CMS searches for exotic signatures

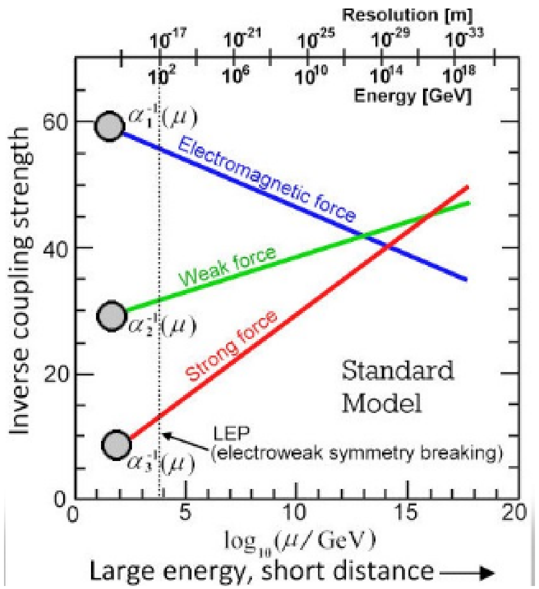
Eirini Tziaferi
National and Kapodistrian University of Athens (NKUA)

on behalf of the CMS collaboration

Introduction: SM successful … but incomplete

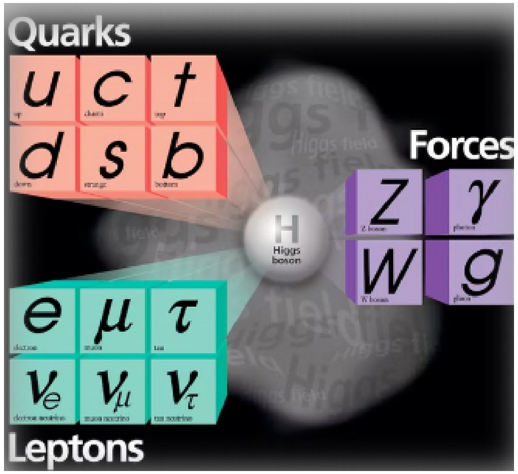
Hierarchy Problem:
- Why is $M_{Pl}/M_{EW} \sim 10^{17}$?

Unification of Gauge couplings:
- Why are gauge couplings so different, are they unified at a higher scale?
- Are there more forces in nature?



Origin of generations:
- Why do quarks and leptons come in three generations?
- Are they elementary particles?

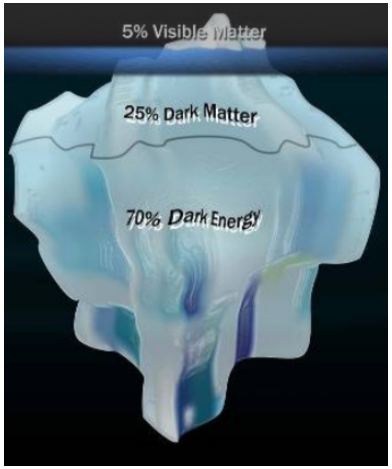
Gravity: SM describes 3 of the 4 fundamental interactions at the quantum level (microscopically) but gravity is only treated classically.



Dark matter:
- What is 25% of the Universe made off, and how does it interact with ordinary matter?

CP Violation:
- What is the origin?

Neutrino masses:
- What is the origin and nature of m_ν?

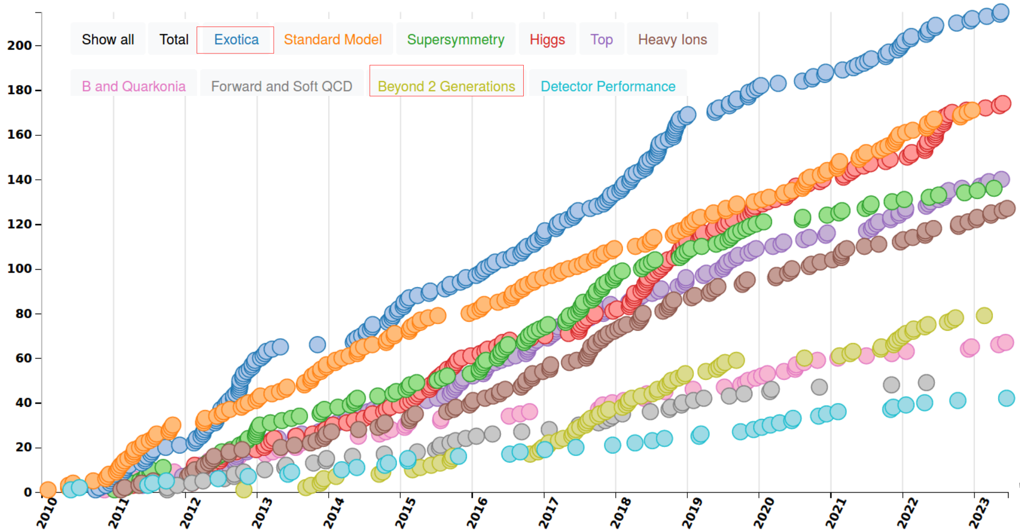


Introduction

- The shortcomings of the SM motivates a **comprehensive program of searches for beyond-the-SM (BSM) physics** at high energy colliders.

- Many BSM models describe new phenomena in the **final states with gluon, light and heavy flavor jets, leptons, and heavy bosons**.

- A selection of analyses with the aforementioned final states, which became public very recently, will be presented.
  - All analyses used data from **full Run II** (2016-2018) with an **integrated luminosity of 138 fb^{-1}**.
  - They belong to the physics analysis groups of CMS: EXOTICA (EXO public results) and B2G (B2G public results).



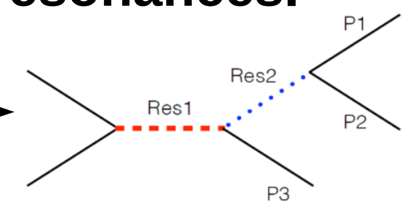
Trijet searches

THREE IS A CHARM!

Physics Briefing

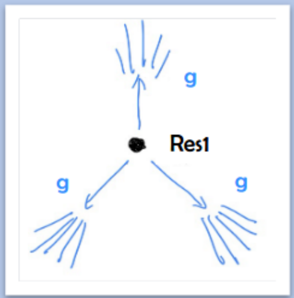
CMS-EXO-22-008

First generic search for <u>singly-produced</u> three-jet, or trijet, resonances.
It is a continuation of the search for trijet (3g) resonances in events with a boosted dijet (EXO-20-007).



Signal Models predicting trijet resonances:

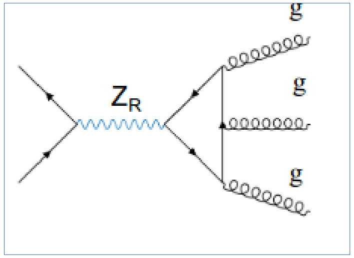
Direct 3-body decay ($X \to jjj$)

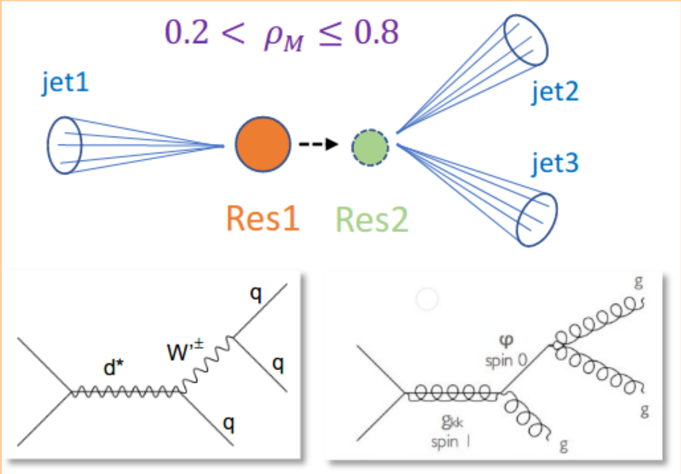


Left-right symmetry Z_R
arXiv:hep-ph/9606311

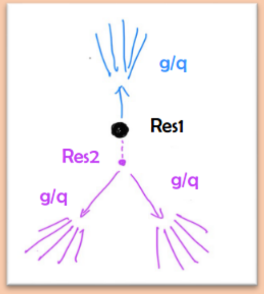
M_{ZR}: [1.75 – 9] TeV

Narrow (0.01%) and Nominal (SM-like coupling, ~3%) width





Cascade decay ($X \to Yj \to jjj$)



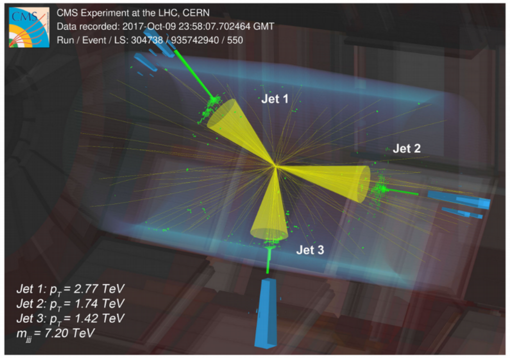
Extra dimensions KK gauge boson
arXiv:1612.00047 [hep-ph]

Compositeness excited quarks
arXiv:1612.00047 [hep-ph]

M_{Res1}: [1.75 – 9] TeV

$\rho_M = M_{Res2} / M_{Res1}$: [0.2-0.8]

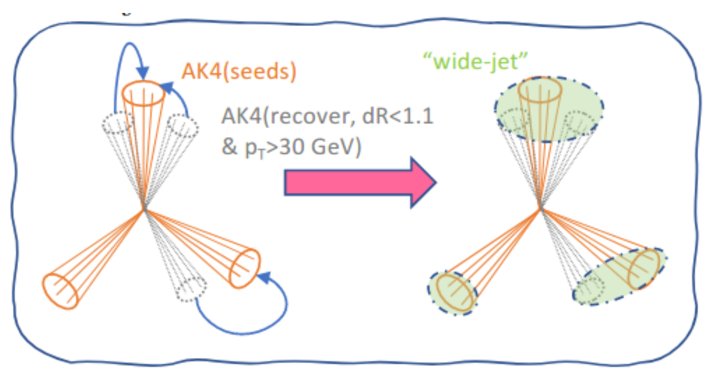
Experimental Signature:
3 resolved jets



Trijet searches

Analysis Criteria:

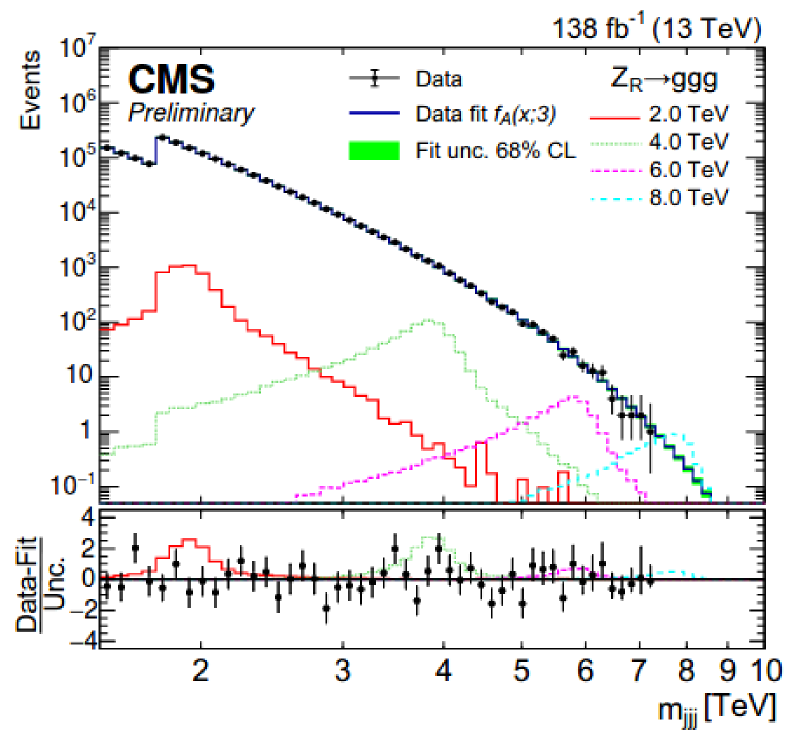
- 3 wide (for recovering FSR) AK4 jets in the tracker coverage
- Δη (between any of the 3 wide jets)<1.6 to suppresses QCD (t-ch.) and enhance signal (s-ch.).
- Trijet invariant mass,m_{jjj}, above a certain threshold to be fully trigger efficient (different for 2016 vs. 2017,2018).



Main backgrounds:

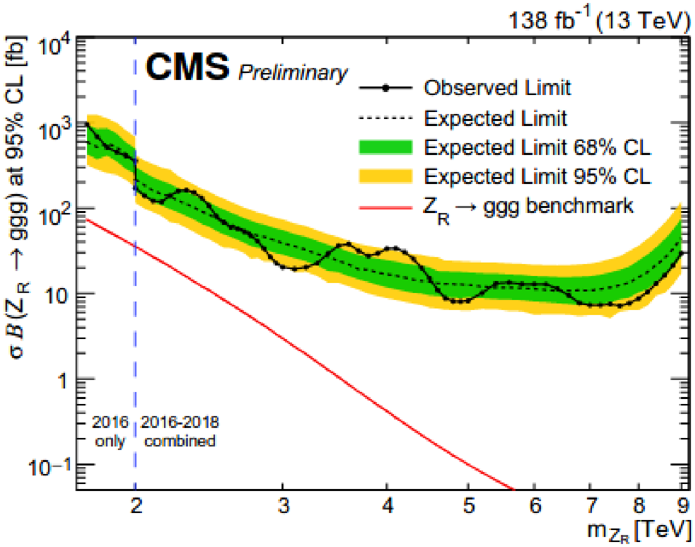
Multijet QCD production estimated with a data-driven method using several smoothly falling empirical functions.

- Discrete profiling (envelope) method to incorporate difference between background function forms.

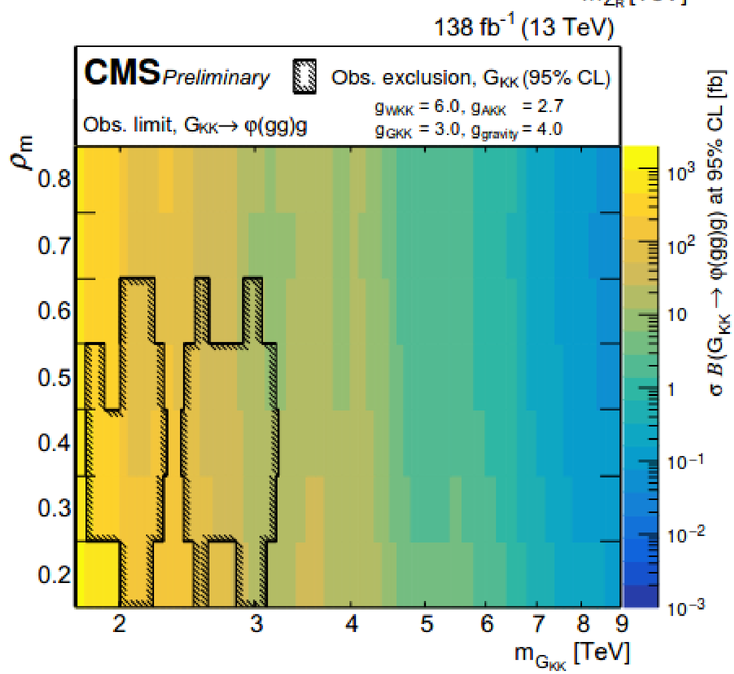


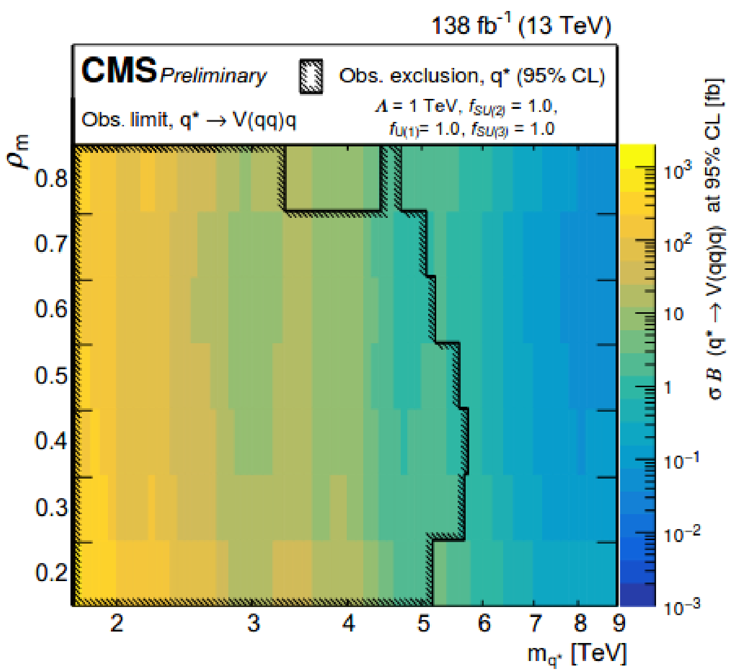
Bump hunt search on m_{jjj} distribution.

Trijet searches



- The current data set does not provide sufficient sensitivity to constrain the Z_R model.
- At ρ_m=0.2, a similar level of sensitivity is achieved to that of a previous CMS search (trijets boosted) for the 3g decay mode.

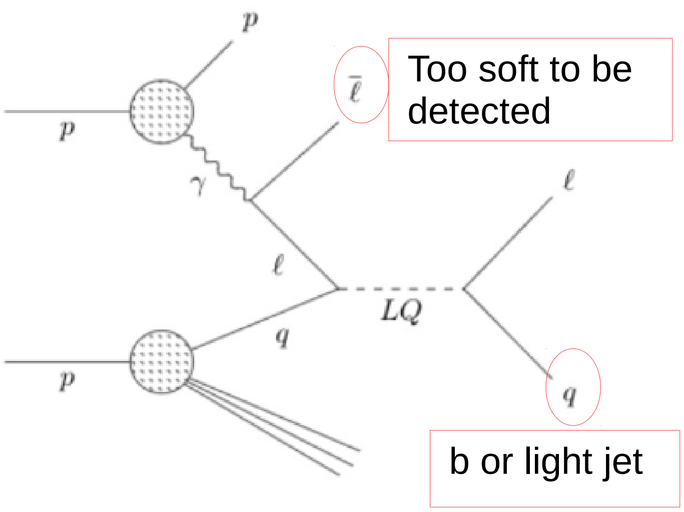




LQs in l-q collisions

CMS-EXO-22-018

- **First search** using LQs produced from **lepton-quark collisions**.
- **Precise signal modeling** made possible by recent [1,2] lepton PDF calculations at NLO with relatively small uncertainties.



Signal characteristics:

- Jet and lepton back-to back → handle to reduce backgrounds
- Second lepton soft and forward → no combinatoric problem to reconstruct LQ mass

Experimental signature:

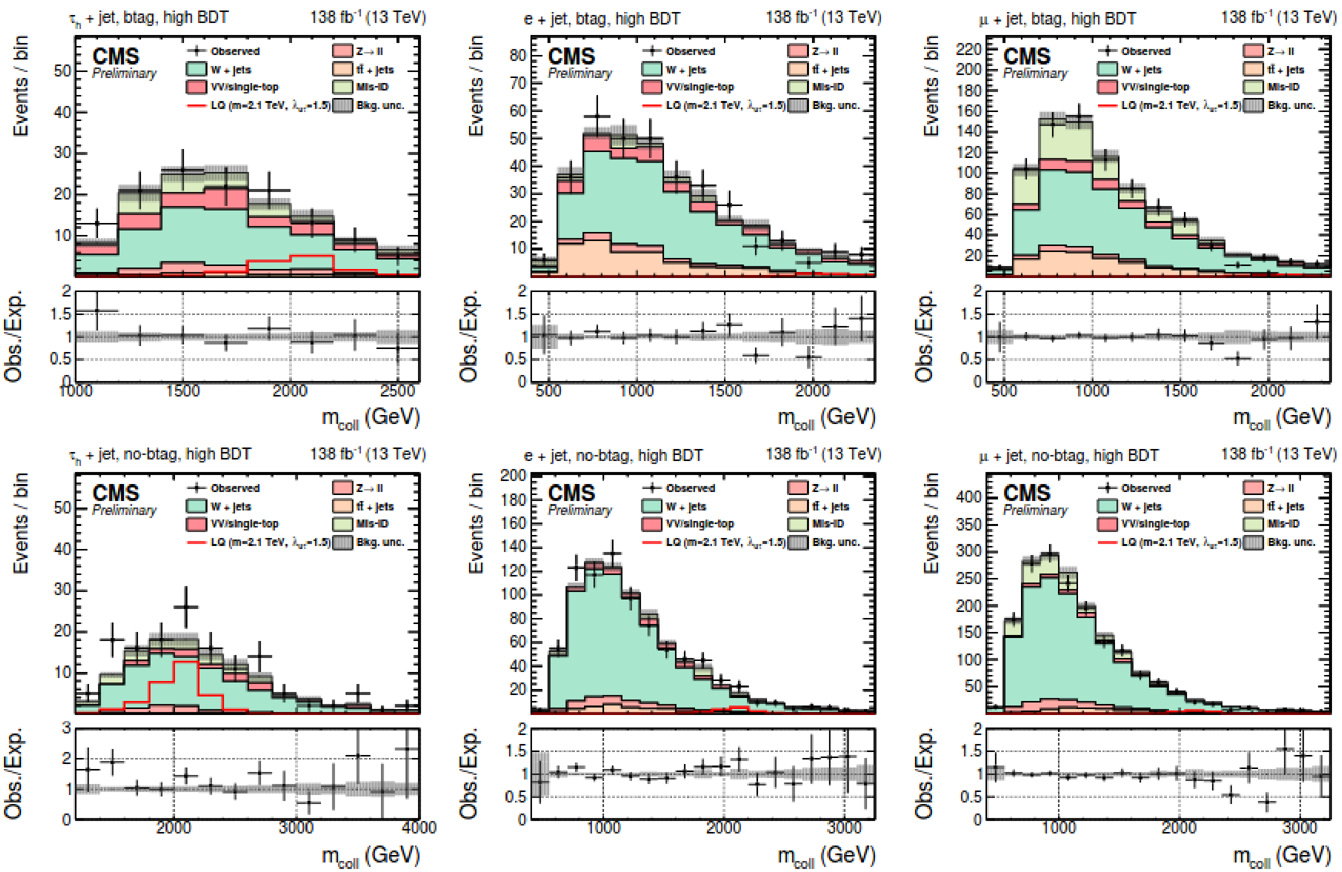
3 final states

- 1 central high-pT τ: reconstructed as τ_h, e, or μ (trigger object)+1 high pT jet
- Veto events with additional leptons (complementarity to single/pair production).

Bump hunt: search for narrow peak in lepton-jet mass distribution.

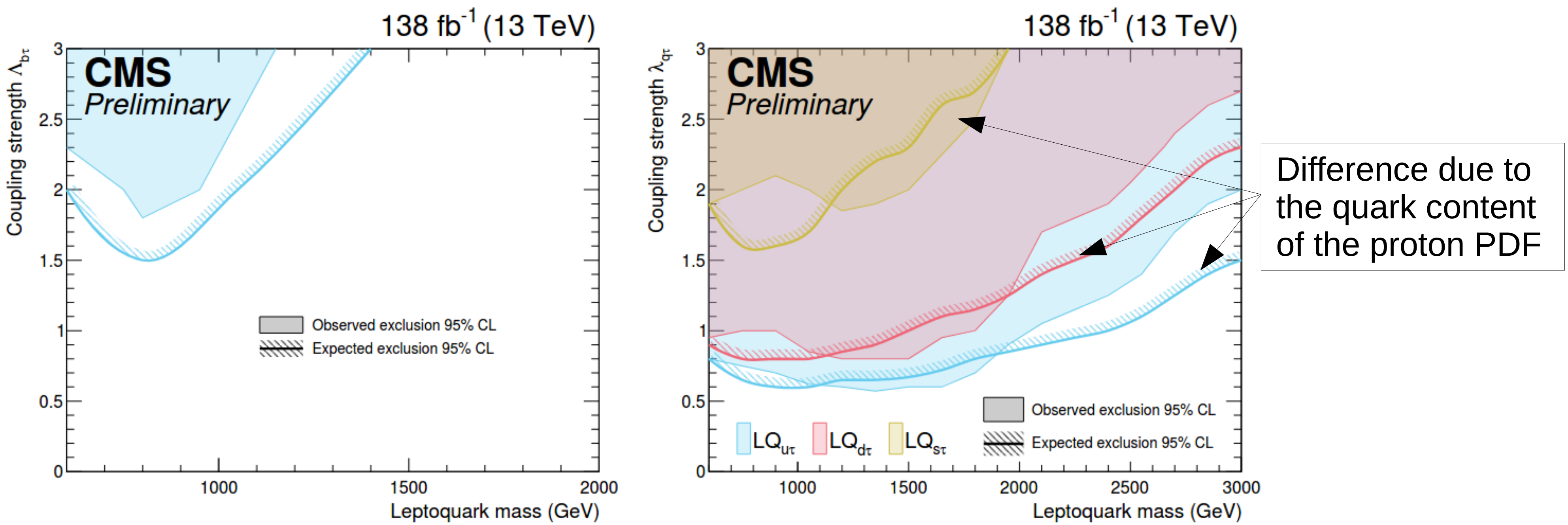
LQs in l-q collisions

Main backgrounds:
- W + jets, DY, VV, single top, ttbar estimated from simulation and normalized to their theoretical cross sections.
- QCD multijet, where a jet is mis-reconstructed, estimated with a "Fake Rate" method.



- LQ mass distribution reconstructed from τ, jet, and MET with collinear assumption.
- Two categories based on "b-tag" of leading jet.
- BDT score: trained with variables independent from LQ mass and jet flavor.

LQs in l-q collisions



- Limits are competitive with those set using other production modes at high mass and coupling values for bτ couplings
- Limits on the couplings of LQs to light-flavor quarks and τ leptons are set for the first time.
- **Probing multi-TeV LQ phase-space** otherwise inaccessible for direct production at the LHC.

High mass μμ resonances with b quarks

CMS-EXO-22-016

Signal Models:

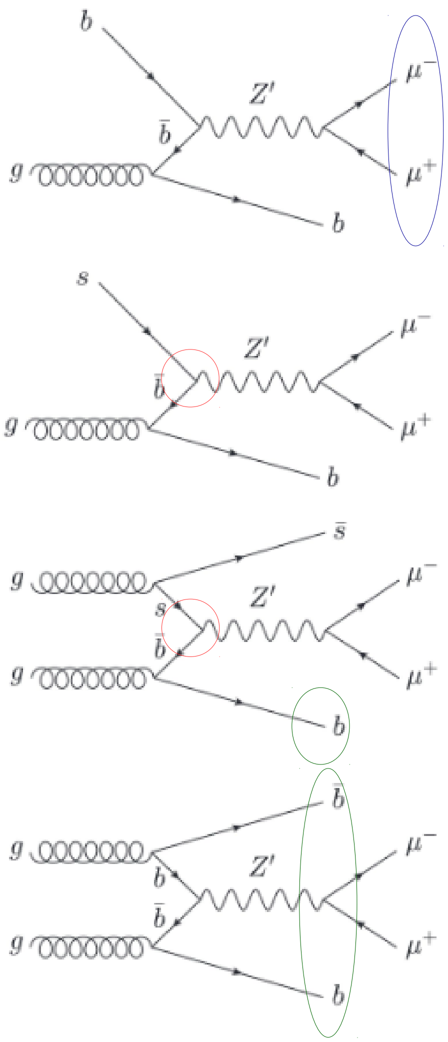
- Z' → μμ in association with ≥ 1 b-jet
- Z' coupling to b & s quarks

Experimental Signature:

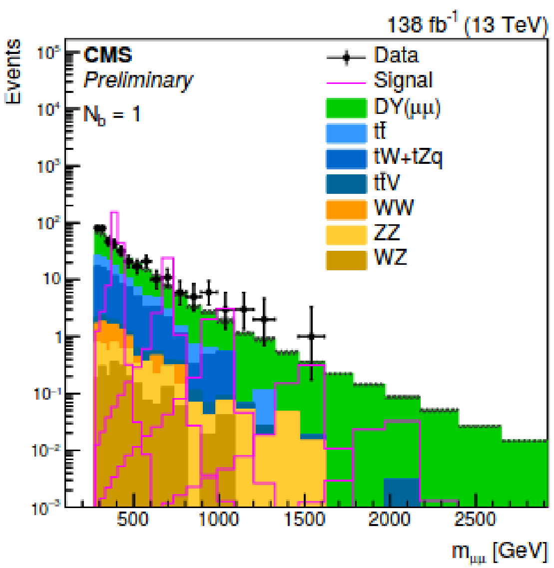
Pair of high pT μ's + at least 1 b jet

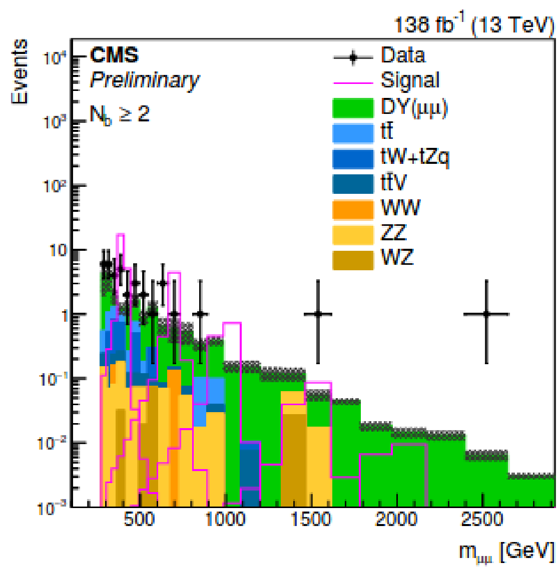
Main background:

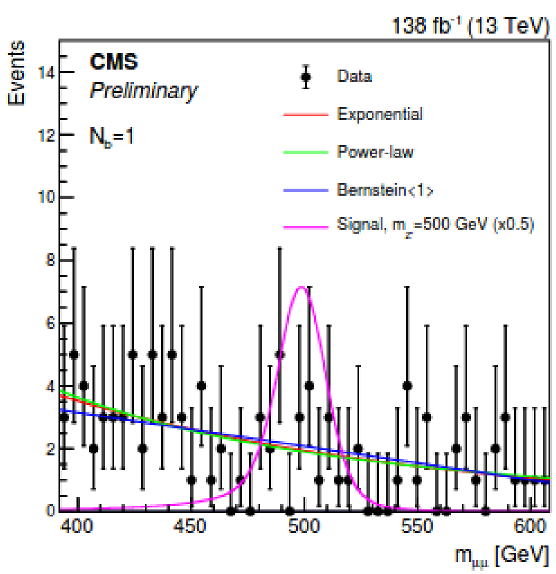
- DY (suppressed by b-jet requirement: $N_b \geq 1$)
- ttbar (suppressed by $m_{\mu b} > m_{top}$ requirement)
- other sub-dominant sources reduced by vetoing events
  - with any additional μ
  - with isolated track

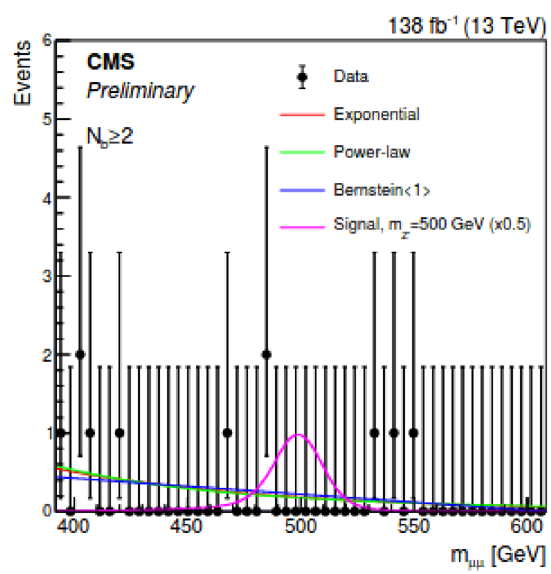


High mass μμ resonances with b quarks







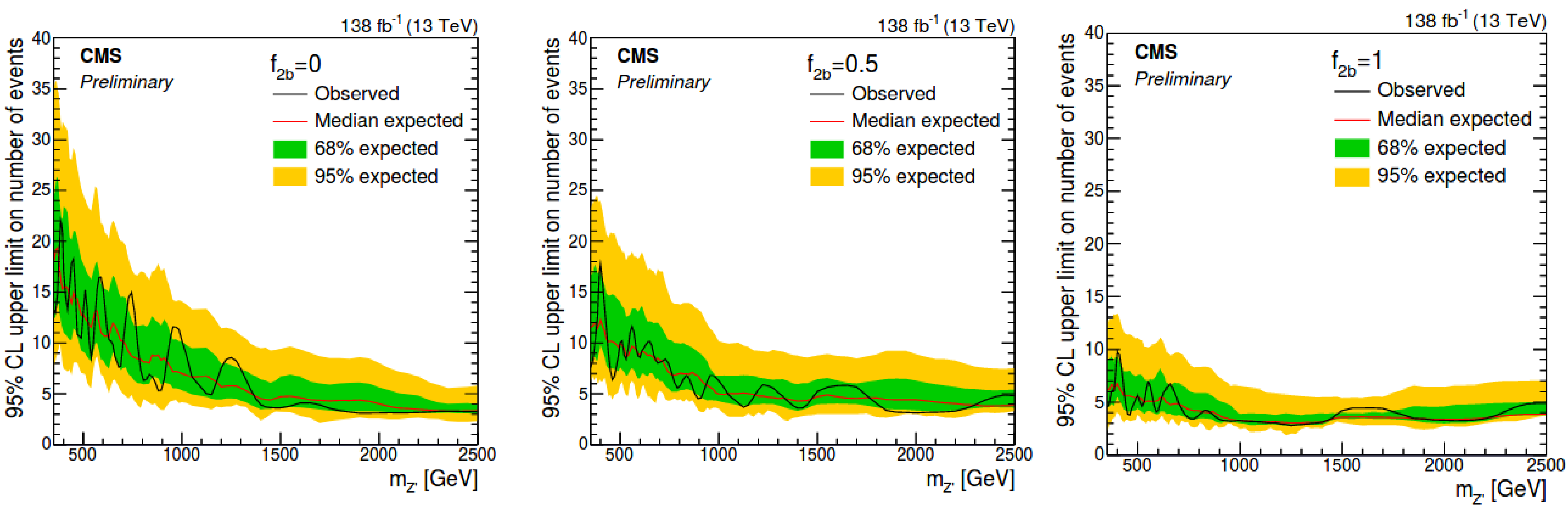


- **Background parametrization:** by analytic functions (exponential, power law & bernstein polynomials)
  - Discrete profiling (envelope) method to incorporate difference between background function forms.
- **Signal parametrization:** by Double-sided Crystal Ball + Gaussian
- **Bump hunt search on $m_{\mu\mu}$ distribution**

High mass μμ resonance with b quarks

Model-independent limits on the number of events with b quark jets.

- Easily re-interpretable for any neutral resonance model.
- Vary relative fraction of events in $N_b \geq 2$ category, $f_{2b} \Rightarrow$ Probe different signal hypotheses.



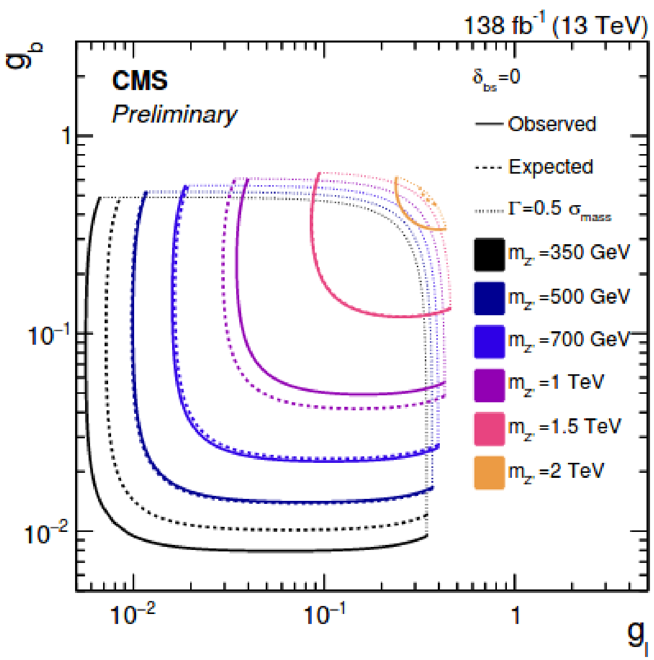
<u>Note for this plot</u>: $g_\ell = g_\nu = g_b$ (scales both Z→bb and Z→sb interactions)= 0.05 and δ_{bs} (scales only Z→sb interactions)= 0

High mass μμ resonance with b quarks

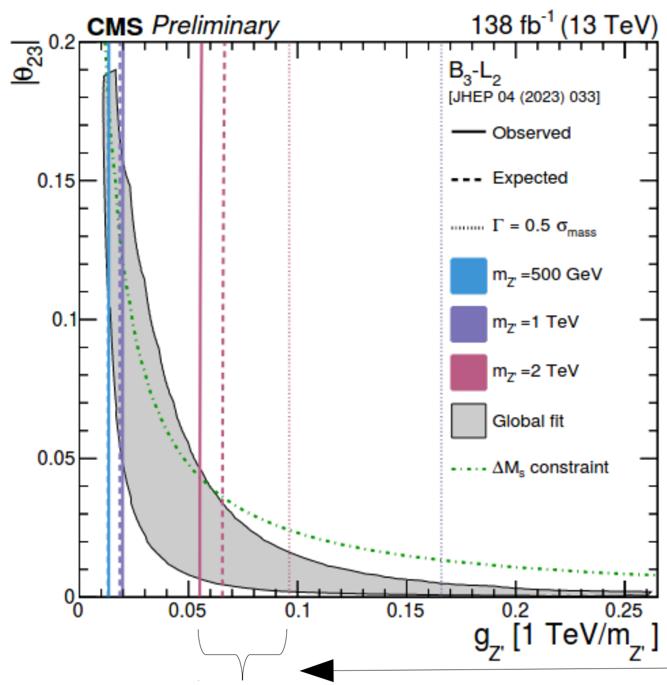
- Interpretation for the simplified **lepton flavor-universal** **model** ($g_\ell = g_\nu$)
  - Narrow-width resonance ⇒ Restrict to parameter space where $\Gamma_{Z'} < 0.5\ \sigma_{mass}$
- Set constraints on **B_3–L_2** **model**

  $g_{Z'}$ = coupling of Z’ to SM fermions

  θ_{23} = mixing angle btw. 2nd and 3rd generation quarks
- Most of the allowed parameter space is excluded for a Z’ with a mass ≤ 500 GeV. The constraints are less stringent for higher Z’ mass hypotheses.



The enclosed regions are excluded.



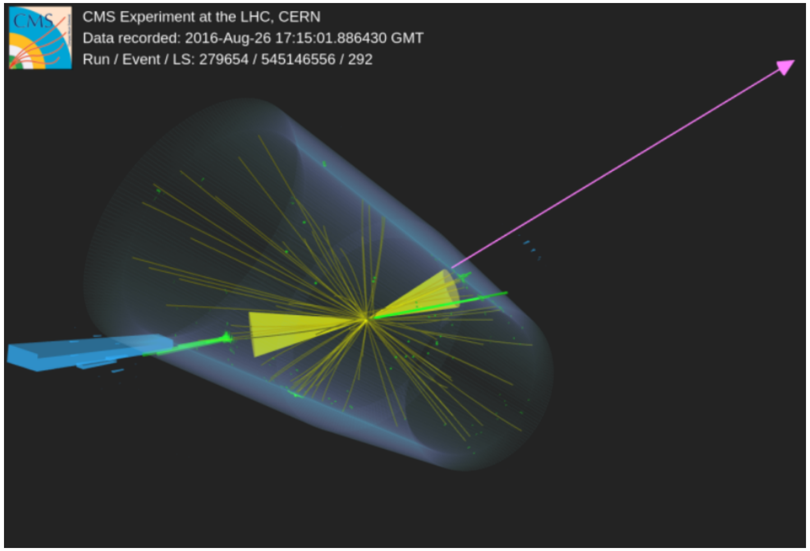
For a given mass, the region enclosed between the solid (dashed) and the dotted lines is (expected to be) excluded.

W' → tb in leptonic final states

CMS-B2G-20-012

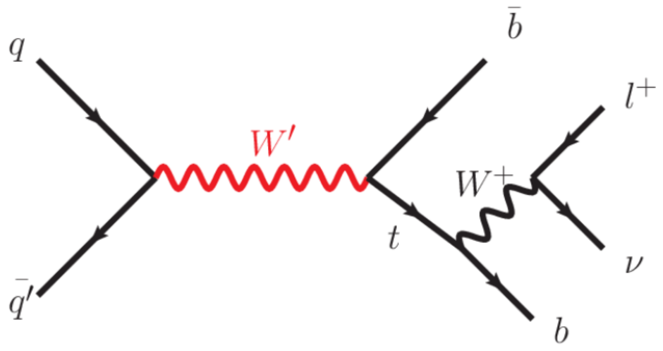
Signal Models:

- Models with W′ bosons couple to 3rd generation fermions → could be involved in the explanation of b physics flavor anomalies.
- Hypotheses: width ($\Gamma_{W'}/m_{W'}$ of 1, 10, 20 and 30%) and chirality (L, R-handed, or a combination of the two) to allow for interpretation in a wide array of models.



Experimental Signature:

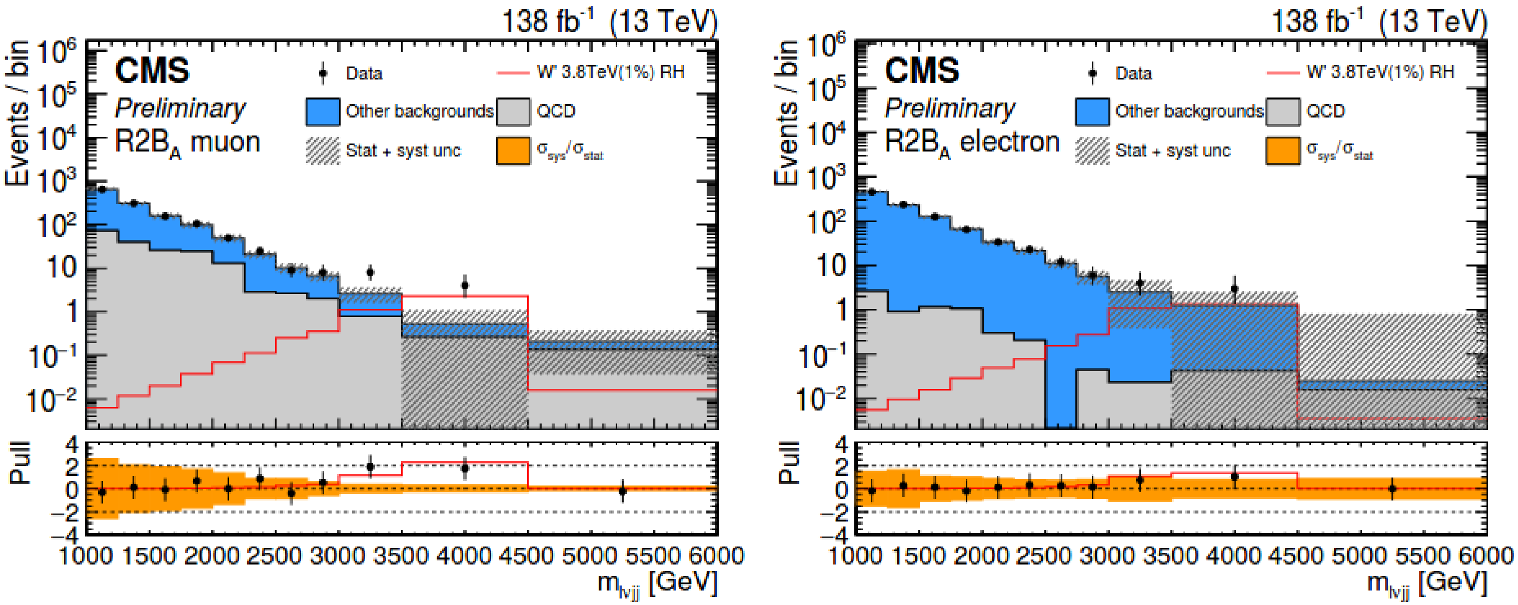
- 1 lepton (μ/e) passing the “mini-Isolation” requirement, 2 high energetic jets, MET
- Top reconstructed with lepton, MET, and a jet.
- W′ reconstructed with the reconstructed top and a jet.



W' → tb in leptonic final states

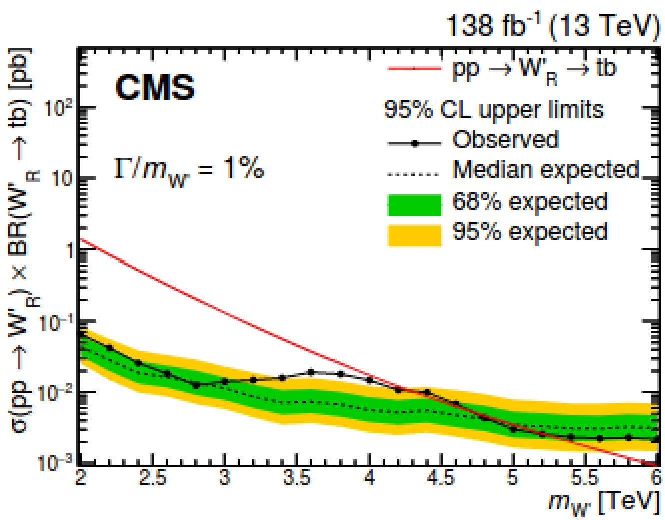
3 Signal Regions (SR): N_b = 1 (depending on whether the AK4 jets that are b tagged are used as jet_{top} or jet_W), ≥2.

Main background:
ttbar (suppressed by vetoing events with additional leptons), single top, W+jet, QCD are estimated from dedicated control regions through transfer factors.



Post fit distribution from the SR having two b-tag jets.

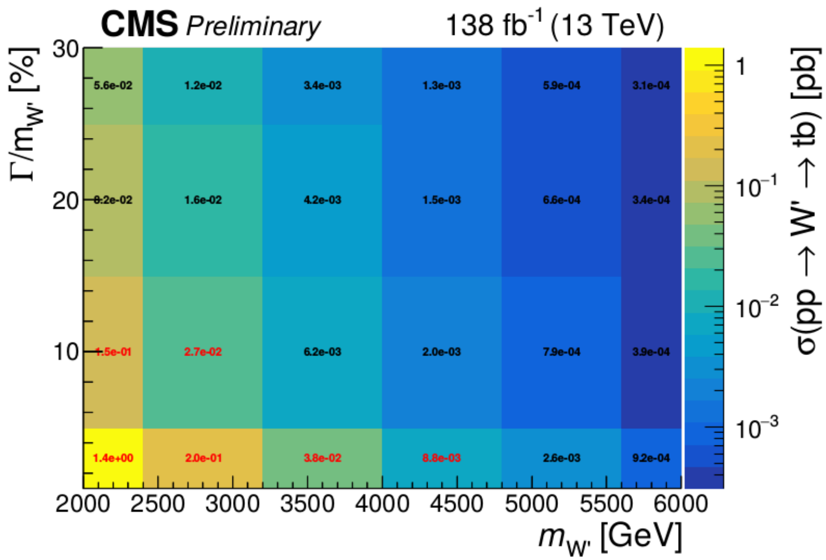
W' → tb in leptonic final states



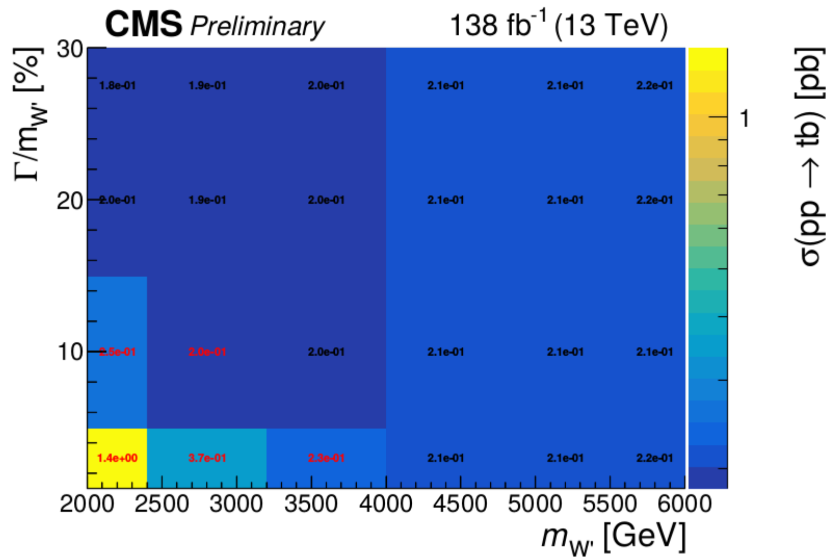
- An **excess** found in the W' boson candidate mass distribution, at **~3.8 TeV**
  → local (global) significance of 2.6 (2.0) σ.

- These are **the most stringent limits** to date on W' bosons decaying to a top and a bottom quark.

R-handed



L-handed



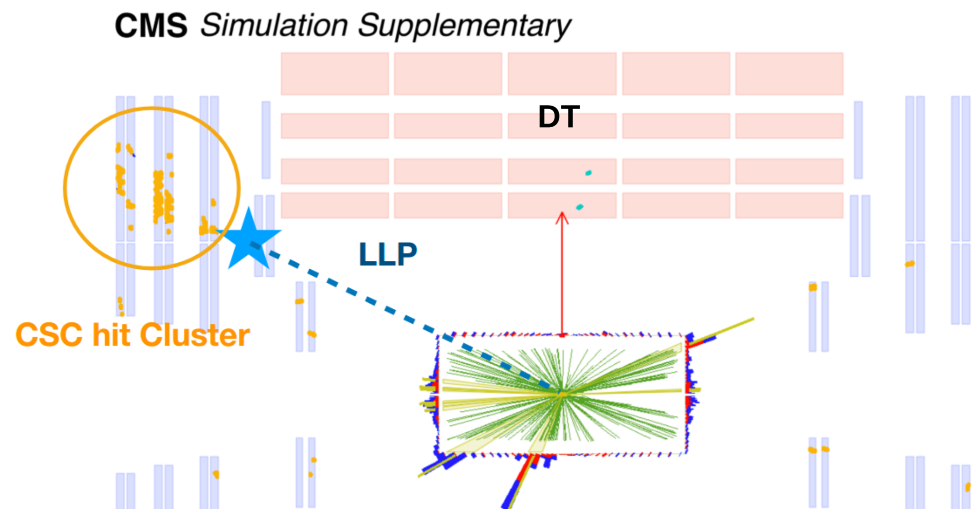
Numbers in red represent values of the excluded xsections < theoretical ones.

LLPs searches with muon detector showers

New at ICNFP 2023

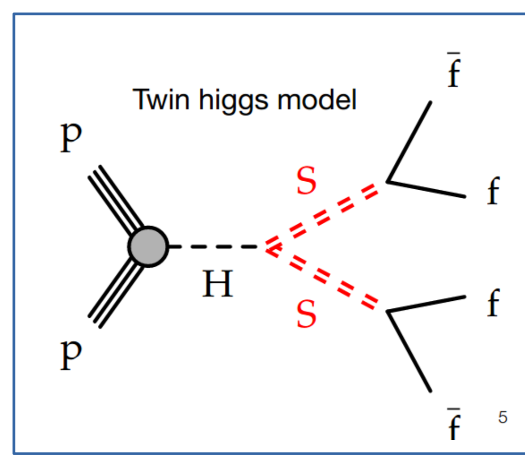
EXO-21-008

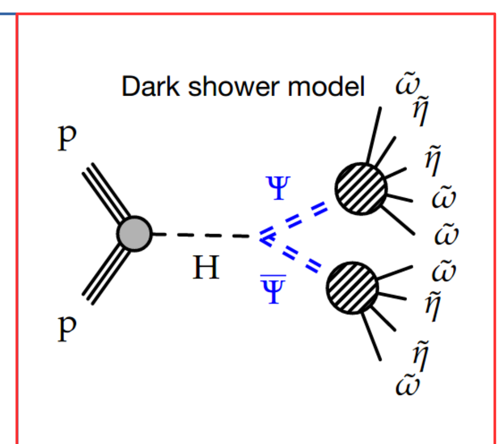
Covers **decays far away from IP** (sensitive to large cτ), complementary to searches using decays in the tracker region.



Signal Models:
While is a model independent search the results are interpreted in two models.

Experimental Signature:
- Large cluster of hits (>100 hits) in the muon system which acts as a sampling calorimeter: sensitive to a broad range of decays: quarks, taus, photons, electrons.
- High MET & ≥ 1 jet





LLPs searches with muon detector showers

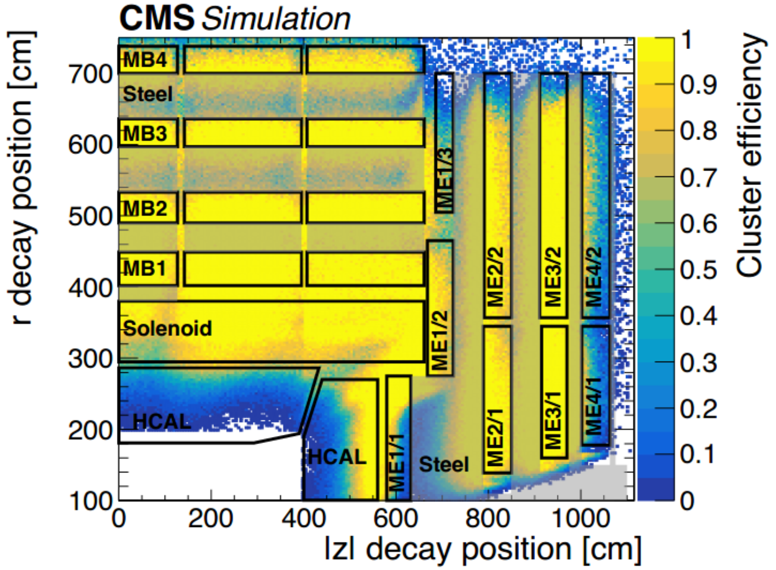
New at ICNFP 2023

Event categories (more sensitive to large, intermediate and low cτ):

- Single DT cluster
- Double clusters (DT-DT, CSC-CSC, DT-CSC)
- Single CSC cluster (no change wrt EXO-20-015)

Main background:
punch-through jets, μ's that undergo bremsstrahlung, and isolated hadrons from pileup, recoils, or underlying events → data-driven ABCD method for background estimation.

High cluster reconstruction efficiency throughout the detector.



Advantages over searches that employ displaced vertices:

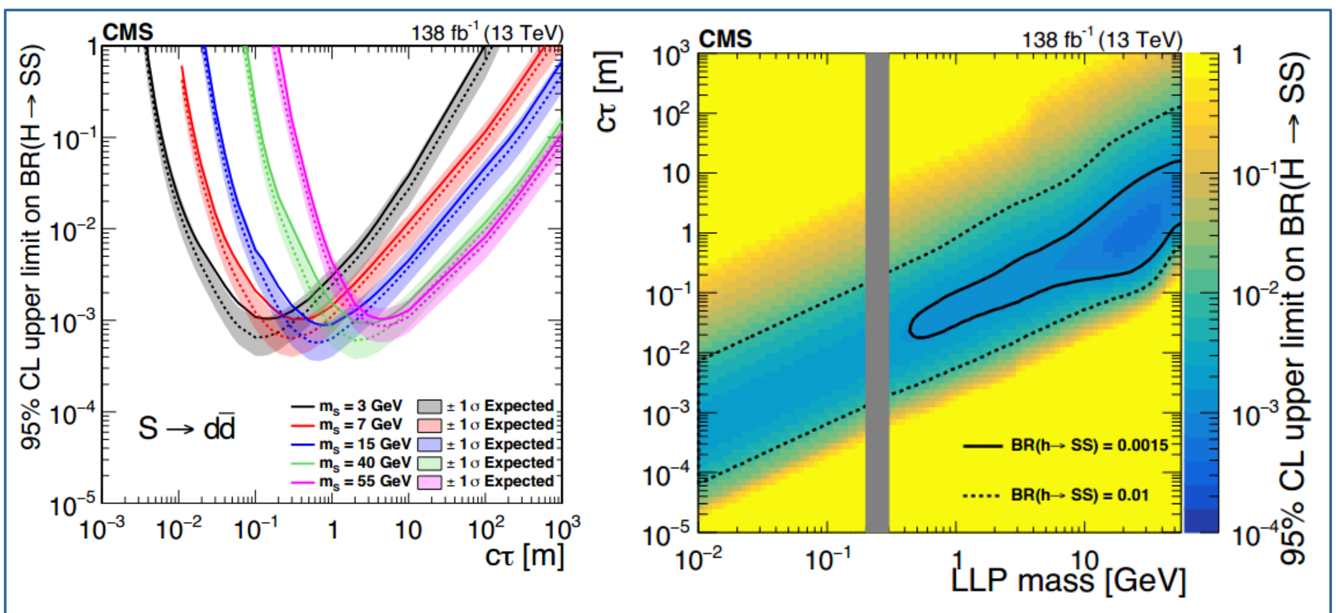
- Excellent background suppression from shielding material → allow detection of single LLP decay
- The calorimetric nature of the particle shower is not sensitive to the LLP mass => this search is equally sensitive to all LLP masses considered.

LLPs searches with muon detector showers

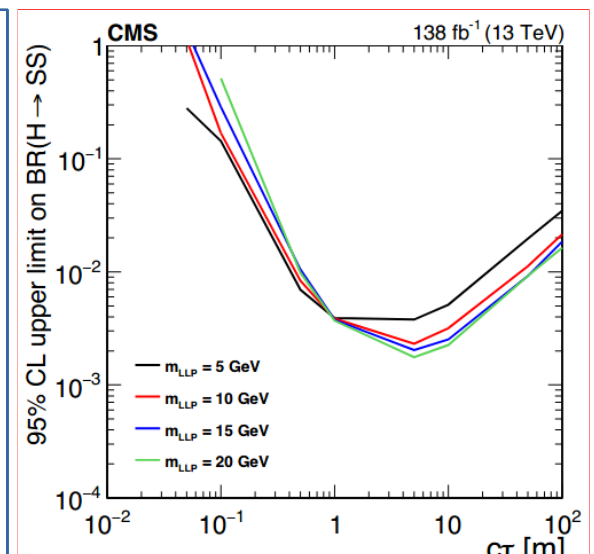
New at ICNFP 2023

- We interpret the search result in **9 different decay modes** with hadronic shower $(b\bar{b}, d\bar{d}, K^+K^-, K^0K^0, \pi^+\pi^-)$, EM shower $(\pi^0\pi^0, \gamma\gamma, e^+e^-)$, or both $(\tau^+\tau^-)$
- Achieve **first sensitivity to sub-GeV mass LLPs at BR (H $\rightarrow$ SS) = 10^{-3} level.**
- Achieve **first sensitivity to dark shower model produced from Higgs decay at BR (H $\rightarrow$ ΨΨ) = 10^{-3} level**.

Twin higgs model



Dark shower model

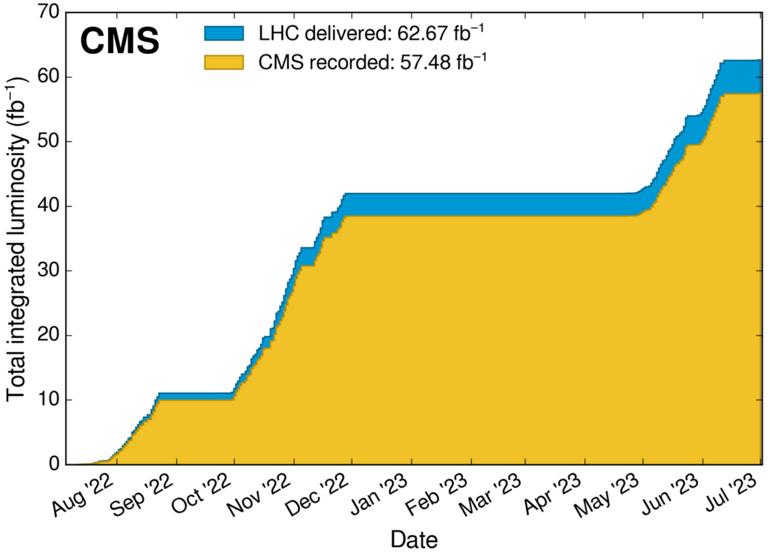


Analyses with the first Run 3 data

The long-awaited **LHC Run 3 started** in July 2022 delivering proton-proton collisions at the **energy of 13.6 TeV**.

CMS recorded and certified high quality physics data**:**

- **in 2022,** ~35 fb^{-1}
- **in 2023,** ~10 fb^{-1} and keep collecting as we speak.



There are already **analyses using the first Run 3 data**, the so-called high priority analyses. Among them are analyses that:

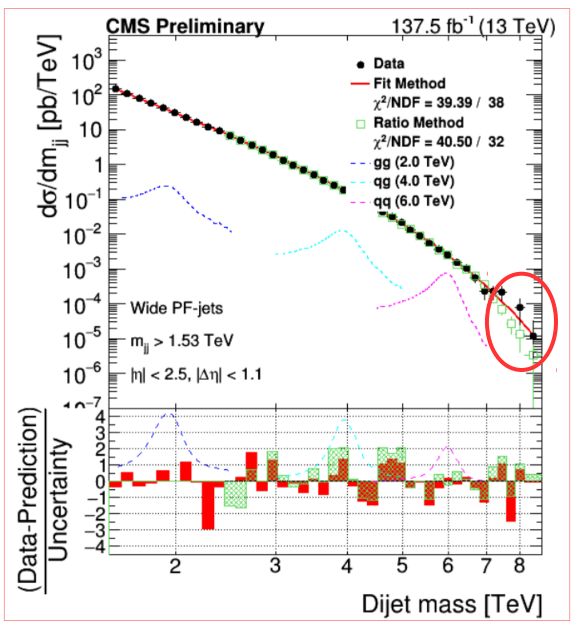
- have been performed before and a level of sensitivity similar to Run 2 can be reached fast
- with a localized excess in the Run 2 data
- with significant signal cross-section increase from 13 → 13.6 TeV
- with improved triggers for the long lived searches

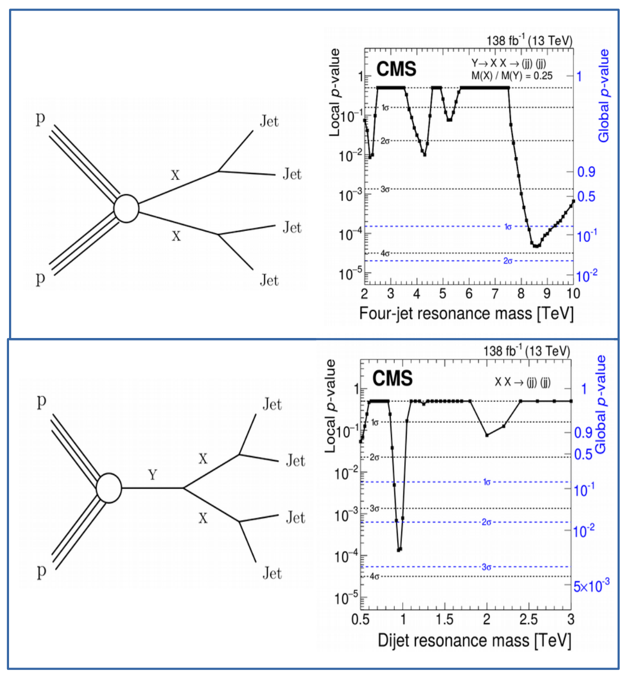
Analyses with the first Run 3 data

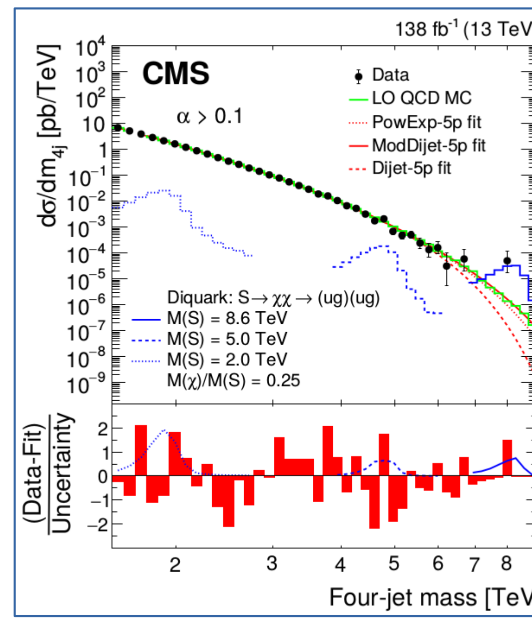
Examples of high priority analyses with the first Run 3 data searching for exotic signatures:

- DiJet resonances:
  X → 2 jets

- Paired Dijet resonances





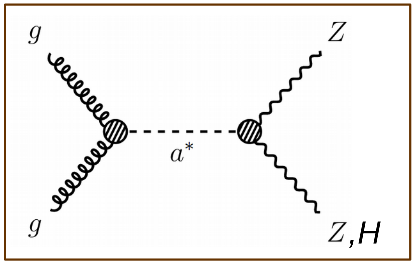


Both CMS and ATLAS are seeing a clustering of events at high mass.

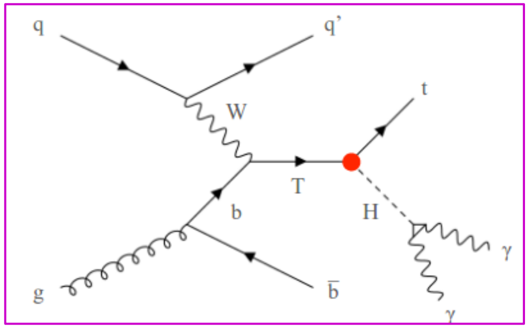
Analyses with the first Run 3 data

Examples of high priority analyses with the first Run 3 data searching for exotic signatures:

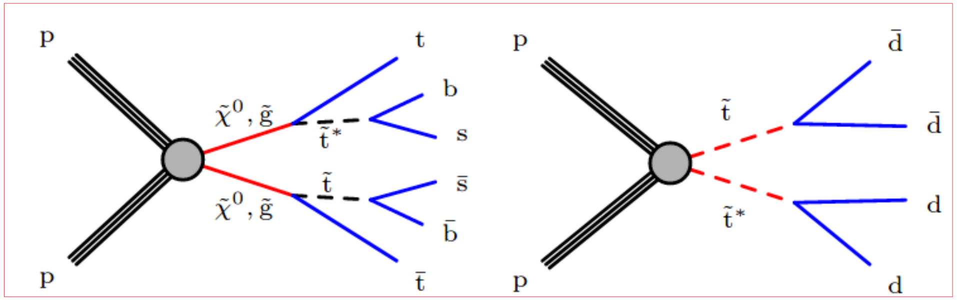
- Diboson resonances: X → ZV



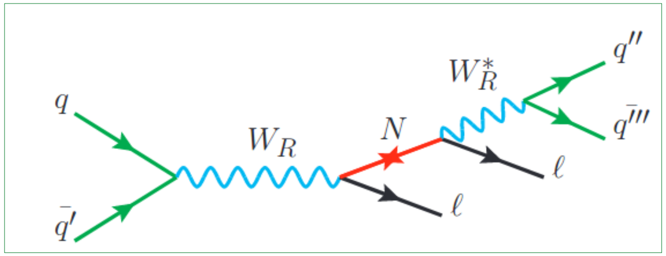
- Vector-like top quark: T' → tH



- Displaced-jets



- W_R → HNL



Summary

- **There is a very rich program for BSM physics at CMS performing generic searches and testing many models of new physics. Many interesting results with Run II data are imminent.**

- Searches for exotic signatures in CMS were presented:
  - No significant deviations from SM so far but **some excesses** to keep an eye and to drive us where to look next.
  - Constraints in several benchmark models.

- Significant **improvements** due to
  - Data driven methods to estimate the background.
  - Increased luminosity with full Run II datasets.
  - New final states are explored.

- **Hope that with all the improvements and advancements** on reconstruction, trigger, analysis approaches and techniques, **we should be able to fully exploit the Run 3 discovery potential and either make a discovery, or improve limits beyond luminosity scaling.**

Thank you!

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Back up

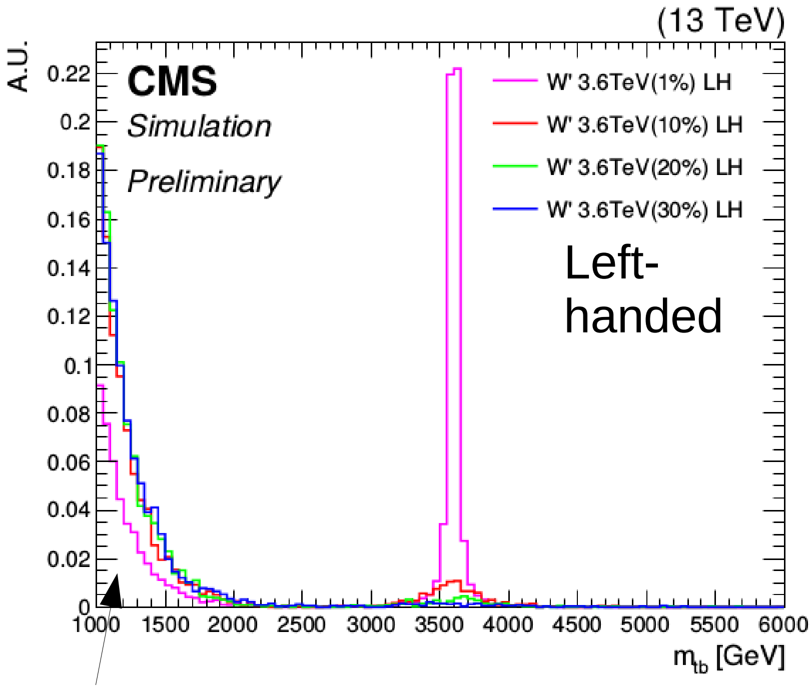
High mass μμ resonance with b quark jets

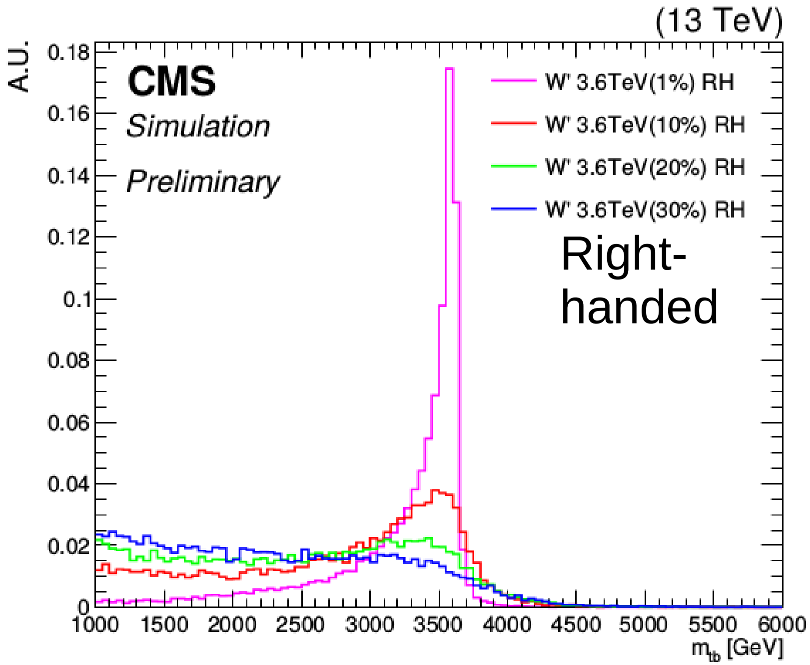
$$\mathcal{L}_{BSM} = Z'_\eta \left\{ g_\ell \sum_{f=\mathrm{e},\mu,\tau} \bar{f}\gamma^\eta P_\mathrm{L} f + g_\nu \sum_{f=\nu_\mathrm{e},\nu_\mu,\nu_\tau} \bar{f}\gamma^\eta P_\mathrm{L} f \right.$$

$$\left. + \; g_\mathrm{b} \left[\bar{\mathrm{b}}\gamma^\eta P_\mathrm{L}\mathrm{b} + \delta_{\mathrm{bs}} \left(\bar{\mathrm{s}}\gamma^\eta P_\mathrm{L}\mathrm{b} + \text{ h.c.} \right) \right] \right\}.$$

W' → tb in leptonic final states

At parton level





dominated by the SM s-ch. production of a tb quark pair.

For large decay widths the tail towards small masses is dominant because of off-shell W' production

LLPs searches with muon detector showers

- large cτ: single DT cluster is the best channel
- Intermediate cτ: double cluster is the best channel
- low cτ: single CSC cluster is the best channel