

# Fully understanding the top quark

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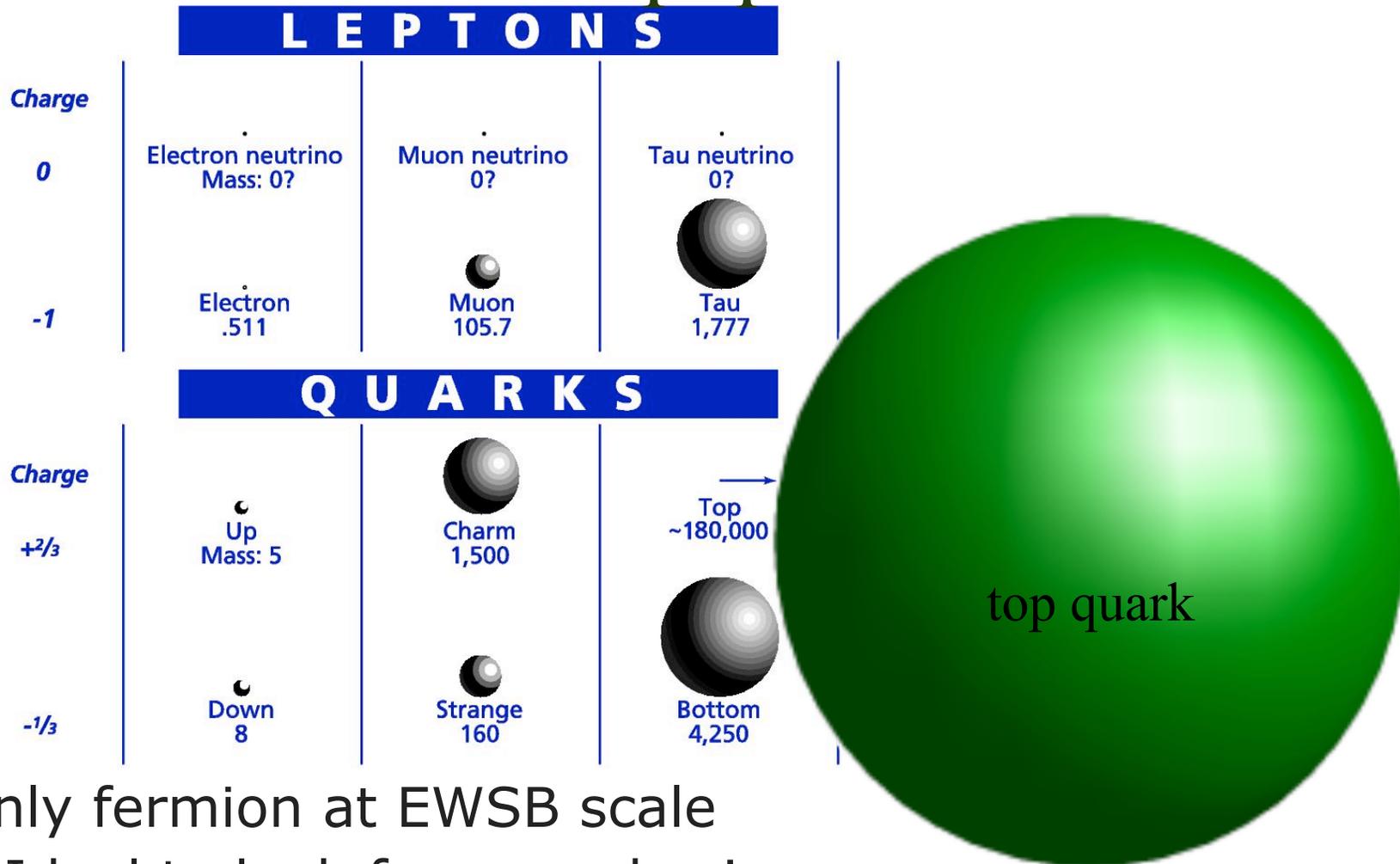
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# Outline

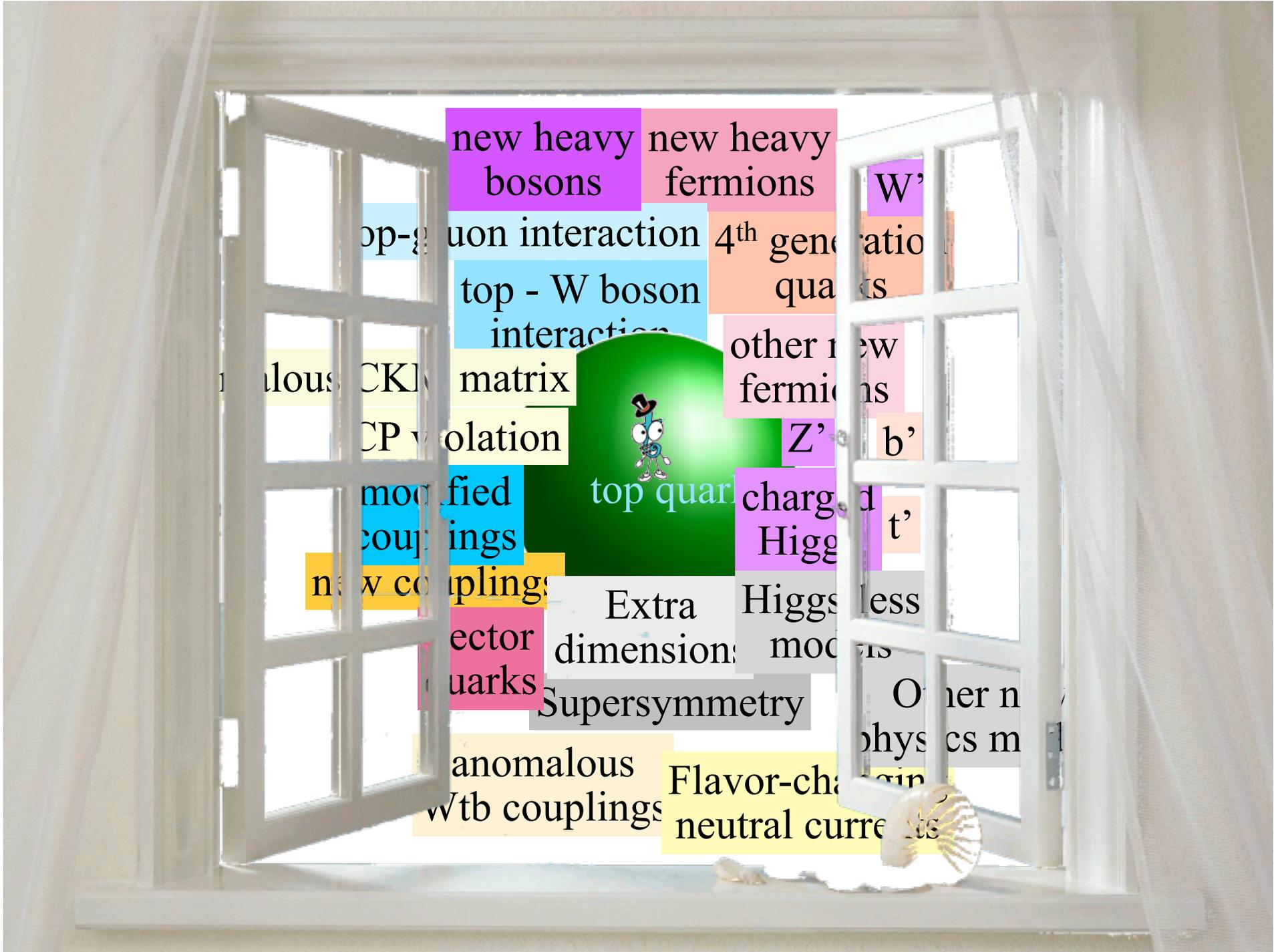
- Introduction
- Top quark precision measurements
  - Top mass
  - Top couplings
- Top quark new physics searches
  - High mass
  - Rare processes
- Top and detectors
  - Top reconstruction
  - Detector calibration
- Summary

# Top quark



- Only fermion at EWSB scale
  - ➔ Ideal to look for new physics
- Decays before hadronization
  - ➔ Ideal to study weak interaction of quarks
- Large samples of top quarks arriving now
  - ➔ Precision measurements become possible

# Top as a window to new physics

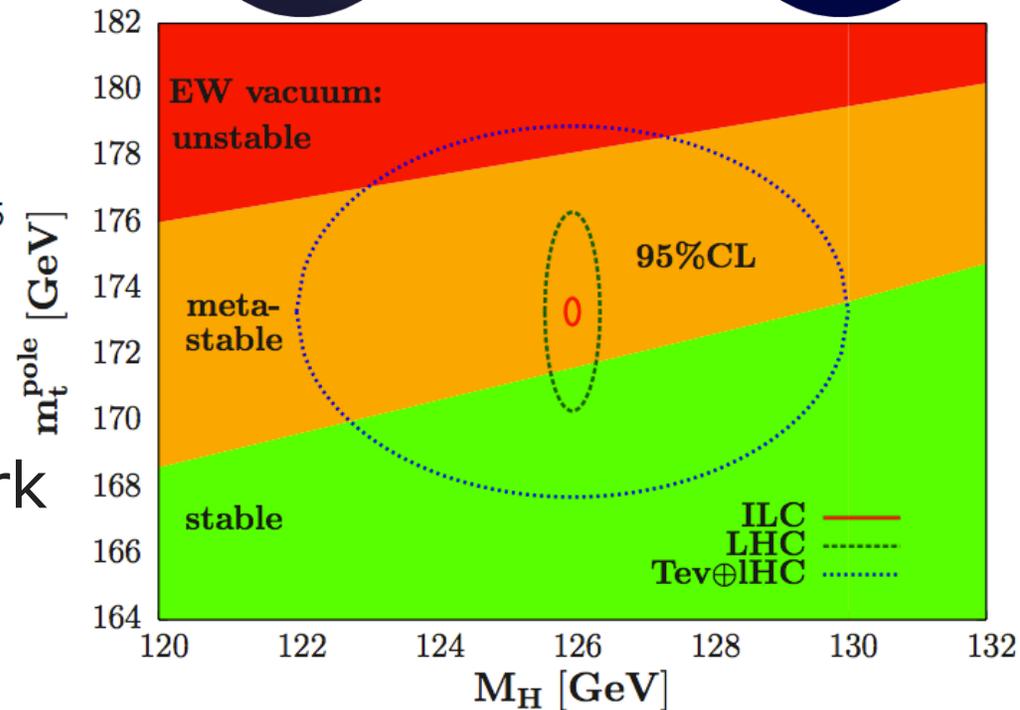
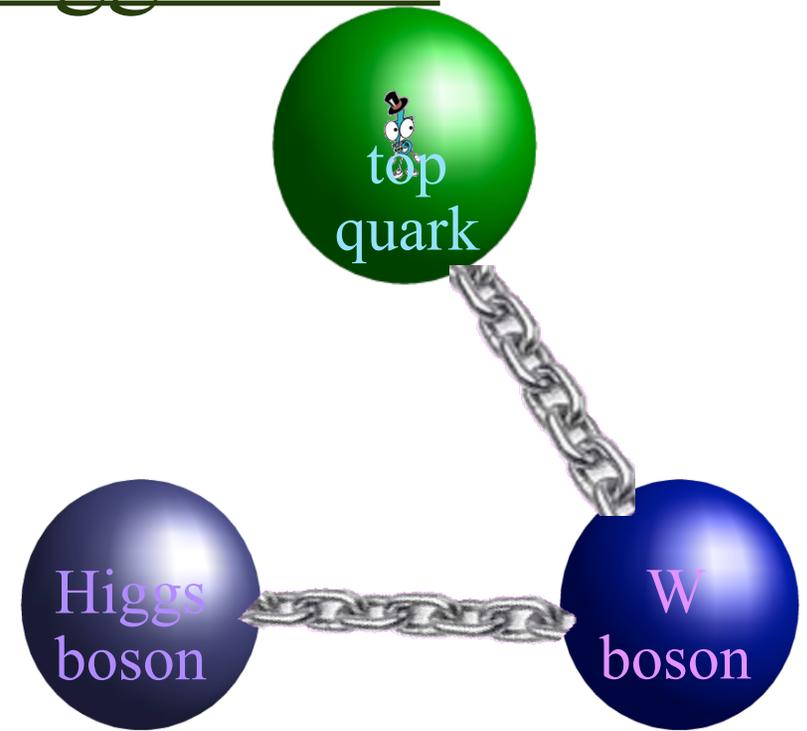
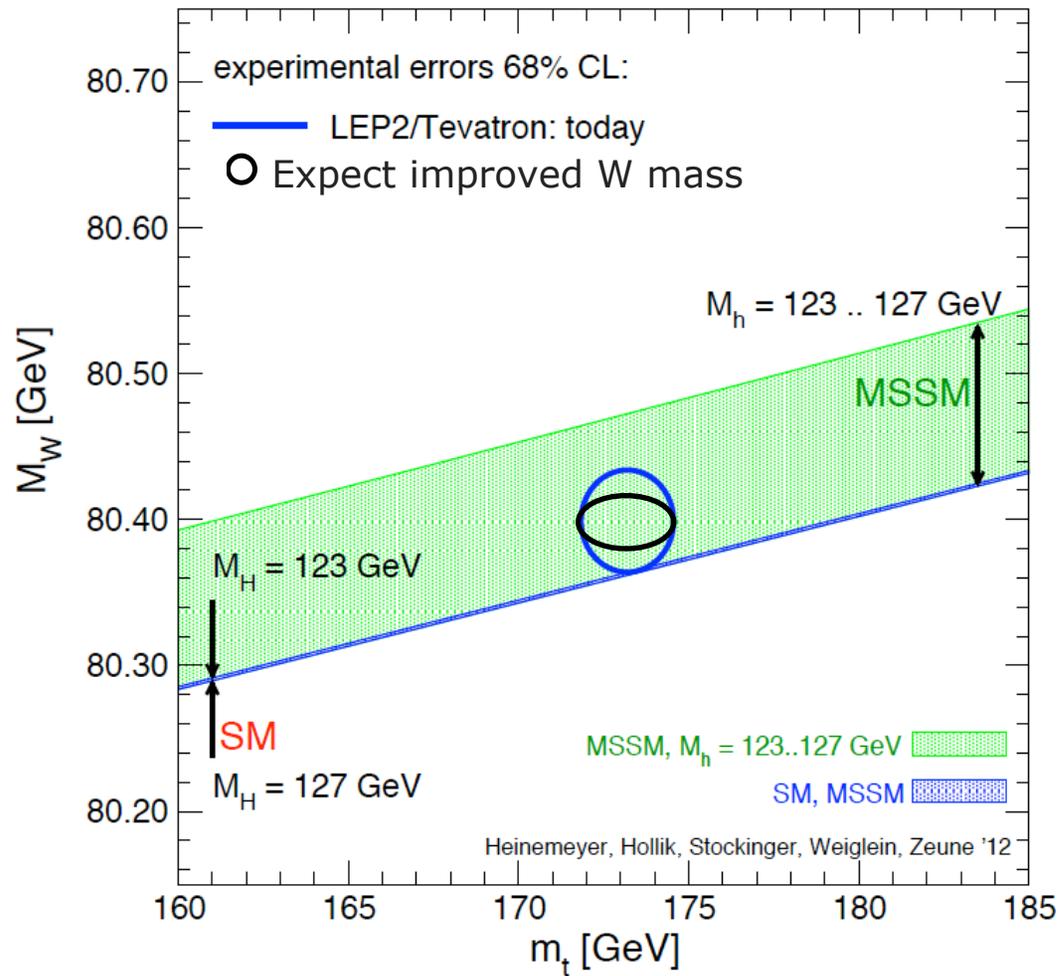


# Top as window to the SM

- 
- Mass
  - Charge
  - Spin
  - QCD coupling
  - Weak coupling
  - CKM matrix

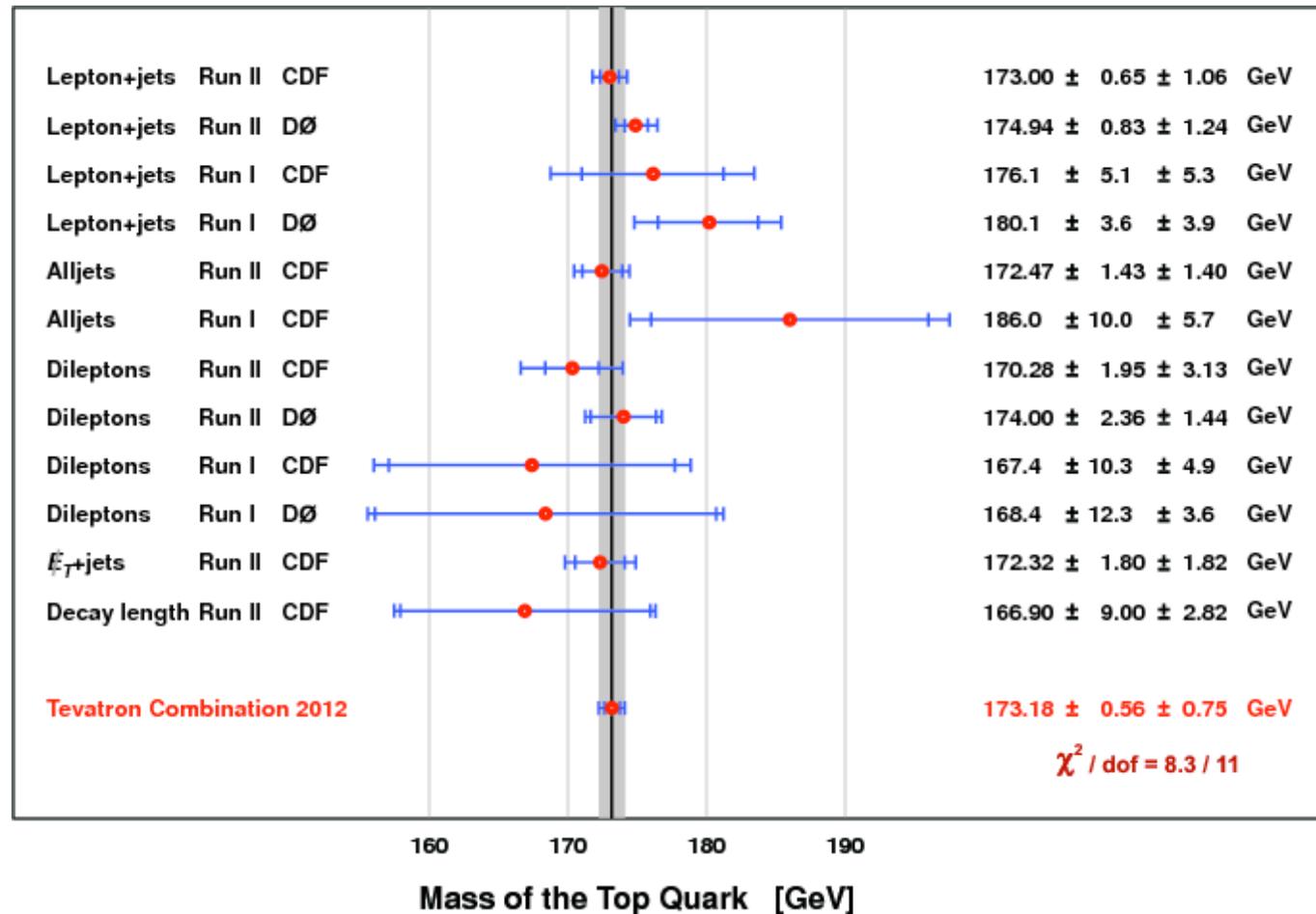
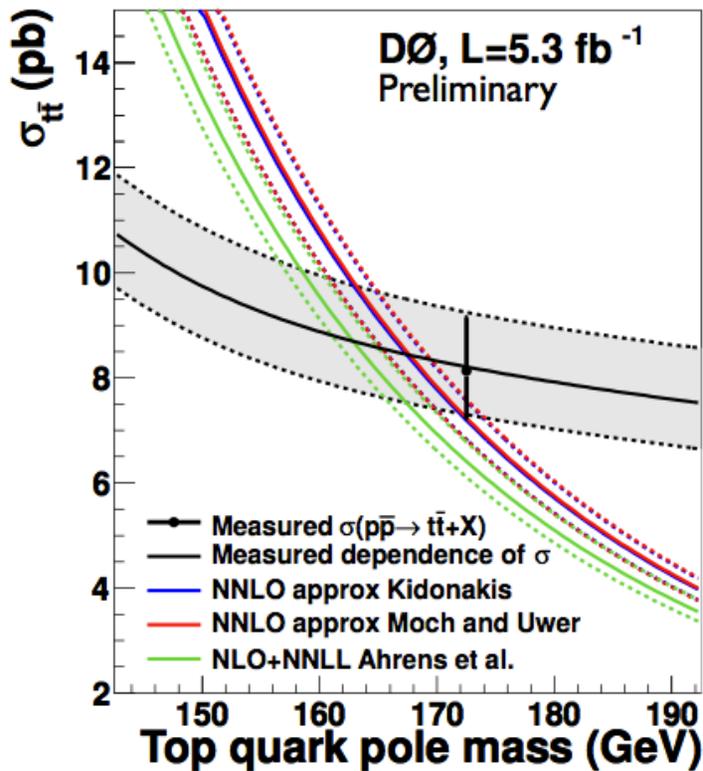
# Top quark precision measurements

# Top quark mass - Higgs mass



- How precisely does the top quark mass need to be measured?

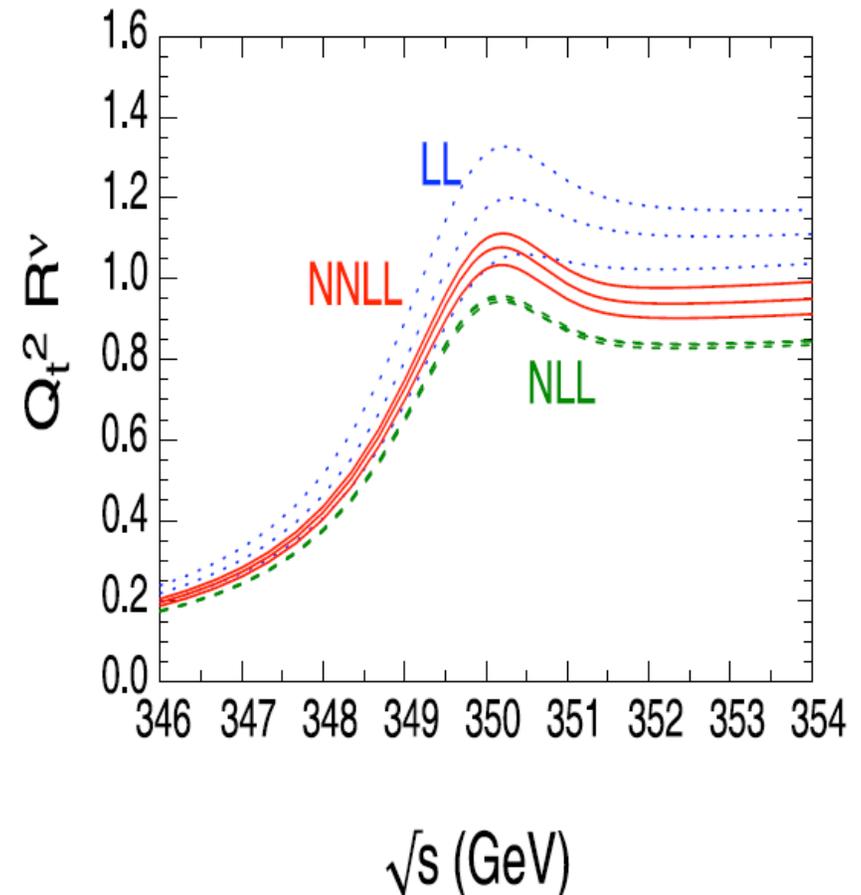
# Top quark mass - which mass?



- At what precision does renormalization scheme dependence become important?

# Top mass at different colliders

- LHC and hadron colliders
  - Top mass from decay
  - Top mass from cross section
- Top mass scan at lepton collider
  - More precise top mass measurement?
  - Complementary to decay measurements?
- Direct measurement of top quark width
  - Compare with EW production measurements
  - Invisible decays?

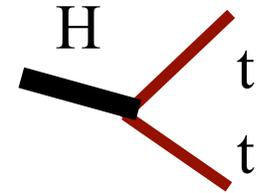
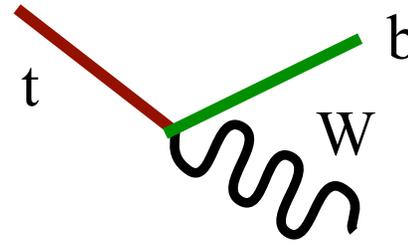
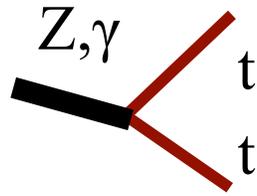
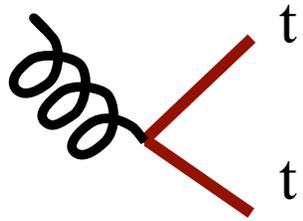


# Top quark mass

- How well can the top quark mass be measured at a hadron and at a lepton collider? Is there a good physics case for measuring the top quark mass with a precision that is significantly better than  $O(1\text{GeV})$ ?
- The top quark mass is a renormalization scheme-dependent quantity. Does this ambiguity have an impact on the measurements of the top quark mass at a hadron collider with the current or ultimate precision?
- Can the total width of the top quark be measured in a model-independent way and to what precision?

# Top quark couplings

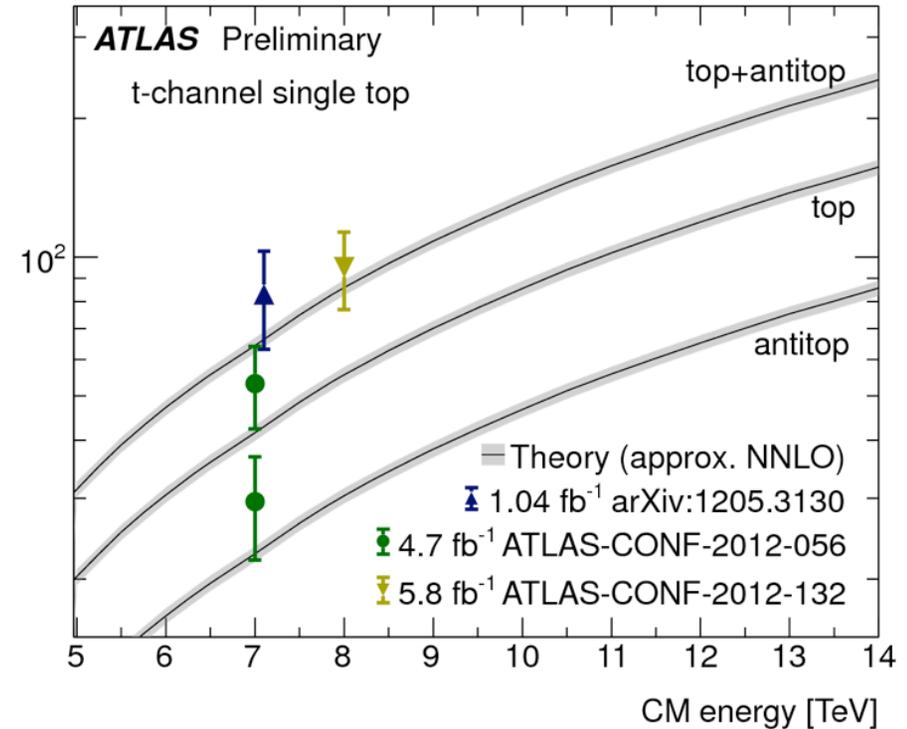
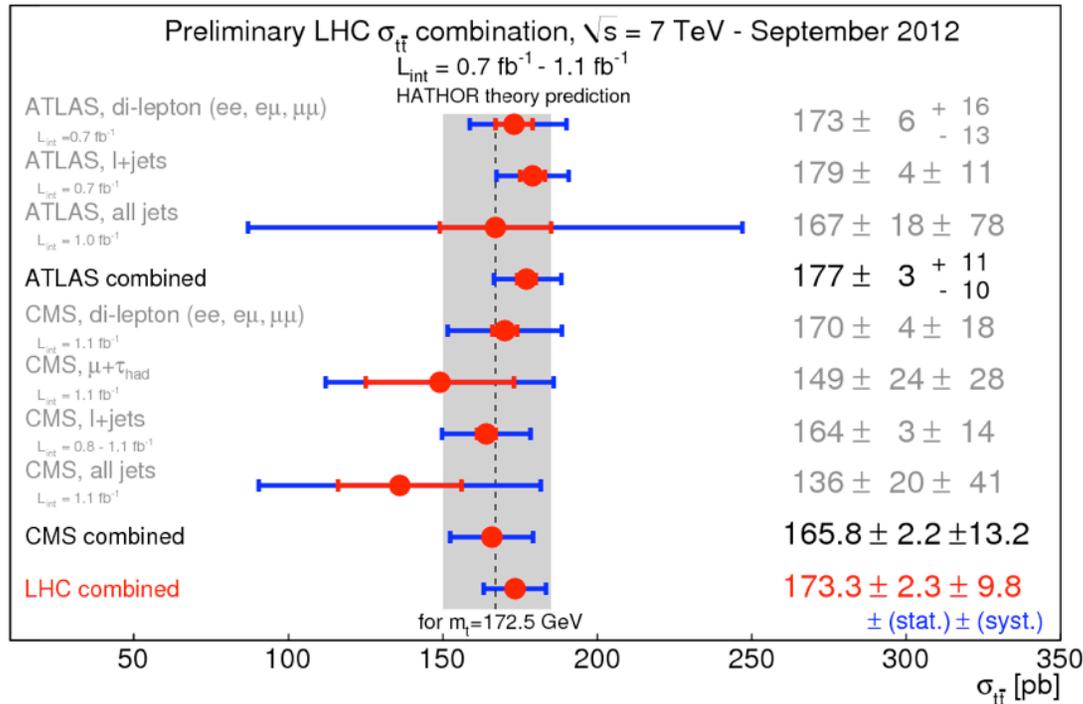
# Top quark couplings



- Measure coupling of top to gauge bosons precisely
  - Deviations from SM predictions?
  - CP violation?
  - CKM matrix?
- Precise calculations of cross sections are challenging
  - → QCD
- Hadron colliders
  - top-gluon coupling in production
  - top-W coupling in decay and in production
  - top-Z, top-photon, top-Higgs are difficult measurements
  - → top Yukawa coupling
- Lepton colliders
  - top-Z, top-photon

# Top quark couplings

## ● LHC: top-gluon and t-W-b coupling in production



- Linear collider: also ttZ coupling
- Requires precision predictions of cross sections
  - For signal and backgrounds
  - For top production and decay

# Top quark coupling - deviations from SM

- Precision measurements with large top quark samples
  - LHC: study  $Wtb$  coupling

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}$$

- Including CKM and complex phases

- Lepton collider: study  $Ztt$  and  $\gamma tt$  couplings

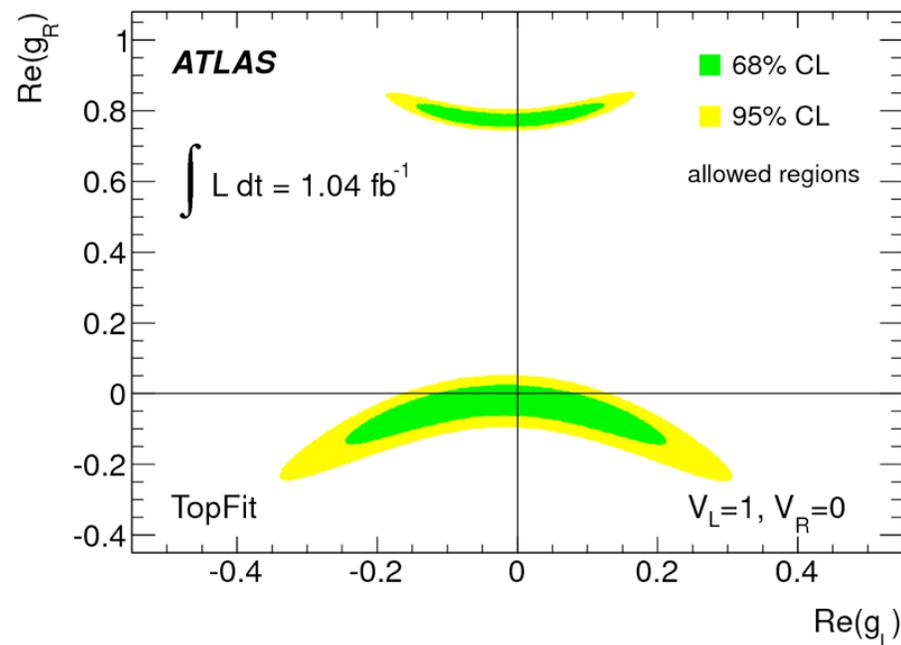
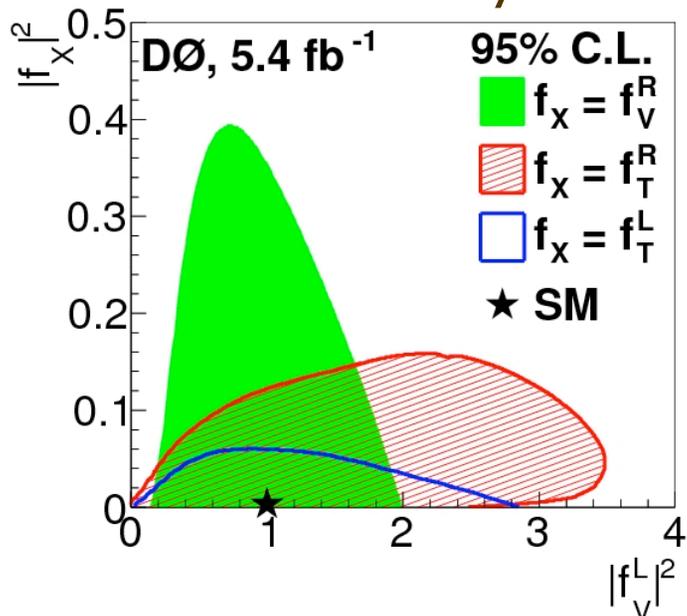
$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W} \bar{t} \gamma^\mu (c_L^t P_L + c_R^t P_R) t Z_\mu - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (d_V^Z + id_A^Z \gamma_5) t Z_\mu$$

$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t} \gamma^\mu t A_\mu - e \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^\gamma + id_A^\gamma \gamma_5) t A_\mu$$

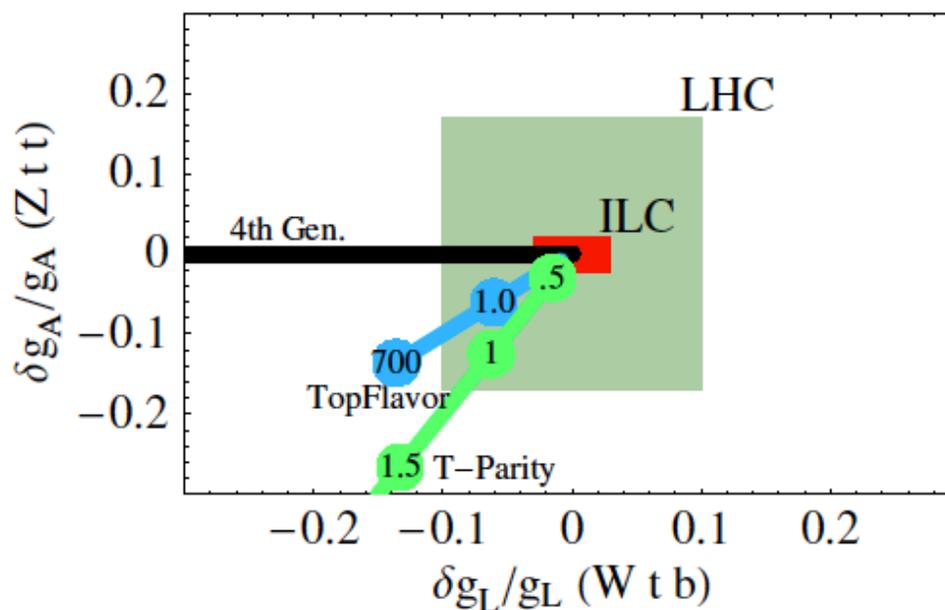
# Top quark coupling - deviations from SM

- Precision measurements with large top quark samples

- LHC: study  $Wtb$  coupling



- Lepton collider: study  $Ztt$  and  $\gamma tt$  couplings



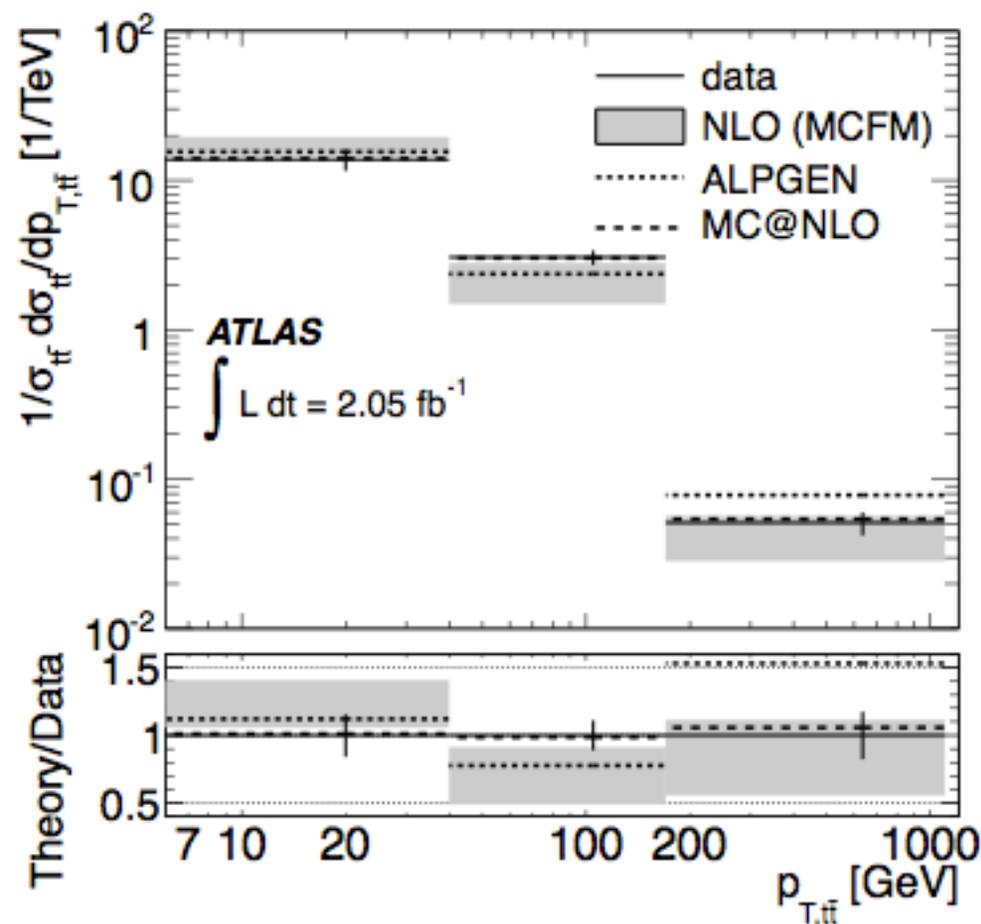
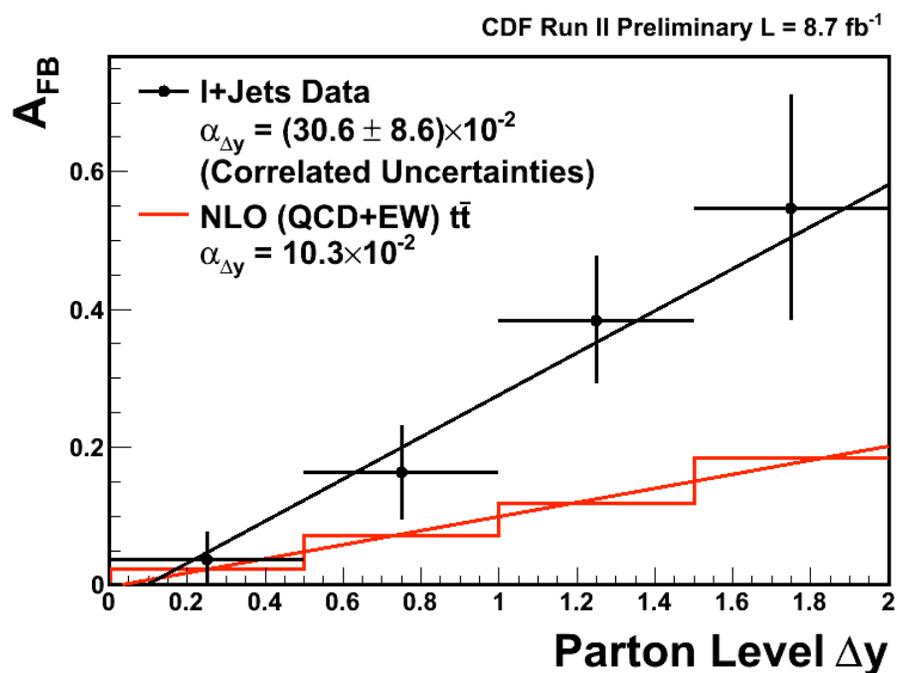
# Top coupling measurements

- What is the best way to parametrize deviations from SM predictions in couplings of top quarks to gluons, electroweak bosons, photons and the Higgs boson?
- What do we know about these deviations in couplings from direct and indirect measurements?
- Are there additional sources of CP-violation in the top-quark sector?
- What are the best ways to measure those couplings at a hadron collider and at a lepton collider? What precision can be obtained?
- Can the resulting determination of the visible decay width of the top quark, combined with a direct measurement of its width (at a lepton collider), have a significant impact on understanding invisible decay channels of the top quark?
- What improvements in experimental techniques and theoretical descriptions of top quark production processes are needed to achieve the ultimate precision?
- What is the impact that precise measurements of the top quark couplings to gauge bosons and the Higgs boson may have on our understanding of BSM physics?

# Top quark kinematics

# Top quark kinematics

- Precise predictions of kinematics are challenging
  - Higher order kinematics - event generators?
- New physics might show up in distributions
- CP violation in top sector?
- Which distributions are most relevant?



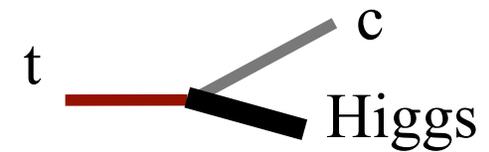
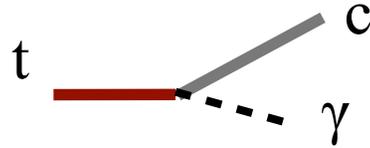
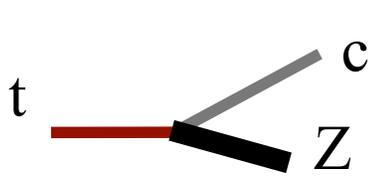
# Top kinematics

- What important SM physics information can be obtained by studying final states with top quarks?
- To what extent can precision studies of cross-sections and kinematic distributions for top-like final states at hadron colliders be used to constrain models of physics beyond the Standard Model?
- Which cross-sections and distributions are particularly important for this purpose? Are existing theoretical predictions for those final states adequate? What are the prospects for improving them?

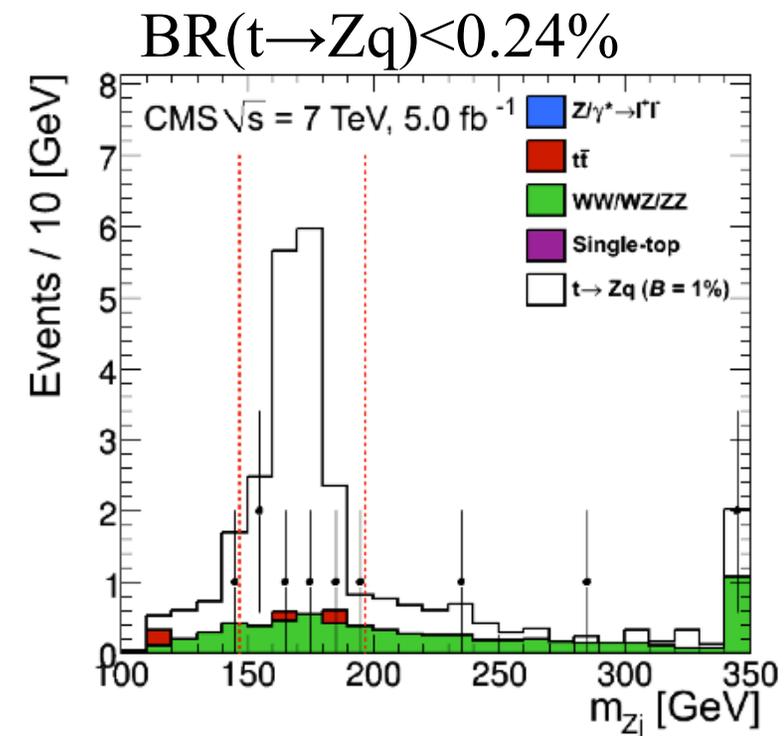
# Searches for new physics with top

# Rare top decays

- Exotic decays?

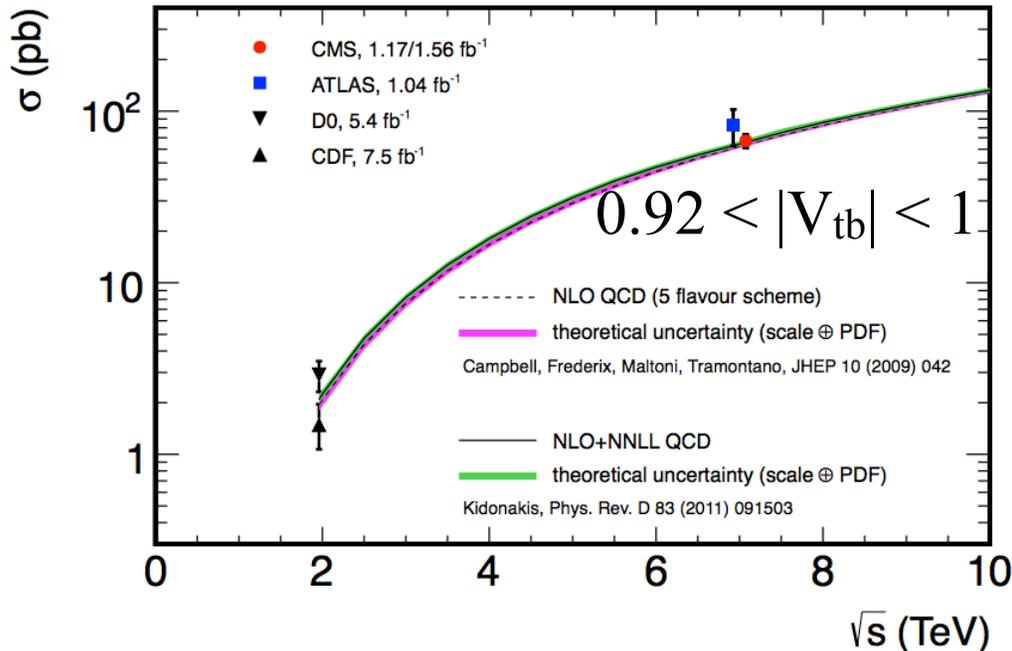
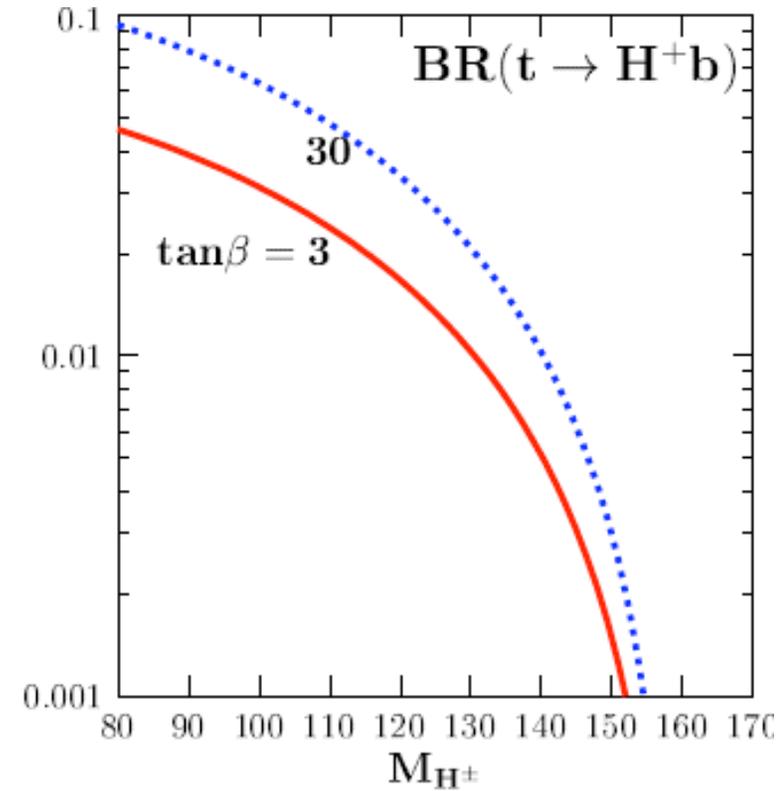


- What sensitivity can be reached at hadron and lepton colliders?
- Study rare processes in top production and decay
- CP violation in top sector?



# Rare top decays

- Exotic decays involving new particles
  - What sensitivity is required to have significant impact on new physics



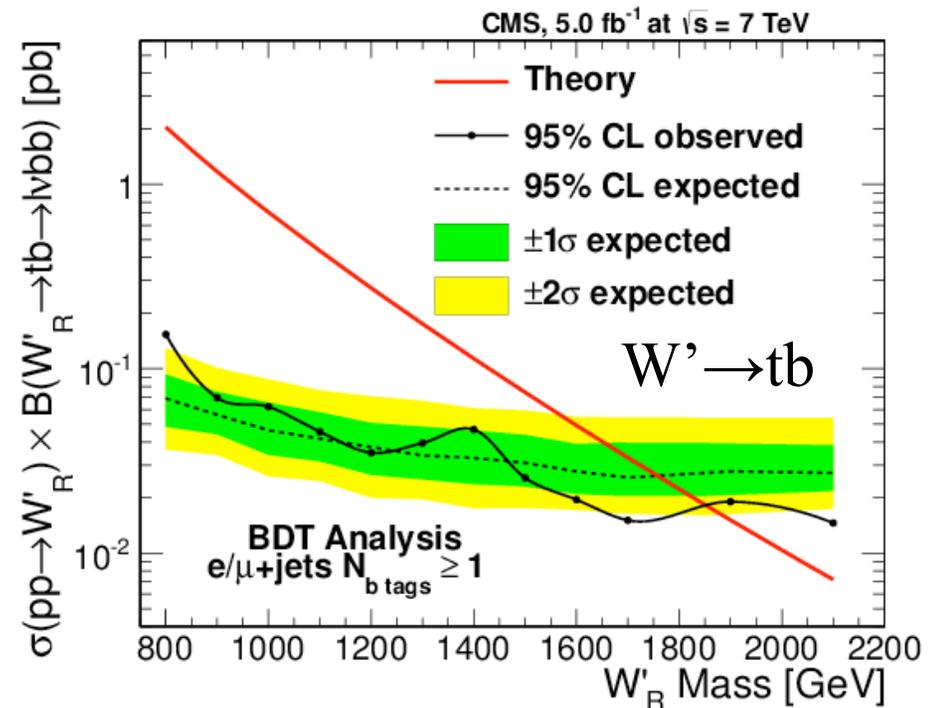
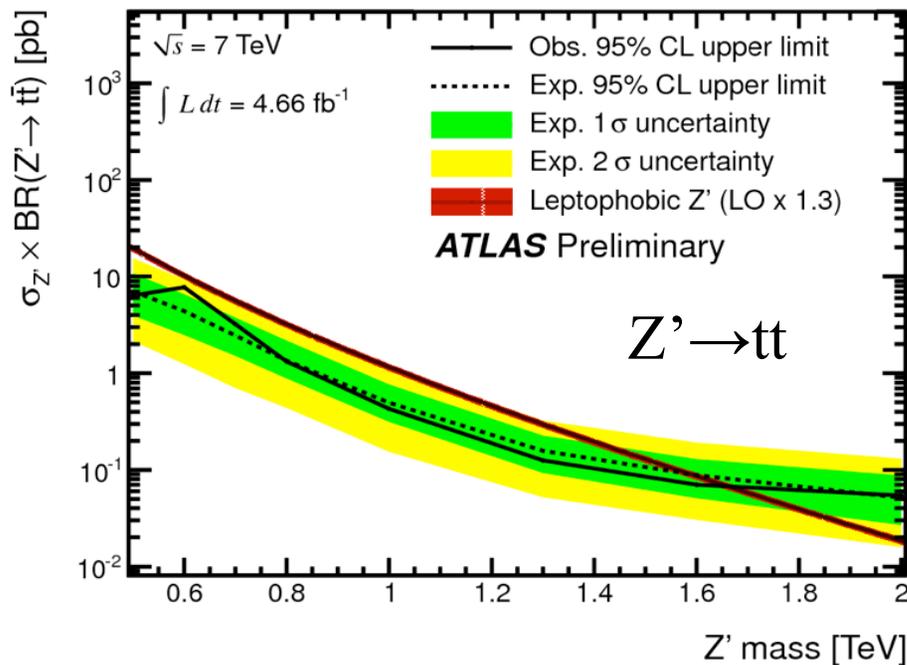
- CKM matrix elements  $V_{ts}$  and  $V_{td}$  from top decays?
  - compare to CKM matrix from top production
  - impact on CKM unitarity?

# Searches in top decay

- Does the top quark decay to exotic final states? SM-like ( $t \rightarrow c Z$  and  $t \rightarrow c H$ ) or BSM-like ( $t \rightarrow b H^+$ )? How well can these decays be measured/constrained at hadron and lepton colliders?
- What sensitivity needs to be reached for these decays in order to have a significant impact on models of physics beyond the SM?
- Can the small CKM-matrix elements  $V_{ts}$  and  $V_{td}$  be directly measured via top quark decays? To what precision? Can this way to measure  $V_{ts}$  and  $V_{td}$  compete with their (possible) determination via top quark production processes? Can such measurements have an impact on understanding CKM-unitarity and provide important constraints on models of physics beyond the SM?

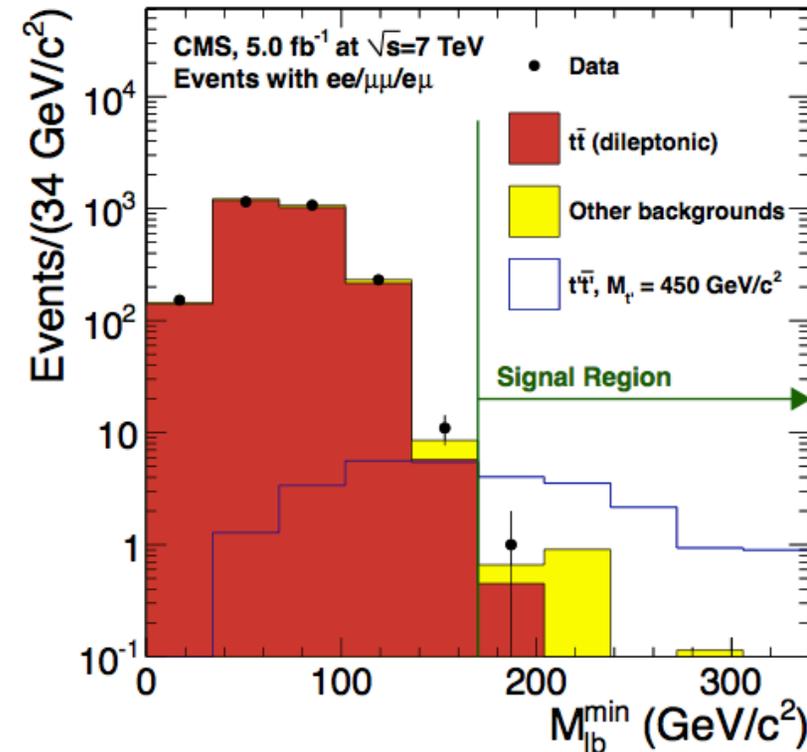
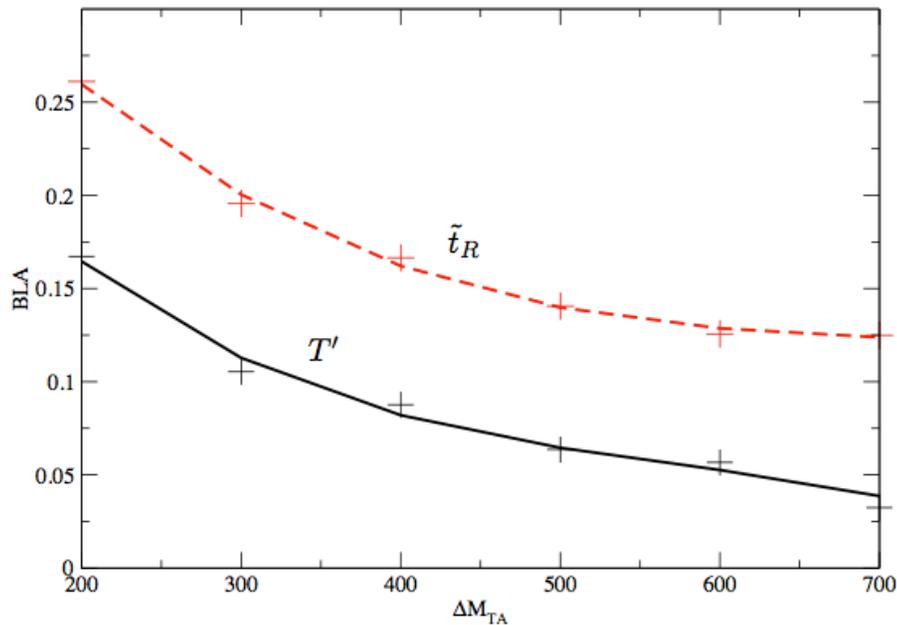
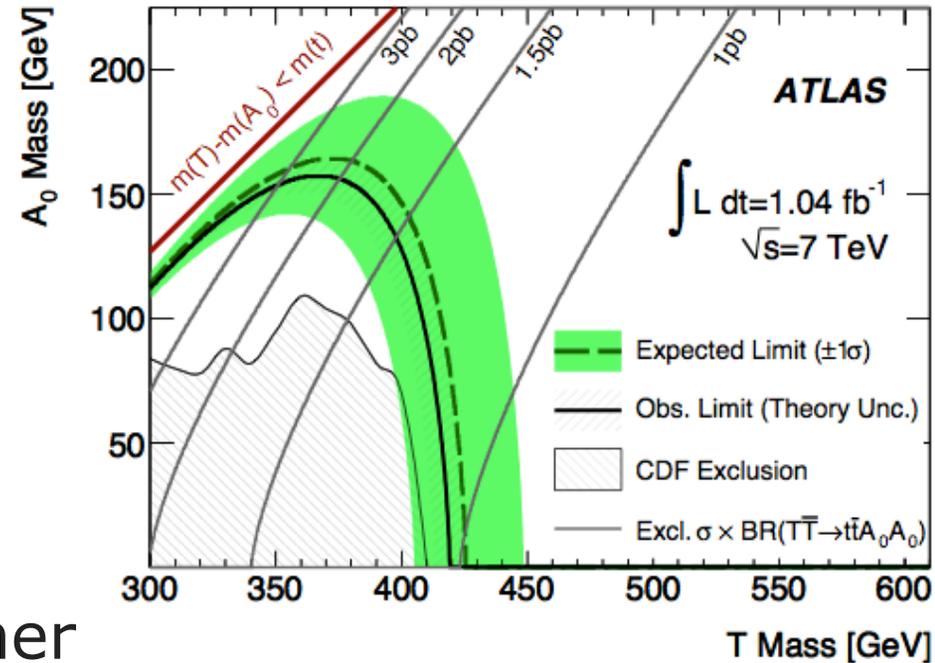
# Searches for new particles

- Heavy resonances decaying to top
- New particles produced with top
- Top partners
- Measuring top couplings to new particles



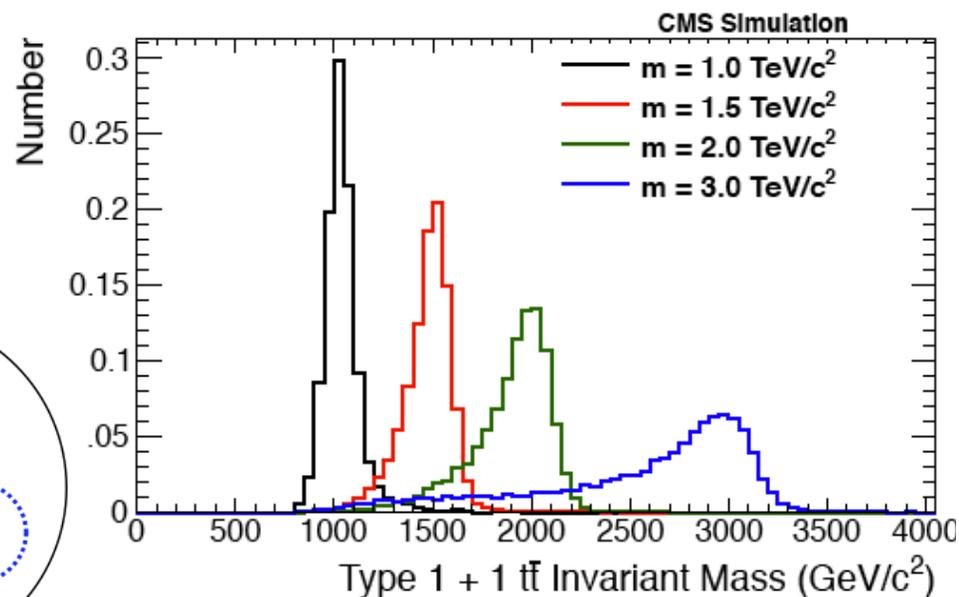
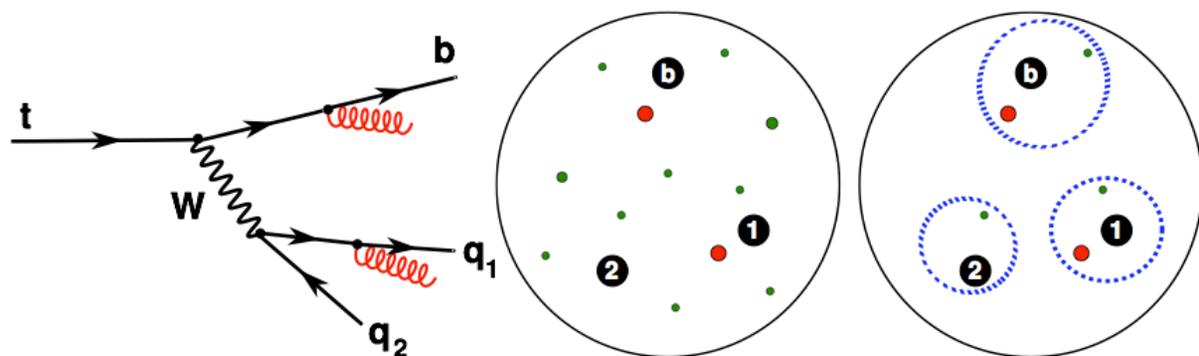
# Top partners

- Heavy particles bring Higgs to weak scale
  - thus coupling to top
- With additional particles
  - Top plus MET
- 4<sup>th</sup> generation
  - exotic quarks, vector-like quarks
- Determine properties of top partner when/if found

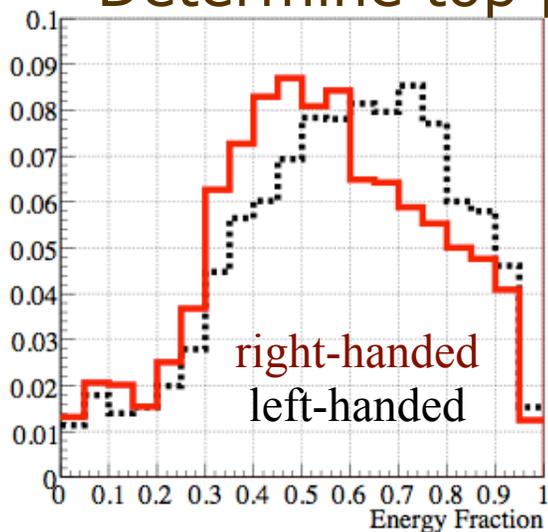


# Boosted top

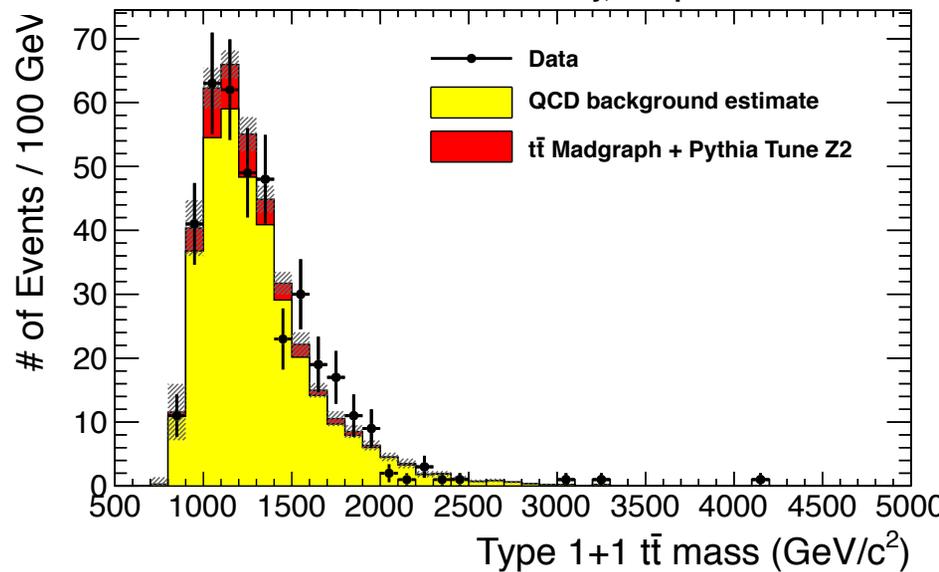
- Top quark with high momentum
  - Decay products merge into single jet



- Classify resonance if found
  - Determine top polarization



CMS Preliminary, 886 pb<sup>-1</sup> at  $\sqrt{s} = 7$  TeV



# Searches for new particles

- Are there new particles that decay to top-like final states and other SM or BSM particles? What are the current constraints on their masses and couplings?
- What are the best ways to search for such particles at a hadron collider? What is the dependence on kinematics and final state? What sensitivity can be reached in such searches?
- Provided that such new particles exist, how well can their properties be measured in top-like final states?
- Are there indirect ways to search for heavy new particles that couple to top quarks (e.g., via their contribution to top quark production) at a sub-TeV lepton collider? What sensitivity can be obtained in such searches? What is the dependence on collider energy?
- Are there particles with top-like final states that could only be found at a multi-TeV lepton collider (especially non-colored ones)?

# Top and detectors

Precision  
measurements

Top and  
detectors

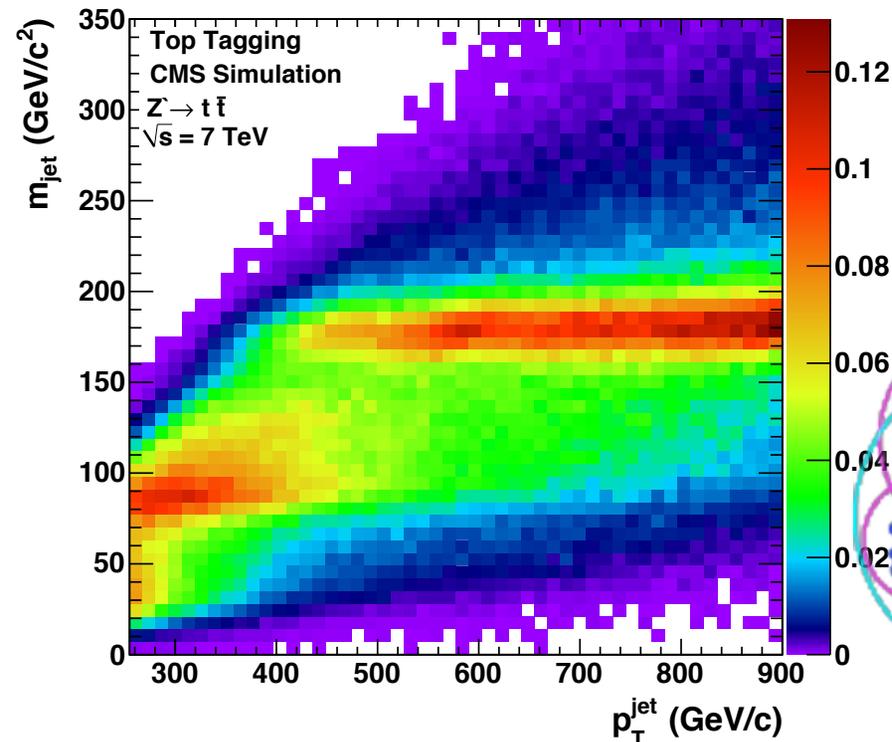
Searches with  
top quarks

# Detectors for top

- Low  $p_T$  top quark reconstruction
  - Precision jet and lepton reconstruction and identification
    - ▶ including flavor
    - ▶ MET is important
- Separating top decay objects from each other and from backgrounds

## Top quark decay

$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
$\tau$	$e\tau$	$\mu\tau$	$\tau\tau$		
$\mu^-$	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
$e^-$	$ee$	$e\mu$	$e\tau$	electron+jets	
$W$ decay	$e^+$	$\mu^+$	$\tau^+$	$u\bar{d}$	$c\bar{s}$

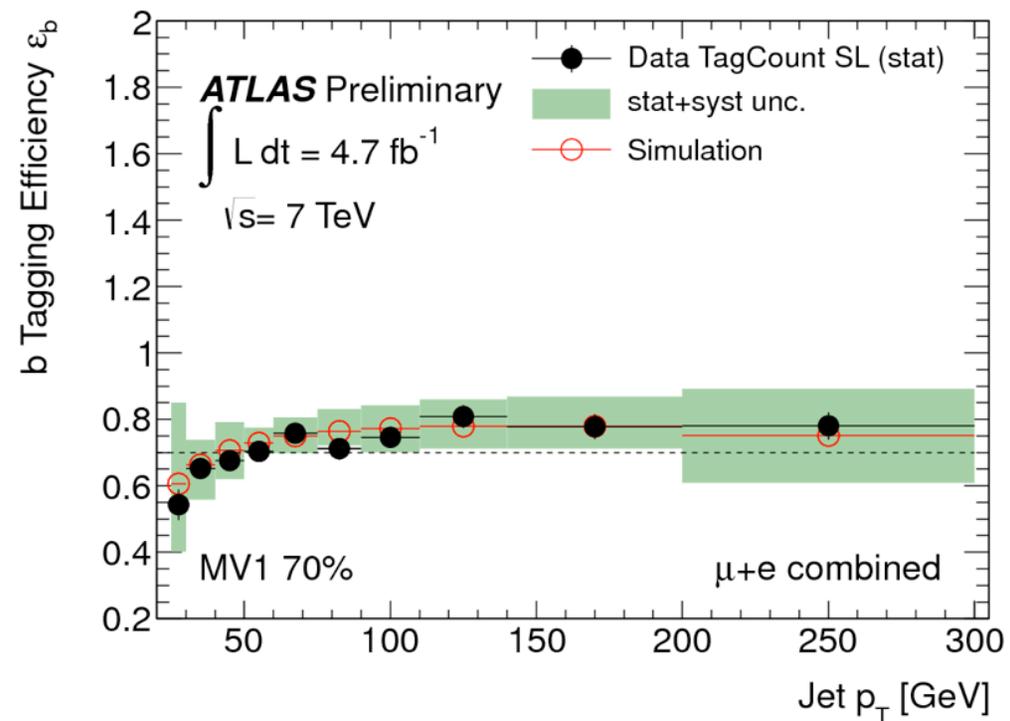
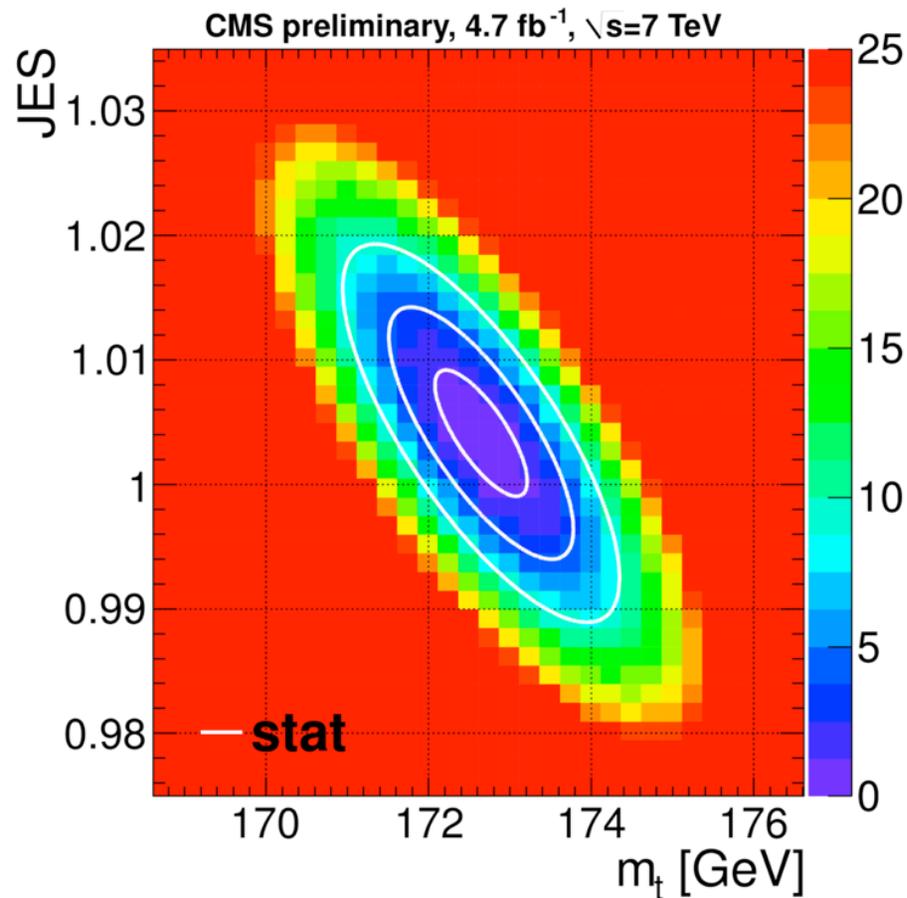


## • Boosted top quarks

- Take full advantage of each detector cell
- Requirements for detector segmentation and resolution?
- boosted lepton+MET+jet

# Top for detectors

- Jet energy scale factor fit simultaneous with top mass
- b-tagging efficiency from top events
- Other calibration/efficiency determination from top?
- Other use for large top samples?



# Top and detectors

- How well can top quarks be reconstructed at low energies and high energies (i.e., boosted top quarks)? What algorithms are available? Can they be improved? What is the impact of such improvements on physics questions discussed in the previous bullets?
- What is the energy resolution, identification and misidentification efficiency for each?
- What is required from the detector to be able to provide this?
- How can top quarks be used to improve b-tagging or jet energy resolution and other detector calibrations?

# Friday night tops

- Discussion of plans for top quark studies on Friday night  
<https://indico.fnal.gov/contributionDisplay.py?sessionId=10&contribId=82&confId=5841>
- Racetrack (WH7W)
- Remote access
  - ReadyTalk connection at phone number 866.740.1260
  - access code 2720540
  - evo: <http://evo.caltech.edu/evoNext/koala.jnlp?meeting=vsvivIeseBIBIIauaeItas>
  - evo password: topsnowmass
- Join us if you intend to study anything related to top quarks!

# Conclusions/Outlook

- Top quarks are the key to physics at the energy frontier
  - Precision measurements and predictions
  - New physics searches
  - Detector challenges
- Bring together people interested in wide range of topics
- Top quarks also appear in every other HEF area:
  - Higgs - top Yukawa coupling
  - EW - precision fits including top mass
  - BSM - searches with top final states
  - QCD - precision calculations
  - Flavor physics - CP violation in top sector
- Aim for consistent treatment of top in all areas
- Help us lay out the path to the top future