New results from searches with highly boosted Top Quarks

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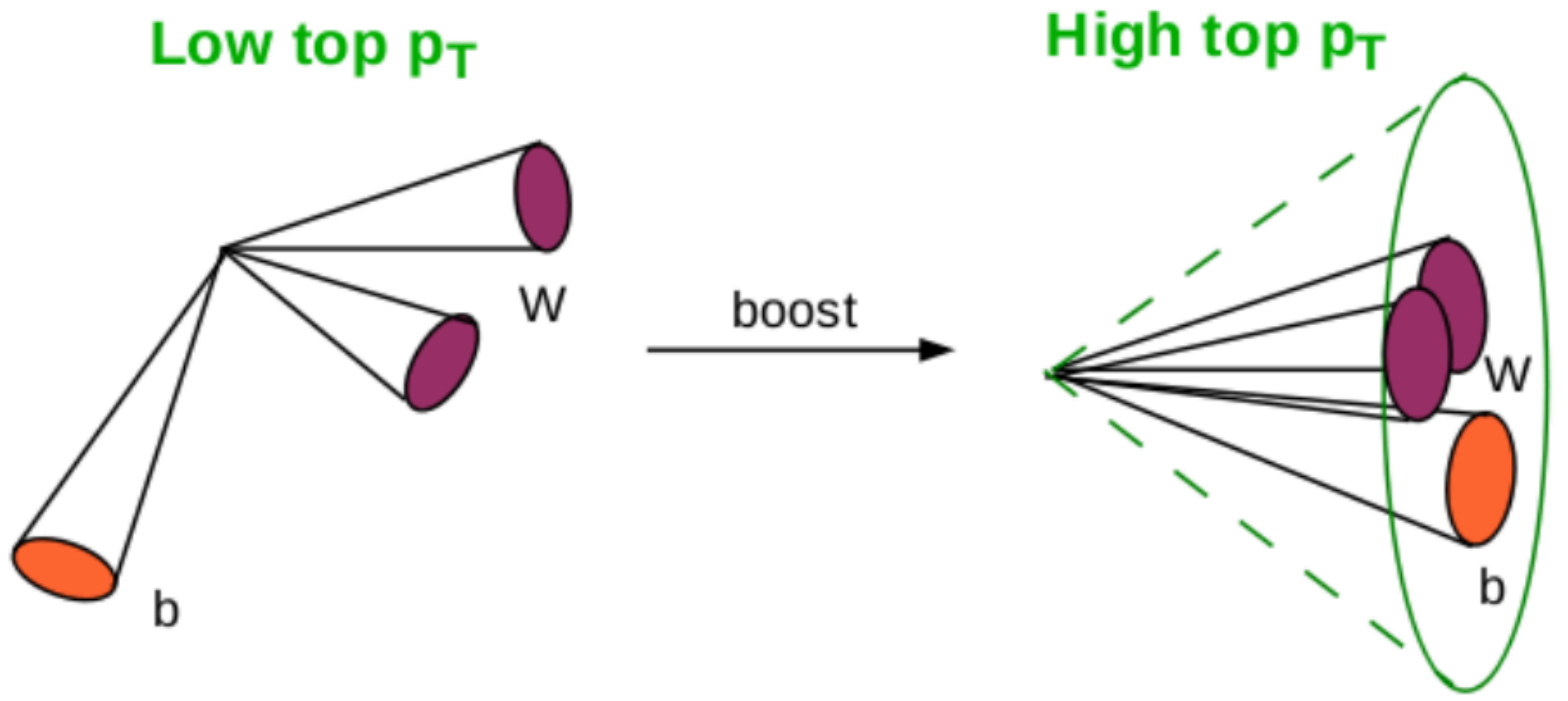
On behalf of the ATLAS and CMS Collaboration

TOP 2020



Why boosted top quarks?

- Top quark is the **most massive fundamental particle** —> role in **EWK symmetry breaking**

- Yukawa coupling ~1; top quark loops contributing to the correction of vacuum expectation of Higgs field.

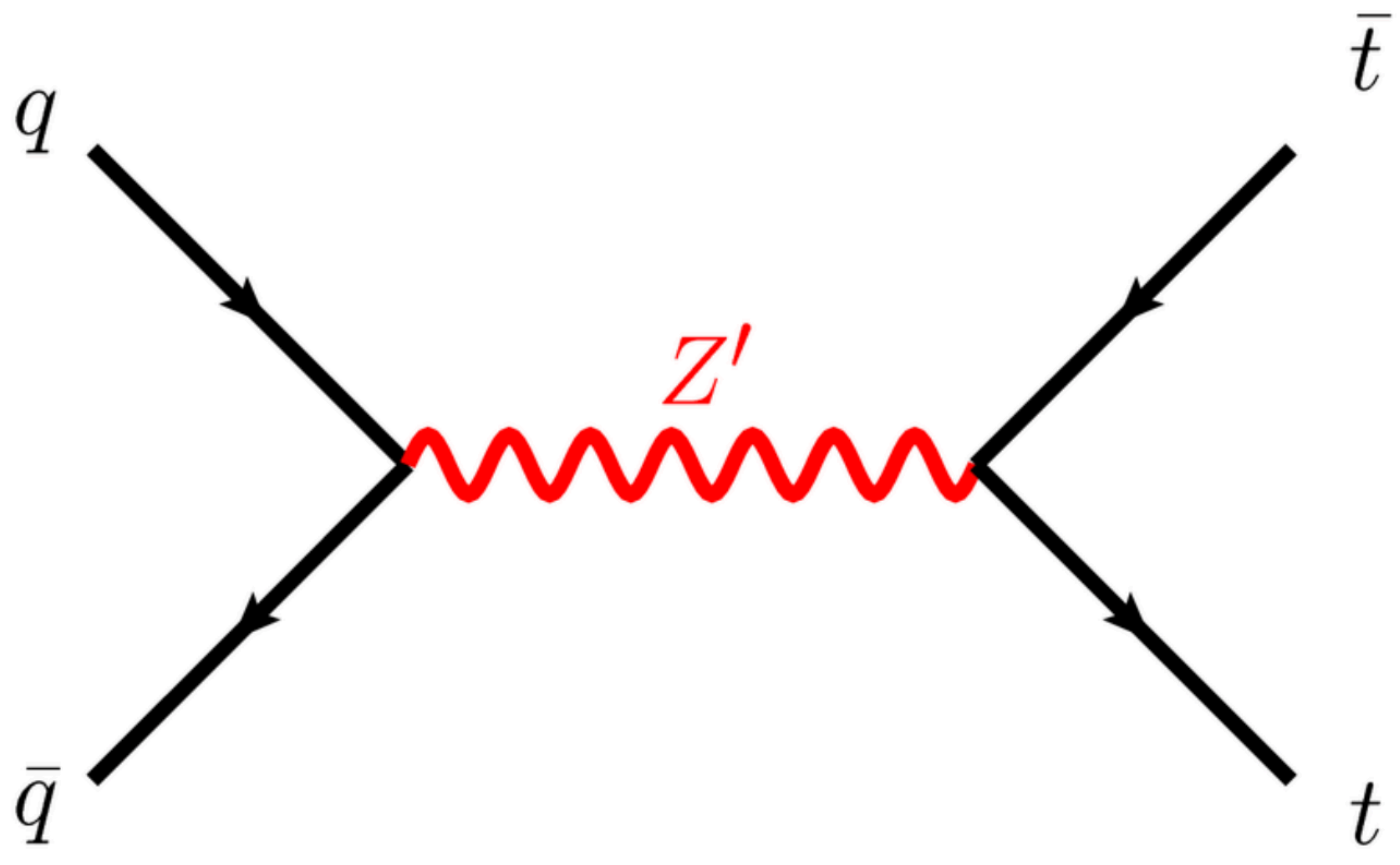
- Many theories beyond the SM predict heavy particles with masses in ~TeV scale—> ***high Lorentz factor*** and decaying to highly boosted particles.

- Boosted top quarks yield partially or fully merged collimated decay products. Angular distance between partons is smaller than the jet clustering distance parameter

  - *Hadronic decay*: Three quarks may be reconstructed as one fat jet

  - *Leptonic decay*: Lepton may appear as non-isolated (too close to b quark)

Search for resonant $t\bar{t}$ production in p-p collisions at $\sqrt{s}$=13 TeV



- Model independent search of Z'—> $t\bar{t}$.
- Search covers all three channels, depending on the decay of the W boson from the top quark:
  - Semileptonic, dileptonic and all hadronic
- Resonances decaying to $t\bar{t}$ can be found in:
  - leptophobic topcolor Z'
  - Randall-Sundrum: Kaluza-Klein excitations of g_{KK} and G_{KK}

https://link.springer.com/article/10.1007/JHEP04(2019)031

Semileptonic channel and background estimation

- **Top Tagging** used to identify boosted top quark using jet substructure variables: *N-subjettiness (τ_N)* and *soft drop mass*

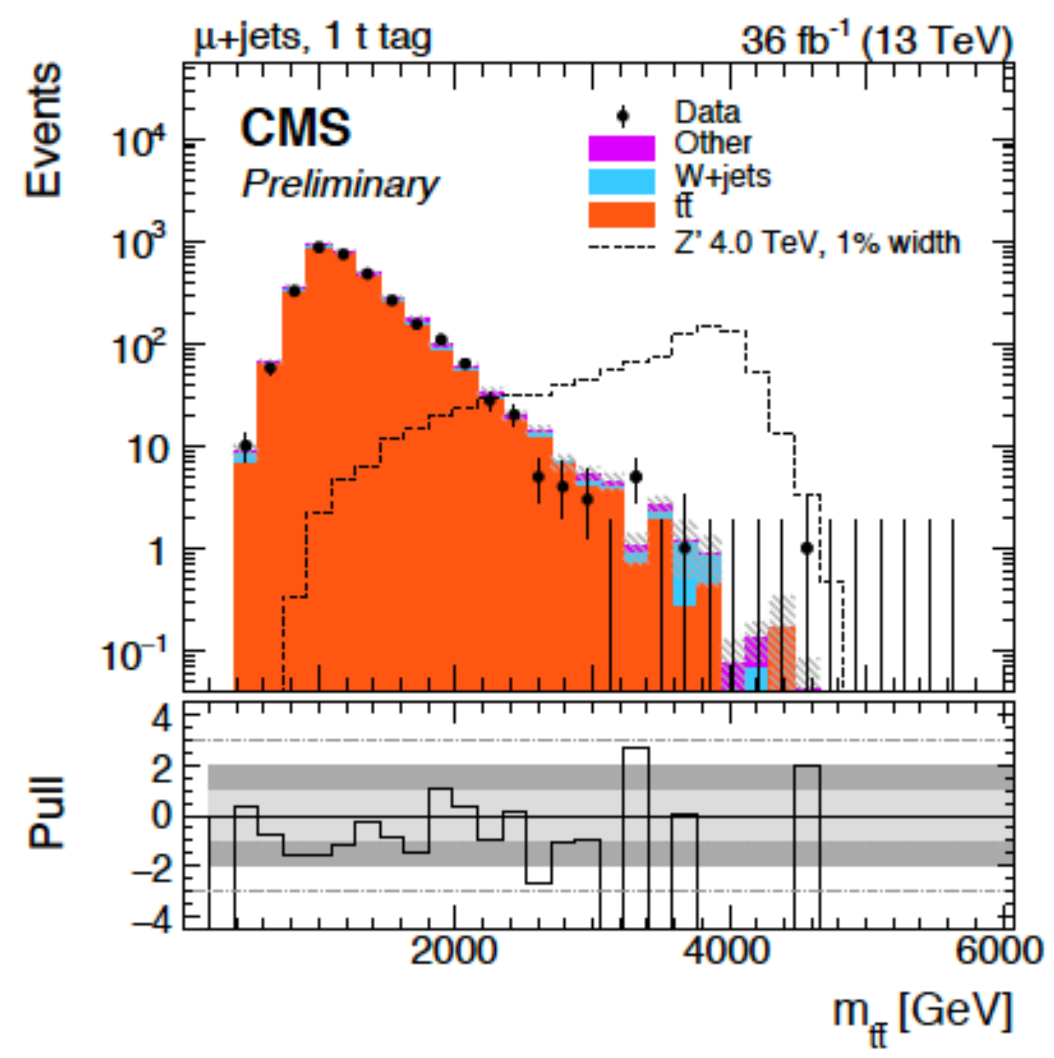
- **$M_{t\bar{t}}$ reconstructed** with the four vectors of the final state; assigning leptonic or hadronic legs.

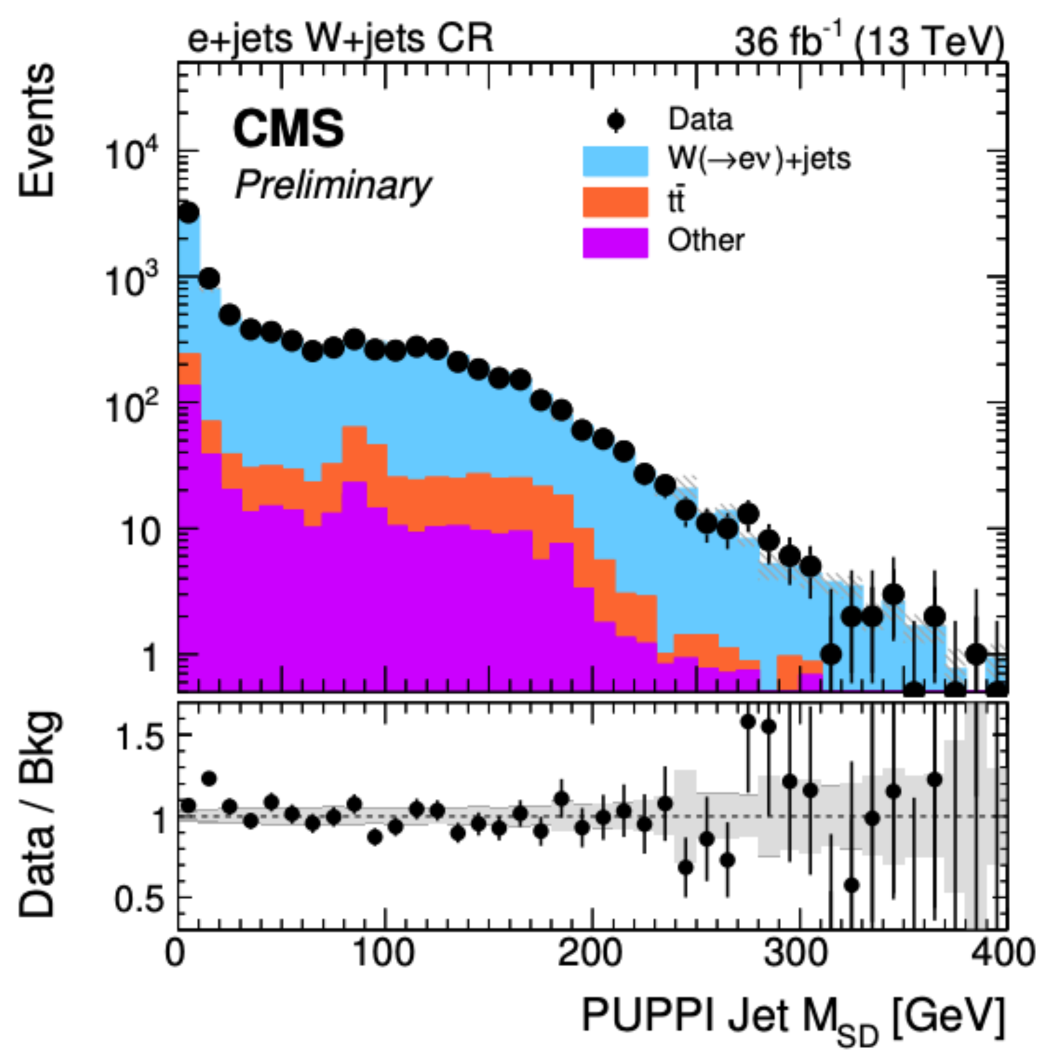
$$\chi^2 = [\frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}}]^2 + [\frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}}]^2$$

- SM backgrounds normalization obtained from **simultaneous binned likelihood fit** to:
  - $M_{t\bar{t}}$ (semi-leptonic & hadronic)
  - S_T (dileptonic channel). $S_T = \sum_{i=1}^{Njet} p_{T\,i} + \sum_{i=1}^{2} p_{T\,i} + \vec{p}_{p_T}^{\,miss}$

Semileptonic

- **SM $t\bar{t}$** -largest irreducible bkg
  - **0 top tag SR** to estimate $t\bar{t}$
  - **1 top tag SR** to get signal rich area.
- **W+jets,** largest reducible bkg - suppressed by **BDT**

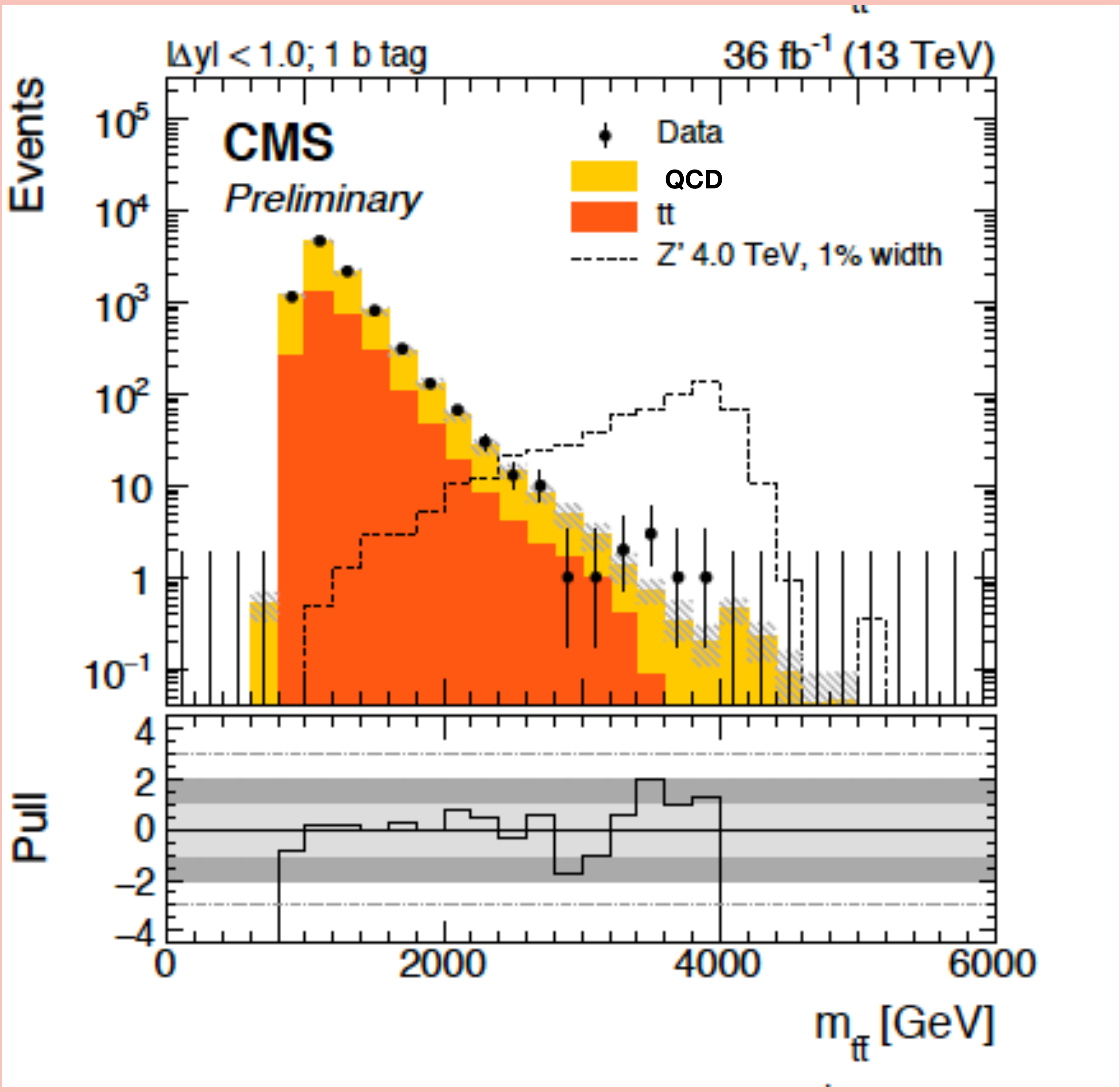




Hadronic and Dileptonic channels in Z'-> $t\bar{t}$

Hadronic

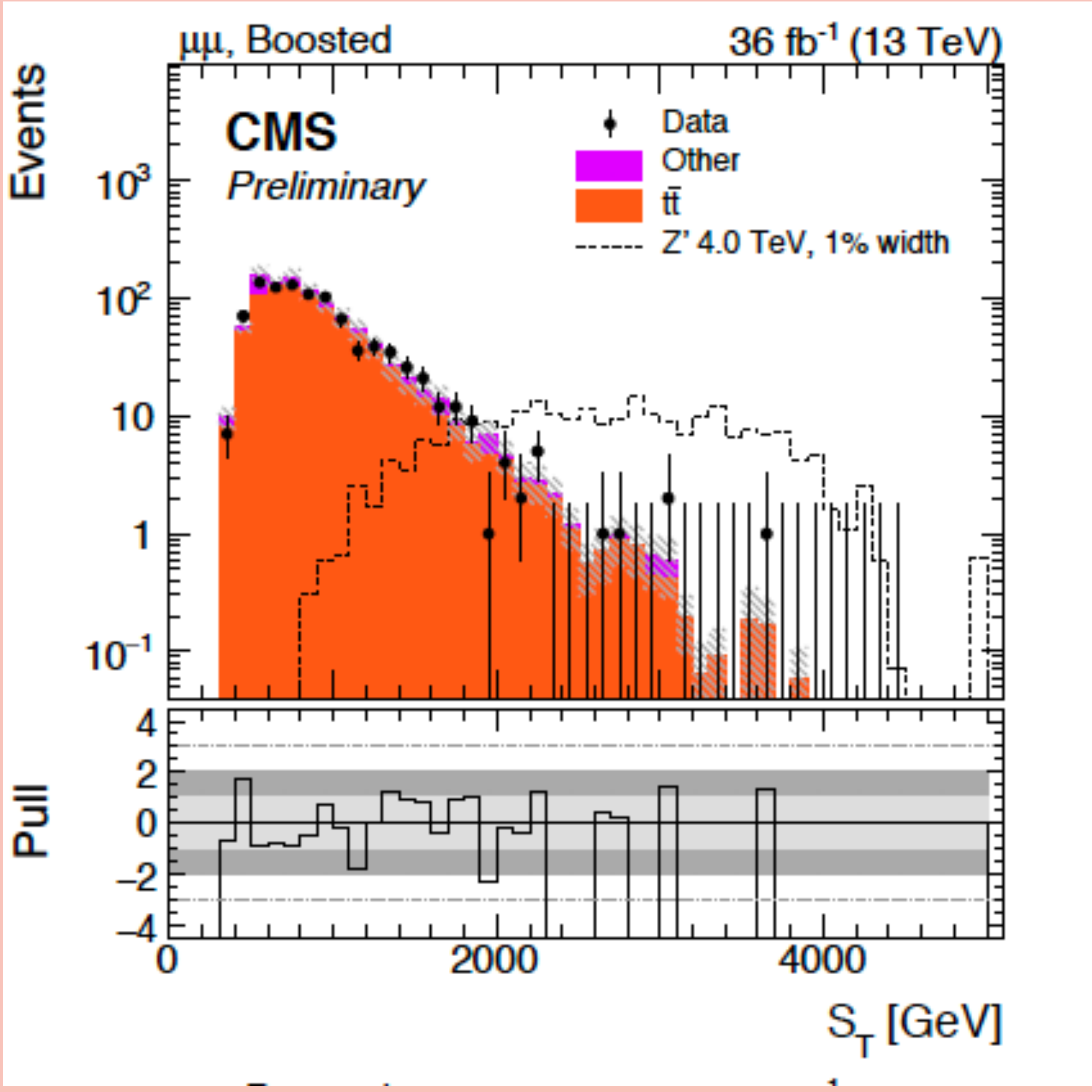
- **QCD and SM $t\bar{t}$** are the dominant bkgs.
- QCD estimated by data-driven methods and reduced by b-tagging.

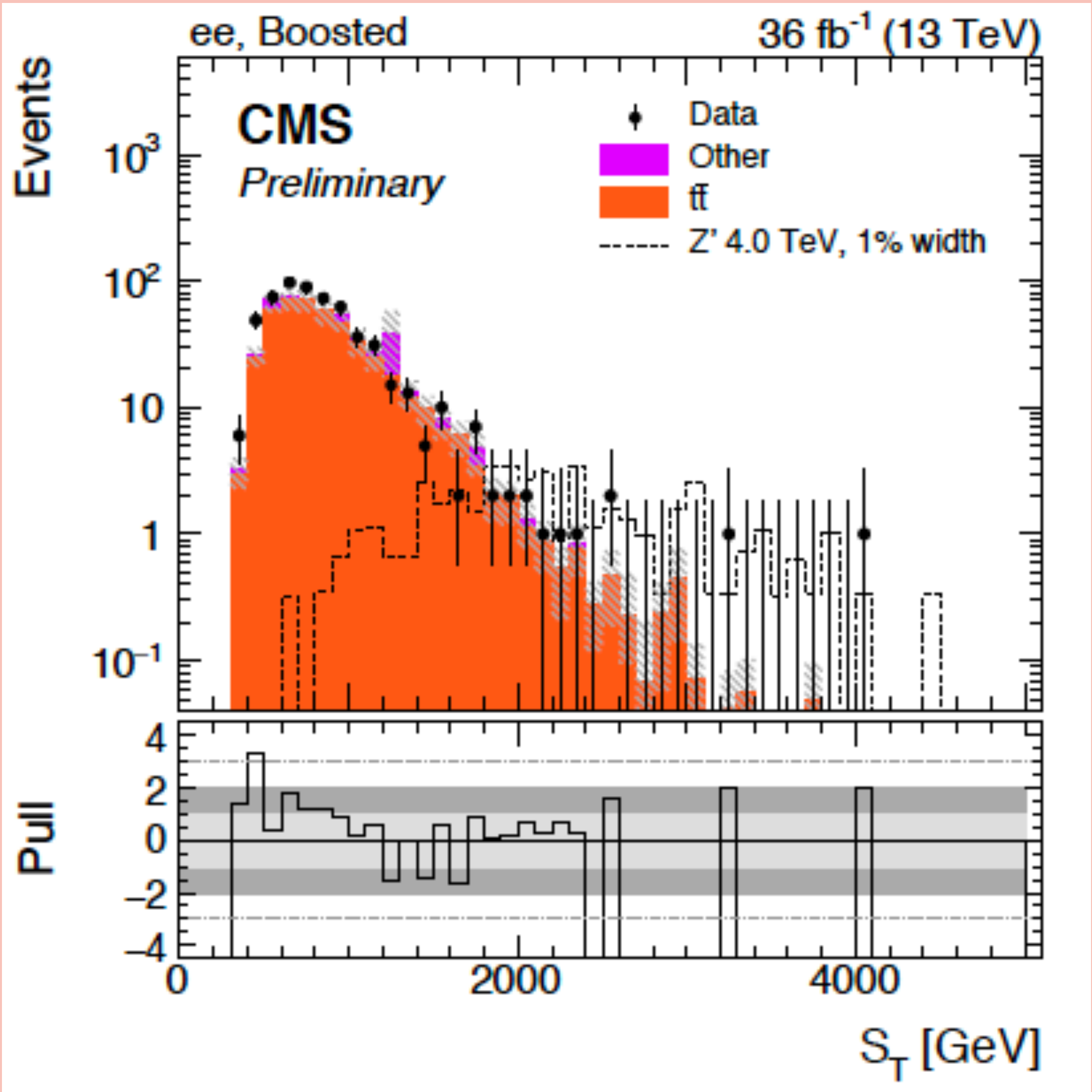


Dileptonic

- **SM $t\bar{t}$** forms the dominant irreducible bkg
- **6 SRs and 3 CRs** are formed to categorize signal and bkg **based on ΔR_{sum}**

$$\Delta R_{sum} = \Delta R_{min}(lepton_1, jet) + \Delta R_{min}(lepton_2, jet)$$





$$S_T = \sum_{i=1}^{Njet} p_{T\,i} + \sum_{i=1}^{2} p_{T\,i} + \vec{p}_{p_T}^{\,miss}$$

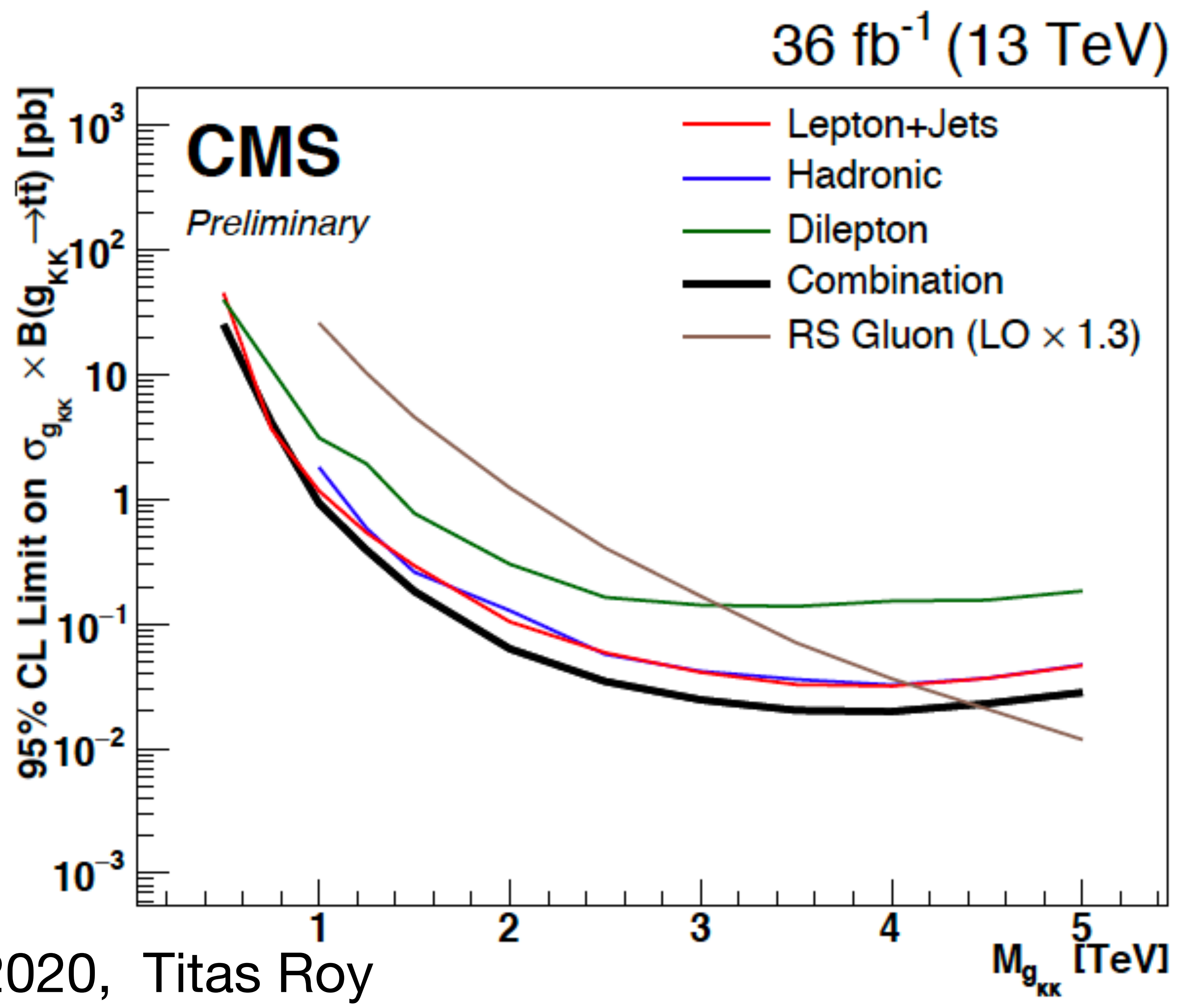
Results

- BSM models considered: topcolor Z' bosons of width-mass ratio of 1%, 10% , 30% & g_{kk}.

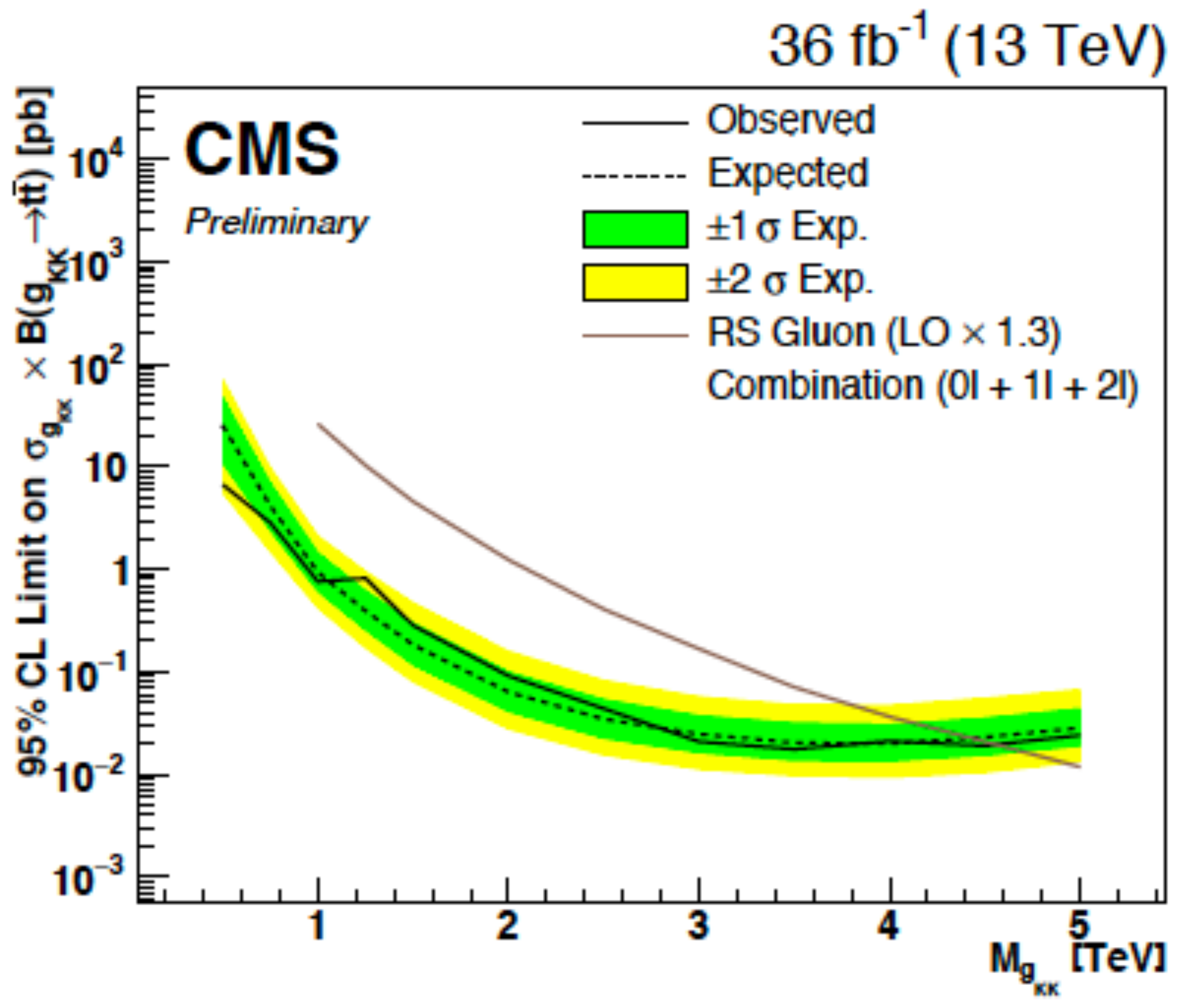
- No signal observed, limits at 95% CL are calculated for the production cross-section of spin 1 resonance.

- Mass ranges excluded in cases of Z' search are now 0.5-3.8 TeV (1%), 0.5-5.0 TeV (10% and 30%).

- KK excitations of gluon in RS model can be excluded between 0.5-4.55 TeV



Expected limits specifically for g_{kk} signal hypothesis as the model has features common to many hypothesis



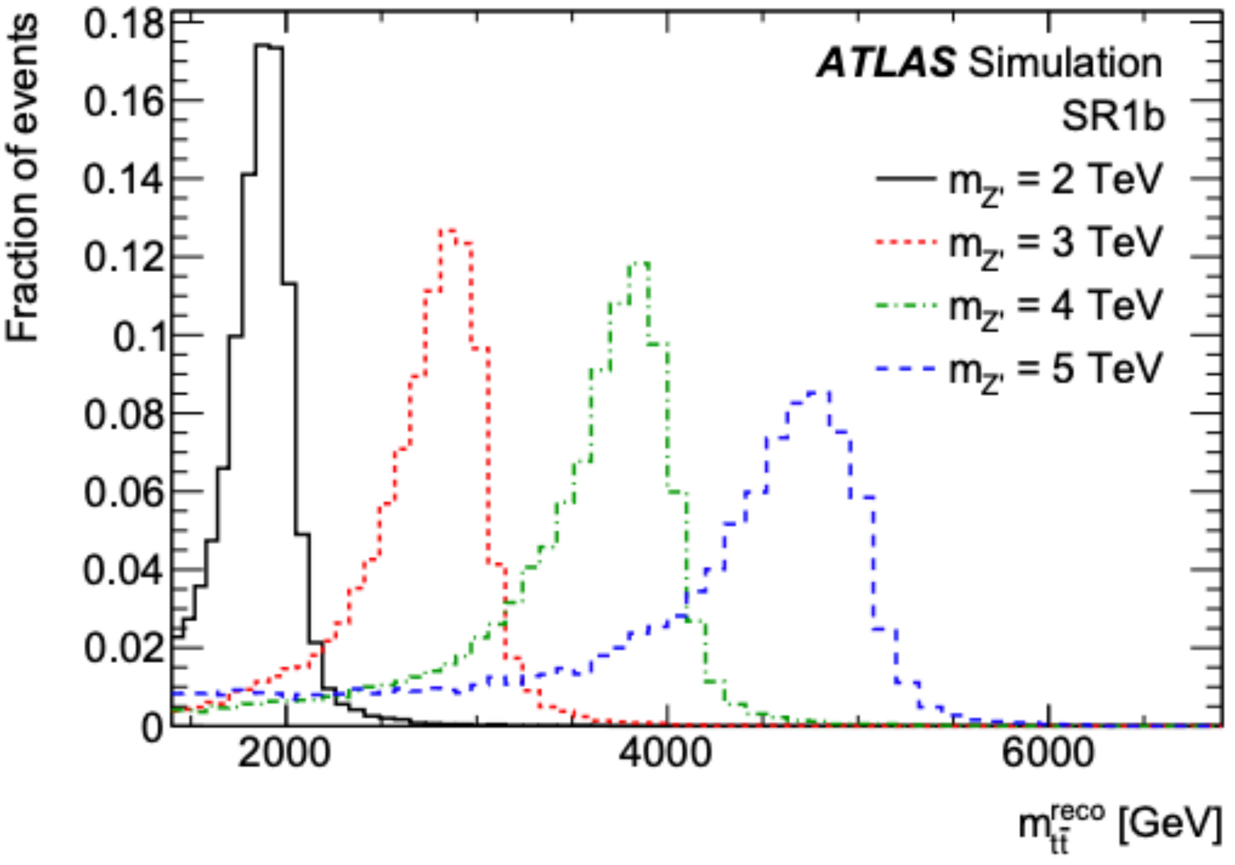
Search for $t\bar{t}$ resonances in fully hadronic final states in p p collisions at $\sqrt{s}$=13 TeV

- Search for new heavy particles decaying into top quark pairs.
- Events are selected keeping the ttbar topology and the hadronic decay in mind.
- Search focuses on resonances greater than 1.4 TeV and uses multivariate techniques with jet substructure variables to identify hadronically decaying top quarks.
- The model used to extract limits in this analysis is for leptophobic Z' boson.

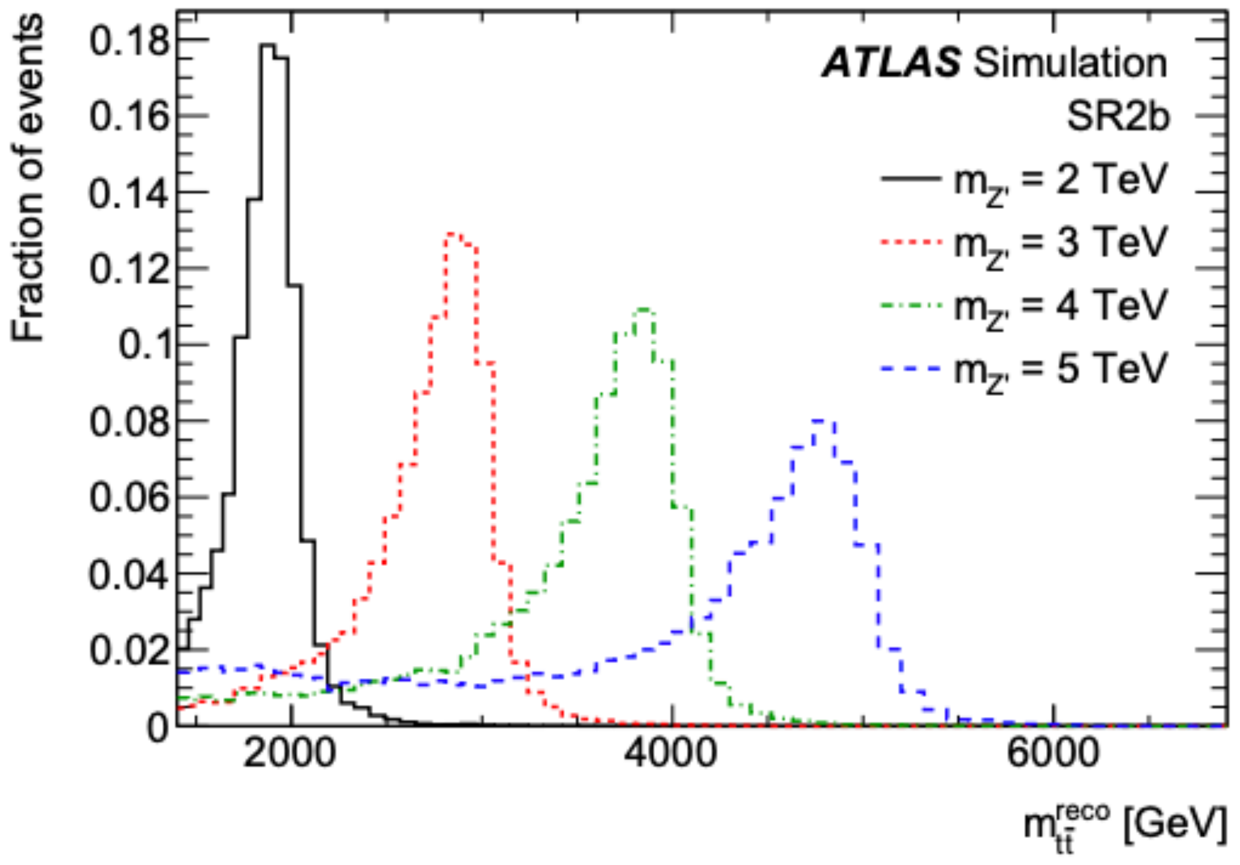
https://arxiv.org/pdf/2005.05138.pdf

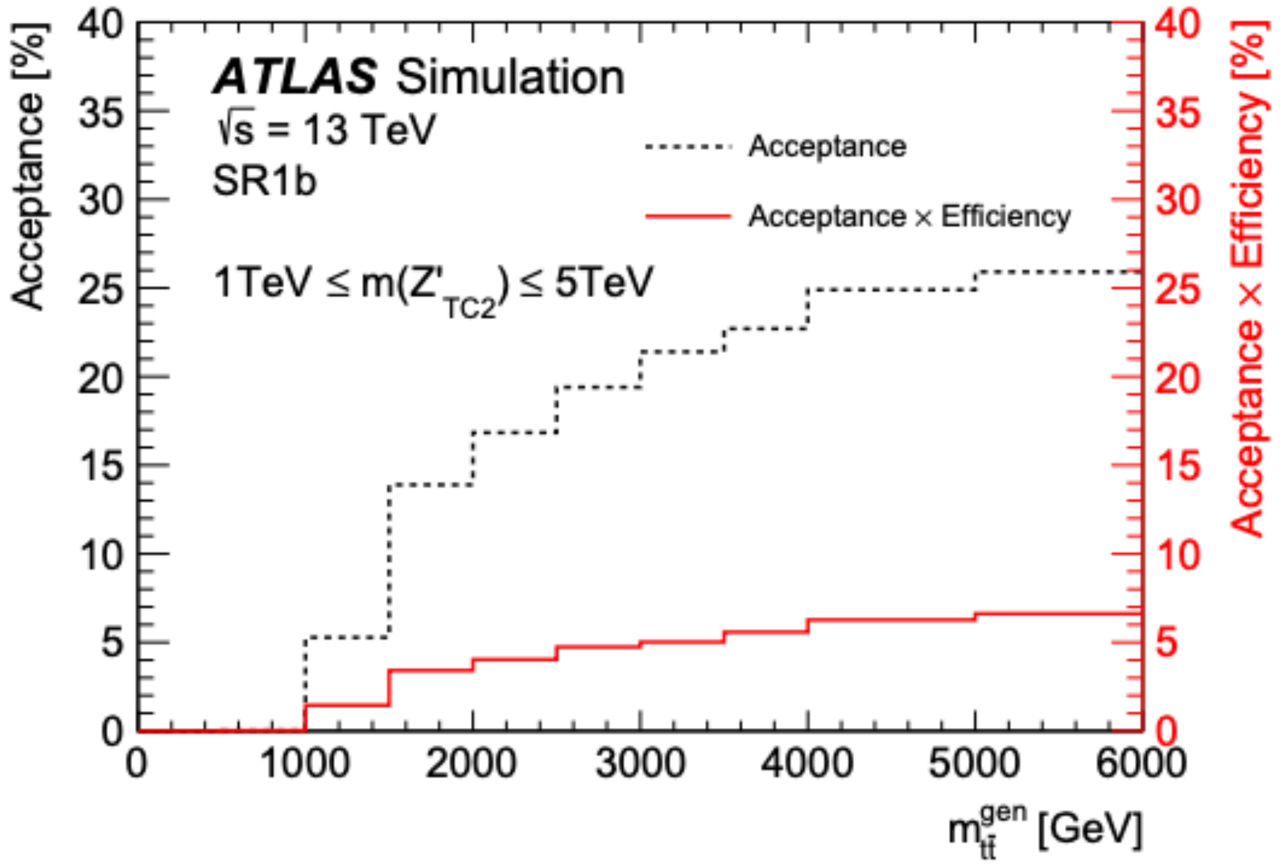
Signal Regions and background estimation

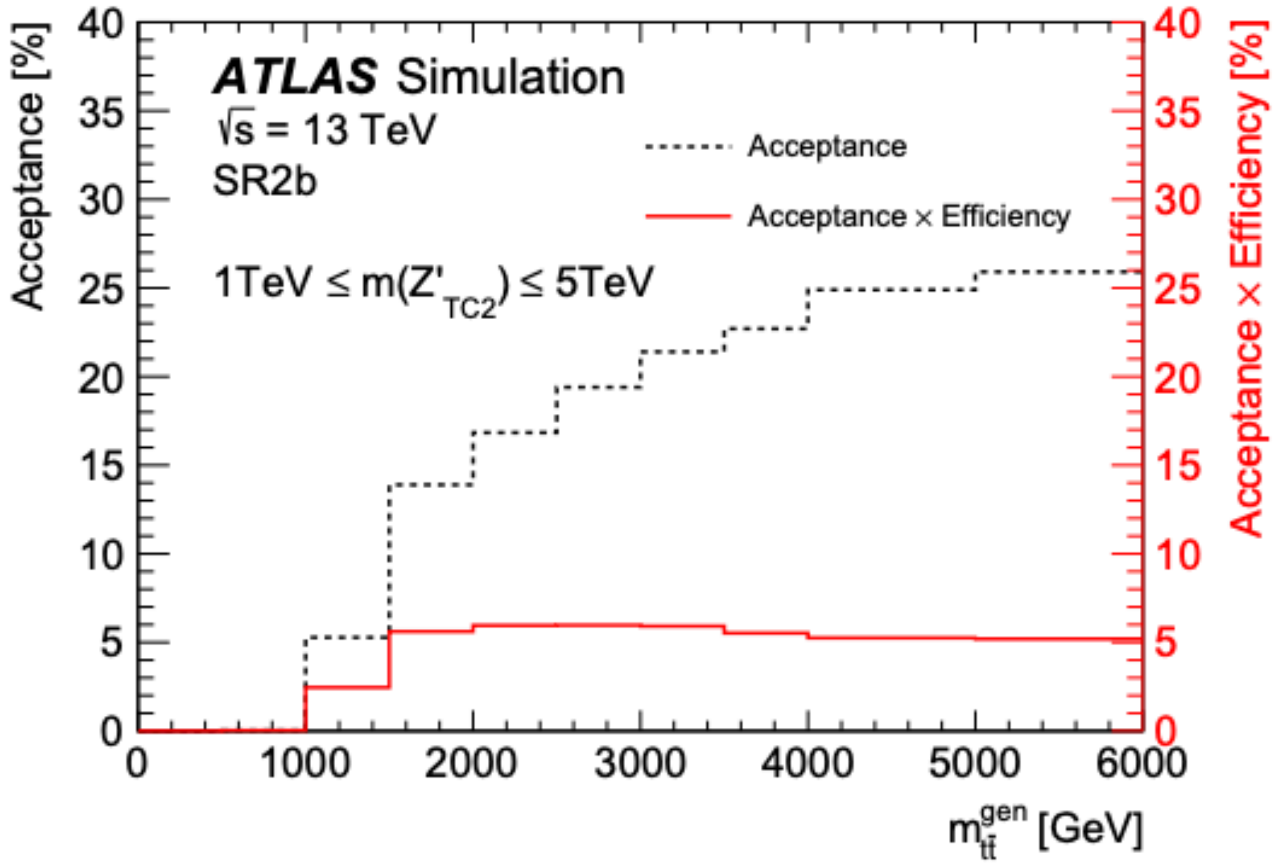
SR1b



SR2b

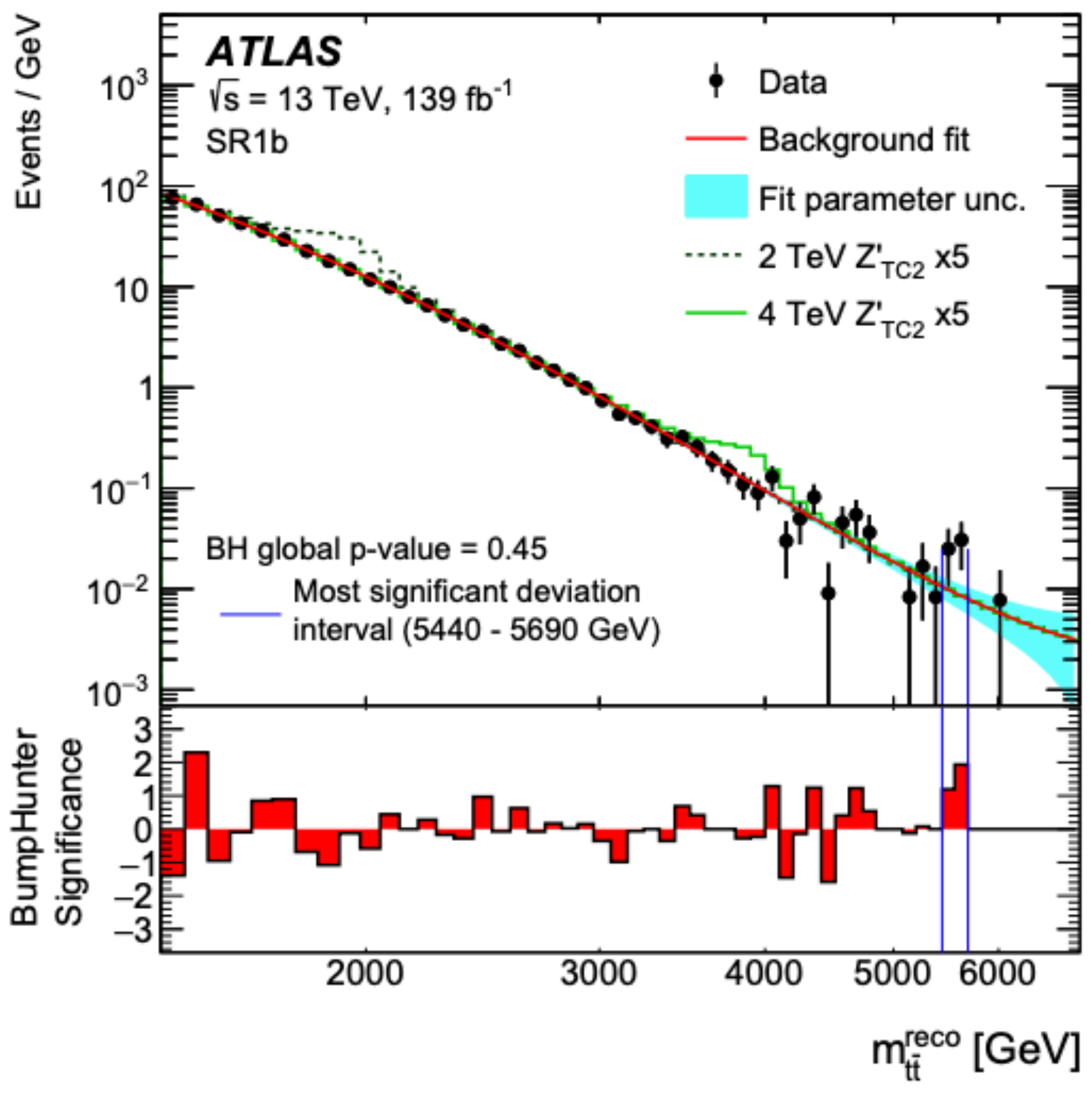


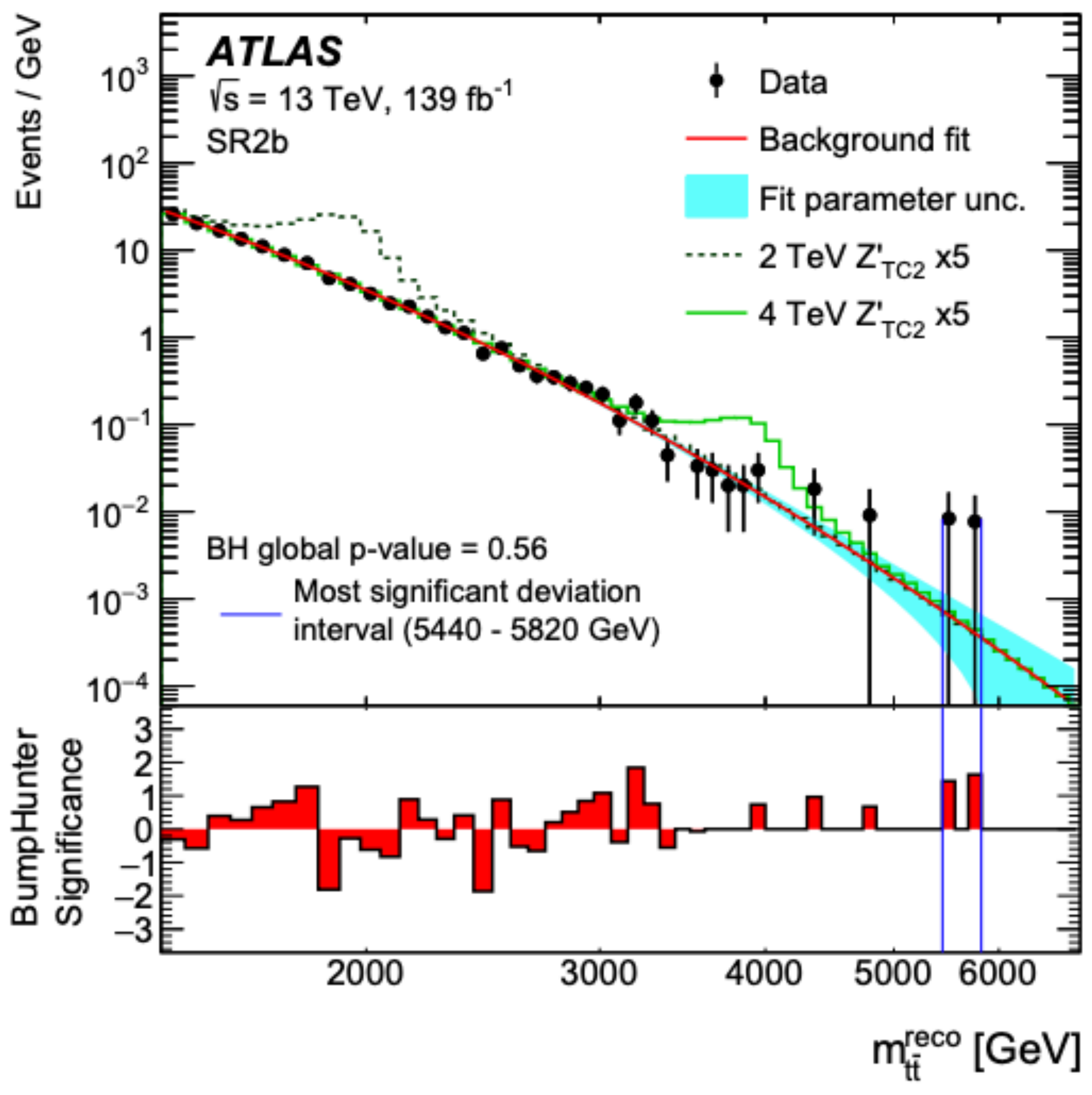


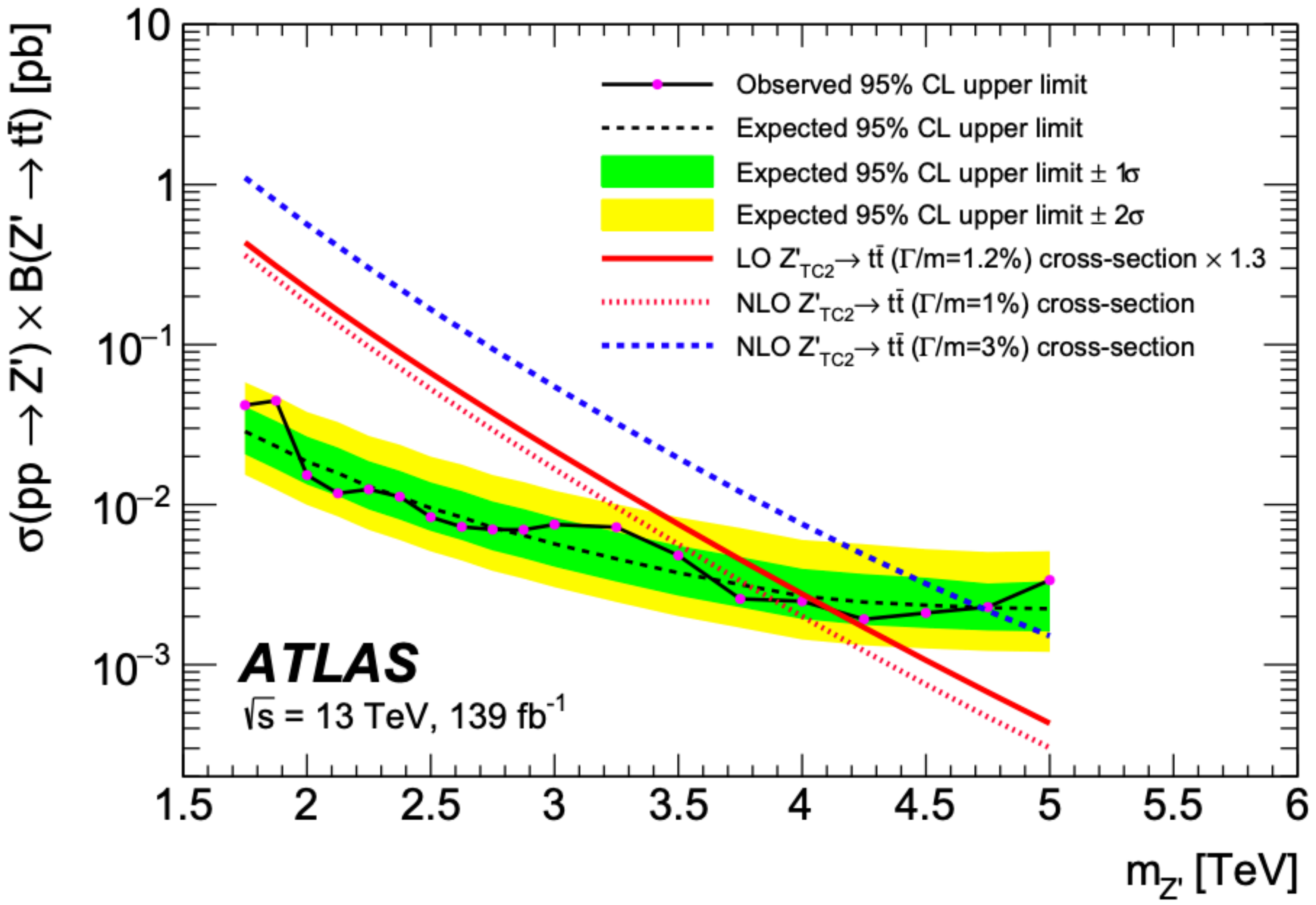


- Selected events categorized into two SRs:
  - **SR1b:** either of the two top-tagged jets associated with b-tagged jet
  - **SR2b:** both top-tagged jets associated with b-tagged jet.
- Main backgrounds: **$t\bar{t}$ and multijet events**.
  - $t\bar{t}$ estimated from data by a fit with a smoothly falling spectrum.
  - Multijet estimated by data dedicated CRs & on whether the large jets pass or fail top and/or b-tag requirements.

Results





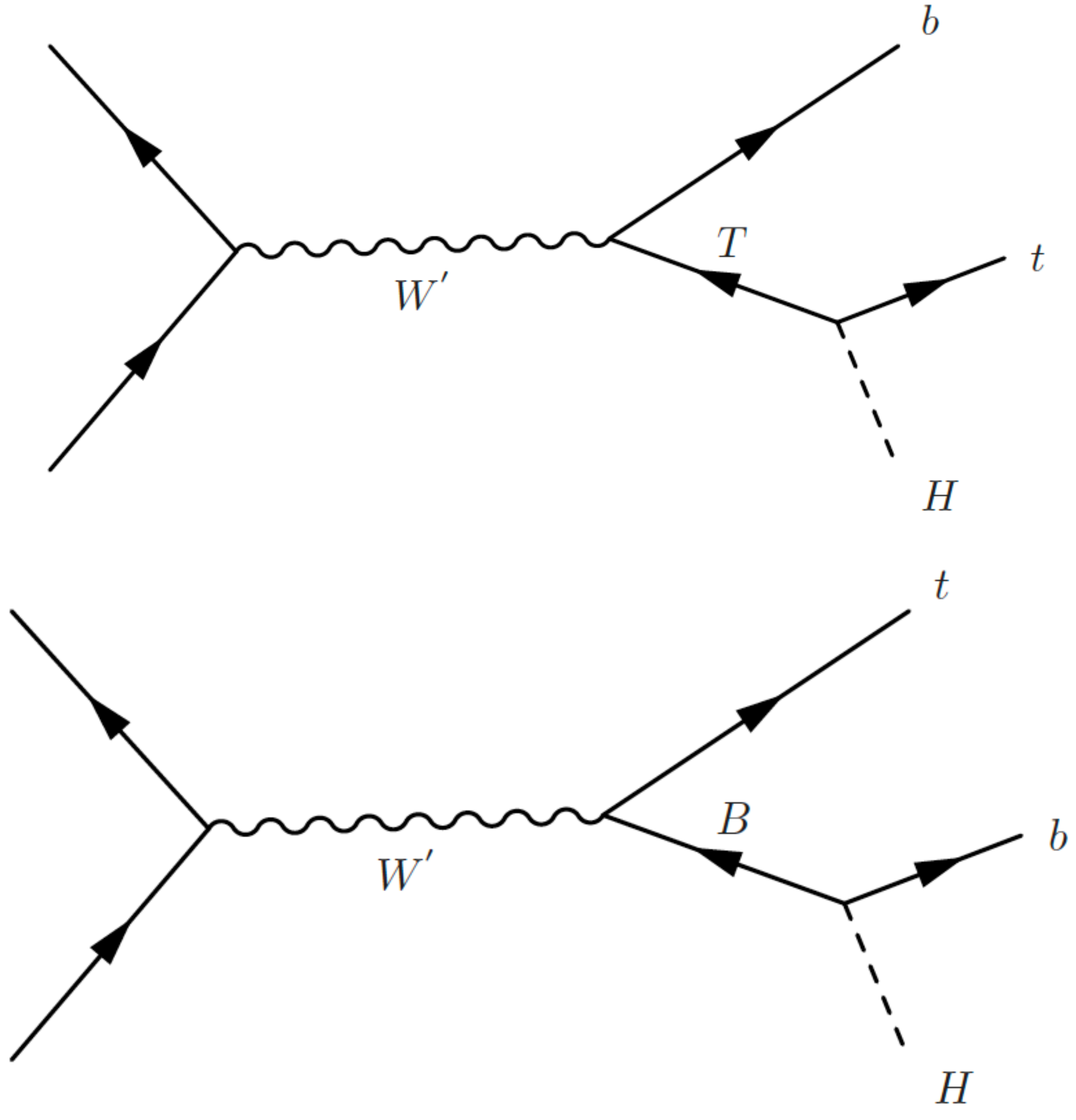


- Fits in the two SRs.
- The BumpHunter[1] tests for compatibility of data, show that the fit describes the data well for both regions.

- Z’ masses 3.9 and 4.7 TeV are excluded for decay widths of 1% and 3% respectively.

[1]arXiv: 1101.0390 [physics.data-an].

Search for a W’ boson decaying to a vector-like quark and a top or bottom quark in the all jets final state

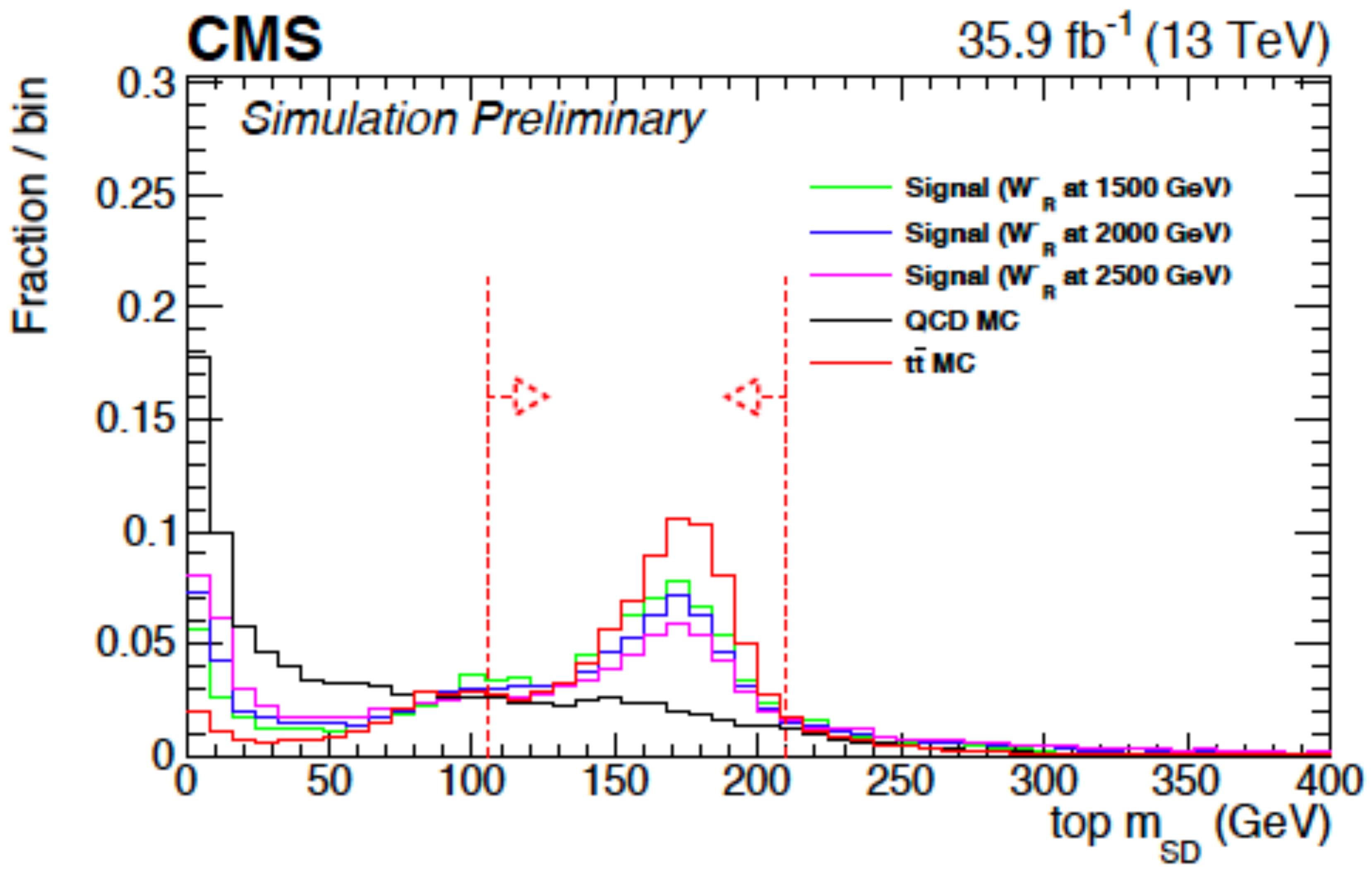


- Heavy W’ —> highly boosted b, t & H
- H and t decay hadronically.
- Assumes equal branching fraction between tB & bT; 50% for each VLQ to qH.

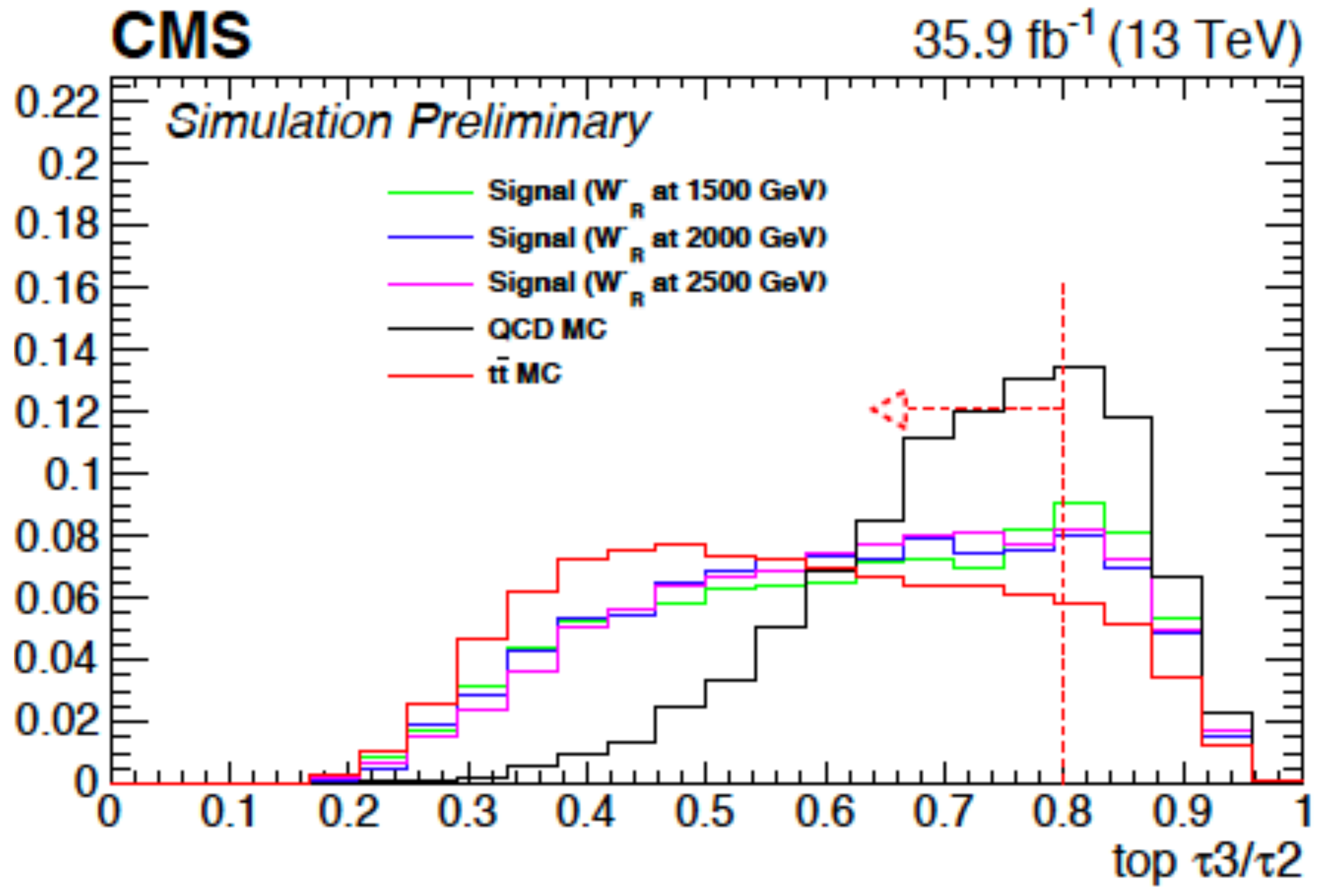
https://link.springer.com/article/10.1007%2FJHEP03%282019%29127

Top Tagging and Higgs Tagging

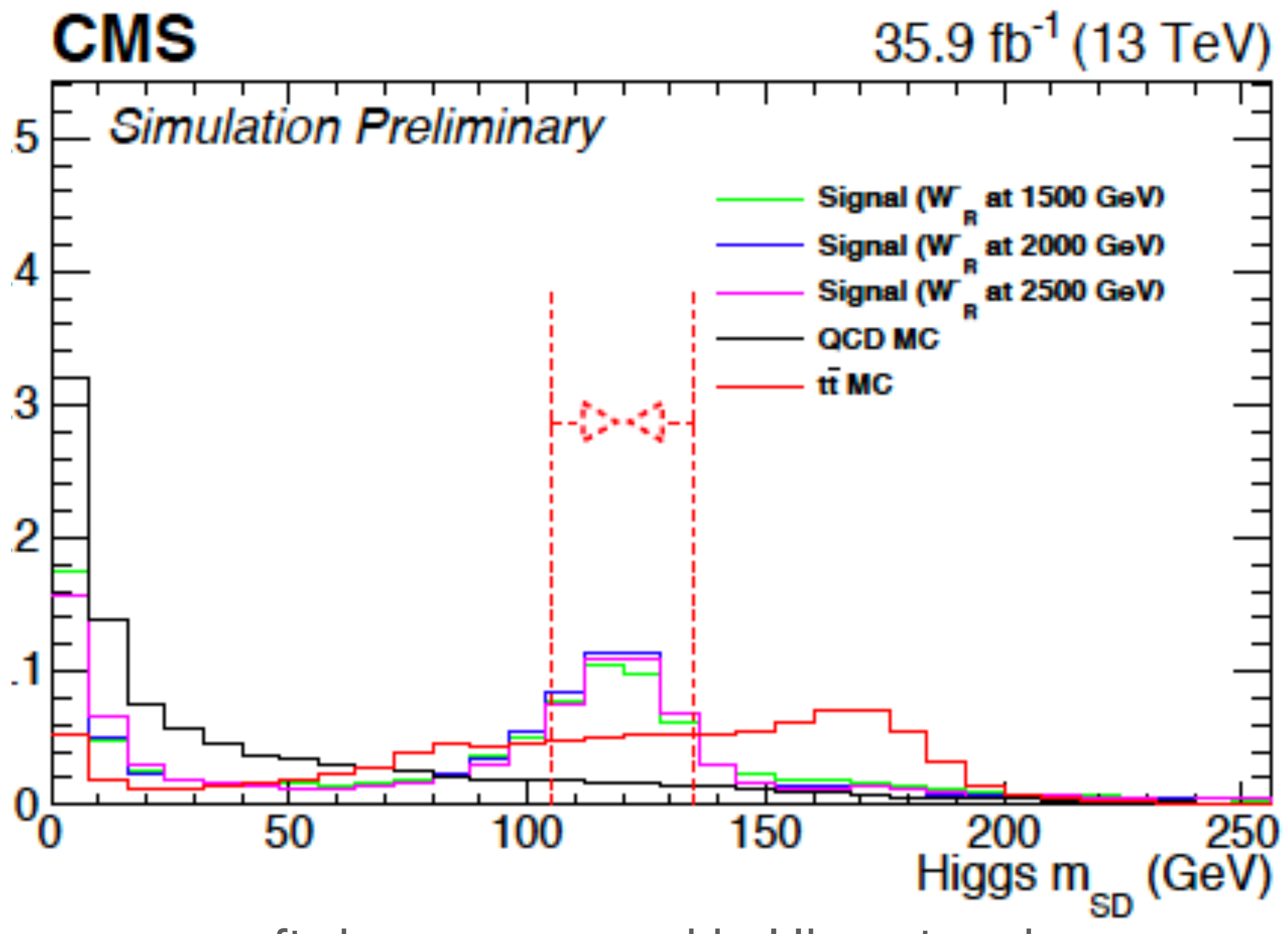
- *Top tagging* used to discriminate a boosted top jet from background. *b-tagging* also used as top jet contains a b-jet.
- *Higgs tagging*: highly boosted Higgs —> $b\bar{b}$ (forms one jet). *Soft drop mass* is used again and so is *double b-tagging*.



soft drop mass used in top tagging

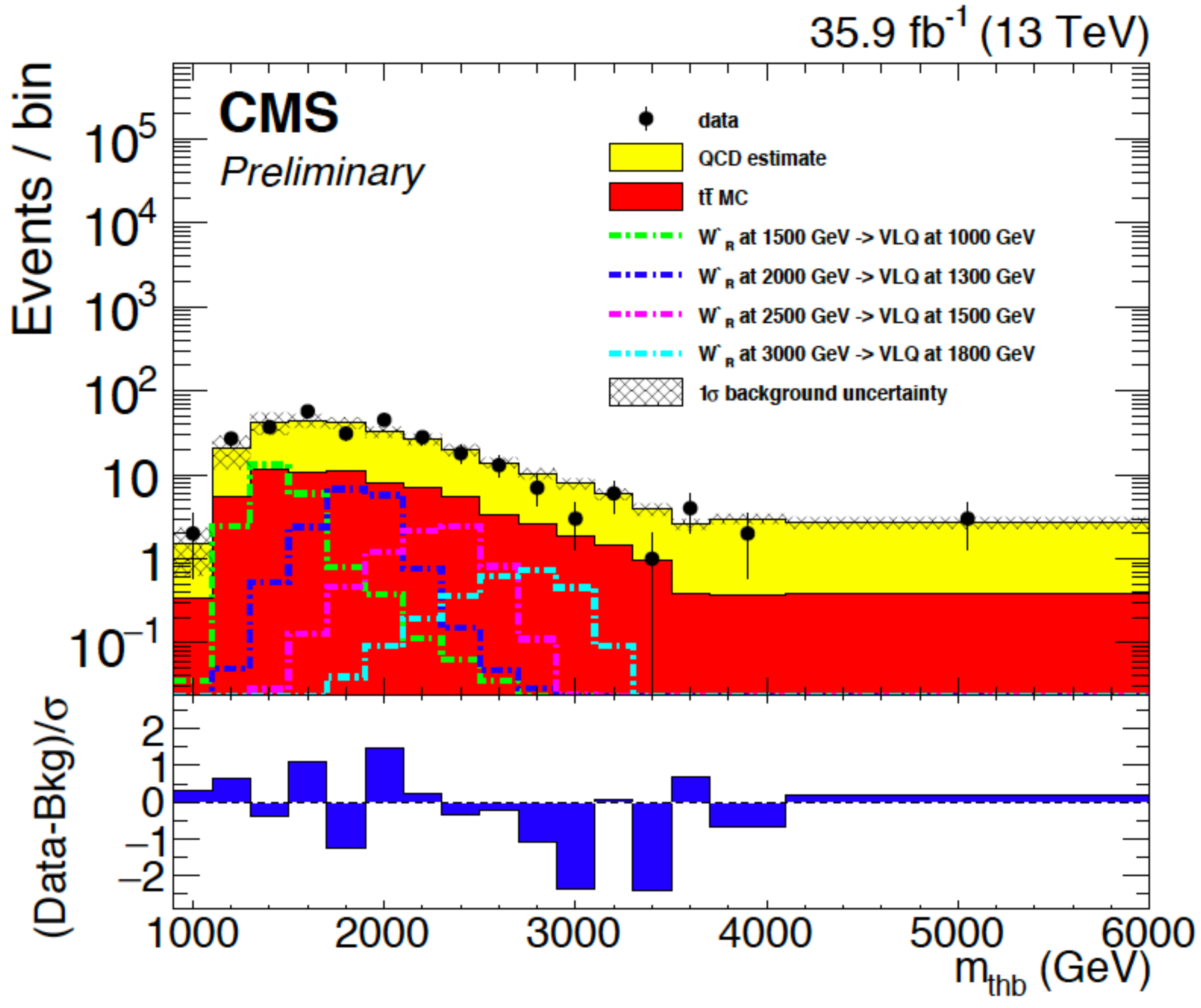


N-subjettiness used in top tagging



soft drop mass used in Higgs tagging

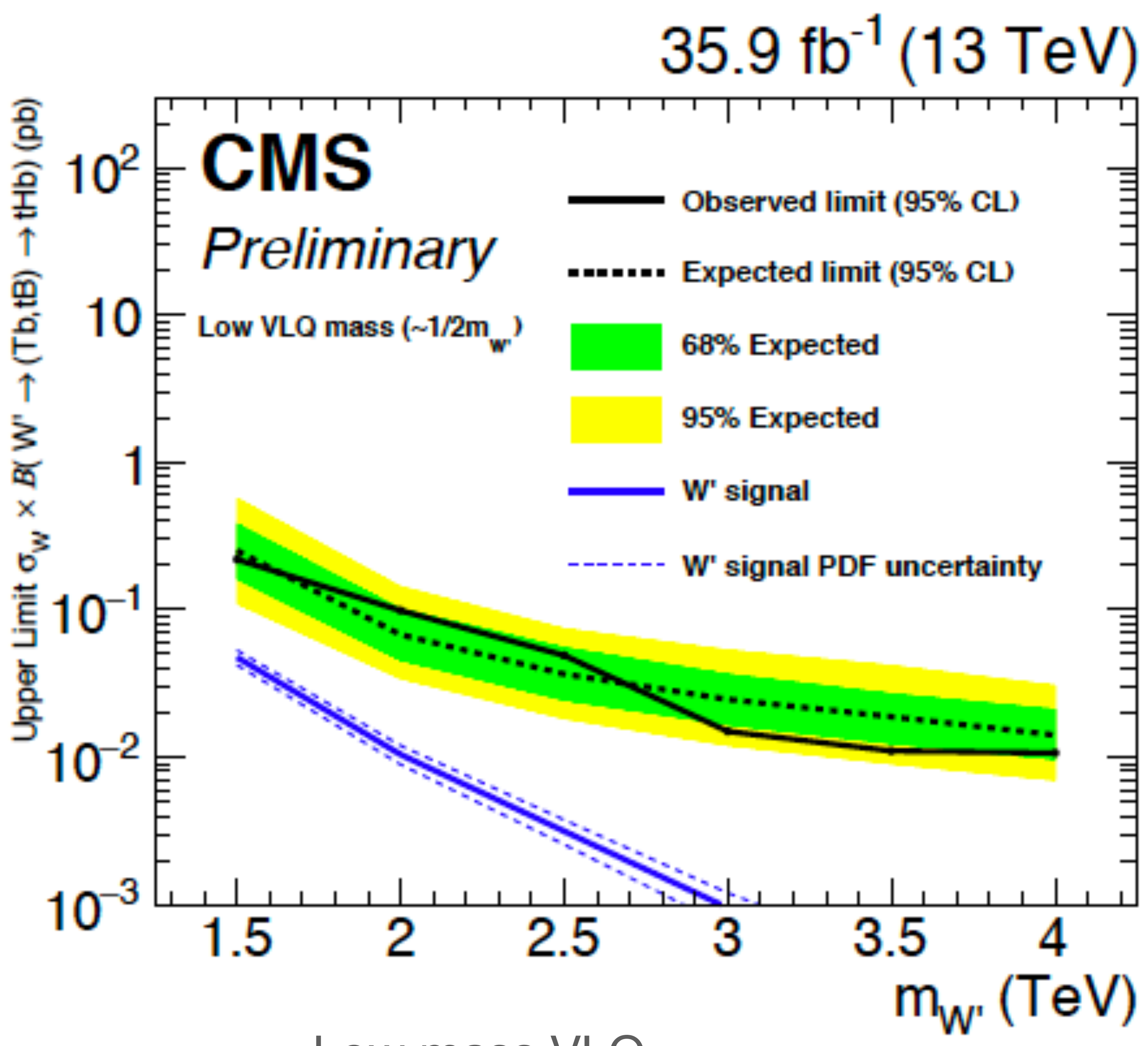
Background estimation



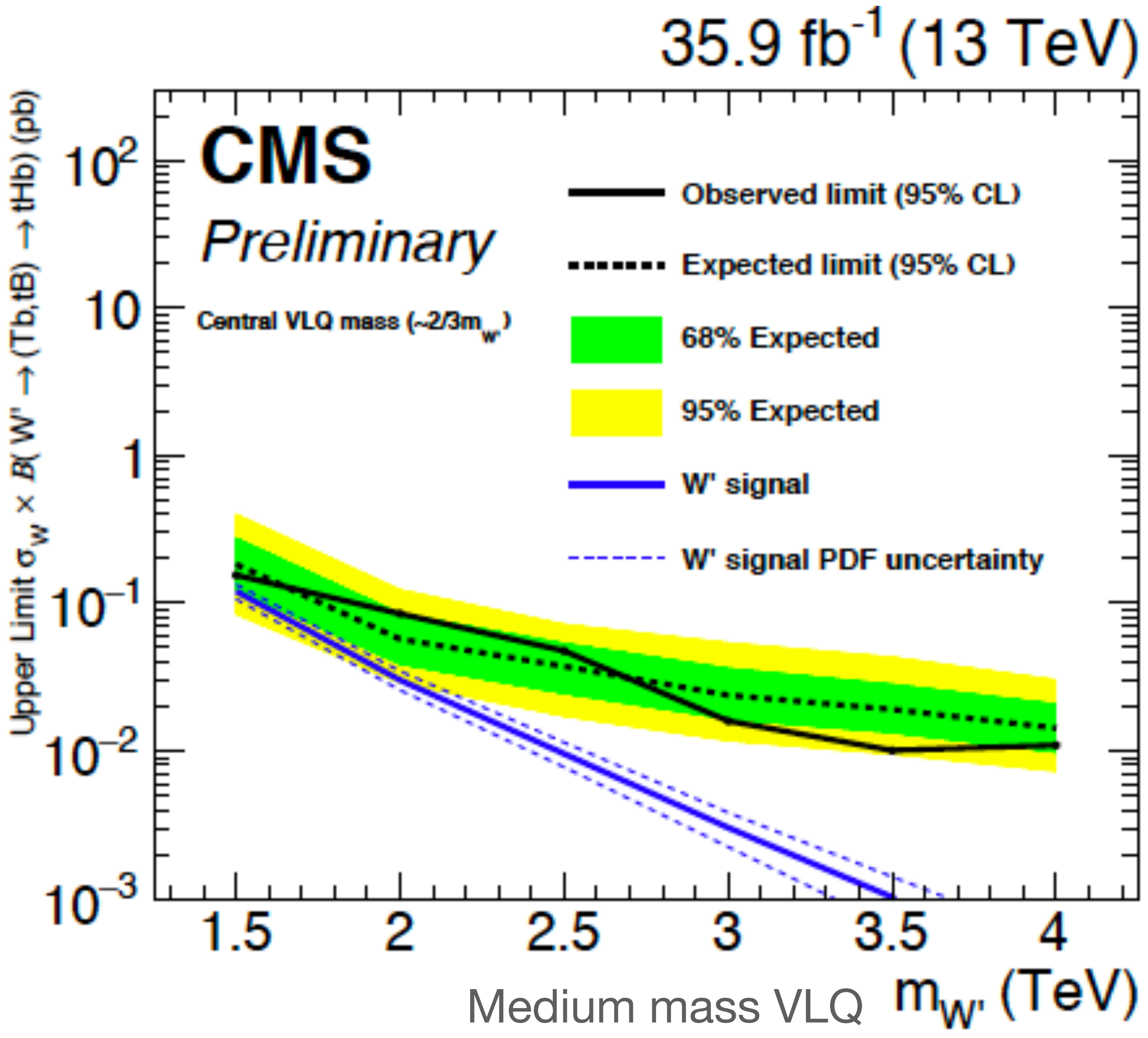
Reconstructed W mass in signal region with estimated background and several signal W' boson models

- Primary background: **QCD**
- **Signal regions** defined using top tagging, H-tagging and b-tagging variables and used to set cross-section upper limits.
- **Control regions** are defined in data by *inverting Higgs and top tagging variable*
  - Used for QCD estimation.
- **Validation regions** are defined *inverting H-tagging,top-tagging & b-tagging variables.*
  - Used for validation of background estimate in data

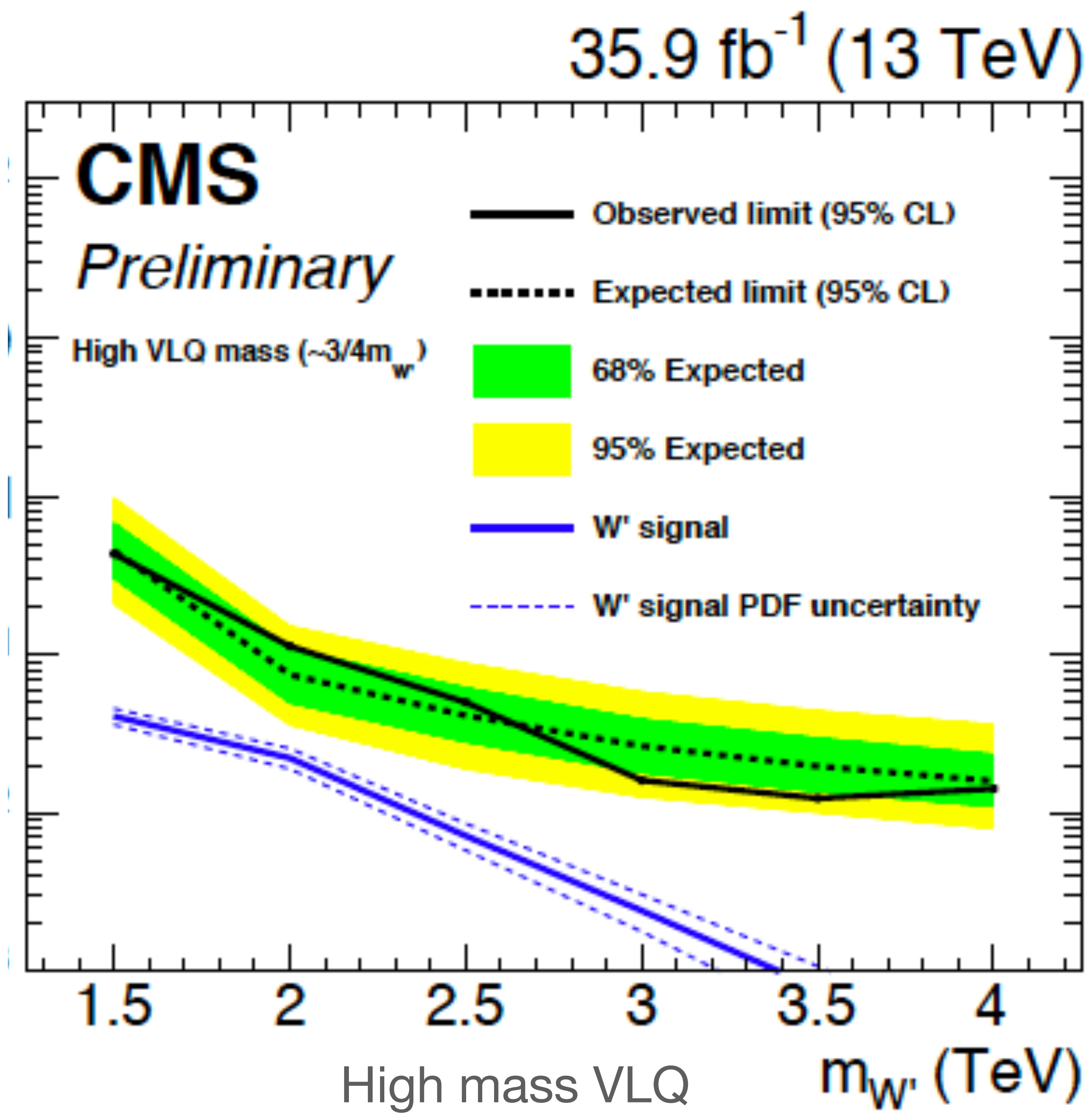
Results



Low mass VLQ



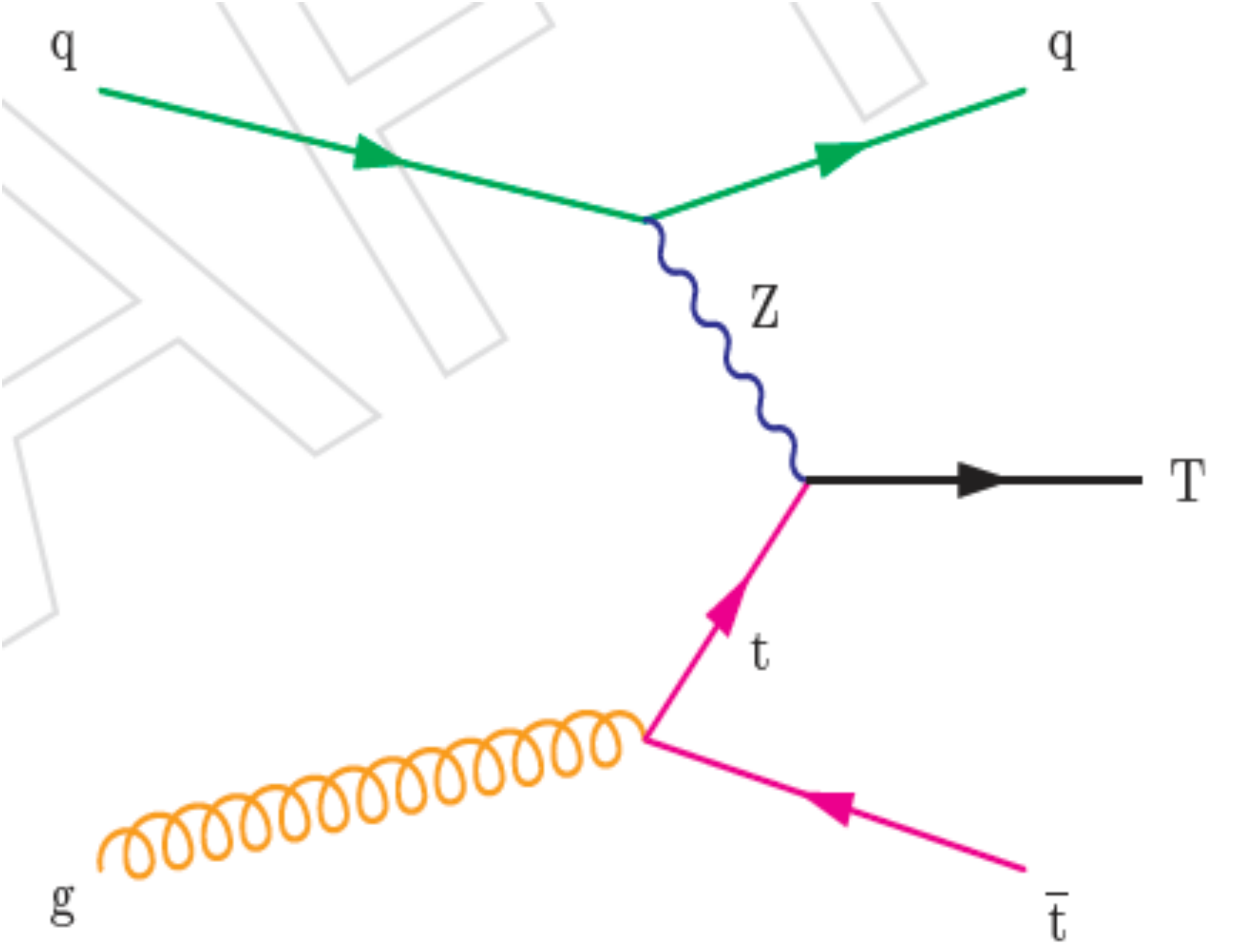
Medium mass VLQ

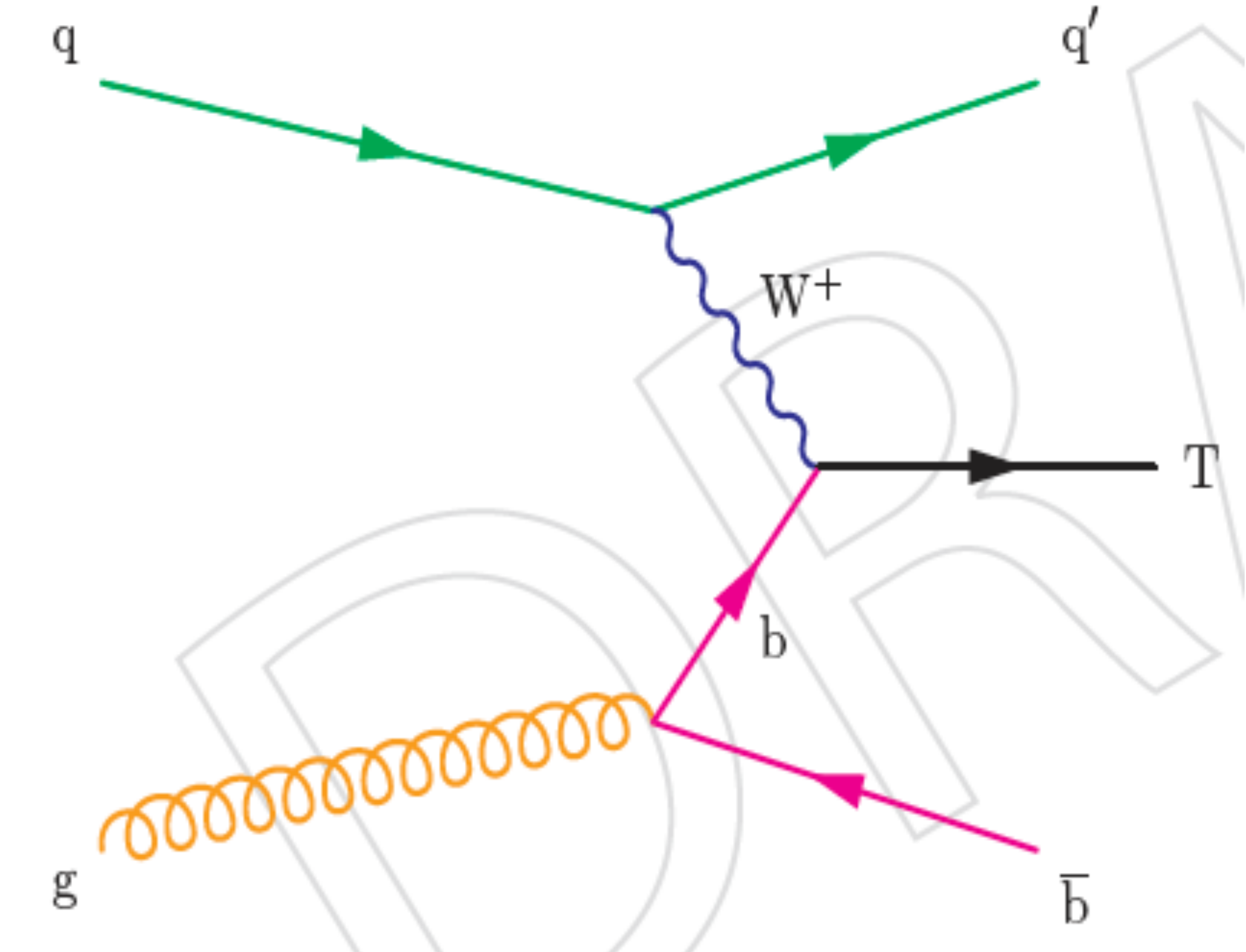


High mass VLQ

- No significant deviation from SM observed.
- These are the first limits for W' mass in this decay channel and cover W' mass between 1.5 - 4.0 TeV

Search for electroweak production of a vector like T quark using fully hadronic final states



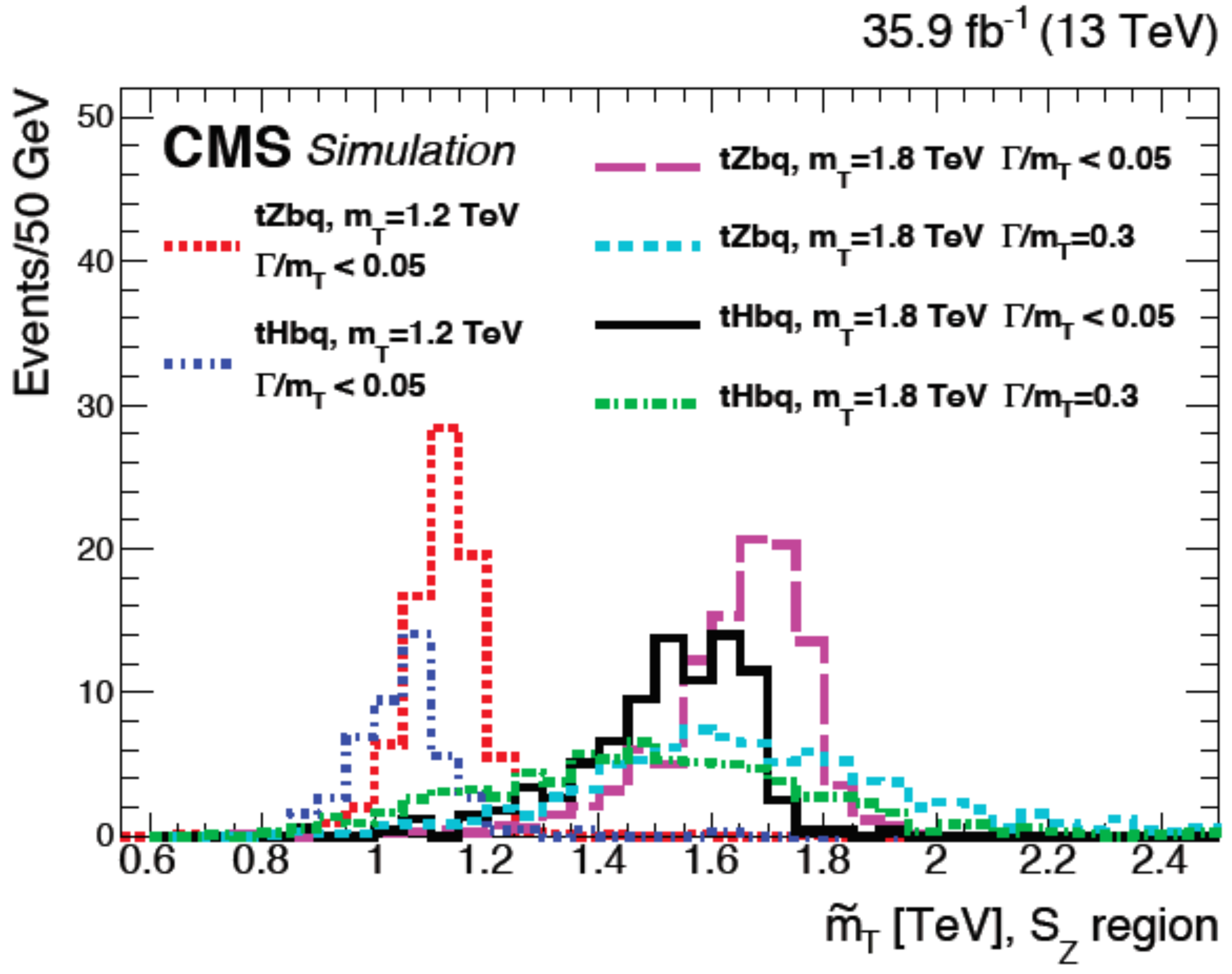


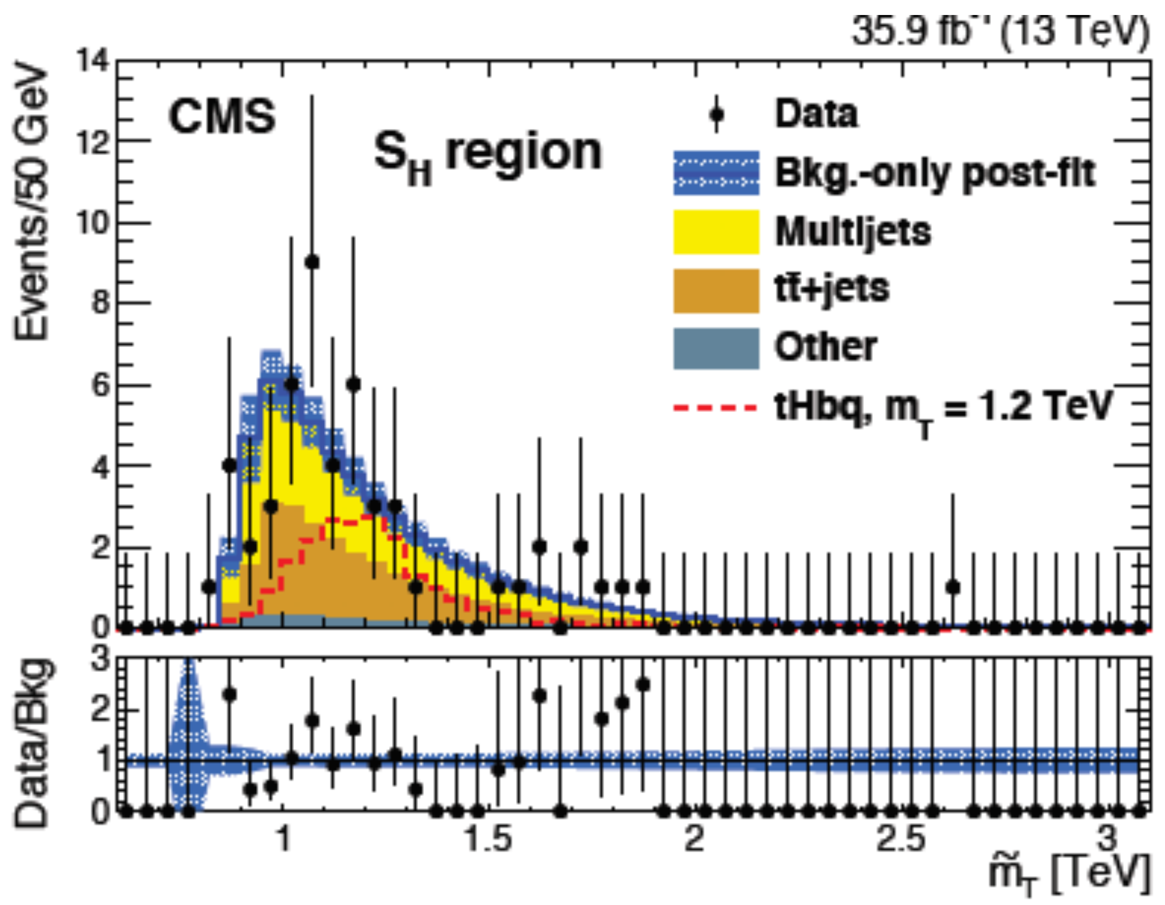
- Search for a new heavy top quark of charge 2/3 and nonchiral couplings.
- Such vector-like quarks do not acquire mass through Yukawa coupling with Higgs boson.
- Vector-like quarks could play a role in stabilizing the Higgs boson mass.
- This search uses the fully hadronic final state from **T—>tZ and T—>tH**

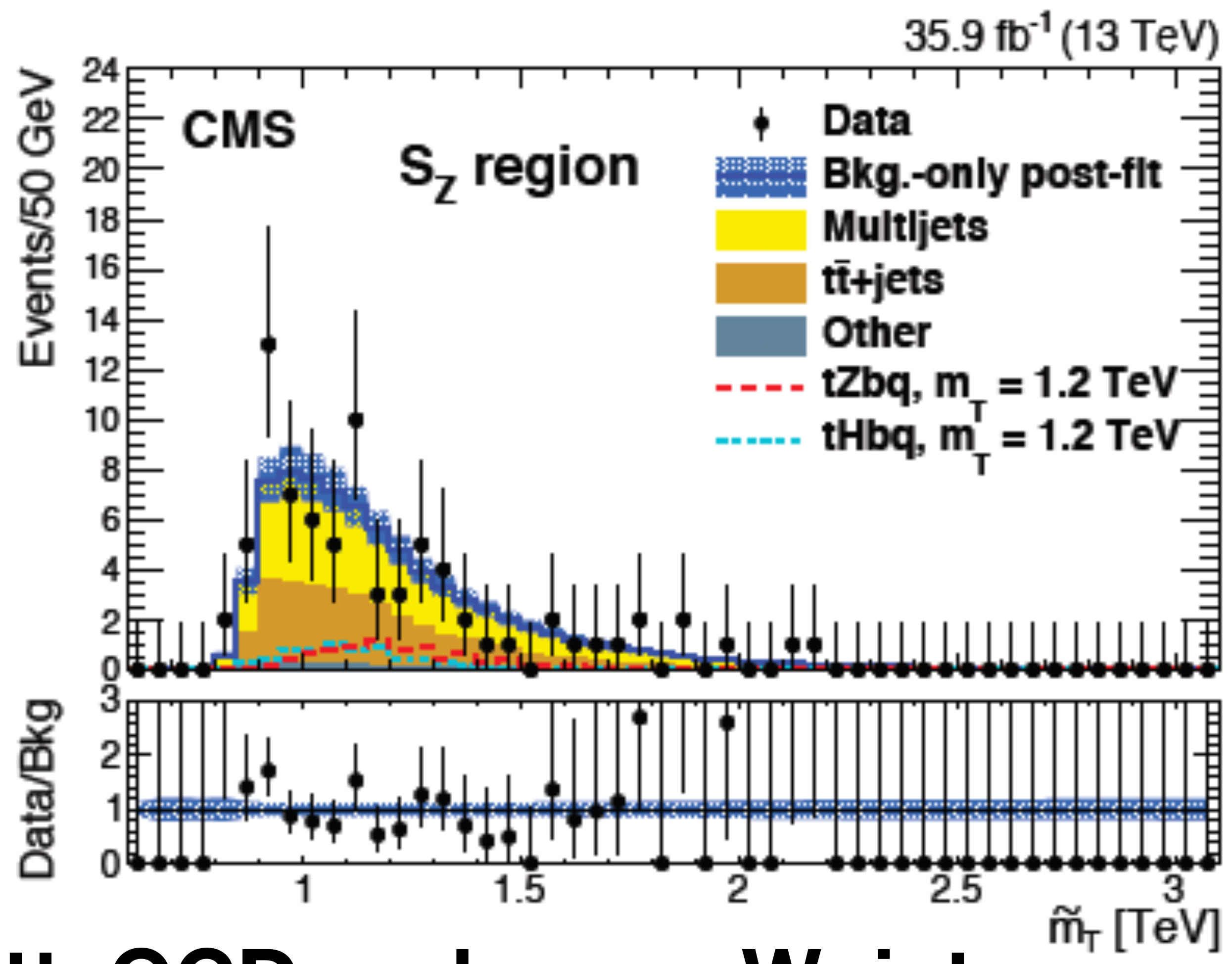
https://link.springer.com/article/10.1007%2FJHEP01%282020%29036

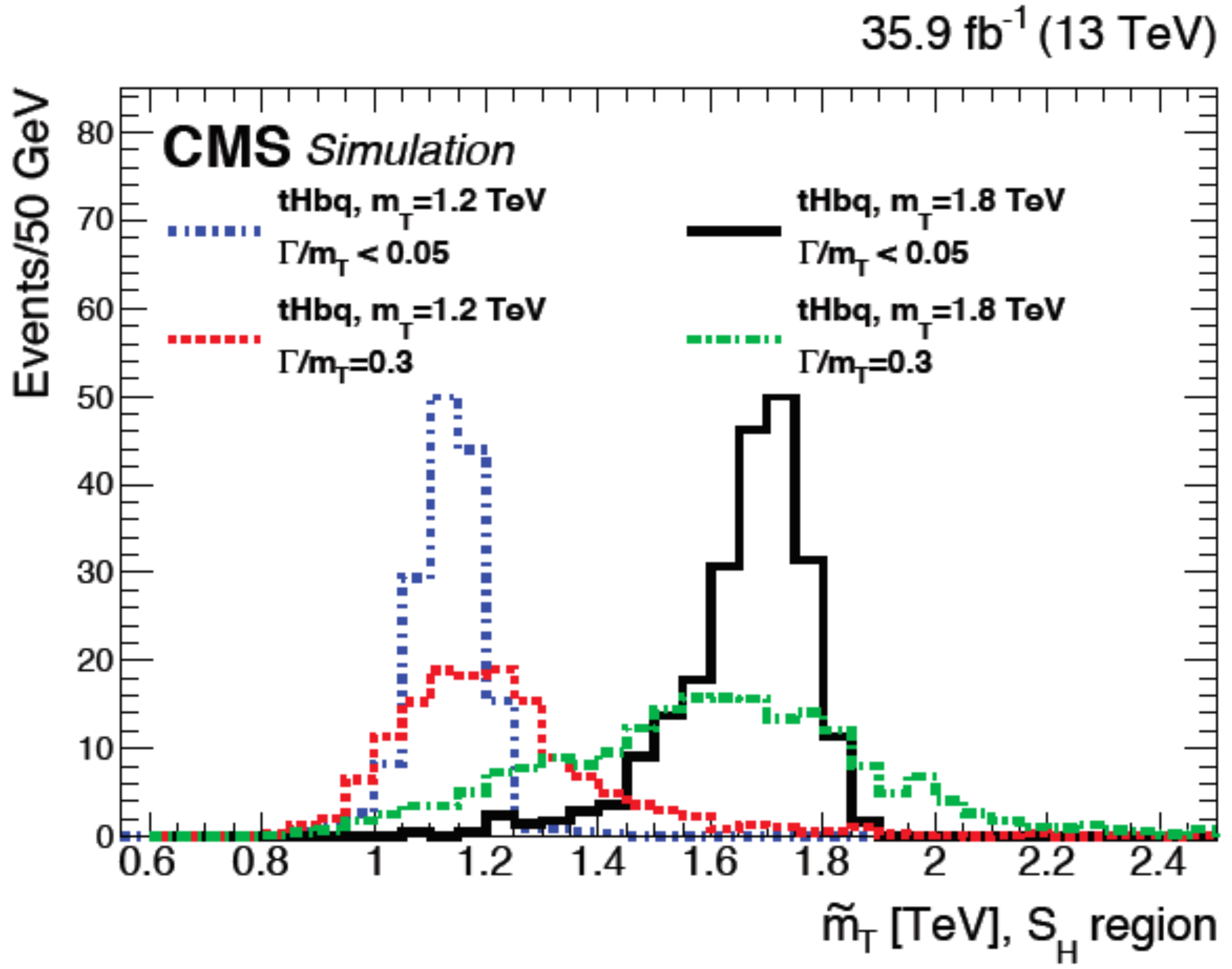
Signal Regions in High Mass search

- This search looks at two distinct signatures:
  - *<u>Low mass (0.6-1.2 TeV)</u>*- Relies on reconstruction of a 5 jet invariant mass
  - **<u>High mass (>1 TeV)</u>**- Relies on reconstruction from two large jets for both T—>tZ and T—>tH.
- *<u>High Mass search</u>*: *<u>Jet substructure variables</u>* are used to identify **H jet, Z jet and t jet. b-tagging** is also used to identify b jets within the larger jets.
- Based on what **combination of tagging criteria** the events satisfy, **Signal regions(S_H & S_Z)for tH and tZ** are identified.



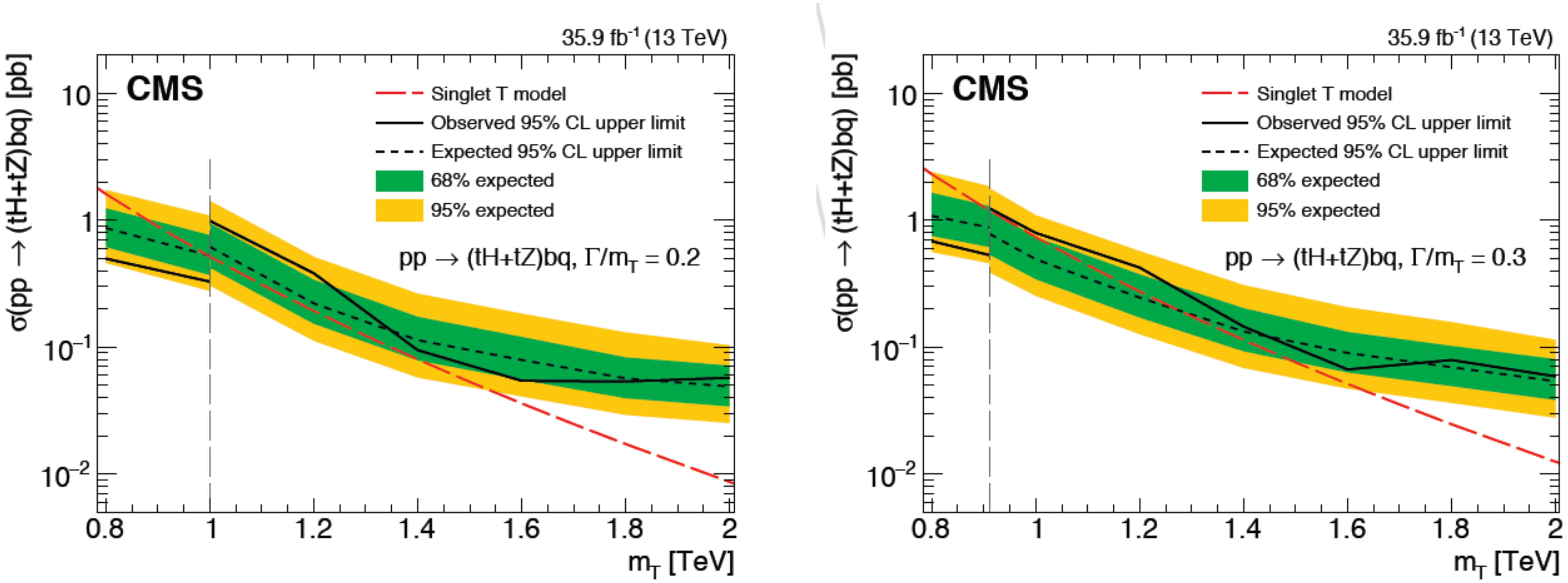




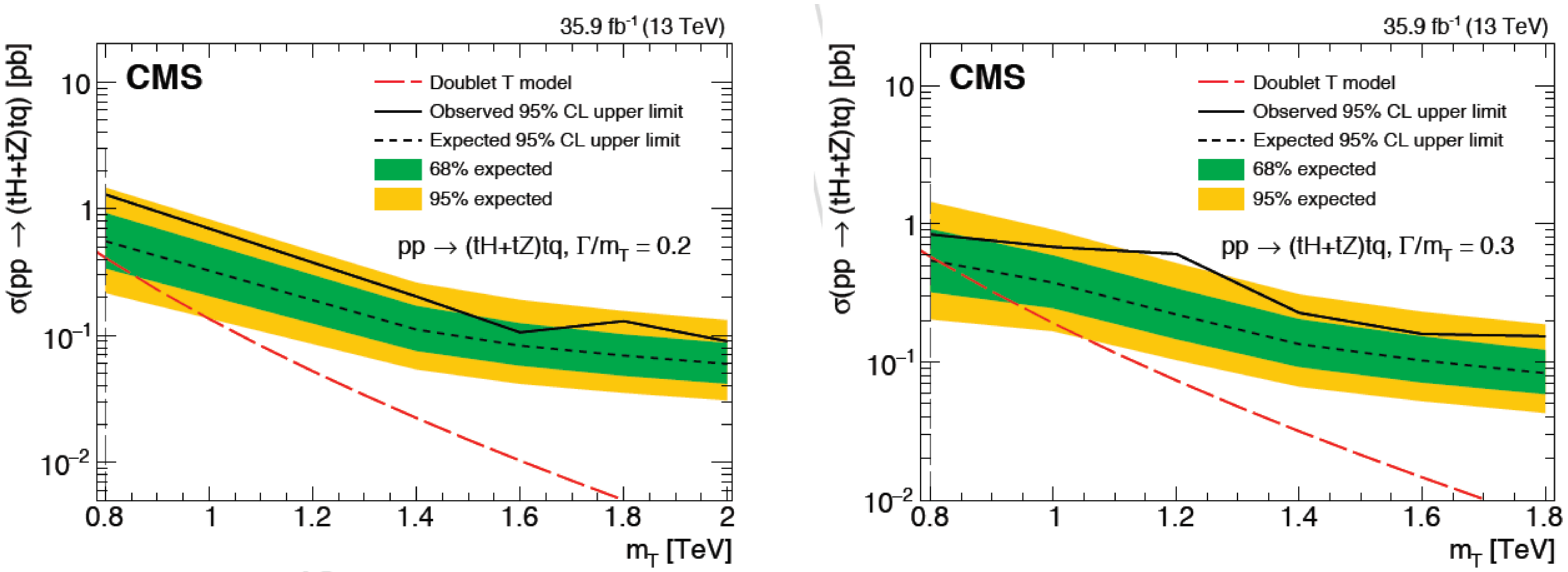


Main background: **SM tt, QCD and some W+jets**

Results



Tbq production for tHbq+tZbq channels

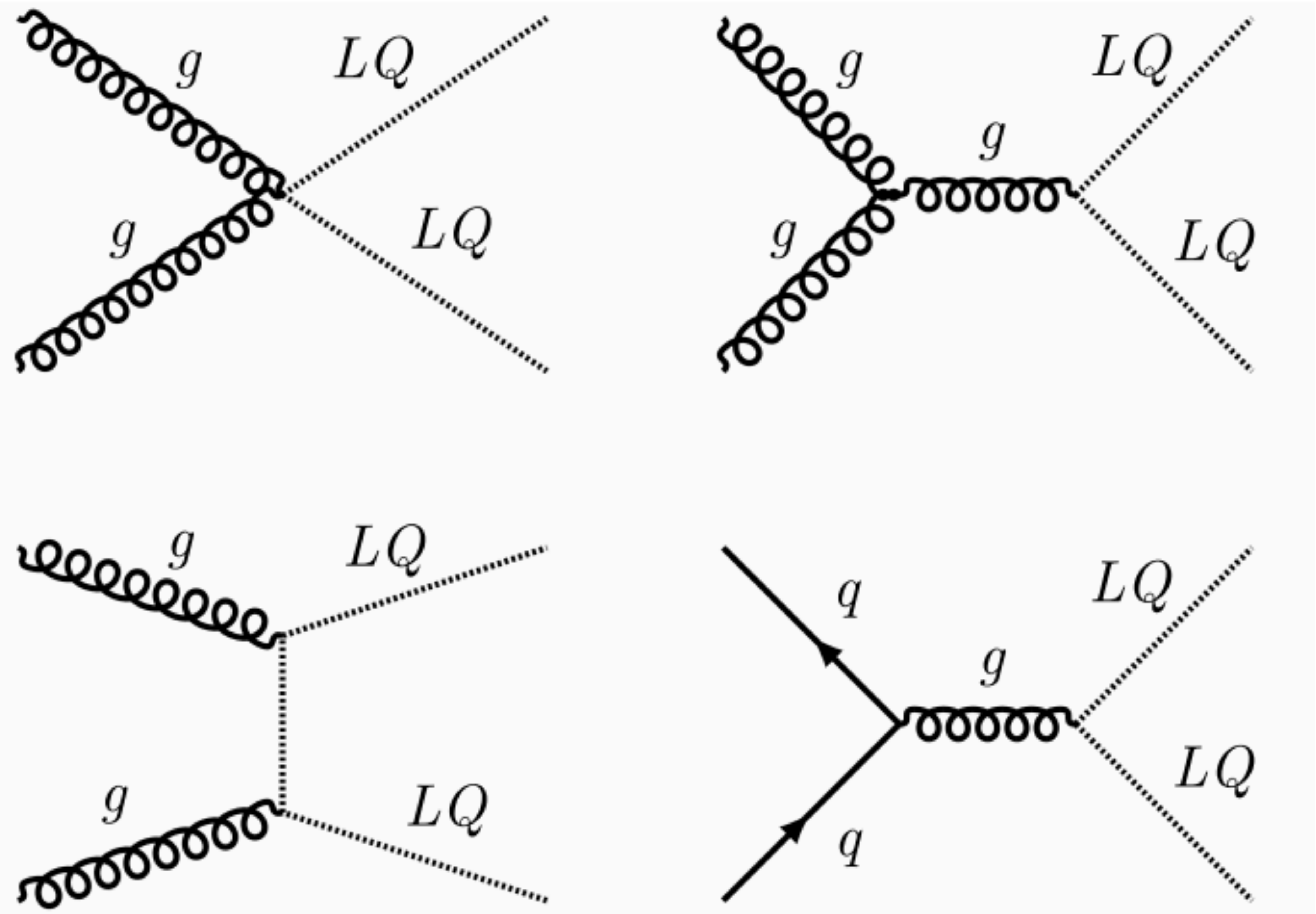


Ttq production for tHtq+tZtq channels

- The search gives the first constraints for T—>tZ with hadronic decays.
- For T masses above 1 TeV, the observed limits are above model predictions so no exclusion at 95% CL is possible.
- No significant excess of data above SM is observed.

Search for pair production of scalar leptoquarks decaying to leptons and top quarks

- Leptoquark are color triplet bosons which couple to both a quark and a lepton

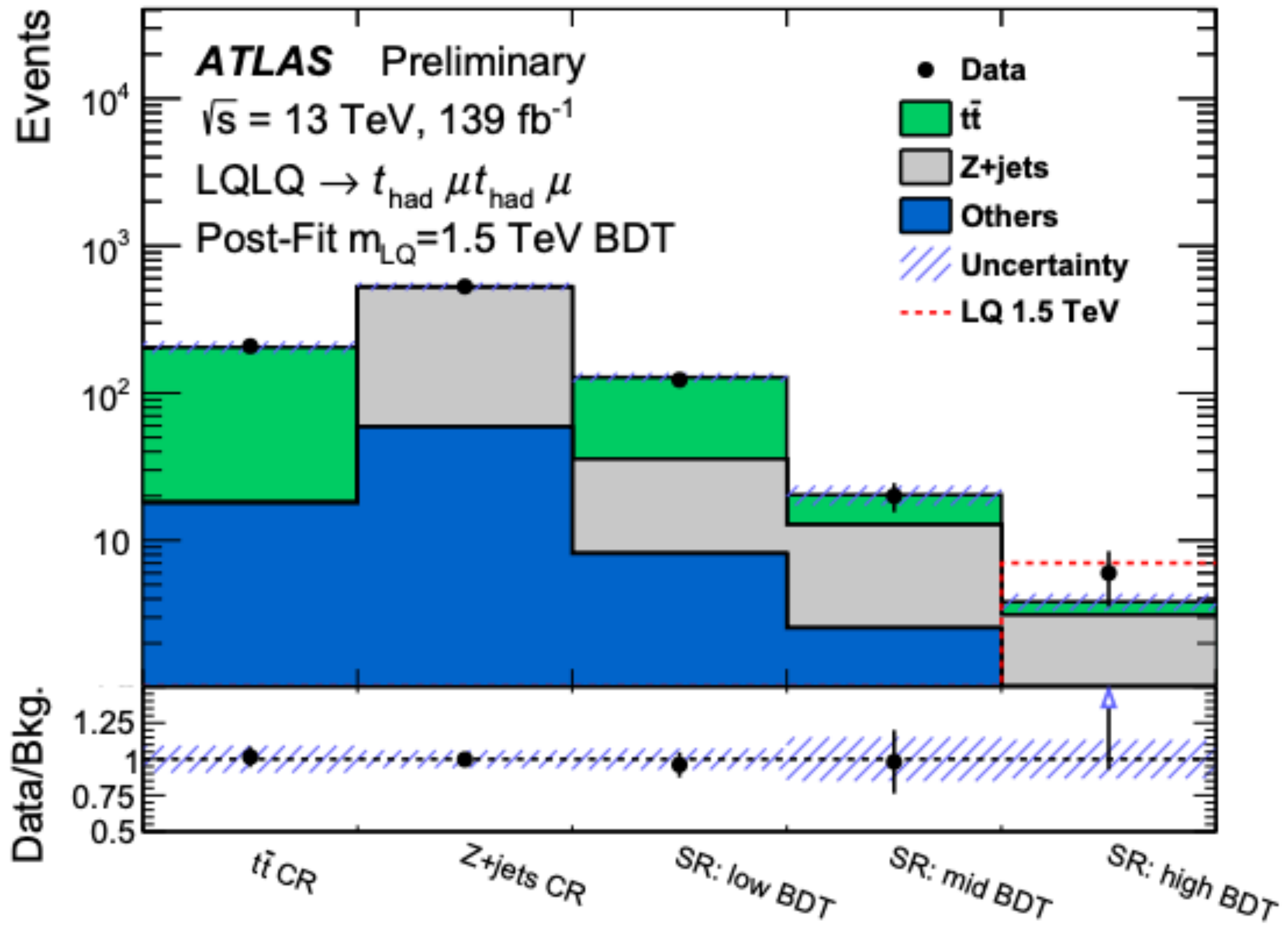


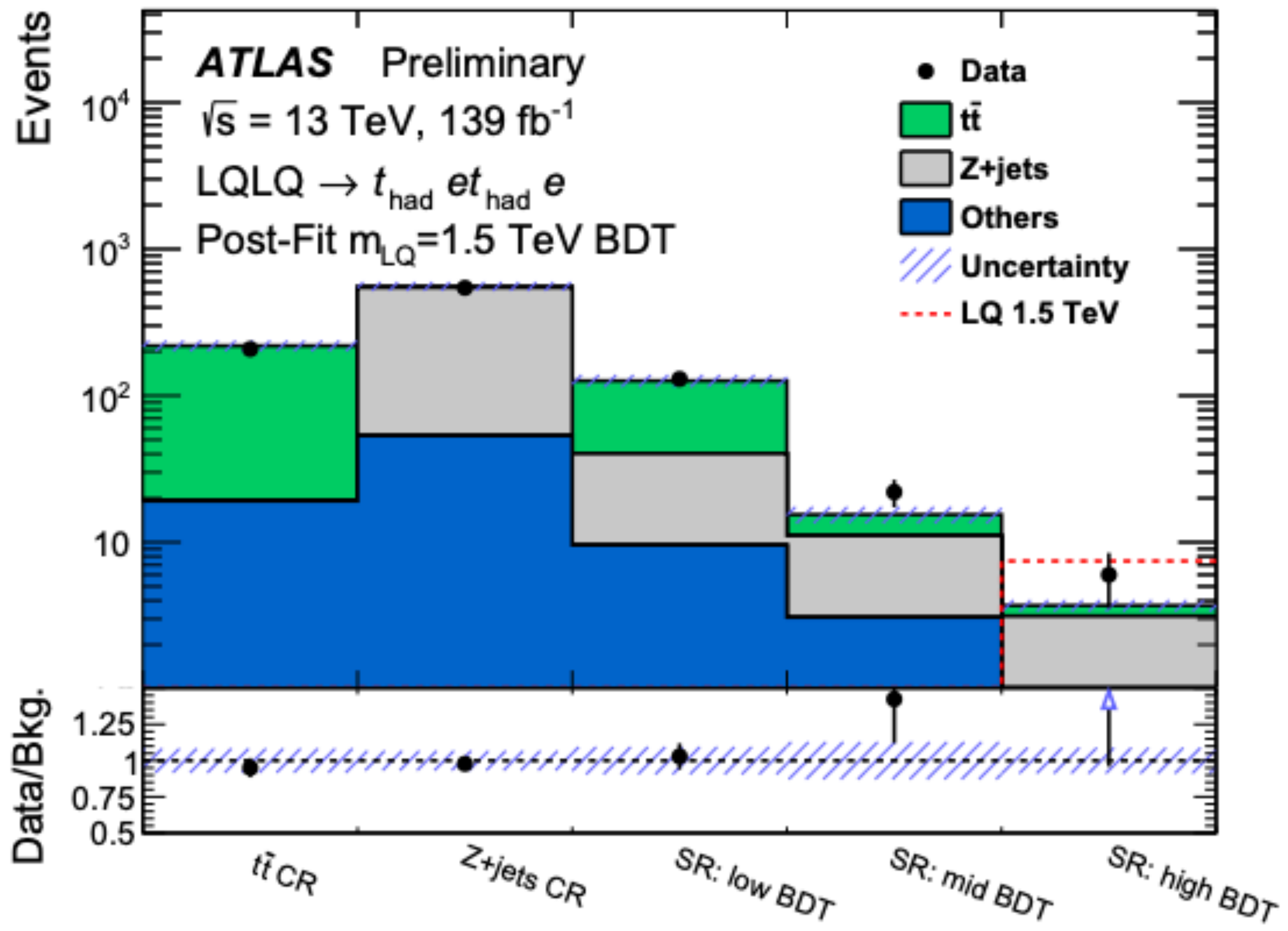
- Each leptoquark decays into a top quark and a lepton.
- Events are selected with **two high p_T, opposite sign, same flavour leptons**, and **two large jets**.
- Dominant **background in SR is $t\bar{t}$ and Z+jets.**
- **Boosted Decision tree** is used to further separate signal from background in the SR.

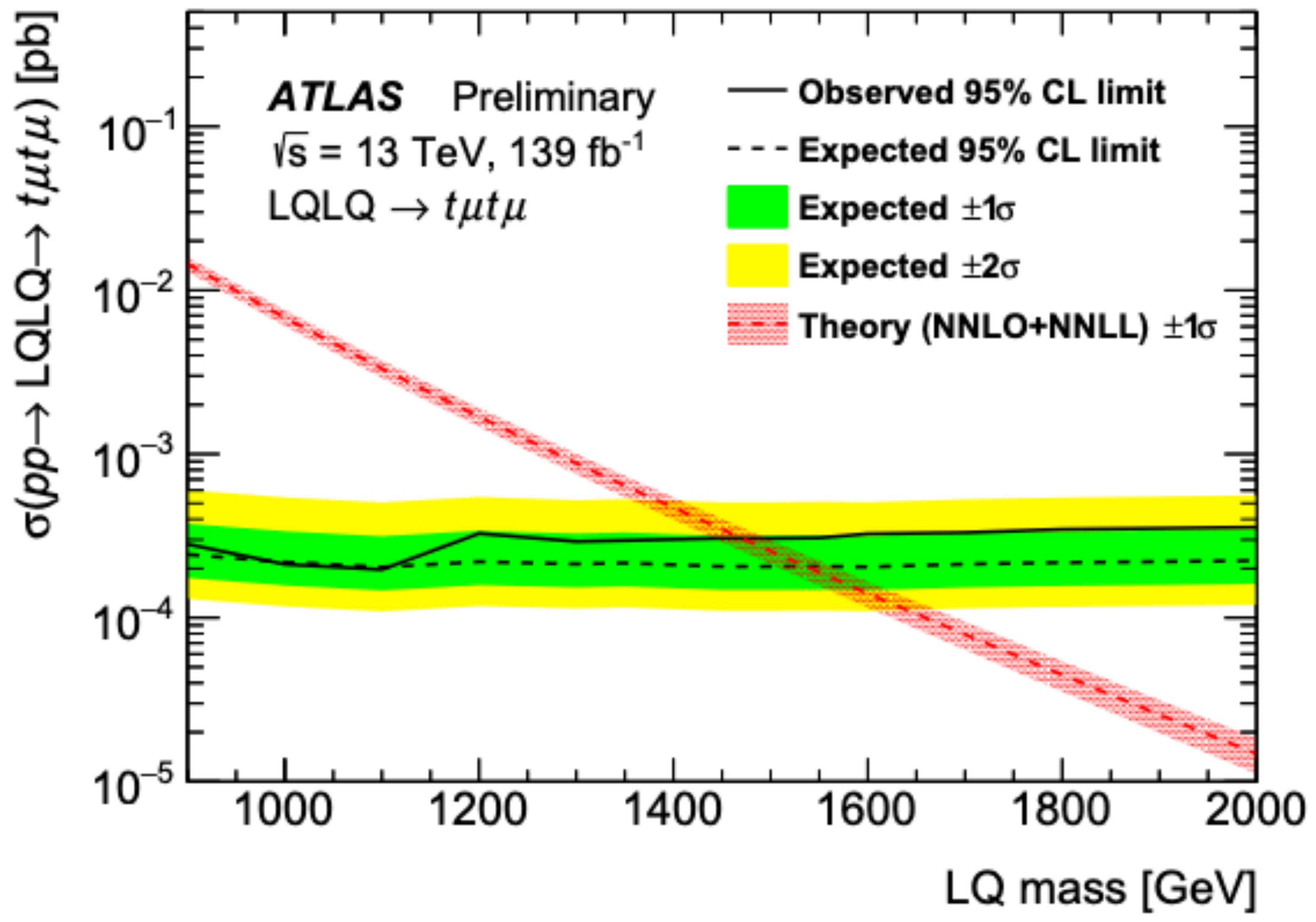
http://cdsweb.cern.ch/record/2725739/files/ATLAS-CONF-2020-033.pdf

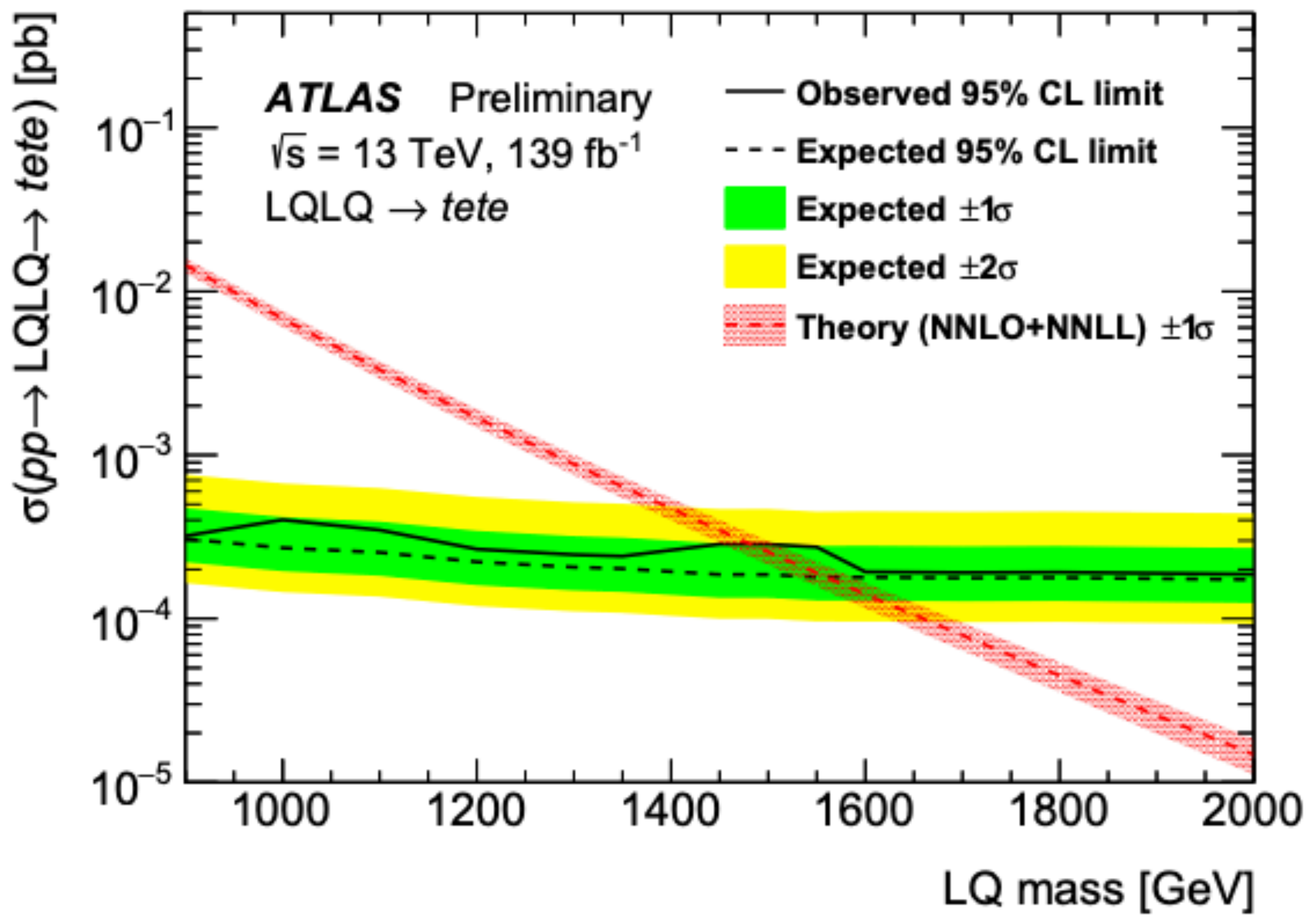
Results

- A simultaneous fit is done in the the SR and the $t\bar{t}$ CR and Z+jets CR.









- Lower limits on the leptoquark masses are set at 1480 GeV and 1470 GeV for the electron and muon masses respectively.

Search for heavy resonances decaying to a top quark and a W boson

NEW!

- b* has an internal structure that could be excited to produce a state with higher mass.
- This analysis considers resonances with mass > 1 TeV resulting in boosted top and W each forming a collimated jet.
- b*—>tW through weak interaction
- The invariant mass **m_{tW} and m_t** is used to search for b*.

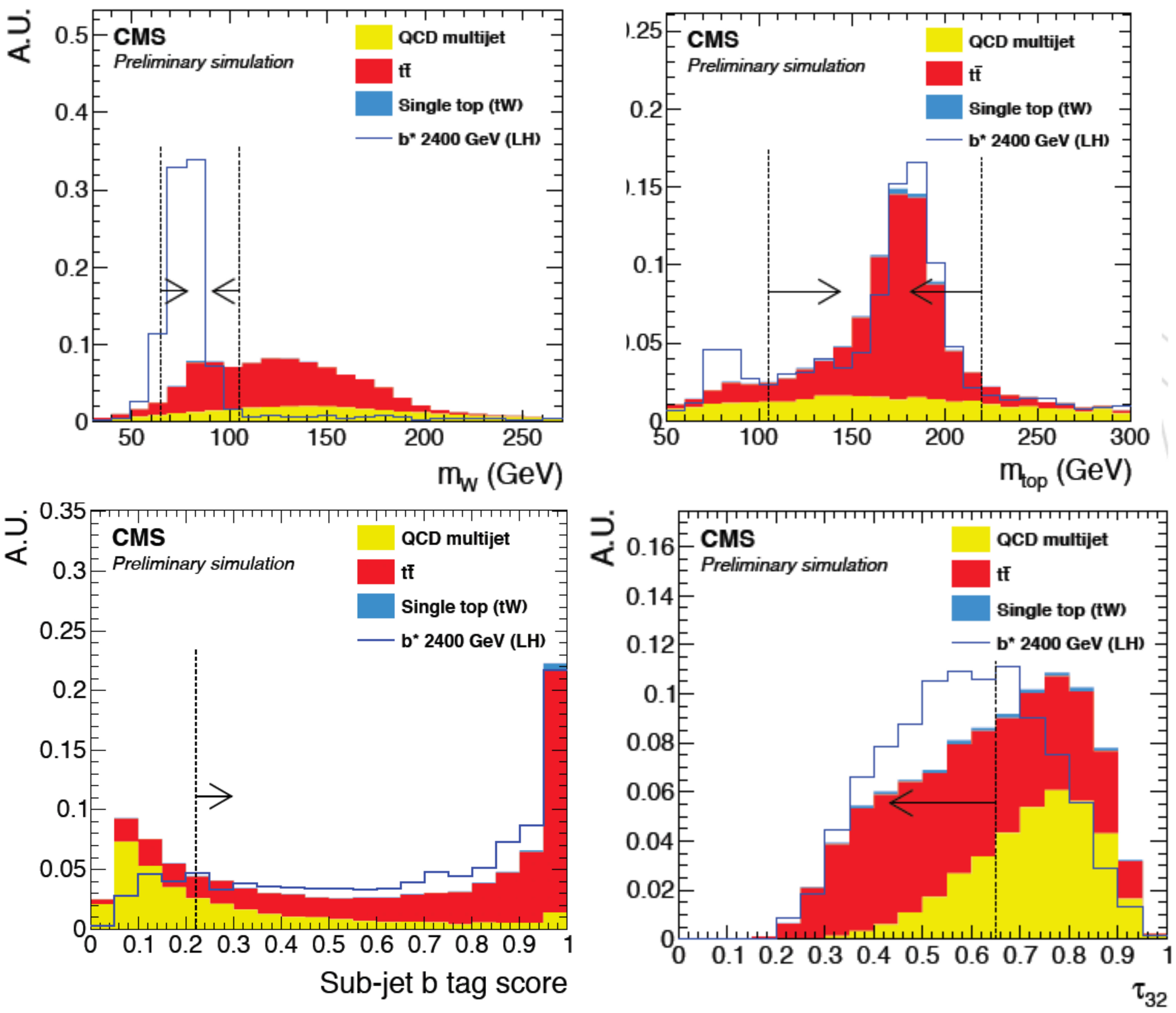
Just approved!

Background estimation

- **QCD** estimated by events in data & MC that pass or fail the top tagging requirement in the **(m_{tW}, m_t)** plane.

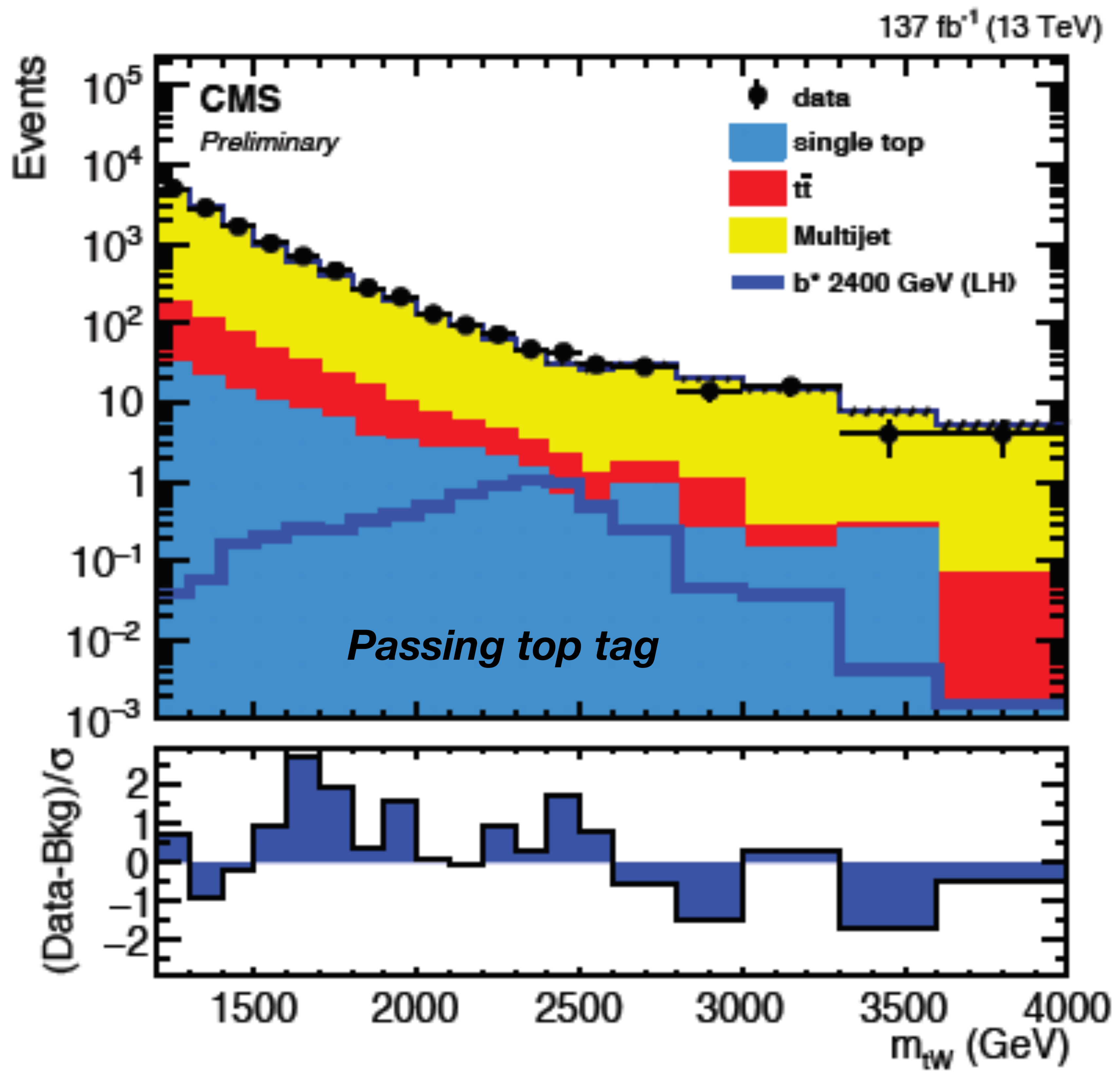
- **$t\bar{t}$ is evaluated in the (m_t,m_{tt}) plane** and only QCD and SM $t\bar{t}$ is considered in this region.

Variables used as discriminants in W and top tagging

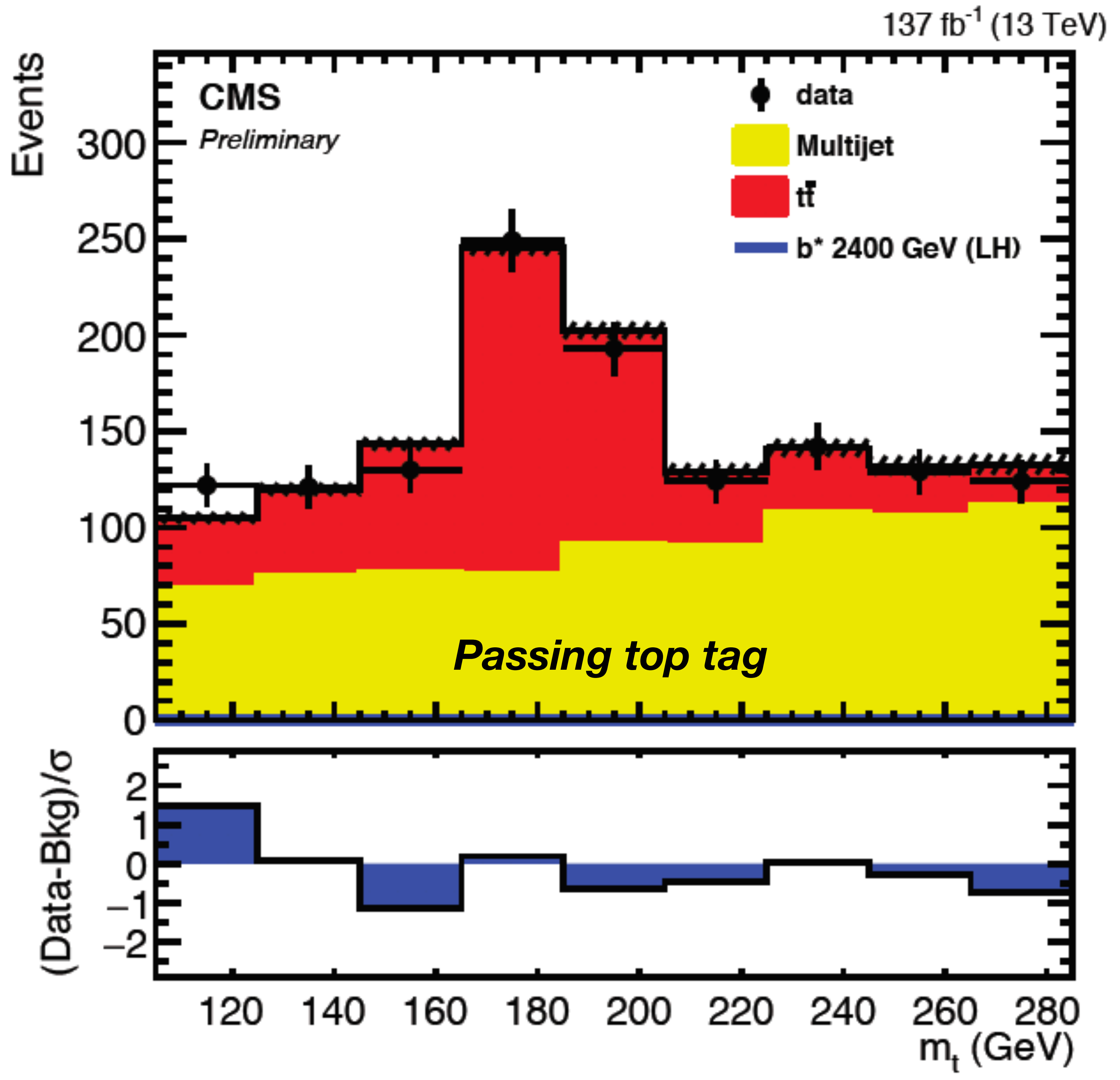


Signal and background regions

- (m_{tW}, m_t) and (m_{tt}, m_t) distributions are used in simultaneous binned maximum likelihood fit.



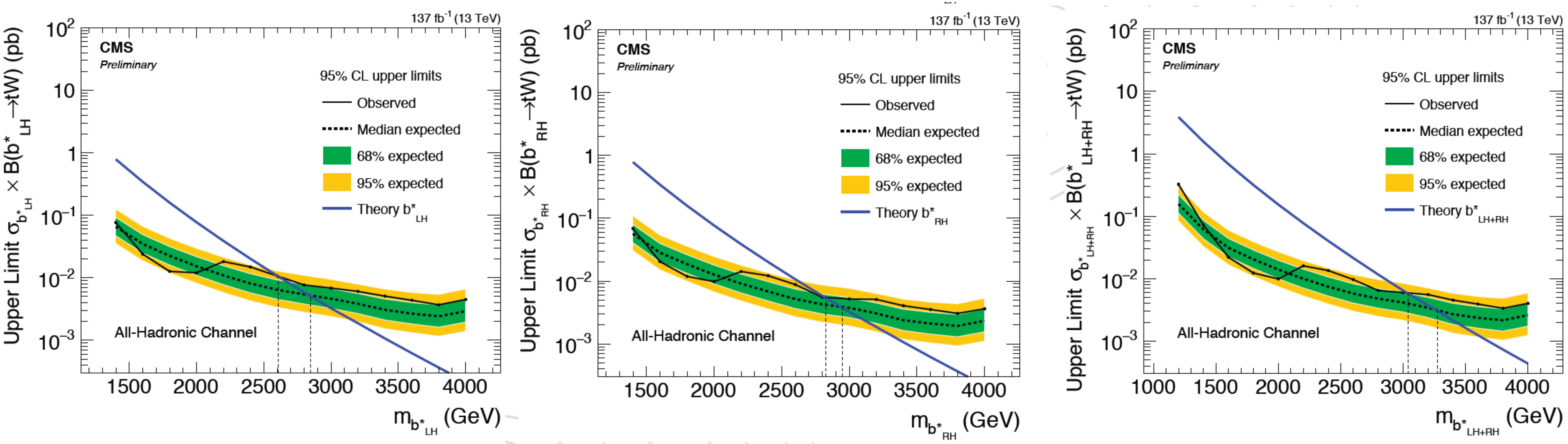
65<m_t<105



1800<m_{tt}<3000

- Signal region projected on m_{tW} axis in slices of m_t.
- tt measurement region projected on m_t axis in slices of m_{tt}.

Results



- b* -left handed, right handed and vector-like chirality, are excluded with 95% CL for masses below 2.6, 2.8 and 3.0 TeV respectively.

- This improved over the 8TeV limits (by almost a factor of two) presented by CMS.

Summary

- We went over several searches performed by the ATLAS and CMS collaborations where new heavy particles decay into boosted top quarks along with other particles.
- Models covered in this talk are: R-S models, leptophobic Z', vector-like quarks, scalar leptoquarks and excited b*-quarks NEW!.
- Top quarks in general and boosted top quarks in this specific case continues to be an opportunity to probe for new heavy particles.
- The searches do not observe any excess in data, however they exclude more mass points from searches thus providing a more accurate search window for next iteration.

Back up

Top Tagging

- Top Tagging used in all CMS analysis uses a combination of N-subjettiness (τ_3/τ_2) and soft drop mass and b-tagging.

- N-subjettiness is a jet shape variable designed to measure how consistent a jet is with a hypothesis of have N subjets.

- The merged top jet can also be discriminated from background by using the large top quark mass. The modified mass drop tagger algorithm , also known as the “soft drop” algorithm with angular exponent b= 0 is used to calculate this mass variable. This algorithm declusters the jet, and removes soft or wide angle radiation.

- Algorithm removes soft and collinear radiation from clustered radiation

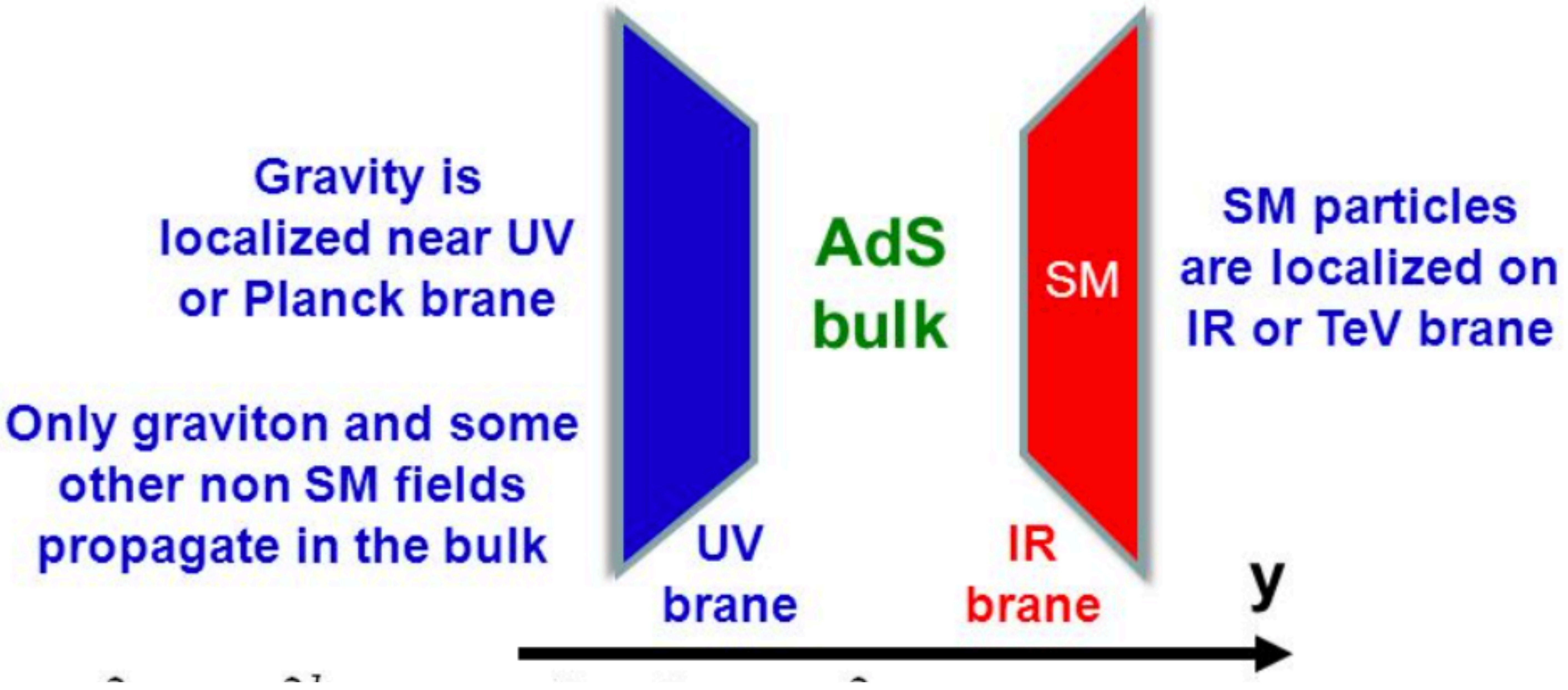
http://cds.cern.ch/record/1647419/files/JME-13-007-pas.pdf

Leptophobic topcolor

- Four models predict, Model IV has the highest cross-section for a neutral gauge boson Z’
- topcolor (ttbar forms a composite Higgs boson) Z’ —> $U(1)_1 \times U(1)_2$ in complete analogy to topcolor imbeding
- Z’ couples strongly to 1st and 3rd generation quarks.
- does not couple to leptons- leptophobic

RS model and Kaluza Klein theory

- RS model solves hierarchy problem with a warped extra dimension of space.
- KK- unified gravitation and eletromagnetism
  - built on a fifth dimension



Search for heavy resonances (b*) decaying to a top quark and a W boson

	Left-handed	Right-handed
1600 GeV	0.10	0.11
2600 GeV	0.10	0.11
3600 GeV	0.09	0.10

Table 2: The selection applied to each region included in the fit.

Preselection
Two AK8 jets
$p_T > 400\,\mathrm{GeV}$
$\eta < 2.4$
$\lvert\Delta\phi\rvert > \pi/2$
$\lvert\Delta y\rvert < 1.6$

tW selection		**$t\bar{t}$ selection**	
Jet 1: W tag		Jet 1: Preselection t tag	
Jet 2: Pass t tag (signal selection)	Jet 2: Fail t tag	Jet 2: Pass t tag ($t\bar{t}$ measurement region)	Jet 2: Fail t tag

Search for electroweak production of a vector like T quark using fully hadronic final states

Table 3: Overview of the criteria used to define the mutually exclusive Q_H, T_H, R_H, S_H, Q_Z, L_Z, R_Z, and S_Z regions. These are based on the particle tagging criteria for t, H, and Z jets and for the reversed-t-tagged, reversed-H-tagged, and reversed-Z-tagged jets using the two highest p_T AK8 jets.

Region	Channel	First jet	Second jet	H/Z tag isolation
Q_H	tH	reversed-t-tagged	reversed-H-tagged	—
T_H	tH	t tag	reversed-H-tagged	—
R_H	tH	reversed-t-tagged	H tag	required
S_H	tH	t tag	H tag	required
Q_Z	tZ	reversed-t-tagged	reversed-Z-tagged	—
L_Z	tZ	t tag	reversed-Z-tagged	—
R_Z	tZ	reversed-t-tagged	Z tag	required
S_Z	tZ	t tag	Z tag	required

Search for a W' boson decaying to a vector-like quark and a top or bottom quark in the all jets final state

Table 2: Selection regions used in the analysis. Cut discriminator selections and regions described in the text are explicitly defined here.

Label	Discriminator selections
H_{tag}	Dbtag$>$ 0.8 and 105$<m_{\text{SD}}<$135 GeV
t_{tag}	$SJ_{\text{csvmax}}>$0.5426 and $\tau_3/\tau_2<0.8$ and 105$<m_{\text{SD}}<$210 GeV
b_{tag}	CSVv2$>$ 0.5426
H_{antitag}	$m_{\text{SD}}<$30 GeV
t_{antitag}	$SJ_{\text{csvmax}}>$0.5426 and $\tau_3/\tau_2>0.65$ and 30$<m_{\text{SD}}<$105 GeV
b_{antitag}	CSVv2$<$ 0.5426

Signal region

Region	top jet	Higgs jet	b jet
SR	t_{tag}	H_{tag}	b_{tag}

Background estimation

Region	top jet	Higgs jet	b jet
CR1	t_{antitag}	H_{antitag}	b_{tag}
CR2	t_{antitag}	H_{tag}	b_{tag}
CR3	t_{tag}	H_{antitag}	b_{tag}

Background validation

Region	top jet	Higgs jet	b jet
CR4	t_{tag}	H_{tag}	b_{antitag}
CR5	t_{antitag}	H_{antitag}	b_{antitag}
CR6	t_{antitag}	H_{tag}	b_{antitag}
CR7	t_{tag}	H_{antitag}	b_{antitag}