# Top Quark Partners with Charge 5*e*/3 ($T_{5/3}$)

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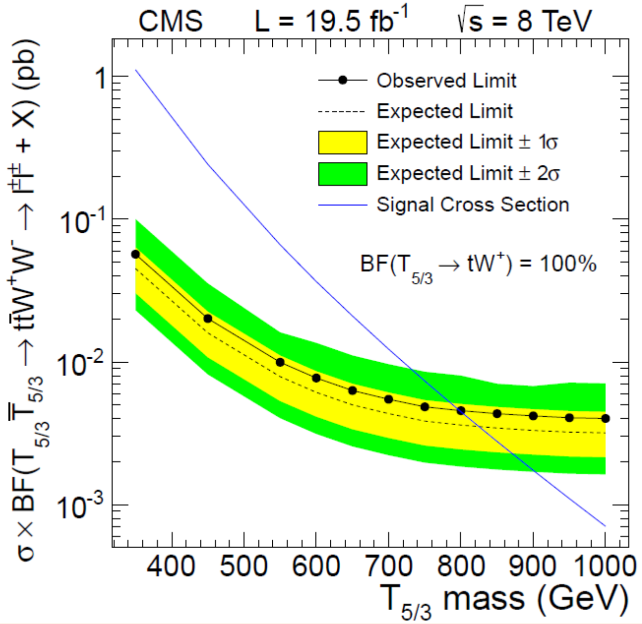
# Top Partners

- Heavy top partners are a common prediction of different theories
  - Couple to 3rd generation quarks
  - Solve hierarchy problem
  - Compatible with 125 GeV Higgs
    - See arXiv:1212.1380 (Int. J. Mod. Phys. A Volume 28 (2013) 1330004)

- Can be found in
  - Composite Higgs
  - Extra dimensions (KK gluons)

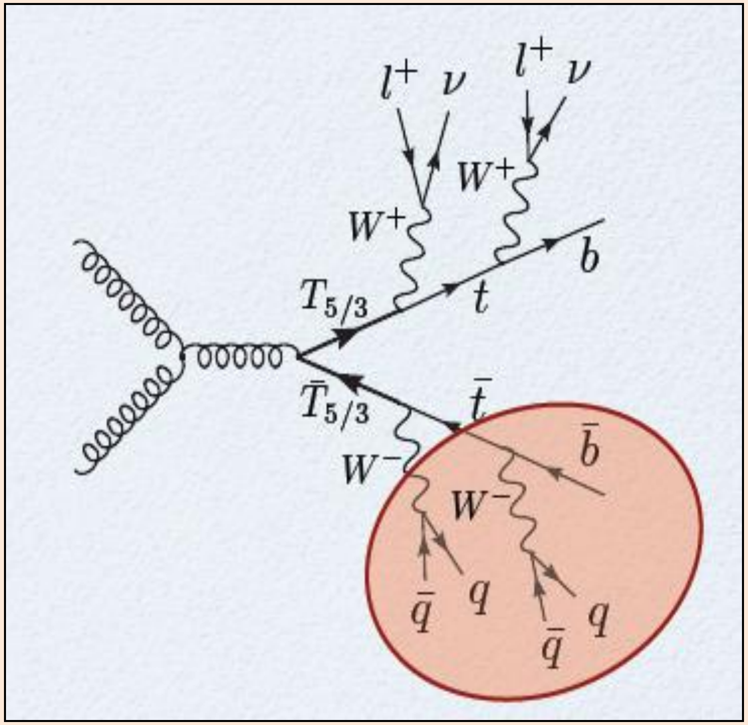
# The $T_{5/3}$




- Top partner models include several particles
  - Focus on quark with charge 5/3
  - Typically the lightest
- Theoretical descriptions
  - ***Contino & Servant***, JHEP 0806:026 (2008)
  - ***Mrazek & Wulzer***, Phys. Rev. D 81, 075006 (2010)
  - ***De Simone et al,*** JHEP 1304:004 (2013)
- Experimental results
  - **arxiv:1312.2391** (8 TeV) excludes $M(T_{5/3}) < 800$ GeV at 95% C.L.
  - **ATLAS-CONF-2012-130** (7 TeV): 670-700 GeV depending on coupling
  - Published result: CDF (Phys.Rev.Lett.104:091801, 2010), 365 GeV

# Model

- $T_{5/3}$ with $Q_e$ = 5/3 and B with $Q_e$ = -1/3 decay into W and top
  - Per Mrazek & Wulzer, B is typically more massive than $T_{5/3}$
  - Focus on $T_{5/3}$




- Most striking signature: same-sign dileptons

$$l^{\pm}l^{\pm} + 2b + 2\mathrm{W}$$

- The hadronically decaying $T_{5/3}$ can be reconstructed

# Backgrounds

- Same sign lepton requirement removes most Standard Model backgrounds

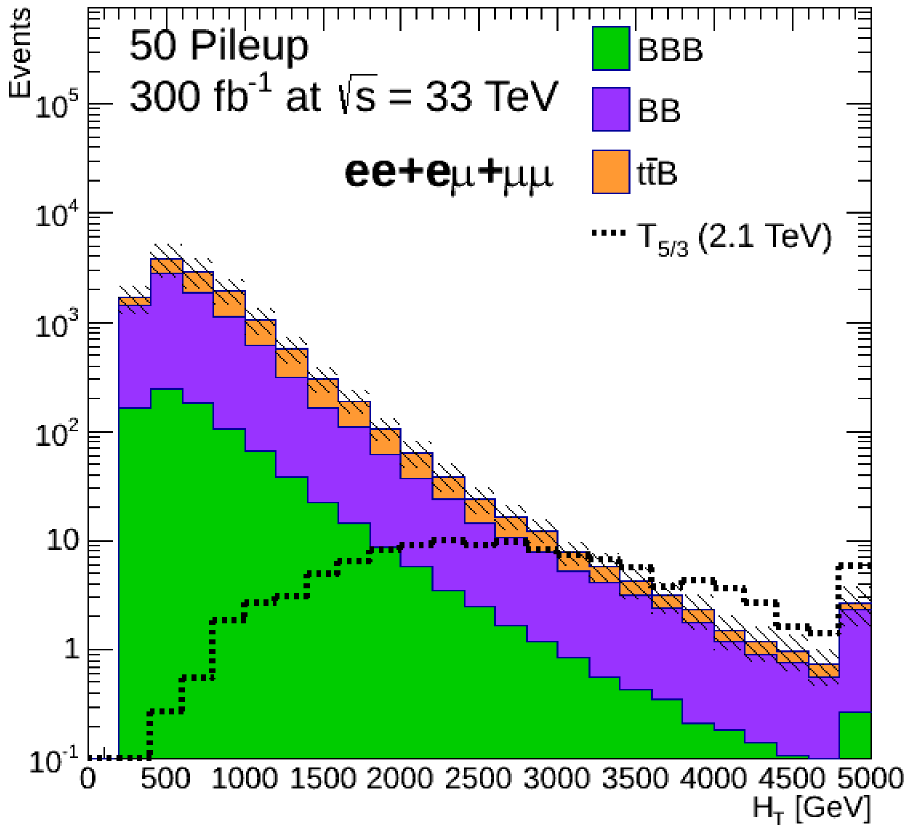
- Remaining backgrounds have lower cross-sections:
  - Dibosons: WW (same-sign), WZ, ZZ, etc.
  - Tribosons: WWW, WWZ, etc.
  - ttbarW, ttbarZ

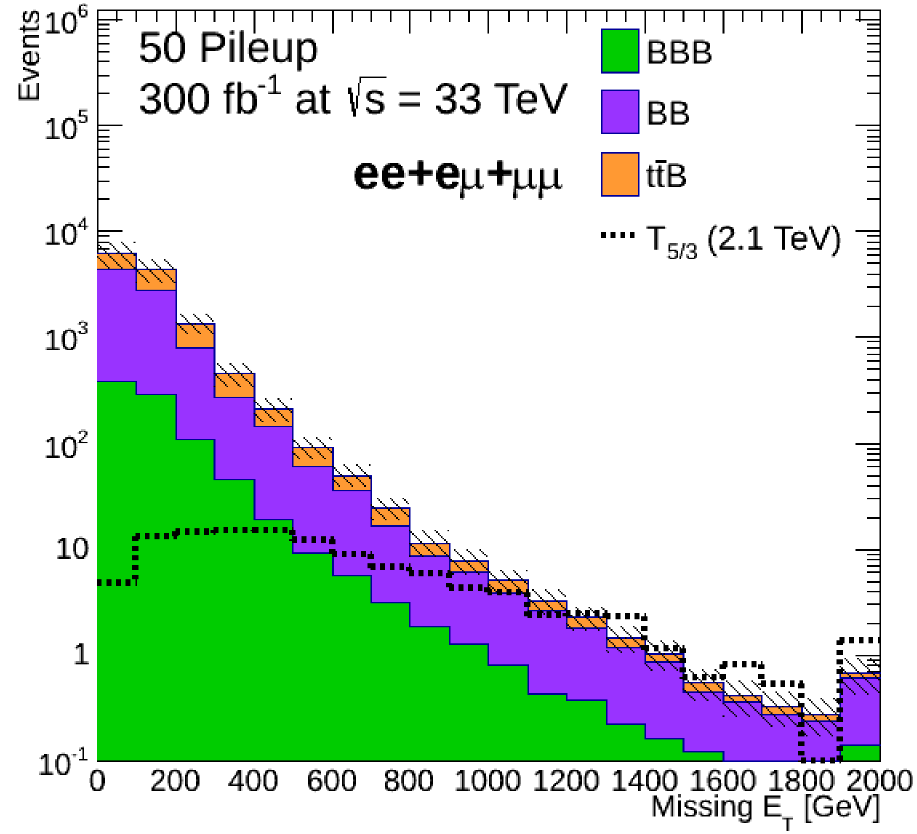
- Instrumental backgrounds
  - Charge misidentification (mainly from Z)
  - Non-prompt leptons

# Snowmass Study

- Looked at $T_{5/3}$ at 14 TeV and 33 TeV
  - **arXiv:1309.2234**
- Pair production only
  - Single production requires additional assumptions regarding couplings
- Snowmass "detector" setup
  - Generate events with MadGraph
  - Simulation with Delphes
  - See **arXiv:1308.1636, arXiv:1309.1057**
- Standard Model backgrounds only

# 33 TeV Distributions After Same-Sign Selection



# Snowmass $T_{5/3}$ Selection

| Parameter | 14 TeV Min [GeV] | 33 TeV Min [GeV] |
|---|---|---|
| Leading lepton $p_T$ | 80 | 150 |
| Second lepton $p_T$ | 30 | 50 |
| Leading jet $p_T$ | 150 | 150 |
| Second jet $p_T$ | 50 | 50 |
| $\not{E}_T$ | 100 | 200 |
| $H_T$ | 1500 | 2200 |
| $S_T$ | 2000 | 3000 |

- In addition, require objects corresponding to at least 7 decay products of the $T_{5/3}$ pair
  - Same-sign leptons account for 2
  - The rest are other leptons or jets
    - Top-tagged jets count as 3, W-tagged jets count as 2

# Snowmass $T_{5/3}$ Results

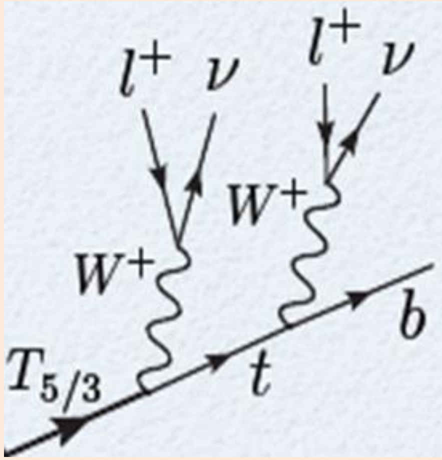
| Collider | Luminosity | Pileup | $3\sigma$ evidence | $5\sigma$ discovery | 95% CL |
|---|---|---|---|---|---|
| LHC 14 TeV | 300 $fb^{-1}$ | 50 | 1.51 TeV | 1.39 TeV | 1.57 TeV |
| LHC 14 TeV | 300 $fb^{-1}$ | 140 | 1.50 TeV | 1.38 TeV | 1.58 TeV |
| LHC 14 TeV | 3 $ab^{-1}$ | 50 | 1.67 TeV | 1.57 TeV | 1.76 TeV |
| LHC 14 TeV | 3 $ab^{-1}$ | 140 | 1.66 TeV | 1.55 TeV | 1.76 TeV |
| LHC 33 TeV | 300 $fb^{-1}$ | 50 | 2.36 TeV | 2.13 TeV | 2.48 TeV |
| LHC 33 TeV | 300 $fb^{-1}$ | 140 | 2.17 TeV | 2.15 TeV | 2.47 TeV |
| LHC 33 TeV | 3 $ab^{-1}$ | 50 | 2.61 TeV | 2.40 TeV | 2.77 TeV |
| LHC 33 TeV | 3 $ab^{-1}$ | 140 | 2.50 TeV | 2.35 TeV | 2.69 TeV |

- At 33 TeV, 95% CL at $T_{5/3}$ mass of about 2.5 to 2.8 TeV

# Considerations for 100 TeV: Trigger

- LHC Run I (7-8 TeV): use dilepton triggers
  - Shared with Higgs, Top, SUSY, etc. groups.

- LHC Run II (13-14 TeV): still dilepton triggers, but customized
  - Higgs, Top, etc. groups prefer low-$p_T$ leptons with tight isolation
  - Top quarks from $T_{5/3}$ are highly boosted
    - Leptons may merge with b-quarks
    - Tight isolation may impact signal efficiency




- At 100 TeV
  - Leptons from top quark **will** merge with b-quarks
  - May need special algorithm for identifying such top quarks

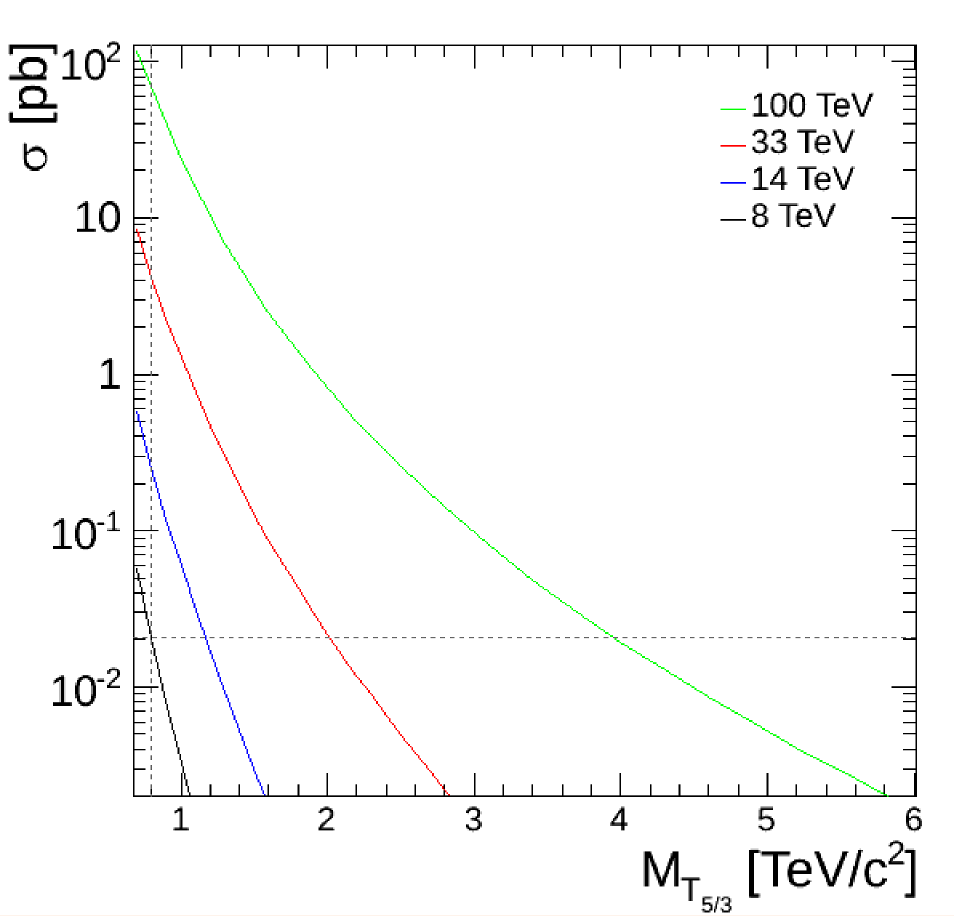
# Considerations for 100 TeV: Jet Substructure

- LHC Run I (8 TeV)
  - W and top tagging based mainly on masses of sub-jet combinations after "grooming" the jet
  - Less successful for very high $p_T$ jets
    - Sub-jets too close
    - Target mass window small compared to energy scale

- LHC Run II (13-14 TeV)
  - n-Subjettiness, other algorithms still being developed

- 100 TeV: Same high $p_T$ problems, but much, much worse
  - Will need new algorithms
  - Consider this when designing detector

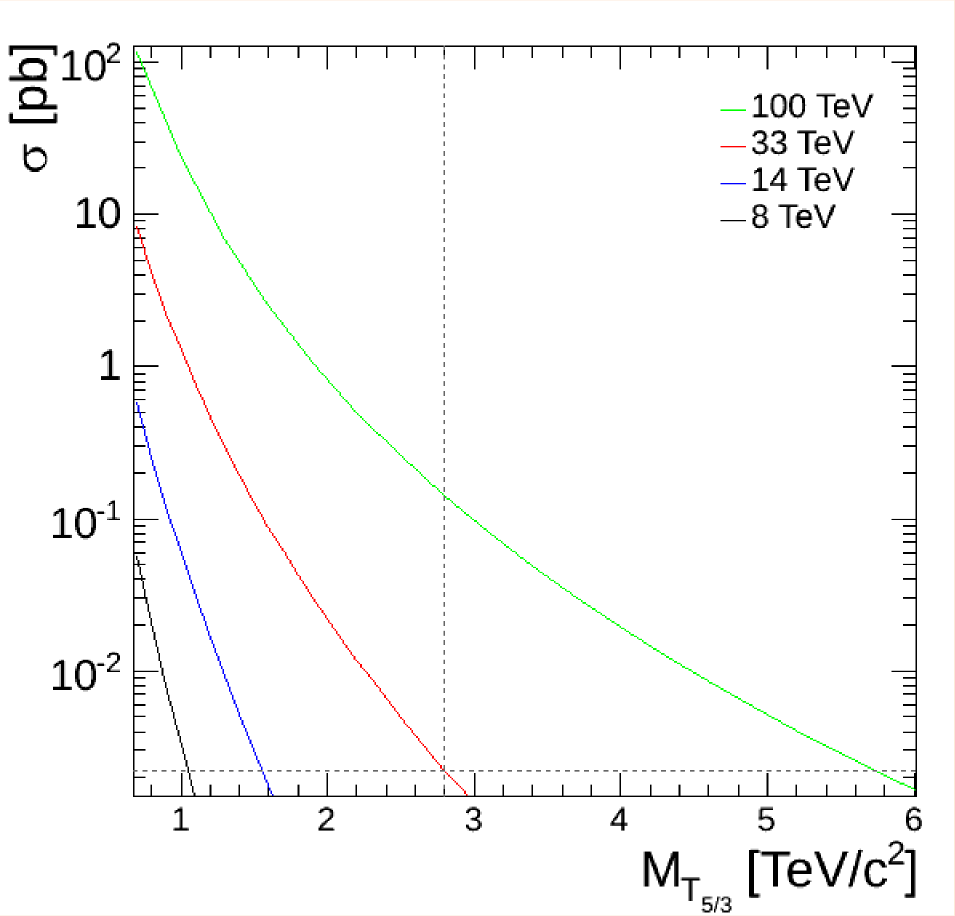
# Cross-Section Extrapolation (8 TeV)




Cross-sections calculated with HATHOR

- 800 GeV limit is from a full-fledged analysis
  - All background, systematics, etc.
- But only 20$fb^{-1}$ of luminosity
- Uncertainty on background is of order 50%
- Assuming similar performance, can exclude $T_{5/3}$ of up to 4 TeV at 100 TeV collider

# Cross-Section Extrapolation (33 TeV)




- 33 TeV limit from Snowmass study
- No non-prompt or charge misidentification backgrounds
- Background uncertainty of order 20%
- With 3ab$^{-1}$, can reach about 5.7 TeV at 100 TeV collider

# Conclusions

- Searches for particles like the $T_{5/3}$ can be done at 100 TeV
  - But need to think about very boosted objects
    - At trigger
    - At reconstruction
- Pair-produced cross-section scaling limits results
  - Will consider single-production
  - Produced in association with top quark so not that different
    - Still same-sign dileptons