Top Quarks and New Physics : Resonances, Spin Correlations and Boosted Top

Ben Auerbach on behalf of the ATLAS and CMS collaborations

Standard Model At The LHC: Freiburg, Germany

Search for $t\bar{t}$ Resonances in ATLAS and CMS

- The electroweak symmetry breaking may have a connection to the top quark mass
- Might there be an additional resonance that decays to a pair of top quarks?
- This is an active area of research for both ATLAS and CMS
- Possible candidates are a KK Gluon or a Z' decay
  - The two candidates mentioned in the coming slides are a Z' with a 1.2% width
    - R. M. Harris and S. Jain, Cross Sections for Leptophobic Topcolor Z' Decaying to Top-Antitop, Eur. Phys. J. C72 (2012) 2072
  - and a KK gluon with a 10% width
    - K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, LHC signals from warped extra dimensions, Phys. Rev. D 77 (2008) 015003

CMS Search for All Hadronic Tops, EXO11006

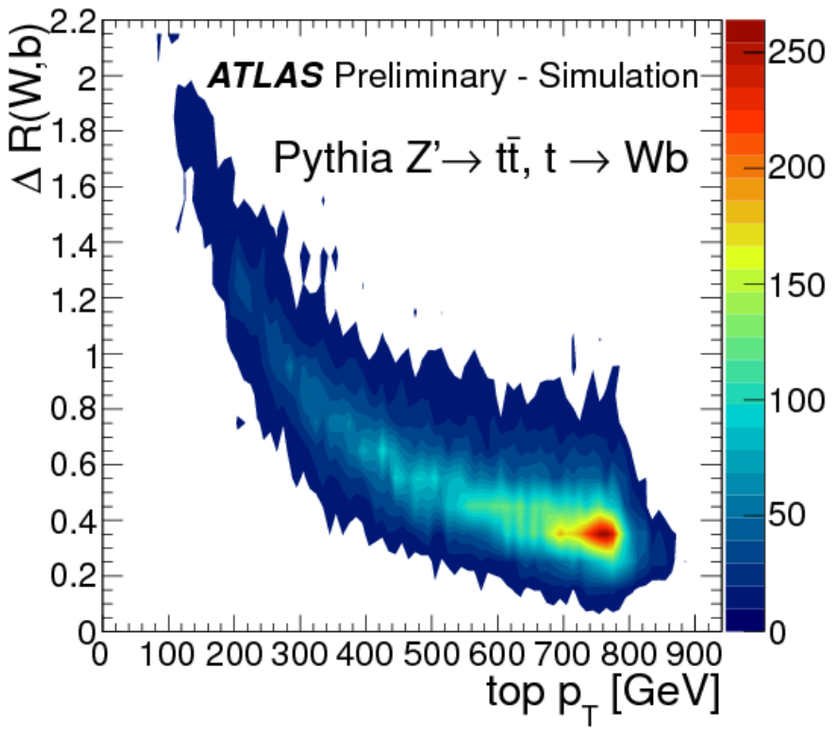
ATLAS Search for All Hadronic Tops,TOPQ-2012-15/

Search for $t\bar{t}$ Resonances in ATLAS and CMS (II) (All Hadronic)

- CMS uses Cambridge-Aachen R=0.8 jets with:
  - p_T>350 GeV, CMS PAS JME-09-001
  - Then the jet must be TopTagged
  - Require 2 jets pass this criteria (type 1+1)
  - If only 1 jet passes this, look for a W-jet and b-jet nearby on the other side

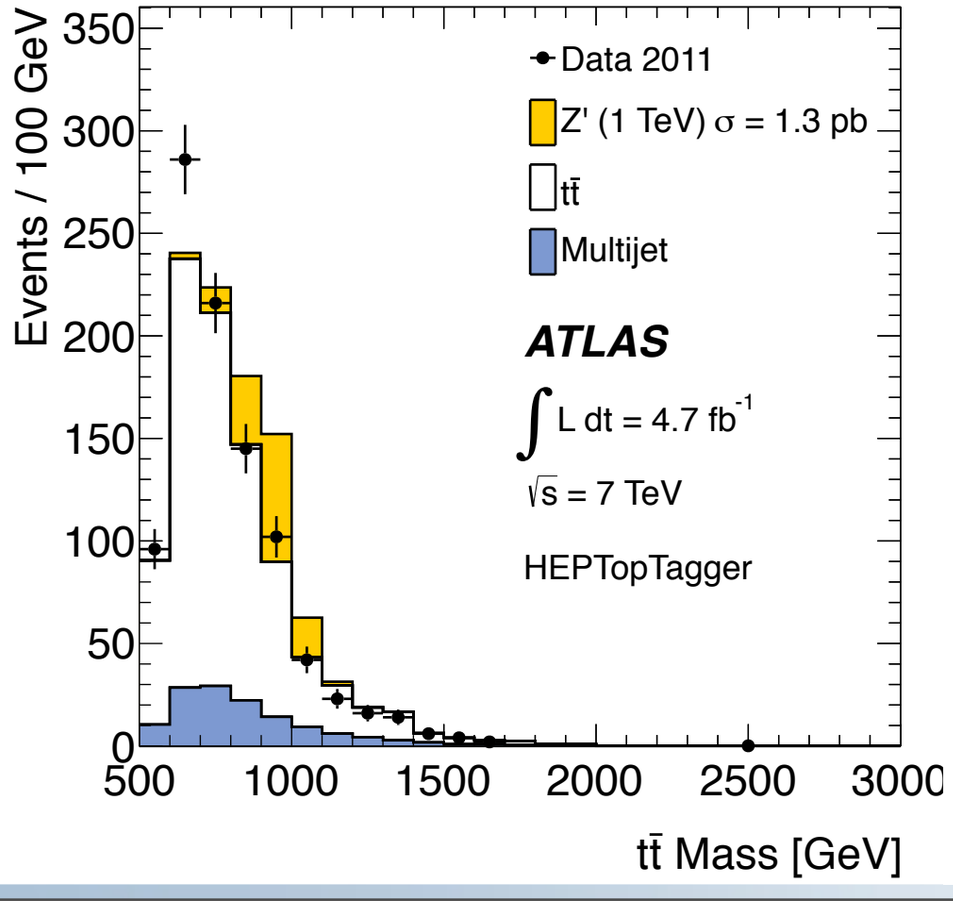
- Expecting all of top's decay products in a small radius

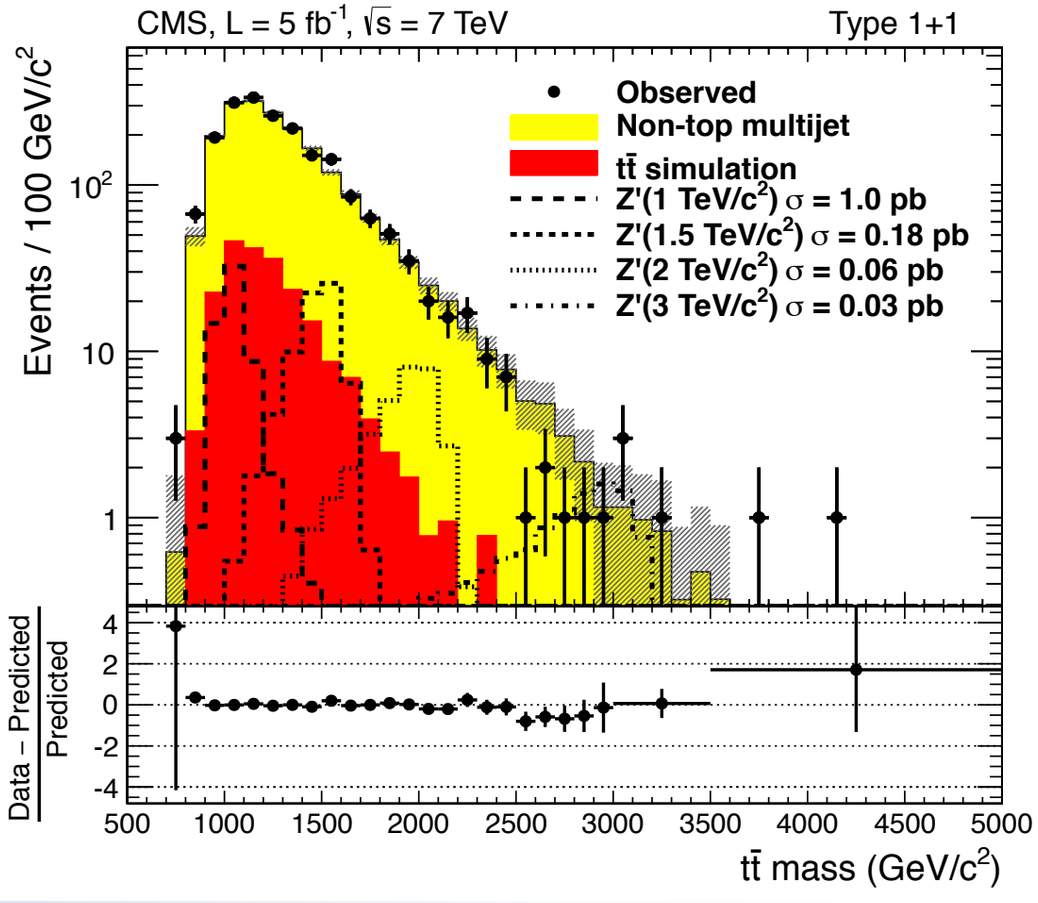
- ATLAS uses HEPTopTagger and TopTemplateTagger:
  - HepTopTagger arXiv:1006.2833
    - Requires 2 b-tag matched
    - Anti-k_t R=1.5 jets
    - pT > 200 GeV
  - TopTemplateTagger arXiv:1006.2035
    - Requires 2 b-tag matched
    - Anti-k_t R=1.0 jets,
    - p_T > 500 (450) GeV



Search for $t\bar{t}$ Resonances in ATLAS and CMS (II) (All Hadronic) (III)

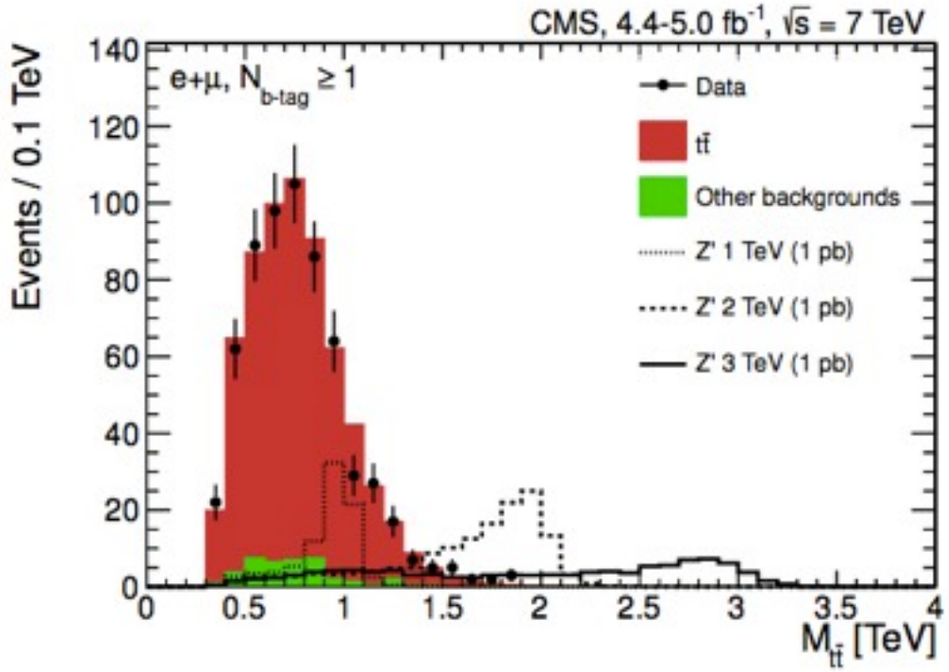
- Search for $t\bar{t}$ resonances using the M($t\bar{t}$) spectrum
- Since no excesses are seen, set limits using a Bayesian approach
- 0.7 TeV <$M_{Z'}$ < 1.0 TeV, & 1.28 < $M_{Z'}$< 1.32 TeV excluded (ATLAS)
- 1.3 TeV< $M_{Z'}$ < 1.5 TeV excluded (CMS)
  - Z' with width = 1.2%
- 0.7 TeV < M_{gKK}< 1.62 TeV excluded (ATLAS)
- 1.4 TeV < M_{gKK}< 1.5 TeV excluded (CMS)
  - g_{KK} width = 10%



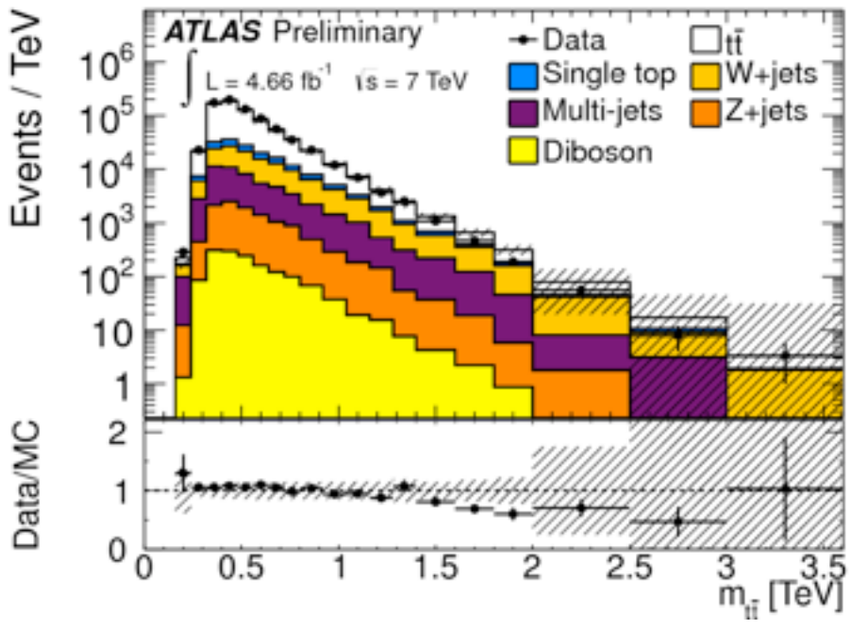


Searching for $t\bar{t}$ mass resonances (l + jets channel)

- Start by identifying isolated lepton, require MET and m_T to cut QCD
- Results are searched for in a Resolved and Boosted Regime
  - Maximize sensitivity to lower and high mass Z'
- The Resolved analyses require χ^2 to combine objects into W and tops
- Boosted analysis can use proximity to combine objects for top or anti-top
- Largest backgrounds in both cases are data-driven



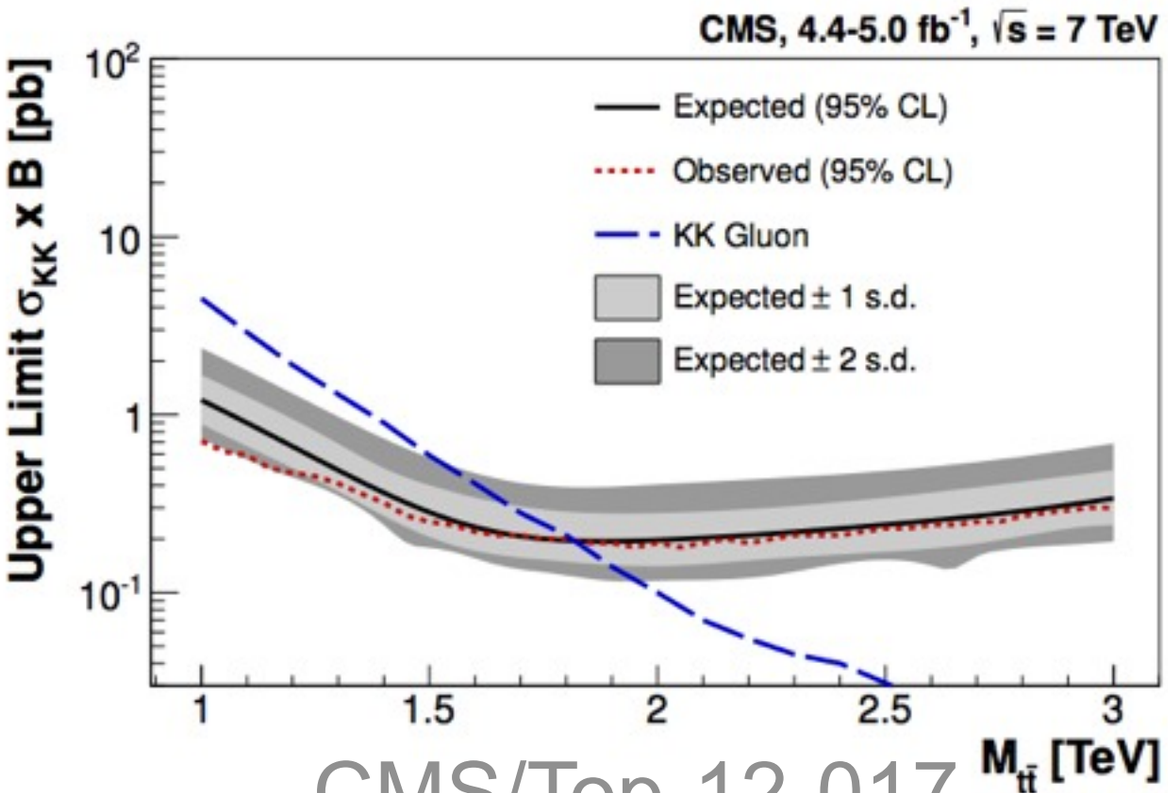
CMS/Top-12-017



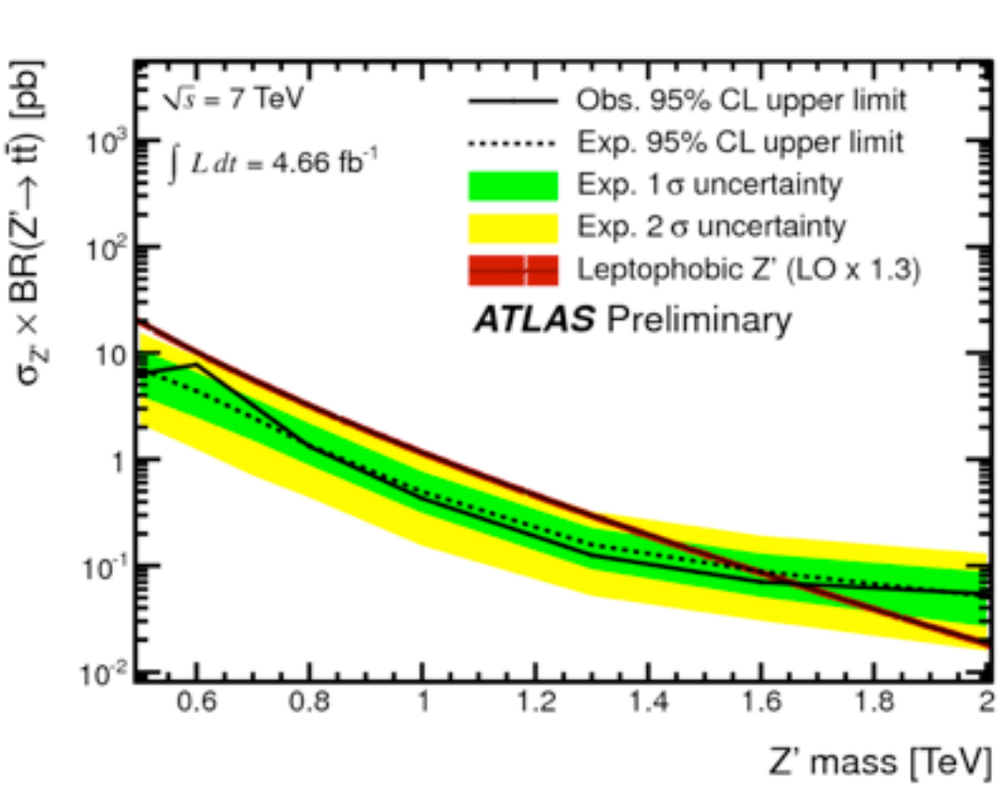
ATLAS-CONF-2012-136

Limits using the boosted and lower p_T $t\bar{t}$ selection

- Limits can be set on both a broad resonance like the KK gluon or a narrow resonance like the Z', g_{KK}
- Z' (1.2% width) is excluded M < 1.7 TeV (ATLAS), 1.53 TeV (CMS)
- g_{KK} is excluded for M < 1.82 TeV (CMS), 1.9 TeV (ATLAS)



CMS/Top-12-017

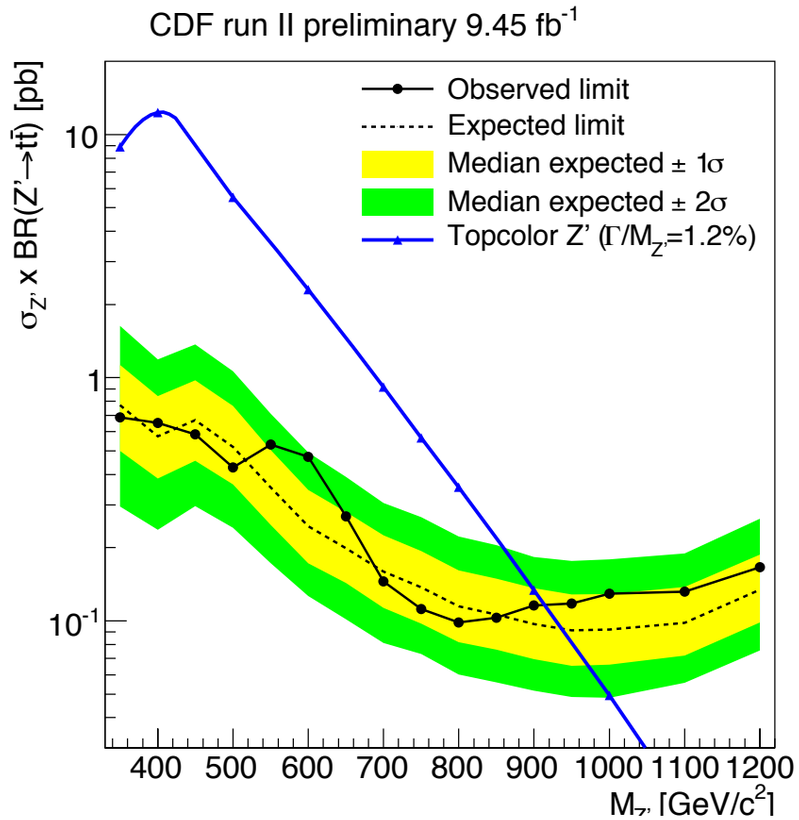


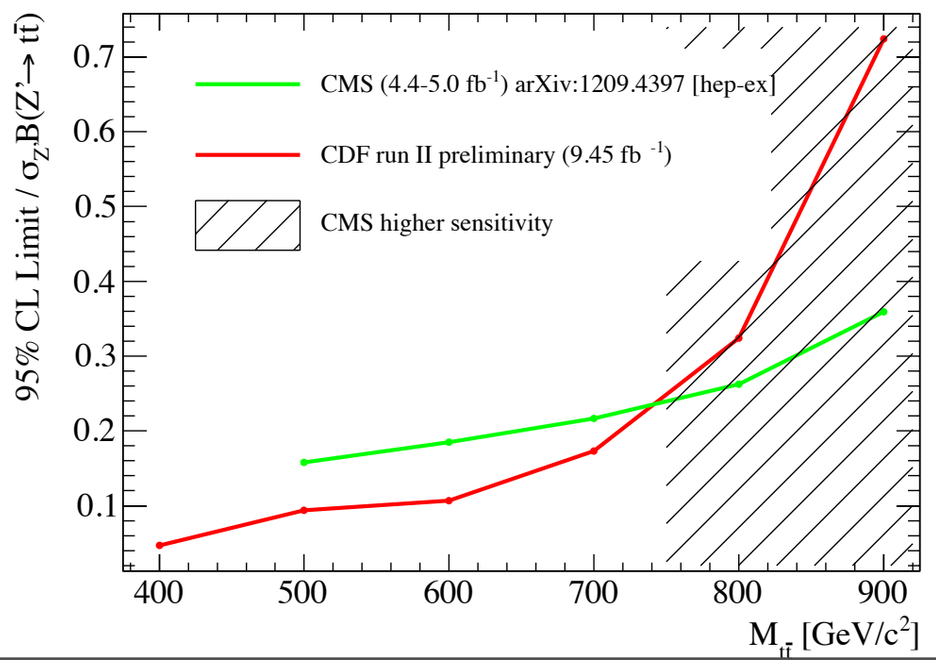
ATLAS-CONF-2012-136

Sensitivity in Perspective (CDF's lepton+jets)

- But CDF's relative sensitivity to low-mass Z' is still higher than at the LHC
  - CDF has set most sensitive relative limits on the low mass Z'
- Important to continue pushing on the Z' searches at the LHC to probe for the unexpected

- M(ttj): arXiv:1210.5686 , Phys. Rev. D 86, 112002 (2012)
- M(tj): arXiv:1203.3894 , Phys. Rev. Lett. 108, 211805 (2012)

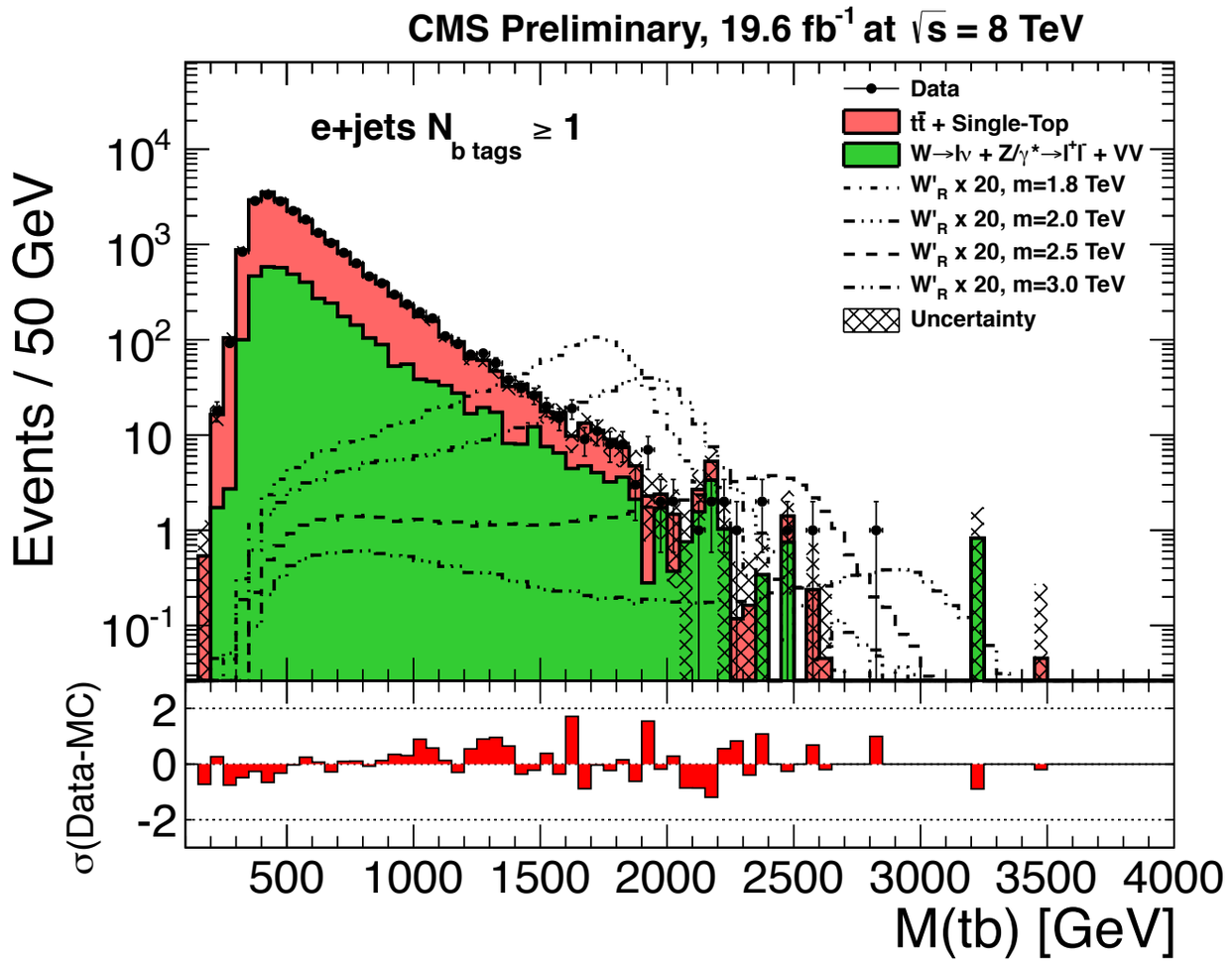




CDF PRL**110, 121802 (2013)**

Search for W' as a top-bottom resonance

- Require an electron, or muon:
- At least two jets are required:
  - Leading jet p_T > 120 GeV
  - Subleading jet p_T > 40 GeV
  - At least one jet is b-tagged

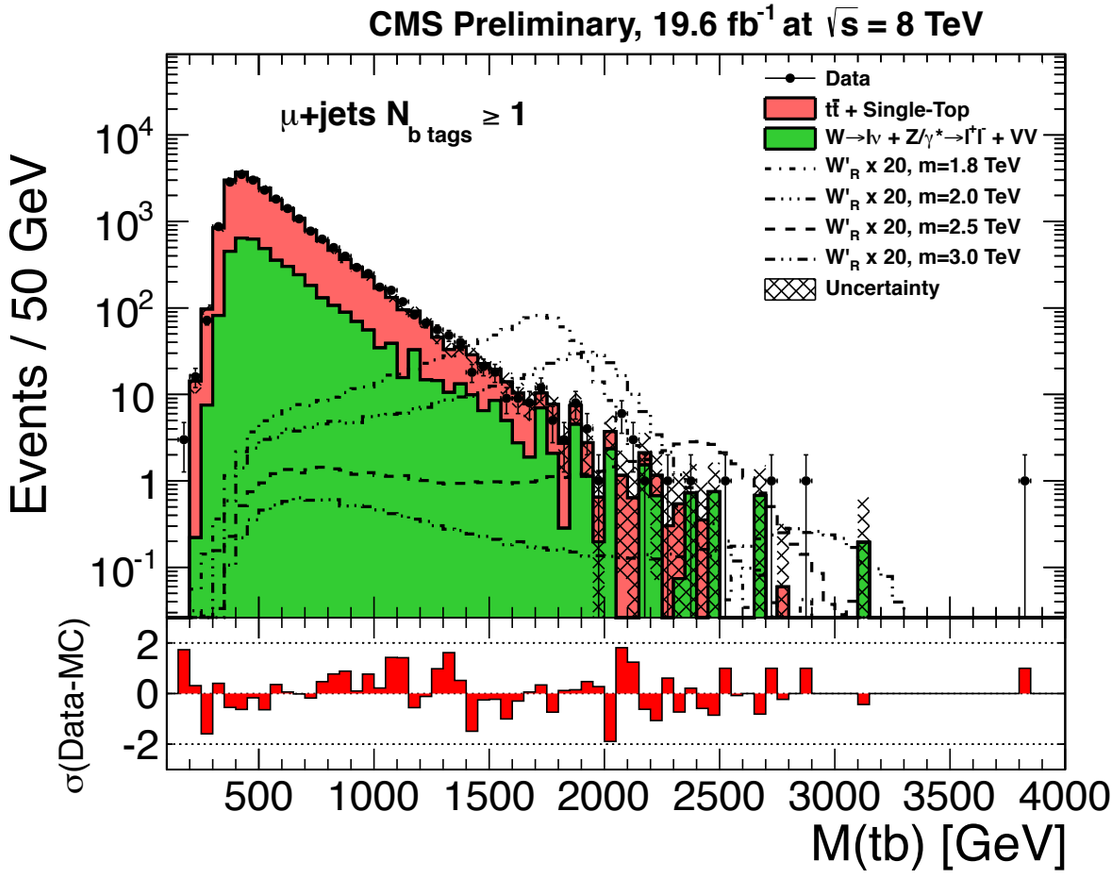


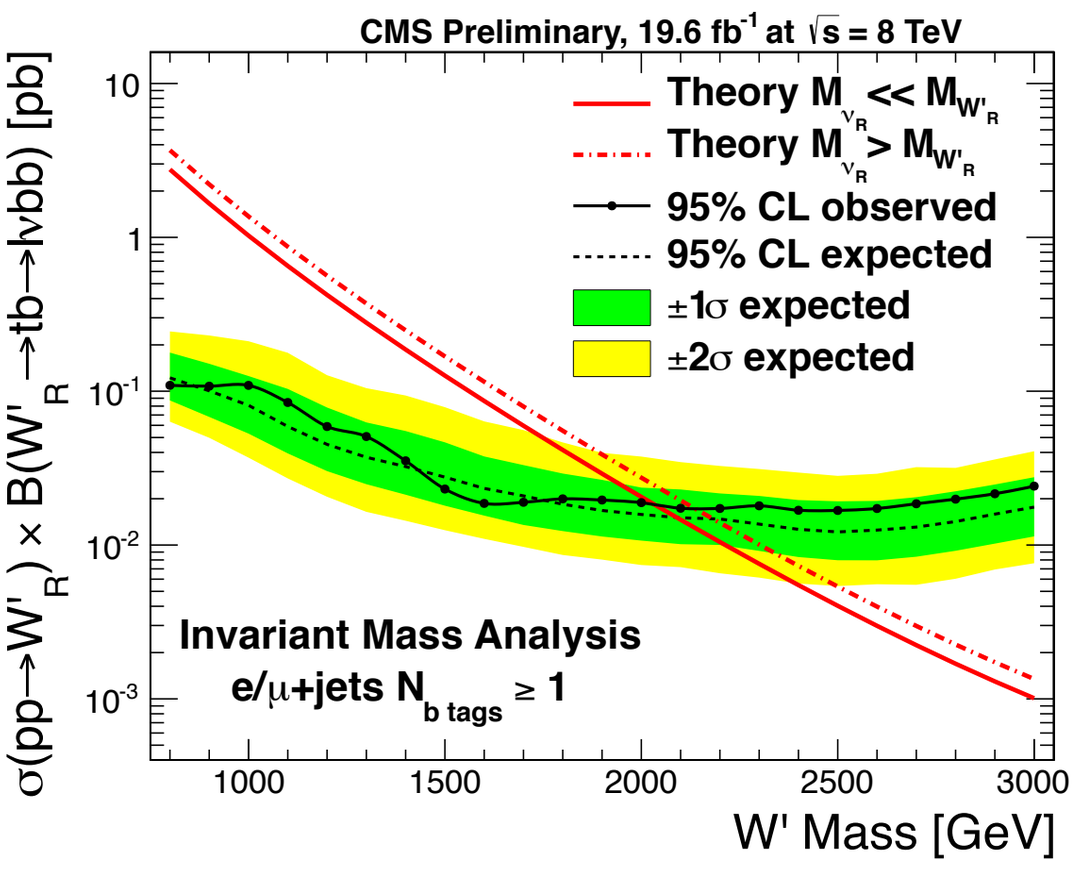
CMS B2G-12-010-pas

- To reconstruct the W' mass:
  - Start by reconstructing the W boson with the lepton and MET
  - Reconstruct top quark from:
    - With best jet which forms a W+jet mass closest to 172.5 GeV
  - Use the highest p_T jet remaining after the top quark reconstruction (jet2)
    - Combine top quark and jet2 to make the W' mass

Search for W' as a top-bottom resonance

- Top and W+jets backgrounds are normalized and corrected using data-driven techniques
- A W' with mass < 2 TeV is excluded at 95 % confidence

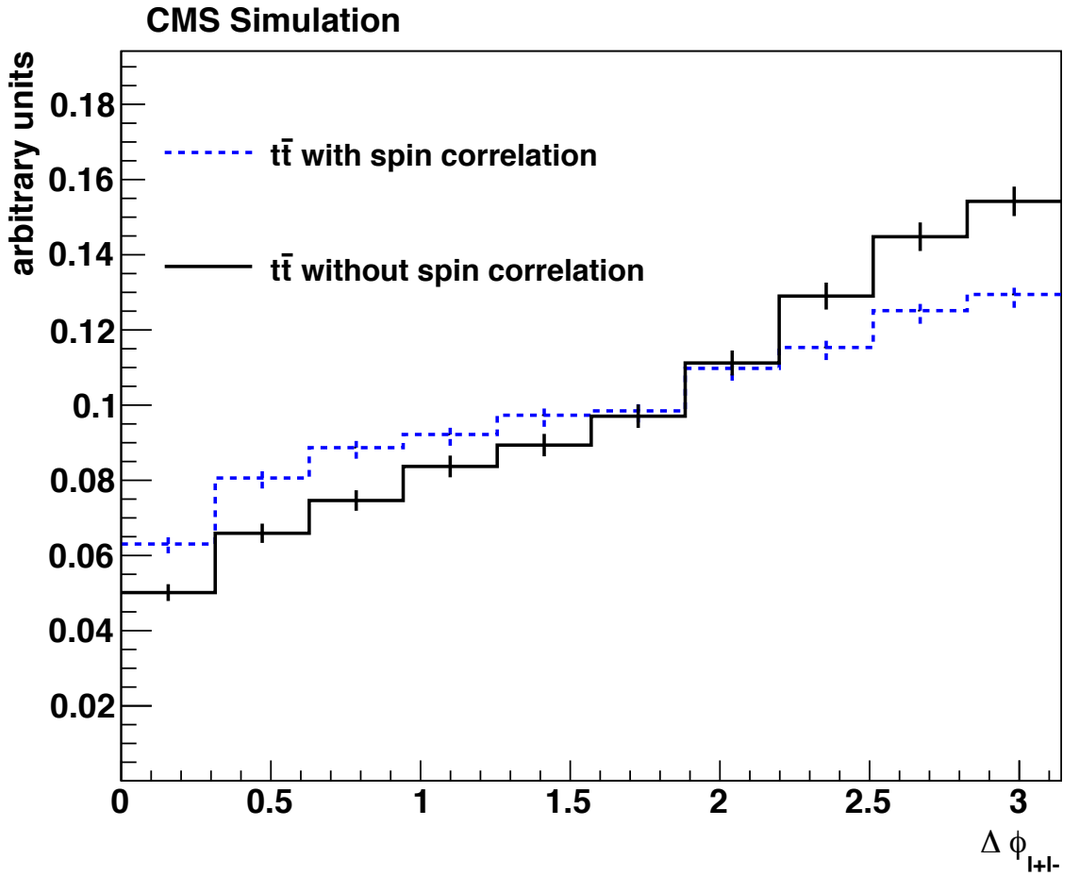




CMS B2G-12-010-pas

Spin Correlations @ LHC

- ATLAS and CMS have searched for $t\bar{t}$ dileptonic decays for spin correlations
- At the LHC $t\bar{t}$ production is dominated by like-helicity gluon pairs
- At higher invariant mass, $t\bar{t}$ production switches to unlike-helicity
- The correlation in the spins can be reconstructed looking at the $\Delta\phi(l^+,l^-)$
- CMS has used 4.9 fb^{-1} @ 7TeV;
  ATLAS has used 2.1 fb^{-1} @ 7TeV
- Both look for ee, eμ, and μμ pairs, and require at least 2 jets and 1 b-tag
- the ee and μμ events require MET/Mass cuts to discriminate against Drell-Yan



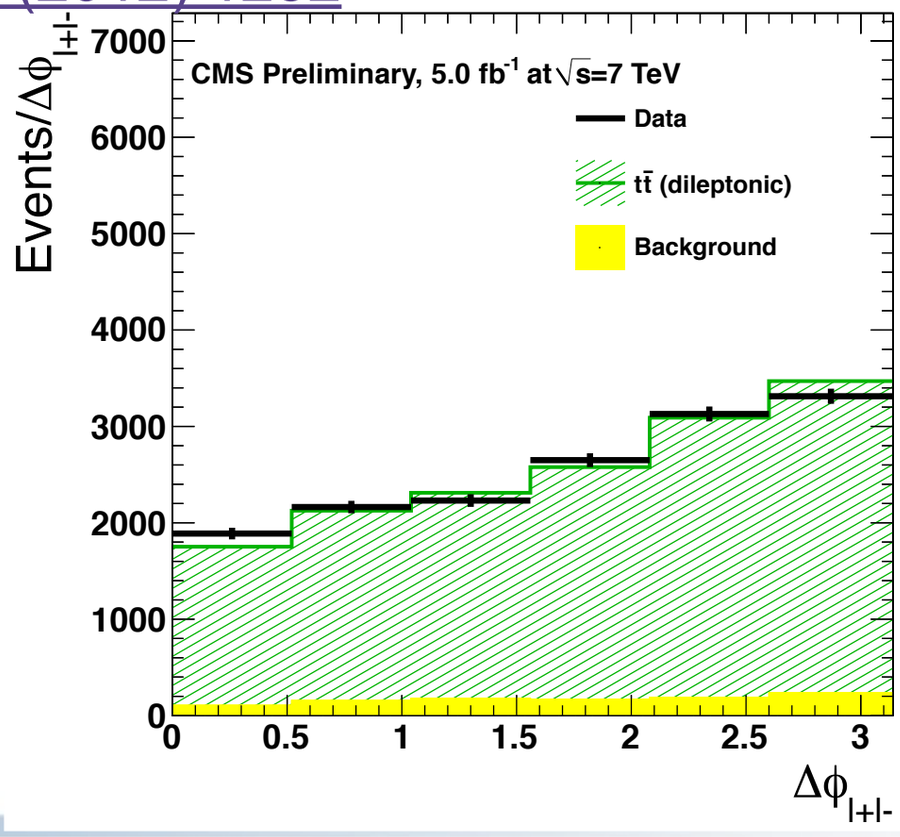
CMS/TOP-12-004-pas

ATLAS/Phys. Rev. Lett. 108, 212001 (2012)

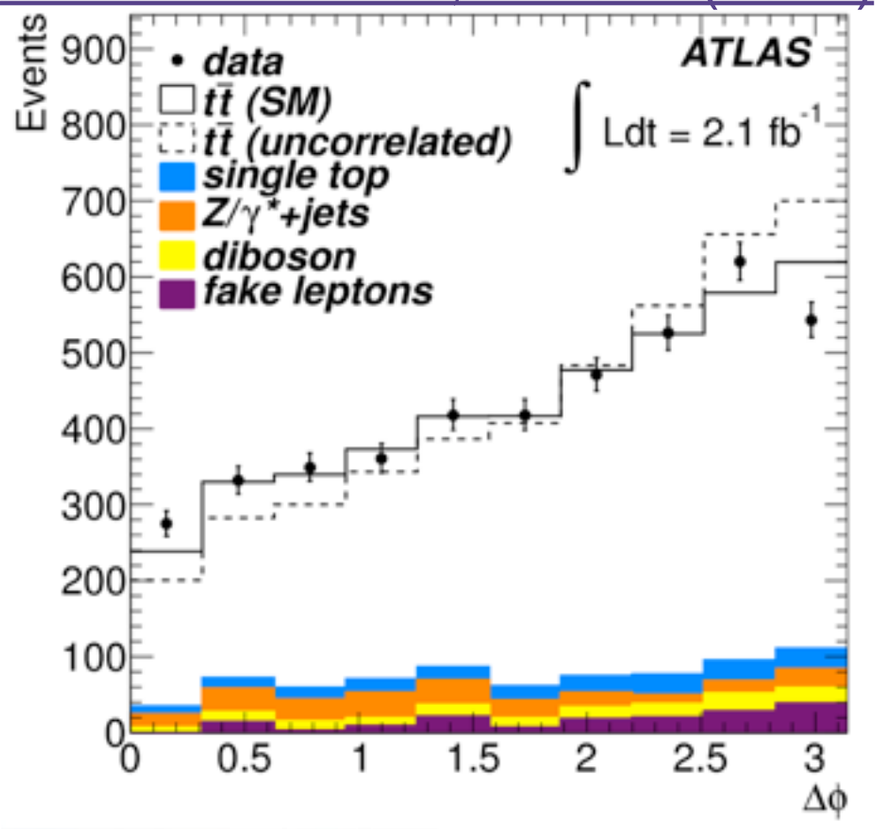
Spin Correlations @ LHC (II)

- A binned likelihood fit is used on the $\Delta\phi(l^+,l^-)$ distribution
  - Looking for the fraction of correlated vs. uncorrelated spin composition, f^{SM}
  - f^{SM} measures how similar to SM predictions the spins are correlated
  - If $f^{SM} = 0$, this would imply the spins are uncorrelated
  - If $f^{SM} > 1$ the spins would be more correlated than the SM
- ATLAS: $f^{SM} = 1.30 \pm 0.14(stat) \pm 0.27(syst)$; CMS: $f^{SM} = 0.74 \pm 0.08(stat.) \pm 0.24(syst.)$.
  - Both are consistent with the SM
- Can use f^{SM} to translate into an asymmetry measurement as well

CMS Phys. Lett. B718 (2012) 1252

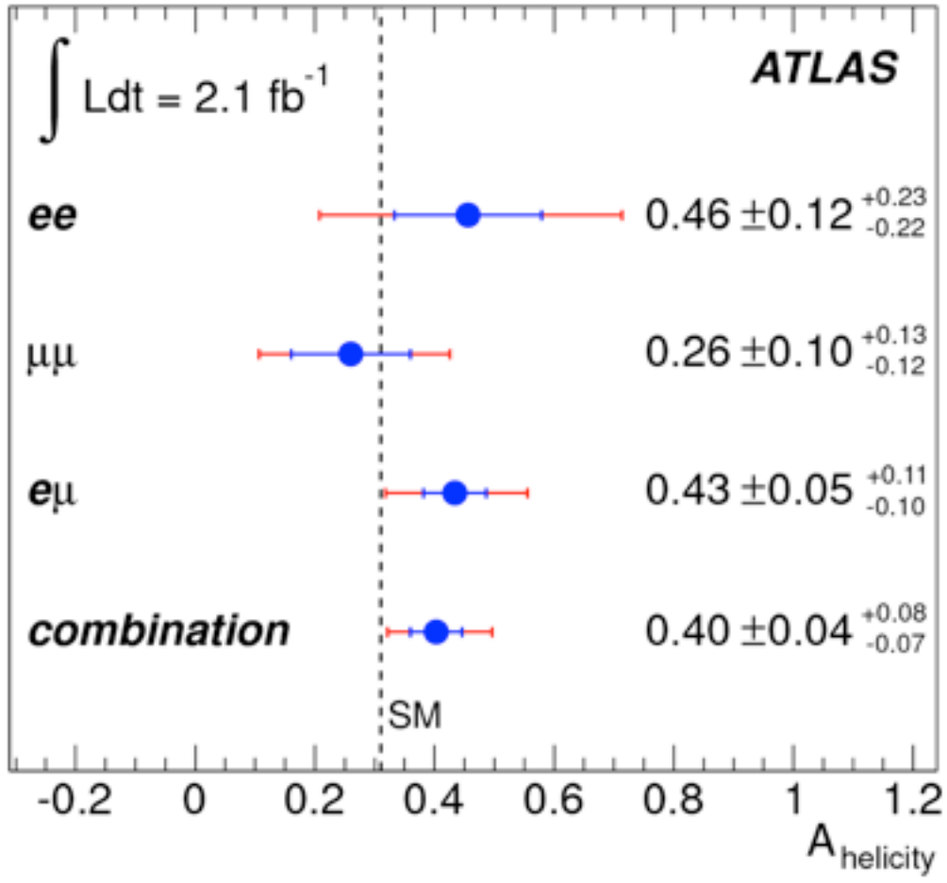


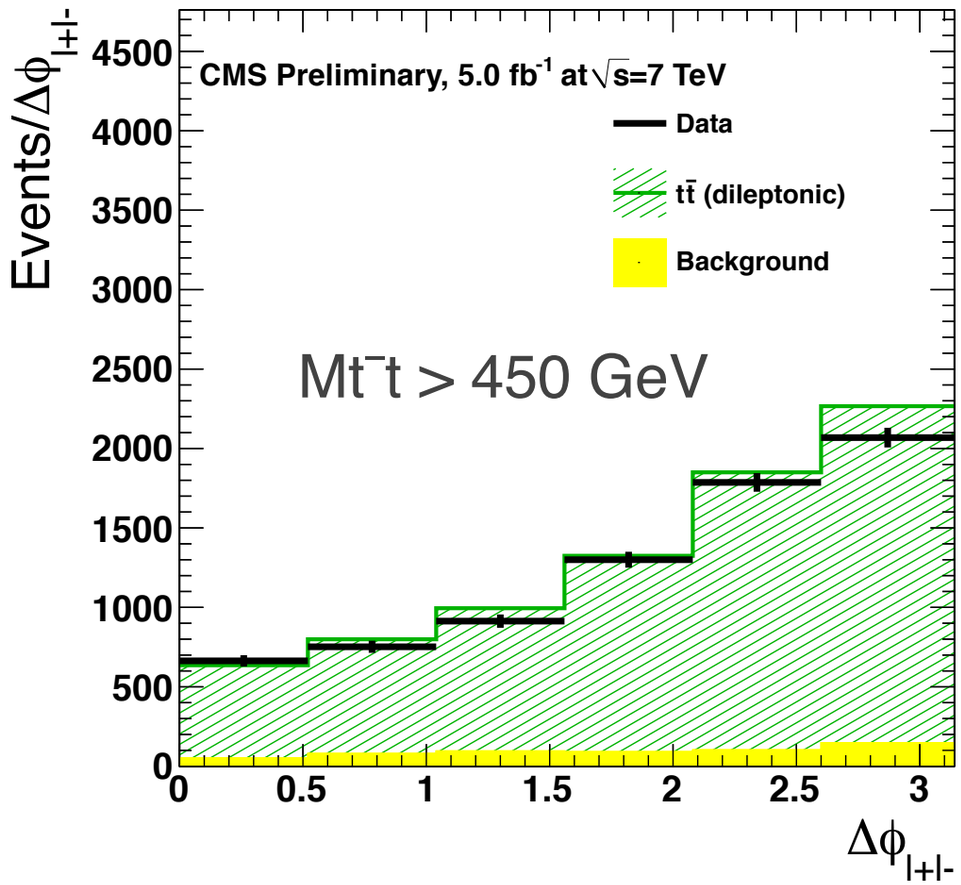
ATLAS Phys. Rev. Lett. 108, 212001 (2012)



Spin Correlations @ LHC (III)

- Using the relation $A_{Helicity} = A_{Helicity}(SM) * f^{SM}$
- CMS: $A_{helicity} = 0.24 \pm 0.02(stat.) \pm 0.08(syst.)$
- ATLAS: $A_{helicity} = 0.40 \pm 0.04\ (stat) +0.08\ (sys.)$
- Standard Model (NLO) prediction* : 0.31
- CMS looks at the asymmetry as a function of $M(t^{-}t)$
- $A_{\Delta\phi}(M(t^{-}t) > 450\ GeV) = - 0.378 \pm 0.019$
- SM $(M(t^{-}t) > 450\ GeV)$ prediction: -0.384 ± 0.003





Both Measurements are Consistent with the Standard Model

- W. Bernreuther and Z.-G. Si, "Distributions and correlations for top quark pair production and decay at the Tevatron and LHC", Nuc. Phys. B 837 (2010) 90

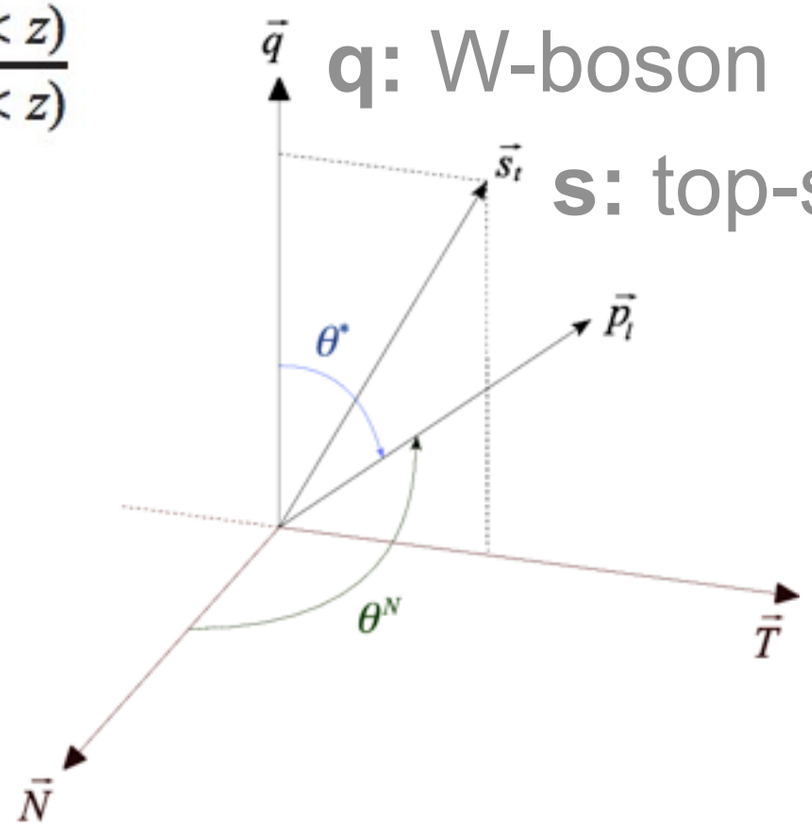
Search for CP violation in Single Top

- CP violation is thought to be the source of the Baryon asymmetry
- But known sources (b hadrons, Kaons) of CP violation, too small for this

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{W}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} + \mathrm{h.c.}$$

$$A_z \equiv \frac{N_{\mathrm{evt}}(\cos\theta > z) - N_{\mathrm{evt}}(\cos\theta < z)}{N_{\mathrm{evt}}(\cos\theta > z) + N_{\mathrm{evt}}(\cos\theta < z)}$$

- **s x q** defines **N**
- Use $\cos(\theta^N)$ as the discriminant
- Can relate $\cos(\theta^N)$ to A_z to $\mathrm{Im}(g_R)$



q: W-boson

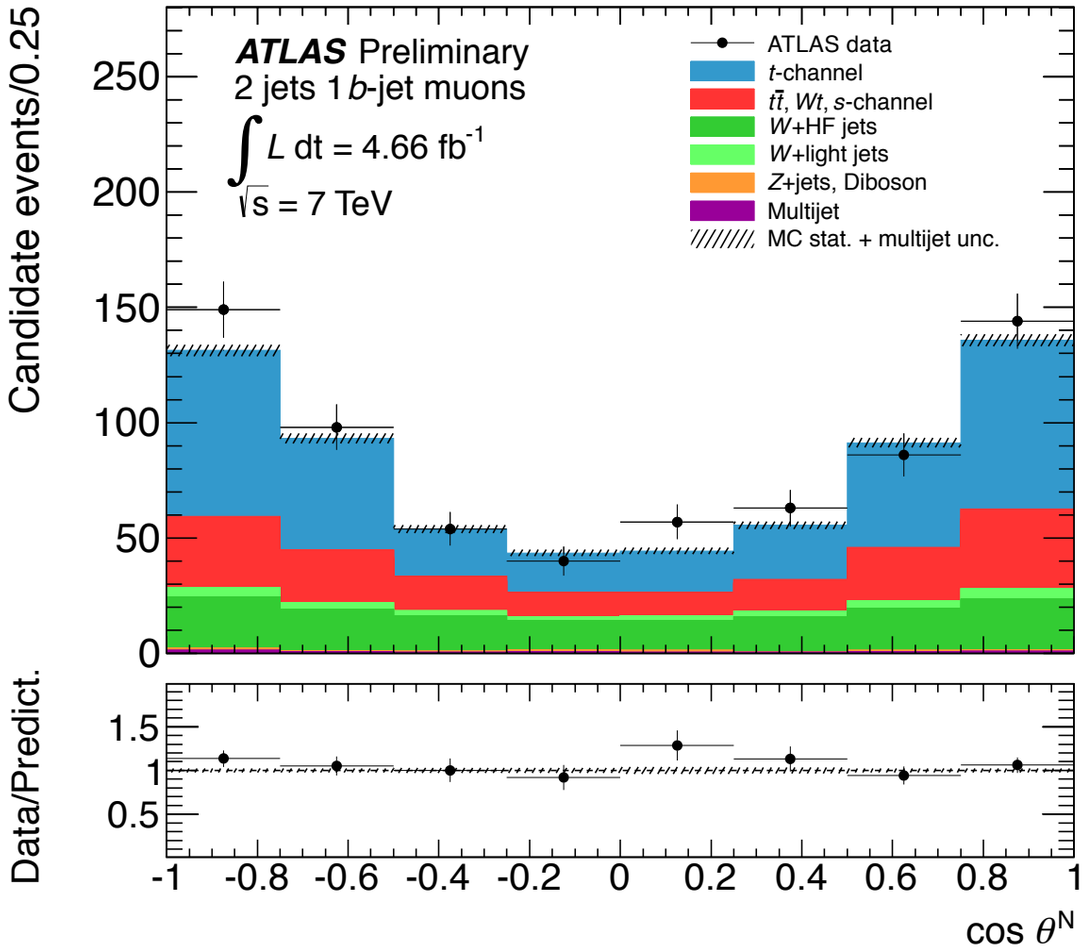
s: top-spin

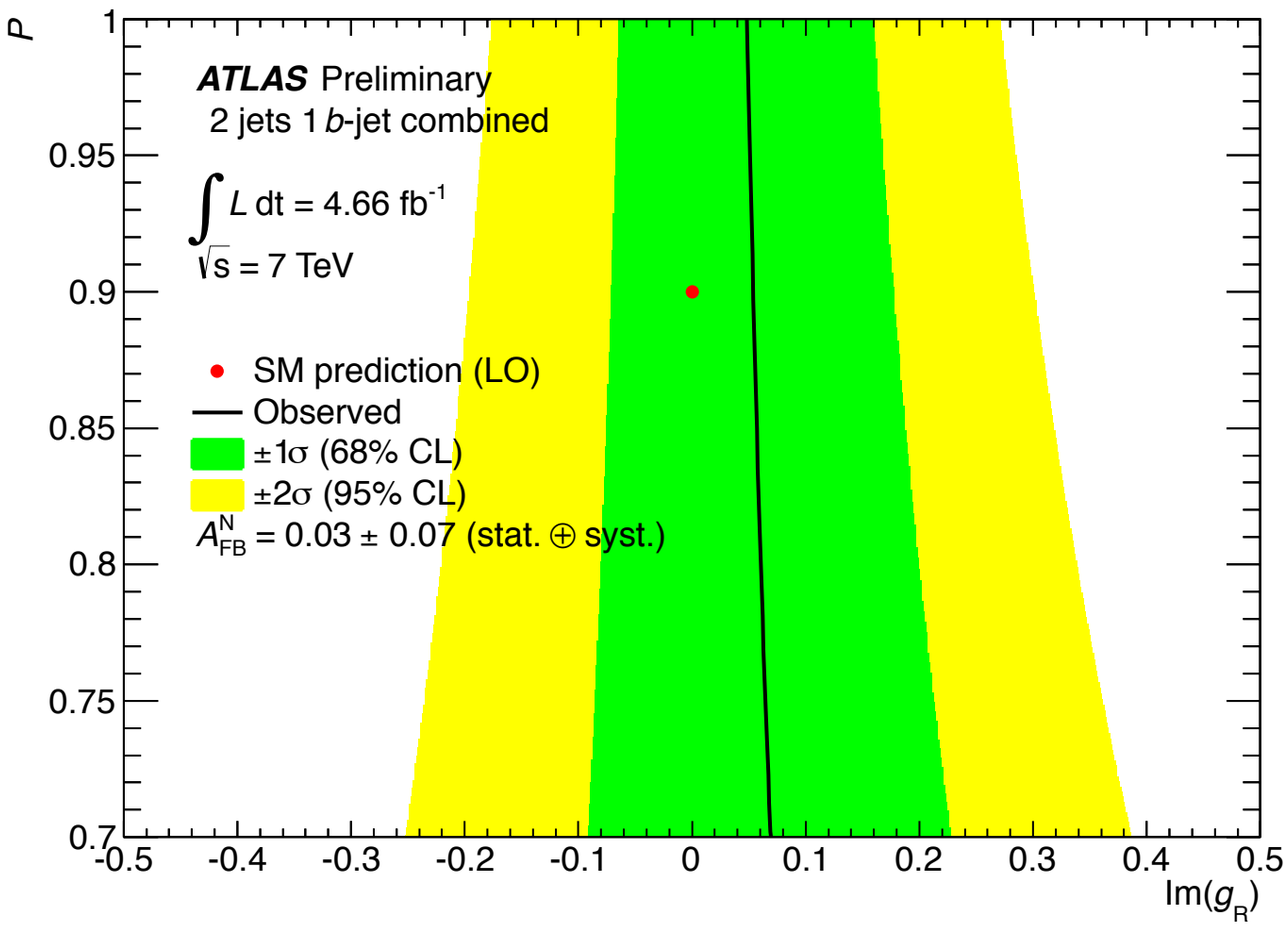
See Kevin Sapp's Talk from Yesterday

ATLAS-CONF-2013-032

Search for CP violation in Single Top (V)

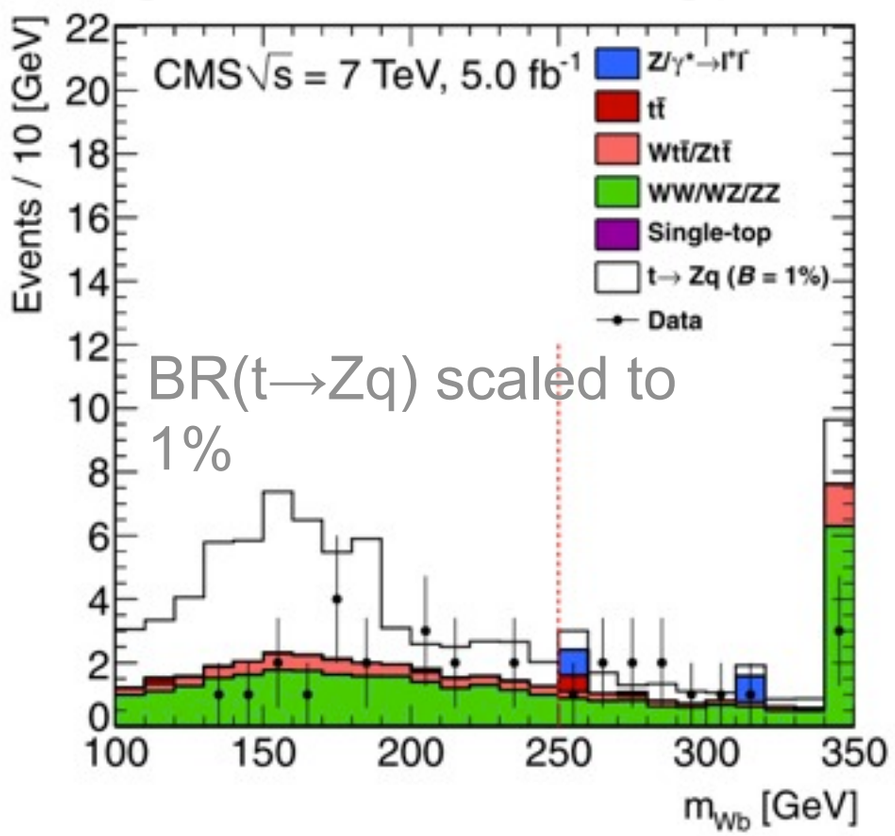
- Limits set on magnitude of $Im(g_R)$ function of top quark polarization
- Limits on $Im(g_R)$ vs. P is in agreement with SM expectations
- $A = 3/4\ P\ (N_R - N_L)$





Top (Pair) Production and FCNC

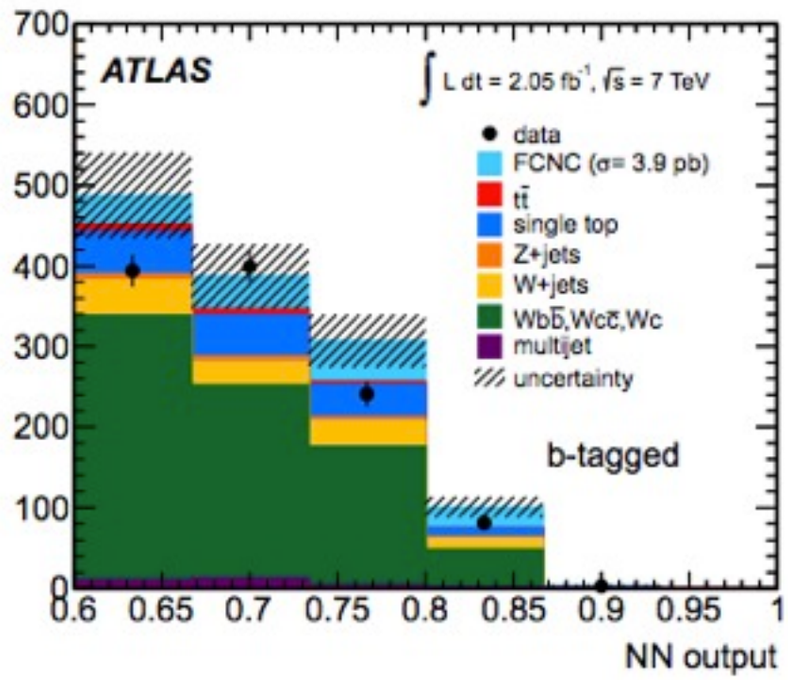
- CMS
- Searching for $t\bar{t}$ production; one top quark decays to a Z and a quark
- Search for 3 leptons: 2 from Z, 1 from W; and large MET, 2 jets
- 2 search regions: b-tagged jet OR large transverse energy S_T



- ATLAS
- Searches for single top signatures
  - One Lepton, MET, mT
  - One b-tagged jet
- Sets limits on K_{ugt}/Λ, K_{cgt}/Λ

$$\mathcal{L}_{\text{eff}} = g_s \sum_{q=u,c} \frac{K_{qgt}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + h.c.$$

- Uses a NN to search for FCNC

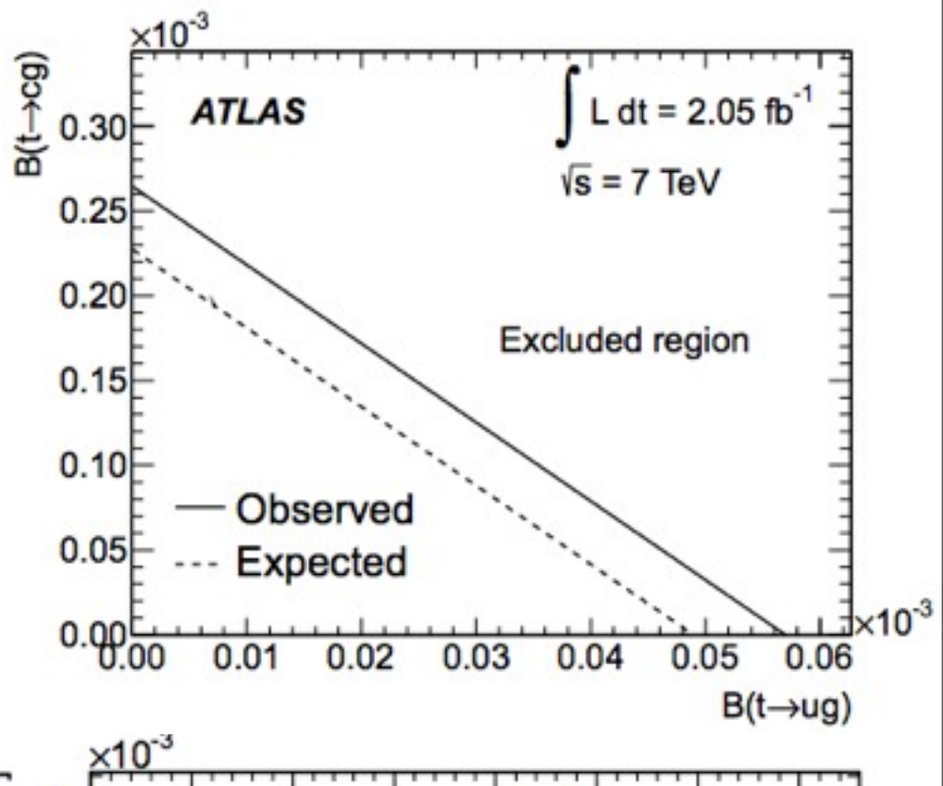


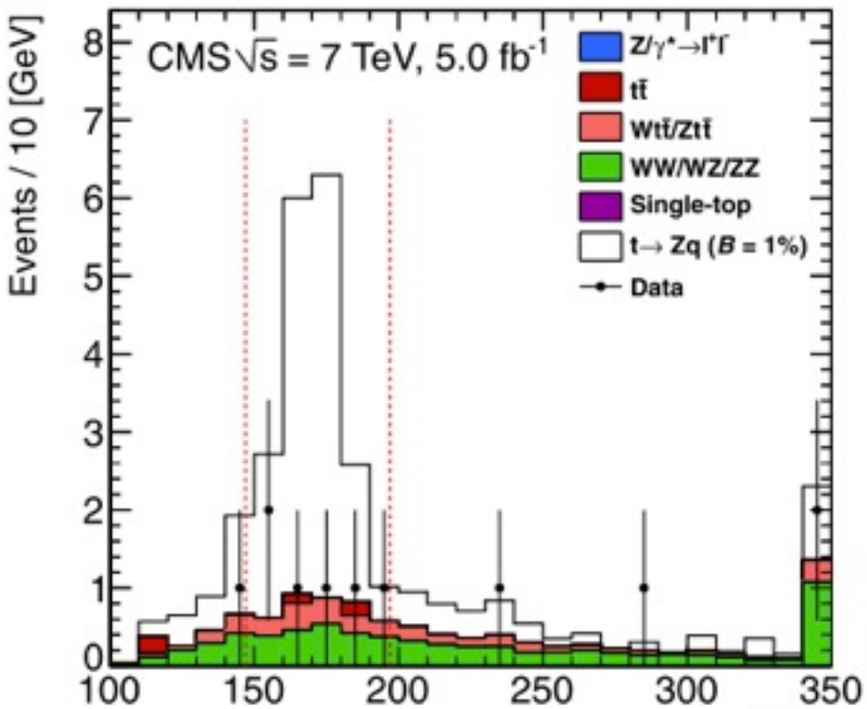
FCNC top is expected to have low p_T

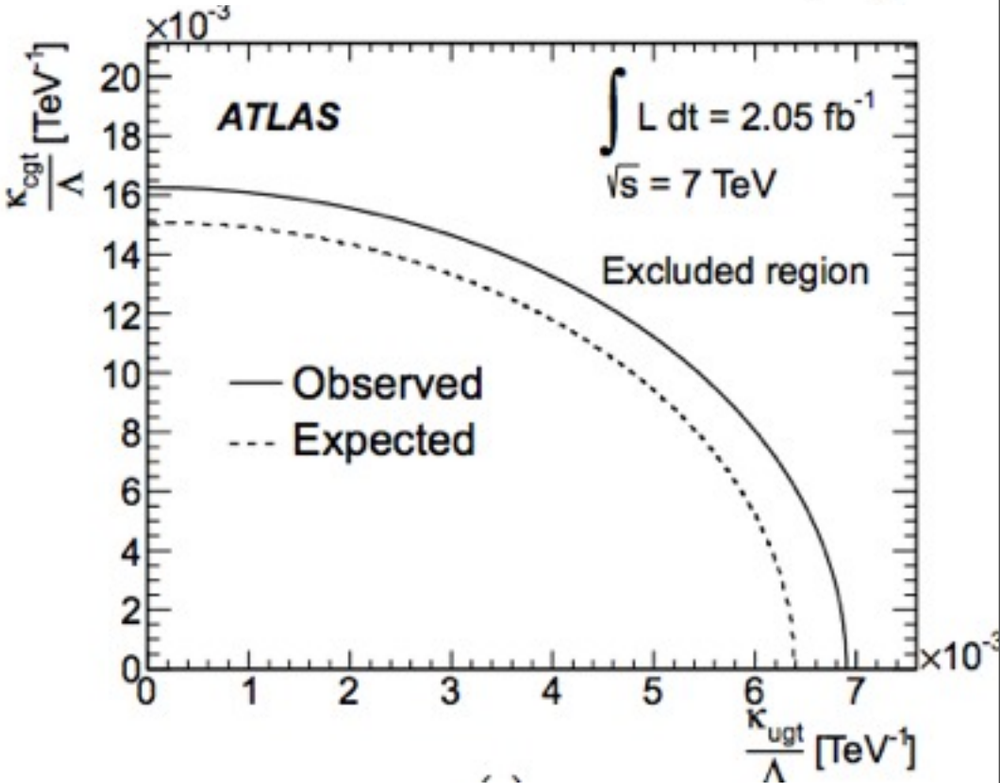
high pT W, b, and back-back

Top (Pair) Production and FCNC

- No excesses of t→Zq observed at CMS
  - BR(t→Zq) < 0.21%
- No excess of g→t c or u observed at ATLAS
  - BR(t → ug) < $5.7 \cdot 10^{-5}$, BR(t → cg) < $2.7 \cdot 10^{-4}$
  - $\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3}$ TeV^{-1},
  - $\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2}$ TeV^{-1}





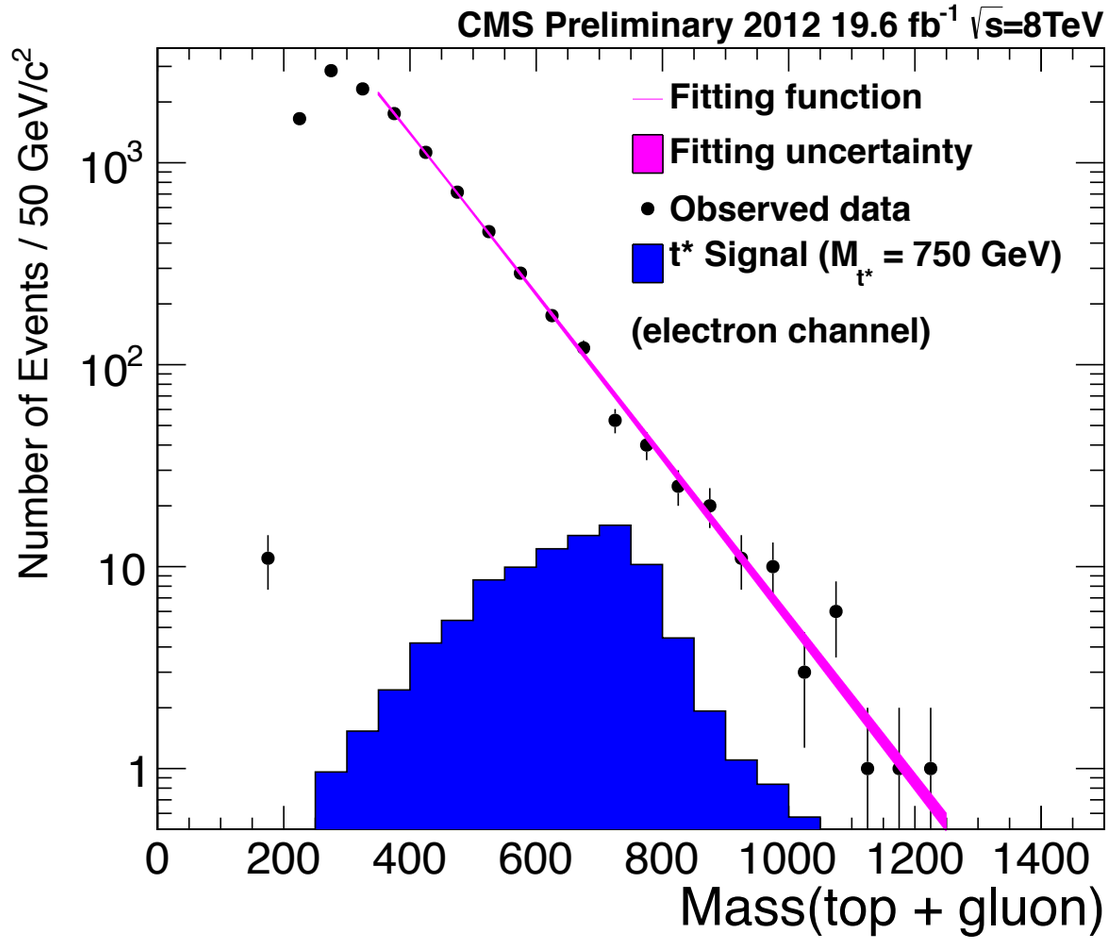


CMS Phys. Lett. B718 (2012) 1252

ATLAS Physics Letters B 712 (2012) 351-36

Search for pair-produced excited top pairs

- The excited top (t*) decays exclusively to a top quark, and gluon
  - Pair production of t*, and at least one top's W decays to an e or μ
- The search looks for a lepton+MET + at least 6 jets (>0 b-tagged jets)
  - Chi-squared value to find best W candidate, top candidate and remaining jets are used to find t* (top +gluon) candidates
  - In each event:
    - $M(l\nu) = M(q\bar{q}) = M_W$
    - $M(l\nu b) = M(q\bar{q}b) = M_{top}$
    - $M(l\nu bg) = M(q\bar{q}bg) = M_{top+g}$
- Using a data-driven background shape to search for a t* bump

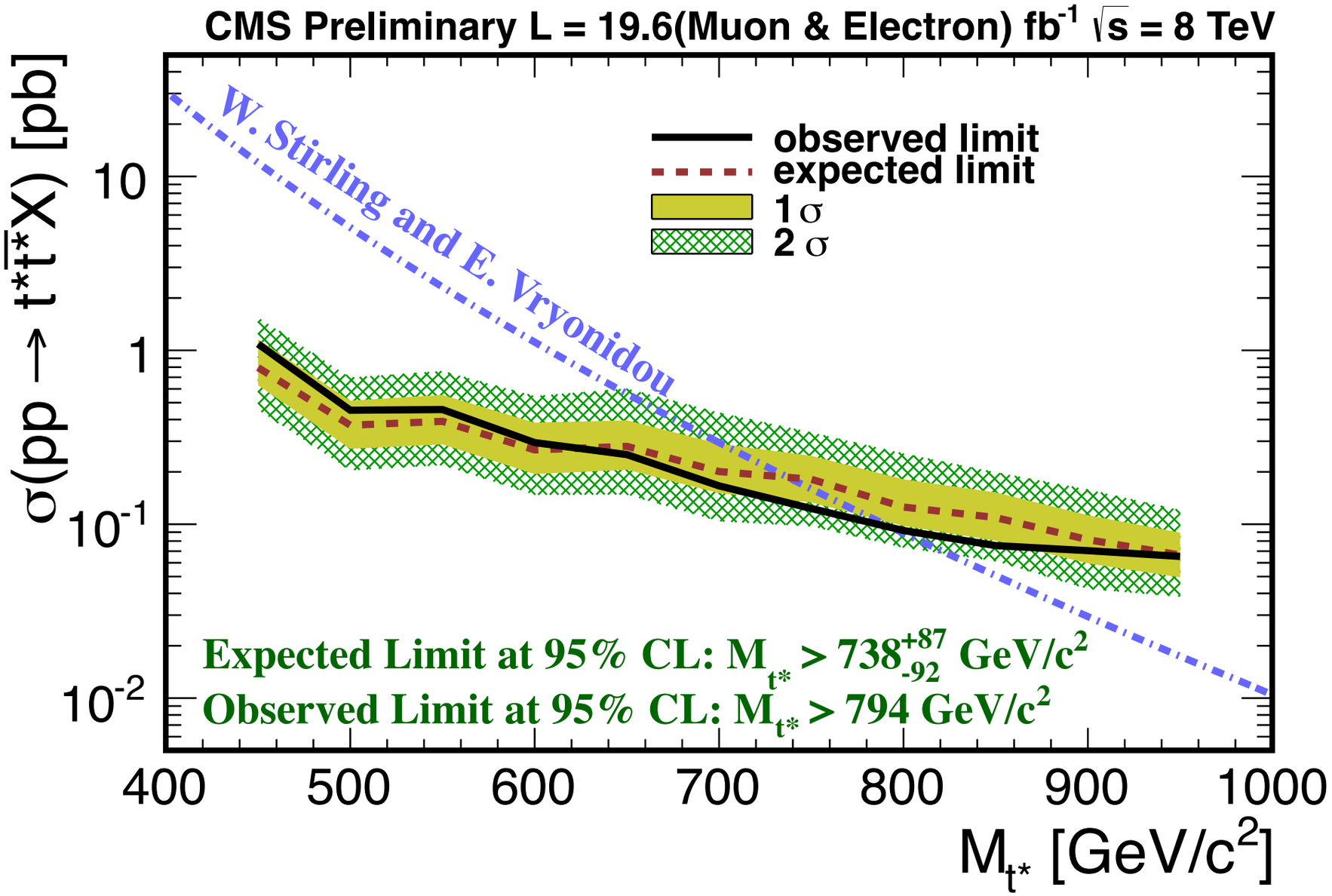


$$f(x) = \frac{a}{1 + e^{\frac{x-b}{c}}}$$

CMS/B2G-12-014

Search for pair-produced excited top pairs

- No excess is observed over the background function and limits are set
- Excited top quark (t*) is excluded with mass < 794 GeV



CMS/B2G-12-014

Conclusions

- Many searches are being conducted to better understand the top quark's properties

- ATLAS and CMS have searched for New Physics in many of tops' properties
  - Angles, bumps, jet-masses

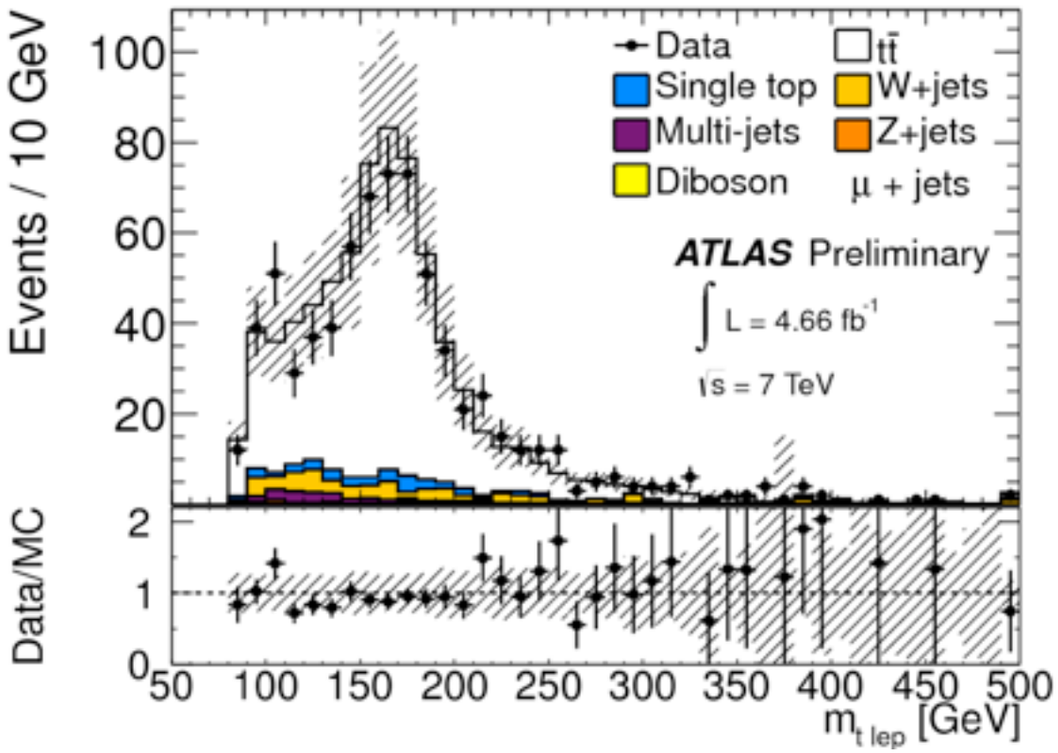
- Searches for top-bjet and $t\bar{t}$ resonances are probing multi-TeV masses
  - No excesses seen so far...more papers and more energy are on the way

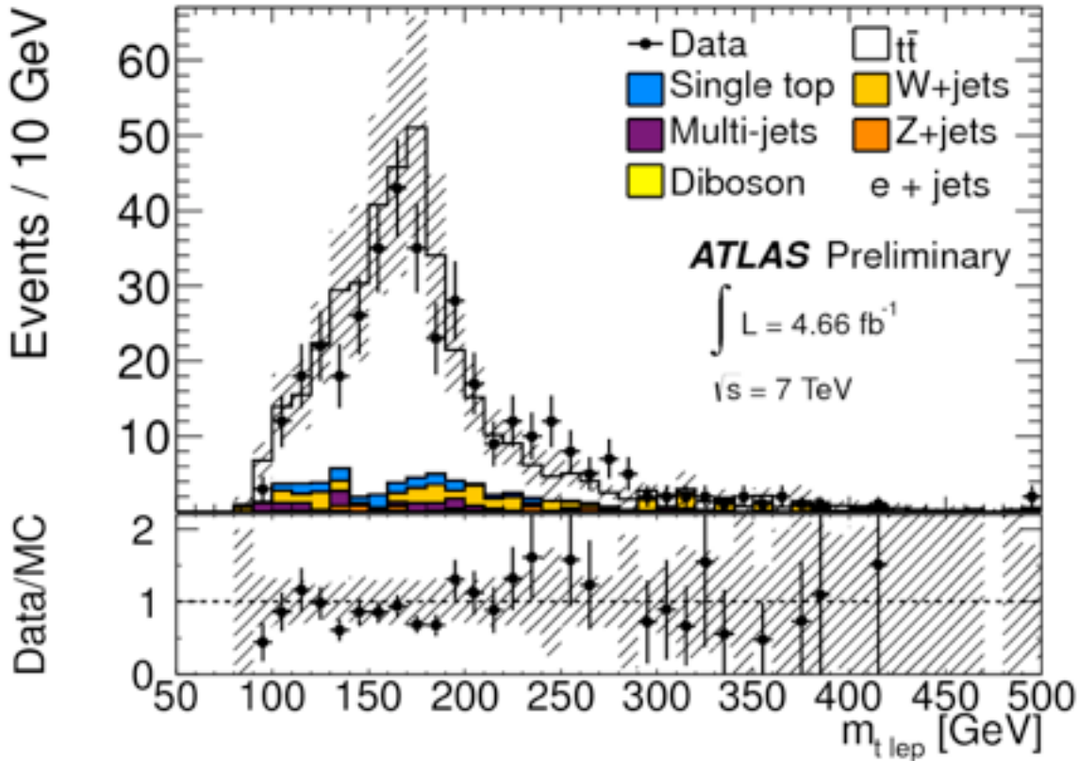
- Spin Correlations of the $t\bar{t}$ system have been measured to be in agreement with the Standard Model
  - Repeating these analyses on the full 2012 dataset would be interesting

- First search for possible CP violation with single top process
  - Results in agreement with SM, but more data could be insightful
- 8TeV search for excited top quarks set limits

Boosted Selection Mass of the Top Quark

- Using a W-mass constraint, reconstruct the top quark mass in both the muon and electron channel

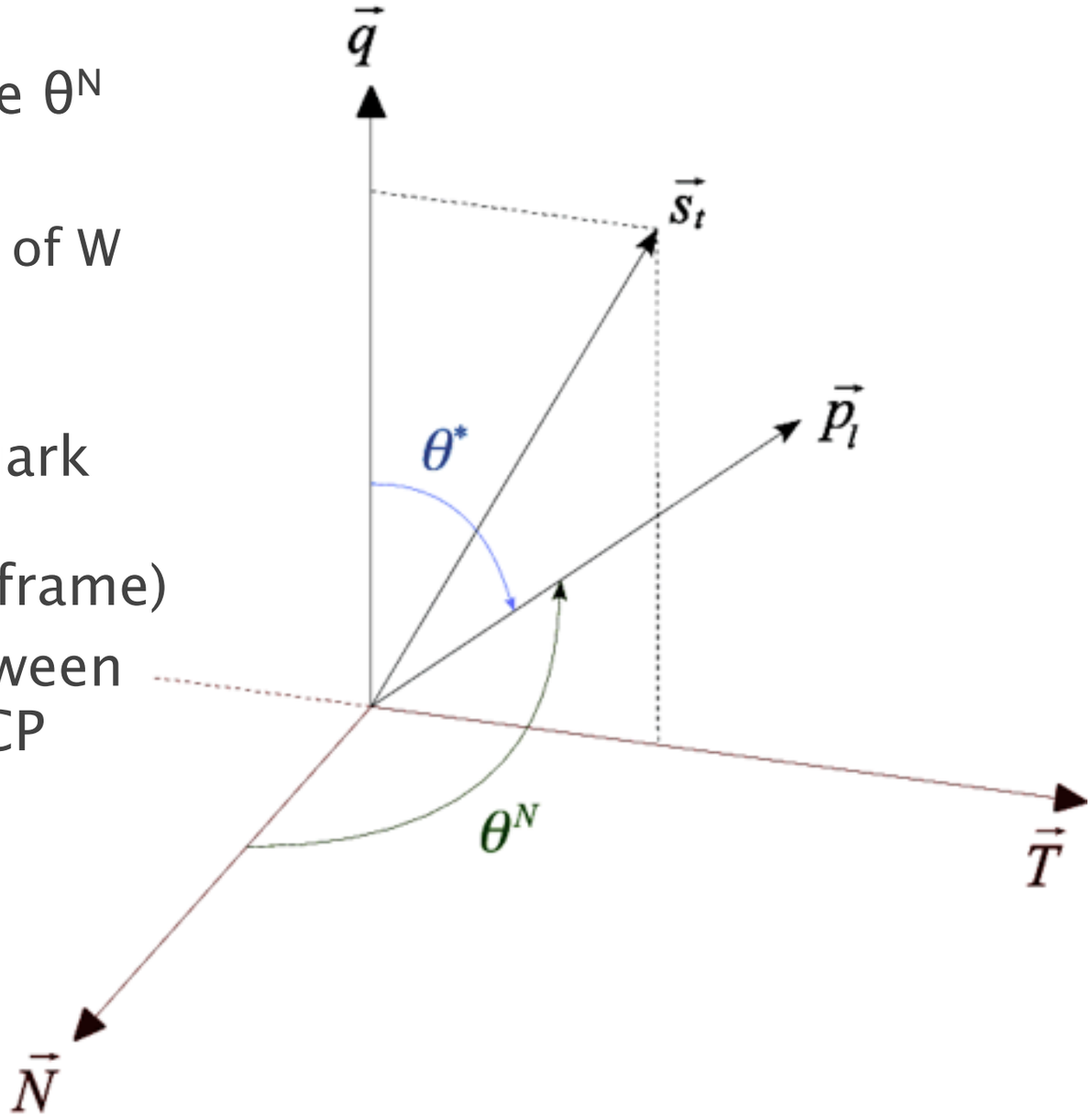




ATLAS-CONF-2012-136

Search for CP violation in Single Top (II)

- Most sensitive angle is found to be θ^N
- Which is defined by:
  - **Normal (N)** = $\mathbf{s}_T$ x **q** (momentum of W boson)
  - **Transverse** = **q** x **N**
- $\mathbf{s}_T$ is the spin-vector of the top quark (also the 3-vector of the spectator quark in top quark rest frame)
- Can use approximate relation between A_{FB}^N and Im(g_R) to set limits on a CP violating term



Search for CP violation in Single Top (III)

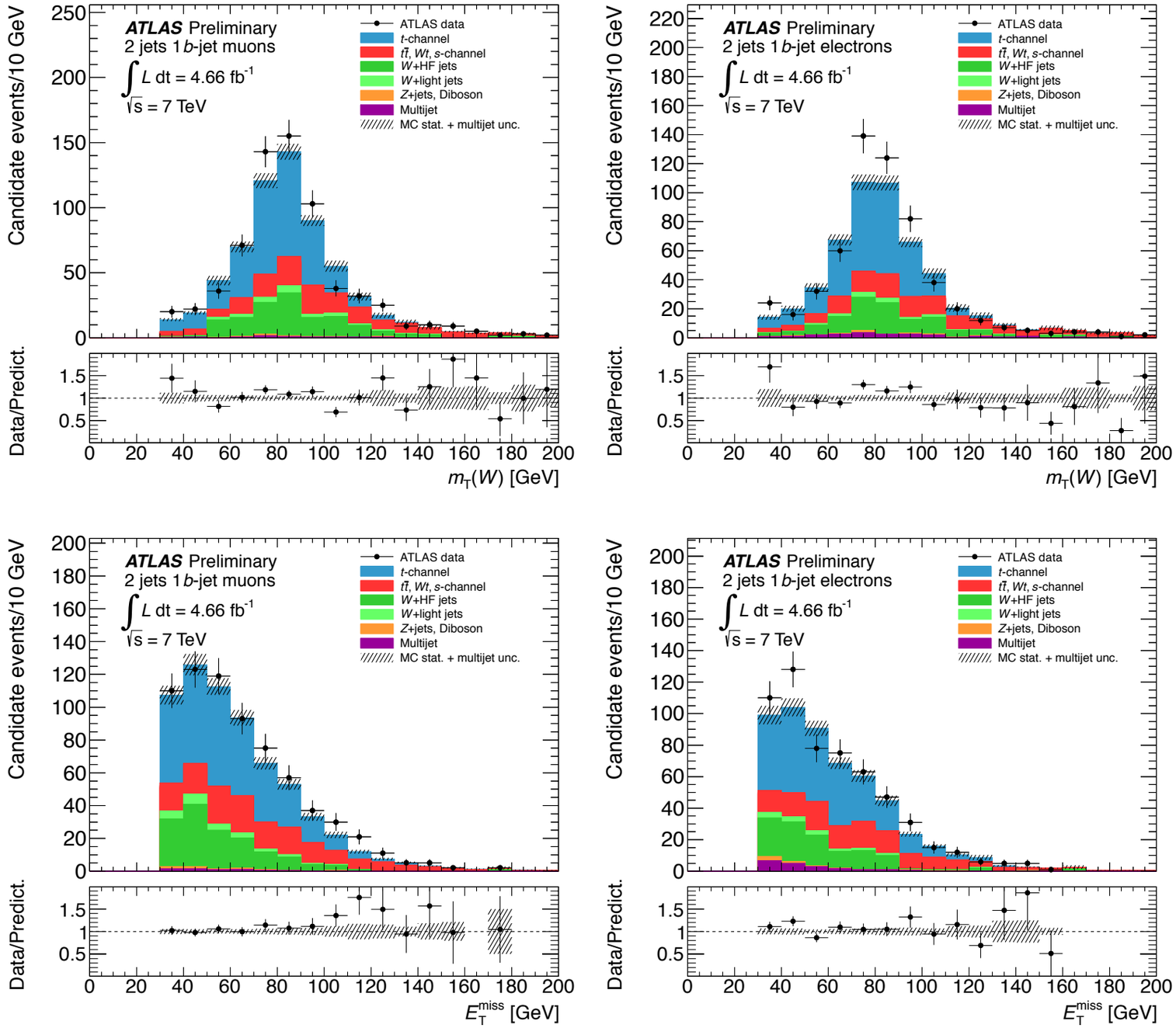
- Event selection, one isolated e or μ, with p_T > 25 GeV
  - electrons $|\eta|$ < 2.47, excluding 1.37<$|\eta|$< 1.52
  - muons $|\eta|$ < 2.5
- Exactly 2 jets with p_T > 30 GeV
  - If 2.75<$|\eta|$ < 3.5, p_T> 35 GeV
  - Exactly one b-tagged jet (55% efficiency) w/ $|\eta|$ < 2.5
  - Exactly one non-b-tagged jet w/ $|\eta|$ < 4.5
- m_T and MET both greater than 35 GeV
- W mass used to determine the 4-vector of the neutrino to reconstruct the top quark 4-vector

To Focus in on Single Top

- H_T > 210 GeV, reconstructed top quark mass is between 150-190 GeV
- difference in η between b and light jet > 1.0

Search for CP violation in Single Top (IV)

- Missing-E_T and M_T well modeled
- Multijet background modeled using matrix method
- The W+HF jets background comes from theoretical predictions
- Then checked using control regions
  - reconstructed top quark mass outside window



Search for $t\bar{t}$ Resonances in ATLAS and CMS (II) (All Hadronic) (II)

- The backgrounds are derived using data-driven techniques
  - CMS calculates the mistag probability rate
    - looking for 2 jets which look like a top quark decay but fail top identification
    - look for a p_T>350 GeV, |rapidity| < 2.4 jet which passes top tagging
    - uses the mistag probability to weight event which enters their kinematic selections
  - ATLAS uses a 4x4 grid to estimate contamination in signal region P
    - Iterative approach start by using background dominated regions to calculate K and M
    - Use K and M from background predictions, and F to calculate background in P
    - Numerous background checks are compared and all are consistent