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Pair-production of heavy vector-like T quarks

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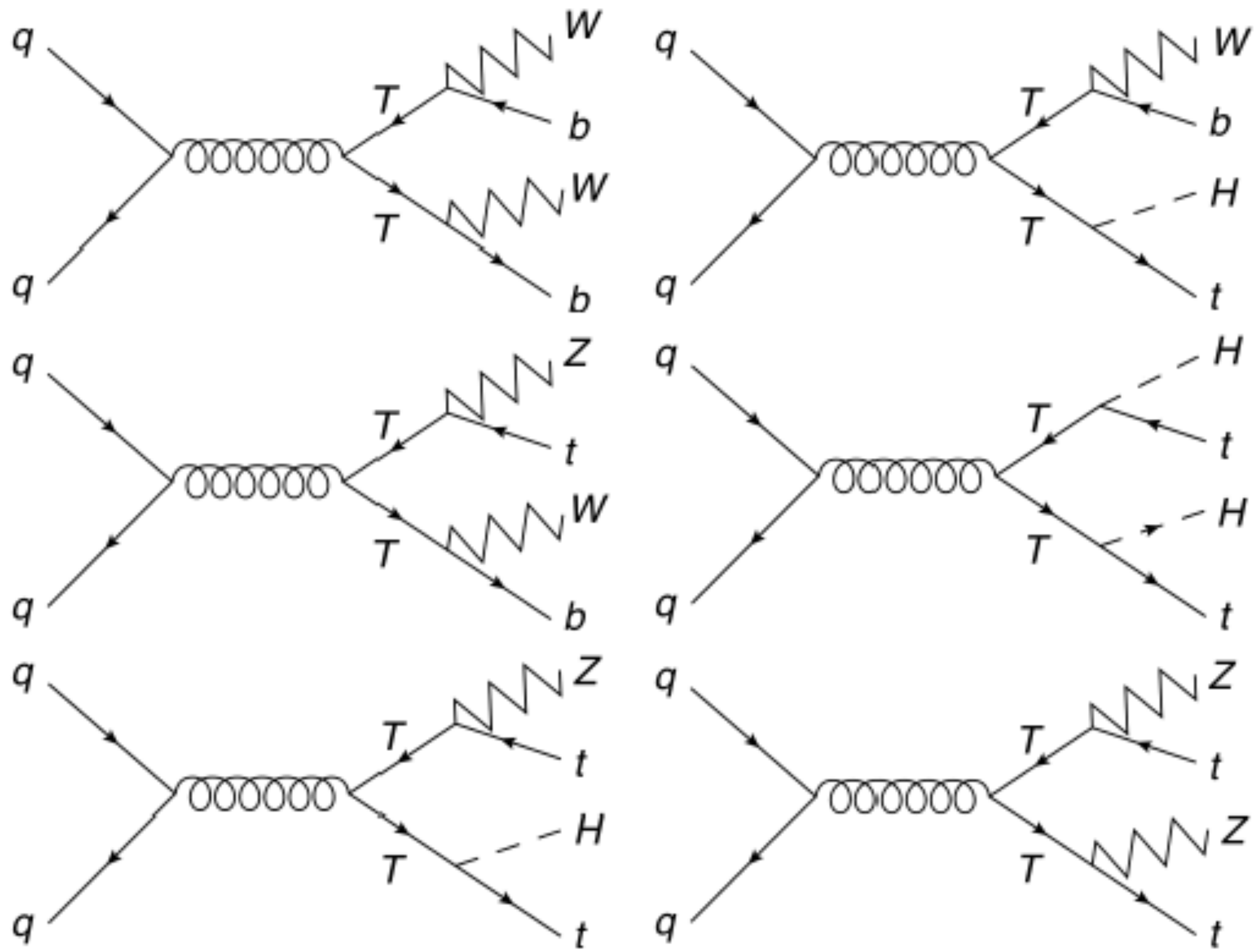
Introduction

- The Standard Model comprises of three generations of chiral quarks.
- Models with 4th generation chiral quarks are severely constrained from electro-weak precision measurements.
- Vector-like quarks are an interesting possibility.
- Such quarks appear in models such as the Little Higgs (along with additional massive gauge fields) and extra dimensions.
- In the present framework, we look at the minimal extension of the standard model involving a vector-like quark.
- Signal sample of TT pair production consists of 6 final states for 3 decay modes of the T to tH, Wb and Zt.
- The T to tH decay channel uses the newly discovered Higgs as a probe for new physics.

Feynman diagrams for TT pair production



Modes of T production include qq annihilation and gluon fusion

The Model [0902.0792]

- A vector-like quark χ is considered, which transforms as (3, 1, 2/3) under the $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge group.
- This additional quark χ may mix with the SM top. Interactions with the first two generations are neglected.
- On imposing electroweak symmetry breaking, the quark mass matrix takes the following form:

$$\mathcal{L} = -\left(\bar{u}_L^3,\ \bar{\chi}_L \right) \begin{pmatrix} \lambda_t(v_H + H/\sqrt{2}) & 0 \\ M_0 & M_x \end{pmatrix} \begin{pmatrix} u_R^3 \\ \chi_R \end{pmatrix} + h.c. \quad (1)$$

- u^3 is the up type quark of the third generation. H is the Higgs boson and VEV, $v_H \approx 174$ GeV.
- M_0, M_χ and the λ_t Yukawa couplings are real.

The Model [0902.0792]

- Transformation equations between gauge and mass eigenstate basis:

$$\begin{pmatrix} t_{L,R} \\ t'_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta_{L,R} & -\sin\theta_{L,R} \\ \sin\theta_{L,R} & \cos\theta_{L,R} \end{pmatrix} \begin{pmatrix} u^3_{L,R} \\ \chi_{L,R} \end{pmatrix} \quad (2)$$

- Here t is the standard model top, hence m_t is 173 GeV. t' is the new quark.
- The mixing angles θ_L and θ_R are defined as :

$$\theta_L = \frac{1}{2}\tan^{-1}\left(\frac{2M_0\lambda_t v_H}{M_\chi^2 + M_0^2 + \lambda_t^2 v_H^2}\right) \quad (3)$$

$$\theta_R = \sin^{-1}\left(\sqrt{\frac{\sin^2\theta_L m_{t'}^2}{\sin^2\theta_L m_{t'}^2 + \cos^2\theta_L m_t^2}}\right) \quad (4)$$

- This model has two additional parameters : $\sin\theta_L$ and mass of the top prime.

Signal cross-sections at $\sqrt{s}$ = 14 TeV

T Mass (GeV)	σ (in pb)
500	4.10091
600	1.44649
700	0.57883
800	0.25400
900	0.11961
1000	0.05948
1100	0.03089
1200	0.01662
1300	0.00920
1400	0.00521
1500	0.00301
1600	0.00177
1700	0.00105
1800	0.00063
1900	0.00038
2000	0.00024

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Signal cross-sections at $\sqrt{s}$ = 33 TeV

T Mass (GeV)	σ (in pb)
500	44.4263
600	18.1717
700	8.35889
800	4.19501
900	2.25365
1000	1.27784
1100	0.75733
1200	0.46586
1300	0.29547
1400	0.19250
1500	0.12836
1600	0.08733
1700	0.06046
1800	0.04253
1900	0.03032
2000	0.02189
2100	0.01598
2200	0.01178
2300	0.00876
2400	0.00657
2500	0.00497
2600	0.00378
2700	0.00290
2800	0.00223
2900	0.00173
3000	0.00134

Analysis Stategy

- Presence of multiple bosons in these processes lead to final states with multiple leptons and b-tagged jets (e.g. TT → bWtH → (b l ν l ν b b b)).
- Search for final states with at least two leptons
  - Opposite signed leptons: Specifically require two leptons.
    - Major irreducible backgrounds: tt, DY.
  - Same signed leptons: Specifically require two leptons.
    - Backgrounds: Instrumental backgrounds from mis-identified leptons and diboson processes.
  - Multi-leptons: Specifically require three or more leptons.
    - Dominant background: rare SM processes (e.g. diboson decays) and mis-identified leptons.

Follows the same strategy as: Inclusive search for a vector-like T quark by CMS (http://cds.cern.ch/record/1557571?ln=en)

Opposite-sign analysis

Two event categories:

- 2-3 Jet Category (OS23): This category includes a Z-veto.
  - Sensitivity in the bWbW mode
  - MET > 30 GeV, 1 b-tag
  - Cuts on HT (sum of the pTs of the selected jets), ST (sum of the pTs of the selected jets, selected leptons and MET) and minMlb (min invariant mass of a bjet and a lepton).
- ≥5 Jet Category (OS5+):
  - Sensitivity to modes with tH, tZ
  - Less DY, no Z-veto
  - MET > 30 GeV, 2 b-tags.
  - Cuts on HT and ST.

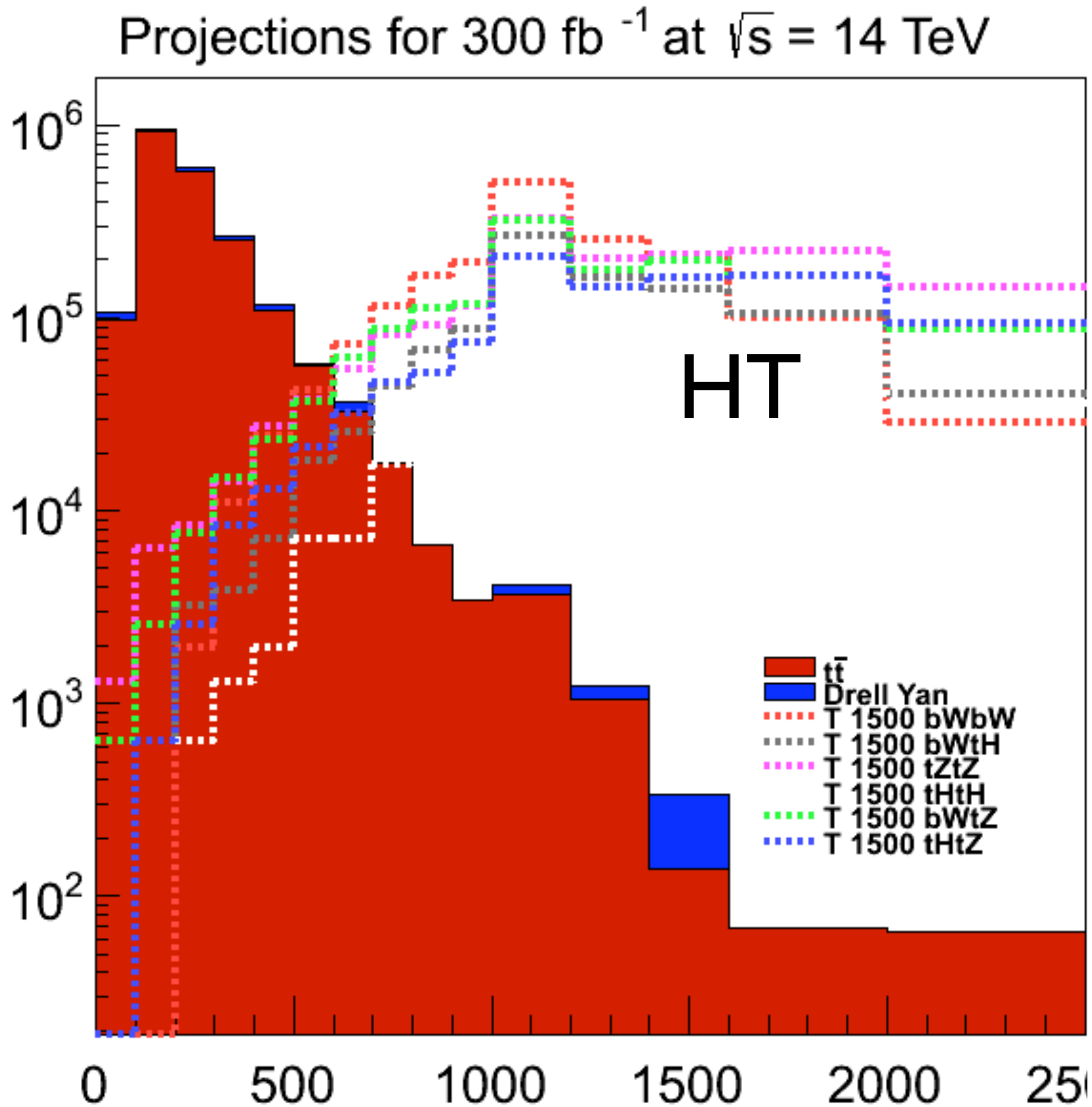
Nominal BR: BR(bW) = 1/2 , BR(tH) = 1/4, BR(tZ) = 1/4

Yields calculated for 14 TeV (COM) and 300 fb^-1.

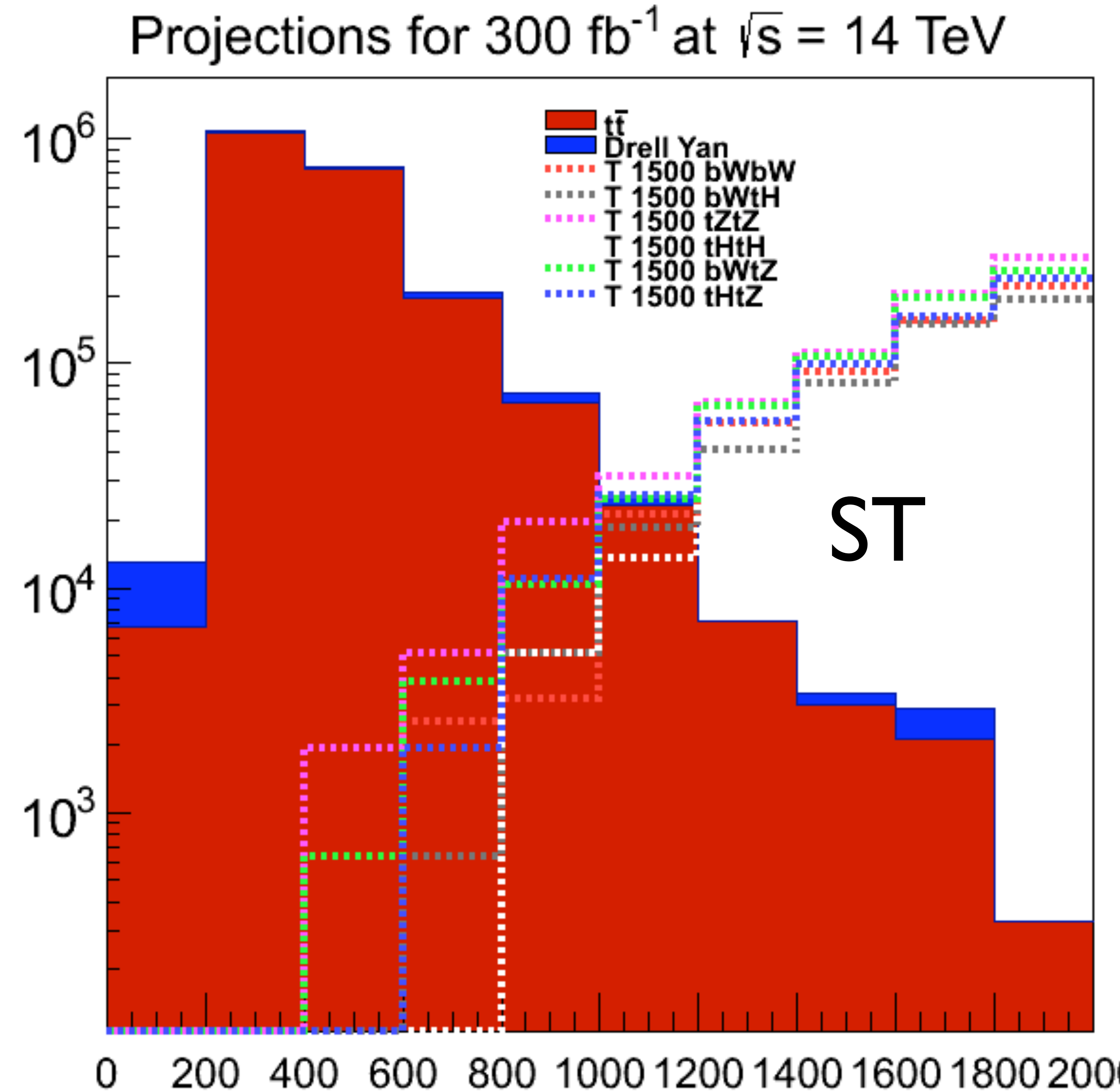
Plots and yields are preliminary results.

Opposite-sign analysis

One b-tag, >= 2 jets and MET > 30 GeV



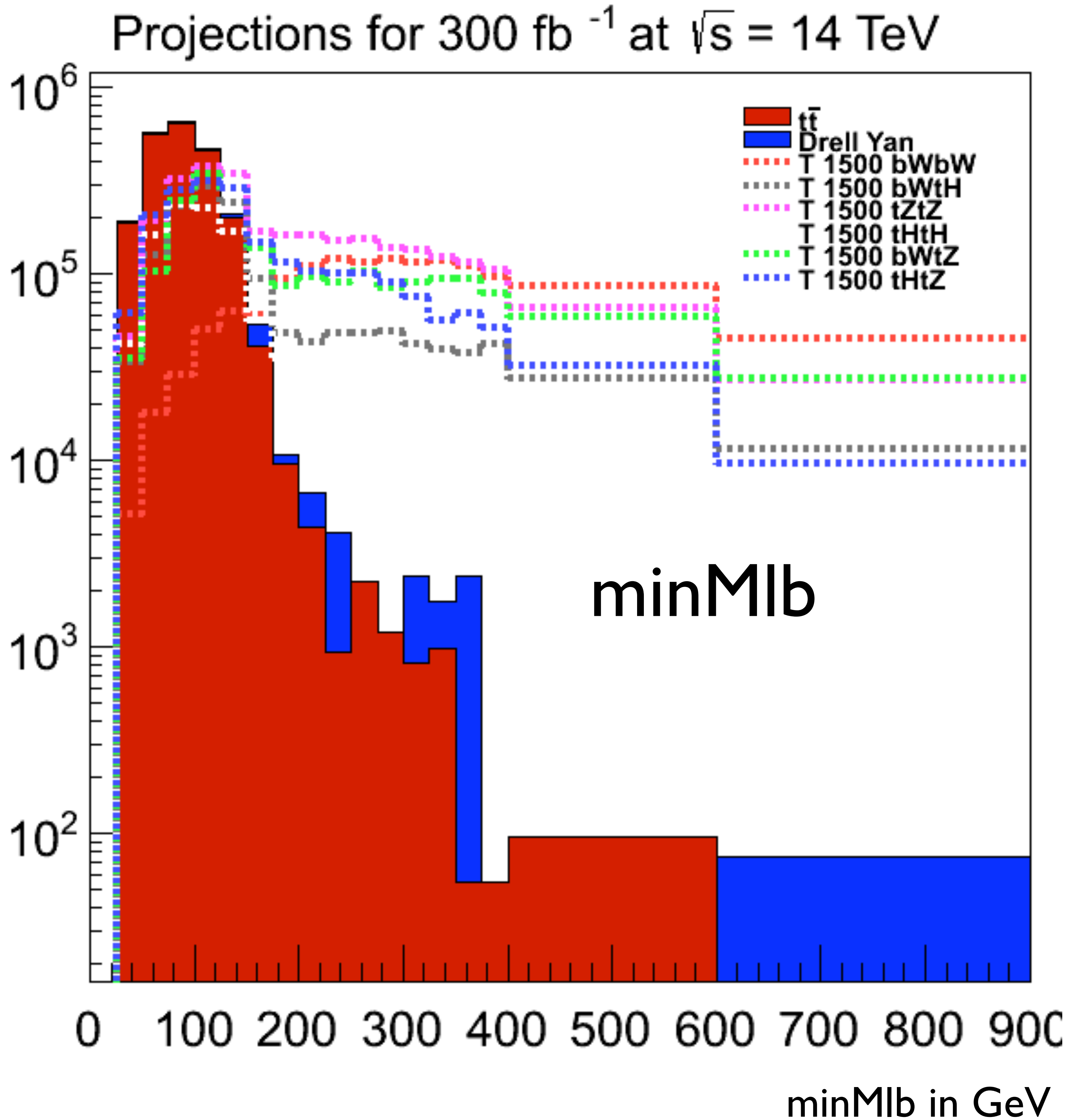
HT in GeV



ST in GeV

The signal is multiplied by 10000.

Opposite-sign analysis



One b-tag, >= 2 jets and MET > 30 GeV

The signal is multiplied by 10000.

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Yields in the OS23 category

Sample	$\mu\mu$	$e\mu$	ee	Sum
Tprime1500_BWBW	1.76 ± 0.15	3.05 ± 0.23	1.66 ± 0.14	6.48 ± 0.44
Tprime1500_BWTZ	0.46 ± 0.06	0.79 ± 0.09	0.47 ± 0.06	1.73 ± 0.15
Tprime1500_BWTH	0.40 ± 0.06	0.68 ± 0.08	0.33 ± 0.05	1.41 ± 0.13
Tprime1500_THTH	0.08 ± 0.02	0.12 ± 0.03	0.03 ± 0.01	0.24 ± 0.04
Tprime1500_THTZ	0.09 ± 0.02	0.18 ± 0.04	0.08 ± 0.02	0.35 ± 0.05
Tprime1500_TZTZ	0.05 ± 0.02	0.21 ± 0.04	0.09 ± 0.02	0.35 ± 0.05
TTbar	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Require: 2-3 jets, 1 btag, MET > 30 GeV, HT > 700 GeV, ST > 1500 GeV, minMlb > 550 GeV. Cuts optimized using $S/\sqrt{B}$ as a first pass.

More realistic modeling of ZJETS/DY background to be done with HT binned samples for better statistics in the tails.

Yields in the OS5+ category

Sample	$\mu\mu$	$e\mu$	ee	Sum
Tprime1500_BWBW	0.18 ± 0.04	0.33 ± 0.05	0.17 ± 0.03	0.68 ± 0.08
Tprime1500_BWTZ	1.63 ± 0.14	0.65 ± 0.08	1.53 ± 0.13	3.81 ± 0.28
Tprime1500_BWTH	0.49 ± 0.06	1.04 ± 0.10	0.36 ± 0.05	1.89 ± 0.16
Tprime1500_THTH	0.70 ± 0.08	1.44 ± 0.13	0.79 ± 0.09	2.93 ± 0.22
Tprime1500_THTZ	2.85 ± 0.22	1.11 ± 0.11	2.54 ± 0.20	6.50 ± 0.44
Tprime1500_TZTZ	3.73 ± 0.27	0.92 ± 0.09	3.39 ± 0.25	8.04 ± 0.53
TTbar	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Require:>= 5 jets,2 btags, MET > 30 GeV, HT > 1700 GeV and ST > 2000 GeV.

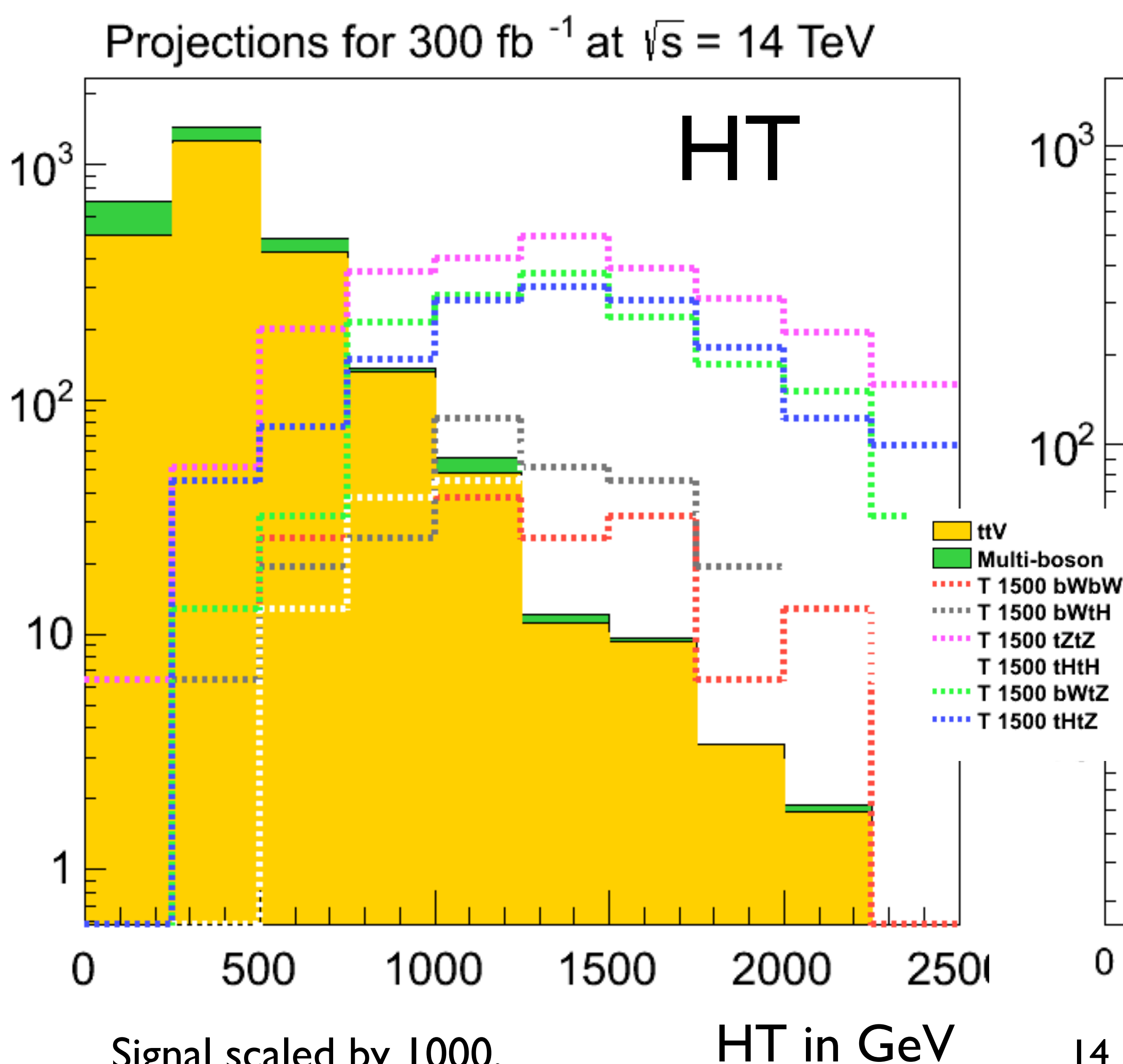
Cuts optimized using $S/\sqrt{B}$ as a first pass.

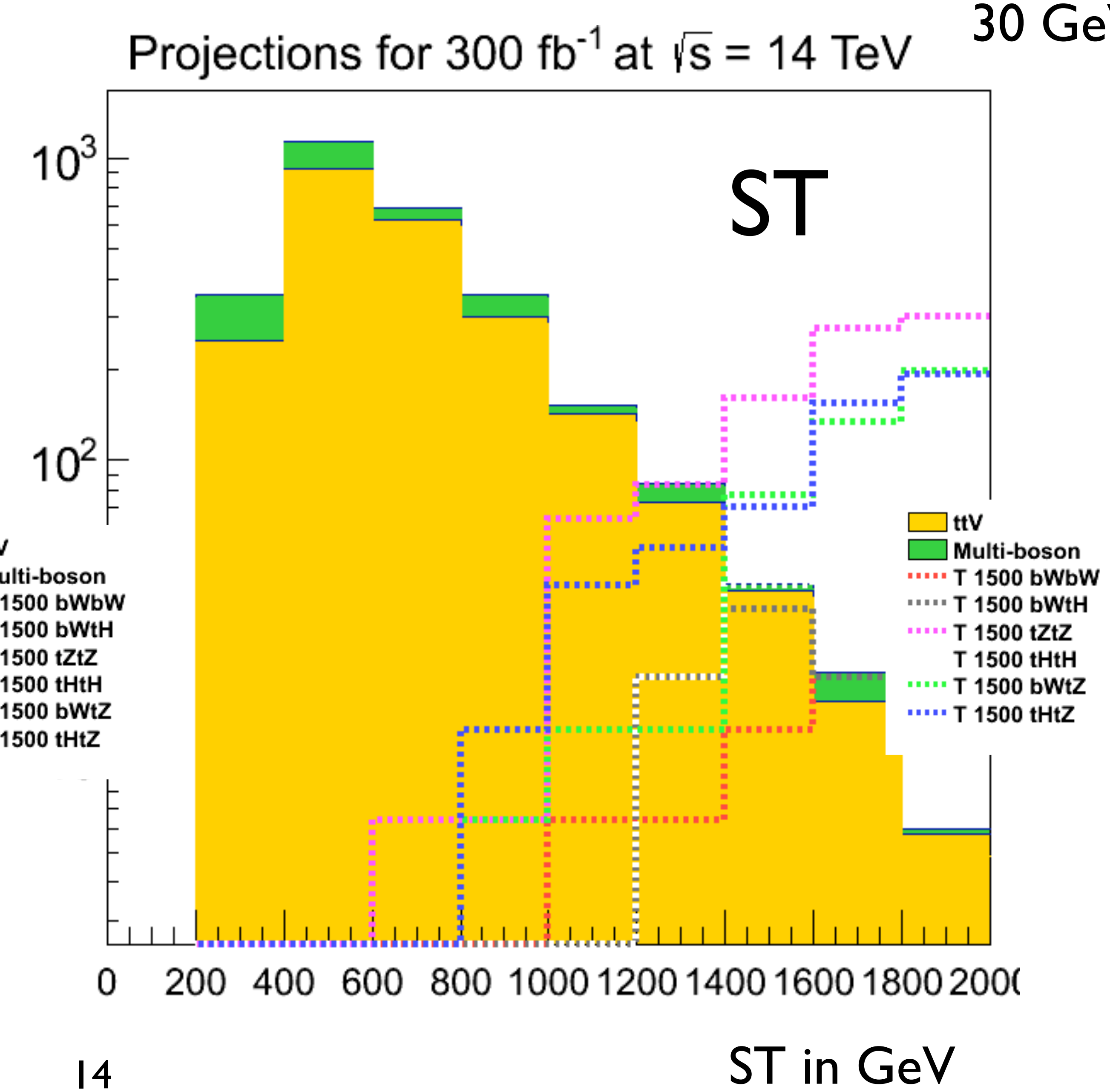
More realistic modeling of ZJETS/DY background to be done with HT binned samples for better statistics in the tails.

Same signed analysis

- Backgrounds are from diboson and triboson decay processes.
- Instrumental backgrounds from mis-identified leptons. In the 8TeV analysis, this was done with a data-driven method.

One b-tag, >= 3 jets and MET > 30 GeV





Signal scaled by 1000.

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Yields in the SS category

Sample	$\mu\mu$	$e\mu$	ee	Sum
Tprime1500_BWTZ	0.10 ± 0.03	0.20 ± 0.04	0.16 ± 0.03	0.46 ± 0.06
Tprime1500_BWTH	0.01 ± 0.01	0.03 ± 0.01	0.04 ± 0.02	0.08 ± 0.02
Tprime1500_THTH	0.02 ± 0.01	0.04 ± 0.02	0.06 ± 0.02	0.12 ± 0.03
Tprime1500_THTZ	0.15 ± 0.03	0.22 ± 0.04	0.16 ± 0.03	0.53 ± 0.07
Tprime1500_TZTZ	0.22 ± 0.04	0.39 ± 0.06	0.23 ± 0.04	0.84 ± 0.09
WZJETS	9.04 ± 6.06	0.00 ± 0.00	0.00 ± 0.00	9.04 ± 6.06
ZZJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WWJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WWW	0.12 ± 0.08	0.12 ± 0.08	0.05 ± 0.04	0.28 ± 0.16
TTBARWW	0.27 ± 0.15	0.32 ± 0.17	0.16 ± 0.09	0.76 ± 0.39
TTBARW	1.77 ± 0.94	2.20 ± 1.16	0.98 ± 0.55	4.95 ± 2.53
TTBARZ	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Total Bkg	11.20 ± 6.14	2.64 ± 1.17	1.19 ± 0.56	15.02 ± 6.58

Require:>= 3 jets, 1 btags, MET > 30 GeV, HT > 1500 GeV and ST > 2200 GeV.

Multilepton (>= 3) analysis

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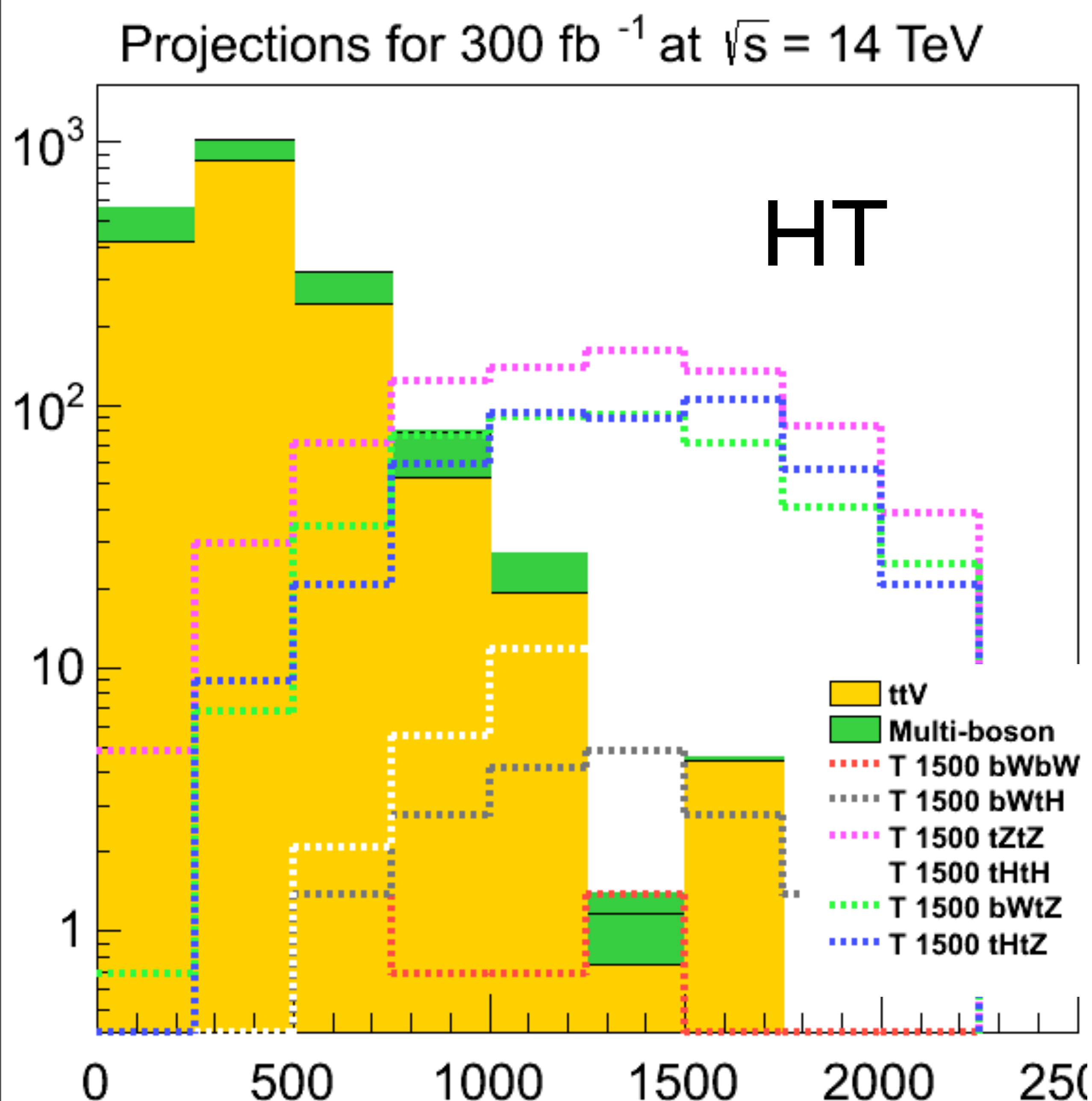
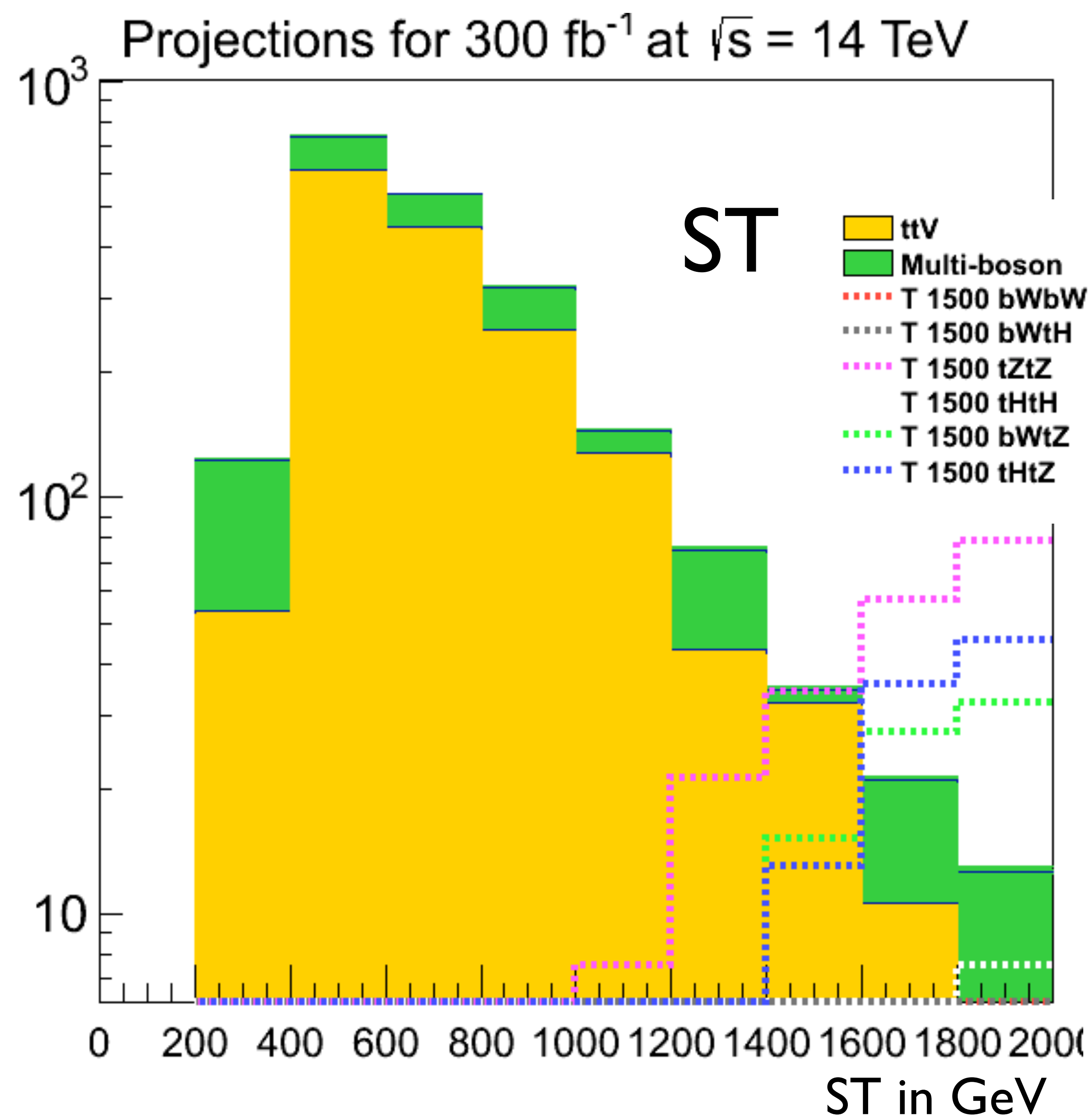
- Backgrounds are from diboson and triboson decay processes.
- Instrumental backgrounds from mis-identified leptons. In the 8TeV analysis, this was done with a data-driven method.

One b-tag, >= 3 jets and MET > 30 GeV





Signal scaled by 100.

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Yields in the multi-lepton (>= 3) category

Sample	$\mu\mu\mu$	$e\mu\mu/ee\mu$	eee	Sum
Tprime1500_BWTZ	0.66 ± 0.08	1.31 ± 0.12	0.65 ± 0.08	2.62 ± 0.21
Tprime1500_BWTH	0.02 ± 0.01	0.08 ± 0.02	0.03 ± 0.01	0.12 ± 0.03
Tprime1500_THTH	0.05 ± 0.02	0.19 ± 0.04	0.06 ± 0.02	0.31 ± 0.05
Tprime1500_THTZ	0.84 ± 0.09	1.46 ± 0.13	0.83 ± 0.09	3.14 ± 0.24
Tprime1500_TZTZ	1.26 ± 0.12	2.64 ± 0.21	1.03 ± 0.10	4.94 ± 0.35
WGJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WWJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WZJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZGJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZZJETS	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WWW	0.13 ± 0.08	0.00 ± 0.00	0.00 ± 0.00	0.13 ± 0.08
ZZZ	0.00 ± 0.00	0.01 ± 0.01	0.00 ± 0.00	0.02 ± 0.01
WWZ	0.13 ± 0.08	0.31 ± 0.17	0.11 ± 0.07	0.55 ± 0.29
WZZ	0.23 ± 0.12	0.25 ± 0.13	0.10 ± 0.06	0.58 ± 0.29
TTBARZ	0.00 ± 0.00	4.06 ± 2.72	0.00 ± 0.00	4.06 ± 2.72
TTBARW	0.66 ± 0.39	0.66 ± 0.39	0.00 ± 0.00	1.31 ± 0.72
TTBARWW	0.17 ± 0.10	0.23 ± 0.13	0.00 ± 0.00	0.41 ± 0.21
Total Bkg	1.31 ± 0.43	5.52 ± 2.76	0.21 ± 0.09	7.05 ± 2.86

Require:>= 3 jets, 1 btags, MET > 30 GeV, HT > 1200 GeV and ST > 1500 GeV. Cuts optimized using $S/\sqrt{B}$ as a first pass.

Conclusion and future work

- This was a first pass feasibility study. If vector-like quarks exist, they can be detected at the LHC at 14TeV.

- To do: Look at DY/ZJets sample produced with HT binning to make sure this background is better predicted.

- To do: Optimize cuts by computing expected limits.

- To do: Look at efficiency over a range of mass points. Samples are available for this study at mass points of (500, 700, 900, 1100, 1300, 1500, 1700, 1900) GeV.

- Study the effect of pile-up with available samples.

- To do: Look at 33 TeV samples.

Back up material