Bottom-Like Vector-Like Quark Pair Production in the Fully Hadronic Mode

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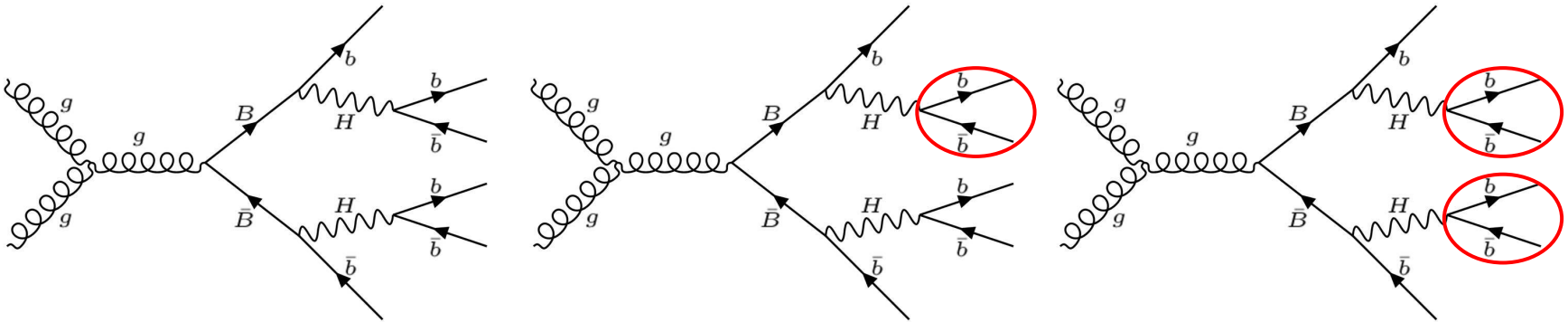
Analysis Overview

- $B\bar{B} \rightarrow bH\bar{b}H \rightarrow b\bar{b}b\bar{b}b\bar{b}$
- 4, 5, or 6 b jets depending on number of merged/boosted Higgs
- χ^2 metric for selecting jet combination
- Single and Double b jet tagging
- Data-driven background estimation
- 137.2 fb^{-1} Integrated Luminosity: 2016 + 2017 + 2018



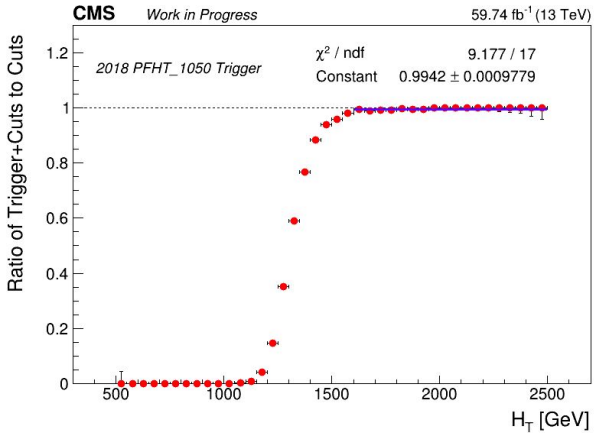
Analysis Procedure

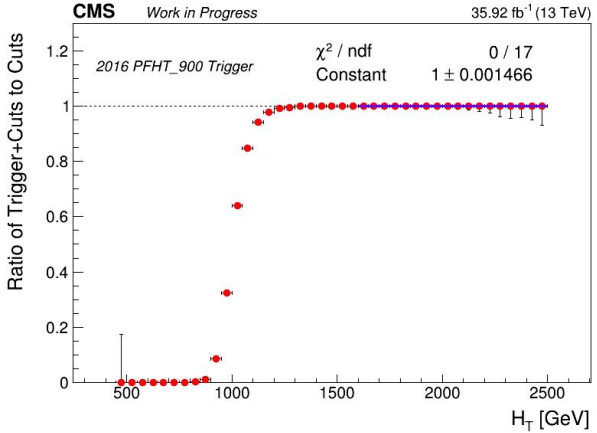
Data: Run II of the LHC (2016, 2017, 2018)

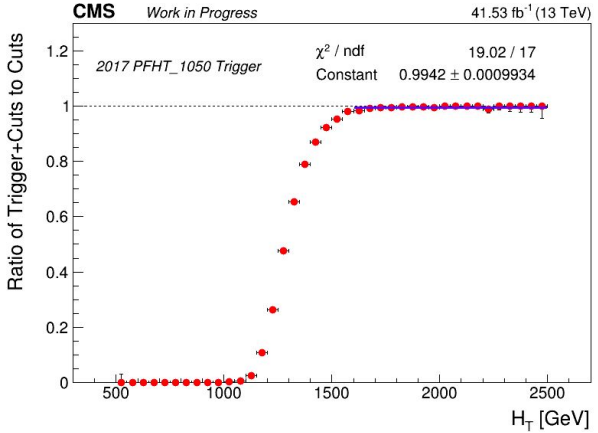
1. Require H_T (sum of scalar jet p_T) greater than 1600 GeV
2. Sort events into “4-Jet”, “5-Jet”, or “6-Jet” events - The number of jets with p_T > 50 GeV and $|\eta| < 2.4$
3. For 4-Jet and 5-Jet events, determine potential merged Higgs candidates
4. Apply a jet multiplicity dependent χ^2 metric to choose best jet combination
5. Apply a χ^2 cut and b-tag requirement to jets
6. Optimize χ^2 and b-tag cuts using the CLs method
7. Determine exclusion by using Higgs Combine for each signal masspoint, data year, and jet multiplicity

Triggers

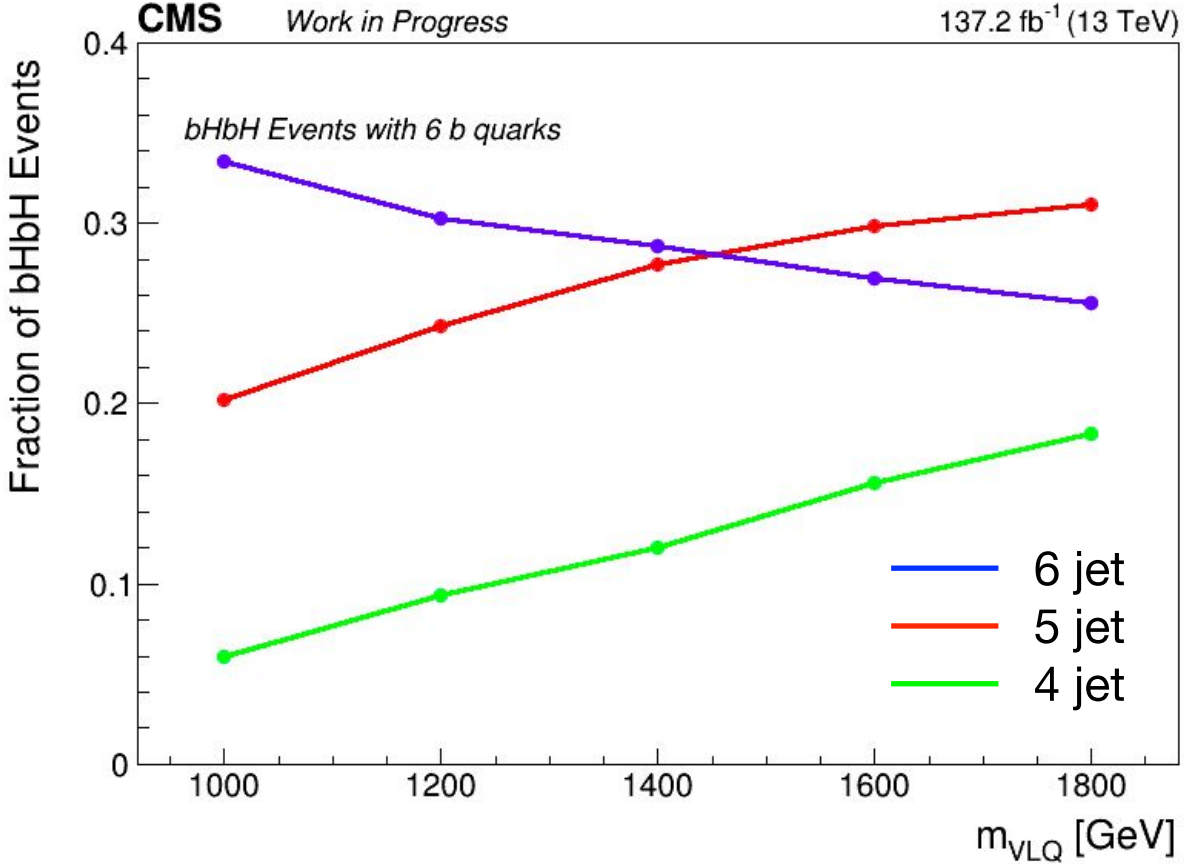
- High Level Trigger:
  - H_T > 900 GeV (2016)
  - H_T > 1050 GeV (2017 & 2018)
- Triggers are 100% efficiency for H_T > 1600 GeV
- Moderate χ^2 cut applied







Jet Multiplicity



4-Jet χ^2 Metric

- Mass of each Higgs Candidate
- Fractional mass difference of VLQ candidates
- Use softdrop mass for merged Higgs candidates
- Parameters determined by jet-MC truth matching

$$\chi^2 = \frac{(M_{H1} - \overline{M_{H1}})^2}{\sigma^2_{\overline{M_{H1}}}} + \frac{(M_{H2} - \overline{M_{H2}})^2}{\sigma^2_{\overline{M_{H2}}}} + \frac{(\Delta M_{VLQ} - \overline{\Delta M_{VLQ}})^2}{\sigma^2_{\overline{\Delta M_{VLQ}}}}$$

Merged Higgs mass

VLQ Mass Difference

5-Jet χ^2 Metric

- Mass of each Higgs Candidate
- Fractional mass difference of VLQ candidates
- ΔR of dijet Higgs candidate
- Use softdrop mass for merged Higgs candidate
- Parameters determined by jet-MC truth matching

Dijet Higgs

VLQ Mass Difference

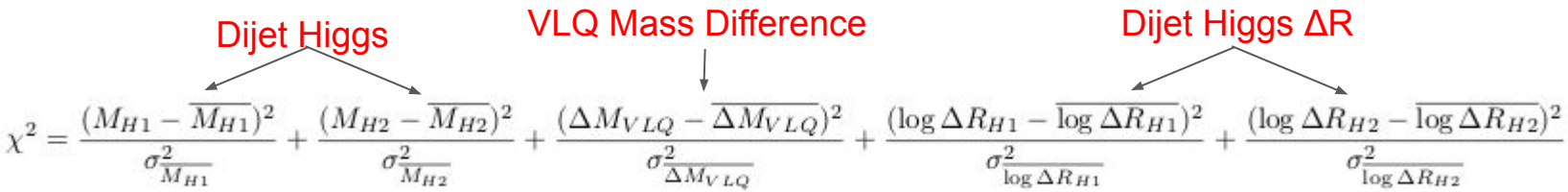
$$\chi^2 = \frac{(M_{H1} - \overline{M_{H1}})^2}{\sigma^2_{M_{H1}}} + \frac{(M_{H2} - \overline{M_{H2}})^2}{\sigma^2_{M_{H2}}} + \frac{(\Delta M_{VLQ} - \overline{\Delta M_{VLQ}})^2}{\sigma^2_{\Delta M_{VLQ}}} + \frac{(\log \Delta R_{H1} - \overline{\log \Delta R_{H1}})^2}{\sigma^2_{\log \Delta R_{H1}}}$$

Merged Higgs

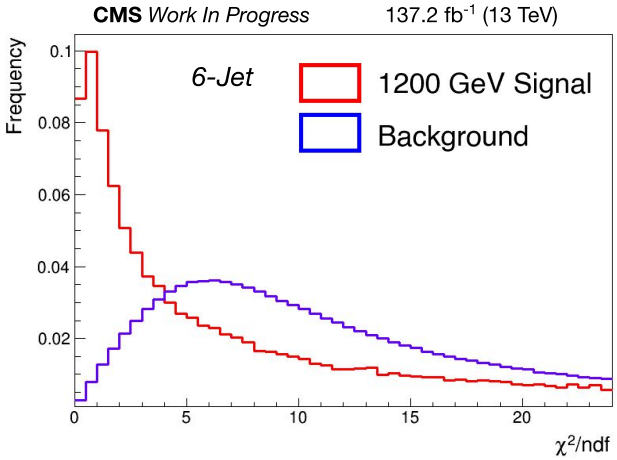
Dijet Higgs ΔR

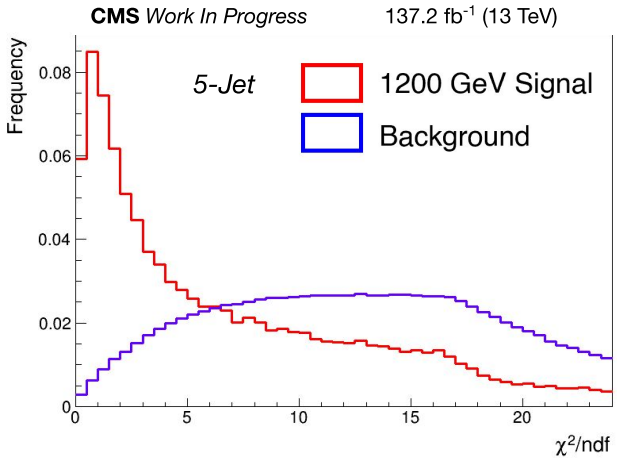
6-Jet χ^2 Metric

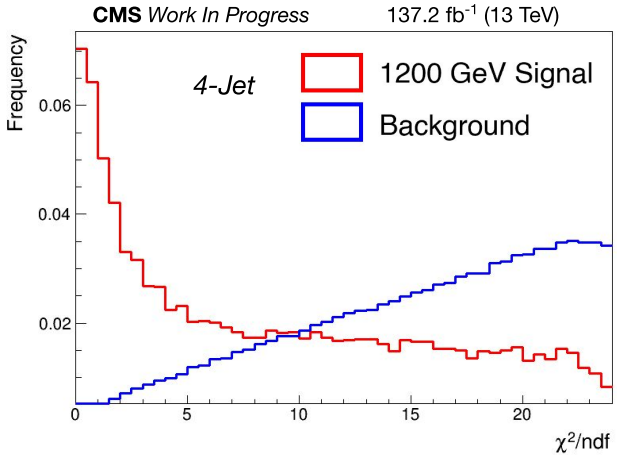
- Mass of each Higgs Candidate
- Fractional mass difference of VLQ candidates
- ΔR of dijet Higgs candidates
- Parameters determined by jet-MC truth matching



χ^2 Distributions



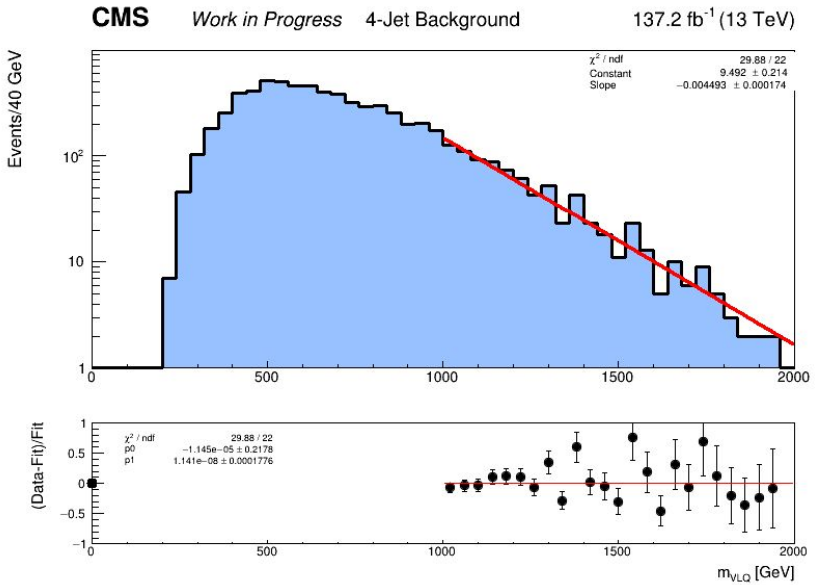




- χ^2 Distributions for 4-Jets, 5-Jet, and 6-Jet
- 1200 GeV Signal and Background

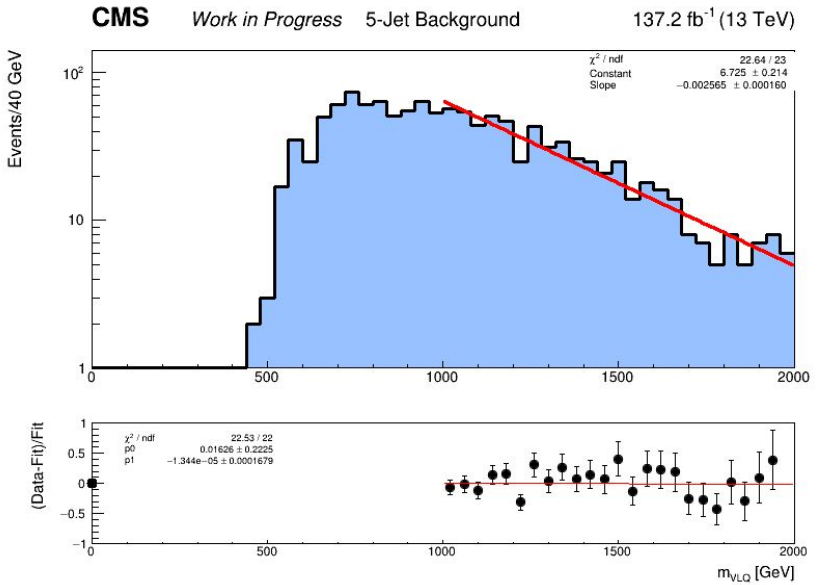
4-Jet Background Estimation

- VLQ Mass dependence of background after a χ^2 cut
- No b-tagging applied yet (blinded)
- Background and error determined from exponential fit
- Fit χ^2/ndf = 29.88 / 22



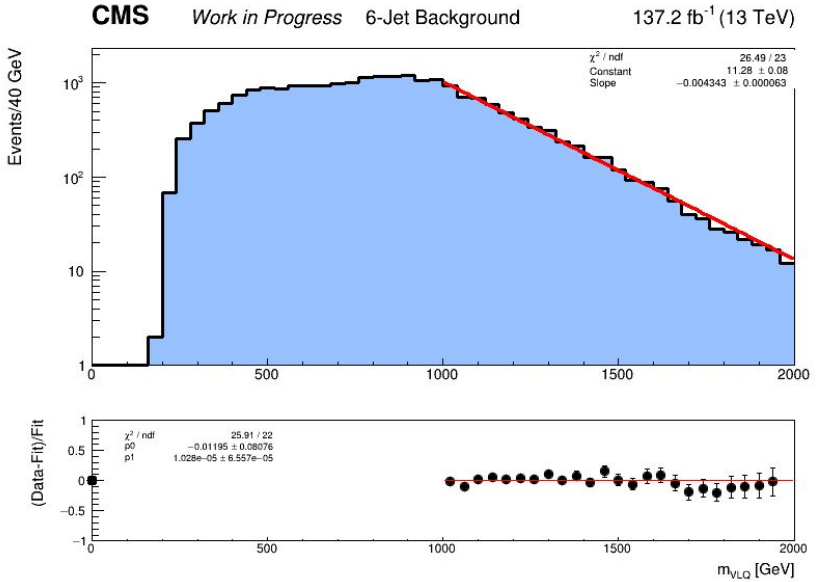
5-Jet Background Estimation

- VLQ Mass dependence of background after a χ^2 cut
- No b-tagging applied yet (blinded)
- Background and error determined from exponential fit
- Fit χ^2/ndf = 22.64 / 23



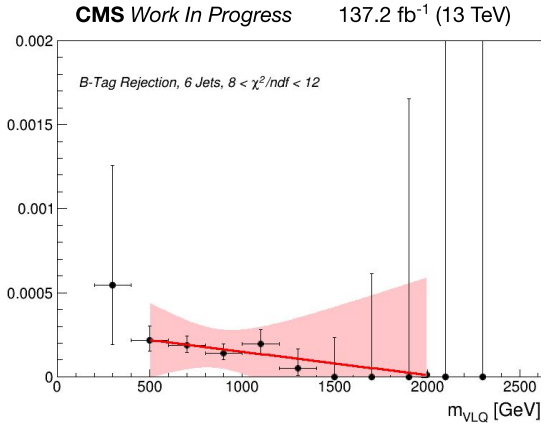
6-Jet Background Estimation

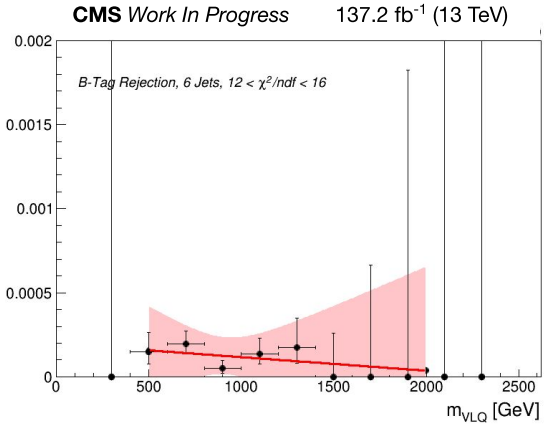
- VLQ Mass dependence of background after a χ^2 cut
- No b-tagging applied yet (blinded)
- Background and error determined from exponential fit
- Fit χ^2/ndf = 26.49 / 23

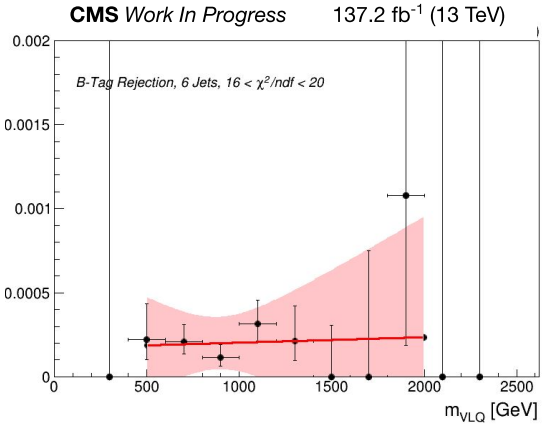


Background Estimation

- Background estimated by shifting χ^2 window to measure b-tag reduction factor.
- b-tag reduction factor has no dependence on the χ^2 window
- Reduction factor in the signal mass window determined by linear fit

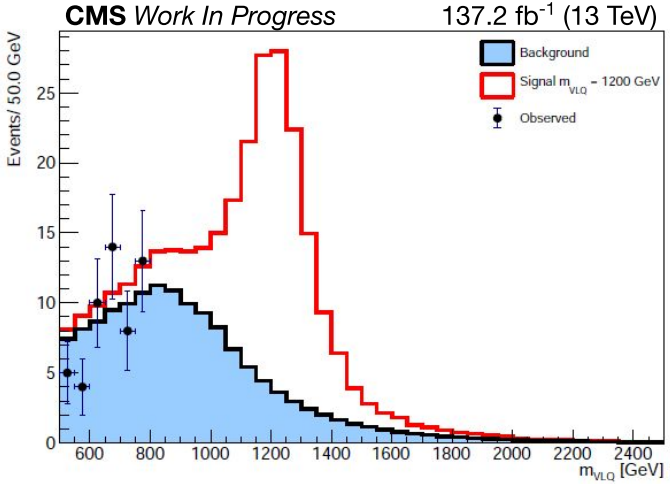






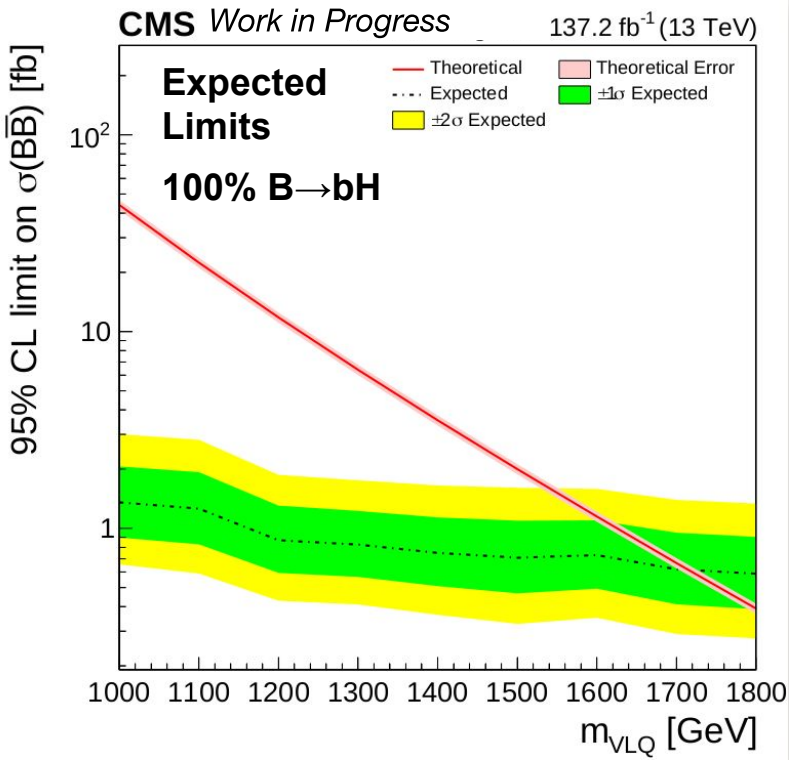
Cut Optimization

- Optimization is performed using the number of expected signal and background events in a ± 75 GeV window about the masspoint
- Use the 1-bin CLs method to calculate the signal cross section required for exclusion
- Systematic errors not included
- χ^2 and b-tag cuts are chosen to minimize this cross section
- Optimization is done separately for each jet multiplicity, year, and masspoint



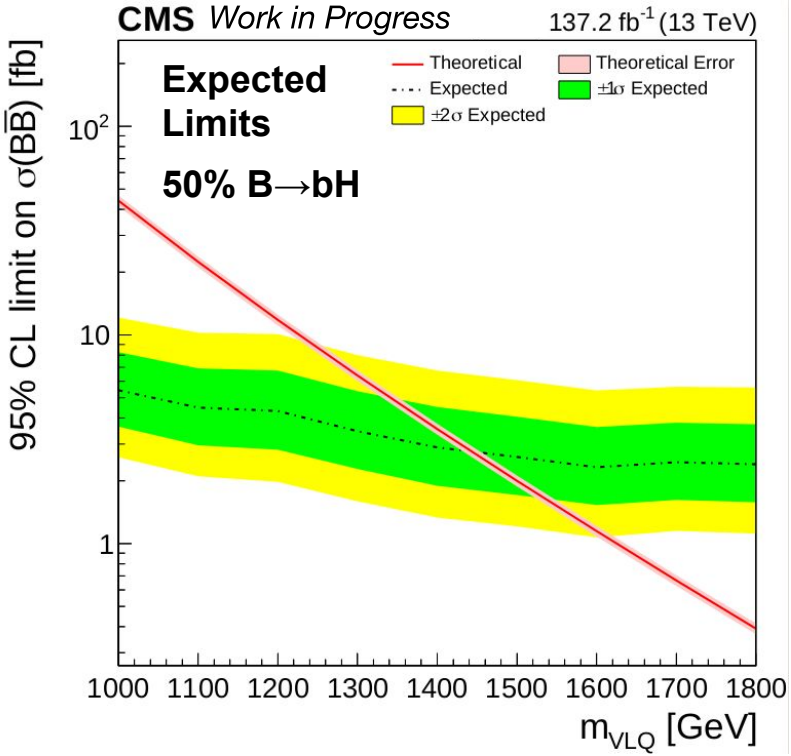
Expected Exclusion

- Assuming 100% B→bH
- Systematic errors not included
- Expected exclusion at 1720 GeV
- Current best published limit is 1010 GeV (Phys. Rev. D 98, 092005 (2018))



Expected Exclusion

- Assuming 50% B→bH
- Systematic errors not included
- Expected exclusion at 1440 GeV



Future Plans

- Include systematic errors in analysis
- Include BB→bHbZ and BB→bZbZ modes
- Determine the expected exclusion as a function of branching ratio
- Recover events by identifying extra jets due to initial-state gluon radiation via machine learning

Thank You!

Backup Slides

χ^2 Parameters

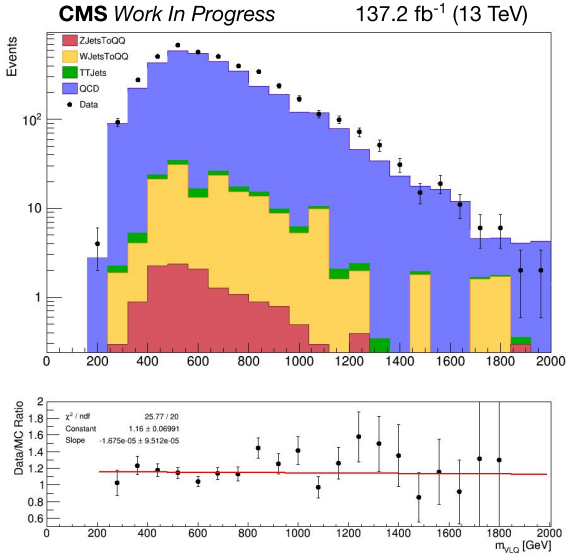
Good events determined by parton matching

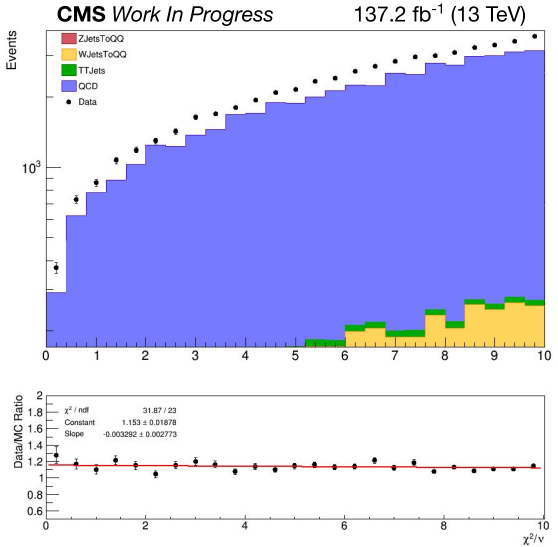
- 6 Jets: 6 one-to-one matches, ΔR < 0.25 to b partons
- 5 Jets: 4 one-to-one matches, ΔR < 0.25 to b partons and 1 match, ΔR < 0.10 to a Higgs parton
- 4 Jets: 2 one-to-one matches, ΔR < 0.30 to b partons and 1 match, ΔR < 0.10 to a Higgs parton

Parameter	Year	Mean	σ
$M_{H_{dijet}}$	2016	123.3	11.8
$M_{H_{dijet}}$	2017	123.4	12.4
$M_{H_{dijet}}$	2018	123.9	11.6
$M_{H_{merged}}$	2016	120.0	11.6
$M_{H_{merged}}$	2017	118.0	11.2
$M_{H_{merged}}$	2018	118.5	11.8
$\log \Delta R_{H_{dijet}}$	2016	0.647	0.310
$\log \Delta R_{H_{dijet}}$	2017	0.653	0.321
$\log \Delta R_{H_{dijet}}$	2018	0.662	0.321
$M_{VLQ_{4jet}}$	2016	0	0.126
$M_{VLQ_{4jet}}$	2017	0	0.141
$M_{VLQ_{4jet}}$	2018	0	0.134
$M_{VLQ_{5jet}}$	2016	0	0.13
$M_{VLQ_{5jet}}$	2017	0	0.13
$M_{VLQ_{5jet}}$	2018	0	0.13
$M_{VLQ_{6jet}}$	2016	0	0.126
$M_{VLQ_{6jet}}$	2017	0	0.119
$M_{VLQ_{6jet}}$	2018	0	0.131

4-Jet Data/MC Comparisons

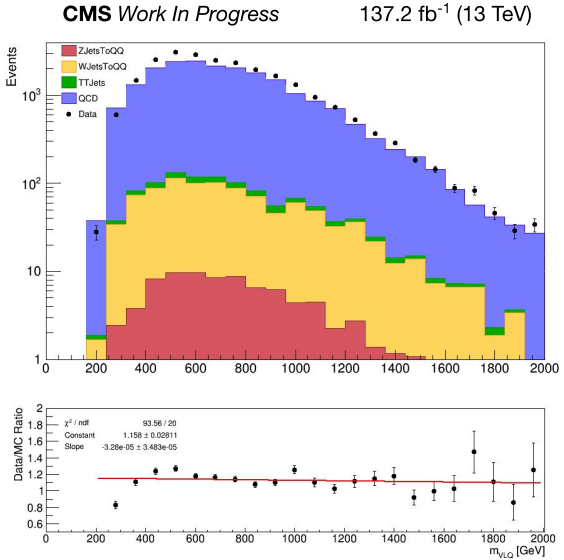
- 15% Data Excess
- No k Factors applied
  - VLQ mass distribution
  - no significant slope of data/MC
  - χ^2 distribution
  - no significant slope of data/MC

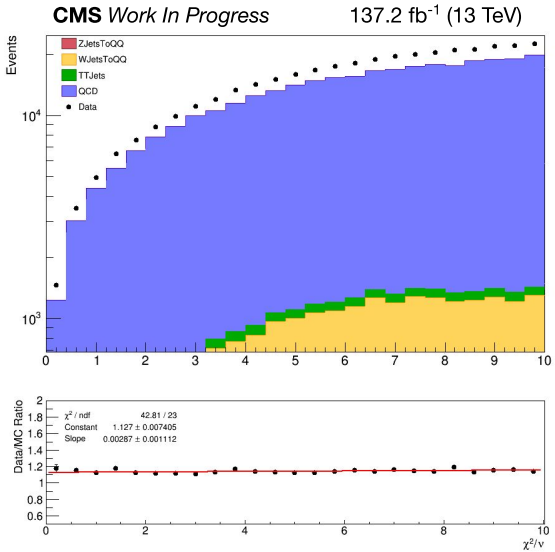




5-Jet Data/MC Comparisons

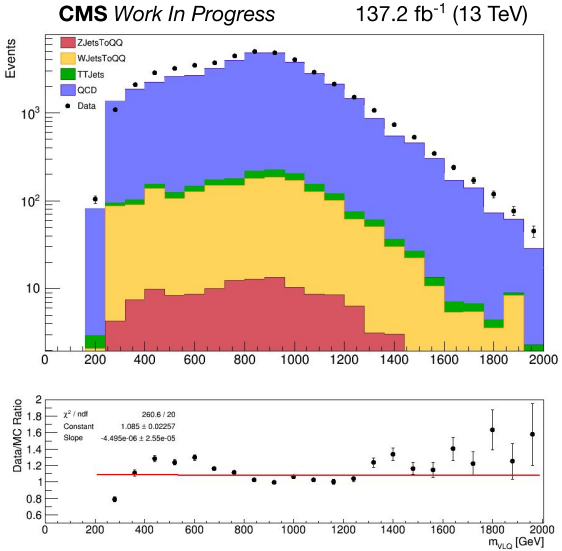
- 15% Data Excess
- No k Factors applied
  - VLQ mass distribution
  - no significant slope of data/MC
  - χ^2 distribution
  - no significant slope of data/MC





6-Jet Data/MC Comparisons

- 15% Data Excess
- No k Factors applied
  - VLQ mass distribution
  - MC deficit at higher masses



- χ^2 distribution
- 1% slope in data/MC