Searches for vector-like quarks in the tH and tW decay channels with CMS

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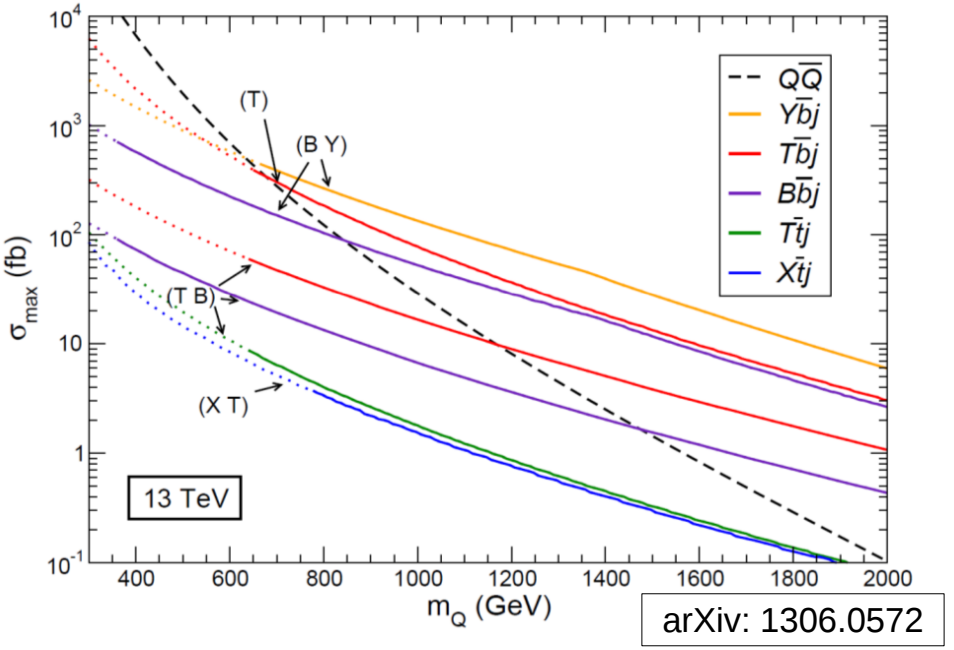
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Introduction

- **Motivated by the discovery of the Higgs boson**
  - Which mechanism stabilizes the Higgs mass?
    - Composite Higgs model
    - Models with extra dimensions
    - Little Higgs model
    - All these models predict heavy vector-like quarks

- **Vector-like quarks (VLQ):**
  - Spin – ½ particles
  - Left- and right-handed components transform in the same way under the standard model symmetry group
  - Various particles: T (+2/3), B (-1/3), X (+5/3), Y (-4/3)
  - Production: single or pair production
  - Single production can become dominant at high VLQ masses



arXiv: 1306.0572

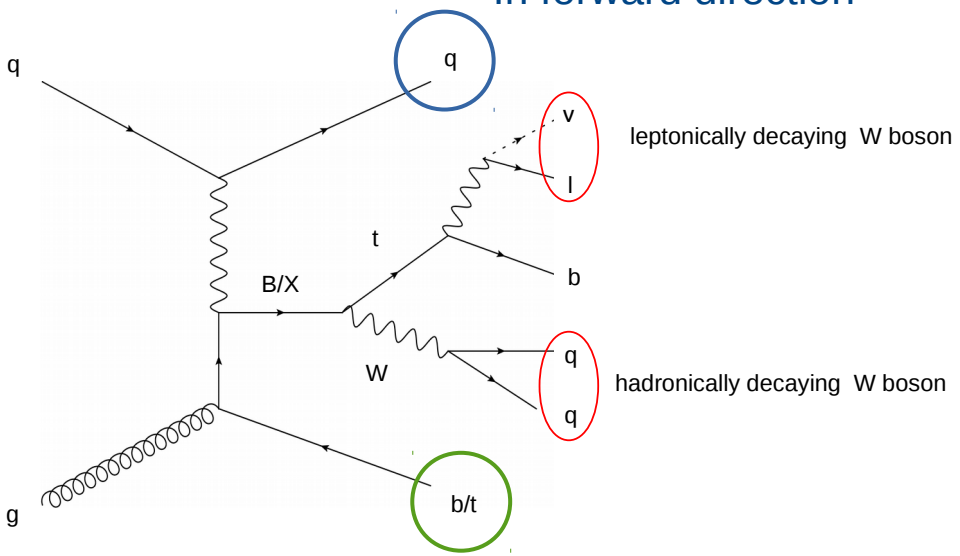
Introduction

$B/X_{5/3} \rightarrow tW$

$qg \rightarrow B/X_{5/3}$ b/t q'

Lepton + jets final state

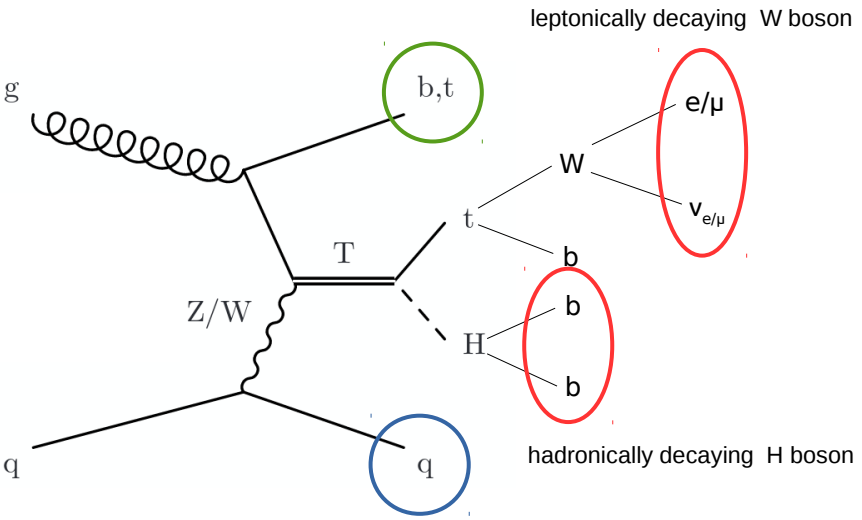
In forward direction



$T \rightarrow tH$

$qg \rightarrow T$ b/t q'

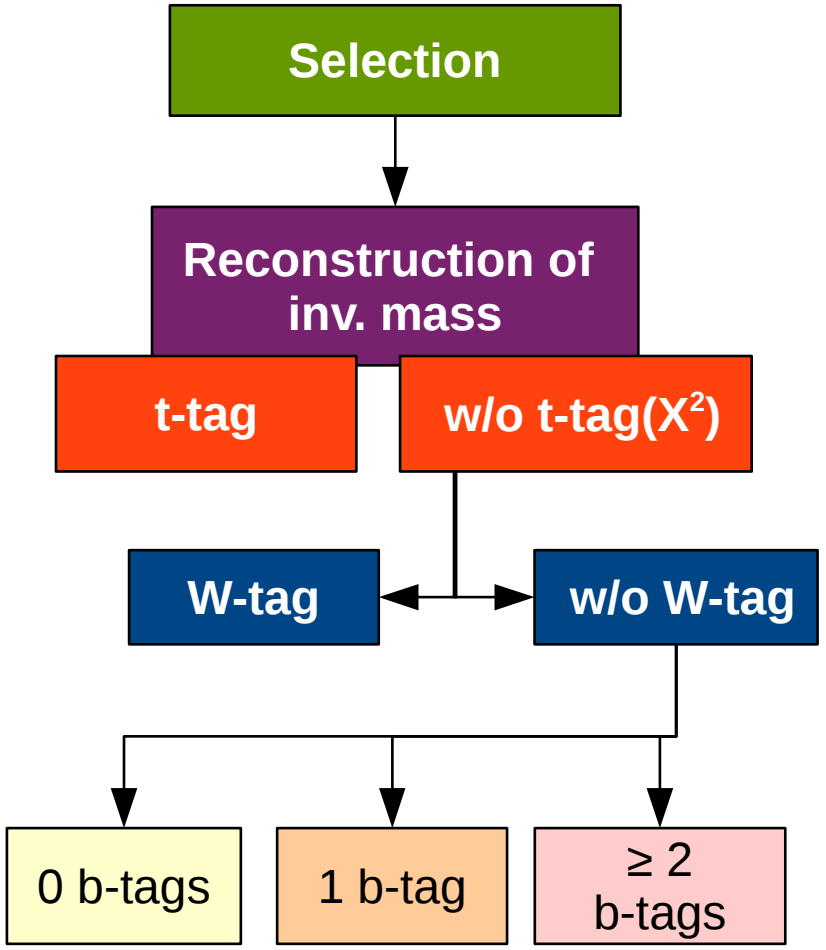
Lepton + jets final state



In forward direction

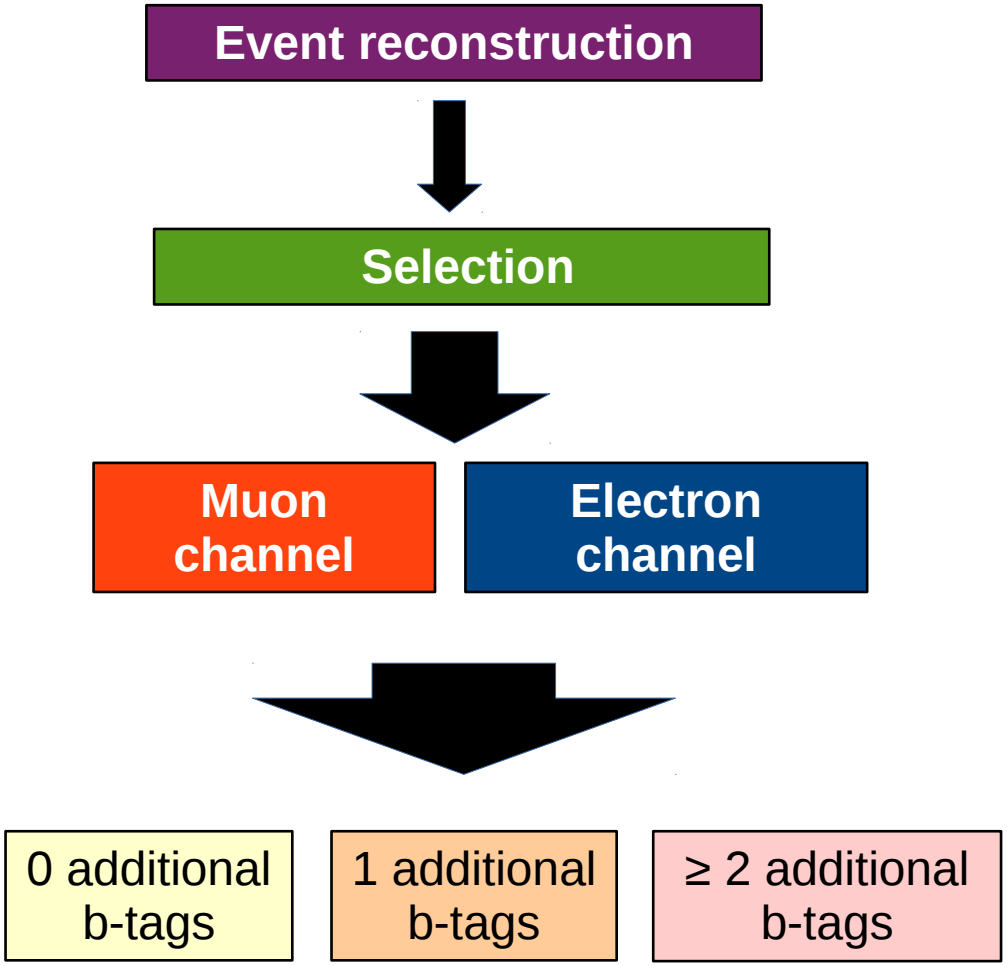
Analysis Strategy

$B/X_{5/3}$



Control Region (central) | Signal Region (forward)

T

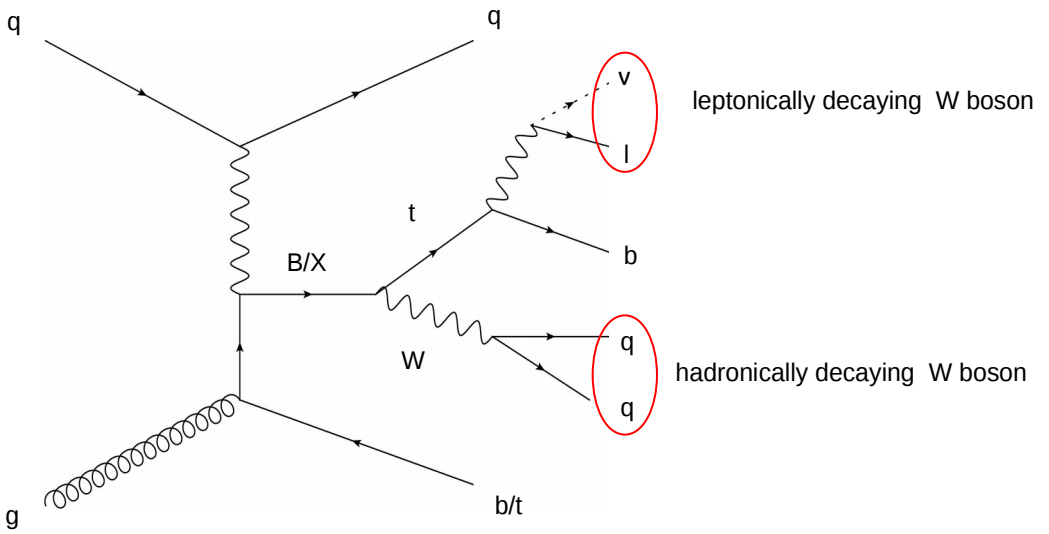


Control Region (central) | Signal Region (forward)

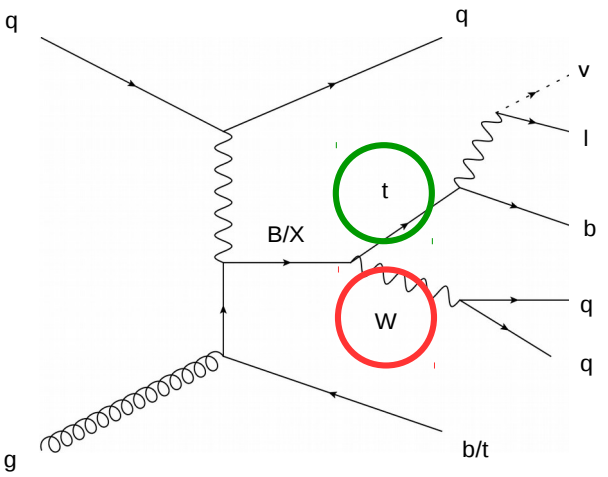
Search for single vector-like $B/X_{5/3}$ quarks

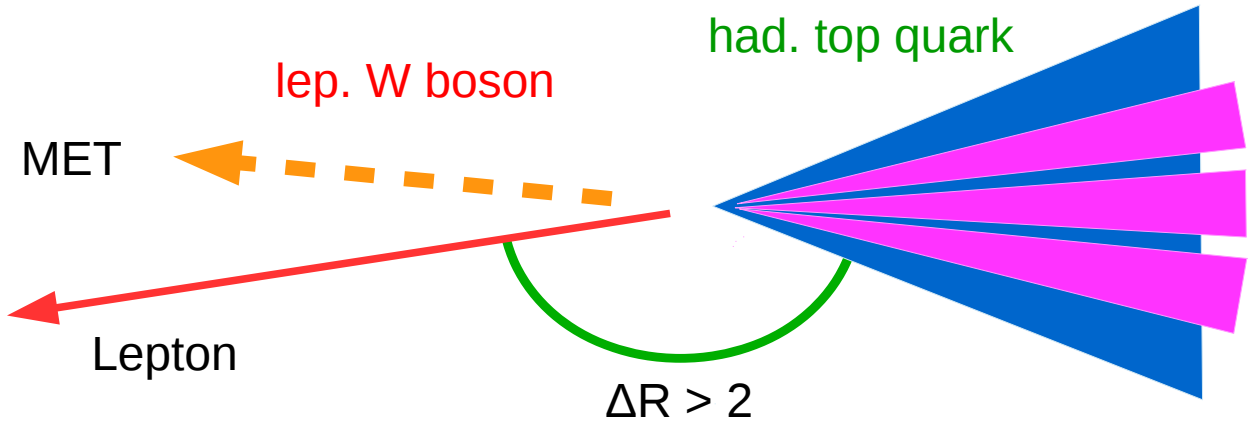
Selection

- 1 Muon (Electron) with p_T > 55 (120) GeV
- 2 AK4-Jets with p_T > 50 GeV
- 1 AK8-Jet with p_T > 175 GeV
- MET > 50 (60) GeV
- MET + lepton: $H_{T,Lep}$ > 240 (290) GeV



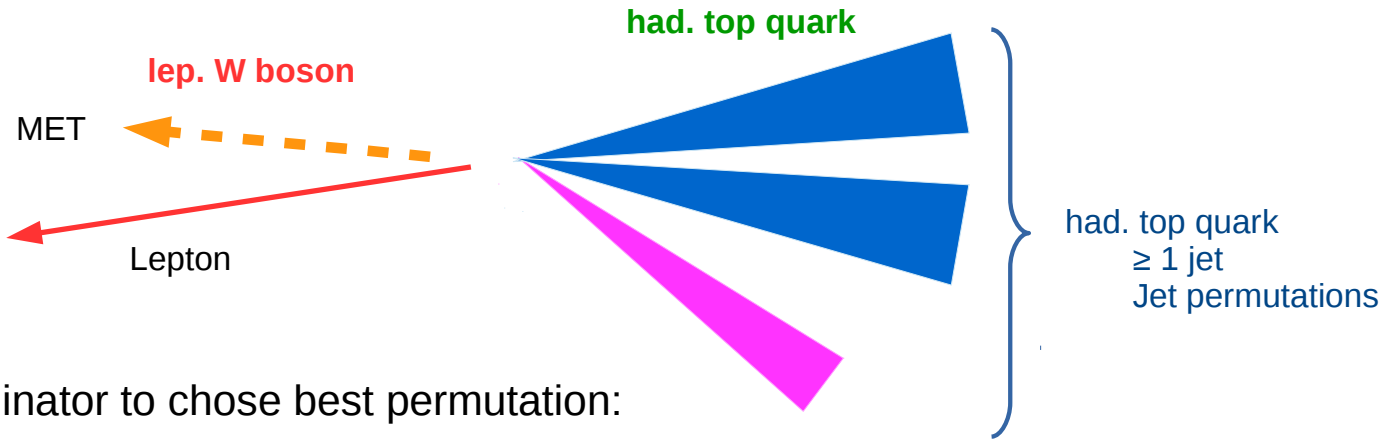
Event reconstruction
with top tag





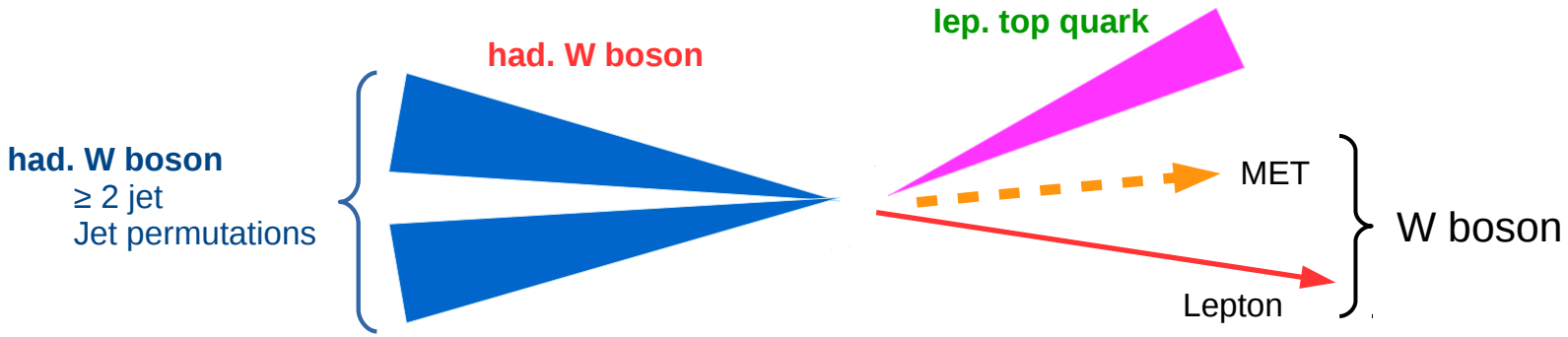
Top tagged Softdrop Ak8 jet

Event reconstruction
without top tag



Discriminator to chose best permutation:

$$\chi^2_{had.top} = \frac{(m^{top}_{reco} - m^{top})^2}{\sigma^{top}_{mass}} + \frac{(3.14 - \Delta R(top_{reco}, W_{reco}))^2}{\sigma^{\Delta R}} + \frac{(1 - p_T^W / p_T^{top})^2}{\sigma^{p_T}}$$



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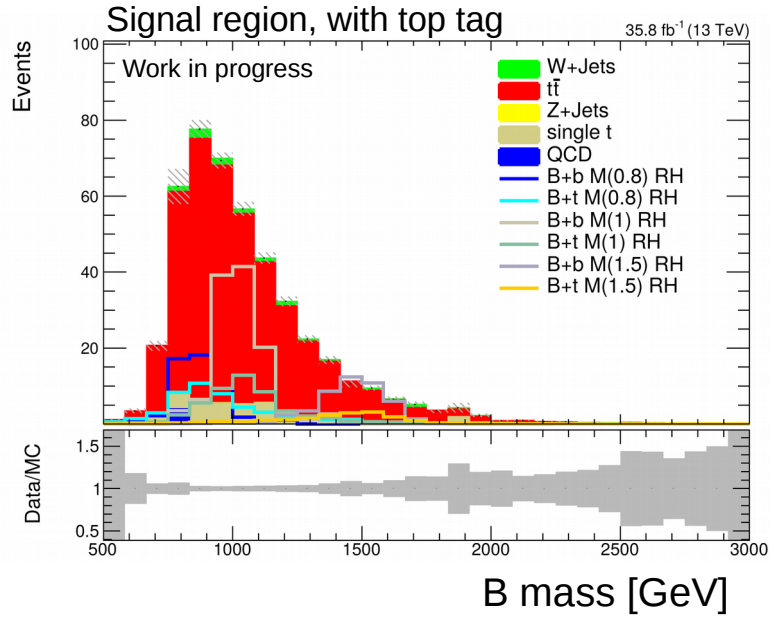
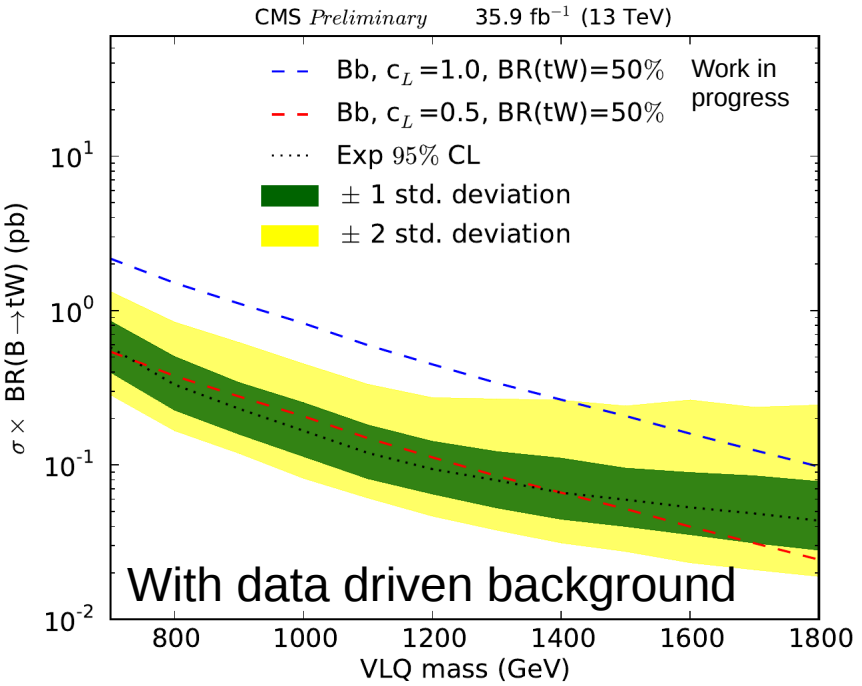
Search for single vector-like T quarks



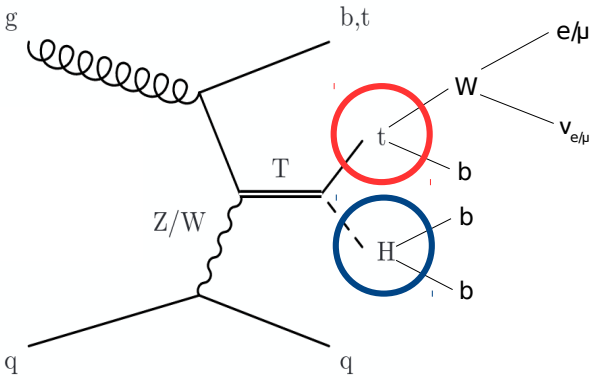


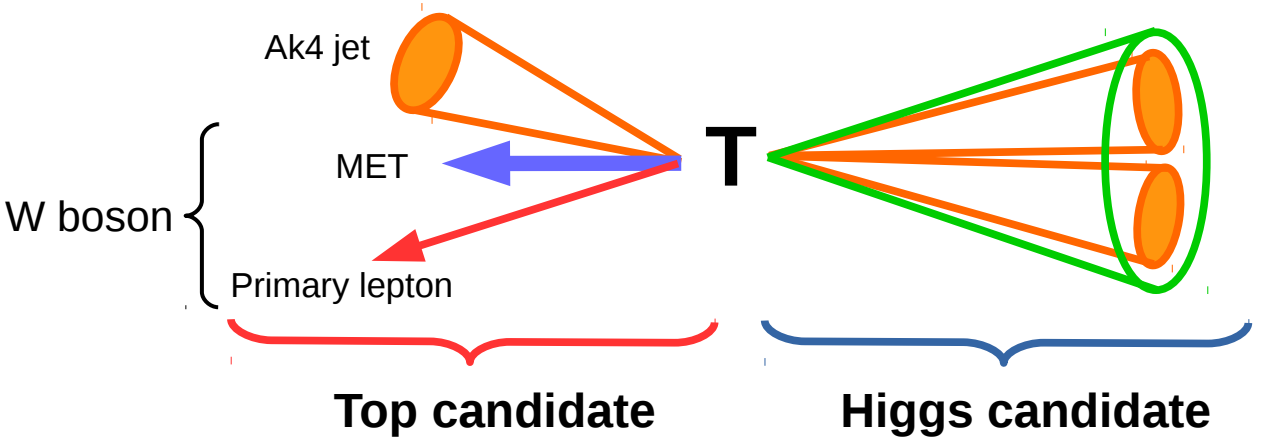
Included syst. Uncertainties:

- Luminosity
- Pileup
- Lepton IDs
- Trigger
- Jet energy scale
- Jet energy resolution
- B-tagging
- t-/W-tagging
- **PDFs**
- **Normalization and factorization**
- Signal region kinematics
- Forward jet scale factor

Search for single vector-like T quarks

Event reconstruction





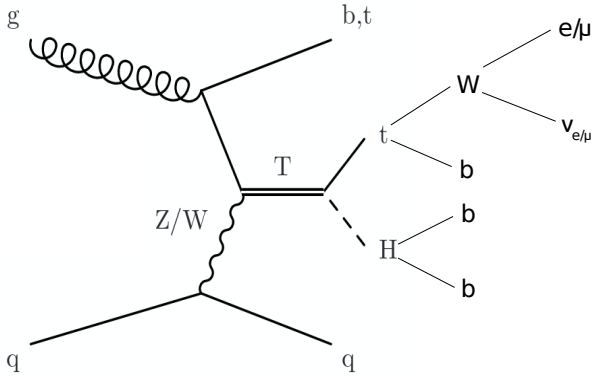
Softdrop Ak8 jet

$90 < M_{AK8} < 160$ GeV

Take the combination with the smallest χ^2

$$\chi^2 = \left(\frac{\Delta M_{\mathrm{H}}}{\sigma_{M_{\mathrm{H}}}}\right)^2 + \left(\frac{\Delta M_{\mathrm{t}}}{\sigma_{M_{\mathrm{t}}}}\right)^2 + \left(\frac{\Delta(dR(\mathrm{H},t))}{\sigma_{dR(\mathrm{H},t)}}\right)^2$$

Selection



≥ 1 lepton with p_T > 55 GeV

≥ 2 jets with p_T > 185 (50) GeV

≥ 1 Higgs candidate

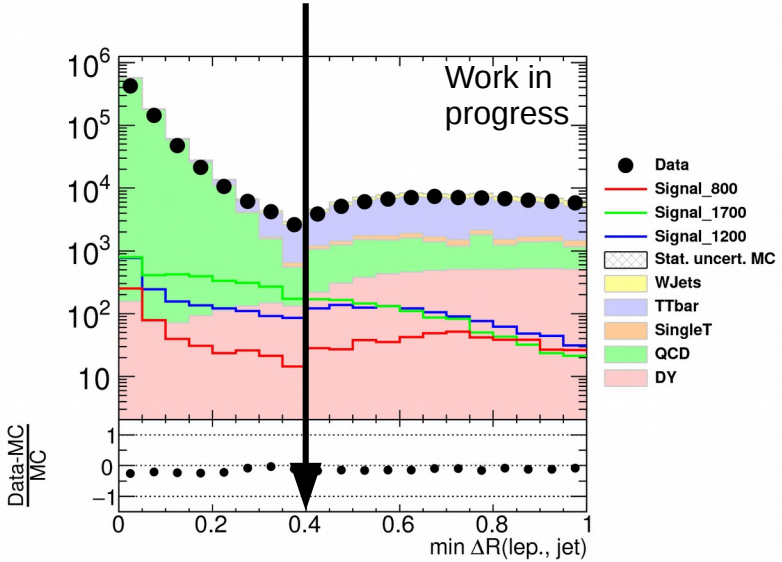
ΔR(top candidate, Higgs candidate > 2)

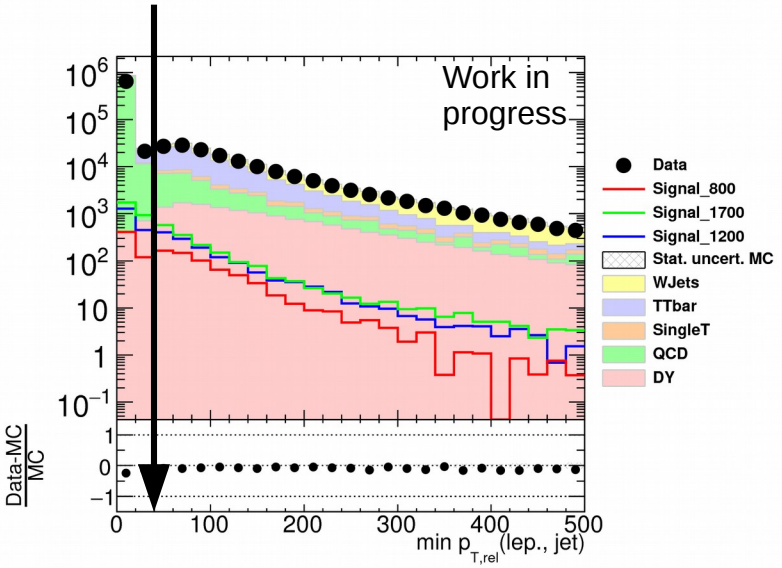
$p_{T,\text{top candidate}}$ > 100 GeV

ST > 400 GeV

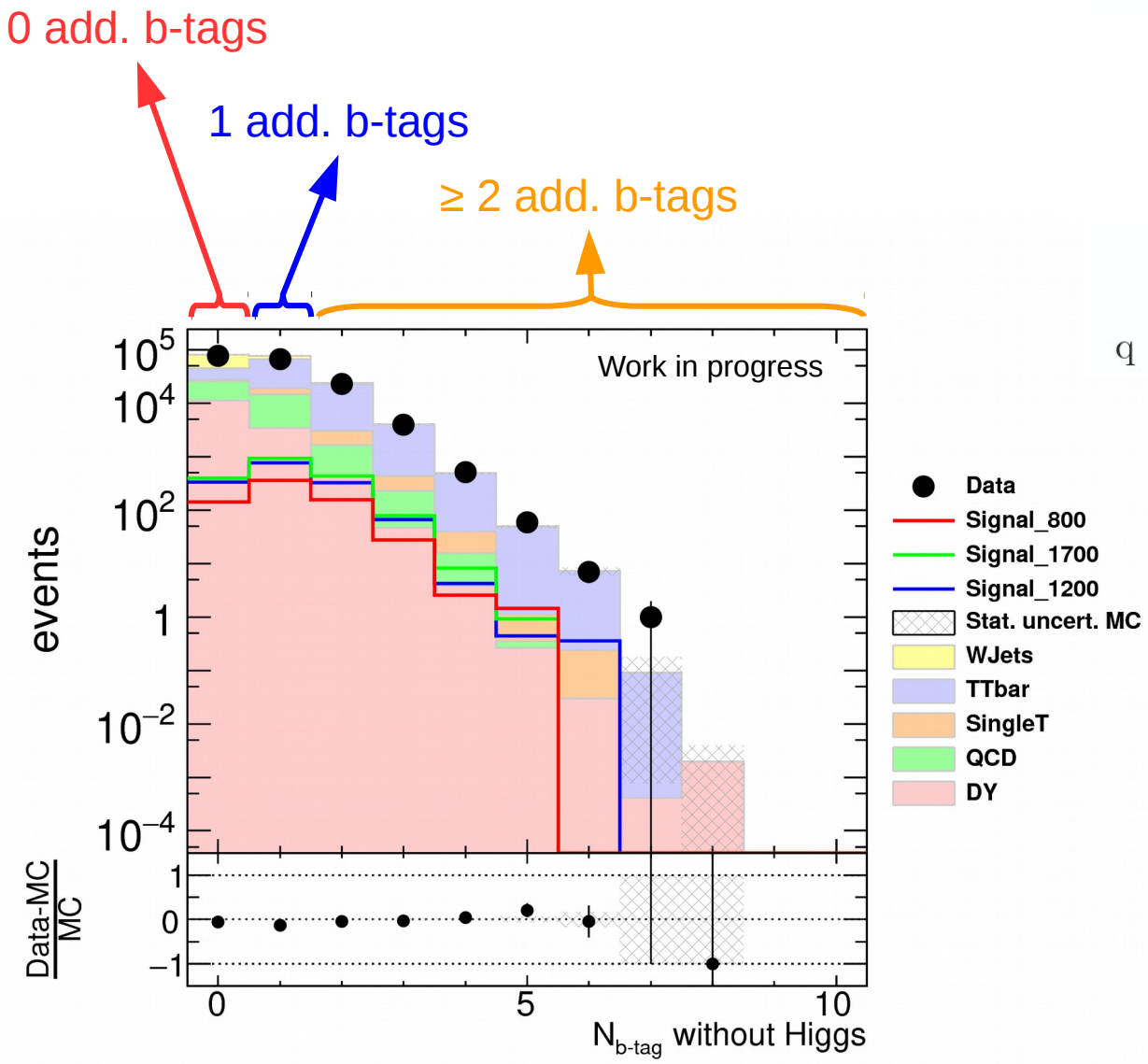
2D cut (ΔR(l,j) > 0.4 || p_T^{rel}(l,j) > 40 GeV)

ST =
p_T of lepton with highest p_T
+ MET
+p_T of $\text{jets}_{>30\text{GeV}}$

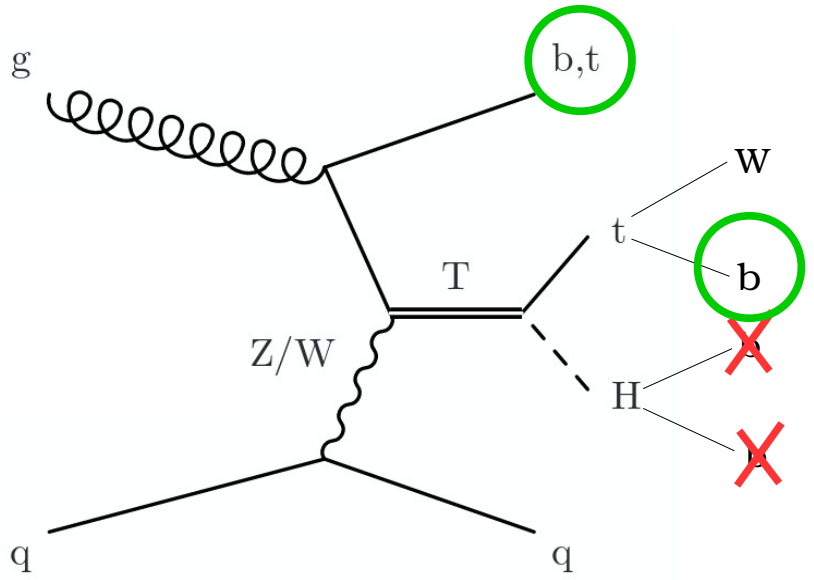




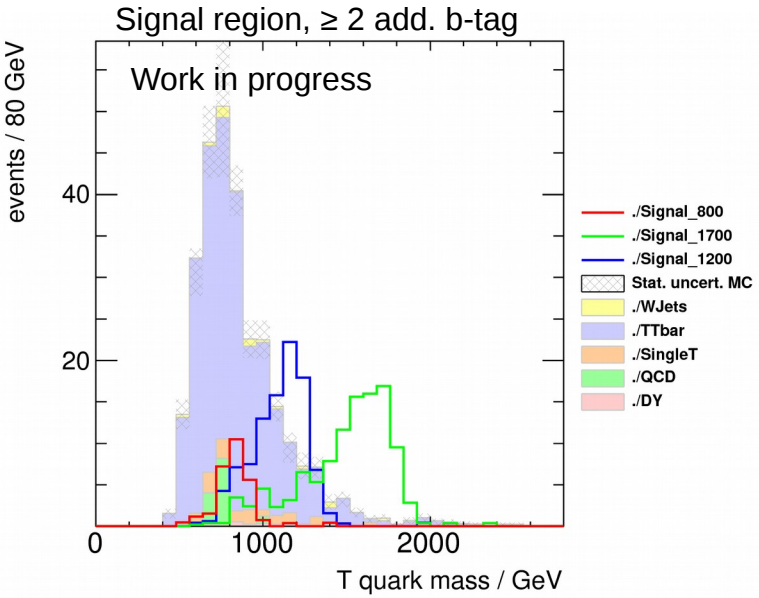
Categories

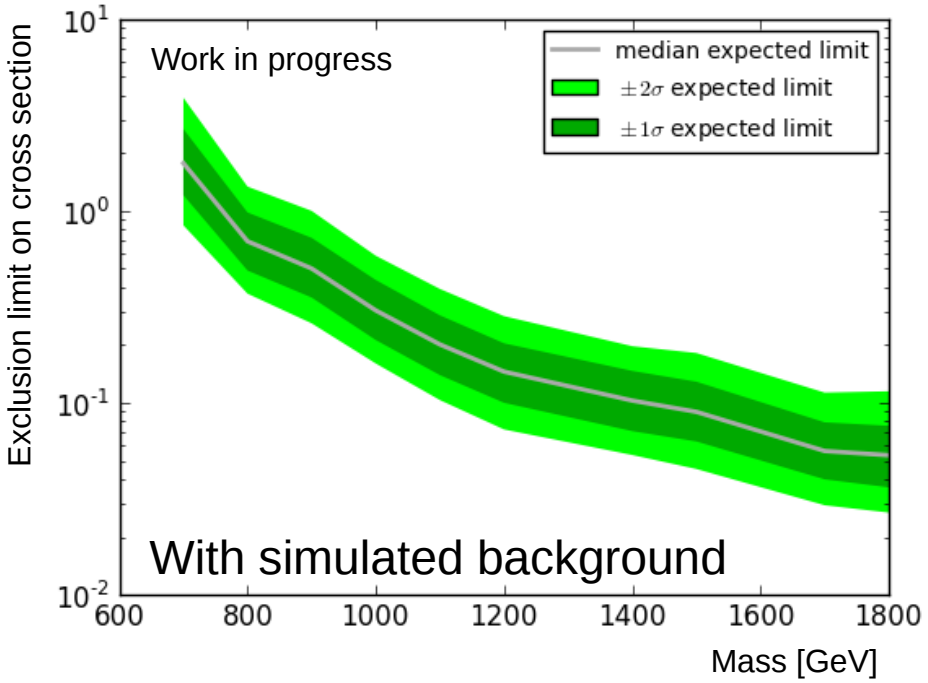


Additional b-tags



	1 subjet b-tag	2 subjet b-tags
0 forward jets	Control region	
≥ 1 forward jets		Signal region





Included syst. Uncertainties:

- Pile up
- Lepton IDs
- Trigger
- **Jet energy scale**
- Jet energy resolution
- B-tagging
- Higgs mass smearing
- **PDFs**

Summary

- Searches for single vector-like T and $B/X_{5/3}$ quarks with full 2016 dataset
- Event reconstruction with substructure techniques
- Data driven background estimate
- Forward jet discriminates well between signal and background

Back up

Selection

- 1 Muon (Electron) with p_T > 55 (120) GeV
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- 1 AK8-Jet with p_T > 175 GeV
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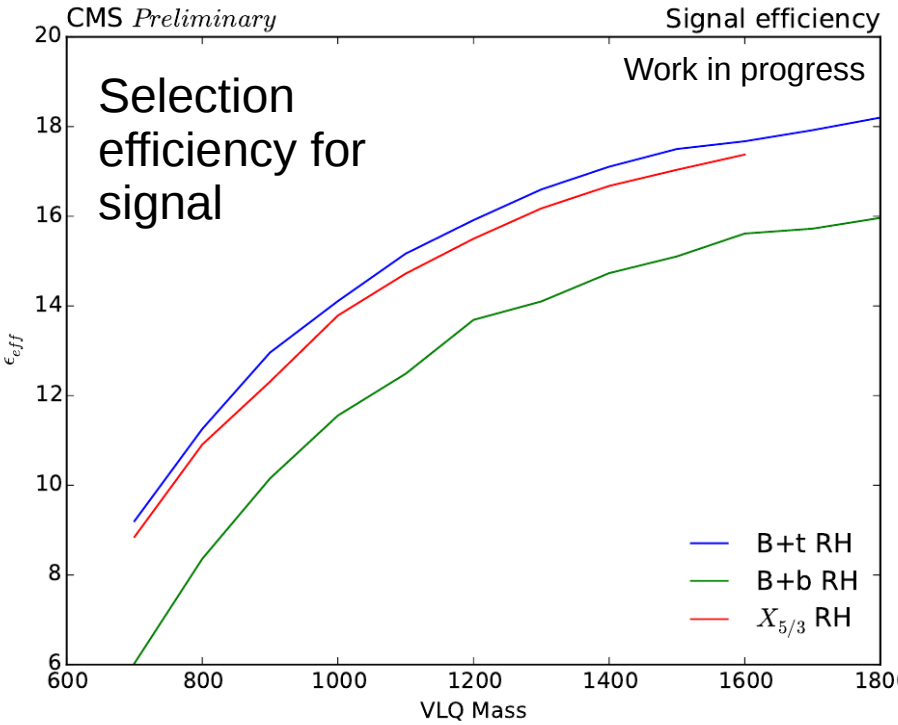
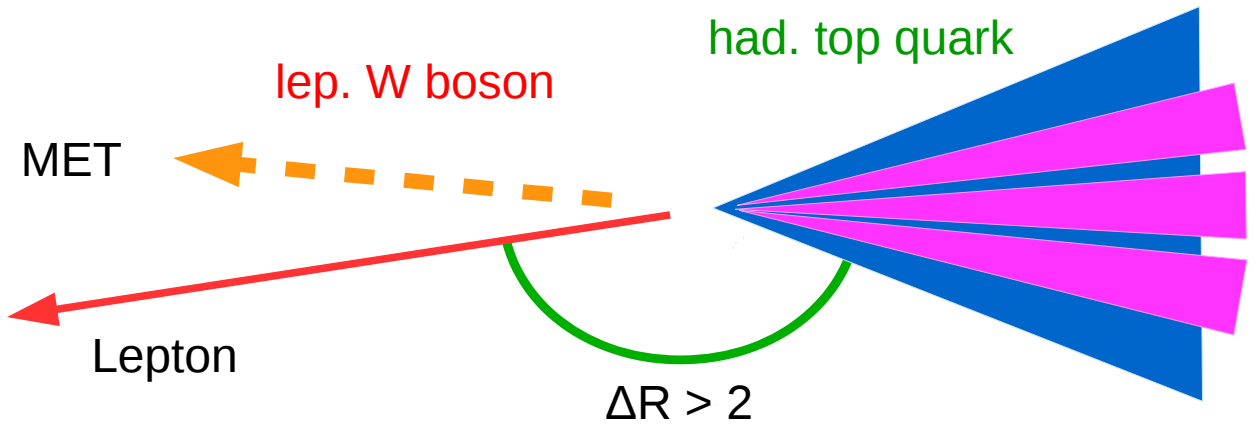
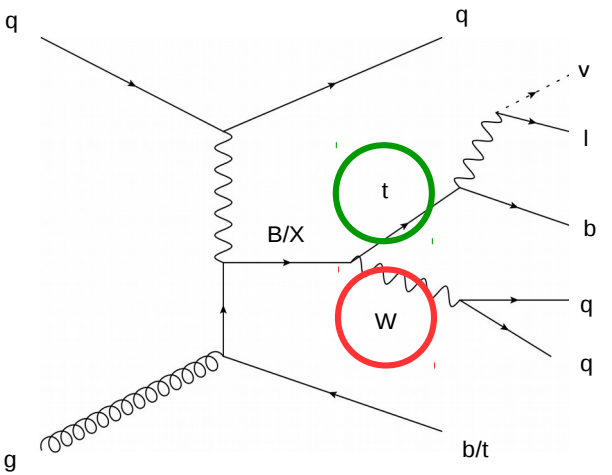
- MET + lepton: $H_{T,Lep}$ > 240 (290) GeV



Event reconstruction
with top tag





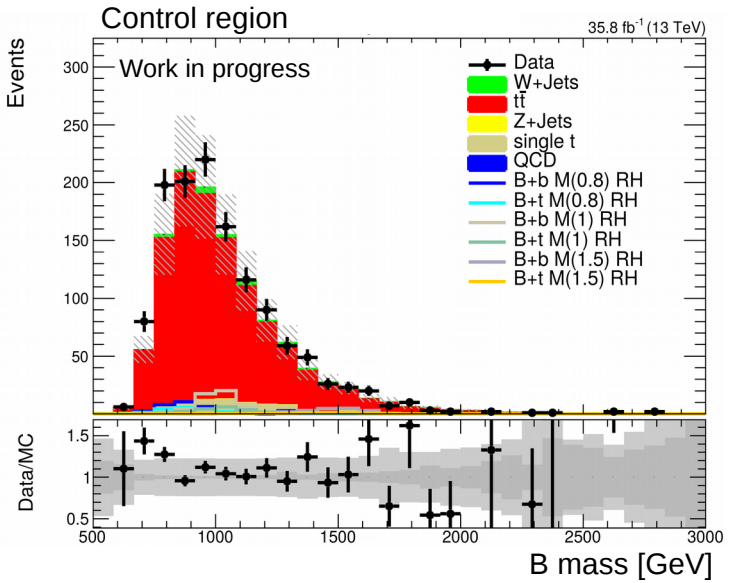
Softdrop Ak8 jet

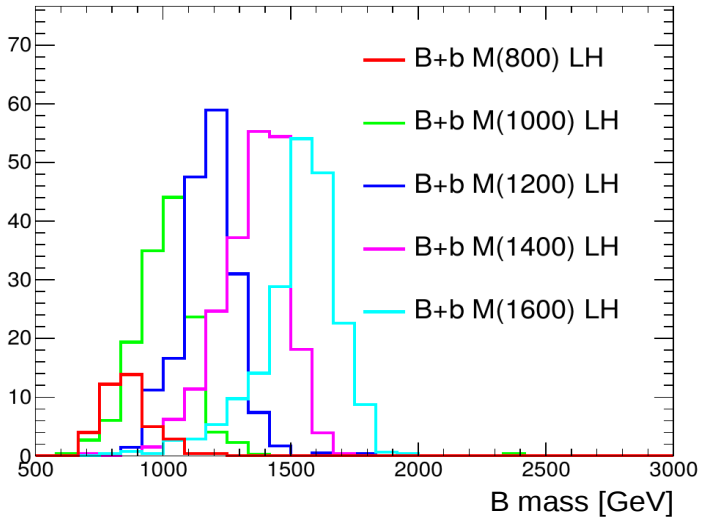
Top tag:

110 GeV < M_{Ak8} < 210 GeV

1 subjet b-tag

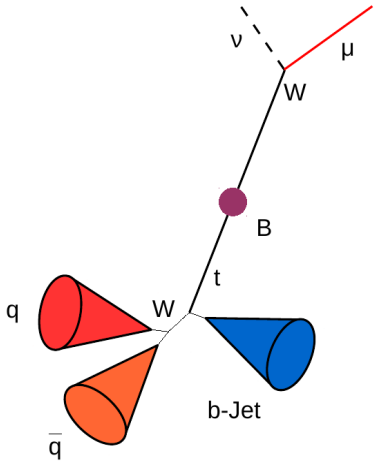
N-subjettiness τ_2/τ_3 < 0.68

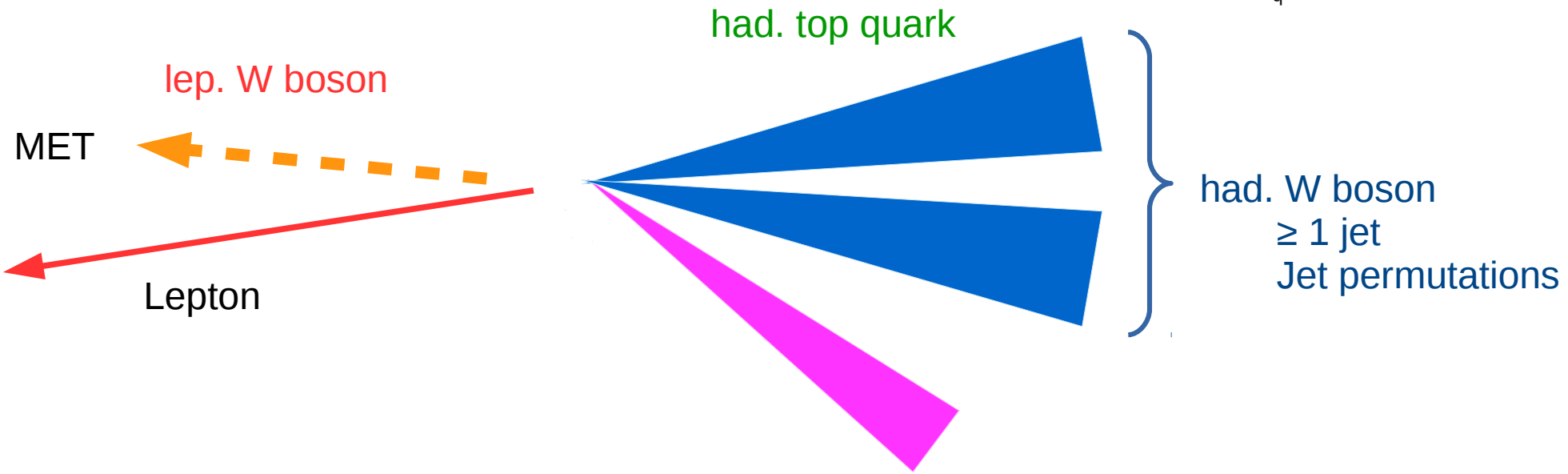




- Very good mass resolution
- Few SM background events
- Low efficiency at low masses

Event reconstruction
without top tag

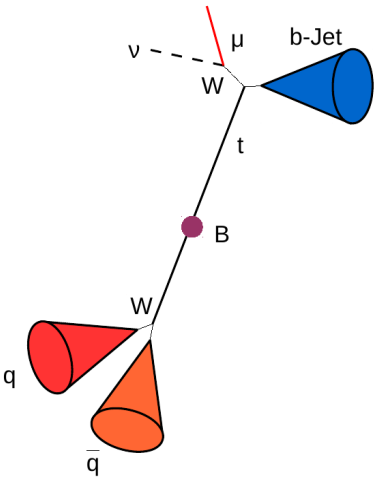


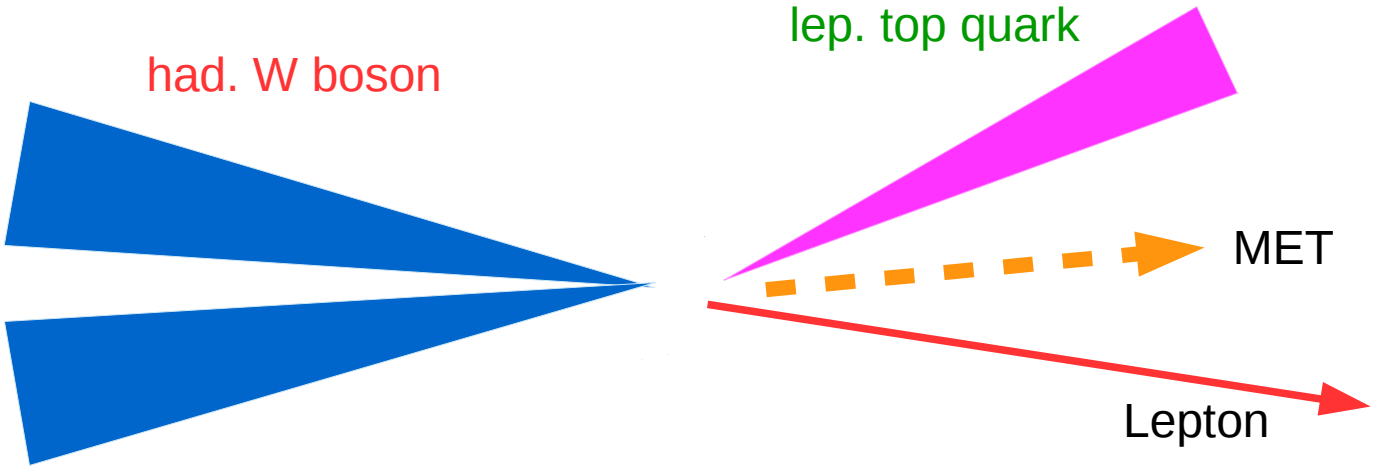


Discriminator to chose best permutation

$$\chi^2_{had.top} = \frac{\left(m^{top}_{reco} - m^{top}\right)^2}{\sigma^{top}_{mass}} + \frac{\left(3.14 - \Delta R\left(top_{reco}, W_{reco}\right)\right)^2}{\sigma^{\Delta R}} + \frac{\left(1 - p_T^W / p_T^{top}\right)^2}{\sigma^{p_T}}$$

Event reconstruction
without top tag





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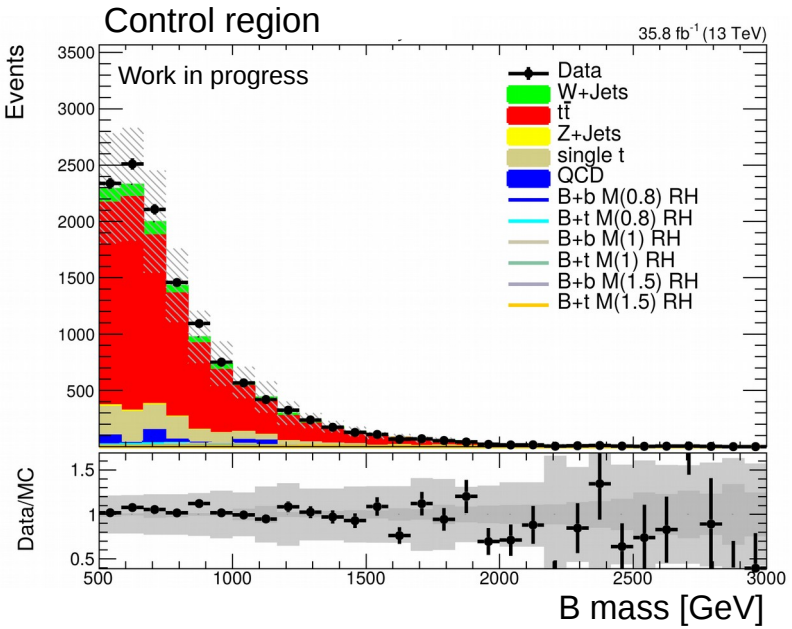
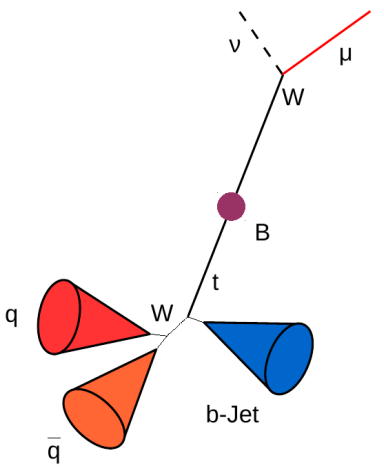
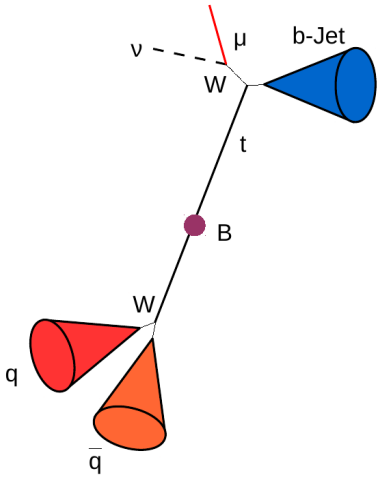
Selection by $Prob.\left(\chi^2, n_{dof}\right)$

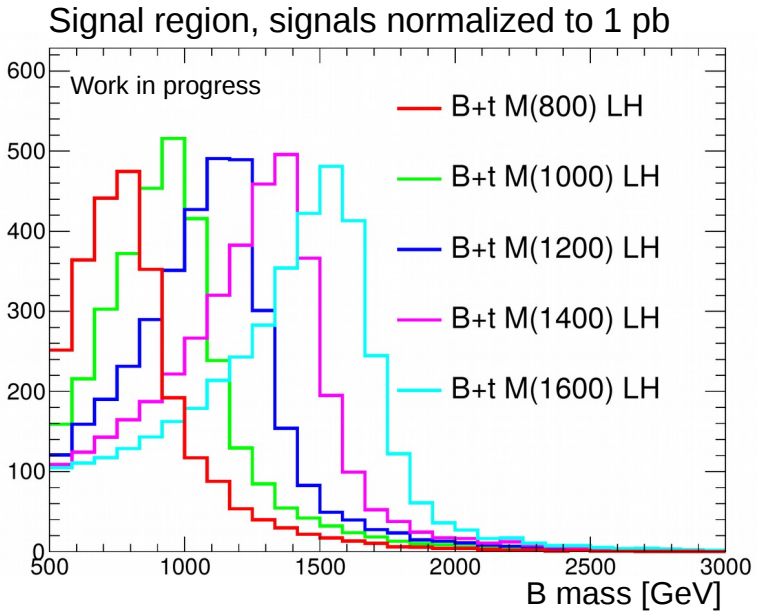
Event reconstruction

without top tag







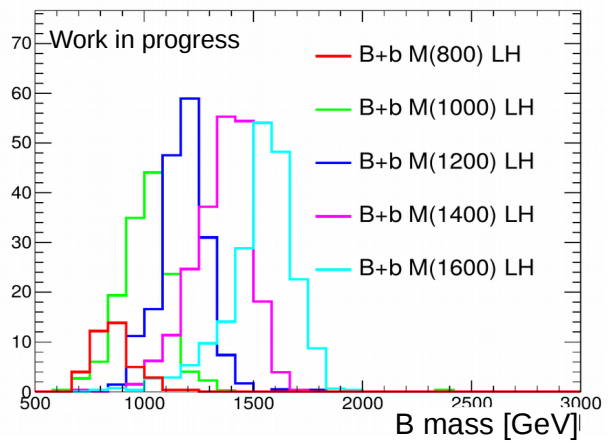


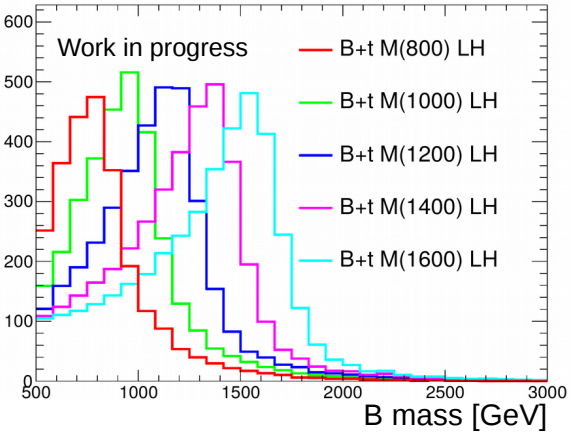
- Good selection efficiencies for low B/$X_{5/3}$ masses
- High number of background events
- Good mass resolution

with top tag

without top tag

Signal region
(signals normalized to 1 pb)



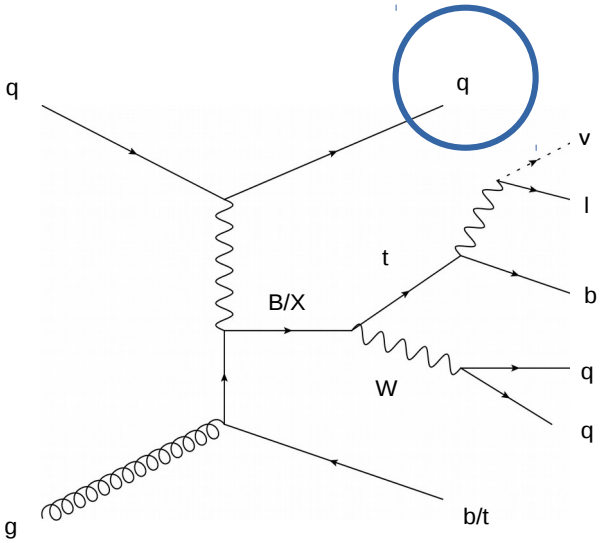


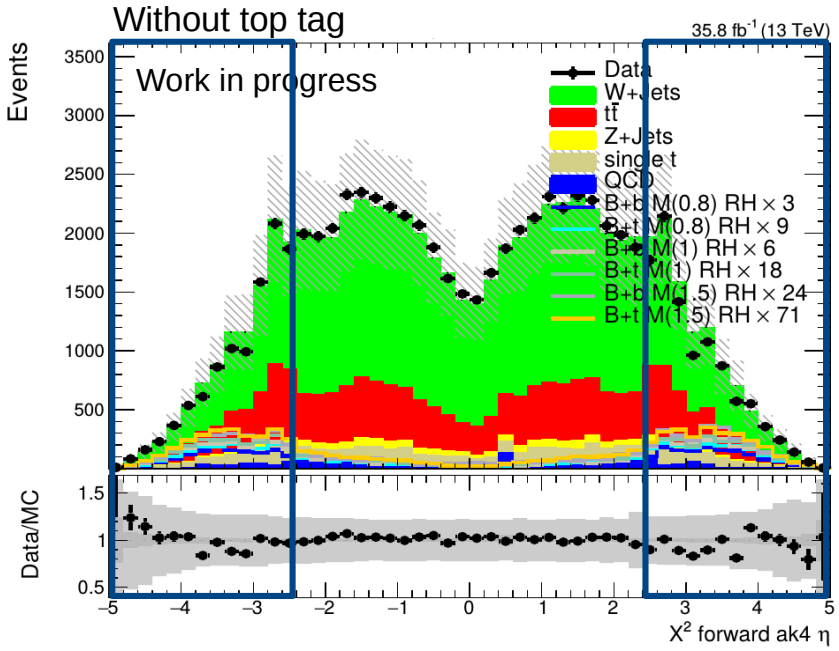
- Very good mass resolution
- Low efficiency at low masses

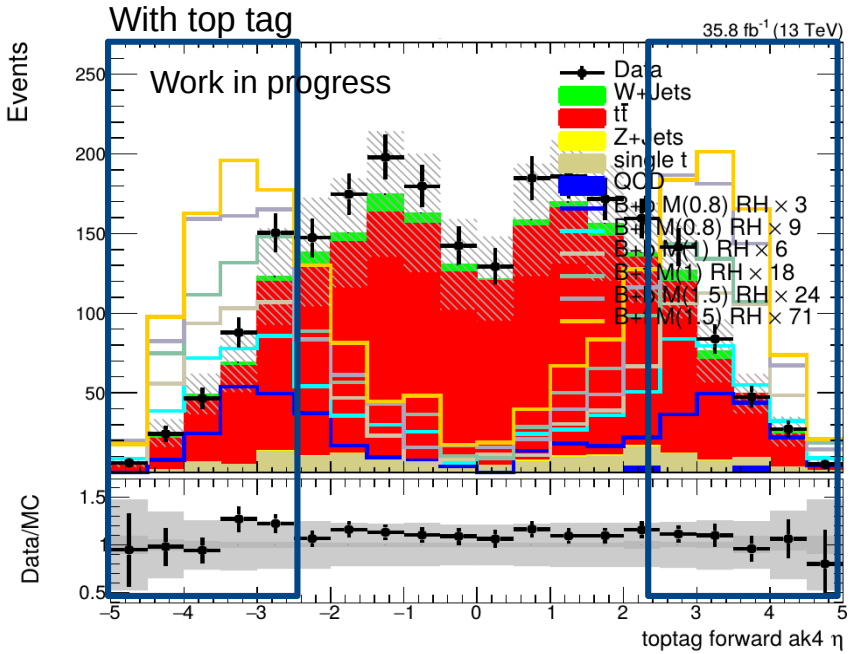
- Good selection efficiencies for low $B/X_{5/3}$ masses
- Good mass resolution

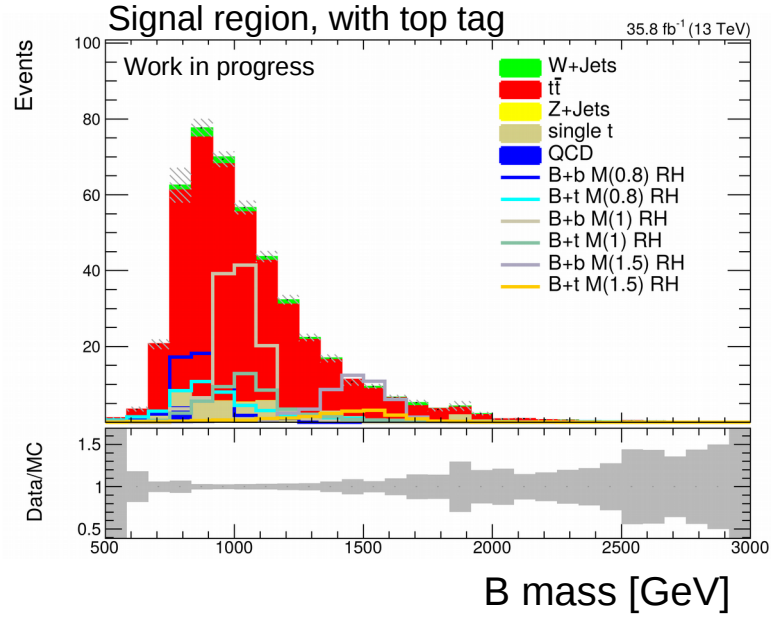
Signal and Sideband region

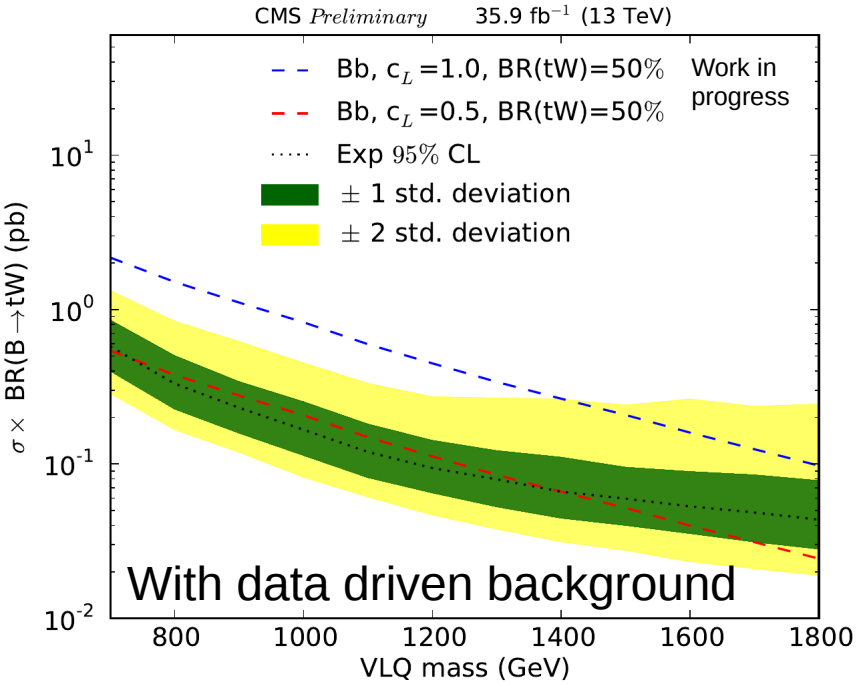
0 forward jets	≥ 1 forward jets
Sideband region	Signal region

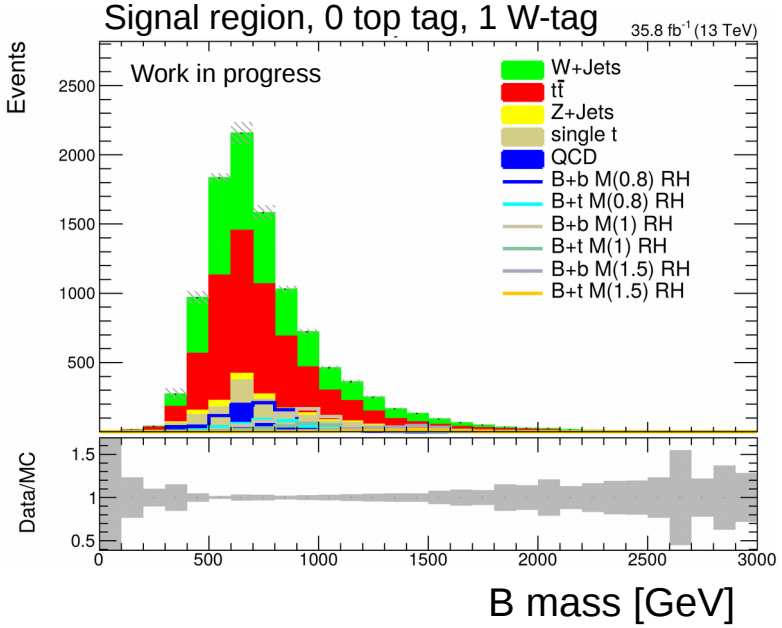








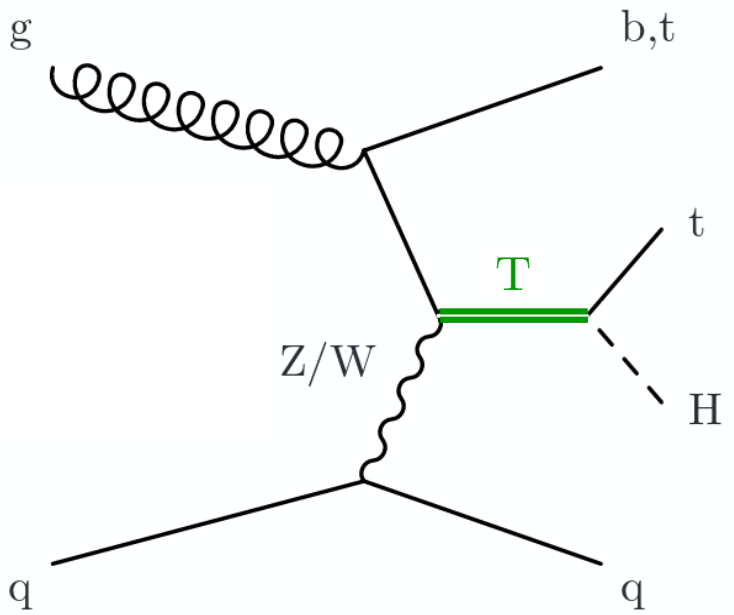




Included syst. Uncertainties:

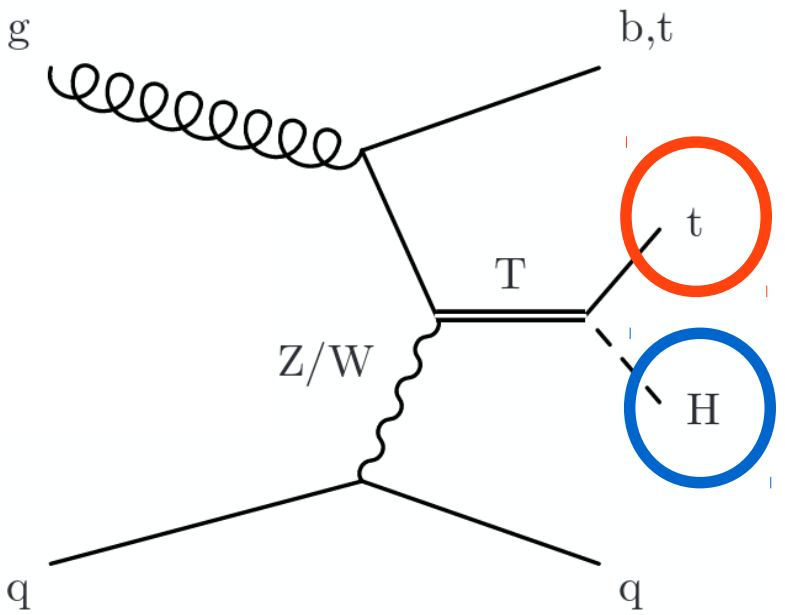
- Luminosity
- Pileup
- Lepton IDs
- Trigger
- Jet energy scale
- Jet energy resolution
- B-tagging
- t-/W-tagging
- PDFs
- Normalization and factorization
- Signal region kinematics
- Forward jet scale factor

Event reconstruction



Goal: Reconstruction of the **T quark** mass

Event reconstruction

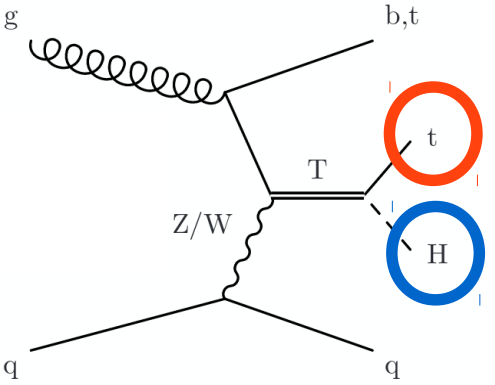


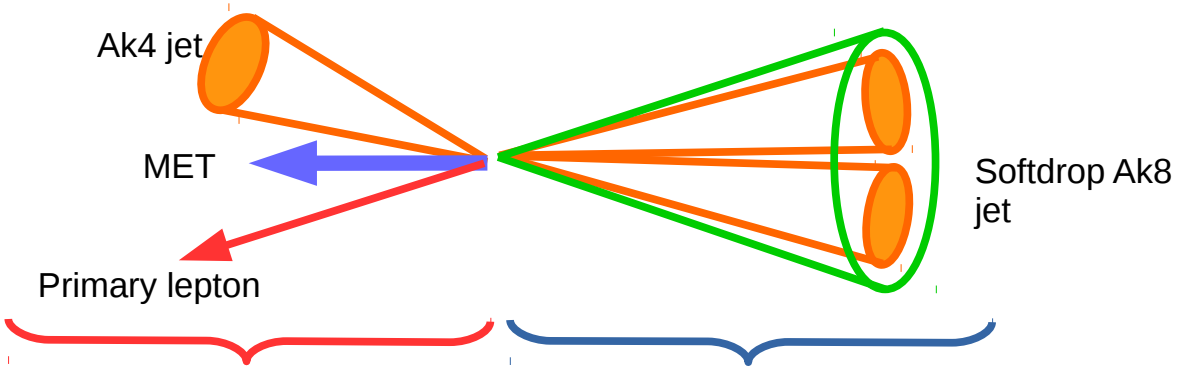
High T mass → boosted top and boosted Higgs

First:

- Reconstruction of the **t quark**
- Reconstruction of the **Higgs**

Event reconstruction





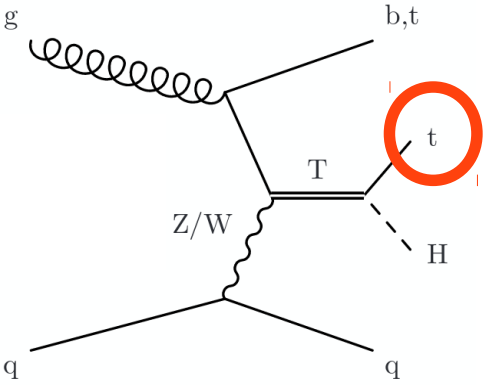
Top candidate

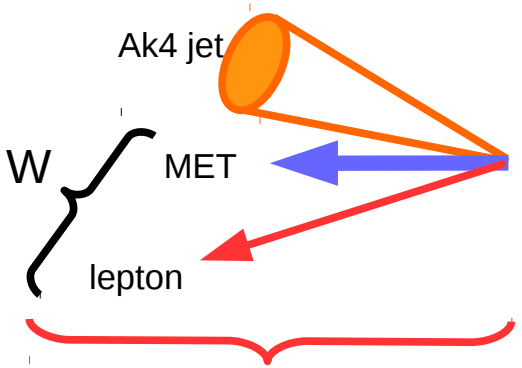
Lepton with highest p_T
+ MET
+ up to 2 jets

Higgs candidate

softdrop Ak8 jet
($90 < M_H < 160$ GeV)

Event reconstruction

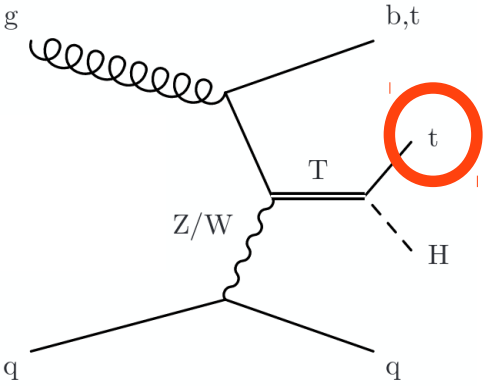


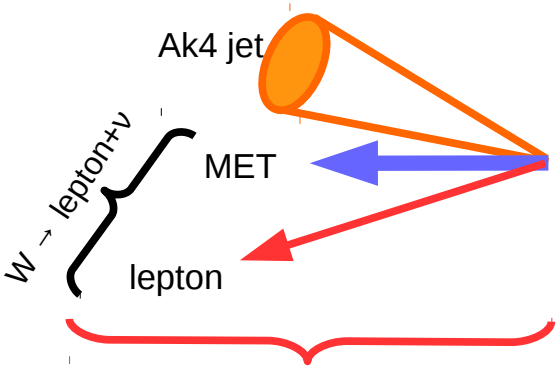


Top candidate

Lepton with highest p_T
+ MET
+ up to 2 jets

Event reconstruction





Top candidate

Lepton with highest p_T
+ MET
+ up to 2 jets

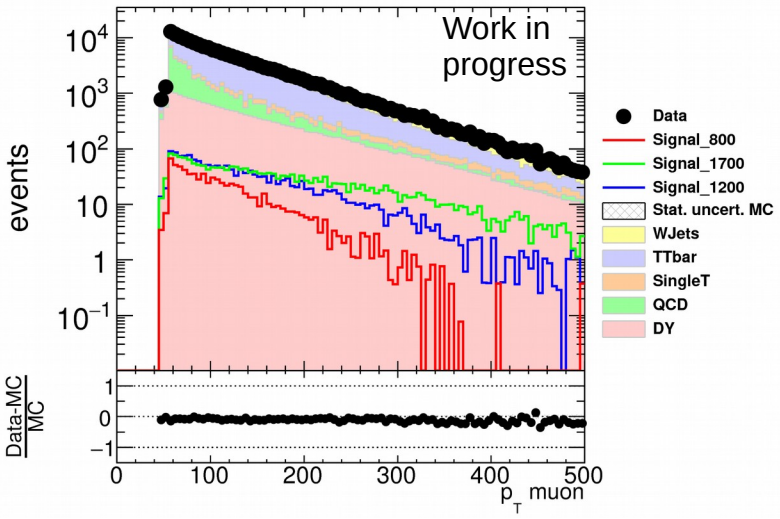
Reconstruction of the neutrino
(lepton + MET + W mass)

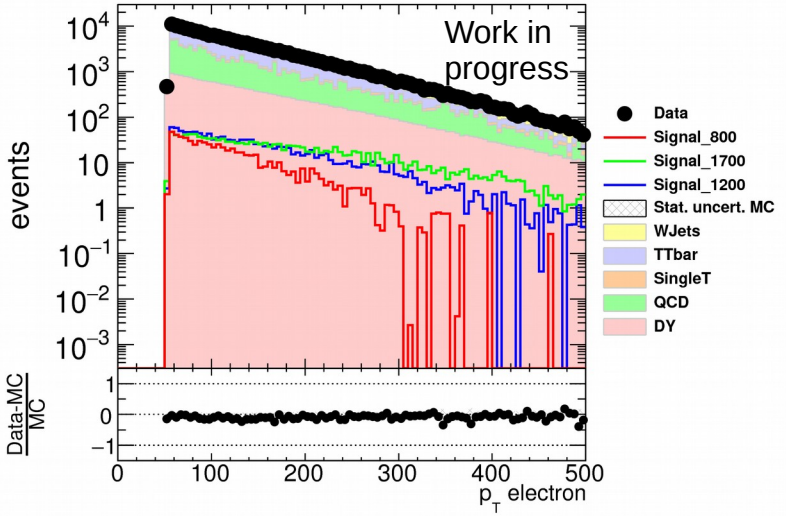
Reconstruction of the W
(lepton + neutrino)

t quark candidate
Reconstructed W + 1-2 Ak4 jets

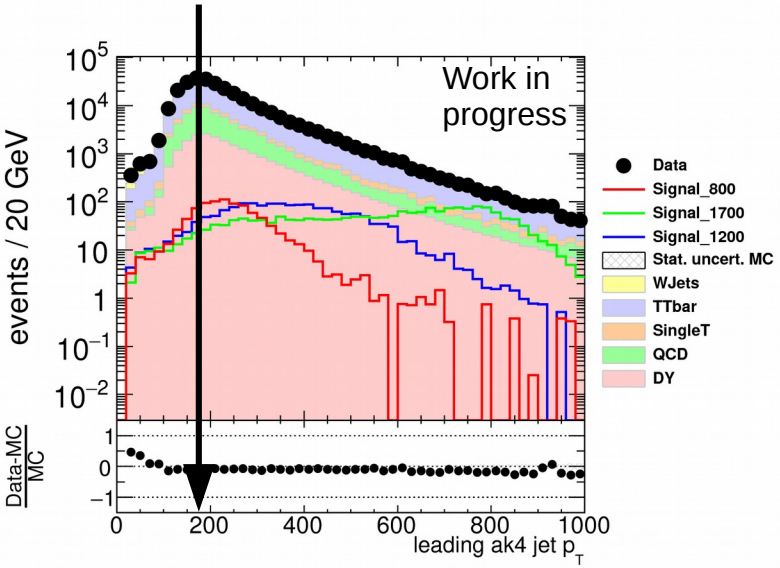
Baseline Selection

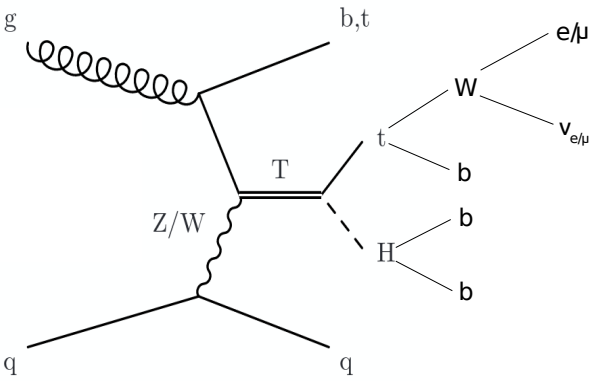
≥ 1 lepton with p_T > 55 GeV





≥ 2 jets with p_T > 185 (50) GeV

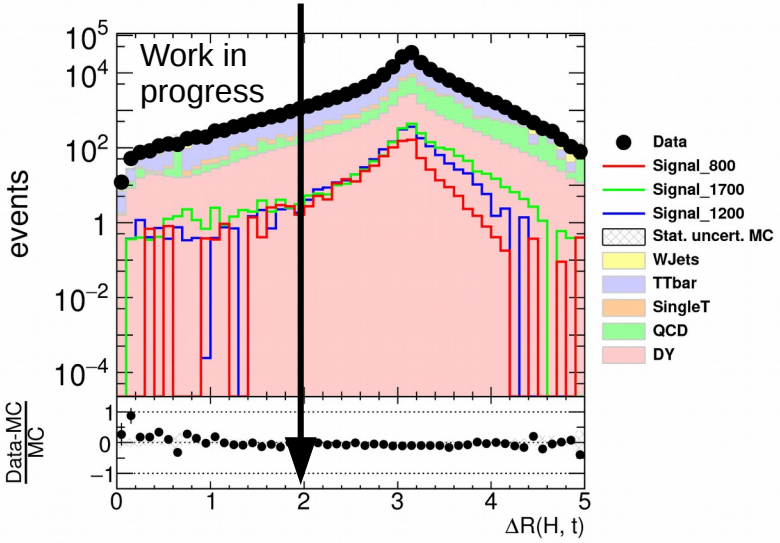


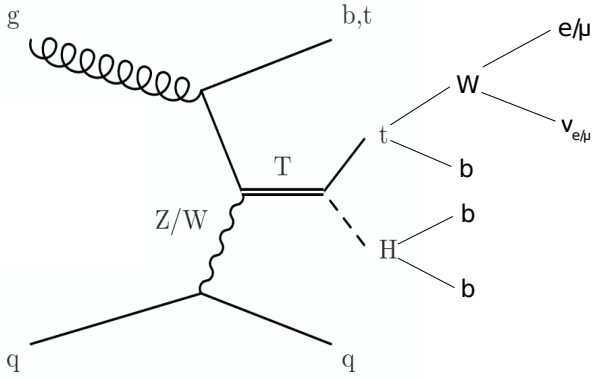


Baseline Selection

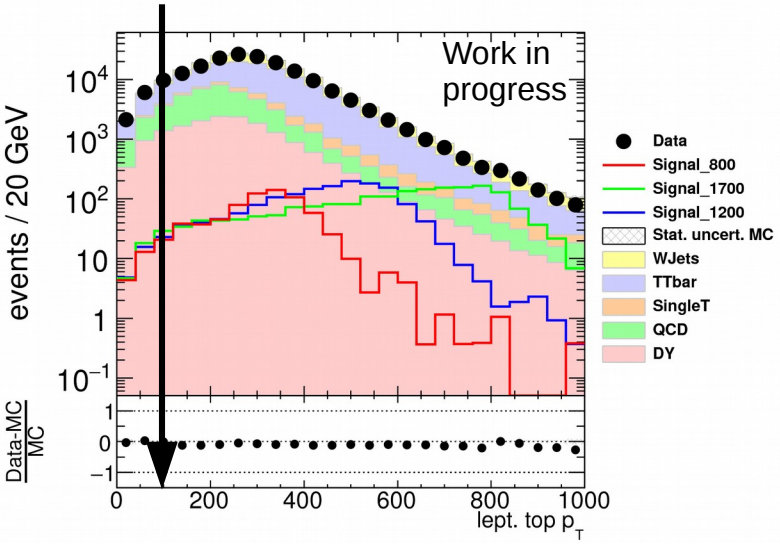
≥ 1 Higgs candidate

ΔR(top candidate, Higgs candidate > 2)



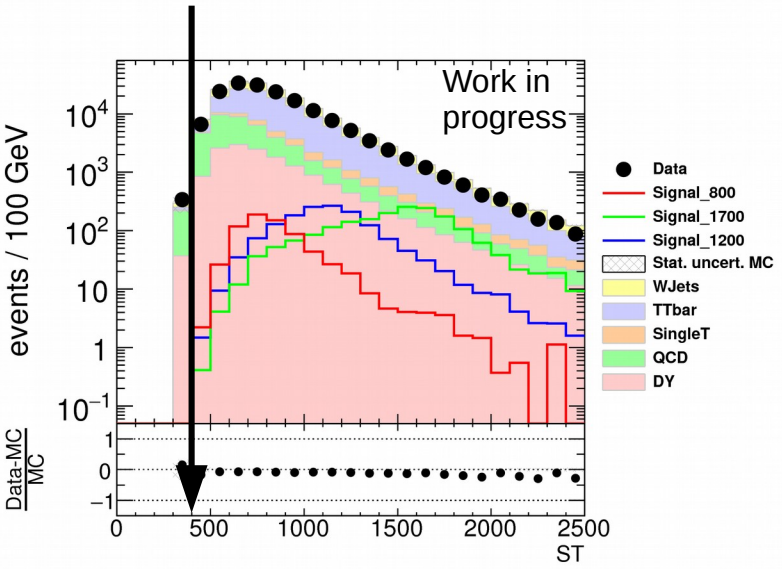


$p_{T,\text{top candidate}}$ > 100 GeV

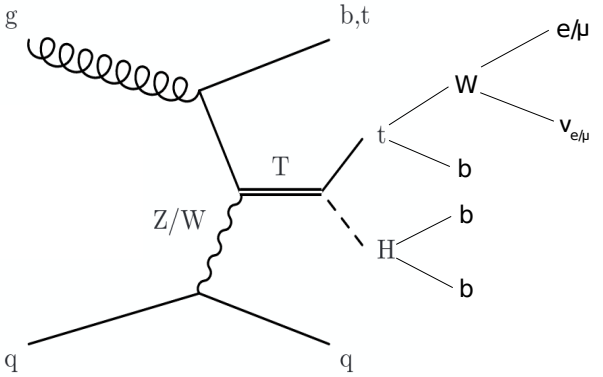


Baseline Selection

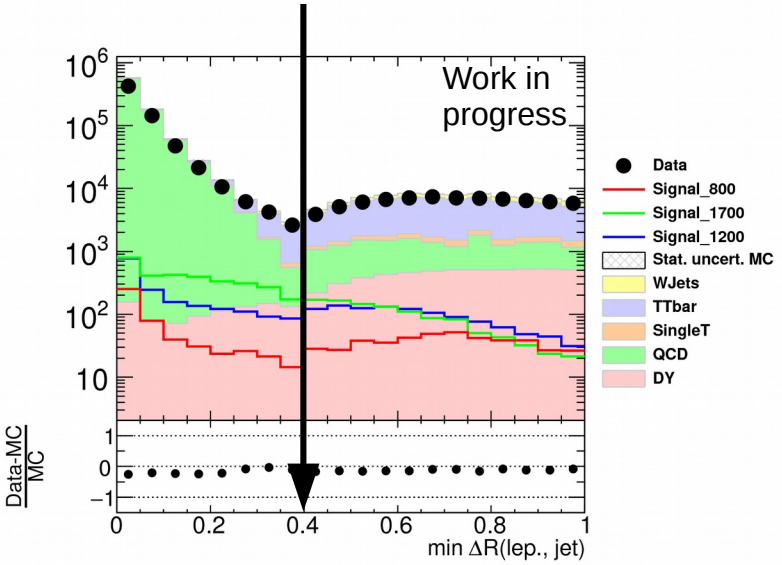
ST > 400 GeV

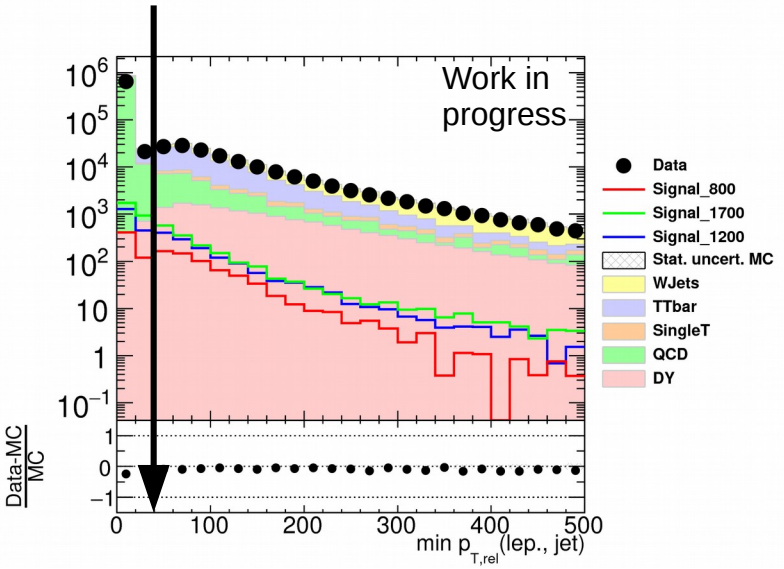


ST =
p_T of lepton with highest p_T
+ MET
+p_T of $jets_{>30GeV}$



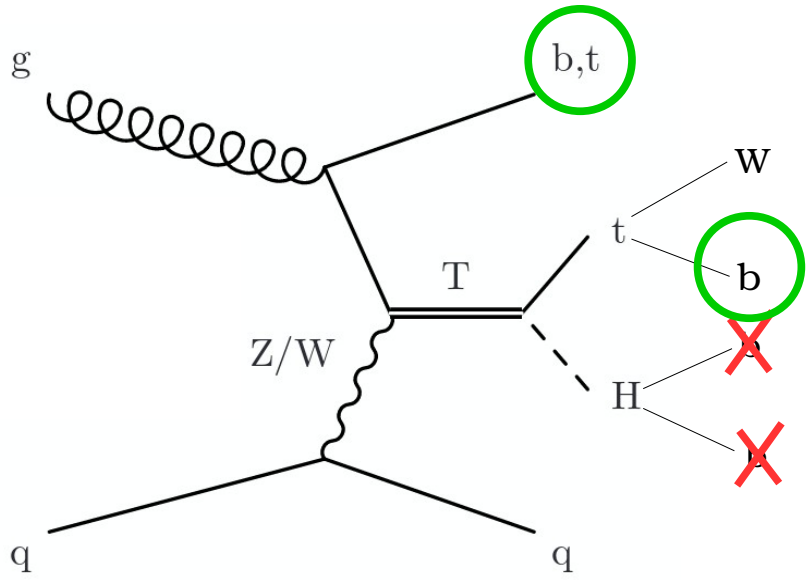
2D cut ($\Delta R(l,j) > 0.4$ || $p_T^{rel}(l,j) > 40$ GeV)





Categories

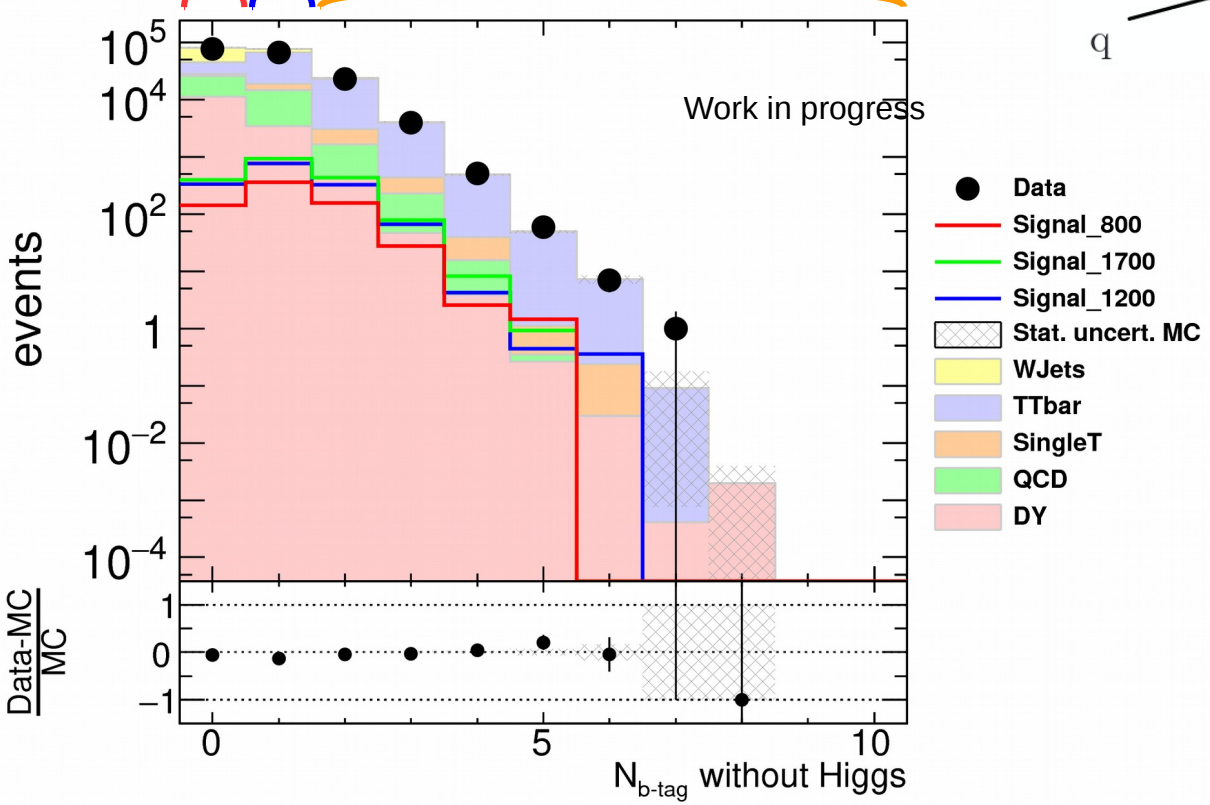
Additional b-tags



0 add. b-tags

1 add. b-tags

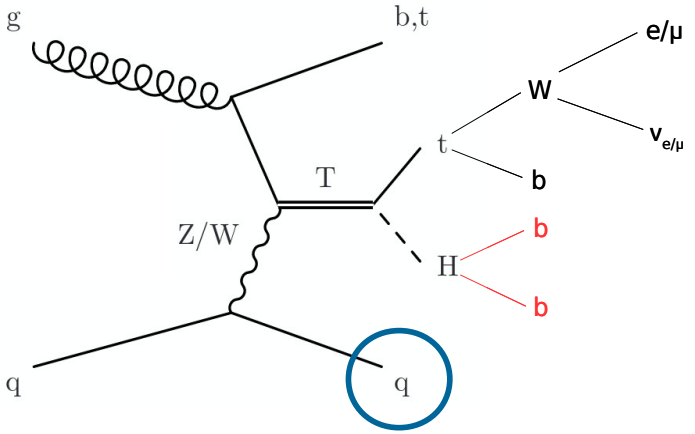
≥ 2 add. b-tags

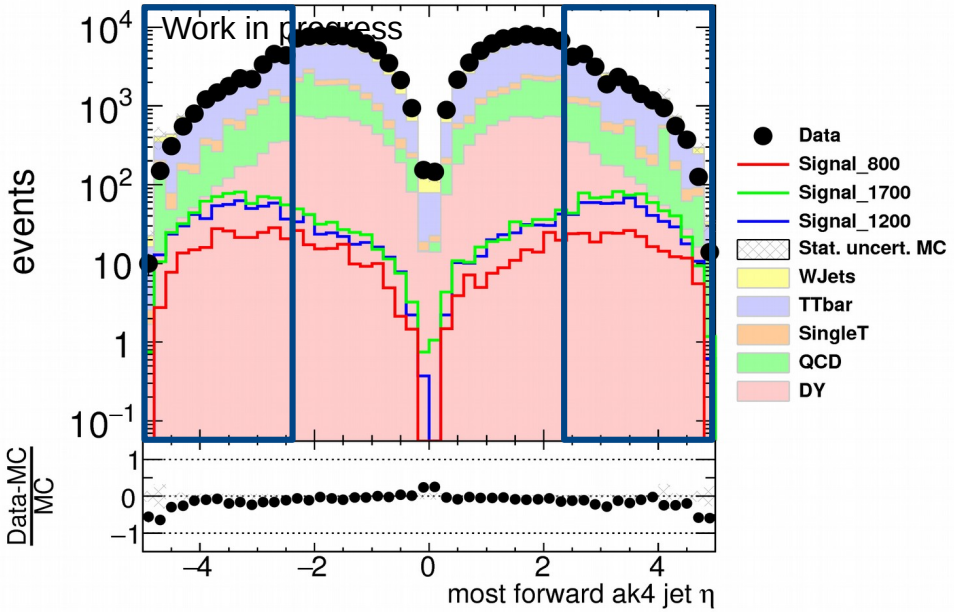


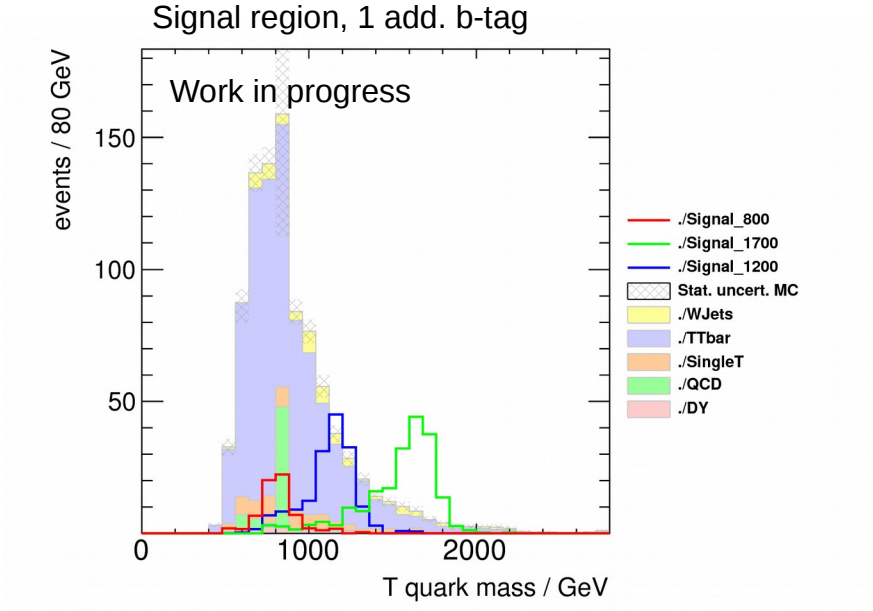
b-tags from Higgs decay are used for definition of Sideband and Signal region

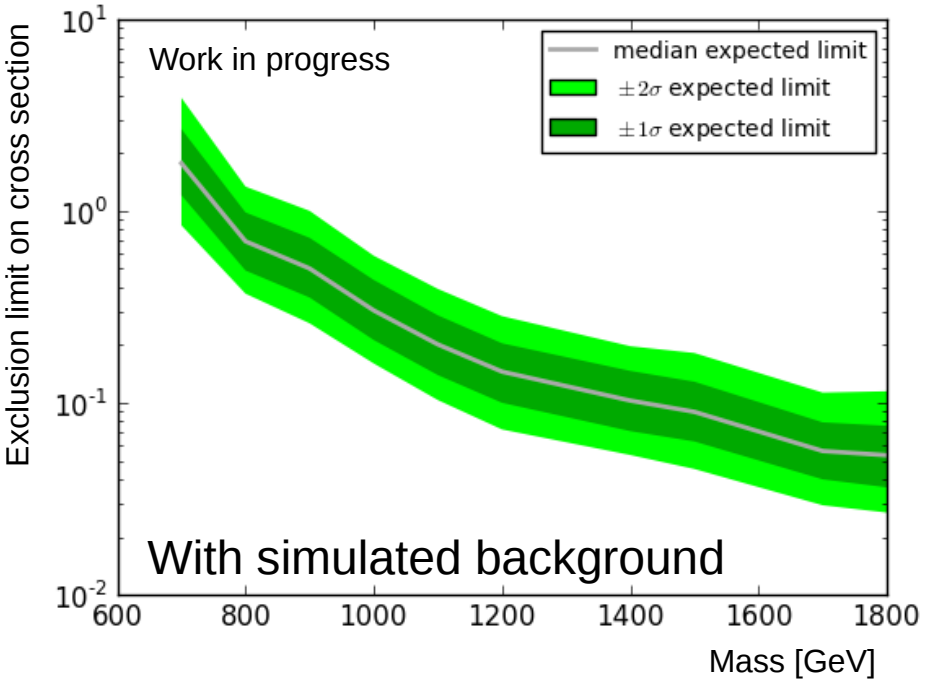
Signal and Sideband region

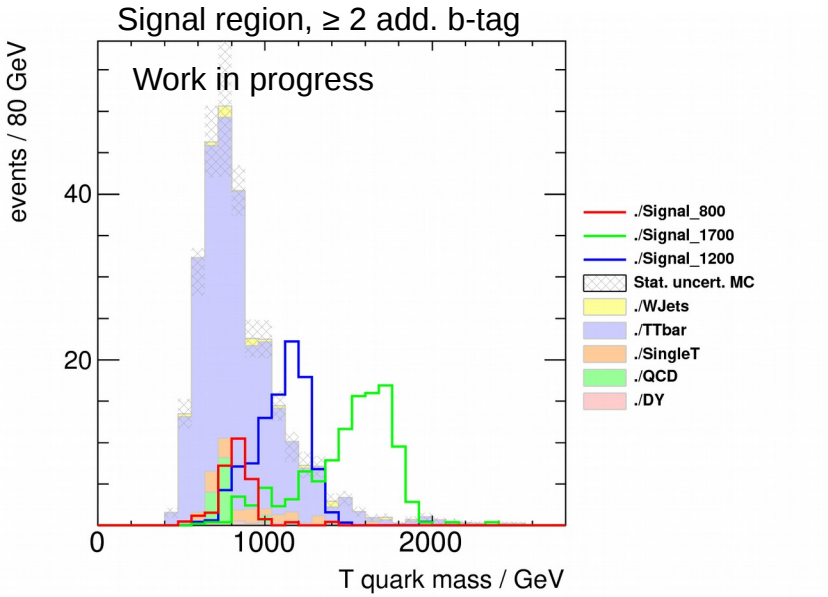
	1 subjet b-tag	2 subjet b-tags
0 forward jets	Sideband region	
≥ 1 forward jets		Signal region











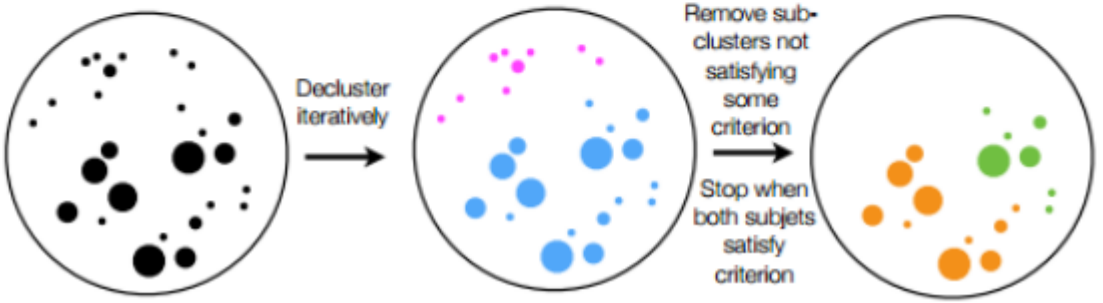
Included syst. Uncertainties:

- Pile up
- Lepton IDs
- Trigger
- Jet energy scale
- Jet energy resolution
- B-tagging
- Higgs mass smearing

Softdrop

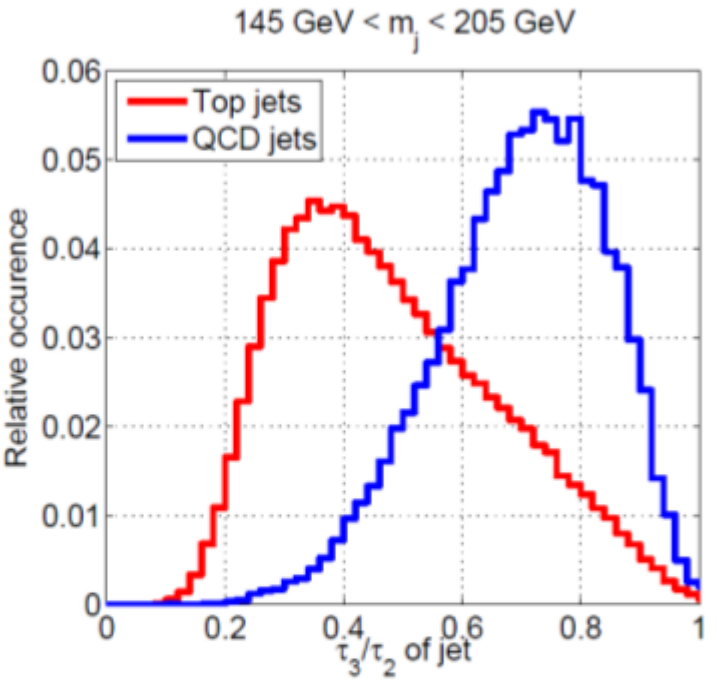
- Softdrop
  - Recursively declustering
  - Remove subjets which do not fullfill algorithm condition
    - $\frac{\min\{p_{T,i},p_{T,j}\}}{p_{T,i}+p_{T,j}} > z_{cut}\left(\frac{R_{ij}}{R}\right)^{\beta}$
  - Removes soft and wide-angle radiation

arXiv:1402.2657v2



N-subjettiness

- Shape variable
- Measures how consistent a jet is with a hypothesis of having N subjets
- $\tau_N = \frac{\sum_{i=1}^{n_{consistuents}} p_{T,i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i}\}}{\sum_{i}^{n_{consistuents}} p_{T,i} R}$
- τ_N is the p_T weighted sum of the angular seperation between each jet consistuent and the closest subjet axis
- Small τ_N represent jets with N or fewer jets → consistuents are closely aligned with the subjet axis
- More effective discriminator → ratio of jet shapes
  - Topjet is expected to have 3 subjets → τ_3/τ_2



arXiv:1011.2268v2