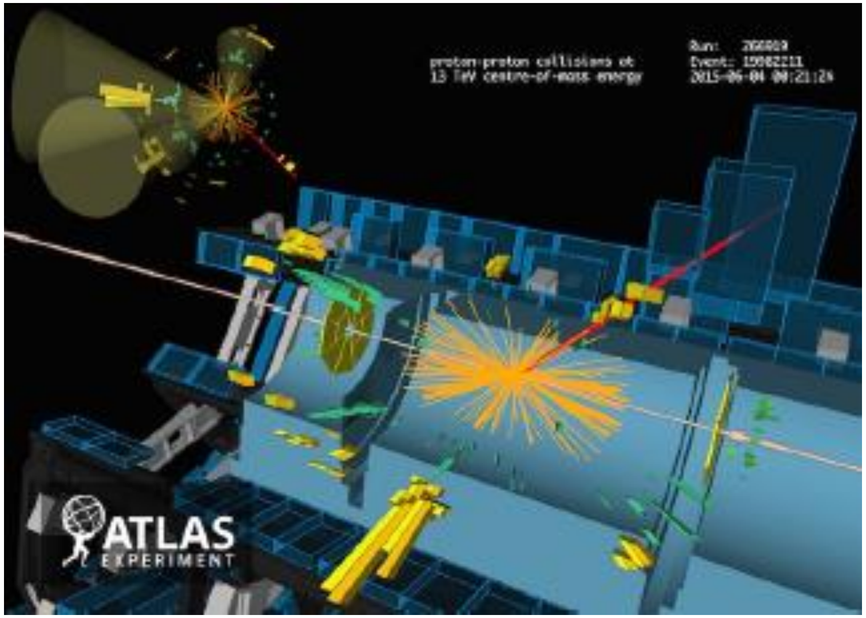
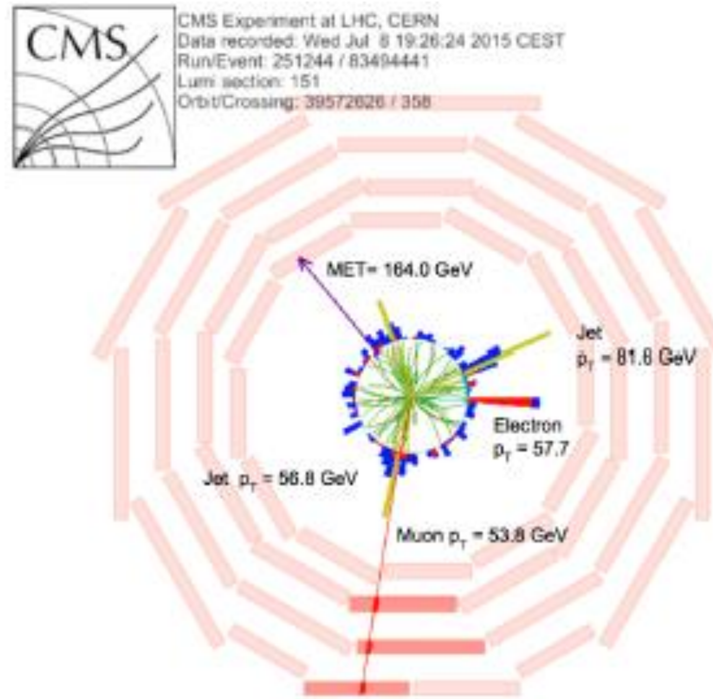


Review of Top Quark Properties at LHC and Tevatron



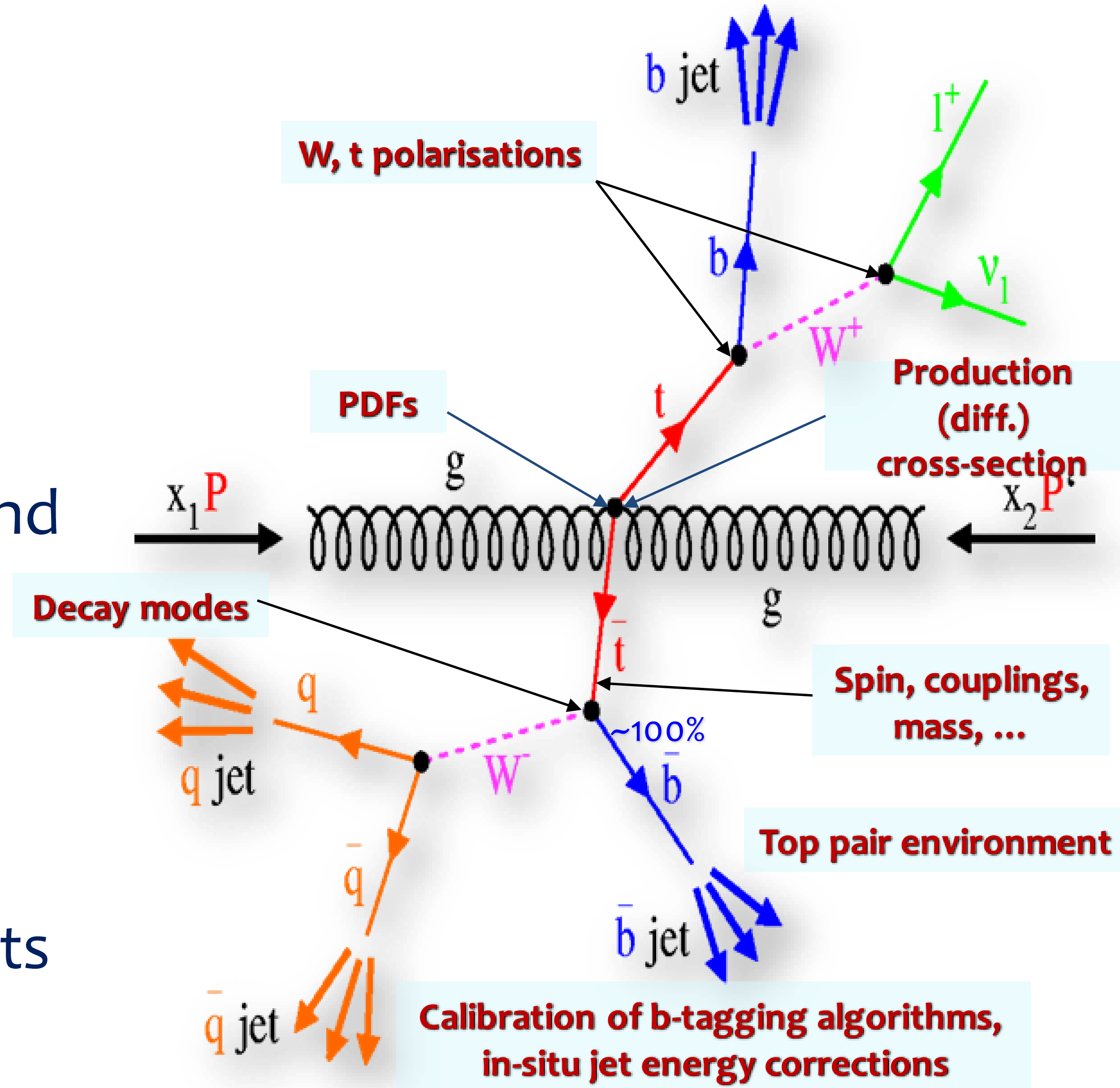
J. Cuevas
U. Oviedo (Spain)

on behalf of the **CMS, ATLAS, DZero and CDF** collaborations

Heavy Quarks and Leptons,
22 – 27th may 2016, Blacksburg, Virginia

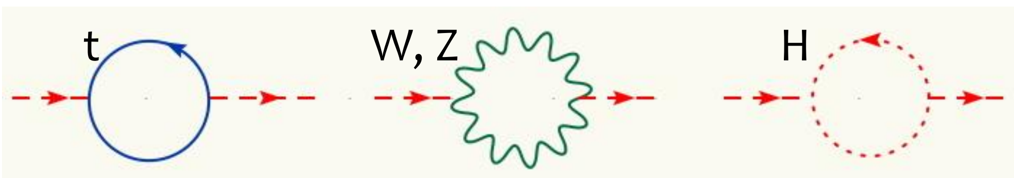
Outline

- Top quark properties
  - spin
  - Charge asymmetry
  - FCNC
  - Associated production
- Results on 7,8 and 13 TeV data, and Tevatron
- Top mass
  - Direct and indirect measurements



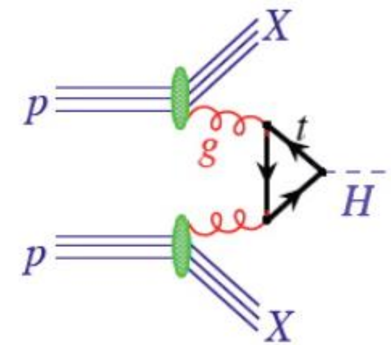
A particle with unique characteristics

- Special because of its enormous mass: heaviest known particle
  - Still a point-like particle in our understanding
  - The top and the Higgs are "strongly" coupled $y_t \approx 1 \quad m_t = y_t \mathrm{v}/\sqrt{2}$
  - The top mass dramatically affects the stability of the Higgs mass
    - If we consider the SM valid up to a certain scale Λ

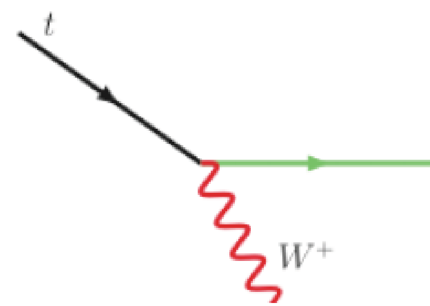


$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

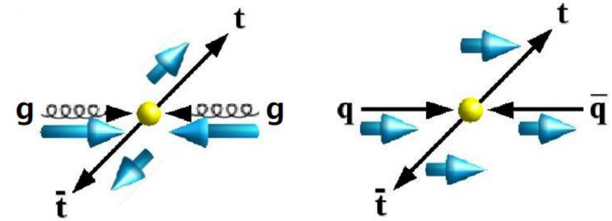


- It is the only quark that does not hadronise
  - ○ $\tau(\mathrm{had}) \sim h/\Lambda_{QCD} \sim 2\ 10^{-24}$ s
  - ○ $\tau(\mathrm{top}) \sim h/\Gamma_{top} \sim 5\ 10^{-25}$ s
  - ○ Compare with $\tau(b) \sim 10^{-12}$ s
  - ➢ Decays before forming a "dressed" top quarks
  - ➢ No bound tq states, its spin properties are directly passed to its decay products
  - ➢ QCD, Flavor and EWK physics at their best !

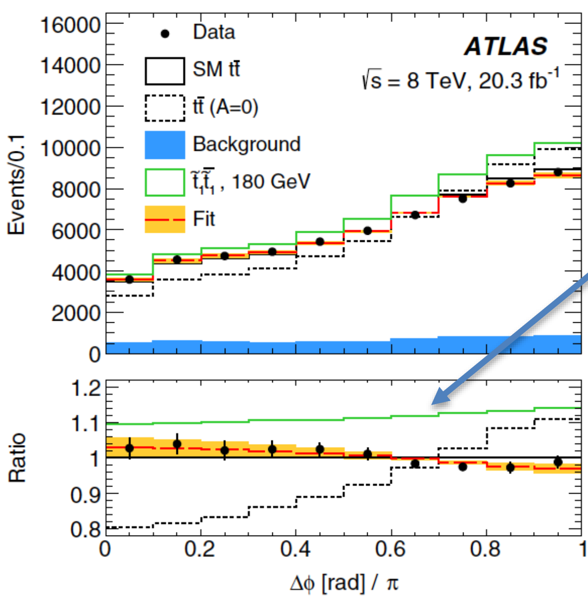


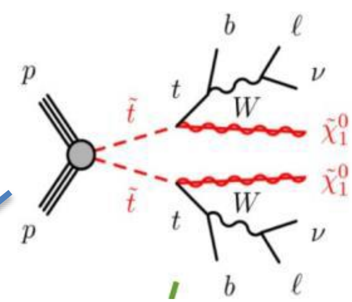
Top quark spin correlations

ATLAS, Phys. Rev. Lett. 114, 142001 (2015)
CMS, Phys. Rev. D 93, 052007 (2016)

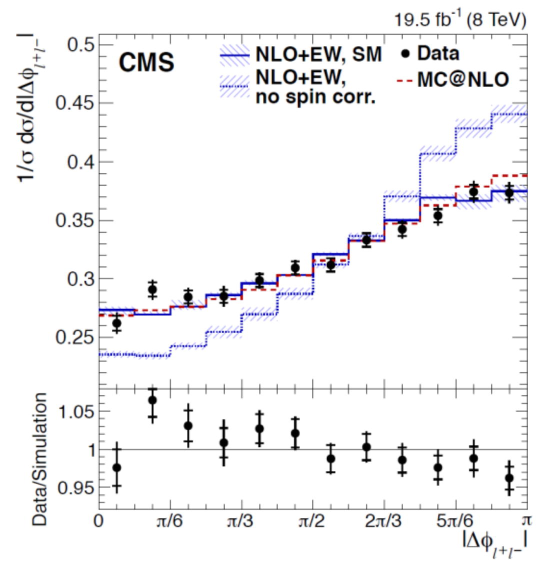


- Top quarks decay before spins de-correlate → measure
- Gluon helicities → top spin correlation → decay product. Max in low M_{tt} regime
- Lepton final state → ~100% transmission (for quark, depends on flavor), 2l channel: access with azimuthal angle between leptons in lab frame or in top rest frame vs a direction basis (helicity,…) …(direct).





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



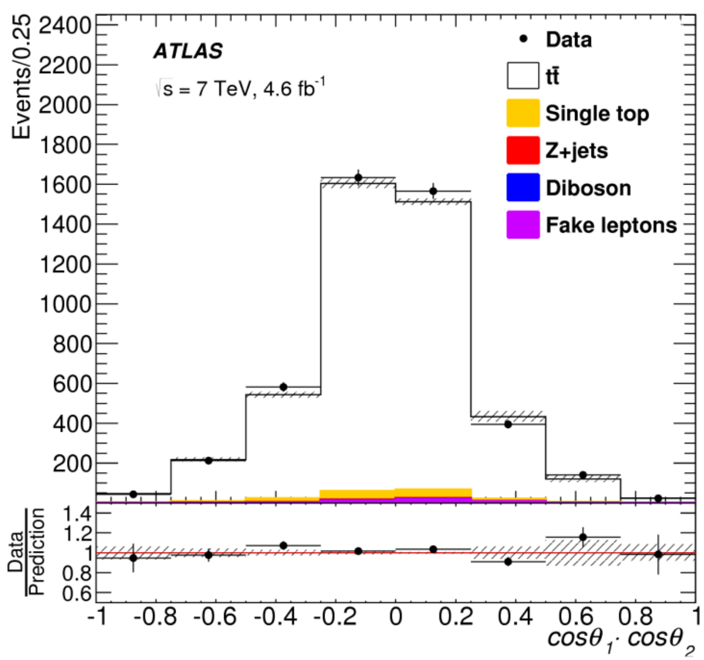
f_{SM}= 1.20 ± 0.05(Stat) ± 0.13(Syst) f_{SM}= 1.14 ± 0.06(Stat) ± 0.13(Syst) −0.11+0.08(theo)

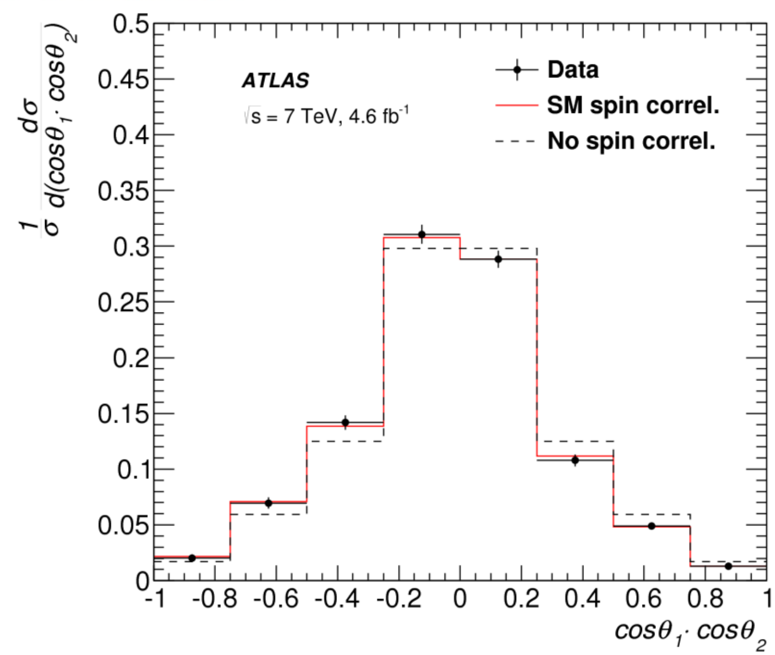
Spin Correlation: direct measurement

ATLAS Phys. Rev. D 93 (2016) 012002

- 2 OS ℓ, ≥ 2 high p_T jet , ≥ 1b, large E_t^{miss}
- Inclusive distrib. unfolded (bayesian) at parton level
- Direct extraction of C = - A $\alpha_1\alpha_2$ $A_{hel} = 0.315 \pm 0.061\ (\text{stat}) \pm 0.049\ (\text{syst})$
- Dominated by: unfolding uncertainties, theoretical modeling and jet reconstruction

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + B_1\cos\theta_1 + B_2\cos\theta_2 - C_{helicity}\cos\theta_1\cos\theta_2)$$



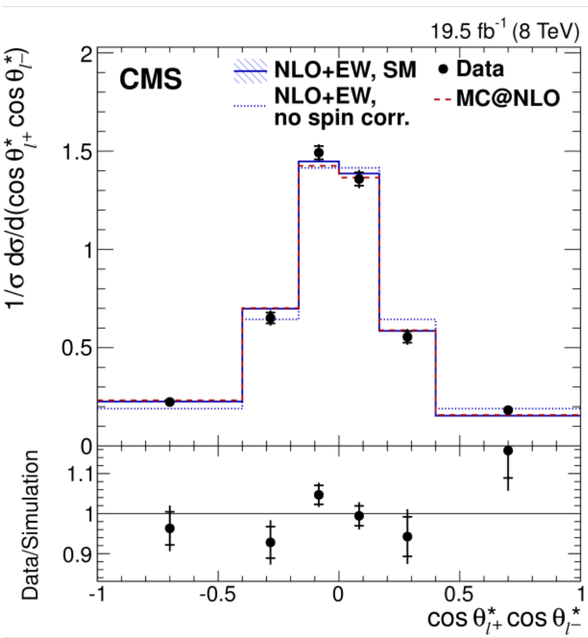


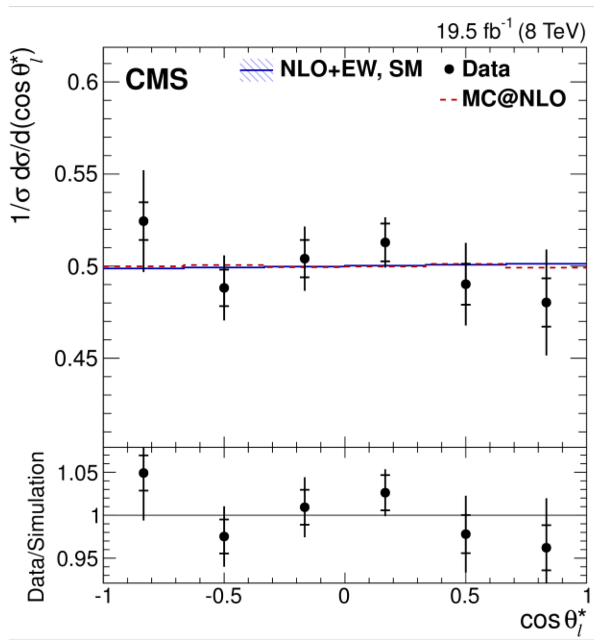
Spin Correlation: direct measurement

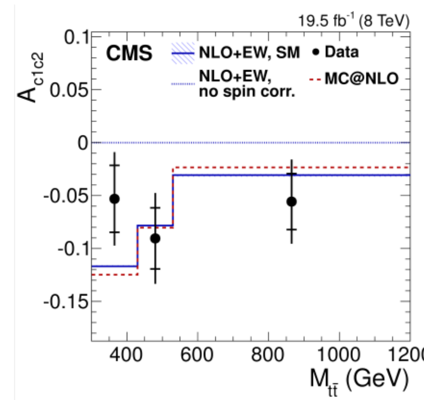
CMS Phys. Rev. D 93, 052007 (2016)

- Dilepton channel, reconstruction of tt final state.
- Unfolding all angular distributions, get asymmetries:

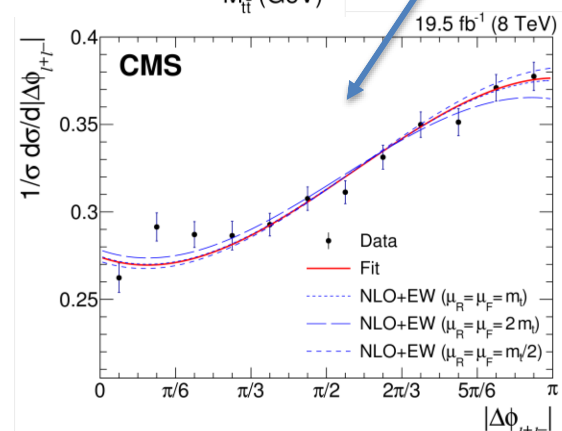
$A_{\Delta\varphi}$, A_h ,$A_{\cos\varphi}$, A_P , they provide direct measurement of spin correlation strength and polarization.







Search for top chromo-magnetic couplings

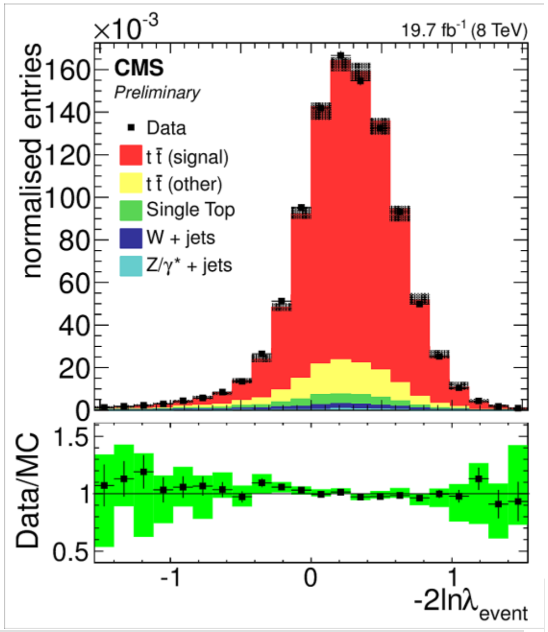


A_h= -0.069 ± 0.013(Stat) ±0.016(Syst)
$\rightarrow f_{SM}$= 0.87 ± 0.17(Stat) ± 0.21(Syst) ±0.04(theo)

A_P= -0.011 ± 0.007(Stat) ± 0.028(Syst)
$P^{CPC} = (-2.2 \pm 5.8)\%$
$P^{CPV} = (-0.0 \pm 1.6)\%$

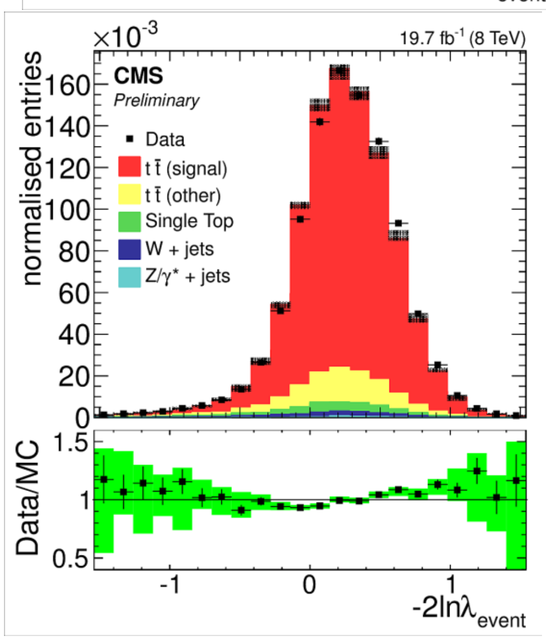
Uncertainties dominated by top p_T modeling and JES

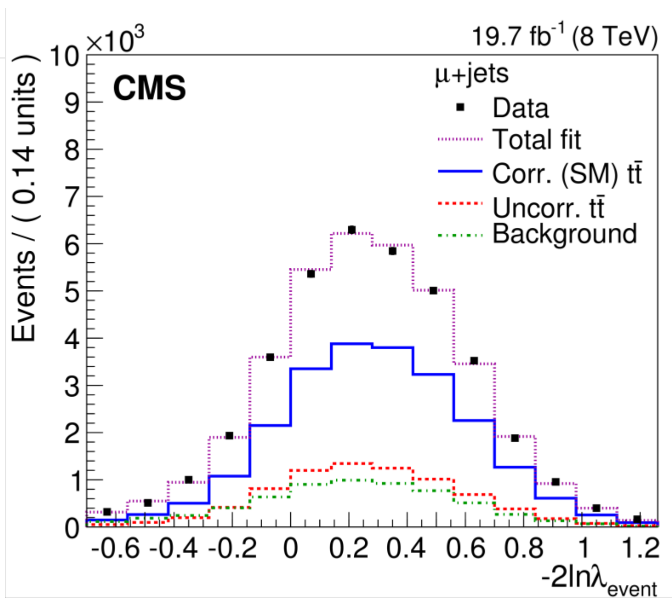
Spin correlation 1l+j 8TeV : ME method

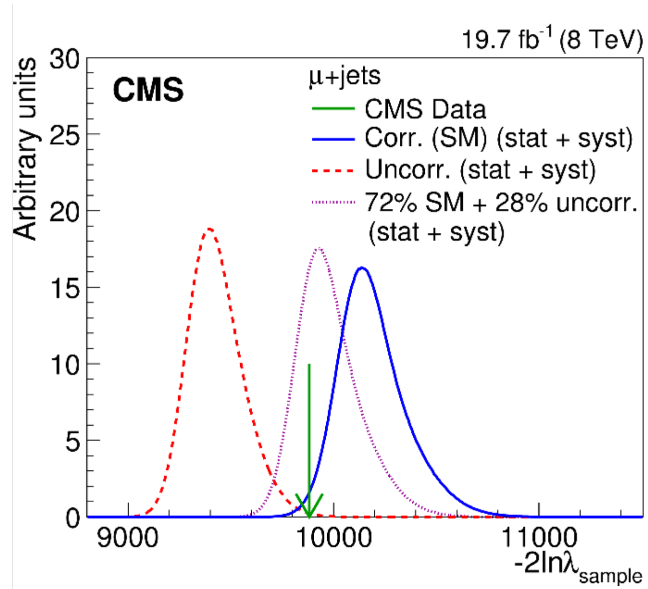


arXiV 1511.06170, accepted PLB

- μ +jets channel with 4,5 jets using kinematic fitter
- LO Matrix Element Method for event likelihoods (MadWeight) under SM or uncorrelated
  - Most precise in lepton+jets



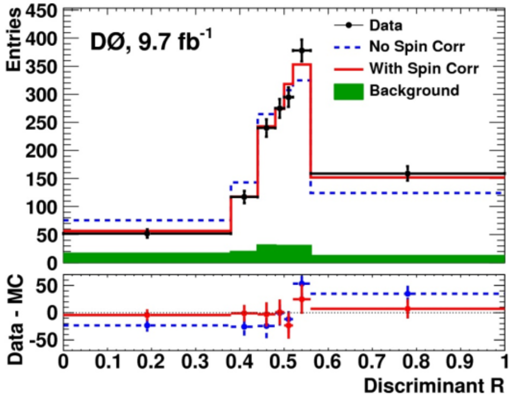




$f_{SM} = 0.72 \pm 0.08(\text{Stat.})\ {}_{-0.13}^{+0.15}(\text{Syst.})$

Spin Correlations and polarization, Tevatron

$$O_{ab} = \langle 4(S_t \cdot \hat{a})(S_{\bar{t}} \cdot \hat{b}) \rangle = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)},$$

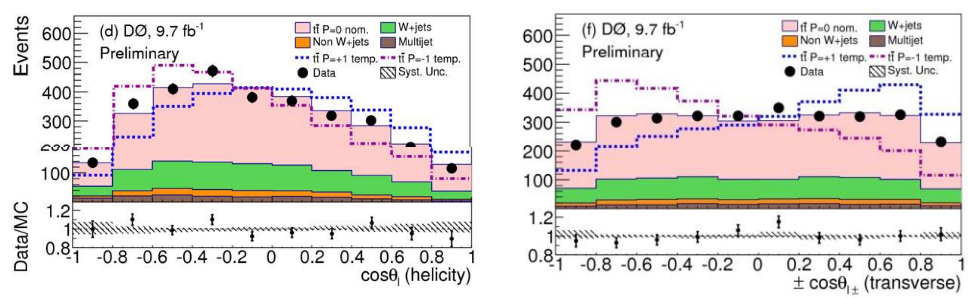


O$_{off}$ = $0.80^{+0.01}_{-0.02}$ predicted in the off-diagonal spin basis (maximal at the Tevatron)
qq has a spin correlation strength of ~0.99
and gluon-gluon of ~-0.36

- Fit the data allowing the total cross section and the fraction of “With Spin Correlations” to Float, arXiv:1512.08818
- **O$_{off}$ = 0.89 ±0.16 (stat)±0.15 (syst)**
- **Exclude** the Uncorrelated scenario at 4.2σ level
- Assuming no BSM contributions, **f$_{gg}$=0.08±0.12(stat) ±0.11(sys)** (NLO prediction 0.135)

Polarization: DZero 6471 (2015)

Tops are almost unpolarized at the Tevatron
Transverse polarization allowed in strong interactions, and BSM can make them bigger
Data are consistent with zero polarization, and with the predicted SM values
First measurement of polarization along the transverse axis at a hadron collider



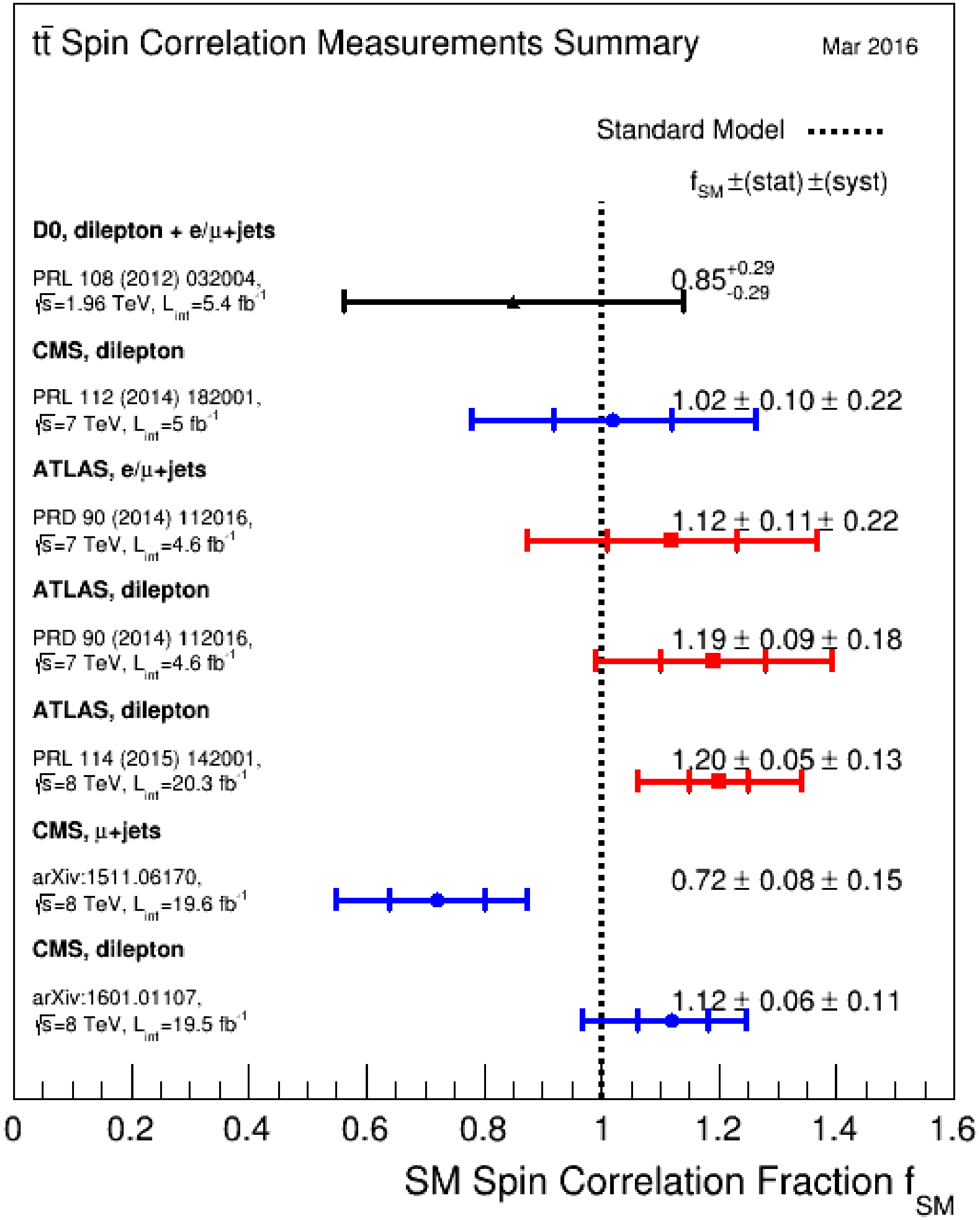
Top quark spin correlations

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

- **ATLAS:**
- $\Delta\phi$ 2ℓ : 1.20 ± 0.14 (8TeV) 1.19 ± 0.20 (7TeV)
- ME 2ℓ : 0.87 ± 0.18 (7TeV)
- $\Delta\phi$ ℓ+j: 1.12 ± 0.25 (7TeV)

- **CMS**
- $\Delta\phi$ 2ℓ : 1.16 ± 0.15 (8TeV)
- D 2ℓ : 0.90 ± 0.16 (8TeV)
- ME ℓ+j: 0.72 $_{-0.13}^{+0.15}$ (8TeV)

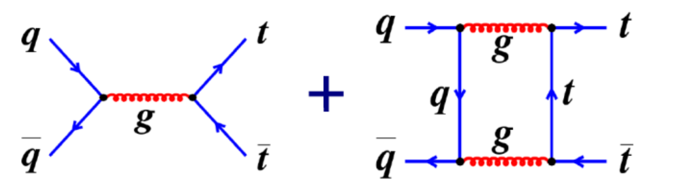
- **Consistent with SM,** already systematic limited for some of the measurements



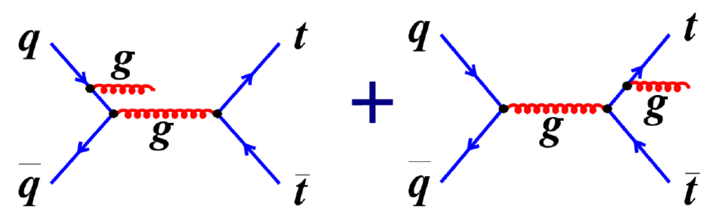
Charge/FB asymmetry

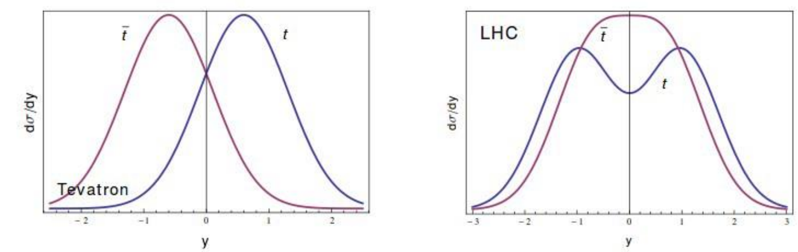
- top quarks pair production at NLO give non zero charge asymmetry from interferences between q--qbar initiated diagrams, gg interaction symmetric
- Measurement of A_{FB} at Tevatron and A_C at LHC are complementary to evaluate new physics models
  - Could be enhanced if new physics present like with W', G, ω, φ, Ω.
- LHC has symmetric initial state (pp):
  - Quarks are mostly valence and anti---quarks are sea quarks
  - PDF's are not symmetric, quarks carry more momentum than anti-quarks
  - Rapidity distribution of tops is broader

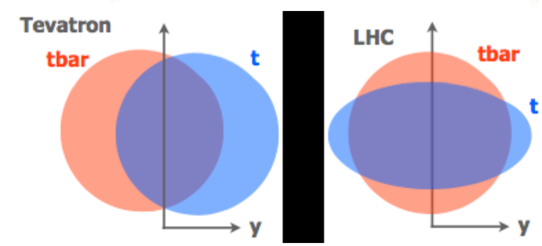
tree-level and box diagram: asymmetry (+)



ISR and FSR: asymmetry (-)







- Evaluate asymmetry based on fully reconstructed top quarks or leptons in dilepton channel

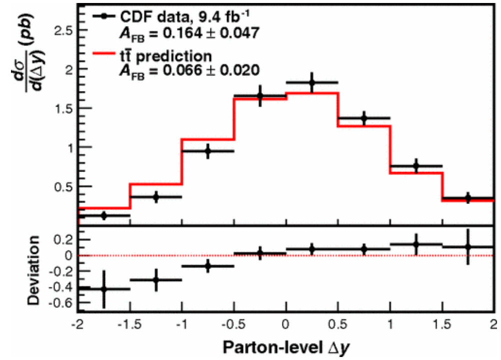
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

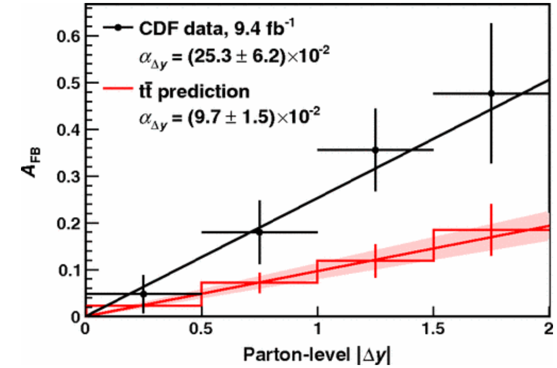
$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

- **Differential distributions (m_{tt}, y_{tt}, $p^T{}_{tt}$) sensitive to BSM physics**

A_{FB} Measurements in tt at the Tevatron

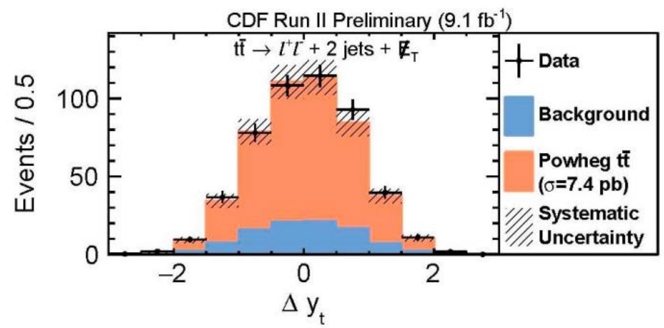
Hot topic since the observation of a larger-than-expected asymmetry from CDF in Lep+Jets: **AFB = 0.164 ± 0.047** and of the asymmetry as a function of Δy and as a function of M_{tt} **Slope$_{\Delta Y}$ = 0.253±0.062** (PRD 87, 092002 (2012))

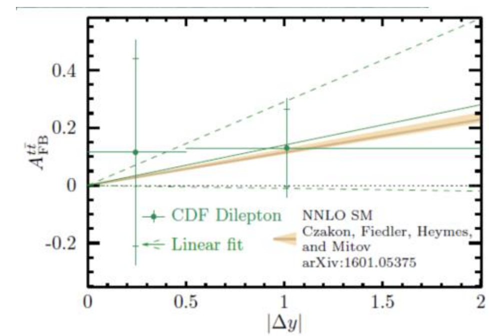




A_{FB} (NNLO SM) = 0.095±0.007
(Czakon, Fiedler & Mitov, PRL 115, 052001 (2015))

Slope$_{\Delta Y}$ (NNLO)= $0.114^{+0.006}_{-0.012}$
(Czakon, Fiedler, Heimes & Mitov, arXiv:1601.05375)





New A_{FB} Results from CDF arXiv: 1602.09015

Results with dilepton data:

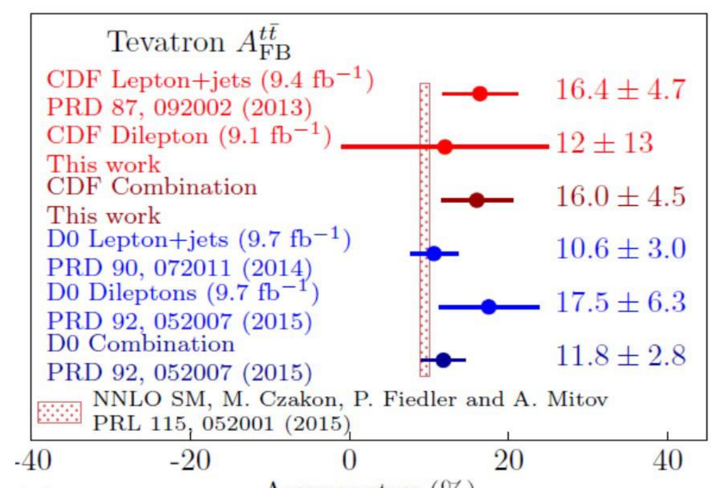
A_{FB} = 0.12±0.11(stat) ±0.07(syst) = 0.12±0.13

Combined with CDF result in lepton+jets

A_{FB} = 0.160±0.045

Consistent with SM and DZero within 1.5σ

– A_{FB} = 0.118±0.028 DZero, PRD 92 052007 (2015)

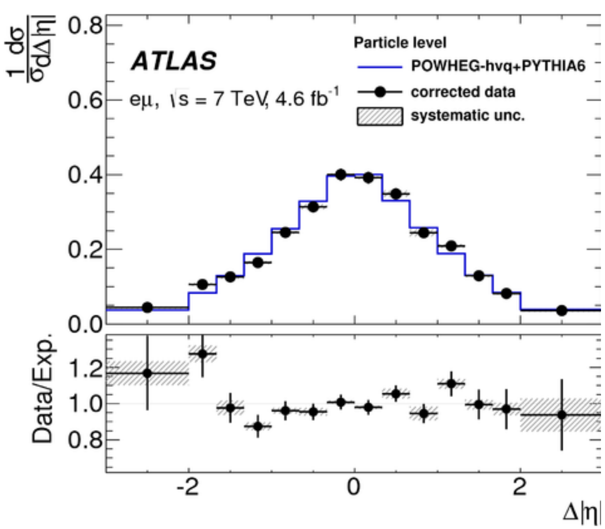


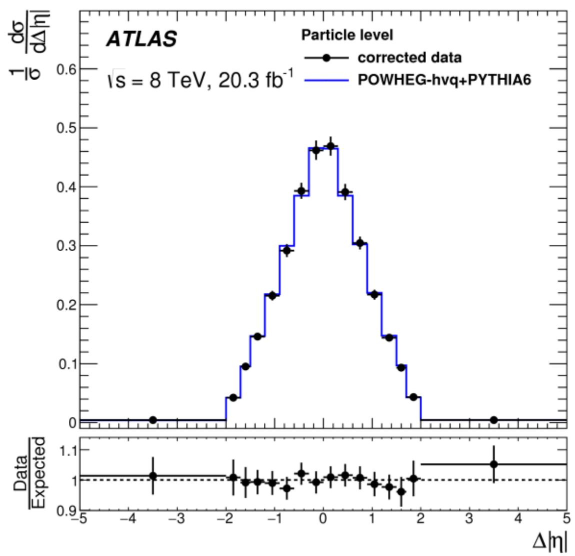
(a)

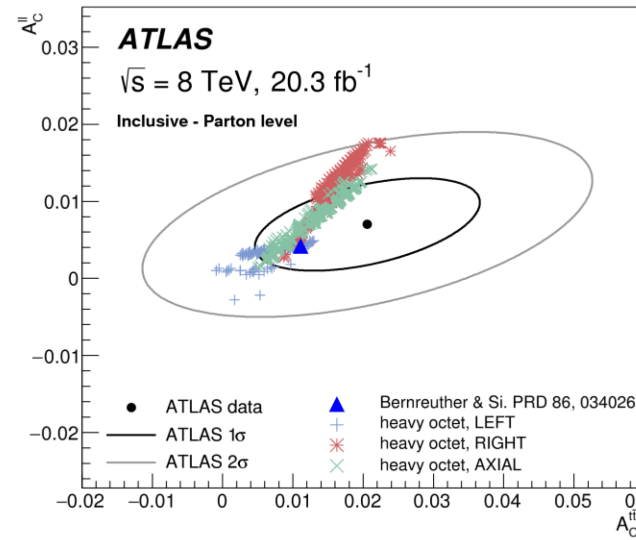
Charge asymmetry: dilepton channel

ATLAS:
7 TeV: JHEP05(2015)061,
8 TeV [arXiv:1604.05538]

- Asymmetry defined with decay leptons and reconstructed tops
- Kinematic reconstruction of the top anti-top quark four momenta.
  - Inclusive measurements corrected to parton level in the full phase space and fiducial regions.
  - Differential measurement in m(tt), |y(tt)|, pT(tt)





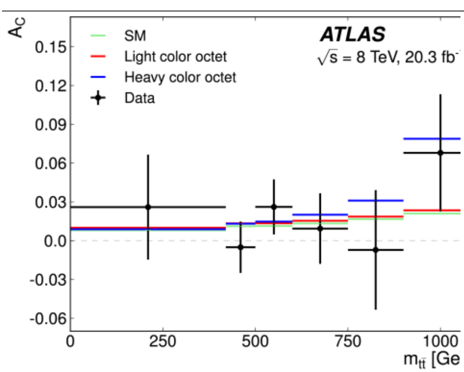


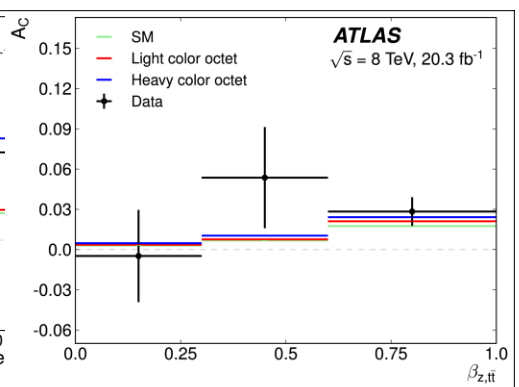
A_C = [0.021 ± 0.017 (stat+syst)] SM pred: (0.0123 ± 0.0005) A_{ll}^{C} = [0.024 ± 0.03 (stat+syst)] SM pred: (0.0070 ± 0.0003)	A_C = [0.021 ± 0.016 (stat+syst)] SM pred: (0.0111 ± 0.0004) A_{ll}^{C} = [0.008 ± 0.006 (stat+syst)] SM pred: (0.0064 ± 0.0003)

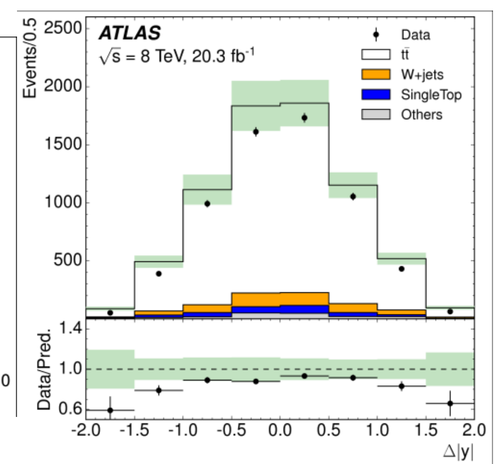
Comparison of the inclusive $A_C^{\ell\ell}$ and A_C^{tt} measurement values in the full phase space to the SM NLO QCD+EW prediction and a benchmark BSM model with a heavy octet with mass with mass beyond the reach of the LHC

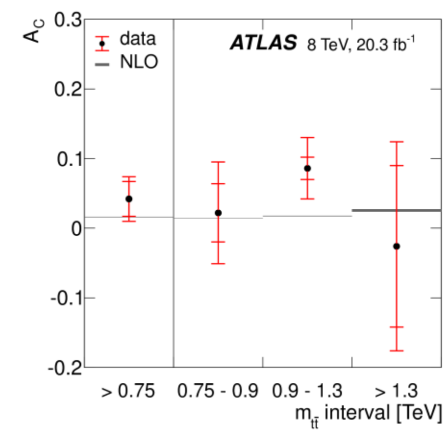
Charge asymmetry: l+jets channel

- **Inclusive** and **differential** measurements unfolded at parton level, using a selection based on: 1 high p_T tight ℓ, large E_t^{miss} and m_T^W. Full event reconstruction with kinematic fit.
- **ATLAS**, 8 TeV, 20.3 fb-1, lepton+jets channel: Eur.Phys.J. C76 (2016) no.2, 87,
  - 3 signal regions: 0, 1, 2 b-tag, Likelihood fit to reconstruct tt, Full Bayesian unfolding, Differential in m(tt), β_z(tt), pT(tt)
- and Phys. Lett. B756 (2016) 52 in the boosted regime: m(tt) > 0.75 TeV
  - Leptonic decay resolved, Hadronic decay reconstructed as large R jet (R=1.0)with substructure, full Bayesian unfolding, differential in m(tt)









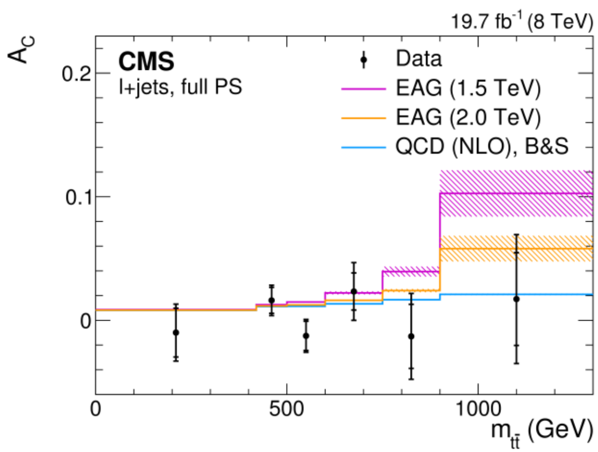
A_C = [0.9 ± 0.5 (stat+syst)] %
SM pred: (1.11 ± 0.04)%

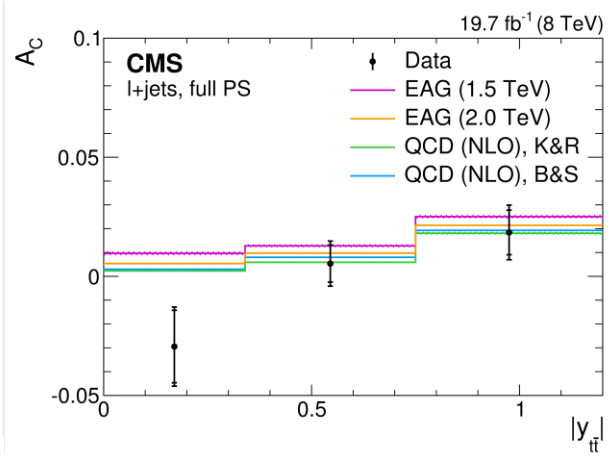
A_C = [4.2 ± 3.2 (stat+syst)] %
SM pred: (1.6 ± 0.04)%, for m(tt) > 0.75 TeV

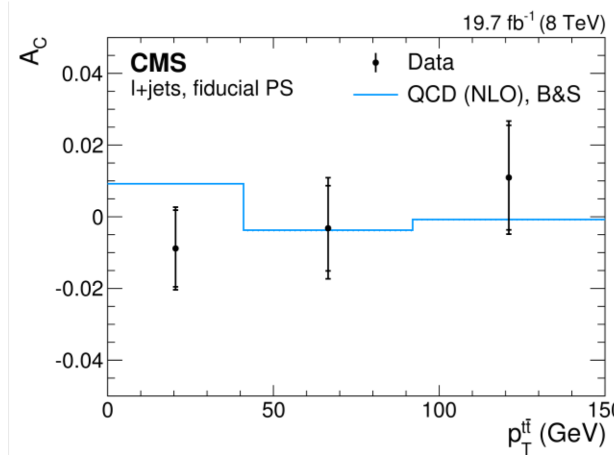
Charge asymmetry: l+jets channel

PLB 757 (2016) 154

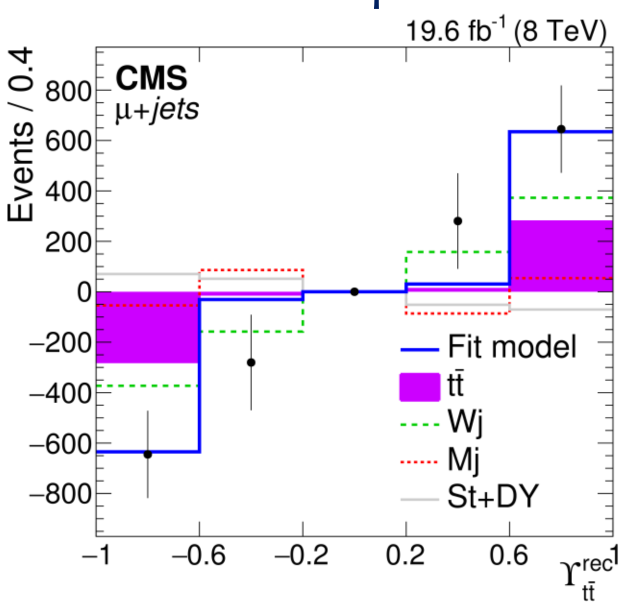
- **CMS 8 TeV: Inclusive** and **differential** measurements unfolded at parton level.





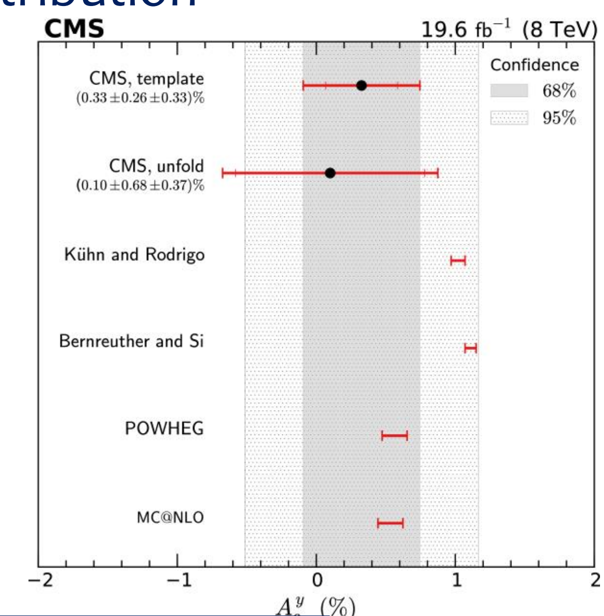


- Alternative template method using shape of Δ|η| distribution



$$\Upsilon_{t\bar{t}} = \tanh \Delta|y|_{t\bar{t}}$$

Observable needs to be bounded.
Use symmetric and asymmetric versión of MC template to fit:
ρ±(X)=(ρ(X) ± ρ(-X))/2
which has a smaller statistical uncertainty than unfolding, larger model dependence.

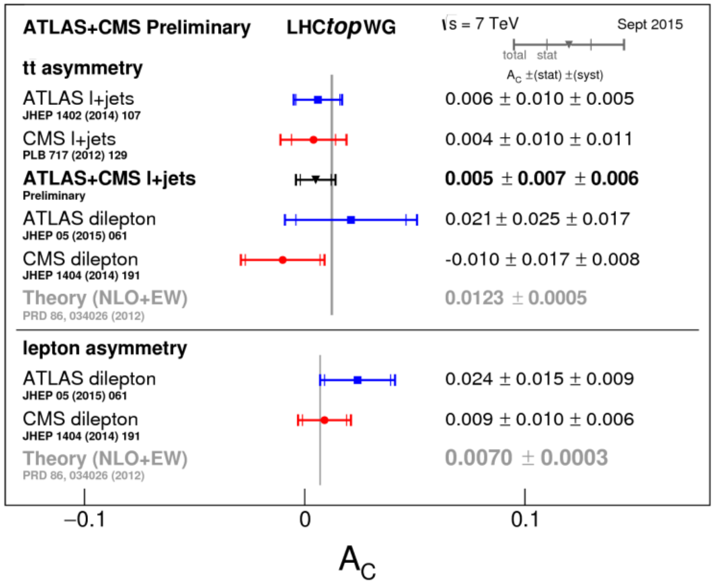


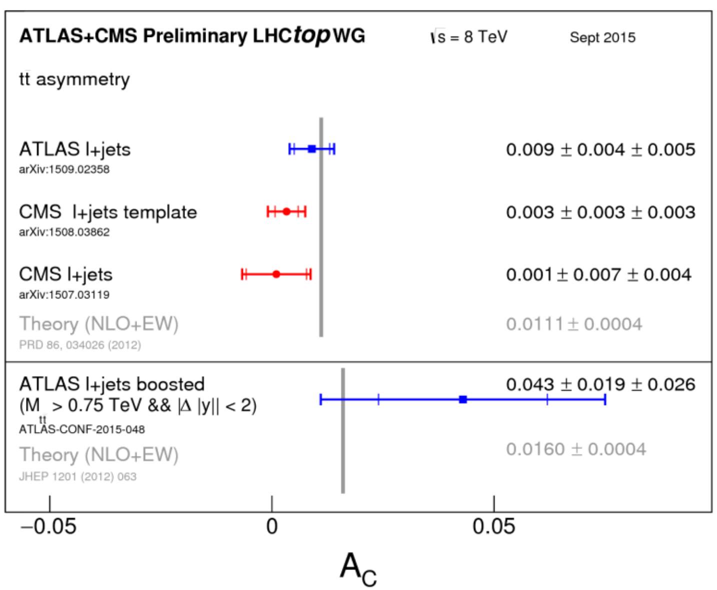
PRD 93 (2016) 034014

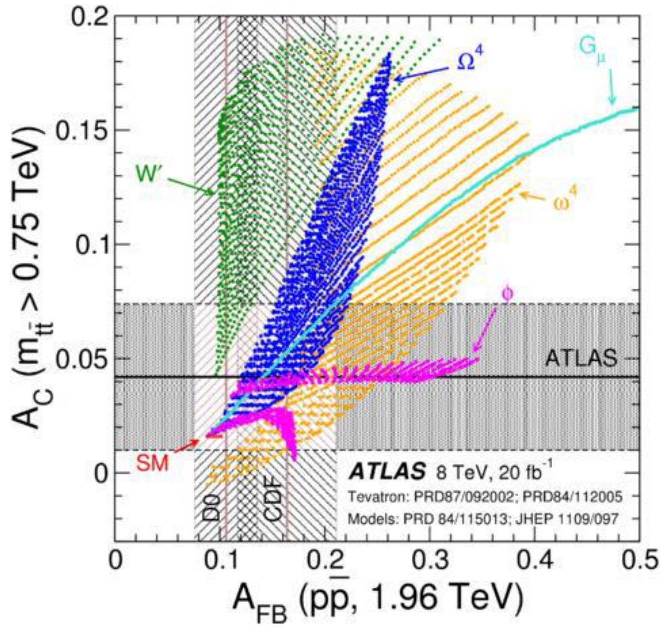
A_C = [0.33 ± 0.26 (stat) ± 0.33 (syst)] %

Charge asymmetry: LHC summary

LHCTOPWG







G_μ : A new color-octet neutral vector boson exchanged in the s channel

W′: A charged color-singlet vector boson Z exchanged in the t channel in dd→ tt

φ : A color-singlet scalar doublet with hypercharge −1/2 exchanged in t channel

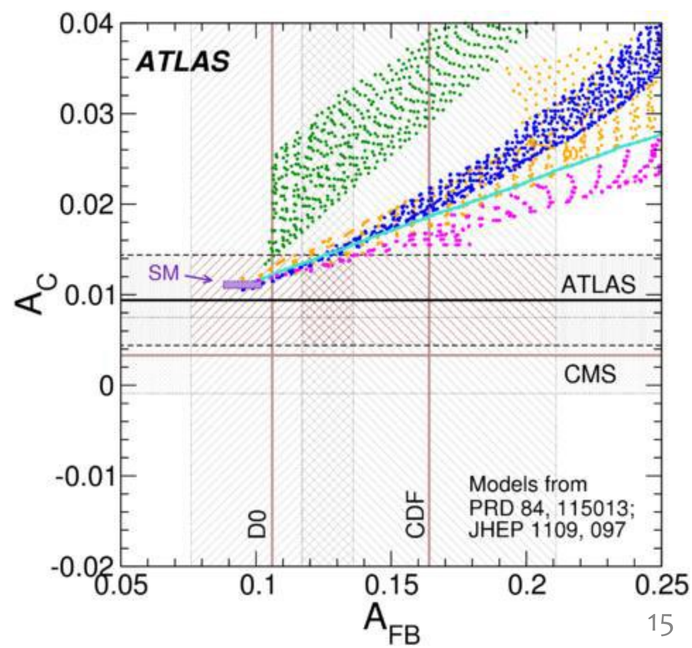
Ω_4 : A charge 4/3 scalar color sextet exchanged in the u channel

ω_4 : A charge 4/3 scalar color triplet exchanged in the u channel

Good agreement between theory and experiment

Statistical and systematic uncertainties are comparable in size

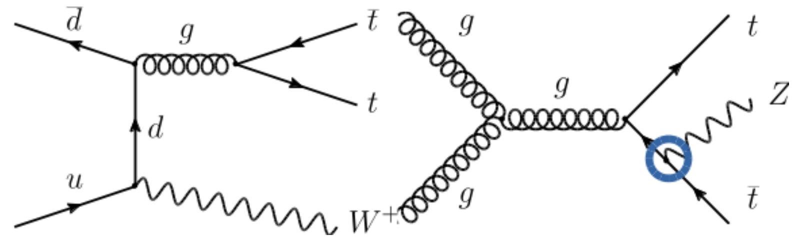
Several differential distributions available + results in high m(tt) region where asymmetry is enhanced



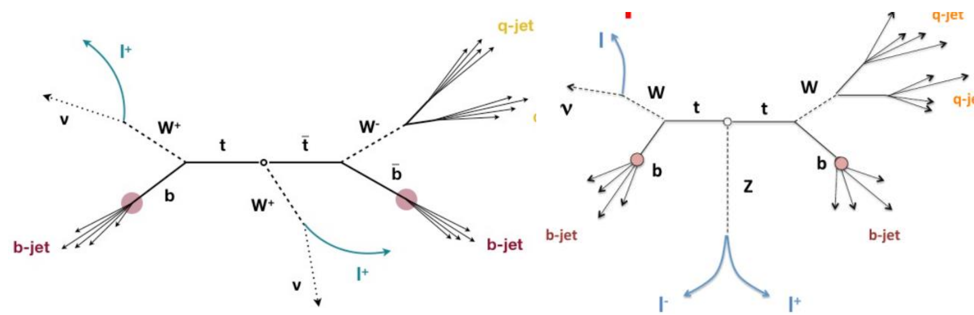
Associated production of top and bosons at 8 TeV

- Measure couplings to bosons

- Important background for BSM searches



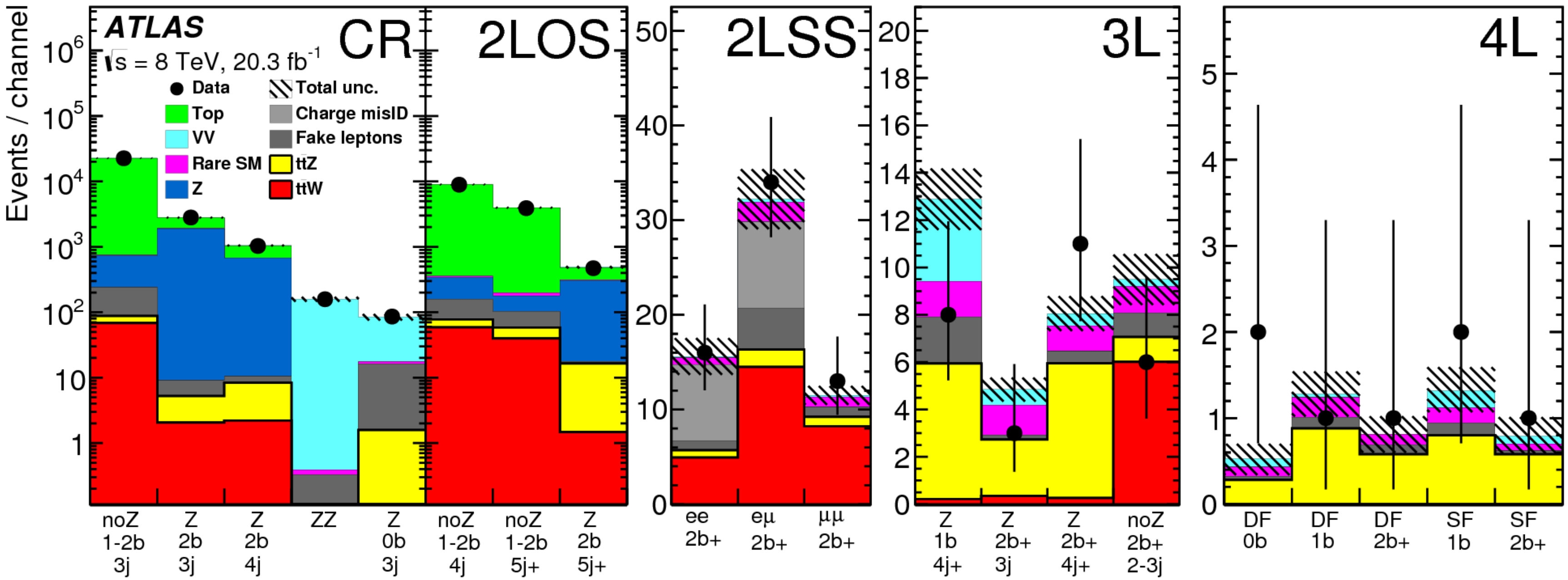
- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons → different admixture of ttW and ttZ processes

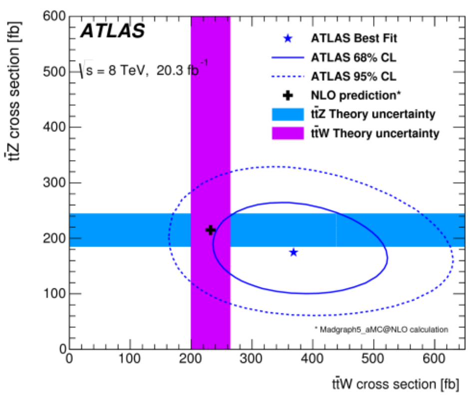


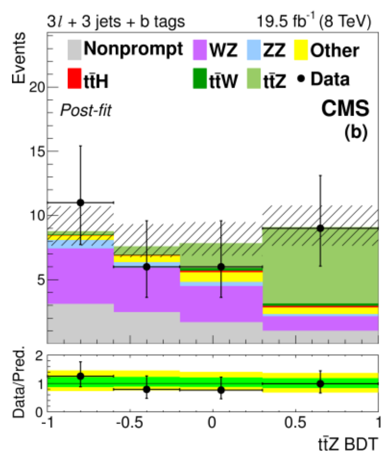
- **ATLAS: tt+W/Z [JHEP 11 (2015) 172]**
  - Four signal regions: opposite sign (OS) dilepton, same sign (SS) dilepton, 3 and 4 lepton.
  - Further split into categories depending on jet multiplicity, number of b-tagged jets and E_T^{miss}, optimised individually to increase sensitivity.
  - Fit for ttZ and ttW simultaneously in a binned likelihood fit

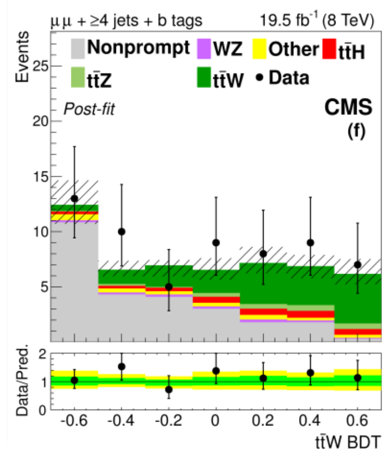
- **CMS: tt+W/Z [JHEP 01 (2016) 096]**
  - Also performed in many channels with different numbers of leptons, jets and b tags
  - Additionally: perform event reconstruction by matching jets and leptons to W/Z bosons and top
    - Combine into linear discriminant
    - Choose best permutation
  - Combine resulting match scores with kinematic quantities in BDTs

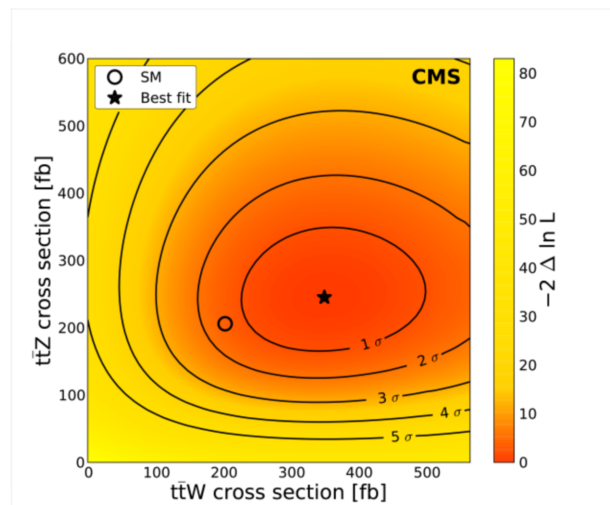
Asociated tt+W/Z production at 8 TeV **established**











- σ(ttW) = 369 $^{+100}_{-91}$ fb - 5.0 obs. (3.2 exp)
- σ(ttZ) = 176$^{+58}_{-52}$ fb - 4.2 obs. (4.5 exp)

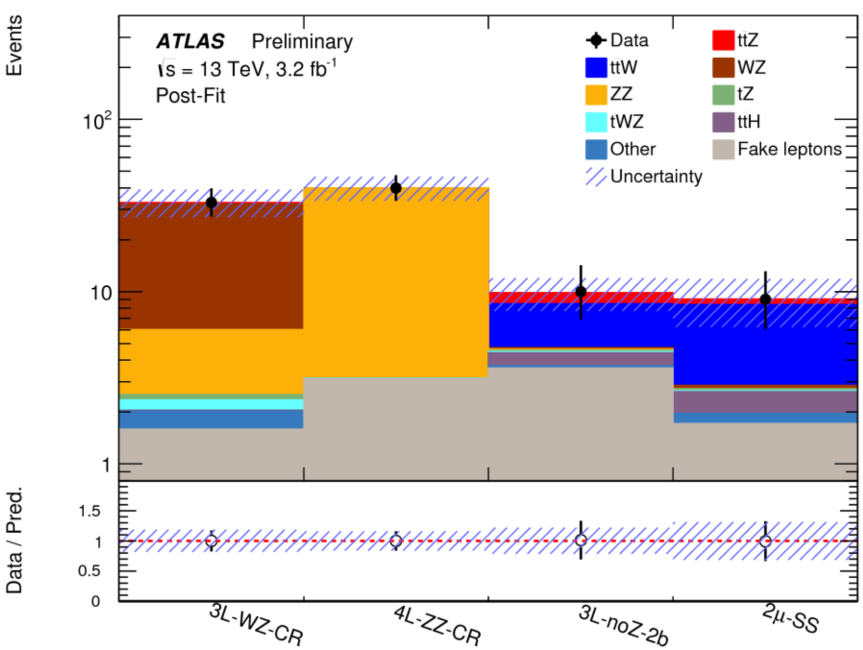
- σ(ttW) = 382$^{+117}_{-102}$ fb - 4.8 obs. (3.2 exp)
- σ(ttZ) = 242$^{+65}_{-55}$ fb - 6.0 obs. (5.7 exp)

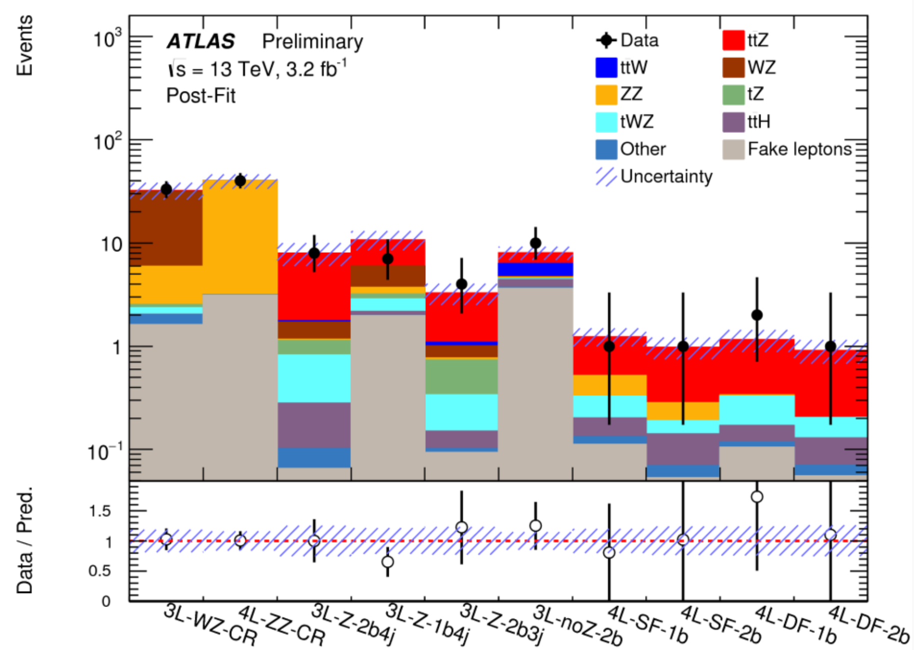
Asociated **tt+W/Z** production at 13 TeV

ATLAS-CONF-2016-003

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^{\pm}$	$(\mu^{\pm}\nu b)(q\bar{q}b)$	$\mu^{\pm}\nu$	SS dimuon
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

- **ttW:** select events with (b) jets and 2 or 3 leptons (one same-sign pair)
- **ttZ:** select events with (b) jets and 3 or 4 leptons (one Z -> ll candidate)
- Diboson backgrounds from control regions:
  - WZ: 3 leptons, 1 Z candidate, 3 untagged jets / ZZ: 4l, 2 Z candidates, low MET





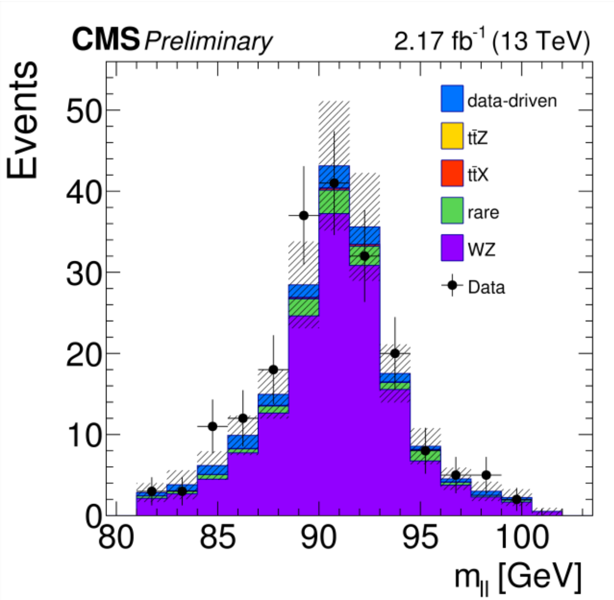
13 TeV	σ(ttW)	σ(ttZ)
ATLAS	**1.38 ± 0.70 (stat) ± 0.33 (syst) pb**	**0.92 ± 0.30 (stat) ± 0.11 (syst) pb**
aMCatNLO	0.57 ± 0.06 pb	0.76 ± 0.08 pb

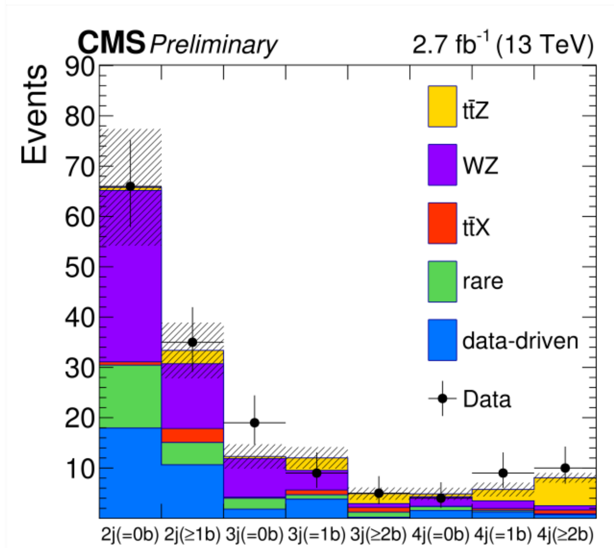
Asociated **tt+Z** production at 13 TeV

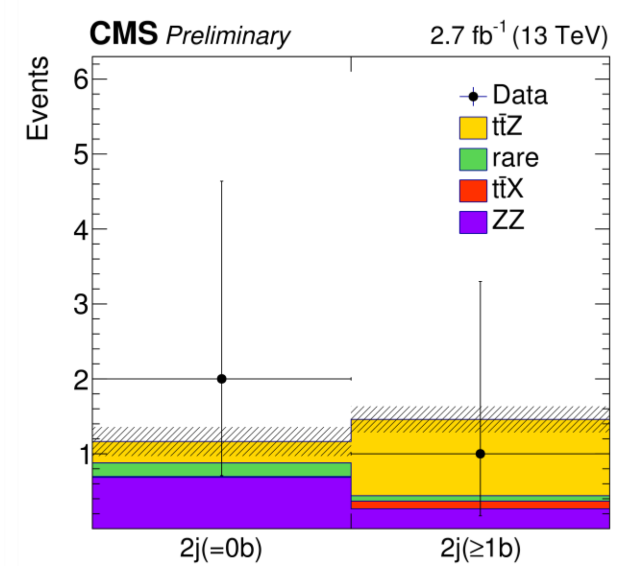
CMS-TOP-PAS-16-009

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^{\pm}$	$(\mu^{\pm}\nu b)(q\bar{q}b)$ $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\mu^{\pm}\nu$ $\ell^{\pm}\nu$	SS dimuon Trilepton
$t\bar{t}Z$	$(\ell^{\pm}\nu b)(q\bar{q}b)$ $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$ $\ell^{+}\ell^{-}$	Trilepton Tetralepton

- Select events with 3 or 4 leptons and at least 2 jets from full 13 TeV dataset
- Data-driven estimates for non-prompt leptons, control regions for WZ and ZZ
- Binned likelihood fit to all categories, including nuisance parameters







Channel	Expected significance	Observed significance
3ℓ analysis	2.9	3.6
4ℓ analysis	1.2	0.9
3ℓ and 4ℓ combined	3.0	3.7

$\sigma(ttZ) = 1.065_{-0.313}^{+0.352}\,(\text{stat.})\,_{-0.142}^{+0.168}\,(\text{syst.})$ pb / aMCatNLO 0.57 ± 0.06 pb

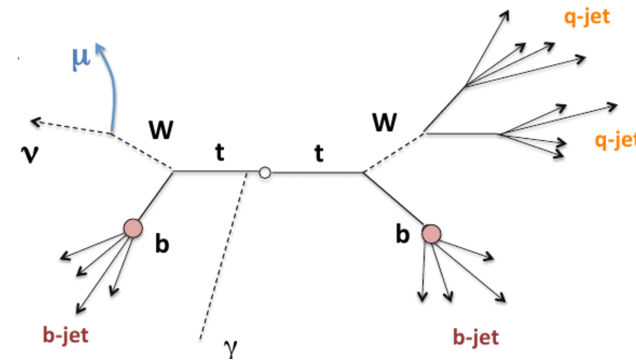
$t\bar{t}+\gamma$ (l+jets, 7TeV) [**ATLAS** PRD 91 (2015) 072007]

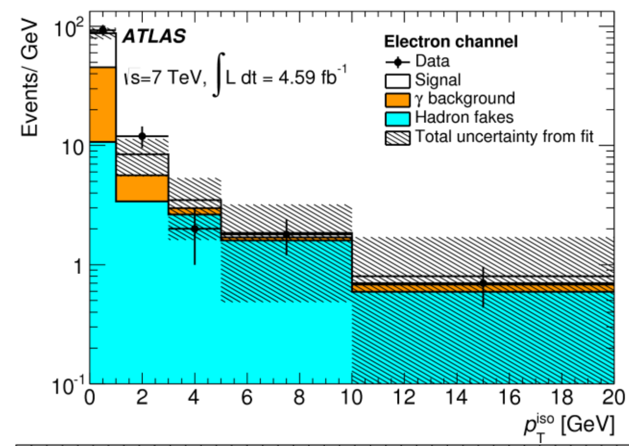
- **Sensitive to tγ coupling and models with composite top quarks and excited top quark production (t* -> tγ)**
- Selection: l+jets + high E_T photon (E_T > 20 GeV)
  - Suppress misidentied γ : $|m_{e\gamma} - m_Z| > 5$ GeV
- Prompt photons estimated from template fit to photon isolation variable
- Largest systematic uncertainties: **jet energy scale.**
- Fiducial cross section:

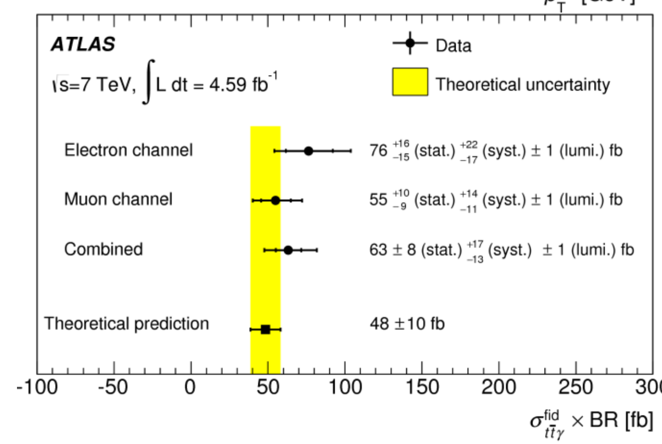
  $\sigma_{tt+\gamma}$ x BR = 63 ± 8(stat)$^{+17}_{-13}$(syst) ± 1(lumi) fb

  per lepton
- **Consistent with SM expectation**

  ($\sigma_{tt+\gamma}$ = 48 ± 10 fb).
- First observation of the process σ=5.3 obs.

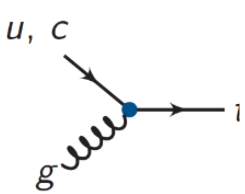


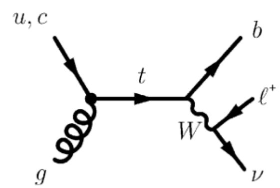




Flavour-changing neutral current

- **SM**: no FCNC at tree level (GIM suppression), BR ~ O(10^{-12} – 10^{-17})
- t ⟶ u/c + X, X = g, γ, Z and H
- **BSM**: 2HDM, MSSM, and others, enhanced couplings, BR as high as 10^{-5}
- FCNC: t⟶qg at 8TeV, Not possible in tt because of multijet bck.



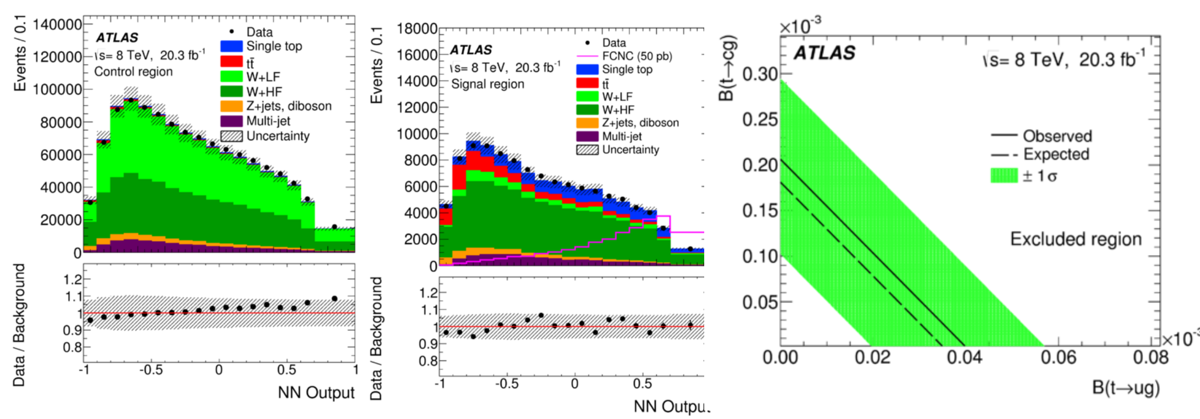


  - t-channel single top selection:
  - 1 lepton,1 b-tagged jet and missing ET
  - Neural network to separate signal from SM background

K. Agashe et al., arXiv:1311.2028

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

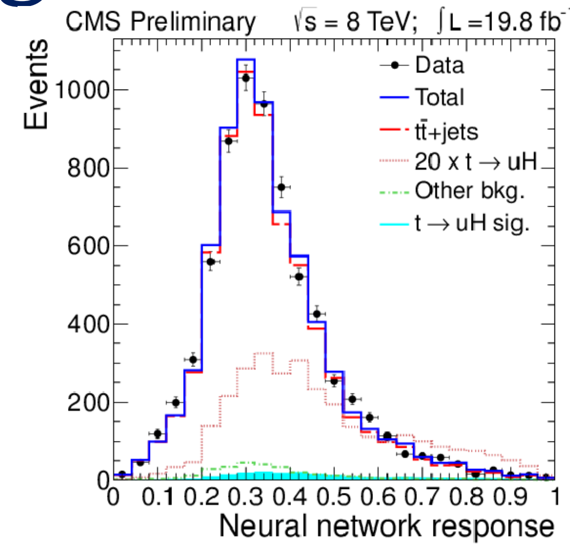
ATLAS, Eur. Phys. J. C (2016) 76:55



$\sigma_{qg\to t} \times \mathcal{B}\,(t\to Wb) < 3.4\ (2.9\ \text{exp})$
$\mathcal{B}\,(t\to ug) < 4 \times 10^{-5}$
$\mathcal{B}\,(t\to cg) < 20 \times 10^{-5}$

Flavour-changing neutral current

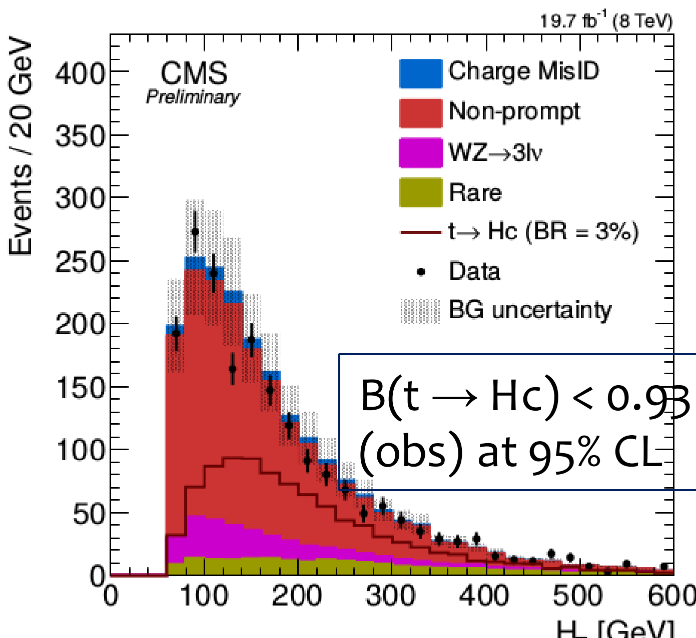
- **CMS**-PAS-TOP-14-020
  - $t \to Hq \to bbq$ and $t \to Wb \to l\nu b$
  - $t \to Hq \to ZZq$ or WWq
- **CMS**-PAS-TOP-14-019
  - $t \to Hq \to \gamma\gamma q$ and
  - $t \to Wb \to l\nu b$ or qqb
- **CMS**-PAS-TOP-13-017
  - $t \to Hq \to ZZq$ or WWq and $t \to Wb \to l\nu b$



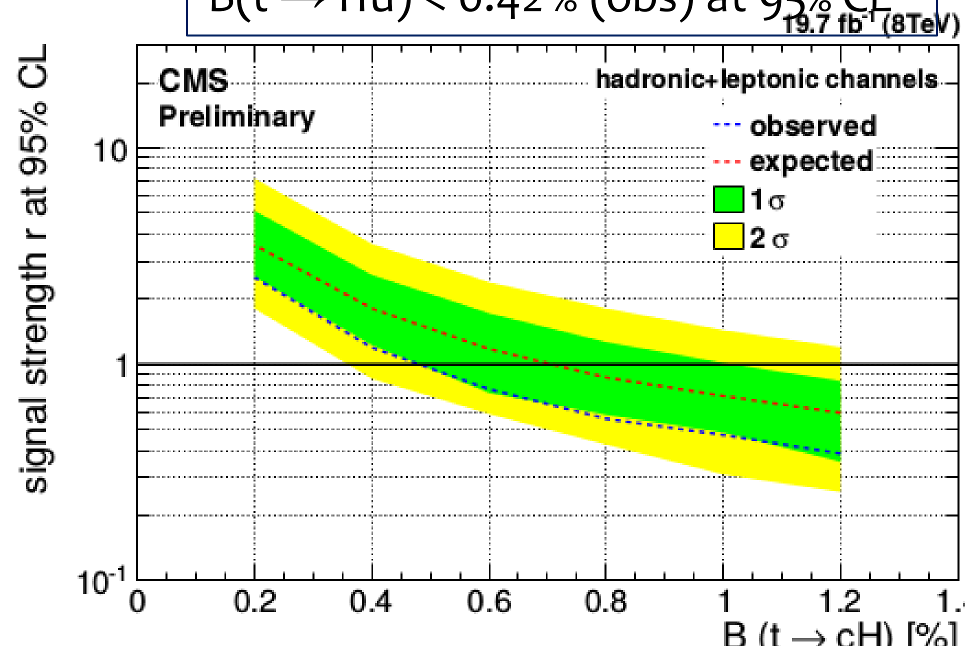
$B(t \to Hc) < 1.16\ \%$ (obs) at 95% CL
$B(t \to Hu) < 1.92\ \%$ (obs) at 95% CL

Similar results from **ATLAS** (JHEP 12 (2015) 061)

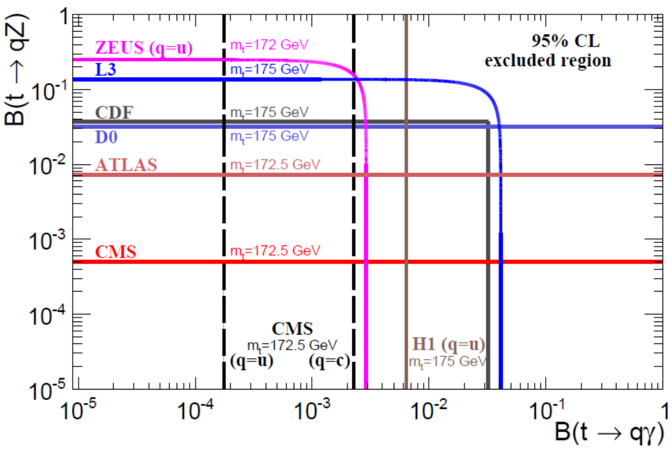
$B(t \to Hc) < 0.47\ \%$ (obs) at 95% CL
$B(t \to Hu) < 0.42\ \%$ (obs) at 95% CL

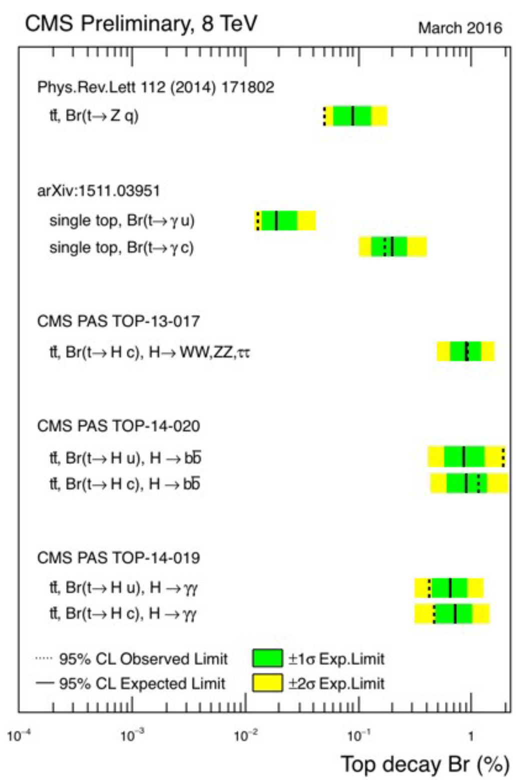


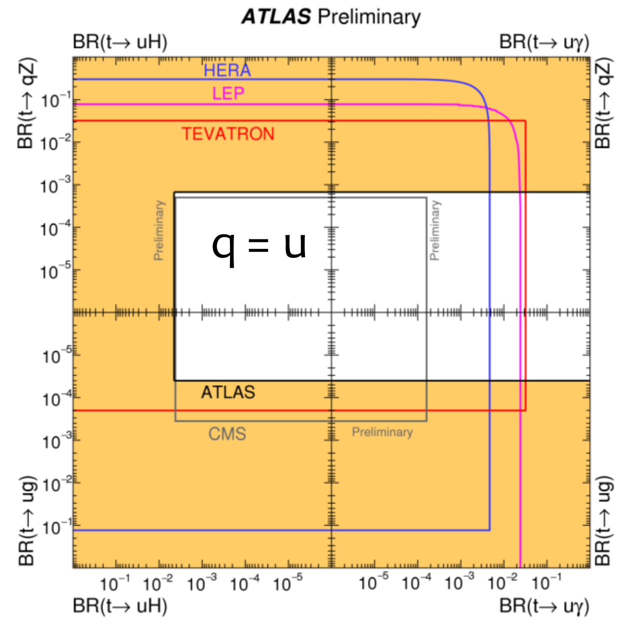
$B(t \to Hc) < 0.93\ \%$ (obs) at 95% CL

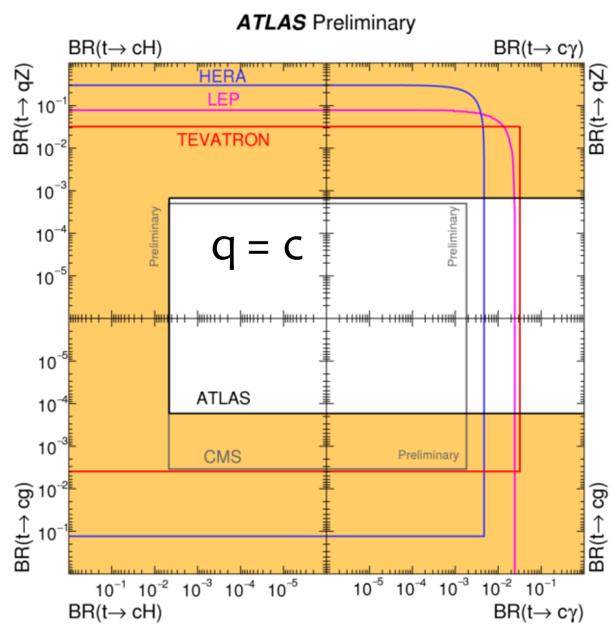


Flavour-changing neutral current: Summary









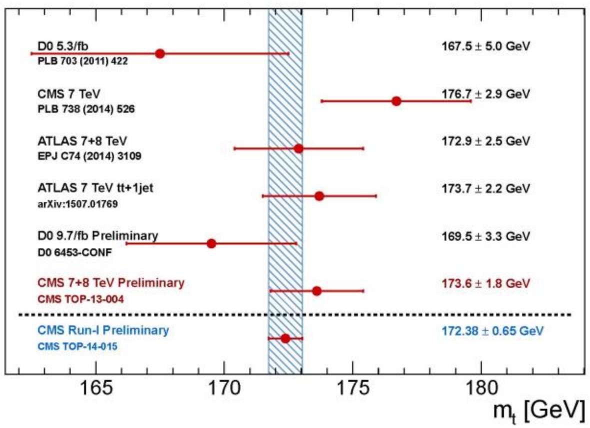
Analyses assume all anomalous couplings are zero, but one.

Still above SM prediction, but sensitivity to certain BSM models getting closer or even already reached.

LEP, HERA, and Tevatron, give complementary results that start to be superseded by LHC.

Constraining the SM with the top mass

- **The top mass, the W mass and the Higgs mass depend on each other**
- **Direct mass measurement at Tevatron** m(top) = 174.18 ± 0.64 GeV (july 2014)
- **Not an observable, i.e. scheme-dependent**
  - **Pole-mass: viewing top quark as a free parton**
    - **inclusive cross section (NNLO) dependent on top-quark pole mass**

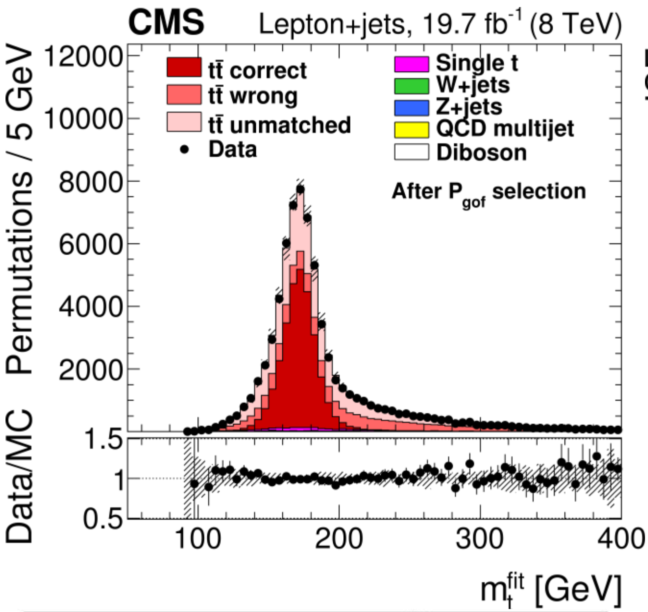


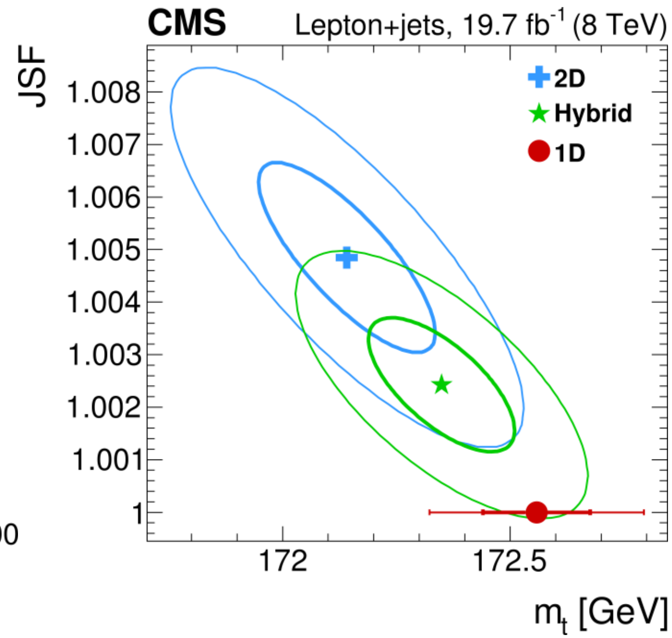
  - MS scheme ("running mass"):
    - "MC mass": (N)LO+PS yet different from pole or MS mass

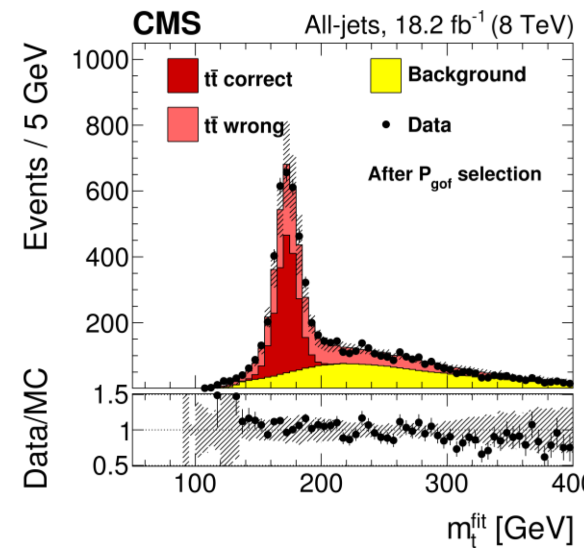
- Direct reconstruction methods
  - ➢ Full reconstruction by resolving the pairing ambiguities (all channels studied)
  - ➢ Use kinematic constrained fitting to improve the mass resolution
    - ○ Constrain the light jet energy scale in situ by using the W mass constraint
  - ➢ Fit the mass with MC template fits or event by event likelihood fits
    - ○ Methods very sensitive to the description of radiation and JES uncertainties
- Indirect methods
  - Use the dependence on the top mass on other variables
    - ○ Top pair cross section
    - ○ Lepton p_T and end-point methods
    - ○ Invariant mass of the system J/Ψ+lepton from W
    - ○ Decay length of the b hadron
  - ➢ Main issue: need of a lot of statistics

CMS (MC) Top mass 8TeV

Phys. Rev. D 93, 072004 (2016)







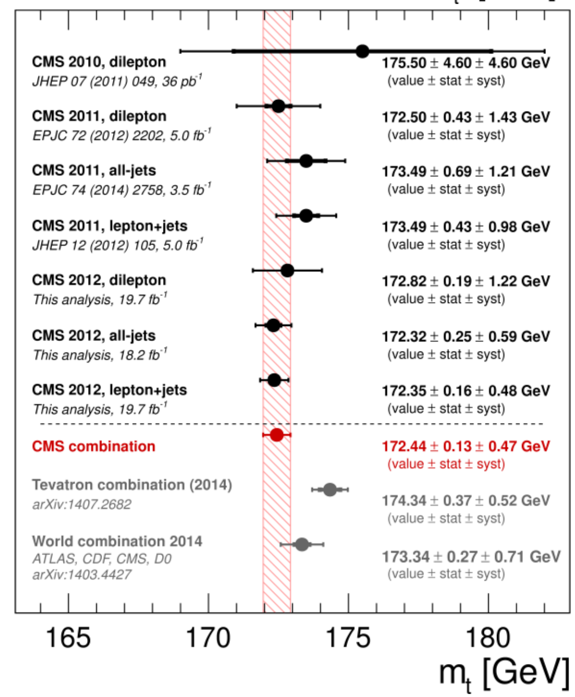
All-jets channel	m_t fit type: 2D δm_t^{2D} (GeV)	2D δJSF	1D δm_t^{1D} (GeV)	hybrid δm_t^{hyb}, (GeV)
Experimental uncertainties				
Method Calibration	0.06	0.001	0.06	0.06
Jet energy corrections				
– JEC: Intercalibration	<0.01	<0.001	+0.02	+0.02
– JEC: In situ calibration	−0.01	<0.001	+0.23	+0.19
– JEC: Uncorrelated non-pileup	+0.06	−0.001	−0.19	−0.16
– JEC: Uncorrelated pileup	+0.04	<0.001	−0.08	−0.06
Jet energy resolution	−0.10	+0.001	+0.03	+0.02
b tagging	+0.02	<0.001	+0.01	+0.02
Pileup	−0.09	+0.002	+0.02	<0.01
Backgrounds	−0.61	−0.007	−0.14	−0.20
Trigger	+0.04	<0.001	−0.01	<0.01
Modeling of hadronization				
JEC: Flavor-dependent				
– light quarks (u d s)	+0.10	−0.001	−0.02	+0.00
– charm	+0.03	−0.001	−0.01	−0.01
– bottom	−0.30	+0.000	−0.29	−0.29
– gluon	−0.17	+0.002	+0.02	−0.02
b jet modeling				
– b fragmentation	+0.08	−0.001	+0.03	+0.04
– Semileptonic b hadron decays	−0.14	<0.001	−0.13	−0.13
Modeling of perturbative QCD				
PDF	0.06	<0.001	0.03	0.03
Ren. and fact. scales	+0.29 ± 0.16	−0.005 ± 0.001	−0.19 ± 0.11	−0.12 ± 0.12
ME-PS matching threshold	+0.18 ± 0.16	−0.002 ± 0.001	+0.12 ± 0.11	+0.13 ± 0.12
ME generator	−0.04 ± 0.20	−0.002 ± 0.002	−0.18 ± 0.14	−0.16 ± 0.14
Top quark p_T	+0.04	+0.001	+0.08	+0.06
Modeling of soft QCD				
Underlying event	+0.27 ± 0.25	−0.002 ± 0.002	+0.13 ± 0.18	+0.14 ± 0.18
Color reconnection modeling	+0.35 ± 0.22	−0.003 ± 0.002	+0.14 ± 0.16	+0.16 ± 0.16
Total systematic	0.95	0.011	0.62	0.59
Statistical	0.33	0.003	0.23	0.24
Total	1.01	0.011	0.66	0.64

m_t^{2D} =172.14 ± 0.19 (stat+JSF) ± 0.59 (syst) GeV
JSF =1.005 ± 0.002 (stat) ± 0.007 (syst)

σ_{tot}= 0.62 GeV

2D fit uncertainty comparable to world average

m_t^{1D} =172.56 ± 0.12 (stat) ± 0.62 (syst) GeV
m_t^{hyb} =172.35 ± 0.16 (stat+JSF) ± 0.48 (syst)



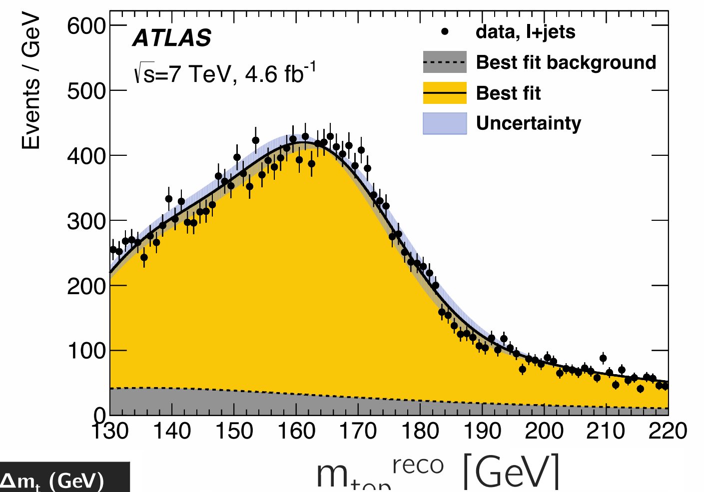
ATLAS (MC) top mass

lepton+jets channel at 7 TeV

Eur. Phys. J. C (2015) 75:330

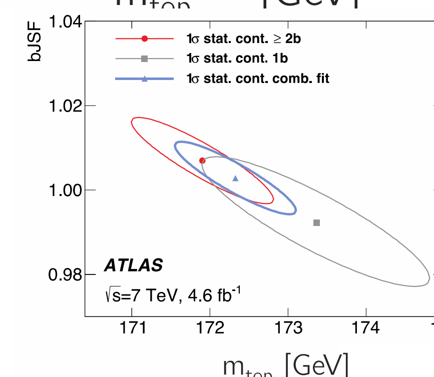
- Event selection similar to CMS lepton+jets result.
  - Separate events into 1 b tag and ≥2 b tags.
- Reconstruct ttbar system with kinematic likelihood fit.
  - Improves purity and assignment of reconstructed jets to partons.
- **Template-based approach with observabes: m_{top}^{reco}, m_W^{reco} and R_{bq} (ratio of $p_T^{b\,had}$ and $p_T^{b\,lep}$ over $p_T^{Wjet1+2}$)**
  - In-situ calibration of JES (m_W^{reco}) and bJES (Rbq), relative to udsg.

Signal + background fit to data

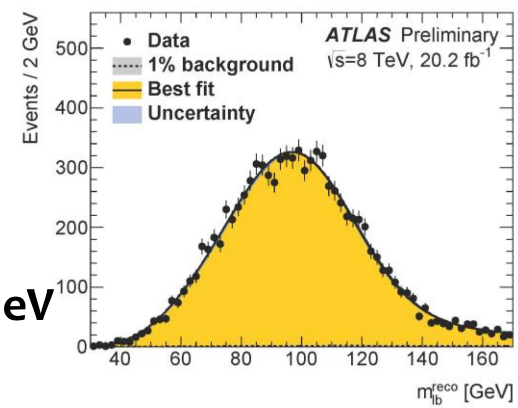


m_t = 172.33 ± 0.75 (stat+JSF+bJSF) ± 1.02 (syst) GeV
JSF = 1.019 ± 0.003 (stat) ± 0.027 (syst)
bJSF = 1.003 ± 0.008 (stat) ± 0.023 (syst)

Systematic uncertainties	Δm_t (GeV)
Jet energy scale	0.58
b jet energy scale	0.06
Pile up	0.02
Detector modeling	0.58
Method and backgrounds	0.33
Signal modeling	0.53
Total	**1.22**



NEW ATLAS result on the **dilepton** channel at 8 GeV
(paper in preparation)

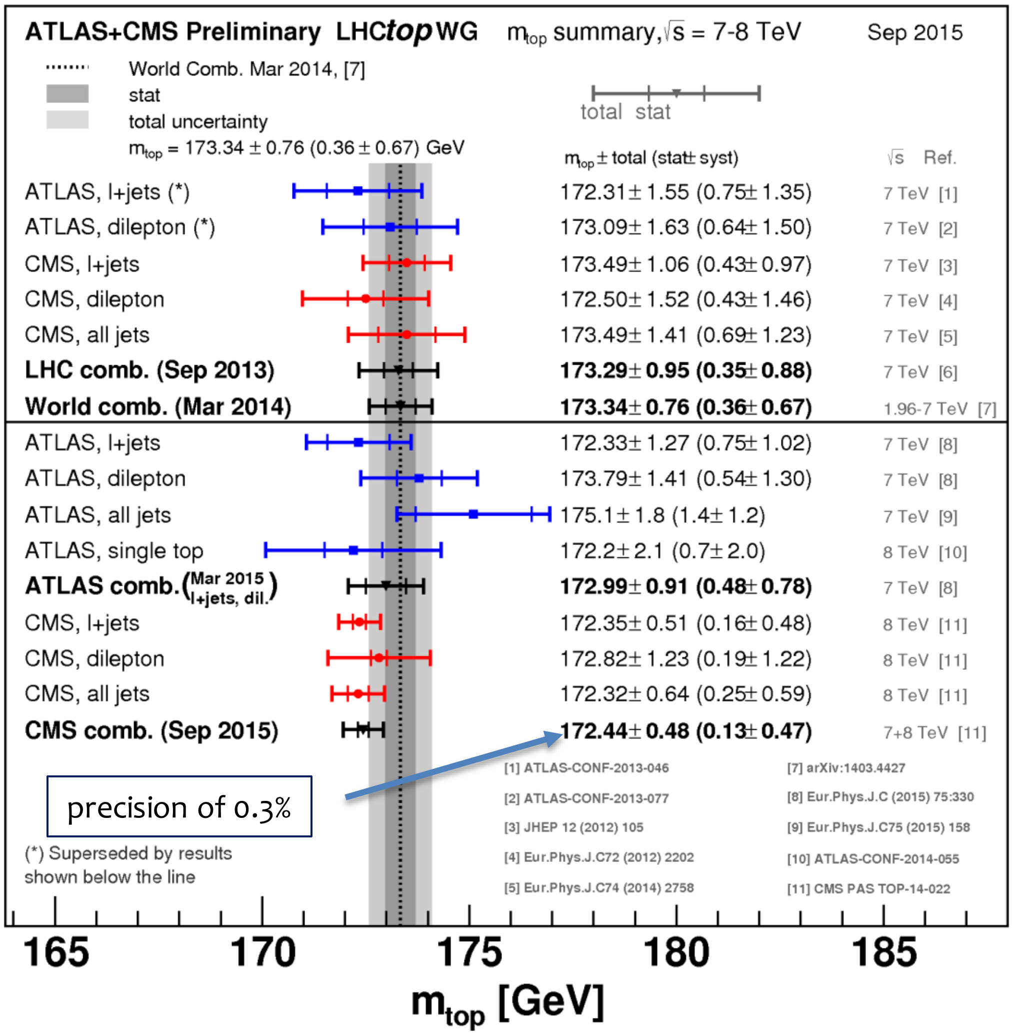


m_{top} = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV
0.84 GeV in total

Combined result:
(+7 TeV dileptons)
m_{top} = 172.84 ± 0.34 (stat) ± 0.61 (syst) GeV,
0.70 GeV, 0.4% relative.

CMS + ATLAS m_{top} (MC)

LHCTOPWG precision of 0.3%



Analysis combined using BLUE, accounts for correlations between all uncertainties.

CMS combination

m_{top} = 172.44 ± 0.48 GeV

ATLAS combination

(OLD) m_{top} = 172.99 ± 0.91 GeV

(NEW) m_{top} = 172.84 ± 0.70 GeV

(not in the combination plot)

Tevatron combination

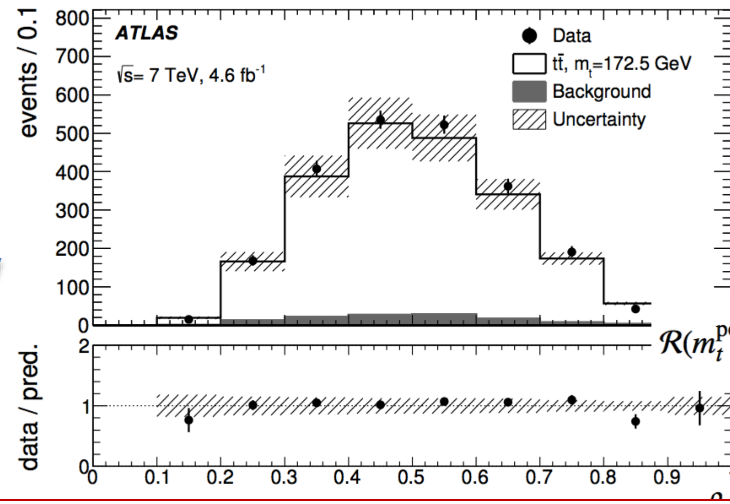
m_{top} = 174.34 ± 0.64 GeV

Total uncertainty is now well below 1 GeV

top mass: Indirect Measurements

Access to top quark pole mass directly

- difference between MC & pole mass *O(1 GeV)* (A. Hoang: arXiv:1412.3649v1)
- **Pole Mass from tt+1 - jet events** @ 7 TeV (**ATLAS**) **JHEP 10 (2015) 121**
- **m_{top} from Production Cross-Section**
  - Can take advantage of low backgrounds of eμ channel
  - Sensitivity not as strong as in direct measurements
  - Systematic uncertainties typically larger
  - **CMS: arXiv:1603.02303**
  - **ATLAS: Eur.Phys.J. C74 (2014) 3109**
- **Measurement of σ_{tt} together with NNLO theoretical prediction allows for extraction of the pole mass (m_{top})**

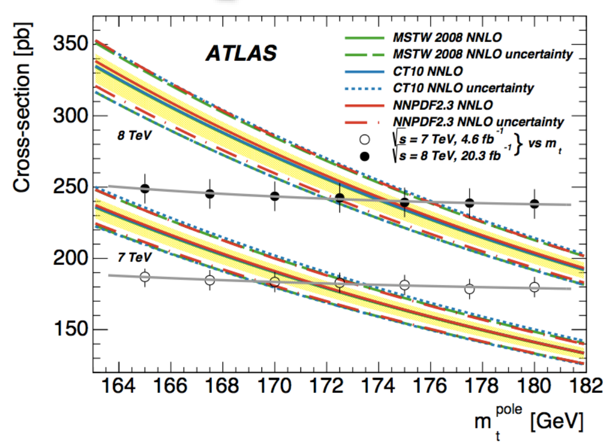


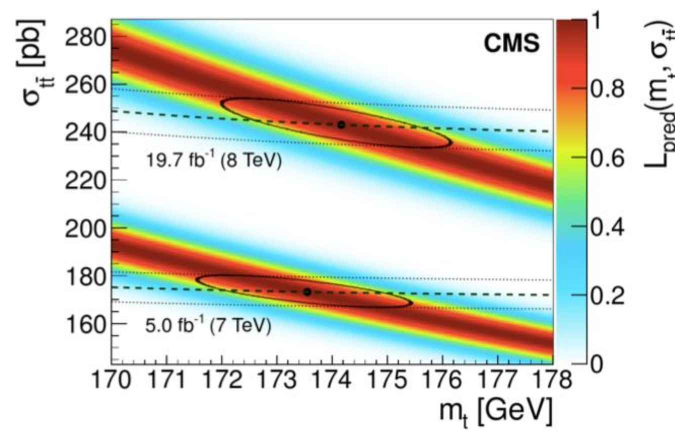
Extract top quark pole mass directly using differential tt-+1-jet cross-section

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

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

$$\boxed{m_t^{\text{pole}} = 173.7 \pm 1.5\ (\text{stat.}) \pm 1.4\ (\text{syst.})\ ^{+1.0}_{-0.5}\ (\text{theory})\ \text{GeV}}$$





$$\boxed{m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\ \text{GeV}}$$

$$\boxed{m_t^{\text{pole}} = 173.8^{+1.7}_{-1.8}\ \text{GeV}}$$

Summary

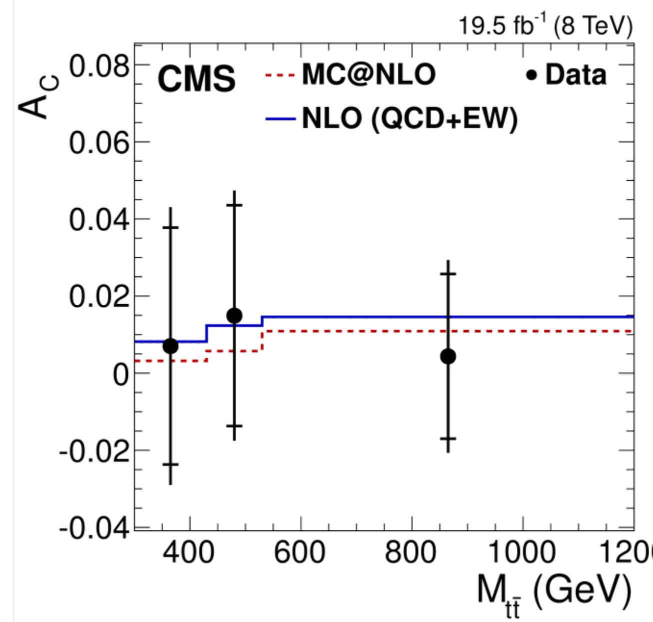
- **Top quark physics is a pillar of the current research program in HEP and provide stringent tests of pQCD . Both the CMS and ATLAS collaborations cover a wide range of top-related topics, as previously D0 and CDF did.**
- Key to QCD, electro-weak and New Physics
  - Ideal probe for constraining (directly + indirectly) the symmetry breaking of the SM
    - The top is way heavy → the Higgs scalar mostly couples to tops
  - Ideal probe for looking for new physics beyond the model itself
    - Via precision measurements or direct searches for new signals
- **Results in agreement with SM predictions**
  - Spin correlations
  - Charge asymmetry
  - Associated production, observation of tt+γ , tt+W/Z, important to study top-Higgs couplings.
  - No signs of FCNC
- **Top mass:**
  - Direct measurement, giving excellent precision **below 0.5 GeV**
  - Indirect measurement (pole mass) precision below 2 GeV and compatible with direct measurement.

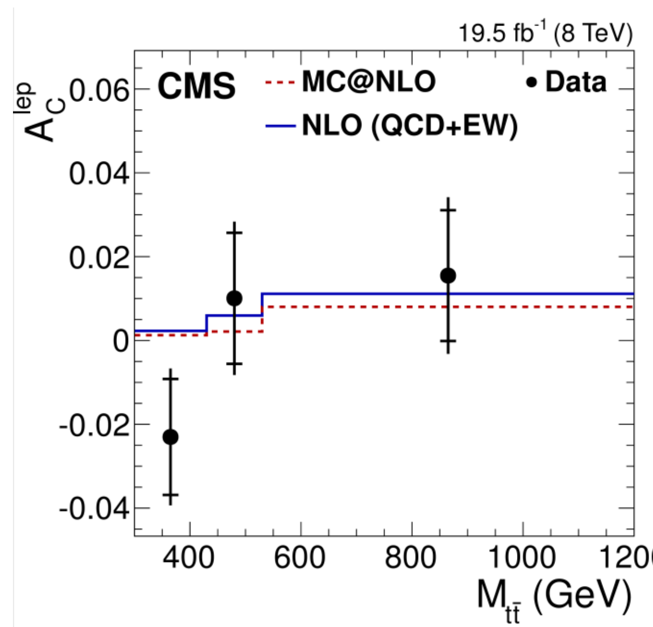
Backup

Charge asymmetry: dilepton channel

- Inclusive distribution unfolded @ parton level
- 2 OS ℓ, ≥ 2 high p_T jet , ≥ 1b, large E_t^{miss}
- Asymmetry defined with decay leptons and reconstructed tops
- Top reconstruction using matrix weighting technique
  - Regularised unfolding to parton level
  - Differential measurement in m(tt), |y(tt)|, pT(tt)
- CMS 8 TeV: arXiv:1603.06221, sub. to PLB

A_C = [1.1 ± 1.3 (stat+syst)] %
SM pred: (1.11 ± 0.04)%
$A_{lep}{}^C$ = [0.3 ± 0.7 (stat+syst)] %
SM pred: (0.64 ± 0.03)%





CP asymmetry in ttbar events

CMS TOP-16-001

- No observable CP violation in tt production in SM
- CP violation sign of new physics
- Probes of CP violation in tt production:
  - Four observables are chosen with asymmetry in presence of CP violation
  - Distributions are probed in 8 TeV data

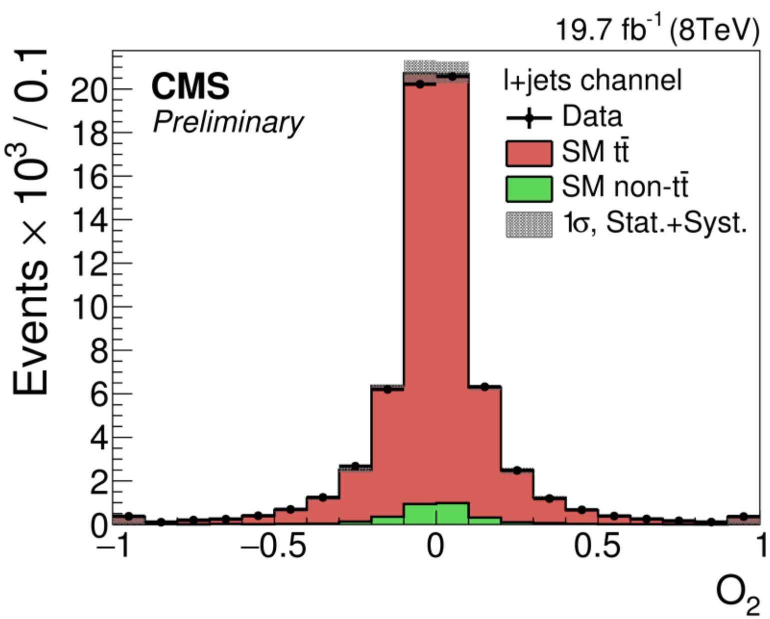
$$O_2 = \epsilon\left(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}\right) \xrightarrow{lab} \propto \left(\vec{p}_b + \vec{p}_{\bar{b}}\right) \cdot \left(\vec{p}_\ell \times \vec{p}_{j1}\right)$$

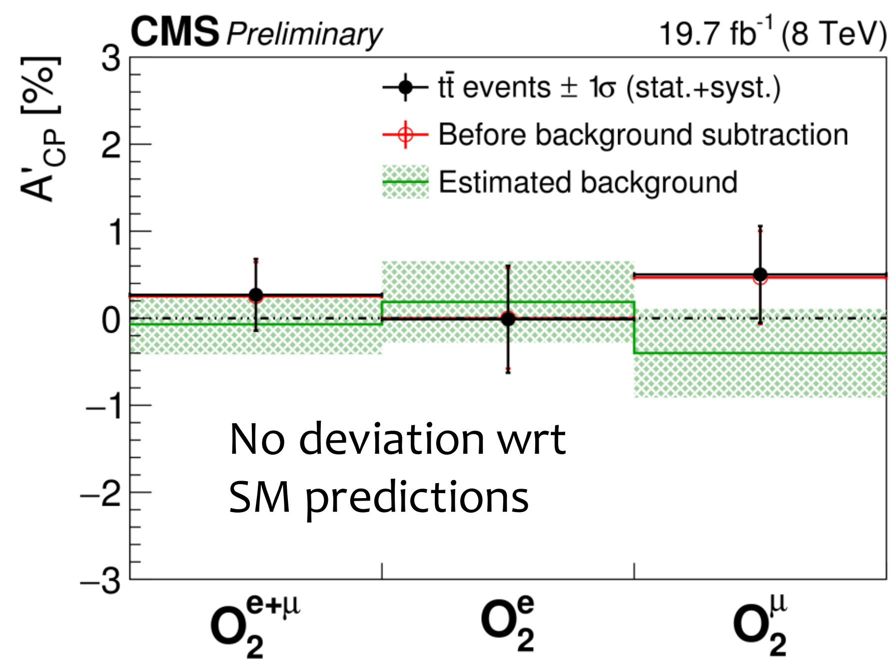
$$O_3 = Q_\ell \epsilon\left(p_b, p_{\bar{b}}, p_\ell, p_{j1}\right) \xrightarrow{b\bar{b}\ CM} \propto Q_\ell \vec{p}_b \cdot \left(\vec{p}_\ell \times \vec{p}_{j1}\right)$$

$$O_4 = Q_\ell \epsilon\left(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}\right) \xrightarrow{lab} \propto Q_\ell \left(\vec{p}_b - \vec{p}_{\bar{b}}\right) \cdot \left(\vec{p}_\ell \times \vec{p}_{j1}\right)$$

$$O_7 = q \cdot \left(p_b - p_{\bar{b}}\right) \epsilon\left(P, q, p_b, p_{\bar{b}}\right) \xrightarrow{lab} \propto \left(\vec{p}_b - \vec{p}_{\bar{b}}\right)_z \left(\vec{p}_b \times \vec{p}_{\bar{b}}\right)_z$$

$$A_{CP}\left(O_i\right) = \frac{N_{events}\left(O_i > 0\right) - N_{events}\left(O_i < 0\right)}{N_{events}\left(O_i > 0\right) + N_{events}\left(O_i < 0\right)}$$

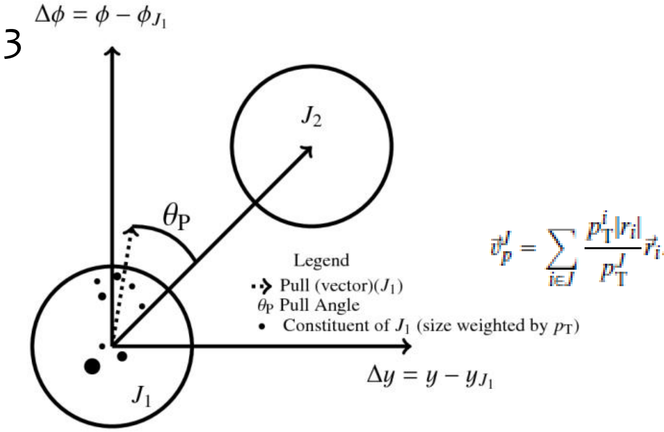


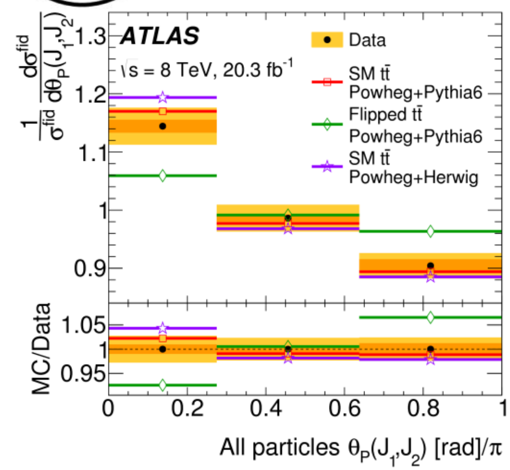


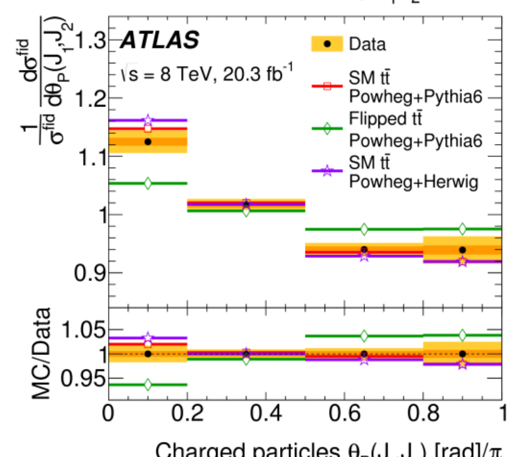
Measurement of colour flow with the jet pull angle in $t\bar{t}$ events using the ATLAS detector at 8 TeV

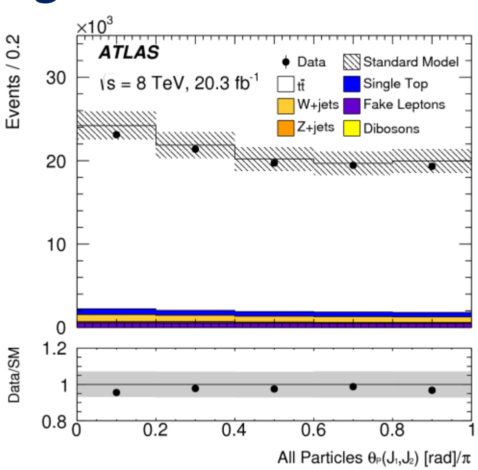
Physics Letters B (2015) 475-493

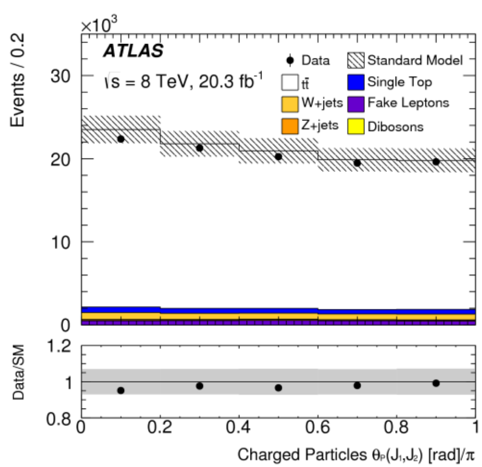
- The distribution and orientation of energy inside jets is predicted to be an experimental handle on colour connections between the hard–scatter quarks and gluons initiating the jets.
- The pull angle is measured for jets produced in $t\bar{t}$ events with one W boson decaying leptonically and the other decaying to jets
- Normalised fiducial $t\bar{t}$ differential cross-section is measured, and compared with SM and colour-octet W boson. **It is found that the jet pull angle characterize the W boson as a colour singlet in agreement with the SM.**







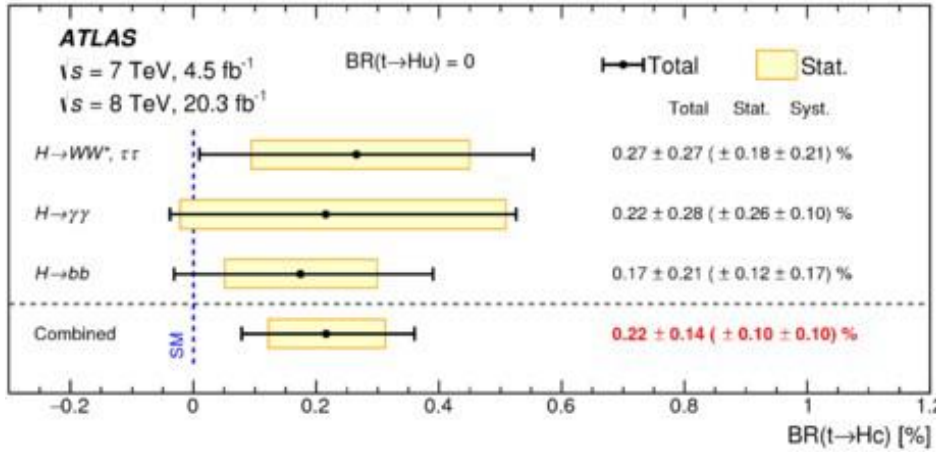




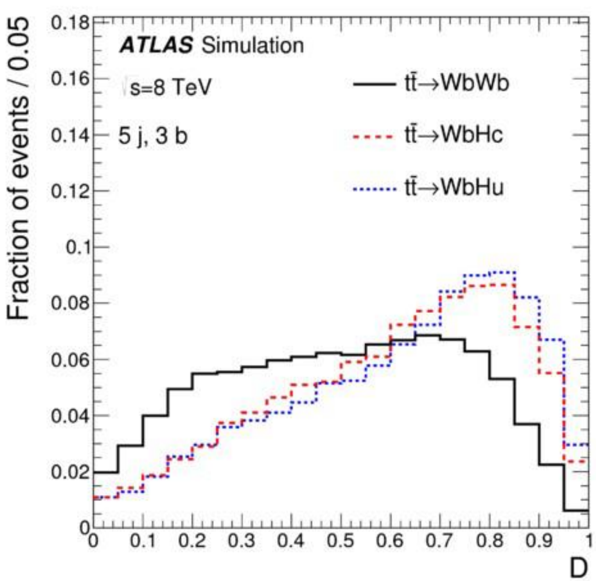
Flavour-changing neutral current

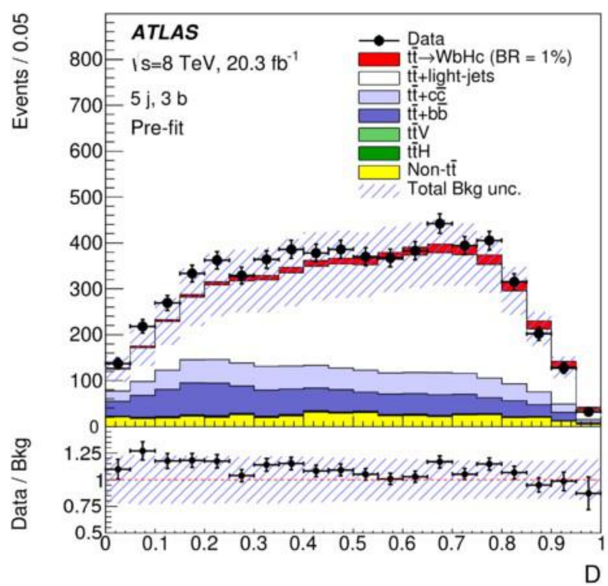
ATLAS: JHEP12 (2015) 061

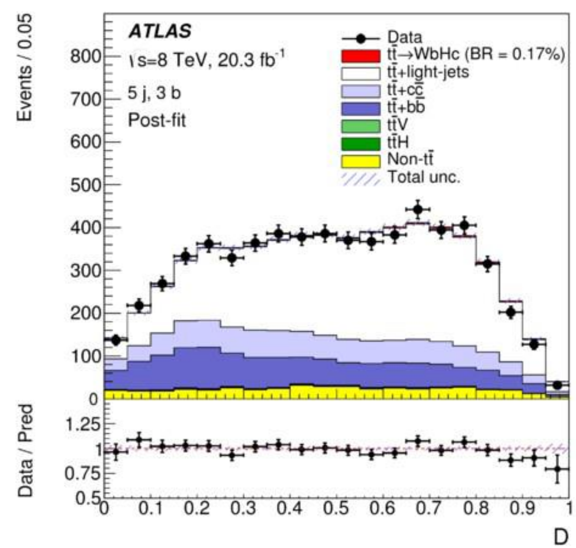
- tt production with t → Hq -> bbq and t → Wb → lνb
- Categories based on jet, b-tag multiplicity, (4 j, 3 b) and (4 j, 4 b) most sensitive
- Signal/background discriminant: with P^{sig}, P^{bkg} PDFs using the resonances and jet flavour content of final state



limit at 95% CL: B(t → Hc) < 0.56 % (obs)
B(t → Hu) < 0.61 % (obs)

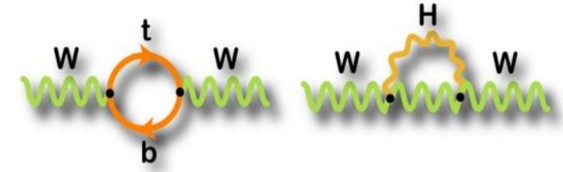






Constraining the SM

- Can use the fact that m_t, m_W, m_H are linked at loop level to constrain the SM
  - **The Higgs/symmetry breaking sector can be explored with more insights coming from top physics**

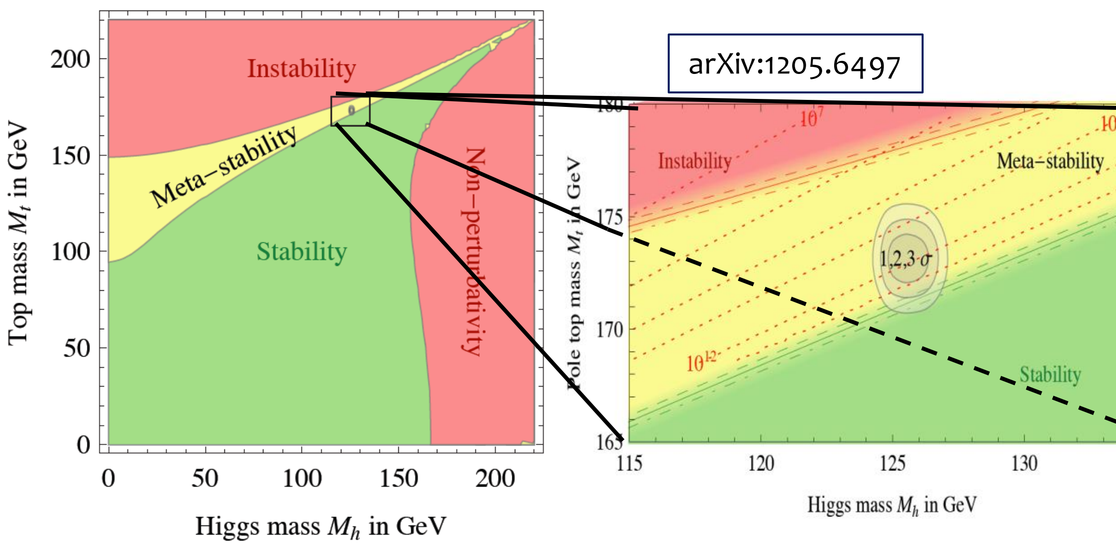


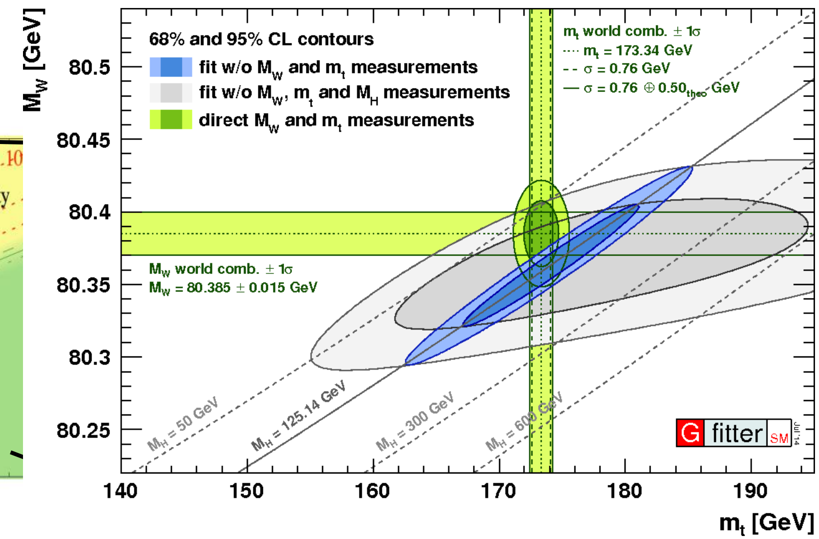
$\propto m_t^2$ $\propto \ln(m_H)$

$$m_W = m_W(m_t^2, \log(m_H))$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij}\, \psi_L^{\ i}\, \psi_R^{\ j}\, \phi$$

λ now known at NNLO QCD. Vacuum meta-stability when the minimum of $V(\Phi)$ is just local





- The top quark also provide other direct constraints to the model
  - Direct access to parameters of the SM (m_t, V_{tb})
  - Other stringent tests of SM (QCD in $d\sigma/dX$, couplings, CPT invariance,…)