Top Quark Properties

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The Top Quark

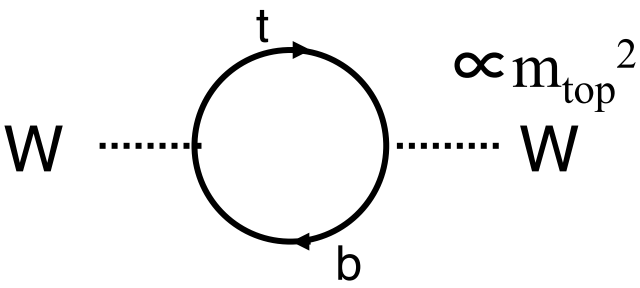
- Discovered at the Tevatron in 1995 by the CDF and DØ experiments through the top pair production mode
- Till the date heaviest known elementary particle

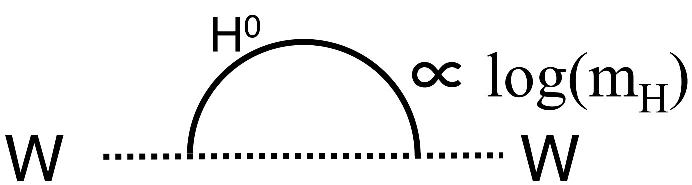
  m_t = 173.34 ± 0.76 GeV [LHCtop WG, Sept, 2015]
- Known properties within the Standard Model (SM):
  - Electric charge +2/3 e
  - Strong & electroweak production
  - Decays before the hadronization [lifetime 0.5×10^{-24} sec]
    - Unique opportunity to study the bare quark
  - $Br(t \to W^{+}b) \approx 100\%$

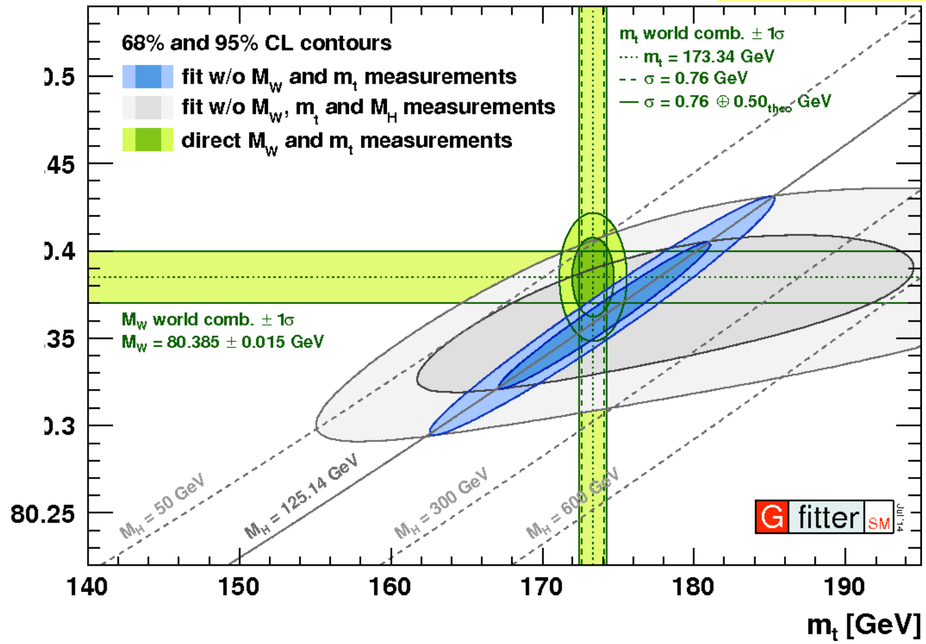
What's special with Top?

- Strong coupling with the Higgs boson
- Constraints the Higgs mass along with W boson mass

arXiv:1407.3792







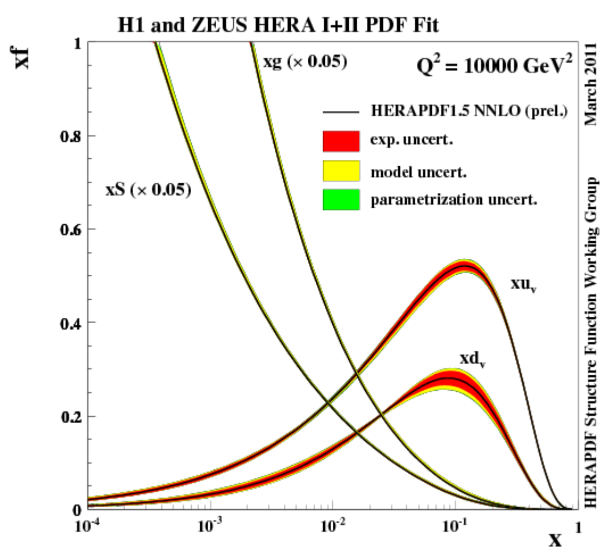
- Many new physics models result in same signature, e.g, SUSY "stop" can decay into top

Top pair production

NNLO+NNLL	x	qq vs gg	cross section	± scales	± pdf
Tev 1.96 TeV	0.18	90% vs 10%	7.164 pb	~2%	~2%
LHC 7 TeV	0.048	15% vs 85%	172.0 pb	~3%	~3%
LHC 8 TeV	0.043	12% vs 88%	245.8 pb	~3%	~2.5%
LHC 14 TeV	0.025	10% vs 90%	953.6 pb	~3%	~2%

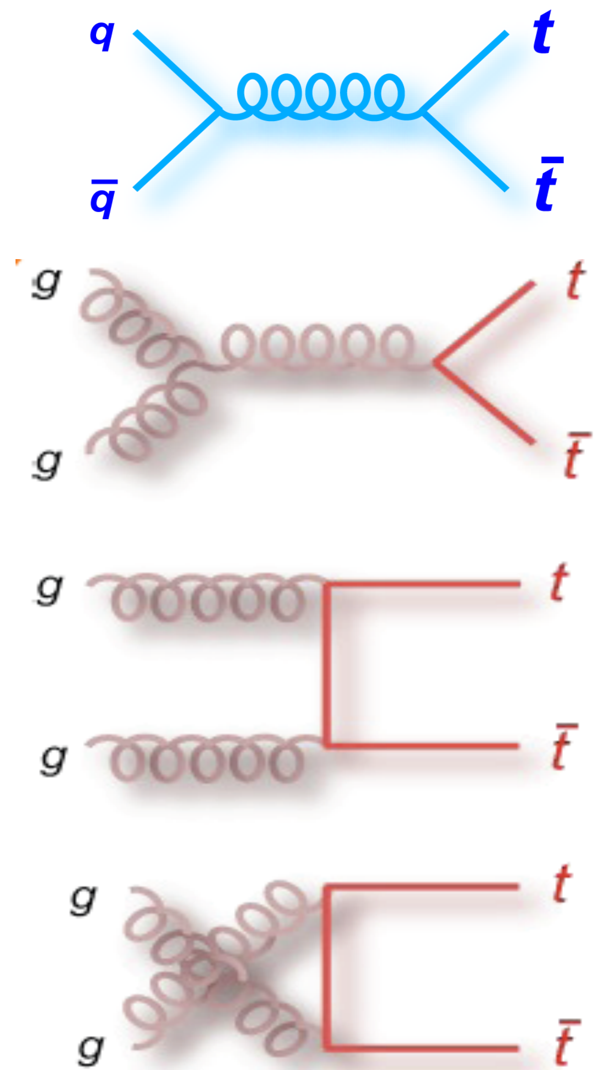
m_t=173.3 GeV, MSTW2008nnlo68cl

arXiv:1303.6254 [hep-ph]



$$\hat{s} = x_i\sqrt{s} \cdot x_j\sqrt{s} \geq (2m_t)^2$$

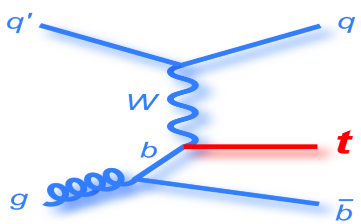
$$x_i \approx \frac{2m_t}{\sqrt{s}}$$



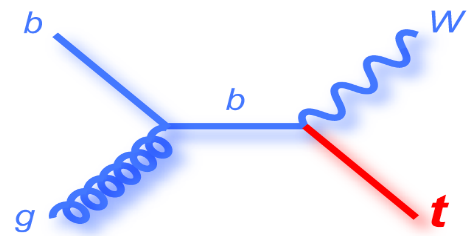
Electroweak Top Production

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

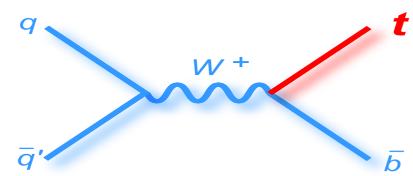
***t*-channel**



***Wt* channel**



***s*-channel**



NLO+NNLL with m_{top}=172.5 GeV

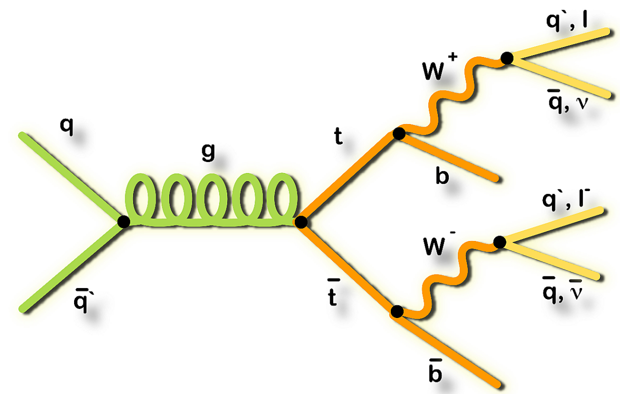
√s (pb)	σ (t-channel)	σ (Wt)	σ (s-channel)
8 TeV	84.69	22.37	5.24
13 TeV	216.99	71.7	10.32

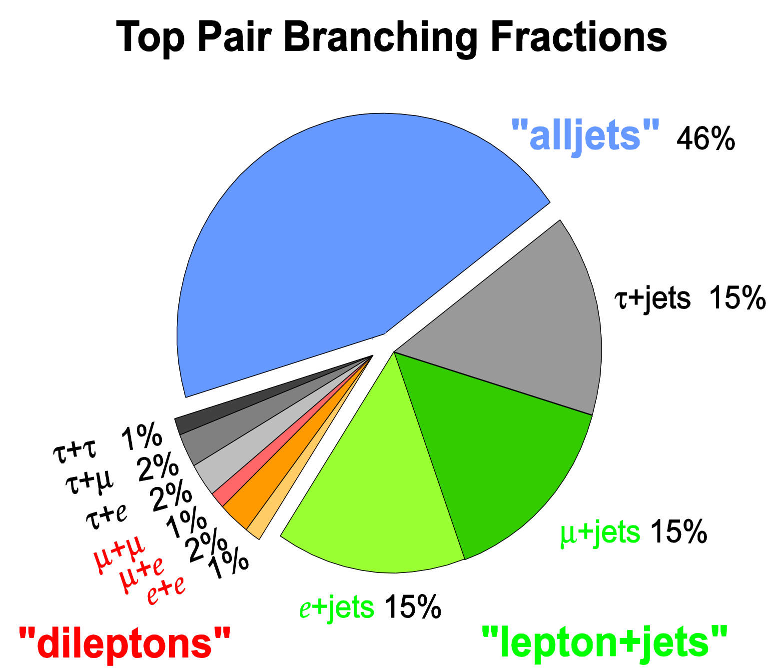
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

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

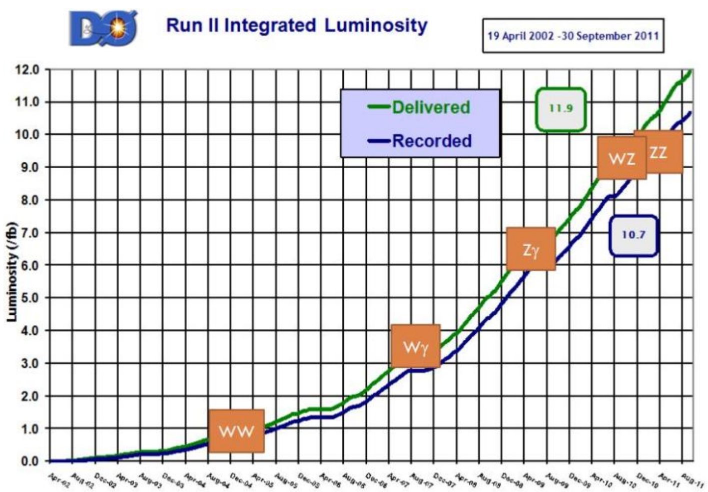
Decay of Top quark

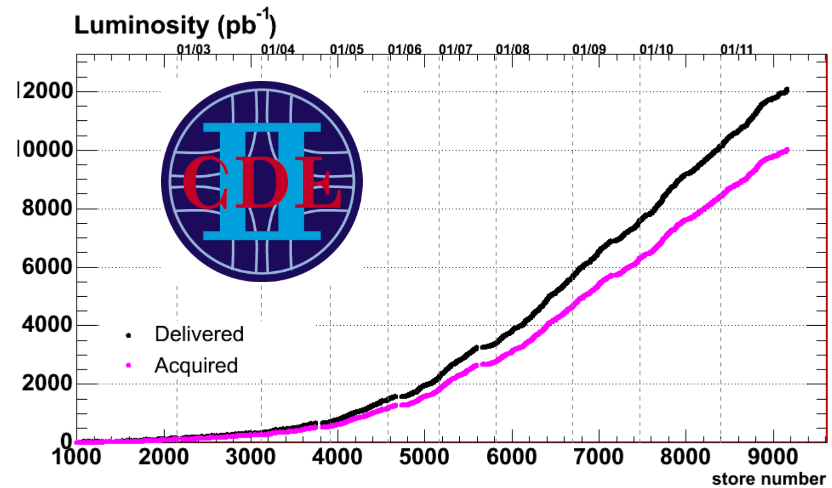
- SM Br(t→W⁺b)=100%
- Final states determined through the decay of W± bosons from top and antitop quarks.
  - All jets: $t\bar{t} \to bW^{+}\bar{b}W^{-} \to b\bar{b}q\bar{q}'q\bar{q}'$
    - **High branching ratio but large QCD background**
    - **≥ 6 jets, 2 b-jets**
  - **lepton+jets:** $t\bar{t} \to bW^{+}\bar{b}W^{-} \to b\bar{b}q\bar{q}'l^{-}\bar{\nu}$
    - 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: $t\bar{b} \to bW^{+}\bar{b} \to b\bar{b}l^{+}\nu$



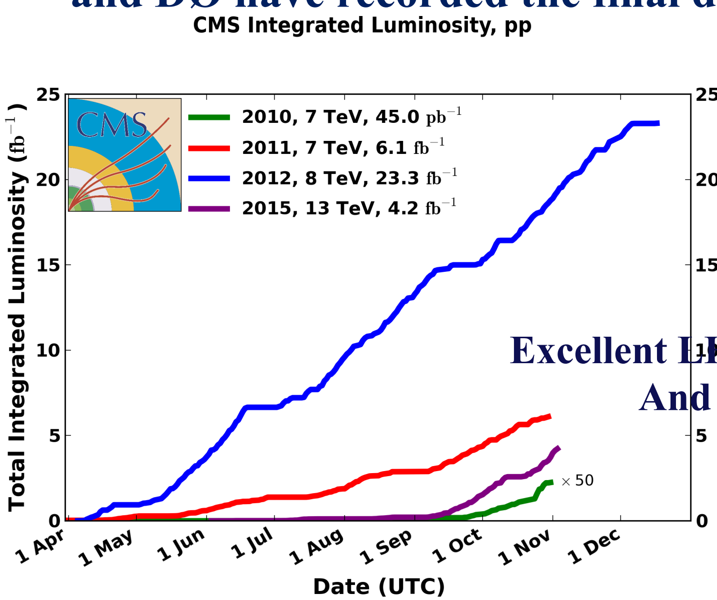


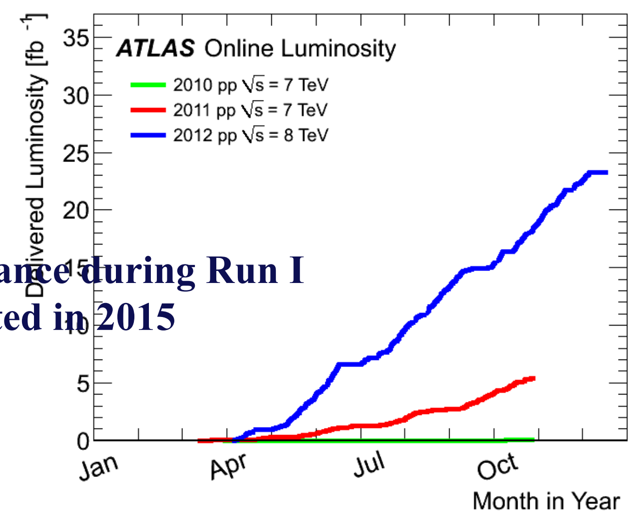
Collider Datasets





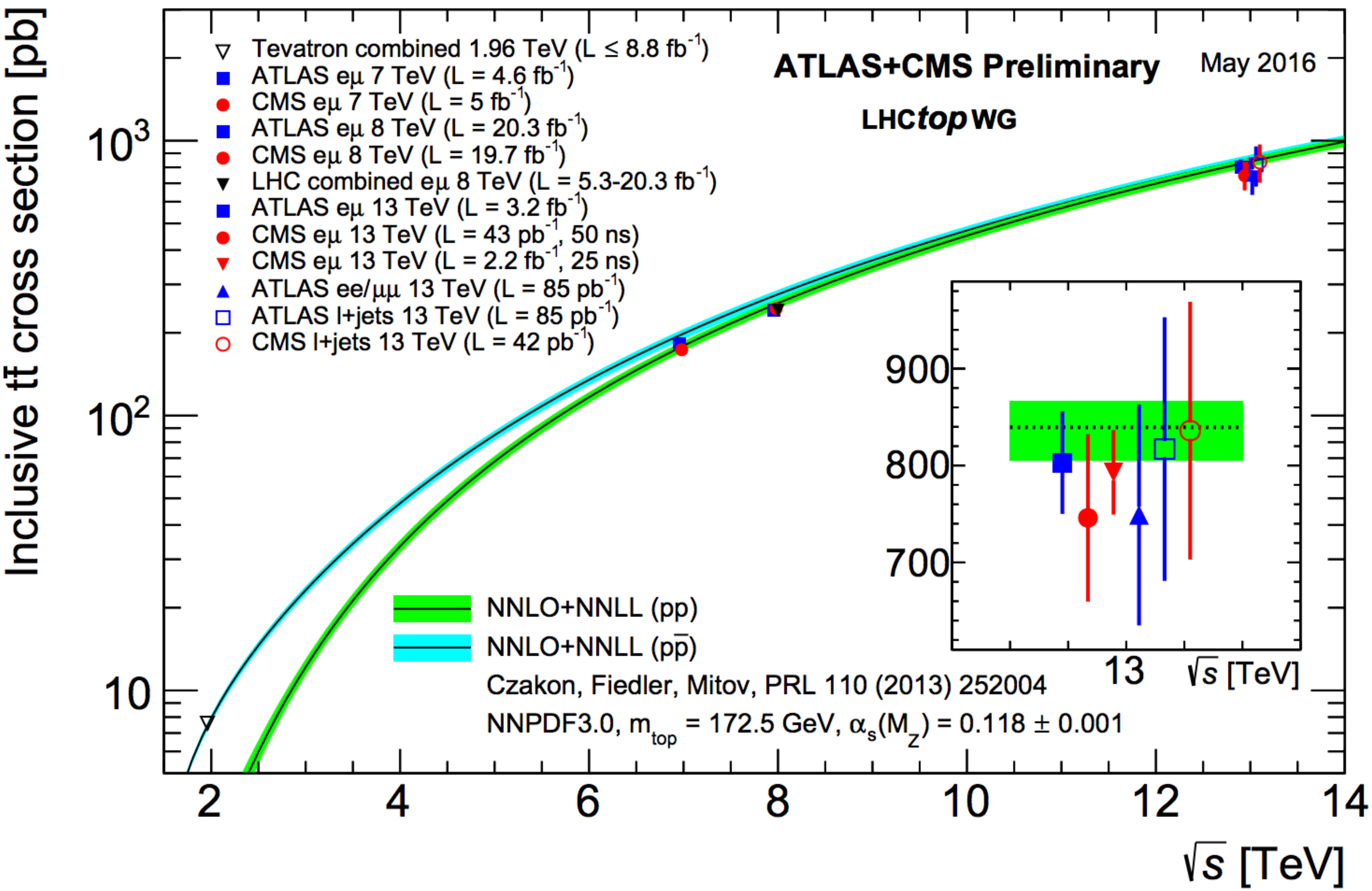
- Tevatron has been shutdown after its glorious journey over two decade. Both CDF and DØ have recorded the final datasets of approximately 10 fb^{-1} per experiment.





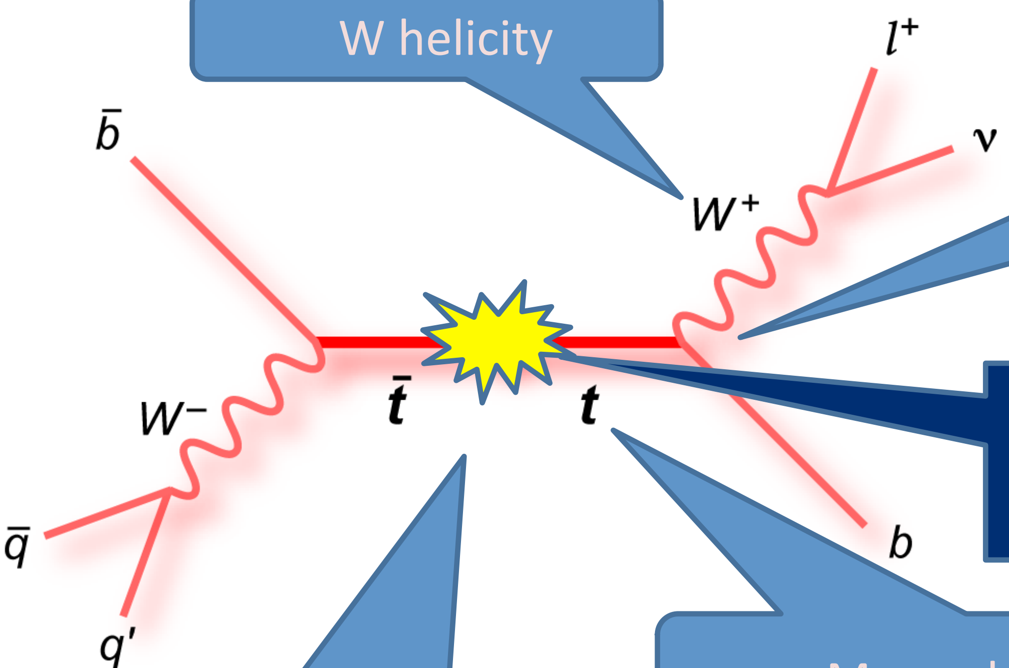
Excellent LHC performance during Run I
And Run II started in 2015

$t\bar{t}$ production cross-section



Top Quark Measurements

Measurements performed in 21 years (Tevatron +LHC)



W helicity

Branching ratio
Rare decays, New physics
Anomalous couplings

Spin correlation
Charge Asymmetry

Mass, charge, width

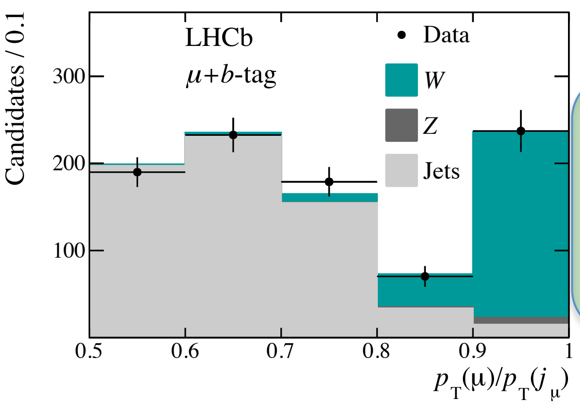
Cross sections
Differential cross sections
New physics

+ electroweak single top production

Observation of top quark in forward region

- First time observation of inclusive top quark production in forward region with a proton-proton dataset of 1 (2) fb^{-1} at $\sqrt{s}=7$ (8) TeV
- Signal signature: $t \to W(\to \mu\nu_\mu)b$ with reconstructed muon track & b-jet
  - The SM predicts 75% (25%) of the inclusive top signature in forward region from top pair produced events (single top or electroweak production of top).
- Major background processes: $W(\to \mu\nu_\mu)+b$, $Z(\to \mu\mu)+b$, QCD bottom pair production
- Event selection:
  - Muons with $p_{T,\mu}>25$ GeV & $2<\eta_\mu<4.5$
  - Secondary Vertex tagged b-jets $50<p_{T,b}<100$ GeV & $2.2<\eta_{\mu b}<4.2$
  - $\Delta R(\mu,j)>0.5$ and $p_T(\mu+b)>20$ GeV
- Good agreement between data & SM predictions

PRL 115 112001 (2016)
arXiv:1506.00903 [hep-ex]



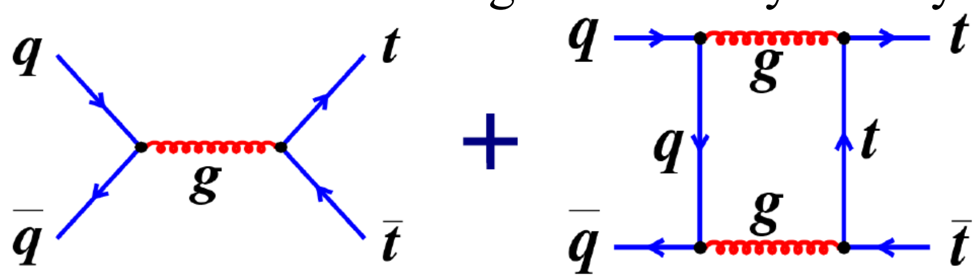
❑ Fiducial cross-section:

$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\,\text{fb}\,,$$
$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\,\text{fb}\,.$$

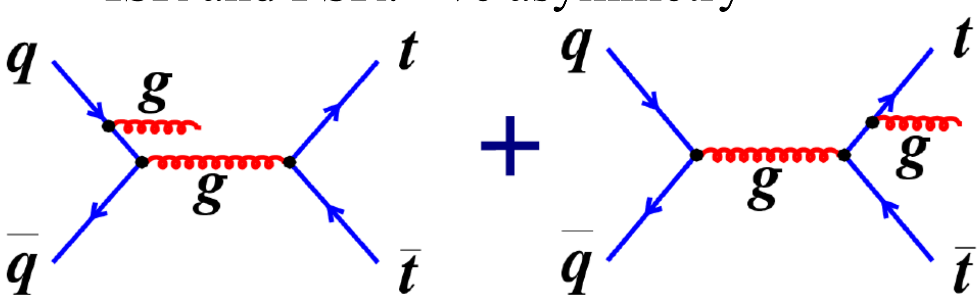
Top Charge Asymmetry

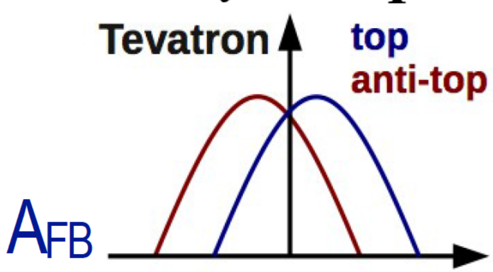
Forward-Backward (A_{FB}) and charge asymmetry (A_C) in $t\bar{t}$ events

tree-level and box diagram: +ve asymmetry



ISR and FSR: −ve asymmetry

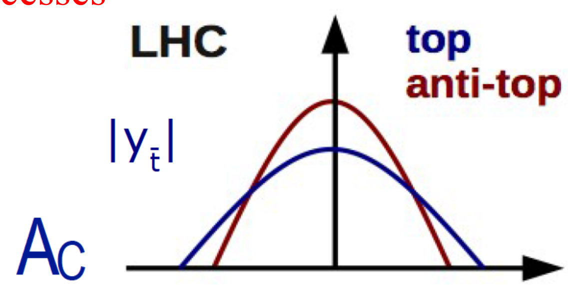




$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

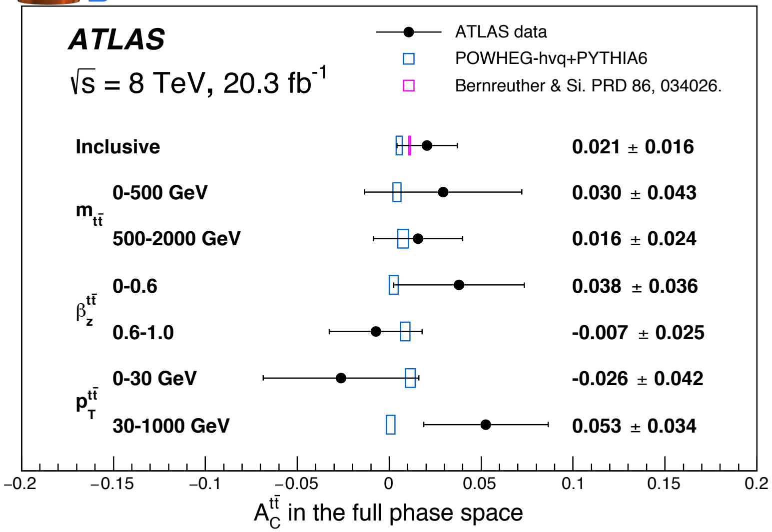
- ✧ No Asymmetry at the LO, neither from gg fusion processes
- ✧ In the SM, small asymmetry originates from the interference between ISR and FSR and, between the LO and box diagrams for quark-antiquark annihilation processes.
- ✧ At Tevatron such interference leads to 5-9% asymmetry (A_{FB}) while 1% asymmetry (A_C) at the LHC.
- ✧ The asymmetry reduces at the LHC mainly due to lower contribution from qq→tt processes

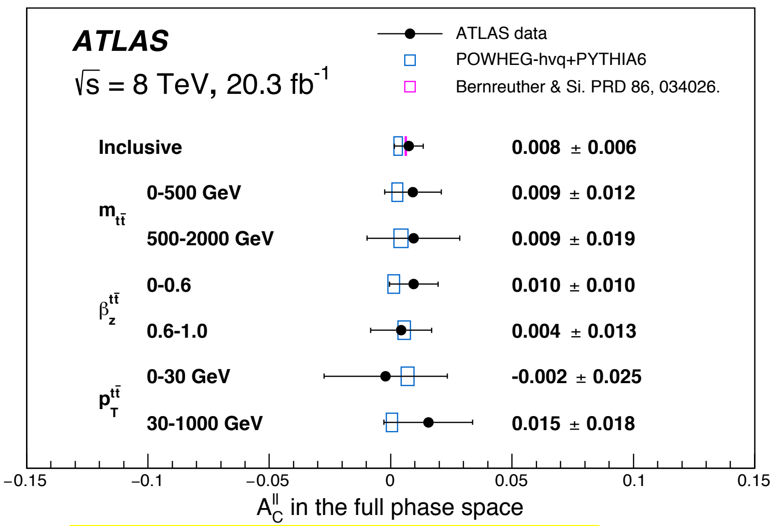


$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

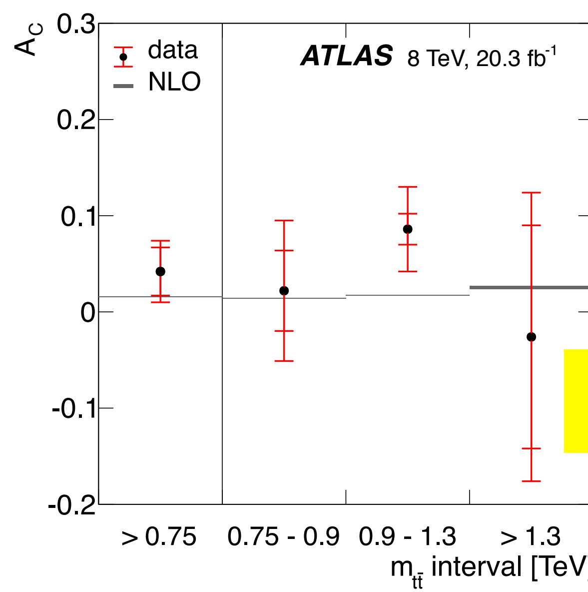
Charge Asymmetry (A_C)





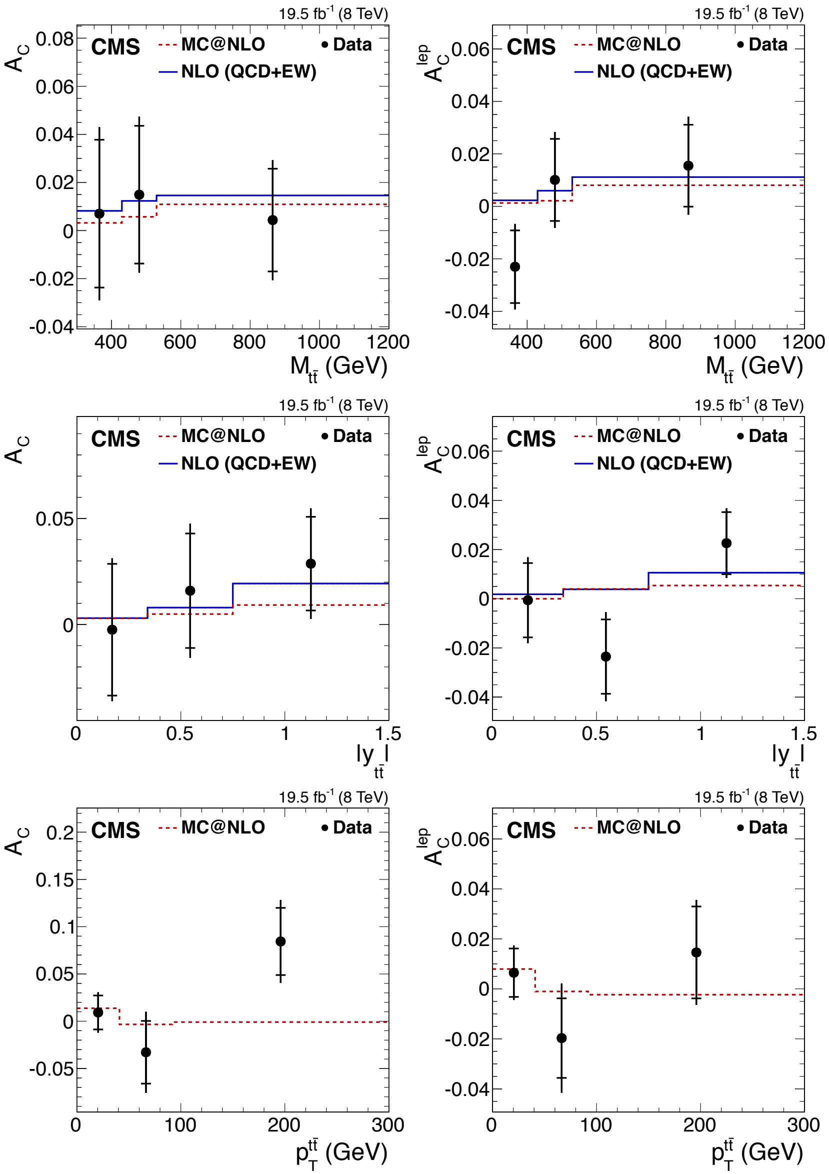
arXiv:1604.5538 [hep-ex]; Submitted to PRD

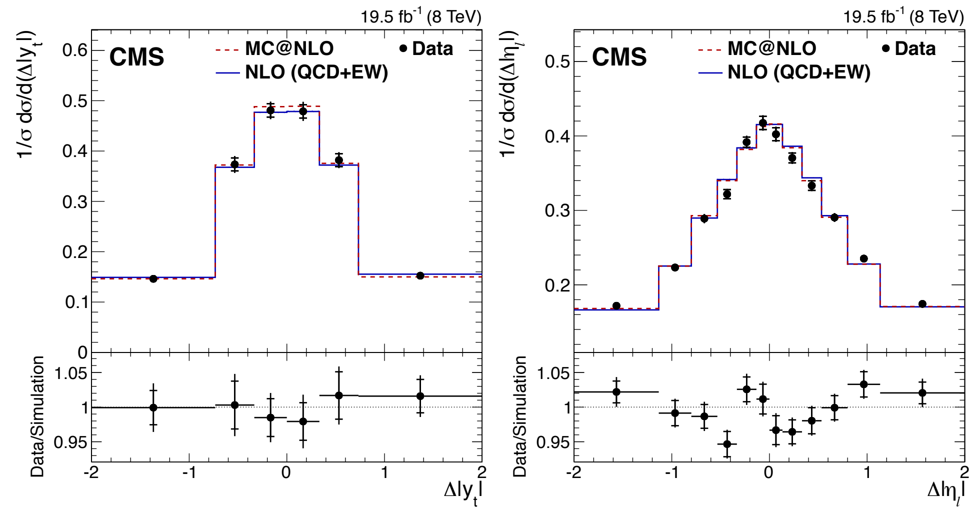
- Dilepton channel: Inclusive as well as differential measurements as functions of m_{tt}, transverse momentum, and longitudinal boost
  - Inclusive measurements (SM predictions)
    - A_C^{ll}=0.008 ± 0.006 (0.0064±0.0003)
    - A_C^{tt}=0.021± 0.016 (0.0064±0.0003)
- Lepton+jets channel measurement in highly boosted top pair produced topology in fiducial region of m_{tt}>0.75 TeV and -2<$|y_t|-|y_{tbar}|$<2
  - A_c^{tt} =0.042±0.032 (in agreement with the SM)



arXiv:1512.06092 [hep-ex]; PLB 756 52 (2016)

Charge Asymmetry (A_C)

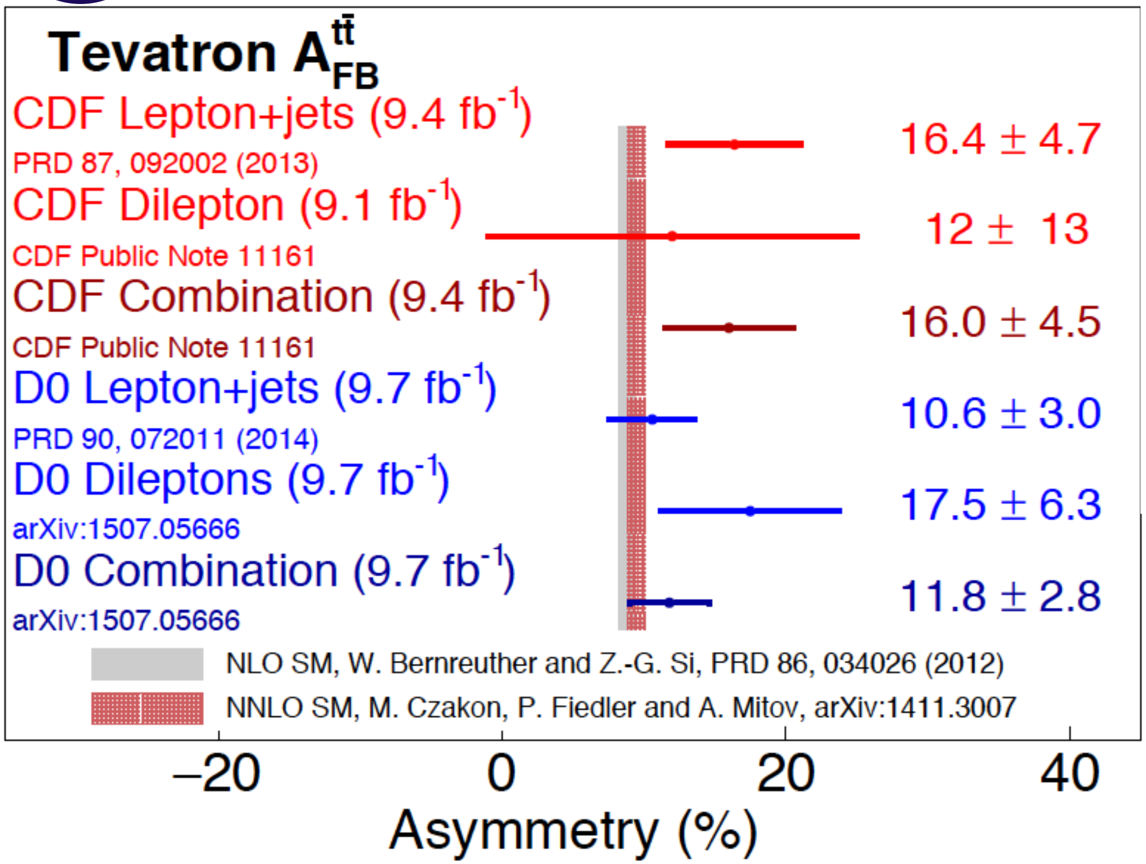


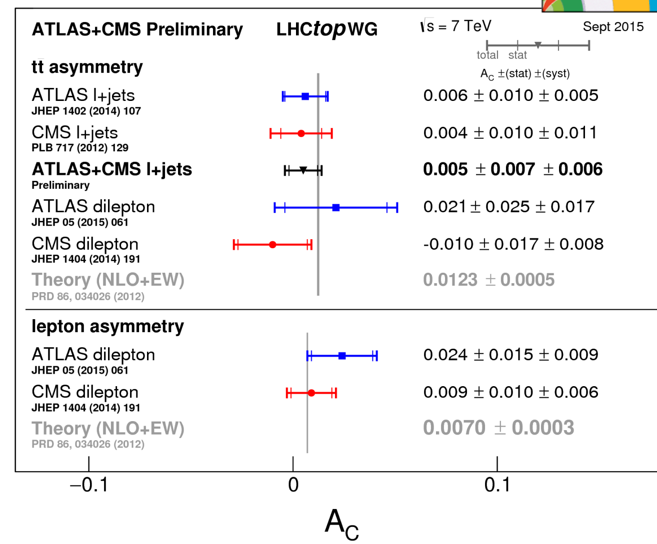


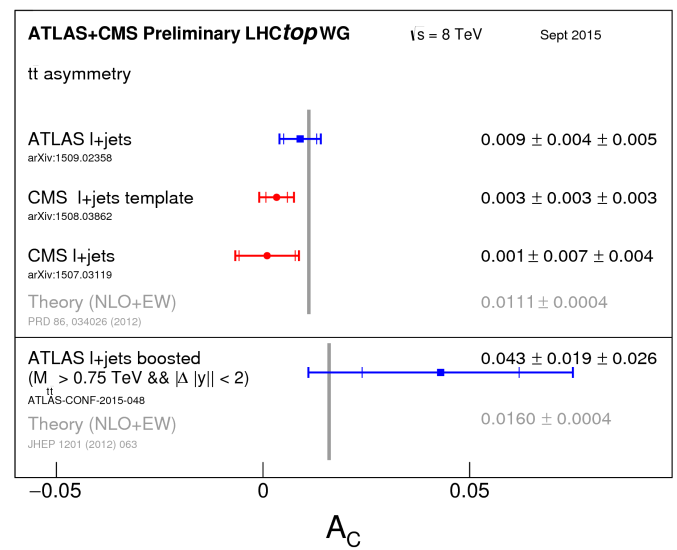
- Dilepton channel: Inclusive as well as differential measurements as functions of m_{tt}, transverse momentum (p_T^{tt}), and $|y_{tt}|$
- Inclusive measurements:
  - A_C^{ll}=0.003±0.006 (stat)±0.003 (syst)
  - A_C^{tt}=0.011± 0.011 (stat)±0.007 (syst)
- Good agreement with the SM predictions

arXiv:1603.0622 [hep-ex]; submitted to PLB

Summary from Tevatron (A_{FB}) & LHC (A_C)







A_C (LHC) vs A_{FB} (Tevatron)

Z': Flavor violating Z' exchanged in t-channel in $u\bar{u} \to t\bar{t}$ and with right-handed Z'tu couplings

W': W' boson with right-handed couplings exchanged in t-channel in $d\bar{d} \to t\bar{t}$

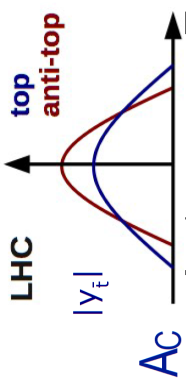
Ω^4: Color-sextet scalar with right-handed flavor violating tu-couplings and exchanged in u-channel

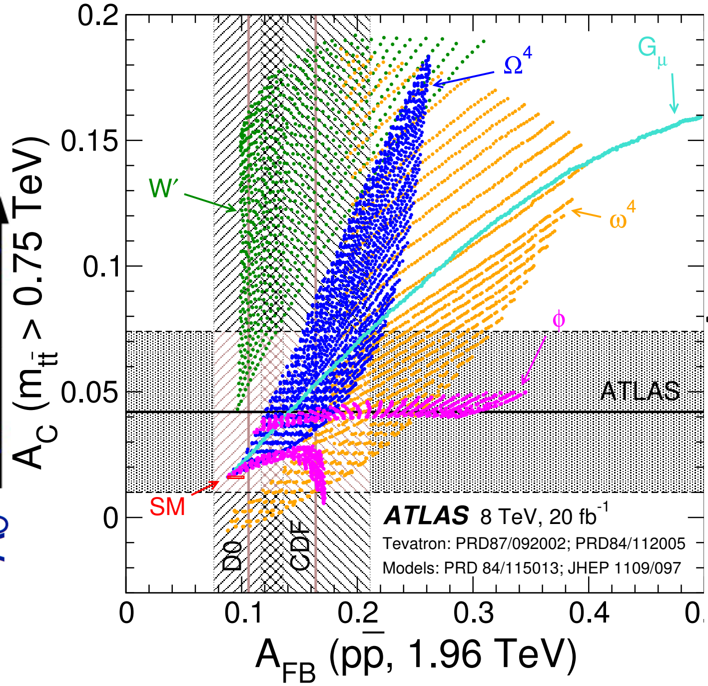
ω^4: Color triplet with flavor violating tu-couplings, right-handed, exchanged in u-channel in $u\bar{u} \to t\bar{t}$

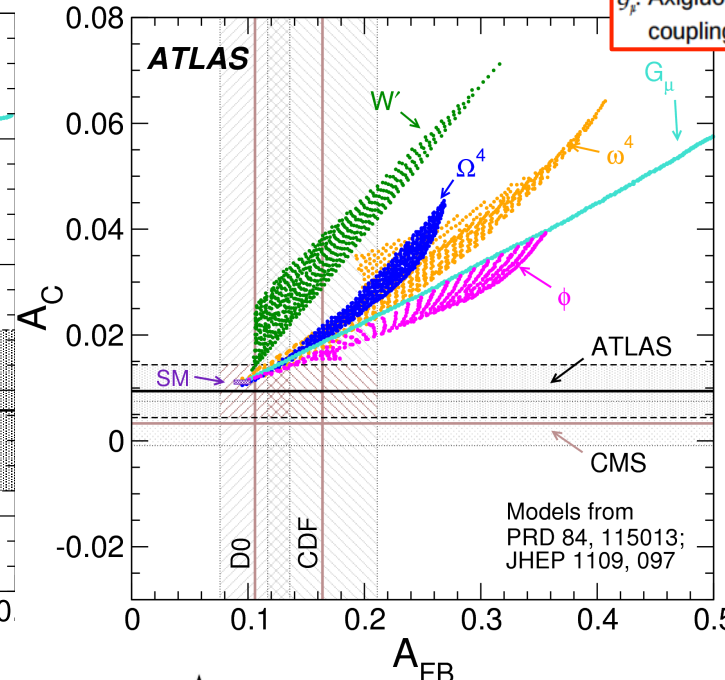
G_μ: Axigluon, color octet vector with axial couplings

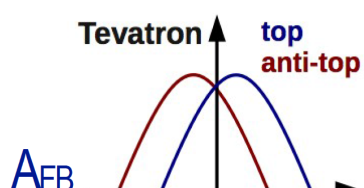
arXiv:1512.06092 [hep-ex]; PLB 756 52 (2016)

arXiv:1509.02358 [hep-ex]; EPJ C76 87 (2016)









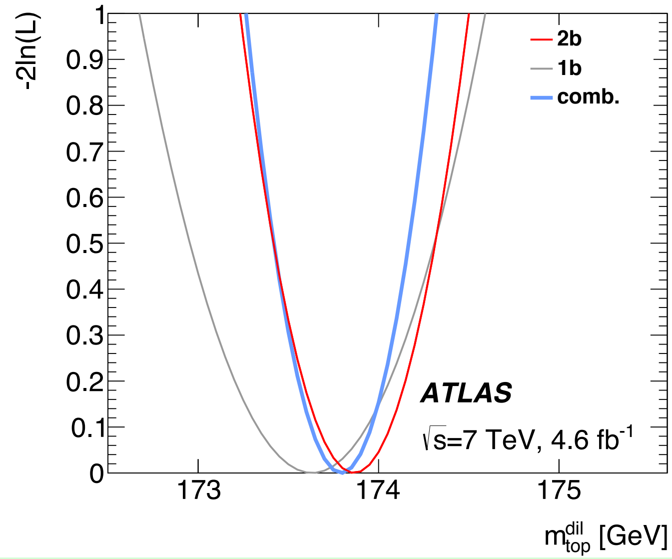
- ✧ Selection criteria based on m_{tt} potentially excludes W' model
- ✧ More data and higher Run II beam energy would improve the sensitivity greatly

Top Mass

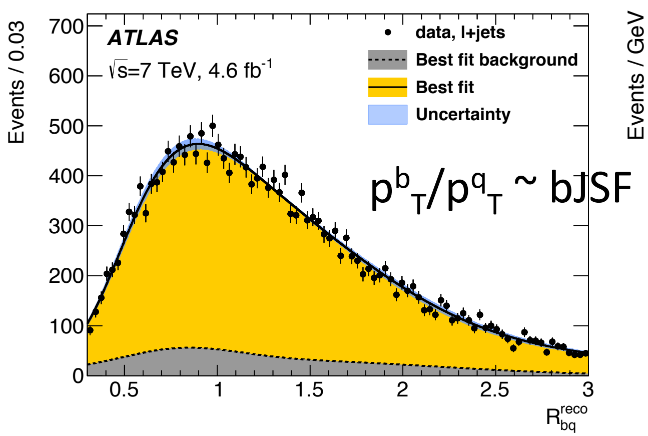
Top quark mass from $t\bar{t}$ events

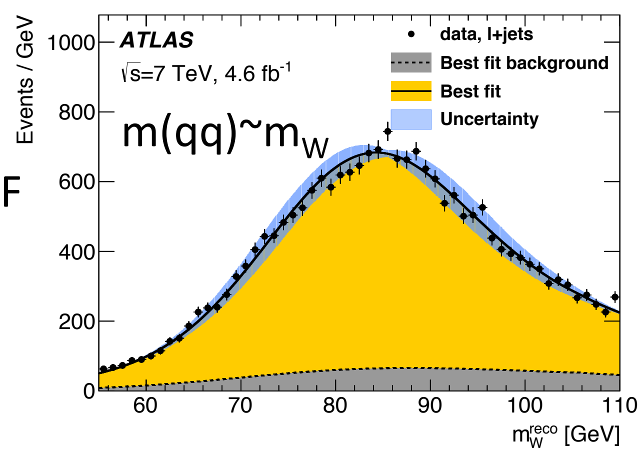
EPJC 75, 330 (2015)
arXiv:1503.05427 [hep-ex]

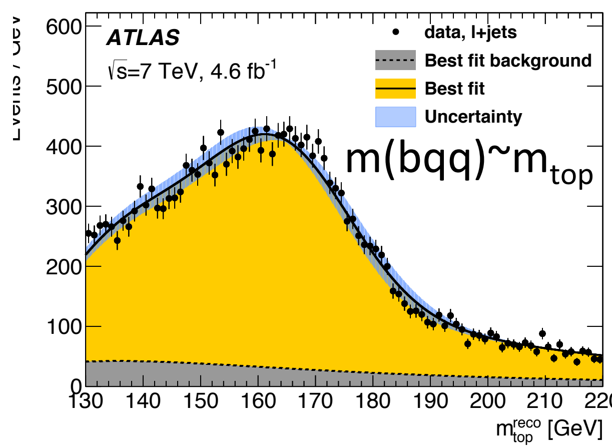
- Many experimental methods to extract the top quark mass
  - Reconstruction of object (e.g., W, top) kinematics for lepton+jets & dilepton events
  - Likelihood fit as functions of Jet Energy Scale Factor (JSF), b-jet JSF (bJSF) with a defined top quark mass MC (expected to be within 1 GeV of pole mass)
  - Dominant Uncertainties stem from
    - Theoretical: MC statistics, ISR/FSR, PDF, Underlying events, hadronization….
    - Experimental: Jet Energy Scale, Jet Energy Resolution, b-tagging, b-jet energy scale, Jet reconstruction efficiency, etc.



m_{top}=172.99 ± 0.48 (stat) ± 0.78 (syst) GeV



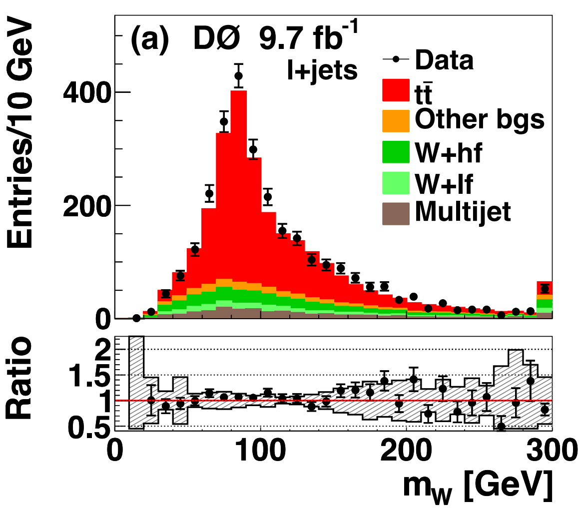


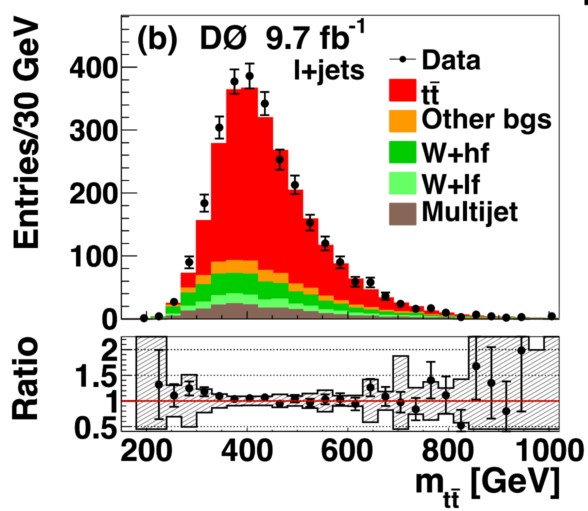


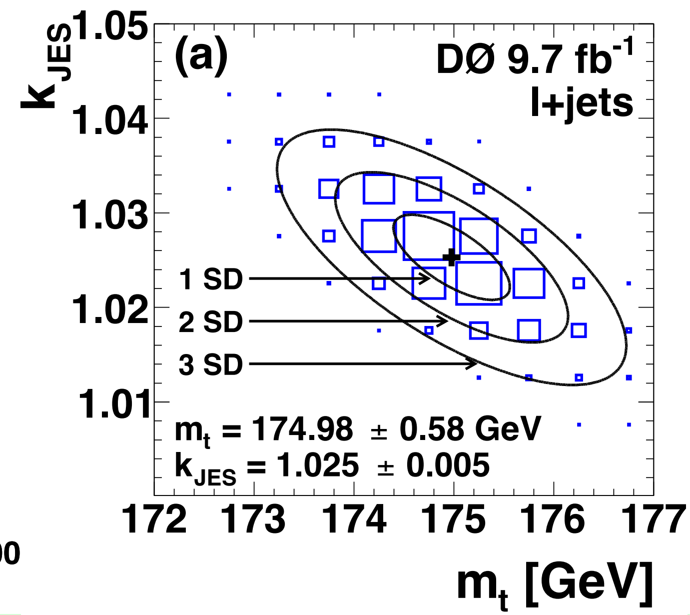
Top quark mass from $t\bar{t}$ events

- Matrix Element (ME) techniques using lepton+jets events considering m_{top}=172.5 GeV and 'in-situ' JES (by W mass).
  - Per-event Probabilility Density function: $P_{evt}=A(x)[f.P_{sig}(x;m_t, k_{JES}) + (1-f).\ P_{bkg}(x;k_{JES})]$; P_{sig}/P_{bkg} are PDs using ME for signal/W+jets and f is the signal fraction. W+jets and multijet events have similar PDs
  - 2D Likelihood fit as functions of JES and m_{top} as,

$$\mathcal{L}(\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N; m_t, k_{\mathrm{JES}})$$





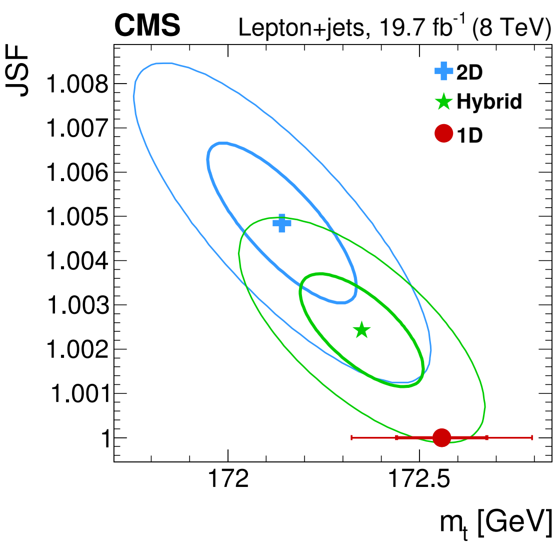


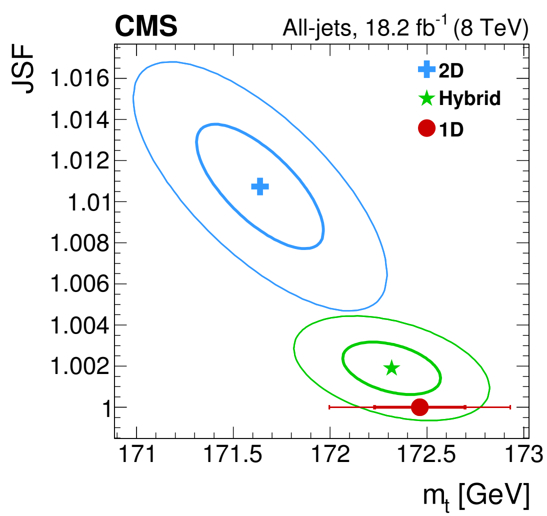
PRL 113, 032002 (2014)/arXiv:1405.1756 [hep-ex]

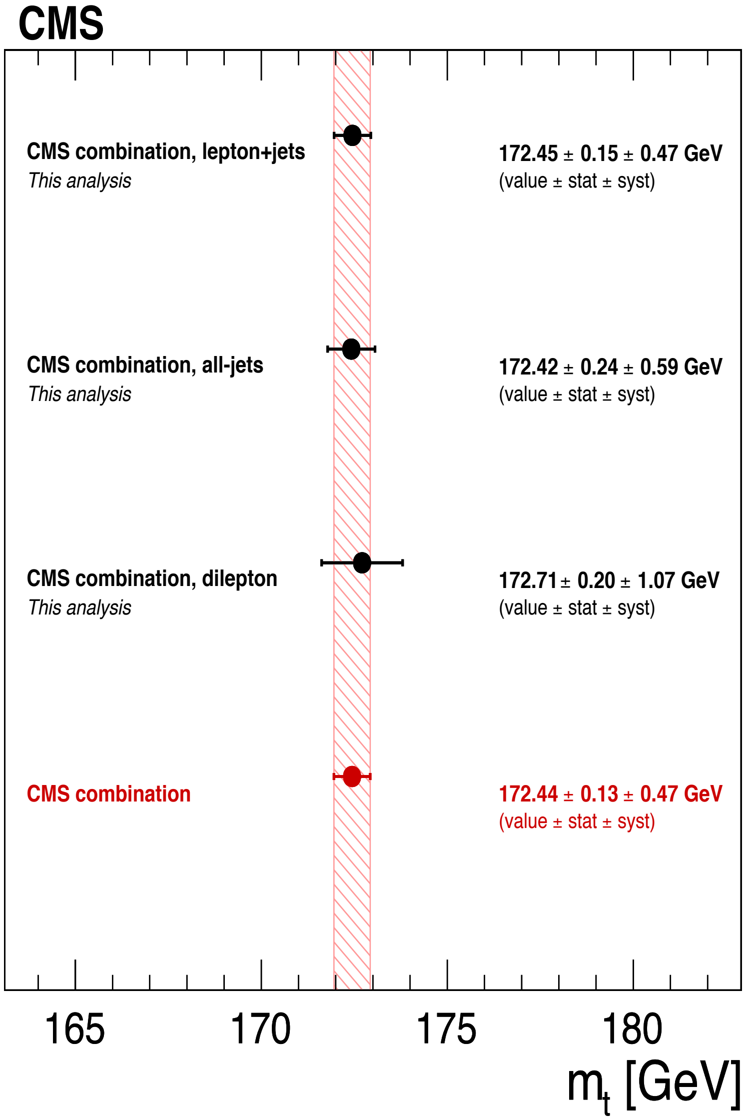
m_{top}=174.98 ± 0.58 (stat) ± 0.49 (syst) GeV

Top quark mass from $t\bar{t}$ events

- Measurement using all-jets, lepton+jets and dilepton events through constraining 'reconstructed W mass' at 80.4 GeV
  - 1-D/2-D Ideogram method for all-jets and lepton+jet channel as functions m_{top}, , and JSF (for 2-D case, i.e., the extra scale factor in addition to Jet Energy Scale Corrections); In 'Hybrid', prior JES knowledge is incorporated through Gaussian constraints.
  - Analytical Matrix Weighting Technique (AMWT) for dilepton channel



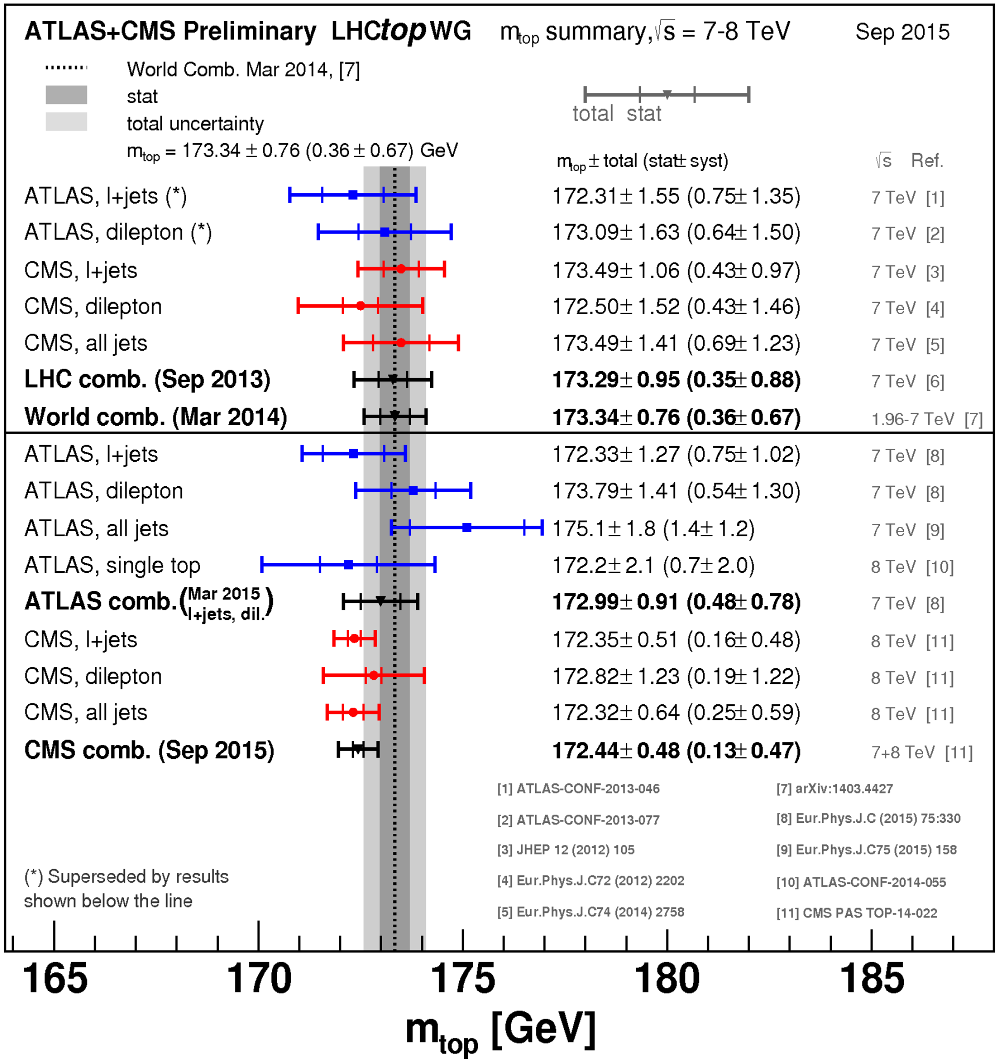




PRD 93, 072004 (2016)/arXiv:1409.04044 [hep-ex]

m_{top}=172.44 ± 0.13 (stat) ± 0.47 (syst) GeV

What's next on m_{top}?

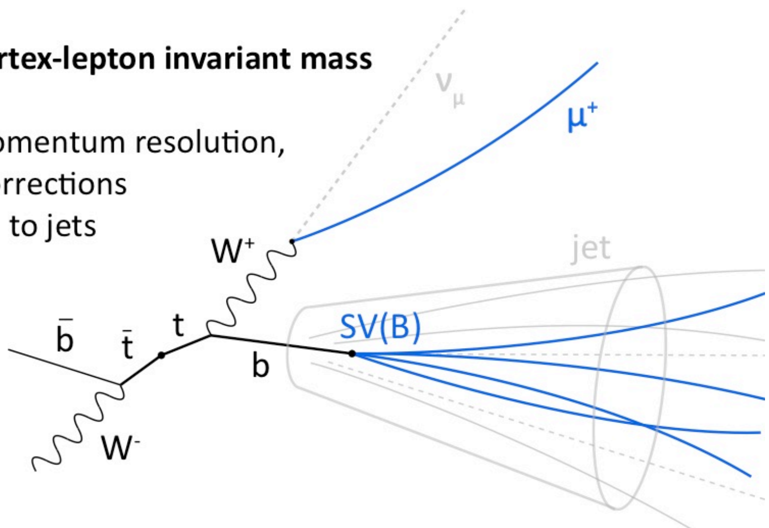


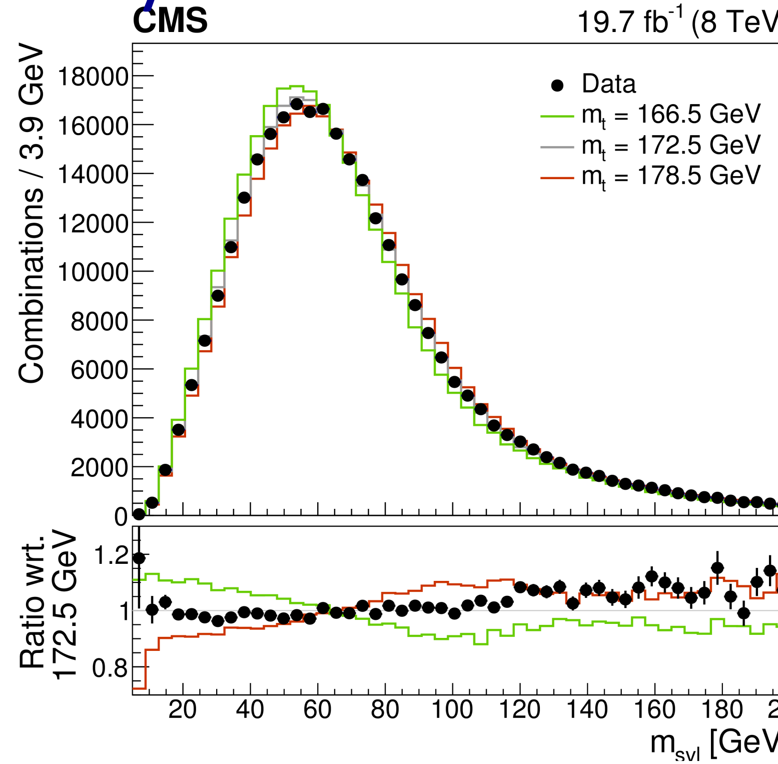
arXiv:1403.4427 [hep-ex]

- Results from Tevatron and LHC experiments are combined together → World Combination
- Reached a precision of 0.5 GeV (<0.3%).
- Precision is limited by the understanding of hadronization modeling
  - Studying Pythia vs Herwig
- Usage of experimentally clear observables avoiding jets
  - charged track & leptons
  - Vertex-lepton invariant mass
  - Using Charm mesons
- Top quark 'pole' mass?

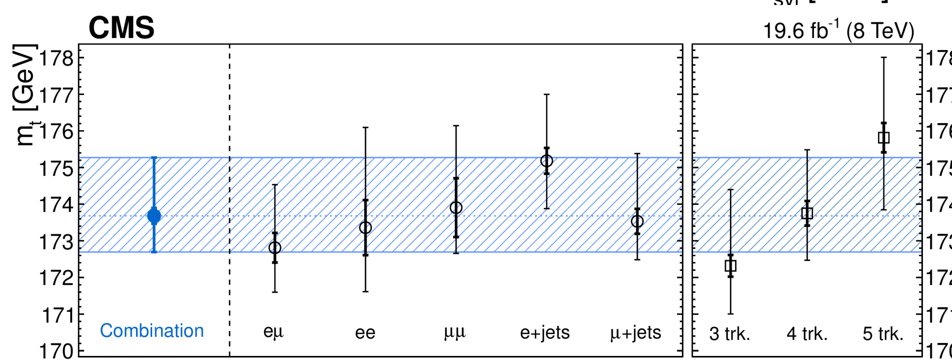
m_{top} using Secondary Vertex tracks

- Reconstruct **secondary vertex** from b-hadron decay
- Exploit **vertex-lepton invariant mass**
- Higher momentum resolution, smaller corrections compared to jets





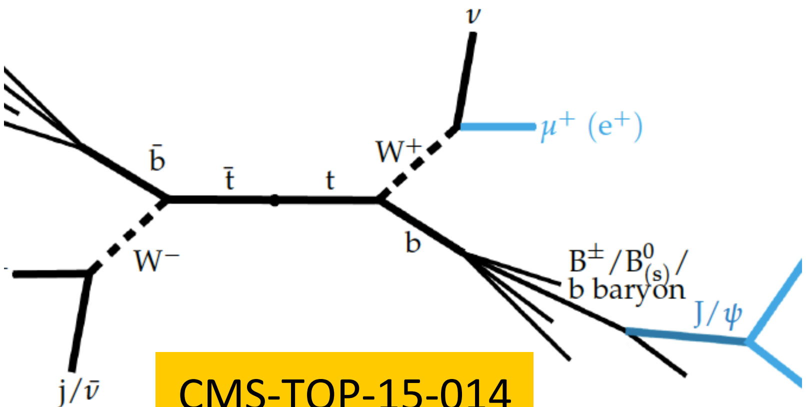
- Mass reconstruction of Lepton + Secondary Vertex in bins of SVX-track multiplicity
- Leading systematic uncertainties
  - B-fragmentation ($^{+1.00}_{-0.54}$ GeV)
  - Top quark p_T ($^{+0.82}$ GeV)
- Total experimental uncertainties <500 MeV



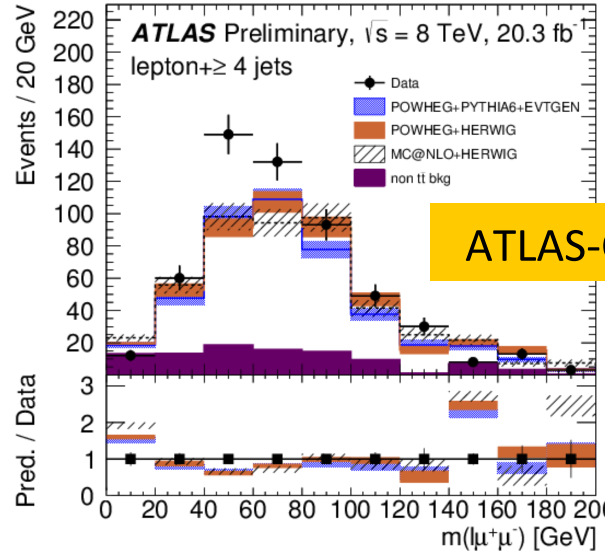
PRD 93, 092006 (2016)/arXiv:1603.06536 [hep-ex]

m_{top}=173.68 ±0.2 (stat)$^{+1.58}_{-0.97}$(syst) GeV

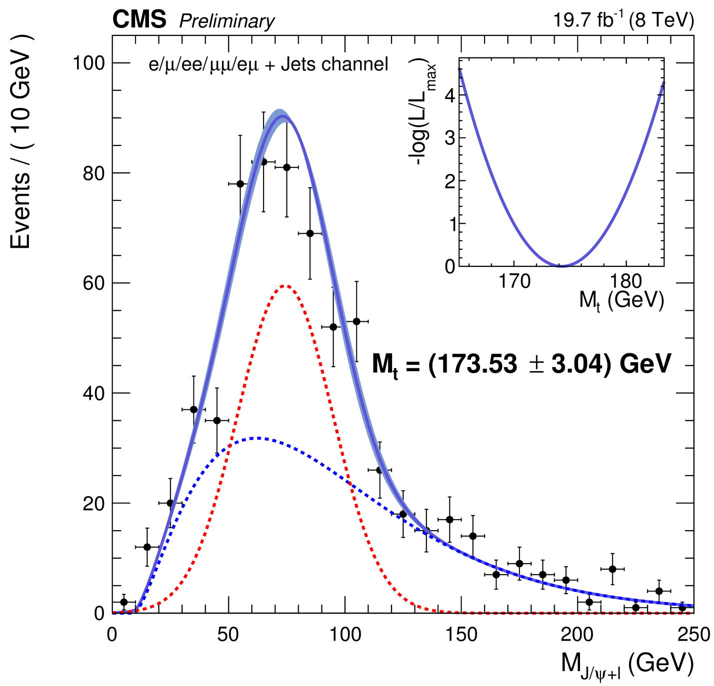
m_{top} using charm meson



CMS-TOP-15-014



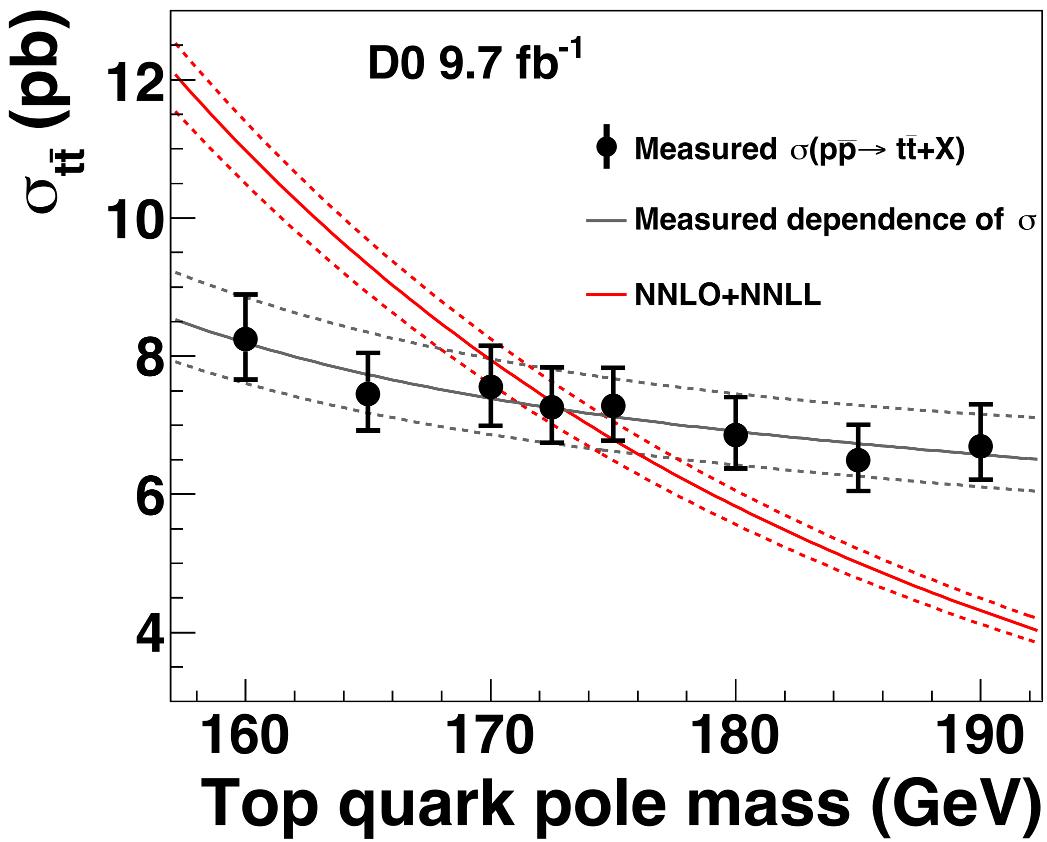
ATLAS-CONF-2015-040



- Reconstruction of Lepton + J/Ψ invariant mass
- Small branching fractions
  - 666 available events in 2012 dataset
  - Statistical uncertainty of 3.0 GeV
- However, systematic uncertainty <1 GeV
  - b-fragmentation ~ 0.3 GeV
  - Limited by top p_T modeling, QCD scales
  - Relevant experimental uncertainties < 100 MeV

CMS: m_{top}=173.5 ± 3.0 (stat) ± 0.9 (syst) GeV

Top quark pole mass



- Extraction of top quark pole mass (m_t^{pole}) from inclusive production cross-section (σ_{tt}) using lepton+jets and dilepton events

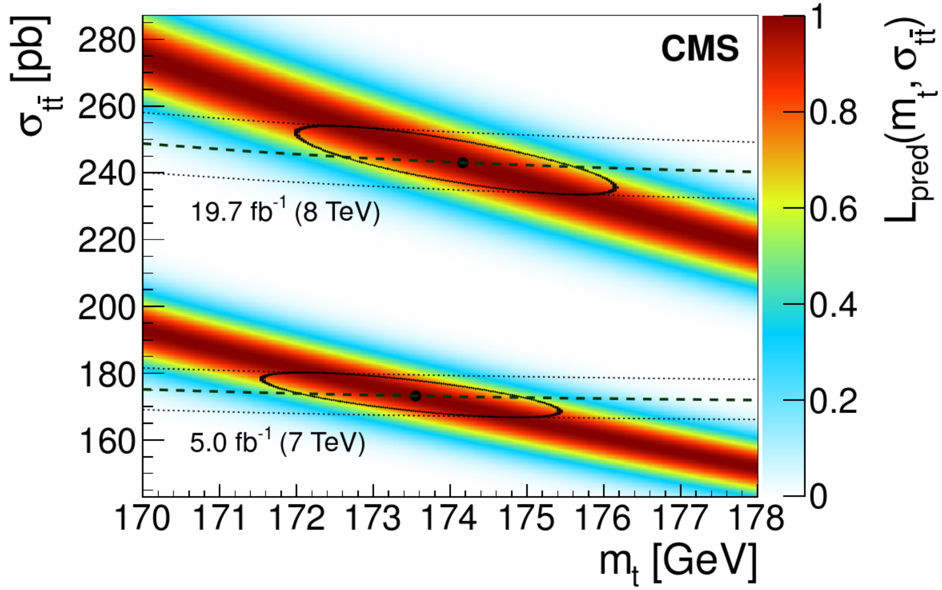
Top quark mass [GeV]	Cross section $\sigma(t\bar{t})$ [pb]
150	$9.70 \pm 0.16\,(\text{stat.})^{+0.73}_{-0.67}\,(\text{syst.})$
160	$8.25 \pm 0.14\,(\text{stat.})^{+0.63}_{-0.57}\,(\text{syst.})$
165	$7.46 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.51}\,(\text{syst.})$
170	$7.55 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.55}\,(\text{syst.})$
172.5	$7.26 \pm 0.12\,(\text{stat.})^{+0.57}_{-0.50}\,(\text{syst.})$
175	$7.28 \pm 0.12\,(\text{stat.})^{+0.54}_{-0.49}\,(\text{syst.})$
180	$6.86 \pm 0.12\,(\text{stat.})^{+0.53}_{-0.47}\,(\text{syst.})$
185	$6.50 \pm 0.11\,(\text{stat.})^{+0.50}_{-0.43}\,(\text{syst.})$
190	$6.70 \pm 0.11\,(\text{stat.})^{+0.60}_{-0.47}\,(\text{syst.})$

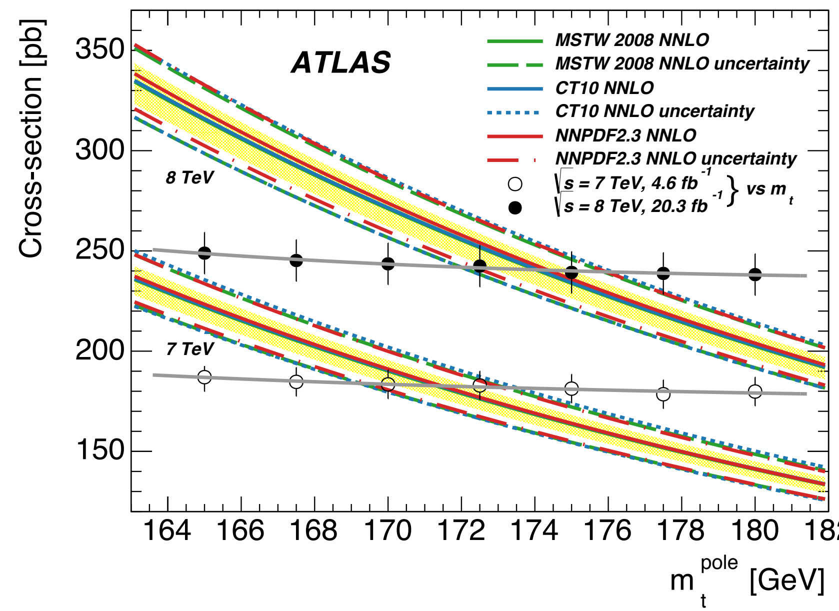
FERMILAB-PUB-16-180-E
Submitted to PRD (May, 2016)

$m_t^{pole} = 172.8\ ^{+3.4}_{-3.2}$ GeV

Top quark pole mass

CMS: arXiv:1603.02303 [hep-ex]
ATLAS: arXiv:1406.5375 [hep-ex]





- Extraction of top quark pole mass (m_t^{pole}) from inclusive production cross-section (σ_{tt})
- σ_{tt} can be calculated theoretically at NNLO for different values of m_t^{pole}
  - Acceptance also depends on m_t^{pole}
  - Fixed value of α_s
- Precision is limited by beam luminosity and beam energy

ATLAS: $m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV
CMS: $m_t^{pole} = 173.8^{+1.7}_{-1.8}$ GeV

Top quark pole mass

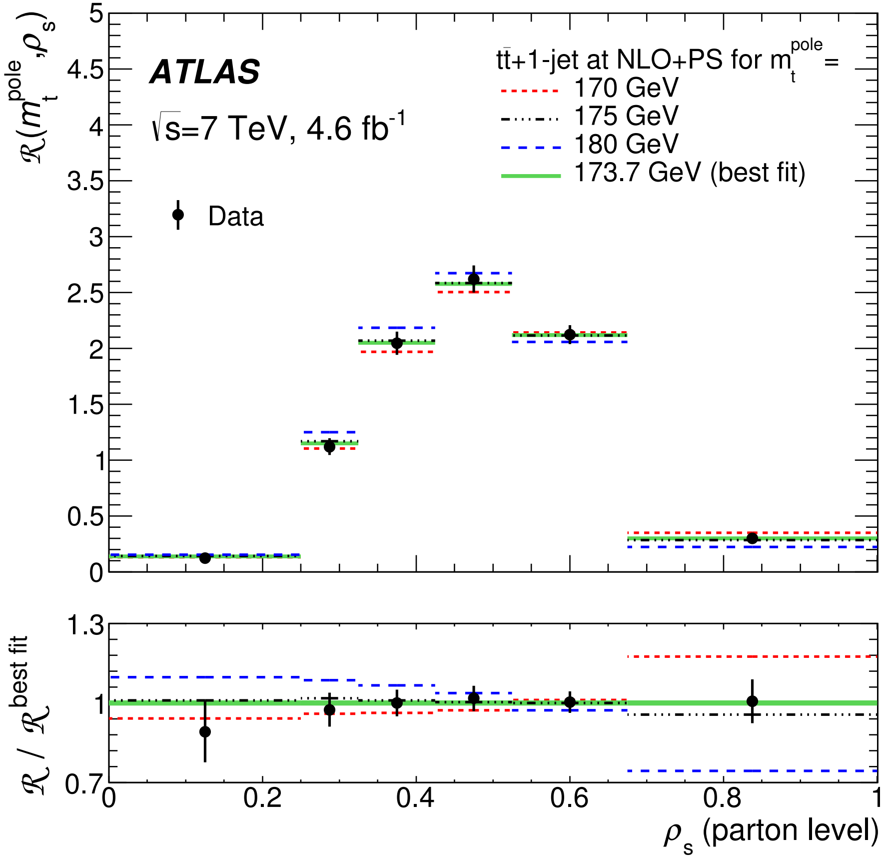
JHEP 10, 121 (2015)
arXiv:1507.01769 [hep-ex]

- Distribution shapes are more sensitive, but not limited by beam uncertainties.
- Normalized differential cross-section (in association with at least one extra jets) as a function of ρ_s is utilized to extract top quark pole mass (m_t^{pole}):

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s),$$

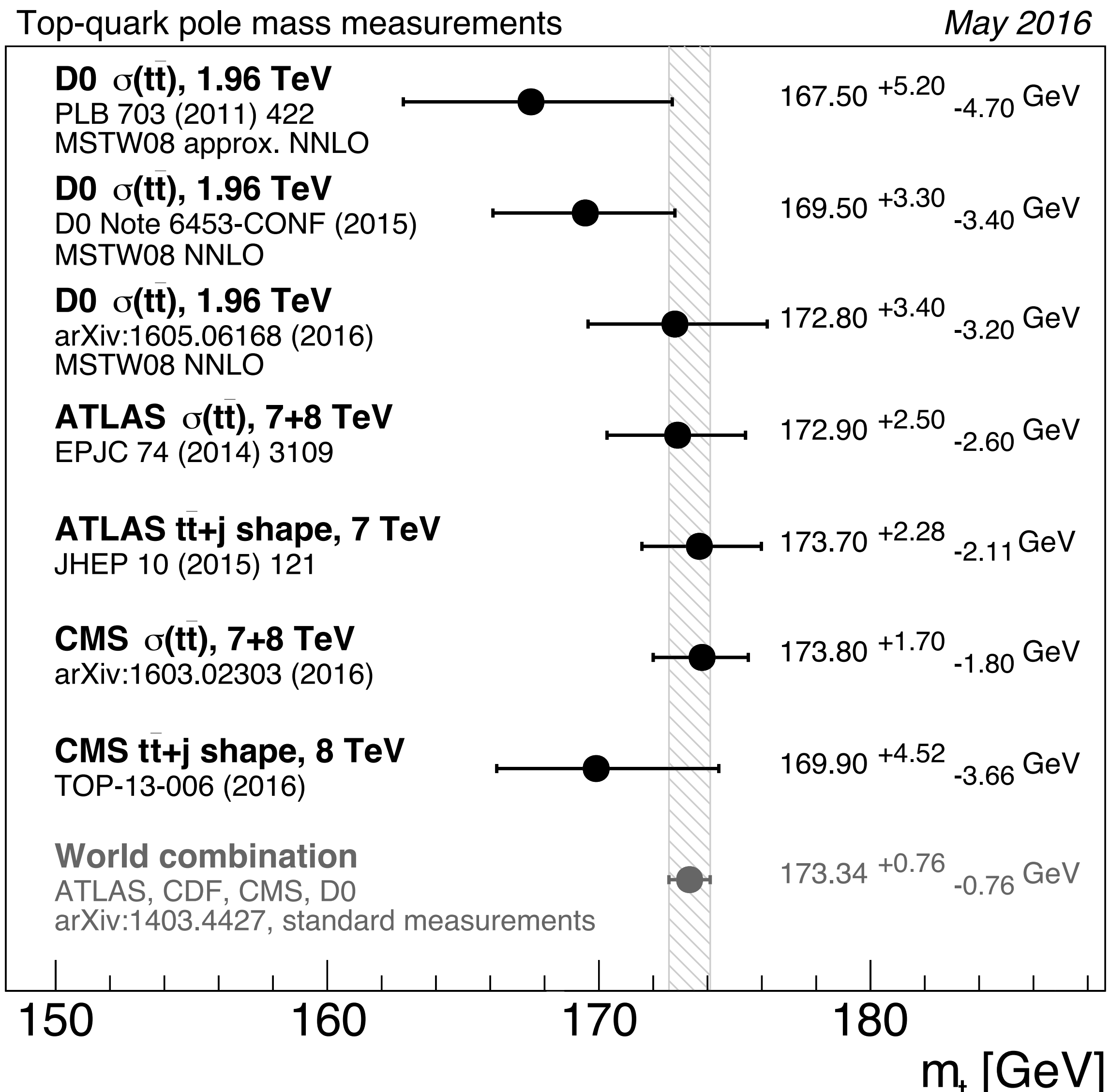
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}},$$

- Unfolded distributions are compared with the NLO MC to extract m_t^{pole}



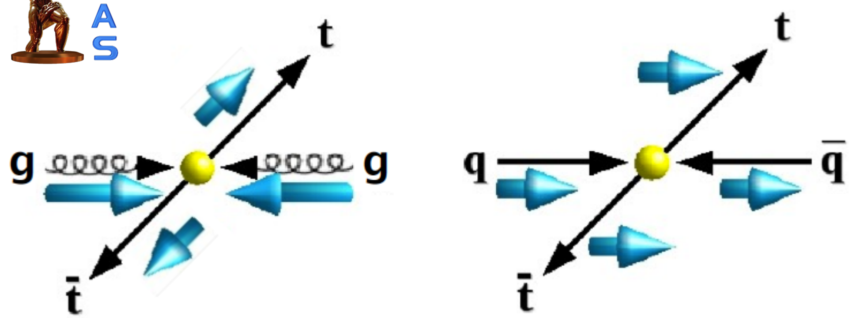
m_t^{pole} = 173.7 ± 1.5 (stat) ± 1.4 (syst) $^{+1.0}_{-0.5}$ (Theo) GeV

Summary on m_t^{pole}



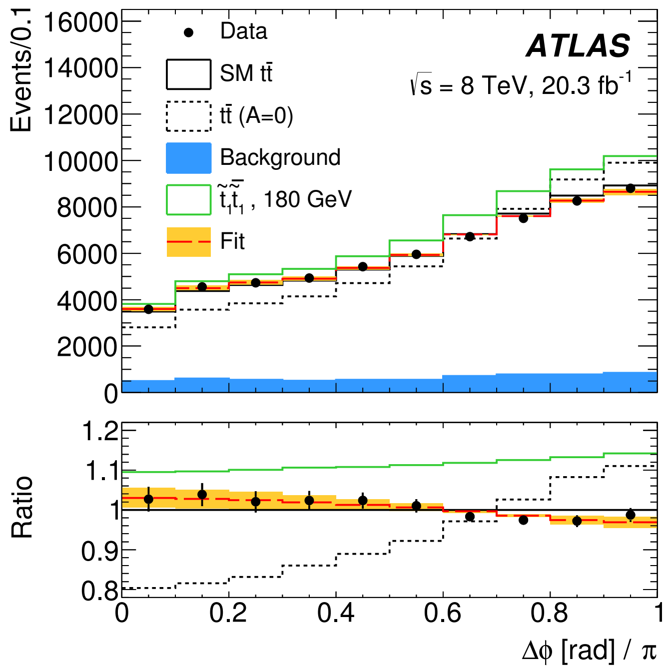
Top Spin correlation

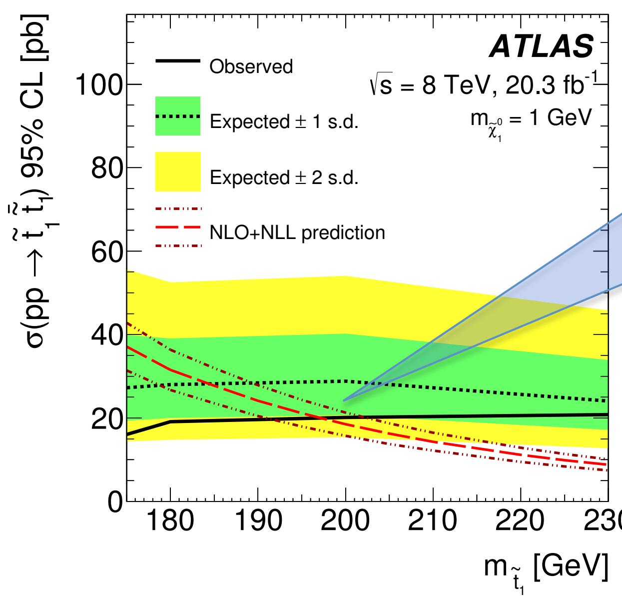
Spin correlation in $t\bar{t}$ events



$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{Uncor}^{t\bar{t}}}$$

- Heavy quark spins are correlated in QCD; Top quarks decay before their spins de-correlate.
- Dilepton angular distributions: $\Delta\varphi$ (in lab frame) or $\cos\theta_1$, $\cos\theta_1\cos\theta_2$,(in top rest frame)
- Can also be used to probe BSM physics
  - e.g, for stop-pair production, enhanced production rate would reduce the spin correlation



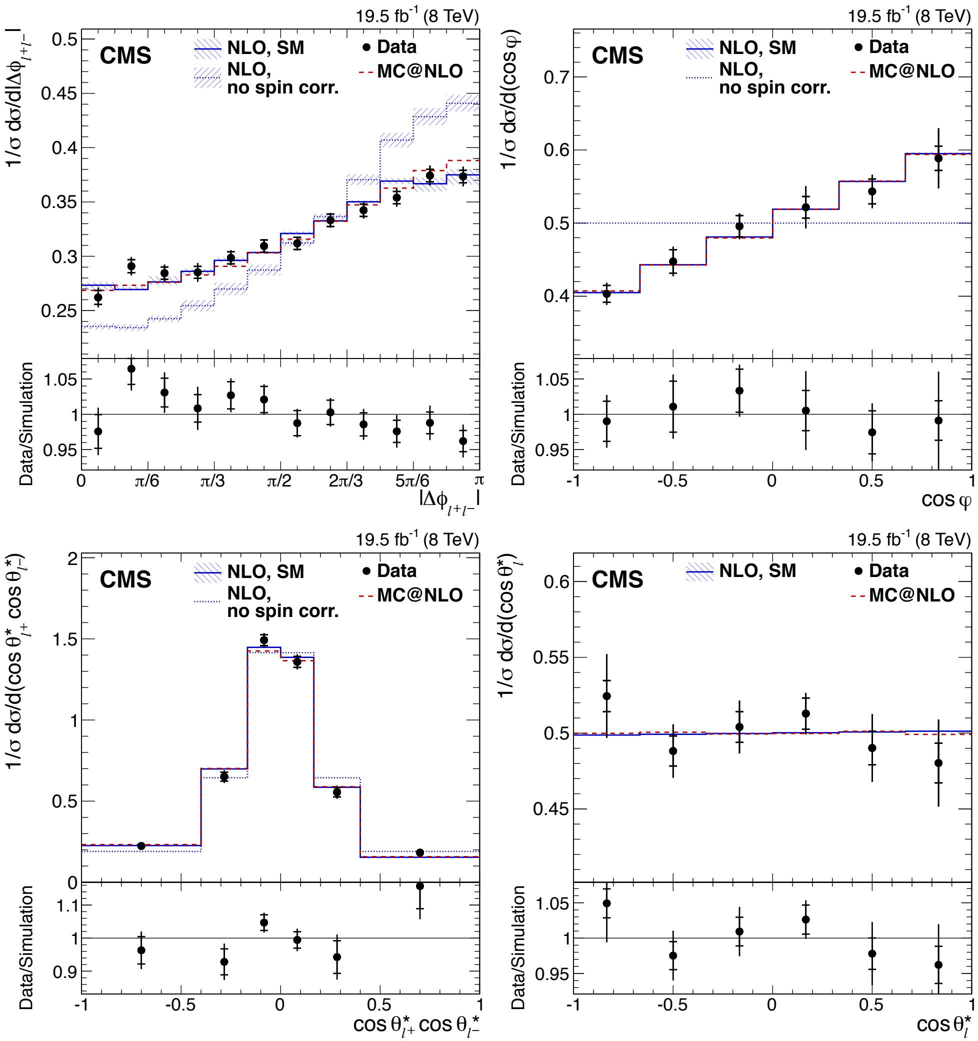


Stop masses excluded in the range of m_{top} and 191 GeV @95%CL

f_{SM} = 1.20 ± 0.05 (stat) ± 0.13 (syst)

arXiv:1412.4742 [hep-ex]; PRL 114, 0142001 (2015)

Spin correlation in $t\bar{t}$ events



- ✧ Inclusive distributions are unfolded at parton level
- ✧ Unfolding the angular distributions to obtain asymmetries:

Variable	$f_{SM} \pm$ (stat) $\pm$ (syst) $\pm$ (theor)	Total uncertainty
$A_{\Delta\phi}$	$1.14 \pm 0.06 \pm 0.13\,^{+0.08}_{-0.11}$	$^{+0.16}_{-0.18}$
$A_{\cos\varphi}$	$0.90 \pm 0.09 \pm 0.10 \pm 0.05$	± 0.15
$A_{c_1c_2}$	$0.87 \pm 0.17 \pm 0.21 \pm 0.04$	± 0.27
$A_{\Delta\phi}$ (vs. $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08\,^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

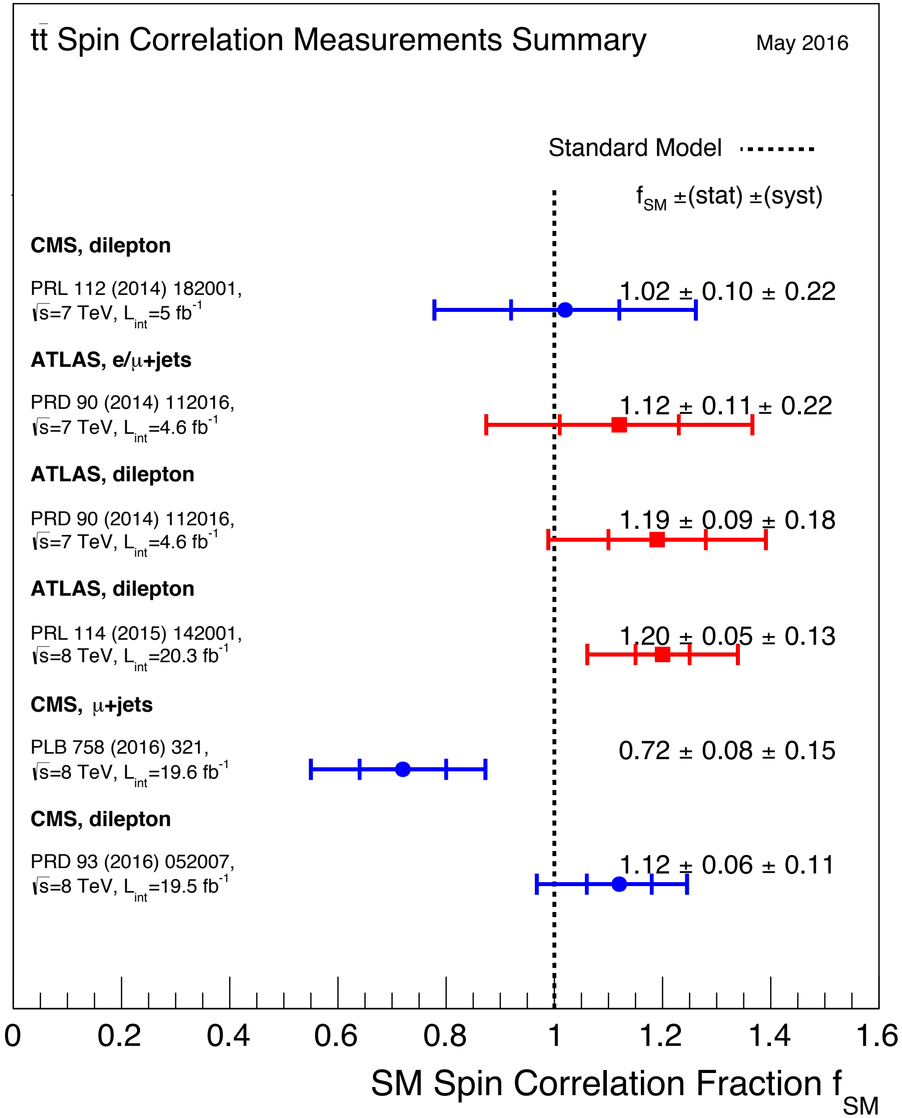
- ✧ Can also be utilized to set limits on chromomagnetic dipole moments e.g., assuming

$$\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|} = \left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|}\right)_{SM} + \mathrm{Re}(\hat{\mu}_t)\left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|}\right)_{NP}$$

$-0.043 < \mathrm{Re}(\mu) < 0.117$ @ 95% CL

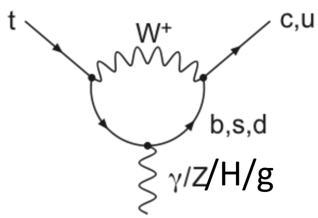
arXiv:1601.01107 [hep-ex]
PRD 93, 052007 (2016)

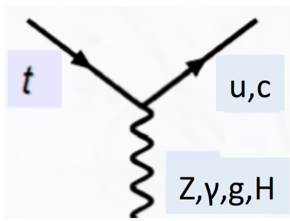
Summary from Tevatron & LHC



Rare decays

Top Flavor-changing neutral (FCN) interactions



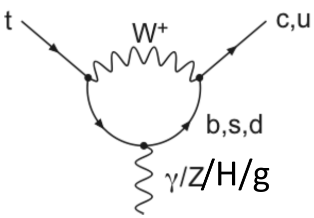


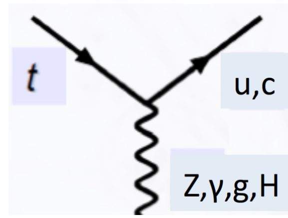
	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	$-$	$-$	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	$-$	$-$	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	$-$	$-$	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	$-$	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

arXiv: hep-ph/0309342
Acta Phys Polon B35 2695 (2004)

- BSM can enhance Flavor-changing Neutral current (FCN) couplings i.e., t→Z/H/γ/g + c/u by many orders of magnitude.
  - SM BR: 10^{-12}-10^{-17} --within the SM the suppression due to the GIM mechanism
  - BSM BR: 10^{-5}-10^{-10} – wide range depending om the BSM model
- t→H/Z + c/u are the largest for BSMs with tree level FCN coupling
- The radiative decays (t→ γ/g + c/u) have large branching ratios in Supersymmetric extensions of the SM.

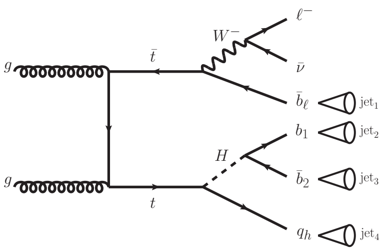
Flavor-changing neutral currents



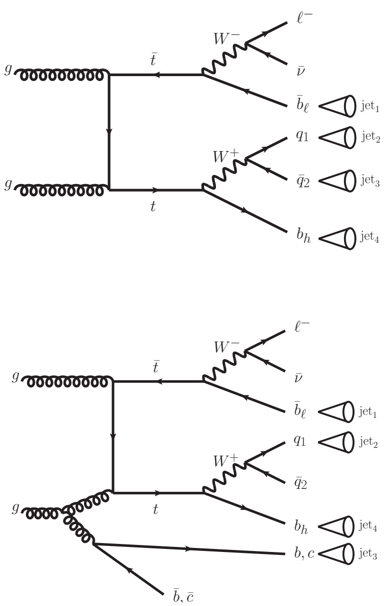


- BSM can enhance Flavor-changing Neutral current (FCNC) couplings by many orders of magnitude.
  - SM BR: 10^{-12}-10^{-17}
  - BSM BR: 10^{-5}-10^{-9}
- BR(t→Hc) and BR(t→Hu) by fitting using discriminant distribution:

$$D(\mathbf{x}) = \frac{P^{\mathrm{sig}}(\mathbf{x})}{P^{\mathrm{sig}}(\mathbf{x}) + P^{\mathrm{bkg}}(\mathbf{x})}$$

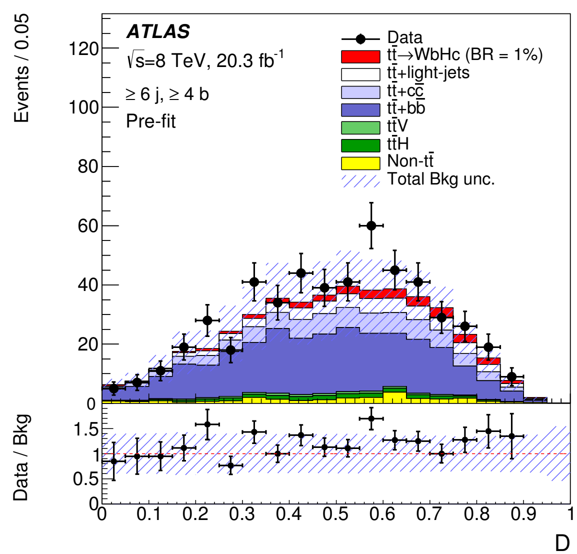


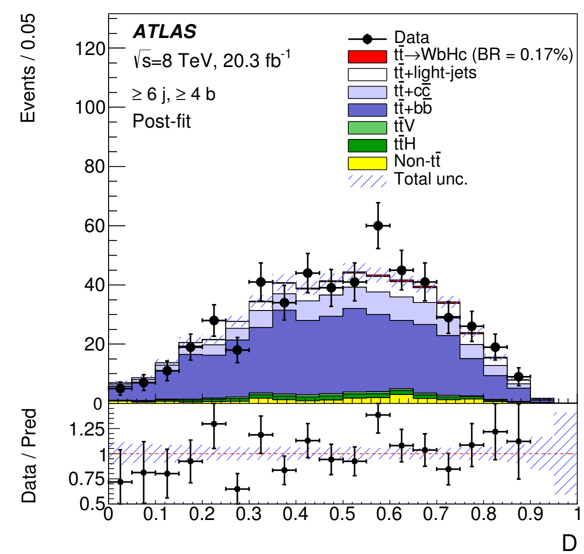
Signal



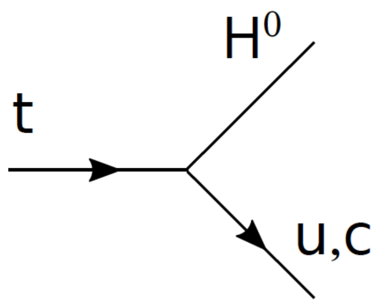
Background

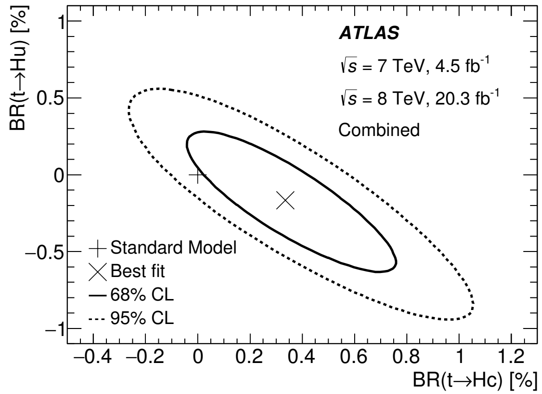
arXiv:1509.06047 [hep-ex]
JHEP 12, 061 (2015)

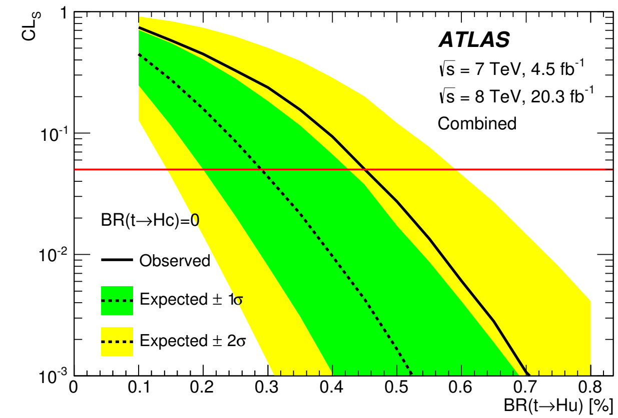




Flavor-changing neutral currents

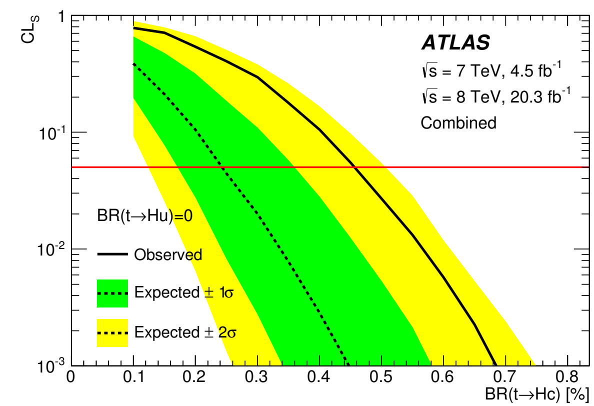


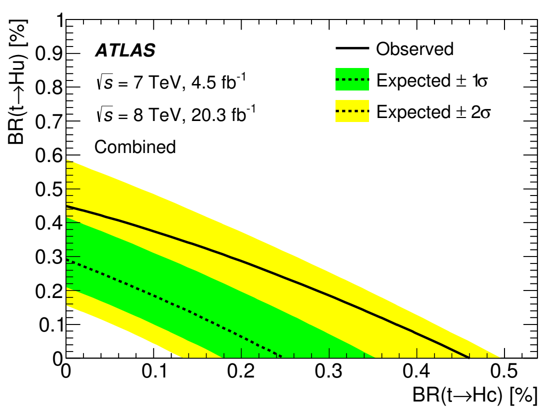


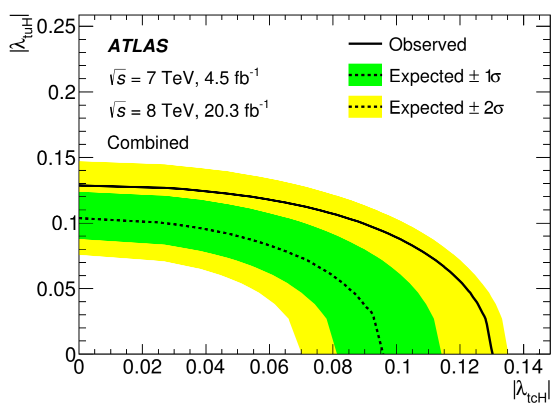


- ✧ **@95%CL Observed (Expected) Upper limits on**
  - ✧ **BR(t→cH): 0.56% (0.42%) – H→bb**
  - ✧ **BR(t→uH): 0.61% (0.64%) – H→bb**
    - ✧ **$|\lambda_{tcH}|$: 0.13 (0.10)**
    - ✧ **$|\lambda_{tuH}|$: 0.13 (0.10)**

In the absence of signal upper limits on BR(t→Hc) and BR(t→Hu)





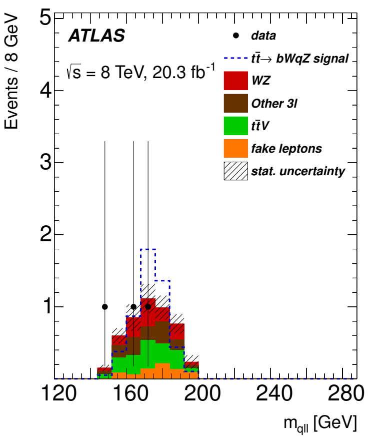


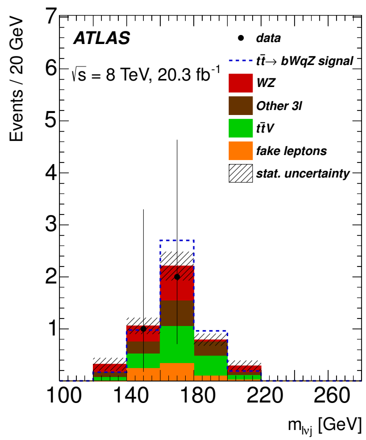
arXiv:1509.06047 [hep-ex]
JHEP 12, 061 (2015)

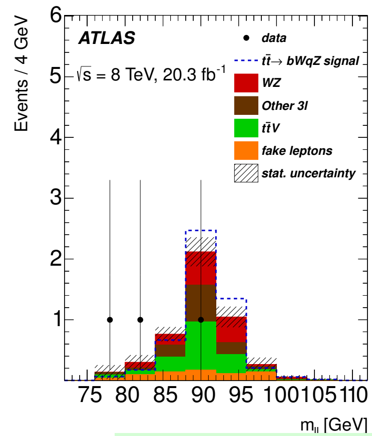
Flavor-changing neutral currents

Maximum allowed BR in different models:

Model:	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	RS
BR($t \to qZ$):	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}

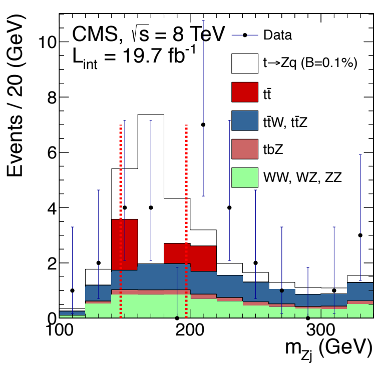


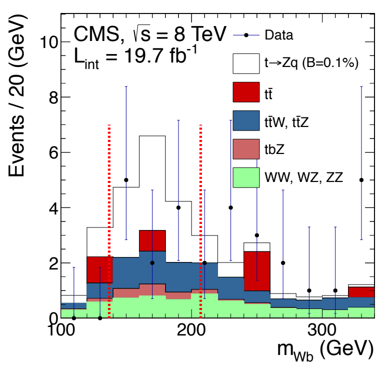


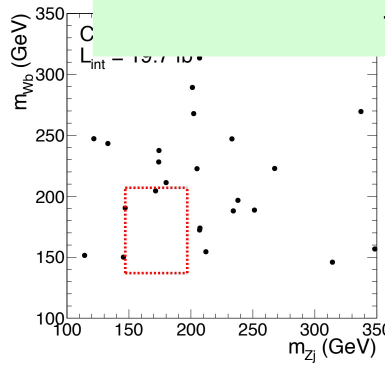


ATLAS: arXiv:1508.05796 [hep-ex]
EPJ C76, 12 (2016)

- ✧ @95%CL Observed (Expected) Upper limits on
  - ✧ ATLAS: BR(t→qZ): 7×10^{-4} (8×10^{-4})
  - ✧ CMS: 0.05% (0.09%)

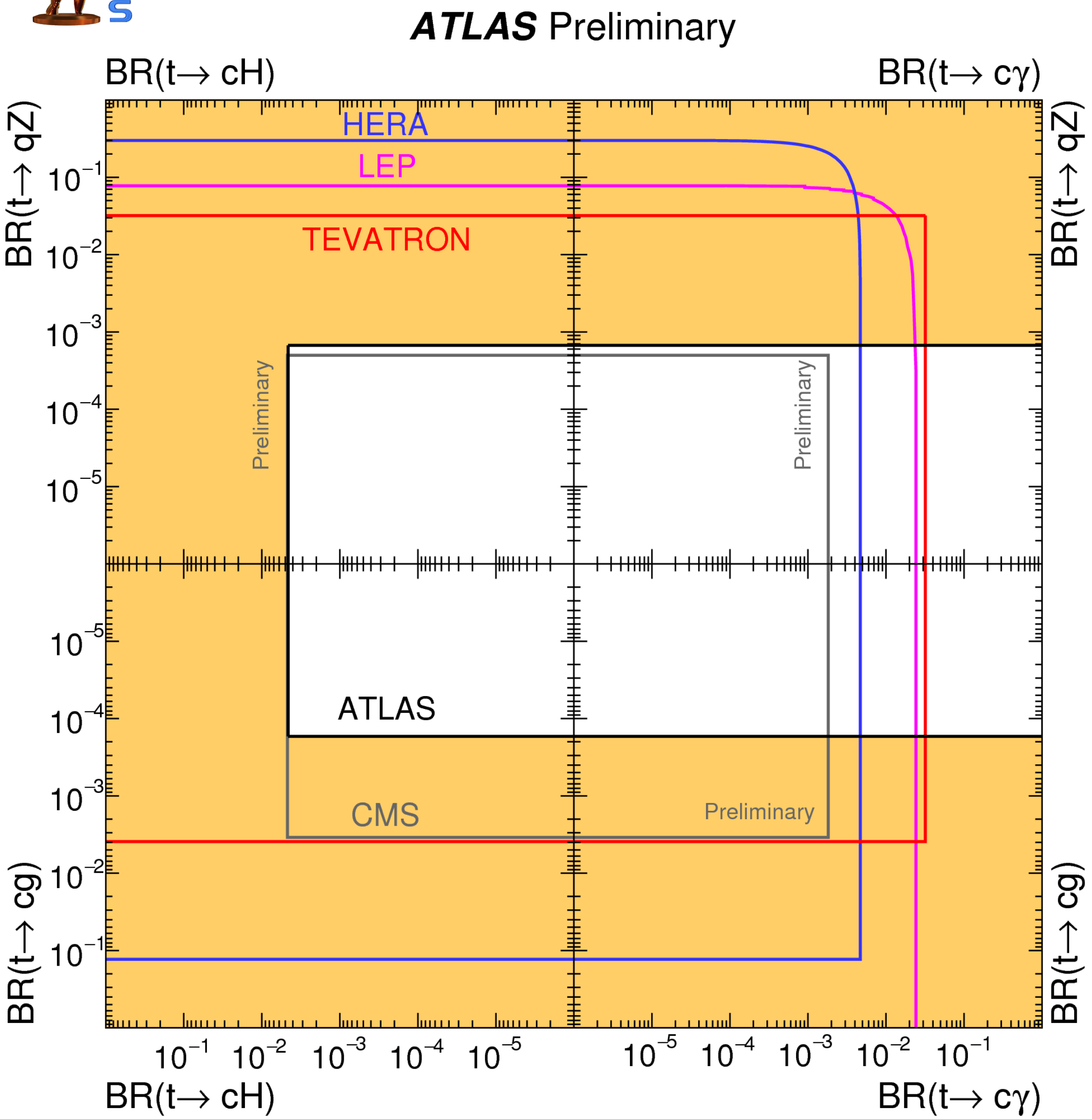






CMS:arXiv:1312.4194 [hep-ex]
PRL 112,, 171802 (2014)

Flavor-changing neutral currents



ATLAS: arXiv:1508.05796 [hep-ex]
EPJ C76, 12 (2016)

CMS:arXiv:1312.4194 [hep-ex]
PRL 112,, 171802 (2014)

- **@95%CL Observed (Expected) Upper limits on**
- **ATLAS: BR(t→qZ): $7\text{x}10^{-4}$ ($8\text{x}10^{-4}$)**
- **CMS: 0.05% (0.09%)**

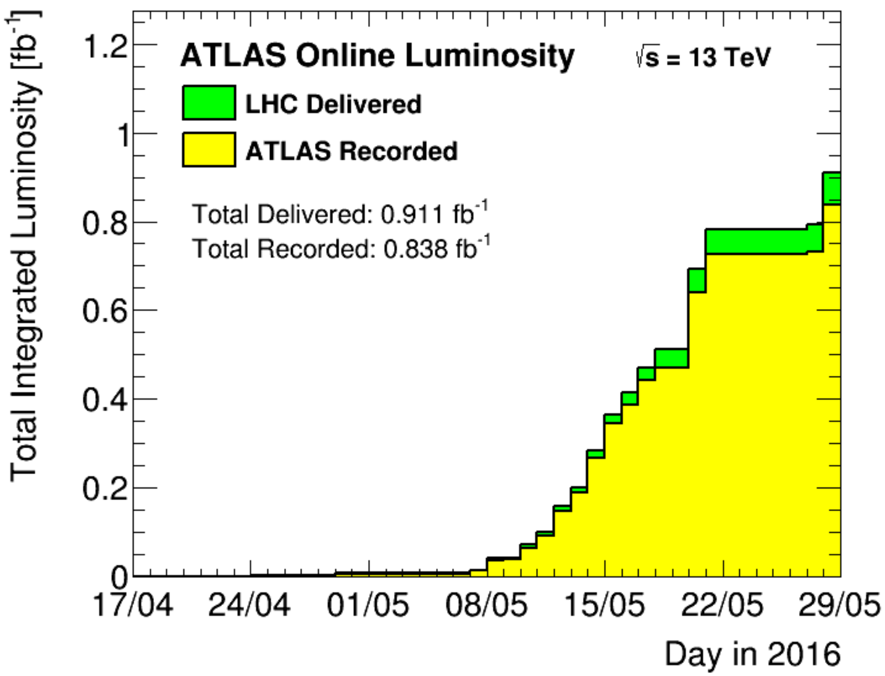
Complementary limits from LEP, HERA, Tevatron are superseded by the LHC ones

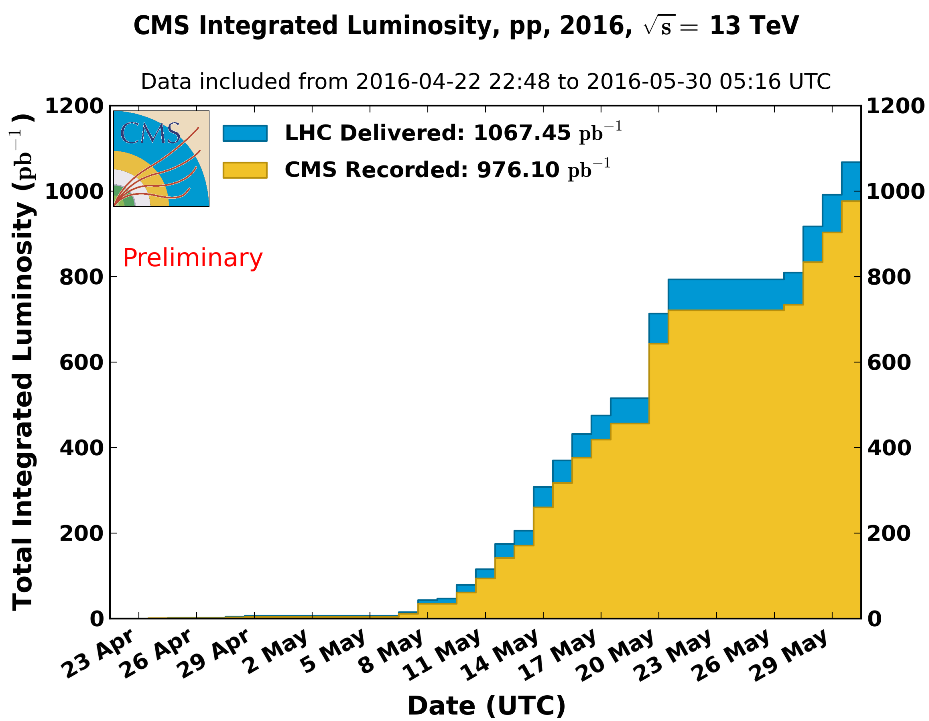
Summary & Conclusions

- Rigorous studies with the top quark events are at full swing
  - Experiments are finishing up the legacy papers (Tevatron & LHC Run I)
- 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 from Tevatron & LHC Run I
  - ttbar spin correlation
  - Forward-backward and Charge Asymmetry
  - Precision on Top quark mass <0.5 GeV; new techniques e.g., SV+lepton mass reconstruction would reduce it further
  - Rare decays e.g., FCNC are being probed
- Challenges for LHC Run II and beyond
  - Analysis with enhanced pile-up events
  - Reducing the systematic uncertainties

LHC Outlook (Run II & beyond)

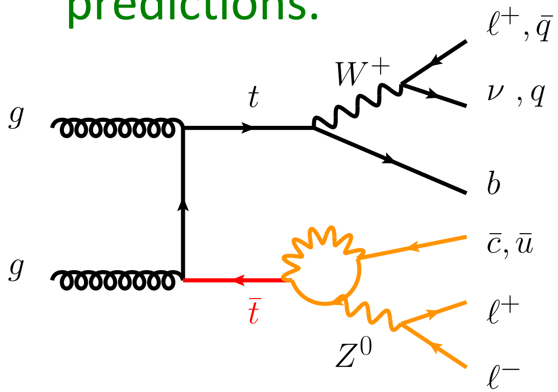
- ✧ LHC Run II at √s=13 TeV just began in 2015; we are in the early days of Run II
- ✧ New Physics discovery may be at the door-step and top quark properties would play the key role



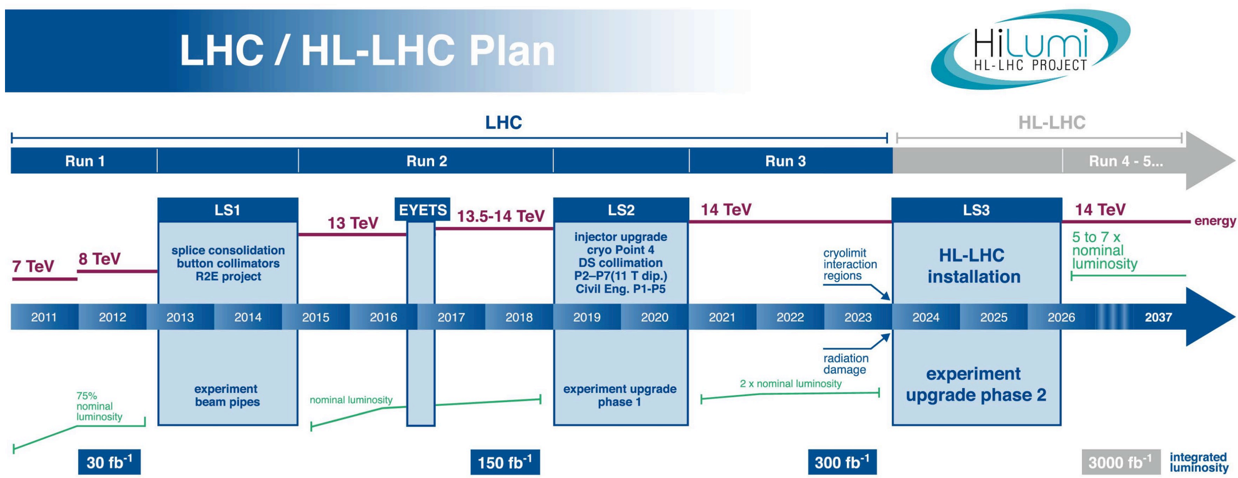


LHC Outlook (Run II & beyond)

- Many more upgrades with the LHC and the detectors are scheduled for next two decades. In addition analyses techniques would be refined further.
- 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.



CMS PAS FTR-13-016



$\mathcal{B}(t \to Zq)$	$19.5\ \mathrm{fb}^{-1}$ @ 8 TeV	$300\ \mathrm{fb}^{-1}$ @ 14 TeV	$3000\ \mathrm{fb}^{-1}$ @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$
1 σ range	0.06 – 0.13%	0.018 – 0.038%	0.007 – 0.014%
2 σ range	0.05 – 0.20%	0.013 – 0.051%	0.005 – 0.020%

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
- ✧ LHCb: http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/LHCb-PAPER-2015-022.html
- ✧ CDF: http://www-cdf.fnal.gov/physics/new/top/public_tprop.html
- ✧ **DØ:http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html**