



Vector-Like Quarks searches at CMS

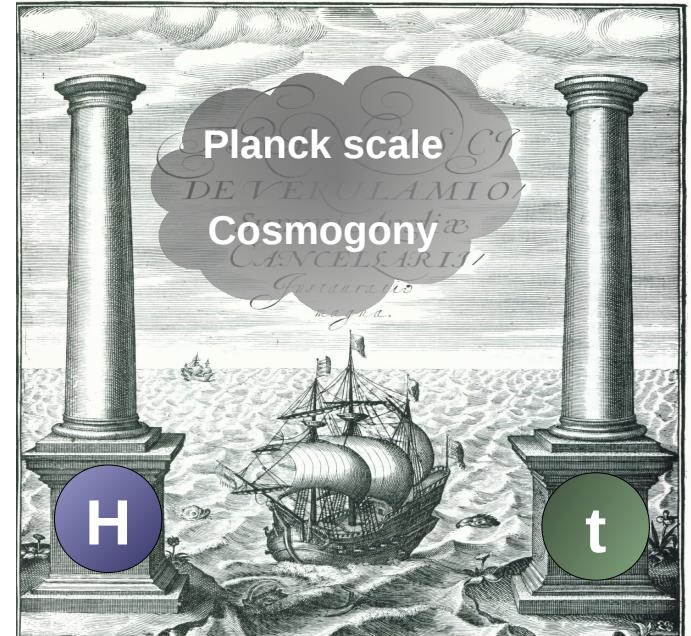
SUSY 2018,
Barcelona, Spain, 25/7/2018

Alberto Orso Maria Iorio
for the CMS collaboration

Particle physics after the Higgs: Non plus ultra?

Going beyond and missing pieces:

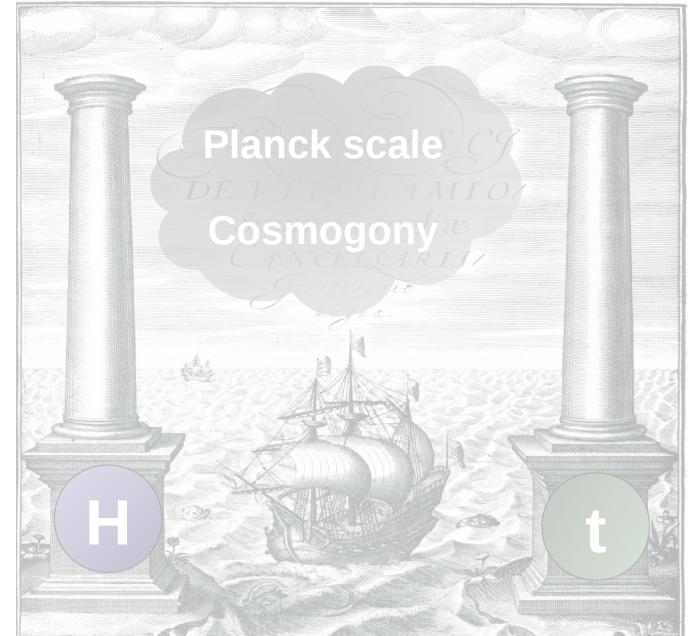
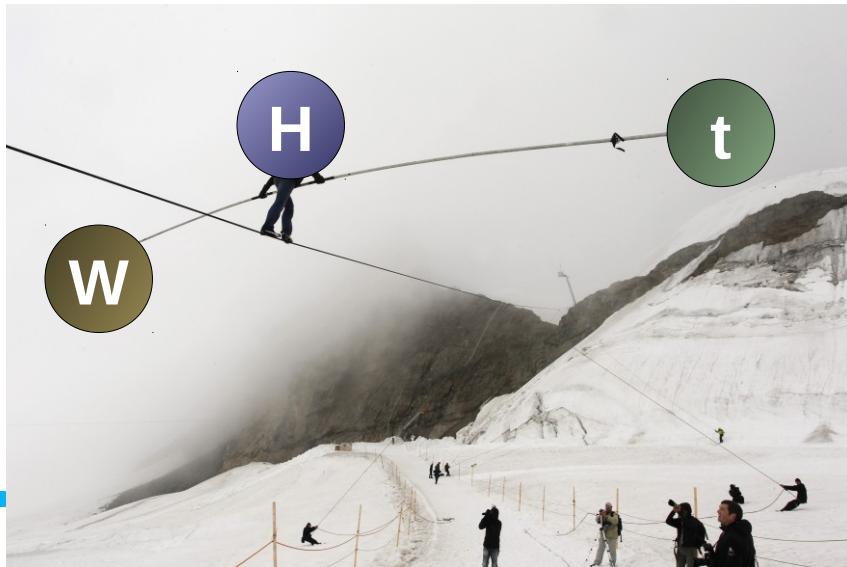
- Inclusion of gravity
- Dark matter, dark energy
- Matter-antimatter asymmetry



Particle physics after the Higgs: Non plus ultra?

Going beyond and missing pieces:

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The SM's “effective theory” vibe:

- Origin of EWK symmetry breaking
- Why does the higgs stay so light?
- Why so many “free” parameters!
- Why the fermion mass hierarchy

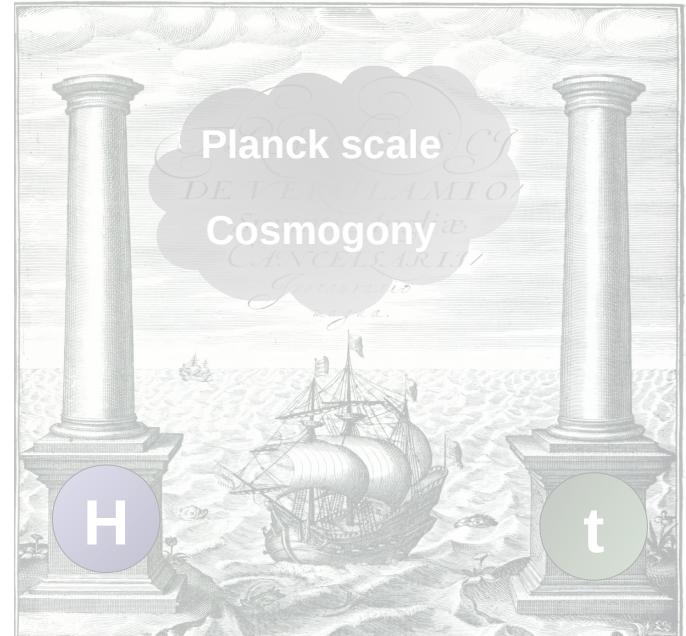
Alberto Orso Maria Iorio

Particle physics after the Higgs: Non plus ultra?

Going beyond and missing pieces:

- Inclusion of gravity
- Dark matter, dark energy
- Matter

Again...why am I
doing this?

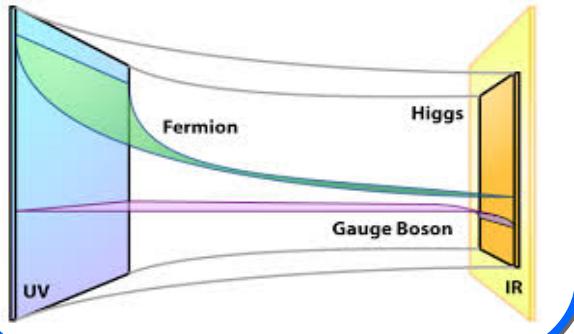


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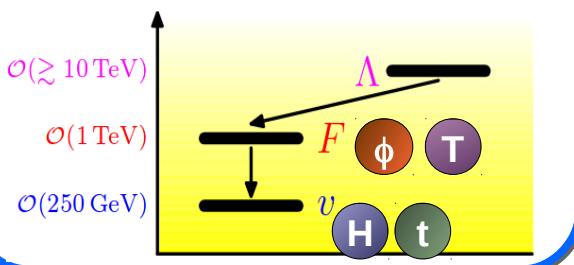
- Origin of EWK symmetry breaking
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- Why so many “free” parameters!
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Some ideas for the Higgs nature conundrum

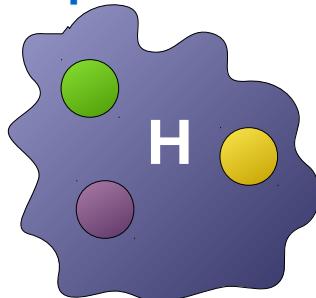
Extra dimensions



Little higgs



Compositeness



New fermions at the TeV scale!

What are the requirements?

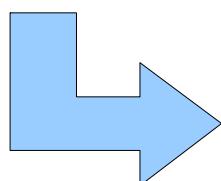
- Should be compatible with the Higgs mass
- Strong and ewk interactions
- Compatible with precision measurements

Vector-like quarks and the SM extensions

“**Vector**” like quarks: left and right chiralities work the same → VLQ current is $\bar{Q} \gamma^\mu Q$
 → **gauge invariant mass term!**

SM	singlets	doublets	triplets
(u) d (c) s (t) b	T B	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$ $\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$ $\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
$SU(2)_L$ 2 $U(1)_Y$ $q_L = 1/6$ $U_R = 2/3$ $d_R = -1/3$	1 $2/3 \quad -1/3$	2 $1/6 \quad 7/6 \quad -5/6$	3 $2/3 \quad -1/3$

- Multiple representations
- $Q = I_3 + Y/2$



Still allowed by experiments! Appear in:

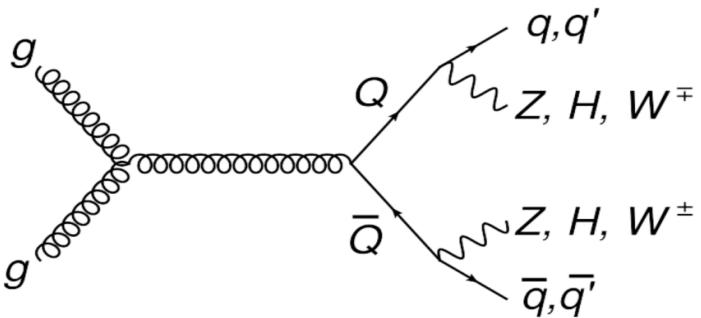
- **Little higgs or composite higgs**
- Warped **extra-dimensions**, Kaluza-Klein etc
- Some non-minimal **SUSY scenarios**

VLQ production

PRD 88 094010

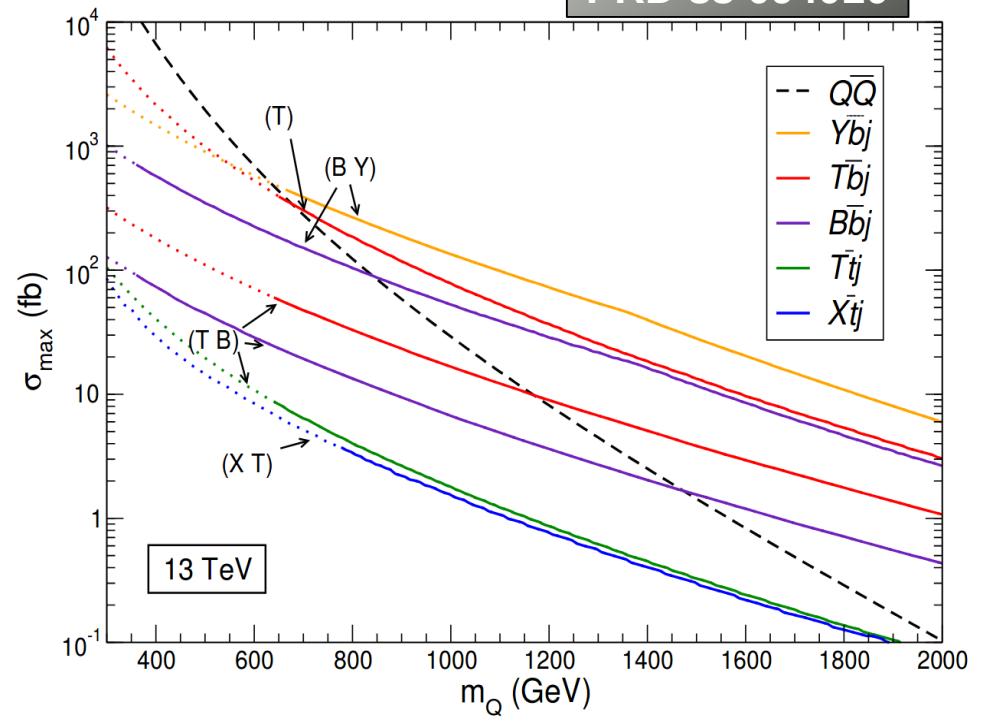
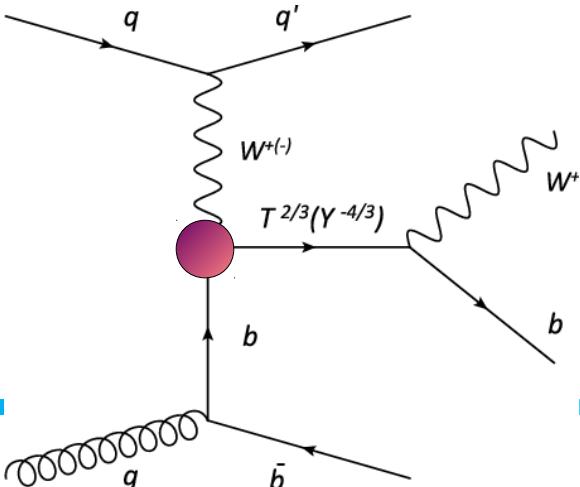
- **Pair-wise strong production:**

- depends only on the **Q mass**



- **Single production.** QqW/Z vertex:

- depends on the **Q mass**
- depends on the **QqW coupling**



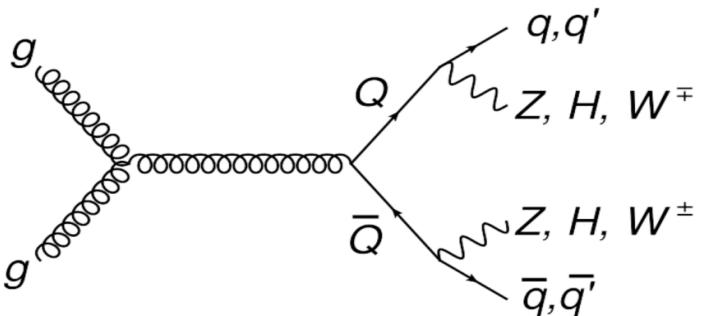
→ Single production falls slower at high masses

→ Can measure right handed and left-handed scenarios

VLQ production

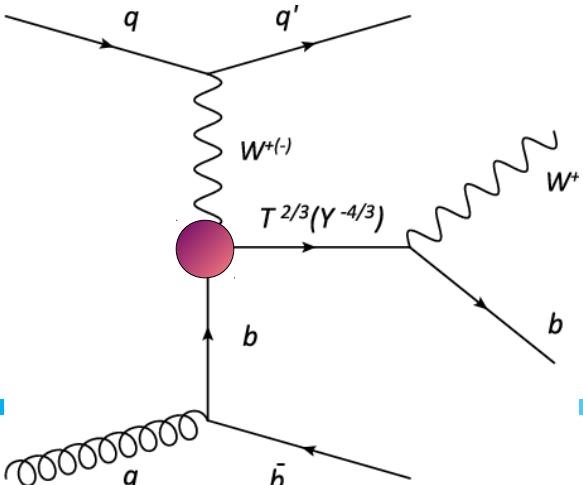
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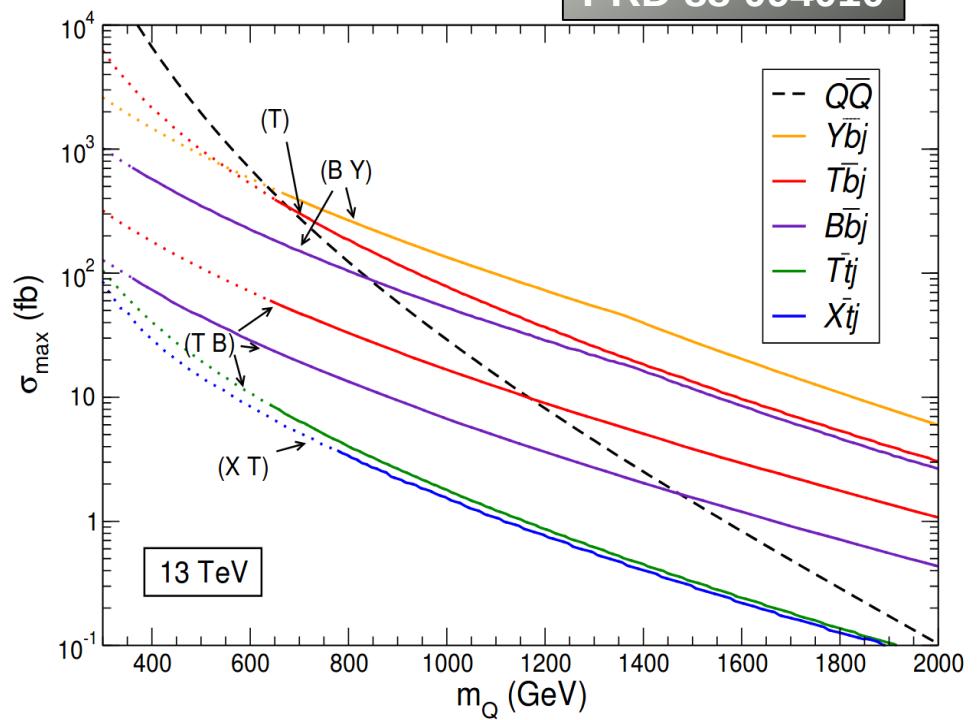


- **Single production.** QqW/Z vertex:

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PRD 88 094010

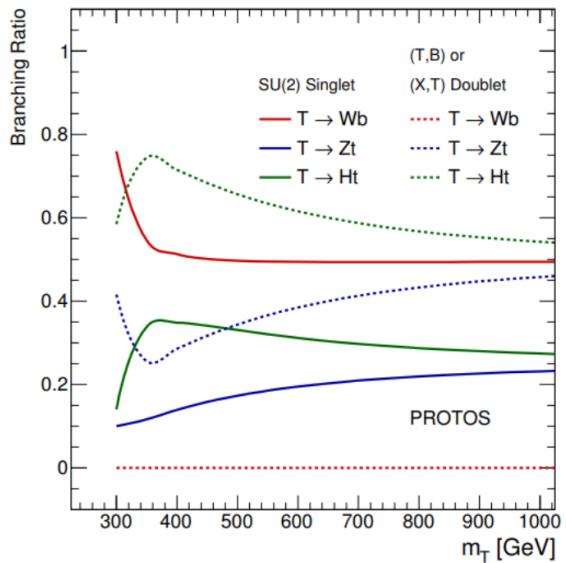
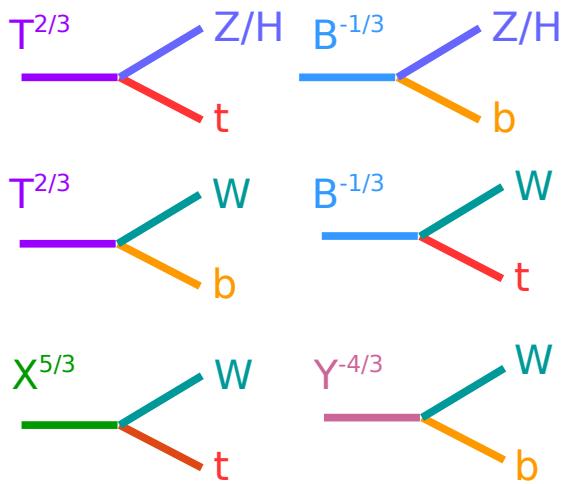


→ Single production falls slower at high masses

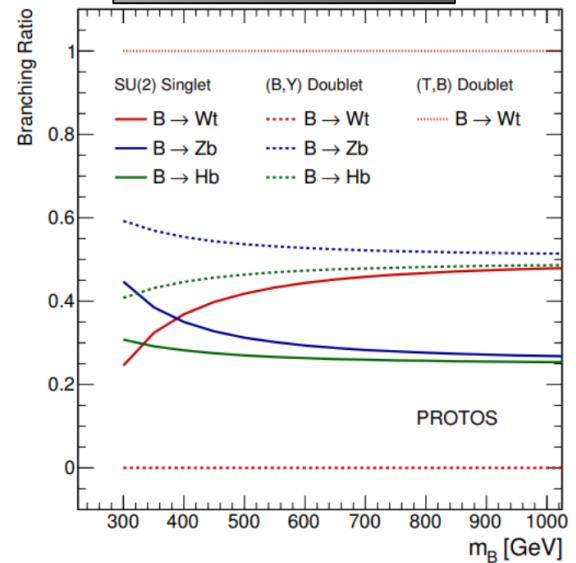
→ Can measure right handed and left-handed scenarios

Also possible: production through new resonances!
- see next talk from Robin!

VLQ decays



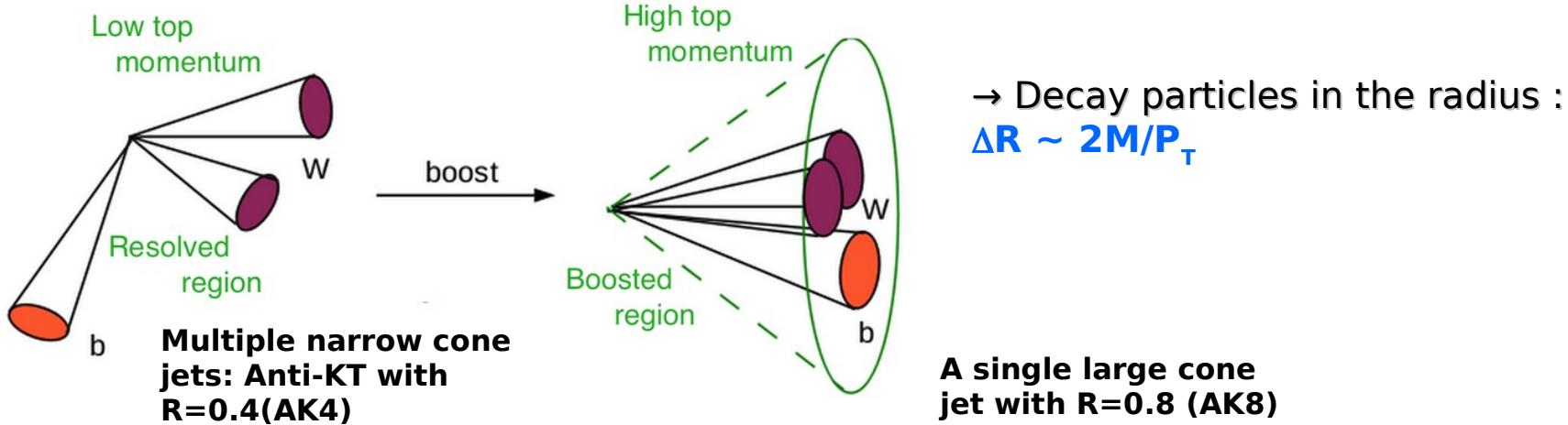
PRD 88 094010



- Depends on the **strength of the coupling** C
- Usual approximation of **Narrow Width**
$$C^2 \hat{\sigma}_{NWA} B(Q \rightarrow qV)$$
- Large decay widths are possible:
 - With large cocouplings in non minimal representations
 - With new physics intervening
 - See also for the large width benchmarks: arXiv 1805.06402

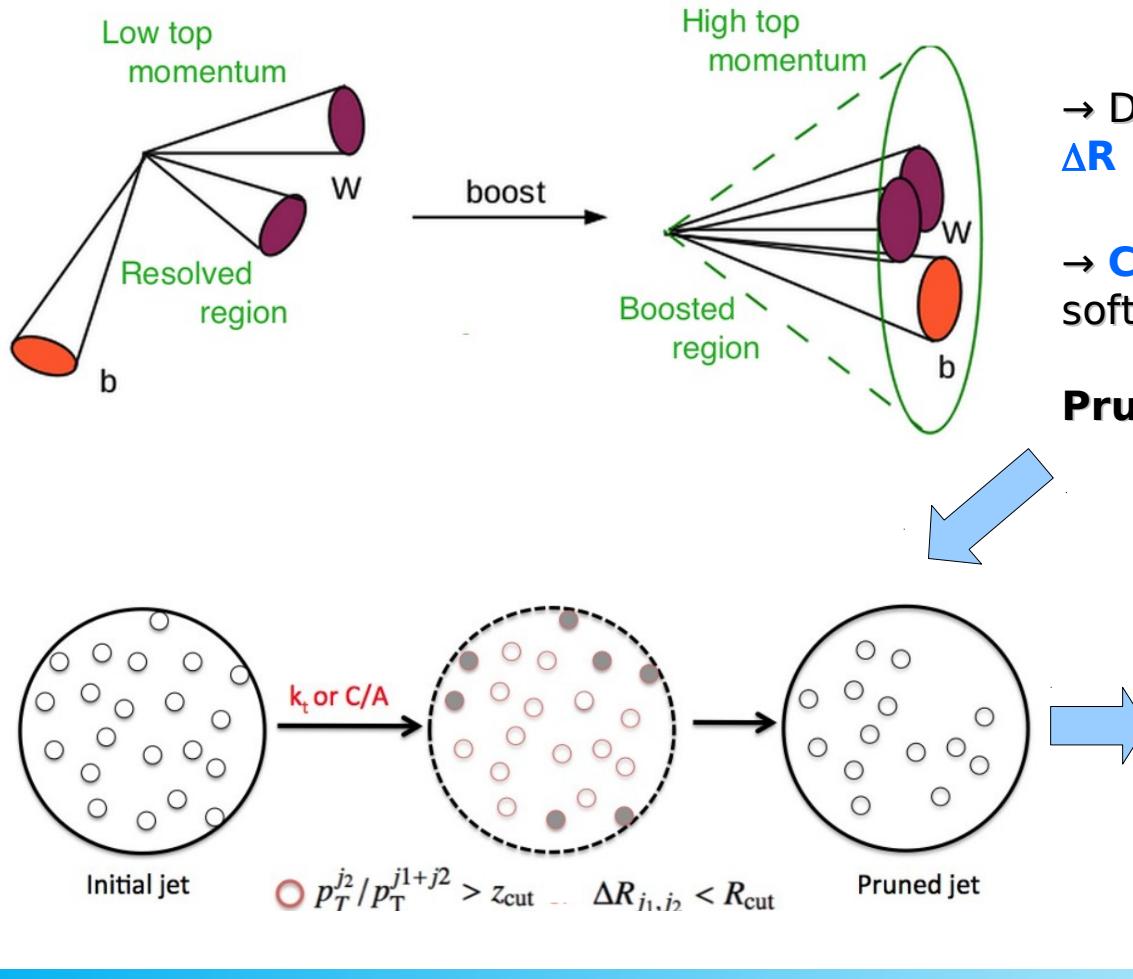
Probing the high-energy regime: boosted topologies

VLQ mass **at the scale of TeV** → relativistic boost for heavy SM particles!



Probing the high-energy regime: boosted topologies

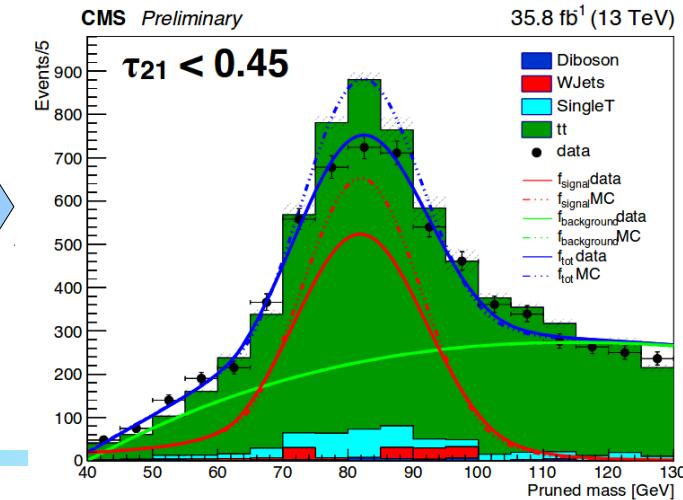
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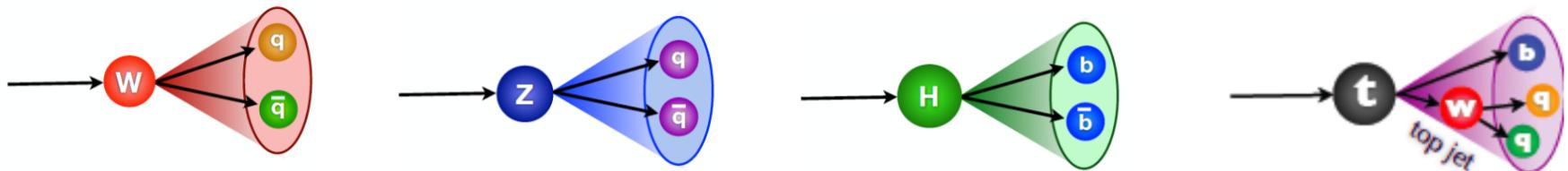
→ Decay particles in the radius :
 $\Delta R \sim 2M/P_T$

→ **Cleaning the jet** of the extra soft radiation necessary, e.g.:

Pruning, Filtering, Soft drop

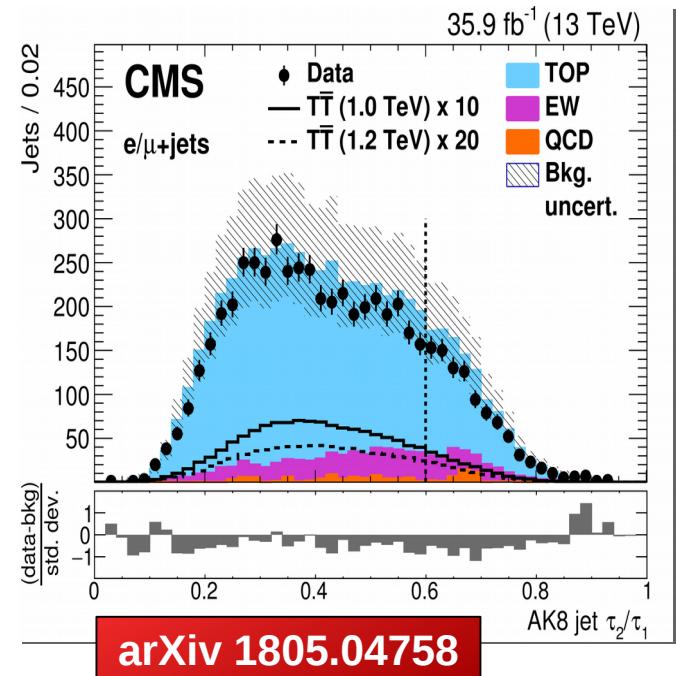


Boosted objects: exploiting the jet structure

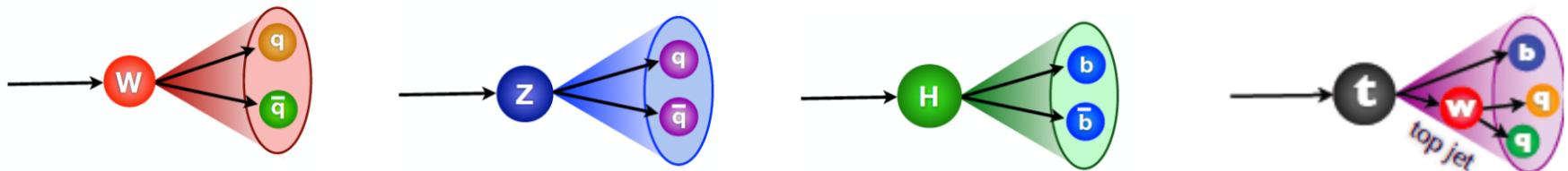


→ Exploit the **2-prong** or **3-prong**
structure: τ_2/τ_1 and τ_3/τ_2 variables

$$\tau_N \equiv \frac{\sum_k p_{T_k} \times \min(\Delta R_{1k}, \Delta R_{2k}, \dots, \Delta R_{Nk})}{\sum p_{T_k} \times R}$$

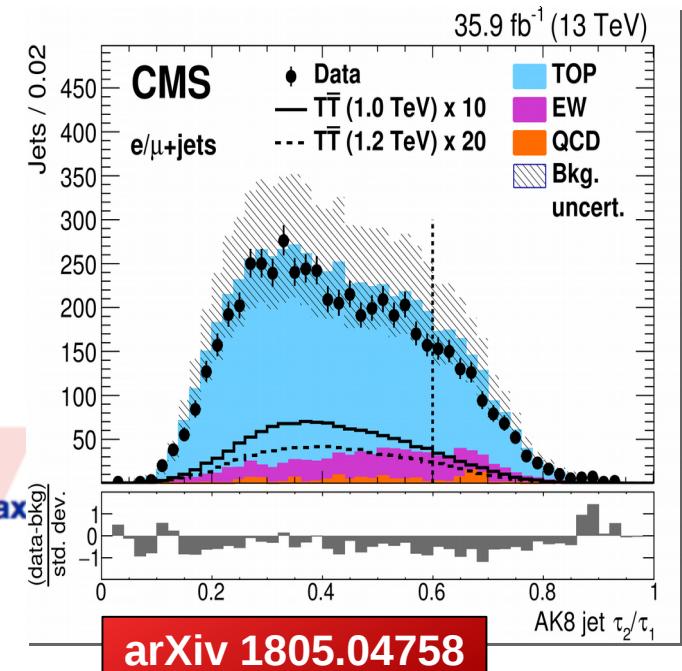
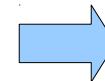
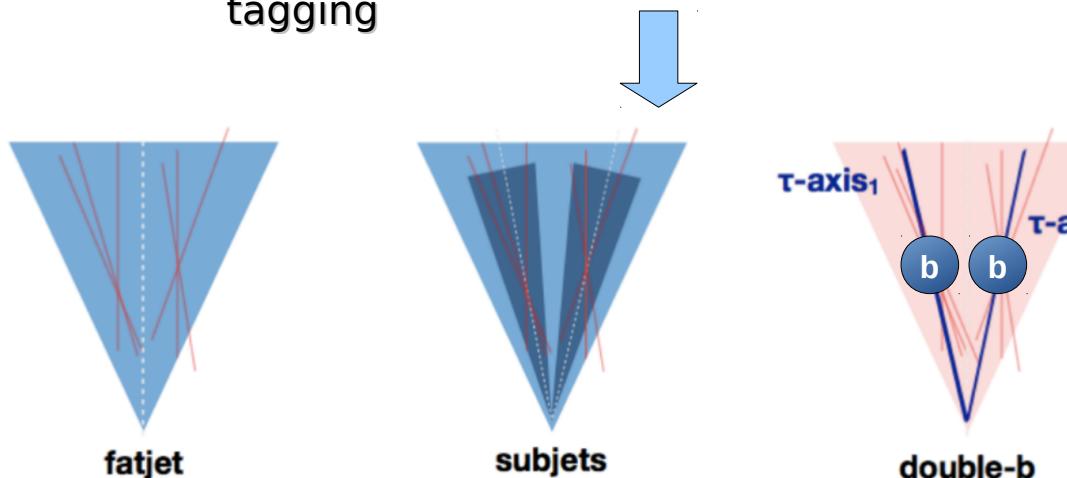


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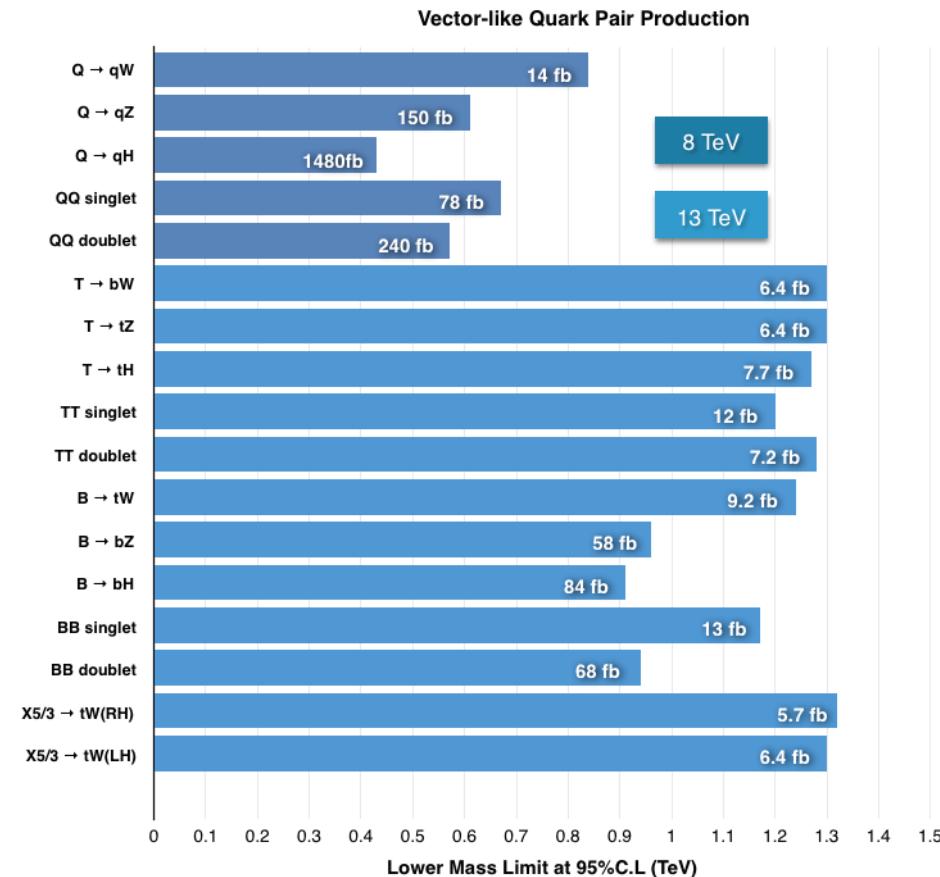


→ Exploit the **2-prong** or **3-prong** structure: τ_2/τ_1 and τ_3/τ_2 variables

→ **Presence of B-hadrons**
in the jet: sub-jet clustering and b-tagging



Pair production



In this talk:

PAS B2G-16-019

PAS B2G-17-008

arXiv 1805.04758

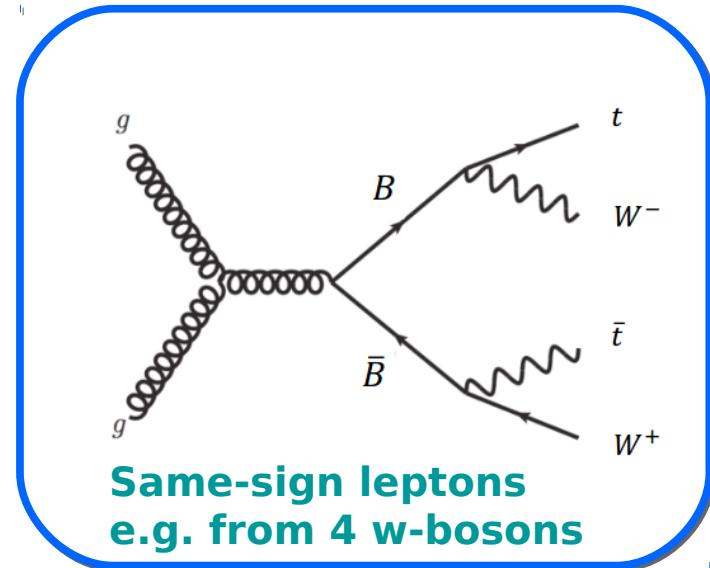
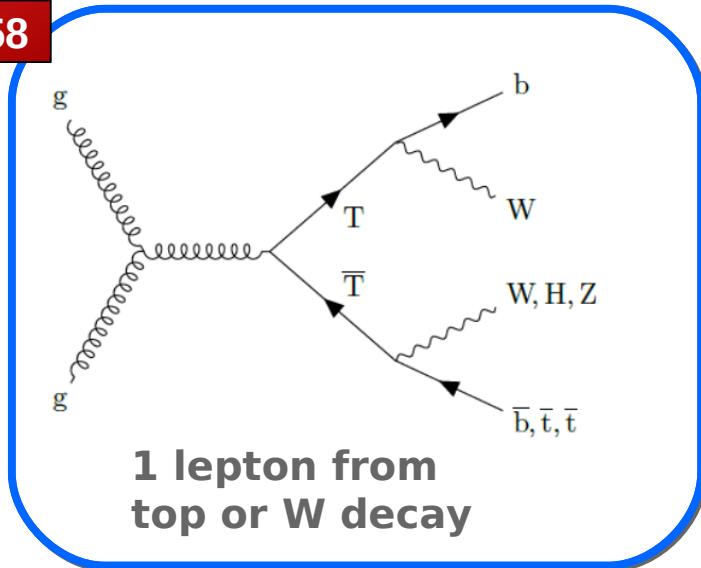
Find other results here:

<http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html>

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html>

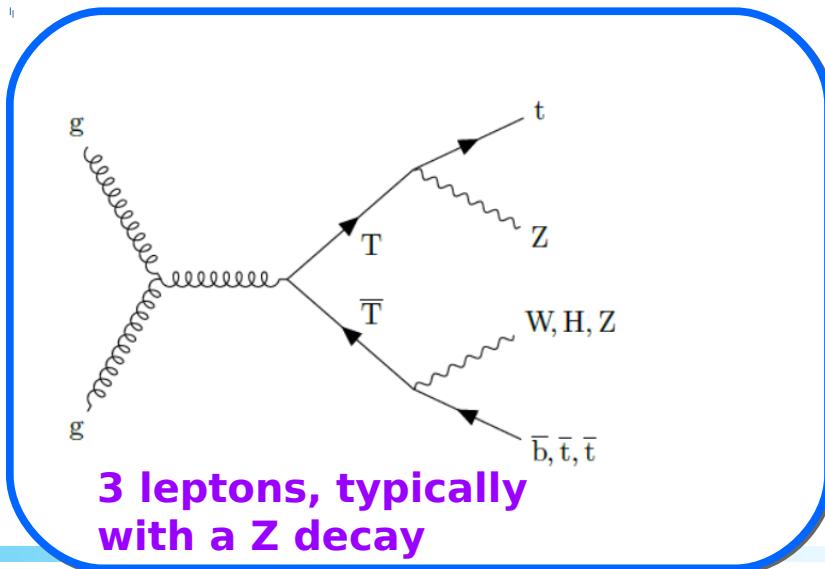
VLQ pair: $T\bar{T}$, $B\bar{B} \rightarrow$ leptons + jets

arXiv 1805.04758



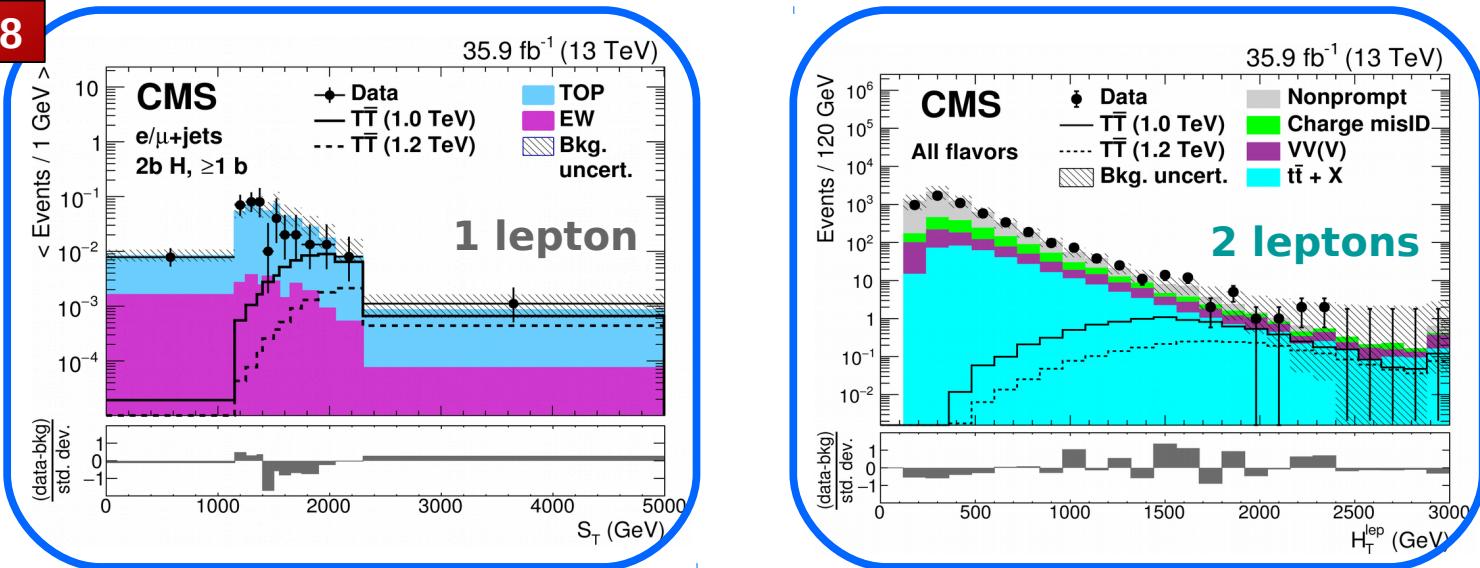
3 topologies:

- **1 lepton and >1 W/H jets , b-jets:**
→ $T\bar{T}$ irreducible background
- **2 leptons** with same sign:
→ Non prompt leptons: from control regions
→ Sign mis-id: from Z mass pair
- **3 leptons**:
→ Non-prompt fakes from jets / photon conversions, etc.



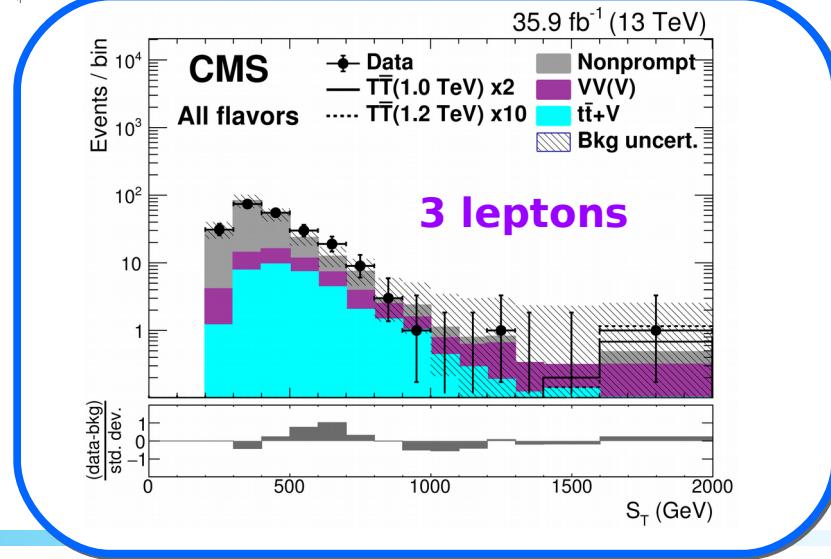
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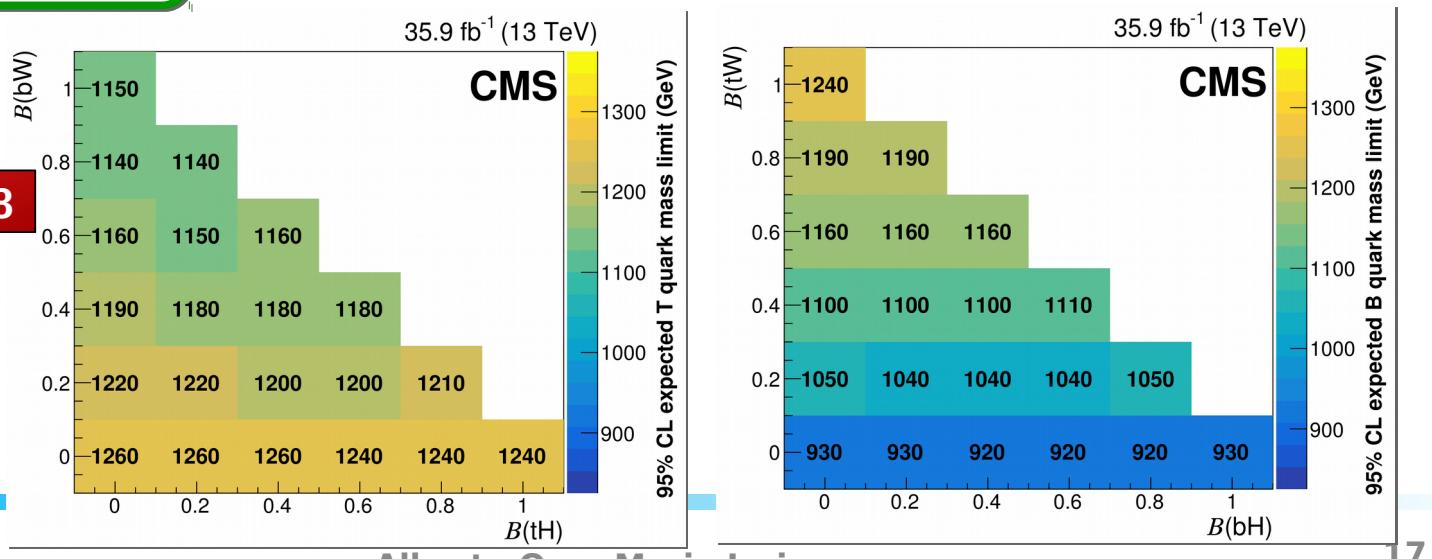
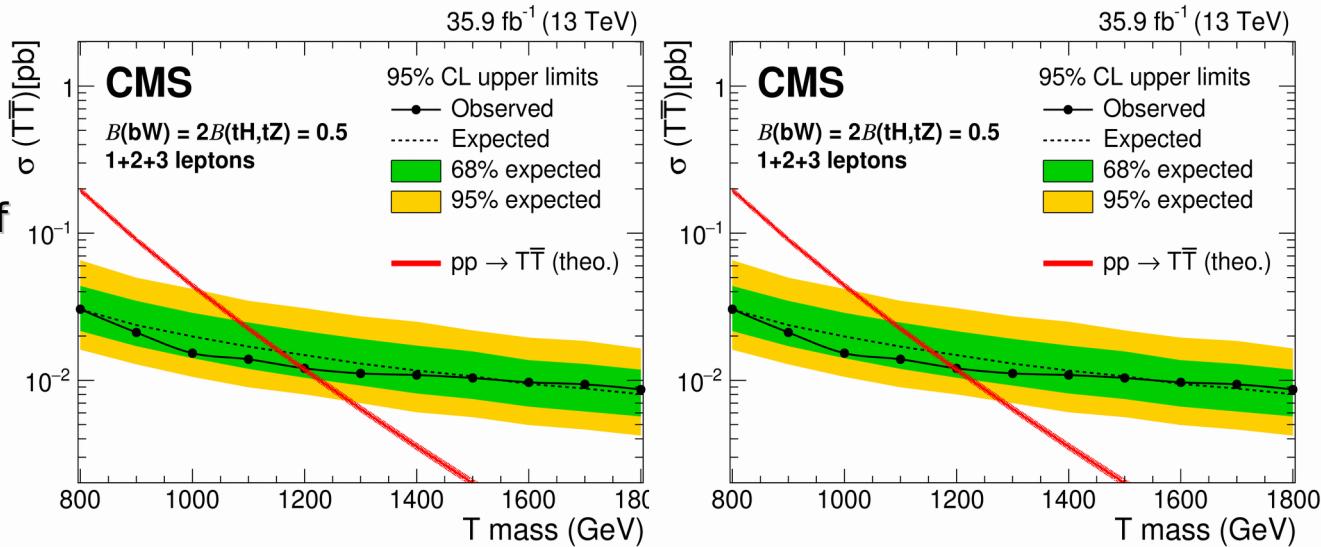
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VLQ pair: $T\bar{T}$, $B\bar{B} \rightarrow$ leptons + jets

- **Combination** of all three analyses
- Also interpreted in terms of **branching ratios** of B/T
- **95%CL exclusion limit** for singlet (Doublet)

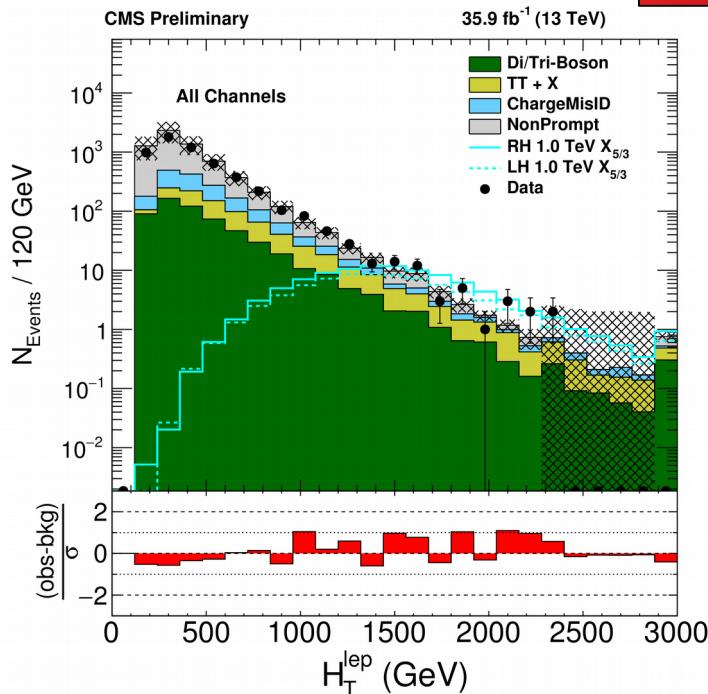
T with $m_T < 1200(1280)$
B with $m_B < 1140(1170)$



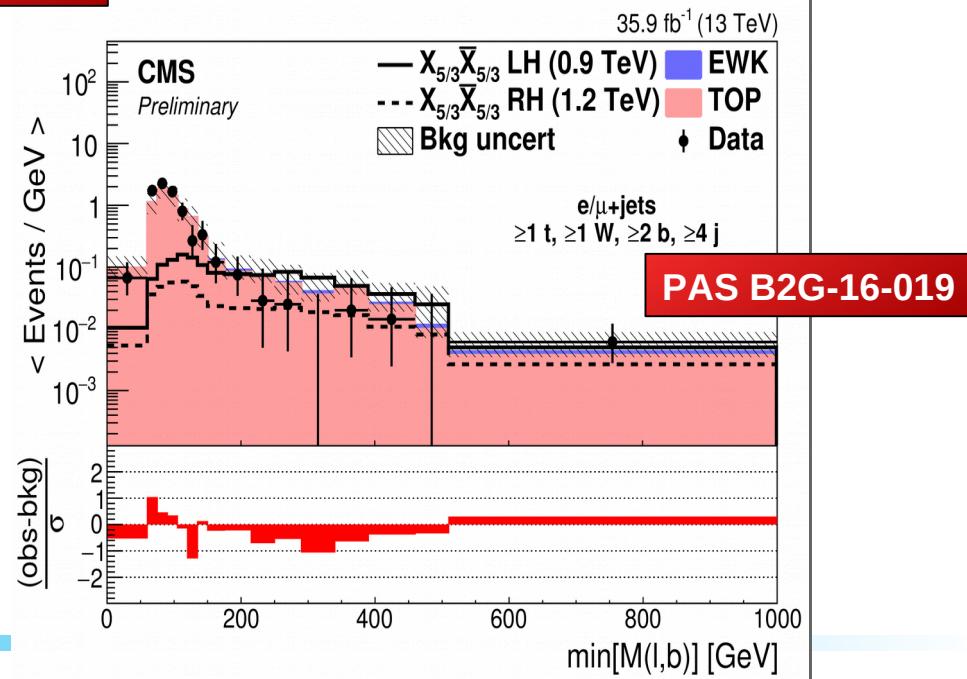
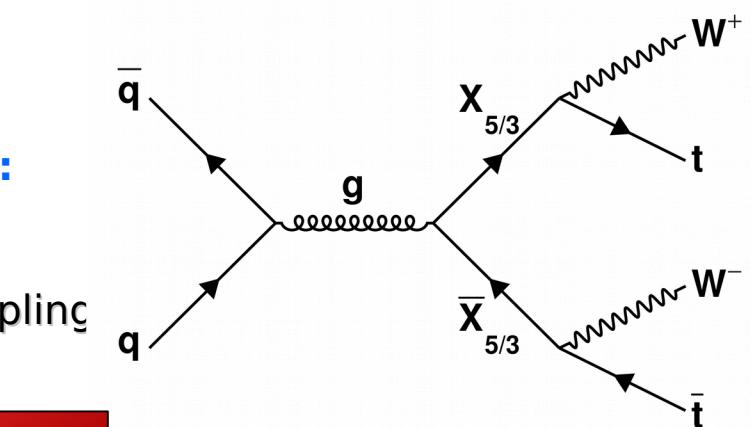
VLQ pair searches: $X^{5/3}X^{5/3}$

- Sought with **same-sign lepton pair** and **> 3 leptons** topologies
- Low SM backgrounds, mostly **non-prompt**: charge mis-ID and fake lepton.
- 95% CL exclusion **Left(Right)** handed coupling

$X^{5/3}$ with $m_X < 1320(1300)$

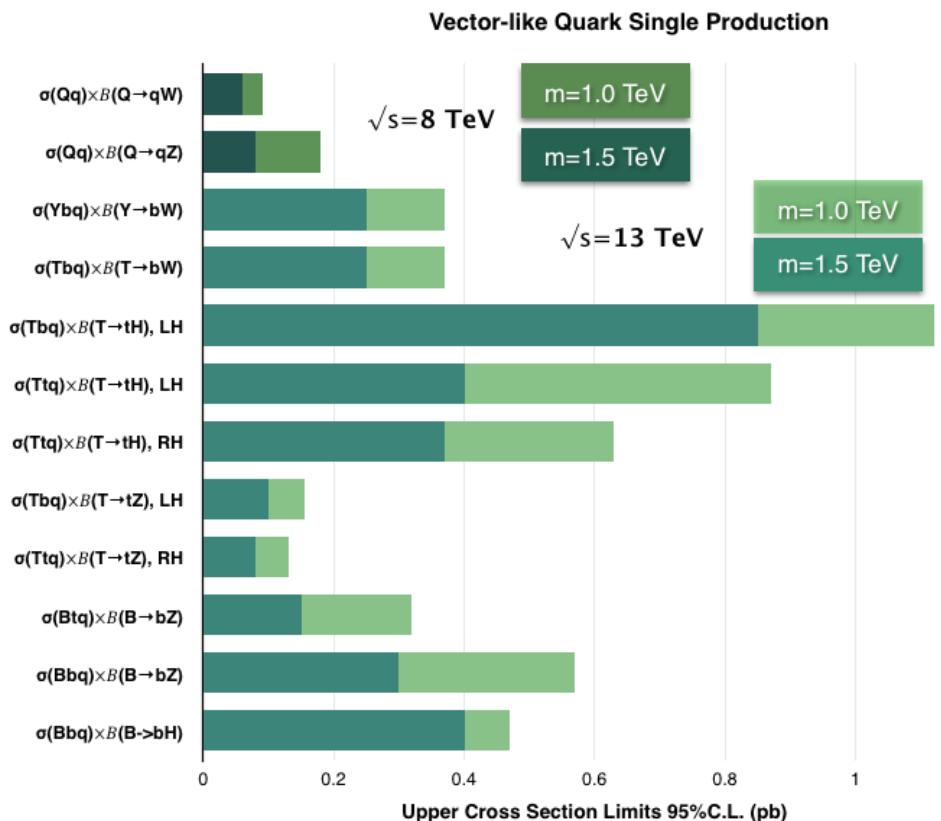


PAS B2G-17-008



PAS B2G-16-019

Single production



In this talk:

JHEP 06(2018)031

PLB 781(2018)574

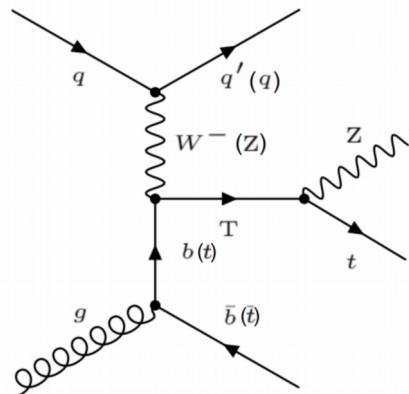
PAS B2G-17-018

Find other results here:

<http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html>

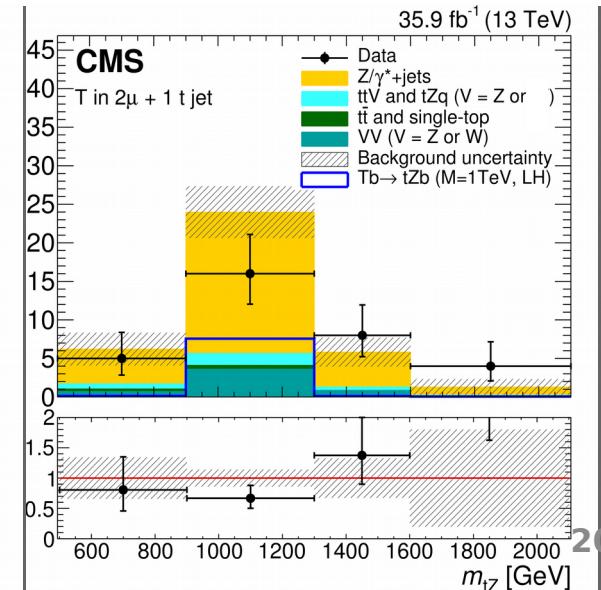
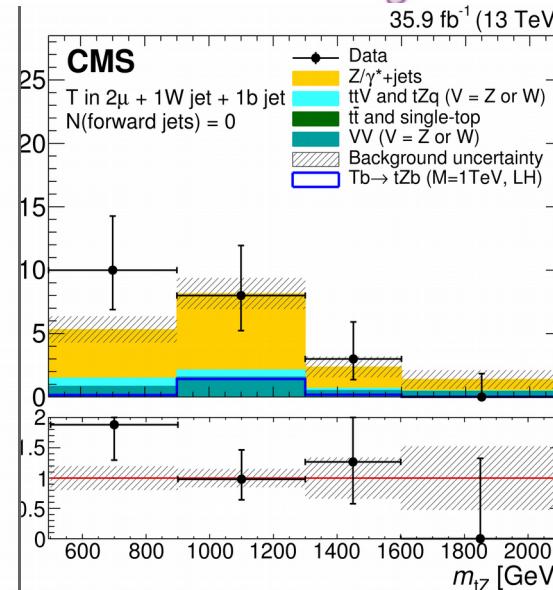
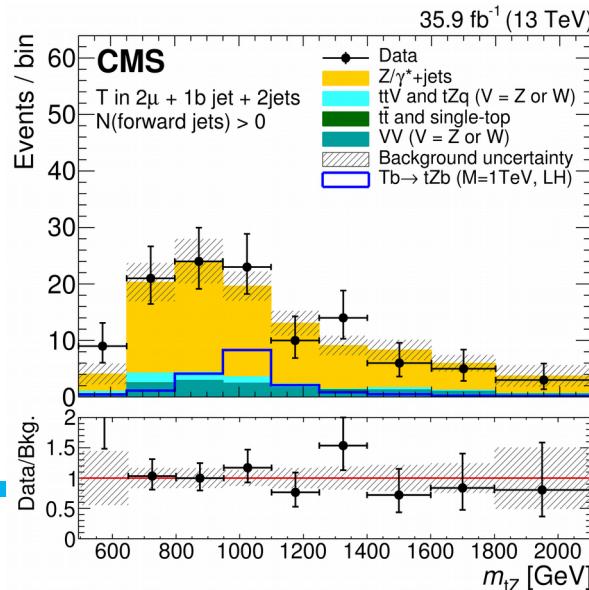
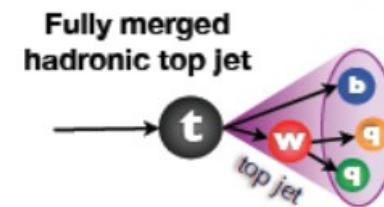
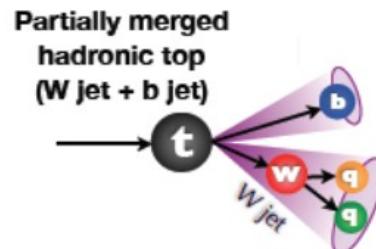
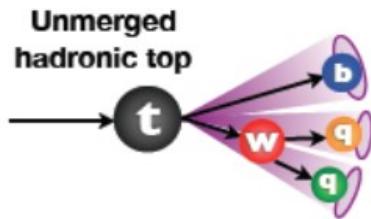
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Single VLQ production: $T \rightarrow tZ(vv)$



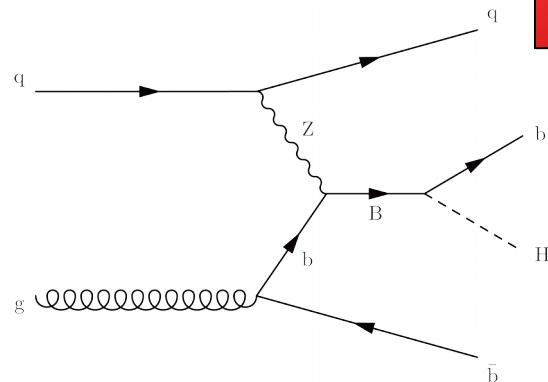
PLB 781(2018)574

- Z decaying to **lepton pair**
- top quark to **hadrons, in different regimes:**
→ lower T masses = unmerged top quarks

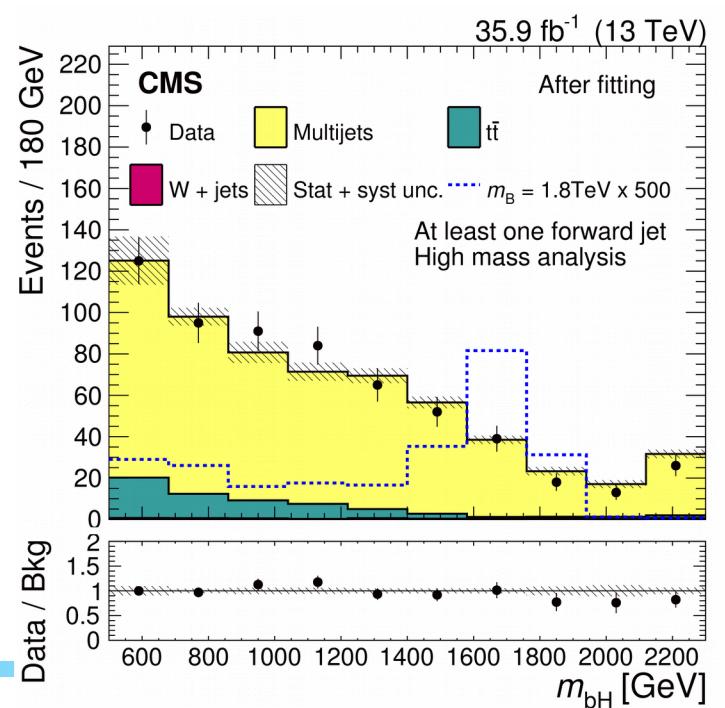
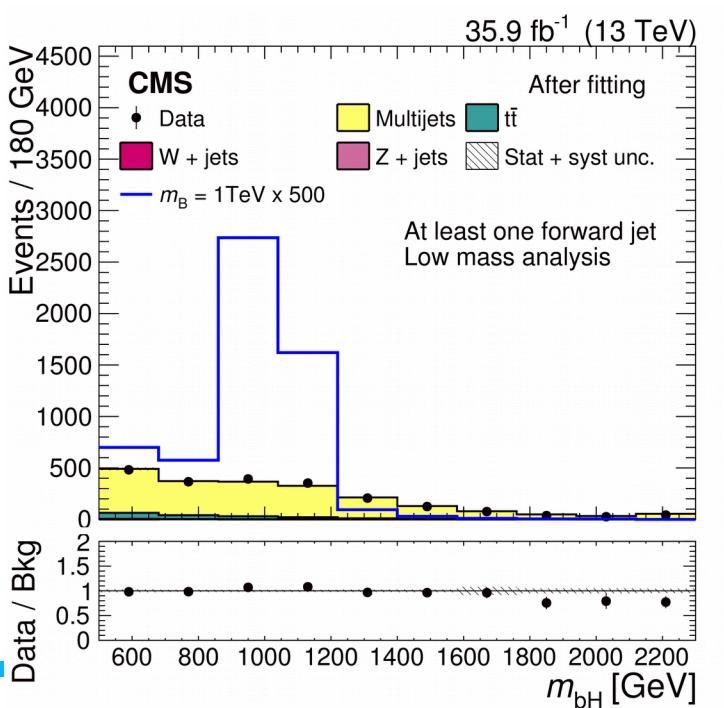


Single VLQ production: $B \rightarrow bH(bb)$

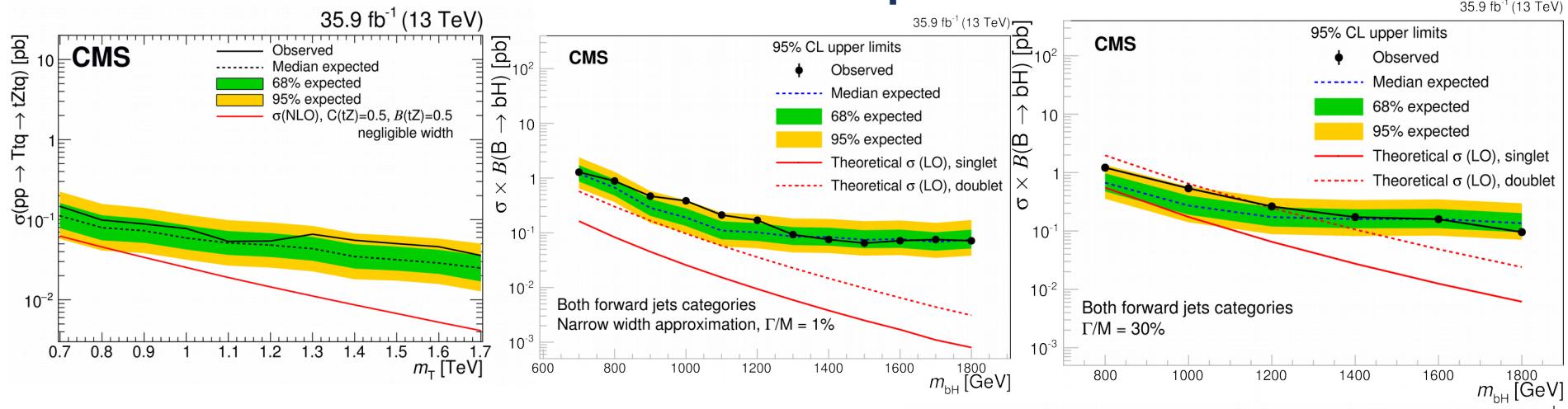
- **H decays to a bb pair:**
→ **2 b-tagged** sub-jets
- Low mass and high mass analyses
→ **different HT requirements**
- **QCD background** from Higgs mass sideband



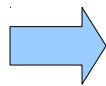
JHEP 06(2018)031



Single T and B: narrow and wide width interpretations

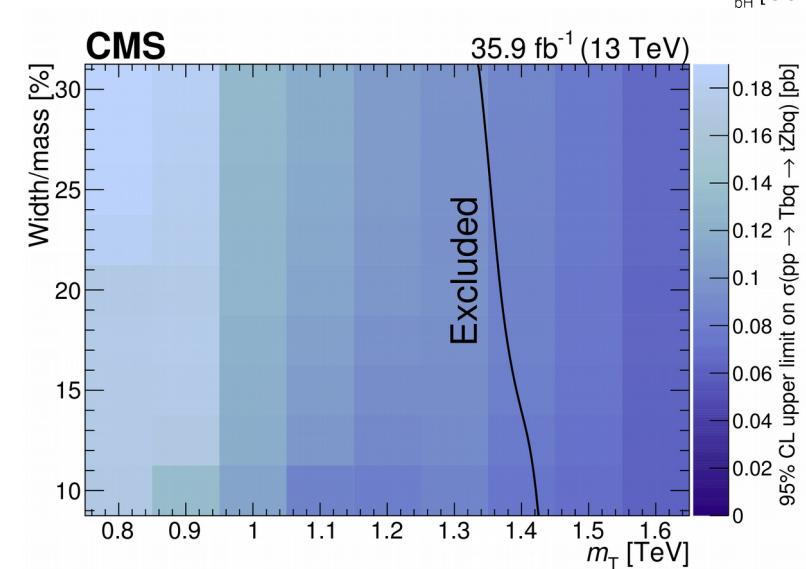


- Limits **cross section x branching fractions** as function of the **T, B mass (LH and RH couplings)**
- Vary **resonance width (1-30% mX)**: changes in acceptance and shapes



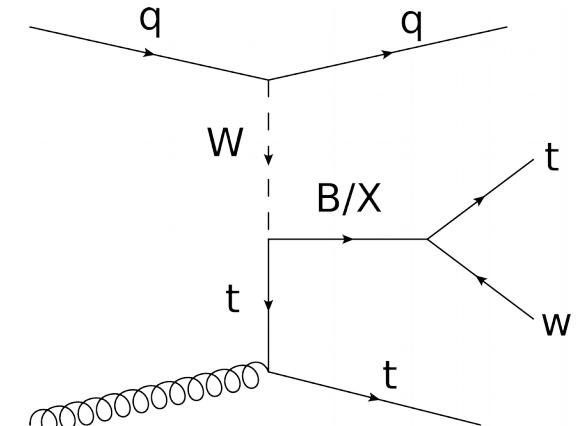
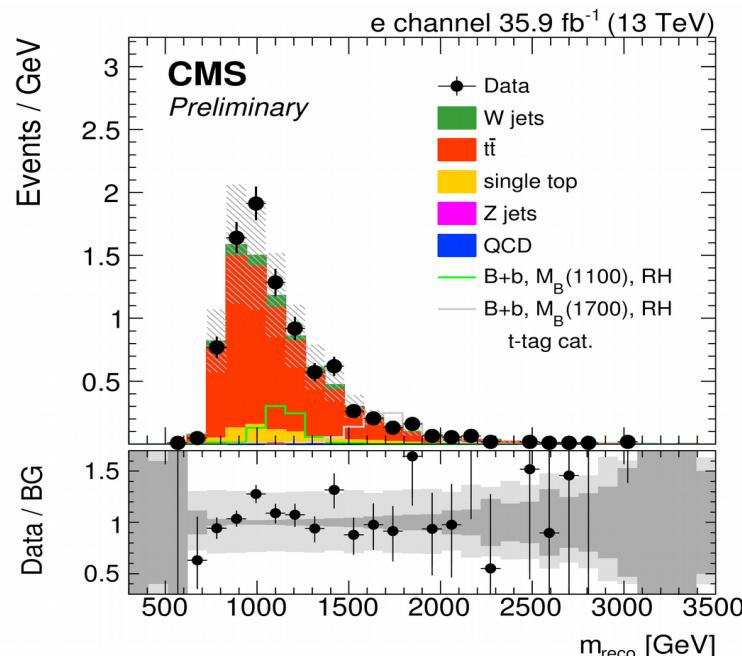
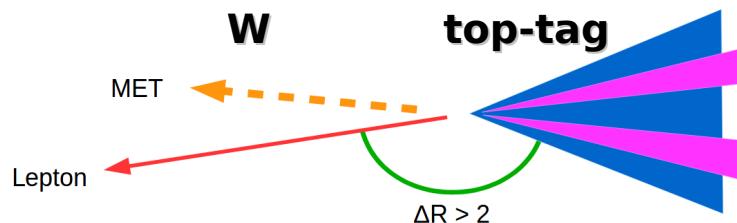
PLB 781(2018)574

JHEP 06(2018)031

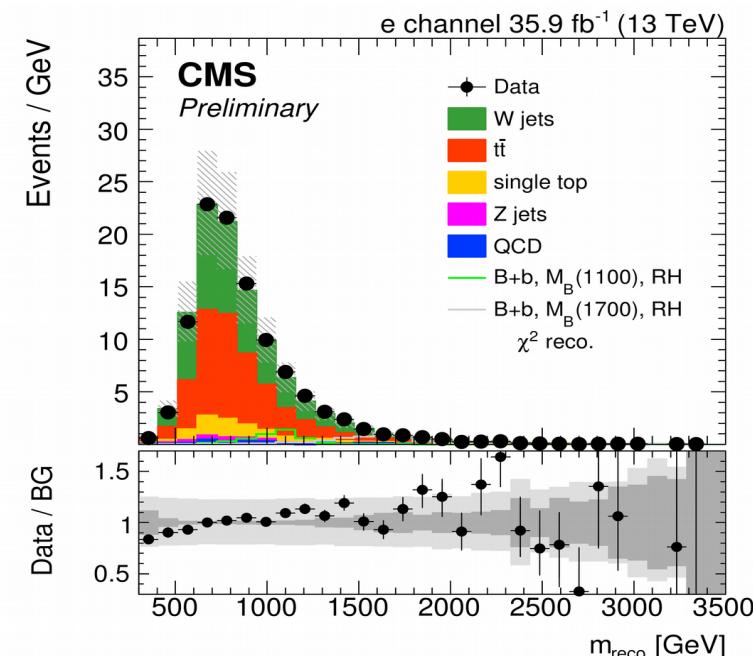


Single VLQ production: $B/X^{5/3} \rightarrow tW$

- Single VLQ production to tW : $\rightarrow B$ and $X^{5/3}$ final state
- **boosted and resolved** top quarks considered
→ best combination of jets using a χ^2 observable



PAS B2G-17-018

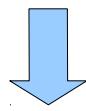


Results on single $B/X^{5/3}$

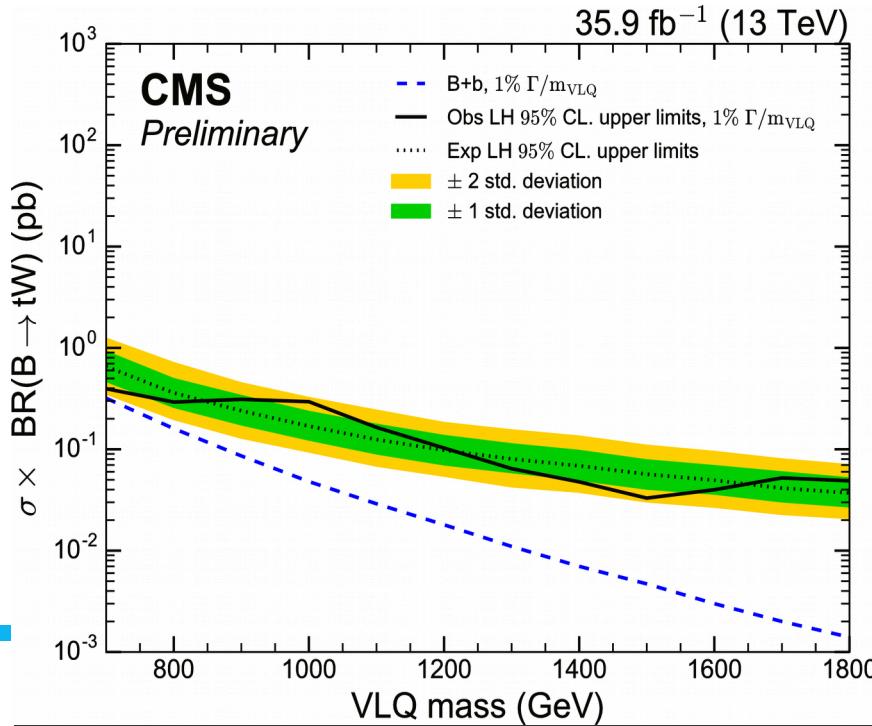
- Simultaneous **fit to signal and control regions**

→ with or without 1 “forward” jet at high $|\eta|$

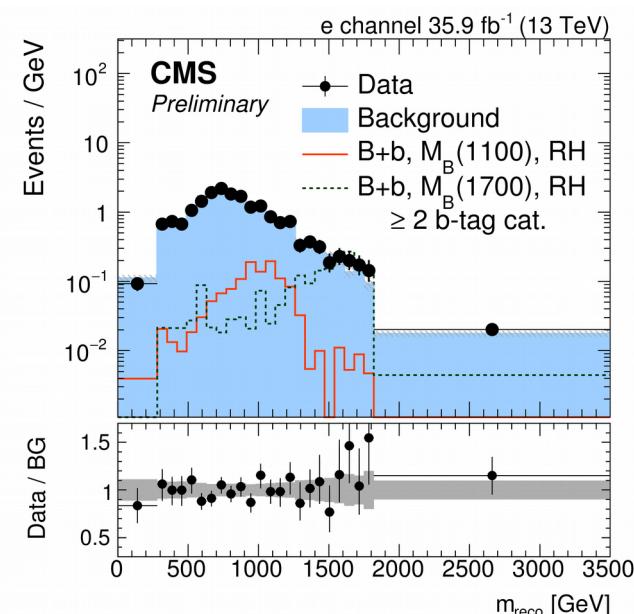
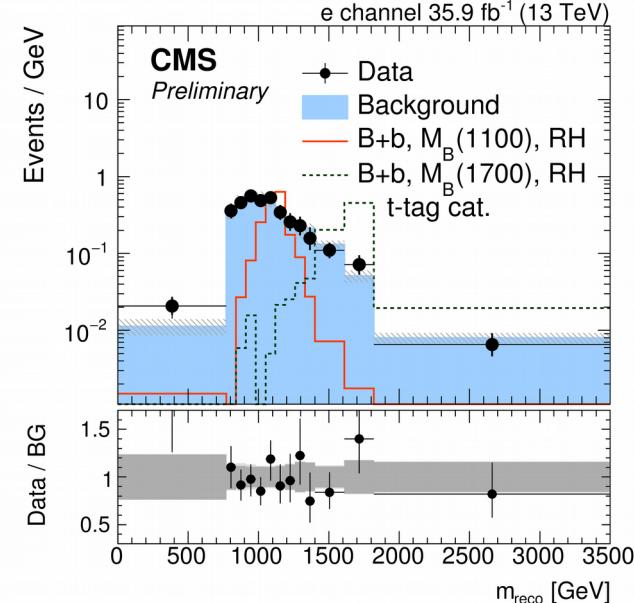
→ results in **narrow and wide widths(10-30%)**



PAS B2G-17-018



o Maria



Summary

- Vector-like quarks: **simplest fermionic top partners** still compatible with data
→ consequence to several SM extensions at the scale of the TeV
- Sought after in **pair** and **single** production

No evidence yet, still many more topologies to probe with the full Run-II Data!

