Top Quark Properties

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Štrbské Pleso, Slovakia

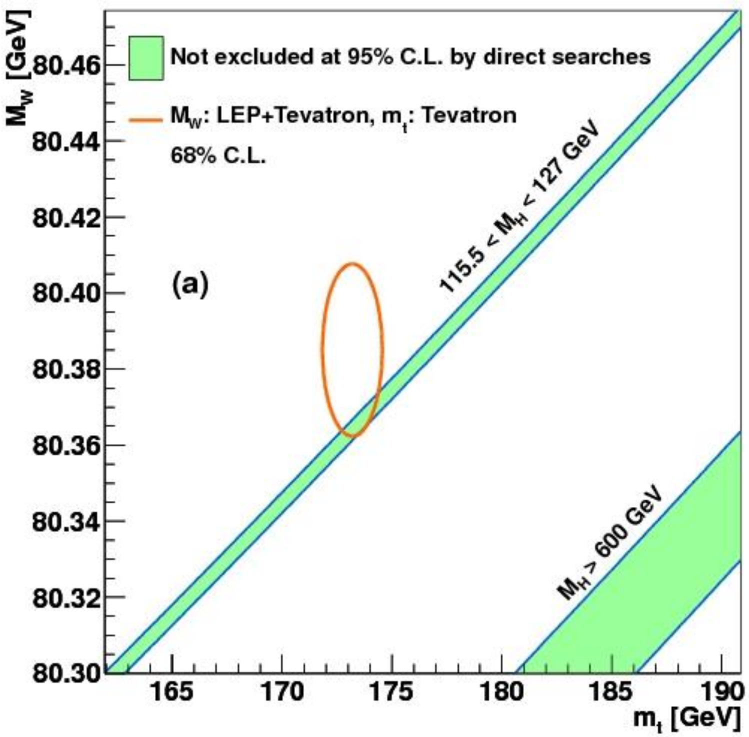
Outline

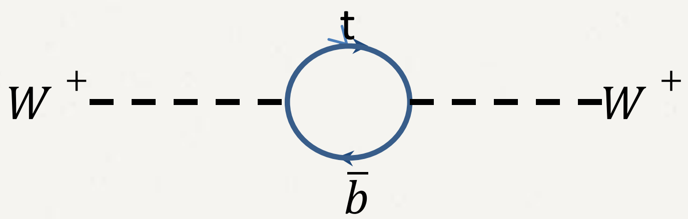
- Top Quark Mass
  - M_t
  - $M_t - M_{\bar{t}}$ mass *difference*
- Top Quark Width
- Top Quark Couplings
  - $t\bar{t}\gamma, t\bar{t}V$ cross section
  - W Helicity
  - Flavor-Changing Neutral Currents
- Spin Correlation

The Mass

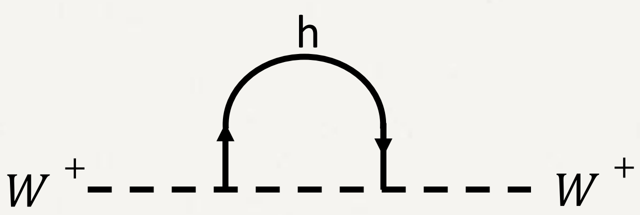
- The top quark plays an important role in electroweak radiative corrections, which are sensitive to its mass. The top quark mass becomes an important precision probe for physics beyond the SM.

arXiv:1207.1069



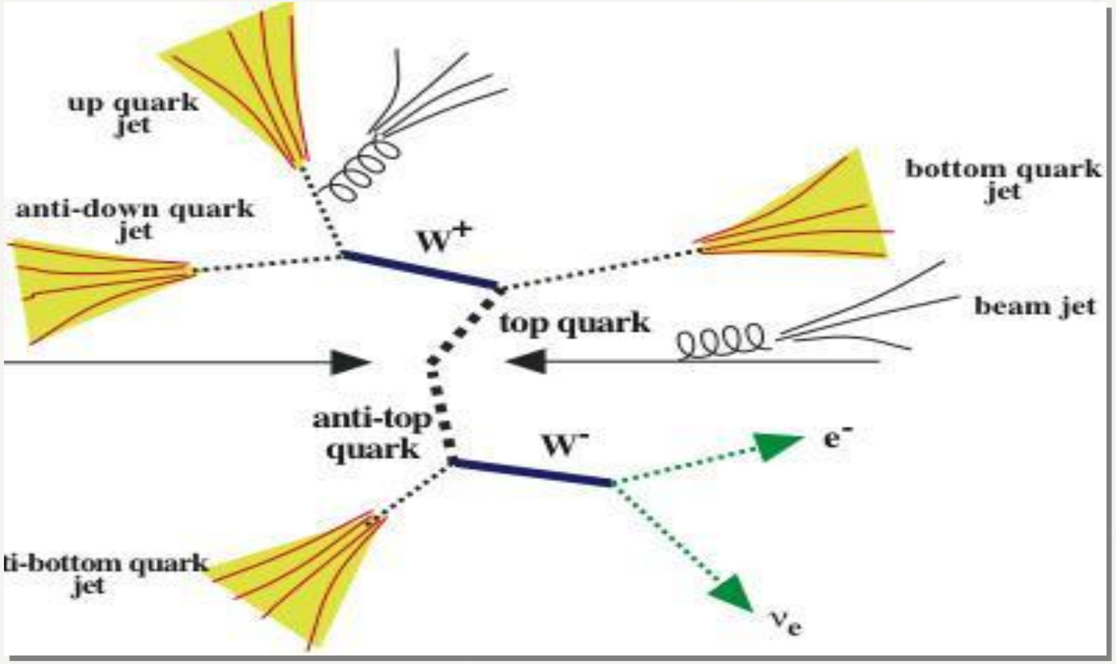


quadratic dependence on m_t



logarithmic dependence on m_h

Mass Reconstruction



Challenges are to:

a)Properly associate measured objects to initial state quarks and leptons (including neutrino(s)).

b)Extract best possible four-vector for each (resolution). Jet energy scale (JES) uncertainty is most important.

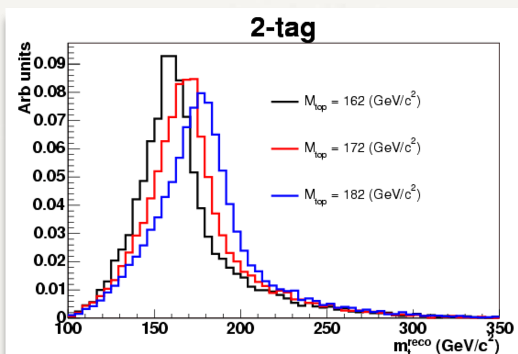
M_t in lepton+jets -

Minimize χ^2 for jet-parton assignment:

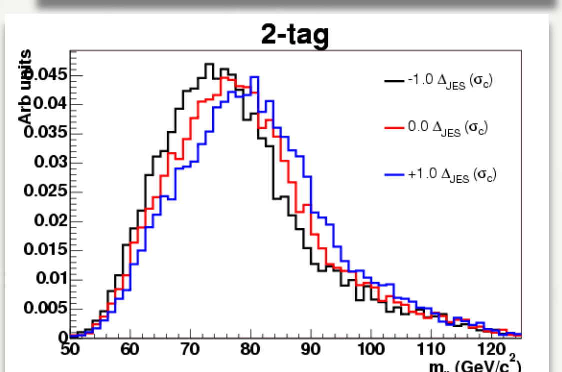
$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit}-p_T^{i,meas})^2}{\sigma_i^2}+\Sigma_{j=x,y}\frac{(U_j^{fit}-U_j^{meas})^2}{\sigma_j^2} + \frac{(M_{jj}-M_W)^2}{\Gamma_W^2}+\frac{(M_{\ell\nu}-M_W)^2}{\Gamma_W^2}+\frac{(M_{bjj}-m_t^{\mathrm{reco}})^2}{\Gamma_t^2}+\frac{(M_{b\ell\nu}-m_t^{\mathrm{reco}})^2}{\Gamma_t^2}$$

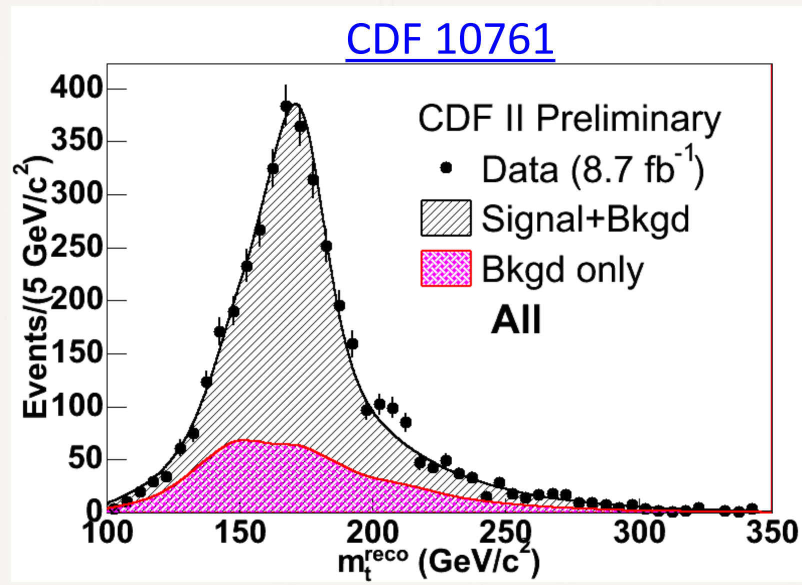
Measurement resolution terms

Distribution of $m_t{}^{reco}$ fit with MC templates:



Constrain jet E scale with simultaneous fit to M_{jj}:





M_t =172.9±0.7 (JES+stat) ± 0.8 (syst) GeV

M_t in dileptons – DØ

Under constrained system due to two neutrinos. Needs additional constraints to solve.

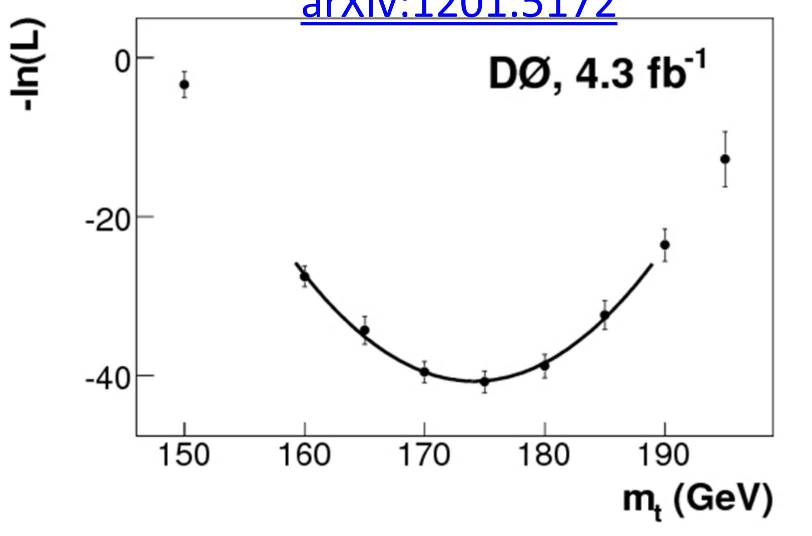
Neutrino weighting

Impose constraints:

$$m(\ell_1\nu_1) = m(\ell_2\nu_2) = m_W$$
$$m(\ell_1\nu_1 b_1) = m(\ell_2\nu_2 b_2)$$

- Integrate of η of both neutrinos
- Calculate neutrino momenta at each (η_1,η_2)
- Compare measured missing E_T with missing E_T calculated from neutrino momenta
- Weight according to likelihood of calculated missing E_T $\rightarrow$ measured missing E_T

arXiv:1201.5172

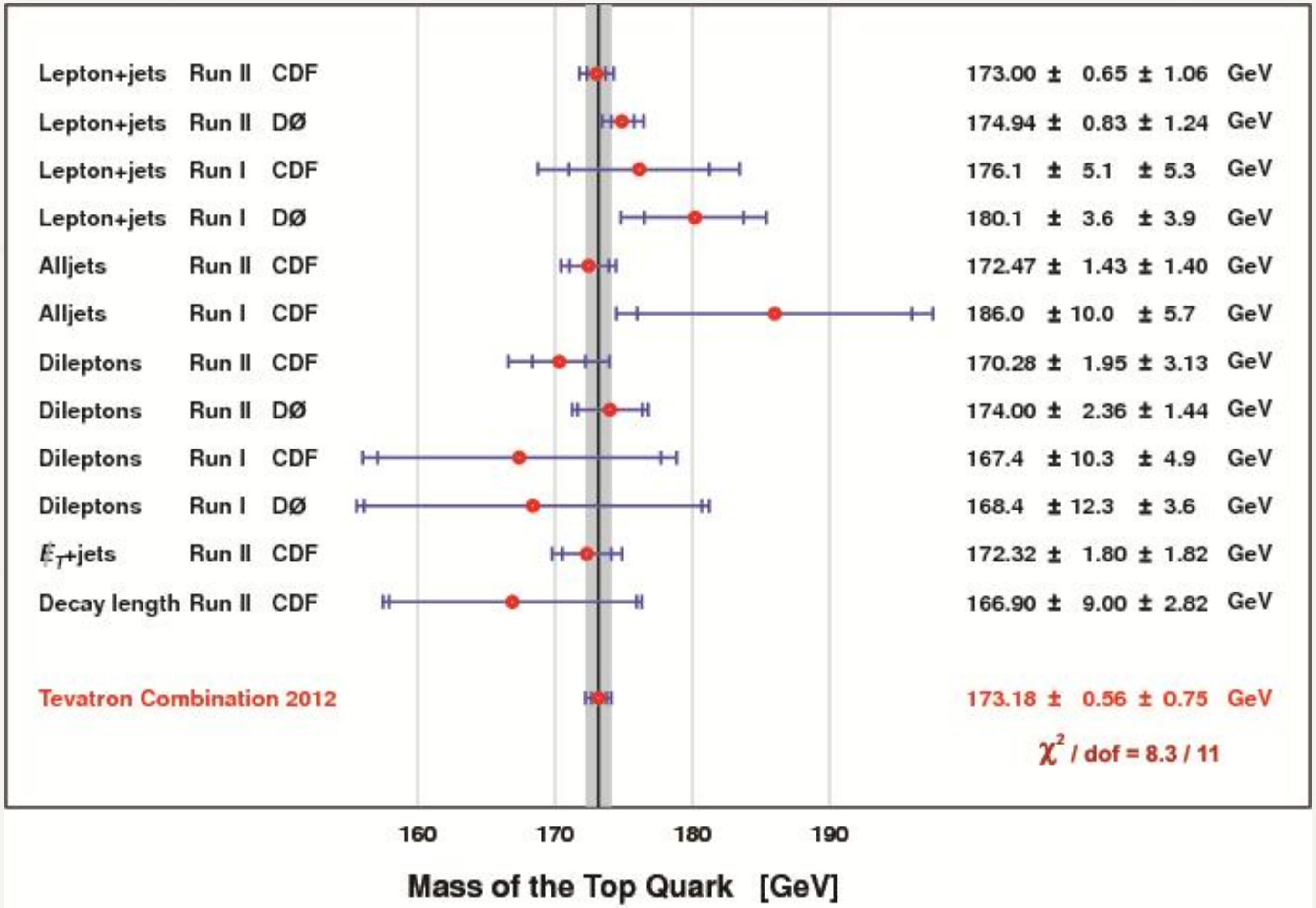


Max likelihood template fit to weight distribution.

$M_t = 174.0 \pm 2.4$ (stat) $\pm$ 1.4 (syst) GeV

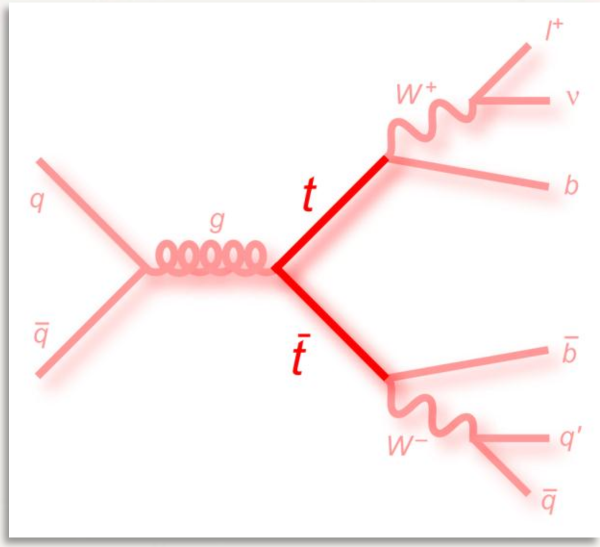
Tevatron Combination

arXiv:1207.1069



$$M_t = 173.18 \pm 0.56 \text{ (stat)} \pm 0.75 \text{ (syst) GeV}$$

Top Mass @ LHC



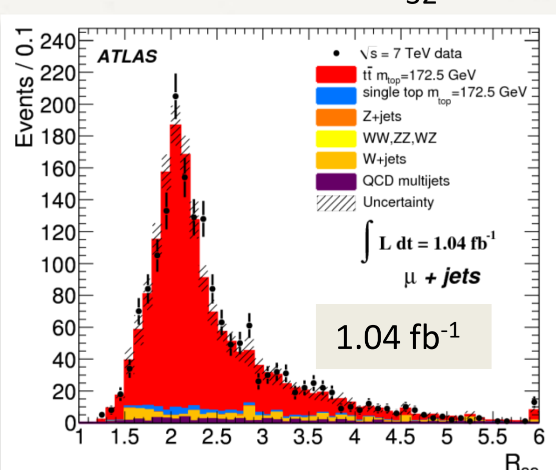
ATLAS 1-D: Measure

$$R_{32} = \frac{M(qqb)}{M(qq)}$$

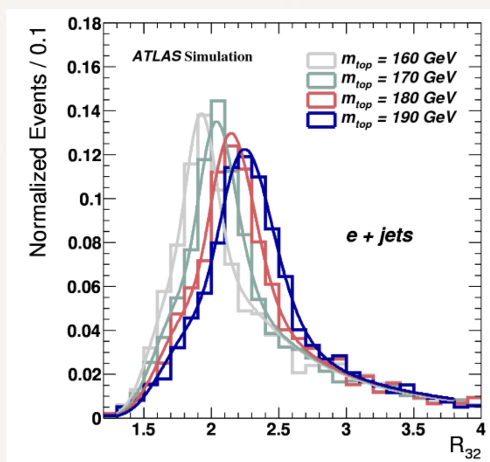
[arXiv:1203.5755](https://arxiv.org/abs/1203.5755)

Uses just the hadronic side – constrains JES with M(qq)~M_W

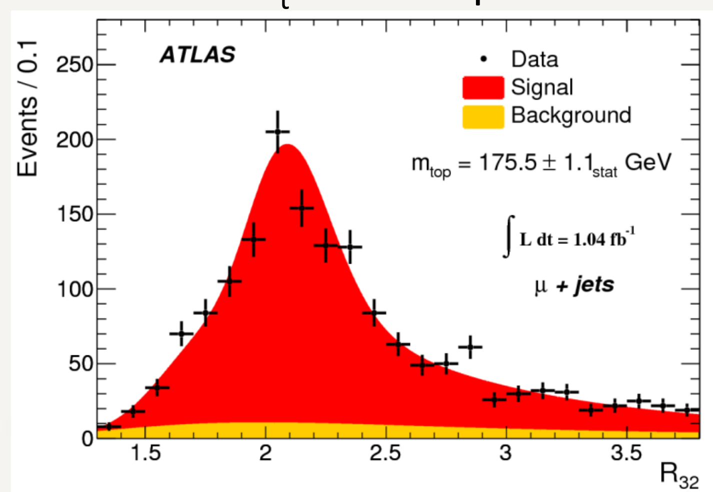
Reconstructed R_{32}



Simulated R_{32} templates for various M_t



Extract M_t with template fit



$$m_t = 174.4 \pm 0.9 \pm 2.5 \text{ GeV } (e+\mu)$$

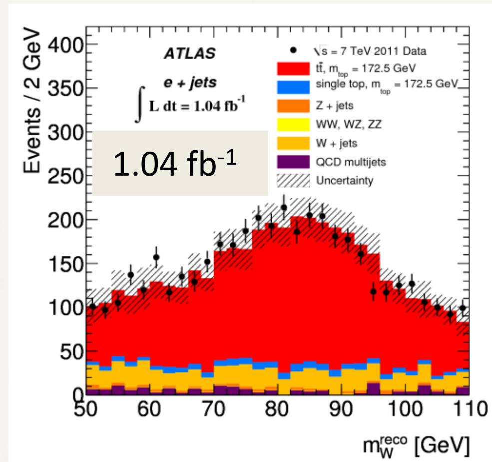
Top Mass @ LHC - 2

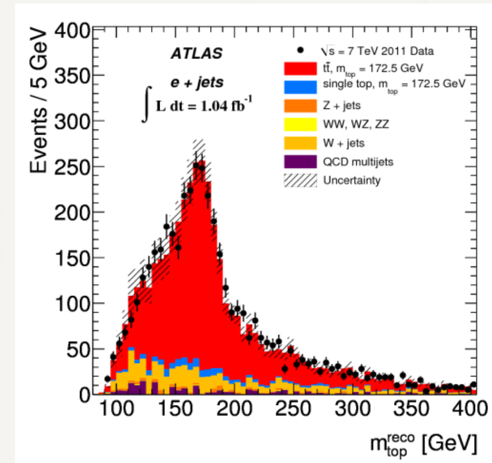
2D method: Measure M_{qq} and M_{qqb} simultaneously

ATLAS: Template fit to *best* assignment

$$m_t = 174.5 \pm 0.6 \pm 2.3 \text{ GeV } (e+\mu)$$

arXiv:1203.5755

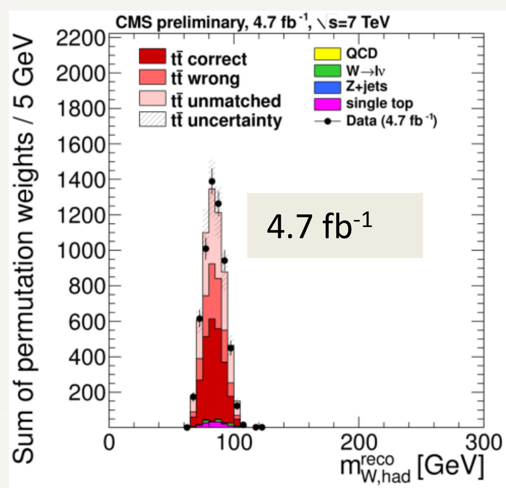


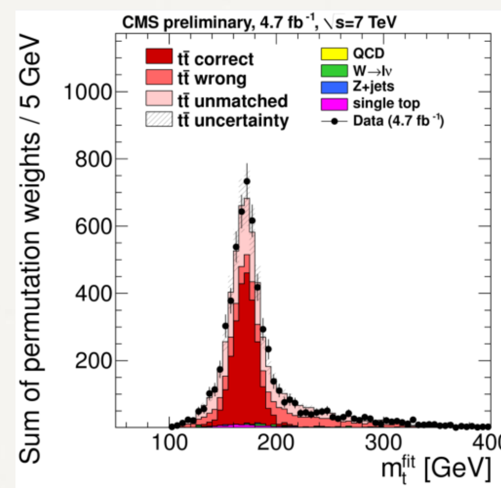


CMS: Use *all* jet-parton pairings, weight by probability (from MC) of pairing being correct (Ideogram method)

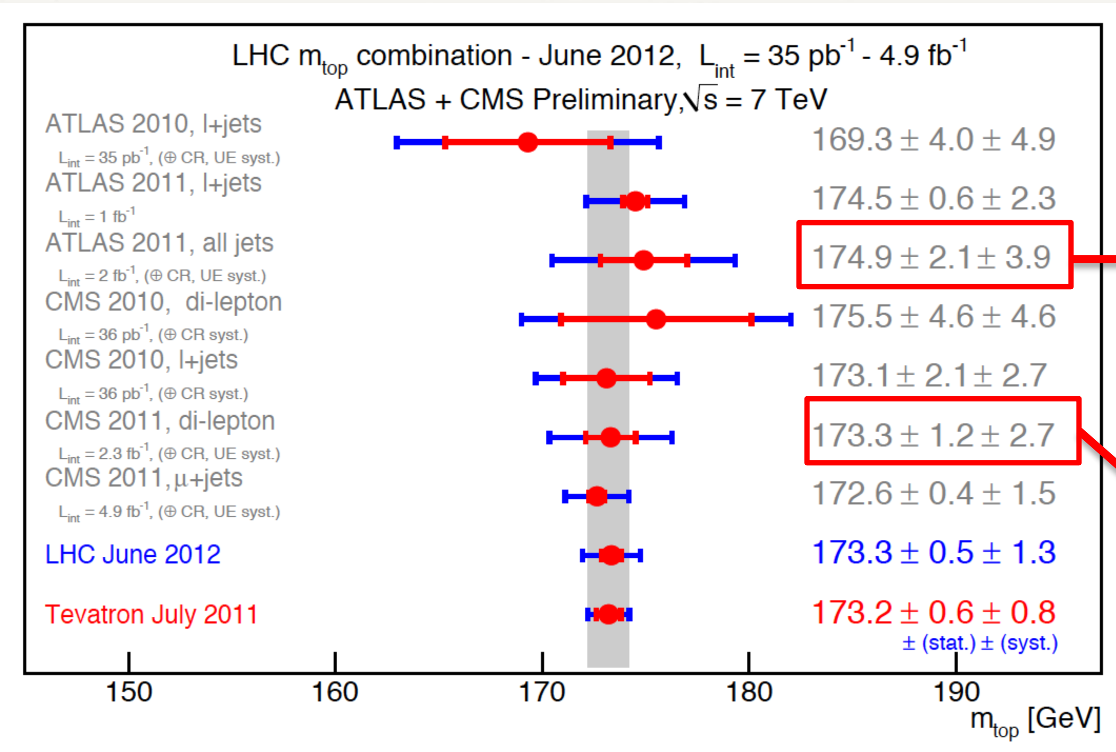
$$m_t = 172.6 \pm 0.6 \pm 1.2 \text{ GeV}$$

CMS PAS TOP-11-015

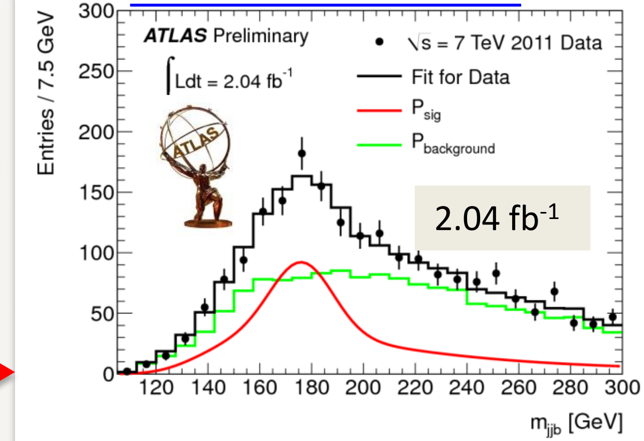


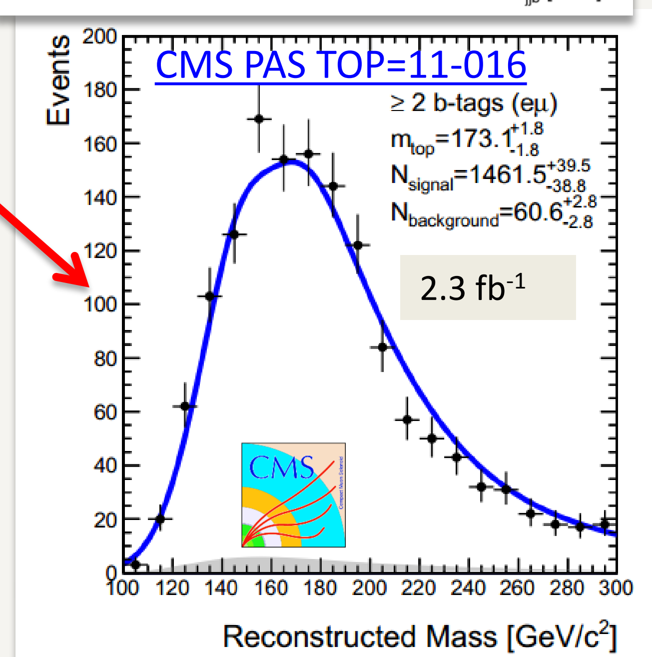


Top Mass LHC



[ATLAS-CONF-2011-030]





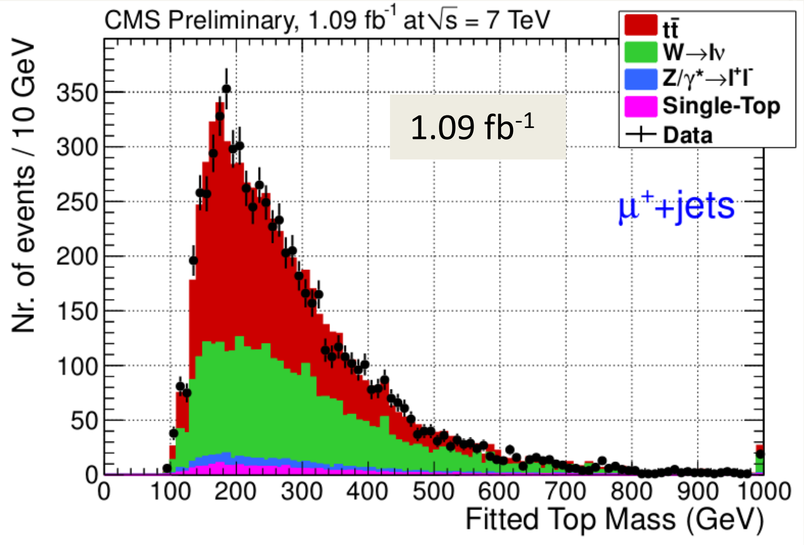
[CMS PAS TOP-12-001]

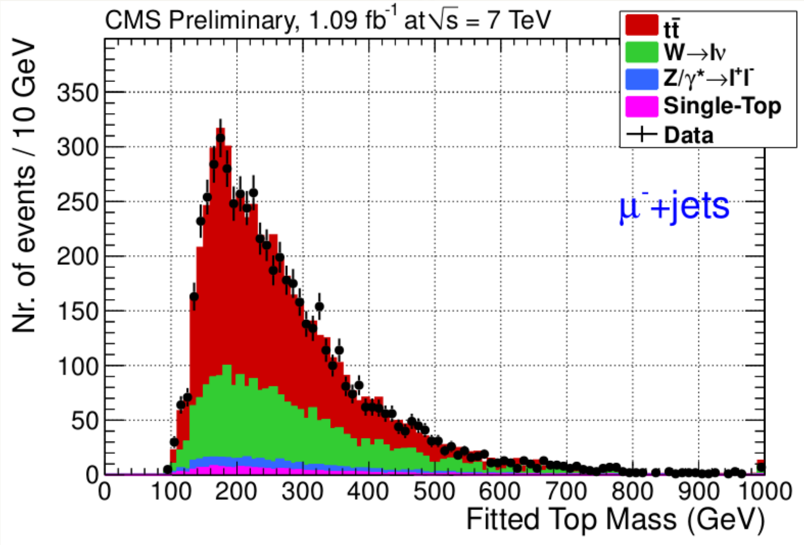
[ATLAS-CONF-2012-095]

$M_t - M_{\bar{t}}$

If CPT is a good symmetry of nature, then $\Delta M_t = M_t - M_{\bar{t}} = 0$

arXiv:1204.2807



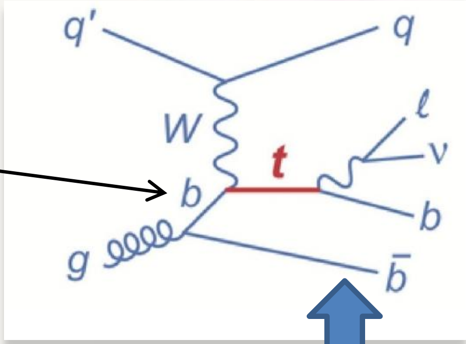


$$\Delta M_t = -0.44 \pm 0.46 \text{ (stat)} \pm 0.27 \text{ (syst) GeV}$$

Top Quark Width & V_{tb}

PRD 85, 091104 (2012)

Wtb vertex $\propto \Gamma(t \longrightarrow Wb)$



Inputs:

$$\sigma\left(p\bar{p} \to tqb + X\right) = 2.90 \pm 0.59 \text{ pb}$$

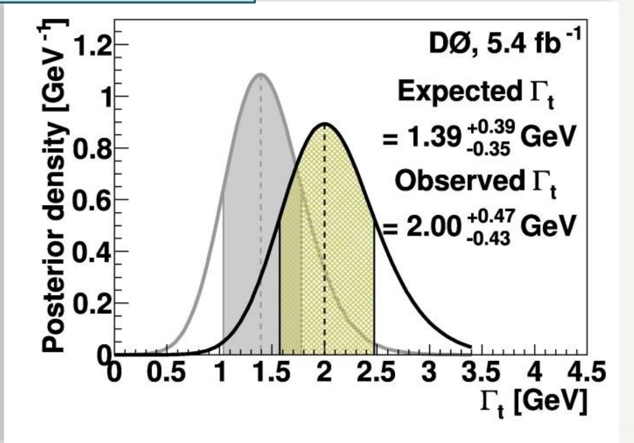
$$\text{R} = B\left(t \to Wb\right) / B\left(t \to Wq\right) = 0.90 \pm 0.04$$

Measured in $t\bar{t}$ events

$$\Gamma\left(t \to Wb\right) = \frac{\sigma_{\text{meas}}\left(t\text{-chan}\right)}{\sigma_{\text{SM}}\left(t\text{-chan}\right)} \Gamma\left(t \to Wb\right)_{\text{SM}} \qquad \Gamma_{\text{total}} = \frac{\Gamma\left(t \to Wb\right)}{B\left(t \to Wb\right)}$$

$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV} \quad \Rightarrow \quad \tau_t = \left(3.29^{+0.90}_{-0.63}\right) \times 10^{-25} \text{ s}$$

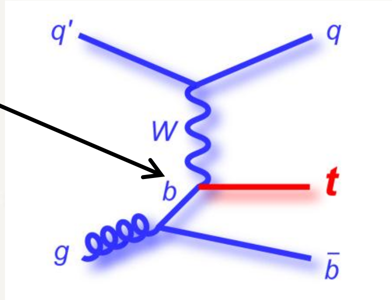
$$0.81 < \left|V_{tb}\right| < 1 \text{ @95\% C.L.}$$



V_{tb} from Single Top

Single-top cross section is $\propto V_{tb}$

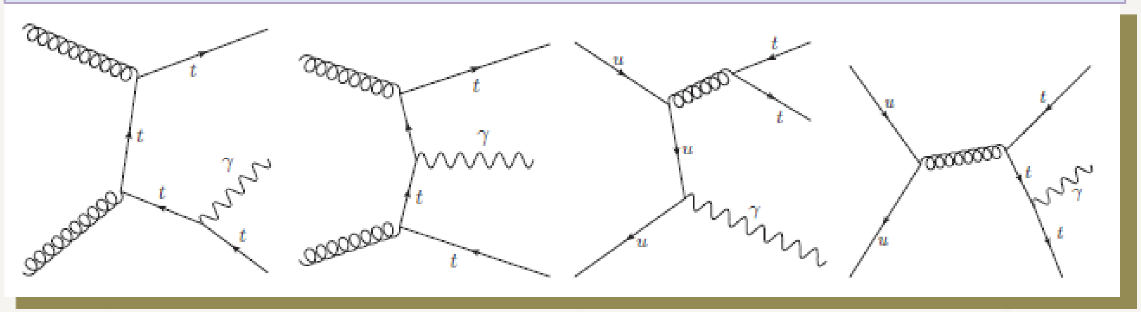
$$\left|V_{tb,\text{meas}}\right|^2 = \frac{\sigma^{1t}_{\text{measured}}}{\sigma^{1t}_{\text{theory}}}\left|V_{tb,\text{SM}}\right|^2$$



		$\left\|V_{tb}\right\|$
ATLAS (1.04 fb^{-1})	arXiv:1205.3130	$1.13^{+0.14}_{-0.13}$
CMS (1.1-1.5 fb^{-1})	CMS-PAS-TOP-11-021	$1.04 \pm 0.09(\text{exp}) \pm 0.02(\text{th})$
CDF (7.5 fb^{-1})	CDF 10793	$0.96 \pm 0.09(\text{exp}) \pm 0.05(\text{th})$
CDF+D0 (3.2, 2.3 fb^{-1})	Fermilab-TM-2440-E	0.88 ± 0.07

$t\bar{t}\gamma$

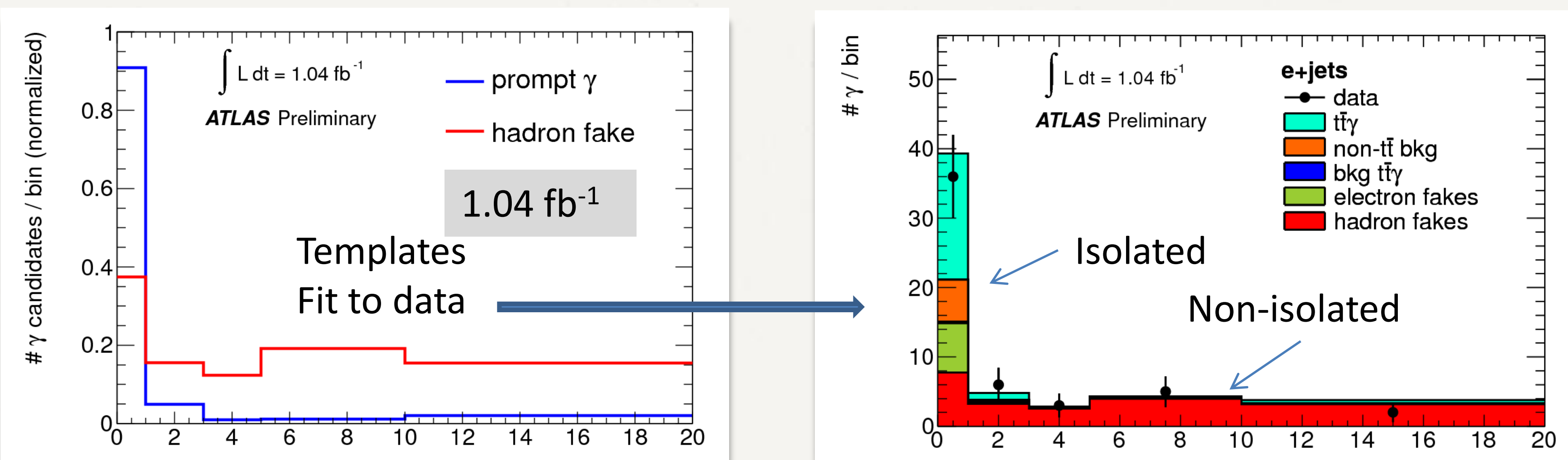
Probe EWK couplings of the top quark



Sensitive to Q_{top} (Q_{top} also directly measured at Tevatron & LHC).

$P_T^{\gamma} > 8$ GeV

SM: 2.1±0.4 pb

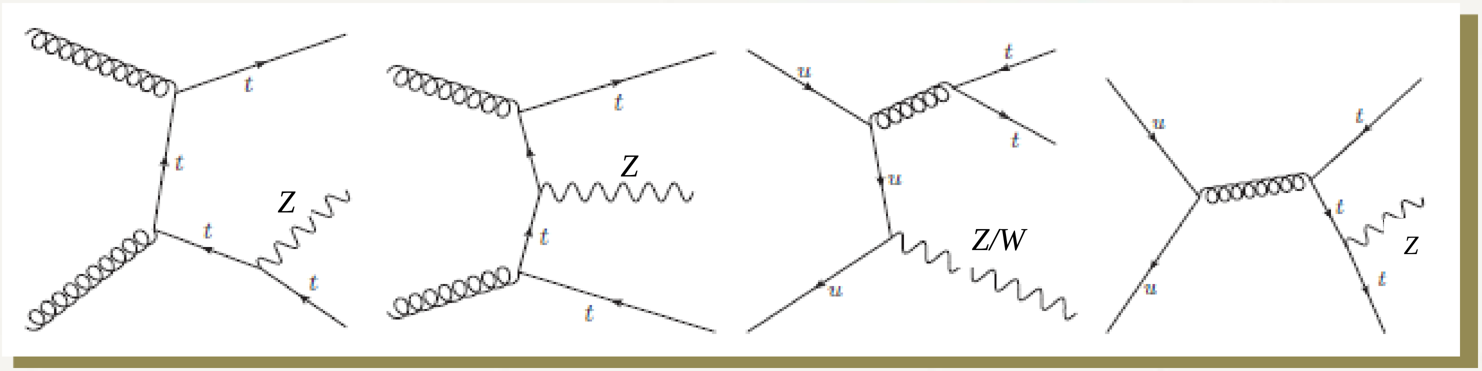


ATLAS-CONF-2010-153

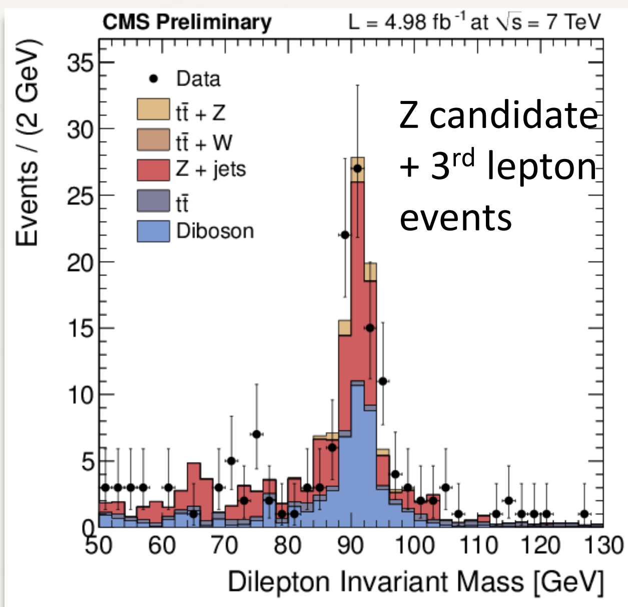
$\sigma_{tt\gamma}$* BR = 2.0±0.5 (stat) ±0.7 (syst) ± 0.8 (lumi) pb

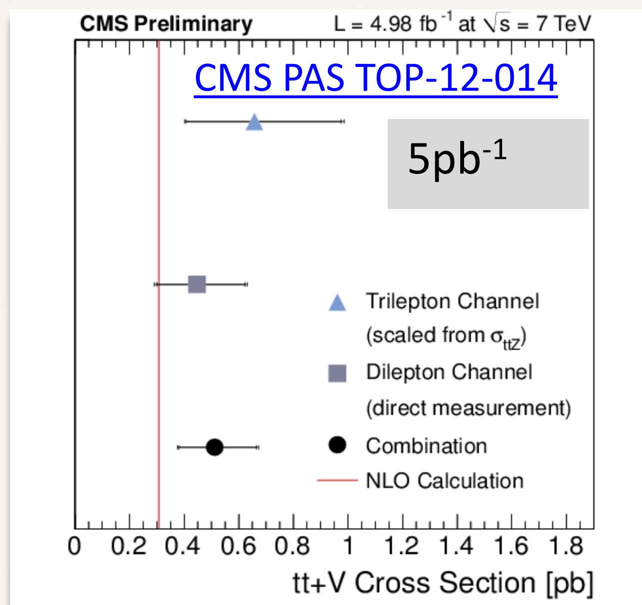
See also P. Federic ATLAS Q_{top} Poster!

$t\bar{t}V$



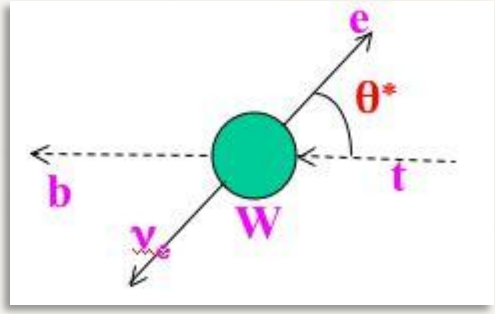
CMS: Trileptons ($t\bar{t}Z$) Same-sign dileptons ($t\bar{t}Z$ and ($t\bar{t}W$))



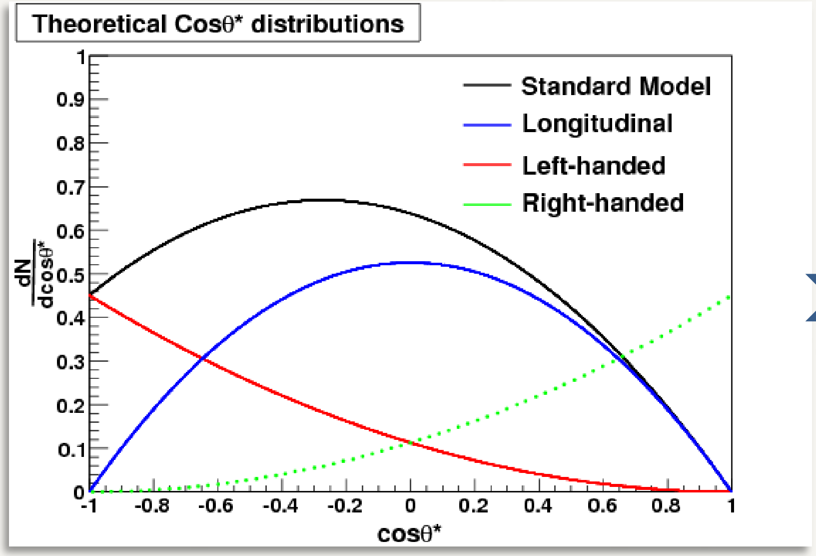


ATLAS 4.7 fb^{-1}: $\sigma(t\bar{t}Z) < 0.71$pb

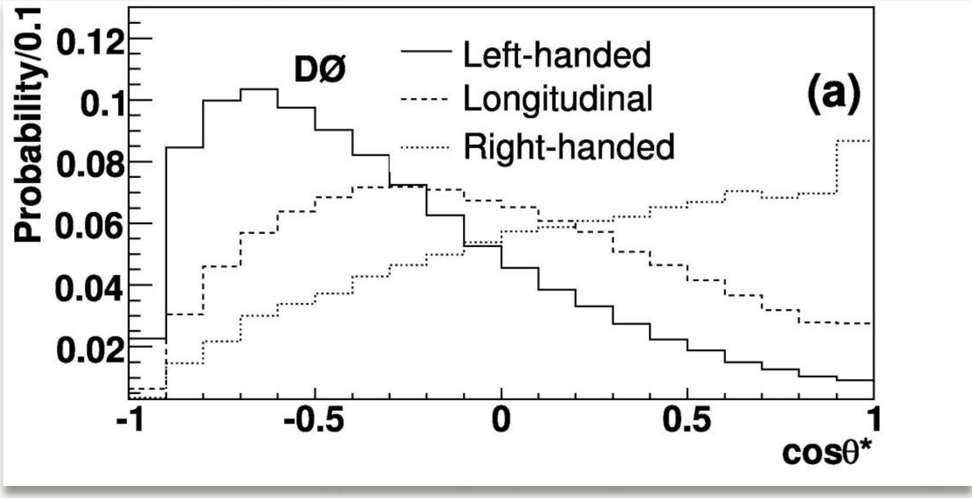
W Helicity



IDEAL



RECONSTRUCTED



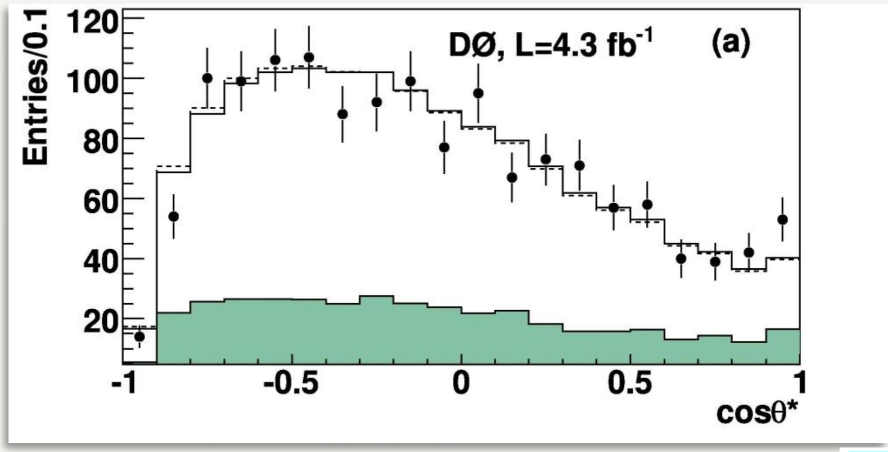
$(1/\Gamma)\ (d\Gamma/d\cos\theta^*) = f_-\ (3/8)\ (1-\cos\theta^*)^2 + f_0\ (3/4)\ (1 - \cos\theta^{*2}) + f_+\ (3/8)\ (1 + \cos\theta^*)^2$

Left-handed, longitudinal, right-handed fractions

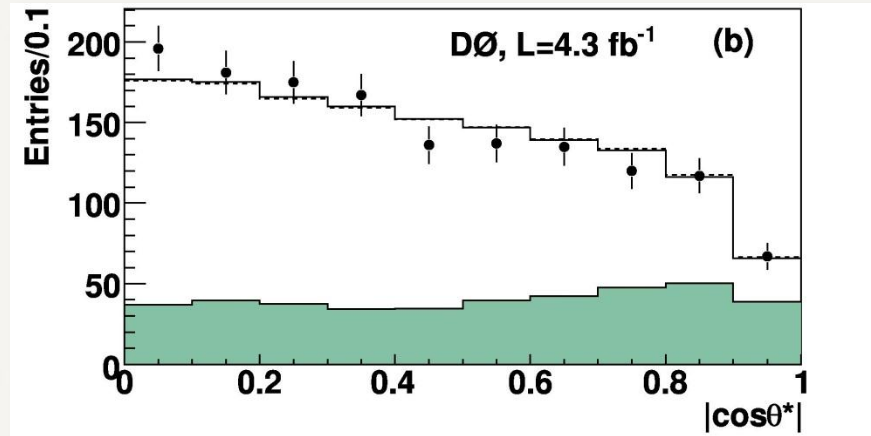
W Helicity – D0

Template method

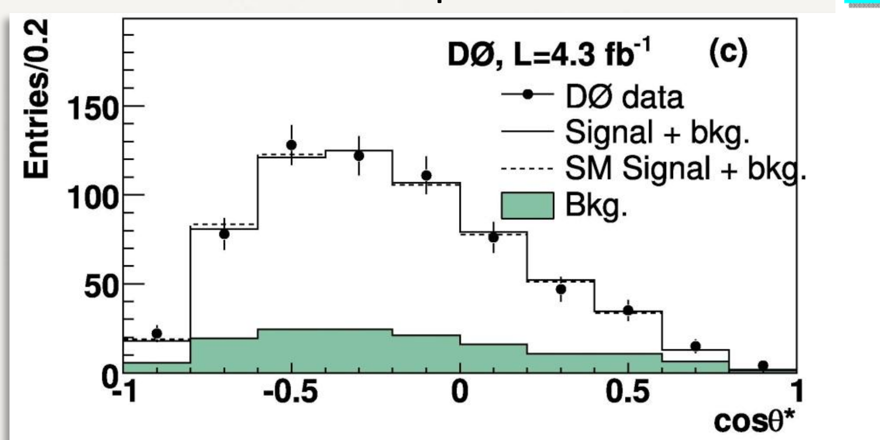
Leptonic W decay



Hadronic W decay



Dileptons



PRD **83**, 032009 (2011)

$$f_0 = 0.669 \pm 0.078(\text{stat}) \pm 0.065(\text{syst})$$

$$f_+ = 0.023 \pm 0.041(\text{stat}) \pm 0.034(\text{syst})$$

W Helicity - CDF

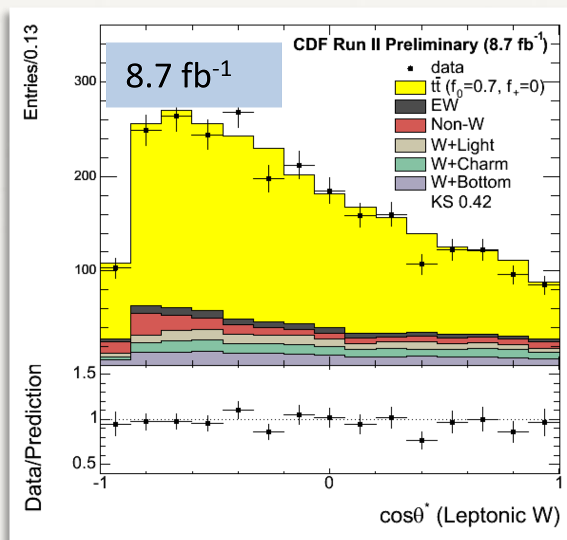
Matrix element likelihood

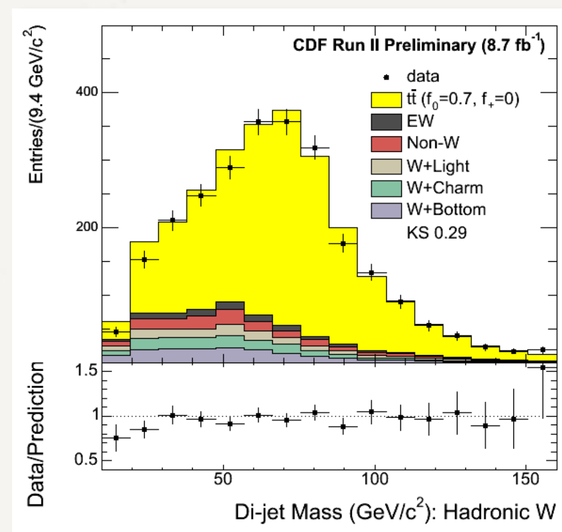
$$\wp(x; f_0, f_+) = \frac{1}{\sigma_{\text{obs}}} \int d\sigma(y, f_0, f_+)\, f_{\text{PDF}}(q_1) f_{\text{PDF}}(q_2) W(x, y)\, dq_1 dq_2$$

$$\wp_{\text{evt}}(x; c_s, f_0, f_+) = c_s \wp_{t\bar{t}}(x; f_0, f_+)/A_s(x; f_0, f_+) + (1 - c_s)\wp_{\text{bkg}}(x)/A_b(x)$$

A_s and A_b are signal and background acceptance terms

$$L(x; c_s, f_0, f_+) = \prod_{\text{events}} \wp_{\text{evt}}(x; c_s, f_0, f_+)$$





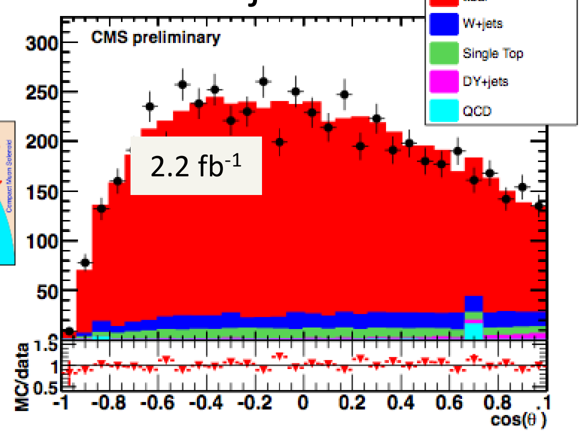
CDF 10855

f_0 = 0.726 ± 0.066 (stat) ± 0.067 (syst)
f_+ = – 0.045 ± 0.043 (stat) ± 0.058 (syst)

W Helicity - CMS & ATLAS

Template Method

CMS: l+jets

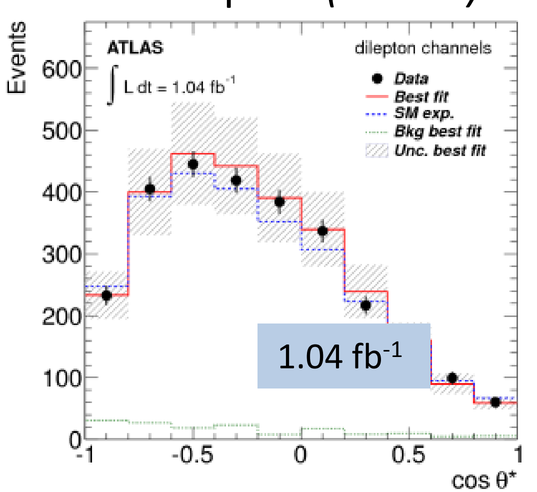


$$F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$$
$$F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.}),$$

CMS PAS TOP-11-020

ATLAS: l+jets

and dilepton *(shown)*

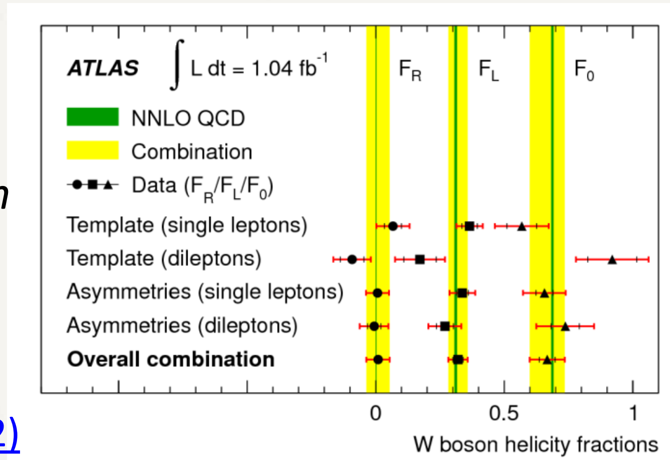


$$F_0 = 0.67 \pm 0.03\ (\text{stat.}) \pm 0.06\ (\text{syst.})\,,$$
$$F_L = 0.32 \pm 0.02\ (\text{stat.}) \pm 0.03\ (\text{syst.})\,,$$
$$F_R = 0.01 \pm 0.01\ (\text{stat.}) \pm 0.04\ (\text{syst.})\,.$$

Combine

l+jets and dilepton

JHEP **1206**, 088 (2012)



Limits on Wtb Anomalous Couplings

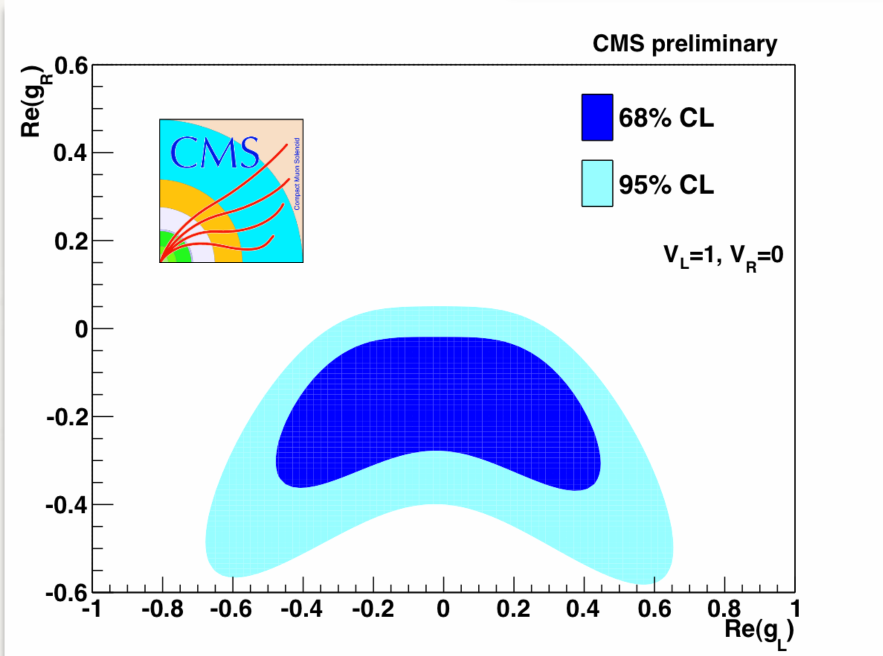
$$L_{Wtb} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L\left(1-\gamma^5\right)+V_R\left(1+\gamma^5\right)\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L\left(1-\gamma^5\right)+g_R\left(1+\gamma^5\right)\right)tW_{\mu}^{-} + h.c.$$

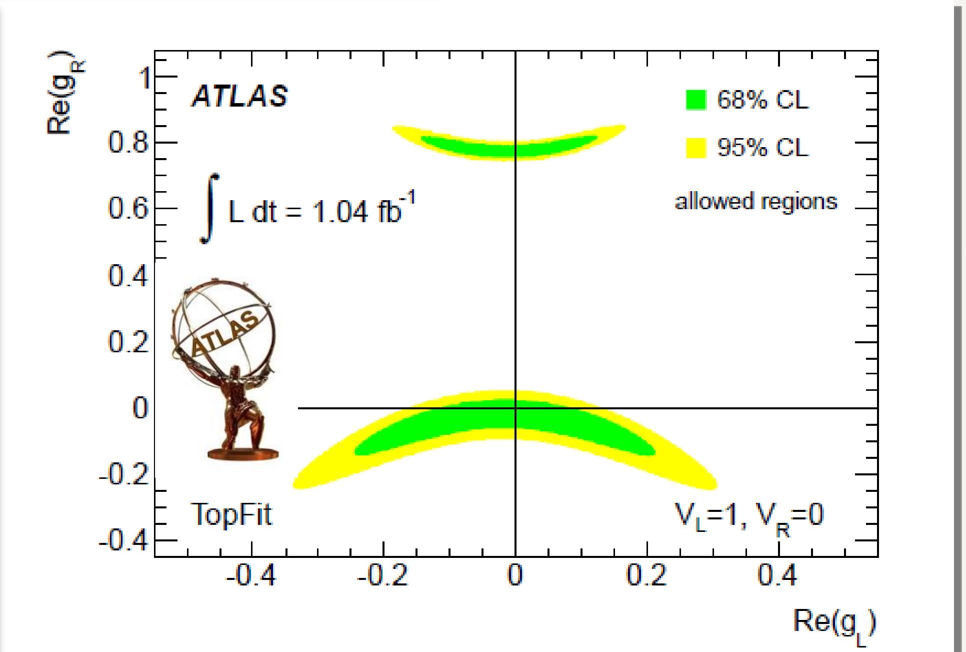
All zero in SM at tree-level

CMS PAS TOP-11-020

Limits on g_R and g_L for V_R=0

JHEP **1206**, 088 (2012)

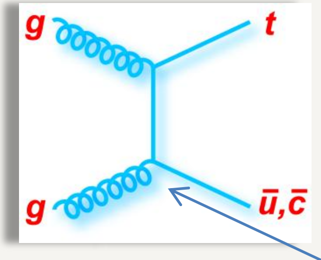


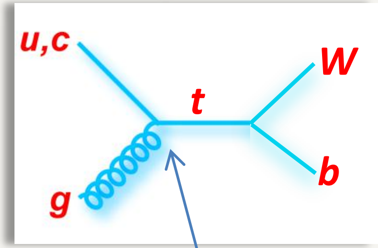


Flavor-Changing Neutral Currents

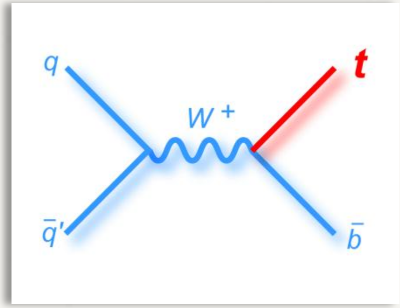
SM has no FCNC couplings at tree-level, and GIM mechanism causes almost perfect cancelation of FCNC at higher-order *if* quarks come in pairs (that's why bottom required top). Many BSM models include FCNC at ~few x 10^{-4} level.

The most sensitive tests in the top sector come from single-top production:



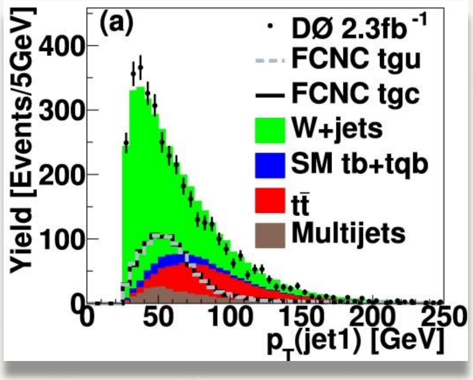


Subtle difference from SM production:



Only sensitive to tgq coupling

But kinematics are different:



Neural networks used for S/B discrimination

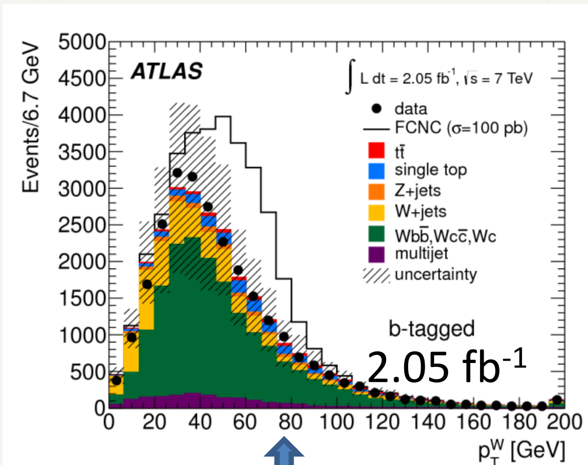
FCNC Limits – Single Top

PLB **712**, 351 (2012)

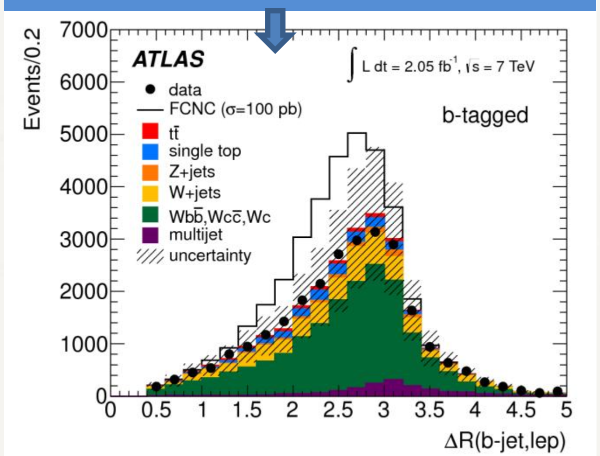
First limits from D0 and CDF:

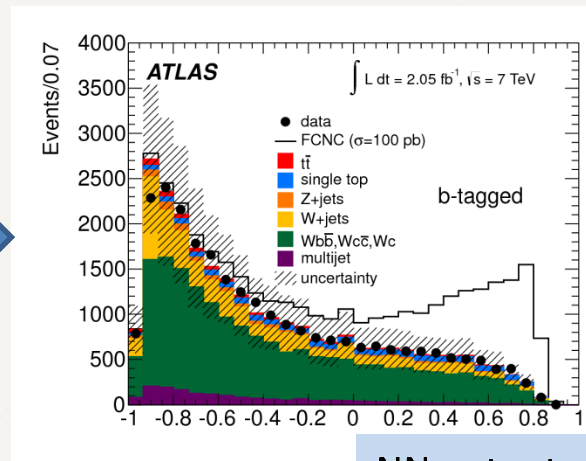
$$B(t \to gu) < 2\times10^{-4} \quad B(t \to gc) < 3.9\times10^{-3} \text{ (D0)}$$

$$\frac{\kappa_{tgu}}{\Lambda} < 0.025 \text{ TeV} \quad \frac{\kappa_{tgc}}{\Lambda} < 0.105 \text{ TeV (CDF)}$$

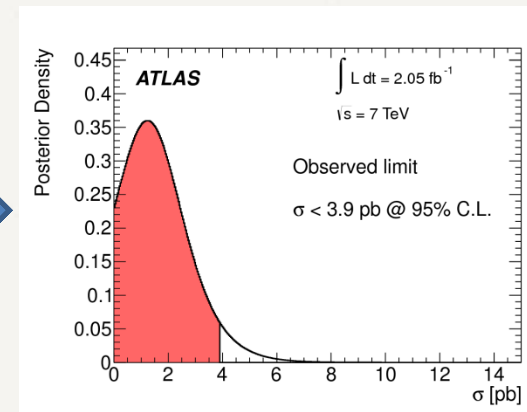


NN inputs (example)





NN output



$\sigma < 3.9$ pb →

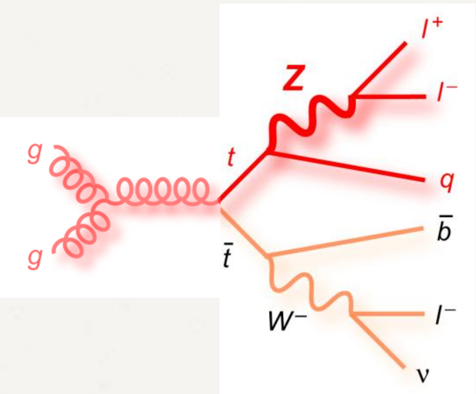
$B(t \to ug) < 5.7 \cdot 10^{-5}$

$B(t \to cg) < 2.7 \cdot 10^{-4}$

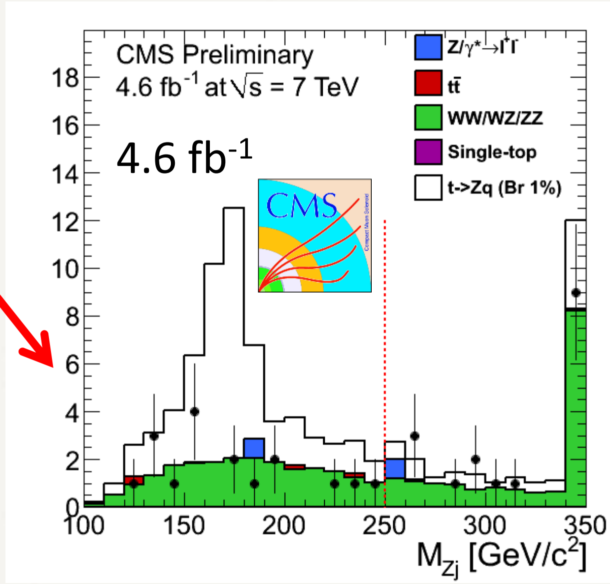
FCNC - t→Zq

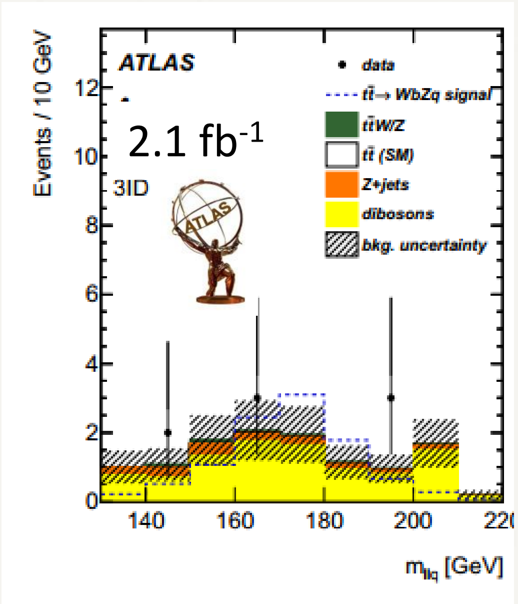
Search for FCNC couplings to Zq through top decay.

Search for $t\bar{t}$→*WbZq* - *One SM decay to Wb, one FCNC decay to Zq*



Tri-lepton signature





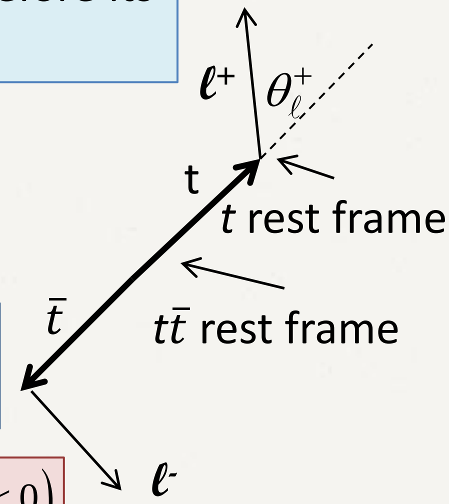
[CMS PAS TOP-11-028]   Z+jet mass=M_t for signal   [arXiv:1206.0257]

Br(t→qZ) < 0.34% at 95% C.L.   Br(t→qZ) < 0.73% at 95% C.L.

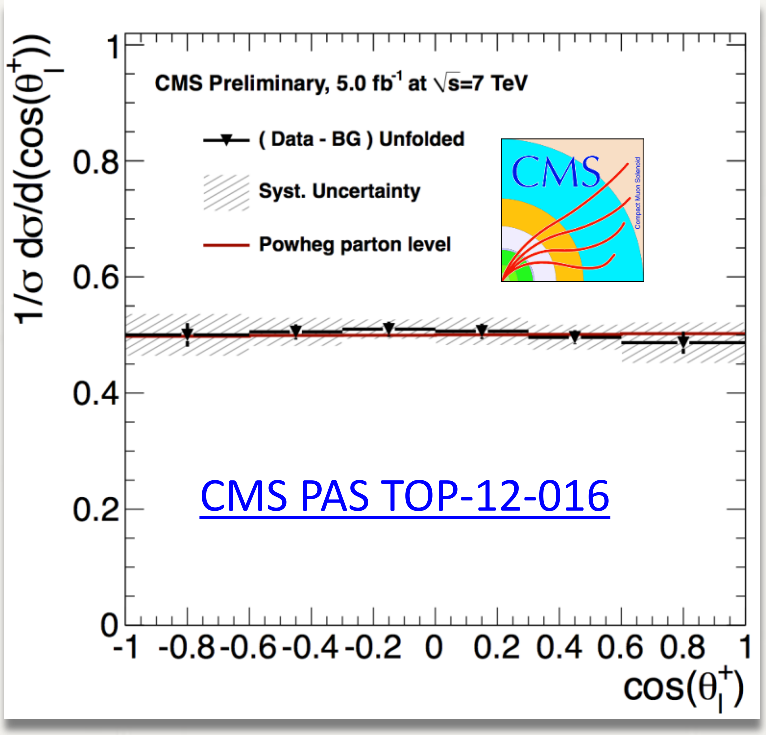
Top quark polarization

Unlike other quarks, top decays before hadronization, and therefore its spin is preserved from production through decay.

$t\bar{t}$ pairs are produced via QCD and the spin is expected to be unpolarized (EWK corrections give a small net polarization).



Unfolded to account for acceptance effects



CMS PAS TOP-12-016

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}\left(1+2P_{\hat{n}}\cos\theta_\ell\right)$$

$$P_n = \frac{N\left(\cos\theta_\ell^+ > 0\right) - N\left(\cos\theta_\ell^+ < 0\right)}{N\left(\cos\theta_\ell^+ > 0\right) + N\left(\cos\theta_\ell^+ < 0\right)}$$

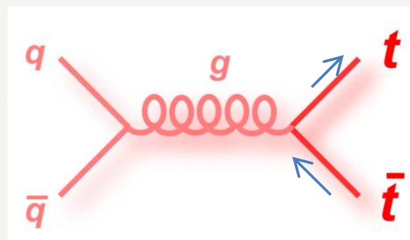
Analytical Matrix Weighting used to reconstruct dilepton system
(L. Sonnenschein PRD **73** 054015 (2006))

$$P_n = -0.009 \pm 0.029 \pm 0.041$$

Spin Correlations

t and $\bar{t}$ may be unpolarized, but their spin directions are *correlated*.

Tevatron (dominant):



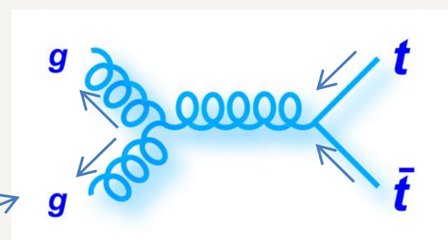
R

L

Opposite helicity (RL or LR)

Low $M_{t\bar{t}}$

Like-helicity gluons



L

L

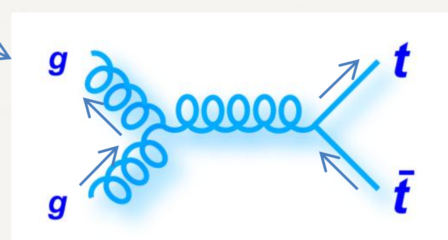
Like helicity (LL or RR)

LHC (dominant):

Mahlon & Parke, PRD 81, 074024 (2010)

High $M_{t\bar{t}}$

Opposite-helicity gluons



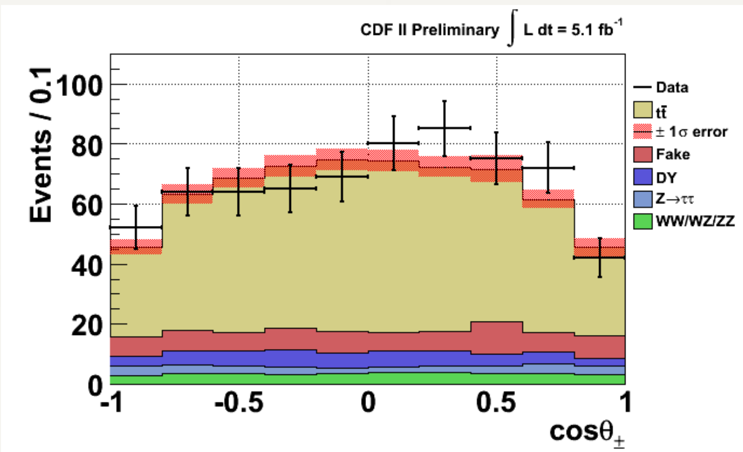
R

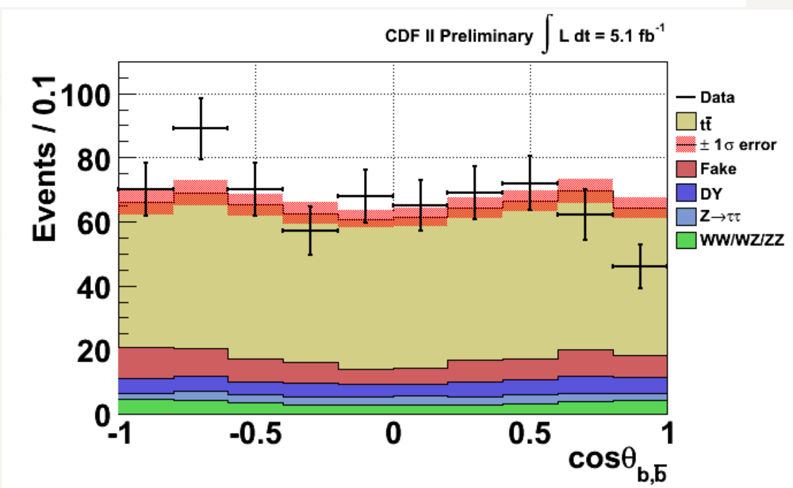
L

Opposite helicity (RL or LR)

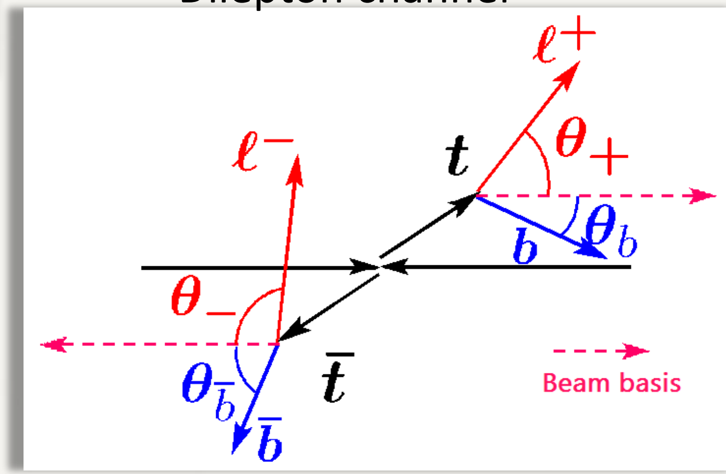
Spin Correlations - CDF

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$





Dilepton channel



$-0.520 < \kappa < 0.605$ (68% C.L.)

OR

$\kappa = 0.042^{+0.563}_{-0.562}$

CDF 10719

Spin Correlations – D0

Matrix element technique in lepton+jets events

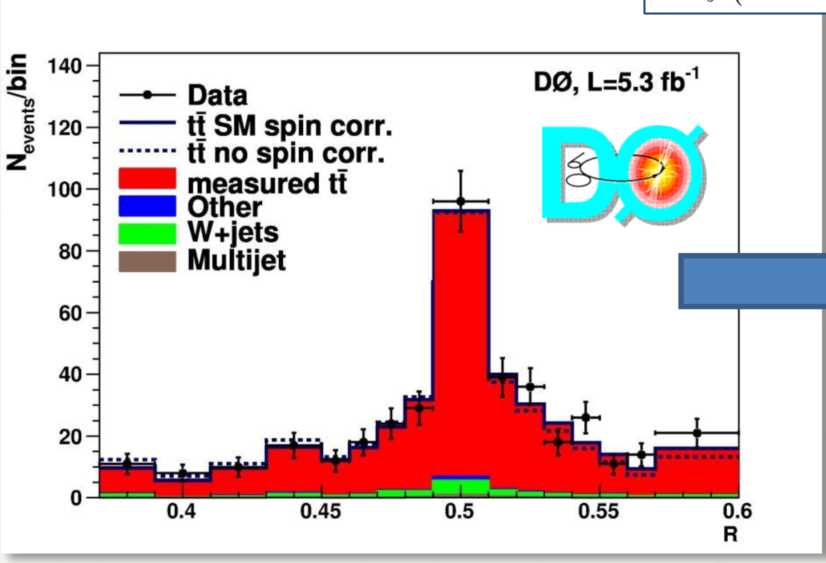
$$\wp(x;H) = \frac{1}{\sigma_{\text{obs}}} \int f_{\text{PDF}}(q_1) f_{\text{PDF}}(q_2)\, dq_1 dq_2 \frac{(2\pi)^4 |M(y,H)|^2}{q_1 q_2 s} W(x,y)\, d\Phi_6$$

$M(y,H)$ is LO matrix element with (H=c) or without (H=u) spin correlations.

Transfer function from partonic y to measured x

Fit R dist. to $f^*R_{corr}+(1-f)^*R_{uncorr}$

$$R = \frac{\wp(x;H=c)}{\wp(x;H=u)+\wp(x;H=c)}$$



Hard to see corr. vs. no corr. Difference. Tough measurement!

$$f = 1.15^{+0.42}_{-0.43}\ (\text{stat+syst})$$

Combined with result in dileptons:

$$f = 0.85 \pm 0.29\ (\text{stat+syst})$$

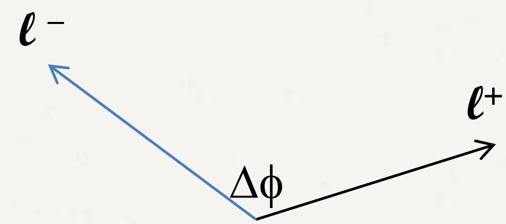
PRL **108**, 032004 (2012)

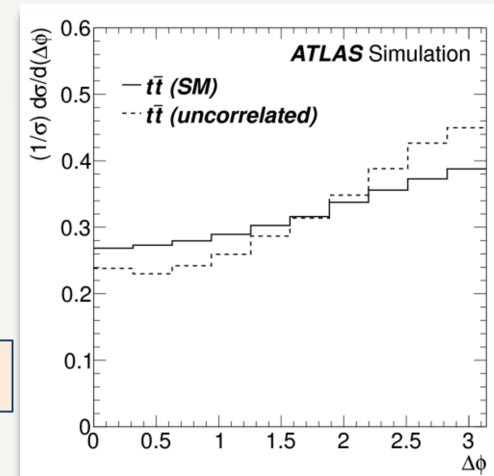
3.1σ evidence for spin correlations

Spin Correlations - ATLAS

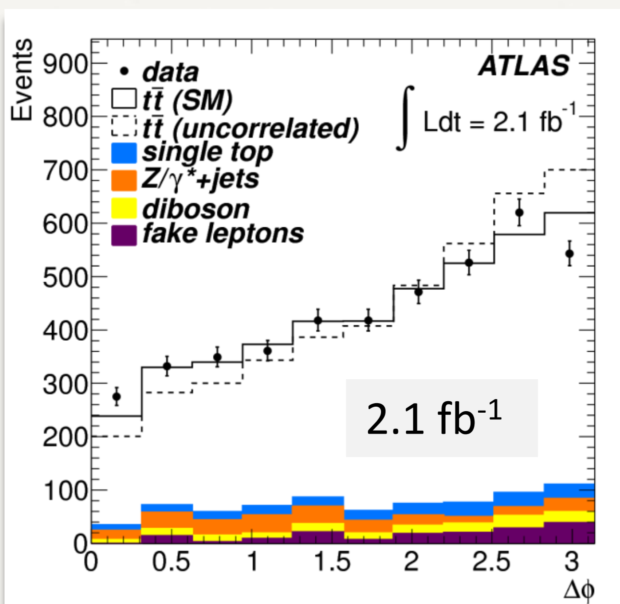
$gg \rightarrow t\bar{t}$ is the dominant production mode at LHC

LL & RR $t\bar{t}$ pairs produce charged leptons with correlated azimuthal angles





Straightforward measurement in dileptons!



Fit $\Delta\phi$ dist. to $f^* \, \Delta\phi_{corr} + (1-f)^* \, \Delta\phi_{uncorr}$

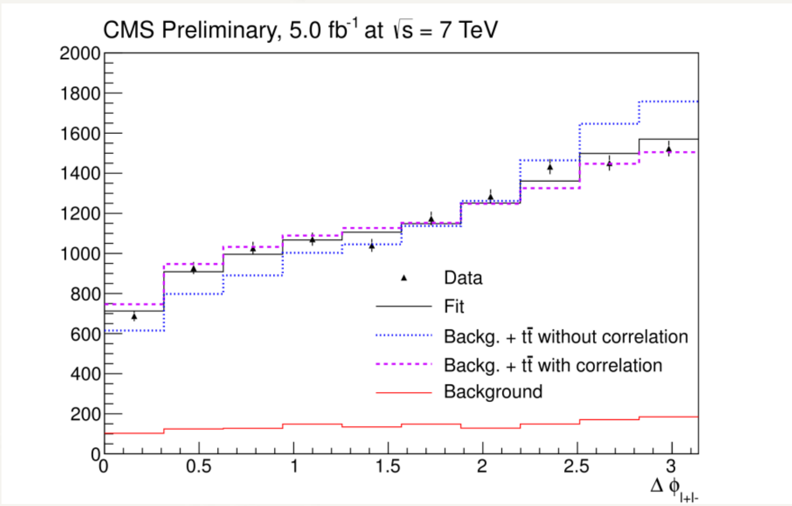
$$f = 1.30 \pm 0.14(\text{stat})\ ^{+0.27}_{-0.22}(\text{syst})$$

f=0 excluded at 5.1σ level.

PRL **108**, 212001 (2012)

Spin Correlations - CMS

Similar analysis to ATLAS, in 5 fb^{-1}



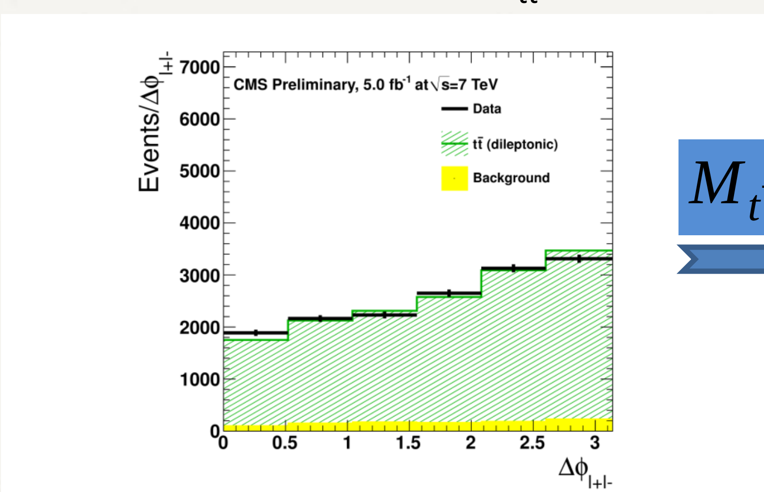
$$f = 0.74 \pm 0.08(\text{stat}) \ \pm 0.24(\text{syst})$$

[CMS PAS TOP-12-004]

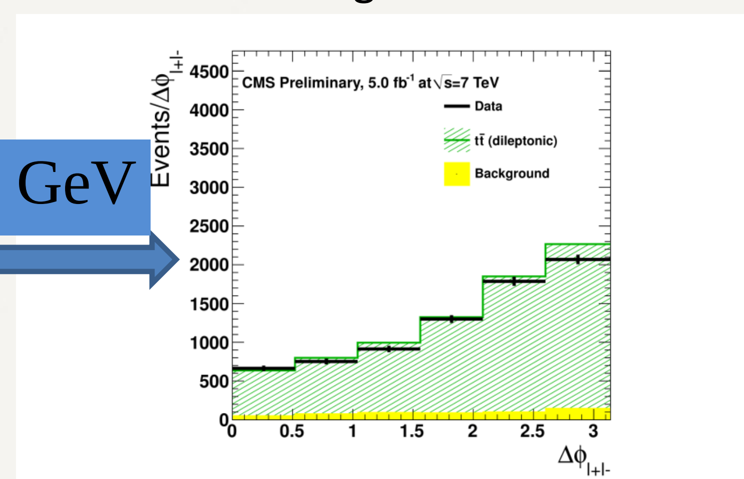
New physics at high M_{tt}?

Signal enhanced w/ M_{tt} cut:

But no sign of PBSM



$$M_{t\bar{t}} > 450 \text{ GeV}$$



Conclusions

- Four experiments are now making relatively precise measurements of top quark properties:
  - Mass
  - Couplings
  - Rare decays
- Tevatron experiments have led the way with many advanced techniques
  - Matrix elements
  - Neural networks
- LHC experiments benefit from the large $t\bar{t}$ and single top cross sections
  - Measurements are already systematics dominated
- So far, all top quark properties are consistent with SM expectations
  - Only the charge asymmetry at the Tevatron stands out as anomalous.

- Stay tuned.