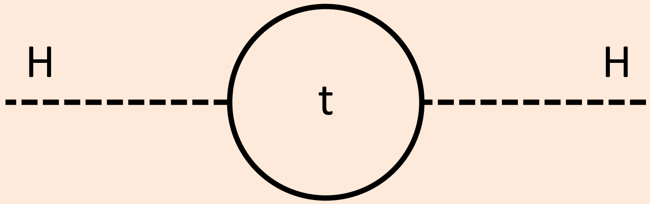
Top Partners at Future Hadron Colliders

Aram Avetisyan

Boston University

Top Partners

- Common feature of several different theories
  - Decay to top + X
  - Couple to 3rd generation quarks
  - Solve hierarchy problem



- Can be found in:
  - Composite Higgs
  - Extra dimensions
  - Little Higgs
  - SUSY (stops)

Models used for studies in this talk

The Snowmass "Detector"

- Generate events with MadGraph
- Hadronization with Pythia
- Simulation with Delphes
  - Configuration based on ATLAS and CMS detectors
- Generated common H_T-binned backgrounds
- See
  - **arXiv:1308.0843**
  - **arXiv:1308.1636**
  - **arXiv:1309.1057**

Vector-Like Quarks

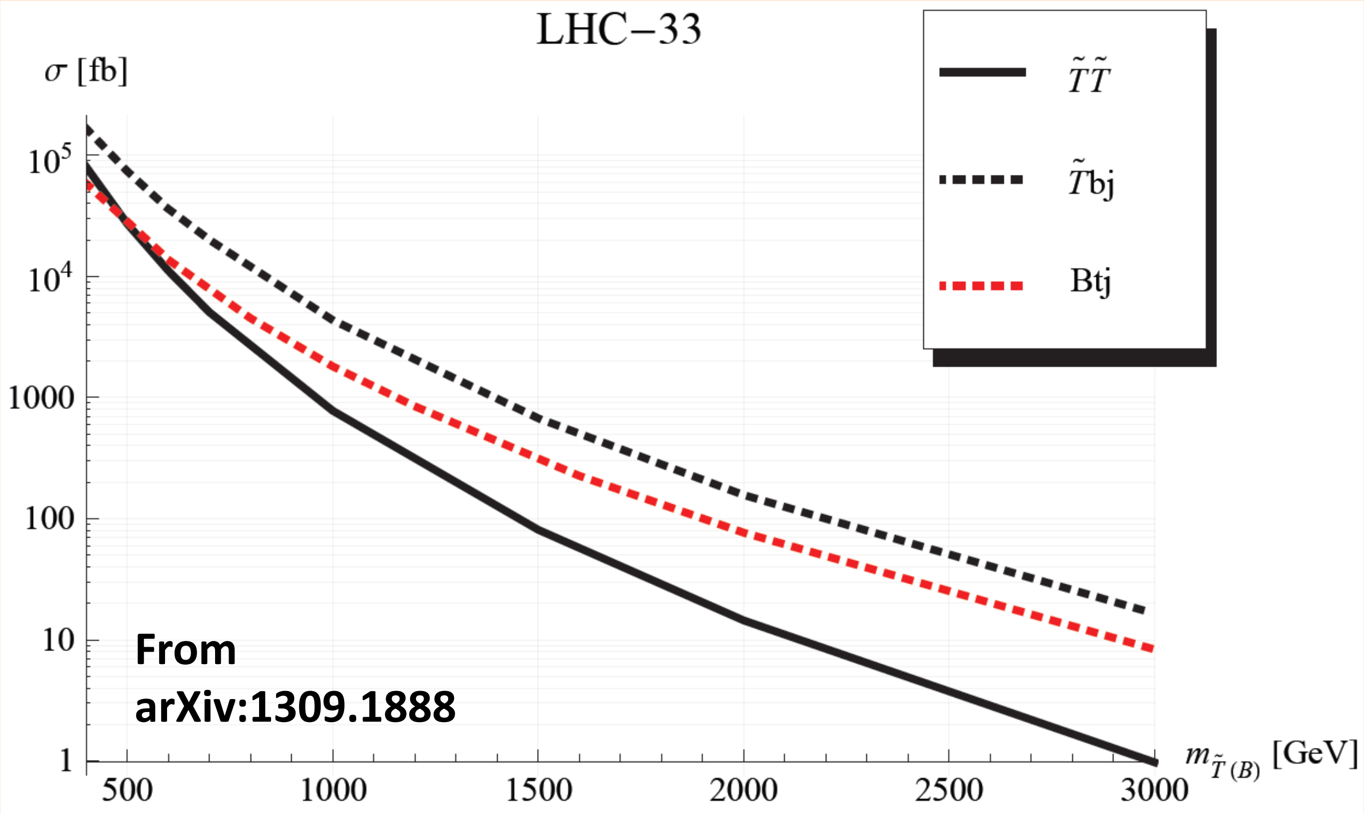
- See JHEP 04:004, 2013 for a detailed theoretical description
- Can appear in a singlet or in a fourplet:

$$\mathcal{Q} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (\mathbf{2},\mathbf{2})_{2/3} \;\; , \;\; \tilde{T} = (\mathbf{1},\mathbf{1})_{2/3}$$

- $T_{5/3}$ and $T_{2/3}$ are the lightest
- $T_{5/3}$ decays exclusively to tW
- $T_{2/3}$, T and T~ and can decay to bW, tZ and tH
  - Some branching ratios may be 0 depending on the model

The Vector-Like T

- Can be produced singly or via pair-production
- Single production: more model dependent, more backgrounds
  - But much higher cross-section at large masses



Single Production of T

- **arXiv:1309.1888** (T. Andeen, C. Bernard, K. Black, T. Childers, L. Dell'Asta and N. Vignaroli)
- Studied T → tZ and T → tH
  - With single production, bW has high backgrounds
- Considered several pileup scenarios
  - Integrated luminosity = 1000 fb^{-1}
  - 0, 50 and 140 pileup
- Same selection for 14 TeV, 33 TeV and 100 TeV
  - May be further optimized with separate selections

Single T $\rightarrow$ tZ Selection

- Look for tri-lepton decays
  - Exactly 3 leptons (e or μ only) with $p_T > 20$ GeV, $|\eta| < 2.5$
  - At least 2 b-tagged Anti k_T $r = 0.5$ jets with $p_T > 30$ GeV, $|\eta| < 5$
  - At least 1 light jet
  - Missing $E_T > 30$ GeV

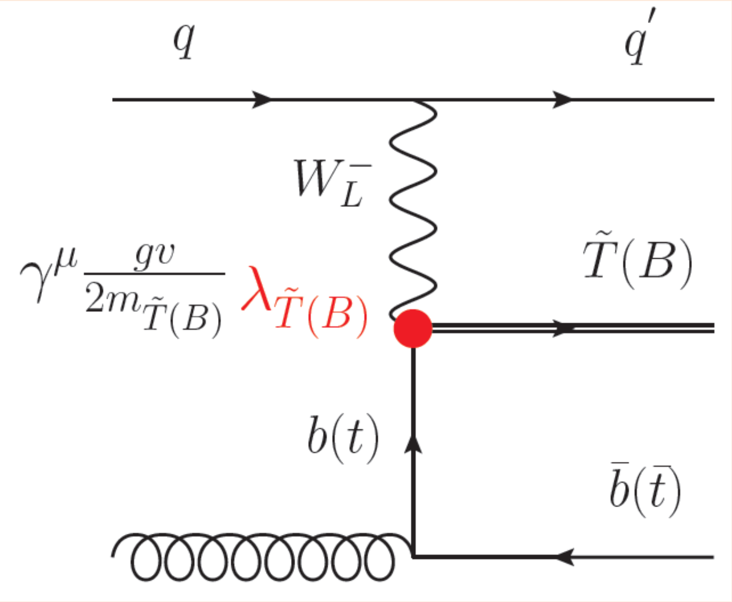
- Reconstruct Z-boson from leptons
  - Invariant mass must be within 10 GeV of M_Z

- Reconstruct W from remaining lepton and missing E_T

- Reconstruct top from W and b
  - Must have mass within 160 GeV < M < 190 GeV

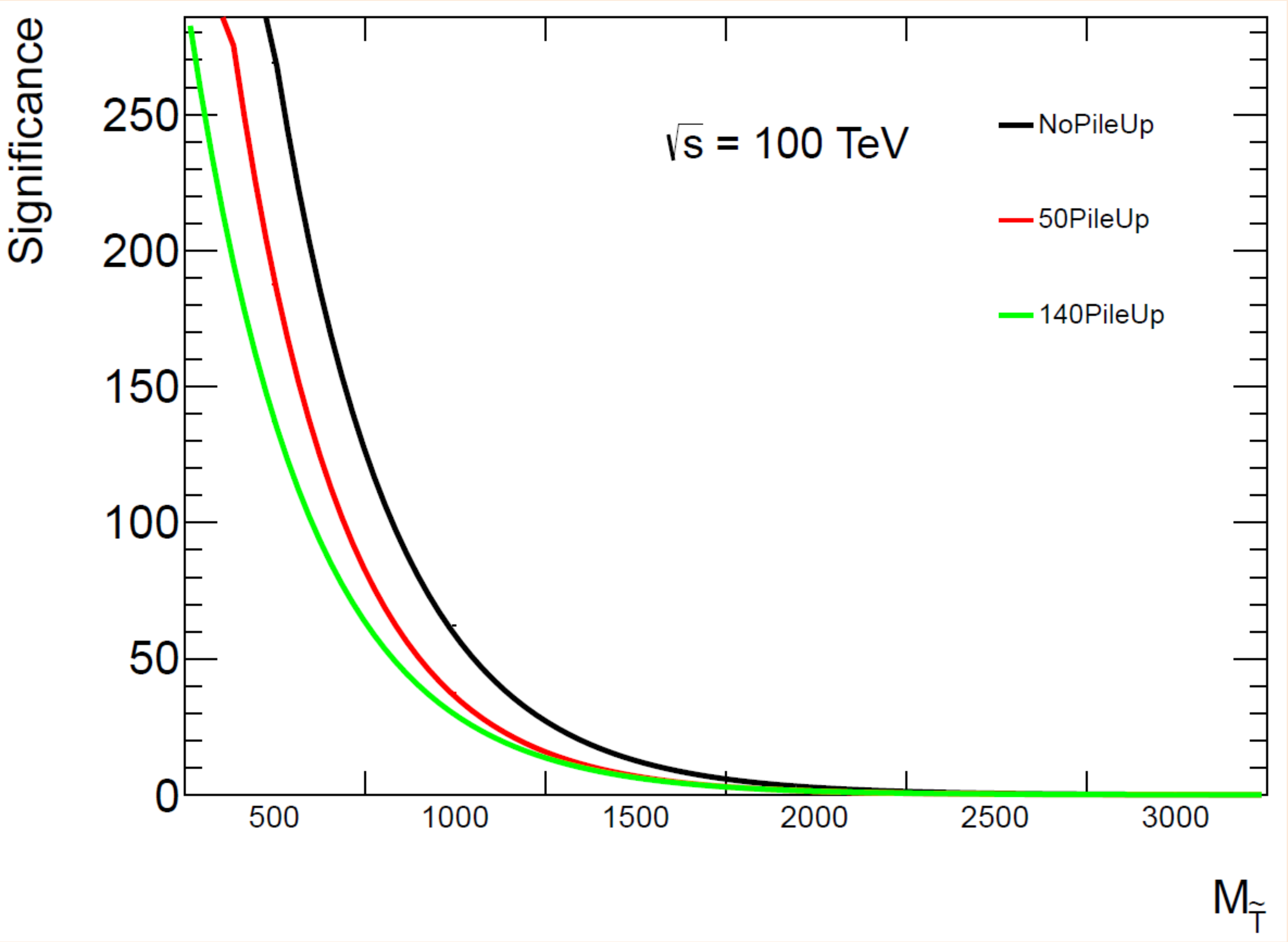
Single T → tH Selection

- Assume H → bb, leptonic top decay
  - One lepton (e or μ only)
    - $p_T > 20$ GeV, $|\eta| < 2.5$
  - Missing $E_T > 30$ GeV
  - 3 b-tagged jets with $p_T > 25$ GeV
  - At least 2 forward jets ($|\eta| > 3.0$)
    - From hard scattering
  - $H_T > 750$ GeV



- Reconstruct W from lepton and missing E_T
- Reconstruct top from b and W
- Cambridge-Aachen jet with 100 GeV < M < 150 GeV (Higgs)

Single T Results



- 5σ significance at around 1.7 TeV

Pair Production of T

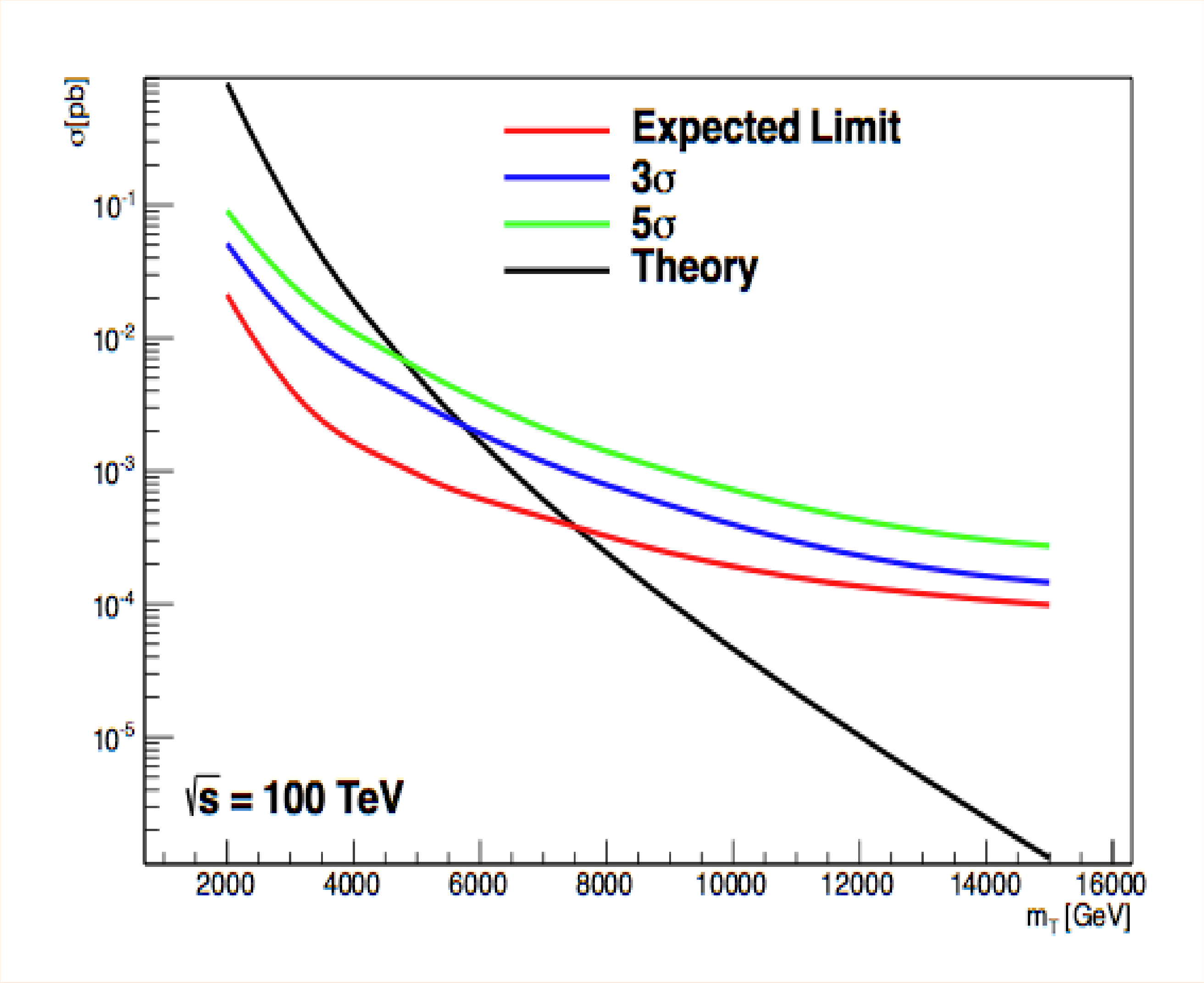
- Study by S. Ahuja
- Lepton+jets channel
  - In all decay modes
  - TT→ tHtH, tZtZ, WbWb, tHtZ, tHWb and tZWb
- Sensitivity studies for VLHC
  - 100 TeV
  - $\int L = 1000\ fb^{-1}$
  - Pileup = 40

Pair T Selection

- Preselection:
  - Exactly one charged lepton (e or μ) with $p_T > 30$ GeV
  - Missing $E_T > 150$ GeV,
  - At least three jets with $p_T > 2000, 1300, 700$ GeV and $|\eta| < 2.5$
  - Leading b-jet $p_T > 1500$ GeV.
  - W-tagged jets $p_T > 200$ GeV
- Event Categories: 8 categories based on jet multiplicities
  - Category l3+nb: At least one W-jet + 0....n b-tagged jets
    - n = 0...3, where n = 3 includes n > 3
  - Category l4+nb: ≥ 4 jets with $p_T > 2000, 1300, 700$ & 150 GeV
    - No requirement on W-jets

Pair T Results

- 95% exclusion limit: ~7.3 TeV
- 3σ discovery: ~5.7 TeV
- 5 σ discovery: ~4.8 TeV

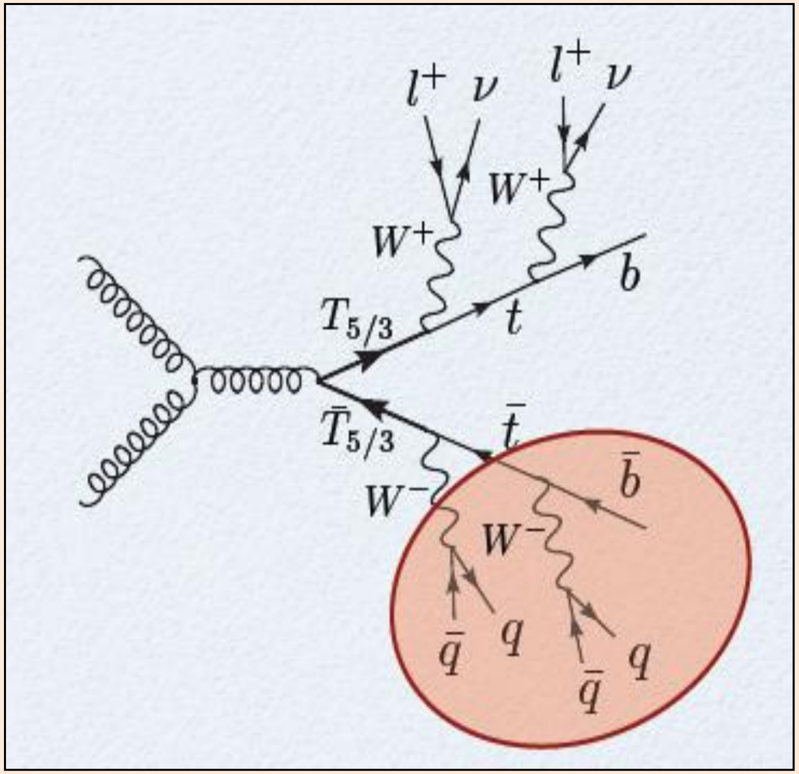


The $T_{5/3}$

- **arXiv:1309.2234** (A. Avetisyan, T. Bose)

- Decays to tW
  - Leads to same-sign dileptons:

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



- Currently pair-production only

- Considered 14 and 33 TeV

- Hadronic $T_{5/3}$ can be reconstructed

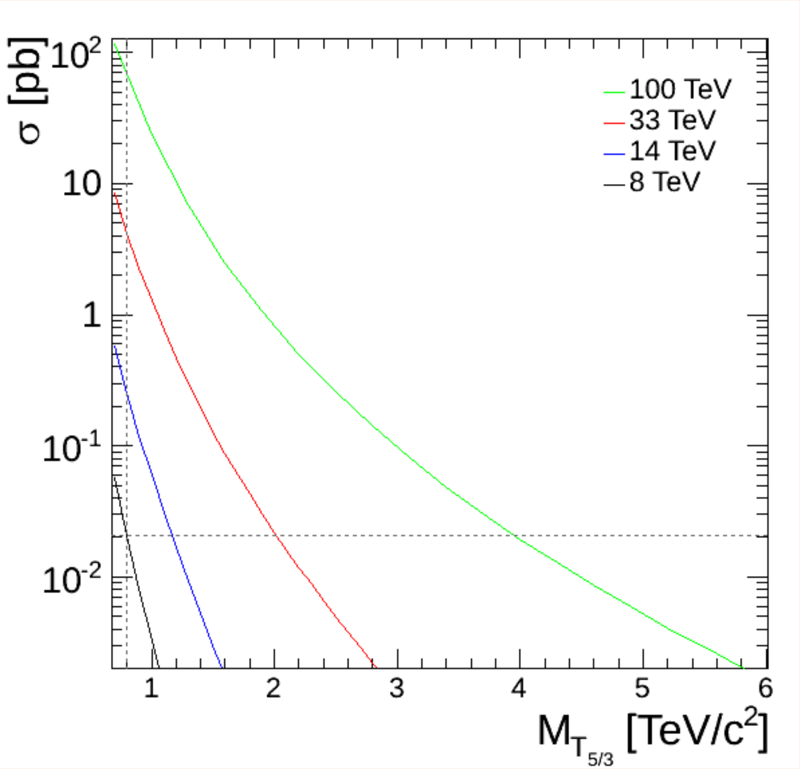
$T_{5/3}$ Selection

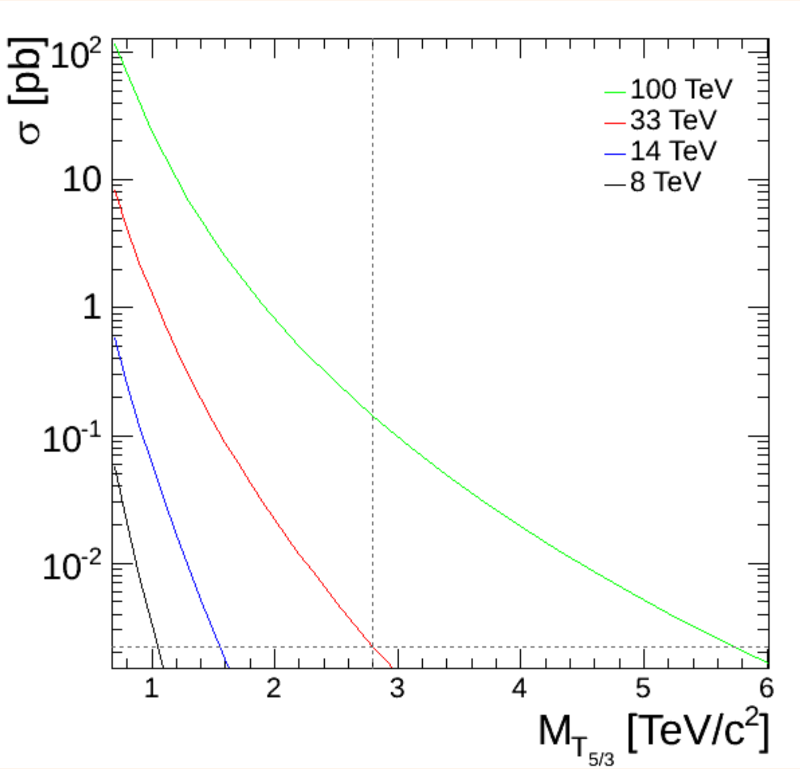
Parameter	14 TeV Min [GeV]	33 TeV Min [GeV]
Leading lepton p_T	80	150
Second lepton p_T	30	50
Leading jet p_T	150	150
Second jet p_T	50	50
$\not{E}_T$	100	200
H_T	1500	2200
S_T	2000	3000

- 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

$T_{5/3}$ Results

- Can extrapolate to 100 TeV based on cross-sections





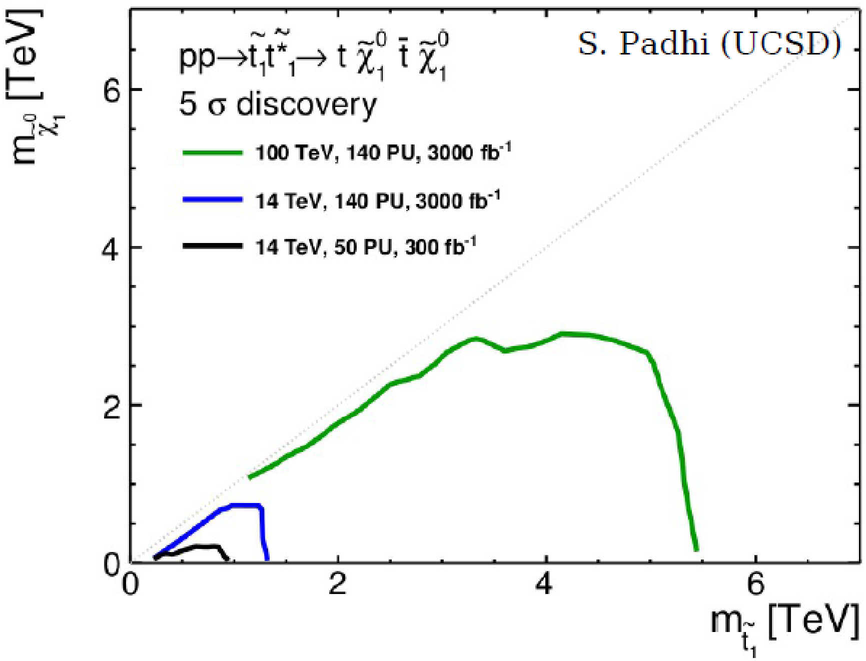
Extrapolate from 8 TeV analysis (PRL 112 (2014) 171801): 95% CL of about 4 TeV

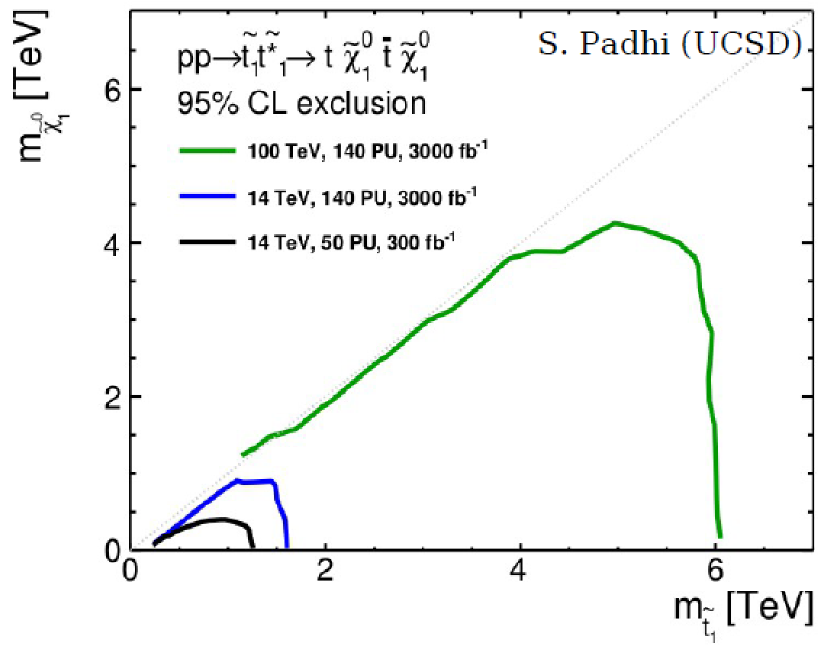
Extrapolate from 33 TeV study: 95% CL of about 5.7 TeV

The Stop

- **arXiv:1309.1514** (D. Stolarski)
- Model with t~ → $t\chi_0$ where the latter is the LSP
- Simulated with MadGraph + efficiencies from ATLAS and CMS
- Selection:
  - All hadronic ttbar decay
  - At least 1 b-tag
  - Tops must be top-tagged jets with $p_T > 500$ GeV
  - Missing $E_T > 600$ GeV

Stop Results





Preliminary results using 1-lepton mode.

→ With 140 PU, stop mass up to 6 TeV can be probed

arXiv:1309.1514

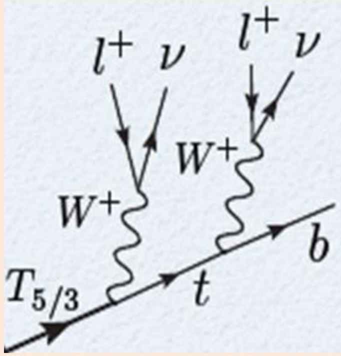
Similarly in all hadronic mode (only with 1 ab^{-1}) mass up to 5.7 TeV can be studied →

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 GeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
VLHC	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

Slide from S. Padhi

Considerations for 100 TeV

- Trigger
  - Top partner studies can generally afford to raise thresholds
  - May need to switch from dilepton triggers to single lepton
    - Leptons from top quark will merge with b-quarks



- Jet Substructure
  - 8 TeV algorithms based on masses after "grooming"
  - Less successful for very high p_T jets
    - Sub-jets too close
    - Target mass window small compared to energy scale
  - New algorithms (e.g. n-Subjettiness) to be used in LHC Run II
    - Will need even better ones at 100 TeV