Top Quark Decay Properties

LHCP2017, May 15-20, 2017
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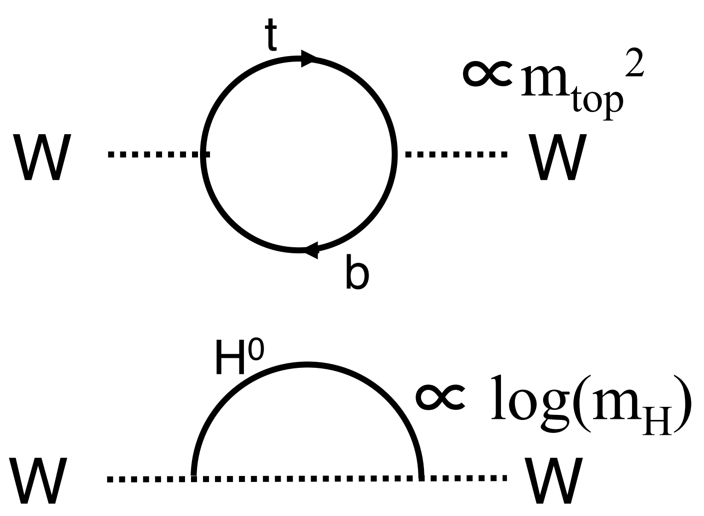
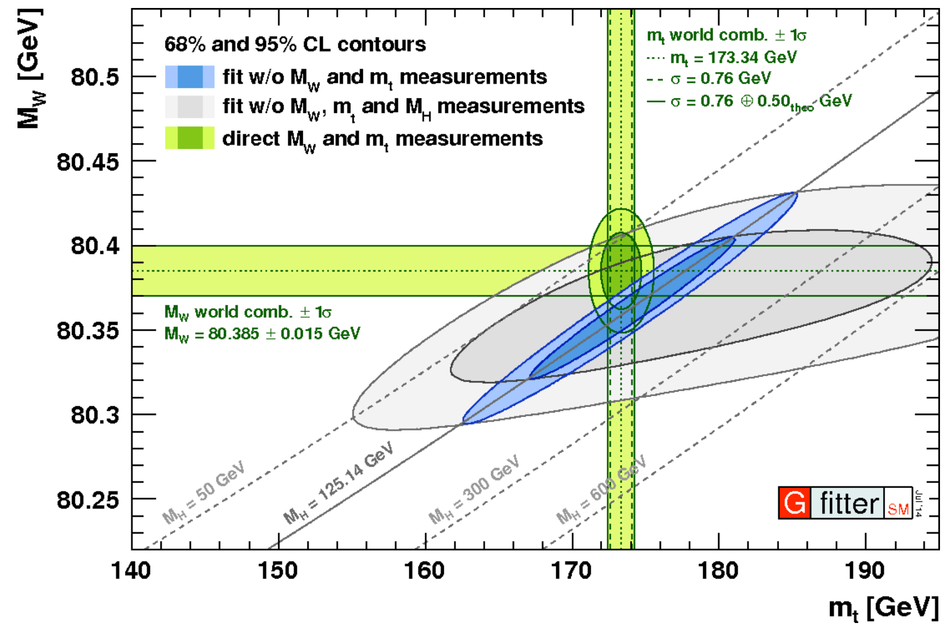
What's special with Top quark?

- Large coupling to the Higgs boson
- Constrains the Higgs mass along with W boson mass

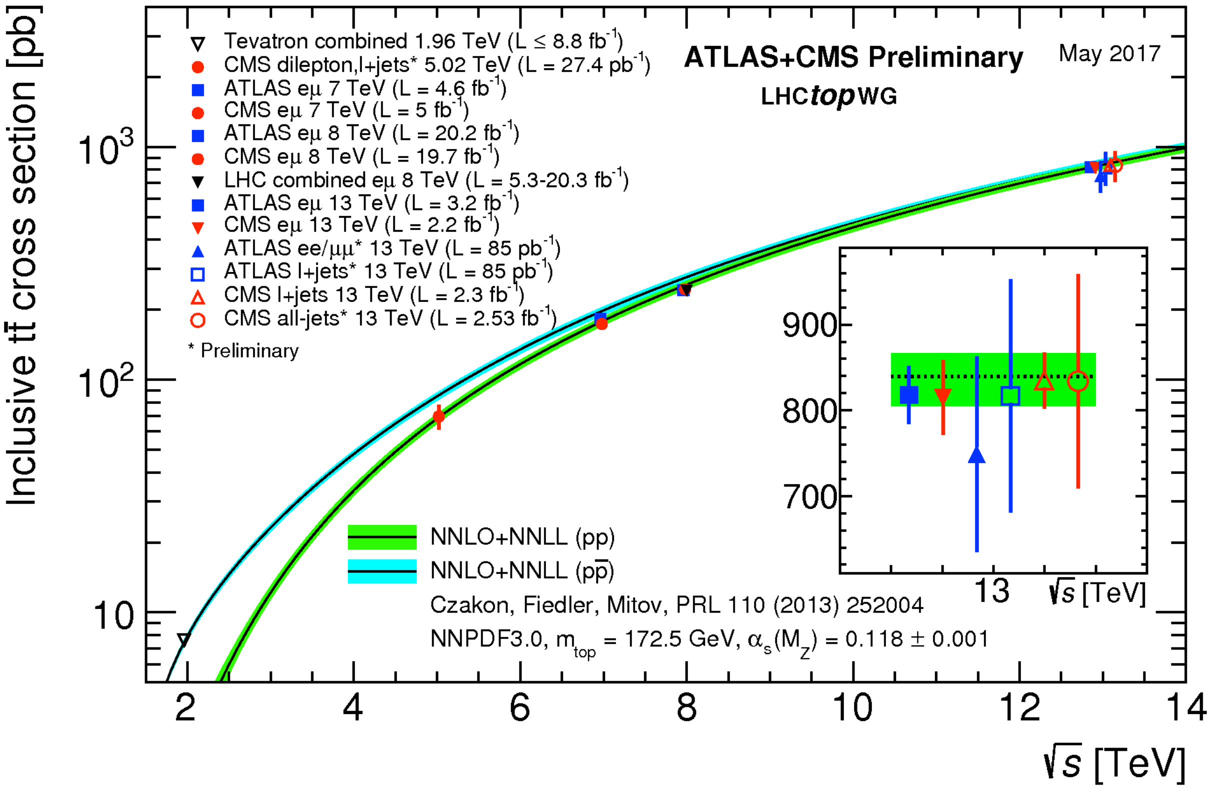
Eur. Phys. J. C 74, 3046 (2014)
arXiv:1407.3792 [hep-ph]

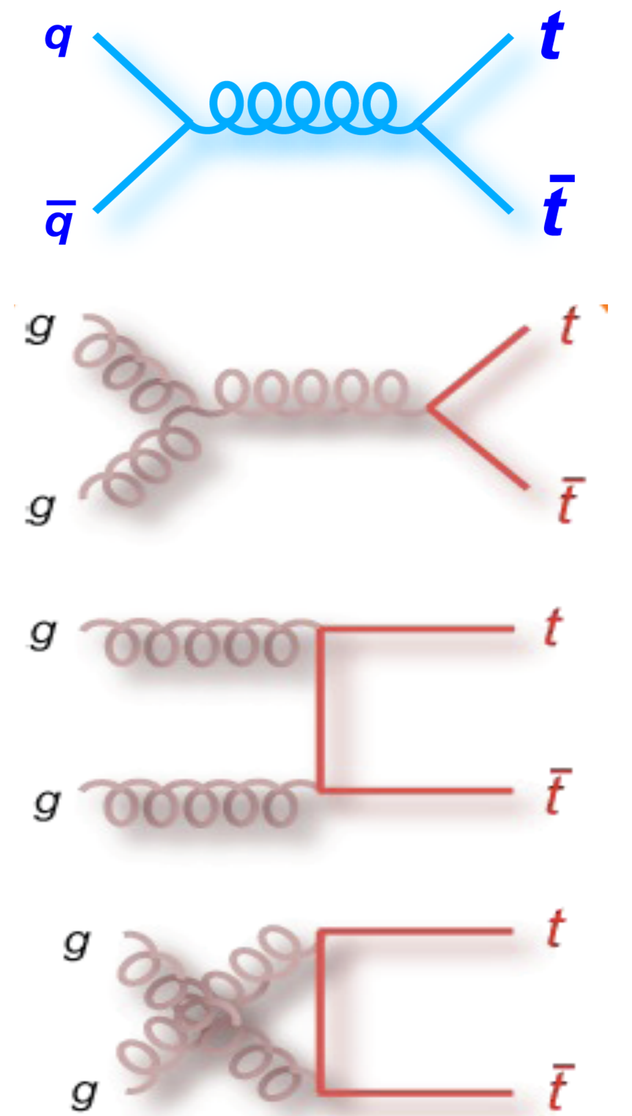




- Many new physics models result in same signature, e.g, SUSY "stop" can decay into top quark

Top pair production



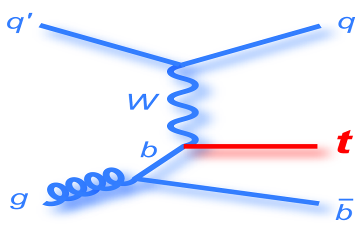


- **gg→ttbar is the dominant production mode**
  - **90% (gg) and 10% (qqbar) at √s=13 TeV for pp collisions**
- **All the measurements are in good agreement with the SM predictions at NNLO+NNLL**

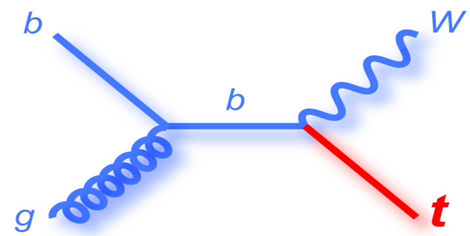
Electroweak Top Production

Single top-quark production via electroweak interaction, involving a *Wtb* vertex

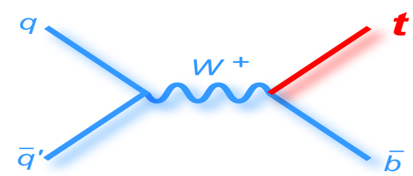
***t*-channel**



***Wt* channel**



***s*-channel**



NLO+NNLL with m_{top}=172.5 GeV

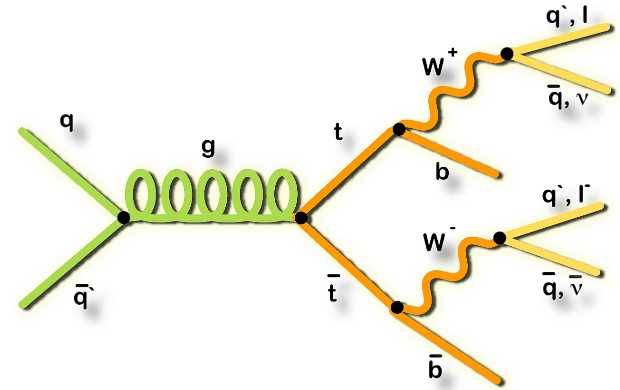
√s (pb)	σ (t-channel)	σ (Wt)	σ (s-channel)
8 TeV	84.69	22.37	5.24
13 TeV	216.99	71.7	10.32

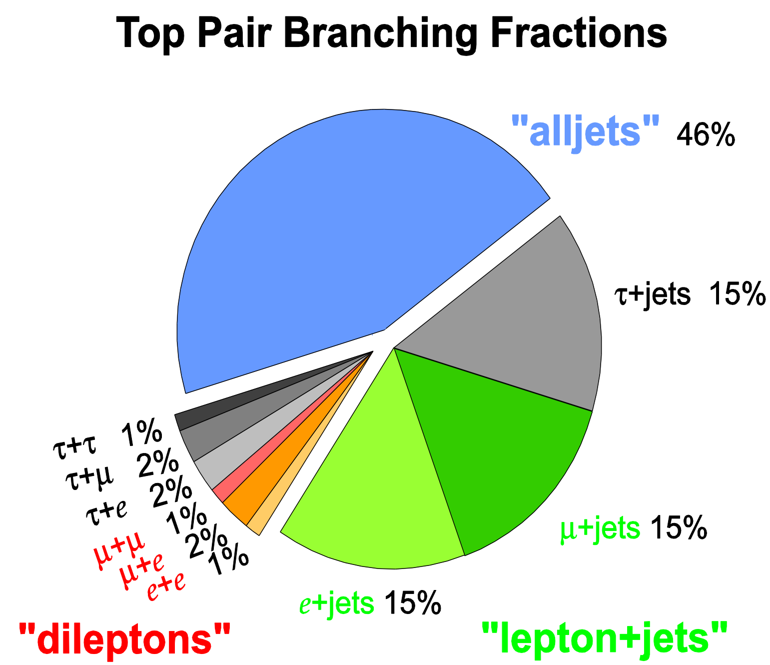
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

- ✧ Direct determination of the CKM Matrix element ($|V_{tb}|$)
- ✧ Background process for Higgs and BSM searches
- ✧ Major probe in BSM physics scenarios

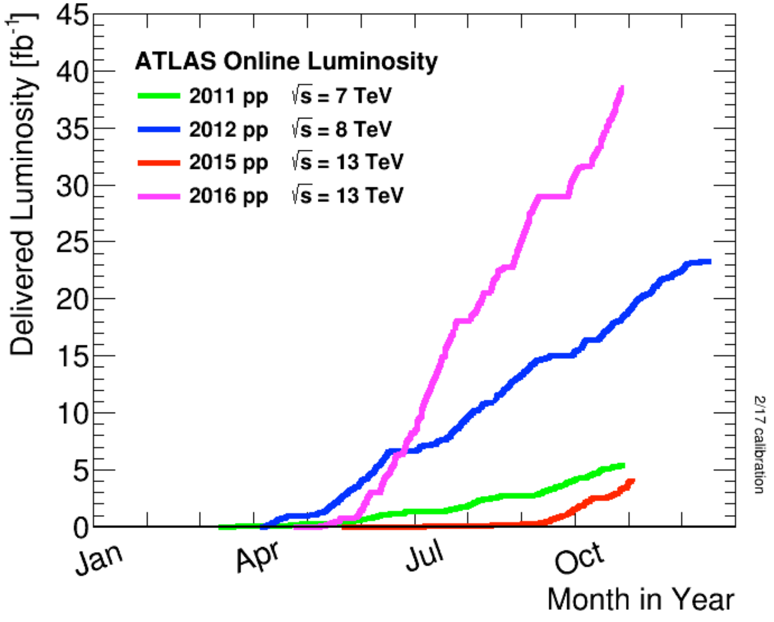
Decay of Top quark

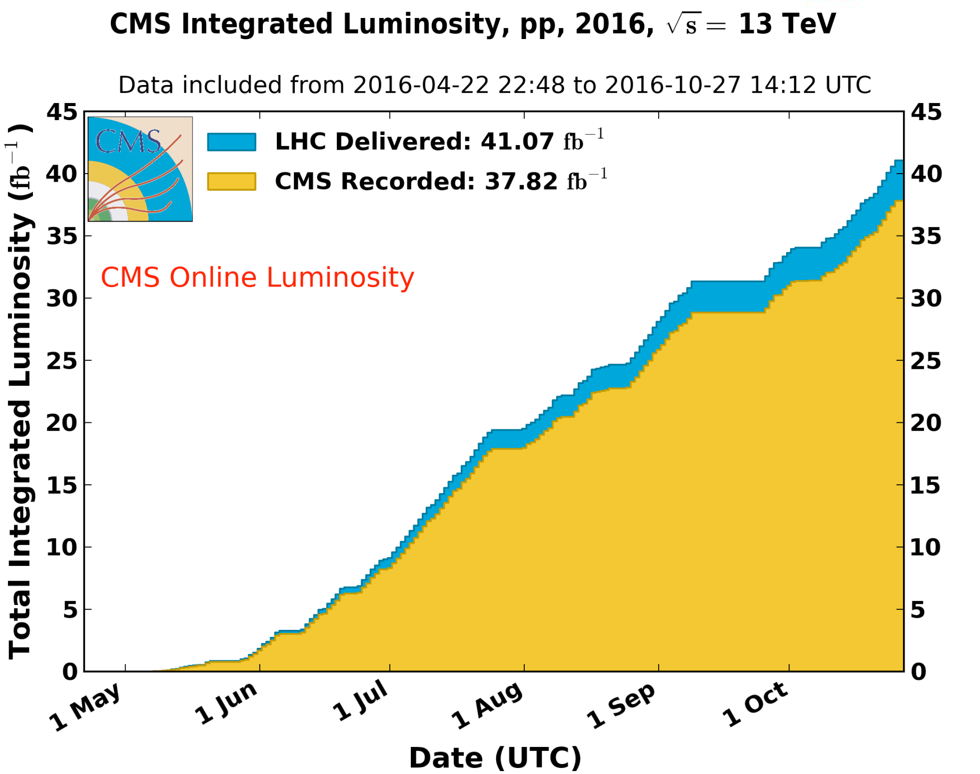
- SM Br(t→W⁺b)=100%
- Final states determined through the decay of W± bosons from top and antitop quarks.
  - All jets: $t\bar{t} \to bW^{+}\bar{b}W^{-} \to b\bar{b}q\bar{q}'q\bar{q}'$
    - **High branching ratio but large QCD background**
    - **≥ 6 jets, 2 b-jets**
  - **lepton+jets:** $t\bar{t} \to bW^{+}\bar{b}W^{-} \to b\bar{b}q\bar{q}'l^{-}\bar{\nu}$
    - Moderately high branching ratio but relatively low background
  - dilepton: $t\bar{t} \to bW^{+}\bar{b}W^{-} \to b\bar{b}l^{+}\nu l^{-}\bar{\nu}$
    - Low branching ratio but clean signal
- Similarly different final states for single top/ electroweak top production
  - Dilepton: $tW^{-} \to bW^{+}W^{-} \to bl^{+}\nu l^{-}\bar{\nu}$
  - Semileptonic s-channel: $t\bar{b} \to bW^{+}\bar{b} \to b\bar{b}l^{+}\nu$

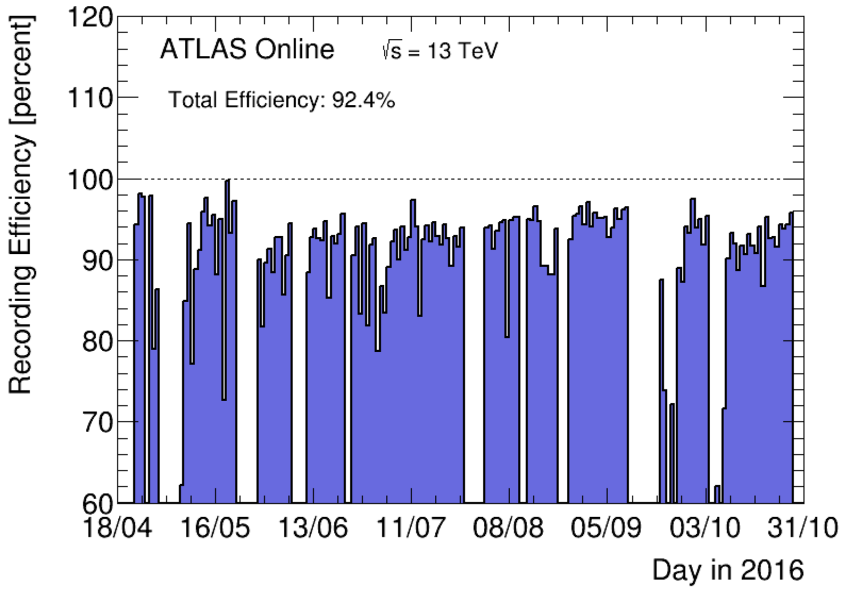




LHC Performance







- LHC Run I datasets at √s=7 TeV (2011) and 8 TeV (2012) have been fully analyzed
- LHC has been performing exceedingly well during Run 2 with delivered luminosity of >40 fb^{-1} in 2016
- Both ATLAS & CMS experiments have recorded data with ~92% efficiency

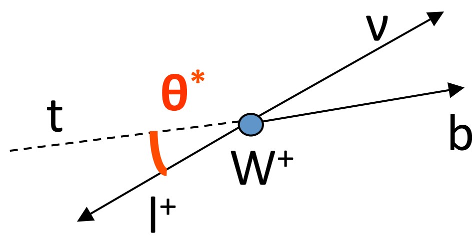
Top Quark Properties

- Since its discovery many properties within the SM have been well established using both strong (top pair production) and electroweak (single top) production modes
- The LHC top measurements (at $\sqrt{s}$=7, 8 and 13 TeV) have entered into a new precision era
- Classification based on the production/decay
  - ttbar spin correlation, polarization, charge asymmetry, electroweak coupling (ttH, ttγ, ttZ), FCNC coupling (tZ, tH)
  - W-helicity from top decay, width, branching ratio, anomalous couplings and rare decays (FCNC)

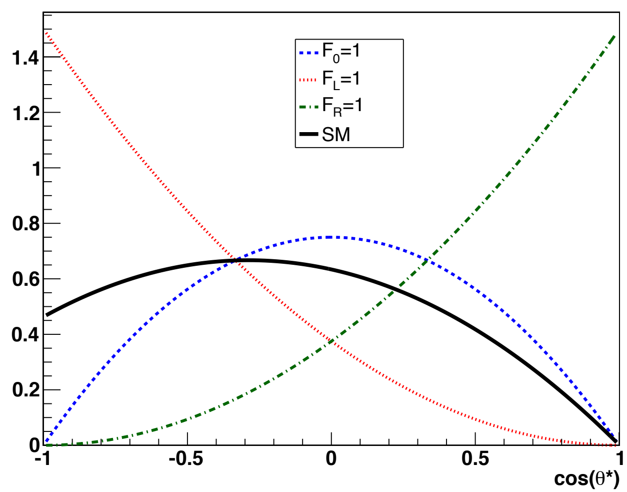
W boson helicity

W helicity

- W boson helicity fractions: $F_{L,R,O}=\Gamma_{L,R,O}/\Gamma_{Total}$ for left-handed, right-handed and longitudinal polarization of W boson respectively
- Helicity angle (θ*) defined as the angle between the direction of the charged lepton/down-type quark (from W) and the direction of the bottom quark [all in the rest frame of W]
- SM (NNLO) Predictions: $F_L=0.311$, $F_O=0.687$ & $F_R=0.001$

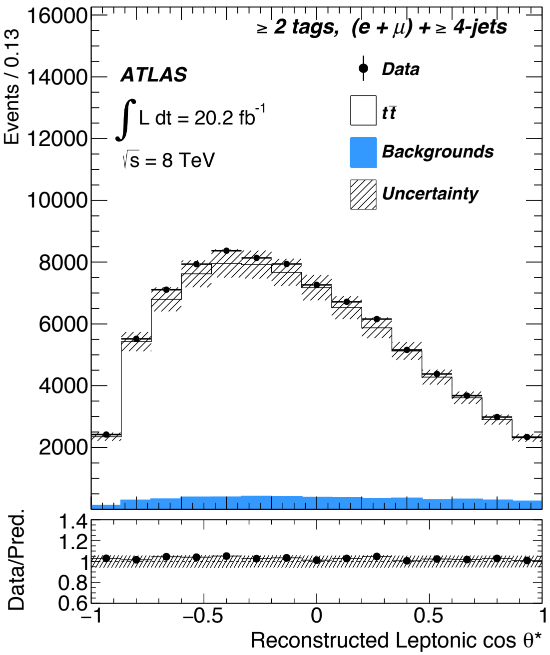


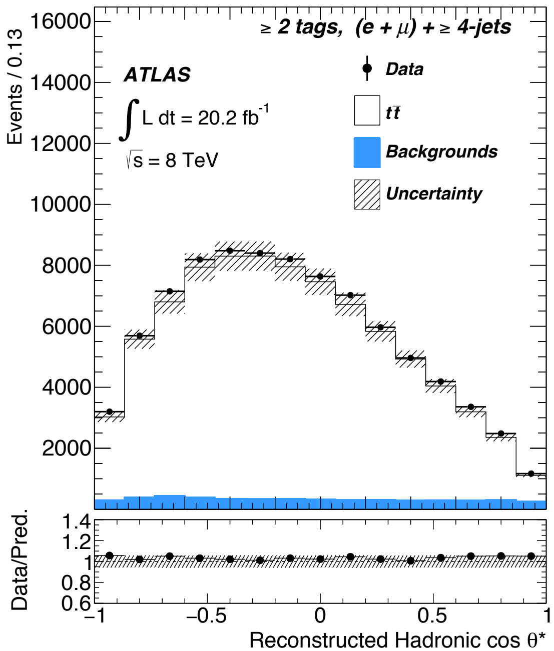
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{4}(\sin\theta^*)^2 F_0 + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

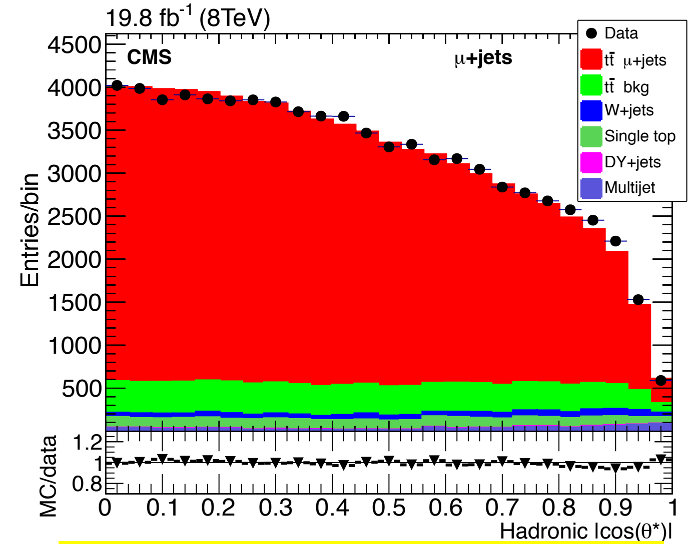


- CMS measurement in ttbar→μ+jets & ttbar→e+jets channel using Run I dataset at √s=8 TeV (19.8 fb^{-1})
- ATLAS measurement in ttbar→ lepton+jets channel with the Run I dataset at √s=8 TeV (20.2 fb^{-1})
- Helicity analysis are done for both leptonic and hadronic W-decays in ttbar events

W helicity (II)

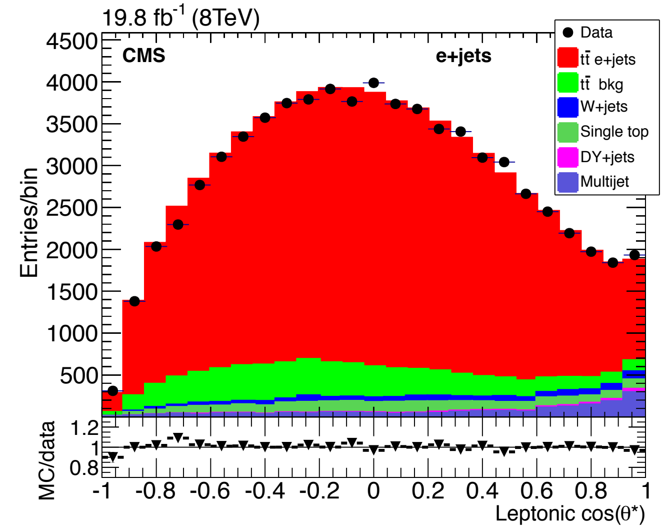






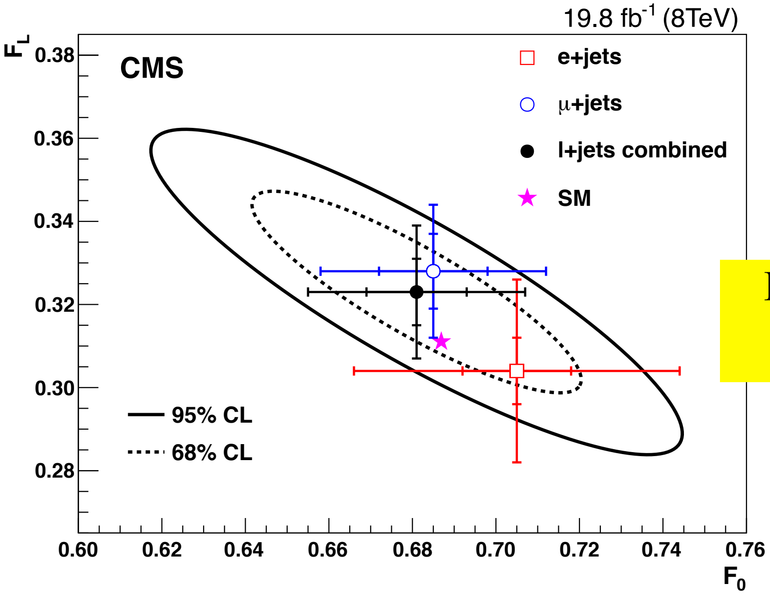
Phys. Lett. B 762, 512 (2016)
arXiv:1605.09047 [hep-ex]

Eur. Physics J. C 77, 264 (2017)
arXiv:1612.02577 [hep-ex]



- ATLAS sub-categorization based on number of b-tagged jets
  - 1 b-tagged jets
  - ≥ 2 b-tagged jets

W helicity (III)



- CMS measurements (with better than 5% accuracy) are limited by the ttbar signal modeling; dominant uncertainties from ttbar scale and top quark mass
  - F_0= 0.681 ± 0.012 (stat) ± 0.023(syst) and F_L= 0.323 ± 0.008 (stat) ± 0.014(syst) with $F_0+F_L+F_R=1$

Phys. Lett. B 762, 512 (2016)
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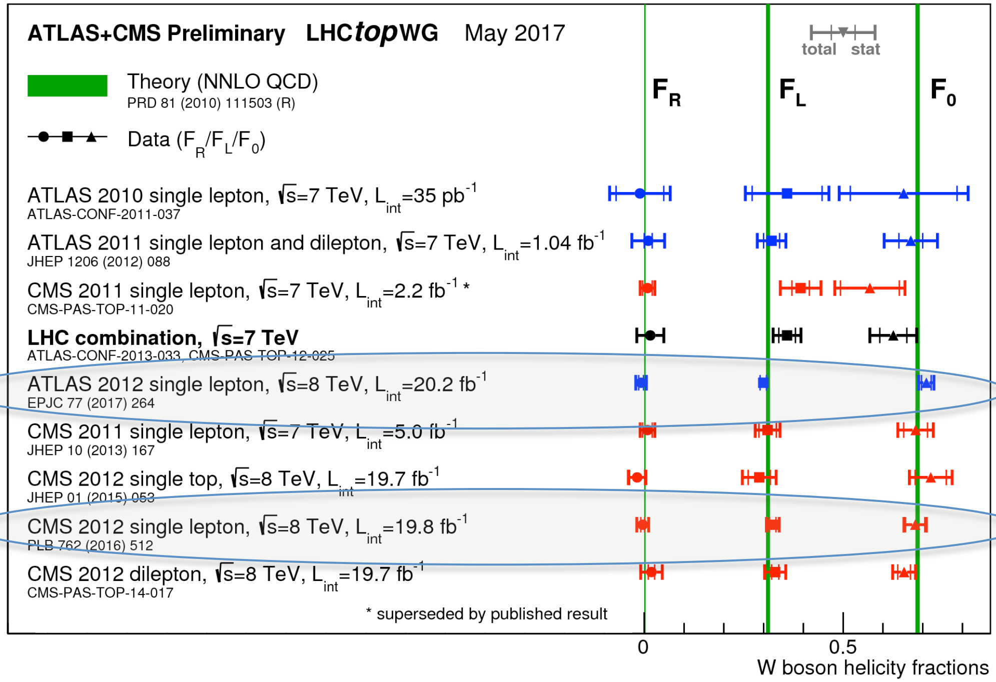


- ATLAS measurements are done using both leptonic analyzer and hadronic analyzer. Leptonic analyzer results (F_0=0.709±0.019 & F_L=0.299±0.015) are more precise than the hadronic one

Eur. Physics J. C 77, 264 (2017)
arXiv:1612.02577 [hep-ex]

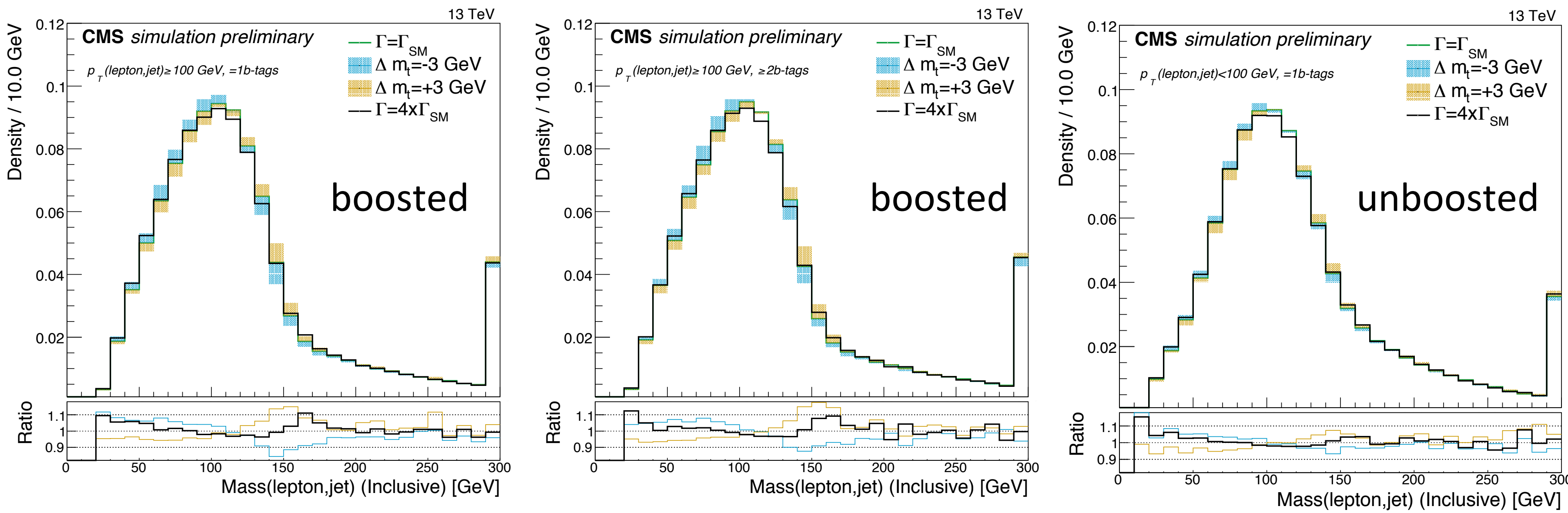
Analyses from 2012 dataset have best sensitivity

Top quark Width

Top Width

- Top width (Γ_t) is inversely proportional to its life-time; NLO SM predicted value (Γ_{SM}) is 1.35 GeV for m_{top}=173.3 GeV and α_s=0.118
- Analysis performed with the ttbar→dilepton (e/μ) +≥ 2 jets (≥1 b-tagged jets, ≥2 b-tagged jets) events at √s=13 TeV (13.1 fb^{-1})
- Discriminating variable $M_{lb}=\sqrt{(m_{top}^2 - m_W^2)}$
- Hypothesis testing with the Powheg-Pythia8 generated templates for Γ_t=1-4xΓ_{SM} and m_{top}=169.5-175.5 GeV

CMS PAS TOP-16-019



Top Width (II)

- Two dimensional likelihood varying the signal strength ($\mu=\sigma_{obs}/\sigma_{SM}$) and sample fraction for alternate hypothesis x:

$$N_{\text{signal}} = \mu\left[(1-x)\cdot N_{\text{SM}} + x\cdot N_{\text{alt}}\right]$$

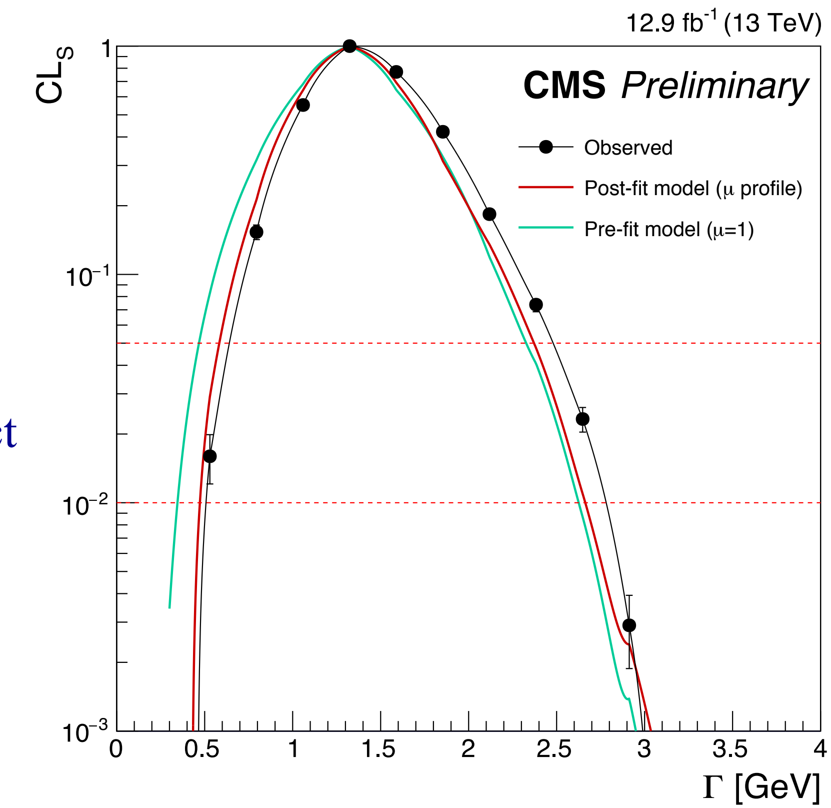
N_{SM} (N_{alt}) being expectation for SM (alternate) hypothesis

CMS PAS TOP-16-019

- Limit extraction with a test statistic:

$$q \equiv -2\cdot\ln\left(\frac{\mathcal{L}_{\text{alt}}}{\mathcal{L}_{\text{SM}}}\right)$$

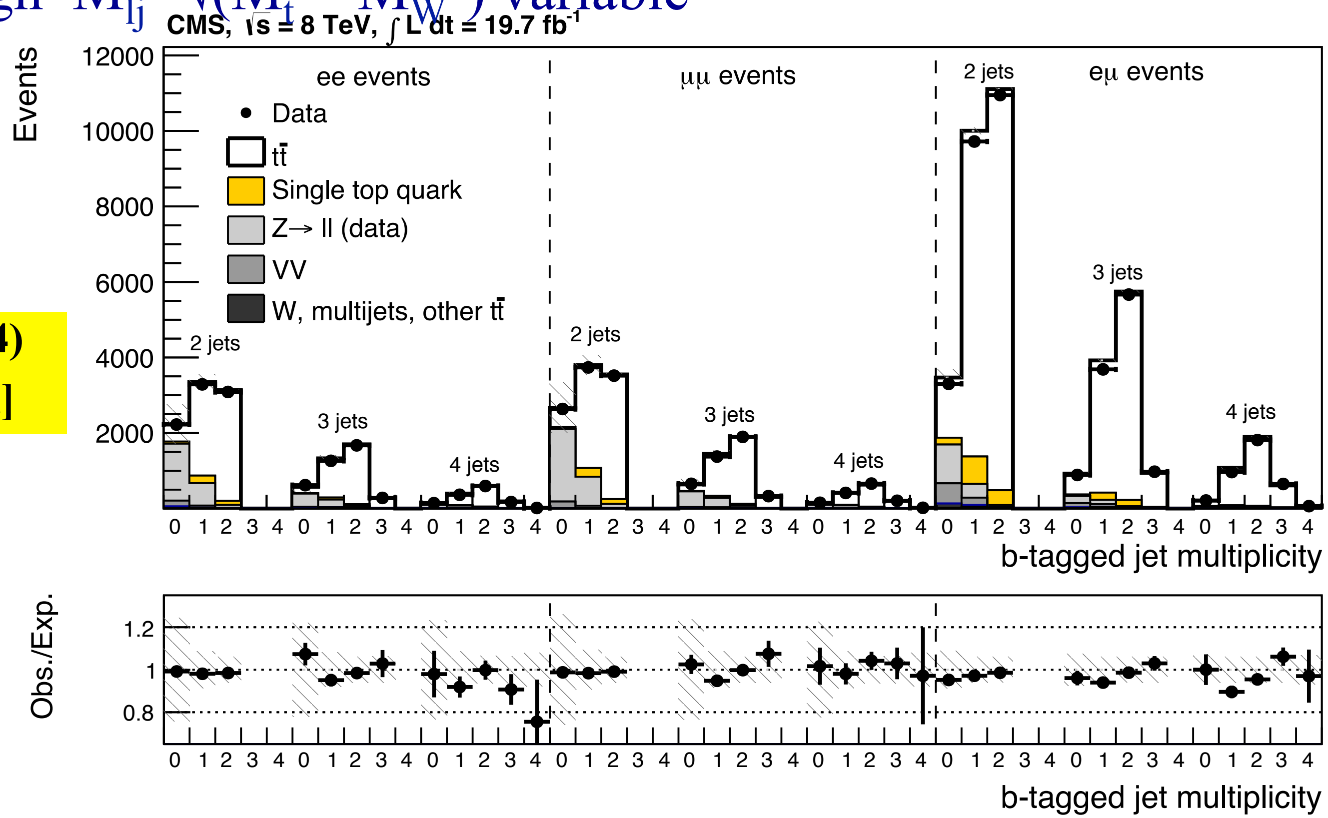
- limits on Γ_t at 95% CL:
  - Observed: $0.6<\Gamma_t<2.5$ GeV (Expected: $0.6<\Gamma_t<2.4$ GeV for m_{top}=172.5 GeV)
- Till the date it is the best precision from direct measurement. Indirect measurements so far result:
  - $\Gamma_t=2.00^{+0.47}_{-0.43}$ GeV [DØ: Phys Rev D 85, 091104 (2012)]
  - $\Gamma_t=1.36\pm0.02$ (stat) $^{+0.14}_{-0.11}$(syst) GeV [CMS: Phys. Lett. B 736, 33 (2014)]



Top Branching Ratio

Branching Ratio

- Measurement of R=Br (t→Wb)/Br(t→Wq) with q=b,s,d
- Estimation of R from ttbar→dilepton+jets dataset at √s=8 TeV (19.7 fb^{-1}) by counting number of b-jets/event
- The fraction of correct pairs of lepton-jet pairs (from top decays) is modeled through $M_{lj}=\sqrt{(M_t^2 - M_W^2)}$ variable



Phys. Lett B 736, 33 (2014)
arXiv: 1404.2292 [hep-ex]

Branching Ratio (II)

Phys. Lett B 736, 33 (2014)
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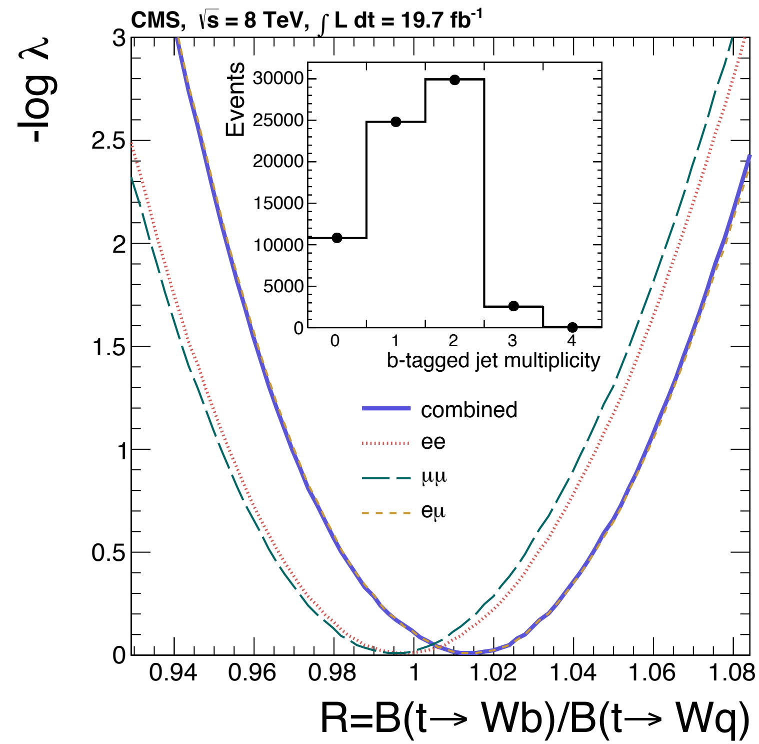


- ✧ Combined measurement of R= 1.014 ± 0.003 (stat) ± 0.032 (syst)
  - ✧ Translates to CKM $|V_{tb}|$ =1.007 ± 0.016 (syst+stat)
- ✧ Imposing R≤1 condition ➔ R>0.955 and CKM $|V_{tb}|$ >0.975 at 95% CL

- ✧ Translated into an indirect Γ_t (top width) measurement using the formula: $$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$ with Γ(t→Wb)= 1.329 GeV

- ✧ Γ_t= 1.36 ± 0.02 (stat) $^{+0.14}_{-0.11}$(syst) GeV

Search for anomalous Wtb coupling

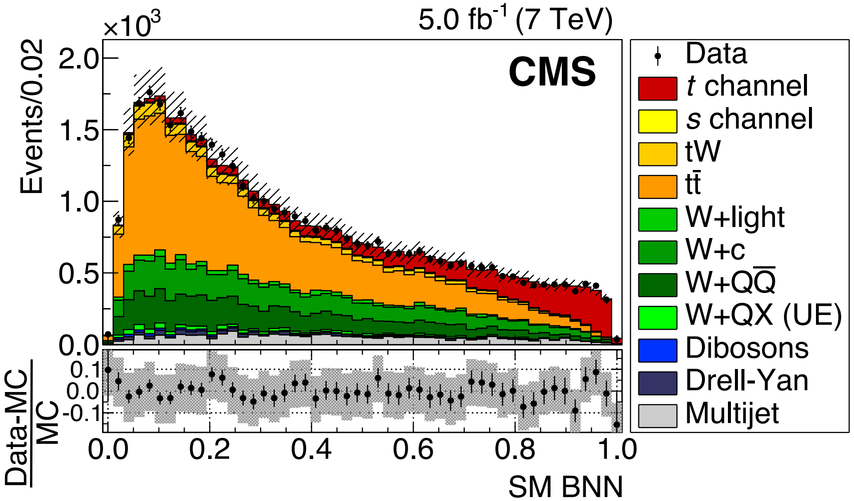
Anomalous Wtb coupling

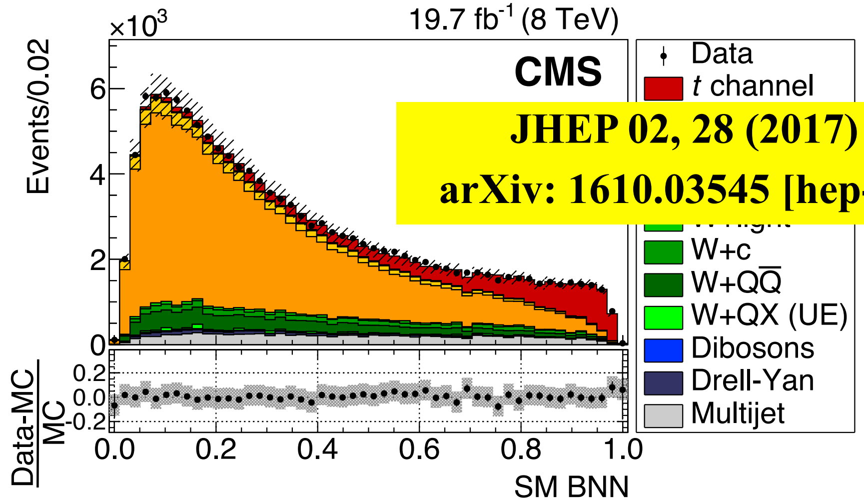
- t-channel single top production is sensitive to possible deviations from the SM predictions; most general CP-conserving Lagrangian:

$$\mathfrak{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^{\mu} \left(f_V^L P_L + f_V^R P_R \right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu} \partial_{\nu} W_{\mu}^{-}}{M_W} \left(f_T^L P_L + f_T^R P_R \right) t + \text{h.c.},$$

f_V^L (f_V^R) and f_T^L (f_T^R) represent left-handed (right-handed) vector and tensor couplings respectively; In SM: $f_V^L = V_{tb}$ and $f_V^R = f_T^L = f_T^R = 0$

- Signal selection: 1 muon + 1 b-tagged jet + 1 light-flavored jet in the forward region
- Dataset: 5 fb^{-1} at $\sqrt{s}$=7 TeV (2011) and 19.7 fb^{-1} at $\sqrt{s}$=8 TeV (2012)
- Baysian Neural Networks (BNN) for SM signal extraction as well as three additional Wtb BNN for separating the contributions for f_V^R, f_T^L, and f_T^R

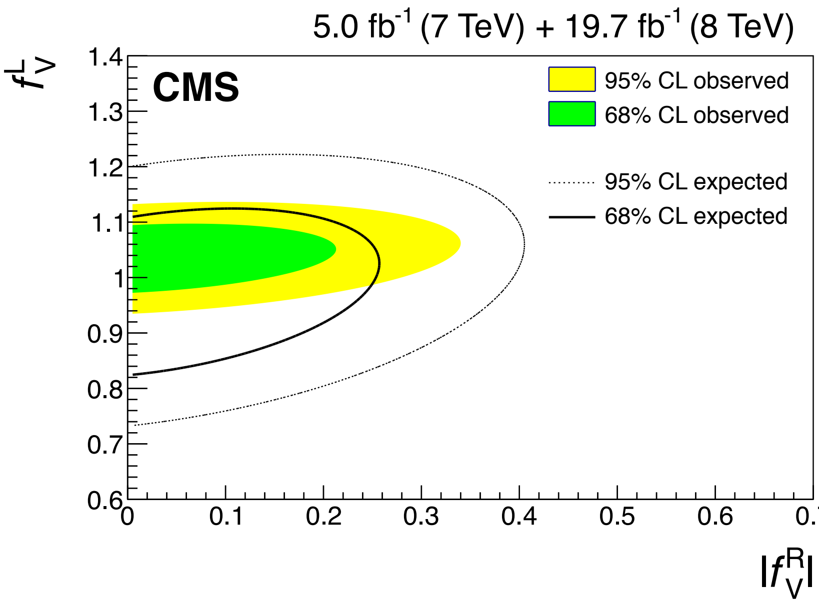


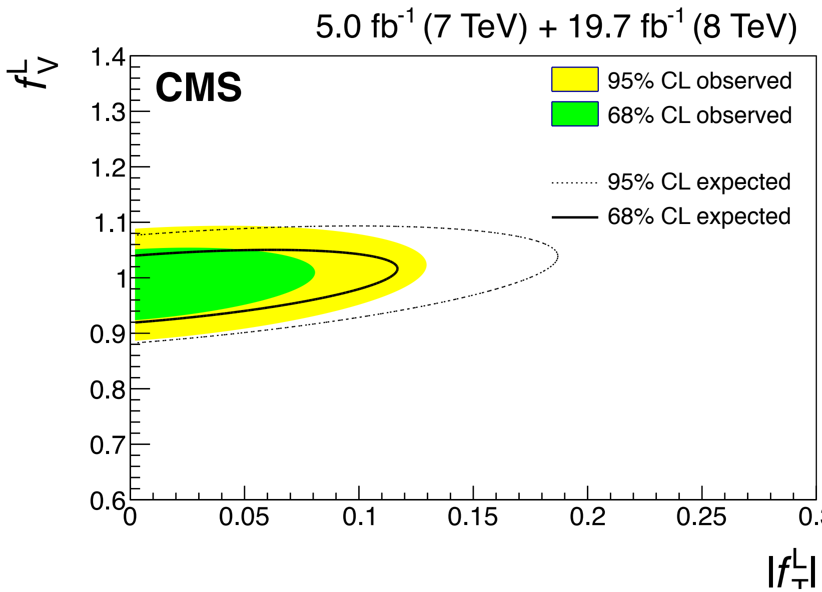


JHEP 02, 28 (2017)

arXiv: 1610.03545 [hep-ex]

Anomalous Wtb coupling (II)





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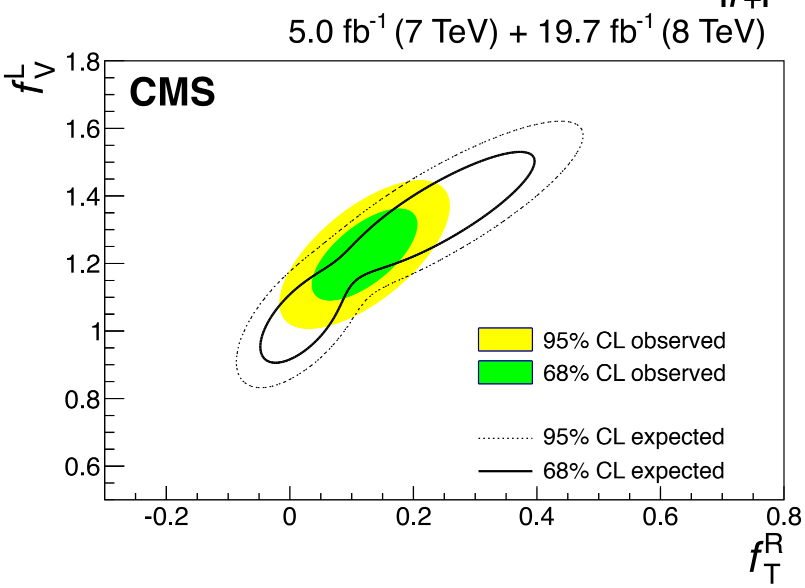
arXiv: 1610.03545 [hep-ex]



- Limits are set at 95% CL
  - $|f_V^R| < 0.16$
  - $|f_T^L| < 0.057$
  - $-0.049 < f_T^R < 0.048$

Anomalous Wtb coupling (III)

- ATLS W-helicity results translated to set limits on anomalous Wtb coupling
- The structure of the Wtb vertex can be expressed as:

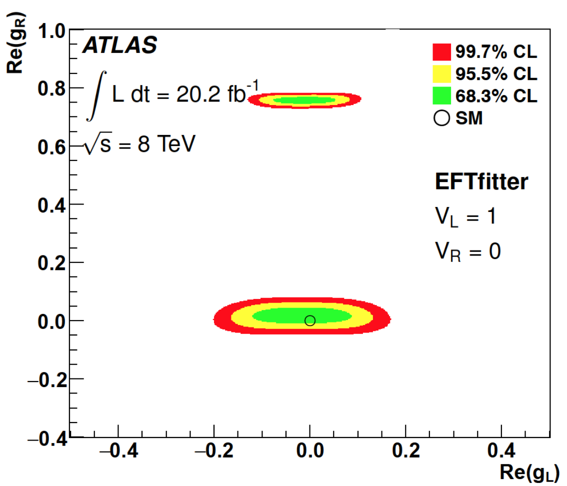
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

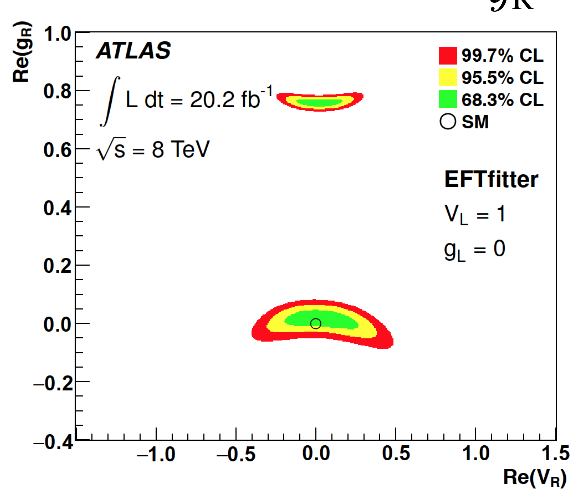
Anomalous couplings can lead to non-vanishing V_R, g_L, g_R

- Limits set on V_R, g_L, g_R at 95% CL

Eur. Physics J. C 77, 264 (2017)
arXiv:1612.02577 [hep-ex]

Coupling	95 % CL interval
V_R	$[-0.24, 0.31]$
g_L	$[-0.14, 0.11]$
g_R	$[-0.02, 0.06]$, $[0.74, 0.78]$



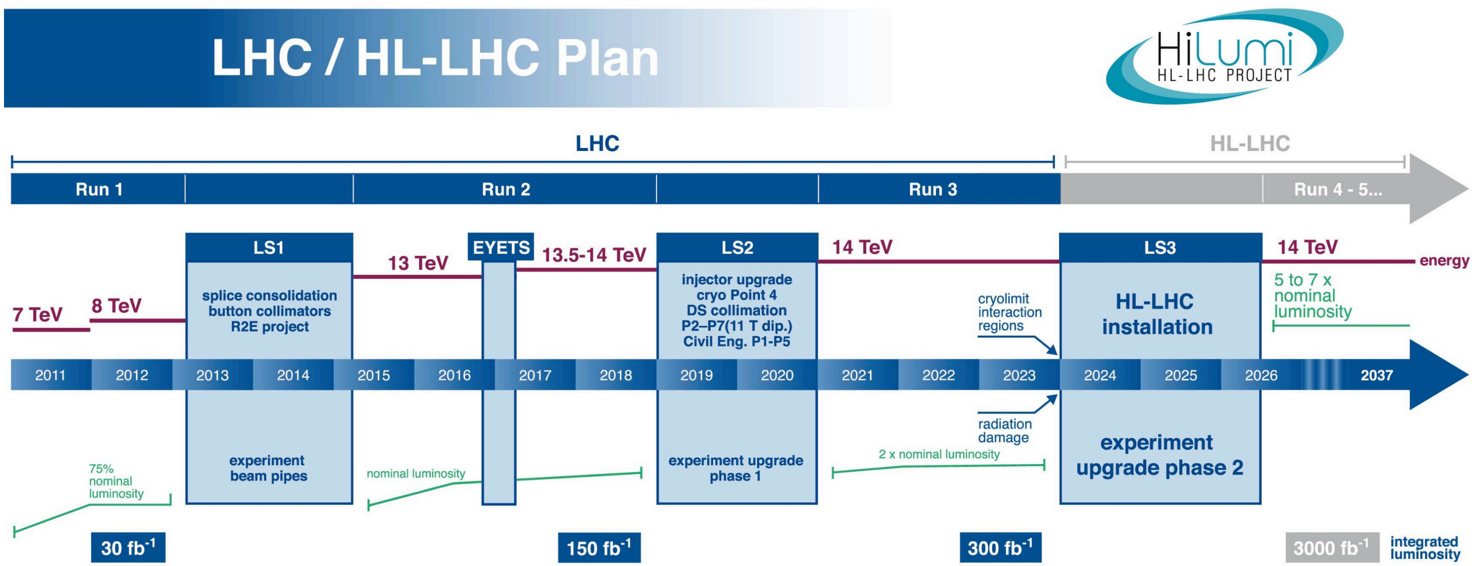


Summary & Conclusions

- During the LHC era, the top quark properties are being measured with unprecedented precision
  - Both ATLAS and CMS have finished up the Run I legacy papers
  - Some measurements are already performed with the Run II dataset
- Measurement of various properties of top quark are providing crucial tests on the SM itself while probing the BSM physics; so far no excess observed over the SM predictions.
- Key measurements on Top decay properties presented here
  - W boson helicity
  - Top quark width (both direct and indirect)
  - Branching Ratio and $|V_{tb}|$
  - Limits on anomalous Wtb couplings
- Some of the limiting systematics affecting these measurements stem from
  - ttbar modeling (top mass, ttbar scale, ttbar matching scale)
  - Experimental uncertainties related to the jets (Jet Energy Scale, Jet Energy Resolution), W+jets and QCD background determination

LHC Outlook (Run II & beyond)

- LHC Run II at √s=13 TeV began in 2015; Top properties from the full 2016 dataset are yet to be measured
- New Physics discovery may be at the door-step and top quark properties would play the key role; In addition, we would also be able to probe tiny SM predictions
- Many more upgrades with the LHC and the detectors are scheduled for next two decades. In addition analyses techniques would be refined further.



References

- ✧ LHCTopWG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
- ✧ ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- ✧ CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP