Search for Heavy Top Partners at the LHC

CMS Collaboration

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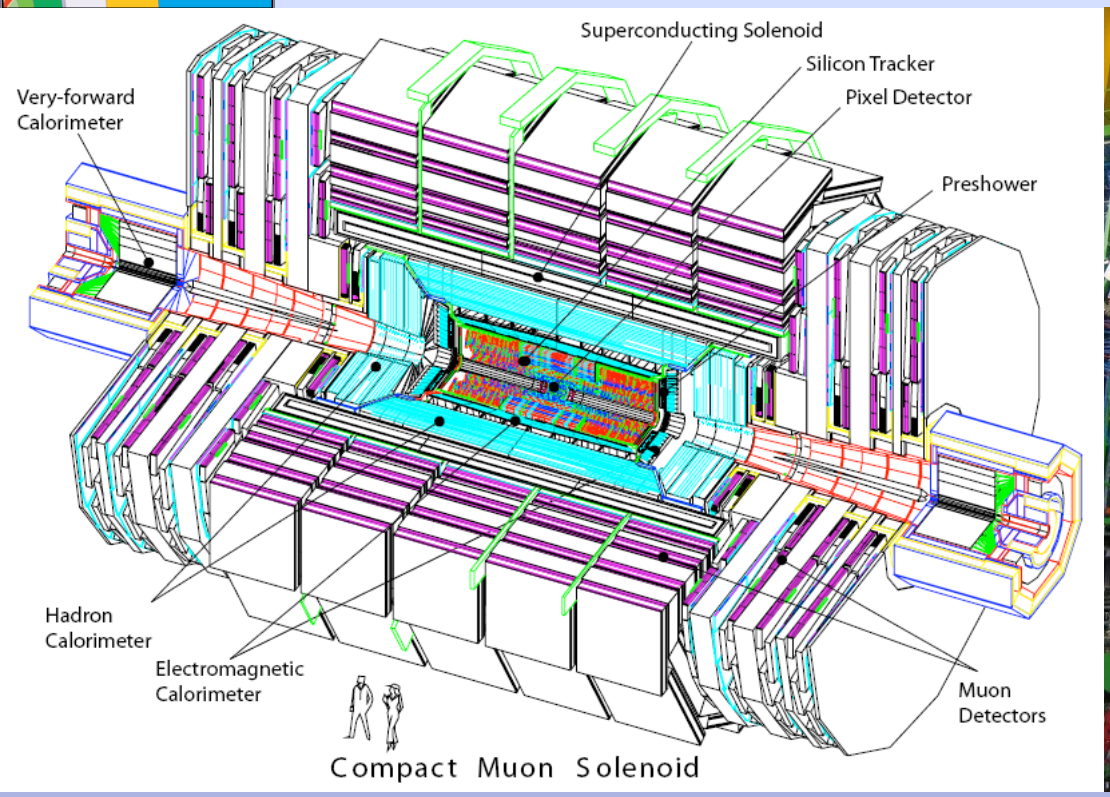
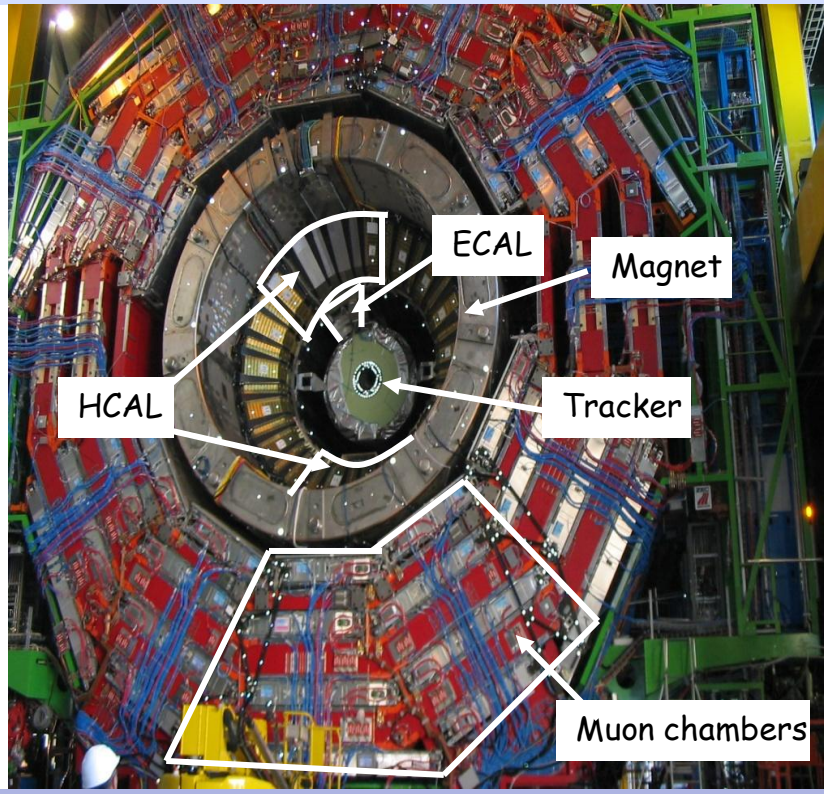
The CMS Experiment

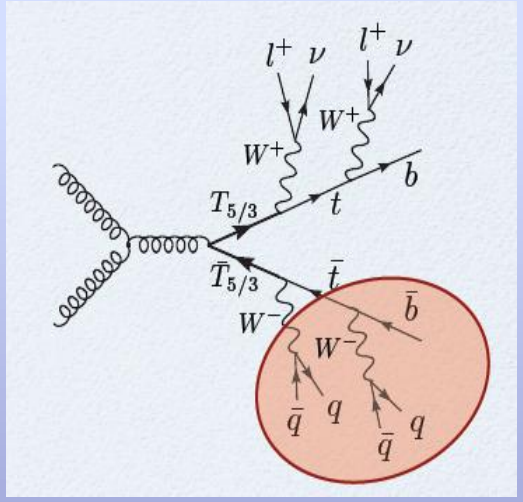


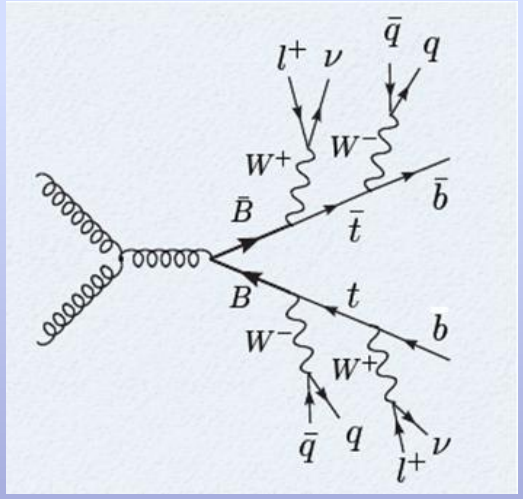


- Compact Muon Solenoid (CMS) Experiment
  - One of two general purpose experiments at the Large Hadron Collider (LHC)
  - Compact: 15m in diameter, 21.5m long, weighs 12500T

$T_{5/3}$ and B Top Partner Model

- Fermionic top partners arise from natural, non-supersymmetric solutions of the hierarchy problem
  - Pseudo-Goldstone boson Higgs
  - $T_{5/3}$ with $Q_e = 5/3$ and B with $Q_e = -1/3$ decay into W and top





- Signature: $l^{\pm}l^{\pm} + n$ jets $(n \geq 5)$
- tW invariant mass peak ($T_{5/3}$)

Model suggested by Contino and Servant: arXiv:0801.1679 (2008) "Discovering the top partners at the LHC using same-sign dilepton final states"

Signal and Physics Backgrounds

- Details in http://cms-physics.web.cern.ch/cms-physics/public/EXO-08-008-pas.pdf
- Mass points of 400, 500, 600 and 700 GeV for the $T_{5/3}$ and B
  - $T_{5/3}$ and B assumed to be degenerate in mass
- Principal physical backgrounds
  - $t\bar{t}W^{\pm} + jets$
  - $t\bar{t}W^{+}W^{-}$
  - $W^{+}W^{-}W^{\pm} + jets$
  - $W^{\pm}W^{\pm} + jets$
- Instrumental backgrounds
  - $t\bar{t} + jets$
  - $W^{\pm} + jets$
  - $Z + jets$
  - $QCD\ multi - jets$
- Event processing:
  - QCD multi-jets generated using Pythia
  - All other samples generated with MadGraph
    - Pythia MLM matching for events with fewer than 5 jets

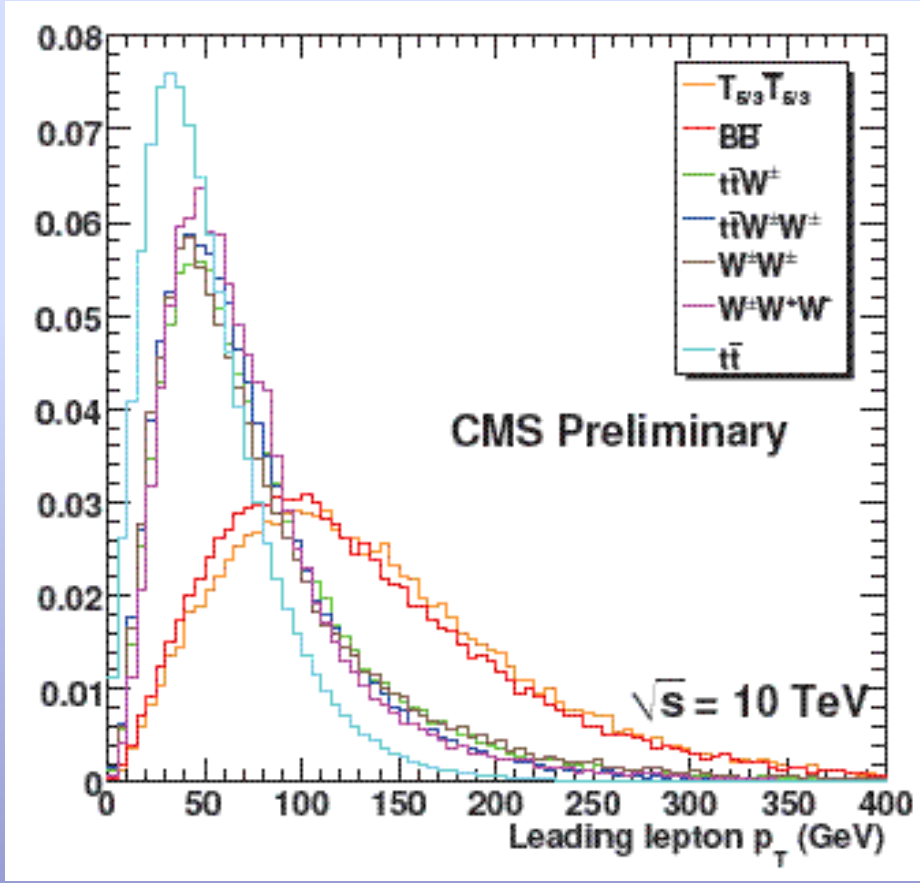
Trigger

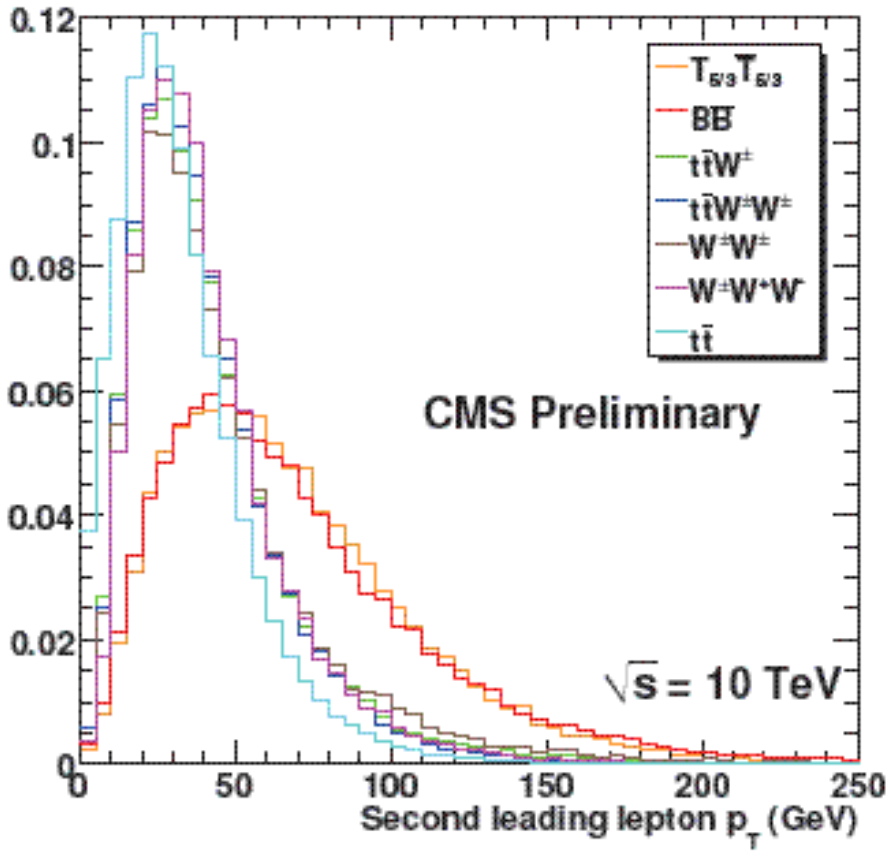
- Signature: 2 high p_T leptons (e or μ)
- Require one of two trigger paths:
  - Single muon based on combined muon system and tracker information with $p_T > 9$ GeV
  - Single electron with $E_T > 15$ GeV
- Efficiency of trigger selection is more than 99% for events passing kinematic cuts

Lepton ID and Isolation

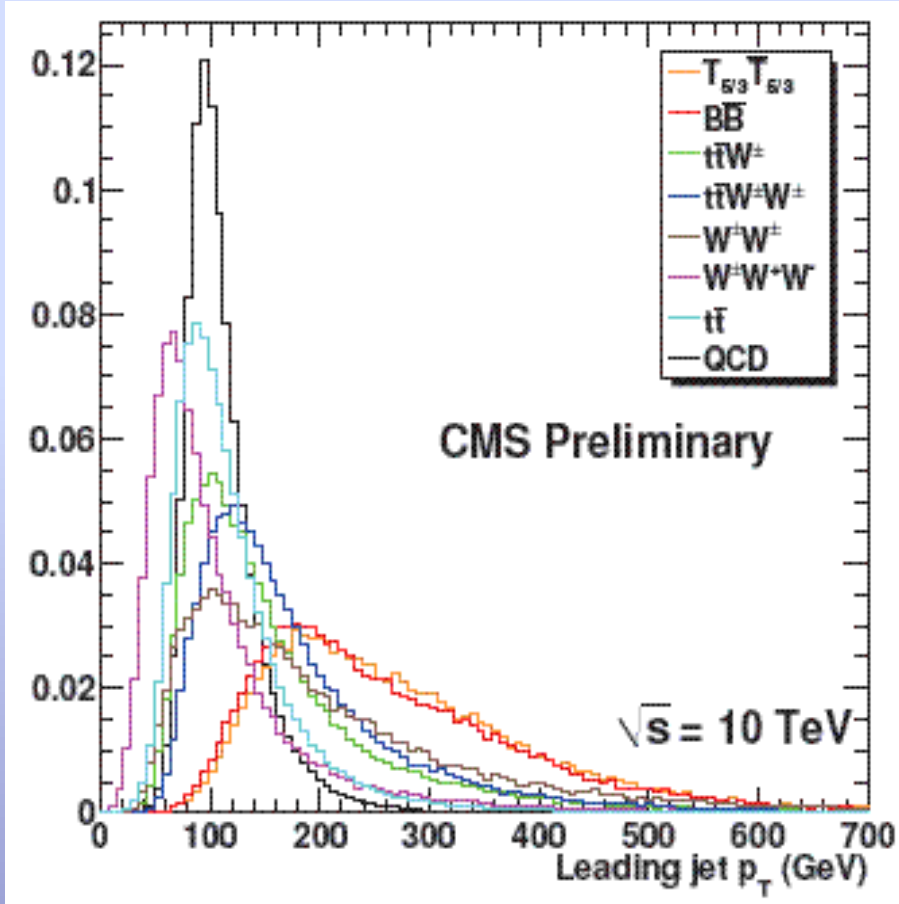
- Let E = scalar sum of the p_T of all particles in the tracker and calorimeters within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ of the lepton
  - $\Delta R < 0.4$ in the calorimeter for electrons
- Define CombRelIso = E / p_T (lepton)
- 3 types of electrons:
  - Loose: No CombRelIso cut
  - Medium: CombRelIso < 0.15
  - Tight: CombRelIso < 0.1
- 2 types of muons:
  - Loose: No CombRelIso
  - Tight: CombRelIso < 0.1

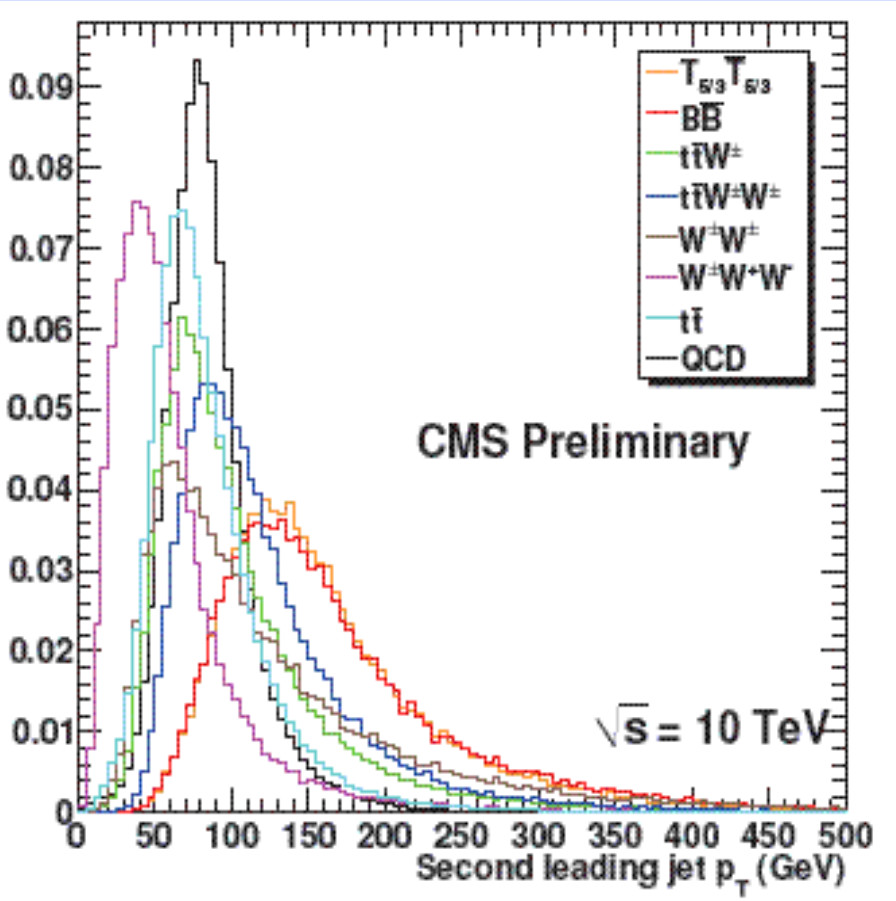
Lepton p_T Distributions (10 TeV)



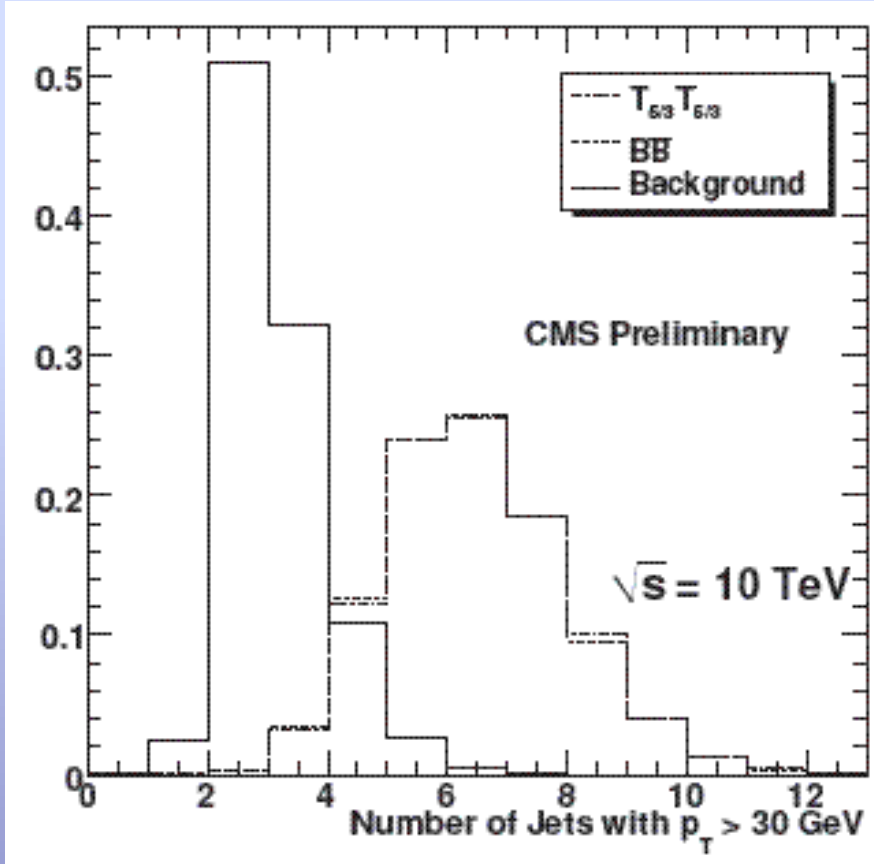


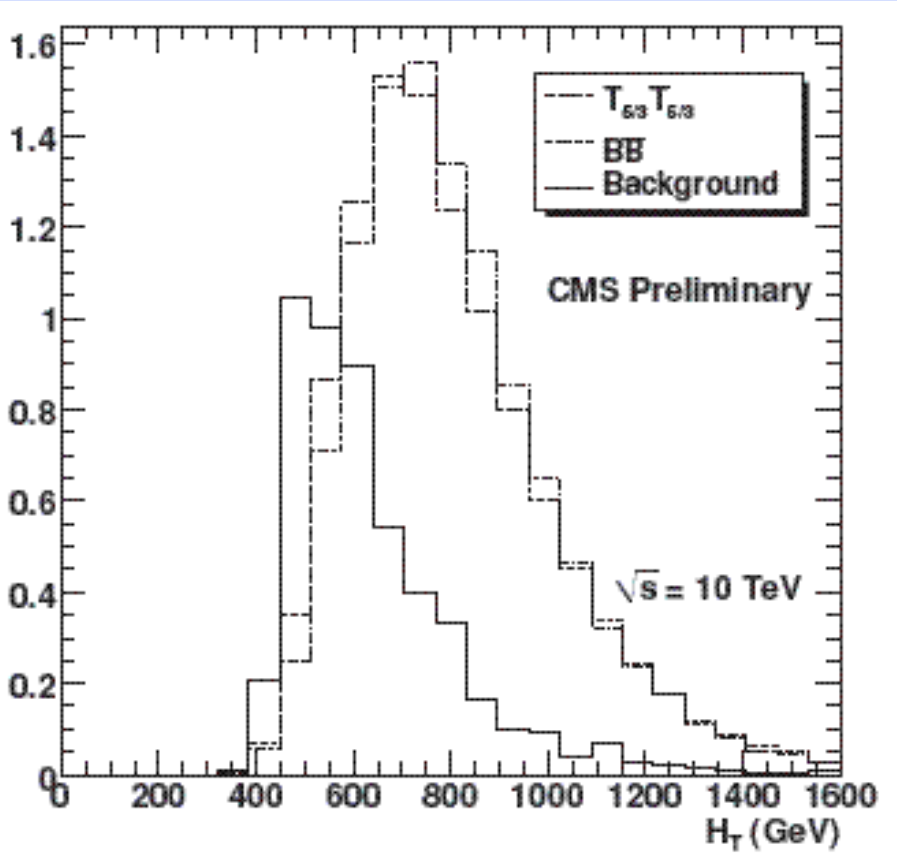
Jet p_T Distributions (10 TeV)



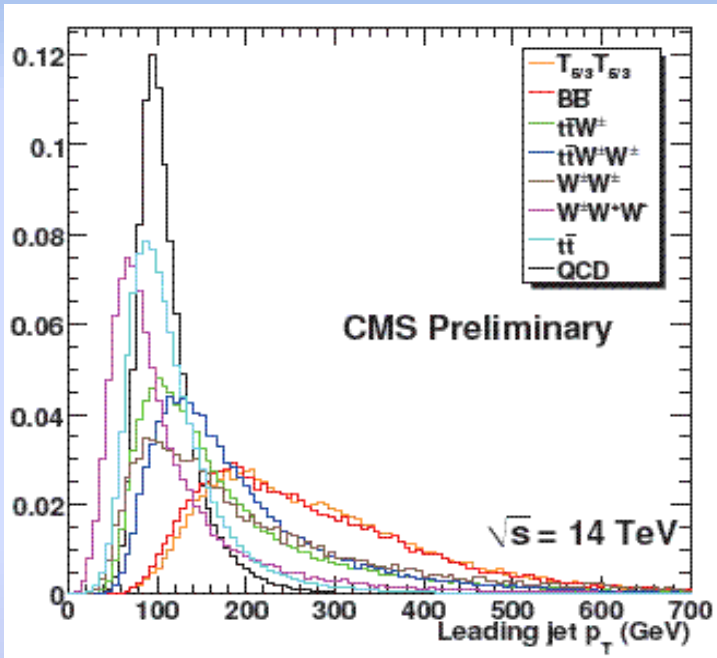


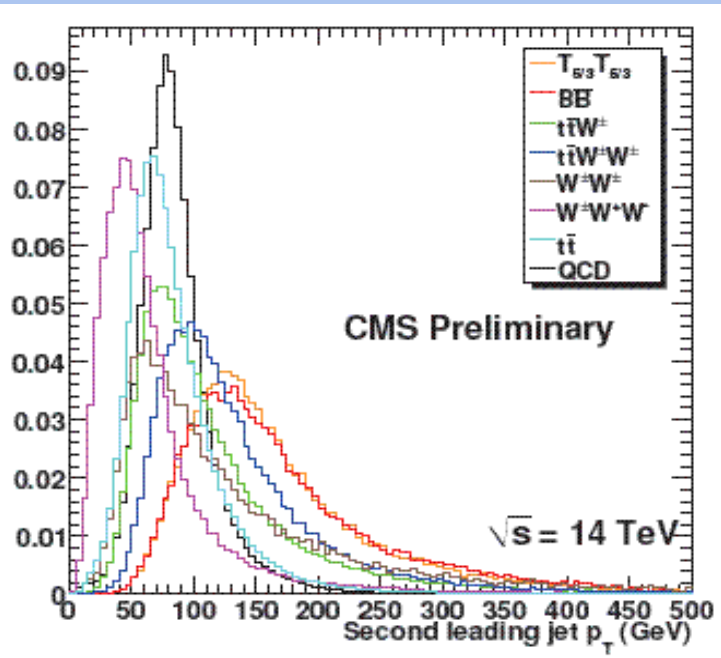
Number of Jets and H_T After Cuts (10 TeV)

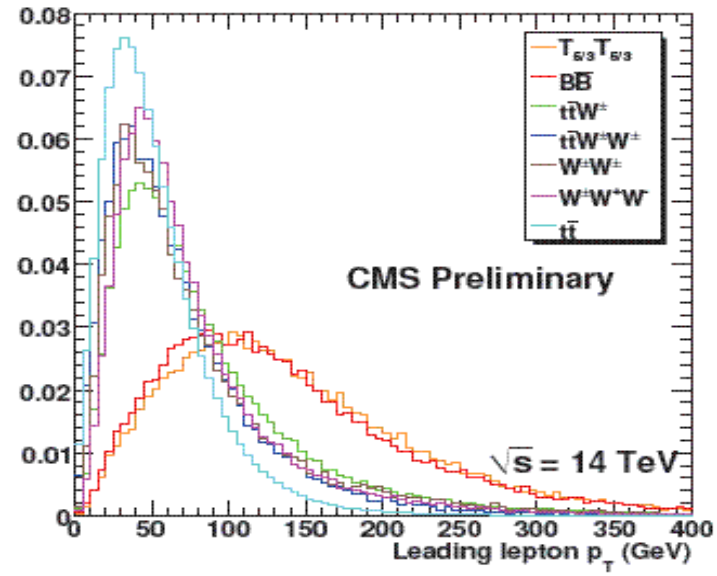


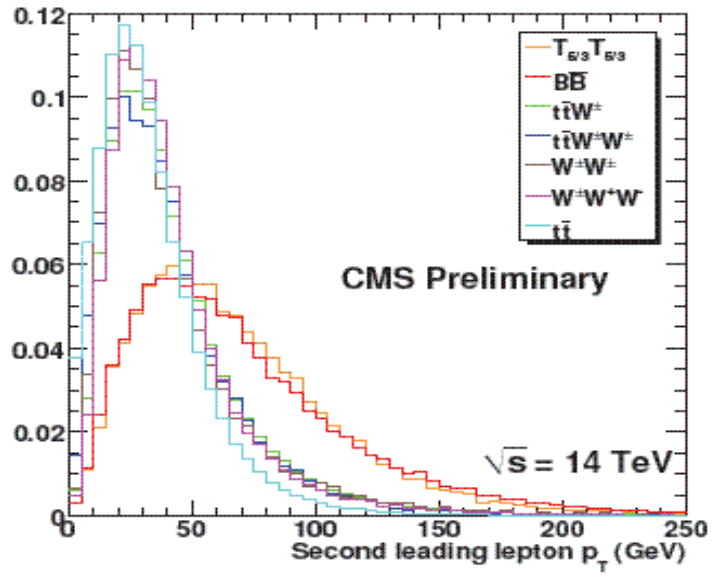


Kinematic Distributions (14 TeV)









Event Selection

- Leptons:
  - $|\eta| < 2.4$
  - Leading $p_T > 50$ GeV, second $p_T > 25$ GeV
  - Same sign charge
  - At least one of
    - "ee": Tight leading electron + Medium second electron
    - "emu": Tight muon + Medium electron
    - "mumu": Two Tight muons
  - 10 GeV veto around Z mass on "ee" channel
- Jets:
  - $|\eta| < 3.5$
  - Leading jet $p_T > 100$ GeV
  - Second leading jet $p_T > 80$ GeV
  - 5 jets with $p_T > 30$ GeV

Event Efficiencies

Sample	σ x BR (fb)	Efficiency	Expected # of events per fb^{-1}
Signal			
$T_{5/3}T_{5/3}$ (BB) M = 400 GeV	127	0.27 (0.25)	33.56 (31.01)
$T_{5/3}T_{5/3}$ (BB) M = 500 GeV	33	0.32 (0.32)	10.83 (10.84)
$T_{5/3}T_{5/3}$ (BB) M = 600 GeV	10.9	0.34 (0.35)	3.70 (3.80)
$T_{5/3}T_{5/3}$ (BB) M = 700 GeV	4.0	0.35 (0.35)	1.38 (1.44)
Background			
$ttW^{\pm}$+jets	6.6	0.041	0.27
$ttW^{\pm}W^{\pm}$	7.7	0.10	0.20
$W^{\pm}W^{+}W^{-}$+jets	2.0	0.0055	0.04
$W^{\pm}W^{\pm}$+jets	5.7	0.010	0.06
tt+jets	4.14×10^{5}	8×10^{-6}	3.32
Z+jets	3.7×10^{6}	8×10^{-8}	0.30
$W^{\pm}$+jets	4.0×10^{7}	$< 1.5 \times 10^{-9}$	< 0.06

Lepton Charge Misidentification

- Tag and Probe method
  - Use $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events where the charge of one lepton is relatively well known
  - Muon Tag: Muon with $E_T > 20$ GeV identified by both the tracker and the muon system
  - Electron Tag: Electron with $|\eta| < 2.5$ passing the trigger
- Muon misID rate is low
  - Use constant value of 5E-4
- Average electron misID rate of approximately 1%
  - Use array of misID values as a function of p_T and $|\eta|$
- Net effect of charge misID on signal is small
  - Included in efficiencies on the previous slide

Z+Jets Background Estimation

- Mostly due to charge mis-identification
- Data driven method:
  - Count number of l^+l^- events with 5 jets in 10 GeV Z mass window
  - Apply two correction factors:
    - For leptons to be identified as same sign
    - For the number of 5 jet events outside the Z mass window
- Leptons being identified as same sign:
  - Obtained from ratio of like sign to unlike sign electrons in Z mass window
  - The ratios inside and outside the window are the same (0.0252 and 0.0256 respectively)
- Number of events with 5 jets outside Z mass window:
  - Extrapolate from the ratios of events inside to outside in 2, 3 and 4 jet events (4.13 in 0.34 fb^{-1})
- Total Z+Jets background: 0.30 events per fb^{-1}

Lepton Misidentification

- Jets can be misidentified as leptons
- Two components to multi-jet background: either just 1 or both leptons are misidentified
- Data driven method for case of both leptons (leads to 0.80 events per fb^{-1}):
  - From QCD multi-jet events, select a sample of events with loose leptons
  - Use factorization method assuming jet and lepton requirements are uncorrelated to get an estimate from data.
  - Derive probability of loose leptons being identified as medium or tight from back to back dijet events (one loose lepton + one jet)
  - Require all jet cuts
  - Relax lepton cuts to allow two loose leptons
  - Multiply by probability of loose leptons being medium or tight
- One misidentified lepton: W+jets sample
  - Allow one loose lepton (the other has to be medium or tight)
  - Less than 0.06 events per fb^{-1}

Data Driven TTbar Estimation

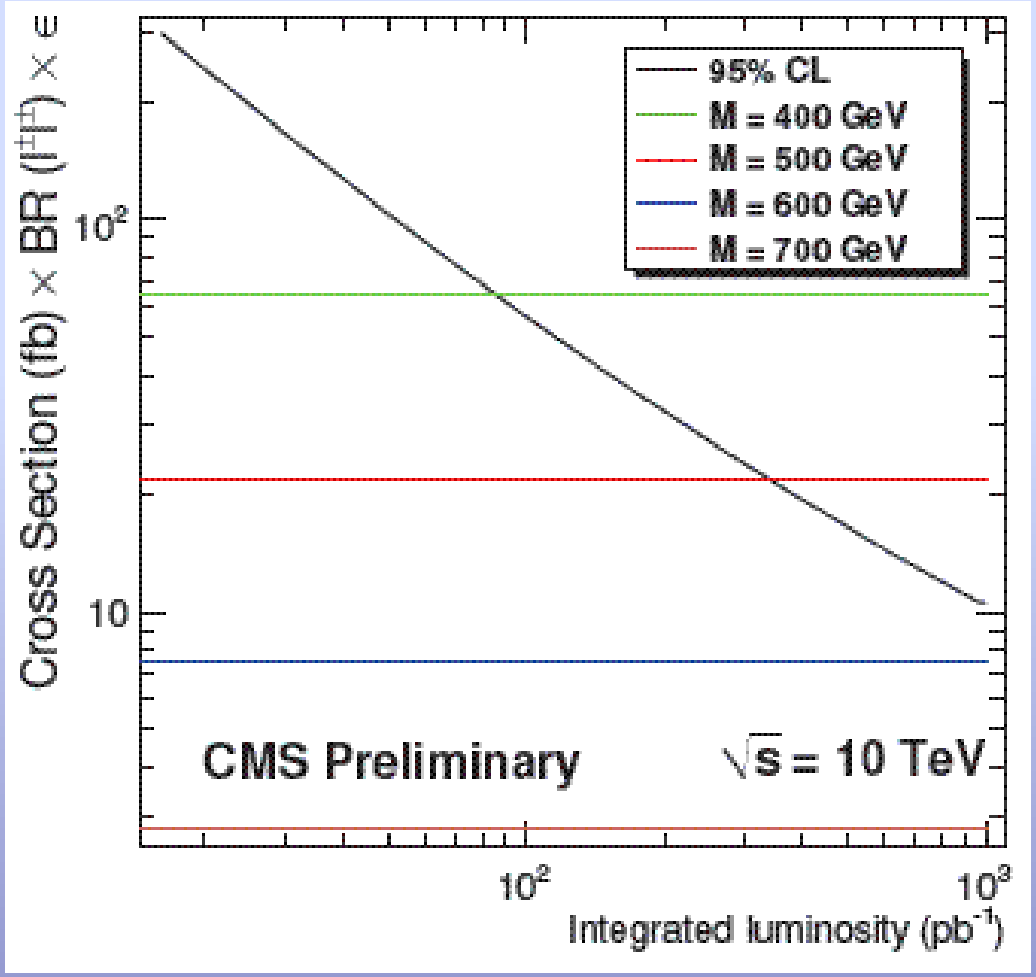
- $t\bar{t}$ + *jets* is the largest background
  - From charge misidentification
  - From semi-leptonic decays with b quark contributing the second lepton
- Use two samples:
  - N_C: control sample of events which pass all cuts except the same sign requirement
  - N_S : Signal sample
- Subtract out the contributions of Z+jets and QCD multi-jet events
  - The remaining events are then due to $t\bar{t}$ with some signal contribution
    - Can lead to overestimate of $t\bar{t}$ in signal sample
- Define:
  - f_{tt} : ratio of same sign to opposite sign events for $t\bar{t}$
  - C_{tt}, S_{tt}: $t\bar{t}$ events in the control sample, signal sample.
- Then $S_{tt} = f_{tt} * C_{tt}$
  - $f_{tt} \sim= 0.026$ leading to $S_{tt} \sim= 3.3$ events per fb^{-1}

Systematic Uncertainties

- Physics Samples:
  - Cross-section: ±25%
    - MadGraph only calculates to leading order
      - ± 11% for $t\bar{t}$ (NLO)
    - Vary the renormalization scale
  - Lepton efficiency: ±3% relative uncertainty
    - Factor out the jets and vary the electron and muon acceptance
  - Jet energy scale: ±5-10%
    - Varied jet p_T by 10%
- QCD backgrounds:
  - Factorization method: ±21%
- Z+Jets: 53% due to statistics

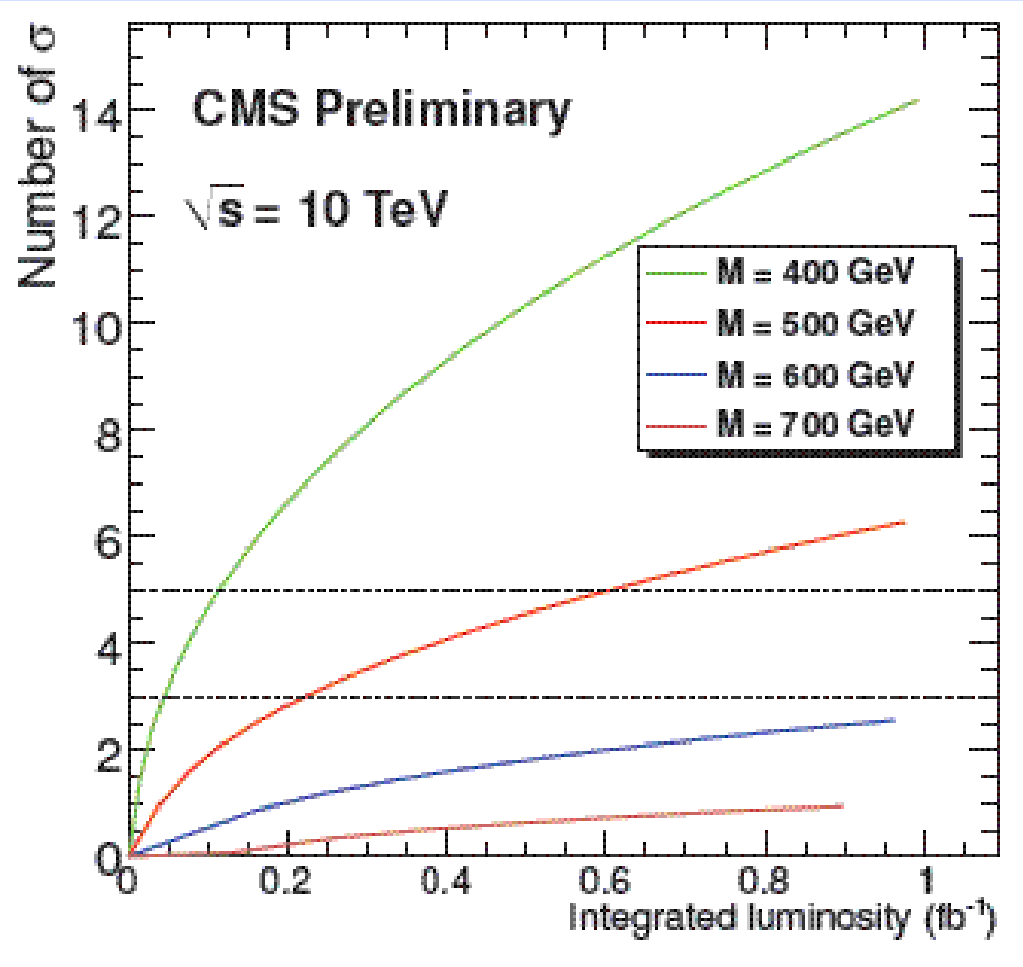
Sample	Expected # of events per fb-1
$ttW^{\pm}$+jets	0.27 ± 0.07
$ttW^{\pm}W^{\pm}$	0.20 ± 0.05
$W^{\pm}W^{+}W^{-}$+jets	0.04 ± 0.01
$W^{\pm}W^{\pm}$+jets	0.06 ± 0.02
tt+jets	3.32 ± 0.40
Z+jets	0.30 ± 0.16
QCD Multi-jets	0.80 ± 0.17
Total Background	4.98 ± 0.48

95% C.L. Limits



- 95% confidence limit calculated using a Bayesian average with the assumption of Poisson statistics
- Cross-section lines correspond to sum of $T_{5/3}$ and B expectations
- We can exclude masses of up to 400 GeV with 80 pb^{-1}, 500 GeV with 340 pb^{-1}

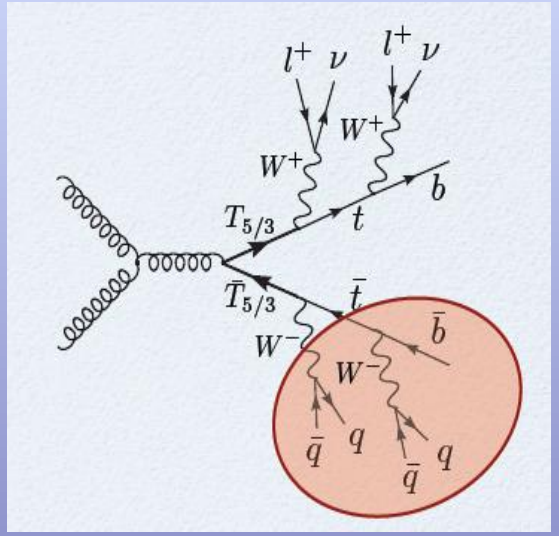
Significance



- For M = 400 GeV
  - 3σ at ~50pb^{-1}
  - 5σ at ~115pb^{-1}
- For M = 500 GeV
  - 3σ at ~220pb^{-1}
  - 5σ at ~600pb^{-1}
- Only 150pb^{-1} at 14 TeV for M =500 GeV

$T_{5/3}$ Invariant Mass

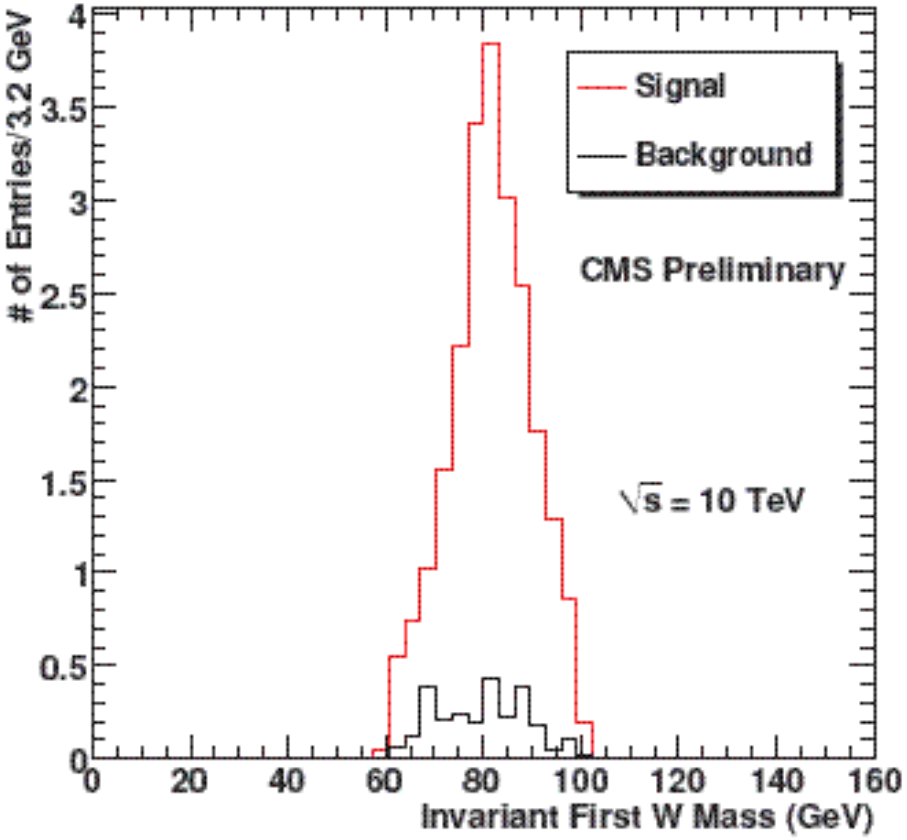
- The $T_{5/3}$ can be reconstructed from the hadronic fraction branch of the decay
- Require all cuts from above and that two jets be tagged as b-jets
- b-jet closest to the lepton with the second highest p_T is assumed to come from leptonic branch of decay
- The remaining jets are then used to reconstruct the two W's, the top and the $T_{5/3}$

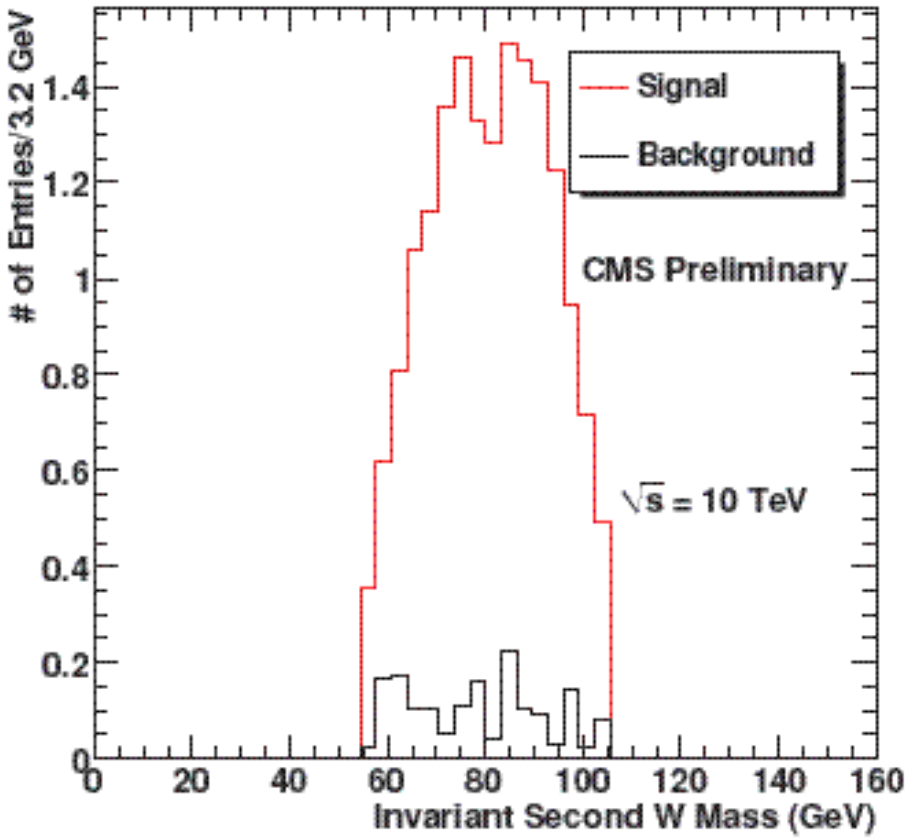


Reconstruction of W bosons

- Reconstruct the best W:
  - Pair of jets with invariant mass closest to W (must be within 20 GeV)
  - Jets must have $\Delta R < 1.5$ and are discarded if used
  - W must have $p_T > 50$ GeV
- Reconstruct the other W:
  - Pair of jets with invariant mass closest to W (must be within 25 GeV)
  - Jets must have $\Delta R < 2.0$ and are also discarded if used
  - W must have $p_T > 30$ GeV

Reconstruction of W's (10 TeV)

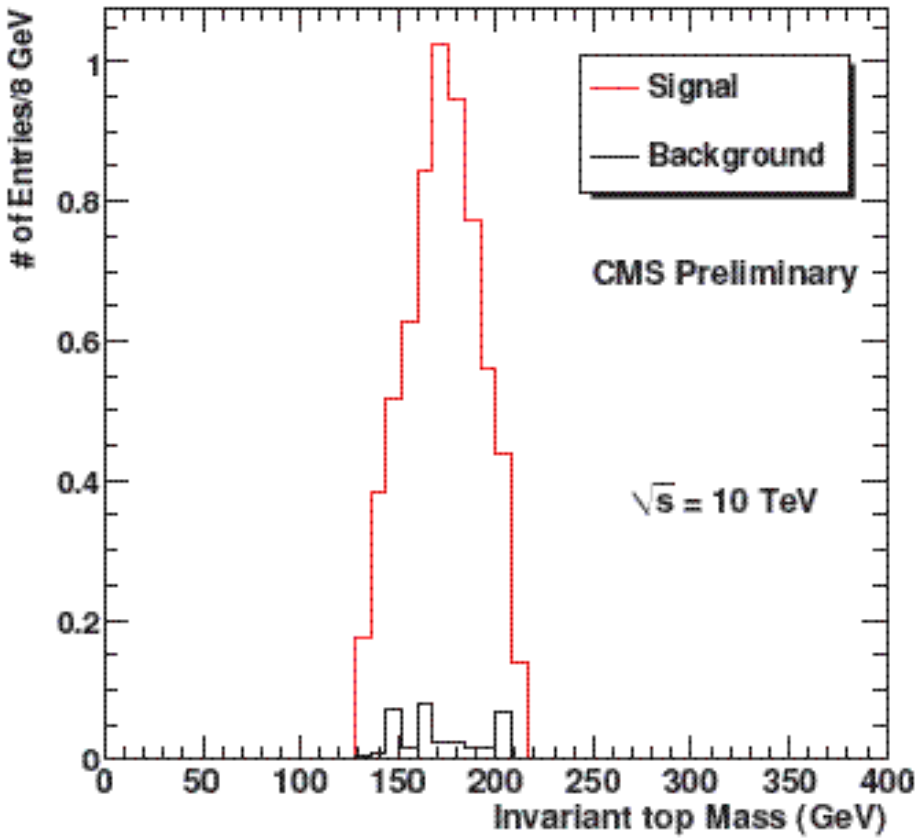


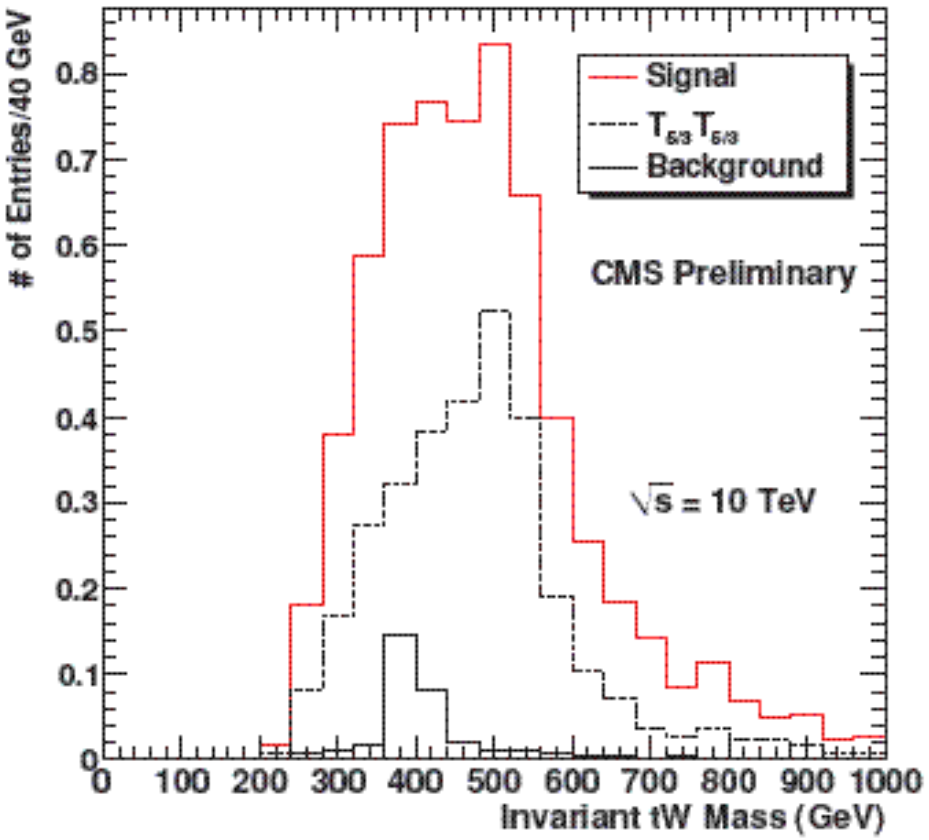


Reconstruction of top and $T_{5/3}$

- Reconstruct top quark:
  - Consider all (W, b-jet) pairs
  - Take combination with invariant mass closest to top quark
  - Must be within 40 GeV
- Reconstruct $T_{5/3}$ from top quark and the unused W
  - At 10 TeV, ~1.6fb^{-1} of integrated luminosity needed for a 5σ observation of sum of $T_{5/3}$ and B

Reconstruction of top and $T_{5/3}$ (10 TeV)





Conclusions

- Constructed a means of searching for exotic partners of the top quark, the $T_{5/3}$ and B
- Exclusion at 95% confidence level:
  - Up to M = 400 GeV with less than $100pb^{-1}$ of integrated luminosity
  - Up to M = 500 GeV with ~$340pb^{-1}$
- A 5σ observation of the top partners with M = 400 GeV is possible with ~$115pb^{-1}$ of data.
- For M = 500 GeV, $220pb^{-1}$ of data is needed for a 3σ evidence