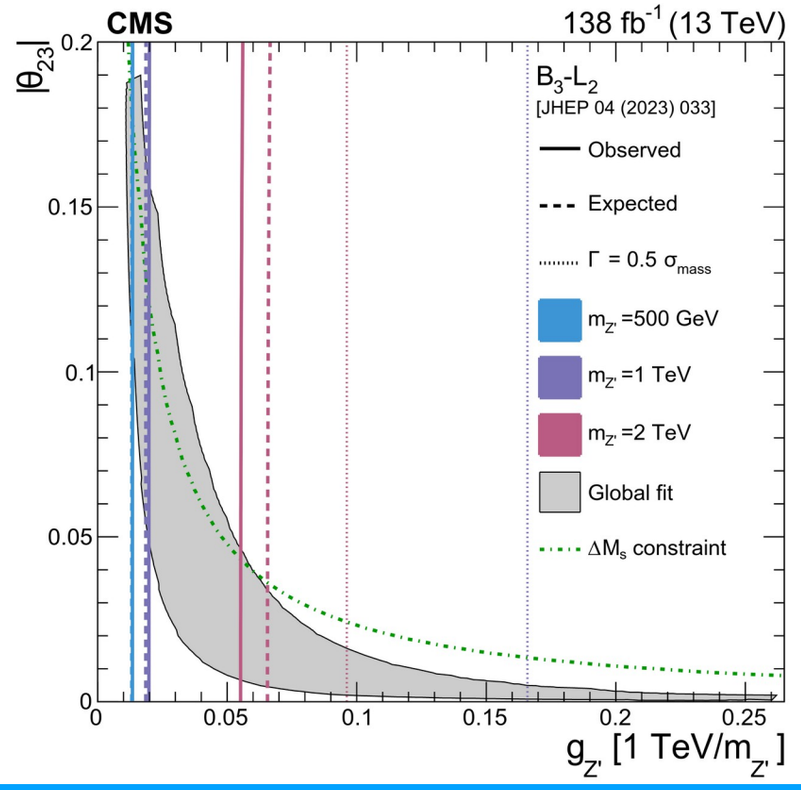
Results

- Narrow-width resonance ⇒
  Restrict to parameter space where $\Gamma_{Z'} < \sigma_{mass} / 2$.
- Interpretation for the **simplified lepton flavor-universal lagrangian** ($g_\ell = g_v$).
- Set constraints on **B_3–L_2 model** of Ref. [1]:
  - $g_{Z'}$ = coupling of Z' to SM fermions.
  - θ_{23} = mixing angle between 2nd & 3rd generation quarks.

Global-fit preferred parameter space completely excluded for some masses!







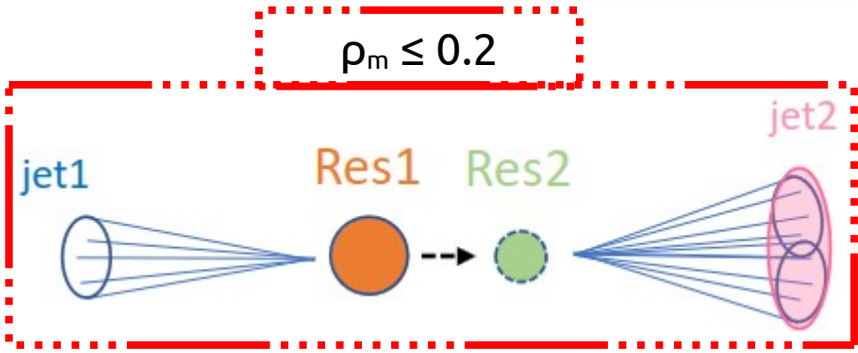
Search for high-mass resonances decaying to a jet and a Lorentz-boosted resonance in proton-proton collisions at √s=13TeV

CMS-PAS-EXO-20-007
Phys. Lett. B, 832, 137263

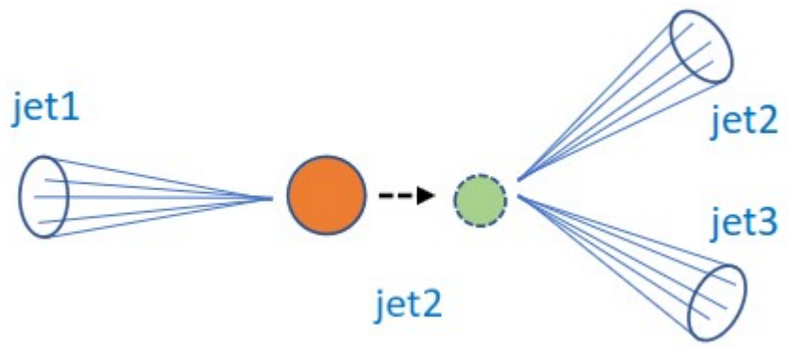
Intermission for context

Analysis Motivation

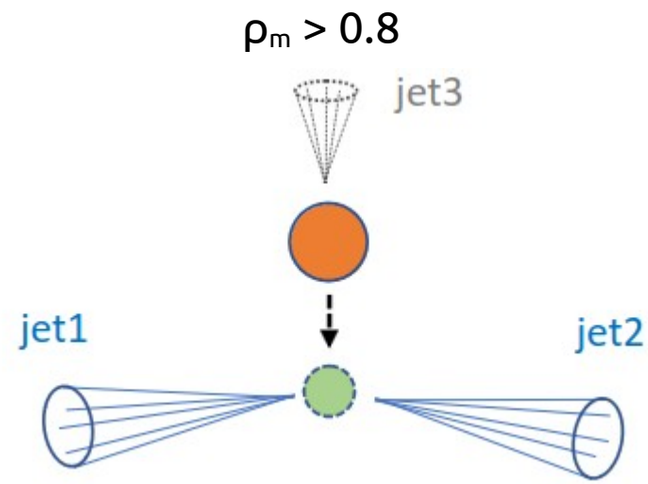
- Physics cases:
  - **Cascade decay** (Res1 → Res2...)
    - Extra dimensions KK gauge boson: $G_{KK} \rightarrow \varphi g \rightarrow ggg$[3]
    - $m_{Res2} / m_{Res1} = \rho_m \leq 0.2 \Rightarrow$ One jet + one **boosted** jet pair ⇒ This analysis.



$0.2 \leq \rho_m \leq 0.8$



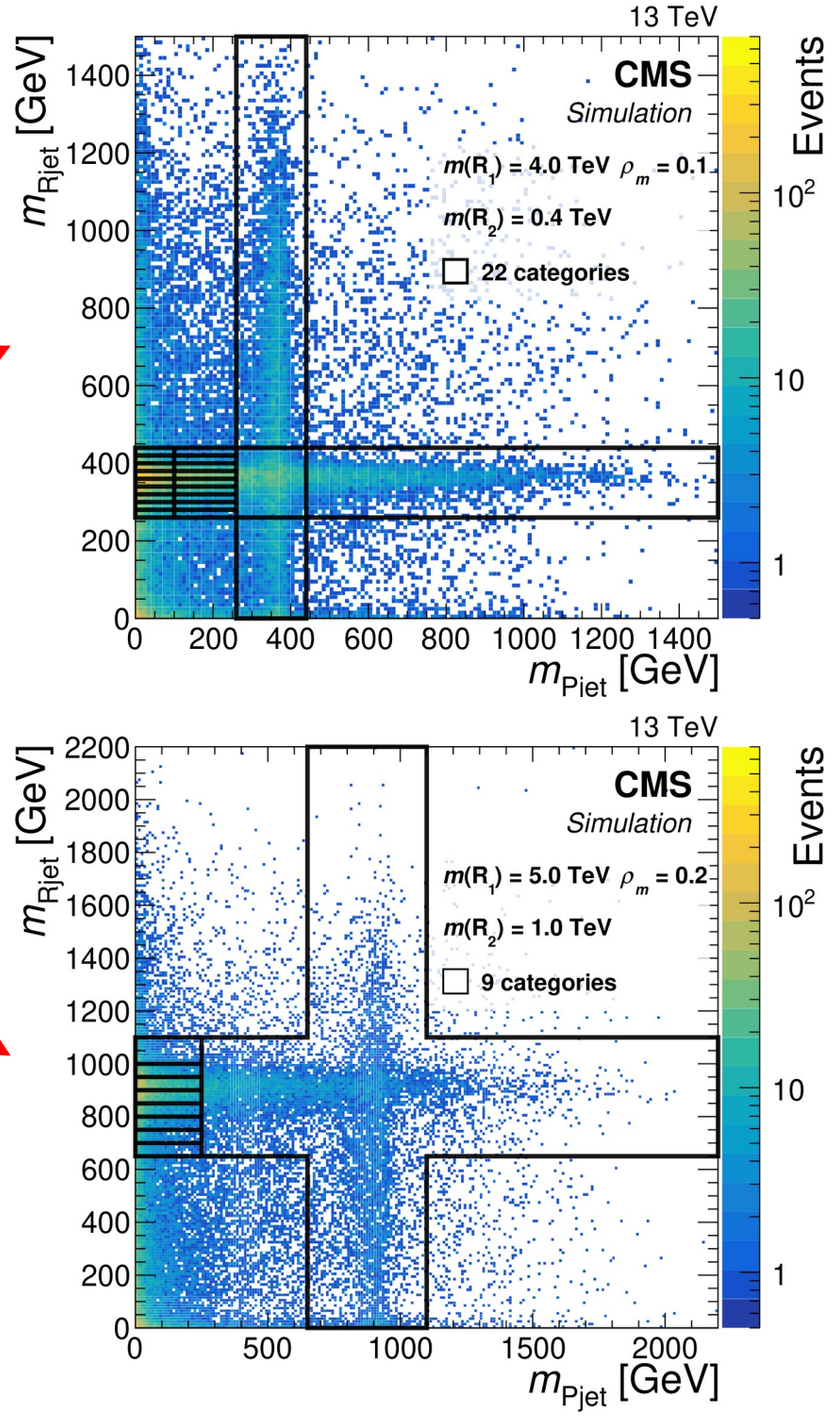
- Reconstruction strategy:
  - **AK15 jets** to recover:
    - Both jets from **Res2**.
    - Hard gluon radiation from **isolated g**.
  - Exploit **N-subjettiness**:
    - Jet with low τ_{21}→ **Res2** candidate!



[3]: arXiv:hep-ph/9606311

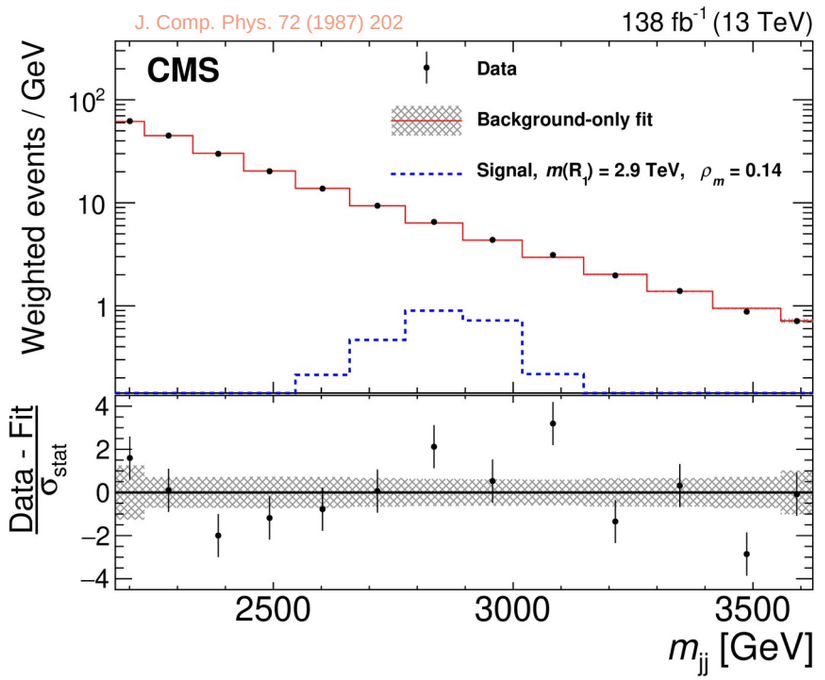
Analysis Strategy

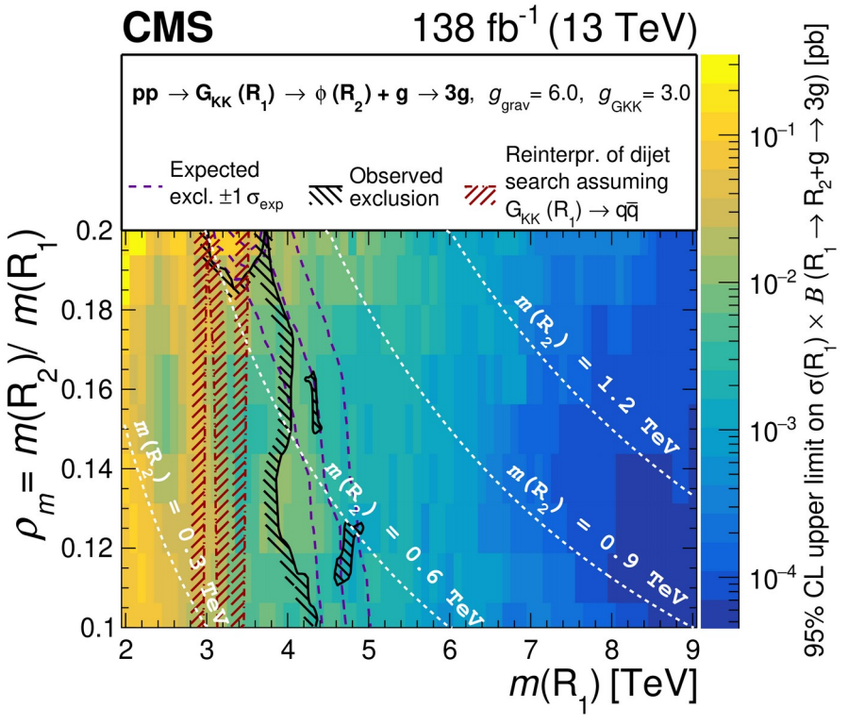
- **Event selection:**
  - 2 AK15 jets (p_T > 100 GeV & |η| < 2.5).
  - $\Delta\eta_{jj}$ < 1.3 (QCD suppression)
  - m_{jj} > 1.6 TeV (trigger selection)
- **Categorization:**
  - Optimize signal significance:
    - $m_{Res2} \leq 0.6$ TeV ⇒ 22 categories
    - $0.6 < m_{Res2} \leq 1.2$ TeV ⇒ 9 categories
    - $m_{Res2} > 1.2$ TeV ⇒ 1 categories
  - Also recovers wrong Res2-jet assignment.
- **Parametrization:**
  - Signal: Double-sided Crystal Ball from simulation.
  - Background: Smoothly falling function from data.



Results

- **Signal extraction:**
  - Binned, simultaneous MLL fit on m_{jj}.
    - Binning determined by m_{jj} resolution (~5%).
  - Fit range → $0.65m_{Res1} \leq m_{jj} \leq 1.15m_{Res1}$
    - Lower bound adjusted/category rejected based on existence of m_{jj} turn-on near signal peak.
- No significant excess observed:
  - Max local(global) significance = 3.2σ(<1.8σ).
- 1st search to probe 3-parton final state using a dijet signature:
  - Significantly extend excluded parameter space for G_{KK} model (~1 TeV).





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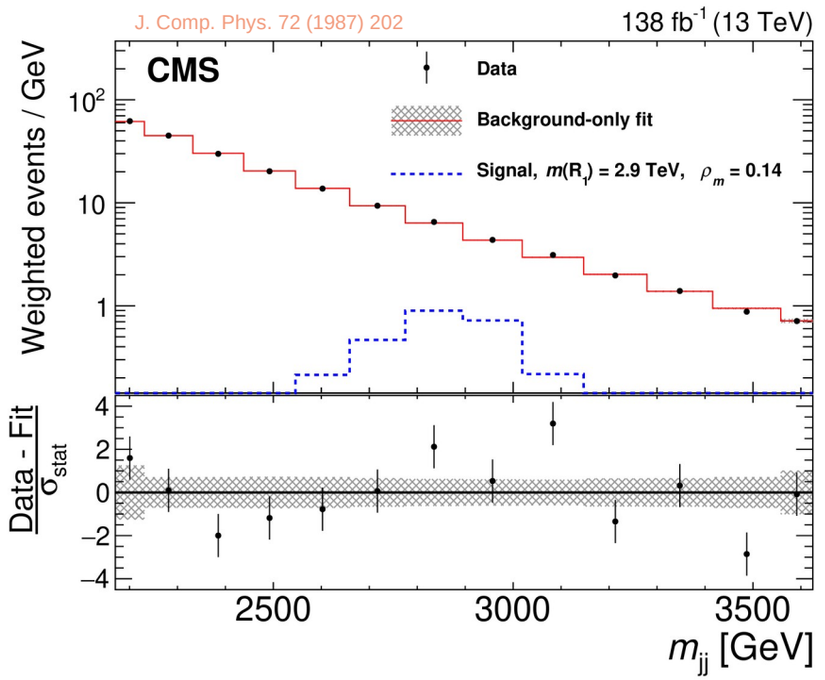
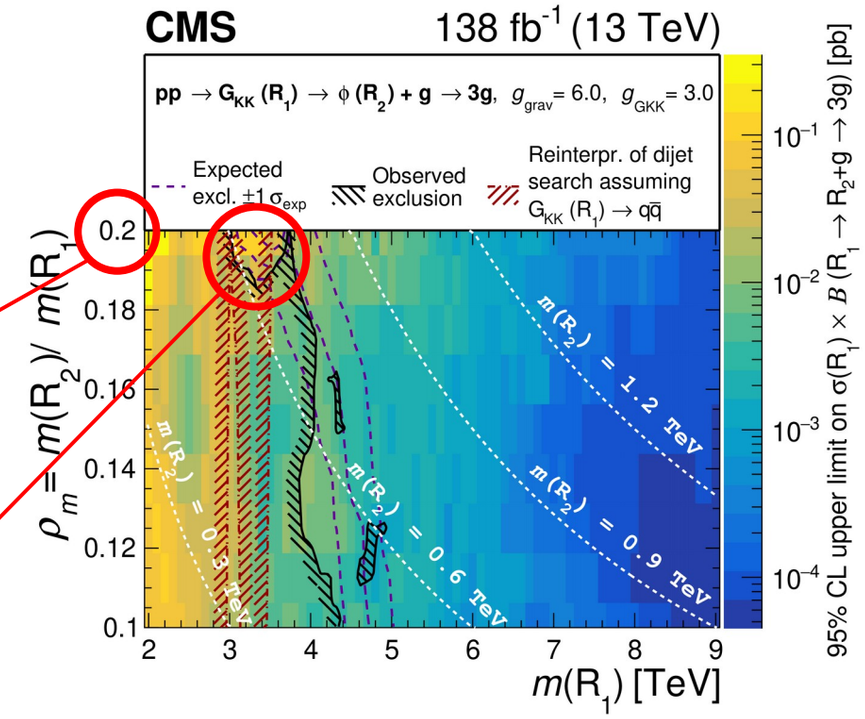




Can we go higher?
Can we complement?

Search for narrow trijet resonances in proton-proton collisions at √s = 13 TeV on CMS

CMS-PAS-EXO-22-008

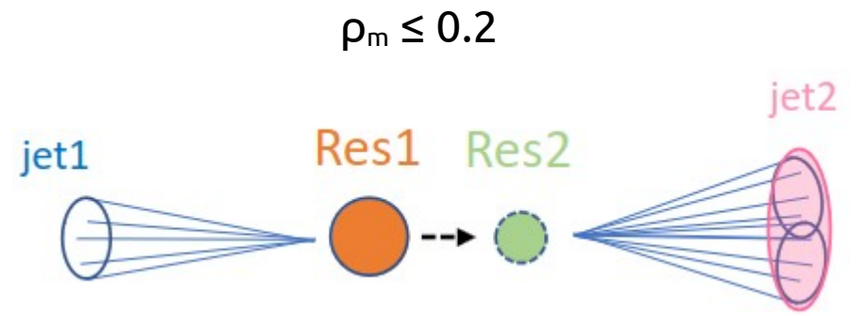
New!

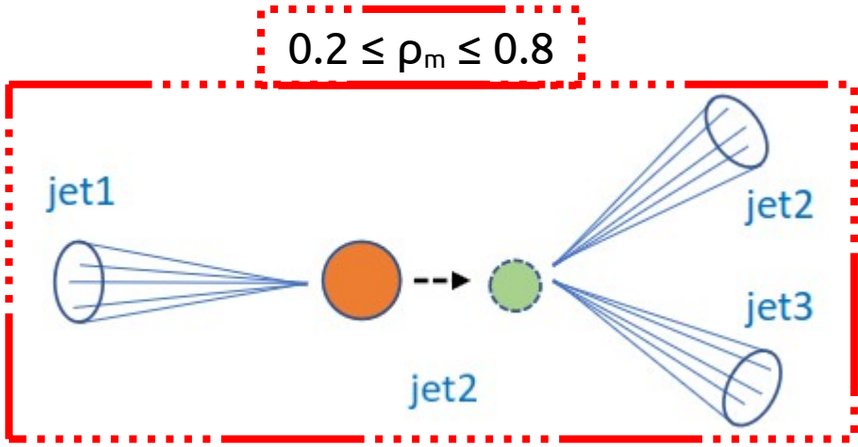
New!

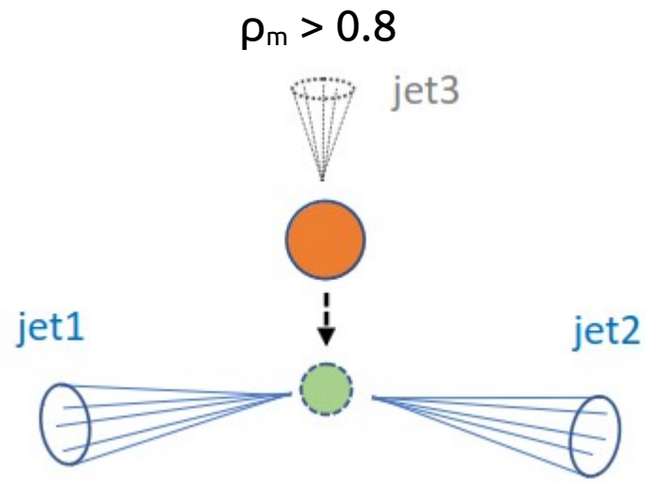
Analysis Motivation

- **1st generic search for 3-jet resonances!**
- Physics cases:
  - **Direct 3-body decay**
    - Benchmark model:
      $Z_R \rightarrow ggg$[4]
      $\Gamma \sim 3(0.01)\%$ for nominal(narrow) hypothesis.
  - **Cascade decay** (Res1 → Res2...)
    - Extra dimensions KK gauge boson:
      $G_{KK} \rightarrow \varphi g \rightarrow ggg$[3]
    - Compositeness excited quarks:
      $q^* \rightarrow W'q \rightarrow qqq$[3]
    - $0.2 \leq \rho_m \leq 0.8 \Rightarrow$

      Three **resolved** jets ⇒ This analysis.
- Analysis based on full Run 2 CMS data set.



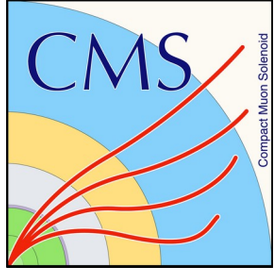




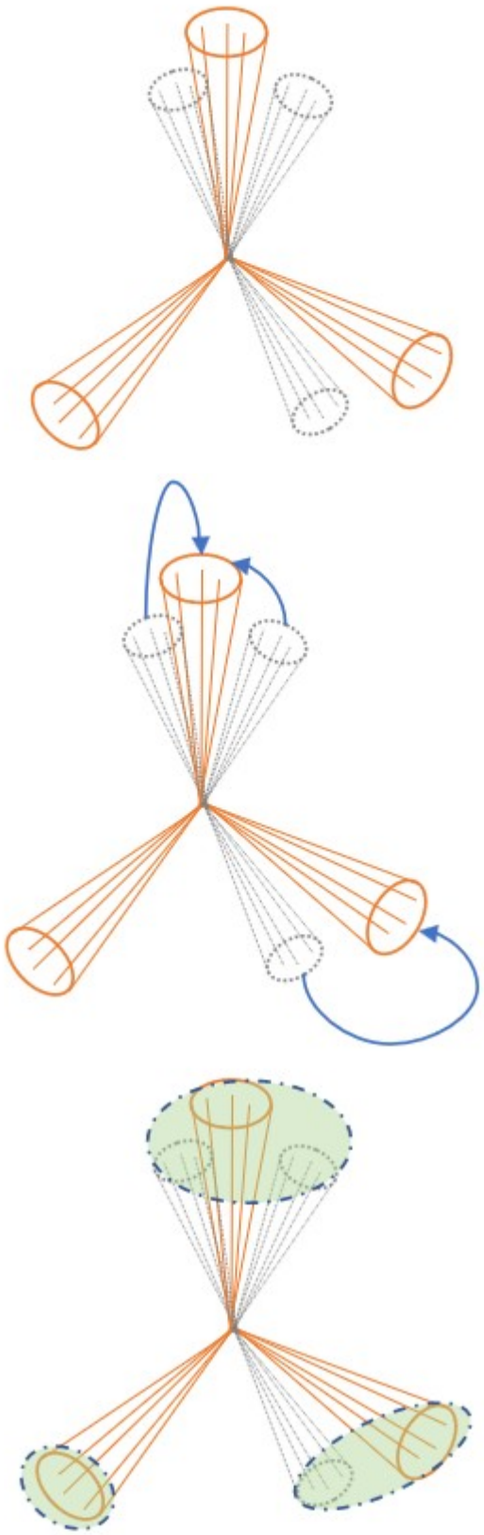
[4]: arXiv:1612.00047

New!

Trijet Selection



- Final state gluons ⇒
  Energy outside the AK4 cone.
  - Add AK4 jets to recover energy:
    - **Seeds**: 3 jets (p_T > 100 GeV & |η| < 2.5).
    - **Combine**: Jets (p_T > 30 GeV & |η| < 2.5) within ΔR < 1.1.
    - **Result**: 3 wide-jets used for selection.

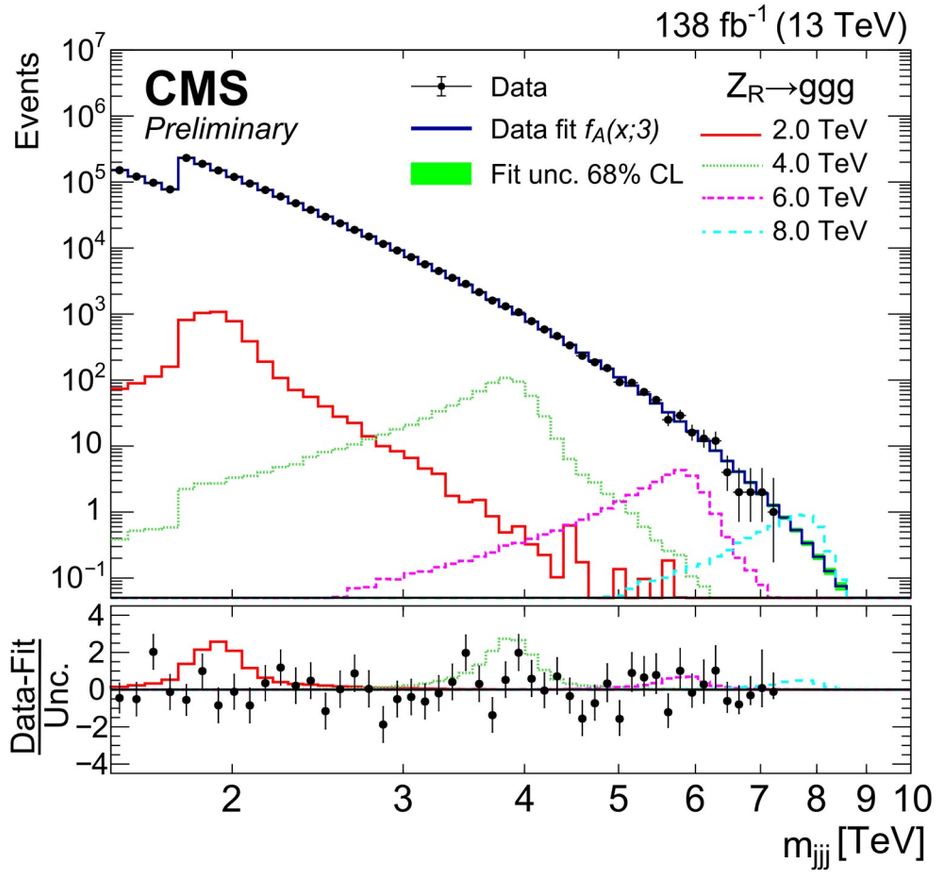


- **Selection**:
  - Optimized by S/√B studies →
    - $\max(\Delta\eta_{jj}) < 1.6$
    - $\max(\Delta R_{jj}) < 3.0$
  - Limited by trigger selection →
    - m_{jjj} > 1.50 TeV for 2016.
    - m_{jjj} > 1.76 TeV for 2017/2018.

New!

Signal & Bkg Modelling

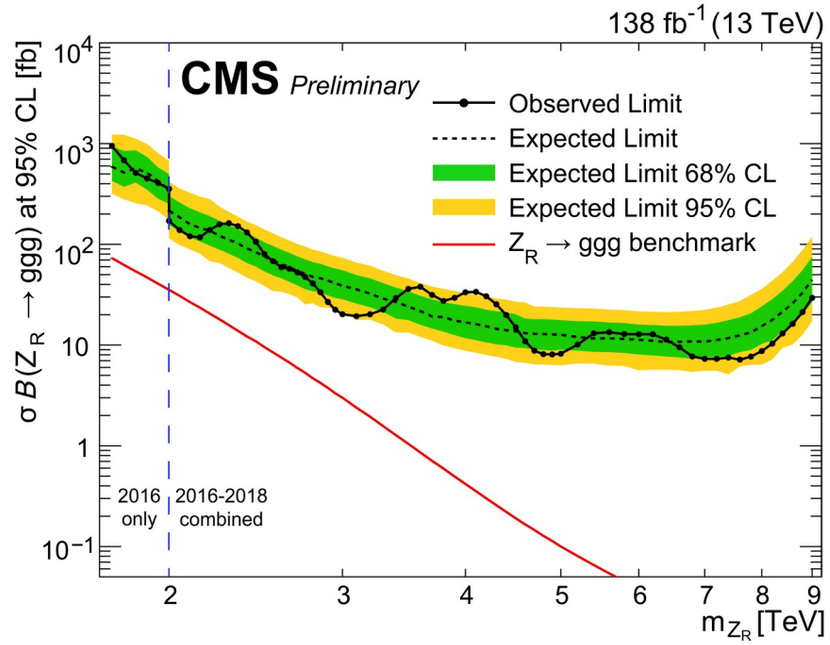
- **Signal extraction**:
  Binned, MLL fit on m_{jjj}.
  - Binning determined by m_{jjj} resolution (2–4%).
- **Signal modelling**:
  Simulation templates.
  - Interpolated using the morphing method:
    - 50 GeV, $m_{jjj} \leq 3$ TeV
    - 100 GeV, $3 < m_{jjj} \leq 5$ TeV
    - 200 GeV, $m_{jjj} > 5$ TeV
- **Background modelling**:
  PDF envelope of empirical functions fit on data.
  - $$f_A(x;\,N) = p_0 \times \frac{(1-x)^{p_1}}{(x)^{\sum_{i=2}^{N} p_i \log^{i-2}(x)}}$$
    $$f_B(x;\,N) = p_0 \times \frac{e^{-p_1(x)}}{(x)^{\sum_{i=2} p_i \log^{i-2}(x)}}$$
    $$f_C(x;\,N) = p_0 \times (x)^{\sum_{i=1}^{N} p_i \log^{i-1}(x)}$$
  - Order determined by Fisher test.

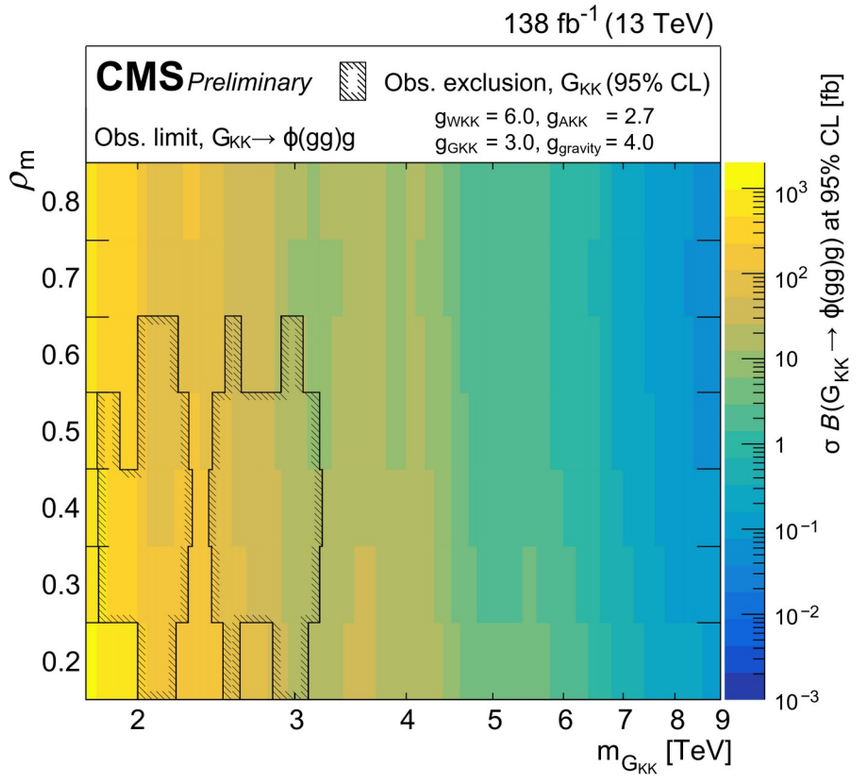


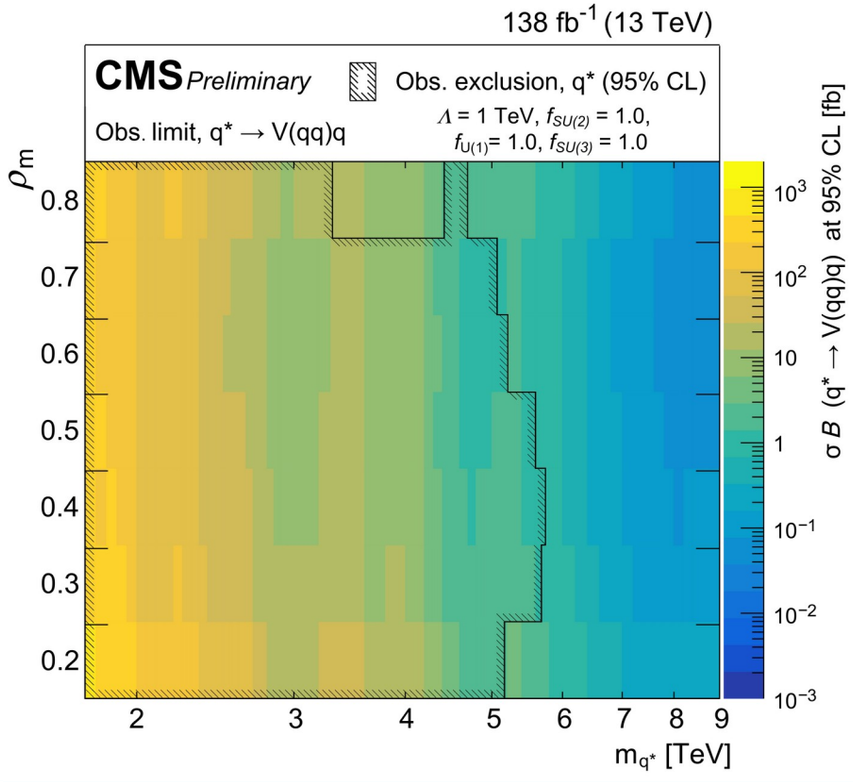
New!

Results

- 1st search of its kind →
  Extended parameter space explored!
- No signicant excess observed:
  - Max local(global) significance = 2.2σ(0.36σ).
- Exclusion limits:
  - No reach for Z_R with current dataset.
  - Res1 → Res2g → ggg excluded up to 3.1 TeV.
  - Res1 → Res2q → qqq excluded up to 6.0 TeV.







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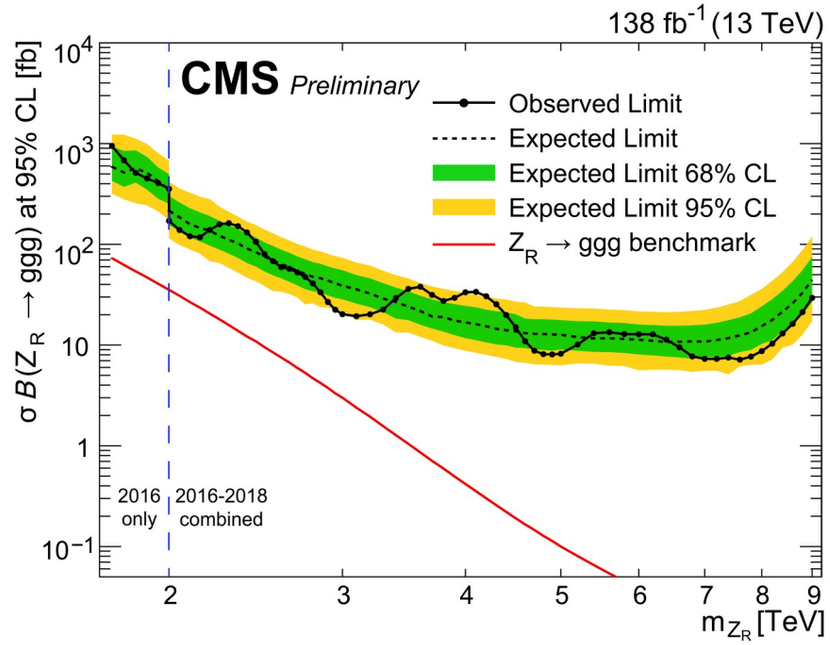
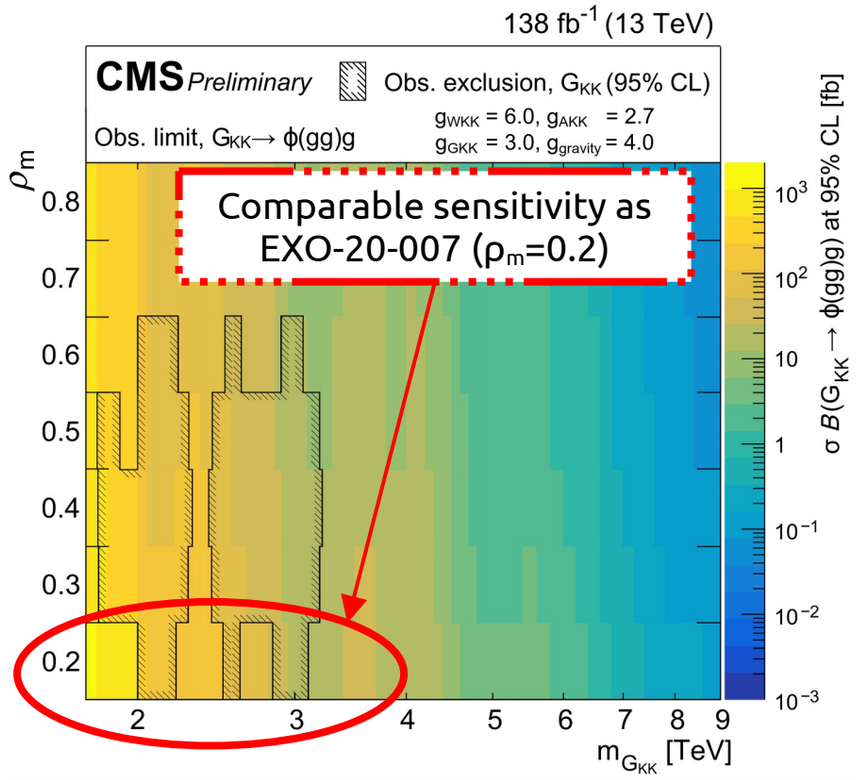
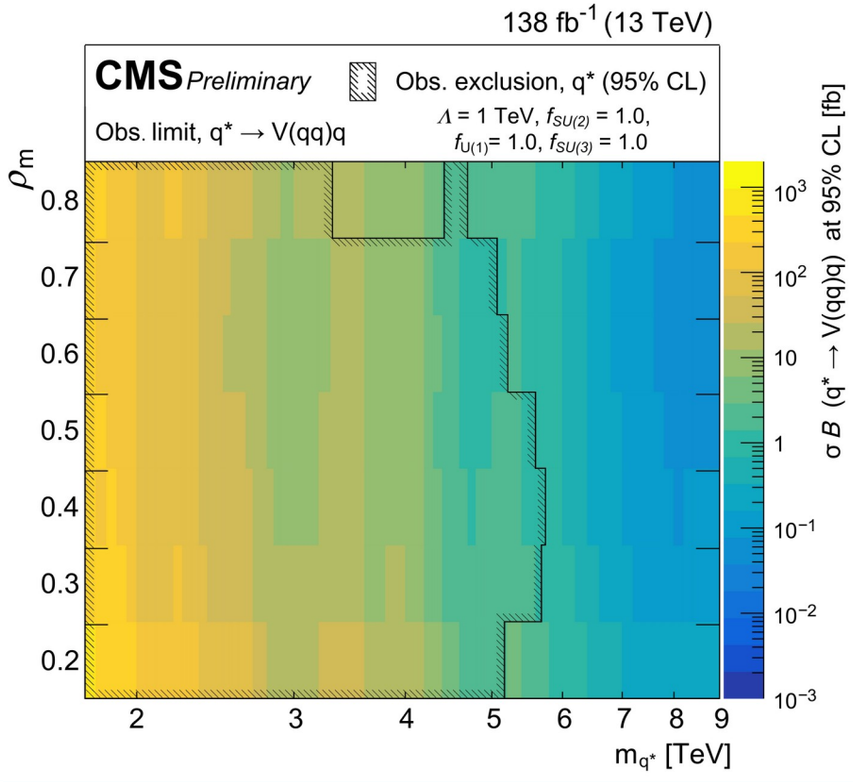
  - Res1 → Res2g → ggg excluded up to 3.1 TeV.
  - Res1 → Res2q → qqq excluded up to 6.0 TeV.







Highlights Summarized

- **Major CMS effort to probe New Physics!**
- Examples of **BSM models**:
  - Z' boson.
  - Warped dimensions.
  - Compositeness.
- **Utilizing all tools** available in novel ways.
  - In this talk: **Jets** as the common tool.
- **What the future holds:**
  - More models to probe!
  - More tools to use!
  - More data to explore!

⇒ More analyses being prepared!