Search for single production of vector-like quarks decaying to a b quark and a Higgs boson

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on behalf of the **CMS** Collaboration

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Result and Perspectives in Particle Physics | Les Rencontres de Physique de la Vallée d'Aoste

PHENOMENOLOGICAL BACKGROUND

ANALYSIS STRATEGY

RESULTS AND INTERPRETATION

PHENOMENOLOGICAL BACKGROUND

Motivation

arXiv:1306.0572

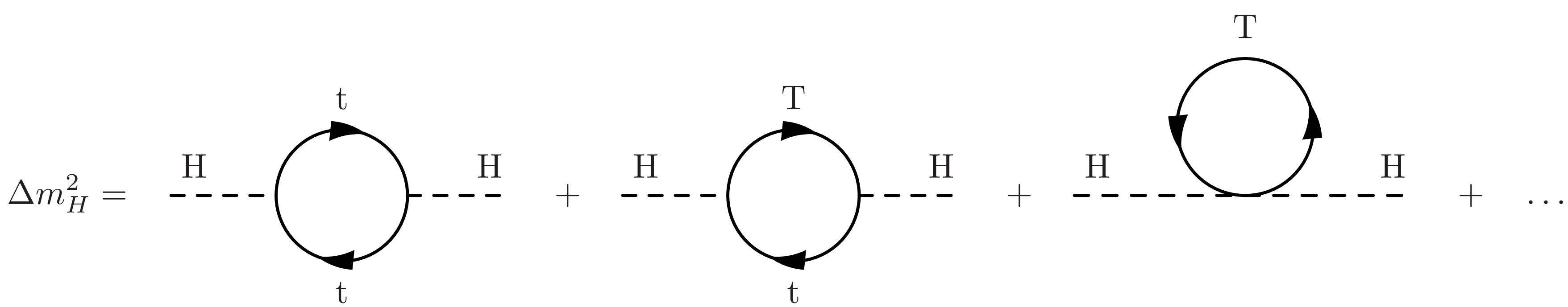
Many extensions of physics beyond the standard model suggest the existence of fermionic partners of bottom/top quarks (Vector-Like Quarks, VLQs)

What are vector-like quarks?

- Spin 1/2, electric and color charged particles
- L and R-handed chiralities transform in the same way under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

Why are we searching for them?

- Such particles might help to solve the fine tuning problem and stabilize the Higgs boson mass



- Their masses are expected to be appear at the TeV scale and are independent on the Higgs boson coupling → not disfavored by the Higgs discovery and its measured production cross sections and decays

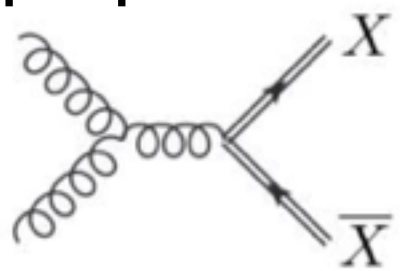
Phenomenology

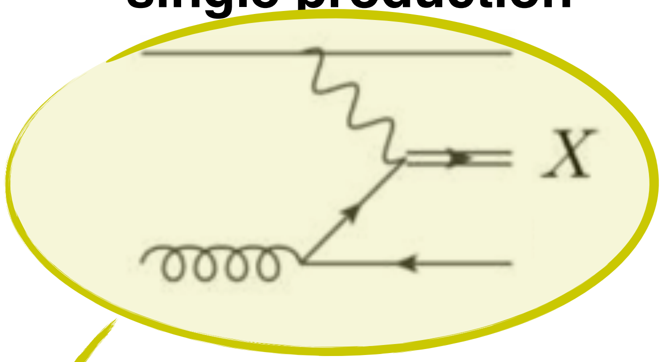
arXiv:1306.0572, arXiv: 1505.04306

production

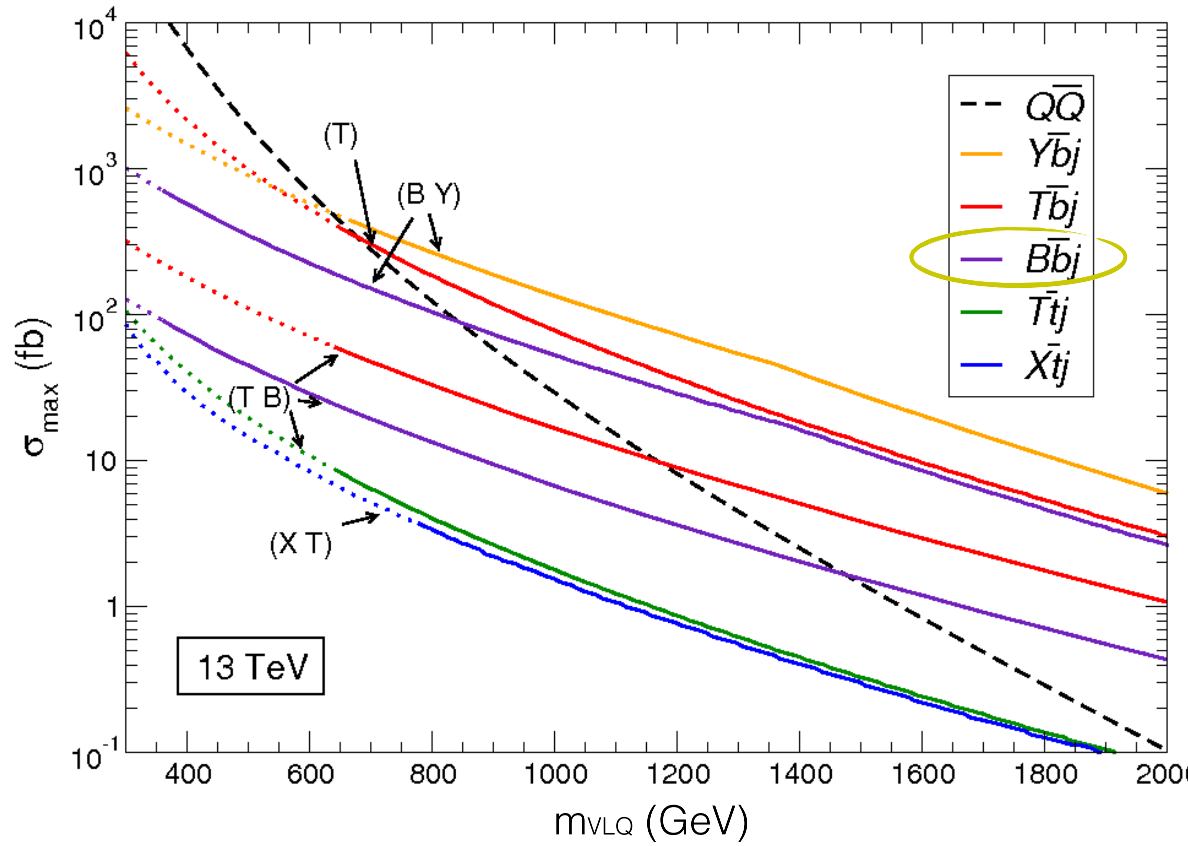
- **in pair:** strong interaction, σ dependent on VLQ mass
- **singly:** ewk interaction, σ dependent on VLQ mass and on the couplings with SM particles
  - becomes dominant for high VLQ masses

pair production **single production**





in this search we focus on the single production



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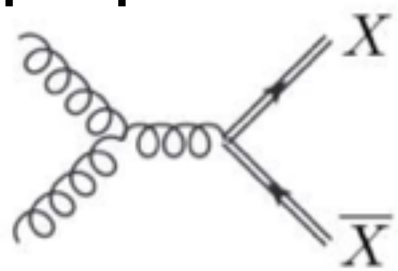
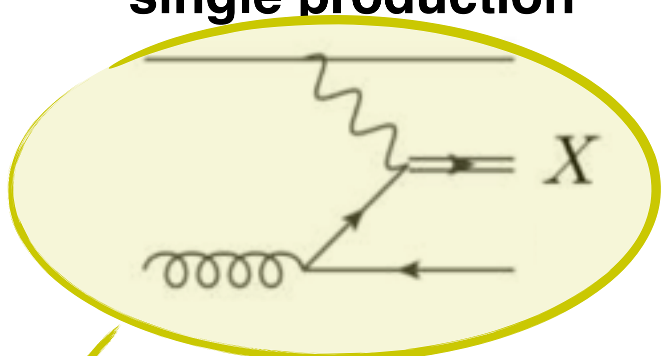
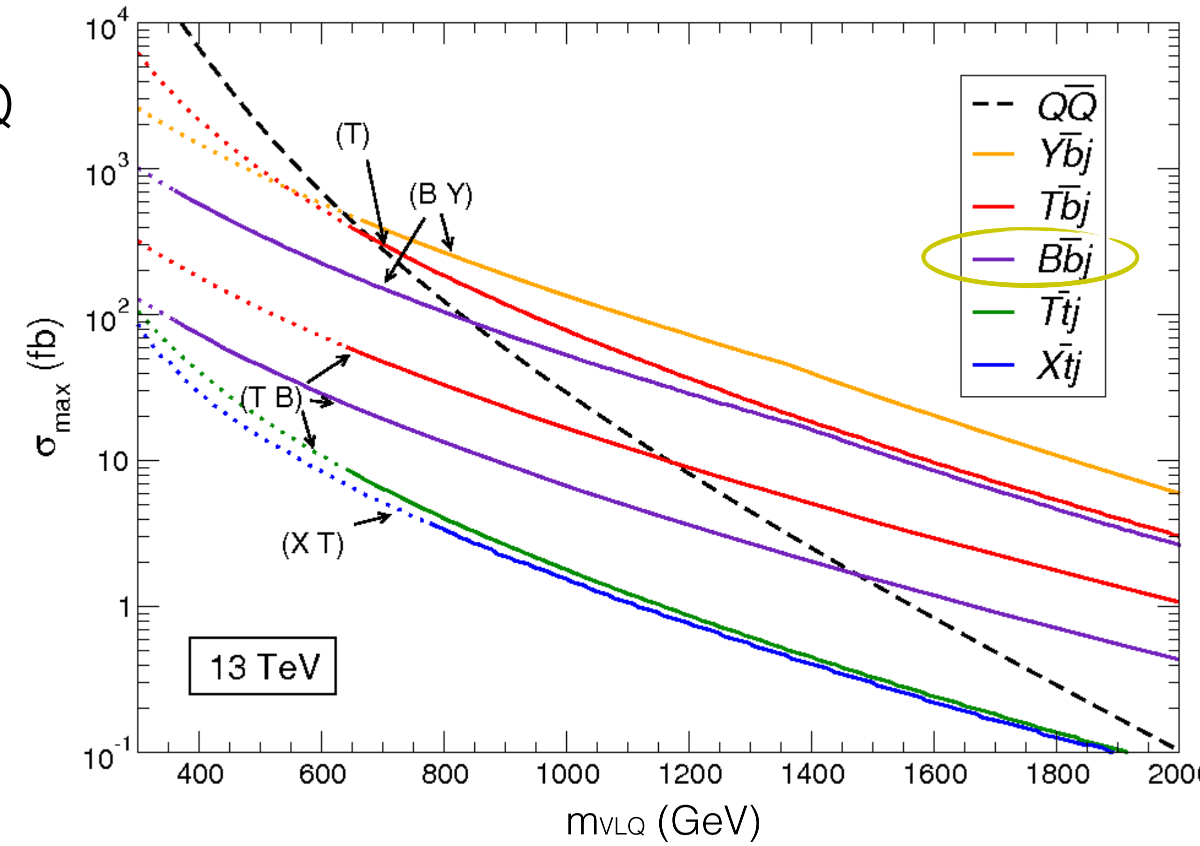
pair production



single production





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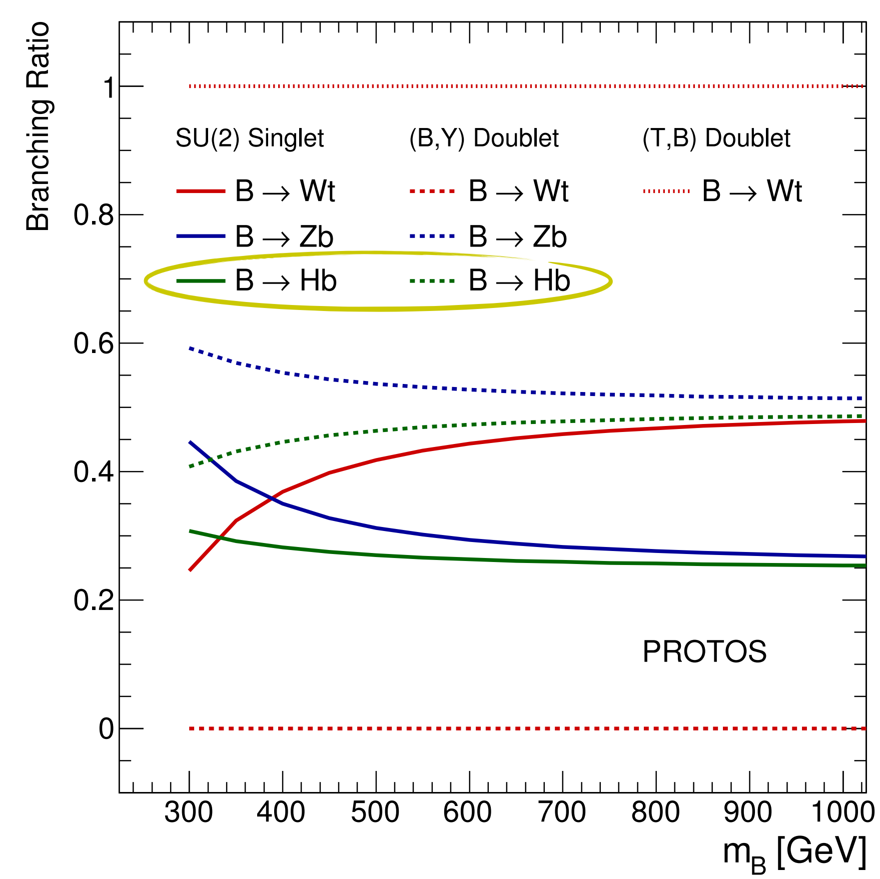
decay

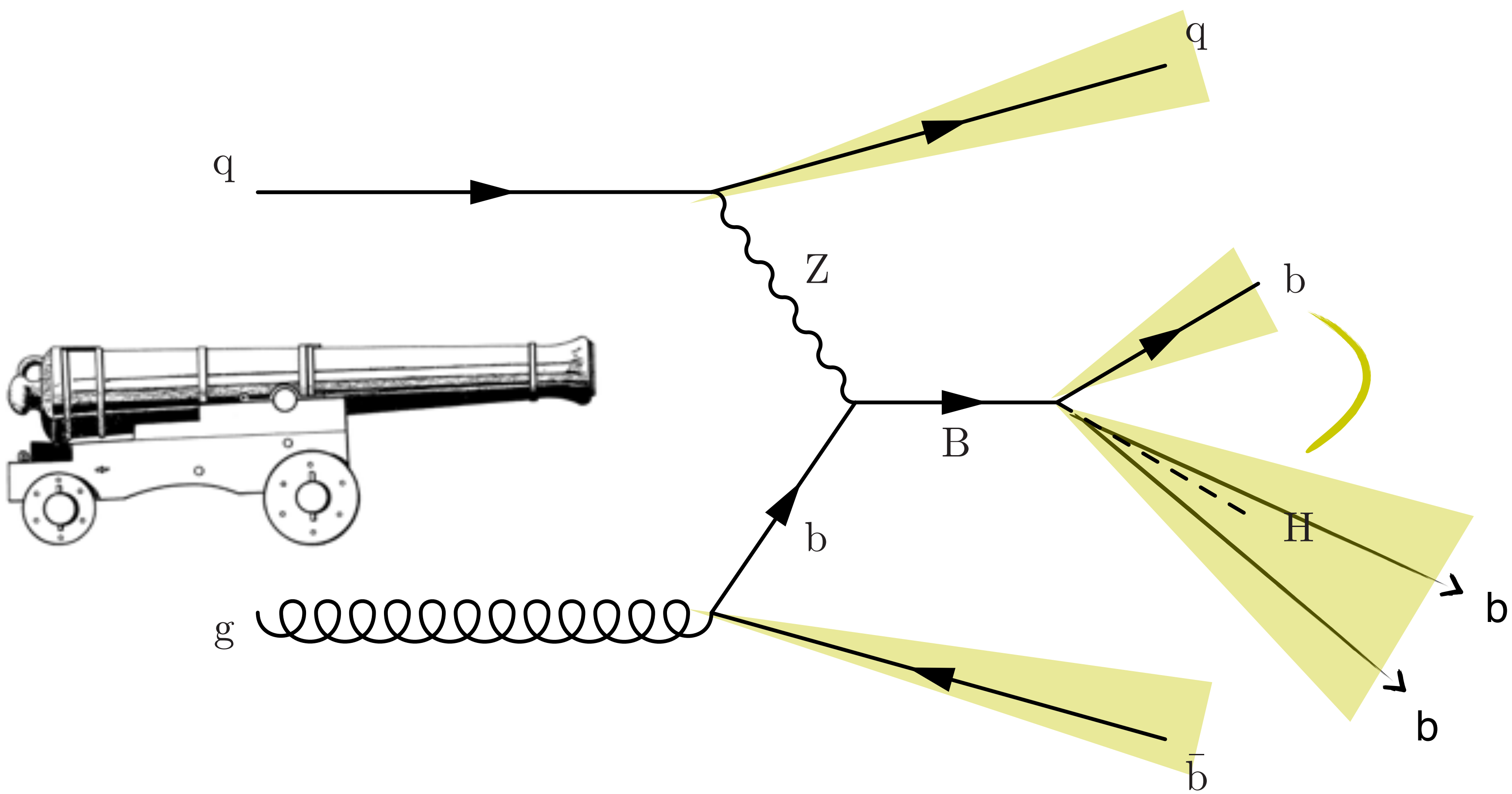
- in a gauge boson and a third-generation SM quark
- BRs depend on the isospin multiplet
  - both singlet and doublet models are considered



B →bH, fully hadronic

arXiv:1802.01486, CMS-B2G-17-009

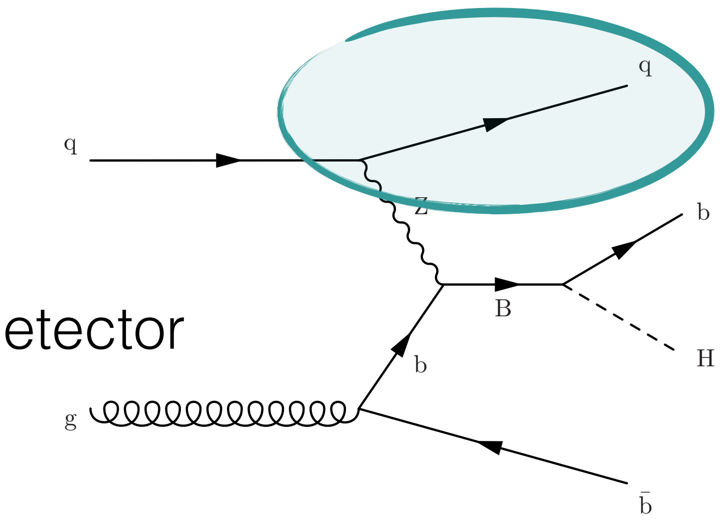
- **single production** of vector-like B quark
  - ewk mechanism, cross section dependent on VLQ mass and couplings to SM particles
- **fully hadronic signature** (and several b-quarks in the final state!)
- main background is QCD **multijet production**
  - minor contributions from TT, W+jets and Z+jets
- **boosted topology**, B is massive (~ O(TeV))
- the VLQ B can be resolved and its **mass reconstructed**



ANALYSIS STRATEGY

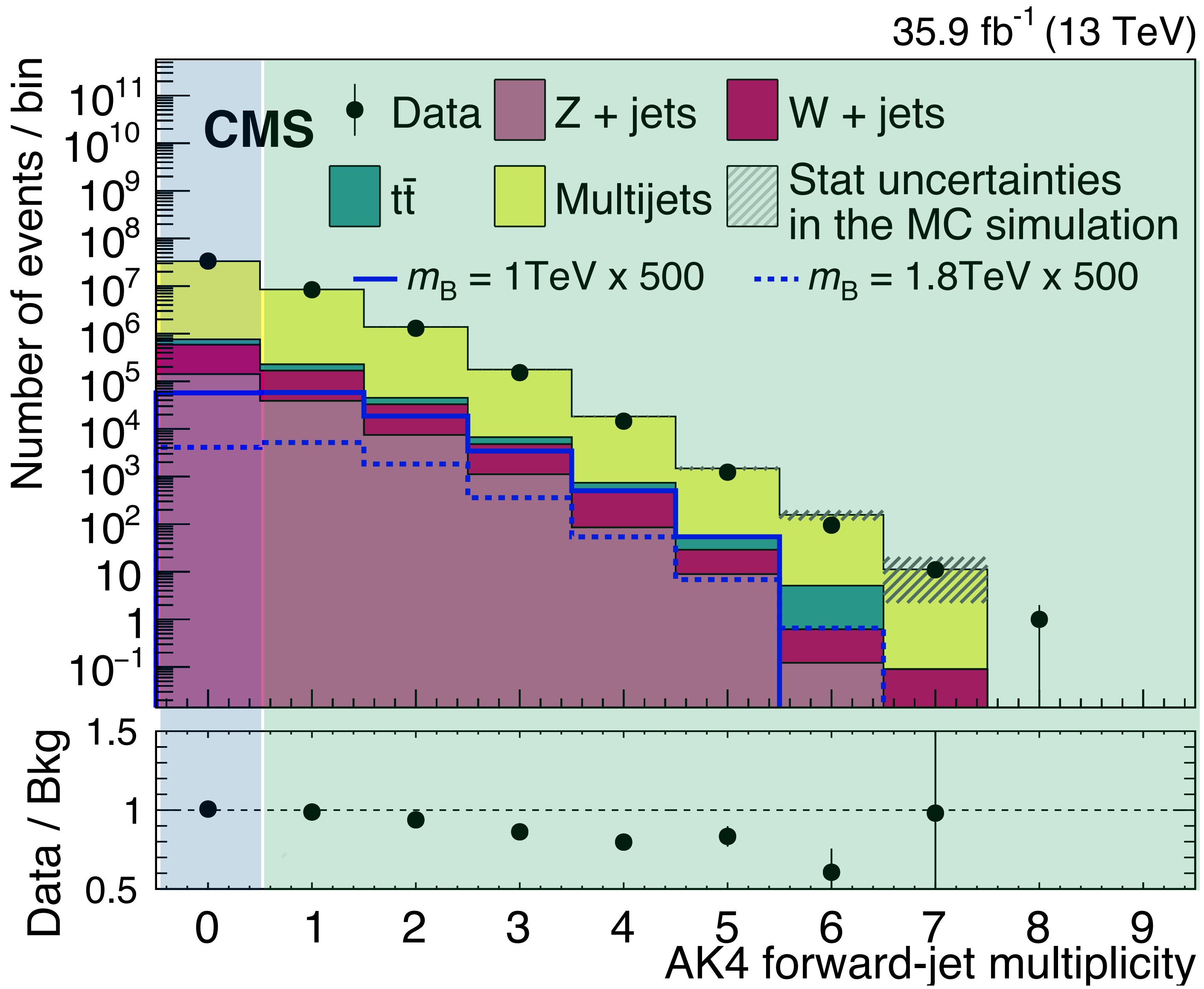
Forward jets

arXiv:1802.01486, CMS-B2G-17-009



additional feature of the signal:

- typically one jet emitted into the forward region (|η|>2.4) of the detector
- enhances discrimination between signal and background



two categories in place:

- **cat0**: 0 fwd jets
- **cat1**: at least 1 fwd jet

- cat1 is the most pure in signal
- cat0 also improves the sensitivity as it is expected to be populated by a large amount of signal events

the combination of the two brings an improvement of 10/20% on the final sensitivity of the analysis, with respect to considering cat 1 only

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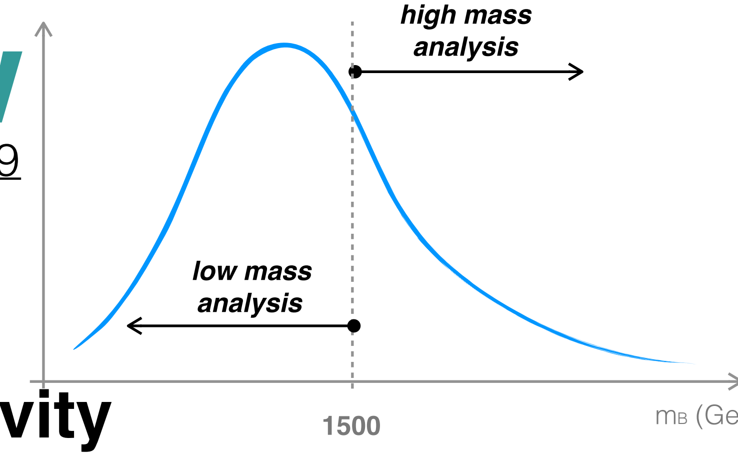
Analysis workflow

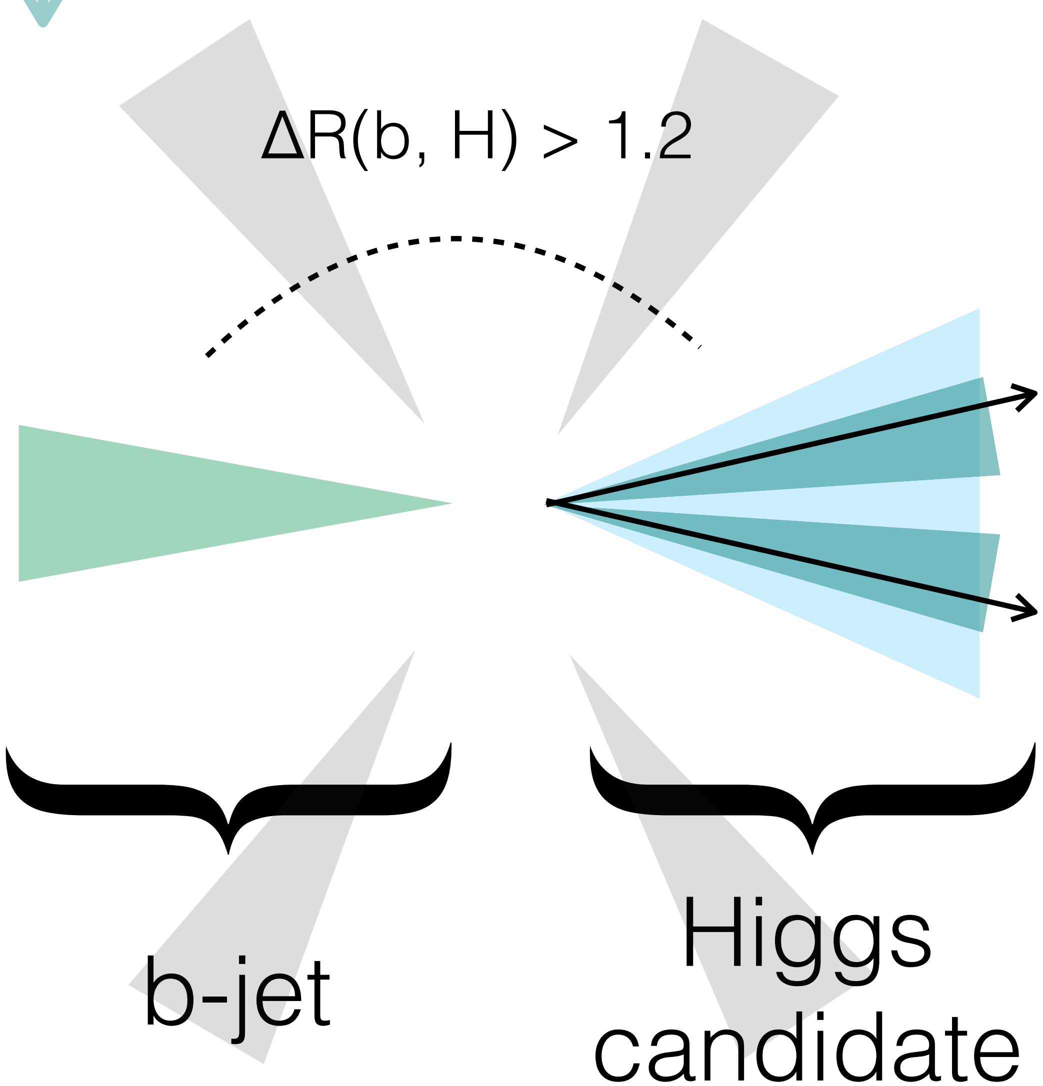
arXiv:1802.01486, CMS-B2G-17-009



Online Selection

- $p_T > 450$ GeV
- $H_T^* > 900$ GeV

* hadronic activity, scalar sum of the jets p_T



Hadronic Activity

- $H_T > 950$ GeV (for m_B<1.5 TeV, ***low mass analysis***)
- $H_T > 1250$ GeV (for m_B≥1.5 TeV, ***high mass analysis***)

Preselection

- ≥ 1 large-cone jet
- ≥ 3 narrow jets
- ≥ 1 b-tagged jet
- lepton veto

(boosted) Higgs tagging

- *pruned* mass in [105, 135] GeV
- 2 b-tagged subjets

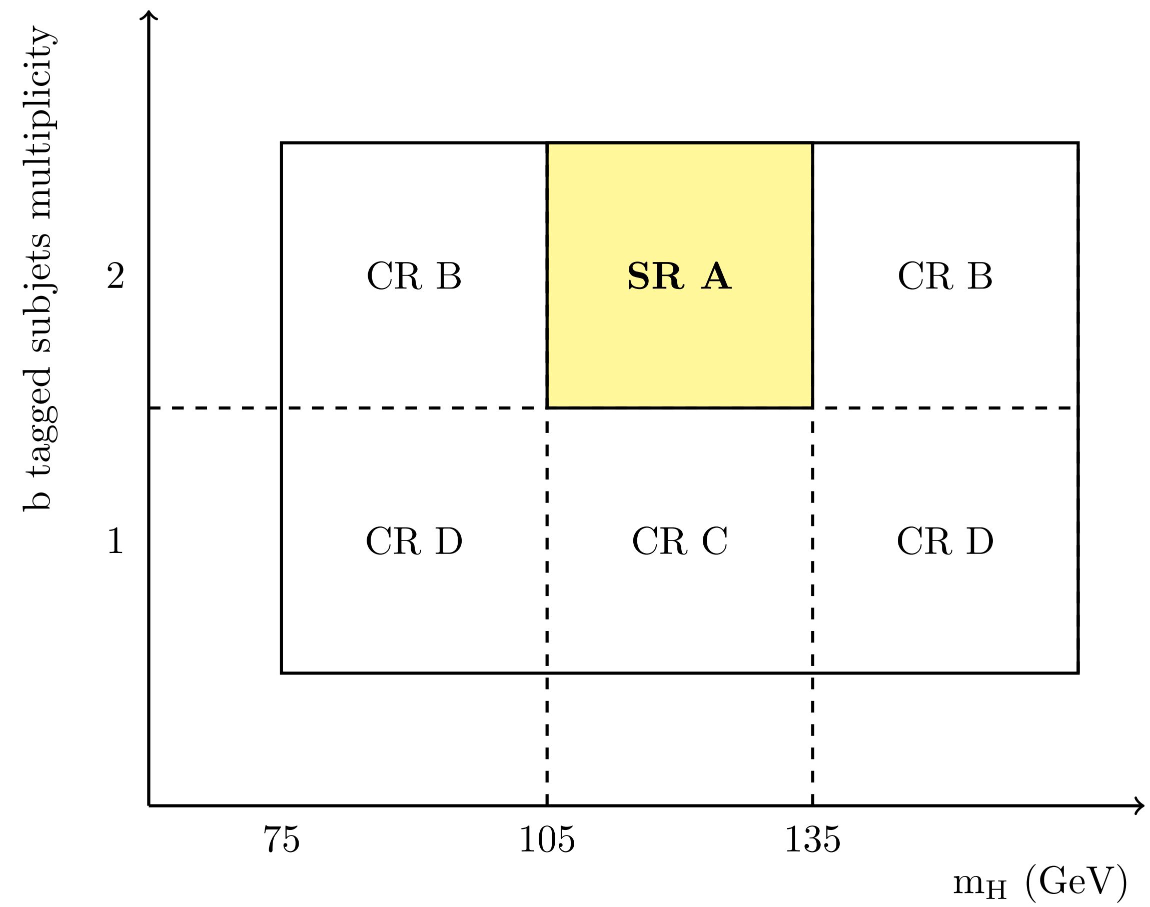
B reconstruction

- using the H jets and the leading b-jet satisfying ΔR(b, H) > 1.2

Background estimation

arXiv:1802.01486, CMS-B2G-17-009

- **ABCD method** is employed to derive QCD multijets background from data
- **3 regions** enriched in QCD are defined by inverting two signal requirements:
  - mass of the Higgs-tagged jet
  - b-tagged subjets multiplicity



Method workflow

1. shape taken from **region C**
2. background normalization expectation in signal region (A):

$$N(A) = N(C) \times N(B) / N(D)$$

3. multiple closure tests performed on simulation and on special validation regions in data to check the validity of the method

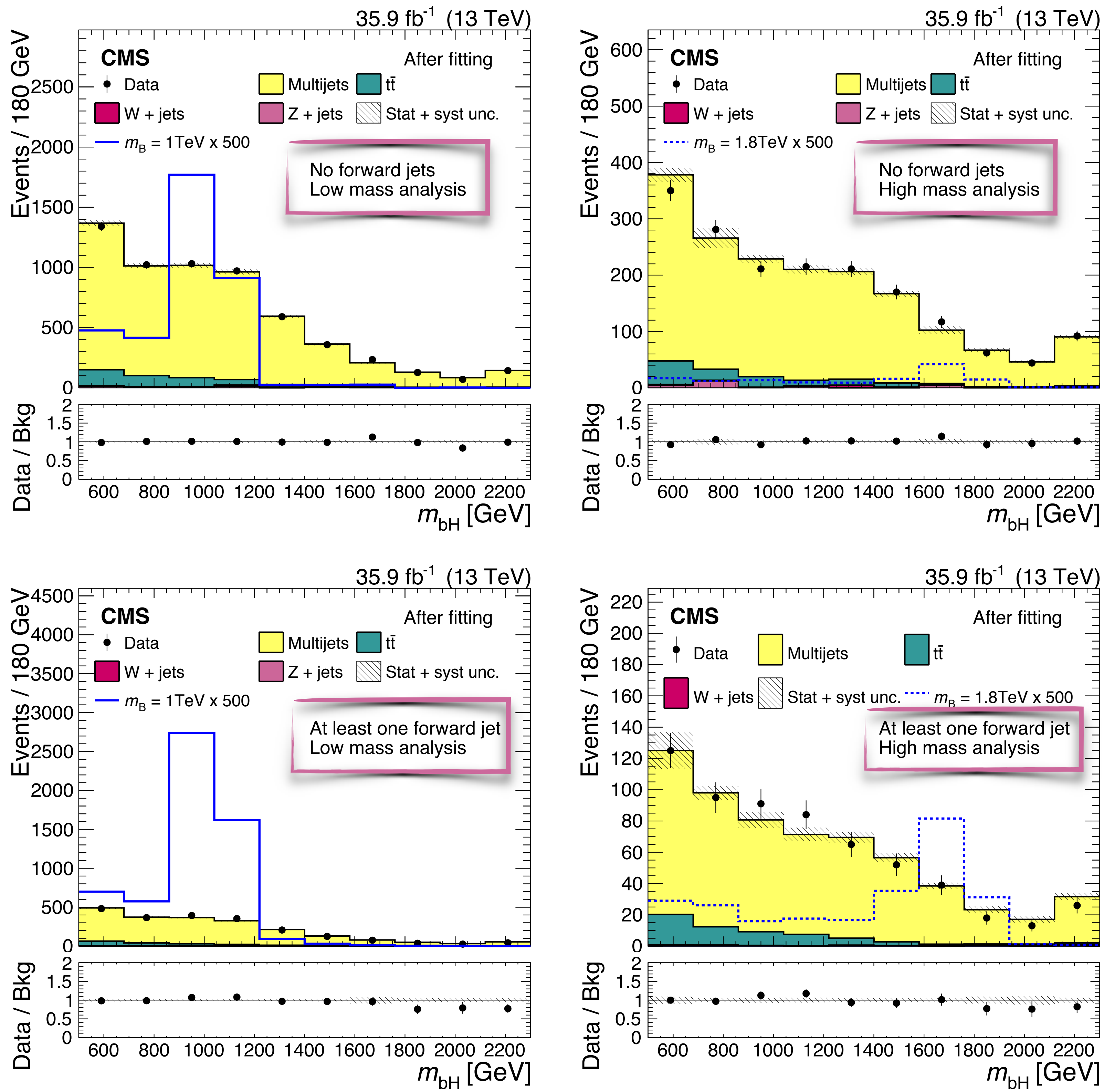
RESULTS AND INTERPRETATION

Results

arXiv:1802.01486, CMS-B2G-17-009

- **a binned maximum likelihood fit is performed:**
  - systematic uncertainties are included and treated as nuisance parameters

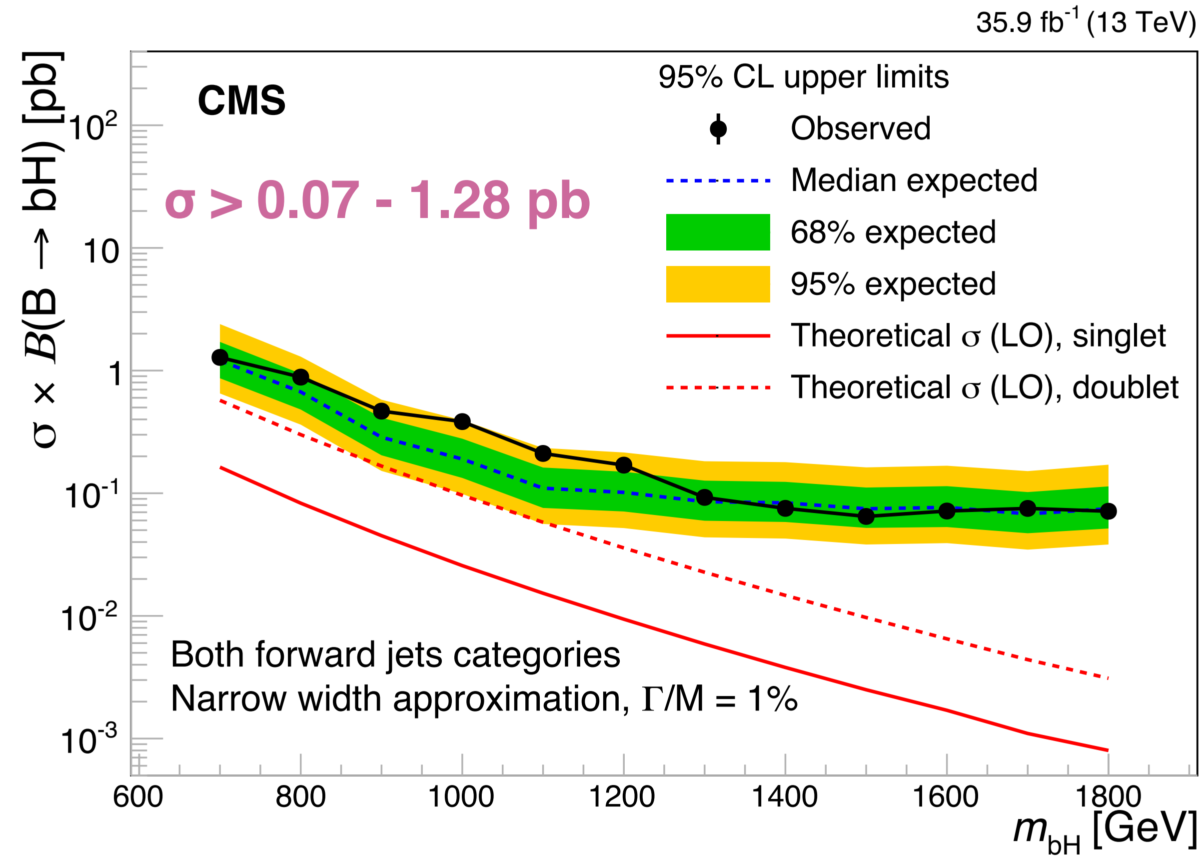
- post-fit distributions of the reconstructed B mass
  - all categories are shown
  - very good agreement between data and MC within uncertainties
  - no excess of data over the SM prediction

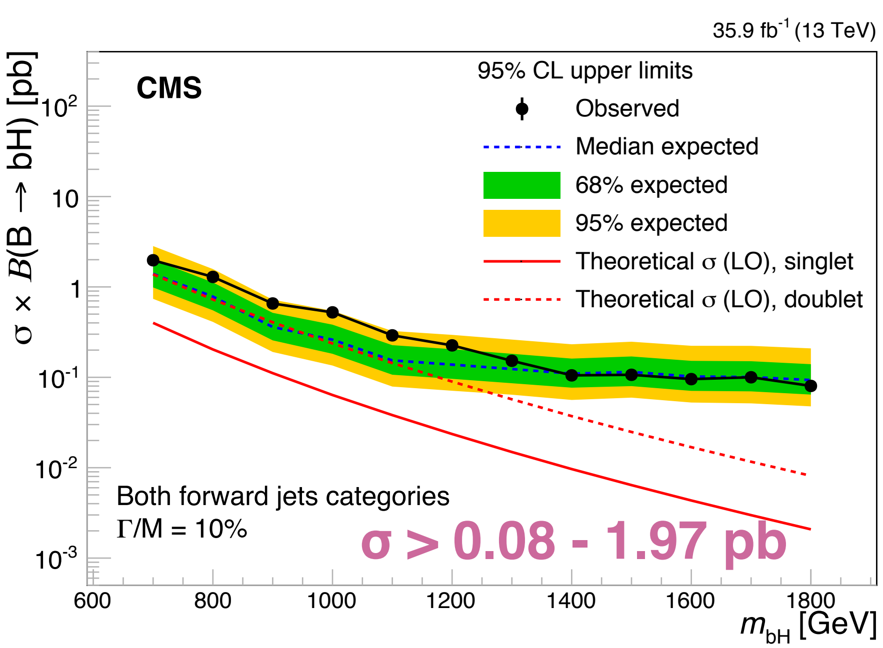


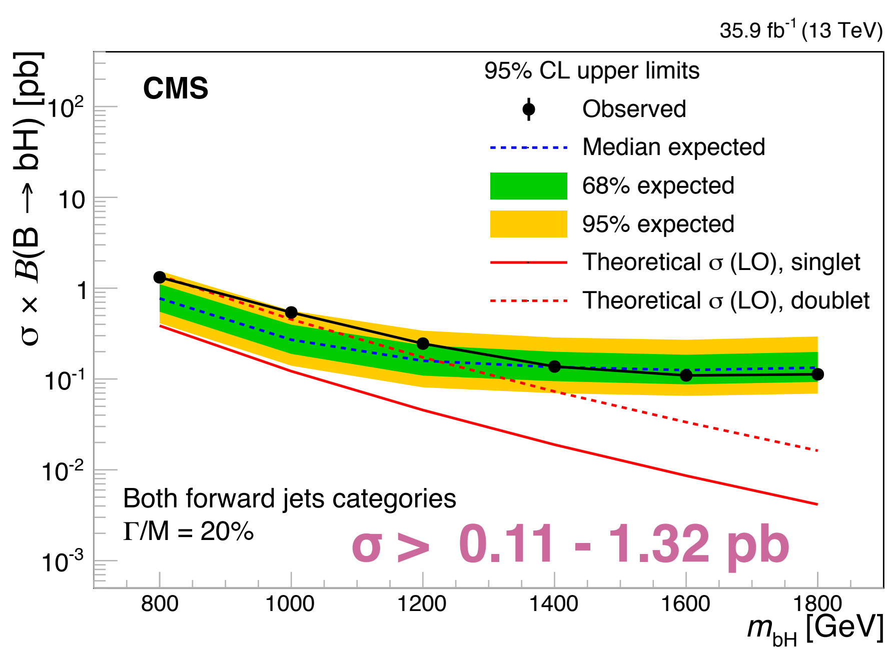
Interpretation

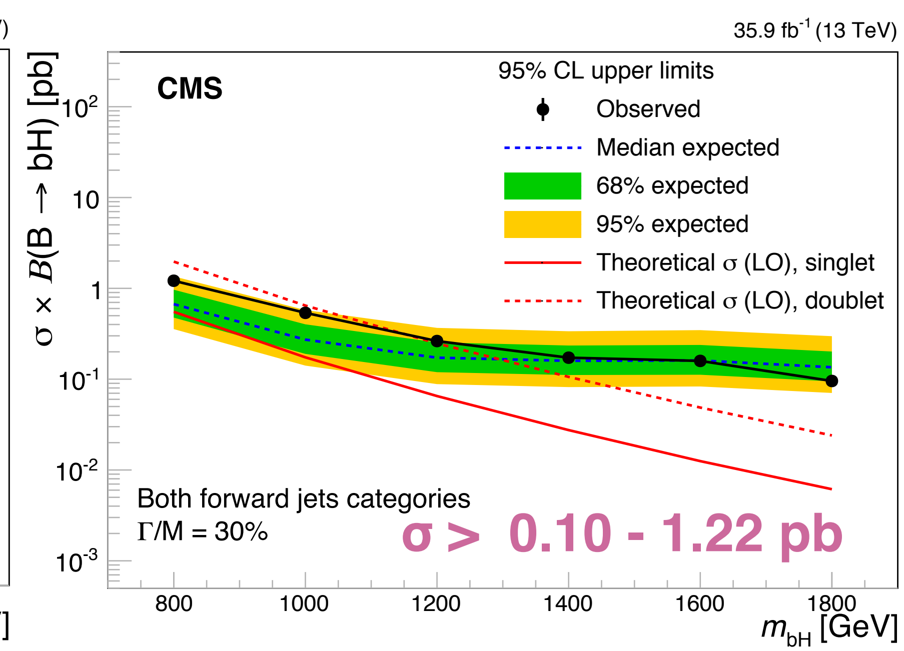
arXiv:1802.01486, CMS-B2G-17-009

- no deviation from SM expectation observed
- upper limits on the signal production cross section times the branching ratio are set as a function of the VLQ B mass
- regime of narrow width approximation considered
  - but also more realistic resonance width/mass scenarios are investigated
- results both for singlet and doublet B quark









Conclusions

- This search **extends existing knowledge on VLQs**

  1) by interpreting the results in a new theoretical framework with non-negligible resonance widths
  2) investigating the final state with a bottom quark and a Higgs boson for the first time

- Upper limits on the production cross section times branching ratio are set

  - similar sensitivities obtained in the two resonance width models
  - both singlet and doublet B quark models considered

Conclusions

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Thanks for your attention!

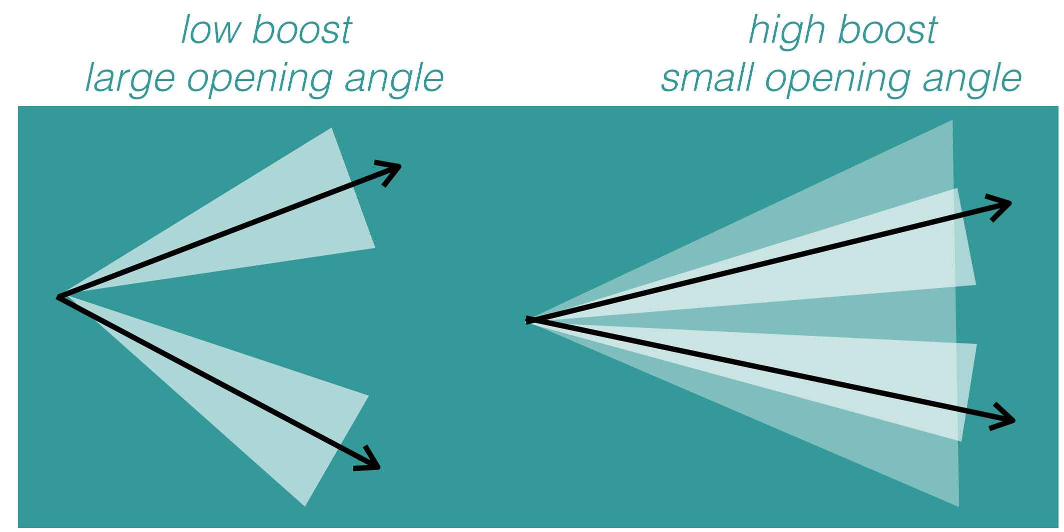
ADDITIONAL MATERIAL

Boosted Higgs-tagging

arXiv:1802.01486, CMS-B2G-17-009

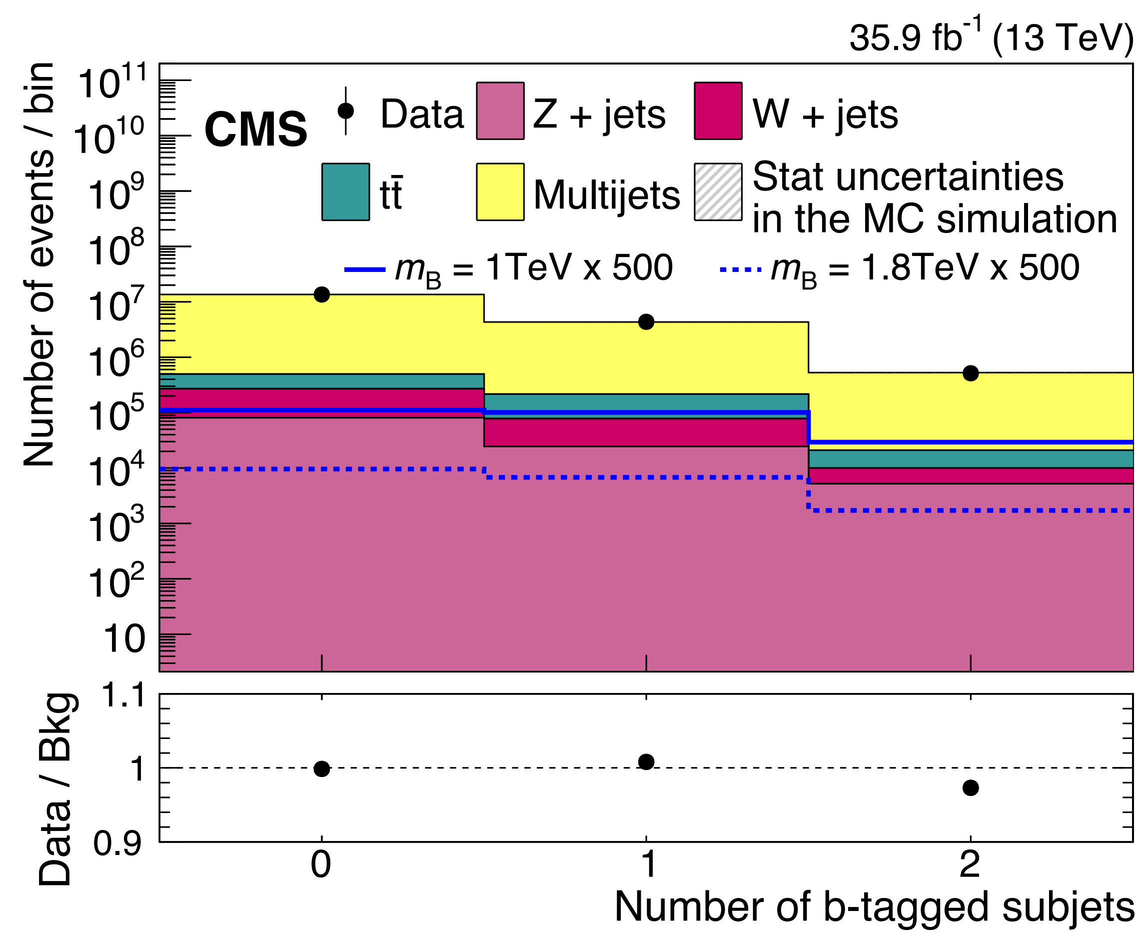
VLQs expected to appear at the **TeV scale**

- their decay products get high boost → **small opening angle** between the two b-quarks from the H decay
- we use **large-cone jets** and **grooming** algorithms (*pruning*: PhysRevD 81 094023)



Higgs candidates used to **reconstruct B mass**

- large-cone jets with p_T > 300 GeV and $|\eta|$ < 2.4
- mass in [105, 135] GeV,
- 2 medium b subjets



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Pruning

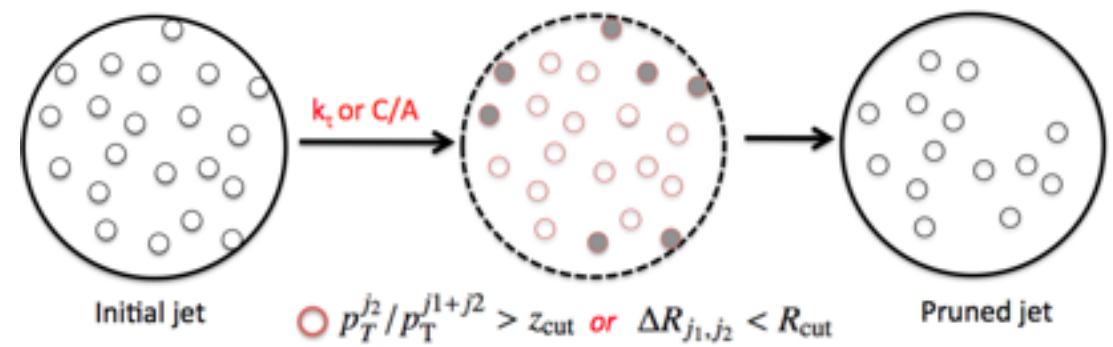
CMS-HIG-14-008 PhysRevD 81 094023

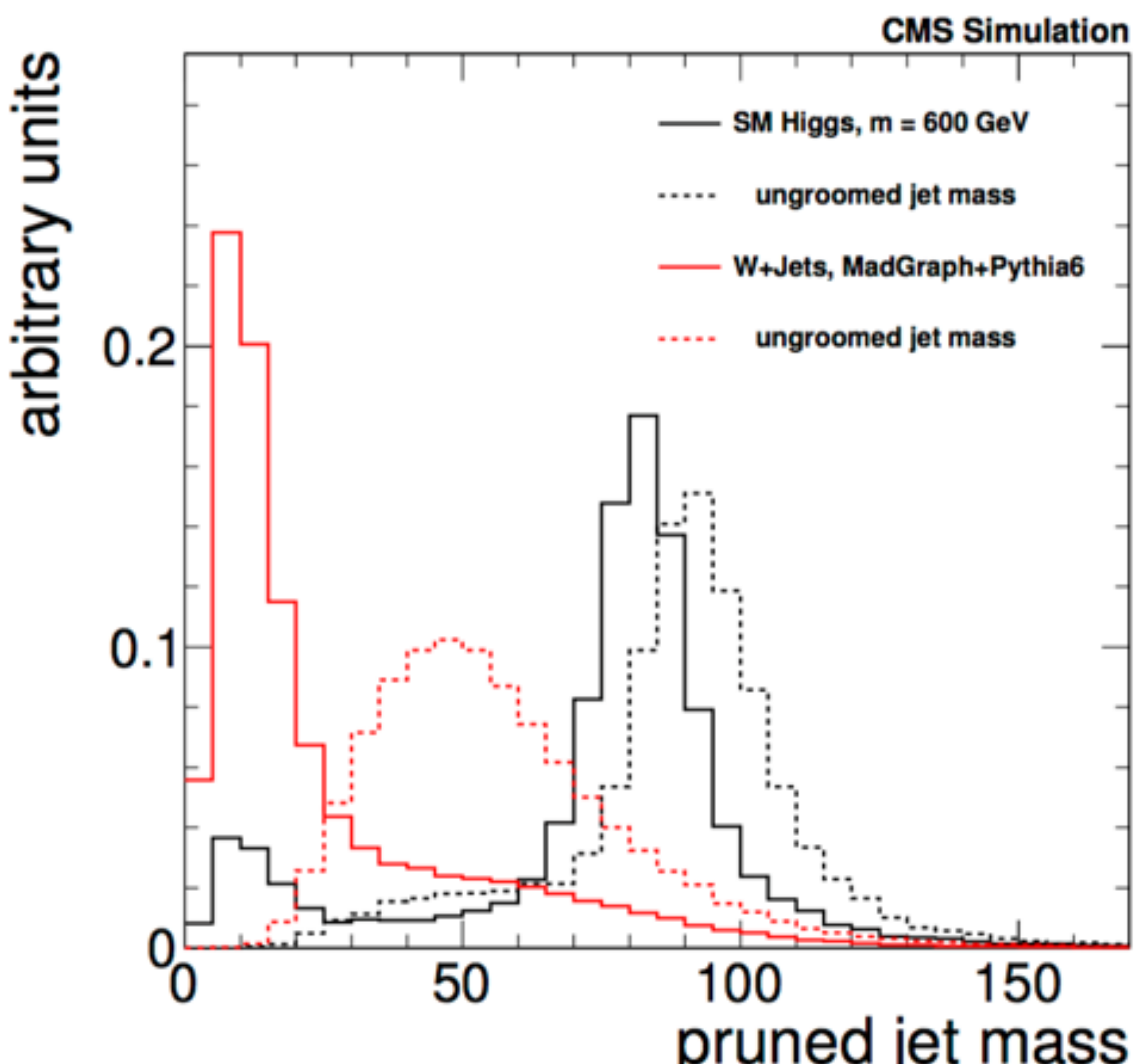
- Pruning removes soft and wide-angle radiation

- Jet pruning reclusters each AK8 jet starting from all its original constituents, through the implementation of the Cambridge- Aachen algorithm to discard “soft” recombinations in each step of the iterative CA procedure. It removes the recombination if

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} < \boxed{0.1} \text{ and } \Delta_{1,2} > \boxed{0.5} \cdot \frac{2m}{p_T}$$

- the pruned jet mass is computed from the sum of the four-momenta of the constituents that are not removed by the pruning





Search for single production of vector-like quarks decaying to a b quark and a Higgs boson

Interpretation framework

Cross section for the single production and decay of a B quark with final state X:

$$\sigma(C_1, C_2, m_B, \Gamma_B, X) = C_1^2\, C_2^2\, \hat{\sigma}_{AW}(m_B, \Gamma_B)$$

production and decay couplings corresponding to the interactions through which a B quark is produced and decays

reduced cross section for a resonance of arbitrary width (AW)

The equation is valid in all regimes, but when Γ_B/m_B approaches zero, it is possible to factorize production and decay and to write the cross section as:

$$\sigma(C_1, C_2, m_B, \Gamma_B) = \sigma_{prod}(C_1, m_B)\mathcal{B}_{B\to X} = C_1^2 \hat{\sigma}_{NWA}(m_B)\mathcal{B}_{B\to X}$$

Interpretation framework

Our assumptions have the B quark decaying into Hb, Zb, and Wt with branching fractions that are specified in the model. The couplings of the B quark to SM bosons and quarks can be parametrized as: $c_Z = e/(2c_w s_w \kappa_Z)$, c_W = e/(trength that can be fixed to obtain the desired width. Numerically, e/(2c s) = 0.370, and 2$s_w \kappa_W$), and c_H = $(m_B \kappa_H)/v$, where e is the ww electric charge of the proton, v = 246 GeV is the vacuum-expectation value for the field of the Higgs boson, c_w and s_w are the cosine and sine of the weak mixing angle θ_W, and κ is a coupling c_W = e/(2s_w) = 0.458. For the process under consideration, we can set $C_1 \equiv c_Z$ and $C_2 \equiv c_H$.

Cross sections, NWA

Table 1: Cross sections for pp $\rightarrow$ Bqb, with the ratio Γ_B/m_B fixed to 1% (NWA). The couplings and branching fractions in simplified models are calculated using the equations in the text. The uncertainties in the production cross sections correspond to the halving and doubling of the QCD renormalization and factorization scales

		Singlet model					Doublet model			
m_B (GeV)	$\hat{\sigma}_{NWA}$ (pb)	κ	$\mathcal{B}_{B\to Wt}$	$\mathcal{B}_{B\to Zb}$	$\mathcal{B}_{B\to Hb}$	σ_{NWA} (pb)	κ	$\mathcal{B}_{B\to Zb}$	$\mathcal{B}_{B\to Hb}$	σ_{NWA} (pb)
700	$31.30^{+28\%}_{-20\%}$	0.18	0.466	0.271	0.263	0.1631	0.25	0.499	0.501	0.5720
800	$21.50^{+29\%}_{-21\%}$	0.16	0.474	0.276	0.260	0.0830	0.22	0.499	0.501	0.3003
900	$15.10^{+30\%}_{-21\%}$	0.14	0.489	0.263	0.258	0.0451	0.19	0.500	0.500	0.1666
1000	$10.80^{+31\%}_{-23\%}$	0.13	0.483	0.261	0.256	0.0257	0.17	0.500	0.500	0.0962
1100	$7.85^{+32\%}_{-22\%}$	0.11	0.486	0.259	0.255	0.0153	0.16	0.500	0.500	0.0580
1200	$5.77^{+33\%}_{-23\%}$	0.10	0.489	0.257	0.254	0.0094	0.15	0.500	0.500	0.0358
1300	$4.29^{+34\%}_{-23\%}$	0.10	0.490	0.256	0.254	0.0059	0.13	0.500	0.500	0.0227
1400	$3.23^{+34\%}_{-23\%}$	0.09	0.492	0.255	0.253	0.0038	0.12	0.500	0.500	0.0147
1500	$2.45^{+35\%}_{-25\%}$	0.08	0.493	0.254	0.253	0.0025	0.12	0.500	0.500	0.0097
1600	$1.86^{+36\%}_{-24\%}$	0.08	0.494	0.254	0.252	0.0017	0.11	0.500	0.500	0.0065
1700	$1.44^{+37\%}_{-24\%}$	0.07	0.494	0.254	0.252	0.0011	0.10	0.500	0.500	0.0044
1800	$1.11^{+37\%}_{-25\%}$	0.07	0.495	0.253	0.252	0.0008	0.10	0.500	0.500	0.0031

Cross sections, AW

Table 2: Cross sections for pp $\rightarrow$ Bbq for three values of the Γ_B/m_B ratio. The conditions assume that singlets and doublets have $\kappa_W = \kappa_Z = \kappa_H \equiv \kappa$, $\kappa_W = 0$ and $\kappa_Z = \kappa_H \equiv \kappa$, respectively. For each Γ_B/m_B, we provide the values of $\tilde{\sigma}_{AW}$ and of the physical cross sections for both the singlet and doublet models, σ_S and σ_D respectively. The uncertainties in the production cross sections correspond to the halving and doubling of the QCD renormalization and factorization scales. The values of κ are listed in the parentheses.

	$\Gamma_B/m_B = 10\%$			$\Gamma_B/m_B = 20\%$			$\Gamma_B/m_B = 30\%$		
m_B (GeV)	$\tilde{\sigma}_{AW}$(pb)	σ_S(fb) (κ)	σ_D(fb) (κ)	$\tilde{\sigma}_{AW}$(pb)	σ_S(fb) (κ)	σ_D(fb) (κ)	$\tilde{\sigma}_{AW}$(pb)	σ_S(fb) (κ)	σ_D(fb) (κ)
700	3.01	400 (0.588)	1378 (0.8010)	1.43	759 (0.832)	2616 (1.130)	0.899	1074 (1.020)	3703 (1.390)
800	2.10	203 (0.508)	726 (0.699)	1.00	386 (0.719)	1377 (0.9880)	0.634	552 (0.880)	1968 (1.210)
900	1.51	111 (0.448)	406 (0.619)	0.719	212 (0.633)	775 (0.876)	0.454	301 (0.776)	1101 (1.070)
1000	1.09	63.7 (0.401)	237 (0.556)	0.523	122 (0.567)	453 (0.787)	0.331	174 (0.694)	647 (0.964)
1100	0.807	38.2 (0.363)	144 (0.505)	0.386	73.2 (0.513)	276 (0.714)	0.246	105 (0.628)	394 (0.875)
1200	0.601	23.6 (0.331)	89.7 (0.463)	0.290	45.5 (0.468)	173 (0.654)	0.185	65.2 (0.574)	248 (0.801)
1300	0.451	14.9 (0.305)	57.1 (0.427)	0.220	29.0 (0.431)	111 (0.603)	0.141	41.9 (0.528)	160 (0.739)
1400	0.342	9.70 (0.283)	37.2 (0.396)	0.167	18.9 (0.400)	72.9 (0.560)	0.108	27.5 (0.489)	106 (0.686)
1500	0.262	6.42 (0.263)	24.9 (0.369)	0.129	12.6 (0.372)	48.9 (0.522)	0.0836	18.4 (0.456)	71.3 (0.640)
1600	0.203	4.34 (0.246)	16.9 (0.346)	0.101	8.61 (0.349)	33.5 (0.489)	0.0651	12.5 (0.427)	48.7 (0.599)
1700	0.158	2.99 (0.232)	11.6 (0.326)	0.0788	5.94 (0.328)	23.2 (0.460)	0.0514	8.71 (0.401)	34.0 (0.564)
1800	0.124	2.08 (0.219)	8.13 (0.307)	0.0621	4.16 (0.309)	16.3 (0.435)	0.0408	6.14 (0.379)	24.0 (0.532)

Systematic Uncertainties

uncertainties on the event yield and on the m_{bH} distribution are taken into account in the statistical inference procedure and are treated as nuisance parameters

- systematics **on the backgrounds**:
  - shape uncertainty due to the MC statistics in the control region C, obtained by a bin-by-bin variation
  - normalization uncertainty as the difference between expected and predicted yields in the closure test
- corrections to account for the **b-tagging efficiency** difference between data and simulation
- the reconstructed jet p_T of jets are varied within the uncertainty on **jet energy scale and resolution**
  - mass corrections are also applied to large-cone jets
- additional uncertainties applied to account for **discrepancies on the modeling of forward jets**
- **theoretical uncertainties** are considered for factorization and normalization scale and as well for Parton Distribution Functions
- more systematics (trigger, integrated luminosity, minimum bias cross section, etc)

Systematic Uncertainties

Summary of systematic uncertainties in background events.

- The quantification of the effects quoted in the table reflects the uncertainties in the event yields.
- All uncertainties are considered in the simulated background events, except the one on background estimation that affects only the data-based estimate of the multijet process.
- All the systematic uncertainties apply to both categories of forward-jet multiplicity, except for the case of the modelling of the forward jets, where the first entry corresponds to the category with no forward jets, and the second entry to the category with at least one jet in the forward region.

Source	Effect
Luminosity	2.5%
b tagging efficiency	0–9%
Misidentification efficiency	0–2%
Pileup modelling	0–12%
Trigger	$< 0.5\%$
PDF	1.0–4.5%
μ_R and μ_F	15–25%
Jet energy scale	1–7%
Jet energy resolution	1.0–1.5%
Jet mass scale	0–5%
Jet mass resolution	0–4%
MC Statistical accuracy	1–4%
Mismodelling of forward jets	0.5/2.0%
Background estimation	5–10%