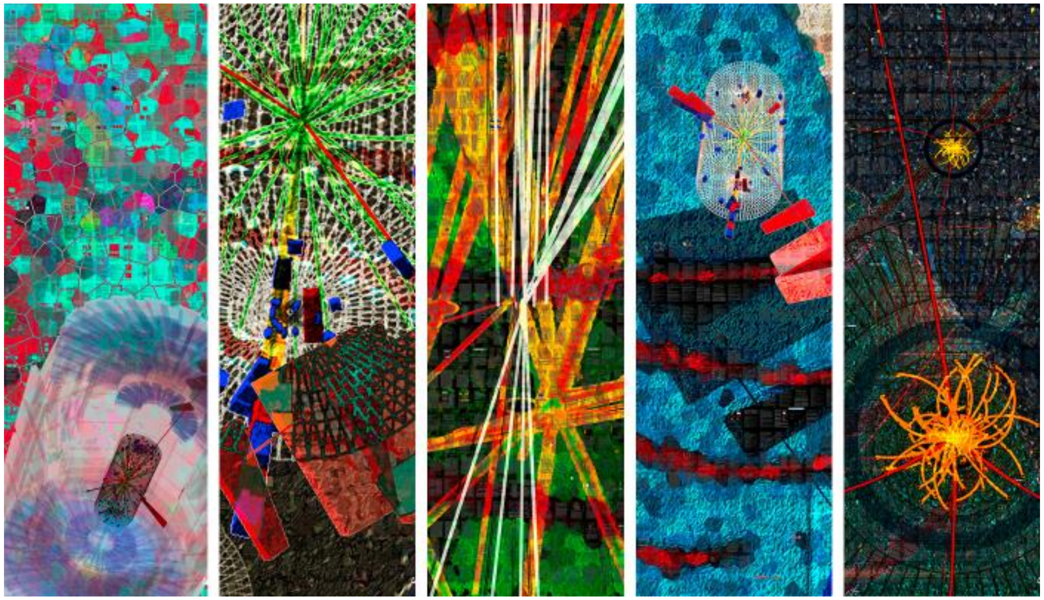
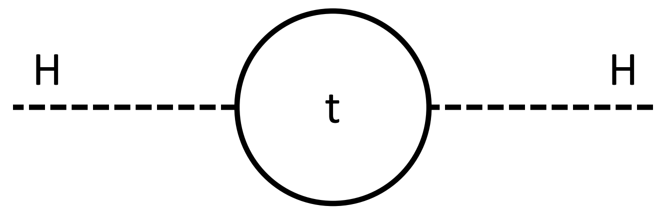
Heavy Quarks and Boosted jets



M. Narain (Brown U.)

Heavy Top Partners

- Common feature of several different theories
  - Couple to 3rd generation quarks
  - Solve hierarchy problem
  - Mostly driven by top quark loop
    - Though also W and Higgs itself
  - Need something to cancel it out



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

Models used for studies in this talk

- Consider two top partners: $T_{5/3}$ and Vector-Like T
  - Decay to top + X

Vector-Like Quarks

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

$$\mathcal{Q} = \left[\begin{array}{cc} T & T_{5/3} \\ B & T_{2/3} \end{array} \right] = (\mathbf{2}, \mathbf{2})_{2/3} \ , \ \tilde{T} = (\mathbf{1}, \mathbf{1})_{2/3}$$

- T5/3 and T2/3 are the lightest
- T5/3 decays exclusively to tW
- T2/3 decays to bW, tZ and tH
- B1/3 decays to bZ, tW, and bH
  - Some branching ratios may be 0 depending on the model

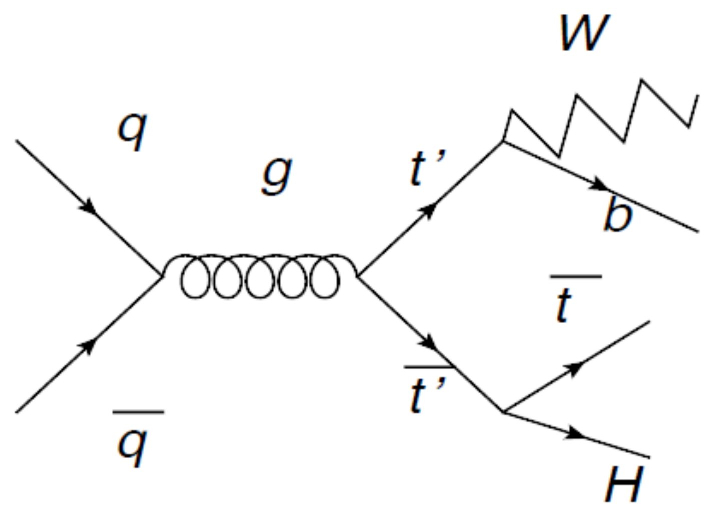
Final State Signatures

- Rich final state signatures, both in single and pair production: 2b, ≥2W, H/Z
- Cast a wide net: study by final state signatures
  - dilepton : opposite and same sign; multi-leptons; lepton+jets; all jets
- Mass Reconstruction and "tags"
  - "merged-jets with large Lorentz boost/object-tags": T, t, W, H/Z
  - Reconstructing mass variables T, B, T5/3, etc
    - optimizing the particular decay modes with 100% BR
    - use to confirm signal after seeing excess above backgrounds
- Slice analyses in multi dimensional space
  - nleptons (0, 1, 2OS, 2SS, ≥3),
  - njets (2,3, ≥4), nbtags (1, ≥2),
  - nW (0, ≥1), nTop (0, ≥1), nHZ (0, ≥1)

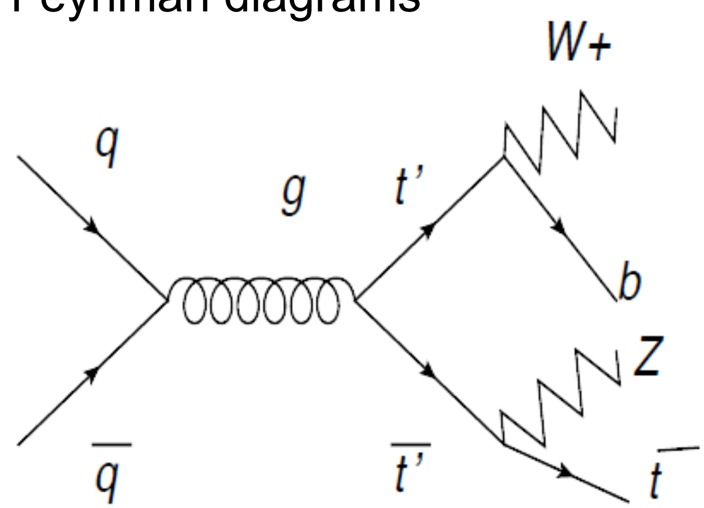
J.A. Aguilar-Saavedra.JHEP, 0911:030, 2009.
Rao, Whiteson, arXiv:1204.4504
etc…

Vector-Like T Quark

- T (aka t’) couples to bW, tZ and tH
  - Vector couplings to W and Z evade electroweak constraints
- Inclusive analysis
- Consider states where at least one W boson decays leptonically



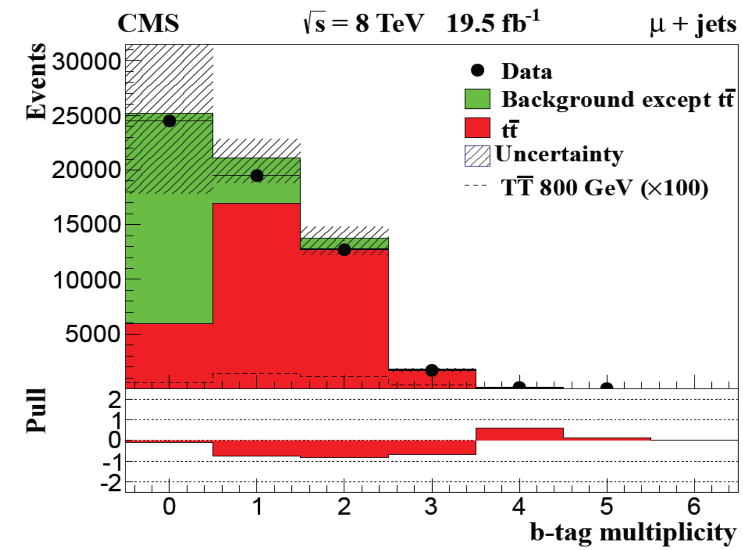
There are many more Feynman diagrams

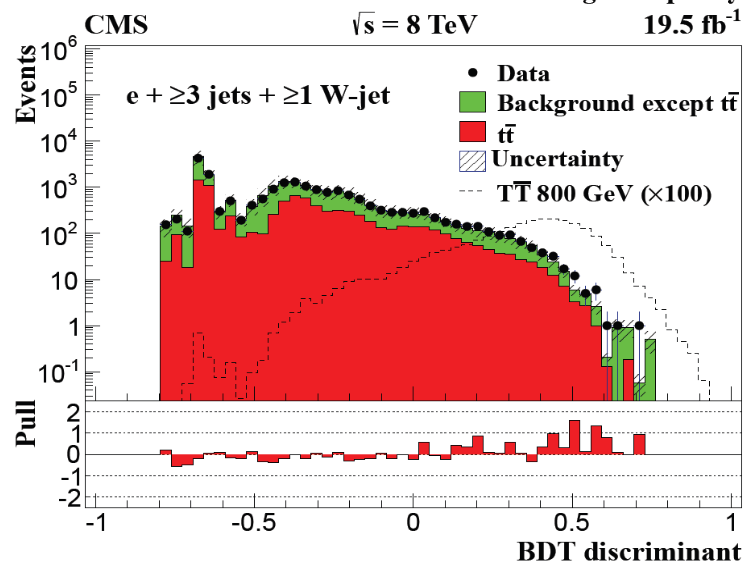


@8 TeV: Single Lepton T

- Basic Selection
  - p_T > 32 GeV lepton (e or mu)
  - 3 high p_T jets
    - One jet must be a W jet or a fourth jet is required
  - Missing E_T > 20 GeV

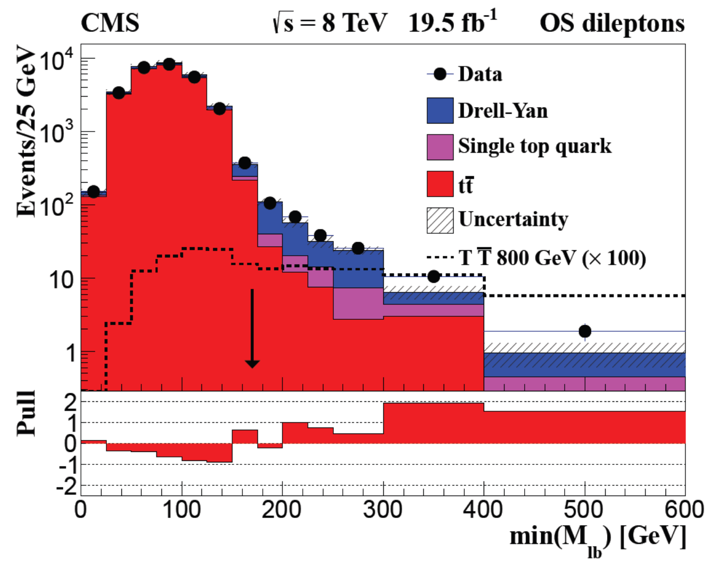
- Use Boosted Decision Tree
  - nJets, nBtags, H_T, missing E_T, p_T of lepton, p_T of 3rd & 4th jets
  - Multiple categories

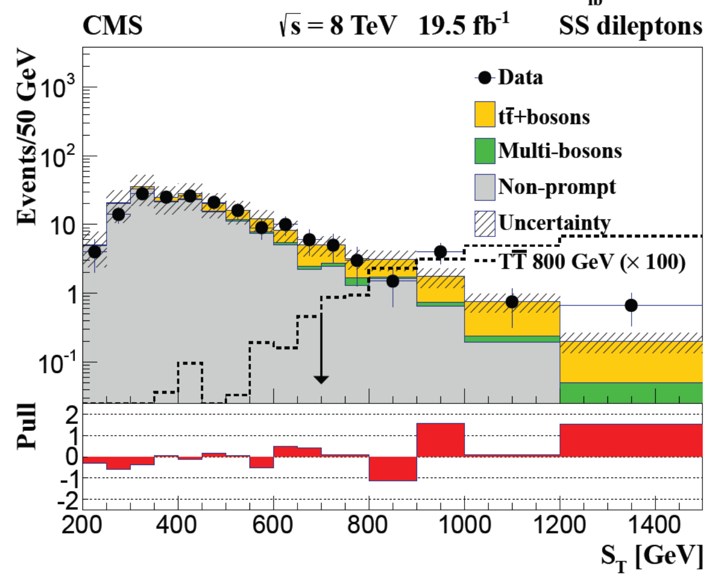




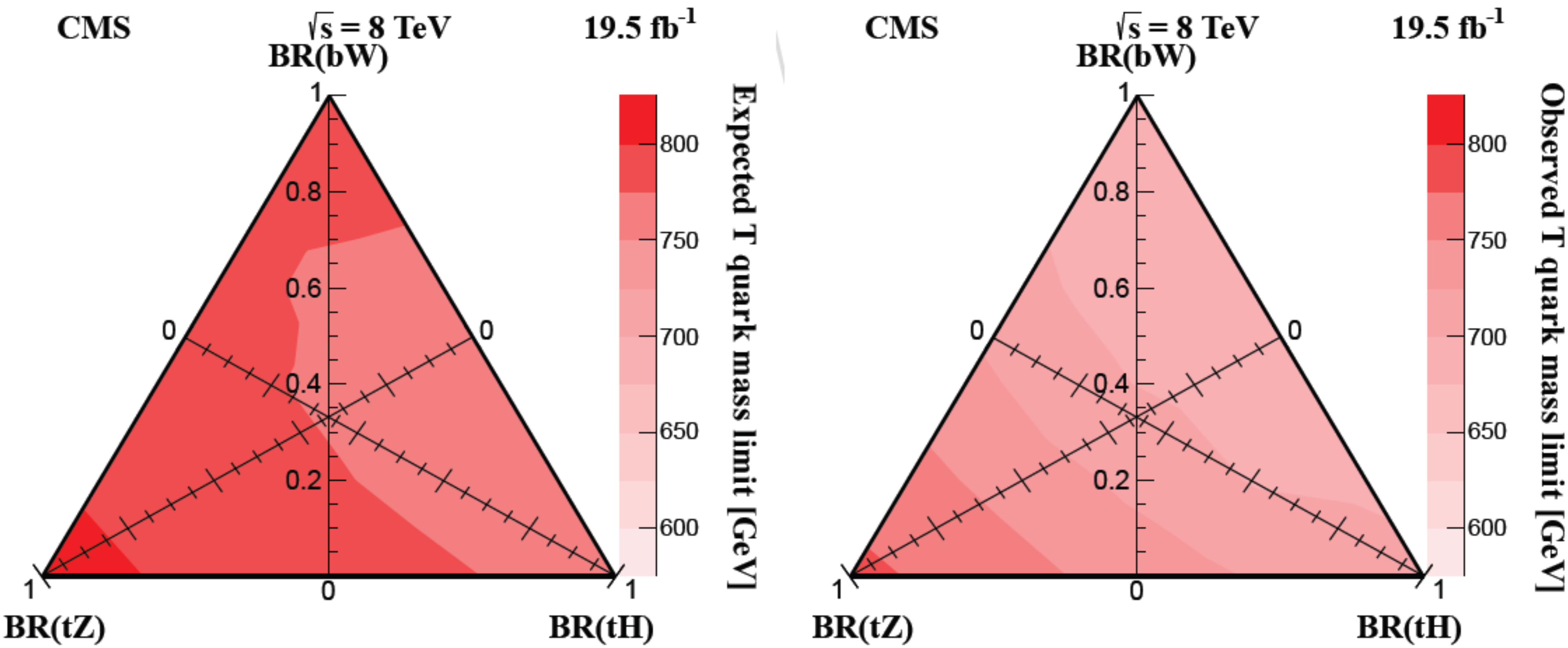
@8 TeV: Multi-Lepton T

- All channels:
  - Two leptons with $p_T > 20$ GeV
  - Missing $E_T > 30$ GeV
  - 1 or more bTags
- Four mutually exclusive categories
  - Opposite sign dileptons, 2-3 jets
    - bWbW
  - Opposite sign dileptons, 5+ jets
    - tH and tZ
  - Same sign dileptons, 3+ jets
  - Trileptons, 3+ jets
  - Different H_T, S_T, Mass(lepton+b), requirements





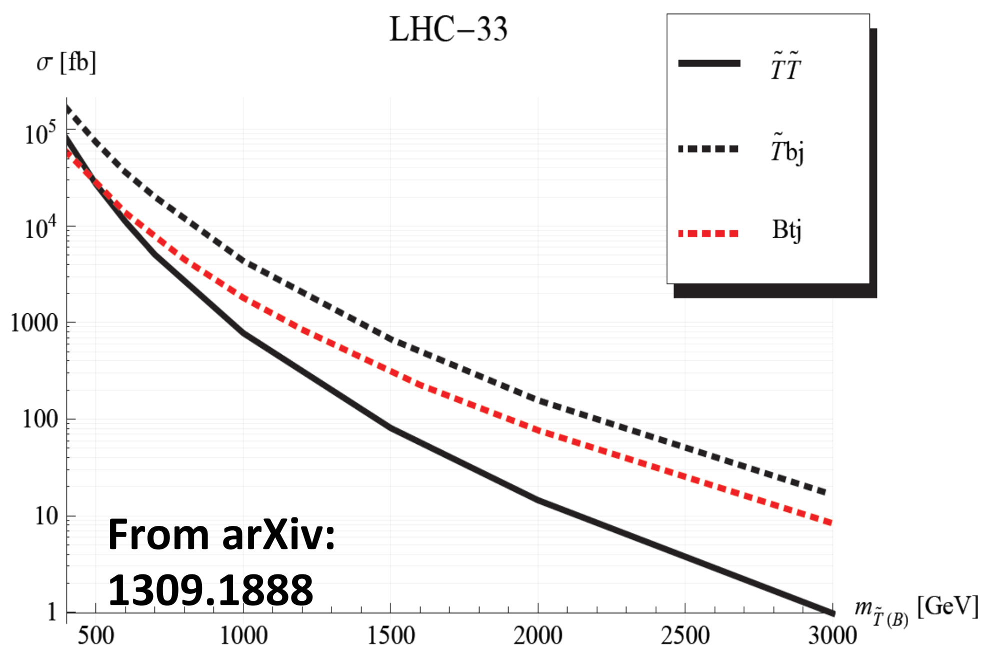
@8 TeV: Vector-Like T Results

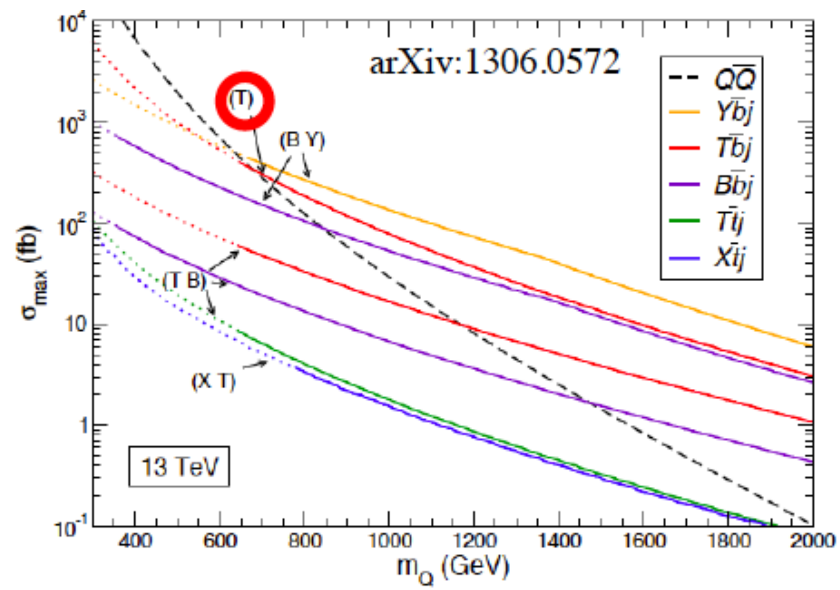


- Exclude T masses between 687 and 782 GeV
  - Inclusive analysis allows a novel interpretation
    - BR(bW) + BR(tH) + BR(tZ) = 1 → Triangle
    - Results available for any branching fraction
- Similar results from ATLAS (Phys.Lett., B718:1284–1302, 2012; Phys.Lett. B718 (2013) 1284-1302)

Future pp colliders: Heavy T

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





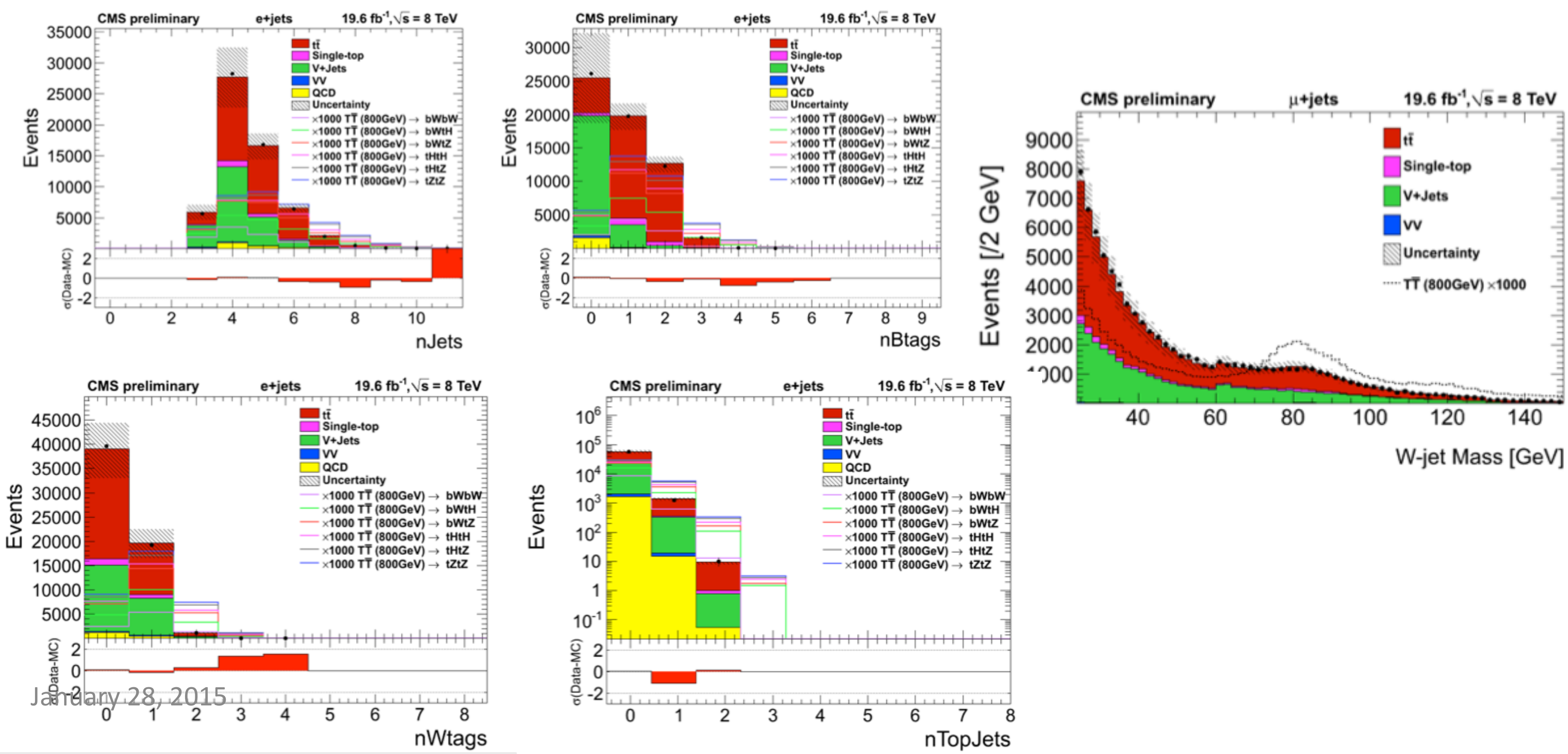
Future pp colliders: TT study

- Studies carried out in lepton+jets channel.
  - Considered all decay modes (TT→ tHtH, tZtZ, WbWb, tHtZ, tHWb, tZWb).
- Sensitivity studies at $\sqrt{s}$ = 14, 33 and 100 TeV
  - at 14 TeV: $\int L = 3\ ab^{-1}$ & Pile-up = 140; & $\int L = 300\ fb^{-1}$ & Pile-up = 40
  - at 33 TeV: $\int L = 3\ ab^{-1}$ & Pile-up = 140
  - at 100 TeV: $\int L = 1\ ab^{-1}$ & Pile-up = 40.
- Signal:
  - Generated using MadGraph & hadronization by PYTHIA.
- Background:
  - HT binned MadGraph samples
    - ttbar, W+jets, Z+jets, single top quark, and diboson.
- Simulation with Delphes
  - Configuration based on ATLAS and CMS detectors

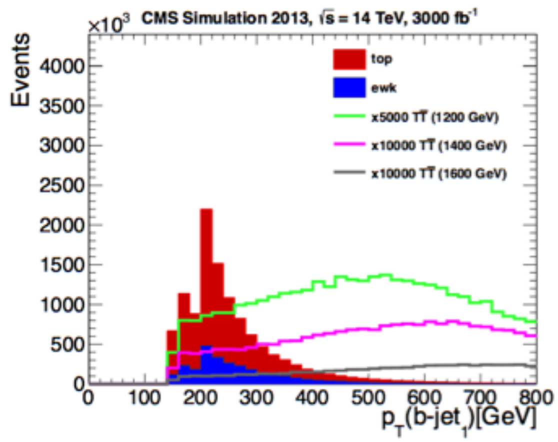
see: arXiv:1308.0843; arXiv:1308.1636; arXiv:1309.1057

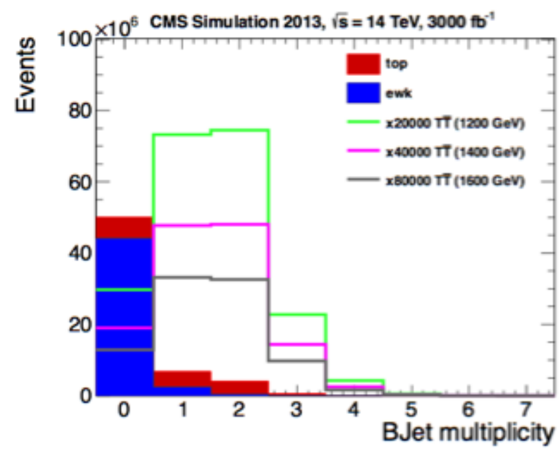
TT@ 8TeV (single leptons)

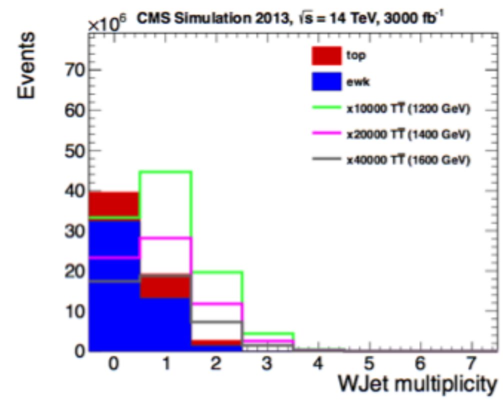
- Distributions below from 8 TeV study show the large number of jets, b-tags, and the presence of merged W-jets and top-quark jets at large T masses.



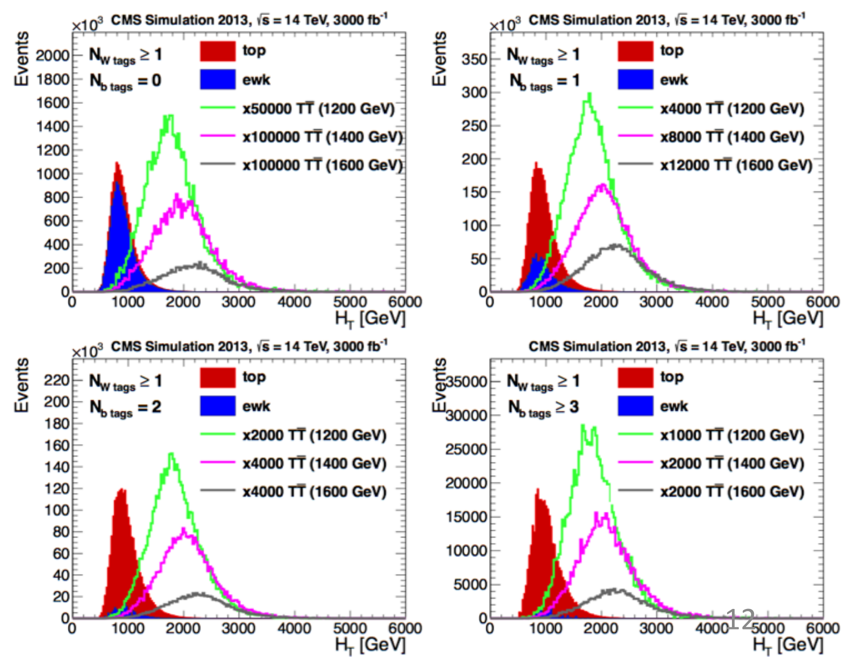
TT @14 TeV (single leptons)







- Presence of
  - Very High pT bjets
  - W tags
- Look at HT distributions for events categorized in b-tags and W-tags

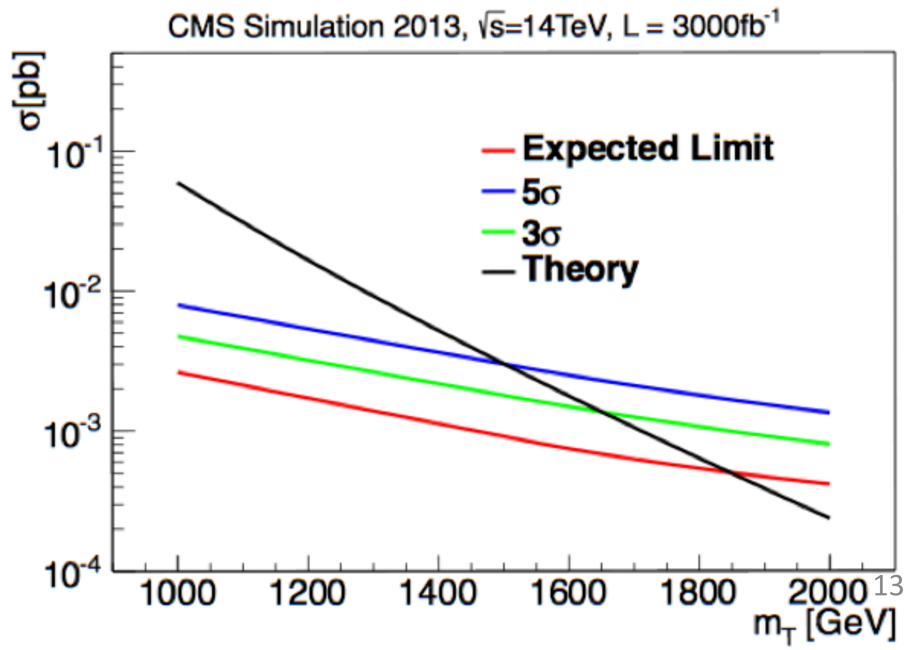


T quark Sensitivity @ 14 TeV

- FTR-13-026 (TT Study for ECFA 2013)
- Also Snowmass 2013 (arXiv:1309.0026)
  - Study T pair production
- 95% exclusion limit ~ 1.85 TeV
- Discovery reach

  3 sigma: ~ 1.65 TeV

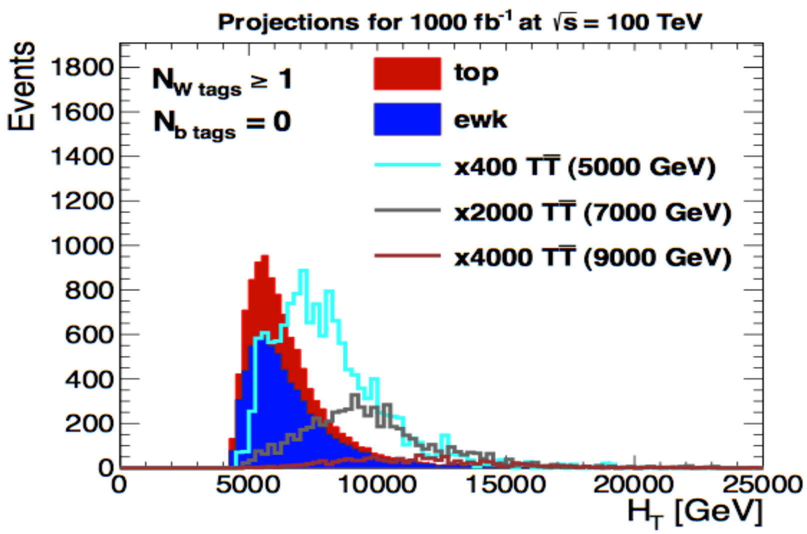
  5 sigma: ~ 1.5 TeV

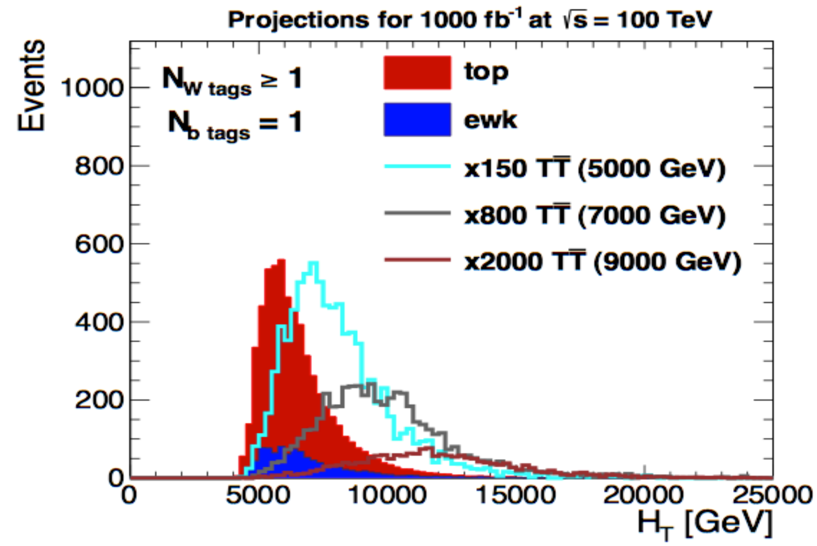


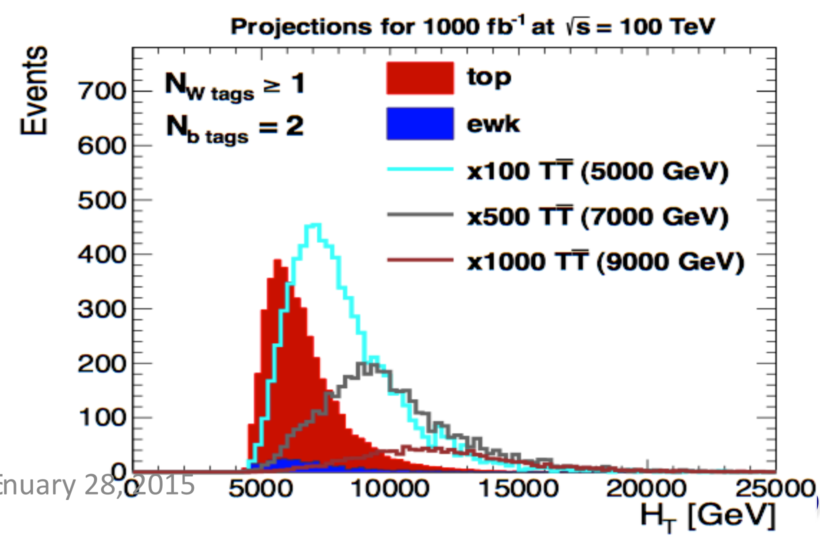
TT selection @100 TeV

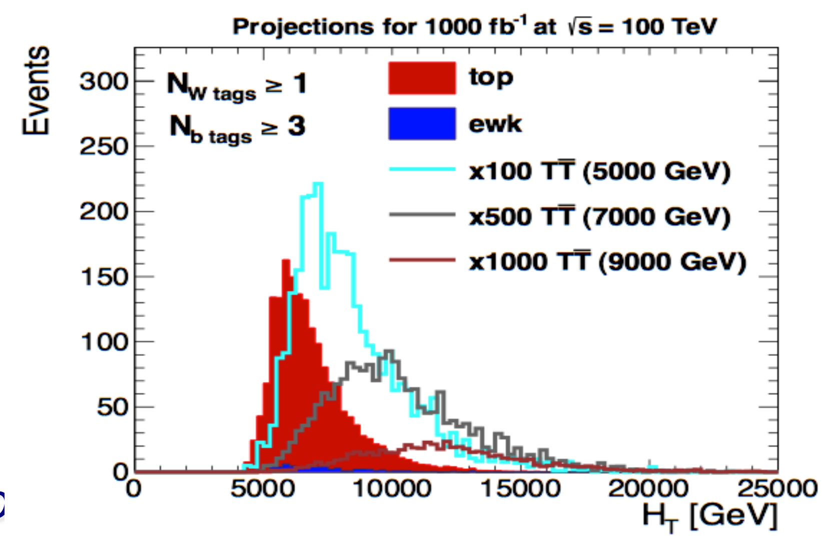
- Pre-selections: (cuts optimized based on S/√B)
  - exactly one charged lepton (electron or muon) with pT > 30 GeV
  - Missing ET > 150 GeV,
  - at least three jets with pT > 2000, 1300, 700 GeV and $|\eta| < 2.5$
  - Leading b-jet pT > 1500 GeV.
  - w-jets pT > 200 GeV
- Event Categories: divided into eight categories based on jet multiplicities – similar to the 14 TeV study
  - Category l3+nb: At least one W-jet + 0....n b-tagged jets (n = 0...3, where n = 3 includes events with at least three b-tagged jets)
  - Category l4+nb: ≥ 4 jets. pT > 2000, 1300, 700 & 150 GeV & no requirement on W-jets
- Signal presence studied using HT distributions

TT: H_T distributions @100 TeV

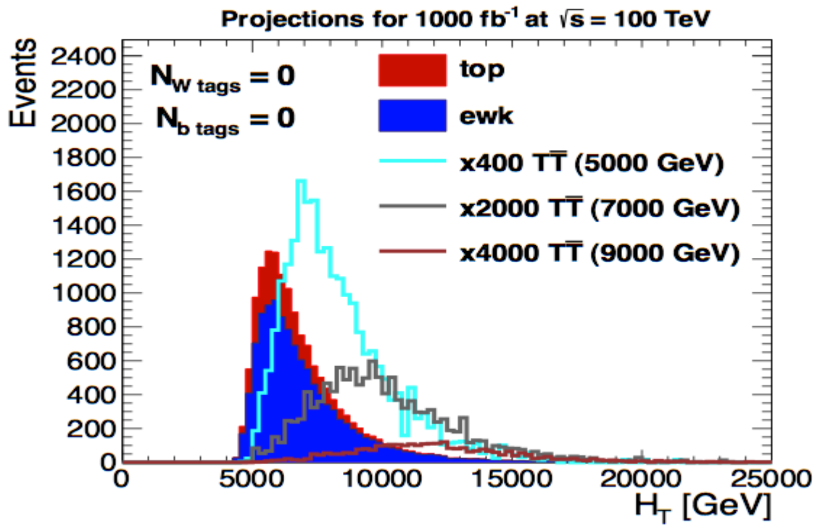


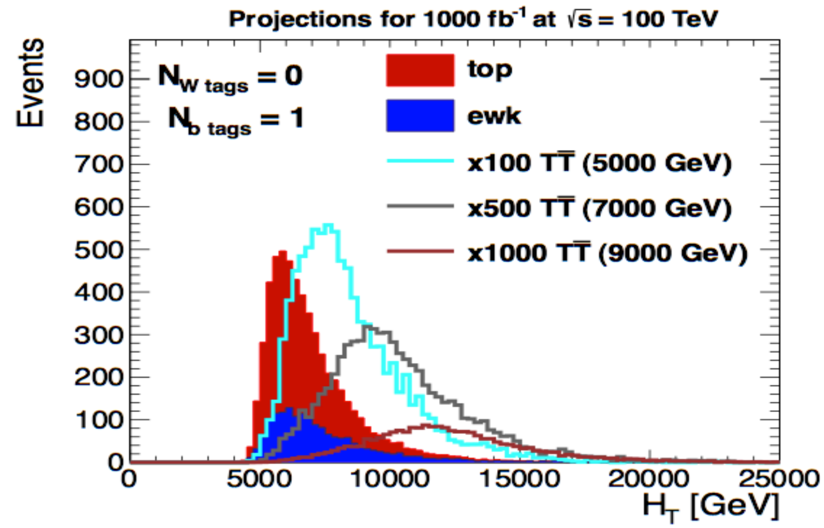


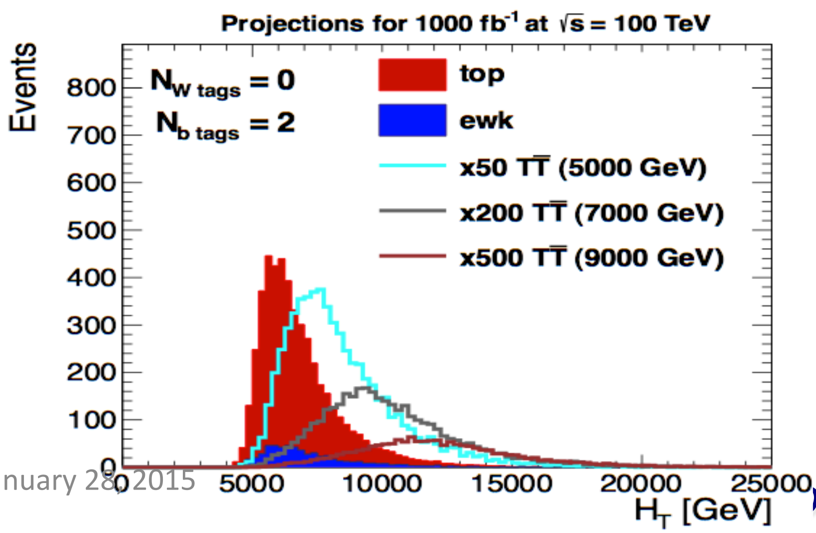


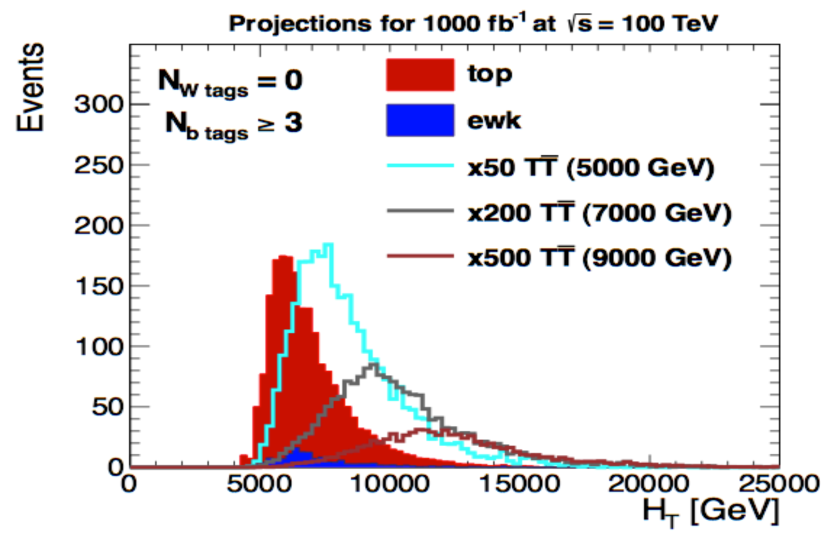


TT: H_T distributions @100 TeV







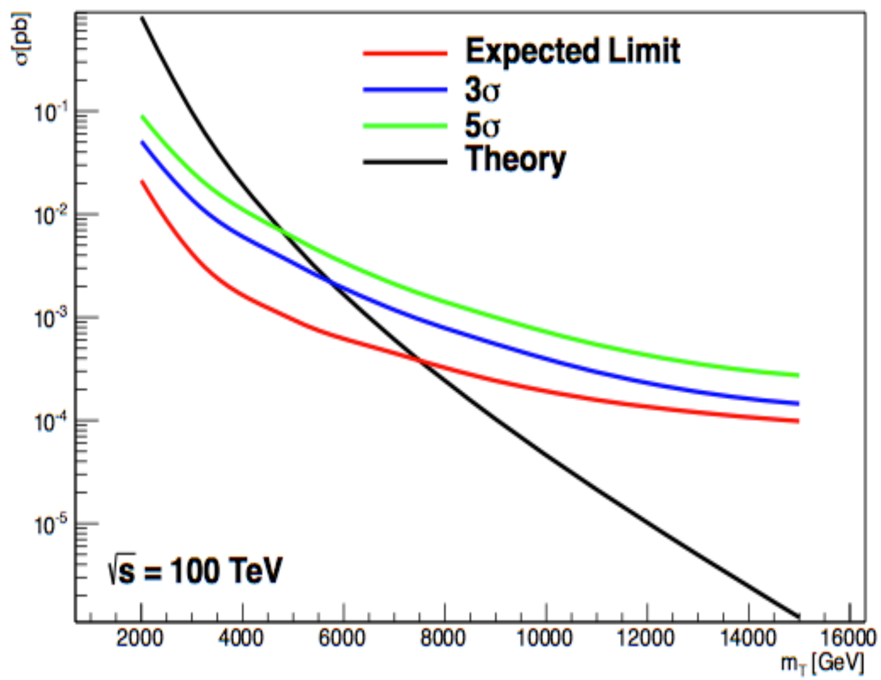


Discovery Reach

- Mass reach for pair production of T quark in lepton+jets channel estimated to be:
- 95% exclusion limit ~ 7.3 TeV
- Discovery reach

  3 sigma: ~ 5.7 TeV

  5 sigma: ~ 4.8 TeV



Sensitivity Comparisons

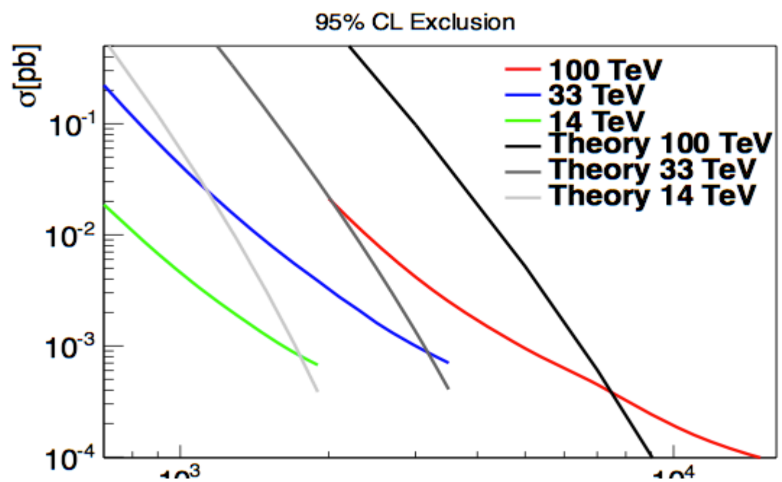
Discovery reaches for

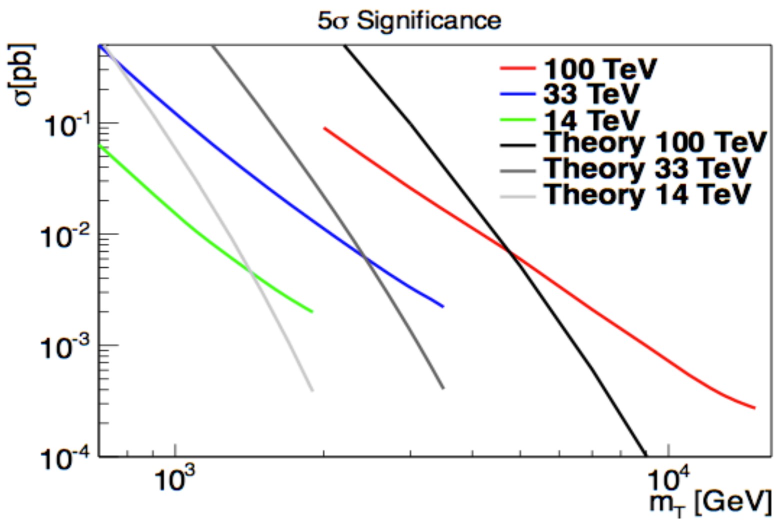
100 TeV vs

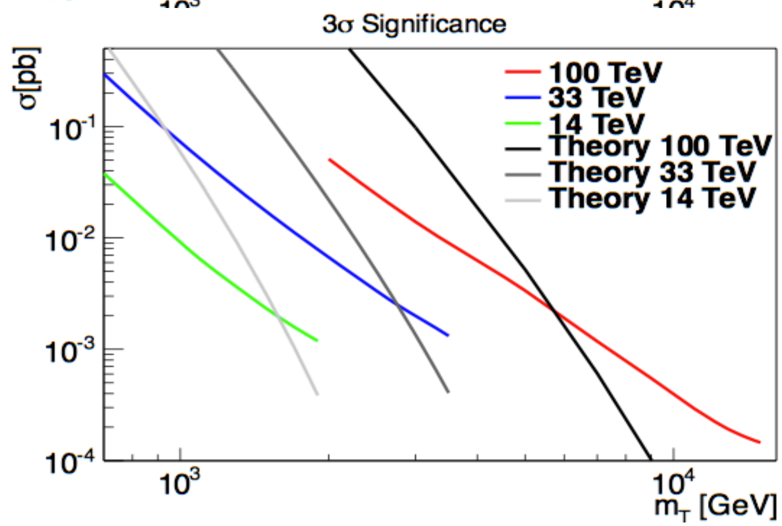
33 TeV vs

14 TeV

colliders







Sudha Ahuja, S. Bhattacharya, Brajesh Chaudhury, Jimin George,
Ulrich Heintz, Ashish Kumar, Meenakshi Narain, John Stupak

Single Production of T

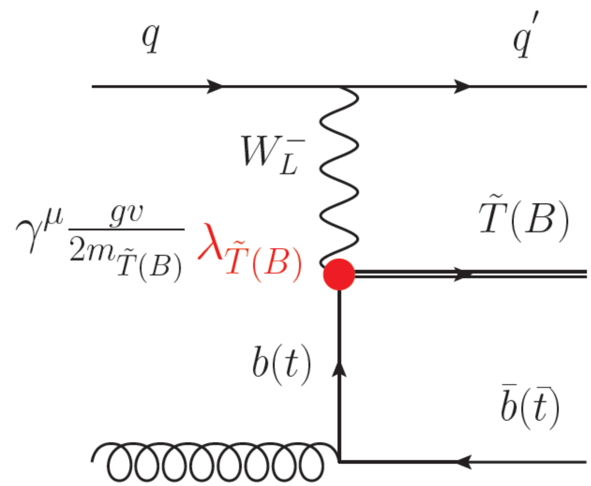
- **arXiv:1309.1888** (T. Andeen, C. Bernard, K. Black, T. Childers, L. Dell'Asta and N. Vignaroli)
- Studied $T \rightarrow tZ$ and $T \rightarrow tH$
  - With single production, bW has high backgrounds
- Considered several pileup scenarios
  - Integrated luminosity = 1000 fb^{-1}
  - 0, 50 and 140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

Single T → tZ Selection

- Look for tri-lepton decays
  - Exactly 3 leptons (e or μ only) with pT > 20 GeV, $|\eta| < 2.5$
  - At least 2 b-tagged Anti kT r = 0.5 jets with pT > 30 GeV, $|\eta| < 5$
  - At least 1 light jet
  - Missing ET > 30 GeV
- Reconstruct Z-boson from leptons
  - Invariant mass must be within 10 GeV of MZ
- Reconstruct W from remaining lepton and missing ET
- 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)
    - pT > 20 GeV, |η| < 2.5
  - Missing ET > 30 GeV
  - 3 b-tagged jets with pT > 25 GeV
  - At least 2 forward jets (|η| > 3.0)
    - From hard scattering
  - HT > 750 GeV

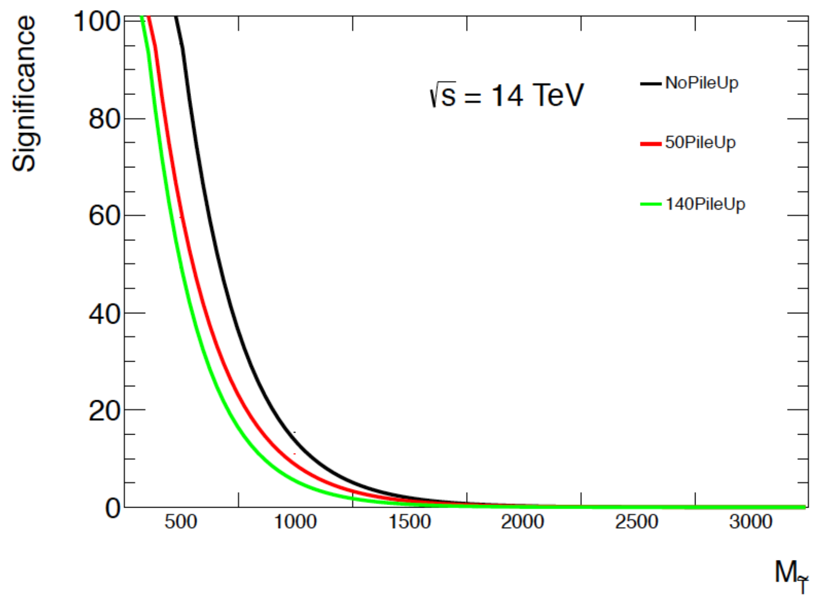


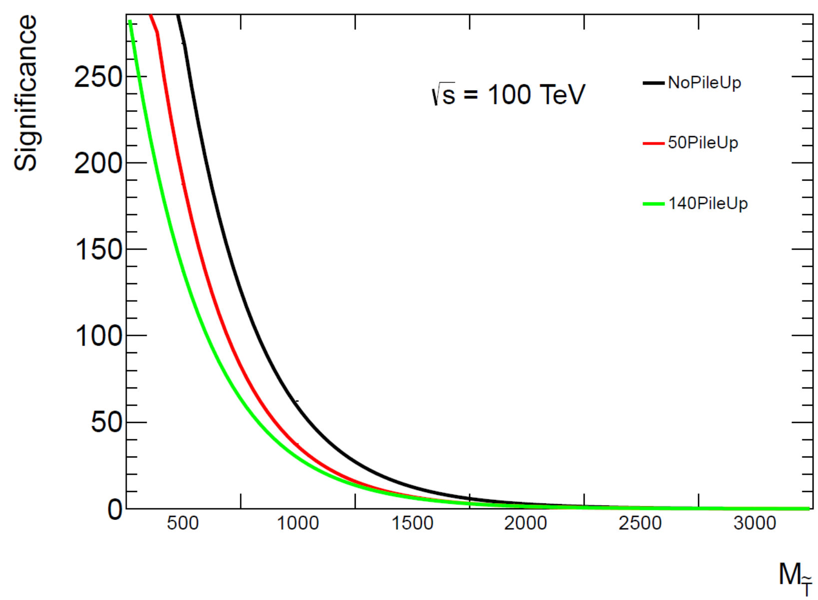
- Reconstruct W from lepton and missing ET
- Reconstruct top from b and W
- Cambridge-Aachen jet with 100 GeV < M < 150 GeV (Higgs)

T quark Sensitivity

- Study single T production

100 TeV collider: 5σ significance at around 1.7 TeV





(arXiv:1309.1888, Andeen et al)

B quark Sensitivity @ 14 TeV

- (arXiv:1309.0788, Varnes et al)
  - Study B pair production

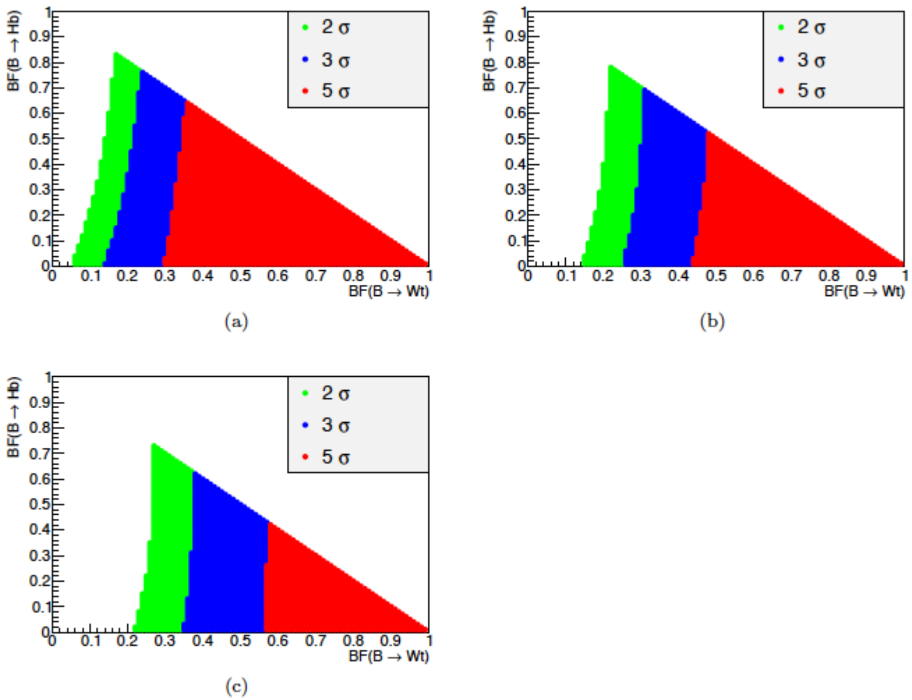


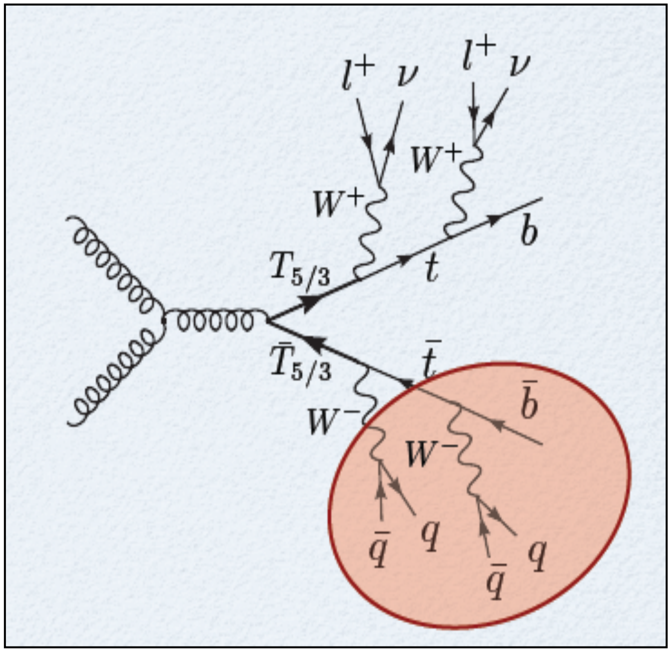
Figure 1: Expected sensitivity to pair production of 1000 GeV B quarks at a 14 TeV LHC, assuming an average of 50 interactions per bunch crossing and an integrated luminosity of 300 fb^{-1}. The assumed systematic uncertainty, expressed as a fraction of the background yield, is 0 for (a), 20% for (b), and 40% for (c).

$T_{5/3}$ Top Partners

- Theoretical descriptions:
  - ***Contino & Servant***, JHEP 0806:026 (2008)
  - ***Mrazek & Wulzer***, Phys. Rev. D 81, 075006 (2010)
- Named for its exotic charge: +5e/3
- Striking signature:

  same-sign dileptons

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



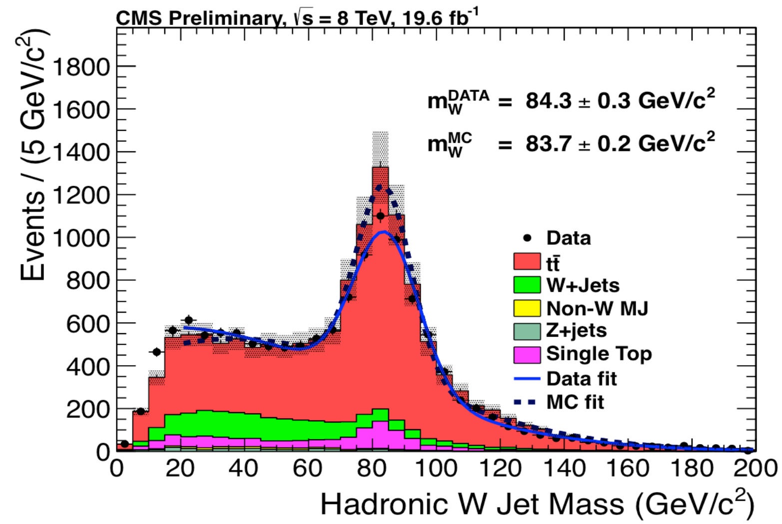
- Hadronically decaying $T_{5/3}$ can be reconstructed

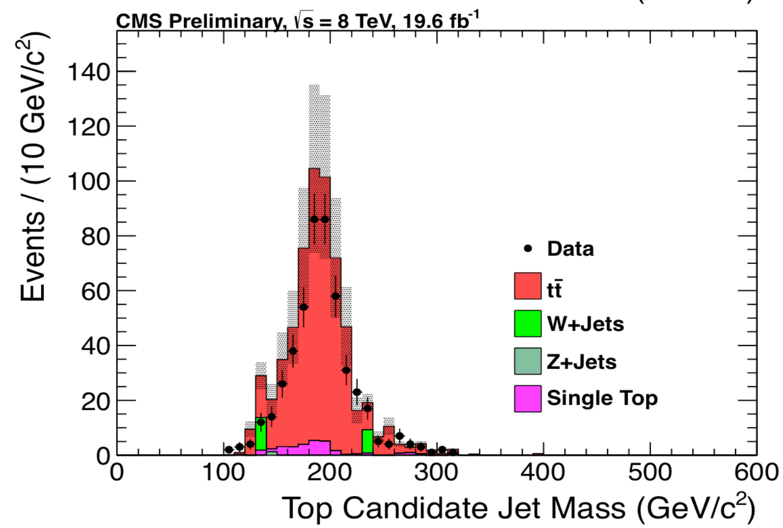
Backgrounds

- 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

Boosted Jet Reconstruction

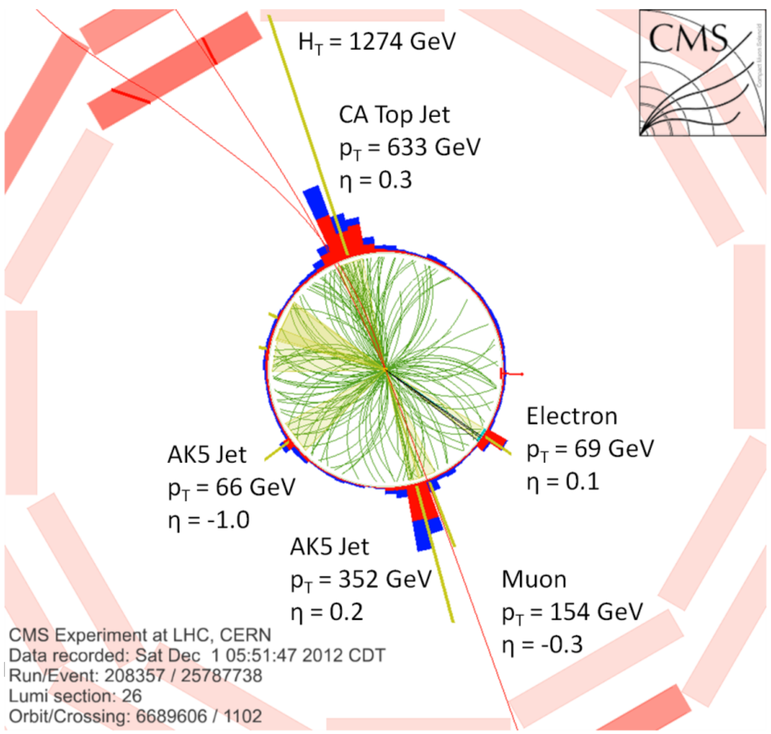
- Jets from W bosons and top quarks merge at high pT
- Reconstruct them with different algorithm (Cambridge-Aachen) and wider cone
- Use jet substructure to identify merged W bosons and top quarks
  - W-jets:
    - 2 subjets
    - Jet mass consistent with W mass
  - Top-jets:
    - 3+ subjets
    - Jet mass consistent with top mass
    - Two subjets must add up to W

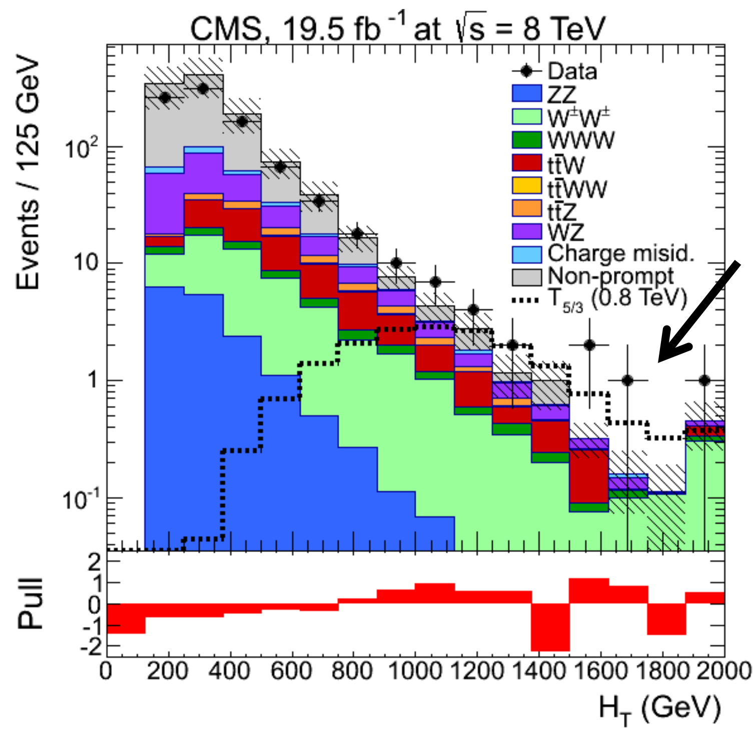




T5/3 Selection @8TeV

- Two same-sign leptons (e or μ) with pT > 30 GeV and |η| < 2.4
- 5 or more "constituents" in addition to the two leptons
  - Top-jets count as 3 constituents, W-jets as 2 and all other jets and leptons as 1
- HT = scalar sum of pT of all good jets and leptons > 900 GeV

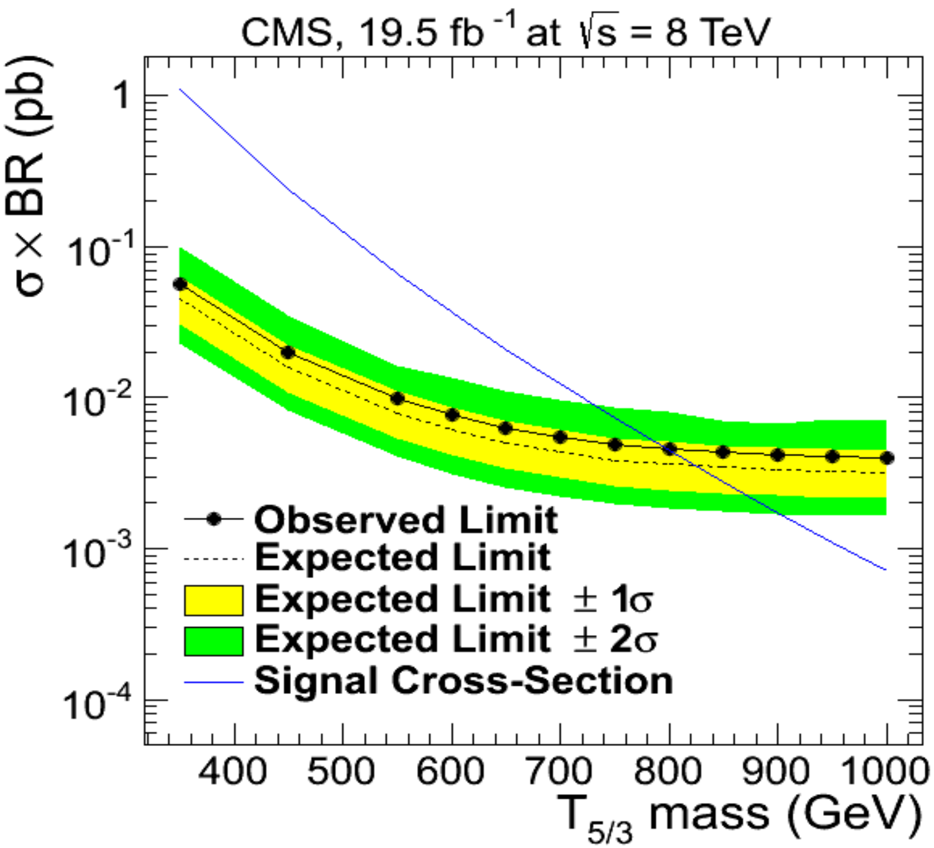


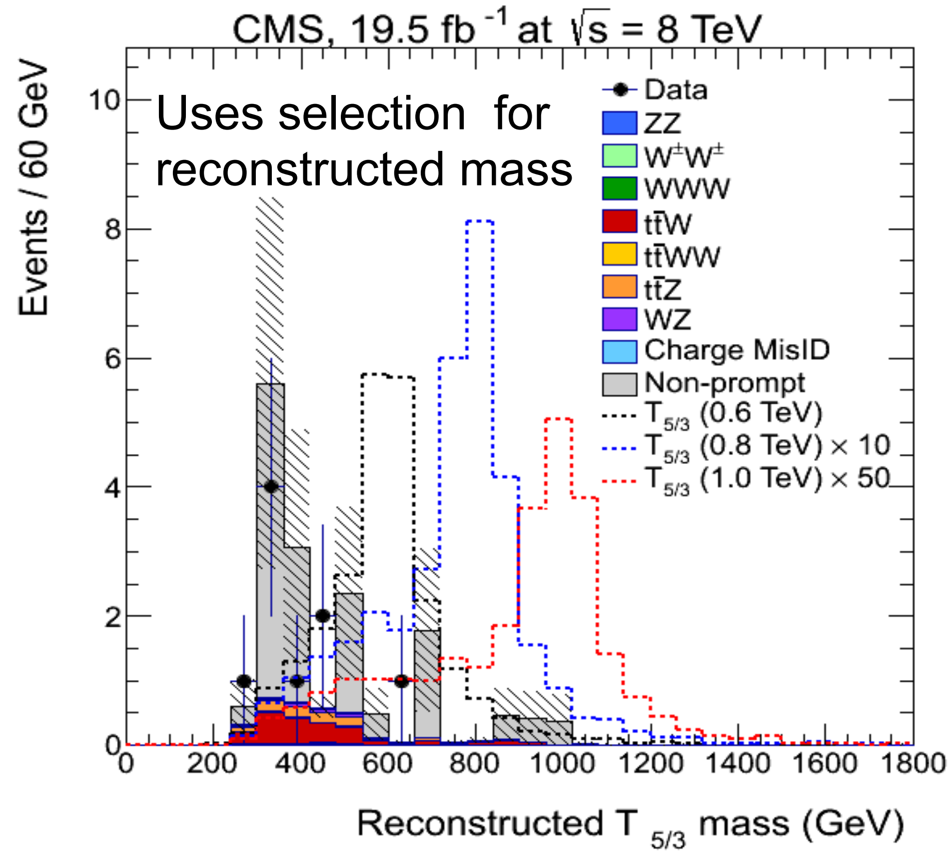


2 same sign leptons and $N_c \geq 2$

$T_{5/3}$ Results @8TeV

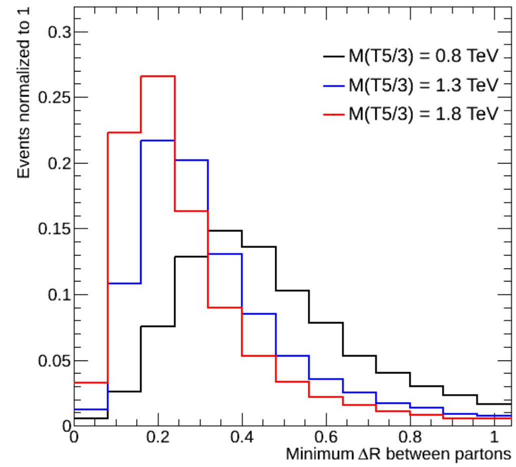
- 6.9 ± 2.1 expected vs. 9 observed
- Exclude the $T_{5/3}$ up to masses of 800 GeV
  - Previous published limit: 365 GeV (CDF)





The T5/3 @14, 33 TeV

- Currently Studied pair-production only
- Considered √=14 and 33 TeV
- Hadronic $T_{5/3}$ can be reconstructed

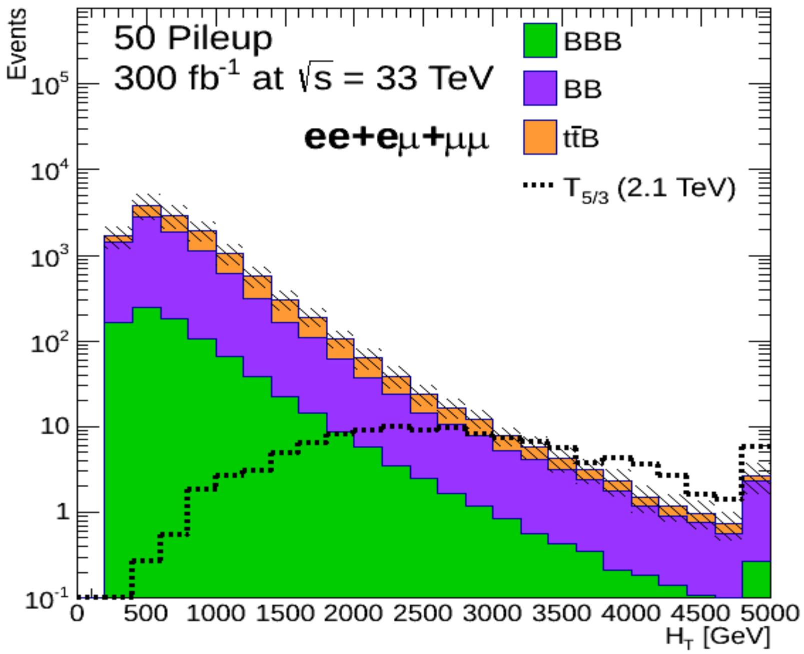


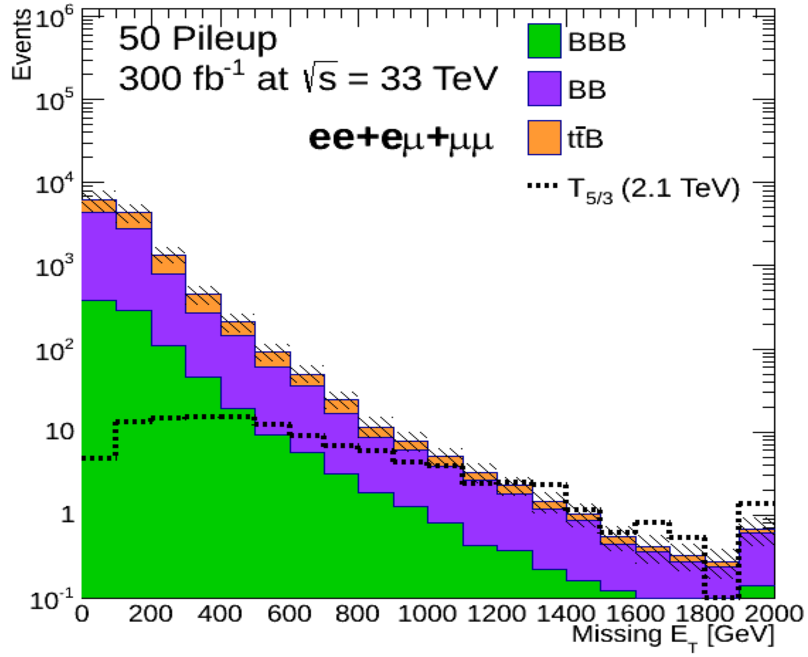
Parameter	14 TeV Min [GeV]	33 TeV Min [GeV]
Leading lepton p_T	80	150
Second lepton p_T	30	50
Leading jet p_T	150	150
Second jet p_T	50	50
$\not{E}_T$	100	200
H_T	1500	2200
S_T	2000	3000

- In addition, require objects corresponding to at least 7 decay products of the T5/3 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

The T5/3 @33 TeV

- After Same-Sign Selection





No non-prompt or charge misidentification backgrounds
Background uncertainty of order 20%
Uncertainty on background is of order 50% @8 TeV

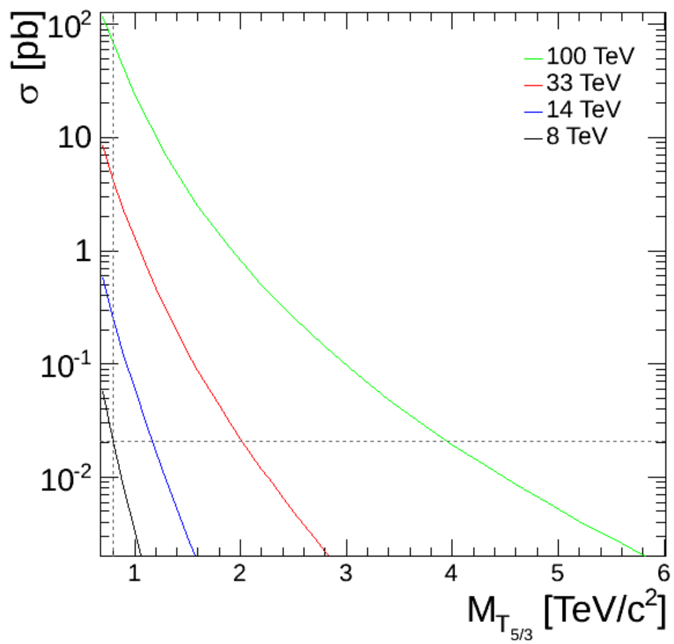
Snowmass $T_{5/3}$ Results

Collider	Luminosity	Pileup	3σ evidence	5σ 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

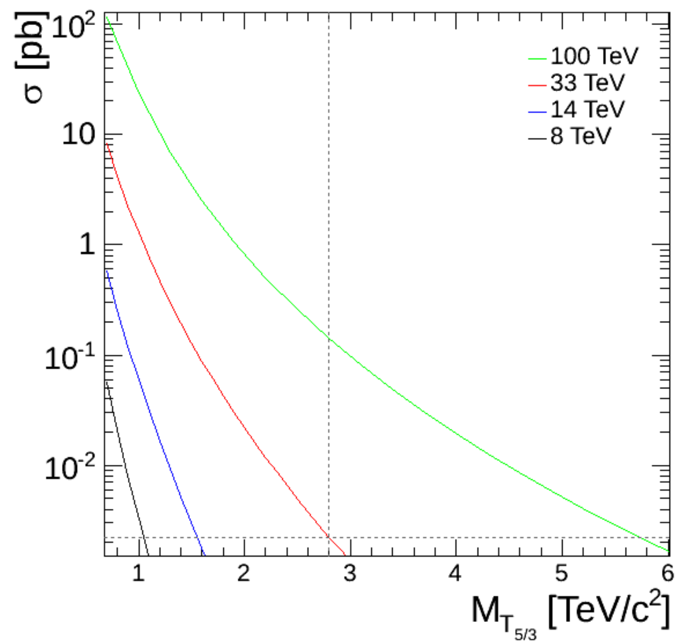
T5/3 Results @100 TeV

- Extrapolate for √s=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:

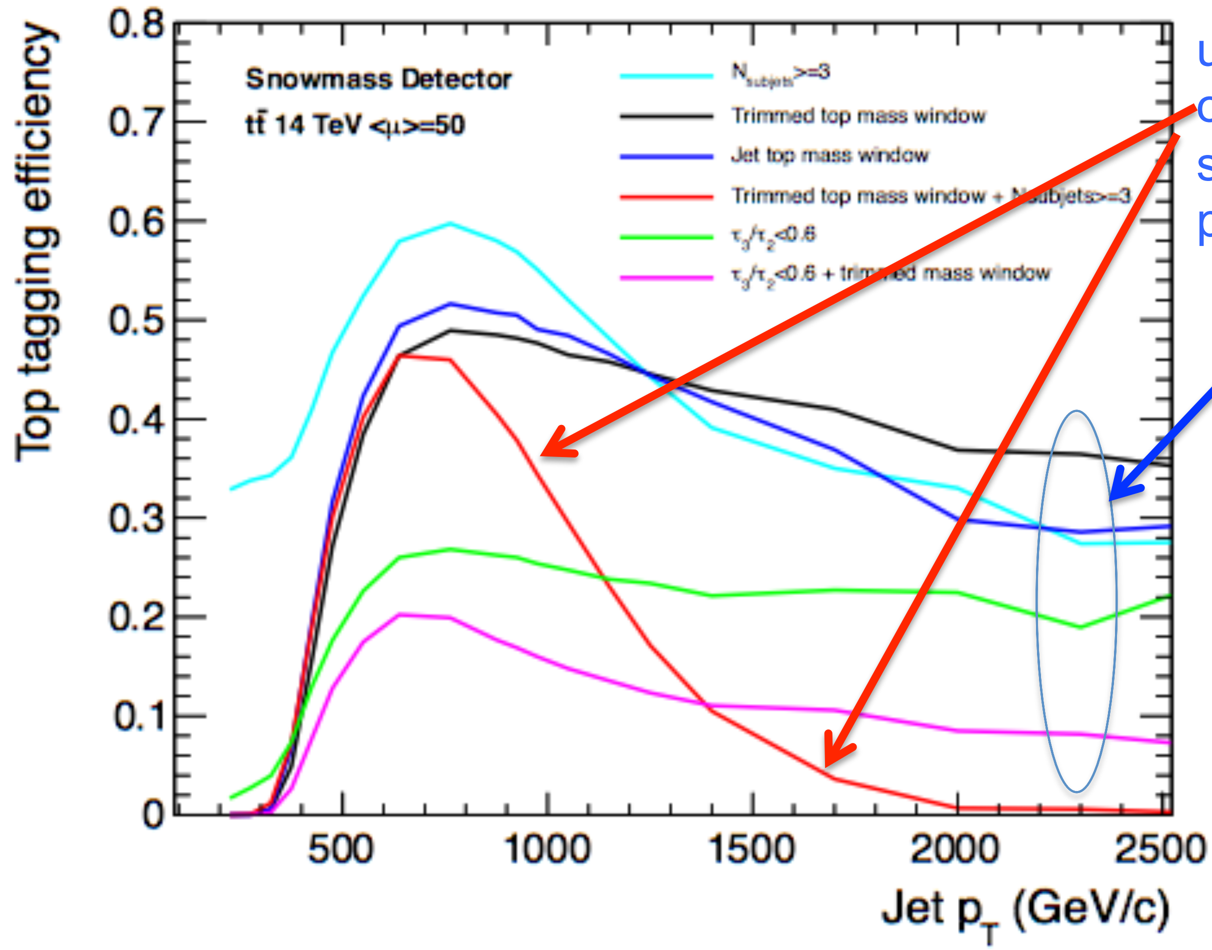
95% CL of about 5.7 TeV

arXiv:1309.2234 (A. Avetisyan et. al.)

Considerations for high pT jets
Jet Substructure

- LHC Run I (8 TeV)
  - 8 TeV algorithms based on masses after "grooming"
  - For the studies at 14, 33 and 100 TeV used the 8 TeV algorithm.
    - Less successful for very high pT jets
    - Sub-jets too close
    - Target mass window small compared to energy scale
- Studies during Snowmass 2013:
  - performed using Herwig++ (14 TeV)
  - ttbar and QCD dijets: pT>0, pT>650, pT>1500 GeV/c
  - Recluster jet constituents to study grooming, substructure variables, etc.

Top tagging at high pT



used for snowmass studies of Heavy Top partners and shown earlier in the presentation

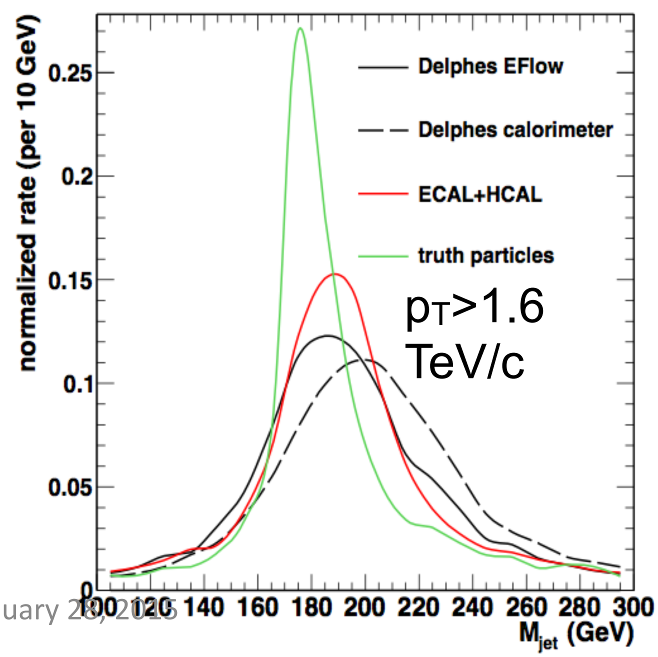
Improvements using other variables:
N-subjettiness and jet mass variables maintain discrimination at high pT (w/ some perf. decrease),

the mass resolution could be significantly improved by better utilizing the ECAL segmentation in Delphes.

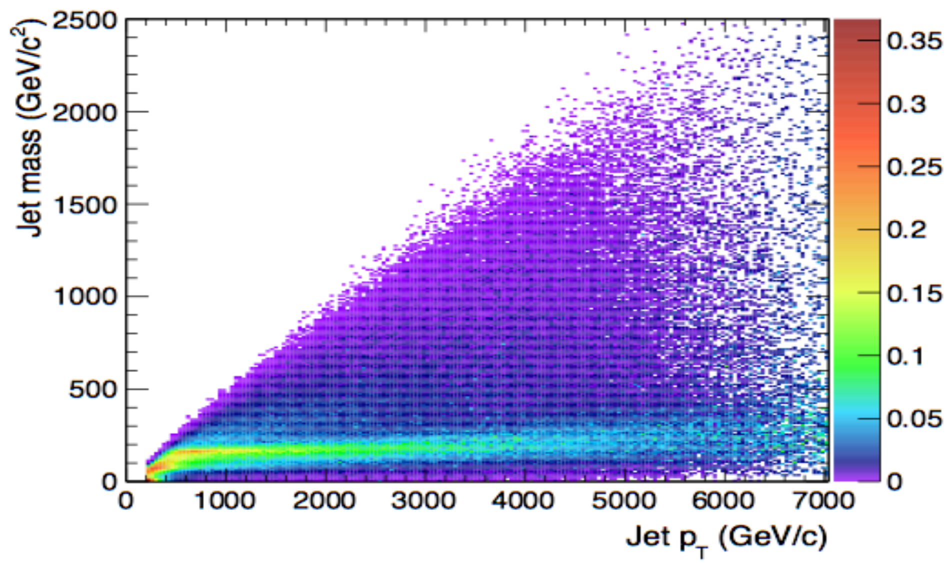
BOOST 2013

High pT jets simulation

- Default Delphes simulation
  - ECAL and HCAL have equal segmentation
  - no decrease in track efficiency for overlapping tracks
- Special Delphes simulation with 2x better eta-phi segmentation
  - Improves top mass peak

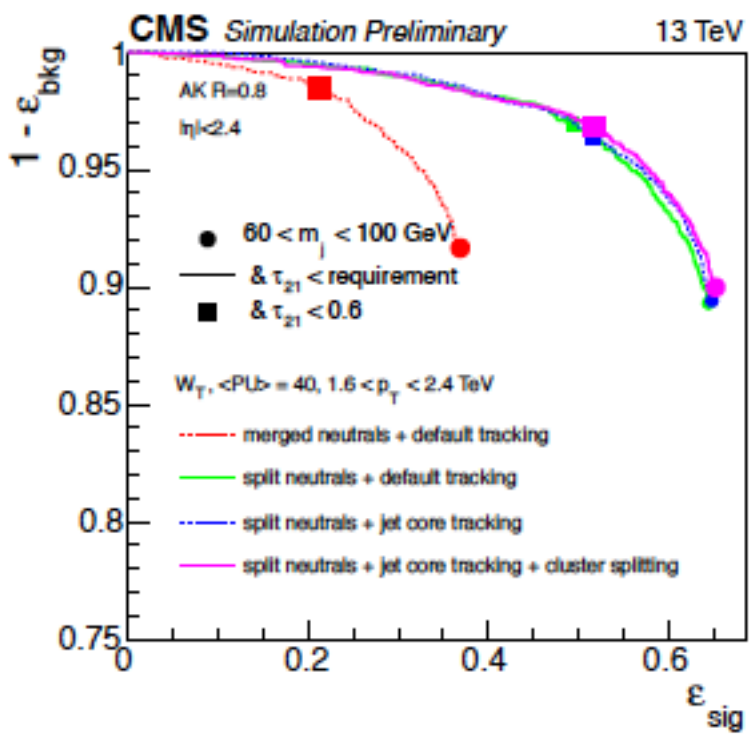


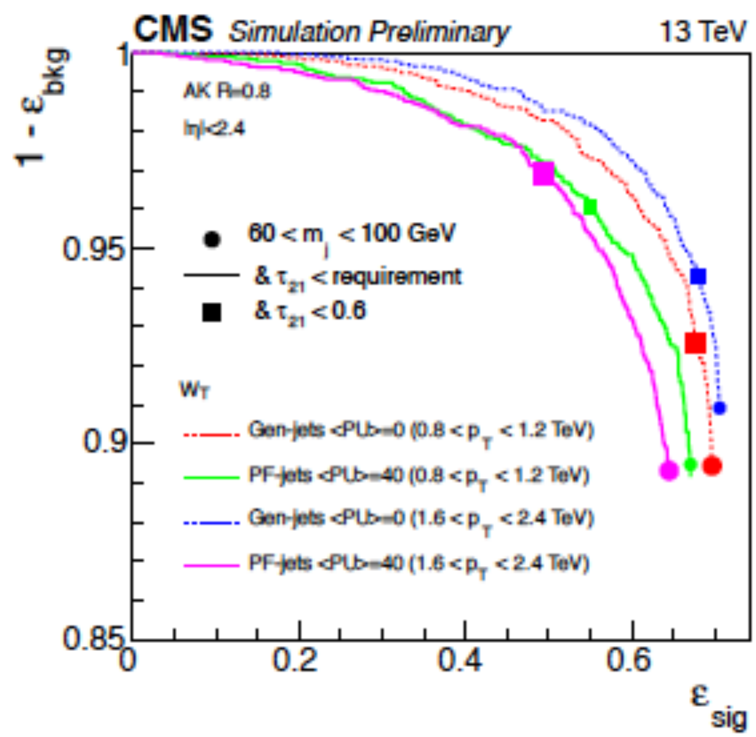
@100 TeV)
Jet matched to top (ΔR<0.5)



W-tagging performance

- Large improvements to the particle flow algorithm. improved ECAL cluster splitting to better utilize the ECAL granularity (along with other changes)
  - the high pT performance is restored
- the W-tagging efficiency and mistag rate can be maintained at the current Run1 performance uptil about 3.5 TeV (CMS PAS JME-14-002)





Conclusions

- Sensitivity for Heavy Quarks presented for 14, 33 and 100 TeV pp colliders
- Improvements in understanding the performance of highly Lorentz boosted jets since Snowmass 2013
  - An ongoing development, also much needed for Run2!
  - What are the calorimeter and tracking limits?
  - What is the effect of hard radiation?
  - affect of algorithm parameters?

- New developments, once incorporated, may lead to better reach

New Particle Reaches

Snowmass 2013

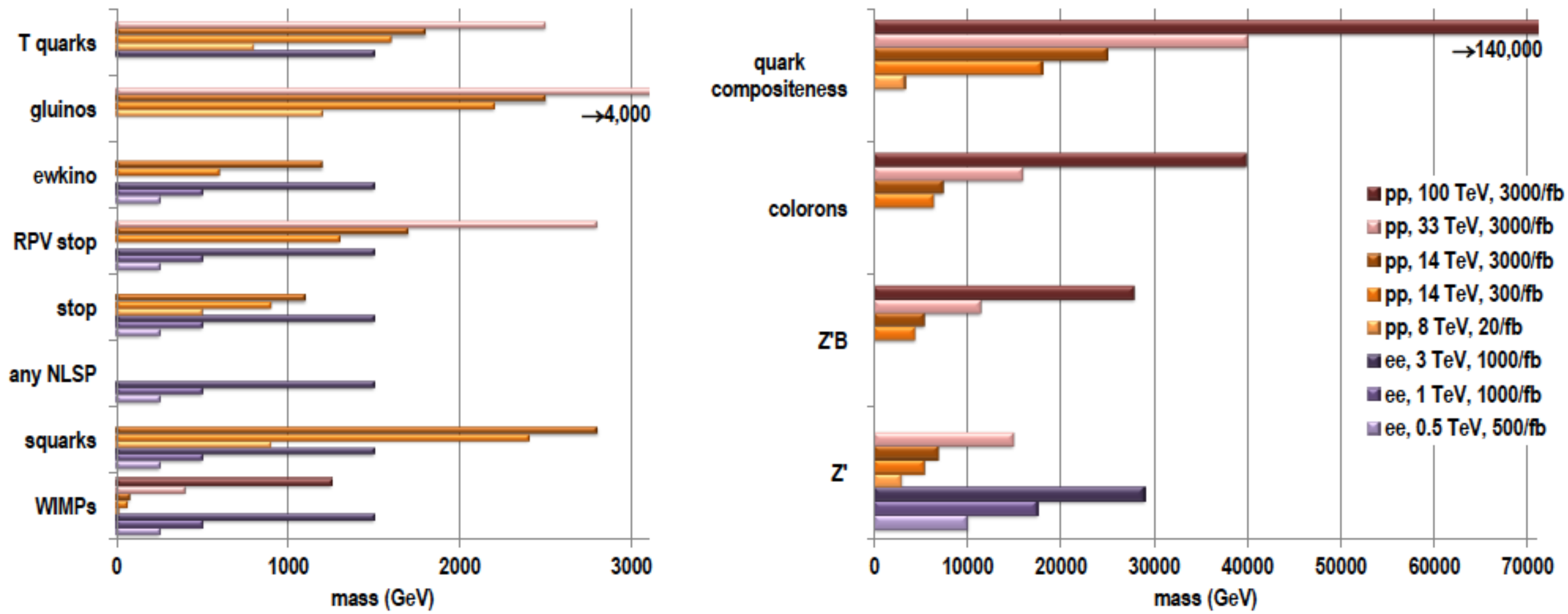


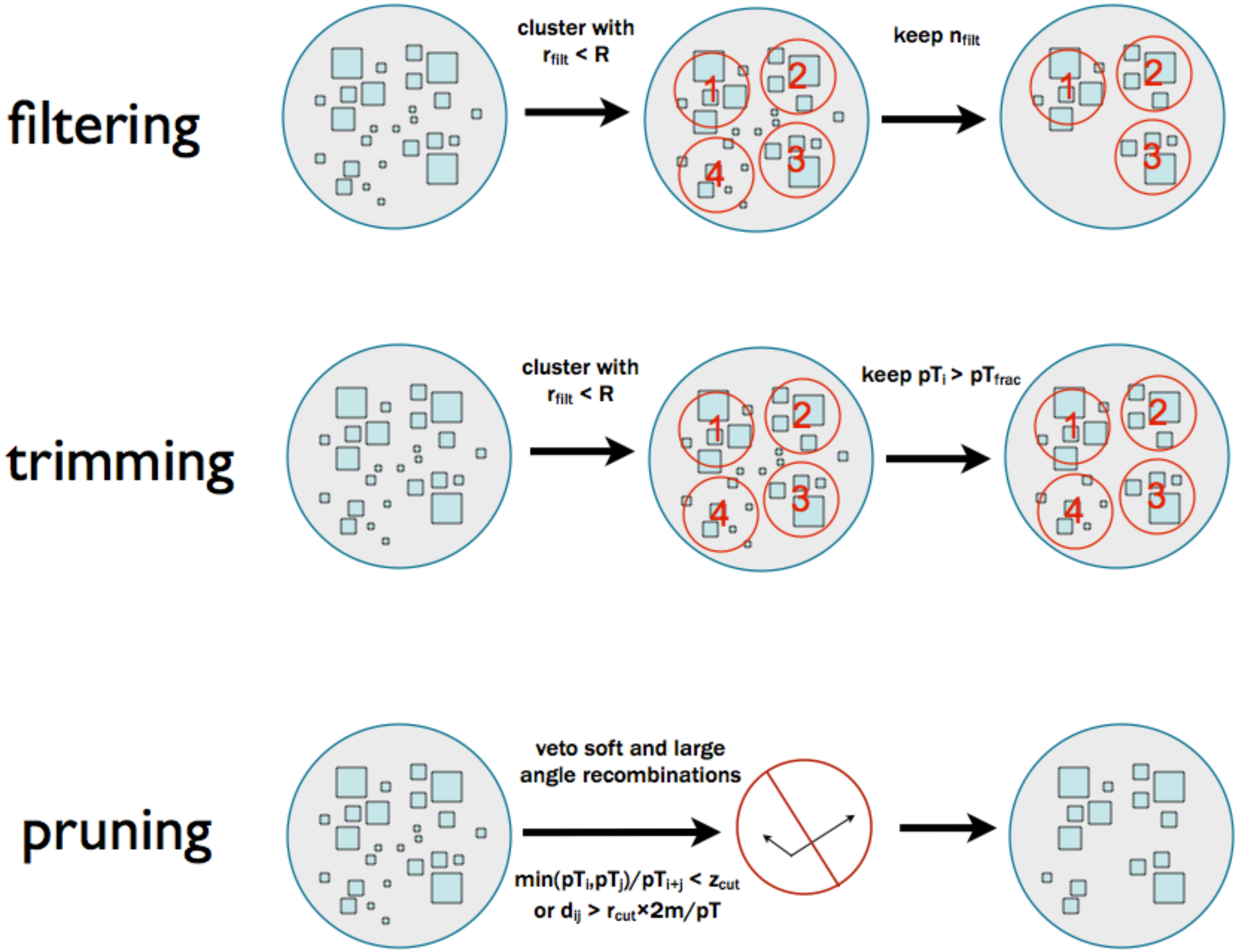
Figure 22-1. *95% confidence level upper limits for masses of new particles beyond the standard model expected from pp and e^+e^- colliders at different energies. Although upper mass reach is generally higher at pp colliders, these searches often have low-mass loopholes, while e^+e^- collider searches are remarkably free of such loopholes.*

Snowmass studies @ LPC including @ 100 TeV

- arXiv:1309.1057: Snowmass Energy Frontier Simulations
  - (Jacob Anderson, Aram Avetisyan, Nitish Dhingra, James Dolen, James Hirschauer, Sudhir Malik, Patricia Mcbride, Kalanand Mishra, Meenakshi Narain, Jim Olsen, Sanjay Padhi, Michael E. Peskin, John Stupak et al
- arXiv:1308.1636: Methods and Results for Standard Model Event Generation at \sqrt{s} = 14 TeV, 33 TeV and 100 TeV Proton Colliders
  - Aram Avetisyan, John M. Campbell, Timothy Cohen, Nitish Dhingra, James Hirschauer, Kiel Howe, Sudhir Malik, Meenakshi Narain, Sanjay Padhi, Michael E. Peskin, John Stupak, Jay G. Wacker
- arXiv:1308.0843: Snowmass Energy Frontier Simulations using the Open Science Grid
  - A. Avetisyan (1), S. Bhattacharya (2), M. Narain (2), S. Padhi (3), J. Hirschauer (4), T. Levshina (4), P. McBride (4), C. Sehgal (4), M. Slyz (4), M. Rynge (5), S. Malik (6), J. Stupak III (7),
- arXiv:1309.2234 Search for top partners with charge 5e/3 (Aram Avetisyan, Tulika Bose)
- arXiv:1309.0026: Prospects for a Heavy Vector-Like Charge 2/3 Quark T search at the LHC with \sqrt{s}=14 TeV and 33 TeV.
  - (Saptaparna Bhattacharya, Jimin George, Ulrich Heintz, Ashish Kumar, Meenakshi Narain, John Stupak)

Backup

Jet Grooming

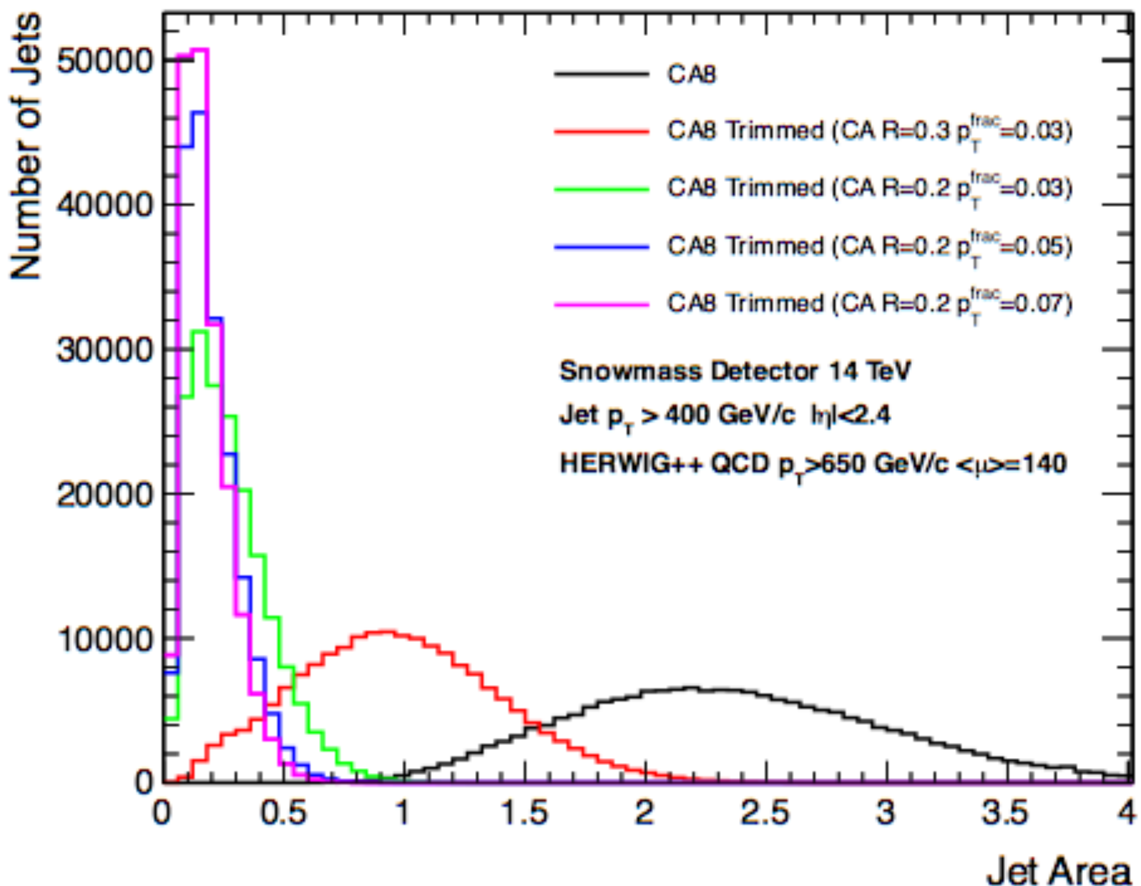


Slide from Nhan Tran

Groomed jet area

Initial jet: CA R=0.8

- Grooming substantially reduces jet area → reduced pileup contamination

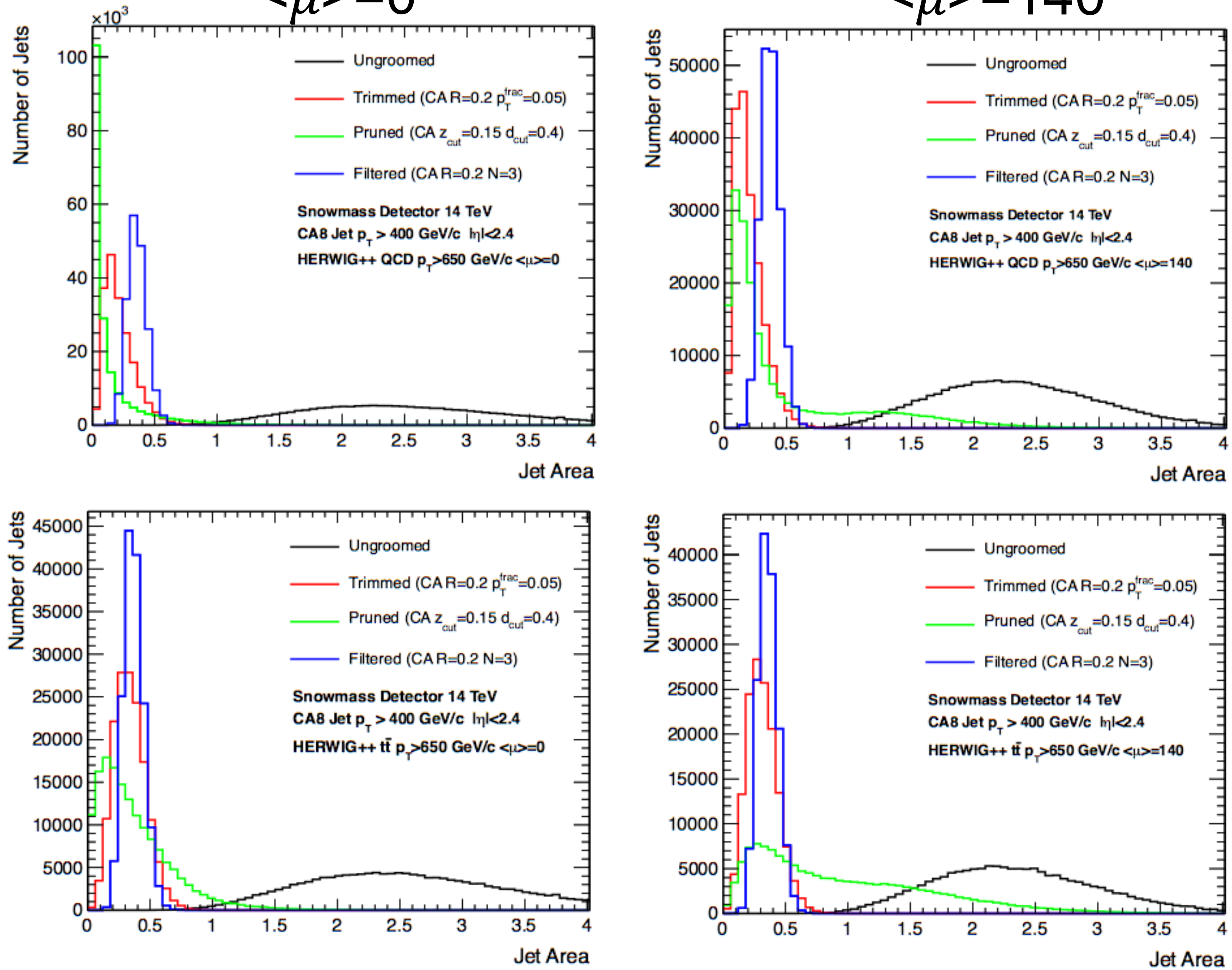


Groomed jet area comparison

$<\mu>=0$ $<\mu>=140$

QCD

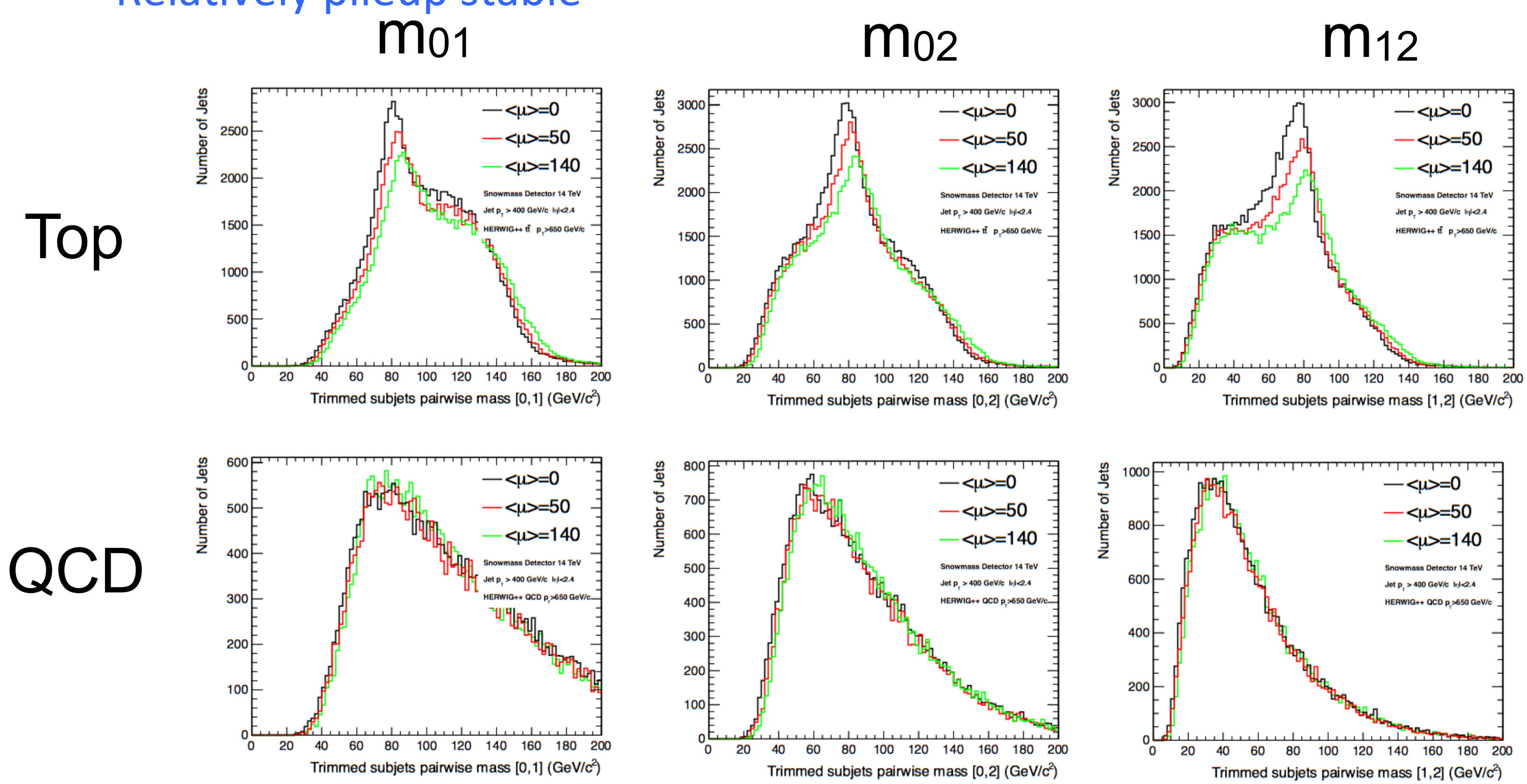
ttbar



Initial jet: CA R=0.8

W mass within top jet

- Subjet pairwise mass for leading 3 subjets in trimmed jets
  - W peak is useful for identifying tops
- Relatively pileup stable



Top Jets at high pT

AK5 jets

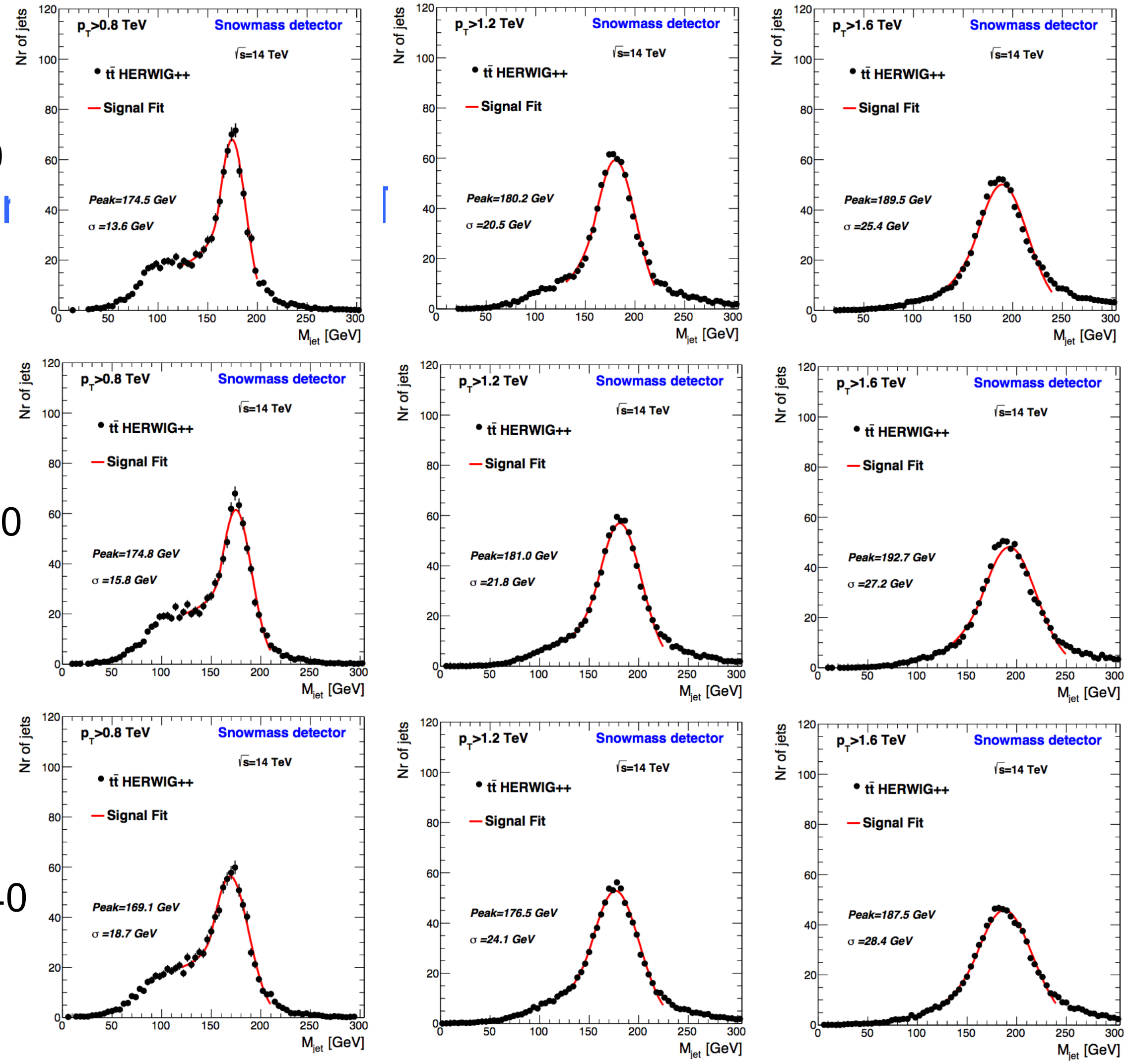
- Top jet mass and width i
  - extra radiation

pT>0.8 pT>1.2 pT>1.6

<μ>=0

<μ>=50

<μ>=140



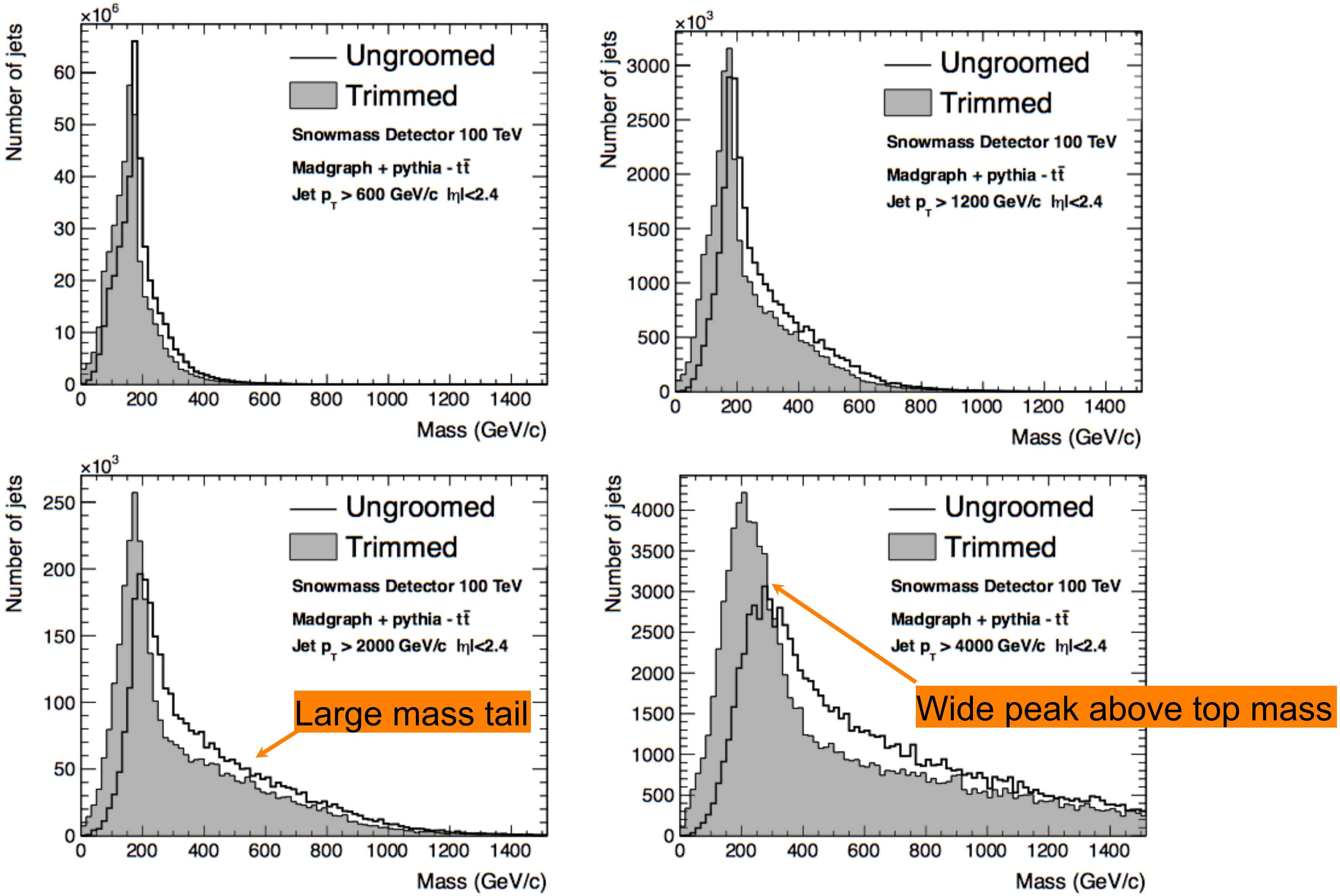
Peak :

	pT>0.8	pT>1.2	pT>1.6
<μ>=0	174.5	180.2	189.5
<μ>=50	174.8	181	192.7
<μ>=140	169.1	176.5	187.5

σ :

	pT>0.8	pT>1.2	pT>1.6
<μ>=0	13.6	20.5	25.4
<μ>=50	15.8	21.8	27.2
<μ>=140	18.7	24.1	28.4

Top Jets at very high pT



Trimmed jets at very high pT

- Above pT=1600 GeV the majority of top jets merge within a R=0.2 trimmed subjet
- High mass tail from radiation