Searches for new physics in CMS in events with jets in the final state

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On behalf of the CMS Collaboration

Outline

- Motivation
- General Methodology
- Results
  - CMS-EXO-19-012
  - CMS-EXO-20-008
  - CMS-EXO-20-007
  - CMS-EXO-20-002
- Conclusions

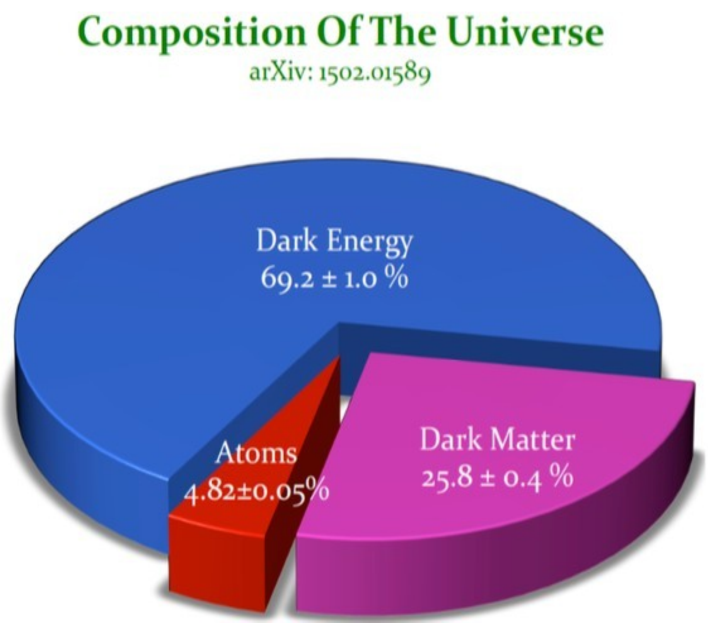
Motivation

- The Standard Model (SM) of particle physics is incomplete :

  - Why is there an imbalance of matter and antimatter in the universe?

  - How does gravity fit into our model? Why are there exactly three families of fundamental particles?

  - What is 95% of the Universe made of?



- Many models of physics that extend the SM often require new particles that couple to quarks and/or gluons and decay to jets.

Jet Resonance Search in CMS

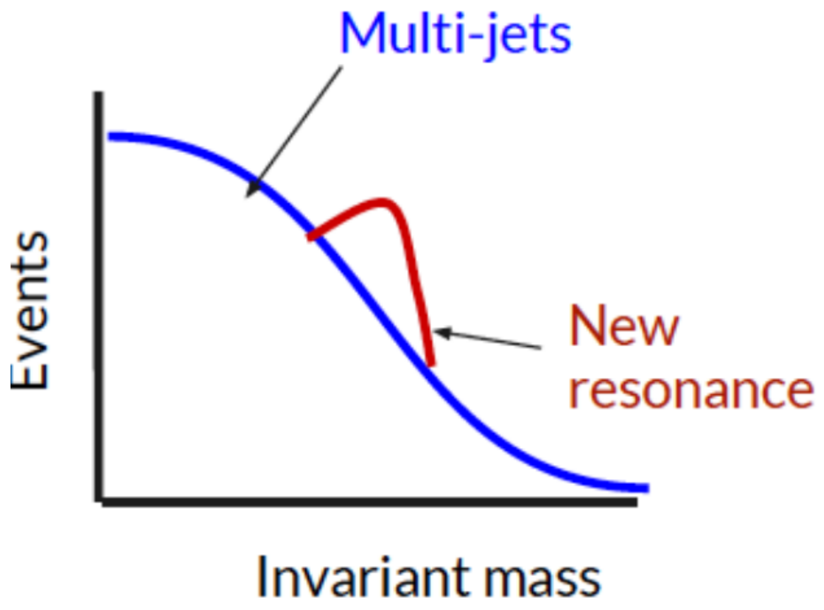
- There is a variety of recent resonance searches in CMS, with jets in final states. A selection of Full Run II results will be discussed in this talk:

  - High Mass Dijet Resonance Search (CMS-EXO-19-012, paper: arXiv:1911.03947)
  - B-tagged Dijet Resonance Search (CMS-EXO-20-008)
  - Trijet Resonance Search(CMS-EXO-20-007)
  - Search for a right-handed W boson and a heavy neutrino (in a final state considering of two same flavor leptons and two quarks). (CMS-EXO-20-002).

General Analysis Methodoloy

- **Analysis Strategy** : search for a narrow or wide resonance on top of a smoothly falling background.

- **Background Estimation** :
  - Data-driven : Fitting the invariant mass with an empirical function.
  - Semi data-driven: Predicting the SM background from control regions with transfer functions to the signal region from simulation.

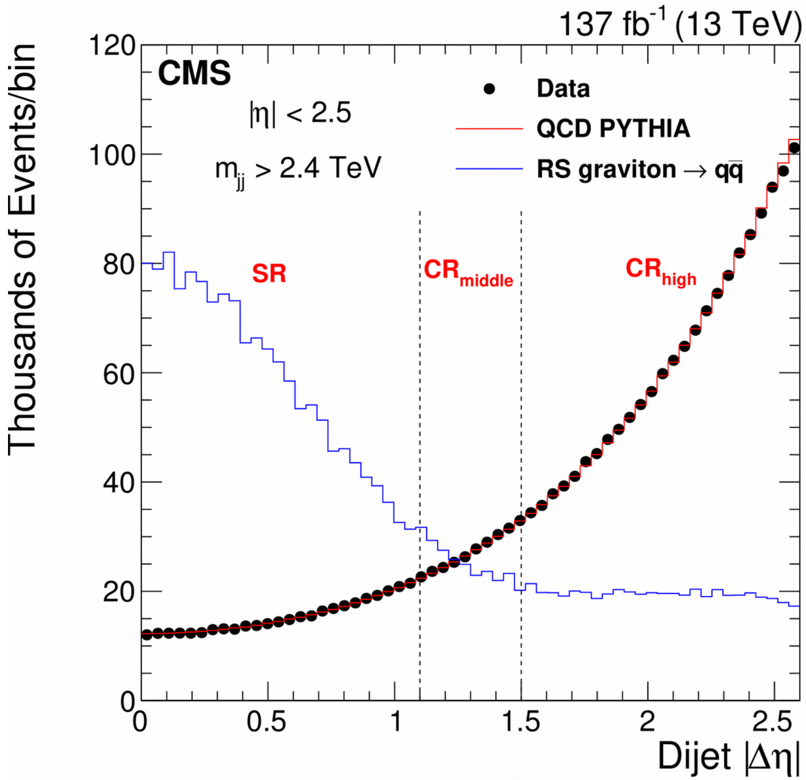


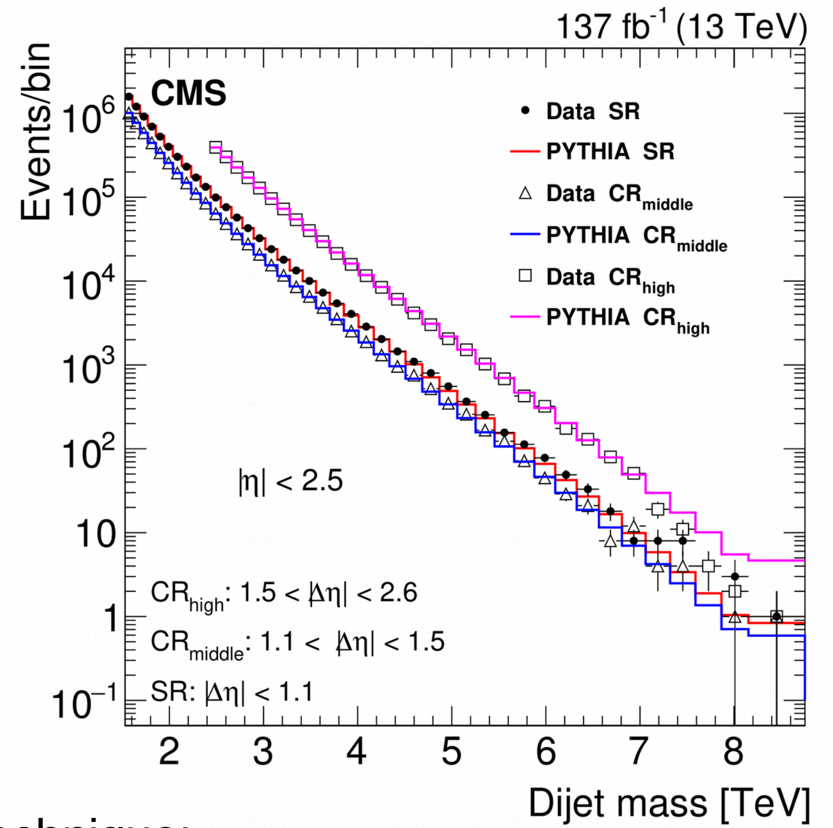
- **Signal Modeling** : Intrinsic signal shape, either narrow (with width smaller than the detector resolution) or wide or using generic gaussian shape.

- **Limit extraction & Significance Estimation**: Fit the jet invariant mass spectrum using background and signal templates with systematics as nuisance parameters.

Dijet High Mass Search: New Background Method

CMS [EXO-19-012]



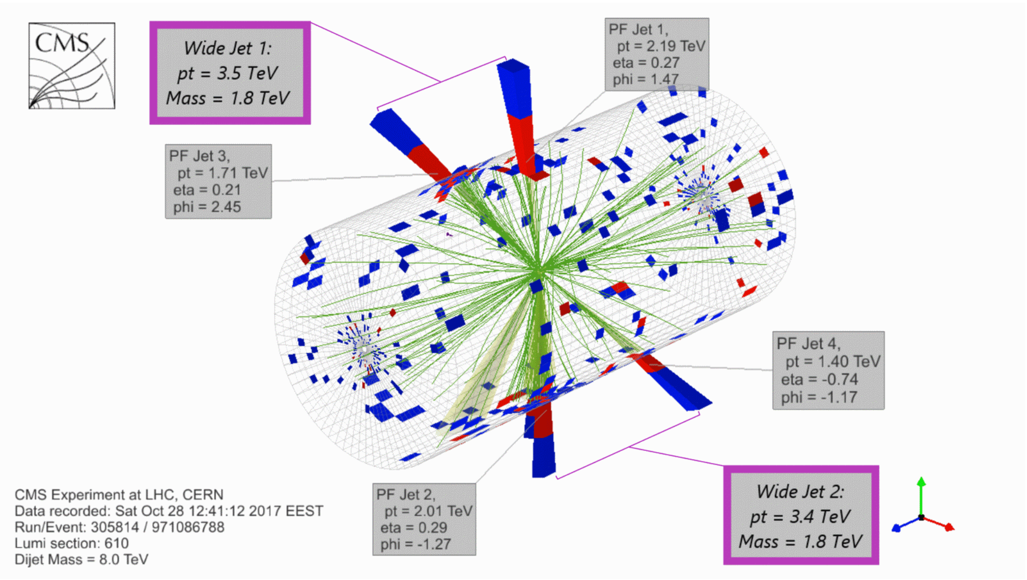


- New data driven background estimation technique:
  - ➢ Ratio Method uses data in the the control region at high $|\Delta\eta|$ to estimate the background in the signal region at low $|\Delta\eta|$.
  - ➢ Robust technique, complementary to the standard fit method, with less dependence on empirical parameterizations.

Second Highest Dijet Mass Event

CMS [EXO-19-012]

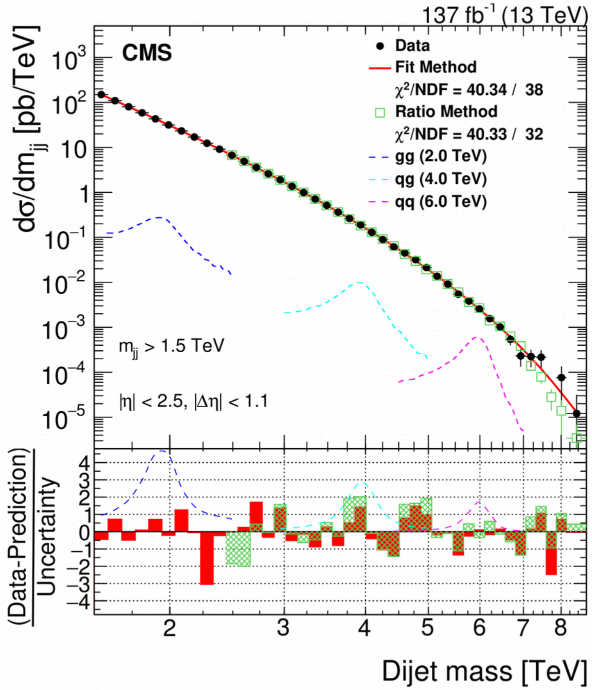
- Second highest dijet mass event from 2017 Data, at 8 TeV has unusual 4-jet topology.
  - ➢ Wide jets each have a mass of 1.8 TeV.
  - ➢ Probability of getting such a 4-jet event from QCD is approximately 10^{-4} .[Dobrescu, Harris and Isaacson, arXiv:1810.09429]

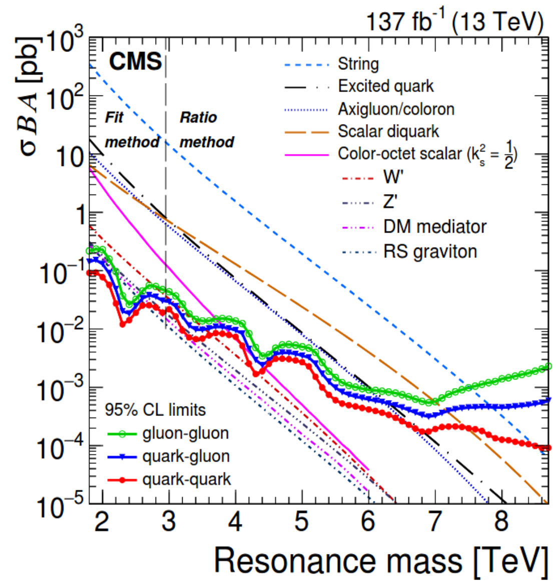


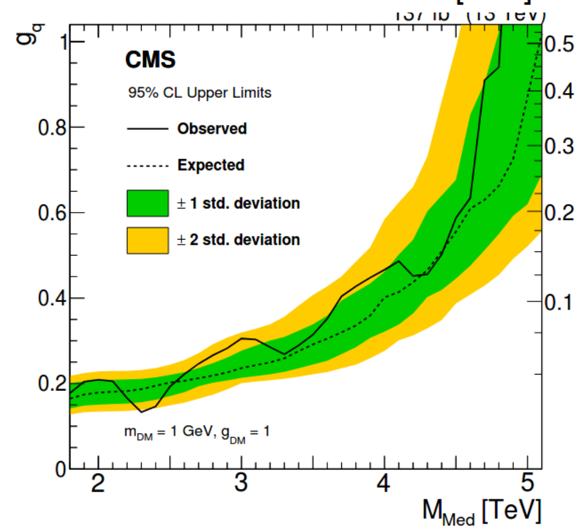
- Possible candidate for a massive resonance decaying to pairs of dijet resonances.

Dijet Mass Spectrum & Limits

CMS [EXO-19-012]







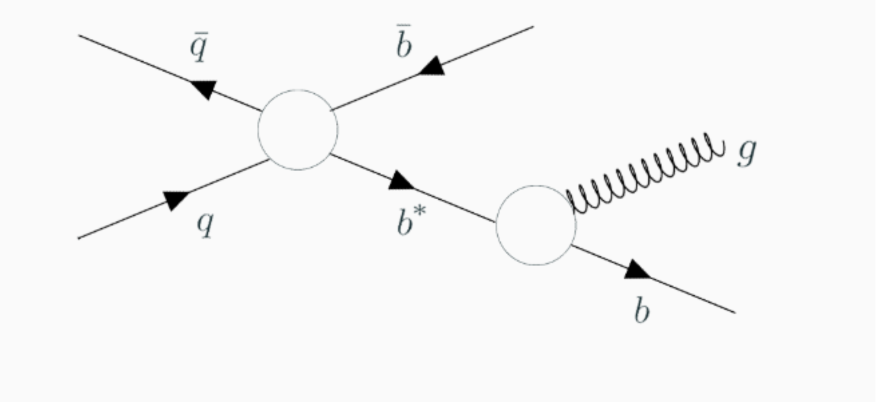
- Data are well described by both methods. There is no evidence for dijet resonance.
- Expected mass limits improve by 300-500 GeV compared to our previously published 2016 results.
- For Γ/M=0.25, this search excludes dark matter mediators with mass less than 4.7 TeV. This is the best LHC limit for searches utilizing jets!

B-tagged Search
CMS [EXO-20-008]

- Search for resonances decaying into b quarks.
- Extension of inclusive dijet resonance search, by requiring one or both leading jets to be b-tagged using the DeepJet tagger.
- Signal Models:
  - ➢ b*→ bg benchmark model (1 b-jet final state). Considered production modes:

    -bg→ b*

    -qq→ b*+b

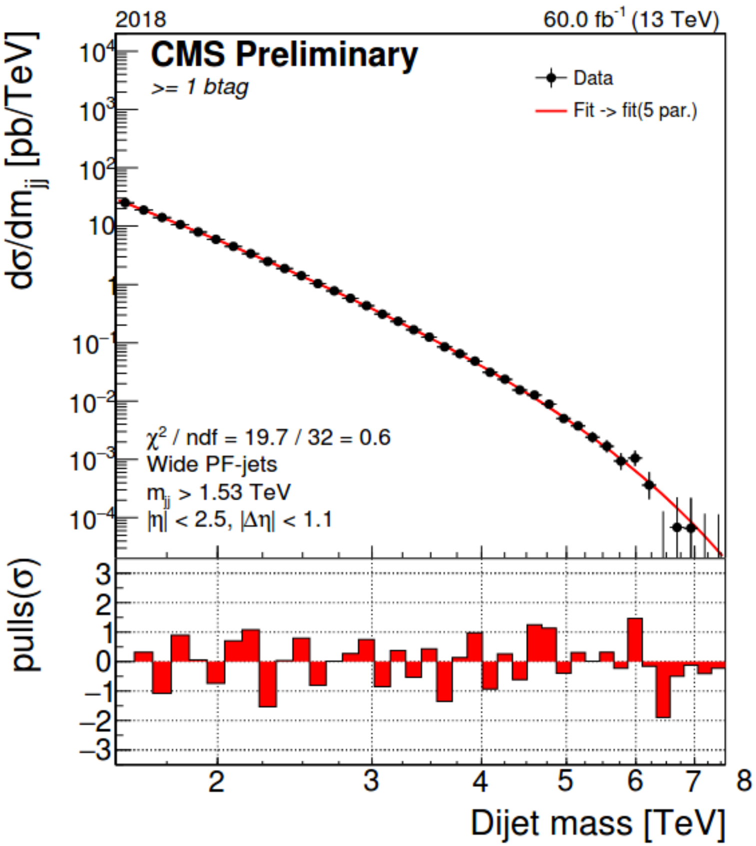


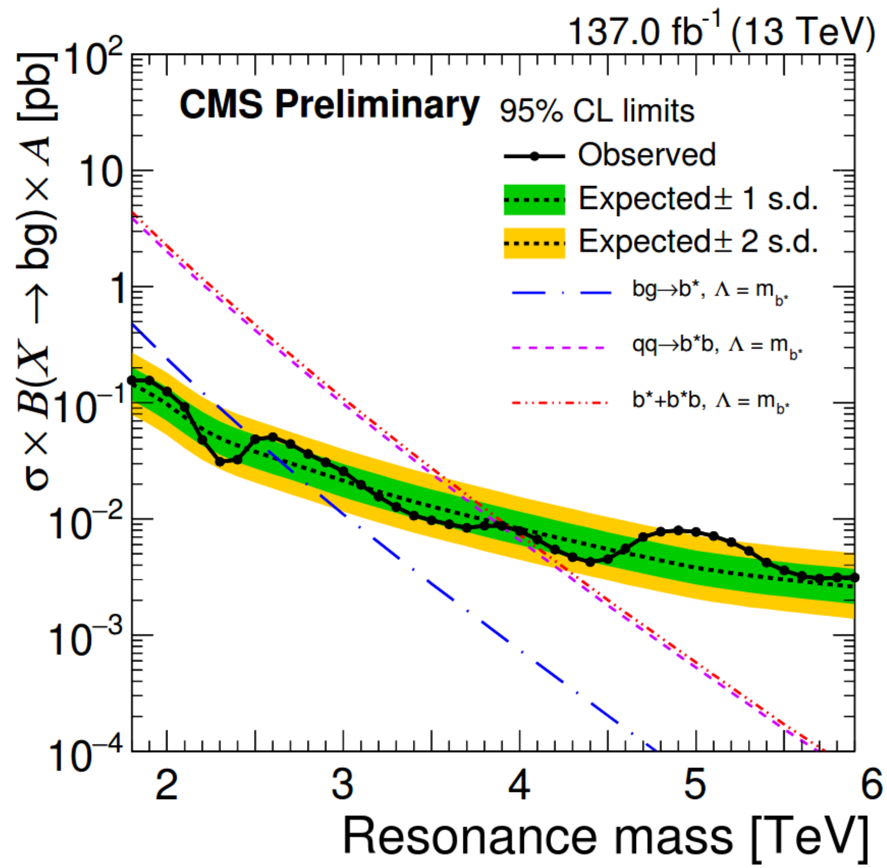
  - ➢ Z’→ bb benchmark model (2 b-jets final state):

    -Heavy Vector Triplet (HTV) model with similar coupling to fermions as to gauge bosons with suppressed fermionic couplings

B-tagged Search: b*

CMS [EXO-20-008]



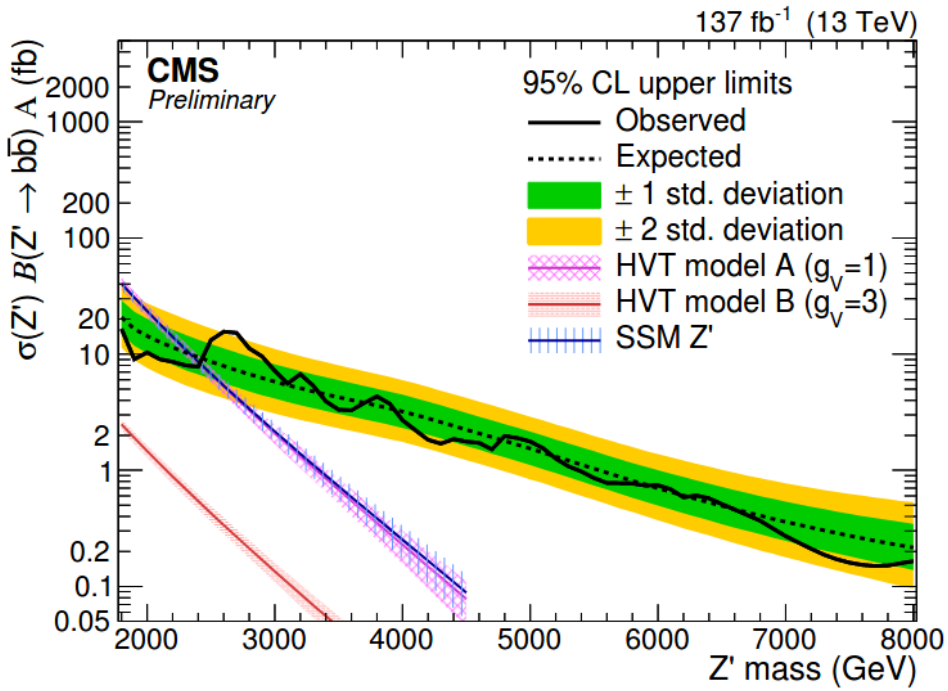


- Data of each year are well described by the fit function. Here we show the 208 Data. There is no evidence for b-tagged resonance.

- The excited b quark is excluded at 95% CL for masses less than 4.0 TeV. This is the most stringent exclusion of the excited b quark.

B-tagged Search: Z’

CMS [EXO-20-008]



- Search with 3 distinct b-tagging categories:
  - One leading jet is b-tagged (1b)
  - Both leading jets are b-tagged (2b)
  - At least one (untagged) jet contains a muon.

- Exclusion of HVT Model and Sequential Standard Model Z’ with $m_{Z'}$<2.4TeV

Trijet Search

CMS [EXO-20-007]

- Search for trijet resonances in events with a boosted dijet.

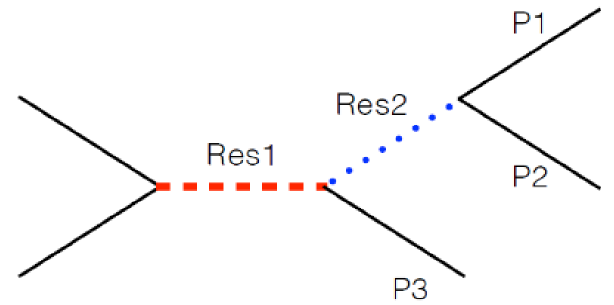
- The minimum angle between P_1 and P_2 depends only on the mass ration ρ_m

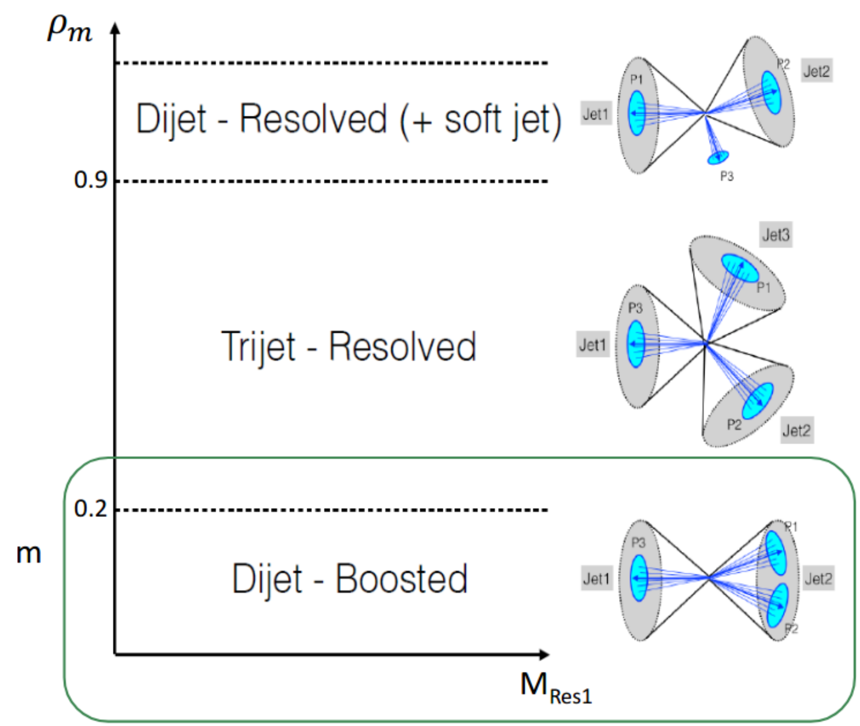
$$\rho_m = M_{Res2}/M_{Res1}$$

$$\alpha_{min} = \frac{2M_{Res2}}{E_{Res2}} \rightarrow \alpha_{min} = \frac{4\rho_m}{1+\rho_m^2}$$

- In this analysis, $\rho_m < 0.2$, and P_1, P_2 jets are merged

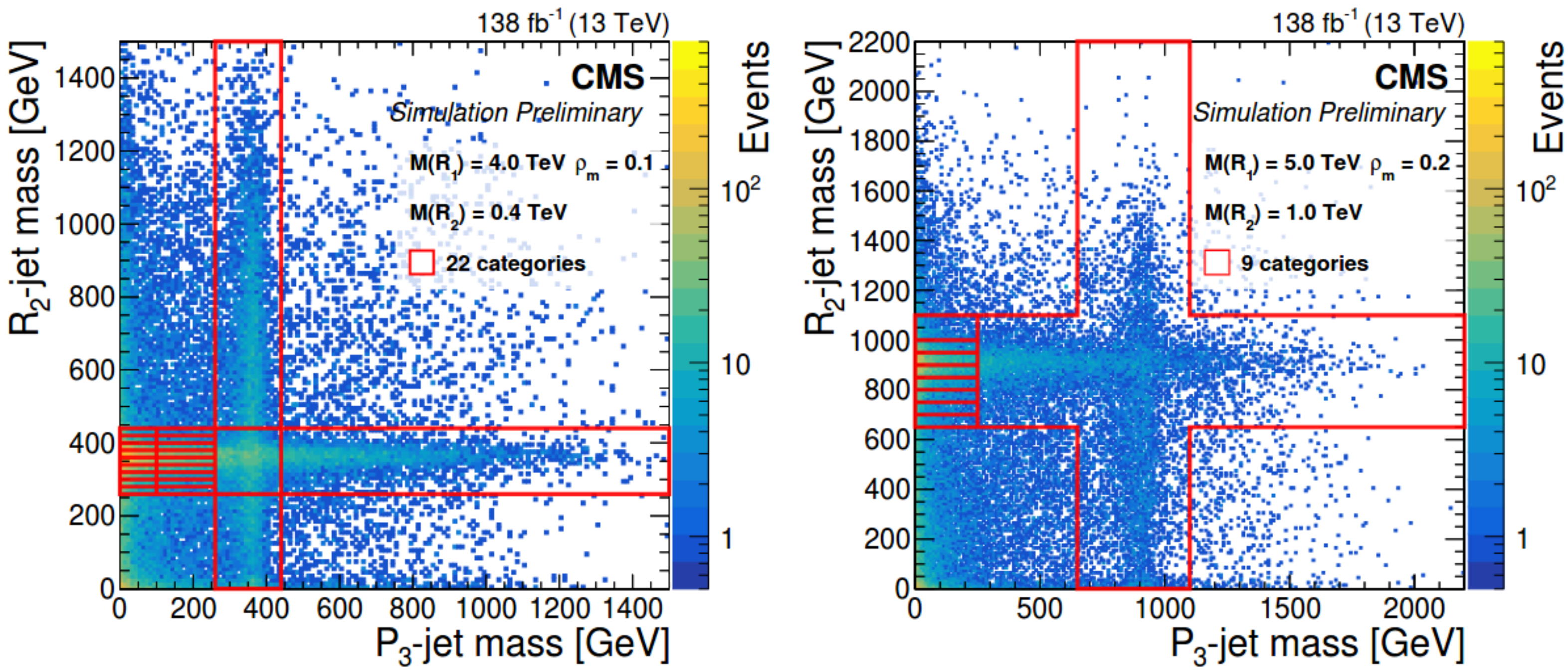
➢ Discrimination between signal and QCD background, by exploiting jet substructure information and kinematics of the decay.





Trijet Search: Event Categories

CMS [EXO-20-007]



- Optimization of the number and ranges of categories, to achieve the best sensitivity:

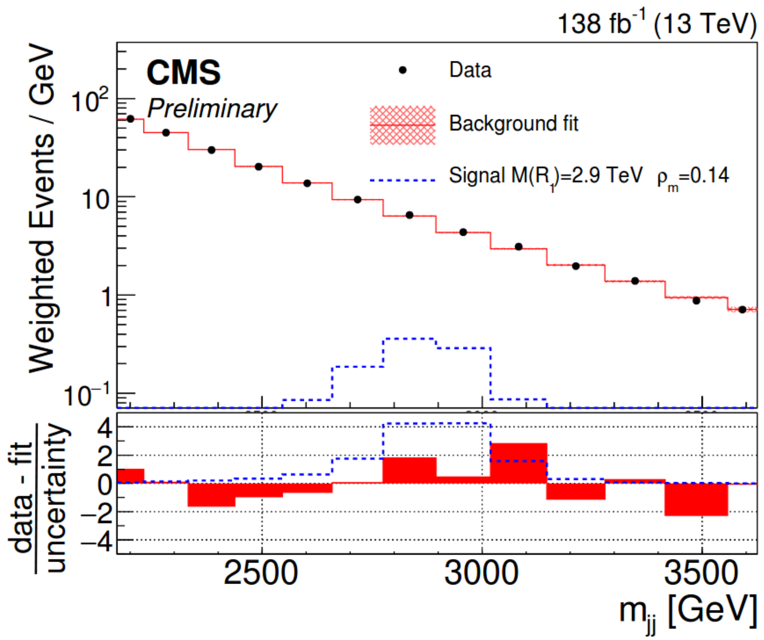
➢ 22 categories for M_{R2}<600 GeV

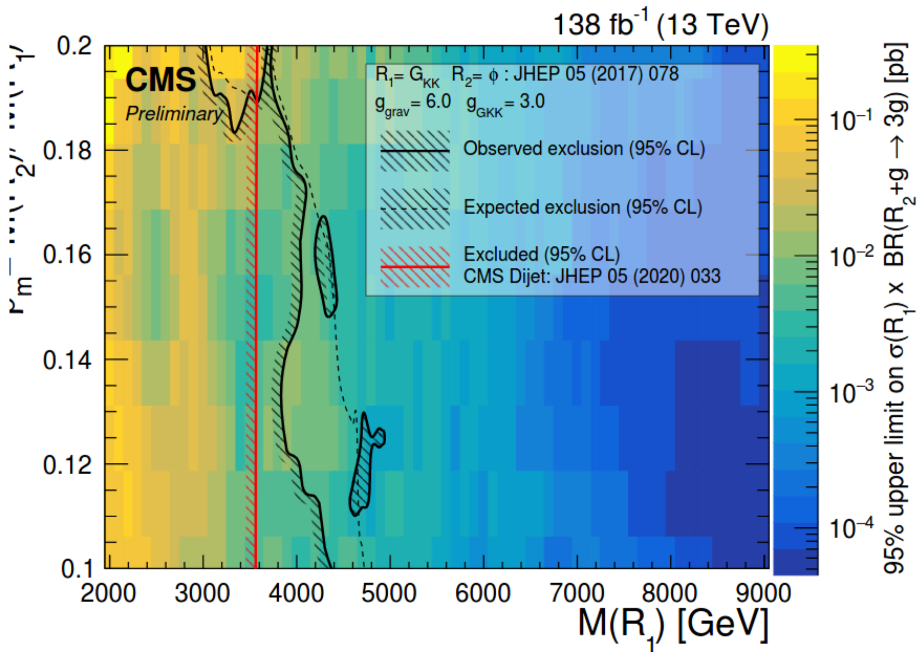
➢ 9 categories for 600GeV<M_{R2}<1200 GeV

➢ a single cross shaped category for M_{R2}>1200 GeV

Trijet Search: Fit & Results

CMS [EXO-20-007]





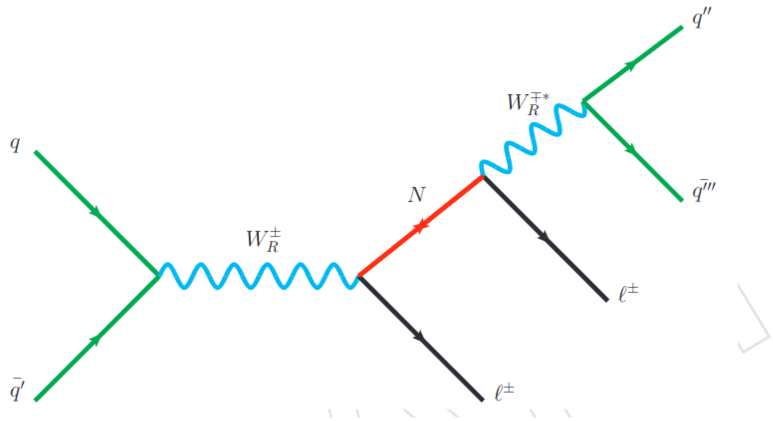
- Simultaneous fits in all categories.

- M_{R1}=2.9 TeV and M_{R2}=0.4 TeV has the highest local significance 3.1 σ and global significance of 2 σ.

- By exploring a novel experimental signature, we extend significantly the experimental exclusion of this benchmark model of new physics at the LHC

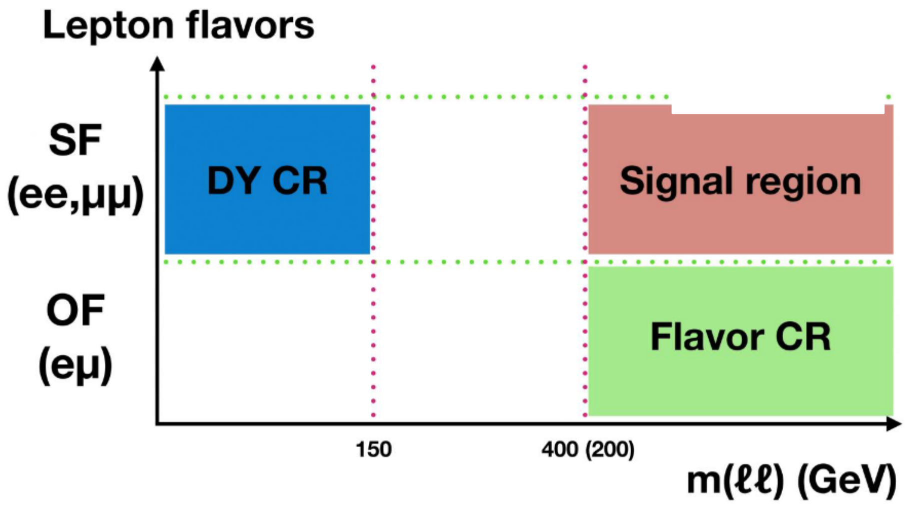
Right Handed W decaying to heavy neutral lepton
CMS [EXO-20-002]

- Search for new charged boson (W_R) and heavy neutrino (N) under the left-right symmetric model (LRSM)

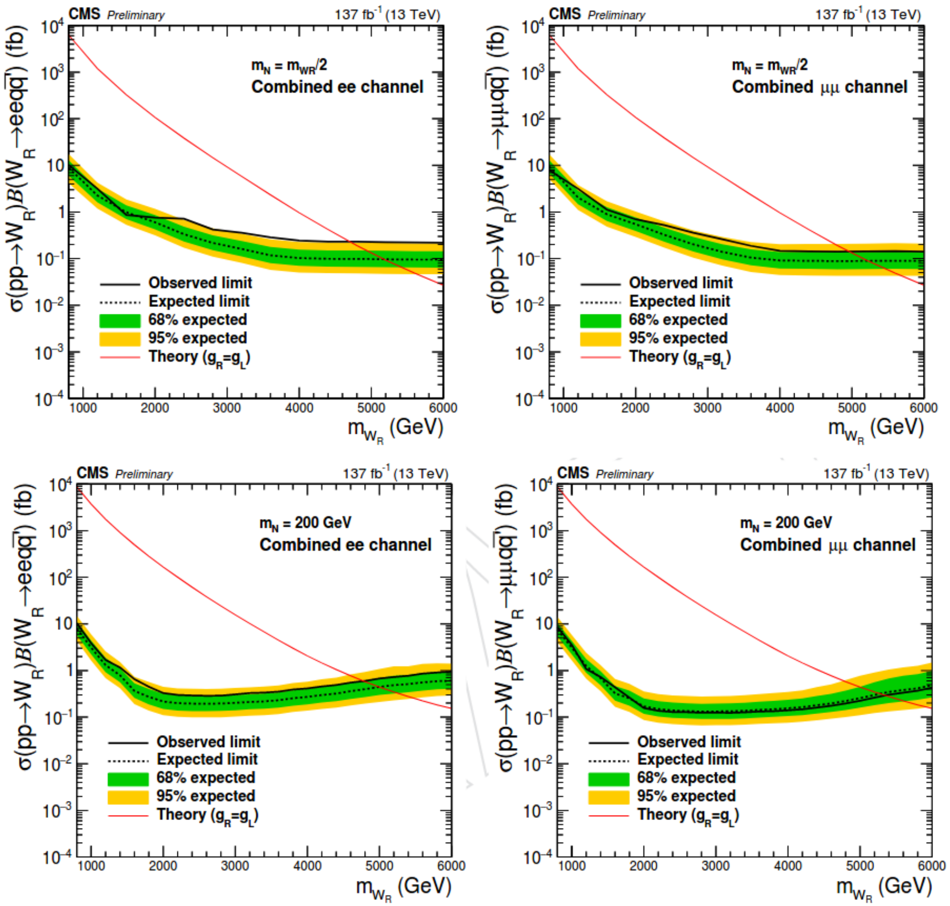


- New search region: Boosted N, using lepton and fastjet mass.

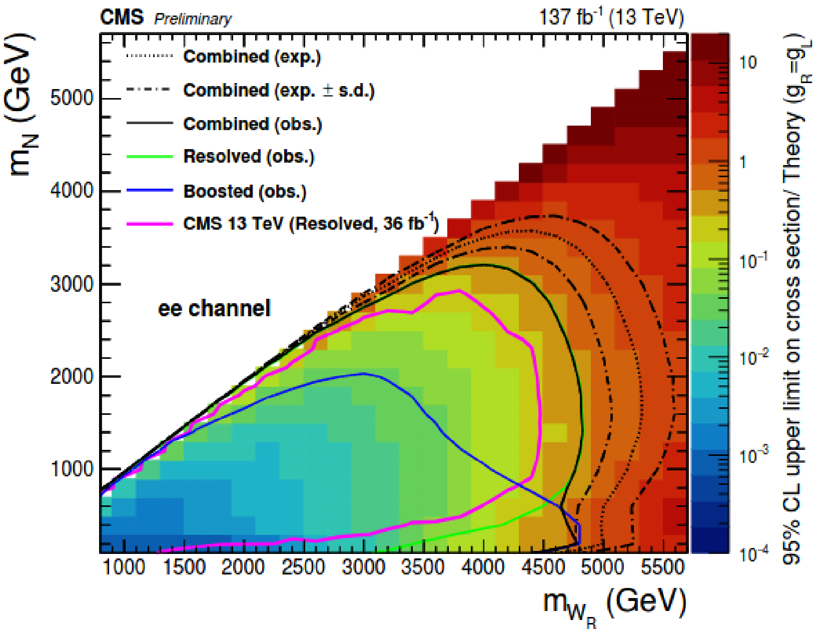
- Analysis regions:
  - ➢Flavor CR used to estimate normalization of tt+tW.
  - ➢DYCR used to derive corrections and estimate normalization of DY MC

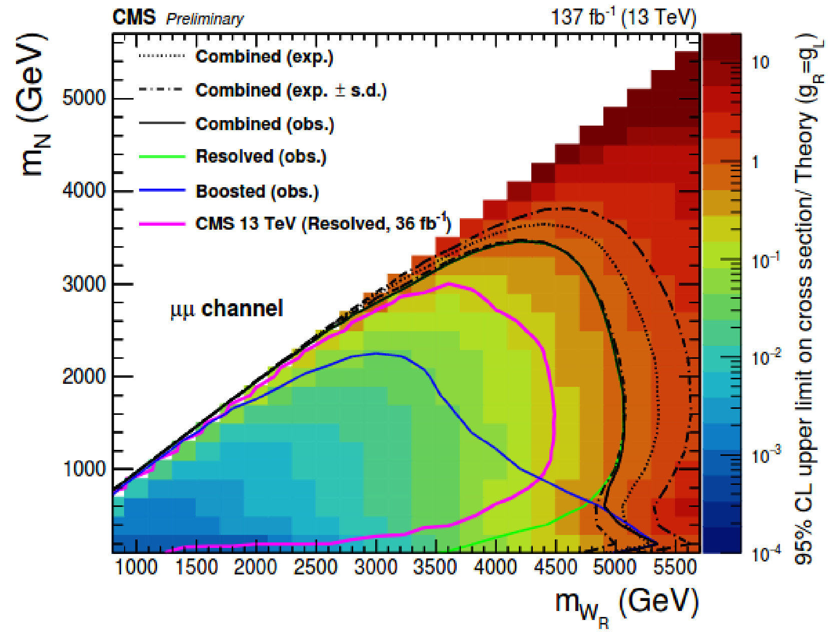


Results
CMS [EXO-20-002]



- Electron channel:local significances of 2.2σ and 2.5σ for the m_{WR},m_N=(5000, 200) GeV and (5000, 3000) GeV mass points
- Muon channel:local significance of 1.0σ for (5000, 3000) GeV mass point





- Resolved and boosted results are combined
- Resolved results
  - For m_N=1/2 m_{WR}, ee: m_{WR} 4500→4800 GeV excluded.
  - For m_N=1/2 m_{WR}, μμ: m_{WR} 4600→5100 GeV excluded
- Significant improvement in boosted channel
  - For m_N=200GeV, ee(μμ): m_{WR} of 4600 (5400) GeV excluded

Conclusions

- Search for hadronic resonances in CMS
  - No significant deviations from SM so far, but a few with < 3 σ excesses.
  - Constraints in several benchmark models
  - More results imminent!

- Significant improvements due to
  - Data driven methods to estimate the background.
  - Increased luminosity with full RunII datasets.
  - New final states

- Run3 is **ahead** of us!

BACK UP

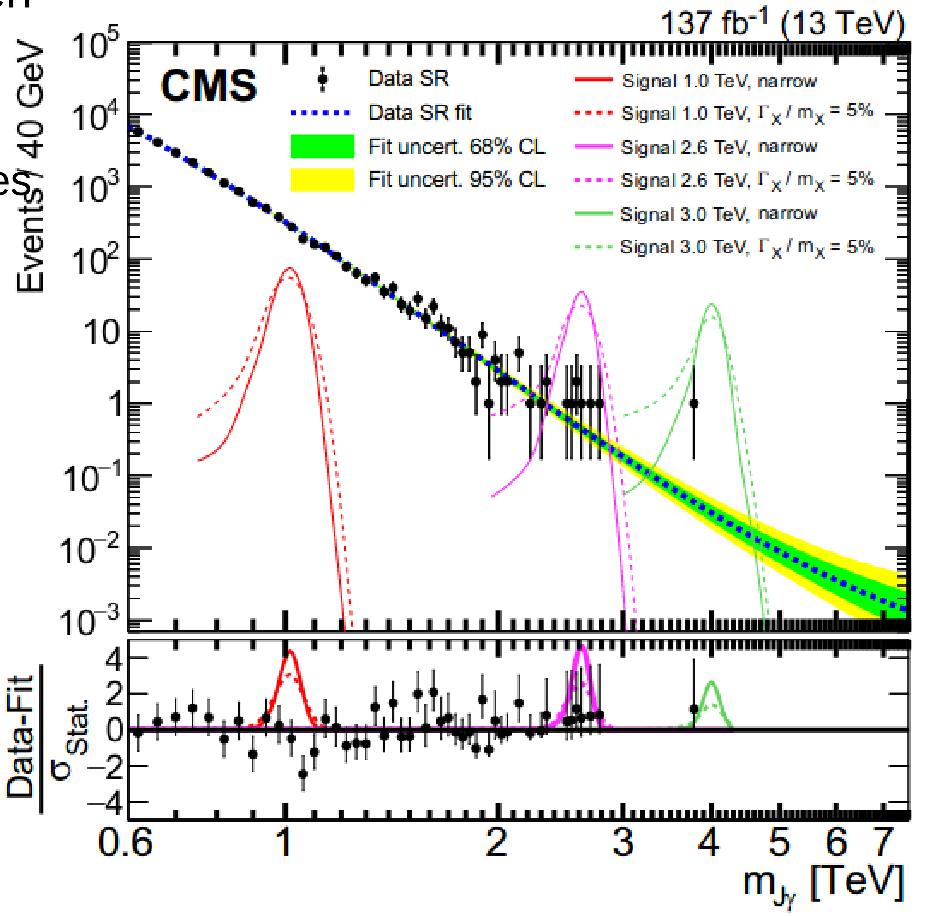
W+γ Search

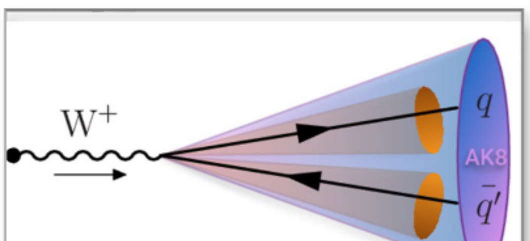
CMS [EXO-20-001], arXiv:2106.10509

- In CMS Hγ and Zγ final states have been extensively studies but Wγ was missing

- W+γ is a signature for multiple BSM theories like:
  - Extended Higgs Sectors
  - Technicolor
  - Heavy Vector Triplet (HTV) models

- Required
  - Boosted W bosons
  - High pT photons

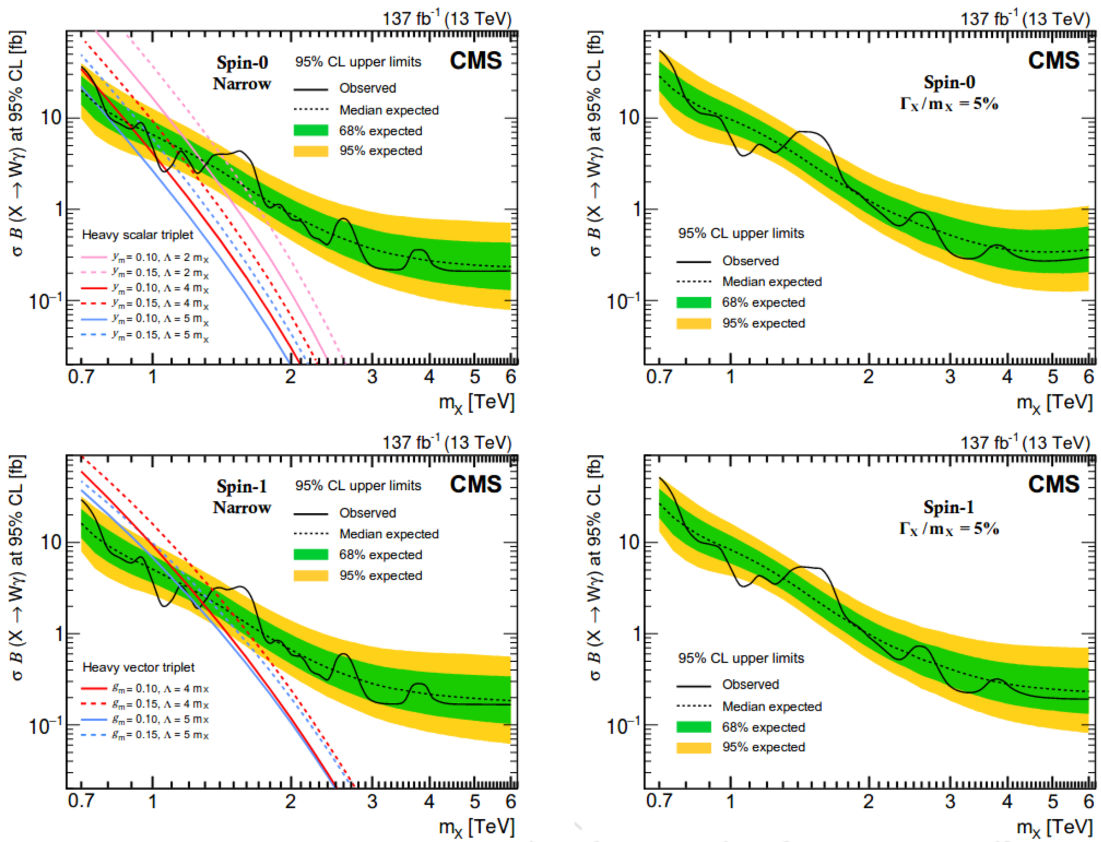




From: arXiv:2008.06282

W+γ Search

CMS [EXO-20-001]



- The largest excess observed at 1.58 TeV corresponds to a local significance of 2.8 (3.1) σ for narrow (broad) signals.

- The results reported are the most restrictive limits384to date on the existence of such resonances

Description of Ratio Method

- The "ratio method" predicts the QCD background in the SR by multiplying the data in CRhigh by a transfer factor determined from the simulation.

$$N_{\mathrm{SR}}^{\mathrm{Prediction}} = R \times N_{\mathrm{CR_{high}}}^{\mathrm{Data}}$$

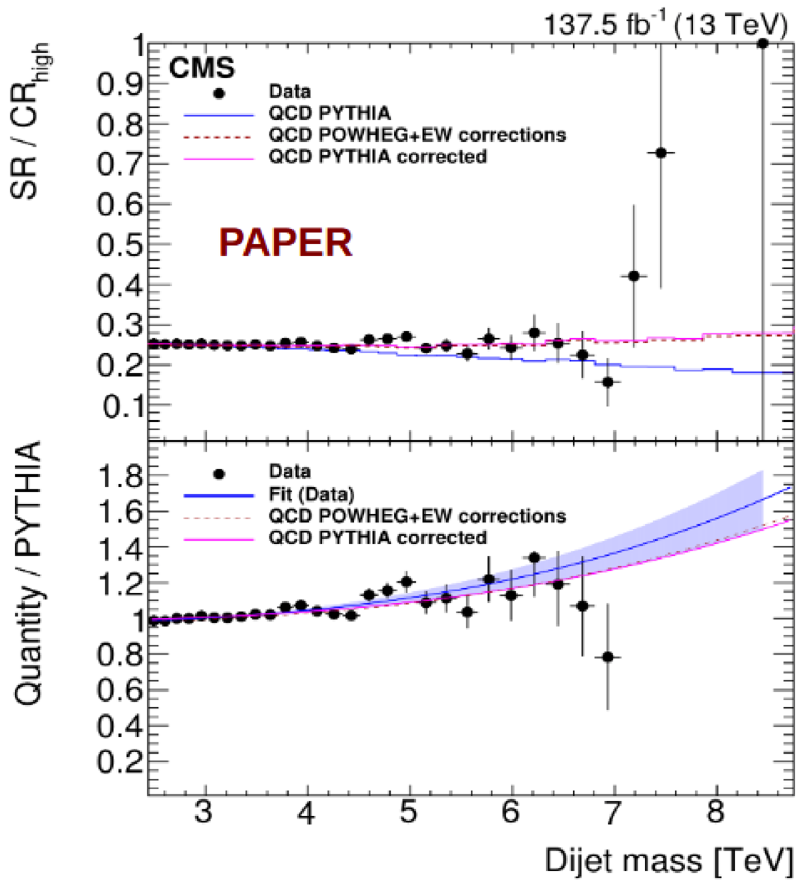
$$R = \mathrm{C} \times N_{\mathrm{SR}}^{\mathrm{Simulation}} / N_{\mathrm{CR_{high}}}^{\mathrm{Simulation}}$$

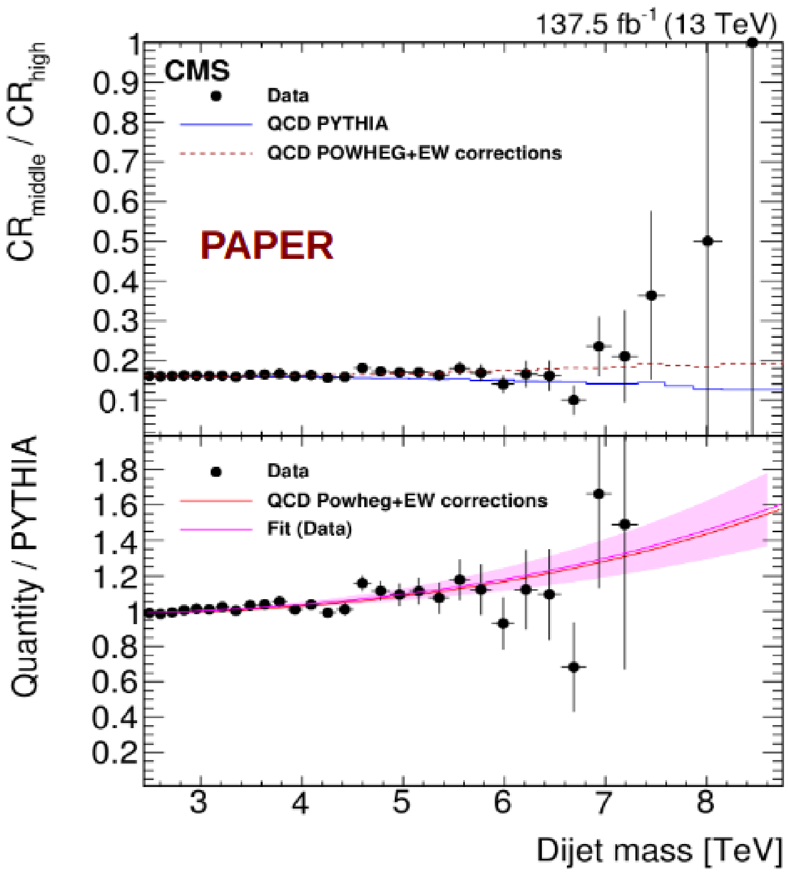
- The transfer factor is corrected with an empirical function, using CRmiddle as a calibration, to account for differences between data and LO simulation (NLO, EW effects, etc.)

$$R_{\mathrm{aux.}} = N_{\mathrm{CR_{middle}}} / N_{\mathrm{CR_{high}}}$$

$$\mathrm{C} = \frac{R_{\mathrm{aux.}}{}^{\mathrm{Data}}}{R_{\mathrm{aux.}}{}^{\mathrm{Simulation}}} = p_0 + p_1 \times (m_{\mathrm{jj}} / \sqrt{s})^3$$

Transfer Factor

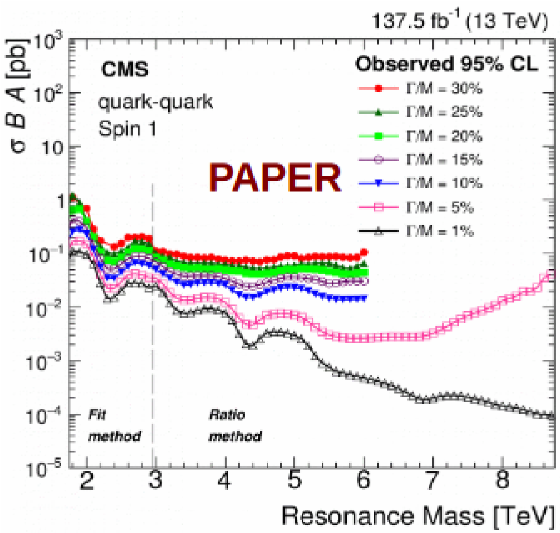




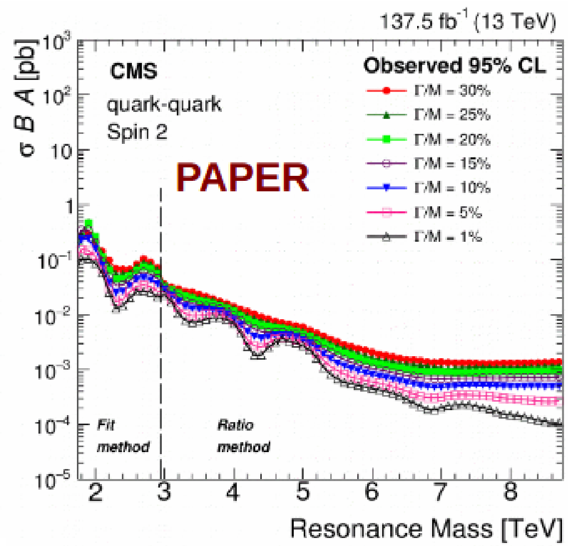
- We correct the simulated transfer factor using a 2-parameter fit to the double ratio
- Using the CR_{middle}/CR_{high} we constraint the theoretical and experimental systematics.

Wide Resonance Limits

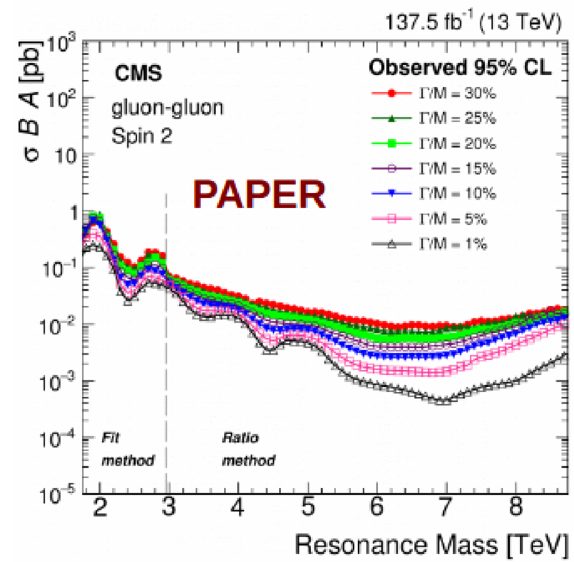
Spin 1 qq



Spin 2 qq



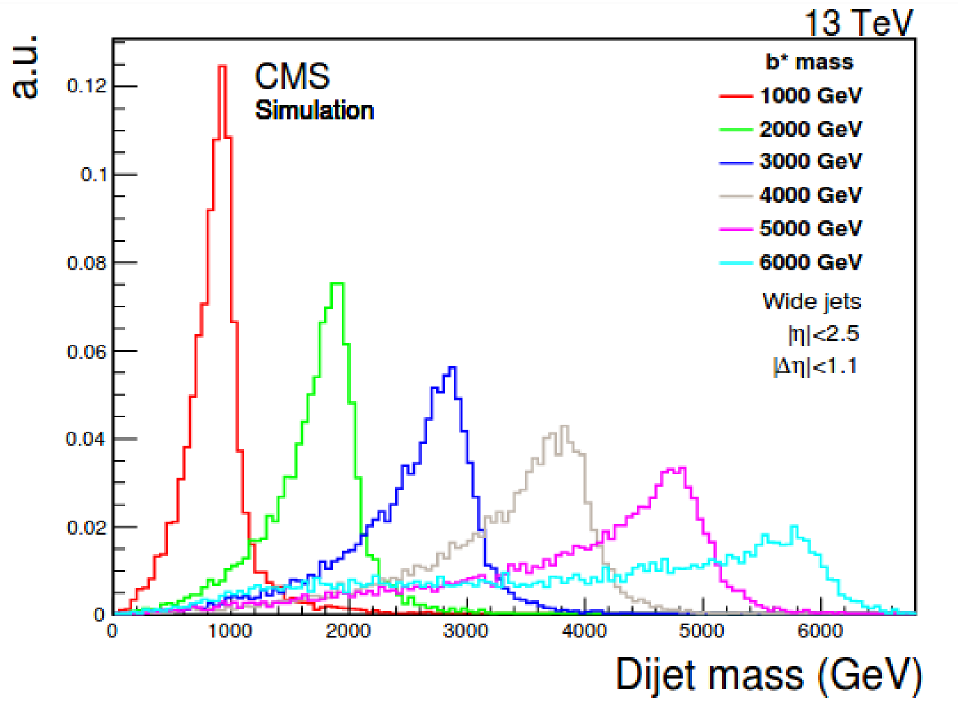
Spin 2 gg



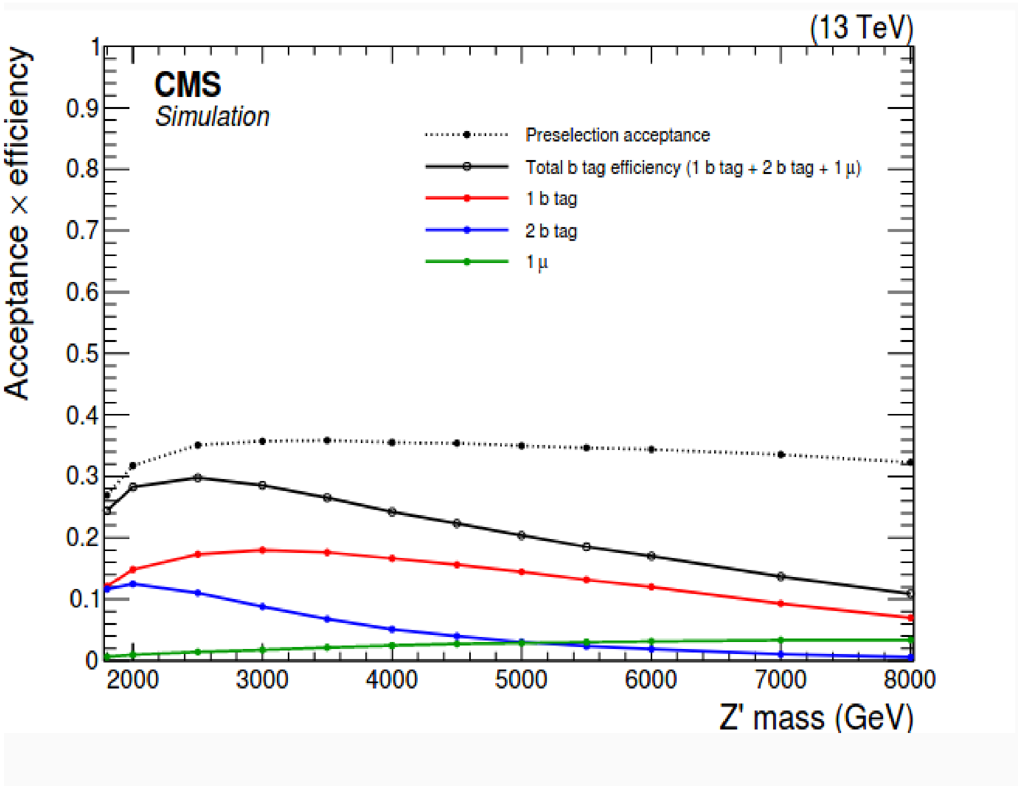
- Wide resonance limits are well behaved as a function of resonance mass and width.

- For Spin1 qq resonances we show limits up to the resonance mass for which we trust the signal Shapes.

b* signal shapes

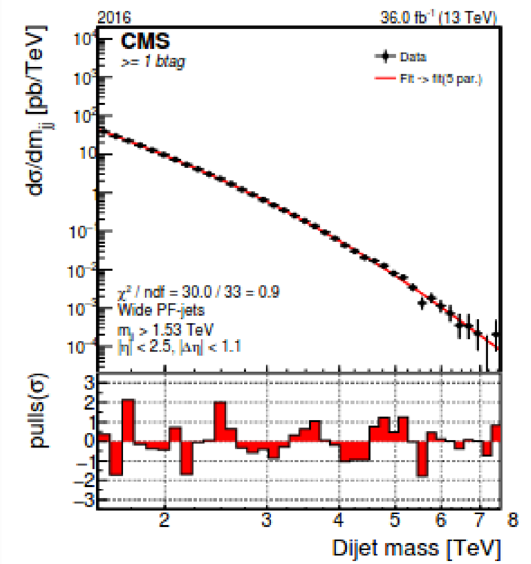


Signal Efficiency vs Z’ mass

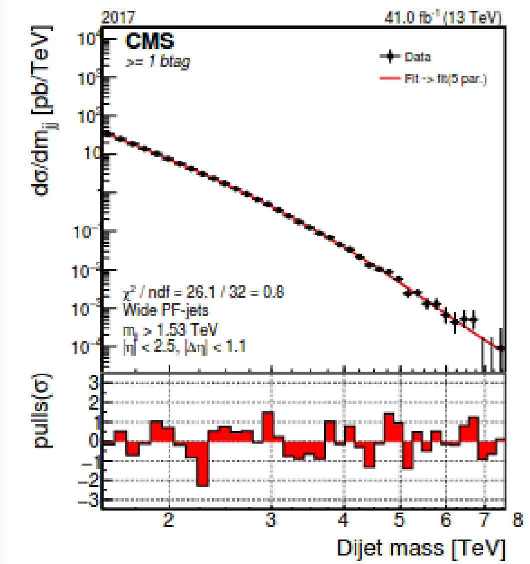


Fits for >=1 btag

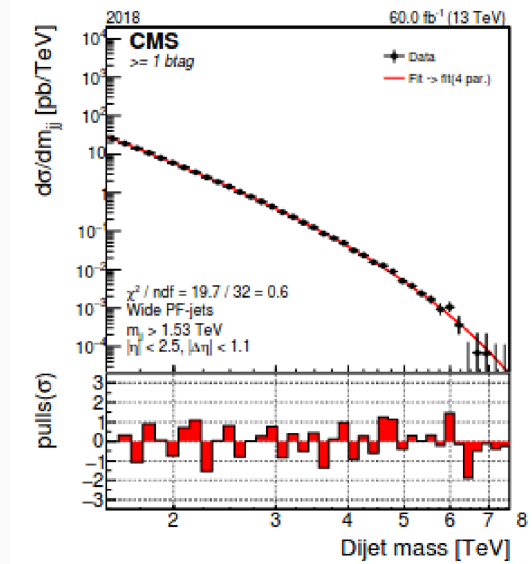
2016



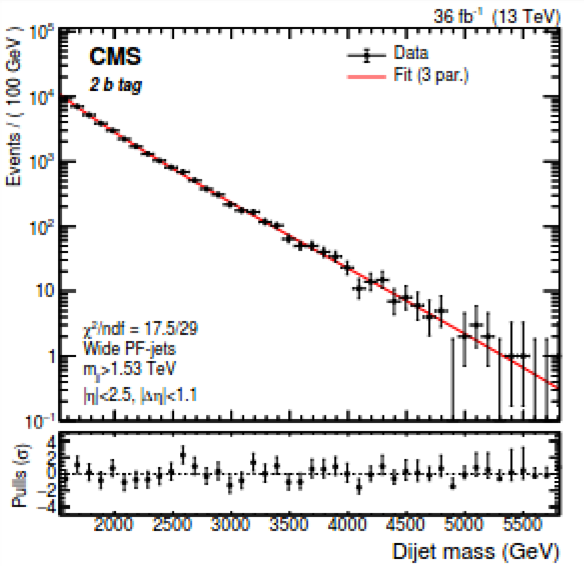
2017

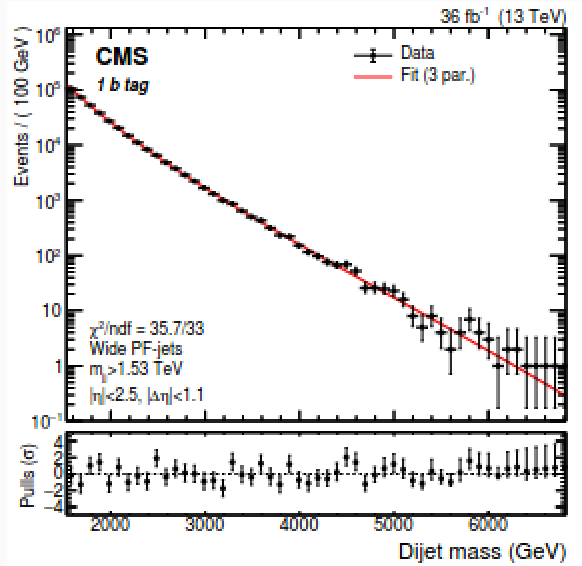


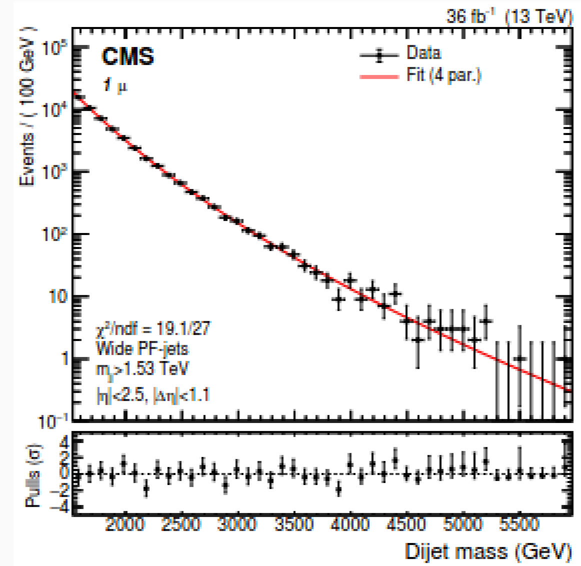
2018

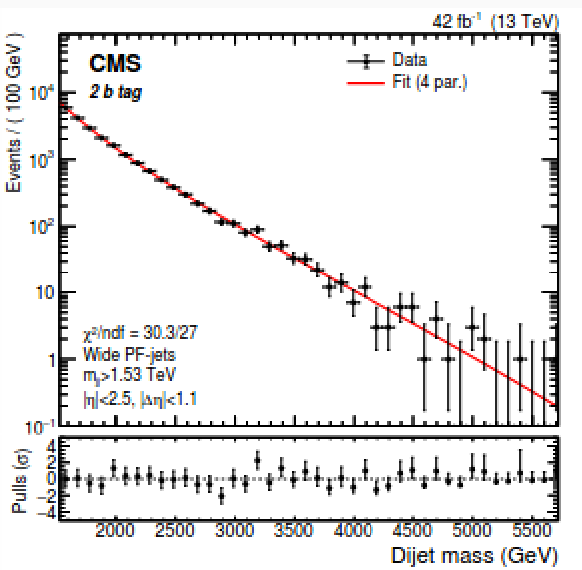


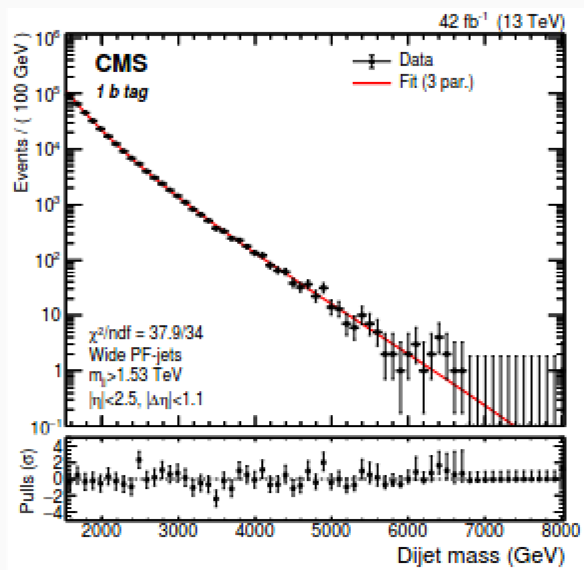
Fits for Z'

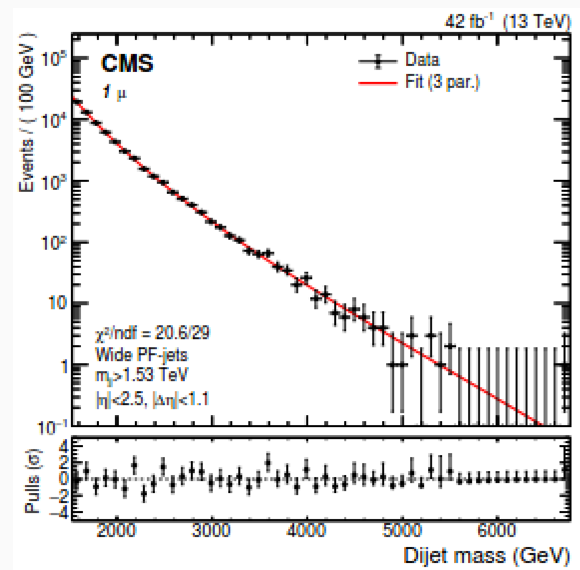

36 fb^{-1} (13 TeV)
CMS
2 b tag
Data
Fit (3 par.)
χ^2/ndf = 17.5/29
Wide PF-jets
m_{jj}>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)


36 fb^{-1} (13 TeV)
CMS
1 b tag
Data
Fit (3 par.)
χ^2/ndf = 35.7/33
Wide PF-jets
m_{jj}>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)

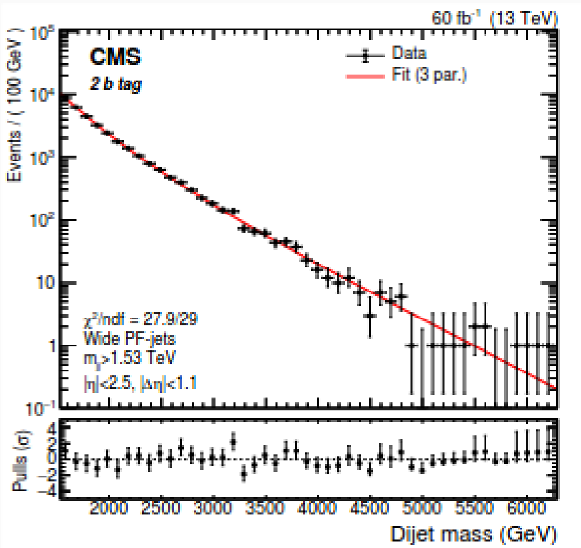

36 fb^{-1} (13 TeV)
CMS
1 μ
Data
Fit (4 par.)
χ^2/ndf = 19.1/27
Wide PF-jets
m_{jj}>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)


42 fb^{-1} (13 TeV)
CMS
2 b tag
Data
Fit (4 par.)
χ^2/ndf = 30.3/27
Wide PF-jets
m_{jj}>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)

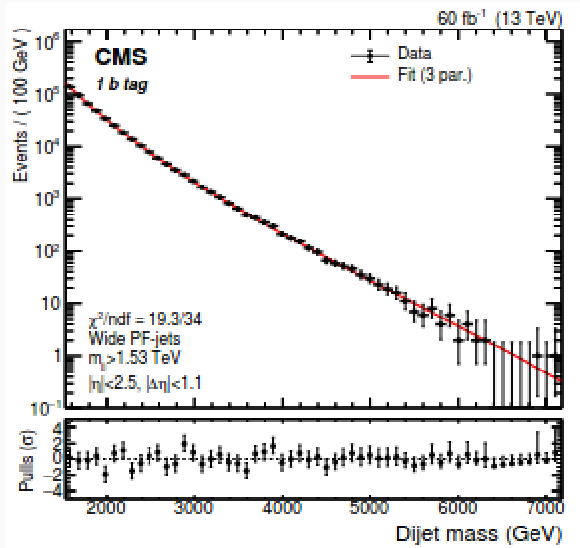

42 fb^{-1} (13 TeV)
CMS
1 b tag
Data
Fit (3 par.)
χ^2/ndf = 37.9/34
Wide PF-jets
m_{jj}>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)


42 fb^{-1} (13 TeV)
CMS
1 μ
Data
Fit (3 par.)
χ^2/ndf = 20.6/29
Wide PF-jets
m_{jj}>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)

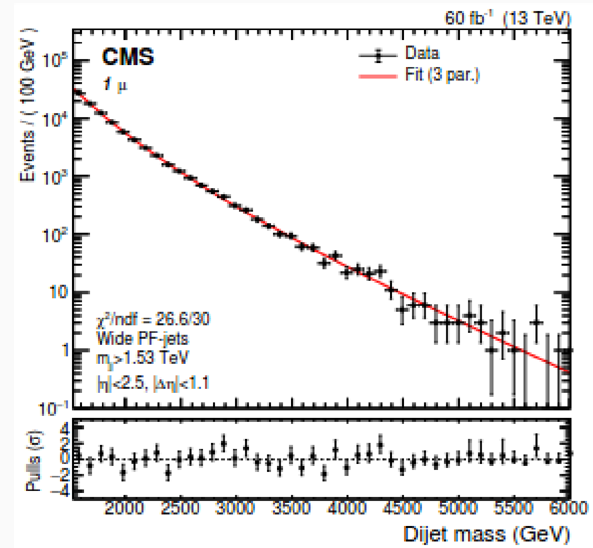
Fits for Z’



60 fb⁻¹ (13 TeV)
CMS
2 b tag
Data
Fit (3 par.)
χ²/ndf = 27.9/29
Wide PF-jets
m_jj>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)



60 fb⁻¹ (13 TeV)
CMS
1 b tag
Data
Fit (3 par.)
χ²/ndf = 19.3/34
Wide PF-jets
m_jj>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)



60 fb⁻¹ (13 TeV)
CMS
1 μ
Data
Fit (3 par.)
χ²/ndf = 26.6/30
Wide PF-jets
m_jj>1.53 TeV
|η|<2.5, |Δη|<1.1
Events / (100 GeV)
Pulls (σ)
Dijet mass (GeV)

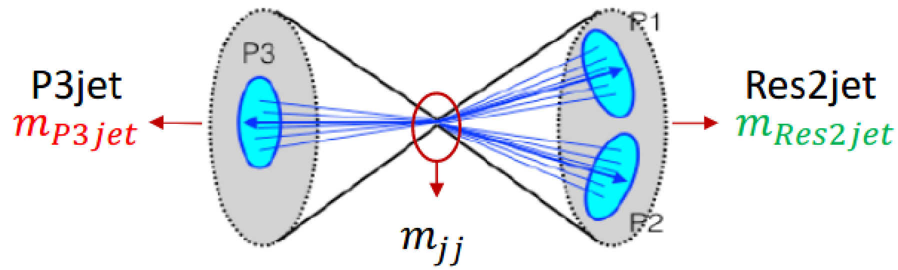
Systematic Uncertainties

Uncertainty Source	Uncertainty	Implementation
Jet Energy Resolution	10%	of RECO resolution
Jet Energy Scale	2%	shift of m_{jj}
Luminosity	2.5% in 2016/2018, 2.3% in 2017	lnN
b tagging SF Weight	0.2–31.2%	lnN
Muon SF Weight	44.9–60.6%	lnN

Observables 3-jet

Physics Observables:

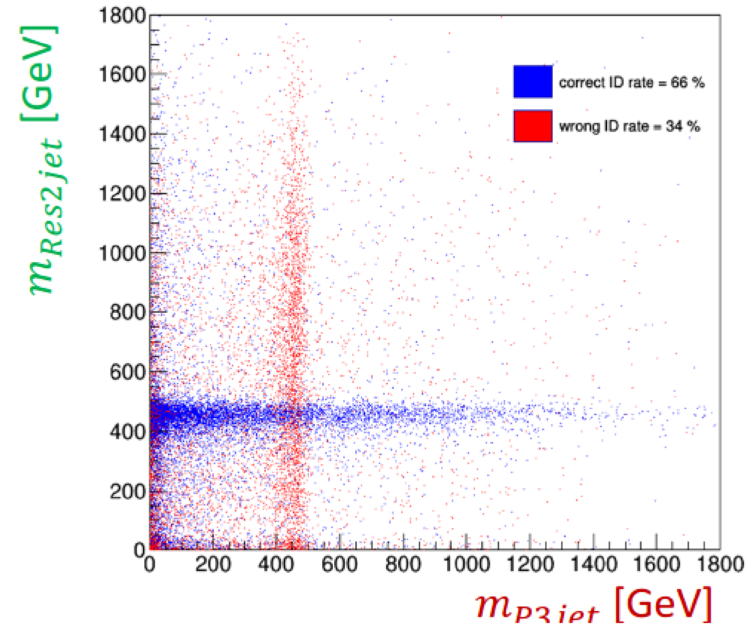
- m_{jj}: dijet mass
- $m_{Res2jet}$: Res2 jet mass
- m_{P3jet}: P3 jet mass



Res2-jet identification:

- Res2 candidate is the jet with <u>*smallest* τ_{21}</u> value (N-subjettiness ratio)
- <u>No cut on τ_{21}</u>
- Wrong ID in ~30% of events (vertical band)

$M_{Res1} = 5000\ GeV \quad \rho_m = 0.1 \quad M_{Res2} = 500\ GeV$



Systematic Uncertainties

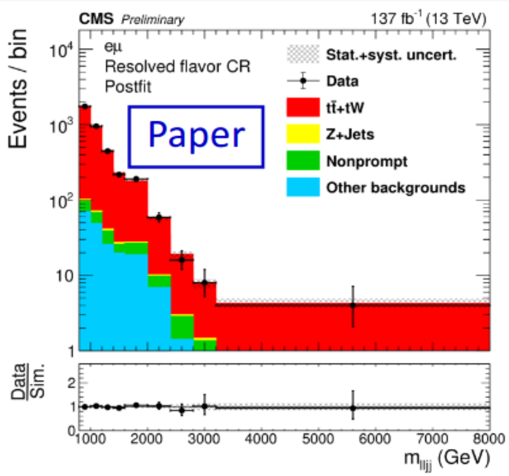
- Main systematic uncertainties:
  - Jet Energy Scale (JES)*: $\sigma_{JES} = \pm 2\%$
  - Jet Energy Res (JER)*: $\sigma_{JER} = \pm 10\%$
  - Jet Mass Scale (JMS)**: $\sigma_{JMS} = \pm 3\%$
  - Jet Mass Res (JMR)**: $\sigma_{JMR} = \pm 10\%$
  - N-subjettiness (τ_{21}): $\sigma_{\tau_{21}} = \pm 10\%$
- Jet uncertainties effects:
  - $JES \Rightarrow$ shift of m_{jj} signal peak
  - $JER \Rightarrow$ smearing of m_{jj} signal peak
  - $JMS,\ JMR, \tau_{21} \Rightarrow$ changes in normalization (Nsig)
- Use of average signal m_{jj} shapes
  - additional uncertainty on signal peak position and width
- Overall impact on xsec upper limits ~10%

JES up fit

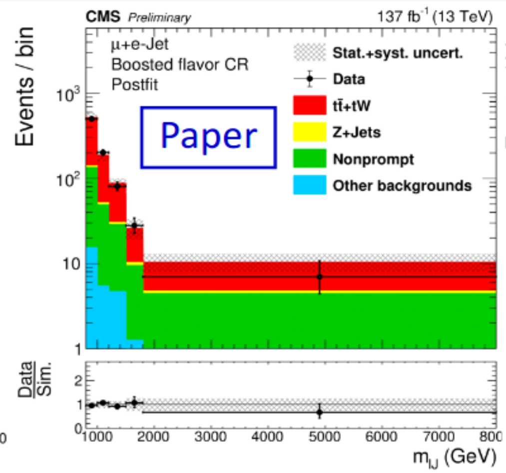
JMS down fit

JER fit

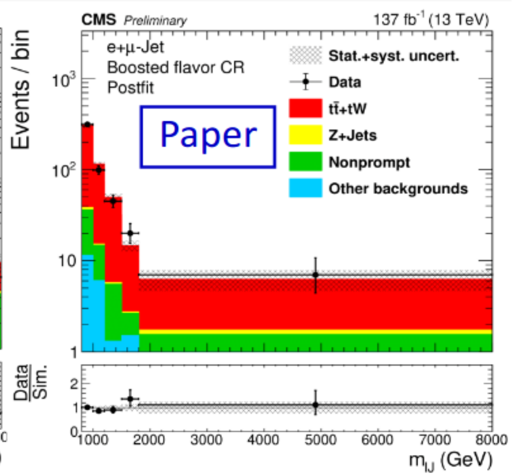
eμ sideband



CR of resolved ee and μμ



CR of boosted ee (μ + e-Jet)



CR of boosted μμ (e + μ-Jet)

Background estimation: DY

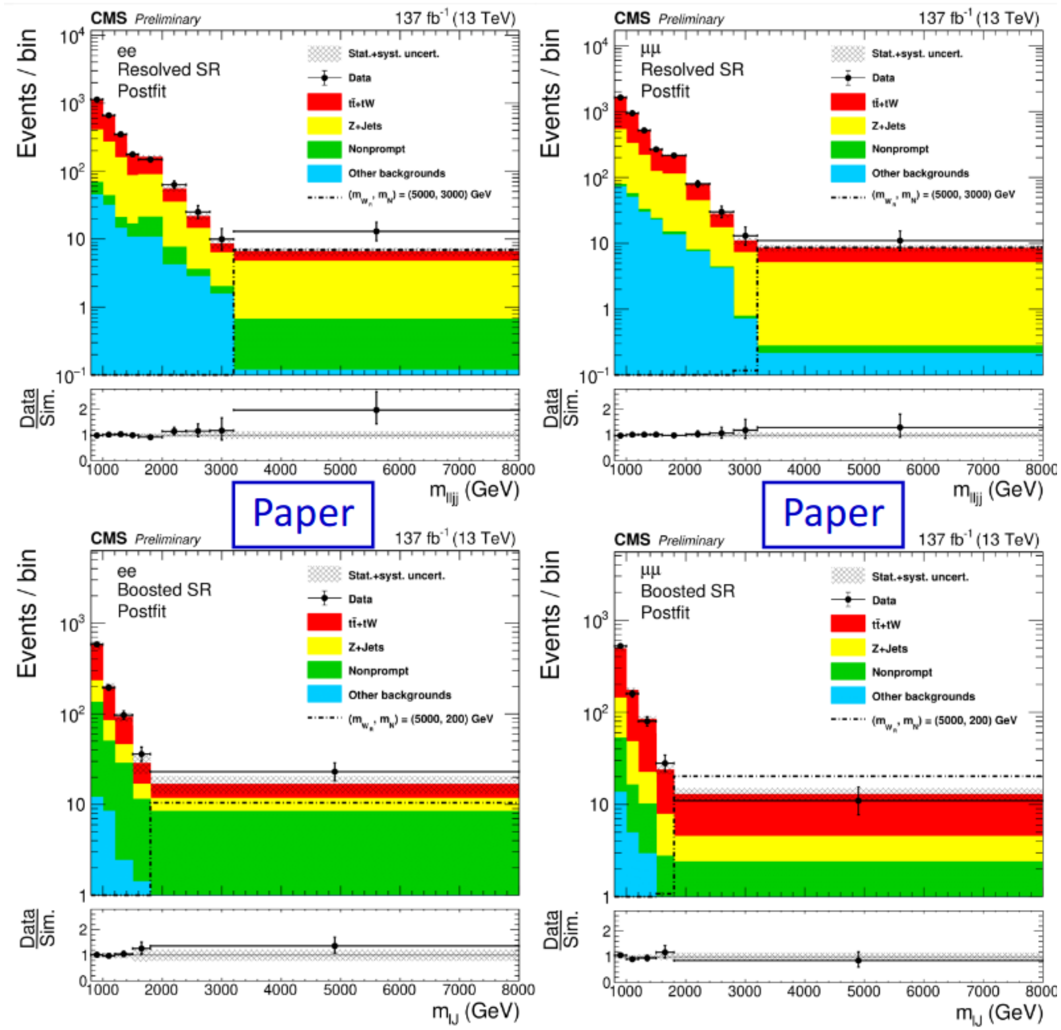
- **DY CR**: same selection as signal region except $60 < m_{ll} < 150$ GeV
  - For boosted,
    - remove LSF > 0.75 requirement
    - no constraint on l_{Loose} direction
- **Z-p_T reweighting** following same procedure as EXO-19-016 except use NLO DY sample instead of data
  - Higher order correction binned in GEN Z mass and p_T applied to LO HT binned DY sample (backup)
- **Normalization scale factor** obtained after Z-p_T reweighting applied

Systematic Uncertainties

Paper

Source	Bkgd./Signal process	Year-to-year treatment	ee bkgd. (%)	ee signal (%)	$\mu\mu$ bkgd. (%)	$\mu\mu$ signal (%)
Integrated luminosity	All bkgd./Signal	Uncorrelated	2.3–2.5 (2.3–2.5)	2.3–2.5 (2.3–2.5)	2.3–2.5 (2.3–2.5)	2.3–2.5 (2.3–2.5)
Electron reconstruction	All bkgd./Signal	Correlated	1.0–1.6 (0.5–0.8)	0.8–1.4 (0.4–0.8)	—	—
Electron energy resolution	All bkgd./Signal	Correlated	< 0.1 (< 0.1)	< 0.1 (< 0.1)	—	—
Electron energy scale	All bkgd./Signal	Correlated	0.5–1.8 (0.5–2.3)	0–0.3 (0–0.5)	—	—
Electron identification	All bkgd./Signal	Correlated	3.1–3.2 (1.8–1.9)	4.1–4.4 (2.1–2.4)	—	—
Electron trigger	All bkgd./Signal	Uncorrelated	0–0.1 (0.2–0.4)	< 0.1 (0.1–0.2)	—	—
Muon reconstruction	All bkgd./Signal	Correlated	—	—	0.4–1.0 (0.3–0.7)	4.4–36.8 (5.6–30.7)
Muon momentum scale	All bkgd./Signal	Correlated	—	—	0.4–2.5 (0.4–3.6)	0.1–0.2 (0.1–0.3)
Muon identification	All bkgd./Signal	Correlated	—	—	0.2–1.2 (0.1–0.6)	0.2–1.1 (0.1–0.5)
Muon isolation	All bkgd./Signal	Correlated	—	—	0.1–0.2 (0–0.1)	0.1–0.2 (0–0.1)
Muon trigger	All bkgd./Signal	Uncorrelated	—	—	0.1–0.2 (0.1–0.2)	0.7–1.6 (0.5–1.3)
Jet energy scale	All bkgd./Signal	Correlated	1.9–4.1 (0.9–2.0)	0–0.2 (0–0.3)	2.1–3.4 (0.6–1.0)	0–0.2 (0–0.4)
Jet energy resolution	All bkgd./Signal	Uncorrelated	0.5–1.4 (0.7–1.9)	0–0.3 (0–0.4)	0.2–1.2 (0.2–1.1)	0–0.3 (0–0.3)
LSF scale factor	All bkgd./Signal	Uncorrelated	— (6.8–8.7)	— (6.7–8.7)	— (5.8–7.1)	— (5.8–7.1)
Pileup modeling	All bkgd./Signal	Correlated	0.2–1.1 (0.5–1.1)	0.1–0.8 (0.2–0.9)	0.3–0.5 (0.3–1.1)	0.1–0.5 (0–0.6)
Z-p_T correction	DY+jets	Correlated	2.7–3.3 (2.7–3.6)	—	2.8–3.2 (2.8–3.4)	—
DY reshape	DY+jets	Correlated	4.2–4.8 (4.9–5.8)	—	4.3–4.8 (5.1–5.5)	—
Nonprompt background normalization	Nonprompt	Uncorrelated	100 (100)	—	100 (100)	—
Rare SM background normalization	Others	Correlated	50 (50)	—	50 (50)	—
PDF error	Signal	Correlated	—	5.9–11.1 (8.8–39.9)	—	2.8–6.8 (17.5–40.6)
α_S	Signal	Correlated	—	0–0.2 (0.2–1.3)	—	0–0.2 (0.2–1.2)
renormalization/factorization scales	Signal	Correlated	—	0–0.1 (0.3–2.3)	—	0–0.1 (2.1–2.9)

Results


CMS Preliminary
137 fb^{-1} (13 TeV)
ee
Resolved SR
Postfit
μμ
Resolved SR
Postfit
ee
Boosted SR
Postfit
μμ
Boosted SR
Postfit
Stat.+syst. uncert.
Data
tt̄+tW
Z+Jets
Nonprompt
Other backgrounds
(m_{W_R}, m_N) = (5000, 3000) GeV
(m_{W_R}, m_N) = (5000, 200) GeV
Events / bin
Data / Sim.
m_{lljj} (GeV)
m_{lJ} (GeV)
Paper
Paper