Search for vector-like quarks and squarks in boosted final states at CMS

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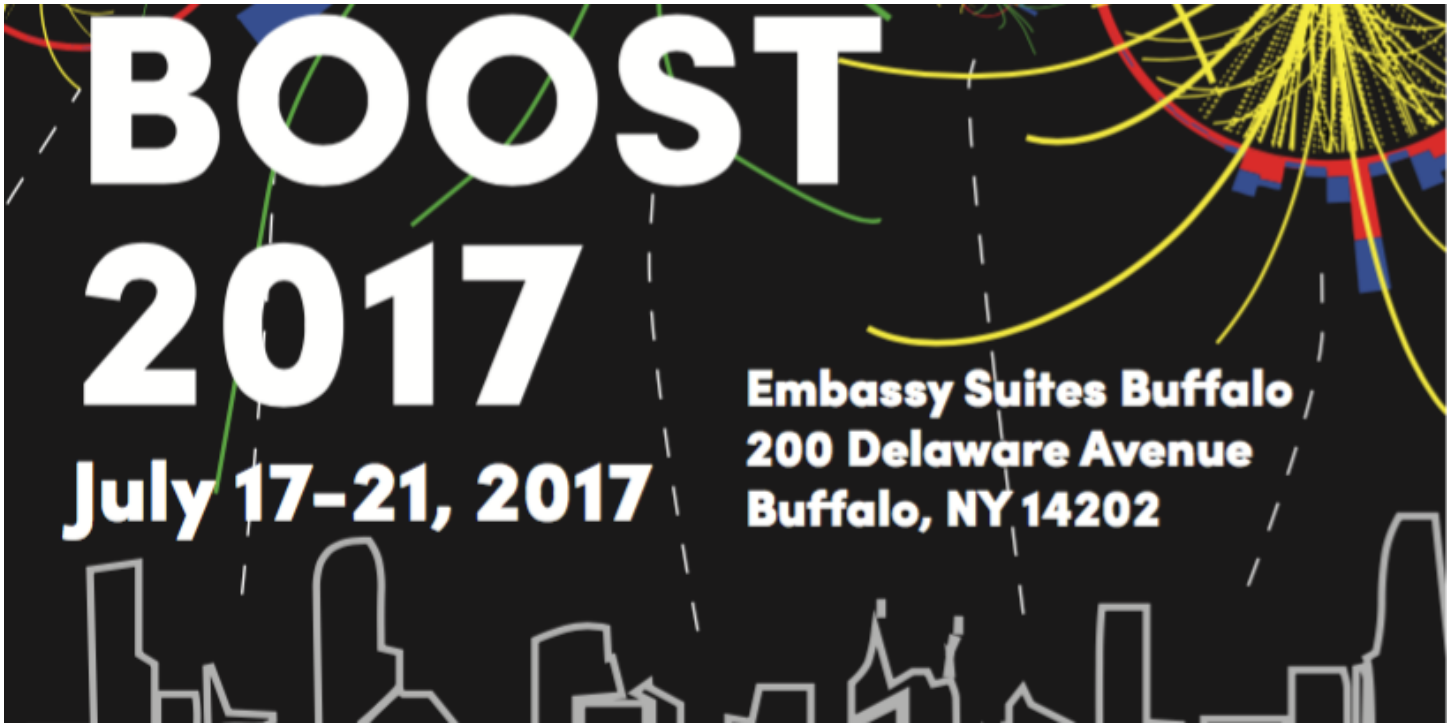
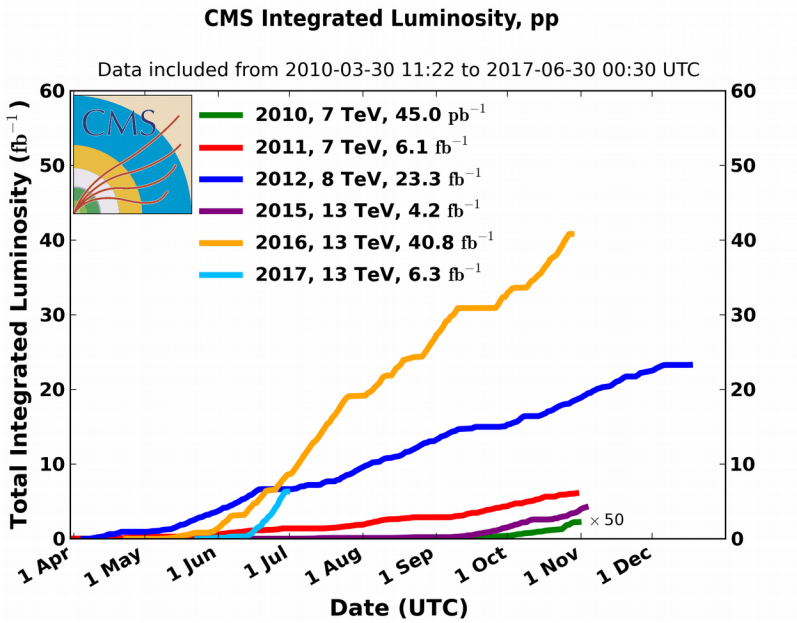
On behalf of the CMS Collaboration



Introduction

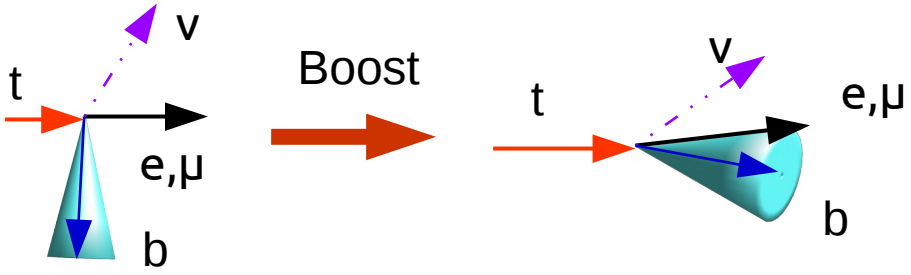
- Additional quarks predicted by many BSM theories
- Heavy objects with preferred coupling to third quark generation
- Plenty of new Data to explore!

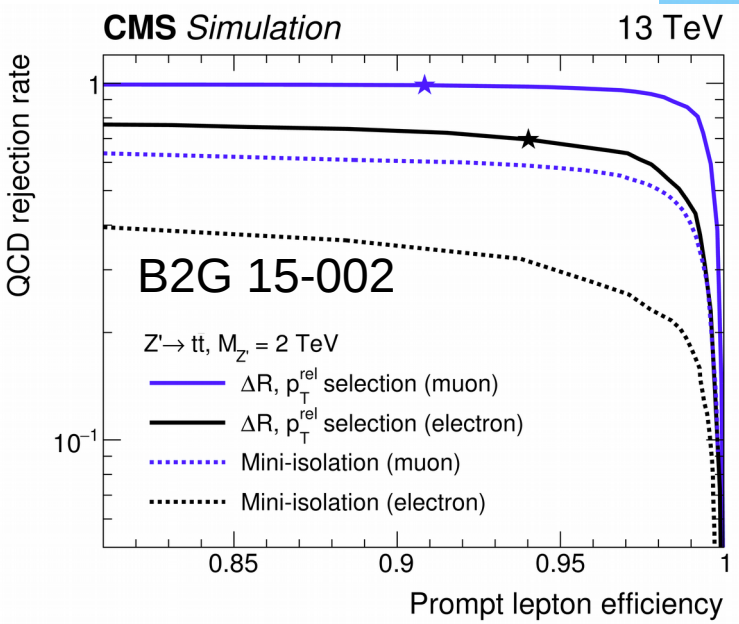


Analyses

- Squark pairs
  - All hadronic, 2016, PAS SUSY 16-050
- Vector like quarks
  - Pair production
    - TT & BB single lepton, 2015, arXiv:1706.03408
    - TT & YY single lepton, 2016, PAS B2G 17-003
    - XX single lepton, 2016, PAS B2G 17-008
  - Single production
    - T dilepton, 2016, PAS B2G 17-007
    - B all hadronic, 2016, PAS B2G 17-009
- Excited quarks
  - Various Boosted final states are work in progress

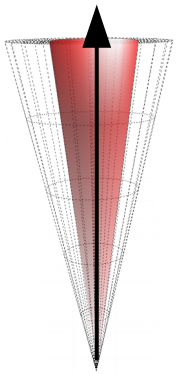
Boosted Leptons



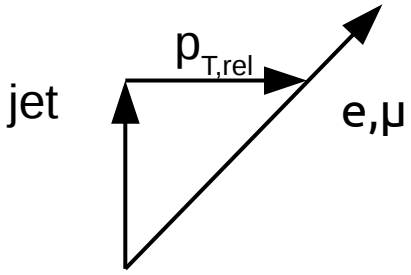


- Lepton often used to reject QCD
- QCD often has fake or low p_T leptons with close by jets

- p_T dependent isolation
  - Sum relative p_T inside cone R_{min} around lepton
  - $R_{min} \sim 1/p_T$, $0.05 < R_{min} < 0.2$

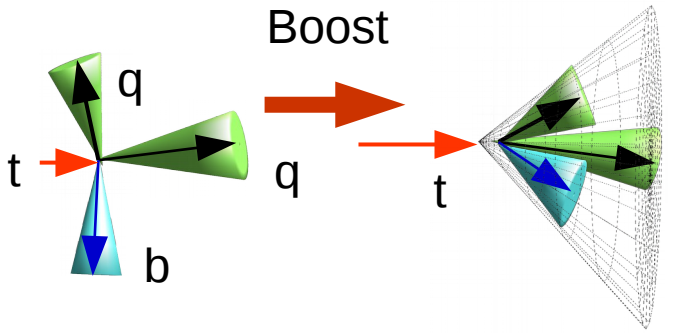


- Relative transverse momentum & angular separation
  - $p_{T,rel} > 40$ GeV || $\Delta R(\text{jet}, l) > 0.4$



Hadronic signatures

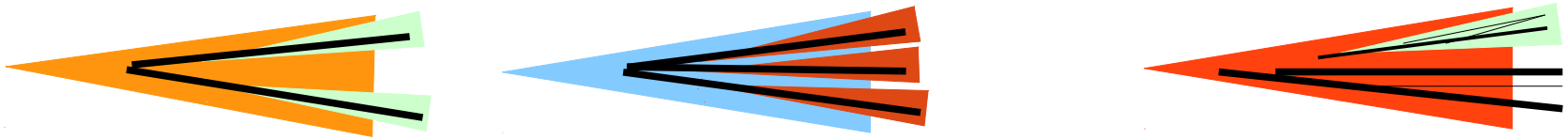
- Boosted objects often reconstructed within anti-k_T ΔR 0.8 jets
- W-, H- & t-tag based on Cambridge-Aachen reclustering with MMDT Soft-Drop



V-tag
- 2 prong
- W-tag, H-tag

t-tag
- 3 prong
- Jet p_T > 400 GeV

Subjet-b-tag



- Jet mass window
- Number of particles
- Mitigate soft radiation

- MMDT Soft-Drop with β=0
- N-Subjetiness ratio τ_n/τ_{n-1}
- Subjet-b-tag

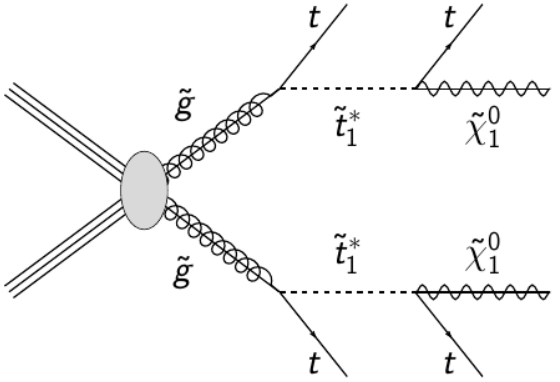
- B meson lifetime
- Decay properties

- Combined secondary vertex
  - Applied to different jets

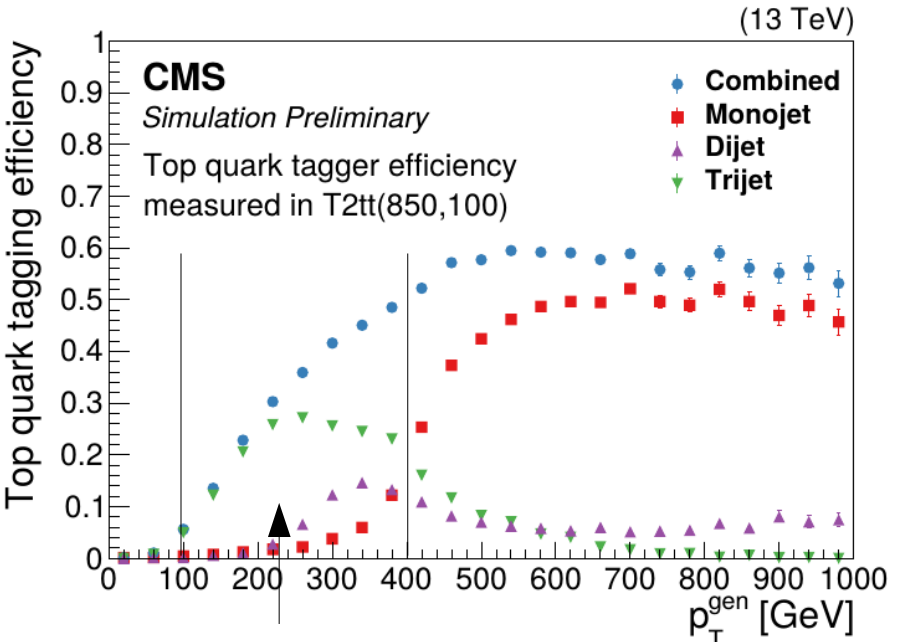
Squarks with t-tag

CMS PAS SUSY-16-050

Full 2016 Dataset



- All hadronic search channel
  - Veto on leptons
- Top reconstruction with anti-k_T jets:
  - Resolved: top with 3 ΔR=0.4 jets
    - Random forest
  - Merged W:
    - W-tag: mass within [65-100] GeV, $\tau_2/\tau_1 < 0.6$
    - Additional ΔR=0.4 jet
    - $0.85 < m_w/m_t < 1.25$
  - Merged top:
    - t-tag: mass within [105-210] GeV, $\tau_3/\tau_2 < 0.65$
  - Combinatorics reduced by ΔR(jet, jet) < 1.5 (1.0)
  - Final top mass between [100-250] GeV

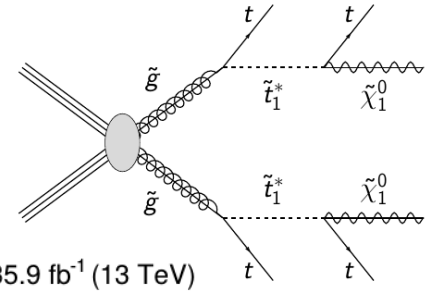


Efficiency at medium p_T region

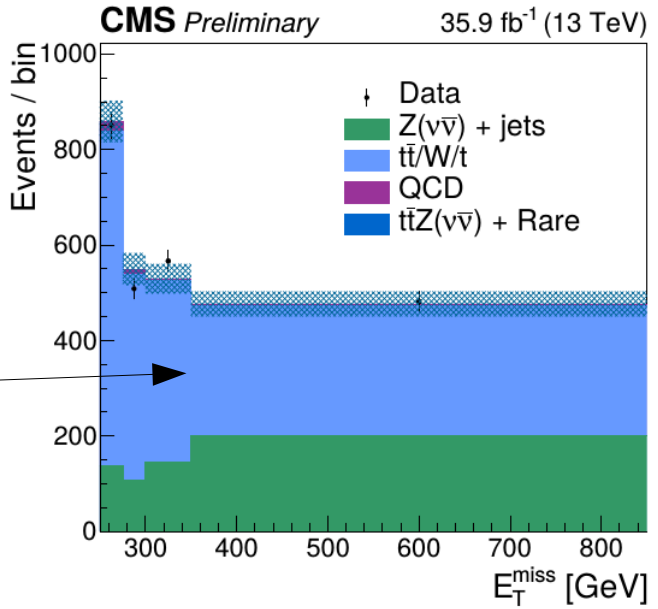
Squarks with t-tag

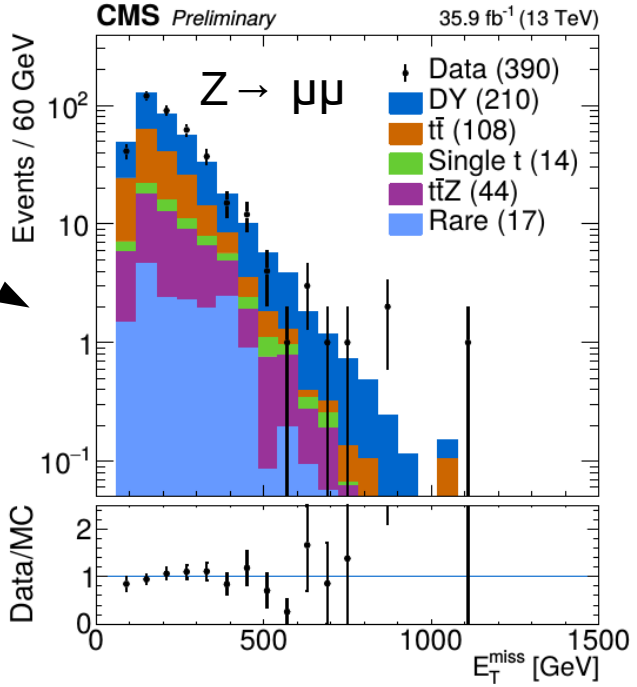
CMS PAS SUSY-16-050

Full 2016 Dataset



- Background estimation
  - Leptonic W processes
    - 1 lepton control region
    - Transfer function from simulation validated in orthogonal region
  - $Z \rightarrow \nu\nu$
    - Opposite sign dilepton sample
    - Simulation is corrected for differences in this channel
  - QCD
    - Low missing E_T region used for correction
  - Other backgrounds are taken from simulation

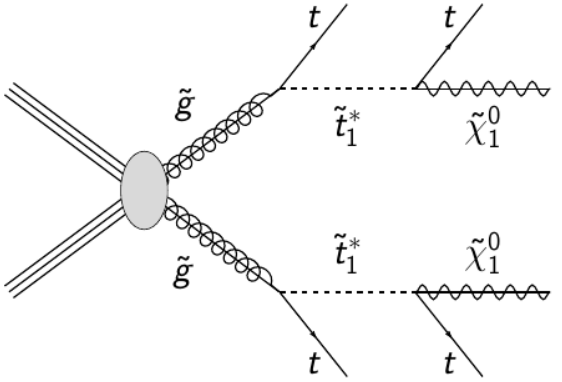




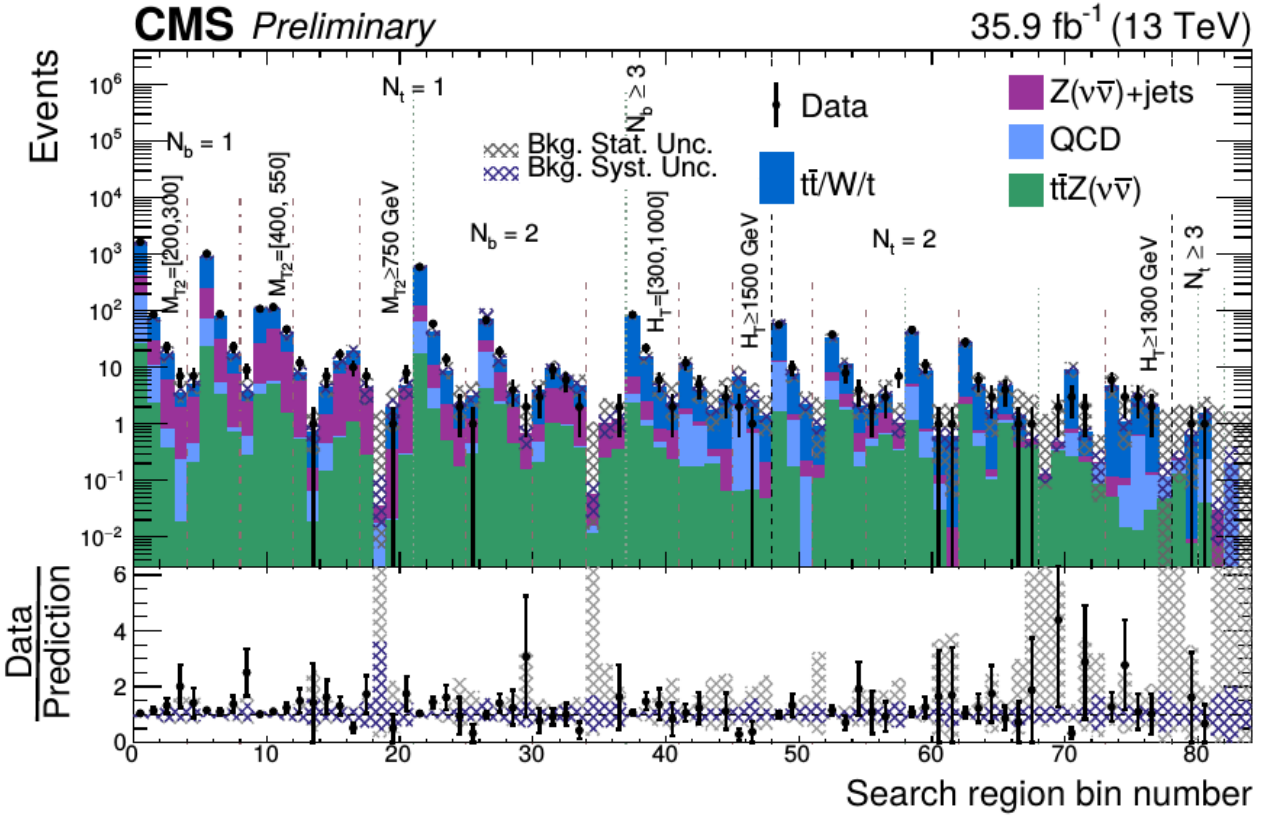
Squarks with t-tag

CMS PAS SUSY-16-050

Full 2016 Dataset



- Selection
  - High hadronic activity H_T > 300 GeV
  - Missing E_T > 250 GeV
  - At least 1 top and 1 b-tag
  - Transverse mass M_{T2} > 200 GeV



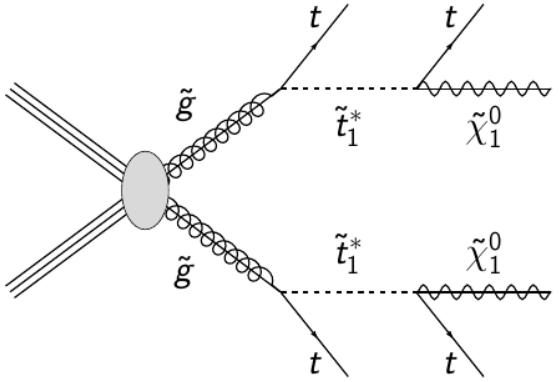
- 84 categories based on top, b-tag, missing E_T and M_{T2}
- Information for reinterpretation provided

  CMS PAS SUSY-16-050

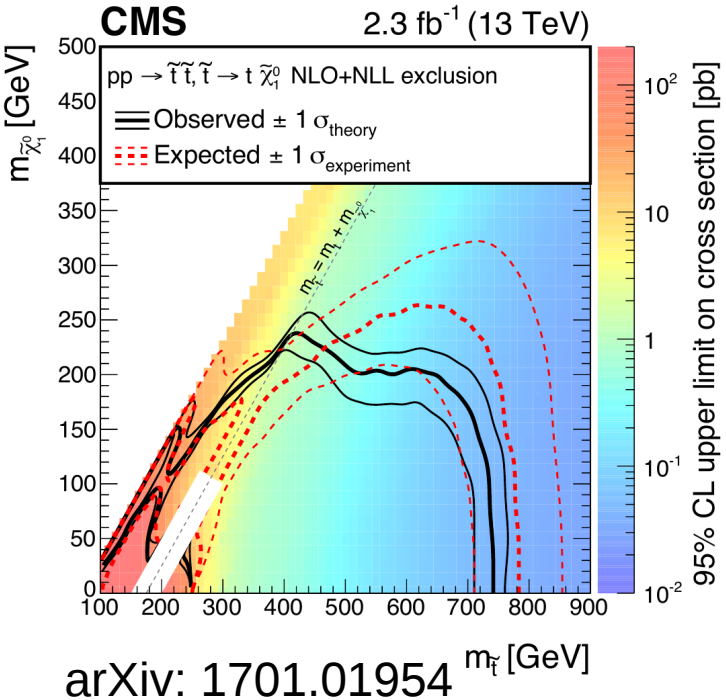
Squarks with t-tag

CMS PAS SUSY-16-050

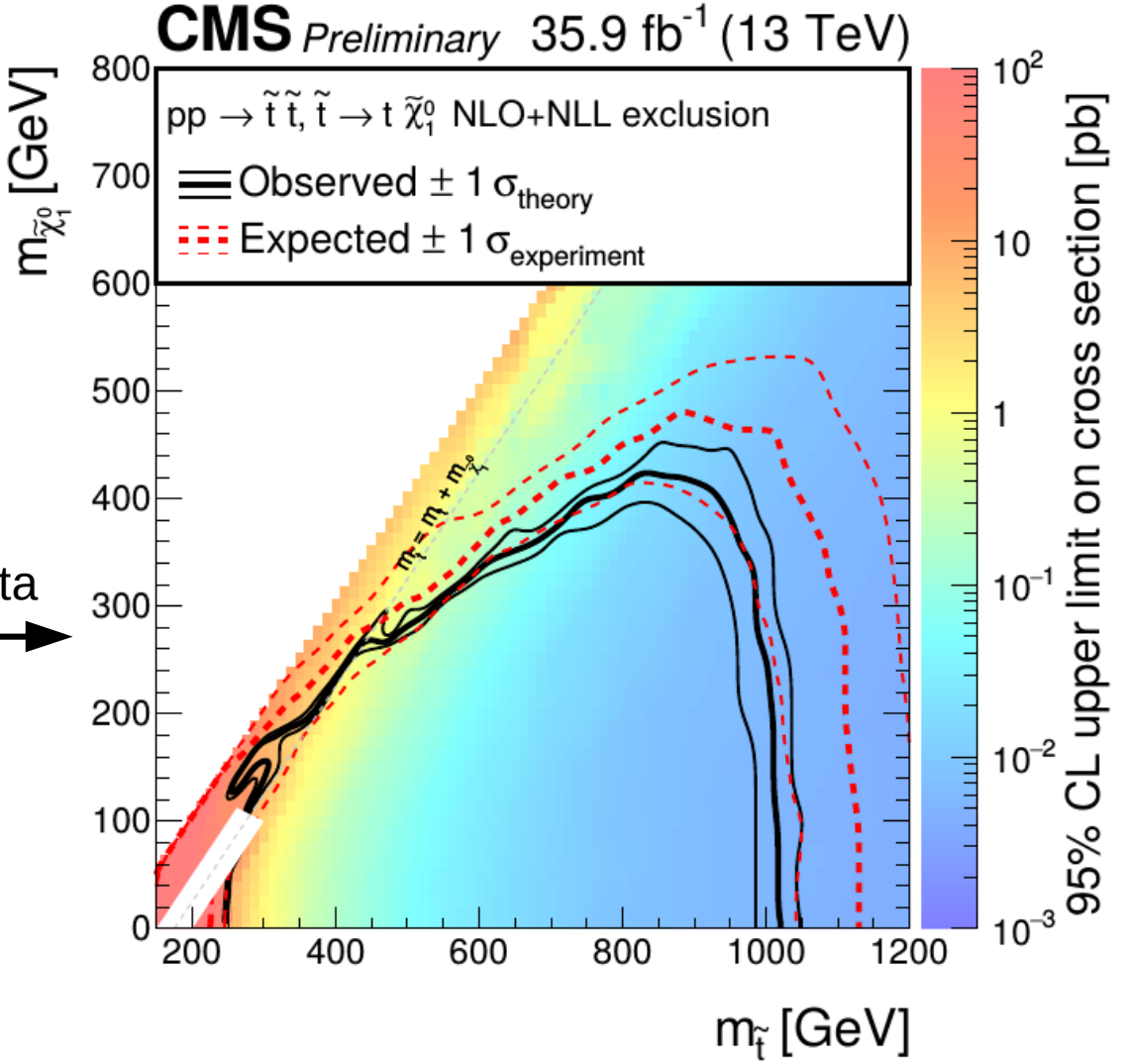
Full 2016 Dataset



- 15 times more data
- Top reconstruction improvements
  - New pairing algorithm
  - Use of W- & t-tag algorithms



~15 x Data

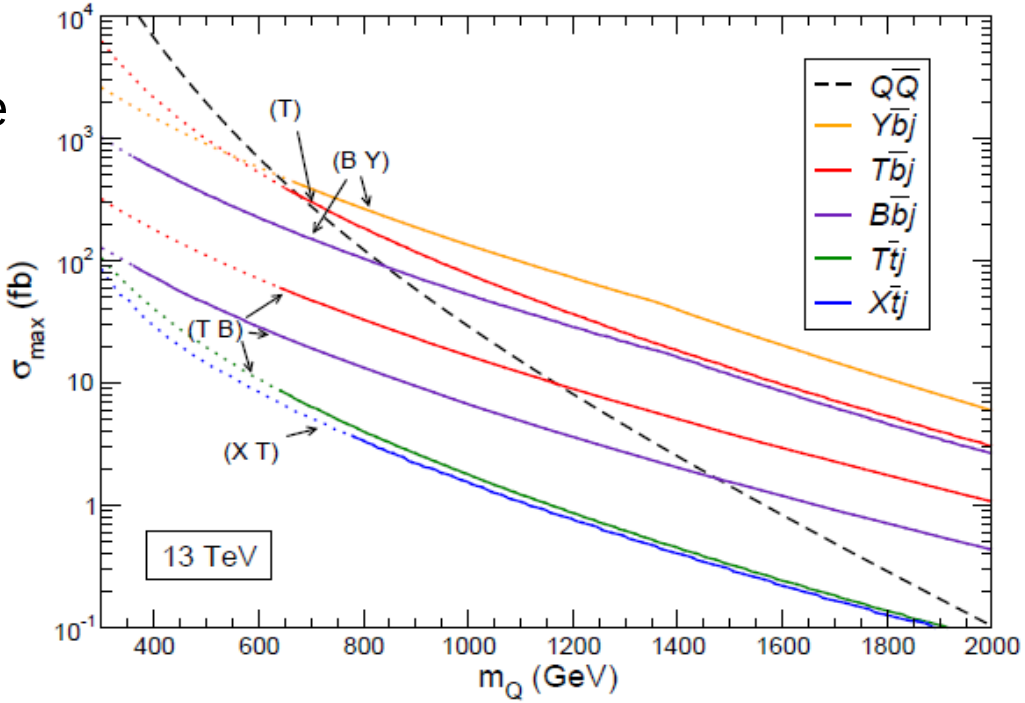


arXiv: 1701.01954

Vector like quarks

- Quarks with left & right handed couplings
  - Preferred couplings: t, b & W, H, Z
  - Different multiplets & particles possible
    - T(2/3), B(-1/3), X(+5/3), Y(-4/3)
- Motivated by many theories
  - Composite Higgs
  - little Higgs
  - warped extra dimensions, …
- Production Mechanism
    - Single → Ewk
    - Pair → QCD

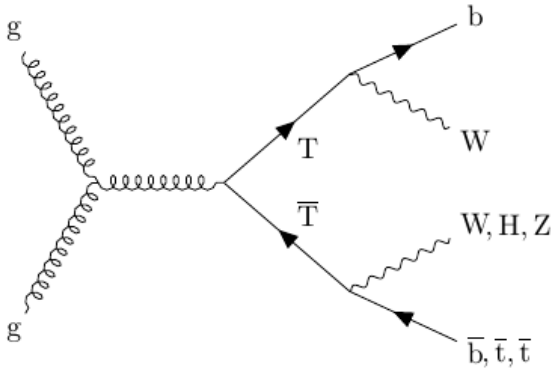
10.1103/PhysRevD.88.094010



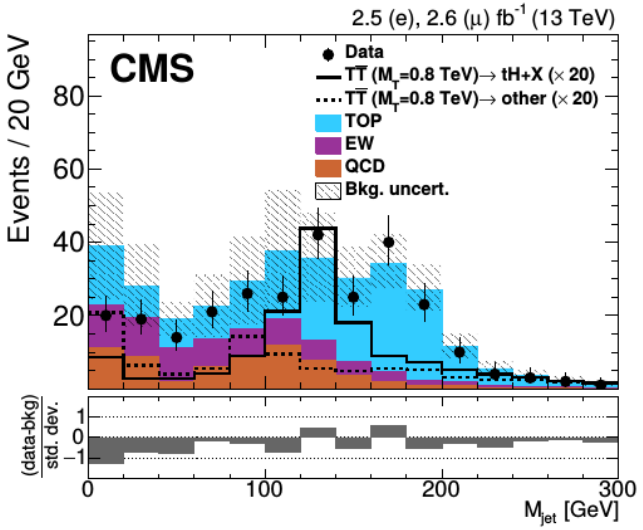
BB and TT single lepton

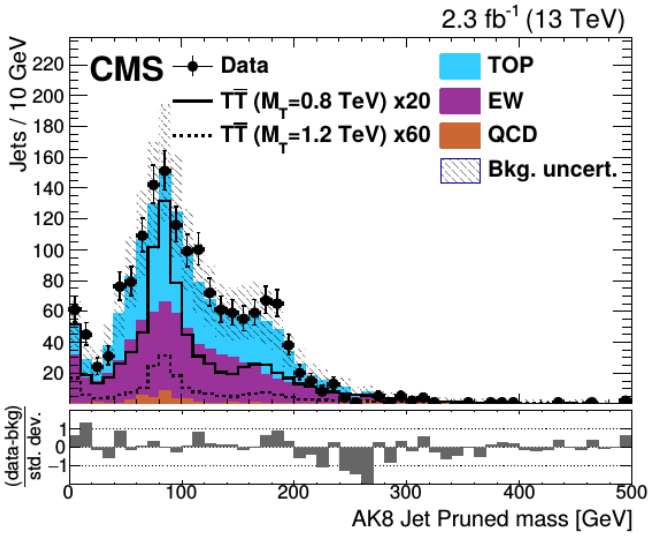
arXiv:1706.03408

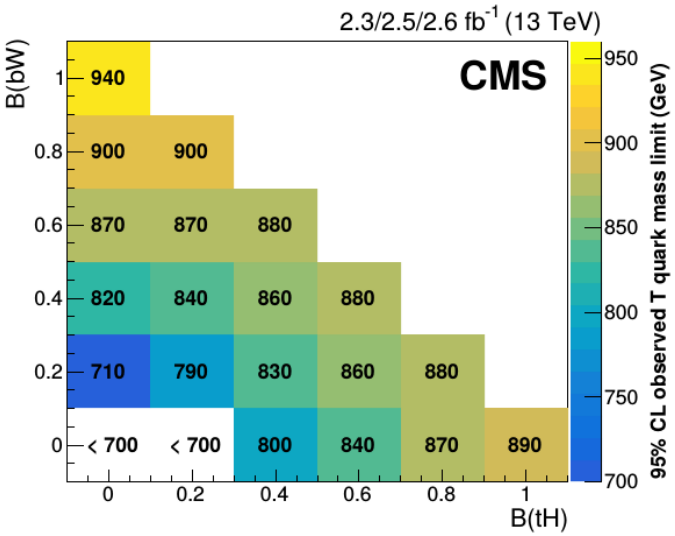
Combination of analyses (2015)



- Boosted Higgs channel
  - H-tag: mass within [60,160] GeV, subjet-b-tag, p_T > 300 GeV
  - H_T + missing E_T + lepton p_T: S_T > 800 GeV
  - 2 high p_T jets
  - Sensitive variable S_T
- Boosted W channel
  - W-tag: mass within [65-105], $\tau_2/\tau_1 < 0.6$
  - 3 high p_T jets
  - Missing E_T > 75 GeV
  - Sensitive variable min[M(l,b)]



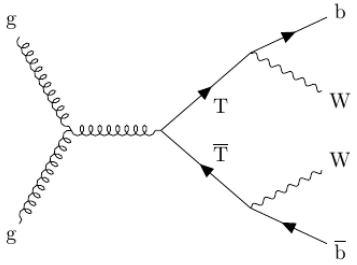




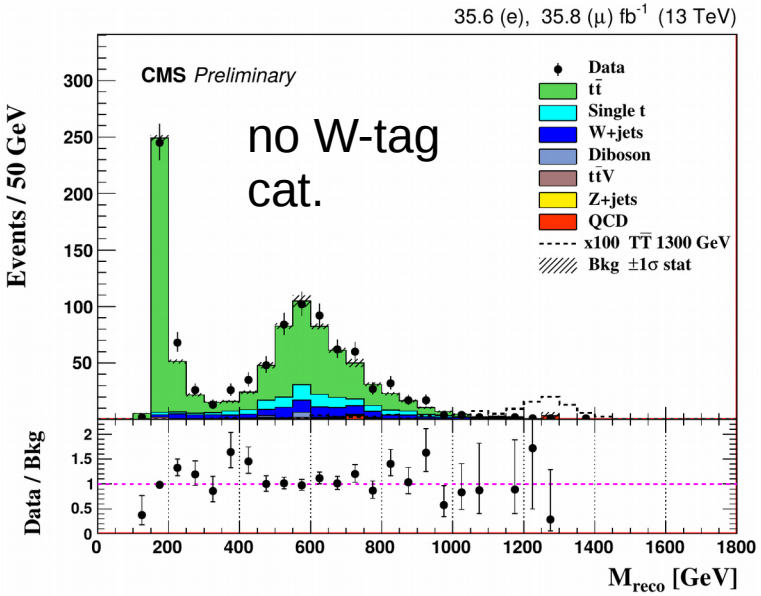
TT single lepton

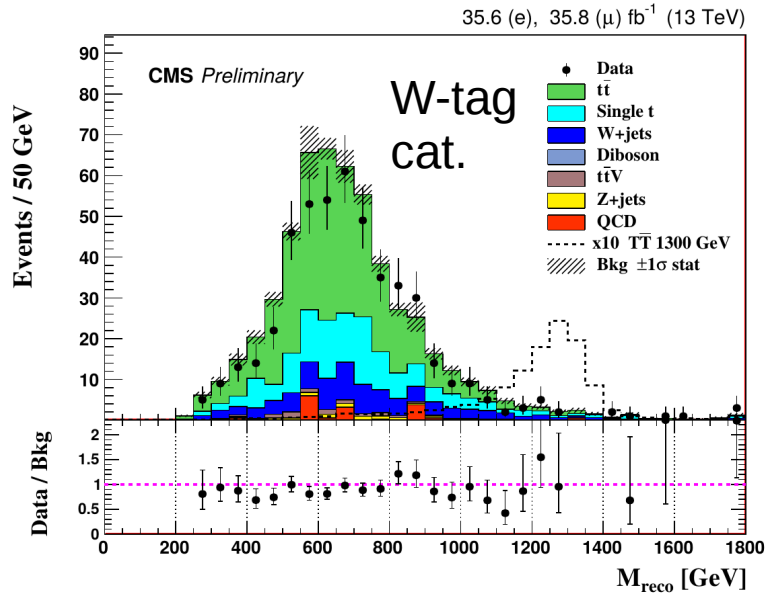
CMS PAS B2G-17-003

Full 2016 Dataset



- 1 isolated lepton
- 4 jets
- Missing E_T > 30 GeV
- High activity S_T > 1 TeV
- W-tag: mass within [60-100] GeV
- Kinematic fit
  - 4 jets or W-tag subjets + 2 jets
  - Lepton
  - Missing E_T as neutrino estimate

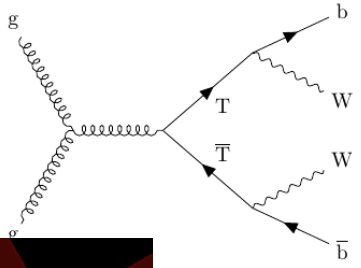


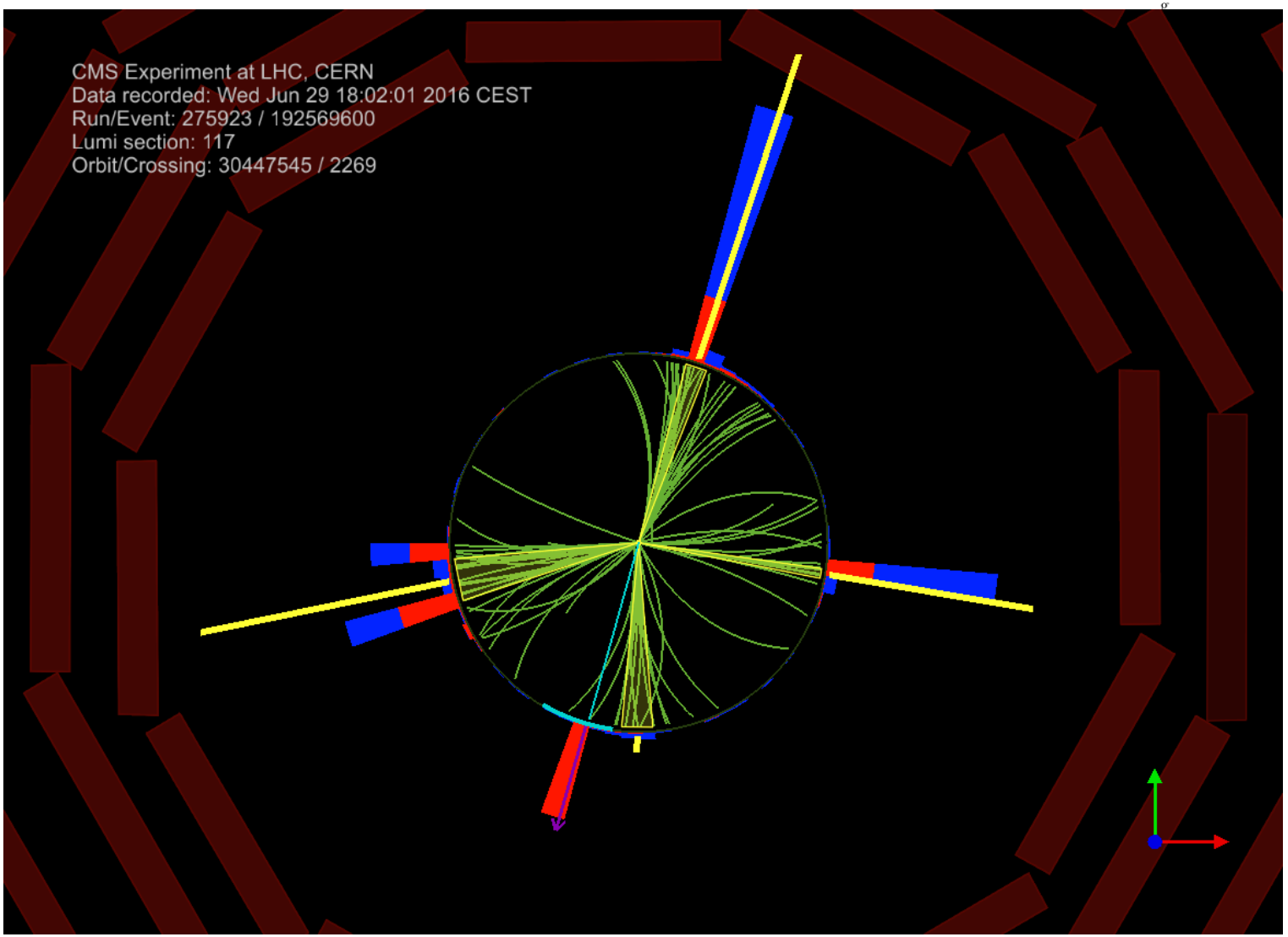


TT single lepton

CMS PAS B2G-17-003

Full 2016 Dataset



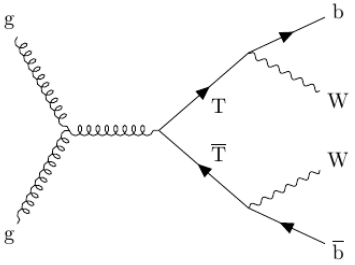


- Event with highest reconstructed mass of 2275 GeV

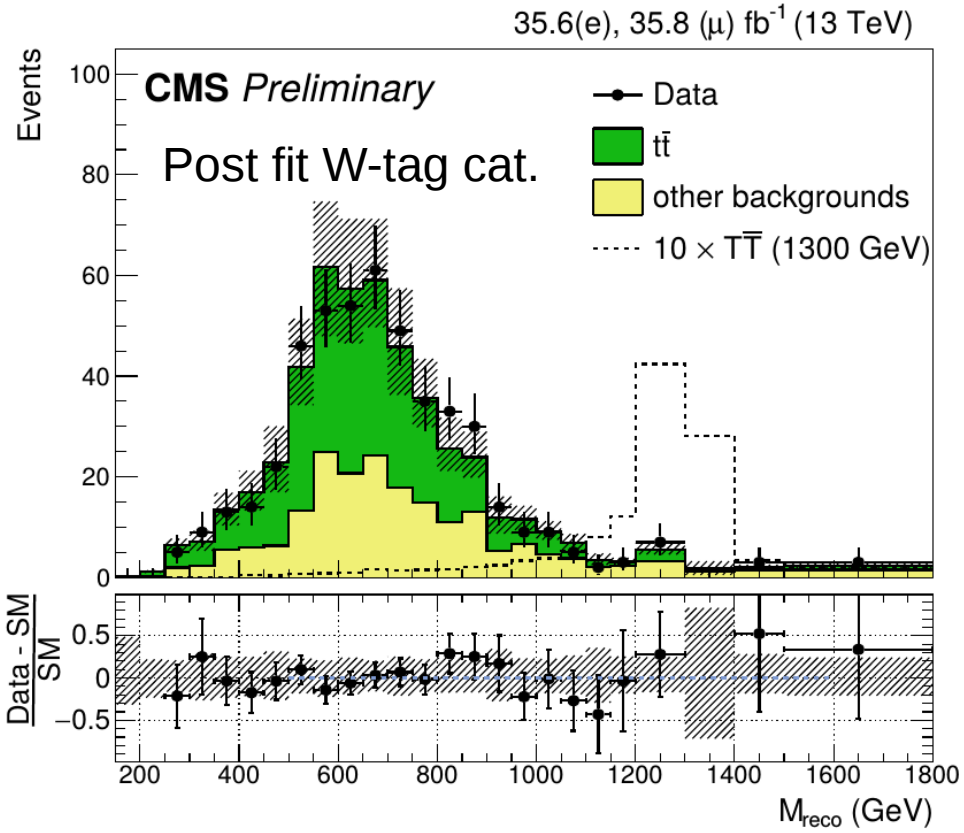
TT single lepton

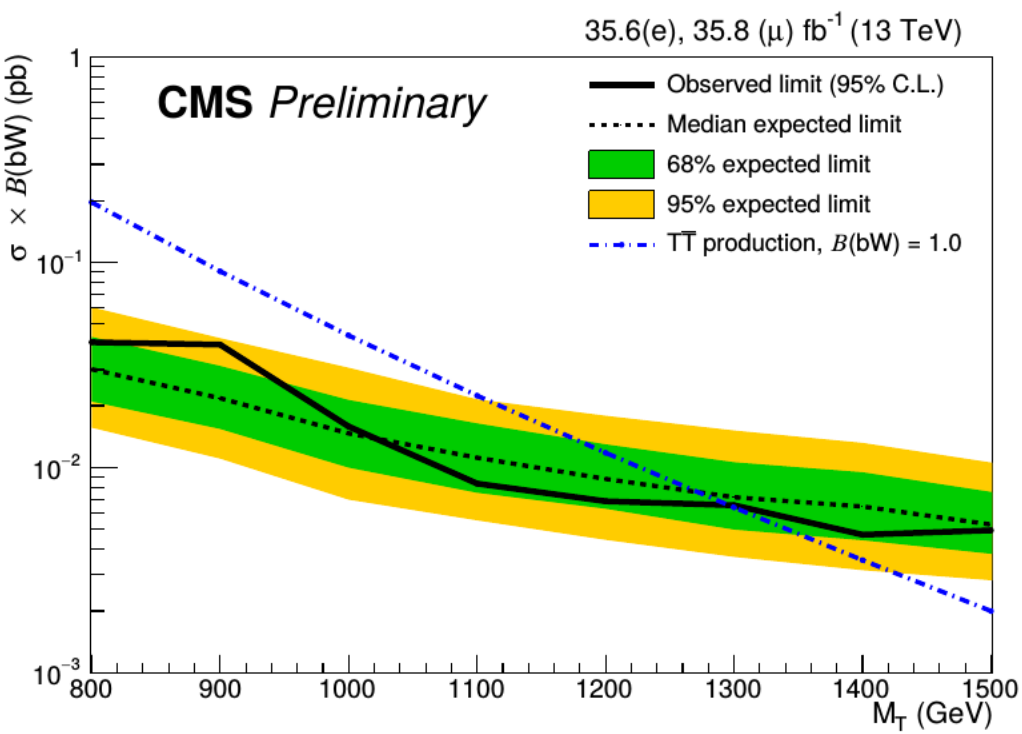
CMS PAS B2G-17-003

Full 2016 Dataset



- The strong pair production of T/Y quarks can be excluded with 95% CL below masses 1295 GeV (1275 GeV expected)
- More sensitive then 2015 combination in T→ bW channel

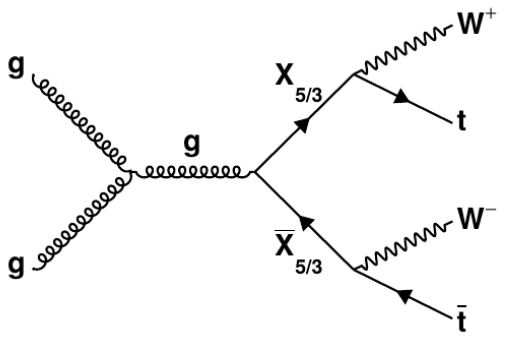




XX single lepton

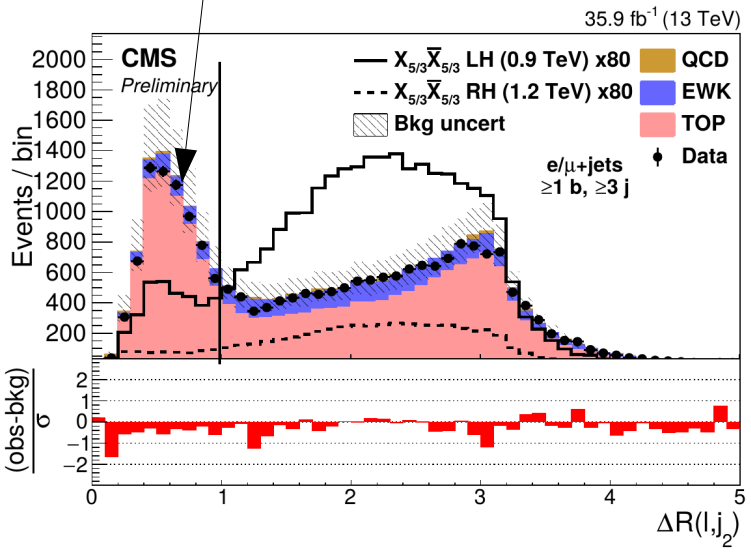
CMS PAS B2G-17-008

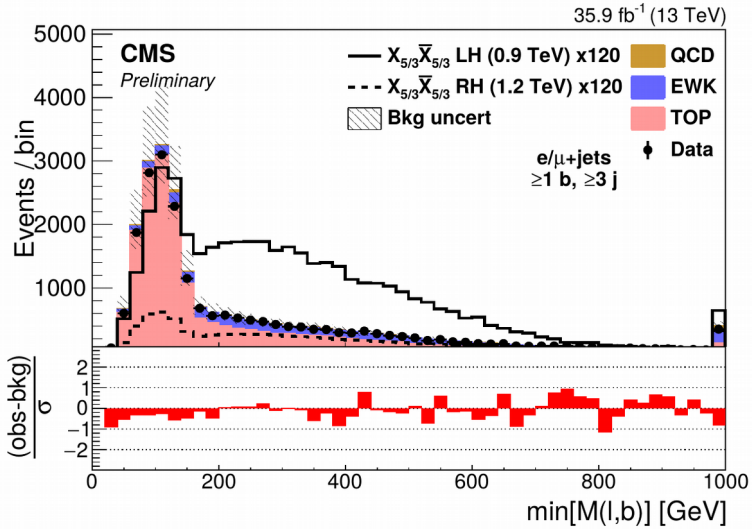
Full 2016 Dataset



- Selection
  - Exactly 1 lepton with angular separation
  - High missing E_T > 100 GeV
  - Hadronic activity H_T > 300 GeV
  - Jet with p_T > 450 GeV (150 GeV)
  - At least 1 b-tag
  - Distance lepton- second jet $\Delta R(l,j_2) > 1$
- Tags
  - W-tag: mass within [65-105] GeV, $\tau_2/\tau_1 < 0.6$
  - t-tag: mass within [105-220] GeV, $\tau_3/\tau_2 < 0.81$
- Most sensitive variable min[M(l,b)]

Validation region





XX single lepton

CMS PAS B2G-17-008

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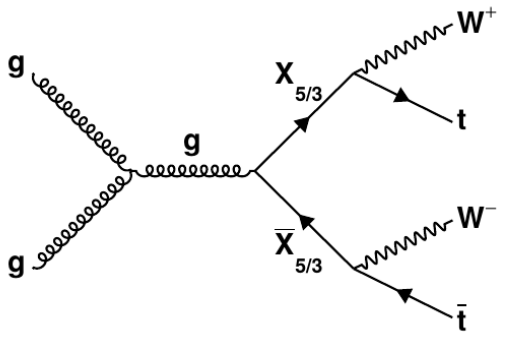
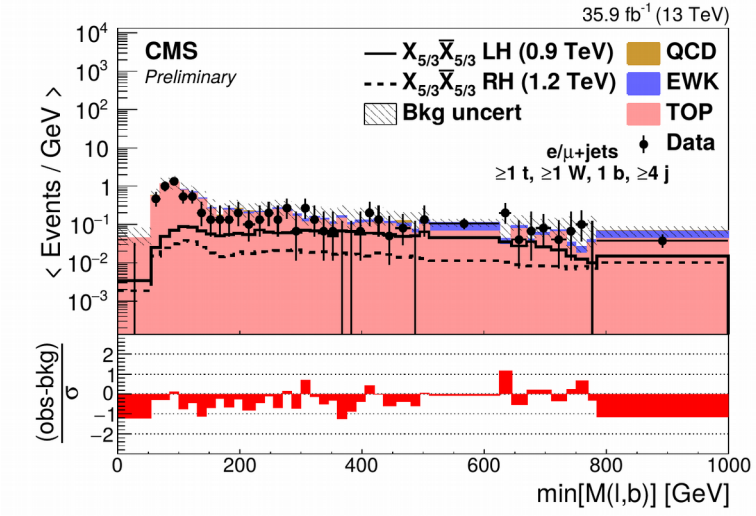
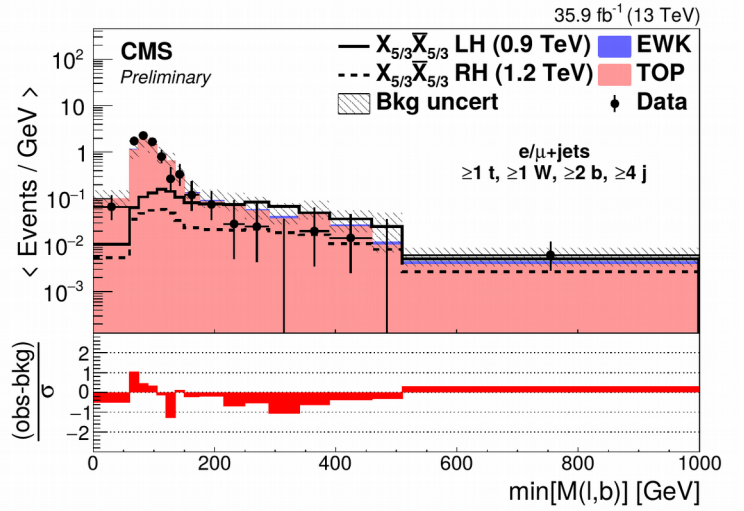
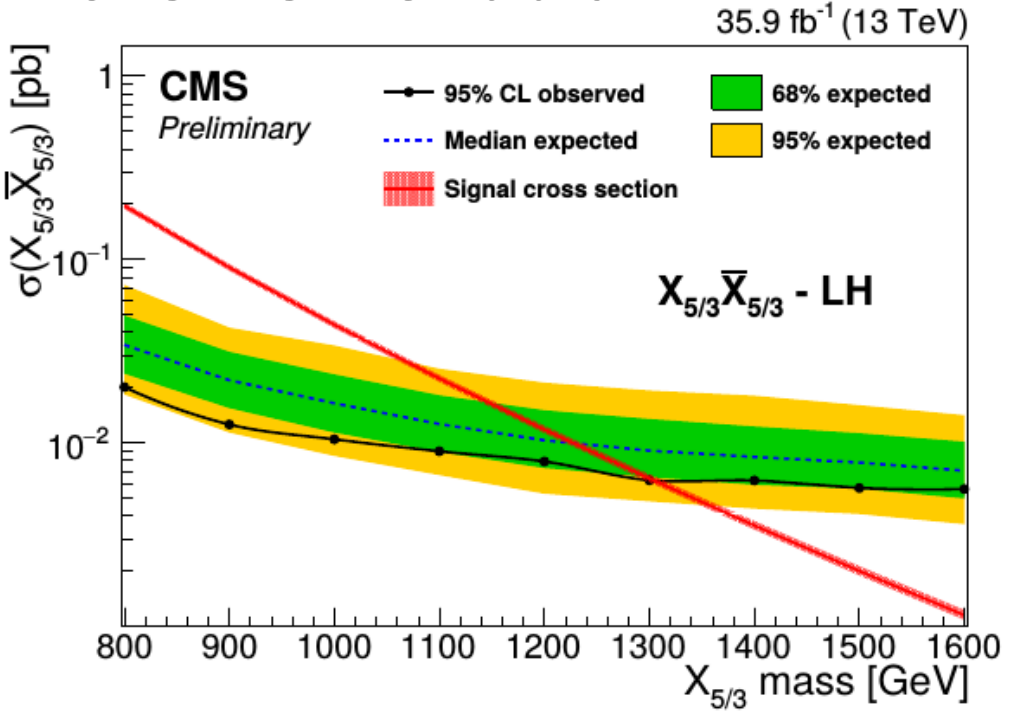






- 16 categories based on
  - Lepton flavor
  - W-tag, b-tag, t-tag
- Excluded with 95% CL for masses below 1.32 (1.30) TeV
- Same sign dilepton analysis performed in CMS PAS B2G-16-019

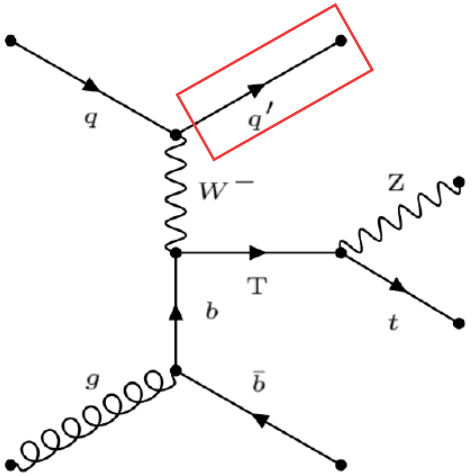


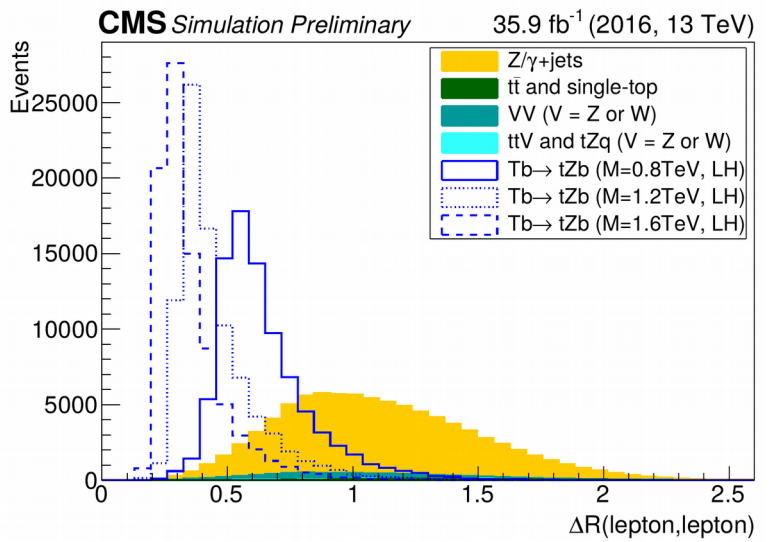
T dilepton

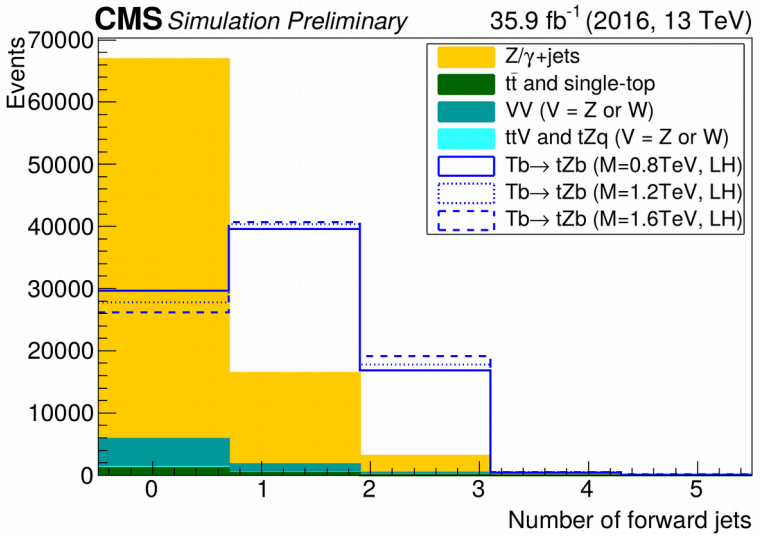
CMS PAS B2G-17-007

Full 2016 Dataset

- Leading lepton p_T > 120 GeV
  - Isolated
- Z-boson
  - Mass [70-110] GeV
  - ΔR(l,l) < 0.6-1.4
- Forward jet: anti-k_T jet with |η| > 2.4
- Top Reconstruction with anti-k_T jets:
  - Resolved:
    - 2 ΔR 0.4 jets + add. b-jet
  - Merged W:
    - W-tag: mass within [65-105] GeV, $\tau_2/\tau_1 < 0.6$ + add. b-jet
  - Merged top:
    - t-tag: mass within [105-220] GeV, $\tau_3/\tau_2 < 0.81$ + subjet-b-tag





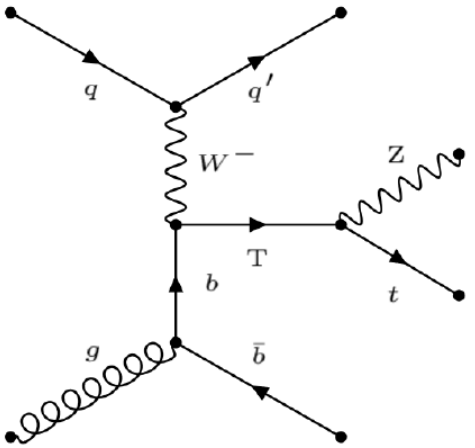


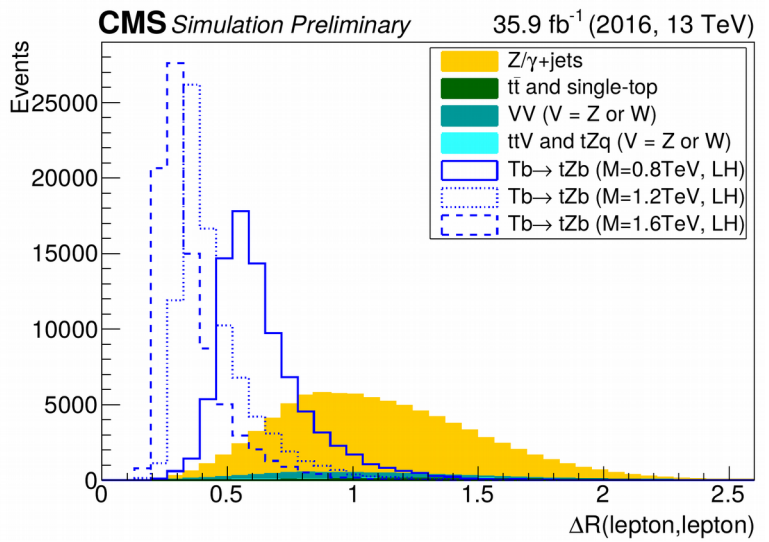
T dilepton

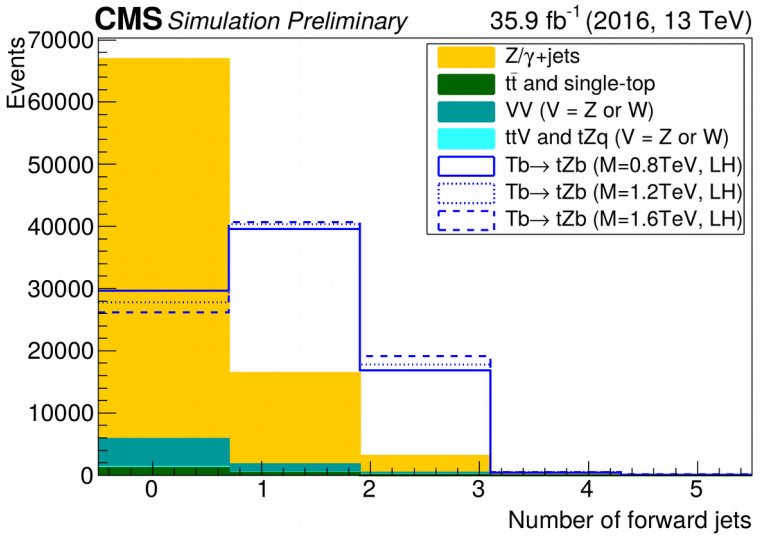
CMS PAS B2G-17-007

Full 2016 Dataset

- Leading lepton p_T > 120 GeV
  - Isolated
- Z-boson
  - Mass [70-110] GeV
  - ΔR(l,l) < 0.6-1.4
- Forward jet: anti-k_T jet with |η| > 2.4
- Top Reconstruction with anti-k_T jets:
  - Resolved:
    - 2 ΔR 0.4 jets + add. b-jet
  - Merged W:
    - W-tag: mass within [65-105] GeV, $\tau_2/\tau_1 < 0.6$ + add. b-jet
  - Merged top:
    - t-tag: mass within [105-220] GeV, $\tau_3/\tau_2 < 0.81$ + subjet-b-tag





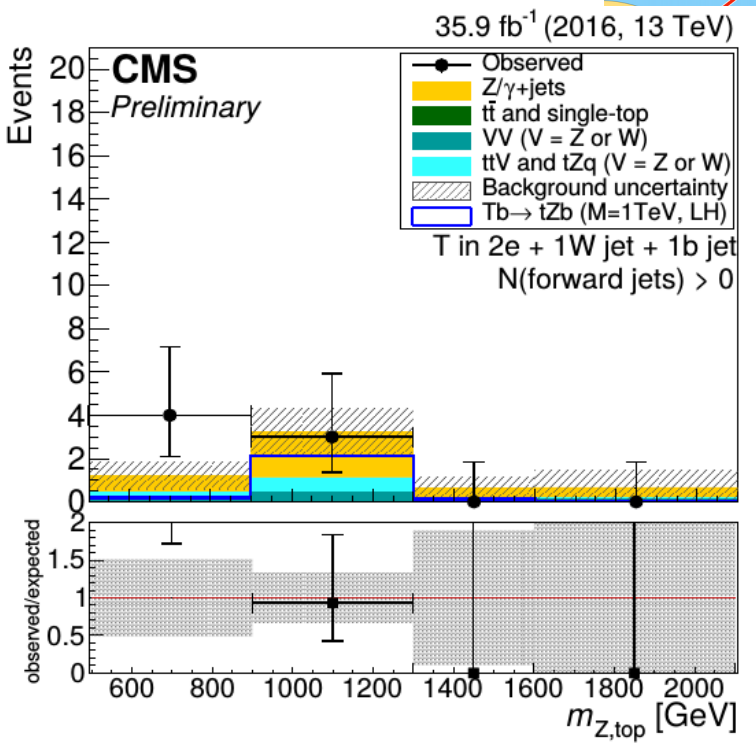


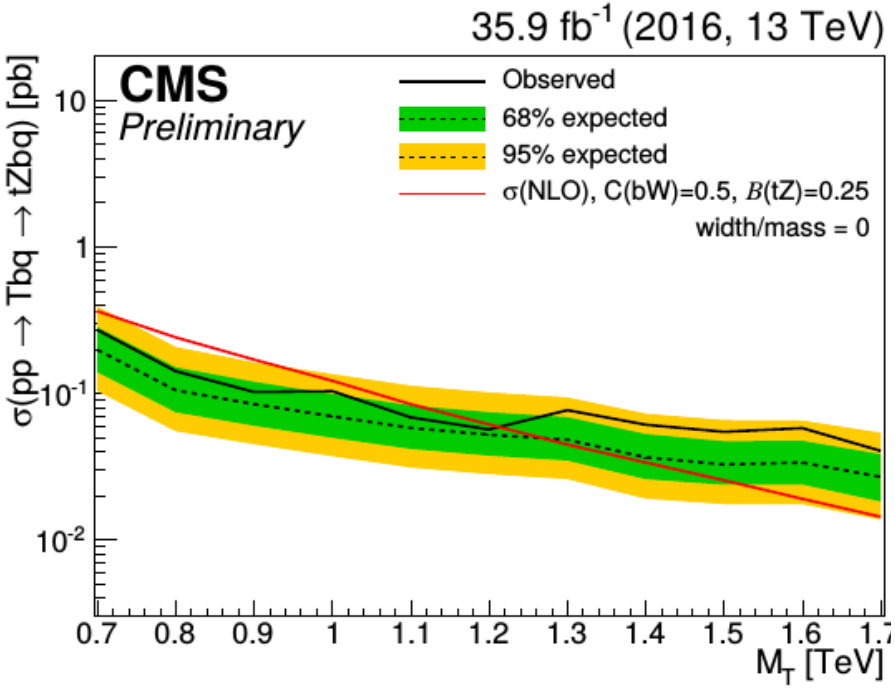
T dilepton

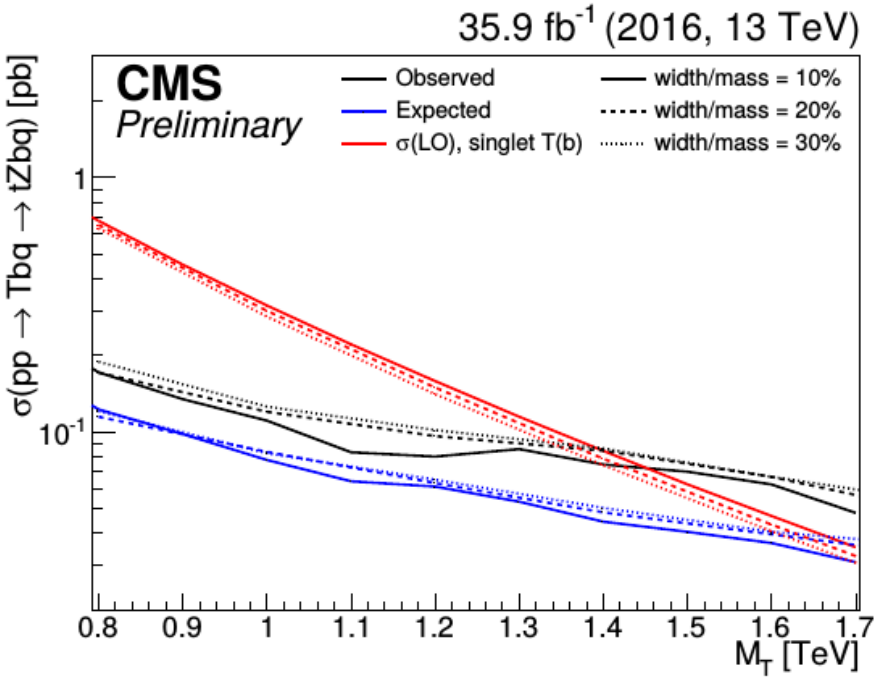
CMS PAS B2G-17-007

Full 2016 Dataset

- 9 categories based on
  - Top topology
  - Lepton flavor
  - Forward jet
- Background extrapolated from control regions
- Width dependency studied for the first time for VLQ



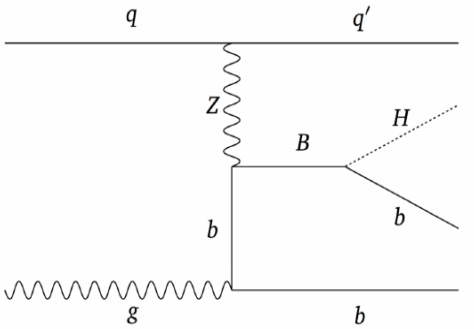




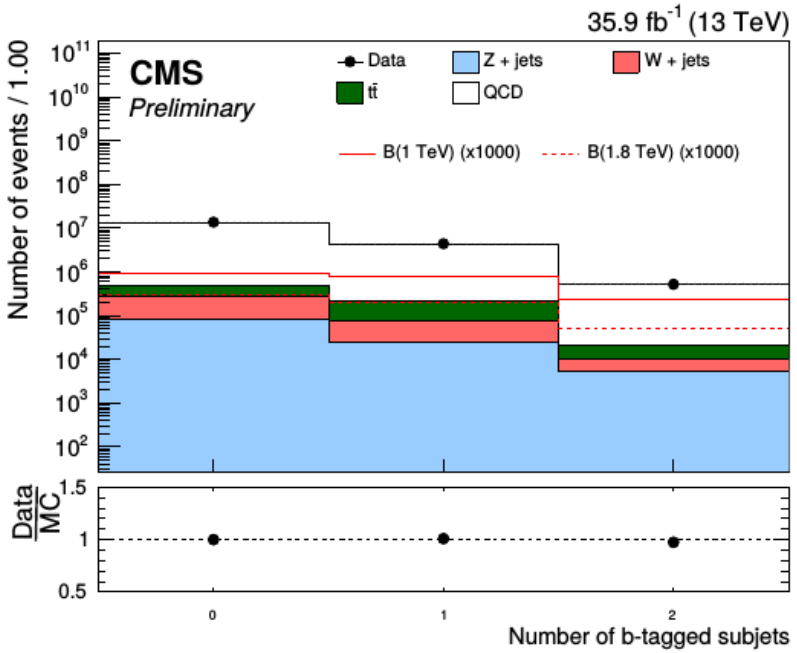
B all hadronic

CMS PAS B2G-17-009

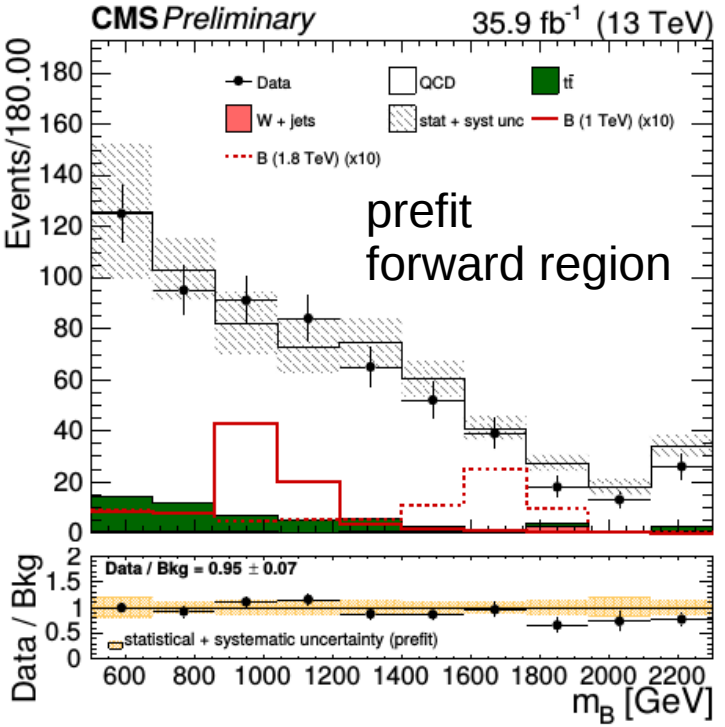
New 2016 result



- Lepton Veto
- High H_T > 950 GeV selection
- 2 high p_T jets
- At least 1 b-tag



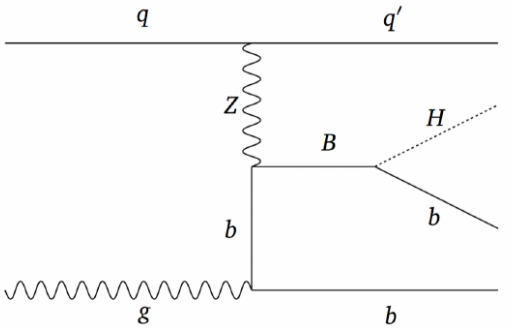
- H-tag: mass within [105-135] GeV + 2 subjet-b-tag
  - Signal efficiency ~10-20%
- Reconstructed B mass from H+b



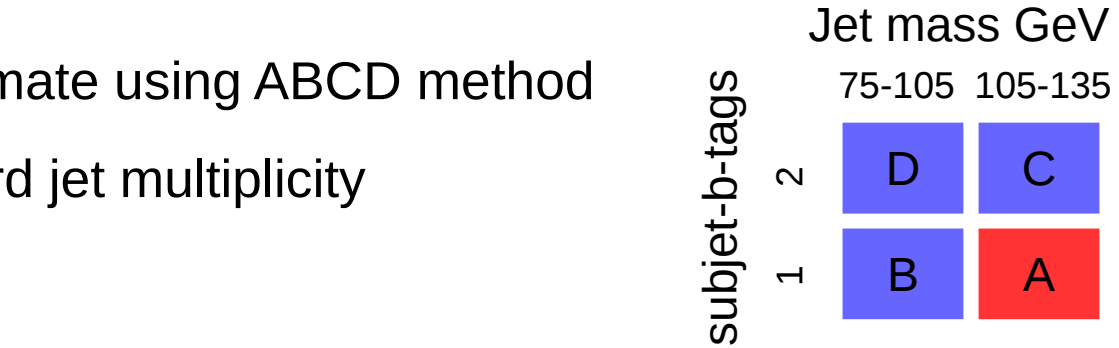
B all hadronic

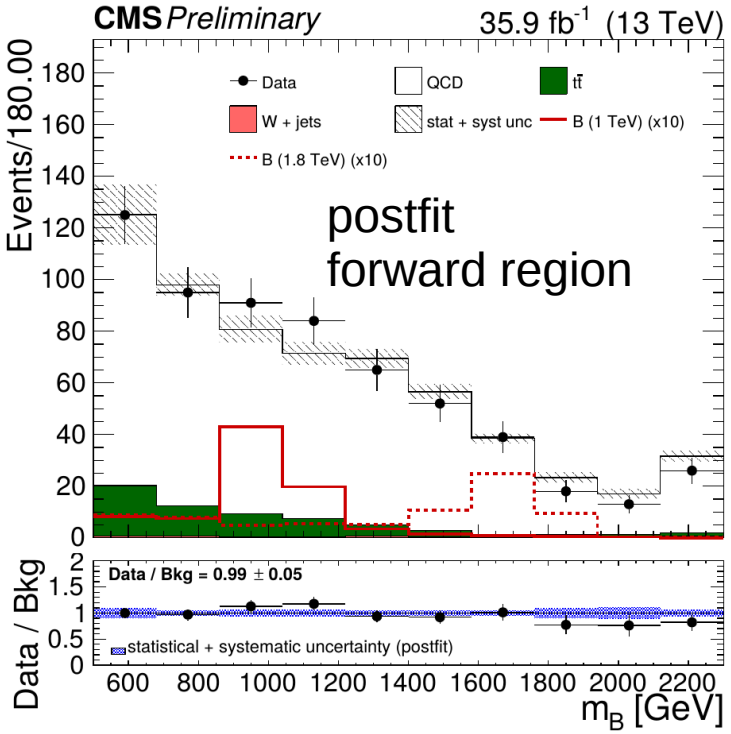
CMS PAS B2G-17-009

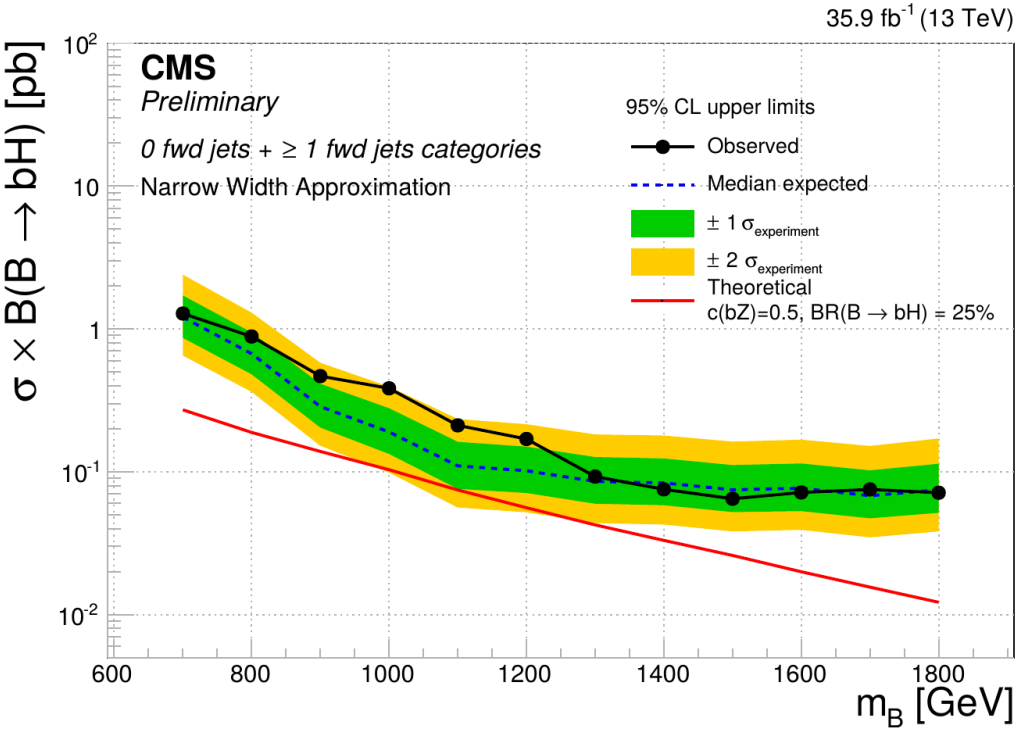
New 2016 result



- Data driven background estimate using ABCD method
- 2 categories based on forward jet multiplicity

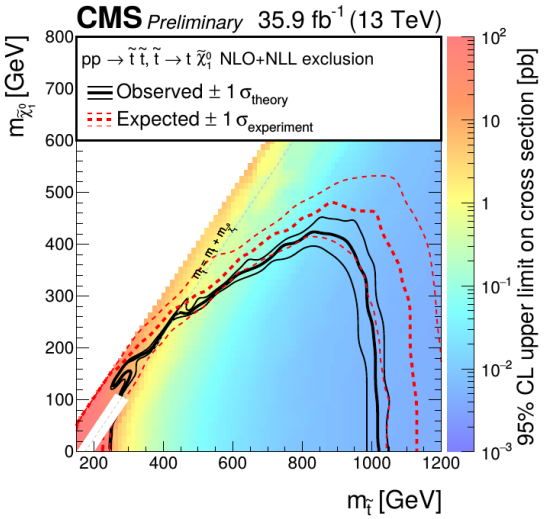


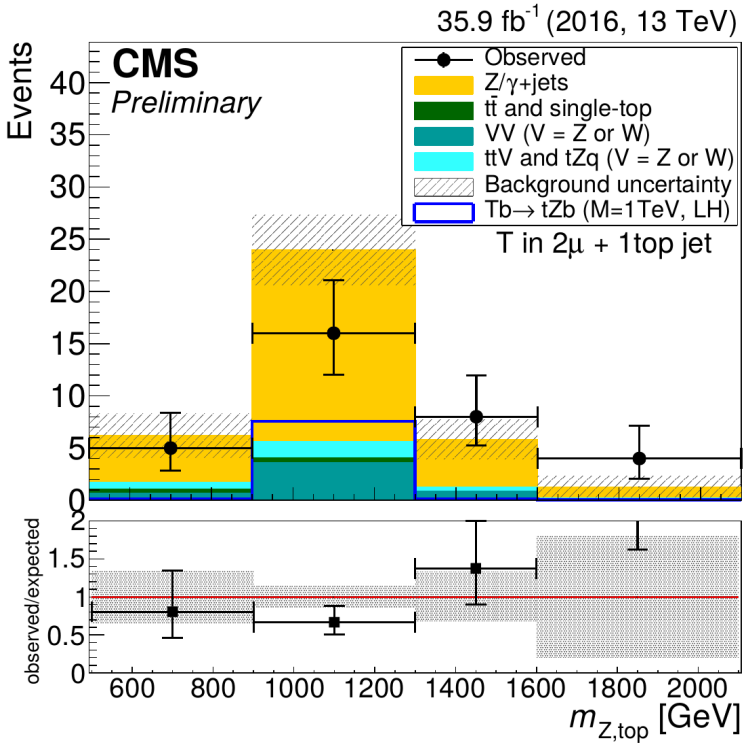


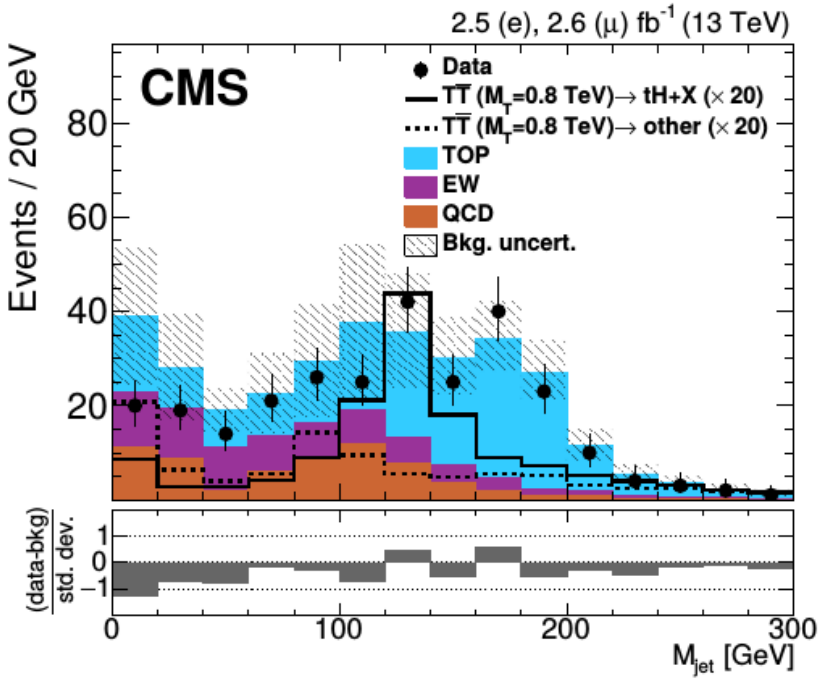


Summary

- Search program for a plethora of final states
- Boosted topologies extend the reach of the analysis for SUSY and VLQ and are broadly used
- Improvements in the algorithms translate to better search results







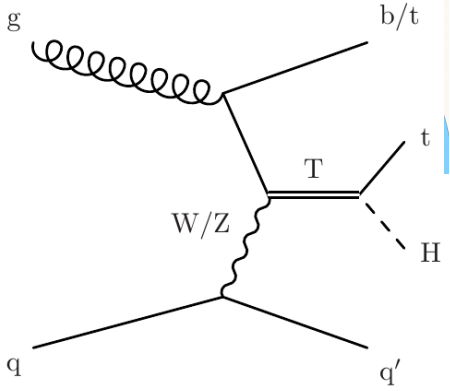
BOOST 2017

Additional Material

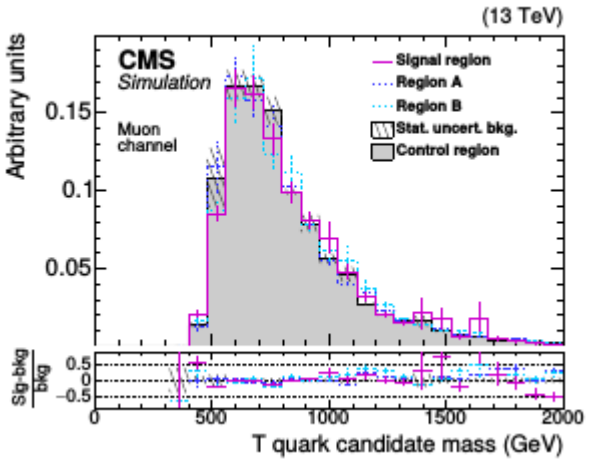
T single lepton

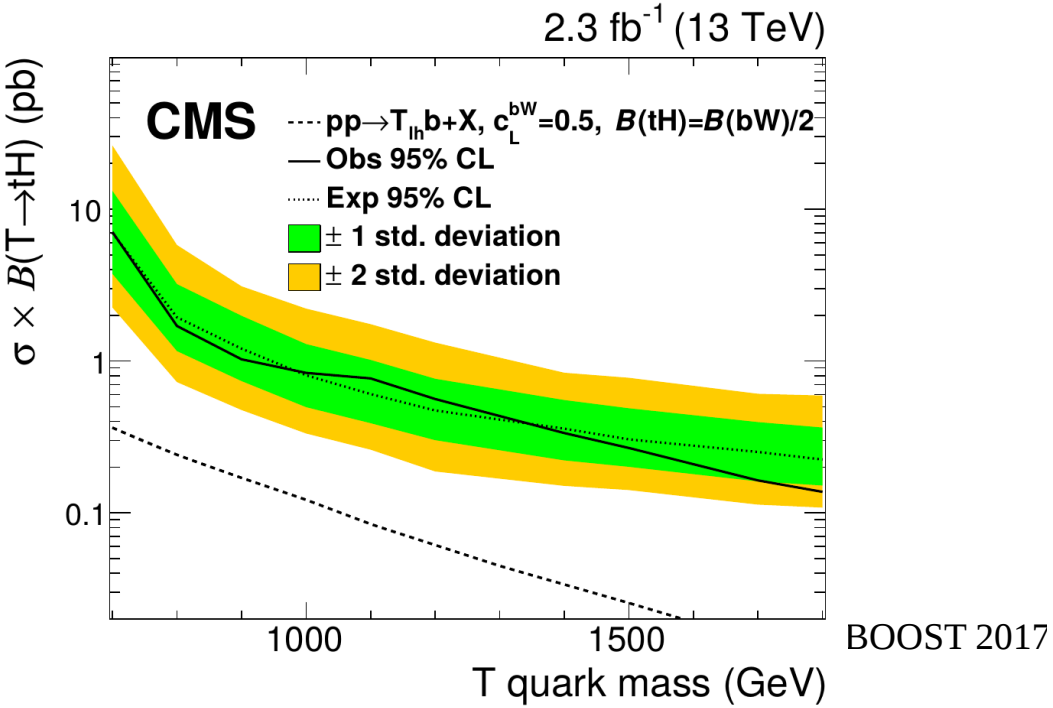
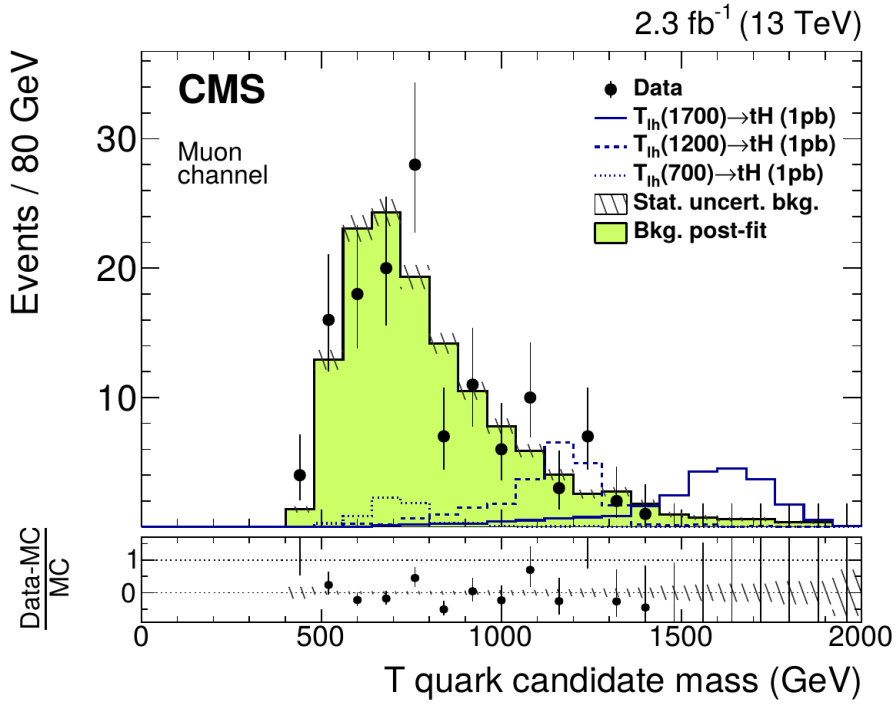
arXiv:1612.00999

2015 Dataset



- Leptonic top quark with angular separation
- High S_T > 400 GeV
- H-tag mass within [90-160] GeV, with subjet-b-tag
- Data driven background estimation
- Sensitive variable: reconstructed M_T





BOOST 2017