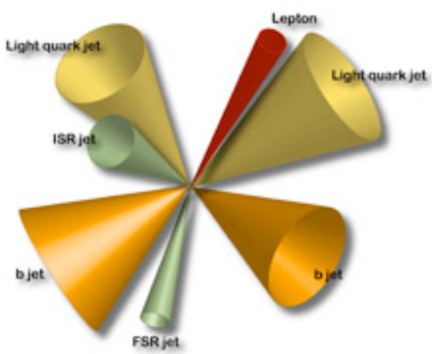
Top Quark Report Highlights

Snowmass 2013 Community Summer Study



Conveners: Kaustubh Agashe, Robin Erbacher, Cecilia Gerber, Kirill Melnikov, Reinhard Schwienhorst

R. Erbacher -- Minneapolis, MN CSS -- July 30, 2013

Top Study Group

Goal: To understand properties of top quarks, how the top quark fits into the bigger picture, and why its properties are relevant to the future of the energy frontier.

Six Working Groups Formed

- Top quark mass *- contacts: A. Mitov, M. Vos, S. Wimpenny*
- Kinematics of top-like final states
  - contacts: M. Schultze, A. Jung, J. Shelton
- Top quark couplings
  - contacts: J. Adelman, M. Baumgart, A. Garcia-Bellido, A. Loginov
- Rare top decays *- contacts: N. Craig, M. Velasco*
- New physics in top-like events
  - contacts: T. Golling, A. Ivanov, J. Hubisz, M. Perelstein
- Top detection and algorithms
  - contacts: S. Chekanov, J. Dolen, J. Pilot, R. Pöschl, B. Tweedie

Received white papers from many contributors, thank you!

Top Quark Mass

Top Quark Mass Questions

- What is the top quark mass parameter being measured at the hadron colliders?
- How precisely should the top quark mass be measured? What do we learn from improvements of factors of two or ten?
- How precisely can we measure the top mass?
- What facilities do we need to measure the top quark mass to the required precision?

Top Mass Parameter

- Fundamental parameter of the SM: enters into calculations of many observables.
- What do we measure? Pole mass differs from $\overline{\text{MS}}$ mass by ~7 GeV.
- Measurement: compare kinematic distribution(s) to theory. Common to use LO + parton shower for theory: "Monte Carlo mass". Not clear how this m_t fits into SM Lagrangian.
- Situation can be mitigated: choose kinematic distributions highly sensitive to m_t and that are IR safe.
  Examples: "Endpoint method" and "J/ψ method".

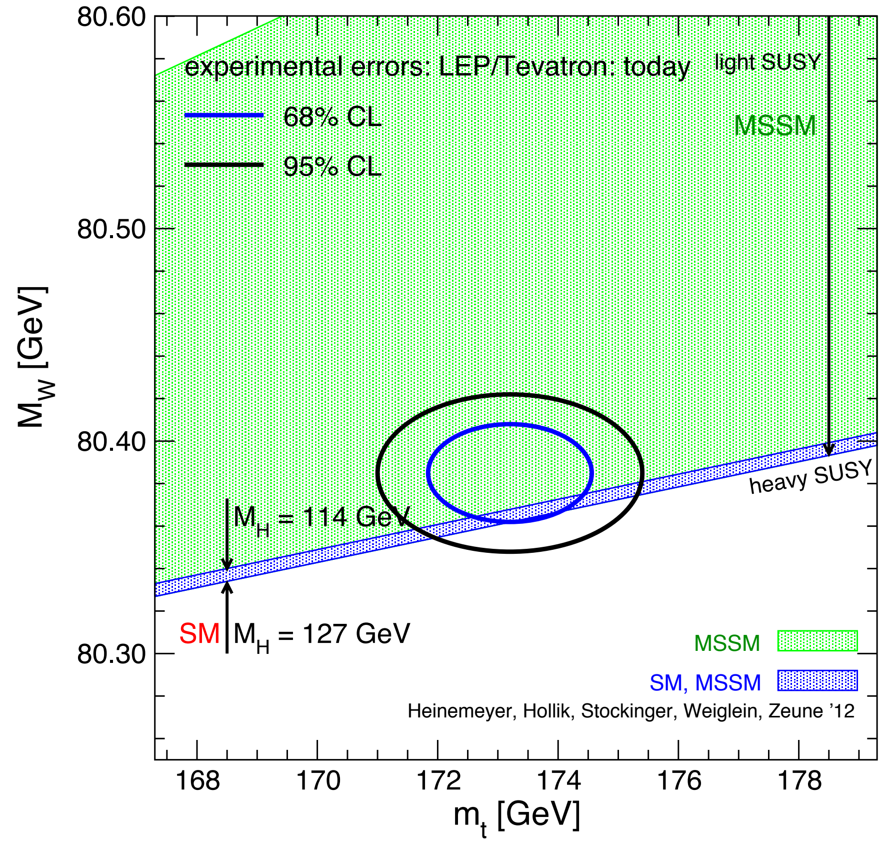
Required Top Mass Precision

- Precision electroweak fits: 5 MeV uncertainty on m_W corresponds to ~0.6 GeV uncertainty on m_t .
(Baak, et al: Eur.Phys.J., C72:2205, 2012)

- EWK Report: LHC $\delta(m_W)$~ 5 MeV, need $\delta(m_t)$<600 MeV.

- ILC/CLIC: $\delta(m_W)$~2.5-5 MeV: need $\delta(m_t)$<300-600 MeV.

- TLEP (early studies) $\delta(m_W)$~1.5 MeV: need $\delta(m_t)$<180 MeV.



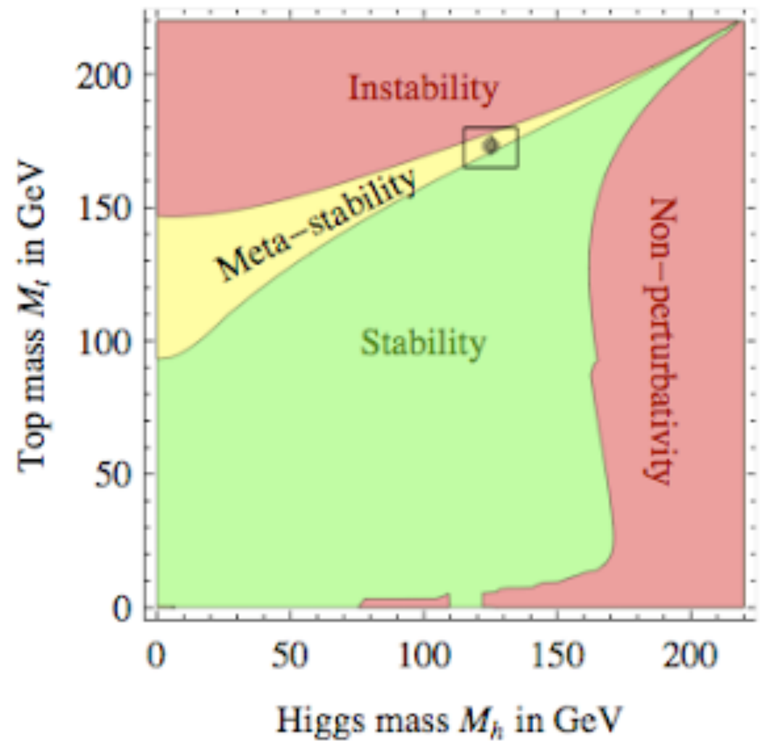
Top Mass and Vacuum Stability

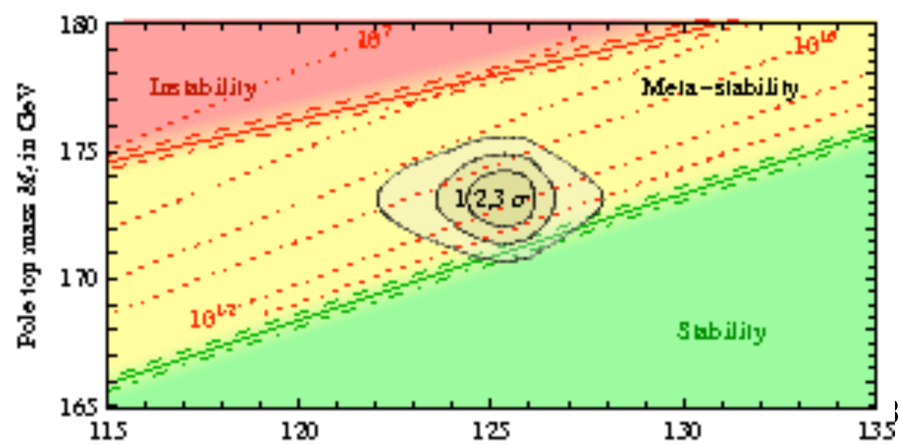
- Exact value of m_t is very important if SM continues to Planck scale with no further extensions.

- ~2 GeV shift on m_t changes RGE scale (where H quartic coupling goes negative) by few orders of magnitude.

- So $\delta(m_t)$~<0.3-0.6 GeV may be important, particularly if no new physics in Run 2 LHC.

- If no new physics to Planck: $\delta(m_H)=150 \leftrightarrow \delta(m_t)=100$ MeV





Top Mass at LHC

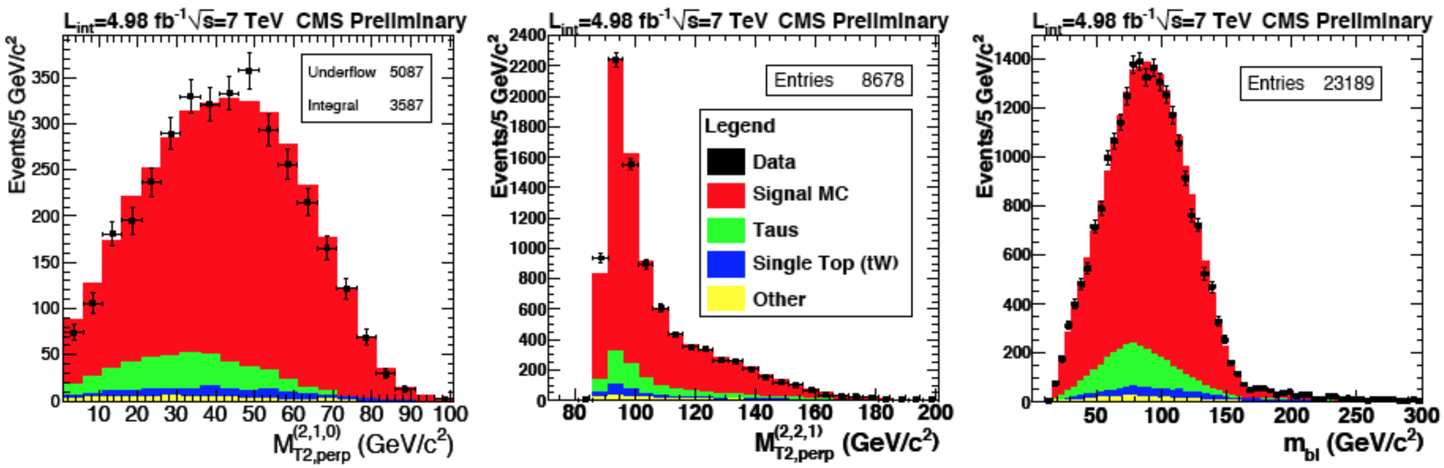
- Traditional measurements (matrix element, template) have achieved tremendous precision: $\delta(m_t)<1$ GeV.
- However, suffer from theoretical ambiguities perhaps not accounted for in systematics. (What is m_t ?)
- High luminosity LHC does not help due to pile-up. May be helped by clever techniques: eg- ATLAS 3D fits mass, b-JES, q-JES. Combinations of methods help also.

	Ref.[12]	Projections				
CM Energy	7 TeV	14 TeV				
Luminosity	$5\,fb^{-1}$	$100\,fb^{-1}$		$300\,fb^{-1}$		$3000\,fb^{-1}$
Pileup	9.3	19	30	19	30	95
Syst. (GeV)	0.95	0.7	0.7	0.6	0.6	0.6
Stat. (GeV)	0.43	0.04	0.04	0.03	0.03	0.01
Total, GeV	**1.04**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**

CMS Projections using Traditional Measurements

“Endpoint” Mass Measurement

- Invariant mass of top decay products- lepton+b-jet - gives sharp edge correlated with top mass. Model independent and theoretically well-understood. Improves with HL-LHC.



	Ref.[13]	Projections		
CM Energy	7 TeV	14 TeV		
Luminosity	$5\,fb^{-1}$	$100\,fb^{-1}$	$300\,fb^{-1}$	$3000\,fb^{-1}$
Syst. (GeV)	1.8	1.0	0.7	0.5
Stat. (GeV)	0.90	0.10	0.05	0.02
Total	**2.0**	**1.0**	**0.7**	**0.5**

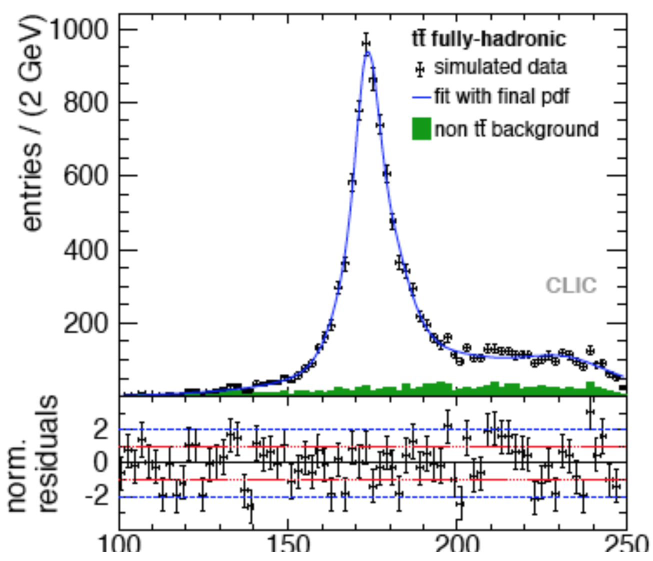
CMS Projections using Endpoint method

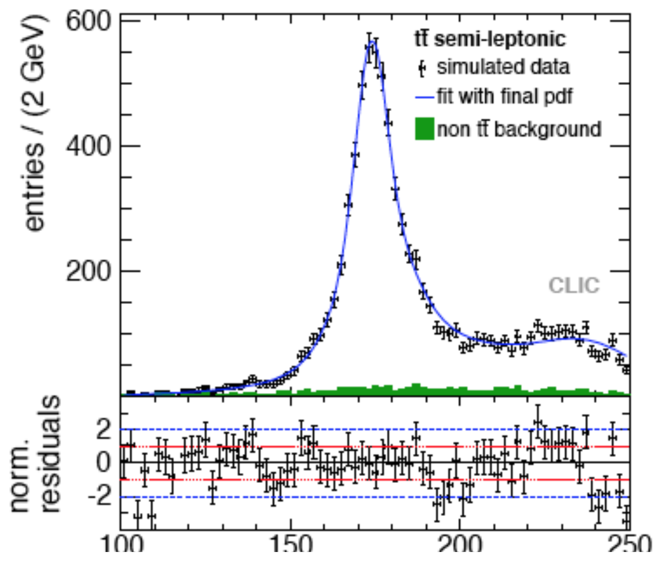
Top Mass at e+e- colliders

- e+e- allows the study of tt pairs sans QCD bkgnds. Clean theoretical interpretation of result makes lepton colliders important, even independent of precision.

- Two methods: mass of bW system and threshold scan, give sufficiently precise results. Threshold scan: $\delta(m_t)$~40 MeV (140 MeV using $\overline{\mathrm{MS}}$); better than needed.

- Full simulation shows small residual backgrounds:





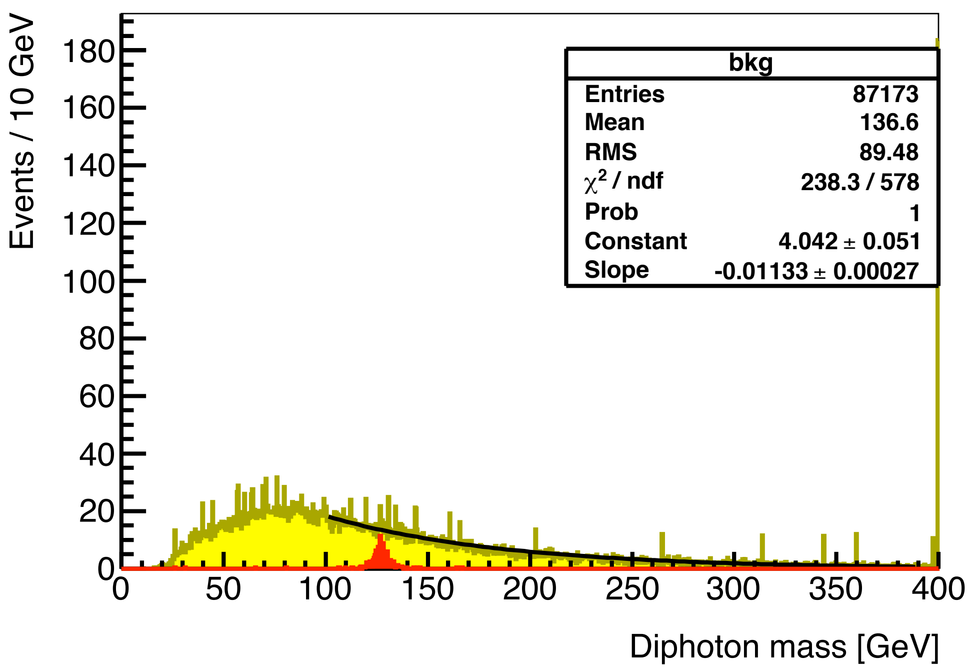
Top Quark Couplings

Top Quark Couplings: Theory

- Measurements of couplings are precision tests of SM.
- New physics, particularly related to the hierarchy problem, likely to modify results.
- Theory: Measurements require predictions at NLO for associated production and backgrounds. Many available (ttZ, ttγ, ttH), including decays of top quarks, parton showers, matching.
- Theory: More robust predictions(e.g. for ttA or admixtures of left/right currents in ttZ, tWb) can be obtained using existing framework.

Top Quark Couplings: Measurements

- Snowmass studies: ttZ (ttγ)- precision ~20-50% (5%) for LHC 14 TeV at 300 fb^{-1}. Factor ~2 expected for 3000 fb^{-1}.
- Single top studies → tWb coupling: ~5% at LHC (2.5% V_{tb}). For anomalous couplings, ~1% or better.
- Yukawa coupling, ttH: Studied heavily in Higgs group, but also contributions to our studies.
- Expect 6σ sensitivity for ttH, H→γγ at 3000 fb^{-1}. Early results: 2σ H→μμ.



Top Quark Couplings: e+e-

- Allows study pure EWK top production, no QCD bkgd.
- Beam polarization permits disentangling of top coupling to γ and to Z. Can also collect samples enriched in left/right-handed helicities.
- Electroweak couplings can thus be determined to a percent level, so that new physics can be probed.
- Coupling to Higgs: ttH: 11 (4)% (with H→bb) at 500 (1000) GeV, with 1000 fb^{-1}.

Collider	LHC		ILC	ILC	CLIC
CM Energy [TeV]	14	14	0.5	1.0	1.4
Luminosity [fb^{-1}]	300	3000	1000	1000	1000
Top Yukawa coupling κ_t	(20 – 25)%	(8 – 20)%	10%	4%	4%

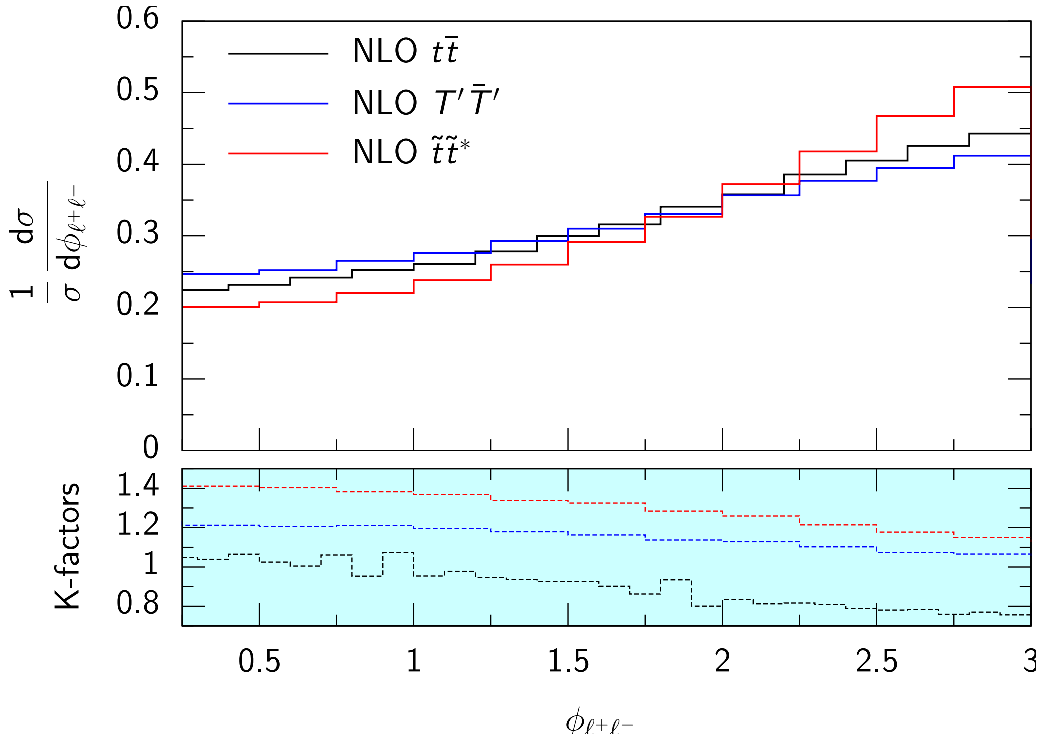
Kinematics of Top-like Final States

Kinematics of Top

- Precision test of the SM: New physics would modify.
- NNLO: predicts top pair cross section to 5% (scale,PDF)
- Basic distributions (NLO) known to 15-20%.
- Accuracy will improve: extend existing theory for kinematics to NNLO and by better understanding of PDFs in relevant kinematic ranges.
- Precision deteriorates, especially for PDFs, in boosted regime.

Kinematics: Spin Correlations

- Normalized kinematic distributions, particularly those sensitive to top spin correlations, can be less sensitive to theory uncertainties than energy-related ones.
- Use of angular distributions to search for new physics could be powerful. (eg- stealthy stop)



Kinematics: Top A_{FB}

- Tevatron measurements of the top pair production forward-backward asymmetry remains an anomaly.
- Can the LHC clarify the issue?
  - Projection: With high luminosity, ATLAS/CMS can conclusively measure asymmetry *if* half of systematics scale with statistics.
  - If asymmetry enhanced as in Tevatron, even better.
  - Complementary study at LHCb: can also measure with sufficient statistics, and combine with ATLAS/CMS.
- May yet be able to solve this issue at the HL-LHC.

New Particles Decaying into Top-like Final States

Stop Squark Searches

- If they exist below ~1 TeV, can solve the hierarchy problem.

Vanilla stop: $\tilde{t} \rightarrow t\tilde{\chi}^0$

- 14 TeV LHC with 3000/fb: barely observe stops to 1 TeV using existing methods (ATL-PHYS-PUB-2012-001)

- New studies-- boosted top, no leptons (all-hadronic):

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	4.6 fb	990 GeV
HL LHC	14 TeV	3 ab^{-1}	1.4 fb	1.2 TeV

- Other strategies studied on stealthy stop, asymmetric stop, gluino-initiated stop, R-parity violating stop are shown in report. Note: Stealthy stop may require e+e- to resolve.

Top Partners

- Popular SUSY alternative that can solve the hierarchy problem, below ~1 TeV for naturalness.
- Several candidates: charge 2/3, -1/3, 5/3
- For charge 2/3 pair production (0 pile-up for now):
  - Reach 95% CL exclusion to 1.4 (1.75) TeV for LHC 14 at 300(3000) fb^{-1}.
- For charge 5/3 pairs (same sign dileptons) (50 pile-up):
  - Reach 5σ discovery at 1.4 (1.6) TeV for 300(3000) fb^{-1}.
  - For 33 TeV and 140 pile-up: 3σ evidence at 2.24 TeV. (preliminary results)

Top Quark Resonances

- New physics (Z'→tt, W'→tb, KK→tt, KKg→tc) couples more strongly to top quarks. Often go hand-in-hand w/ top partners.
- Recent CMS study in dilepton channel for 300 fb^{-1} and 50 pile-up gives 3.9 TeV Z' →tt exclusion at 95%, or 3.0 TeV discovery at 5σ.
- Study by ATLAS group using substructure: statistics-only limits for 3 TeV Z' →tt are 1.8 (0.5) x SM cross-section, with 300/fb (3000/fb) at LHC14.
- Phenomenology study ongoing: apply template-overlap technique (less sensitive to pile-up effects) to improve reach for KK gluon (fully hadronic and leptonic).

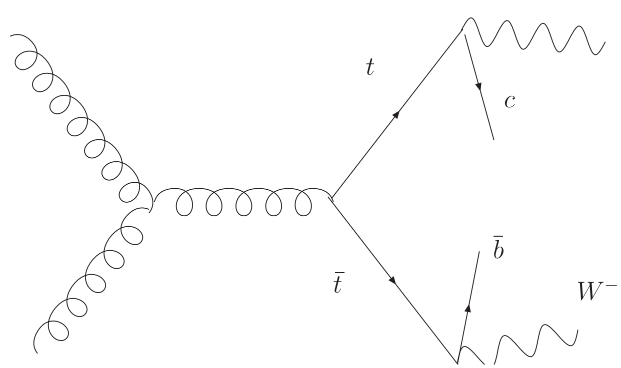
Top Quark Rare Decays

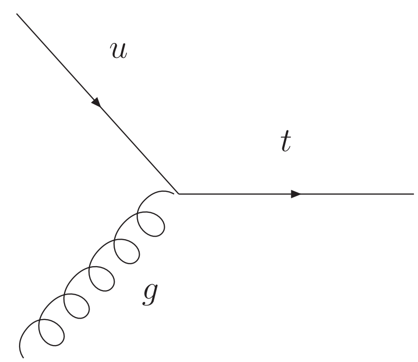
Top Quark Rare Decays

- SM prediction is << New Physics prediction: observation would mean new physics!

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

- Search with top pair flavor-changing decays or single top





Rare Decays: Current Status

- Not quite probing interesting parameter space yet.

Table 1: Current direct limits on top FCNC. (*) denotes unofficial limits obtained from public results. The q in the final state denotes sum over $q = u, c$.

Process	Br Limit	Search	Dataset
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV
$t \to gu$	5.7×10^{-5}	ATLAS $qg \to t \to Wb$	2.05 fb^{-1}, 7 TeV
$t \to gc$	2.7×10^{-4}	ATLAS $qg \to t \to Wb$	2.05 fb^{-1}, 7 TeV
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV

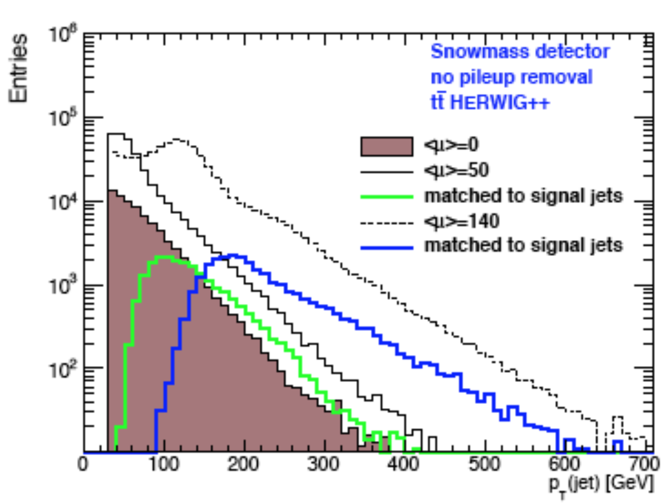
Rare Decays: Projections

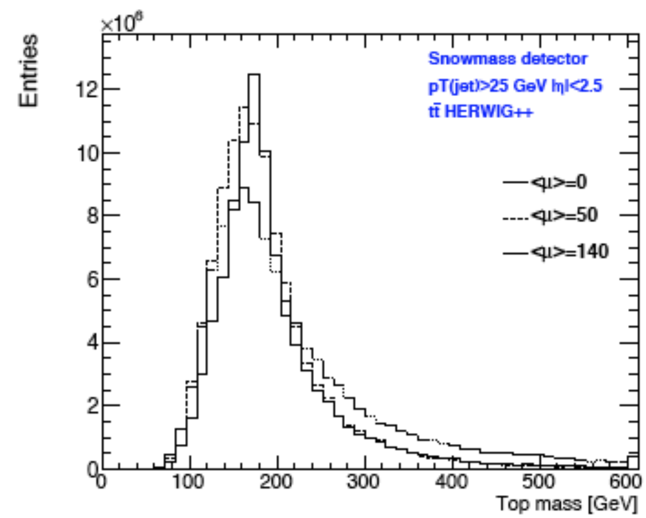
- LHC 14 GeV:
  - Rare decays of top quarks can be measured at $\sim 10^{-5}$ level.
  - High luminosity gains a factor of two sensitivity to rare decays.
- In general, LHC and ILC /CLIC reach similar sensitivities.
- LHC and ILC/CLIC are complementary:
  - LHC: more channels are accessible, including flavor-changing couplings of tops to gluons, though reach is difficult.
  - ILC/CLIC: better for understanding Lorentz structure of couplings if observation is made.
- At 250 GeV ILC can already use single top production.

Top Algorithms and Detectors

Threshold Pair Production

- Reach of precision measurements, whether SM or new physics searches, based on reconstruction of jets < p_T~100 GeV, is reduced at high instantaneous luminosities.
- Pile-up corrections lead to large uncertainty in jet energy scale, different than typical detector-related effects.
- Top production close to threshold, where decay jets have lower p_T, will suffer from these difficulties. Unlikely to achieve precisions better than theory uncertainties in this regime.





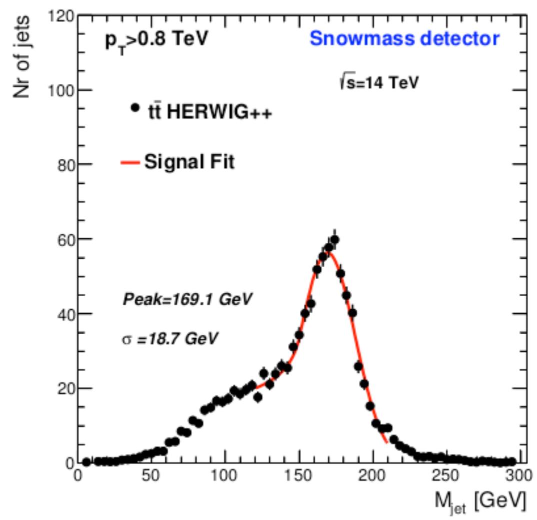
Boosted Tops

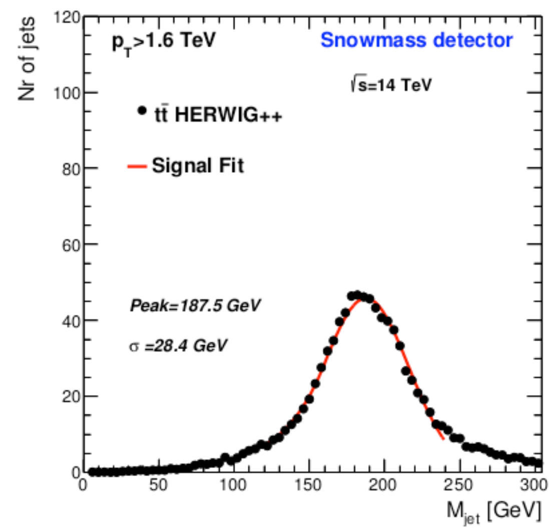
- In the truly boosted regime (p_T of jet > 0.8 TeV) at LHC14: decay products of top quark will be within cone of R = 0.5. Jet substructure algorithms help to identify boosted tops.

- Efficiency of such algorithms degrades with as p_T> 1 TeV due to ISR/FSR contamination & (hadronic) calorimeter granularity.

- Above effect is mitigated by substructure-based jet grooming, using decreasing cone sizes, "particle flow", and segmentation.

Jet mass distributions for =<140> pileup events. Width of top mass peak increases by factor of two without special treatments.

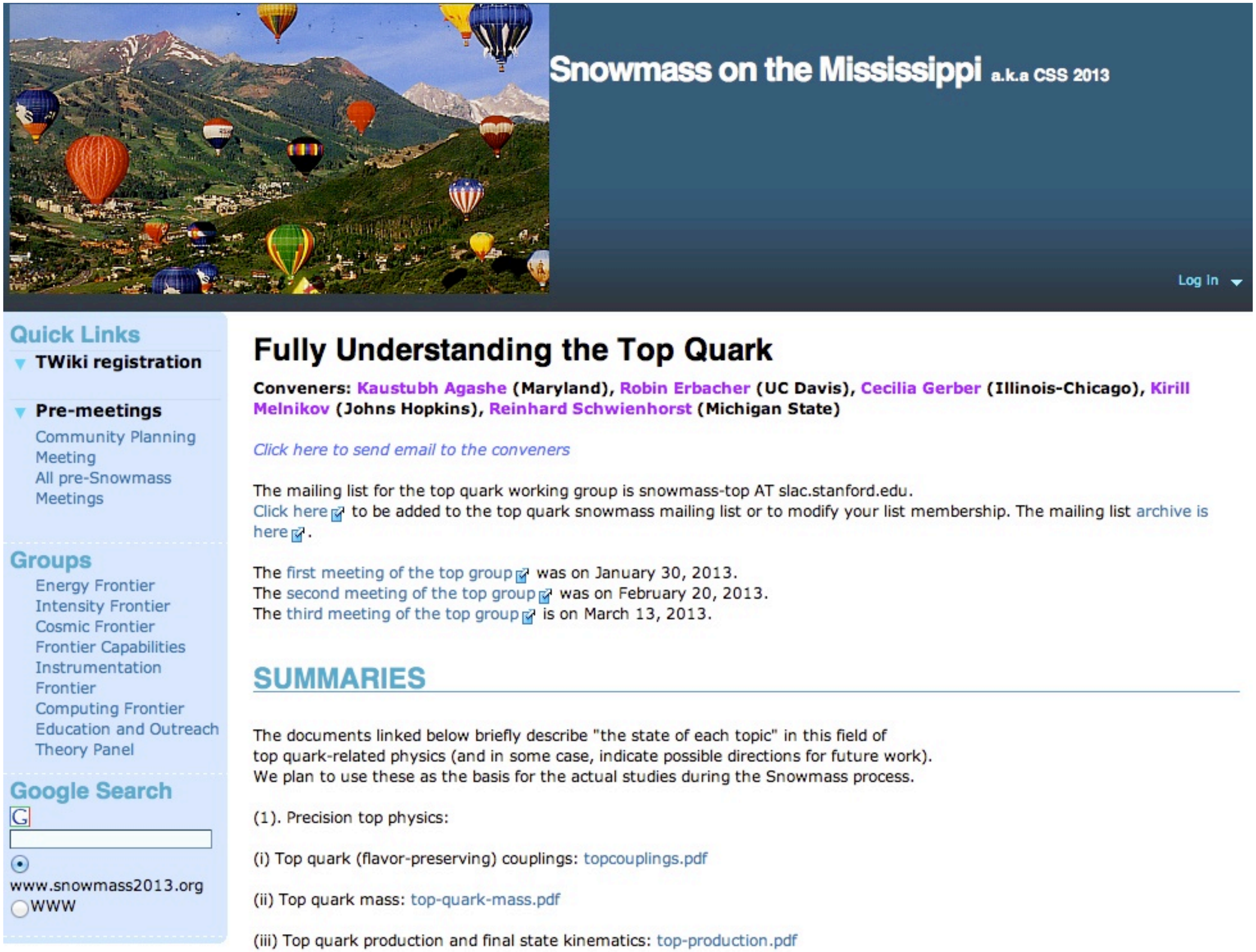




ILC/CLIC/TLEP

- Any residual pile-up (overlay events from photon collisions) are under control in the lepton colliders.
- Charge of bottom quark can be measured at purity of 60%. Useful for many observables like top forward-backward asymmetry.
- To achieve goal of percent level precision in EW couplings, luminosity and beam polarizations have to be measured precisely: current estimates suggest that this can be done to better than 0.5%, so good enough.
- Detector granularity expected to be adequate for top physics.

Charge, summaries, work, report draft



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www.snowmass2013.org

WWW

Fully Understanding the Top Quark

Conveners: Kaustubh Agashe (Maryland), Robin Erbacher (UC Davis), Cecilia Gerber (Illinois-Chicago), Kirill Melnikov (Johns Hopkins), Reinhard Schwienhorst (Michigan State)

Click here to send email to the conveners

The mailing list for the top quark working group is snowmass-top AT slac.stanford.edu.
Click here to be added to the top quark snowmass mailing list or to modify your list membership. The mailing list archive is here.

The first meeting of the top group was on January 30, 2013.
The second meeting of the top group was on February 20, 2013.
The third meeting of the top group is on March 13, 2013.

SUMMARIES

The documents linked below briefly describe "the state of each topic" in this field of top quark-related physics (and in some case, indicate possible directions for future work). We plan to use these as the basis for the actual studies during the Snowmass process.

(1). Precision top physics:

(i) Top quark (flavor-preserving) couplings: topcouplings.pdf

(ii) Top quark mass: top-quark-mass.pdf

(iii) Top quark production and final state kinematics: top-production.pdf

http://www.snowmass2013.org/tiki-index.php?page=Fully+Understanding+the+Top+Quark

Top Study in Minneapolis

Three meeting sessions this week:

- Wednesday 8:30 - 10:00 am - Contributed talks
- Friday 8:30 - 11:00 am - Discussion of Top Report
- Saturday 8:30 - 11:00 am - Contributed talks & Discussion

Please come join us, your input is wanted. We expect to finalize conclusions this week.

Summary

- Top mass: necessary precision is driven by W mass for precision EWK fits and Higgs mass for vacuum stability.
- Top mass not expected to be limiting factor from any machine.
- To understand the top mass parameter (meaning of the measured value), HL-LHC helps for theoretically clean methods. e+e- collider extremely clean, can strongly clarify.
- HL-LHC probes broad range of couplings in interesting range. e+e- does much better mainly for ttH, ttγ and ttZ.
- Forward-backward asymmetry issue may be addressed by HL-LHC if half of systematics scale with statistics.
- LHCb can also help to address A_{fb} issue.

Summary

- Rare top quark decays difficult: HL-LHC & e+e- have similar reach. e+e- can help disentangle couplings in rare decays.

- New physics in top-like final states: LHC 14 TeV extends reach. HL-LHC doesn't help as much as expected due to pile-up, but boosted top techniques can make up for some loss in efficiency. High energy LHC would push further.

- At high luminosity LHC, pile-up degrades top measurements that rely on jets and jet activities.

- Using and tuning jet substructure techniques can improve physics reach for most top studies in the boosted regime, and algorithms can ameliorate pile-up effects.

- Finer detector segmentation will help with pile-up issues.

- Discussion of facility conclusions will continue Friday!